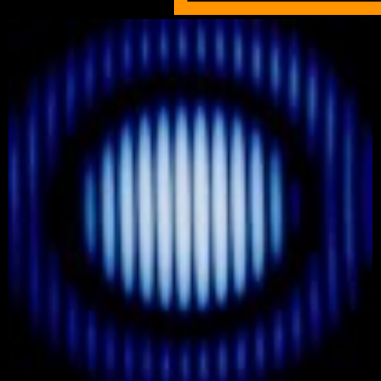
INTERFEROMETRY AND EXOPLANETS

Roxanne Ligi

June 15, 2021



OUTLINE of the LECTURE

- **What do we know about exoplanets?**
- **Exoplanets and stars: the role of interferometry**
- **The Kernel phase approach**
  Toward the detection of exoplanets with interferometry
- **Going beyond**
  Kernel-nuller, SKA…

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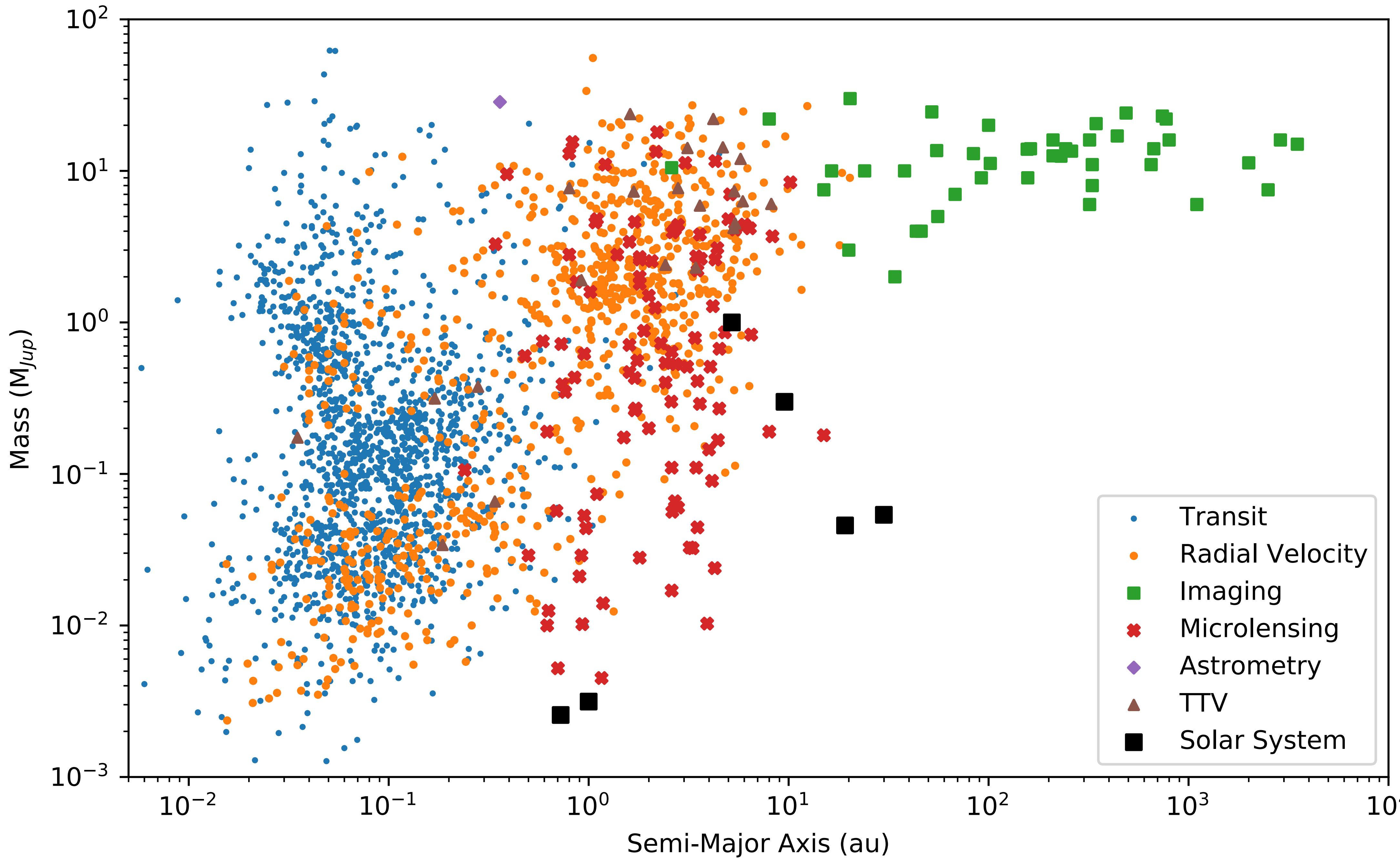
EXOPLANETS

~ 4300 exoplanets detected so far
Wide diversity of methods
Raise many questions!



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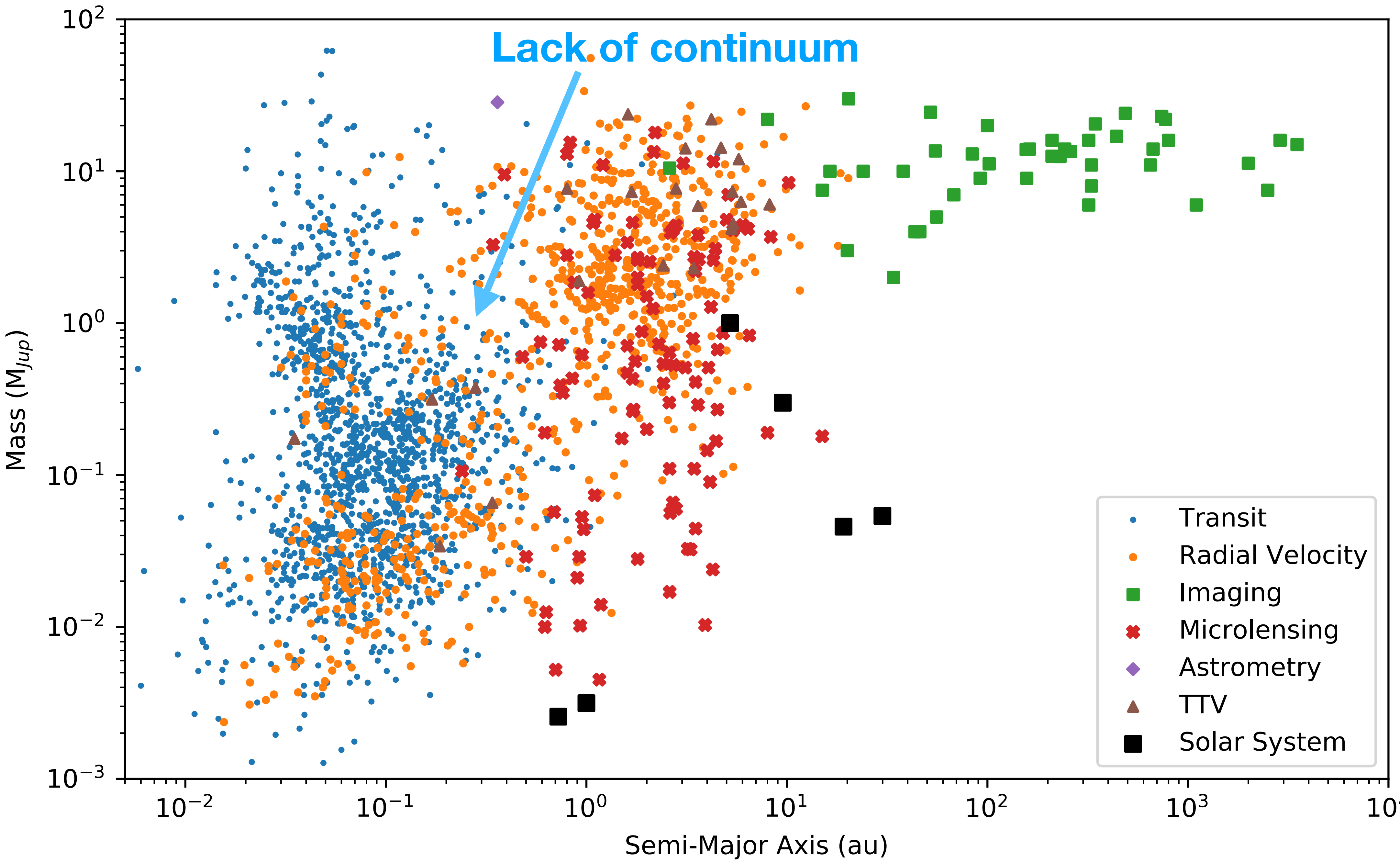

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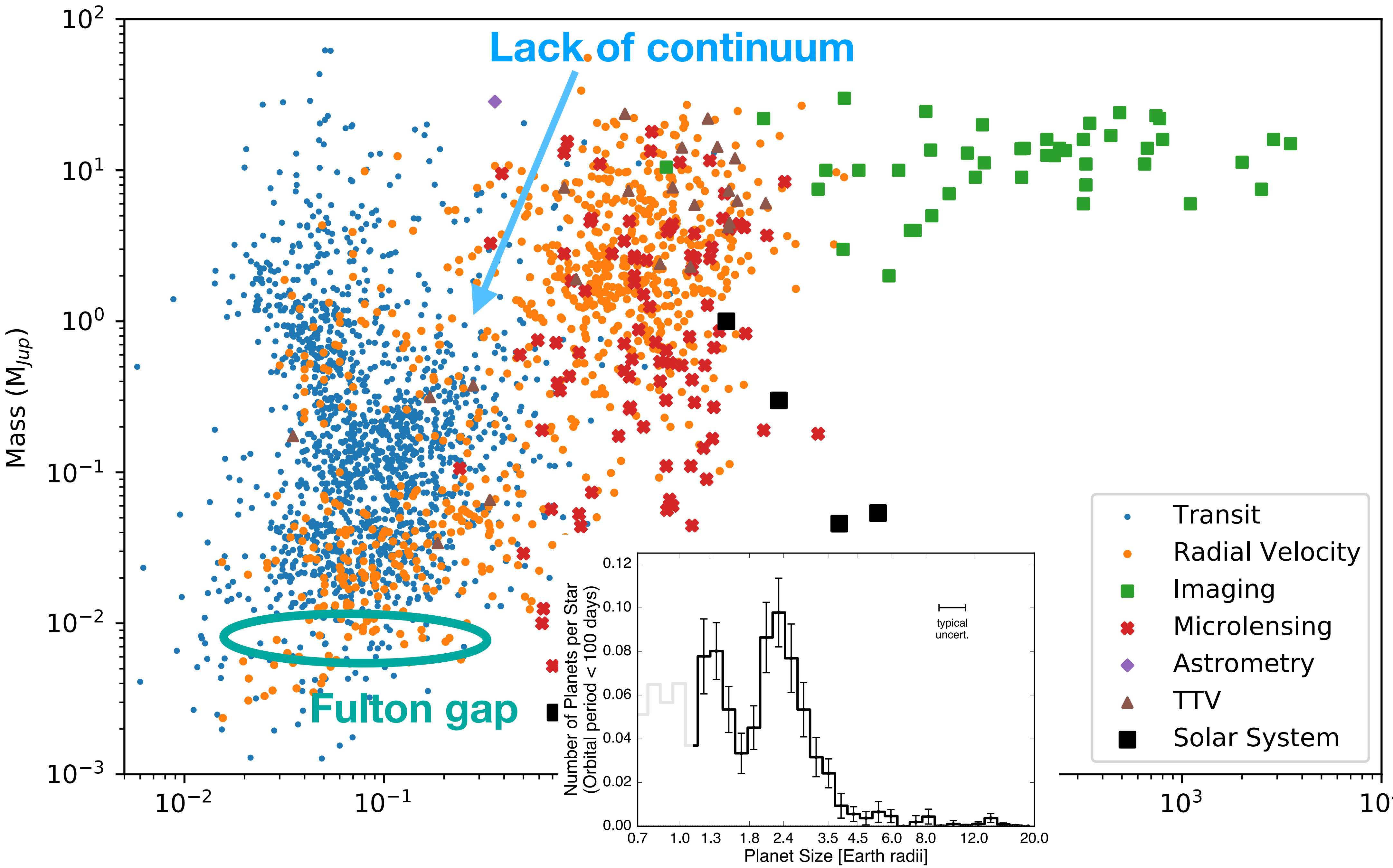

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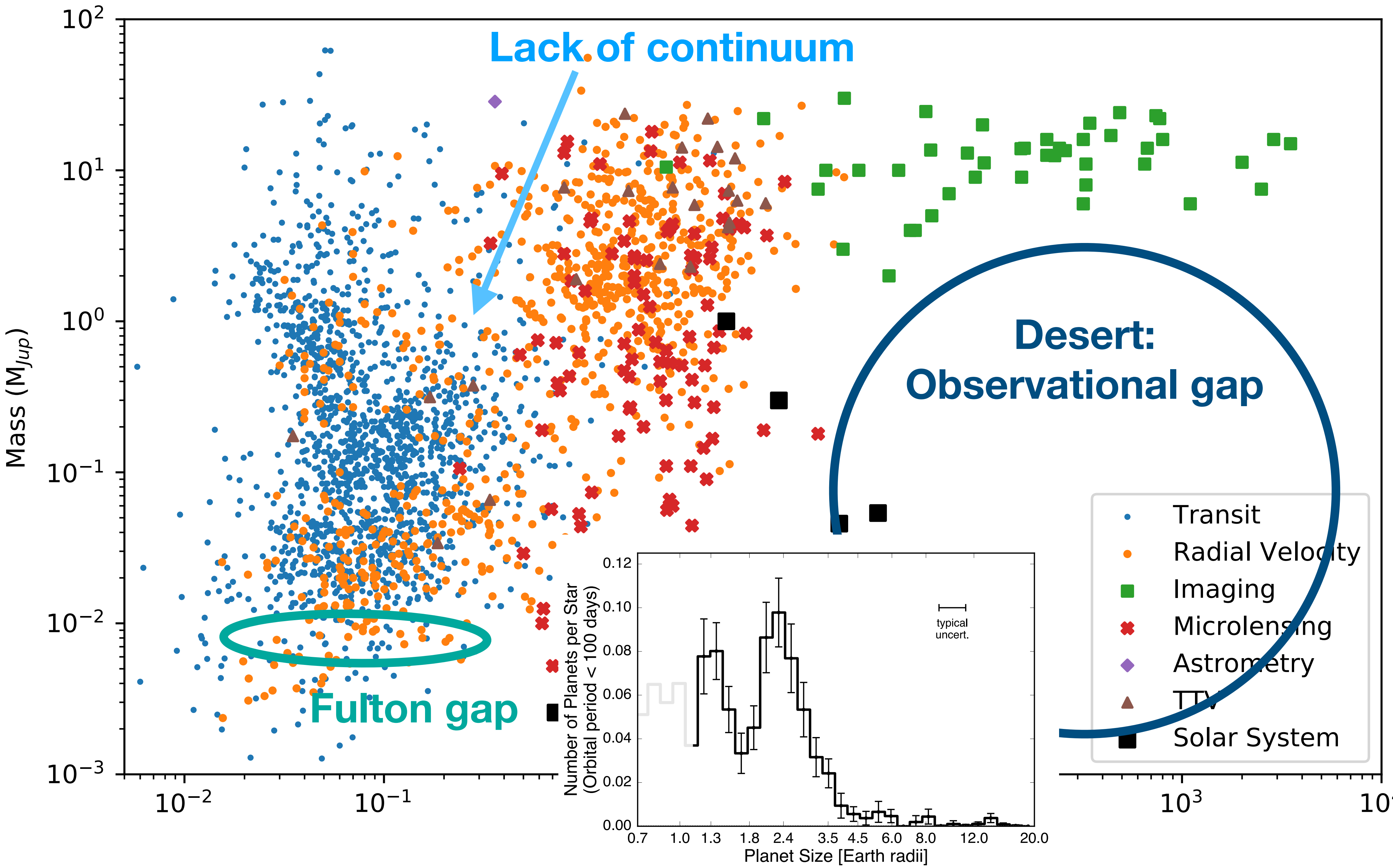
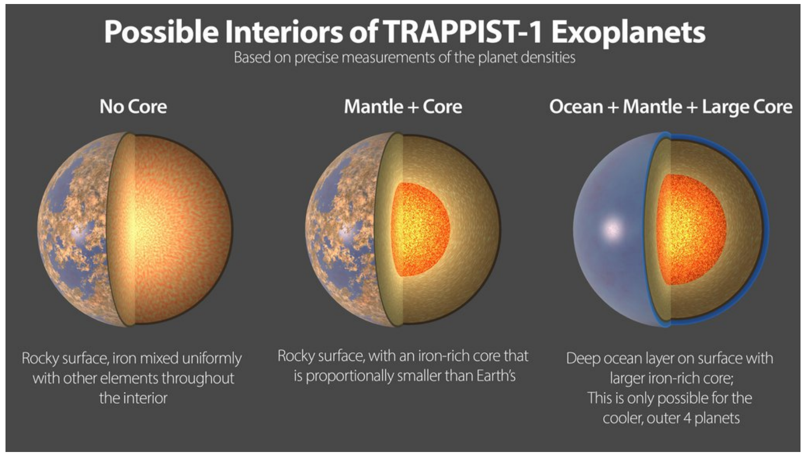


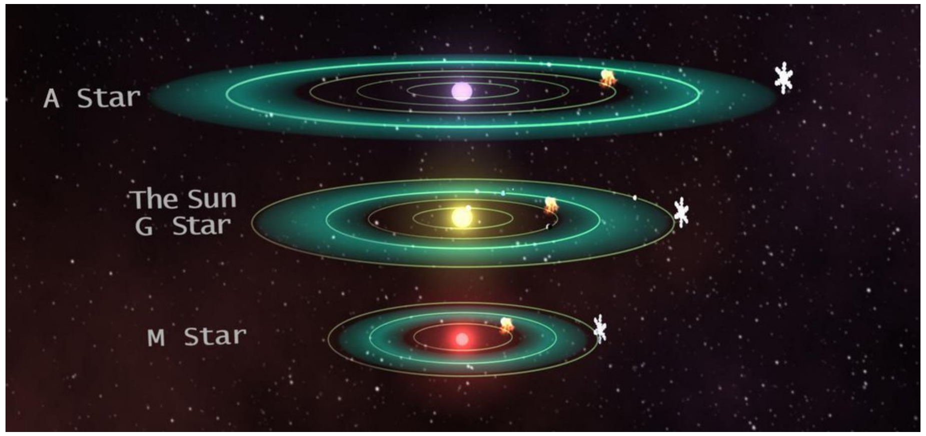
EXOPLANETS: Several problematics



- Nature of the planets?
  ➔ Composition, size…

- Formation?
  ➔ Place of birth, migration…

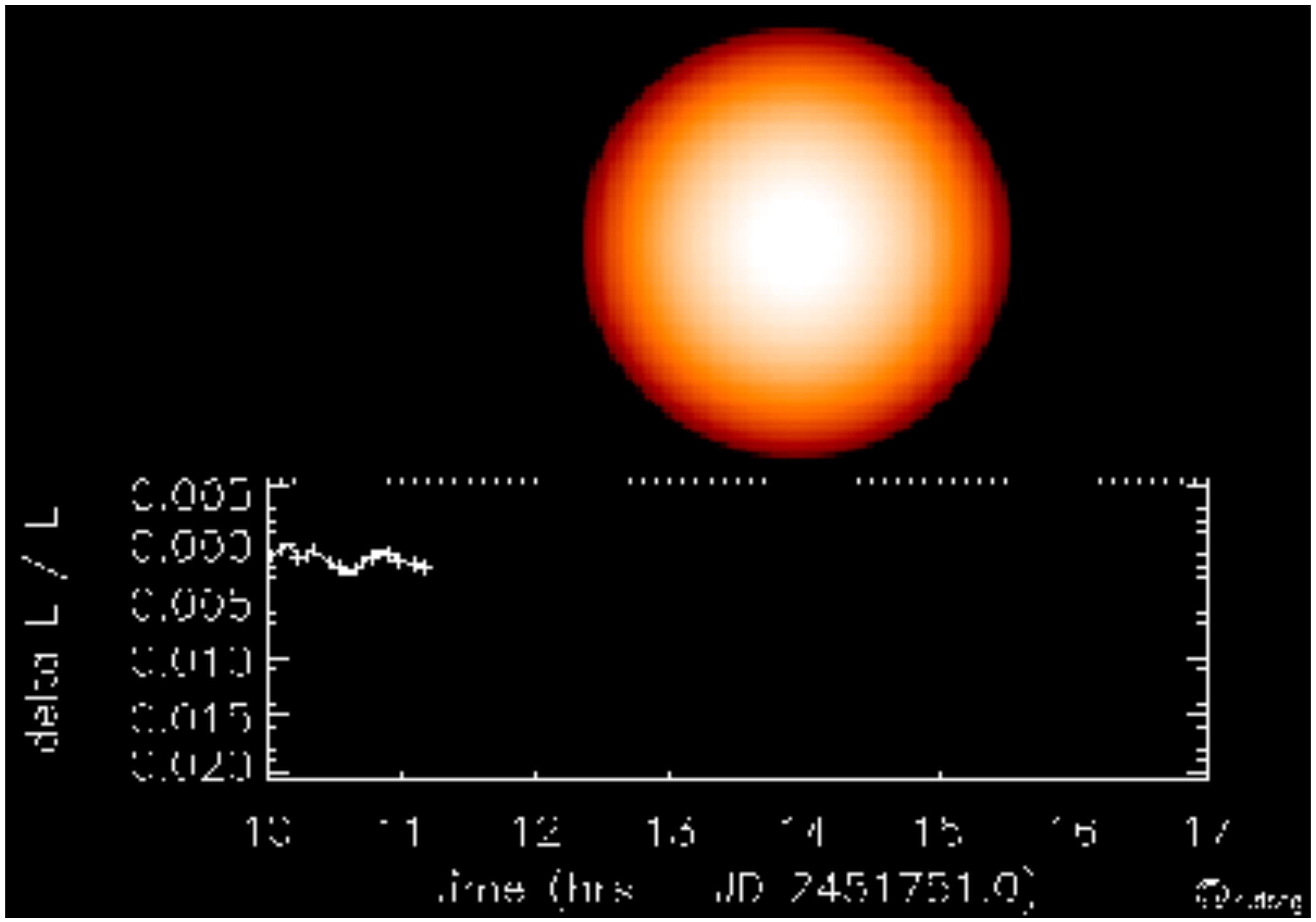
- « Habitability »?
  ➔ Distance to the star (temperature), tectonic…



- Is our solar system unique?
  ➔ Need to probe many systems!

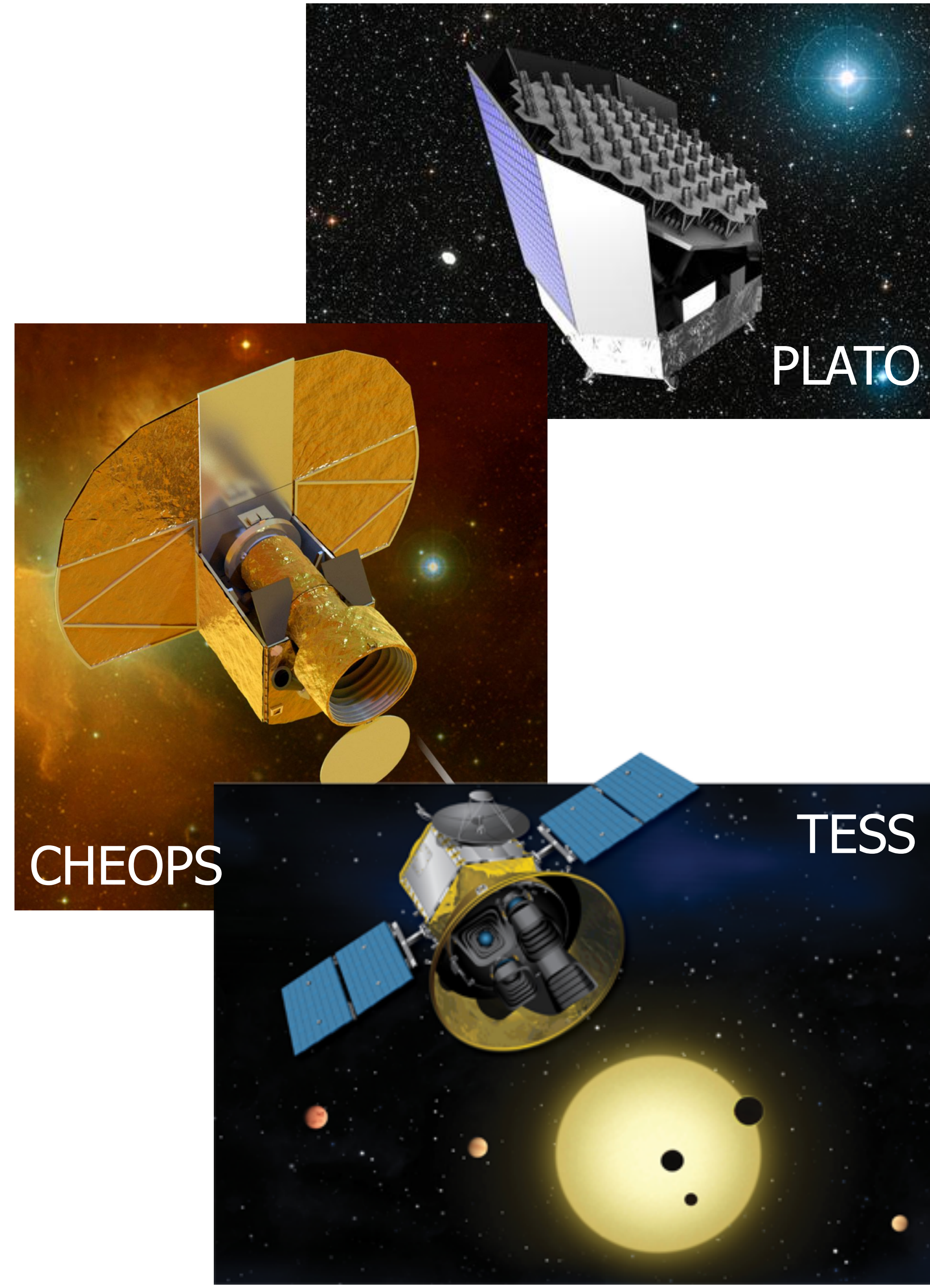
EXOPLANETS: Indirect detection methods

Transit method



$$\frac{\Delta F}{F} = \left(\frac{R_P}{R_\star}\right)^2$$

→ Knowing **R_p** depends on **$R_\star$**



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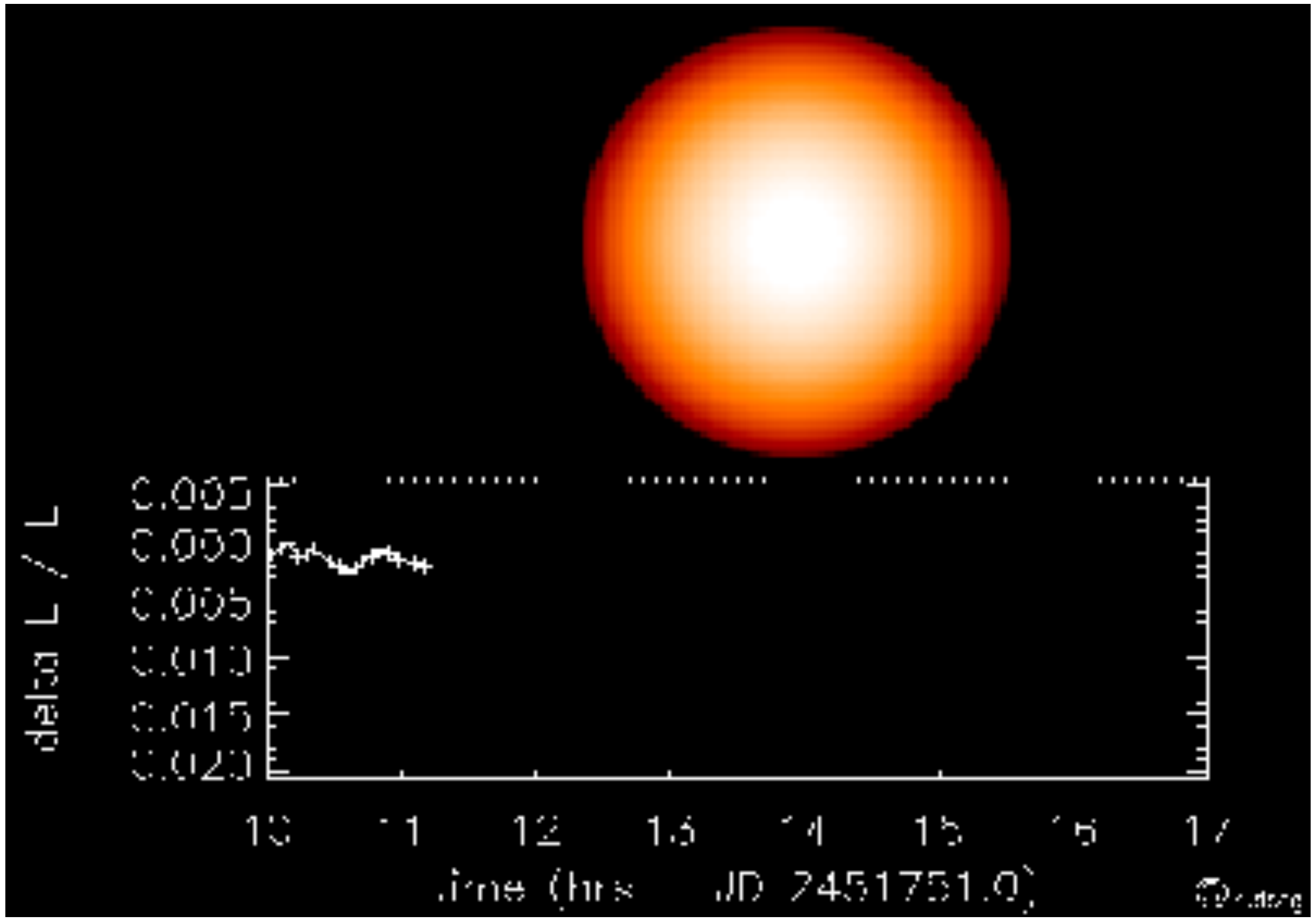

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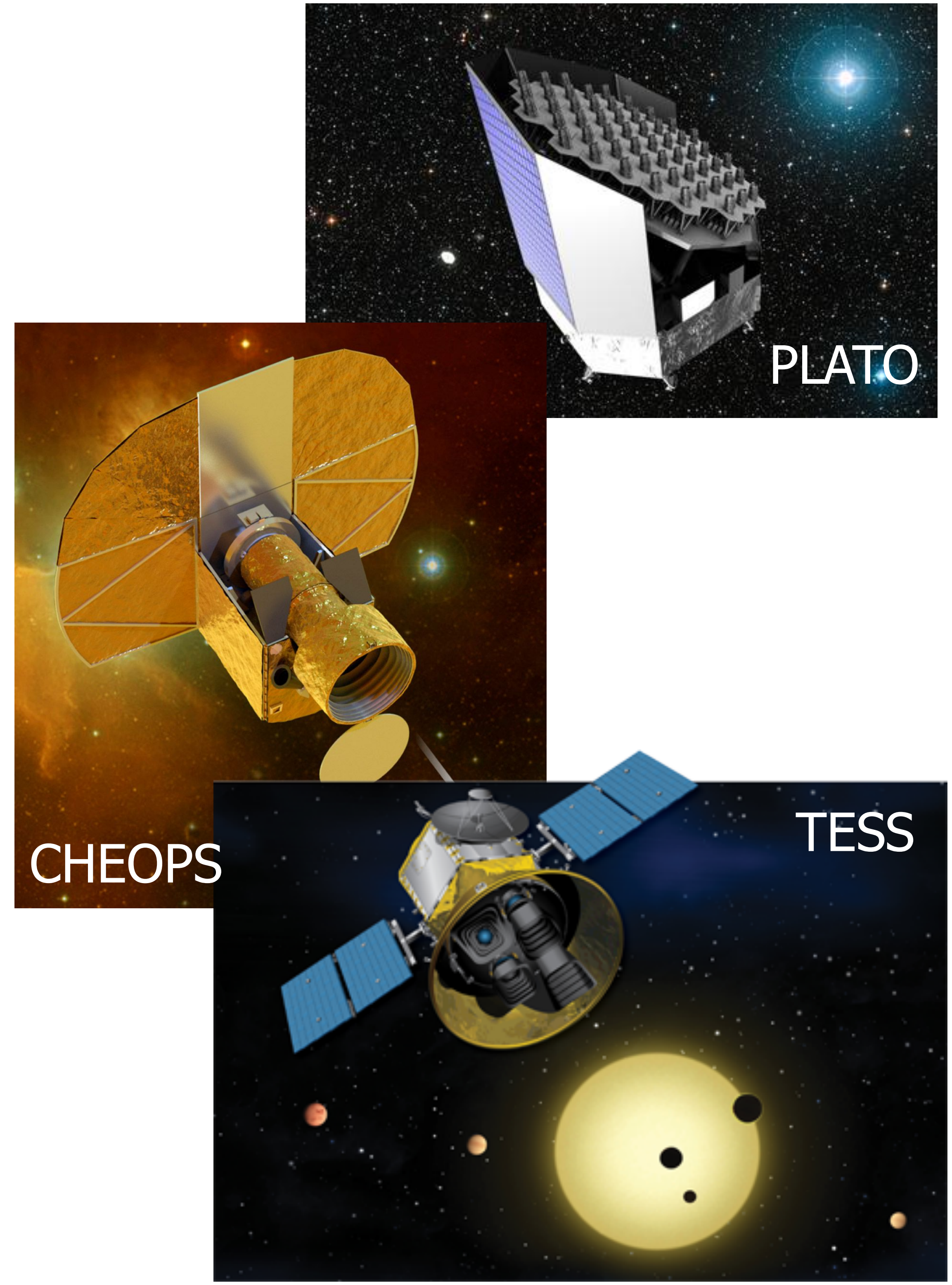
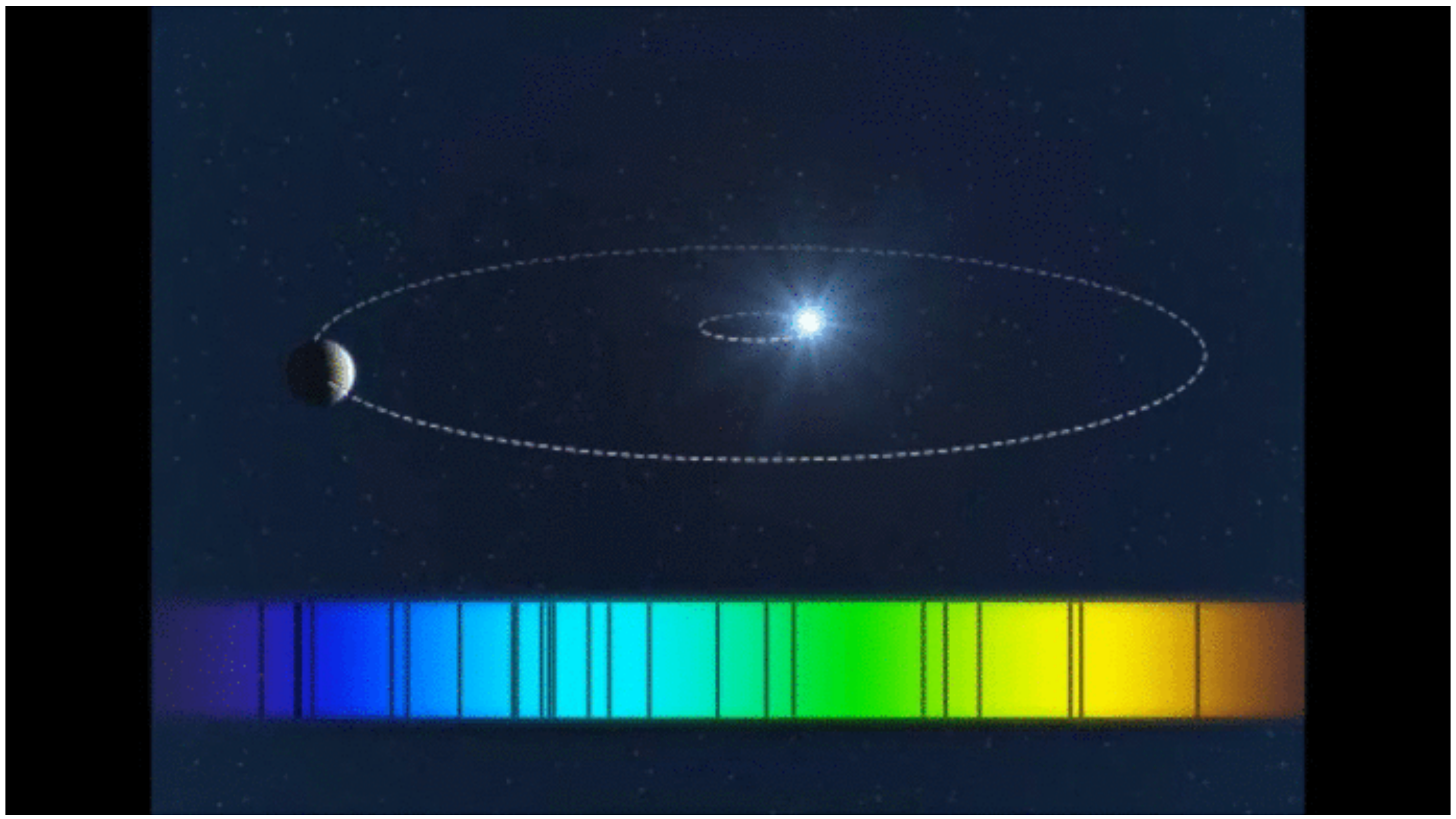


