The new observing modes of the GRAVITY+ Adaptive Optics

- Integration to ASPRO -

Anthony Berdeu, Jean-Baptiste Le Bouquin,
Guillaume Mella, Laurent Bourgès, Jean-Philippe Berger, …

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Observatoire de Paris | PSL
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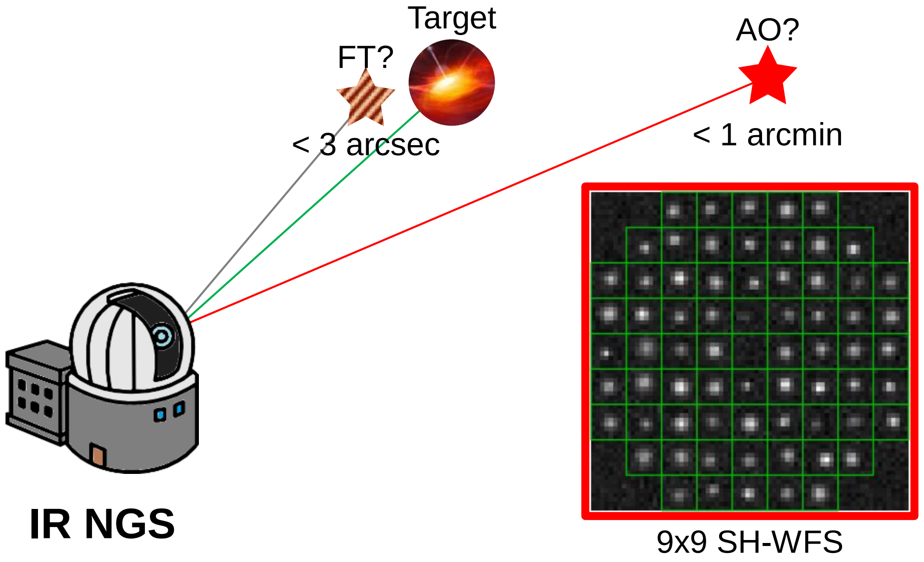
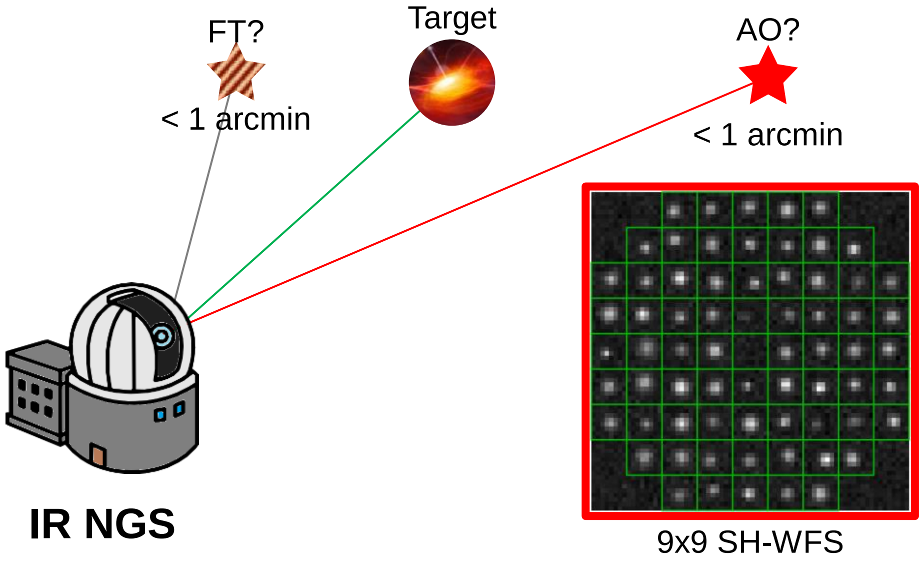
Laboratoire d'Études Spatiales et d'Instrumentation en Astrophysique

