TAUP Conference @ Sendai
Sep 11 2007

Cosmic rays emitted by PBHs in a 5D RS braneworld

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Overview

Strategy

Cosmic-ray observations

Modified theories of formation and evaporation of PBHs

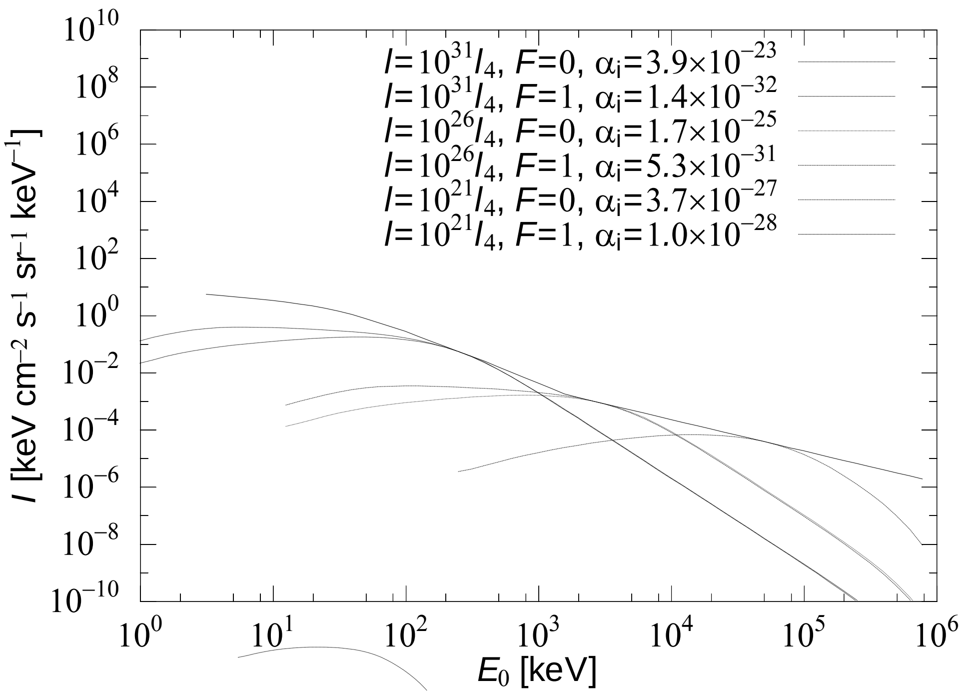
Exotic models for Universe

Now, *Braneworld*

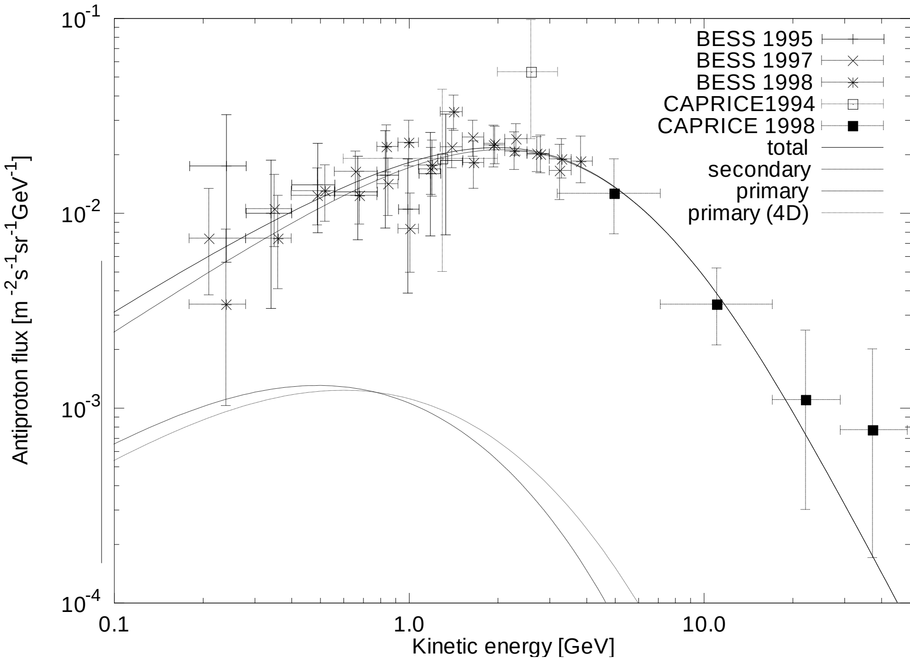
What to do

- ◆Too many PBHs would disturb standard cosmology
- ◆Cosmic-ray spectra differently dependent on extra dimension
- ◆Implications to braneworld and PBHs

Gamma-ray



Antiproton



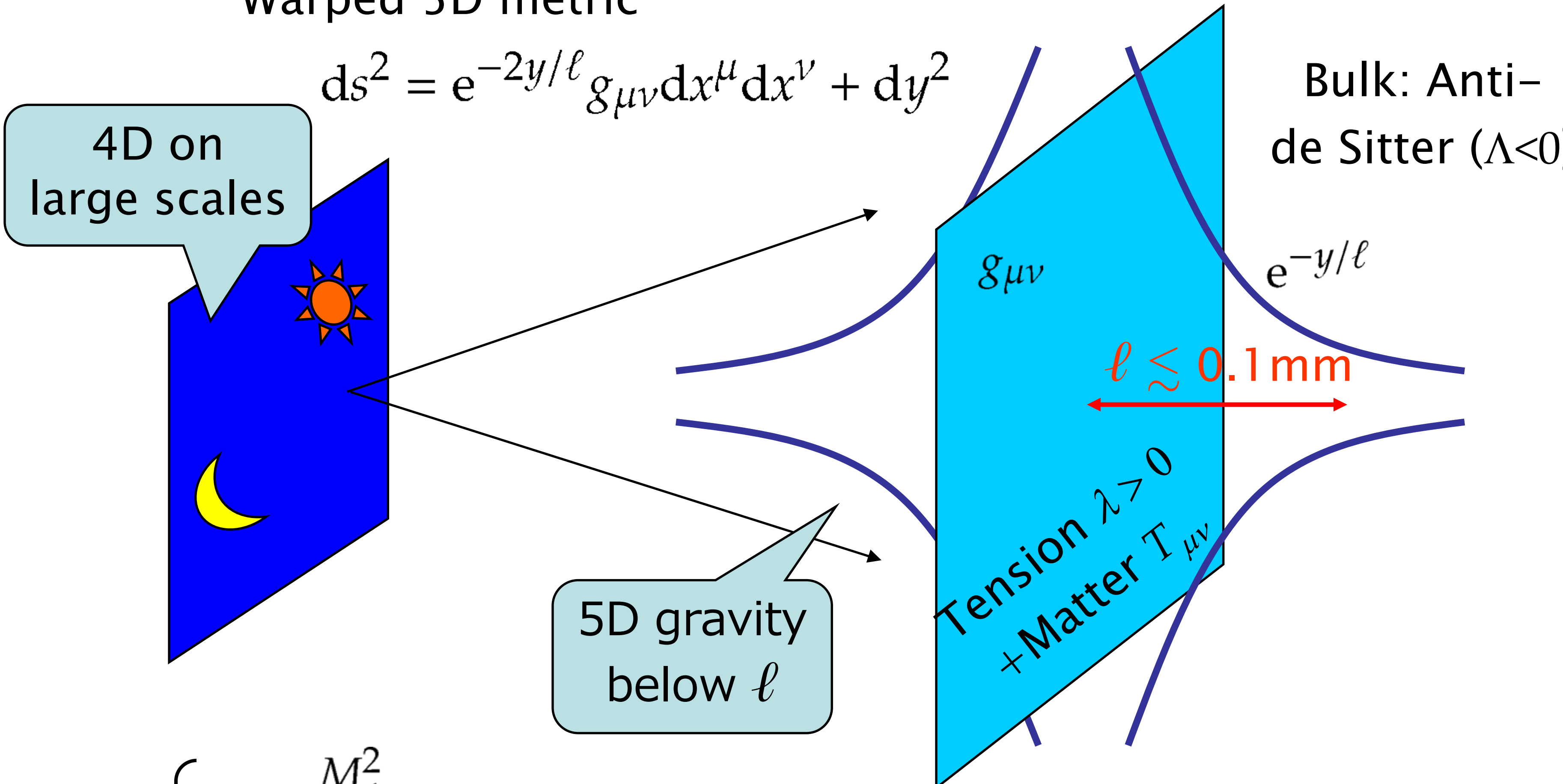
Braneworld and PBHs

RS2 Braneworld

[Randall & Sundrum (1999a,b)]

Warped 5D metric

$$\mathrm{d}s^2 = \mathrm{e}^{-2y/\ell} g_{\mu\nu}\mathrm{d}x^\mu \mathrm{d}x^\nu + \mathrm{d}y^2$$