EXOPLANETS: Indirect detection methods

Radial velocity method



$$\frac{(m_p \sin i)^3}{(M_\star + m_p)^2} = \frac{P}{2\pi G} K^3 (1-e)^{3/2}$$

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HARPS/La Silla

HARPS-N/TNG

EXOPLANETS: Indirect detection methods

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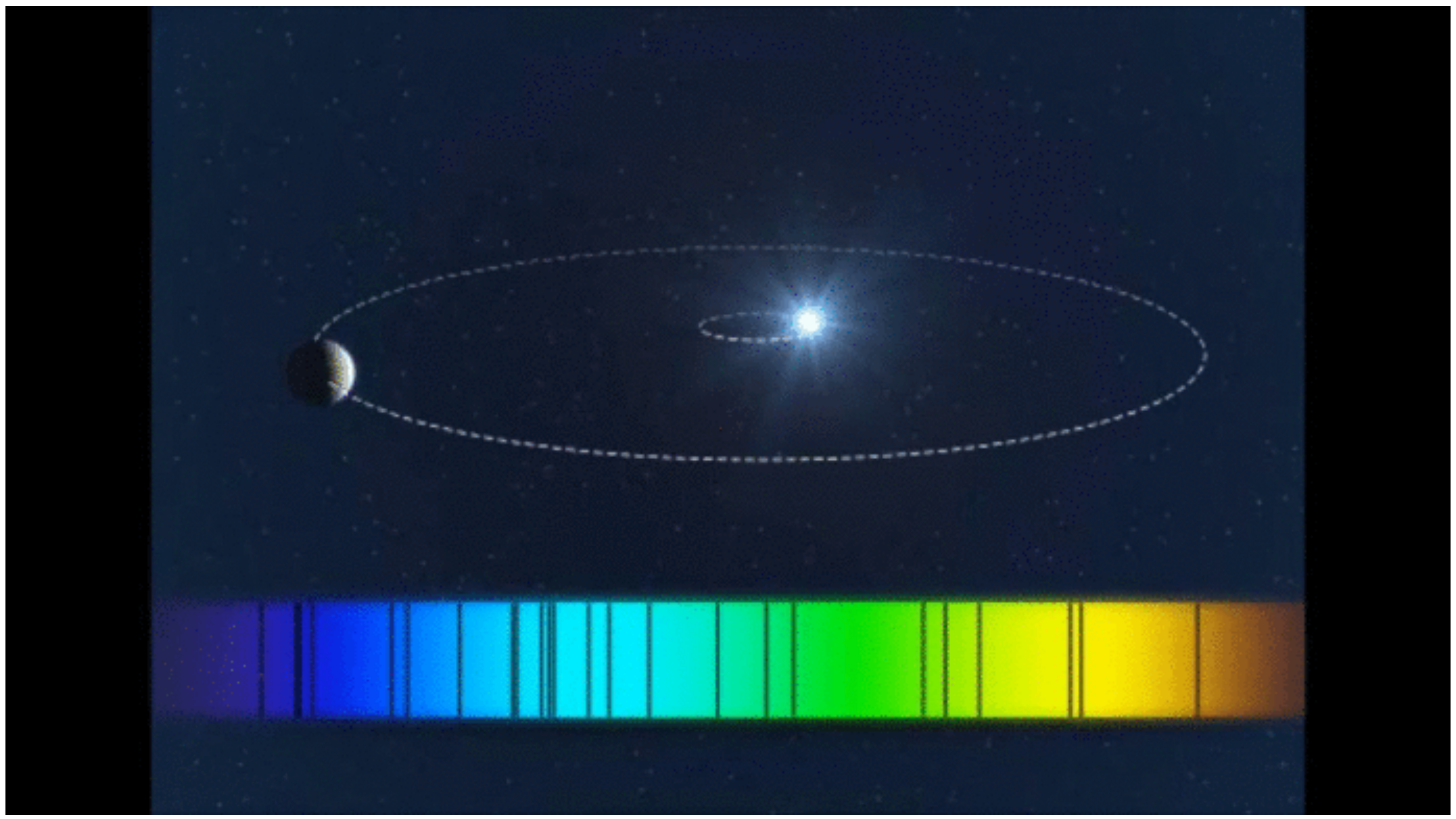

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HARPS/La Silla

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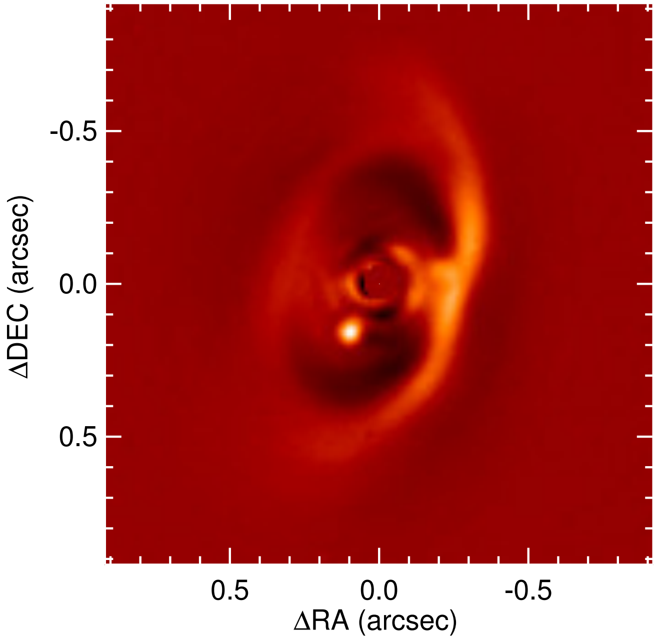
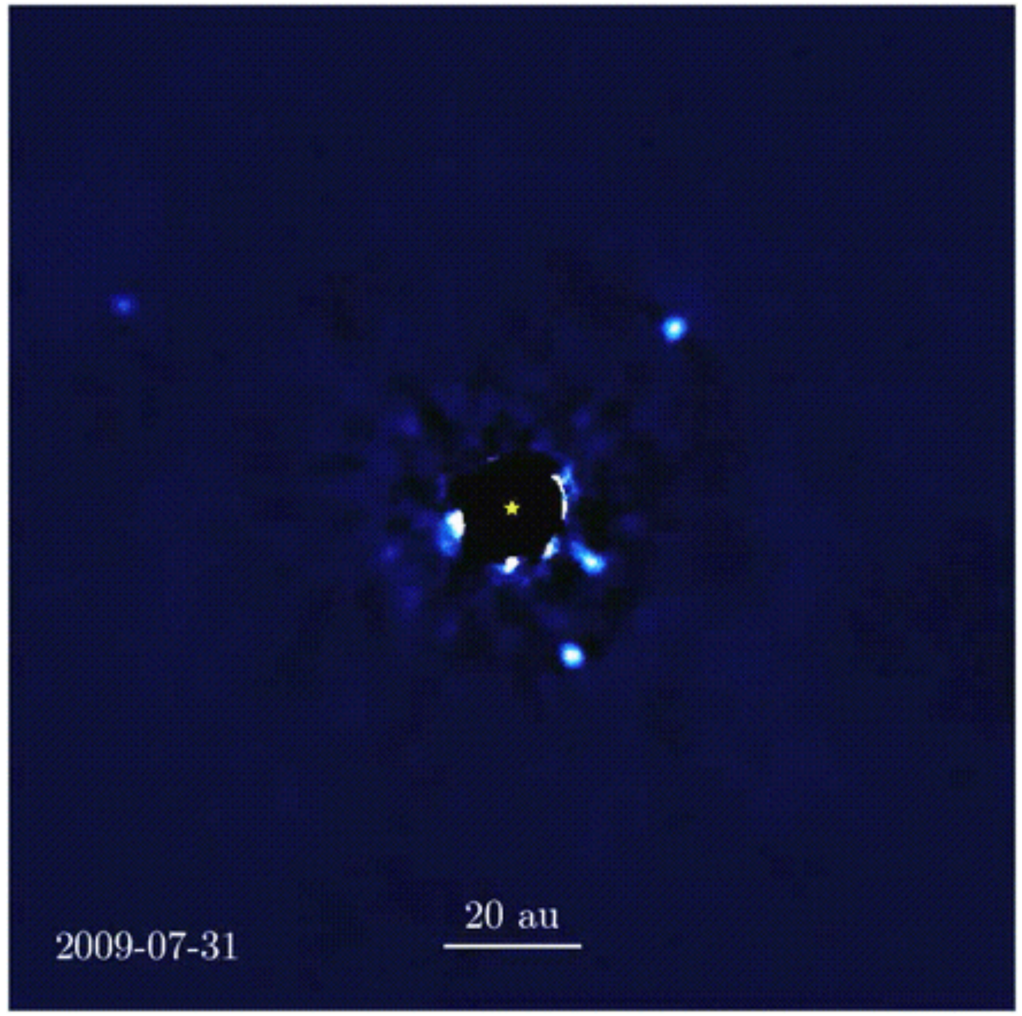
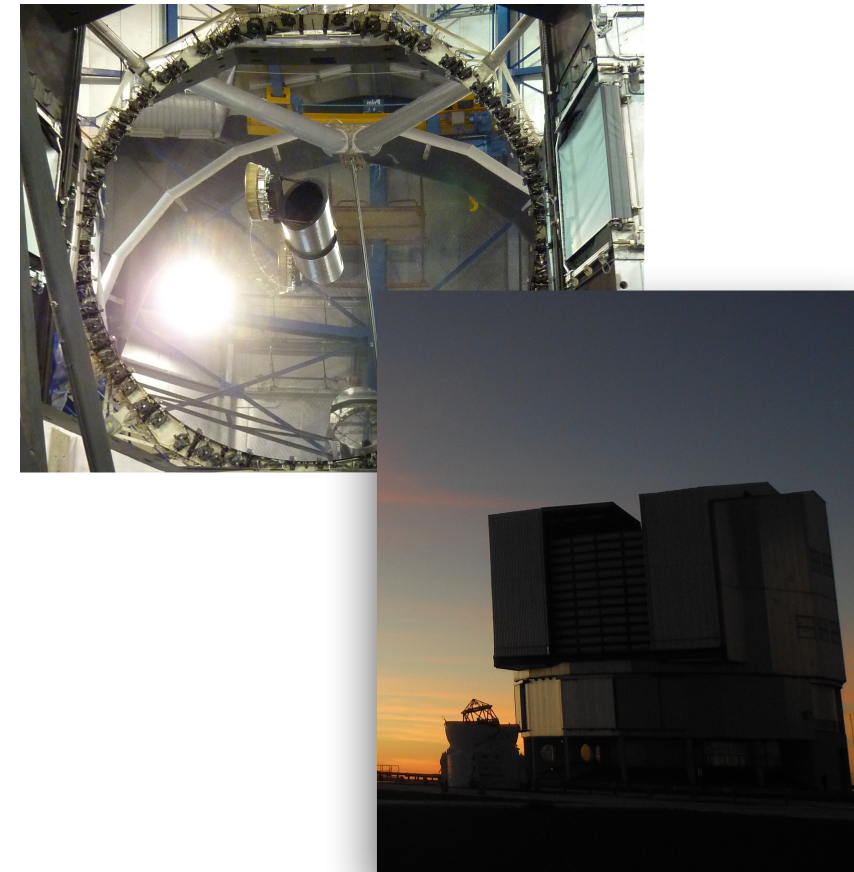
EXOPLANETS: Direct detection methods

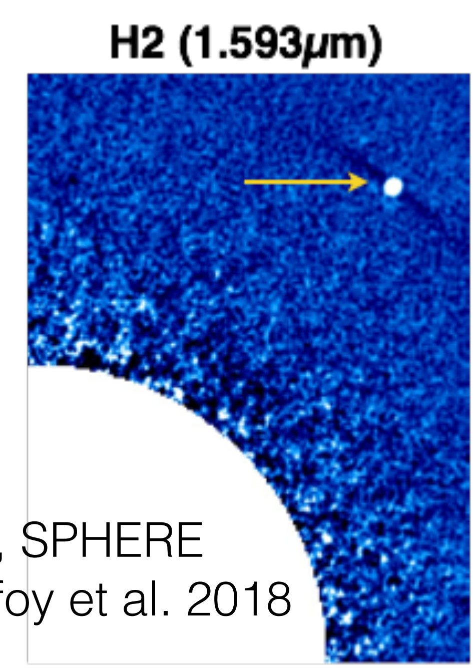
Direct imaging



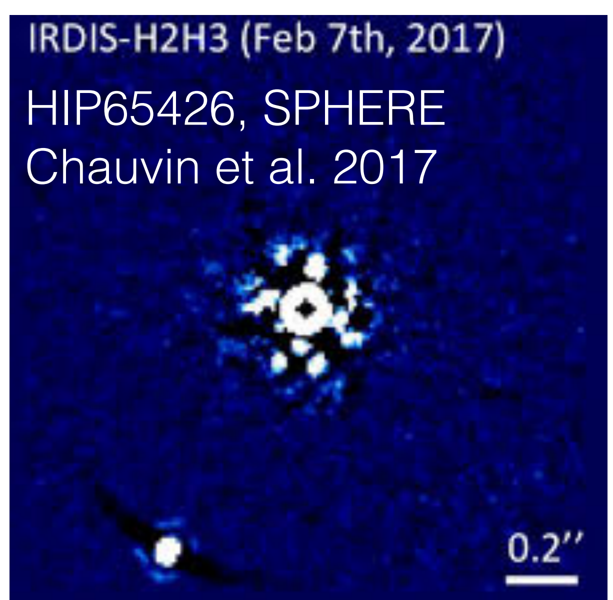
PDS70, SPHERE
Muller et al. 2018



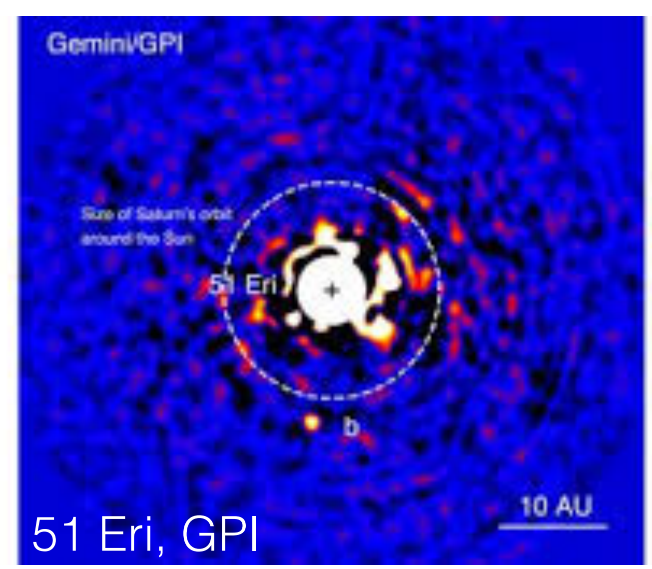




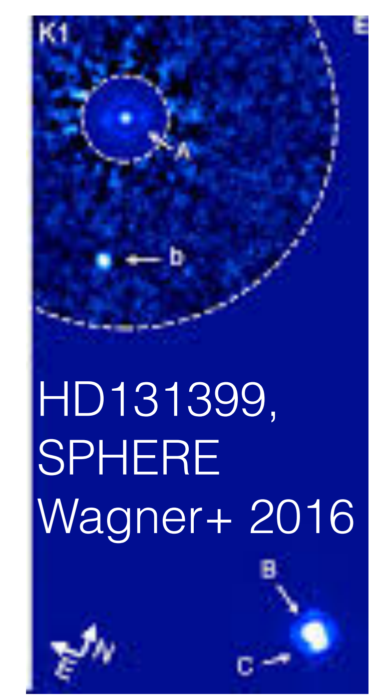
GJ504, SPHERE
Bonnefoy et al. 2018



HIP65426, SPHERE
Chauvin et al. 2017



51 Eri, GPI
Macintosh+2015



HD131399,
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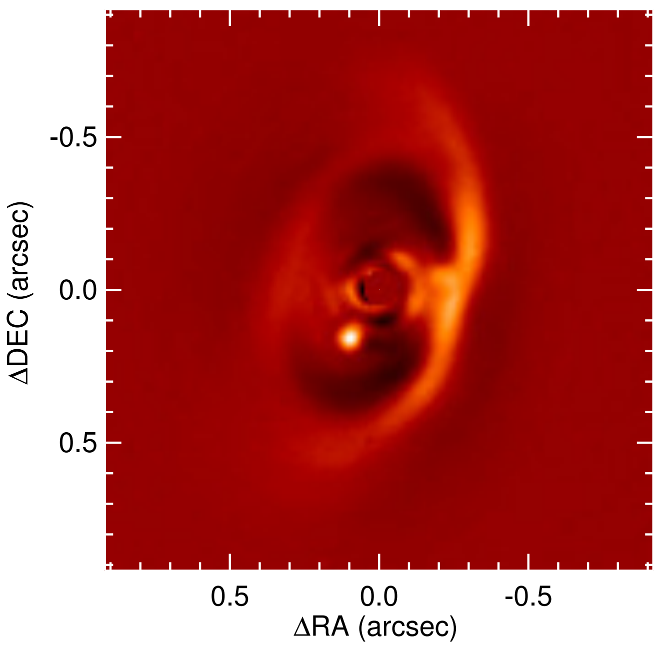
Wagner+ 2016

EXOPLANETS: Direct detection methods

Direct imaging



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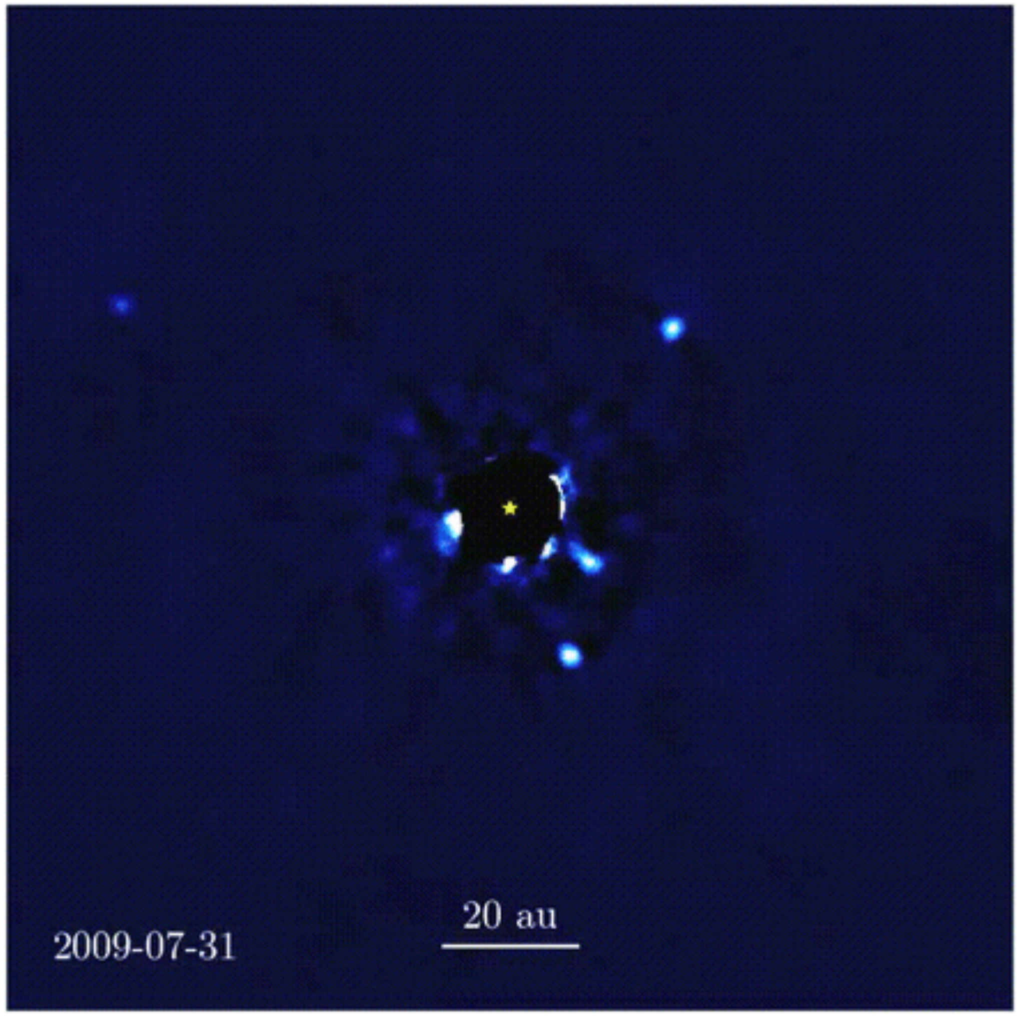

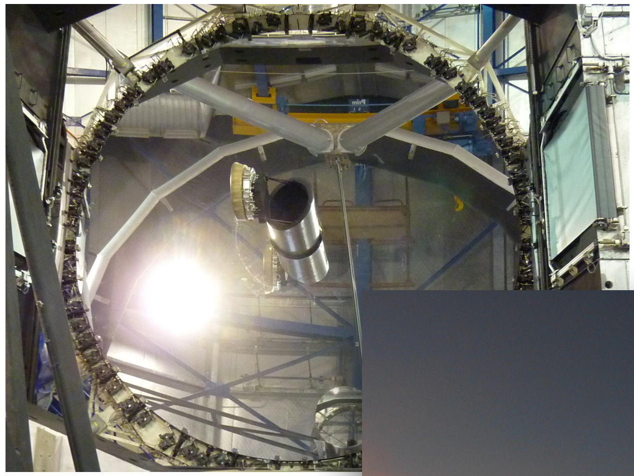

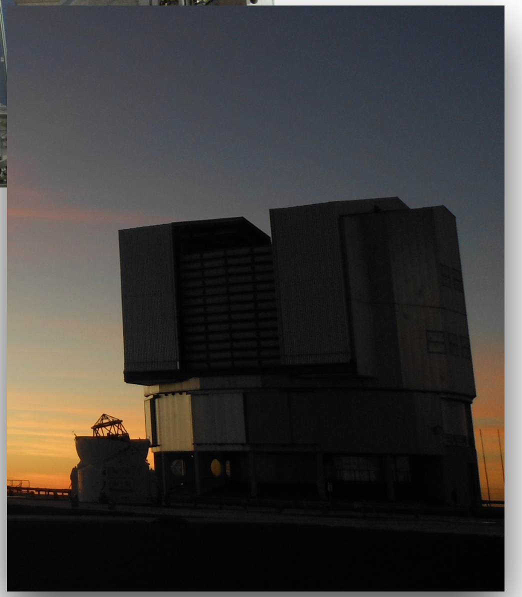

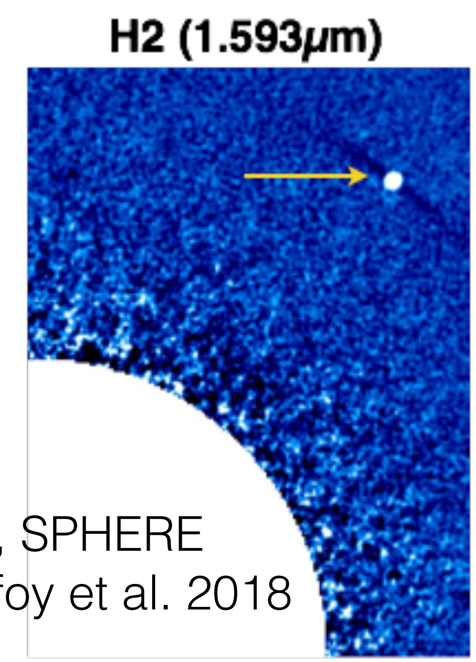

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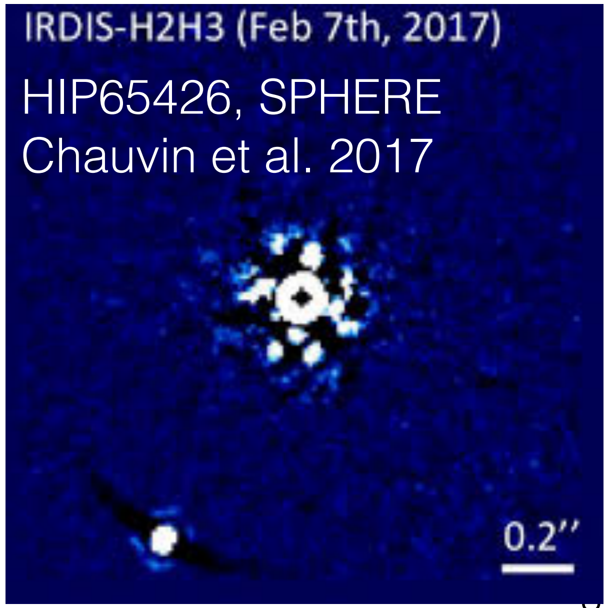

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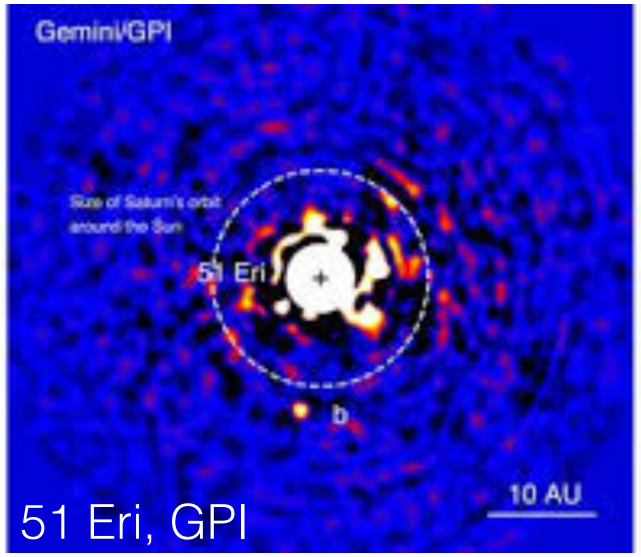

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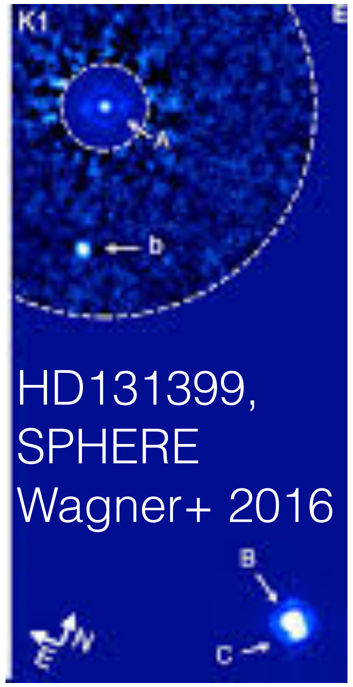

HD131399,
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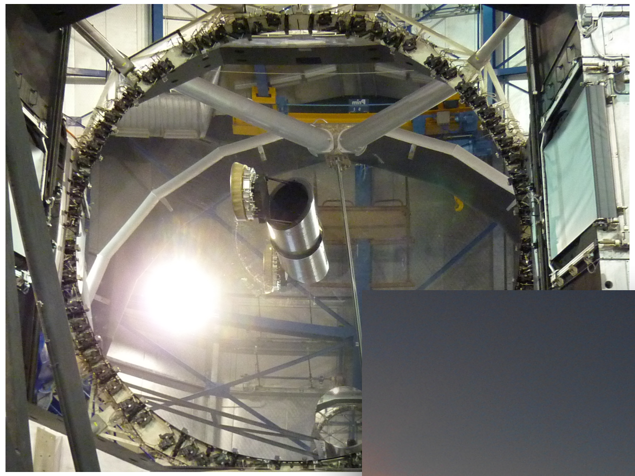
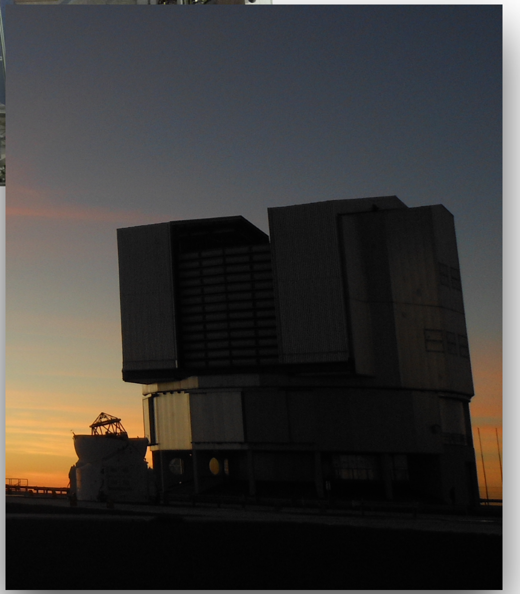
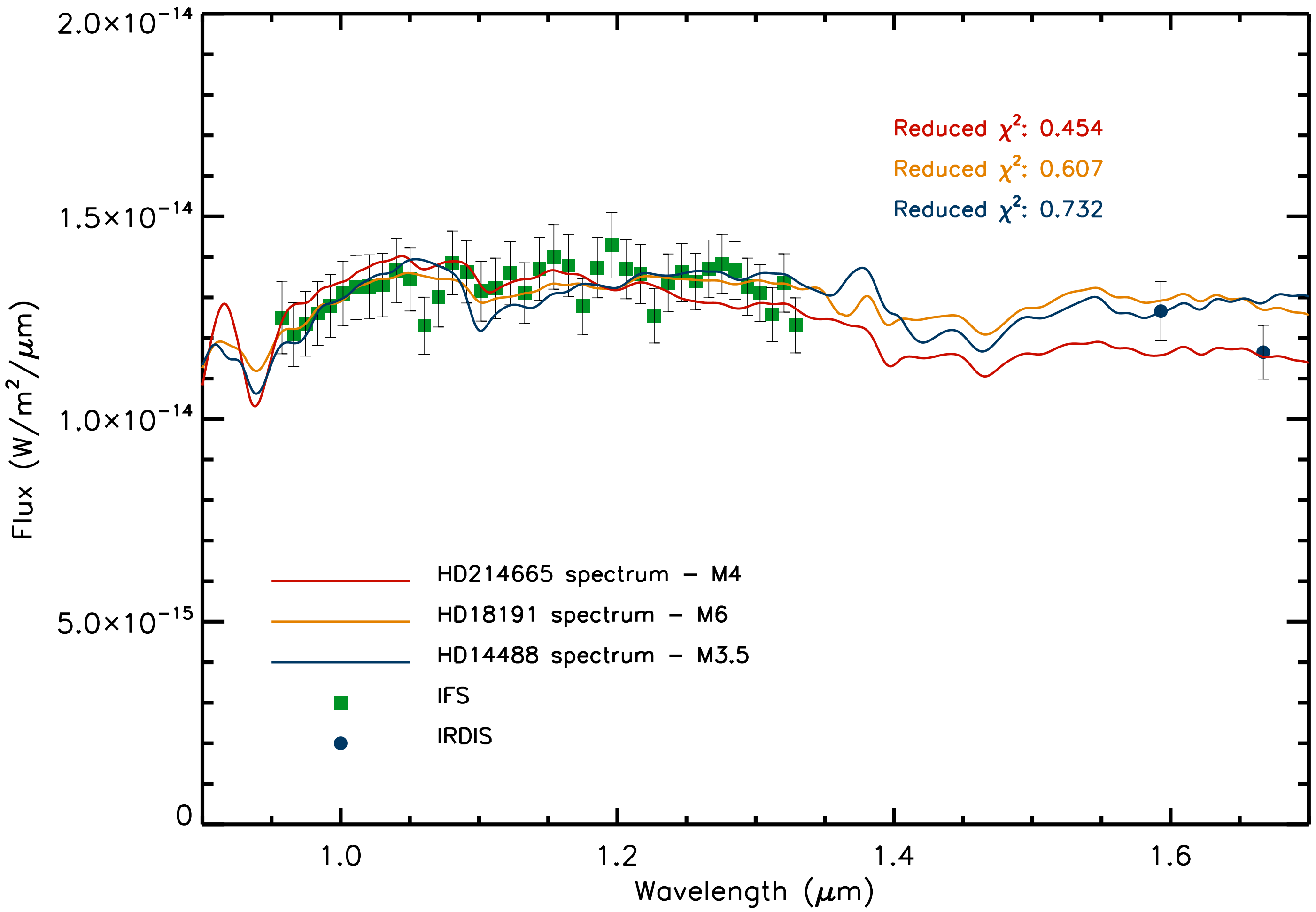
STARS AND PLANETS: Parameters dependence





Direct imaging

- Provides separation, position angle, orbit, spectrum.
- Need a model to derive the nature of the companion, and this model depends on stellar parameters: age, and mass in particular.



