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# Bounded-phase chaotic dynamics in a vectorial laser

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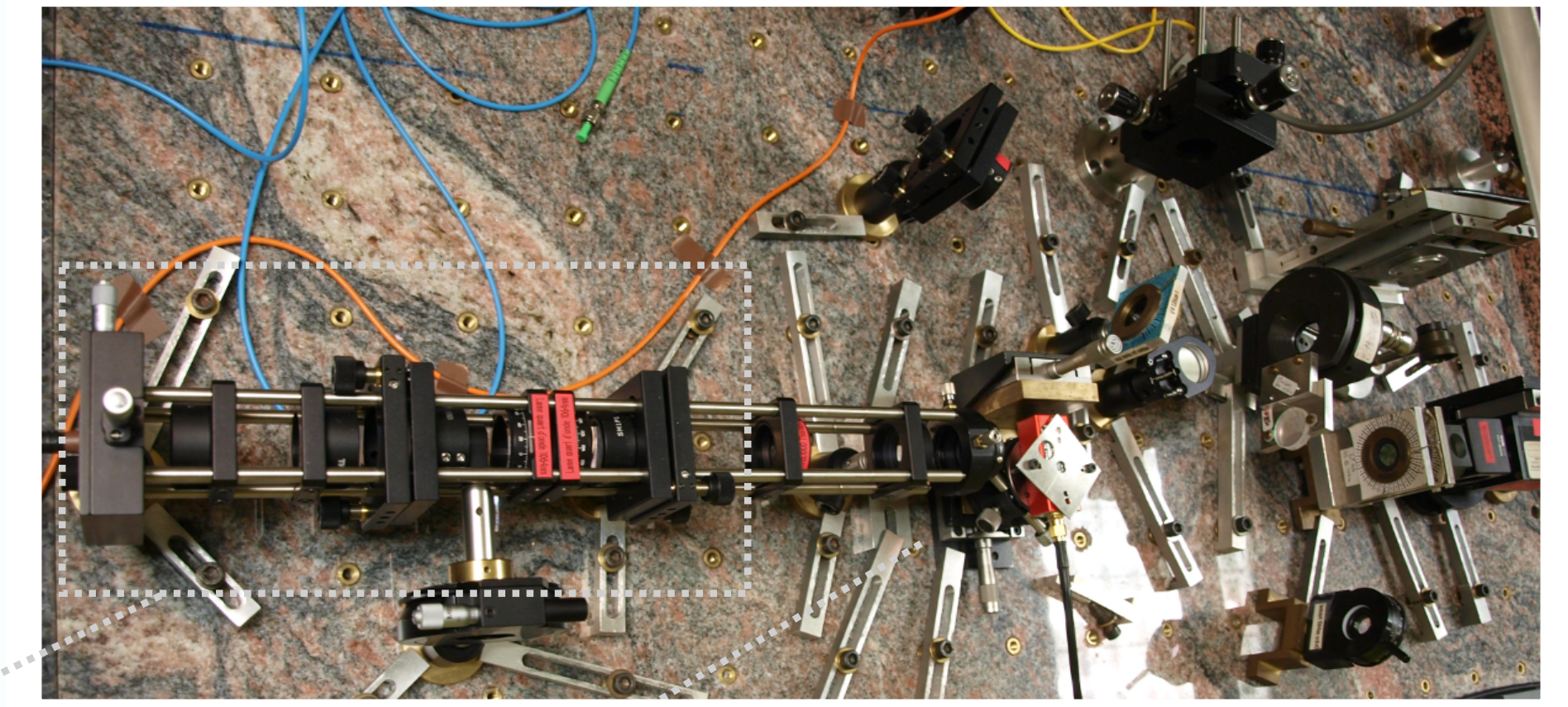
**ABSTRACT :** We show experimentally that the beat-note signal of the two polarization modes of a dual-frequency laser can be chaotic and at the same time be frequency-locked to a master radio-frequency oscillator.

