Point spread function reconstruction at W.M. Keck Observatory : progress and beyond

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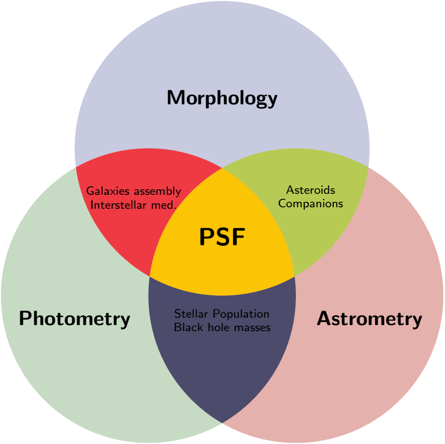
Outline

1. PSF-R: Scientific motivations
2. Methodology : from telemetry to PSF
3. Towards best-fit PSF-R
4. Summary

What do we care about getting the system PSF?



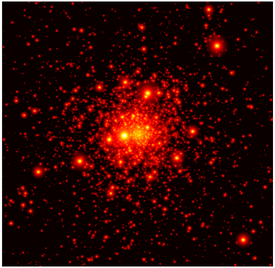
The object brightness distribution is convolved with the PSF :

$$\text{Im} = \text{Obj} \otimes \text{PSF}$$

Getting the real object properties requires a **deconvolution** process of focal-plane images

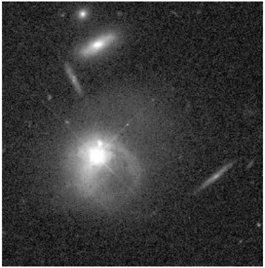
What are exactly the needs?

Galactic center



- Aims : measuring astrometry at 0.1 mas accuracy for tracking orbits around the central black hole
- Issue : sources confusion caused by overlapping
- Method : PSF model-fitting

Quasi stellar objects



- Aims : measuring masses of the host galaxy bulge and central black hole to evaluate potential correlation
- Issue : 3-4 order of magnitude on QSO/host galaxy contrast
- Method : PSF subtraction

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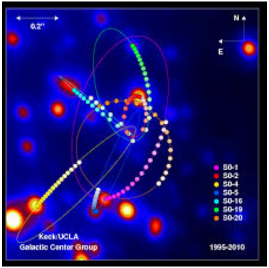

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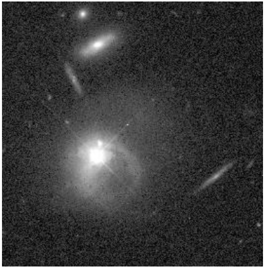

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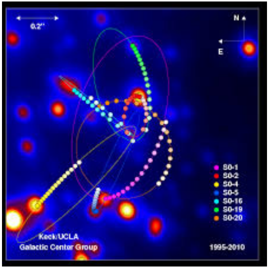

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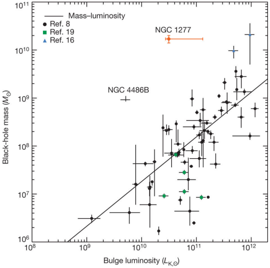

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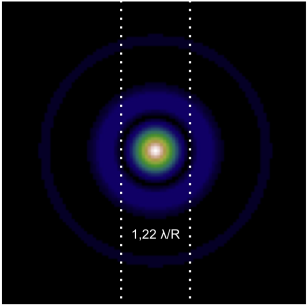
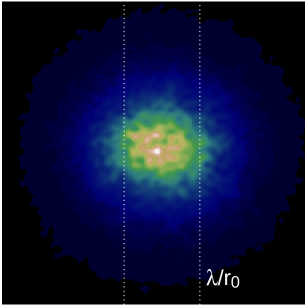
What does the PSF look like

Diffraction-limited



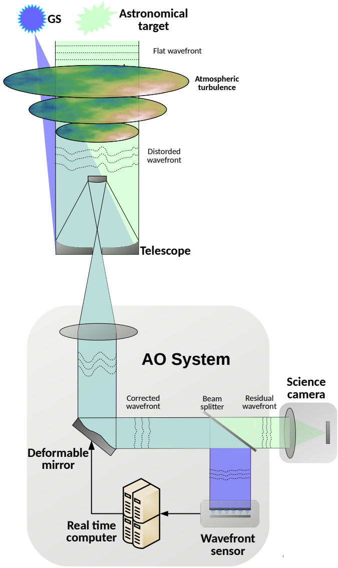
PSF characterized by the pupil shape, FWHM $= \lambda/D$

Seeing-limited



PSF characterized by the atmosphere seeing, FWHM $= \lambda/r_0$

What about the PSF after AO correction ?



