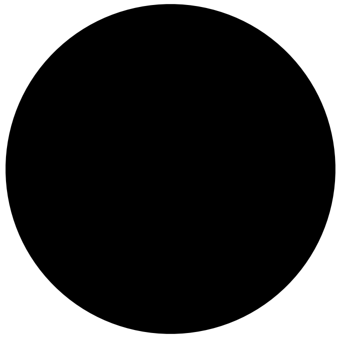
What if Planet 9 was a Primordial Black Hole?



Jakub Scholtz
based on work with James Unwin
[1909.11090]

for the Pandemic Seminar

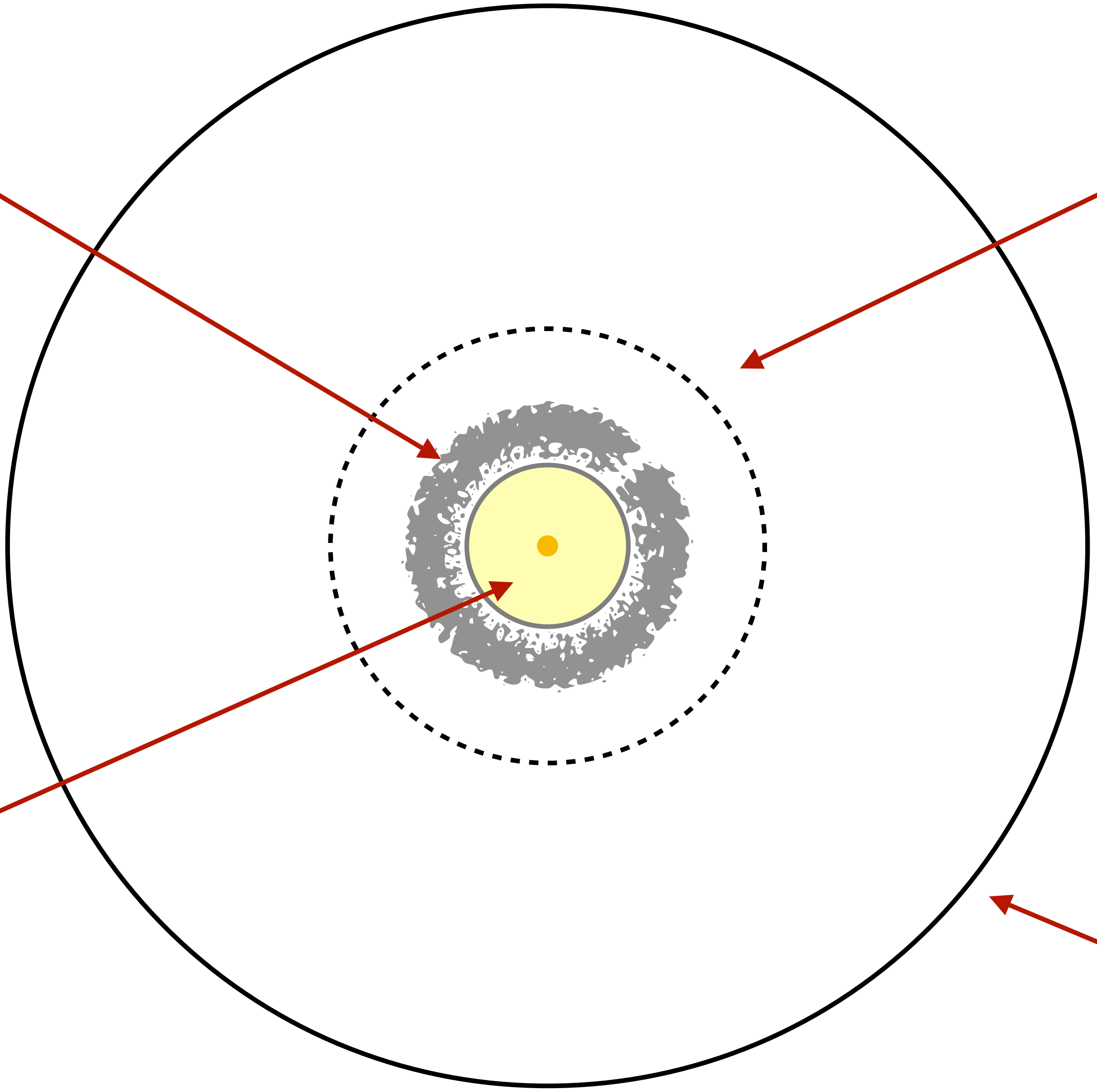
Outline

- Anomaly #1: What is Planet 9?
- Anomaly #2: OGLE anomaly
- What is the capture probability?
- How do we find it?
- Conclusions

Planet 9

based on [1902.10103]