## Dual-frequency laser with frequency-shifted feedback

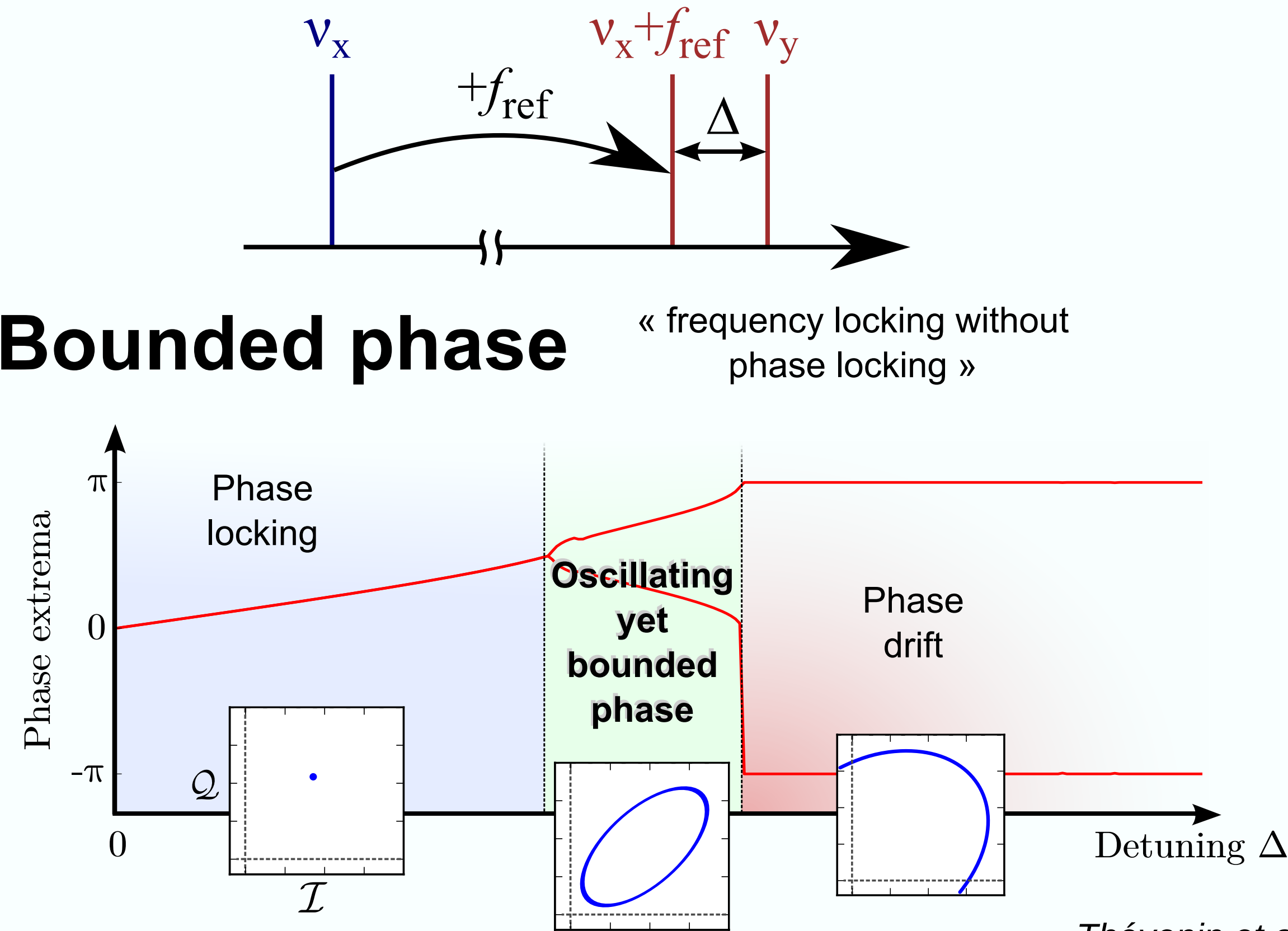
Context : dual-polarisation dual-frequency laser → opto-RF source can be stabilized and/or synchronized on an external reference by an electronic or optical feedback.

