The Secret Life of Primordial Black Holes

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17th May 2023

Based on:

Scholtz & Unwin
PRL (2020), arXiv:1909.11090.

Chanda, Scholtz, & Unwin
arXiv:2209.07541.

The Secret Life of Primordial Black Holes

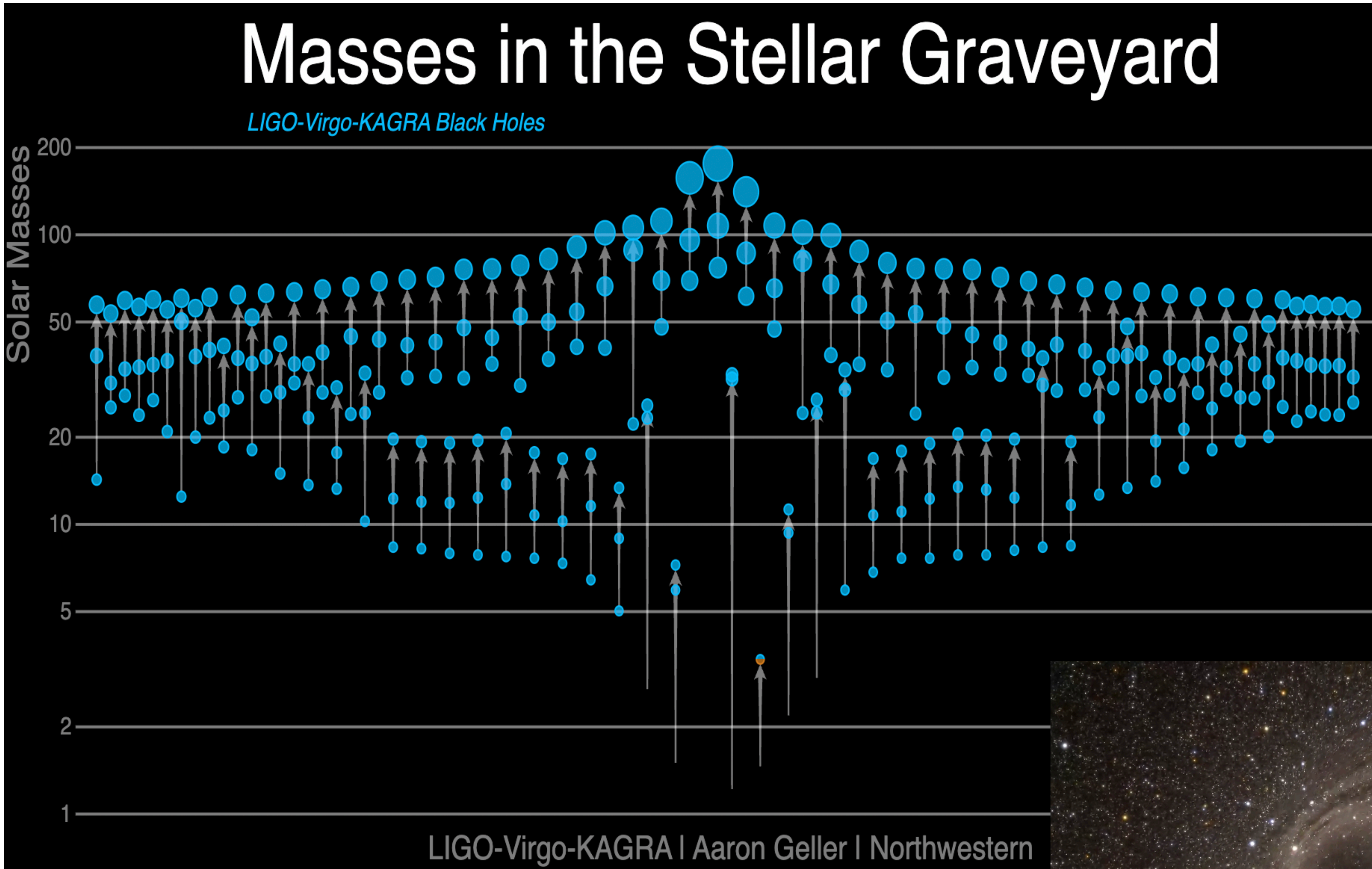
I. Primordial Black Holes and Dark Matter

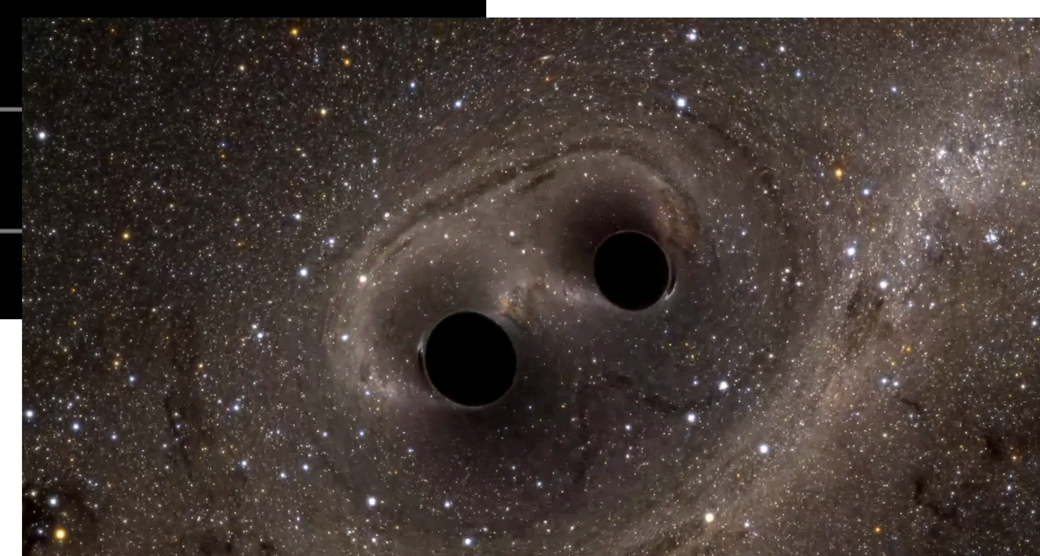
II. Halos around Primordial Black Holes

III. Anomalous Orbits in our Solar System

I. Primordial Black Holes and Dark Matter

Black Holes Exist





Lower mass for an Astrophysical Black Hole $\sim M_{\odot}$.

Primordial Black Holes

Primordial Black Hole (PBH) first proposed in:

SOVIET ASTRONOMY – AJ VOL. 10, NO. 4 JANUARY-FEBRUARY, 1967

THE HYPOTHESIS OF CORES RETARDED DURING EXPANSION AND THE HOT COSMOLOGICAL MODEL

Ya. B. Zel'dovich and I. D. Novikov

Translated from Astronomicheskii Zhurnal, Vol. 43, No. 4, pp. 758–760, July–August, 1966
Original article submitted March 14, 1966

Hypothesis is that **PBH form from fluctuations** in the Early Universe if sufficiently dense.

Mon. Not. R. astr. Soc. (1971) **152**, 75–78.

GRAVITATIONALLY COLLAPSED OBJECTS OF VERY LOW MASS

Stephen Hawking

(Communicated by M. J. Rees)

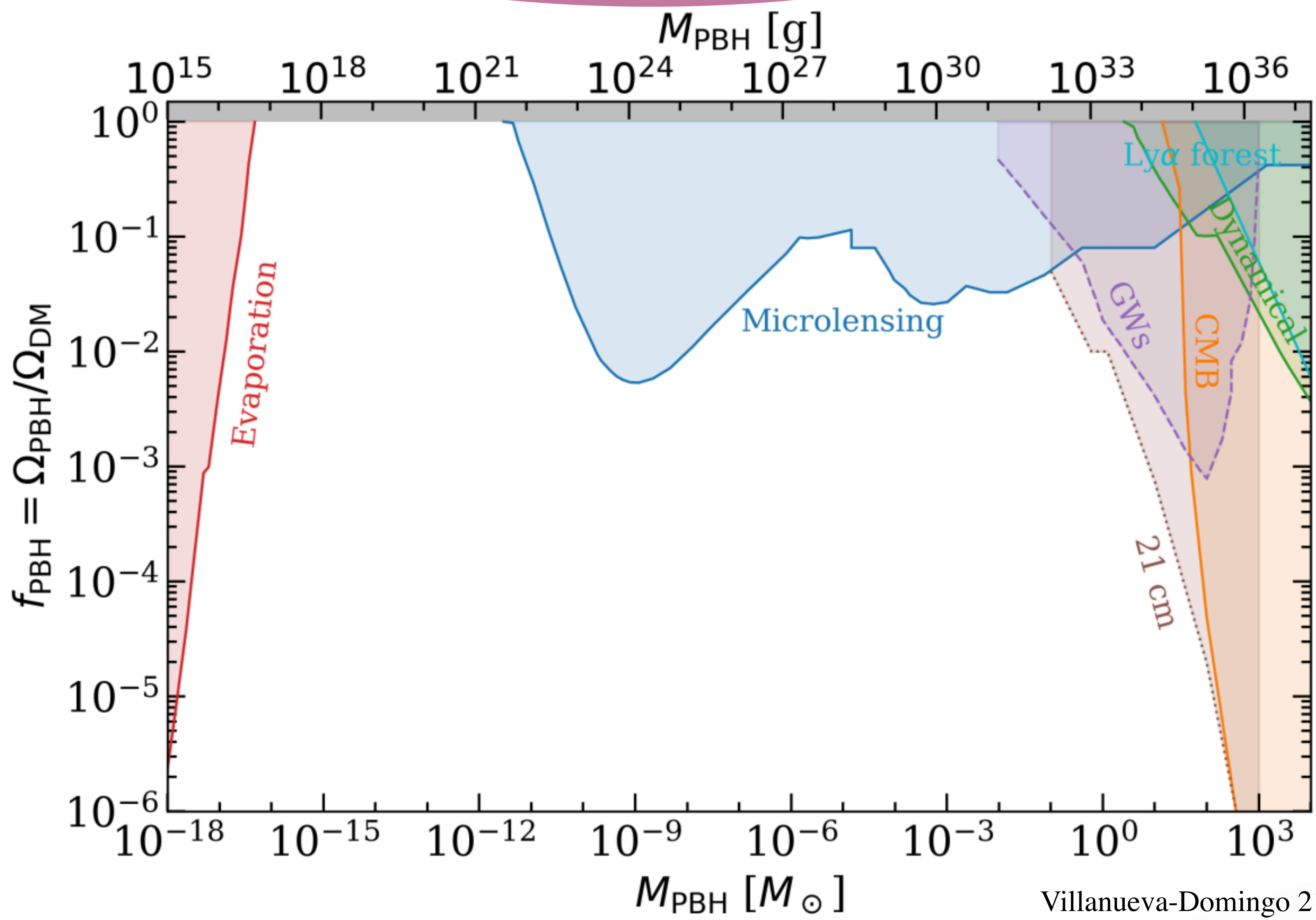
(Received 1970 November 9)

Rich literature of possible formation scenarios, many tied to specific models of cosmology.

Also, a possible **dark matter candidate** if they account for the full present day abundance:

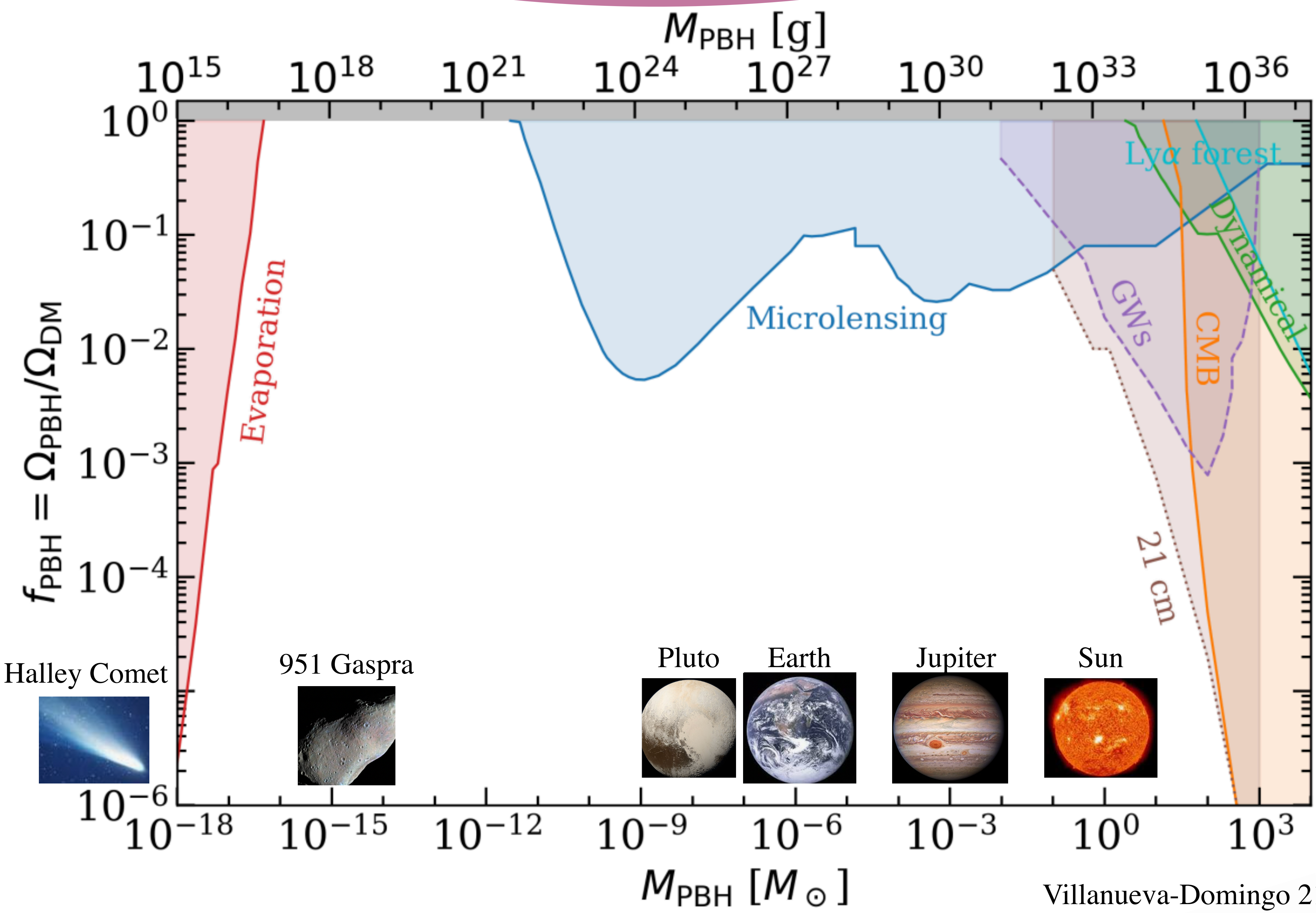
$$\Omega_{\rm DM} \approx 0.26.$$

Limits on Primordial Black Holes



Villanueva-Domingo 2103.12087

Limits on Primordial Black Holes



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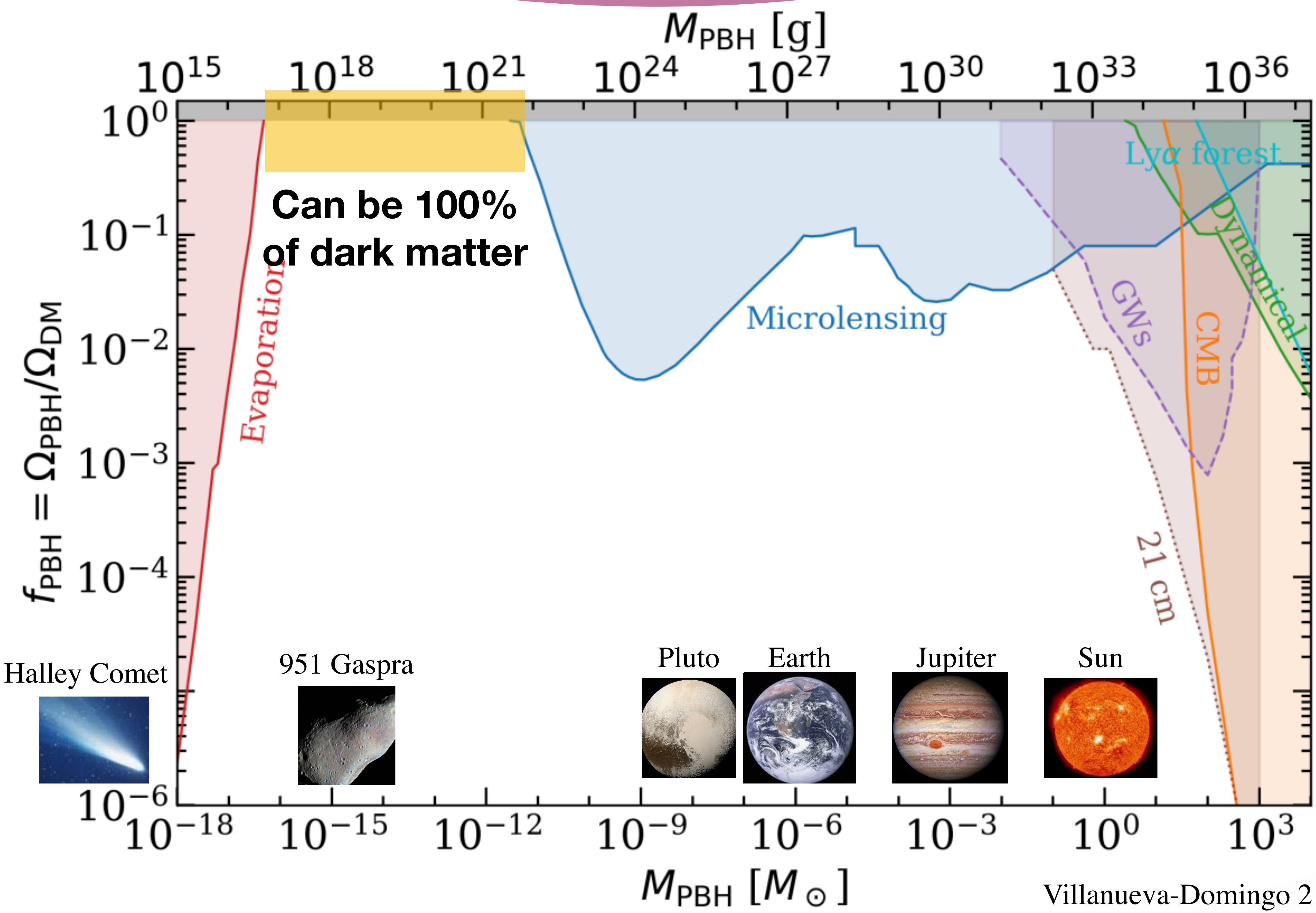

