UNIVERSITY OF CAMBRIDGE

Finding planets with astrometry

Mathias Nowak

Gavin Boyle Fellow in Exoplanetary Science,
Institute of Astronomy, University of Cambridge

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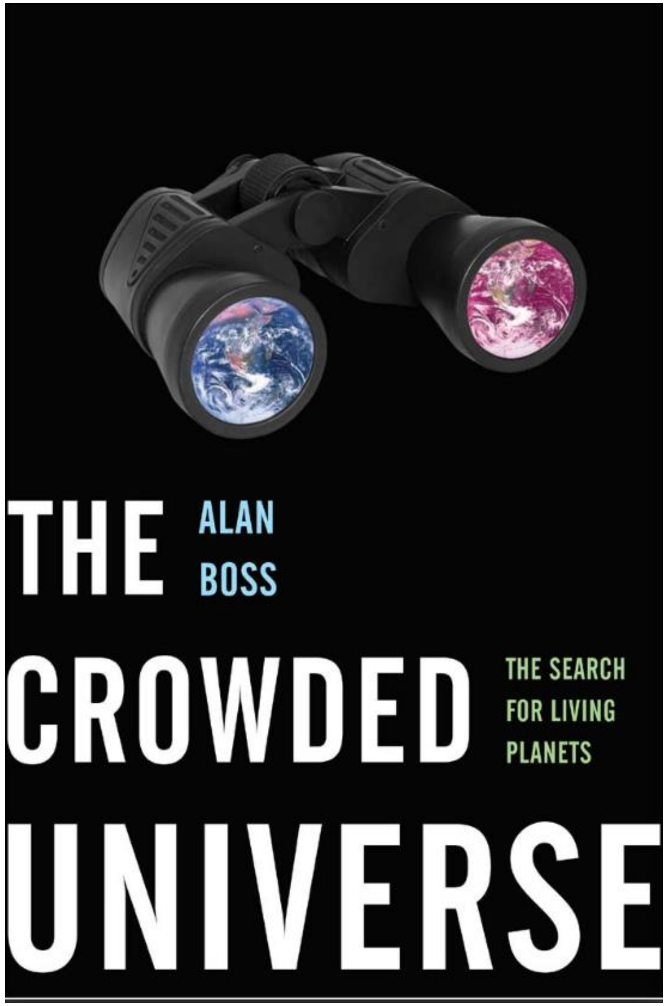
A bad reputation?



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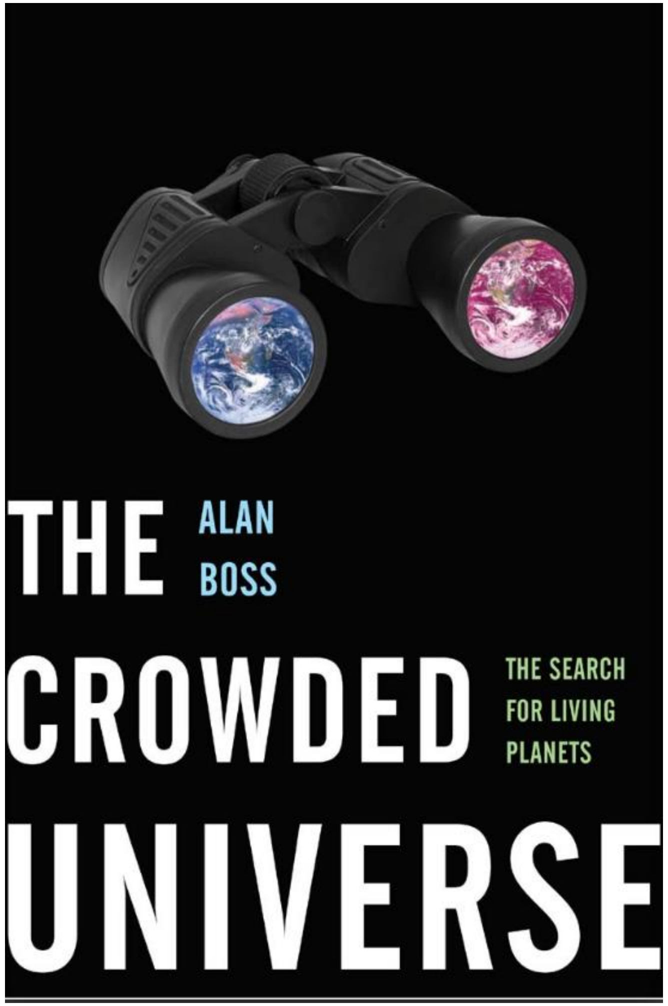

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Alan Boss, "The Crowded Universe", 2009

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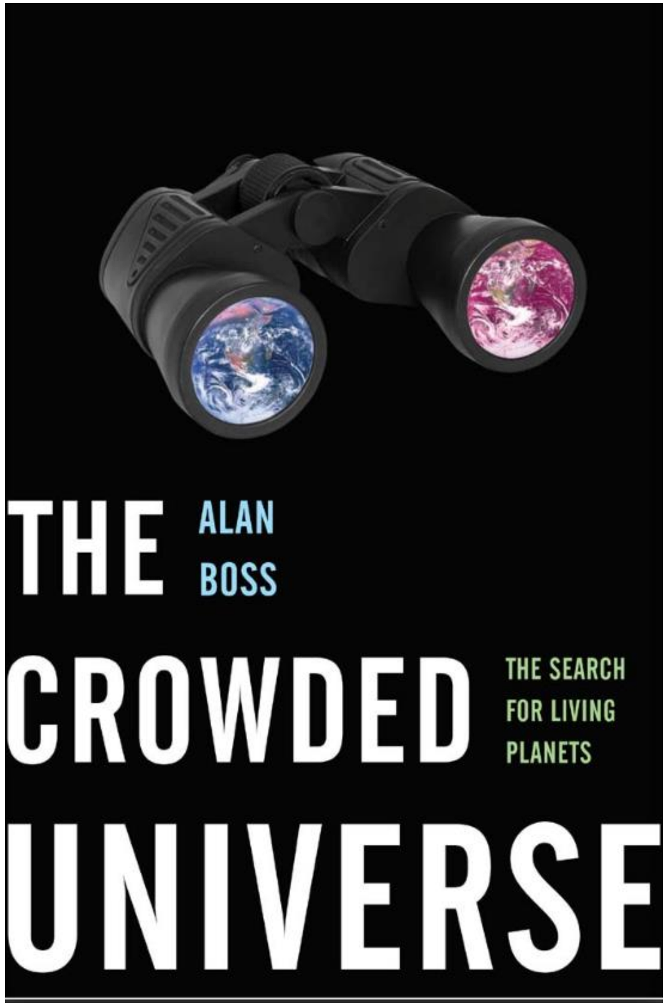

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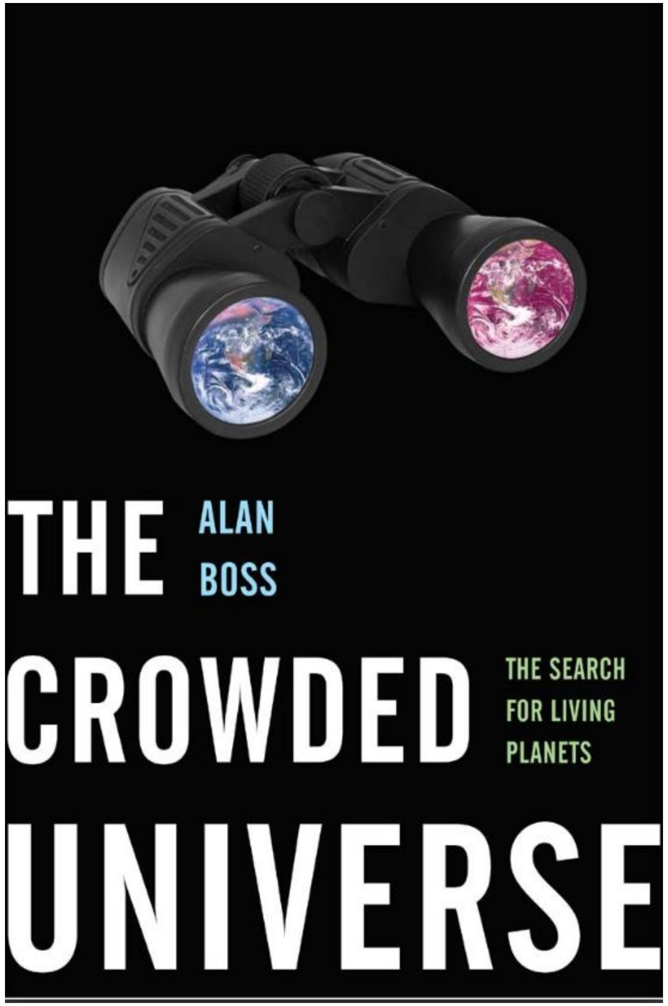

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What is different now?

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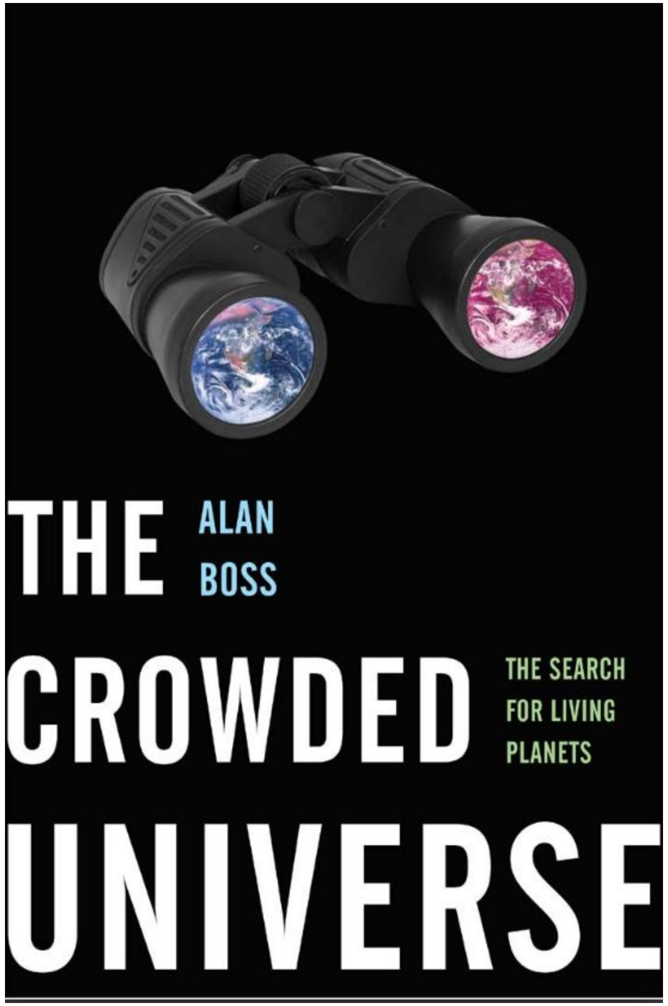

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What is different now?

Space-based observations:

- No atmospheric turbulence
- Dedicated telescopes
- Gliese 876b with Hubble in 2002
- Gaia/Hipparcos

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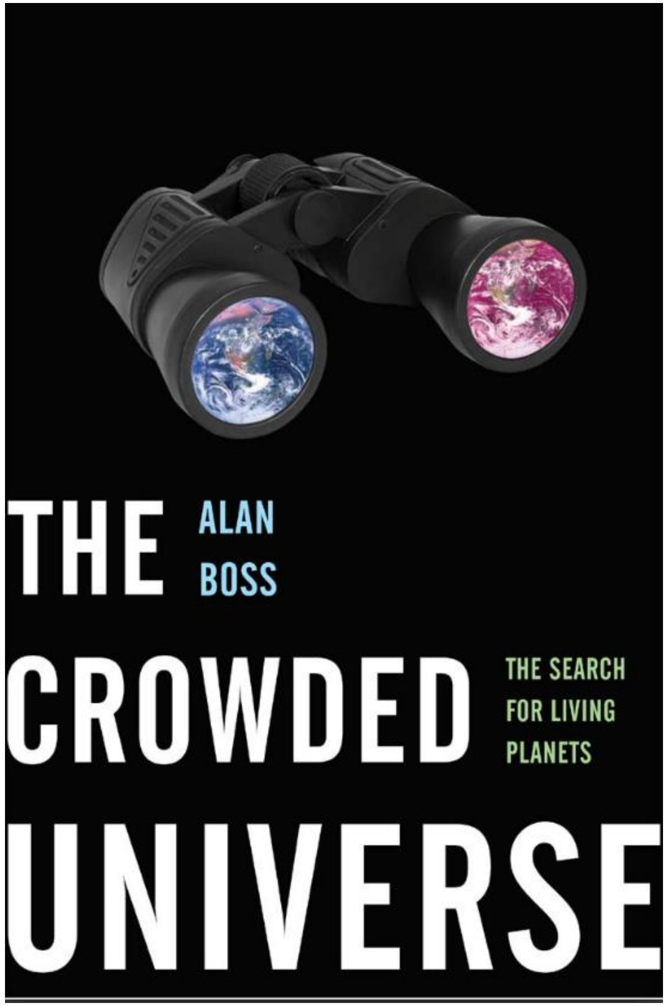

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Long-baseline interferometry:

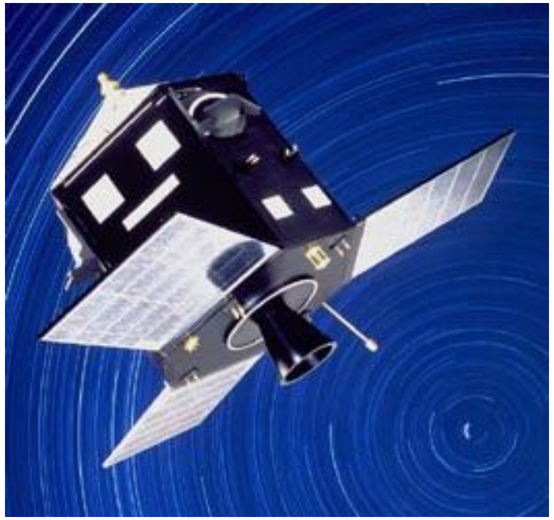
- High precision astrometry
- Phase-referencing
- HD176051 with PHASES in 2010
- GRAVITY

Astrometry works from space

Hipparcos

Mission:
- High precision astrometry on 100 000 stars
- Astrometry (lower precision) on at least 1 million stars

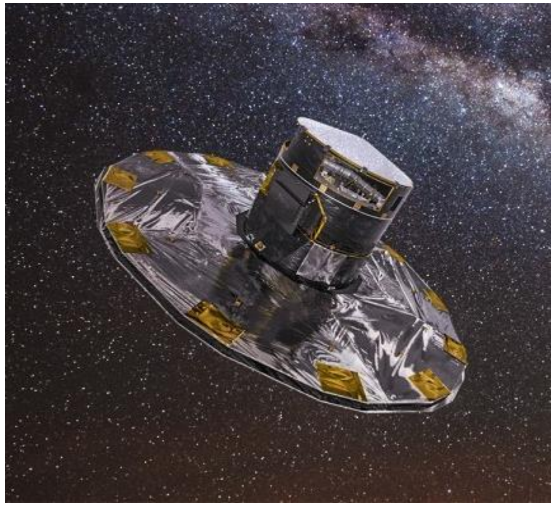
Launch: 1989
Status: completed (1993)



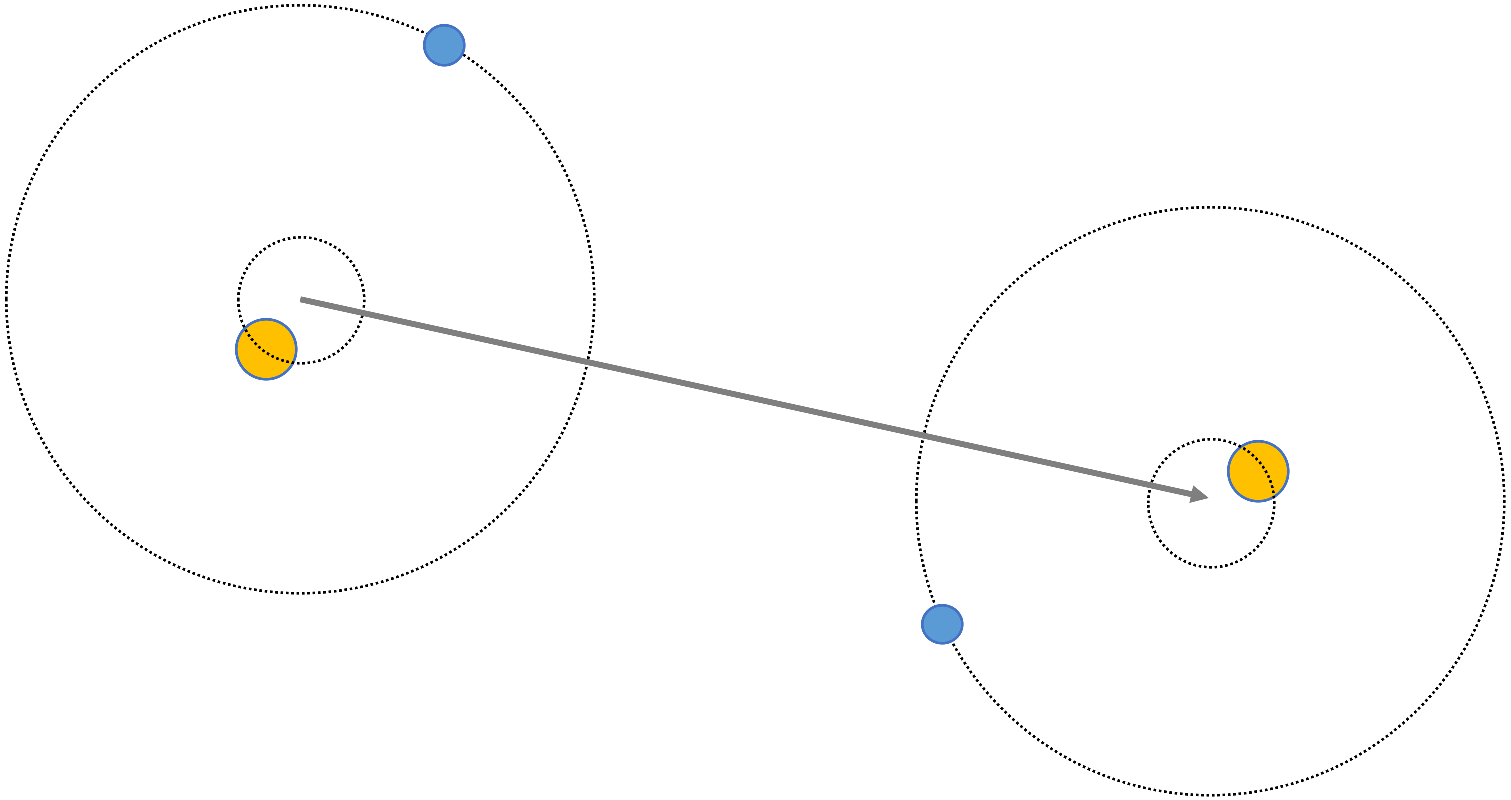
Gaia

Mission:
- Measure the positions and velocity of approximately one billion stars in our Galaxy

Launch: 2013
Status: extended mission (2022 – 2025?)



Proper Motion anomaly (PMa)



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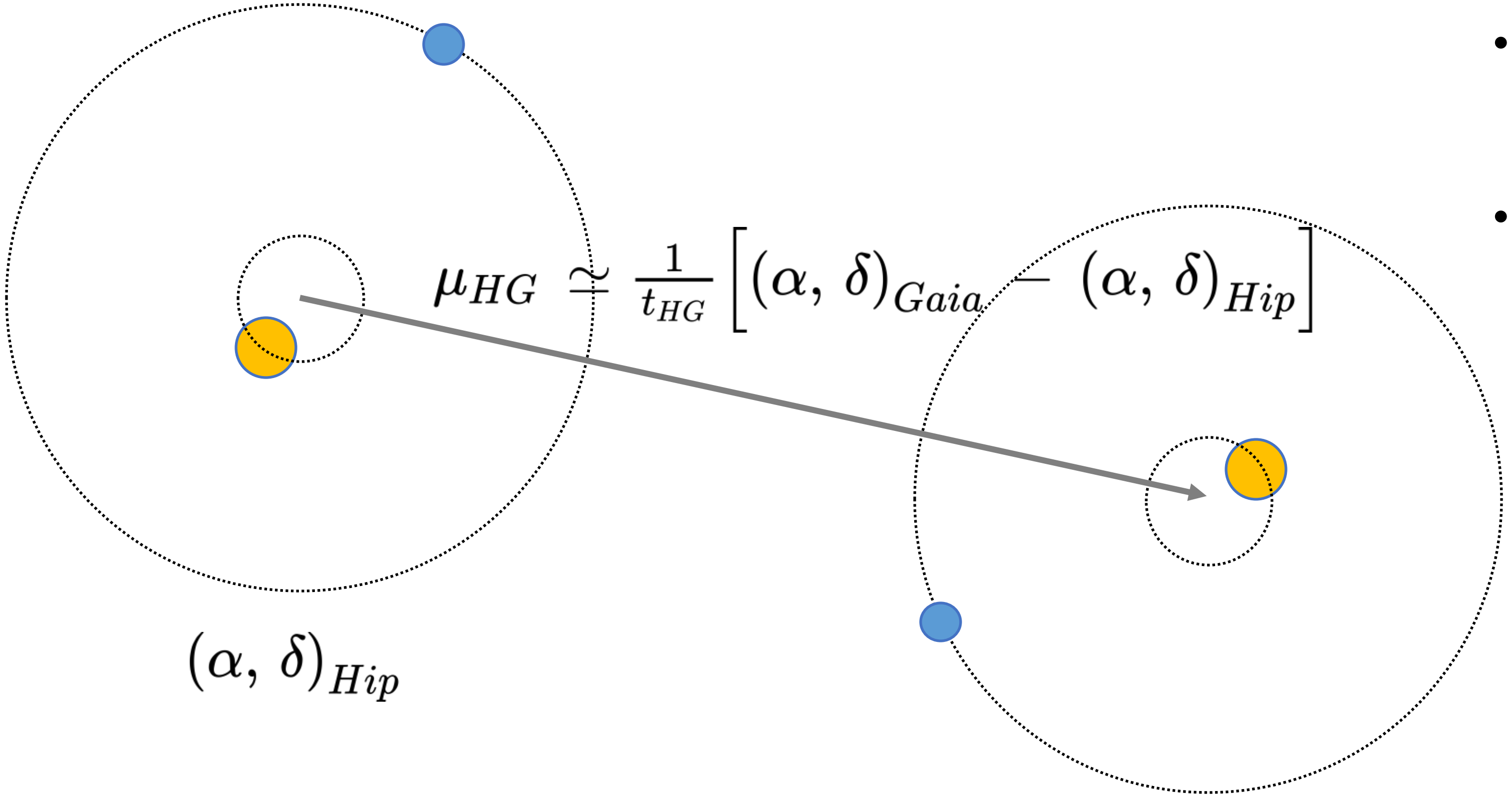


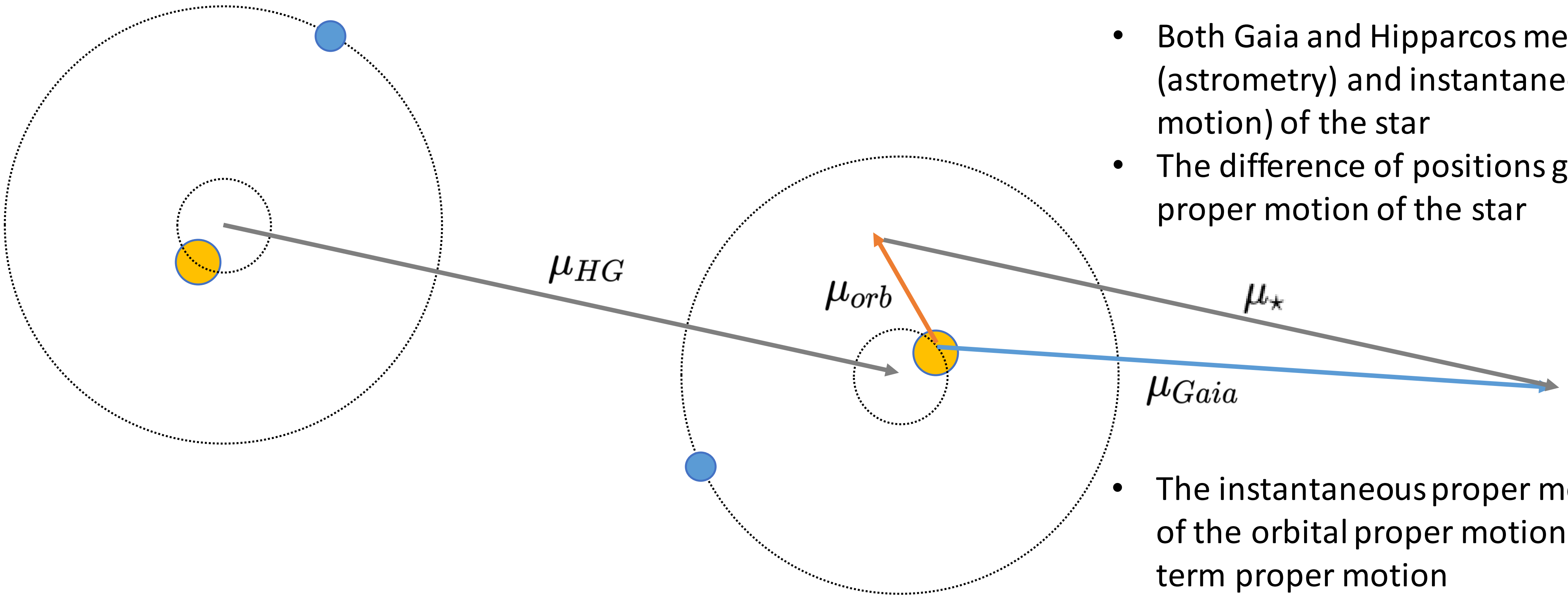
$$\mu_{HG} \simeq \frac{1}{t_{HG}} \left[(\alpha, \delta)_{Gaia} - (\alpha, \delta)_{Hip} \right]$$

$(\alpha, \delta)_{Hip}$

$(\alpha, \delta)_{Gaia}$

- Both Gaia and Hipparcos measured the position (astrometry) and instantaneous velocity (proper motion) of the star
- The difference of positions gives the long term proper motion of the star

Proper Motion anomaly (PMa)