Optical frequency-shifted feedback (FSF).

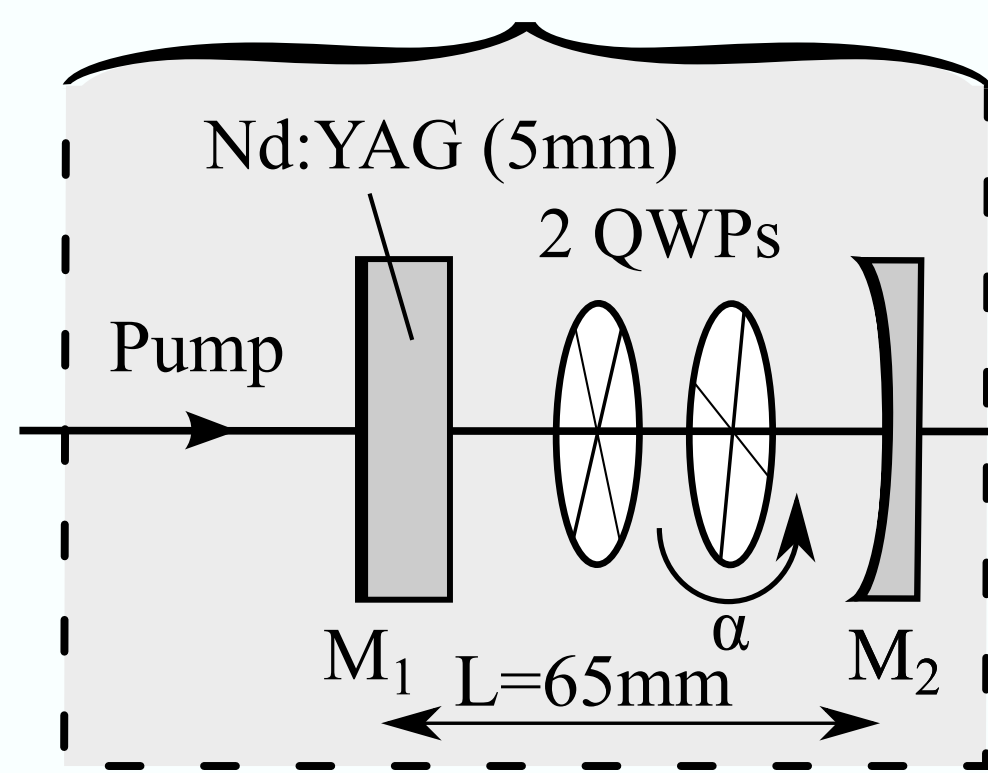
→ coupling between modes through external driving at  $f_{ref}$  with intensity  $\Gamma$  and **frequency detuning**  $\delta\nu - f_{ref}$ .



