

Fourth Aegean Summer School

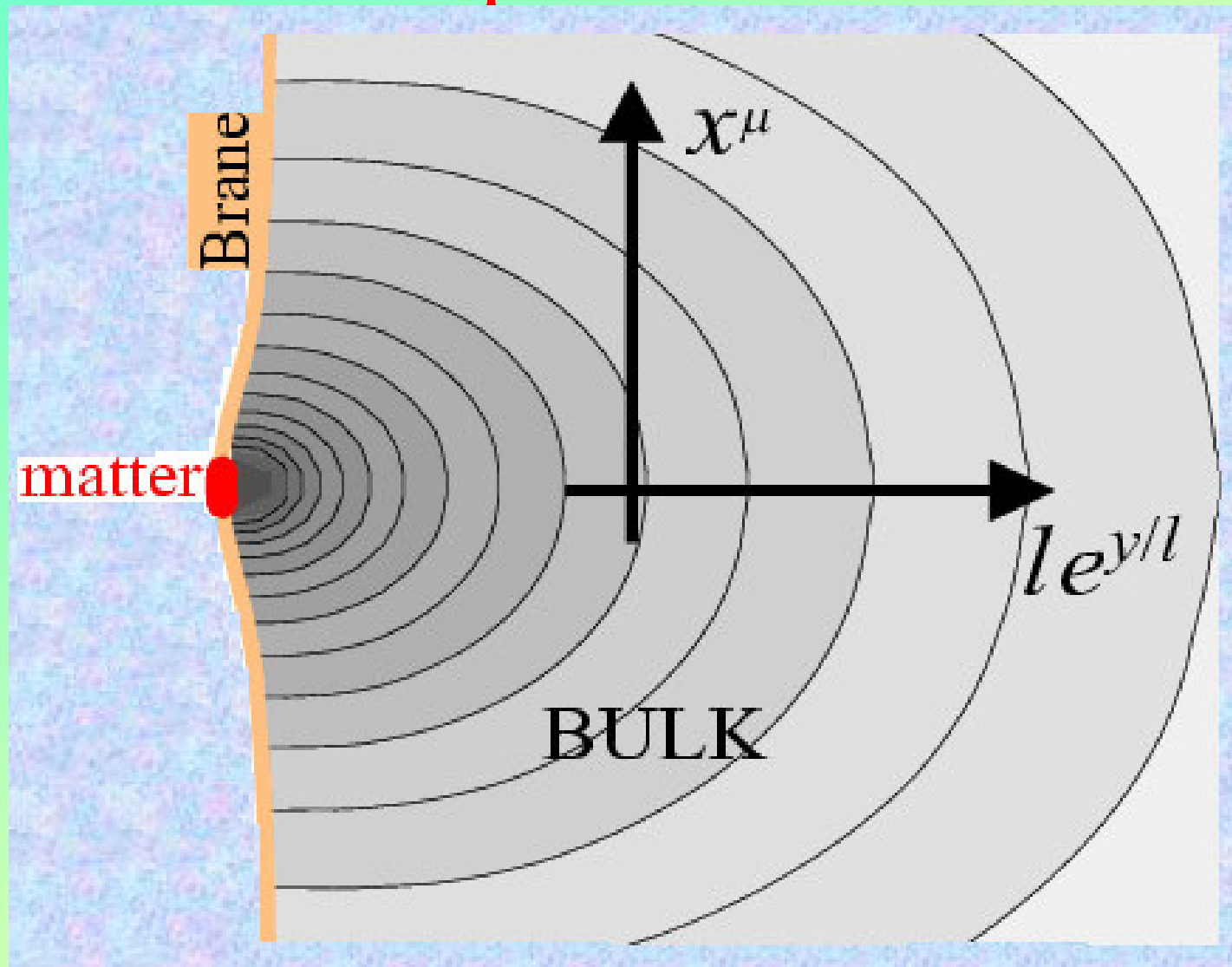
Primordial black holes in Randall-Sundrum one brane Cosmology

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Plan

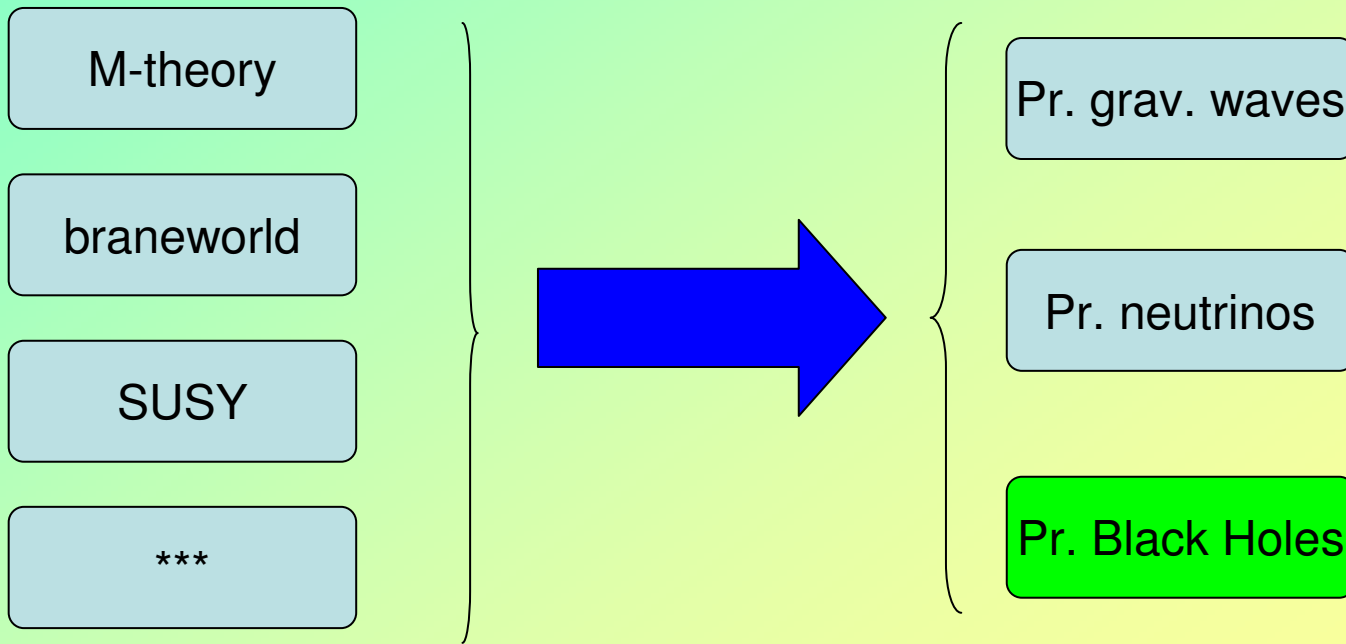
- **Introduction (RS2 and M-theory, gravity tests)**
- **Accretion on PBHs in RS2 braneworld**
 - collisionless approximation
 - PBH mass growth in RS2
 - new accretion efficiency
 - new PBH mass growth coefficient
- **New PBH constraints in RS2 braneworld**
 - constraints in 4D case
 - constraints from the total matter density
 - constraints from the diffuse photon background
 - constraints from the antiprotons excess
 - constraints from He abundance
 - constraints from D photo-disintegration
 - constraints from CMB spectrum distortion
 - constraints from H ionization
- **Conclusion**

