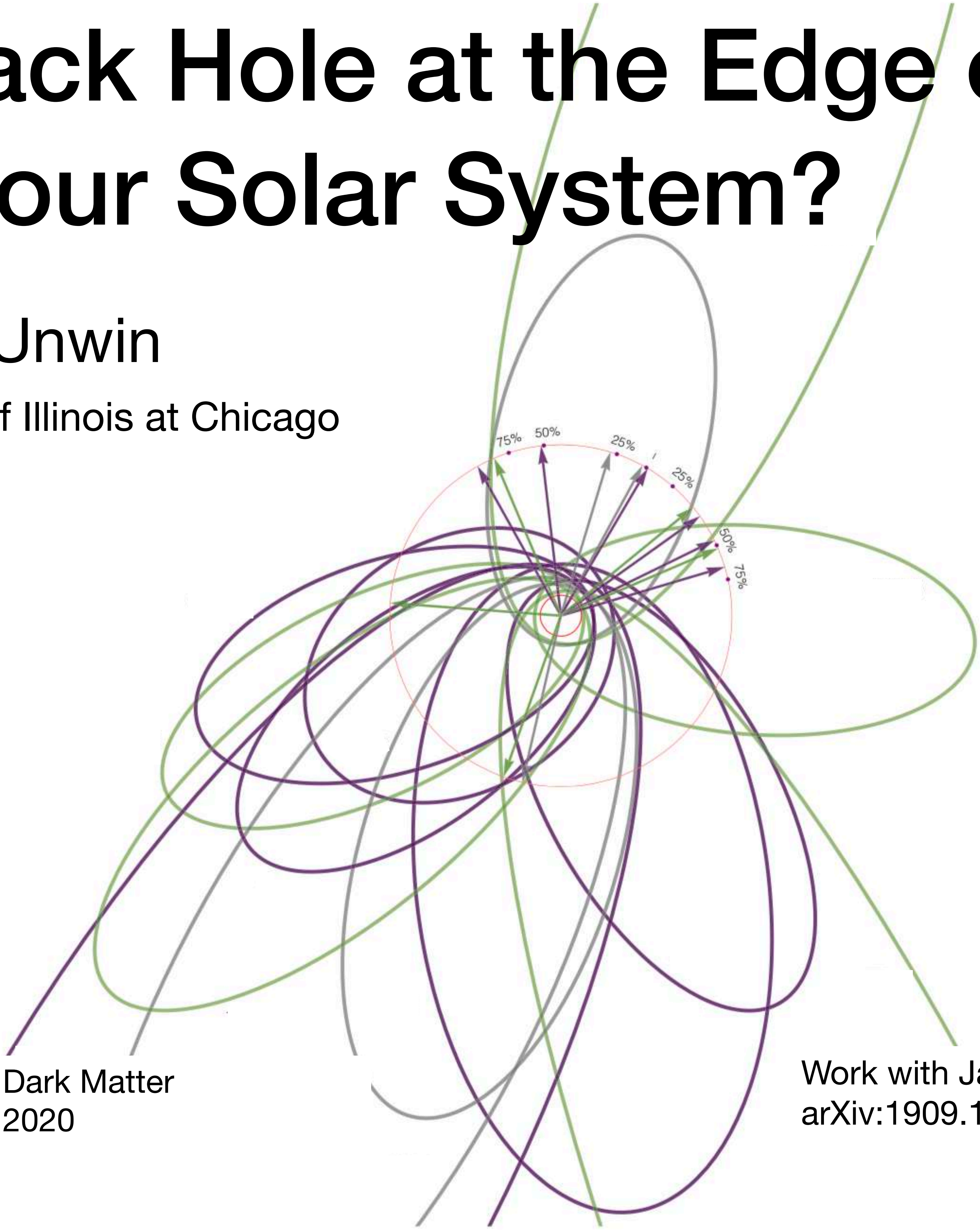
A Black Hole at the Edge of our Solar System?