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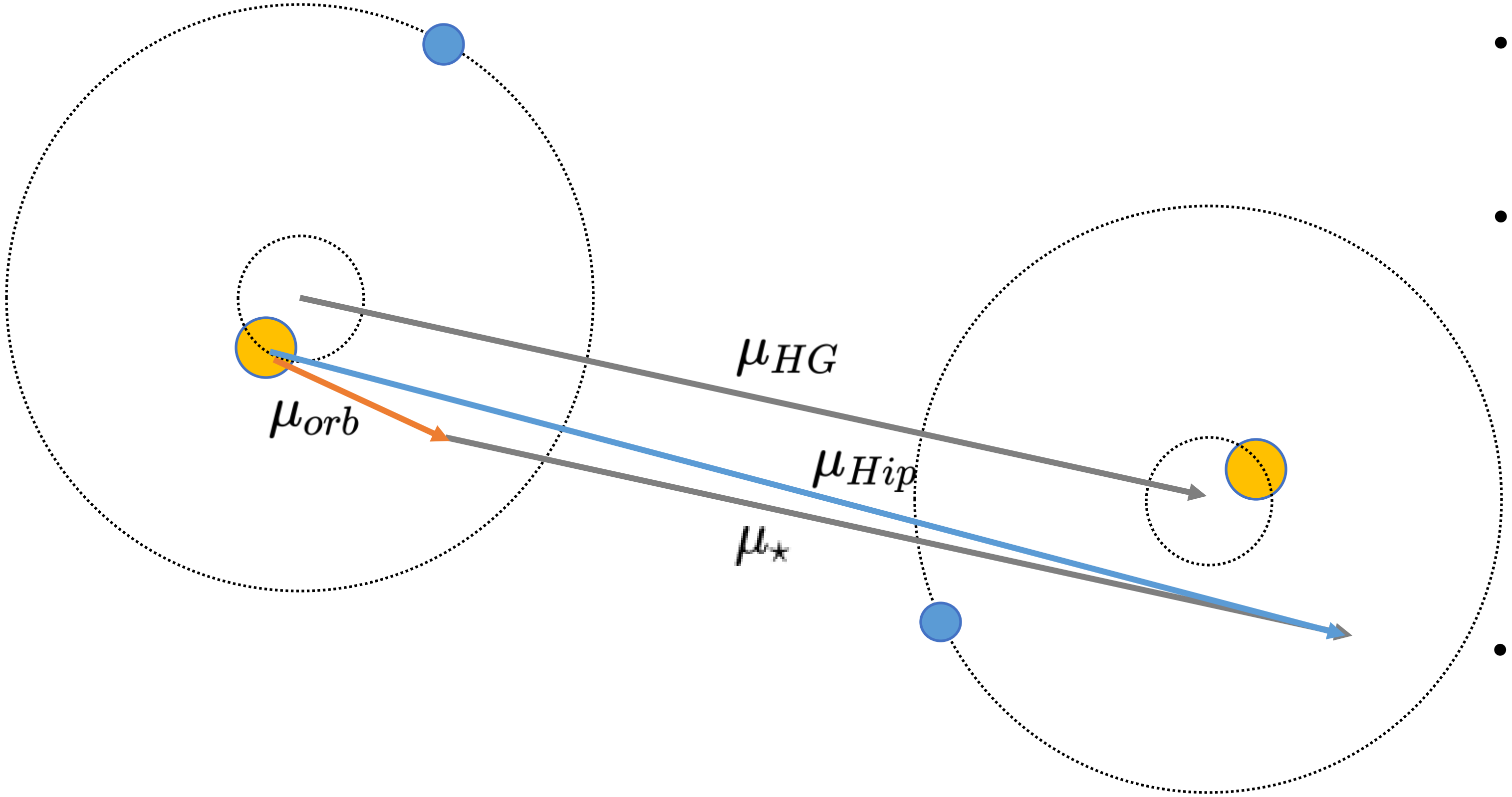
- The instantaneous proper motion is the sum of the orbital proper motion and the long term proper motion
- The difference between the instantaneous and long term proper motions is the proper motion anomaly (PMa):

$$\Delta\mu_{Gaia} = \mu_{Gaia} - \mu_{HG} = \mu_{orb}$$

Proper Motion anomaly (PMa)



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- The instantaneous proper motion is the sum of the orbital proper motion and the long term proper motion
- The difference between the instantaneous and long term proper motions is the proper motion anomaly (PMa):

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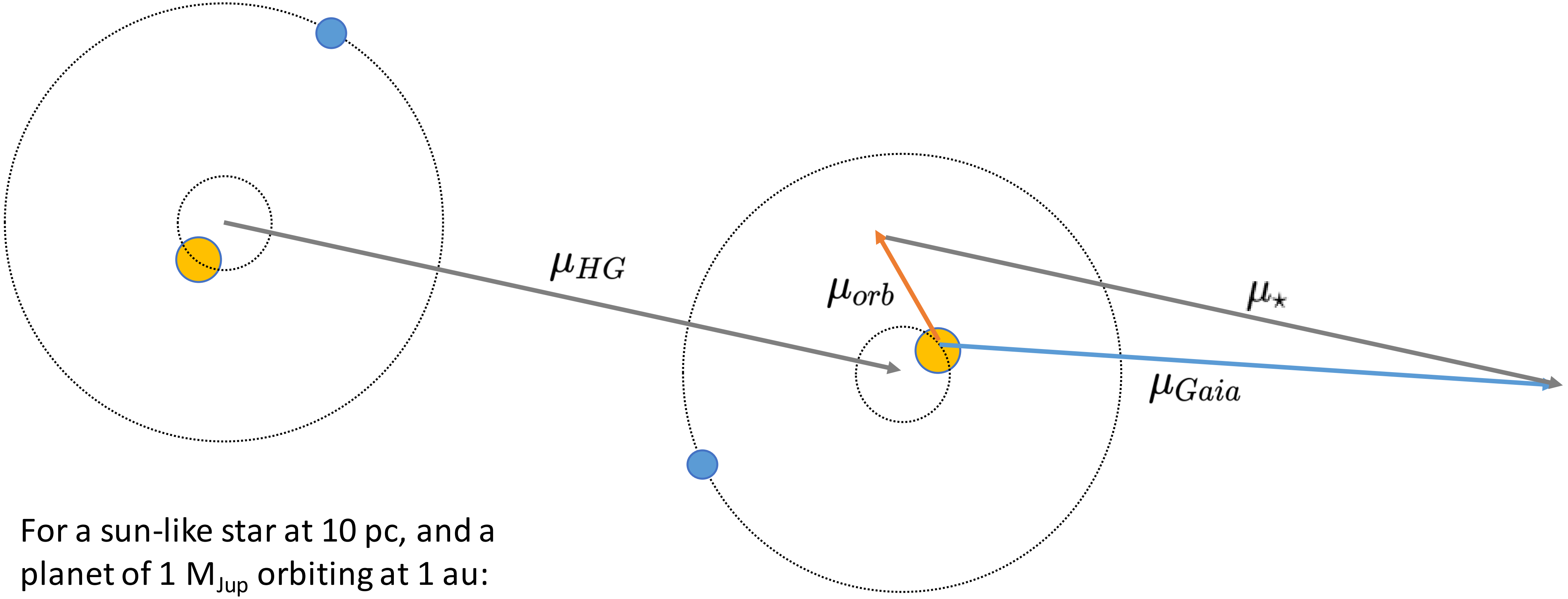
Proper Motion anomaly (PMa)



For a sun-like star at 10 pc, and a planet of 1 M_{Jup} orbiting at 1 au:

$$v_\star = \frac{2\pi \frac{M_{planet}}{M_\star} a}{\sqrt{\frac{a^3}{M_\star}}} = 30\, m/s$$

$$\mu_{orb} = v_\star / d = 6\, mas/yr$$

For a planet orbiting at 5 au:

$$\mu_{orb} \propto M_{planet} M_\star^{-1/2} a^{-1/2} d^{-1}$$

$$\mu_{orb} = 0.26\, mas/yr$$

Precision on the PMa can range from 0.5 to 5 mas/yr

Proper Motion anomaly (PMa)

In practice, getting the PMa is easy (others have done the hardwork!)

Retrieve target HIP number form Simbad

↓

Get corresponding Gaia source id from Brandt+2018 catalog (could also be retrieved from Simbad)

↓

Retrieve Gaia and Hipparcos astrometry and proper motion measurements

↓

See Kervella+2019

Correct Gaia astrometry (Lindegren+2018)

↓

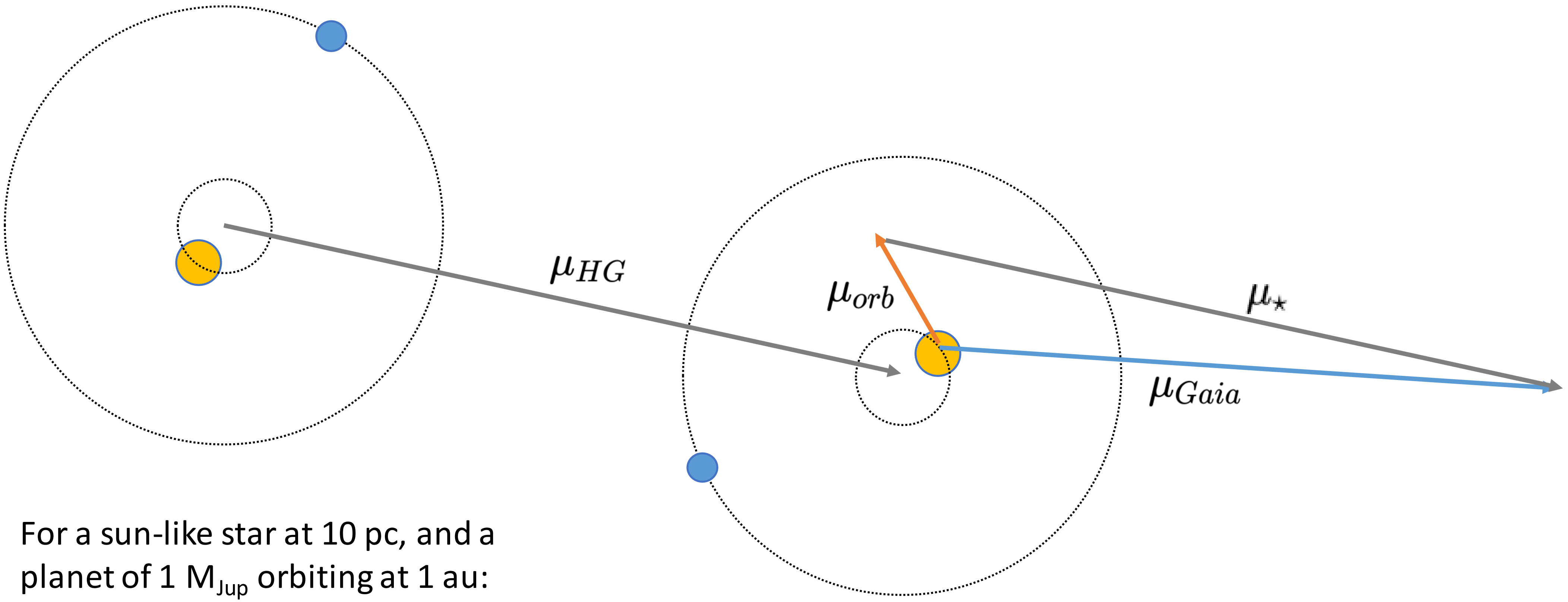
Following Kervella+2019, the Hipparcos distance is replace by the Gaia distance backpropagated to the Hipparcos epoch

↓

The anomaly is calculated as a difference of velocity in the ICRS frame, and projected on the sky plane to get a proper motion

```
import numpy as np
import matplotlib.pyplot as plt
plt.ion()
import astropy.units as u
from astropy.coordinates import SkyCoord, CartesianDifferential
from astroquery.gaia import Gaia
from astroquery.esasky import ESASky
from astropy.io import fits
from astroquery.simbad import Simbad

tgt = "51 Peg" # target name
thg = 24.25 # time between Hip and Gaia epochs

# query simbad to get HIP number of the target
tgt_ids = Simbad.query_objectids(tgt)
ind = [id.find("HIP") for id in tgt_ids["ID"]].index(0)
tgt_hip_id = int(tgt_ids["ID"][ind].split("HIP")[1])

# Hipparcos/Gaia associations (from Brandt+2018)
hgca = fits.open("HGCA_vDR2.fits")[1].data
hip_id = hgca.hip_id
gaia_source_id = hgca.gaia_source_id

# gaia source id of the target
tgt_gaia_source_id = gaia_source_id[np.where(hip_id == tgt_hip_id)][0]

# retrieve gaia and hipparcos data for the target
job_gaia = Gaia.launch_job("select * from gaiadr2.gaia_source WHERE source_id = "+str(tgt_gaia_source_id), dump_to_file=False,
output_format='votable')
job_hip = Gaia.launch_job("select * from public.hipparcos as hip where hip.hip = "+str(tgt_hip_id), dump_to_file=False,
output_format='votable')

# extract position and velocity from gaia data
results_gaia = job_gaia.get_results()[0]
x_gaia = np.array([results_gaia["ra"], results_gaia["dec"], 1000.0/results_gaia["parallax"]])
v_gaia = np.array([results_gaia["pmra"], results_gaia["pmdec"], results_gaia["radial_velocity"]])

# and from hipparcos
results_hip = job_hip.get_results()[0]
x_hip = np.array([results_hip["ra"], results_hip["de"], 1000.0/results_hip["plx"]])
v_hip = np.array([results_hip["pmra"], results_hip["pmde"], 0])

# correct the gaia data for plx zeropoint and frame rotation (see Lindegren+2018)
x_gaia[2] = 1000.0/(1000.0/x_gaia[2]+0.029)
wx, wy, wz = -0.086, -0.114, -0.037
v_gaia[0] = v_gaia[0]+wx*np.sin(x_gaia[1]/180.0*np.pi)*np.cos(x_gaia[0]/180.0*np.pi)+wy*np.sin(x_gaia[1]
/180.0*np.pi)*np.sin(x_gaia[0]/180.0*np.pi)-wz*np.cos(x_gaia[1]/180.0*np.pi)
v_gaia[1] = v_gaia[1]-wx*np.sin(x_gaia[0]/180.0*np.pi)+wy*np.cos(x_gaia[0]/180.0*np.pi)

# create 6d coordinates vector in ICRS frame and replace hipparcos distance by propagated gaia distance
c_gaia = SkyCoord(ra=x_gaia[0]*u.degree, dec=x_gaia[1]*u.degree, distance = x_gaia[2]*u.pc, pm_ra_cosdec =
v_gaia[0]*u.mas/u.yr, pm_dec = v_gaia[1]*u.mas/u.yr, radial_velocity = v_gaia[2]*u.km/u.s, frame = "icrs")
c_gaia_hip = c_gaia.apply_space_motion(dt=-thg*u.yr)
c_hip = SkyCoord(ra=x_hip[0]*u.degree, dec=x_hip[1]*u.degree, distance = c_gaia_hip.spherical.distance, pm_ra_cosdec =
v_hip[0]*u.mas/u.yr, pm_dec = v_hip[1]*u.mas/u.yr, radial_velocity = v_gaia[2]*u.km/u.s, frame = "icrs")

# calculate long term velocity vector
v_x = (c_gaia.cartesian.x - c_hip.cartesian.x)/(thg*u.yr)
v_y = (c_gaia.cartesian.y - c_hip.cartesian.y)/(thg*u.yr)
v_z = (c_gaia.cartesian.z - c_hip.cartesian.z)/(thg*u.yr)

# get the proper motion corresponding to the LT velocity using astropy transformations
c_hg_hip = SkyCoord(x = c_hip.cartesian.x, y = c_hip.cartesian.y, z = c_hip.cartesian.z, v_x = v_x, v_y = v_y, v_z = v_z,
frame="icrs", representation_type="cartesian", differential_type="cartesian")
c_hg_gaia = SkyCoord(x = c_gaia.cartesian.x, y = c_gaia.cartesian.y, z = c_gaia.cartesian.z, v_x = v_x, v_y = v_y, v_z = v_z,
frame="icrs", representation_type="cartesian", differential_type="cartesian")
v_hg_hip = c_hg_hip.proper_motion
v_hg_gaia = c_hg_gaia.proper_motion

# calculate the proper motion anomalies
pma_hip = np.sqrt(np.sum((c_hip.proper_motion - v_hg_hip)**2))
pma_gaia = np.sqrt(np.sum((c_gaia.proper_motion - v_hg_gaia)**2))

print("VHG [HIP]:", v_hg_hip)
print("PMa HIP:", pma_hip)
print("VHG [GAIA]:", v_hg_gaia)
print("PMa GAIA:", pma_gaia)
```

Order of magnitudes



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$$\mu_{orb} = v_\star / d = 6\, mas/yr$$

$$\frac{M_{planet}}{a^{1/2}} = \frac{d M_*^{1/2}}{2\pi} \Delta\mu$$

Valid for a circular, face-on orbit!

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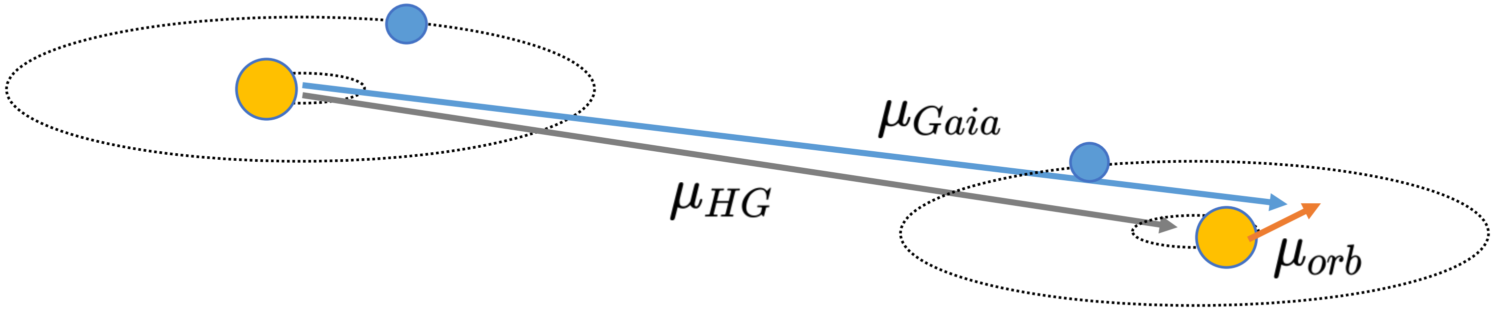

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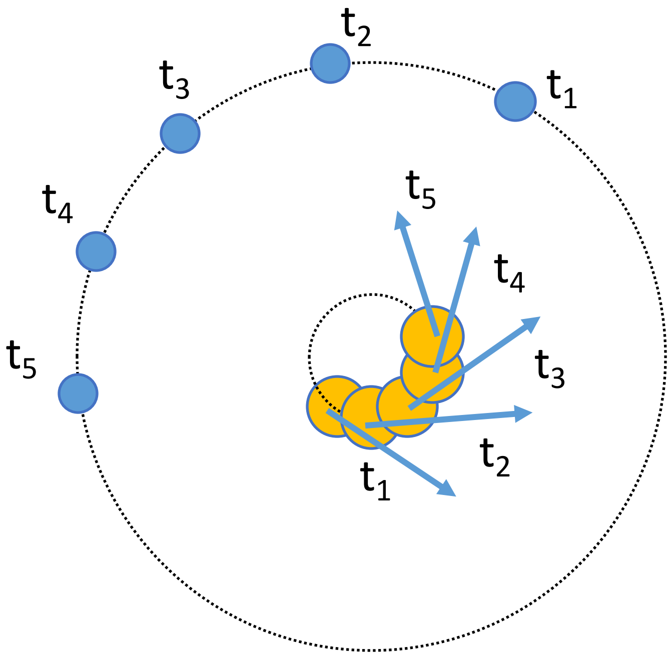
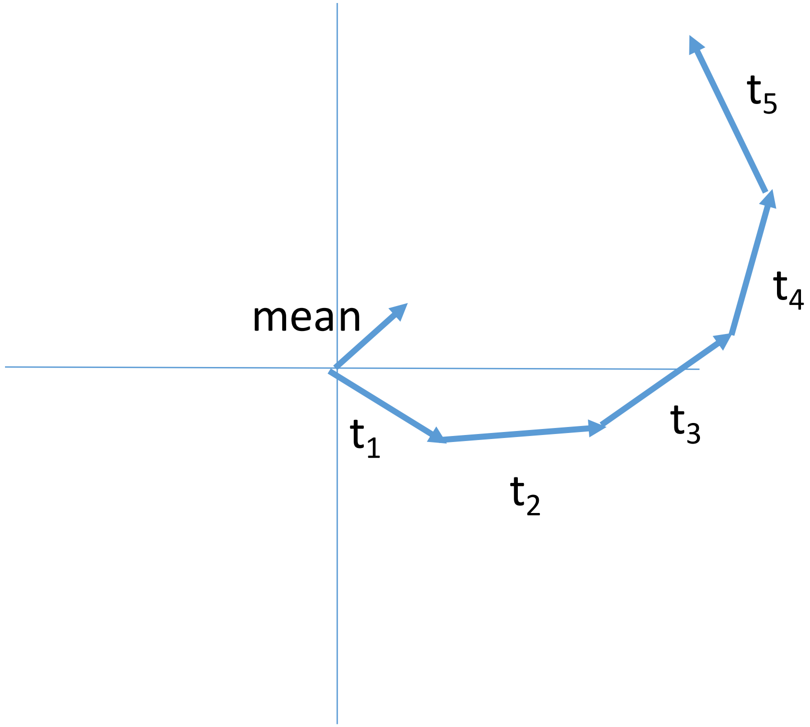
In practice, the measured anomaly is reduced by a mean factor of 0.87 by the inclination and eccentricity (Kervella+2019). This gives:

$$M_{planet} = \frac{dM_*^{1/2}}{2\pi} \frac{\Delta\mu}{0.87} a^{1/2}$$

Small period limit

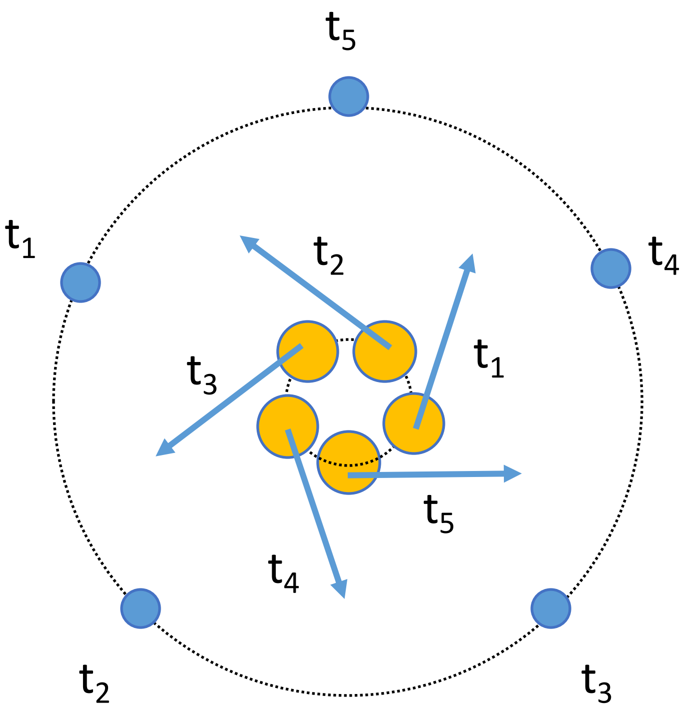


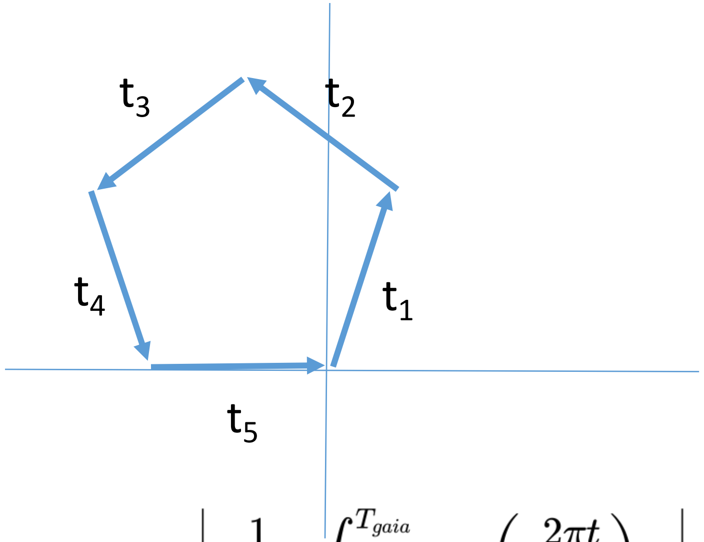


- In practice, neither Gaia nor Hipparcos truly measures the instantaneous proper motion
- Gaia measured the mean over a period of 665 days (DR2)
- Hipparcos measured the mean over a period of 1227 days

- This reduces the measured PMa

Small period limit





- Worst case scenario: the orbital period is the same as the period over which measurements are averaged
- The measured PMa is 0
- Gaia/Hipparcos PMa measurements are blind to certain periods, and not sensitivie at small period

