JOURNÉES SF2A
04-07 June 2024
Marseille, France

LESIA Observatoire de Paris | PSL

Simplified model(s) of the GRAVITY+ adaptive optics system(s) for performance prediction

A. Berdeu[a], J.-B. Le Bouquin[b], G. Mella[b,c], L. Bourgès[b,c], J.-P. Berger[b], T. Paumard[a], F. Millour[d], F. Eisenhauer[e], P. Garcia[f,g], C. Straubmeier[h], L. Kreidberg[i], S. F. Hönig[j], D. Defrère[k], and GRAVITY+ collaboration

Contact: anthony.berdeu@obspm.fr

[a] LESIA, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, Université de Paris 5 place Jules Janssen, 92195 Meudon, France
[b] Univ. Grenoble Alpes, CNRS, CNES, IPAG, 38000 Grenoble, France / [c] Univ. Grenoble Alpes, CNRS, IRD, INRAE, Météo France, OSUG, 38000 Grenoble, France
[d] Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, Laboratoire Lagrange, France / [e] Max Planck Institute for extraterrestrial Physics, Giessenbachstraße 1, 85748 Garching, Germany
[f] CENTRA - Centro de Astrofísica e Gravitação, IST, Universidade de Lisboa, 1049-001 Lisboa, Portugal / [g] Universidade do Porto, Faculdade de Engenharia, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal
[h] 1st Institute of Physics, University of Cologne, Zülpicher Straße 77, 50937 Cologne, Germany / [i] Max Planck Institute for Astronomy, Königstuhl 17, 69117 Heidelberg, Germany
[j] School of Physics & Astronomy, University of Southampton, University Road, Southampton SO17 1BJ, UK / [k] Institute of Astronomy, KU Leuven, Celestijnenlaan 200D, B-3001, Leuven, Belgium

Abstract

GRAVITY and the VLT Interferometer (VLTI) have transformed optical interferometry with groundbreaking results on the Galactic Center (see Nobel Prize in Physics 2020), active galactic nuclei, and exoplanets. Through its upgrades – off-axis fringe-tracking, extreme adaptive optics (AO) and laser guide stars for the four 8-m unit telescopes (UTs) – GRAVITY+ will open up the extragalactic sky for milli-arcsec resolution interferometric imaging, and give access to targets as faint as K = 22 mag. GRAVITY+ will measure the black hole masses of active galactic nuclei across cosmic time, and obtain high quality exoplanet spectra and orbits.

This poster describes the brand-new AO system of GRAVITY+ and the different observation modes that will be offered after its deployment. In this context, for given targets and turbulence conditions, new tools must be developed for the observer to choose the best AO configuration among the four that will be available.

