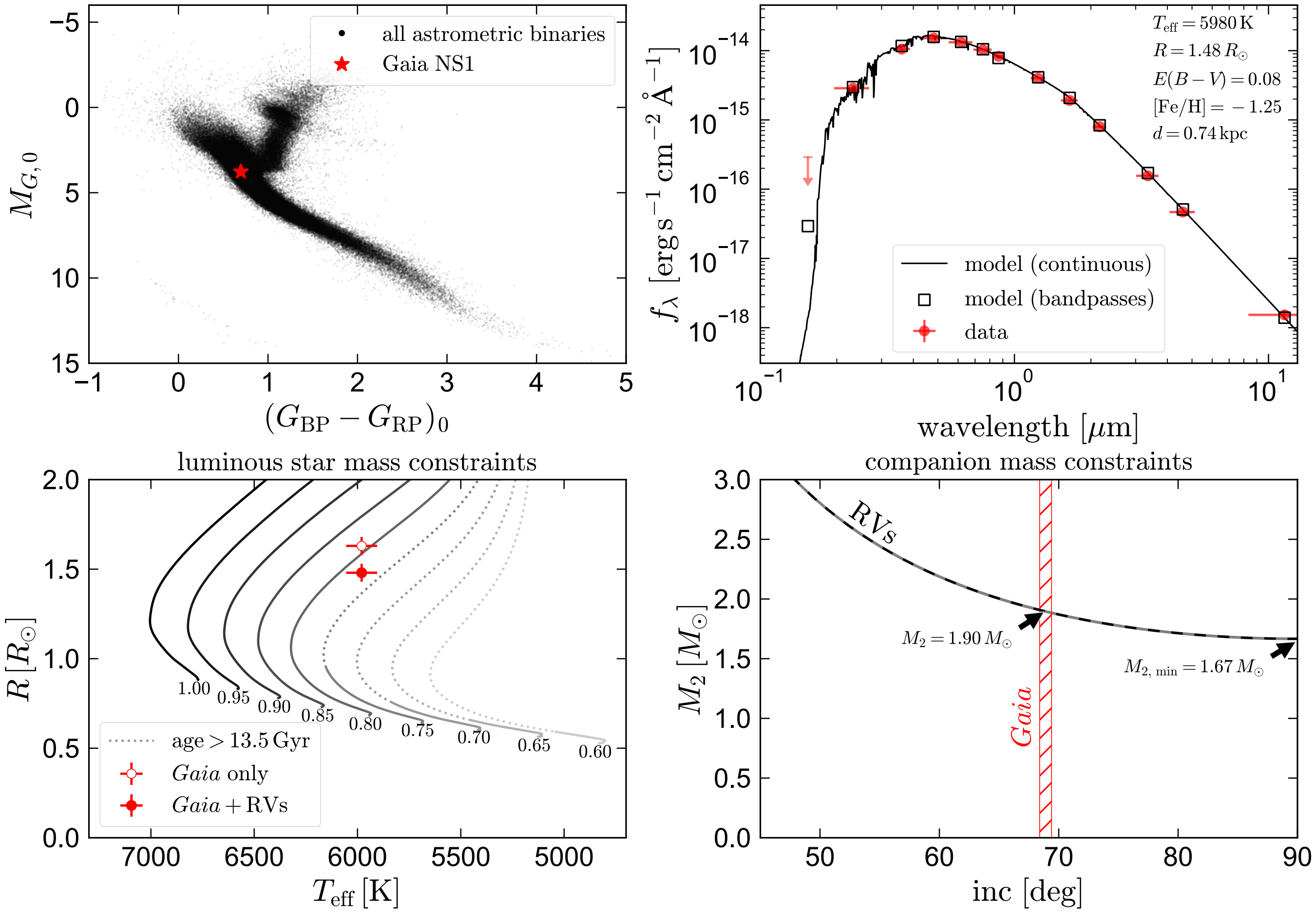
Observational Cosmology Journal Club
February 19, 2024 Yasushi Suto

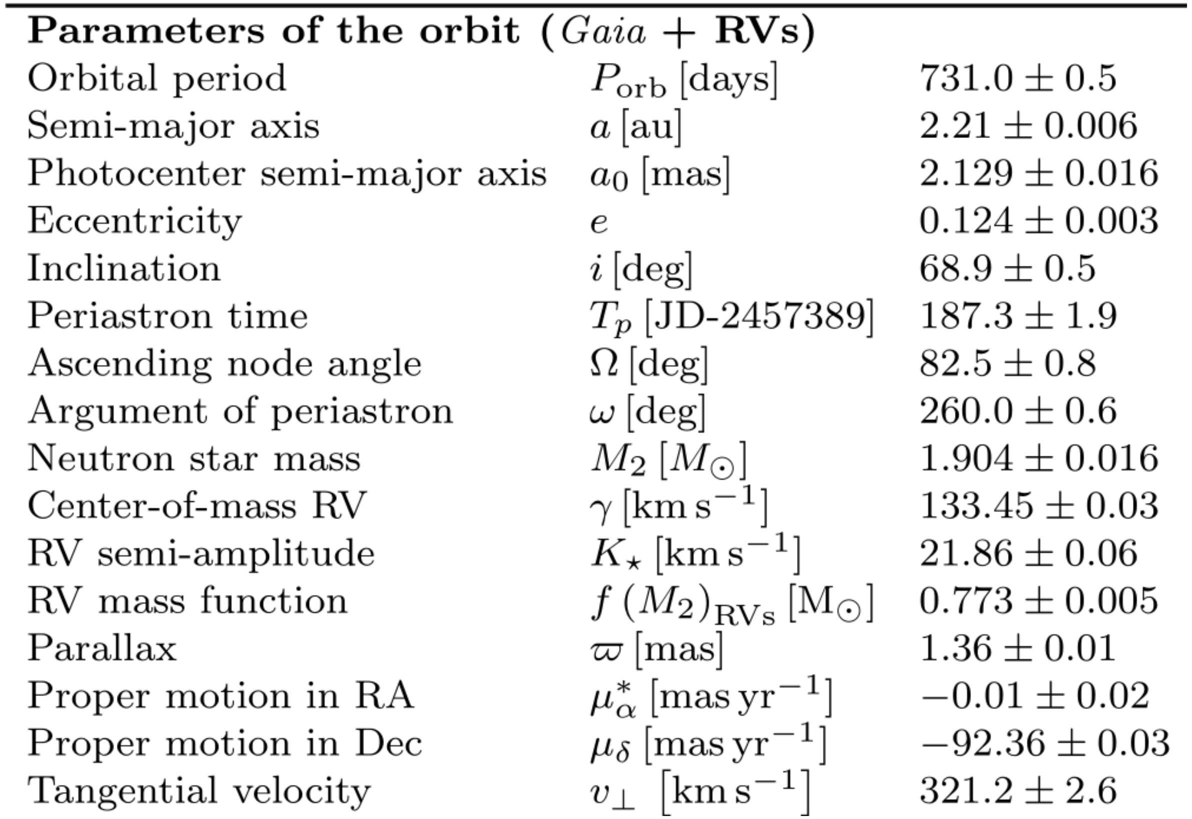
1. A 1.9$M_\odot$ neutron star candidate in a 2-year orbit
   Kareem El-Badry et al. arXiv:2402.06722
2. Does the missing mass problem signal the breakdown of Newtonian gravity?
   Jacob Bekenstein and Mordehai Milgrom ApJ 286(1984)7
3. Robust evidence for the breakdown of standard gravity at low acceleration from statistically pure binaries free of hidden companions
   Kyu-Hyun Chae ApJ 960(2024)114 arXiv:2309.10404
4. Strong constraints on the gravitational law from Gaia DR3 wide binaries
   Indranil Banik et al. MNRAS 527(2024) 4573 arXiv:2311.03436
5. The planet nine hypothesis Konstantin Batygin, Fred C. Adams, Michael E. Brown, and Juliette C. Becker Physics Report 805(2019)1-53, arXiv:1902.1010
6. A Pan-STARRS1 Search for Planet Nine
   Michael Brown, Mathew Holman, and Konstantin Batygin, arXiv:2401.17977

1. A 1.9$M_\odot$ neutron star candidate in a 2-year orbit

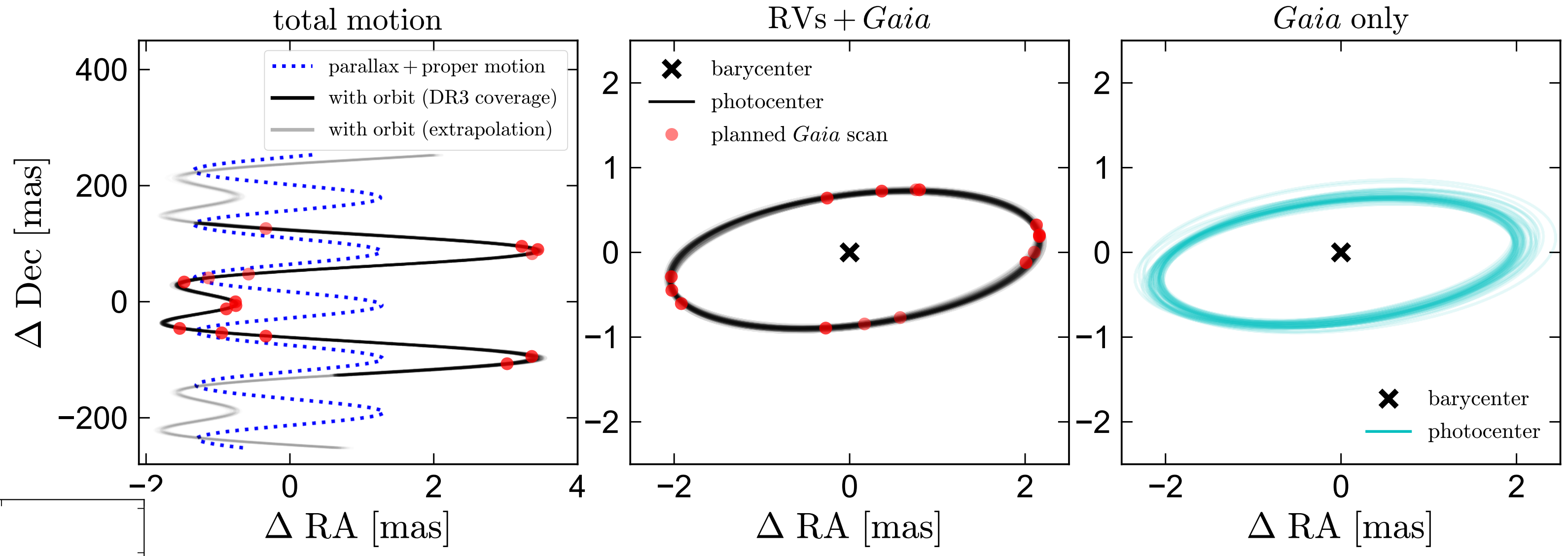
- Discovery and characterization of a main-sequence G star orbiting a dark object with mass 1.90±0.04$M_\odot$ with an orbital period of 731 days.
- The luminous star is a $\gtrsim$ 12Gyr- old, low-metallicity halo star near the main-sequence turnoff ($T_{\mathrm{eff}} \approx 6000$ K; $\log g/\mathrm{cm\ s^{-2}} \approx 4.0$; $[\mathrm{Fe/H}] \approx -1.25$; $M \approx 0.79M_\odot$) with a highly enhanced lithium abundance
- The RV mass function sets a minimum companion mass for an edge-on orbit of $M_2 > 1.67M_\odot$, well above the Chandrasekhar limit. The Gaia inclination constraint, $i = 68.8 \pm 1.4$ deg, then implies a companion mass of $M_2 = 1.90 \pm 0.04\ M_\odot$.
- Gaia NS1 is likely a progenitor of symbiotic X-ray binaries (WD/NS + accreting M giant) and long-period millisecond pulsars. Its discovery challenges binary evolution models.

