Primordial Black Holes as a unique tool for early Universe exploration

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1. General Properties of 4- and extradimensional (ED) Primordial Black Holes (PBH)
2. Stationary spherically symmetric hydrodynamical accretion of Ultra Relativistic Plasma (URP) onto ED-PBH
3. Astrophysical constraints on PBH distribution in braneworld cosmology
4. Interaction of multidimensional PBH with compact objects
1. General Properties of 4- and extradimensional Primordial Black Holes (PBH)
Ya. B. Zeldovich together with I.D. Novikov are first inventors of PBH

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

The existence of bodies with dimensions less than $R_g = 2GM/c^2$ at the early stages of expansion of the cosmological model leads to a strong accretion of radiation by these bodies. If further calculations confirm that accretion is catastrophically high, the hypothesis on cores retarded during expansion [3, 4] will conflict with observational data.

Ambartsumyan has long held the view that stars and galaxies formed from hypothetical superdense same expression, in order of magnitude, for the mass variation of the body. The formula for non-
PBH: "universal" objects

Form from initial inhomogeneities, carry information about formation epoch

\[ M_{PBH} = 10^{-5} \, gr - 10^6 \, M_\odot, \quad t_{PBH} = 10^{-35} \, s - 10^{82} \, yr \]

Phase Transitions

Primordial fluctuations

Cosmic Rays

Recombination Kinetic

Hydrogen ionization

"Their discovery would provide a unique probe of at least four areas of physics: the early Universe; gravitational collapse; high energy physics; and quantum gravity"

"Their study may place interesting constraints on the physics relevant to these areas even if they never formed!"
Previous results of AP Group in RINP

\[ M < M_{WD} \leq 1.3M_{\text{sun}} \]


V.I. Dokuchaev was pointed our group to the problem of WD absorption.
Braneworlds

Compact ED - ADD (1998)
In all Braneworlds matter is localized, but gravity can propagate in all dimensions

\[ R_5 \sim 10^{15} \text{ cm} \]
\[ R_6 \sim 10^{-1} \text{ cm} \]

Noncompact ED - RSII (1999)
Joining of two \( Z_2 \) - symmetric regions of the AdS\(_5 \) - space

\[ G_4 = \frac{G_5}{l} , \quad H^2 = \frac{8\pi G_4}{3} \rho \left( 1 + \frac{\rho}{2\sigma} \right) \]
\[ t_c \approx \frac{l}{2} \]

How D-RD epoch will affect on PBH?
Properties of multidimensional Black Holes

Schwarzschild-Tangherlini solution (1963):

\[ ds = -\left(1 - \frac{r_g^{D-3}}{r^{D-3}}\right) dt^2 + \frac{dr^2}{1 - \frac{r_g^{D-3}}{r^{D-3}}} + r^2 d\Omega_{D-2}^2 \]

\[ r_g = \frac{1}{\sqrt{\pi}} \left( \frac{M_{BH}}{M_D} \right)^{\frac{1}{D-3}} \left( \frac{8\Gamma \left( \frac{D-1}{2} \right)}{D-2} \right) \frac{1}{D-3} , \quad T_H = \frac{D-3}{4\pi r_g} , \]

(D>4)-bigger, colder, live longer than in D=4

Generalization of Birkhoff's theorem: S-T solution is just one static vacuum solution for D-dimensional asymptotically flat space-time

\[ r_g \ll R_D , l \Rightarrow g_{\mu\nu} \rightarrow \text{Tends to S-T solution for any Braneworld} \]