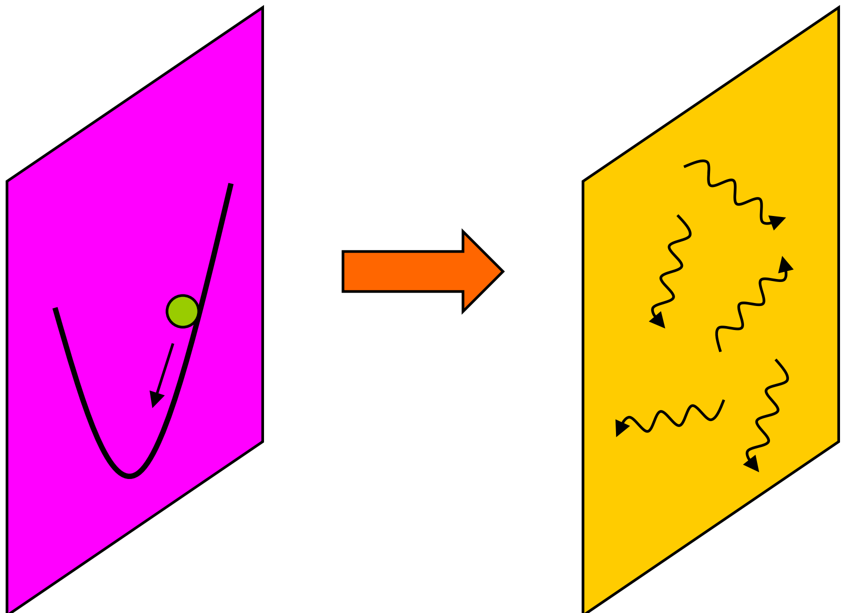


Scales

$$M_5^3 = \frac{M_4^2}{\ell} \sim 200\ell_{0.1\mathrm{mm}}^{-1}(10^8\ \mathrm{GeV})^3$$

$$\lambda = \frac{3M_4^2}{4\pi\ell^2} \sim 100\ell_{0.1\mathrm{mm}}^{-2}(10^3\ \mathrm{GeV})^4$$

Cosmology



Inflation

$V \sim$ const. $\gg \lambda$

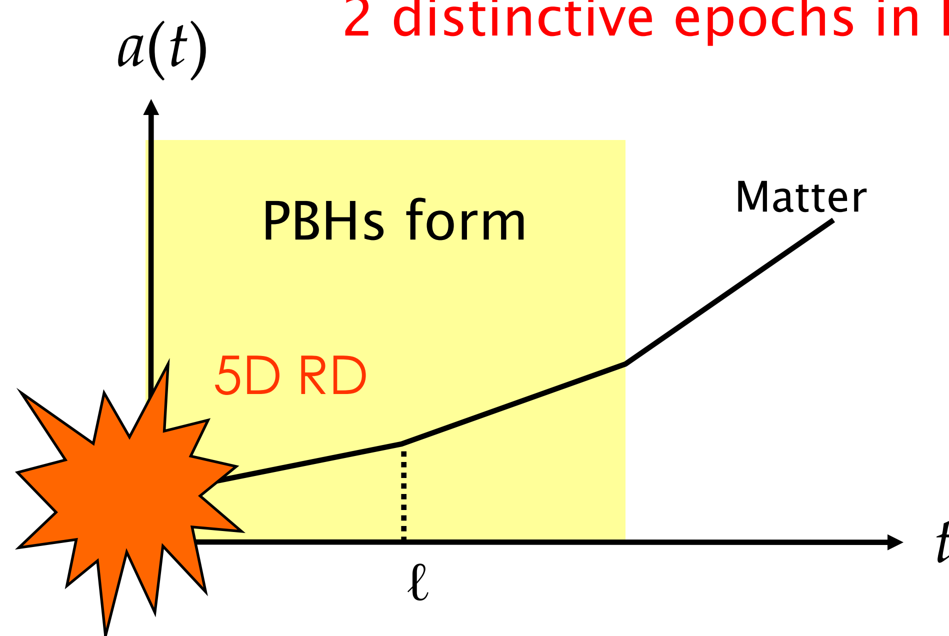
Friedmann eq.

$$H^2 = \frac{8\pi}{3M_4^2}\rho\left(1 + \frac{\rho}{2\lambda}\right)$$

$\rho \propto a^{-4}$

$$\begin{cases} \rho \gg \lambda \rightarrow a(t) \propto t^{1/4} \\ \rho \ll \lambda \rightarrow a(t) \propto t^{1/2} \end{cases}$$

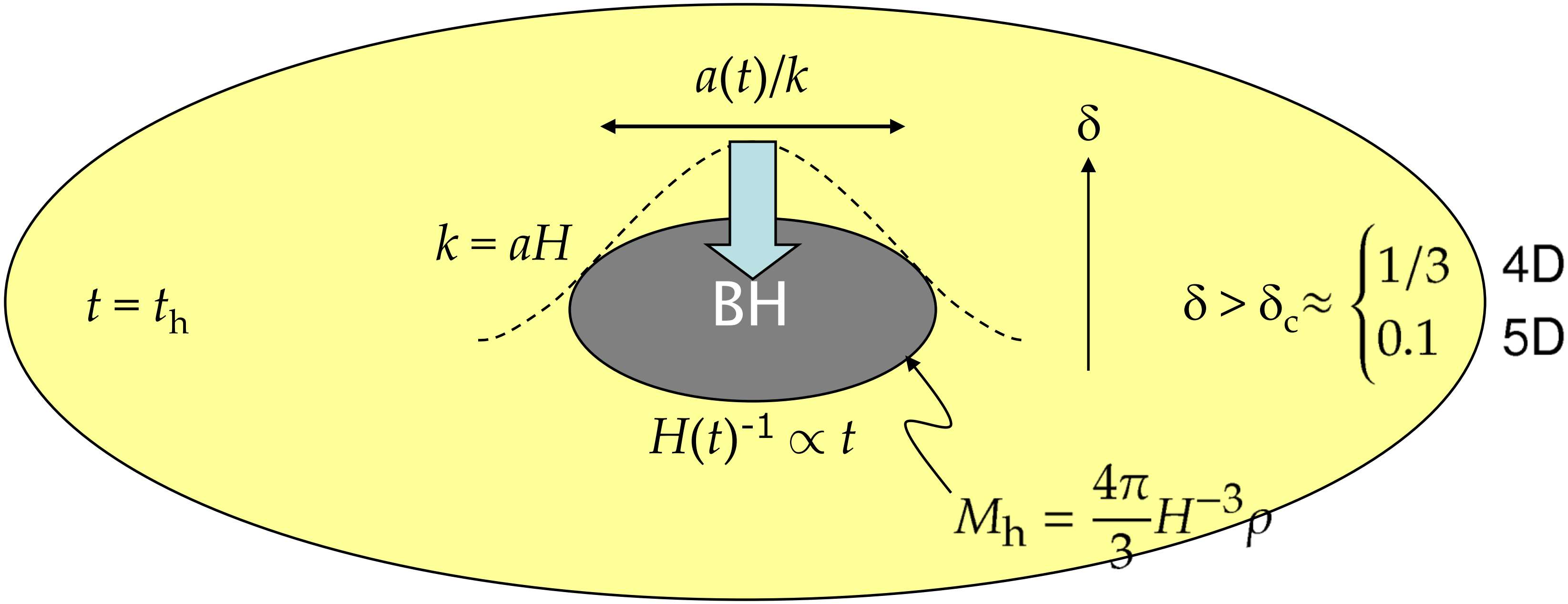
2 distinctive epochs in RD



Primordial Black Hole

[Carr (1975), Guedens *et al*. (2002), Kawasaki (2004)]

◆In RD: Jeans length ~ Hubble radius ~ Schwarzschild radius



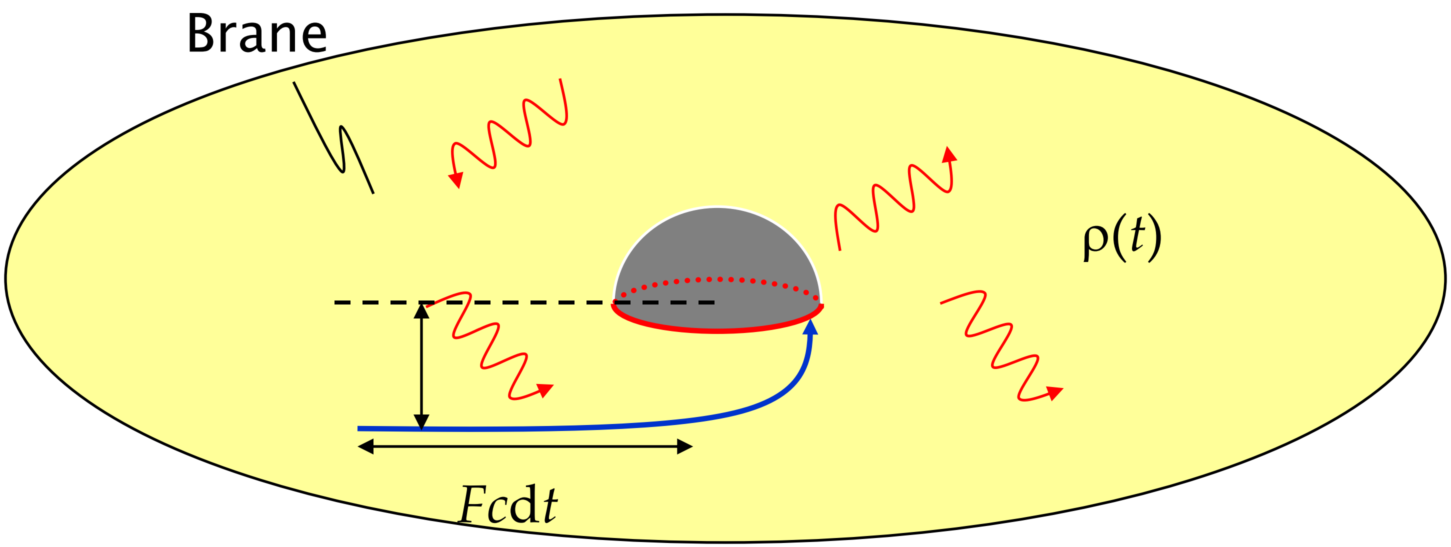
5D Schwarzschild ($r_S \ll \ell$) $\quad M_{bh} \sim M_h(t_h)$

$$ds^2 = -\left[1 - \left(\frac{r_S}{r}\right)^2\right] dt^2 + \left[1 - \left(\frac{r_S}{r}\right)^2\right]^{-1} dr^2 + r^2 d\Omega_2^2$$