Gravitational field penetrates into the bulk



from Roy Maartens gr-qc/0312059

THEORY EXPERIMENT



Randall Sundrum one brane (RS2) model

$$S = \frac{1}{16\pi G_5} \int d^5 x G^{1/2} \left[{}^5R(G_{AB}) - 2\Lambda_5 \right] +$$
$$\int d^4 x g^{1/2} \left(\frac{1}{8\pi G_5} {}^4R(g_{\mu\nu}) - \sigma + L_{matter}(g_{\mu\nu}, \psi, \partial\psi) \right)$$

$$\sigma = \frac{3}{4\pi G_5 l} \quad \text{-- brane tension (4D cosmological constant),}$$

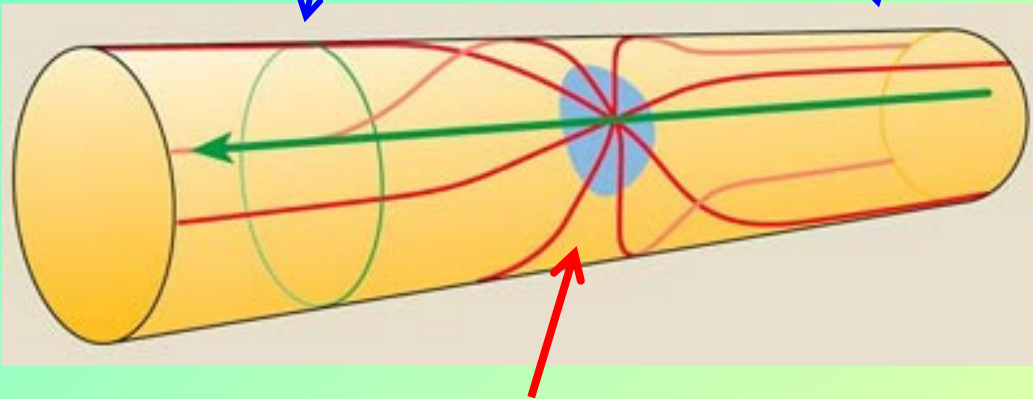
$$\Lambda_5 = -\frac{6}{l^2} \quad \text{-- 5D cosmological constant,}$$

l – **curvature radius,**

Λ_5 and σ are, thus, *fine tuned* \Rightarrow effective $\Lambda_4 = 0$ 5

Geometry modification at $r \sim l$

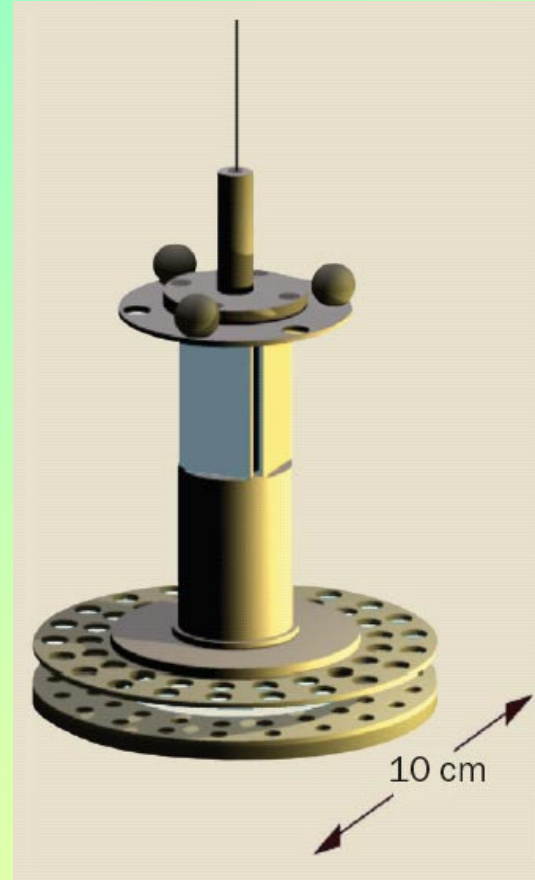
$$ds^2 = -(1 - r_0 / r) dt^2 + \frac{1}{1 - r_0 / r} dr^2 + r^2 d\Omega_2^2, \quad V(r) \approx \frac{GM}{r} \left(1 + \frac{2l^2}{3r^2} \right), \quad r \gg l,$$



$$V(r) \approx \frac{GMl}{r^2}, \quad r \ll l,$$

$$ds^2 = -(1 - r_0^2 / r^2) dt^2 + \frac{1}{1 - r_0^2 / r^2} dr^2 + r^2 d\Omega_2^2, \quad (1)$$

$$r_0 = \sqrt{\frac{8}{3\pi}} \sqrt{\frac{l}{l_4}} \sqrt{\frac{M}{M_4}} l_4 \quad \text{-- 5D PBH ("Schwarzschild") radius}$$



