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# 1 **Neo-formation of chromosomes in bacteria**

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13 **ABSTRACT**

14 Although the bacterial secondary chromosomes/megaplasmiids/chromids, first noticed  
15 about forty years ago, are commonly held to originate from stabilized plasmids, their  
16 true nature and definition are yet to be resolved. On the premise that the integration of a  
17 replicon within the cell cycle is key to deciphering its essential nature, we show that the  
18 content in genes involved in the replication, partition and segregation of the replicons  
19 and in the cell cycle discriminates the bacterial replicons into chromosomes, plasmids,  
20 and another class of essential genomic elements that function as chromosomes. These  
21 latter do not derive directly from plasmids. Rather, they arise from the fission of a multi-  
22 replicon molecule corresponding to the co-integrated and rearranged ancestral  
23 chromosome and plasmid. All essential replicons in a distributed genome are thus neo-  
24 chromosomes. Having a distributed genome appears to extend and accelerate the  
25 exploration of the bacterial genome evolutionary landscape, producing complex  
26 regulation and leading to novel eco-phenotypes and species diversification.

## 27 INTRODUCTION

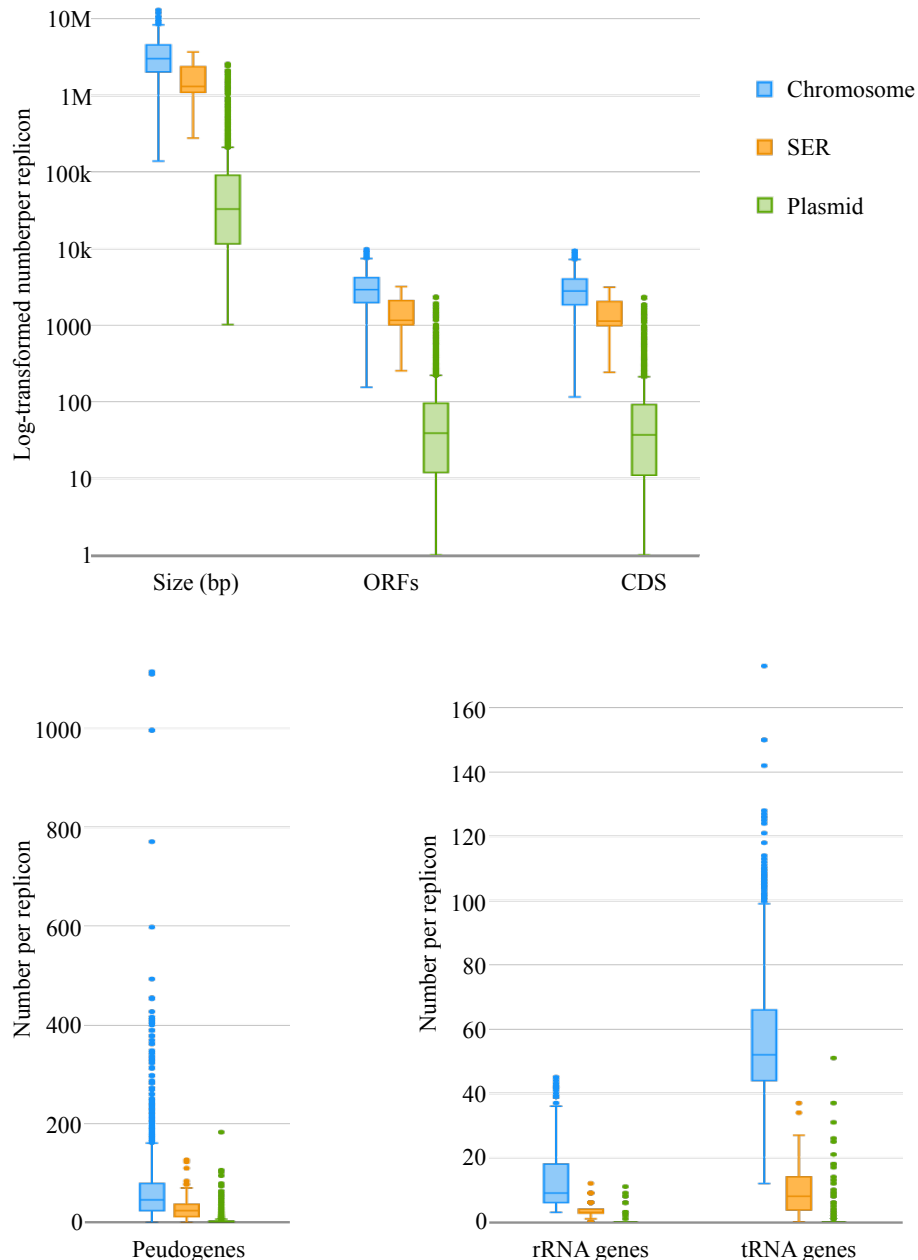
28 Chromosomes are the only components of the genome that encode the necessary  
29 information for replication and life of the cell/organism under normal growth conditions.  
30 Their number varies across taxa, a single chromosome being the standard in bacteria  
31 (Krawiec and Riley, 1990). Evidence accumulated over the past forty years is proving  
32 otherwise: bacterial genomes can be distributed on more than one chromosome-like  
33 autonomously replicating genomic element (replicon) (Casjens, 1998; diCenzo and  
34 Finan, 2017; Mackenzie et al., 2004). The largest, primary, essential replicon (ER) in a  
35 multipartite genome corresponds to a *bona fide* chromosome and the additional,  
36 secondary, ERs (SERs) are expected to derive from accessory replicons (plasmids  
37 (Lederberg, 1998)). The most popular model of SER formation posits that a plasmid  
38 acquired by a mono-chromosome progenitor bacterium is stabilized in the genome  
39 through the transfer from the chromosome of genes essential to the cell viability  
40 (diCenzo and Finan, 2017; diCenzo et al., 2013; Slater et al., 2009). The existence in  
41 SERs of plasmid-like replication and partition systems (Dubarry et al., 2006; Egan and  
42 Waldor, 2003; Livny et al., 2007; MacLellan et al., 2004, 2006; Slater et al., 2009;  
43 Yamaichi et al., 2007) as well as experimental results (diCenzo et al., 2014) support this  
44 view. Yet, the duplication and maintenance processes of SERs contrast with the typical  
45 behaviour of plasmids for which both the timing of replication initiation and the  
46 centromere movement are random (Million-Weaver and Camps, 2014; Reyes-Lamothe  
47 et al., 2014). Indeed, the SERs share many characteristic features with chromosomes:  
48 enrichment in Dam methylation sites of the replication origin (Egan and Waldor, 2003;  
49 Gerding et al., 2015), presence of initiator titration sites (Egan and Waldor, 2003;  
50 Venkova-Canova and Chattoraj, 2011), synchronization of the replication with the cell  
51 cycle (De Nisco et al., 2014; Deghelt et al., 2014; Egan and Waldor, 2003; Egan et al.,



52 2004; Fiebig et al., 2006; Frage et al., 2016; Kahng and Shapiro, 2003; Rasmussen et al.,  
53 2007; Srivastava et al., 2006; Stokke et al., 2011), KOPS-guided FtsK translocation (Val  
54 et al., 2008), FtsK-dependent dimer resolution system (Val et al., 2008), MatP/matS  
55 macrodomain organisation system (Demarre et al., 2014), and similar fine-scale  
56 segregation dynamics (Fiebig et al., 2006; Frage et al., 2016). Within a multipartite  
57 genome, the replication of the chromosome and that of the SER(s) are initiated at  
58 different time points (De Nisco et al., 2014; Deghelt et al., 2014; Fiebig et al., 2006;  
59 Frage et al., 2016; Rasmussen et al., 2007; Srivastava et al., 2006; Stokke et al., 2011),  
60 and use replicon-specific systems (Drevinek et al., 2008; Egan and Waldor, 2003;  
61 Galardini et al., 2013; MacLellan et al., 2004, 2006; Slater et al., 2009). Yet, they are  
62 coordinated, hence maintaining the genome stoichiometry (Deghelt et al., 2014; Egan et  
63 al., 2004; Fiebig et al., 2006; Frage et al., 2016; Stokke et al., 2011). In the few species  
64 where this was studied, the replication of the SER is initiated after that of the  
65 chromosome (De Nisco et al., 2014; Deghelt et al., 2014; Fiebig et al., 2006; Frage et al.,  
66 2016; Rasmussen et al., 2007; Srivastava, 2006; Stokke et al., 2011) under various  
67 modalities. In the Vibrionaceae, the replication of a short region of the chromosome  
68 licenses the SER duplication (Baek and Chatteraj, 2014; Kemter et al., 2018), and the  
69 advancement of the SER replication and segregation triggers the divisome assembly  
70 (Galli et al., 2016). In turn, the altering of the chromosome replication does not affect  
71 the replication initiation control of the SER in  $\alpha$ -proteobacterium *Ensifer/Sinorhizobium*  
72 *meliloti* (Frage et al., 2016).

73 Beside the exploration of the replication/segregation mechanistic, studies of multipartite  
74 genomes, targeting a single bacterial species or genus (diCenzo et al., 2013, 2014;  
75 Dubarry et al., 2006; Mackenzie et al., 2004; Slater et al., 2009) or using a more  
76 extensive set of taxa (diCenzo and Finan, 2017; Harrison et al., 2010), relied on

77 inadequate (replicon size, nucleotide composition, coding of core essential genes for  
 78 growth and survival (diCenzo and Finan, 2017; Harrison et al., 2010; Liu et al., 2015);  
 79 Figure 1) and/or oriented (presence of plasmid-type systems for genome maintenance  
 80 and replication initiation (Harrison et al., 2010)) criteria to characterize the SERs.



81

82

**Figure 1. Structural features of the replicons**

83 Boxplots of the lengths (base pairs) and numbers of genes (ORFs), protein-coding genes (CDS), pseudogenes,  
 84 ribosomal RNA genes and transfer RNA genes for the 2016 chromosomes (blue), 129 SERs (orange), and 2783  
 85 plasmids (green) included in the final dataset (4928 replicons).

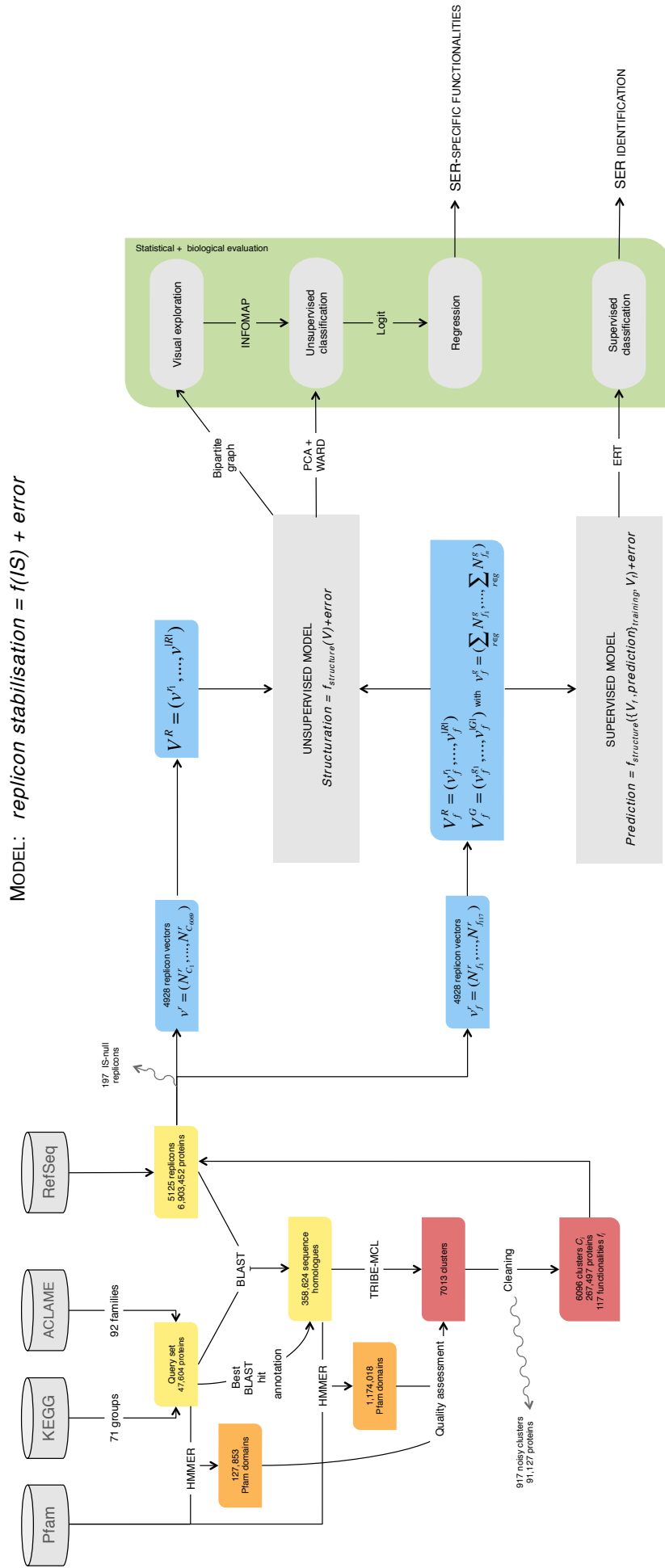
86 While clarifying the functional and evolutionary contributions of each type of replicon  
87 to a multipartite genome in given bacterial lineages (Galardini et al., 2013; Harrison et  
88 al., 2010; MacLellan et al., 2004; Slater et al., 2009), these studies produced no absolute  
89 definition of SERs (diCenzo and Finan, 2017; Harrison et al., 2010) or universal model  
90 for their emergence (diCenzo and Finan, 2017; diCenzo et al., 2013, 2014; Galardini et  
91 al., 2013; Harrison et al., 2010). We thus set out investigating the nature(s) and origin(s)  
92 of these replicons using as few assumptions as possible.

## 93 **RESULTS**

### 94 **Replicon inheritance systems as diagnostic features**

95 We did not limit our study to a particular multipartite genome or a unique gene family.  
96 Rather, we performed a global analysis encompassing all bacterial replicons whose  
97 complete sequence was available in public sequence databases (Figure 2). We reasoned  
98 that the key property discriminating the chromosomes from the plasmids is their  
99 transmission from mother to daughter cells during the bacterial cell cycle. The functions  
100 involved in the replication, partition and maintenance of a replicon, *i.e.*, its inheritance  
101 systems (ISs), thence are expected to reflect the replicon degree of integration into the  
102 host cycle.

103 We first faced the challenge of identifying all IS functional homologues. The inheritance  
104 of genetic information requires functionally diverse and heterogeneous actuators  
105 depending on the replicon type and the characteristics of the organism. Also, selecting  
106 sequence orthologues whilst avoiding false positives (*e.g.*, sequence paralogues) can be  
107 tricky since remote sequence homology most likely prevails among  
108 chromosome/plasmid protein-homologue pairs.



**Figure 2. Analytical procedure**

110 Starting from an initial dataset of 5125 replicons, we identified 358,624 putative IS  
 111 functional homologues, overall corresponding to 1711 Pfam functional domains (Figure  
 112 3a), using a query set of 47,604 chromosomal and plasmidic IS-related proteins selected  
 113 from the KEGG and ACLAME databases (Tables 1 and 2).

114 **Table 1. ACLAME families used in the building of the query set**

PROCESS	FAMILY	PROTEIN DESCRIPTION
Replication	32	RepB, pi, initiator protein, RepE, RepA
	76	Rep, RepB, Rep of rolling circle initiator, RepA, RepU, OrfB, Rep2
	107	RepC, RepCa1, RepCa2, RepCd
	114	Helicase, UrvD rep helicase, helicase super family 1, Yga2F, helicase II
	118	CdsE, CdsJ
	133	RepA, W0005, RepA1/A2
	171	RepA, RepB, putative theta replicative protein
	207	replicative DNA helicase, DnaB, pGP1
	208	RepA, W0013, W0041, RepFIB
	224	long form TrfA, TrfA1, TrfA2, S-TrfA, plasmid initiation protein
	237	RepA, putative RepA, truncated RepA
	244	RepA, RepB, CopB, repA1/A2, w0004
	294	Rop regulatory protein, RNAI modulator, RNA modulator, plasmid copy number control
	297	primase activity/DNA initiation, LtrC/LtrC-like hypothetical protein, PcfD
	330	DNA repair/ DNA helicase, type III restriction enzyme, res subunit, DEAD/DEAH box helicase
	377	replicase, replication initiation, RepC, RepJ, RepE, RepL
	383	RepA, Rb100
	404	RepA, RepB, RepW
	412	Rep, RepA
	423	truncated RCR replication, RepRC, RepB, OrfA
	426	cell division control protein 6 homolog
	440	Rep 14-4, rm protein, RepA hypothetical protein
	451	RepA, host type : <i>Corynebacterium</i>
	477	Rep, RepS, RepE, host type : <i>Bacillus</i> , RepS, RepR
	612	RepL, replication initiation
	775	DNA helicase activity, RepA, putative helicase
	854	DNA helicase activity, RepC, putative initiator protein
	921	RepA
	931	DNA replication initiation, putative protein, CdsD
	1005	helicase activity, putative protein, hypothetical helicase
	1055	RNA polymerase $\sigma$ factor, $\sigma$ 70 family, bacteriocin uviA, sigF/V/G, tetR, host type : <i>Clostridium</i>
	1095	DNA repair/helicase, RuvB, DNA pol III $\gamma$ and $\tau$ subunits, DNA pol $\delta$ subunit
1099	putative theta replicase, RepB, Rep2	
1187	DNA replication, RepH, RepI	
1288	RepA	
1345	DNA primase activity, DNA primase, primase CHC2 family	
1398	helicase activity, GcrE, GcrC	