- **Atmospheric turbulence** :
  Introduce Δ OPD of 1-10 μm
- **Deformable mirror** :
  Restores the wavefront flatness by pushing/pulling on actuators
- **Wavefront sensor** :
  Provides the phase gradient over the pupil
- **Real-time computer** :
  Converts recursively WFS measurements to DM commands

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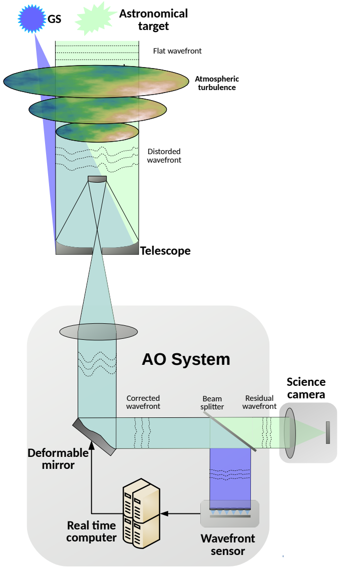
From telemetry to PSF



Generally we have :

$$\text{PSF}_\varepsilon = \left|\mathcal{F}\left[P(\boldsymbol{r})\exp(i\phi_\varepsilon(\boldsymbol{r}))\right]\right|^2$$

- **Residual phase** :

$$\phi_\varepsilon = \underbrace{\phi_{\boldsymbol{\varepsilon}_\parallel}}_{\text{AO residual}} + \underbrace{\phi_{\text{NCPA}} + \phi_{\text{Field}}}_{\text{Static aberrations}} + \underbrace{\phi_\Delta}_{\text{Anisoplanatism}} + \underbrace{\phi_\perp}_{\text{Fitting error}}$$

- **WFS measurements** :
  $\boldsymbol{s} = \mathbf{G}\phi_{\boldsymbol{\varepsilon}_\parallel} + \boldsymbol{\eta} \implies \widehat{\phi_{\boldsymbol{\varepsilon}_\parallel}} = R \times \boldsymbol{s}$
- **Static aberrations** : Must be calibrated
- **Anisoplanatism** : Statistics known from the $C_n^2(h)$ profile and the separation
- **Fitting error** : Statistics known from the seeing

The OTF calculation

PSF obtained from the OTF :

$$\mathrm{PSF}_\varepsilon = \mathcal{F}^{-1}\left[\mathrm{OTF}_\varepsilon\right]$$

Residual OTF is expressed from the covariance matrix of the residual phase :

$$\mathrm{OTF}_\varepsilon(\boldsymbol{u}/\lambda) = \iint_{\mathcal{P}} \boldsymbol{dr} P(\boldsymbol{\rho}) P(\boldsymbol{r}+\boldsymbol{u}) \times \exp\left(\mathcal{C}_\varepsilon(\boldsymbol{r}, \boldsymbol{r}+\boldsymbol{u}) - \mathcal{C}_\varepsilon(0,0)\right)$$

Getting the OTF/PSF is a matter of estimating the covariance of the residual phase

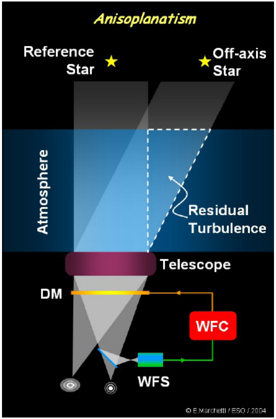
$$\mathcal{C}_\varepsilon(\theta) = \underbrace{\mathcal{C}_{\boldsymbol{\varepsilon}_\parallel}}_{\text{AO residual}} + \underbrace{\mathcal{C}_\Delta(\theta, C_n^2(h))}_{\text{Aniso model}} + \underbrace{\mathcal{C}_{\mathrm{NCPA}} + \mathcal{C}_{\mathrm{Field}}(\theta)}_{\text{static aberrations}} + \underbrace{\mathcal{C}_\perp(r_0)}_{\text{Fitting model}}$$