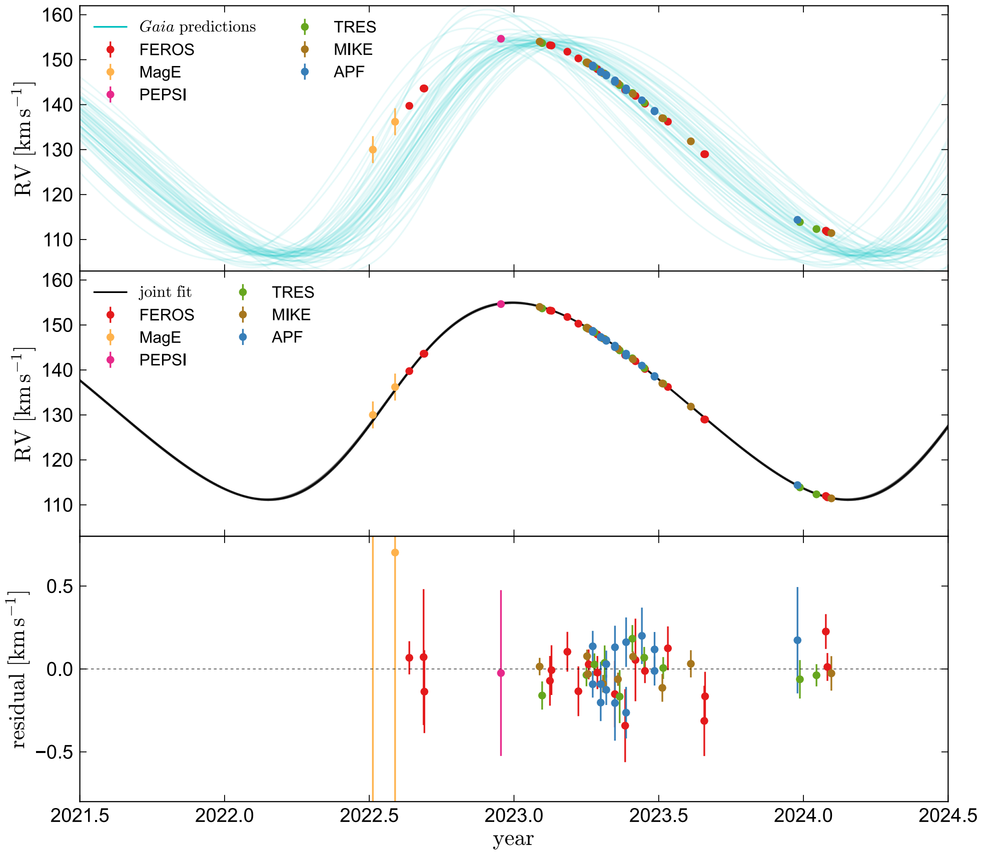
Properties of Gaia-NS1





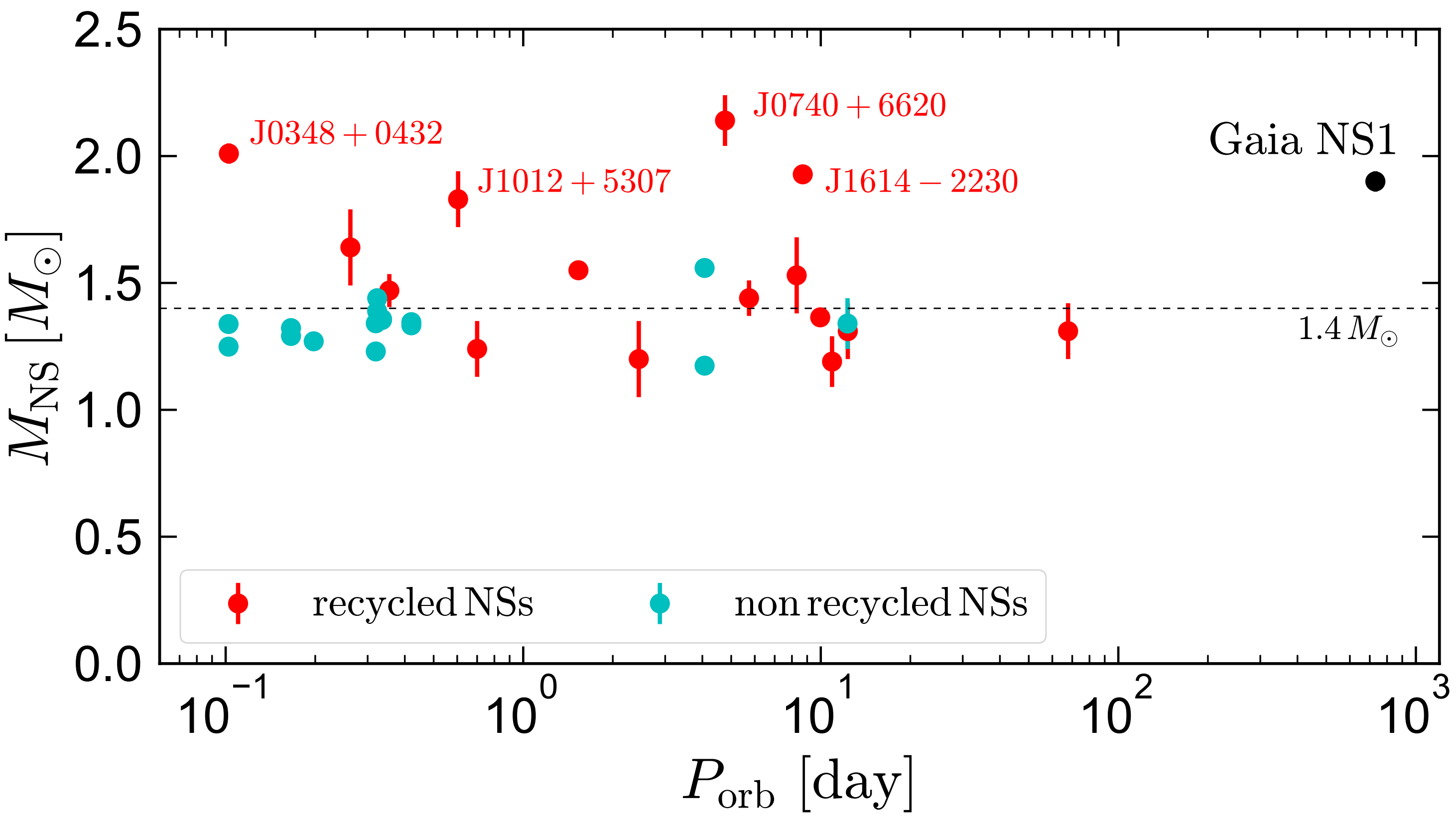
Parameters of the orbit (*Gaia* + RVs)		
Orbital period	$P_{\rm orb}$ [days]	731.0 ± 0.5
Semi-major axis	a [au]	2.21 ± 0.006
Photocenter semi-major axis	a_0 [mas]	2.129 ± 0.016
Eccentricity	e	0.124 ± 0.003
Inclination	i [deg]	68.9 ± 0.5
Periastron time	T_p [JD-2457389]	187.3 ± 1.9
Ascending node angle	Ω [deg]	82.5 ± 0.8
Argument of periastron	ω [deg]	260.0 ± 0.6
Neutron star mass	$M_2\,[M_\odot]$	1.904 ± 0.016
Center-of-mass RV	γ [km s^{-1}]	133.45 ± 0.03
RV semi-amplitude	$K_\star$ [km s^{-1}]	21.86 ± 0.06
RV mass function	$f\,(M_2)_{\rm RVs}$ [M$_\odot$]	0.773 ± 0.005
Parallax	ϖ [mas]	1.36 ± 0.01
Proper motion in RA	μ_α^* [mas yr^{-1}]	-0.01 ± 0.02
Proper motion in Dec	μ_δ [mas yr^{-1}]	-92.36 ± 0.03
Tangential velocity	$v_\perp$ [km s^{-1}]	321.2 ± 2.6





Radial velocity and orbit of Gaia-NS1

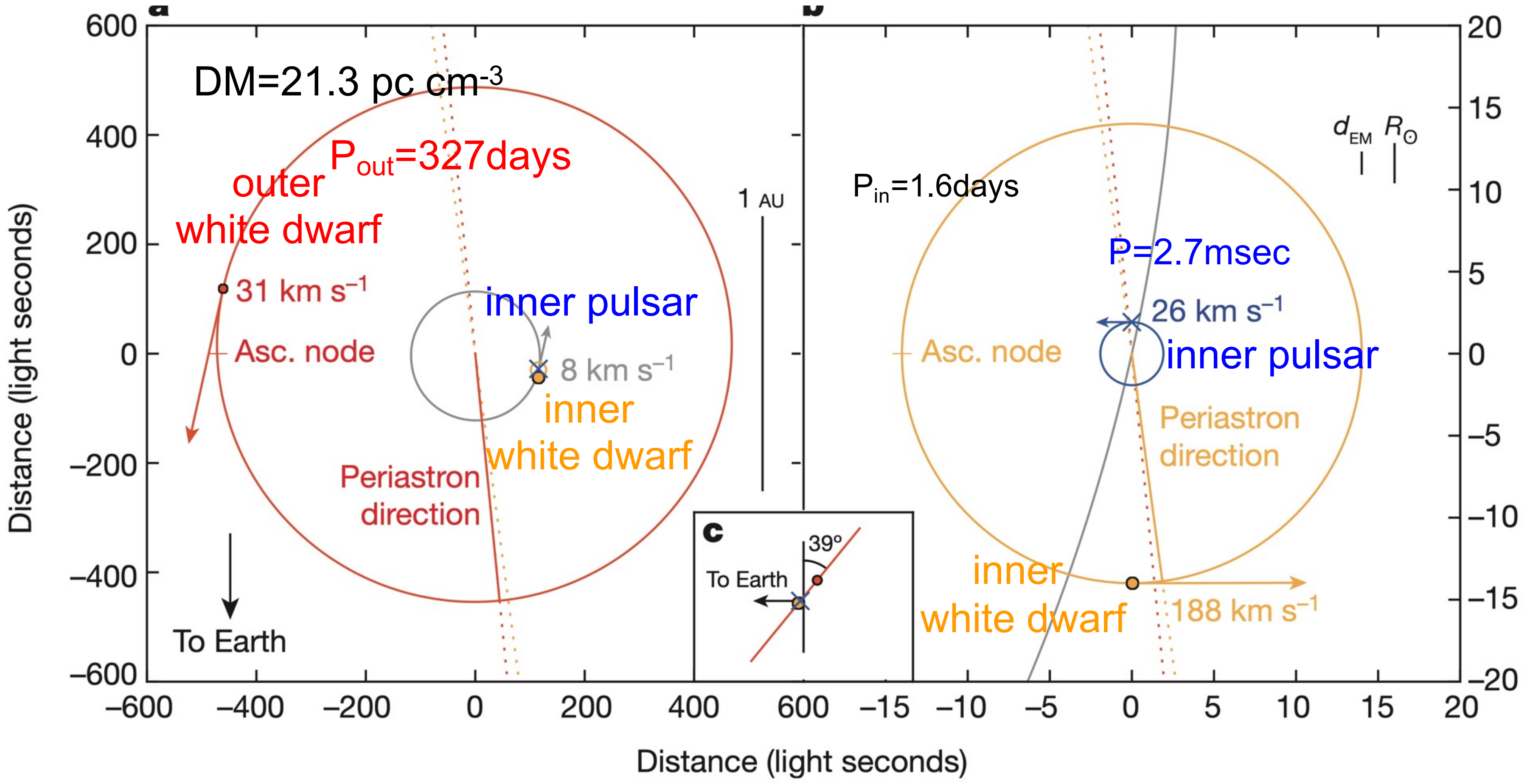
Masses and periods of well-characterized NSs



Gaia NS1 is the fourth most massive object with only the recycled pulsars J0740+6620, J0348+0432, and J1614-2230 having higher masses. If the dark object is indeed a single NS, there is no plausible scenario in which it gained mass since its formation, so it would be one of the strongest known cases for a NS being born massive.

A millisecond pulsar in a stellar triple system

S. M. Ransom[1], I. H. Stairs[2], A. M. Archibald[3,4], J. W. T. Hessels[3,5], D. L. Kaplan[6,7], M. H. van Kerkwijk[8], J. Boyles[9,10], A. T. Deller[3], S. Chatterjee[11], A. Schechtman-Rook[7], A. Berndsen[2], R. S. Lynch[4], D. R. Lorimer[9], C. Karako-Argaman[4], V. M. Kaspi[4], V. I. Kondratiev[3,12], M. A. McLaughlin[9], J. van Leeuwen[3,5], R. Rosen[1,9], M. S. E. Roberts[13,14] & K. Stovall[15,16]



Ransom et al.
Nature
505 (2014)
520

2. Does the missing mass problem signal the breakdown of Newtonian gravity?

- MOND (MOdified Newtonian Dynamics)
  - Newton's 2nd law is modified, but the gravity law is still Newtonian (unchanged)
  - but it is also possible to interpret MOND as a modification to the gravity law in practice

$$F = m\underset{\substack{\uparrow \\ \text{acceleration}}}{a} \rightarrow m\underbrace{\mu\left(\frac{a}{a_0}\right)}_{\text{arbitrary function}} a$$

a_0: characteristic acceleration

$$a \gg a_0: \quad \mu\left(\frac{a}{a_0}\right) \rightarrow 1 \quad \rightarrow \quad F = ma$$

$$a \ll a_0: \quad \mu\left(\frac{a}{a_0}\right) \rightarrow \frac{a}{a_0}$$

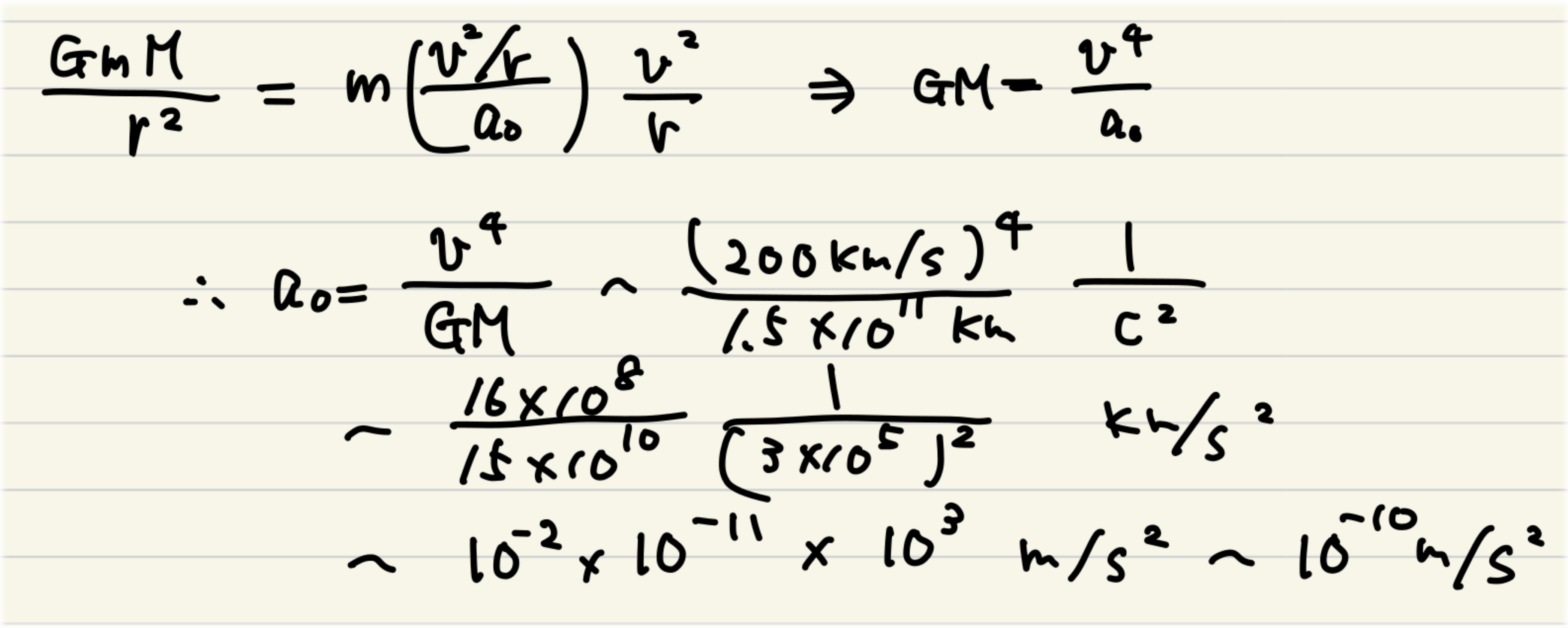
circular orbit $\rightarrow$ $v = \omega r \quad a = \omega^2 r = \frac{v^2}{r}$

$$\frac{GmM}{r^2} = m\,\mu\left(\frac{v^2/r}{a_0}\right) \times \frac{v^2}{r}$$

flat rotation curve $\Rightarrow$ $v = \text{const}$ for $r \rightarrow \infty$

$$\Rightarrow \mu\left(\frac{v^2/r}{a_0}\right) \propto \frac{1}{r} = \frac{1}{a_0}\frac{v^2}{r}$$

required value of fundamental acceleration scale a_0



$$\frac{GmM}{r^2} = m\left(\frac{v^2/r}{a_0}\right)\frac{v^2}{r} \Rightarrow GM = \frac{v^4}{a_0}$$

$$\therefore a_0 = \frac{v^4}{GM} \sim \frac{(200\,km/s)^4}{1.5\times10^{11}\,km}\,\frac{1}{c^2}$$

$$\sim \frac{16\times10^8}{15\times10^{10}}\,\frac{1}{(3\times10^5)^2}\quad km/s^2$$

$$\sim 10^{-2}\times10^{-11}\times10^3\ m/s^2 \sim 10^{-10}\,m/s^2$$

Note that this value is close to $cH_0 \sim 3\times10^8$ m/s/(3×10^{17} s) by chance(?)

violation of momentum conservation in MOND

$$m\,\mu\left(\frac{a_m}{a_0}\right) a_m = \frac{GMm}{r^2} = M\,\mu\left(\frac{a_M}{a_0}\right) a_M$$

if Newton's 3rd law ↔ (momentum conservation)

$m a_m = M a_M$ is valid,

$$\mu\left(\frac{a_m}{a_0}\right) = \mu\left(\frac{a_M}{a_0}\right) \rightarrow \mu(x) \equiv 1 .$$

$$\updownarrow$$

inconsistent with

the required form of $\mu(x)$

⇔ gravity law in MOND is just phenomenological

and not based on any consistent theory

(or momentum is not conserved in our world!)