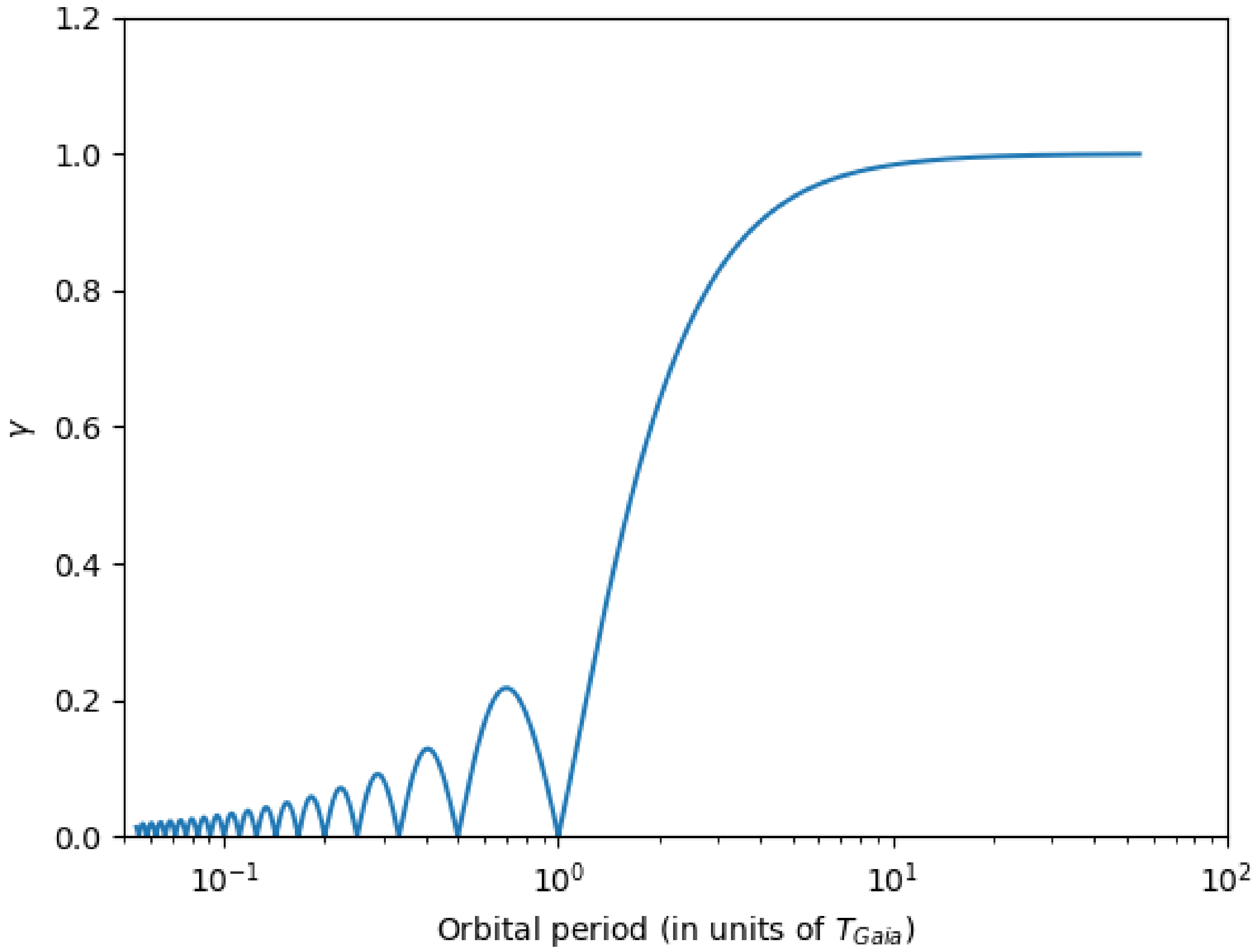
$$\begin{aligned} \mu_{gaia} &= \mu \times \left| \frac{1}{T_{gaia}} \int_0^{T_{gaia}} \exp\left(i\frac{2\pi t}{P}\right) dt \right| \\ &= \mu \times \left| \frac{P}{i2\pi T_{gaia}} \left[e^{i\frac{2\pi T_{gaia}}{P}} - 1 \right] \right| \\ &= \mu \times \frac{P}{\pi T_{gaia}\sqrt{2}} \sqrt{1 - \cos\left(\frac{2\pi T_{gaia}}{P}\right)} \end{aligned}$$

$$\lim_{P \to +\infty} \gamma = 1$$

$$\lim_{P \to 0} \gamma = 0$$

$$\gamma = 0 \text{ when } \frac{T_{Gaia}}{P} \in \mathbb{N}$$

Small period limit



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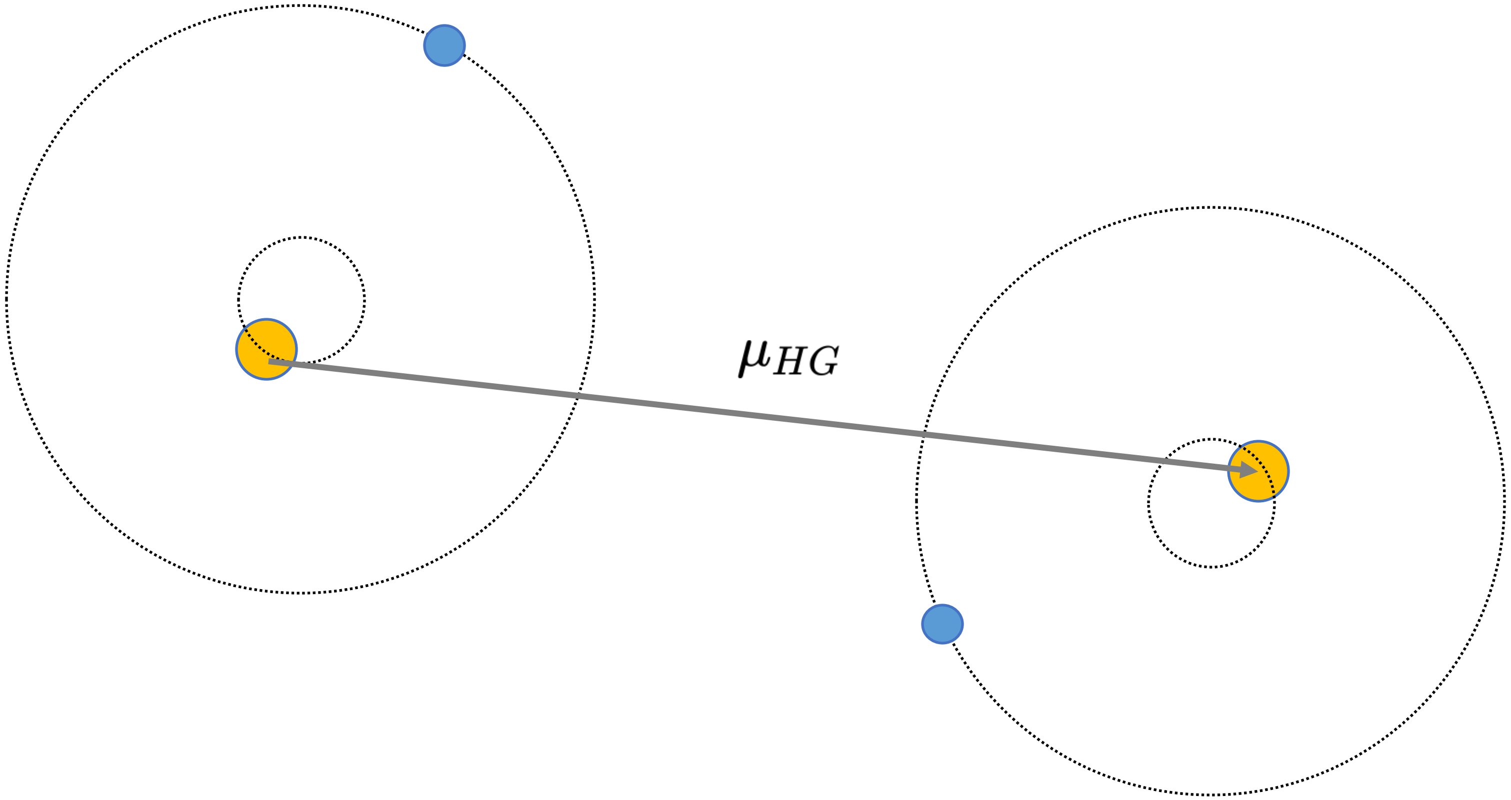

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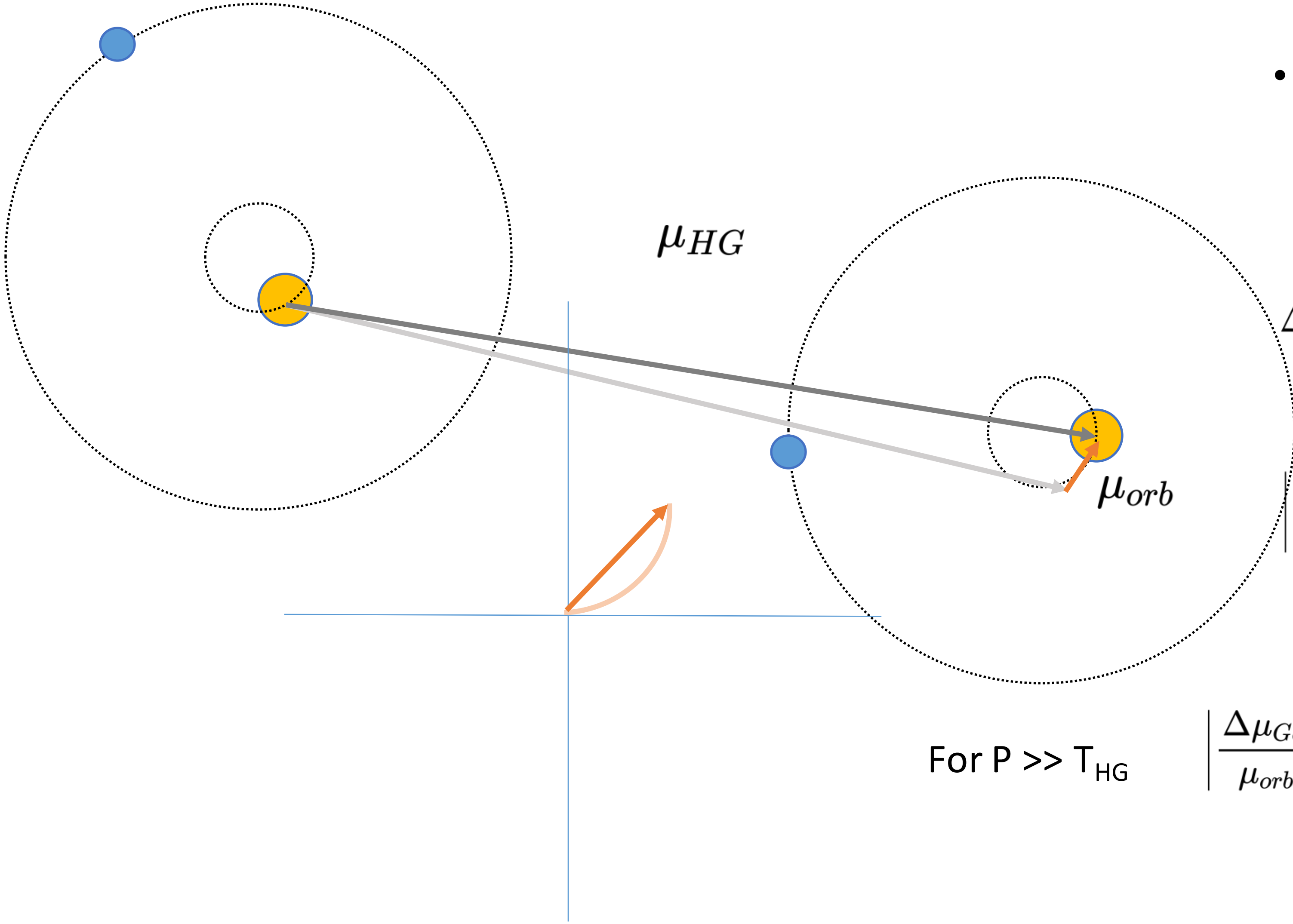


- The long term proper motion of the star as measured from Hipparcos and Gaia data can include the orbital velocity for long period planets

$$\Delta\mu_{Gaia} = \mu_{orbit} + \mu_\star - \left[\mu_\star + \frac{\mu_{orbit}}{T_{HG}} \int_0^{T_{HG}} \exp\left(\frac{i2\pi}{P}t\right) dt\right]$$

$$\mu_{orbit} = |\mu_{orbit}| \exp(i\theta_0)$$

$$\left|\frac{\Delta\mu_{Gaia}}{\mu_{orbit}}\right| = \left|\exp(i\theta_0) + \frac{\exp(i\theta_0)}{T_{HG}} \int_0^{T_{HG}} \exp\left(\frac{i2\pi}{P}t\right) dt\right|$$

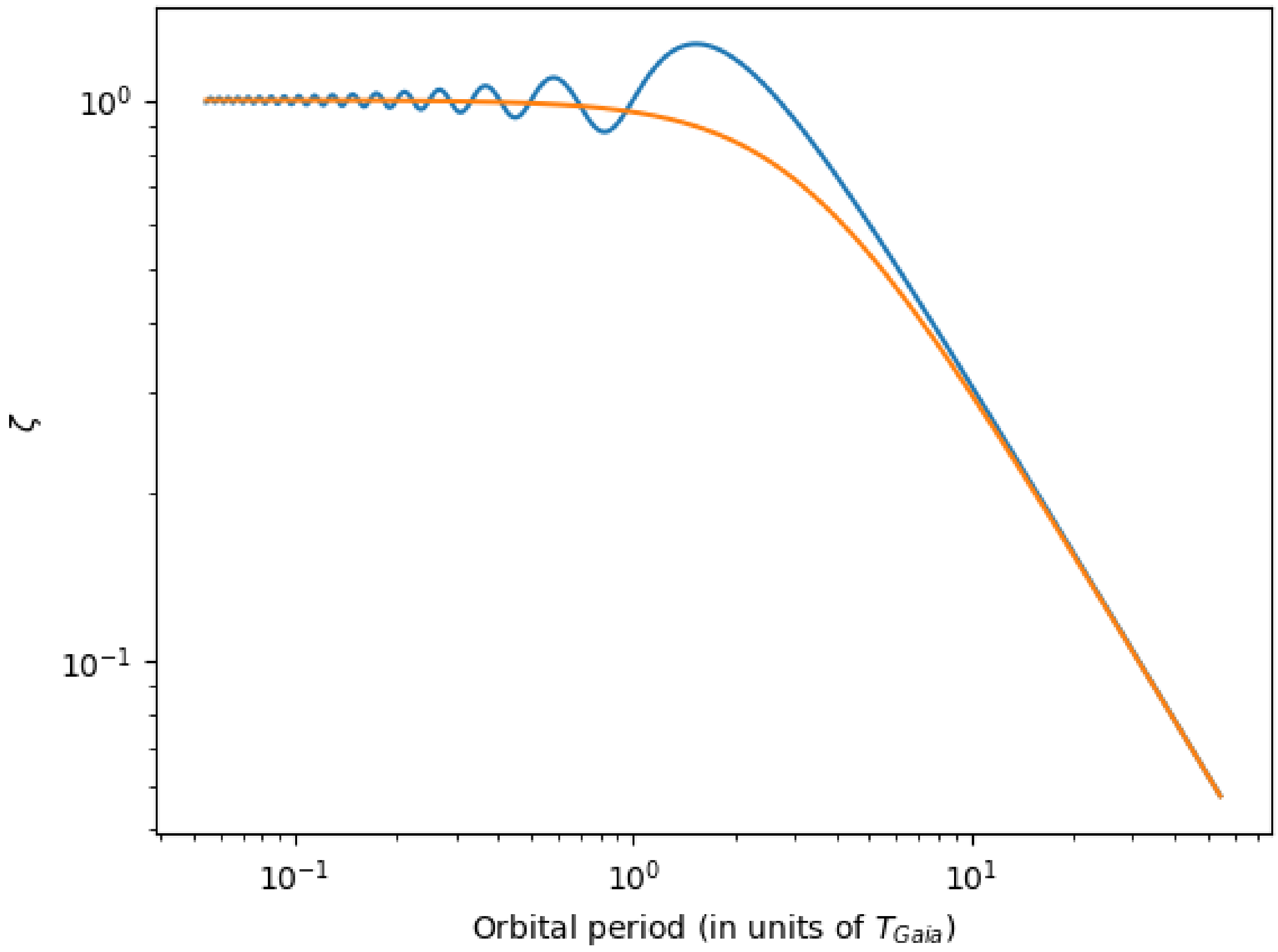
$$= \left|1 - \frac{iP}{2\pi T}\left[\cos\left(\frac{2\pi T}{P}\right) + i\sin\left(\frac{2\pi T}{P}\right) - 1\right]\right|$$

For P >> T_{HG}

$$\left|\frac{\Delta\mu_{Gaia}}{\mu_{orbit}}\right| = \left|1 - \frac{iP}{2\pi T_{HG}}\left(1 - \frac{1}{2}\left(\frac{2\pi T_{HG}}{P}\right)^2 + i\frac{2\pi T_{HG}}{P} - 1\right)\right|$$

$$= \left|\frac{\pi T_{HG}}{P}\right|$$

Long period limit

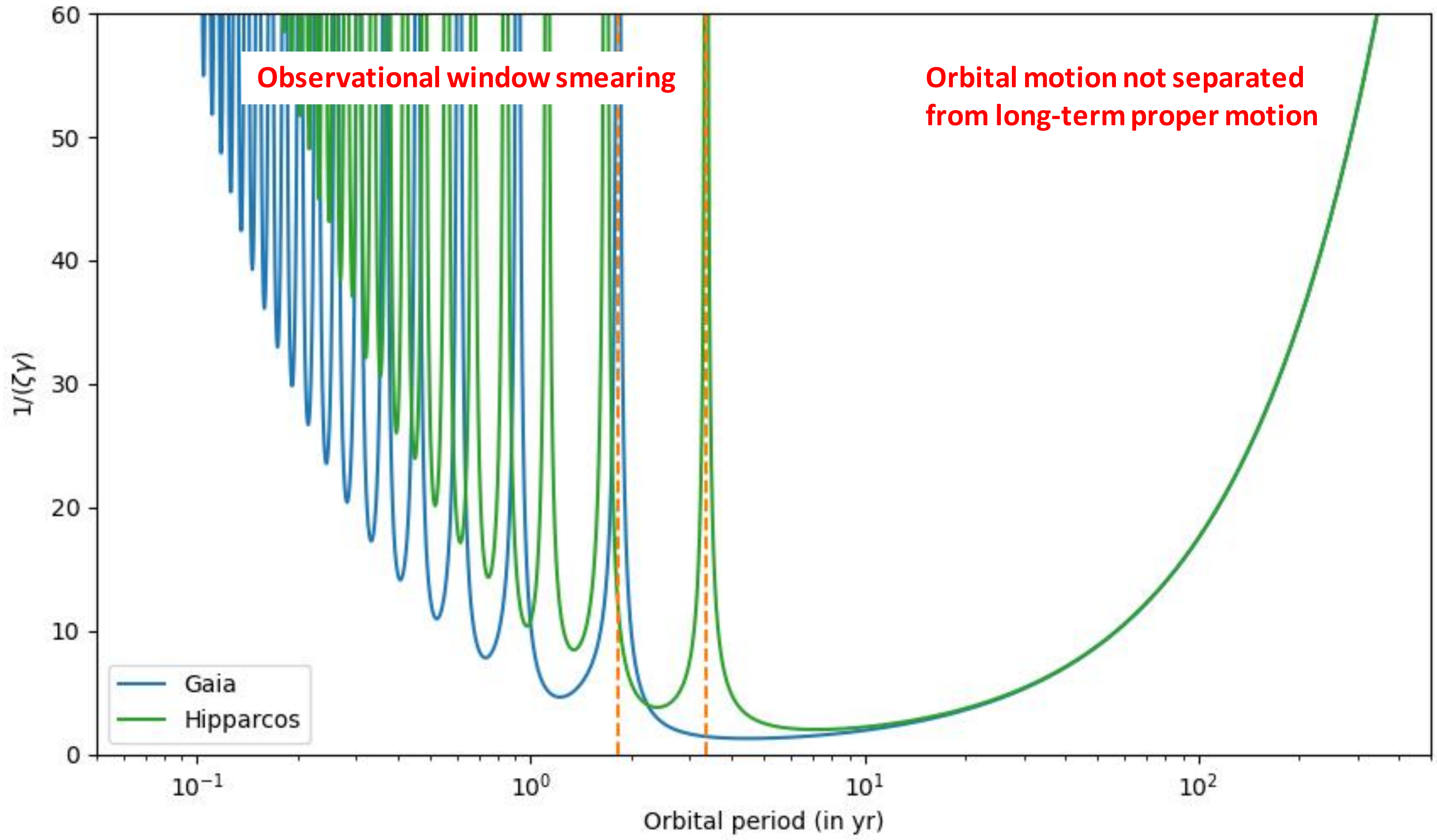


$$\left|\frac{\Delta\mu_{Gaia}}{\mu_{orbit}}\right| = \frac{\pi T_{HG}}{P} \quad \text{for } P \gg T_{HG}$$

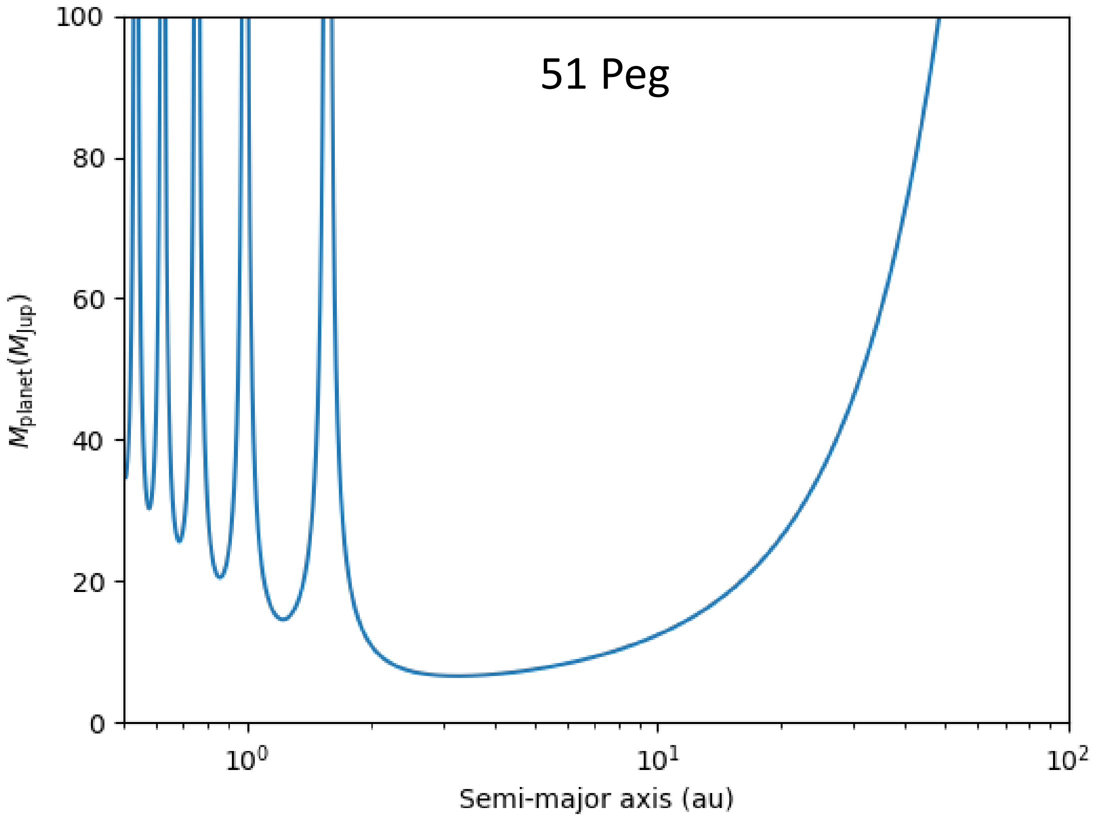
A reasonable approximation is:

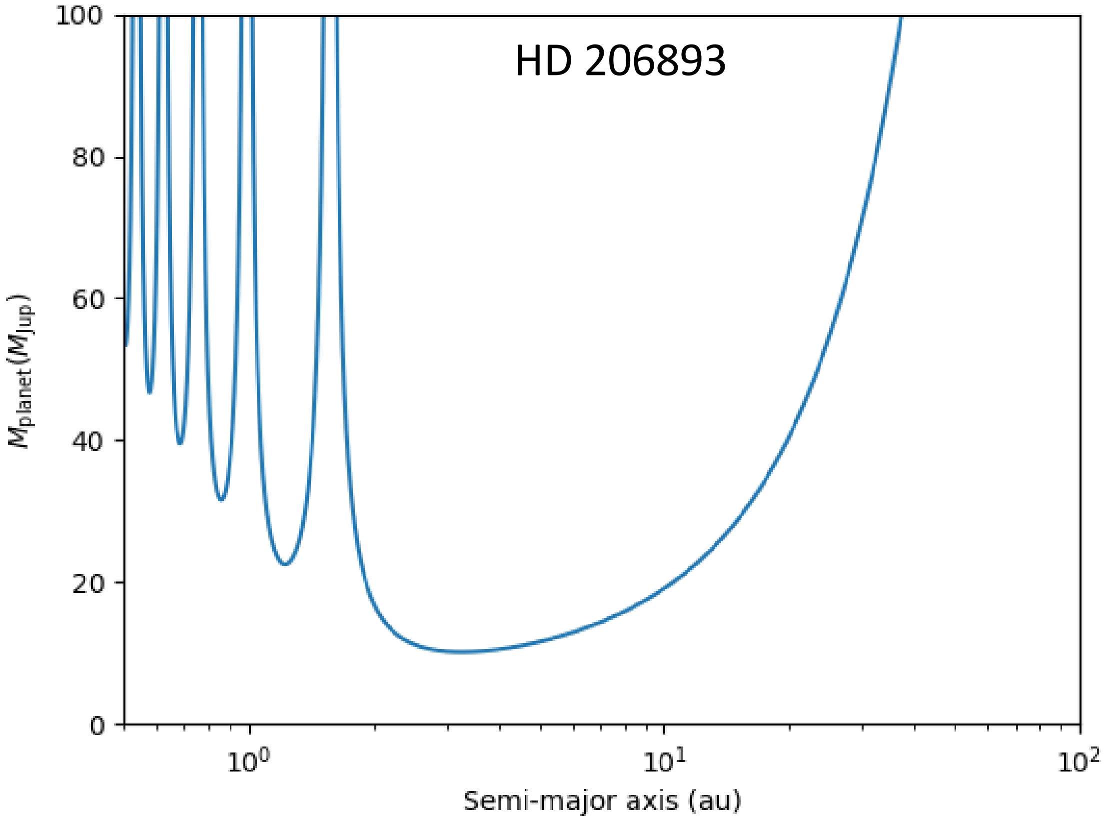
$$\left|\frac{\Delta\mu_{Gaia}}{\mu_{orbit}}\right| \simeq \sqrt{\frac{1}{1+\left(\frac{T_{HG}}{\pi P}\right)^2}}$$