	1652	DNA repair/exonuclease activity, DNA exonuclease protein, SbcCD related protein
	1837	putative replication protein
	2881	RepC-like, Pif
Partition	4	plasmid partition protein, ParA, ParA IncC protein, ParA Inc1/ Inc2, SopA, virC1
	14	RepB, RepB partitioning, KorB repressor and partitioning, ParB-like domain, YefA, YdeB, ParB, ParB-like
	102	DNA binding, partitioning protein, control protein, ParB, VirB, partition protein B
	128	DNA segregation/DNA translocase activity, cell division FtsK/ SpoIIIE, SpoI, TraB
	289	ParM family, go : translocase, hypothetical protein, rode shape protein, putative ATPase of class HSP70
	316	microfilament motor activity, ParM family, StbA protein, stable inheritance protein, ParA
	318	ATPase, regulation of cell division, chromosome partition, GumC, ExoP related protein, EpsB, MPA1 family
	427	ATPase family, ParR family, ParB, StbB, mediator of plasmid stability
	875	DNA binding, partitioning protein family ParB/Spo0J, YPMT1.28c
	876	DNA binding, partitioning protein family ParB/Spo0J, YPMT1.29c
	983	DNA binding, ParB, CopG
	1227	DNA plasmid copy number control, CopG
	2158	RepC
	2894	DNA binding
	Dimer resolution	5
10		tyrosine-based recombinase, integrase, putative integrase, Xer, recombinase-like SAM
101		plasmid dimer resolution, tyrosine-based recombinase, yld, SAM-like protein
170		tyrosine-based recombinase, OrfA, hypothetical protein
589		tyrosine based protein, Fis protein
688	tyrosine based protein, SAM like protein, XerD	
Maintenance	100	Postsegregational killing system vapBC/vag
	136	Postsegregational killing system parDE
	156	Postsegregational killing system epsilon-zeta
	201	Postsegregational killing system higBA
	212	Postsegregational killing system parDE
	293	Postsegregational killing system mazEF
	319	Postsegregational killing system relBE
	326	Postsegregational killing system mazEF
	335	Postsegregational killing system HOK/SOK
	338	Postsegregational killing system parDE
	356	Postsegregational killing system parDE
	366	Postsegregational killing system vapBC/vag
	380	Postsegregational killing system phD-doc
	428	Postsegregational killing system ccd
	470	Postsegregational killing system yacA
	474	Postsegregational killing system relBE
	515	Postsegregational killing system relBE
	556	Postsegregational killing system higBA
	563	Postsegregational killing system ccd
	588	Postsegregational killing system higBA
	677	Postsegregational killing system higBA
	798	Postsegregational killing system mazEF
	916	Postsegregational killing system relBE
1031	Postsegregational killing system HOK/SOK	
1180	Postsegregational killing system vapXD	
1308	Postsegregational killing system HicAB	
1559	Postsegregational killing system epsilon-zeta	
1927	Postsegregational killing system mazEF	

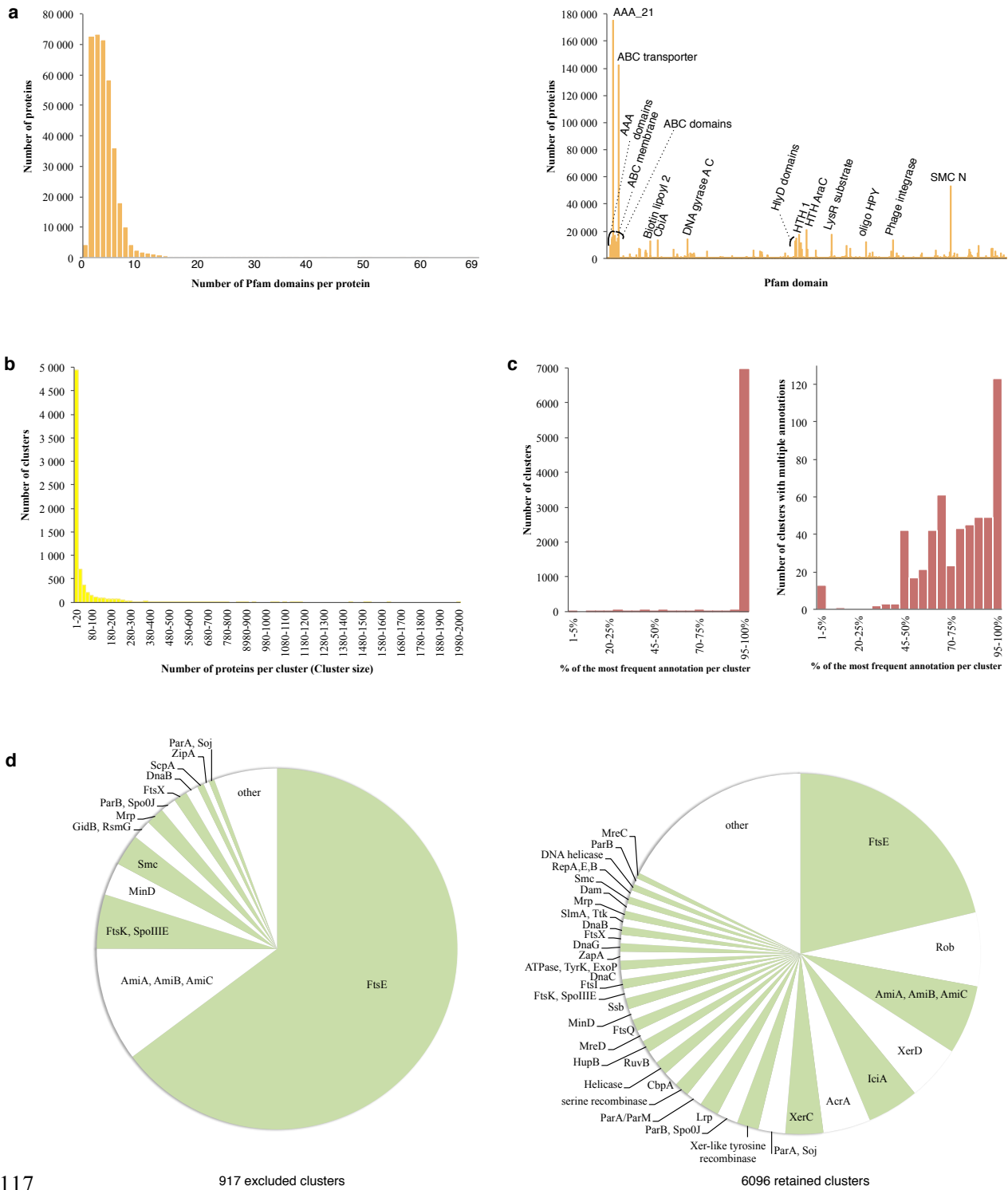
3357	Postsegregational killing system, plasmid maintenance
4776	Postsegregational killing system, parC
4777	Postsegregational killing system parDE, parD
16584	Postsegregational killing system vapXD

115 **Table 2. KEGG “Prokaryotic-type chromosome” orthology groups used in the building of the**  
116 **query set**

BRITE HIERARCHY	KEGG ENTRY	NAME	DEFINITION	
Chromosome replication	<i>K02313</i>	DnaA	chromosomal replication initiator protein	
	<i>K02314</i>	DnaB	replicative DNA helicase [EC:3.6.4.12]	
	<i>K03346</i>	DnaB2, DnaB	replication initiation and membrane attachment protein	
	<i>K02315</i>	DnaC	DNA replication factor, helicase loader	
	<i>K02316</i>	DnaG	DNA primase [EC:2.7.7.-]	
	<i>K11144</i>	DnaI	primosomal protein DnaI	
	<i>K05787</i>	HupA	DNA-binding protein HU-alpha	
	<i>K03530</i>	hupB	DNA-binding protein HU-beta	
	<i>K04764</i>	IhfA, HimA	integration host factor subunit alpha	
	<i>K05788</i>	IhfB, HimD	integration host factor subunit beta	
	<i>K03111</i>	ssb	single-strand DNA-binding protein	
	Terminus site-binding protein	<i>K10748</i>	Tus, Tau	DNA replication terminus site-binding protein
	DNA methylation enzyme	<i>K06223</i>	Dam	DNA adenine methylase [EC:2.1.1.72]
	Prevention of re-replication factors	<i>K10763</i>	Hda	DnaA-homolog protein
		<i>K03645</i>	SeqA	negative modulator of initiation of replication
Chromosome partition	<i>K03632</i>	MukB	chromosome partition protein MukB	
	<i>K03804</i>	MukE	chromosome partition protein MukE	
	<i>K03633</i>	MukF	chromosome partition protein MukF	
	Condensin-like complex	<i>K03529</i>	Smc	chromosome segregation protein
		<i>K05896</i>	ScpA	segregation and condensation protein A
		<i>K06024</i>	ScpB	segregation and condensation protein B
	Divisome proteins	<i>K03585</i>	AcrA	membrane fusion protein
		<i>K01448</i>	AmiA, AmiB, AmiC	N-acetylmuramoyl-L-alanine amidase [EC:3.5.1.28]
		<i>K13052</i>	DivIC, DivA	cell division protein DivIC
		<i>K03590</i>	FtsA	cell division protein FtsA
		<i>K05589</i>	FtsB	cell division protein FtsB
		<i>K09812</i>	FtsE	cell division transport system ATP-binding protein
		<i>K03587</i>	FtsI	cell division protein FtsI [EC:2.4.1.129]
		<i>K03466</i>	FtsK, SpoIIIE	DNA segregation ATPase FtsK/SpoIIIE, S-DNA-T family
		<i>K03586</i>	FtsL	cell division protein FtsL
		<i>K03591</i>	FtsN	cell division protein FtsN
		<i>K03589</i>	FtsQ	cell division protein FtsQ
		<i>K03588</i>	FtsW, SpoVE	cell division protein FtsW
		<i>K09811</i>	FtsX	cell division transport system permease protein
		<i>K03531</i>	FtsZ	cell division protein FtsZ
<i>K09888</i>		ZapA	cell division protein ZapA	
<i>K03528</i>		ZipA	cell division protein ZipA	
Inhibitors of FtsZ assembly		<i>K04074</i>	DivIVA	cell division initiation protein
	<i>K06286</i>	EzrA	septation ring formation regulator	

	<i>K03610</i>	MinC	septum site-determining protein MinC	
	<i>K03609</i>	MinD	septum site-determining protein MinD	
	<i>K03608</i>	MinE	cell division topological specificity factor	
	<i>K05501</i>	SlmA, Ttk	TetR/AcrR family transcriptional regulator	
	<i>K09772</i>	SepF	cell division inhibitor SepF	
	<i>K13053</i>	SulA	cell division inhibitor, FtsZ assembly inhibitor	
Other chromosome partitioning proteins	<i>K04095</i>	Fic	cell filamentation protein	
	<i>K04094</i>	Gid, TrmFO	methylenetetrahydrofolate--tRNA-[uracil-5-]-methyltransferase [EC:2.1.1.74]	
	<i>K03495</i>	GidA, MnmG, MTO1	tRNA uridine 5-carboxymethylaminomethyl modification enzyme	
	<i>K03501</i>	GidB, RsmG	16S rRNA [guanine527-N7]-methyltransferase [EC:2.1.1.170]	
	<i>K03569</i>	MreB	rod shape-determining protein MreB and related proteins	
	<i>K03570</i>	MreC	rod shape-determining protein MreC	
	<i>K03571</i>	MreD	rod shape-determining protein MreD	
	<i>K03593</i>	Mrp	ATP-binding protein involved in chromosome partitioning	
	<i>K03496</i>	ParA, Soj	chromosome partitioning protein	
	<i>K03497</i>	ParB, SpoJ	chromosome partitioning protein, ParB family	
	<i>K02621</i>	ParC	topoisomerase IV subunit A [EC:5.99.1.-]	
	<i>K02622</i>	ParE	topoisomerase IV subunit B [EC:5.99.1.-]	
	<i>K11686</i>	RacA	chromosome-anchoring protein RacA	
	<i>K05837</i>	RodA, MrdB	rod shape determining protein RodA	
	<i>K03645</i>	SeqA	negative modulator of initiation of replication	
	<i>K03733</i>	XerC	integrase/recombinase XerC	
	<i>K04763</i>	XerD	integrase/recombinase XerD	
	Nucleoid	HNS (histone-like nucleoid structuring protein)	<i>K03746</i>	H-NS
<i>K11685</i>			StpA	DNA-binding protein StpA
HU (heat unstable protein)		<i>K05787</i>	HupA	DNA-binding protein HU-alpha
		<i>K03530</i>	HupB	DNA-binding protein HU-beta
IHF (integration host factor)		<i>K04764</i>	IhfA, HimA	integration host factor subunit alpha
		<i>K05788</i>	IhfB, HimD	integration host factor subunit beta
Other nucleoid associated proteins		<i>K05516</i>	CbpA	curved DNA-binding protein
		<i>K12961</i>	DiaA	chromosomal replication initiator protein
		<i>K02313</i>	DnaA	DnaA initiator-associating protein
		<i>K04047</i>	Dps	starvation-inducible DNA-binding protein
		<i>K03557</i>	Fis	Fis family transcriptional regulator, factor for inversion stimulation protein
		<i>K03666</i>	Hfq	host factor-I protein
		<i>K05596</i>	IciA	chromosome initiation inhibitor, LysR family transcriptional regulator
		<i>K03719</i>	Lrp	leucine-responsive regulatory protein, Lrp/AsnC family transcriptional regulator
<i>K05804</i>		Rob	right origin-binding protein, AraC family transcriptional regulator	





117

917 excluded clusters

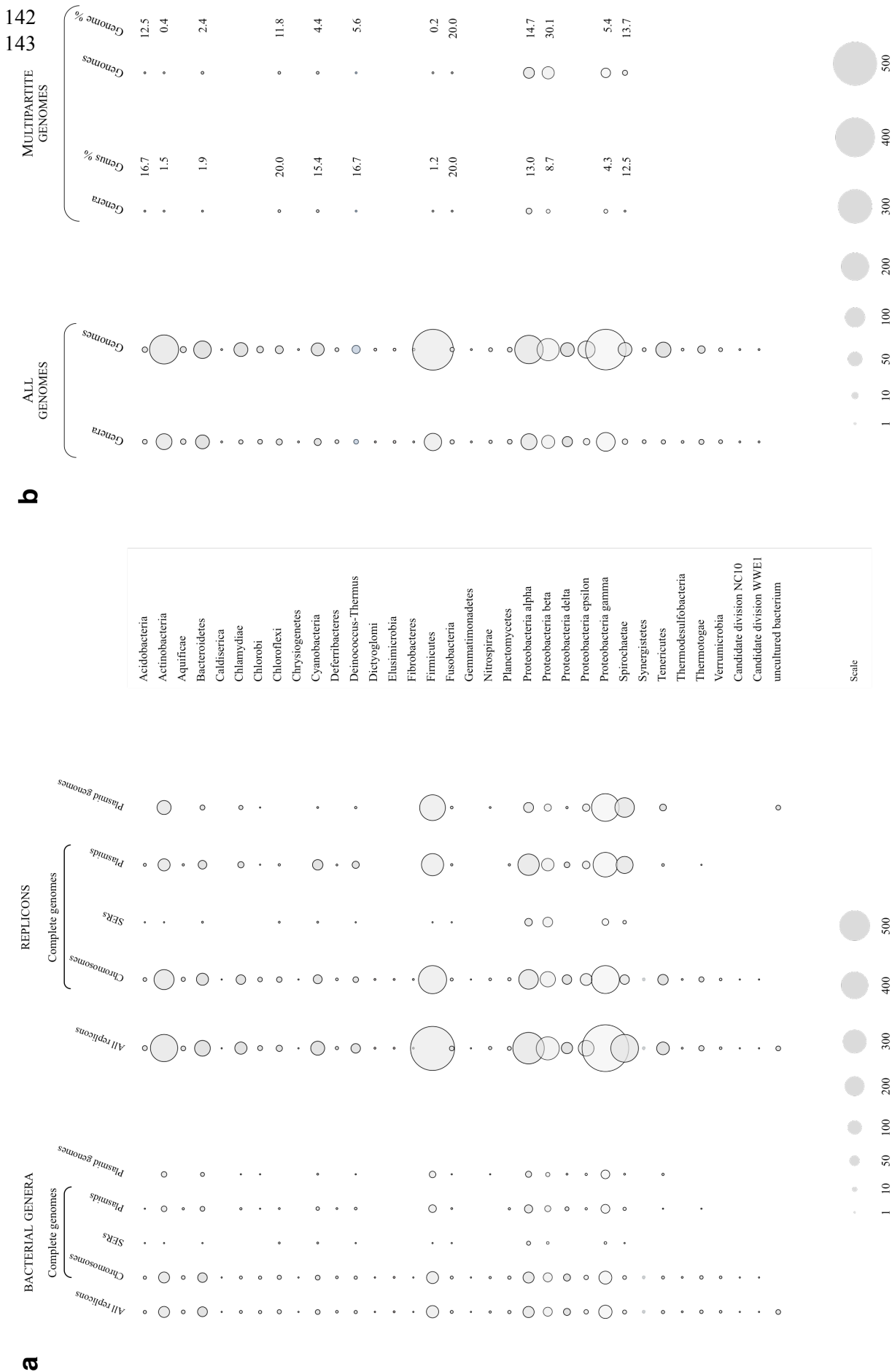
6096 retained clusters

118

### Figure 3. Properties of the IS clustering

119 (a) Frequency distribution of the 358,624 putative IS protein homologues according to their number of functional domains (0 to 120 69) per protein (left), and occurrences of the 1711 functional Pfam domains (right). The 20 top most frequently encountered 121 functional domains are indicated. (b) Size distribution of the 7013 clusters, each comprising from a single to 1990 proteins. (c) Percentage distribution of the most frequent annotation per cluster among all clusters (left) and among clusters with multiple 123 annotations (right). (d) Distribution of the most frequent annotation per cluster among the 917 excluded clusters (left) and the 124 6096 clusters retained for the analysis (right).