James Unwin

University of Illinois at Chicago



New Trends in Dark Matter
8th December 2020

Work with Jakub Scholtz
arXiv:1909.11090

Outline

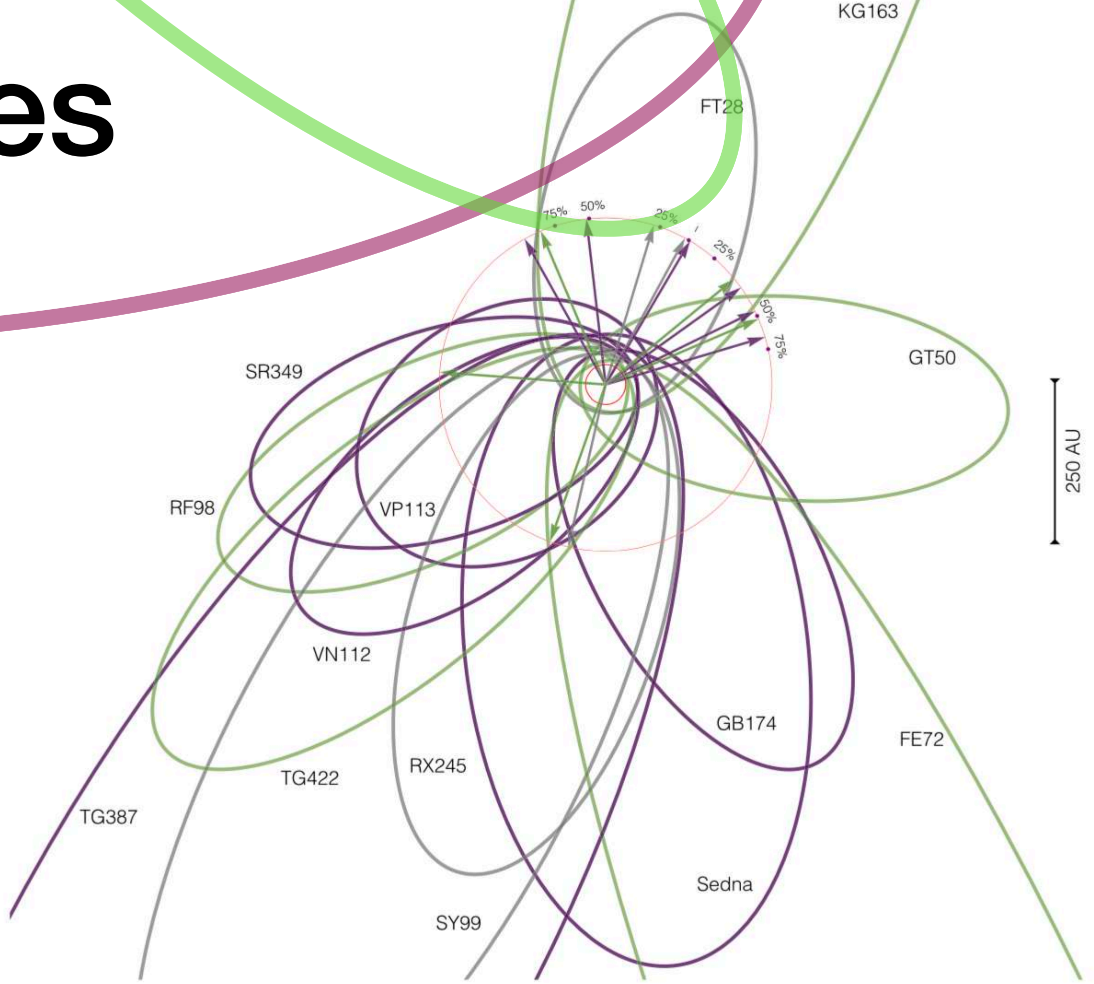
1. The Case for Planet 9

2. Something in the Outer Solar System

3. Dark Matter around PBHs

I. The Case for Planet 9

TNO Anomalies

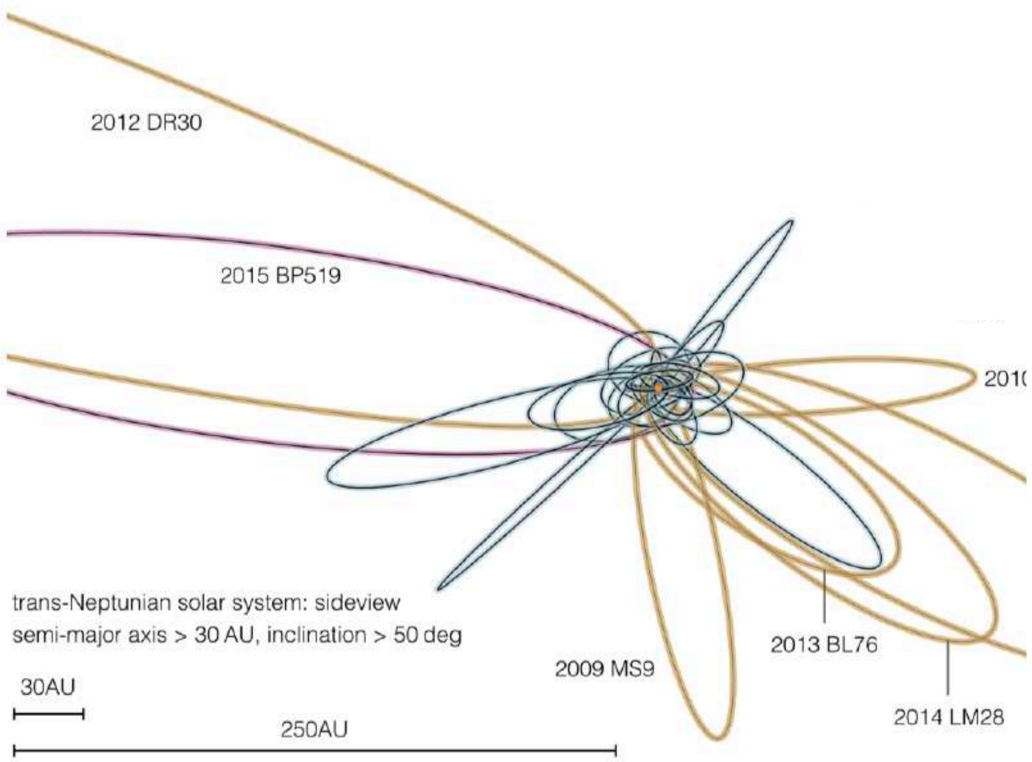


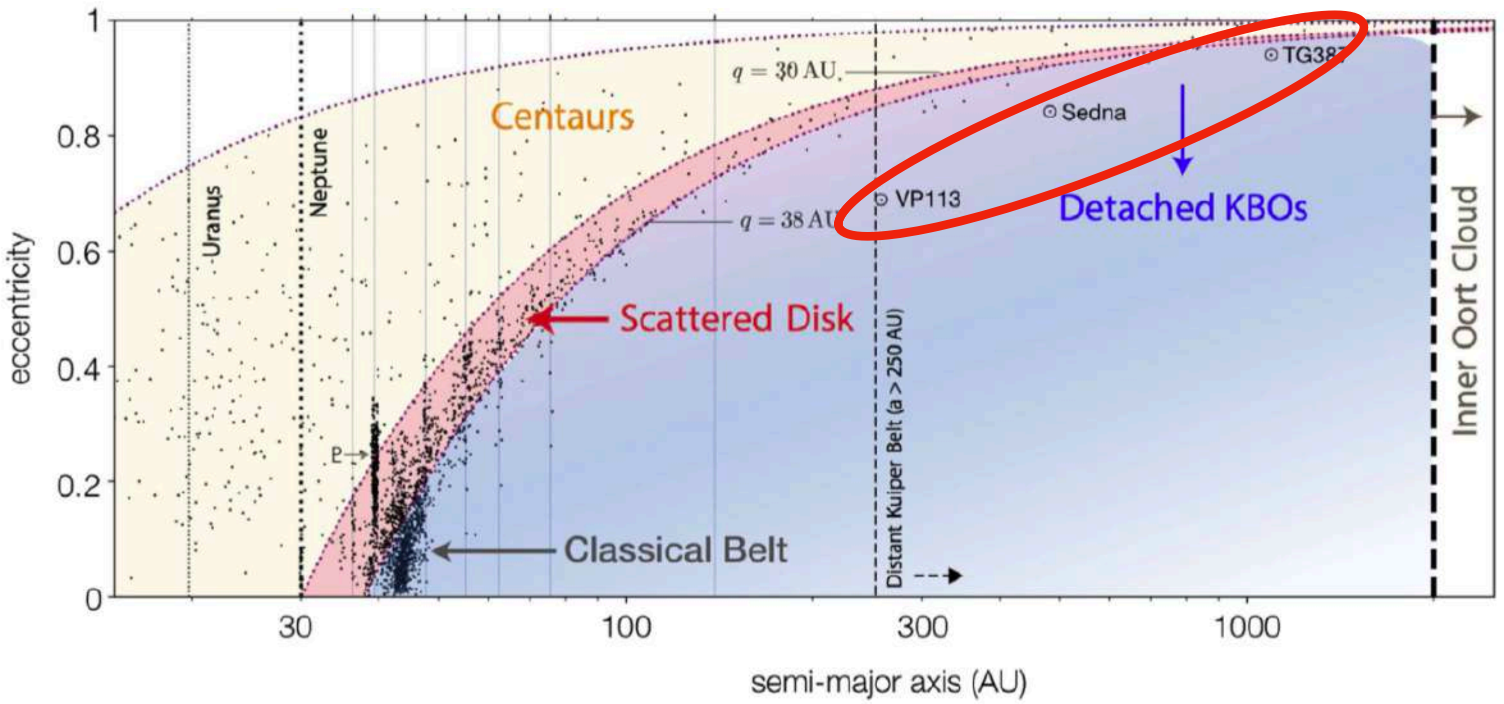
There are several Trans-Neptunian anomalies:

i) Unexpected clustering in eTNO orbits

ii) The existence of high perihelia ($q \sim 70$ AU) TNOs, such as Sedna, collectively called Sednoids

iii) TNOs moving roughly perpendicularly to the planetary plane (with inclination $i \gtrsim 50°$)





Batygin, Adams, Brown, & Becker, Phys. Rep. (2019), arXiv:1902.10103.

Planet 9

Chance of random alignment of TNOs ~ 1 in 15,000.

Batygin & Brown [1601.05438].

Observational bias is claimed to be accounted for.

Brown [1706.04175].

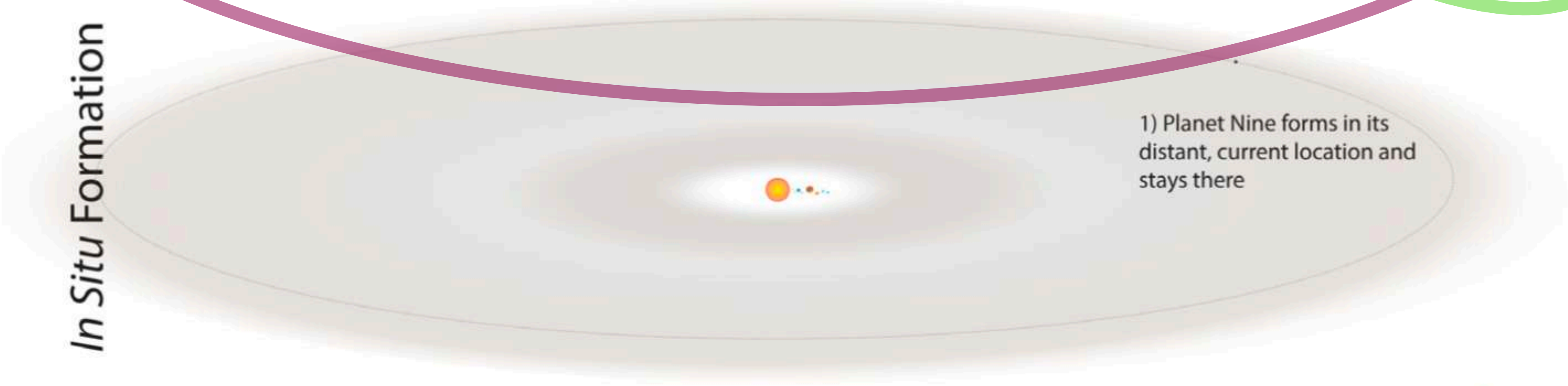
All of the TNO anomalies can be simultaneously explained by a new gravitational source in the outer Solar System: Planet 9.

From simulations best fits:

Benchmark	a (AU)	e	i (deg)
$5M_\oplus$	450	0.2	20
$10M_\oplus$	700	0.4	15

II. Something in the Outer Solar System

Origins of Planet 9



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

Batygin, et al [arXiv:1902.10103].