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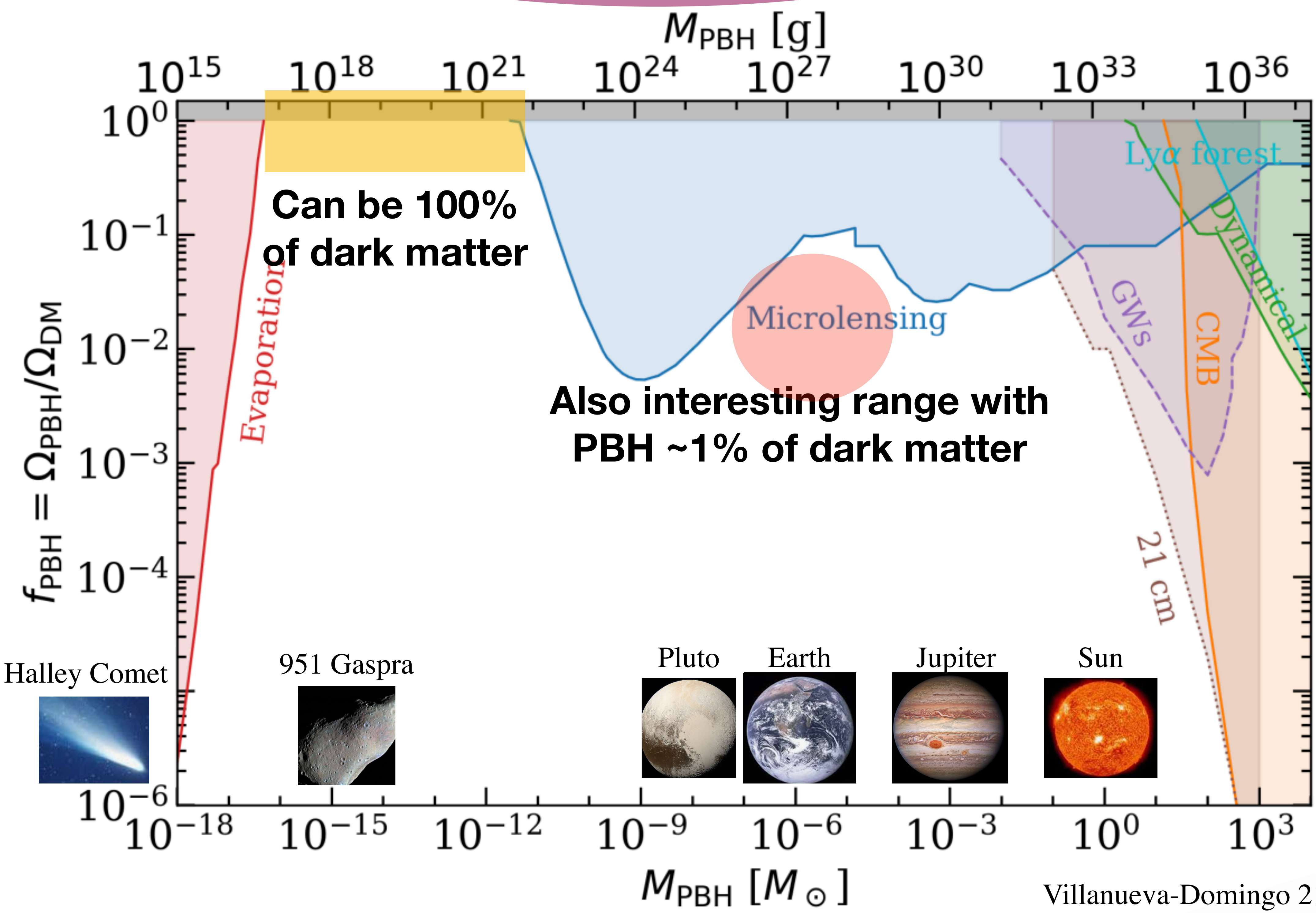
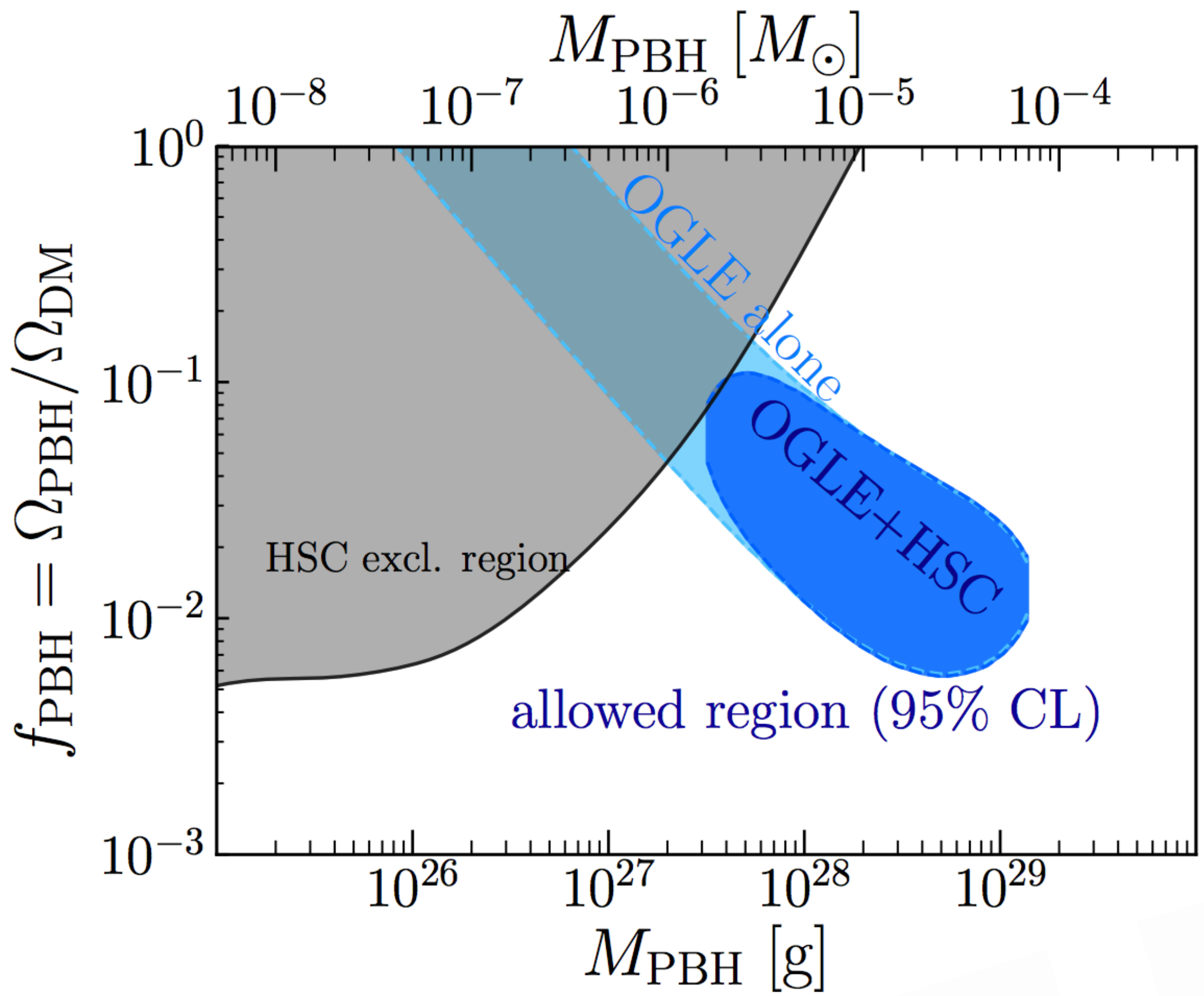


Villanueva-Domingo 2103.12087

The OGLE Excess

Indeed, there is a tentative unexplained excess in microlensing events seen by the OGLE telescope consistent indicative of PBH population with

$$M \in [0.5 M_\oplus, 20 M_\oplus] \;\; ; \quad f_{\rm PBH} \in [0.005, 0.1]$$



H. Niikura, et al. PRD 99 (2019) 8, 083503

II. Signals for Primordial Black Holes

Thermal Dark Matter

If $f_{\rm PBH} \neq 1$ (as with OGLE) we still need to reproduce the observed dark matter.

Natural to suppose $\Omega_{\rm DM} = \Omega_{\rm PBH} + \Omega_{\rm pDM}$ with new **particle dark matter**.

PBH fraction:

$$f_{\rm PBH} = \frac{\Omega_{\rm PBH}}{\Omega_{\rm DM}} = \frac{\Omega_{\rm PBH}}{\Omega_{\rm PBH} + \Omega_{\rm pDM}}$$

Simplest possibility is **WIMP** and parameterise cross section with expansion:

$$\langle \sigma v \rangle = \sigma_s + \sigma_p \frac{3}{2x} + \sigma_d \frac{15}{8x^2} + \cdots$$

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$$\langle \sigma v \rangle = \boxed{\sigma_s} + \boxed{\sigma_p} \frac{3}{2x} + \boxed{\sigma_d} \frac{15}{8x^2} + \cdots \qquad \text{with } x^{-1} \propto T \propto v^2$$

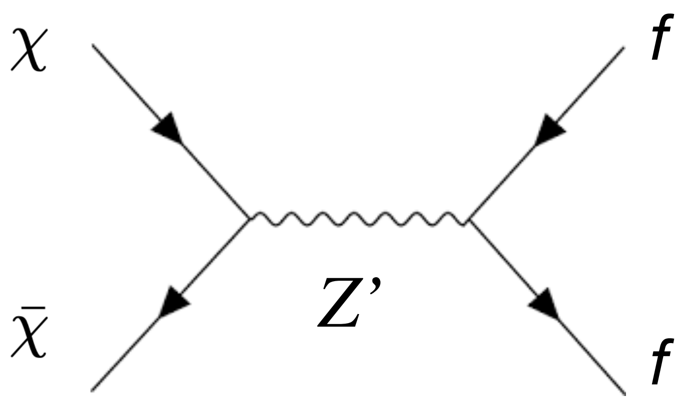
s-wave: $\boxed{\sigma_s \neq 0}$ then for $\Omega_{\rm pDM} = \Omega_{\rm DM} \approx 0.26$. need $\sigma_s \sim 3 \times 10^{-26} {\rm cm}^3/{\rm s}$

p-wave: $\sigma_s = 0$ and $\boxed{\sigma_p \neq 0}$ implies $\langle \sigma v \rangle \propto v^2$

d-wave: $\boxed{\sigma_d}$ is the leading term; implies $\langle \sigma v \rangle \propto v^4$

Thermal Dark Matter

s-wave



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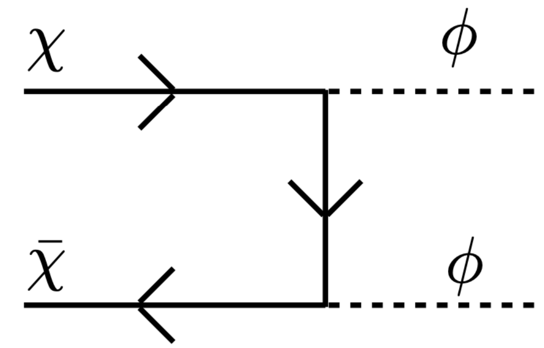

d-wave

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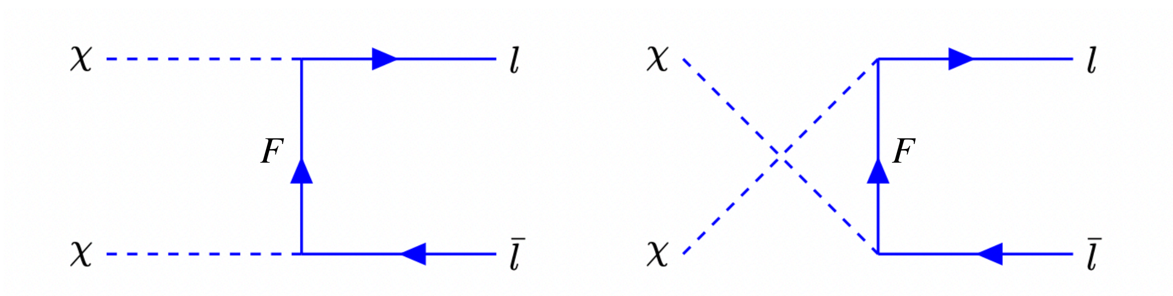
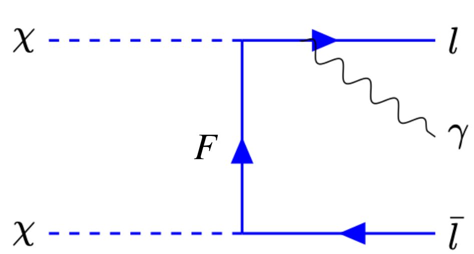


s-wave:

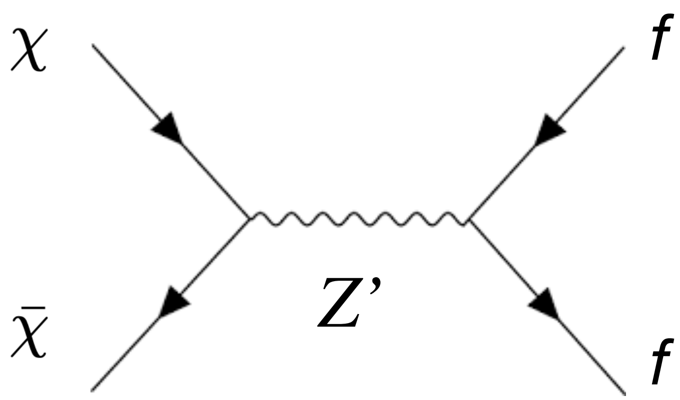


. . .

Giacchino, et al [1307.6480].

Thermal Dark Matter

s-wave



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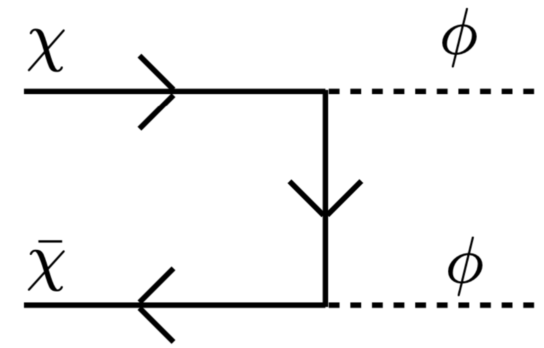
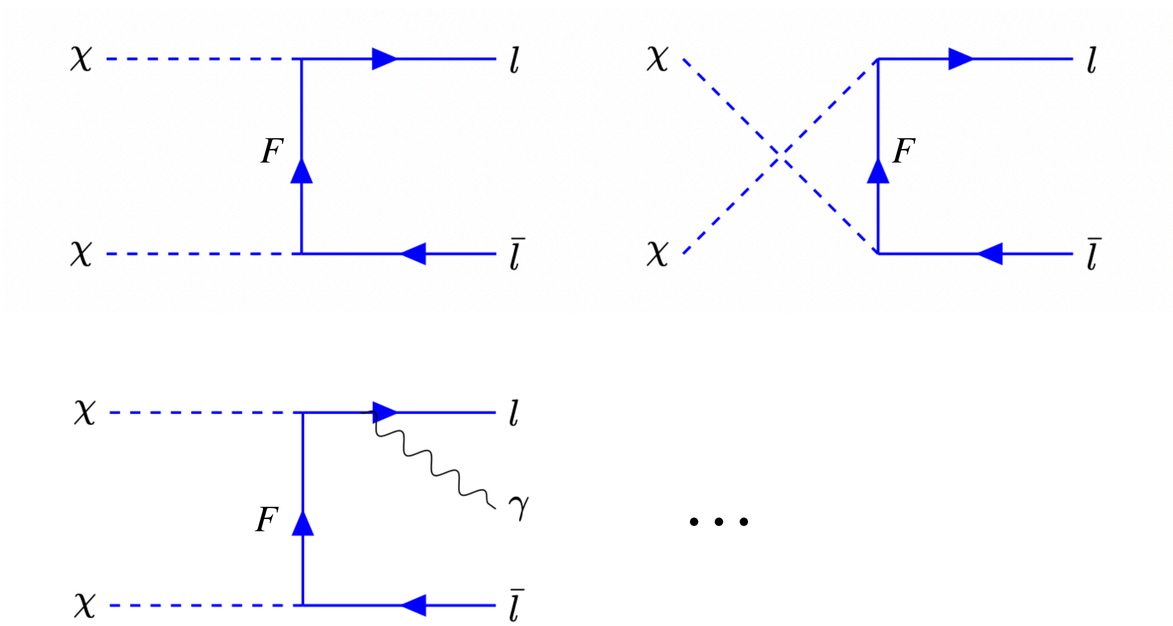


d-wave

d-wave:

s-wave:



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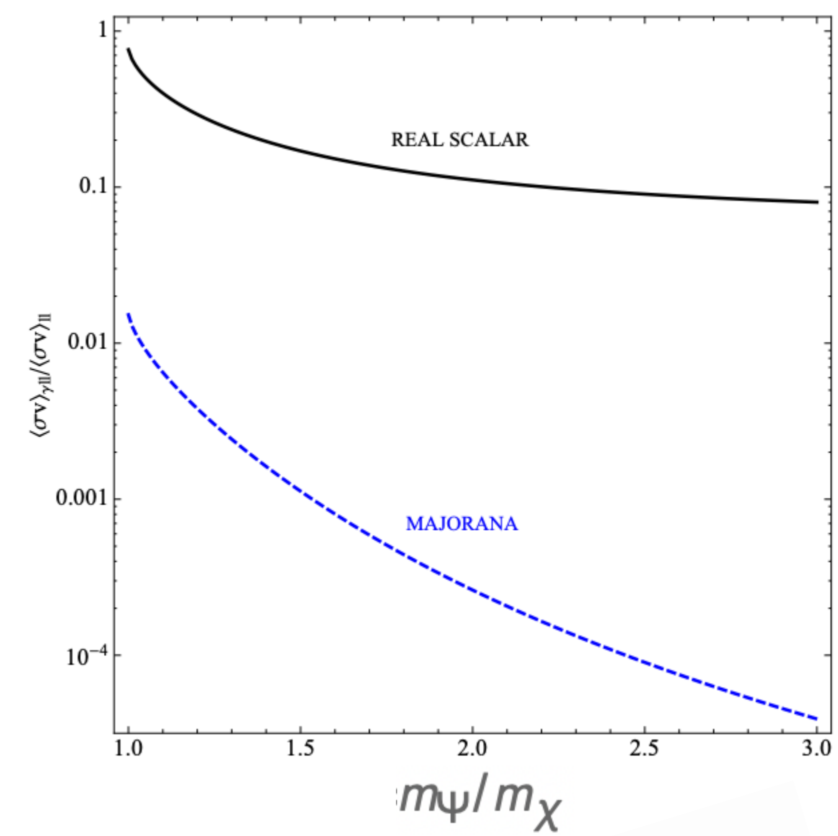

The PBH Halo

The particle dark matter with generically form a **dense halo** around the PBH.

For PBHs formed before kinetic decoupling, a dark matter **halo of constant density** this is equal to the background dark matter **at kinetic decoupling:** $\rho(t_{\rm kd}) = \rho_c \Omega_{\rm pDM} m_\chi / (x_{\rm kd} T_0)$.

The **density profile evolves** and at late time is characteristically $\rho(r) \propto r^{-9/4}$ (Bertschinger 1985)

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More carefully, it is determined by some complicated integral:

$$\rho(\tilde{r}) = \frac{8}{\tilde{r}} \int_0^\infty d\beta_i \beta_i \int_0^\infty d\tilde{r}_i \tilde{r}_i \rho_i(\tilde{r}_i) f(\beta_i, \tilde{r}_i) \left(\frac{1}{\tilde{r}_i} - \beta_i^2\right)^{3/2} \int_{\sqrt{\mathcal{Y}_m}\Theta(\mathcal{Y}_m - 0)}^1 \frac{dy}{\sqrt{y^2 - \mathcal{Y}_m}}$$

Boudaud et al [2106.07480]

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Evaluate in **light/intermediate/heavy** regime:

$$M_\bullet \leq M_1 \sim 3 \times 10^{-10} M_\odot \left(\frac{100\ \text{GeV}}{m_\chi}\right)^3 \left(\frac{10^4}{x_{\rm kd}}\right)^{3/2}$$

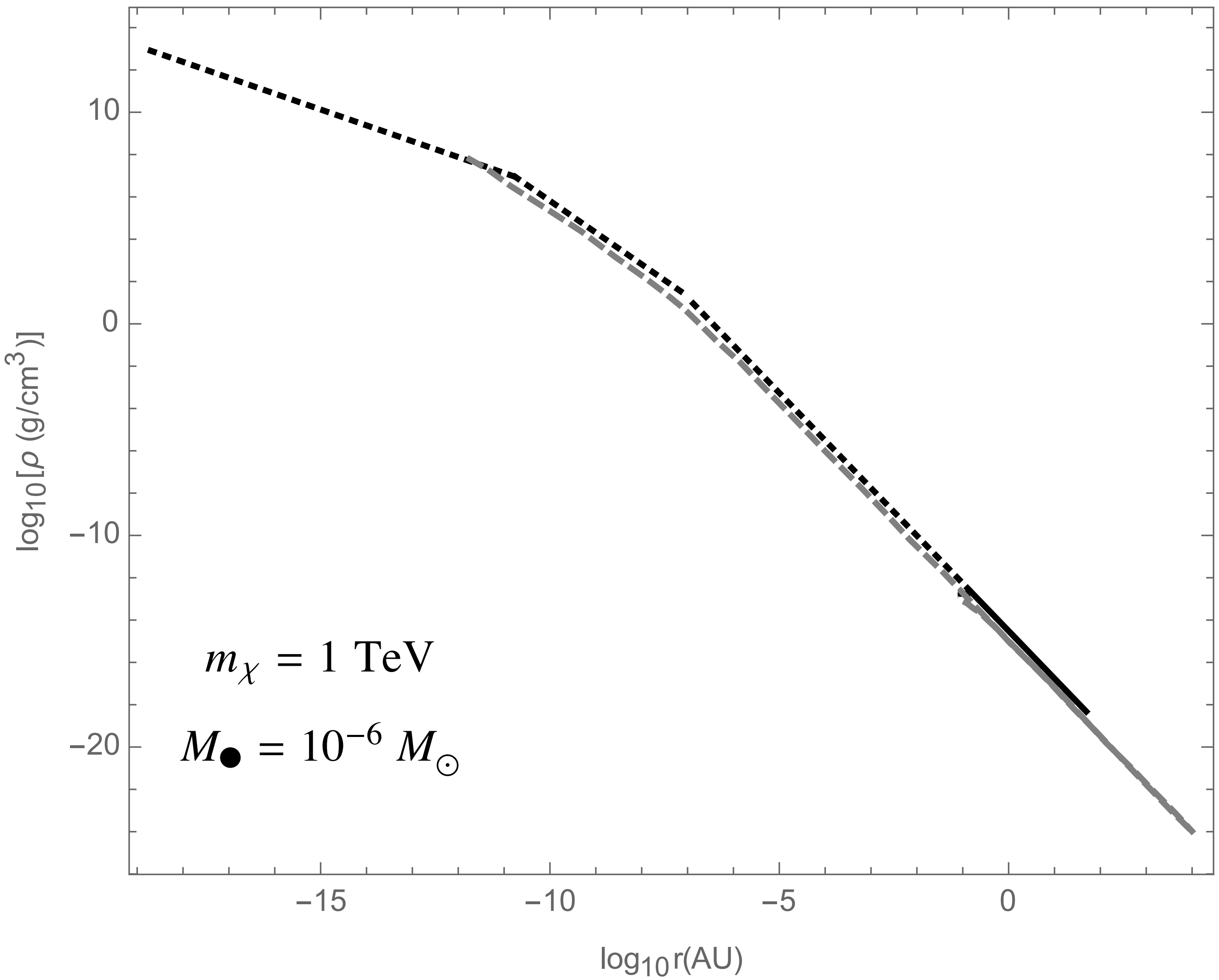
$$M_\bullet > M_2 \sim 3 \times 10^{-3} M_\odot \left(\frac{100\ \text{GeV}}{m_\chi}\right)^2 \left(\frac{10^4}{x_{\rm kd}}\right)^{1/2}$$

$$\rho_{\rm light}(r) \propto \begin{cases} r^{-3/4} & r < r_A \\ r^{-3/2} & r_A < r < r_T \\ 0 & r_T < r \end{cases}$$

$$\rho_{\rm heavy}(r) \propto \begin{cases} r^{-3/2} & r < r_C \\ r^{-9/4} & r_C < r < r_T \\ 0 & r_T < r \end{cases}$$

