



VLT 2030  
Garching, June 17-20 2019



# A New Generation Fringe Tracker for the VLTI

## Optimizing the VLTI for AGN observations

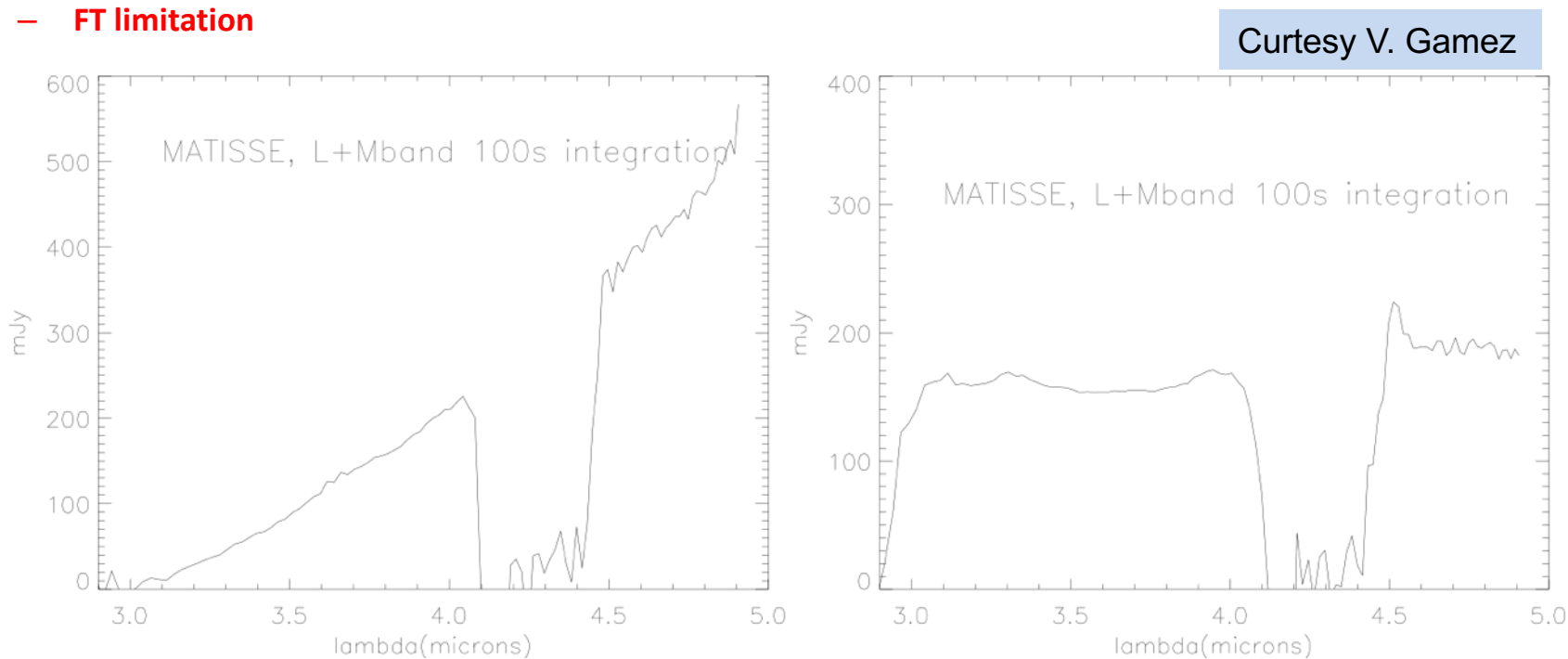
**Romain G. Petrov**

With the HFT + SPICA/CHARA FT joint venture and the MATISSE Consortium

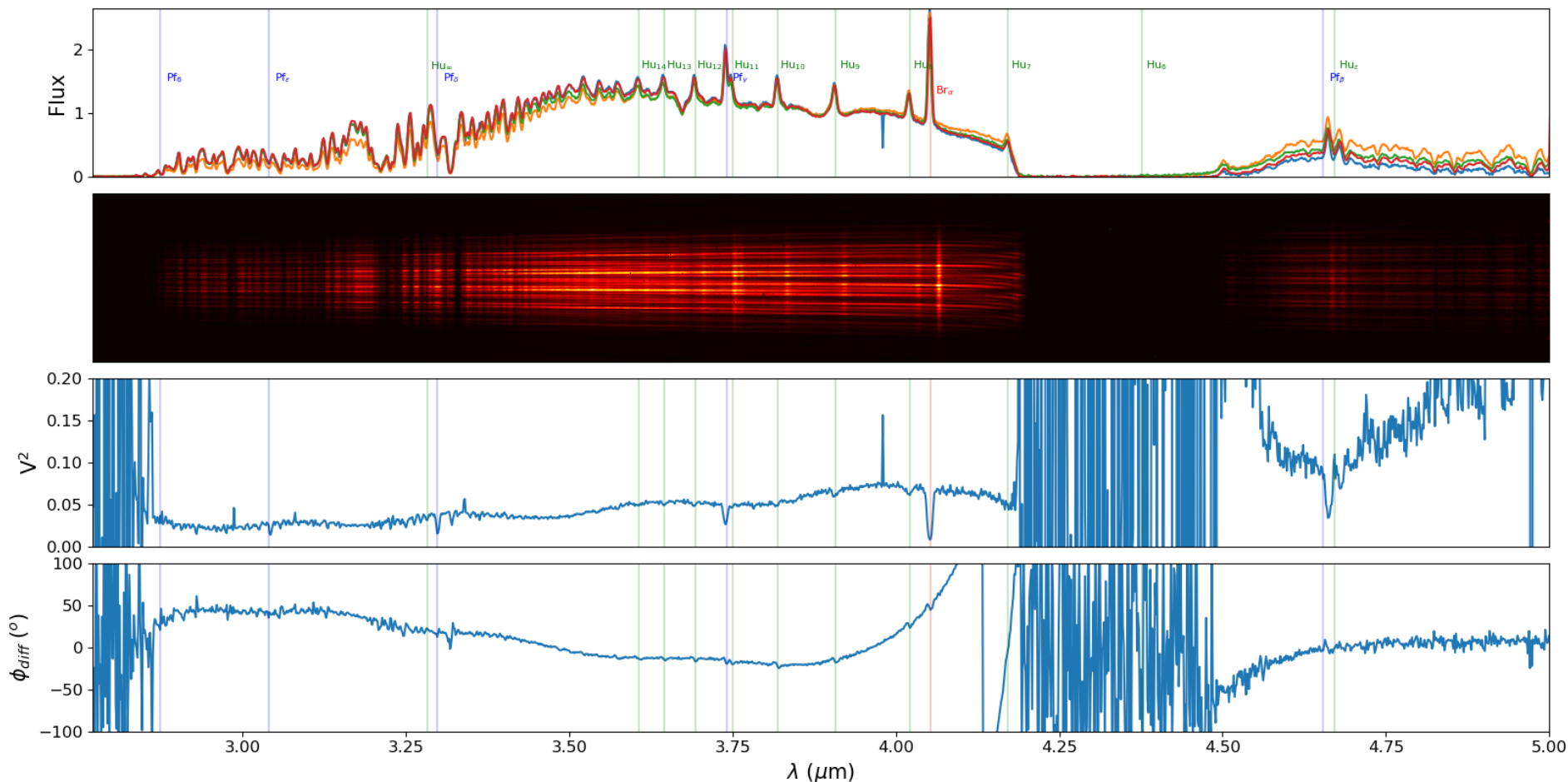
A. Boskri, F. Allouche, K. Agabi, Ch. Baillet, Z. Benkhaldoun, Ph. Berio, Y. Bresson, J. Dejonghe, T. Elhakouj, J.-P. Folcher, S. Lagarde, B. Lopez, A. Matter, A. Meilland, D. Mourard, S. Rakshit

- **Quasars with optical interferometry**
  - An old dream
  - An AMBER science goal: BLRs with differential interferometry
  - AMBER+ upgrade and OASIS proposal → work on new Fringe Tracker concepts
  - GRAVITY breakthrough
- **AGNs with MATISSE**
  - A key science goal
  - Extension, structure and kinematics of the dust distribution with UTs
  - Imaging dust structure on Sy2: an UT and **AT** program
  - BLRs of SY1
  - Dust torus size of GRAVITY BLRs targets
  - **The full potential of MATISSE needs FT at K~15 (UTs) and K~11 (ATs): 2012**
  - External FT propositions
  - GRA4MAT
- **A new generation, new concept, external Fringe Tracker: the HFT,**
  - **In a visitor instrument optimized for AGNs in the J Band**
  - **Connected to MATISSE**
- **Synergy with GRAVITY+, ASGARD, BIFROST**

- **MIDI showed a large variety of dust structures**
- **Major component of MATISSE GTO (40% on UTs) and immediate General User interest**
- **MATISSE to increase number of observed AGNs**
  - **MATISSE L band sensitivity in coherent flux with UTs: 15-30 mJy ( $\rightarrow K \sim 12.5$  &  $V \sim 17$  for a Luminous Quasar)**
  - **AO limitation**
  - **Decisive need for Imaging with ATs, to go beyond NGC1068, Circinus and Cen A  $\rightarrow K > 11$  on ATs**
  - **Need for higher spectral resolution of AGNs with MATISSE  $\rightarrow K > 13$  on UTs**
  - **FT limitation**