Projection onto brane:

\[ ds = -\left(1 - \frac{r_g^{D-3}}{r^{D-3}}\right) dt^2 + \frac{dr^2}{1 - \frac{r_g^{D-3}}{r^{D-3}}} + r^2 d\Omega_2^2 \quad r_g \ll R_D \rightarrow D-PBH \]
URP Accretion

\[ CF: \quad l_{sc} > r_g \quad l_{sc} = \frac{1}{\sigma n} \quad \sigma \approx \frac{\alpha^2}{T^2} \quad n \approx \frac{\rho}{3T} \]

\[ \frac{dM}{dt} = F \pi r_{eff}^2 (r_g) \rho_\infty, \quad r_{eff} = \left( \frac{D-1}{2} \right)^{1/(D-3)} \left( \frac{D-1}{D-3} \right)^{1/2} r_g \]

\[ F - \text{ accretion efficiency parameter} \]

\[ F = 1 \quad - CF, \quad F = \left. \frac{dM}{dt} \right|_{HD} : \left. \frac{dM}{dt} \right|_{CF} = ? \quad - HD \]
Accretion of continuous medium

4D:

$$r_{\text{eff}} = \frac{3\sqrt{3}}{2} r_g, \quad \rho = \frac{3M_4^2}{32\pi t^2}, \quad \frac{dM}{dt} = F \pi r_{\text{eff}}^2 \rho(t) \Rightarrow M(t) = M_i \frac{t}{At + (1 - A)t_i}$$

$$0 < A < 1, \quad M(t) \rightarrow \frac{M_i}{A} \approx M_i,$$

PBH mass growth negligible


5D:

$$r_{\text{eff}} = 2r_g, \quad \rho = \frac{3}{32} \frac{M_4^2}{\pi t_c t}, \quad \frac{dM}{dt} = F \pi r_{\text{eff}}^2 \rho(t)$$

$$\Rightarrow \frac{M(t)}{M_i} = \left( \frac{t}{t_i} \right)^{\frac{2}{\pi}} \gg 1$$

Exponential PBH mass growth is possible, **even in CF**

(A.S. Majumdar, PRL (2003) 90, 031303)
Limitation of CF regime in 5D accretion \( F = 1 \)

\[ M_{i,\text{min}} \leq M_{i,1} \leq M_{\text{max}} = M_i(t_c) \]

\[ M_i \sim M_H(t_i) \sim t_i^2 \]

\[ M_{i,1} : r_g(M(t_c)) = l_{sc}(t_c), \]

At \( t_i > t_{i,1} \) CF approximation becomes invalid.
Unfortunately, it turns out that the results in the high-energy regime are exponentially sensitive to the value of $F$, and therefore we keep it in the calculations that follow. By contrast, the recent paper by Majumdar [4] assumed $F = 1$ throughout.

possible. However, we have highlighted the extreme sensitivity of the resulting growth to the assumed accretion efficiency, which cannot be accurately computed. Accretion therefore adds considerable uncertainty to the evolution of individual PBHs after formation in the braneworld scenario.


well, namely an incidental relativistic particle can be regarded as a collisionless point particle and its spin can be ignored, $F$ should be almost unity, otherwise smaller. Due to the lack of knowledge of this issue, we are forced to treat $F$ as a free parameter throughout discussions.

2. Stationary spherically symmetric hydrodynamical accretion of URP onto ED-PBH
Model of D-HD accretion

\[ \nabla_v T^{\mu\nu} = 0 \]
\[ T^{\mu\nu} = (\rho + p)u^\mu u^\nu + p g^{\mu\nu} \]
\[ v'v = -\frac{D-3}{2r} \left( \frac{r_g}{r} \right)^{D-3} - \frac{p'}{p + \rho} \left( 1 - \left( \frac{r_g}{r} \right)^{D-3} \right) + v^2 \]

\[ \nabla_\mu (\sigma u^\mu) = 0 \]
\[ 2 \frac{v'}{r} + \frac{\sigma'}{\sigma} = 0 \quad v \equiv u^r, \partial x / \partial r \equiv x' \]