AQUAL (A QUAdratic Lagrangian) for MOND

$$L_N = -\int d^3r \left\{ \rho\varphi_N + \frac{1}{8\pi G}(\nabla\varphi_N)^2 \right\}$$

$$\rightarrow \nabla\cdot\nabla\varphi_N = 4\pi G\rho$$

$$\Downarrow$$

$$L = -\int d^3r \left\{ \rho\varphi + \frac{1}{8\pi G}\, a_0^2\, F\left[\frac{(\nabla\varphi)^2}{a_0^2}\right] \right\}$$

$$\rightarrow \nabla\cdot\left[\mu\left(\frac{\nabla\varphi}{a_0}\right)\nabla\varphi\right] = 4\pi G\rho$$

where $\mu(x) = \frac{d}{dx}F(x^2)$

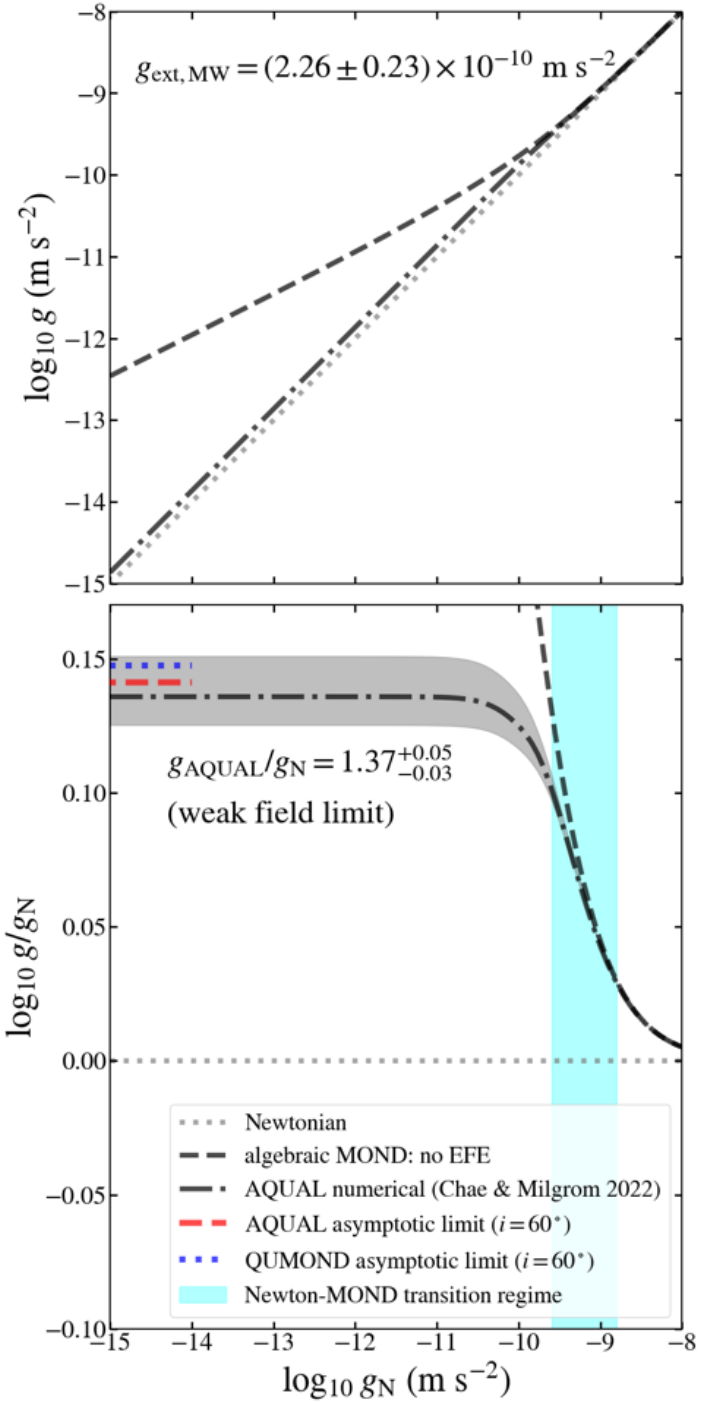
$$\therefore \nabla\cdot\left(\mu(\nabla\varphi/a_0)\nabla\varphi - \nabla\varphi_N\right) = 0$$

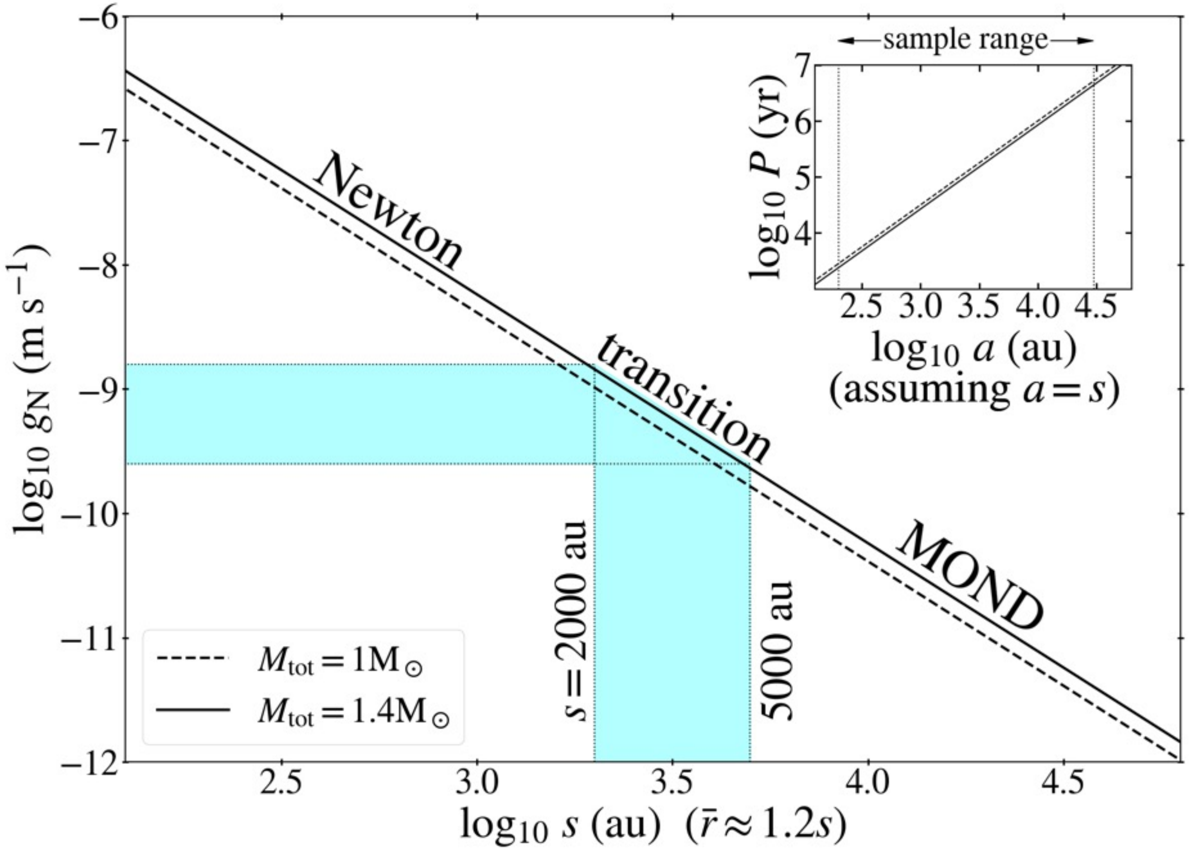
$$\rightarrow \mu\left(\frac{\nabla\varphi}{a_0}\right)\underbrace{\nabla\varphi}_{\substack{\vec{g} \\ \text{(Mond)}}} = \underbrace{\nabla\varphi_N}_{\substack{\vec{g}_N \\ \text{(Newton)}}} \left(+ \underbrace{\mathrm{rot}\,\vec{h}}_{\text{if this is neglected}}\right)$$

3. Robust evidence for the breakdown of standard gravity at low acceleration from statistically pure binaries free of hidden companions

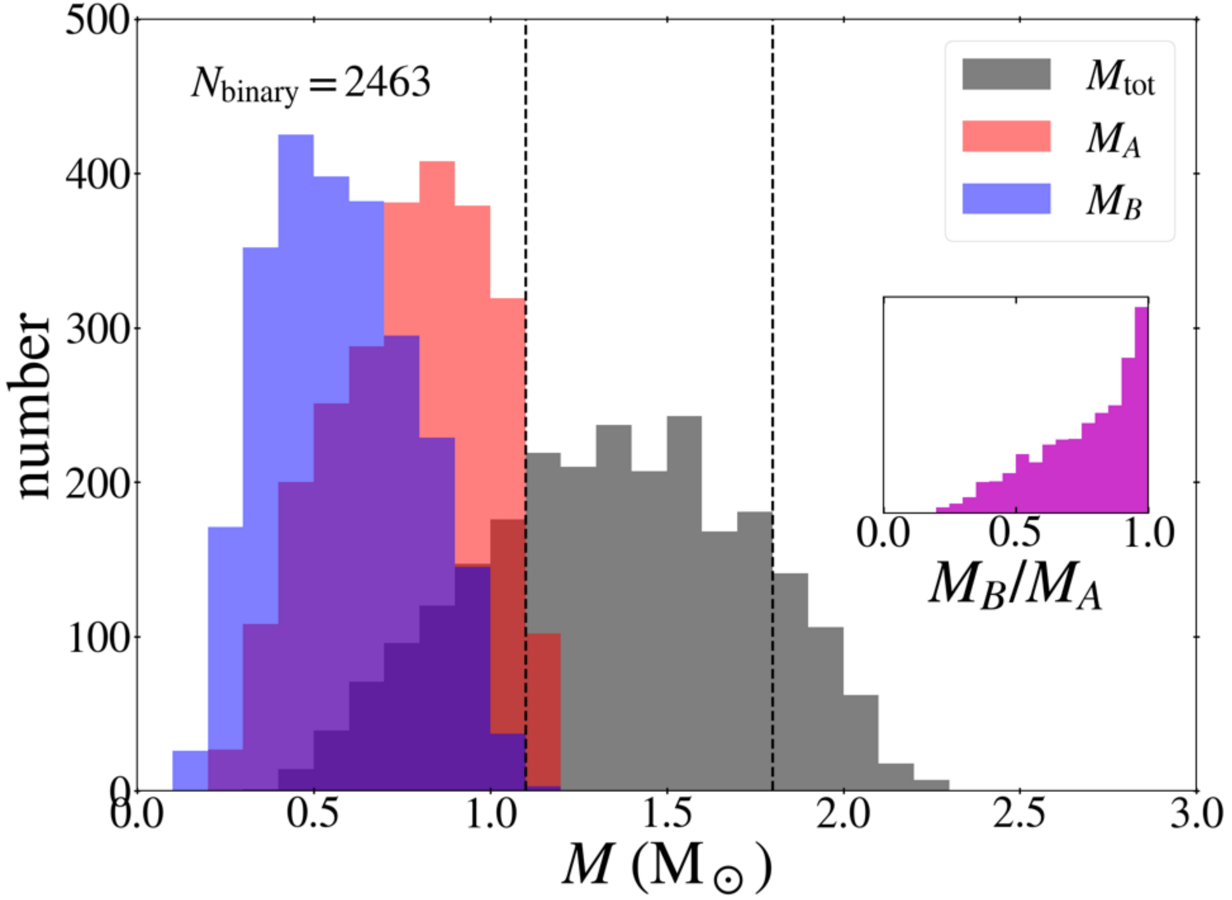
- pure binaries selected from GaiaDR3 show a systematic deviation from the Newtonian expectation for $s \gtrsim 2$ kau.
- an observed to Newtonian predicted kinematic acceleration ratio is $1.49^{+0.21}_{-0.19}$ for acceleration $\lesssim 10^{-10}$ m s^{-2}
- The observed velocity profile matches the Newtonian predicted profile for $s \lesssim 2$ kau, but shows a clear deviation at a larger separation with a significance of $\approx 5.0\sigma$. The projected velocity boost factor for $s \gtrsim 5$ kau is 1.20 ± 0.06 (stat) ± 0.05 (sys)
- Finally, for a small sample of 40 binaries with exceptionally precise radial velocities (fractional error < 0.005) the directly measured relative velocities in the 3D space also show a boost at larger separations.