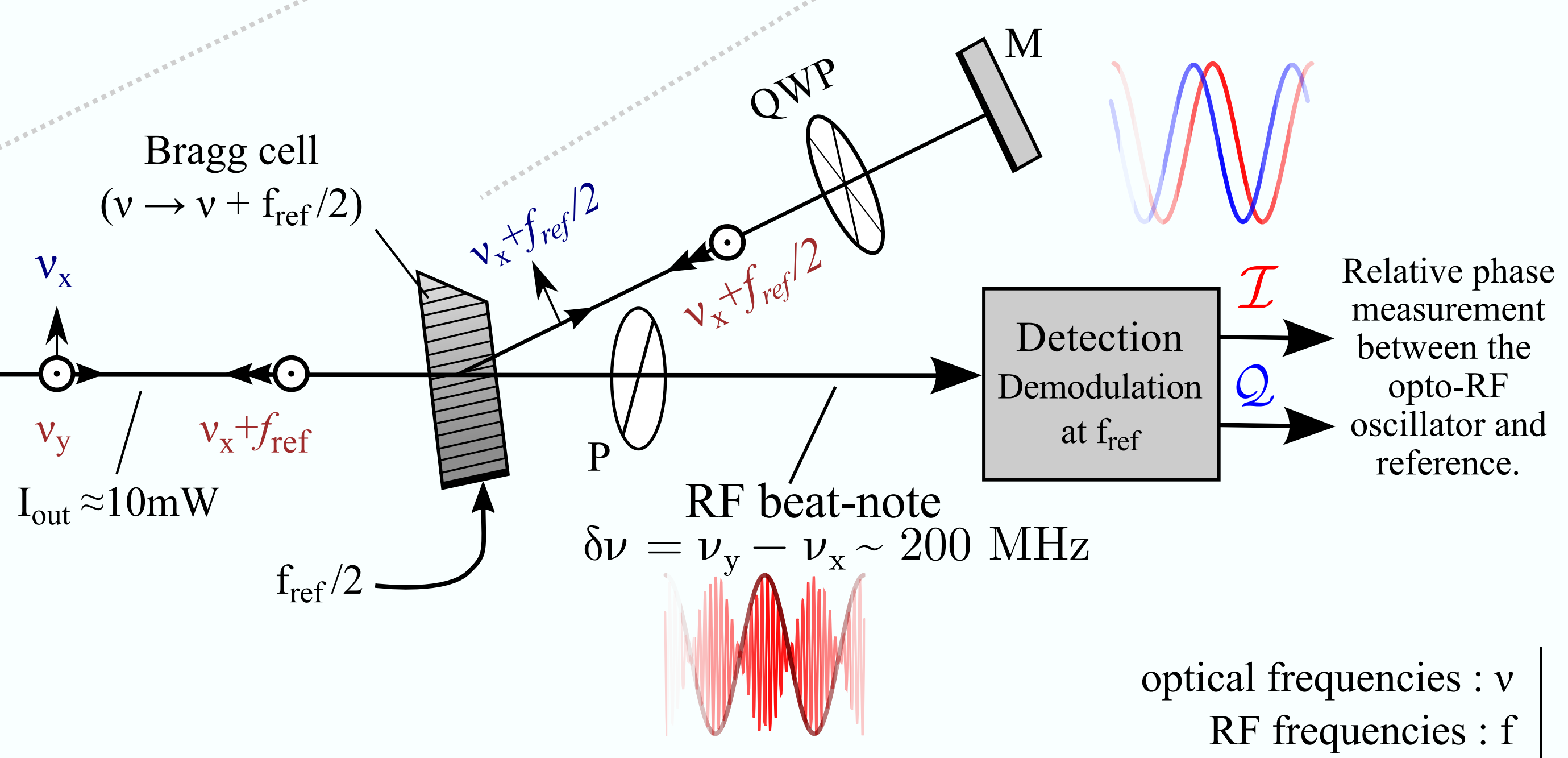
### Bounded phase



Solid-state laser @  $\lambda=1,06\mu\text{m}$  dual-polarization dual-frequency (cavity with tunable birefringence)



$$\delta\nu = \frac{2\alpha}{\pi} \frac{c}{2L}$$



optical frequencies :  $\nu$   
RF frequencies :  $f$

Strong injection → supercritical Hopf bifurcation

- Thévenin et al., "Phase and intensity dynamics of a two-frequency laser submitted to resonant frequency-shifted feedback," PRA **86**, 33815 (2012).  
- Romanelli et al., "Measuring the universal synchronization properties of driven oscillators across a Hopf instability," Optics Express **22**, 7364 (2014).

