Binaries
Gaia
Astrometric Gaia
Astrometric Binaries
Binaries in Gaia

Zephyr Penoyre (they/any), IoA Cambridge

w. Vasily Belokurov, Wyn Evans, Semyeong Oh, Andrew Everall, Shion Andrews & Sergey Koposov

Binaries

Binaries

Opportunities

Binaries

Opportunities

Inconveniences

Binaries

Opportunities

Inconveniences

Sources & Sinks of E & L

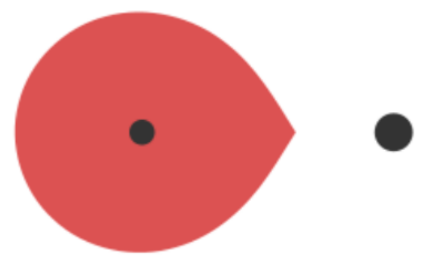
Binaries

Opportunities

Inconveniences

Sources & Sinks of E & <u>L</u>

Interaction



Binaries

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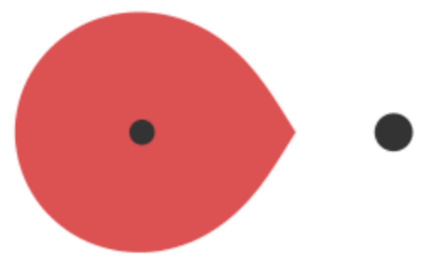
Sources & Sinks of E & $\underline{L}$

Interaction - tidal



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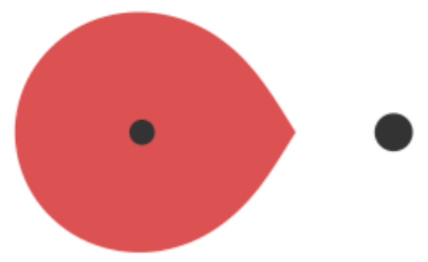
Interaction - tidal

- thermodynamic



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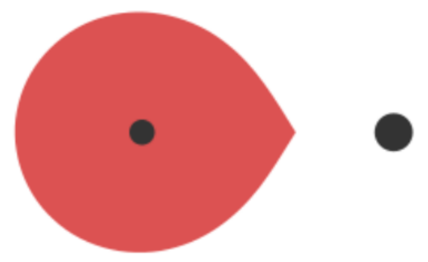

- tidal
- thermodynamic
- mass transfer

Binaries

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- tidal
- thermodynamic
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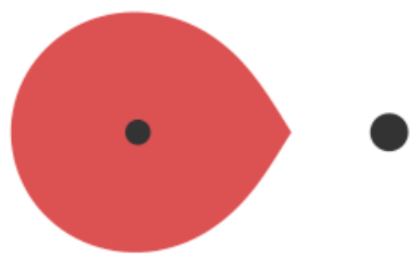

Free mass! (for light)

Binaries

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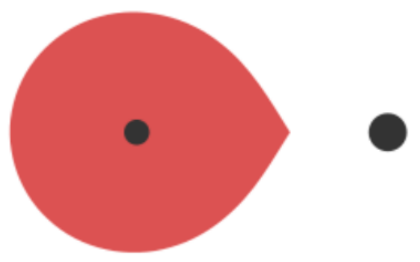

Free mass! (for light)

More detailed classification

Inconveniences

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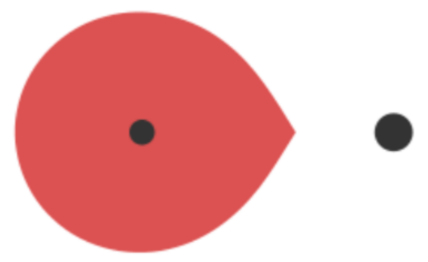

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Extra motion

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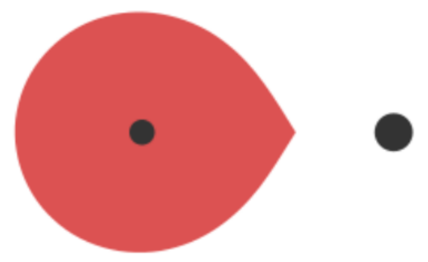

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Harder to model

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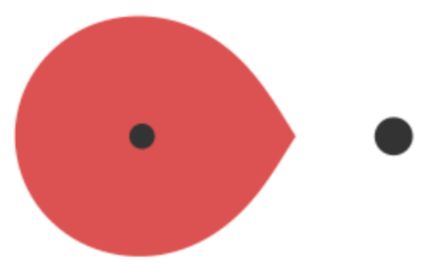

Free mass! (for light)

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Harder to model

Time-evolving

Binaries

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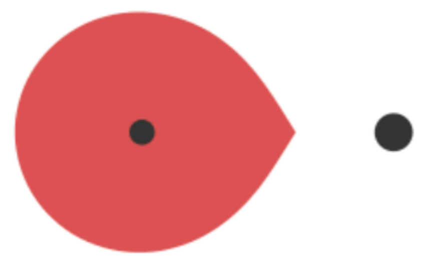
Interaction - tidal
- thermodynamic
- mass transfer



Free mass! (for light)

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Harder to model

Time-evolving

Exotic systems

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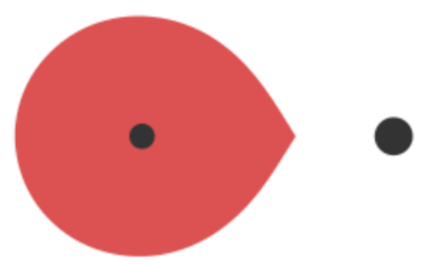

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Uncertain dynamics

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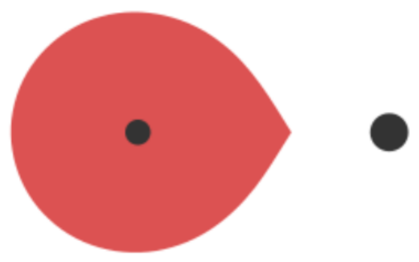

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Higher dimensional fit

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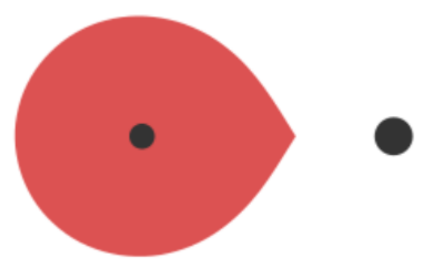

Free mass! (for light)

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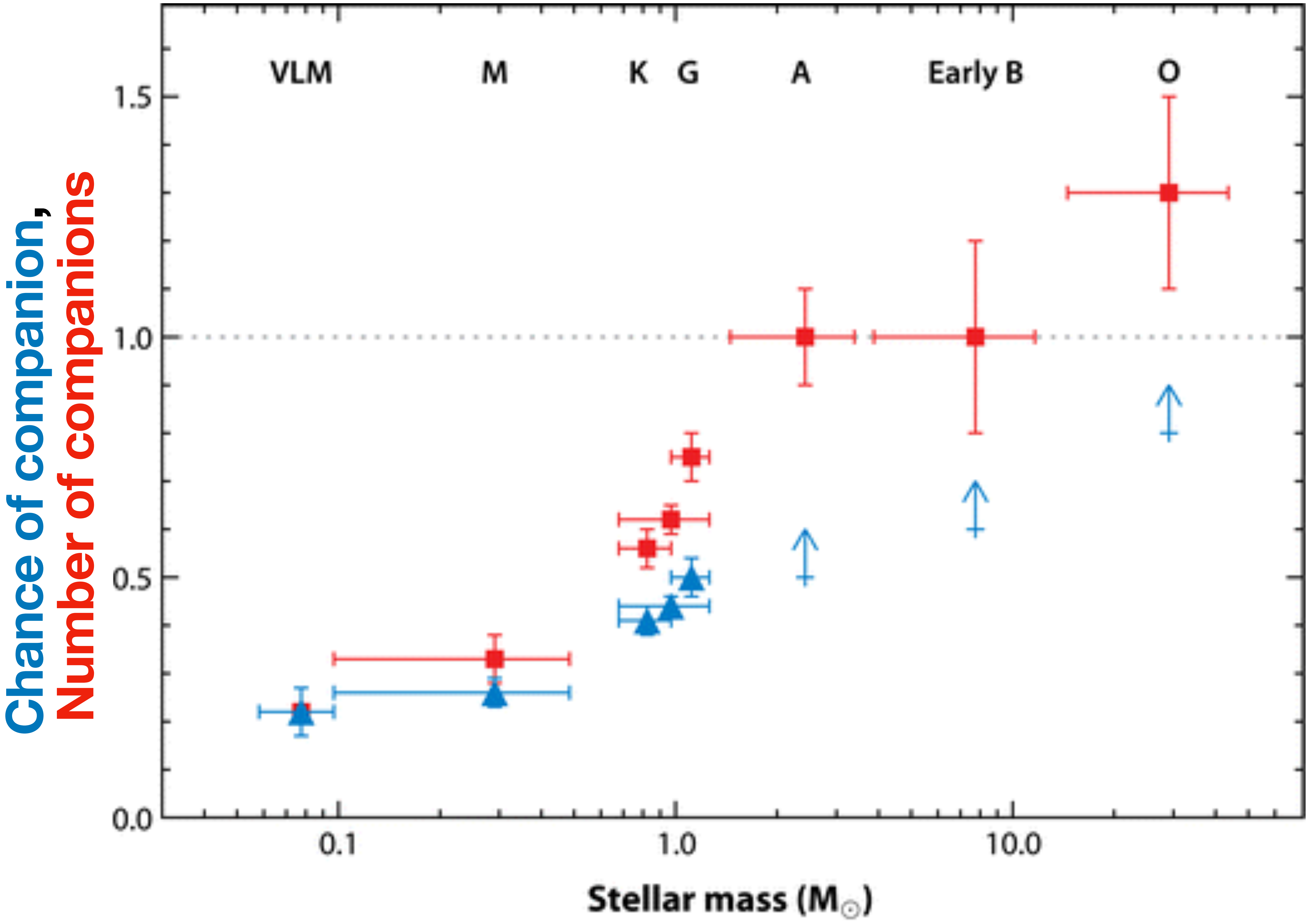
Higher dimensional fit

Bias on velocity and parallax

Binaries

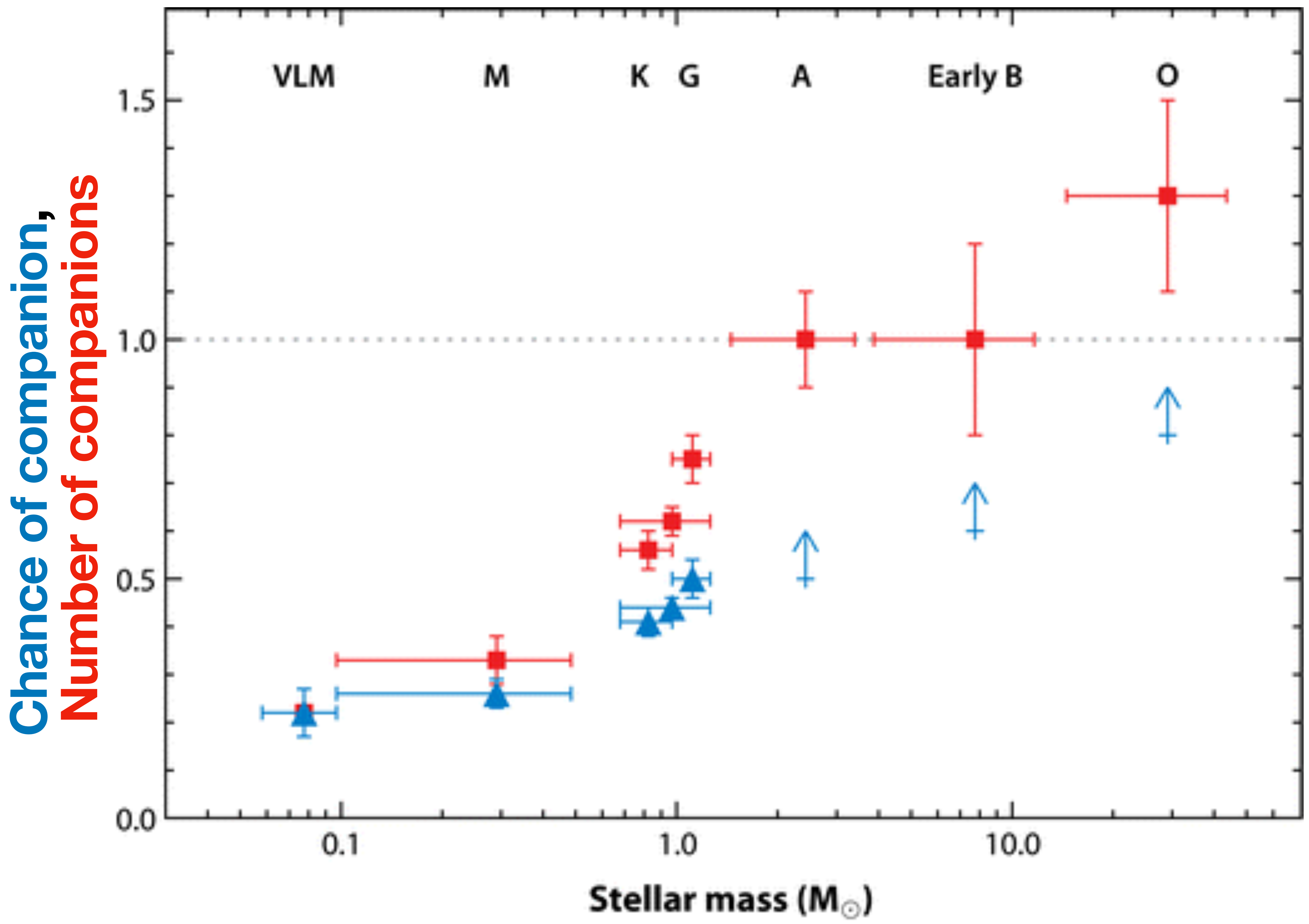
Multiplicity



Duchene & Kraus 2013

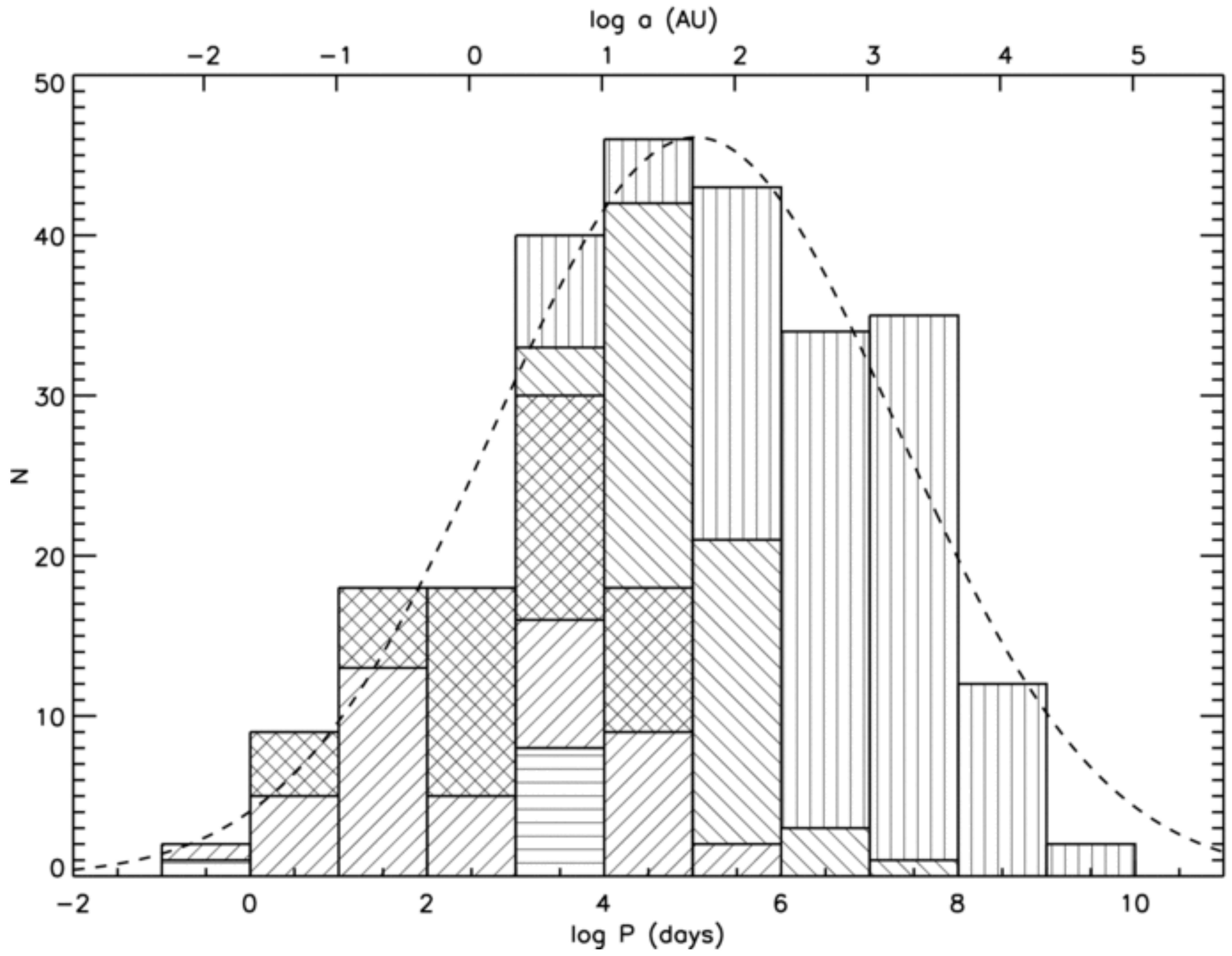
Binaries

Multiplicity



Duchene & Kraus 2013

Period



Raghavan et al. 2010

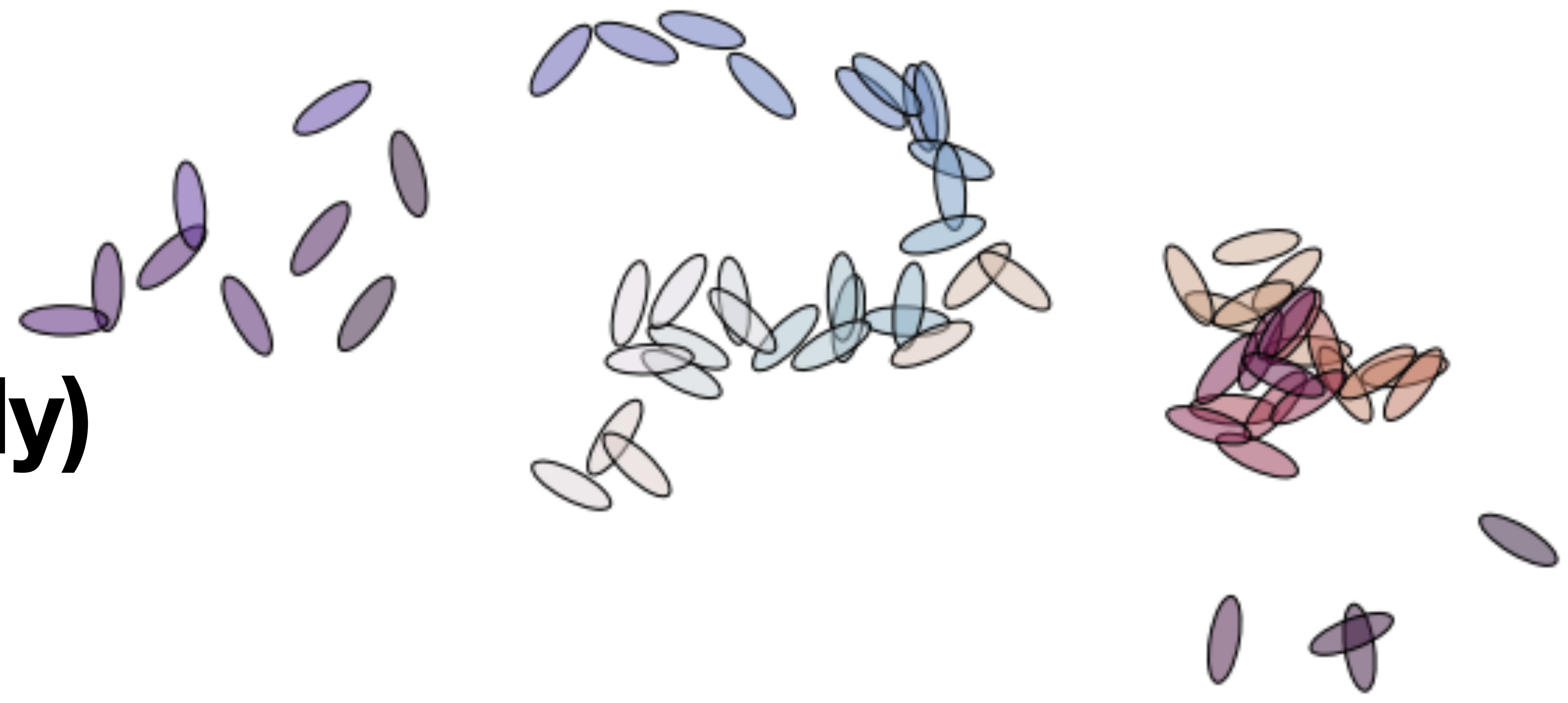
Gaia

Gaia

2013-2025 (hopefully)

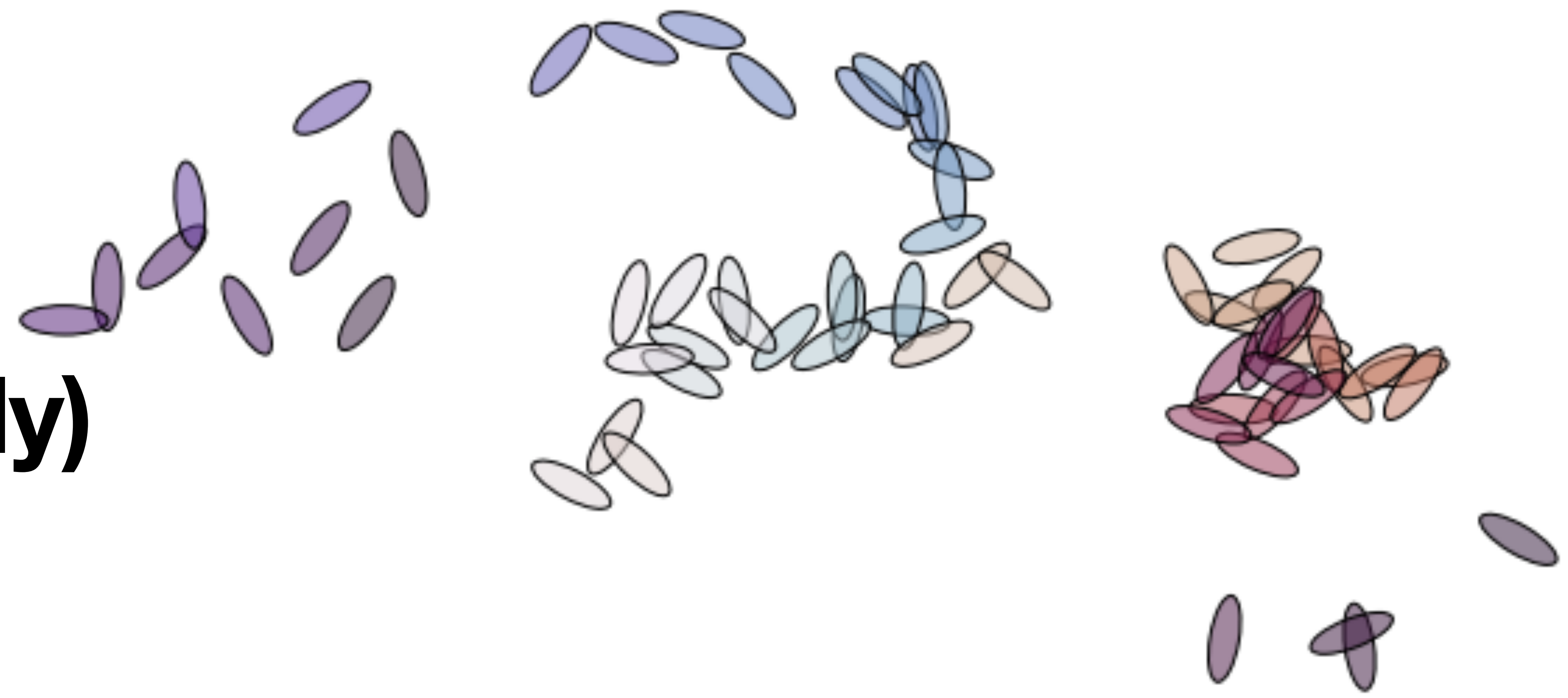
Gaia

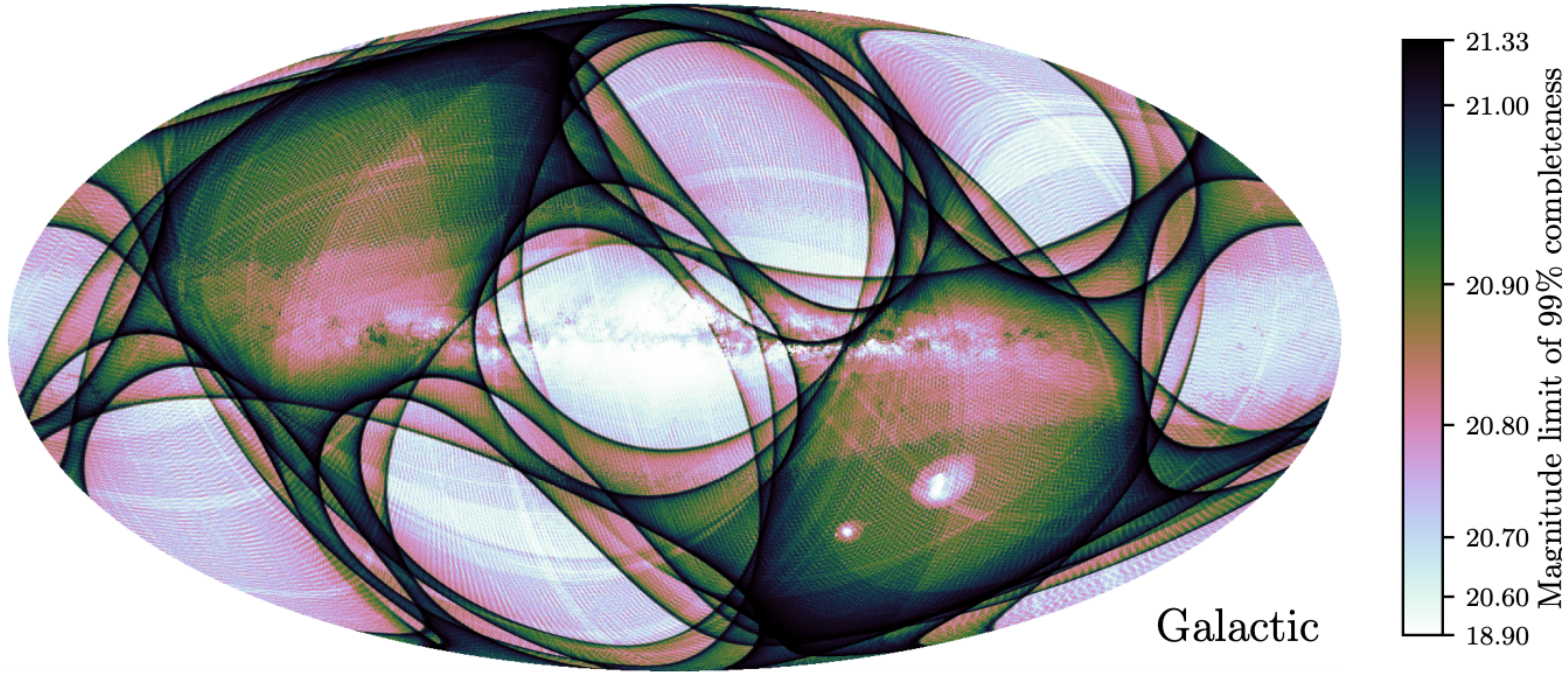
2013-2025 (hopefully)



Gaia

2013-2025 (hopefully)