(Very) Rough Sketch of our Solar System



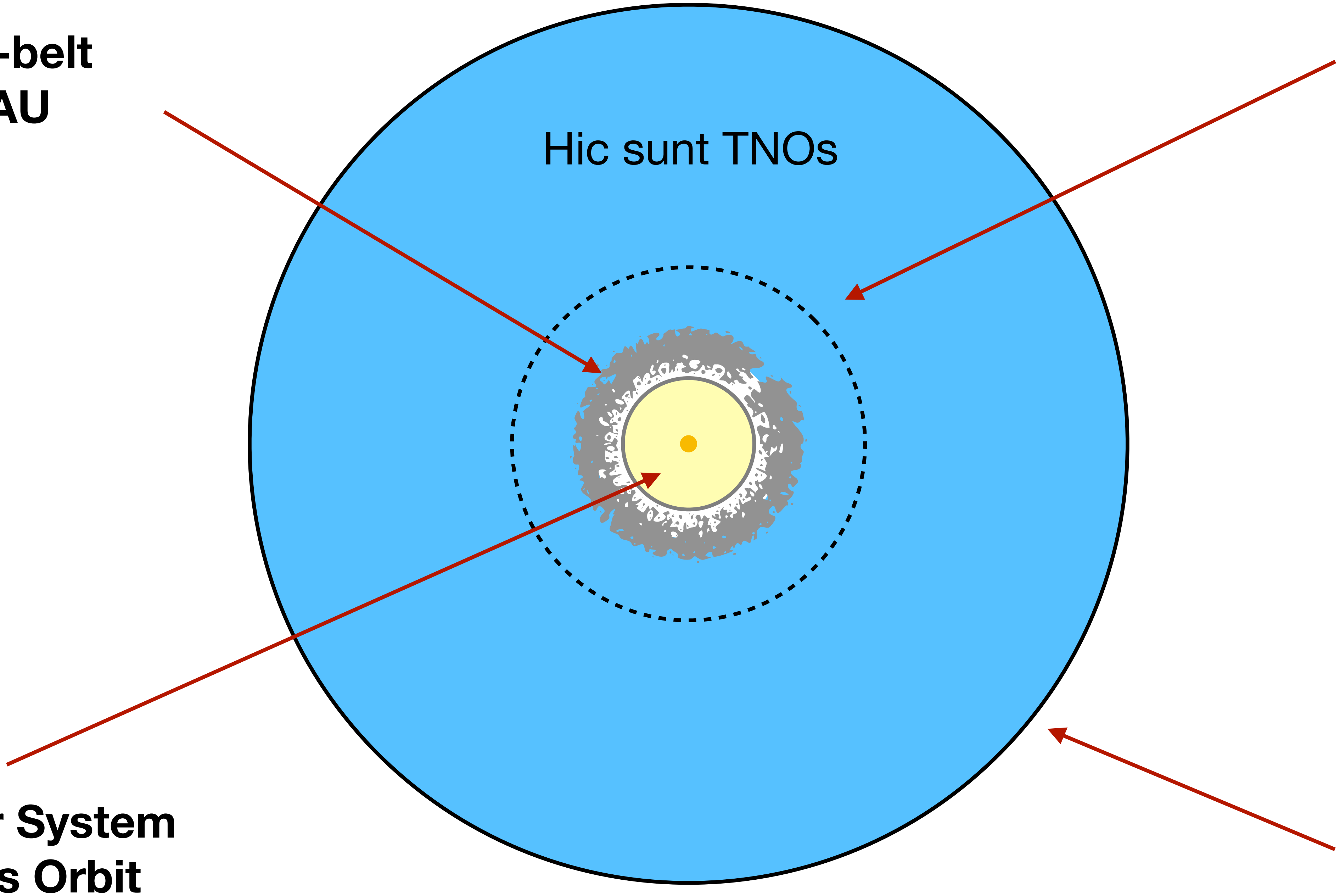
Kuiper-belt
30+ AU

Heliosphere
~100AU

Inner Solar System
Neptune's Orbit
~30AU

Oort Cloud
2000+ AU

(Very) Rough Sketch of our Solar System



Hic sunt TNOs

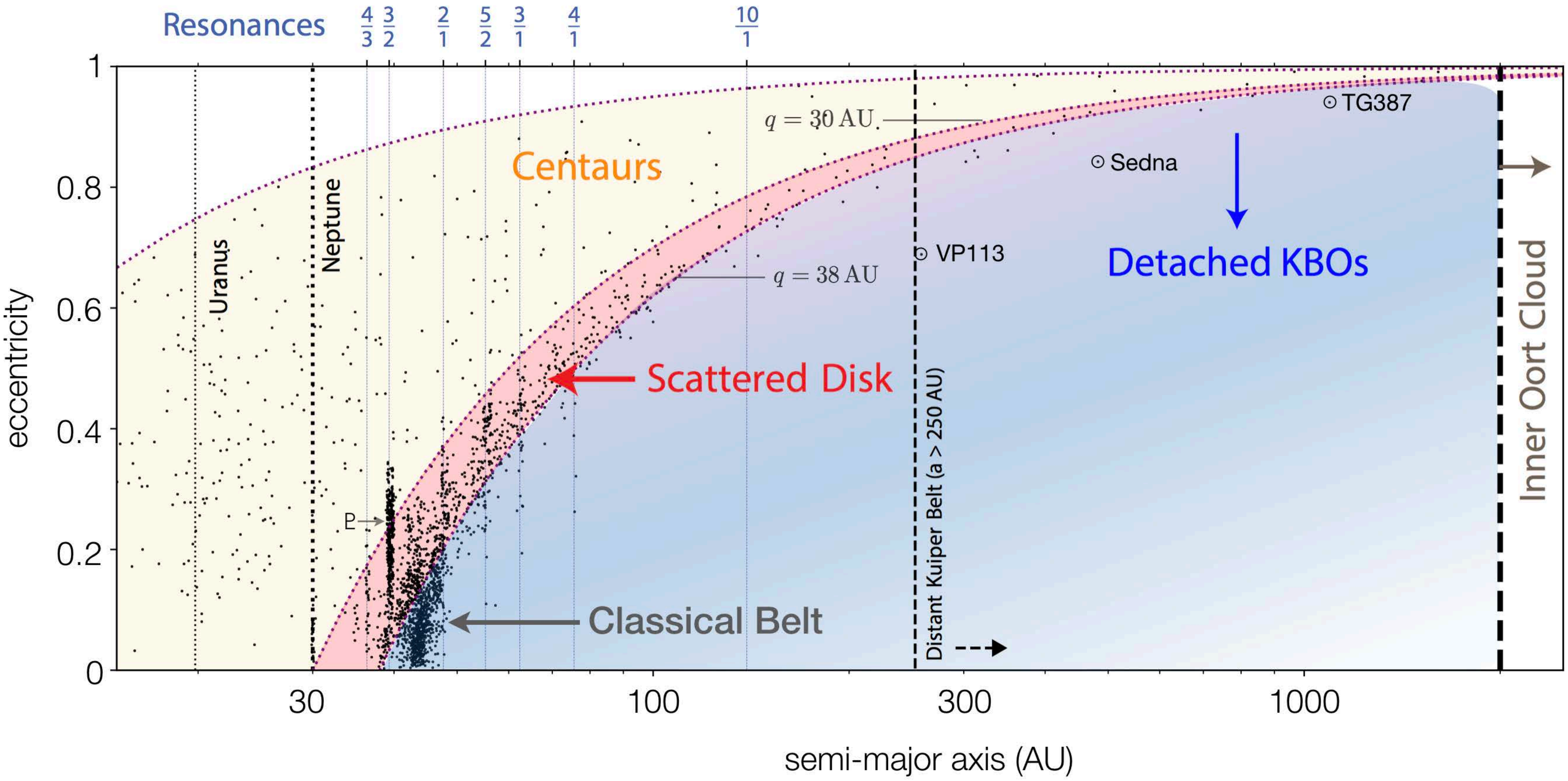
Kuiper-belt
30+ AU

Heliosphere
~100AU

Inner Solar System
Neptune's Orbit
~30AU

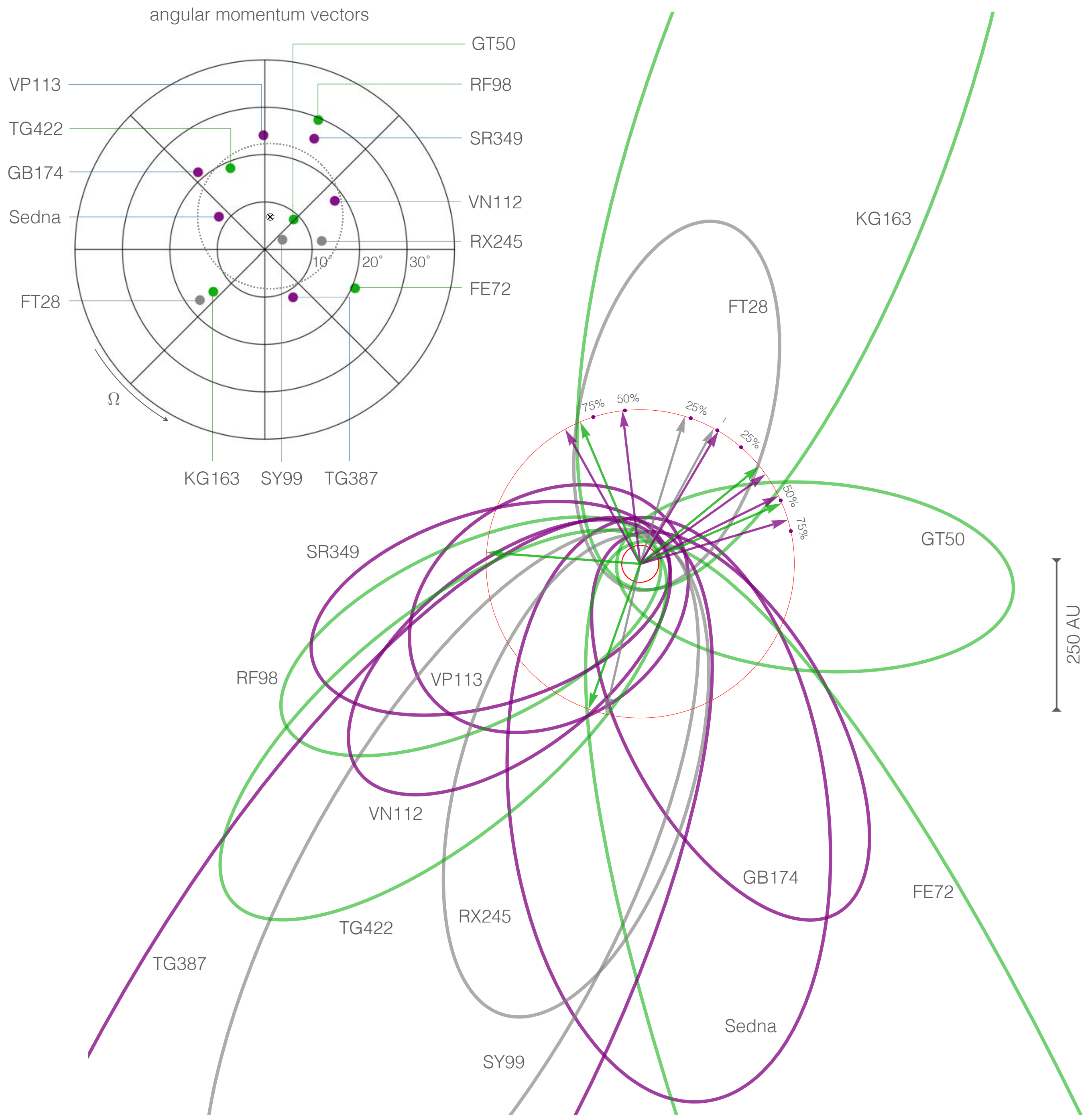
Oort Cloud
2000+ AU

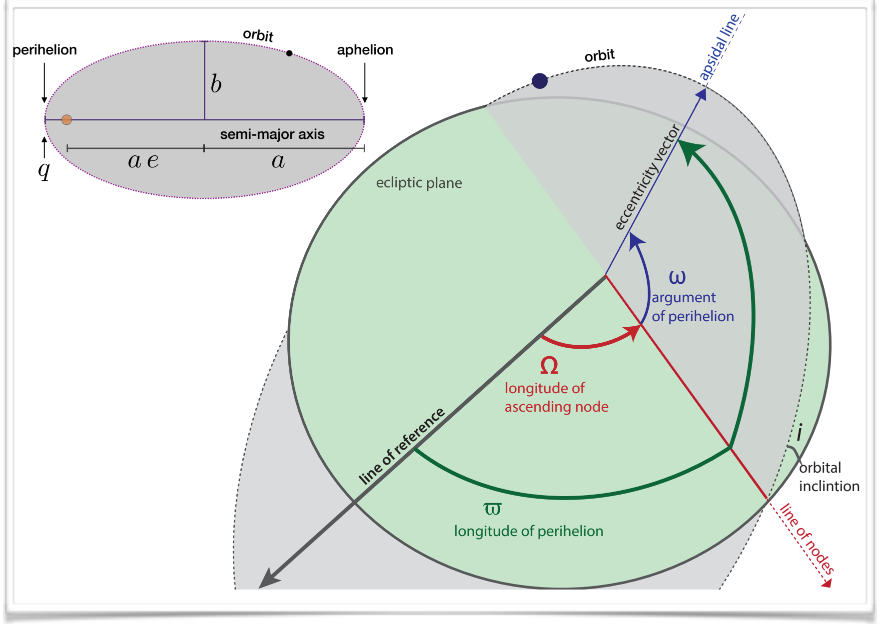
It’s pretty busy out-there

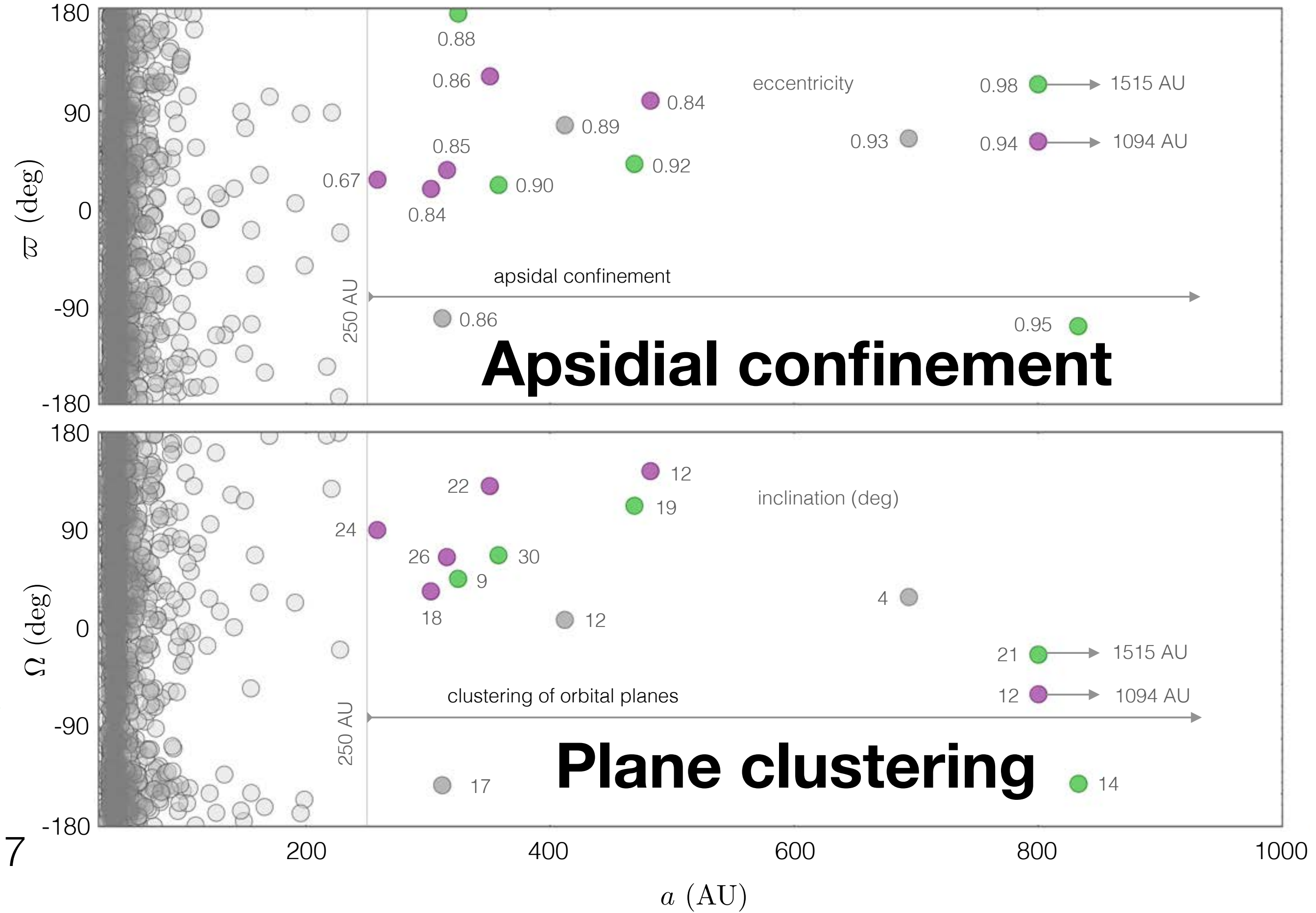


q - perihelion

Not just busy — also strange I



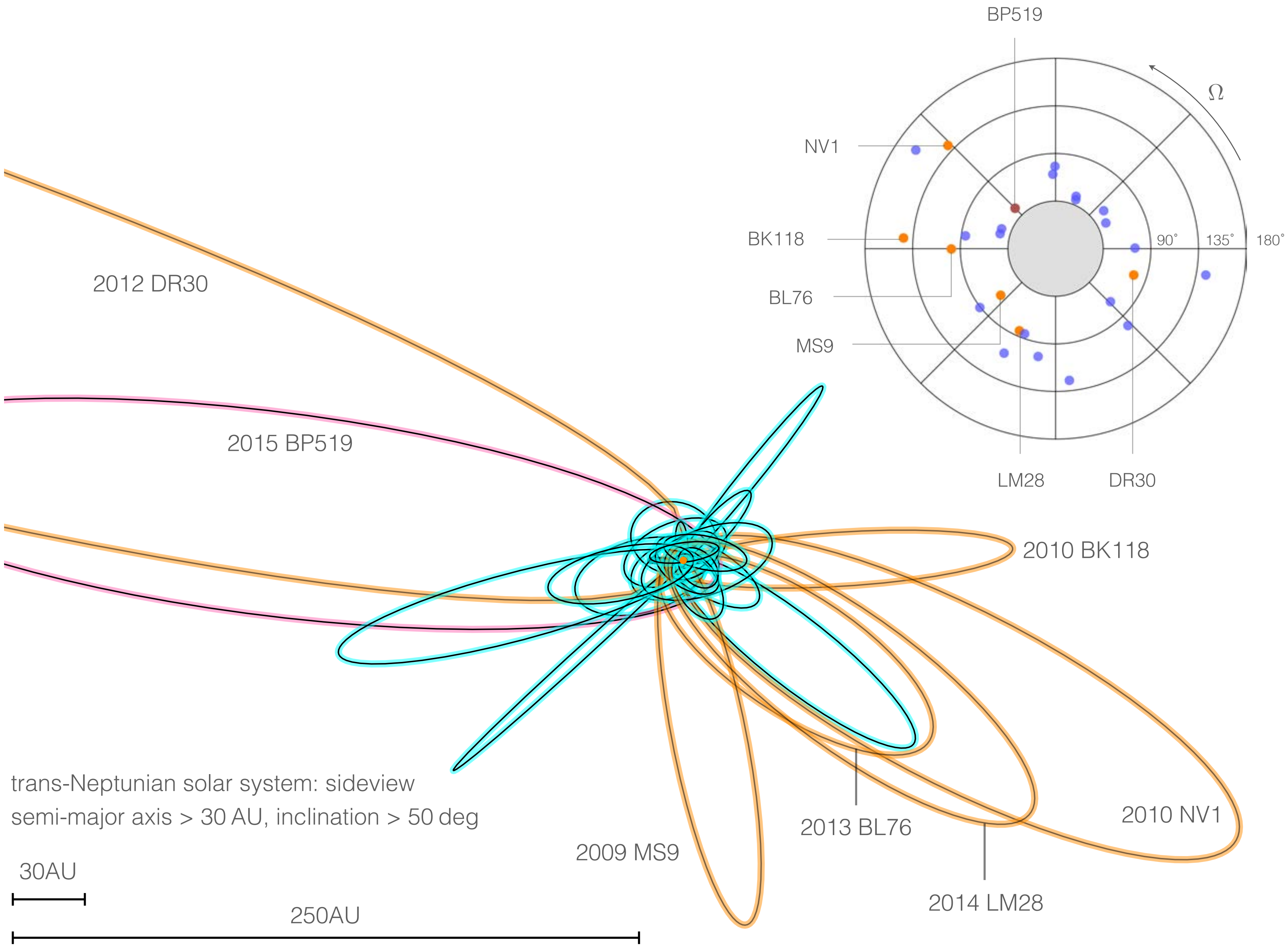




Apsidial confinement

Plane clustering

Not just busy — also strange II



High inclinations

We do not expect to see any objects with i>30

Strange and ephemeral…

- Apsidial Confinement: 4% chance
- Plane Clustering: together with Apsidial confinement: 0.2%
- High Inclinations: bias favours low inclinations. The reality is worse than the sample.
- Typical timescale to erase these: 10-100 million years.