**Torsion pendulum puts
the inverse-square law to the test at $r \sim 0.1$ mm**

upper l experimental bound: $l < 0.2 \mu m \approx 10^{30} l_4$

S.J. Smullin et al. *Phys.Rev.D72:122001,2005.*

lower l bound is determined by Hawking evaporation:

$$t_{evap} = \frac{1}{g_{eff}} \left(\frac{l}{l_4} \right) \left(\frac{M_f}{M_4} \right)^2 t_4 \quad \text{— time of PBH evaporation}$$

$$M_{max} = M_4 \frac{l}{l_4} \quad \text{— maximum 5D PBH mass}$$

$$M_f < M_{max}, \quad t_{evap} \geq t_H \Rightarrow \frac{l}{l_4} > 10^{20}$$

$$l/l_4 = 10^{20} - 10^{30},$$

High-energy phase of RSII cosmological expansion

$$H^2 = \left(\frac{\dot{a}}{a} \right)^2 = \frac{8\pi G}{3} \left(\rho + \frac{\rho^2}{2\lambda} \right) - \frac{k}{a^2}$$

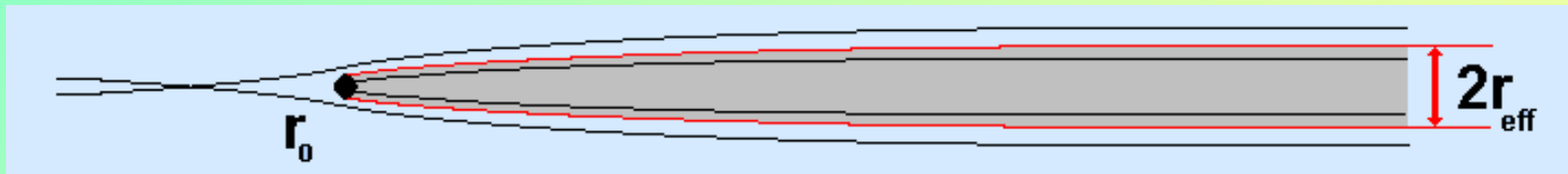
$$a(t) = a_0 \left(\frac{t}{t_0} \right)^{1/4}, \quad \rho = \frac{3M_4^2}{32t_c t}, \quad t < t_c = l/2$$

$$a(t) = a_0 \left(\frac{t}{t_0^{1/2} t_c^{1/2}} \right)^{1/2}, \quad \rho = \frac{3M_4^2}{32t^2}, \quad t > t_c = l/2$$

Accretion efficiency problem

Collisionless ultrarelativistic particles: $l_{sc} \gg r_0$

$$l_{sc} \approx \frac{1}{n\sigma} \qquad \sigma \sim \frac{\alpha^2}{T^2}$$



accretion rate $\frac{dM}{dt} = \pi r_{eff}^2 \rho(t)$

4D case: $\rho = \frac{3M_4^2}{32t^2}$, $r_{eff} = \frac{3\sqrt{3}}{2}r_0$, $A = 1 - \frac{81}{32}fF > 0$, $f \ll 1$

$$M(t) = M_i \frac{t}{At + (1-A)t_i} \rightarrow \frac{M_i}{A} \approx M_i$$

B.J. Carr, S.W. Hawking, *MNRAS*, 168, 399 (1974);

B.J. Carr, *Astrophys. J.* 205, 1 (1975).

PBH mass growth is negligible

Frequent particle collision limit: $l_{sc} \ll r_0$

$$\frac{dM}{dt} = \mathbf{F} \pi r_{eff}^2 \rho(t) \quad \mathbf{F} \text{ is accretion efficiency}$$

4D case don't changes due to F is only coefficient, which didn't change a structure of equation

5D case: $\rho = \frac{3 M_4^2}{32 t_c t}$, $r_{eff} = 2r_0$

$$M(t) = M_i \left(\frac{t}{t_i} \right)^{\frac{2}{\pi} \mathbf{F}}$$

A.S. Majumdar, PRL 90(2003) 031303

considerable PBH mass growth is possible

$\mathbf{F} > 1$ or $\mathbf{F} < 1$?

$F < 1 ?$

- R. Guedens** et al, *Phys. Rev. D*66, 083509 (2002);
- D. Clancy** et al, *Phys. Rev. D*68, 023507 (2003);
- Y. Sendouda** et al, *Phys. Rev. D*68, 103510 (2003);
- Y. Sendouda** et al, *Phys. Rev. D*71, 063512 (2005).

no, $F > 1 !$

- V. V. Tikhomirov and Yu. A. Tsalkou**, *Phys. Rev. D*72, 121301 (2005).