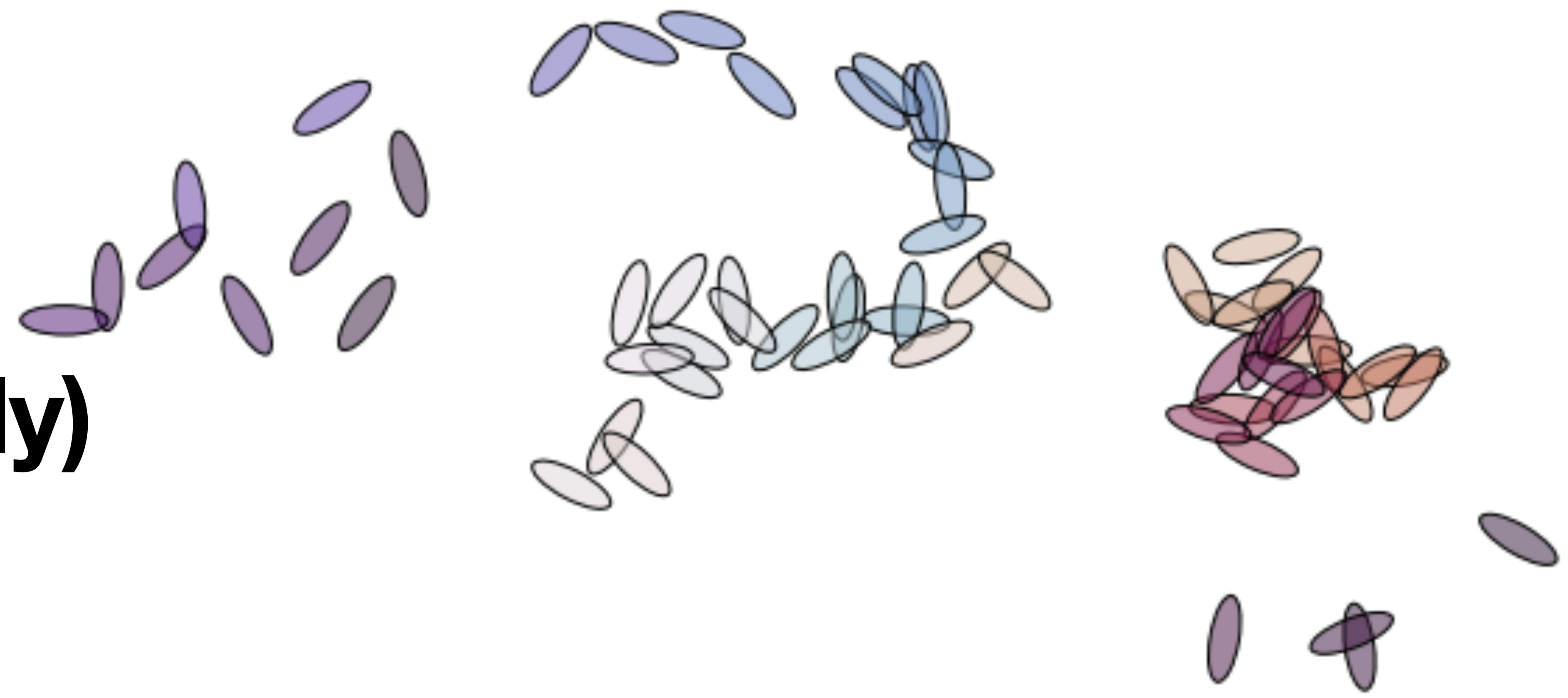


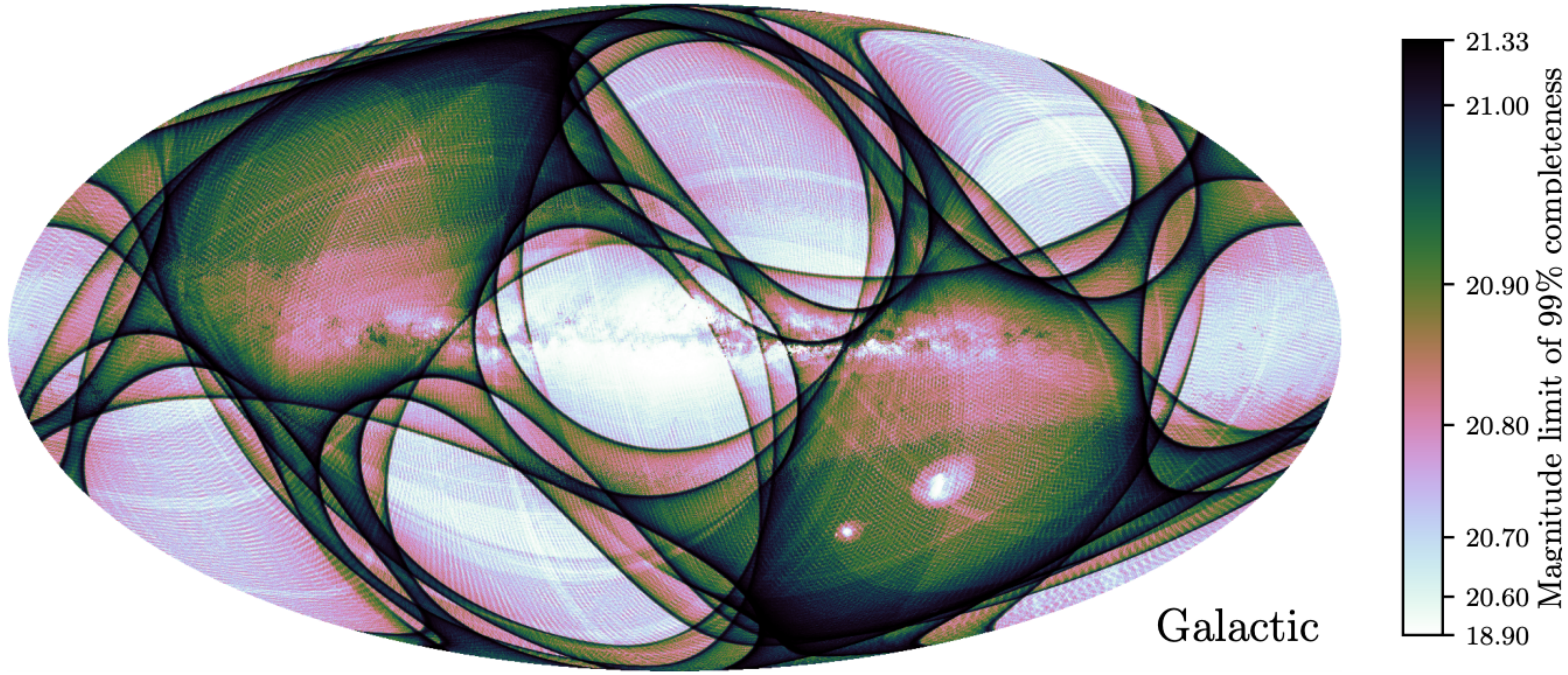


Boubert & Everall 2020

Gaia

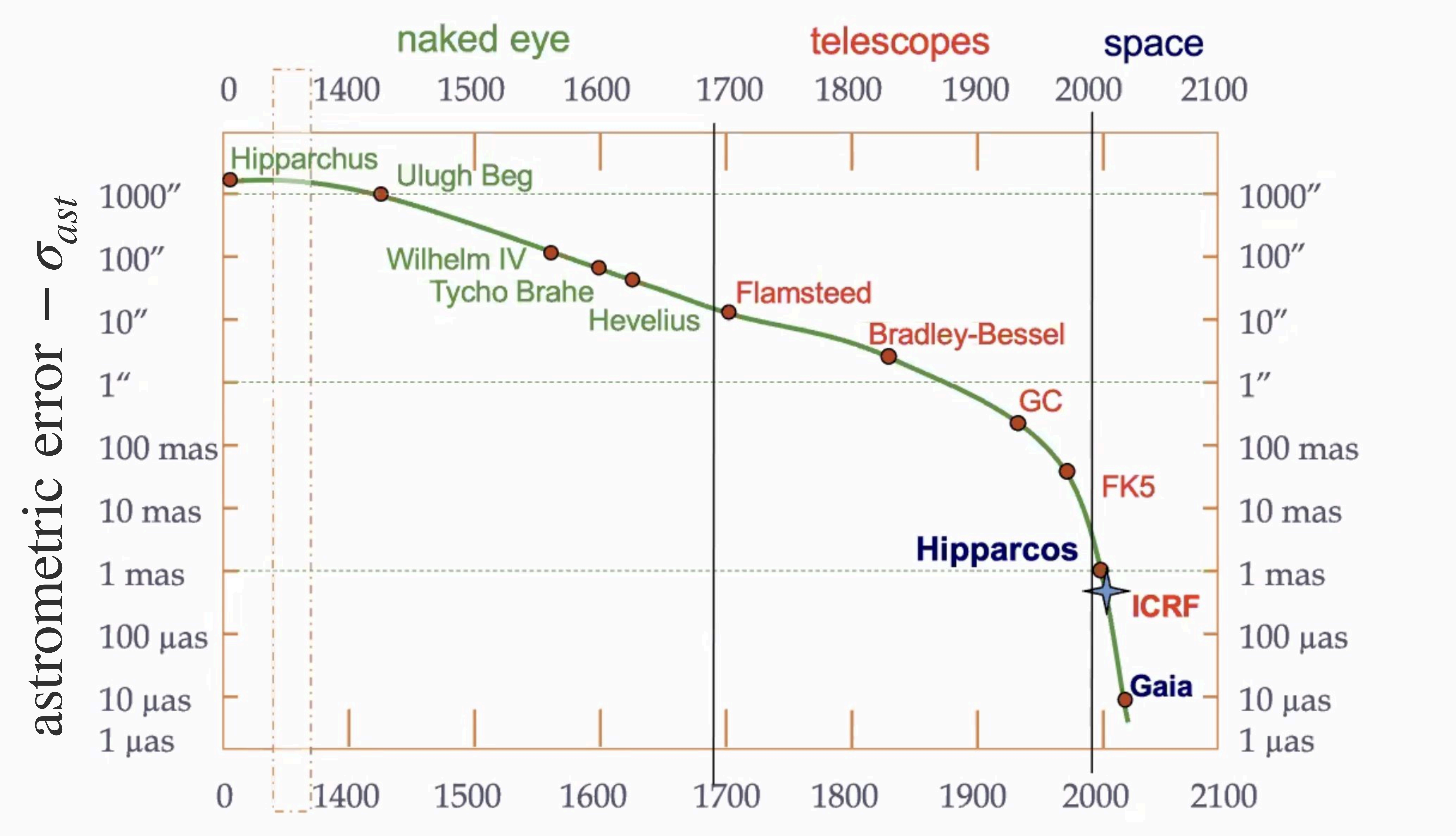
2013-2025 (hopefully)





Boubert & Everall 2020

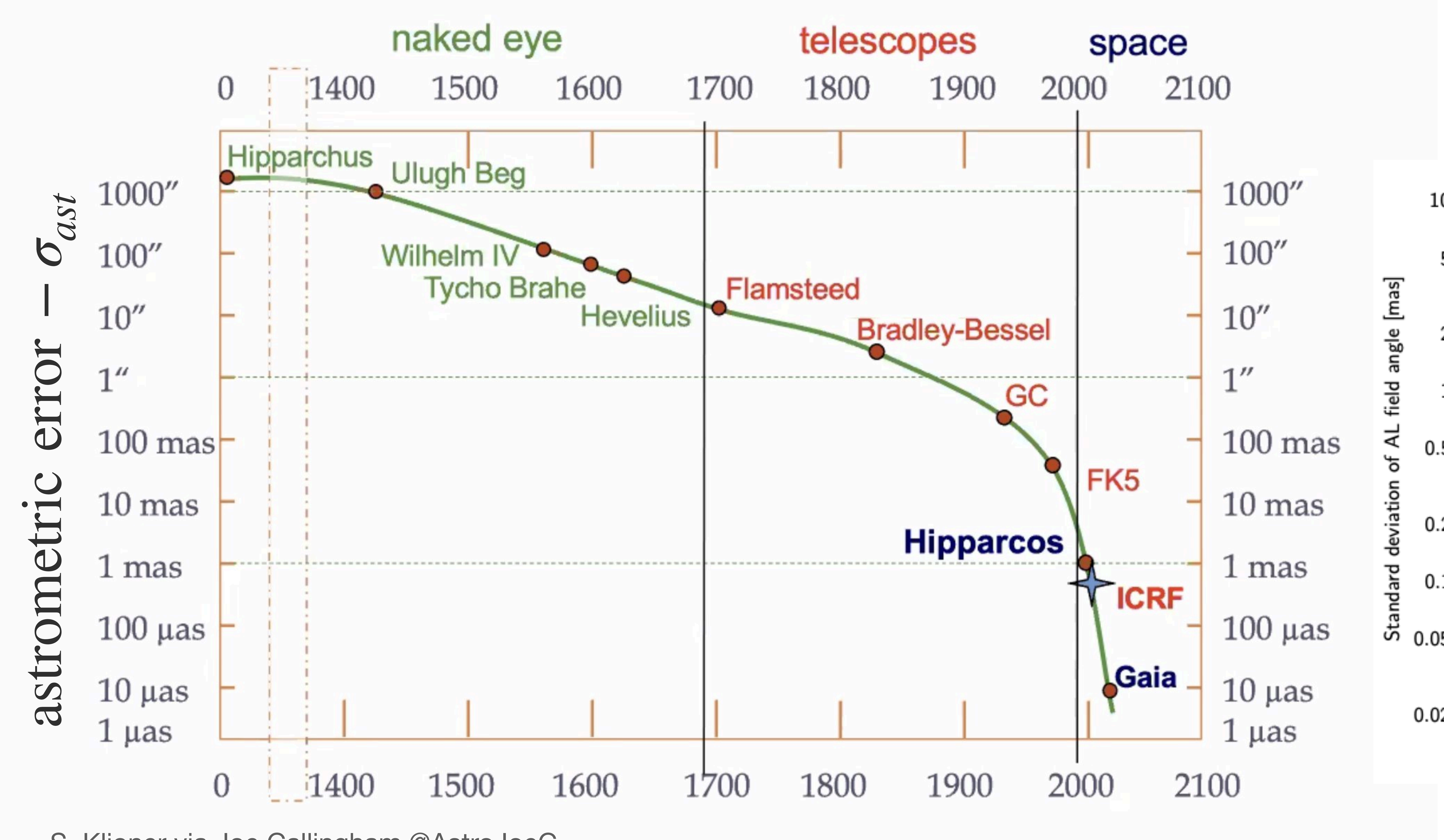
Gaia



S. Klioner via Joe Callingham @AstroJoeC

Gaia

DR2 - 22 months
(e)DR3 - 34 months



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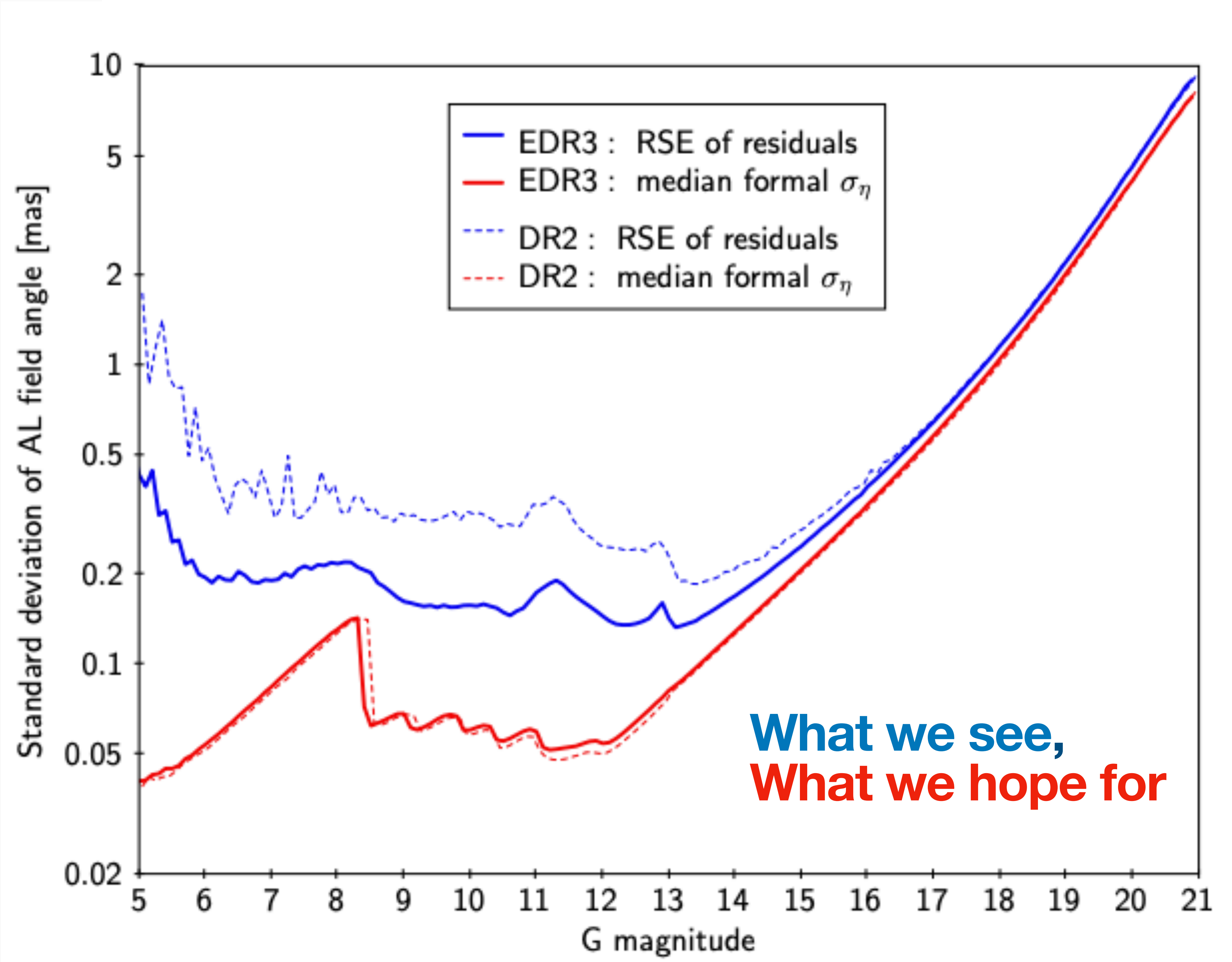
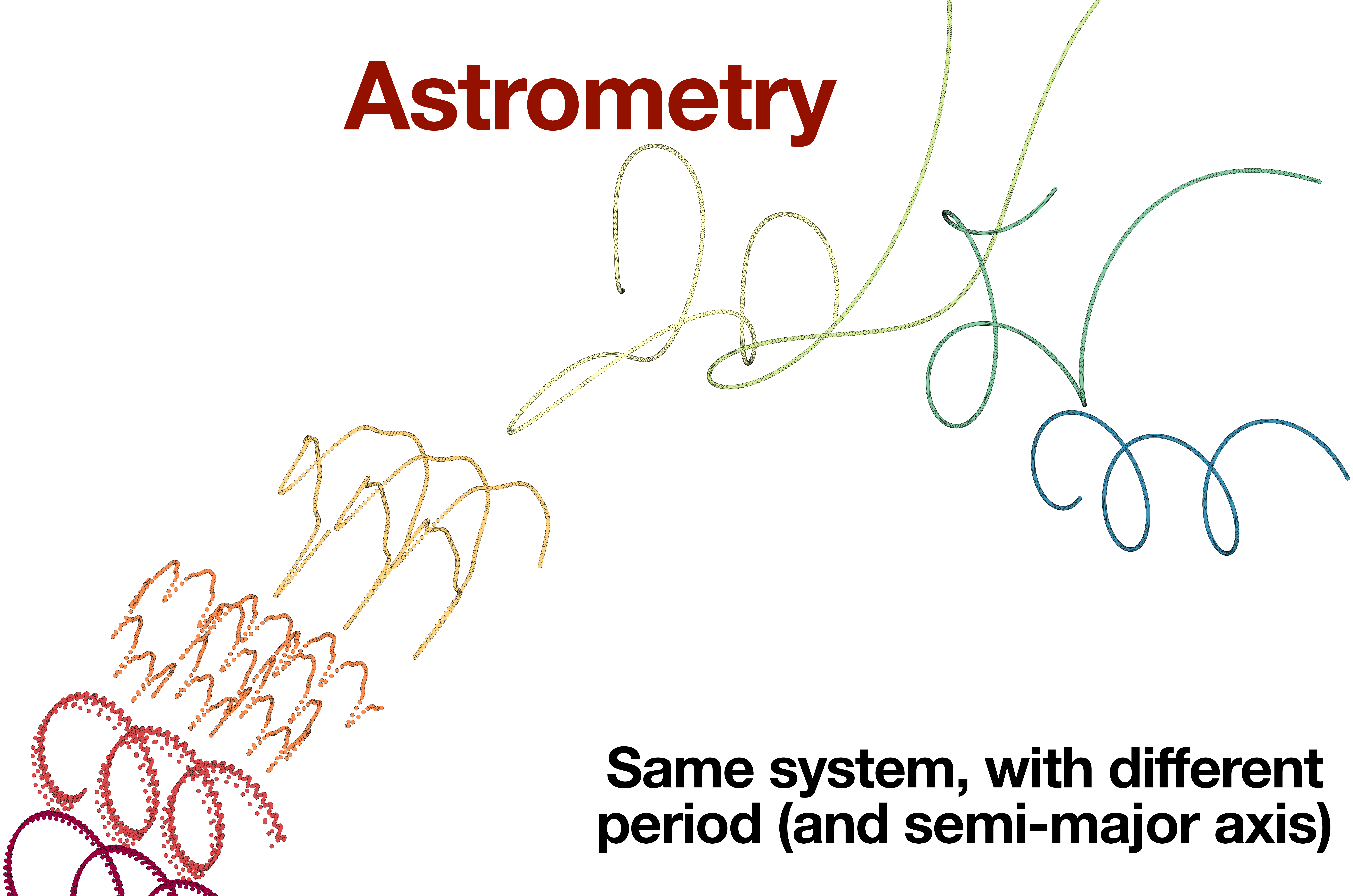


Lindegren et al 2020

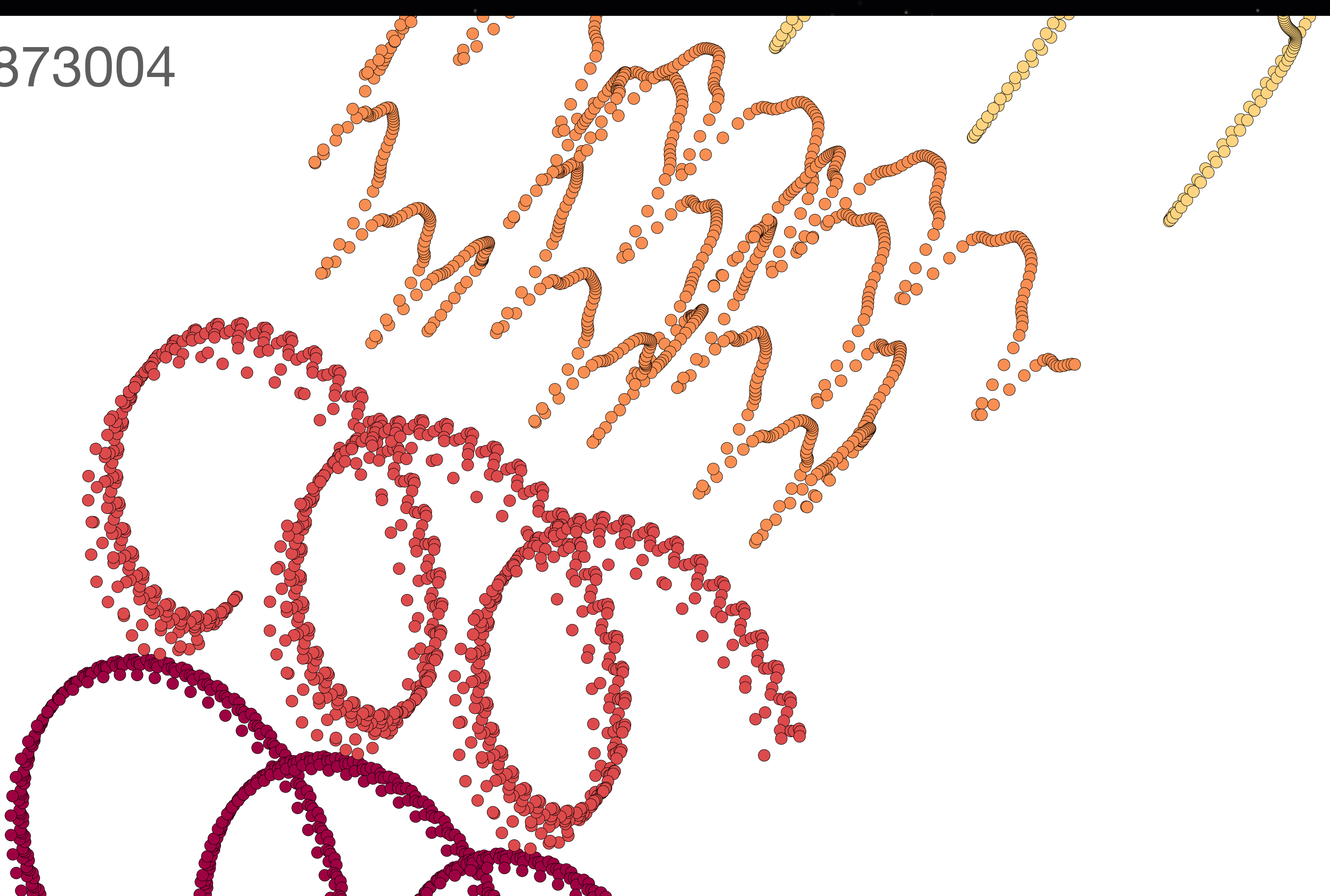
Astrometry

Astrometry



Same system, with different period (and semi-major axis)