Curtesy A. Meilland and J. Woillez



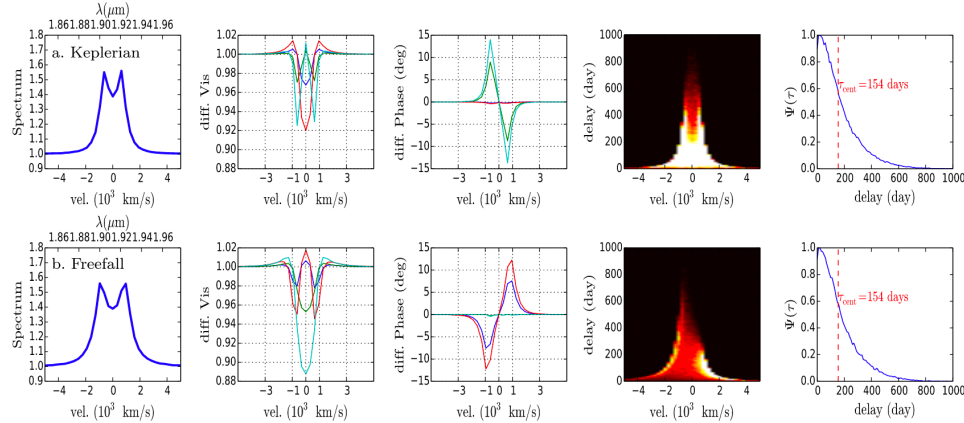
Tracking and observing at (very) different wavelengths

- Not new, but MIDI and MATISSE\_N have to make short exposures anyway
- MATISSE\_L needs long exposures in the higher spectral resolution modes
- **Fringe jumps issue**

# BLRs and Optical Interferometry

- The importance of SMBH masses...
  - Co-evolution of SMBH and Galaxies
- Reverberation Mapping estimates:
  - Up to 300% dispersion on individual sources in mass-luminosity diagrams
  - Large morphological variety
  - Need for independent constraints
- Non resolved targets → differential interferometry
  - Petrov, 2002; Marconi+, 2003; Rakshit+, 2015
  - The photocenter displacement interpretation is model dependent
  - Need to combine RM, differential phase, differential visibility
- GRAVITY 3C273 break through
  - Fringe Tracking decisive

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**Figure 8.** Spectrum (left), differential visibility (left-middle), differential phase (middle), 2D response function (middle-right), 1D response function (right) is plotted for different velocity profiles and for flat geometry cases; Keplerian (upper row) and free-fall inflow (lower row). OI observables are computed using U1 (red), U2 (cyan), U3 (blue) and U4 (green) baselines.

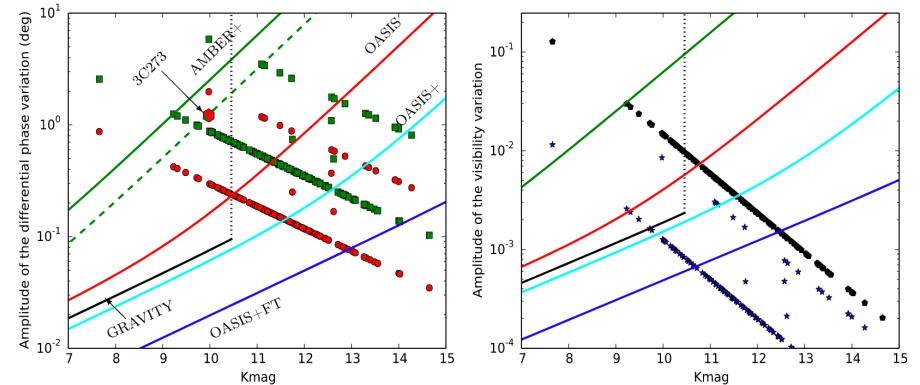
All available measures (RM, Differential phase and differential visibility must be combined to reduce the mass estimate uncertainty due to bad knowledge of the morphology.

A significant number of targets give access to some visibility information. The differential visibility signal is multiplied by  $2^2$  in the J band.

None of the individual measures (Diff. phase -or- RM -or- Diff. Visibility) alone allows unambiguous SMBH mass estimate

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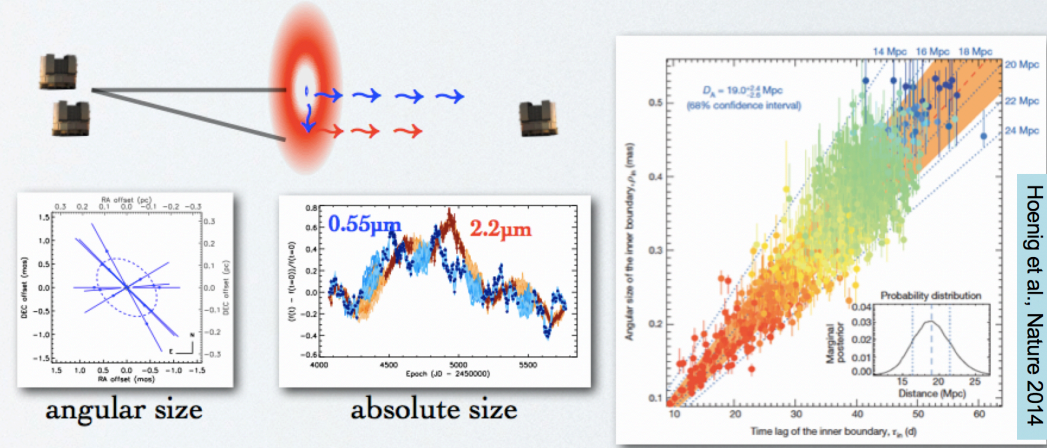
S. Rakshit+, 2015



**Figure 13.** Feasibility of observation of BLR with maximum VLTI 135 m baseline. The left image shows the accuracy of the differential phase in degrees, for the different instruments described in the text (full lines labelled by the instrument name). The differential phase error is dominated by fundamental noise at least down to  $0.05^\circ$ . The points represent the expected differential phase for all Sy1 AGNs and QSOs brighter than  $K = 15$  observable in Paranal ( $\delta < 15^\circ$ ). Each source is represented by a red circle, corresponding to the minimum differential phase signal from the RM BLR size estimates, and a green square, corresponding to the maximum differential phase for a skewed continuum image. The 3C 273 point (red octagon) represents the actual differential phase accuracy obtained with AMBER+. This value is on the dotted green line corresponding to the actual spectral channel binning and observation time on 3C 273. The right image represents the differential visibility accuracy from the fundamental noises for different instruments (full lines). The systematic error on differential visibility is below  $10^{-3}$ . For instruments used without an FT (AMBER+, OASIS, OASIS+), the absolute visibility accuracy cannot be better than 0.03. For instruments operated with an FT (GRAVITY, OASIS+FT), we expect to go below 0.003. The points represent the absolute visibility (black polygons) and the differential visibility (blue stars) expected for each source, according to the inner rim size estimated from its luminosity. The horizontal scale gives the estimated  $K$  magnitude of the central source.

# Dust parallax and BLR parallax

- What about direct distance probes at high redshift?
- Distance scale discrepancy
- "Local" variations of expansion

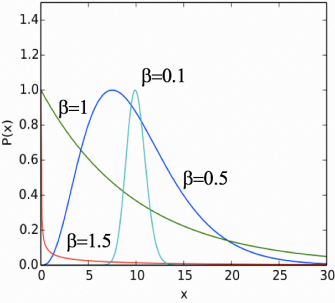


Hoenig et al., Nature 2014

- NGC 4151:  $D_A = 19.0 \text{ Mpc} (+/- 13\%)$
- Relevance for **cosmology** and **black hole mass calibration**

Slide from Hoenig, Hires 2014

- Critical to have strong constraints on the morphology
- **→ Combine Differential phase, Reverberation Mapping and Differential visibility on as many targets as possible**



Chapter 4. Geometrical and kinematical model of BLR

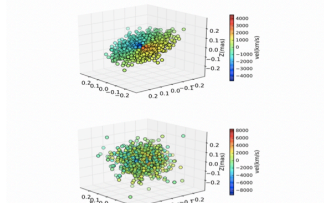
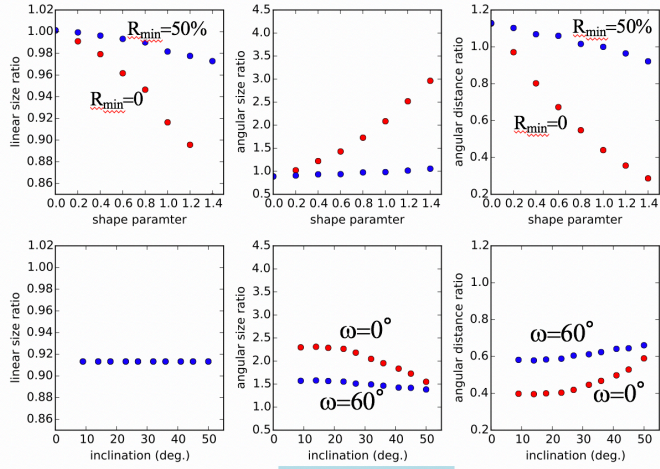