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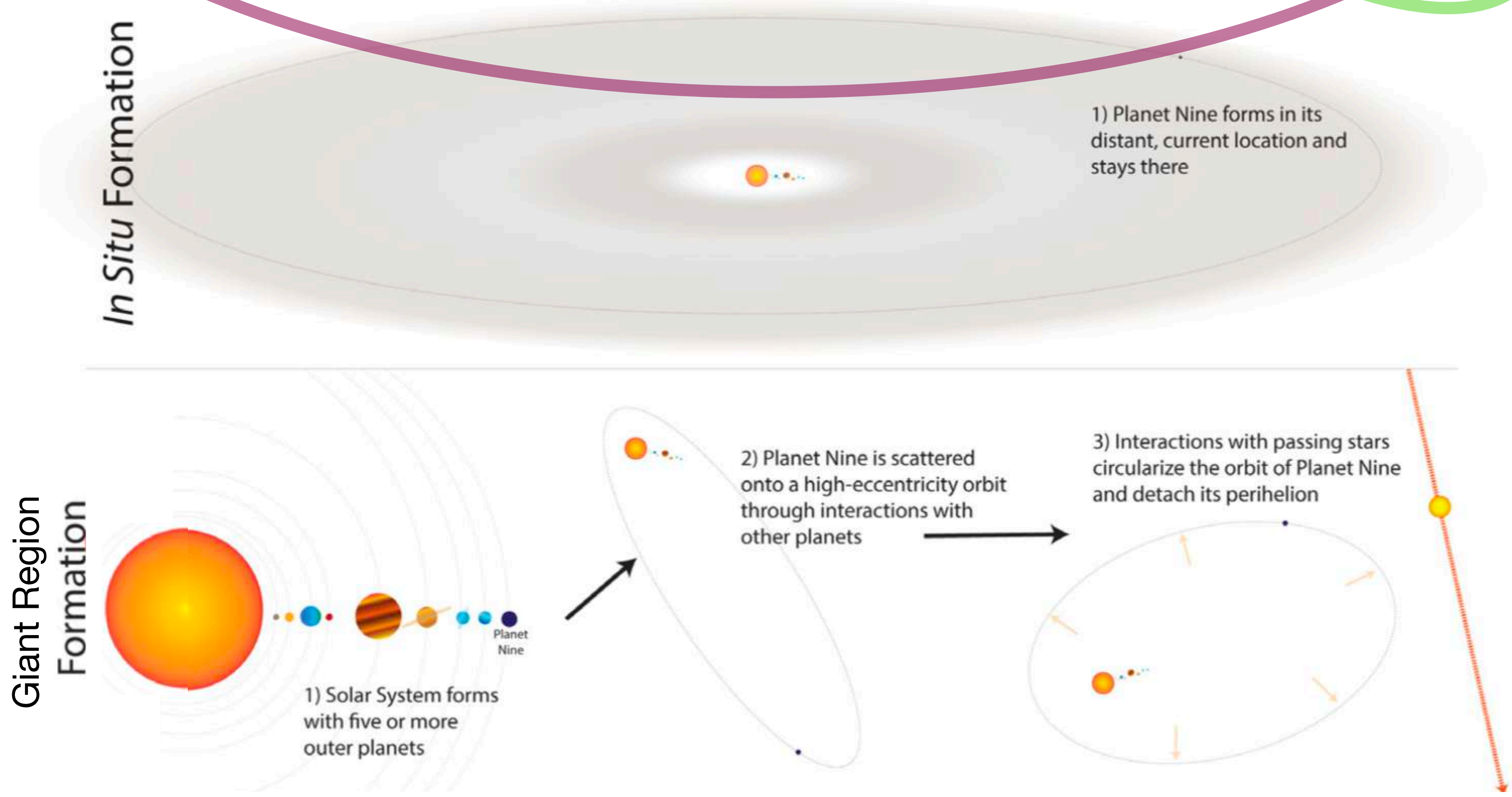

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1) Solar System forms with five or more outer planets

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

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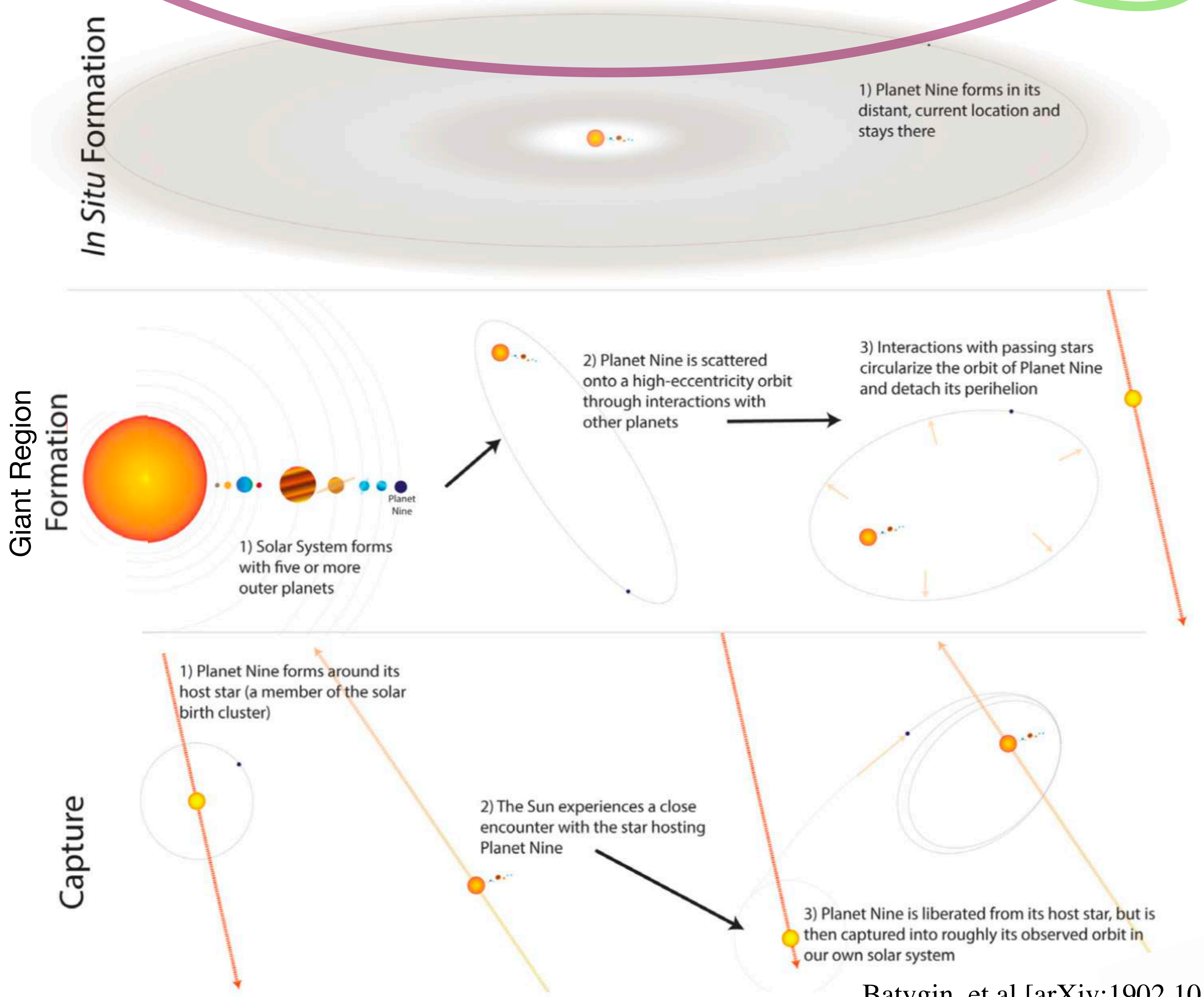

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1) Planet Nine forms around its host star (a member of the solar birth cluster)

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

Batygin, et al [arXiv:1902.10103].

“Something” Out There?

The evidence is quite compelling… But the claim is extraordinary.

Not least because it’s HIGHLY unlikely to get a large planet into that orbit.

