Title: New Cosmological Constraints on Primordial Black Holes

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Abstract: Constraints on the formation of primordial black holes - especially the ones which are small enough to evaporate - provide a unique probe of the early universe, high energy physics and extra dimensions. For evaporating black holes, the dominant constraints are associated with big bang nucleosynthesis and the extragalactic photon background, but there are also other limits associated with the cosmic microwave background, cosmic rays and various types of relic particles. For larger non-evaporating black holes, important constraints come from their gravitational and astrophysical effects. Small non-primordial evaporating black holes may be produced in the LHC if there are large extra dimensions and this would also have important implications for the early universe.

NEW COSMOLOGICAL CONSTRAINTS ON PRIMORDIAL BLACK HOLES *

Bernard Carr
Queen Mary University London
CITA, University of Toronto

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Hs as probe of early Universe

inhomogeneities, phase transitions, inflation, non-Gaussianity

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PBH explosions, cosmic rays, photospheres

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Hs as probe of high energy physics
PBH explosions, cosmic rays, photospheres

Hs as probe of dark side
dark matter, dark energy, dark dimensions

* Carr, K. Kohri, Y. Sendouda & J. Yokoyama, astro-ph/0912.5297

;LACK HOLE FORMATION

$_S = 2GM/c^2 = 3(M/M_O)$ km => $\rho_S = 10^{18}(M/M_O)^{-2}$ g/cm^3

tellar BHs ($M \sim 10M_O$) and SMBHs ($M \sim 10^8 M_O$) form now

mall "primordial" BHs can only form in early Universe

f. cosmological density $\rho \sim 1/(Gt^2) \sim 10^6 (t/s)^{-2}$g/cm^3

⇨ PBHs have horizon mass at formation

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10^{-5}g at 10^{-43}s (minimum)

$M_{PBH} \sim c^3t/G =$ 10^{15}g at 10^{-23}s (evaporating now)

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econd inflation phase or domain walls => larger maximum?

… AND EVAPORATION

Black holes radiate thermally with temperature

$$T = \frac{hc^3}{8\pi GkM} \sim 10^{-7}\left[\frac{M}{M_0}\right]^{-1} K$$

(Hawking 1974)

=> evaporate completely in time $t_{evap} \sim 10^{64}\left[\frac{M}{M_0}\right]^{3} y$

$M \sim 10^{15}$g => final explosion phase today (10^{30} ergs)

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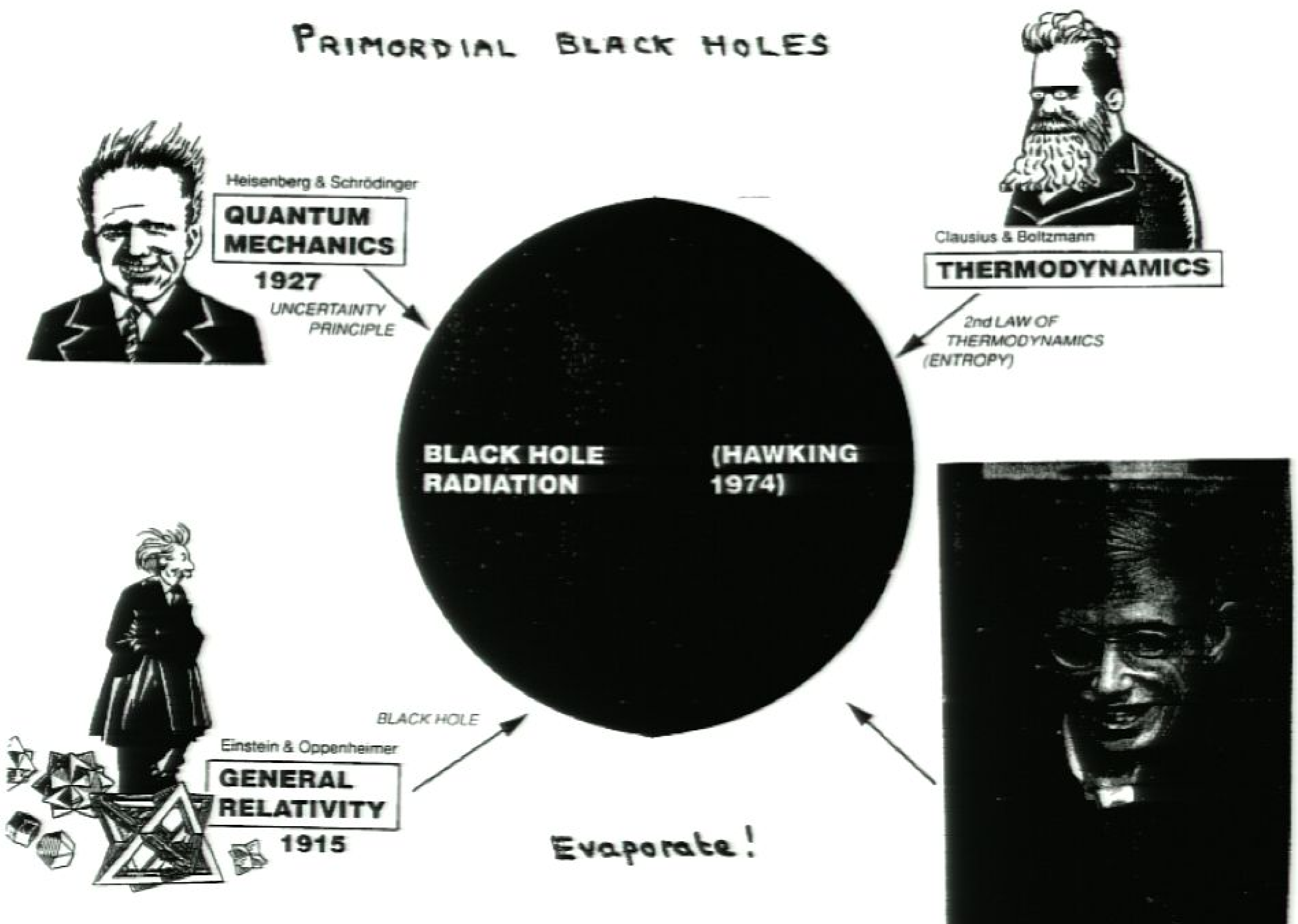
γ-ray bgd at 100 MeV => $\Omega_{PBH}(10^{15}g) < 10^{-8}$

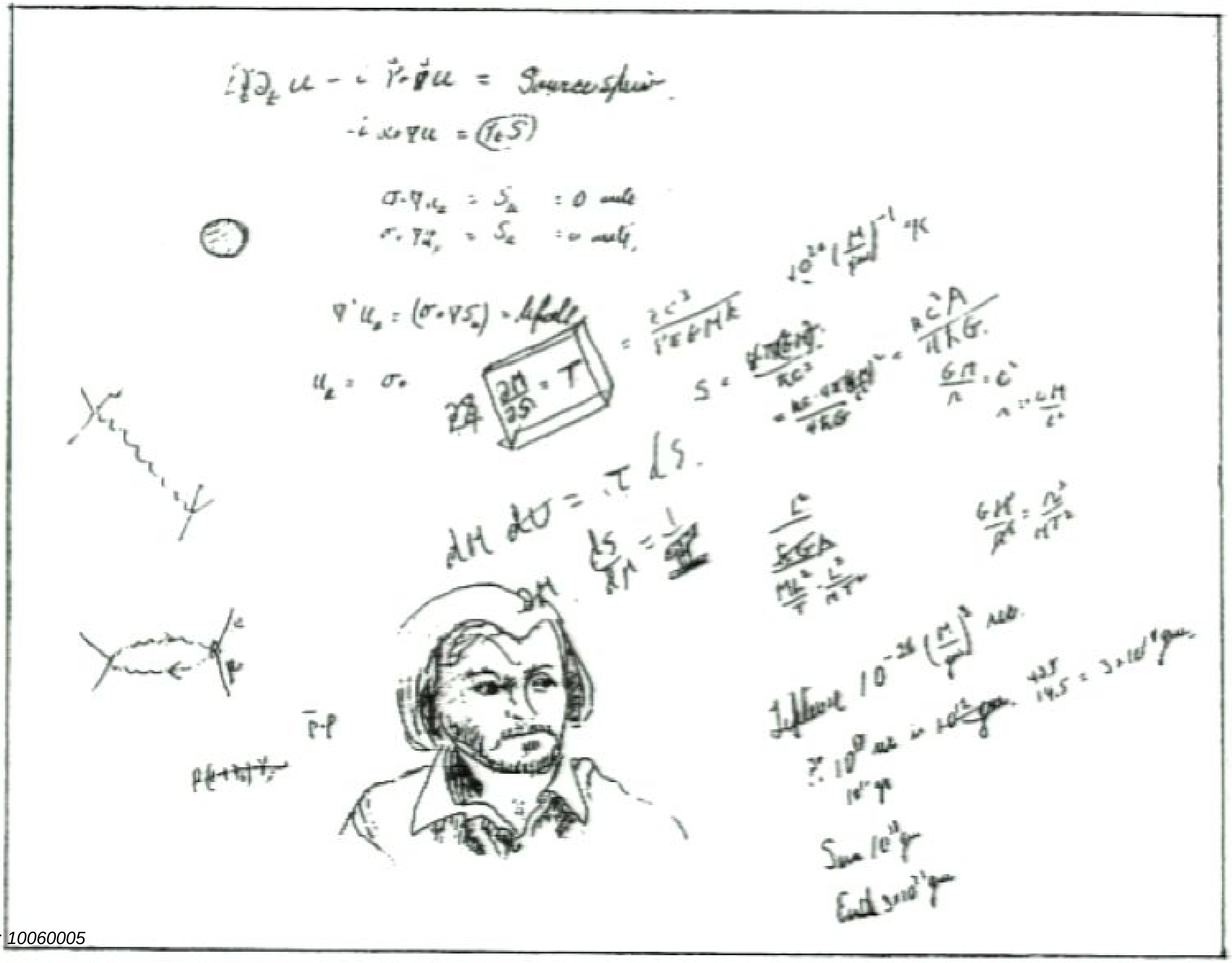
(Page & Hawking 1976)

=> explosions undetectable in standard particle physics model



Hs important even if never formed!

Feynman's envelope!



1975

W PBHS FORM

ɔW PBHS FORM

ʼrimordial inhomogeneities

W PBHS FORM

rimordial inhomogeneities

nflation

ressure reduction

ow PBHS FORM

- rimordial inhomogeneities
- nflation
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- ubble collisions
- osmic strings

)W PBHS FORM

'rimordial inhomogeneities

nflation

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3ubble collisions

Cosmic strings

String necklaces

Domain walls

HAT PBHS DO

›W PBHS FORM

›rimordial inhomogeneities

›nflation

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›ubble collisions

(See CKSY for references)

›osmic strings

›tring necklaces

›omain walls

HAT PBHS DO

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robe fundamental physics **(M~10^{-5}g)**

anck-mass relics

tra dimensions and higher dimensional BHs

ane cosmology

V quantum gravity

HAT PBHS DO

robe fundamental physics (M~10^{-5}g)

anck-mass relics
tra dimensions and higher dimensional BHs
ane cosmology
V quantum gravity

robe early universe (M<10^{15}g)

ryosynthesis
cleosynthesis
avitino/neutrino production
moving monopoles/domain walls
ionization

Probe high energy physics ($M \sim 10^{15}$g)

Cosmological and Galactic γ-rays

Cosmic ray antiprotons and positrons

Gamma-ray bursts

Annihilation line radiation from Galactic centre

Ultra-high-energy cosmic rays

Probe high energy physics ($M \sim 10^{15}$g)

Cosmological and Galactic γ-rays

Cosmic ray antiprotons and positrons

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Annihilation line radiation from Galactic centre

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Probe gravity ($M > 10^{15}$g)

Cold dark matter candidate

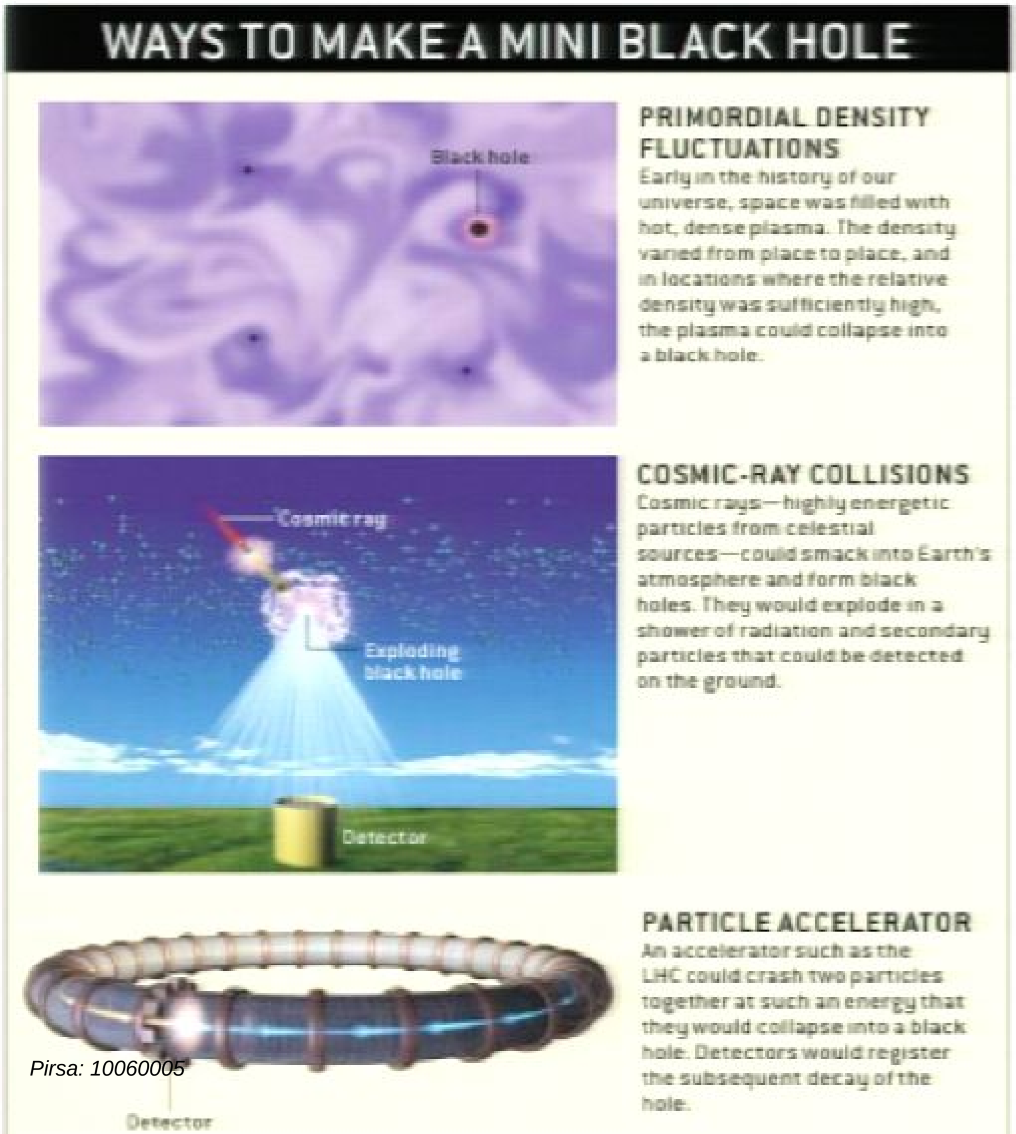
Dynamical/lensing effects

Gravitational waves

Large-scale structure

Black holes in galactic nuclei

BLACK HOLES AS A PROBE OF HIGHER DIMENSIONS



WAYS TO MAKE A MINI BLACK HOLE

PRIMORDIAL DENSITY FLUCTUATIONS
Early in the history of our universe, space was filled with hot, dense plasma. The density varied from place to place, and in locations where the relative density was sufficiently high, the plasma could collapse into a black hole.

COSMIC-RAY COLLISIONS
Cosmic rays—highly energetic particles from celestial sources—could smack into Earth's atmosphere and form black holes. They would explode in a shower of radiation and secondary particles that could be detected on the ground.

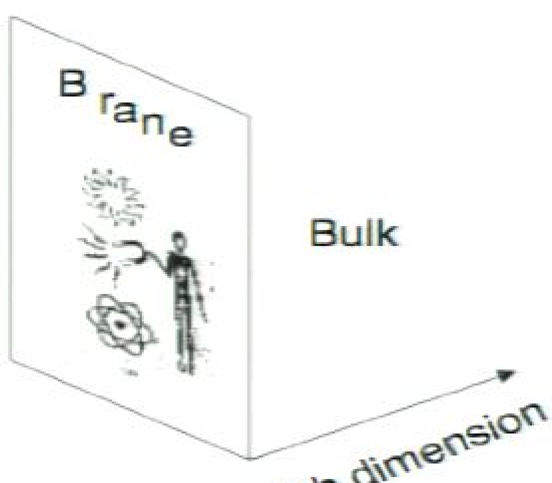
PARTICLE ACCELERATOR
An accelerator such as the LHC could crash two particles together at such an energy that they would collapse into a black hole. Detectors would register the subsequent decay of the hole.

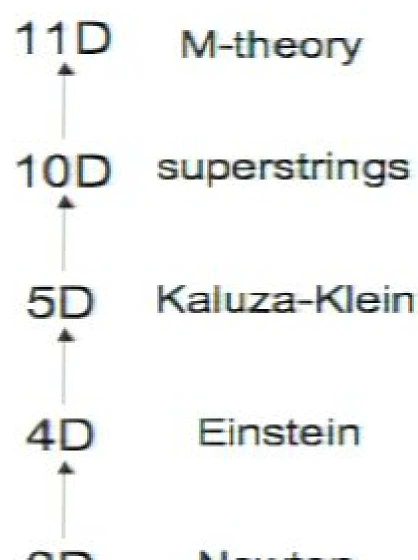
Scientific American
May 2005
Carr and Giddings

BLACK HOLES AND EXTRA DIMENSIONS

Higher dimensions => $M_P^{n+2} V_n \sim M_4^2$

V_n is volume of compactified or warped space





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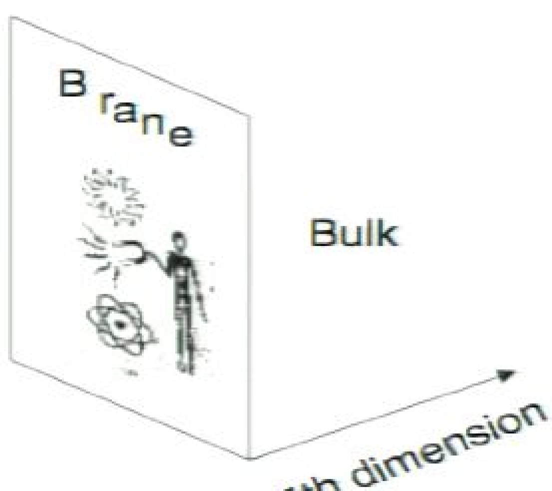

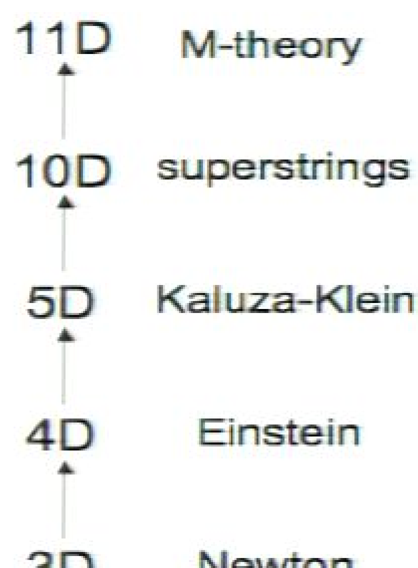

BLACK HOLES AND EXTRA DIMENSIONS

Higher dimensions => $M_P^{n+2} V_n \sim M_4^2$

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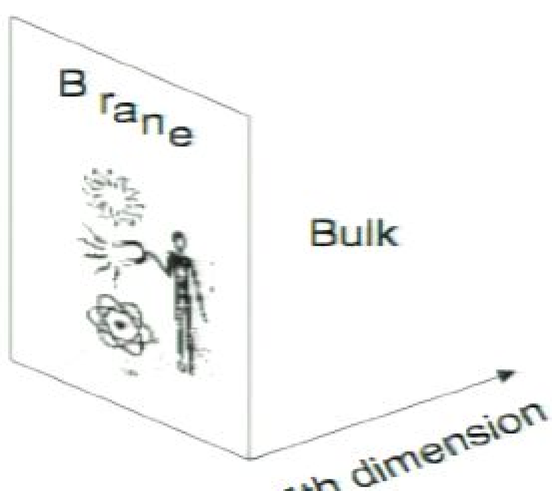
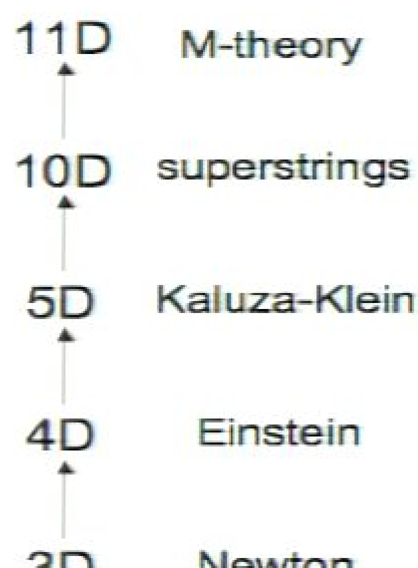
Standard model => $V_n = M_P^{-n}$, $M_P = M_4$,
Large extra dimensions => $V_n >> M_P^{-n}$, $M_P << M_4$





LHC, cosmic rays => higher dim BHs

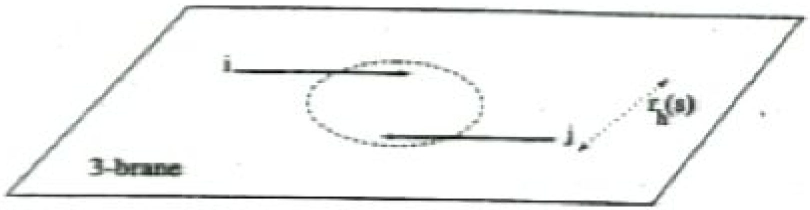


Figure 1: Two partons, i and j, form a black hole by passing within the event horizon determined by the Schwarzschild radius associated with the center of mass energy $\sqrt{s}$.

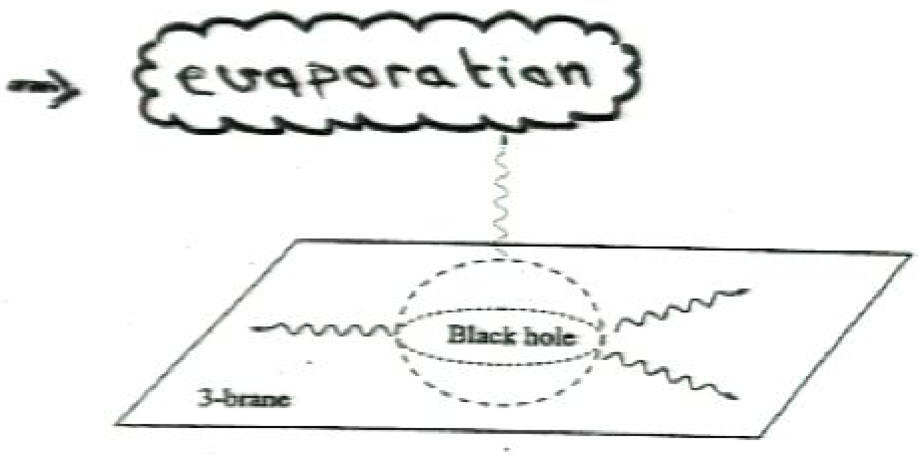


Figure 2: A D-dimensional black hole bound to a 3-brane. The black hole emits Hawking radiation predominantly into brane modes (solid lines) and also into bulk modes (dotted lines). Grey body factors for brane modes are determined from the metric induced by the D-dimensional black hole geometry on the brane.