06-07th of February 2024

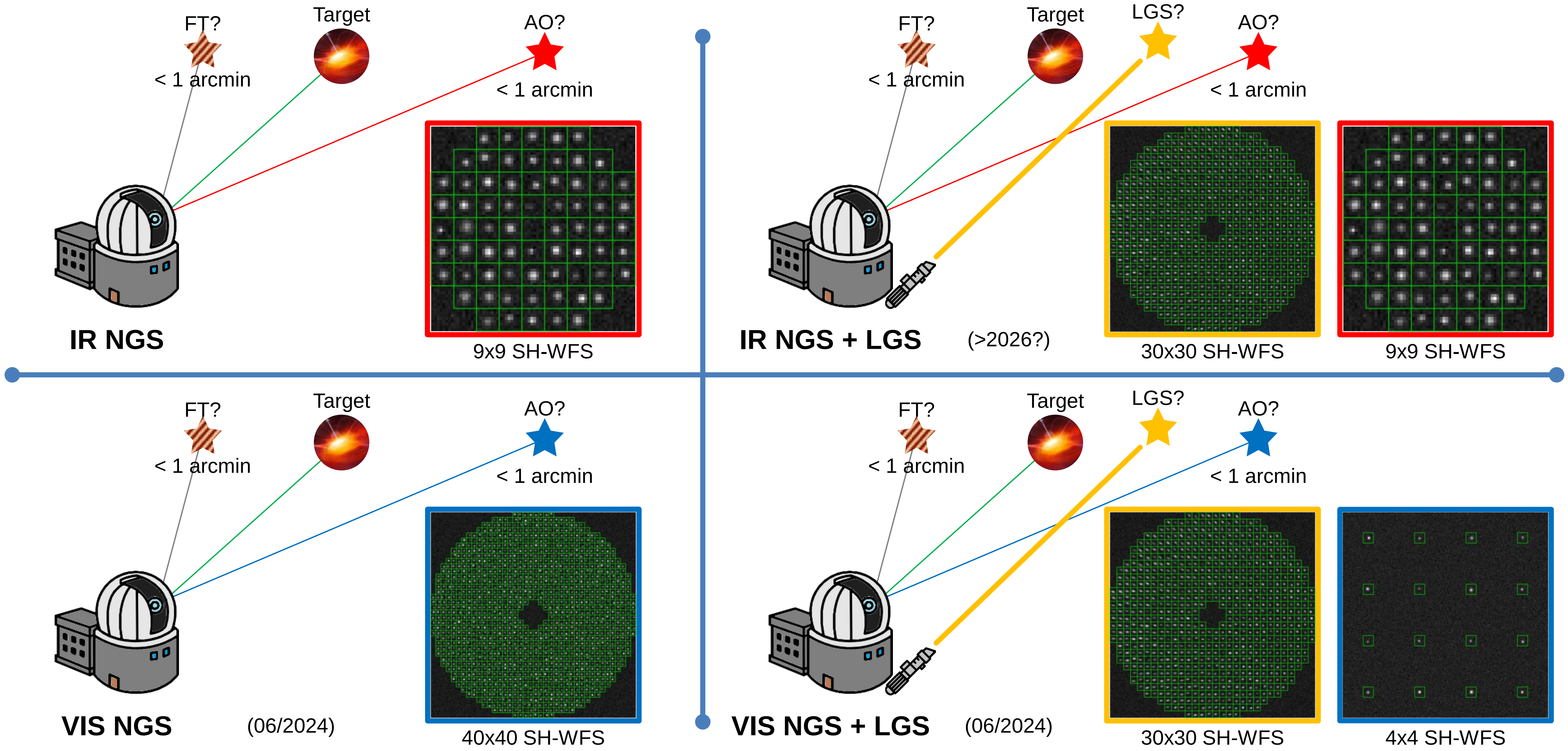
Once upon a time… was GRAVITY…



Then came GRAVITY+/WIDE…



Now comes GRAVITY+/Adaptive Optics...