## Chaotic bounded phase: simulation and observation

Normalized « rate equations » dynamical model for the two polarization modes:

$$\begin{cases} \frac{de_x}{ds} = \frac{m_x + \beta m_y}{1 + \beta} \frac{e_x}{2} \\ \frac{de_y}{ds} = \frac{m_y + \beta m_x}{1 + \beta} \frac{e_y}{2} + i\Delta e_y + \Gamma e_x \end{cases}$$

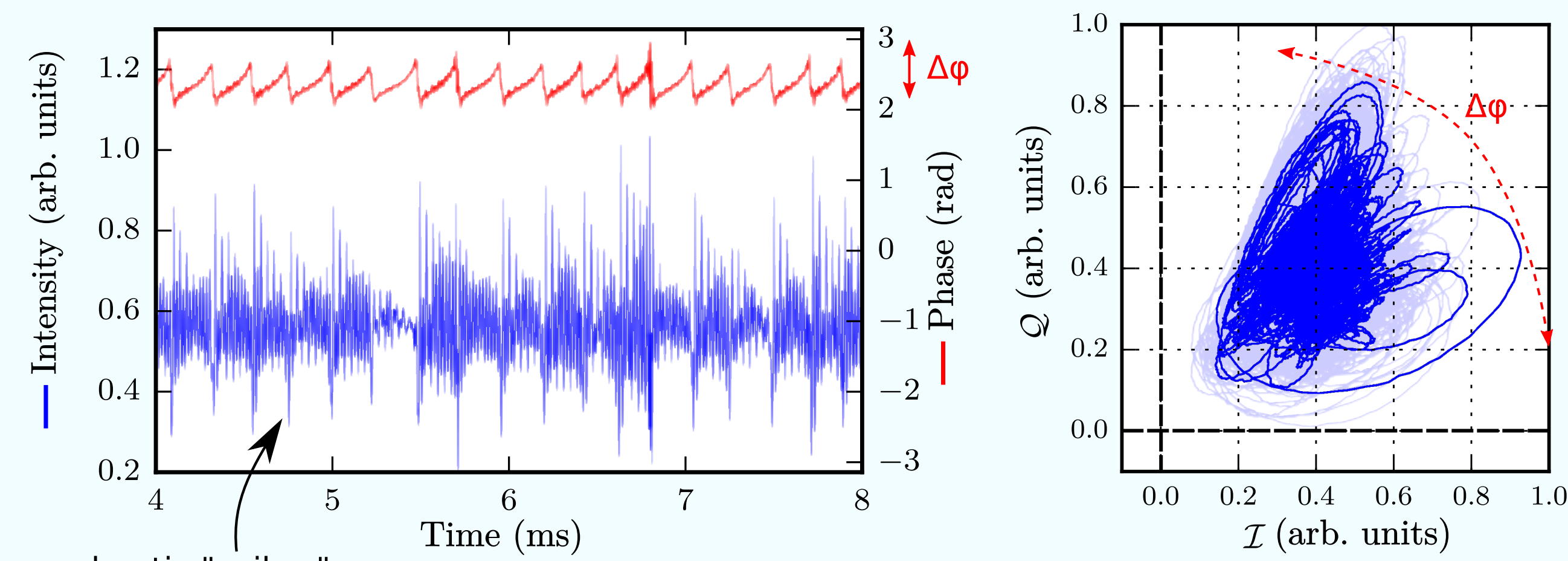
Coupling by reinjection  $e_x \rightarrow e_y$