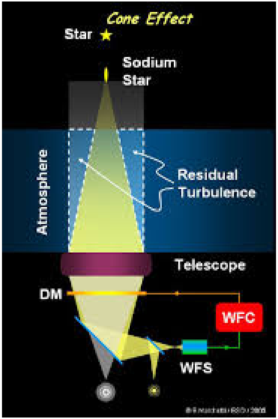
$$\mathcal{C}_{\boldsymbol{\varepsilon}_\parallel} = \mathrm{R} \times \left\langle \boldsymbol{s}\boldsymbol{s}^t \right\rangle \mathrm{R}^t - \mathcal{C}_\eta + \mathcal{C}_{\mathrm{alias}}$$

Anisoplanatism effect

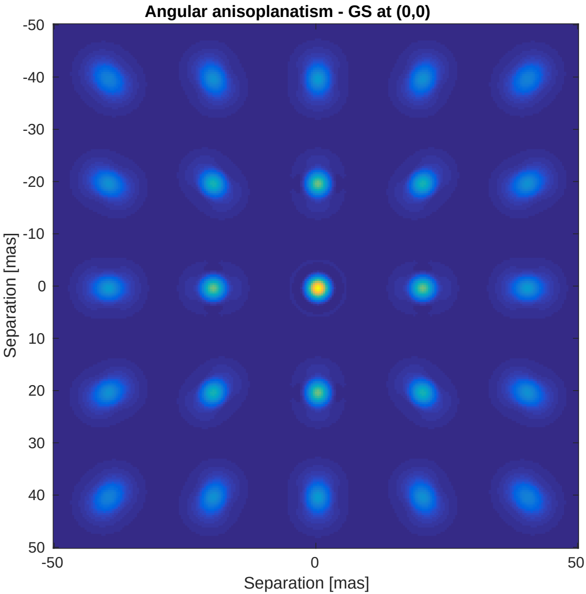
Anisoplanatism is produced by altitude turbulence during AO closed-loop operations and caused by the spatial correlation of the residual phase across the field :

- *Angular anisoplanatism* : phase correlation between two separated cylinders
- *Focal anisoplanatism* : phase correlation between a cone (LGS) and a cylinder
- *Tip-tilt anisoplanatism* : angular anisoplanatism on tip-tilt modes only





PSF elongation



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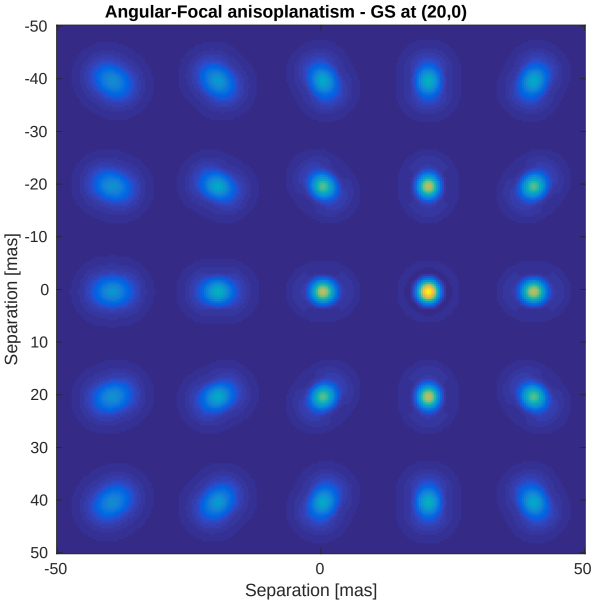
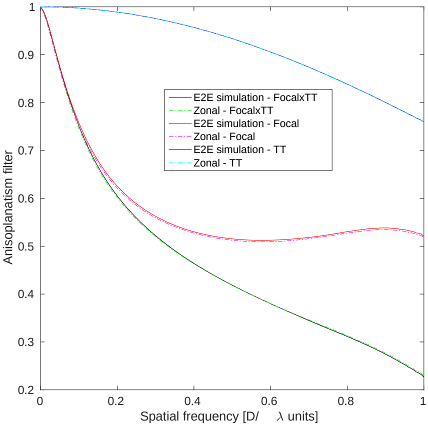