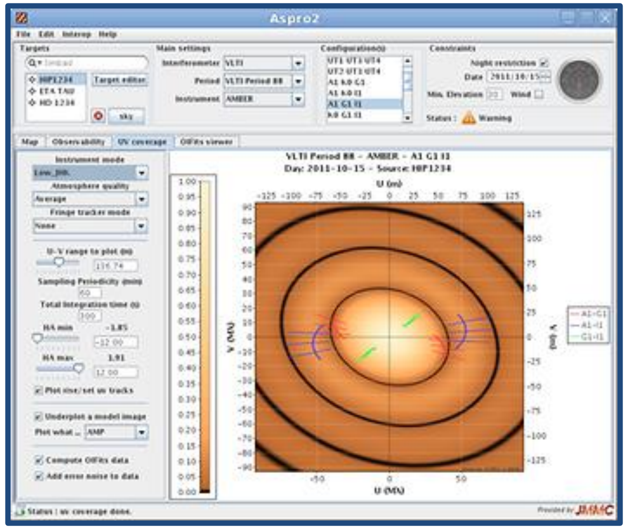


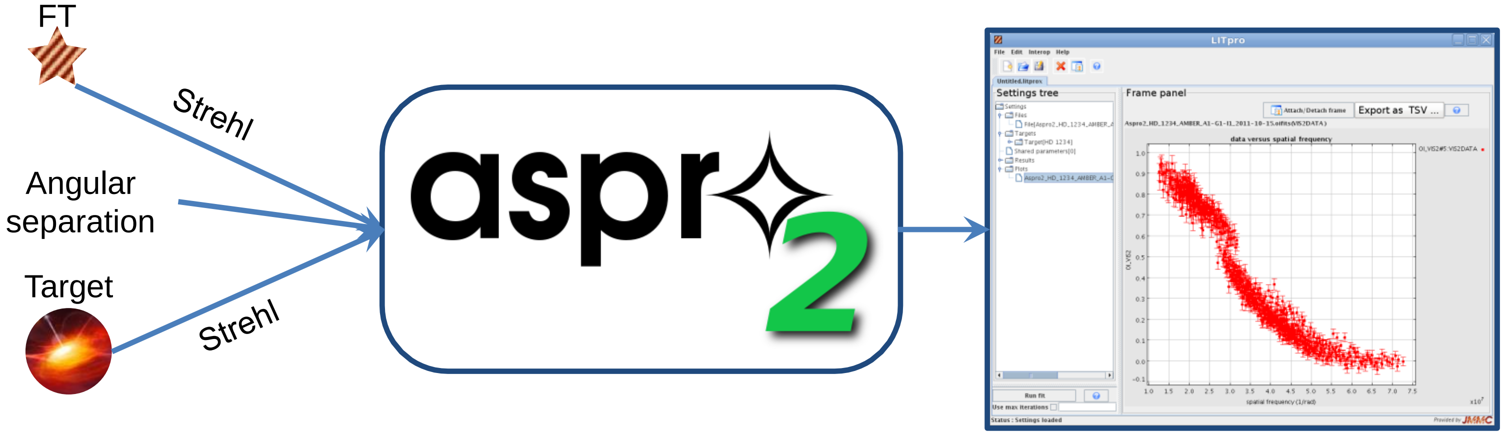
Now comes GRAVITY+/Adaptive Optics…

- Take home messages: GPAO comes with ~~3~~ 4 modes:
  - 9x9 **IR NGS** (+ 30x30 **LGS**)
  - 40x40 **visible NGS**
  - 4x4 **visible NGS** + 30x30 **LGS**

How to update $ASPRO_2$?

- New questions when planning the observations:
  - NGS vs LGS?
  - IR vs visible?
  - Which target for the NGS WFS?
  - Which target for fringe tracker?
  - Where to place the LGS?





Data simulator

- Need to upgrade $ASPRO_2$
  - For the simulator
  - To rank the stars for the fringe tracker and the NGS WFS
  - To rank the GPAO modes

- Needs/constraints
  - Only the Strehl on the FT and target
  - Need to be **fast** to compute (ranking lots of stars / real time application for the user)
  - Need to be **easy** to compute (embedded in the JavaScript code)
  - (Would be good to have the statistics of the Strehl…)

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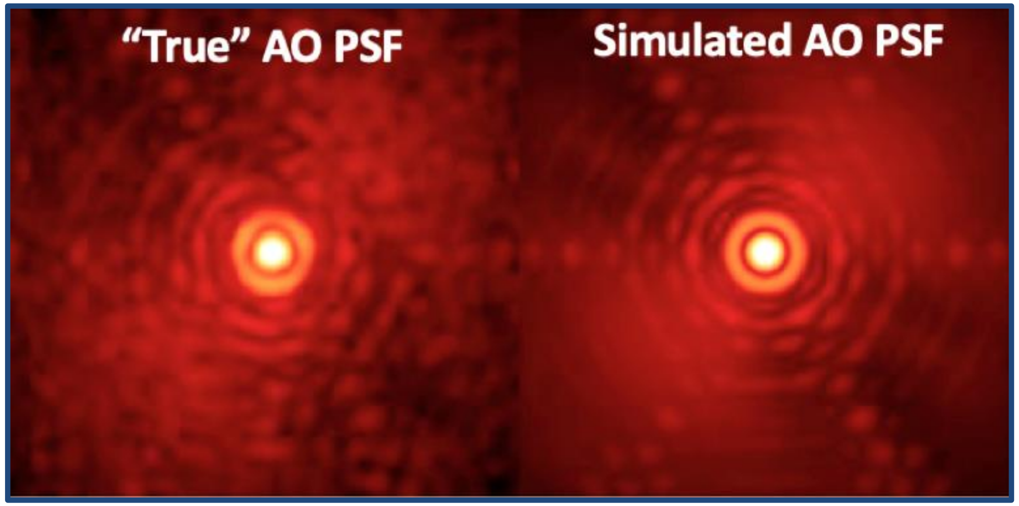
Using TIPTOP, a PSF simulator?

TIPTOP: a new tool to efficiently predict your favorite AO PSF, B. Neichel et. al., SPIE 2020
TIPTOP: cone effect for single laser adaptive optics systems, G. Agapito et. al., AO4ELT, 2023



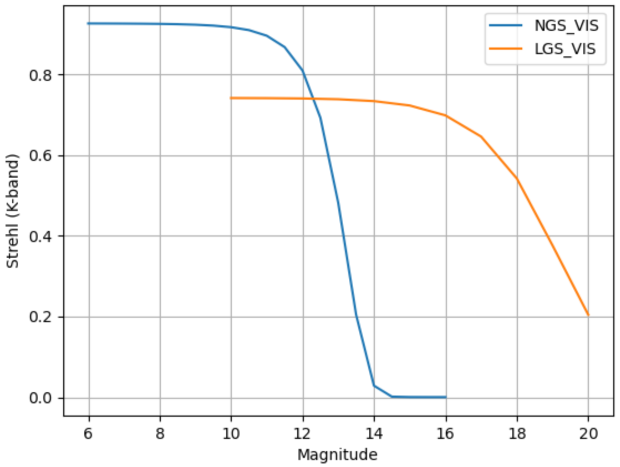
- A tool base on the power spectrum density approach:
  - Open source in Python
  - Actively developed at LAM for the ELT
  - Can simulate short term and long term exposures
  - Fast to compute (for the NGS, a bit less for the LGS…)

- For GPAO:
  - Include the LGS mode / cone effect
  - Include the isoplanetism
  - Easy to extract the Strehl