125 We then inferred 7013 homology groups using a clustering procedure and named the  
126 clusters after the most frequent annotation found among their proteins (Figure 3b,c). Most  
127 clusters were characterized by a single annotation whilst the remaining few (4.7%) each  
128 harbored from 2 to 710 annotations, the most frequent annotation in a cluster generally  
129 representing more than half of all annotations (Figure 3c). The removal of false positives  
130 left 267,497 IS protein homologues distributed in 6096 clusters (Figure 3d) and coded by  
131 4928 replicons out of the initial replicon dataset. Following the Genbank/RefSeq  
132 annotations, our final dataset comprised 2016 complete genome sets corresponding to  
133 3592 replicons (2016 chromosomes, 129 SERs, and 1447 plasmids) and 1336 plasmid  
134 genomes (Supplementary table 1), irregularly distributed across the bacterial phylogeny  
135 (Figure 4a). Multi-ER genomes are observed in 5.0% of all represented bacterial genera  
136 and constitute 5.7% of the complete genomes (averaged over genera) available at the time  
137 of study (Figure 4b). They are merely incidental (0.2% in Firmicutes) or reach up to  
138 almost one third of the genomes (30.1% in  $\beta$ -Proteobacteria) depending on the lineage,  
139 and are yet to be observed in most bacterial phyla, possibly because of the poor  
140 representation of some lineages. Although found in ten phyla, they occur more than once  
141 per genus in only three of them: Bacteroidetes, Proteobacteria and Spirochaetae.

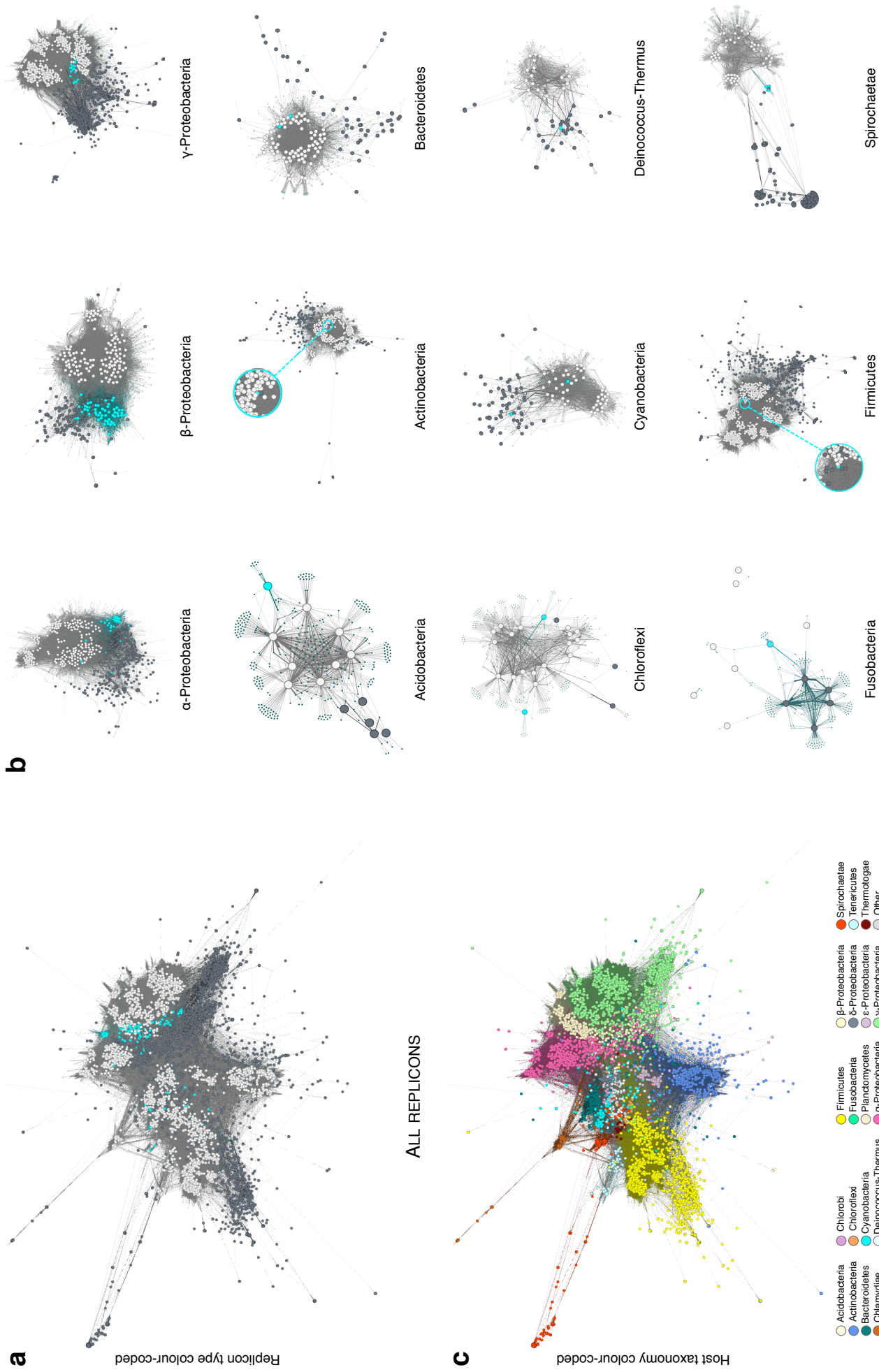


**Figure 4. Taxonomic structure of the replicon dataset**

Numbers of replicons (a) and complete genomes (b), and represented bacterial genera are shown according to datasets and host taxonomy. Surfaces represent the numbers of bacterial genera, replicons or genomes within each category. Percentages of multipartite genomes and corresponding bacterial genera are calculated for each host phylum or class (Proteobacteria).

## 144 **Exploration of the replicon diversity**

145 We explored the differences and similarities of the bacterial replicons with regard to  
146 their IS usage using a data mining and machine learning approach (Methods). The 6096  
147 retained IS clusters were used as distinct variables to ascribe each of the 4928 replicons  
148 with a vector according to its IS usage profile. We transformed these data into bipartite  
149 graphs depending on the number of proteins from the IS clusters coded by each replicon.  
150 Bipartite graphs display both the vectors (replicons) and the variables (protein clusters)  
151 together with their respective connections, and allow the interactive exploration of the  
152 data. The majority of the replicons are interconnected (Figure 5) as testimony of the  
153 shared evolutionary history of their IS sequences. Chromosomes and plasmids form  
154 overall distinct groups and communities with varying degree of connectivity depending  
155 on their functional specificities (Figure 5a) as well as on the bacterial taxonomy of their  
156 hosts (Figure 5c). They nonetheless share many ISs, bearing witness to the continuity of  
157 the genomic material and the extensive exchange of genetic material within bacterial  
158 genomes. The occurrence of poorly IS cluster-connected plasmids within a group of  
159 chromosomes did not consistently reflect a true relationship and rather resulted from  
160 shared connections to a very small number (as low as one) of common ISs. While being  
161 interconnected to both chromosomes and plasmids *via* numerous IS clusters, the SERs  
162 generally stand apart from either these types of replicons and gather at the chromosome-  
163 plasmid interface (Figure 5a,b). Their IS usage is neither chromosome-like nor plasmid-  
164 like, suggesting that they may constitute a separate category of replicons. This is most  
165 tangible in the case of the proteobacterial lineages where SERs occur most frequently  
166 (top of Figure 5b).



**Figure 5. Visualisation of the replicon IS-based relationships**

Gephi-generated bipartite-graphs for the whole dataset (a and b) or groups of replicons following the host taxonomy (c). Nodes correspond to the replicons (large dots) or the clusters of IS proteins (small dots). Edges linking replicons and protein clusters reflect the presence on a replicon of at least one protein of a protein cluster. Colouring according to replicon type (a and c): chromosomes (white), plasmids (grey), or according to host taxonomy (b).

169 All SERs in the  $\beta$ - and  $\gamma$ -Proteobacteria, and most in the  $\alpha$ -Proteobacteria are linked to  
170 remarkable chromosome-type IS clusters, such as AcrA, IciA, FtsE, HN-S and Lrp, as  
171 well as to plasmid-like ParA/ParB, Rep and PSK IS clusters. A similar pattern is  
172 observed for the SERs in actinobacterium *Nocardiopsis dassonvillei*, firmicute  
173 *Butyrivibrio proteoclasticus*, and chloroflexi *Sphaerobacter thermophilus* and  
174 *Thermobaculum terrenum* (Figure 5b). Interestingly, DNA primase DnaG-annotated  
175 clusters connect the SERs present in all but one *Burkholderia* species ( $\beta$ -Proteobacteria)  
176 as well as the chromosomes of all other bacteria. Since the sole exception,  
177 *B. rhizoxinica*, possesses a SER-less reduced genome as an adaptation to intracellular life,  
178 the *Burkholderia* SERs likely originated from a single event prior to the diversification  
179 of the genus, possibly in relation to the speciation event that gave rise to this lineage.  
180 The second SERs harbored by only some *Burkholderia* species exhibit a higher level of  
181 interconnection to plasmids, as do the SERs in  $\alpha$ -proteobacterium *Sphingobium*,  
182 cyanobacterium *Cyanothece* sp. ATCC 51142, *Deinococcus radiodurans* (*Deinococcus*-  
183 *Thermus*) and fusobacterium *Ilyobacter polytropus*. This points to an incomplete  
184 stabilization of the SERs into the genome that may reflect a recent, ongoing, event of  
185 integration and/or differing selective pressures at play depending on the bacterial  
186 lineages. At odds with these observations, some SERs group unambiguously with  
187 chromosomes. The SERs in  $\alpha$ -Proteobacteria *Asticcacaulis excentricus* and *Paracoccus*  
188 *denitrificans*, Bacteroidetes *Prevotella intermedia* and *P. melaninogenica*,  
189 acidobacterium *Chloracidobacterium thermophilum*, and cyanobacterium  
190 *Anabaena* sp. 90 bear higher levels of interconnection to chromosomes than to plasmids  
191 or other SERs. Indeed, the SERs in *Prevotella* spp. are hardly linked to plasmids, and  
192 the few plasmid-like IS proteins that *C. thermophilum* SER codes (mostly Rep, Helicase  
193 and PSK), albeit found in plasmids occurring in other phyla, are observed in none of the

194 Acidobacteria plasmids. An extreme situation is met in *Leptospira* spp. (Spirochaetae)  
195 whose SERs are each linked to only three or four (out of a total of six) chromosome-like  
196 IS clusters, always including ParA and ParB. Interestingly, the ParA cluster appears to  
197 be specific to Spirochaetae chromosomes with the notable exception of one plasmid  
198 found in Leptospiraceae *Turneriella parva*.

### 199 **IS-based relationships of the replicons**

200 We submitted the bipartite graph of the whole dataset to a community structure  
201 detection algorithm (INFOMAP) that performs a random walk along the edges  
202 connecting the graph vertices. We expected the replicon communities to be trapped in  
203 high-density regions of the graph. We also performed a dimension reduction by  
204 Principal Component Analysis followed by a hierarchical clustering procedure  
205 (WARD). The clustering solutions (Supplementary tables 2 and 3) were meaningful  
206 (high values reached by the stability criterion scores), and biologically relevant (efficient  
207 separation of the chromosomes from the plasmids; high *homogeneity* values) using  
208 either method (Table 3). In another experiment, we considered each genus as a unique  
209 sample and averaged the variables over the replicons of the different species for each  
210 replicon type. The aim was to control for the disparity in taxon representation of the  
211 replicons. This dataset produced overall similar albeit slightly less stable clusters (lower  
212 *homogeneity* values). Taxonomically homogeneous clusters of chromosomes were best  
213 retrieved using the coupling of dimension reduction and hierarchical clustering with a  
214 large enough number of clusters (*homogeneity* scores up to 0.93). In turn, the  
215 community detection algorithm was more efficient in recovering the underlying  
216 taxonomy of replicons (higher value of *completeness*), and was sole able to identify  
217 small and scattered plasmid clusters (Supplementary tables 2 and 3).

218 **Table 3. Evaluation of the replicon IS-based clusterings**

		INDEX <sup>a</sup>	USING IS PROTEIN SEQUENCES				USING IS FUNCTIONS	
CLUSTERING			INFOMAP		PCA+ WARD <sup>b</sup>		PCA+ WARD <sup>b</sup>	
PROCEDURE	Dataset <sup>c</sup>		$V^R$	$\bar{v}_{genus}^R$	$V^R$	$\bar{v}_{genus}^R$	$V_f^R$	$\bar{v}_{f,genus}^R$
	Parameters		500 iterations		$\begin{cases} k = 200 \\ pc = 30 \end{cases}$	$\begin{cases} k = 200 \\ pc = 30 \end{cases}$	$\begin{cases} k = 50 \\ pc = 4 \end{cases}$	$\begin{cases} k = 20 \\ pc = 4 \end{cases}$
	Number of clusters		223	77	175	75	49	19
	PCA explained variance				57%	58%	87%	85%
	Stability criterion ( $\Delta^{Kl}$ ) <sup>d</sup>		0.82	0.76	0.85	0.74	0.80	0.71
EVALUATED SEPARATION	Chromosomes vs. Plasmids	<i>homogeneity</i>	0.82	0.63	0.93	0.83	0.85	0.68
		<i>completeness</i>	0.15	0.15	0.25	0.20	0.30	0.23
		<i>V-measure</i>	0.25	0.24	0.43	0.32	0.44	0.35
	Chromosomes <i>per</i> host phylum	<i>homogeneity</i>	0.93	0.69	0.93	0.80	0.50	0.44
		<i>completeness</i>	0.60	0.61	0.35	0.40	0.27	0.33
		<i>V-measure</i>	0.73	0.65	0.51	0.53	0.35	0.38
	Chromosomes <i>per</i> host class	<i>homogeneity</i>	0.85	0.64	0.93	0.80	0.47	0.37
		<i>completeness</i>	0.80	0.82	0.16	0.58	0.36	0.41
		<i>V-measure</i>	0.82	0.72	0.66	0.67	0.41	0.39
	Plasmids <i>per</i> host phylum	<i>homogeneity</i>	0.88	0.78	0.06	0.01	0.02	0.02
		<i>completeness</i>	0.33	0.35	0.16	0.14	0.10	0.30
		<i>V-measure</i>	0.48	0.48	0.08	0.02	0.03	0.03
	Plasmids <i>per</i> host class	<i>homogeneity</i>	0.84	0.74	0.07	0.02	0.03	0.02
		<i>completeness</i>	0.43	0.51	0.28	0.36	0.25	0.28
		<i>V-measure</i>	0.57	0.60	0.12	0.03	0.05	0.03

219 <sup>a</sup> *V-measure* according to Rosenberg and Hirschberg (2007)

220 <sup>b</sup> *k*: number of input clusters; *pc*: principal components used in WARD

221 <sup>c</sup>  $V_f^R$ : Ensemble of all IS function-based replicon vectors ( $v_f^r$ );  $\bar{v}_{f,genus}^R$ : Ensemble of IS function-based genus-normalized replicon vectors ( $v_{f,genus}^r$ )

223 <sup>d</sup> Stability criterion according to Hennig (2007)

224 The plasmid clusters obtained using PCA+WARD lacked taxonomical patterning and,

225 although highly stable, only reflected the small Euclidian distances existing among the

226 plasmid replicons (e.g., one cluster of 2656 plasmids had a stability score of 0.975). The



227 clusters obtained with INFOMAP mirrored the taxonomical structure of the data,  
 228 suggesting that the taxonomic signal, expected to be associated to the chromosomes, is  
 229 preserved among the IS protein families functionally specifying the plasmids. The  
 230 presence of a majority of the SERs amongst the chromosome clusters generated by  
 231 INFOMAP confirmed the affinities between these two genomic elements and the clear  
 232 individuation of the SERs from the plasmids. However, the larger number of  
 233 chromosomal ISs often caused the PCA+WARD approach to place SERs into plasmid  
 234 clusters. The SERs in *Butyrivibrio*, *Deinococcus*, *Leptospira* and *Rhodobacter* spp.  
 235 grouped consistently with plasmids while the SERs in *Vibrionaceae* and *Brucellaceae*  
 236 formed specific clusters (Table 4). Burkholderiales and *Agrobacterium* SERs, whose  
 237 homogenous clusters tended to be unstable, exhibited a higher affinity to plasmids  
 238 overall. The SERs of *Asticcacaulis*, *Paracoccus* and *Prevotella* spp. associated stably  
 239 with chromosomes using the two clustering methods (Table 4a,b) and possess IS profiles  
 240 that set them apart from both the plasmids and the other SERs.