Raises the question: **Does it need to be a planet?**

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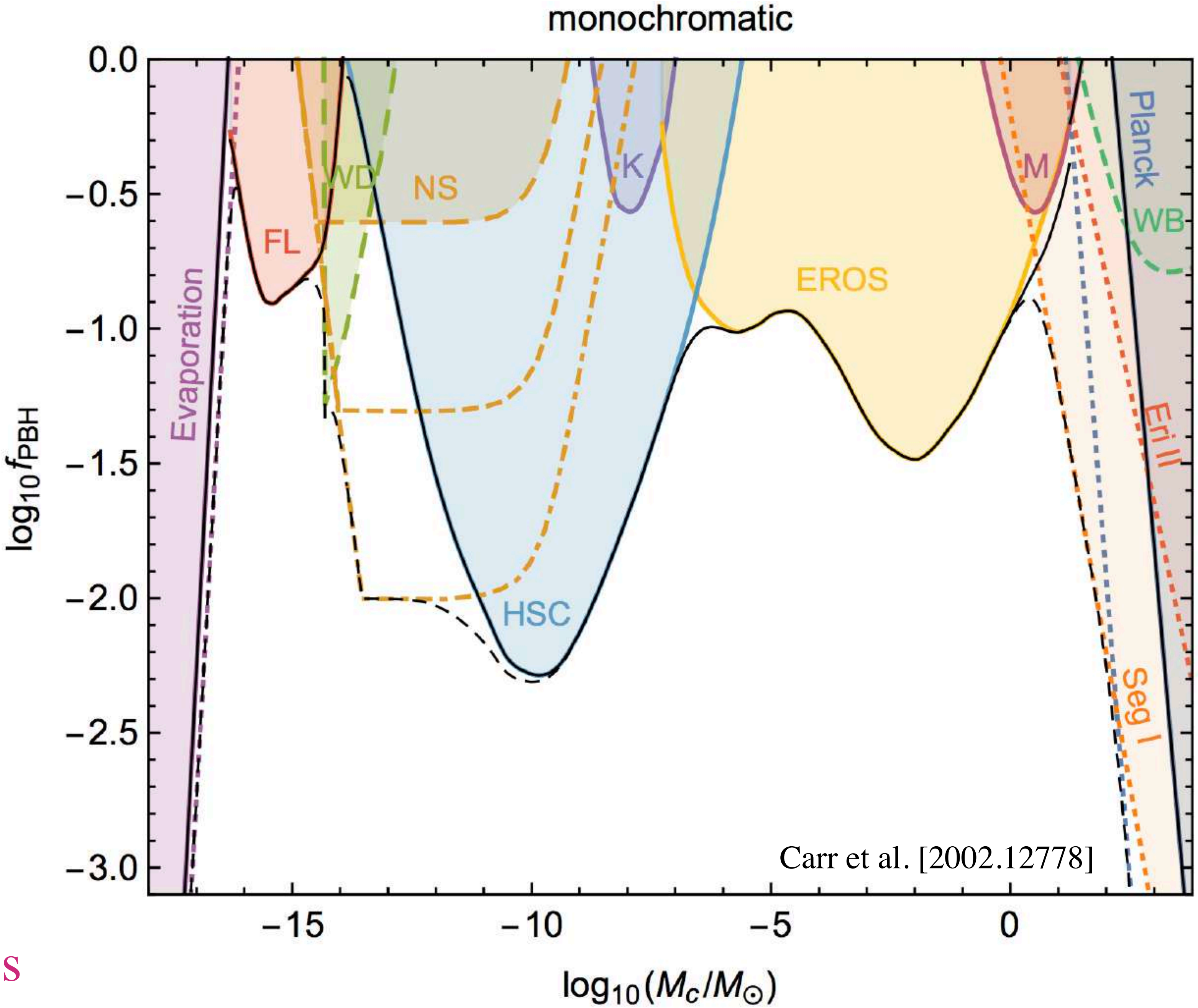
Alternatives:

- A compact dark matter microhalo.
- An axion minicluster
- Exotic Bose/Fermi/Dark Matter star
- Or perhaps, a Primordial Black Hole.

Mechanism of gravitational capture for planet or more “exotic” massive object similar, except for relevant parameter values.

Primordial Black Holes

A prime candidate for an “exotic” astrophysical mass object are Primordial Black Holes (PBH).



Carr et al. [2002.12778]

Astrophysical black holes form from stellar collapse implying

$$M_{\rm BH} \sim M_\odot \sim 10^{30}\ {\rm kg}$$

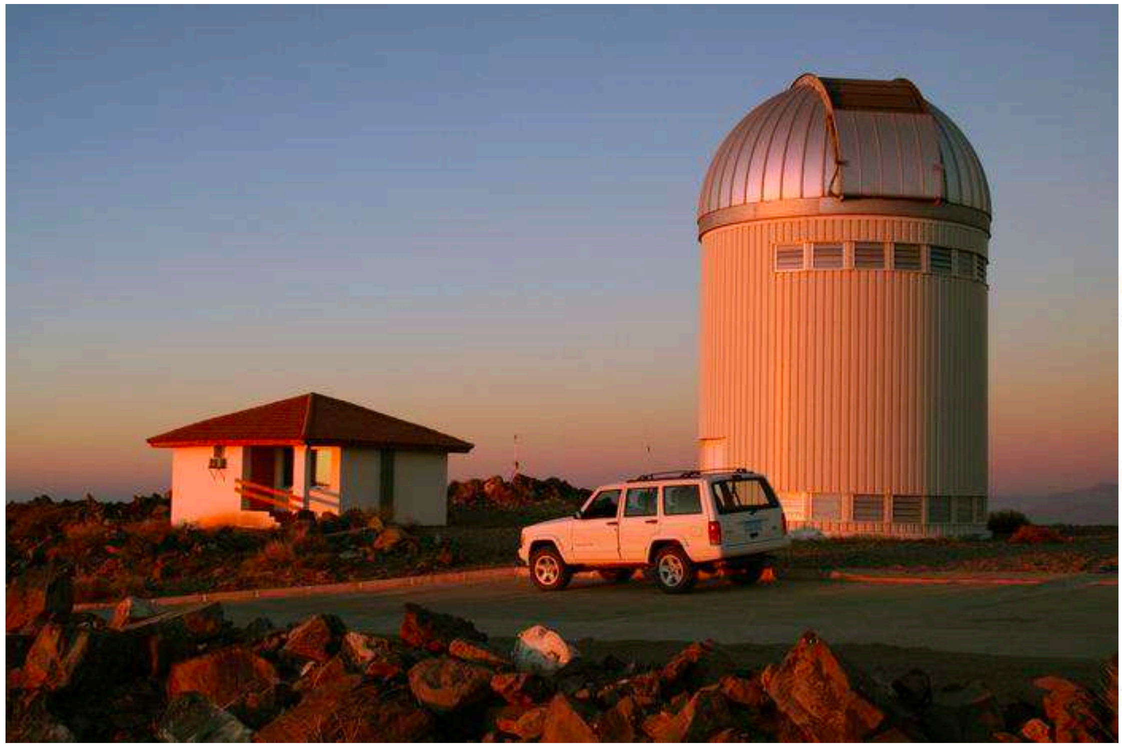
PBHs form from primordial over-densities in the Early Universe.

PBH can have a large range of masses depending on model of cosmology.