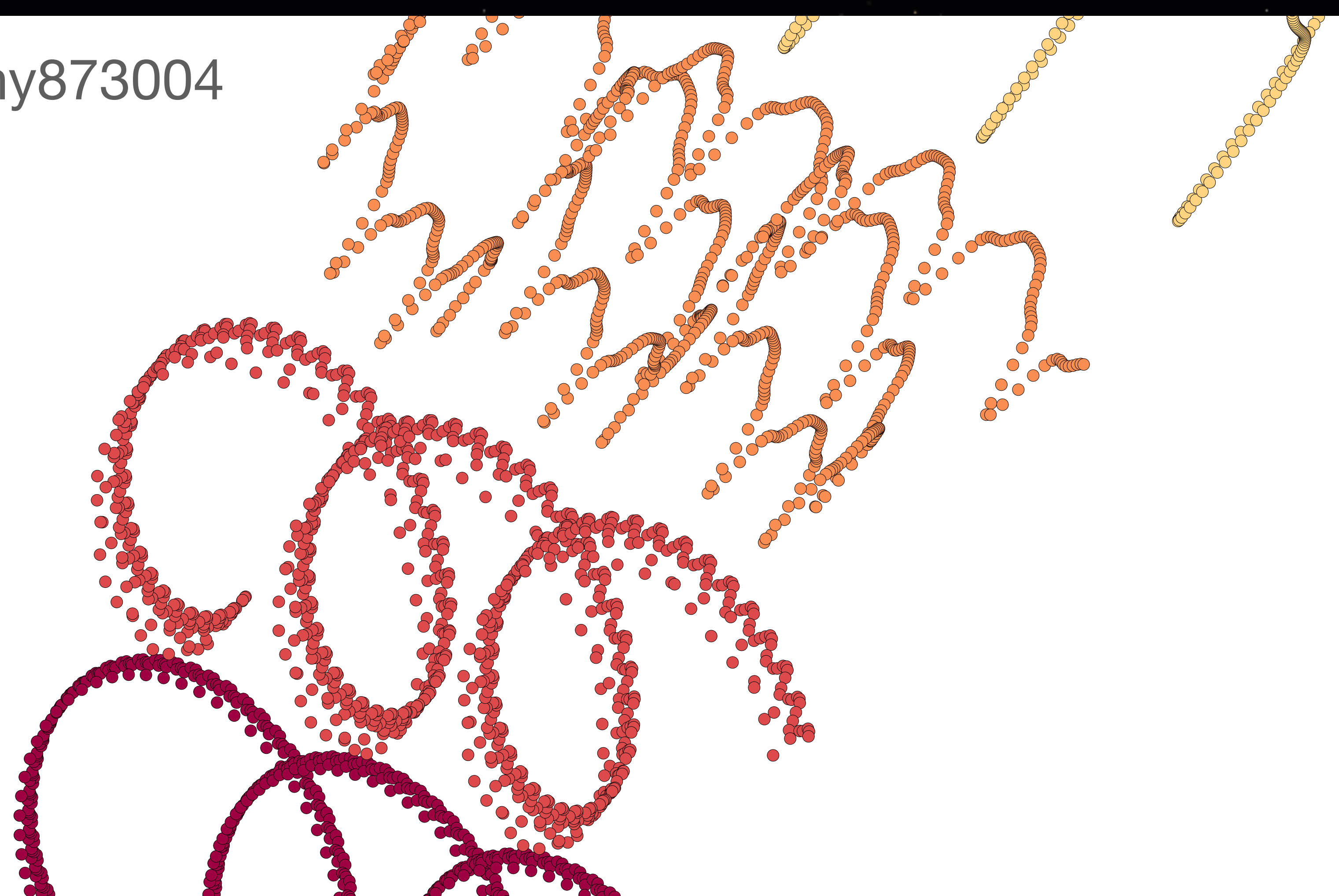
Tony Dunn, @Tony873004

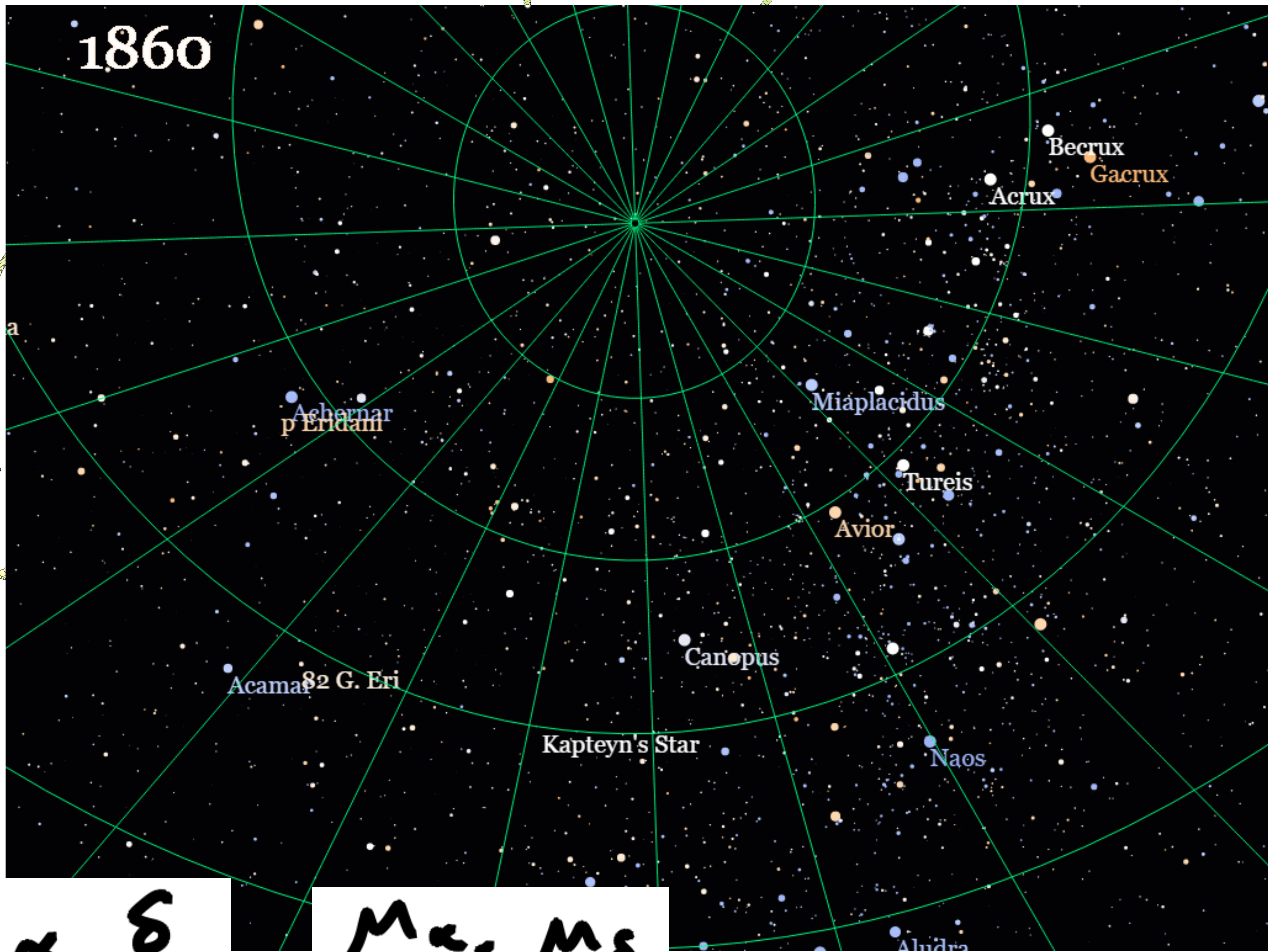


ϖ, α, δ

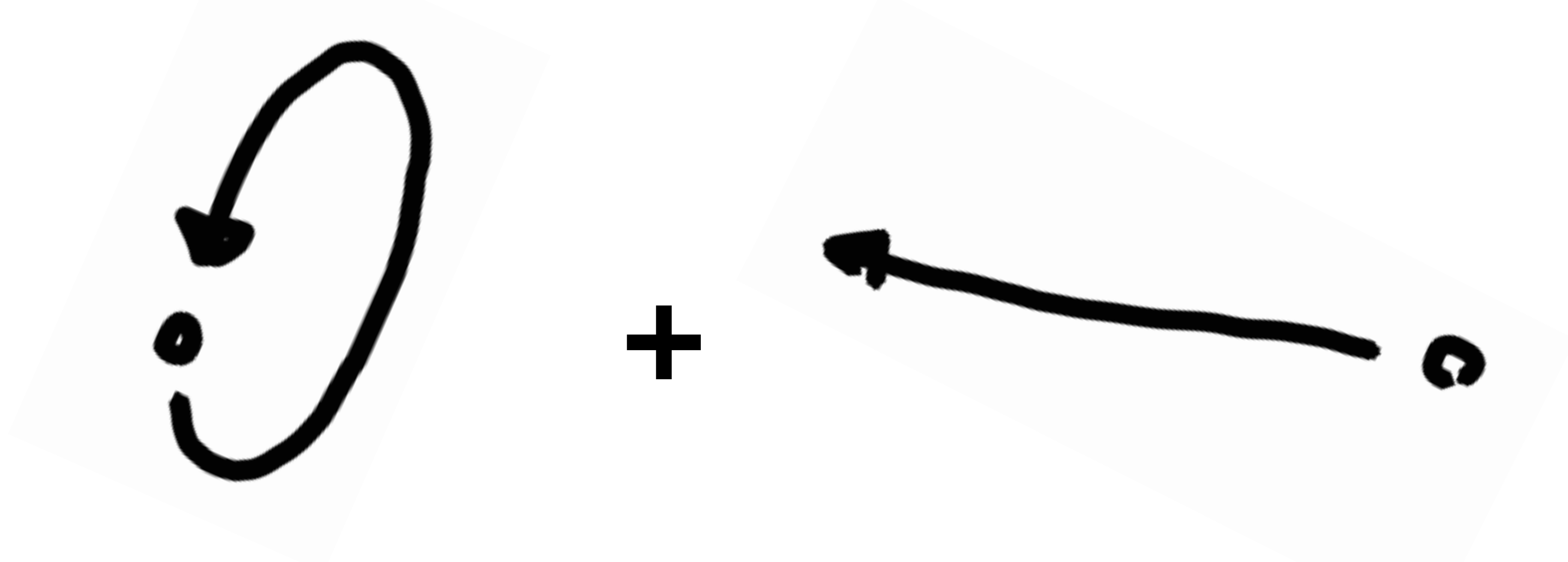
Earth's motion

Tony Dunn, @Tony873004



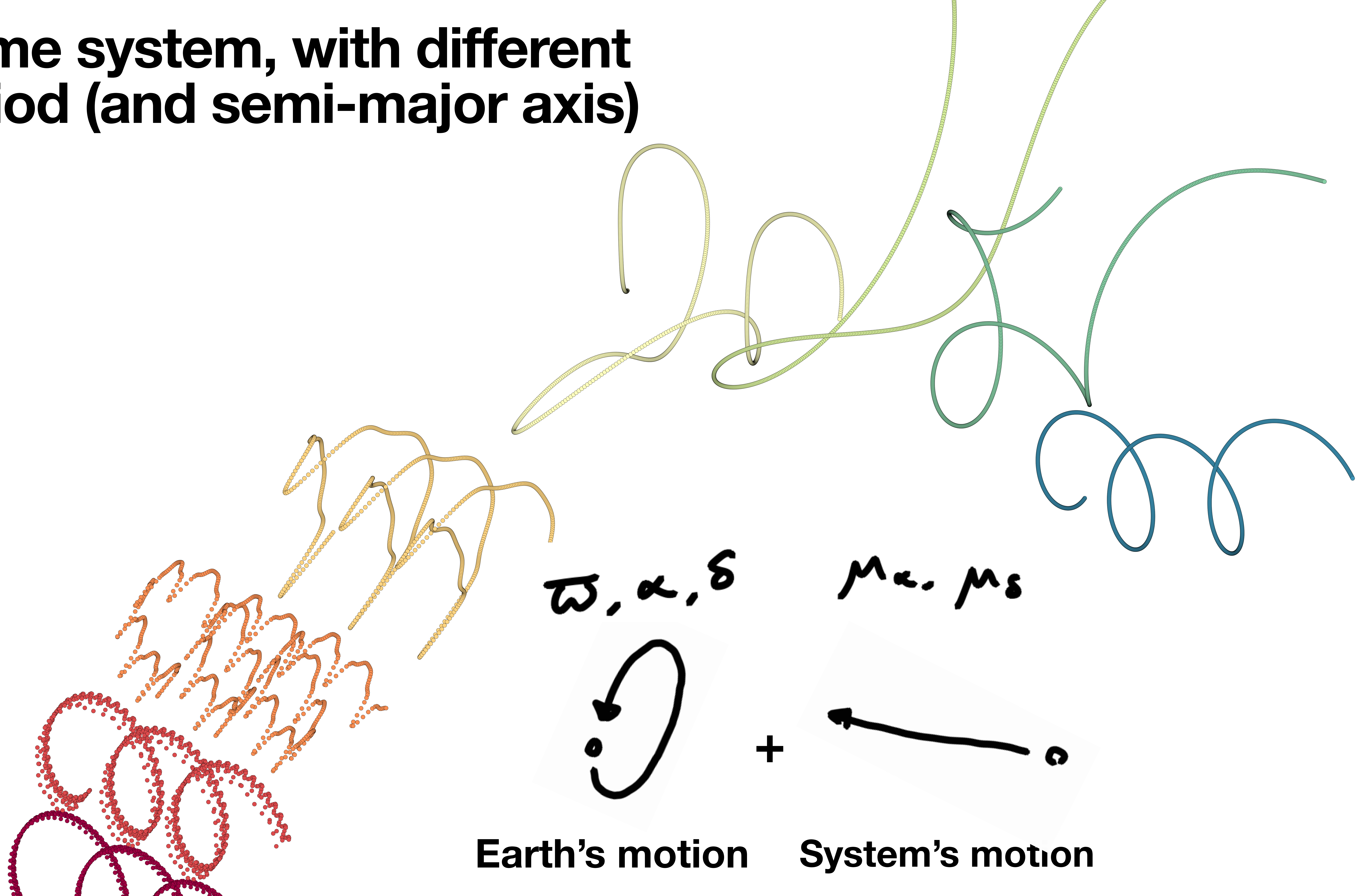


ϖ, α, δ μ_α, μ_δ



Earth's motion **System's motion**

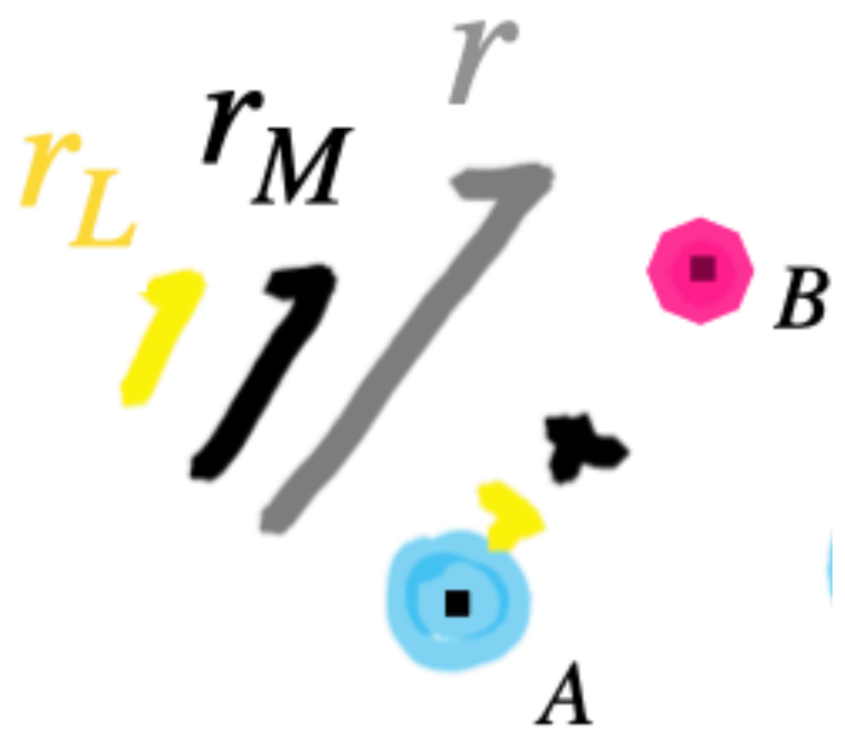
Same system, with different period (and semi-major axis)



ϖ, α, δ μ_α, μ_δ

Earth's motion + System's motion

Astrometry of unresolved binaries

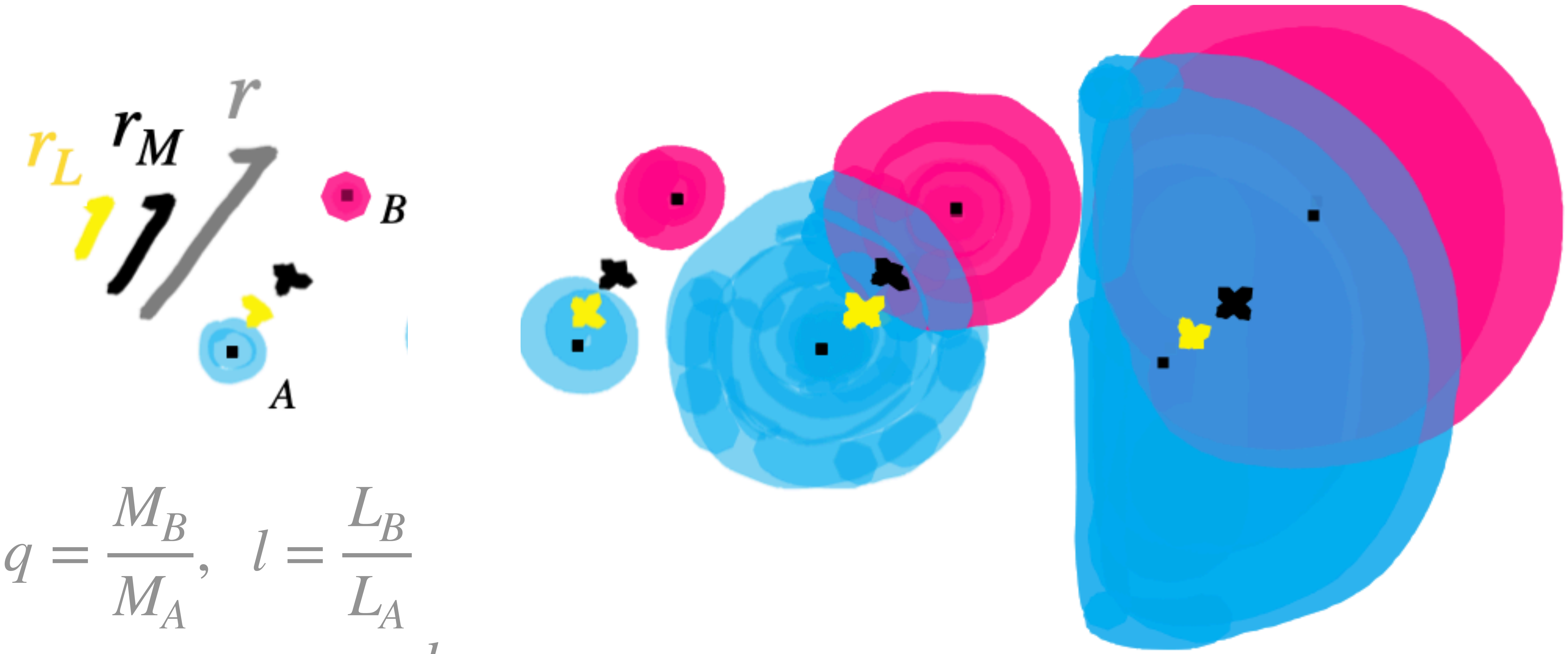


$$q = \frac{M_B}{M_A}, \quad l = \frac{L_B}{L_A}$$

$$r_M = \frac{q}{1+q} r, \quad r_L = \frac{l}{1+l} r$$

$$\Delta = \frac{r_M - r_L}{r} = \frac{q - l}{(1+q)(1+l)}$$

Astrometry of unresolved binaries



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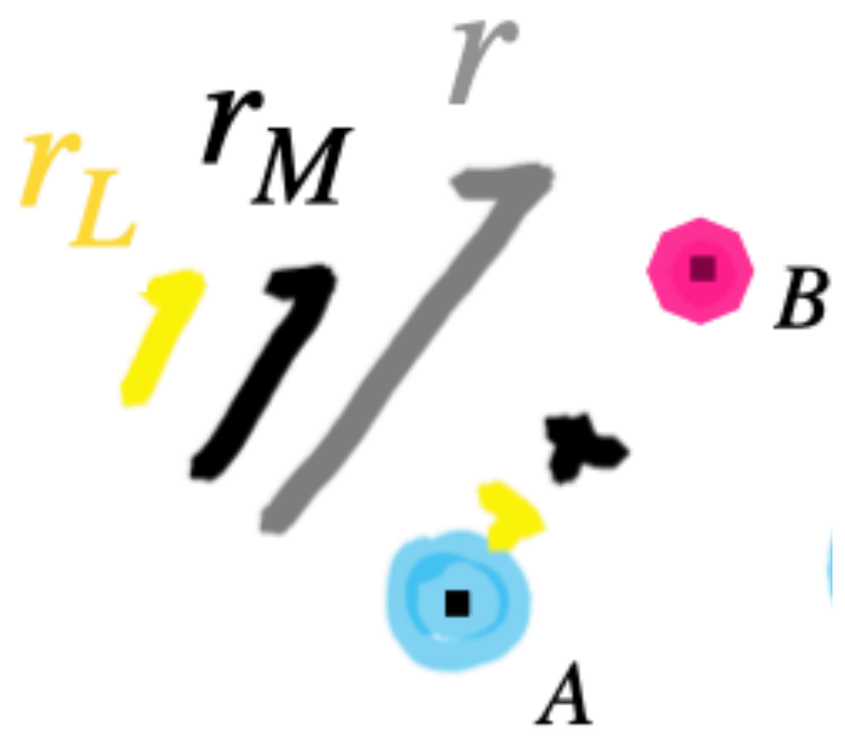
Lower resolution (Larger distance)

Gaia's PSF >> Gaia's astrometric error

Astrometry of unresolved binaries



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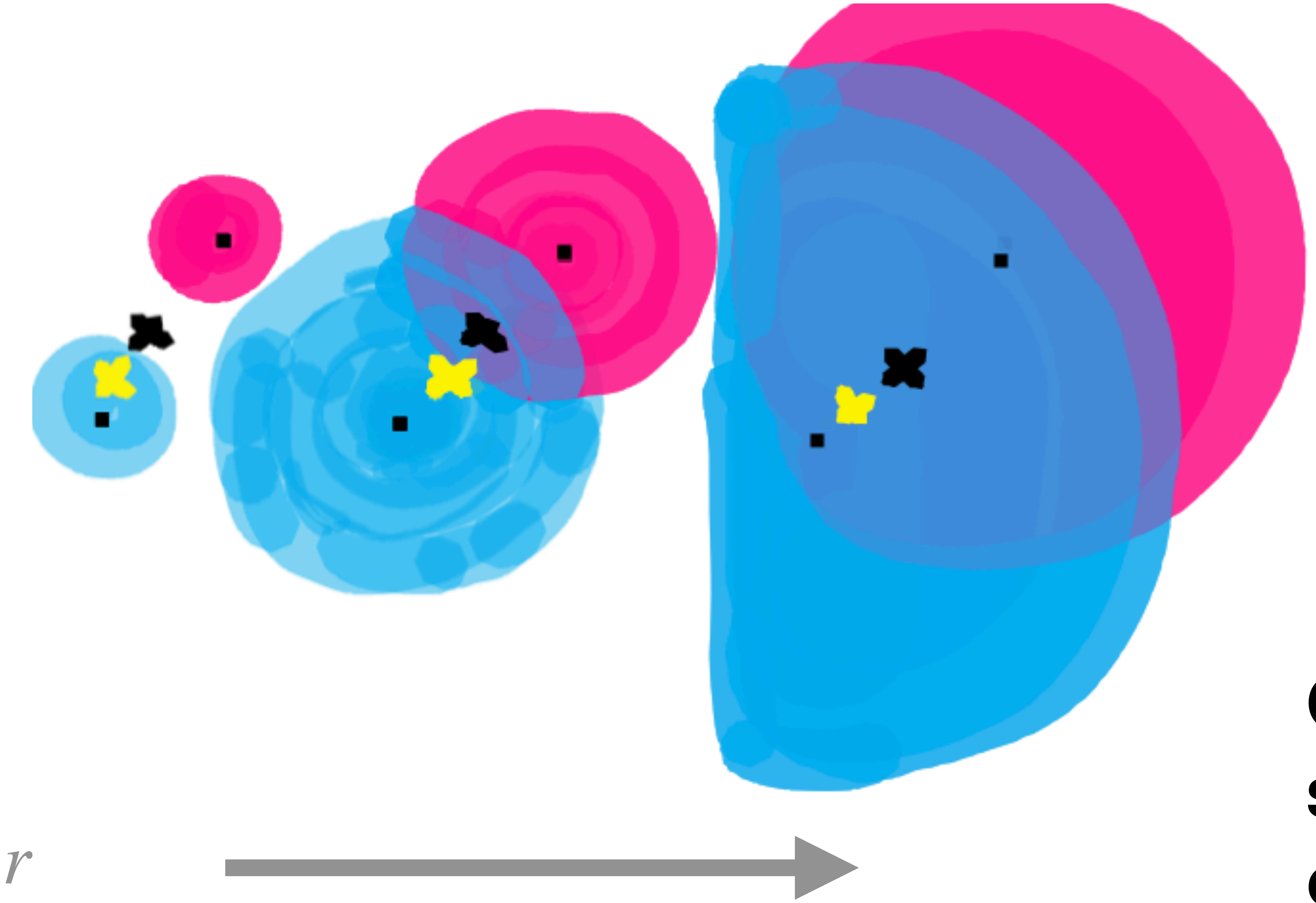


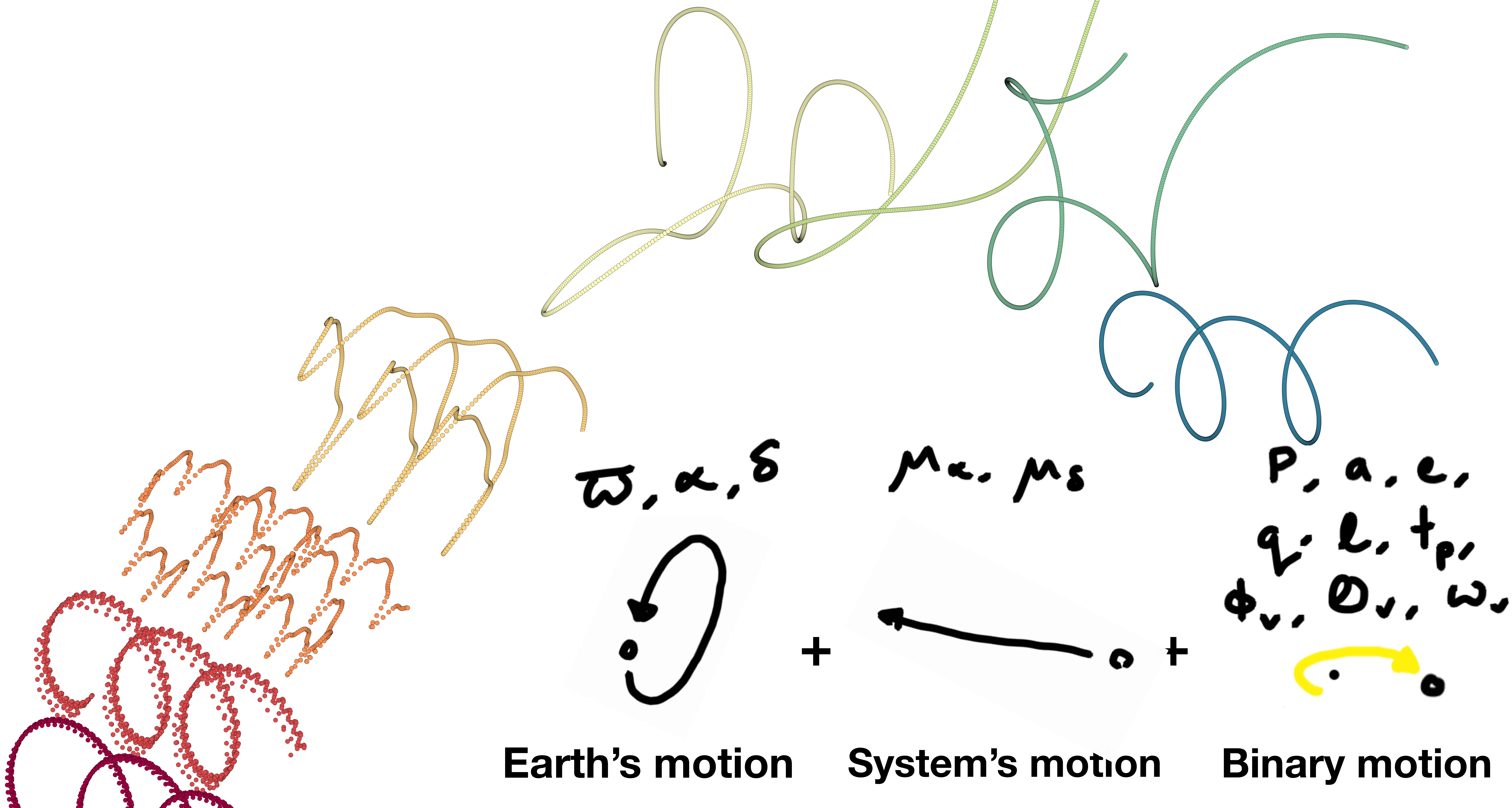
Lower resolution
(Larger distance)

Gaia sees a single source, with combined properties

Located at the centre of light, orbiting the centre of mass

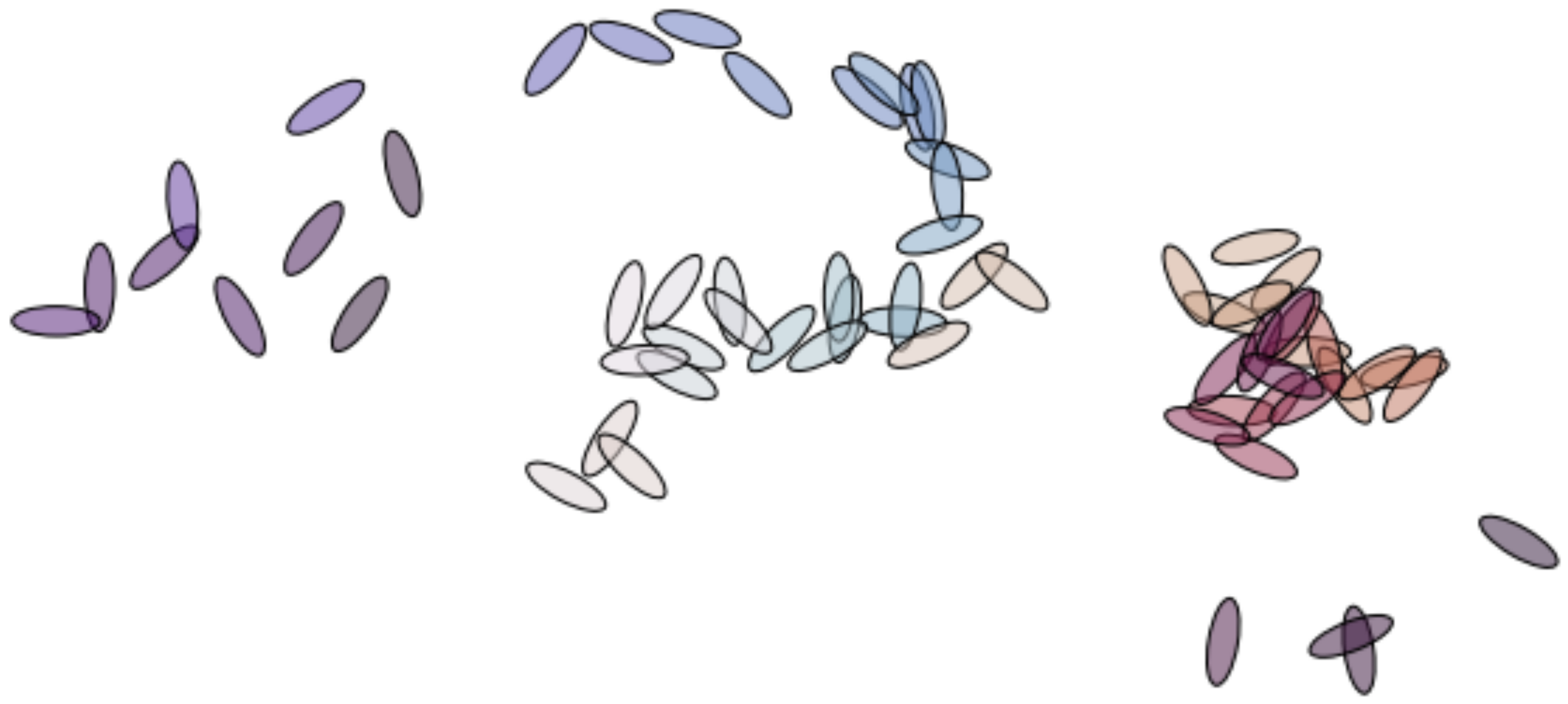
Gaia’s PSF >> Gaia’s astrometric error

Same system, with different period (and semi-major axis)