241 **Table 4. IS protein cluster-based unsupervised classification of SERs**

242 a. INFOMAP clustering solution

Bacterial genus	$C^a$	CHR%	SER%	PLD%	$wBHI^b$	$\overline{\Delta C}^c$	$\overline{\Delta r}^d$
<i>Agrobacterium</i>	3	38	35	27	0.90	0.47	0.61
<i>Aliivibrio</i>	1	0	100	0	1.00	0.95	1.00
<i>Anabaena</i>	1	98	1	1	1.00	0.90	1.00
<i>Asticcacaulis</i>	1	96	1	3	1.00	0.97	1.00
<i>Brucella</i>	1	0	95	5	1.00	0.87	1.00
<i>Burkholderia</i>	2	64	17	19	0.99	0.77	0.99
<i>Butyrivibrio</i>	1	0	50	50	1.00	0.83	1.00
<i>Chloracidobacterium</i>	1	91	<1	9	0.82	0.86	0.00
<i>Cupriavidus</i>	1	73	18	9	0.99	0.72	1.00
<i>Cyanothece</i>	1	0	6	94	0.89	0.61	0.33
<i>Deinococcus</i>	1	0	4	96	0.71	0.61	1.00
<i>Ilyobacter</i>	1	91	<1	9	0.82	0.86	0.25
<i>Leptospira</i>	1	0	88	12	1.00	1.00	1.00

<i>Nocardiopsis</i>	1	91	<1	9	0.97	0.97	1.00
<i>Ochrobactrum</i>	1	0	95	5	1.00	0.87	<i>n.a.n.</i> <sup>e</sup>
<i>Paracoccus</i>	1	96	1	3	1.00	0.97	1.00
<i>Photobacterium</i>	1	96	1	3	0.99	0.79	1.00
<i>Prevotella</i>	1	96	2	2	0.95	0.92	1.00
<i>Pseudoalteromonas</i>	1	96	1	3	0.99	0.79	0.56
<i>Ralstonia</i>	1	73	18	9	0.99	0.72	1.00
<i>Rhodobacter</i>	1	0	40	60	1.00	0.71	1.00
<i>Ensifer (Sinorhizobium)</i>	2	0	2	98	0.96	0.65	0.67
<i>Sphaerobacter</i>	1	0	50	50	1.00	1.00	1.00
<i>Sphingobium</i>	2	77	1	22	0.95	0.90	0.50
<i>Thermobaculum</i>	1	91	<1	9	0.82	0.86	1.00
<i>Variovorax</i>	1	73	18	9	0.99	0.72	0.90
<i>Vibrio</i>	1	0	100	0	1.00	0.95	0.89

- 243 <sup>a</sup> number of clusters containing SERs of a given bacterial genus  
244 <sup>b</sup> weighted biological homogeneity index value for the phylum of the replicons in the clusters  
245 <sup>c</sup> mean value of the cluster stability estimator, weighted by the cluster sizes  
246 <sup>d</sup> mean value of the SER stability estimator for a given bacterial genus  
247 <sup>e</sup> “*n.a.n.*”, standing for “not a number”, indicates that the replicon appeared in none of the bootstrap replications  
248 performed in the clustering procedure

#### 249 b. PCA+WARD clustering solution

Bacterial genus	$C^a$	CHR%	SER%	PLD%	$wBHI^b$	$\overline{\Delta^c}$	$\overline{\Delta^d}$
<i>Agrobacterium</i>	2	0	29	71	0.94	0.76	1.00
<i>Aliivibrio</i>	2	0	56	44	1.00	0.60	0.33
<i>Anabaena</i>	1	98	2	0	0.97	0.84	0.00
<i>Asticcacaulis</i>	1	88	8	4	1.00	0.88	1.00
<i>Brucella</i>	2	0	33	67	0.96	0.53	0.97
<i>Burkholderia</i>	7	0	79	21	0.97	0.69	0.84
<i>Butyrivibrio</i>	1	<1	1	99	0.27	0.98	1.00
<i>Chloracidobacterium</i>	1	<1	1	99	0.27	0.98	1.00
<i>Cupriavidus</i>	2	0	92	8	1.00	0.69	0.92
<i>Cyanothece</i>	1	<1	1	99	0.27	0.98	1.00
<i>Deinococcus</i>	1	<1	1	99	0.27	0.98	1.00
<i>Ilyobacter</i>	1	<1	1	99	0.27	0.98	1.00
<i>Leptospira</i>	1	<1	1	99	0.27	0.98	1.00
<i>Nocardiopsis</i>	1	0	2	98	0.58	0.40	1.00
<i>Ochrobactrum</i>	1	0	100	0	1.00	1.00	1.00
<i>Paracoccus</i>	1	88	8	4	1.00	0.88	1.00
<i>Photobacterium</i>	1	0	100	0	1.00	0.55	1.00
<i>Prevotella</i>	2	95	5	0	1.00	0.73	0.50
<i>Pseudoalteromonas</i>	2	<1	1	99	0.28	0.82	0.83
<i>Ralstonia</i>	1	0	68	32	1.00	0.81	0.83
<i>Rhodobacter</i>	2	0	6	94	0.65	0.43	0.58
<i>Ensifer (Sinorhizobium)</i>	2	0	21	79	0.94	0.46	0.25
<i>Sphaerobacter</i>	1	0	20	80	0.93	0.52	0.50

<i>Sphingobium</i>	1	0	39	61	1.00	0.66	0.83
<i>Thermobaculum</i>	1	<1	1	99	0.27	0.98	1.00
<i>Variovorax</i>	1	0	67	33	1.00	0.48	0.00
<i>Vibrio</i>	2	0	56	44	1.00	0.60	0.79

- 250 <sup>a</sup> number of clusters containing SERs of a given bacterial genus  
251 <sup>b</sup> weighted biological homogeneity index value for the phylum of the replicons in the clusters  
252 <sup>c</sup> mean value of the cluster stability estimator, weighted by the cluster sizes  
253 <sup>d</sup> mean value of the SER stability estimator for a given bacterial genus

254 We reached similar conclusions when performing a PCA+WARD clustering using the  
255 117 functional annotations of the IS protein clusters rather than the IS clusters  
256 themselves (Tables 3 and 5; Supplementary table 4).

257 **Table 5. Function-based unsupervised classification of SERs using PCA+WARD**

Bacterial genus	C <sup>a</sup>	CHR%	SER%	PLD%	wBHI <sup>b</sup>	$\overline{\Delta}^c$	$\overline{\Delta}^d$
<i>Agrobacterium</i>	3	64	21	15	0.86	0.60	0.81
<i>Aliivibrio</i>	1	0	70	30	1.00	0.70	0.67
<i>Anabaena</i>	1	77	4	19	0.21	0.64	1.00
<i>Asticcacaulis</i>	1	99	1	0	0.51	0.60	1.00
<i>Brucella</i>	1	43	32	25	0.75	0.80	1.00
<i>Burkholderia</i>	6	31	42	27	0.92	0.68	0.81
<i>Butyrivibrio</i>	1	77	4	19	0.21	0.64	1.00
<i>Chloracidobacterium</i>	1	1	<1	99	0.29	0.98	0.00
<i>Cupriavidus</i>	1	5	95	0	1.00	0.66	0.66
<i>Cyanothece</i>	1	1	<1	99	0.29	0.98	1.00
<i>Deinococcus</i>	1	1	<1	99	0.29	0.98	1.00
<i>Ilyobacter</i>	1	77	4	19	0.21	0.64	1.00
<i>Leptospira</i>	1	1	<1	99	0.29	0.98	1.00
<i>Nocardiopsis</i>	1	77	4	19	0.21	0.64	1.00
<i>Ochrobactrum</i>	1	90	8	2	1.00	0.40	0.73
<i>Paracoccus</i>	1	92	5	3	0.89	0.32	0.53
<i>Photobacterium</i>	1	0	70	30	1.00	0.70	0.36
<i>Prevotella</i>	2	86	3	11	0.34	0.62	0.50
<i>Pseudoalteromonas</i>	1	77	4	19	0.21	0.64	0.29
<i>Ralstonia</i>	1	0	70	30	1.00	0.70	0.22
<i>Rhodobacter</i>	2	27	32	41	0.84	0.73	0.83
<i>Ensifer (Sinorhizobium)</i>	2	25	48	27	0.86	0.76	0.63
<i>Sphaerobacter</i>	1	100	<1	0	0.35	0.60	1.00
<i>Sphingobium</i>	2	62	17	21	0.34	0.64	0.86
<i>Thermobaculum</i>	1	77	4	19	0.21	0.64	1.00
<i>Variovorax</i>	1	0	70	30	1.00	0.70	1.00

*Vibrio* 4 31 37 32 0.97 0.57 0.92

258 <sup>a</sup> number of clusters containing SERs of a given bacterial genus  
259 <sup>b</sup> weighted biological homogeneity index value for the phylum of the replicons in the clusters  
260 <sup>c</sup> mean value of the cluster stability estimator, weighted by the sizes of the clusters  
261 <sup>d</sup> mean value of the SER stability estimator for a given bacterial genus

262 Remarkably, in this latter analysis, the chromosomes in the multipartite genomes of  
263 *Prevotella intermedia* and *P. melaninogenica* were more similar to plasmids than to  
264 other groups of chromosomes and to single chromosomes in other *Prevotella* species  
265 (*P. denticola* and *P. ruminicola*).

### 266 **SER-specifying IS functions**

267 Next, we searched which of the IS functions are specific to the SERs. We performed  
268 several logistic regression analyses to identify over- or under-represented ISs and to  
269 assess their respective relevance to each class of replicons. Because of their  
270 comparatively small number, all SERs were assembled into a single group despite their  
271 disparity. A hundred and one IS functionalities (96% of KEGG-annotated chromosome-  
272 like functions and 72% of ACLAME-annotated plasmid-like functions) were  
273 significantly enriched in one replicon category over the other (Table 6). The large  
274 majority of the IS functions differentiates the chromosomes from the plasmids. The  
275 latter are only determined by ISs corresponding to ACLAME annotations Rep, Rop and  
276 TrfA, involved in initiation of plasmid replication, and ParA and ParB, dedicated to  
277 plasmid partition. Some KEGG-annotated functions, *e.g.*, DnaA, DnaB or FtsZ, appear  
278 to be more highly specific to chromosomes (higher *OR* values) than others such as  
279 DnaC, FtsE or H-NS (lower *OR* values). Strikingly, very few functions distinguish  
280 significantly the chromosomes from the SERs, by contrast with plasmids.

281

**Table 6. IS usage comparison between replicon categories**

282

Between classes of replicons logistic regressions for each IS function. Model significance:  $0 < P\_value < 0.01$ :

283

significant;  $0.01 < P\_value < 0.05$ : poorly significant;  $0.05 < P\_value$ : non significant (not shown). Odd-ratio (*OR*)

284

favouring the first class:  $10^0 \leq OR$ , or the second class:  $OR < 10^0$ . IS functions biased to the same order of magnitude

285

in chromosomes and SERs when compared to plasmids are highlighted (blue).

IS function	Chromosomes vs. Plasmids		Chromosomes vs. SERs		SERs vs. Plasmids	
	<i>P</i> _value	<i>OR</i>	<i>P</i> _value	<i>OR</i>	<i>P</i> _value	<i>OR</i>
CbpA	$8.20 \times 10^{-27}$	2,608.4	$9.90 \times 10^{-13}$	22.8	$5.60 \times 10^{-07}$	36.1
Dam	$6.90 \times 10^{-16}$	16.7	$3.60 \times 10^{-02}$	2.0	$2.40 \times 10^{-02}$	4.3
DiaA	$1.50 \times 10^{-15}$	81.9	$1.20 \times 10^{-03}$	38.4		
DnaA	$3.00 \times 10^{-44}$	2,118.9	$1.10 \times 10^{-19}$	239.6	$3.50 \times 10^{-03}$	8.3
DnaB	$1.10 \times 10^{-43}$	1,992.9	$5.10 \times 10^{-19}$	429.4	$8.20 \times 10^{-03}$	3.7
DnaB2	$6.70 \times 10^{-03}$	12.6				
DnaC	$6.00 \times 10^{-12}$	2.6			$4.60 \times 10^{-02}$	1.5
DnaG	$2.10 \times 10^{-50}$	1,861.5	$1.90 \times 10^{-21}$	205.3	$2.50 \times 10^{-03}$	4.5
DnaI	$5.20 \times 10^{-03}$	18.0				
Dps	$9.10 \times 10^{-21}$	65.3	$3.50 \times 10^{-05}$	8.4	$8.70 \times 10^{-03}$	6.7
Fis	$5.80 \times 10^{-07}$	180.9	$3.30 \times 10^{-03}$	7.9	$1.40 \times 10^{-02}$	25.1
Hda	$7.30 \times 10^{-07}$	149.1	$5.30 \times 10^{-03}$	7.9	$1.90 \times 10^{-02}$	18.0
Hfq	$1.40 \times 10^{-12}$	121.7	$3.00 \times 10^{-04}$	6.9	$8.10 \times 10^{-04}$	19.3
H-NS	$1.10 \times 10^{-05}$	2.8			$3.80 \times 10^{-04}$	2.8
HupA	$2.70 \times 10^{-04}$	15.1				
HupB	$1.20 \times 10^{-53}$	97.6	$2.30 \times 10^{-08}$	6.7	$2.40 \times 10^{-07}$	11.6
IciA	$7.10 \times 10^{-20}$	3.2			$4.50 \times 10^{-07}$	1.8
IhfA, HimA	$1.70 \times 10^{-12}$	63.8	$1.40 \times 10^{-03}$	10.5	$4.90 \times 10^{-02}$	6.9
IhfB, HimD	$1.20 \times 10^{-14}$	68.4	$4.90 \times 10^{-04}$	8.4	$8.40 \times 10^{-03}$	9.9
Lrp	$1.60 \times 10^{-19}$	8.4			$5.40 \times 10^{-11}$	8.1
Rob	$6.30 \times 10^{-19}$	5.3			$3.40 \times 10^{-08}$	4.2
SeqA	$1.60 \times 10^{-03}$	25.9				
ssb	$5.90 \times 10^{-41}$	298.3	$5.00 \times 10^{-18}$	160.6		
Fic	$3.10 \times 10^{-09}$	10.3			$8.60 \times 10^{-03}$	7.2
GidA, MmG,	$5.20 \times 10^{-13}$	1,477.2	$2.90 \times 10^{-08}$	110.6	$4.30 \times 10^{-02}$	18.2
GidB, RsmG	$6.70 \times 10^{-17}$	6,059.9	$2.20 \times 10^{-15}$	252.5	$9.00 \times 10^{-03}$	32.2
MreB	$1.30 \times 10^{-21}$	1,598.2	$3.90 \times 10^{-12}$	40.1	$1.40 \times 10^{-05}$	24.1
MreC	$2.90 \times 10^{-11}$	1,311.2	$1.30 \times 10^{-08}$	46.3	$8.90 \times 10^{-03}$	32.8
MreD	$1.80 \times 10^{-08}$	459.2	$6.80 \times 10^{-05}$	19.8	$1.90 \times 10^{-02}$	18.2
Mrp	$6.60 \times 10^{-17}$	2,599.3	$1.30 \times 10^{-14}$	35.0	$2.50 \times 10^{-05}$	86.2
MukB	$2.30 \times 10^{-03}$	27.4			$1.90 \times 10^{-02}$	18.2
MukE	$3.10 \times 10^{-03}$	21.0			$1.90 \times 10^{-02}$	18.2
MukF	$3.70 \times 10^{-03}$	19.6			$1.90 \times 10^{-02}$	18.2
ParA, Soj	$2.70 \times 10^{-38}$	9.9	$9.00 \times 10^{-06}$	2.6	$8.40 \times 10^{-06}$	3.8
ParB, SpoIJ	$2.50 \times 10^{-44}$	13.7	$3.00 \times 10^{-03}$	2.1	$2.30 \times 10^{-06}$	4.1
ParC	$3.00 \times 10^{-27}$	4,149.3	$3.00 \times 10^{-16}$	134.0	$4.60 \times 10^{-04}$	12.3
ParE	$7.30 \times 10^{-26}$	5,842.4	$5.70 \times 10^{-15}$	350.1	$2.40 \times 10^{-04}$	15.8
RodA, MrdB	$2.80 \times 10^{-12}$	1,233.1	$9.70 \times 10^{-10}$	33.0	$2.60 \times 10^{-03}$	55.3
TtmFO, Gid	$1.50 \times 10^{-06}$	182.5	$4.40 \times 10^{-03}$	8.3	$1.90 \times 10^{-02}$	18.0
XerC	$1.70 \times 10^{-43}$	55.0	$3.10 \times 10^{-08}$	8.8	$1.80 \times 10^{-04}$	6.7
XerD	$1.30 \times 10^{-38}$	26.6	$4.10 \times 10^{-08}$	3.4	$2.50 \times 10^{-06}$	6.2
ScpA	$1.40 \times 10^{-11}$	789.4	$5.70 \times 10^{-07}$	42.9	$2.10 \times 10^{-02}$	16.6
ScpB	$7.50 \times 10^{-32}$	102.5	$1.80 \times 10^{-07}$	25.8		
ScpF	$1.80 \times 10^{-07}$	68.8	$1.40 \times 10^{-02}$	12.3		
SlmA, Ttk	$3.80 \times 10^{-09}$	52.3	$1.20 \times 10^{-02}$	4.6	$1.50 \times 10^{-02}$	7.5
Smc	$1.60 \times 10^{-08}$	3,090.5	$1.40 \times 10^{-05}$	131.9		
SulA	$3.30 \times 10^{-06}$	17.5			$1.50 \times 10^{-02}$	10.7
AcrA	$6.60 \times 10^{-19}$	2.8	$1.70 \times 10^{-02}$	1.1	$5.30 \times 10^{-10}$	2.7
AmiA, AmiB,	$6.40 \times 10^{-36}$	46.4	$2.90 \times 10^{-10}$	8.9	$4.60 \times 10^{-03}$	3.0
DiviC, DivA	$4.90 \times 10^{-05}$	90.5	$4.70 \times 10^{-02}$	8.1		
DivIVA	$4.10 \times 10^{-06}$	128.0	$1.10 \times 10^{-02}$	13.4		
EzrA	$1.00 \times 10^{-02}$	13.7				
FtsA	$9.50 \times 10^{-12}$	742.7	$2.20 \times 10^{-08}$	24.6	$2.50 \times 10^{-03}$	41.7
FtsB	$1.10 \times 10^{-06}$	167.2	$5.40 \times 10^{-03}$	16.1		
FtsE	$4.20 \times 10^{-24}$	2.3	$1.30 \times 10^{-06}$	1.1	$4.00 \times 10^{-11}$	1.9
FtsI	$9.80 \times 10^{-09}$	47.0	$7.00 \times 10^{-16}$	3.9	$2.20 \times 10^{-07}$	76.7
FtsK, SpoIIIE	$2.80 \times 10^{-37}$	76.9	$2.70 \times 10^{-08}$	15.8	$1.40 \times 10^{-02}$	4.2
FtsL	$1.20 \times 10^{-05}$	91.5	$2.70 \times 10^{-02}$	9.8		
FtsN	$1.60 \times 10^{-04}$	53.0				
FtsQ	$1.70 \times 10^{-15}$	2,135.0	$1.30 \times 10^{-11}$	99.3	$9.00 \times 10^{-03}$	28.8
FtsW, SpoVE	$5.70 \times 10^{-16}$	4,266.4	$4.40 \times 10^{-16}$	87.7	$8.20 \times 10^{-04}$	55.0
FtsX	$9.30 \times 10^{-12}$	972.9	$1.30 \times 10^{-08}$	13.8	$4.80 \times 10^{-04}$	146.2
FtsZ	$3.10 \times 10^{-31}$	2,747.0	$1.20 \times 10^{-19}$	101.6	$9.70 \times 10^{-04}$	16.5
MinC	$4.40 \times 10^{-09}$	172.3	$1.20 \times 10^{-02}$	3.0	$5.80 \times 10^{-05}$	76.8
MinD	$3.10 \times 10^{-19}$	42.8	$1.60 \times 10^{-04}$	2.3	$5.40 \times 10^{-11}$	81.5
MinE	$9.00 \times 10^{-09}$	152.9	$3.10 \times 10^{-02}$	2.6	$5.90 \times 10^{-05}$	75.2
ZapA	$8.20 \times 10^{-09}$	602.8	$7.40 \times 10^{-06}$	17.3	$7.30 \times 10^{-03}$	56.1
ZipA	$7.90 \times 10^{-05}$	66.0				