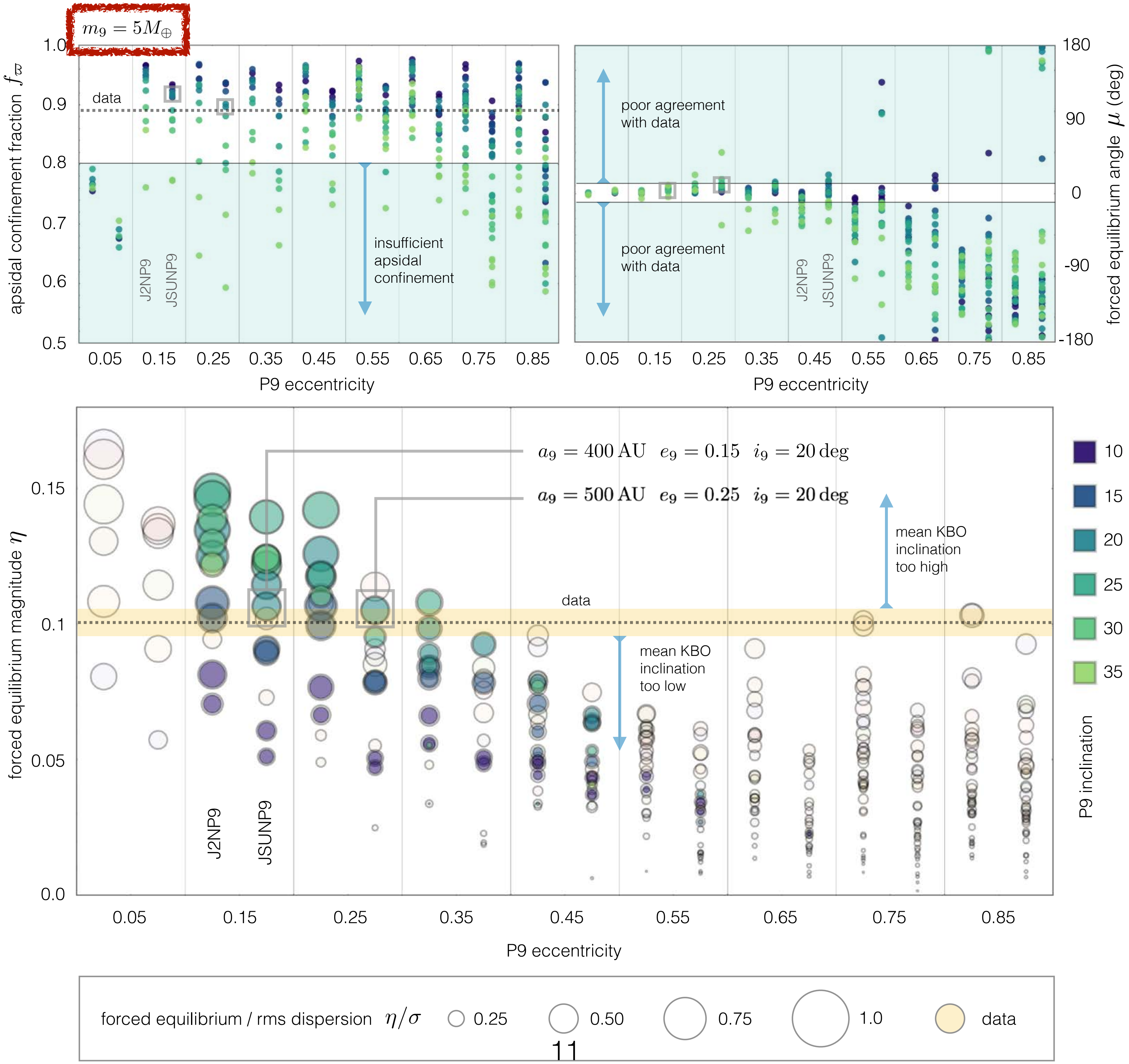
Is there a shepherd around?

- Since the KBOs and TNOs are so strangely distributed, perhaps, there is an object that sets and helps them maintain their orbits.

- Such object should:
    1. have non-zero eccentricity
    2. non-zero inclination
    3. be reasonably far/massive

- Brown, Batygin et al. performed an extensive suite of simulations to determine its properties (mass and orbit).

Shepherd I



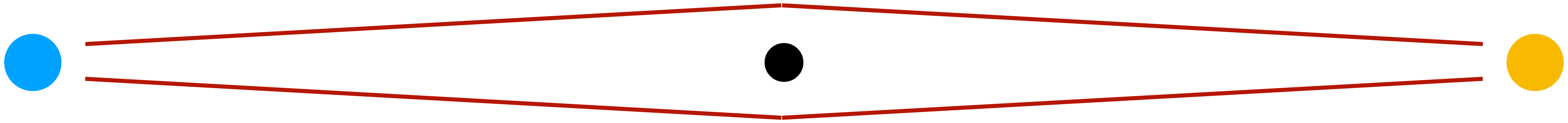
$m_9 = 5M_\oplus$
apsidal confinement fraction f_ϖ
1.0
0.9
0.8
0.7
0.6
0.5
data
J2NP9
JSUNP9
insufficient apsidal confinement
0.05
0.15
0.25
0.35
0.45
0.55
0.65
0.75
0.85
P9 eccentricity
poor agreement with data
poor agreement with data
180
90
0
-90
-180
forced equilibrium angle μ (deg)
forced equilibrium magnitude η
0.15
0.1
0.05
0.0
$a_9 = 400\,\mathrm{AU}$ $e_9 = 0.15$ $i_9 = 20\,\mathrm{deg}$
$a_9 = 500\,\mathrm{AU}$ $e_9 = 0.25$ $i_9 = 20\,\mathrm{deg}$
mean KBO inclination too high
mean KBO inclination too low
P9 inclination
10
15
20
25
30
35
forced equilibrium / rms dispersion η/σ
0.25
0.50
0.75
1.0

Planet 9 — take away

Each of the above dynamical effects can be understood from purely analytic grounds within the framework of the Planet Nine hypothesis. Simplified models of this sort, based on secular perturbation theory, are presented in section 4. Detailed comparison with the data, however, requires the fabrication of a synthetic population of long-period KBOs using large-scale N-body simulations. The results of thousands of such simulations are described in section 5, and collectively point to a revised set of physical and orbital parameters for Planet Nine. Specifically, compared to the original results (Batygin and Brown, 2016a), where P9 was reported to have $m_9 \approx 10 M_\oplus$ and occupy an $a_9 = 700\,\mathrm{AU}$ orbit with $e_9 = 0.6$, the current simulations (reviewed in section 5), point towards a marginally lower-mass planet that resides on a somewhat more proximate and less dynamically excited orbit, with $m_9 \approx 5 - 10 M_\oplus$, $a_9 \sim 400 - 800\,\mathrm{AU}$, $e_9 \sim 0.2 - 0.5$, and $i_9 \sim 15 - 25\,\mathrm{deg}$. Perhaps counterintuitively, the increase in brightness due to a smaller heliocentric distance more than makes up for the decrease in brightness due to a slightly diminished physical radius, suggesting that Planet Nine is more readily discoverable by conventional optical surveys than previously thought.

Gravitational Lensing

Gravitational Lensing

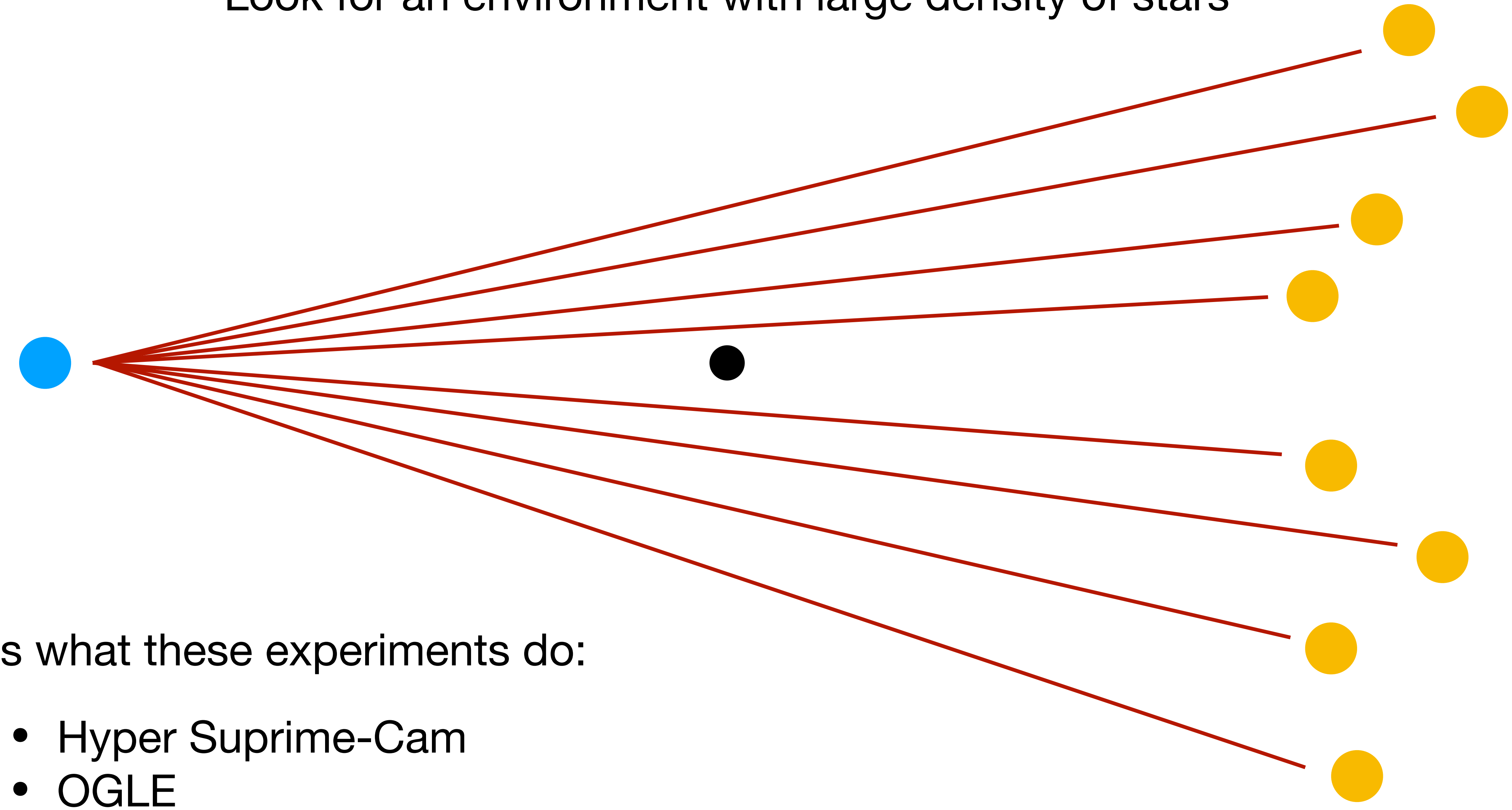


For an Earth mass object this corresponds to an angle:

$$\theta_{\rm E} = 2.7 \times 10^{-11} {\rm rad}$$

Gravitational Lensing

Look for an environment with large density of stars

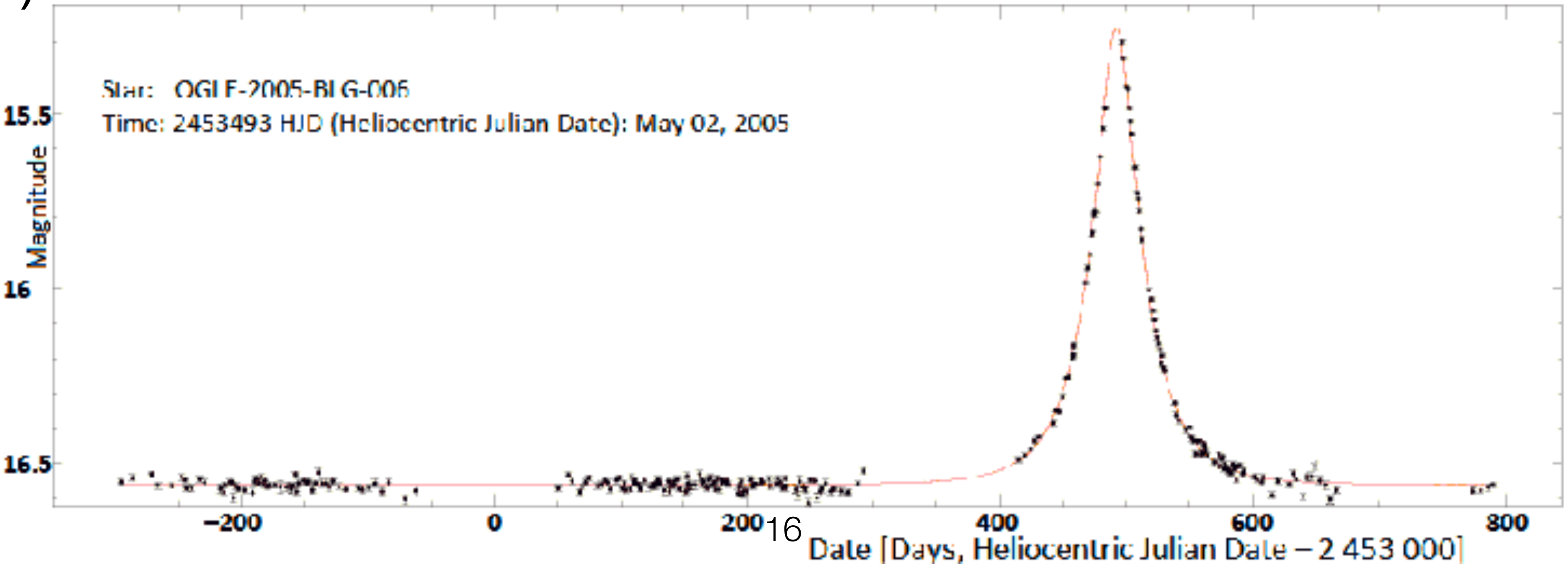


That's what these experiments do:

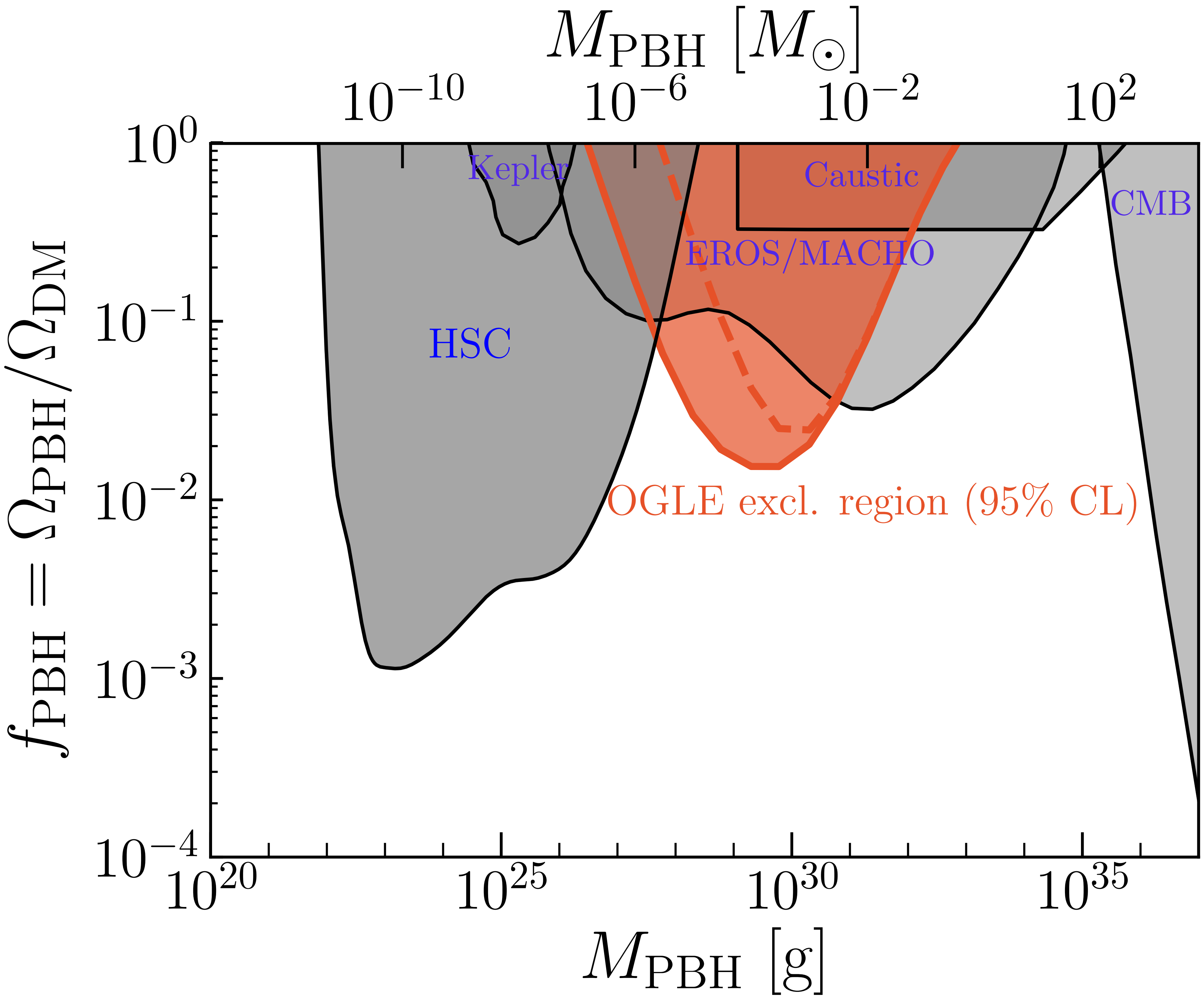
- Hyper Suprime-Cam
- OGLE
- MACHO
- EROS

OGLE

- OGLE = Optical Gravitational Lensing Experiment
- The look for changes in the stars' brightness. Either due to occultation or lensing.
- If periodic, this implies an orbiting planet.
- If not periodic, it implies a transit (or long period)



Current Status

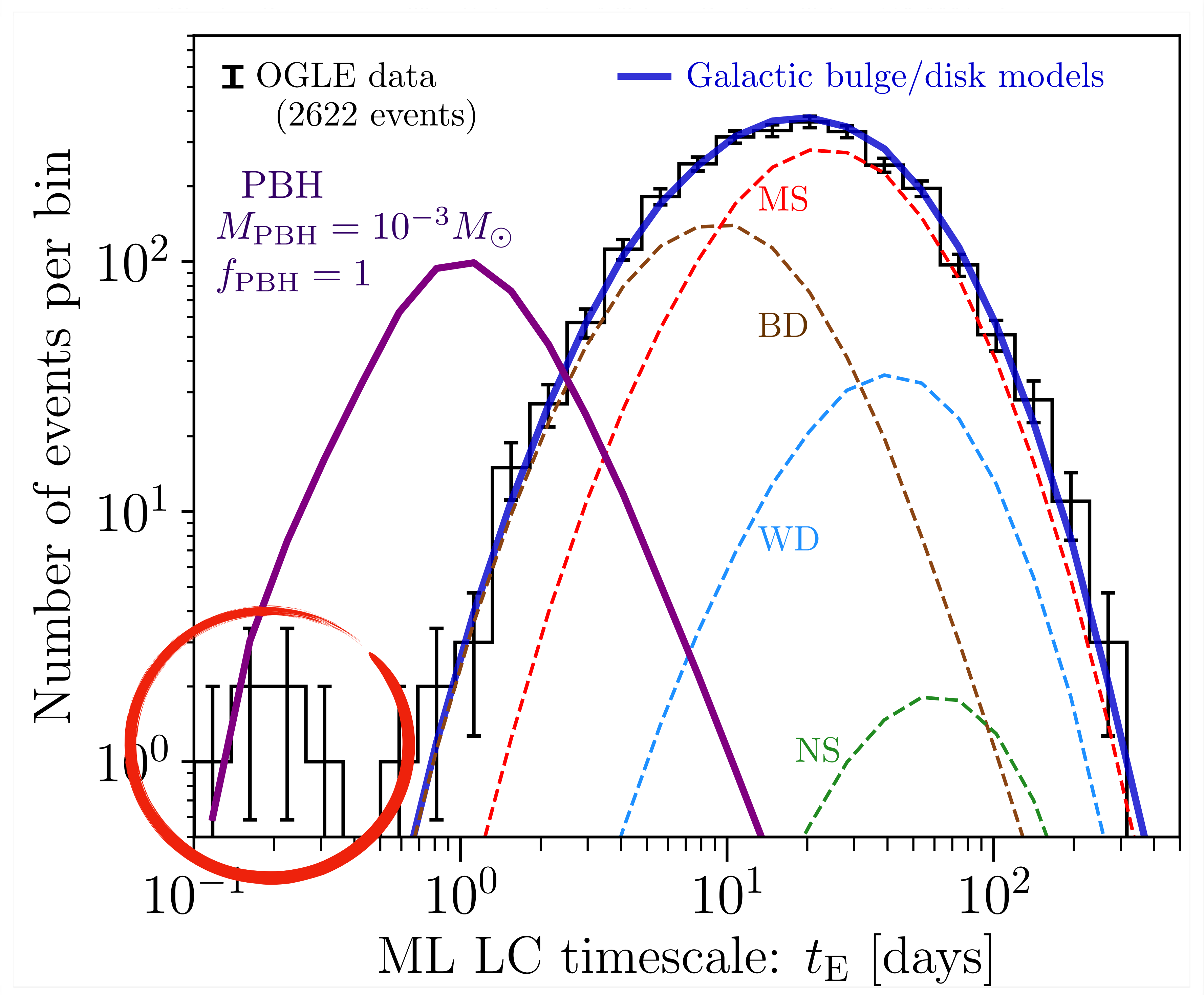


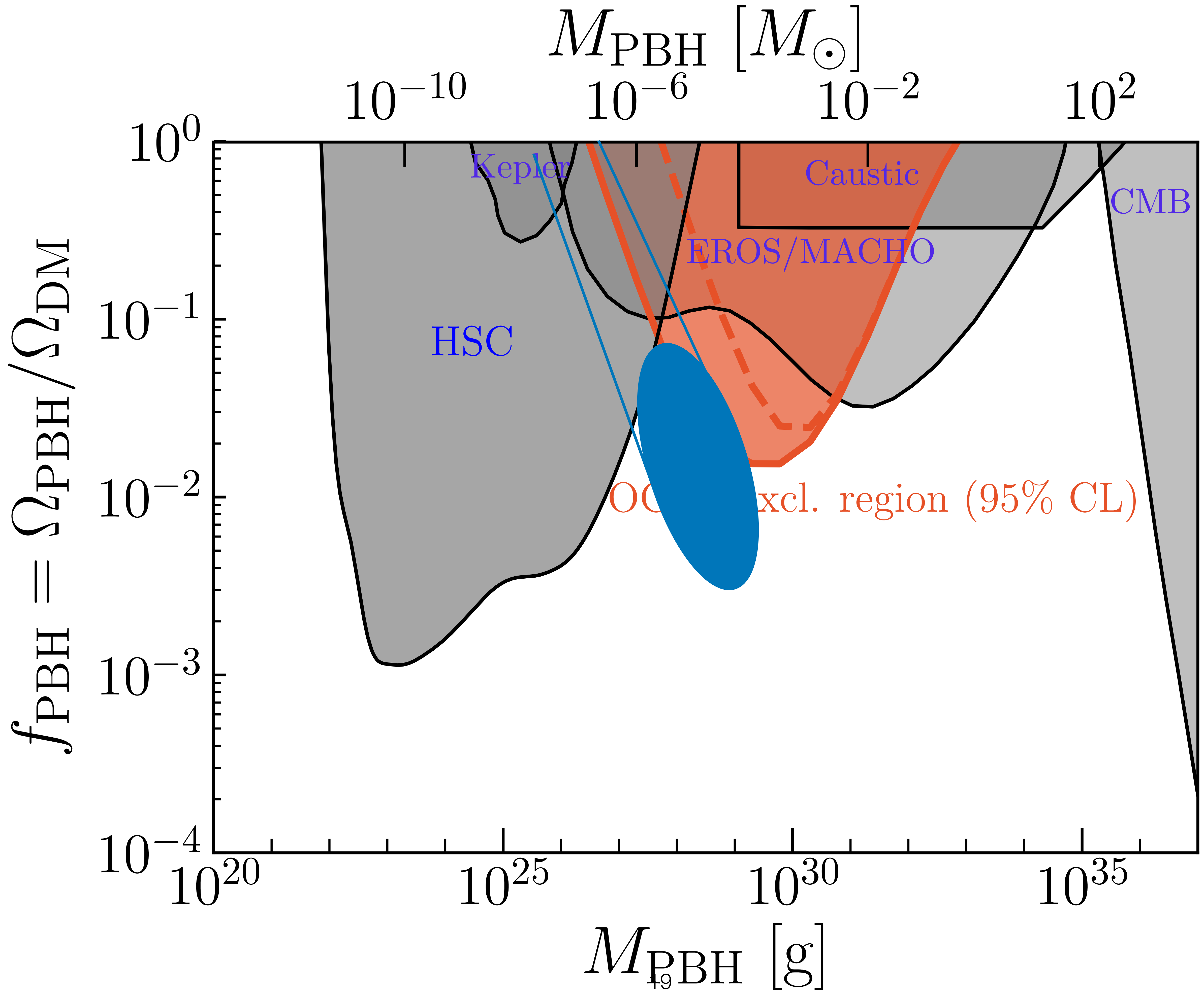
Constraints on Earth-mass primordial black holes from OGLE 5-year microlensing events

Hiroko Niikura,[1, 2, *] Masahiro Takada,[2, †] Shuichiro Yokoyama,[3, 2] Takahiro Sumi,[4] and Shogo Masaki[5]