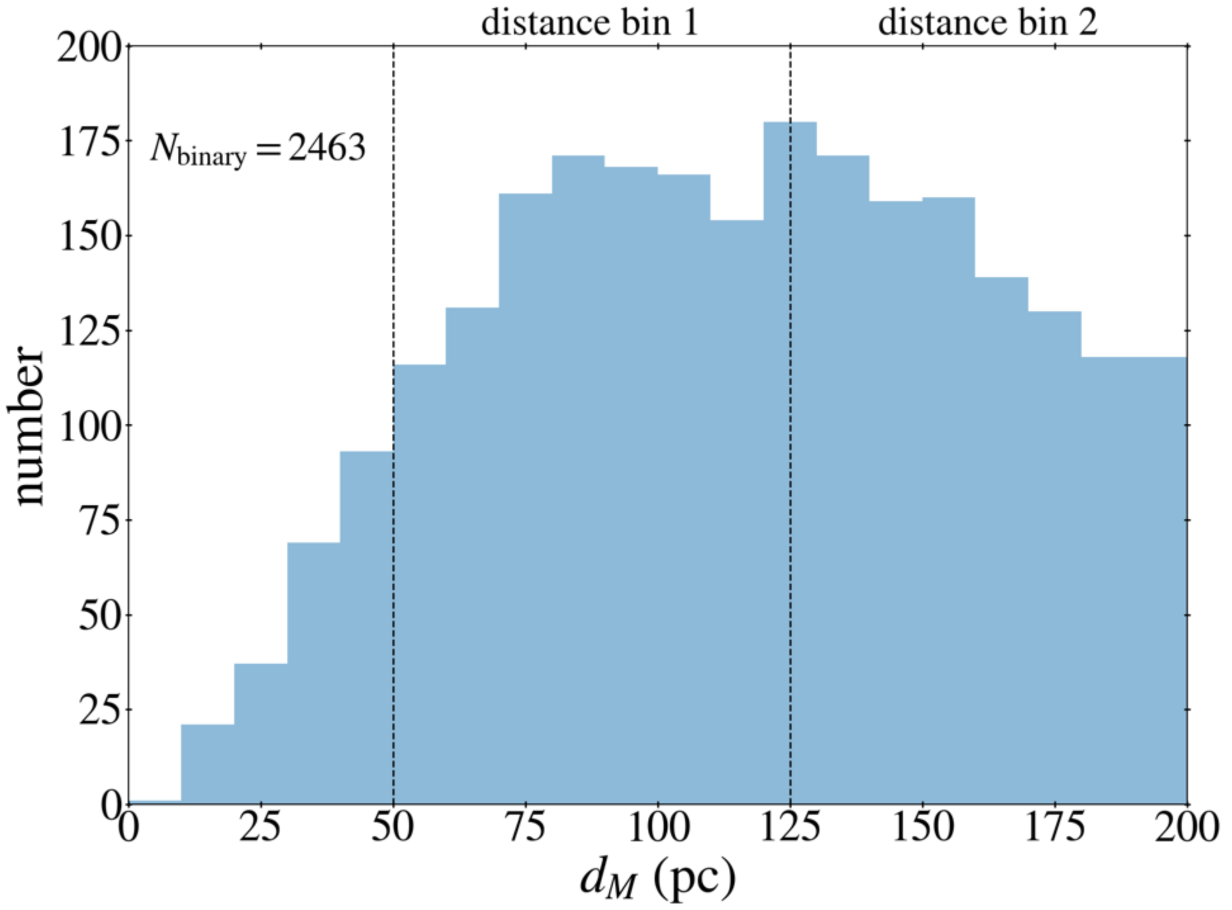
expected difference between Newtonian and MOND



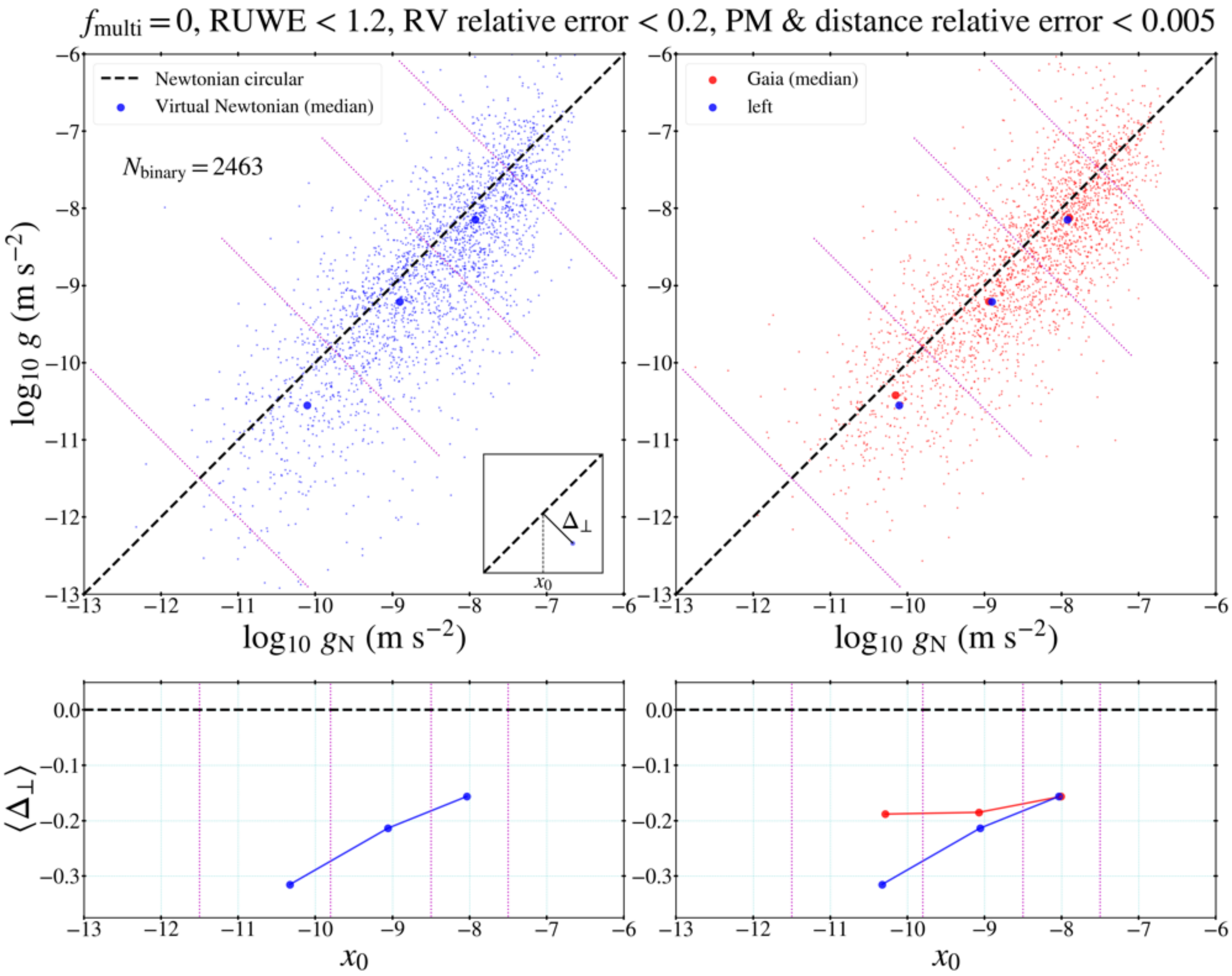


selected pure binaries from Gaia DR3

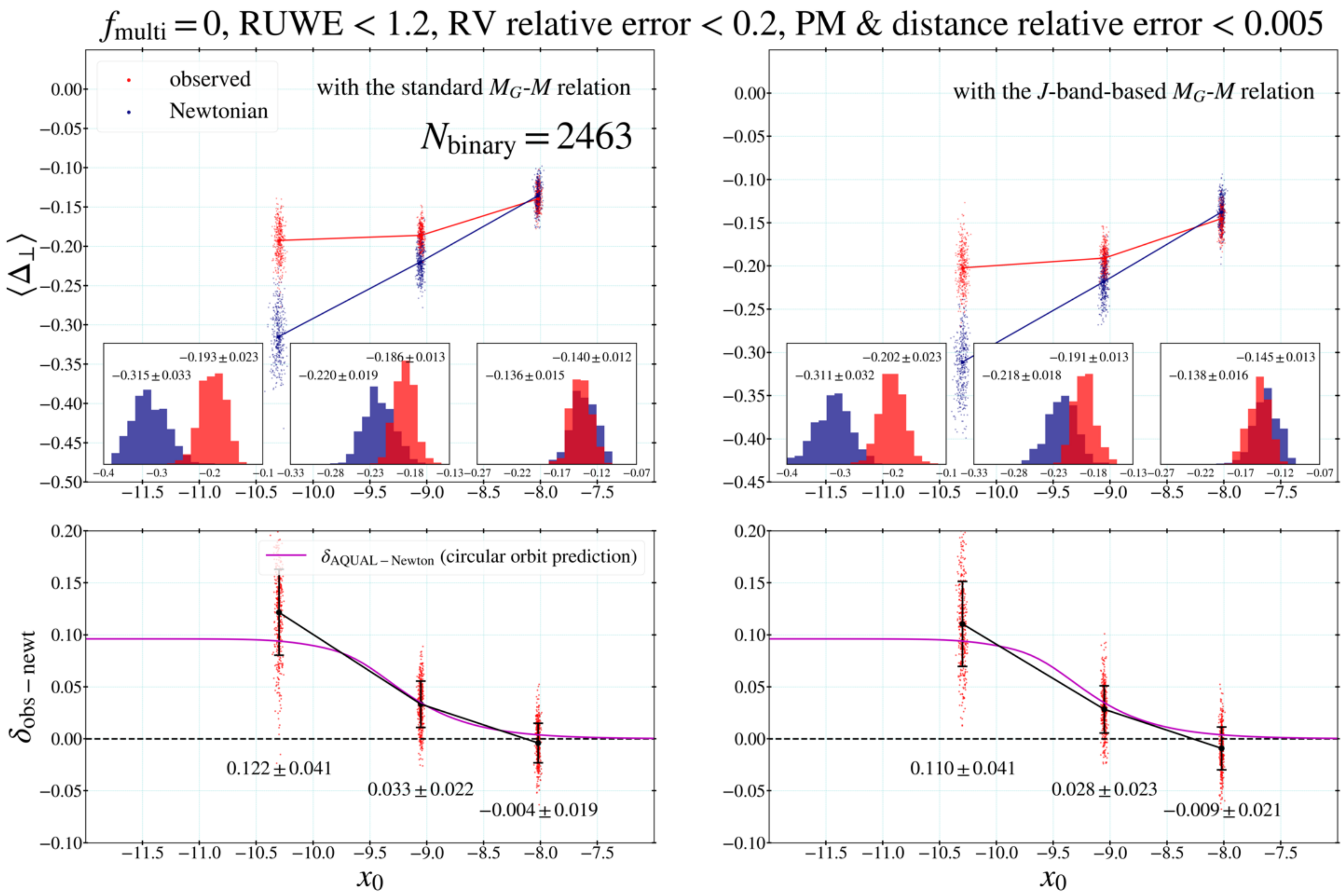




Monte-Carlo realized sample distribution of 2463 pure binaries on acceleration plane