Gaia/Hipparcos PMa efficiency



Examples of Gaia planet candidates





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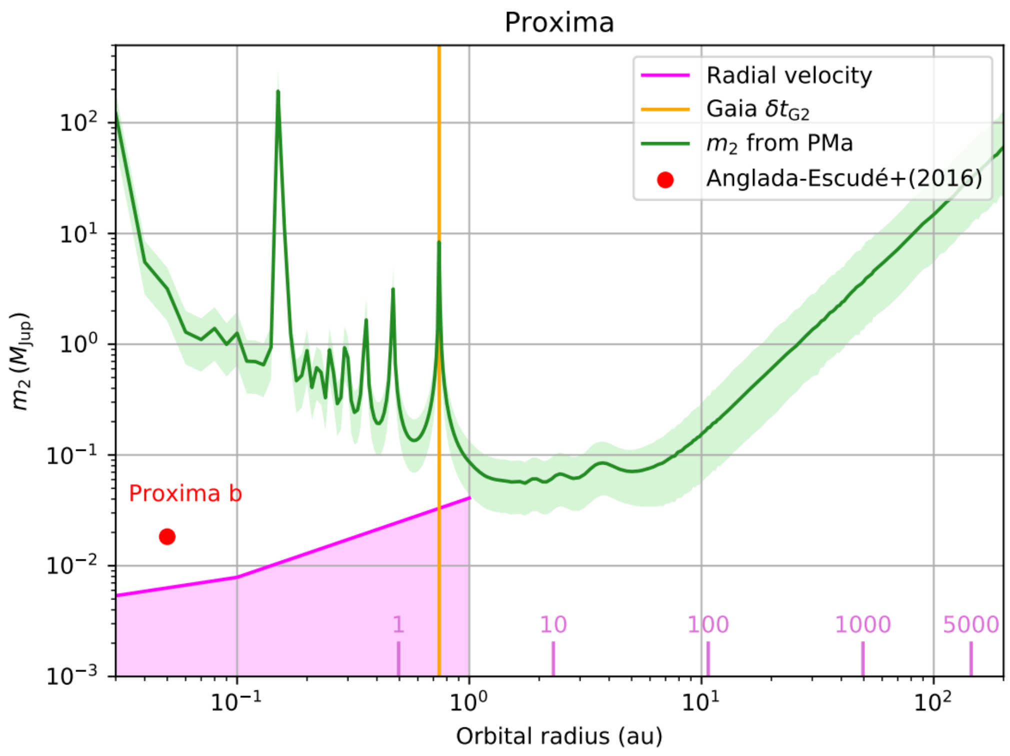
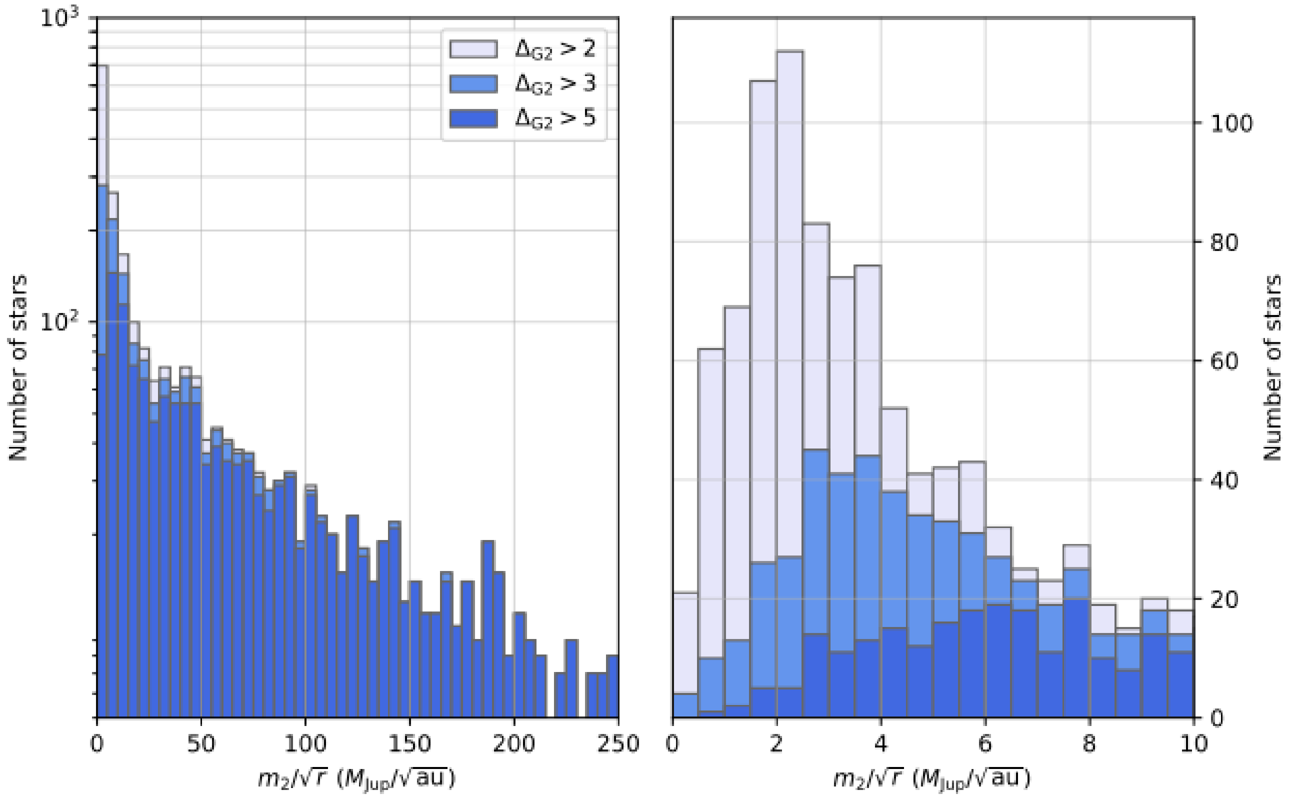
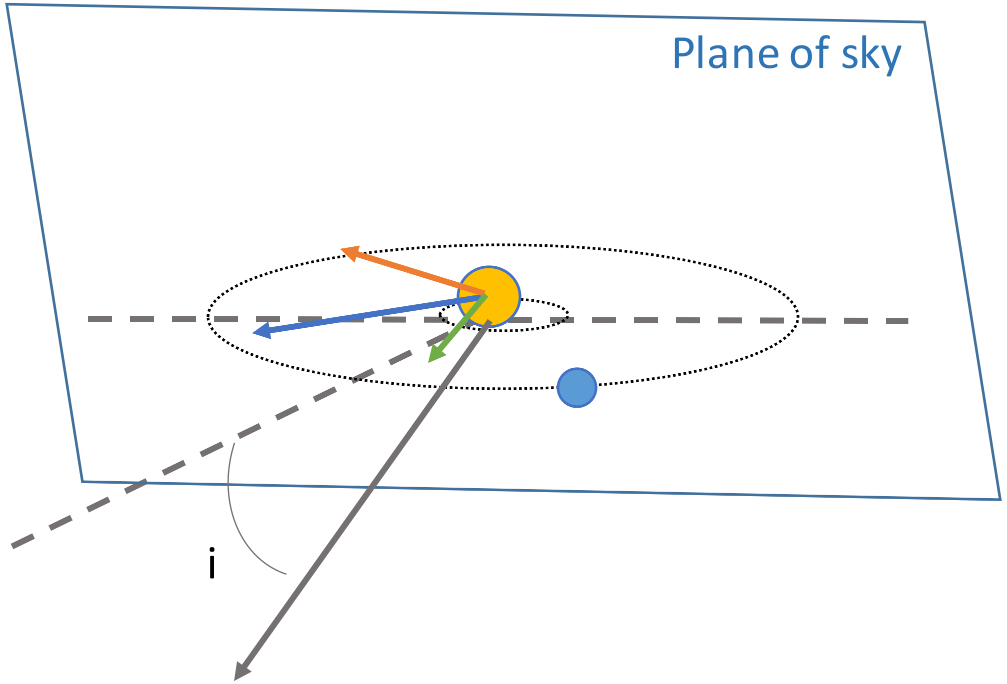




(Figures from Kervella+2019)

The mass of Proxima c



- In principle, if a star could be followed with astrometry, it would be possible to measures P, thus a, M_{planet} and the inclination, since:

$$\mu = 2\pi M_{planet} a^{1/2} M_\star^{-1/2} \binom{\cos(\theta)}{\sin(\theta)\cos(i)}$$

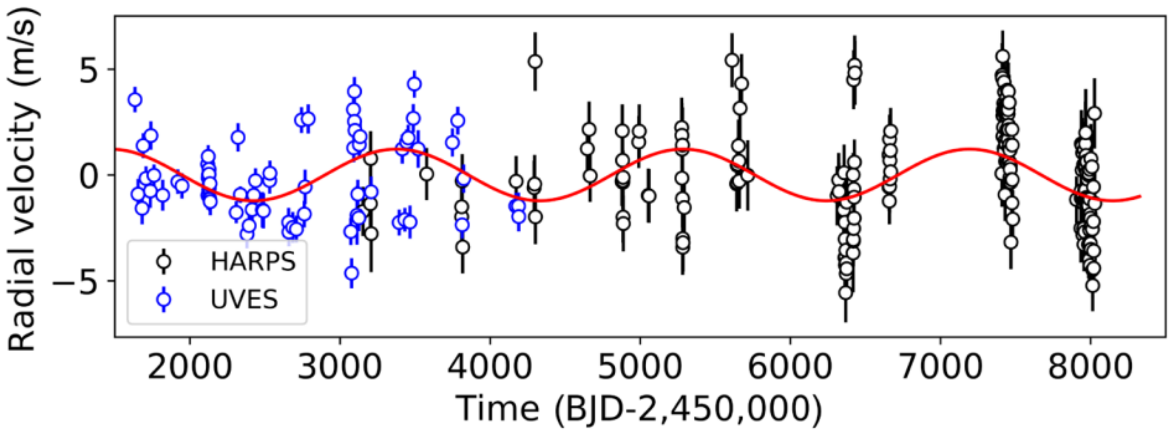
- In practice, with a single (or two) measurements, there is a number of degeneracies

- Adding in radial velocity measurements:

$$v_r = 2\pi M_{planet} a^{1/2} \sin(i)\ \sin(\theta)$$

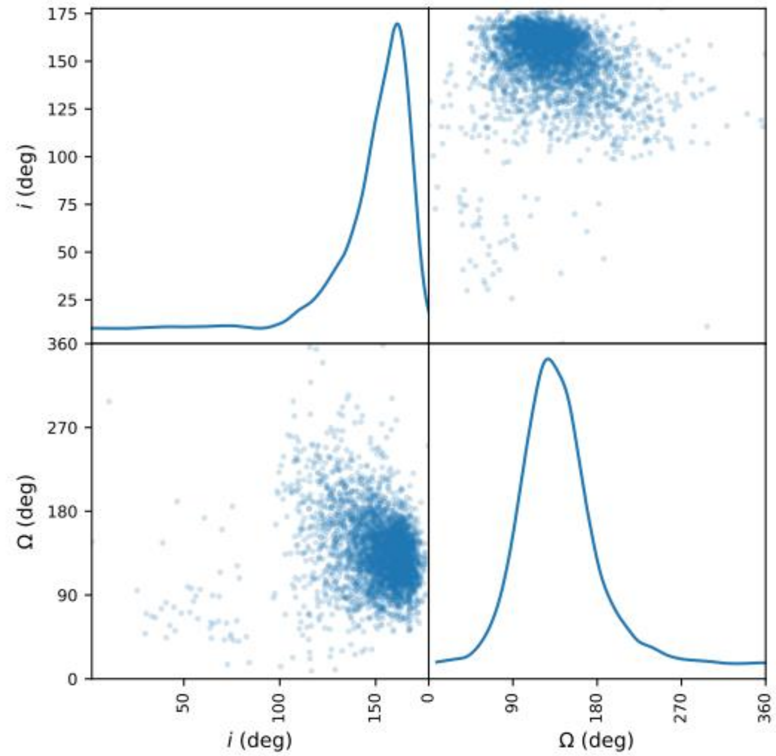
$$\frac{\mu_Y}{v_r} = \tan(i)$$

The mass of Proxima c



Radial velocity (residuals after subtracting Proxima b) showing the signal of planet c (Damasso+2020)

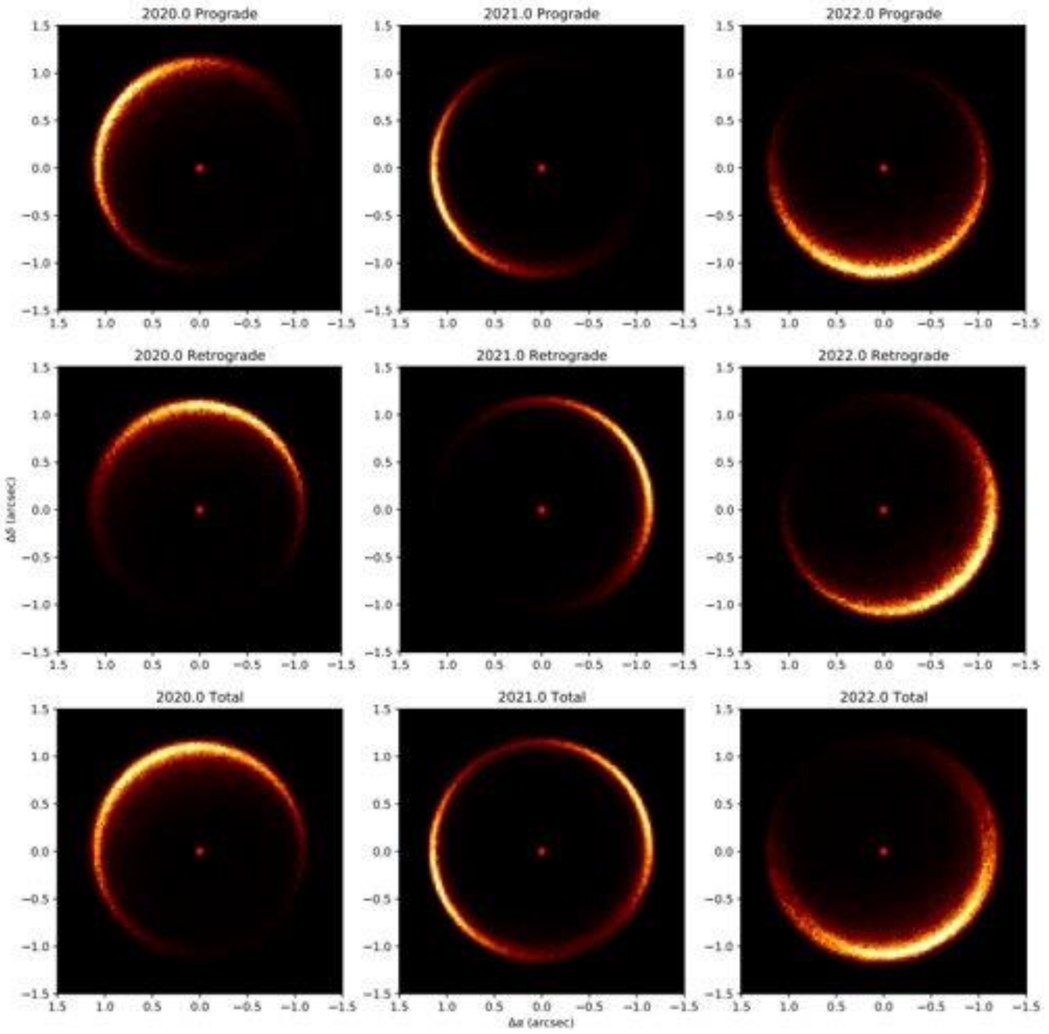
- Orbital period P = 1900 +-90 days
- Time of the inferior conjnction 5892 +- 101 days
- Msin(i) = 5.8 +- 2 M_{Earth}

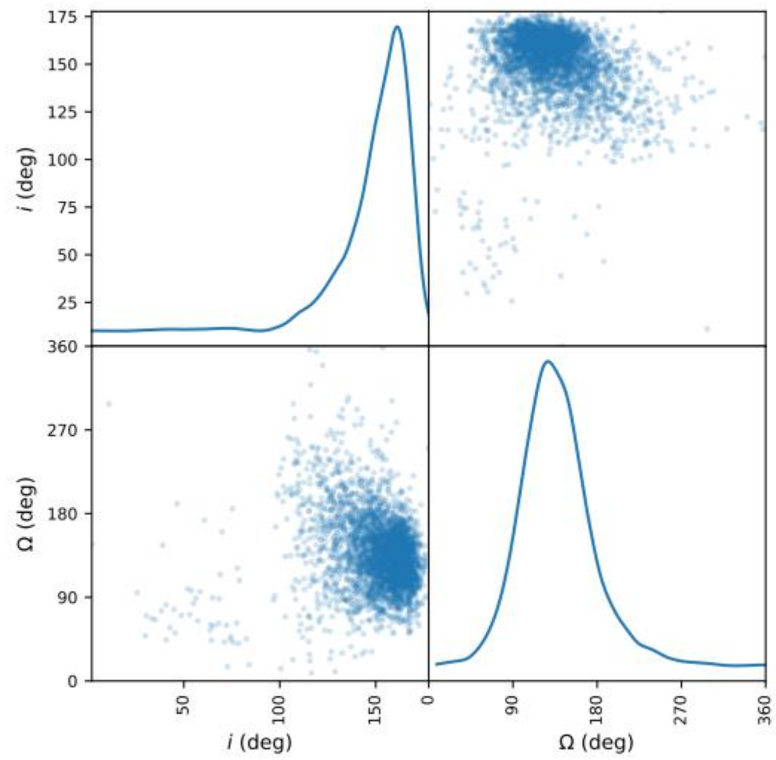


Adding the Gaia PMa anomaly (Kervella+2020):

- sin(I) = 0.46 +- 0.2
- M = 12 [7-24] M_{Earth}

The mass of Proxima c

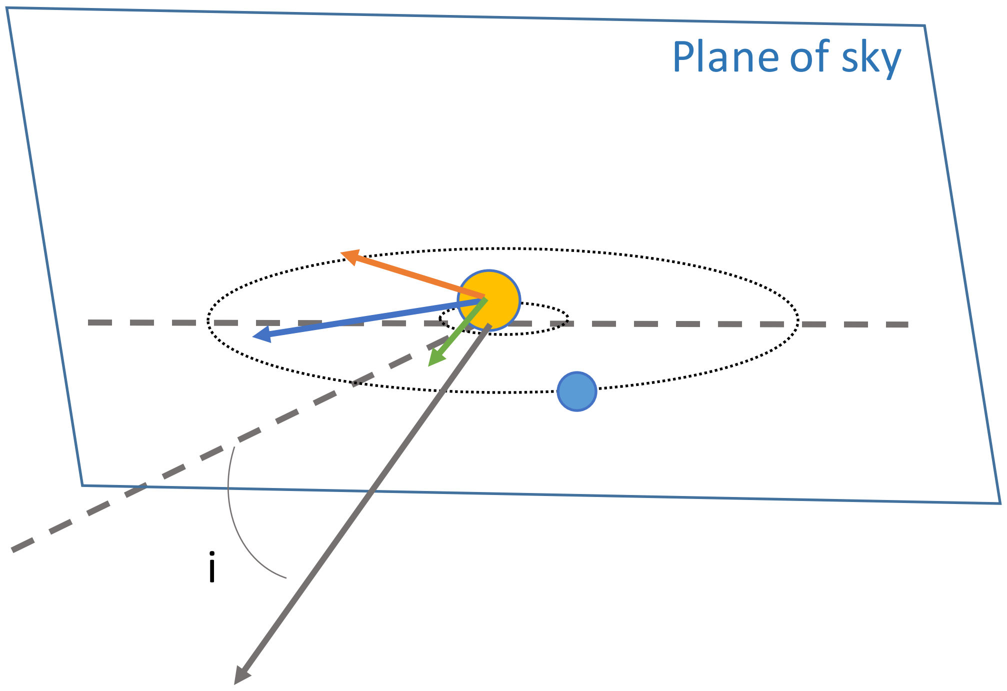




Adding the Gaia PMa anomaly (Kervella+2020):

- sin(i) = 0.46 +- 0.2
- M = 12 [7-24] M_{Earth}

The mass of Proxima c



- In principle, if a star could be followed with astrometry, it would be possible to measures P, thus a, M_{planet} and the inclination, since:

$$\mu = 2\pi M_{planet} a^{1/2} M_\star^{-1/2} \begin{pmatrix} \cos(\theta) \\ \sin(\theta)\cos(i) \end{pmatrix}$$

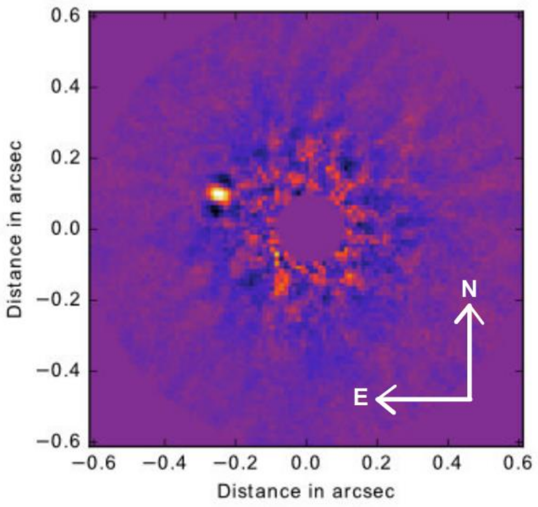
- In practice, with a single (or two) measurements, there is a number of degeneracies

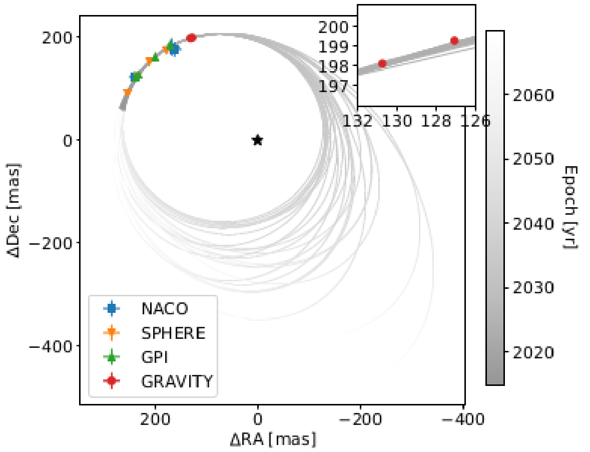
- Adding in radial velocity measurements:

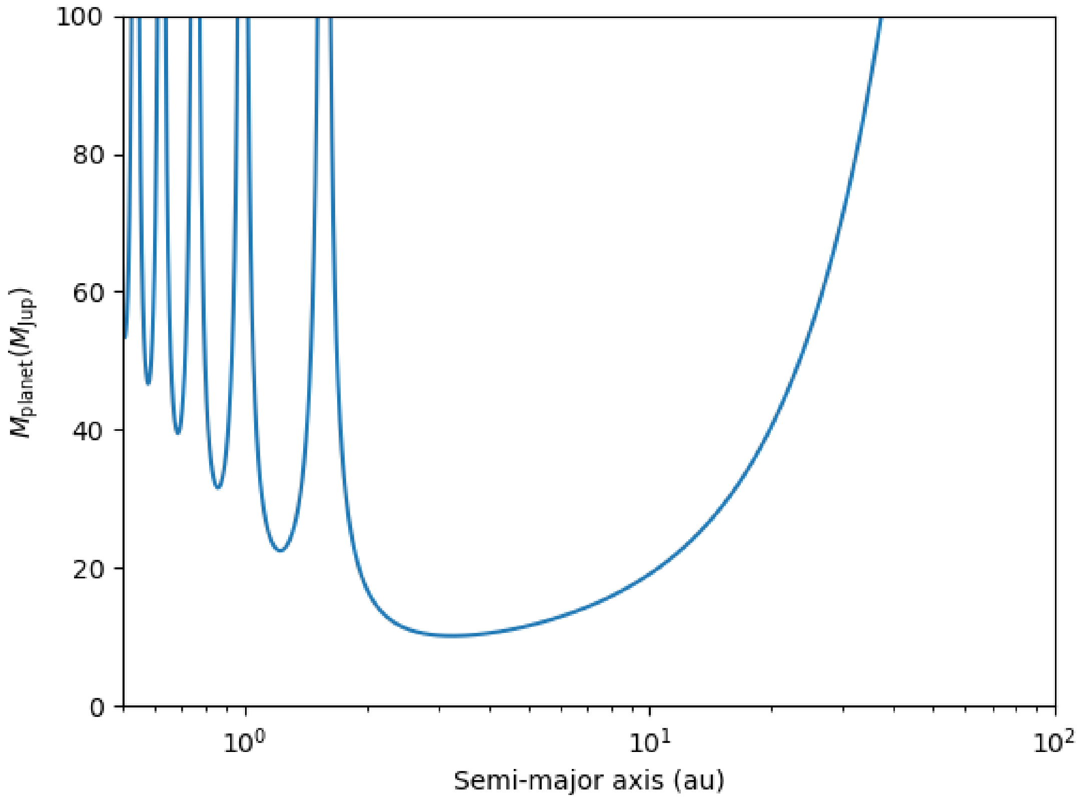
$$v_r = 2\pi M_{planet} a^{1/2} \sin(i) \sin(\theta)$$

$$\frac{\mu_Y}{v_r} = \tan(i)$$

HD 206893 c from Direct imaging and Gaia?

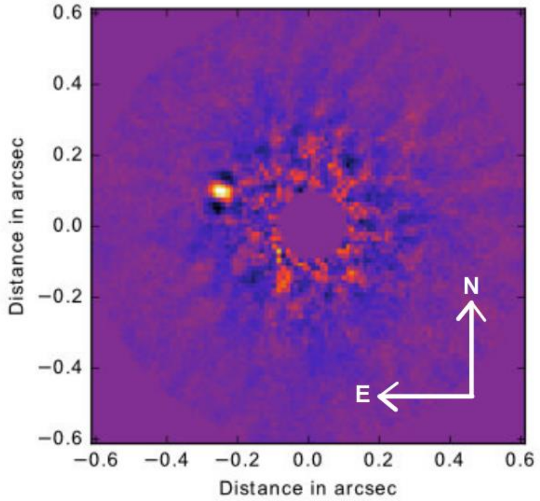


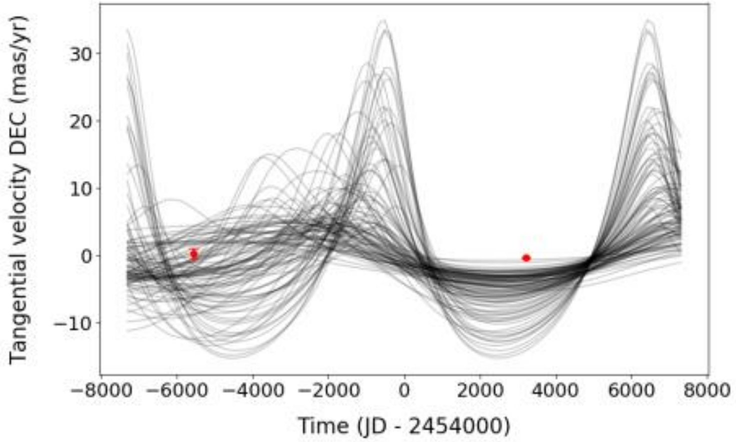


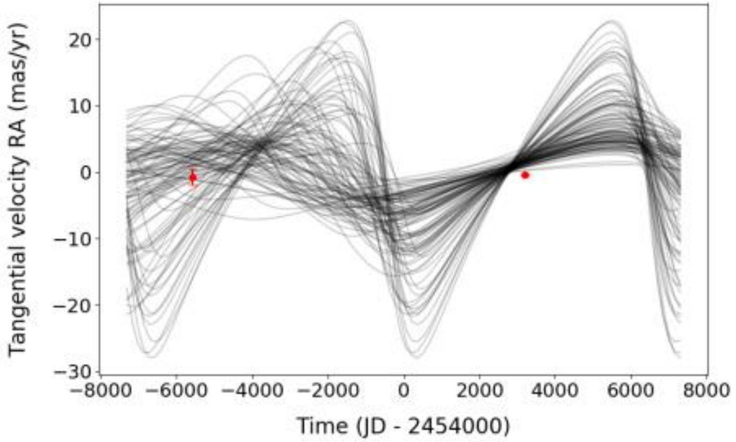


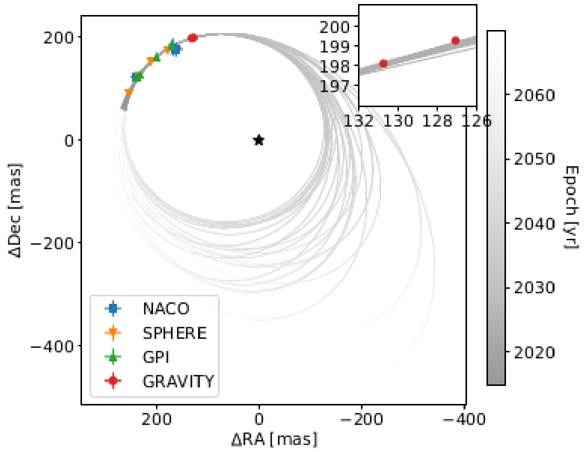
(Figures from Mili+2017, Grandjean+2019, and Kammerer+2021)

HD 206893 c from Direct imaging and Gaia?