Forming black holes by collisions

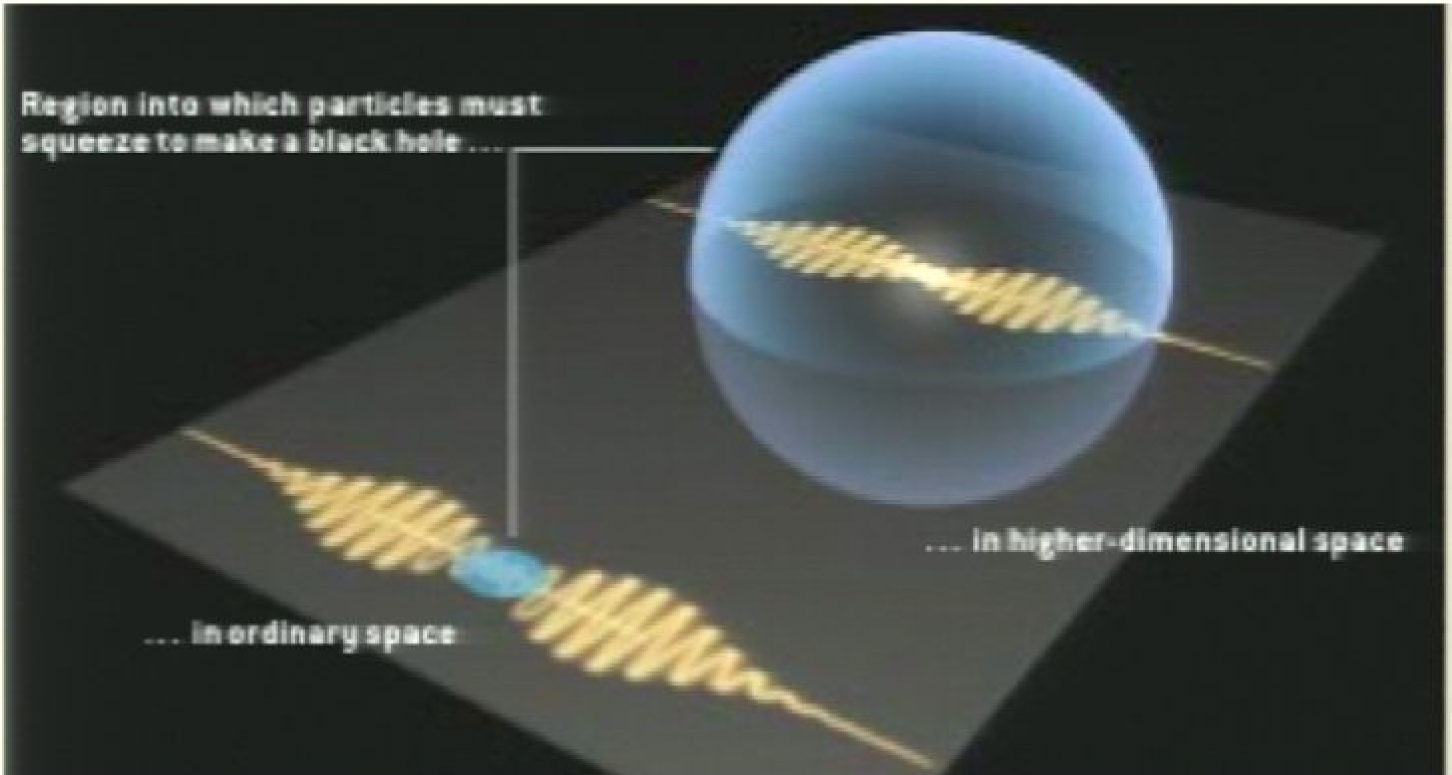
centre of mass energy

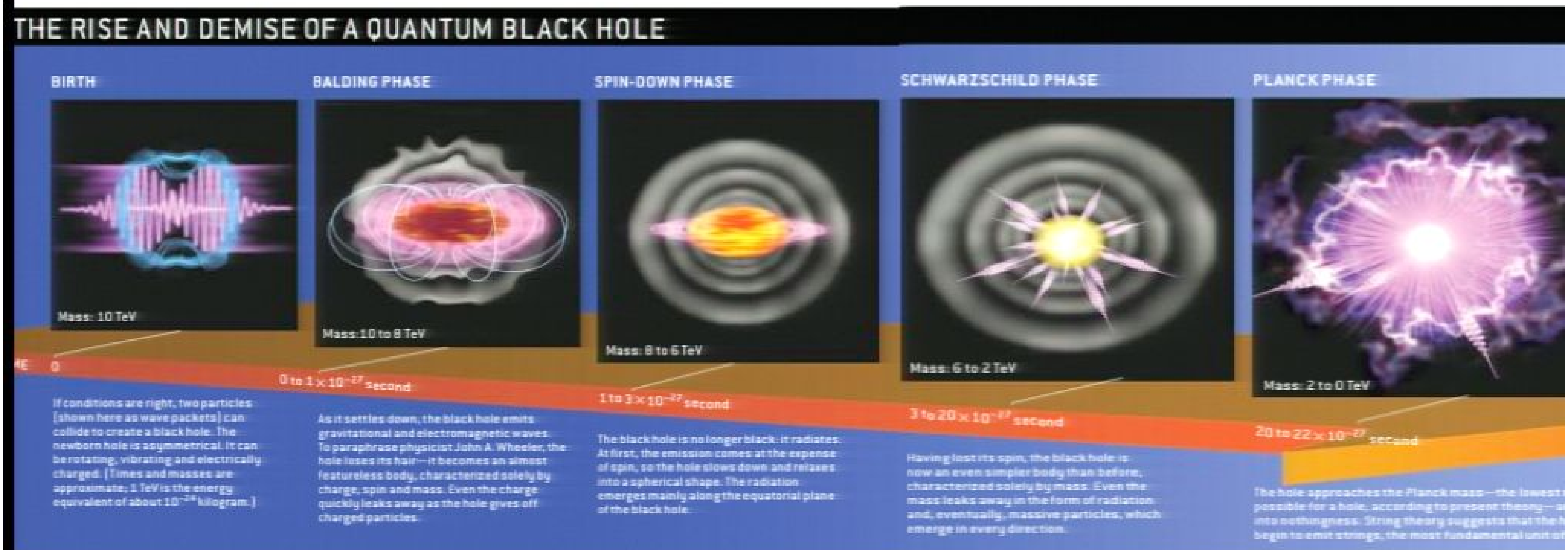
Cross-section $\sigma(ij \rightarrow BH) = \pi r_S^2 \Theta(E - M_{BH}^{min})$

Schwarzschild radius $r_S = M_P^{-1}(M_{BH}/M_P)^{1/(1+n)}$

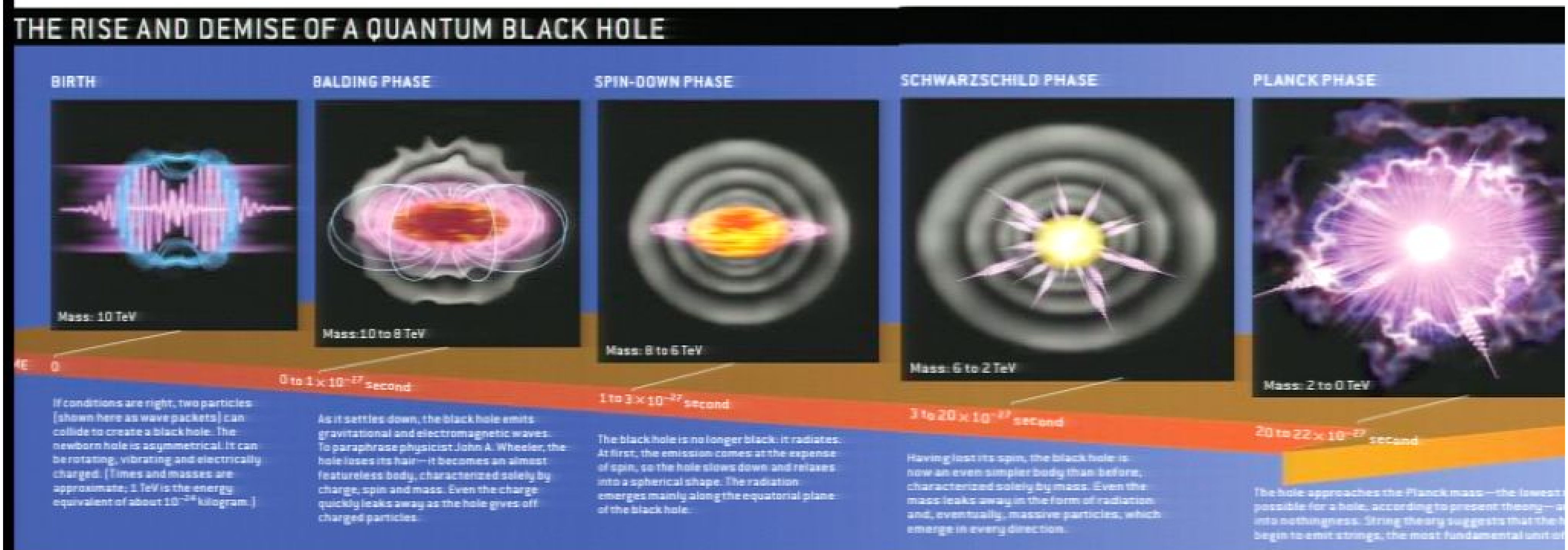
Temperature $T_{BH} = (n+1)/r_S$ < 4D case

Lifetime $\tau_{BH} = M_P^{-1}(M_{BH}/M_P)^{(n+3)/(1+n)}$ > 4D case





THE RISE AND DEMISE OF A QUANTUM BLACK HOLE
BIRTH
BALDING PHASE
SPIN-DOWN PHASE
SCHWARZSCHILD PHASE
PLANCK PHASE
Mass: 10 TeV
Mass: 10 to 8 TeV
Mass: 8 to 6 TeV
Mass: 6 to 2 TeV
Mass: 2 to 0 TeV
0
0 to 1 × 10^−27 second
1 to 3 × 10^−27 second
3 to 20 × 10^−27 second
20 to 22 × 10^−27 second
If conditions are right, two particles (shown here as wave packets) can collide to create a black hole. The newborn hole is asymmetrical. It can be rotating, vibrating and electrically charged. (Times and masses are approximate; 1 TeV is the energy equivalent of about 10^−24 kilogram.)
As it settles down, the black hole emits gravitational and electromagnetic waves. To paraphrase physicist John A. Wheeler, the hole loses its hair—it becomes an almost featureless body, characterized solely by charge, spin and mass. Even the charge quickly leaks away as the hole gives off charged particles.
The black hole is no longer black: it radiates. At first, the emission comes at the expense of spin, so the hole slows down and relaxes into a spherical shape. The radiation emerges mainly along the equatorial plane of the black hole.
Having lost its spin, the black hole is now an even simpler body than before, characterized solely by mass. Even the mass leaks away in the form of radiation and, eventually, massive particles, which emerge in every direction.
The hole approaches the Planck mass—the lowest
possible for a hole, according to present theory—
into nothingness. String theory suggests that the
begin to emit strings, the most fundamental unit of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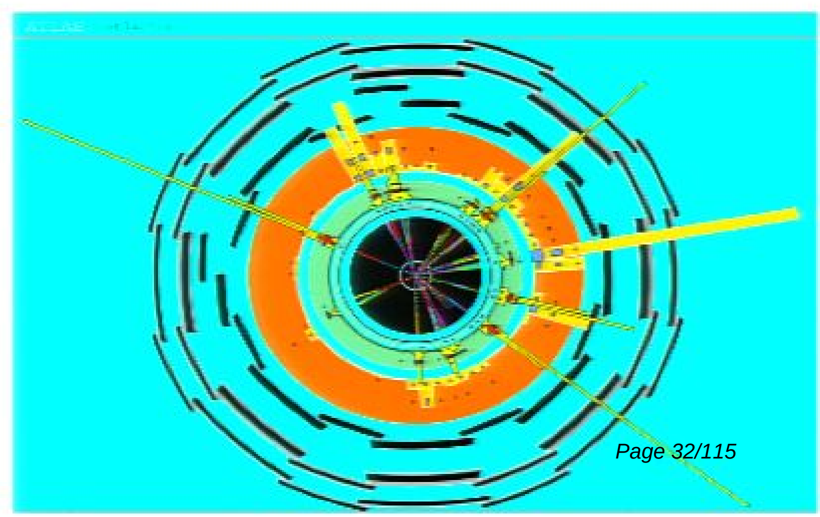

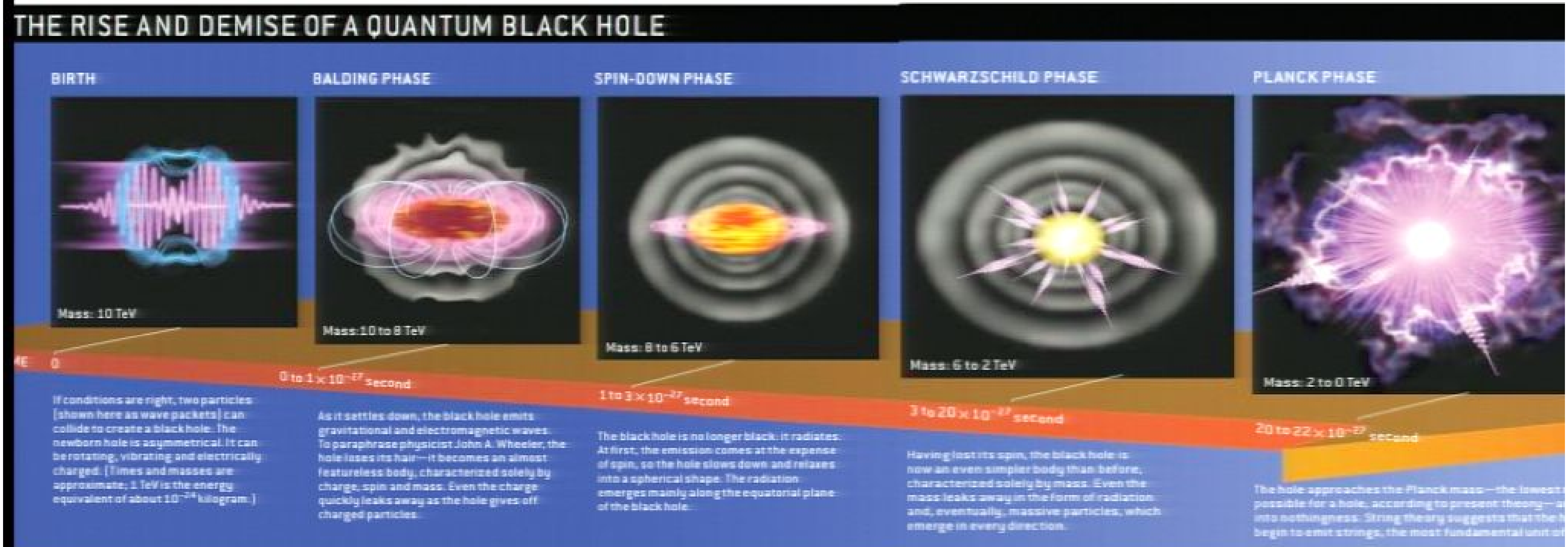
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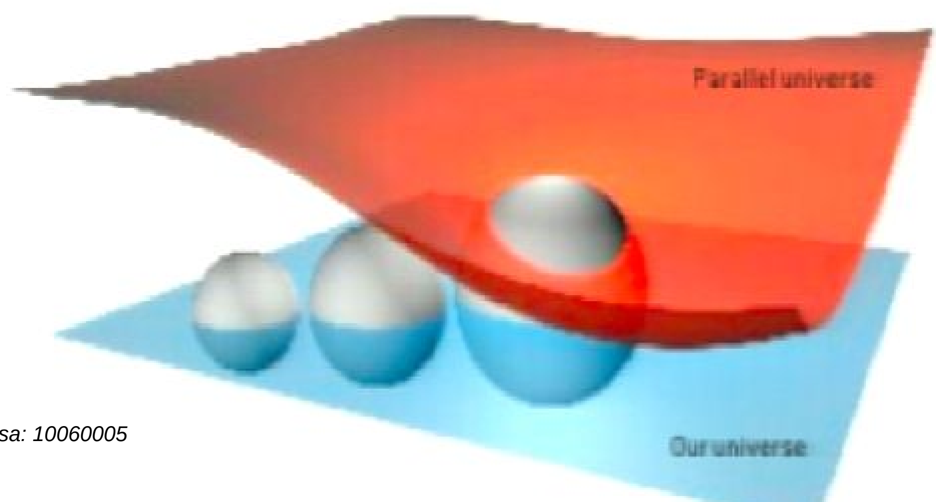
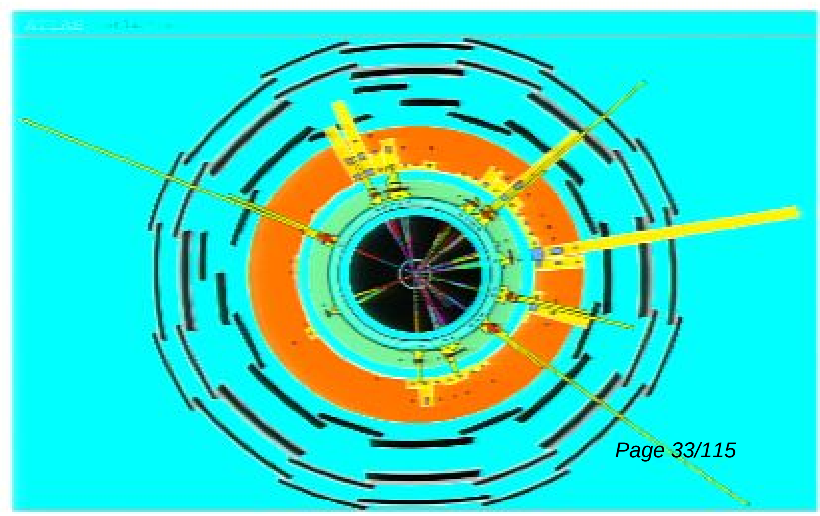
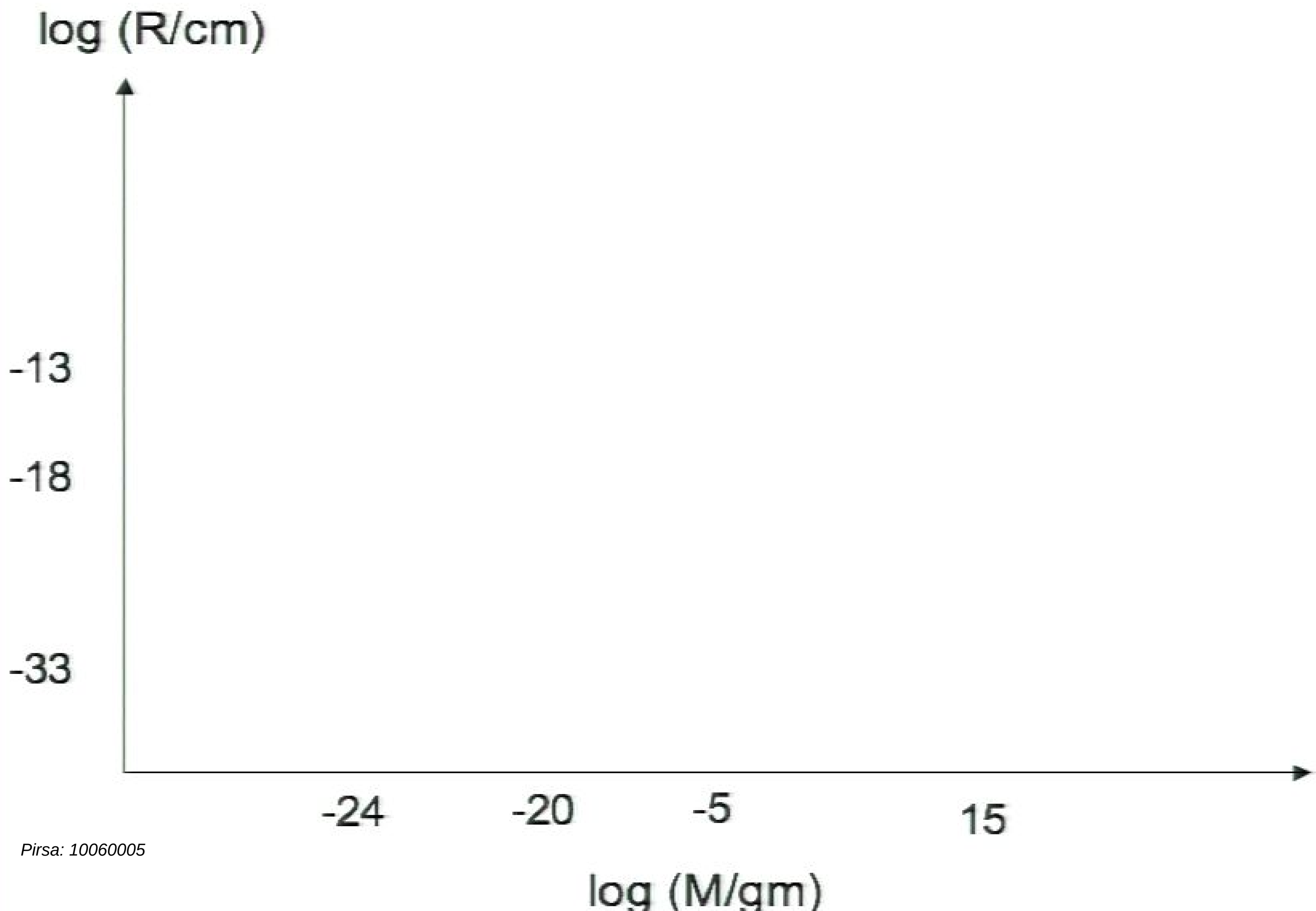
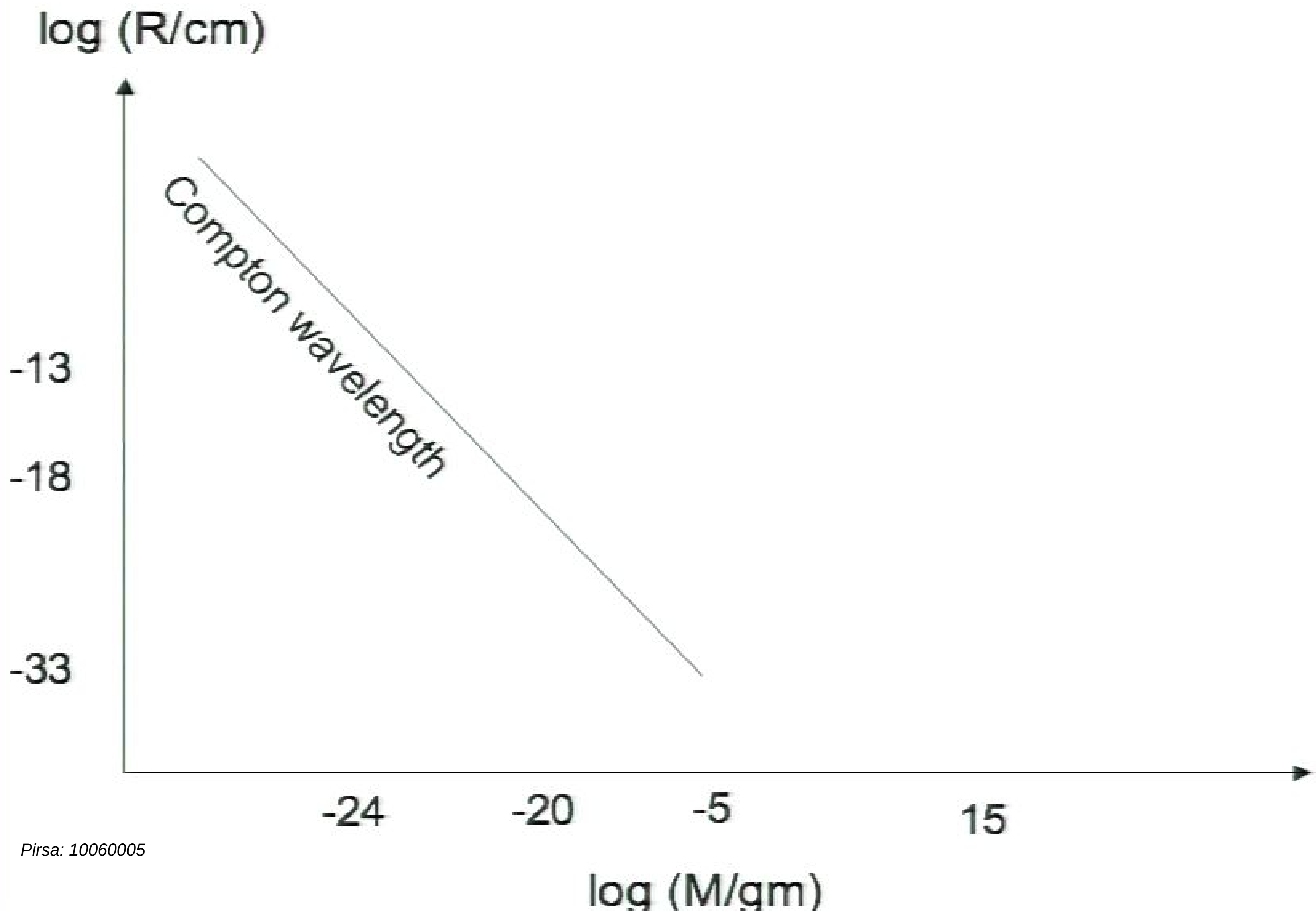

Parallel universe
Our universe




log (R/cm)
-13
-18
-33
-24
-20
-5
15
log (M/gm)

Uncertainty Principle $\Delta \mathbf{x} > \frac{h}{\Delta p}$ => $R > \frac{h}{Mc}$



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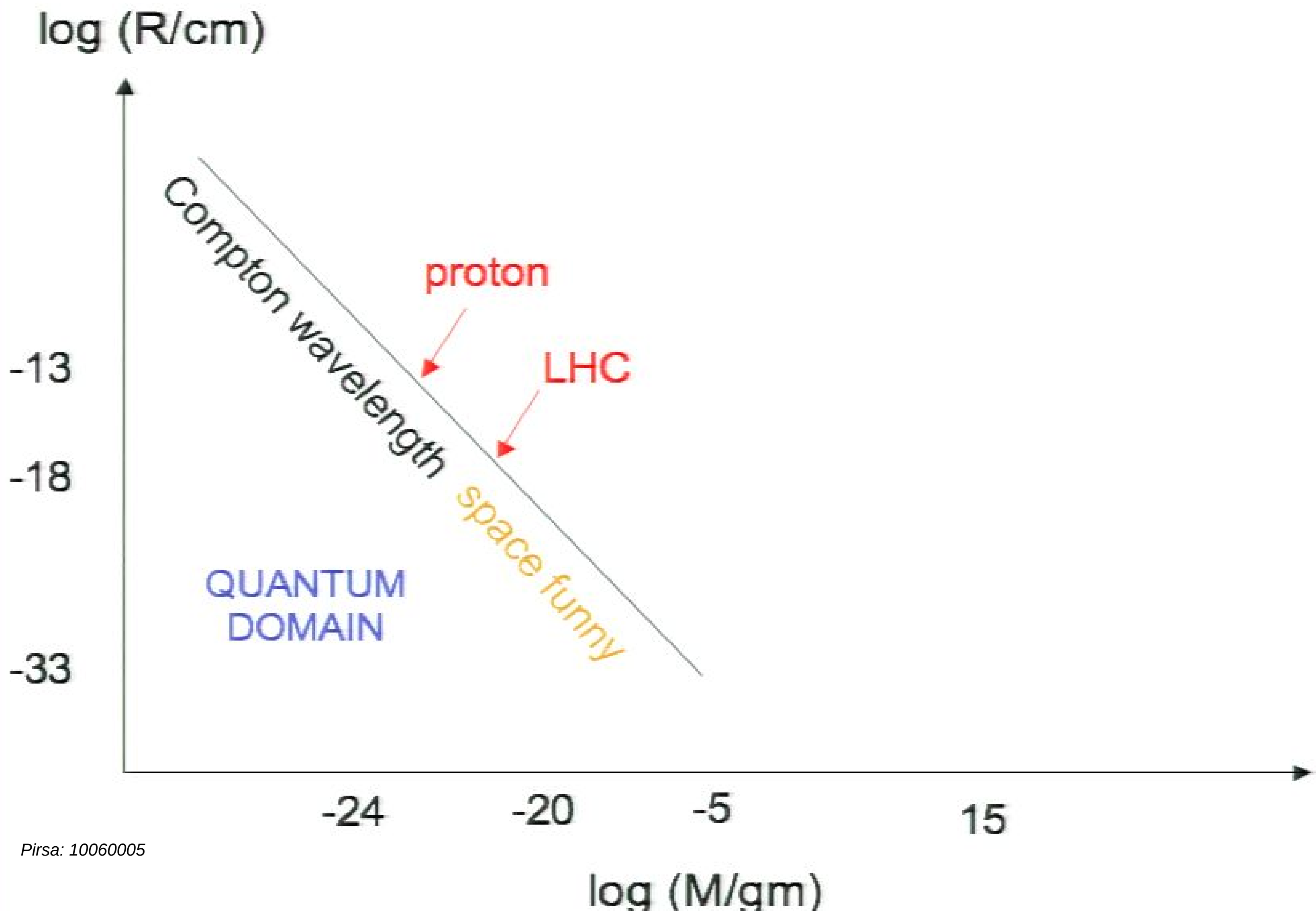