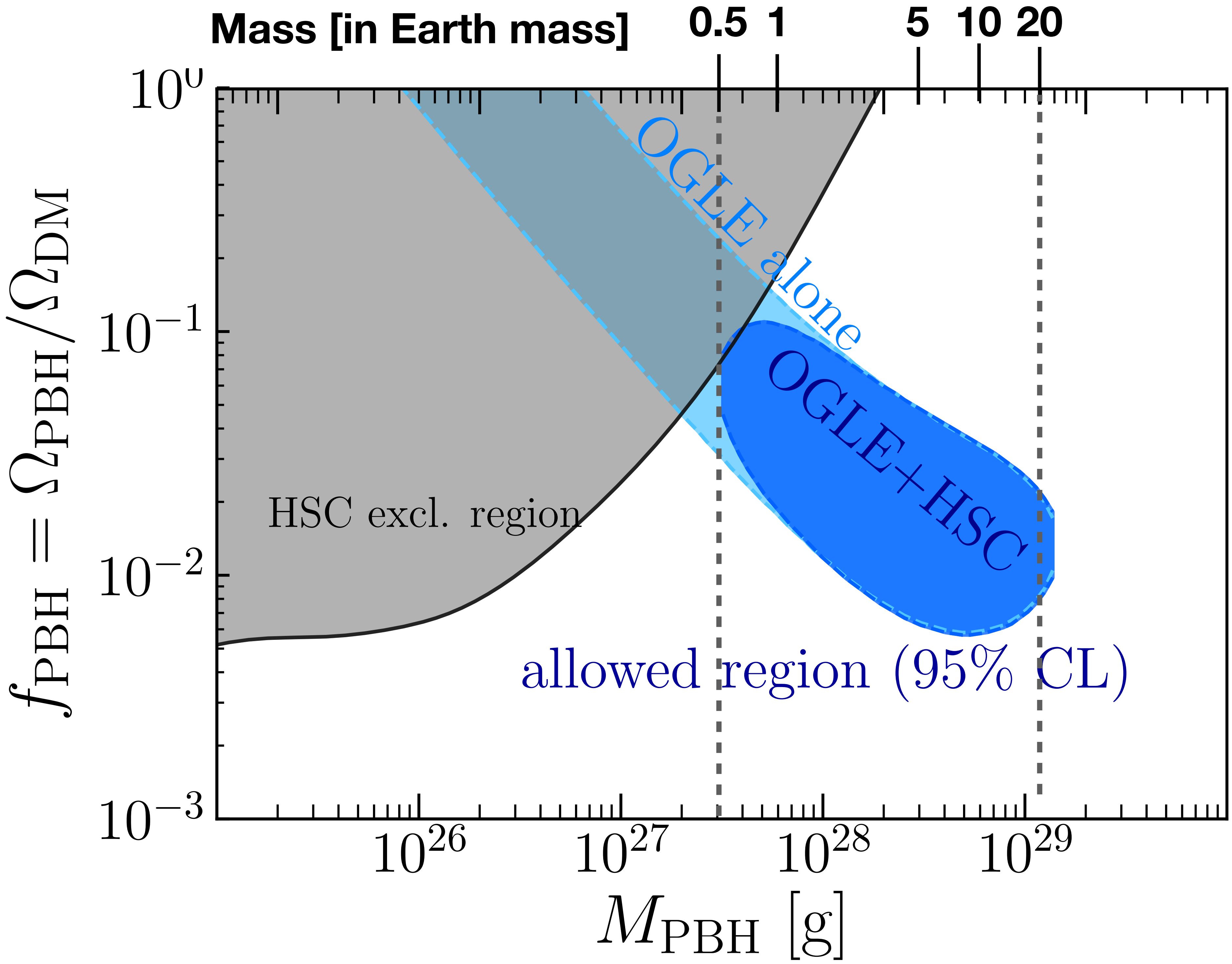
[5] *Dep*

Japan



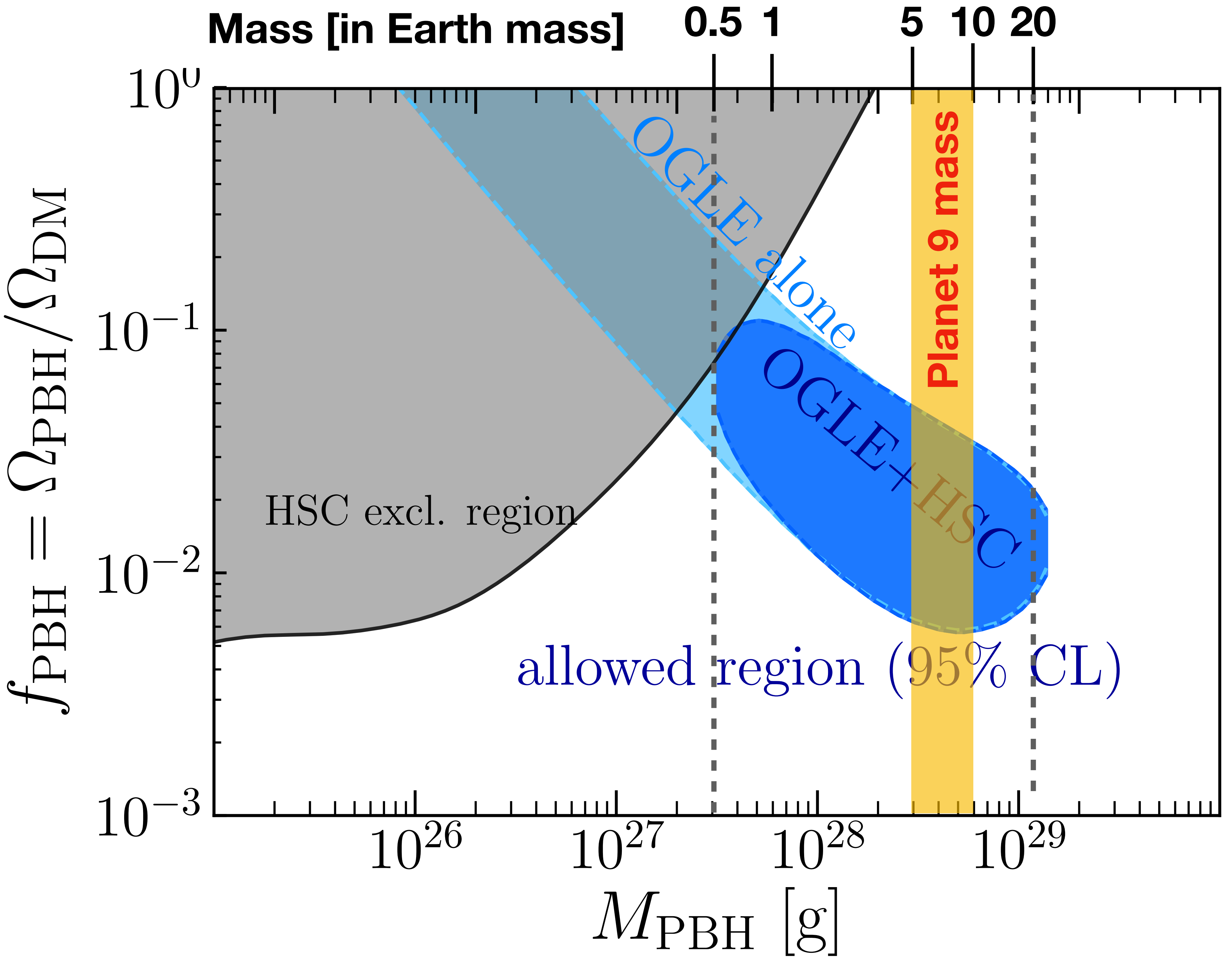

$M_{\rm PBH}\ [M_\odot]$
10^{-10}
10^{-6}
10^{-2}
10^{2}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$f_{\rm PBH} = \Omega_{\rm PBH}/\Omega_{\rm DM}$
Kepler
Caustic
CMB
EROS/MACHO
HSC
OC
xcl. region (95% CL)
10^{20}
10^{25}
10^{30}
10^{35}
$M_{\rm PBH}\ [{\rm g}]$

Are they black holes?



1901.07120

Are they black holes?



1901.07120

Possible Scenarios

The Reasonable Conclusion

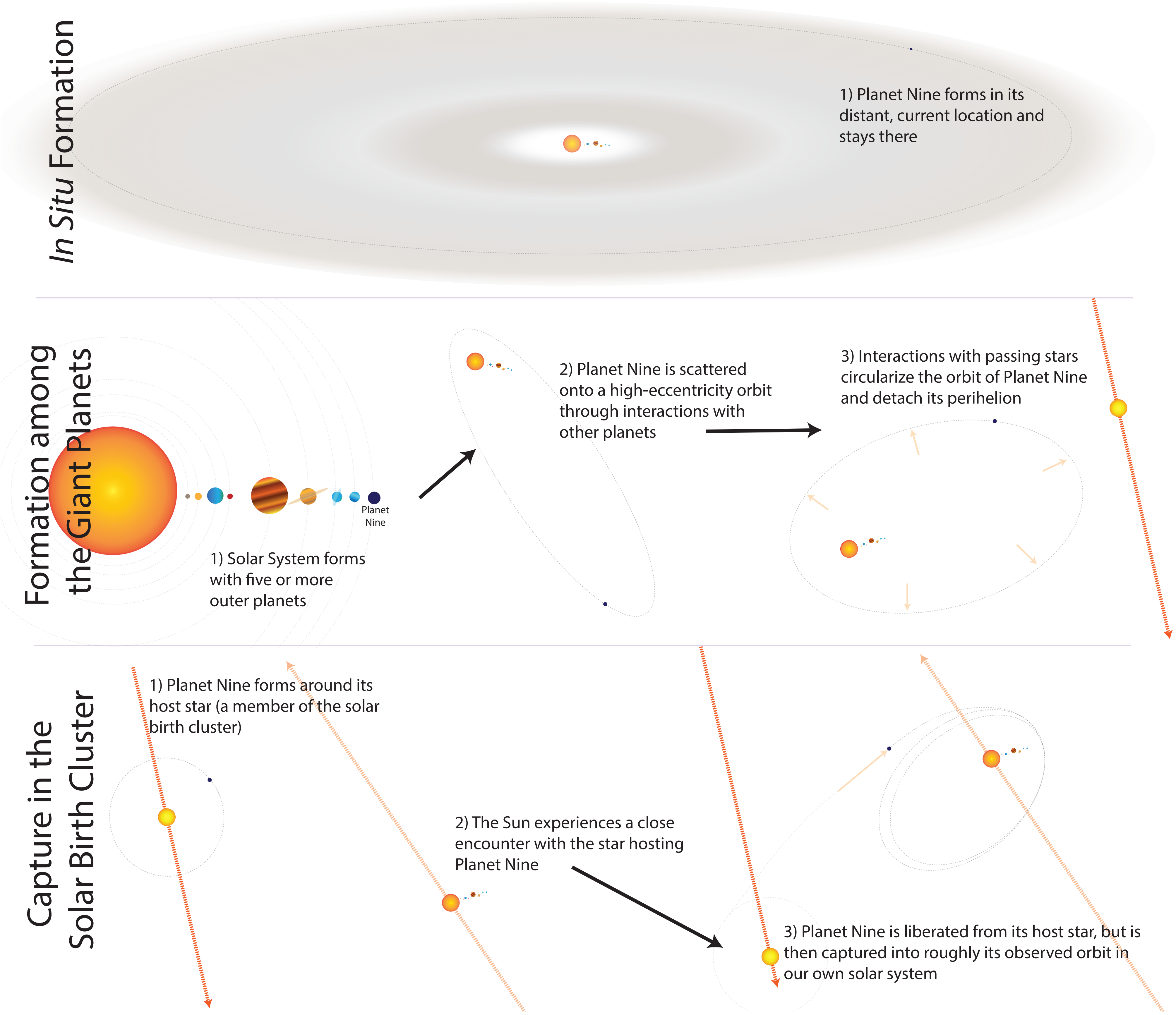
- OGLE sees free floating planets.
- Maybe, our solar system captured one of those
- This is where Planet 9 comes from.
- We should keep looking for a planet

The Fun Conclusion

- OGLE sees primordial black holes.
- Maybe, our solar system captured one of those
- Planet 9, is not a planet. It is a tiny black hole.
- We should start looking for a black hole.

WHAT IS THE DIFFERENCE?

How would Planet 9 get here?



In Situ Formation

1) Planet Nine forms in its distant, current location and stays there

Formation among the Giant Planets

1) Solar System forms with five or more outer planets

2) Planet Nine is scattered onto a high-eccentricity orbit through interactions with other planets

3) Interactions with passing stars circularize the orbit of Planet Nine and detach its perihelion

Capture in the Solar Birth Cluster

1) Planet Nine forms around its host star (a member of the solar birth cluster)

2) The Sun experiences a close encounter with the star hosting Planet Nine

3) Planet Nine is liberated from its host star, but is then captured into roughly its observed orbit in our own solar system

Courtesy of [1902.10103]

They all suffer from issues

- In-situ does not really work… planet formation disks are never extended as far as 400AU. It seems impossible to form a planet this far…

- Upscatter is really tricky too: once a planet is this far, it is very vulnerable to any other scatters…plus you really need two scatters…

- Capture is also unlikely. It is more likely in the solar birth cluster, but also vulnerable in the cluster…

- But then, as unlikely they are, all of the above mechanisms are more likely than the orbital anomalies they explain.

Capture Probability

$$\Gamma = \int n_0 F(v) v \frac{d\sigma}{dv} \mathrm{d}v \xrightarrow{\text{[1705.10332]}} \frac{\Gamma_{\rm BH}}{\Gamma_{\rm FFP}} \simeq \frac{n_{\rm BH}}{n_{\rm FFP}} \frac{F_{\rm PBH}(v_{\odot,\rm PBH})}{F_{\rm FFP}(v_{\odot,\rm FFP})}$$

We make an assumption: the primordial Black Holes have the distributions identical to dark matter

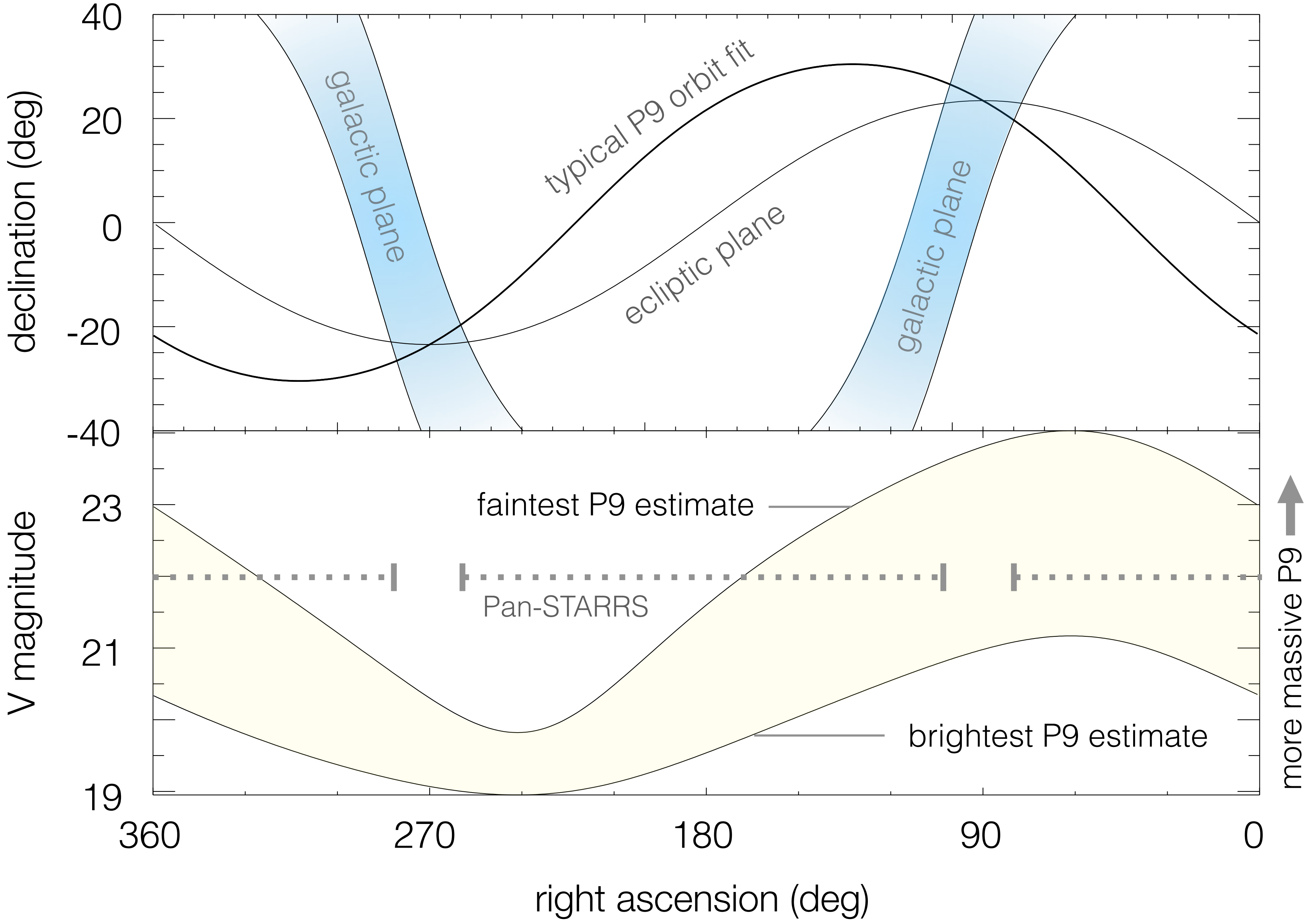
$$n_{\rm BH} = f_{\rm PBH} \left(\frac{\rho_{\rm DM}}{M_{\rm BH}}\right) \sim 35 \mathrm{pc}^{-3} \left(\frac{f_{\rm BH}}{0.05}\right) \left(\frac{5 M_\oplus}{M_{\rm BH}}\right)$$

We make another assumption: there is about one free floating planet per star and they have the same velocity dispersion.

$$\frac{\Gamma_{\rm BH}}{\Gamma_{\rm FFP}} \sim 1 \times \left(\frac{0.2 \mathrm{pc}^{-3}}{n_{\rm FFP}}\right) \left(\frac{40 \mathrm{km/s}}{\sigma_{\rm FFP}}\right)^3 \left(\frac{f_{\rm BH}}{0.05}\right) \left(\frac{5 M_\oplus}{M_{\rm BH}}\right)$$

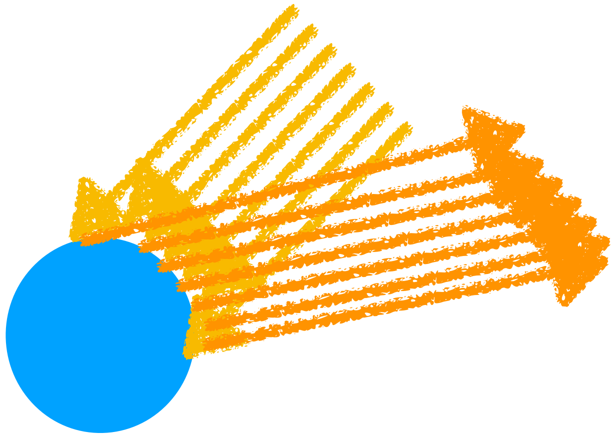
How could we find it?