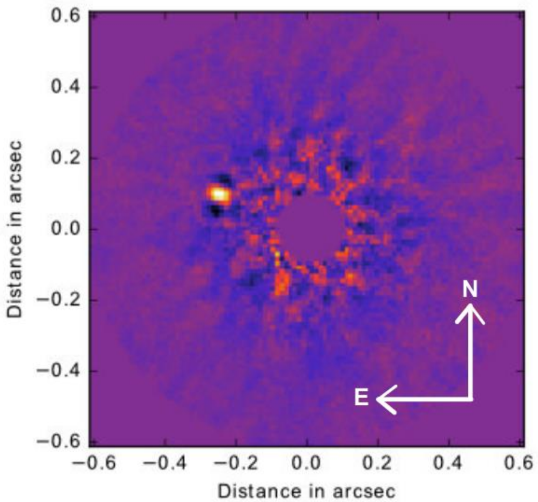


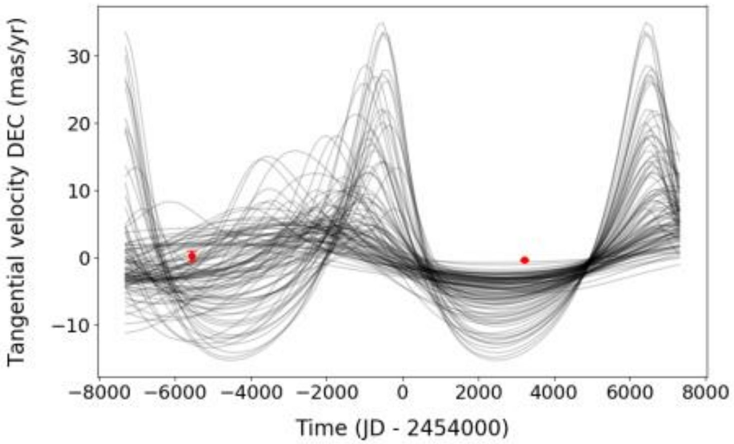


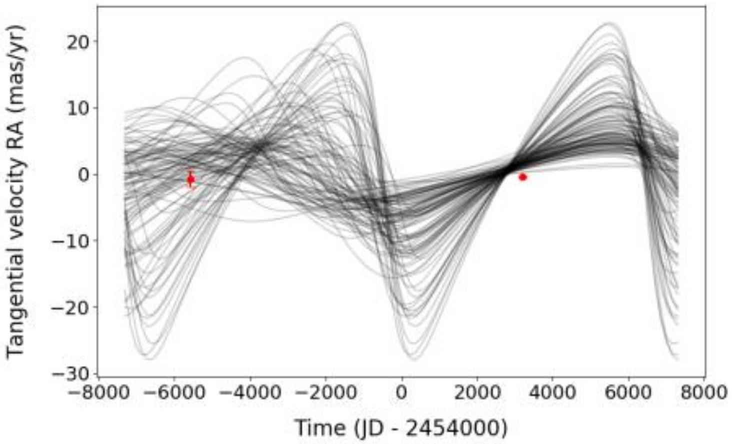


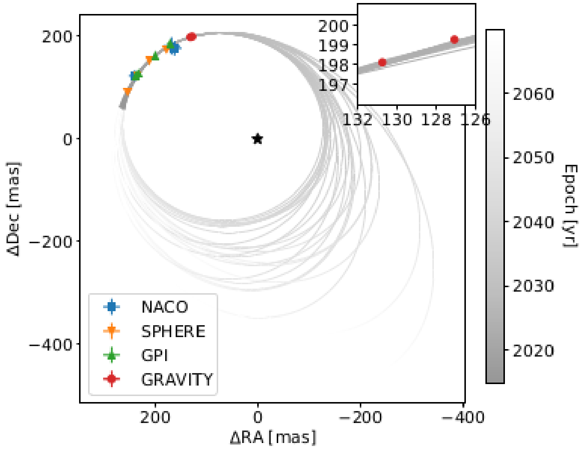
(Figures from Mili+2017, Grandjean+2019, and Kammerer+2021)

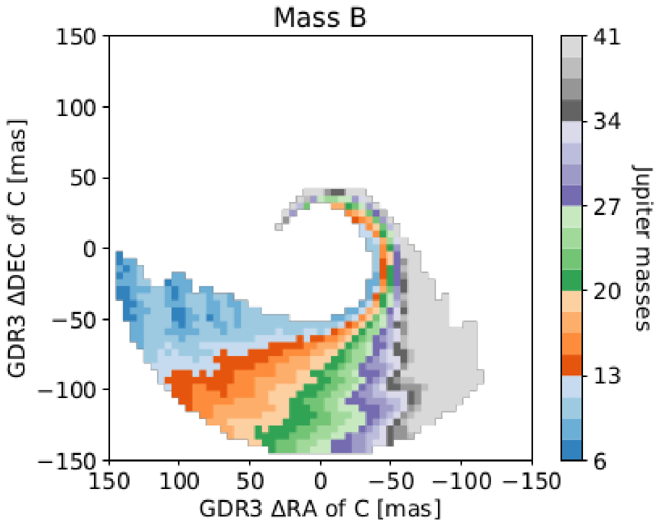
HD 206893 c from Direct imaging and Gaia?

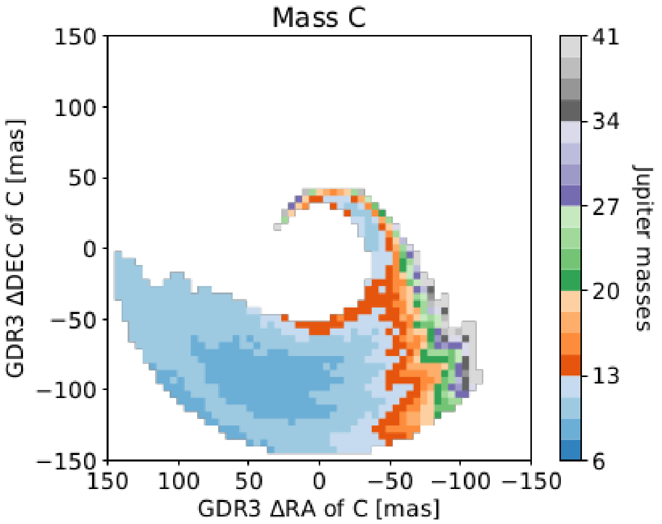






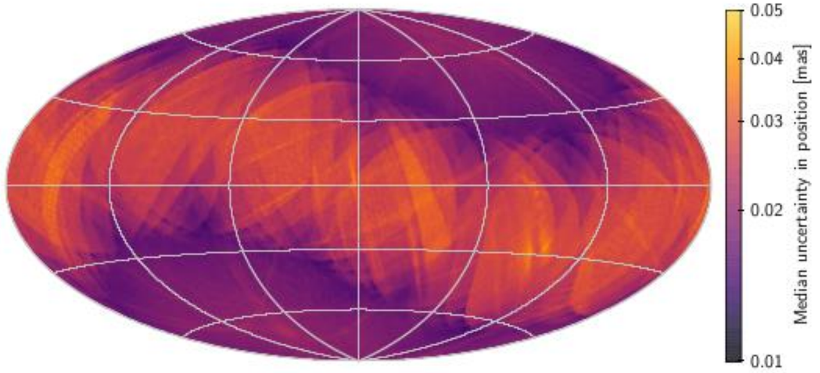


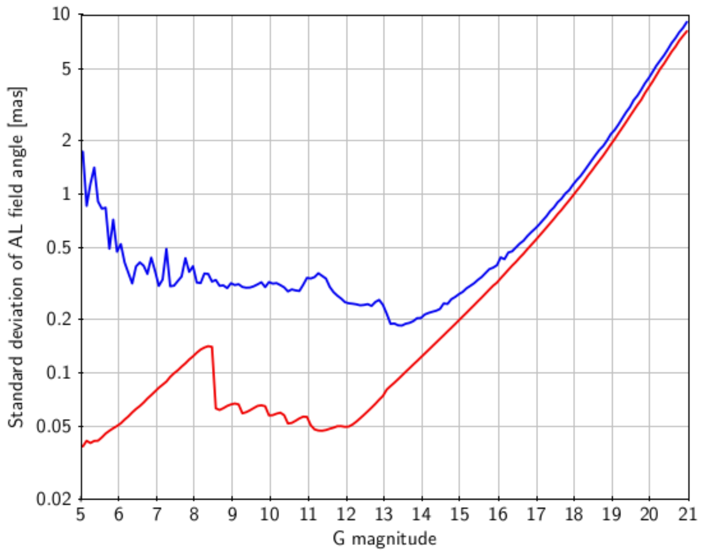




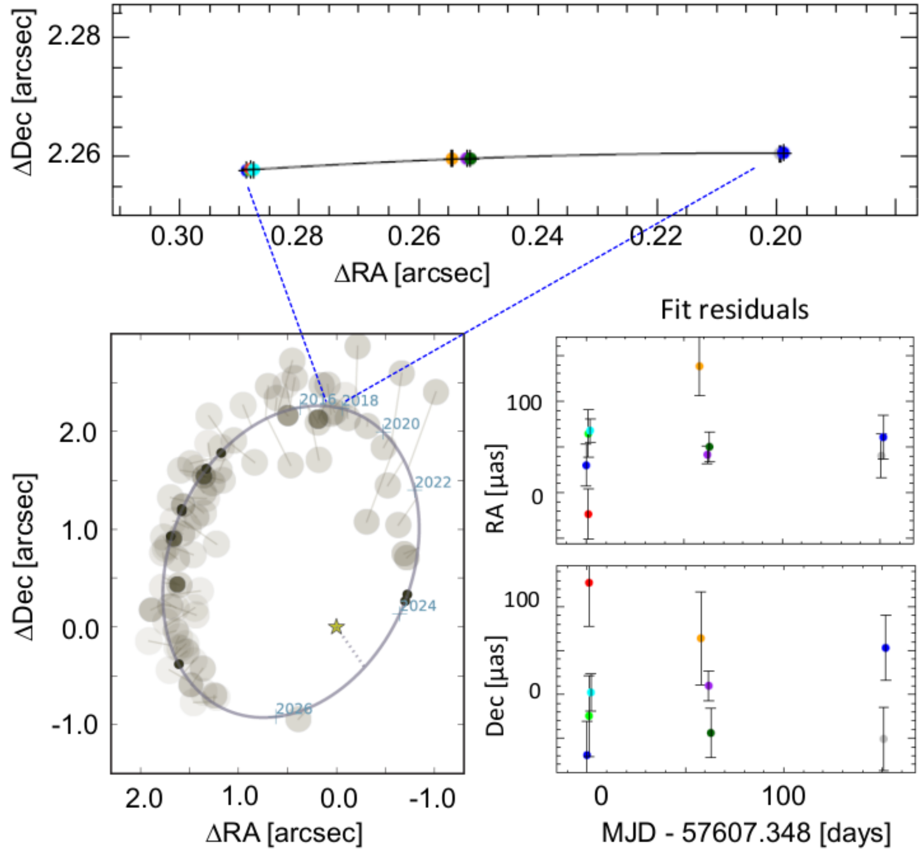
(Figures from Mili+2017, Grandjean+2019, and Kammerer+2021)

Another instrument for high-precision astrometric measurements: GRAVITY





Lindegren+2018, 2021

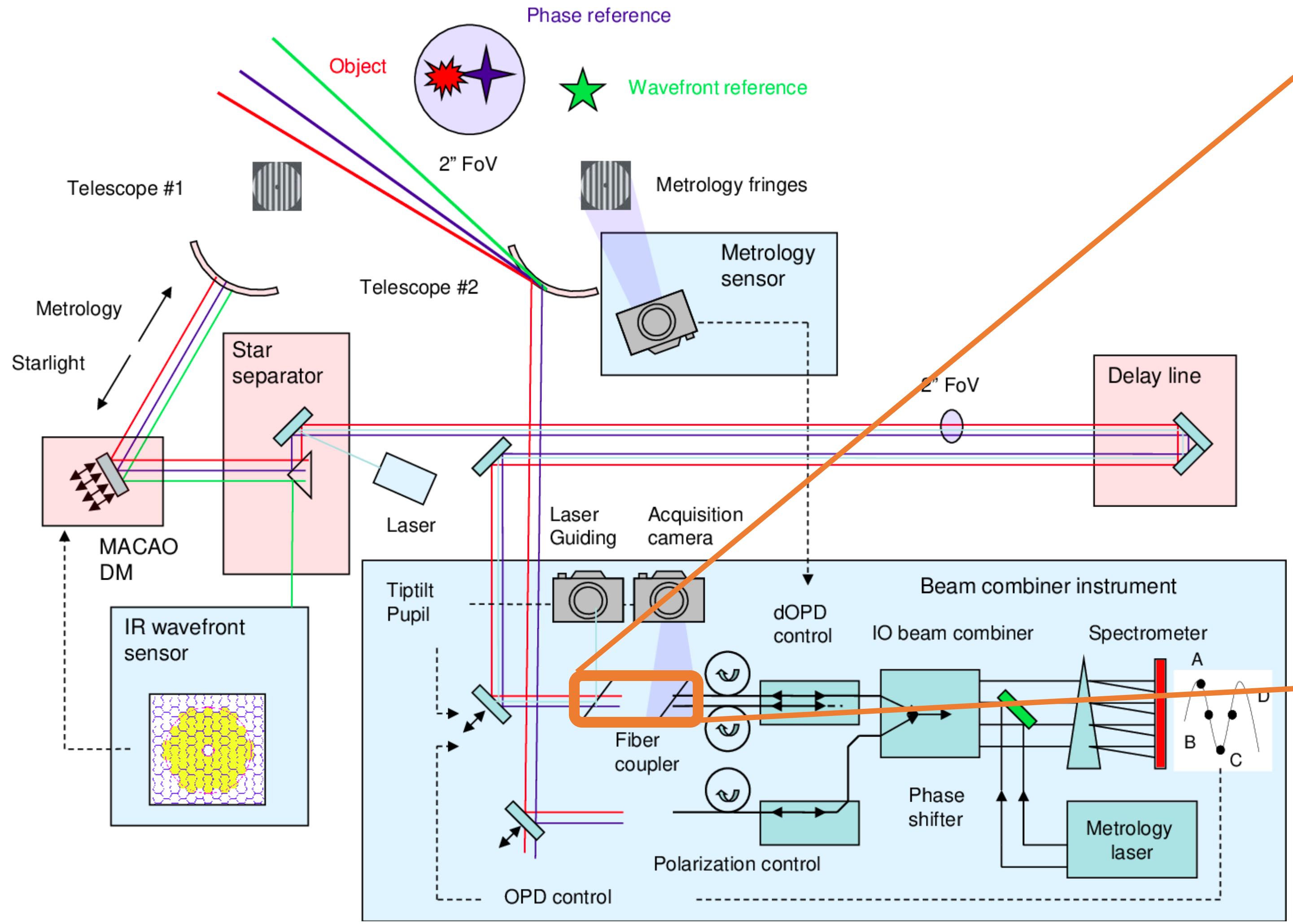


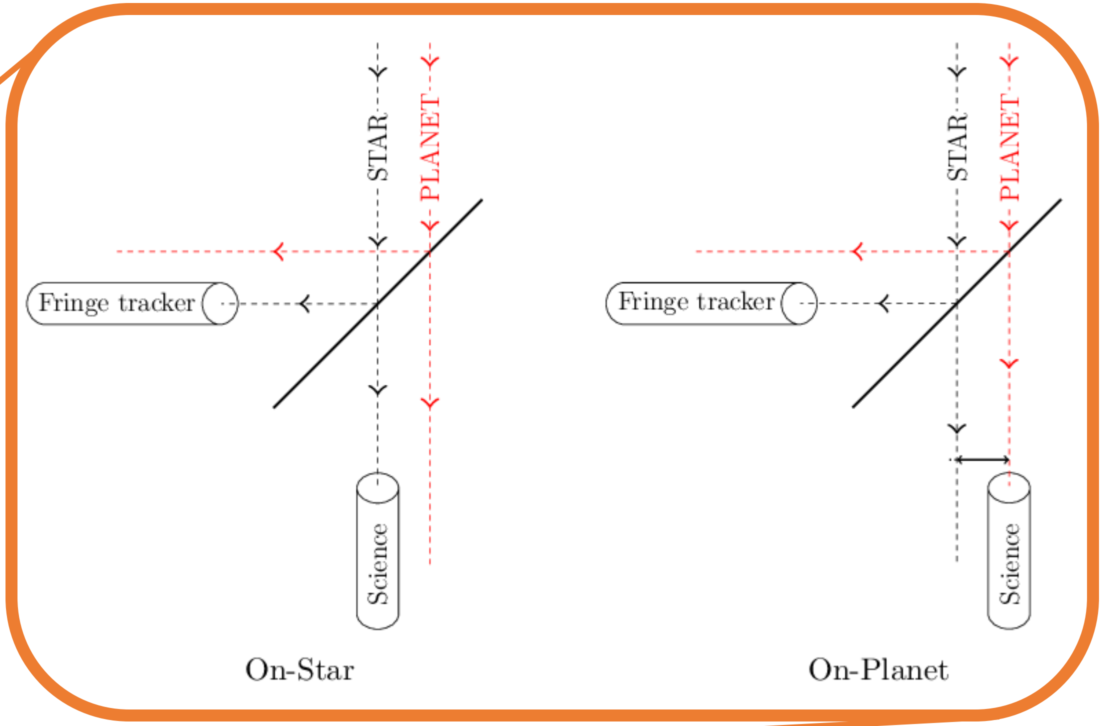
GRAVITY Collaboration 2017

Typical precision with GRAVITY: 10-50 umas

Typical precision with GAIA: 50-200 umas (DR2); up to 10 to 50 umas (eDR3)

VLTI/GRAVITY: a fibered interferometer (and a complicated instrument...)

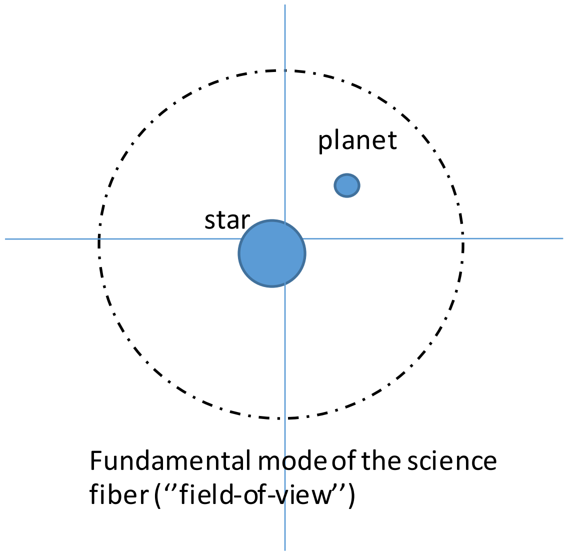




GRAVITY Collaboration (2017)

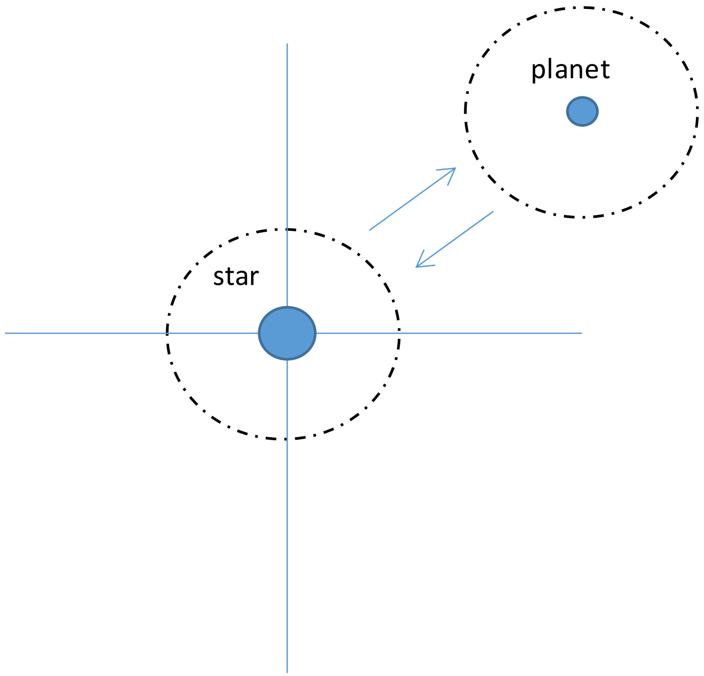
Single-field and dual field interferometry

"Single-field" interferometry



- Binary object unresolved by each telescope of the array
- Science fiber on the photocenter
- Light of both components is injected into the fiber
- Measured signal: visibility modulus and/or closure phase

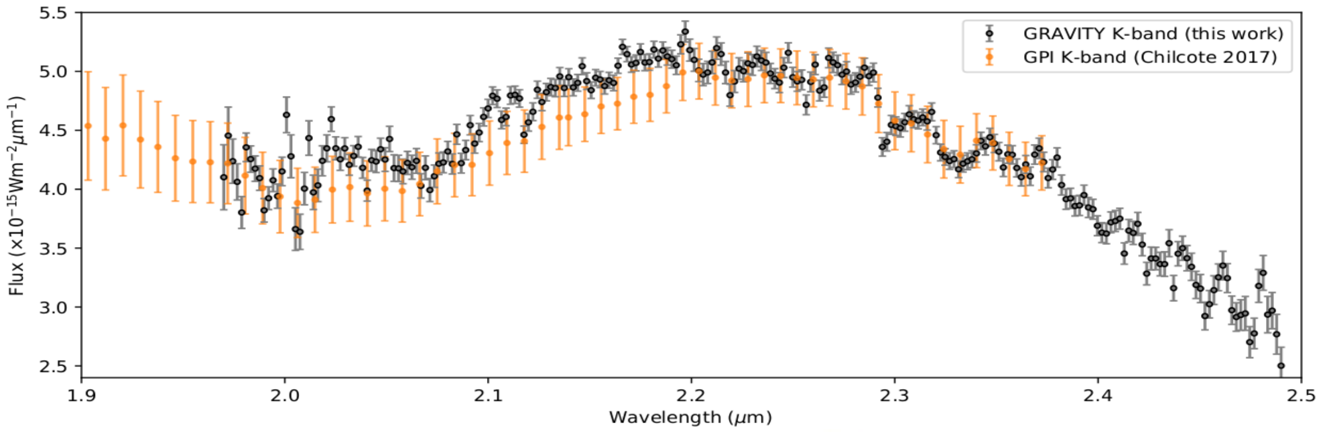
"Dual-field phase-referenced" interferometry

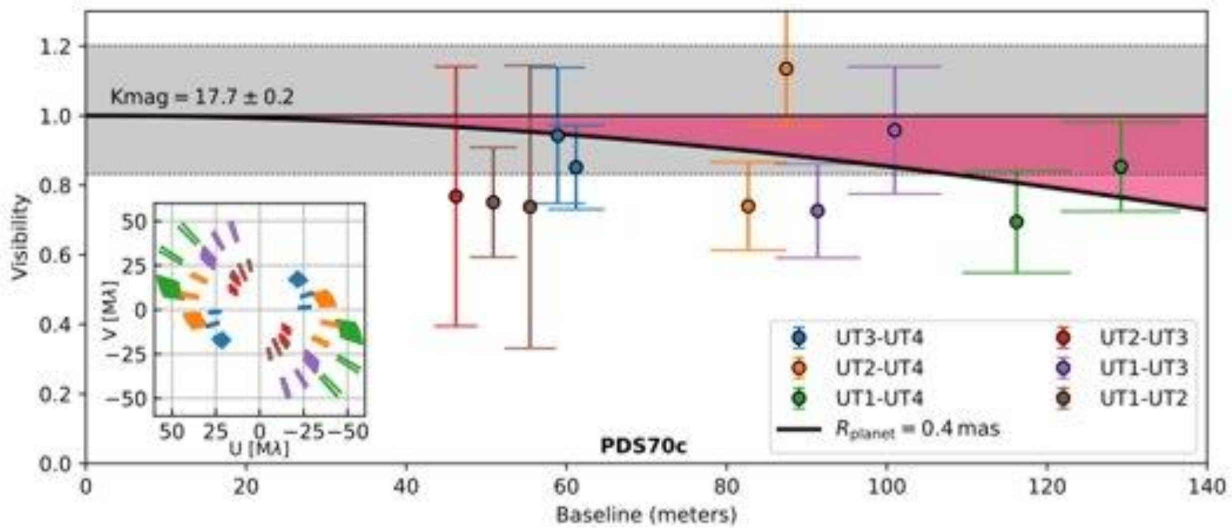


- Binary object resolved by each telescope of the array
- Science fiber moves from one component to the other
- Measured signal: complex visibilities referenced to the star