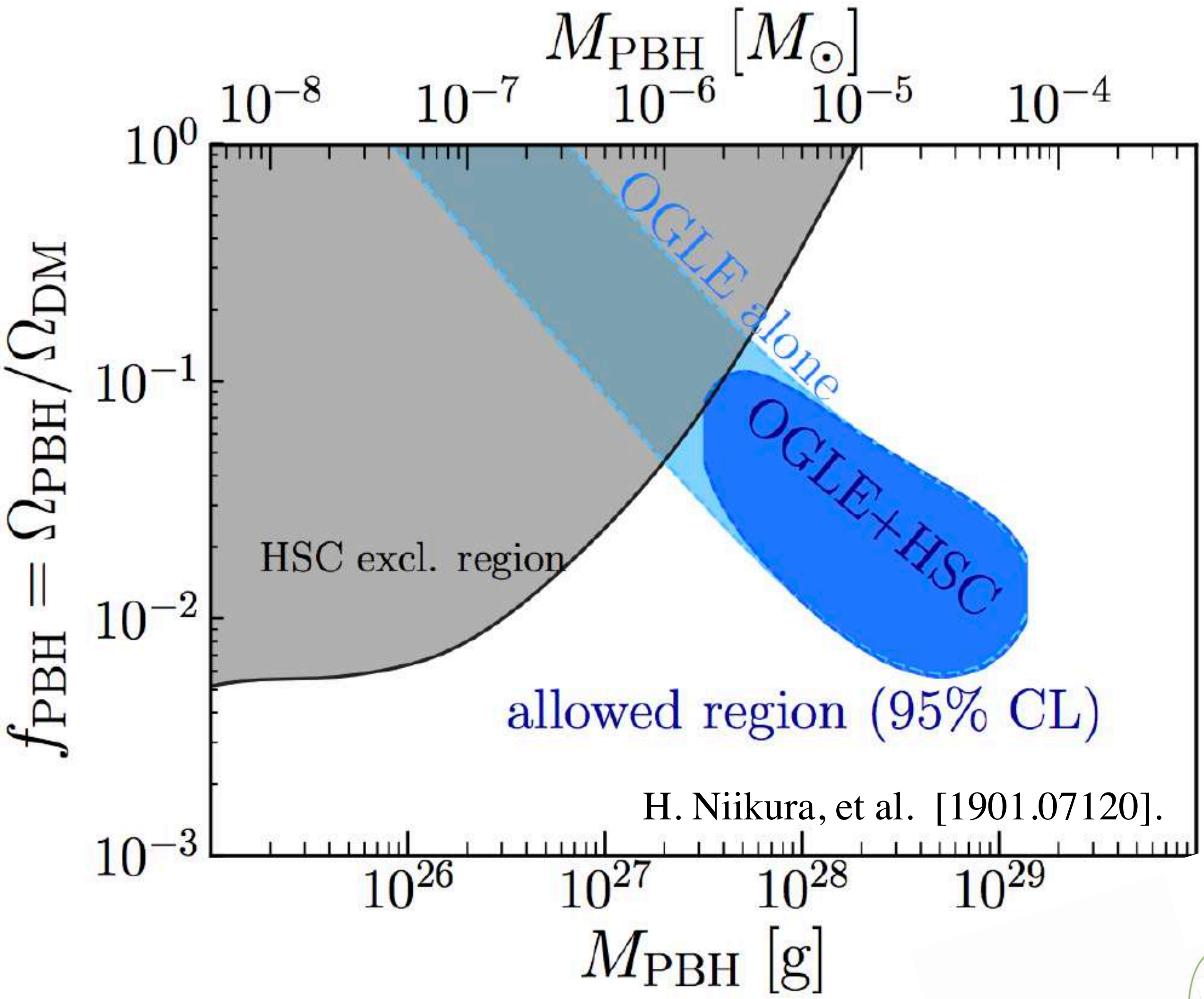
The OGLE Excess

Notably, another tentative experimental excess in unexplained microlensing events seen by the OGLE telescope consistent with the Planet 9 mass range.

Indicative of PBH population with $M \in [0.5 M_\oplus, 20 M_\oplus]$; $f_{\rm PBH} \in [0.005, 0.1]$



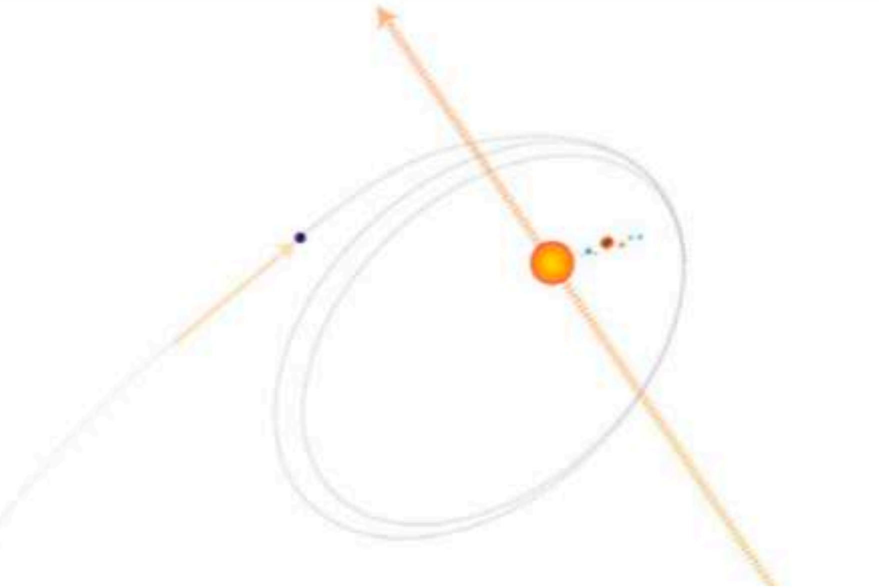
Optical Gravitational Lensing Experiment



H. Niikura, et al. [1901.07120].

Catching a PBH

Find probability of Solar System catching a PBH *vs* planet.



Gravitational capture rate of an object is given by

$$\Gamma = \int n_0 F(v + v_{\odot,r}) \frac{\mathrm{d}\sigma}{\mathrm{d}v} v \mathrm{d}v$$

where $F(.)$ and n_0 are velocity distribution and density of the objects to be captured and $v_{\odot,r}$ is the velocity of the Sun with respect to the rest frame of the objects.

Goulinski and Ribak [1705.10332].

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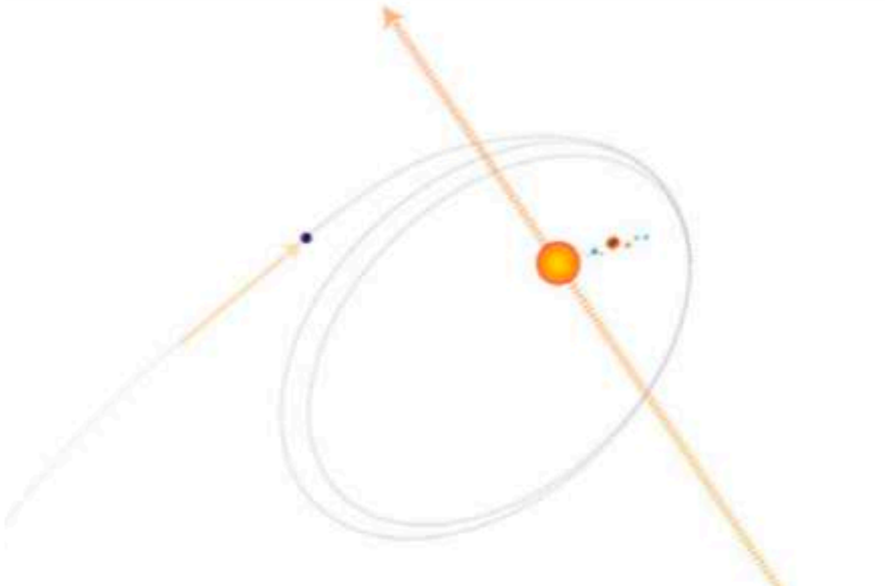

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Note, velocity dispersions are well approximated by the zero-order value $F(v_\odot)$.

Then to test PBH hypothesis vs captured free floating planet (FFP), we consider ratio of capture rates. Common factors drop out, yielding:

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

III. Dark Matter around PBHs

Dark Matter Microhalo

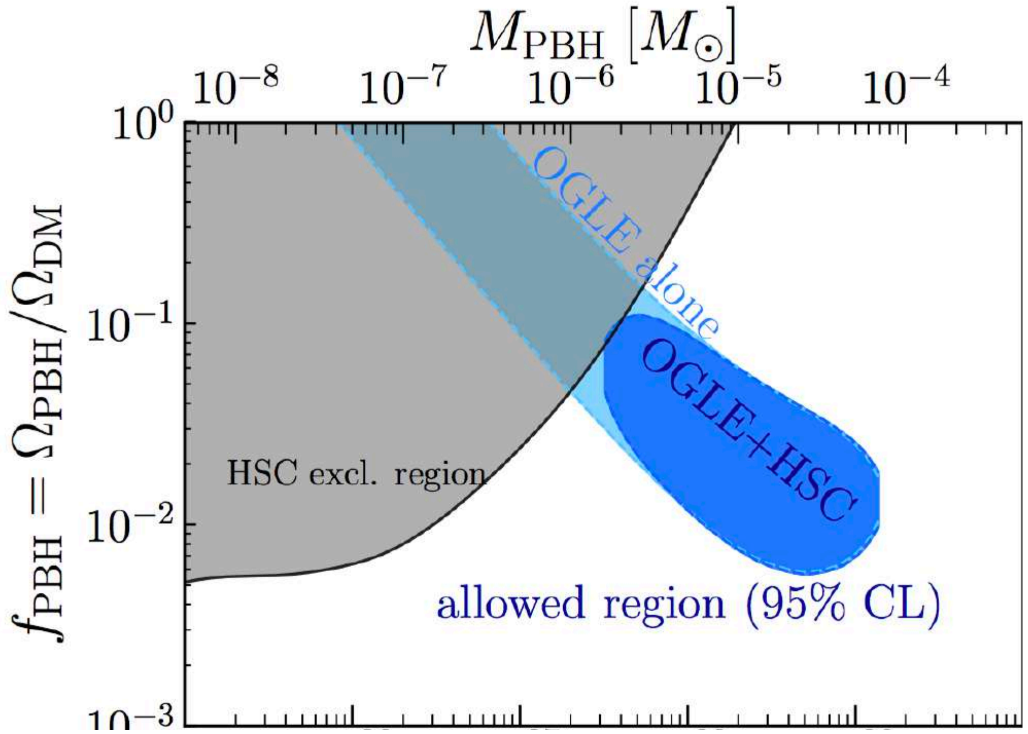
For $f_{\rm PBH} \in [0.005, 0.1]$ implies also particle dark matter.

Generically this leads to dark matter halos around the PBH.