If it is a planet



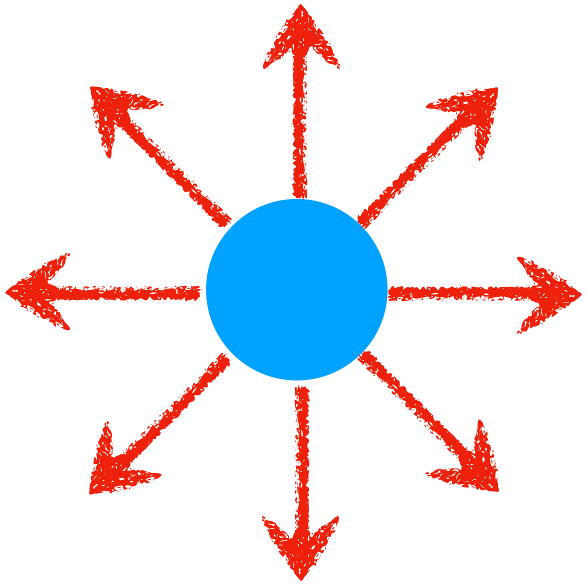
Looking for a Planet

<u>Using Reflected Light</u>
(Visible light)



Pan-STARRS

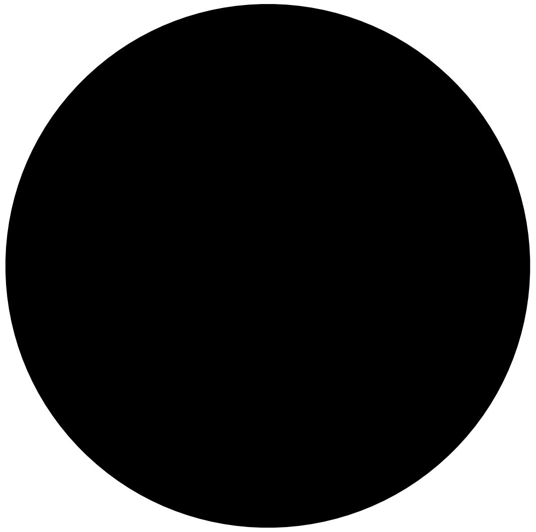
<u>Using Radiated Light</u>
(Infrared)



So Far: No Discovery!

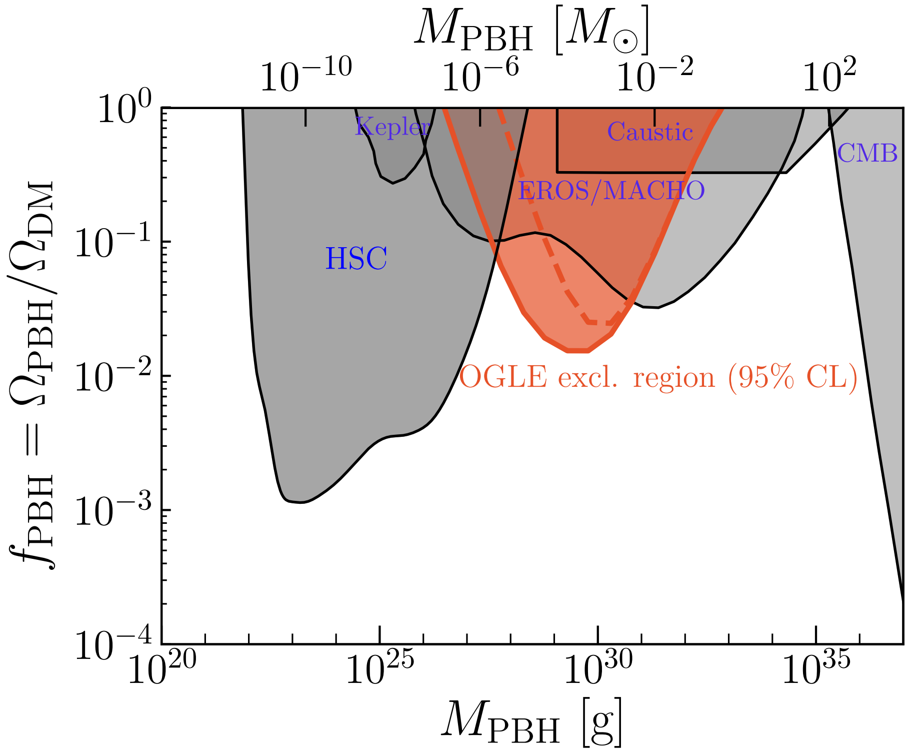
What if it is a PBH?

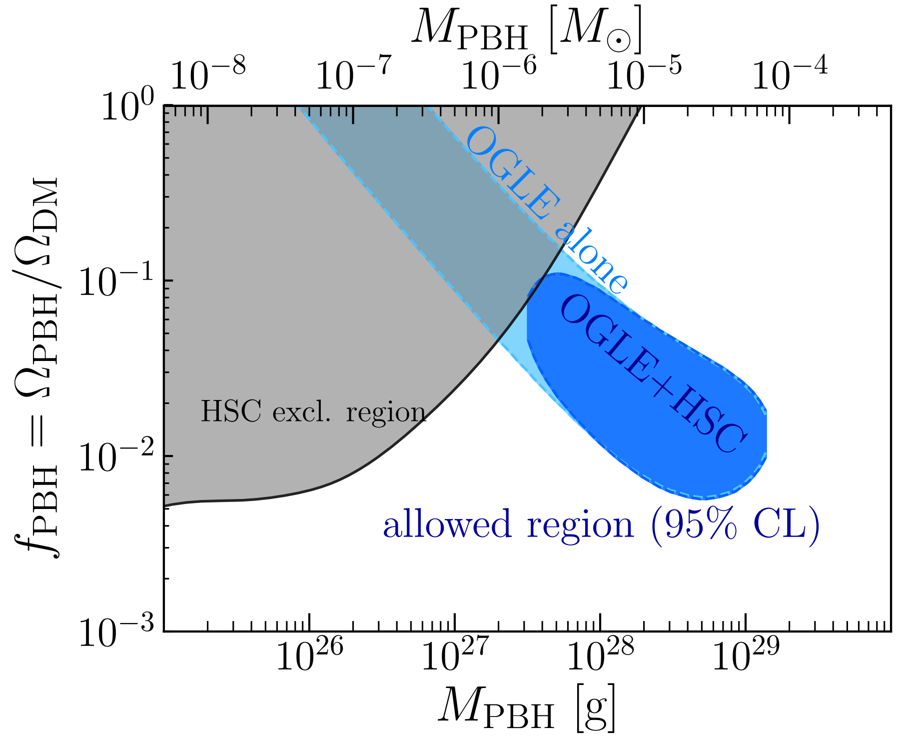
- It is very small: 10-20cm across.
- It is very dark: its Hawking temperature is T ~ 0.004K.
- Probably does not have an accretion disk: too small, not enough material around.
- No hope for lensing: Einstein angle is 4 mas.



Fun facts about PBHs

- BH below solar mass are too light to form from collapsed stars.
- If they exist, they were formed during early Universe [Hawking 1970s]
- This could be due to statistical fluctuations, phase transitions, early matter domination …
- For most masses, they can't be 100% of dark matter. (especially for us)
- Since they can't be all of dark matter, we are going to assume that there is particle dark matter around.





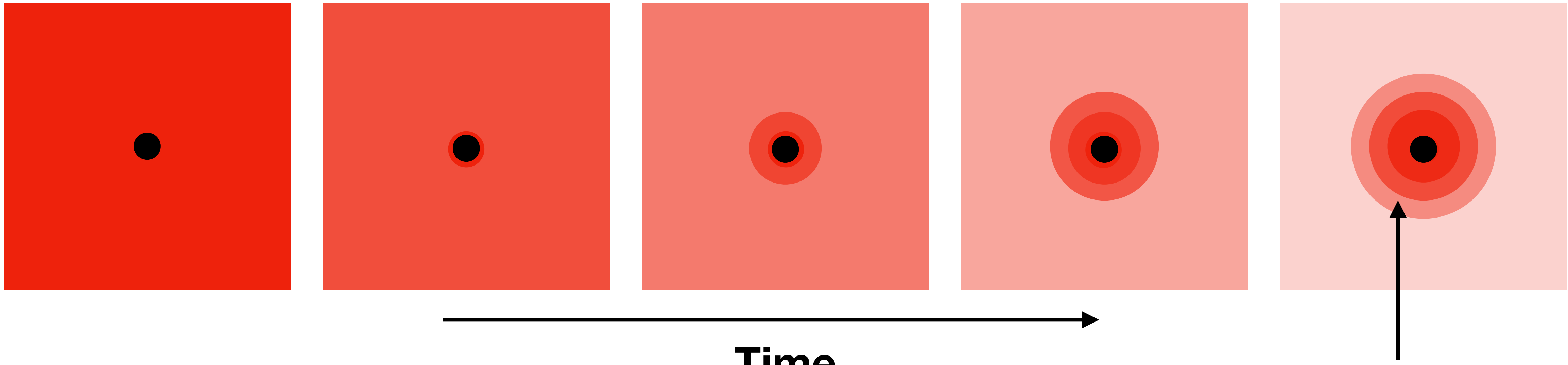
Primordial Black Holes form Dark Matter halos around them during early Universe

Smooth Universe

Time

$$\rho \sim \rho_0 \left(\frac{r}{r_0}\right)^{-9/4}$$

Smooth Universe with a Primordial Black Hole

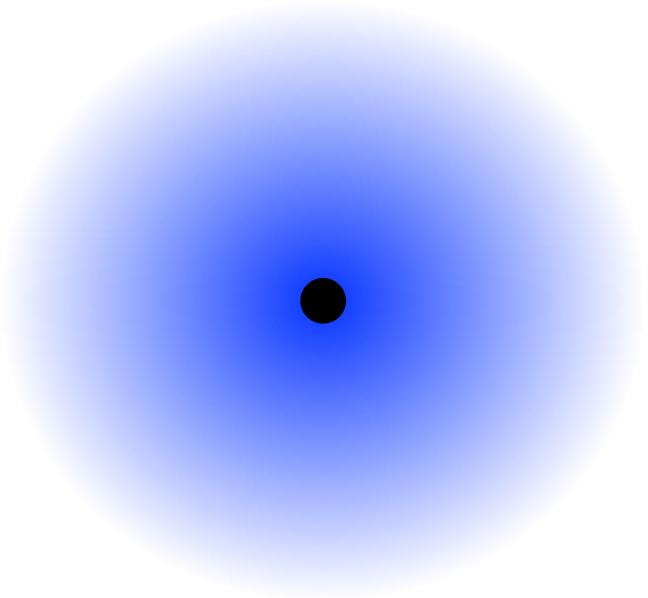


Time

Eventually Mostly Dark Matter

Dark Halo properties

- Typically this dark matter halo is large and diffuse — even more massive than its host black hole. This would lead to a discrepancy between its full mass and the mass that causes lensing.
- However, our black hole has had encounters that stripped parts of the halo. The key parameter is the Roche limit — the effective region where tidal forces are not stripping material.
- In order to get captured, the black hole would have speed very similar to Sun. Based on that we can estimate it has ‘encountered’ about 10^5 stars, which would give us a typical closest approach of order 600 AU. This strips that halo down to ~40AU, with about couple Earth masses of total halo mass.
- Once it settles on an orbit around the Sun, it gets stripped down to about 8AU, which further reduces the halo mass below one Earth mass.