The PBH Halo

For an intermediate mass PBH (assuming halo evolution only due to gravity) an example halo **density profile** is:



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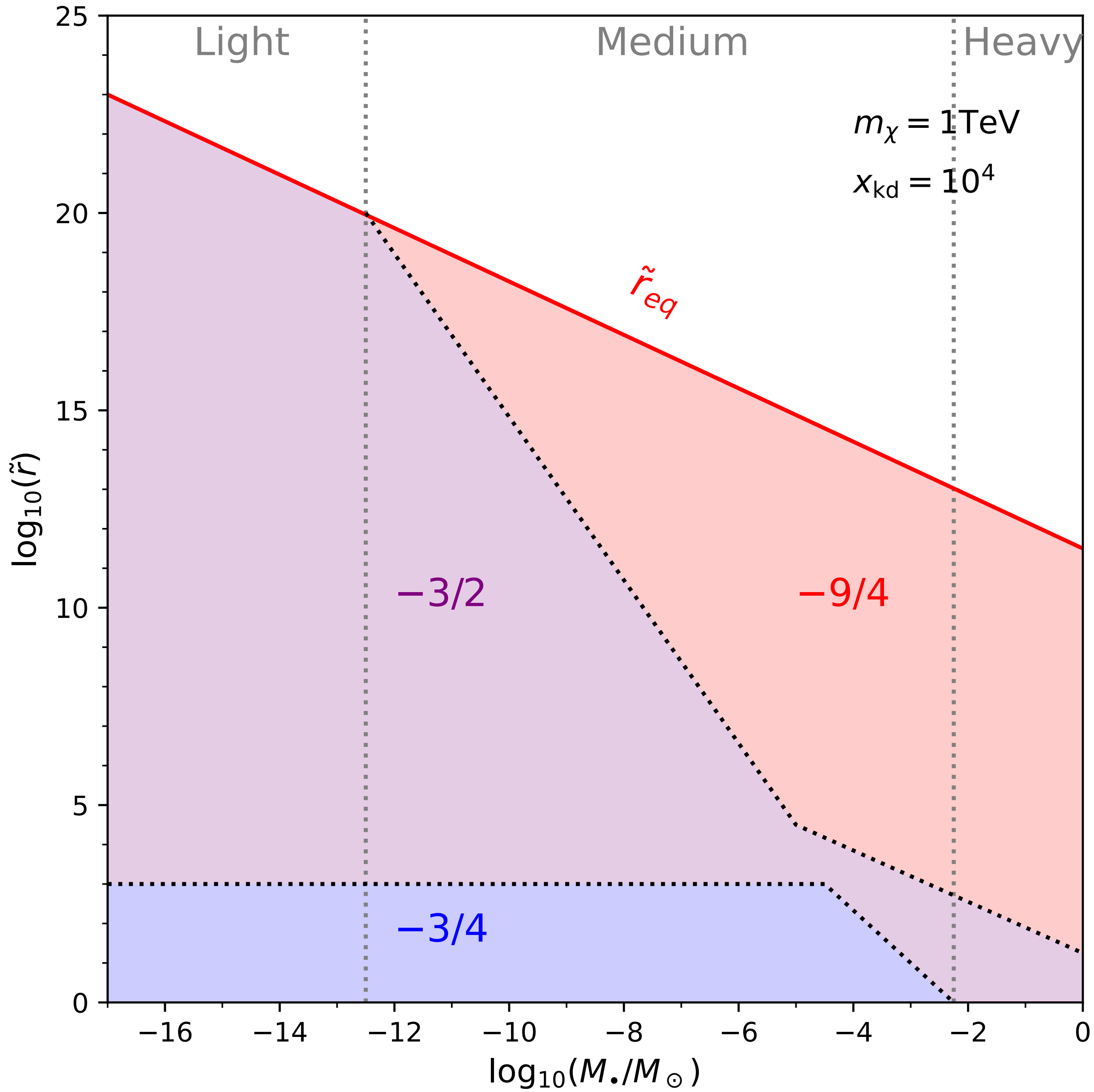

Diagram shows the scaling for different PBH masses at different scales.

Annihilations in the Core

Other phenomena can alter this picture. For instance particle dark matter **annihilations will deplete the centre** which is high density.

The annihilation rate is:

$$\Gamma_{\rm ann} \sim n_\chi(z)\langle\sigma v\rangle$$

Depleted central density reaches

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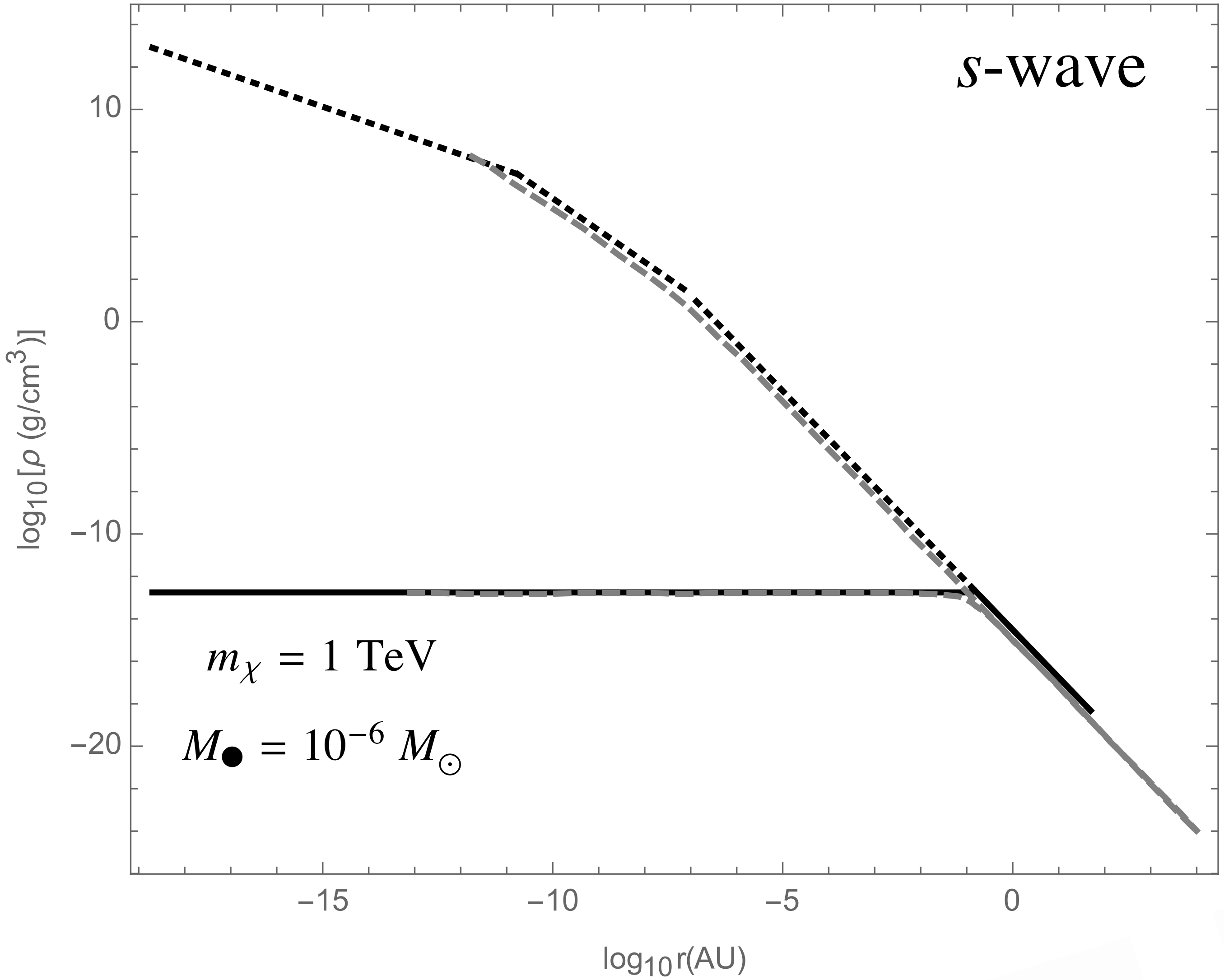
Depleted central density reaches a **maximum density**

$$\rho_{\rm max} \approx m_\chi n_\chi \sim \frac{m_\chi \Gamma_{\rm ann}}{\langle\sigma v\rangle}$$

$$\sim \frac{m_\chi}{\langle\sigma v\rangle t_{\rm halo}},$$



take $\Gamma_{\rm ann} \sim 1/t_{\rm halo}$, with $t_{\rm halo} \sim 10^{10}$ years

Annihilations in the Core

The **maximum density core** depends on the cross section

$$\rho_{\rm max} \quad \sim \frac{m_\chi}{\langle \sigma v \rangle t_{\rm halo}},$$

s-wave case implies constant density.

More generally

$$\langle \sigma v \rangle = \sigma_s + \sigma_p \frac{3}{2x} + \sigma_d \frac{15}{8x^2} + \cdots$$

which may be **velocity dependent**.

Note, velocity changes throughout the halo

$$v(r) \simeq \sqrt{GM_\bullet / r}$$

leading to **interesting halo profiles**.

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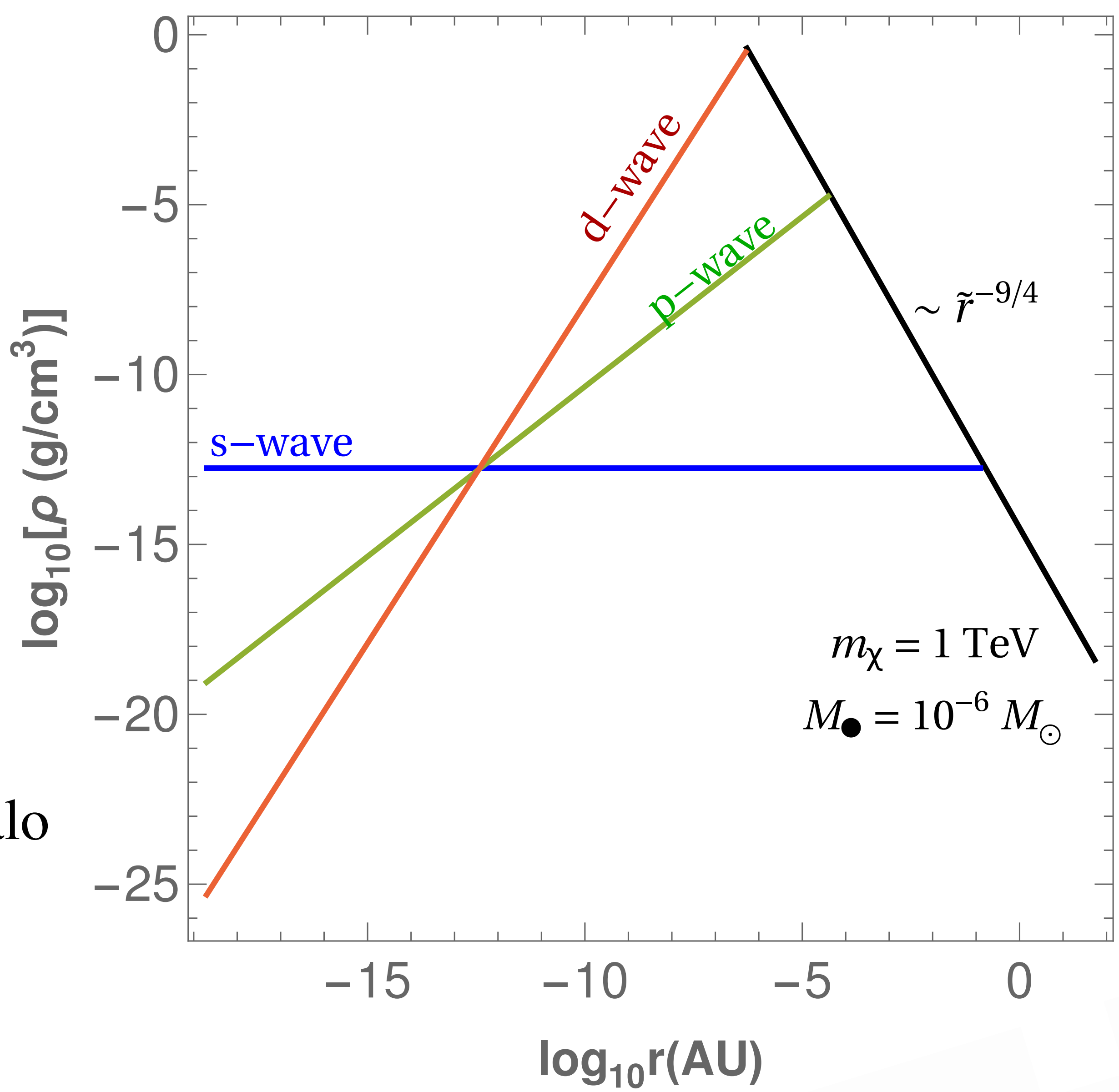
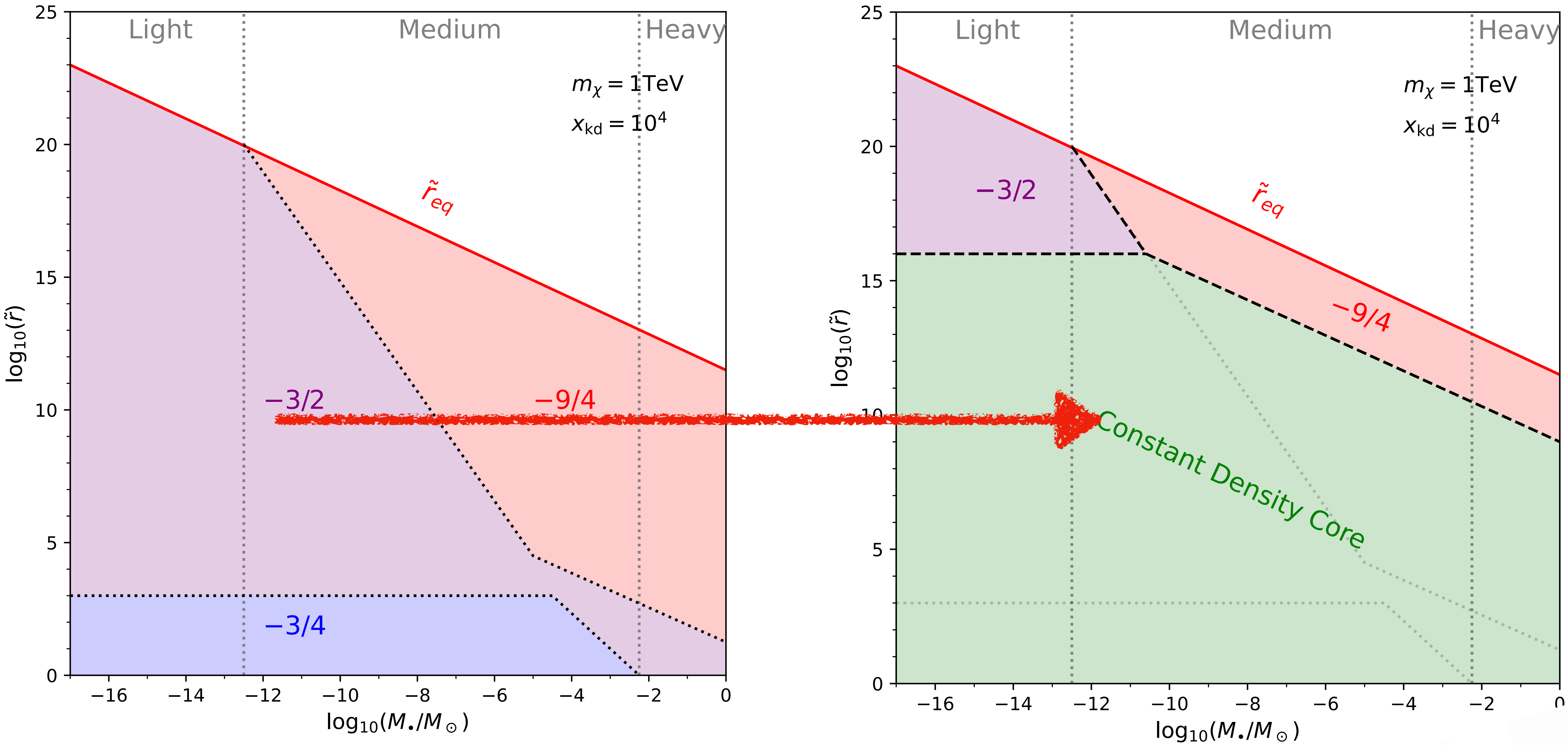


Annihilations in the Core

Density core cuts out some scaling. For the s-wave case:



Halo Stripping

For galactic PBH **close encounters** with stars strip the exterior of the PBH's dark matter halo

$$r_T = \left(\frac{\rho_{\rm halo}}{2\rho_B}\right)^{1/3} \sim d\left(\frac{M_{\rm halo}}{2M_B}\right)^{1/3}$$

PBH will have traversed the galaxy for 10^{10} years typical PBH speed to be ~ 200 km/s

Typical spacing of stars is 0.01pc in bulge **each PBH will have encountered** $N_\star \sim \mathcal{O}(10^8)$ stars

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Suppose stars form a regular square lattice with $l = 10^{-2}$ pc spacings, then **closest encounter**:

$$d \sim \frac{l}{\sqrt{N}} = 10^{-6}{\rm pc}.$$

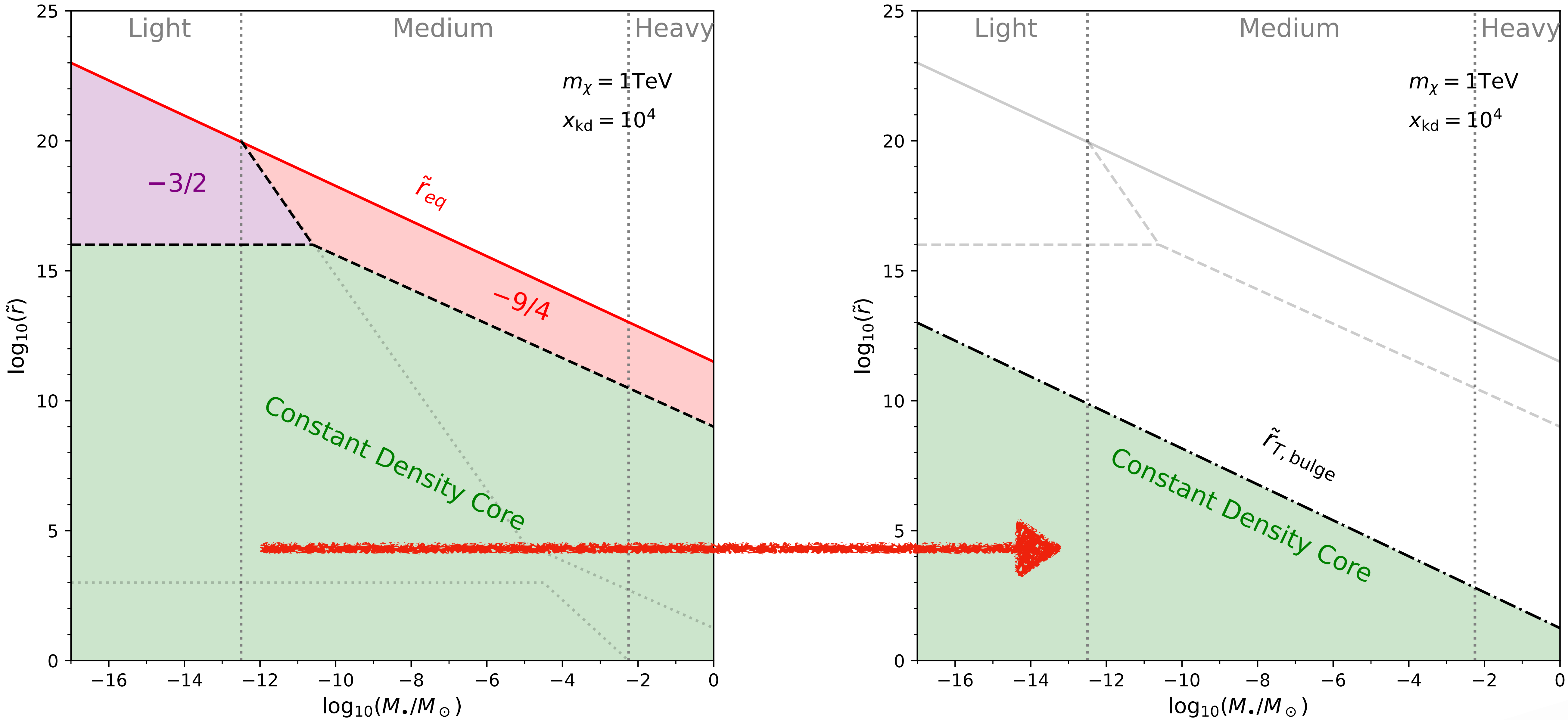
By it follows that the **terminal radius** for the PBH halo is:

$$r_T({\rm bulge}) \sim d\left(\frac{M_{\rm halo}}{2M_\odot}\right)^{\frac{1}{3}} \sim 10^{-6}{\rm pc}\left(\frac{d}{10^{-6}~{\rm pc}}\right)\left(\frac{M_{\rm halo}}{1M_\odot}\right)^{\frac{1}{3}}$$

$$r_T({\rm disk}) \sim 10^{-3}{\rm pc}\left(\frac{d}{10^{-3}~{\rm pc}}\right)\left(\frac{M_{\rm halo}}{1M_\odot}\right)^{\frac{1}{3}}$$

Halo Stripping

Stripping will alter the halo, assuming PBH in the bulge: $r_T(\text{bulge}) \sim d\left(\frac{M_{\rm halo}}{2M_\odot}\right)^{\frac{1}{3}} \sim 10^{-6}\text{pc}\left(\frac{d}{10^{-6}\text{ pc}}\right)\left(\frac{M_{\rm halo}}{1M_\odot}\right)^{\frac{1}{3}}$



Extragalactic γ-ray sources may not have been significantly stripped, leads to stronger limits.