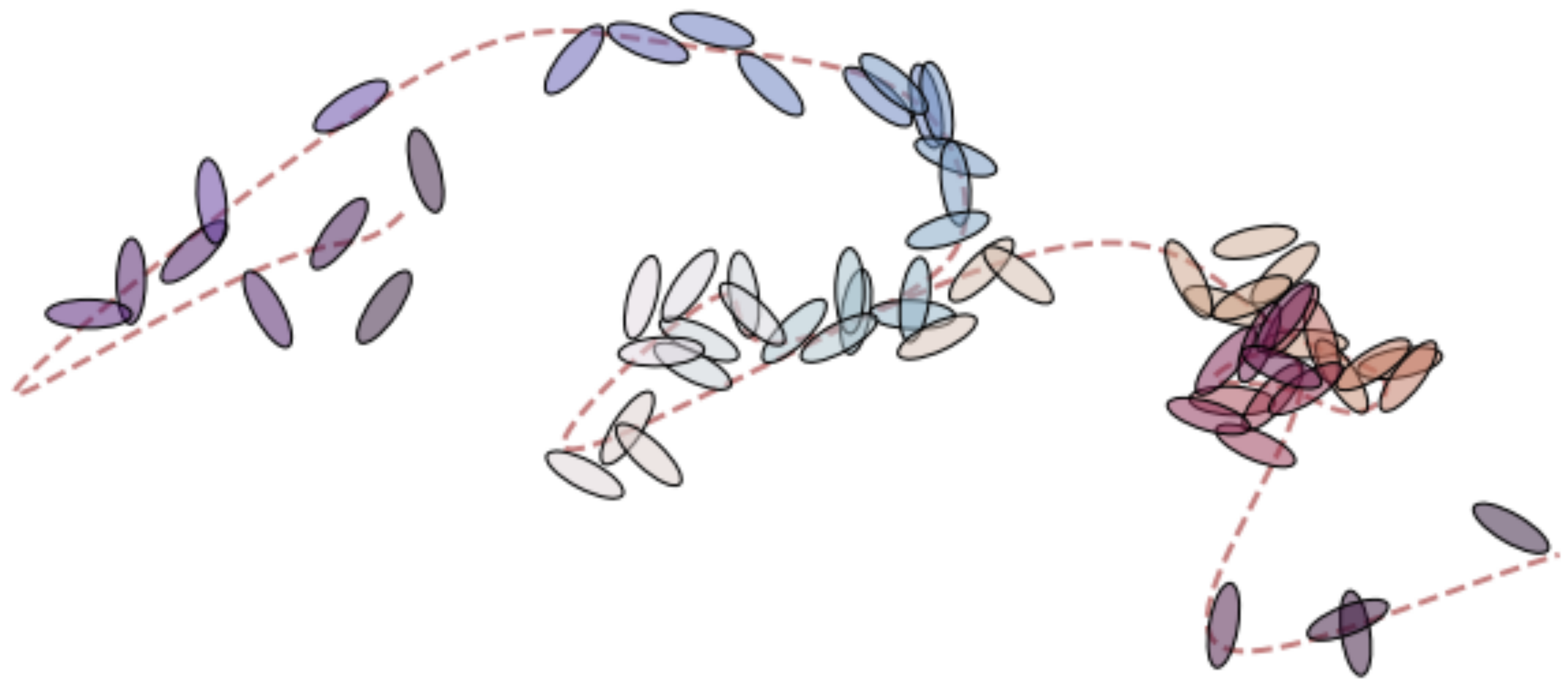


Same system, with different period (and semi-major axis)

Gaia Astrometry



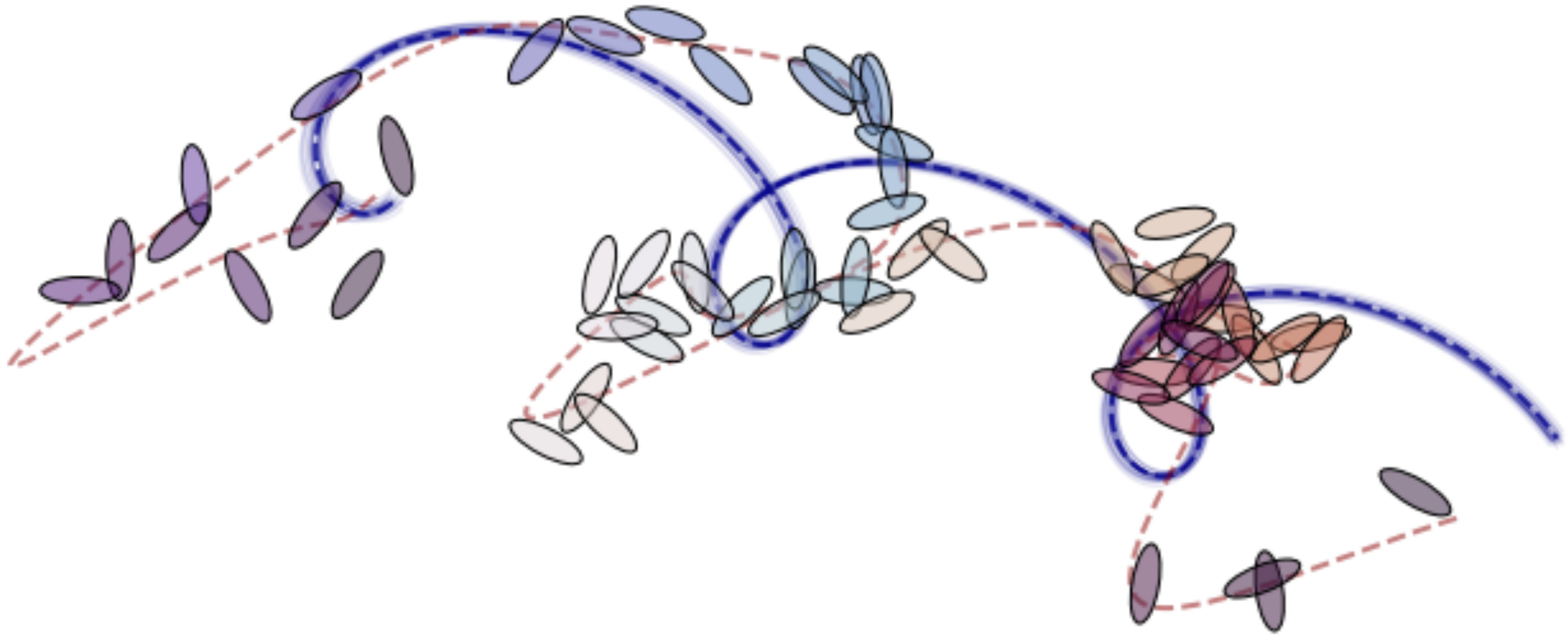
Gaia Astrometry



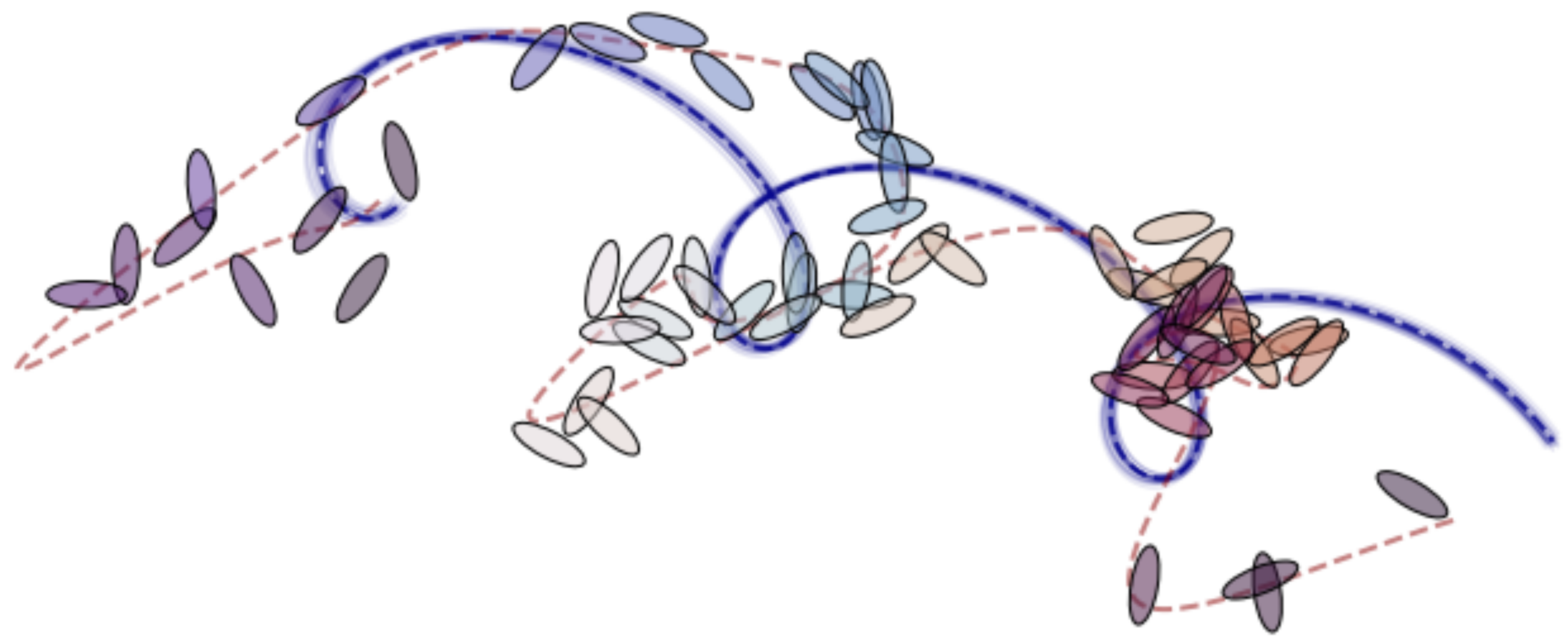
Fit for Position, Parallax & Proper Motion (5 parameters)

Gaia Astrometry

Fit for Position, Parallax & Proper Motion (5 parameters)



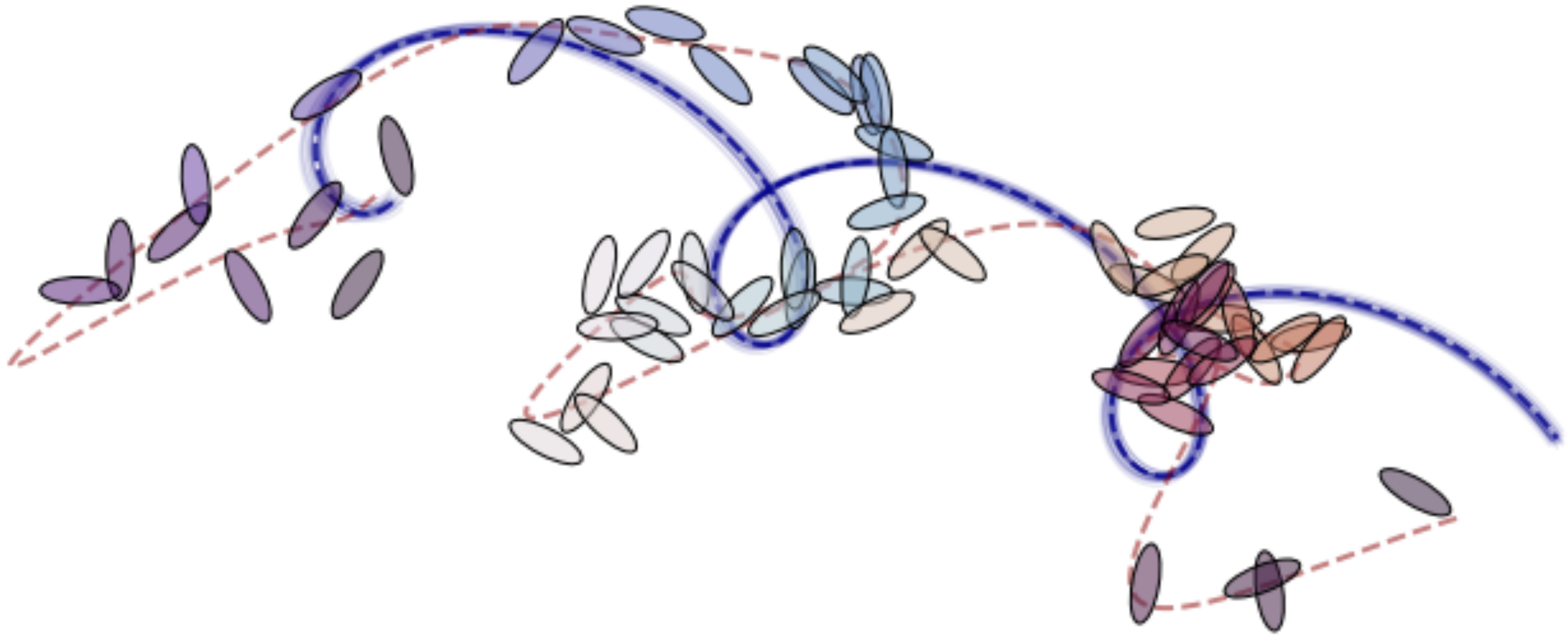
Gaia Astrometry



Fit for Position, Parallax & Proper Motion (5 parameters)

& Error!

Gaia Astrometry

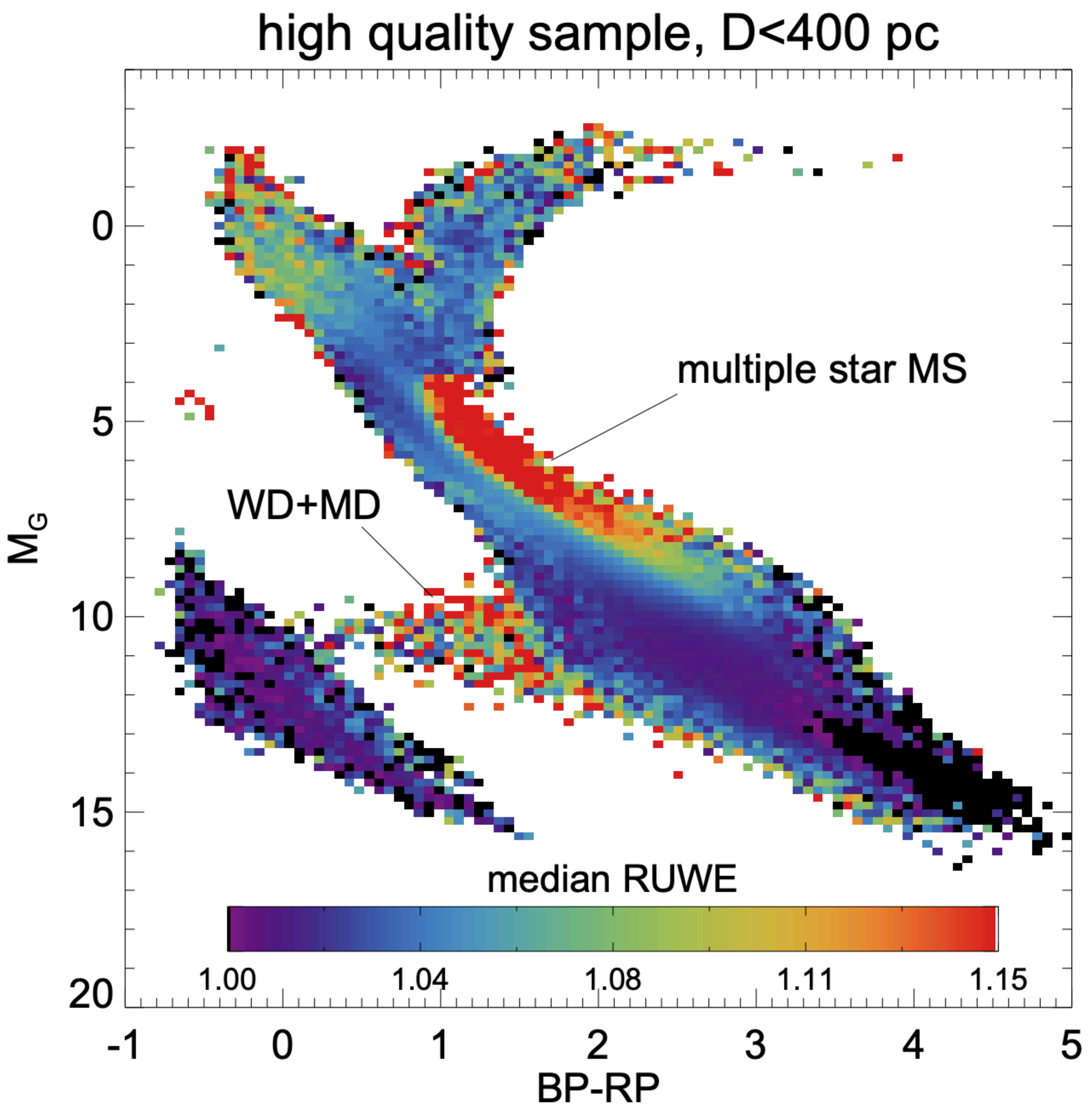


Fit for Position, Parallax & Proper Motion (5 parameters)

& Error!

$$UWE_{obs} = \sqrt{\frac{\sum_i^{N_{obs}} (\alpha_{obs,i} - \alpha_{model,i})^2 + (\delta_{obs,i} - \delta_{model,i})^2}{\sigma_{ast}^2 (N_{obs} - 5)}}$$

Unit Weight Error - UWE



Belokurov, Penoyre et al. 2020

Fit for Position, Parallax & Proper Motion (5 parameters)

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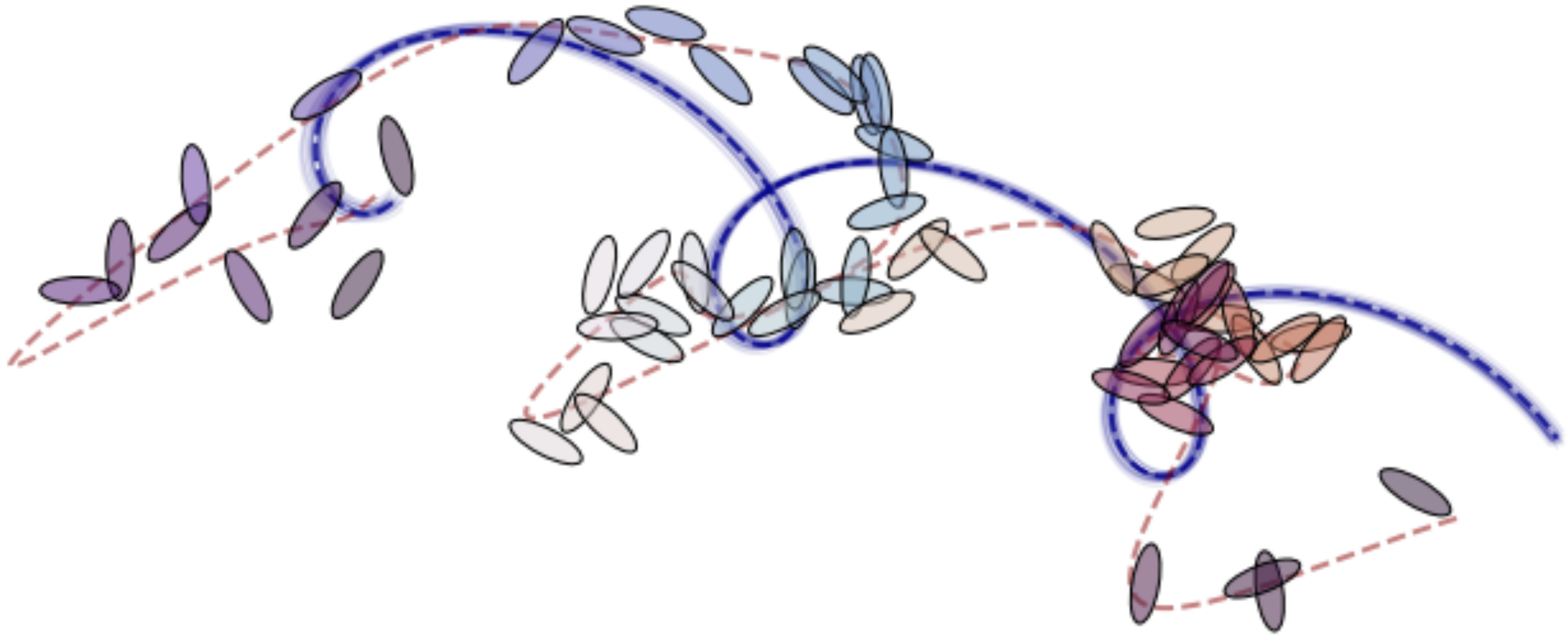
Unit Weight Error - UWE

Gaia Astrometry



Fit for Position, Parallax & Proper Motion (5 parameters)

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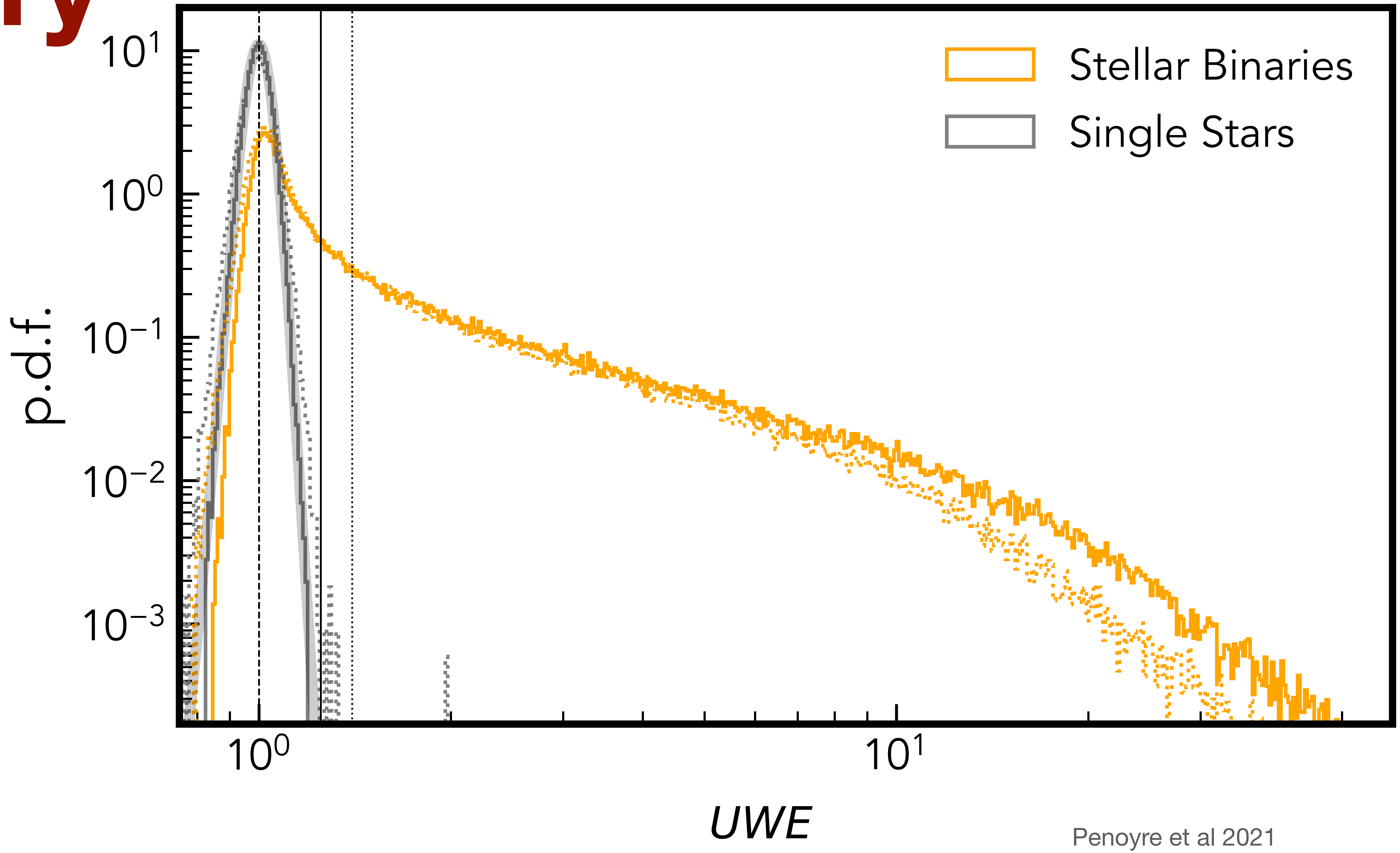
$$UWE_{obs} = \sqrt{\frac{\sum_i^{N_{obs}} (\alpha_{obs,i} - \alpha_{model,i})^2 + (\delta_{obs,i} - \delta_{model,i})^2}{\sigma_{ast}^2 (N_{obs} - 5)}}$$