URP: \[ \rho(T) = 3P(T) = \frac{\pi^2}{30} g_{\text{eff}} T^4, \quad \sigma(T) = \frac{2\pi^2}{45} g_{\text{eff}} T^3 \]

\[ \begin{cases} 
  v'v = -\frac{D-3}{2r} \left( \frac{r_g}{r} \right)^{D-3} - \frac{T'}{T} \left( 1 - \left( \frac{r_g}{r} \right)^{D-3} \right) + v^2 \\
  3 \frac{T'}{T} + 2 \frac{v'}{r} + \frac{v}{v} = 0
\end{cases} \]
Model of D- HD accretion

\[ T^2 \left( 1 + v^2 - \left( \frac{r_g}{r} \right)^{D-3} \right) = C_2 = T_b^2, \quad D=5 \]

\[ v r^2 T^3 = C_1 \sim \frac{dM}{dt} \]
1. Subsonic accretion/outflow
2. Supersonic ejection
3. **Transonic accretion** \( \max(C_1) \rightarrow SP \ DEqs \rightarrow F \)
Model of D- HD accretion  \( F > 1 \) или \( F < 1 \)?

Special point – sonic point:

\[
    r_s = \sqrt[3]{D-1} \left\langle \frac{D - 1}{2} \right\rangle r_g, \quad v_s = v(r_s) = \sqrt{\frac{D - 3}{2(D - 1)}}
\]

\[
\frac{d\Sigma}{dt} = 4\pi r_s^2 \sigma(r_s) v_s = 4\pi r_g^2 \sigma(T_b) \times \frac{8}{3\sqrt{3}} \quad \Rightarrow \quad \frac{dM}{dt} = F \pi r_{eff}^2 \rho(t)
\]

• \( F < 1 \)?


• **нет, \( F > 1 \)!**


\[
    F = \frac{8}{3\sqrt{3}} \approx 1.54 > 1, \ \forall D
\]
Model of D- HD accretion: PBH mass growth

\[
F = \begin{cases}
1, & l_{sc} > r_g, \\
\frac{8}{3\sqrt{3}}, & l_{sc} < r_g.
\end{cases}
\]

\[
\frac{M(t)}{M_i} = \left(\frac{t}{t_i}\right)^{\frac{2}{\pi} F} \gg 1
\]

- Huge PBH mass growth in pho-square phase in RSII
- HD regime is important for wide region of mass PBH spectra.

PBH mass growth at \(l/l_4 = 10^{21}, 10^{26} \text{ и } 10^{31}\) for F=1.54 (solid), F=1 (dashed) and F=0.5 (dotted).
3. Astrophysical constraints on PBH distribution in braneworld cosmology
Constraints on PBH distribution

\[ \alpha(M_i, t) \equiv \frac{\rho_{pbh,M_i}(t)}{\rho_{rad}(t)} \quad \text{– PBH mass fraction} \]

\[ \alpha_i(M_i, t_i) = \alpha(M_i, t_{ev}) \frac{M_i}{M(t_c)} \frac{a(t_i)}{a(t_{ev})}, \qquad \frac{M(t_c)}{M_i} = \left( \frac{t}{t_i} \right)^{2F} \]

\[ \frac{a(t_i)}{a(t_{ev})} = \left( \frac{t_i}{t_c} \right)^{1/4} \left( \frac{t_c}{t_{eq}} \right)^{1/2} \left( \frac{t_{eq}}{t_{ev}} \right)^{2/3} \quad , \quad t_{ev} > t_{eq} \]

\[ \frac{a(t_i)}{a(t_{ev})} = \left( \frac{t_i}{t_c} \right)^{1/4} \left( \frac{t_c}{t_{ev}} \right)^{1/2} \quad , \quad t_{ev} < t_{eq} \]
Constraints on PBH distribution

- Matter density

\[ \alpha(t_H) < \frac{0.3\rho_{cr}}{\rho_{rad}(t_H)} \Rightarrow \]

\[ l_{\text{min}}(t_{ev}) : \quad r_g(M_{\text{max}}) = l \]
Constraints on PBH distribution