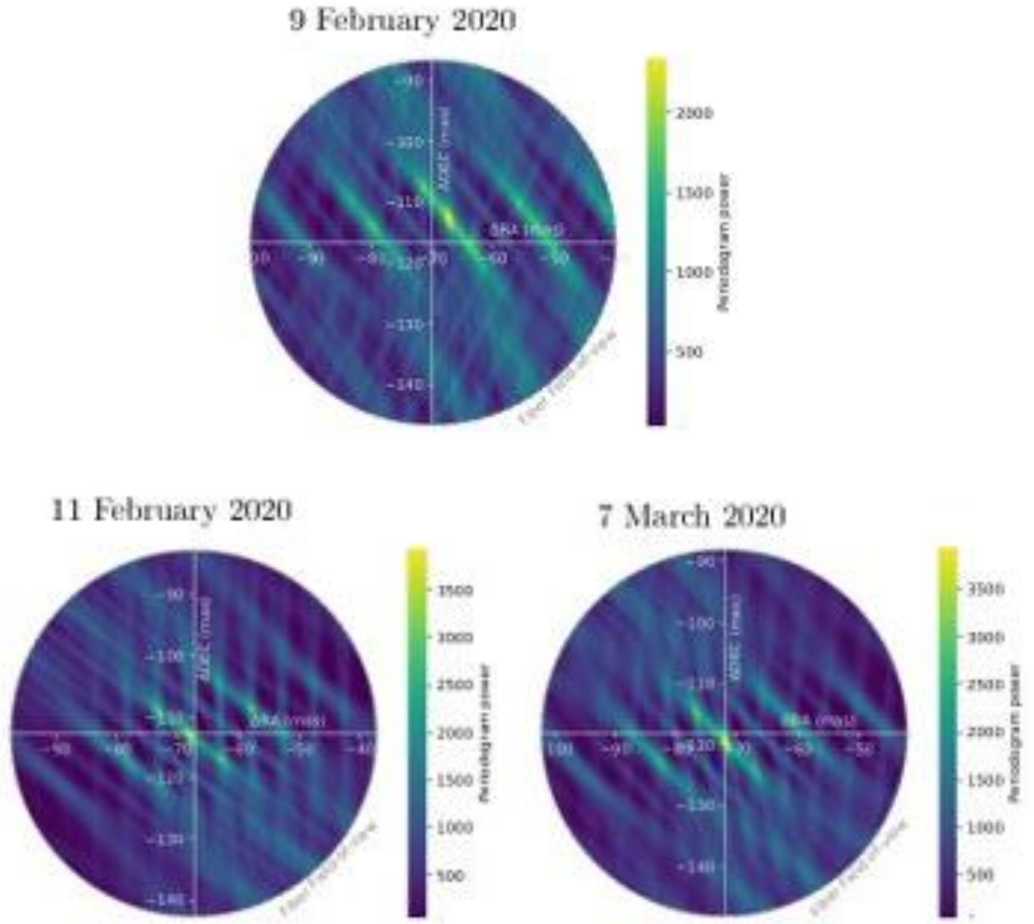
ExoGRAVITY results

Medium resolution K-band spectroscopy on beta Pic b



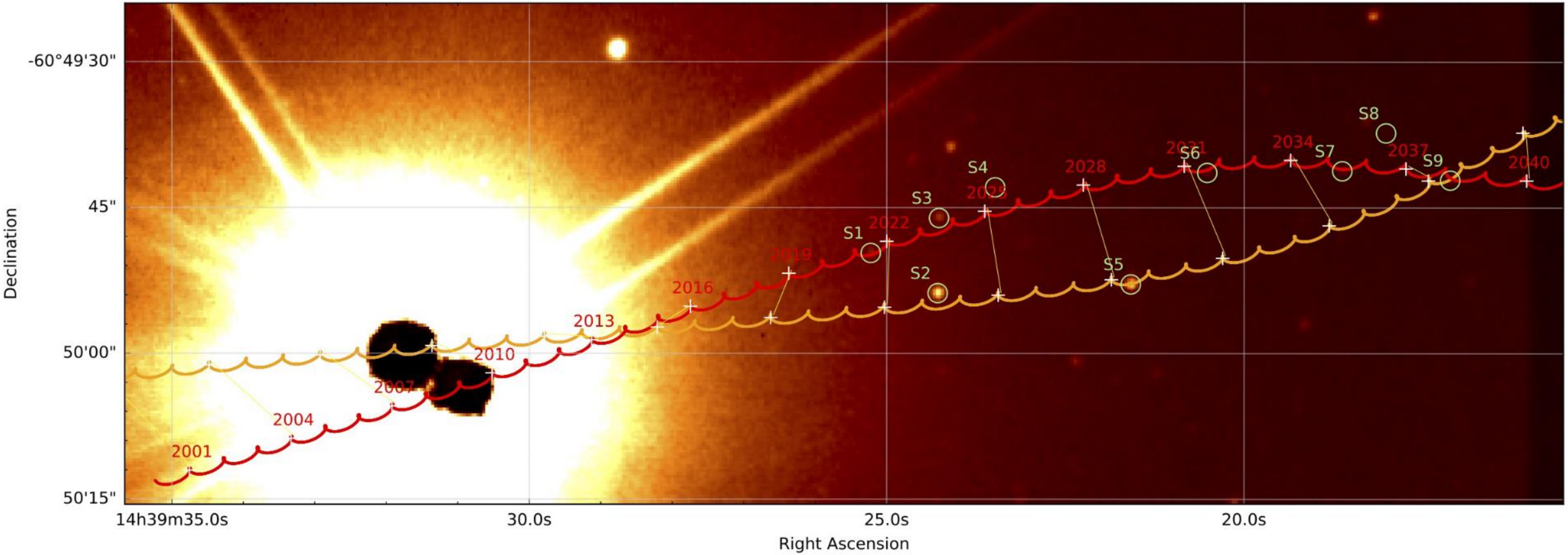


Constraining the size of any circumplanetary disk around PDS70c

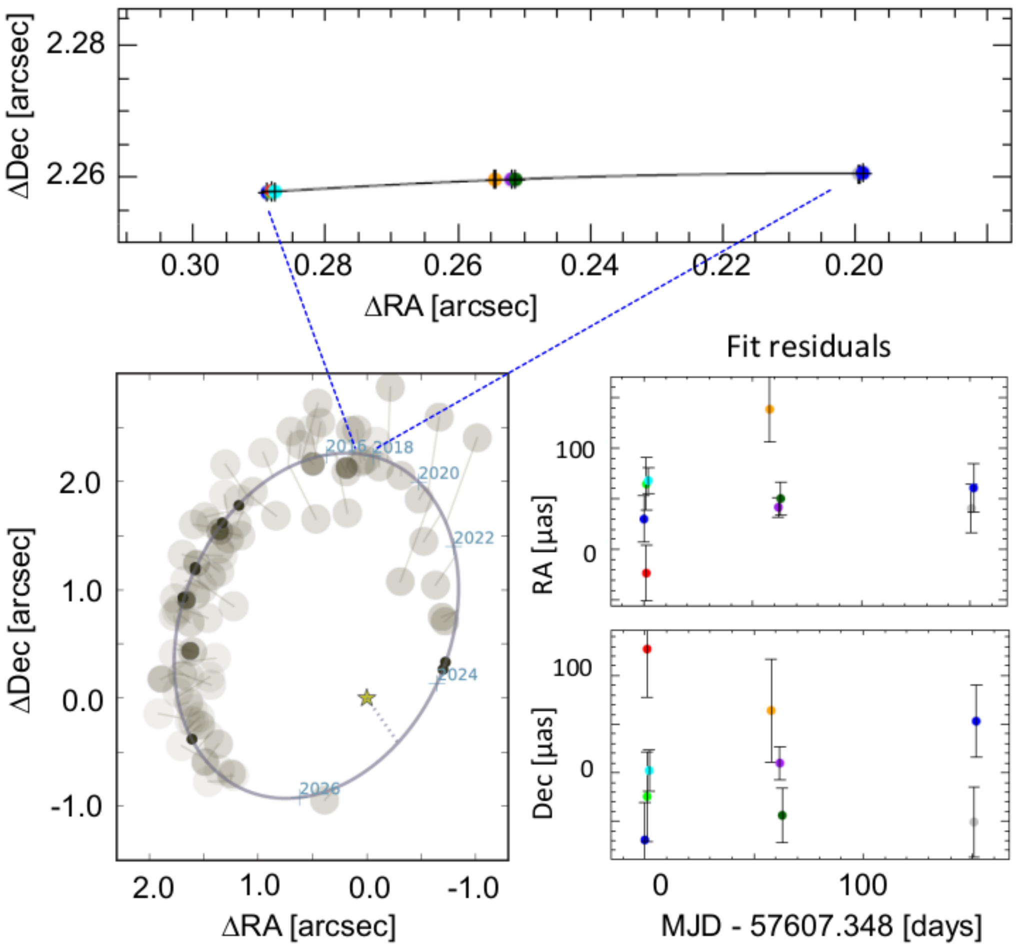


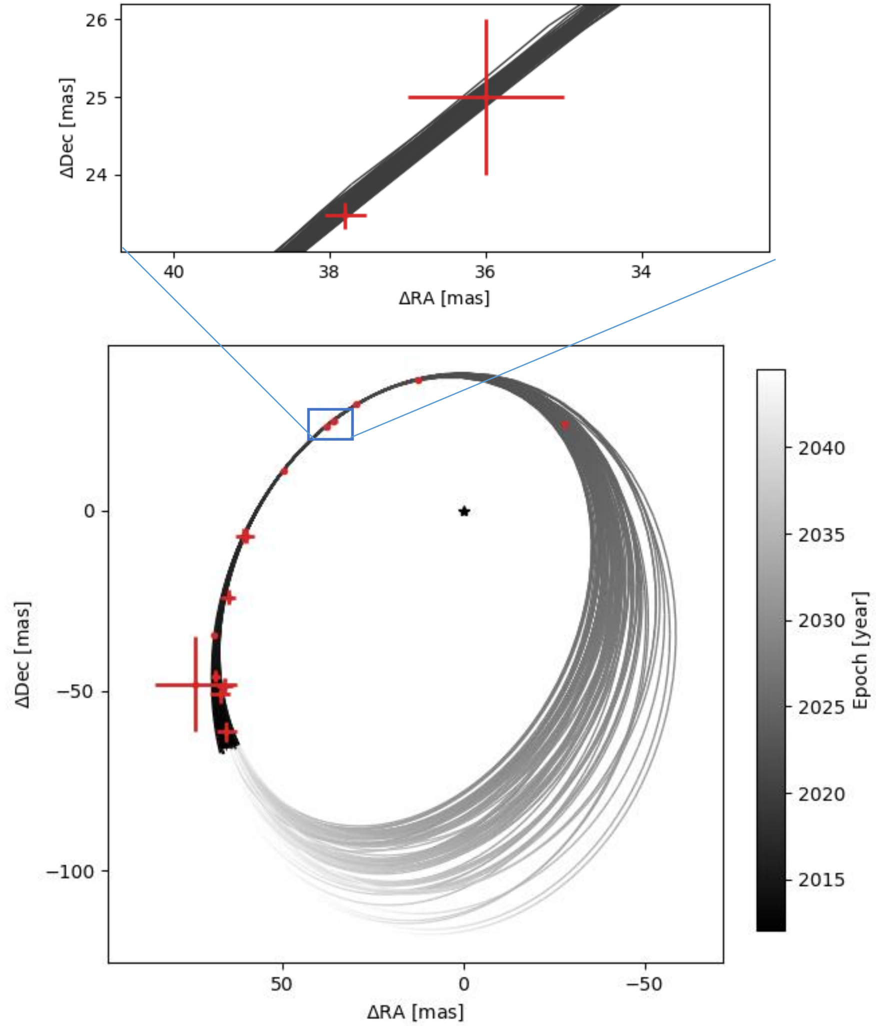
Direct detection of the RV planet beta Pic c

Long term astrometric survey with multiple stellar conjunctions



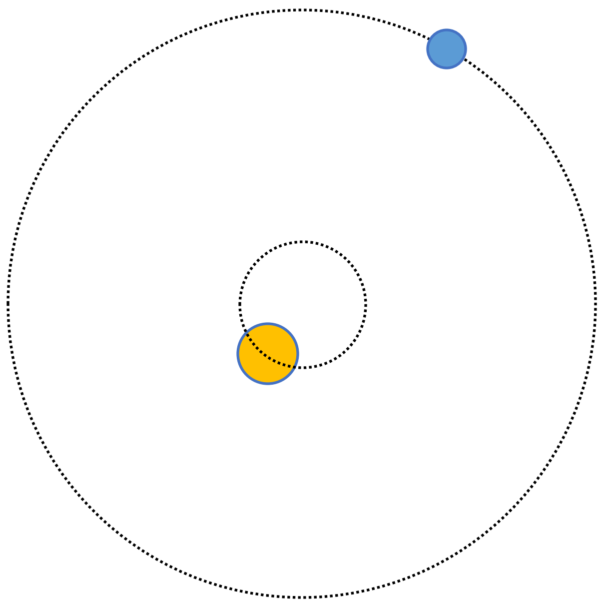
- Apparent motion of Alpha Cen A and B on the sky, with conjunctions with several stars over the next 30 years (Kervella+2016)
- Each conjunction gives the opportunity to observe with GRAVITY





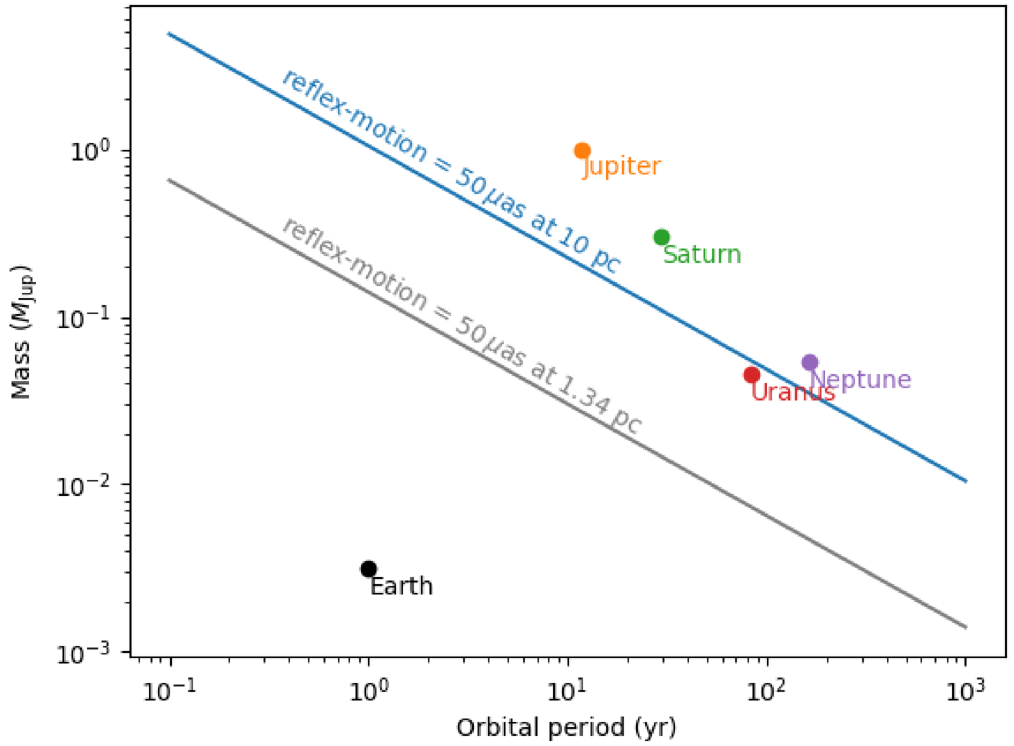
Gravity Collaboration et al. 2017)

Long term astrometric survey with multiple stellar conunctions

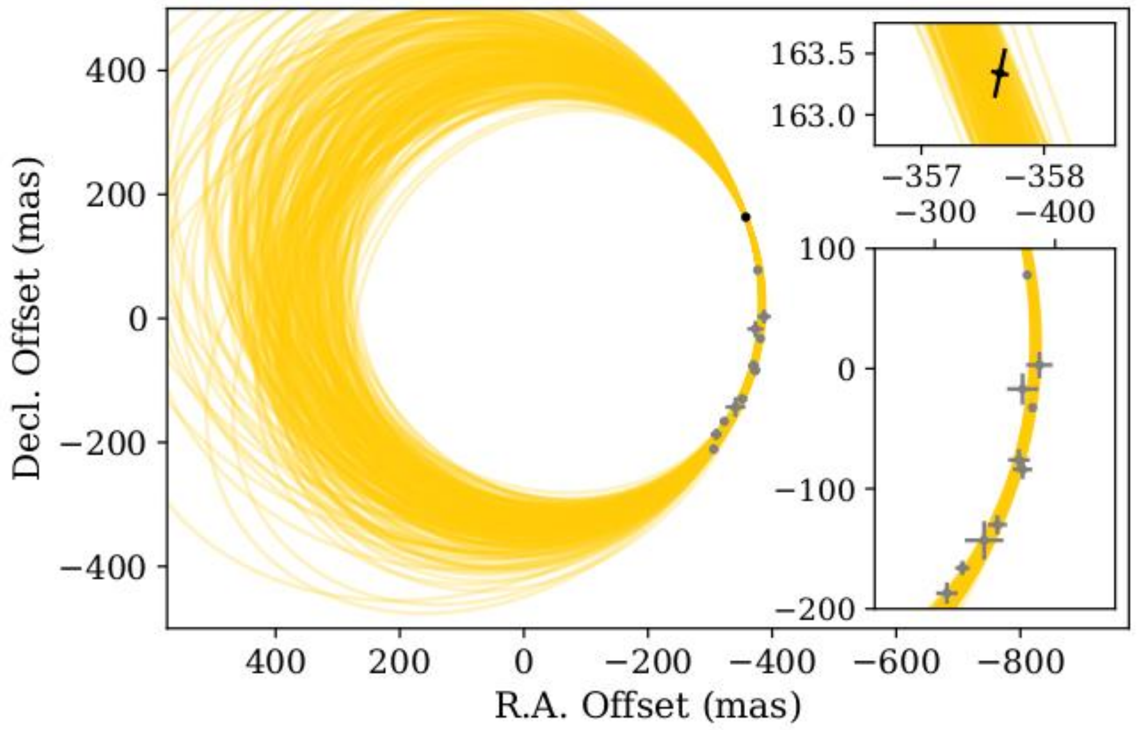


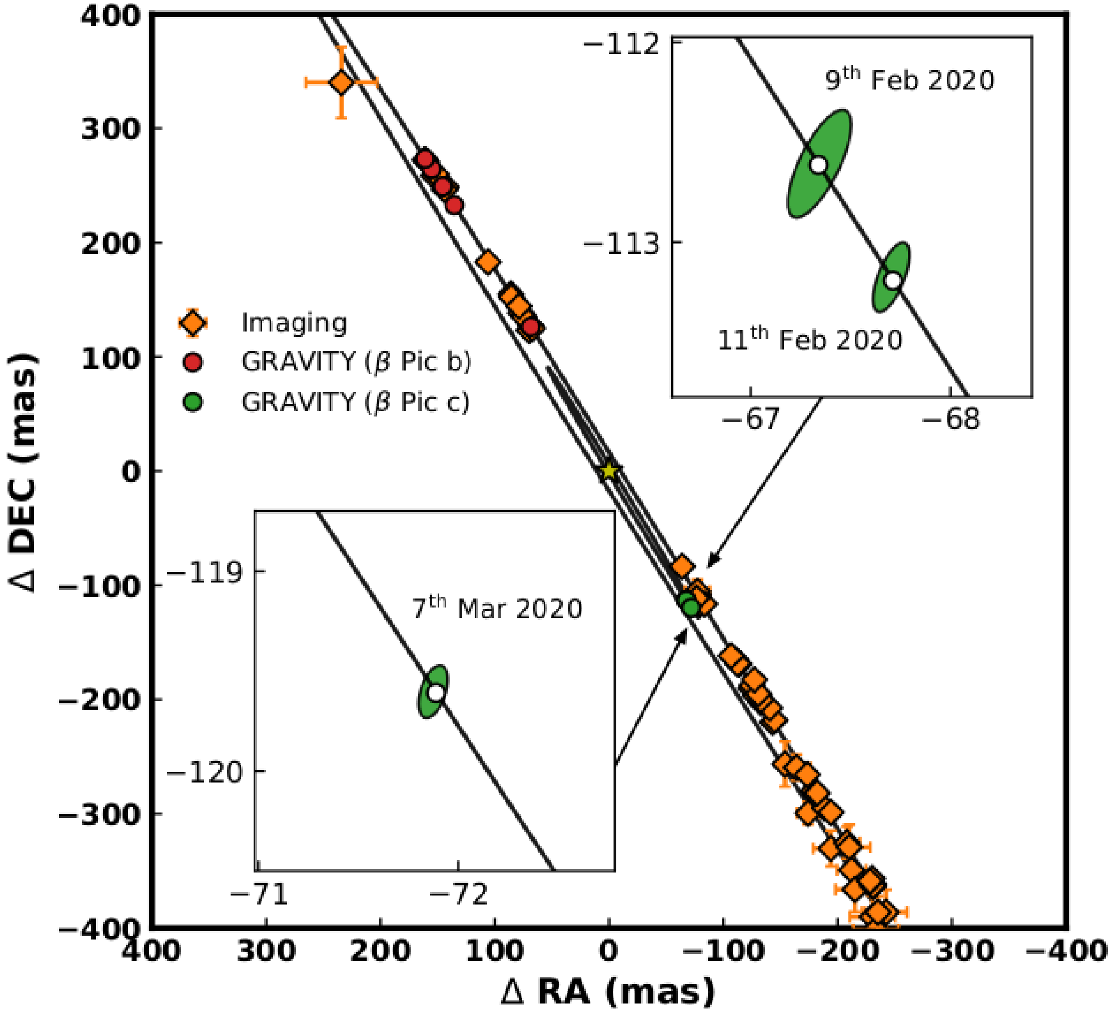
For a sun-like star at 10 pc, and a planet of 1 M_{Jup} orbiting at 1 au:

$$\begin{pmatrix}\Delta\alpha \\ \Delta\delta\end{pmatrix} = \frac{M_{planet}}{M_{star}} \frac{a}{d} \begin{pmatrix}\cos\left(\frac{2\pi}{P}t\right) \\ \sin\left(\frac{2\pi}{P}t\right)\end{pmatrix}$$



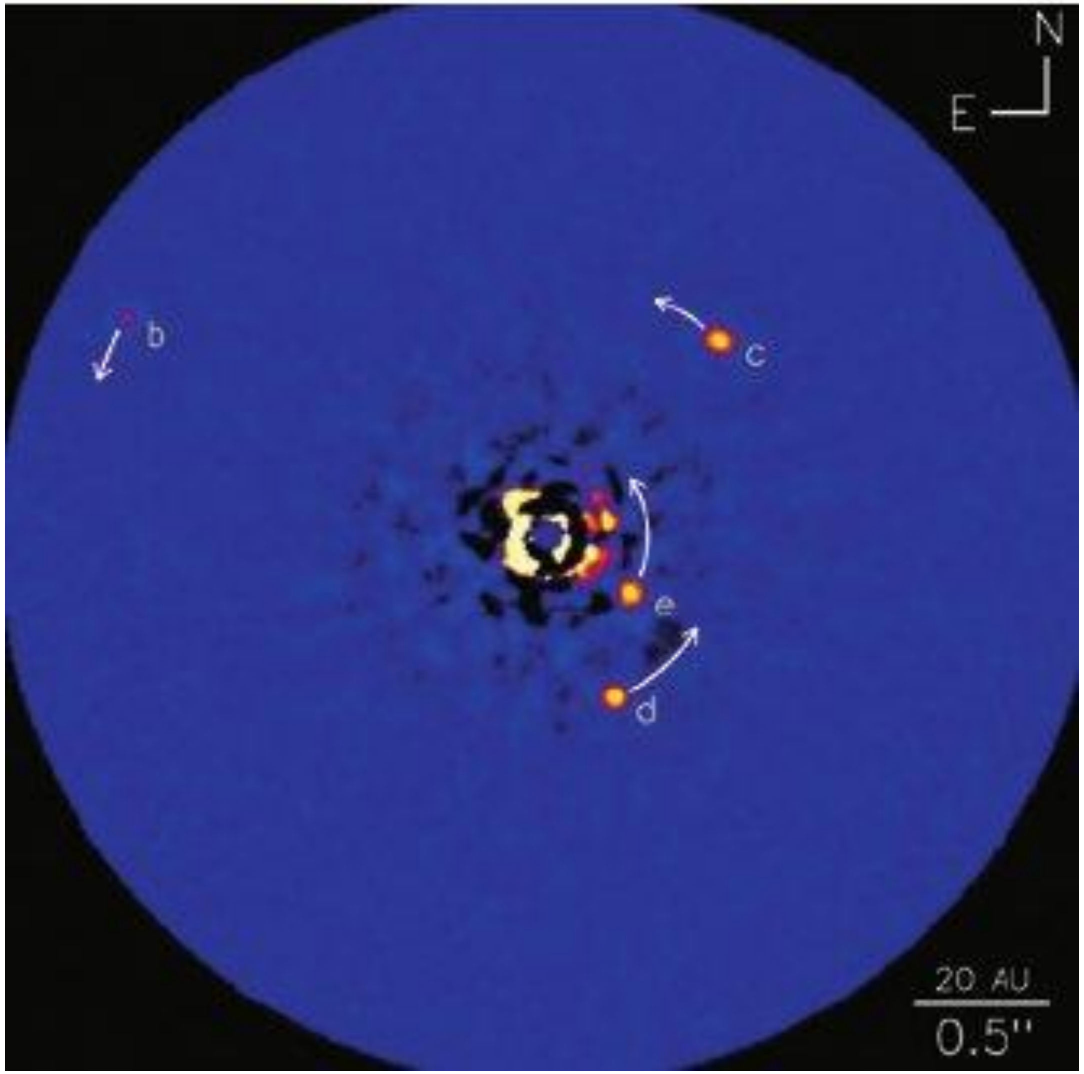
High precision astrometry on exoplanets

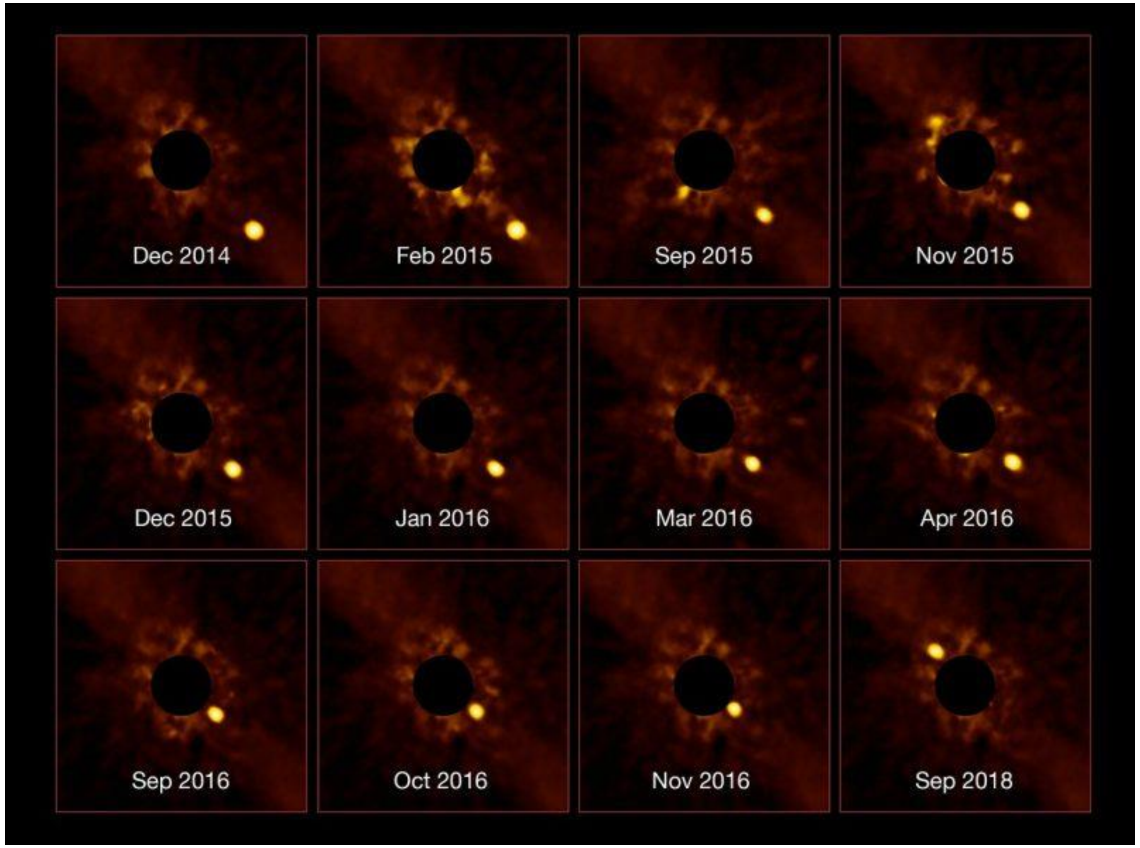




- The 50 umas precision obained with GRAVITY only loosely depends on the magnitude
- This level of precision is also obtained on planet to star relative astrometry