Ligi+ 2018b

STARS AND PLANETS: Parameters dependence

Stellar parameters drive our knowledge of exoplanets

$$T_{\mathrm{env}} = \alpha T_{\mathrm{eff}} \sqrt{\frac{R_\star}{2a}}$$

The « basic » planetary parameters depend on the stellar mass, radius, density…

$$\frac{(m_p \sin i)^3}{(M_\star + m_p)^2} = \frac{P}{2\pi G} K^3 (1-e)^{3/2}$$

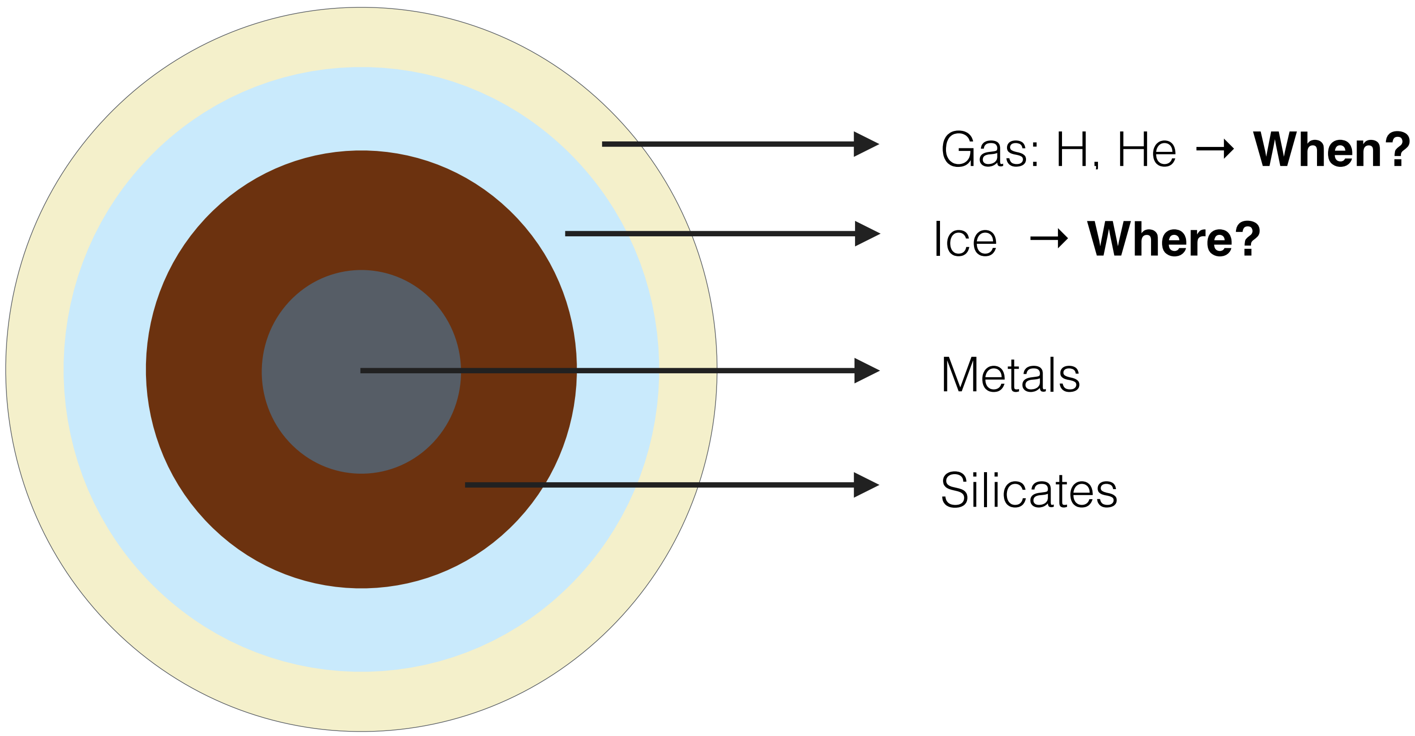
$$\frac{\Delta F}{F} = \left(\frac{R_P}{R_\star}\right)^2$$

Parameter	Prior range	Distribution
Core radius r_{core}	(0.01–1) $r_{\mathrm{core+mantle}}$	Uniform in r^3_{core}
Fe/Si$_{\mathrm{mantle}}$	0 – Fe/Si$_{\mathrm{star}}$	Uniform
Mg/Si$_{\mathrm{mantle}}$	Mg/Si$_{\mathrm{star}}$	Gaussian
f_{mantle}	0.–0.2	Uniform
Size of rocky interior $r_{\mathrm{core+mantle}}$	(0.01–1) R_{p}	Uniform in $r^3_{\mathrm{core+mantle}}$
Pressure imposed by gas envelope P_{env}	20 mbar–100 bar	Uniform in log-scale
Temperature of gas envelope α	0.5–1	Uniform
Mean molecular weight of gas envelope μ	16–50 g mol^{-1}	Uniform

Ligi+ 2019

Models of planetary interiors depend on many stellar parameters: radius, mass, density, abundances…

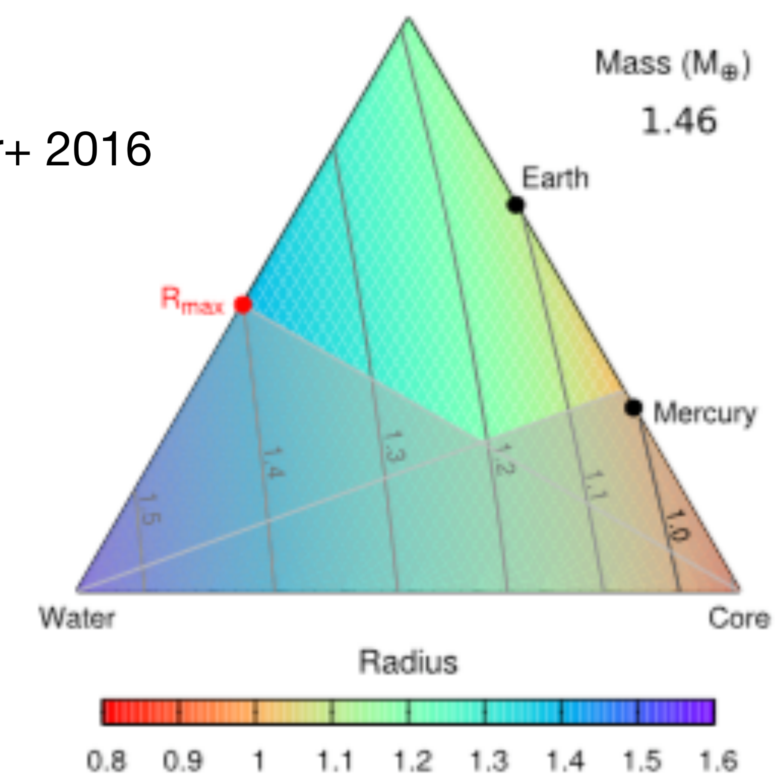
STARS AND PLANETS: Internal composition

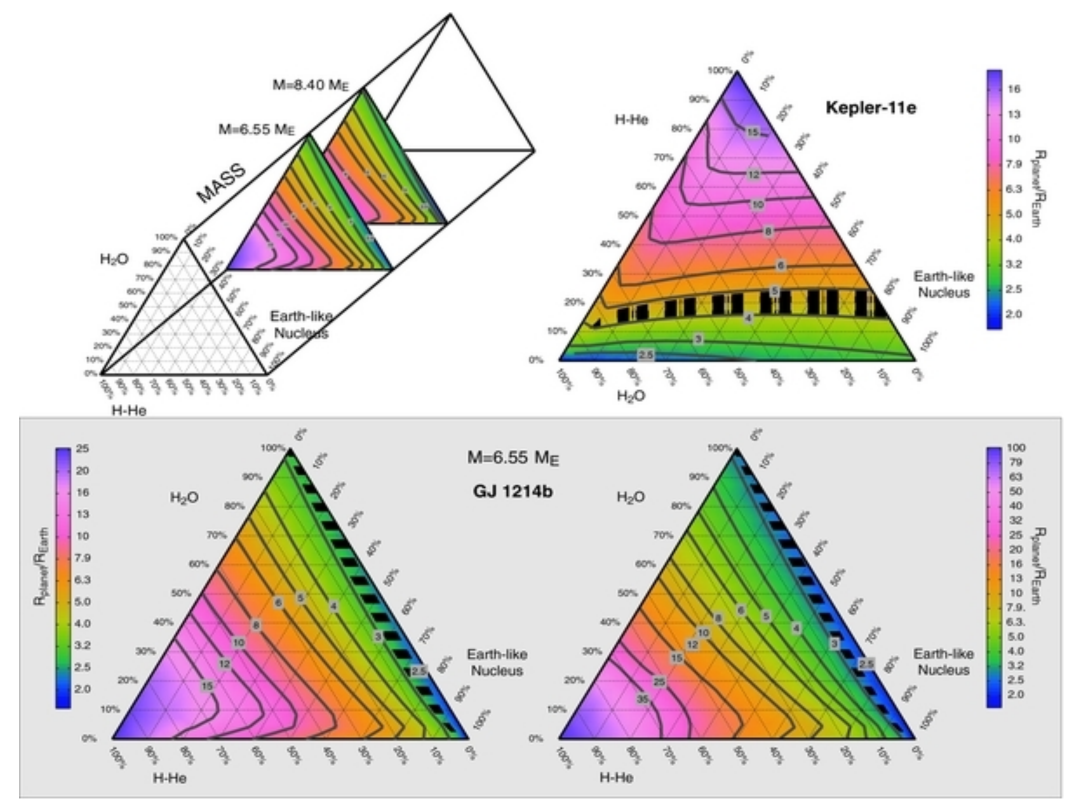


The internal composition of exoplanets is inferred from planetary interior models:

- Need parameters as inputs (stellar and planetary)
- Hint toward formation and habitability
- Suffer from degeneracy

Brugger+ 2016

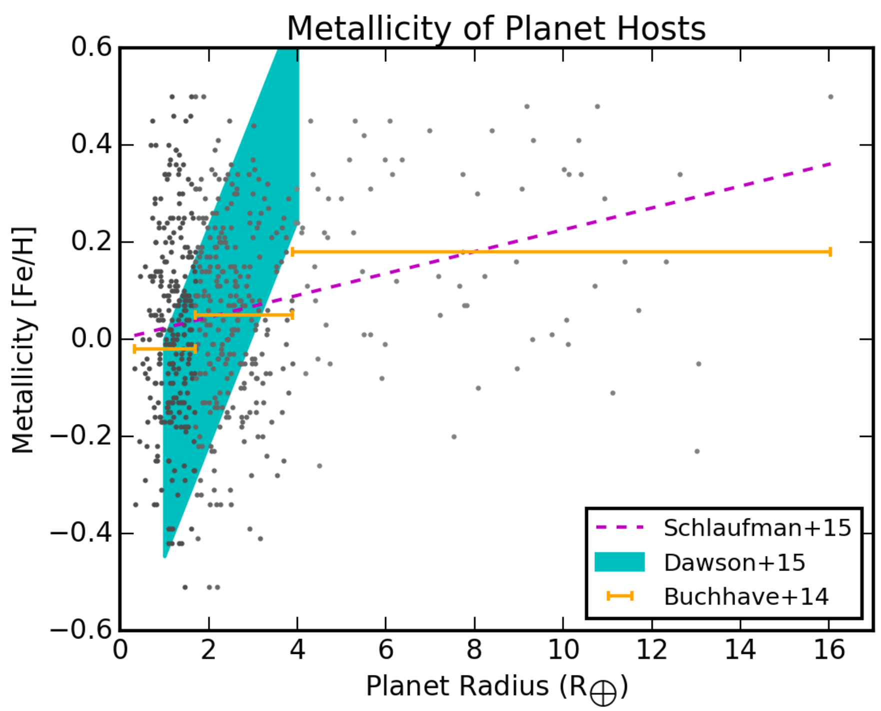




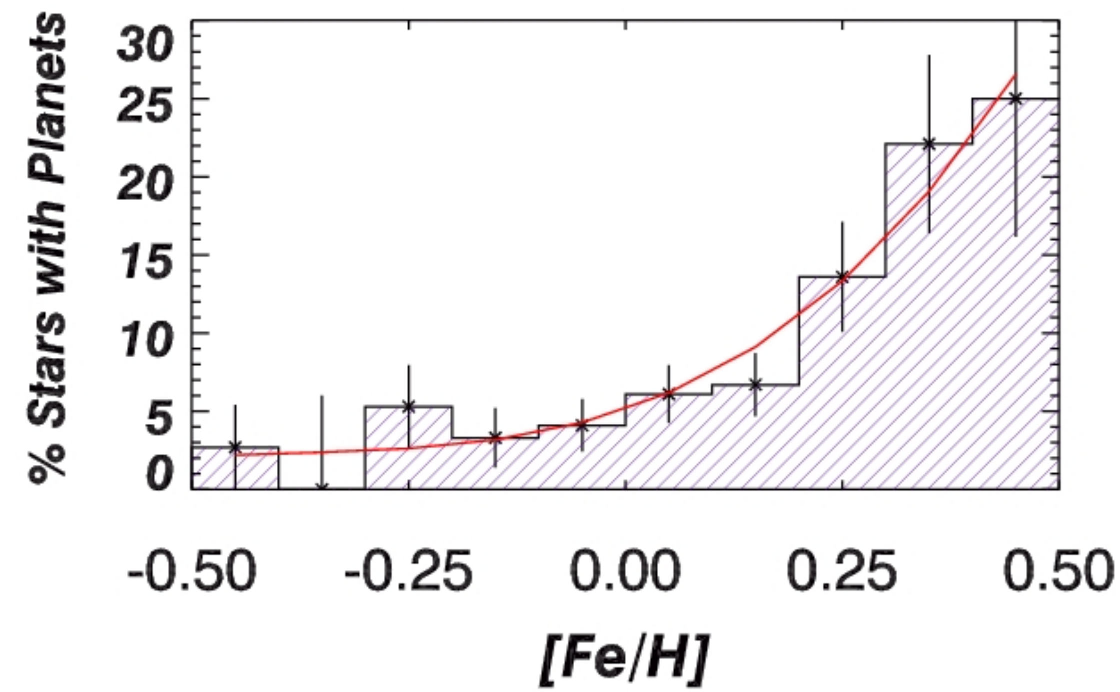
Valencia et al. 2013
(Bulk Composition of GJ 1214b and Other Sub-Neptune Exoplanets)

STARS AND PLANETS: Populations

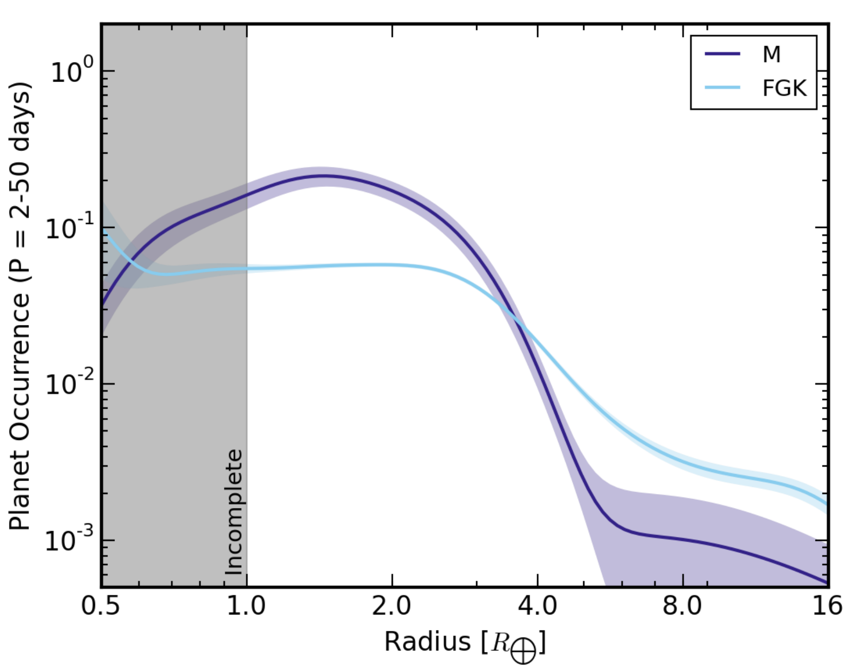
Trends are found between stellar parameters and exoplanets occurence/type.



From Mulders 2018



Fischer & Valenti 2005



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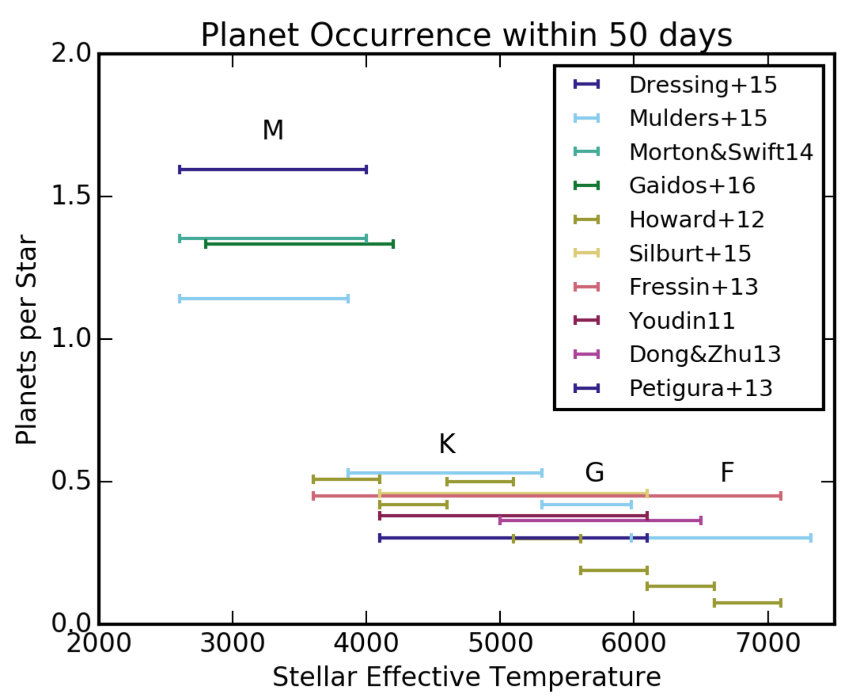
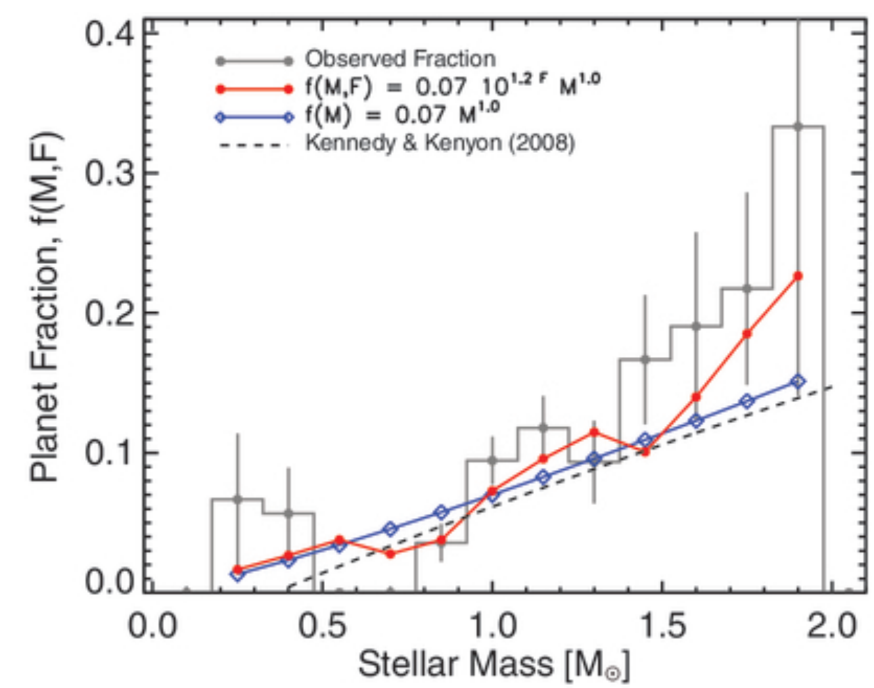


Mulders+ 2015c

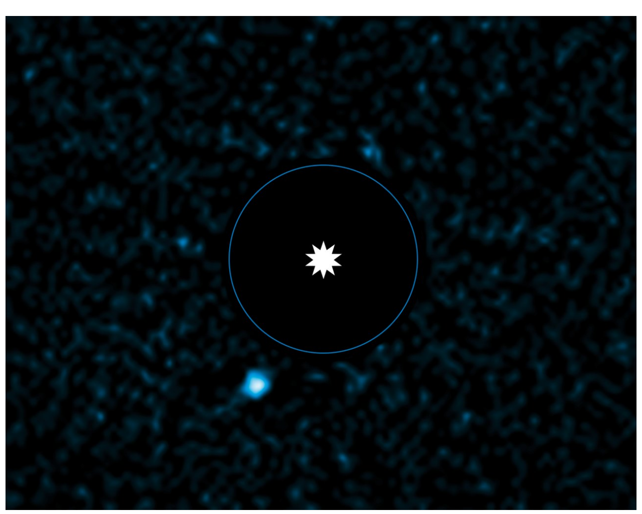


Johnson+ 2010

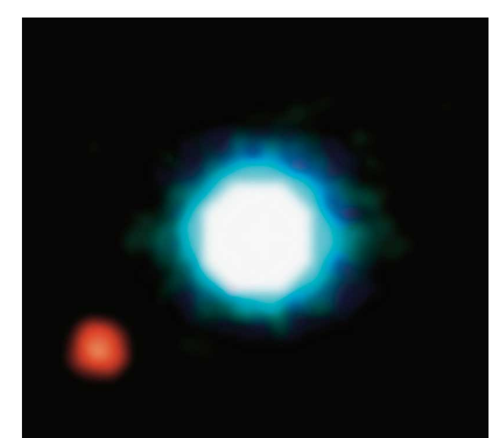
Mulders 2018, arXiv:1805.00023v1

EXOPLANETS: Limitations in the detection

Contrast



Resolution



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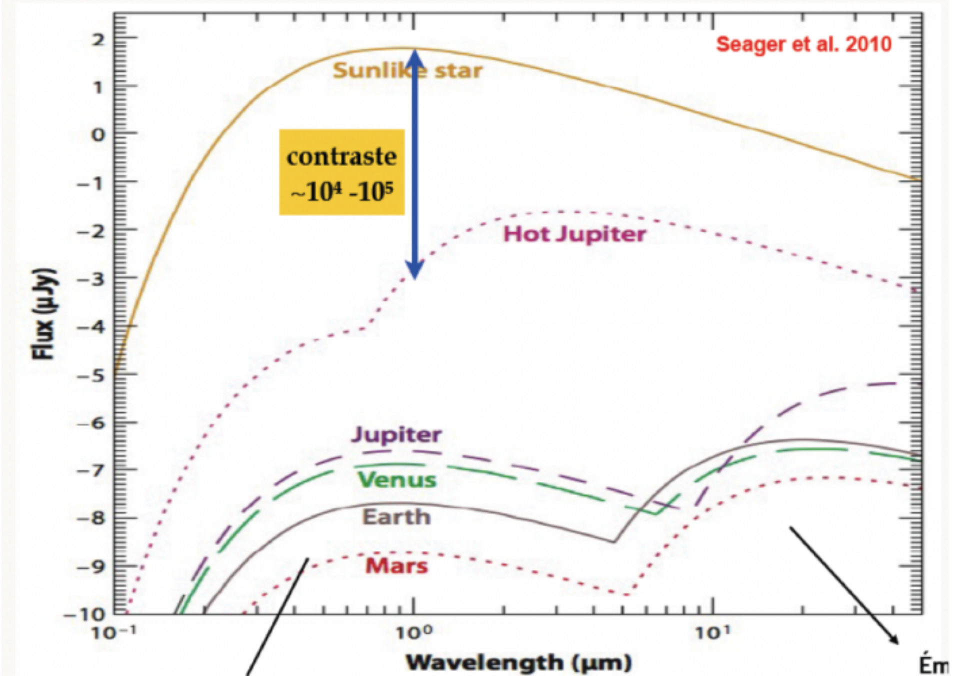
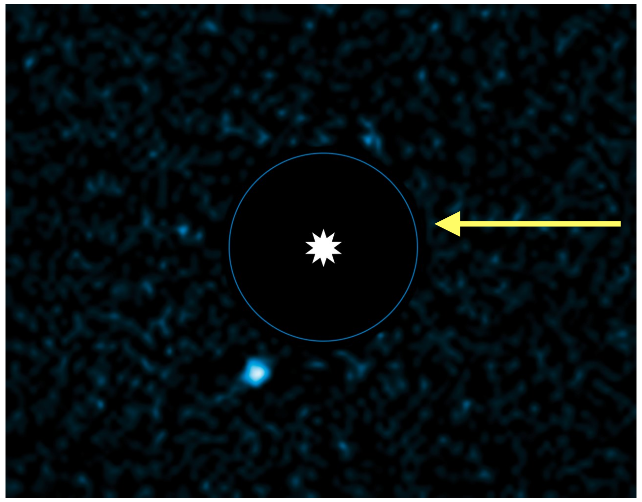
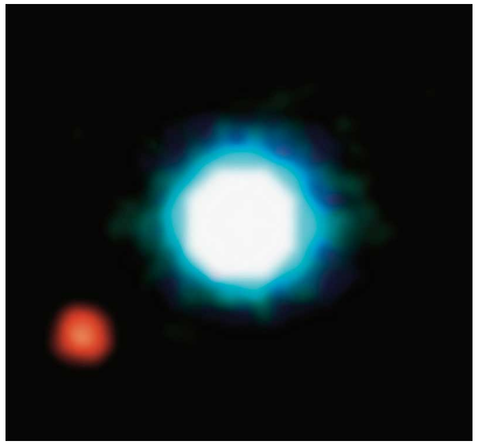




- Need to hide the star
- Problem very close to the star



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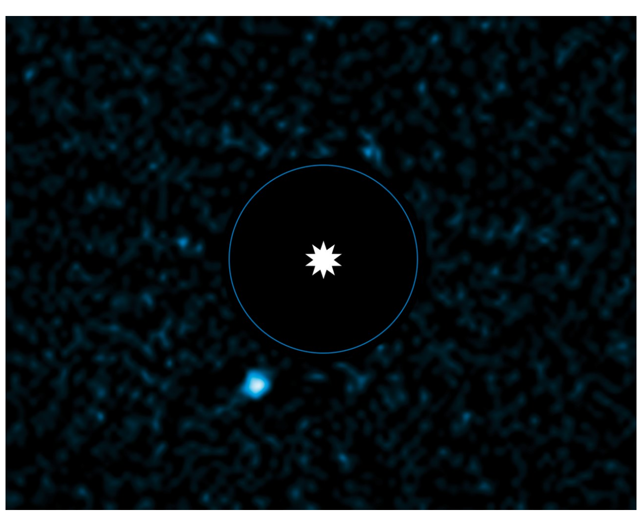

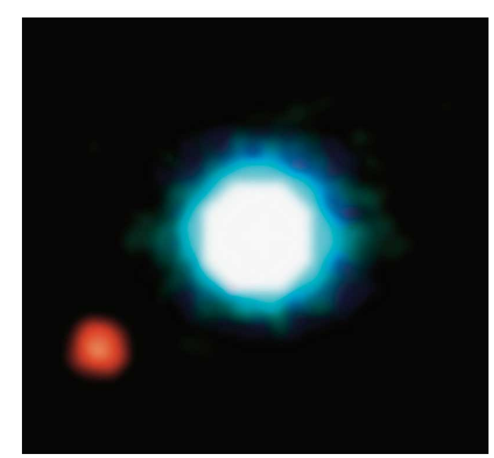

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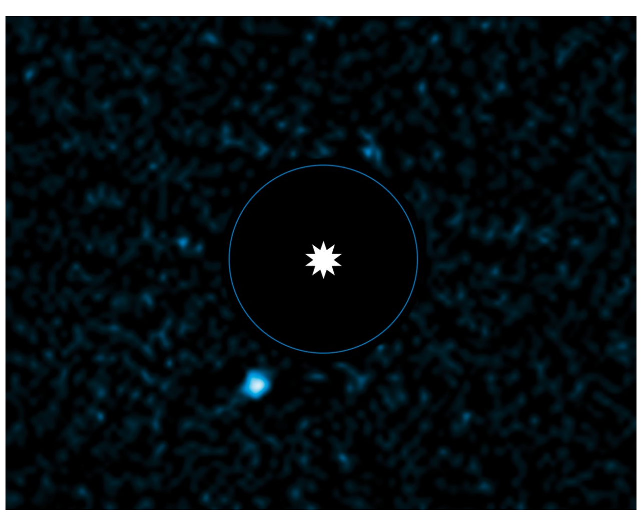
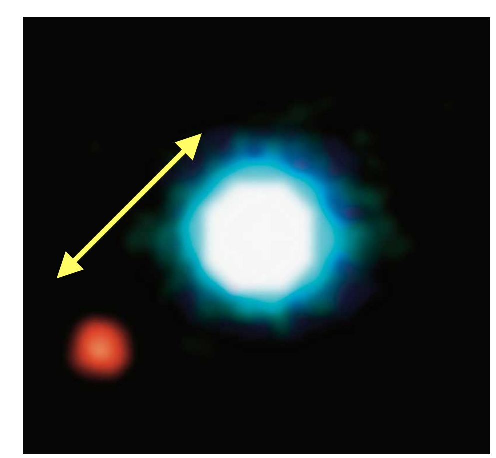


Resolution

1 mas = 2 peaces of 2€ in Bretain seen by the slidefrom Nice !

- Stellar diameter of the order of the millisecond of arc (mas)
- Separation from star and planet of a few mas to a few arcs



EXOPLANETS: Summary

We've seen that:

- Direct and indirect methods do not provide the same observables.
- Need of stellar parameters to derive exoplanets properties.
- Often, need of a model to derive additional parameters, that are important to characterize the system (like the stellar age).
- Open questions on the link between stellar parameters and exoplanets population.

What can interferometry do in this context?

Characterization

- Interferometry allows an almost direct measurement of stellar radii
  → transits and other parameters

Detection

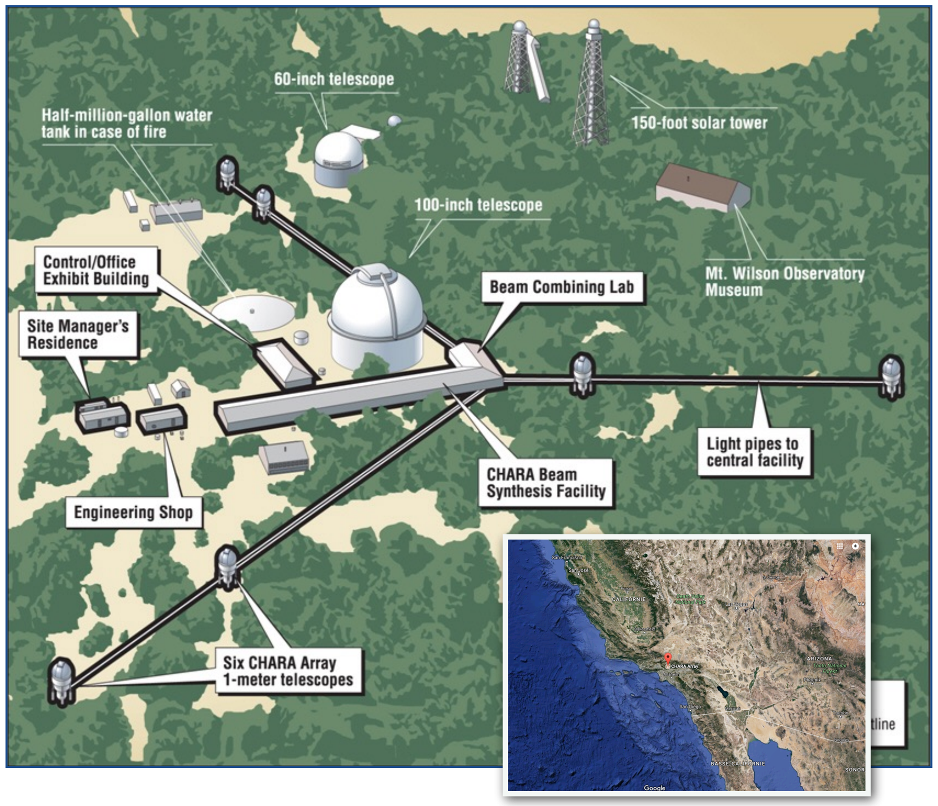
- Closure phases and kernel phase can be used to detect exoplanets
  → mix between imaging and interferometry

OUTLINE of the LECTURE

- **What do we know about exoplanets?**
- **Exoplanets and stars: the role of interferometry**
- **The Kernel phase approach**
  Toward the detection of exoplanets with interferometry
- **Going beyond**
  Kernel-nuller, SKA…

INTERFEROMETERS WORLDWIDE

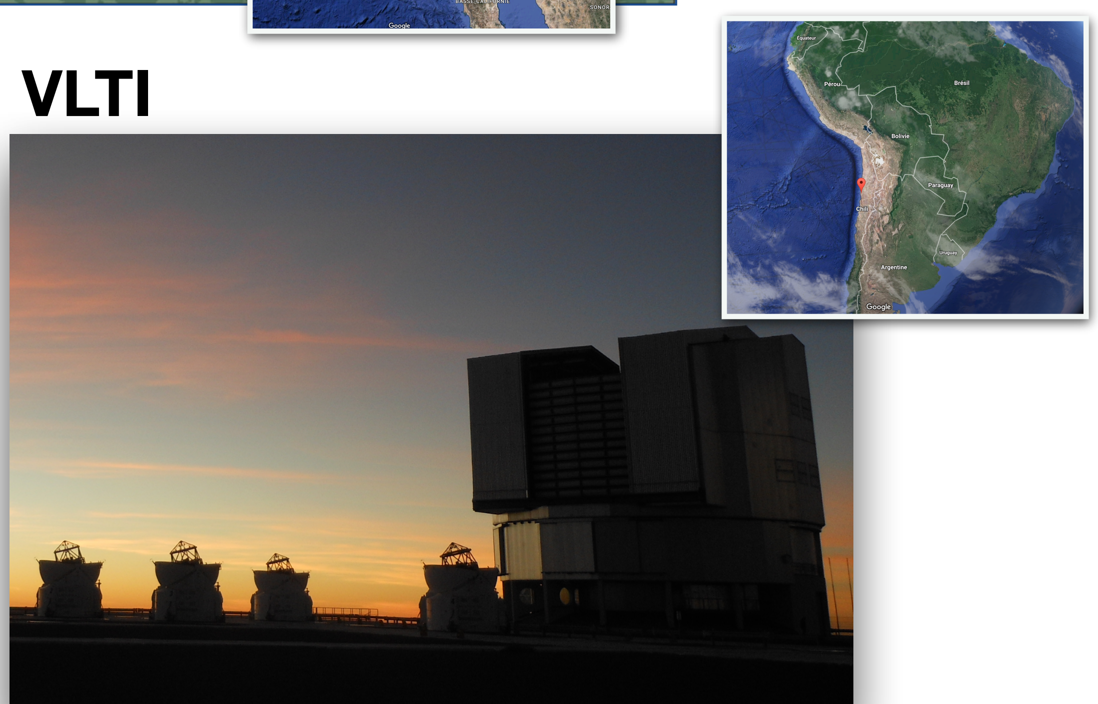
CHARA



SUSI

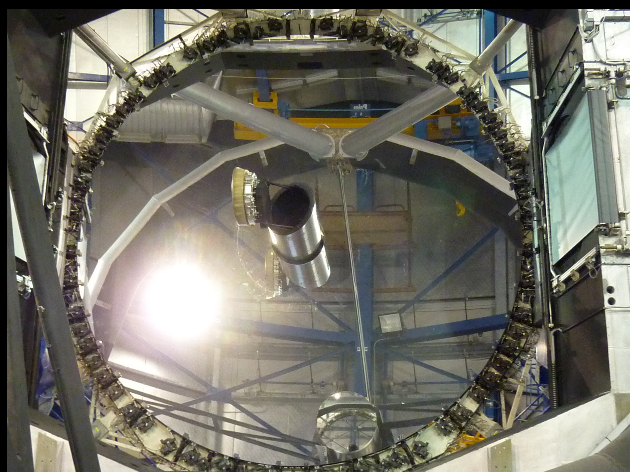
NPOI

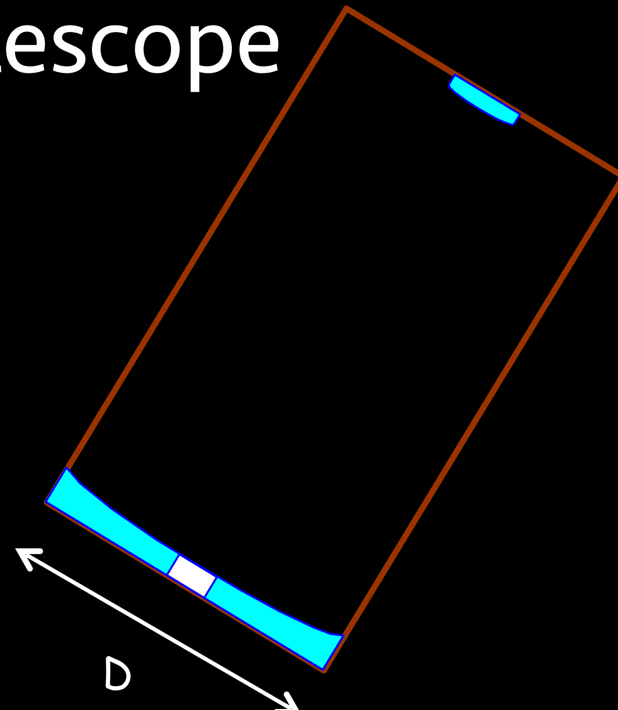
VLTI



INTERFEROMETRY: Recalls

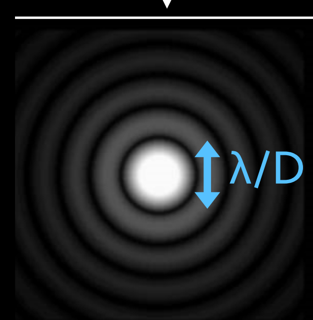
Classical telescope



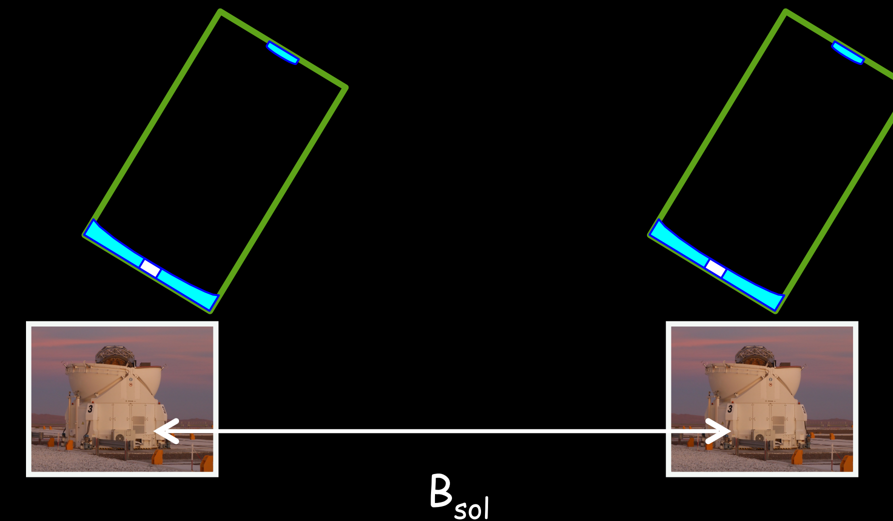


Angular resolution
≈ λ/D

➜ larger sensitivity
➜ fainter objects

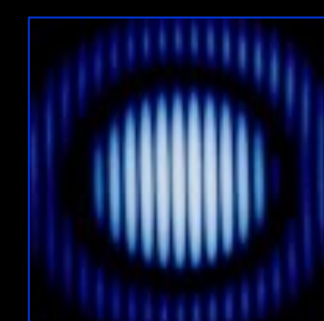


Interferometer



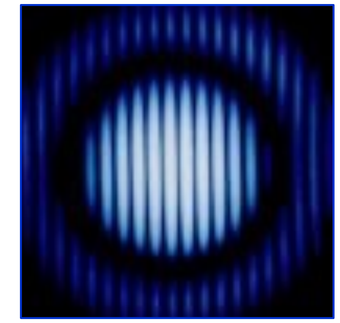
Angular resolution
≈ λ/B

➜ larger resolution
➜ smaller objects



Inter-fringes λ/B

INTERFEROMETRY: Recalls

I =  ⊗ 

Contrast of fringes
= Complex visibility (V)
= FT of the surface brightness distribution of the star