$$UWE_{pred} = \sqrt{1 + \left(\frac{\delta\theta}{\sigma_{ast}}\right)^2}$$

$$\delta\theta \propto \Delta\varpi \, a$$

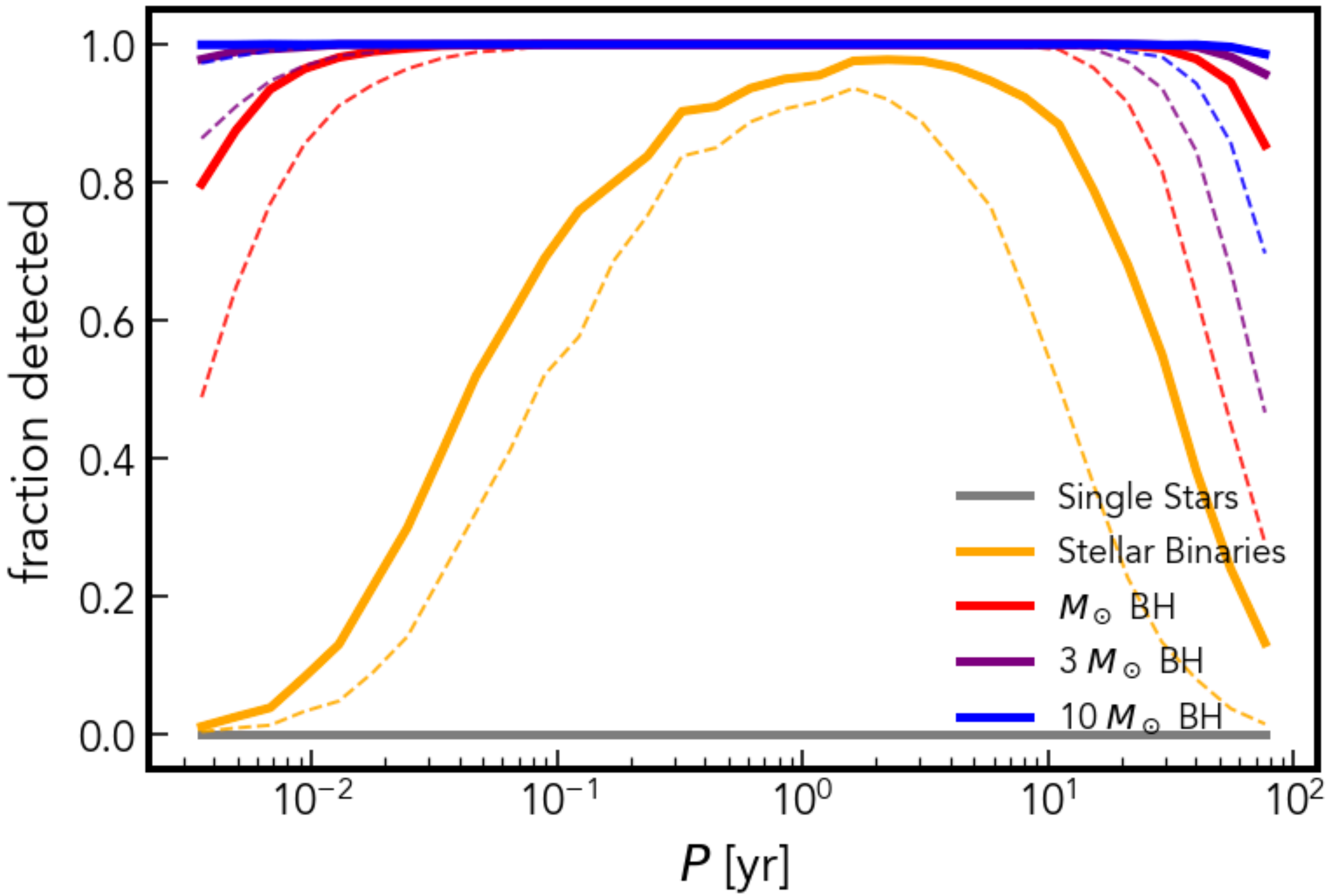
Unit Weight Error - UWE

Gaia Astrometry



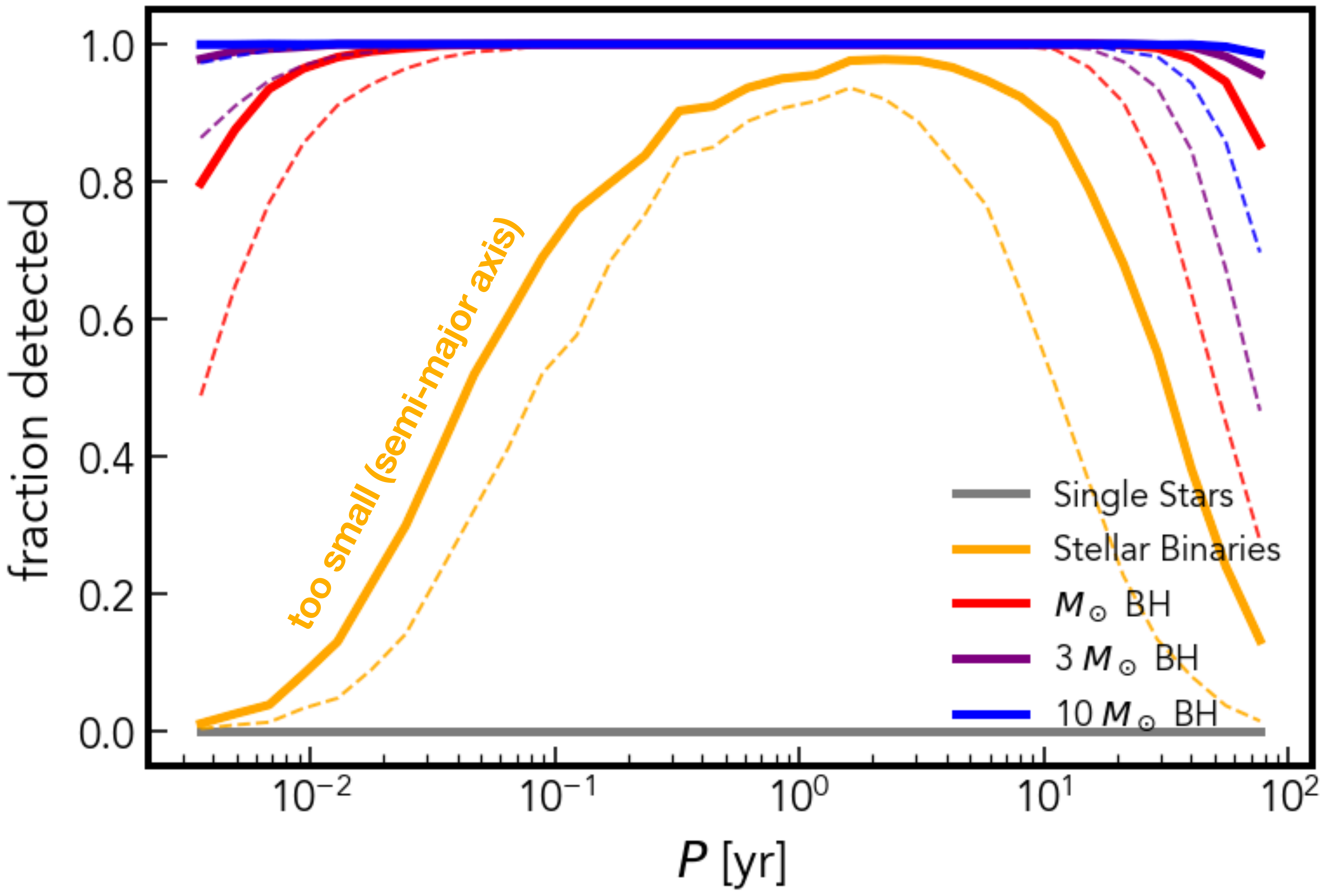
Penoyre et al 2021

Gaia Astrometry



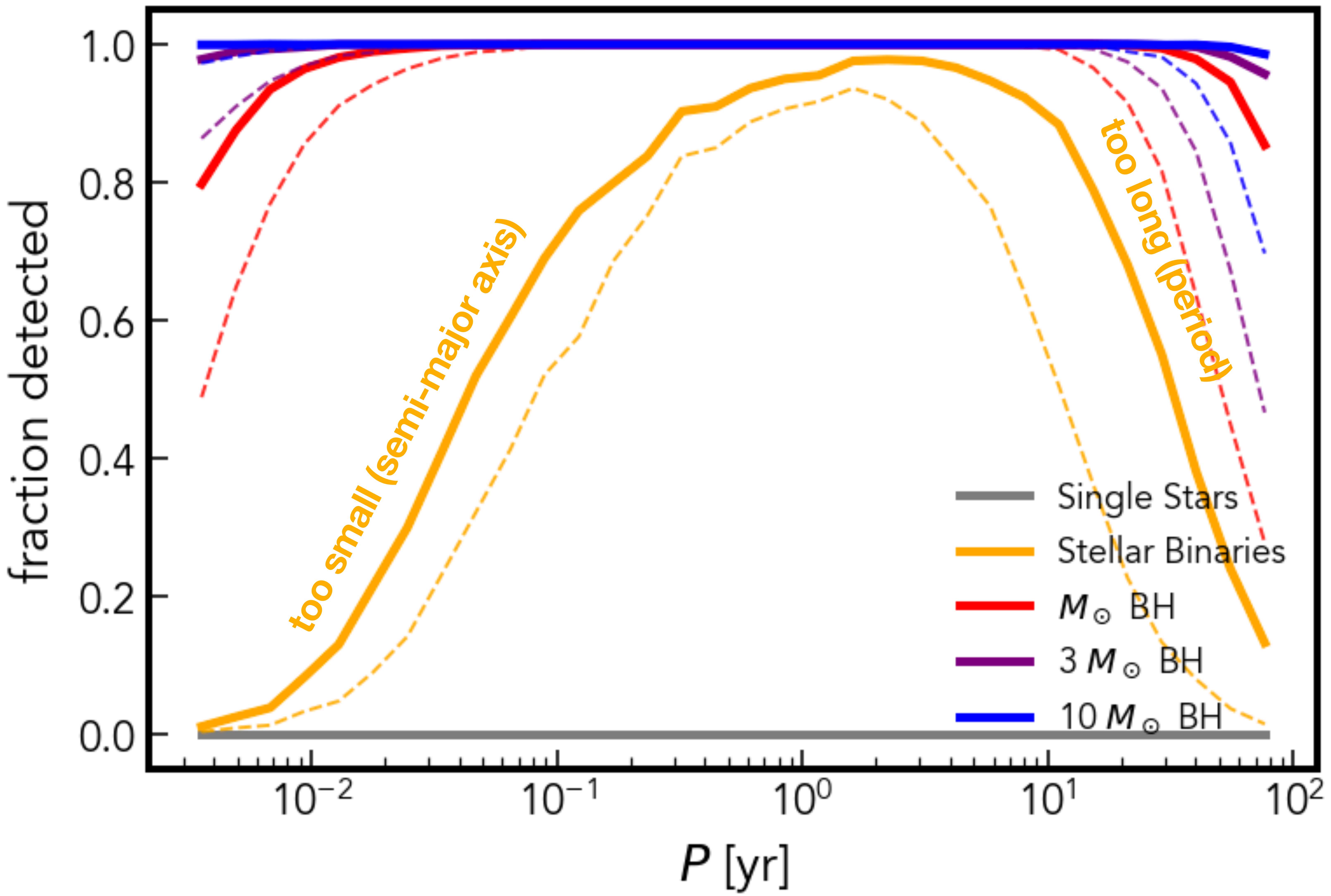
Penoyre et al 2021

Gaia Astrometry



Penoyre et al 2021

Gaia Astrometry



Penoyre et al 2021

Gaia Astrometry

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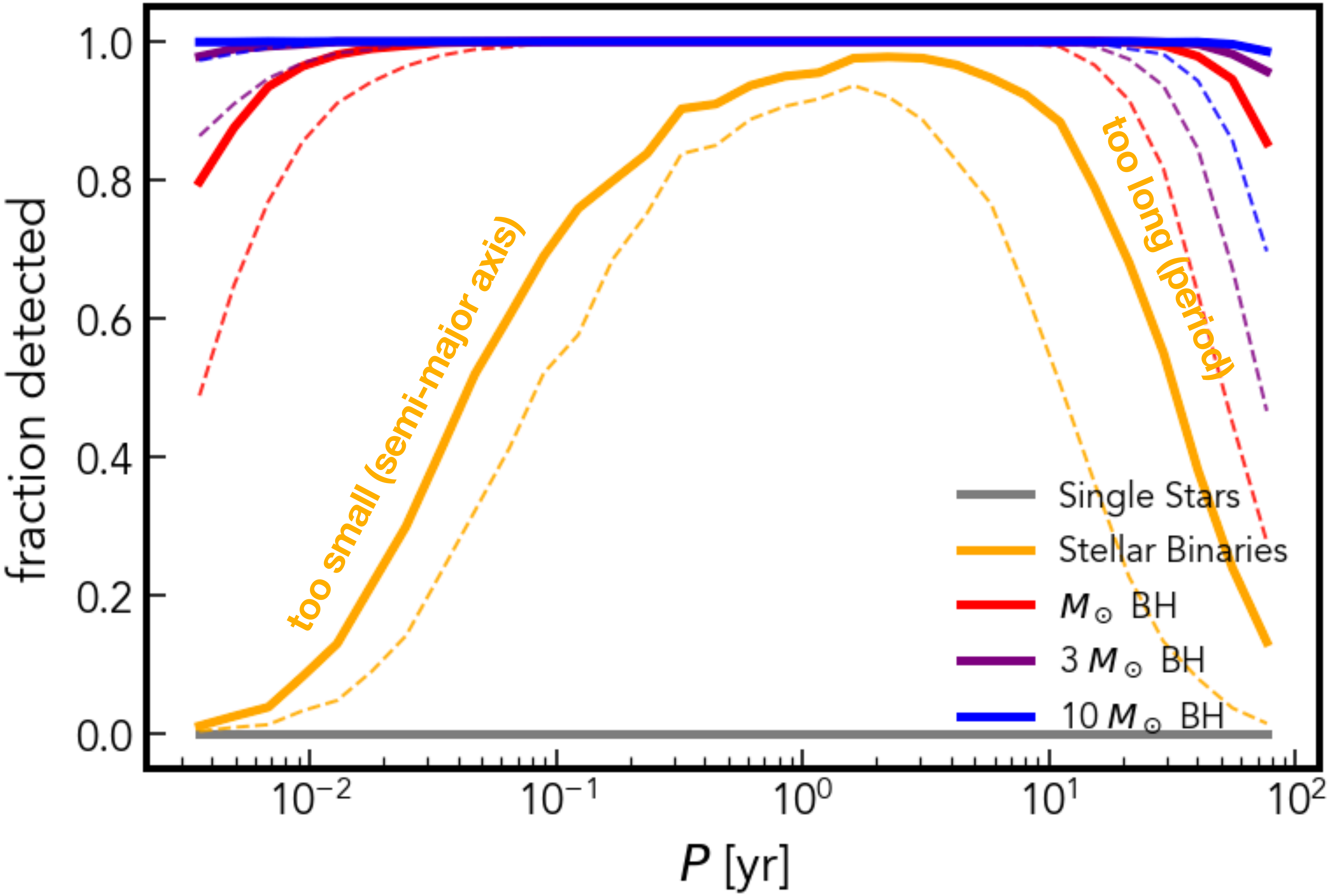


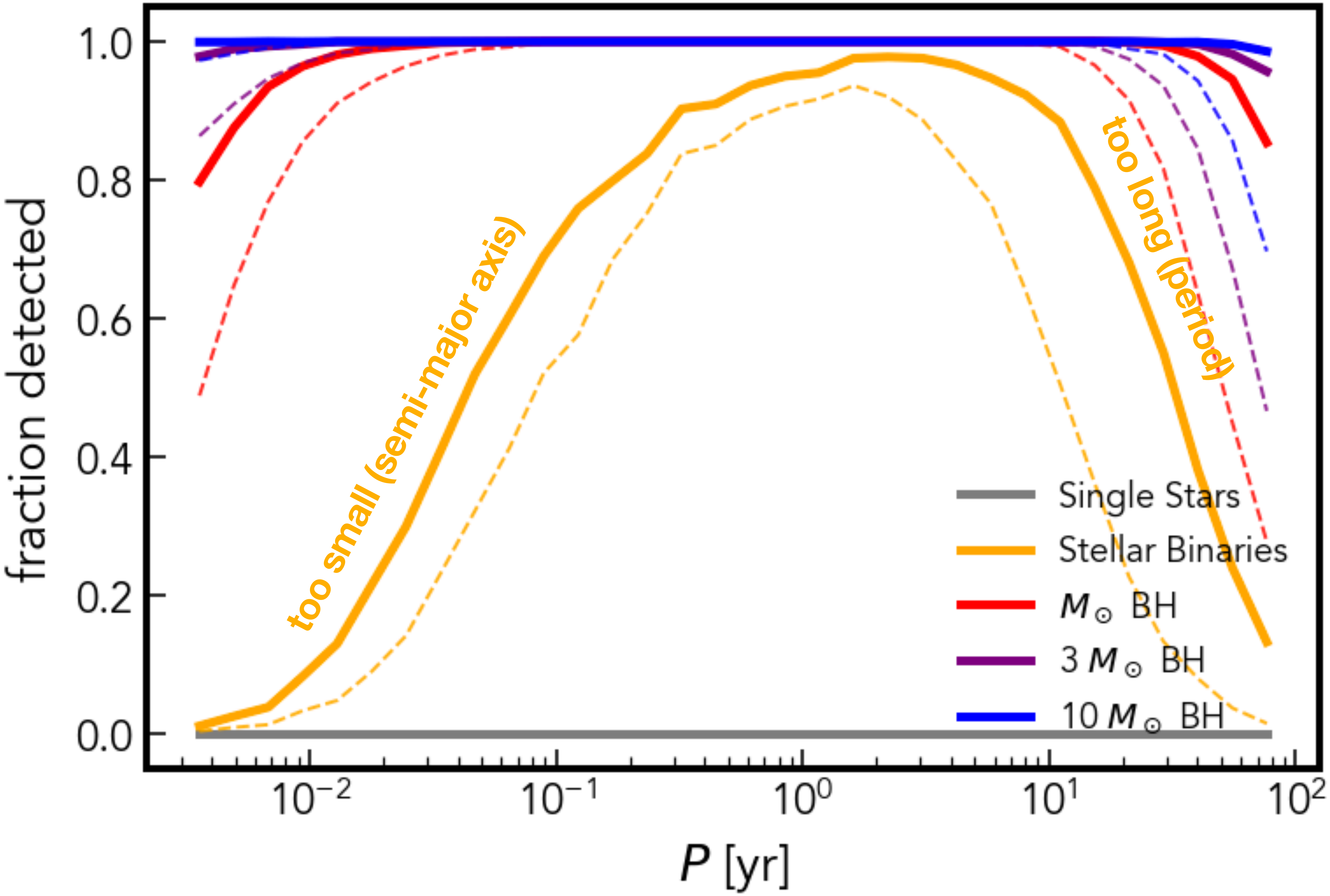
Penoyre et al 2021

Gaia Astrometry

$$UWE_{pred} = \sqrt{1 + \left(\frac{\delta\theta}{\sigma_{ast}}\right)^2}$$

$$\delta\theta \propto \Delta\varpi \, a$$

$$\delta\theta^* \propto N_{orb}^2 \Delta\varpi \, a \quad \text{for} \quad N_{orb} < 1$$



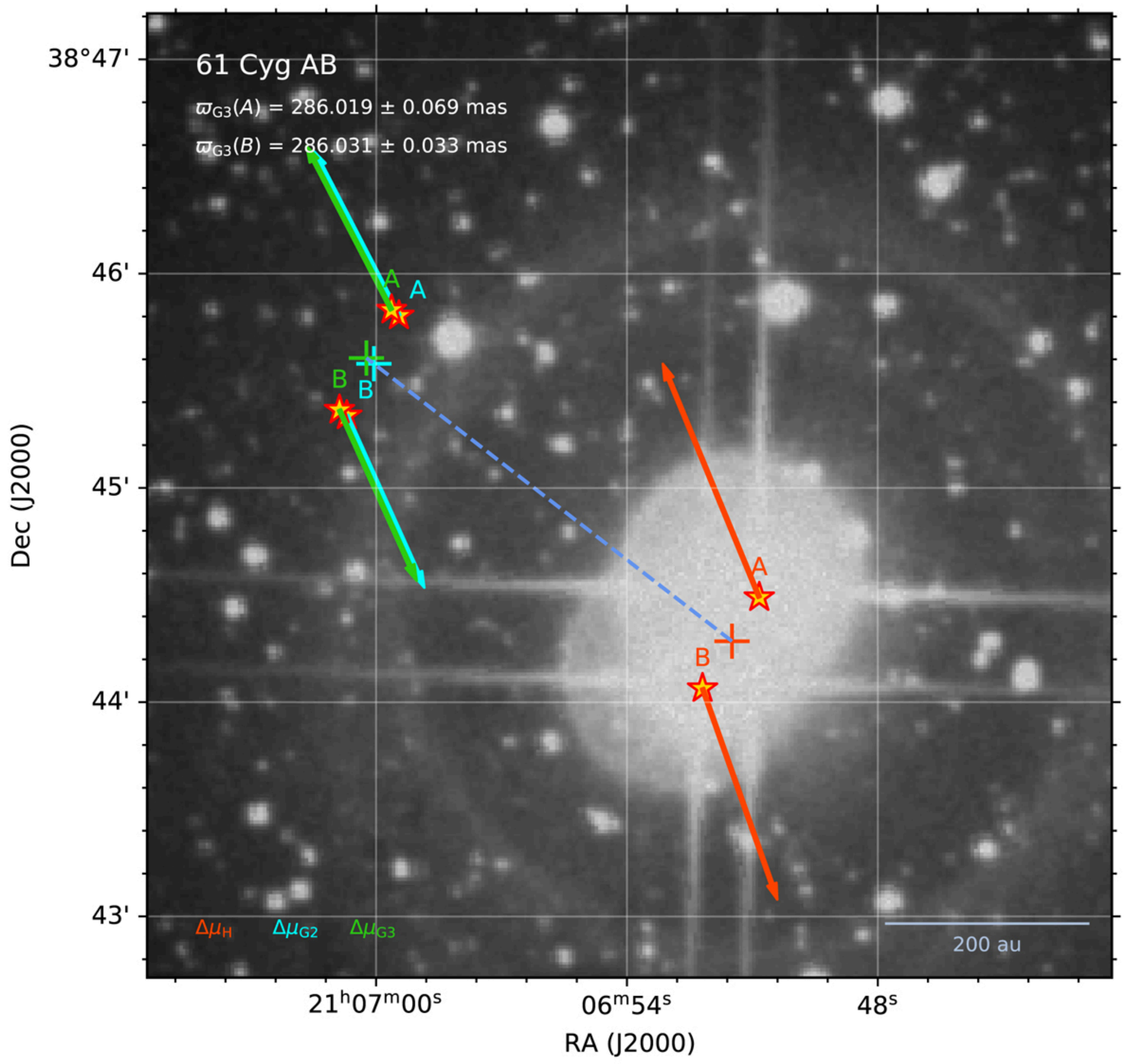
Penoyre et al 2021

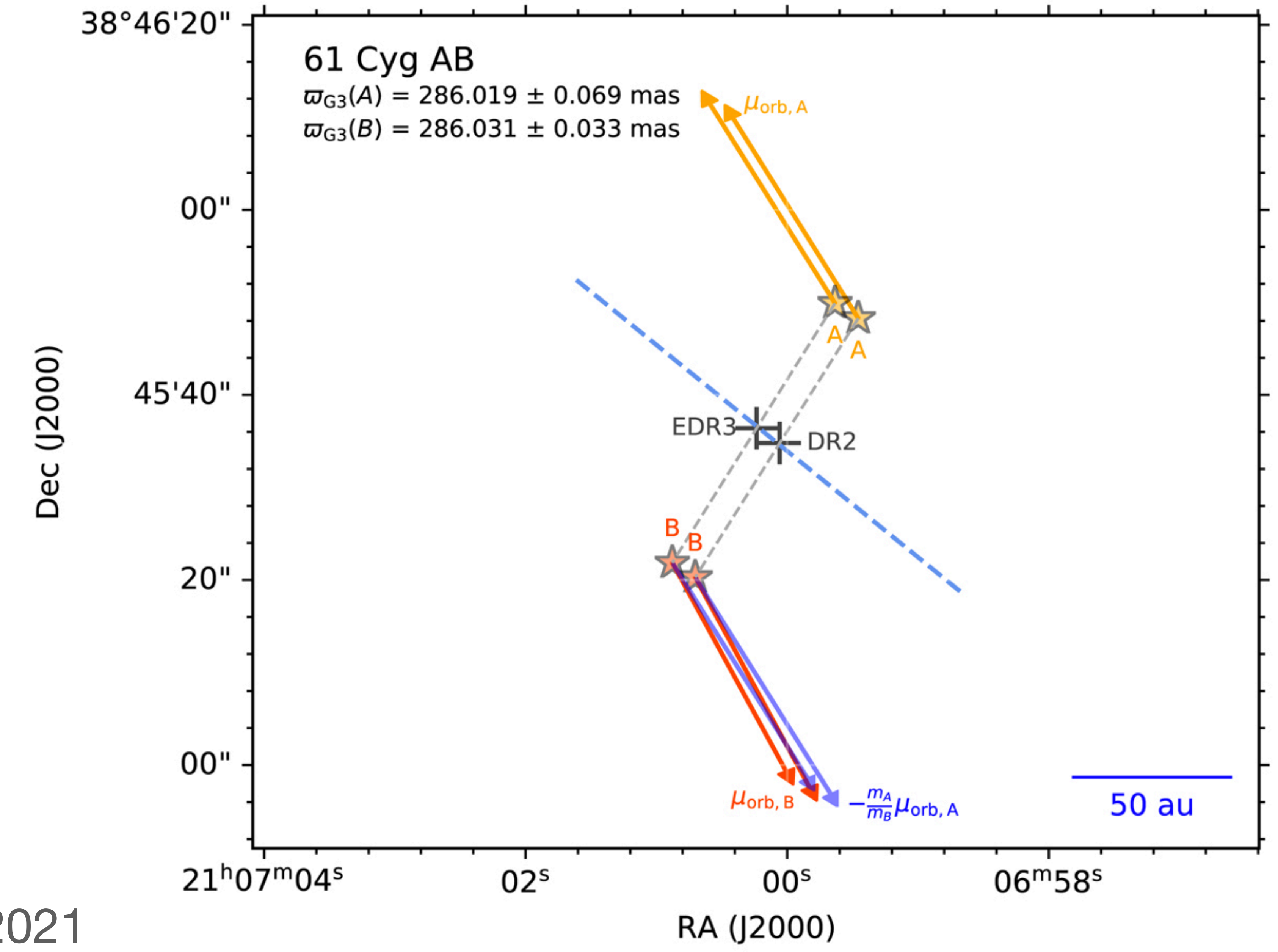
Gaia Astrometry

Proper motion anomaly

Gaia Astrometry

Proper motion anomaly

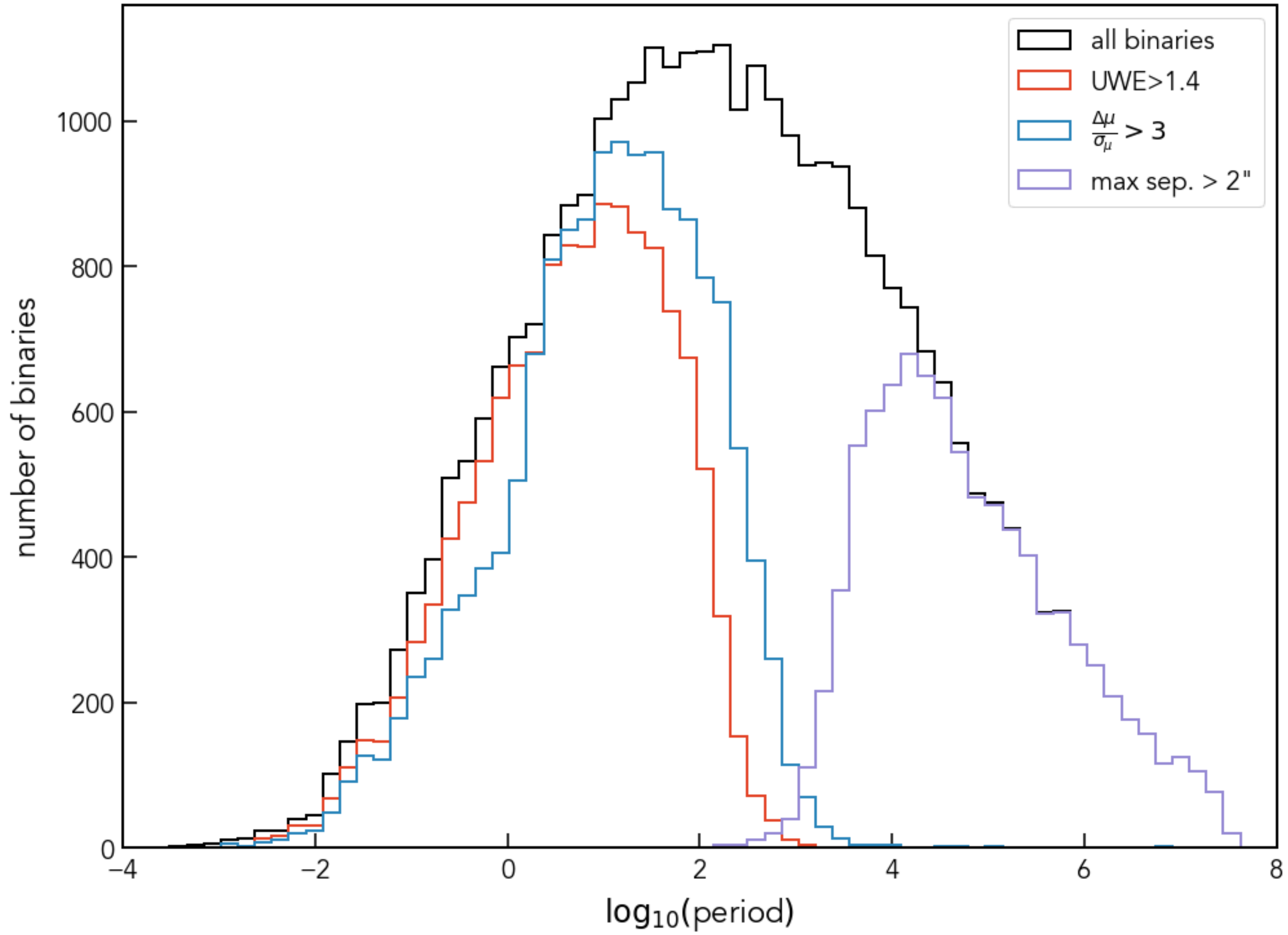




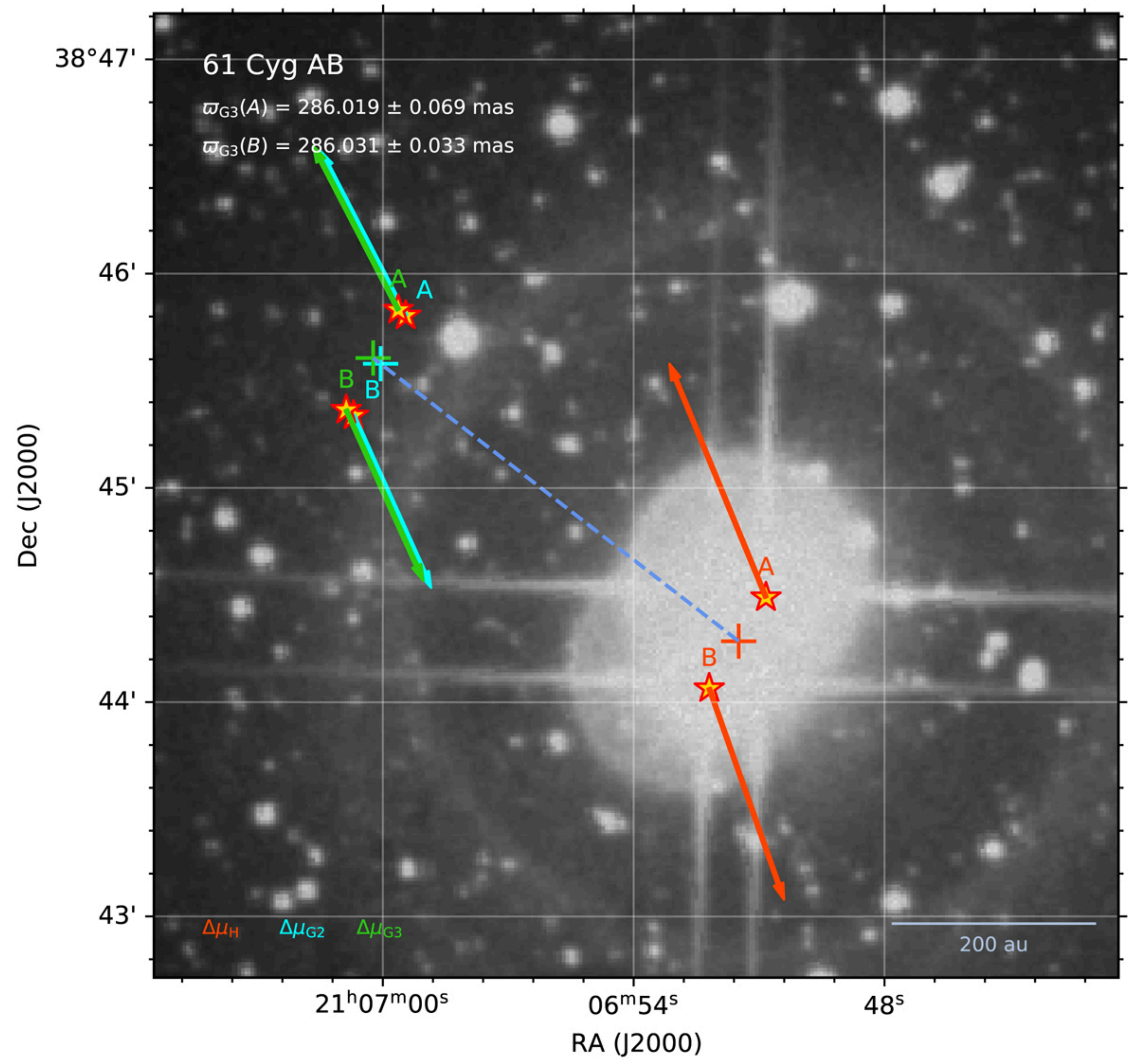
Kervella et al 2021

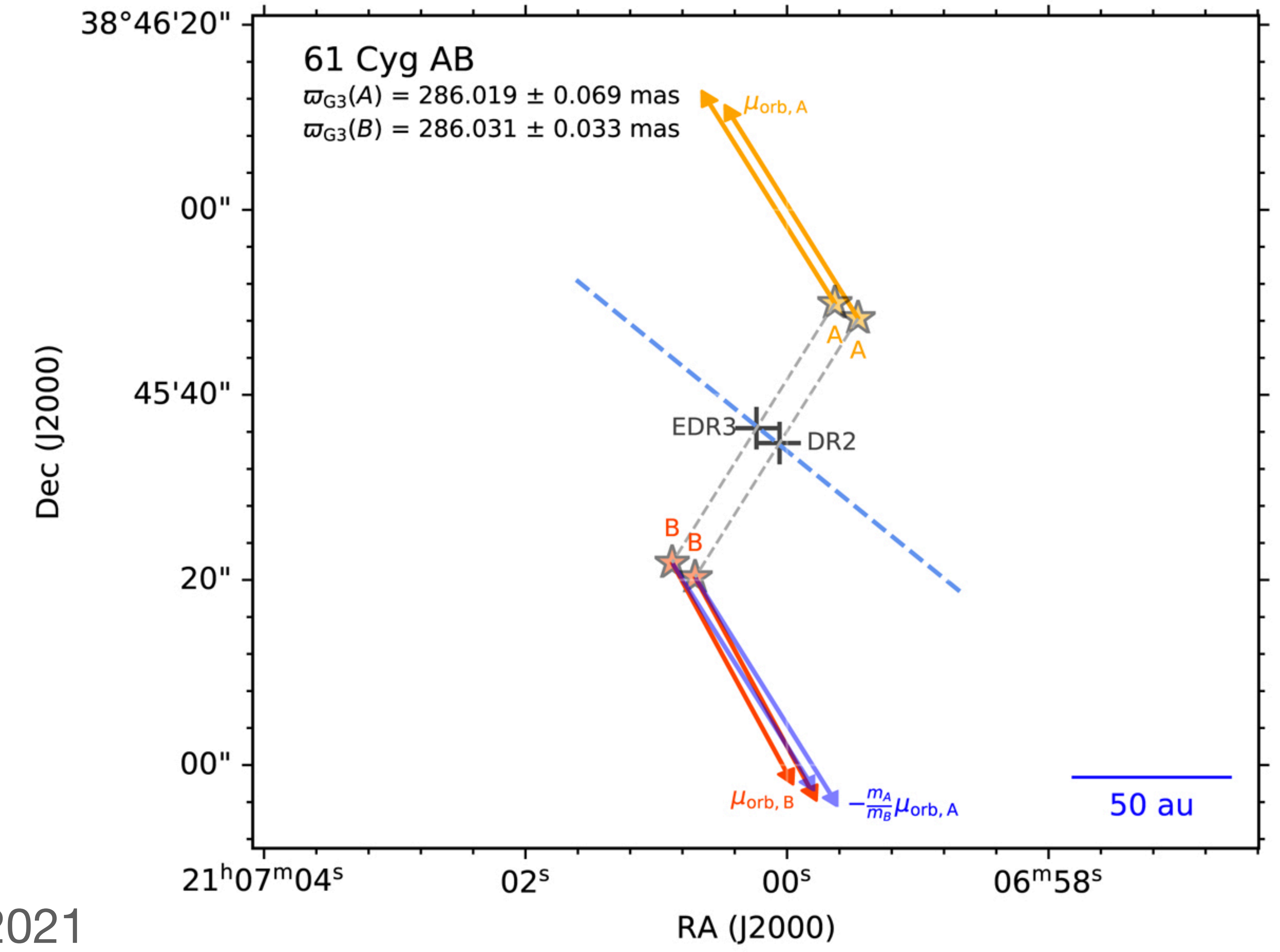
Gaia Astrometry

Proper motion anomaly



Penoyre et al 2022 (in prep.)