**Cosmological background accretion
in *continuous* approximation**

$$\begin{cases} (\rho + P) u_{i;k} u^k = -P_{,i} - u_i P_{,k} u^k, \\ (\sigma u^k)_{;k} = 0. \end{cases}$$

$$\rho(T) = 3P(T) = \frac{\pi^2}{30} g_{eff} T^4, \quad \sigma(T) = \frac{2\pi^2}{45} g_{eff} T^3$$

$$\left\{ \begin{aligned} uu' + \frac{r_0^2}{r^3} + \frac{T'}{T} \left(1 + u^2 - \frac{r_0^2}{r^2} \right) &= 0, \\ 3 \frac{T'}{T} + \frac{u'}{u} + \frac{2}{r} &= 0 \end{aligned} \right.$$

At the “sonic” point:

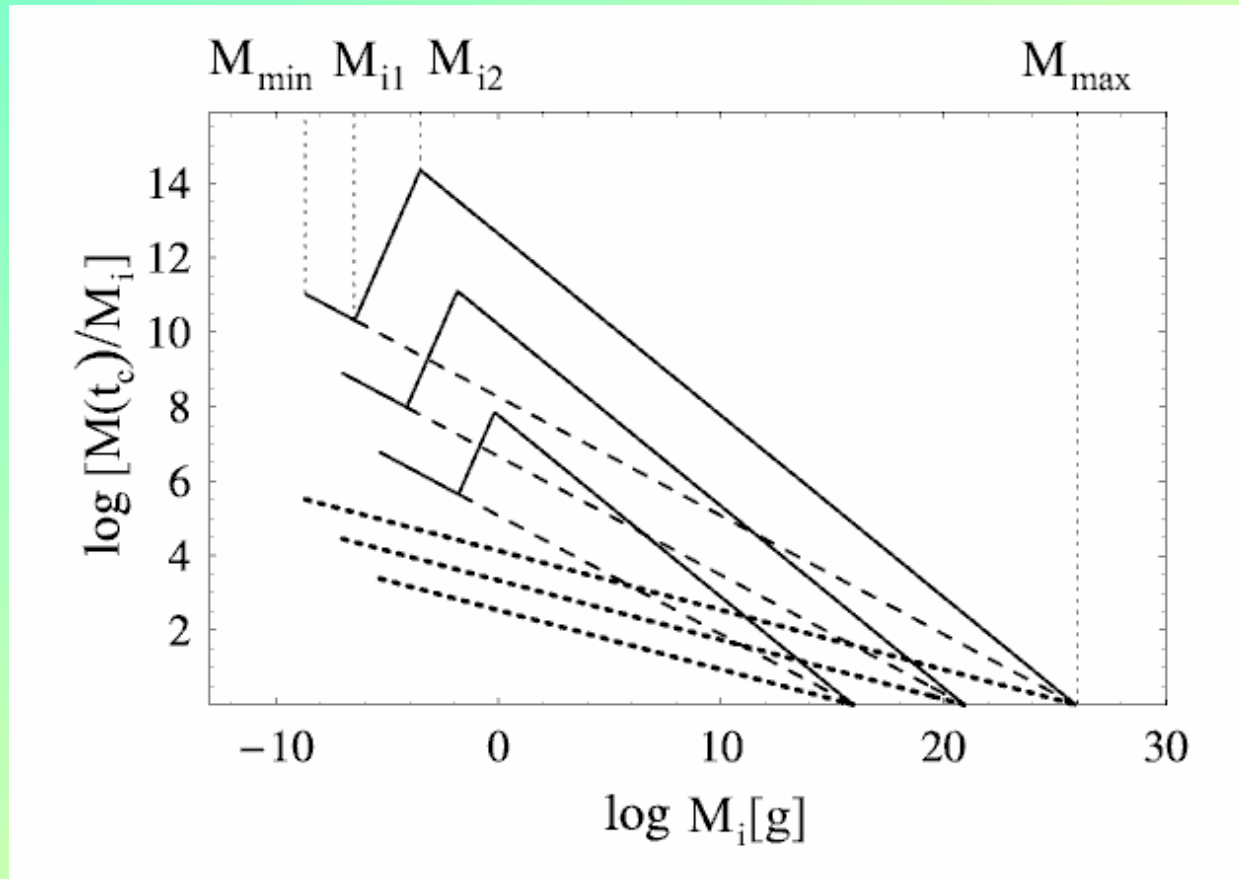
$$r = r_s = \sqrt{2} r_0, \quad u_s = u(r_s) = \frac{1}{2}; \quad T^2 \left(1 + u^2 - \frac{r_0^2}{r^2} \right) = \text{const} = T_b^2$$

$$\frac{d\Sigma}{dt} = 4\pi r^2 \sigma(r) u(r) = 4\pi r_0^2 \sigma(T_b) \times \frac{8}{3\sqrt{3}}$$