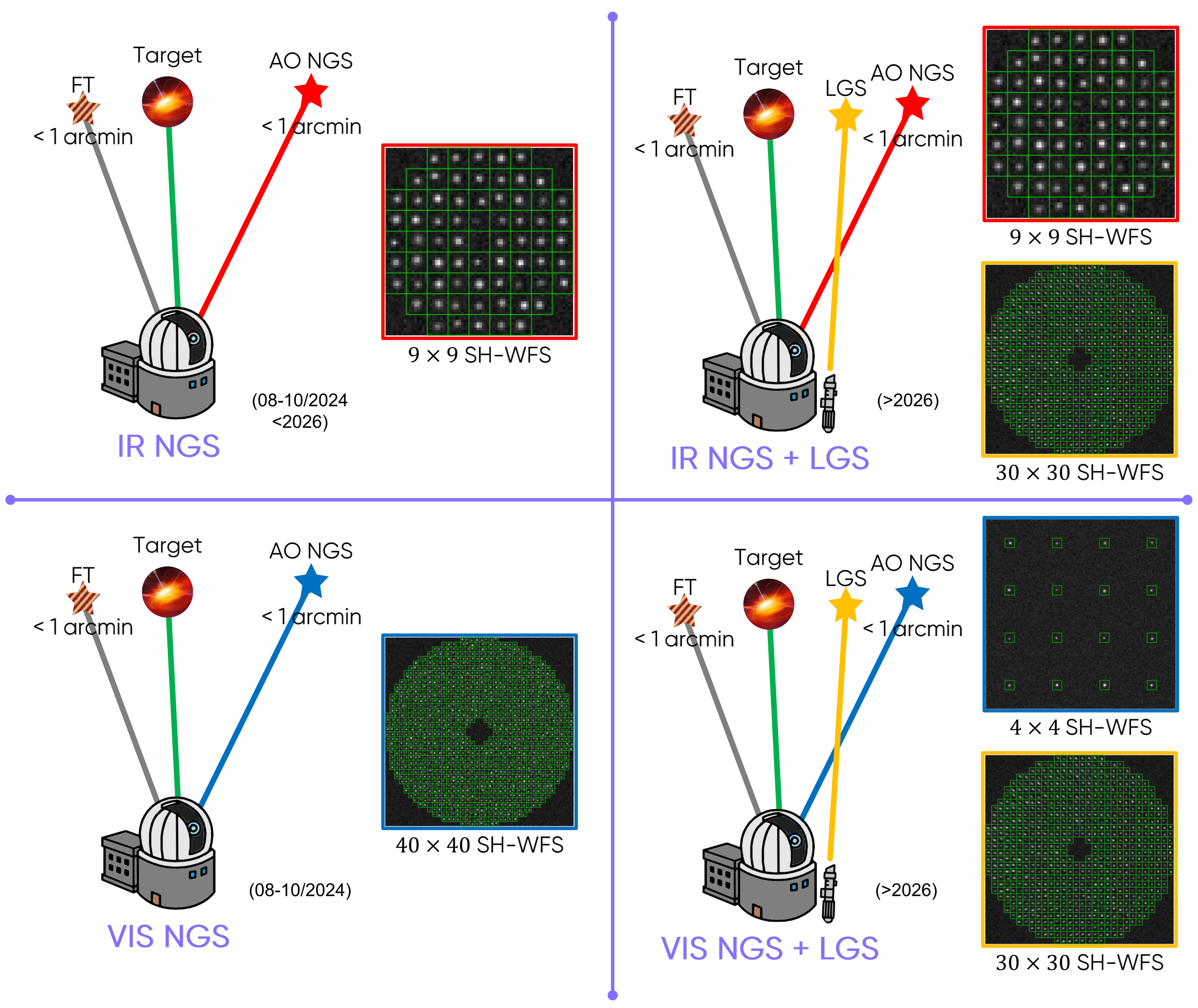
GRAVITY+ Adaptive Optics

The GRAVITY+ AO system, this is for each unit of the Very Large Telescope Interferometer (VLTI):

- A 43 × 43 ALPAO DM with 1453 active actuators,
- Four different AO configurations,
- Four different Shack-Hartmann wavefront sensors (SH-WFS) for low order (LO) and high order (HO) sensing.

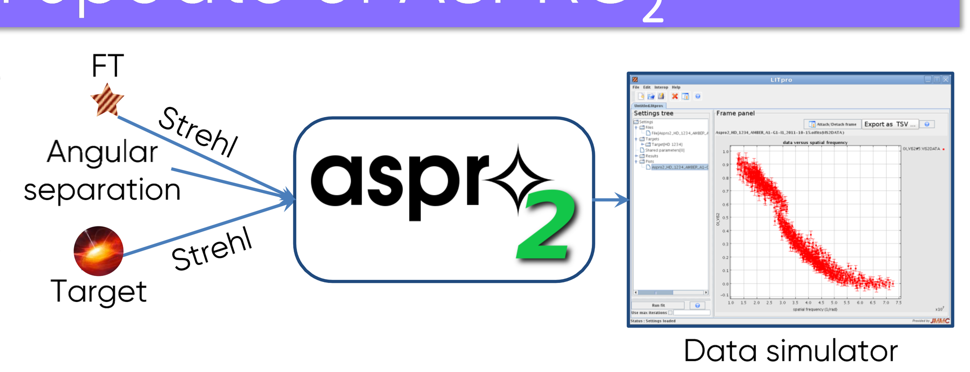
SH-WFS size	9 × 9 / LO	4 × 4 / LO	40 × 40 / HO	30 × 30 / HO
SH-WFS type	IR NGS	VIS NGS	VIS NGS	LO/HO NGS
Pixels/box	8	12	6	8
Pixel scale	0.51"	0.21"	0.42"	0.8"
Sensor	SAPHIRA	OCAM2	OCAM2	OCAM2