Accretion

[Guedens *et al.*, Majumdar (2002)]

◆Radiation accretes due to “slow” expansion in 5d era



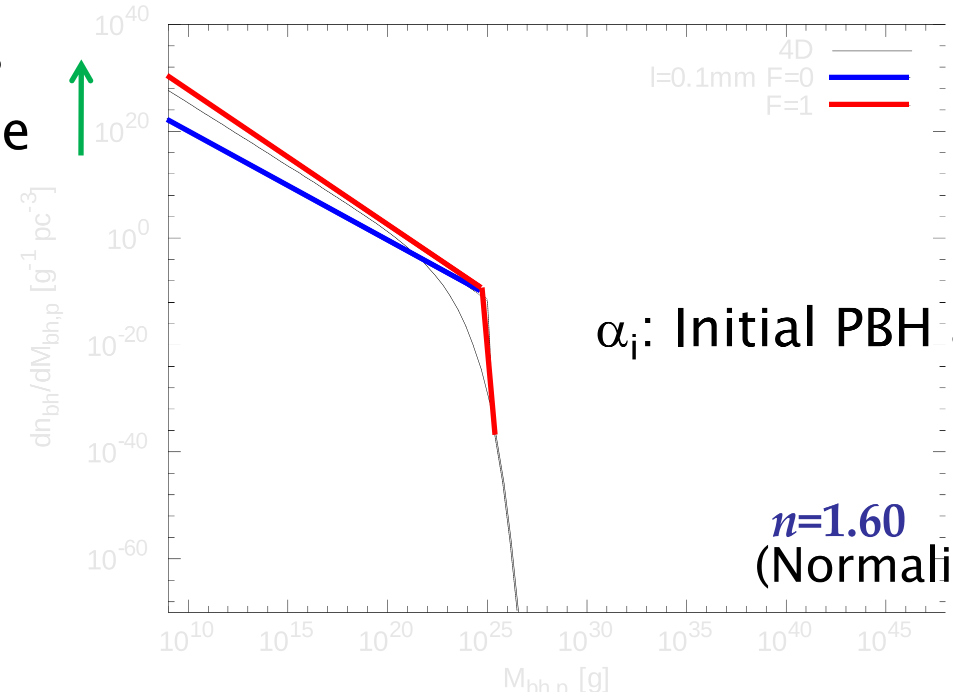
Efficiency $(0 < F < 1)$

Mass growth

$$M_{\rm bh}(t) = \left(\frac{t}{t_{\rm h}}\right)^{2F/\pi} M_{\rm bh,i}$$

Primordial Mass Function

◆Accretion leads to a huge increase



α_i: Initial PBH abundance

n=1.60
(Normalised at Lyα Forest)

◆Formula to calculate from inflationary perturbation

[YS *et al.*, JCAP 0606 (2006) 003]

$$\frac{dn_{bh}}{dM_{bh}} = \sqrt{\frac{2}{\pi}}\frac{3+n}{4}\frac{\rho_{eq}M_{eq}^{1/2}}{(1+z_{eq})^3}\nu e^{-\nu^2/2}$$

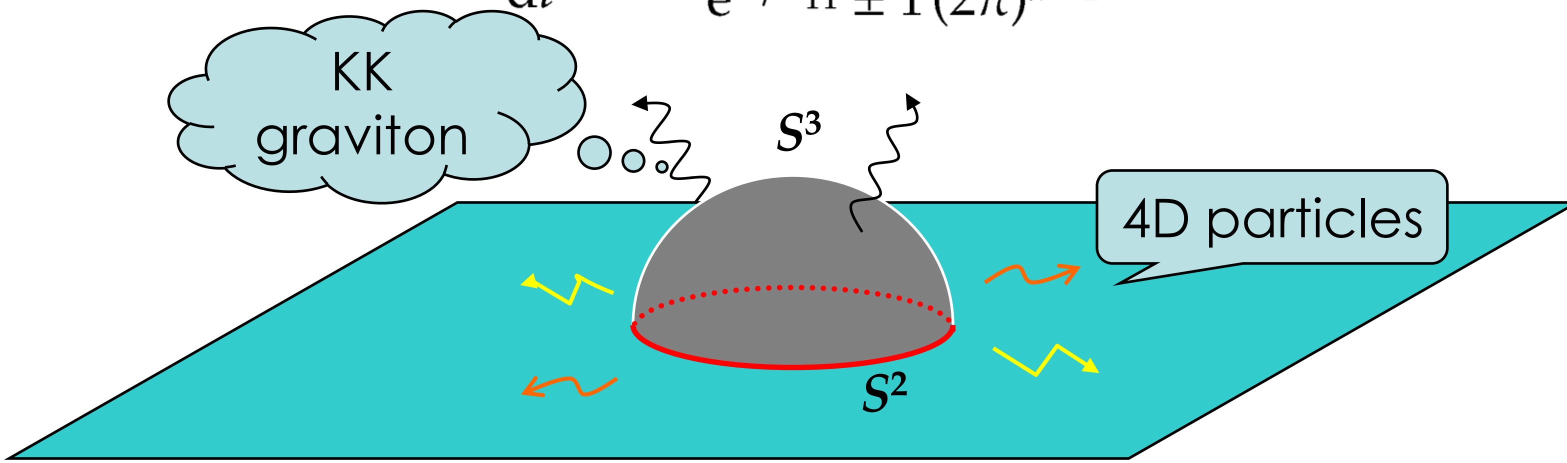
"Tilt"

$$\times\begin{cases} f^{3/2}M_{bh}^{-5/2} & M_{bh} \gtrsim fM_c \\ \frac{3}{4}\left(1+\frac{8}{9}\mathcal{F}\right)16^{\mathcal{F}} f^{9/8+\mathcal{F}} M_c^{-3/8+\mathcal{F}} M_{bh}^{-17/8-\mathcal{F}} & M_{bh} \lesssim fM_c \end{cases}$$

Scale invariant

Hawking Radiation

Black body $\frac{\mathrm{d}^2 N_j}{\mathrm{d}t} = g_j \frac{\sigma_j}{\mathrm{e}^{E/T_{\mathrm{H}}} \pm 1} \frac{\mathrm{d}k^{d-1}}{(2\pi)^{d-1}}$



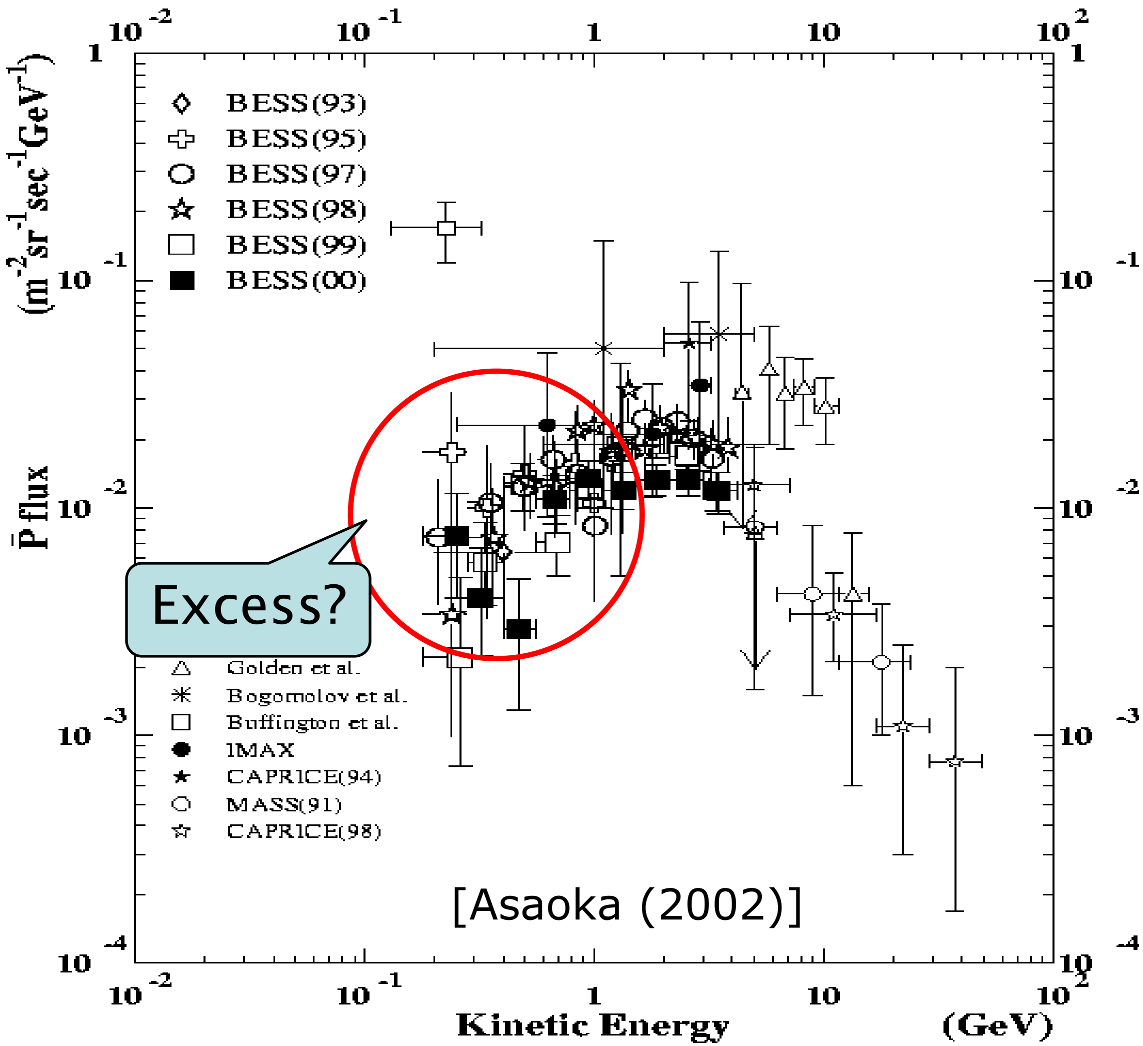
◆Temperature and mass of a "critical" PBH lifetime being 13.7Gyr