ACLAME Families (plasmid-like)							
REPLICATION	CdsD			$4.40 \times 10^{-02}$	0.1		
	DNA helicase	$5.80 \times 10^{-21}$	33.6	$2.70 \times 10^{-04}$	4.1	$1.30 \times 10^{-04}$	9.8
	Helicase-I	$1.60 \times 10^{-27}$	71.1	$1.90 \times 10^{-13}$	20.0	$1.10 \times 10^{-04}$	4.6
	DNA repair	$2.20 \times 10^{-04}$	34.0			$5.70 \times 10^{-04}$	43.6
	primase, LtrC	$3.10 \times 10^{-02}$	1.8				
	RepA	$5.90 \times 10^{-03}$	0.7				
	RepAEB	$1.70 \times 10^{-16}$	0.0	$1.90 \times 10^{-04}$	0.1		
	RepC					$9.60 \times 10^{-03}$	2.7
	RepCJE			$4.40 \times 10^{-02}$	0.1		
	RepRSE	$1.30 \times 10^{-02}$	0.0	$4.90 \times 10^{-02}$	0.1		
	RNA polymerase	$3.20 \times 10^{-02}$	6.3				
	Rop	$3.20 \times 10^{-02}$	0.0	$4.40 \times 10^{-02}$	0.1		
	RuvB	$1.20 \times 10^{-08}$	433.0	$5.70 \times 10^{-08}$	17.7	$1.40 \times 10^{-05}$	37.8
	TrfA	$1.40 \times 10^{-02}$	0.3				
PARTITION	ATPase, TyrK,	$2.20 \times 10^{-20}$	19.4			$8.50 \times 10^{-07}$	9.3
	CopG			$2.70 \times 10^{-02}$	0.2	$4.60 \times 10^{-03}$	23.1
	DNA-binding protein			$4.40 \times 10^{-02}$	0.1		
	FtsK, SpoIIE	$1.90 \times 10^{-07}$	6.0			$9.90 \times 10^{-05}$	9.8
	ParA, ParM	$1.50 \times 10^{-10}$	0.4	$4.00 \times 10^{-06}$	0.3		
	ParB	$5.70 \times 10^{-12}$	0.1	$1.40 \times 10^{-05}$	0.2		
	serine recombinase	$2.50 \times 10^{-06}$	1.4	$1.50 \times 10^{-03}$	2.9	$1.80 \times 10^{-02}$	0.4
	tyrosine recombinase	$3.40 \times 10^{-04}$	3.3			$7.40 \times 10^{-04}$	8.7
	Xer-like Tyrosine	$7.60 \times 10^{-11}$	2.0			$6.30 \times 10^{-03}$	1.6
	Ccd (PSK)	$4.60 \times 10^{-02}$	3.9				
	HicAB (PSK)	$4.30 \times 10^{-05}$	25.2			$4.80 \times 10^{-03}$	15.1
	HigBA (PSK)	$3.30 \times 10^{-15}$	3.4	$2.40 \times 10^{-02}$	1.5	$1.20 \times 10^{-03}$	2.5
	MazEF (PSK)	$1.20 \times 10^{-11}$	5.2	$2.90 \times 10^{-02}$	2.6		
	ParC (PSK)			$4.40 \times 10^{-02}$	0.1		
MAINTENANCE	ParDE (PSK)	$5.50 \times 10^{-08}$	2.3			$7.80 \times 10^{-05}$	3.4
	PhD, Doc (PSK)	$3.20 \times 10^{-07}$	11.9			$2.90 \times 10^{-03}$	8.8
	plasmid maintenance			$4.40 \times 10^{-02}$	0.1		
	RelBE (PSK)	$2.70 \times 10^{-08}$	3.5			$6.10 \times 10^{-04}$	4.2
	VapBC/Vag (PSK)	$1.20 \times 10^{-09}$	3.9			$1.40 \times 10^{-05}$	5.8

286 Chromosome-signature ISs are also present on the SERs, and some of them are enriched  
287 to the same order of magnitude in both classes but not in plasmids (highlighted in  
288 Table 6). Among these latter, helicase loader DnaC participates to the replication  
289 initiation of the chromosome (Chodavarapu et al., 2016) whilst Walker-type ATPase  
290 ParA/Soj interacts with ParB/Spo0J in the *parABS* chromosomal partitioning system,  
291 and is required for proper separation of sister origins and synchronous DNA replication  
292 (Murray and Errington, 2008). The other ISs have a regulatory role, either locally or  
293 globally. Nucleoid-associated proteins (NAPs; Dillon and Dorman, 2010) contribute to  
294 the replication regulation: H-NS (histone-like nucleoid structuring protein), IciA  
295 (chromosome initiator inhibitor, LysR family transcriptional regulator), MukBEF  
296 (condensin), and Rob/ClpB (right arm of the replication origin binding protein/curved  
297 DNA-binding protein B, AraC family transcriptional regulator) influence both the  
298 conformation and the functions of chromosomal DNA, replication, recombination and

299 repair. The NAPs also have pleiotropic regulatory roles in global regulation of gene  
300 transcription depending on cell growth conditions (H-NS, IciA, Lrp (leucine-responsive  
301 regulatory protein, Lrp/AsnC family transcriptional regulator), and Rob/ClpB).  
302 Similarly, the membrane fusion protein AcrA is a growth-dependent regulator, mostly  
303 known for its role as a peripheral scaffold mediating the interaction between AcrB and  
304 TolC in the AcrA-AcrB-TolC Resistance-Nodule-cell Division-type efflux pump that  
305 extrudes from the cell compounds that are toxic or have a signaling role (Du et al.,  
306 2018). It is central to the regulation of cell homeostasis and proper development (Anes  
307 et al., 2015; Du et al., 2018; Webber et al., 2009) as well as biofilm formation (Alav et  
308 al., 2018). Fic (cell filamentation protein) targets the DNA gyrase B (GyrB) to regulate  
309 the cell division and cell morphology (Lu et al., 2018) whereas Sula inhibits FtsZ  
310 assembly, hence causing incomplete cell division and filamentation (Chen et al, 2012).  
311 FtsE is involved in the Z-ring assembly and the initiation of constriction, and in late  
312 stage cell separation (Meier et al, 2017).

313 The main divergence between SERs and chromosomes lies in the distribution patterns of  
314 the ACLAME-annotated ISs ( $OR < 10^0$  in the chromosomes vs. SERs comparison). Their  
315 higher abundance on the SERs suggests a stronger link of SERs to plasmids. This  
316 pattern may also arise from the unbalanced taxon representation in our SER dataset due  
317 to a single bacterial lineage. For example, the presence of RepC is likely to be specific to  
318 Rhizobiales SERs (Pinto et al., 2012).

### 319 **Identification of candidate SERs**

320 Since the IS profiles constitute replicon-type signatures, we searched for new putative  
321 SERs or chromosomes among the extra-chromosomal replicons. We used the IS

322 functions as features to perform supervised classification analyses with various training  
 323 sets (Table 7).

324 **Table 7. Performance of the ERT classification procedures**

TRAINING SET <sup>a</sup>	$CV_{score}$ <sup>b</sup>	$\sigma_{CV_{score}}$ <sup>c</sup>	$OOB_{score}$ <sup>d</sup>	$\sigma_{OOB_{score}}$ <sup>e</sup>
$\{E_{SER}, E'_{plasmid}\}$	0.96	-	0.96	-
$\{E_{SER}, E'_{plasmid}\}^{it}$	0.92	0.02	0.93	0.02
$\{E_{chromosome}, E'_{plasmid}\}$	1.00	-	1.00	-
$\{E_{SER}, E_{chromosome}\}^{it}$	0.98	0.00	0.98	0.01

325 <sup>a</sup>  $E_{chromosome}$  and  $E_{SER}$  are host genus-normalized sets of chromosomes or SERs, respectively (cf.  
 326 Table 13).  $E'_{plasmid}$  is derived from the INFOMAP clustering solution, by discarding plasmids belonging to  
 327 clusters also harbouring SERs or chromosomes, and normalized according to host genus. “it” designates the  
 328 iterative procedure.

329 <sup>b</sup> Cross-validation score or mean of iteration cross-validation scores.

330 <sup>c</sup> Standard deviation of iteration cross-validation scores.

331 <sup>d</sup> Out-of bag estimate or mean of iteration Out-of bag estimates.

332 <sup>e</sup> Standard deviation of iteration Out-of bag estimates.

333 The coherence of the SER class (overall high values of the probability for a SER to be  
 334 assigned to its own class in Tables 7 and 8) confirmed that the ISs are robust genomic  
 335 markers for replicon characterization. The low SER probability scores presented by a  
 336 few SERs (Table 8) likely result from a low number of carried ISs (e.g., *Leptospira*), or  
 337 from the absence in the data of lineage-specific ISs (e.g., SER idiosyncratic replication  
 338 initiator RtcB of Vibrionaceae).

339 **Table 8. SER probability to belong to the SER class**

Genus	$\bar{P}_{SER}(SER)^a$
<i>Agrobacterium</i>	0.90
<i>Aliivibrio</i>	0.87
<i>Anabaena</i>	0.94
<i>Asticcacaulis</i>	0.95



<i>Brucella</i>	0.92
<i>Burkholderia</i>	0.89
<i>Butyrivibrio</i>	0.83
<i>Chloracidobacterium</i>	0.88
<i>Cupriavidus</i>	0.94
<i>Cyanothece</i>	0.86
<i>Deinococcus</i>	0.78
<i>Ensifer/Sinorhizobium</i>	0.90
<i>Ilyobacter</i>	0.88
<i>Leptospira</i>	0.54
<i>Nocardiopsis</i>	0.90
<i>Ochrobactrum</i>	0.96
<i>Paracoccus</i>	0.96
<i>Photobacterium</i>	0.95
<i>Prevotella</i>	0.92
<i>Pseudoalteromonas</i>	0.91
<i>Ralstonia</i>	0.95
<i>Rhodobacter</i>	0.69
<i>Sphaerobacter</i>	0.88
<i>Sphingobium</i>	0.73
<i>Thermobaculum</i>	0.78
<i>Variovorax</i>	0.83
<i>Vibrio</i>	0.76

340 <sup>a</sup> SER probability, averaged per host genus, to belong to the *SER* class in the supervised classification  
341 using  $\{E_{SER}, E_{plasmid}\}^{it}$  as training set.

342 We detected a number of candidate SERs among the plasmids (Table 9a), most of which  
343 are essential to the cell functioning and/or the fitness of the organism (*cf.* Box 1).  
344 Whereas most belong to bacterial lineages known to harbour multipartite genomes,  
345 novel taxa emerge as putative hosts to complex genomes (Rhodospirillales and, to a  
346 lesser extent, Actinomycetales). In contrast, our analyses confirmed only one putative  
347 SER (*Ruegeria* sp. TM1040) within the *Roseobacter* clade (Petersen et al., 2013).  
348 Remarkably, we identified eight candidate chromosomes corresponding to two plasmids,  
349 also identified as candidate SERs, that encode ISs hardly found in extra-chromosomal

350 elements (*e.g.*, DnaG, DnaB, ParC and ParE), and six SERs that part of, or all, our  
 351 analyses associate to standard chromosomes (Table 9b). Notably, *Prevotella intermedia*  
 352 SER (CP003503) shows a very high probability ( $> 0.98$ ) to be a chromosome while its  
 353 annotated chromosome (CP003502), unique of its kind, falls within the plasmid class.  
 354 This approach can thus be extended to test the type of replicon for (re)annotation  
 355 purposes.

### 356 **Table 9. Identification of ERs among the extra-chromosomal replicons**

#### 357 a. Candidate-SERs identified among plasmids

REPLICON	PROBABILITY <sup>a</sup>
<i>Acaryochloris marina</i> MBIC11017 plasmid pREB1 [CYANOBACTERIA : Chroococcales] (CP000838)	0.578
<i>Acaryochloris marina</i> MBIC11017 plasmid pREB2 [CYANOBACTERIA : Chroococcales] (CP000839)	0.582
<i>Agrobacterium</i> sp. H13-3 plasmid pAspH13-3a [ $\alpha$ -PROTEOBACTERIA : Rhizobiales] (CP0022)	0.565
<i>Arthrobacter chlorophenolicus</i> A6 plasmid pACHL01 [ACTINOBACTERIA : Actinomycetales] (CP001342)	0.648
<i>Azospirillum brasilense</i> Sp245 plasmid AZOBR_p1 [ $\alpha$ -PROTEOBACTERIA : Rhodospirillales] (HE577328)	0.878
<i>Azospirillum brasilense</i> Sp245 plasmid AZOBR_p2 [ $\alpha$ -PROTEOBACTERIA : Rhodospirillales] (HE577329)	0.591
<i>Azospirillum brasilense</i> Sp245 plasmid AZOBR_p3 [ $\alpha$ -PROTEOBACTERIA : Rhodospirillales] (HE577330)	0.603
<i>Azospirillum lipoferum</i> 4B plasmid AZO_p1e [ $\alpha$ -PROTEOBACTERIA : Rhodospirillales] (FQ311869)	0.722
<i>Azospirillum lipoferum</i> 4B plasmid AZO_p2 [ $\alpha$ -PROTEOBACTERIA : Rhodospirillales] (FQ311870)	0.609
<i>Azospirillum lipoferum</i> 4B plasmid AZO_p4 [ $\alpha$ -PROTEOBACTERIA : Rhodospirillales] (FQ311872)	0.645
<i>Azospirillum</i> sp. B510 plasmid pAB510a [ $\alpha$ -PROTEOBACTERIA : Rhodospirillales] (AP010947)	0.732
<i>Azospirillum</i> sp. B510 plasmid pAB510c [ $\alpha$ -PROTEOBACTERIA : Rhodospirillales] (AP010949)	0.545
<i>Azospirillum</i> sp. B510 plasmid pAB510d [ $\alpha$ -PROTEOBACTERIA : Rhodospirillales] (AP010950)	0.530
<i>Burkholderia phenoliruptrix</i> BR3459a plasmid pSYMBR3459 [ $\beta$ -PROTEOBACTERIA : Burkholderiales] (CP003865)	0.663
<i>Burkholderia phymatum</i> STM815 plasmid pBPHY01 [ $\beta$ -PROTEOBACTERIA : Burkholderiales] (CP001045)	0.733
<i>Burkholderia</i> sp. Y123 plasmid byi_1p [ $\beta$ -PROTEOBACTERIA : Burkholderiales] (CP003090)	0.846
<i>Clostridium botulinum</i> A3 str. Loch Maree plasmid pCLK [FIRMICUTES : Clostridiales] (CP000963)	0.531
<i>Clostridium botulinum</i> Ba4 str. 657 plasmid pCLJ [FIRMICUTES : Clostridiales] (CP001081)	0.531
<i>Cupriavidus metallidurans</i> CH34 megaplasmid [ $\beta$ -PROTEOBACTERIA : Burkholderiales] (CP000353)	0.883
<i>Cupriavidus necator</i> N-1 plasmid BB1p [ $\beta$ -PROTEOBACTERIA : Burkholderiales] (CP002879)	0.500
<i>Cupriavidus pinatubonensis</i> JMP134 megaplasmid [ $\beta$ -PROTEOBACTERIA : Burkholderiales] (CP000092)	0.513
<i>Deinococcus geothermalis</i> DSM 11300 plasmid1 [DEINOCOCCUS-THERMUS : Deinococcales] (CP000358)	0.622
<i>Deinococcus gobiensis</i> I-0 plasmid P1 [DEINOCOCCUS-THERMUS : Deinococcales] (CP002192)	0.812
<i>Ensifer/Sinorhizobium fredii</i> HH103 plasmid pSfHH103e [ $\alpha$ -PROTEOBACTERIA : Rhizobiales] (HE616899)	0.915
<i>Ensifer/Sinorhizobium fredii</i> NGR234 plasmid pNGR234b [ $\alpha$ -PROTEOBACTERIA : Rhizobiales] (CP000874)	0.894
<i>Ensifer/Sinorhizobium medicae</i> WSM419 plasmid pSMED01 [ $\alpha$ -PROTEOBACTERIA : Rhizobiales] (CP000739)	0.942
<i>Ensifer/Sinorhizobium medicae</i> WSM419 plasmid pSMED02 [ $\alpha$ -PROTEOBACTERIA : Rhizobiales] (CP000740)	0.836
<i>Ensifer/Sinorhizobium meliloti</i> 1021 plasmid pSymA [ $\alpha$ -PROTEOBACTERIA : Rhizobiales] (AE006469)	0.818
<i>Ensifer/Sinorhizobium meliloti</i> 1021 plasmid pSymB [ $\alpha$ -PROTEOBACTERIA : Rhizobiales] (AL591985)	0.949
<i>Ensifer/Sinorhizobium meliloti</i> BL2C plasmid pSINMEB01 [ $\alpha$ -PROTEOBACTERIA : Rhizobiales] (CP002741)	0.800
<i>Ensifer/Sinorhizobium meliloti</i> BL2C plasmid pSINMEB02 [ $\alpha$ -PROTEOBACTERIA : Rhizobiales] (CP002742)	0.961
<i>Ensifer/Sinorhizobium meliloti</i> Rm41 plasmid pSYMA [ $\alpha$ -PROTEOBACTERIA : Rhizobiales] (HE995407)	0.922
<i>Ensifer/Sinorhizobium meliloti</i> Rm41 plasmid pSYMB [ $\alpha$ -PROTEOBACTERIA : Rhizobiales] (HE995408)	0.960
<i>Ensifer/Sinorhizobium meliloti</i> SM11 plasmid pSmeSM11c [ $\alpha$ -PROTEOBACTERIA : Rhizobiales] (CP001831)	0.877
<i>Ensifer/Sinorhizobium meliloti</i> SM11 plasmid pSmeSM11d [ $\alpha$ -PROTEOBACTERIA : Rhizobiales] (CP001832)	0.947
<i>Methylobacterium extorquens</i> AM1 megaplasmid [ $\alpha$ -PROTEOBACTERIA : Rhizobiales] (CP001511)	0.538
<i>Novosphingobium</i> sp. PP1Y plasmid Mpl [ $\alpha$ -PROTEOBACTERIA : Sphingomonadales] (FR856861)	0.523
<i>Pantoea</i> sp. At-9b plasmid pPAT9B01 [ $\gamma$ -PROTEOBACTERIA : Enterobacteriales] (CP002434)	0.527