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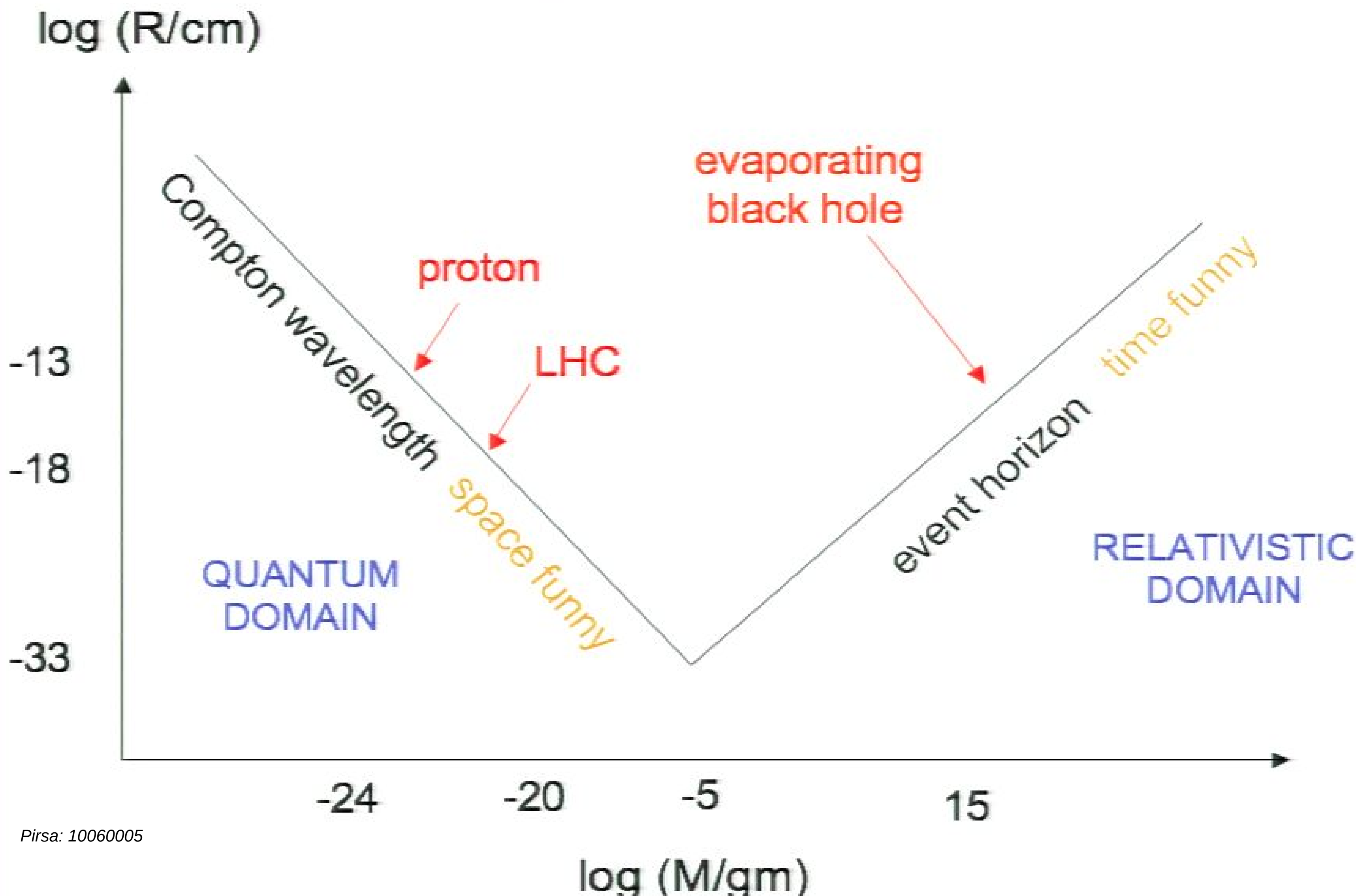
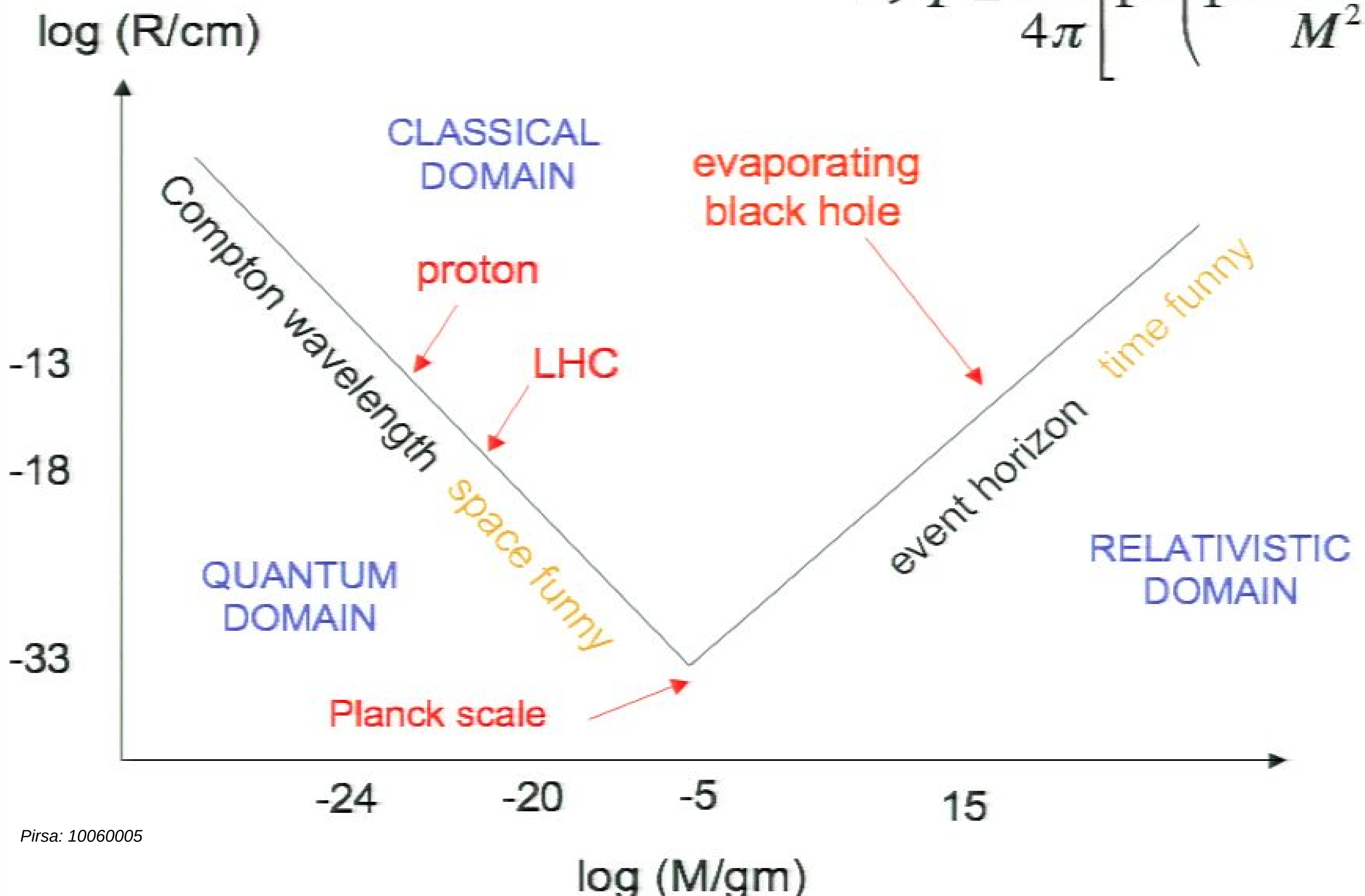


Generalized Uncertainty Principle $\Delta x > \frac{h}{\Delta p} + l_P^2 \frac{\Delta p}{h}$

Black hole radius $r_S = 2GM/c^2$ $\Rightarrow T = \frac{M}{4\pi}\left[1-\left(1-\frac{M_P^{\ 2}}{M^2}\right)^{1/2}\right] \approx \frac{M}{8\pi}$



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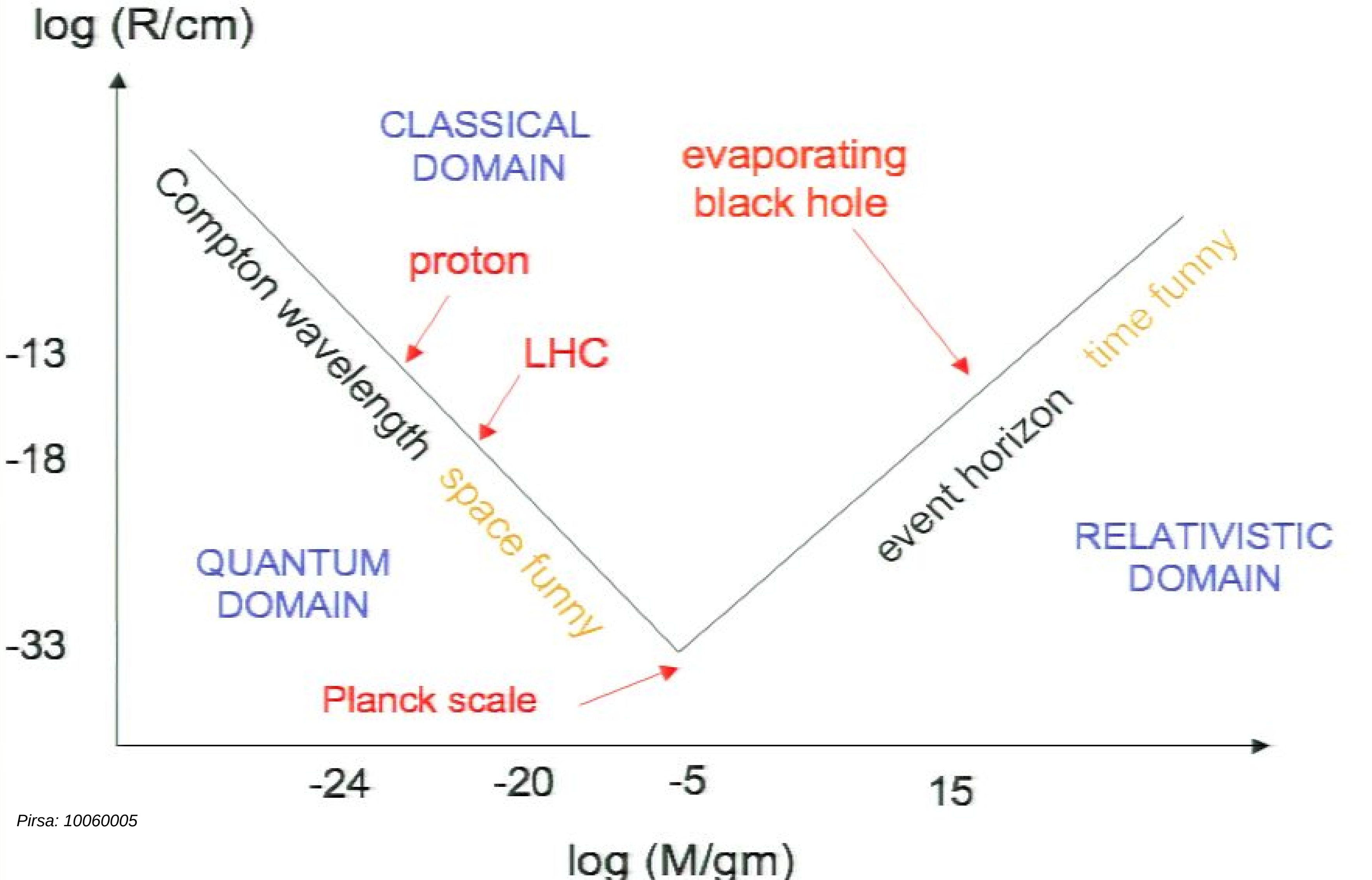

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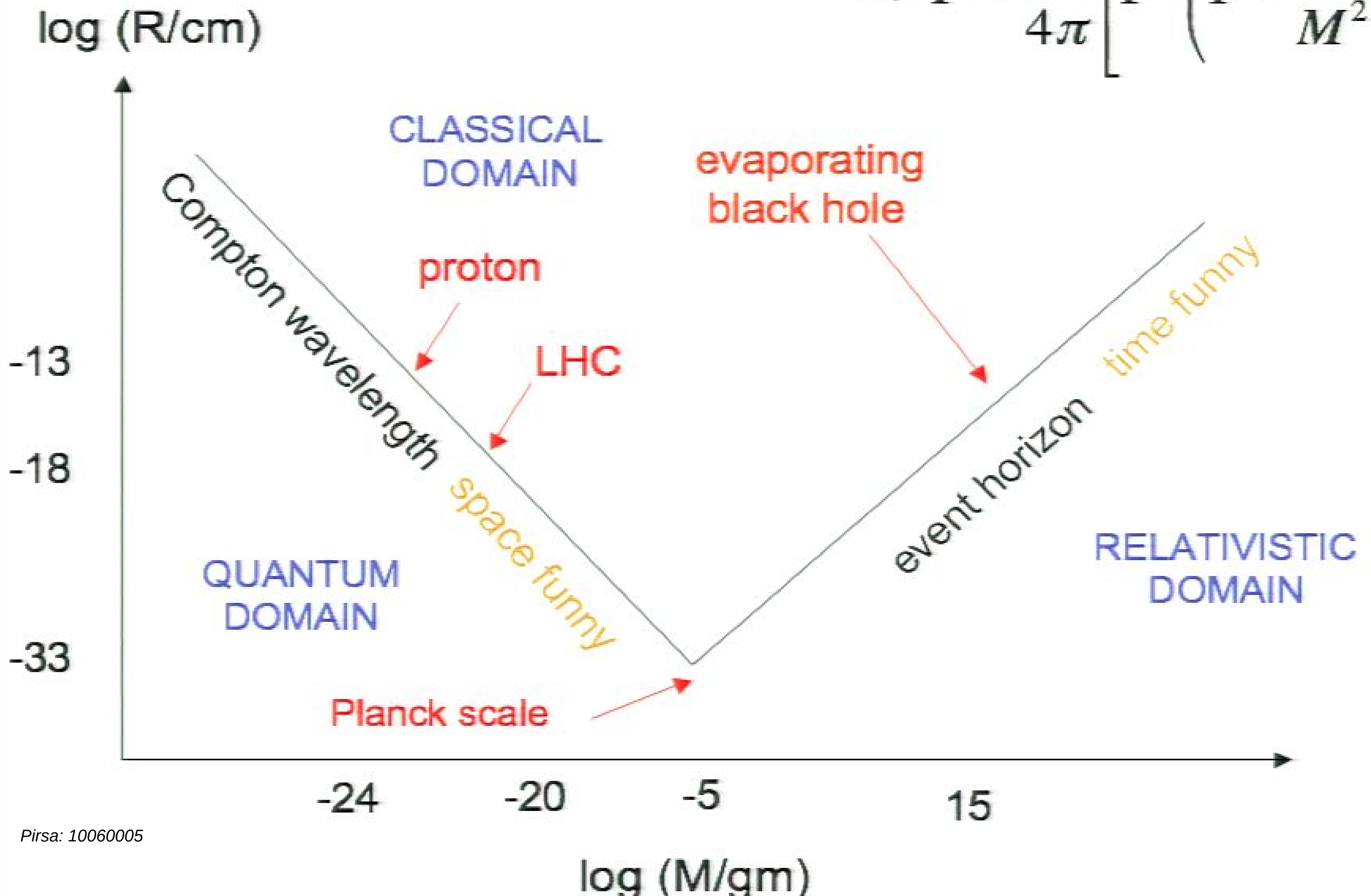

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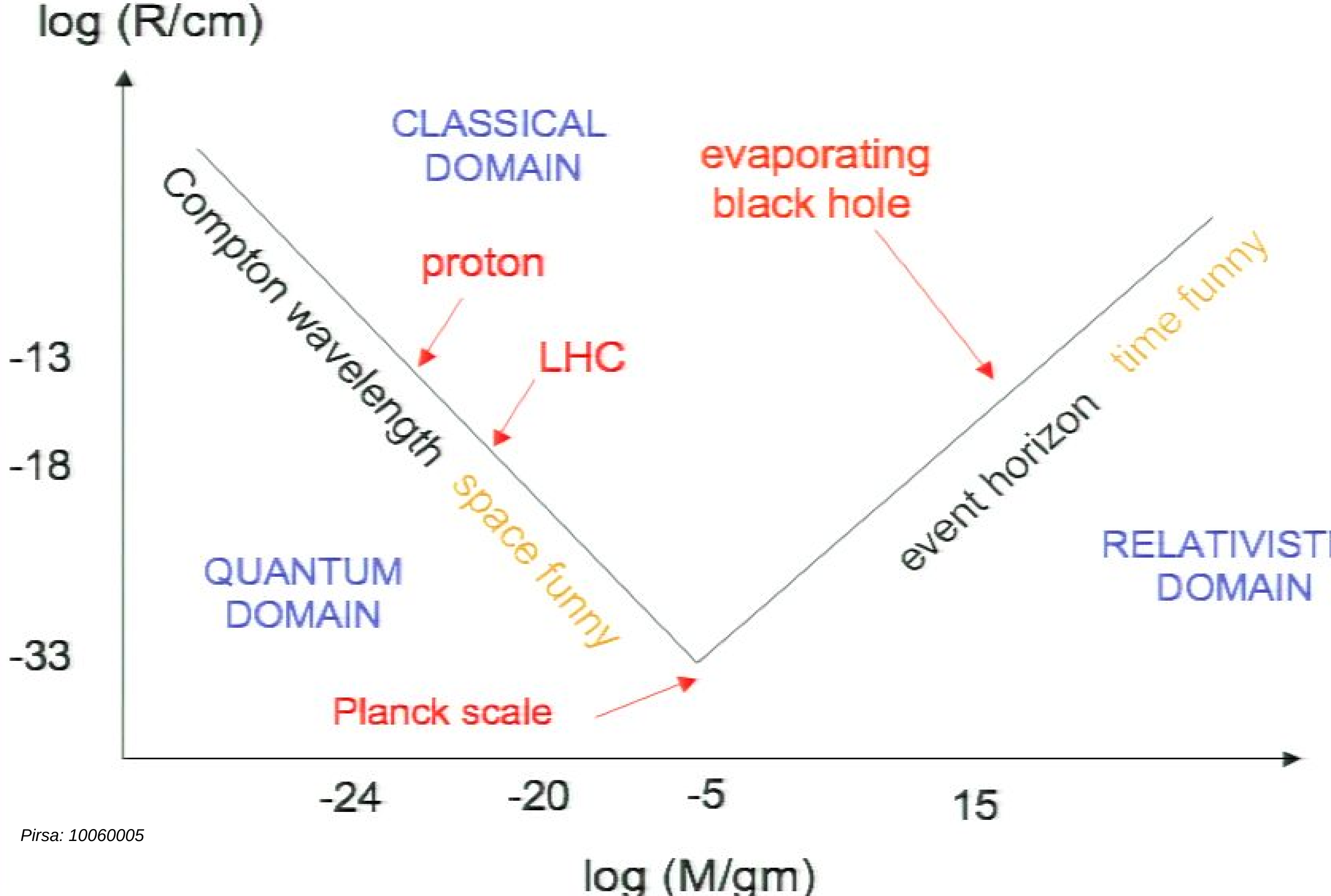

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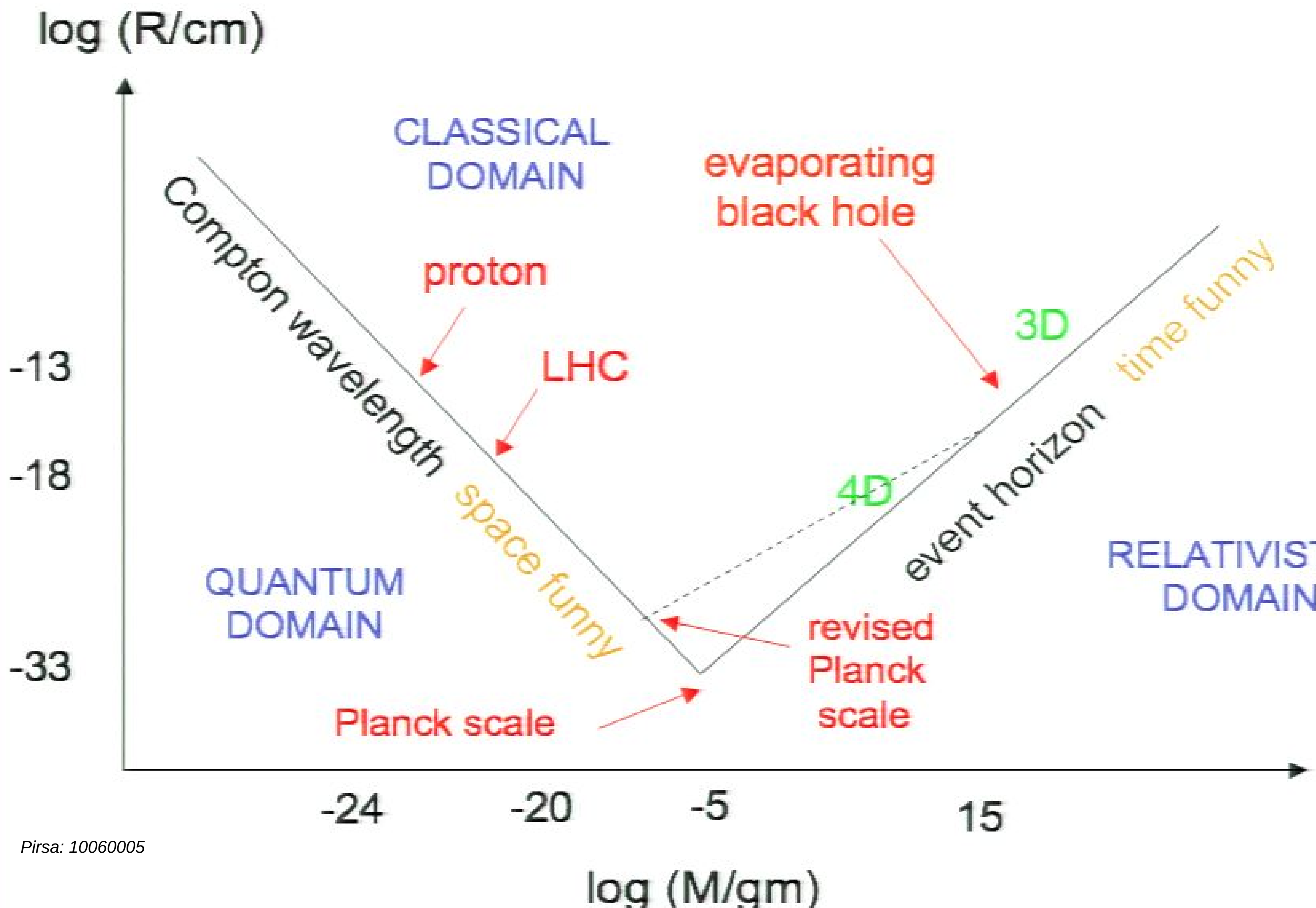


RANE COSMOLOGY (Bowcock et al. 2000, Mukohyama et al. 2000)

ane can be viewed as moving through 5^{th} dimension in static bulk
scribed by 5D Schwarzschild-anti de Sitter solution:

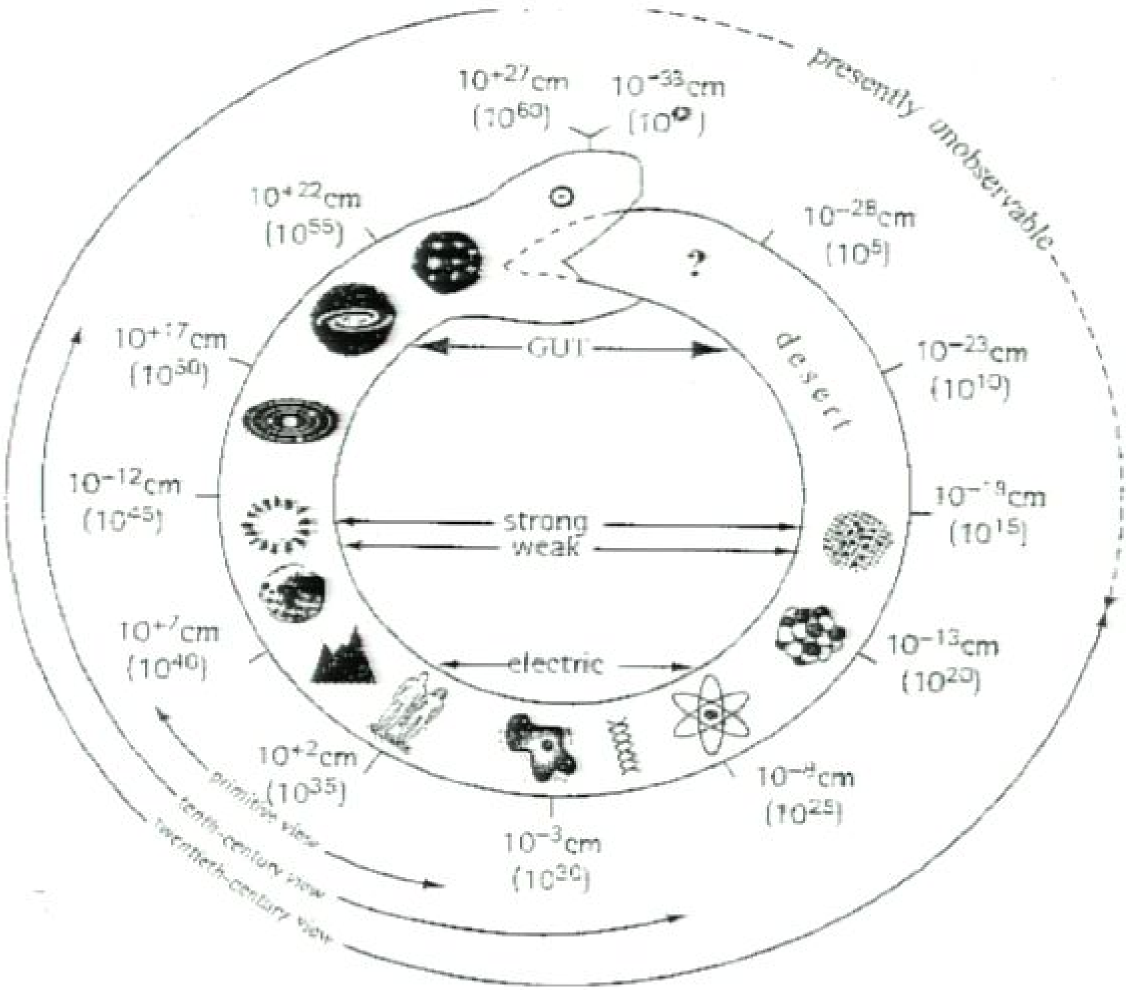
$$ds^2 = -F(R)dT^2 + F(R)^{-1}dR^2 + R^2 [(1-Kr^2)^{-1}dr^2 + r^2 dW^2],$$

$$F(R) = K - m/R^2 + (R/L)^2$$

0, +1, -1

dimension is identified with cosmic scale factor R=a(t)