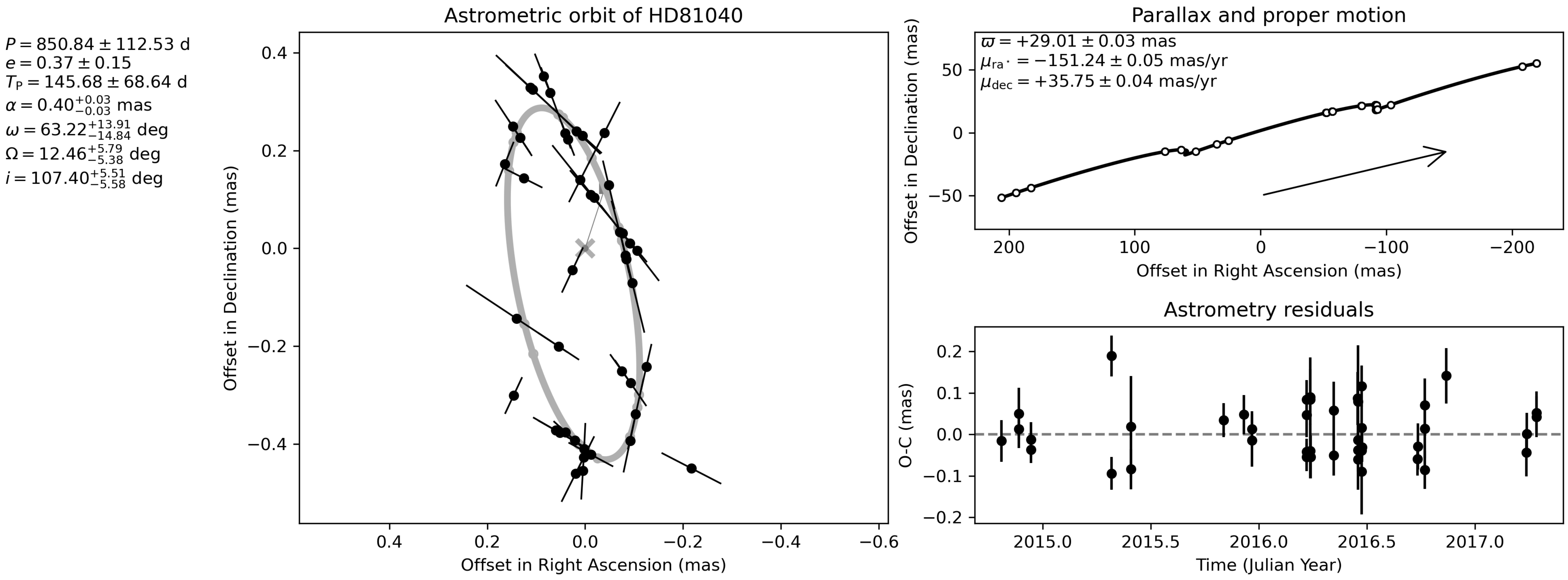
Kervella et al 2021

Gaia Astrometry

Epoch astrometry fitting

Gaia Astrometry

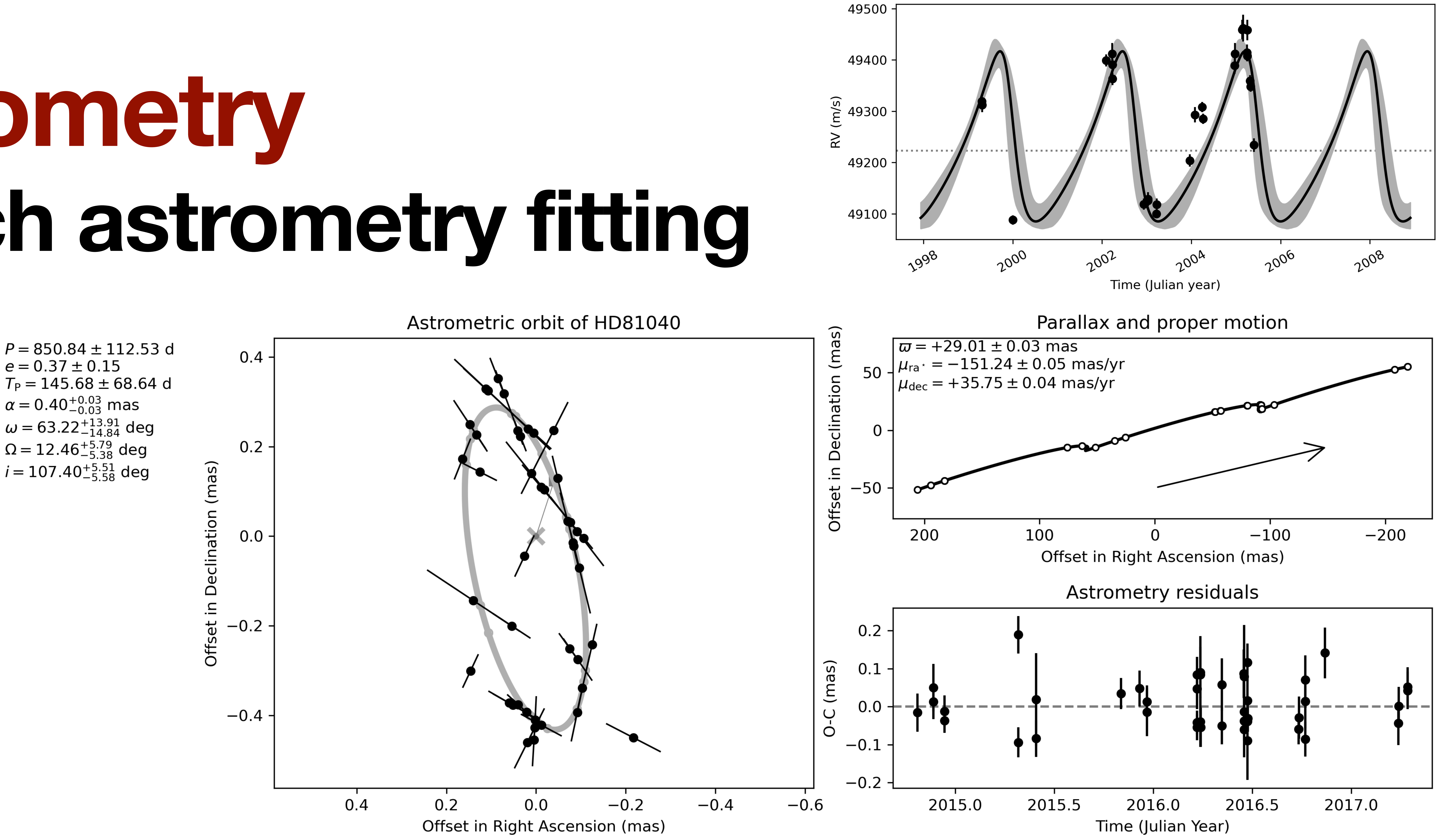
Epoch astrometry fitting



ESA/Gaia/DPAC/CU4-CU3, Johannes Sahlmann et al

Gaia Astrometry

Epoch astrometry fitting

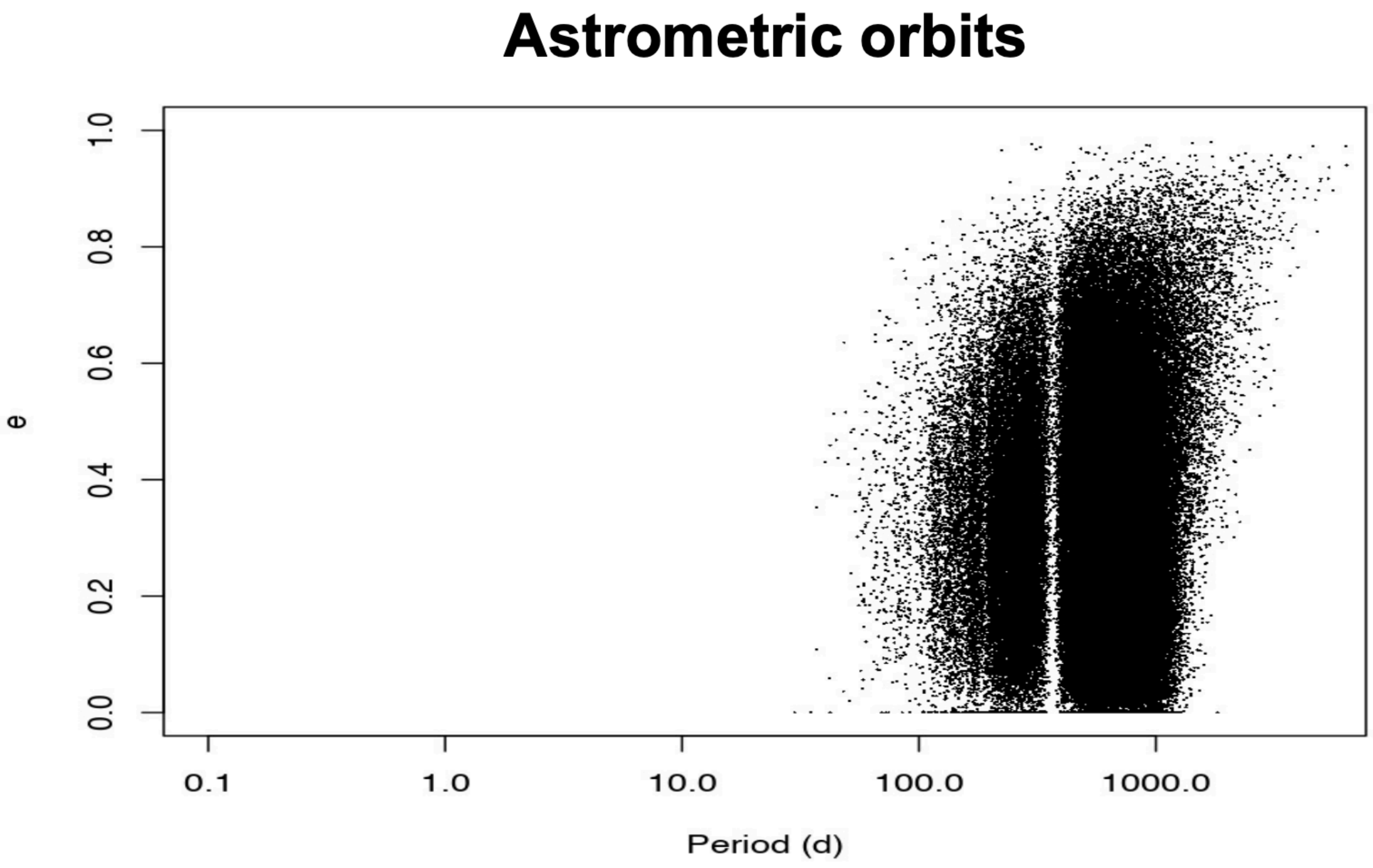


ESA/Gaia/DPAC/CU4-CU3, Johannes Sahlmann et al

Gaia Binaries

Includes spectroscopic measurements of bright stars

Few 100,000 multiple systems in DR3 (June 2022)



Frédéric Arenou, EAS talk 2021

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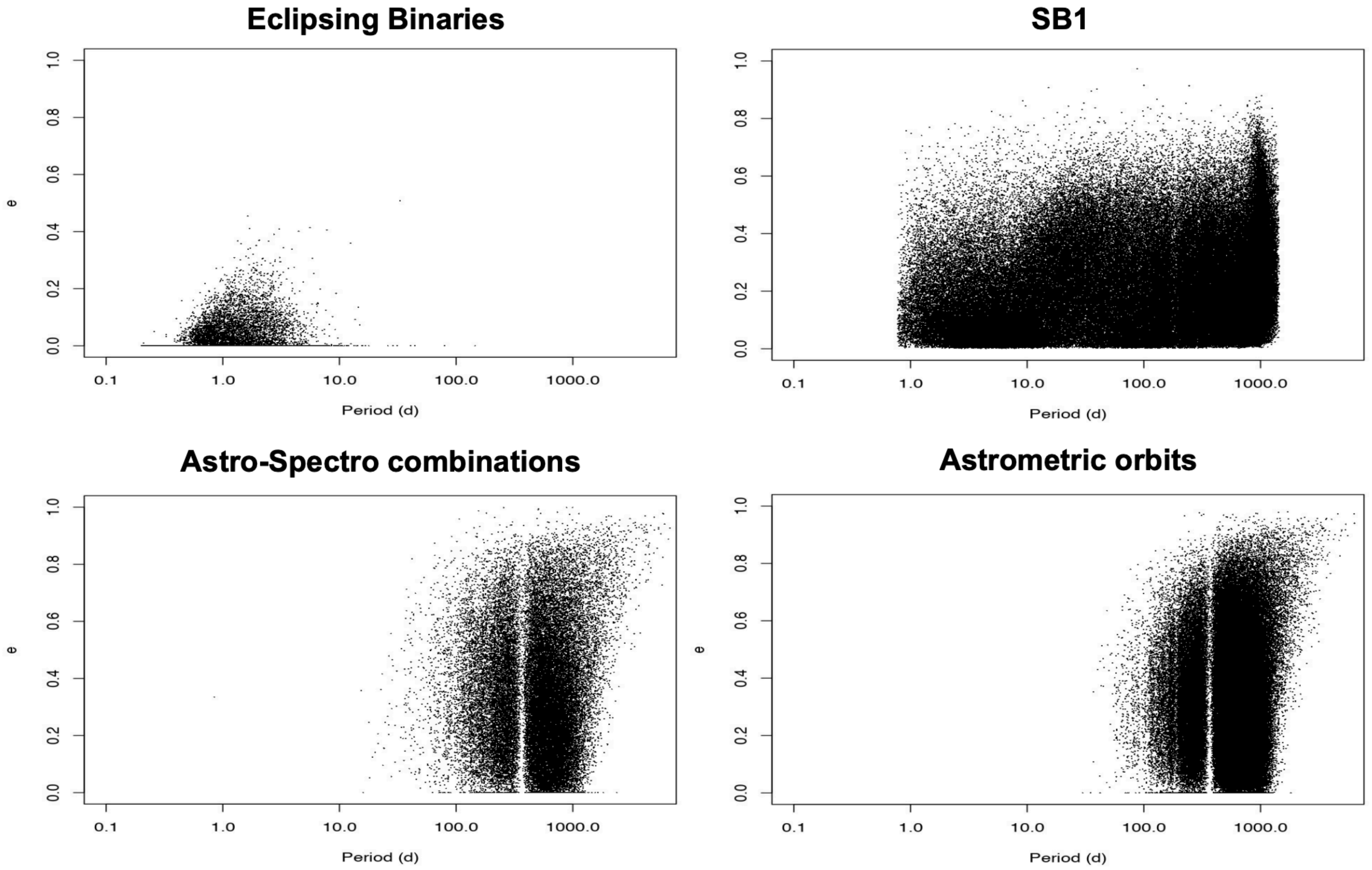

Frédéric Arenou, EAS talk 2021

Conclusions

Binaries fundamentally change the behaviour of stellar populations

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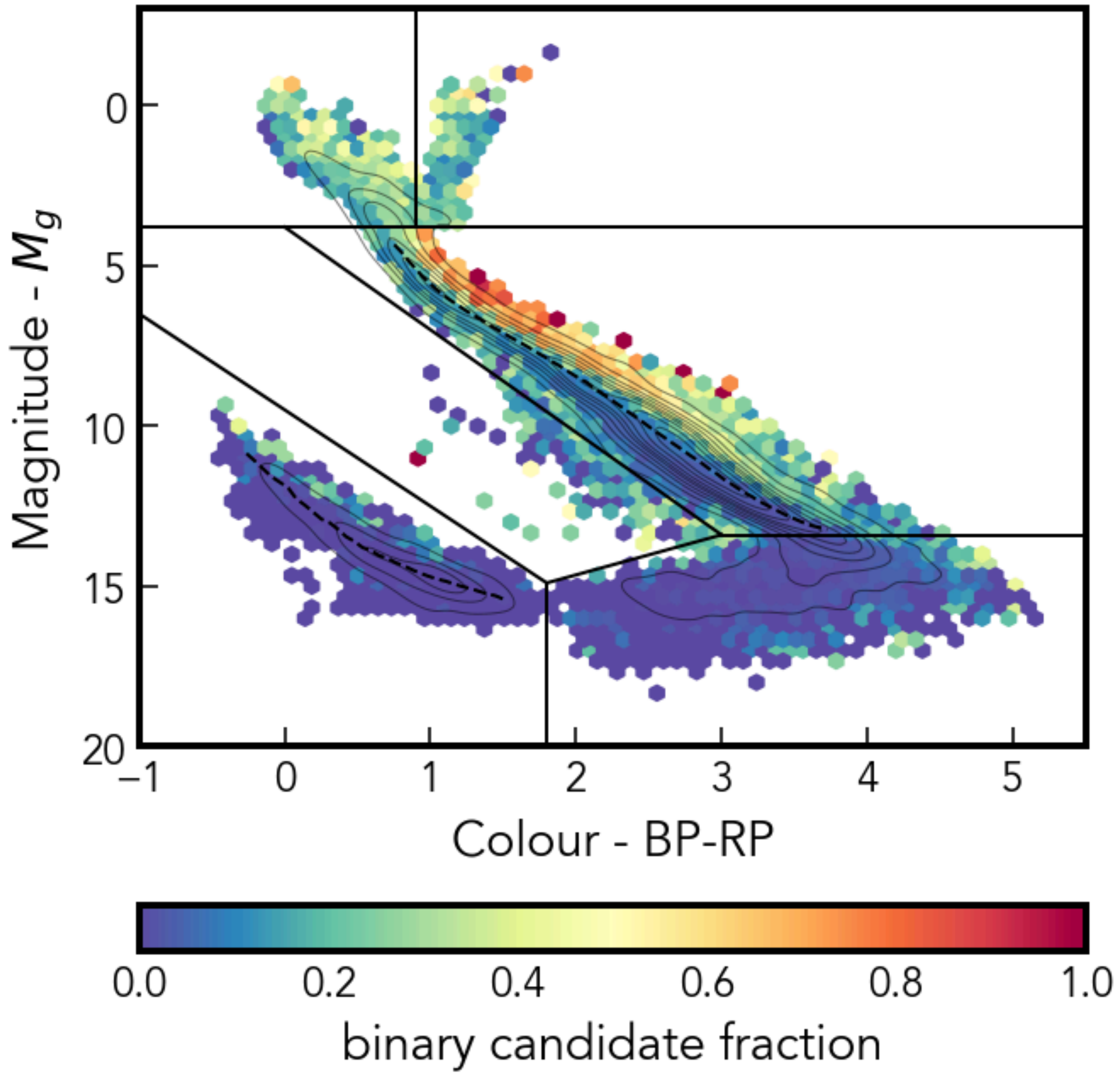
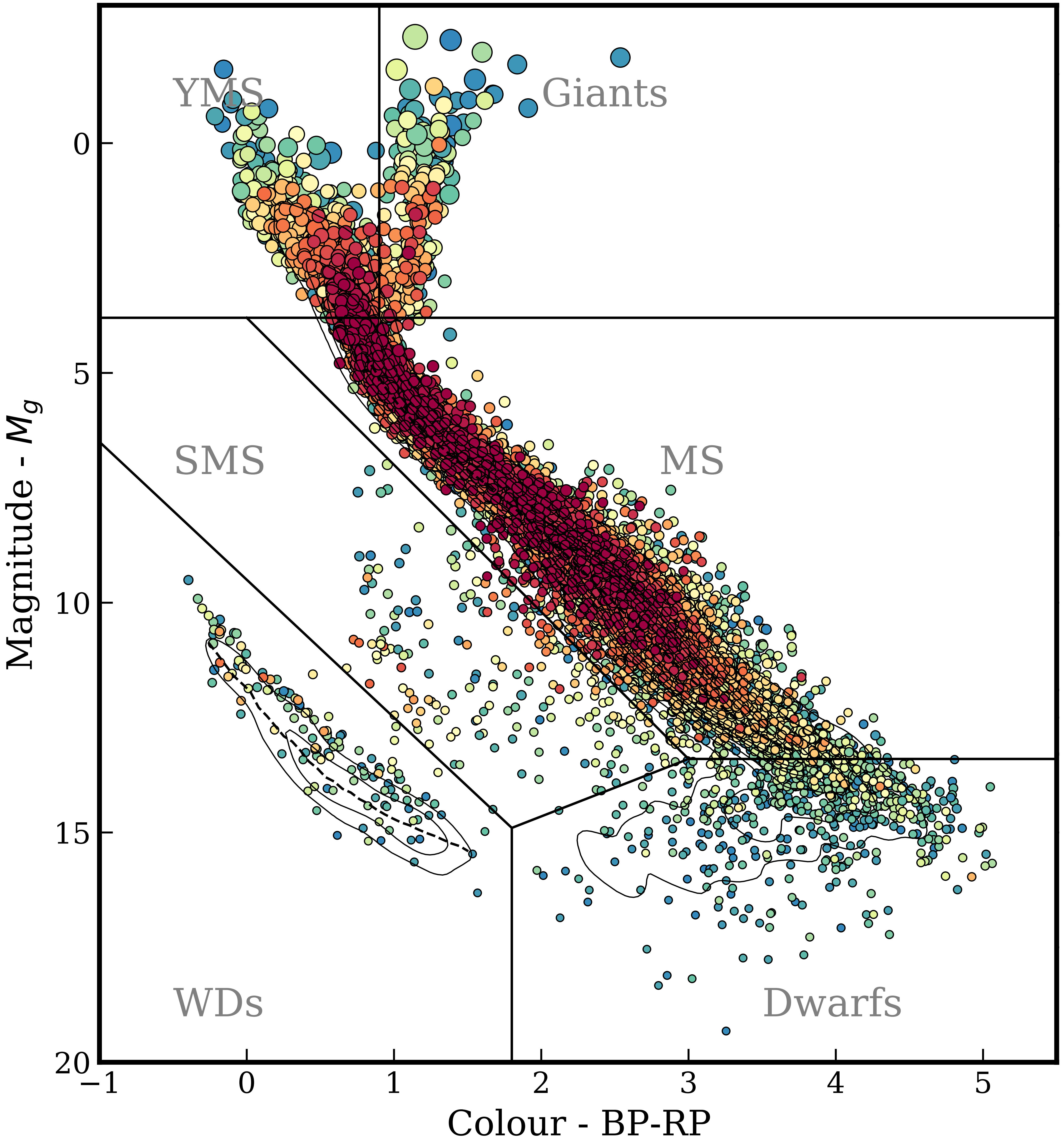
Astrometric binaries are already visible in their thousands, perhaps millions, with Gaia