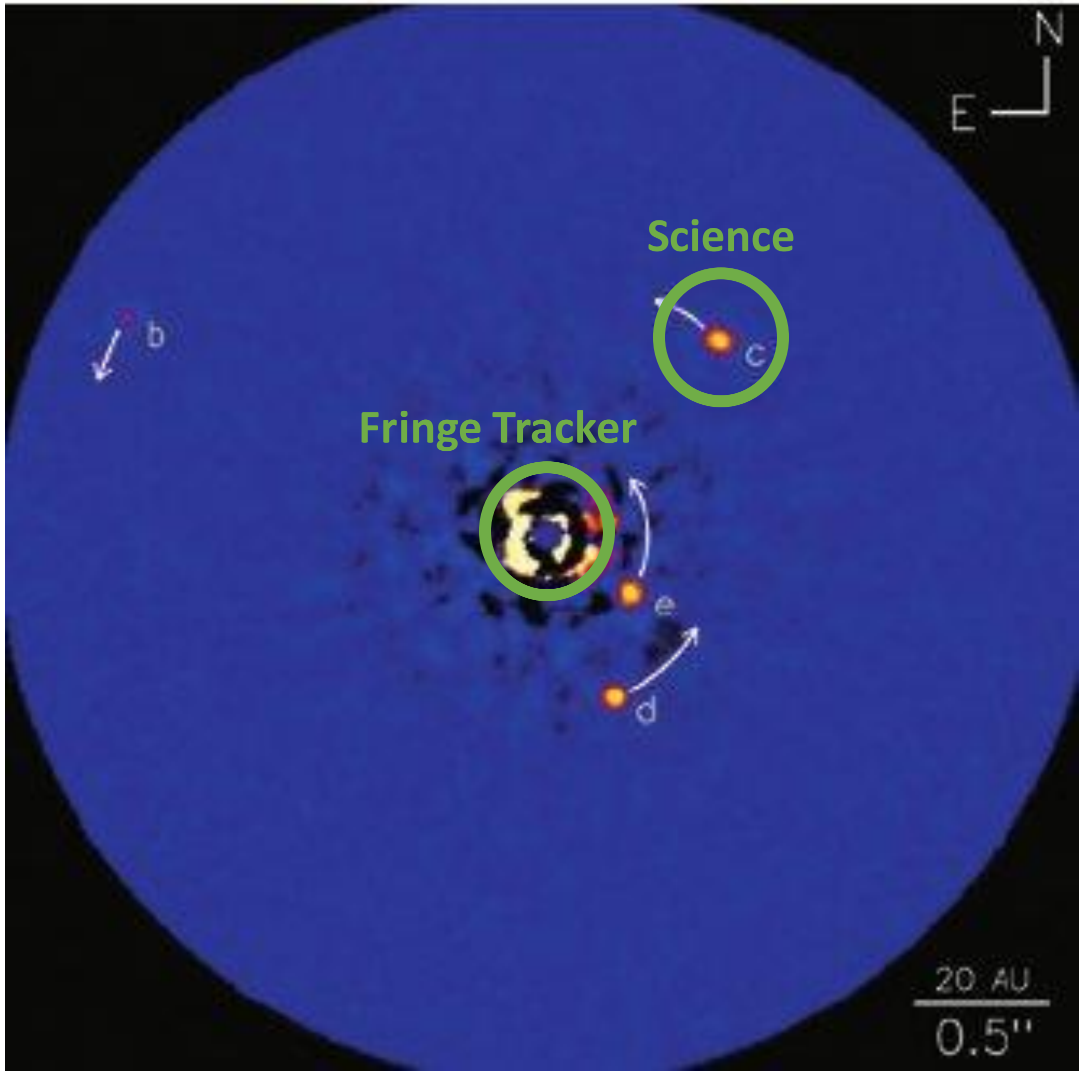
"Stellar astrometry" relative to the planet

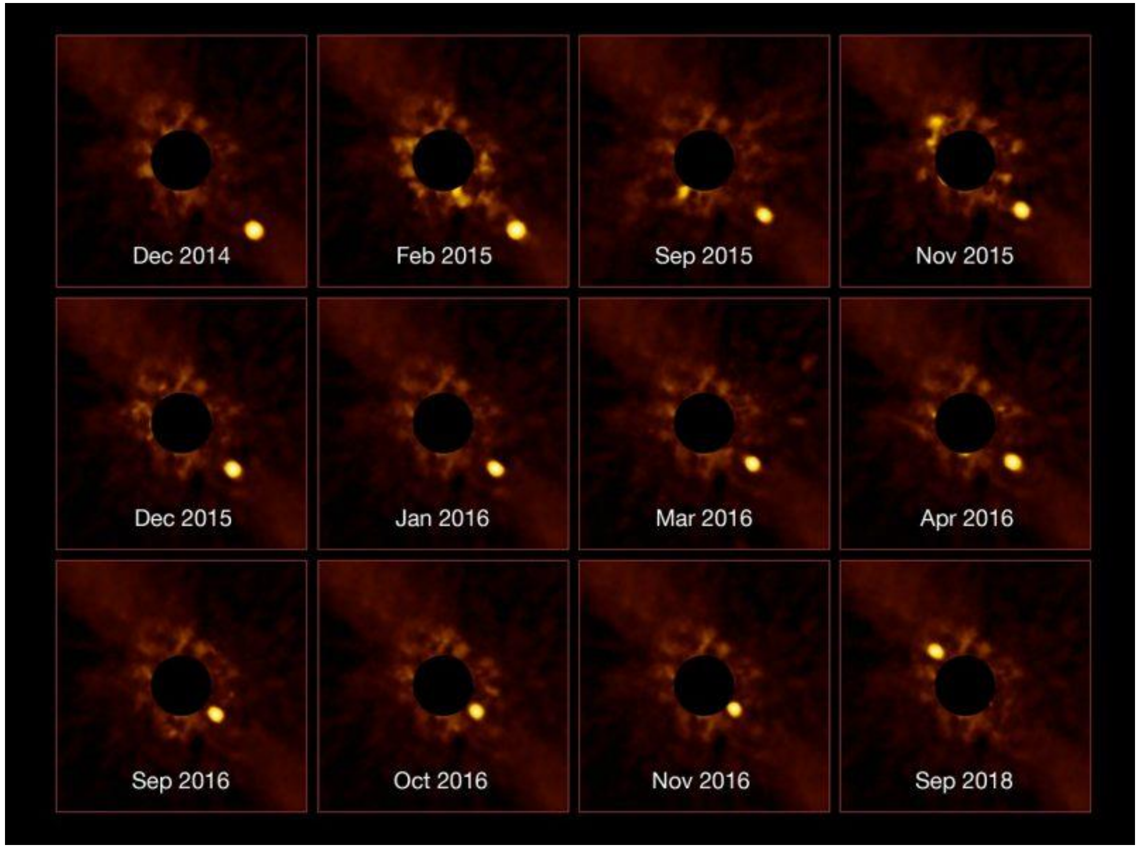




- A star-planet system is also a binary!
- So... can we use the planet as a reference point for doing stellar astrometry?

"Stellar astrometry" relative to the planet





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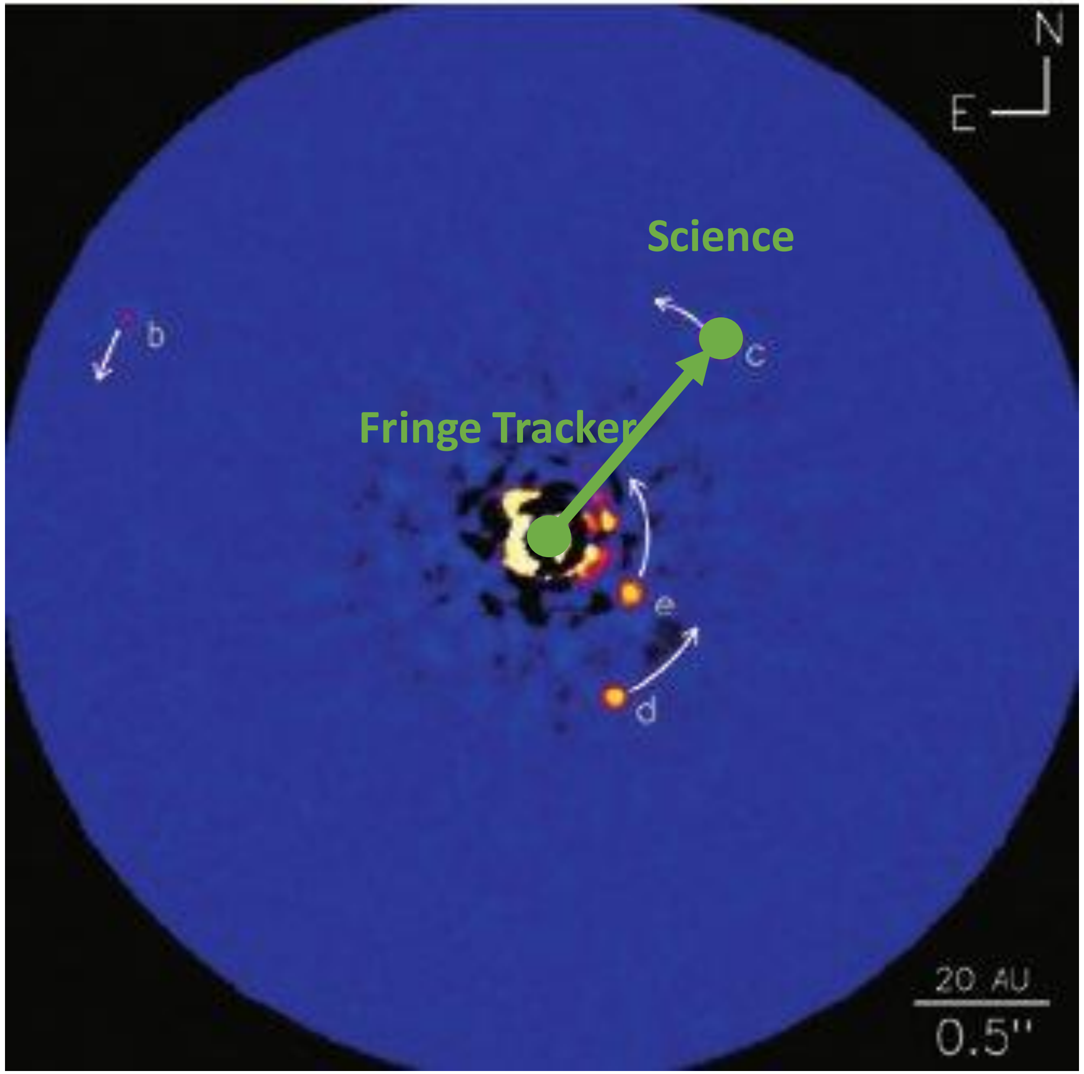

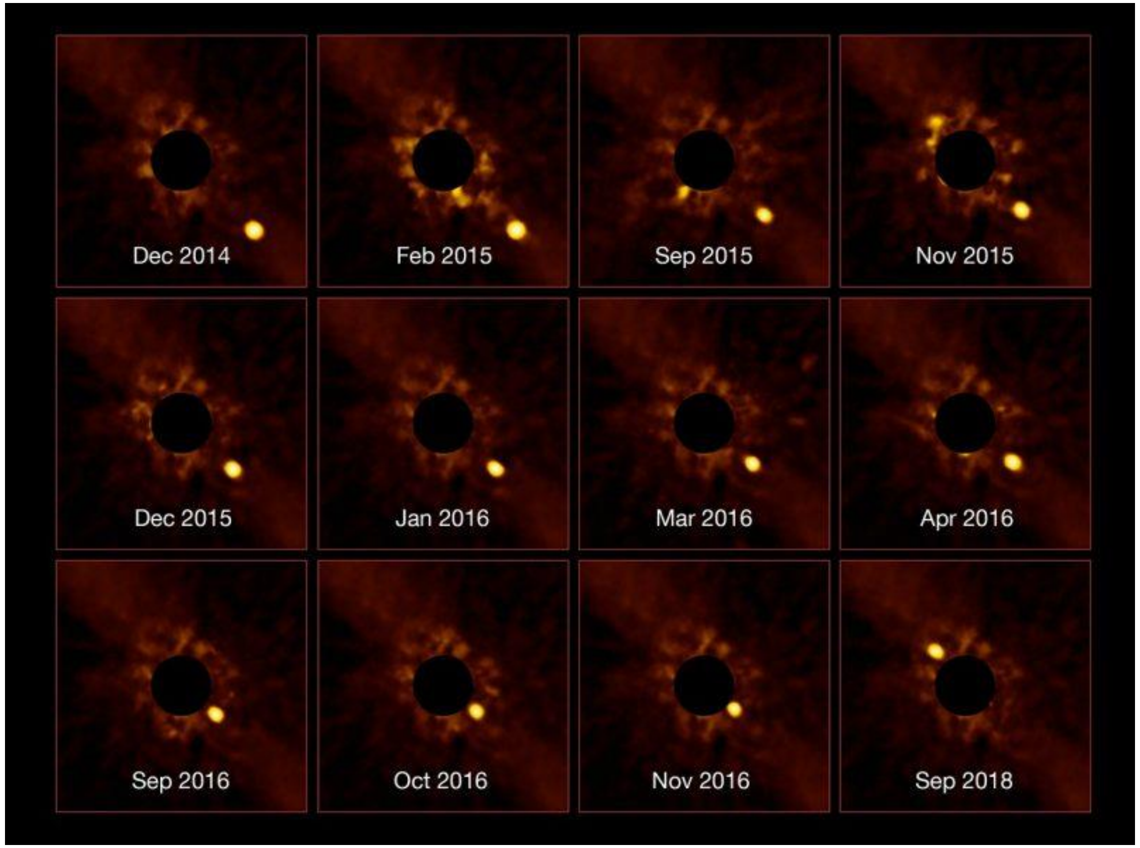

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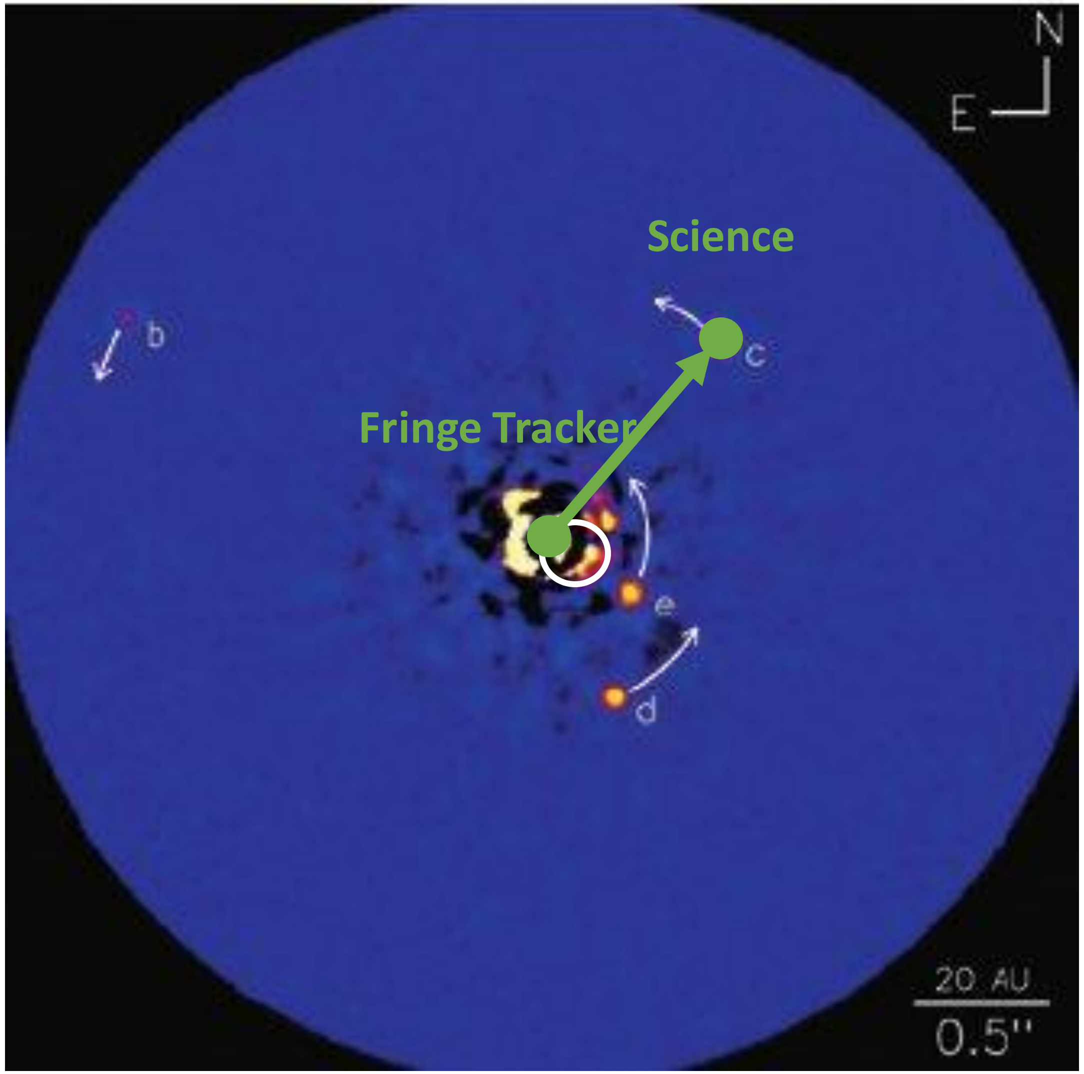

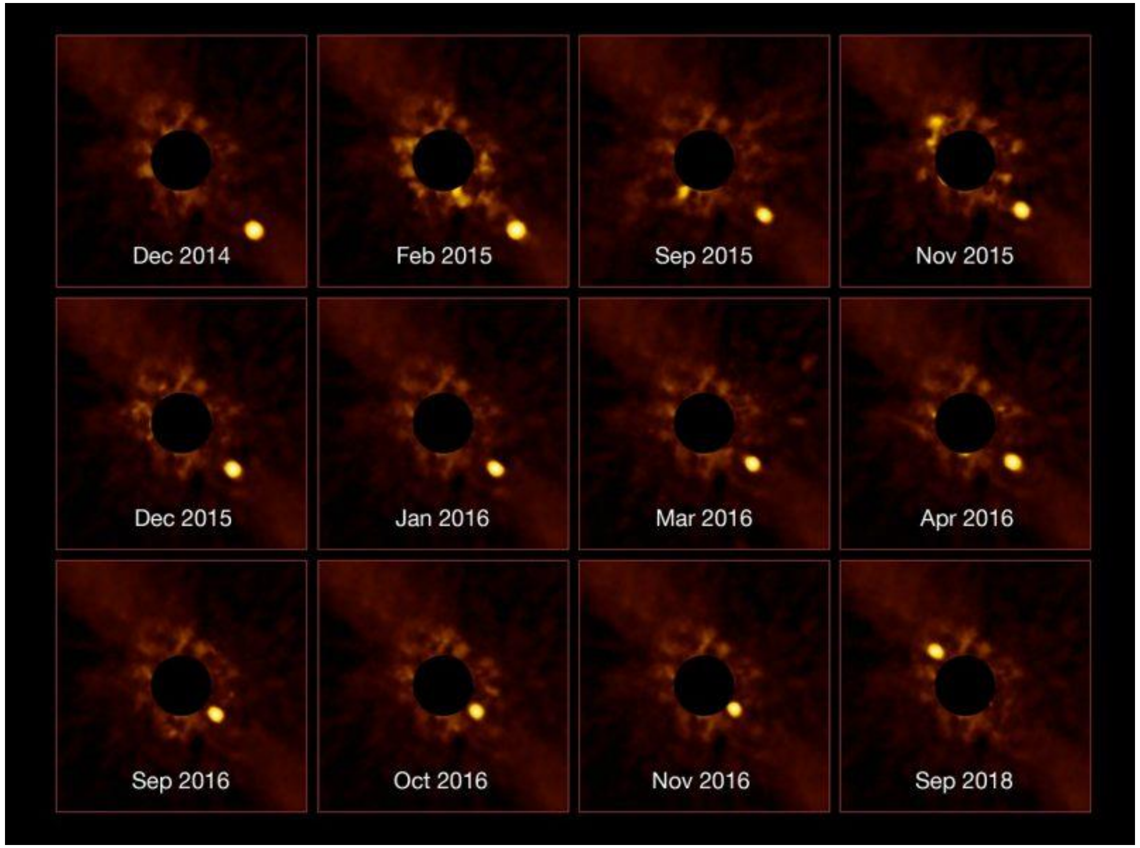

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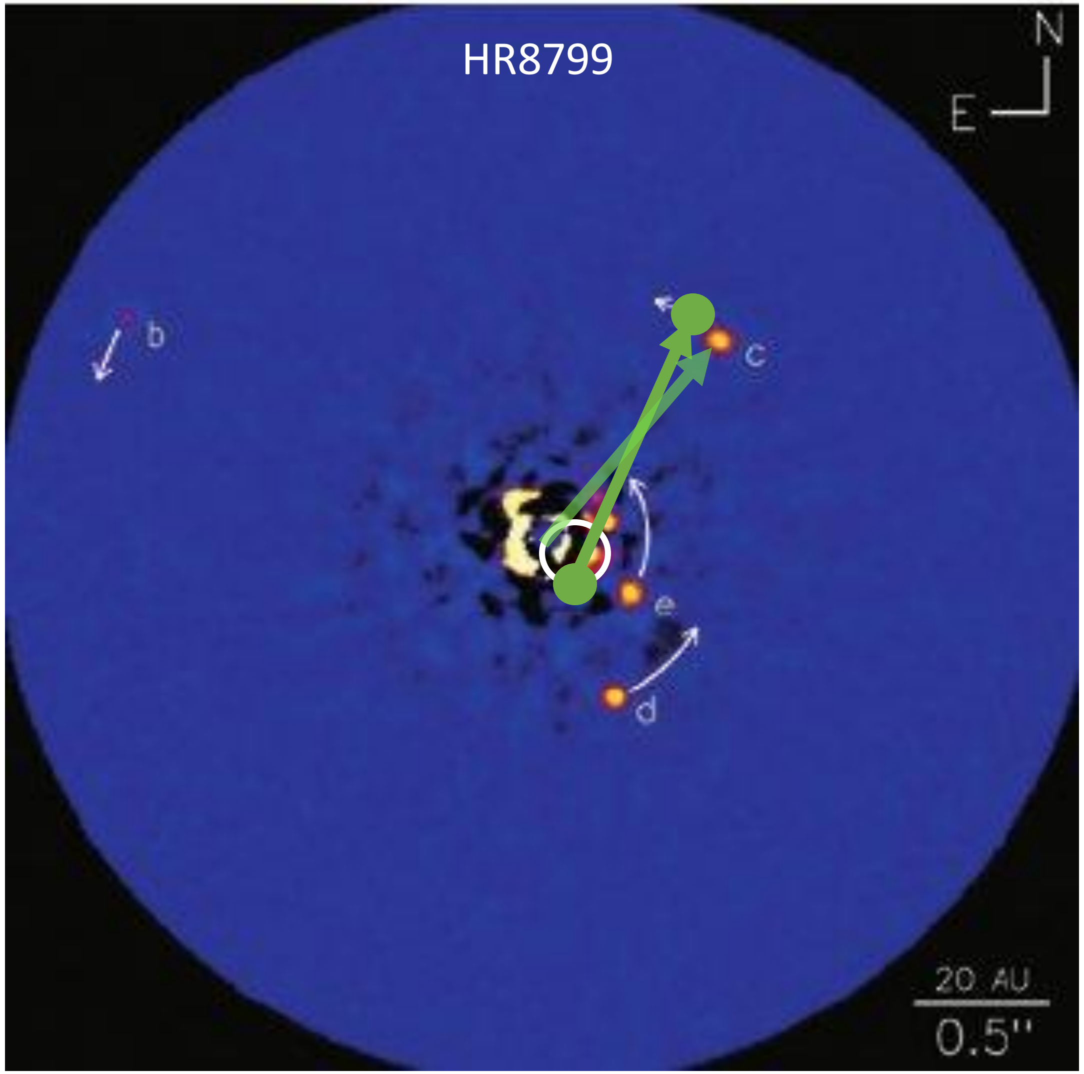
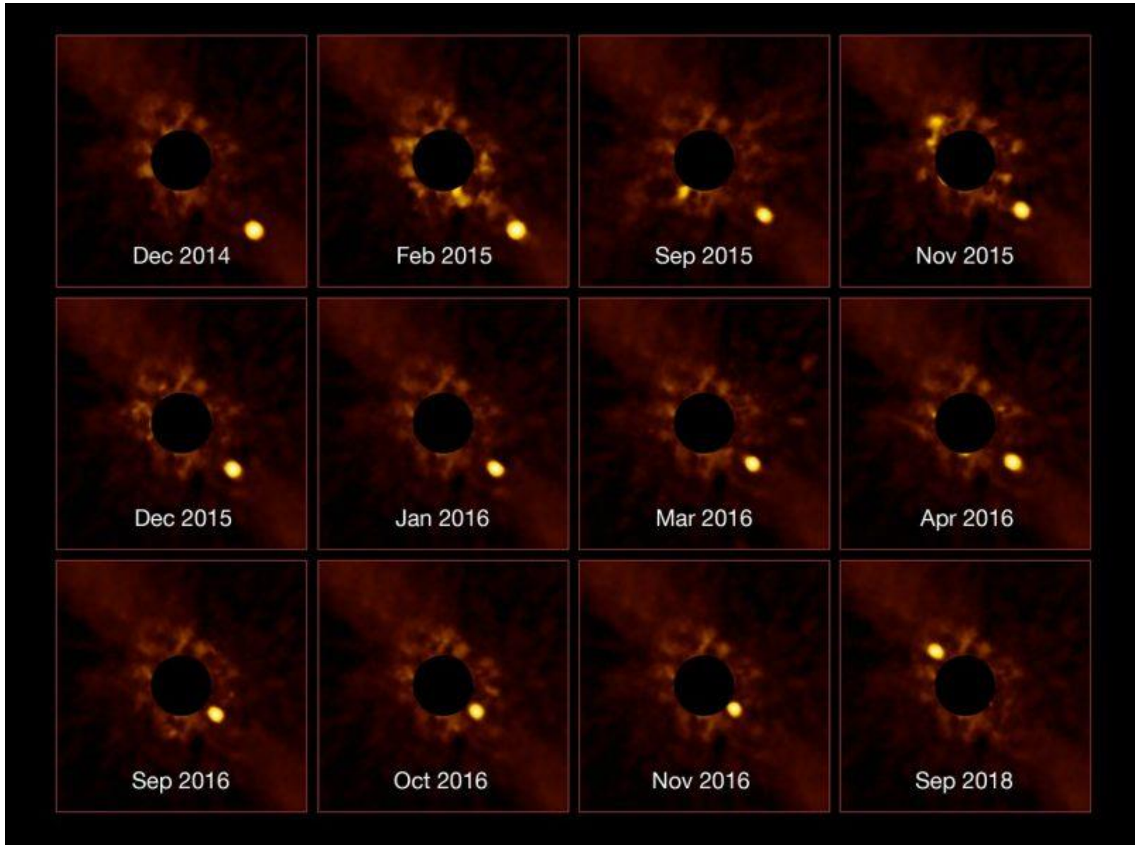
"Stellar astrometry" relative to the planet