Annihilations Signals

Extragalactic γ-ray background gives leading constraints.

For extragalactic γ-ray flux need to **integrate over z**

$$\left.\frac{\mathrm{d}\Phi_\gamma}{\mathrm{d}E\mathrm{d}\Omega}\right|_{\mathrm{ExGal}} = \int_0^\infty dz\ \frac{\hat{\Gamma}(z)n_{\mathrm{PBH}}}{8\pi H(z)}e^{-\tau(z,E)}\frac{\mathrm{d}N_\gamma}{\mathrm{d}E}$$

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Optical depth (Cirelli, et al [1012.4515])

Energy distribution (Cembranos [1009.4936])

Annihilation rate $\hat{\Gamma}_\bullet|_{z=0} = \Gamma_\bullet$ with

$$\Gamma_\bullet = 4\pi\int dr\ r^2\left(\frac{\rho(r)}{m_\chi}\right)^2\langle\sigma v\rangle$$

z-dependance is complicated depends on dark matter velocity dependance and PBH mass.

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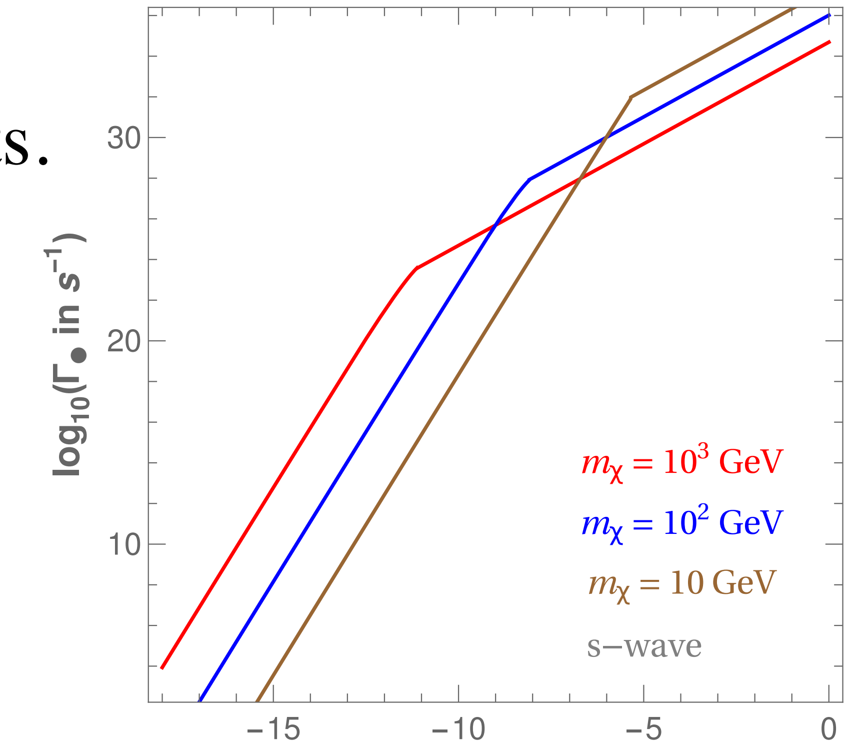
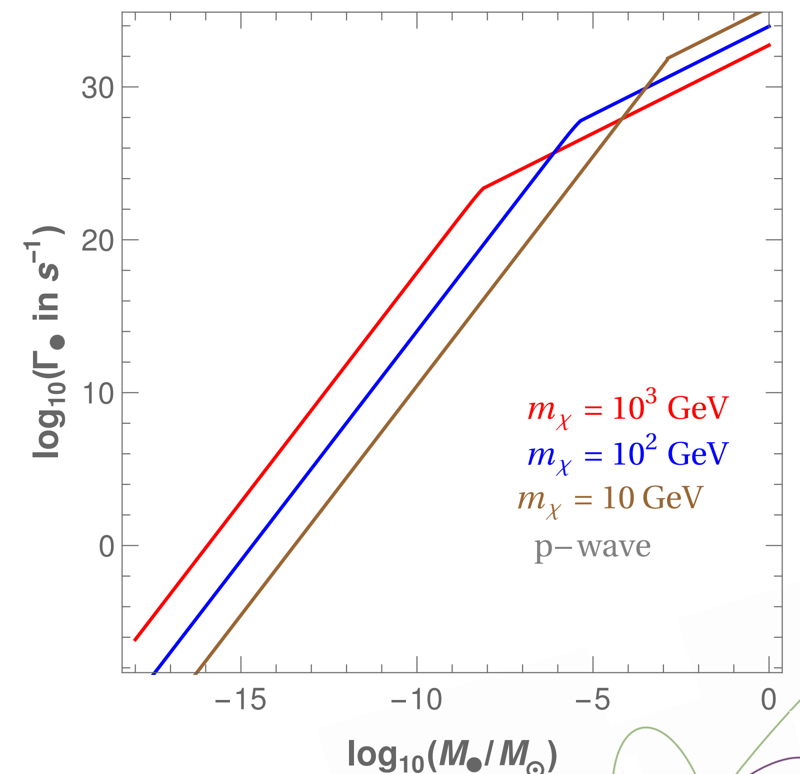
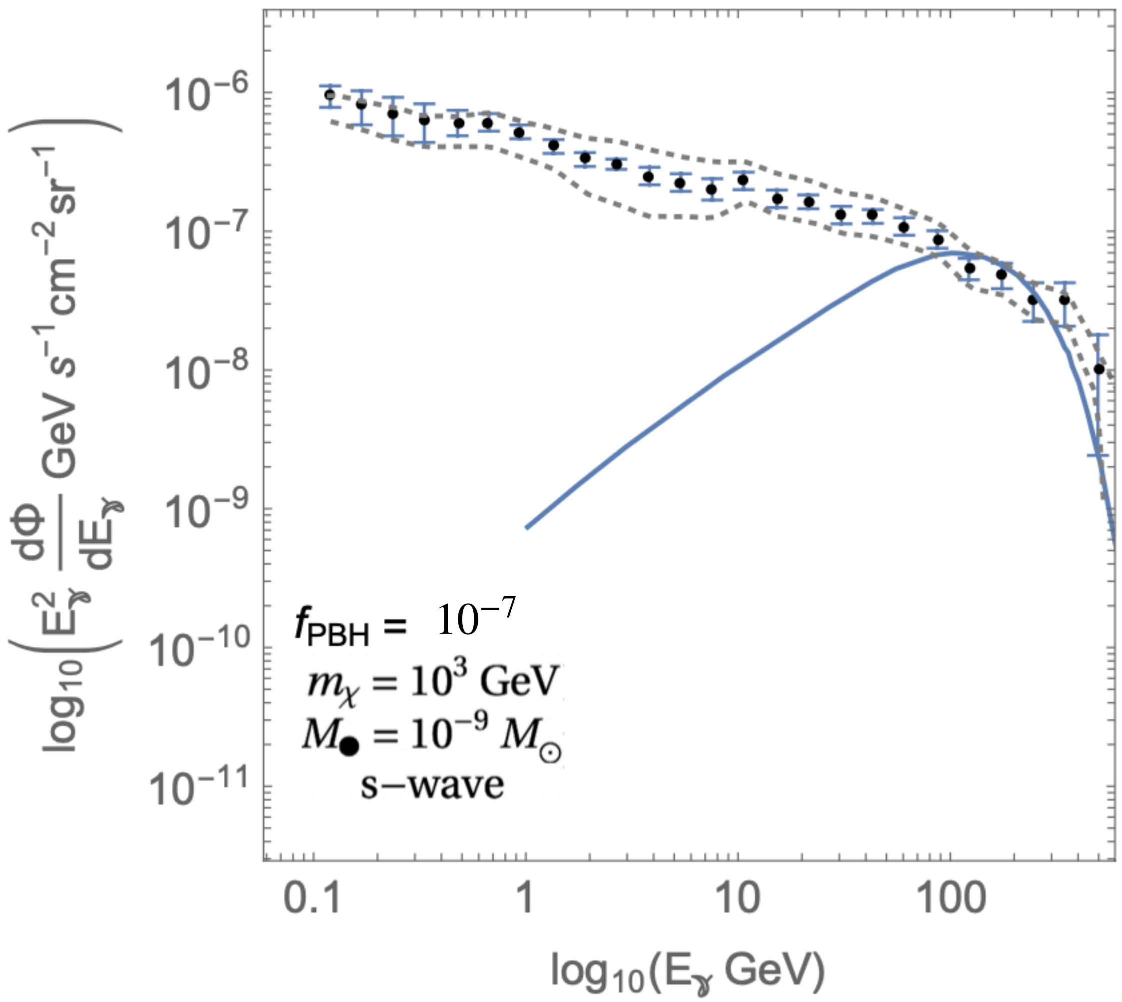


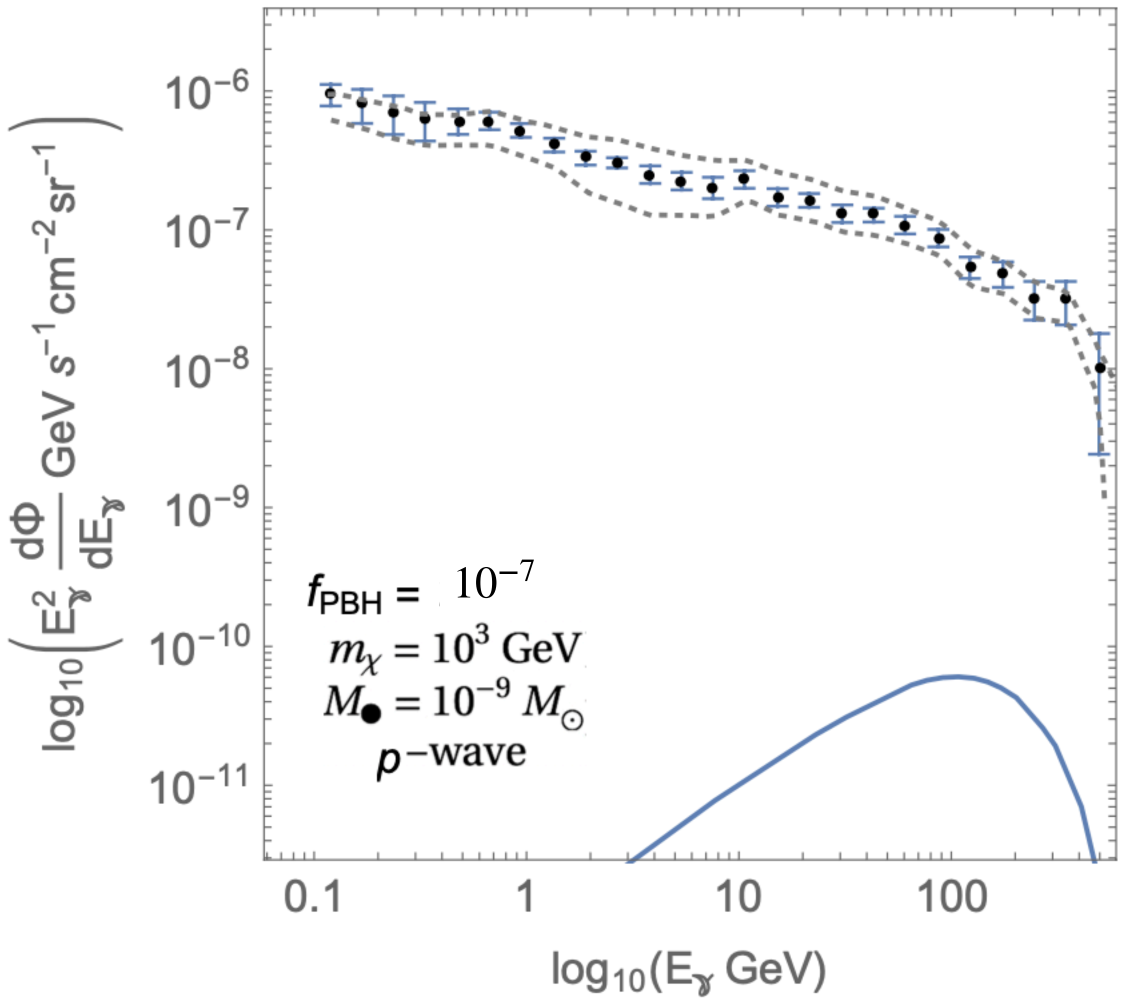


Fermi Extragalactic Flux

Compare the estimated flux to the **Fermi-LAT observations** of extragalactic γ-rays.

Find the maximum PBH abundance $f_{\rm PBH} < f_{\rm MAX}$ such that do not exceed γ-ray background.

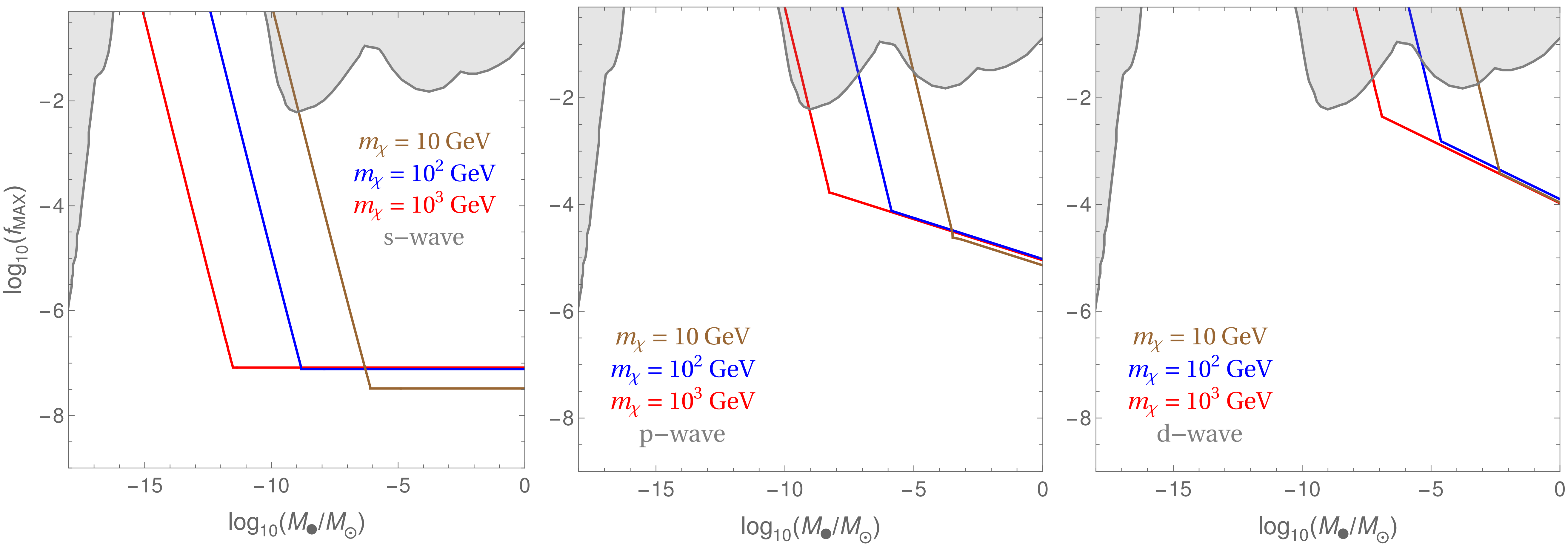




Data: Fermi collab., arXiv:1501.05464].

Limits on Annihilations around PBH

Plot f_{MAX} such that $f_{\mathrm{PBH}} < f_{\mathrm{MAX}}$ as function of PBH mass $M_\bullet$ for s/p/d wave annihilating DM:

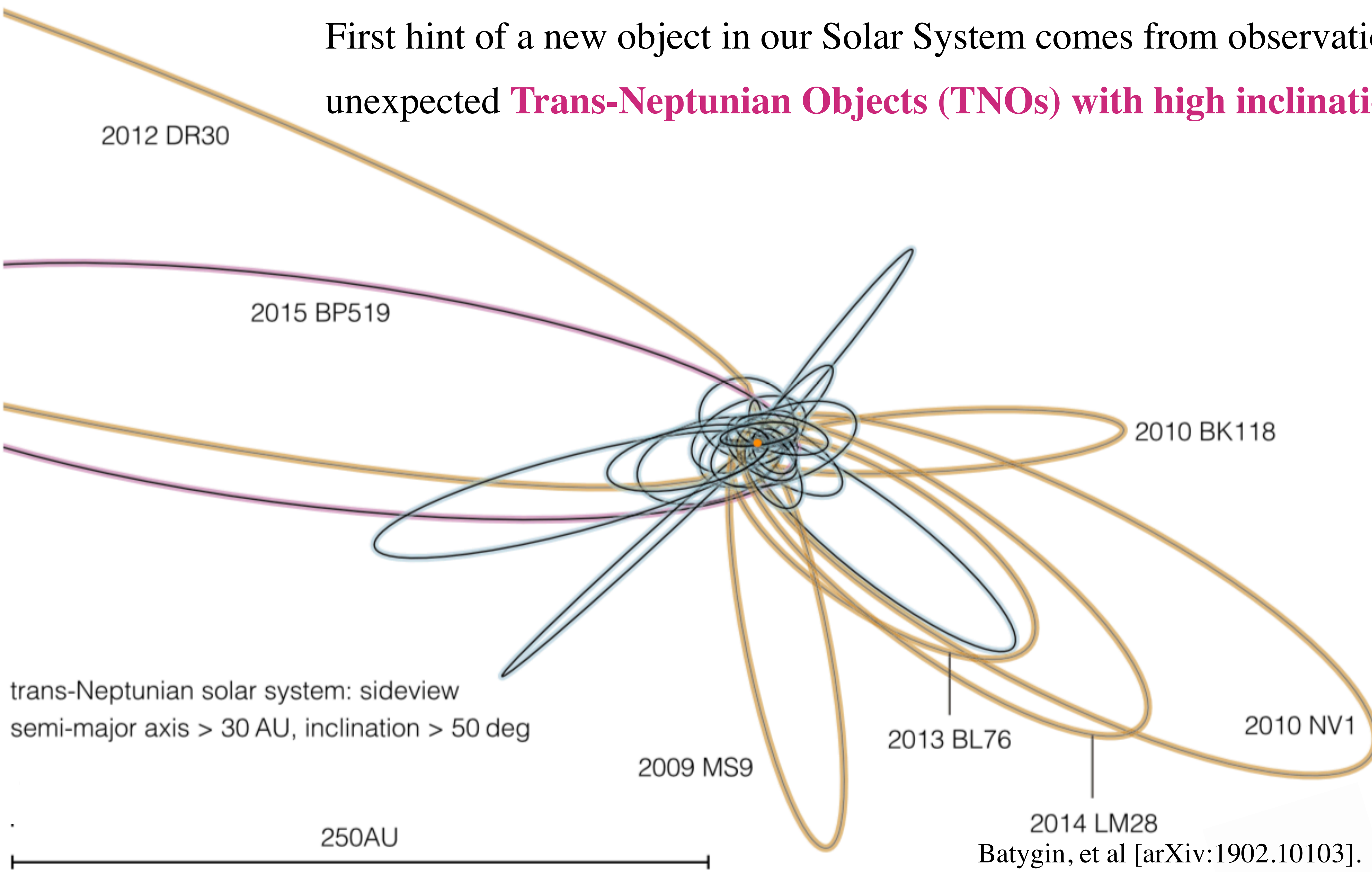


For p-wave this assumes s-wave contribution is exactly zero (see paper for full case).