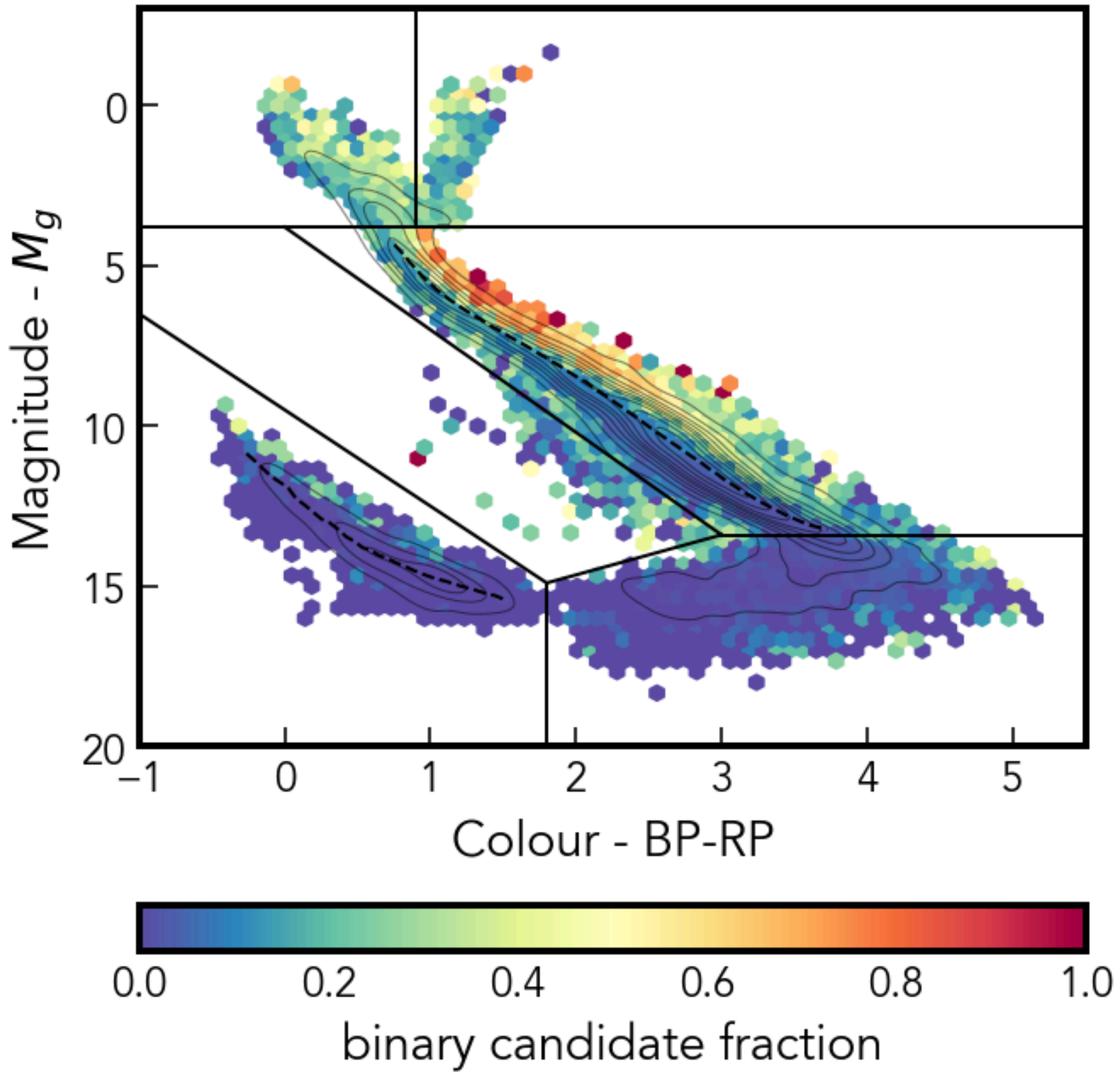


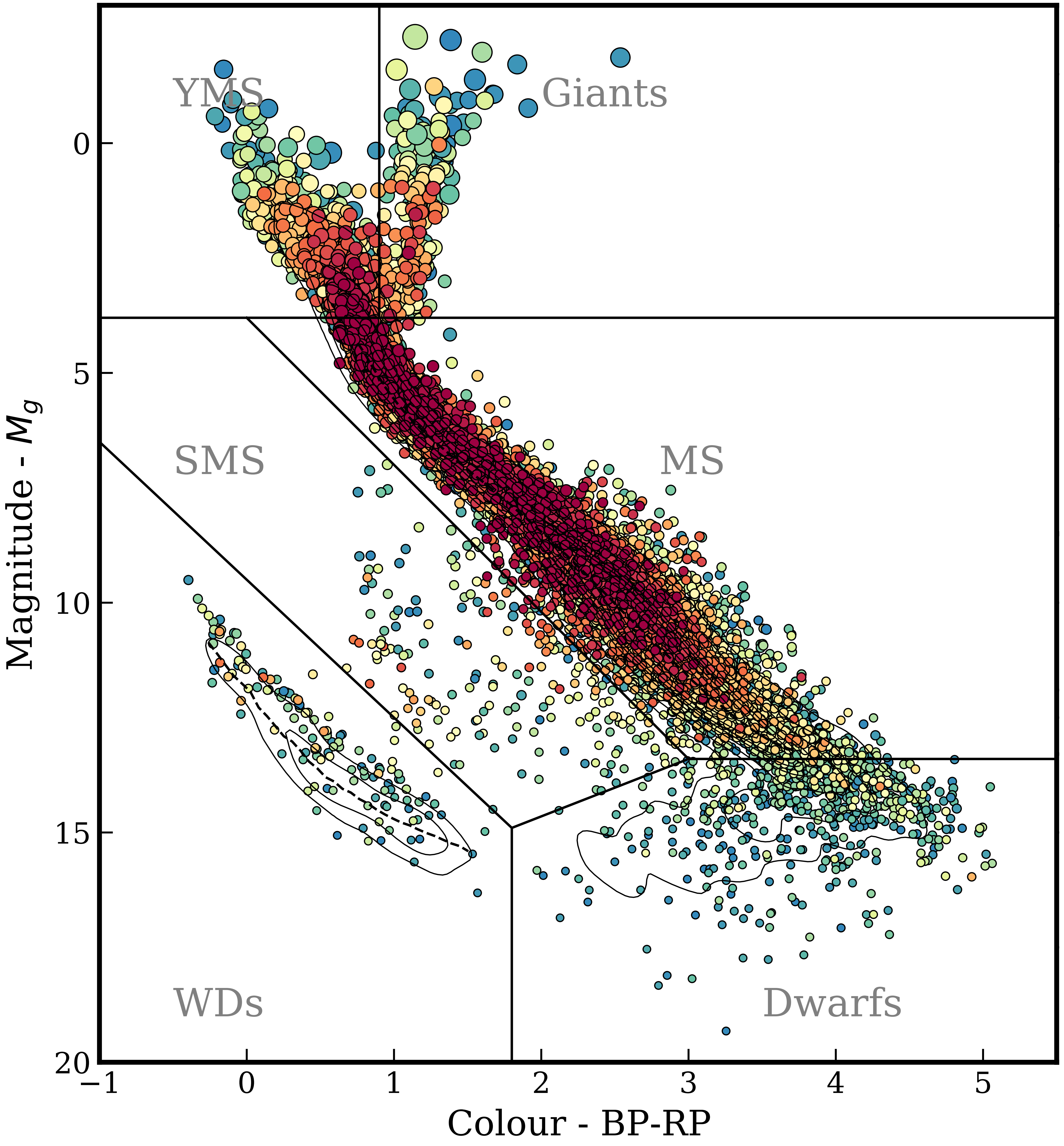
Penoyre et al 2022

Conclusions

Binaries fundamentally change the behaviour of stellar populations

- **Astrometric binaries are already visible in their thousands, perhaps millions, with Gaia**
  - **More & better data is coming over the second half of the Gaia mission**





Penoyre et al 2022

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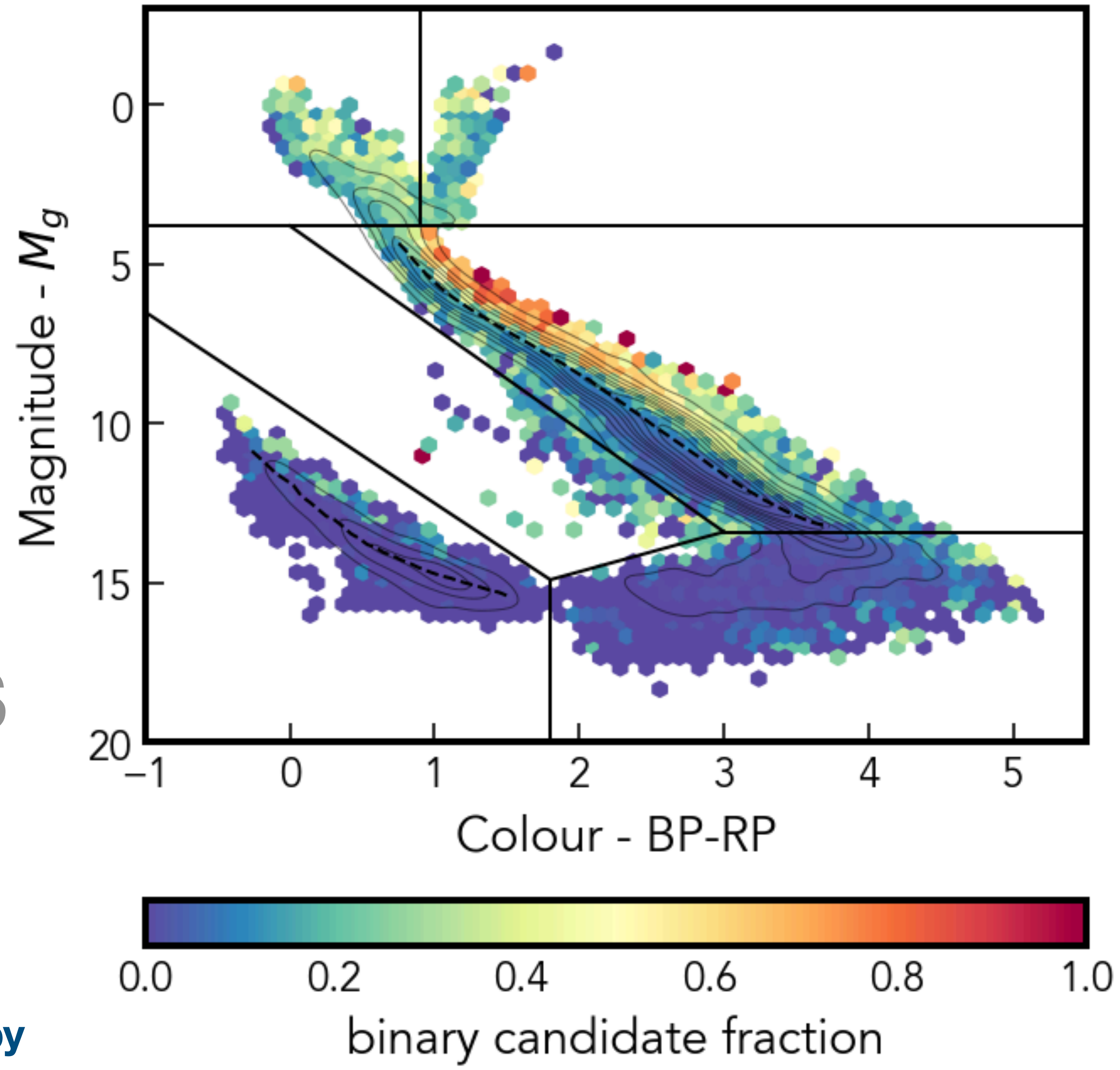
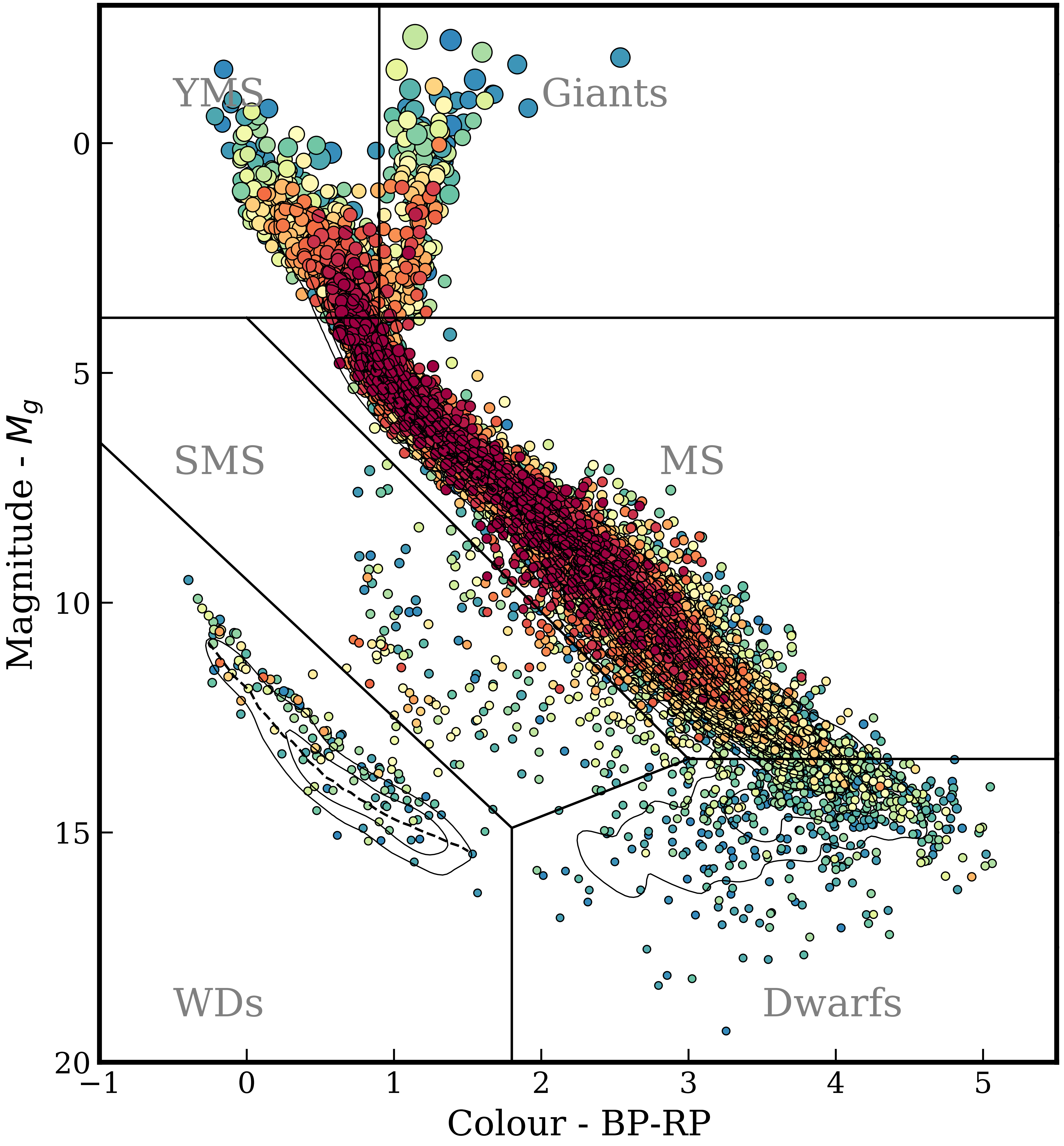


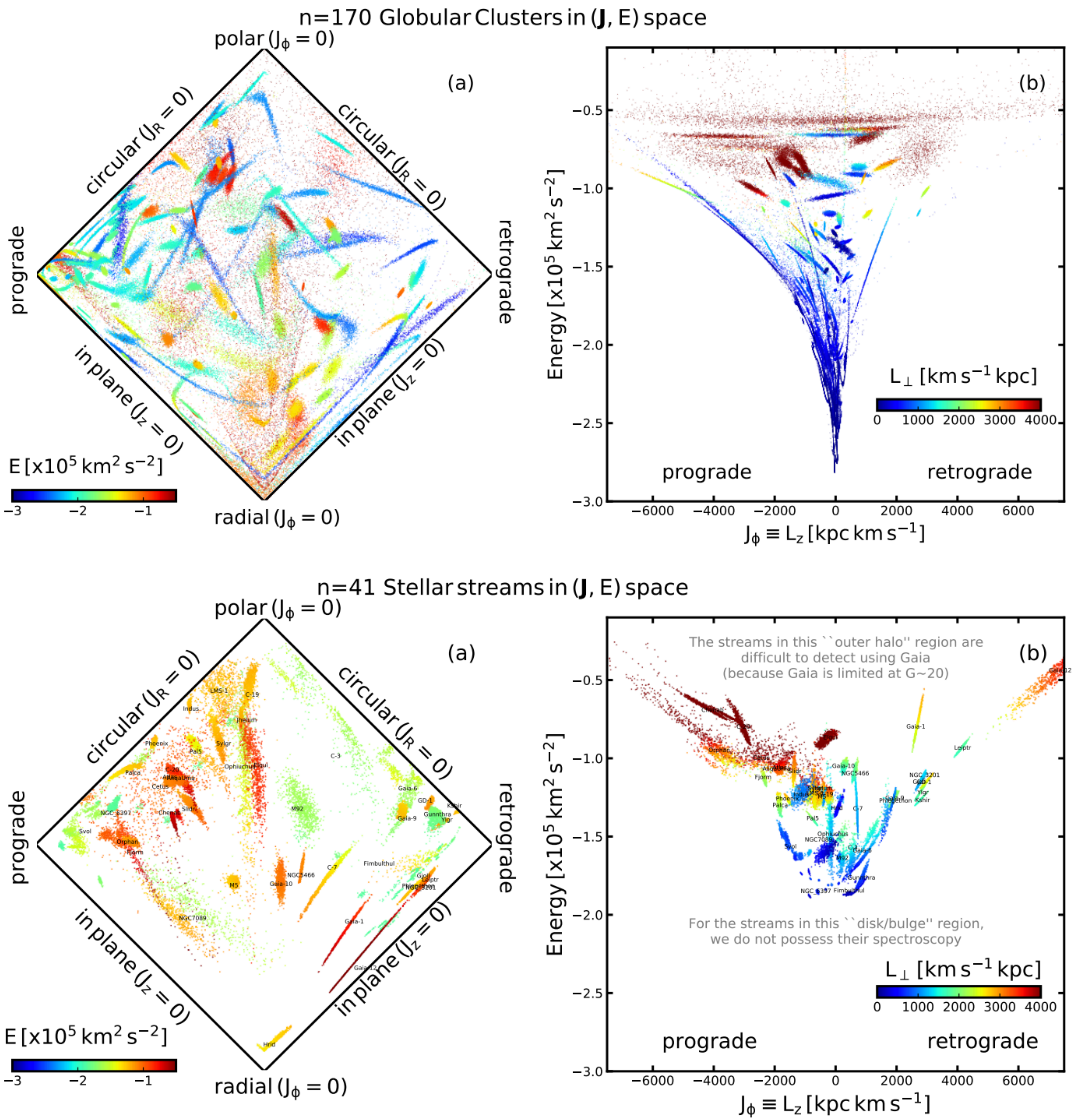


Penoyre et al 2022

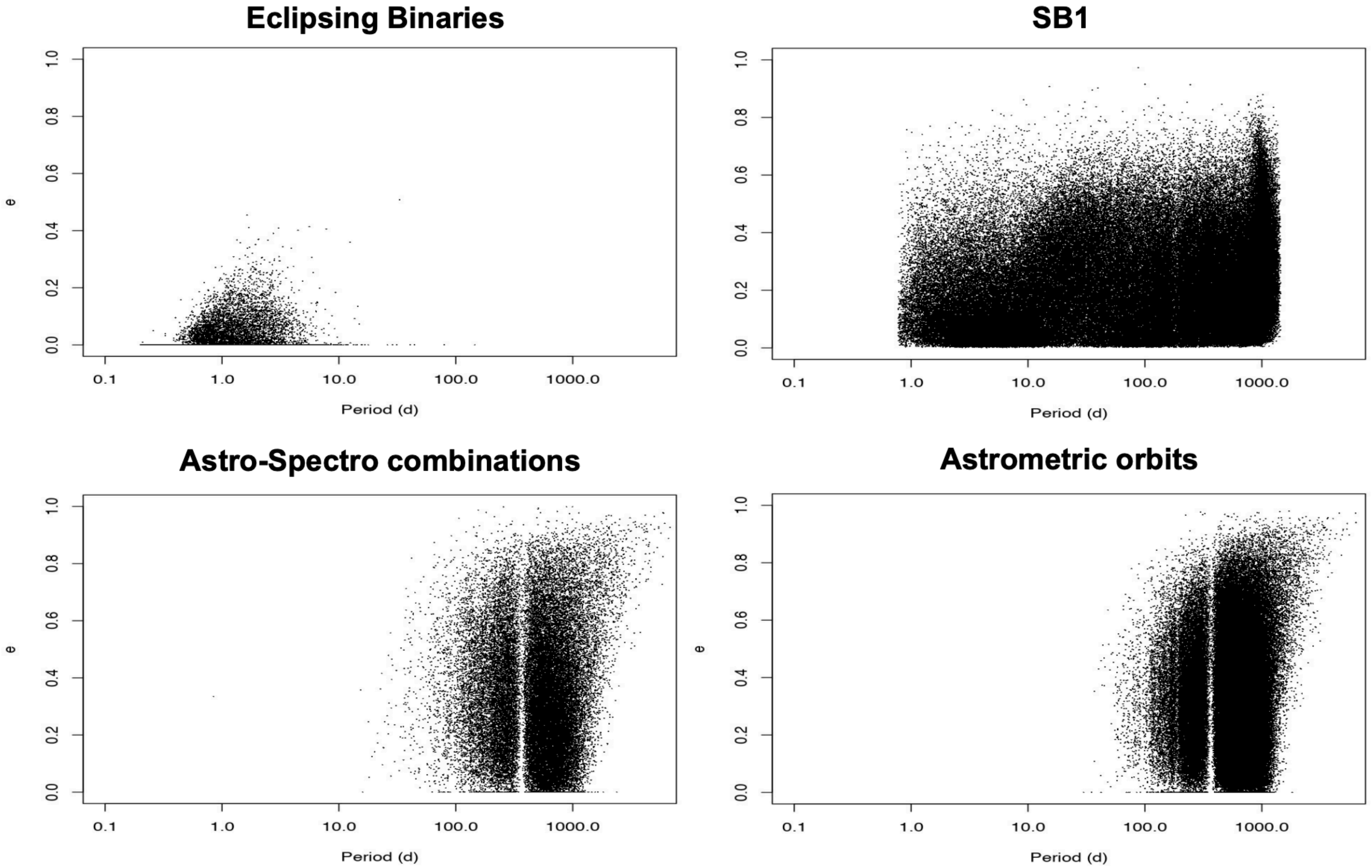
tracks and fits from astromet.py:

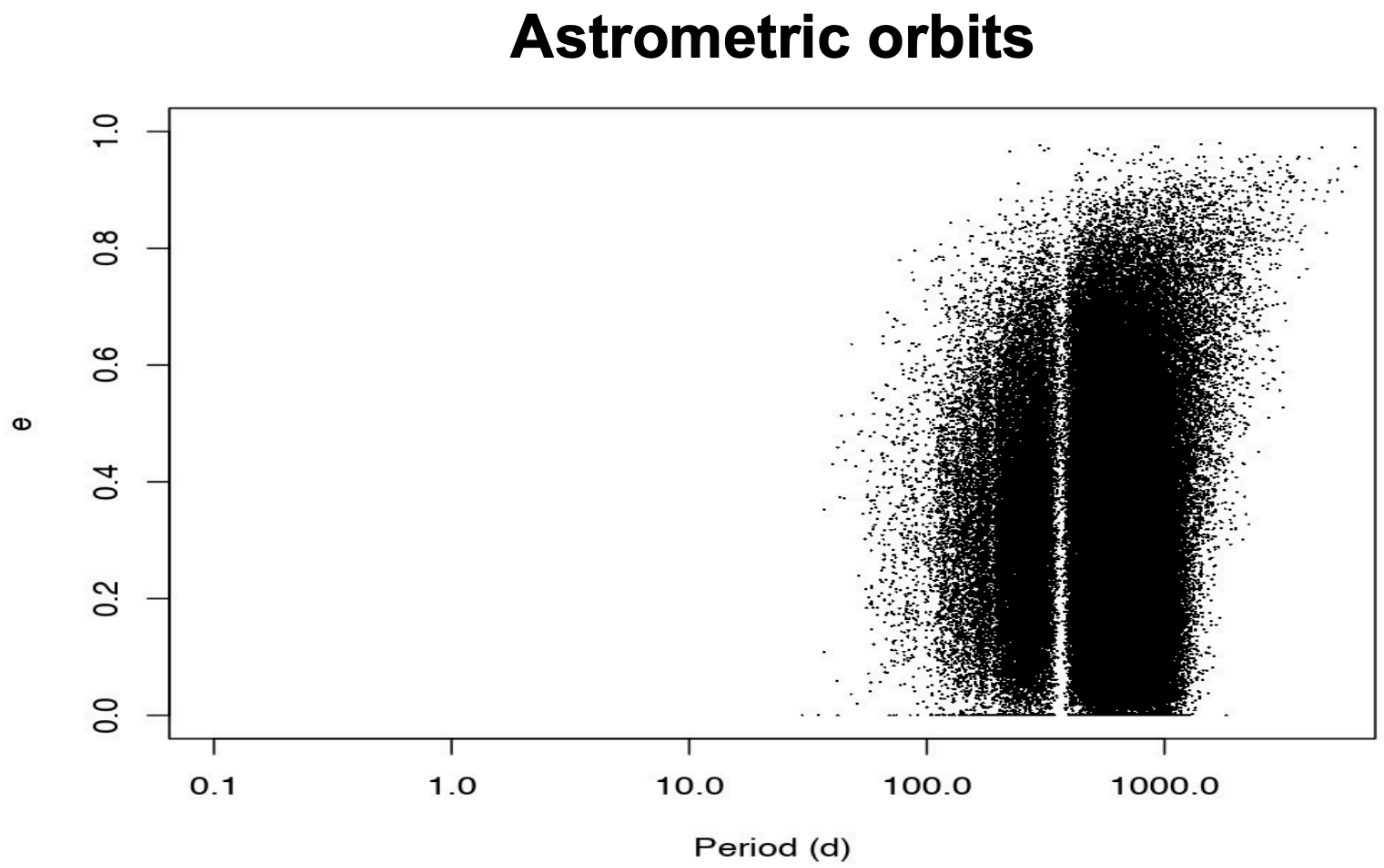
https://github.com/zpenoyre/astromet.py

Gaia



Malhan et al 2022


Eclipsing Binaries
SB1
Astro-Spectro combinations
Astrometric orbits
e
Period (d)
0.0
0.2
0.4
0.6
0.8
1.0
0.1
1.0
10.0
100.0
1000.0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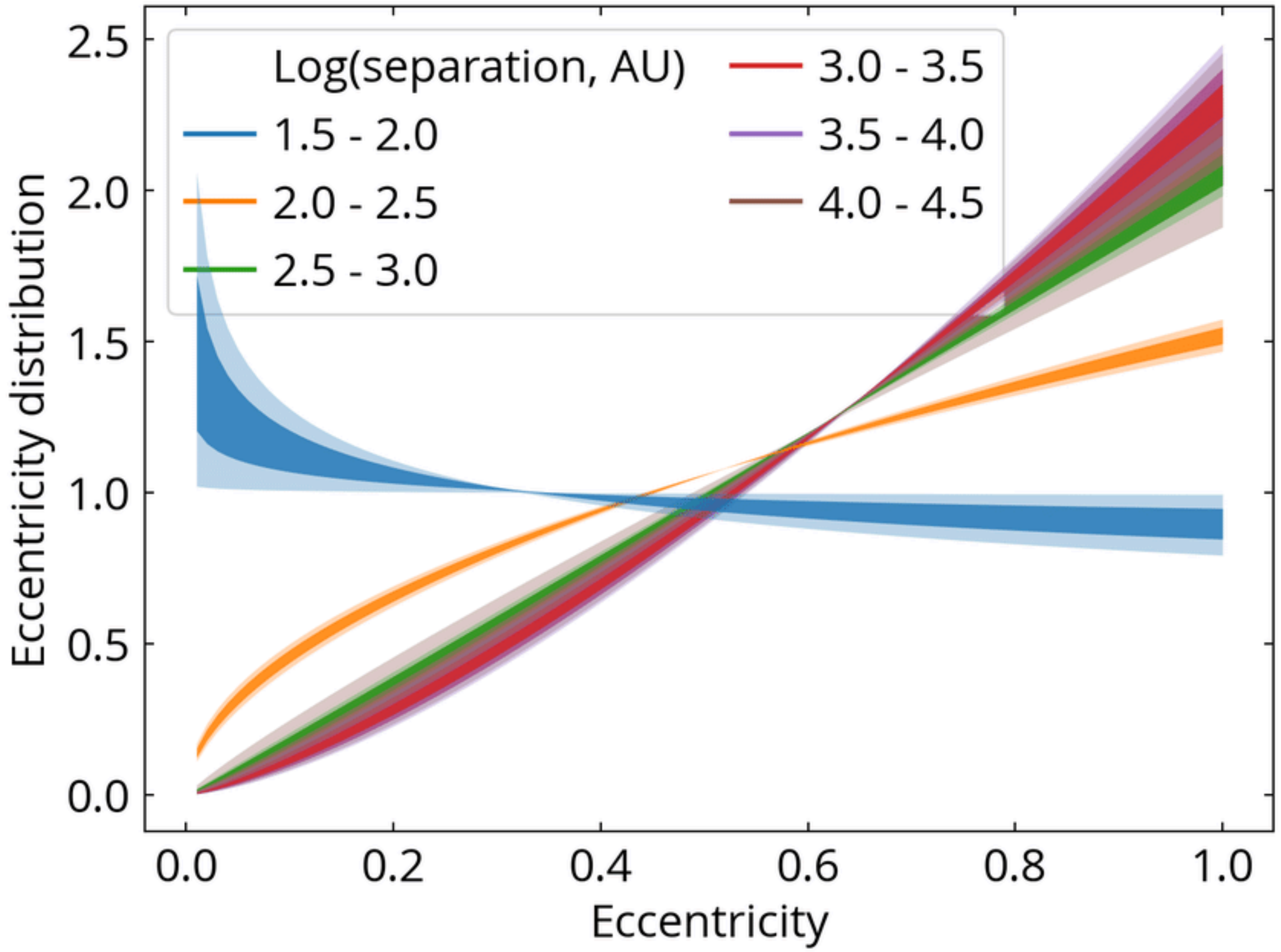
Binaries