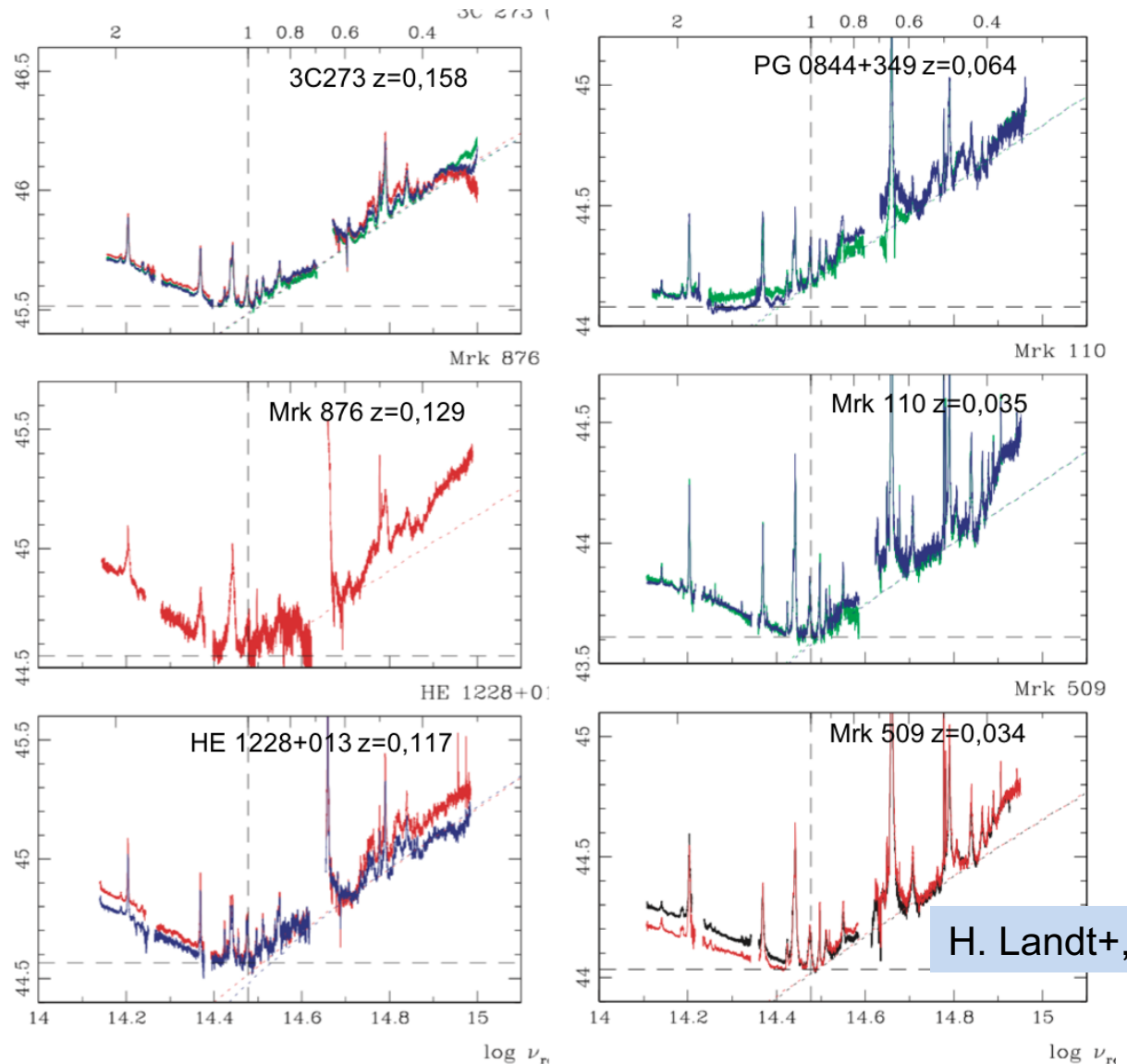
FIGURE 4.3: Cloud distribution with the velocity (km/s) in color code.  $M_{BH} = 10^6 M_{\odot}$ ,  $i = 30^\circ$ ,  $R_{in} = 1000 R_g$ ,  $\sigma_{in} = 0.1 \text{ mas}$  with flat Keplerian disk geometry  $\omega = 0^\circ$  (upper plot) and spherical geometry  $\omega = 90^\circ$  (lower plot).



Rakshit, thesis, 2015

# VLTI BLR observations in the J band

- In addition to GRAVITY+
- Lines !
  - H  $\alpha$  0.653  $\rightarrow$   $0.7 < z < 1.13$
  - He I 1.083  $\rightarrow$   $0.02 < z < 0.29$
  - Pa  $\beta$  1.282  $\rightarrow$   $0 < z < 0.28$
  - Pa  $\delta$  1.005  $\rightarrow$   $0.09 < z < 0.04$