(ven Citter-Zernicke theorem)

I = **O** ⊗ **PSF**

TF(**I**) = TF(**O**) x TF(**PSF**)

TF(**I**) = V(**B**) = $|\gamma(0)|$

Phase Φ

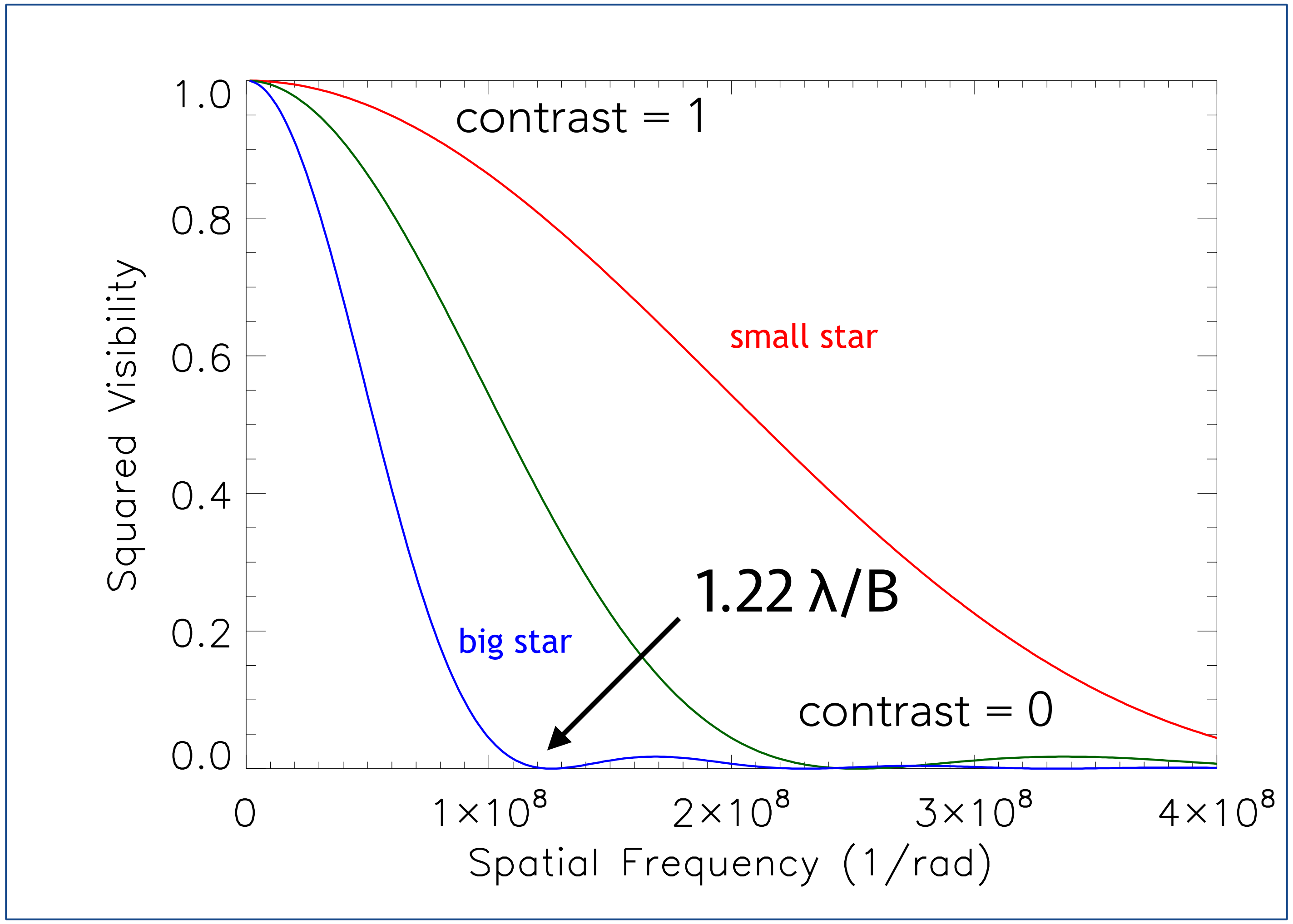
Modulus |V|

In the case of a uniform disk:

$$V_\lambda^{\,2}\left(\frac{B}{\lambda}\right) = 4\left|\frac{J_1(z)}{z}\right|^2 \qquad \text{with} \qquad z = \pi\theta_{UD}\,{}^{B}/_{\lambda}$$

angular diameter of the star

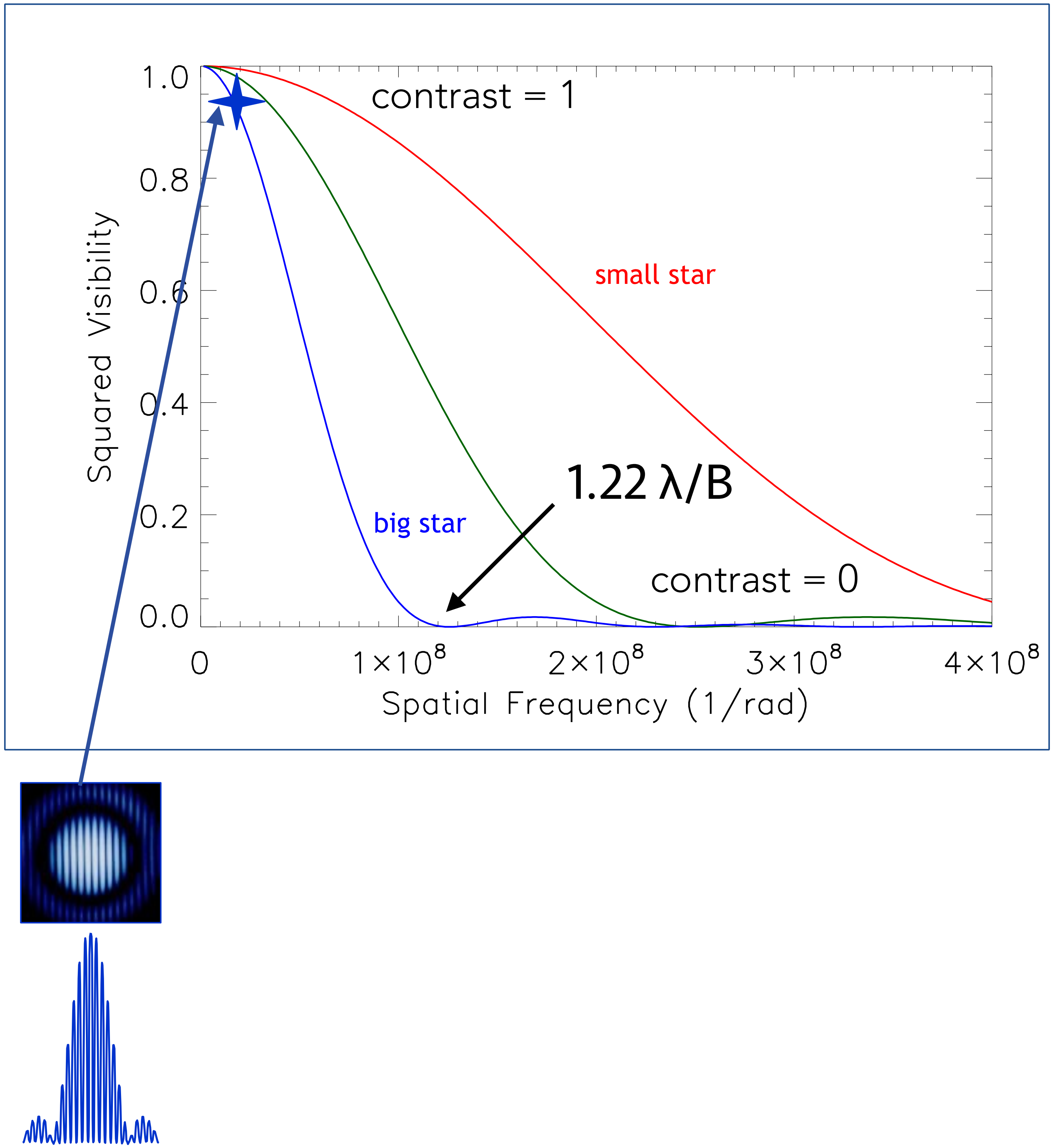
INTERFEROMETRY: Recalls



Point source → contrast = 1 (Young).

Extended source
→ several fringe patterns which don't overlap exactly
→ contrast < 1, depends on telescope separation (baseline).

INTERFEROMETRY: Recalls



Point source → contrast = 1 (Young).

Extended source
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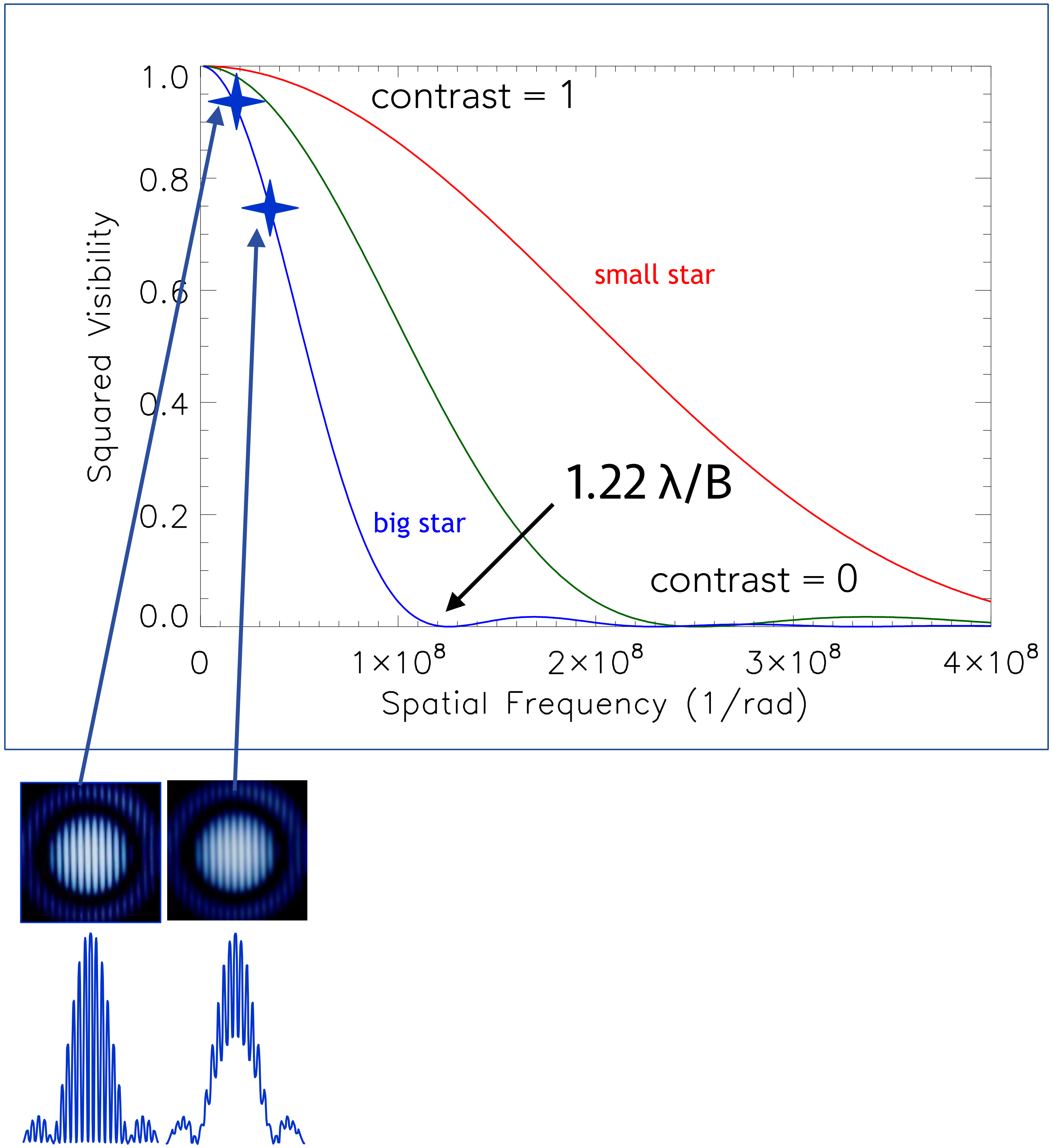
→ contrast < 1, depends on telescope separation (baseline).

INTERFEROMETRY: Recalls



Point source → contrast = 1 (Young).

Extended source
→ several fringe patterns which don’t overlap exactly
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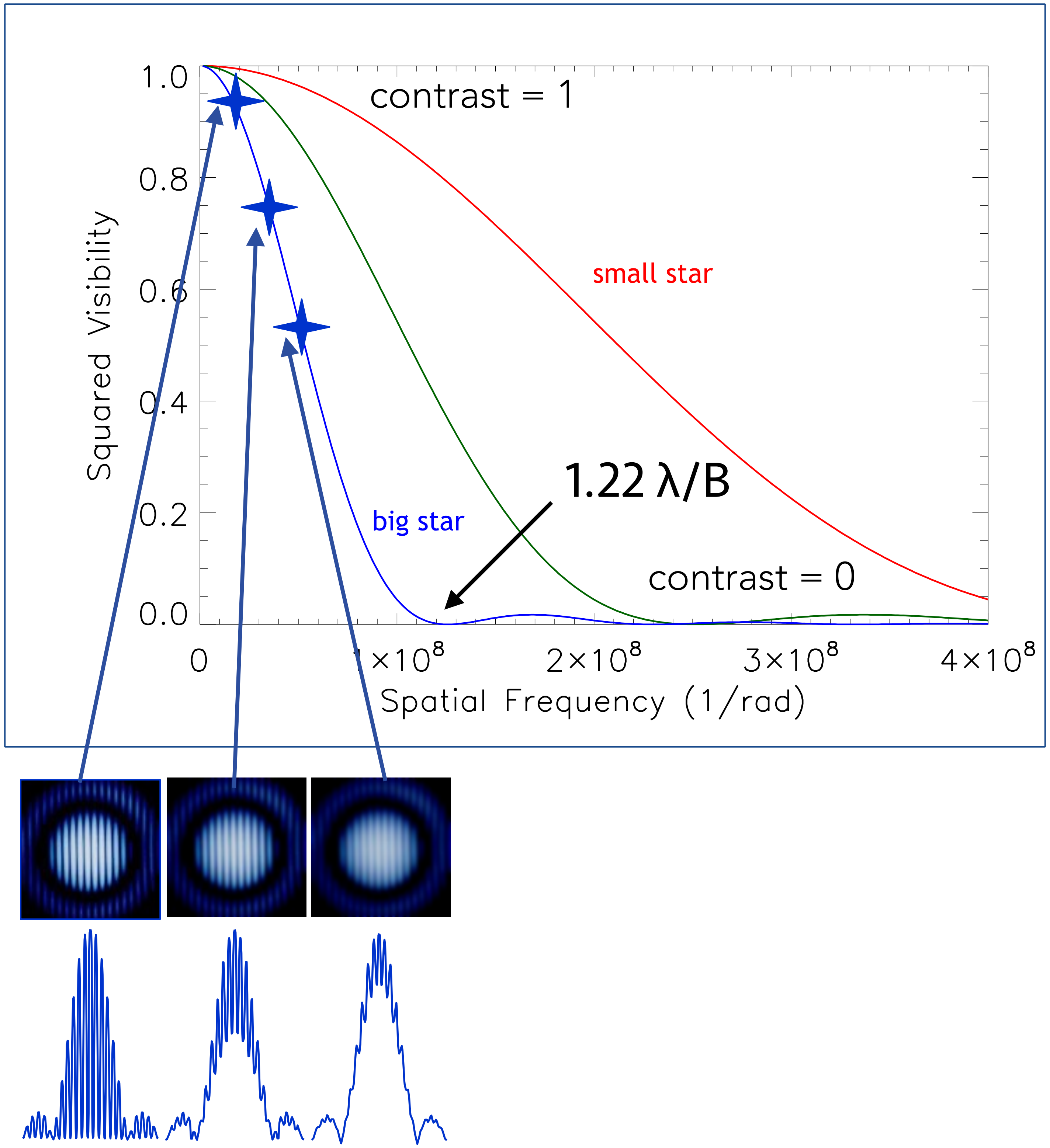
INTERFEROMETRY: Recalls



Point source → contrast = 1 (Young).

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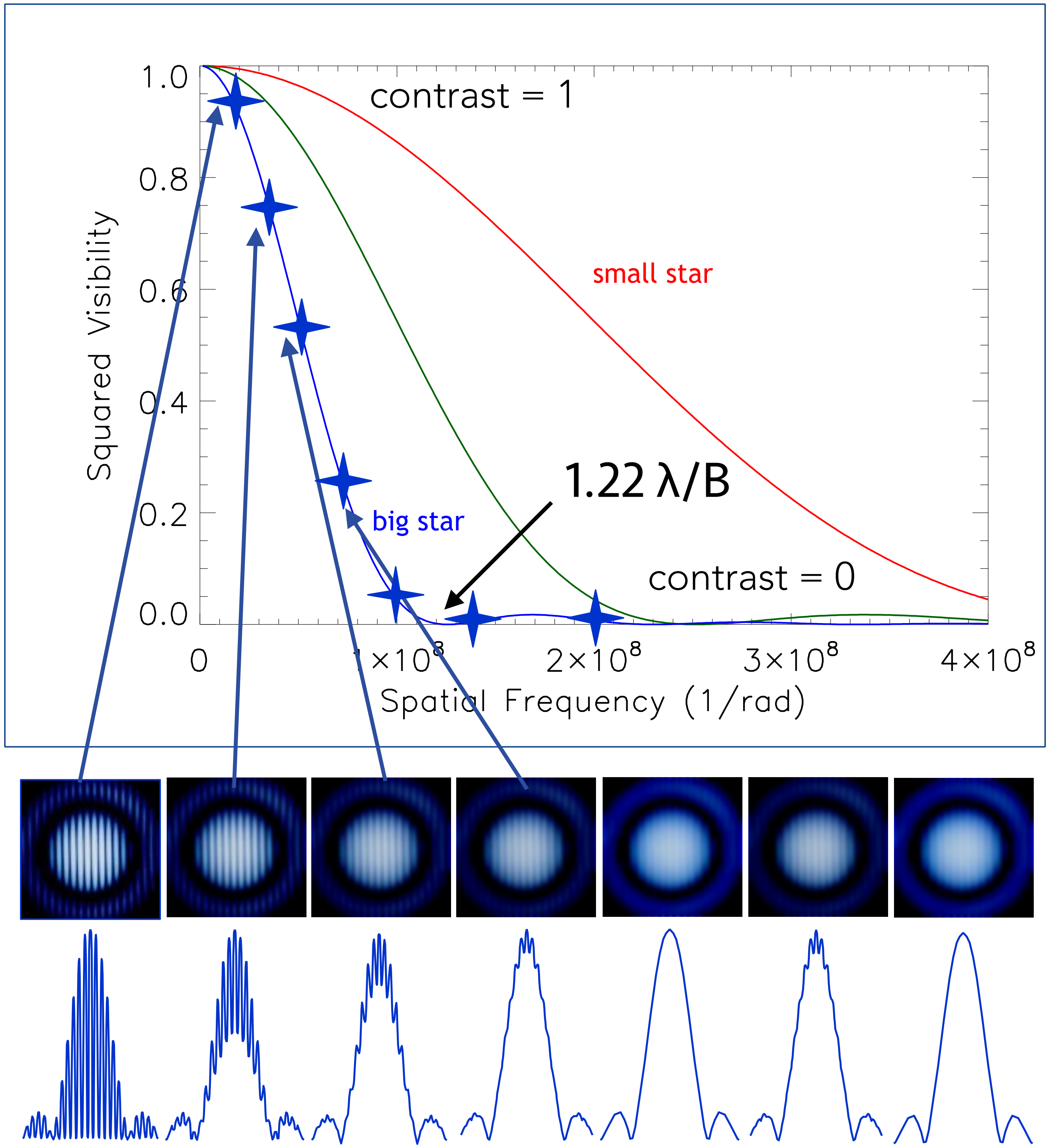
INTERFEROMETRY: Recalls



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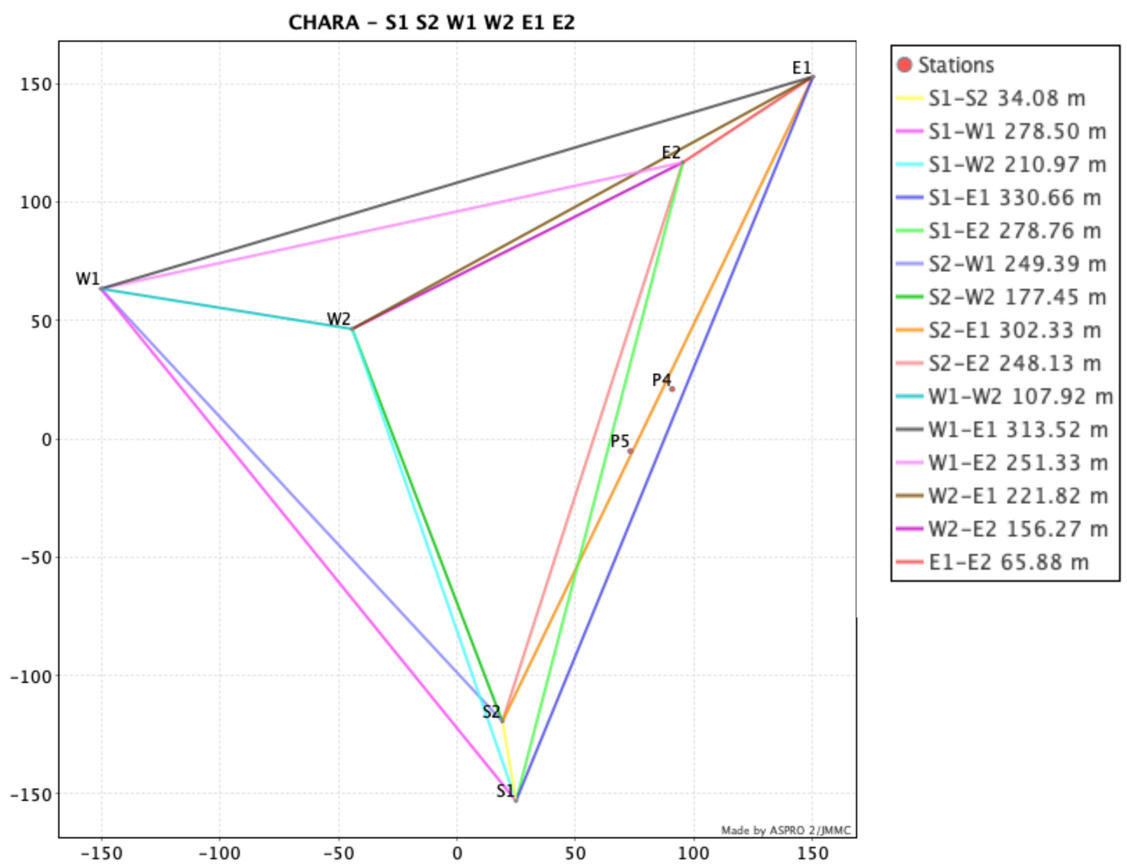
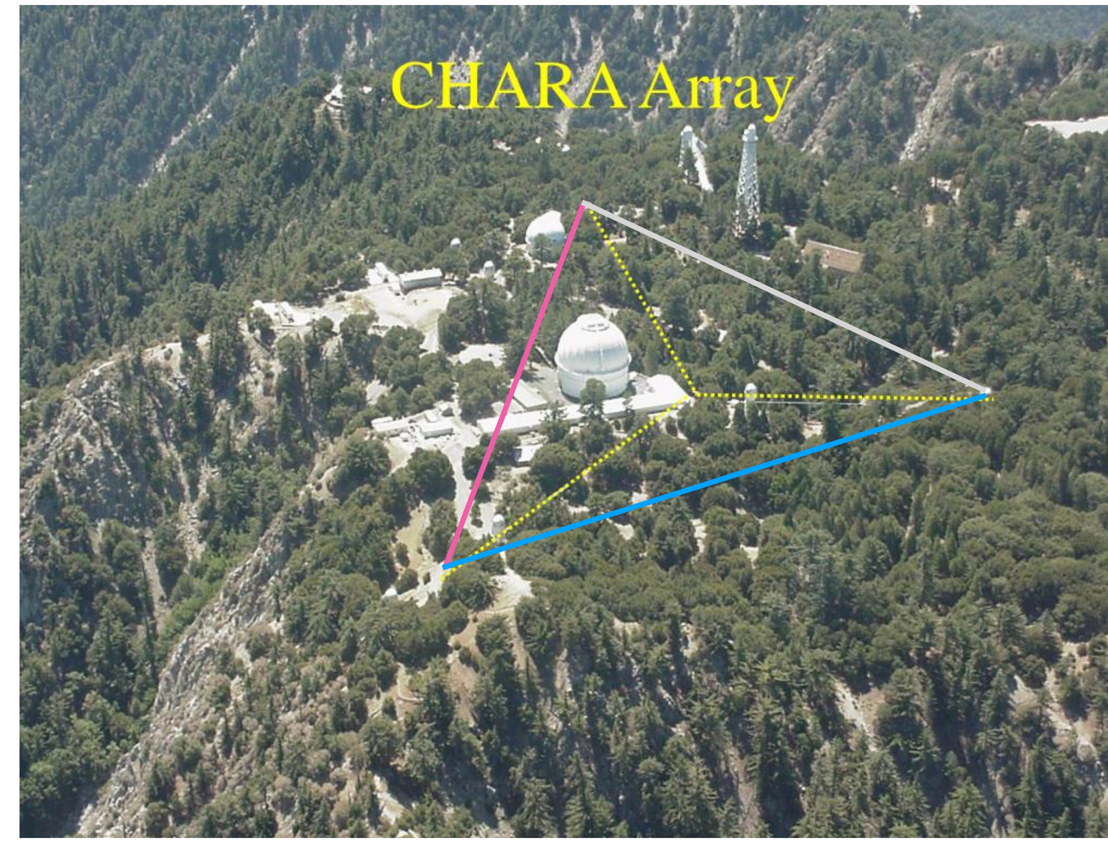
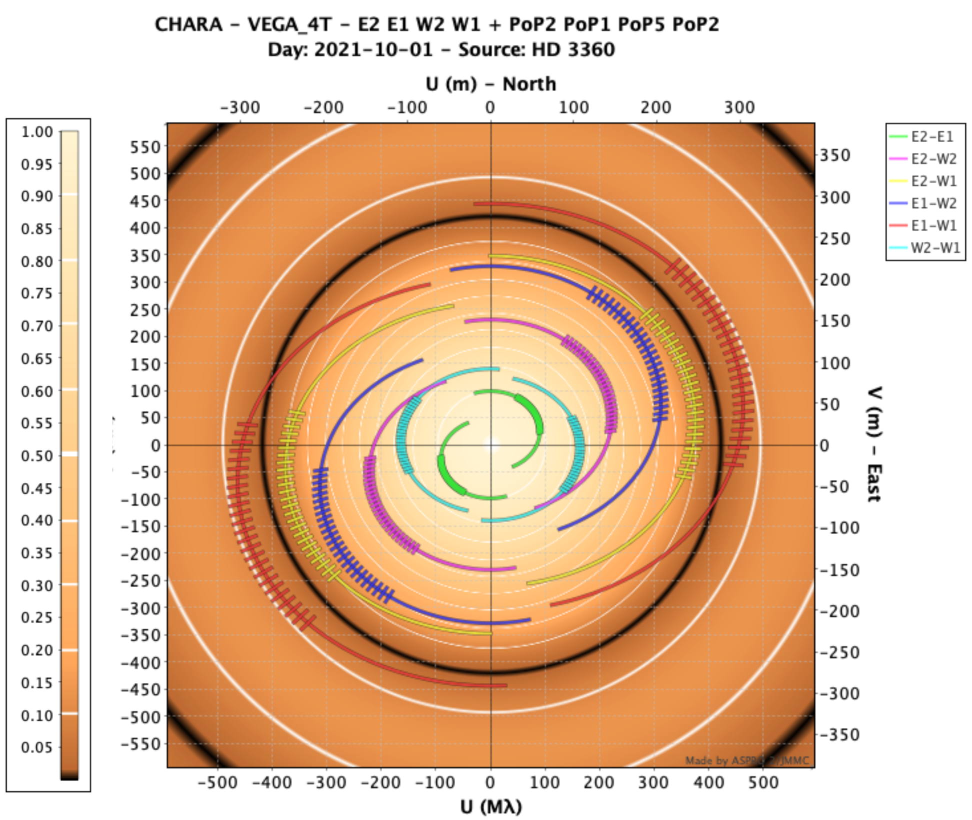
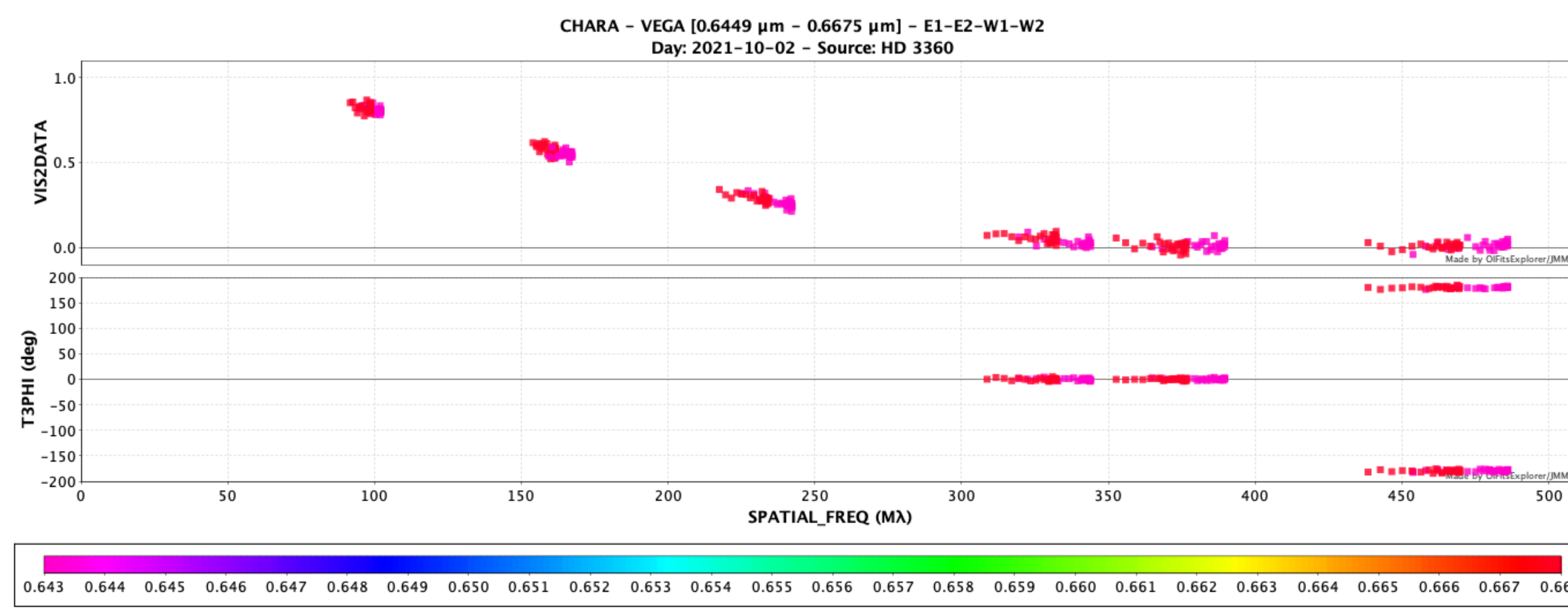
INTERFEROMETRY: Recalls









Aspro2

INTERFEROMETRY: The problem of limb-darkening

Claret & Bloemen 2011

the linear law

$$\frac{I(\mu)}{I(1)} = 1 - u(1-\mu),$$

the quadratic law

$$\frac{I(\mu)}{I(1)} = 1 - a(1-\mu) - b(1-\mu)^2,$$

the square root law

$$\frac{I(\mu)}{I(1)} = 1 - c(1-\mu) - d(1-\sqrt{\mu}),$$

the logarithmic law

$$\frac{I(\mu)}{I(1)} = 1 - e(1-\mu) - f\mu\ln(\mu),$$

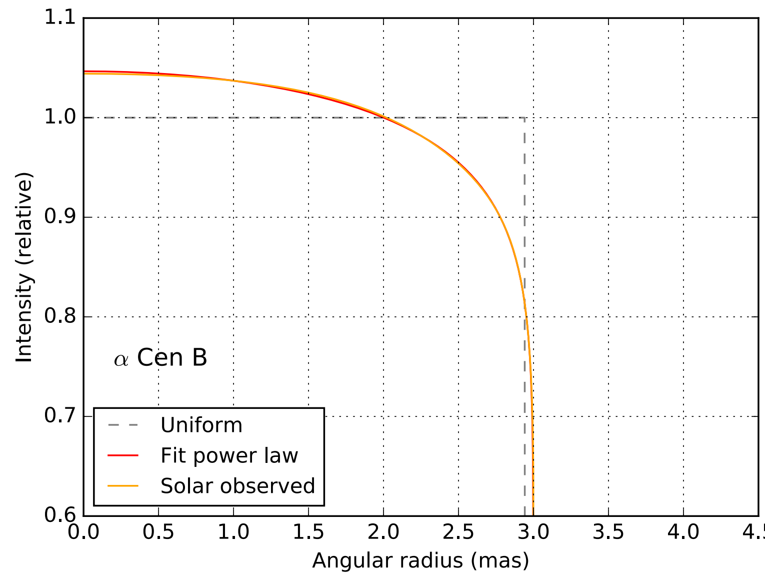


Fig. 9. Comparison of the best-fit power law intensity profiles of α Cen A and B (red curves) with the observed solar profile in the *H* band (orange curves) measured by Pierce et al. (1977). The horizontal scale is the same for both diagrams to show the difference in size of the two stars.