<i>Paracoccus denitrificans</i> PD1222 plasmid1 [ $\alpha$ -PROTEOBACTERIA : Rhodobacterales] (CP000491)	0.769
<i>Ralstonia solanacearum</i> GMI0 plasmid pGMI0MP [ $\beta$ -PROTEOBACTERIA : Burkholderiales] (AL646053)	0.861
<i>Ralstonia solanacearum</i> Po82 megaplasmid [ $\beta$ -PROTEOBACTERIA : Burkholderiales] (CP002820)	0.865
<i>Ralstonia solanacearum</i> PSI07 megaplasmid [ $\beta$ -PROTEOBACTERIA : Burkholderiales] (FP885891)	0.827
<i>Rhizobium etli</i> CFN 42 plasmid p42e [ $\alpha$ -PROTEOBACTERIA : Rhizobiales] (CP000137)	0.700
<i>Rhizobium etli</i> CFN 42 plasmid p42f [ $\alpha$ -PROTEOBACTERIA : Rhizobiales] (CP000138)	0.555
<i>Rhizobium etli</i> CIAT 652 plasmid pA [ $\alpha$ -PROTEOBACTERIA : Rhizobiales] (CP0010)	0.701
<i>Rhizobium etli</i> CIAT 652 plasmid pC [ $\alpha$ -PROTEOBACTERIA : Rhizobiales] (CP001077)	0.792
<i>Rhizobium leguminosarum</i> bv. trifolii WSM1325 plasmid pR132501 [ $\alpha$ -PROTEOBACTERIA : Rhizobiales] (CP001623)	0.711
<i>Rhizobium leguminosarum</i> bv. trifolii WSM1325 plasmid pR132502 [ $\alpha$ -PROTEOBACTERIA : Rhizobiales] (CP001624)	0.741
<i>Rhizobium leguminosarum</i> bv. trifolii WSM2304 plasmid pRLG201 [ $\alpha$ -PROTEOBACTERIA : Rhizobiales] (CP001192)	0.777
<i>Rhizobium leguminosarum</i> bv. trifolii WSM2304 plasmid pRLG202 [ $\alpha$ -PROTEOBACTERIA : Rhizobiales] (CP001193)	0.630
<i>Rhizobium leguminosarum</i> bv. viciae 3841 plasmid pRL11 [ $\alpha$ -PROTEOBACTERIA : Rhizobiales] (AM236085)	0.731
<i>Rhizobium leguminosarum</i> bv. viciae 3841 plasmid pRL12 [ $\alpha$ -PROTEOBACTERIA : Rhizobiales] (AM236086)	0.718
<i>Ruegeria</i> sp. TM1040 megaplasmid [ $\alpha$ -PROTEOBACTERIA : Rhodobacterales] (CP000376)	0.667
<i>Streptomyces cattleya</i> NRRL 8057 plasmid pSCA [ACTINOBACTERIA : Actinomycetales] (FQ859184)	0.727
<i>Streptomyces cattleya</i> NRRL 8057 plasmid pSCATT [ACTINOBACTERIA : Actinomycetales] (CP003229)	0.702
<i>Streptomyces clavuligerus</i> ATCC 27064 plasmid pSCL4 [ACTINOBACTERIA : Actinomycetales] (CM000914)	0.642
<i>Streptomyces clavuligerus</i> ATCC 27064 plasmid pSCL4 [ACTINOBACTERIA : Actinomycetales] (CM001019)	0.642
<i>Thermus thermophilus</i> HB8 plasmid pTT27 [DEINOCOCCUS-THERMUS : Thermales] (AP008227)	0.500
<i>Thermus thermophilus</i> JL-18 plasmid pTTJL1801 [DEINOCOCCUS-THERMUS : Thermales] (CP0033)	0.557
<i>Tistrella mobilis</i> KA081020-065 plasmid pTM2 [ $\alpha$ -PROTEOBACTERIA : Rhodospirillales] (CP003238)	0.578
<i>Tistrella mobilis</i> KA081020-065 plasmid pTM3 [ $\alpha$ -PROTEOBACTERIA : Rhodospirillales] (CP003239)	0.797

## 358 b. Candidate chromosomes identified among extra-chromosomal replicons

REPLICON	PROBABILITY <sup>a</sup>
<i>Anaeba</i> sp. 90 chromosome chANA02 [CYANOBACTERIA : Chroococcales] (CP003285)	0.638
<i>Asticcacaulis excentricus</i> CB 48 chromosome 2 [ $\alpha$ -PROTEOBACTERIA : Caulobacterales] (CP002396)	0.637
<i>Azospirillum brasilense</i> Sp245 plasmid AZOBR_p1 [ $\alpha$ -PROTEOBACTERIA : Rhodospirillales] (HES77328)	0.774
<i>Methylobacterium extorquens</i> AM1 megaplasmid [ $\alpha$ -PROTEOBACTERIA : Rhizobiales] (CP001511)	0.669
<i>Nocardioides dassonvillei</i> DSM 43111 chromosome 2 [ACTINOBACTERIA : Actinomycetales] (CP002041)	0.539
<i>Paracoccus denitrificans</i> PD1222 chromosome2 [ $\alpha$ -PROTEOBACTERIA : Rhodobacterales] (CP000490)	0.778
<i>Prevotella intermedia</i> 17 chromosome II [BACTEROIDETES : Bacteroidales] (CP0033)	0.984
<i>Prevotella melaninogenica</i> ATCC 845 chromosome II [BACTEROIDETES : Bacteroidales] (CP002123)	0.698

359 <sup>a</sup> Probability for an extra-chromosomal replicon, *i.e.*, plasmid or SER, to belong to the SER (a) or Chromosome  
360 (b) class according to the supervised classification procedures.

### 361 **BOX 1. CHARACTERISTICS OF CANDIDATE SERS**

362 According to the literature, most candidate SERS that we detected among plasmids (Table 9a) were  
363 expected to be essential to the cell functioning and/or to the fitness of the organism.

364 • *Azospirillum* genomes are constituted of multiple replicons, at least one of which is expected to be  
365 essential. The largest extra-chromosomal replicon in *A. brasilense* was proposed to be essential for  
366 bacterial life (Wisniewski-Dyé et al., 2011) since it encodes well-conserved housekeeping genes involved  
367 in DNA replication, RNA metabolism and biosynthesis of nucleotides and cofactors, as well as in  
368 transport and protein post-translational modifications. This replicon is unambiguously identified as a SER  
369 by our analyses, as additional replicons found in *A. lipoferum* and *A. sp.* B510, expected homologues

370 to *A. brasilense* SER (Acosta-Cruz et al., 2012). In contrast, other extra-chromosomal replicons classified  
371 as chromids by Wisniewski-Dyé et al. (2012) are unlikely to be true essential replicons. They were not  
372 retrieved among our candidate SERs.

373 • In *Rhizobium etli* CFN42, functional interactions among sequences scattered in the different  
374 extrachromosomal replicons are required for successful completion of life in symbiotic association  
375 with plant roots or saprophytic growth (Brom et al., 2000). p42e (CP000137) is the only replicon other  
376 than the chromosome that contains genes involved in the primary metabolism (Landeta et al., 2011;  
377 Villaseñor *et al.* 2011) and evades its elimination by co-integration with other replicons including the  
378 chromosome (Landeta et al., 2011). Furthermore, homologues to this replicon were identified in the  
379 genomes of other *R. etli* strains as well as other *Rhizobium* species: *R. etli* CIAT652 pA,  
380 *R. leguminosarum* bv. *viciae* 3841 pRL11, *R. leguminosarum* bv. *trifolii* WSM2304 pRLG202 and  
381 *R. leguminosarum* bv. *trifolii* WSM1325 pR132502 (CP001075, AM236085, CP001193, and CP001624,  
382 respectively) (Landeta et al., 2011; Villaseñor et al., 2011). These replicons were thus proposed to be  
383 secondary chromosomes (Landeta et al., 2011).

384 • The genome of *Ensifer/Sinorhizobium meliloti* AK83 was the single multipartite-annotated  
385 *Ensifer/Sinorhizobium* genomes present in our dataset. This bacterium carries two large extra-  
386 chromosomal replicons that are involved in the establishment of the nitrogen fixation symbiosis with  
387 legume plants. pSymA contains most of the genes involved in the nodulation and nitrogen fixation  
388 whereas pSymB carries exopolysaccharide biosynthetic genes, also required for the establishment of the  
389 symbiosis. Our analyses identifies candidate SERs similar to *S. meliloti* AK83 pSymA and pSymB in  
390 other *S. meliloti* strains as well as in *S. fredii* and *S. medicae*. pSymB has been referred to as second  
391 chromosome for carrying genes encoding essential house-keeping functions (Blanca-Ordóñez et al., 2010 ;  
392 Galardini et al., 2011). It shows a higher level of conservation across strains and species than pSymA  
393 (Galardini et al., 2013). pSymA, generally thought to be as stable as pSymB, greatly contribute to the  
394 bacterial fitness in the rhizosphere (Blanca-Ordóñez et al., 2010; Galardini et al., 2013).

395 • The identification of *Methylobacterium extorquens* AM1 1.2 Mb megaplasmid as a SER is supported by  
396 its presence in the genome in a predicted one copy number, by its coding a truncated *luxI* gene essential  
397 for the operation of two chromosomally-located *luxI* genes, as well as the single *umuDC* cluster involved  
398 in SOS DNA repair, and by the presence of a 130 kb region syntenic to a region of similar length in the

399 chromosome of *Methylobacterium extorquens* strain DM4 (Vuilleumier et al., 2009).

400 • The megaplasmid (821 kb) in *Ruegeria* sp. TM1040 carries more rRNA operons (3) than the  
401 chromosome (1) and several unique genes (Moran et al., 2007). *Ruegeria* sp. TM1040 is the only species  
402 in the *Roseobacter* group that possesses a SER. None of the plasmids in the other species included in our  
403 datasets qualified as SERs according to our results in contrast to the commonly held view (Petersen et al.,  
404 2013).

405 • In *Burkholderia* genus, additional ERs possess a centromere whose sequence is distinct from, but  
406 strongly resembles that of the chromosome centromere (Dubarry et al., 2009). However, these  
407 centromeres have a common origin and a plasmid ancestry (Passot et al., 2012). The evolution of these  
408 replicons into SERs is best accounted for by the high level of plasticity observed in the *Burkholderia*  
409 genomes, with extra-chromosomal replicons going through extensive exchange of genetic material among  
410 them as well as with the chromosomes (Maida et al., 2014).

411 • *Acaryochloris marina* MBIC11017 pREB1 (CP000838) and pREB2 (CP000839) plasmids were  
412 identified as candidate SERs. Both these megaplasmids code for metabolic key-proteins, and are thus  
413 likely to contribute to the bacterium fitness (Swingley et al., 2008).

414 • The genomes of *Streptomyces cattleya* NRRL8057 and *S. clavuligerus* ATCC27064 harbour a linear  
415 megaplasmid (1.8 Mb) that shows a high probability ( $P \approx 0.7$ ) to be a SER. The megaplasmid of  
416 *S. cattleya* NRRL8057 encodes genes involved in the synthesis of various antibiotics and secondary  
417 metabolites and is expected to be important to the life of the bacterium in its usual habitat (Barbe et al.,  
418 2011; O'Rourke et al., 2009). In *S. clavuligerus* ATCC27064, none of the megaplasmid-encoded genes are  
419 expected to belong to the core genome (Medema et al., 2010). However, the megaplasmid is likely to  
420 contribute to the bacterium fitness. It represents more than 20% of the coding genome and constitutes a  
421 large reservoir of genes involved in bioactive compound production and cross-regulation with the  
422 chromosome (Medema et al., 2010). Furthermore, *S. clavuligerus* chromosome requires the SER-encoded  
423 *tap* gene involved in the telomere replication.

424 • *Butyrivibrio proteoclasticus* B316 harbours two plasmid, one of which, pCY186 plasmid (CP001813),  
425 was identified as a candidate SERs by our analysis, albeit with a low probability (0.56). In support to this,  
426 it carries numerous genes coding for proteins involved in replication of the chromosome (Yeoman et al.,  
427 2011). The second plasmid in that strain, pCY360 (CP001812), also proposed to be an essential replicon

428 in that bacterium (Yeoman et al., 2011), presents too low a probability ( $P = 0.32$ ) in our analysis to qualify  
429 as a SER.

## 430 **DISCUSSION**

431 The SERs clearly stand apart from plasmids, including those that occur consistently in a  
432 bacterial species, *e.g.*, *Lactobacillus salivarius* pMP118-like plasmids (Li et al., 2007).

433 The replicon size proposed as a primary classification criterion to separate the SERs  
434 from the plasmids (diCenzo and Finan, 2017; Harrison et al., 2010) proves to be  
435 inoperative. The IS profiles accurately identify the SERs of *Leptospira* and *Butyrivibrio*  
436 despite their plasmid-like size, and unambiguously ascribe the chromosomes in the  
437 reduced genomes of endosymbionts (sizes down to 139 kb) to the chromosome class.

438 Conversely, they assign *Rhodococcus jostii* RHA1 1.12 Mb-long pRHL1 replicon to the  
439 plasmid class, and do not discriminate the megaplasmids ( $>350$  kb (diCenzo and Finan,  
440 2017)) from smaller plasmids. Plasmids may be stabilized in a bacterial population by  
441 rapid compensatory adaptation that alleviates the fitness cost incurred by their presence  
442 in the cell (San Millan et al., 2014; Hall et al., 2017; Stalder et al., 2017). This  
443 phenomenon involves mutations either on the chromosome only, on the plasmid only, or  
444 both, and does not preclude the segregational loss of the plasmid. On the contrary, SERs  
445 code for chromosome-type IS proteins that integrate them constitutively in the species  
446 genome and the cell cycle. The SERs thence qualify as essential replicons regardless of  
447 their size and of the phenotypical/ecological, possibly essential, functions that they  
448 encode and which vary across host taxa.

449 Yet, SERs also carry plasmid-like ISs, suggesting a role for plasmids in their formation.

450 The prevailing opinion assumes that SERs derive from the amelioration of  
451 megaplasmids (diCenzo and Finan, 2017; diCenzo et al., 2013; Harrison et al., 2010;

452 MacLellan et al., 2004; Slater et al., 2009): a plasmid bringing novel functions for the  
453 adaptation of its host to a new environment is stabilized into the bacterial species  
454 genome through the transfer from the chromosome of essential genes (diCenzo and  
455 Finan, 2017; Slater et al., 2009). However, the generalized presence of chromosome-like  
456 ISs in the SERs of the various taxa with multipartite genomes is unlikely to derive from  
457 the action of environment-specific and lineage-specific selective forces. In reverse, all  
458 bacteria with similar lifestyle and exhibiting some phylogenetic relatedness may not  
459 harbor multiple ERs (*e.g.*,  $\alpha$ -proteobacterial nitrogen-fixing legume symbionts). Also,  
460 the gene shuttling from chromosome to plasmid proposition fails to account for the  
461 situation met in the multipartite genomes of *Asticacaulis excentricus*, *Paracoccus*  
462 *denitrificans* and *Prevotella* species. Their chromosome-type ISs are evenly distributed  
463 between the chromosome and the SER whereas their homologues in the mono- or  
464 multipartite genomes of most closely related species are primarily chromosome-coded  
465 (see Table 10 for an example). This pattern, mirrored in their whole gene content (Naito  
466 et al., 2016; Poirion, 2014), hints at the stemming of the two essential replicons from a  
467 single chromosome by either a splitting event or a duplication followed by massive gene  
468 loss. Neither mechanism informs on the presence of plasmid-type maintenance  
469 machinery on one of the replicons. The severing of a chromosome generates a single  
470 true replicon carrying the chromosome replication origin and an origin-less remnant,  
471 whilst the duplication of the chromosome produces two chromosomal replicons with  
472 identical maintenance systems. Whereas multiple copies of the chromosome are known  
473 to cohabit constitutively in polyploid bacteria (Ohtani et al., 2010), the co-occurrence of  
474 dissimilar chromosomes bearing identical replication initiation and partition systems is  
475 yet to be described in bacteria.

**Table 10. IS profiles of *Paracoccus denitrificans* vs. *Rhodobacter sphaeroides* (Rhodobacterales)**

Chromosome-like IS functions coded only by the SER in *P. denitrificans* or *R. sphaeroides* whilst by the chromosome in other Rhodobacterales are indicated by an asterisk. Numbers corresponds to the number of homologues (*P. denitrificans* PD1222) or the percentage of function-coding replicons (*R. sphaeroides* and Rhodobacterales genomes).