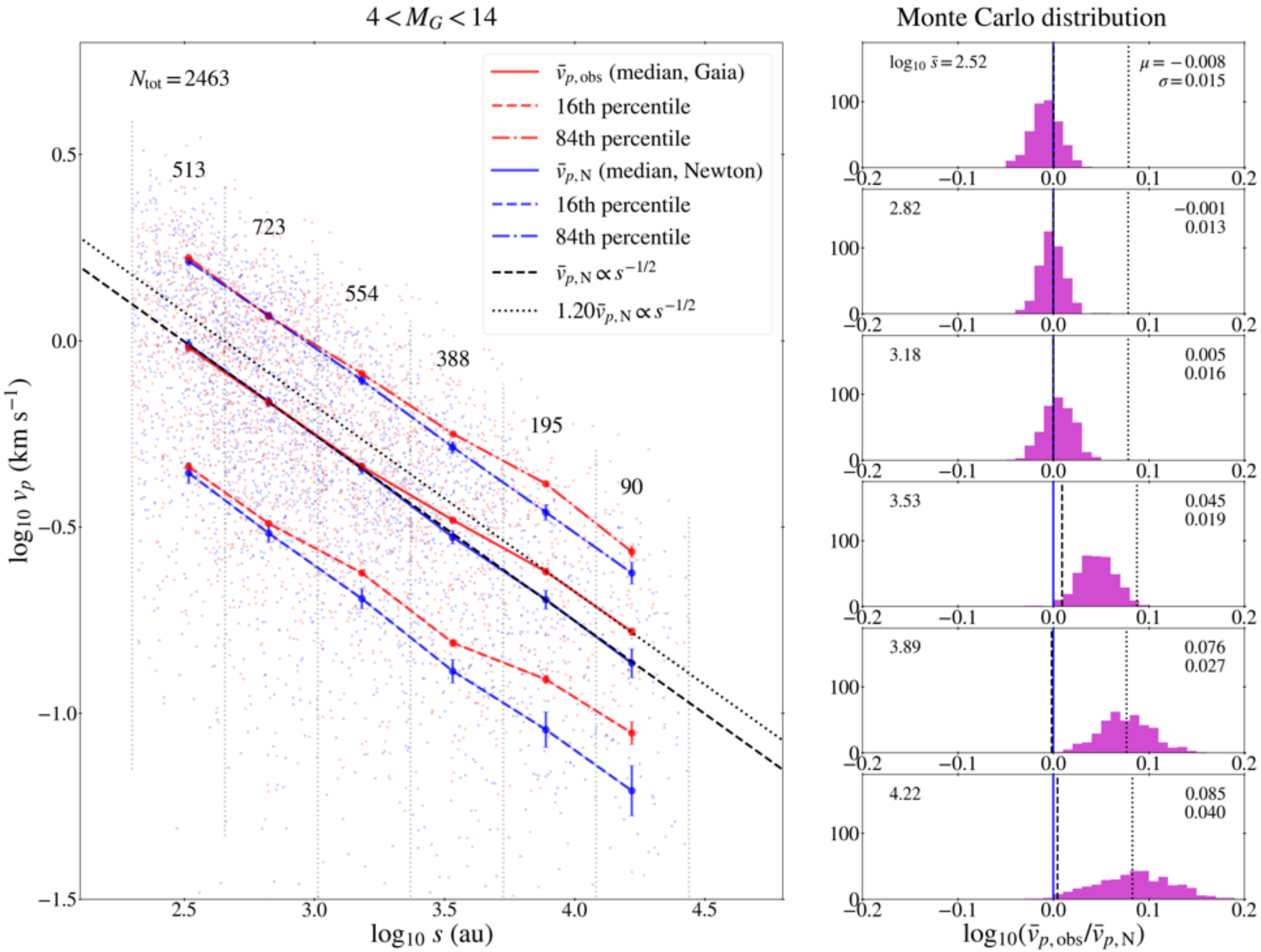


Deviation from Newtonian acceleration

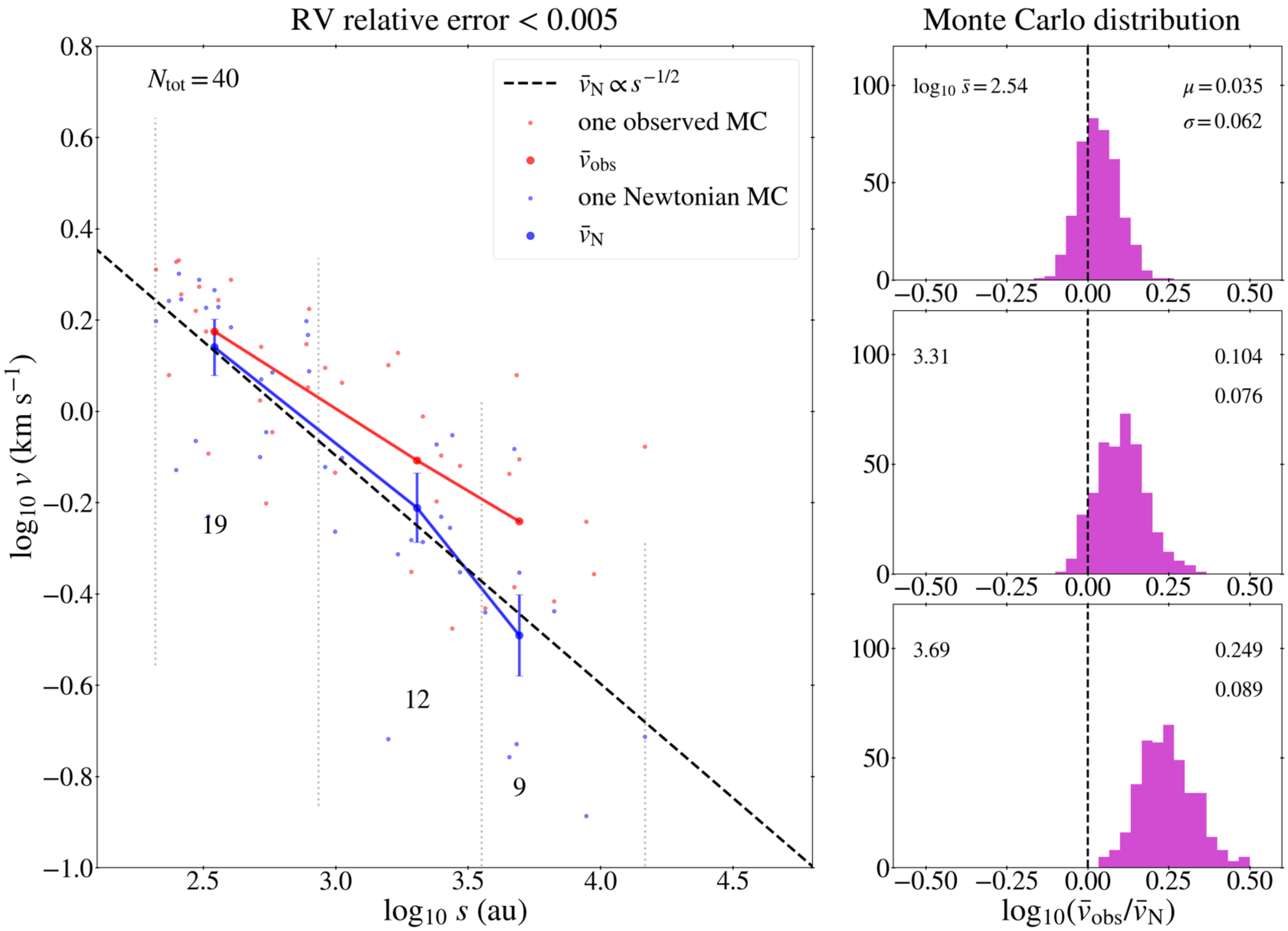


$f_{\rm multi} = 0$, RUWE < 1.2, RV relative error < 0.2, PM & distance relative error < 0.005

Deviation from Newtonian projected velocity



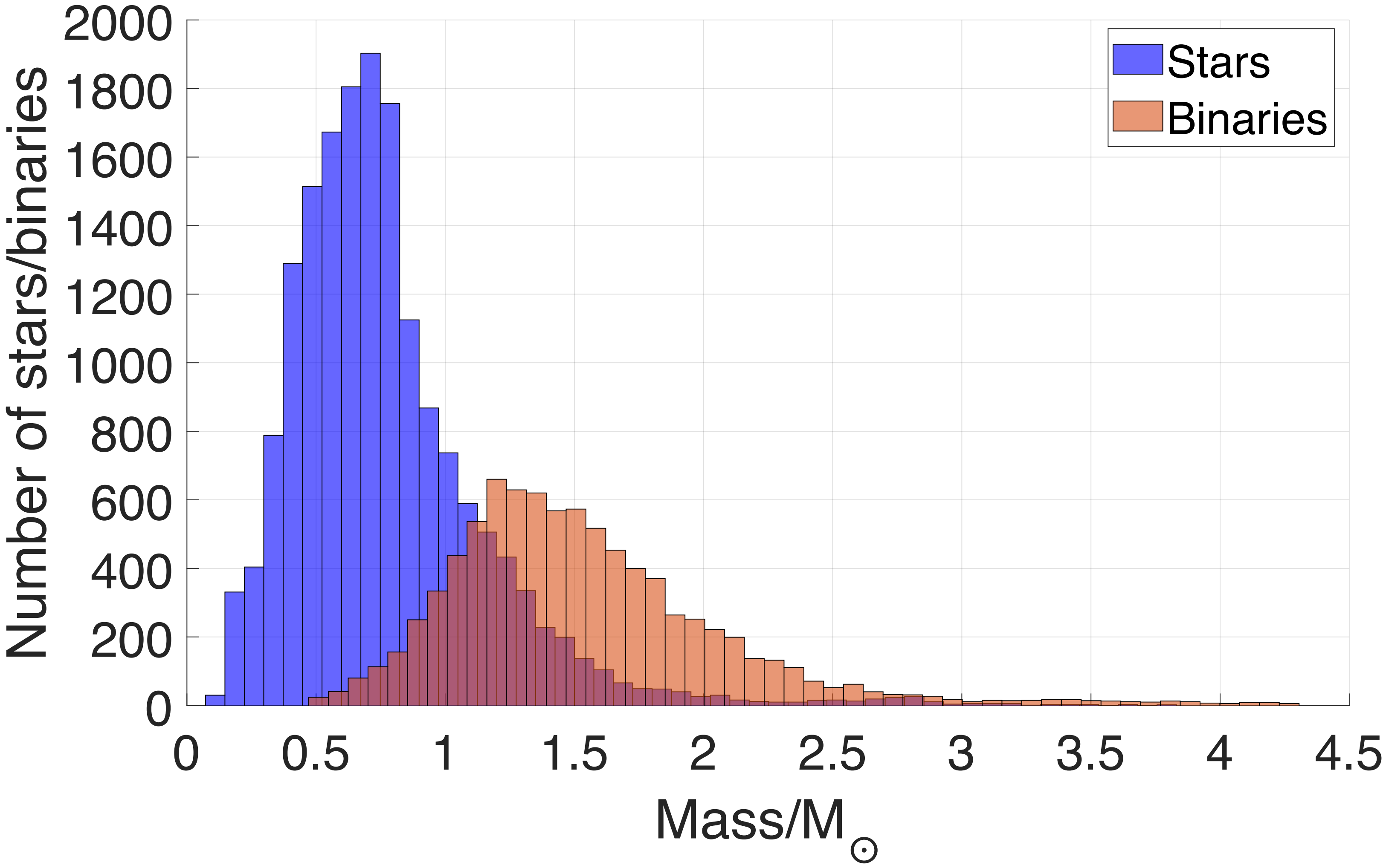
Deviation from Newtonian 3D velocity



4. Strong constraints on the gravitational law from Gaia DR3 wide binaries

- Testing Milgromian dynamics (MOND) using wide binary stars (WBs) with separations of 2–30 kAU from Gaia DR3.
- Comparison between the Newtonian and Milgromian predictions indicates that the result is fully consistent with Newtonian gravity but excludes MOND at 16σ confidence.
- Although our best-fitting model does not fully reproduce the observations, an overwhelmingly strong preference for Newtonian gravity remains.
- We conclude that MOND must be substantially modified on small scales to account for local WBs.

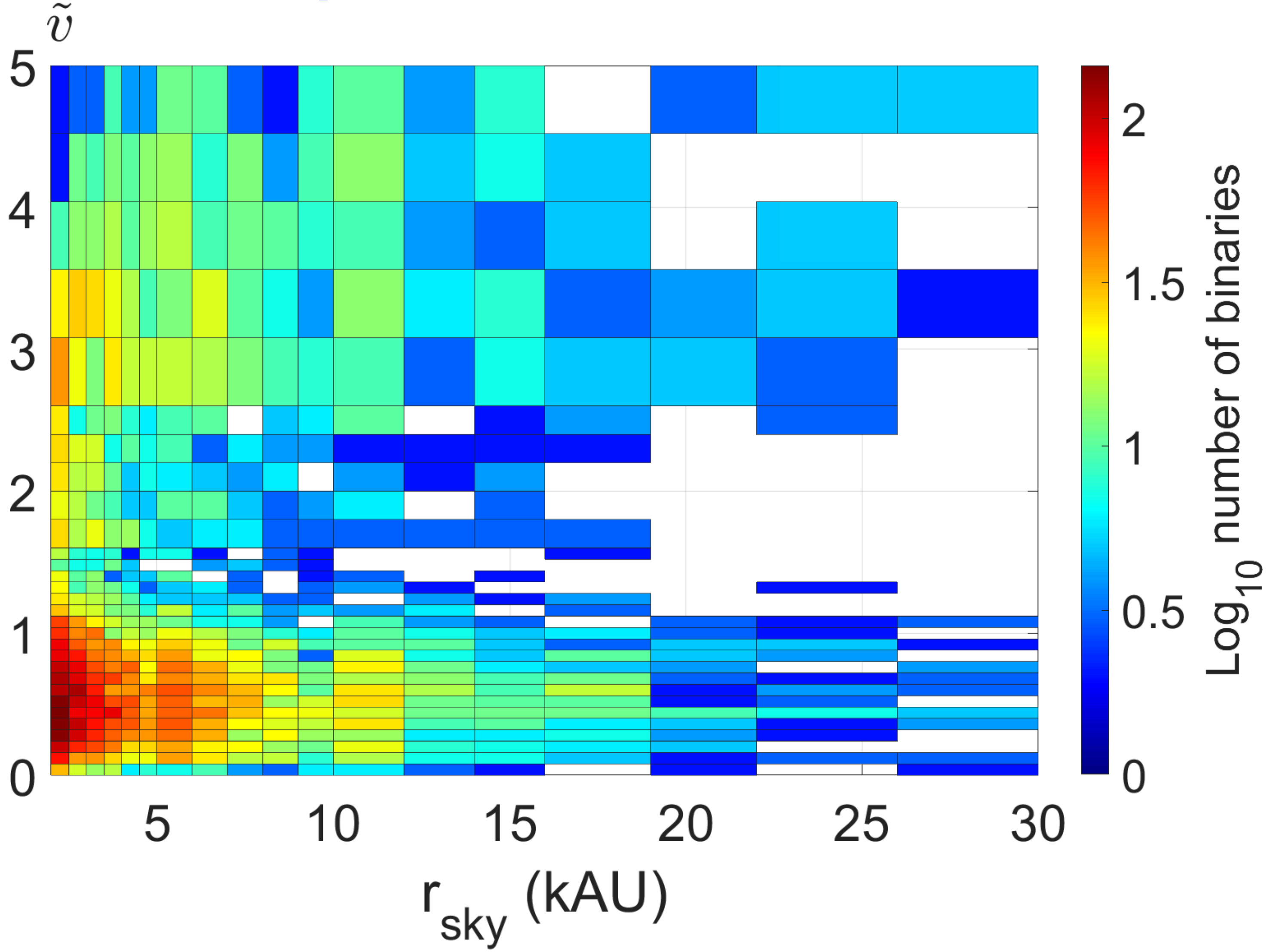
mass distribution of single stars and binaries