- Diffuse gamma background

\[ U(t_0) = \int dM_i \frac{dn(M_i)}{dM_i} \int_{t_{dec}}^{t_0} dt \frac{d^2N}{dEdt} \left( \frac{a(t)}{a(t_0)} \right)^4, \]

\[ I(t_0, E) = \frac{c}{4\pi} \frac{U(t_0)}{E} \approx \frac{c}{4\pi} \frac{M(t_c)}{E} n(t_0, M_i(M^*)) \]

\[ n(t, M_i(M^*)) \rightarrow n(t_c, M_i(M^*)) \rightarrow n(t_0, M_i(M^*)) \sim \alpha_i, \quad T_{BH} : 250 \text{ keV} \div 150 \text{ MeV} \]
Constraints on PBH distribution

- Generation of antiproton

\[
\Phi_{\tilde{p}} \propto \int_0^{M_{\text{GeV}}} dM \frac{d^2 N_{\tilde{p}}}{dE dt} \frac{d\tilde{n}}{dM} \propto M_{\text{GeV}} \frac{d\tilde{n}}{dM} \bigg|_{M_{\text{GeV}}} \sim \frac{dM_i}{dM^*} \frac{M_{\text{GeV}}^2}{M_i M^*} G n(t_0, M_i(M^*))
\]

\[
\Phi_{\tilde{p}} \propto G \alpha_i l^{p_k(F)}, k = 1, 2
\]

\[
p_1 = \frac{40F - 13\pi}{16(\pi - F)}
\]

\[F \leq 1 \implies p_1 < 0\]

\[F > 1 \implies p_1 > 0\]

\[p_2 < 0 \quad \text{"Mix" accretion}\]
Constraints on PBH distribution

- H ionization

\[ x_H \equiv \frac{p}{H} = 0.7 \frac{m_p c^2}{E_0} \frac{\rho_{PBH}}{\rho_{bar}} < 10^{-4} \]

- residual H ionization

\[ 150 < z \leq 1100 \]

\[ z > 15 \text{ (PIIIS)} \]

Conversion:

\[ 0.7 E_{HawRad} \]

\[ e^- \rightarrow \gamma \]

\[ \alpha(t_e) < x_H \frac{E_0}{0.7 \times m_p c^2} \frac{\Omega_b}{\Omega_{CMB}(t_e)} \]

\[ \alpha(t_i) < x_H \frac{1.2 \times 10^{-4}}{(1 + z_{ev})} \times \]

\[ \frac{m_i(t_{ev}, l)}{m_{ev}(t_{ev}, l)} \frac{t_e(t_{ev}, l) \cdot t_c}{t_{eq}^2} \left( \frac{t_{eq}}{t_{ev}} \right)^{2/3} \]
Constraints on PBH distribution

- He abundance

\[
\delta Y_p \equiv \delta \left( \frac{2n}{n + p} \right) < 0.9\%
\]

\[
\alpha(t_{ev}) < 1.7 \times 10^{-10} \sqrt[4]{\frac{m(t_c)}{m_4}} \sqrt[4]{m_{ev}(t_{ev}, l)} \cdot \frac{t_i(t_{ev}, l)}{t_{ev}^2}
\]

\[ t_{ev} = 1 \text{s} \]