The total mass of the halo satisfies

$$M_{\rm BH} = \frac{4\pi}{3}\rho(t) r_{\rm in}^3(t)$$

$r_{\rm in}$ is radius within which PBH dominates the potential.



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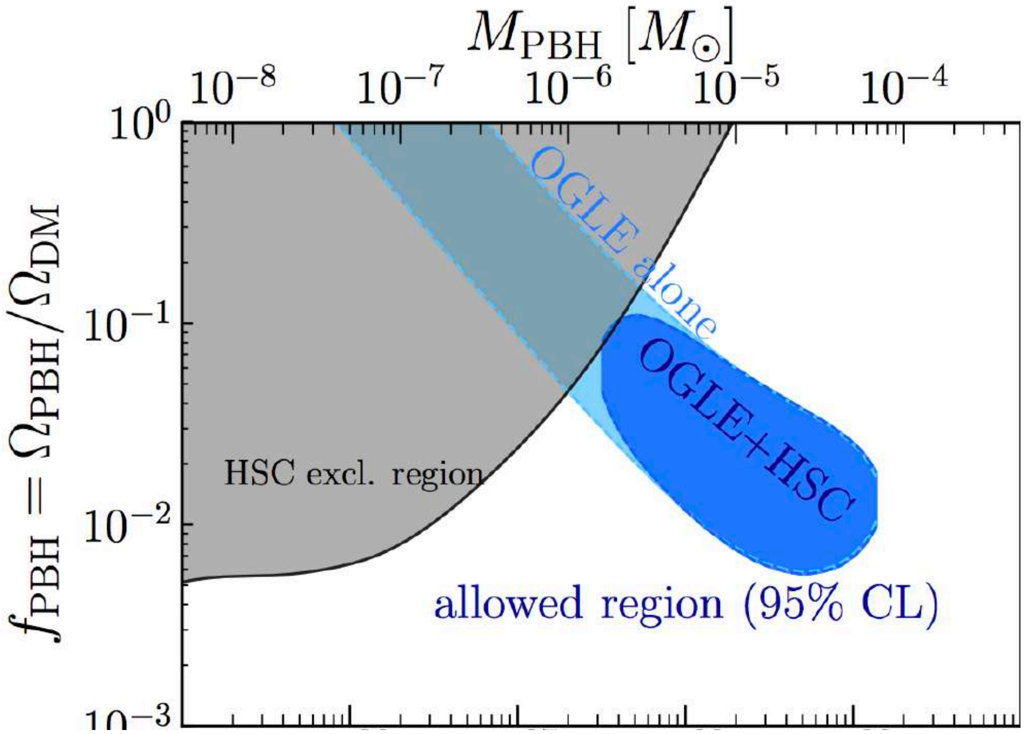

Defining $r_{\rm eq} \equiv r_{\rm in}(t_{\rm eq}) \sim 220\ {\rm AU} \times (M_{\rm BH}/5M_\oplus)^{1/3}$

evaluated at matter-radiation equality and for which $\rho_{\rm eq} \equiv \rho(t_{\rm eq}) \simeq 2.1\times 10^{-19}\ {\rm g/cm^3}$

With density profile (nb. requires some care) $\rho(r) = \frac{\rho_{\rm eq}}{2}\left(\frac{r_{\rm eq}}{r}\right)^{9/4}$

Eroshenko [1607.00612]

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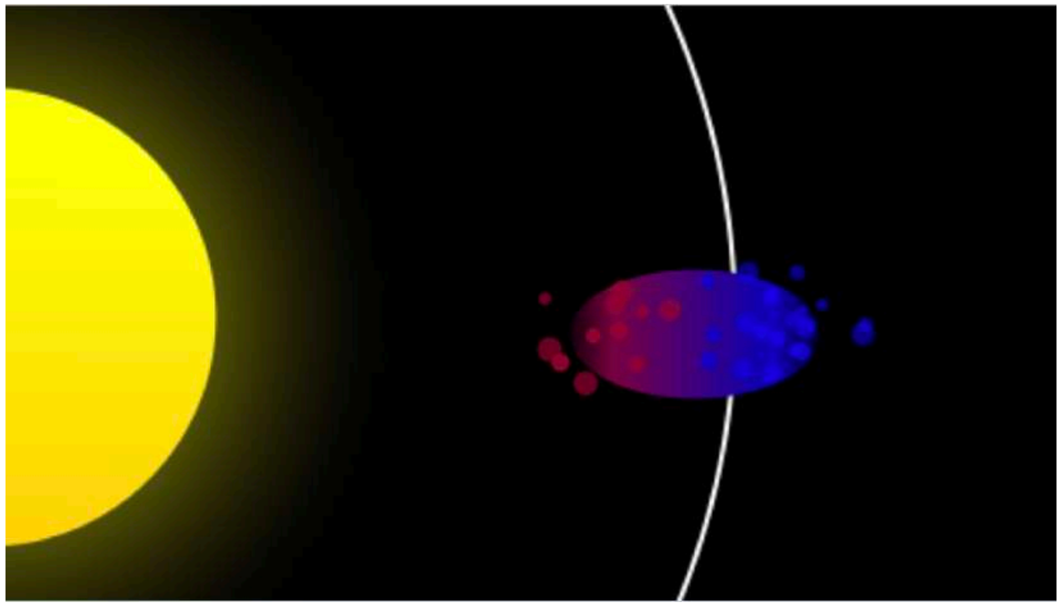
Tidal Stripping



Profile terminates at certain radius.

Following formation the PBH halo can be subsequently stripped by encounters with out bodies.

Tidal stripping radius given by the Roche limit:

$$r_{t,\star} \sim r_* \left(\frac{M_{\rm initial}}{2M_\odot}\right)^{\frac{1}{3}}$$

where r_* is distance between two bodies and $M_{\rm initial}$ refers to the body being stripped.

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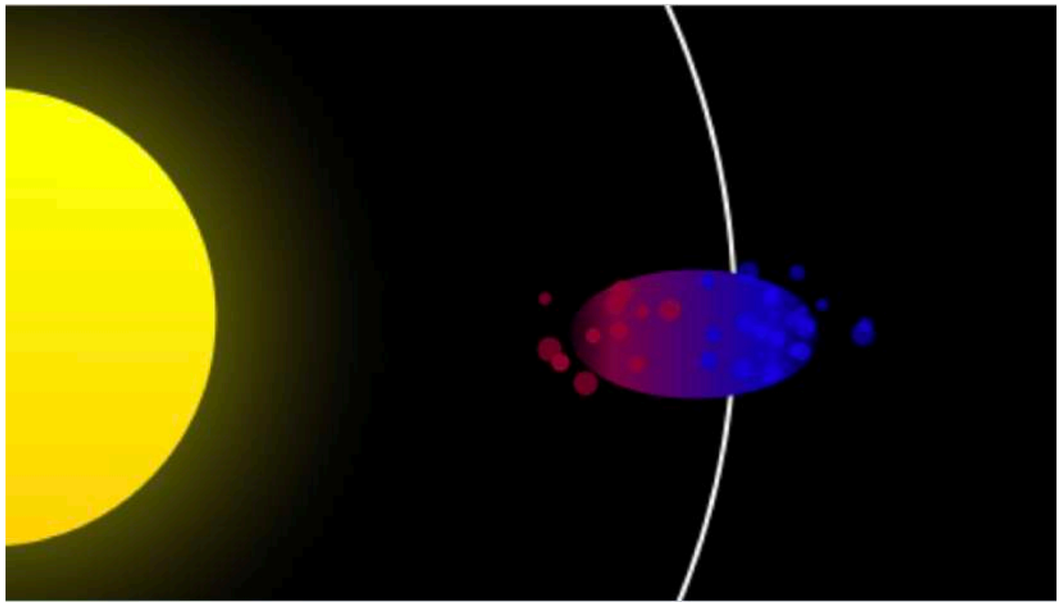

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Thus once the PBH settles into an orbit around the Sun, tidal radius cuts off the PBH halo at