various dynamics are computed in the resonant injection regime

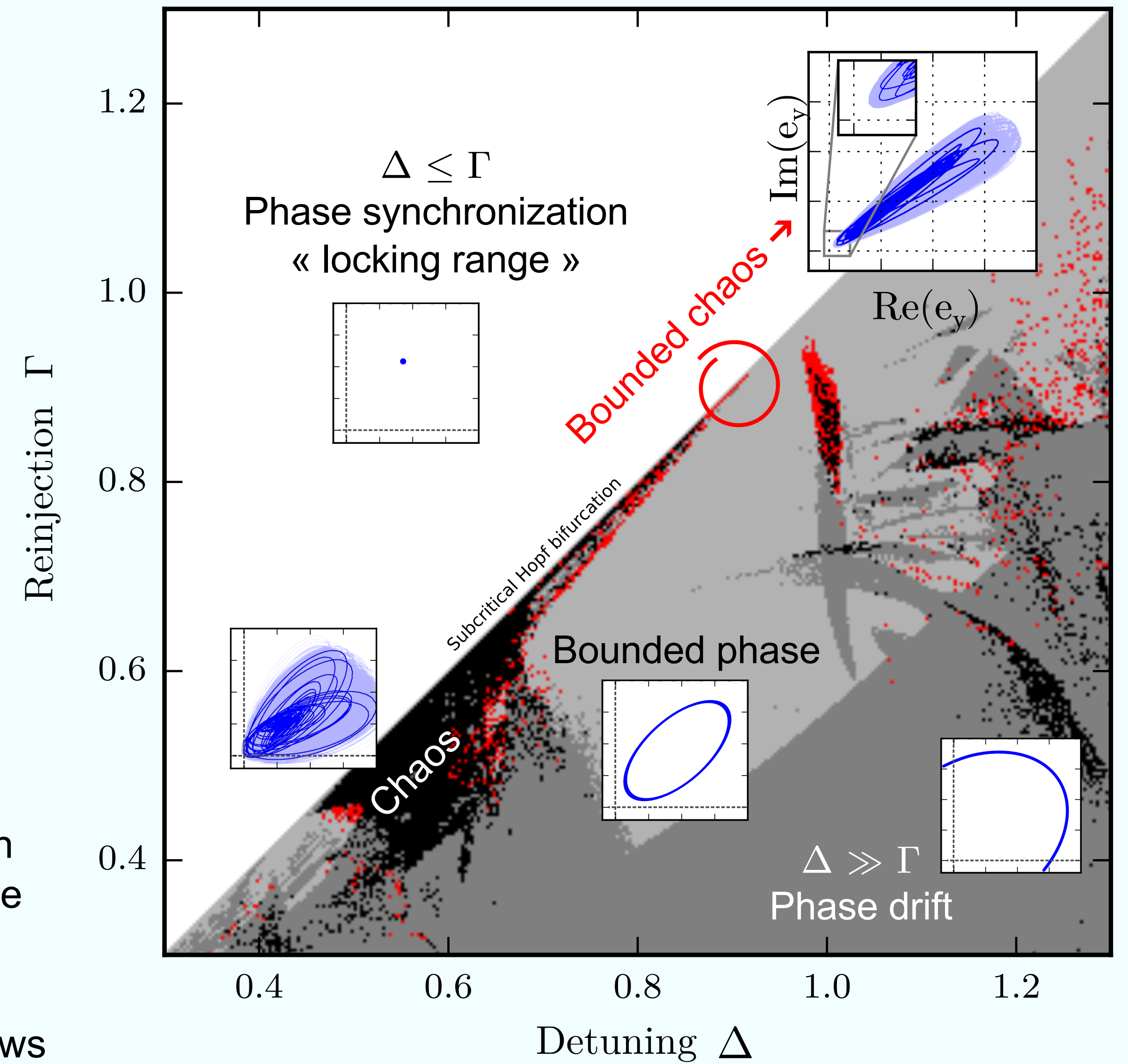
$$\frac{dm_{x,y}}{ds} = 1 - (|e_{x,y}|^2 + \beta|e_{y,x}|^2) - \varepsilon[1 + (\eta - 1)(|e_{x,y}|^2 + \beta|e_{y,x}|^2)]$$

$s = 2\pi f_R t$  : characteristic time of the system, based on relaxation oscillations frequency ( $f_R=70\text{kHz}$ )  
 $\Delta = (\delta\nu - f_{ref})/f_R$  : frequency detuning.  
 $\Gamma$  : reinjection strength.