FT: Fringe tracker NGS: Natural Guide Star LGS: Laser Guide Star IR: InfraRed VIS: Visible



Towards an update of ASPRO$_2$

The Astronomical Software to PRepare Observations (ASPRO) is a tool to simulate the performances of a VLTI instrument (UV-plane coverage, signal over noise ratio, visibility models, ...) for a given set of configuration, target and turbulence condition.



The tools predicting the Strehl ratios (FT and science) must be updated to accommodate for the new GRAVITY+ configurations and performances. Different questions and needs are at stake.

Which GRAVITY+ AO mode? Where to place the LGS? ⇒ fast tool for mode and stars/objects ranking

Which targets for the NGS and FT? Predicted SNR? ⇒ easy tool for portability, integration and calibration

Mérachal approximation (NGS)

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

Geometry → $\sigma^2_{\text{geom}} = \alpha_{\text{geom}} \left(\frac{d_{\text{actu}}}{\chi^{-3/5} r_{\text{sci}}}\right)^{5/3}$

Servo-lag → $\sigma^2_{\text{lag}} = \alpha_{\text{lag}} \left(\frac{v_0}{\chi^{-3/5} r_{\text{sci}}.f.g}\right)^{\beta_{\text{lag}}}$

Isoplanetism → $\sigma^2_{\text{iso}} = \alpha_{\text{iso}} \left(\frac{\theta_{\text{sci,ngs}} \chi h_0}{\chi^{-3/5} r_{\text{sci}}}\right)^{\beta_{\text{iso}}}$

Photon → $\sigma^2_{\text{ph}} = \underbrace{\alpha_{\text{ph}} \left(\frac{\lambda_{\text{ngs}}}{\lambda_{\text{sci}}}\right)^2}_{\text{Centroiding scaled to the science}} \underbrace{\frac{g}{2-g} 2. N_{\text{ph,ngs}}}_{\text{EM-CCD shot noise variance}} \underbrace{1/N^2_{\text{ph,ngs}}}_{\text{Signal}}$

Readout → $\sigma^2_{\text{ron}} = \alpha_{\text{ron}} \underbrace{\alpha^2_{\text{pix}} N^4_{\text{pix}} \sigma^2_{\text{pix}} \frac{g}{2-g}}_{\text{Readout noise + centroiding method}} \underbrace{1/N^2_{\text{ph,ngs}}}_{\text{Signal}}$

* $\beta \neq 5/3$ (external scale of the turbulence)