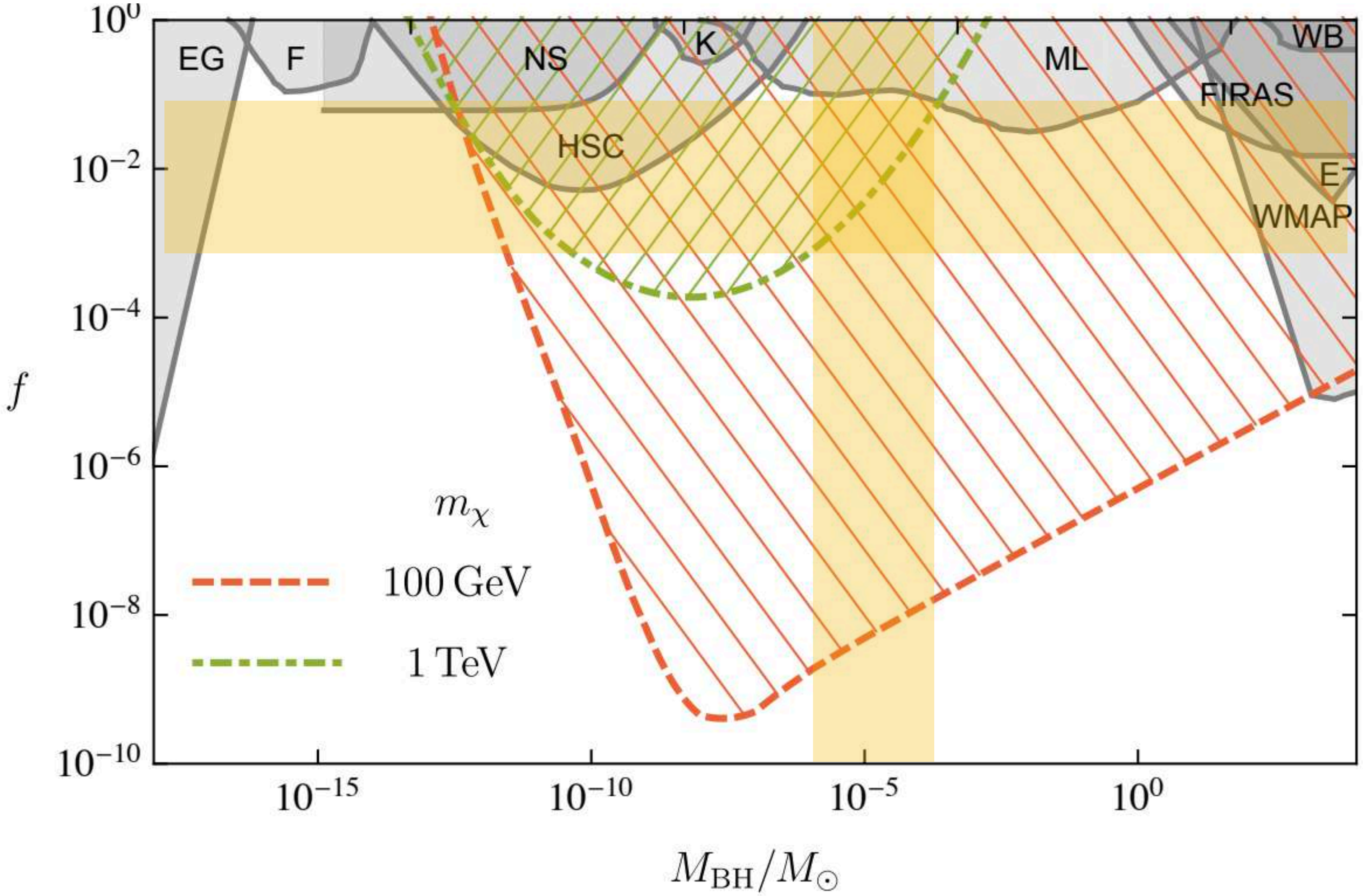
$$r_{t,\odot} \sim r_p \left(\frac{M_{\rm BH}}{2M_\odot} \right)^{\frac{1}{3}} \sim 8{\rm AU} \left(\frac{r_p}{400{\rm AU}} \right) \left(\frac{M_{\rm BH}}{5M_\oplus} \right)^{\frac{1}{3}}$$

Note that 8 AU is 10^9 km, compare this to Earth mass PBH with diameter 10cm!

Mostly WIMP Scenario

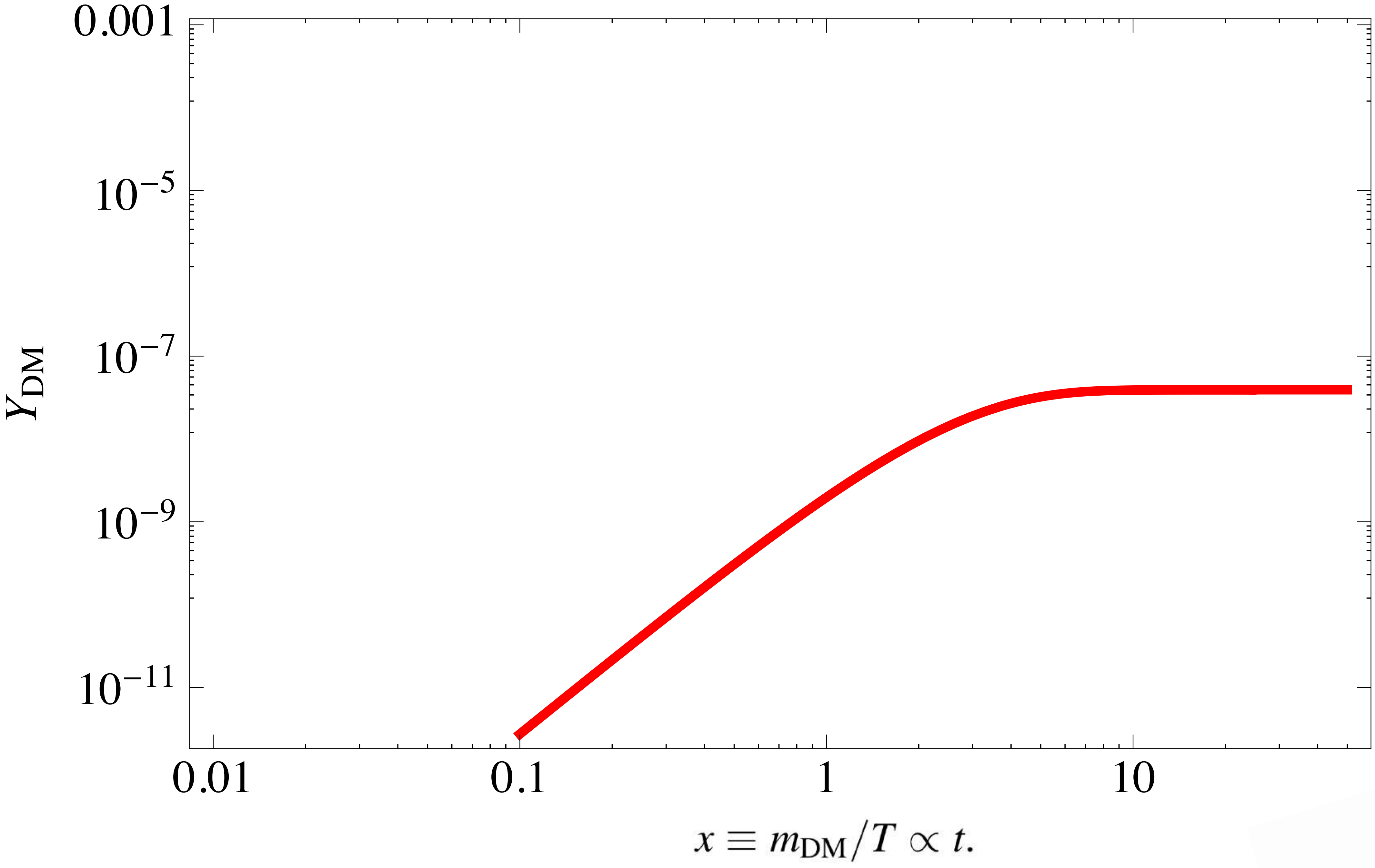
Consider the OGLE PBG population $M \in [0.5M_{\oplus}, 20M_{\oplus}]; \;\; f_{\rm PBH} \in [0.005, 0.1]$

For a WIMP DM cross section $\langle \sigma v \rangle_0 \sim 3 \times 10^{-26} {\rm cm}^3/{\rm s}$ this is VERY excluded.

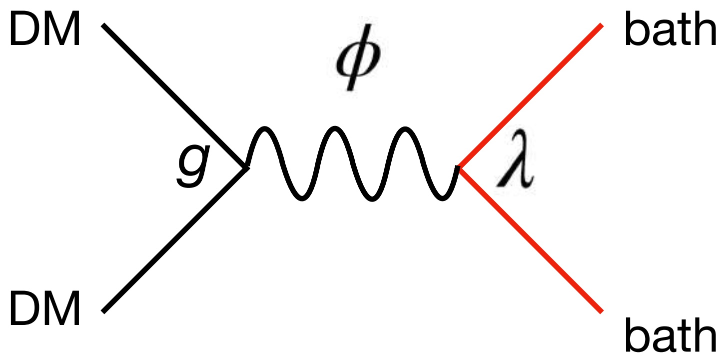


Freeze-in Dark Matter

An alternative to WIMPs which have much smaller annihilation is Freeze-in.