Multiverse **Higher dimensions** M-theory



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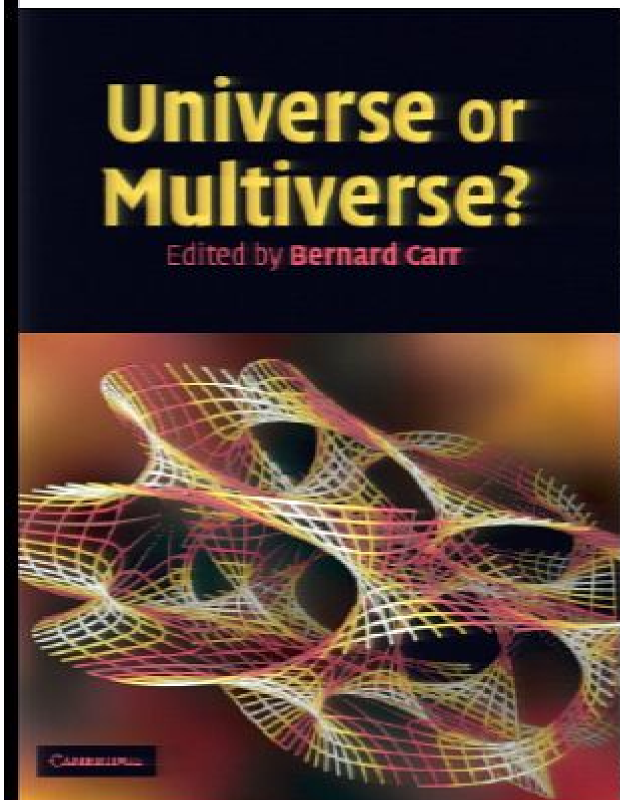

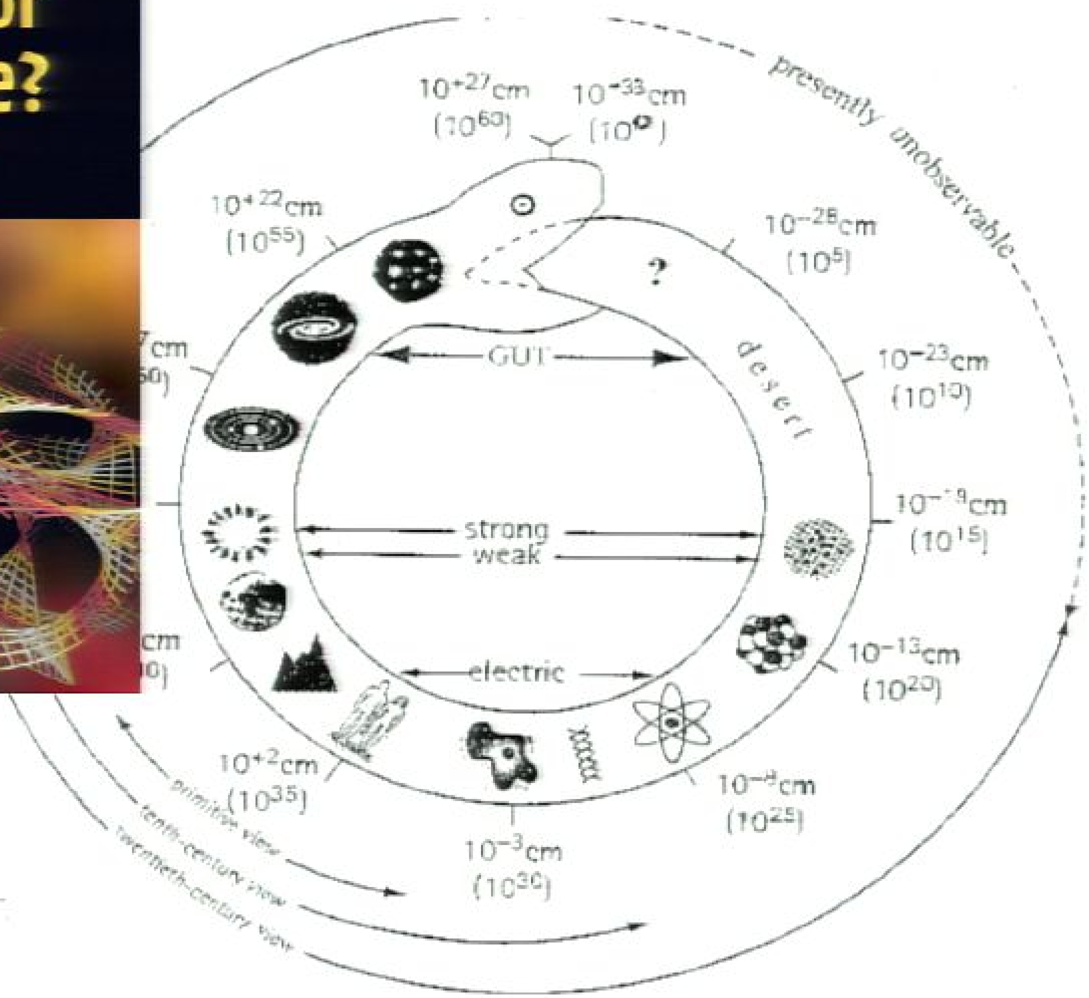

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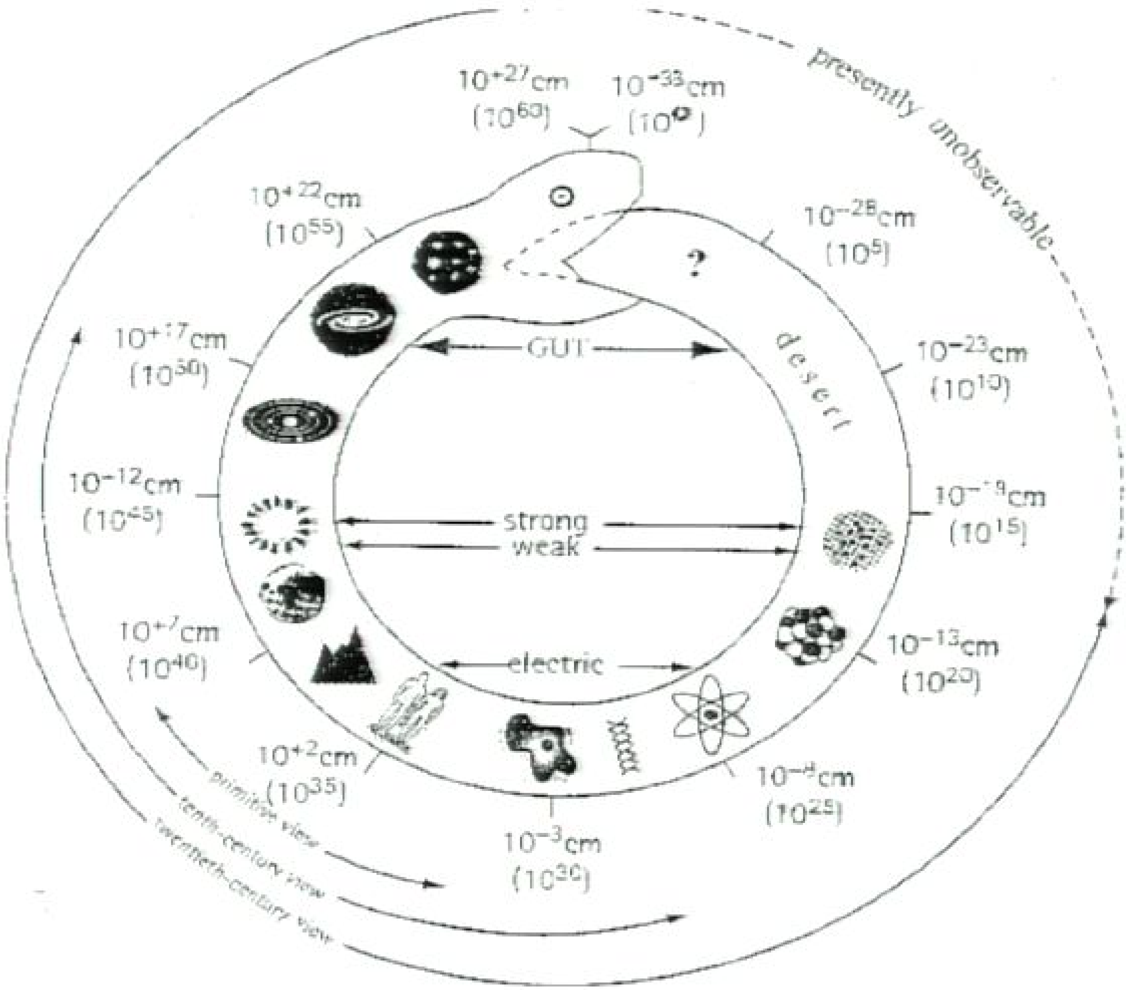
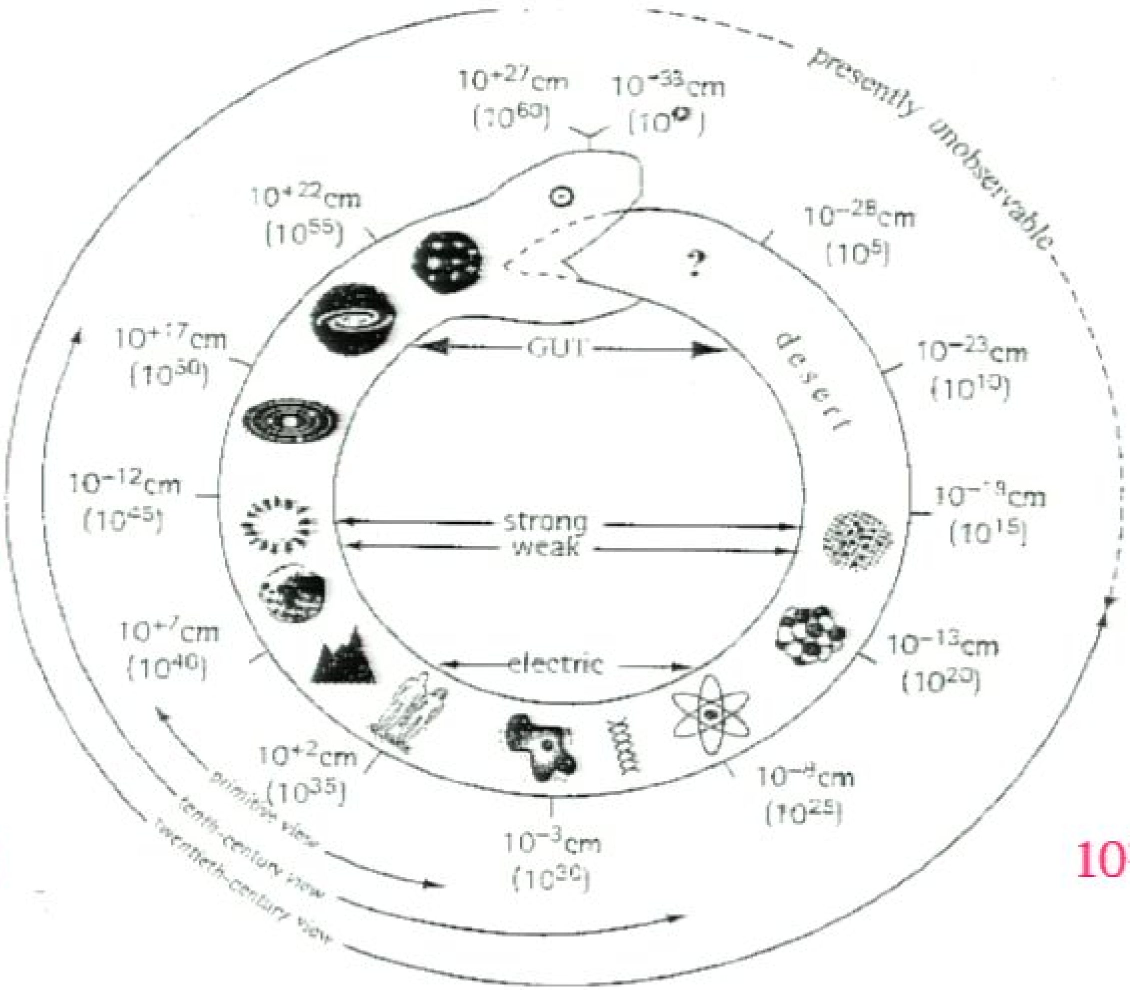


Multiverse **Higher dimensions** M-theory

10^{-5}g Planck



10^6 M_O

10^{15}g Exploding

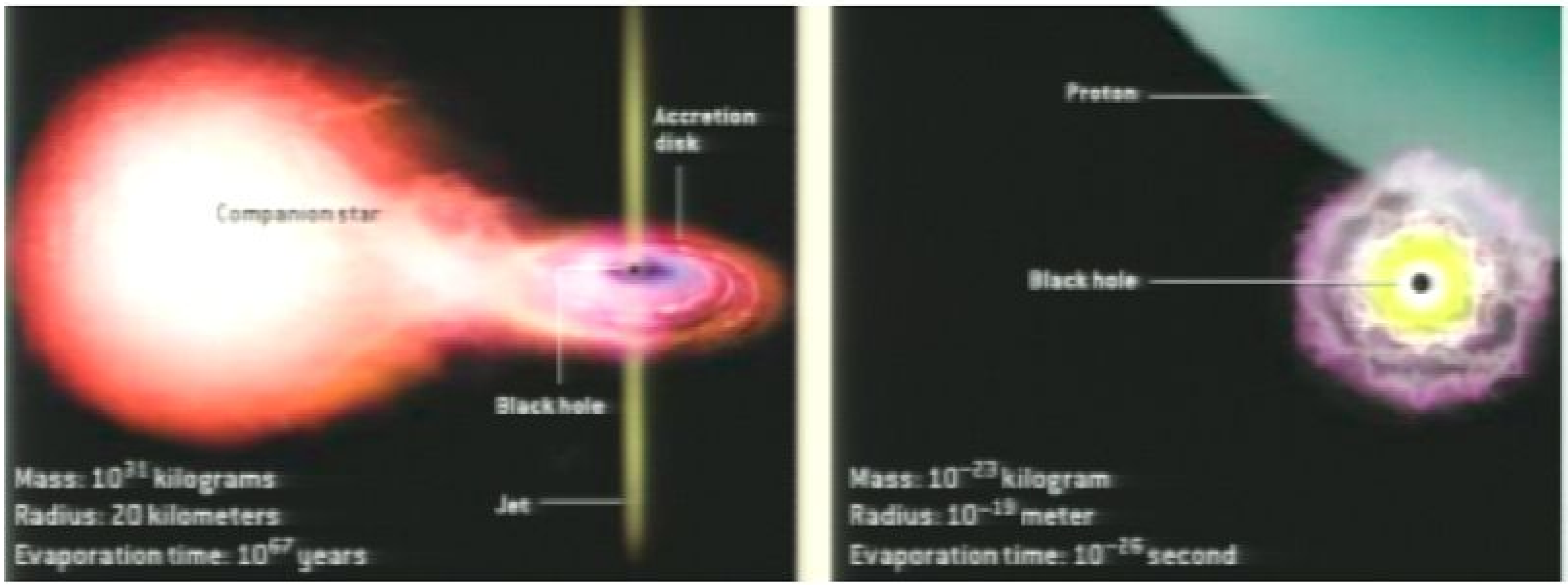
Stellar 1 M_O

10^{21}g Lunar

BLACK HOLES

LARGE VERSUS SMALL BLACK HOLES

Observational aspects



Limit on fraction of Universe collapsing

β(M) **fraction of density in PBHs of mass M at formation**

General limit

$$\frac{\rho_{PBH}}{\rho_{CBR}} \approx \frac{\Omega_{PBH}}{10^{-4}}\left[\frac{R}{R_0}\right] \Rightarrow \beta < 10^{-6}\,\Omega_{\mathrm{PBH}}\left[\frac{t}{\mathrm{sec}}\right]^{1/2} < 10^{-18}\,\Omega_{\mathrm{PBH}}\left[\frac{M}{10^{15}g}\right]$$

MIDWAY MESSAGE

luge potential mass range of PBHs makes them a powerful robe of both macrophysics and microphysics.

PBHs could provide unique information about higher dimension elevant to accelerator experiments and creation of Universe.

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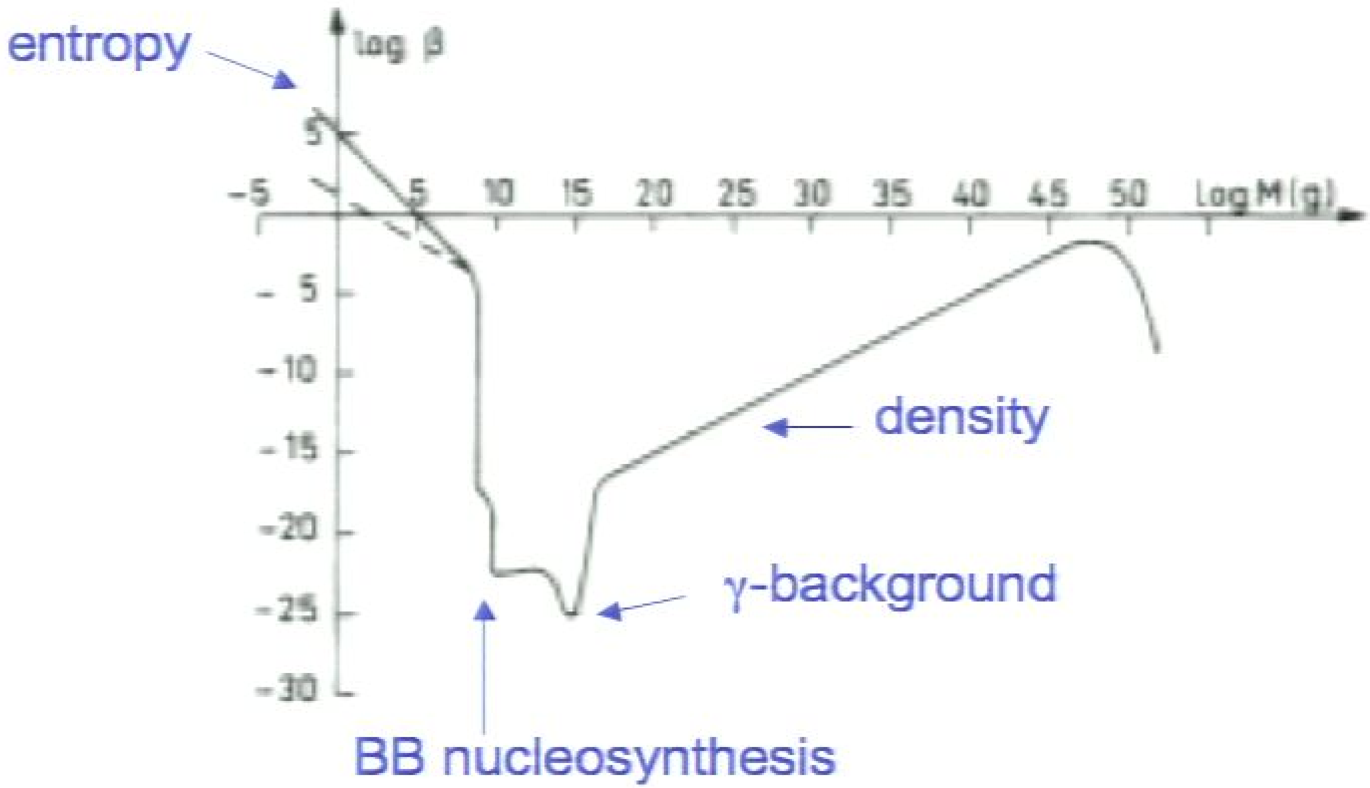
Unevaporated $M > 10^{15}g \Rightarrow \Omega_{PBH} < 0.25$ **(CDM)**
Evaporating now $M \sim 10^{15}g \Rightarrow \Omega_{PBH} < 10^{-8}$ **(EGB)**
Evaporated in past

$M < 10^{15}g \Rightarrow$ **constraints from entropy, γ-background, BBN**

Novikov et al. (1979)



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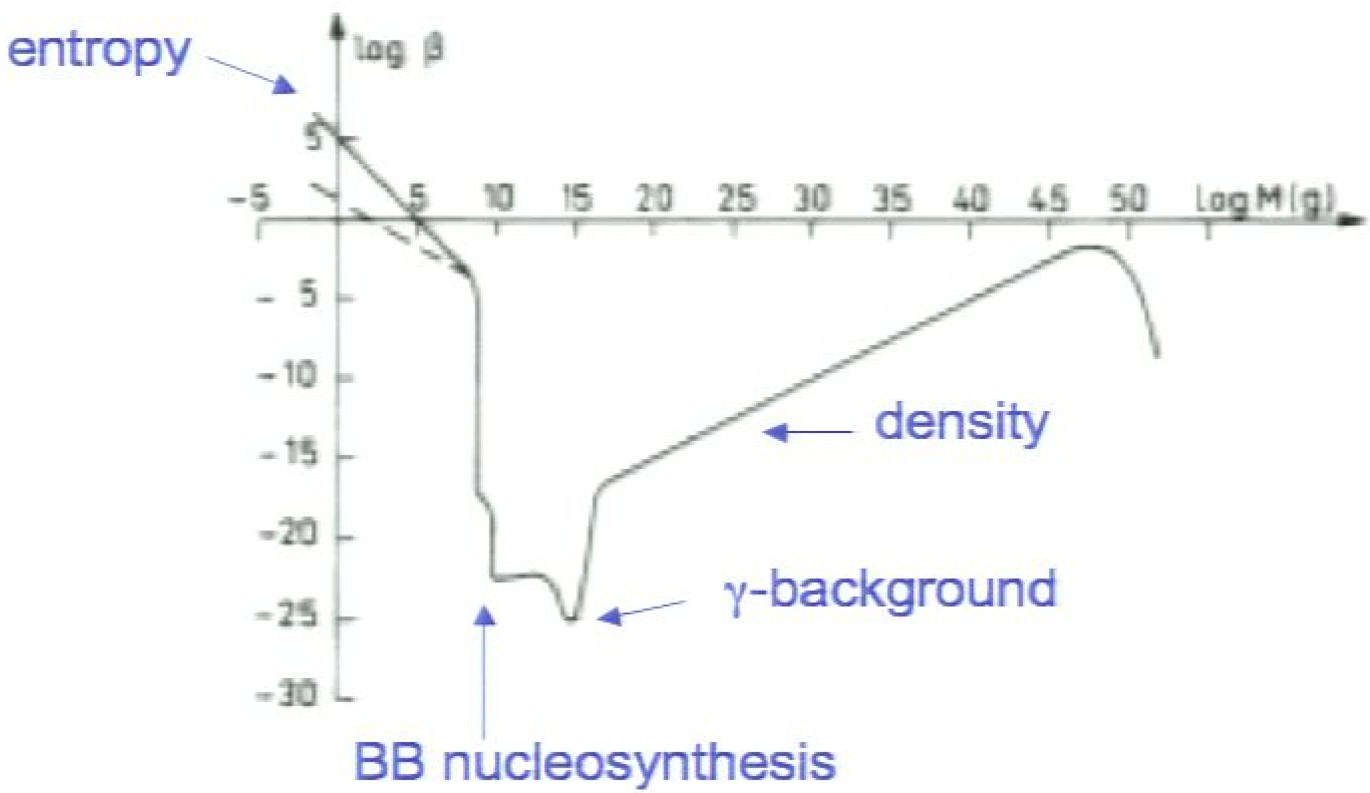

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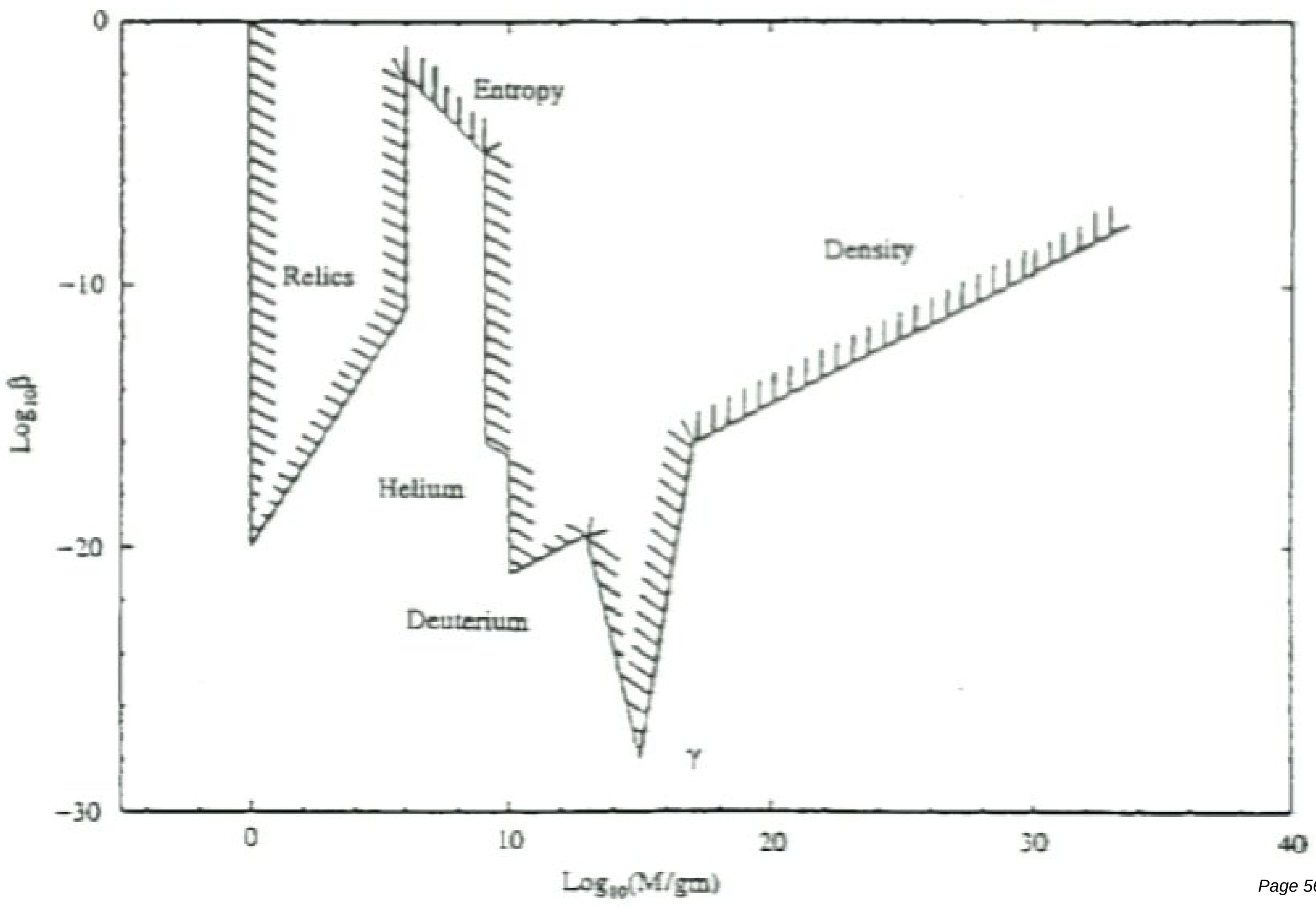