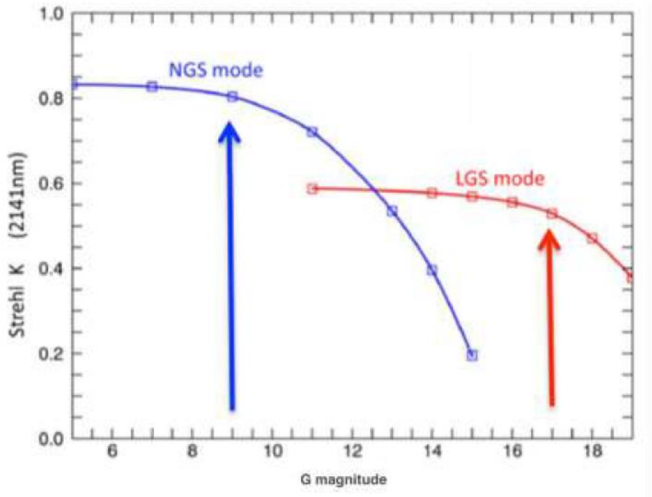
- But: too complicated to be included in $ASPRO_2$

- A solution: parametrize a "meta"-Maréchal approximation?

GPAO and TIPTOP



GPAO E2E simulations



Actors in the play

----- ATMOSPHERE and SOURCES -----

$r_l = \mathrm{r}_0(\lambda_l/\lambda_0)^{6/5}$, the **Fried parameter** at λ_l of the turbulence layer

h_0 / h_{lgs}, the **altitude** of the turbulence layer / LGS

v_0, **velocity** of the turbulence layer

$\chi = \sec\zeta = 1/\cos\zeta$, the secant of the **zenith angle** ζ

Φ_l, **photon flux** of the source l $(\mathrm{ph/m^2/s})$ (with telescope transmission)

λ_0, reference **wavelength** of the atmosphere

λ_{sci}, **wavelength** of the science

λ_{ngs}, **wavelength** of the natural guide star (HO in NGS, LO in LGS)

λ_{lgs}, **wavelength** of the laser guide star (HO in LGS)

----- AO system -----

g, the loop gain

f, the **frequency of the loop**

$\theta_{l,l'}$, **angular distance** between the sources l and l'

N_{modes}, **number of GPAO modes** $\leftrightsquigarrow d_{\mathrm{actu}} = D_{\mathrm{tel}}/2\sqrt{N_{\mathrm{modes}}/\pi}$, inter-actuator distance

D_{tel}, diameter of the telescope

T_{tel}, transmission of the telescope including the SF-WFS

N_{wfs}, number of lenslets in the wavefront sensor across the diameter

$D_{\mathrm{wfs}} = D_{\mathrm{tel}}/N_{\mathrm{wfs}}$, diameter of a SH-pupil

N_{pix}, number of pixel in a WFS box (side)

$N_{\mathrm{ph},l} = \Phi_l T_{\mathrm{tel}} \frac{D_{\mathrm{wfs}}^2}{f}$, number of photons in a lenslet for one short exposure for the source l

σ_{pix}, pixel readout noise

α_{pix}, the pixel scale of the WFS

Ξ_l, FWHM of the source l

NGS mode

- Total variance

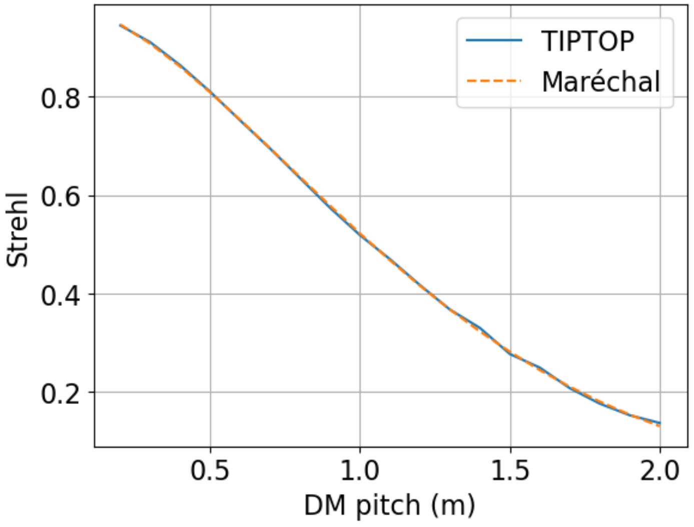
$$\sigma^2_{\text{tot}} = \underbrace{\sigma^2_{\text{geom}}}_{\sigma^2_{\text{fitting}}+\sigma^2_{\text{aliasing}}} + \sigma^2_{\text{lag}} + \underbrace{\sigma^2_{\text{ph}} + \sigma^2_{\text{ron}}}_{\sigma^2_{\text{noise}}} + \sigma^2_{\text{iso}}$$