AO system

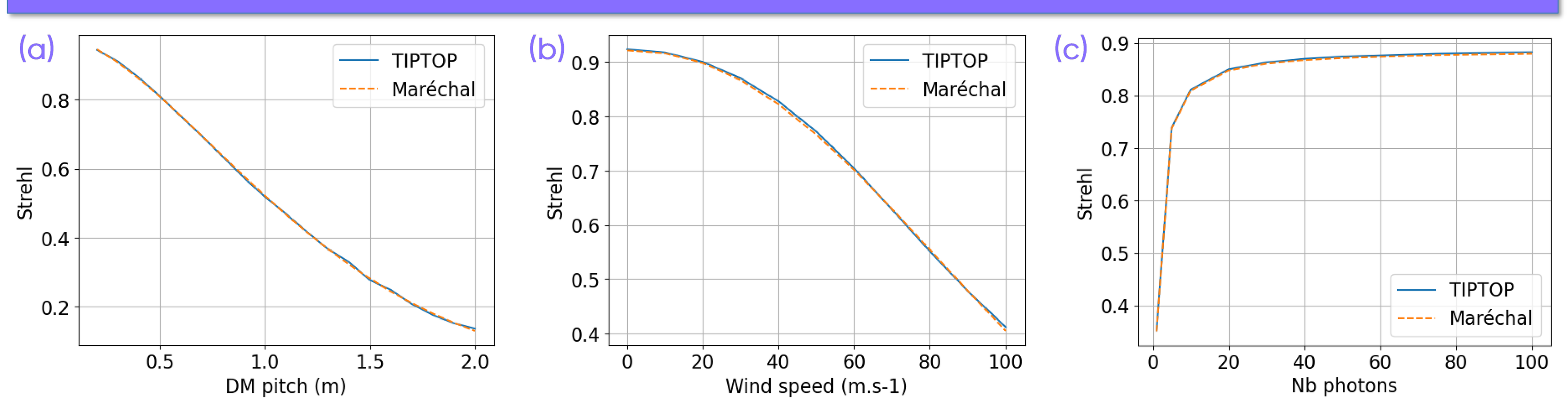
f, loop frequency* / g, loop gain
$\theta_{l,l'}$, angular distance* between $l \leftrightarrow l'$
N_{modes}, number of GPAO modes*
$d_{\text{actu}} = D_{\text{tel}}/2\sqrt{N_{\text{modes}}/\pi}$, inter-actuator distance
N_{pix}, pixel number in a SH-WFS box
$N_{\text{ph},l} = \Phi_l \frac{D^2_{\text{wfs}}}{f}$, number of photons in a lenslet
σ_{pix}, pixel readout noise / α_{pix}, the pixel scale

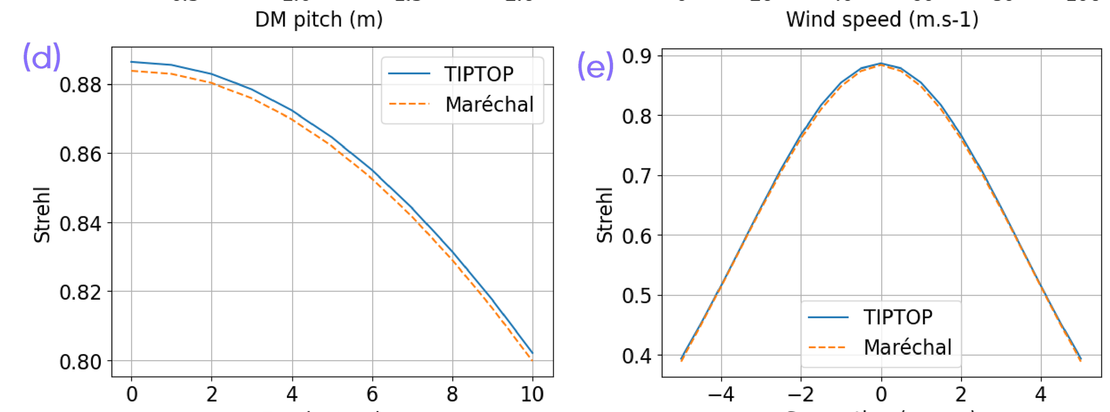
Atmosphere and sources

$l \in \{0, \text{lgs}, \text{ngs}, \text{sci}\}$, source*
λ_l, the wavelength* ($l \in \{0, \text{lgs}, \text{ngs}, \text{sci}\}$)
$r_l = r_0(\lambda_l/\lambda_0)^{6/5}$, the Fried parameter*
h_0 / h_{lgs}, the altitude* of the turbulence layer / LGS
v_0, velocity* of the turbulence layer
$\chi = 1/\cos\zeta$, the secant of the zenith angle* ζ
Φ_l, photon flux* of the source l (ph/m^2/s)
Ξ_l, FWHM of the source l