$$F = \frac{8}{3\sqrt{3}} \approx 1.54 > 1$$

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

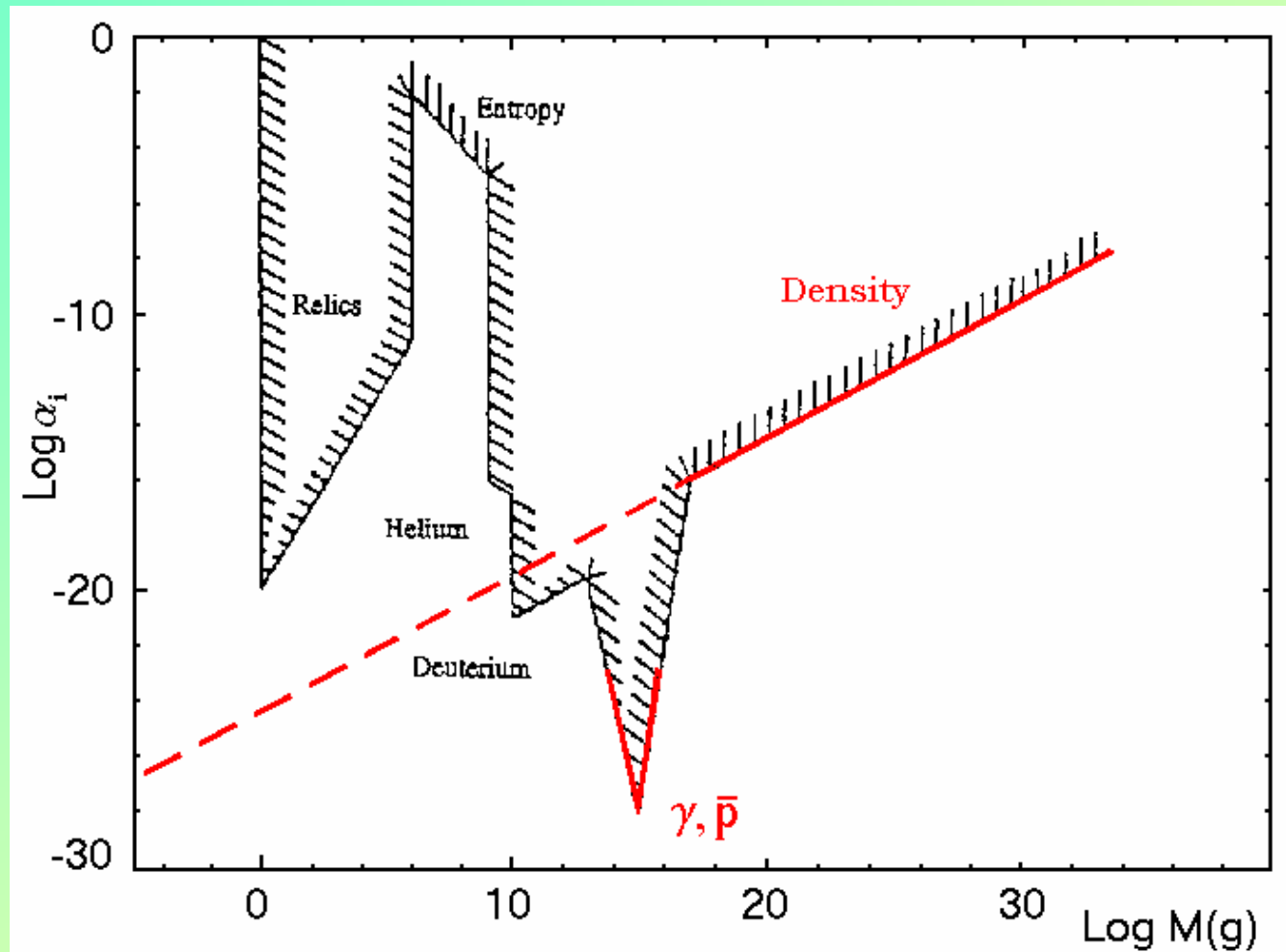
PBH mass growth can be quite substantial:



Mass growth coefficient for $l/l_4 = 10^{21}$, 10^{26} and 10^{31} for $F=1.54$ (solid), $F=1$ (dashed) and $F=0.5$ (dotted lines).

Experimental PBH search

Constraints on 4D PBHs



Paper “Search for Gravitational Waves from PBH Binary Coalescence in the Galactic Halo”

arXiv:gr-qc/0505042 v1 10 May 2005

Search for Gravitational Waves from Primordial Black Hole Binary Coalescences in the Galactic Halo

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Constraints on initial PBH mass fraction by the total matter density

at a moment $t_i \ll t_c \equiv \frac{l}{2}$ PBHs form with masses $M_i = f 8M_4^2 \frac{t_i^2}{t_c}$

$\alpha(M_i, t) \equiv \frac{\rho_{pbh, M_i}(t)}{\rho_{rad}(t)}$ – PBH mass fraction at moment

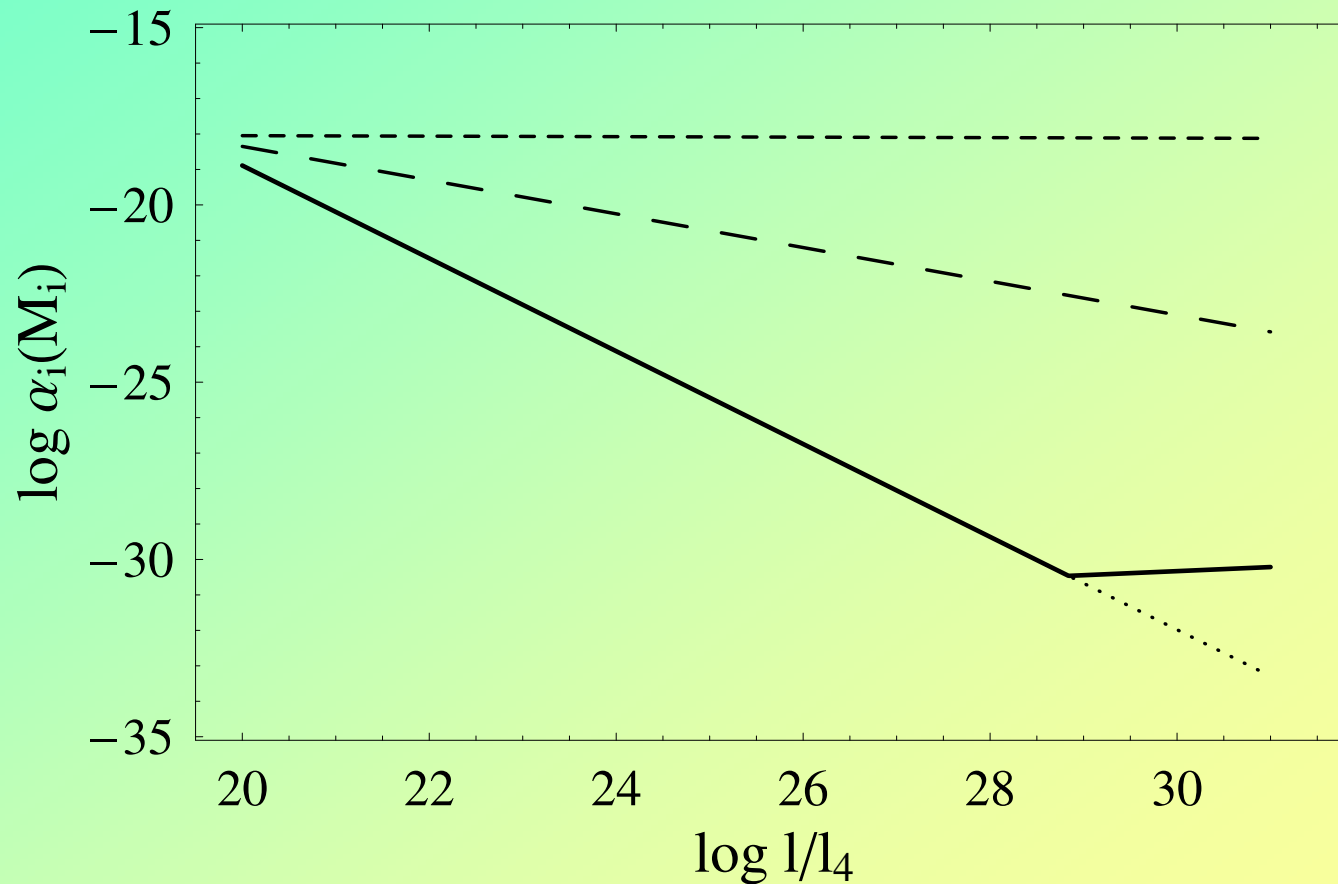
$\alpha_i \equiv \alpha(M_i, t_i)$ – initial mass fraction