$$\rho \sim \rho_0 \left(\frac{r}{r_0}\right)^{-9/4}$$

DM halo around PBH

$$r_R \approx r_{\min} \left(\frac{M_{\rm obj}}{M_{\rm enc}}\right)^{1/3}$$

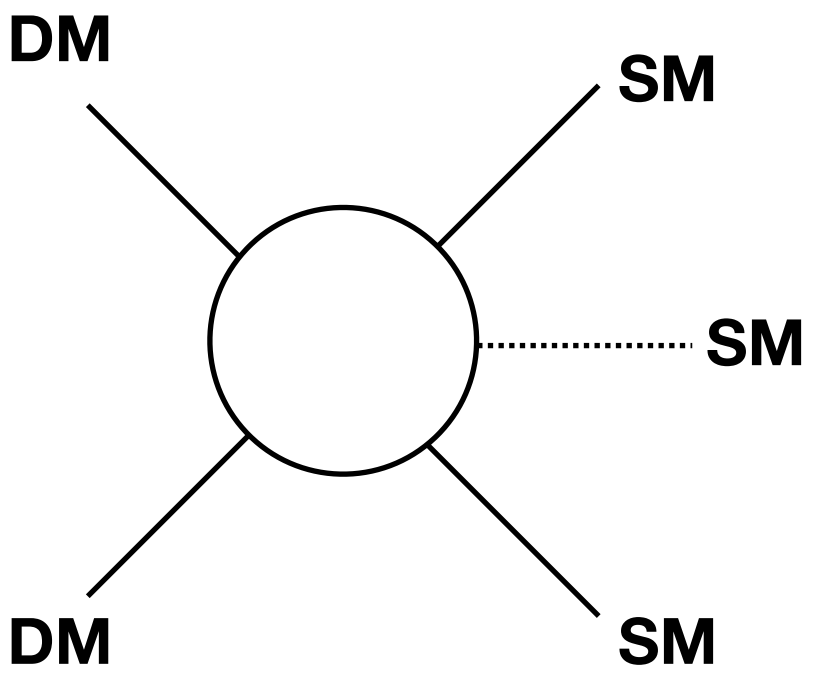
Roche limit

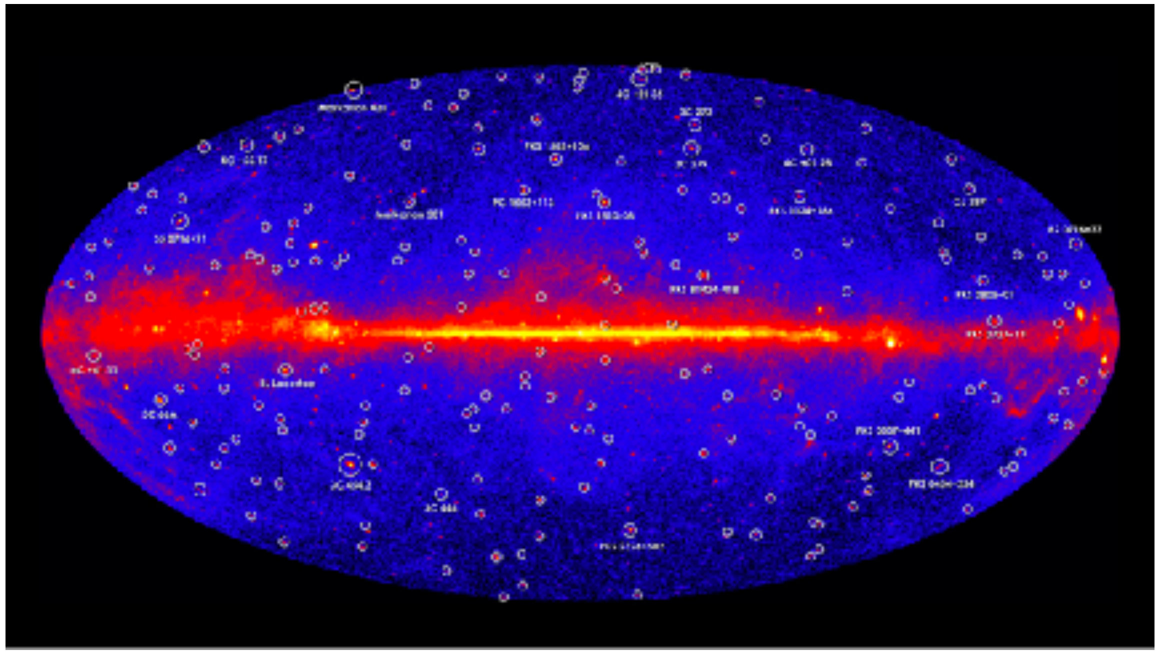
Dark Matter Annihilations

- Since we would like to explain why there is about as much DM as there are baryons, it is possible (in fact preferred) that DM annihilates into SM particles.

- Since this is one of the more generic features of many DM models, many experiments are looking for such signatures.

- The energy scale of the products depends on the DM particle mass.
- This annihilation rate is proportional to the local dark matter density. Good targets are:
    A. The Galactic Center
    B. Dwarf galaxy satellites (Large Magellanic Clouds, Draco, Fornax…)
    C. The Center of Andromeda





Two signals

$$\Gamma = 4\pi \int r^2 \mathrm{d}r \left(\frac{\rho(r)}{m} \right)^2 \langle \sigma v \rangle$$

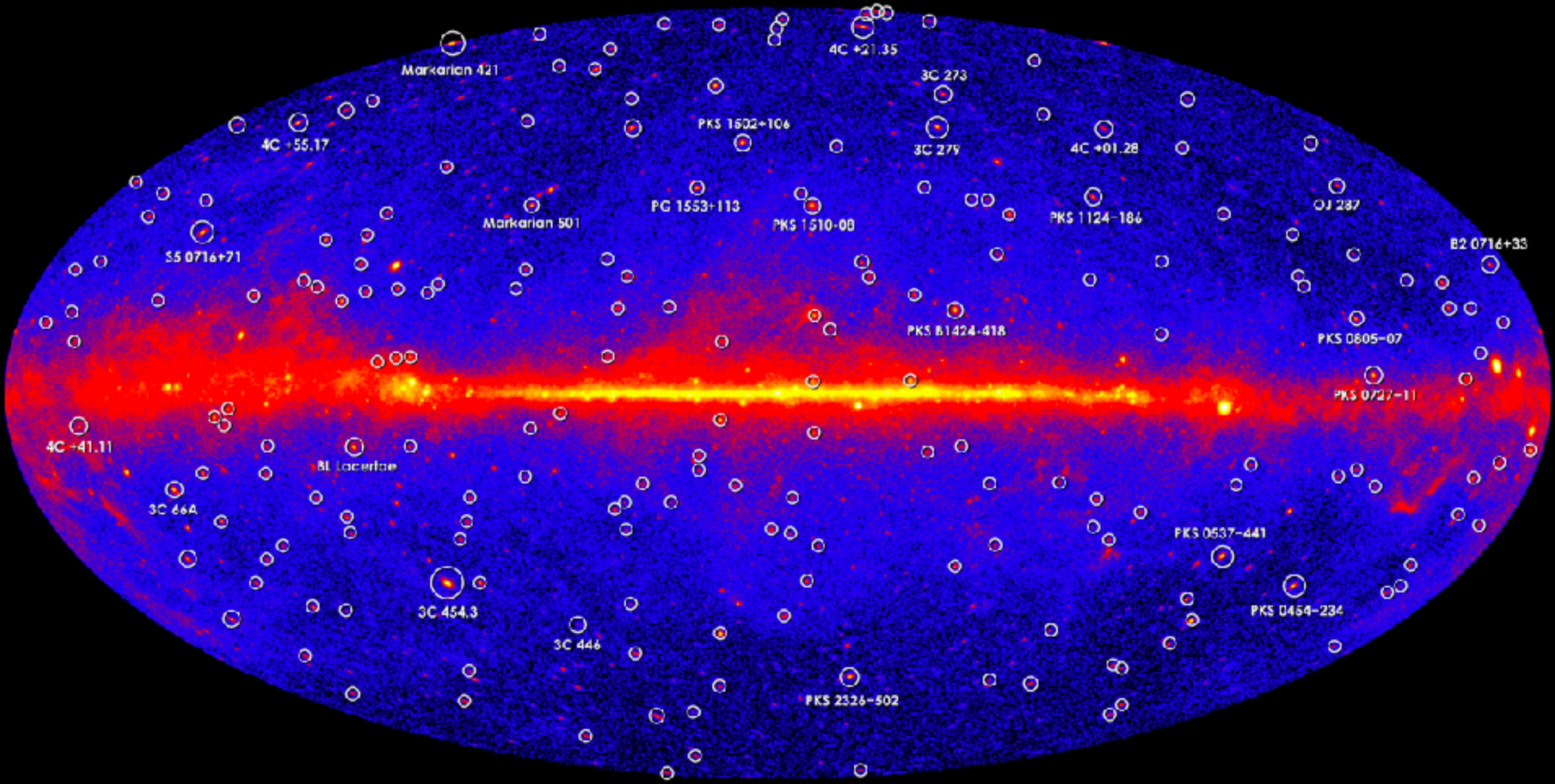
- The entire PBH population in the Galaxy and outside it is shining in x-rays/gamma rays. This is called the diffuse emission — there are severe constraints on this. We need to avoid these.

- We would like to see the 'Planet 9' PBH, which is much closer (hence brighter), but alone. And it is moving.

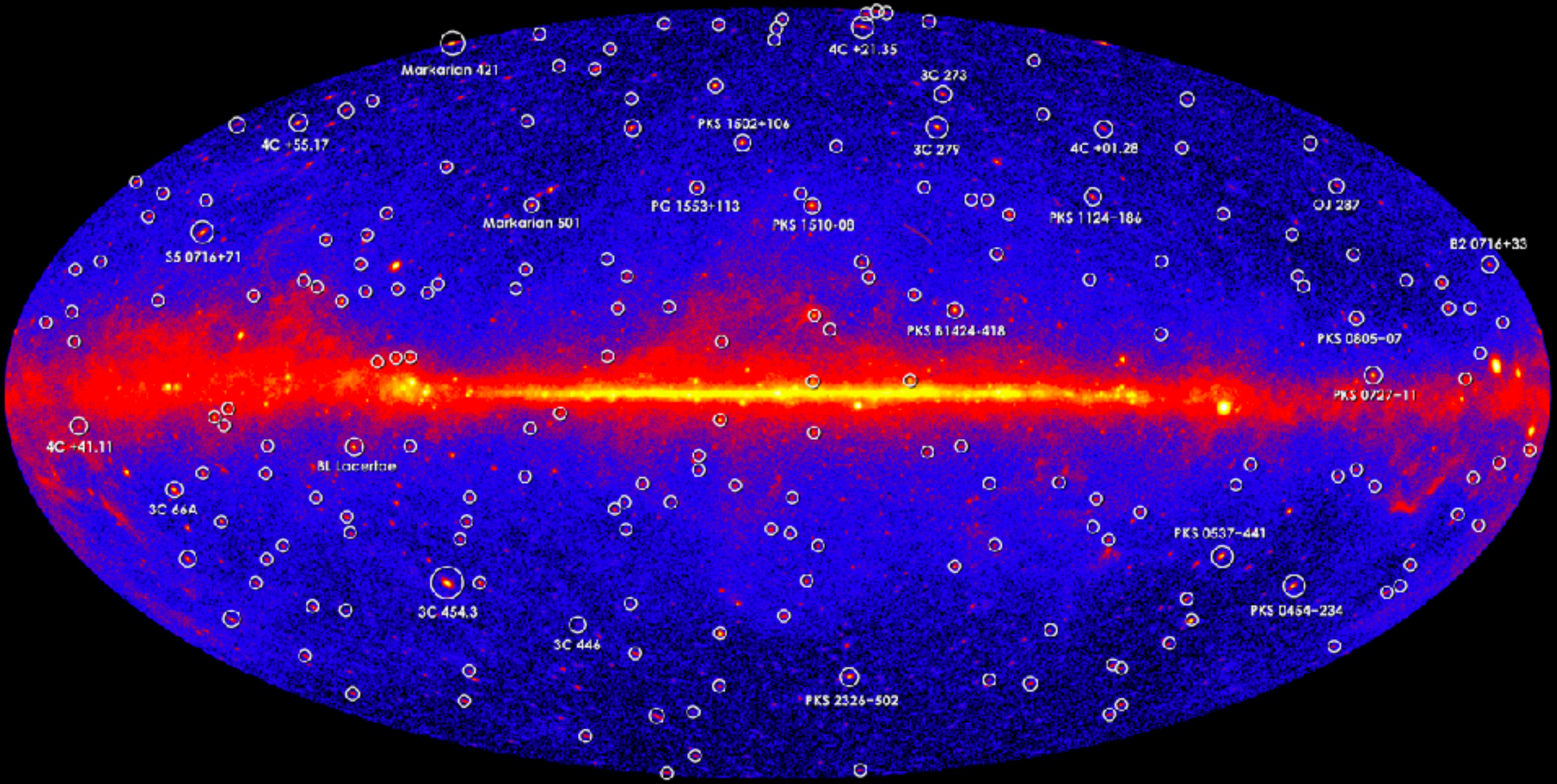
- If the DM is produced through thermal freeze-out (one 'accepted' scenario) then we are dead. The diffuse emission alone would be orders of magnitude above what FERMI sees. [well known result, e.g. 0712.3499]

- It is produced through different mechanisms such as Freeze-in, p-wave dark matter, or it is partially asymmetric (does not annihilate as readily), then we are safe, and there is a potentially observable signal.

The sky as seen by FERMI-LAT



The sky as seen by FERMI-LAT - with ‘Planet 9’



How do you look for moving signal?

- This is a classic problem: it has already been encountered when we search for asteroids, or TNOs and KBOs.

- Since FERMI detects each photon (gamma ray) individually, we have a unique opportunity:

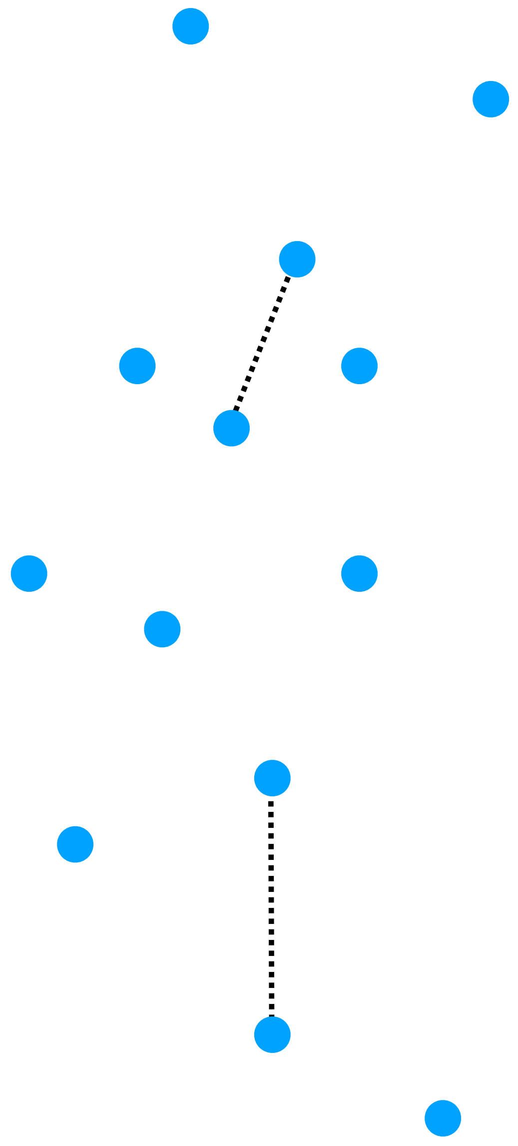
    1. Select a window

    2. For all pairs of photons, form the quantity $\alpha = \Delta\phi/\Delta t$ (the angular distance between the photons divided by their time difference.