D=5 (RS)		D=4
$T_{\mathrm{H}}^{*} \sim (G_{\mathrm{N}} \ell M_{\mathrm{bh}})^{-1/2} \sim 100 \ell_{0.1\mathrm{mm}}^{-1/4}$ keV	$\ll$	$T_{\mathrm{H}}^{*} \sim (G_{\mathrm{N}} M_{\mathrm{bh}})^{-1} \sim 100$ MeV
$M_{\mathrm{bh}}^{*} \sim 10^9 \ell_{0.1\mathrm{mm}}^{-1/2}$ g		$M_{\mathrm{bh}}^{*} \sim 10^{15}$ g

Galactic Antiprotons

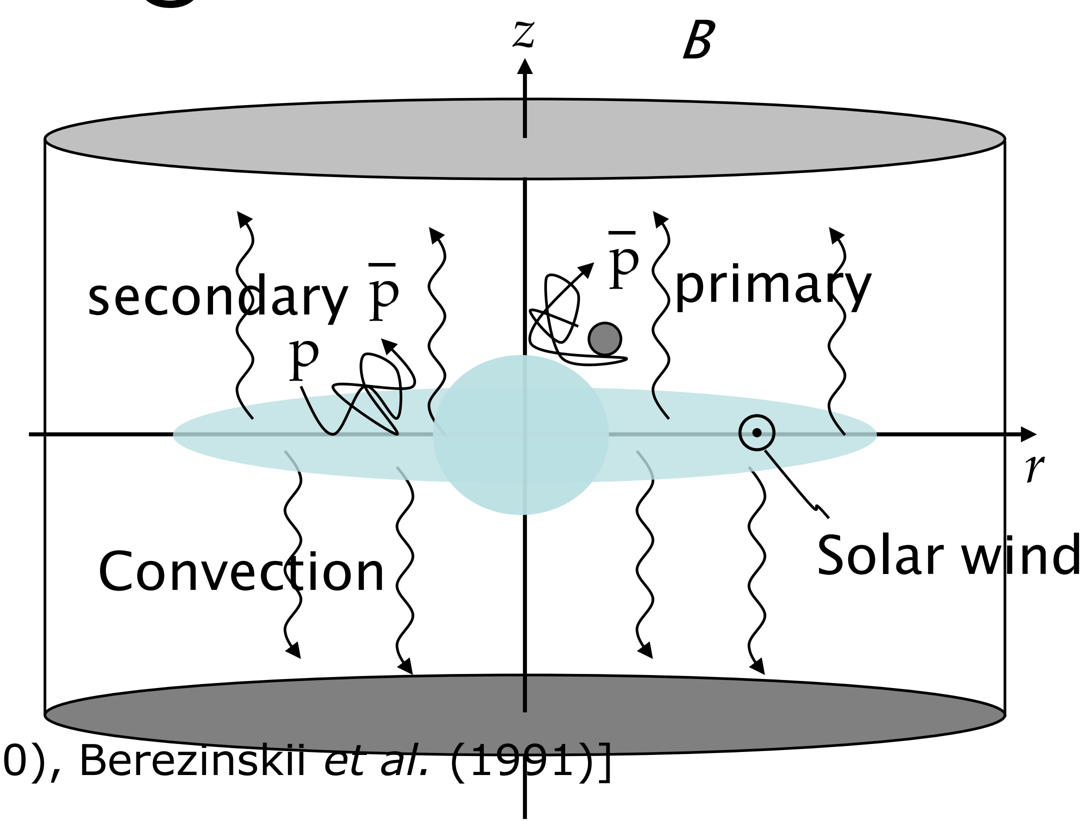
[YS *et al*., PRD 71 (2005) 063512]

Observations



http://www.kek.jp/newskek/2002/mayjun/bess1.html

Propagation



◆Source

- •NFW density profile
- •QCD Jets treated with PYTHIA

◆Diffusion eq

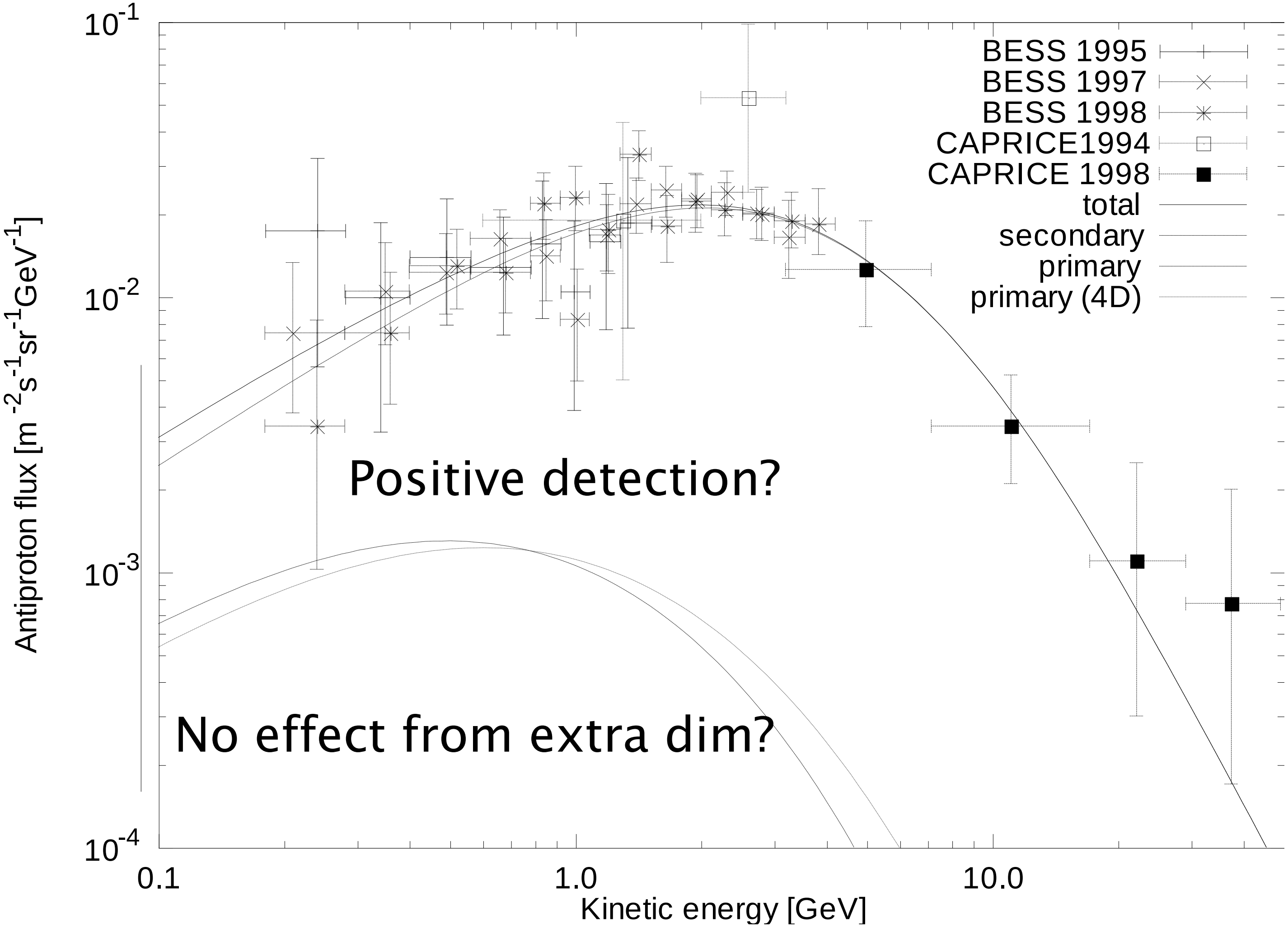
[Ginzburg, Khazan & Ptuskin (1980), Berezinskii *et al.* (1991)]
[Webber, Lee & Gupta (1992)]

$$0 = \frac{\partial N}{\partial t} = \vec{\nabla}\cdot[K(E)\vec{\nabla}N(r,z,E) - \vec{V}_c(r,z)N(r,z,E)]$$
$$+ \frac{\vec{\nabla}\cdot\vec{V}_c(r,z)}{3}\frac{\partial}{\partial E}\left[\frac{p^2}{E}N(r,z,E)\right] - \Gamma(E)N(r,z,E)$$
$$+ Q(r,z,E) + \frac{\partial}{\partial E}\left[-b(E)N(r,z,E) + \beta^2 K_{pp}(E)\frac{\partial N(r,z,E)}{\partial E}\right]$$