- With
  - Fitting and aliasing $\rightarrow \sigma^2_{\text{geom}} \propto \left(\frac{d_{\text{actu}}}{\chi^{-3/5} r_{\text{sci}}}\right)^{5/3}$
  - Servo-lag ~~$\rightarrow \sigma^2_{\text{lag}} \propto \left(\frac{v_0}{\chi^{-3/5} r_{\text{sci}} . f . g}\right)^{5/3}$~~ $\sigma^2_{\text{lag}} = \alpha \left(\frac{v_0}{\chi^{-3/5} r_{\text{sci}} . f . g}\right)^{\beta}$
  - Photon noise $\rightarrow \sigma^2_{\text{ph}} \propto \underbrace{\left(\frac{\lambda_{\text{ngs}}}{\lambda_{\text{sci}} / D_{\text{wfs}}}\right)^2}_{\text{Spot positionning incertainty scaled to the science wavelength}} \frac{g}{2-g} \underbrace{2. N_{\text{ph,ngs}}}_{\text{Shot noise variance 2 is for excess noise of EMCCD}} \underbrace{1/N^2_{\text{ph,ngs}}}_{\text{Signal}\rightarrow\text{squared number of photons}}$
  - Readout noise $\rightarrow \sigma^2_{\text{ron}} \propto \underbrace{\alpha^2_{\text{pix}} N^4_{\text{pix}} \sigma^2_{\text{pix}}}_{\text{Readout noise variance that depends on the centroiding method}} \frac{g}{2-g} \underbrace{1/N^2_{\text{ph,ngs}}}_{\text{Signal}\rightarrow\text{squared number of photons}}$
  - Isoplanetism ~~$\rightarrow \sigma^2_{\text{iso}} \propto \left(\frac{\theta_{\text{sci,ngs}} \chi h_0}{\chi^{-3/5} r_{\text{sci}}}\right)^{5/3}$~~ $\sigma^2_{\text{iso}} = \alpha \left(\frac{\theta_{\text{sci,ngs}} \chi h_0}{\chi^{-3/5} r_{\text{sci}}}\right)^{\beta}$

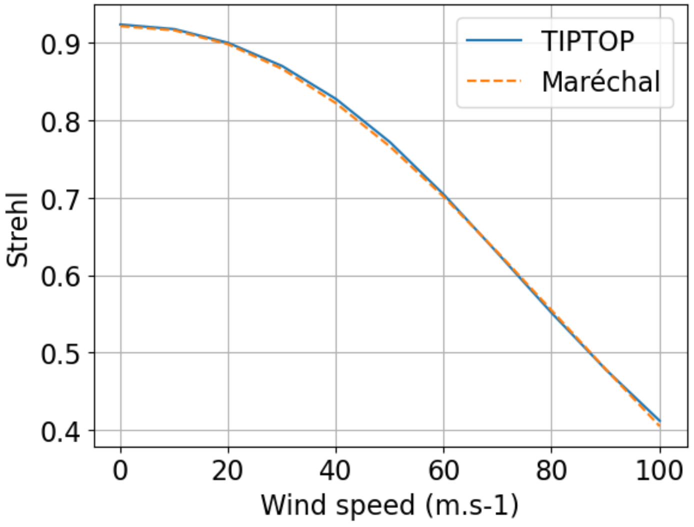
- Take home messages:
  - ∝ coefficients calibrated with TIPTOP
  - Should be double-checked with E2E simulations
  - And refined on-sky