    3. Points that come from a track cluster in a particular bin that corresponds to that proper motion on the sky.

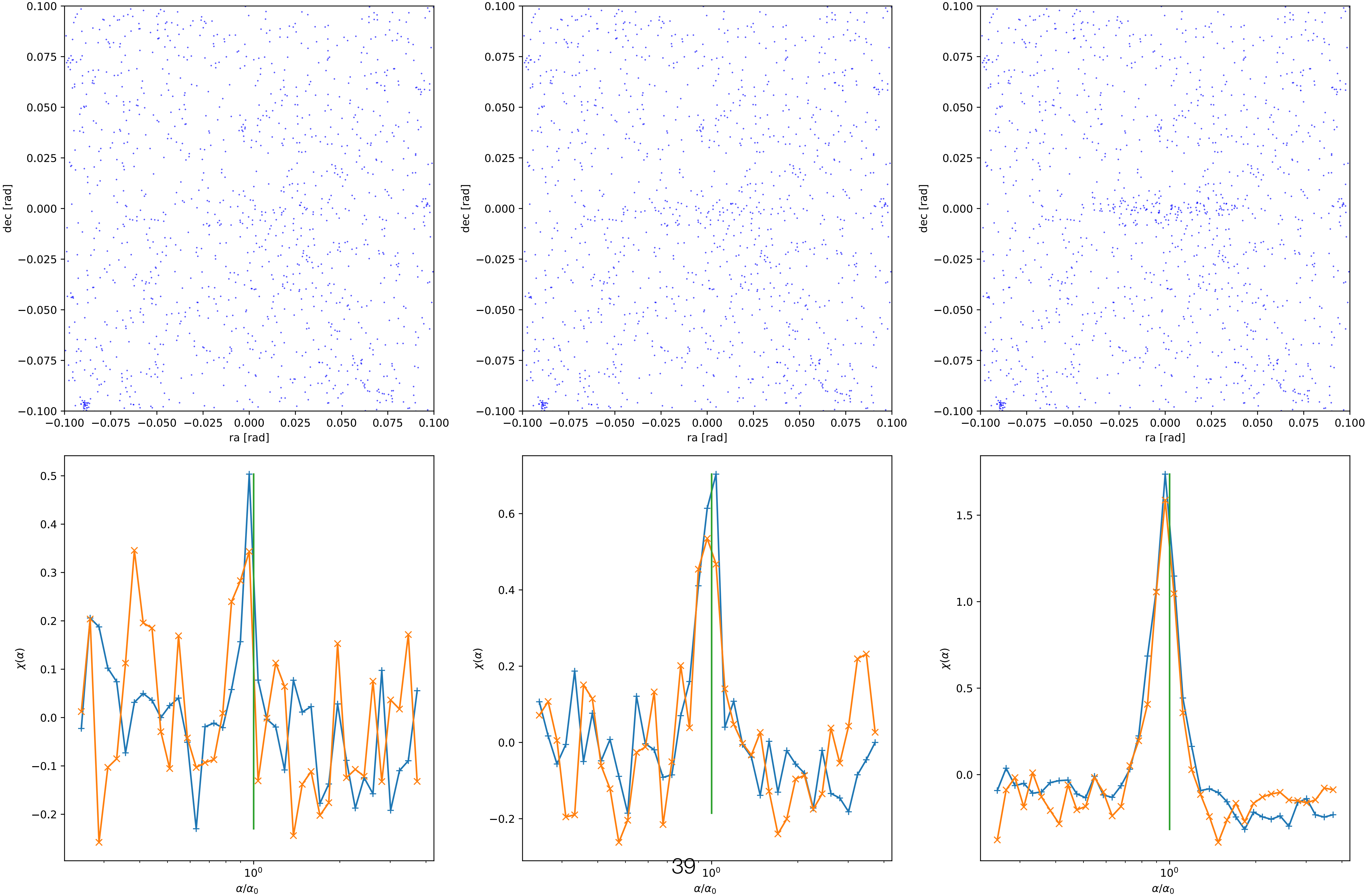
    4. Show the histogram of number of photon pairs with a given α.

    5. One can be more sophisticated and normalise this histogram by another histogram that generate from a random sample to remove effects of boundaries, time dependent sensitivity etc.

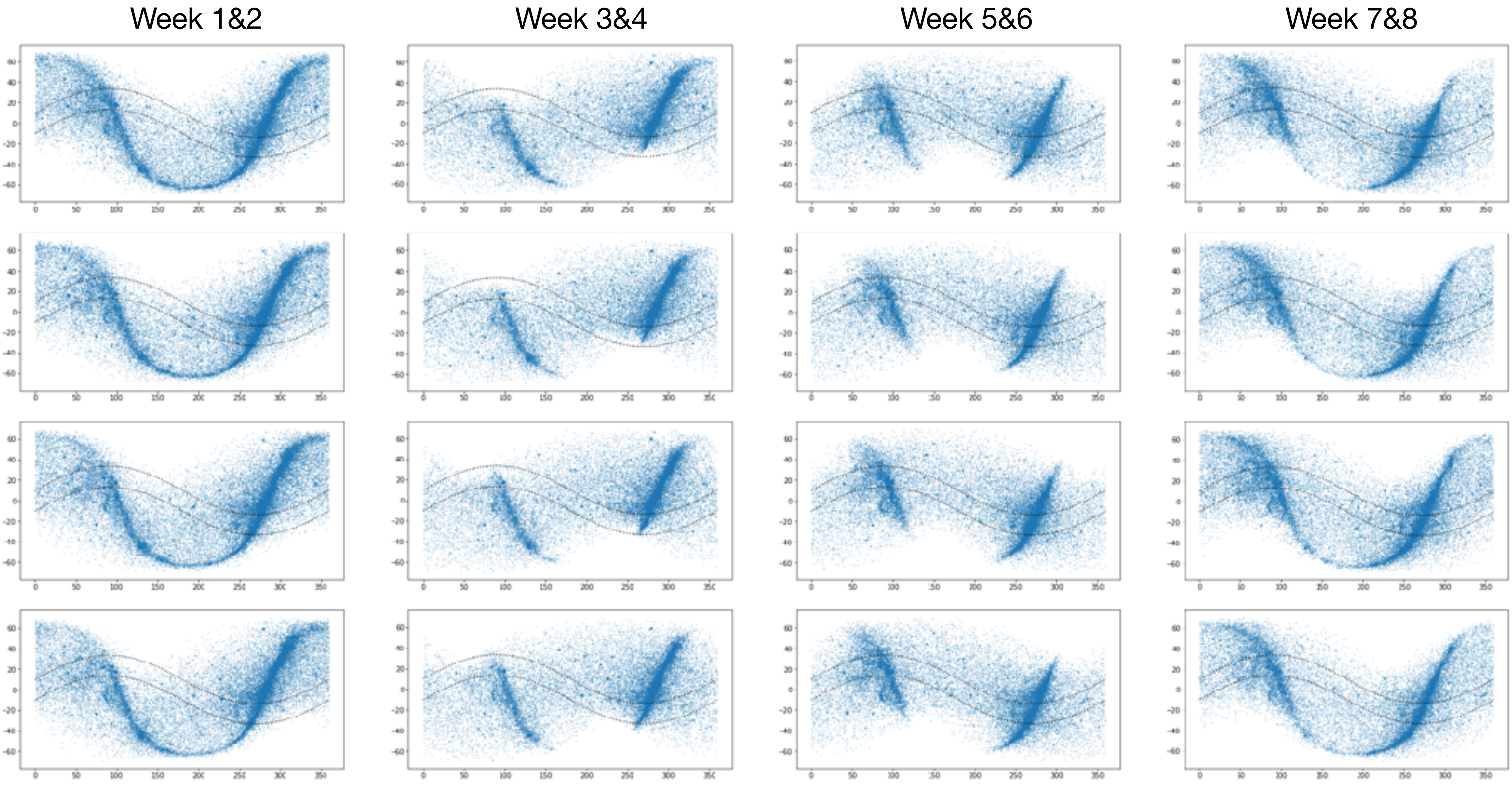


[1012.1873]

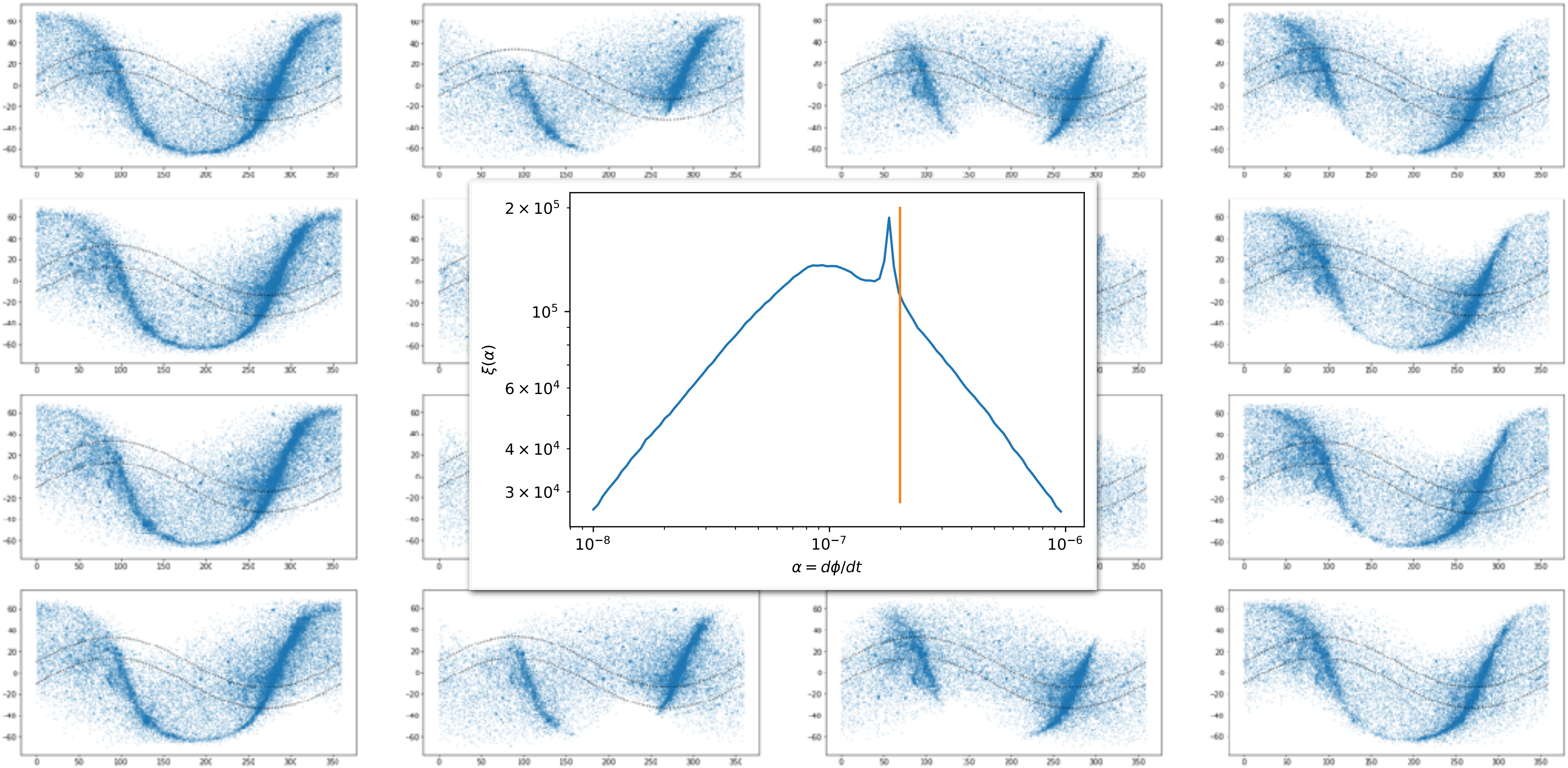
Very Preliminary — Test signal



There are spurious signals…



This is not easy… there are spurious signals



Week 1&2

Week 3&4

Week 5&6

Week 7&8

Interesting Directions

- E. Witten: Searching for a Black Hole in the Outer Solar System [2004.14192]
- Loeb & Siraj: Searching for Black Holes in the Outer Solar System with LSST [2005.12280]
- Arbey & Auffingen: Detecting Planet 9 via Hawking radiation [2006.02944]

Conclusion

- Orbits of TNOs give us evidence that there exists an extra body in the outer Solar System with mass 5-20 Earth masses far away: 100s of AUs

- The OGLE data set hints that throughout our Galaxy there is an unusual population of objects with masses between 0.5 and 20 Earth masses.

- This could be a pure coincidence, statistical fluke, etc.

- Both of these could be due to a new population of free floating planets, one of which got caught by the solar system. Then we should keep up our search for ‘Planet 9’ in the conventional way (and we should).

- Or, more excitingly, this could be explained by a Primordial Black Hole in the outer solar system. Then we should look through the already existing data (which is free) and see if we can find it (and we are doing this).

- If this were true, we would make remarkable leap in our understanding of our Universe (on top of being extremely lucky).

Thank You