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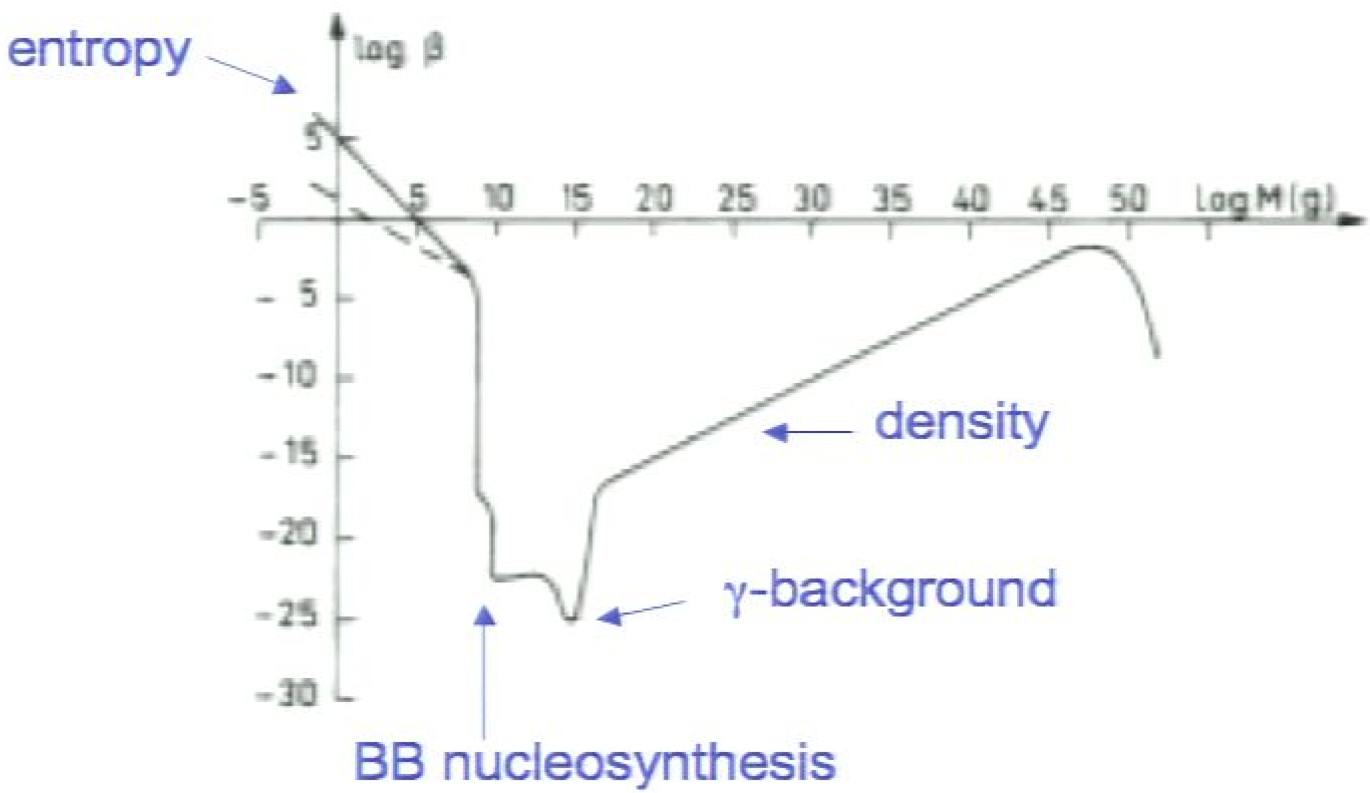

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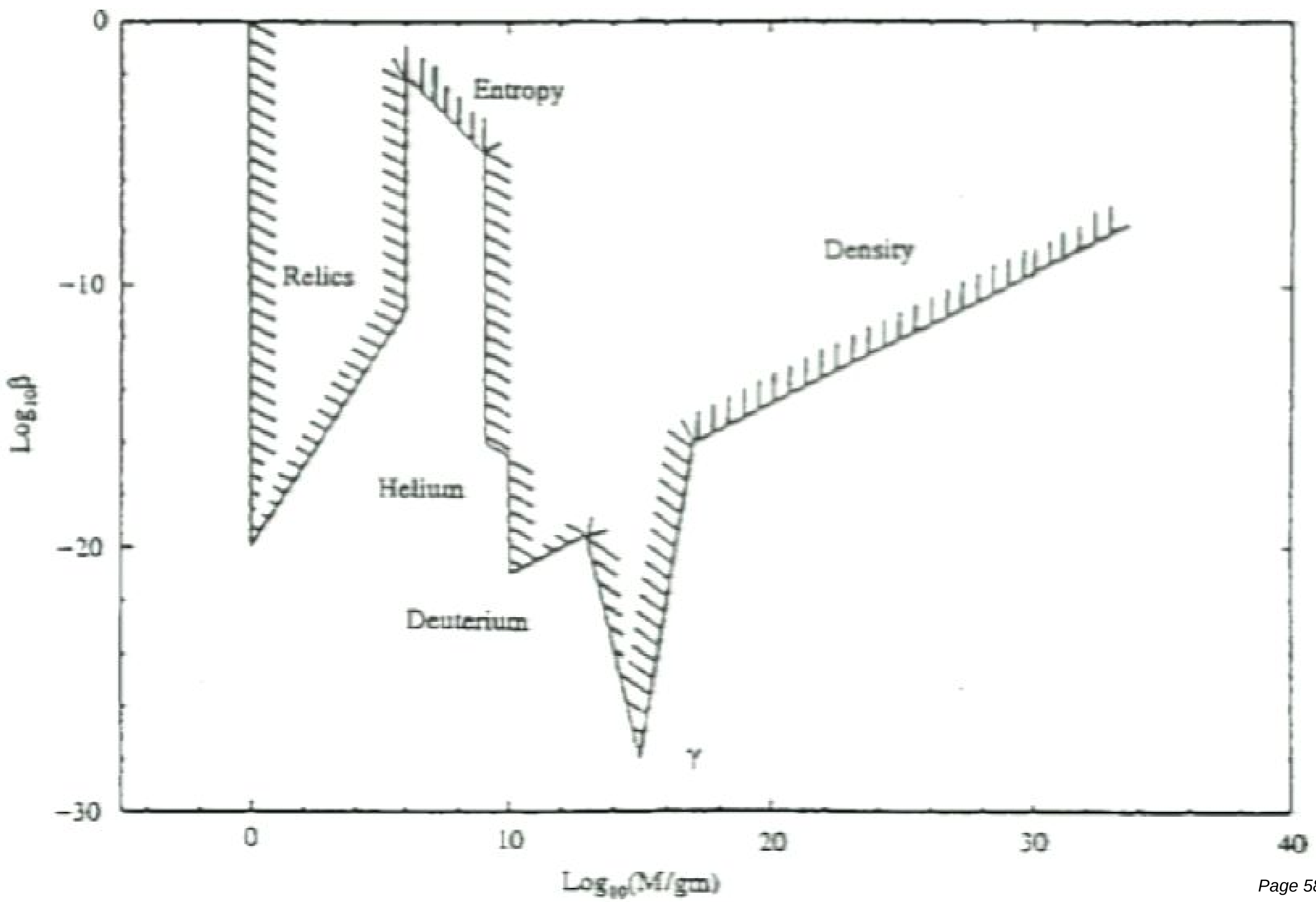
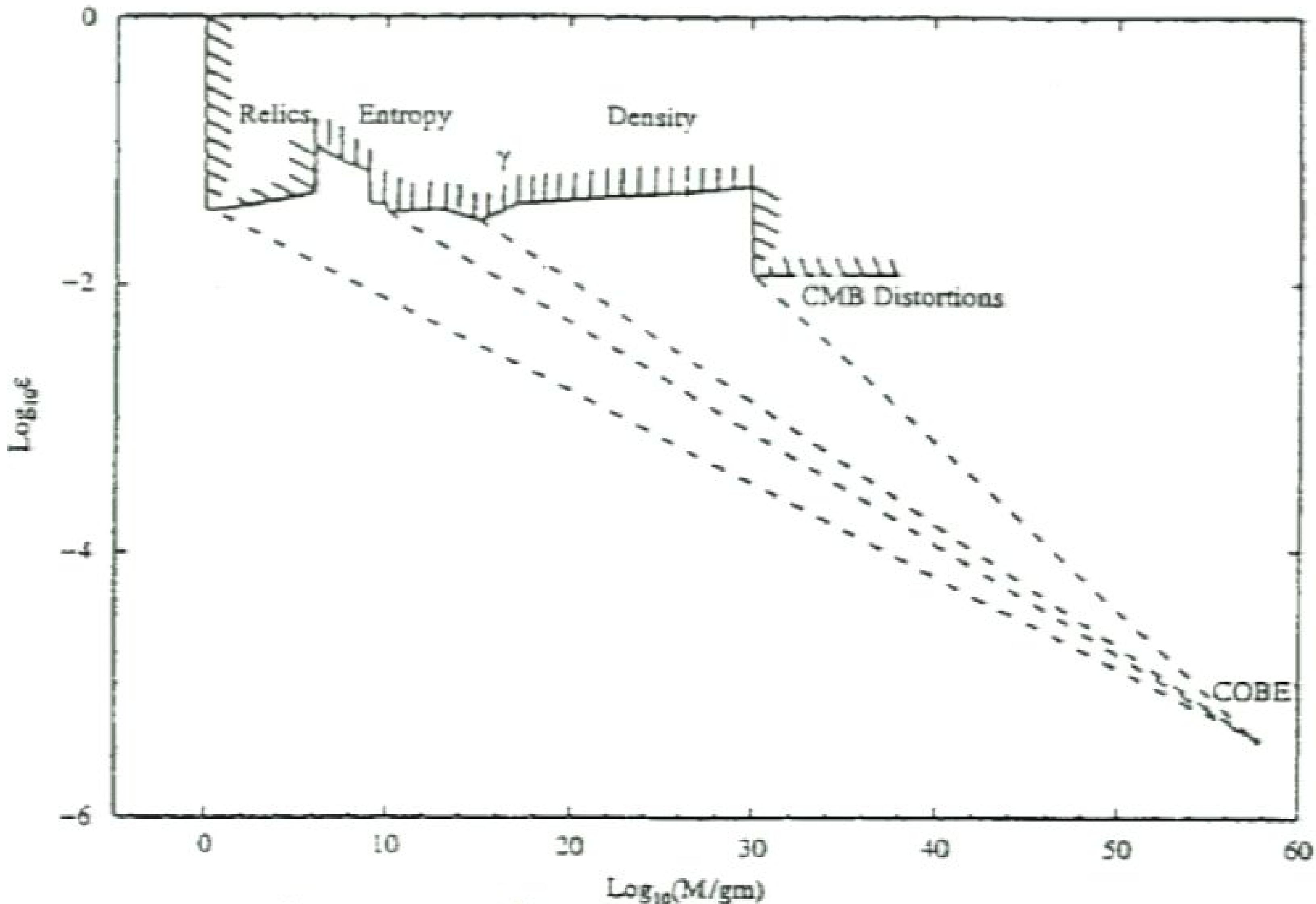
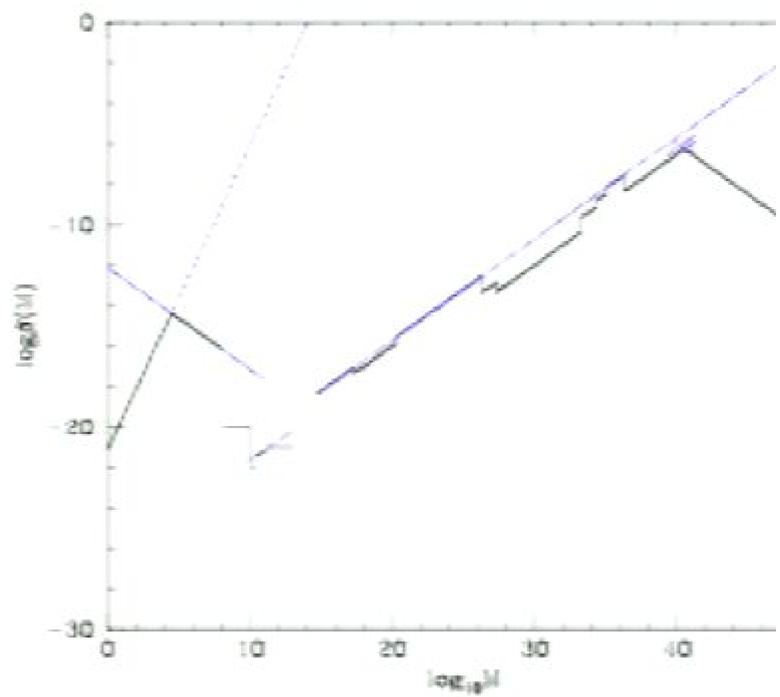


Constraints on amplitude of density fluctuations at horizon epoch ε(M



$$\beta(M) \sim \varepsilon(M) \exp\left[-\frac{1}{18\,\varepsilon(M)^2}\right]$$

Josan et al. (2009)



Carr, Kohri, Sendouda & Yokoyama, PRD 81, 104019 (2010)

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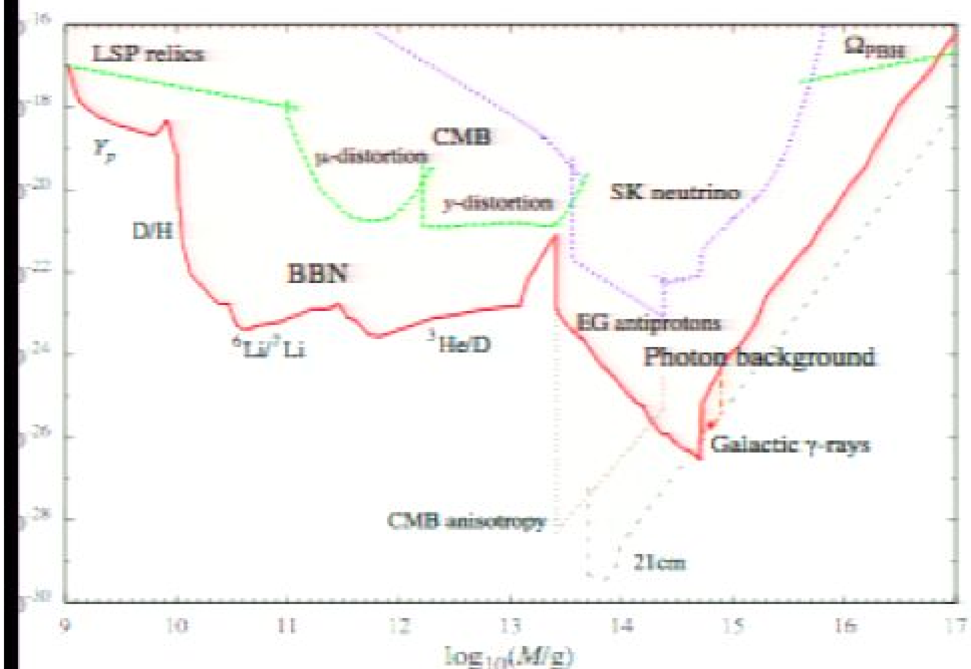

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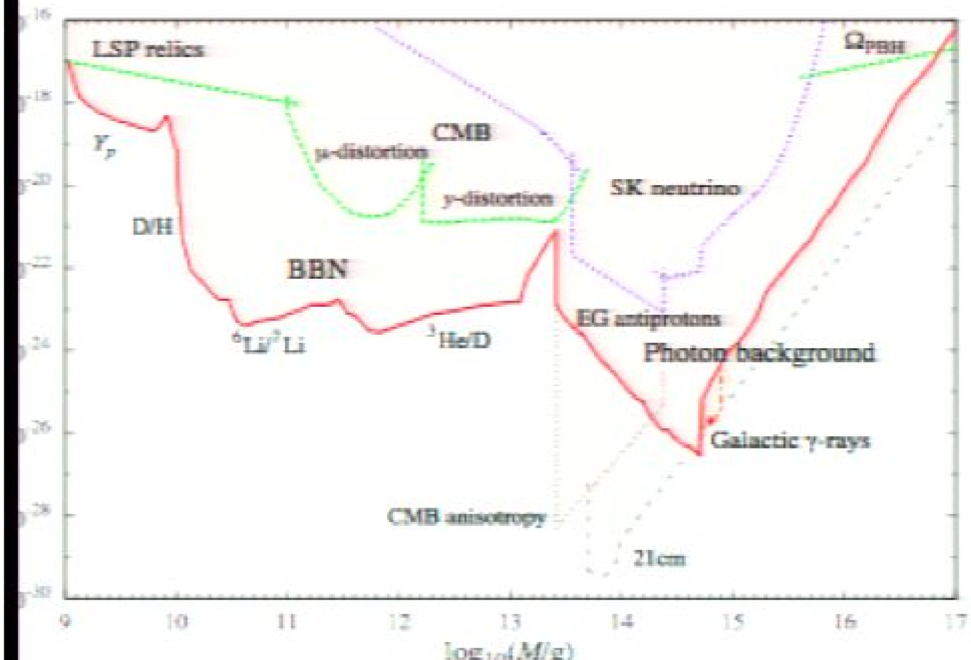

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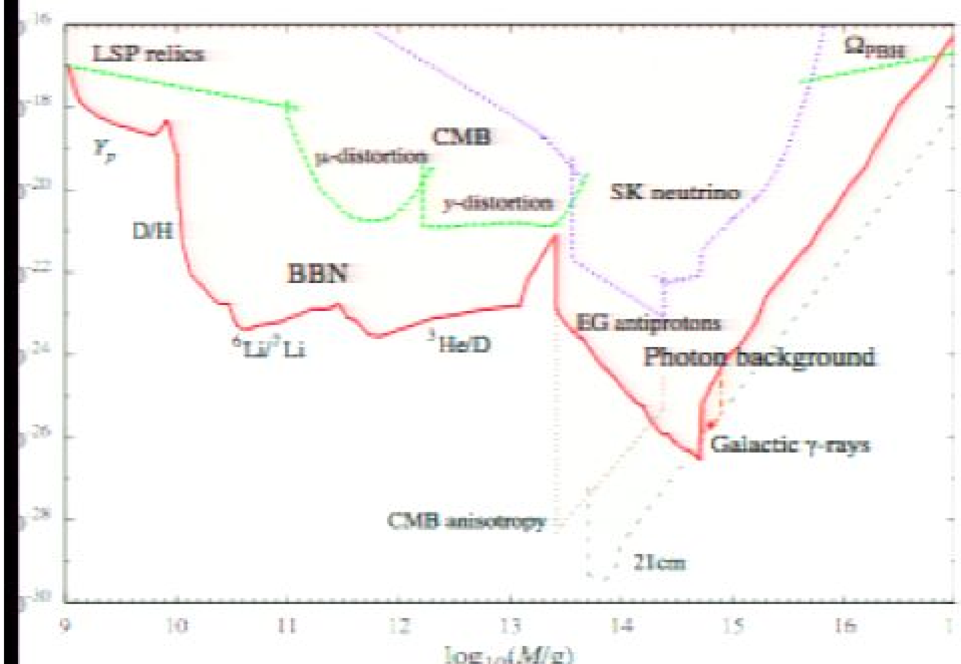
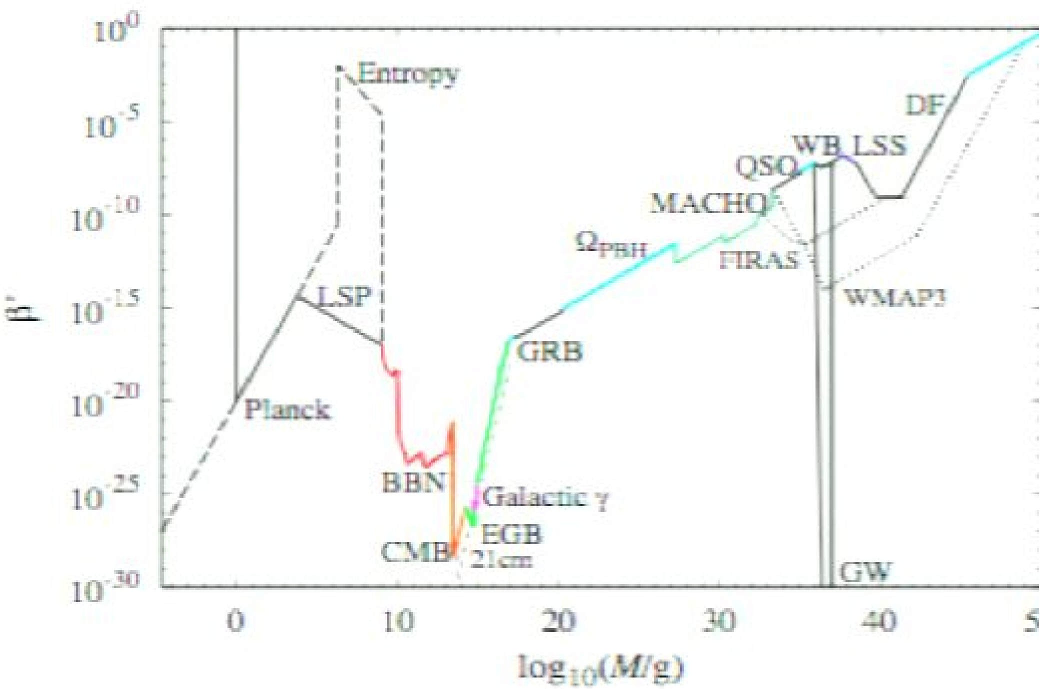




Cosmology Λ_{CDM}, h=0.72, Ω_{CDM}=0.25 $H^2 = \frac{8\pi G}{3}\rho_r = \frac{4\pi^3 G}{45} g_* T^4$

PBH mass $M = \gamma M_{PH} = \frac{4\pi}{3}\gamma \rho H^{-3} \approx 2.03 \times 10^5 \gamma \left(\frac{t}{1\,s}\right) M_\odot\,.$

0.2 in simple analysis, critical phenomena << 1, extended overdensity >>

Density parameter $\Omega_{PBH} = \frac{M\, n_{PBH}(t_0)}{\rho_{cr}} \approx \left(\frac{\beta(M)}{1.15 \times 10^{-8}}\right) \gamma^{1/2} \left(\frac{g_{*i}}{106.75}\right)^{-1/4} \left(\frac{M}{M_\odot}\right)^{-1/2}$

Ω_{CDM}< 0.25

value for t<10^{-5}s

CDM density limit $\beta(M) < 2.03 \times 10^{-18} \gamma^{-1/2} \left(\frac{g_{*i}}{106.75}\right)^{1/4} \left(\frac{M}{10^{15}\,g}\right)^{1/2} \quad (M \gtrsim 10^{15}\,g)\,.$

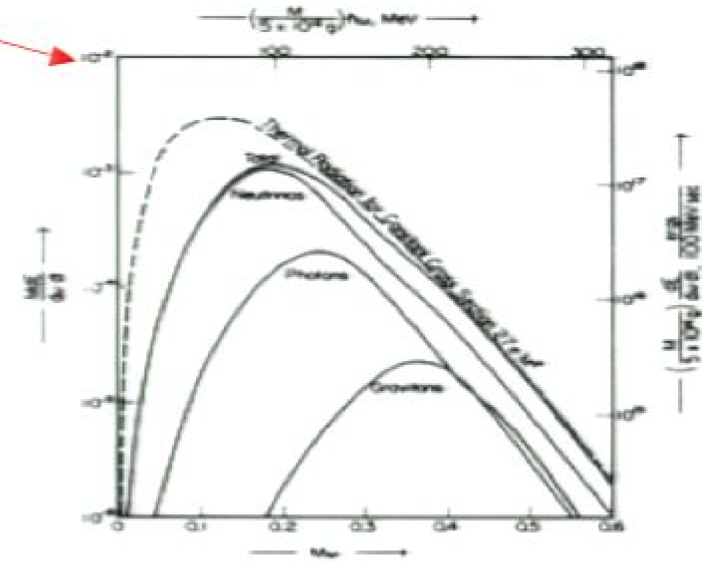
Renormalization $\beta'(M) \equiv \gamma^{1/2} \left(\frac{g_{*i}}{106.75}\right)^{-1/4} \beta(M)$

cumulative number density from 0 to M

General mass function $n_{PBH}(M,t) \equiv \frac{dN_{PBH}(M,t)}{d\ln M}$

Monochromatic case $N_{PBH}(M,t) = n_{PBH}(t)\,\theta(M-m)$

grey-body



PBH temperature $T_{\rm BH} = \frac{1}{8\pi G M} \approx 1.06\, M_{10}^{-1}\,{\rm TeV}$

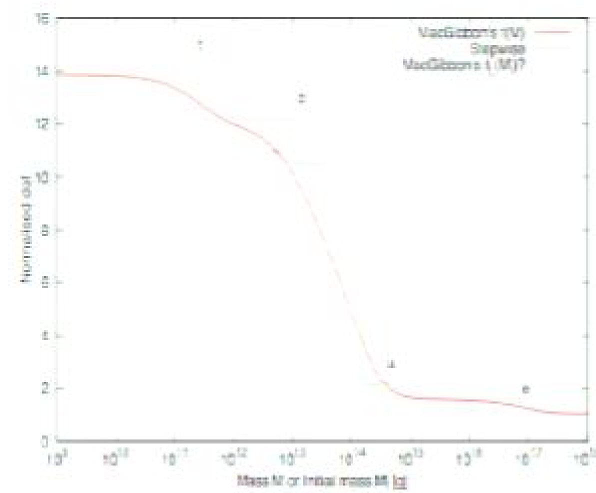
Peak in flux $E_{s=1/2} = 4.02 T_{bh}$, $E_{s=1} = 5.77 T_{bh}$, $E_{s=0} \approx 2.81 T_{bh}$.