Characteristic cross section



In this scenario the relic density of dark matter scales as follows

$$\Omega_{\rm DM} \propto m Y_{\rm FI} \propto \lambda^2$$

Parametrically

$$\Omega_{\rm DM} \simeq 0.2 \left(\frac{m}{100~{\rm GeV}}\right)\left(\frac{\lambda}{6\times 10^{-12}}\right)^2\left(\frac{10~{\rm TeV}}{M_\phi}\right)$$

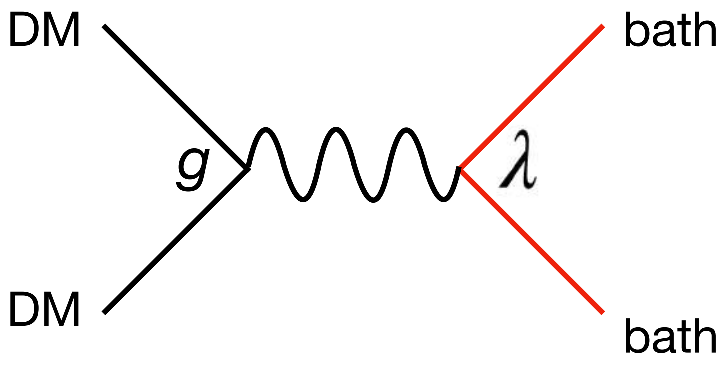
With these benchmark values it implies an annihilation cross section

$$\langle\sigma v\rangle_{\rm ch} \simeq 1.3\times 10^{-56}{\rm cm}^3/{\rm s}\times\left(\frac{g}{10^{-2}}\right)^2.$$

The coupling g is largely unfixed.

Annihilation Rate

The dark matter annihilation rate is given by



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

Using the density profile from earlier: $$\rho(r) = \frac{\rho_{\rm eq}}{2}\left(\frac{r_{\rm eq}}{r}\right)^{9/4}$$

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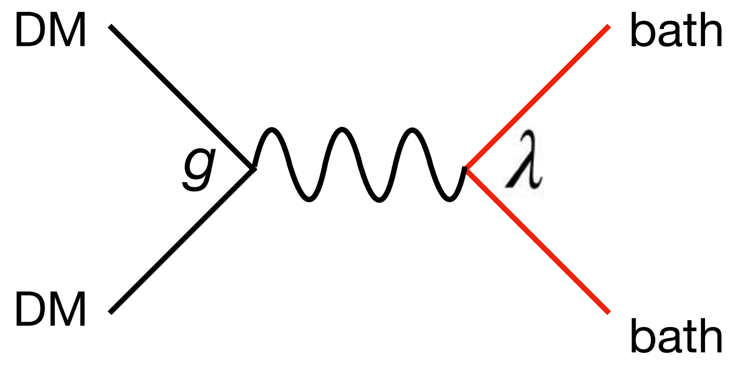

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Putting this together, the annihilation rate for Freeze-in dark matter is

$$\Gamma = \sqrt{\frac{3\rho_{\rm eq}}{8\pi G^3}}\frac{\langle\sigma v\rangle}{m^2} = 10^{20}\mathrm{s}^{-1}\left(\frac{\langle\sigma v\rangle}{\langle\sigma v\rangle_{\rm ch}}\right)\left(\frac{100\mathrm{GeV}}{m}\right)^2$$

Limits from Flux

The photon flux from annihilation in a distribution a distance r_9 from Earth:

$$\Phi_\gamma = \frac{\kappa_1 \Gamma}{4\pi r_9^2}$$

where κ_1 is the average number of photons per annihilation; take $\kappa_1 \sim 10$

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The smallest detectable in 8 year FERMI-LAT catalog has

$$\Phi_\gamma = 8.8 \times 10^{-12} \mathrm{photons/cm^2/s}$$

Since Γ depends on the annihilation cross section, this implies a limit:

$$\langle \sigma v \rangle < 5.1 \times 10^{-56} \mathrm{cm^3/s} \left(\frac{m}{100\mathrm{GeV}} \right)^2$$

And is satisfied freeze-in model: $\langle \sigma v \rangle_{\rm ch} \simeq 1.3 \times 10^{-56} \mathrm{cm^3/s} \times \left(\frac{g}{10^{-2}} \right)^2$

Conclusions

There is tentative evidence from observations of TNO orbits for a 9th Planet.

OGLE has unexpected microlensing events indicative of new compact bodies.

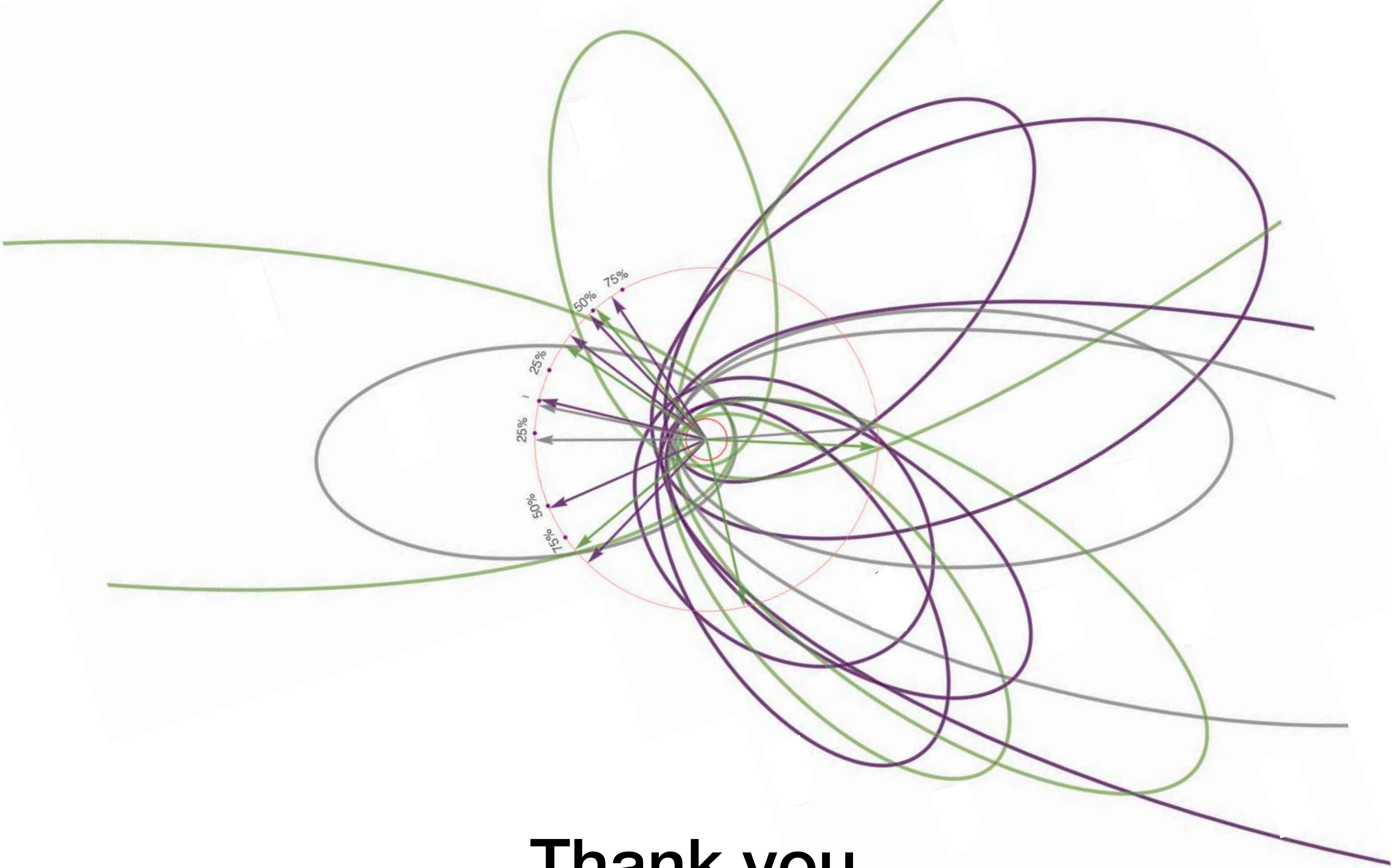
Remarkably these two excesses hint at the same mass range: around $5\,M_\oplus$

Interpreting the OGLE excess as PBH, the capture probability similar to a planet

Looking for a PBH requires distinct searches compared to looking for a planet

For some interesting directions see:

Witten: 2004.14192
Siraj & Loeb: 2005.12280
Henghes et al [DES]: 2009.12856



Thank you

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