Focal + TT anisoplantism

High-order/tip-tilt modes measured using a LGS/NGS at a different location

$$\mathcal{C}_\Delta(C_n^2(h)) = \mathcal{C}_\Delta^{\text{lgs}}(C_n^2(h)) + \mathcal{C}_\Delta^{\text{TT}}(C_n^2(h))$$

Extrapolating the PSF anywhere in the field requires the knowledge of the $C_n^2(h)$ profile : could be provided by external profiler (MASS/DIMM@Mauna Kea)



Which metrics for evaluating PSF-R ?

How can we evaluate the efficiency of PSF-R? which metrics should we consider?

PSF characteristics

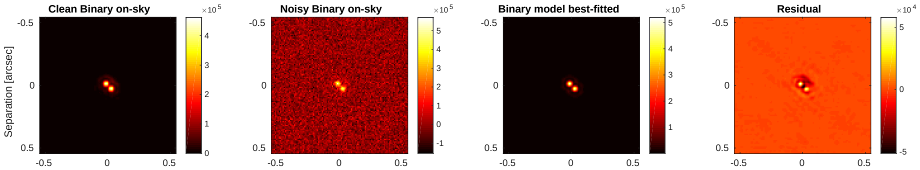
- Strehl ratio - FWHM - Encircled energy - PSF profile - Reconstruction residual

Science estimates

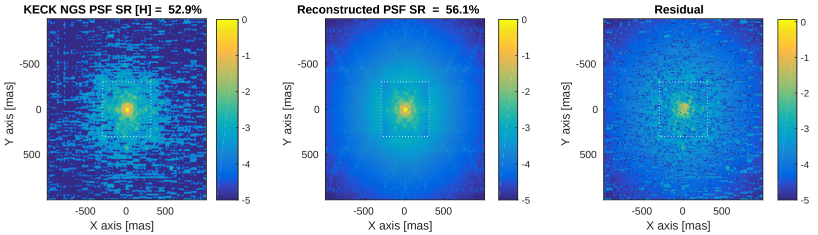
- Photo-astrometry accuracy

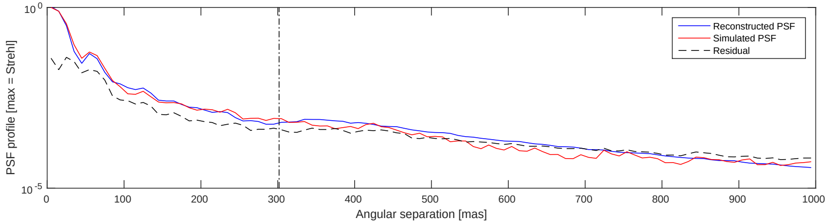
$$\mathcal{B}\left(\boldsymbol{\alpha}, \mathrm{PSF}, \boldsymbol{p}\right) = p(1) \times \left(\mathrm{PSF}\left(\alpha_x, \alpha_y\right) + \mathrm{PSF}\left(\alpha_x + p(2), \alpha_y + p(3)\right)\right)$$

$$\varepsilon^2\left(\boldsymbol{p}\right) = \left|\left|\mathcal{B}\left(\boldsymbol{\alpha}, \mathrm{PSF}_\varepsilon, \boldsymbol{p}_{\mathrm{ref}}\right) - \mathcal{B}\left(\boldsymbol{\alpha}, \widehat{\mathrm{PSF}}_\varepsilon, \boldsymbol{p}\right)\right|\right|_2^2$$