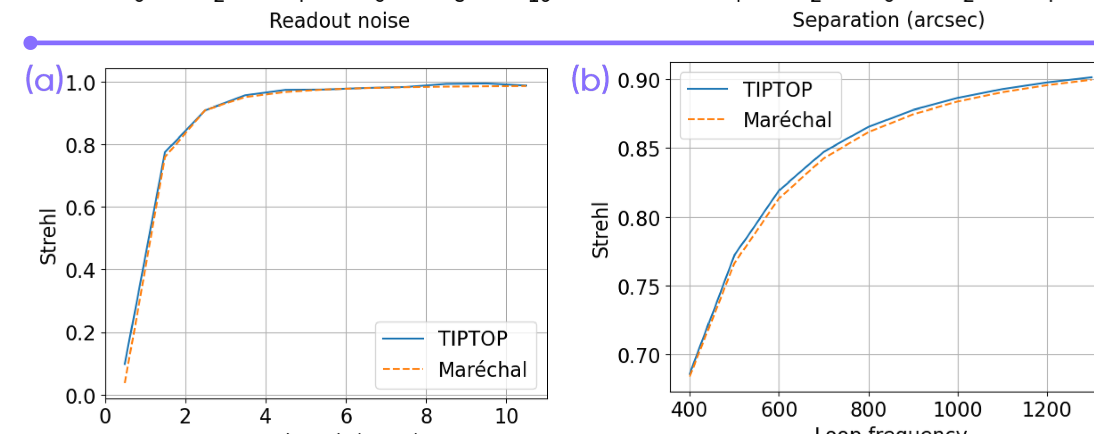
*ASPRO model parameters

Calibration with TIPTOP

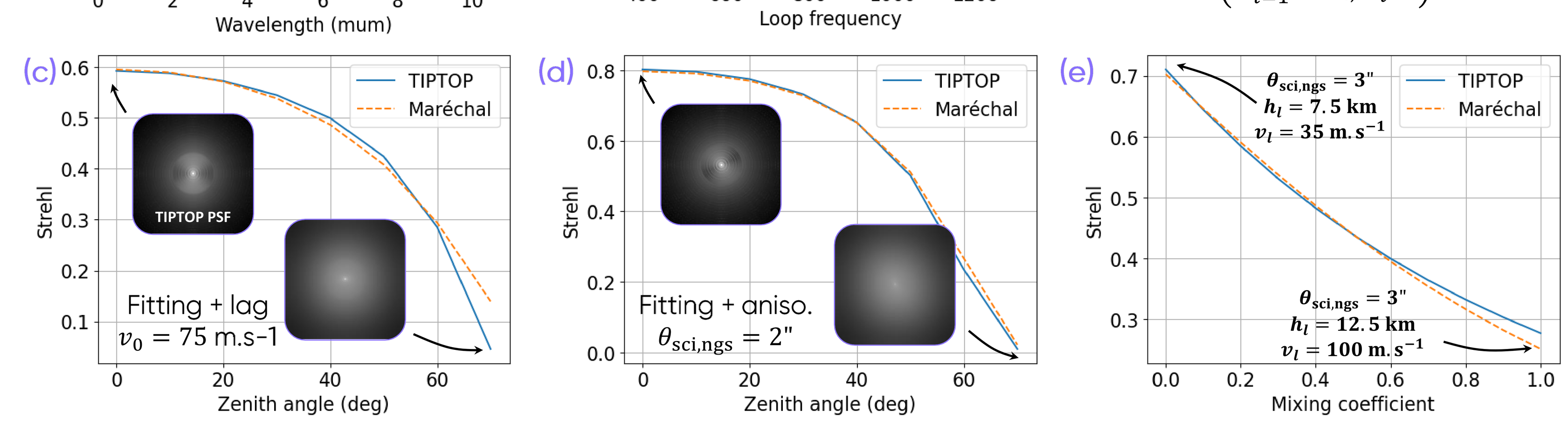




- Using the AO-PSF simulator TIPTOP to calibrate the different α and β.
- Playing on each error term by varying independent parameters
- Good fit of the geometry (a), servo-lag (b), photon (c) and sensor (d) noise, isoplanetism (e) errors.