$e_x = E_x e^{-2i\pi\nu_x t}$  : normalized electric field.  
 $e_y = E_y e^{-2i\pi(\nu_x + f_{ref})t}$  : demodulated at  $f_{ref}$ , contains phase information.  
 $\beta = 0,6$  : coupling within active medium.  
 $\varepsilon = 0,096$  : cavity/active medium losses ratio.  
 $\eta = 1,2$  : pump parameter.



experimental observation of the beat-note amplitude  $|e_x + e_y|^2$   
IQ demodulation at  $f_{ref}$  allows to monitor the phase.

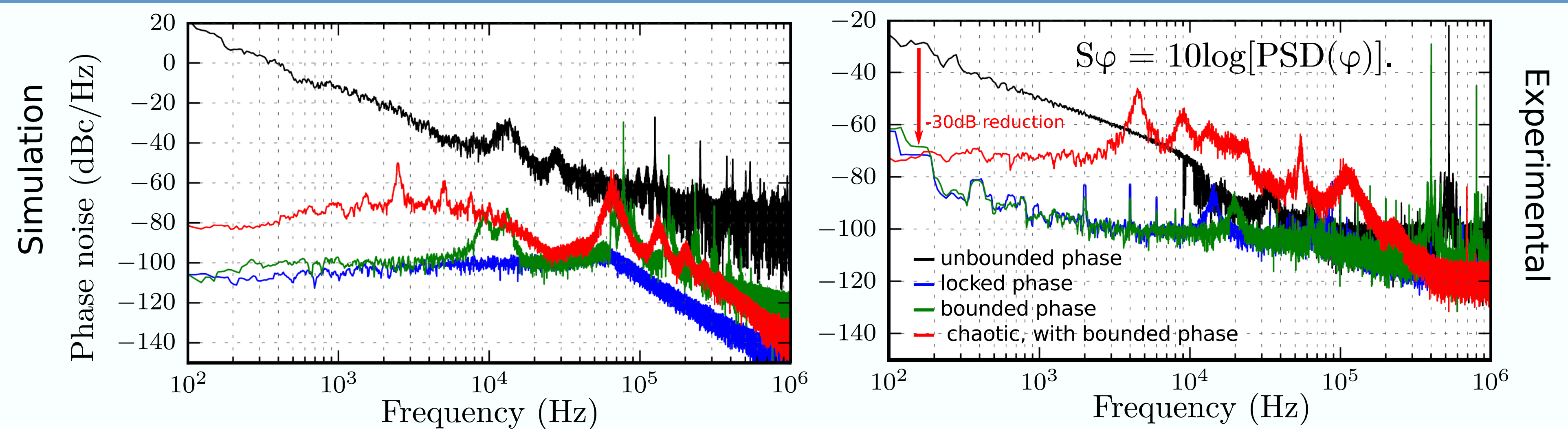


Legend  
□ locking (stable limit point)  
■ at least one chaotic attractor.  
■ existence of a chaotic attractor with bounded phase.  
■ bounded phase (at least one limit cycle with bounded phase)  
■ phase drift (limit cycle without bounded phase)

## Stability (phase noise spectrum)

Is frequency locking still efficient ?  
→ quantifying the quality of the opto-RF oscillator.

In the same way the bounded phase regime preserves the reference spectral purity, the chaotic bounded phase regime still allows to retain the long-time stability of the reference.



## Conclusion

- Experimental demonstration of a chaotic bounded-phase regime (frequency locking with chaotic variations of intensity and phase).
- Spectral purity and long-term stability of the reference partially transferred to the opto-RF oscillator.
- Possible applications : chaotic Lidar-Radar proof-of-concept (ongoing, promising results) ; transfer to higher frequencies using semiconductor lasers.

Article : Thorette et al. "Frequency-locked chaotic opto-RF oscillator", Optics Letters **41**, 2839 (2016). Also on <https://arxiv.org/abs/1606.09464>

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