III. Anomalous Orbits in our Solar System

High Inclination TNOs

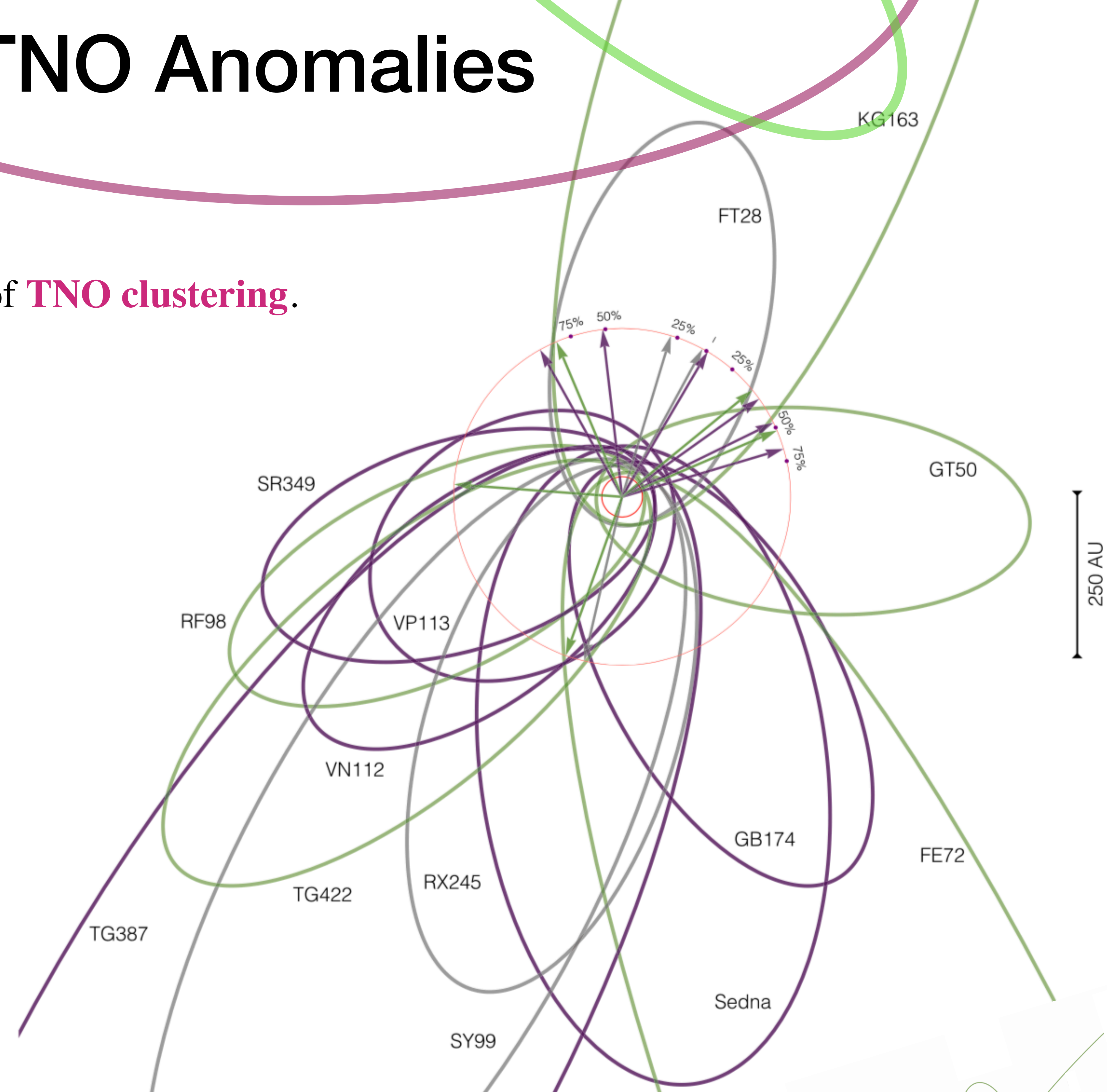
First hint of a new object in our Solar System comes from observations of unexpected **Trans-Neptunian Objects (TNOs) with high inclinations.**



Batygin, et al [arXiv:1902.10103].

TNO Anomalies

A second hint is observation of **TNO clustering**.



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TNO Anomalies

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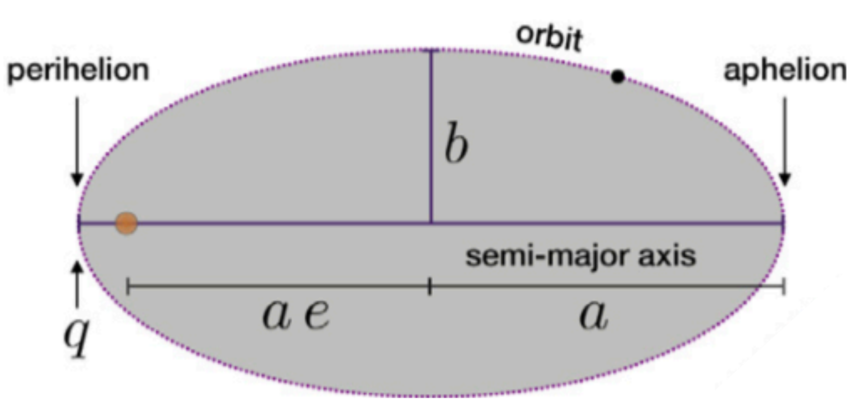
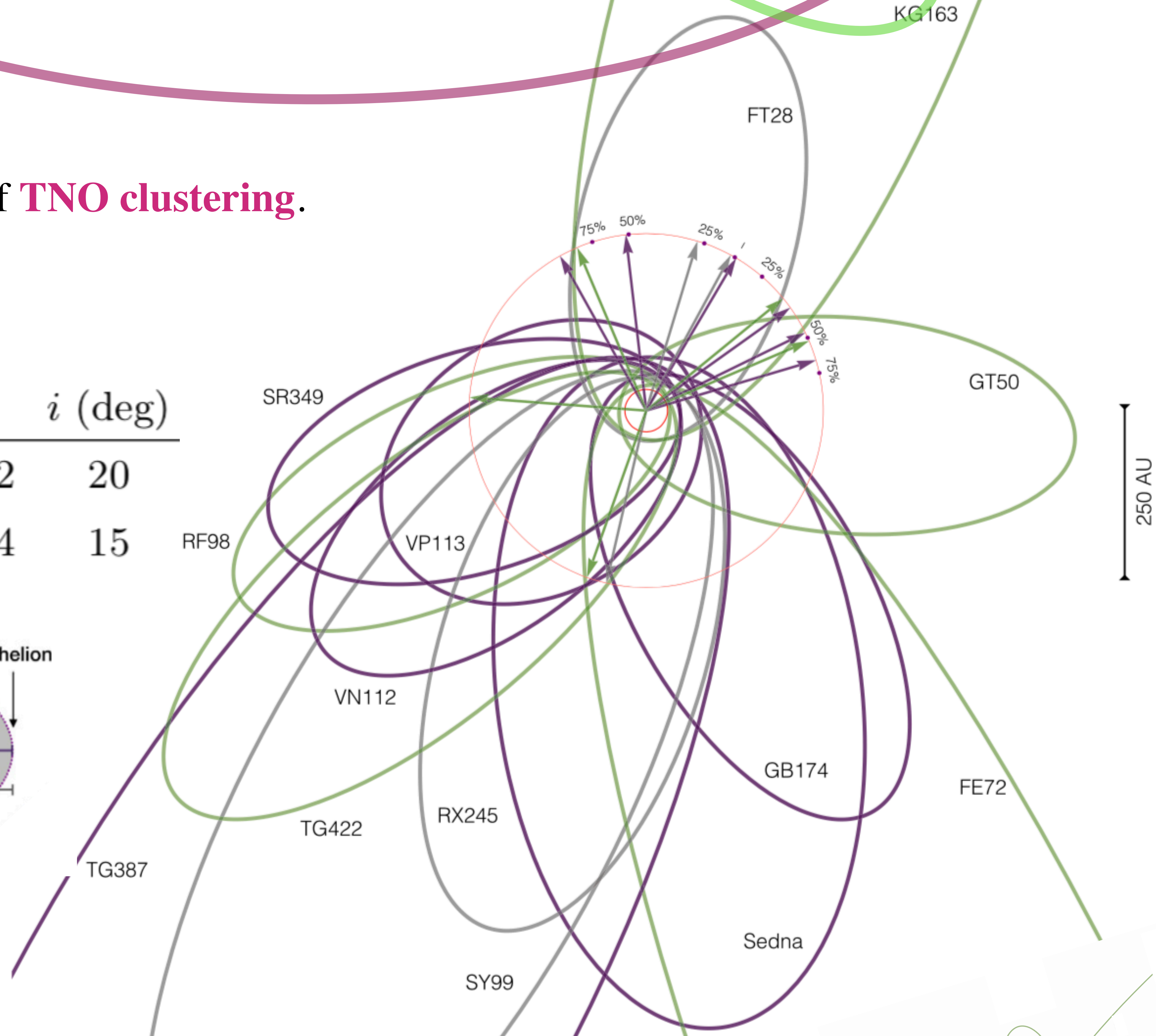
Indicative of new planet with:

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





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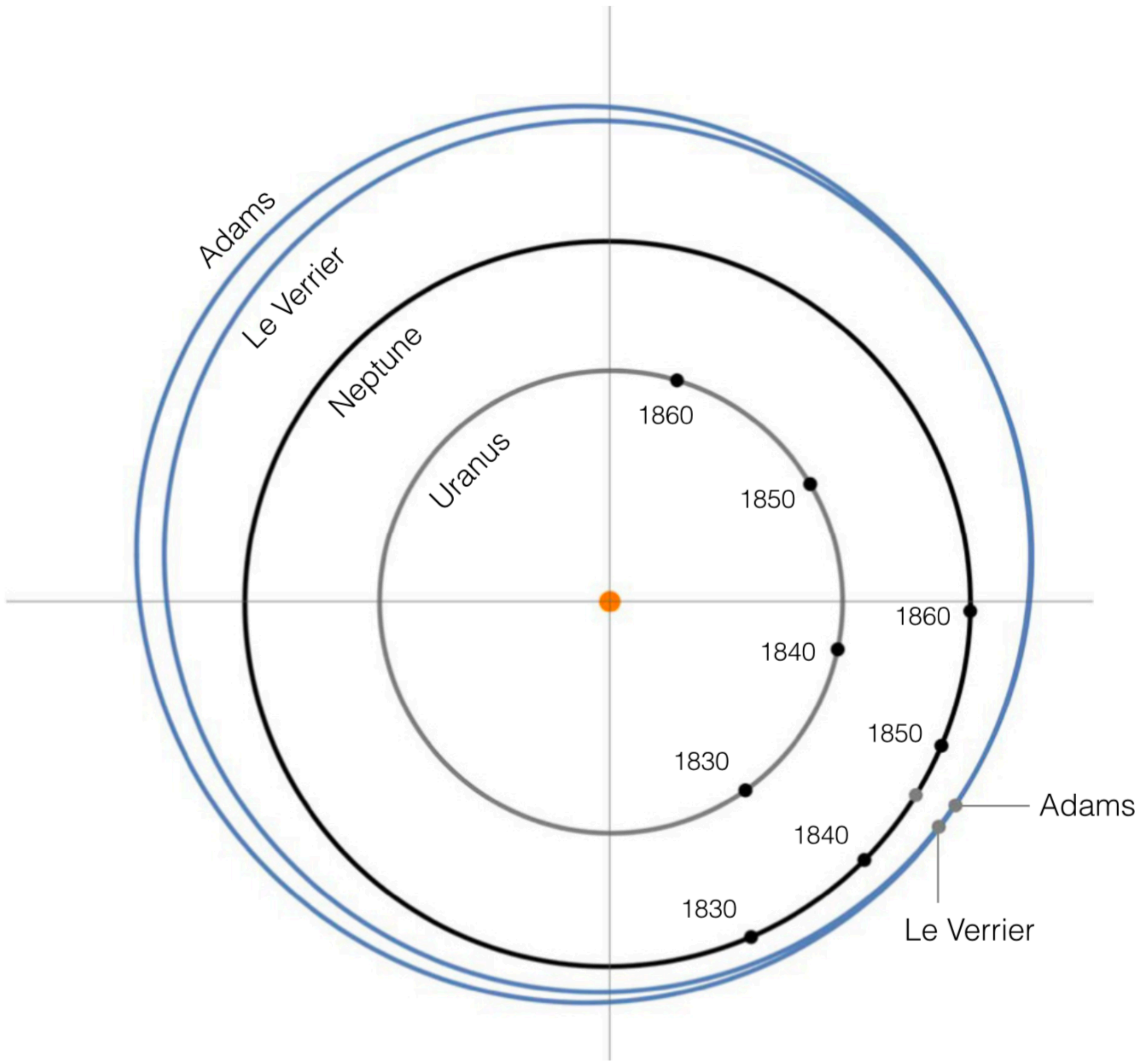
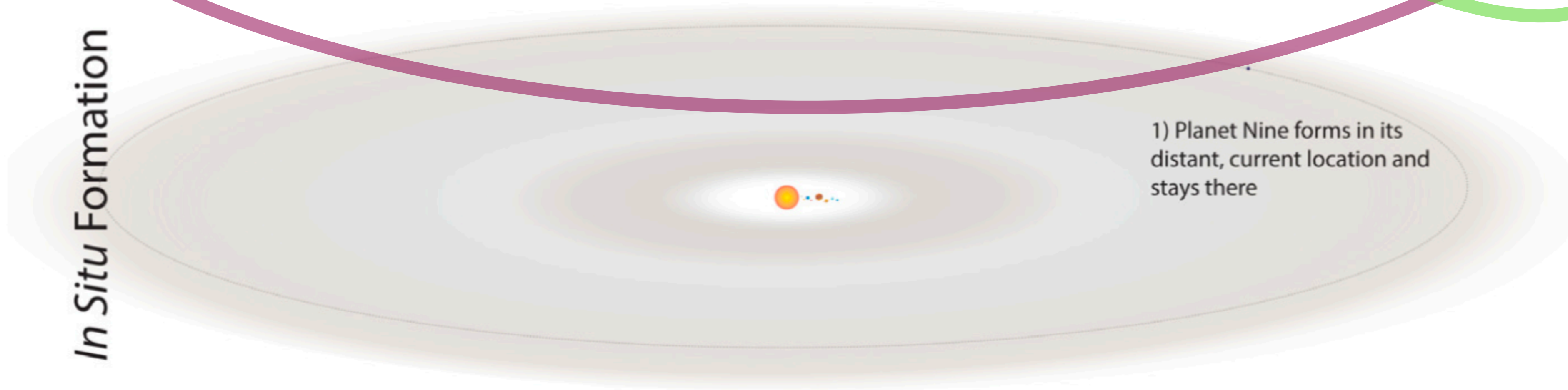
Unexpected Objects

Neptune predicted in 1846 from irregularities in the orbit of Uranus.



Could TNO orbits be hinting at a Ninth Planet?

Origins of Planet 9



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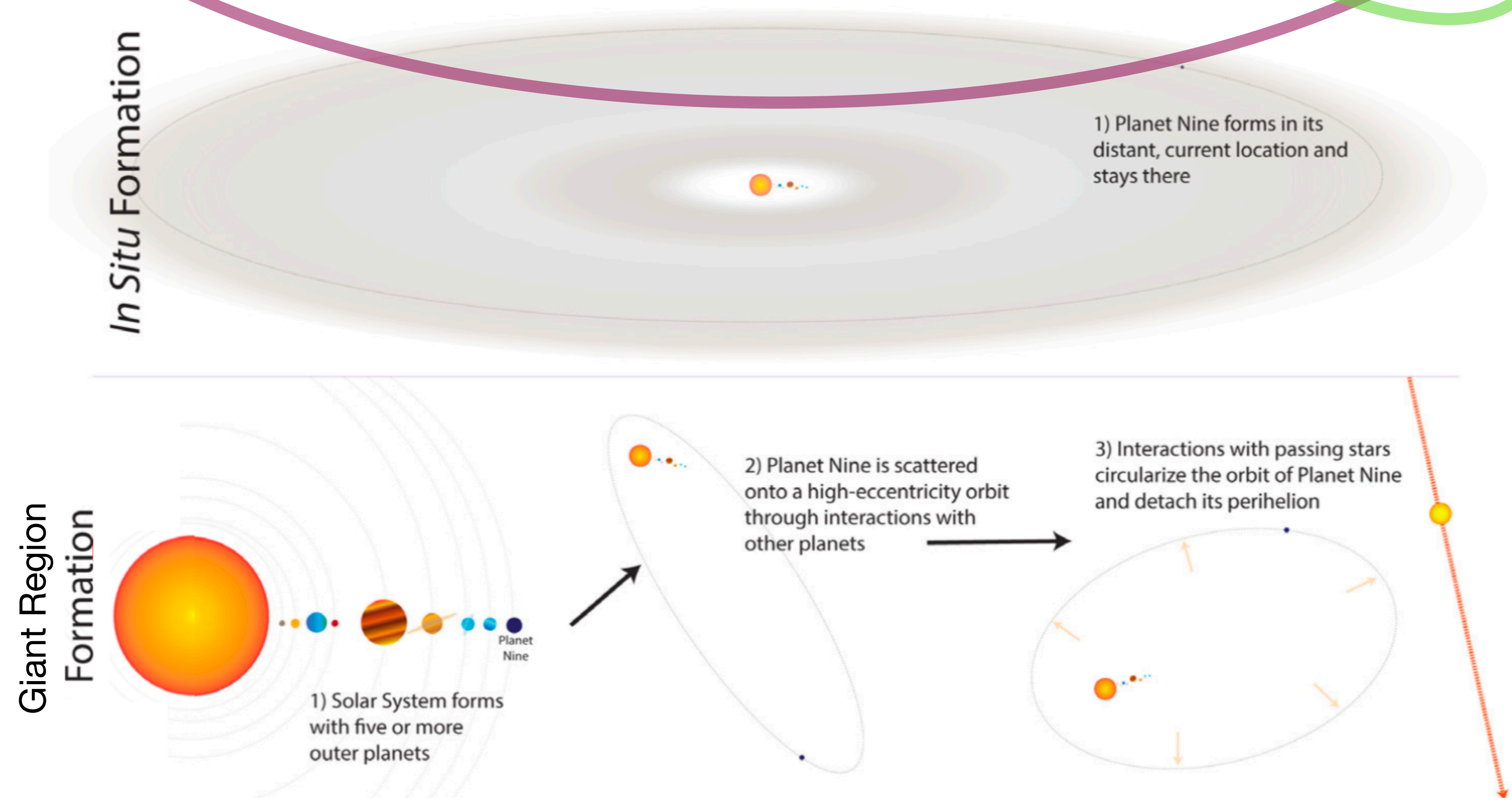
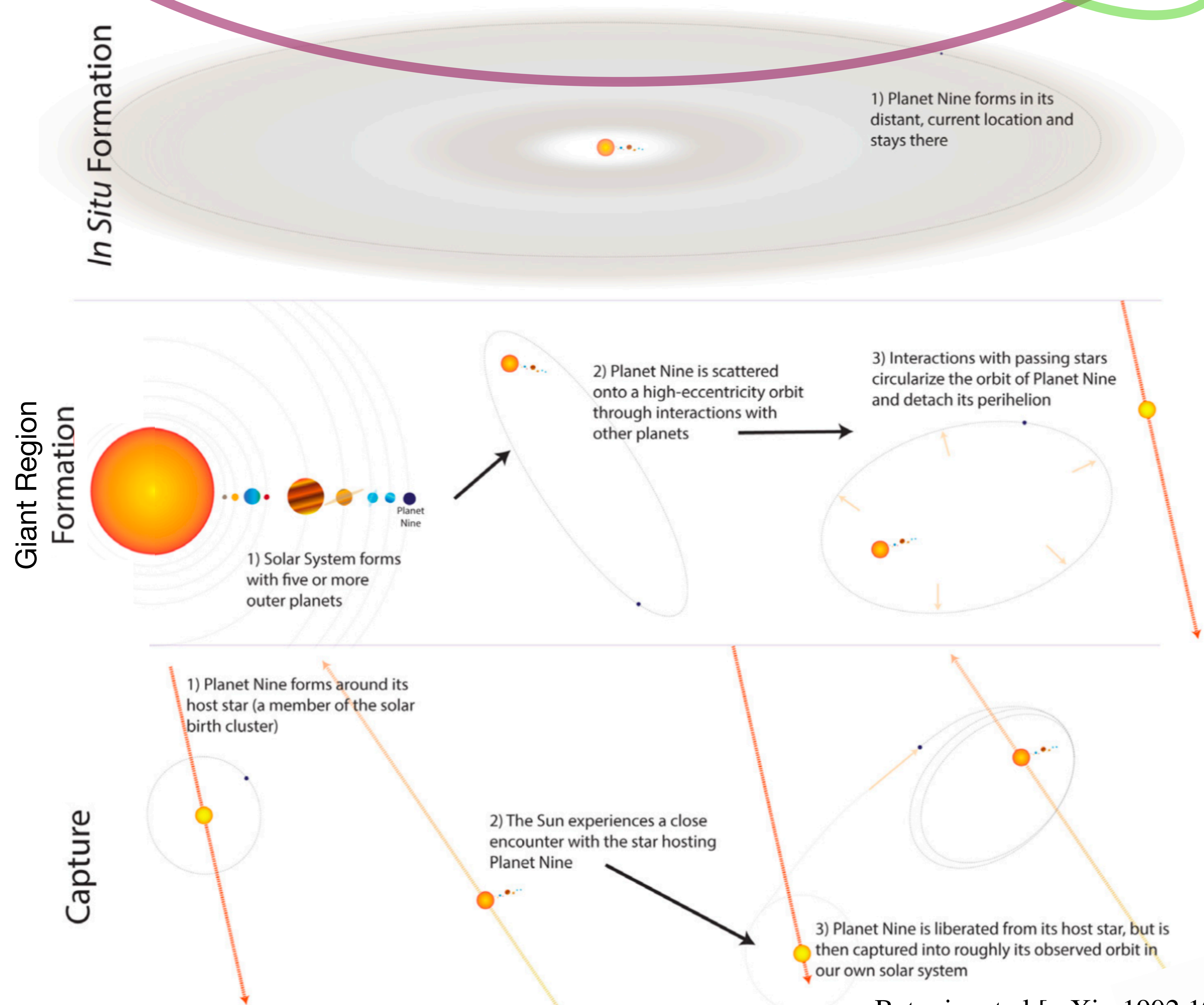


Batygin, et al [arXiv:1902.10103].