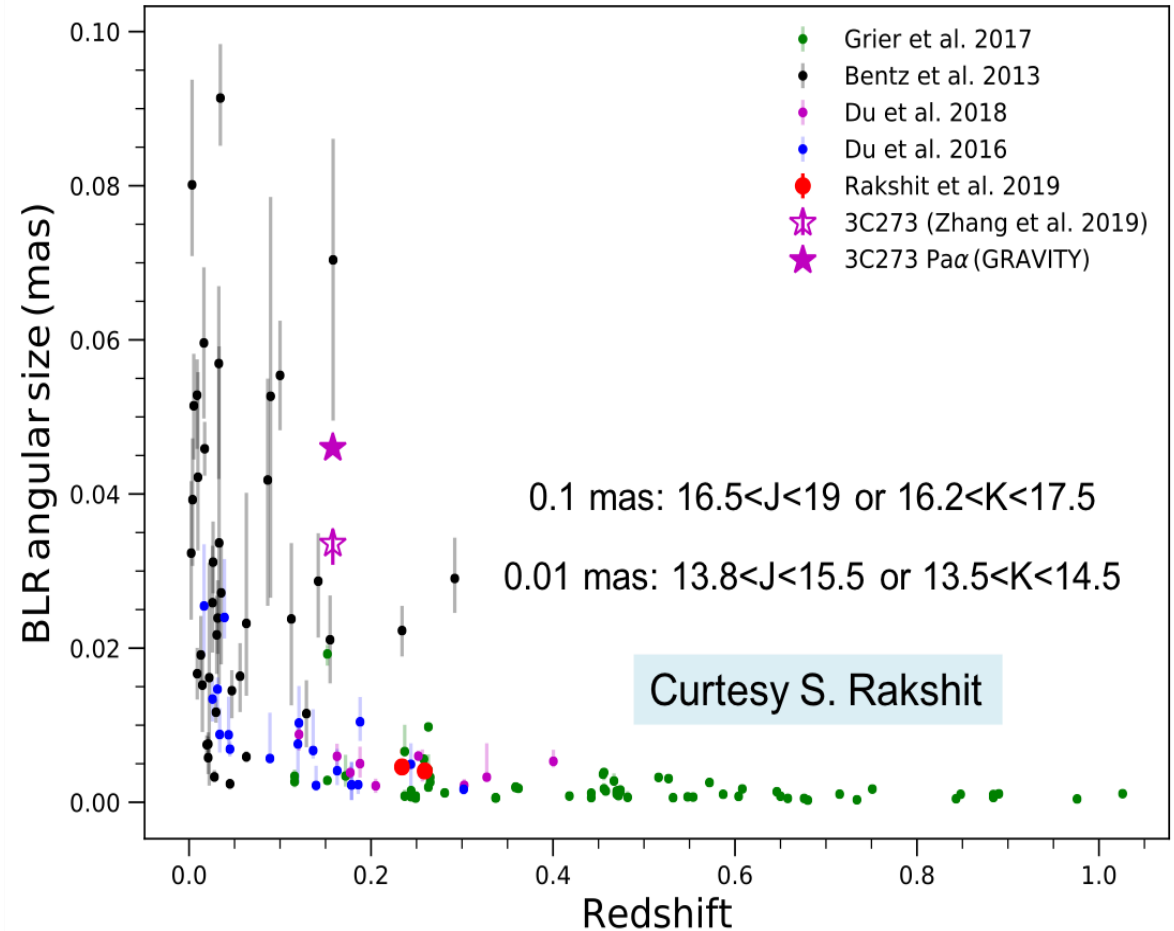


H. Landt+, 2011



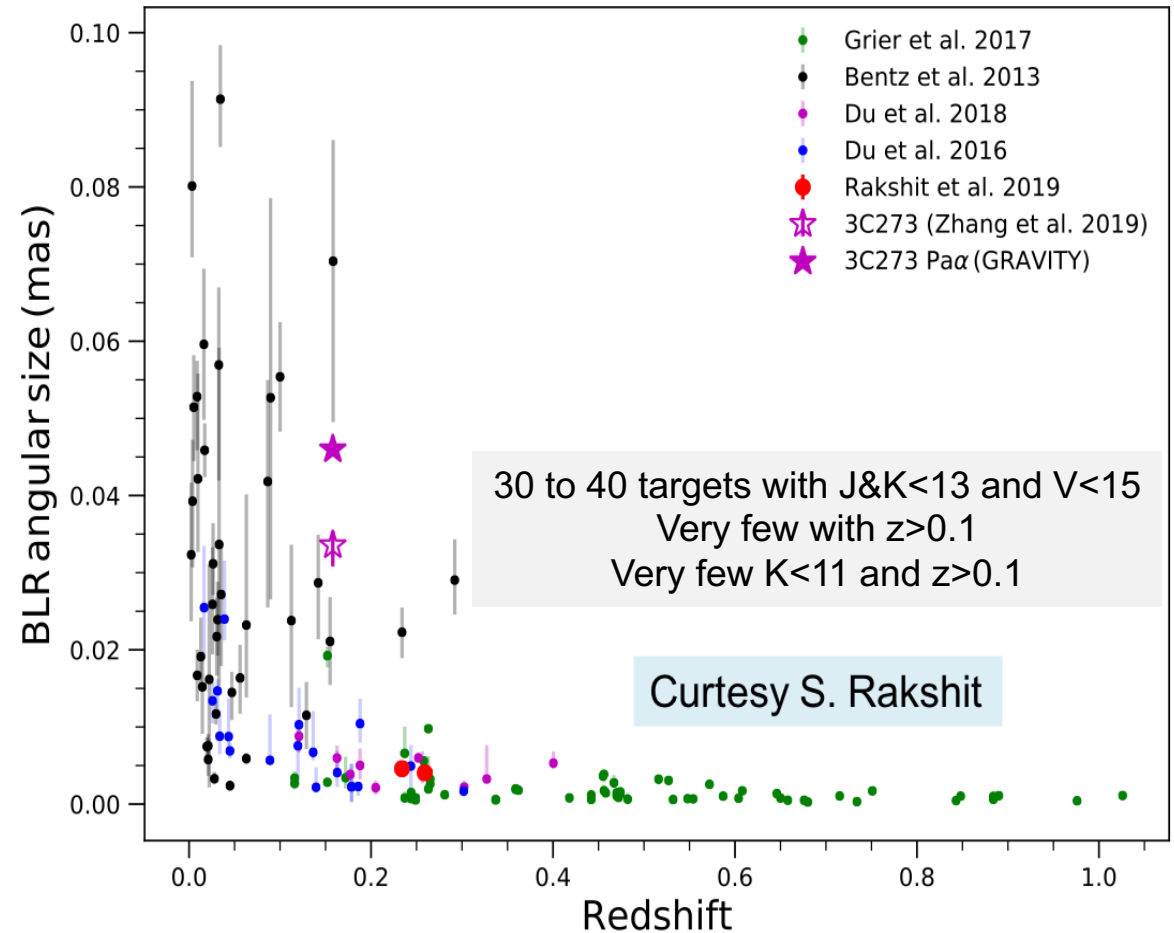
# VLT/BLR observations in the J band

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- Strong lines visible with smaller redshifts
  - Complementary list of targets
  - Better compatibility with RM programs
  - More targets with some differential visibility constraints on size
- Some targets accessible with the VLT/BLR infrastructure as it is.
- Complementarity with BIFROST



# VLT/BLR observations in the J band

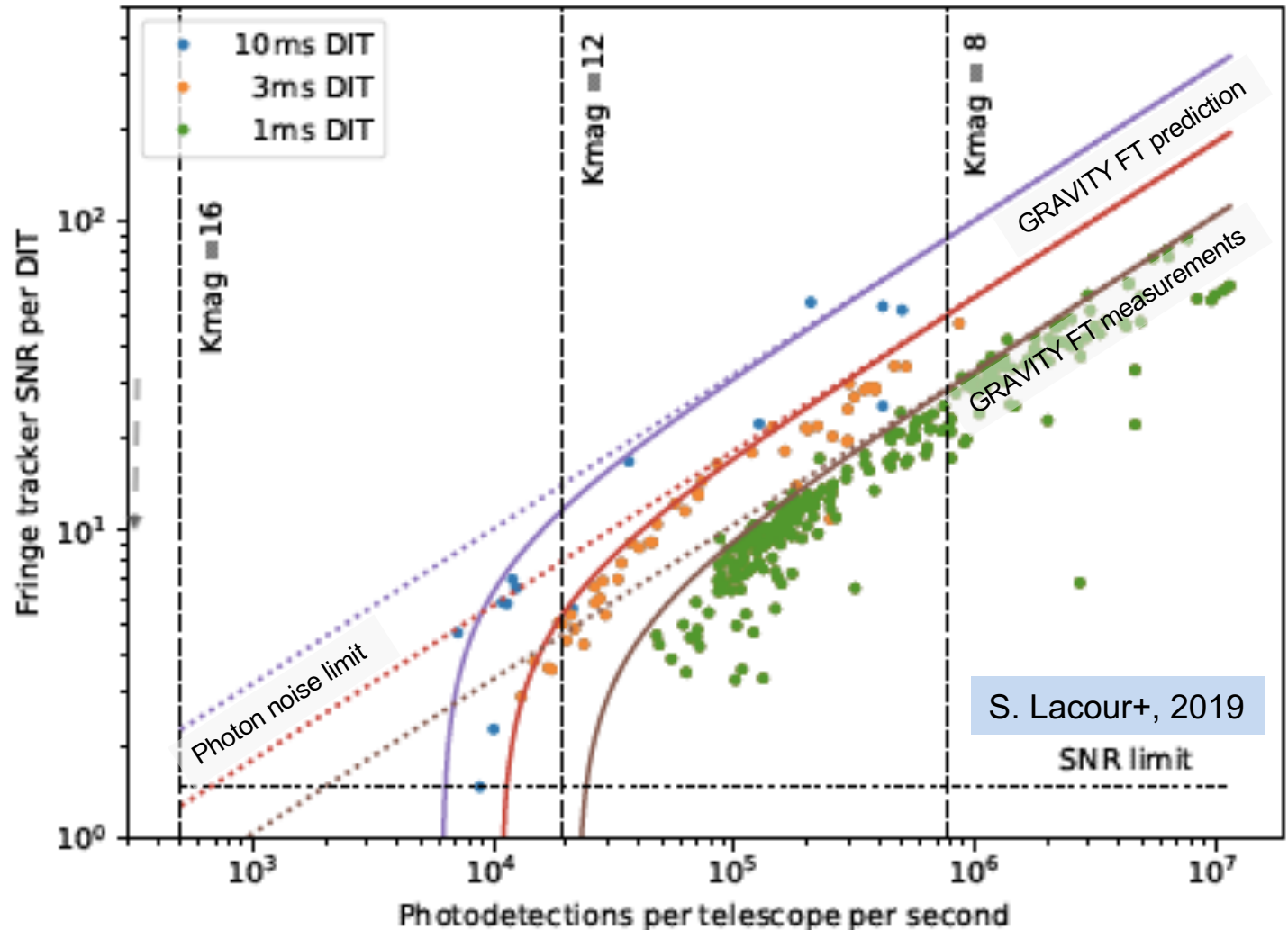
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# Why bothering with FT concepts?

In spite of SAPHIRA detector the GRAVITY FT does not reach its photon noise limit performance

Reducing the number of measures and/or the division of the signal to the minimum would optimize the FT

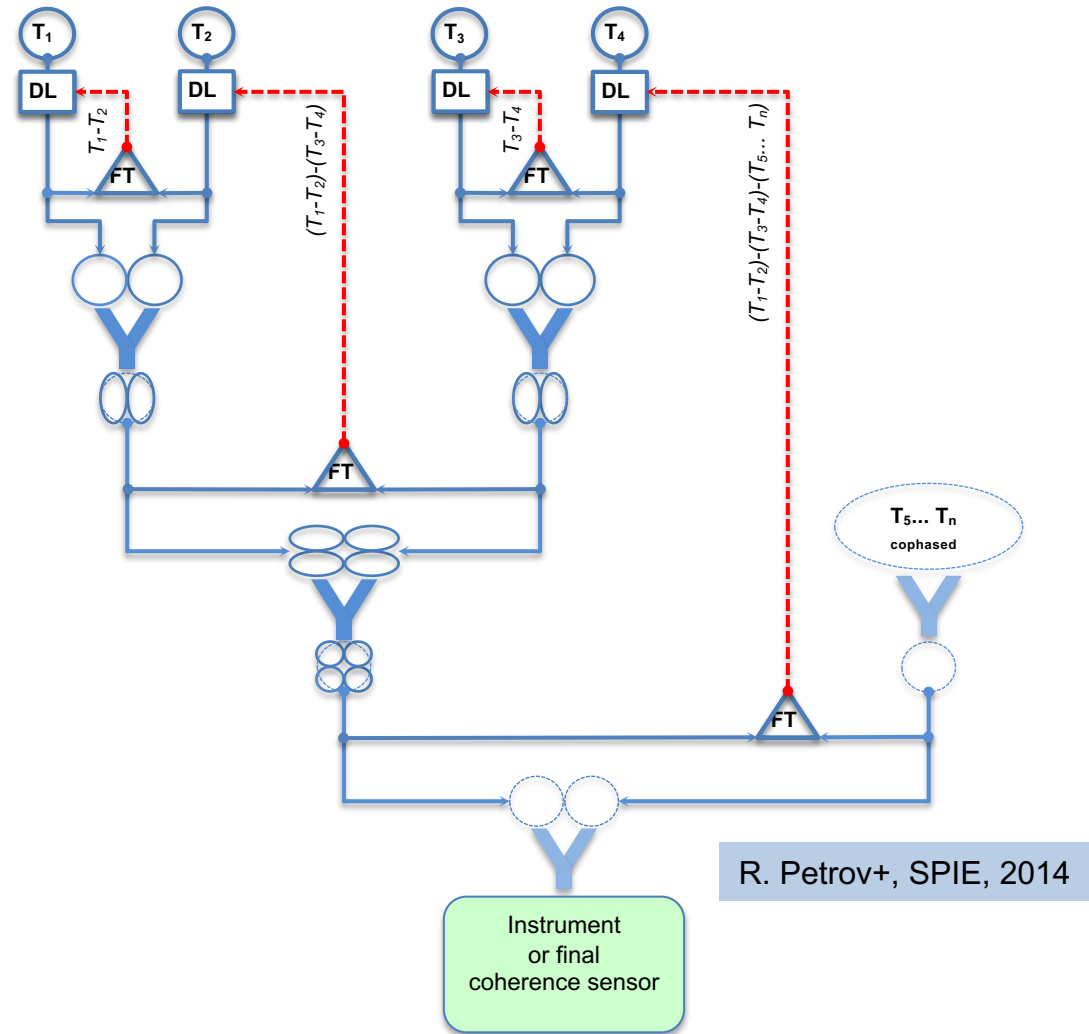


# Hierarchical Fringe Tracking

- Cophase pairs
  - then pairs of pairs
  - then groups of cophased apertures
- If at each level we keep > 50% of flux for lower levels

then

- Performance are set by first pair
- Flux increases with level
- A solution for the arrays with many telescopes:
  - VLTi 4T
  - CHARA 6T
  - VLTi + 8T
  - PFI...