Mass loss $\frac{{\rm d}M_{10}}{{\rm d}t} = -5.34\times 10^{-5}\, f(M)\, M_{10}^{-2}\,{\rm s}^{-1}$

effective no.species emitted, 1 for massless

$f_{s=0} = 0.267\,.\quad f_{s=1} = 0.060\,.\quad f_{s=3/2} = 0.020\,.\quad f_{s=2} = 0.007\,.$

$f_{s=1/2} = 0.147\ ({\rm neutral})\,.\quad f_{s=1/2} = 0.142\ ({\rm charge}\ \pm e)\,.$



Quark and gluon jet emission

$T_{BH} > \Lambda_{QCD}$ = 250-300 MeV => big f increase

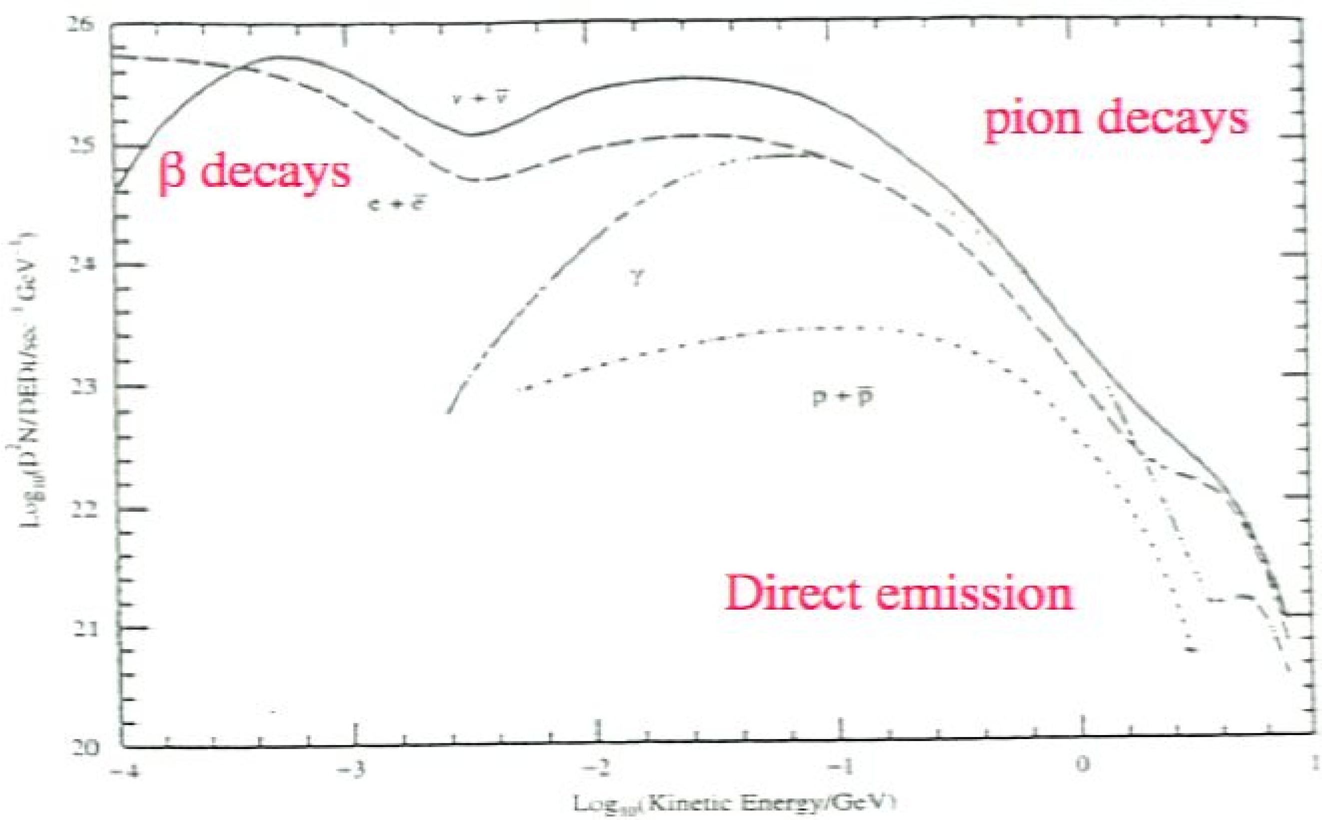
PBH lifetime $\tau \approx 407 \left(\frac{f(M)}{15.35}\right)^{-1} M_{10}^{3}\,{\rm s}$

TeV BHs

Mass evaporating today $M_* \approx 1.02\times 10^{15}\left(\frac{f_*}{15.35}\right)^{1/3}{\rm g} \approx 5.1\times 10^{14}\,{\rm g}$ (f_*=1.9, T_*=21MeV)

MacGibbon and Webber (1990)

T > Λ_{QCD} = 250-300 MeV => secondary emission from jet decays with only pions emitted below Λ_{QCD}



Instantaneous emission from 1GeV black hole

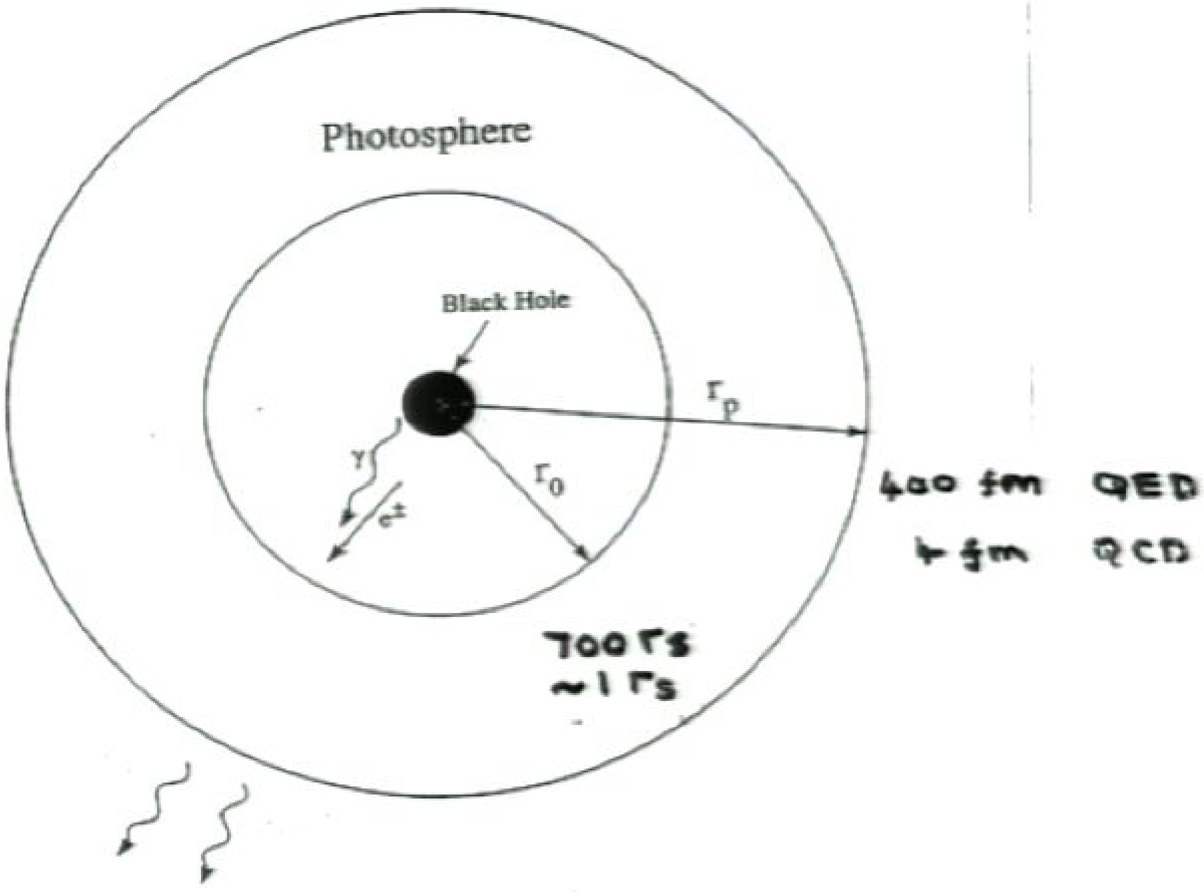
DO EVAPORATING PBHS FORM PHOTOSPHERES?

QED interactions => $e^+e^-\gamma$ photosphere

$T_{BH} > T_{crit} \sim 45$GeV => $M_{BH} < 2 \times 10^{12}$g

$$e + e \rightarrow e + e + \gamma$$

$$e + \gamma \rightarrow e + e^+ + e^-$$



Heckler (1997, 1998)

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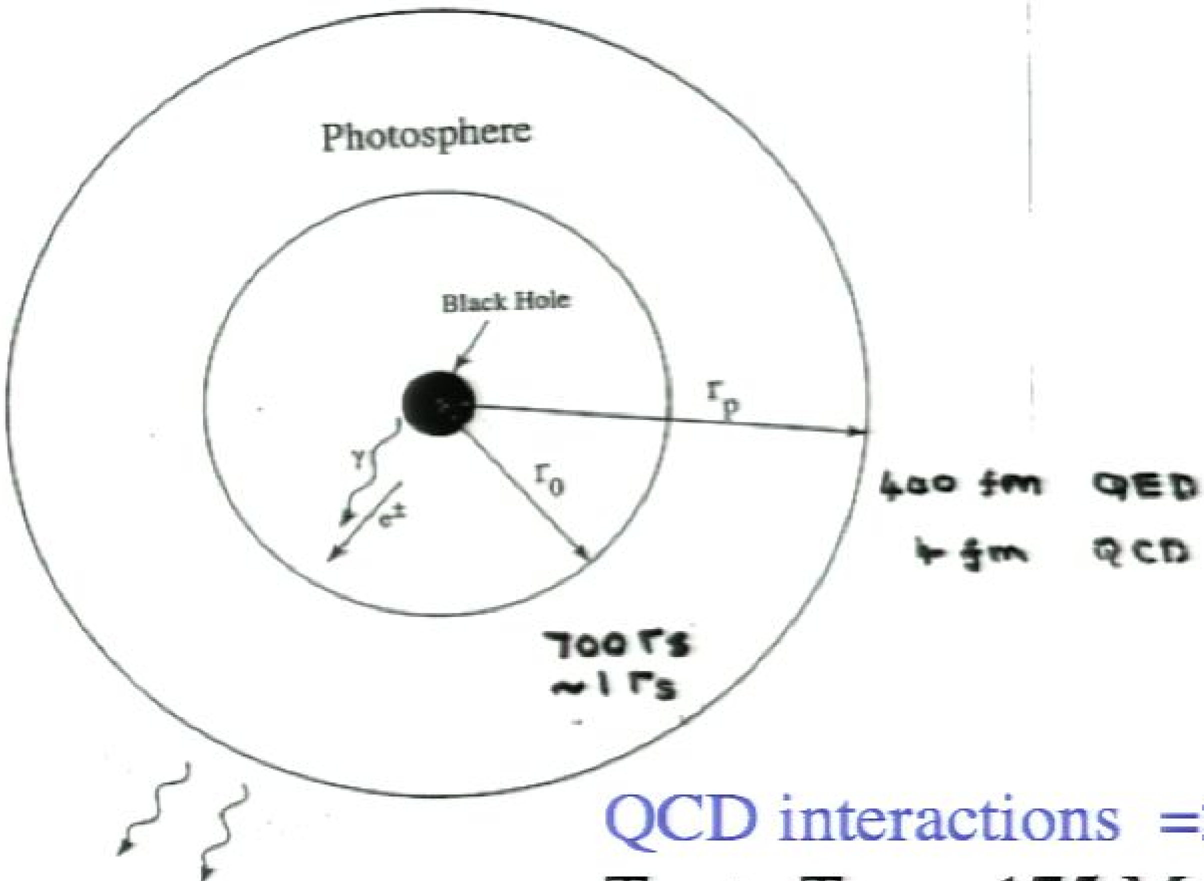
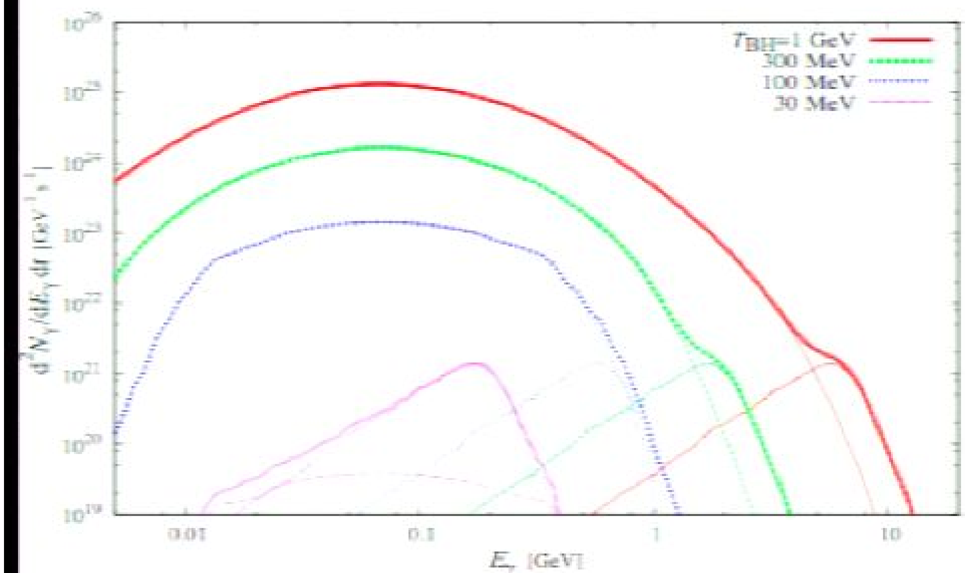


Heckler (1997, 1998)

QCD interactions => quark-gluon photosphe

$T_{BH} > T_{crit} \sim 175\ \text{MeV} \Rightarrow M_{BH} < 5 \times 10^{14}\text{g}$



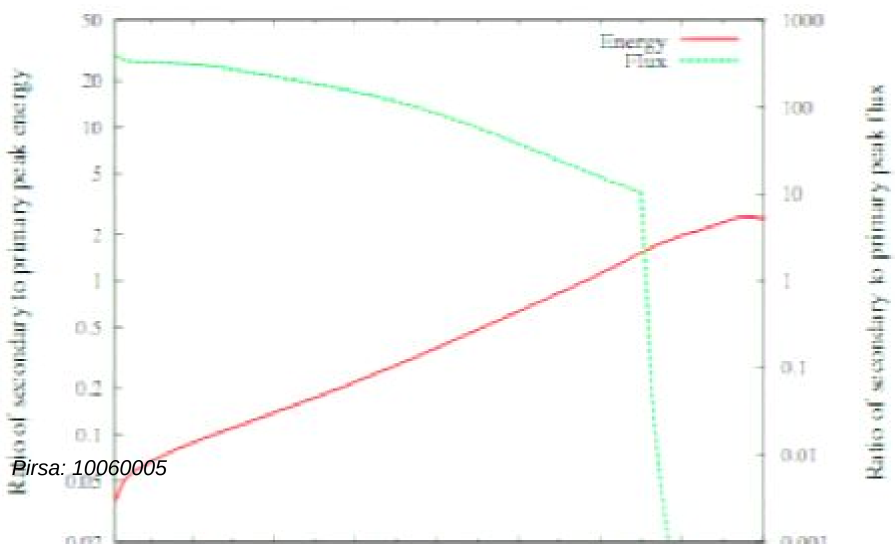
PYTHIA CODE

$$\frac{d\dot{N}_\gamma}{dE_\gamma}(E_\gamma, M) = \frac{d\dot{N}_\gamma^{\rm pri}}{dE_\gamma}(E_\gamma, M) + \frac{d\dot{N}_\gamma^{\rm sec}}{dE_\gamma}(E_\gamma, M),$$

fraction of jet energy going into pions

1.6 x 10^{-3}

$$\frac{d\dot{N}_\gamma^{\rm sec}}{dE_\gamma}(E_\gamma = m_{\pi^0}/2) \simeq 2\,\frac{d\dot{N}_{\pi^0}}{dE_{\pi^0}}(E_{\pi^0} = m_{\pi^0}) \simeq 2 \sum_{i=q,g} \mathcal{B}_{i\to\pi^0}(\overline{E}, m_{\pi^0})\,\frac{\overline{E}}{m_{\pi^0}}\,\frac{d\dot{N}_i^{\rm pri}}{dE_i}(E_i \simeq \overline{E})$$



Secondary emission below $M_q \approx 0.4 M_*$

$M = M_*(1-\mu)$ =>

$M(t_0) = (3\mu)^{1/3}(1-\mu+\mu^2/3)^{1/3} M_*$ < M_q for μ < 0.02

so secondary fraction drops off very rapidly above M_*

REVIOUS BIG BANG NUCLEOSYNTHESIS CONSTRAINTS

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Injection of neutrinos (Vainer & Naselskii 1978)

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$$\beta'(M) < 3 \times (10^{-18} - 10^{-15})\, M_{10}^{1/2} \quad (M = 10^9\text{–}3 \times 10^{11}\,\mathrm{g})$$

Injection of photons (Miyama & Sato 1978)

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Injection of nucleons (Zeldovich 1977)

$$\beta'(M) < \begin{cases} 6 \times 10^{-18} M_{10}^{-1/2} & (M = 10^9\text{–}10^{10}\,\text{g})\,, \\ 6 \times 10^{-22} M_{10}^{-1/2} & (M = 10^{10}\text{–}5 \times 10^{10}\,\text{g})\,. \\ 3 \times 10^{-23} M_{10}^{5/2} & (M = 5 \times 10^{10}\text{–}5 \times 10^{11}\,\text{g}) \\ 3 \times 10^{-21} M_{10}^{-1/2} & (M = 10^{11}\text{–}10^{13}\,\text{g})\,. \end{cases}$$

Photodissociation of deuterons (Lindley 1980)

Particle reactions

High energy nucleons => extra interconversion between backg'd p and n
High energy hadrons dissociate helium into light elements
High energy photons from cascade further dissociate helium

$$\frac{dn_N}{dt} + 3\,H\,n_N = \left[\frac{dn_N}{dt}\right]_{\rm SBBN} - \left[\frac{dn_N}{dt}\right]_{\rm conv} - \left[\frac{dn_N}{dt}\right]_{\rm hadron} + \left[\frac{dn_N}{dt}\right]_{\gamma} \quad (N = p, n)\,,$$

$$\frac{dn_{A_i}}{dt} + 3\,H\,n_{A_i} = \left[\frac{dn_{A_i}}{dt}\right]_{\rm SBBN} + \left[\frac{dn_{A_i}}{dt}\right]_{\rm hadron} + \left[\frac{dn_{A_i}}{dt}\right]_{\gamma} \quad (A_i = {\rm D, T, {}^3He, {}^4He, {}^6Li, {}^7Li})$$

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hadronic reactions

TABLE I: Hadronic reactions with $p_{\rm bg}$ and $\alpha_{\rm bg}$ included in our calculation.

Process	$i = n$	$i = p$
$(i, p_{\rm bg}, 1)$	$n + p_{\rm bg} \to n + p$	$p + p_{\rm bg} \to p + p$
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$(i, p_{\rm bg}, 3)$	$n + p_{\rm bg} \to n + n + \pi^+$	$p + p_{\rm bg} \to p + n + \pi^+$
$(i, \alpha_{\rm bg}, 4)$	$n + \alpha_{\rm bg} \to n + \alpha$	$p + \alpha_{\rm bg} \to p + \alpha$
$(i, \alpha_{\rm bg}, 5)$	$n + \alpha_{\rm bg} \to {\rm D} + {\rm T}$	$p + \alpha_{\rm bg} \to {\rm D} + {}^3{\rm He}$
$(i, \alpha_{\rm bg}, 6)$	$n + \alpha_{\rm bg} \to p + n + {\rm T}$	$p + \alpha_{\rm bg} \to 2p + {\rm T}$
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$(i, \alpha_{\rm bg}, 9)$	$n + \alpha_{\rm bg} \to 2p + 3n$	$p + \alpha_{\rm bg} \to 3p + 2n$
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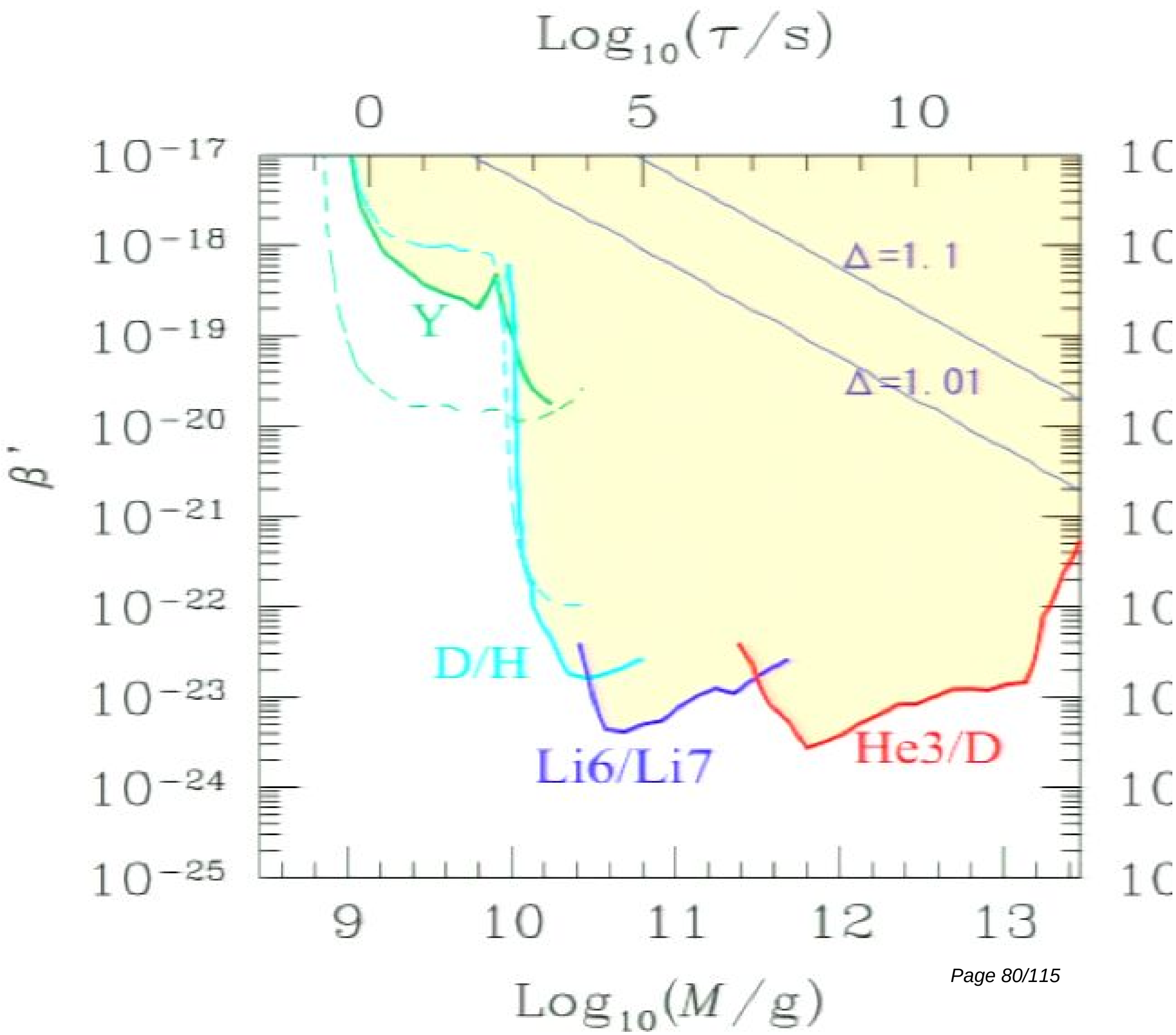
Abundance constraints

TABLE II: Observational constraints on abundances of light elements at 2σ to be used in the present paper.

Element	Constraints	Refs.
^{4}He	$Y_p = 0.2516 \pm 0.0080$	[181–186]
	${\rm D/H} < 5.16 \times 10^{-5}$	[187, 188]
^{3}He	$^3{\rm He/D} < 1.37$	[189]
^{6}Li	$^6{\rm Li}/^7{\rm Li} < 0.302$	[190, 191]



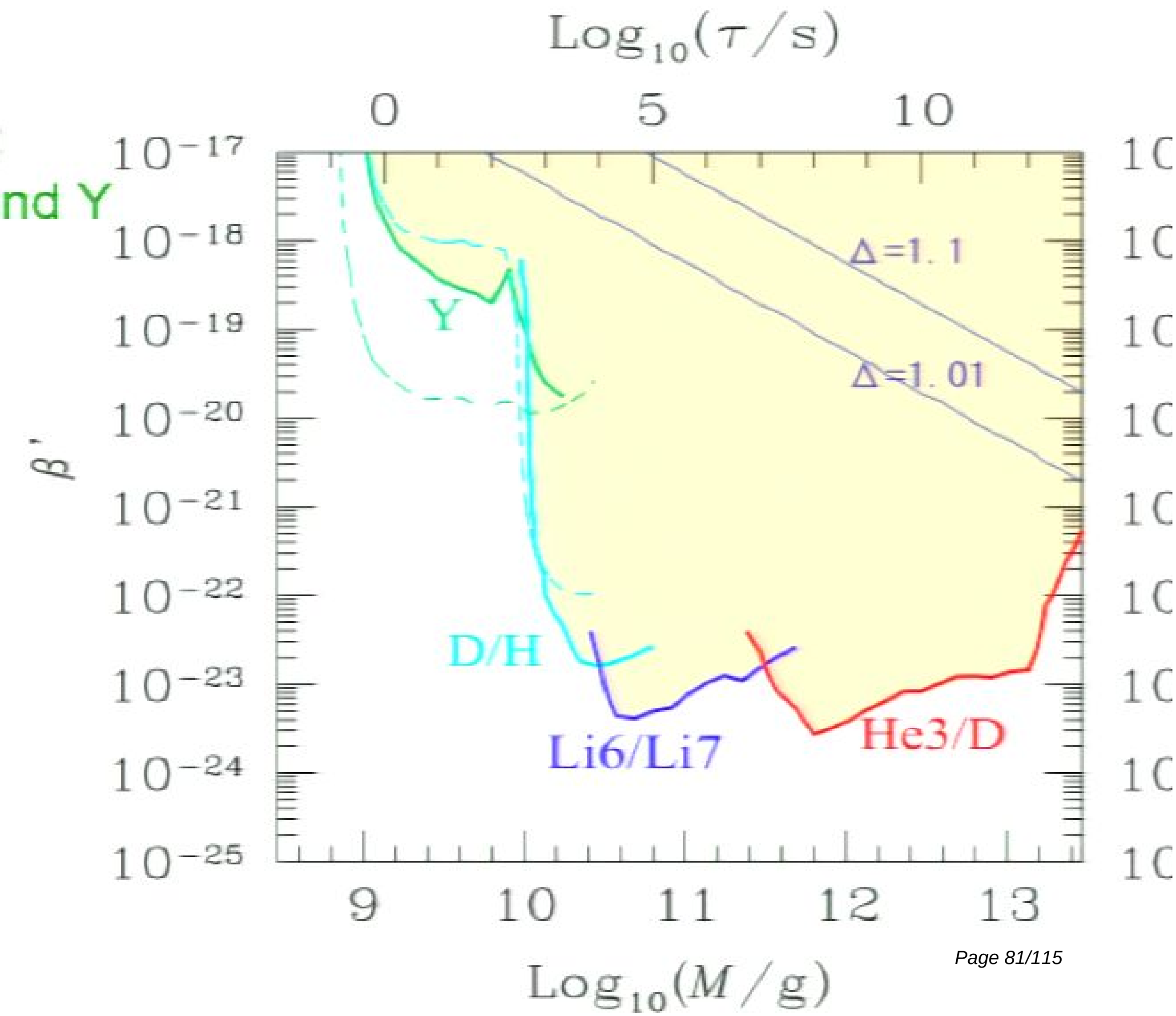
Log10(τ/s)
0
5
10
10−17
10−18
10−19
10−20
10−21
10−22
10−23
10−24
10−25
β'
Δ=1. 1
Δ=1. 01
Y
D/H
Li6/Li7
He3/D
9
10
11
12
13
Log10(M/g)