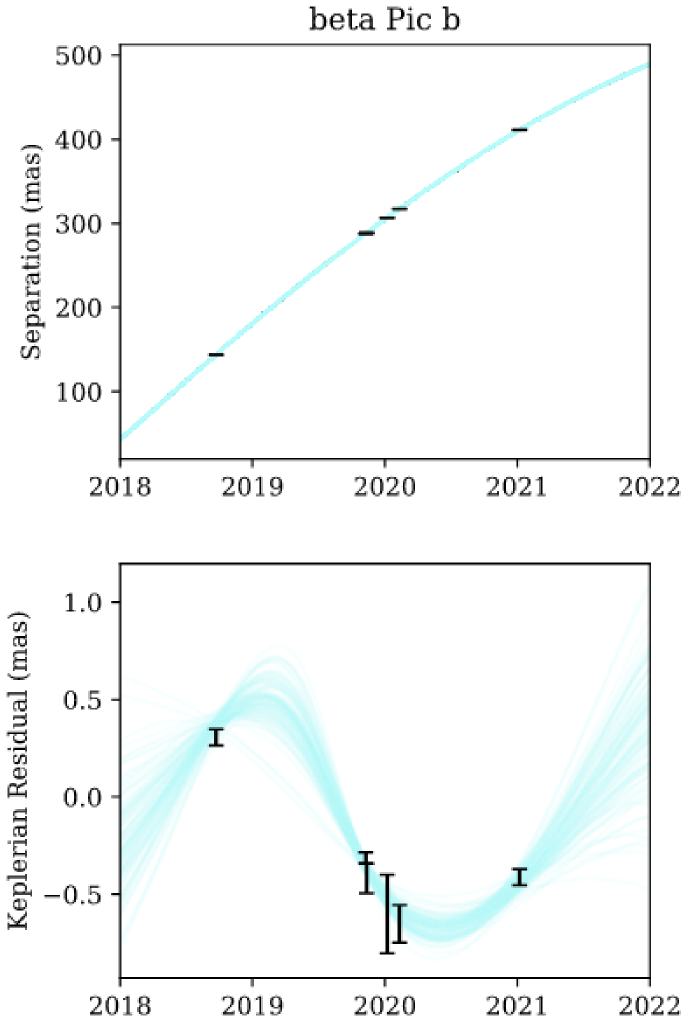


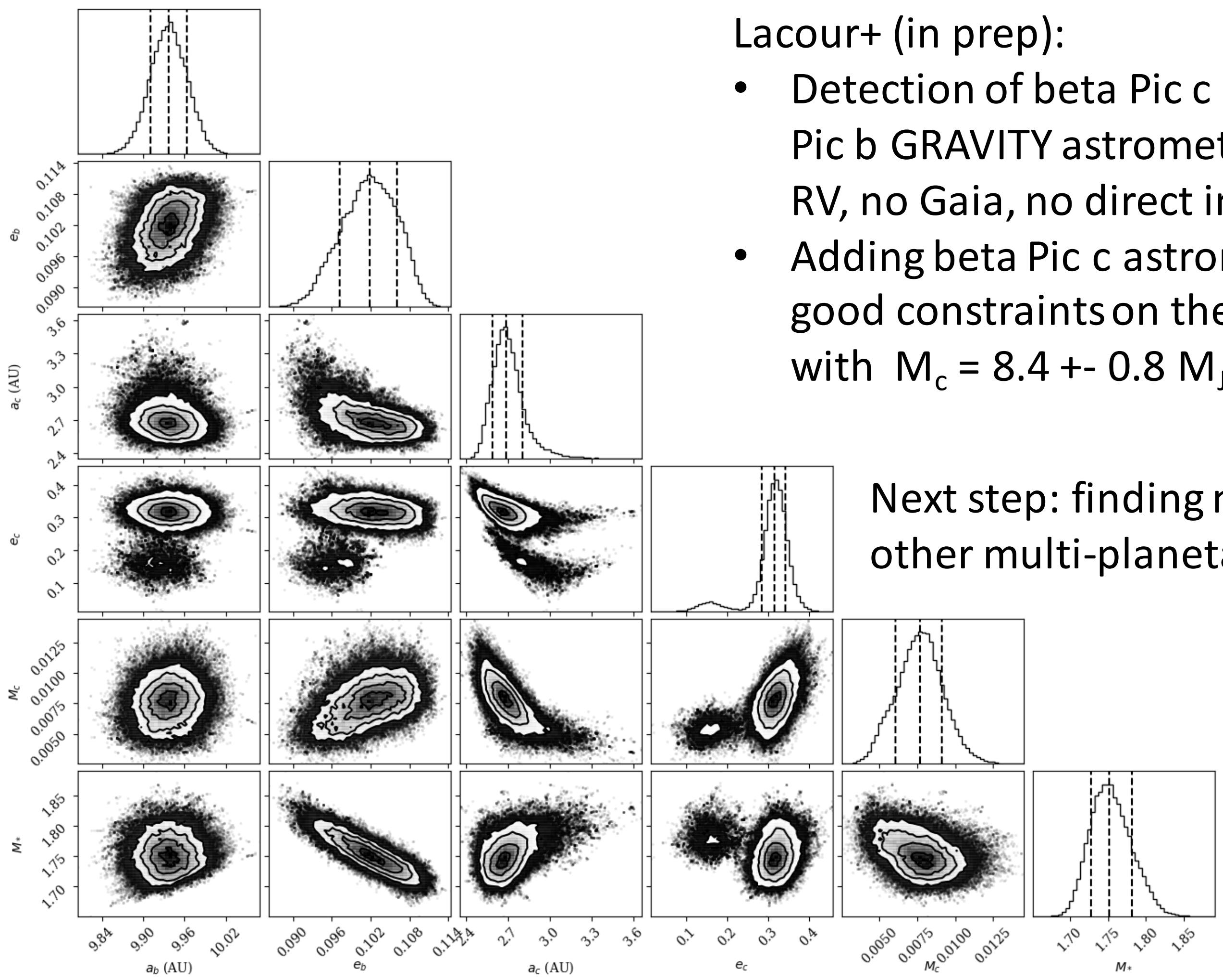


Lagrange (2018)

- A star-planet system is also a binary!
- So... can we use the planet as a reference point for doing stellar astrometry? -- Yes!

Detecting inner planets from non Keplerian deviations



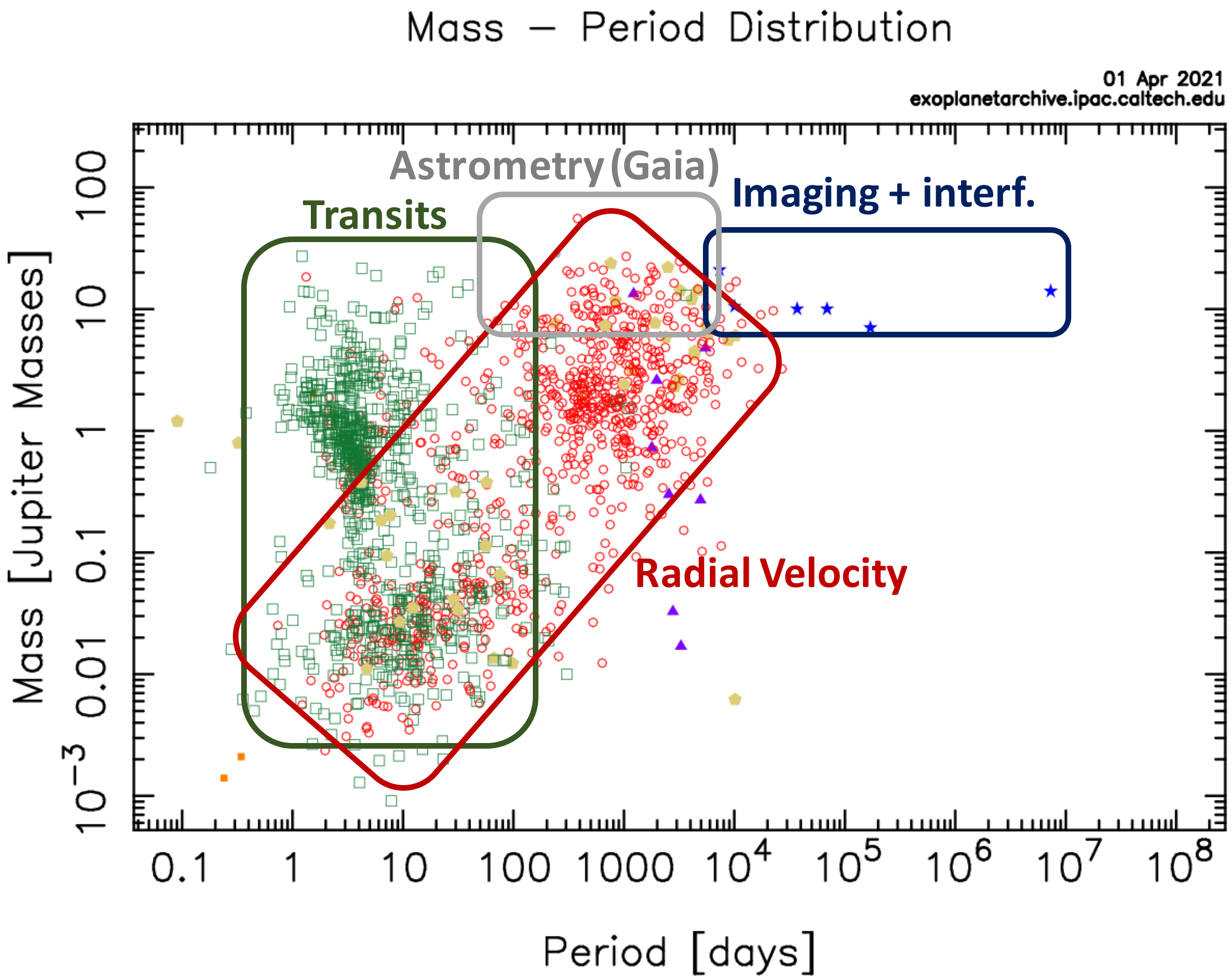


Lacour+ (in prep):

- Detection of beta Pic c from beta Pic b GRAVITY astrometry only (no RV, no Gaia, no direct imaging)
- Adding beta Pic c astrometry gives good constraints on the mass of c with M_c = 8.4 +- 0.8 M_{Jup}

Next step: finding new planets in other multi-planetary systems?

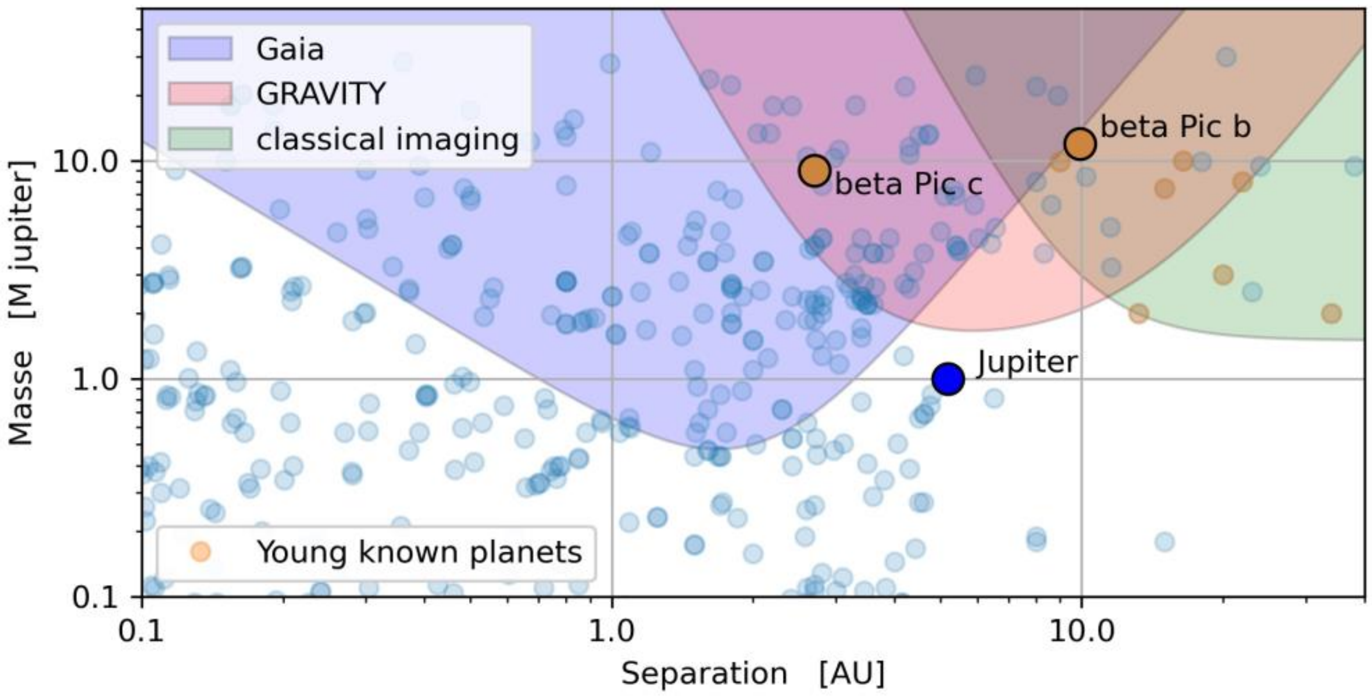
Testing formation models

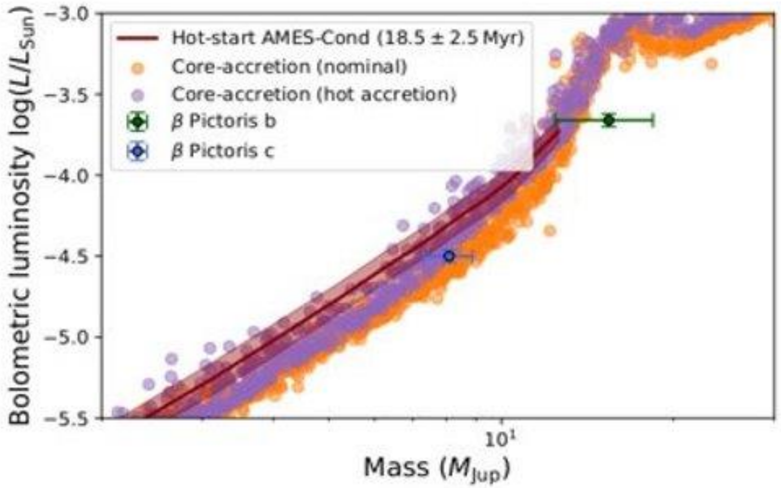


- Astrometry can be used to look for giant planets (M_{Jup}) at 1 to 10 au, which aren't as easy to detect with other methods
- Excellent tool to test formation theories such as the exclusion zone in Tidal Downsizing

$$a_{exc} = 1.33\ \mathrm{AU} \left(\frac{M_p}{1\, M_J}\right)^{2/3}$$

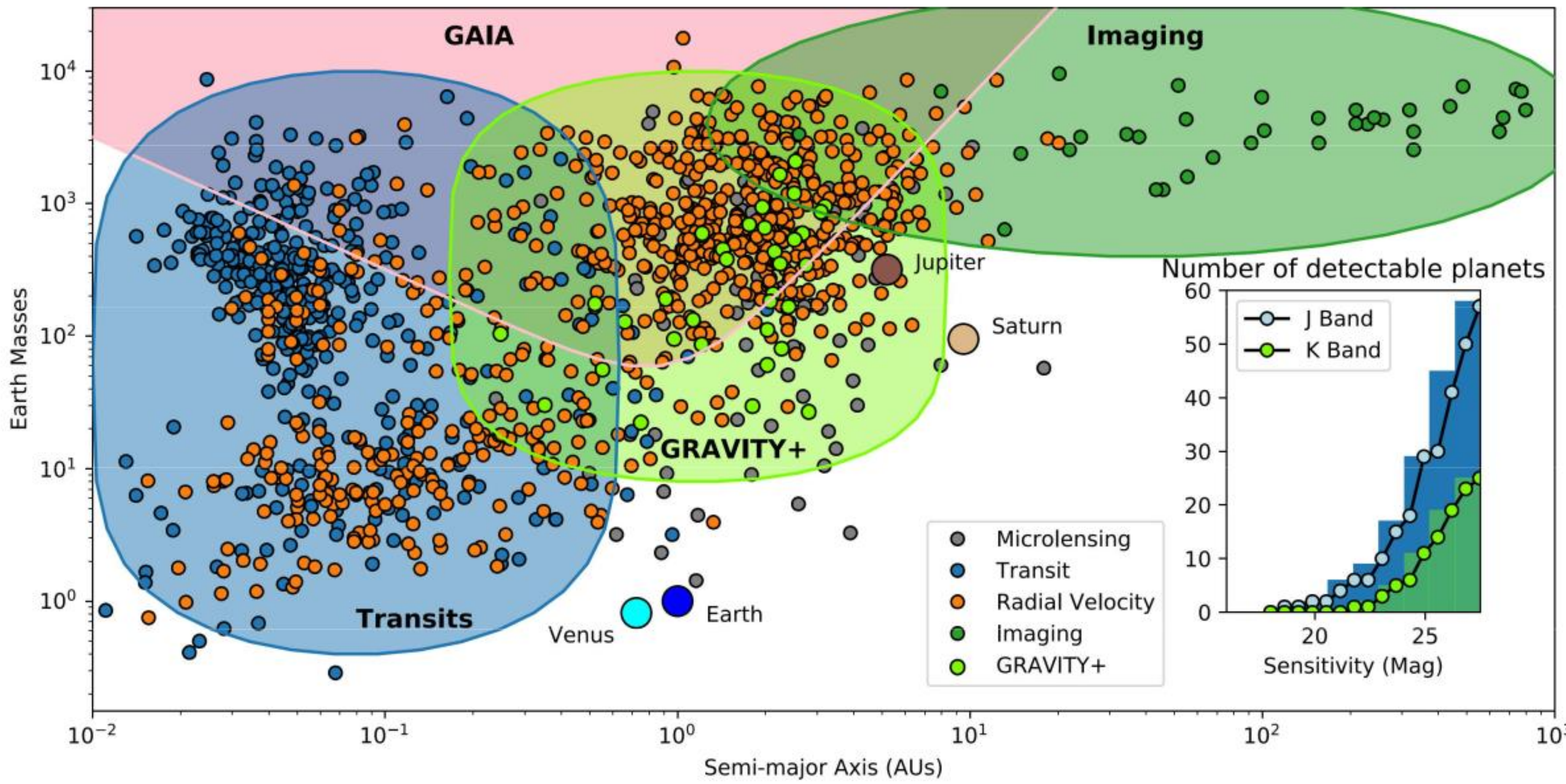
Testing formation models



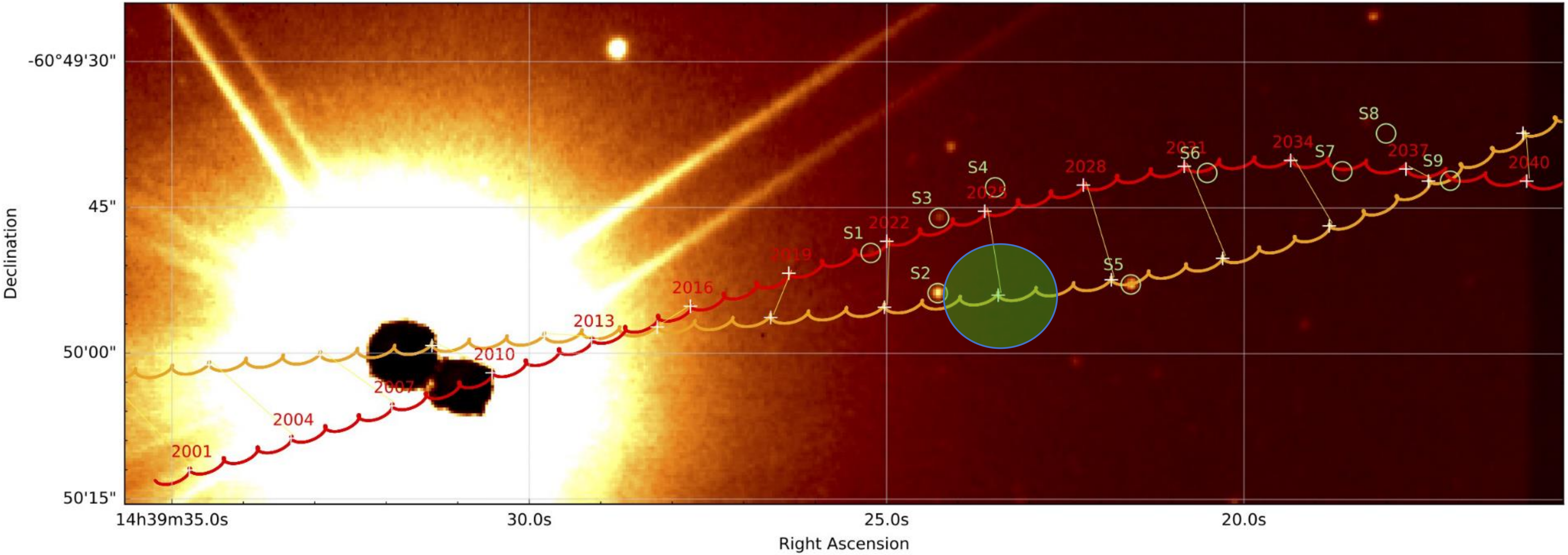


- Astrometry in combination with direct imaging and interferometry will be a powerful tool to populate M/L diagram
- Follow up at small separation with GRAVITY difficult because of the unknown location of Gaia planets
- Stellar accelaration in Gaia future releases?

GRAVITY+

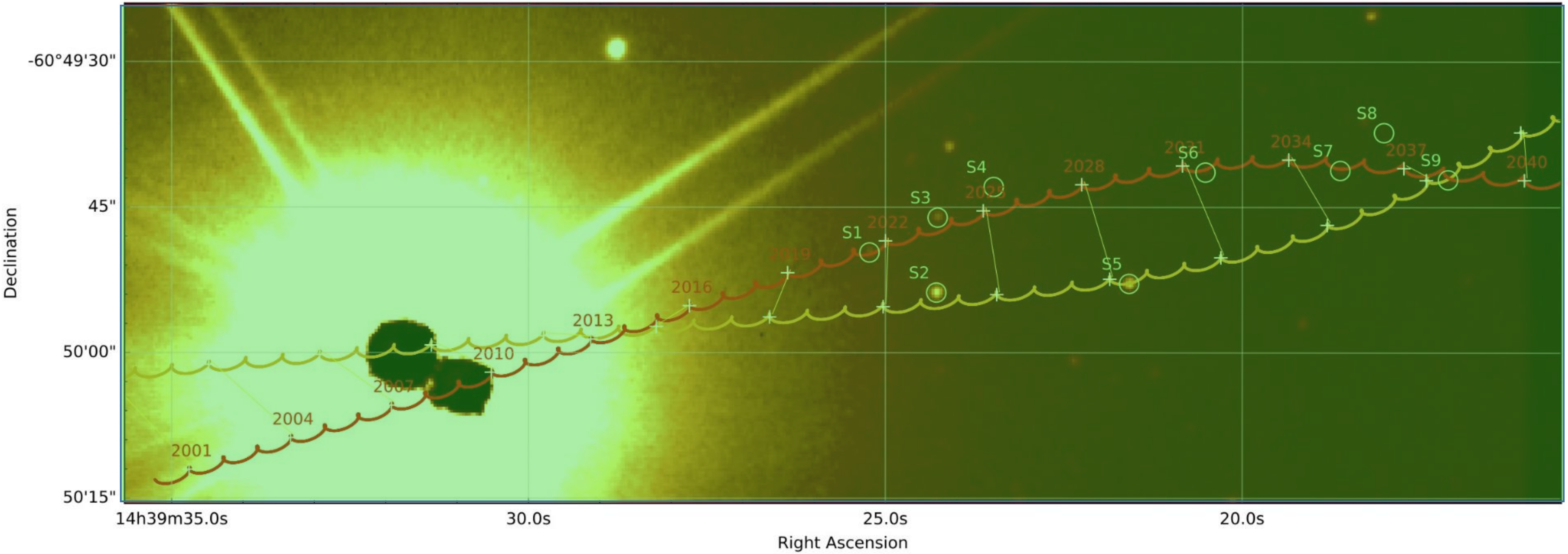

GAIA
Imaging
Transits
GRAVITY+
Jupiter
Saturn
Earth
Venus
Earth Masses
Semi-major Axis (AUs)
Microlensing
Transit
Radial Velocity
Imaging
GRAVITY+
Number of detectable planets
J Band
K Band
Sensitivity (Mag)

GRAVITY+



GRAVITY dual-field max separation: 2 as

GRAVITY+



GRAVITY dual-field max separation: 2 as → GRAVITY+ dual-field max separation: >30 as