# Two Beams Spatial Filter

- When the input beams are cophased, most of the flux is transmitted, as coming from a single spatial filter.
- When they are not cophased, flux is reflected toward “piston sensor”

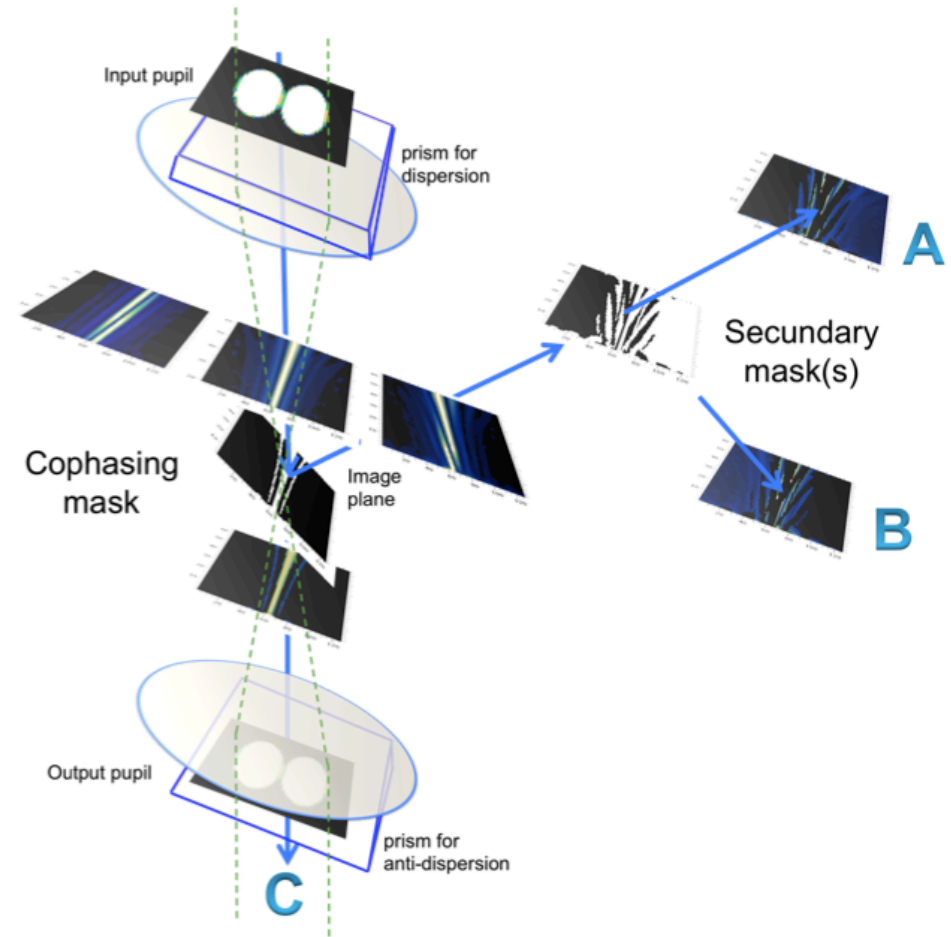
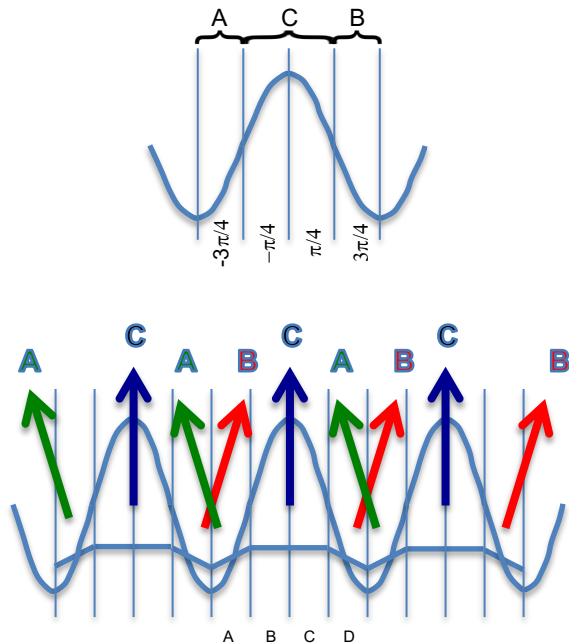
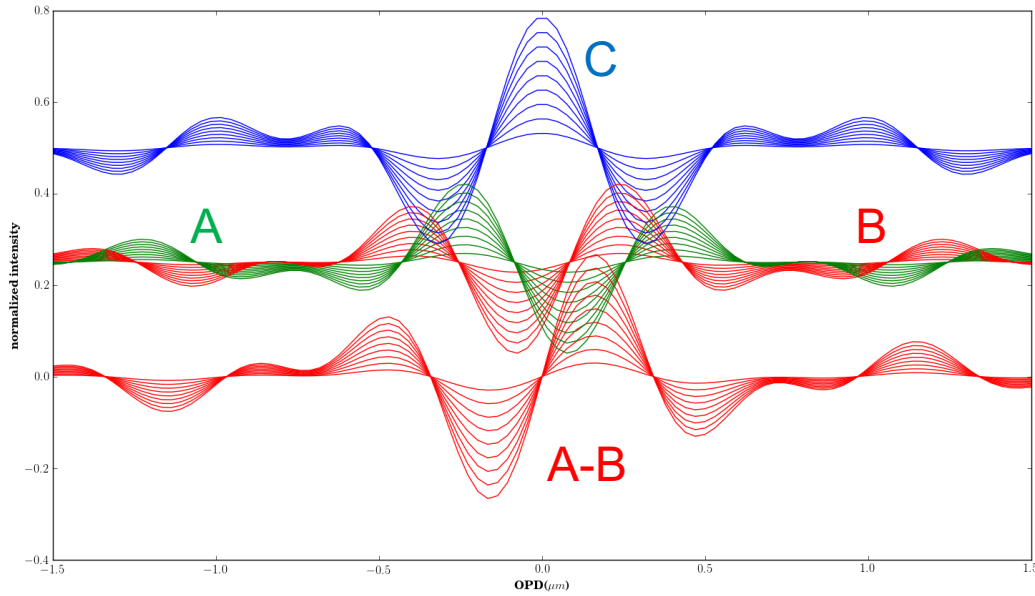


Figure 3: A broadband dispersed fringes achromatic 2 telescopes spatial filter and piston sensor.