$\rho_{pbh, M_i}(t) \propto a(t)^{-3}$, $\rho_{rad}(t) \propto a(t)^{-4} \Rightarrow \alpha(M_i, t) \propto M(t)a(t)$

$\alpha(t_H) < \frac{0.3\rho_{cr}}{\rho_{rad}(t_H)} \Rightarrow$ Dark Matter density limit on α_i

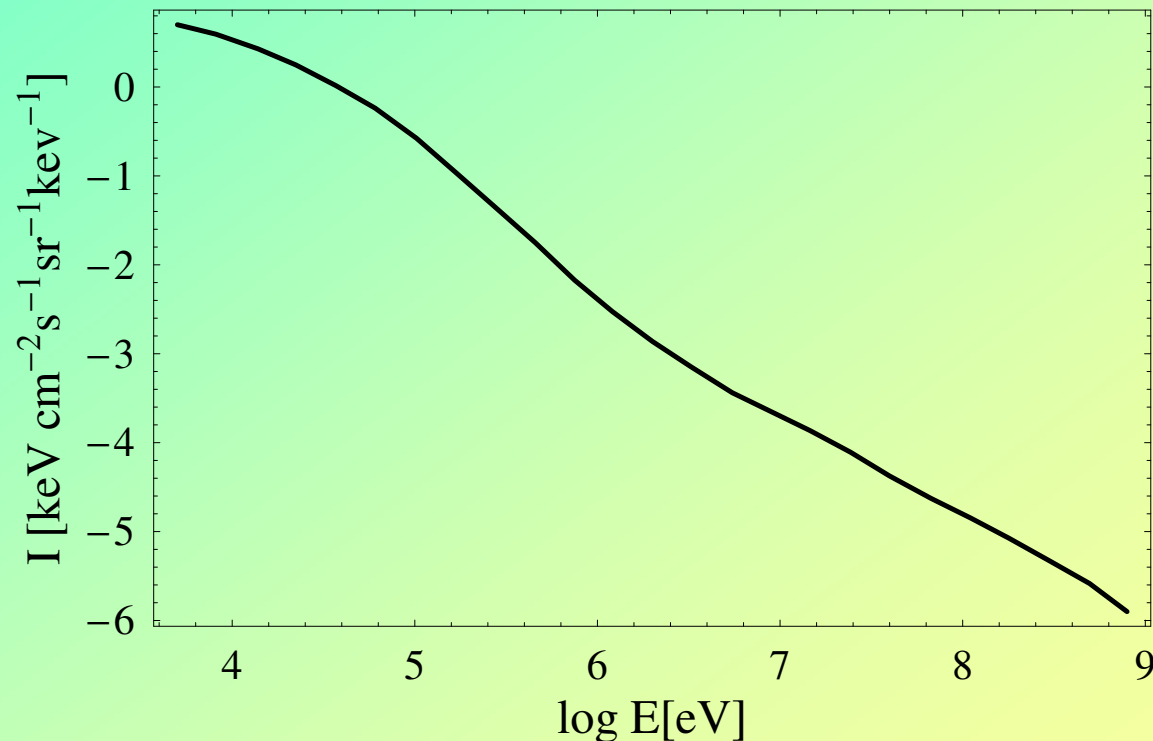
here $t_H \equiv t_{present} \approx 13.5\text{Gyr}$

Constraints on initial PBH mass fraction by the **total matter density**



Dotted, long dashed and short dashed lines correspond to fixed accretion efficiencies $F=1.54$, 1 and 0.5, respectively.

Constraints on initial PBH mass fraction by the high-energy diffuse photon background



Diffuse photon background measure by HEAO-1 A2 (3-60keV), HEAO-1 A4 (80-450keV), SMM (0.45-1MeV), EGRET (~1MeV)

Constraints on initial PBH mass fraction by the high-energy diffuse photon background