(+Solar modulation)

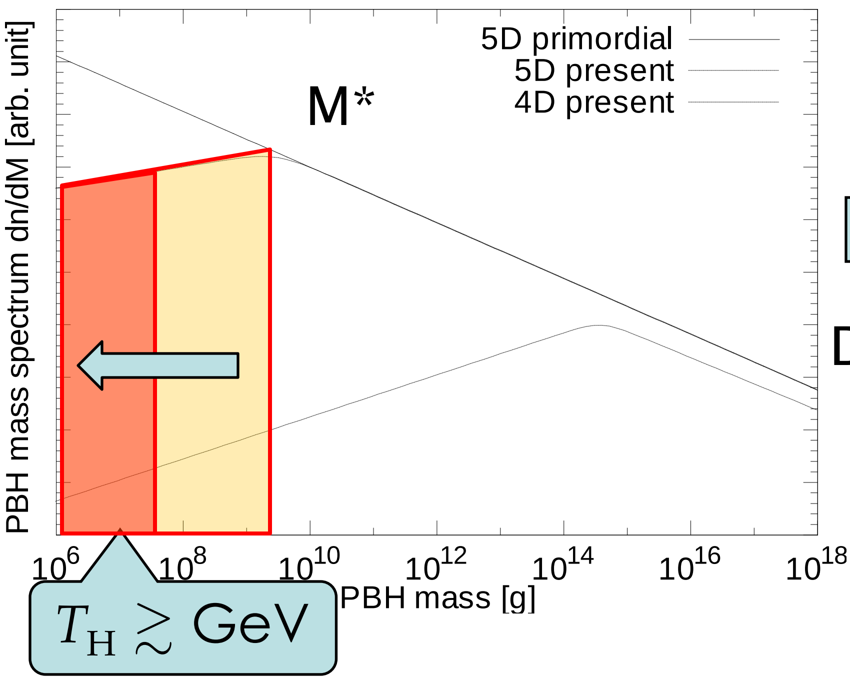
Typical Flux

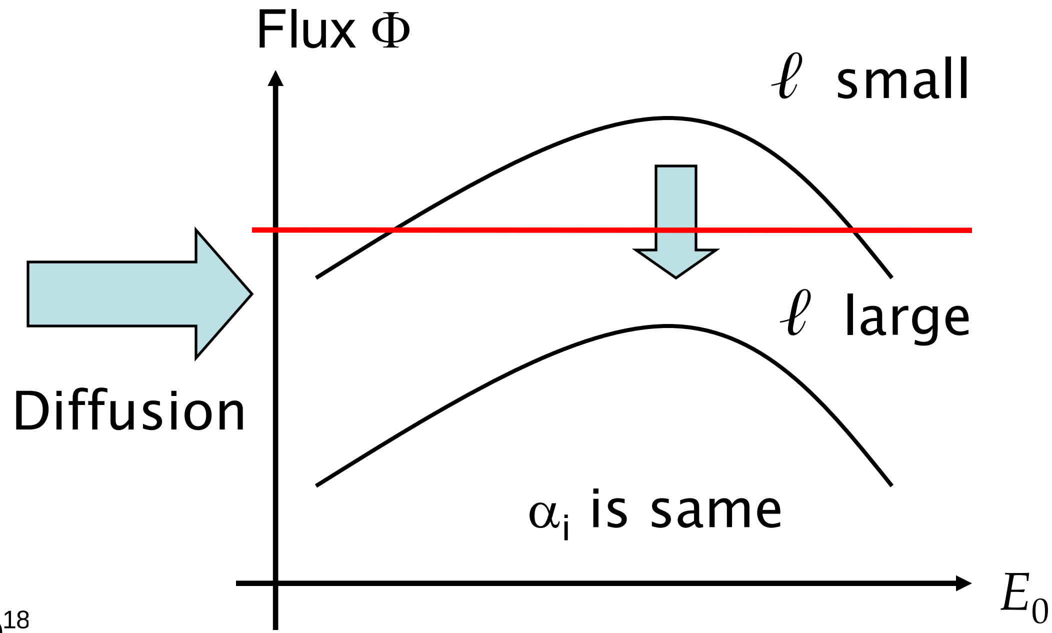
◆Fitted to solar-minimum data



Extra-dim Dependence

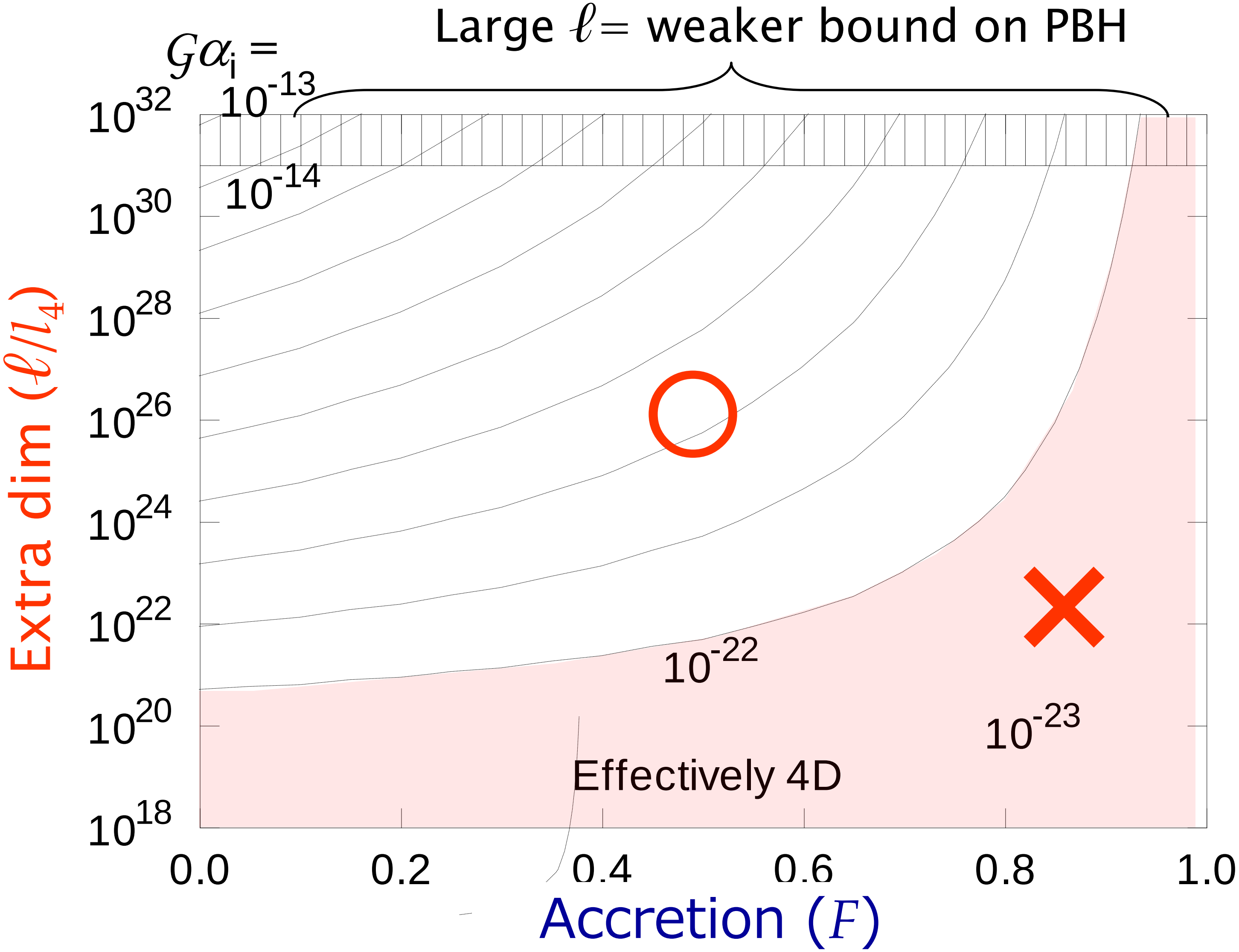
Mass function (present-day)





- Contribution only from those currently evaporating
- But spectrum unchanged
- Flux proportional to → decreasing function of ℓ