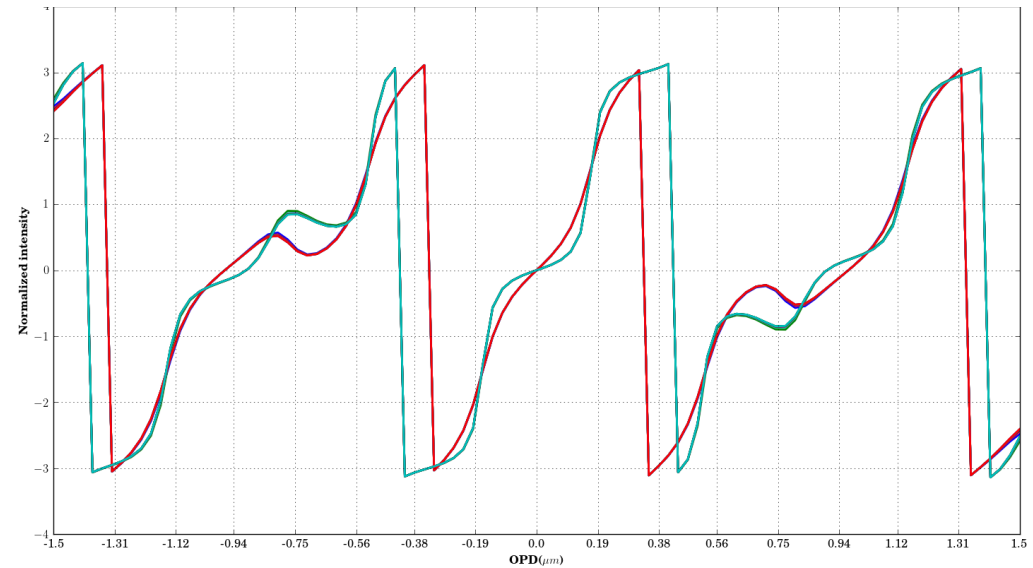
# HFT signals and phase measurement

A, B, C and A-B as a function of piston

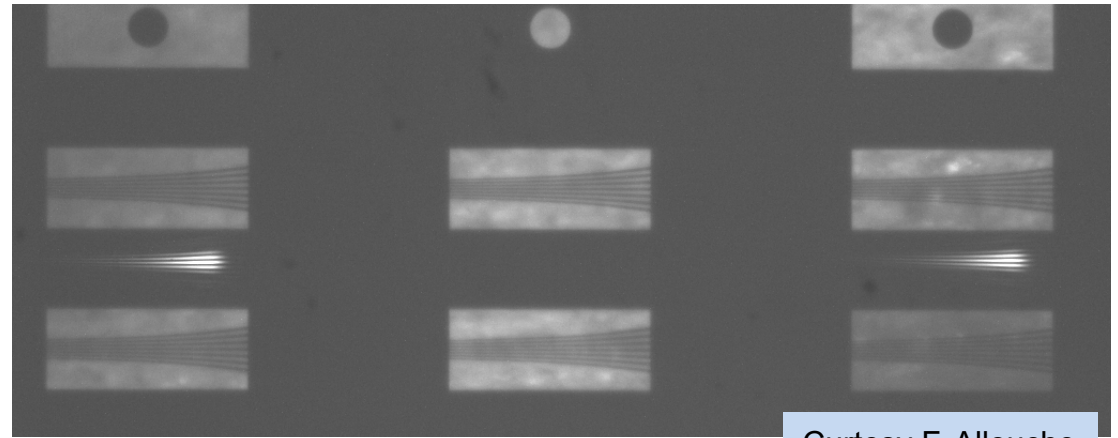
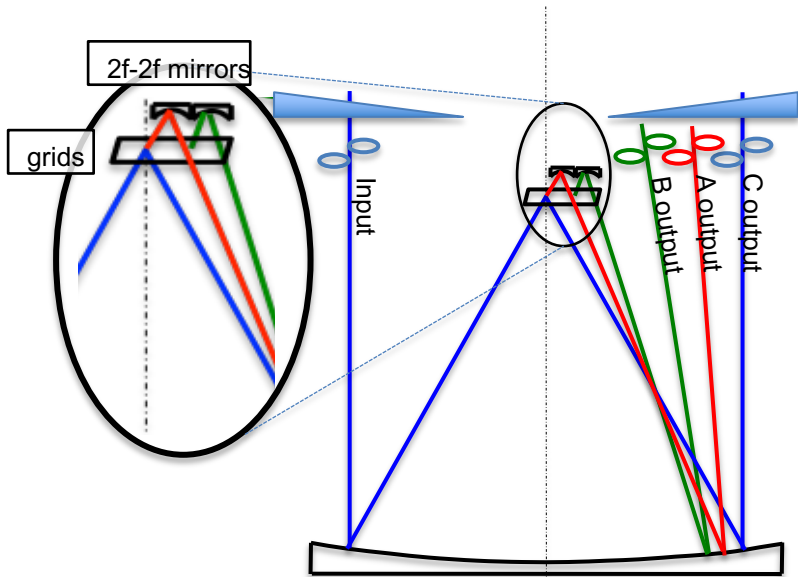


A. Boskri, PhD thesis

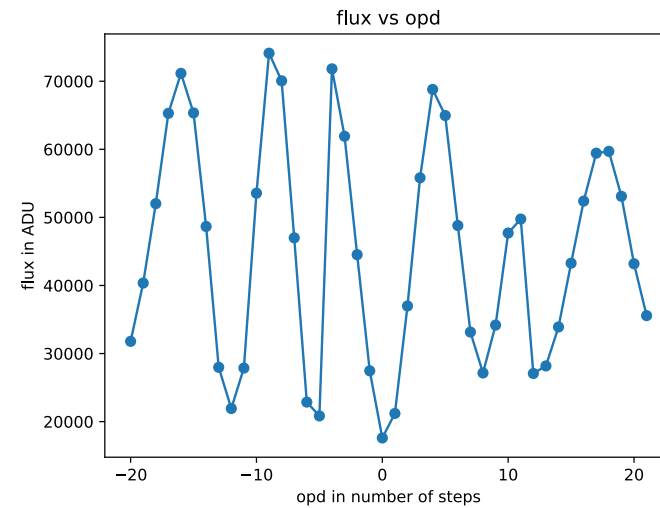
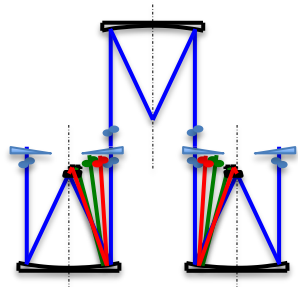
Phase delay estimation  $2\pi\rho/\lambda = \phi = \tan^{-1}[(A-B)/(C-A-B)]$   
*Independent from photometry or visibility changes*



# A compact bulk optics prototype for a 4T HFT

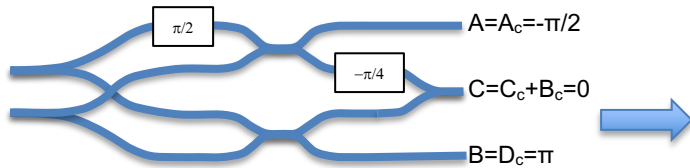
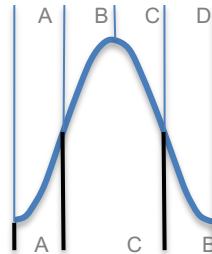
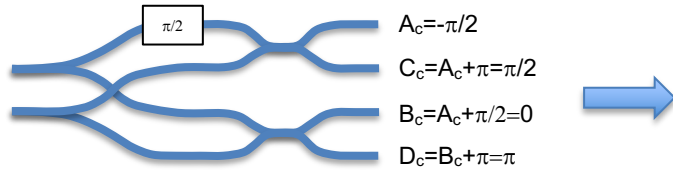


Courtesy F. Allouche



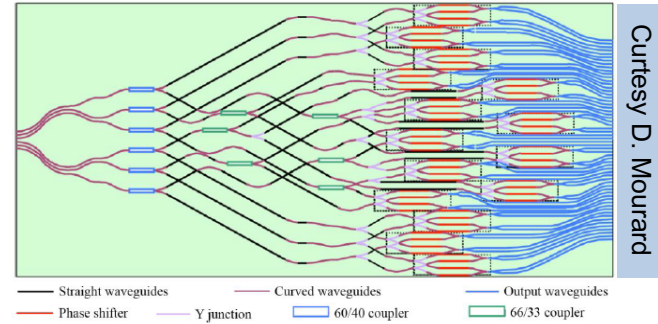
# Integrated Optics solutions for the CHARA/SPICA FT