Constraints on PBH initial mass fraction $\alpha_i$

<table>
<thead>
<tr>
<th>Source</th>
<th>$\alpha_i(l_{\text{max}})$</th>
<th>$l_{\text{min}}/l_4$</th>
<th>$\alpha_i(l_{\text{min}})$</th>
<th>$l^*/l_4$</th>
<th>$\alpha_i(l^*)$</th>
<th>$\alpha_i$ in 4D</th>
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<tbody>
<tr>
<td>DM density</td>
<td>-30</td>
<td>20</td>
<td>-18</td>
<td>30</td>
<td>-31</td>
<td>-18</td>
</tr>
<tr>
<td>Pbar excess</td>
<td>-35</td>
<td>20</td>
<td>-28</td>
<td>30</td>
<td>-36</td>
<td>-29</td>
</tr>
<tr>
<td>D decay at 400 s</td>
<td>-27</td>
<td>15</td>
<td>-20</td>
<td>20</td>
<td>-28</td>
<td>-18</td>
</tr>
<tr>
<td>D decay at $10^8$ s</td>
<td>-28</td>
<td>16</td>
<td>-20</td>
<td>24</td>
<td>-29</td>
<td>-19</td>
</tr>
<tr>
<td>D decay at $10^{13}$ s</td>
<td>-30</td>
<td>18</td>
<td>-19</td>
<td>27</td>
<td>-30</td>
<td>19</td>
</tr>
<tr>
<td>He decay</td>
<td>-27</td>
<td>14</td>
<td>-17</td>
<td>19</td>
<td>-25</td>
<td>-17</td>
</tr>
<tr>
<td>SZ effect $z = 2 \cdot 10^6$</td>
<td>-30</td>
<td>16</td>
<td>-21</td>
<td>24</td>
<td>-31</td>
<td>-21</td>
</tr>
<tr>
<td>SZ effect $z = 1100$</td>
<td>-34</td>
<td>18</td>
<td>-22</td>
<td>27</td>
<td>-34</td>
<td>-21</td>
</tr>
<tr>
<td>H ionization $z = 1100$</td>
<td>-41</td>
<td>18</td>
<td>-29</td>
<td>27</td>
<td>-41</td>
<td>-28</td>
</tr>
<tr>
<td>H ionization at $z = 20$</td>
<td>-41</td>
<td>19</td>
<td>-29</td>
<td>28</td>
<td>-42</td>
<td>-28</td>
</tr>
</tbody>
</table>
AdS/CFT PBH

(Emparan, 03):

“The black hole solutions localized on the brane in the AdS$_{D+1}$ braneworld which are found by solving the classical bulk equations in AdS$_{D+1}$ with the brane boundary conditions, correspond to quantum-corrected black holes in D dimensions, rather than classical ones”

• Classical 5-colution describe quantum BH evaporation

• Duality $4D \ r_{BH} > L$

• Huge number of CFT-modes $\sim (L/L_4)^2 \Rightarrow$

$$\frac{dM}{dt} = -\frac{\alpha (L^2 / L_4^2)}{(M)^2}$$

$t_{evap}(M_\odot) \sim 10^3 \ yr$ !!!

i.e. possible to trace PBH with $r_{BH} > L$

BUT: Pau Figueras, Toby Wiseman PhysRevLett. 2011
\[ \frac{dn}{dM_{\text{PBH},i}} = \sqrt{\frac{2}{\pi}} \frac{3+n}{4} \frac{\rho_{eq} M_{eq}^{1/2}}{(1+z_{eq})^3} \delta_{h,\text{min}} e^{-\frac{\delta_{h,\text{min}}^2}{2\sigma_h(M_{\text{PBH},i})}} \begin{cases} \frac{3}{4} f^{9/8} M_c^{-3/8} M_{\text{PBH},i}^{-17/8}, & M_{\text{PBH},i} < f M_c \\ f^{3/2} M_{\text{PBH},i}^{-5/2}, & M_{\text{PBH},i} > f M_c \end{cases} \]

Y. Sendouda, Y. Nagataki, K. Sato, JCAP 6, 3 (2006)

\[ \Delta_\delta(k) = A \left( \frac{k}{k_0} \right)^{n-1}, \quad A = A_s \left( \frac{k_0}{k_1} \right)^{n_{\text{obs}}-1} \]