Constraints on α_i or ℓ

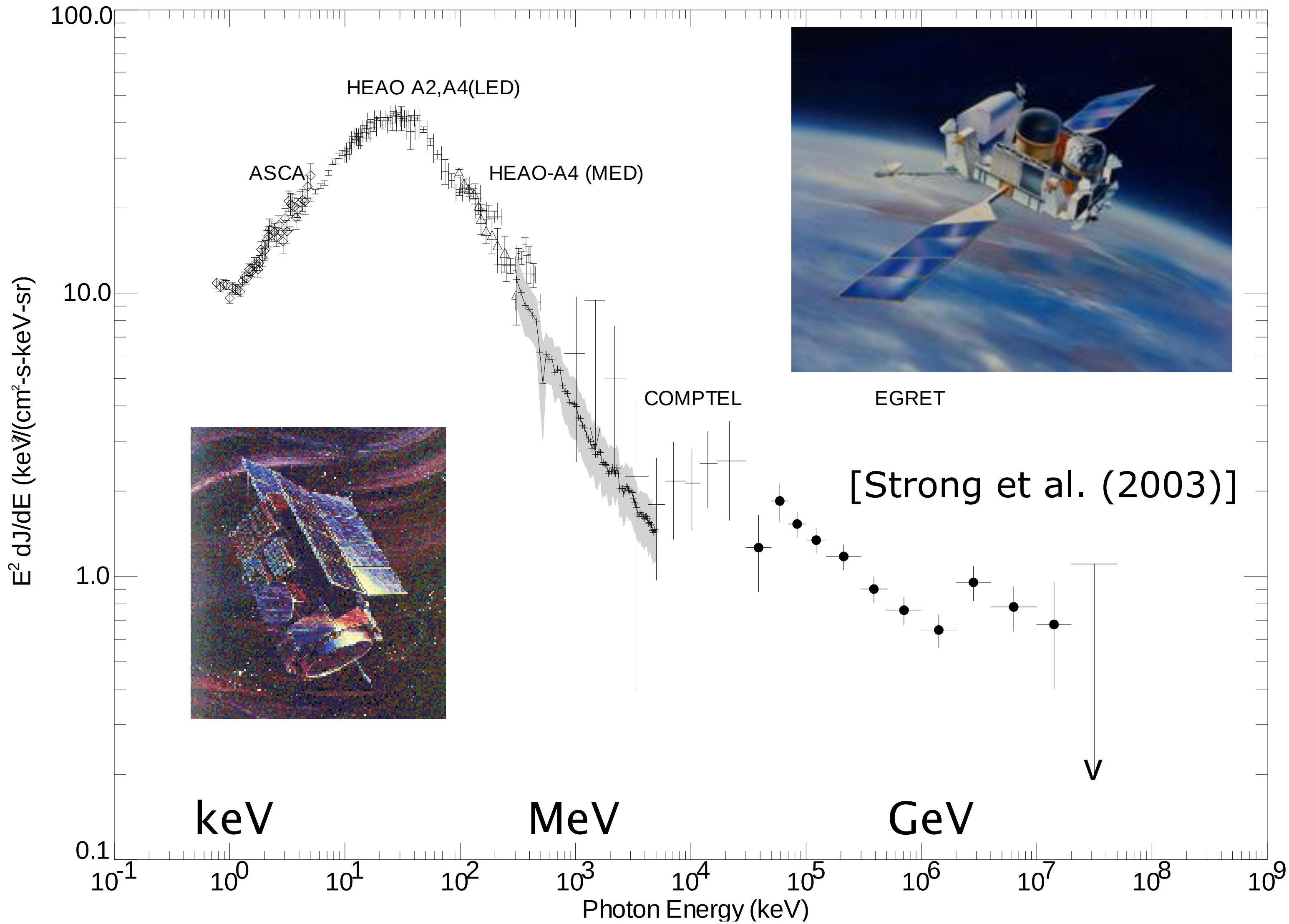


Density contrast $\mathcal{G} \sim 10^5$

Extragalactic X/γ-ray Background

[YS *et al*., PRD 68 (2003) 103510]