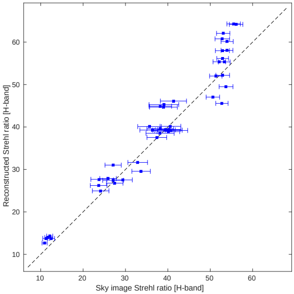
NGSs results

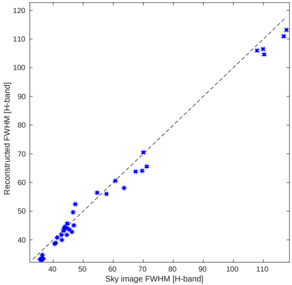


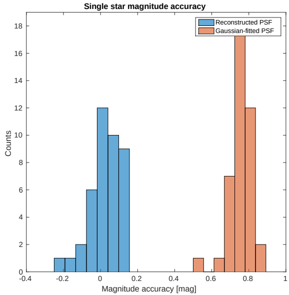


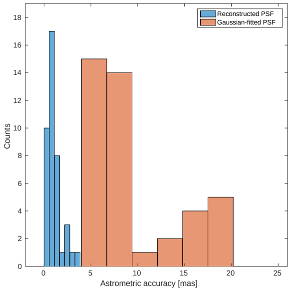
NGSs results

Residual	Units	Bias (R. vs G.)	1-σ std
SR	pts	1.4	4
FWHM	mas	2.4	2.8
Photo	mag	0.01/0.75	0.08/0.74
Astro	mas	1.5/2.5	3.9/5.5

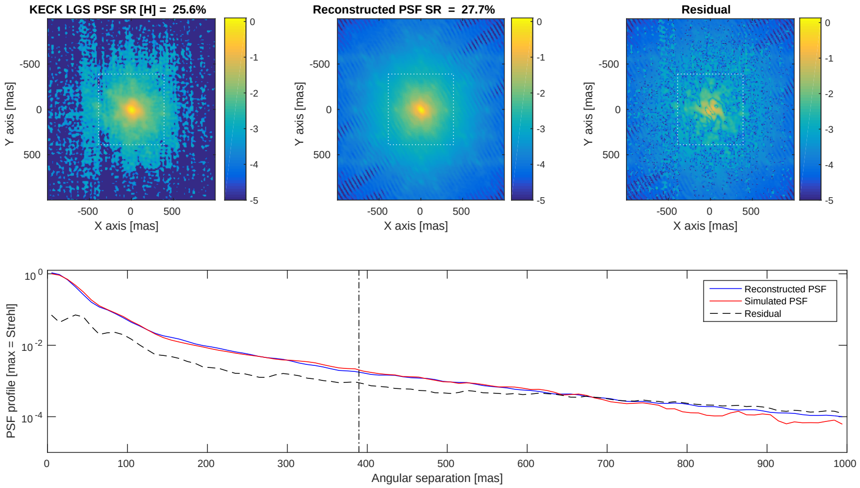






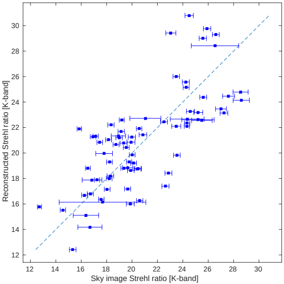


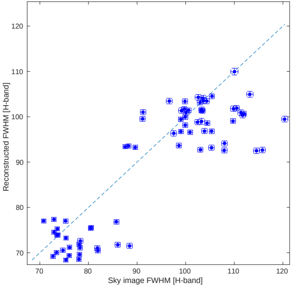
LGSs results

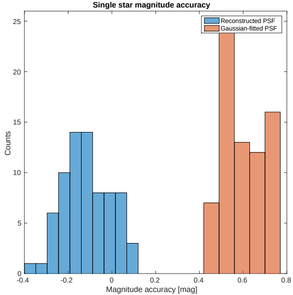


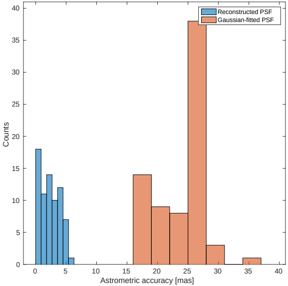
LGSs results

Residual	Units	Bias (R. vs G.)	1-σ std
SR	pts	-0.13	2.7
FWHM	mas	3.5	14.4
Photo	mag	-0.13/0.57	0.15/0.61
Astro	mas	2.05/7.6	2.8/8.0