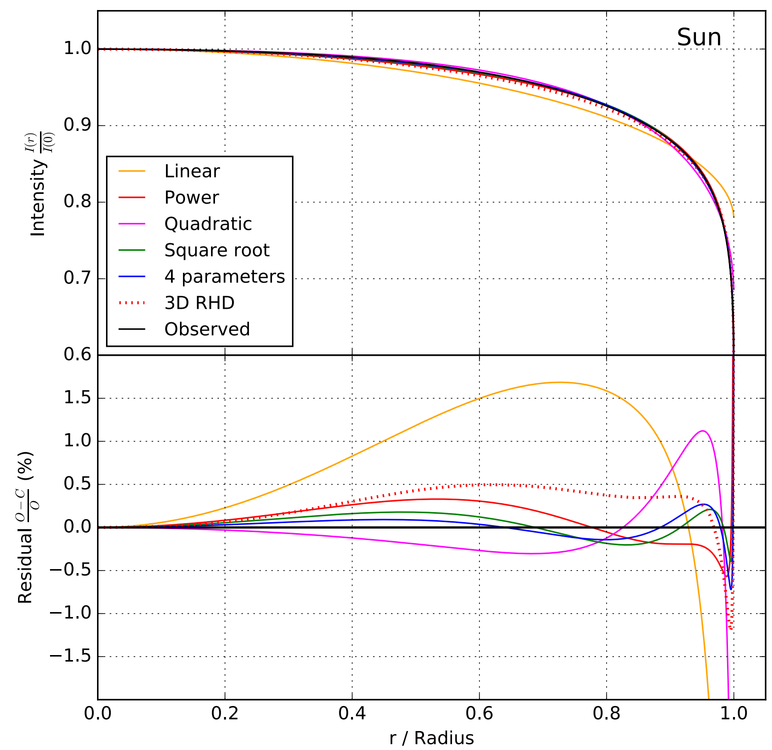
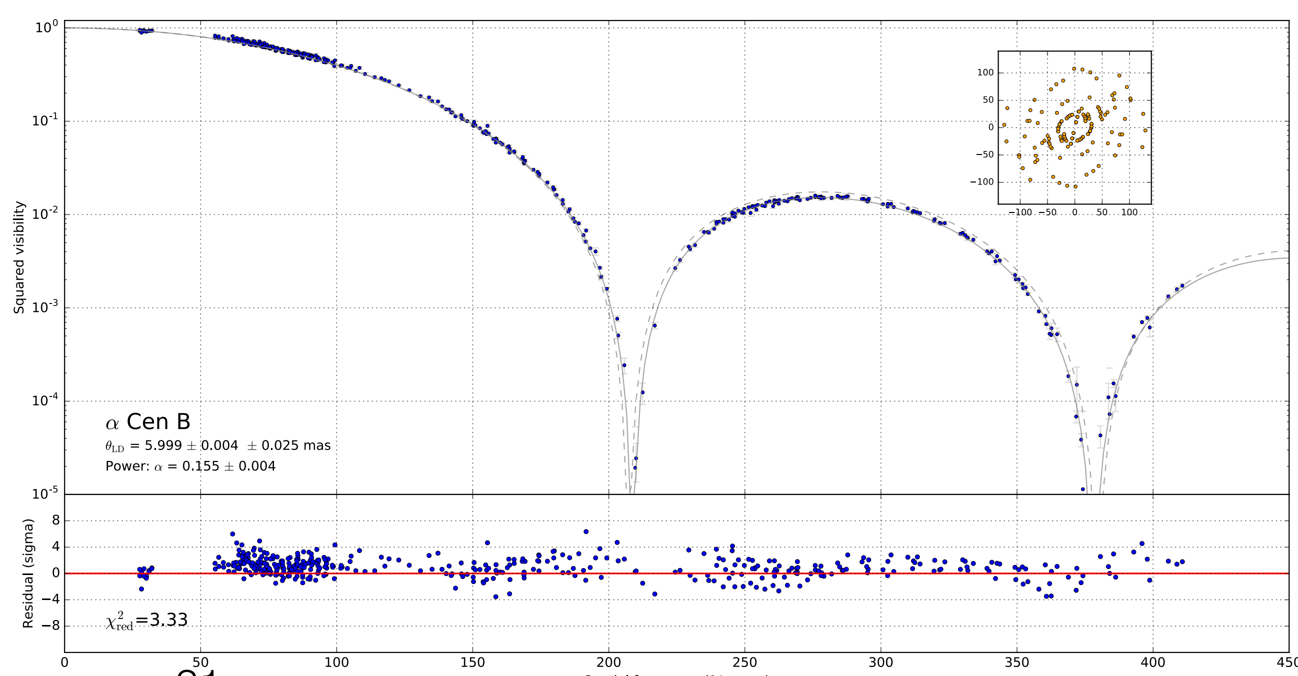


Fig. 2. Comparison of different parametric limb darkening models of the Sun with the observed limb darkening profile measured by Pierce et al. (1977) in the *H* band. The residuals in percentage of the observed intensity profile are shown in the *lower panel*.

Kervella+ 2017



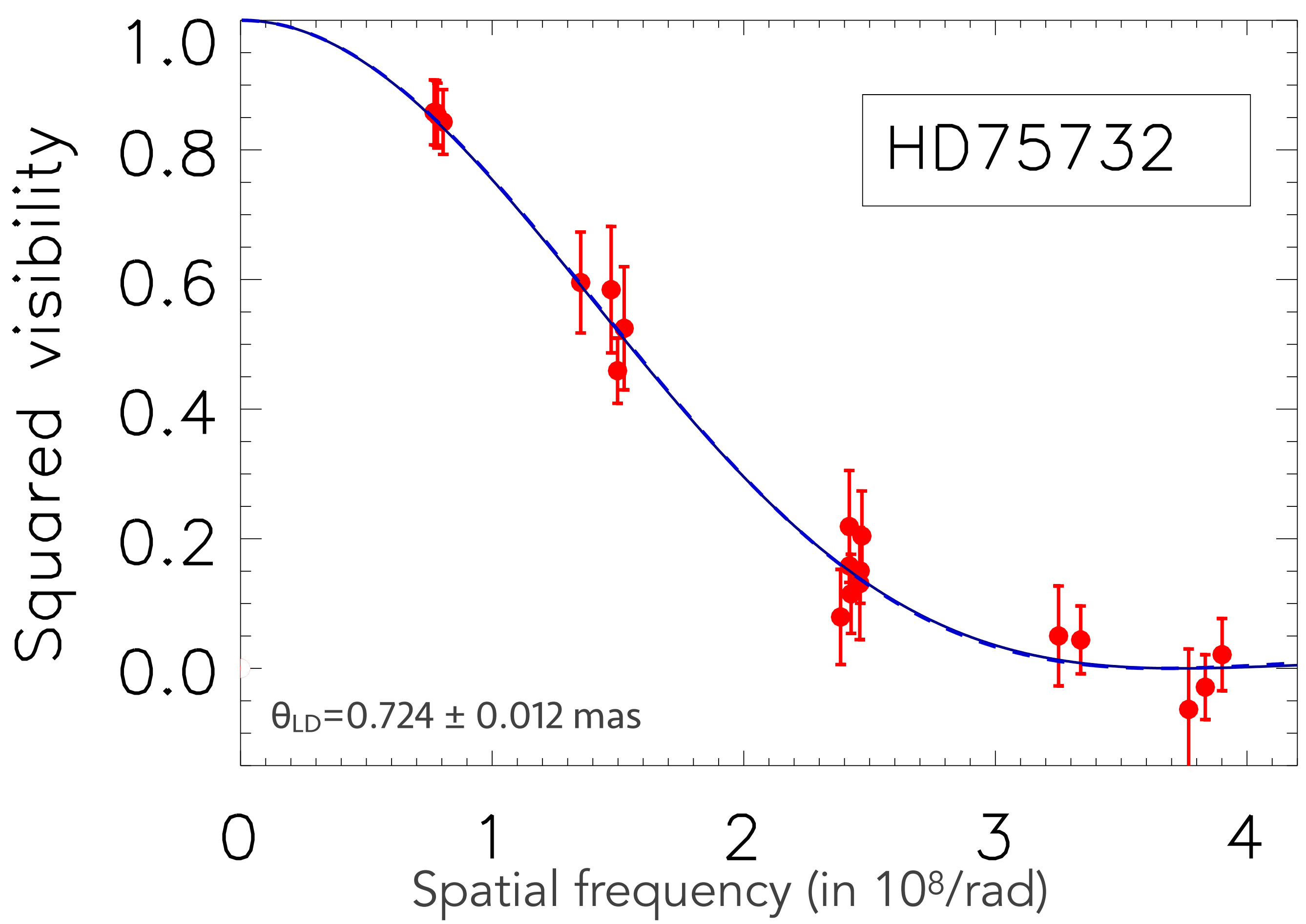
- Difficult to measure the LD
- Discrepancies between transit/interferometry and different laws
- Impact on final radius

INTERFEROMETRY: Measure of the radius

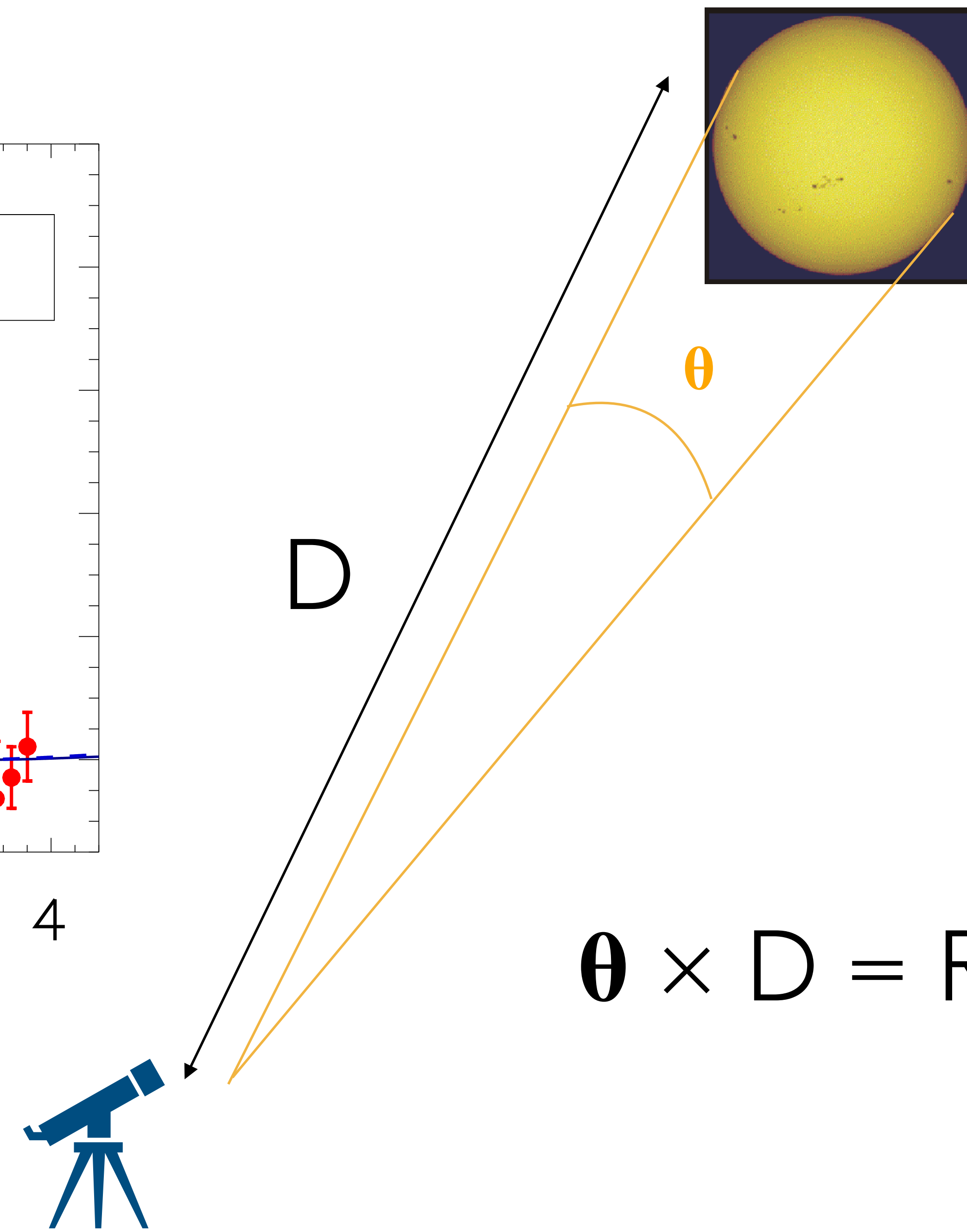
Interferometric angular diameter

Gaia distance

$$R_{\star\,[R_\odot]} = \frac{\theta_{\mathrm{LD\,[mas]}} \times d_{\mathrm{[pc]}}}{9.305} \,.$$



Ligi+ 2016



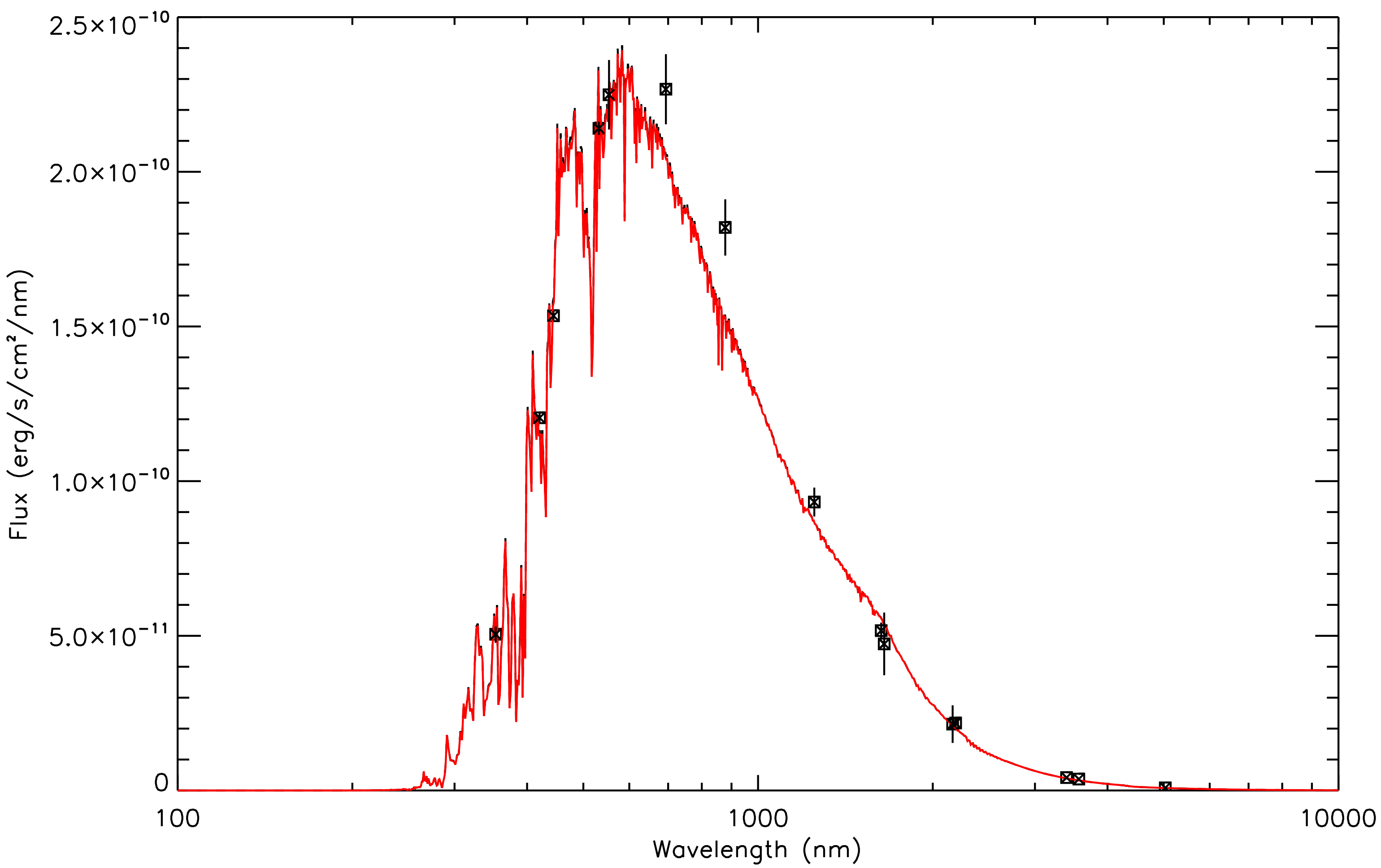
$$\theta \times D = R_\star$$

INTERFEROMETRY: Effective temperature

Interferometric angular diameter

Gaia distance

$$R_{\star[R_\odot]} = \frac{\theta_{\mathrm{LD[mas]}} \times d_{\mathrm{[pc]}}}{9.305} .$$



Catalogues:

Gaia

2MASS

...

→ see Photometric Viewer (CDS)

e.g.

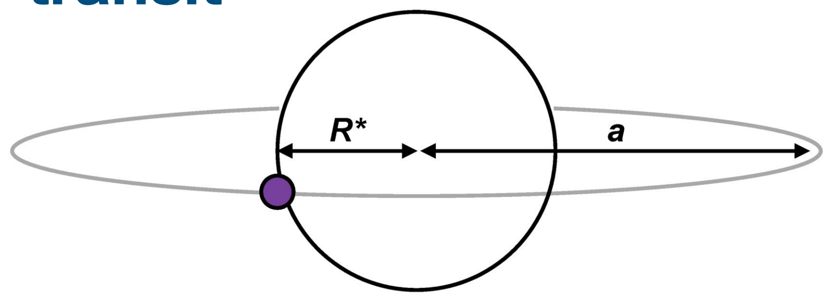
SED

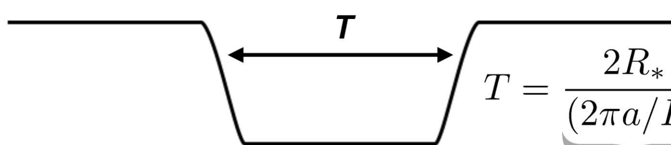
$$T_{\mathrm{eff},\star} = \left(\frac{4 \times F_{\mathrm{bol}}}{\sigma_{\mathrm{SB}}\theta_{\mathrm{LD}}^2}\right)^{0.25}$$

Interferometric angular diameter

INTERFEROMETRY: Density and mass

Planetary transit





$$T = \underbrace{\frac{2R_*}{(2\pi a/P)}}_{\lim e \to 0}$$

3rd Kepler law

$$\frac{P^2}{4\pi^2} = \frac{a^3}{G\,(M_* + M_p)} \simeq \frac{a^3}{GM_*}$$

Measure of stellar density $\rho_\star$

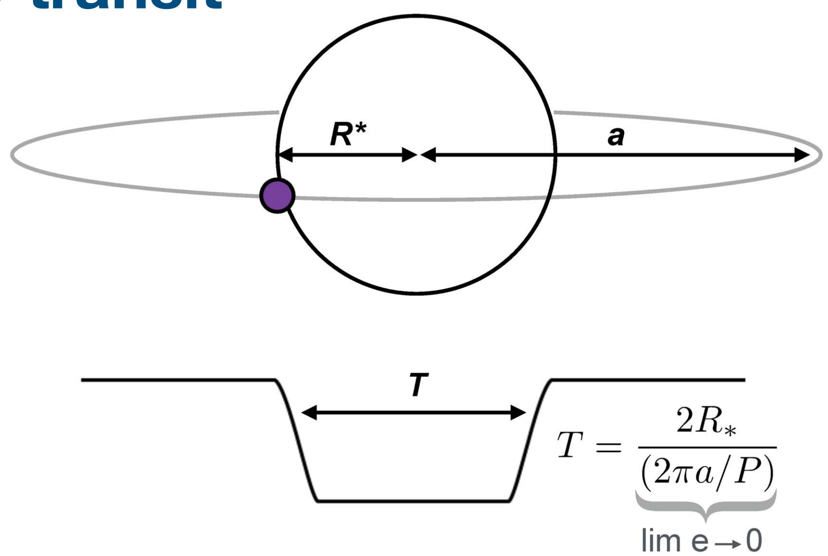
(Maxted et al. 2015, Seager & Mallén-Ornelas 2003)

$P/T^3 = (\pi^2 G/3)\,\rho_\star$

$$\rho_* \equiv \frac{M_*}{R_*^3} = \left(\frac{4\pi^2}{P^2 G}\right)\left\{\frac{\left(1+\sqrt{\Delta F}\right)^2 - b^2\left[1-\sin^2(t_T\pi/P)\right]}{\sin^2(t_T\pi/P)}\right\}^{3/2}$$ with $$\Delta F \equiv \frac{F_{\text{no transit}} - F_{\text{transit}}}{F_{\text{no transit}}} = \left(\frac{R_p}{R_*}\right)^2$$

INTERFEROMETRY: Density and mass

Planetary transit



3rd Kepler law

$$\frac{P^2}{4\pi^2} = \frac{a^3}{G(M_* + M_p)} \simeq \frac{a^3}{GM_*}$$

Measure of stellar density $\rho_\star$

(Maxted et al. 2015, Seager & Mallén-Ornelas 2003)

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Measure of stellar mass $M_\star = (4\pi/3) R_\star^3 \rho_\star$

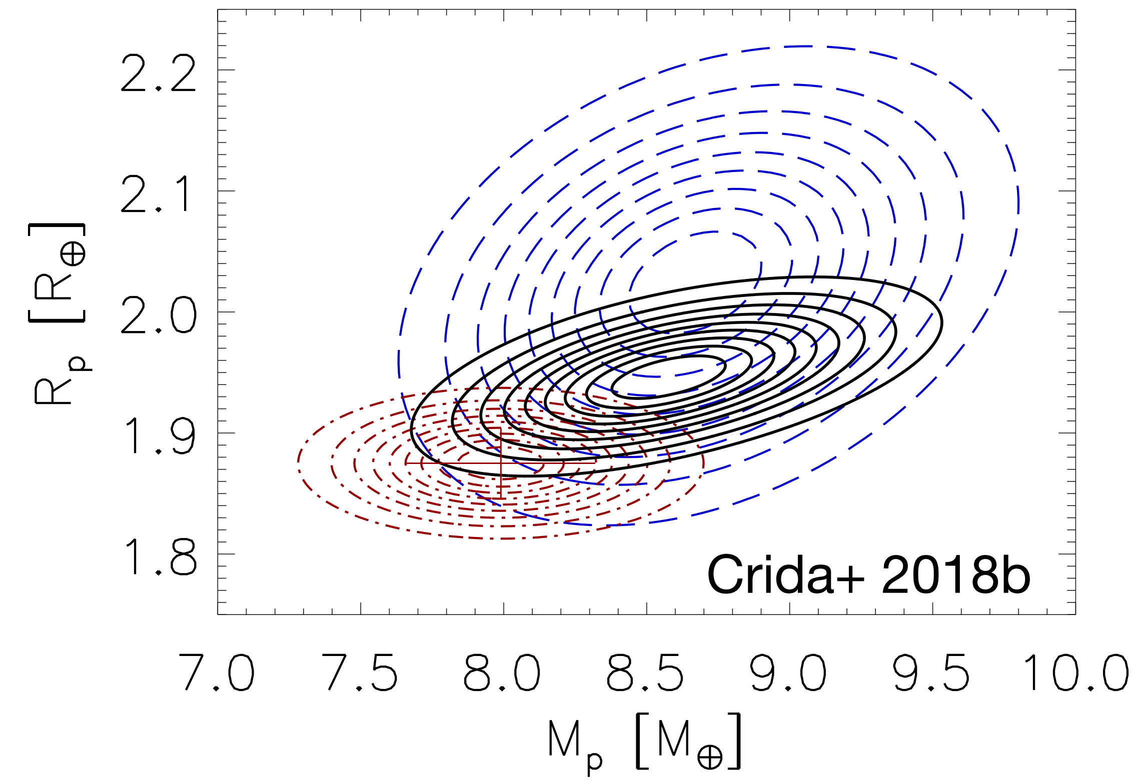
Interferometry

INTERFEROMETRY: Density and mass

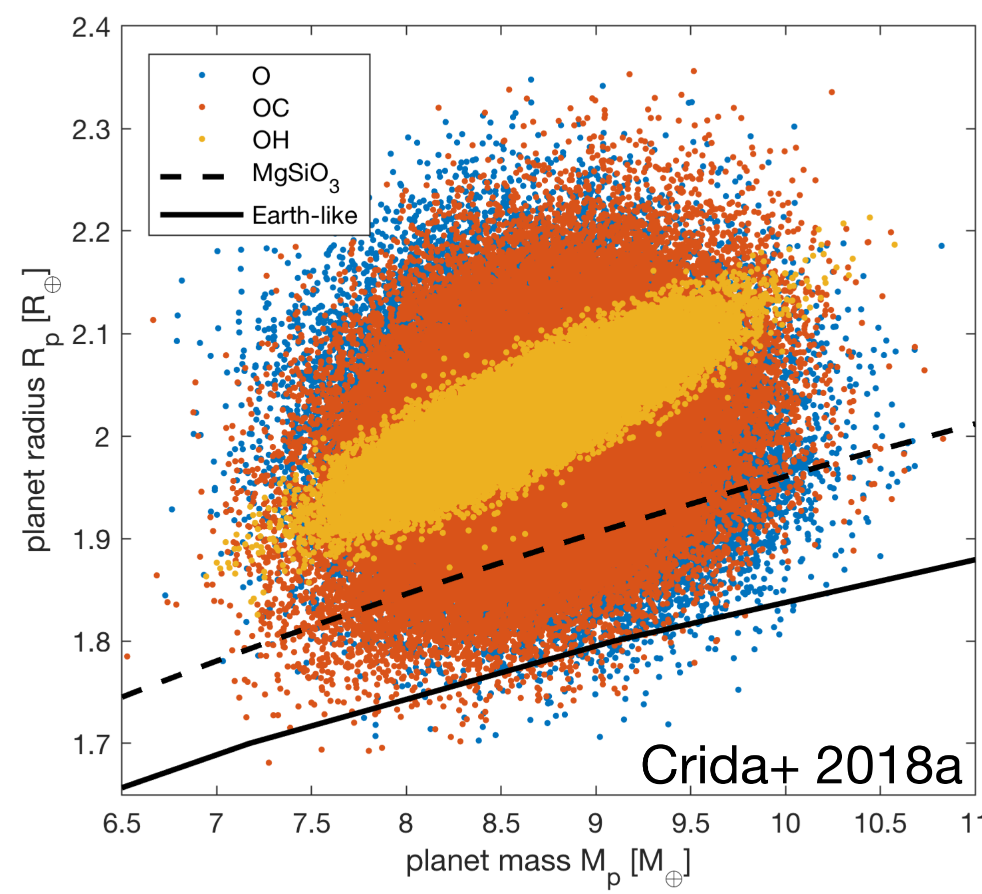
Probability Distribution Function of M_p and R_p

$$f_p(M_p, R_p) \propto \iint \exp\left(-\frac{1}{2}\left(\frac{K(M_p, M_\star) - K_e}{\sigma_K}\right)^2\right) \times \exp\left(-\frac{1}{2}\left(\frac{TD(R_p, R_\star) - TD_e}{\sigma_{TD}}\right)^2\right) \times \mathcal{L}_{MR\star}(M_\star, R_\star)\, \mathrm{d}M_\star\, \mathrm{d}R_\star$$

Crida+ 2018a



The correlation between R_p and M_p avoid a density not in agreement with R_p and M_p. The twisted ellipse decreases the number of possible densities.

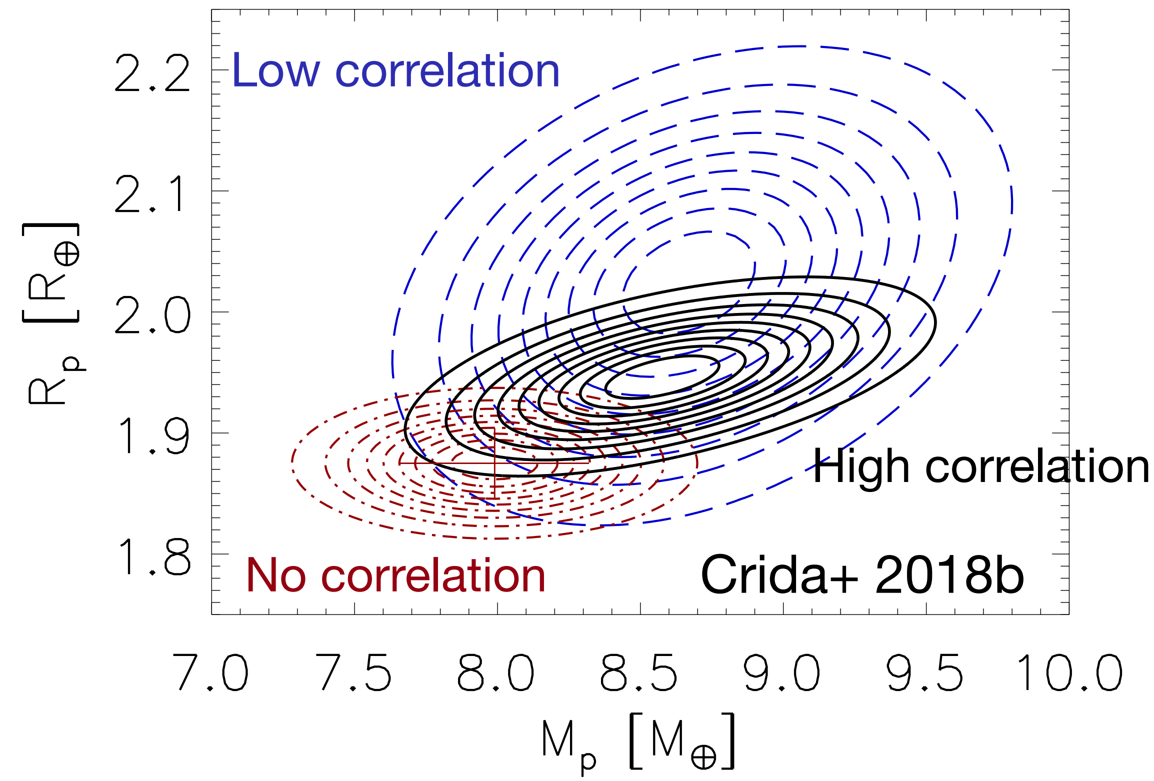


INTERFEROMETRY: Density and mass

Probability Distribution Function of M_p and R_p

$$f_p(M_p, R_p) \propto \iint \exp\left(-\frac{1}{2}\left(\frac{K(M_p, M_\star) - K_e}{\sigma_K}\right)^2\right) \times \exp\left(-\frac{1}{2}\left(\frac{TD(R_p, R_\star) - TD_e}{\sigma_{TD}}\right)^2\right) \times \mathcal{L}_{MR\star}(M_\star, R_\star)\, \mathrm{d}M_\star\, \mathrm{d}R_\star$$

Crida+ 2018a



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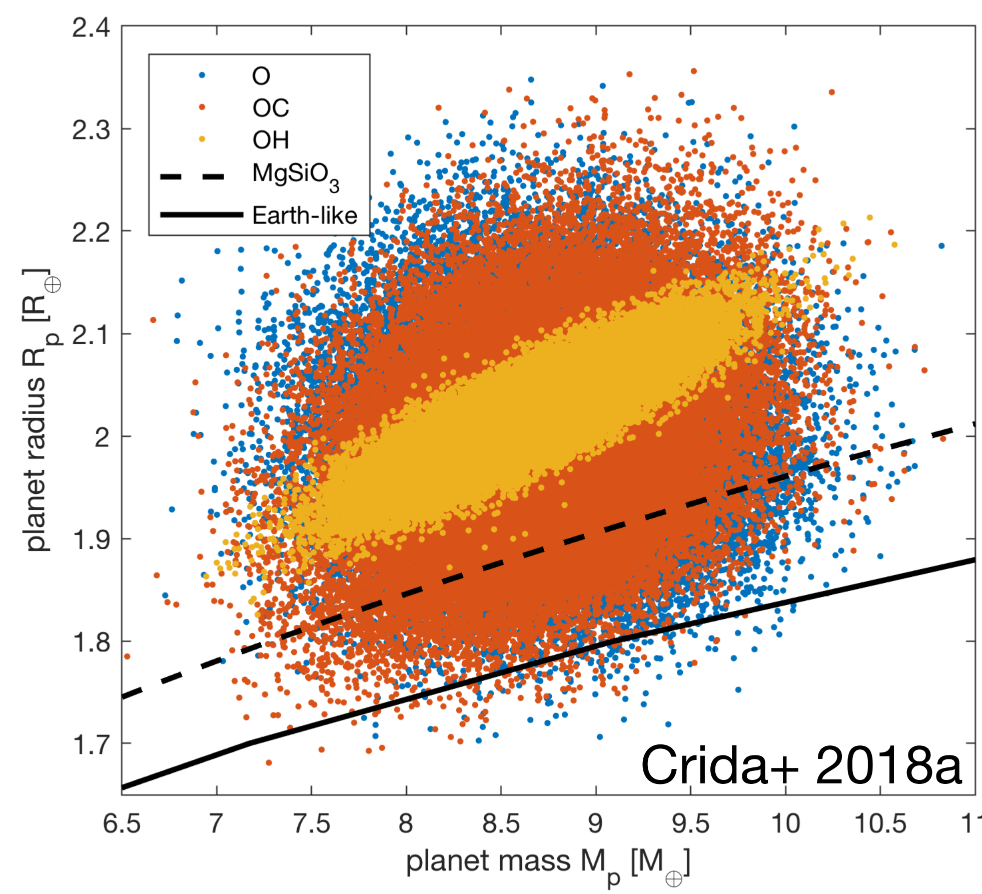
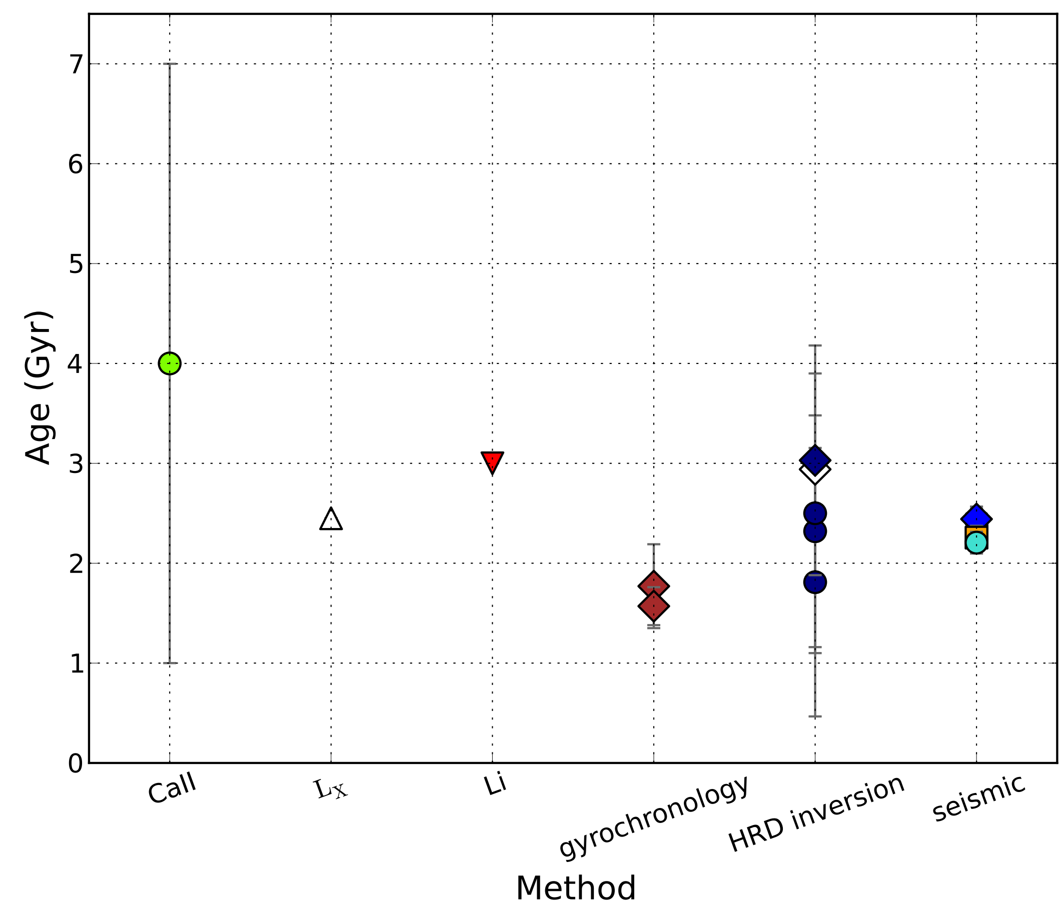


INTERFEROMETRY: Density and mass

HD97658 (Ellis et al., in rev.)