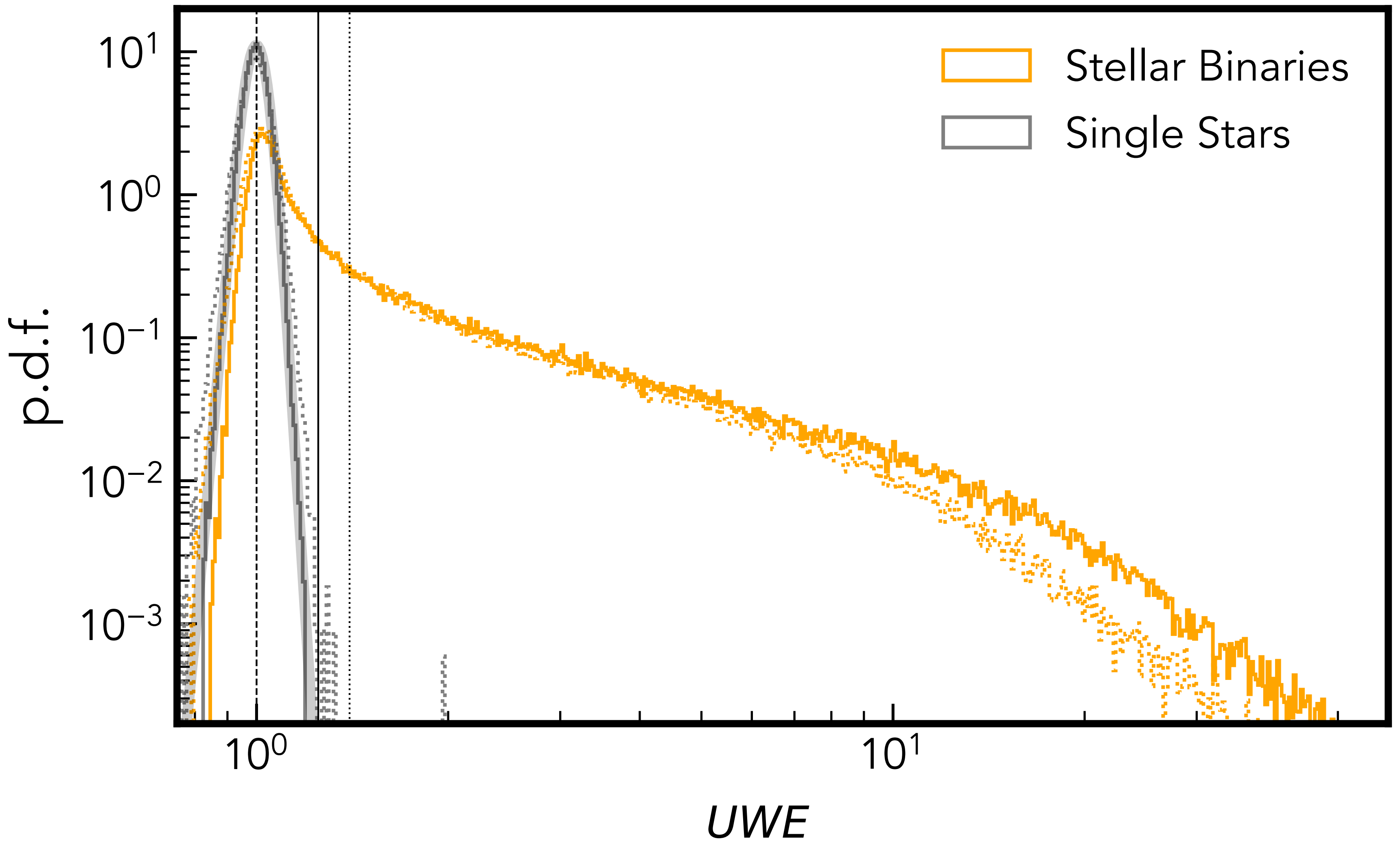
Eccentricity

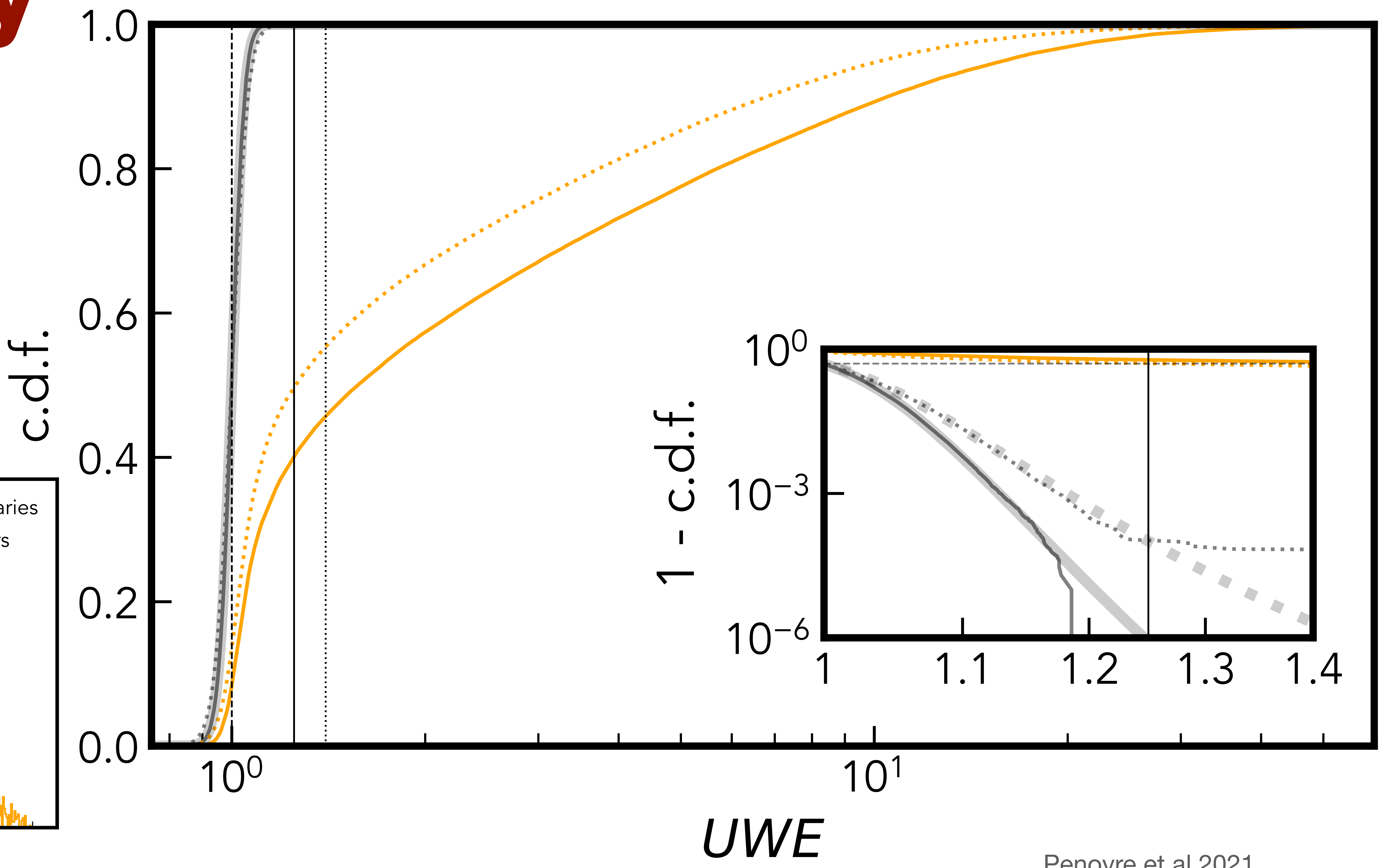


Hwang et al. 2021

Gaia Astrometry

$UWE_{eDR3}>1.25 \approx UWE_{DR2}>1.4$





Penoyre et al 2021

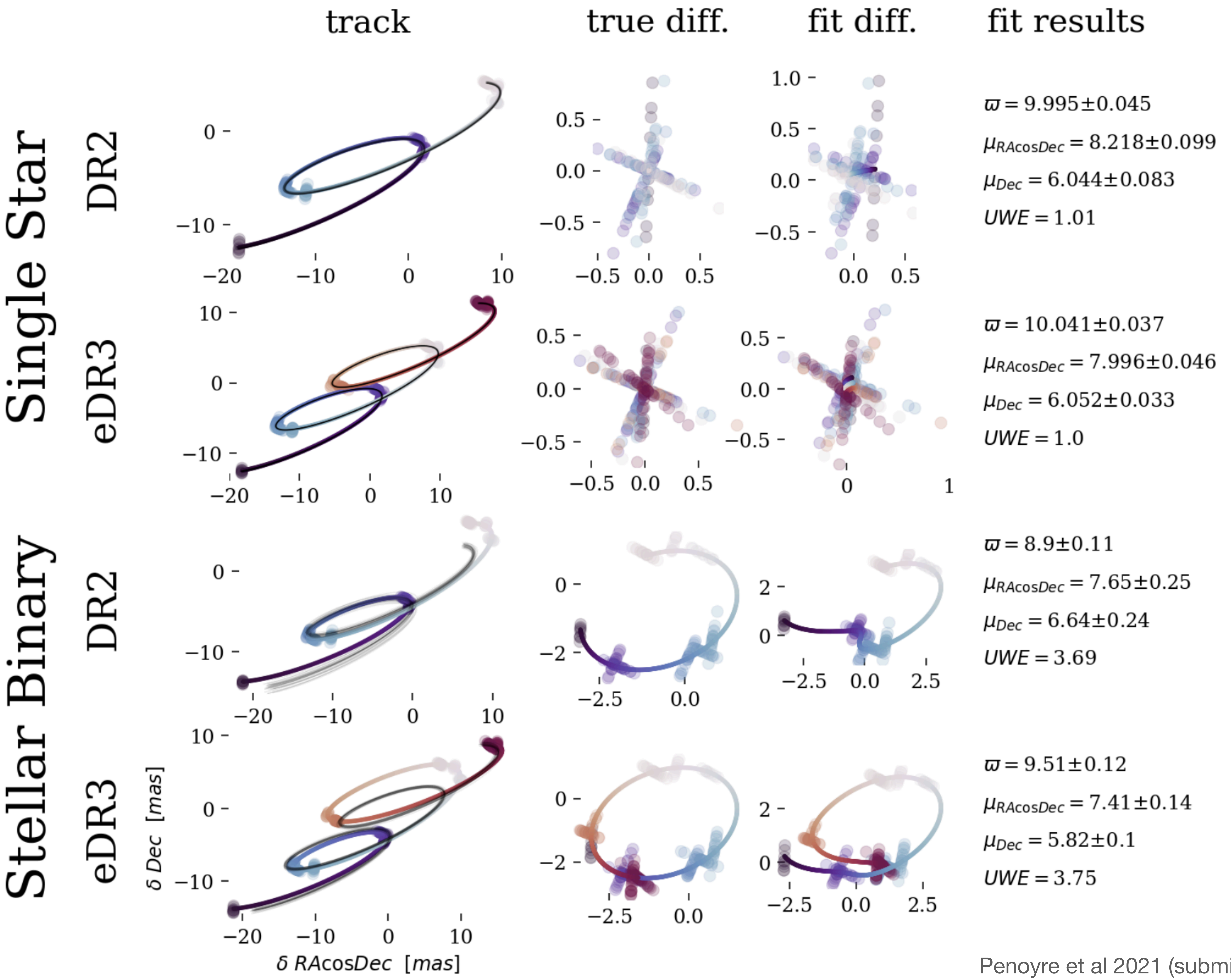
Changing astrometry

eDR3 released in Dec 2020

Essentially same data as DR2, but half as long again

tracks and fits from astromet.py:

https://github.com/zpenoyre/astromet.py



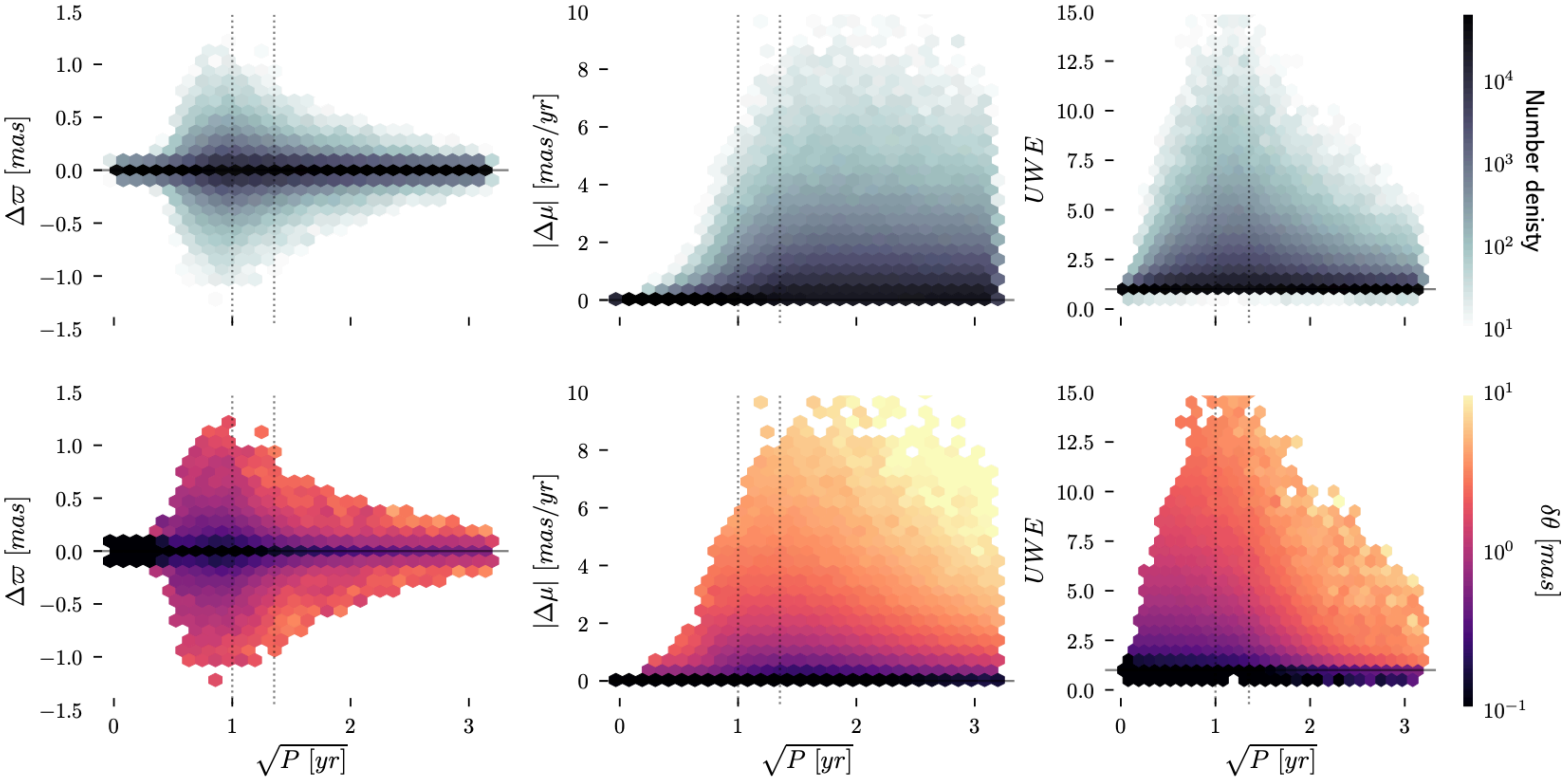
Penoyre et al 2021 (submitted)

Simulating binaries (DR2)

Penoyre et al 2020

Remember - UWE~1 for a single star, >>1 for some binaries

Strong function of period!



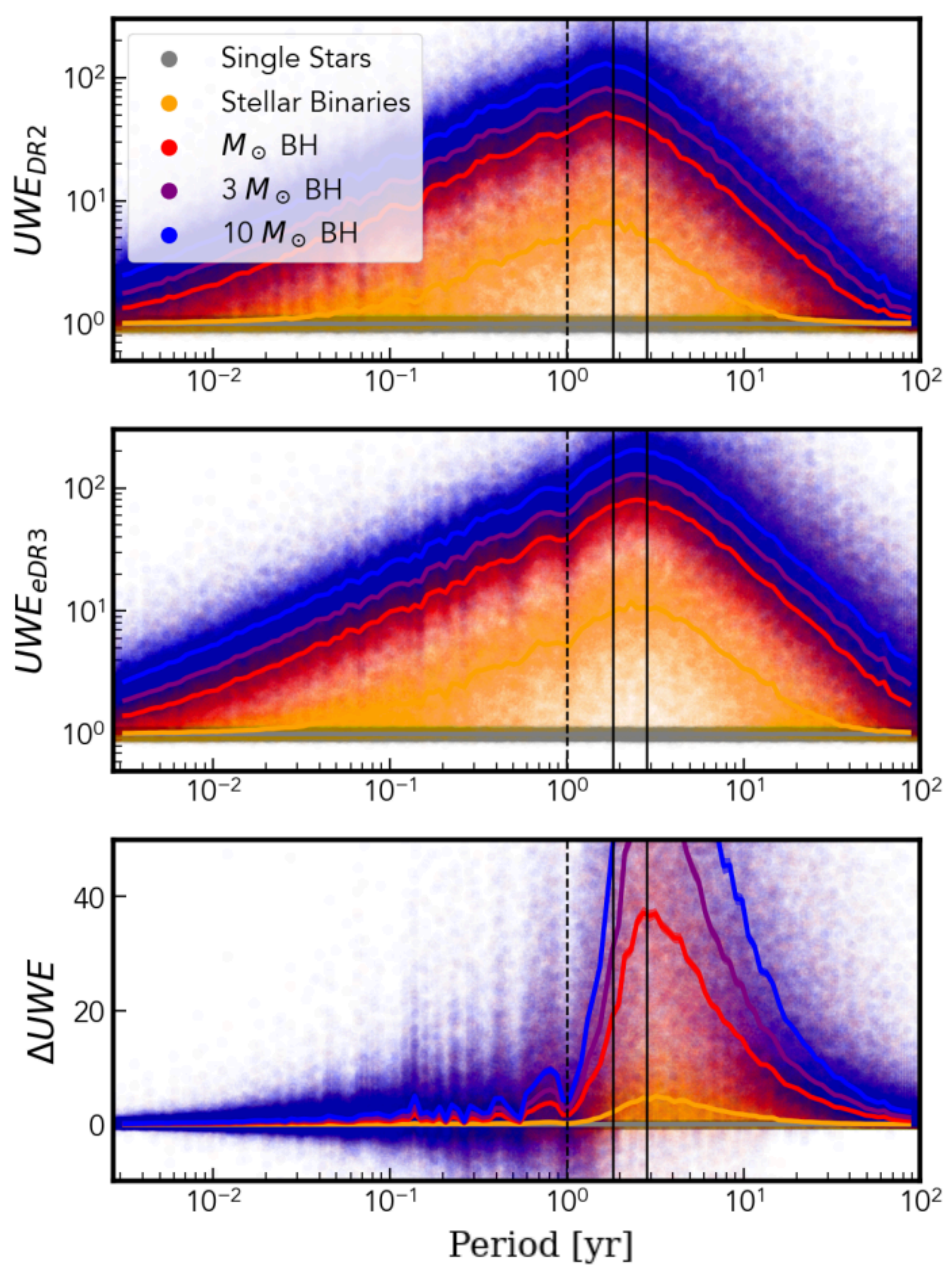
UWE works!

Changing astrometry

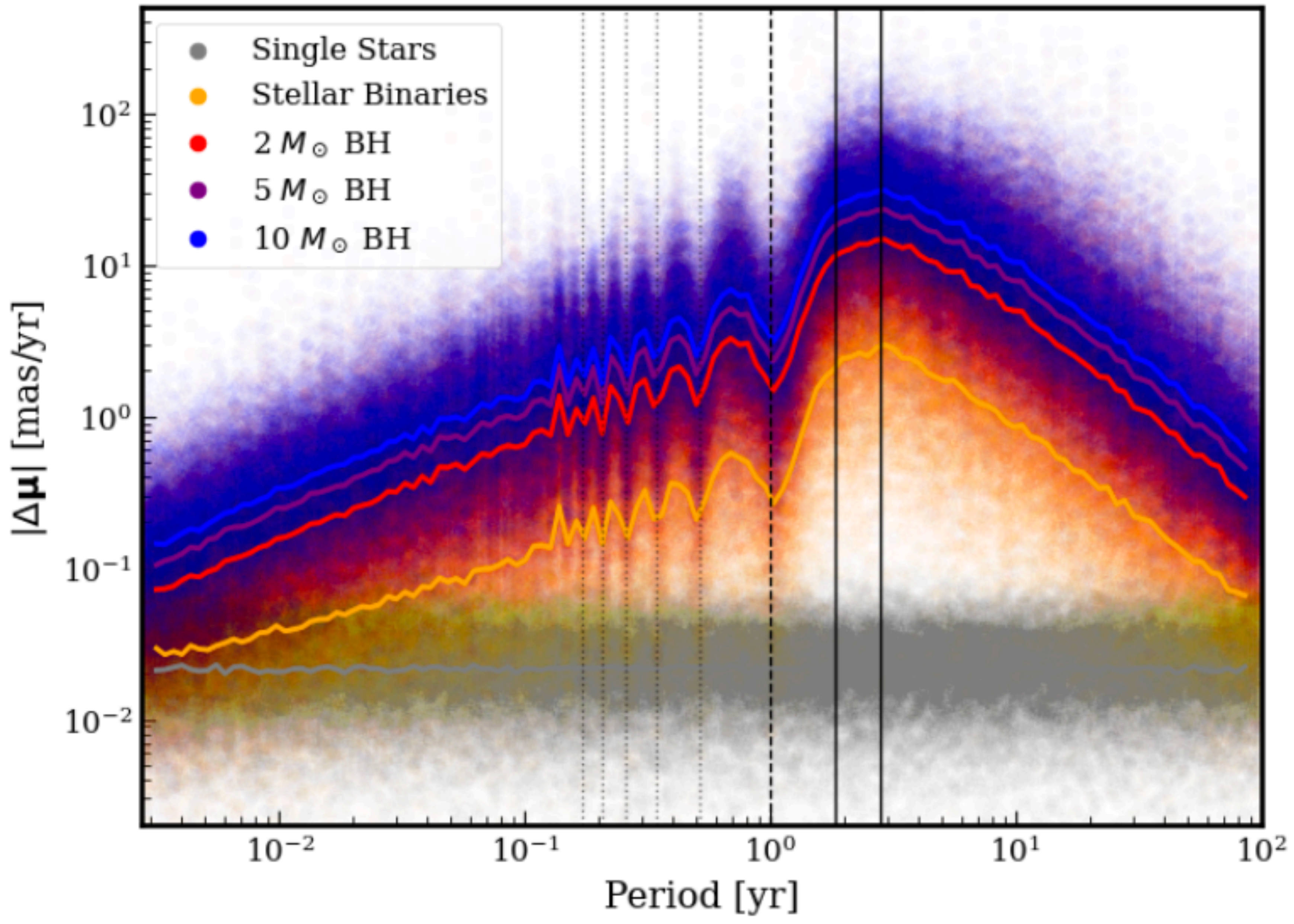
Resolve longer period systems

Less random noise

UWE increases!



Can also calculate Proper Motion Anomaly (PMA) between DR2 and eDR3



Penoyre et al 2021

Penoyre et al 2020

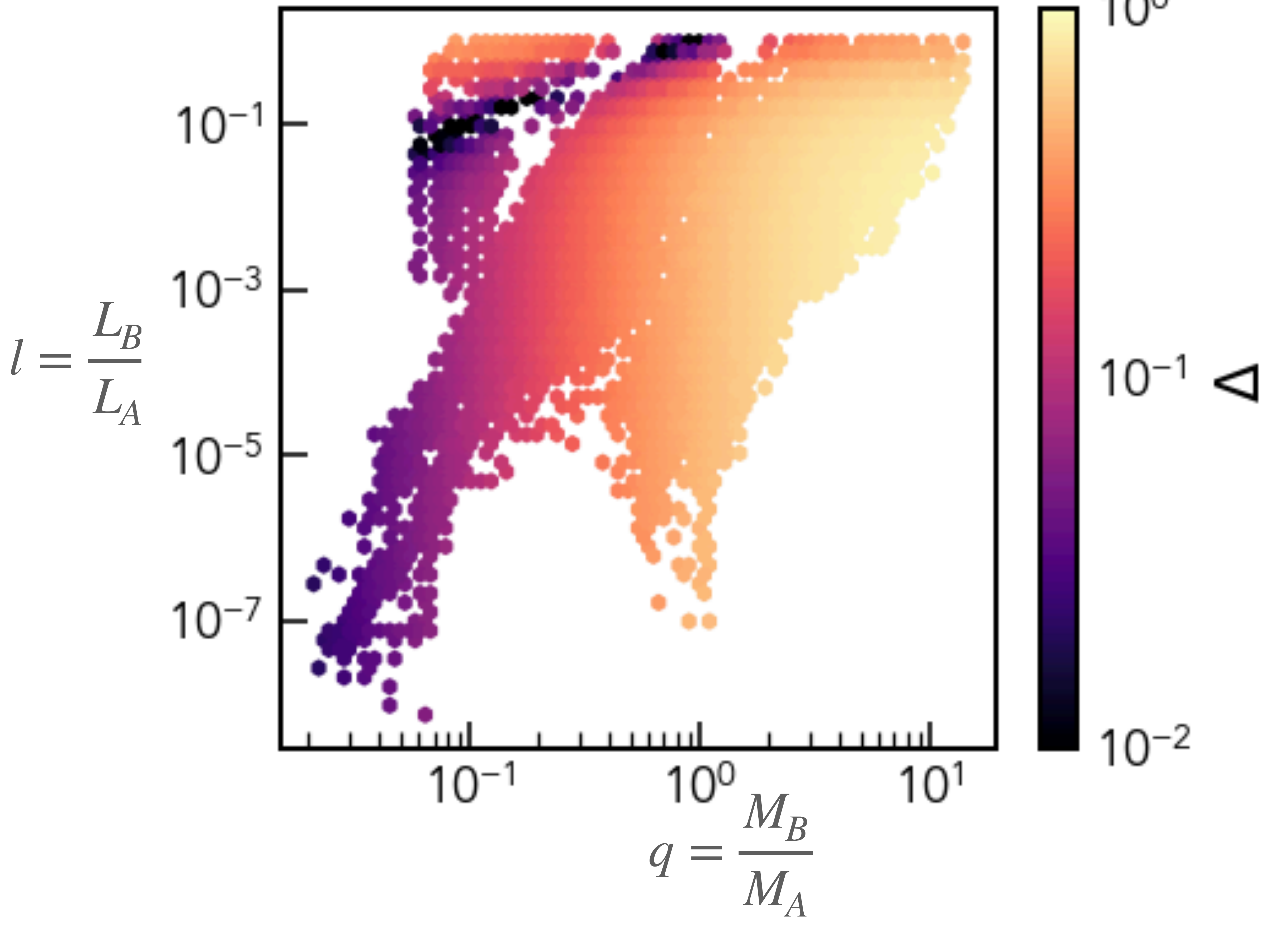
$$UWE_{pred} = \sqrt{1 + \left(\frac{\delta\theta}{\sigma_{ast}}\right)^2}$$

$$\delta\theta = \varpi \; a \;\; \Delta(q, l) \;\; \beta(\theta_v, \phi_v, e)$$

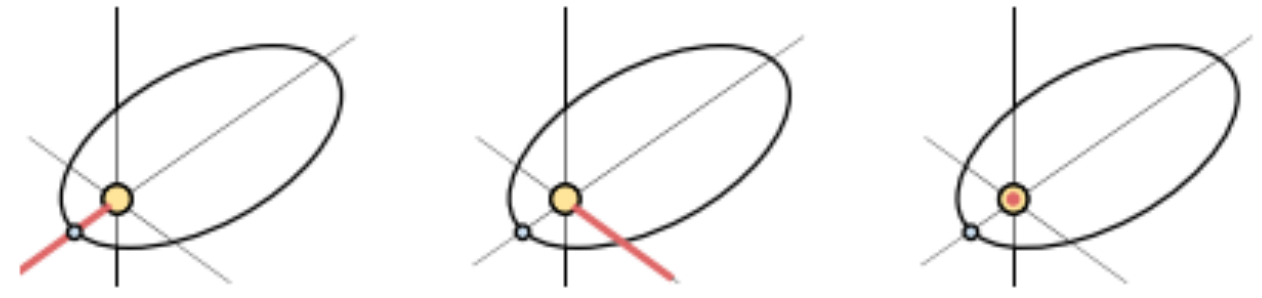
$$\Delta(q, l) = \frac{|q - l|}{(1+q)(1+l)}$$

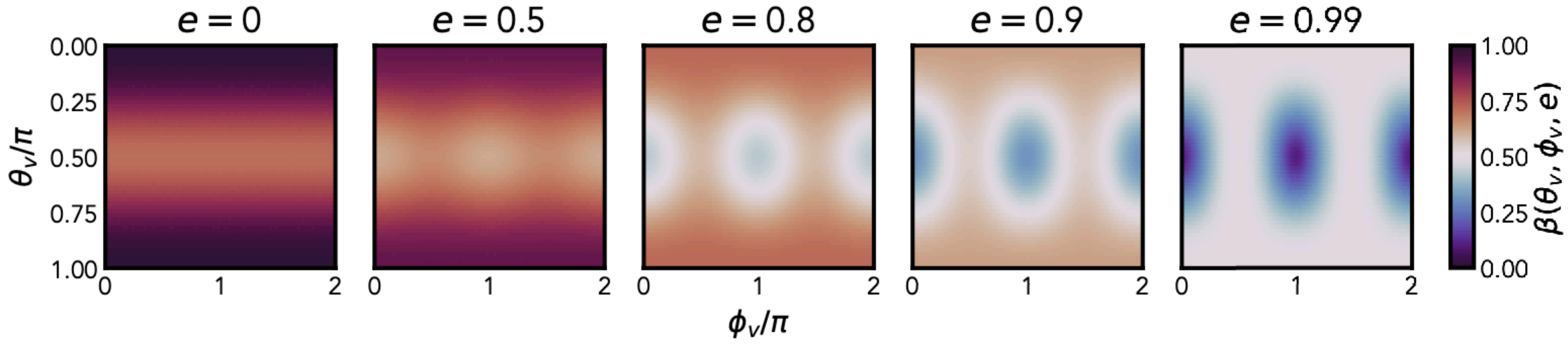
$$\beta(\theta_v, \phi_v, e) = \sqrt{1 - \frac{\sin^2\theta_v}{2} - e^2\frac{3 + \sin^2\theta_v(\cos^2\phi_v - 2)}{4}}$$

Penoyre et al 2022 (in prep.)



	Edge-on Periapse-Aligned	Periapse-Misaligned	**Oblique**
θ_v	$\frac{\pi}{2}$	$\frac{\pi}{2}$	$\frac{\pi}{3}$
ϕ_v	0	$\frac{\pi}{2}$	$\frac{\pi}{4}$





Penoyre et al 2021