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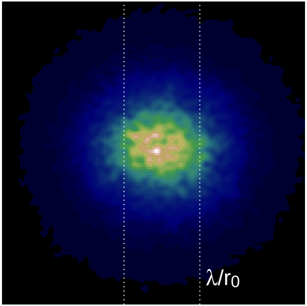
Tracking the anisoplanatism from focal-plane images

Seeing limited



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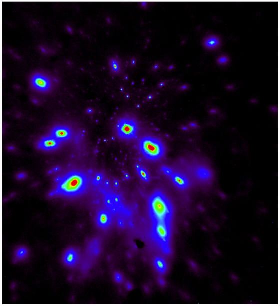
Seeing is measurable from focal-plane PSF FWHM

AO-correction



⇓

$C_n^2(h)$ profile is measurable from focal-plane PSF morphology

Focal Plane Profiler: concept

Classical PSF-R

- Reconstruct the on-axis PSF from the telemetry
- Grab the $C_n^2(h)$ profile from an external profiler
- Extrapolate the PSF off-axis from an anisoplanatism model

$\Downarrow$

Errors on anisoplanatism model and $C_n^2(h)$ estimation generate reconstruction deviations

Focal Plane Profiler

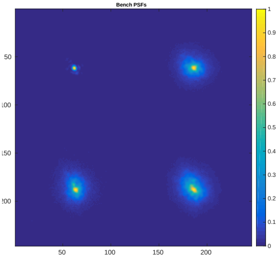
- Reconstruct the on-axis PSF from the telemetry
- Pre-compute normalized $(C_n^2(h) = 1)$ $\mathcal{C}_\Delta$ and Fitting/Aliasing PSDs
- Model-fit the $C_n^2(h)$ by minimizing difference PSF model/observations

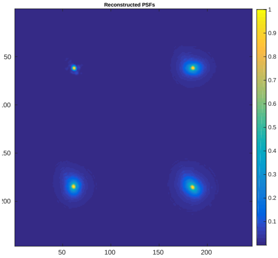
$\Downarrow$

Errors on anisoplanatism model are compensated and the $C_n^2(h)$ profile is estimated from focal-plane images

Application to the HeNOS bench off-axis

Asterism radius	50"
Sources wavelength	670 nm
r_0	0.8297 670 nm
fractional r_0	74.3% ,17.4%,8.2%
altitude layer	(0.6, 5.2, 16.3) km
source height	98.5 km
Telescope diameter	8.13 m
DM actuator pitch	0.813 m





	LGS On-axis			LGS 2			LGS 3			LGS 4		
	Ref	PSFR	FPP	Ref	PSFR	FPP	Ref	PSFR	FPP	Ref	PSFR	FPP
FWHM	21.1	22.6	22.6	116.6	97	112	90	80	93	100	77	91

	r_0	$fr_0(1)$	$fr_0(2)$	$fr_0(3)$
Ref	82.97 cm	74.3%	17.4%	8.2%
Fitted	82.88 cm $\pm$ 2.07	68.10%$\pm$4.5	23.35%$\pm$2.7	8.5%$\pm$1.2

Summary

- **PSF-R 4 Science**
  - GC : estimate photo-astrometry in crowded field to get stars orbits around the BH
  - QSO : subtract the PSF to reveal the host galaxy and obtain galaxy/SMBH masses
  - PSF-R : provide the AO-compensated PSF from telemetry + models + calibrations
- **Results on Keck in NGS/LGS mode**
  - Preliminary results : reconstruction in on-axis NGS/LGS with 3 pts/10 mas of accuracy on Strehl/FWHM
  - 0.1mag/2 mas -ish of accuracy on photometry/astrometry
  - Next step : getting a better evaluation of the photo-astrometry accuracy through StarFinder
- **Focal plane profiler**
  - $C_n^2(h)$ retrieval from the AO-compensated focal plane images
  - Successfully applied to HeNOS : error FWHM $20\% -> 5\%$
  - Next step : test FPP on NIRC2/OSIRIS images to compare with MASS/DIMM

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