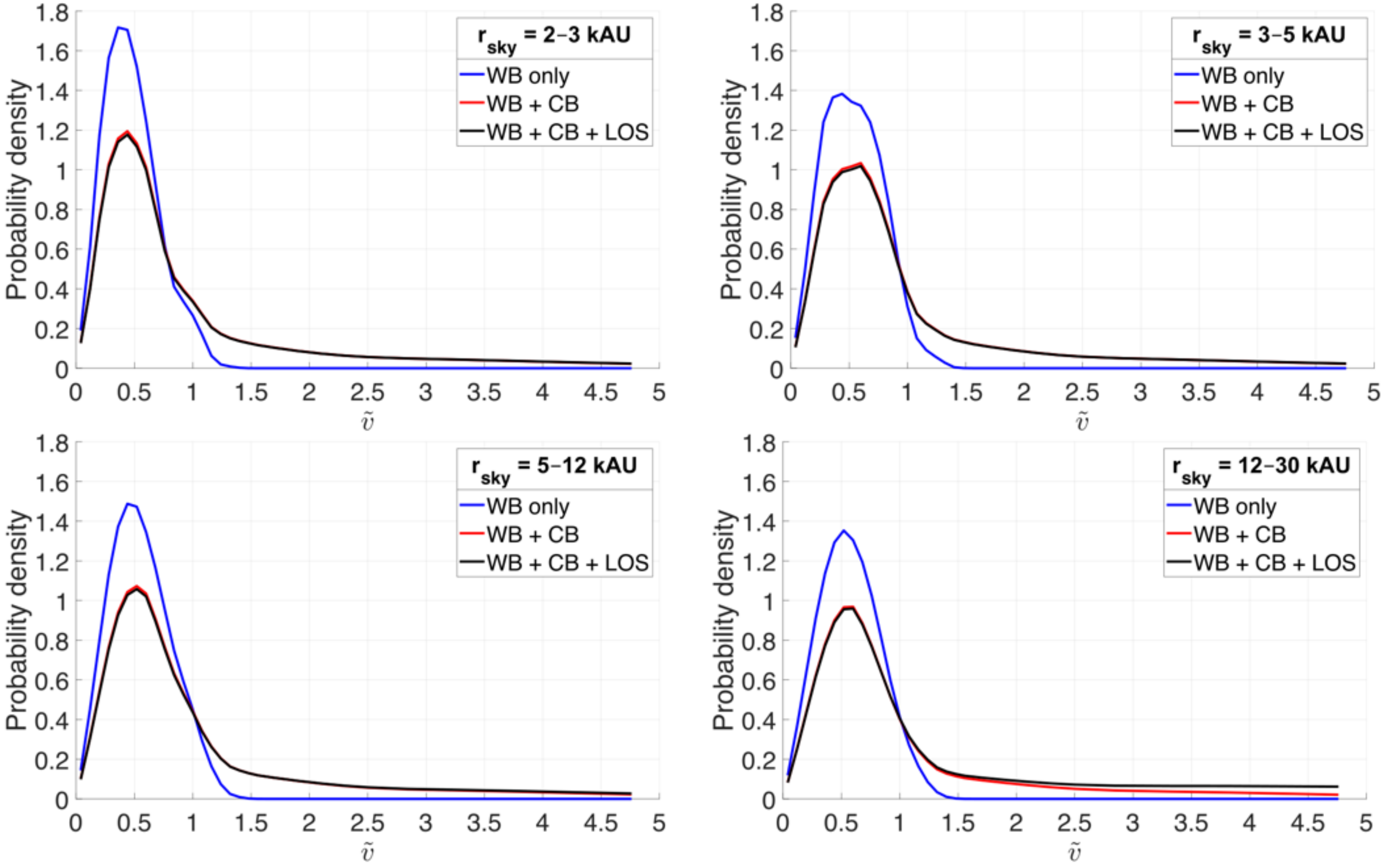
distribution of normalized velocity parameter against sky projected separation of binaries

$$\widetilde{v} \equiv v_{\rm rel} \div \overbrace{\sqrt{\frac{GM}{r_{\rm sky}}}}^{\text{Newtonian } v_c},$$

This is not equal to unity even in Newtonian gravity due to the projection effect of both $v_{\rm rel}$ and $r_{\rm sky}$ (thus Monte Carlo simulation is needed)



effect of undetected CB (close binary) companion

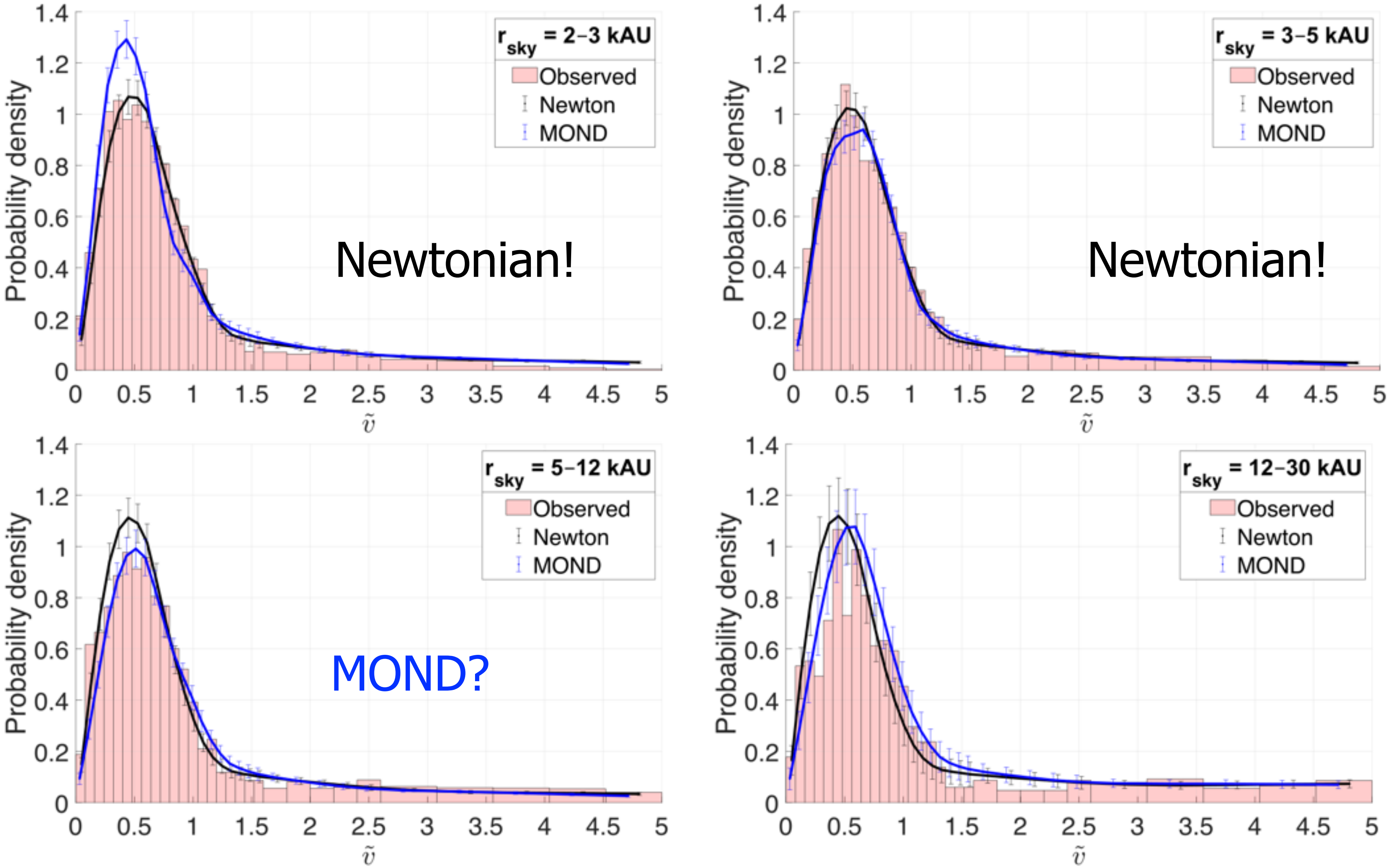


undetected close binary companion significantly affects the result (of course)

↓

estimate of the CB fraction is the key

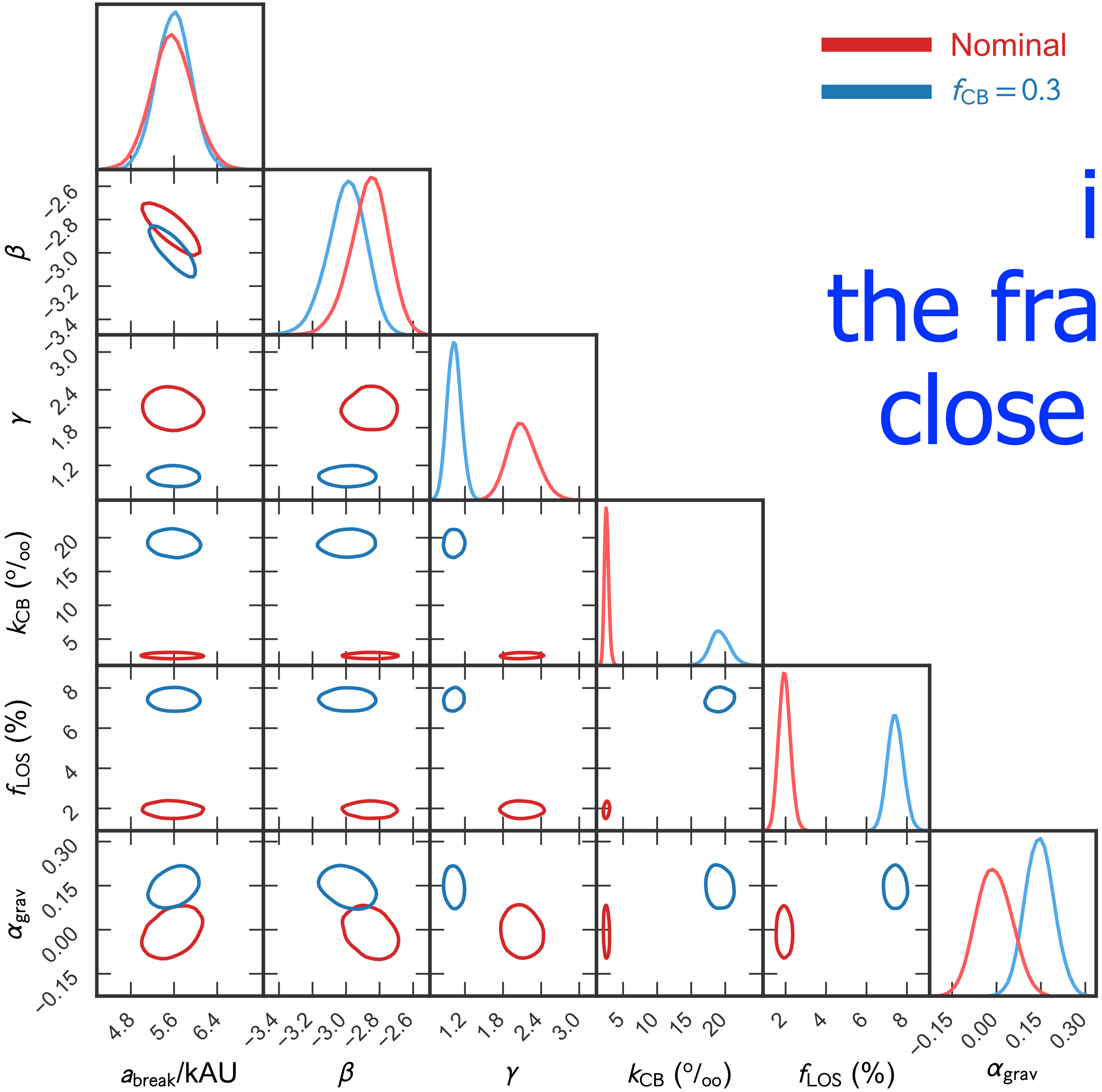
Observed vs Newtonian/MOND velocity distribution



Newtonian!

Newtonian!

MOND?

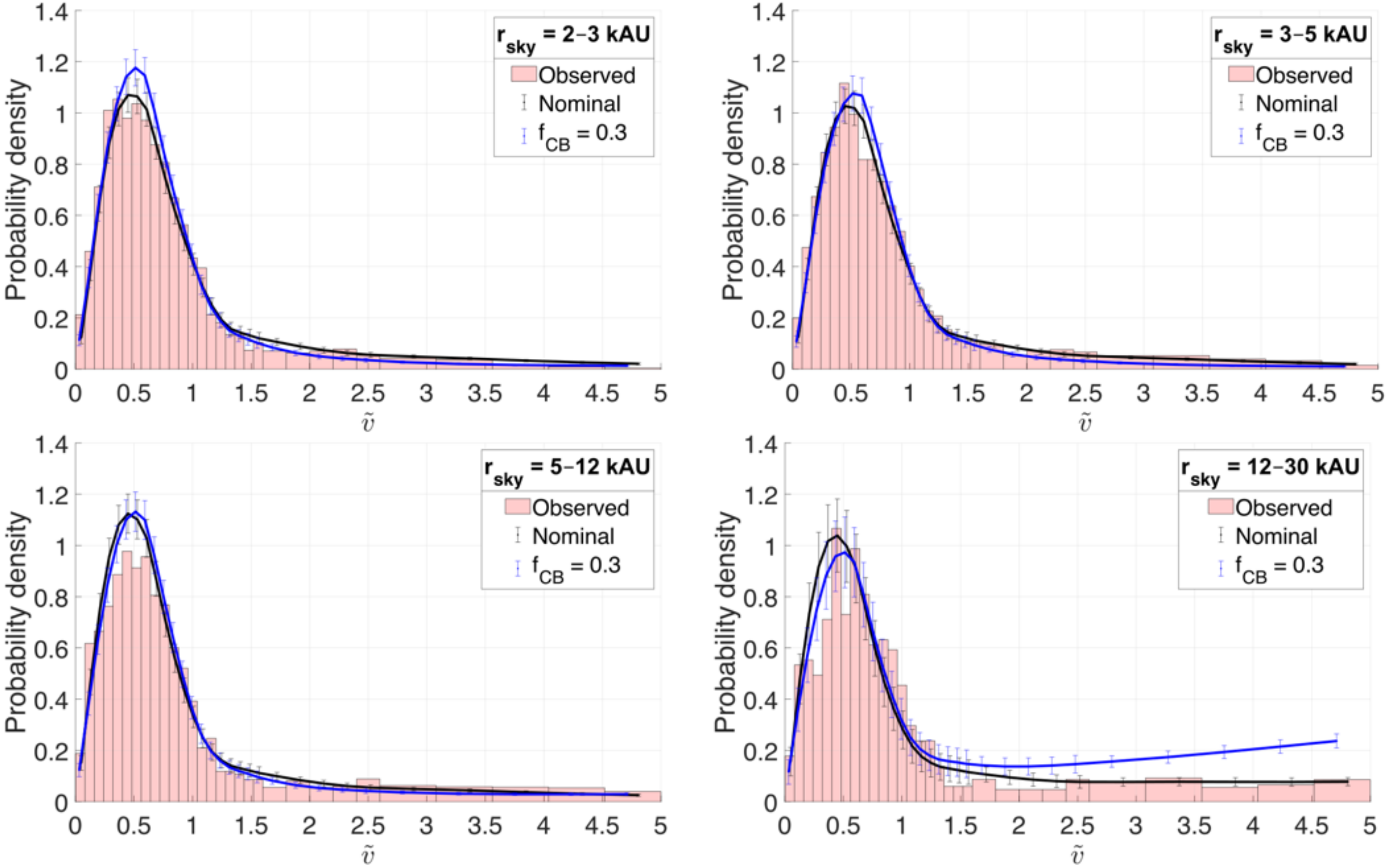


importance of the fraction of undetected close binary companion

If CB fraction is fitted simultaneously, Newton is preferred.