NGS → Maréchal *vs* calibration

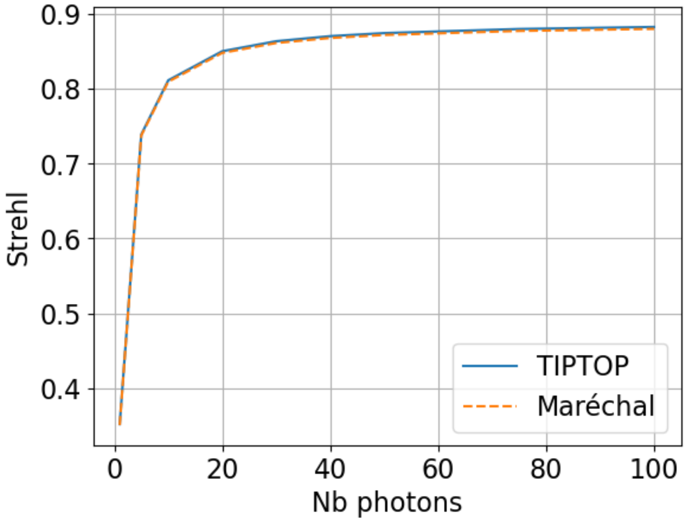
Readout noise



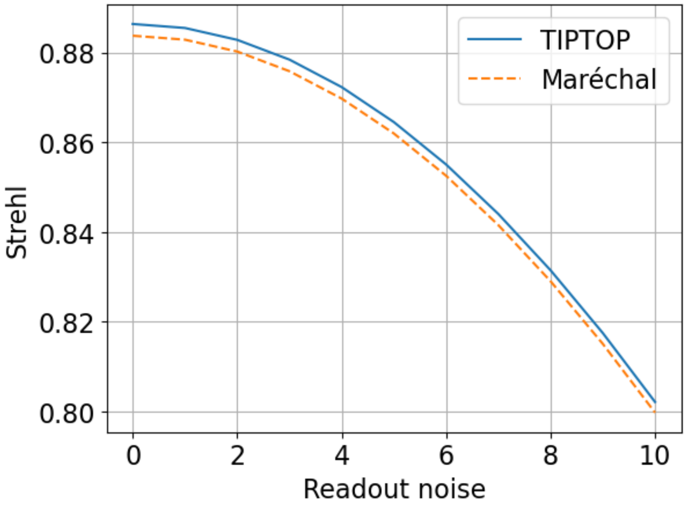
Servo-lag



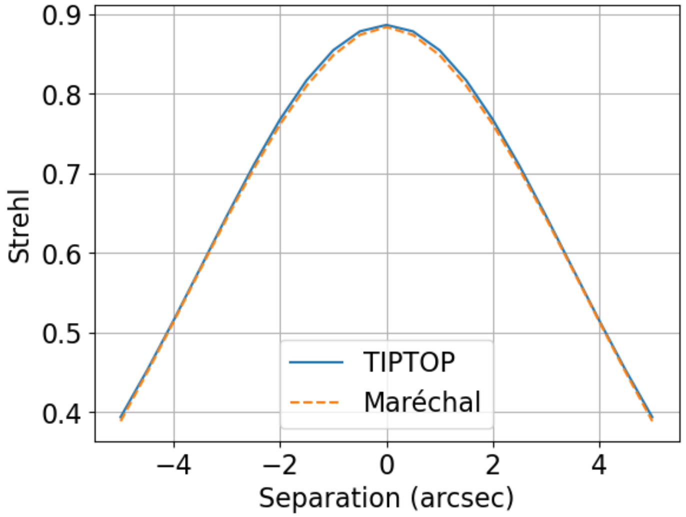
Photon noise (magnitude)