$<10^{-2}s \Rightarrow M<10^{9}g$

no trace

10^{-2}-$10^{2}s \Rightarrow M=10^{9}$-$10^{10}g$

hadrons increase $(n/p)_F$ and Y



<10^{-2}s => M<10^{9}g

no trace

10^{-2}-10^{2}s => M=10^{9}-10^{10}g

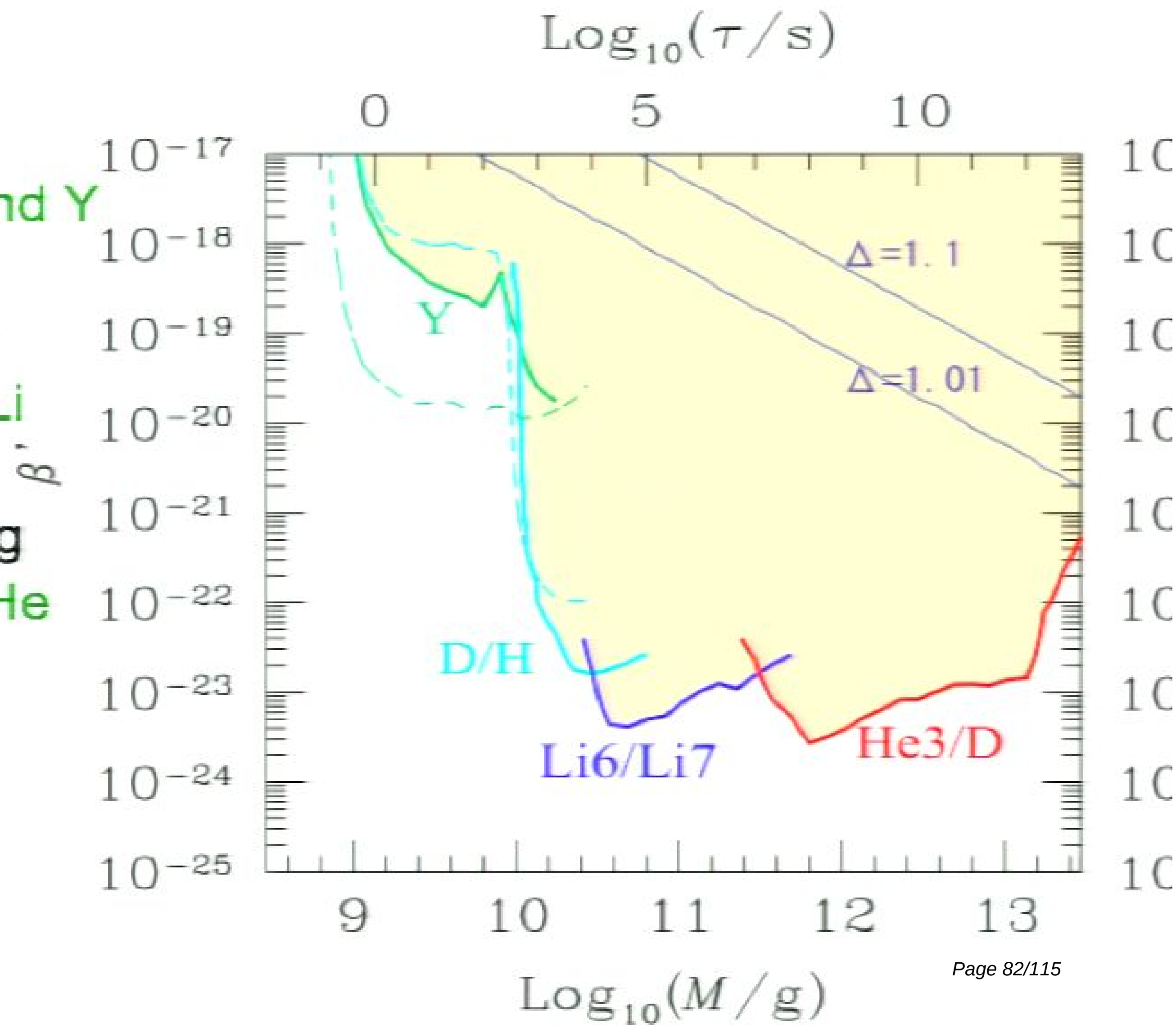
hadrons increase $(n/p)_F$ and Y

10^{2}-10^{7}s => M=10^{10}-10^{12}g

hadrons increase D and ^{6}Li

10^{7}-10^{12} s => M=10^{12}-10^{13}g

photons increase D and ^{3}He



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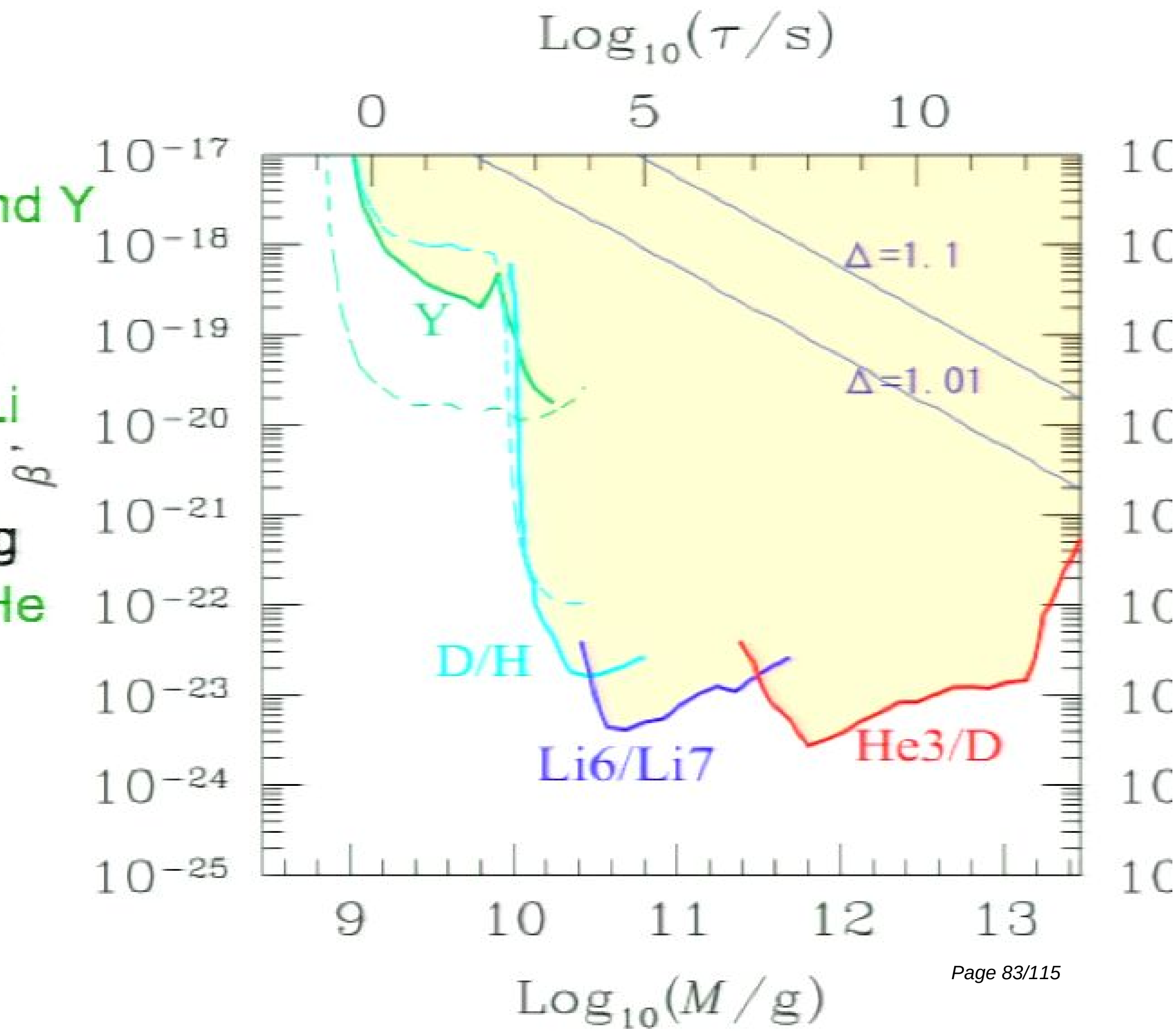
hadrons increase D and ^{6}Li

10^{7}-10^{12} s => M=10^{12}-10^{13}g

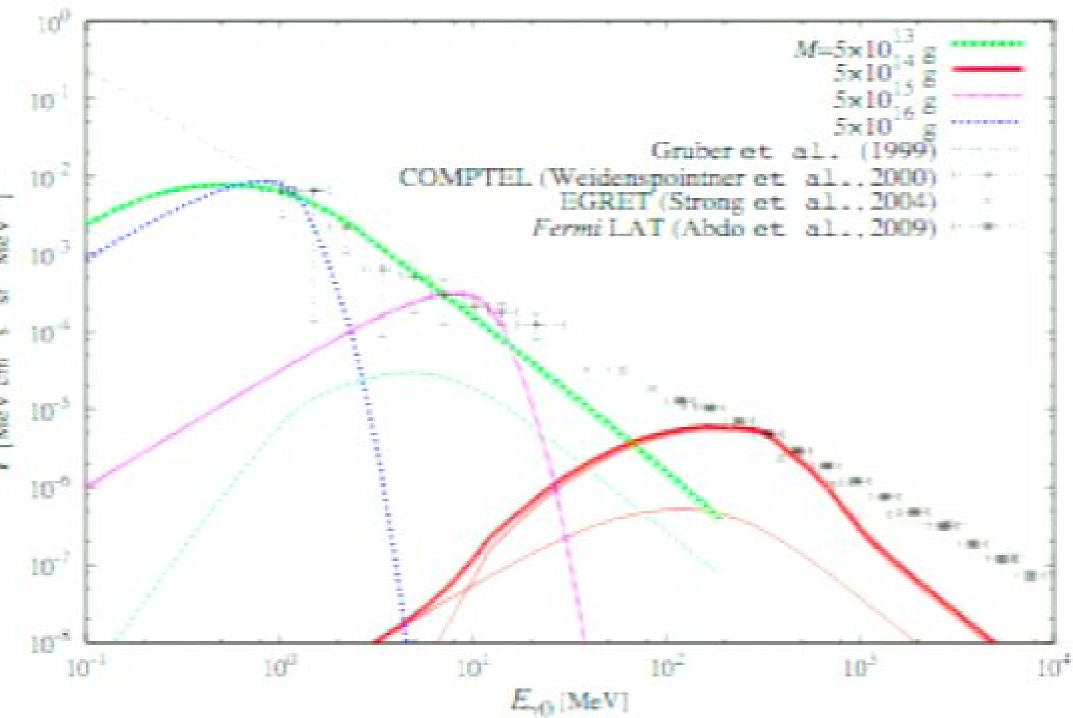
photons increase D and ^{3}He

>10^{12}s => M>10^{13}g

no effect but $M^{7/2}$ cut-off from low-mass tail



CKSY



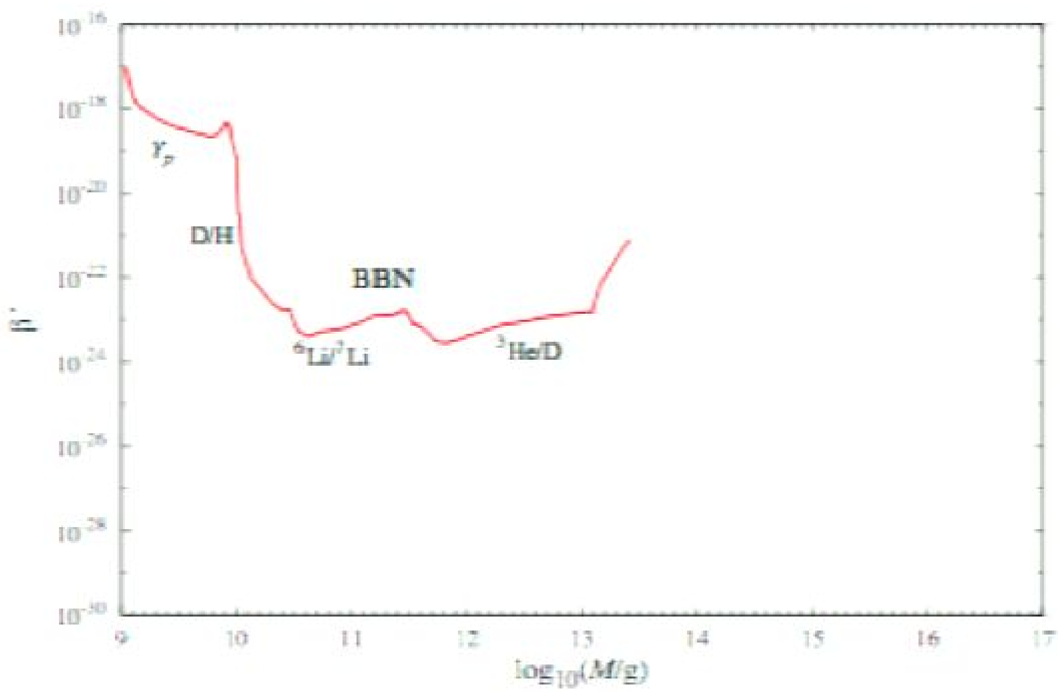
Diffuse γ-ray background

$$\frac{\mathrm{d}n_\gamma}{\mathrm{d}t}(E_\gamma, t) \simeq n_{\mathrm{PBH}}(t)\, E_\gamma\, \frac{\mathrm{d}\dot{N}_\gamma}{\mathrm{d}E_\gamma}(M(t), E_\gamma)$$

$$n_{\gamma 0}(E_{\gamma 0}) = \int_{t_{\mathrm{dec}}}^{\min(t_0,\tau)} \mathrm{d}t\,(1+z)^{-3}\,\frac{\mathrm{d}n_\gamma}{\mathrm{d}t}((1+z)\,E_{\gamma 0}, t)$$

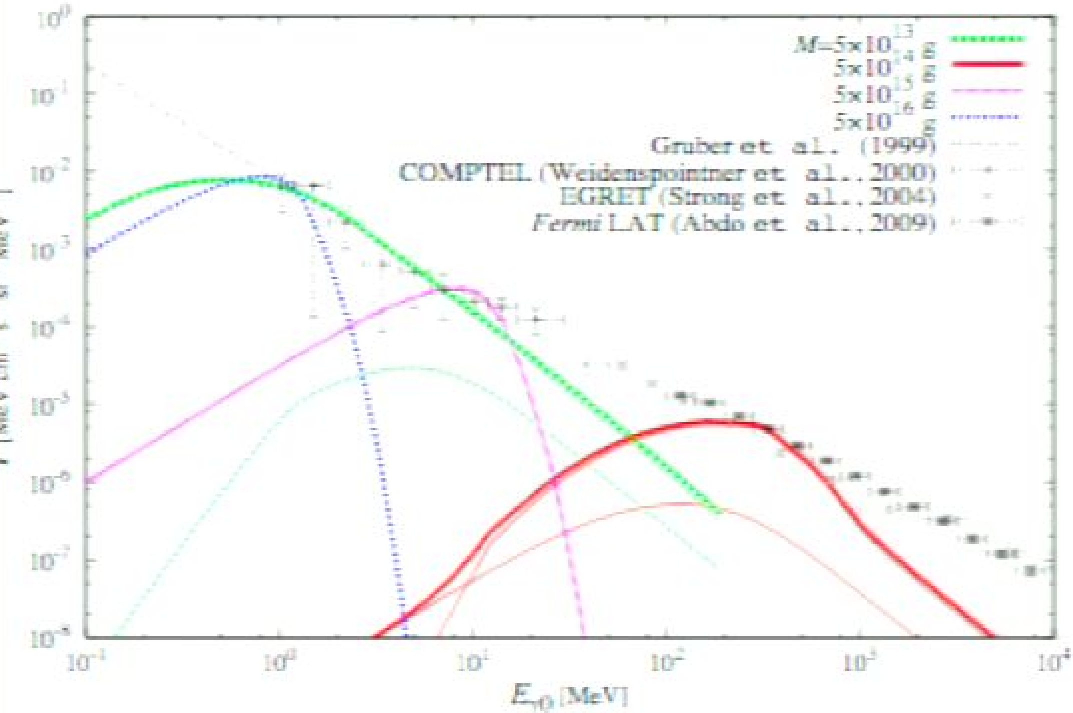
$$= n_{\mathrm{PBH0}}\, E_{\gamma 0} \int_{t_{\mathrm{dec}}}^{\min(t_0,\tau)} \mathrm{d}t\,(1+z)\,\frac{\mathrm{d}\dot{N}_\gamma}{\mathrm{d}E_\gamma}(M(t), (1+z)\,E$$

$$I \equiv \frac{c}{4\pi}\, n_{\gamma 0} \qquad I^{\mathrm{obs}} \propto E_{\gamma 0}^{-(1+\epsilon)} \qquad \epsilon \approx 0.2\text{–}0.3$$



BBN
D/H
Y_p
$^6Li/^7Li$
$^3He/D$
β'
$\log_{10}(M/g)$

CKSY



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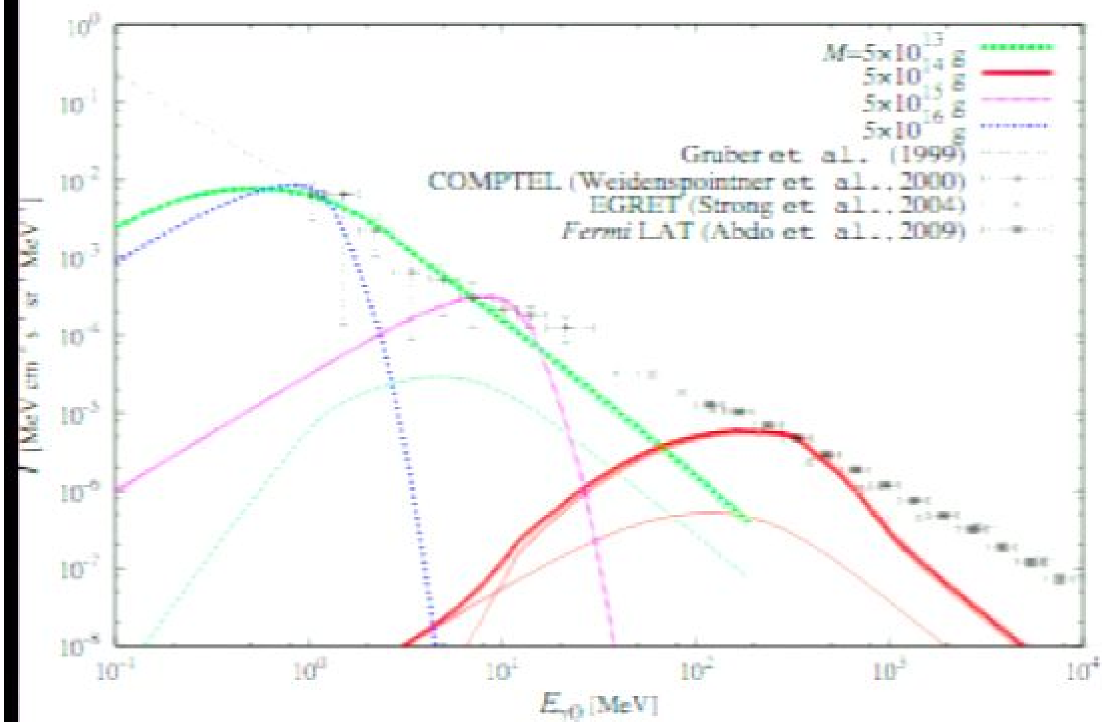

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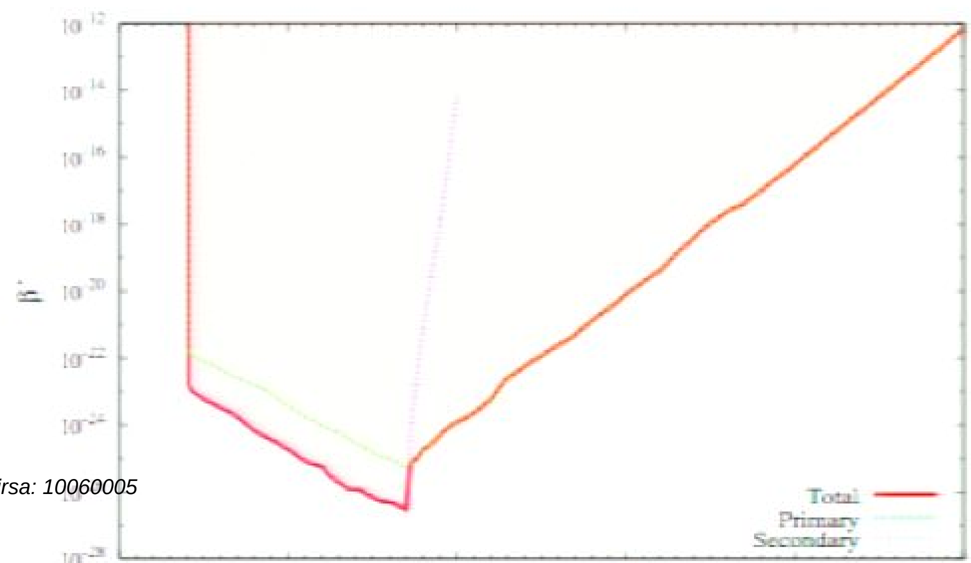
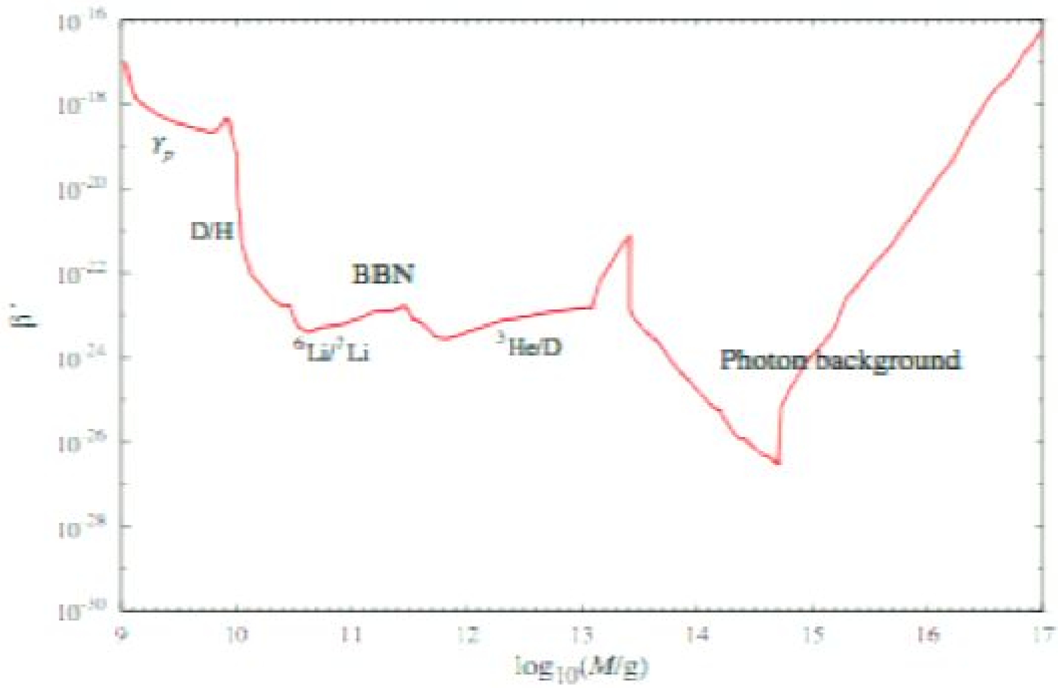


Constraints on β(M)

$$\beta'(M) \lesssim 3 \times 10^{-27} \left(\frac{M}{M_*}\right)^{-5/2-2\epsilon} \qquad (M < M_*)$$



10^{-16}
10^{-18}
10^{-20}
10^{-22}
10^{-24}
10^{-26}
10^{-28}
10^{-30}
β'
Y_p
D/H
BBN
^{6}Li/^{7}Li
^{3}He/D
Photon background
9
10
11
12
13
14
15
16
17
$\log_{10}(M/g)$