If CB fraction is fixed as 0.3, the deviation from Newton emerges

Observed vs Newtonian velocity distribution with different CB fraction



5. The planet nine hypothesis

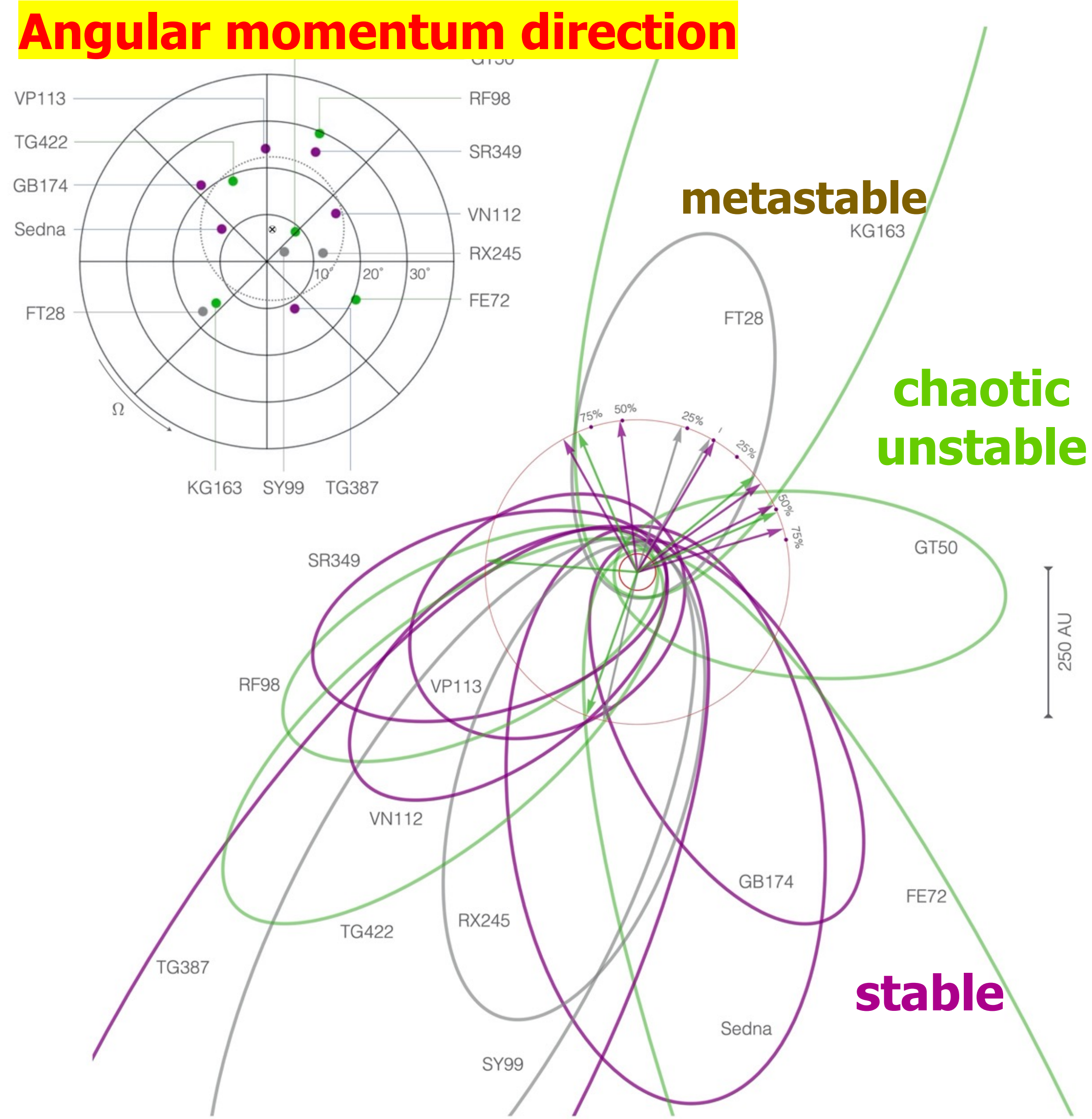
Planet Nine : $m_9 = (5 - 10)M_\oplus$

$0.2 < e_9 < 0.5$, $400 < a_9 < 800$ au, $15 < i_9 < 25$ deg.

Four primary evidence in favor of P9

1. Orbital alignment of P>4000 years KBOs
2. Broad range of perihelion distance for KBOs & those with q>40au that cannot be scattered by known giant planets
3. Excitation of extreme TNO inclinations (i>50 deg. & a>250au)
4. Production of highly-inclined, and even strongly retrograde shorter-period (a<100au) objects

Anomalous architecture of distant KBOs



Angular momentum direction

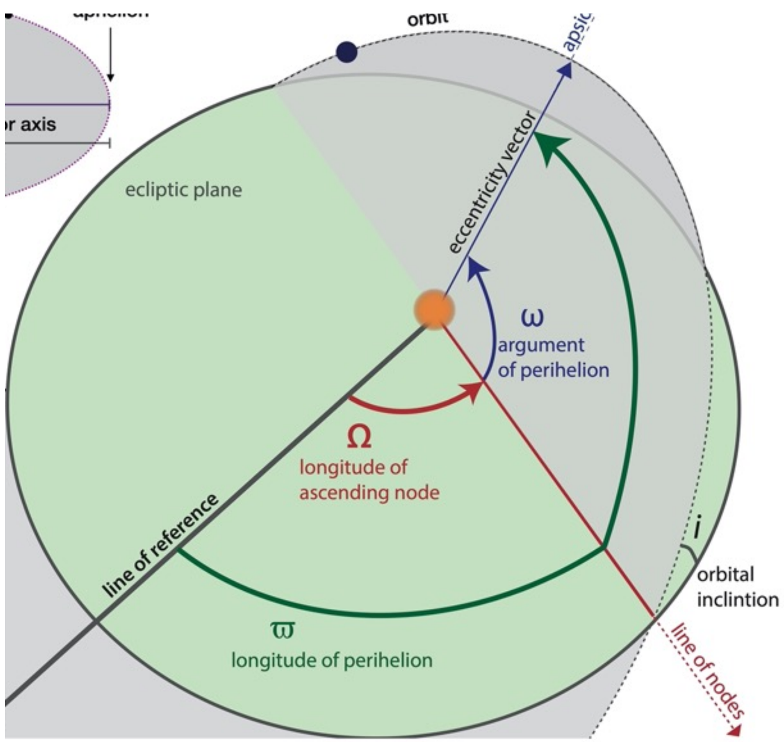
metastable

chaotic unstable

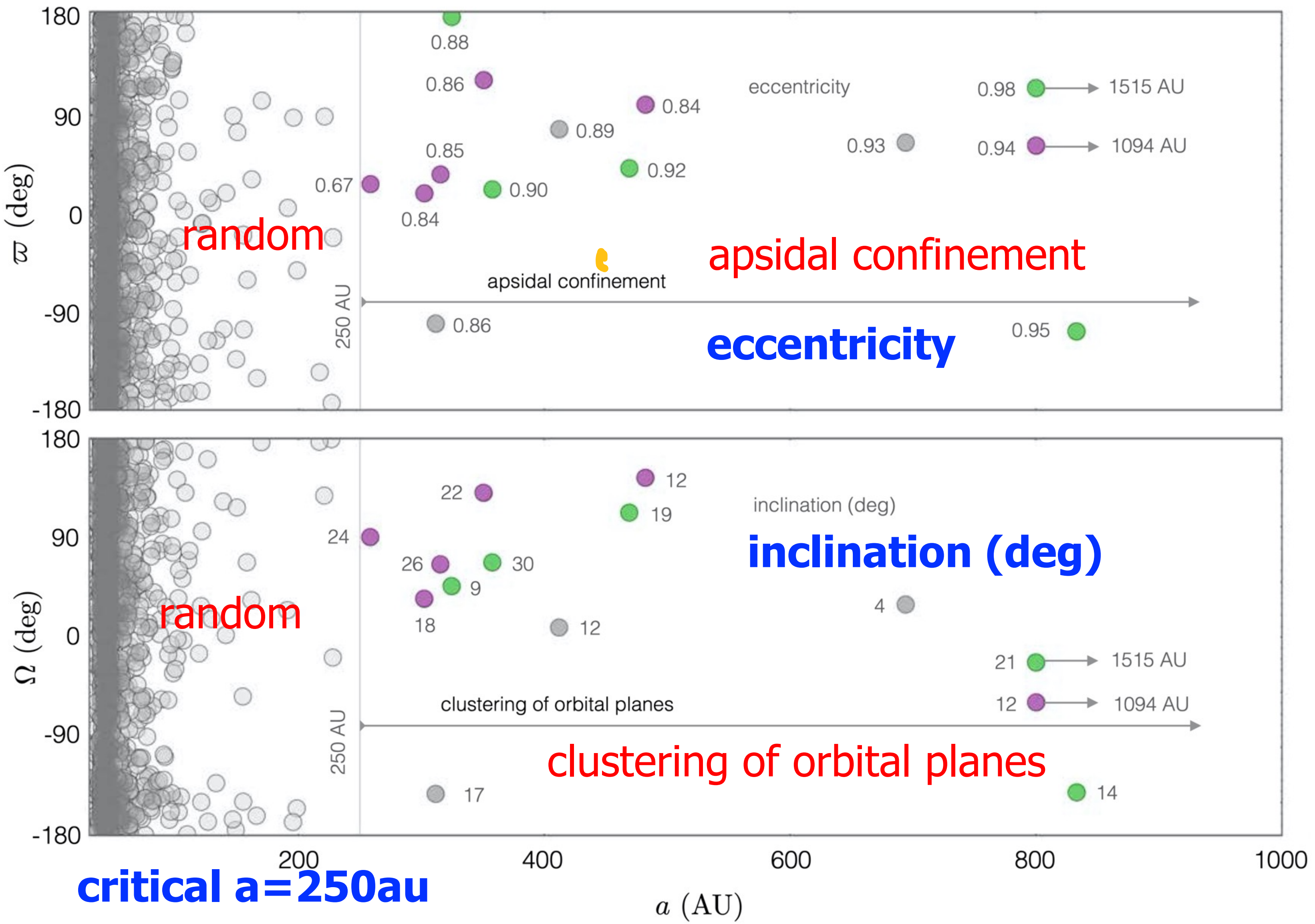
stable

- 14 KBOs (Kuiper Belt Objects) with a(1-e)>30au & a>250au
  - 6 stable
  - 3 metastable
  - 5 unstable
- Their angular momentum vectors are well-aligned (<30 deg.)

Distribution of orbital elements of the 14 distant KBOs



stable
metastable
unstable



random

apsidal confinement

eccentricity

random

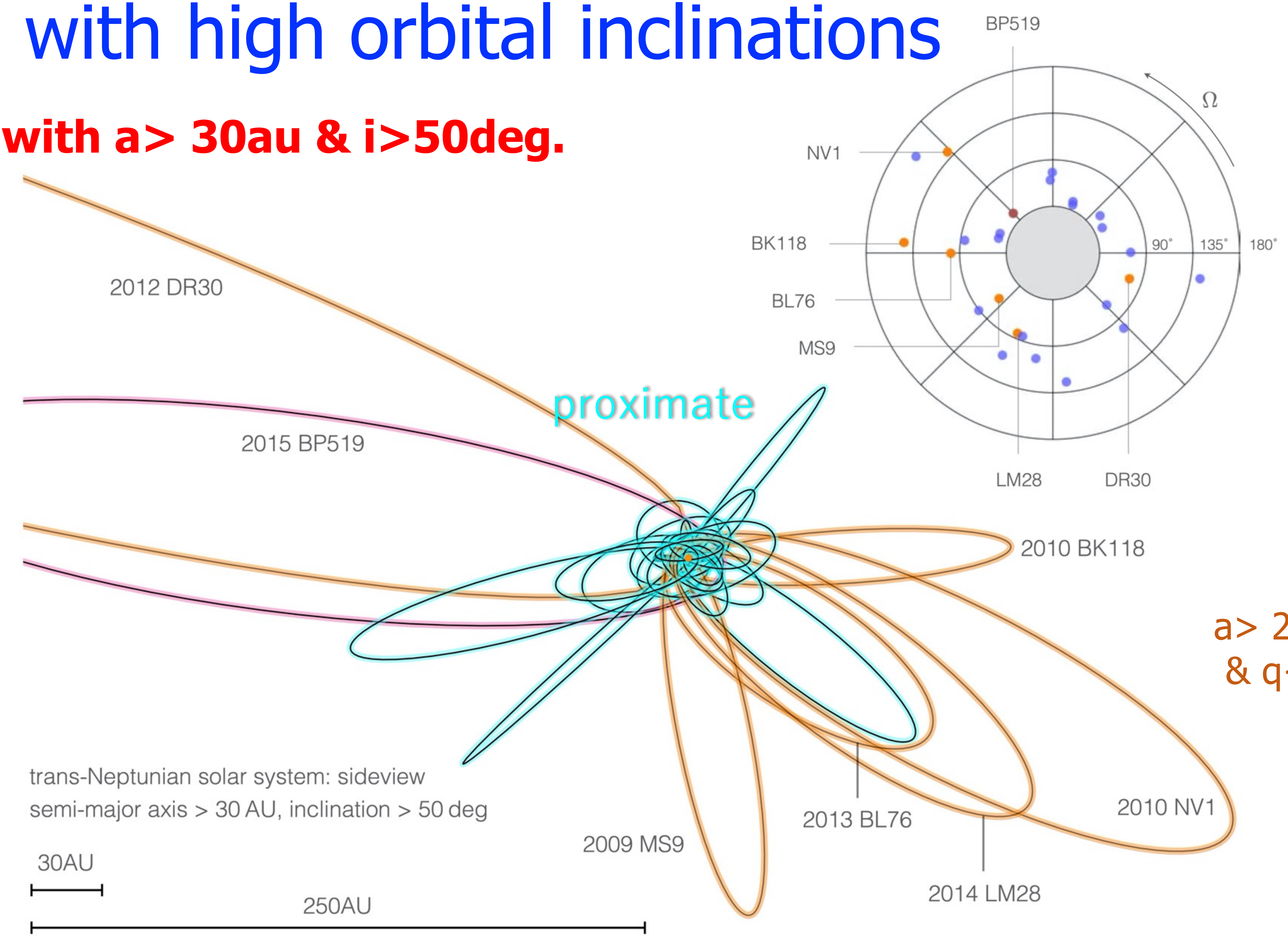
inclination (deg)

clustering of orbital planes

critical a=250au

TNOs with high orbital inclinations

TNOs with a> 30au & i>50deg.