476  
477

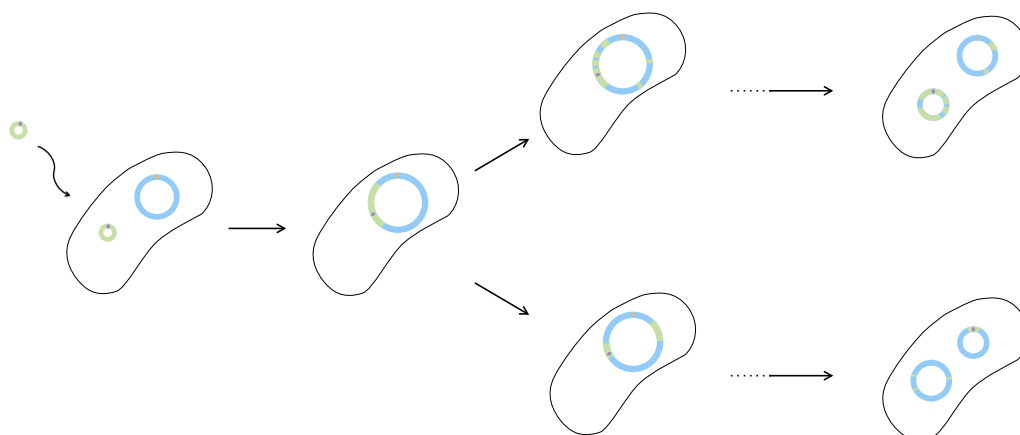
IS FUNCTION GROUP		<i>Paracoccus denitrificans</i> PD1222			<i>Rhodobacter sphaeroides</i>			Other Rhodobacterales		
		chromosome1 (CP000489)	chromosome2 (CP000490)	plasmid1 (CP000491)	chromosome % (n=12)	SER % (n=12)	plasmid % (n=14)	chromosome % (n=12)	plasmid % (n=33)	
KEGG entry (chromosome-like)	REPLICATION	CbpA	1				100		75	
	Dam	1				50	75		25	
	DnaA	*	1			100			92	
	DnaB	*	1			100			100	
	DnaC					25			3	
	DnaG	*	1			100			100	
	Dps	1							50	
	Fis	*	1			100			75	
	Hda								42	
	Hfq	*	1			100			100	
	H-NS	2	2			100		29	67	
	HupA								17	
	HupB	1				100			100	
	IciA	1						36	67	
	IhfA, HimA	1				100			100	
	IhfB, HimD	*	1			*	100		100	
	Lrp	4	1	3		100	25	50	100	
	Rob					25			8	
	ssb	1	3			100	100		100	
	Fic							7	8	
	GidA, MnmG, MTO1	1				100			100	
	GidB, RsmG	1				100			100	
	MreB	*	1			100			92	
	MreC	*	1			100			92	
	MreD	*	1			100			92	
Mrp	1				100			100		
ParA, Soj	4	1			100			100		
ParB, Spo0J	3	1	1		100	75		100		
ParC	1	1			100			100		
ParE	1				100			100		
RodA, MrdB	*	1			100			92		
TrmFO, Gid	*	1			100			100		
XerC	1				100			100		
XerD	1				100	25	7	100		
SEGREGATION	ScpA	1			100			100		
ScpB	1				100			100		
Smc	1				100			100		
AcrA	2	2			*	100	7	58		
AmiA, AmiB, AmiC	1				100			100		
FtsA	*	1			100			83		
FtsE	1				100		7	92		
FtsI	1				100			92		
FtsK, SpoIIIE	1				100			100		
FtsQ	*	1			100			92		
FtsW, SpoVE	1				100			100		
FtsX	1				100		7	92		
FtsZ	*	1			100			100		
MinC				1						
MinD				1			75	75		
MinE				1						
ZapA	1				100			100		
ACLAME family (plasmid-like)	REPLICATION	DNA helicase				25	50	7	25	
	Helicase-1	1	1			100	50		92	
	Helicase-2								8	
	DNA repair								8	
	RepA	2	2					43	42	
	RepAEB			1			100	7	15	
	RepC	1				50		43	8	
	RuvB	1				100		7	92	
	ATPase, TyrK, ExoP	2				100	50	14	75	
	ParA, ParM		1	1			100	100	8	
	ParB					75	100	93	25	
	plasmid dimer resolution							14	15	
	Serine recombinase	3				25		50	50	
	Tyrosine recombinase					25		7	33	
	Xer-like tyrosine recombinase		1			25	50		33	
	XerD					25				
	MAINTENANCE	Ccd (PSK)						7		
	HicAB (PSK)							7		
	HigBA (PSK)	2						14	17	
	MazEF (PSK)							7	6	
ParDE (PSK)	2	6			25	50	7	8		
PhD, Doc (PSK)							7			
RelBE (PSK)	1							3		
VapBC/Vag (PSK)	3	2					14	8		



479 We propose that the requirement for maintenance system compatibility between co-  
480 occurring replicons is the driving force behind the presence of plasmid-type replication  
481 initiation and maintenance systems in bacterial SERs. Indeed, genes encoding  
482 chromosome-like replication initiators (DnaA) are hardly found on SERs. When they  
483 are, in *Paracoccus denitrificans*, *Prevotella intermedia* and *P. melaninogenica*, the  
484 annotated chromosome in the corresponding genome does not carry one. Similarly,  
485 chromosomal centromeres (*parS*) are found on a single replicon within a multipartite  
486 genome, which is the chromosome in all genomes but one. In *P. intermedia*  
487 (GCA\_000261025.1), both replication initiation and partition systems define the SER as  
488 the *bona fide* chromosome and the annotated chromosome as an extra-chromosomal  
489 replicon. The harmonious coexistence of different replicons in a cell requires that they  
490 use divergent enough maintenance systems. In the advent of a chromosome fission or  
491 duplication, the involvement of an autonomously self-replicating element different from  
492 the chromosome is mandatory to provide one of the generated DNA molecules with a  
493 (non-chromosomal) maintenance machinery.

494 ‘Plasmid-first’ and ‘chromosome-first’ hypotheses can be reconciled into a unified,  
495 general Fusion-Shuffling-Scission model of SER emergence where a chromosome and a  
496 plasmid combine into a cointegrate (Fig. 6). Plasmids are known to merge or to integrate  
497 chromosomes in both experimental settings (Brom et al., 2000 ; Guo et al., 2003;  
498 Iordănescu, 1975 ; Sýkora, 1992) and the natural environment (Cervantes et al., 2011;  
499 Naito et al., 2016; Sýkora, 1992), as are the SER and chromosome of a multipartite  
500 genome (Val et al., 2014; Xie et al., 2017; Yamamoto et al., 2018). When integrated, the  
501 plasmids/SERs can thus replicate with the chromosome and persist in the bacterial  
502 lineage through several generations (Cervantes et al., 2011; Val et al., 2014; Xie et al.,  
503 2017). The co-integrate may resolve into its original components (Guo et al., 2003; Val

504 et al., 2014) or give rise to novel genomic architectures (Guo et al., 2003; Cervantes et  
 505 al., 2011; Val et al., 2014). The co-integration state likely facilitates inter-replicon gene  
 506 exchanges and genome rearrangements that may lead to the translocation of large  
 507 chromosome fragments to the resolved plasmid (Guo et al., 2003; Val et al., 2014).  
 508 Multiple cell divisions, and possibly several merging-resolution rounds, could provide  
 509 time and opportunity for the plasmid-chromosome re-assortment to take place, and for  
 510 multiple essential replicons and a viable distributed genome to form ultimately. In the  
 511 novel genome, one ER retains the chromosome-like origin of replication and  
 512 centrosome, and the other the plasmidic counterparts. The novel ERs differ from the  
 513 chromosome and plasmid that gathered in the progenitor host at the onset. They thus  
 514 constitute neo-chromosomes that carry divergent maintenance machineries and can  
 515 cohabit and function in the same cell. Depending on the number of cell cycles spent as  
 516 co-integrate, the level of genome reorganization, the acquisition of genetic material and  
 517 the environmental selective pressure acting upon the host, the final essential replicons  
 518 may exhibit diverse modalities of genome integration (Figure 6).



519  
 520 **Figure 6. Fusion-Shuffling-Scission model of distributed genome evolution**

521 Origins of replication are represented by diamonds.

522

523 The Fusion-Shuffling-Scission model of genome evolution that we propose accounts for  
524 the extreme plasticity met in distributed genomes and the eco-phenotypic flexibility of  
525 their hosts. Indeed, having a distributed genome appears to extend and accelerate the  
526 exploration of the genome evolutionary landscape, producing complex regulation  
527 (diCenzo et al., 2018; Galardini et al., 2015; Jiao et al., 2018) and leading to novel eco-  
528 phenotypes and species diversification (*e.g.*, Burkholderiaceae and Vibrionaceae).  
529 Furthermore, this model may explain the observed separation of the replicons according  
530 to taxonomy. Chromosomes and plasmids thus appear as extremes on a continuum of a  
531 lineage-specific genetic material.

## 532 **MATERIALS AND METHODS**

533 To understand the relationships between the chromosomal and plasmidic replicons, we  
534 focused on the distribution of Inheritance System (IS) genes for each replicon and built  
535 networks linking the replicons given their IS functional orthologues (Fig. 2).

### 536 **Retrieval of IS functional homologues**

537 A sample of proteins involved in the replication and segregation of bacterial replicons  
538 and of the bacterial cell cycle was constructed using datasets available from the  
539 ACLAME (Leplae et al., 2010) and KEGG (Kanehisa et al., 2012) databases. Gene  
540 ontologies for “replication”, “partition”, “dimer resolution”, and “genome maintenance”  
541 (Table 11) were used to select related ACLAME plasmid protein families (Table 1)  
542 using a semi-automated procedure.

543  
544

**Table 11. Gene ontologies related to plasmid ISs used to select groups of orthologous proteins from the ACLAME database**

PROCESS	ONTOLOGY	DESCRIPTION
Replication	<i>go:0006270</i>	DNA replication initiation
	<i>phi:0000268</i>	plasmid vegetative DNA replication
	<i>go:0003896</i>	DNA primase activity
	<i>go:0003887</i>	DNA-directed DNA polymerase activity
	<i>go:0045020</i>	error-prone DNA repair
	<i>go:0006260</i>	DNA replication
	<i>phi:0000114</i>	DNA helicase activity
	<i>go:0006281</i>	DNA repair
	<i>phi:0000196</i>	plasmid copy number control
	<i>go:0003677</i>	DNA binding
Partition	575	plasmid partitioning protein family ParB/Spo0J
	<i>go:0015616</i>	DNA translocase activity
	576	plasmid partitioning protein family ParM
	<i>go:0000146</i>	microfilament motor activity
	<i>go:0007059</i>	chromosome segregation
	<i>go:0015616</i>	DNA translocase activity
	<i>go:0007059</i>	chromosome segregation
	<i>go:0016887</i>	ATPase activity
	<i>go:0030541</i>	plasmid partitioning
	<i>go:0051302</i>	regulation of cell division
Dimer resolution	<i>phi:0000196</i>	plasmid copy number control
	<i>phi:0000134</i>	site specific DNA excision
	<i>phi:0000144</i>	serine based recombinase activity
	<i>phi : 0000131</i>	site specific DNA recombinaison
	<i>phi : 0000143</i>	Tyrosine-based recombinase activity
	<i>phi : 0000304</i>	plasmid dimer resolution
	<i>go : 0015616</i>	DNA translocase activity
	<i>phi:0000136</i>	transpositional recombination
Maintenance	<i>go : 0016740</i>	transferase activity
	<i>phi : 0000262</i>	toxin
	<i>phi:0000322</i>	PSK
	547	TA family parDE
	544	TA family epsilon zeta
	<i>go:0009008</i>	DNA methyltransferase activity
	<i>phi : 0000264</i>	nucleoid associated protein
	<i>go : 0006276</i>	plasmid maintenance

545 KEGG orthology groups were selected following the KEGG BRITE hierarchical  
 546 classification (Table 2). Then, the proteins belonging to the relevant 92 ACLAME  
 547 protein families and 71 KEGG orthology groups (3,847 and 43,757 proteins,  
 548 respectively) were retrieved and pooled. Using this query set amounting to a total of

549 47,604 proteins, we performed a *blastp* search of the 6,903,452 protein sequences  
550 available from the 5,125 complete sequences of bacterial replicons downloaded from  
551 NCBI Reference Sequence database (RefSeq) (Pruitt et al., 2007) on 30/11/2012. We  
552 identified 358,624 putative homologues using BLAST default parameters (Camacho et  
553 al., 2009) and a  $10^{-5}$  significance cut-off value. We chose this *E*-value threshold to  
554 enable the capture of similarities between chromosome and plasmid proteins whilst  
555 minimizing the production of false positives, *i.e.*, proteins in a given cluster exhibiting  
556 small *E*-values despite not being functionally homologous. Using RefSeq ensured the  
557 annotation consistency of the genomes included in our dataset.

#### 558 **Clustering of IS functional homologues**

559 Using this dataset, we inferred clusters of IS functional homologues by coupling of an  
560 *all-versus-all blastp* search using a  $10^{-2}$  *E*-value threshold and a TRIBE-MCL (Enright et  
561 al., 2002) clustering procedure. As input to TRIBE-MCL, we used the matrix of log  
562 transformed *E*-value,  $d(p_i, p_j) = -\log_{10}(e_{value}(p_i, p_j))$ , obtained from the comparisons  
563 of all possible protein pairs. Using a granularity value of 4.0 (see below), we organized  
564 the 358,624 IS homologues into 7013 clusters, each comprising from a single to 1990  
565 proteins (Figure 3). We annotated IS homologues according to their best match (BLAST  
566 hit with the lowest *E*-value) among the proteins of the query set, *i.e.*, according to one of  
567 the 117 functions of the query set (71 from KEGG and 46 from ACLAME). Then, we  
568 named the clusters of functional homologues using the most frequent annotation among  
569 the proteins in the cluster. We used the number of protein annotations in a cluster to  
570 determine the cluster quality, a single annotation being optimal. To select the best  
571 granularity and to estimate the consistency of the clusters in terms of functional  
572 homologues, we computed the weighted Biological Homogeneity Index (*wBHI*,

573 modified from the *BHI* (Datta and Datta, 2006), each cluster being weighted by its size)  
574 and the Conservation Consistency Measure (*CCM*, similar to the *BHI* but using the  
575 functional domains of the proteins to define the reference classes), which both take into  
576 account the size distribution of the clusters (See next paragraph for details on index  
577 calculation). The former gives an estimation of the overall consistency of clusters  
578 annotations according to the protein annotations whereas the latter gives an estimation of  
579 cluster homogeneity according to the protein domains identified beforehand. To build  
580 the sets of functional domains, we performed an *hmmscan* (Finn et al., 2011) procedure  
581 against the Pfam database (Finn et al., 2016) of each of the 358,624 putative IS  
582 homologues. We annotated each protein according to the domain match(es) with *E*-value  
583  $< 10^{-5}$  (individual *E*-value of the domain) and *c-E*-value  $< 10^{-5}$  (conditional *E*-value that  
584 measures the statistical significance of each domain). If two domains overlapped, we  
585 only considered the domain exhibiting the smallest *E*-value. We estimated *wBHI* and  
586 *CCM* indices for the clustering of the IS homologues and compared with values obtained  
587 for random clusters simulated according to the cluster size distribution of the IS proteins,  
588 irrespective of their length or function. For each of the clustering obtained for different  
589 granularities, we constructed a random clustering following the original cluster size  
590 distribution (assessed with a  $\chi^2$  test) and composed with simulated proteins according to  
591 the distributions of the type and number of functional domains of the data collected from  
592 the 358,624 IS homologues. Overall, the clusters obtained using a granularity of 4.0 with  
593 the TRIBE-MCL algorithm appeared to be homogenous in terms of proteins similarities  
594 toward their best BLAST hits and their functional domain distributions (see below).

### 595 **Evaluation of the clustering procedures**

596 In order to select the best granularity and to estimate the consistency of the clusters in

597 terms of functional homologs, we computed the *weighted Biological Homogeneity Index*  
 598 (*wBHI*) and the *Conservation Consistency Measure (CCM)*. The former gives an  
 599 estimate of the overall consistency of clusters annotations according to the protein  
 600 annotations whereas the latter gives an estimate of cluster homogeneity according to  
 601 protein domains identified beforehand. Although close to the *Biological Homogeneity*  
 602 *Index (BHI)* introduced by Datta and Datta (2006), both these indices take into account  
 603 the size distribution of the clusters.

604 The *BHI* was originally introduced to measure the biological homogeneity of clusters  
 605 according to reference classes to evaluate clusters obtained with microarray data (Datta  
 606 and Datta, 2006). Given a clustering  $C = \{C_1, \dots, C_k\}$  of  $k$  clusters with  $n_i$  the size of the  
 607 cluster  $C_i$ , a set of  $m$  proteins  $P = \{P_1, \dots, P_m\}$  and a set  $r$  of reference classes  $R$  where each  
 608 class  $R_i$  could be linked to the  $m$  proteins, the *BHI* is defined as:

$$BHI = \frac{1}{k} \sum_{i=0}^{i < k} c_i$$

609 where  $c_i$  is defined as:

$$c_i = \frac{1}{(n_i(n_i - 1))} \sum_{P_i, P_j \in C_i} d(P_i, P_j)$$

610 where  $d(P_i, P_j) = 1$  if  $P_i$  and  $P_j$  share at least one common reference class, and  $d(P_i, P_j) = 0$   
 611 otherwise. The reference classes here are the annotations defined according to the  
 612 protein best BLAST hit. The *BHI* is thus an easy-to-interpret measure, which value is  
 613 maximal when, for all clusters, all the proteins in a cluster share at least one annotation.