	Planetary Properties	
Transit Depth [ppm]	712±38	§4 Exofast
Period [days]	$9.48971157 \pm 0.00000077$	§4 Exofast
T_0 [BJD]	2458904.9366 ± 0.0008	§4 Exofast
$R_p/R_\star$	0.02668±0.0007	§4 Exofast
Inclination [deg]	$89.05^{+0.41}_{-0.24}$	§4 Exofast
Impact Parameter	$0.39^{+0.11}_{-.018}$	§4 Exofast
Eccentricity	$0.054^{+0.039}_{-0.034}$	§4 Exofast
Mass [$M_\oplus$]	7.52±0.86	§4 Exofast
$a/R_\star$	24.16 ± 0.69	§4 Exofast
R_p [$R_\oplus$]	2.12±0.061	§4
ρ_p [g cm^{-3}]	3.681 ± 0.51	§4
T_{Eq}[K]	749 ± 12	§4
	Stellar and Planetary Properties from Transit Observables	
$\rho_\star$ [g cm^{-3}]	3.11 ± 0.27	§4
$M_\star$ [$M_\odot$]	0.85 ± 0.08	§4
$\log(g)$ [cgs]	4.64±0.04	§4
Corr($R_\star$,$M_\star$)	0.41	§4
ρ_p [g cm^{-3}]	4.835 ± 0.70	§4
R_p [$R_\oplus$]	2.11±0.059	§4
Mass [$M_\oplus$]	8.25±1.01	§4
Corr(R_p, M_p)	0.09	§4

Lebreton & Goupil 2014



- Discrepancies between models, methods, measures
- Need measures to calibrate models

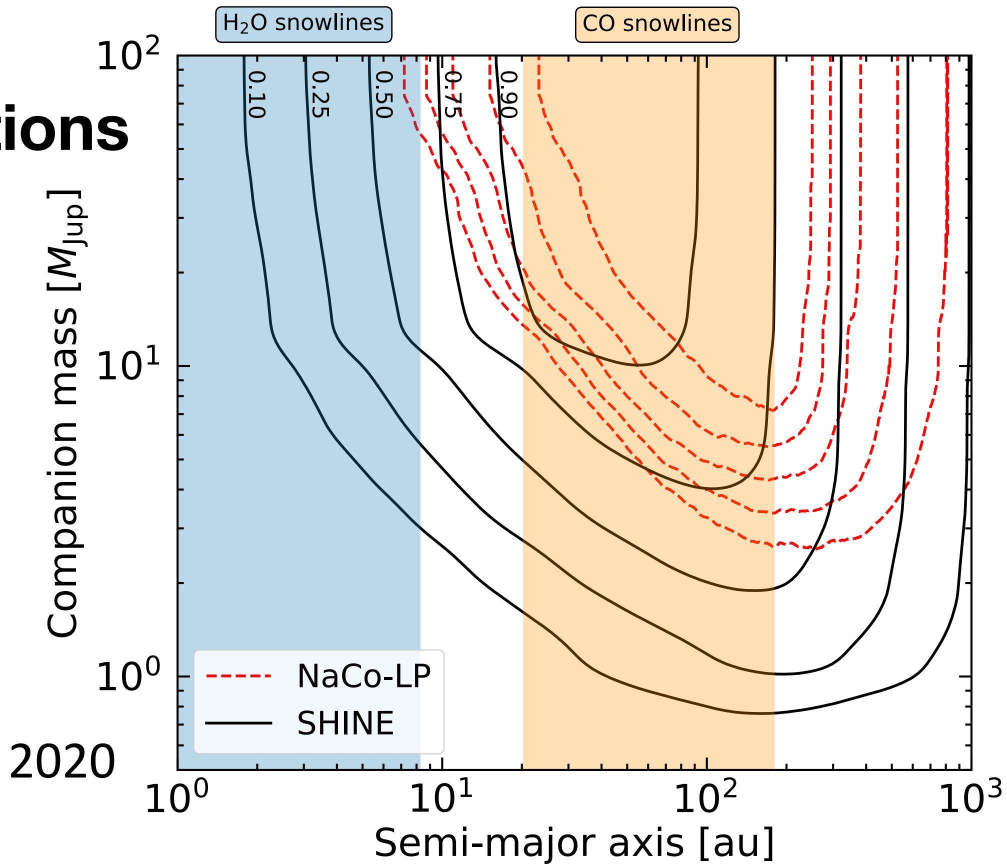
→ Interferometry + planetary transits can bring very important information on usually non-measurable properties

OUTLINE of the LECTURE

- **What do we know about exoplanets?**
- **Exoplanets and stars: the role of interferometry**
- **The Kernel phase approach**
  Toward the detection of exoplanets with interferometry
- **Going beyond**
  Kernel-nuller, SKA…

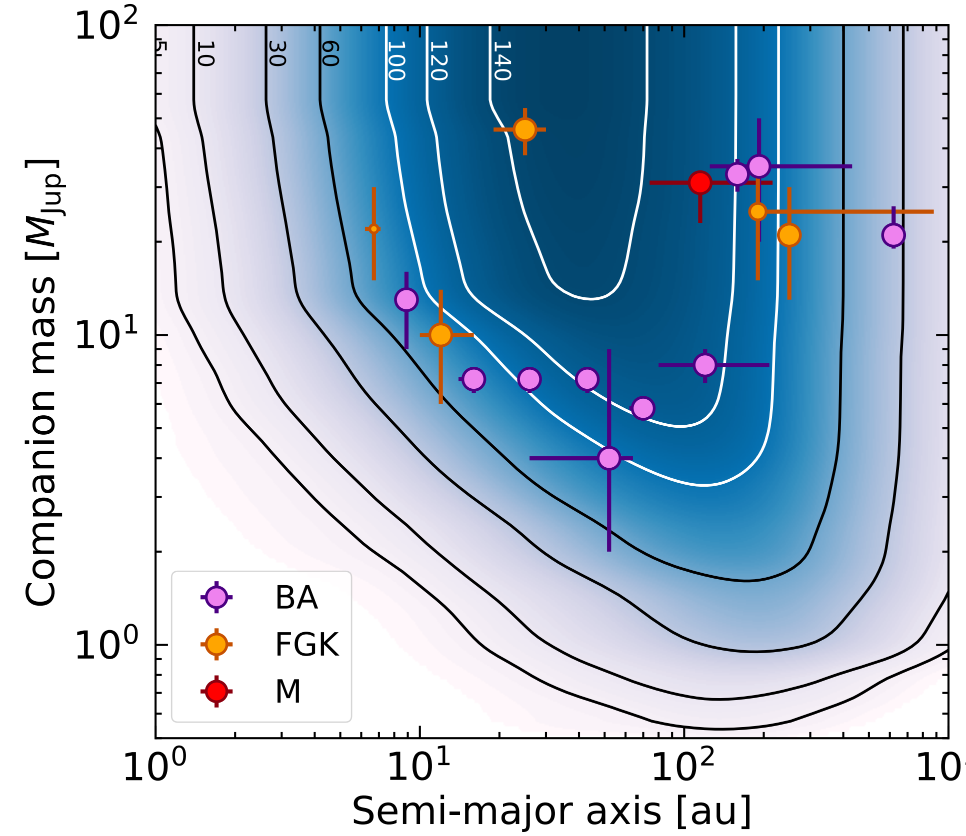
THE KERNEL APPROACH

Predictions



Langlois+ 2020

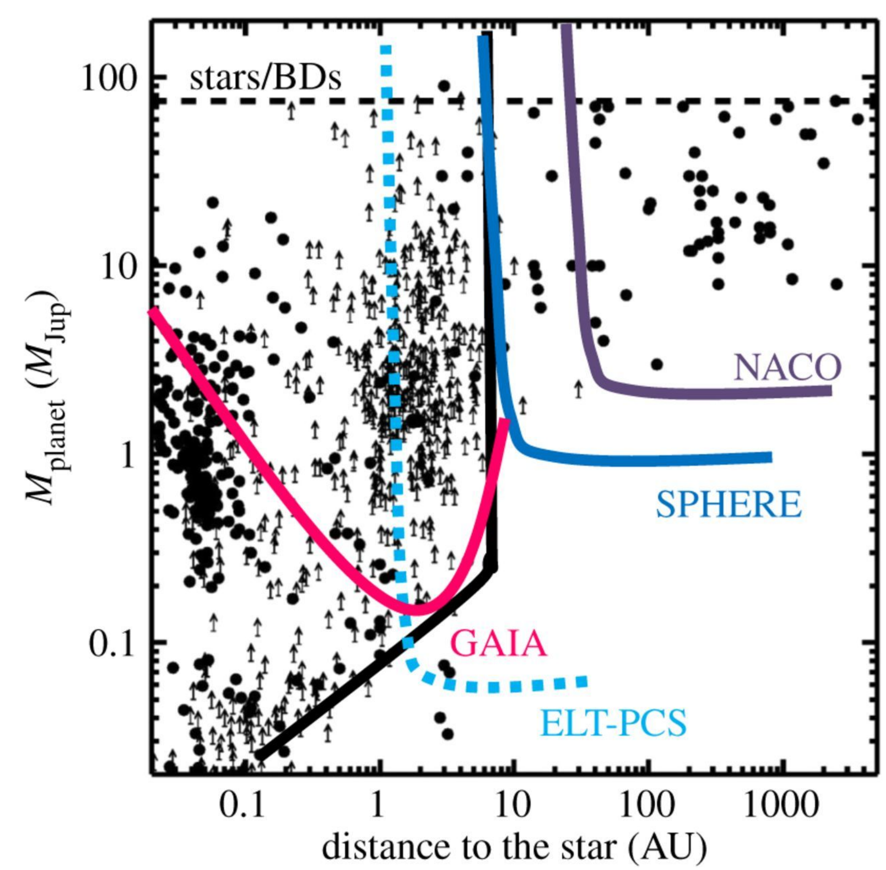
Reality



Vigan+ 2020

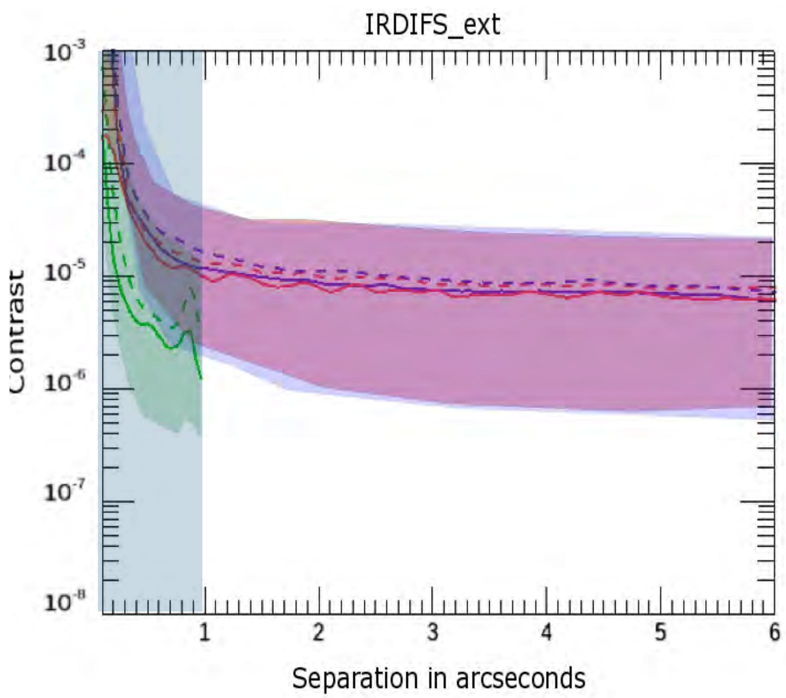
Problematics for direct imaging:

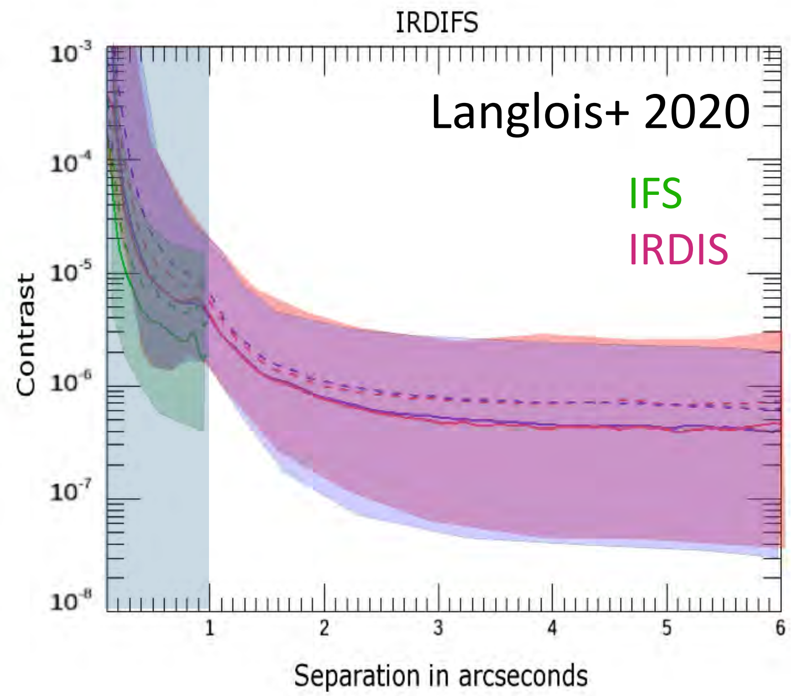
- Detection close to the star but stars are bright compared to planets
  → Detection around young stars, because young planets are hotter thus brighter
- Perturbations: diffraction-limited images, piston, calibration errors…

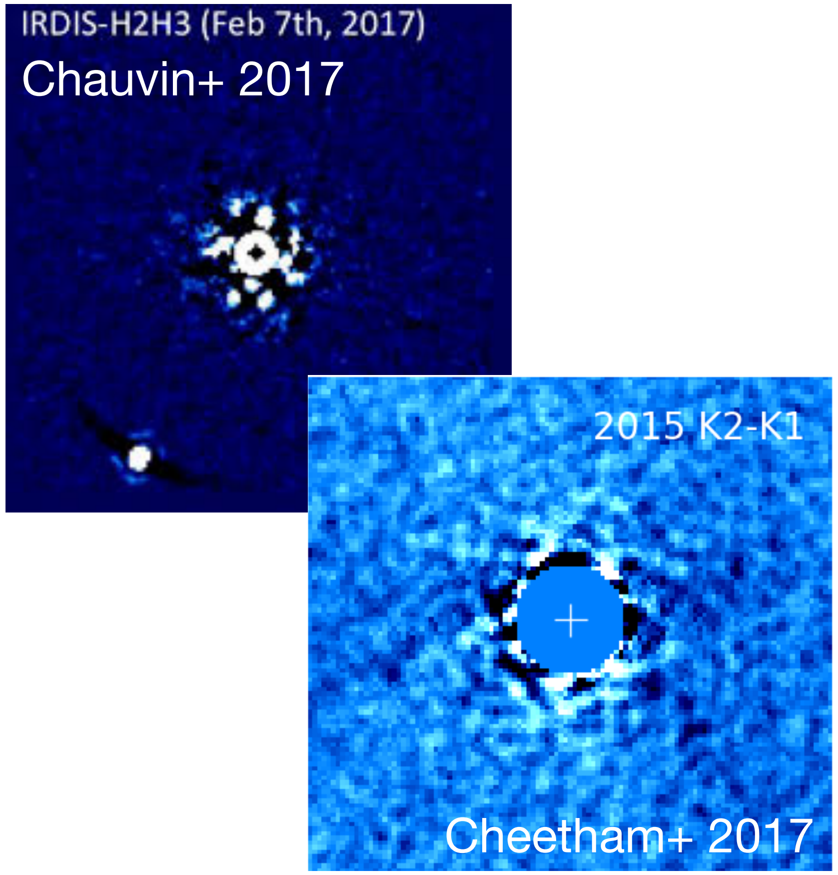


Lagrange+ 2014

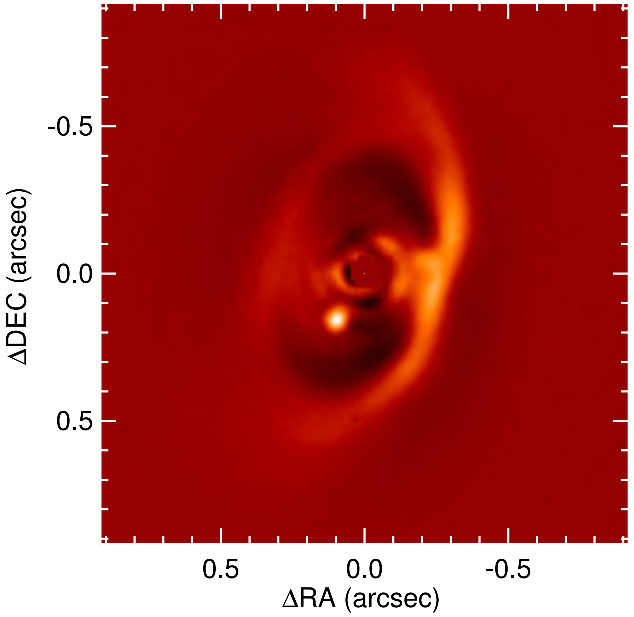
THE KERNEL APPROACH



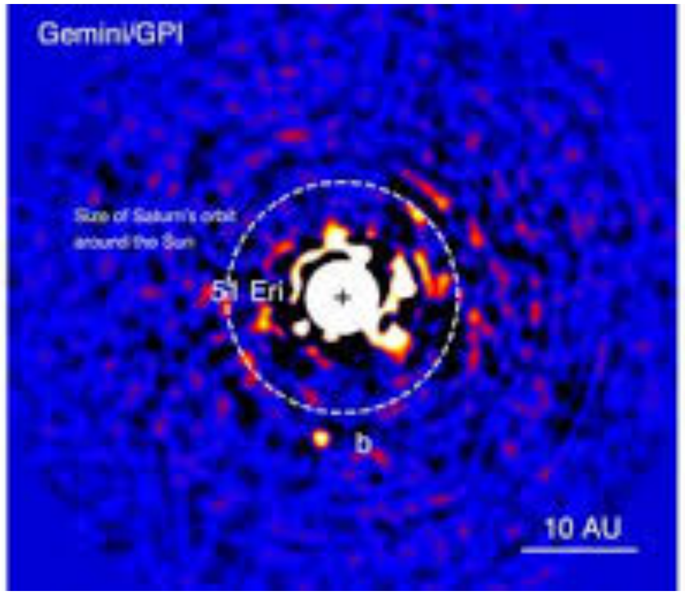




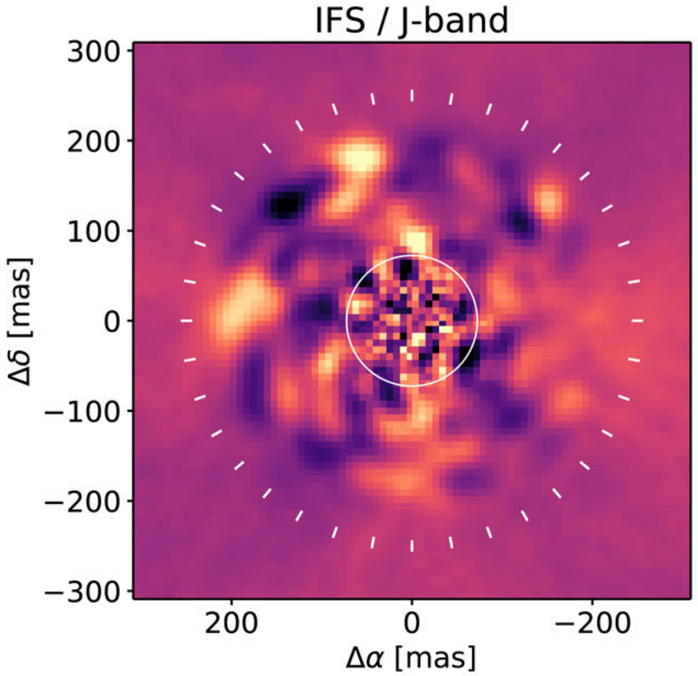
Difficult to detect at <1 as



PDS70, SPHERE
Muller et al. 2018

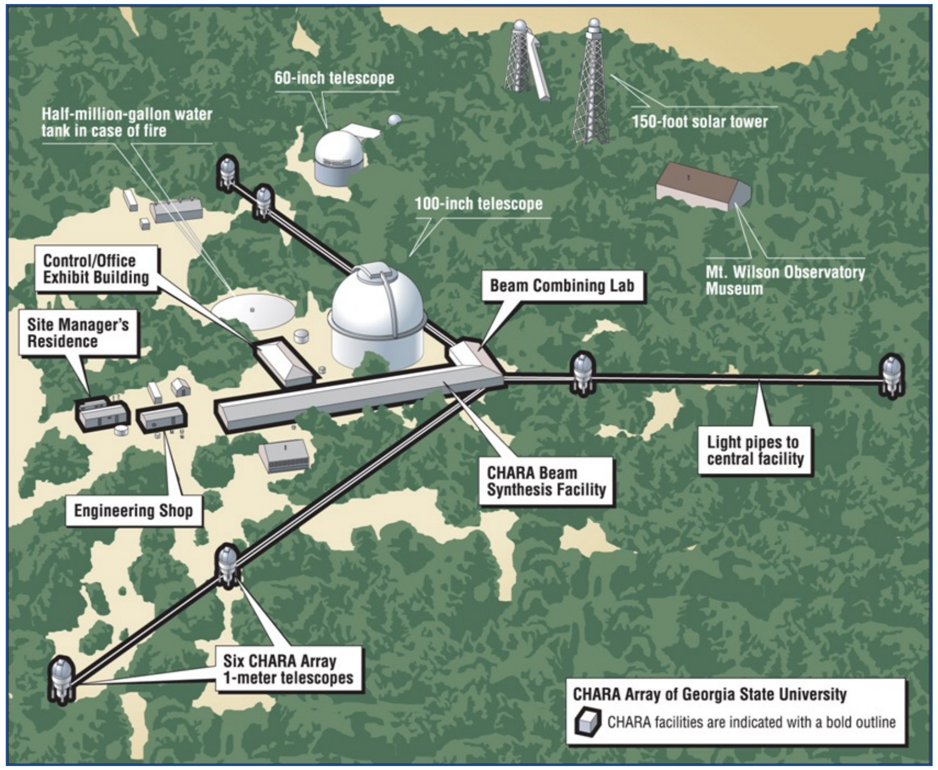


51 Eri, GPI
Macintosh et al. 2015

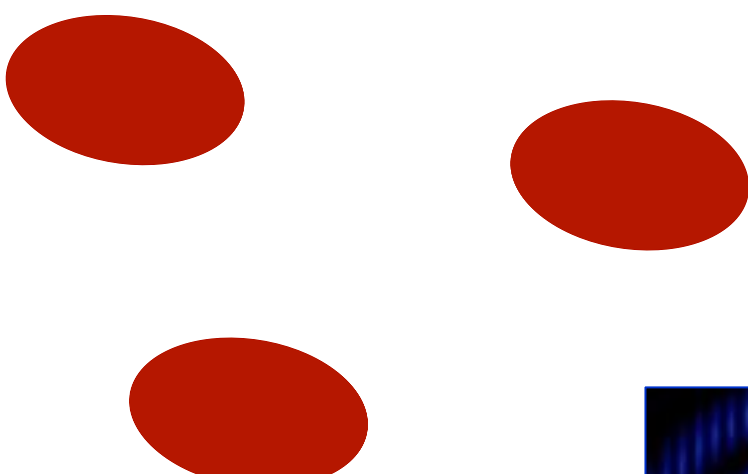


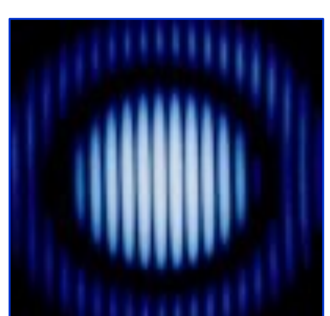
HD169142, SPHERE
Ligi+ 2018

THE KERNEL PHASE PRINCIPLE



Transformation of a 1-dish telescope into an interferometer





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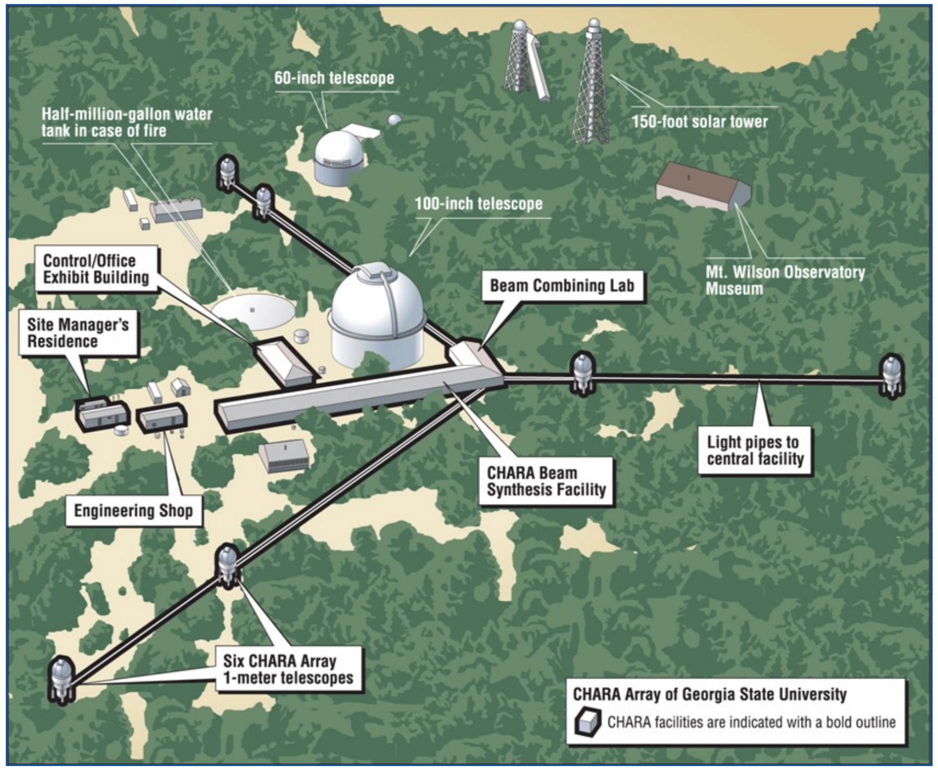

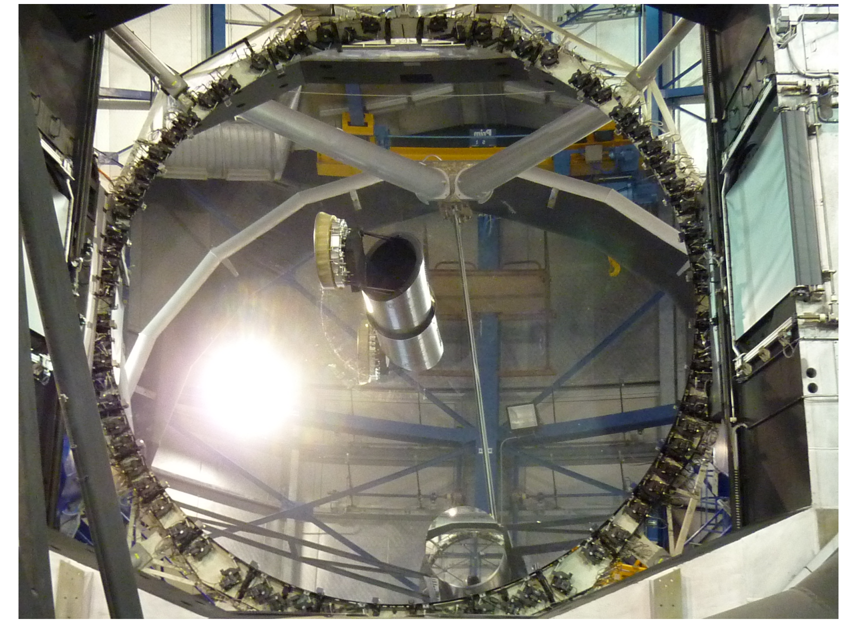

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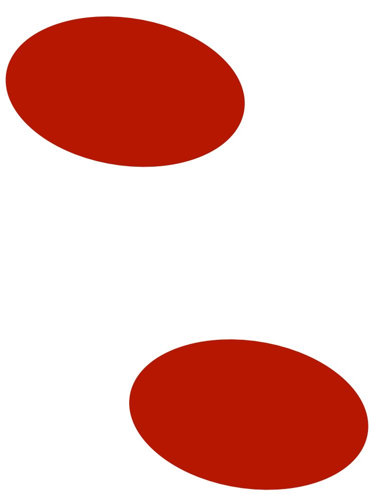
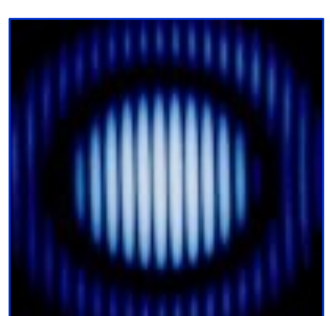
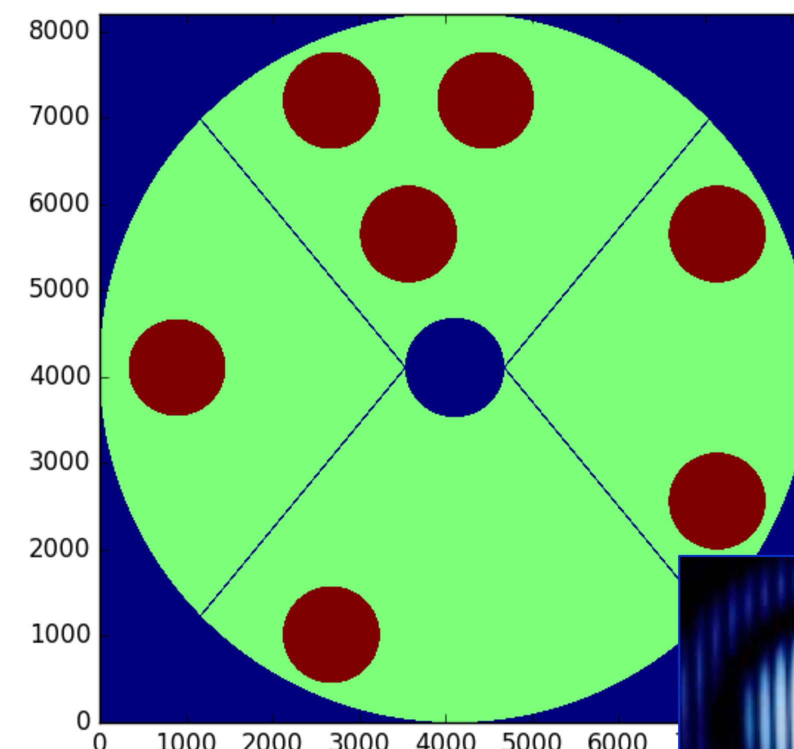
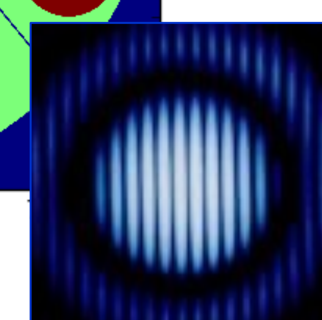
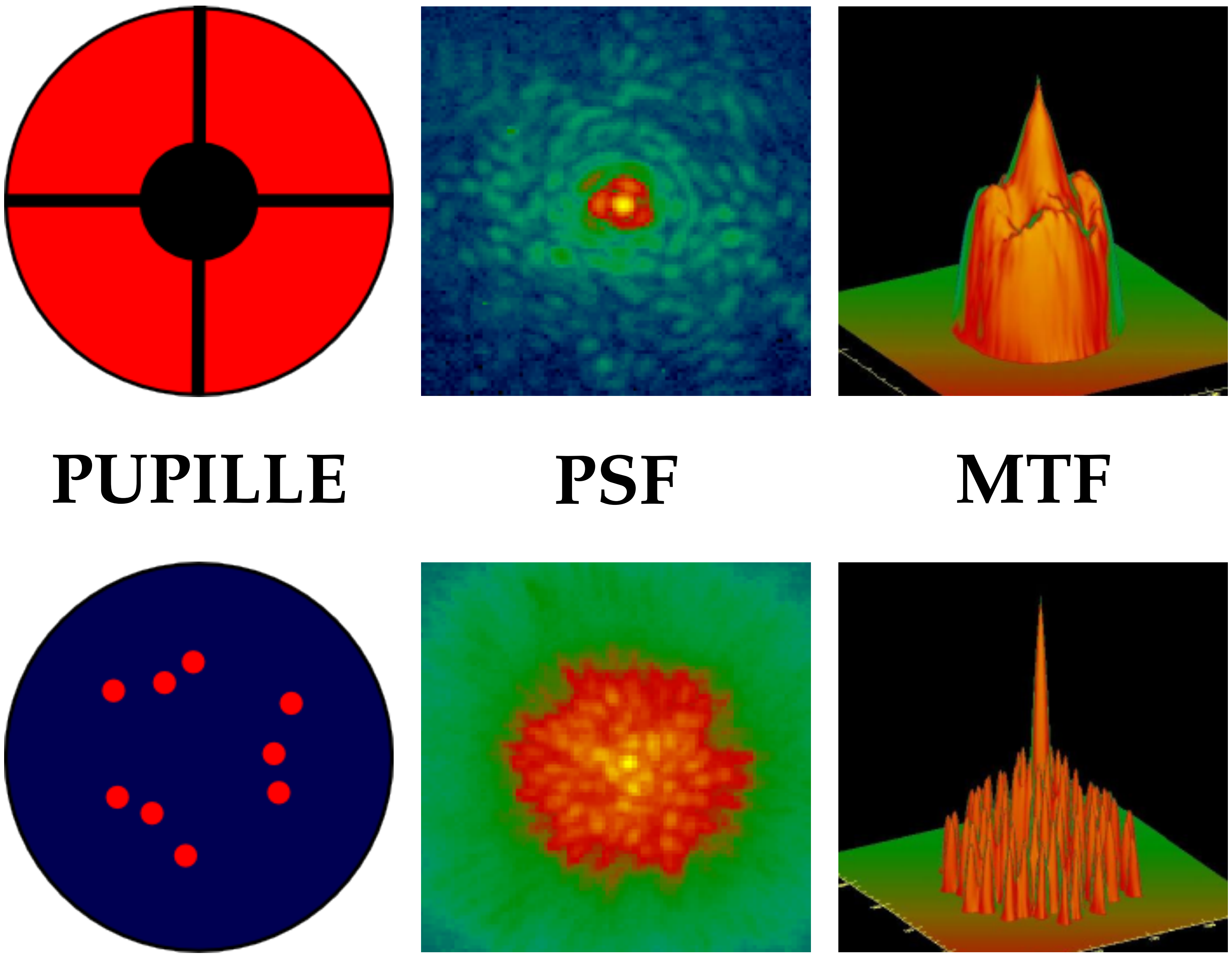








THE KERNEL PHASE PRINCIPLE

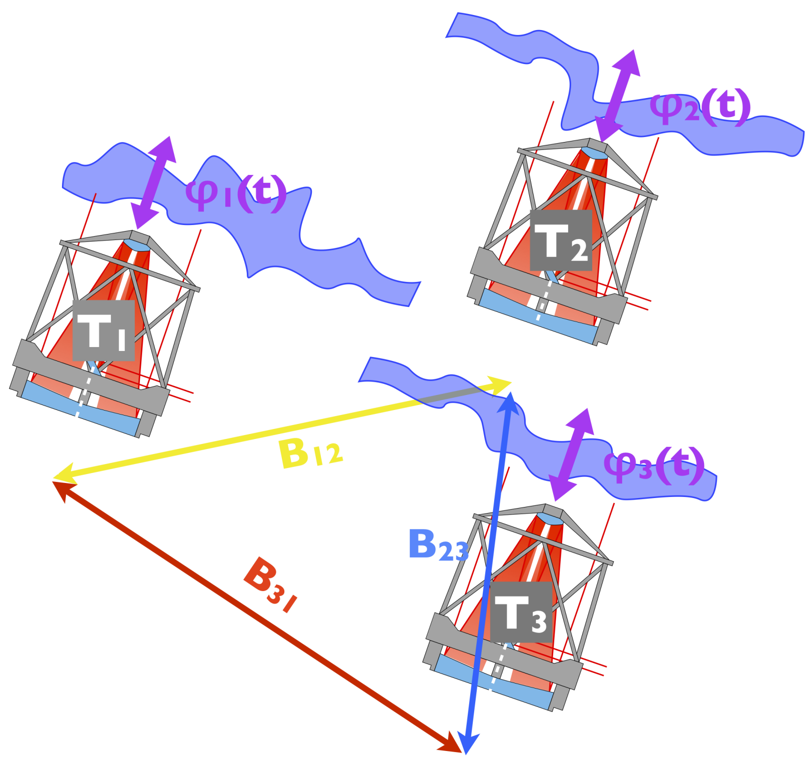


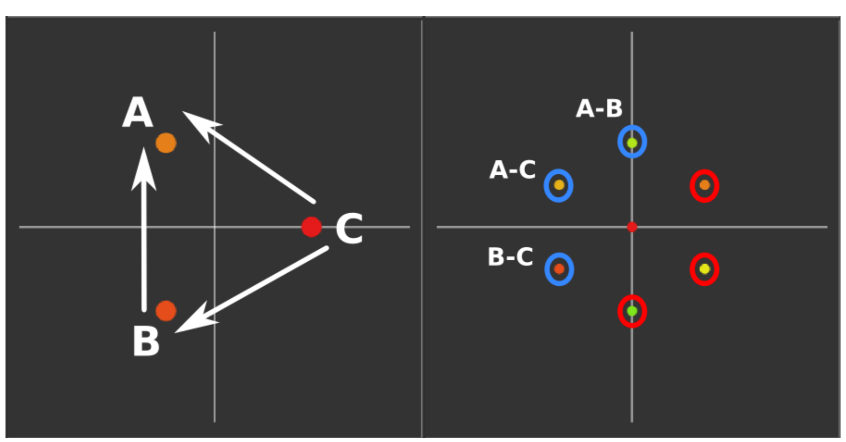
Many residuals due to the correction of AO.