proximate

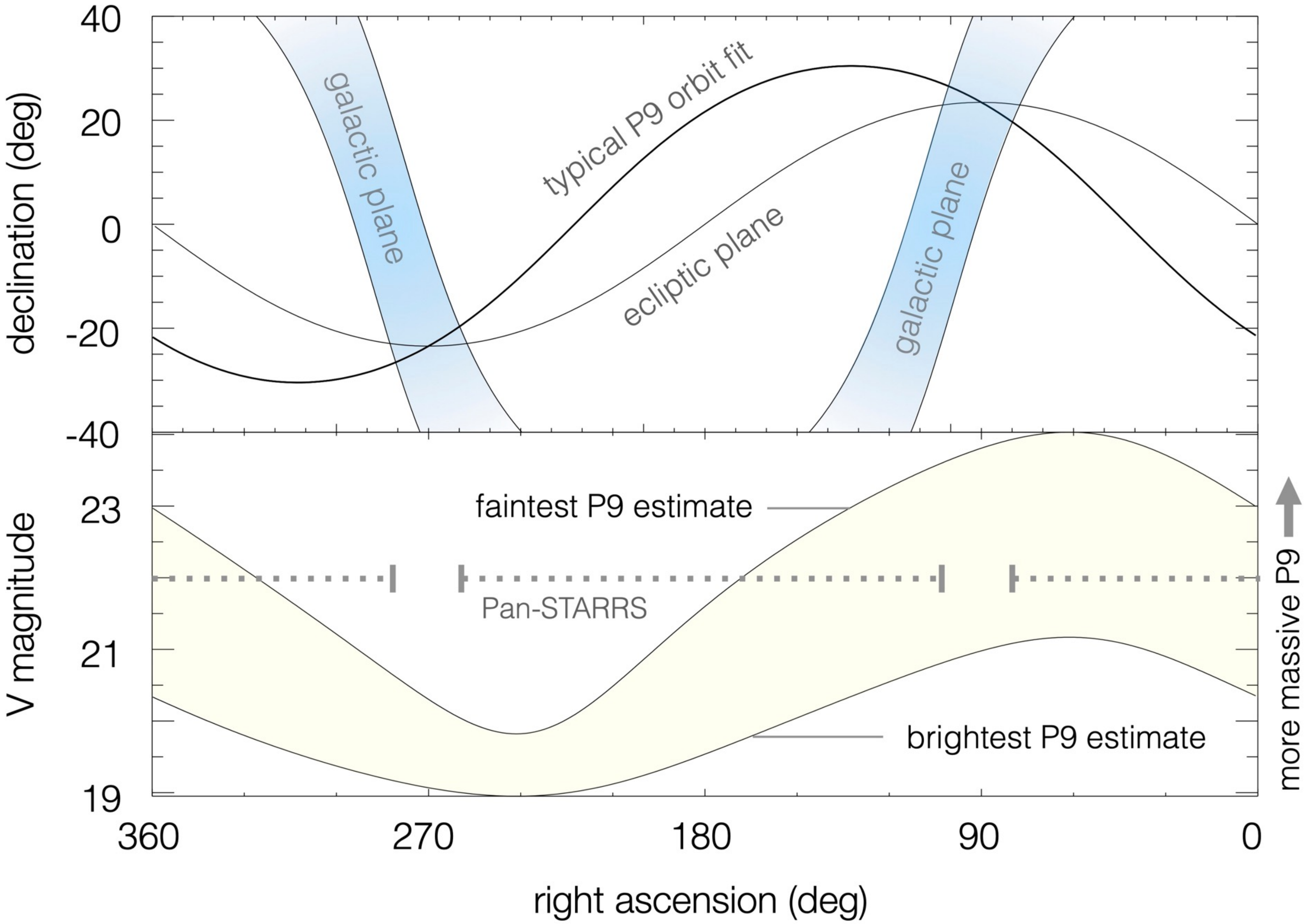
trans-Neptunian solar system: sideview
semi-major axis > 30 AU, inclination > 50 deg

a> 250au
& q<30au

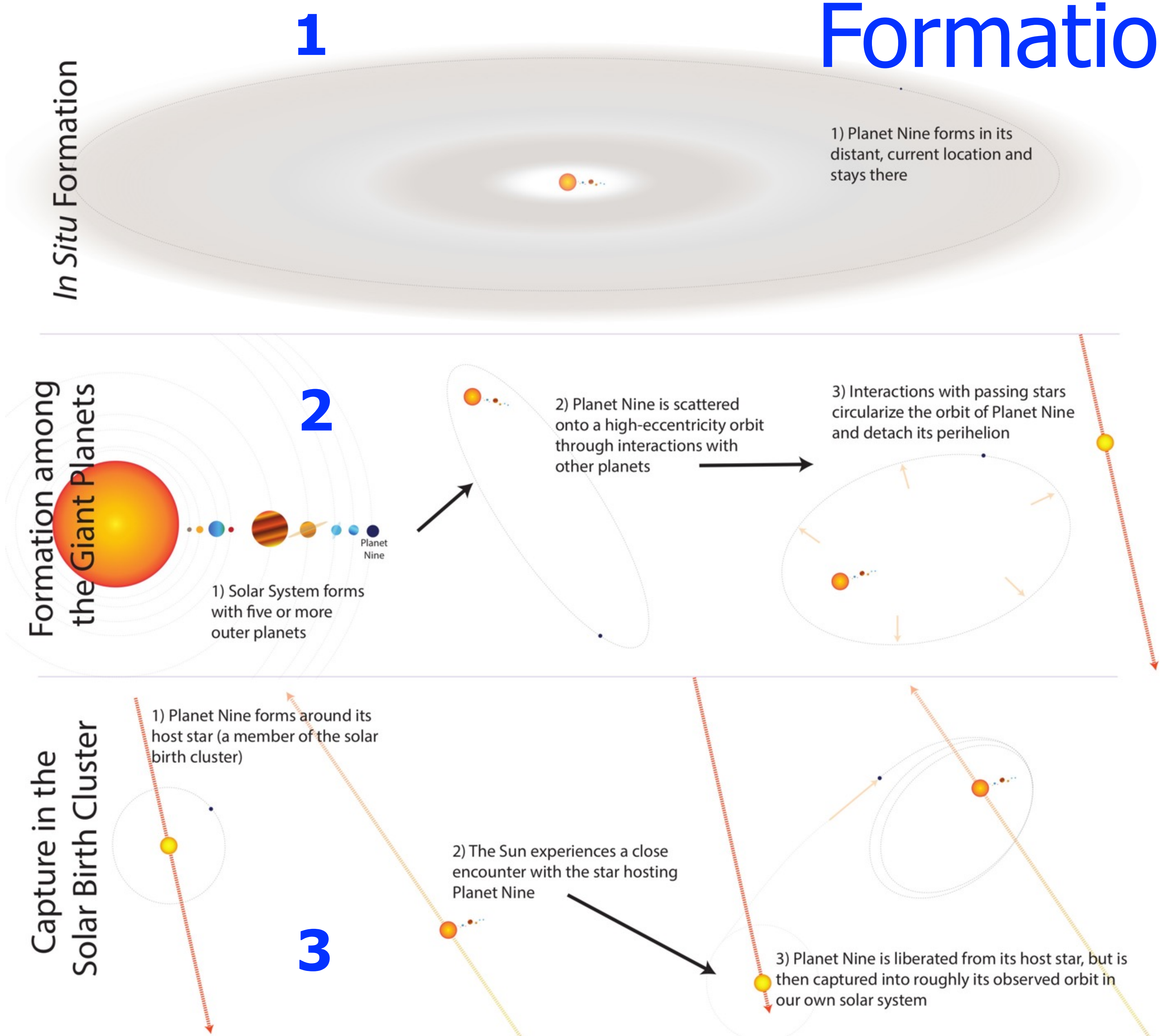
Observational prospects

- Optical surveys
  - Reflected visible light: V=20-24mag.
  - Detectable with Pan-STARRS, DES, HSC, LSST
- Infrared and microwave surveys
  - Thermal emission
  - WISE, future CMB S-4
- Gravitational detection
  - Precise determination of (anomalous) ephemeris of Pluto, but may be too small to be detected

On-sky properties of a typical P9 orbit



Formation scenarios of P9



Difficult because outer region would be tidally truncated

Ejection and capture of P9 is very unlikely (fine-tuning)

6. Pan-STARRS1 Search for Planet Nine

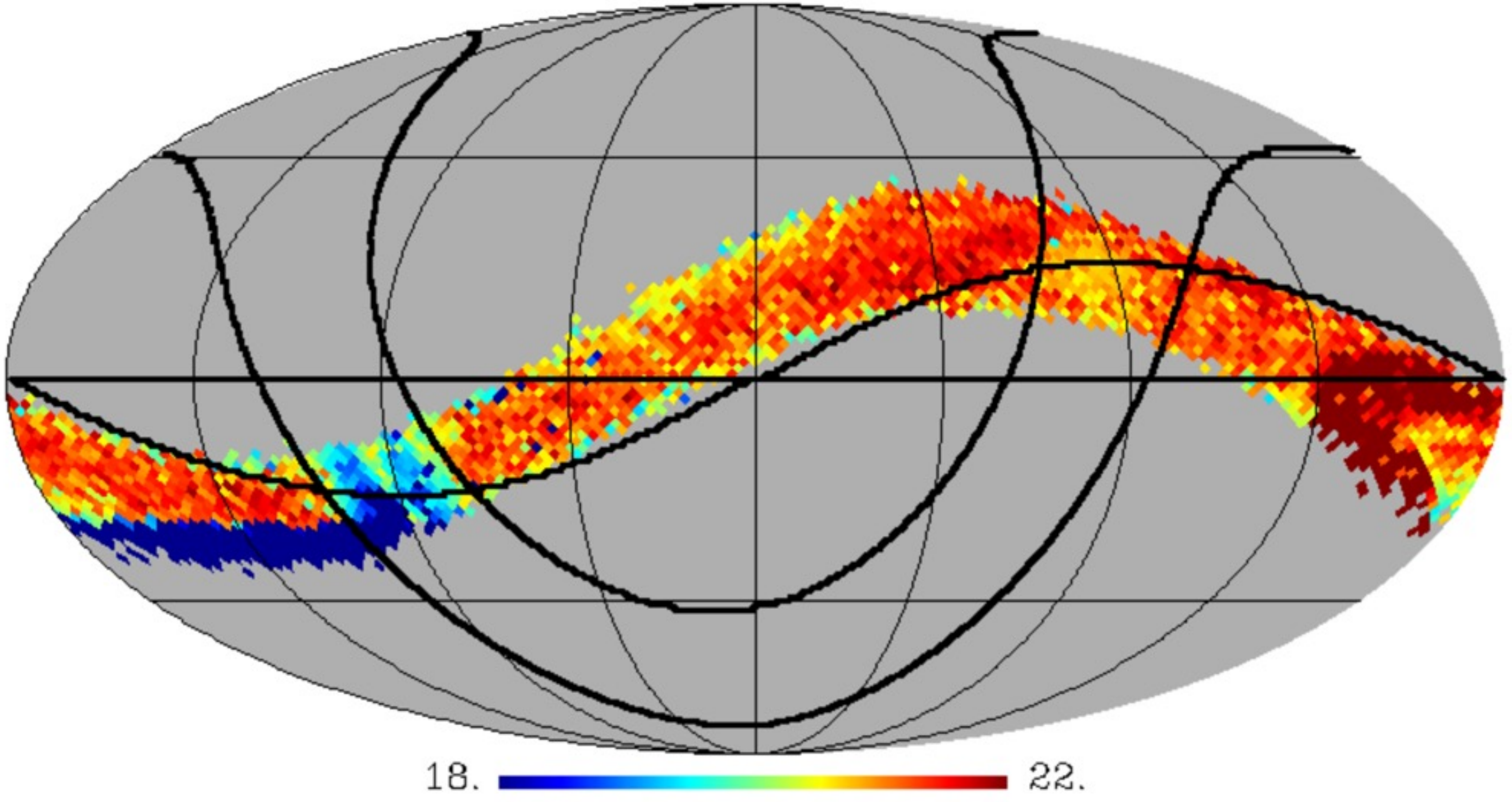
- We present a search for Planet Nine using the second data release of the Pan- STARRS1 survey.
- We rule out the existence of a Planet Nine with the characteristics of that predicted in Brown & Batygin (2021) to a 50% completion depth of V = 21.5.
- This survey, along with previous analyses of the Zwicky Transient Facility (ZTF) and Dark Energy Survey (DES) data, rules out 78% of the Brown & Batygin parameter space.
- Much of the remaining parameter space is at V > 21 in regions near and in the area where the northern galactic plane crosses the ecliptic.

Search strategy

- The Pan-STARRS1 survey covered the approximately 3п steradians of the sky north of a declination of -30◦. Each area in the sky was covered approximately 12 times from 2009 to 2015 in each of 5 broadband filters (grizy reaching a single epoch depth of approximately 22.0, 21.8, 21.5, 20.9, 19.7, respectively).
- If Planet Nine was detected by PS1, it would appear as a single night transient in each detection.
- To search for Planet Nine, we will search for collections of single night transients which appear at locations consistent with a Keplerian motion moving on an orbit within the range of parameters predicted by Brown & Batygin (2021).

The combined V -band magnitude limits of the ZTF, DES, and PS1 surveys for Planet Nine

- at which there is a 95% or higher probability that a moving object would be detected 9 or more times in the portion of the PS1 data that intersects the predicted locations of P9, reconstructed from detections of the synthetic reference population.
- The data are shown in a Mollweide equal area projection in equatorial coordinates. Right ascension of 360 is on the left with 180 in the middle and 0 on the right. The ecliptic is indicated by a line, as well as galactic latitudes of ±15◦.



The probability density function of on-sky location of the BB22 Planet Nine reference population that would remain undetected after the ZTF, DES, and PS1 surveys