Readout noise

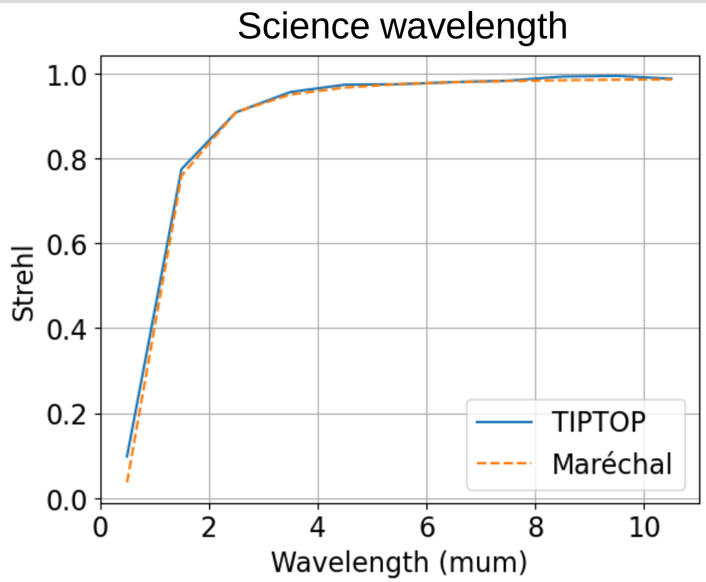


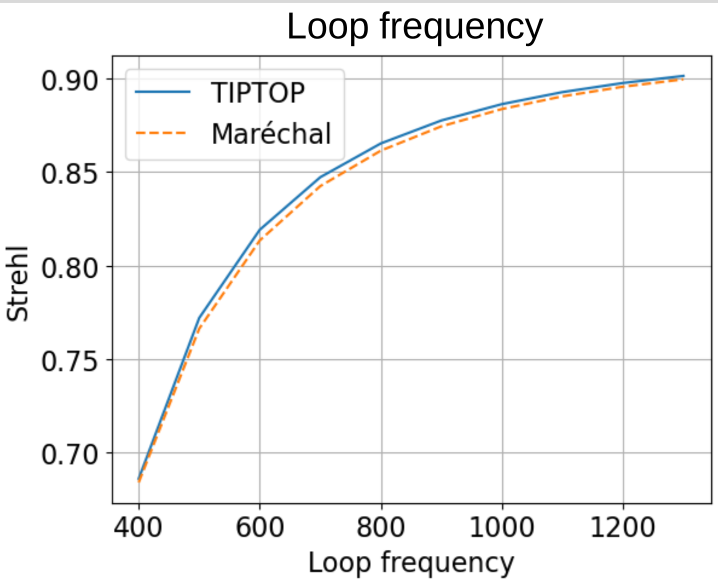
Isoplanetism error

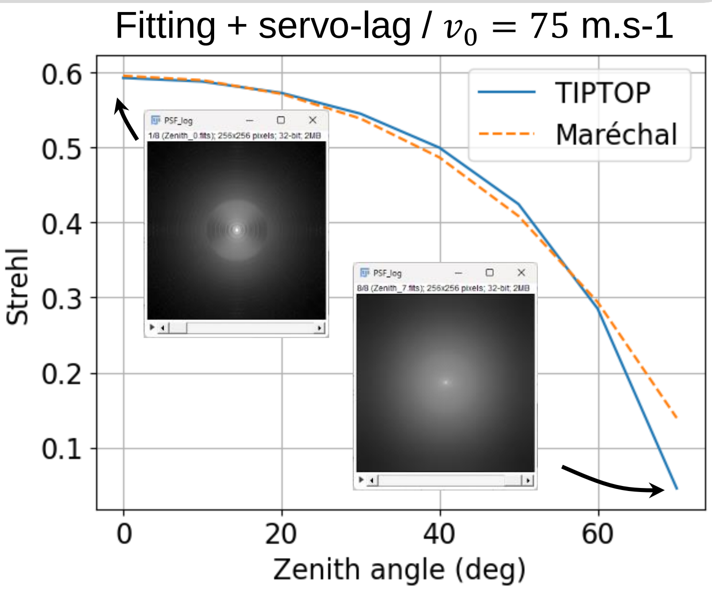


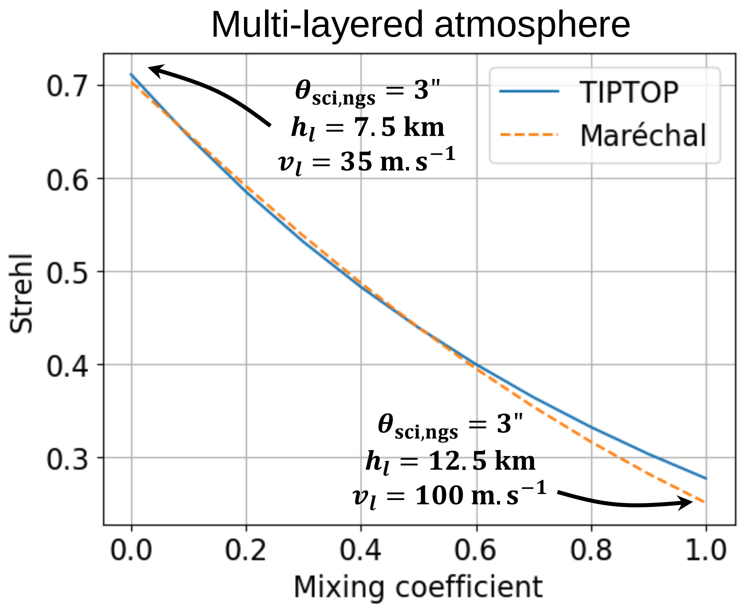
- Overall very good fit, but assuming that the power law of the servo-lag and the separation is not 5/3….

NGS → Maréchal *vs* other parameters







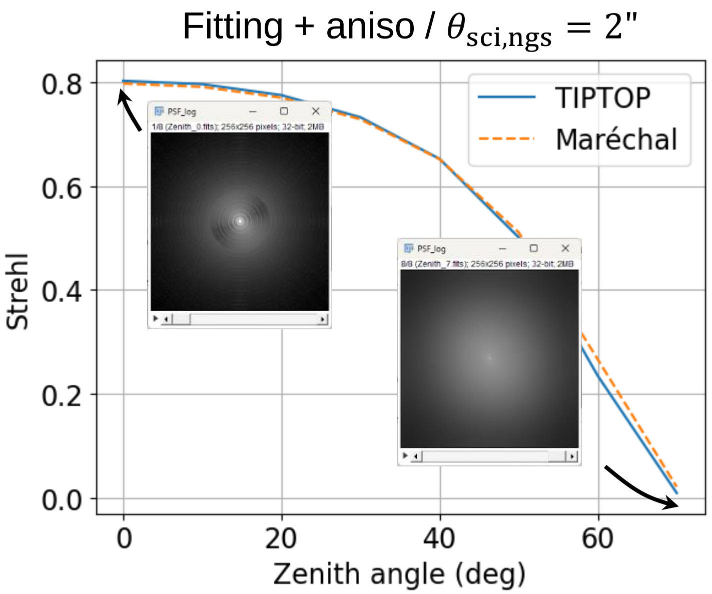


- For the Maréchal approximation:

$$v_0 = \left(\sum_{l \in \mathrm{layers}} C_{n,l}^2\, v_l^{5/3}\right)^{3/5}$$

$$h_0 = \left(\sum_{l \in \mathrm{layers}} C_{n,l}^2\, h_l^{5/3}\right)^{3/5}$$

- Test by mixing two layers with $C_{n,1}^2 = 1 - C_{n,0}^2$



Towards the LGS mode…

- Total variance

$$\sigma^2_{\text{tot}} = \sigma^2_{\text{geom}} + \sigma^2_{\text{lag,HO}} + \sigma^2_{\text{lag,LO}} + \sigma^2_{\text{ph,HO}} + \sigma^2_{\text{ph,LO}} + \sigma^2_{\text{ron,HO}} + \sigma^2_{\text{ron,LO}} + \underbrace{\sigma^2_{\text{iso,HO}}}_{\text{isoplanetism}} + \underbrace{\sigma^2_{\text{iso,LO}}}_{\text{isokinetism}} + \sigma^2_{\text{cone,sci}}$$

