A Black Hole at the Edge of our Solar System?

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New Trends in Dark Matter
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Work with Jakub Scholtz
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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 $i \gtrsim 50^\circ$)

Chance of random alignment of TNOs $\sim 1$ in 15,000.

Observational bias is claimed to be accounted for.

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:

<table>
<thead>
<tr>
<th>Benchmark</th>
<th>$a$ (AU)</th>
<th>$e$</th>
<th>$i$ (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$5M_\oplus$</td>
<td>450</td>
<td>0.2</td>
<td>20</td>
</tr>
<tr>
<td>$10M_\oplus$</td>
<td>700</td>
<td>0.4</td>
<td>15</td>
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</tbody>
</table>
II. Something in the Outer Solar System
Origins of Planet 9


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Origins of Planet 9

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

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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Origins of Planet 9


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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?
“Something” Out There?

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

Astrophysical black holes form from stellar collapse implying

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

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

Optical Gravitational Lensing Experiment

[Graph showing the allowed region (95% CL) for $f_{\text{PBH}} = \Omega_{\text{PBH}}/\Omega_{\text{DM}}$ vs. $M_{\text{PBH}}$]
Find probability of Solar System catching a PBH vs planet.

Gravitational capture rate of an object is given by

\[ \Gamma = \int n_0 F(v + v_\odot, r) \frac{d\sigma}{dv} \, vdv \]

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].
Catching a PBH

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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.

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:

\[ \frac{\Gamma_{BH}}{\Gamma_{FFP}} \sim \frac{n_{BH}}{n_{FFP}} \frac{F_{PBH}(v_{\odot}, PBH)}{F_{FFP}(v_{\odot}, FFP)} \sim 1 \times \left( \frac{0.2 \text{pc}^{-3}}{n_{FFP}} \right) \left( \frac{40 \text{km/s}}{\sigma_{FFP}} \right)^3 \left( \frac{f_{BH}}{0.05} \right) \left( \frac{5M_{\odot}}{M_{BH}} \right). \]
III. Dark Matter around PBHs
For $f_{\text{PBH}} \in [0.005, 0.1]$ implies also particle dark matter.

Generically this leads to dark matter halos around the PBH.

The total mass of the halo satisfies

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

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

Eroshenko [1607.00612] Adamek, Byrnes, Gosenca, & Hotchkiss [1901.08528].
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Defining $r_{\text{eq}} \equiv r_{\text{in}}(t_{\text{eq}}) \sim 220 \text{ AU} \times (M_{\text{BH}}/5M_\odot)^{1/3}$

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

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

Eroshenko [1607.00612] Adamek, Byrnes, Gosenca, & Hotchkiss [1901.08528].

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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**:

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

where $r_\star$ is distance between two bodies and $M_{\text{initial}}$ refers to the body being stripped.
Thus once the PBH settles into an orbit around the Sun, tidal radius cuts off the PBH halo at

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

Note that 8 AU is $10^9$ km, compare this to Earth mass PBH with diameter 10cm!
Consider the OGLE PBG population $M \in [0.5M_\oplus, 20M_\oplus]$; $f_{\text{PBH}} \in [0.005, 0.1]$

For a WIMP DM cross section $\langle \sigma v \rangle_0 \sim 3 \times 10^{-26}\text{cm}^3/\text{s}$ this is VERY excluded.
An alternative to WIMPs which have much smaller annihilation is Freeze-in.
In this scenario the relic density of dark matter scales as follows

\[ \Omega_{DM} \propto m Y_{FI} \propto \lambda^2 \]

Parametrically

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

With these benchmark values it implies an annihilation cross section

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

The coupling \( g \) is largely unfixed.
The dark matter annihilation rate is given by

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

Using the density profile from earlier:

$$\rho(r) = \frac{\rho_{eq}}{2} \left( \frac{r_{eq}}{r} \right)^{9/4}$$

and the characteristic cross section:

$$\langle \sigma v \rangle_{ch} \simeq 1.3 \times 10^{-56} \text{cm}^3/\text{s} \times \left( \frac{g}{10^{-2}} \right)^2$$
The dark matter **annihilation rate** is given by

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

And the characteristic cross section: \( \langle \sigma v \rangle_{ch} \simeq 1.3 \times 10^{-56} \text{cm}^3/\text{s} \times \left( \frac{g}{10^{-2}} \right)^2 \)

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

\[ \Gamma = \sqrt{\frac{3 \rho_{eq}}{8\pi G^3}} \frac{\langle \sigma v \rangle}{m^2} = 10^{20} \text{s}^{-1} \left( \frac{\langle \sigma v \rangle}{\langle \sigma v \rangle_{ch}} \right) \left( \frac{100 \text{GeV}}{m} \right)^2 \]
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 $\kappa_1$ 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

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

Since $\Gamma$ depends on the annihilation cross section, 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 is satisfied freeze-in model: $\langle \sigma v \rangle_{\text{ch}} \approx 1.3 \times 10^{-56} \text{cm}^3/\text{s} \times \left( \frac{g}{10^{-2}} \right)^2$
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 $5 \, M_\odot$

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

arXiv:1909.11090