614 The *wBHI* is a modification of the *BHI*, where each cluster is weighted by its size  $m$ .  
 615 Following the previous notation scheme, the *wBHI* is defined as:

$$wBHI = \frac{1}{m} \sum_{i=0}^{i < k} 2 \cdot c_i \cdot n_i$$

616 The *CCM* is similar to the *BHI* but the functional domains of the proteins are used to  
 617 define the reference classes. The distance between the proteins is here computed as the  
 618 Jaccard distance between the functional domain sets of the proteins. Every protein  $P_i$  can  
 619 be described as a vector of functional domains,  $D_{P_i} = \{d_1, \dots, d_x\}$ . The Jaccard distance  
 620 between the two sets of domains  $d_2(P_i, P_j)$  can be defined as:

$$d_2(P_1, P_2) = 1 - \frac{|D_{P_1} \cap D_{P_2}|}{|D_{P_1} \cup D_{P_2}|}$$

621 where  $D_{P_1}$  and  $D_{P_2}$  are the clans or domains (when no clan could be assigned) identified  
 622 in  $P_1$  and  $P_2$  respectively. For a given cluster  $C_i$ , the *CCM* is calculated as:

$$CCM = \frac{1}{m} \sum_{i=0}^{i < k} 2 \cdot c'_i \cdot n_i$$

623 where  $c'_i$  is defined as:

$$c'_i = \frac{1}{(n_i(n_i - 1))} \sum_{P_i, P_j \in C_i} d_2(P_i, P_j)$$

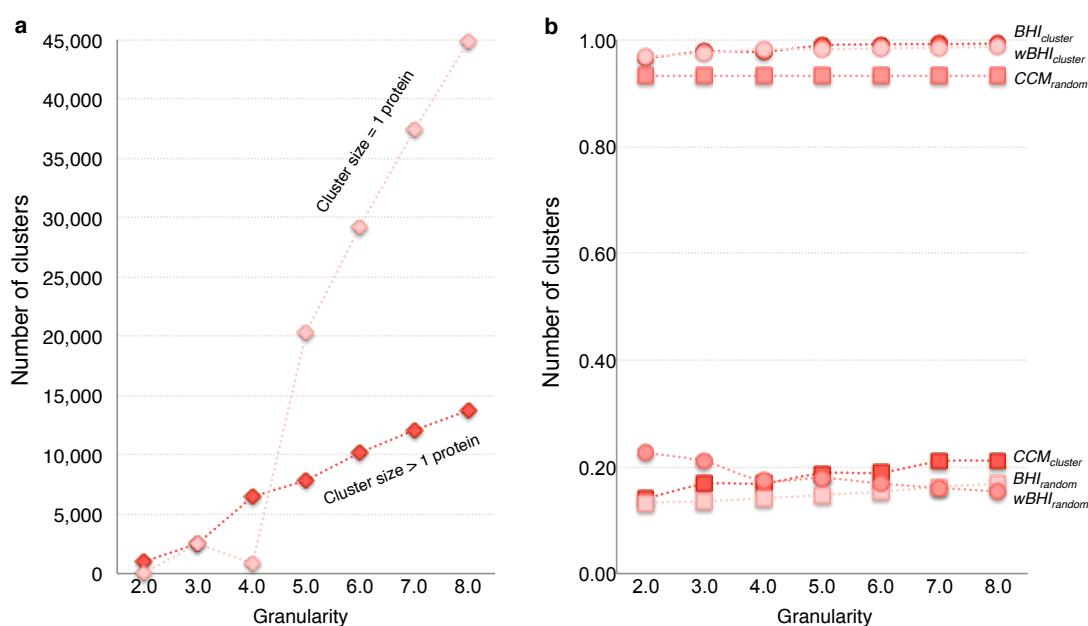
624 Clusters which proteins have similar domains result in a *CCM* value close to 0, whereas  
 625 a *CCM* value close to 1 indicates that the clusters hold proteins with little domain  
 626 overlap.

### 627 **Choice of the clustering granularity**

628 We tested several levels of granularity to optimize the TRIBE-MCL clustering and  
 629 obtain the most informative IS clustering in terms of functional linkage. Too low a  
 630 granularity would produce large clusters containing multiple functional families. In turn,  
 631 increasing the granularity results in the tightening of the cluster. A high granularity tends  
 632 to split clusters harboring different protein subfamilies (*e.g.*, a cluster composed of  
 633 proteins from the tyrosine recombinase superfamily) and to produce multiple clusters of  
 634 proteins belonging to a single function family according to their level of sequence



635 dissimilarity. Furthermore, too high a granularity would result in the formation of  
 636 numerous single protein clusters, and would dramatically increase the computation times  
 637 of the following analyses. A granularity level of 4.0 constituted a good compromise  
 638 (Figure 8). Values of *CCM* and *BHI* are slightly improved compared to granularities of  
 639 2.0 and 3.0, and the high but still workable number of clusters is expected to prevent the  
 640 formation of clusters mingling distinct protein subfamilies.



641 **Figure 8. Influence of granularity on the clustering**  
 642 (a) Number of clusters with more than one protein (dark diamonds) or clusters holding a single protein (pale  
 643 diamonds). (b) *BHI* (dark), *wBHI* (pale) and *CCM* (medium) scores obtained with random clusters (squares) and  
 644 normal clusters (circles), respectively.

### 645 **Assessment of the homogeneity of IS functional homologues**

646 The homogeneity towards the functions of the proteins in the query set relied on the  
 647 assumption that the first BLAST cut-off ( $10^{-5}$  *E*-value) was stringent enough to capture  
 648 only functional homologues to the query proteins. Potential bias might nevertheless arise  
 649 from query proteins possessing a supplementary functional domain unrelated to the IS  
 650 role, or from the selection of proteins belonging to the same superfamily but differing in

651 function. To address these issues, we calculated the functional vectors associated to each  
 652 KEGG group or ACLAME family of the query set, as well as those for all obtained  
 653 clusters. For a protein  $P_i$ , we defined the associated functional vector with respect to its  
 654 set of identified domains  $D_{P_i}$  and to the set of all identified domains  $D=\{d_1, \dots, d_x\}$  as:

$$v_{P_i} = (n_{d_1}^{P_i}, \dots, n_{d_x}^{P_i})$$

655 where  $n_{d_i}^{P_i}$  is the number of time  $d_i$  is found in  $D_{P_i}$ . The functional vector associated to a given  
 656 cluster of proteins  $C_i$  could then be defined as:

$$v_{C_i} = (n_{d_1}^{C_i}, \dots, n_{d_x}^{C_i})$$

657 where  $n_{d_i}^{C_i}$  is defined as:

$$n_{d_i}^{C_i} = \frac{1}{|C_i|} \sum_{P_j \in C_i} n_{d_x}^{P_j}$$

658 For each cluster  $C_0$ , the cosine distance between its associated vector  $v_{C_0}$  and the associated  
 659 vector  $v_{C_a}$  of the corresponding KEGG group or ACLAME family annotations  $C_a$  was then  
 660 computed as:

$$d_{\cosine}(v_{C_a}, v_{C_0}) = 1 - \frac{\sum_{i=1}^X n_{d_i}^{C_0} \cdot n_{d_i}^{C_a}}{\sqrt{\sum_{i=1}^X n_{d_i}^{C_0^2} \cdot \sum_{i=1}^X n_{d_i}^{C_a^2}}}$$

661 For each cluster  $C_0$ , the cosine distance between its associated vector  $v_{C_0}$  and the  
 662 associated vector  $v_{C_a}$  of the corresponding KEGG group or ACLAME family  
 663 annotations  $C_a$  was then computed as:

$$d_{\cosine}(v_{C_a}, v_{C_0}) = 1 - \frac{\sum_{i=1}^X n_{d_i}^{C_0} \cdot n_{d_i}^{C_a}}{\sqrt{\sum_{i=1}^X n_{d_i}^{C_0^2} \cdot \sum_{i=1}^X n_{d_i}^{C_a^2}}}$$

664 The  $d_{\cosine}(v_{C_a}, v_{C_0})$  values were compared with those obtained using random clusters  
 665  $C_r$  of the same size than  $C_0$ . For each  $C_0$  and its corresponding  $C_a$ , 200 random clusters  
 666 and their associated distances  $d_{\cosine}(v_{C_a}, v_{C_r})$ , from which the corresponding empirical

667 distribution  $D_e$  was constructed, were computed.  $C_0$  is then considered as noise if  
 668  $d_{\cosine}(v_{C_a}, v_{C_0}) \notin Q_{10\%}^{D_e}$  where  $Q_{10\%}^{D_e}$  is the 0.1-quantile of  $D_e$ .

### 669 **Unsupervised analyses of the replicon space**

670 We represented the bacterial replicons (Supplementary Table 1) as vectors according to  
 671 their content in IS genes. The number of IS protein clusters retained for the analysis  
 672 determined the vector dimension and the number of proteins in a replicon assigned to  
 673 each cluster gave the value of each vector component. We built matrices  
 674  $P = \begin{bmatrix} p_{1,1} & \cdots & p_{1,m} \\ \vdots & \ddots & \vdots \\ p_{n,1} & \cdots & p_{n,m} \end{bmatrix}$ , where  $n$  is the number of replicons,  $m$  the number of protein  
 675 clusters, and  $p_{i,j}$  the number of proteins of the  $j^{th}$  cluster encoded by a gene present on the  
 676  $i^{th}$  replicon. We constructed several datasets to explore both the replicon type and the  
 677 host taxonomy effects on the separation of the replicons in the analyses (Table 12).

678 **Table 12. Reference classes used in the evaluation of the replicon IS protein-based**  
 679 **unsupervised clustering solutions**

EVALUATED SEPARATION	ENSEMBLE	NORMALIZED ENSEMBLE <sup>a</sup>
Chromosomes vs. Plasmids	$\{R^{\{chromosome\}}, R^{\{plasmid\}}\}$	$\{\overline{K}l_{genus}^{chromosome}, \overline{K}l_{genus}^{plasmid}\}$
Chromosomes <i>per</i> host phylum	$Kl_{phylum}^{chromosome}$	$\overline{K}l_{genus}^K   K \in Kl_{phylum}^{chromosome}$
Chromosomes <i>per</i> host class	$Kl_{class}^{chromosome}$	$\overline{K}l_{genus}^K   K \in Kl_{class}^{chromosome}$
Plasmids <i>per</i> host phylum	$Kl_{phylum}^{plasmid}$	$\overline{K}l_{genus}^K   K \in Kl_{phylum}^{plasmid}$
Plasmids <i>per</i> host class	$Kl_{class}^{plasmid}$	$\overline{K}l_{genus}^K   K \in Kl_{class}^{plasmid}$

680 <sup>a</sup> Normalisation according to host genus

681 The taxonomic representation bias was taken into account by normalizing the data with

682 regard to the host genus: a consensus vector was built for each bacterial genus present in  
683 the datasets. The value of each vector attribute was calculated as the mean of the  
684 attribute values in the vectors of the replicons that belong to the same bacterial genus.

685 As a first approach, we transformed data into bipartite graphs whose vertices are the  
686 replicons and the proteins clusters. The graphs were spatialized using the force-directed  
687 layout algorithm ForceAtlas2 (Jacomy et al., 2014) implemented in Gephi (Bastian et al.,  
688 2009). Bipartite graphs are a powerful way of representing the data by naturally drawing  
689 the links between the replicons while enabling the detailed analysis of the IS cluster-  
690 based connections of each replicon by applying forces to each node with regard to its  
691 connecting edges. To investigate further the IS-based relationships of the replicons, we  
692 applied the community structure detection algorithm INFOMAP (Rosvall and  
693 Bergstrom, 2008) using the *igraph* python library (Csardi and Nepusz, 2006). We also  
694 performed a WARD hierarchical clustering (Johnson, 1967) after a dimension reduction  
695 of the data using a Principal Component Analysis (Hotelling, 1933). To select an  
696 optimal number of principal components, we relied on the measurements of the cluster  
697 stabilities using a *stability criterion* (Hennig, 2007) and retained the first 30 principal  
698 components (57% of the total variance). For consistency purpose, the number of clusters  
699 in the WARD analysis was chosen to match that obtained with the INFOMAP  
700 procedure. The number of clusters used was assessed by the stability index by Fang and  
701 Wang (2012) (Table 3). The quality of the projection and clustering results were  
702 confirmed using the V-measure indices (Rosenberg and Hirschberg, 2007) (*homogeneity*,  
703 *completeness*, *V-measure*) as external cluster evaluation measures (Table 3). The  
704 *homogeneity* indicates how uniform clusters are towards a class of reference. The  
705 *completeness* indicates whether reference classes are embedded within clusters. The *V-*  
706 *measure* is the harmonic mean between these two indices and indicates the quality of a

707 clustering solution relative to the classes of reference. These three indices vary between  
708 0 and 1, with values closest to 1 reflecting the good quality of the clustering solution.  
709 The type of replicons (*i.e.*, plasmid or chromosome) and the taxonomic affiliation  
710 (phylum or class) for chromosomes or plasmids were used as references classes (Table  
711 12). Additionally, the *stability criterion* (Hennig, 2007) of individual clusters, weighted  
712 by their size, for a given clustering result was evaluated using the bootstrapping of the  
713 original dataset as re-sampling scheme. Individual Jaccard coefficient for each replicon  
714 were computed as the number of times that a given replicon of a cluster in a clustering  
715 solution is also present in the closest cluster in the resampled datasets.

#### 716 **Functional characterization of the replicons and genomes**

717 In order to characterize the functional bias of the replicons, 117 IS functionalities (46  
718 from ACLAME and 71 from KEGG) were considered. When equivalent in plasmids and  
719 chromosomes, functions from ACLAME and KEGG databases were considered to be

720 distinct. A  $n*m$  matrix  $F = \begin{bmatrix} f_{1,1} & \cdots & f_{1,m} \\ \vdots & \ddots & \vdots \\ f_{n,1} & \cdots & f_{n,m} \end{bmatrix}$  with  $n$  the number of replicons and  $m$  the

721 number of IS functionalities, was used as input to the projection algorithms.  $f_{i,j}$   
722 represents the number of times that genes coding for proteins annotated with the  $j^{th}$   
723 function are present on the  $i^{th}$  replicon. Several datasets were analysed using PCA  
724 dimension reduction of the data followed by WARD hierarchical clustering (Table 3).

#### 725 **Logistic regression analyses**

726 Several reference classes of replicons and complete genomes were considered for  
727 comparison (Table 13). Ambiguous, *i.e.*, potentially adapted, plasmids belonging to  
728 INFOMAP clusters of plasmid replicons partially composed of SERs and/or  
729 chromosomes were removed from the plasmid class. When appropriate, the taxonomic

730 representation bias was taken into account by normalizing the data with regard to the  
 731 host genus as before. Logistic regressions (McCullagh and Nelder, 1989) were  
 732 performed for the 117 IS functions using the R glm package coupled to the python  
 733 binder rpy2. The computed  $P_{value}$  measured the probability of a functionality to be  
 734 predictive of a given group of replicons/genomes and the *Odd-Ratio* estimated how the  
 735 functionality occurrence influenced the belonging of a replicon/genome to a given  
 736 group.

737 **Table 13. Datasets used in the logistic regression analyses**

ENSEMBLE OF REPLICONS OR GENOMES	NOTATION	DATASET	DIMENSION <sup>a</sup>
Genus-normalized SERs	$E_{SER}$	$\bar{V}_{f,genus}^{R\{SER\}}$	(28, 117)
Genus-normalized plasmids	$E_{plasmid}$	$\bar{V}_{f,genus}^{R\{plasmid\}}$	(262, 117)
Genus-normalized chromosomes	$E_{chromosome}$	$\bar{V}_{f,genus}^{R\{chromosome\}}$	(560, 117)

738 <sup>a</sup> (Number of replicons, number of functions)

### 739 **Supervised classification of replicons and genomes**

740 In order to identify putative ill-defined SERs and chromosomes amongst plasmids, we  
 741 performed supervised classification analyses using random forest procedures (Geurts et  
 742 al., 2006). We used the IS functionalities as the set of features and the whole sets of  
 743 chromosomes, plasmids and SER as sets of samples to build four classification studies  
 744 (Table 7) and detect SER candidates (plasmids vs. SERs) and chromosome candidates  
 745 (chromosomes vs. SERs or chromosomes vs. plasmids). Because of the unbalanced sizes  
 746 of the training classes (SERs vs. chromosomes and plasmids), iterative sampling  
 747 procedures were performed using 1000 random subsets of the largest class, with a size

748 similar to that of the smallest class. The ensuing results were averaged to build the class  
749 probabilities and relative importance of the variables. We also used the whole set of  
750 plasmids when compared to SERs, to identify more robust SER candidates. The  
751 discarding of plasmids in the iterative procedure increases the classifier sensitivity while  
752 reducing the rate of false negatives by including more plasmid-annotated putative true  
753 SERs, whereas it decreases the classifier precision while increasing the rate of false  
754 positives. The ExtraTreeClassifier (a classifier similar to Random Forest) class from the  
755 Scikit-learn python library (Pedregosa et al., 2011) was used to perform the  
756 classifications, with  $K=1000$ ,  $max\_feat=sqrt(number\ of\ variables)$  and  $min\_split=1$ . For  
757 each run, the *feature\_importances* and *estimate\_proba* functions were used to compute,  
758 respectively, the relative contribution of the input variables and the class probabilities of  
759 replicons/genomes. The statistical probability of a replicon/genome belonging to a class  
760 was calculated as the average predicted class of the trees in the forest. The relative  
761 contribution of the input variables was estimated according to Breiman (2001). The  
762 choices of the number of trees in the forest  $K$ , the number of variables selected for each  
763 split  $max\_feat$ , and the minimum number of samples required to split an internal node  
764  $min\_split$  were cross-validated using a *Leave-One-Out* scheme. The performance of the  
765 *Extremely-randomized-trees* classification procedures was assessed using a stratified 10-  
766 fold cross-validation procedure following Han *et al.* (2012), and the out-of-bag estimate  
767 (OOB score) (Izzenman, 2008; Pedregosa et al., 2011) computed using the *oob\_score*  
768 function of Scikit-learn python library.

#### 769 **Data availability**

770 The data supporting the findings of this study are available within the Article and  
771 its Supplementary Information or are available from the authors.

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1131 **SUPPLEMENTARY TABLES**

1132 Table 1. Replicon dataset

1133 Table 2. INFOMAP IS protein-based clustering solution of the 4928 replicons

1134 Table 3. PCA + WARD IS protein-based clustering solution of the 4928 replicons

1135 Table 4. PCA + WARD IS function-based clustering solution of the 4928 replicons