Accretion onto 5D PBH:

\[ \frac{dn}{dM_{\text{PBH},p}} = \frac{dM_{\text{PBH},p}}{dM_{\text{PBH},i}} \frac{dn}{dM_{\text{PBH},i}}, \quad M_{\text{PBH},p} = \left( \frac{t_c}{t_i} \right)^{2F/\pi} = (16 f M_c)^{F/\pi} M_{\text{PBH},i}^{(\pi-F)/\pi} \]

\[ \frac{dn}{dM_{\text{PBH},t}} \bigg|_{t>p} = \frac{dM_{\text{PBH},p}}{dM_{\text{PBH},t}} \frac{dM_{\text{PBH},i}}{dM_{\text{PBH},i}} \frac{dn}{dM_{\text{PBH},i}}, \quad \frac{dM_{\text{PBH},p}}{dM_{\text{PBH},t}} = \begin{cases} \frac{M_{\text{PBH},t}}{\sqrt{M_{\text{PBH},t}^2 + t\alpha}}, & r_g(M_{\text{PBH},t}) < L \\ \left( M_{\text{PBH},t}^3 + 3t\alpha \right)^{2/3}, & r_g(M_{\text{PBH},t}) > L \end{cases} \]
\[ n = 1, \ t > t_{\text{init}} \]
Thus CFT-decay leads to the prediction of the sharp peak in the mass spectrum of PBHs. PBHs from the peak leads to the existence of significant energy release during cosmological evolution.
4. Interaction of multidimensional PBH with compact objects
Absorption of celestial bodies regarded since pioneering works.


GRAVITATIONALLY COLLAPSED OBJECTS OF VERY LOW MASS

Stephen Hawking

(Communicated by M. J. Rees)

(Received 1970 November 9)

SUMMARY

It is suggested that there may be a large number of gravitationally collapsed objects of mass \(10^{-5}\) g upwards which were formed as a result of fluctuations in the early Universe. They could carry an electric charge of up to \(\pm 30\) electron units. Such objects would produce distinctive tracks in bubble chambers and could form atoms with orbiting electrons or protons. A mass of \(10^{17}\) g of such
Compact object absorption by D-PBH

\[ \mathcal{R}_B (M) = \left[ \frac{(D - 3) k_D M}{4 \sqrt{\kappa_s (\infty) M_D^{D-2}}} \right]^{\frac{1}{D-3}} \]

\[ \mathcal{R}_B = \mathcal{R}_D \implies M_f = M(t_{cr}) > M_{4Haw} \]

\[ M_7 \approx 1 \text{T}\text{eV} \]

\[ 1 \text{T}\text{eV} < M_6 < 10^3 \text{T}\text{eV} \]

\[ 1 \text{T}\text{eV} < M_6 < 10^6 \text{T}\text{eV} \]
Relativistic D-accretion

\[ \nabla_v T^{\mu\nu} = 0 \]

\[ T^{\mu\nu} = (\rho + p)u^\mu u^\nu + p g^{\mu\nu} \]

\[ v'v = -\frac{D-3}{2r} \left( \frac{r_g}{r} \right)^{D-3} - \frac{p'}{p + \rho} \left( 1 - \left( \frac{r_g}{r} \right)^{D-3} + v^2 \right) \]

\[ \nabla_\mu (n u^\mu) = 0 \]

\[ \frac{2}{r} + \frac{v'}{v} + \frac{n'}{n} = 0 \]

\[ v \equiv u^r, \partial x / \partial r \equiv x' \]

**EoS:**

\[ p = K n^\Gamma \]
Relativistic D-accretion

\[
\frac{dM}{dt} = 4\pi v(r)r^2 mn(r) = \text{const},
\]

\[
\left(1 - \frac{a_s(r_s)^2}{\Gamma - 1}\right)^2 \left(1 - \frac{D-7}{D-3} a_s(r_s)^2\right) = \left(1 - \frac{a_{\infty}^2}{\Gamma - 1}\right)^2
\]

\[
\begin{align*}
\frac{r_s^{D-3}}{r_g^{D-3}} &= \frac{D-3 - a_s^2(D-7)}{4a_s^2} \\
\nu_s^2 &= \frac{a_s^2(D-3)}{(D-3) + a_s^2(7-D)}
\end{align*}
\]

\[D = 4 \implies \text{S. L. Shapiro, S. A. Teukolsky} \quad (1983)\]

\[c_s \ll 1 \implies \text{S. Giddings, M. Mangano} \quad (2008)\]
Time of WD absorption