ABCD analyser

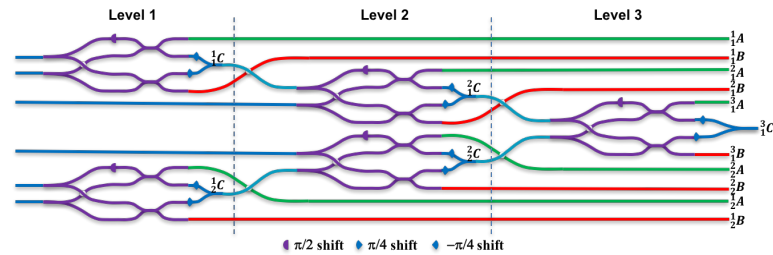


ACB analyser →  
Two Beams Spatial filter

6T ABCD Fringe Sensor



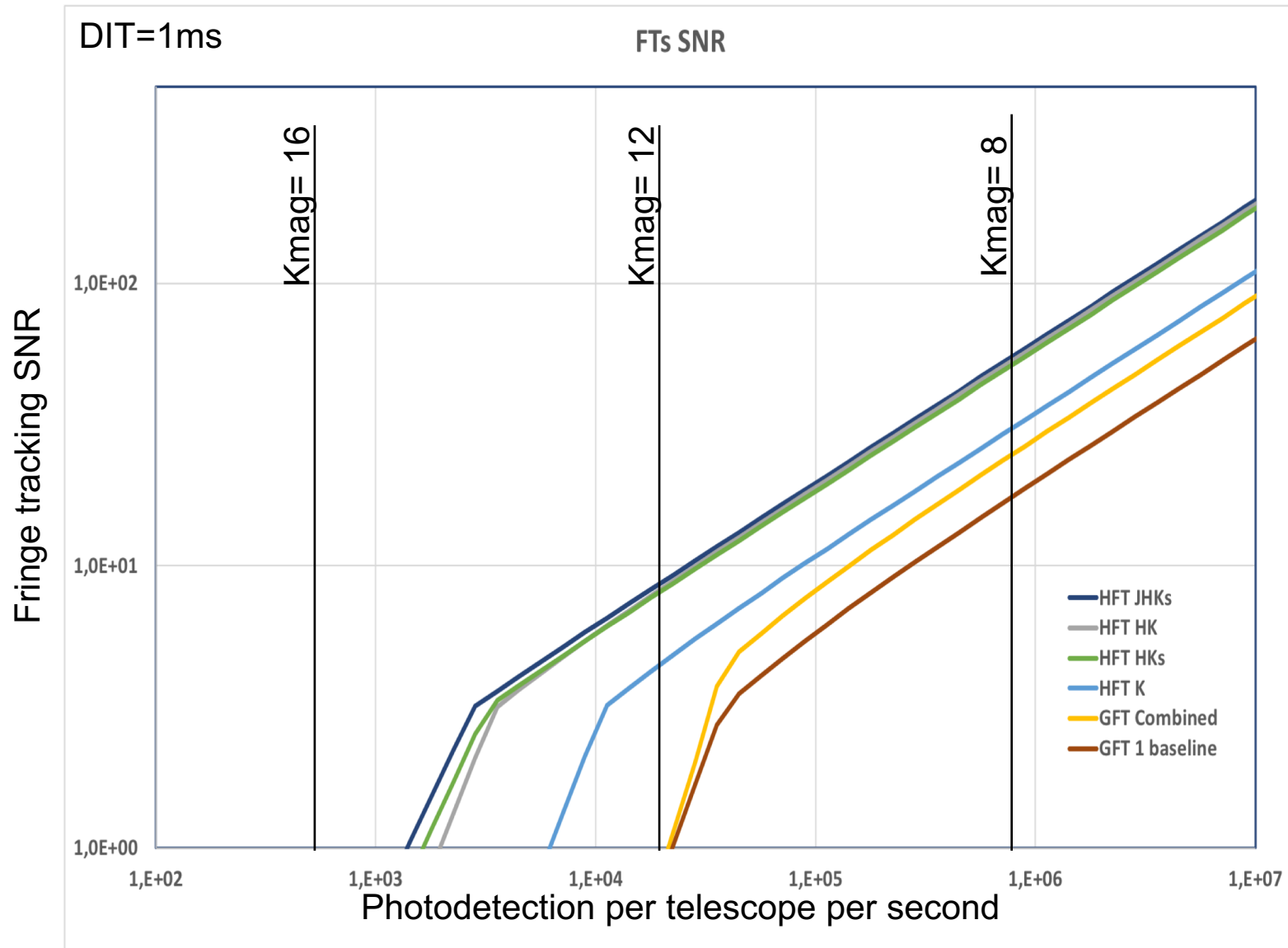
Courtesy D. Mourard



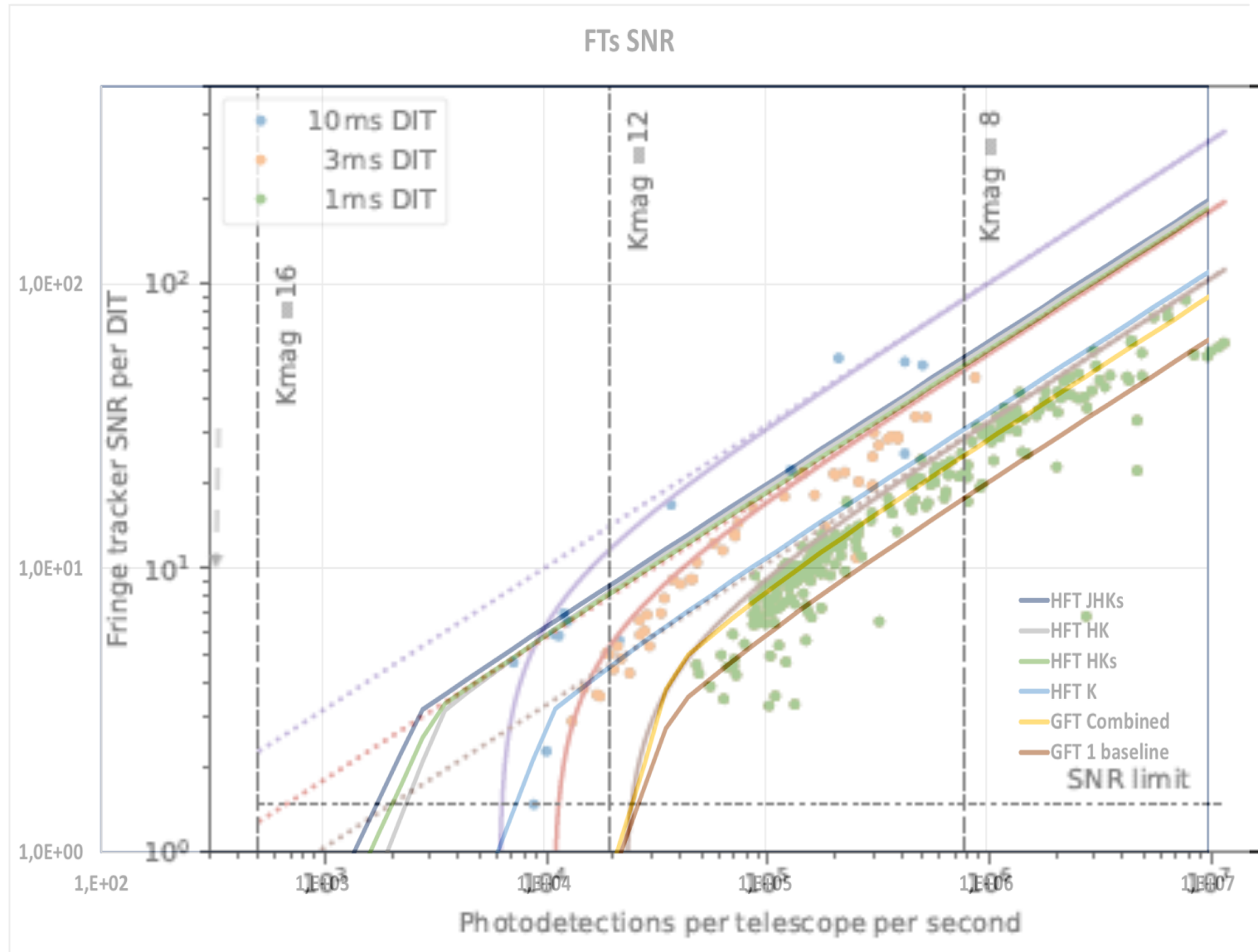
6T HFT Fringe Sensor



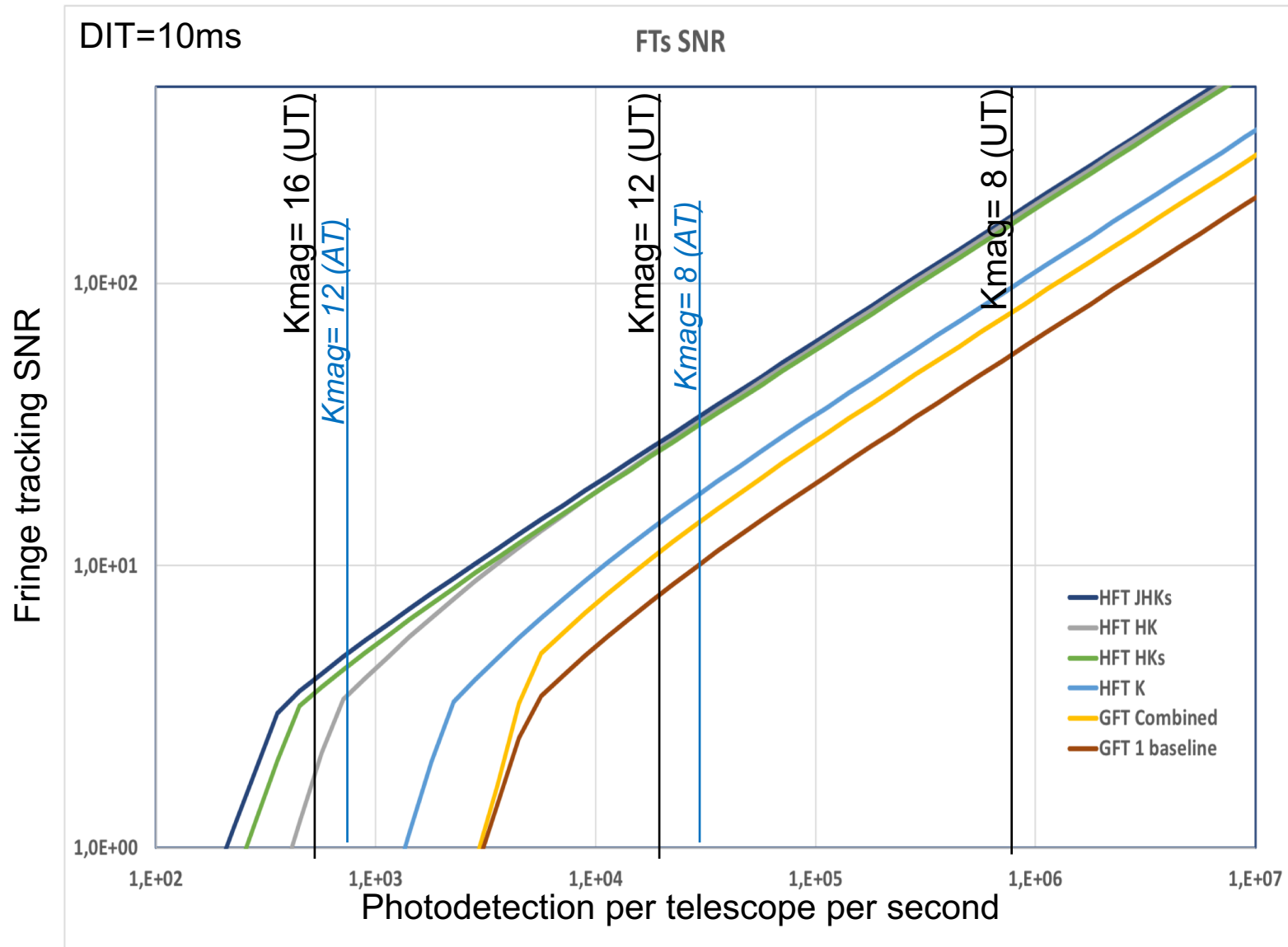
# HFT potential and GFT performance



# GFT estimate over GFT measures

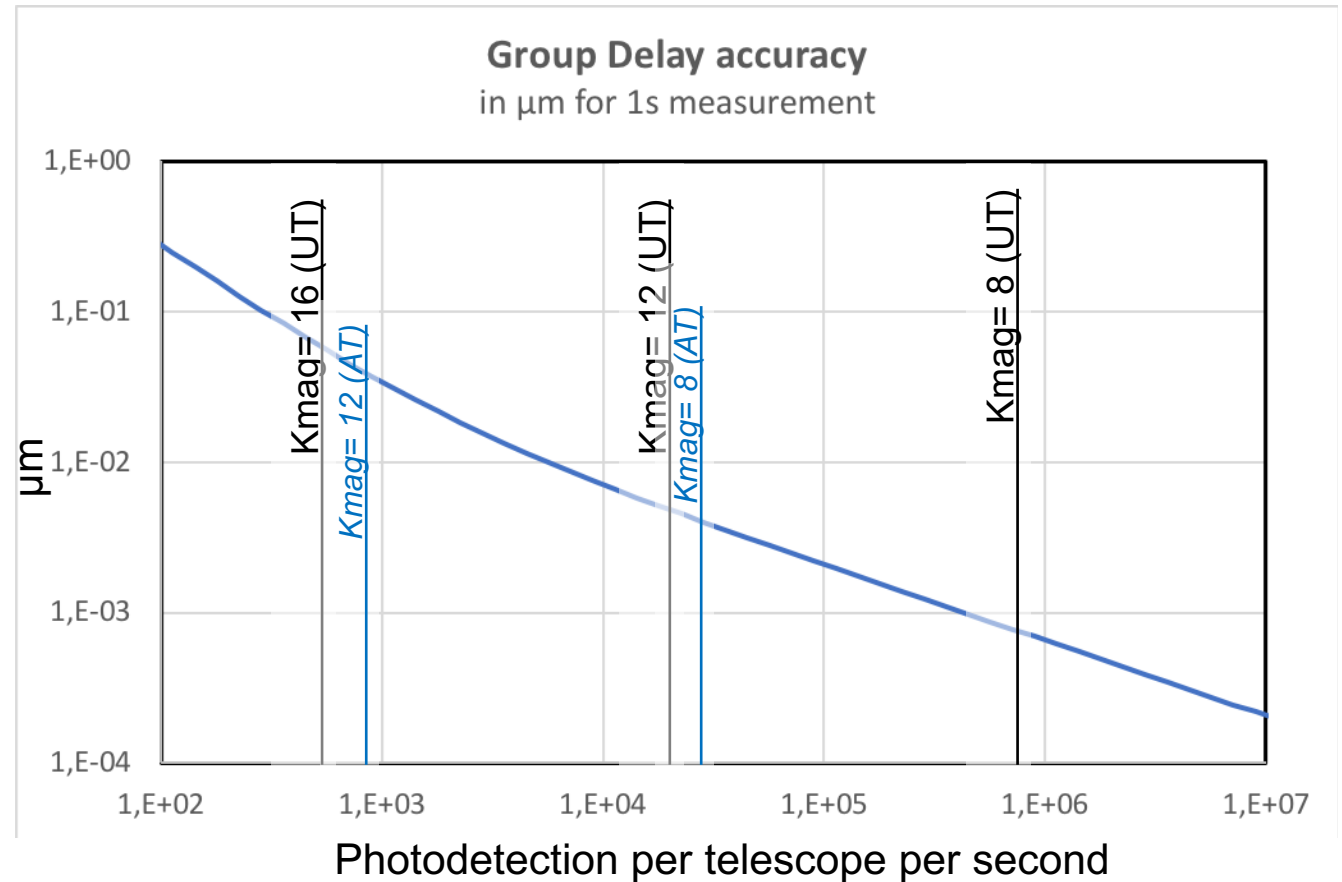


# With ATs or an improved infrastructure on UTs



# Group Delay « post SF2B »

The group delay measurement will not limit the HFT performance at 4T

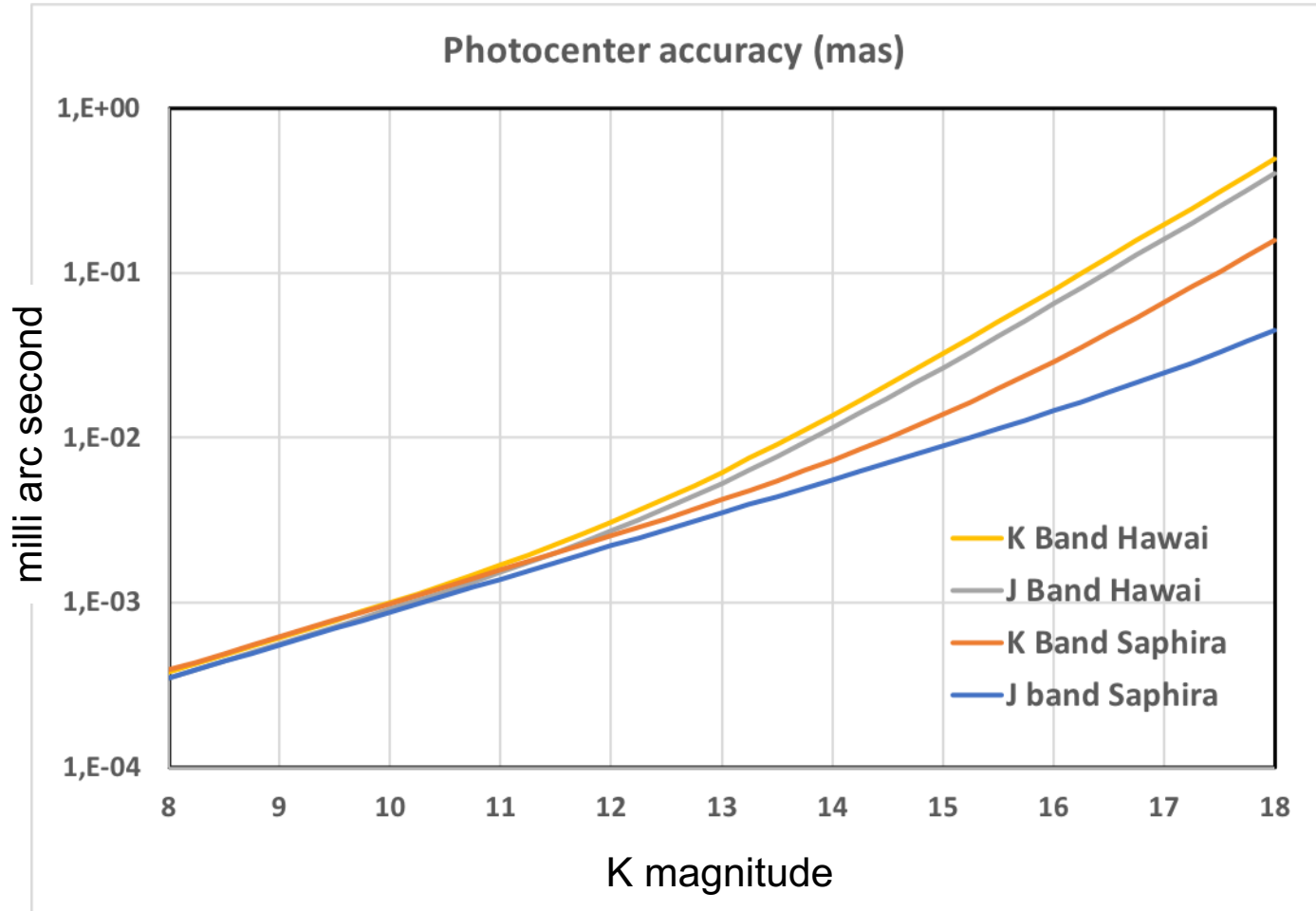


# Photocenter displacement accuracy in J and in K

The photocenter accuracy will be better in J than in K,

for the median J-K value for Sy1,

in median seeing conditions the gain in resolution and source photons more than compensate the loss in Strehl and in Visibility



# Development plan

- GRA4MAT finalized early 2020 and analyzed 2020
  - Actual performances of MATISSE+GRA4MAT
  - The « fringe jumps » issue
  - Chromatic OPD correction
  - Using GFT data for MATISSE high accuracy
- HFT Bulk optics prototype of a 4T HFT sensor finalized by early 2020
- Comparative tests of Integrated Optics ABCD and HFT chips in the CHARA/SPICA FT in 2020 (UCA funding)