- With
  - $\sigma^2_{\text{geom}} \propto \left(\chi \frac{d_{\text{actu}}}{r_{\text{sci}}}\right)^{5/3}$, fitting and aliasing
  - $\sigma^2_{\text{lag,HO/LO}} \propto \left(\chi \frac{v_0}{r_{\text{sci}} . f_{\text{HO/LO}} . g_{\text{HO/LO}}}\right)^{5/3}$
  - $\sigma^2_{\text{ph,HO}} \propto \left(\frac{\Xi_{\text{lgs}}}{\lambda_{\text{sci}} / D_{\text{wfs,HO}}}\right)^2 2 \frac{g}{2-g} \frac{1}{N_{\text{ph,lgs}}(\text{HO})} \rightarrow \Xi_{\text{lgs}} \simeq 1 \text{ arcsec}$
  - $\sigma^2_{\text{ph,LO}} \propto \left(\frac{\Xi_{\text{ngs}}}{\lambda_{\text{sci}} / D_{\text{wfs,LO}}}\right)^2 2 \frac{g}{2-g} \frac{1}{N_{\text{ph,ngs}}(\text{LO})} \rightarrow \Xi_{\text{ngs}} \simeq \boldsymbol{S_{\text{LO}}} \left(\frac{\lambda_{\text{lgs}}}{D_{\text{wfs,LO}}}\right)^2 + (1 - \boldsymbol{S_{\text{LO}}}) \left(\frac{\lambda_{\text{lgs}}}{r_{\text{lgs}}}\right)^2$
  - $\sigma^2_{\text{ron,HO/LO}} \propto \alpha^2_{\text{pix,HO/LO}} N^4_{\text{pix,HO/LO}} \sigma^2_{\text{pix,HO/LO}} \frac{g}{2-g} \frac{1}{N^2_{\text{ph,lgs/ngs}}(\text{HO/LO})}$
  - $\sigma^2_{\text{iso,HO/LO}} \propto \left(\chi \frac{\theta_{\text{sci,lgs/sci,ngs}} h_0}{r_{\text{sci}}}\right)^{5/3}$, isoplanetism / isokinestism
  - $\sigma^2_{\text{cone,sci}} \propto \left(\chi \frac{D_{\text{tel}}}{r_{\text{sci}}} \frac{h_0}{h_{\text{lgs}}}\right)^{5/3}$

- Remarks:
  - $\boldsymbol{S_{\text{LO}}}$ → Trade-off between a seeing limited and a diffraction limited spot in the LO WFS with S_{LO} the Strehl on the LO-WFS

Strehl on the LO-WFS

- $\boldsymbol{S_{\mathrm{LO}}} = e^{-\sigma^2_{\mathrm{LO}}}$ with

$$\sigma^2_{\mathrm{LO}} = \sigma^2_{\mathrm{geom}} + \sigma^2_{\mathrm{lag,HO}} + \sigma^2_{\mathrm{ph,HO}} + \sigma^2_{\mathrm{ron,HO}} + \sigma^2_{\mathrm{iso}} + \sigma^2_{\mathrm{cone,lgs}}$$

- With
  - $\sigma^2_{\mathrm{geom}} \propto \left(\chi \frac{d_{\mathrm{actu}}}{r_{\mathrm{ngs}}}\right)^{5/3}$, fitting and aliasing
  - $\sigma^2_{\mathrm{lag,HO}} \propto \left(\chi \frac{v_0}{r_{\mathrm{ngs}} \cdot f_{\mathrm{HO}} \cdot g_{\mathrm{HO}}}\right)^{5/3}$
  - $\sigma^2_{\mathrm{ph,HO}} \propto \left(\frac{\Xi_{\mathrm{lgs}}}{\lambda_{\mathrm{ngs}} / D_{\mathrm{wfs,HO}}}\right)^2 2 \frac{g}{2-g} \frac{1}{N_{\mathrm{ph,lgs}}(\mathrm{HO})} \rightarrow \Xi_{\mathrm{lgs}} \simeq 1 \text{ arcsec}$
  - $\sigma^2_{\mathrm{ron,HO}} \propto \alpha^2_{\mathrm{pix,HO}} N^4_{\mathrm{pix,HO}} \sigma^2_{\mathrm{pix,HO}} \frac{g}{2-g} \frac{1}{N^2_{\mathrm{ph,lgs}}(\mathrm{HO})}$
  - $\sigma^2_{\mathrm{iso}} \propto \left(\chi \frac{\theta_{\mathrm{lgs,ngs}} h_0}{r_{\mathrm{ngs}}}\right)^{5/3}$, isoplanetism
  - $\sigma^2_{\mathrm{cone,lgs}} \propto \left(\chi \frac{D_{\mathrm{wfs,LO}}}{r_{\mathrm{ngs}}} \frac{h_0}{h_{\mathrm{lgs}}}\right)^{5/3}$

- Remarks:
  - Trade-off between a seeing limited and a diffraction limited spot in the LO WFS with S_{LO} the Strehl on the LO-WFS
  - All the terms « LO » disappears with the assumption that the LO order loop freezes the low orders. We just make the assumption that the HO are averaged to get a statistical meaning of the Strehl in the LO loop.
  - $\underbrace{\sigma^2_{\mathrm{iso,LO}}}_{\mathrm{isokinetism}}$, no isokinestism → here to grasp the phase variance between science and tip/tilt star

Conclusions

- Need to develop a tool to upgrade $ASPRO_2$
  - Compute the Strehl for the different AO system configuration (magnitude, separations, laser *vs* natural)
  - Easy to implement in JavaScript

- Solution : using a Maréchal “meta”-approximation
  - Calibrating the coefficients with TIPTOP
  - The coefficients need to be calibrated for the visible and IR modes
  - The coefficients will have to be refined on-sky…

- Current status
  - NGS model seems to be good enough → currently tested in SearchFTT
  - LGS model → need to be calibrated against TIPTOP and implemented in SearchFTT
  - SPIE communication to come (June 2024)…

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