- Validating the Maréchal equation on other terms...
- ... independent (a,b), ...
- ... coupling different errors (c,d), ...
- ... and multi-layer atmospheres (e) of layer parameters γ_l and of mean parameter: $p_0 = \left(\sum_{l=1}^{n_{\text{layer}}} c^2_{n,l} p_l^{5/3}\right)^{3/5}$



Perspectives

- NGS model already integrated the SearchFFT ranking tool (Aspro$_2$ coming soon...)
- To be used for the commissioning plan of GRAVITY+
- (α, β) parameters to be refined on real data (calibration on the VLT beacons, on-sky, ...)
- Work is on-going to develop and validate a LGS Maréchal approximation

$$\sigma^2_{\text{tot}} = \sigma^2_{\text{geom}} + \sigma^2_{\text{lag,HO}} + \sigma^2_{\text{lag,LO}} + \sigma^2_{\text{ph,HO}}(\Xi_{\text{lgs}} \simeq 1'') + \sigma^2_{\text{ph,LO}}(\Xi_{\text{ngs}}) + \sigma^2_{\text{ron,HO}} + \sigma^2_{\text{ron,LO}} + \underbrace{\sigma^2_{\text{iso,HO}}}_{\text{isoplanetism}} + \underbrace{\sigma^2_{\text{iso,LO}}}_{\text{isokinetism}} + \underbrace{\sigma^2_{\text{cone,sci}}}_{\text{cone effect}}$$

$$\Xi^2_{\text{ngs}} \simeq \underbrace{S_{\text{LO}} \left(\frac{\lambda_{\text{lgs}}}{D_{\text{wfs,LO}}}\right)^2 + (1 - S_{\text{LO}}) \left(\frac{\lambda_{\text{lgs}}}{r_{\text{lgs}}}\right)^2}_{\text{Tradeoff between a seeing and a diffraction limited LO spot}}$$

$$S_{\text{LO}} = e^{-\sigma^2_{\text{LO}}} \text{ with } \sigma^2_{\text{LO}} = \sigma^2_{\text{geom}} + \sigma^2_{\text{lag,HO}} + \sigma^2_{\text{ph,HO}} + \sigma^2_{\text{ron,HO}} + \sigma^2_{\text{iso}} + \sigma^2_{\text{cone,lgs}}$$

$$\sigma^2_{\text{cone,sci}} \propto \left(\frac{D_{\text{tel}}}{\chi^{-3/5} r_{\text{sci}}} \frac{h_0}{h_{\text{lgs}}}\right)^{5/3} \qquad \sigma^2_{\text{iso,HO/LO}} \propto \left(\frac{\theta_{\text{sci,lgs/sci,ngs}} \chi h_0}{\chi^{-3/5} r_{\text{sci}}}\right)^{5/3}$$

References & Acknowledgments

① *The GRAVITY+ Project: Towards All-sky, Faint-Science, High-Contrast Near-Infrared Interferometry at the VLTI*, Gravity+ Collaboration, Abuter, R., Alarcon, P., et al. 2022, The Messenger, 189, 17
② *TIPTOP: a new tool to efficiently predict your favorite AO PSF*, B. Neichel et. al., SPIE 2020
③ *TIPTOP: cone effect for single laser adaptive optics systems*, G. Agapito et. al., AO4ELT, 2023

The authors warmly thank Guido Agapito and Benoit Neichel for their great help in using TIPTOP.
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreements No 101004719.
This research has made use of the Jean-Marie Mariotti Center Aspro$_2$ service, available at http://www.jmmc.fr/aspro.