Evolution of PBH number density:

$$n(M_i, t_i) = \alpha_i(M_i) \frac{\rho_{rad}(t_i)}{M_i} \quad \text{– initial PBH number density}$$

$$n(M_f, t_c) = \frac{a(t_i)^3}{a(t_c)^3} n(M_i, t_i) \quad \text{– PBH number density after accretion}$$

$$\text{completion at } t = t_c \equiv \frac{l}{2}, \quad M_f \equiv M(t_c) \quad \text{– final PBH mass}$$

$$n(M_f, t) = \frac{a(t_c)^3}{a(t)^3} n(M_f, t_c) \quad \text{– present PBH number density}$$

$$t_{\text{evap}} = \frac{1}{g_{\text{eff}}} \left(\frac{l}{l_4} \right) \left(\frac{M_f}{M_4} \right)^2 t_4 \quad \text{– time of PBH evaporation}$$

$$M_{\text{max}} = M_4 \frac{l}{l_4} \quad \text{– maximum 5D PBH mass}$$

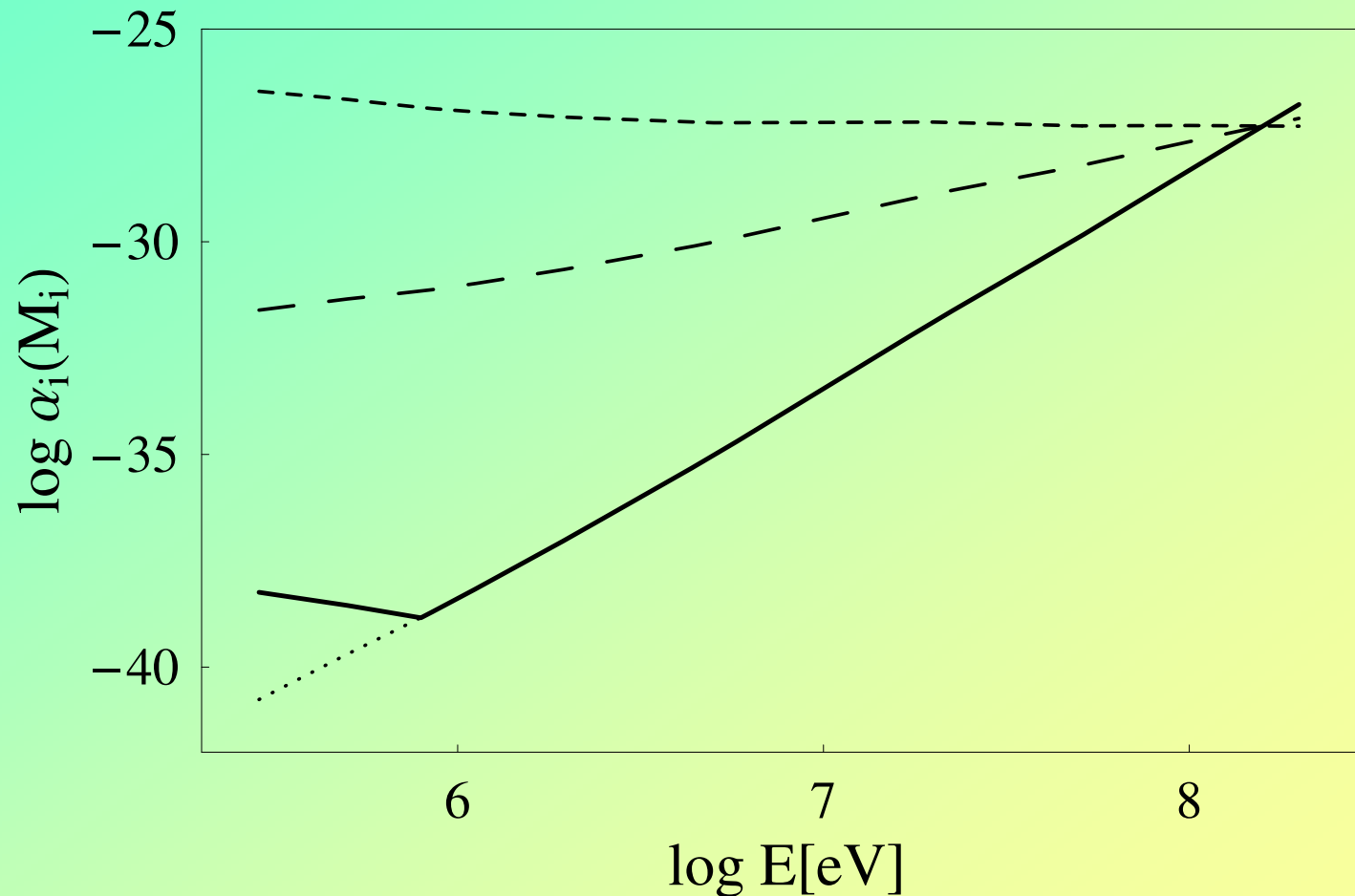
$$M_f < M_{\text{max}}, \quad t_{\text{evap}} \geq t_H \Rightarrow \frac{l}{l_4} > 10^{20}$$

$$M^* \approx 3 \cdot 10^9 \left(\frac{l}{10^{31} l_4} \right)^{-1/2} g \quad \text{– mass of PBHs evaporating at present}$$

$$E_\gamma \sim 5T_{\text{BH}} = \frac{5}{2\pi r_0(M^*, l)} \approx 0.4 \left(\frac{l}{10^{31} l_4} \right)^{-1/4} \text{MeV} \quad \text{– typical energy of Hawking radiation}$$

$$I(E_\gamma) \sim \frac{c}{4\pi} \frac{M^*}{E_\gamma} n(M^*, t_H) \quad \text{– observed photon spectrum}$$

Constraints on initial PBH mass fraction by the high-energy diffuse photon background



Dotted, long dashed and short dashed lines correspond to fixed accretion efficiencies $F=1.54$, 1 and 0.5, respectively.