Origins of Planet 9



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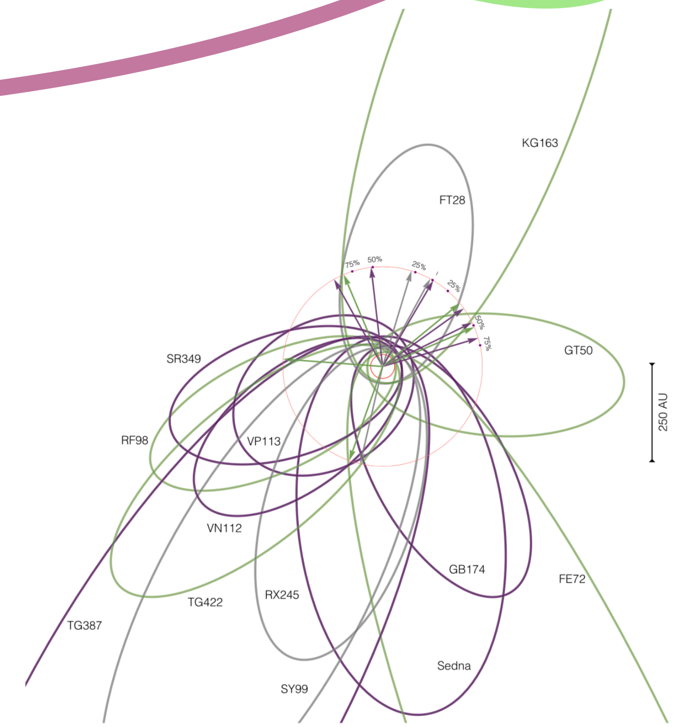
A Tale of Two Anomalies

Recall, TNO orbits indicative of new planet with:

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



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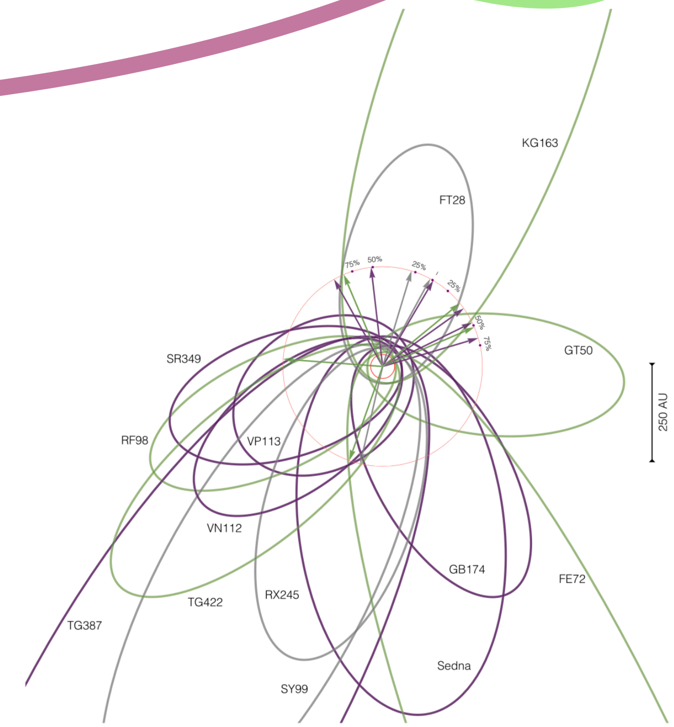
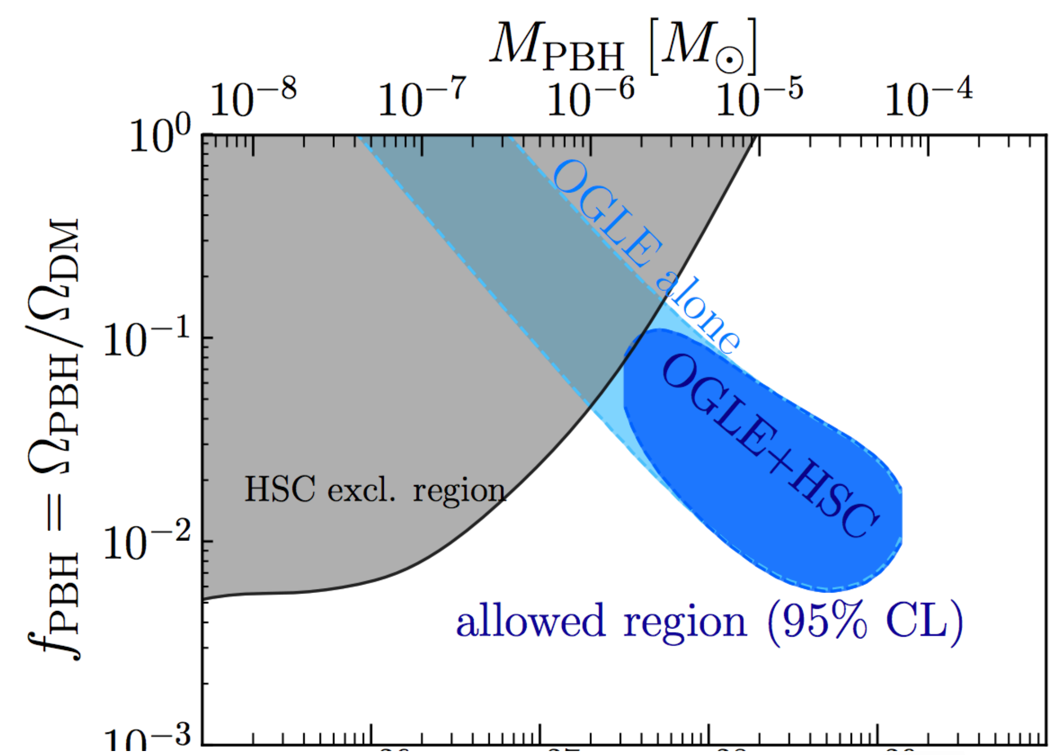


OGLE microlensing hinting at PBH with

$$M \in [0.5M_\oplus, 20M_\oplus]$$

$$f_{\rm PBH} \in [0.005, 0.1]$$



Remarkable coincidence of masses!

Could there be an “OGLE” PBH captured in our Solar System?

How many “OGLE” PBH?

The number density of PBH locally is given by $n_{\rm BH} = f_{\rm PBH}\left(\frac{\rho_{\rm DM}}{M_{\rm BH}}\right)$

Since they constitute a fraction of local dark matter: $\rho_{\rm DM} = 0.4~{\rm GeV/cm^3}$

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

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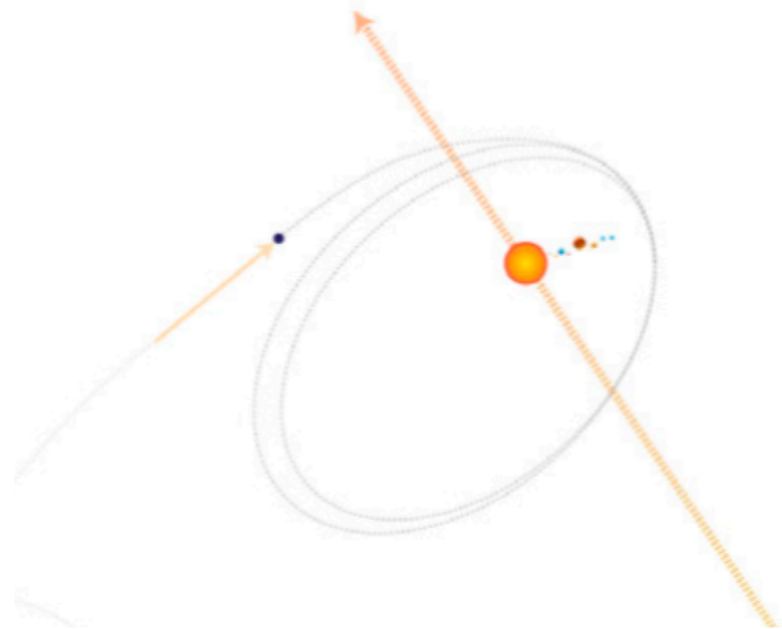
This implies the local number density is

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

Roughly ~35 PBH per star in our region of the galaxy.

Catching a PBH



How likely are you to "catch" a PBH vs a planet?

With the indicated PBH parameters form OGLE

$$M \in [0.5 M_\oplus, 20 M_\oplus] \;\; ; \quad f_{\rm PBH} \in [0.005, 0.1]$$

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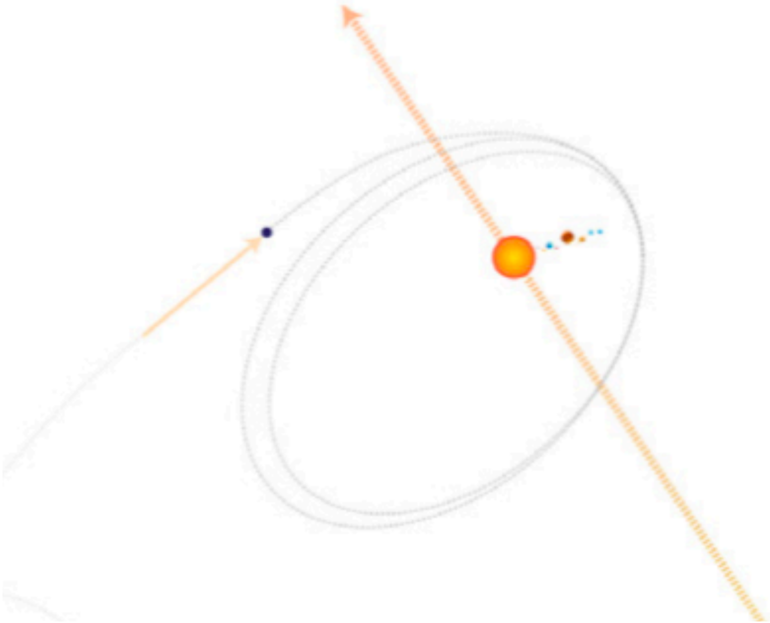

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$$M \in [0.5M_\oplus, 20M_\oplus] \ ; \quad f_{\rm PBH} \in [0.005, 0.1]$$

Relative capture rate: $$\frac{\Gamma_{\rm BH}}{\Gamma_{\rm FFP}} \sim \frac{n_{\rm BH}}{n_{\rm FFP}}\left(\frac{\sigma_{\rm FFP}}{\sigma_{\rm BH}}\right)^3$$ Goulinski and Ribak [1705.10332].

where σ are the velocity dispersions for each set of objects.

If we find that $\frac{\Gamma_{\rm BH}}{\Gamma_{\rm FFP}} \ll 1$ then the PBH hypothesis dead by Occam's razor.

Catching a PBH

The PBH velocity distribution is taken to be the same as the dark matter velocity dispersion $\sigma_{\rm PBH} \sim 160$ km/s and recall for OGLE PBH:

Drukier, Freese, and Spergel, Phys. Rev. D 33 (1986) 3495.

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

Free Planets have different velocity dispersion $\sigma_{\rm FFP} \sim 40$ km/s and their number density is estimated to be $n_{\rm FFP} \sim 0.2{\rm pc}^{-3}$

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Putting this together for "OGLE" PBH one estimates that

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

Thus we need not immediately discard the prospect of PBH capture.

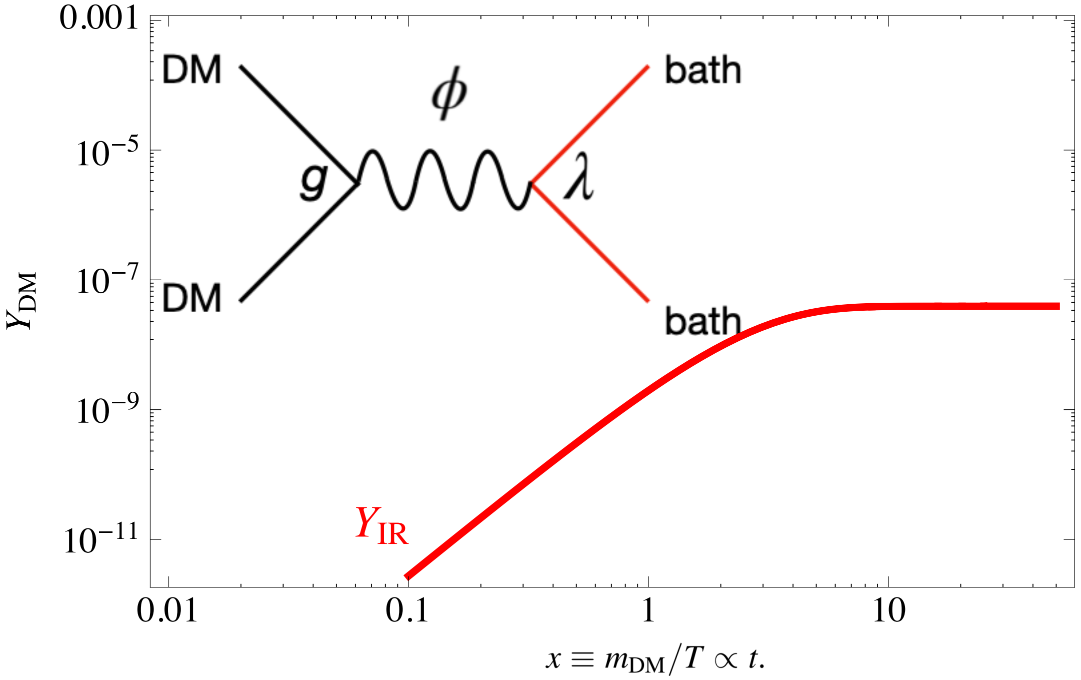
Scholtz & Unwin, PRL 125 (2020) 5, 051103

Dark Matter Story

Since $f_{\rm PBH} \neq 1$ we require some particle dark matter.

To evade detection we consider Freeze-in dark matter. The relic density scales as

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



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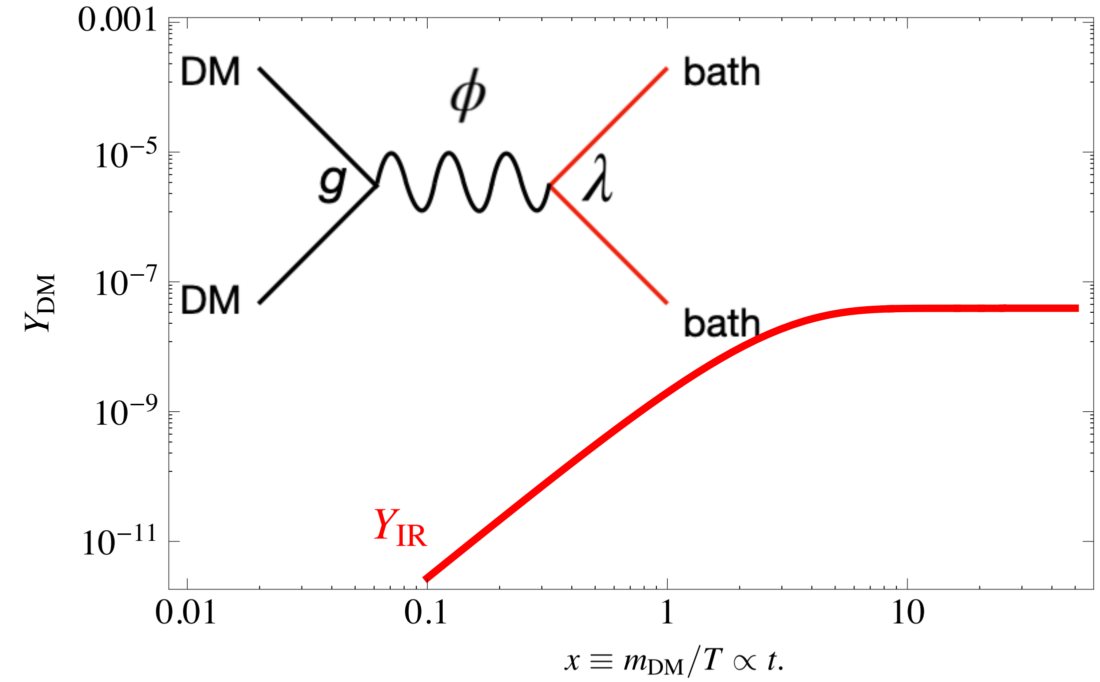

Parametrically

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

With these benchmark values it implies an annihilation cross section

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

The coupling g is largely unfixed.

Dark Matter Story

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

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

κ_1 is the average number of photons per DM annihilation. We take: $\kappa_1 \sim 10$

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The smallest detectable in 8 year FERMI-LAT catalog was J2143.0-5501 with

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

Since $\Gamma = 4\pi \int r^2 \mathrm{d}r \left(\frac{\rho(r)}{m}\right)^2 \langle \sigma v \rangle$, this implies a limit:

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

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

Searching in our Solar System

The Astrophysical Journal Letters, 898:L4 (3pp), 2020 July 20
https://doi.org/10.3847/2041-8213/aba119

Searching for Black Holes in the Outer Solar System with LSST

Amir Siraj and Abraham Loeb
Department of Astronomy, Harvard University, 60 Garden Street, Cambridge, MA 02138, USA; amir.siraj@cfa.harvard.edu, aloeb@cfa.harvard.edu
Received 2020 May 23; revised 2020 June 23; accepted 2020 June 29; published 2020 July 16

Search for accretion flares from impacts of small Oort cloud objects. LSST projection:

Searching in our Solar System

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CrossMark

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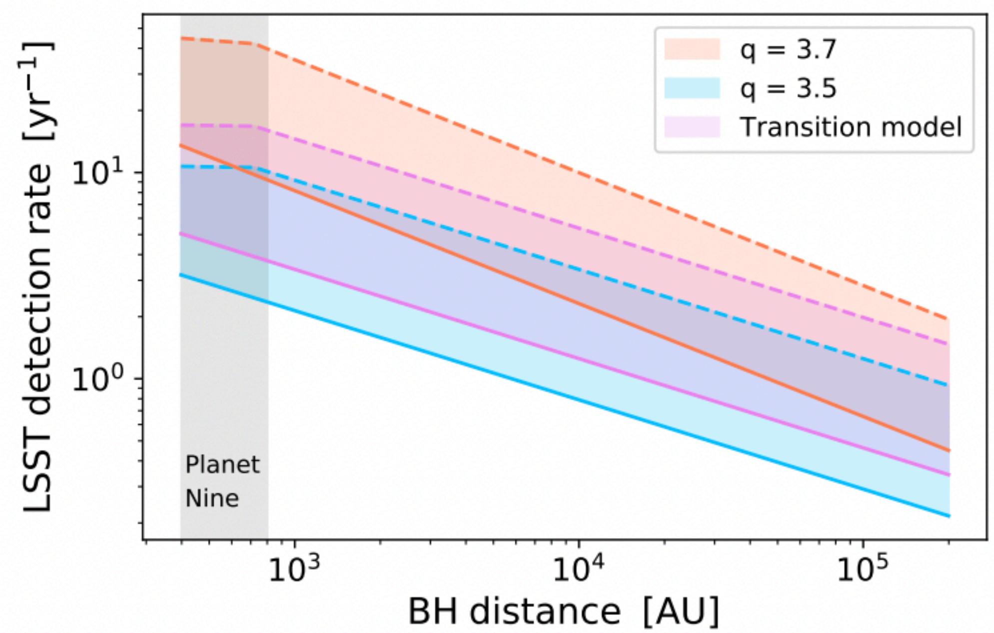


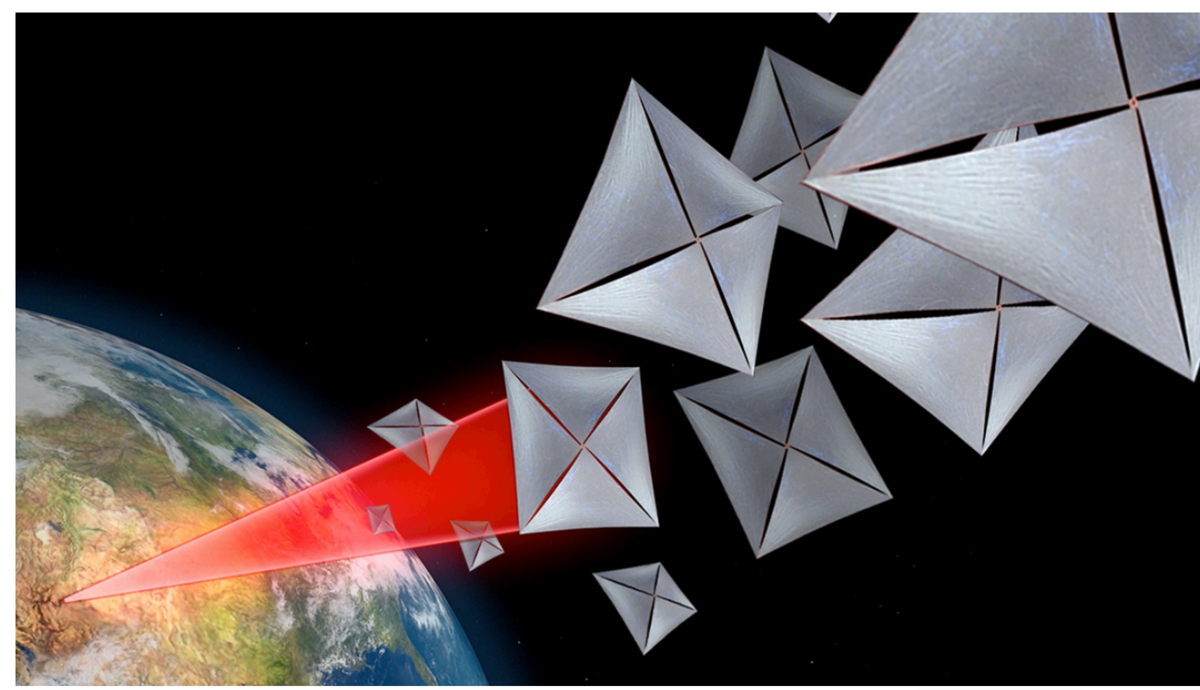
Figure 2. LSST detection rate per year as a function of the BH distance from the Sun (in AU), for $q \sim 3.7$, $q \sim 3.5$, and a broken power-law transition between the two slopes at impactor size $r \sim 10$ m. The range of possible Planet Nine distances are shown for reference. The dotted lines correspond to $M_{BH} \sim 10 M_\oplus$ and the solid lines to $M_{BH} \sim 5 M_\oplus$.