« Clean » visibility.

F. Martinache HDR

THE KERNEL PHASE PRINCIPLE





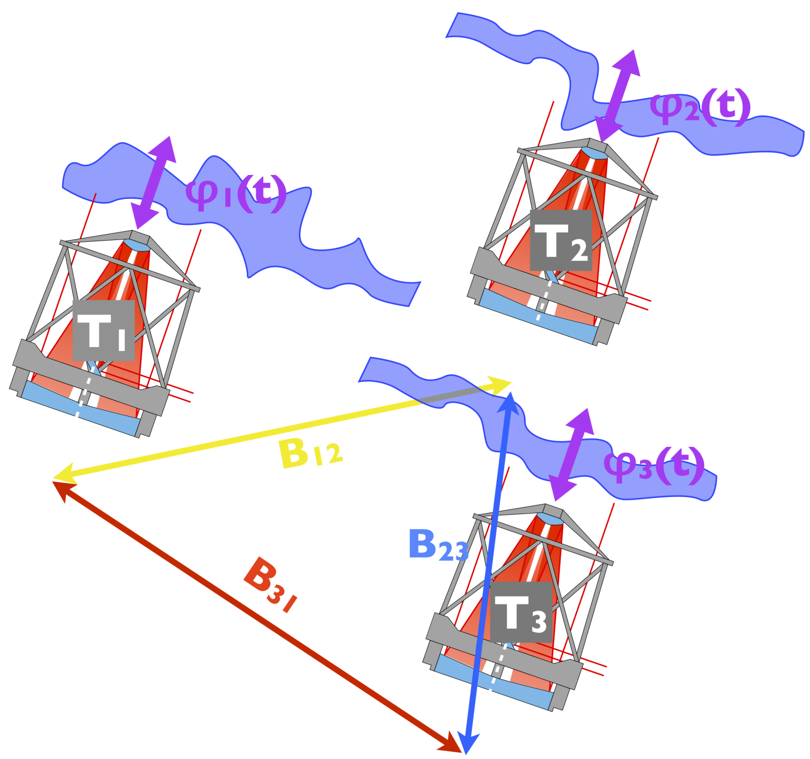
Closure phase

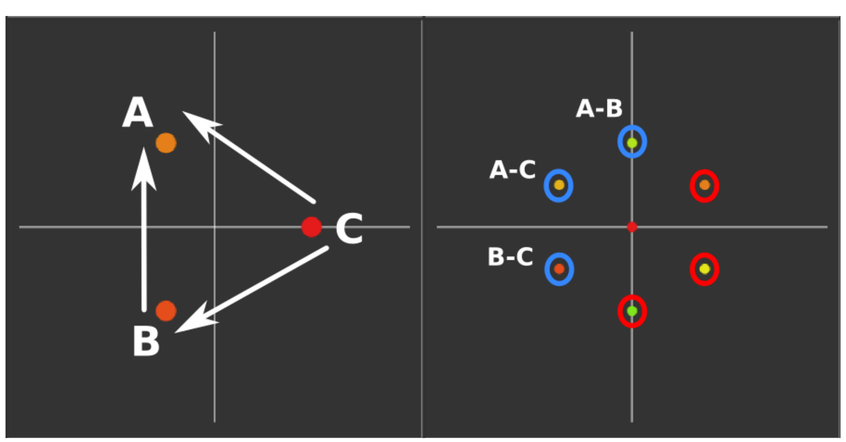
$$\begin{aligned}
\Phi(A-B) &= \Phi_O(A-B) + (\varphi_A - \varphi_B) \\
\Phi(A-C) &= \Phi_O(A-C) + (\varphi_A - \varphi_C) \\
\Phi(B-C) &= \Phi_O(B-C) + (\varphi_B - \varphi_C).
\end{aligned}$$

Measured Expected Piston

F. Martinache HDR, Martinache+ 2020

THE KERNEL PHASE PRINCIPLE





Generalization of the Closure phase

$$\Phi = \Phi_O + \mathbf{R}^{-1} \cdot \mathbf{A} \cdot \varphi$$

$$\mathbf{K} \cdot \mathbf{R}^{-1} \cdot \mathbf{A} = 0.$$

A Baseline mapping matrix
(subapertures + baselines)

R Redundancy matrix
(number of subapertures contributing to the phase of one baseline)

$\longrightarrow$

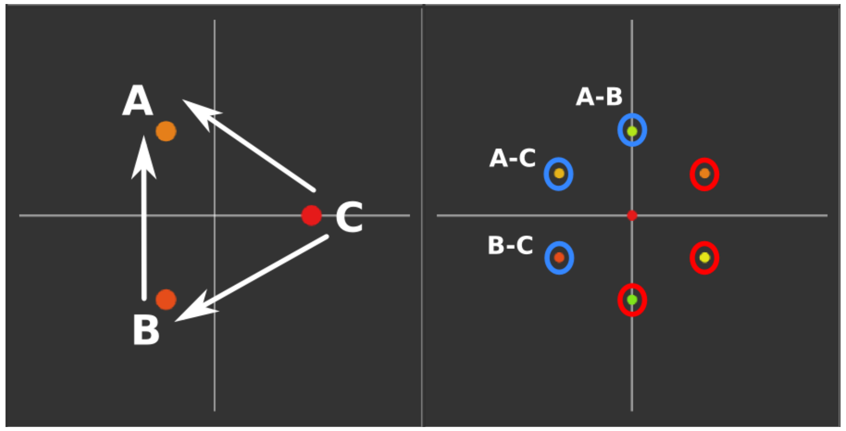
Phase transfert matrix
$\mathbf{R}^{-1}.\mathbf{A}$
(description of the propagation of pupil phase aberration into the Fourier plane)

Kernel-phase **K**

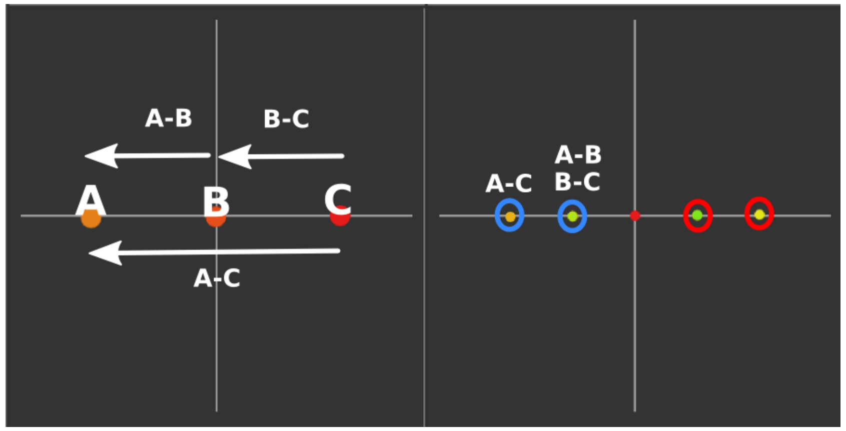
Projection of the Fourier phase into a subspace theoretically untouched by residual aberrations.

F. Martinache HDR, Martinache+ 2020

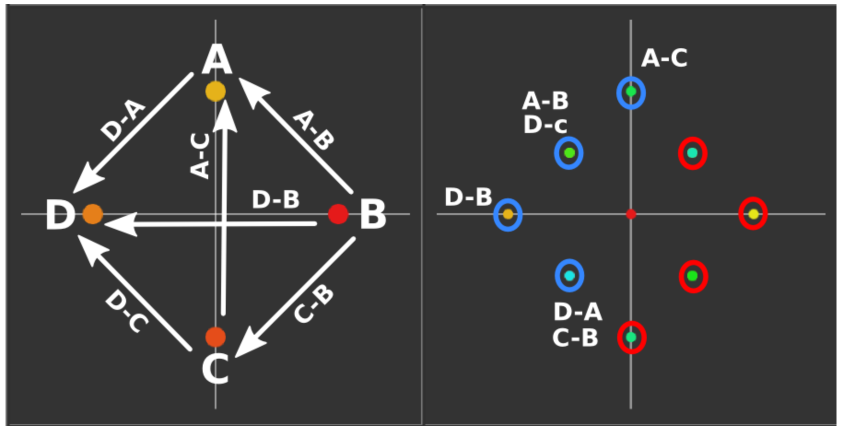
THE KERNEL PHASE PRINCIPLE



Non redundancy



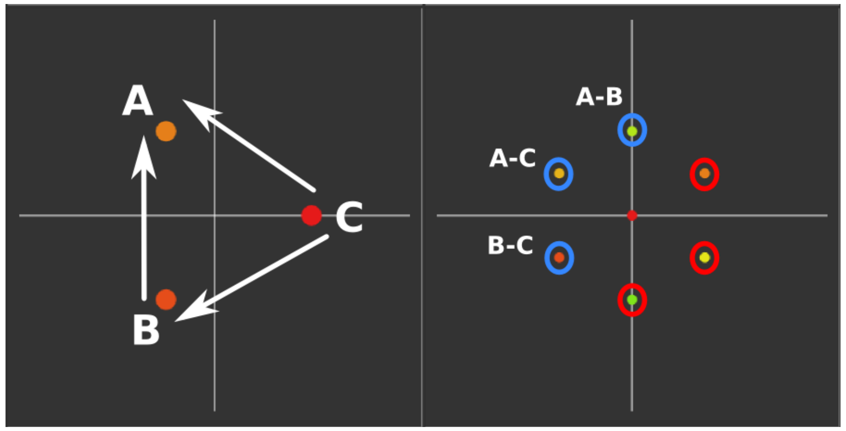
Redundancy:
repeated baseline
(distance+orientation)



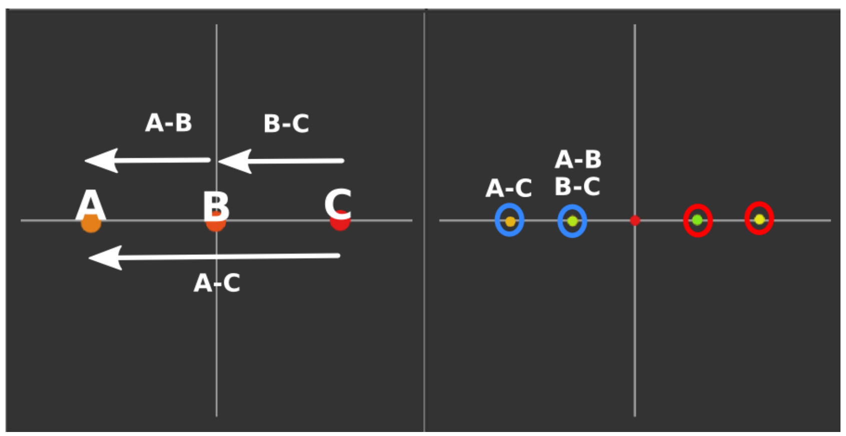
Redundancy

HDR F. Martinache

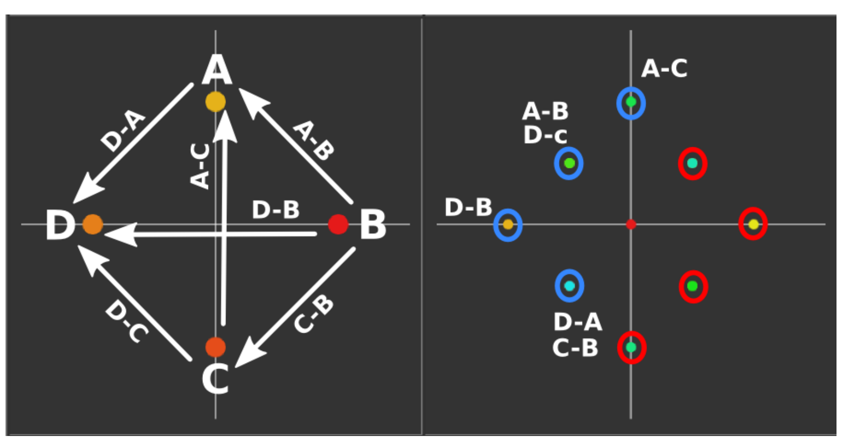
THE KERNEL PHASE PRINCIPLE



Non redundancy



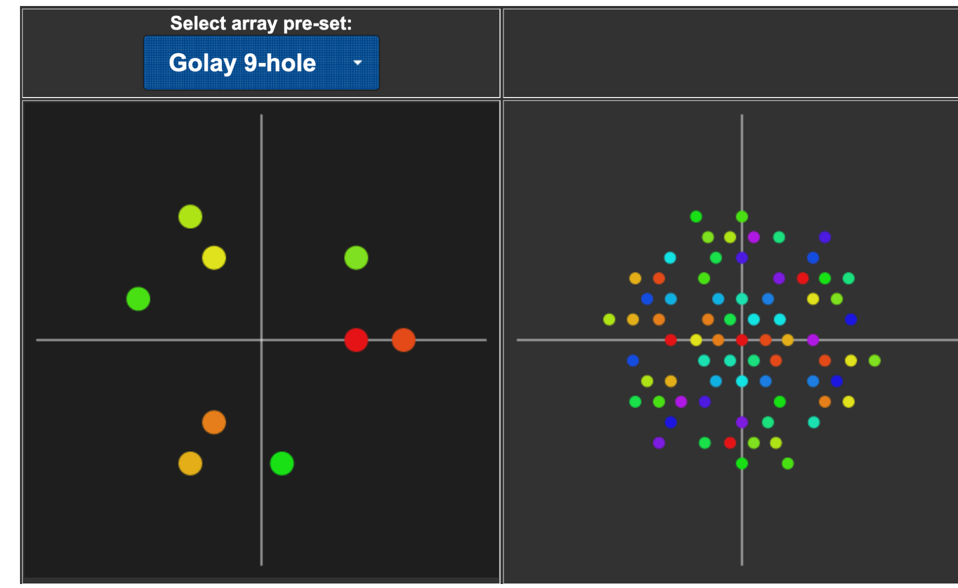
Redundancy:
repeated baseline
(distance+orientation)

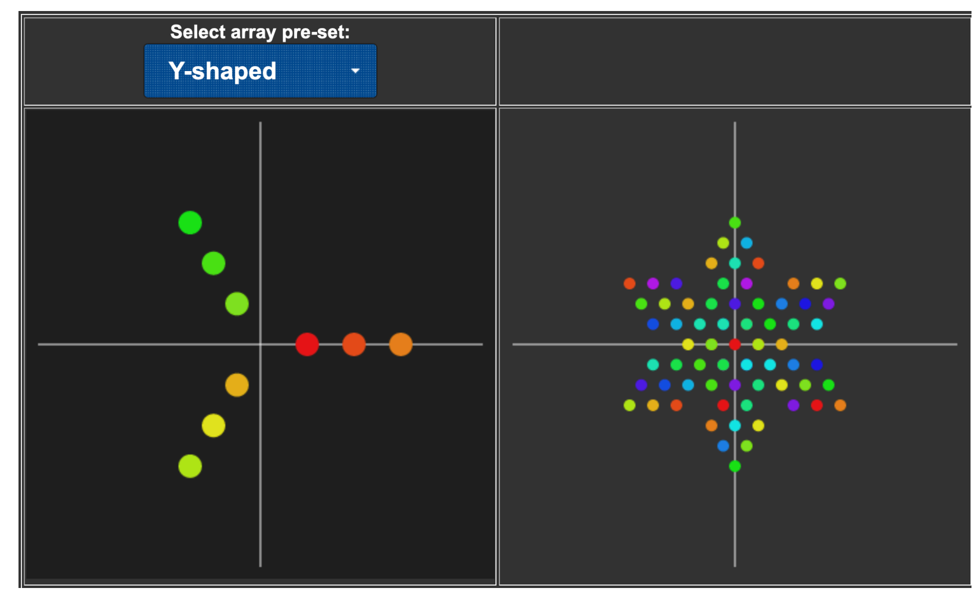


Redundancy

HDR F. Martinache

Examples of masks

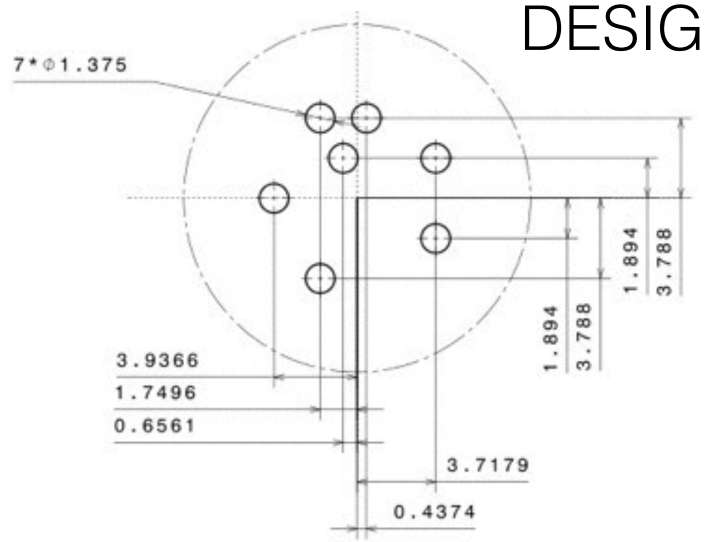


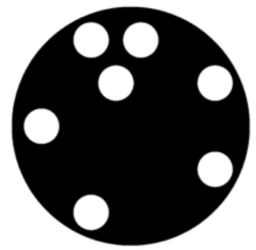


http://frantzmartinache.eu/static/index.html

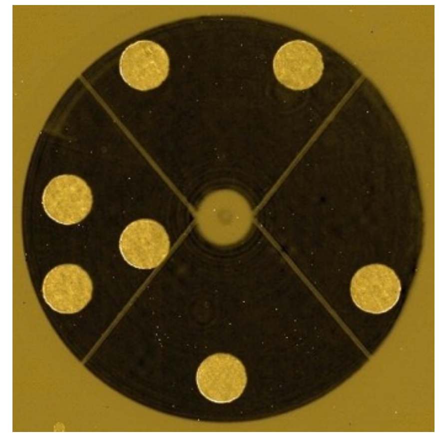
THE KERNEL PHASE: Example of NRM

DESIGN



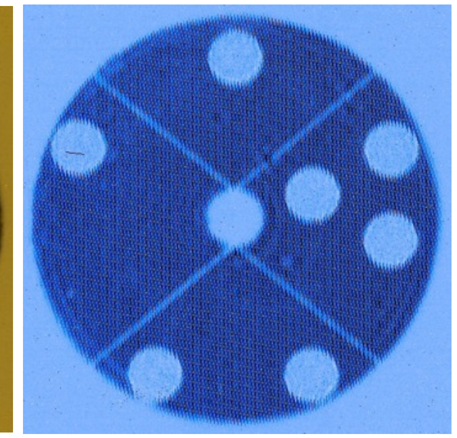


IRDIS



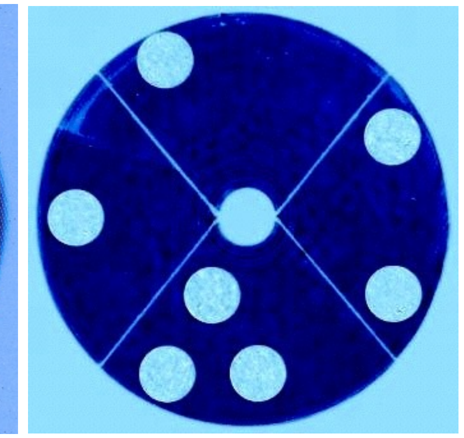
H3

IFS



YJ

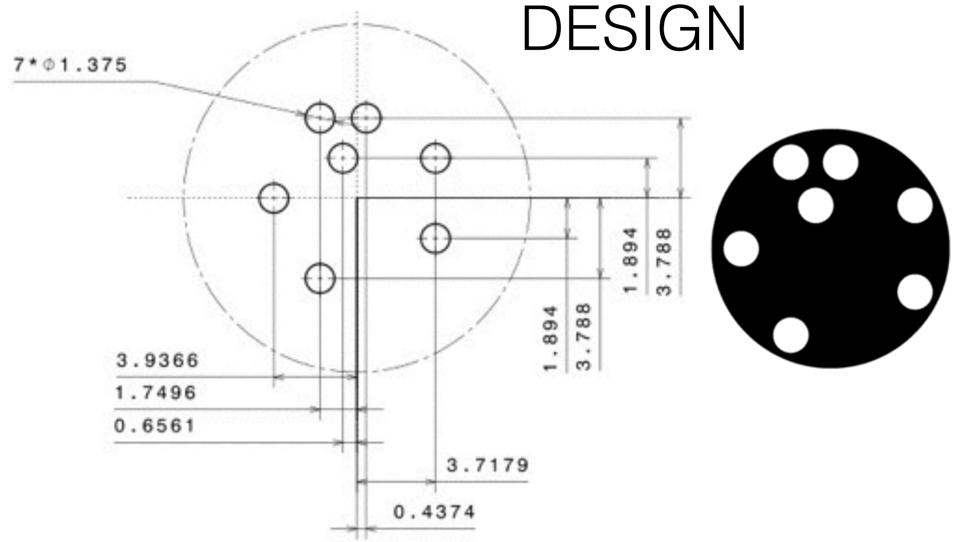
ZIMPOL



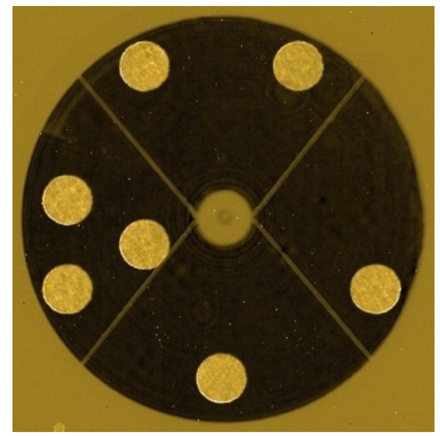
N_R

THE KERNEL PHASE: Example of NRM

DESIGN

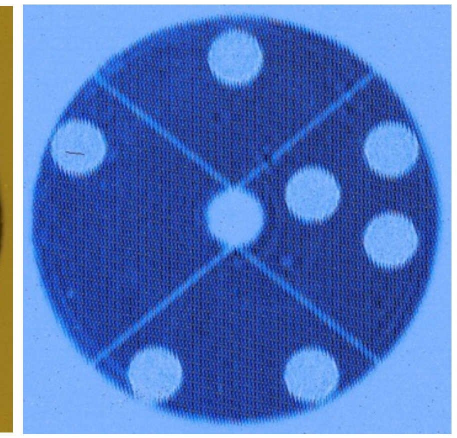


IRDIS



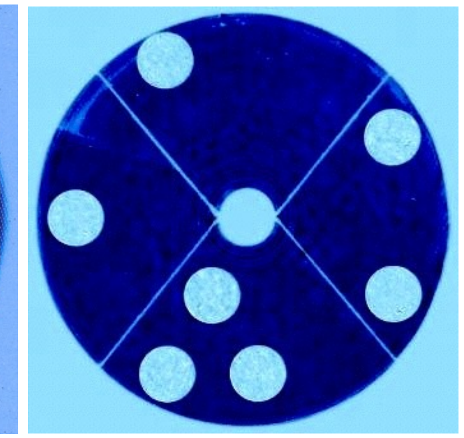
H3

IFS



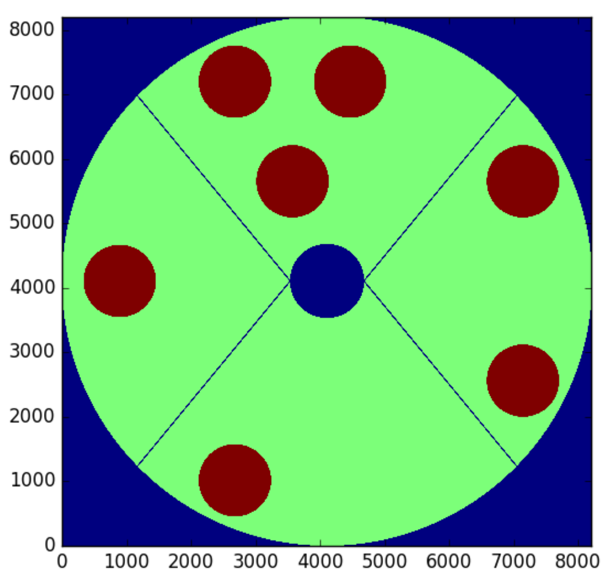
YJ

ZIMPOL



N_R

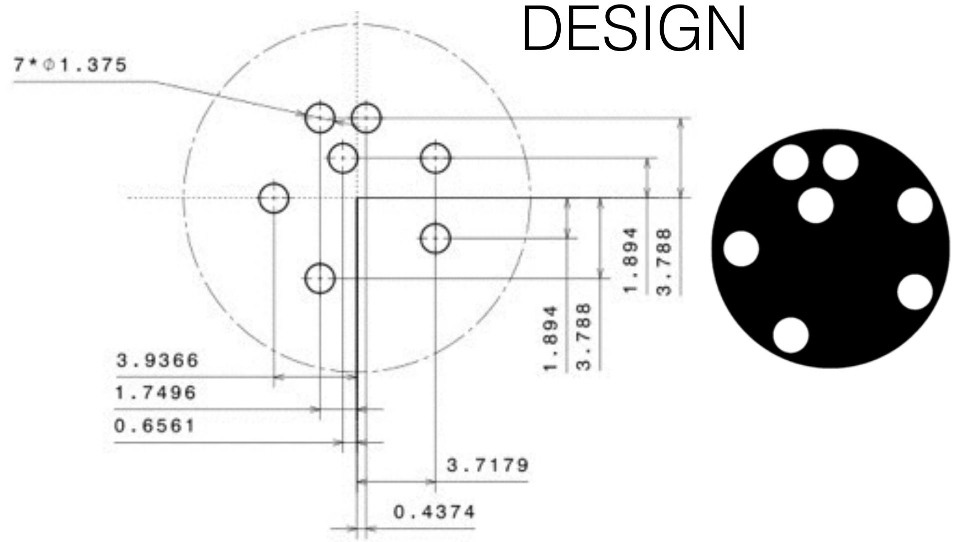
Model of the mask



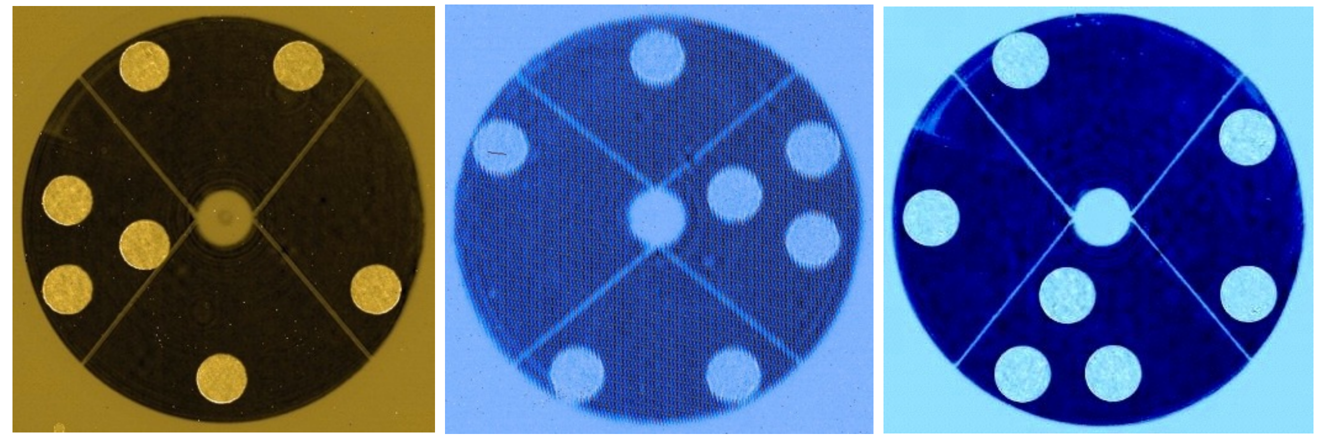
KERNEL erc

THE KERNEL PHASE: Example of NRM

DESIGN

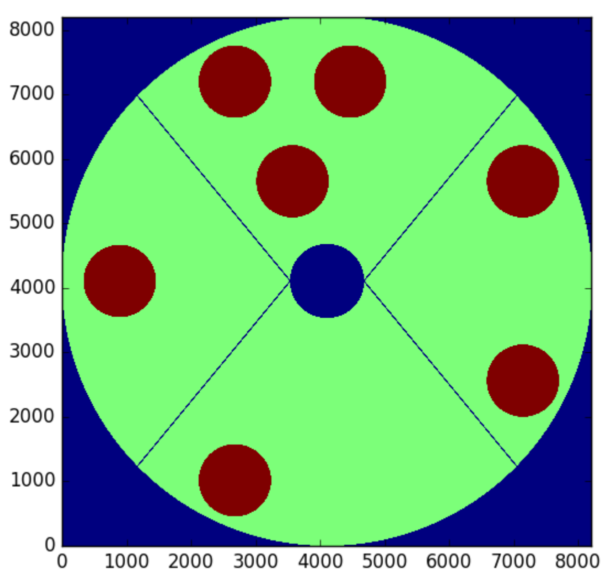


IRDIS IFS ZIMPOL

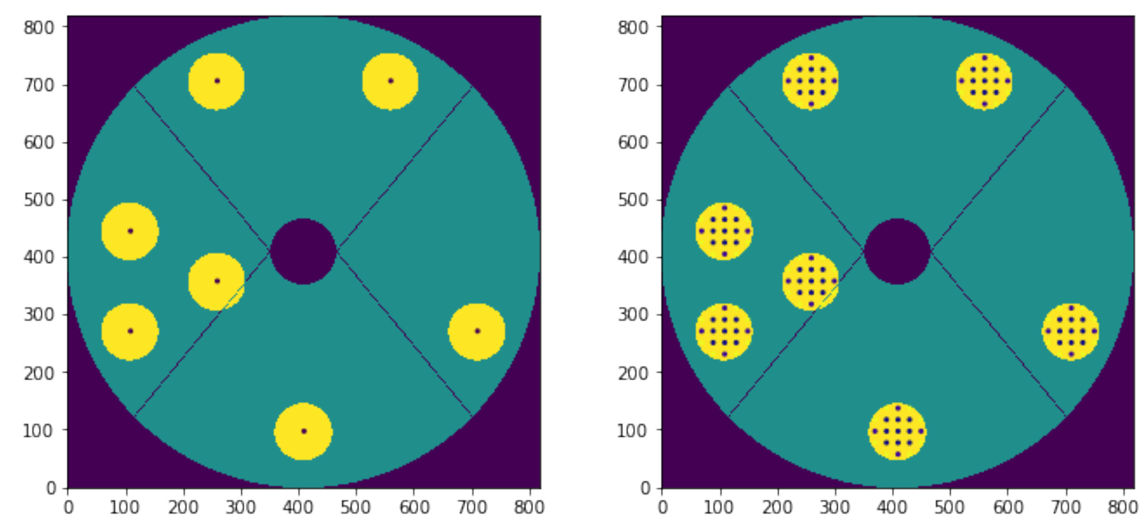


H3 YJ N_R

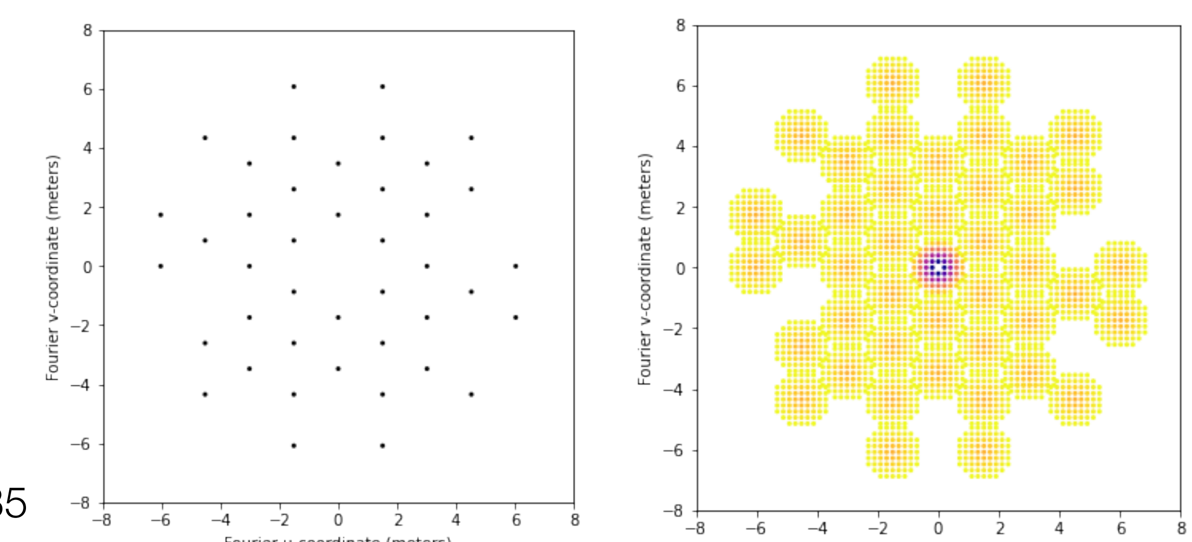
Model of the mask



Model of the aperture



Associated u-v coverage



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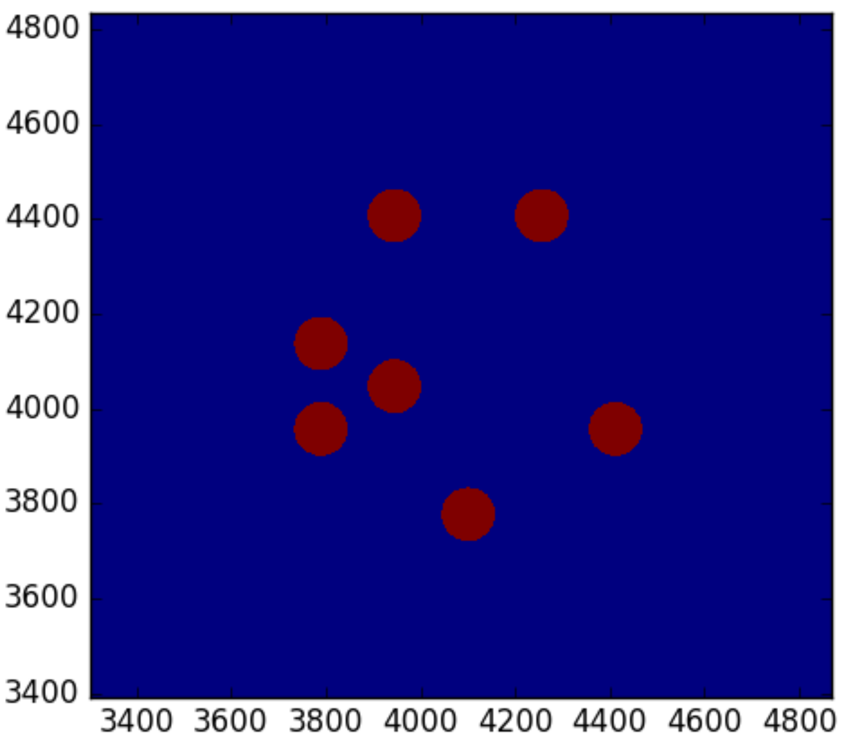
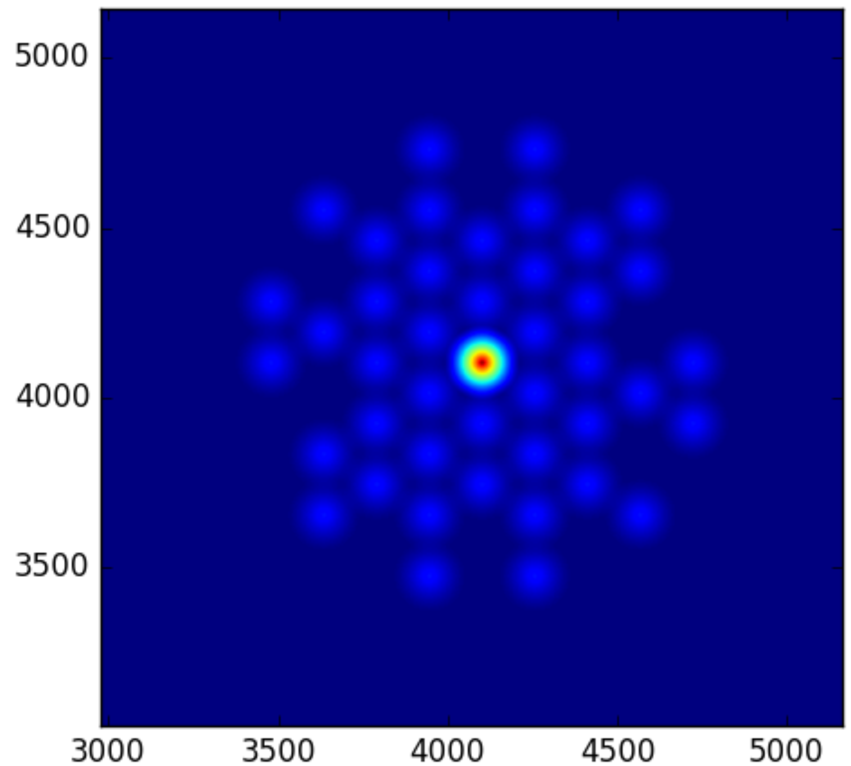
THE KERNEL PHASE: Example of NRM