Constraints on initial PBH mass fraction by H ionization

$$x \equiv \frac{P}{H} < 10^{-4}$$

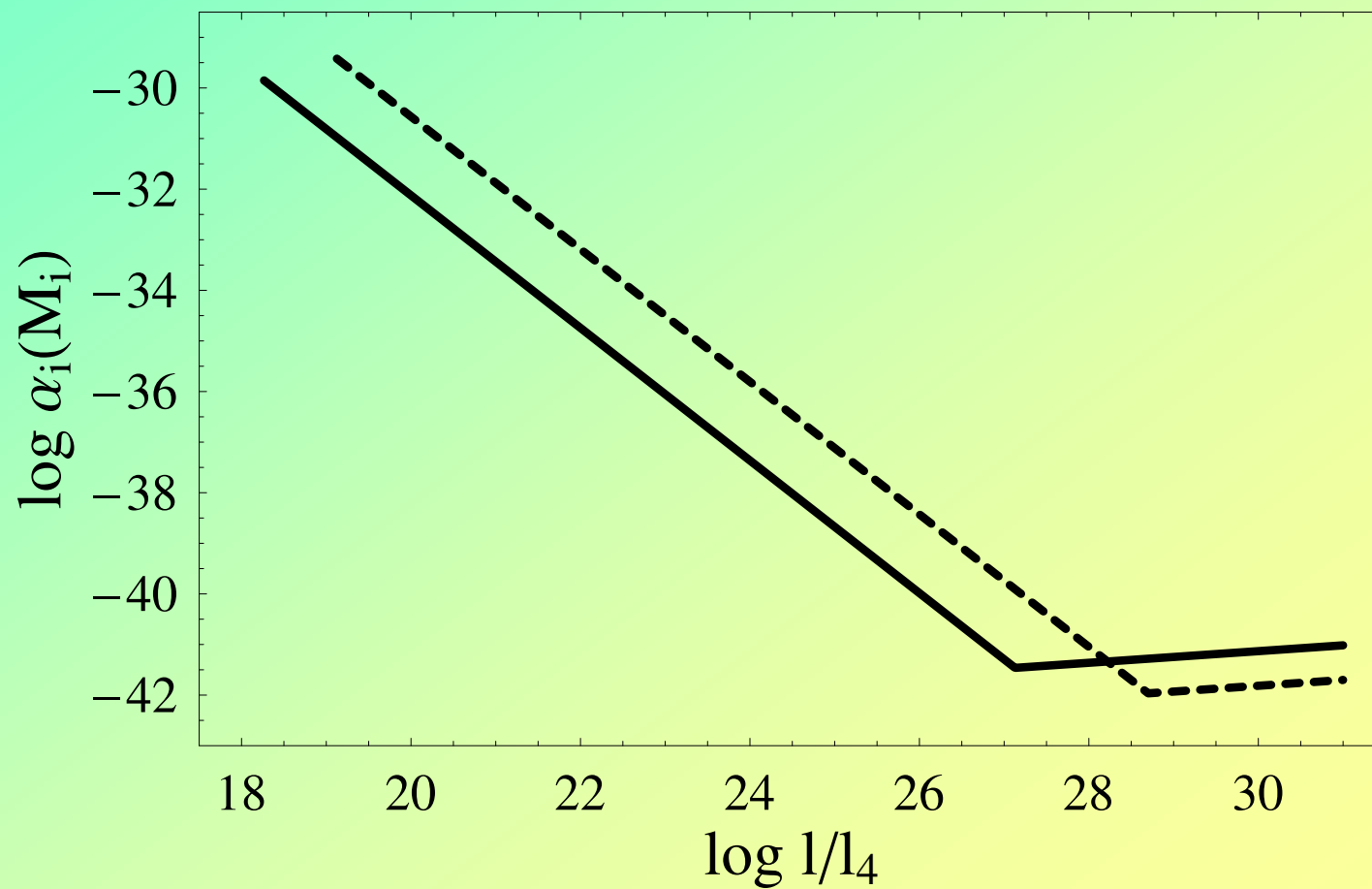
$$\alpha(t_{ev}) < 10^{-4} \frac{100 eV}{0.7 \times m_p c^2} \frac{\Omega_b}{\Omega_{CMB}(t_{ev})}$$

$$\alpha(t_i) < 10^{-4} \frac{100}{0.3 \times 938 \times 10^6} \frac{0.3}{5.06 \times 10^{-5} (1+z_{ev})} \frac{m_i(t_{ev}, l)}{m_{ev}(t_{ev}, l)} \sqrt[4]{\frac{t_i(t_{ev}, l) \cdot t_c}{t_{eq}^2}} \left(\frac{t_{eq}}{t_{ev}} \right)^{\frac{2}{3}}$$

P.D.Nael'skii, Pis'ma Astron. Zh. 4, 387 (1978) [Sov. Astron. Lett. 4, 209 (1979)].

Constraints on initial PBH mass fraction by H ionization

Constraints imposed by ionization at $z = 1100$ and 20



Constraints on initial PBH mass fraction α_i

at $l = l_{min}$, $l = l_{max}$ and maximum constraints at $l = l^*$

<i>Source of constraint</i>	<i>Logarithms of</i>					
	$\alpha_i(l_{max})$	l_{min}/l_4	$\alpha_i(l_{min})$	l^*/l_4	$\alpha_i(l^*)$	α_i in 4D
Total mass density	-30	20	-18	30	-31	-18
Diffuse photon background	-39	20	-27	30	-39	-27
Antiproton excess	-35	20	-28	30	-36	-29
D destruction at 400 sec	-27	15	-20	20	-28	-18
D destruction at 10^8 sec	-28	16	-20	24	-29	-19
D destruction at 10^{13} sec	-30	18	-19	27	-30	19
He destruction	-27	14	-17	19	-25	-17
SZ effect at $z = 2 \cdot 10^6$	-30	16	-21	24	-31	-21
SZ effect at $z = 1100$	-34	18	-22	27	-34	-21
H Ionization at $z = 1100$	-41	18	-29	27	-41	-28
H Ionization at $z = 20$	-41	19	-29	28	-42	-28

Unexampled constraints
on PBH initial mass fraction exist
In braneworld RS2 scenario

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Thanks for you attention