Fast WD absorption by ED-PBH
Capture of PBH by WD

PBH Capture rate:
\[ \Gamma(\nu_{WD}) = \int d^3\nu f(\nu, \sigma_{BH}) \pi b^2 | \nu - \nu_{WD} | \]

Structure of DM-halo

\[ f(\nu, \sigma_{BH}) = \frac{1}{(2\pi\sigma_{BH})^{3/2}} \exp \left( -\frac{\nu^2}{2\sigma_{BH}^2} \right) \]
\[ \sigma_{BH} = 1.6 \times 10^5 M_c \]

\[ n_{PBH}(R, z) = 1.8 \times 10^{-24} \left( \frac{10^3 \kappa_2}{M_{PBH}} \right) \left( \frac{a^2 + R_0^2}{a^2 + R^2 + z^2} \right) \Omega_{PBH} M^{-3} \]

CL:
\[ b^2 \approx \frac{2G_4M_{WD}R_{WD}}{| \nu - \nu_{WD} |^2}, \quad \frac{M(\nu - \nu_{WD})^2}{2} < | \Delta E | \]

- energy loss for PBH crossing WD

\[ \langle \Gamma \rangle = 3\sqrt{2\pi} G_4 M_{WD} R_{WD} \frac{1}{\sqrt{\sigma_{BH}^2 + \sigma_{WD}^2}} \frac{| \Delta E |}{E_{av}} \]

Losses:
- accretion
- dynamical friction

\[ E_{av} = 3 \frac{M(\sigma_{BH}^2 + \sigma_{WD}^2)}{2} \]
Capture of PBH by WD

\[
\frac{dE_{\text{abs}}}{dz} = -\frac{1}{M} \frac{E}{v} \frac{dM}{dt}
\]

\[
\Delta E \approx \left( \frac{dE_{\text{abs}}}{dz} + \frac{dE_{\text{tr}}}{dz} \right) 2R_{\text{WD}}
\]

\[
P_{\text{capt}} = 2\pi \langle \Gamma \rangle \int_{-\infty}^{\infty} dz \int_{0}^{\infty} dRRn_{BH}(R, z)n_{WD}(R, z)
\]

\[
\approx 4 \times 10^{16} \Omega_{\text{PBH}} \left( \frac{10^3 \text{kg}}{M} \right) \left| \frac{\Delta E}{E_{\text{av}}} \right| \text{yr}^{-1}
\]

\[
n_{\text{WD}} = 6.2 \times 10^{-61} N_{\text{WD}} (e^{-|z|/z_{\text{thin}}} + e^{-|z|/z_{\text{thick}}}) e^{-R/R_d} M^{-3}
\]


1 event for 10 years throughout Galaxy
NS absorption by PBH

\[ p = Kn^{\Gamma} \]

Bethe - Johnson \quad \Gamma = 2.54

\[ 0.1 \text{ fm}^{-3} \leq n \leq 3 \text{ fm}^{-3} \]

Compression of matter on sound point: QGP?

\( QGP : n \sim 10 \text{ fm}^{-3} \)
NS absorption by PBH

V. V. Tikhomirov, S. E. Yuralevich (2002)

\[
\frac{dM_6}{dt} \sim \left( \frac{r_{g6}}{r_{g4}} \right)^2 \sim 10^{32}
\]
Constraint on $M_6$ due to NS absorption

$M_6 < 10^4 \text{eV}$

WD comparable NS, but Unlike WD constraints, NS apply for extended region of $M_6$

Astroparticle methods together with respective observational statistics are powerful and useful in comparison with collider earth-base experiments.
Thank for Your attention