- Propose a VLTI visitor instrument HFT + R=1000 in J band by 2020
  - Discuss synergy and joint development with BIFROST
  - Comparative analysis of specification and performances with ASGARD FT
  - Synergy with GRAVITY+
    - All infrastructure improvements (vibrations, AO) would boost the HFT
    - The HFT would increase the sky coverage for off-axis tracking.

# Conclusion

- An external FT can extend the capability of the VLTI with the current infrastructure, and allow observations with  $K > 14$  (UT) and  $K > 12$  (AT)
- This would have immediate applications for an AGN program in the J band and for the MATISSE AGN program
- Improvements on the VLTI UT vibrations would allow a very substantial gain on UTs  $\rightarrow K \sim 16$
- The limiting magnitude for Differential Interferometry of BLRs is  $K \sim 17$  or  $J \sim 17$
- The main limitation on the number of targets, at any step of improvement of the FT sensitivity will be the Adaptive Optics
  - The median V-K magnitude difference for Sy I is  $\sim 4$
  - $K < 15$  and  $V < 15 \rightarrow 160$  Sy I
  - $K < 15$  and  $V < 17 \rightarrow 660$  Sy I
  - $K < 17$  and  $V < 19 \rightarrow 2900$  Sy I
- Statistics on “large numbers” of SMBH masses and Quasar distance would be disruptive
- This needs a global understanding of BLR and Torus morphology.