Searching in our Solar System

Searching for a Black Hole in the Outer Solar System

Edward Witten

Institute for Advanced Study
Einstein Drive, Princeton, NJ 08540 USA



Breakthrough Starshot Project

Searching in our Solar System

Breakthrough Starshot aims to use lasers to **accelerate gram mass spacecraft to 0.2c**

Aim is to reach study nearby **stars and exoplanets**.

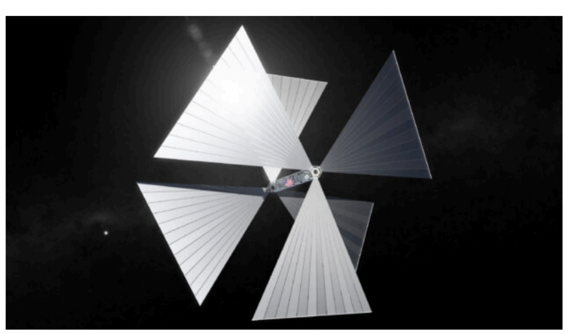
Studying **small deviations** of craft in path through solar system can constrain new large bodies.

Already studies of **Cassini, Pioneer, Voyager** place limits on the Planet 9 orbit

Holman, Payne 2016 AJ 152 94
Standish 1993 AJ 105 5

Care is needed with **noise** from density and magnetic fluctuations at edge of Solar System

Hoang & Loeb (2020) AJ. Lett., 895, L35,



Searching for a Black Hole

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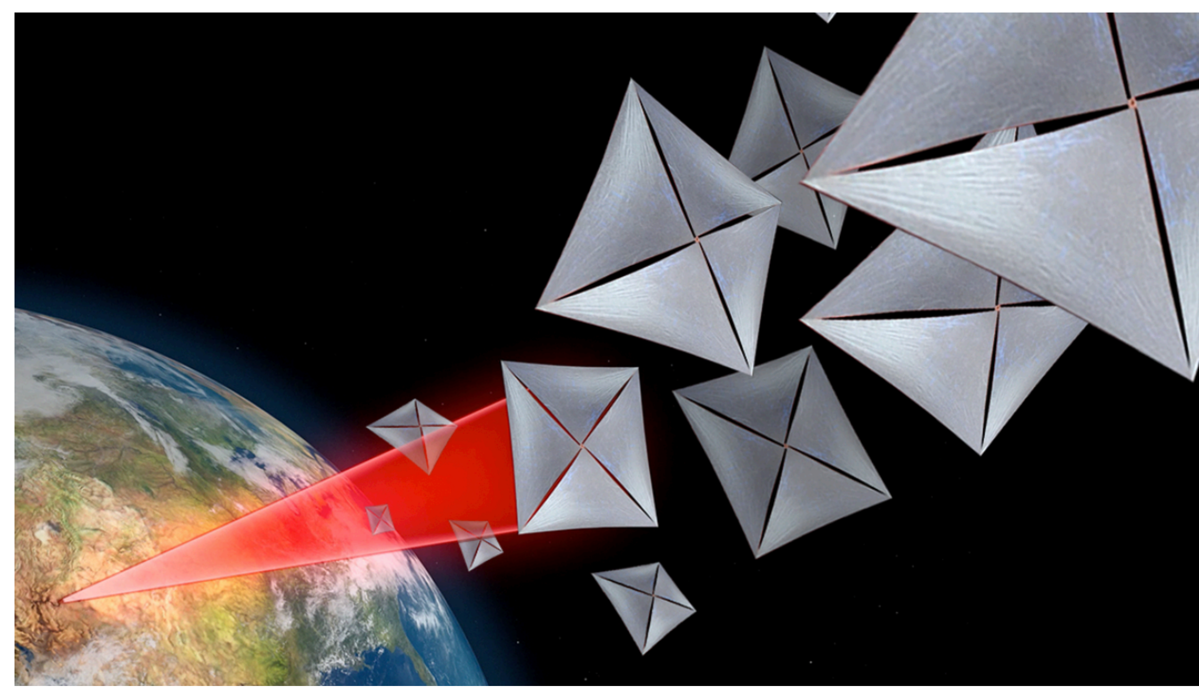


Breakthrough Starshot Project

Conclusions

Primordial Black Holes are fascinating hypothetical astrophysical bodies.

Scenarios with both particle dark matter and PBH can have enhanced signals.

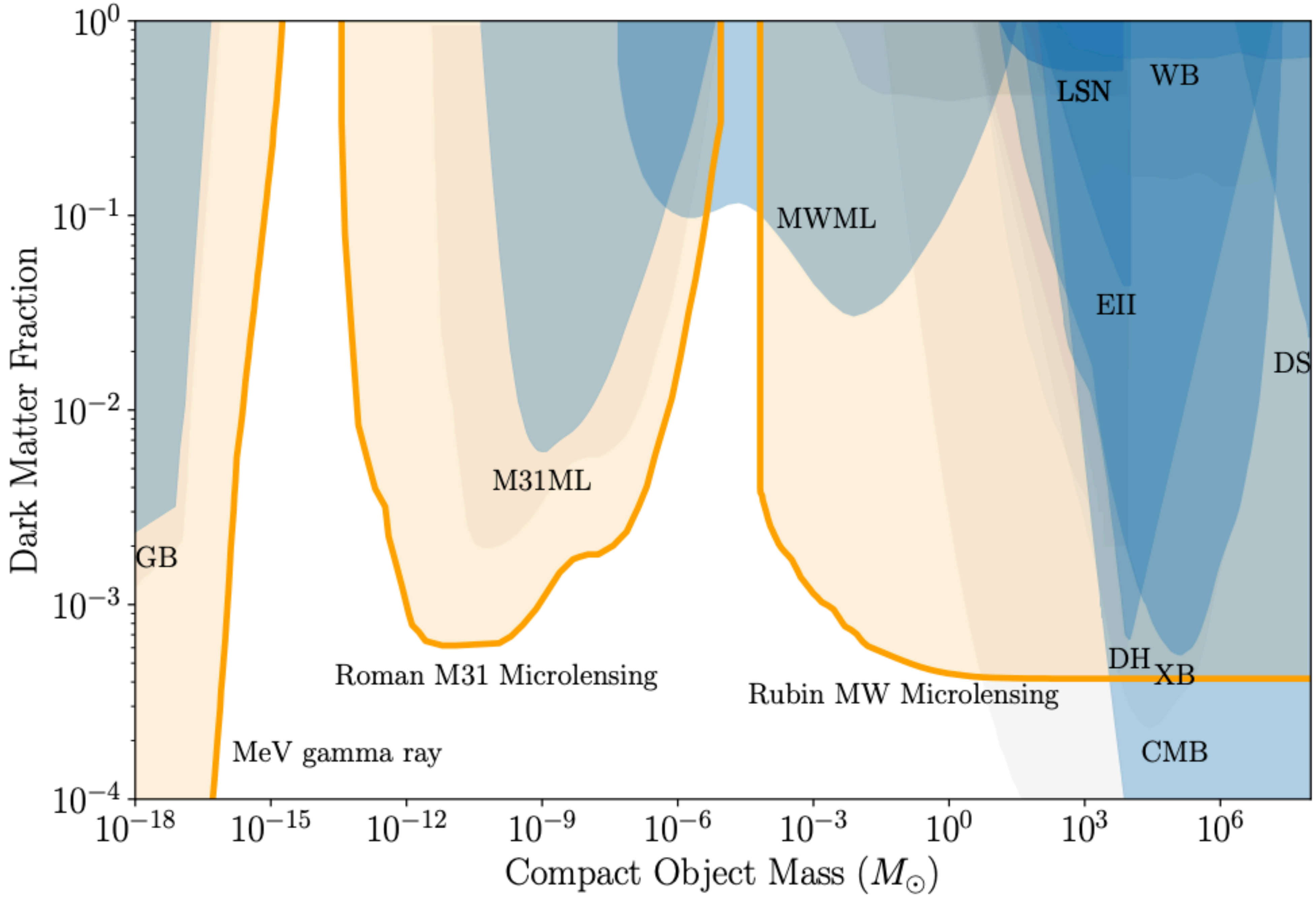
There is tentative evidence from TNO orbits for an extra body orbiting the sun.

Detection of a PBH would give insights on cosmology & fundamental physics.

Many upcoming experiments will continue the search for PBH.

New Scientist. 31 March 2021

Future Limits on PBH



Blue: Current constraints
Gold: Future constraints

Bird et al arxiv: 2203.08967

Mixed s-wave/p-wave

In p-wave model, one expects the ***s*-wave channel is non-zero** but negligible at freeze-out.

$$\langle \sigma v \rangle = \sigma_s + \sigma_p \frac{3}{2x} + \sigma_d \frac{15}{8x^2} + \cdots$$

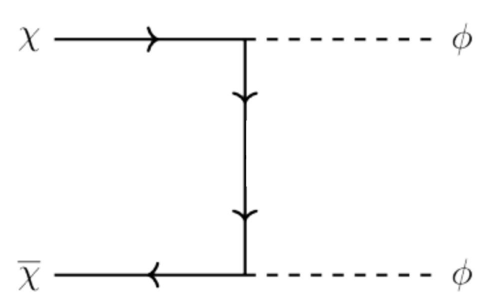
For p-wave processes to be **dominant at freeze-out** one requires a suppression of order

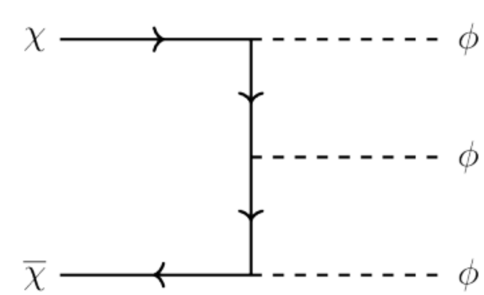
$$\mathcal{F} \equiv \sigma_s / \sigma_p \lesssim \mathcal{O}(10^{-3})$$

Simple models can readily give suppressions of

$$\mathcal{F}_{\rm loop} \sim g^2/16\pi^2 \sim 10^{-3} \left(\frac{g}{0.5}\right)^2 \qquad \mathcal{F}_{\rm chiral} \sim \left(\frac{m}{m_\chi}\right)^2 \sim 10^{-6} \left(\frac{10^{-3}}{m_\chi/m}\right)^2$$

Suppression factors also arise when 2→2 is p-wave but **2→3 is s-wave**, recall d-wave case, also for p-wave model:





Bell et al. 1705.01105

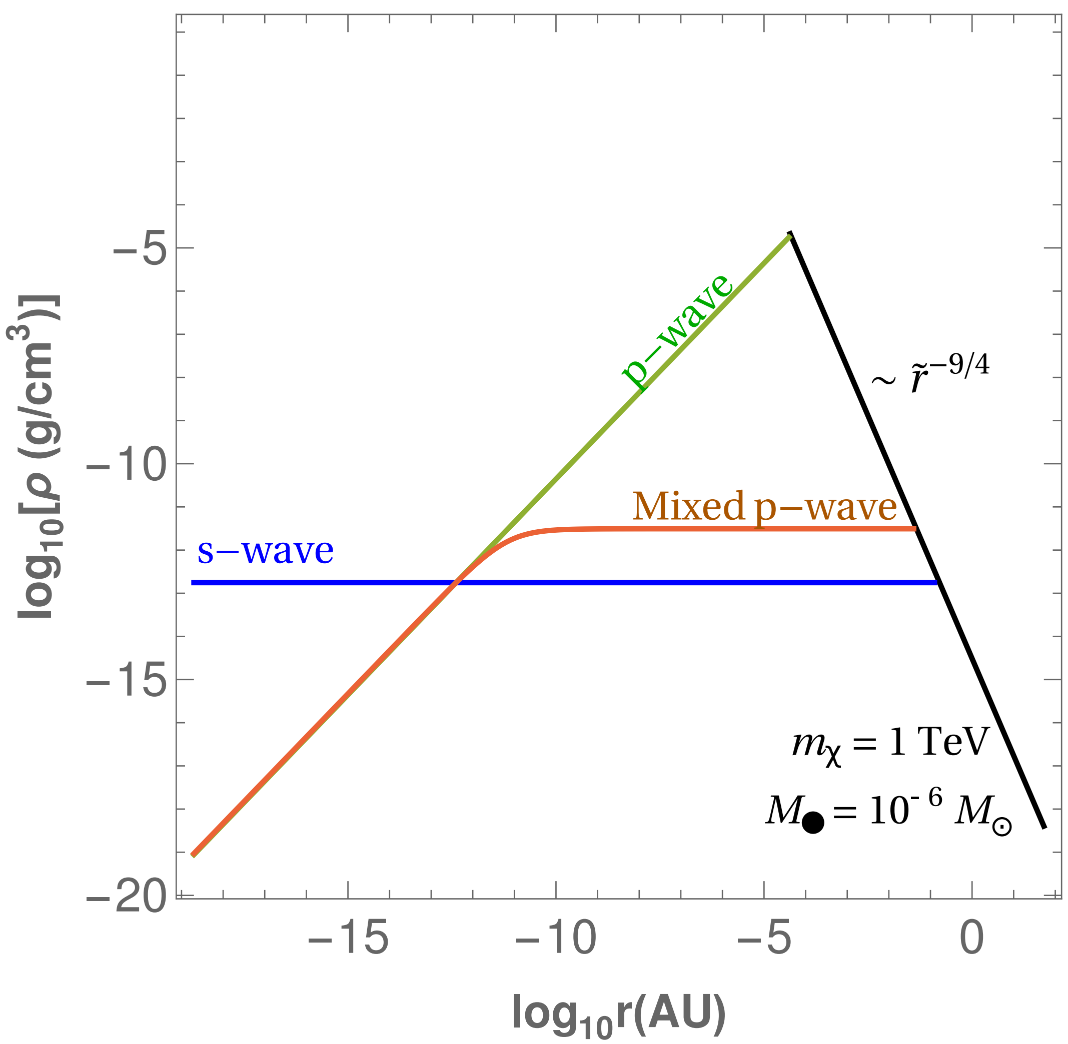
Mixed s-wave/p-wave

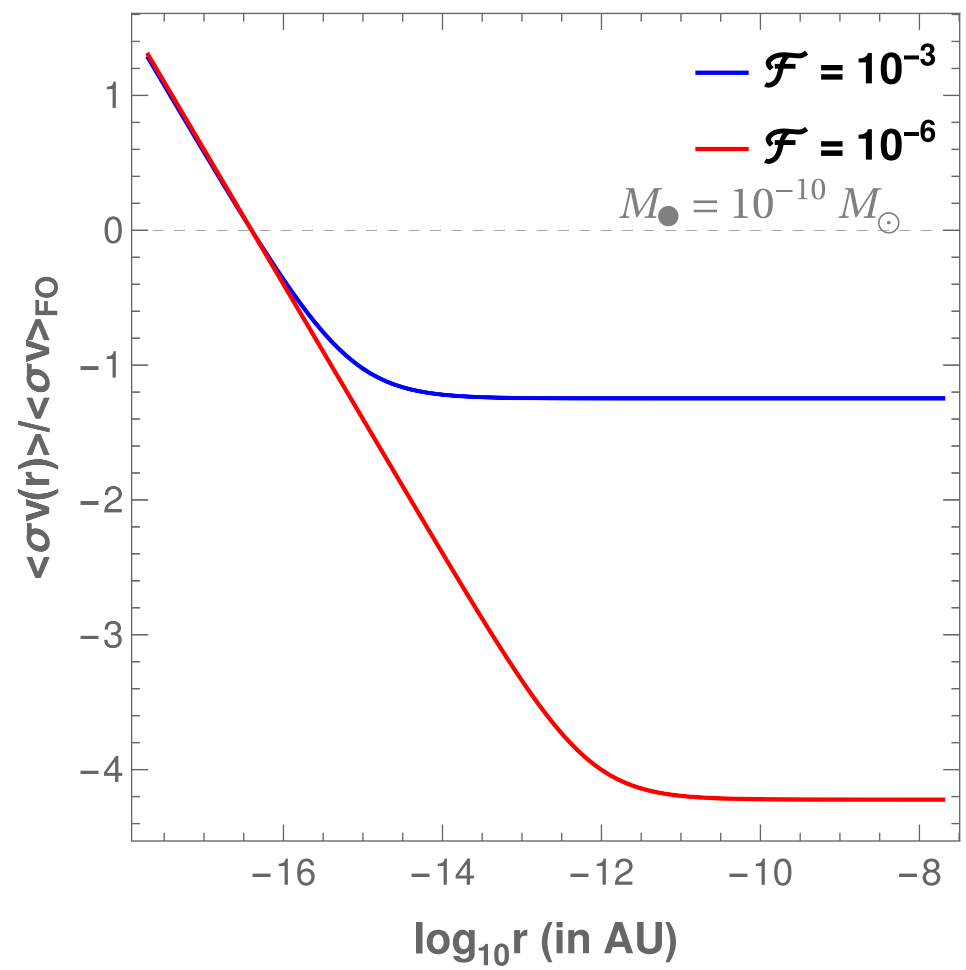
The dark matter velocity in the halo is not the velocity at freeze-out, but **velocity varies within halo**

$$v(r) = \sqrt{\frac{G}{r}(M_\bullet + M_{\rm halo}(r))}$$

Thus **cross section varies with radius**, plateau indicates s-wave dominance.

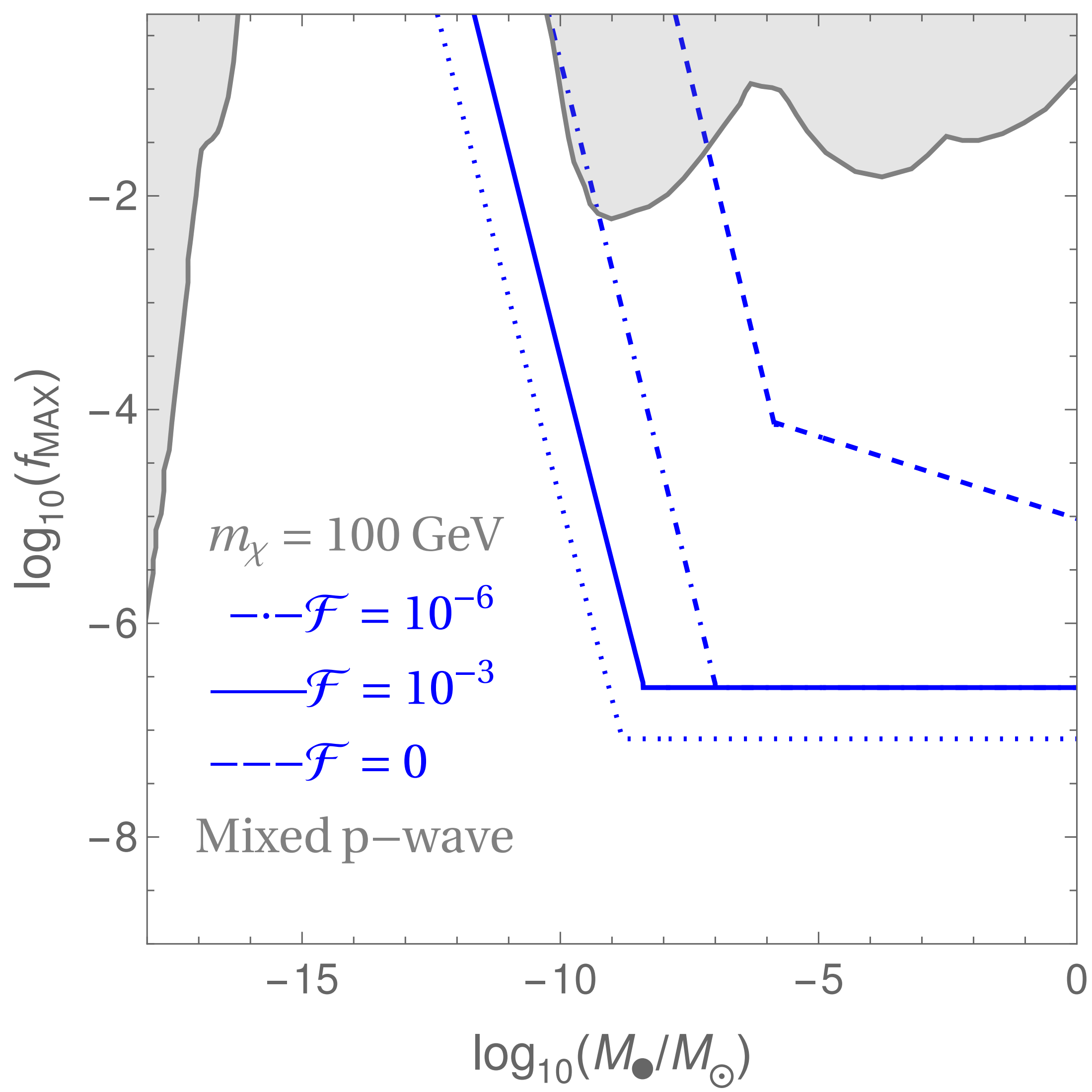
Implies at some critical radius expect dominant process to **switch from s-wave to p-wave**.