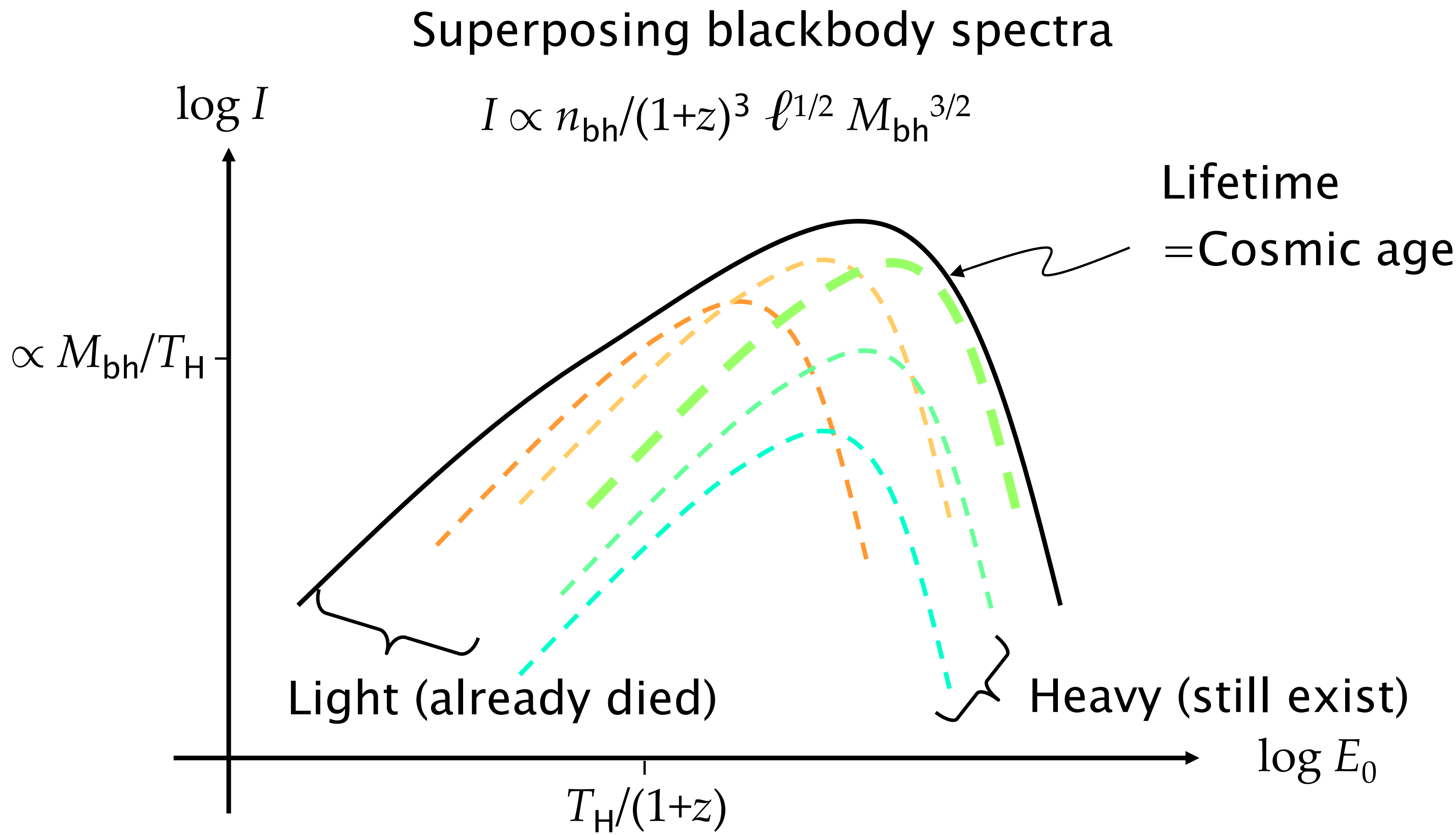
Observations



http://cossc.gsfc.nasa.gov/docs/cgro/images/home/Cartoon_CGRO.jpg

http://heasarc.gsfc.nasa.gov/Images/heao1/heao1_sat_small2.gif

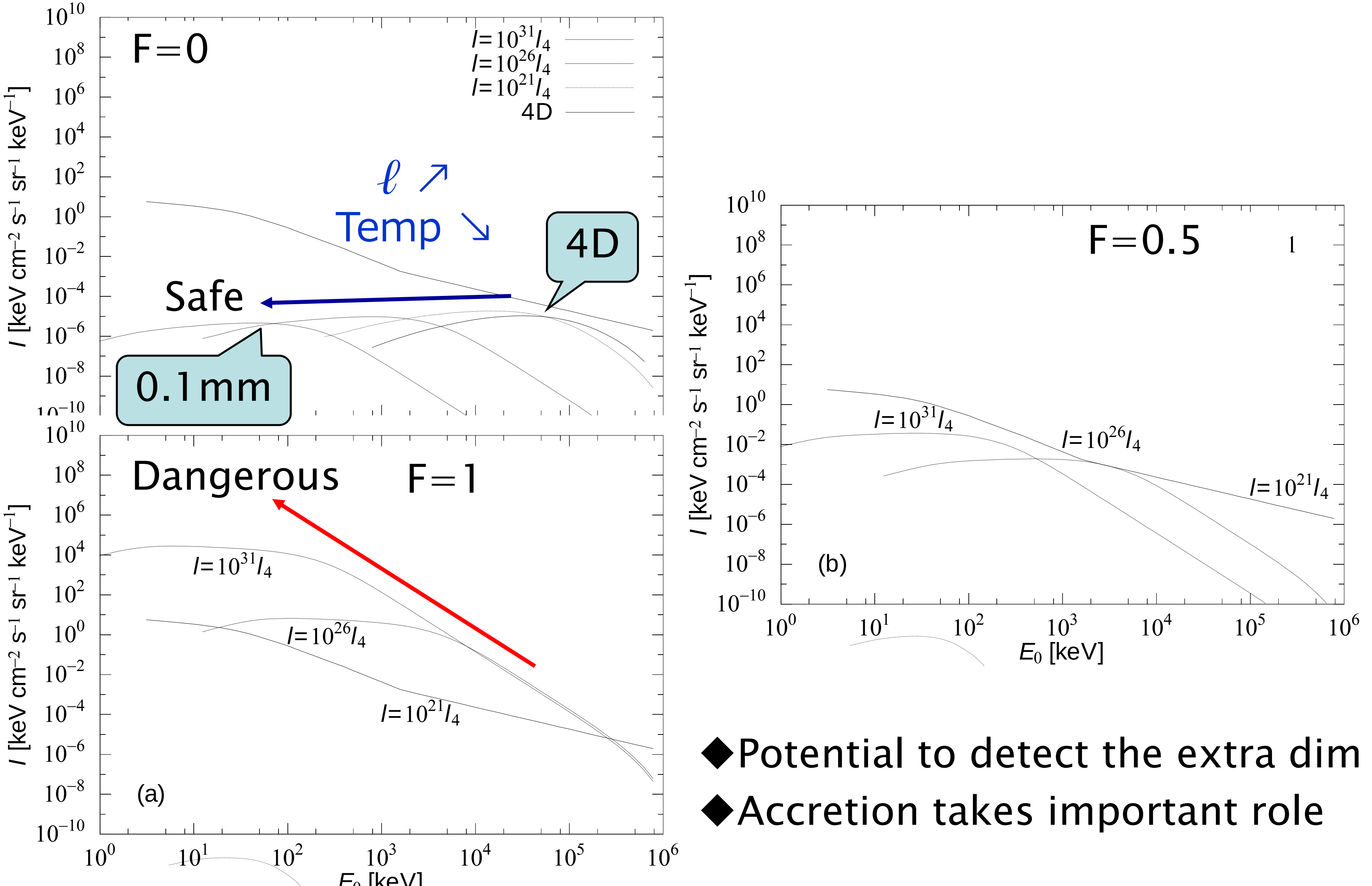
Spectrum



Sensitive to extra dimension

$I \sim U_0/E_0$

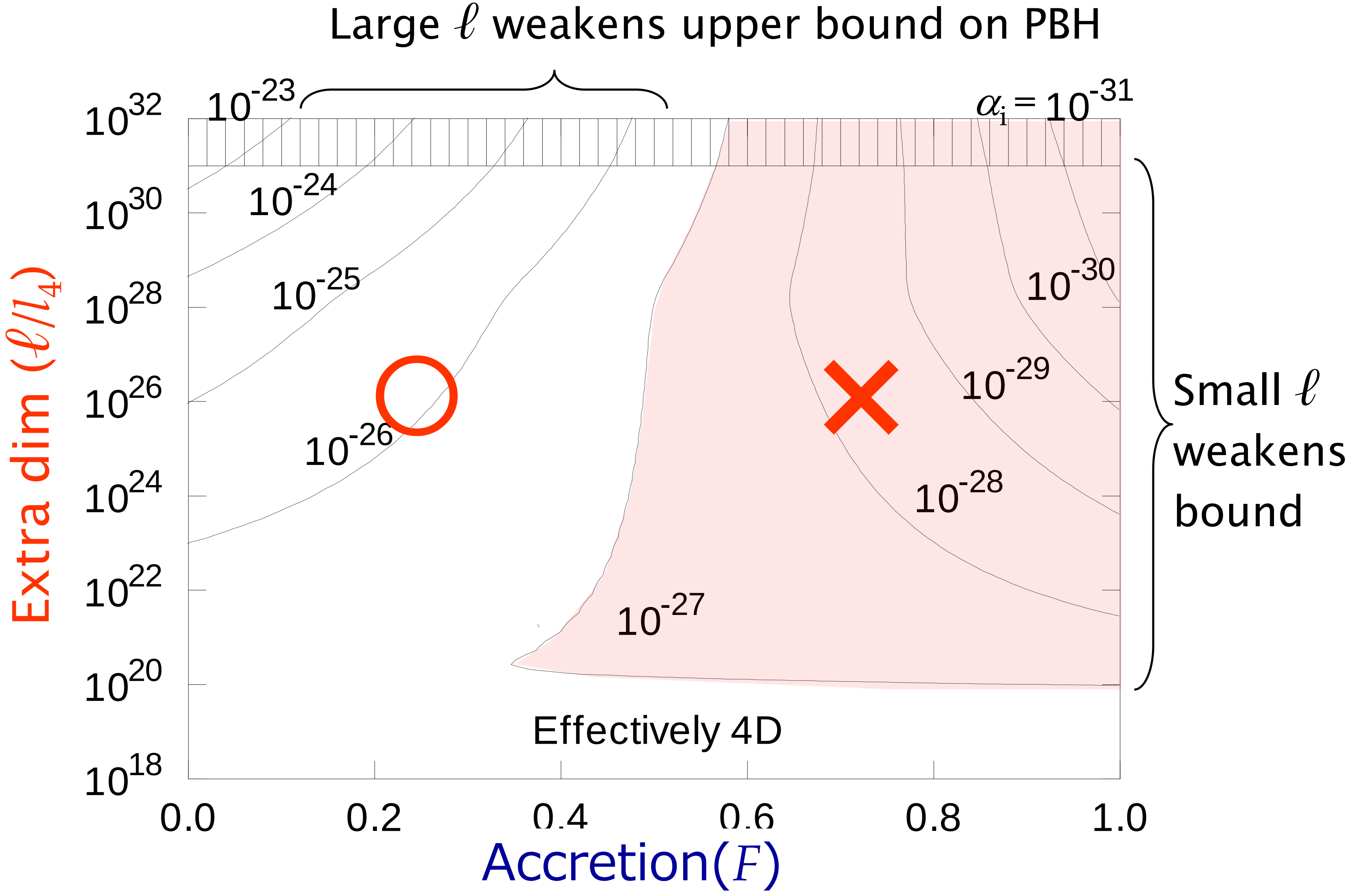
Extra-dim Dependence



◆Potential to detect the extra dim

◆Accretion takes important role