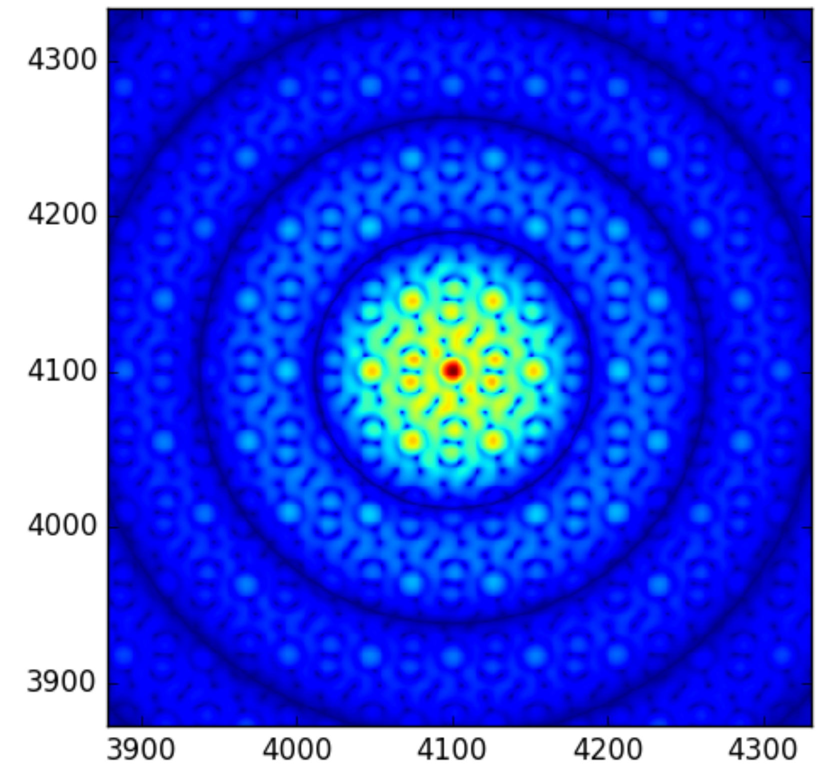
Pupil



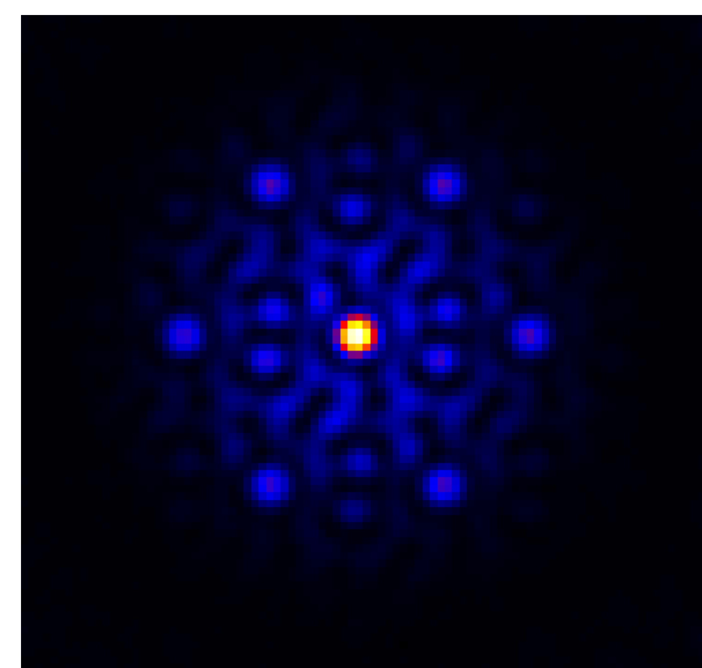
TF



Image



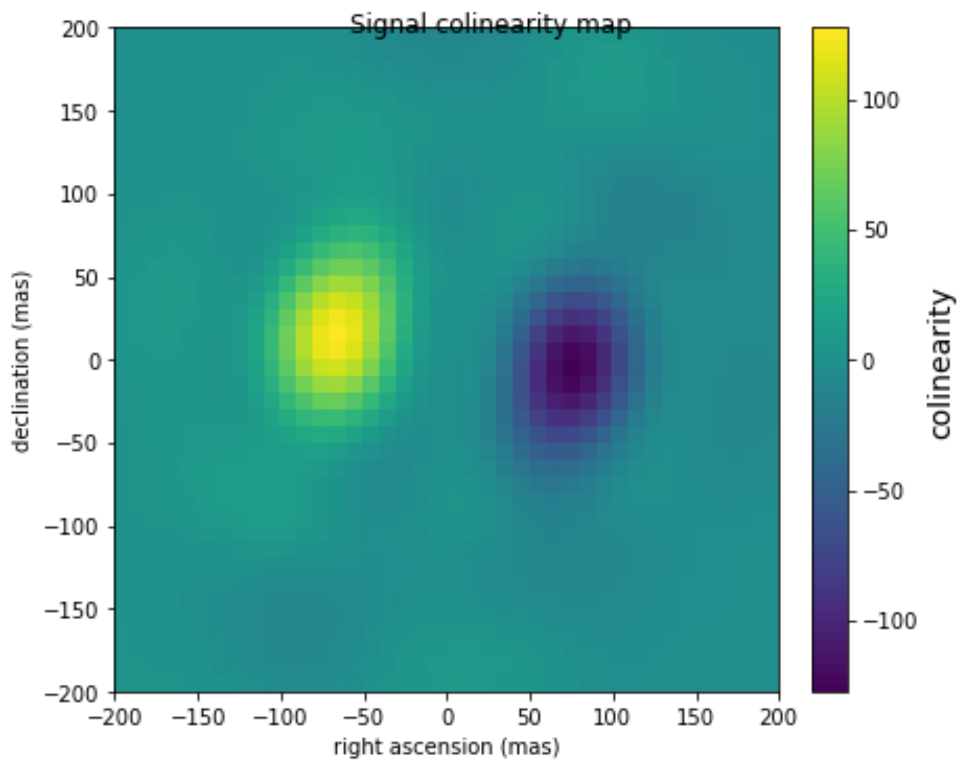
SPHERE data



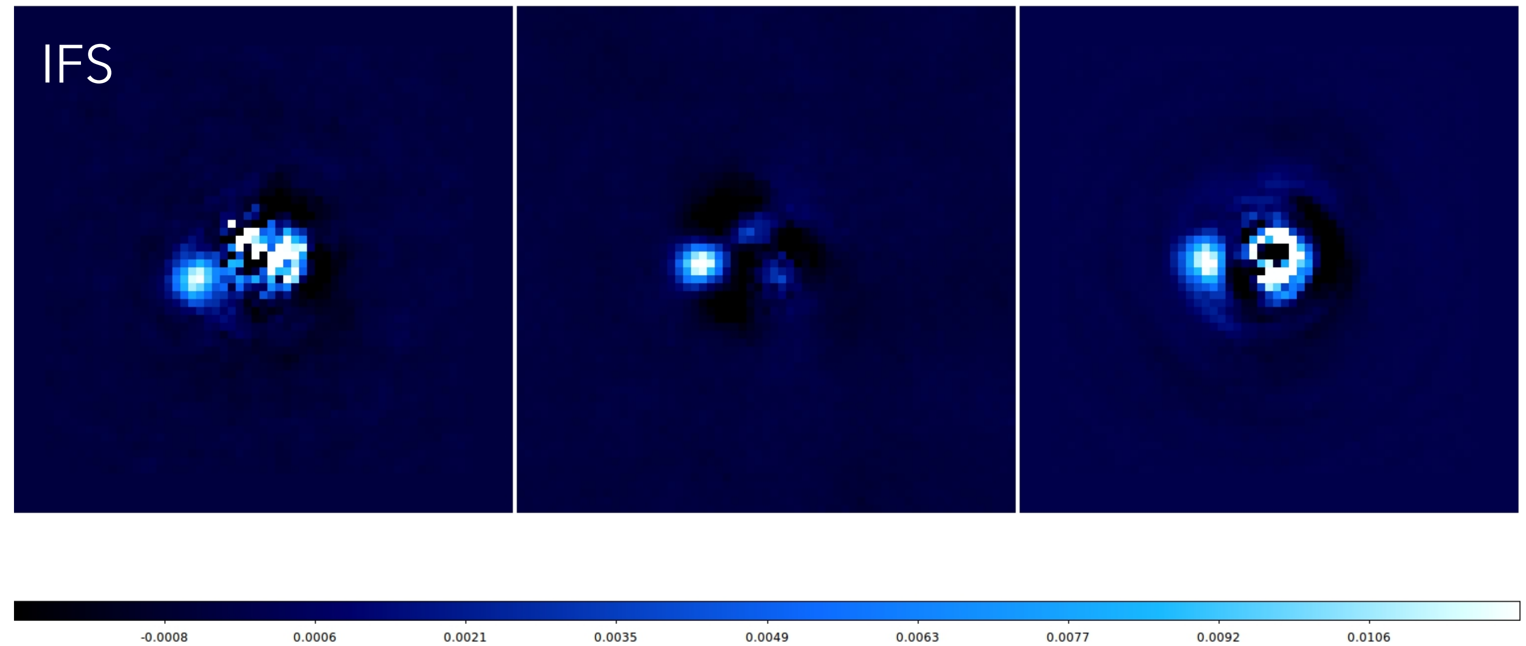
HD142527

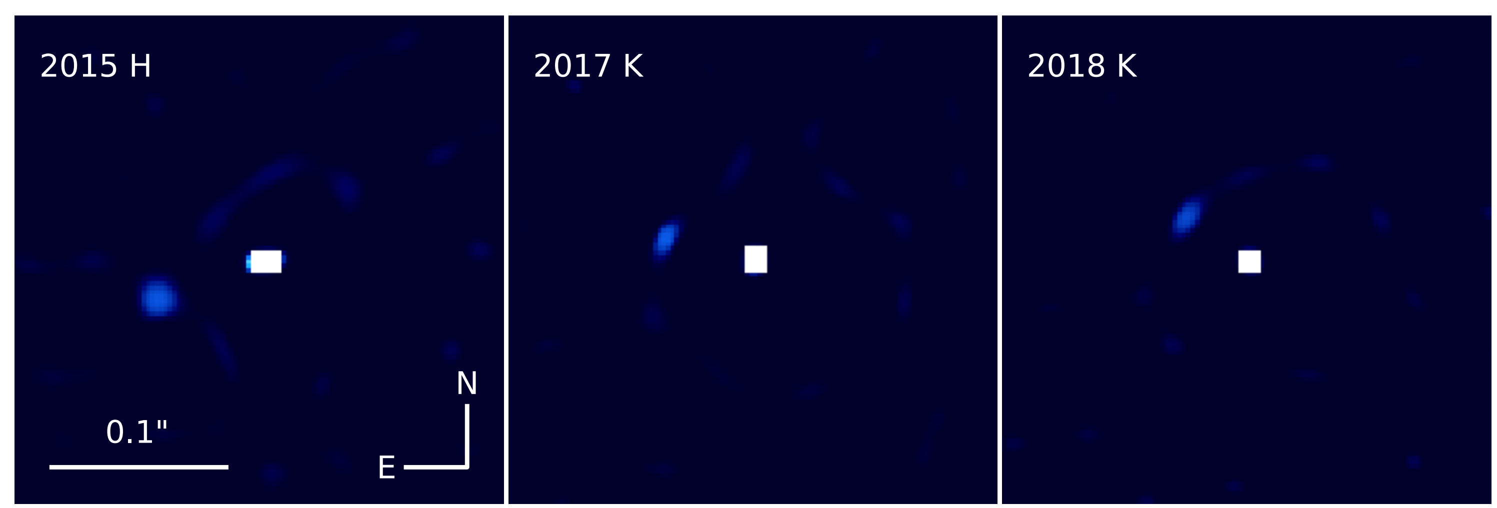
THE KERNEL PHASE: Example of SPHERE data

HD142527 and its companion at 73 mas (11.4 au), Claudi+ 2019



Ligi+, in prep.

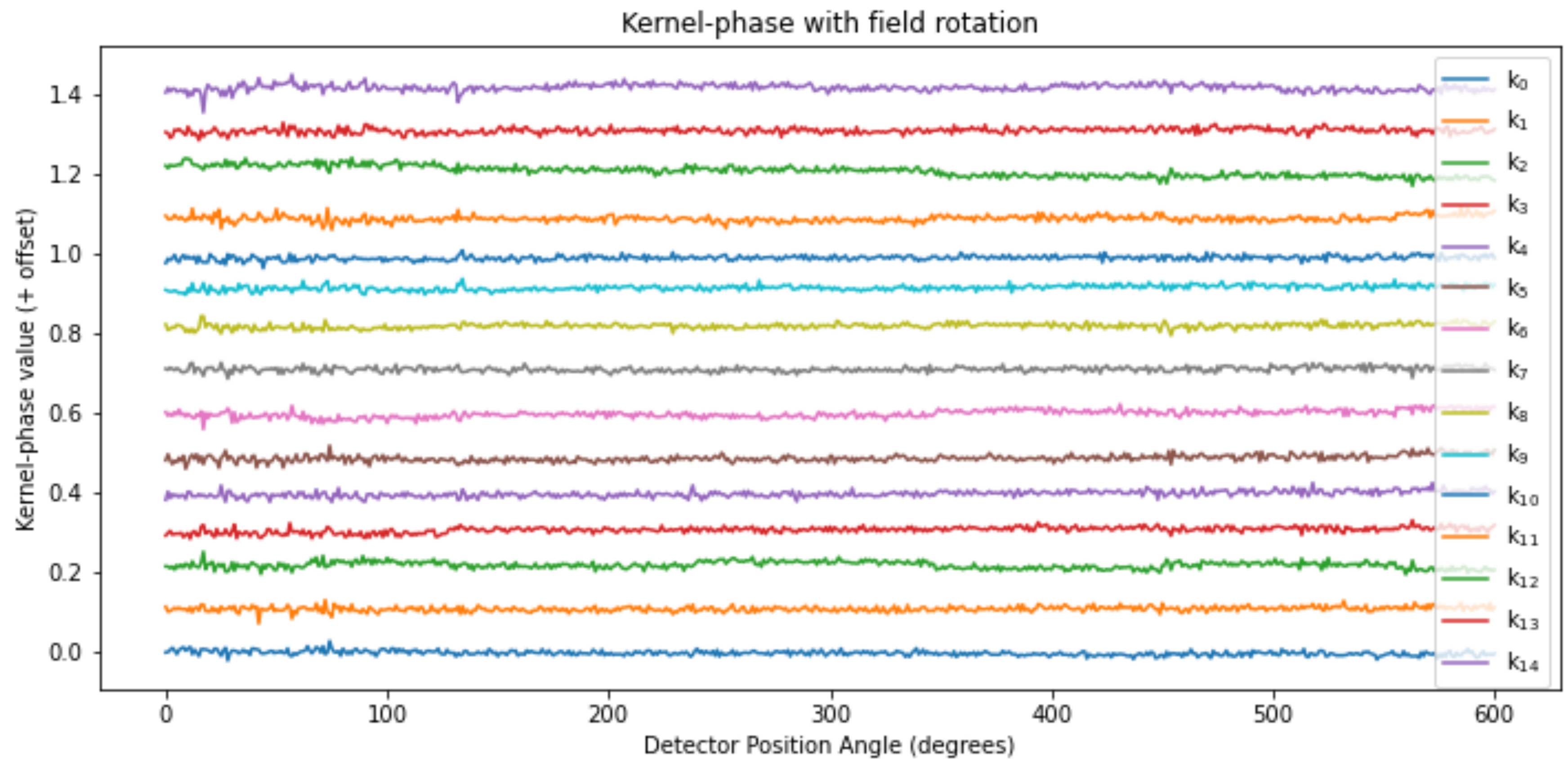




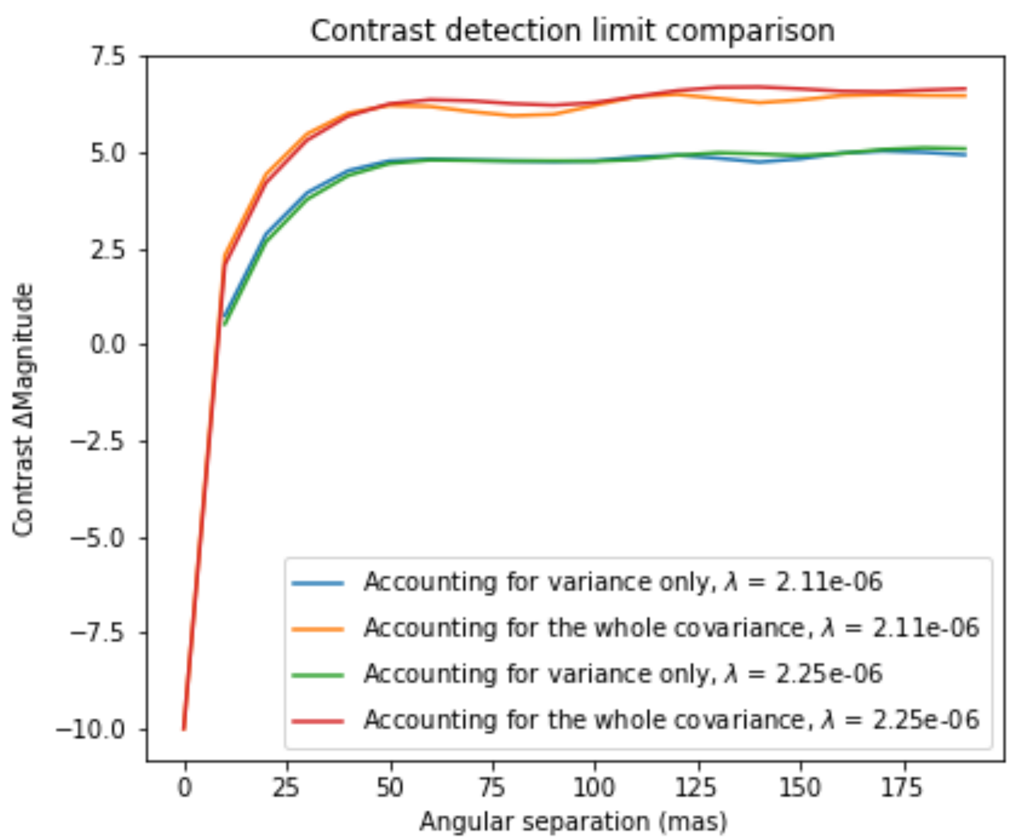
SAM
(reconstruction with MiRA)

THE KERNEL PHASE: Example of SPHERE data

15th first kernels



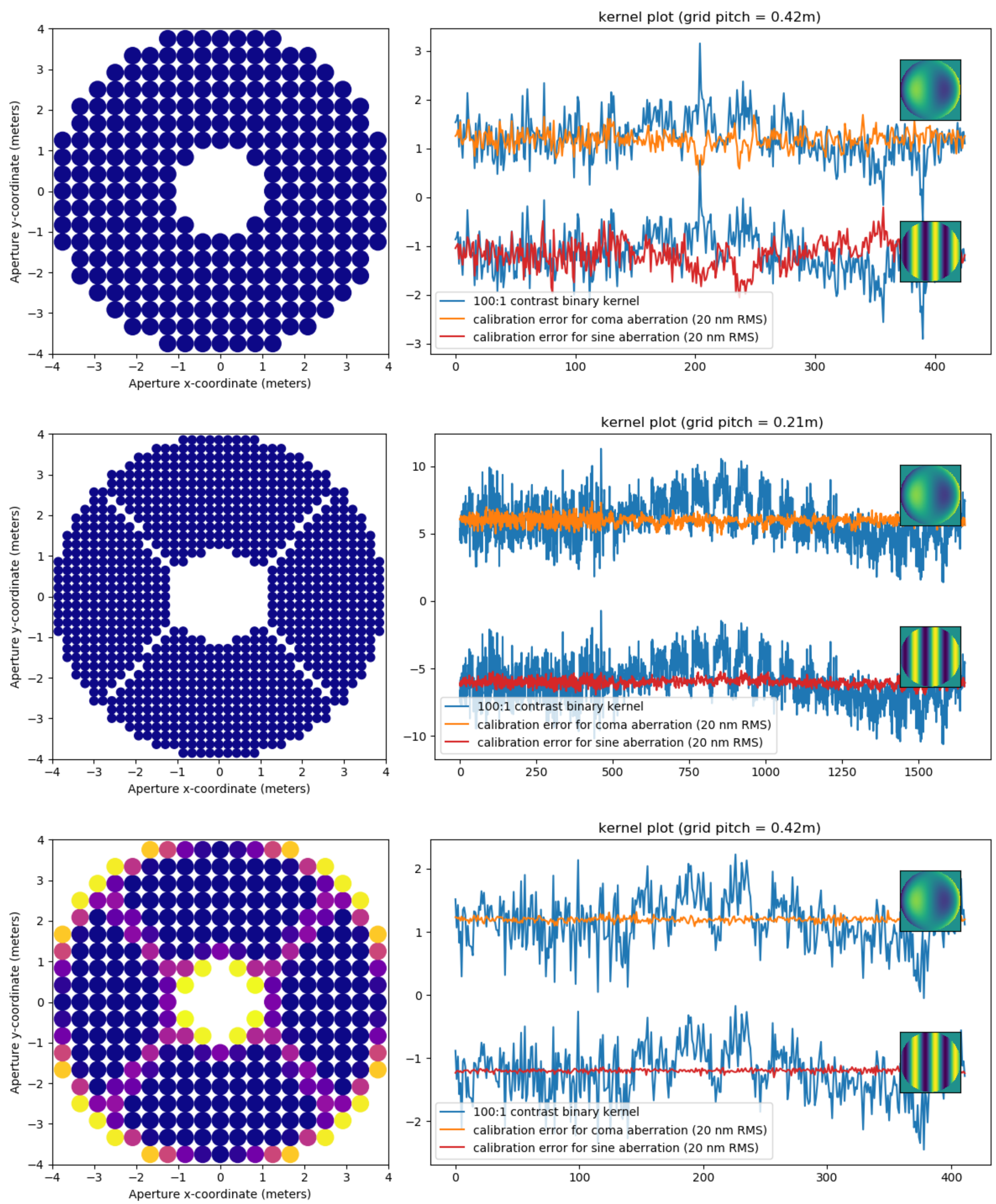
Contrast limits



Ligi+, in prep.

THE KERNEL PHASE: Example of PHARO data

PHARO



Denser aperture model
Transmission model
→ Reduction of the calibration signal

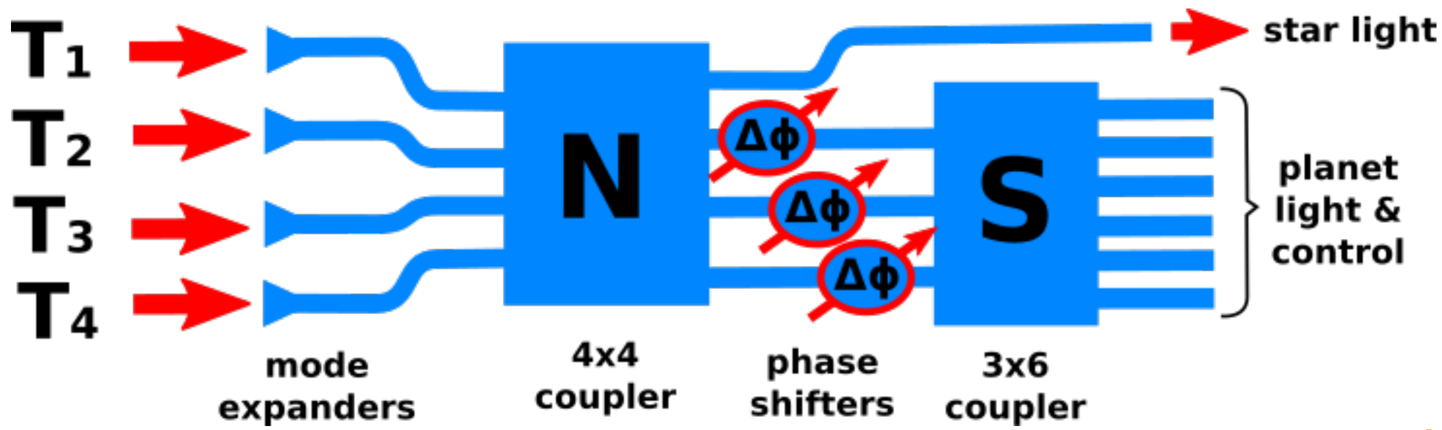
Martinache+ 2020

OUTLINE of the LECTURE

- **What do we know about exoplanets?**
- **Exoplanets and stars: the role of interferometry**
- **The Kernel phase approach**
  Toward the detection of exoplanets with interferometry
- **Going beyond**
  Kernel-nuller, SKA…

The Kernel nuller

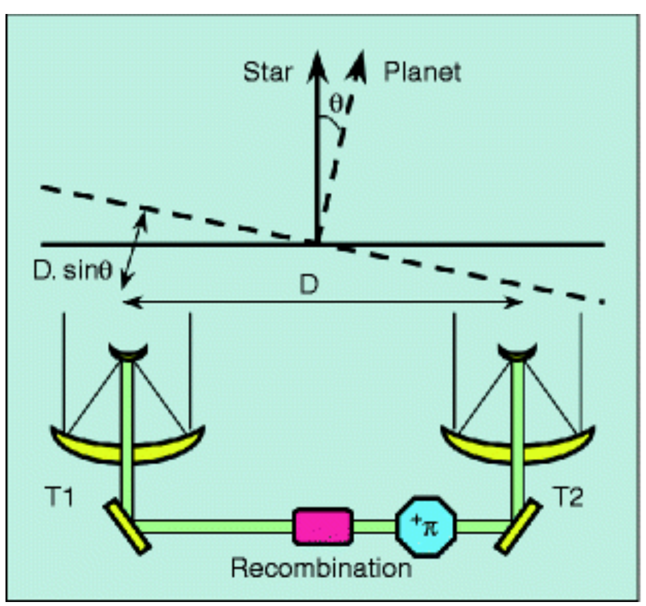
Idea first introduced by Bracewell (1978).

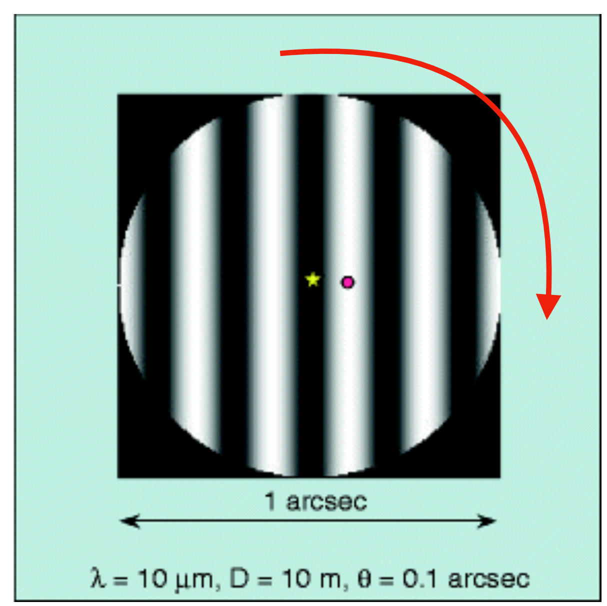


Bright output

Dark output

Where we look at the signal of the planet





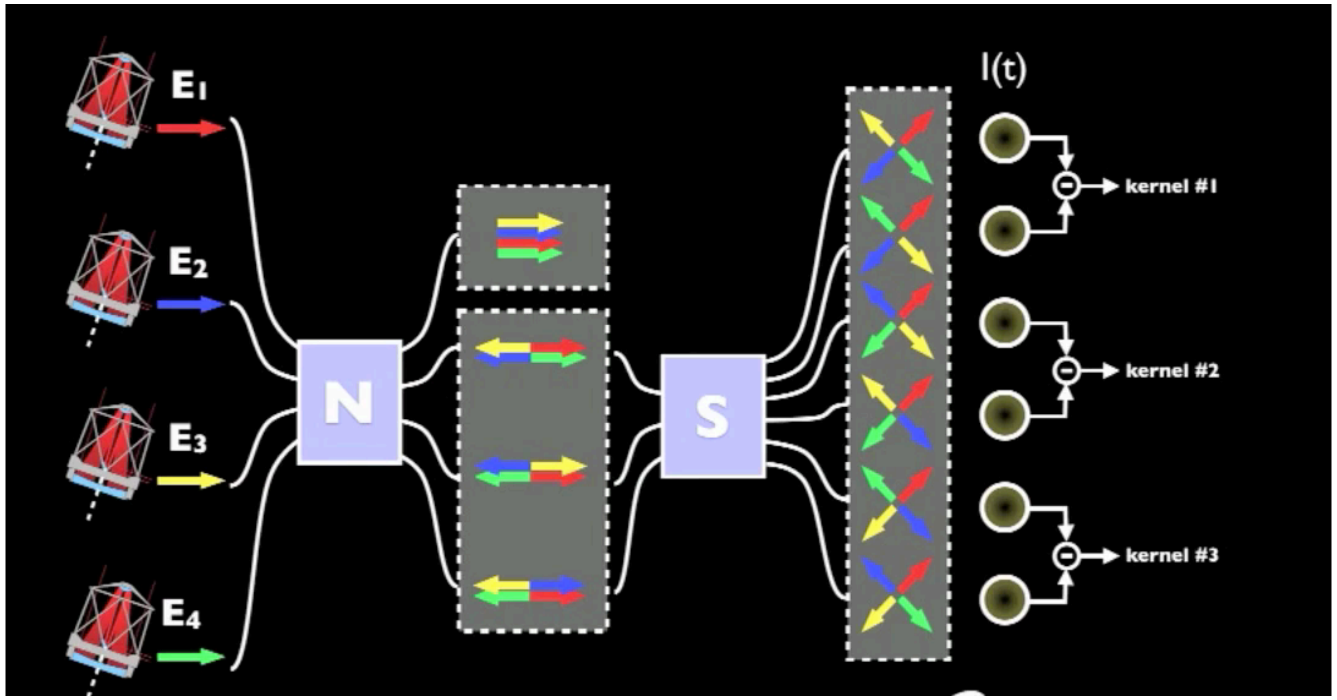
Rotation of the interferometer with the star at the center

- Star constantly nulled
- Modulation of the signal where the planet is

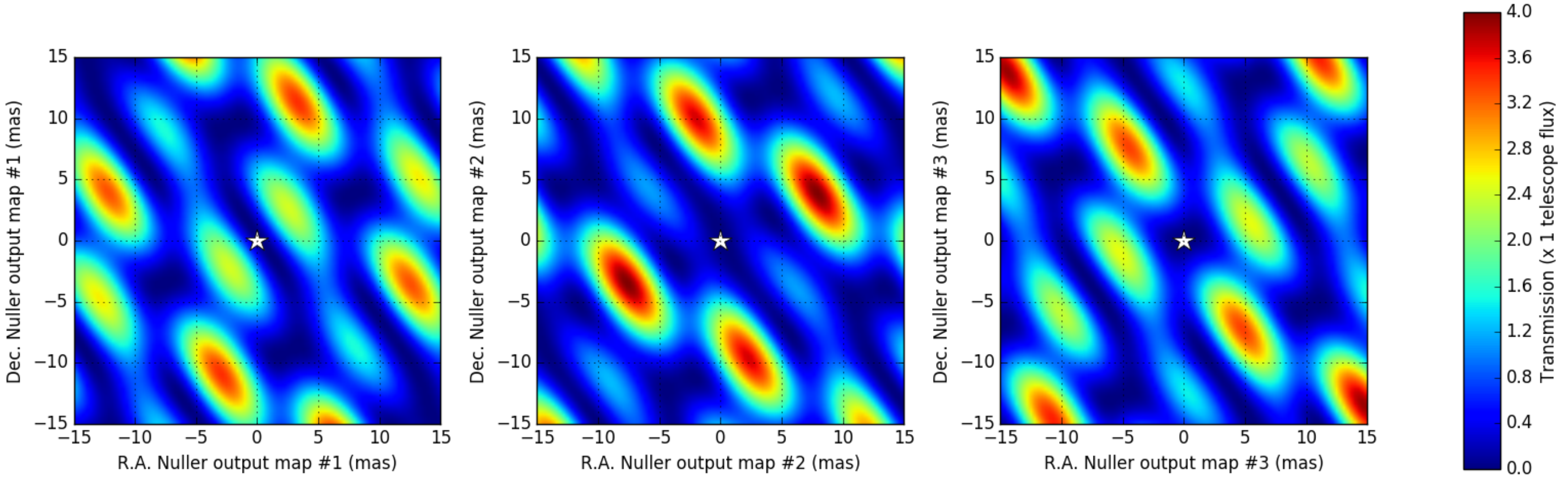
Martinache+ 2018
https://www.youtube.com/watch?v=vn6280hGTL8

The Kernel nuller

Idea first introduced by Bracewell (1978).
Application to the case of the VLTI: 4 telescopes



Kernel « cleaned » from perturbations
Same properties as closure phases

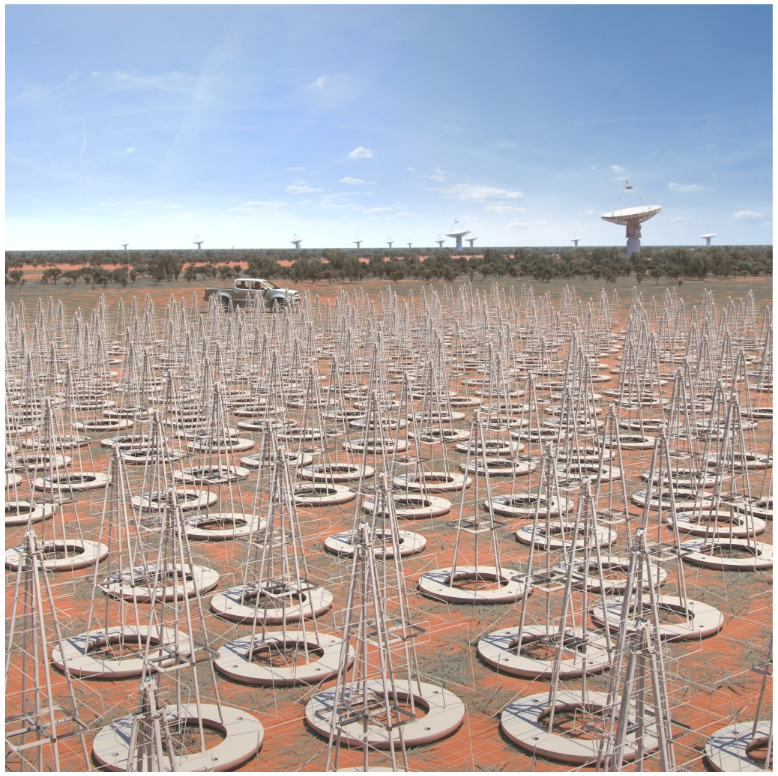


Martinache+ 2018
https://www.youtube.com/watch?v=vn6280hGTL8

KERNEL erc

THE SKA FOR EXOPLANETS


SKA in South Africa


SKA in Australia

(artist impression, www.skatelescope.org)

SKA (Square Kilometer Array): Radio wavelengths interferometer array

« Cradle of life » section

- Detect radio-emission from earth-analogous high-power radars (Siemion+ 2014)
- Magnetic field of exoplanets (aurorae)
- Search for pre-biotic molecules and amino acids
- Grain growth (cm-sized) particules in proto-planetary disks (Hoare+ 2014)

Thank you!

Roxanne Ligi
June 15, 2021