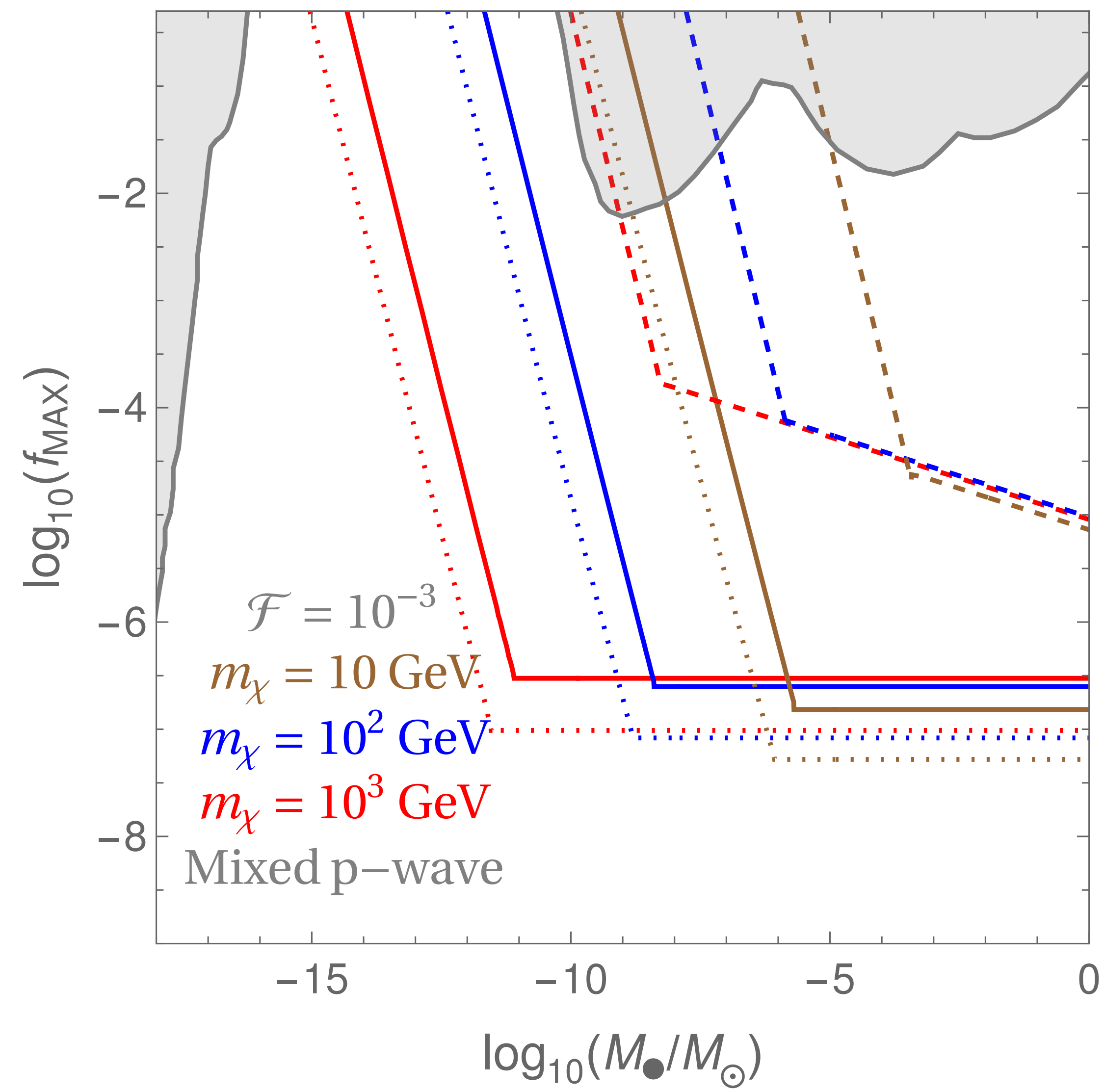




Mixed s-wave/p-wave

Accordingly, realistic p-wave models have **limits far closer to s-wave** models.





Solid: $\mathscr{F} = 10^{-}3$, Dotted: s-wave, Dashed p-wave.

Annihilation Rate

Redshift dependance of $\hat{\Gamma}_\bullet$ can complicated.

Comes from fact that **over time $\rho = \rho(z)$ changes** due to annihilations

Similarly stripping events occur over time.

Thus the halos evolve. For different scenarios **redshift dependance changes**.

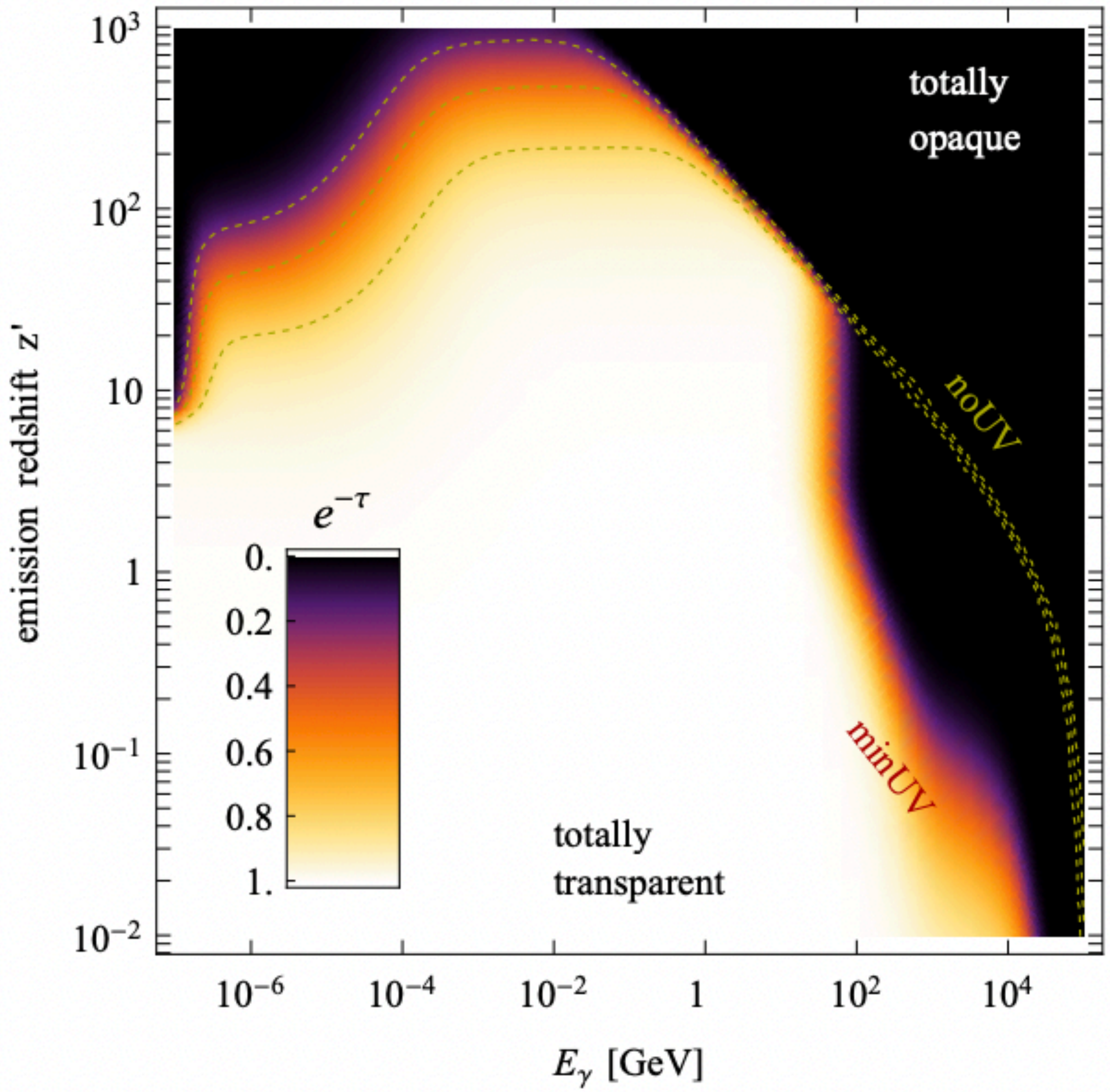
Parameterise $\hat{\Gamma}_\bullet = \Gamma_\bullet(h(z))^x$ where $h = H(z)/H_0$ and x is to be determined.

For light and heavy PBH one has

$$\hat{\Gamma}^L_\bullet \propto \begin{cases} 1 + \mathcal{O}(\log[h(z)]) & s\text{—wave} \\ h^{2/5}(z) & p\text{—wave} \\ h^{4/7}(z) & d\text{—wave} \end{cases} , \qquad \hat{\Gamma}^H_\bullet \propto \begin{cases} h^{2/3}(z) & s\text{—wave} \\ h^{10/13}(z) & p\text{—wave} \\ h^{14/17}(z) & d\text{—wave} \end{cases} .$$

Optical Depth

Optical depth parameterises absorption at different redshifts



Cirelli, et al [1012.4515]

Energy Spectrum

For quarks and leptons, energy spectrum can be parameterised

$$x^{1.5}\frac{\mathrm{d}N_\gamma}{\mathrm{d}x} = a_1 \exp\left(-b_1 x^{n_1} - b_2 x^{n_2} - \frac{c_1}{x^{d_1}} + \frac{c_2}{x^{d_2}}\right) + q\, x^{1.5} \ln\left[p(1-x)\right] \frac{x^2 - 2x + 2}{x}$$

Fitting from Pythia:

WIMP mass (GeV)	b_1	n_1	n_2	c_1	d_1	p
50	19.5	6.48	0.710	0.365	0.393	57.8
100	17.1	5.80	0.695	0.403	0.360	138
200	13.1	5.01	0.680	0.415	0.340	281
500	8.76	4.04	0.660	0.431	0.319	623
1000	6.00	3.36	0.647	0.447	0.305	1030
2000	4.60	2.85	0.640	0.460	0.294	1620
5000	3.00	2.26	0.634	0.479	0.280	2670
8000	2.35	2.00	0.629	0.490	0.274	3790

$a_1 = 10.0$; $b_2 = 11.0$; $c_2 = 0.0151$; $d_2 = 0.550$; $q = 2.60 \cdot 10^{-4}$

Table XXII: b **quark**: b_1, n_1, n_2, c_1, d_1 and p parameters corresponding to expression (6) in the $b\bar{b}$ channel for different WIMP masses. Mass independent parameters in (6) for this channel are presented at the bottom of the table.

Cembranos [1009.4936]

Prospect of Nearby PBH

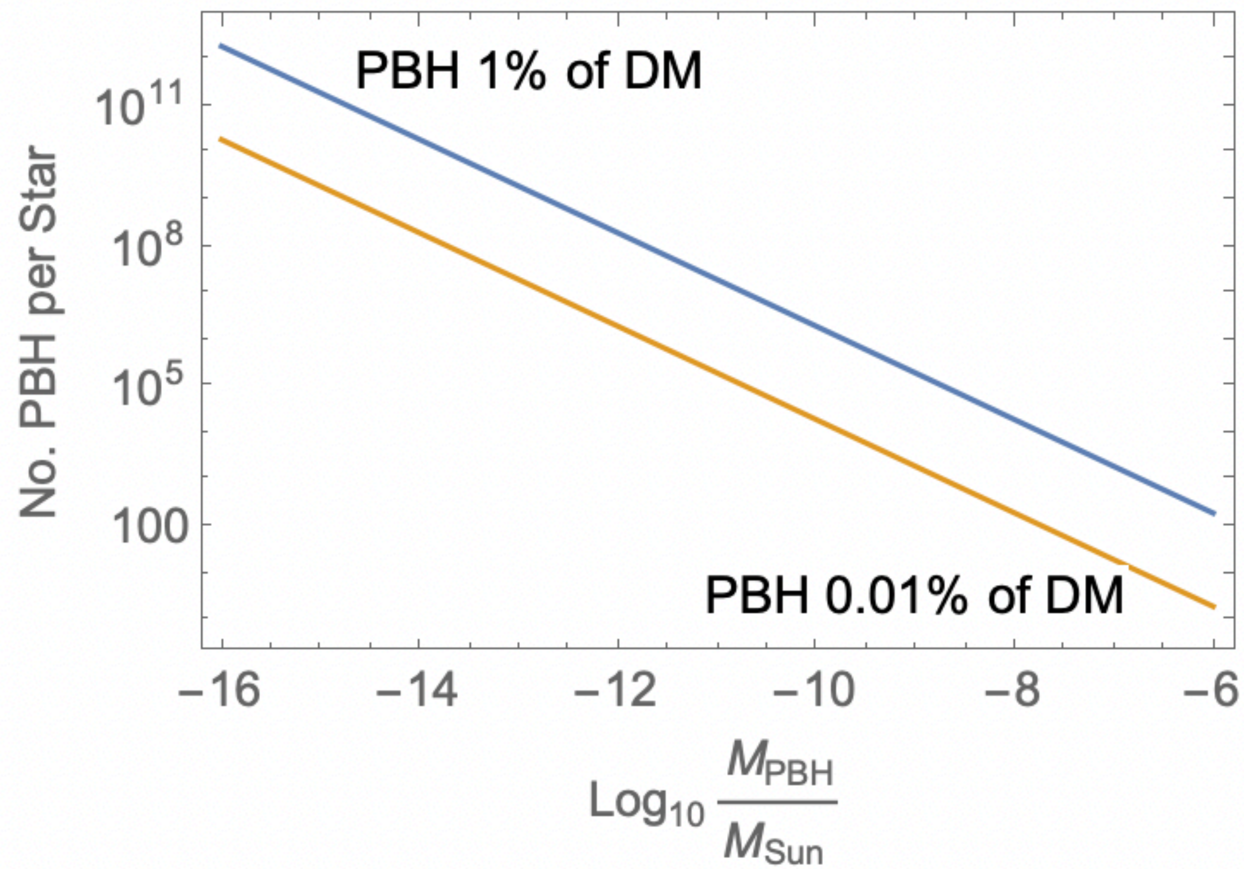
Recall for the OGLE PBH population $M \in [0.5M_{\oplus}, 20M_{\oplus}]$; $f_{\rm PBH} \in [0.005, 0.1]$

The number of nearby PBH was: $n_{\rm BH} \sim 35{\rm pc}^{-3}\left(\frac{f_{\rm BH}}{0.05}\right)\left(\frac{5M_{\oplus}}{M_{\rm BH}}\right)$

Ignoring OGLE excess, the value could be much higher:

$$\frac{n_{\rm PBH}}{n_*} \sim \frac{1}{n_*}\left(\frac{f_{\rm PBH}\rho_{\rm DM}}{M_{\rm PBH}}\right)$$

$$\sim 200 \times \left(\frac{1\,M_{\oplus}}{M_{\rm BH}}\right)\left(\frac{f_{\rm PBH}}{0.01}\right)$$



Prospect of nearby PBH could be great, even with small $f_{\rm PBH}$.

PBH Formation

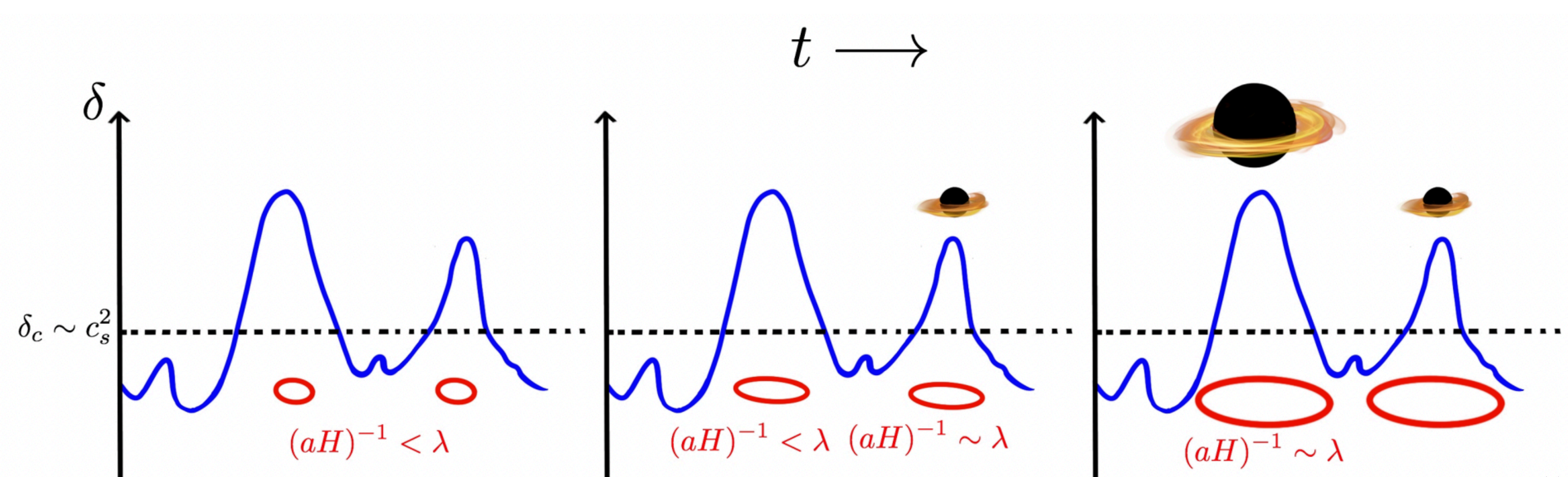
For PBH formation, require densities at least the mean inside the BH horizon $\rho_c \sim \rho_S = M_{\rm PBH}/(4\pi R_S^3/3)$

$$\sim 10^{18}(M/M_\odot)^{-2}\ \mathrm{g\ cm^{-3}}$$

The mass of the resulting PBHs should be of the order of the horizon mass at that time
i.e., the mass within a region of the size of the Hubble horizon

$$M_{\rm PBH} \sim M_{\rm H} = \frac{4}{3}\bar{\rho}\left(\frac{c}{H}\right)^3 = \frac{c^3}{2GH} \sim 10^{15}\ \mathrm{g}\ \left(\frac{t}{10^{-23}\mathrm{s}}\right)$$

Since the PBH mass is roughly the horizon mass, fluctuations entering the horizon can collapse into PBHs.

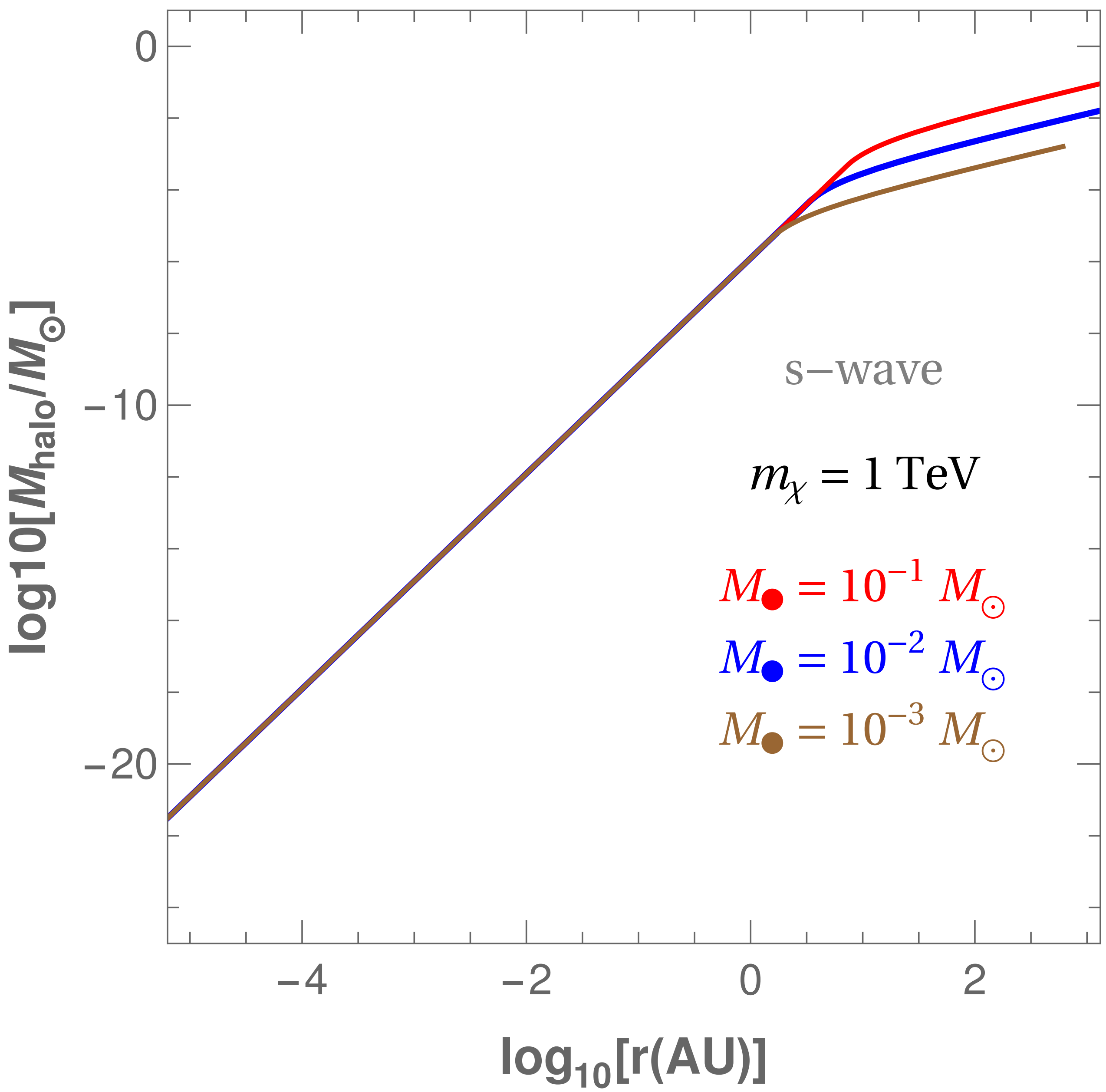


Villanueva-Domingo 2103.12087

FIG. 1: Sketch of the formation of PBHs from overdensities for three different successive moments. When fluctuations larger than a critical threshold $\delta_c \sim c_s^2$ enter the horizon, i.e., their wavelength $\lambda = 2\pi/k$ (which characterizes the size of the perturbation) is of the order of the Hubble horizon $(aH)^{-1}$, the overdense region collapses and a PBH is produced.

Extra Slide: PBH Halo

Mass enclosed at given radius.



Fractional mass loss due to annihilations.