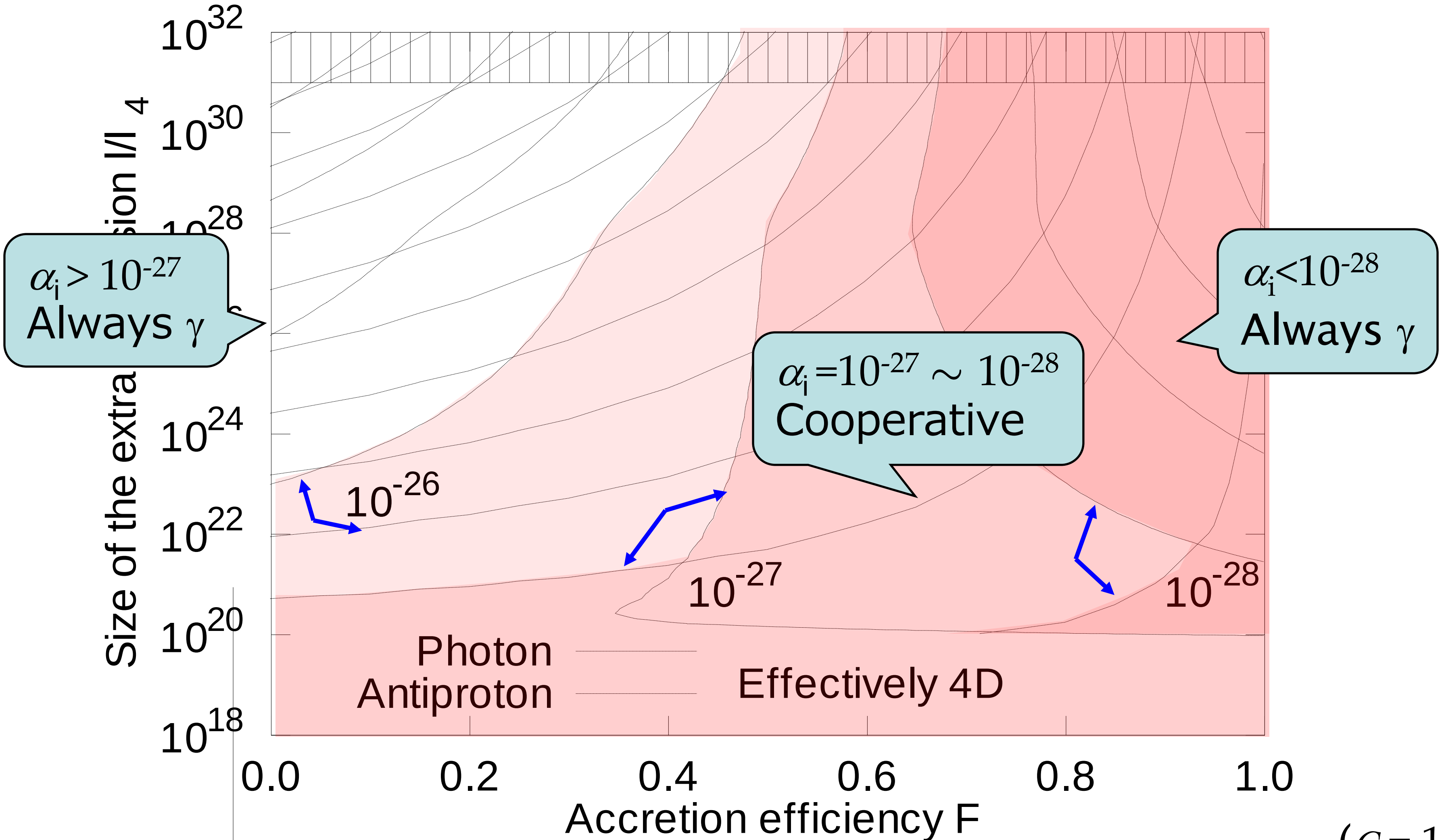
Constraints



Conclusions

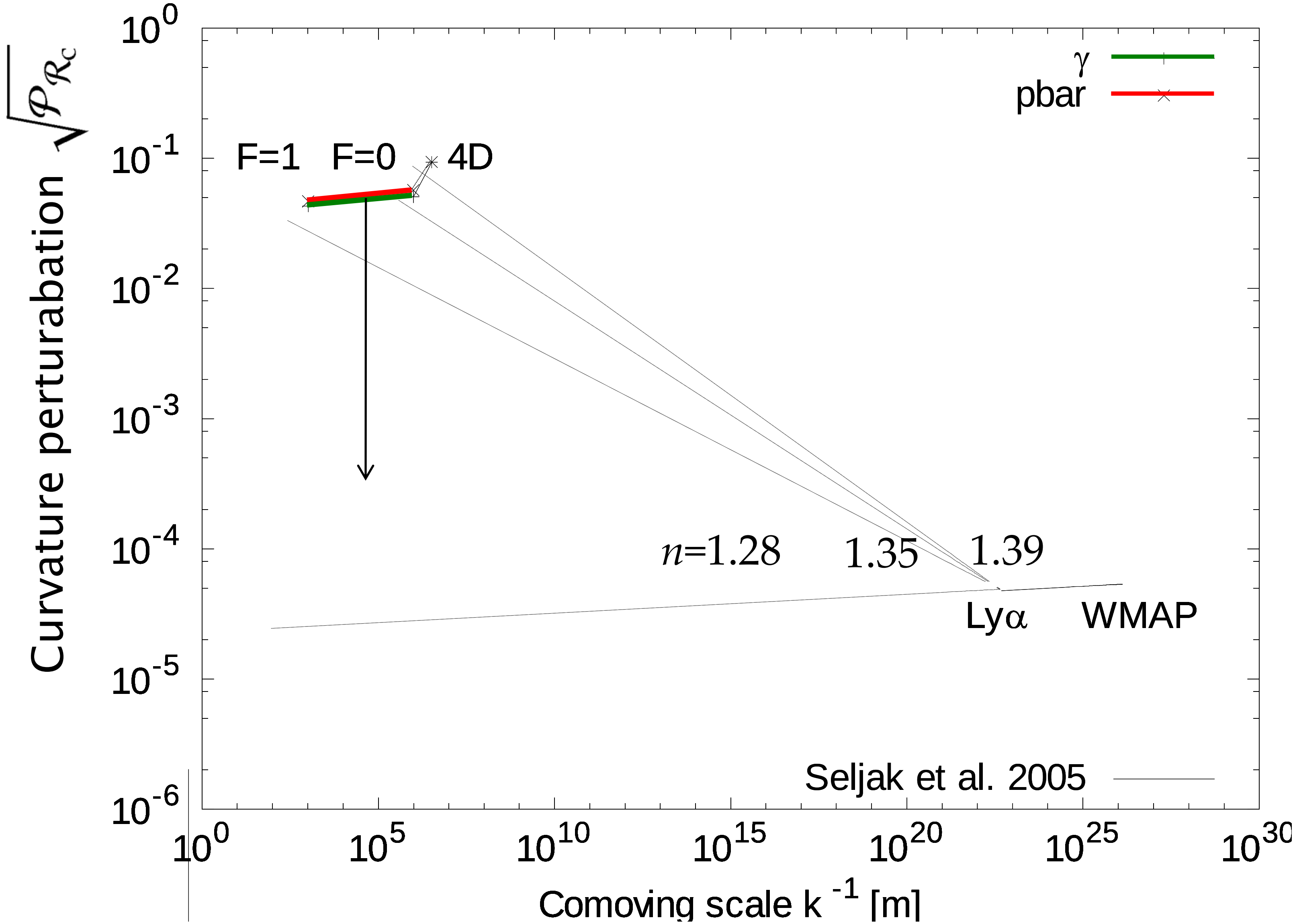
Comparison

As the constraint on ℓ



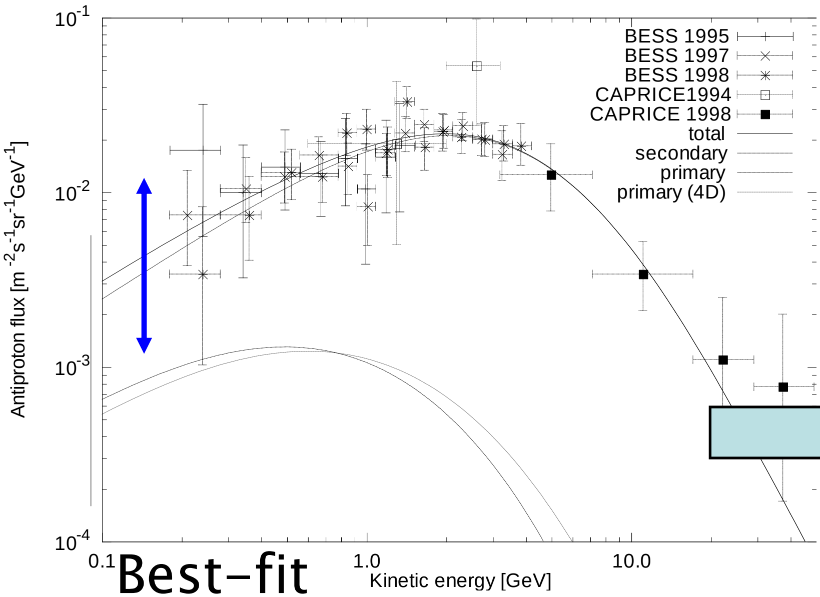
$(\mathcal{G} = 10^5)$

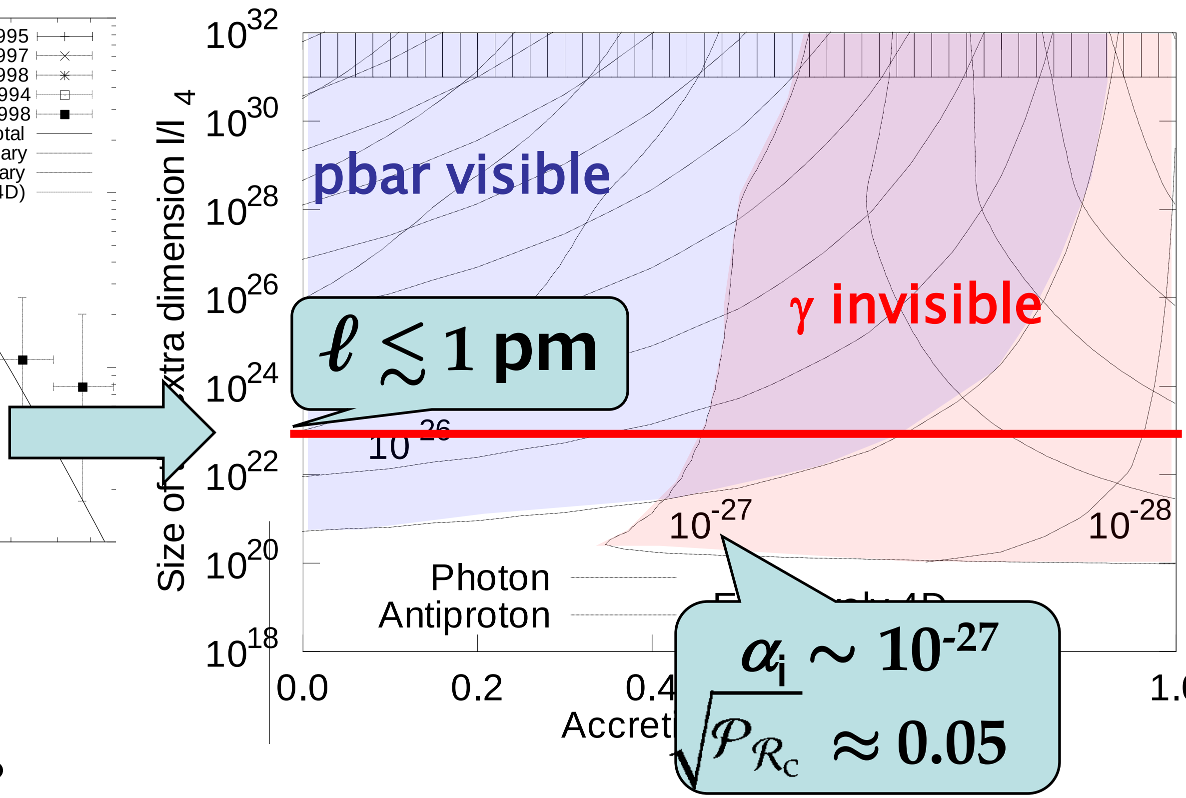
Firm Limit on Inflation



Being Speculative

◆If the sub-GeV pbar excess is real, allowed parameter region is very restrictive





◆Braneworld disfavoured?

◆Bess-Polar 2007 should give a hint