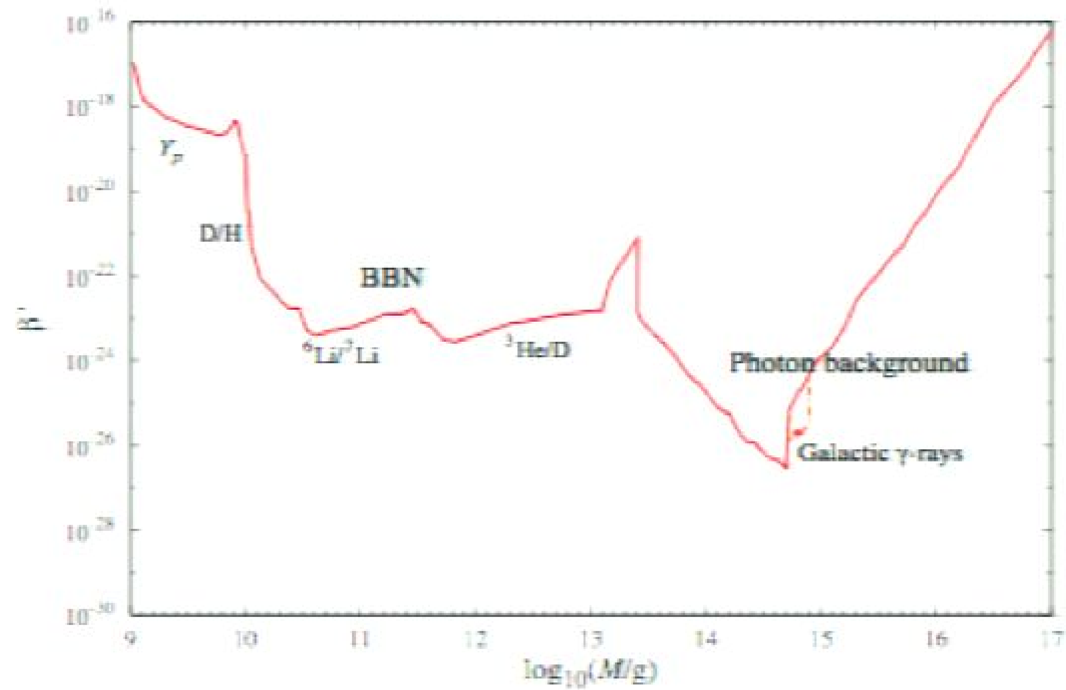
GALACTIC γ-BACKGROUND

Extragalactic γ-background => $\Omega_{PBH}(M_*) < 5 \times 10^{-10}$

OTHER CONSTRAINTS ON EVAPORATING PBHS

OTHER CONSTRAINTS ON EVAPORATING PBHS

Galactic γ-rays

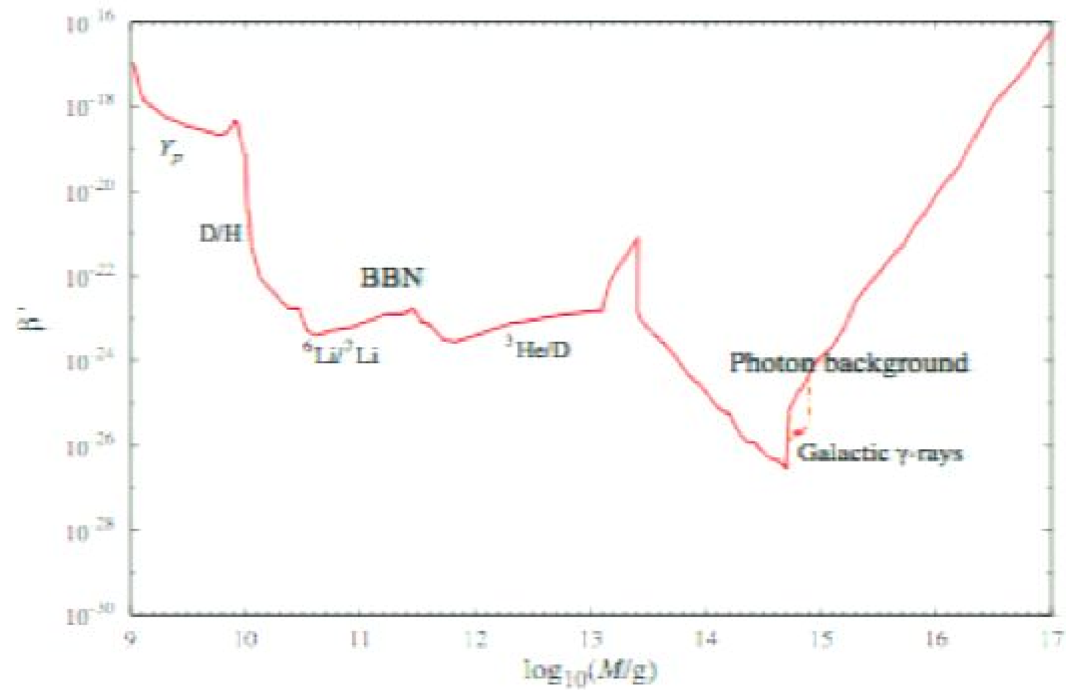


OTHER CONSTRAINTS ON EVAPORATING PBHS

Galactic γ-rays

Galactic cosmic rays

Extragalactic cosmic rays



OTHER CONSTRAINTS ON EVAPORATING PBHS

Galactic γ-rays

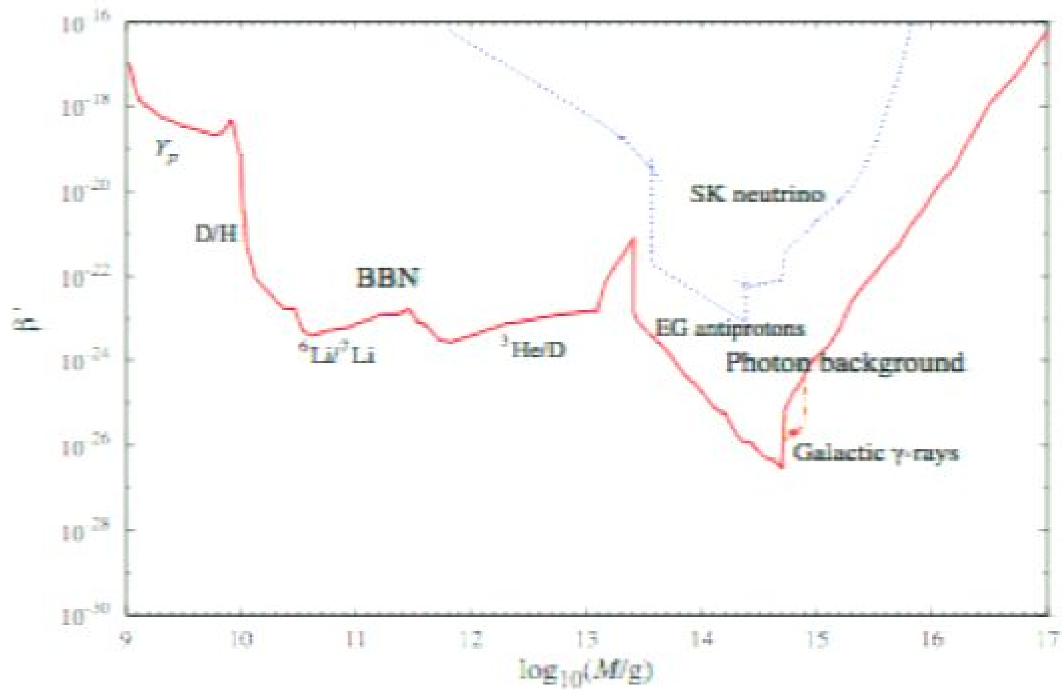
Galactic cosmic rays

Extragalactic cosmic rays

PBH explosions

Neutrino relics

LSP relics



OTHER CONSTRAINTS ON EVAPORATING PBHS

Galactic γ-rays

Galactic cosmic rays

Extragalactic cosmic rays

PBH explosions

Neutrino relics

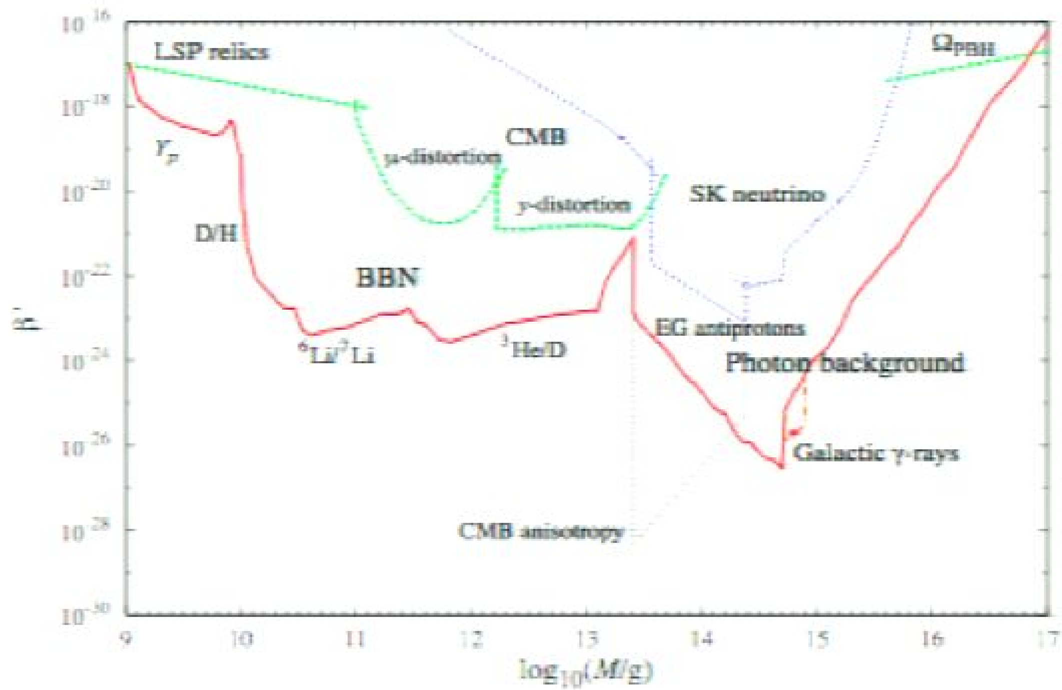
LSP relics

CMB distortions

Dark matter

CMB anisotropies

Reionization and 21cm



LSPs from PBHs => $\beta'(M) \lesssim 10^{-18} \left(\frac{M}{10^{11}\,\mathrm{g}}\right)^{-1/2} \left(\frac{m_{\mathrm{LSP}}}{100\,\mathrm{GeV}}\right)^{-1} \quad \left(M < 10^{11} \left(\frac{m_{\mathrm{LSP}}}{100\,\mathrm{GeV}}\right)^{-1} \mathrm{g}\right)$

(Lemoine 2000)

COULD COLD DARK MATTER BE PBHS?

10^{17}-10^{20}g PBHs excluded by femtolensing of GRBs
10^{26}-10^{30}g PBHs excluded by microlensing of LMC

But no constraints below 10^{17}g or for 10^{20}-10^{26}g or above 10^{30}g

Planck relics?

DAMPING OF SMALL-SCALE CMB ANISOTROPIES

CKSY

Similar effect to that of decaying particles (Zhang et al 2007)

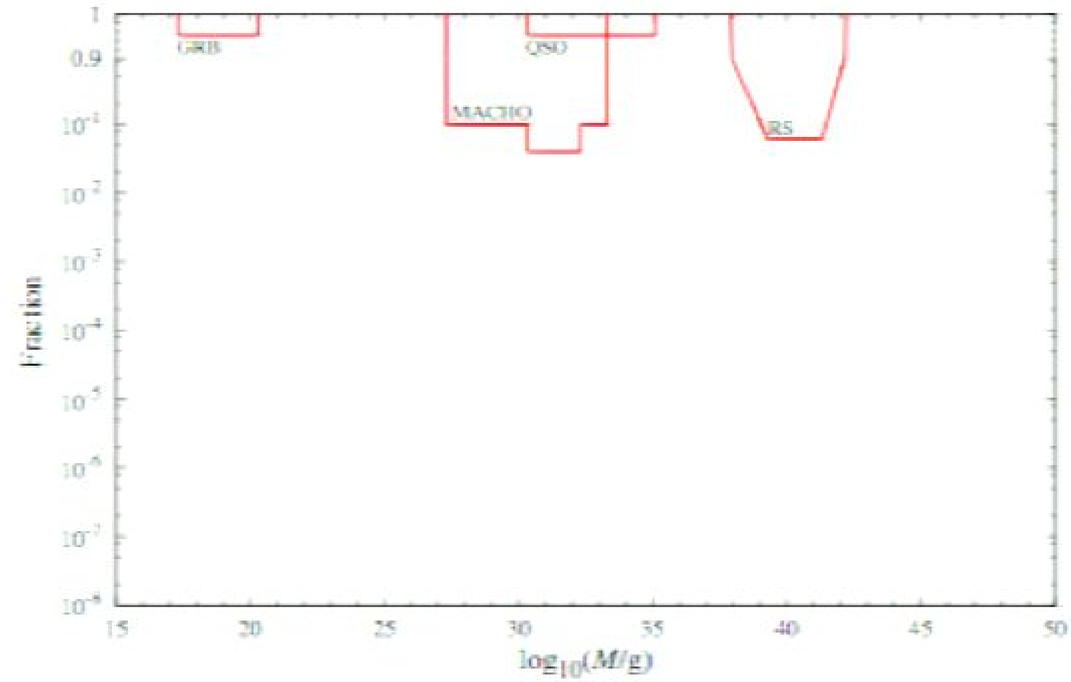
$$\log_{10}\zeta < -10.8 - 0.50x + 0.085x^2 + 0.0045x^3, \quad x \equiv \log_{10}(\Gamma/10^{-13}\,\mathrm{s}^{-1})$$

decay rate

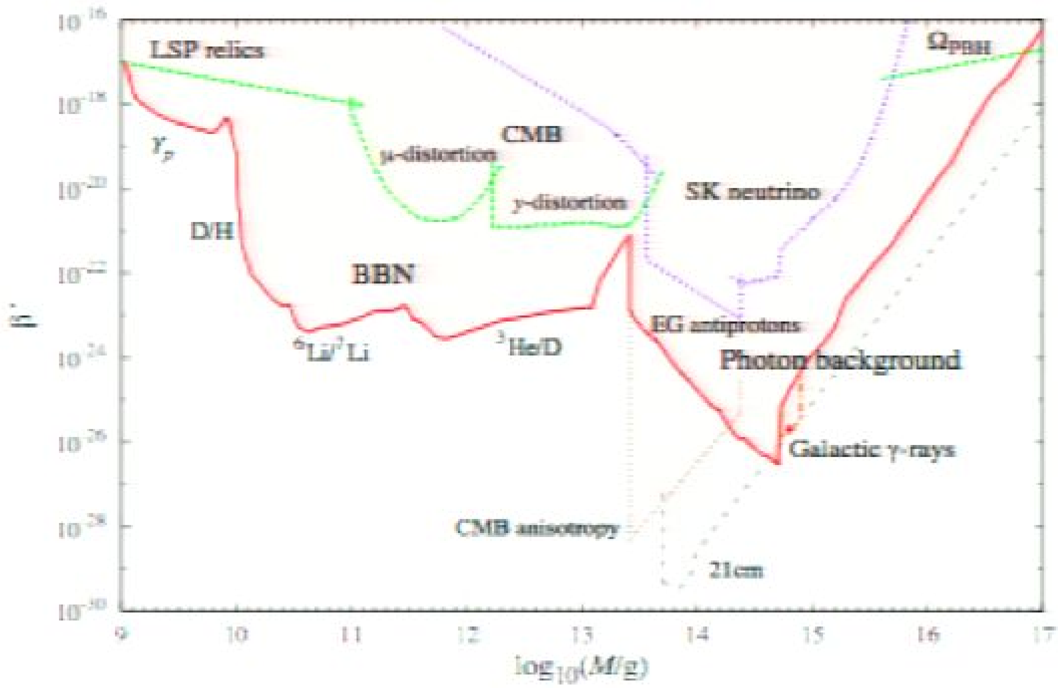
CDM fraction in PBHs

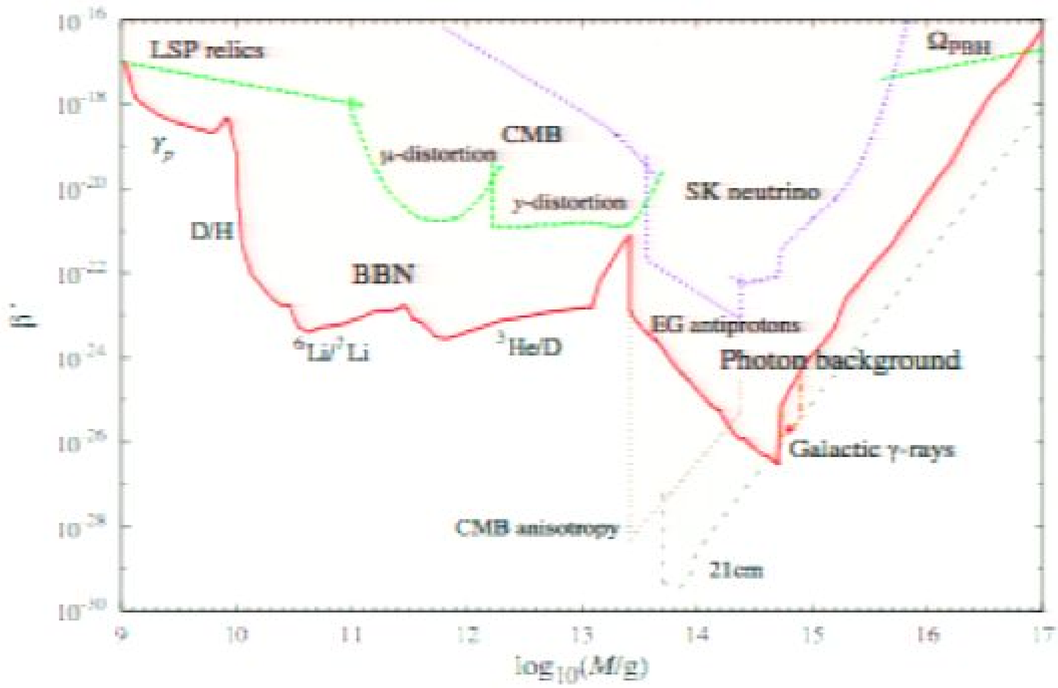
=> $\beta'(M) < 3 \times 10^{-30}(f_H/0.1)^{-1}(M/10^{13}\mathrm{g})^{3.1} \quad (2.5 \times 10^{13}\mathrm{g} \lesssim M \lesssim 2.4 \times 10^{14}\mathrm{g})$

LENSING LIMITS



$$f \equiv \frac{\Omega_{\rm PBH}}{\Omega_{\rm CDM}} \approx 4.8\,\Omega_{\rm PBH} = 4.11 \times 10^{8}\beta'(M)\left(\frac{M}{M_{\odot}}\right)^{-1/2}$$


LSP relics
Ω_{PBH}
CMB
μ-distortion
y-distortion
SK neutrino
γ_p
D/H
BBN
^{6}Li/^{7}Li
^{3}He/D
EG antiprotons
Photon background
Galactic γ-rays
CMB anisotropy
21cm
β'
$\log_{10}(M/g)$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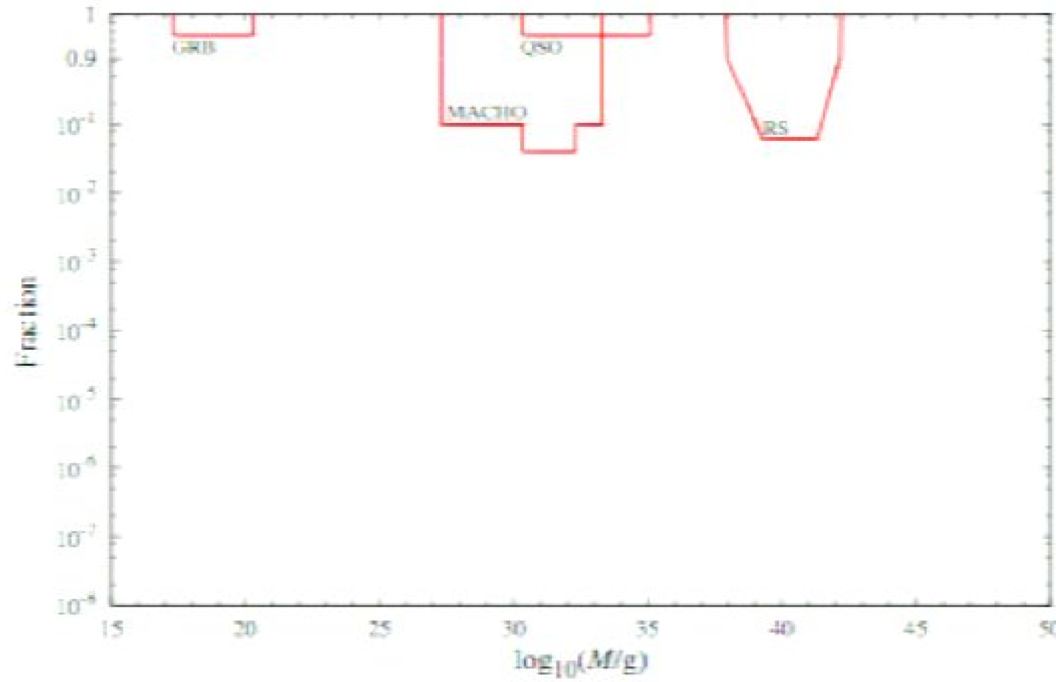
LENSING LIMITS



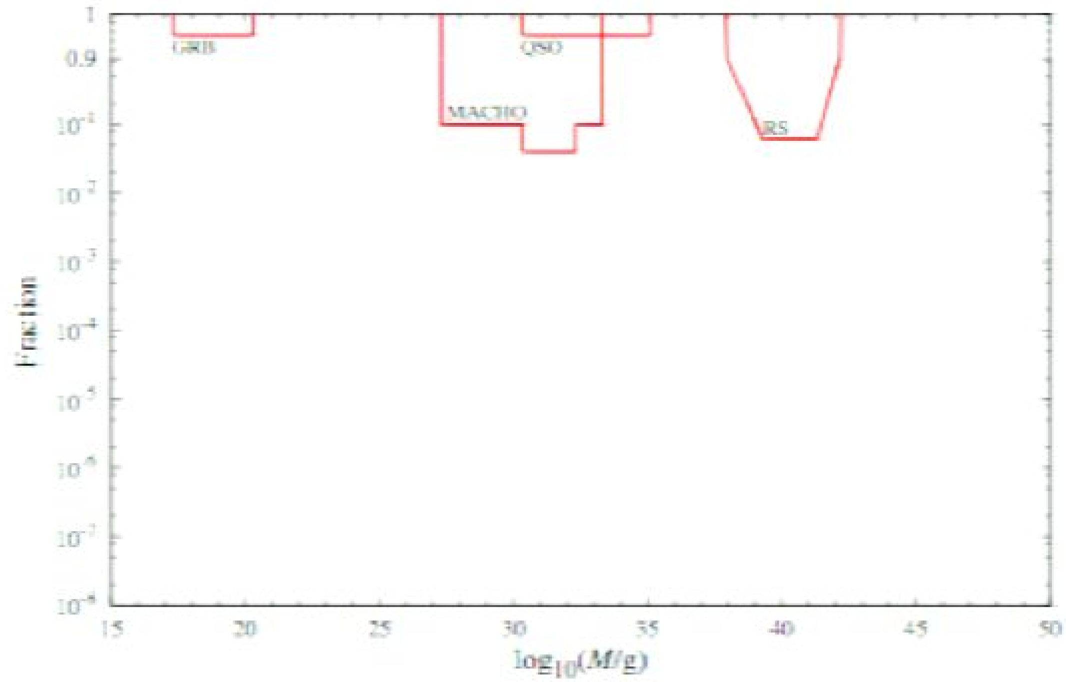
$$f \equiv \frac{\Omega_{\rm PBH}}{\Omega_{\rm CDM}} \approx 4.8\,\Omega_{\rm PBH} = 4.11 \times 10^{8} \beta'(M) \left(\frac{M}{M_\odot}\right)^{-1/2}$$

LENSING LIMITS

MACHO microlensing

$$f(M) < \begin{cases} 1 & (6 \times 10^{-8} M_\odot < M < 30 M_\odot) \\ 0.1 & (10^{-6} M_\odot < M < M_\odot) \\ 0.04 & (10^{-3} M_\odot < M < 0.1 M_\odot). \end{cases}$$

Femtolensing GRBs



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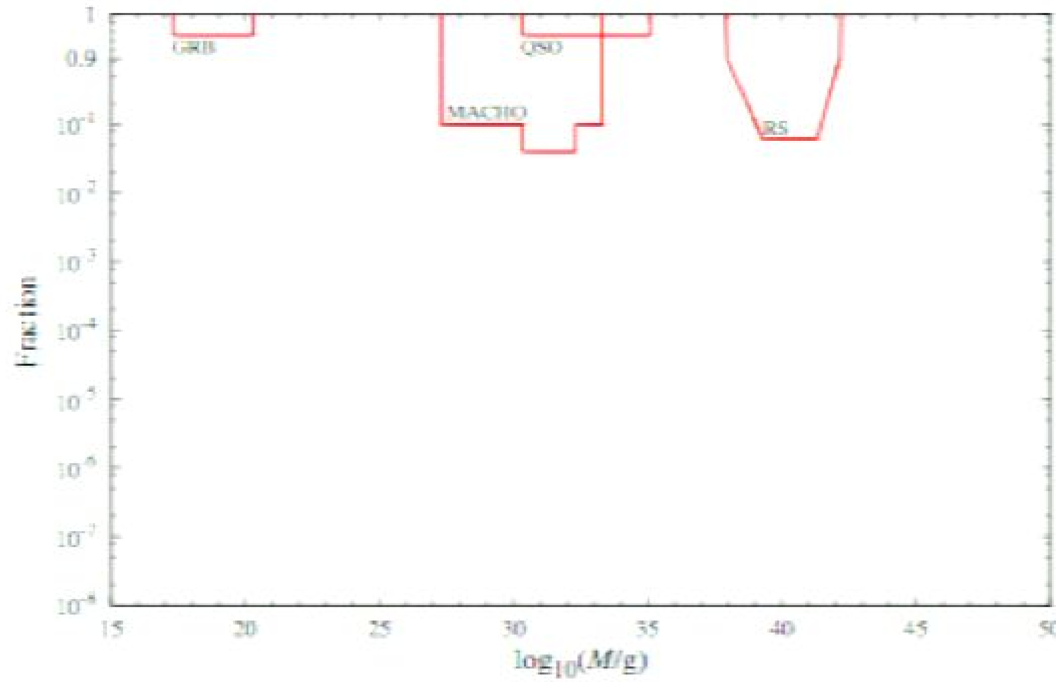


Femtolensing GRBs

$f < 1$ for $10^{-16} M_\odot < M < 10^{-13} M_\odot$

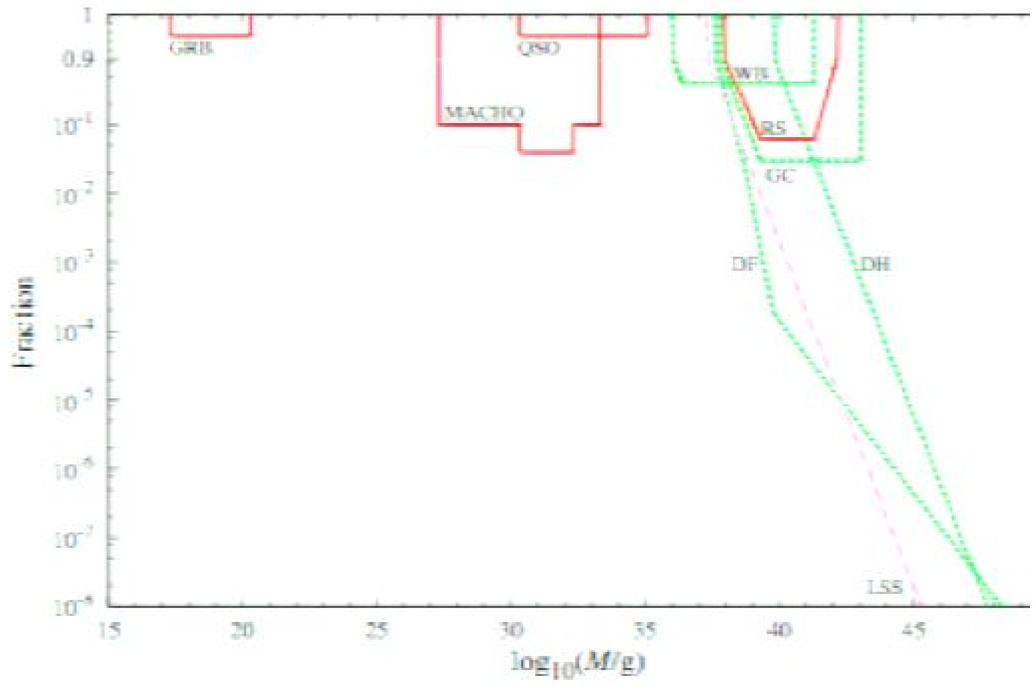
Microlensing QSOs

$f < 1$ for $10^{-3} M_\odot < M < 60 M_\odot$

$$f \equiv \frac{\Omega_{\rm PBH}}{\Omega_{\rm CDM}} \approx 4.8\,\Omega_{\rm PBH} = 4.11 \times 10^8 \beta'(M) \left(\frac{M}{M_\odot}\right)^{-1/2}$$

Millilensing Compact Radio Sources

DYNAMICAL LIMITS

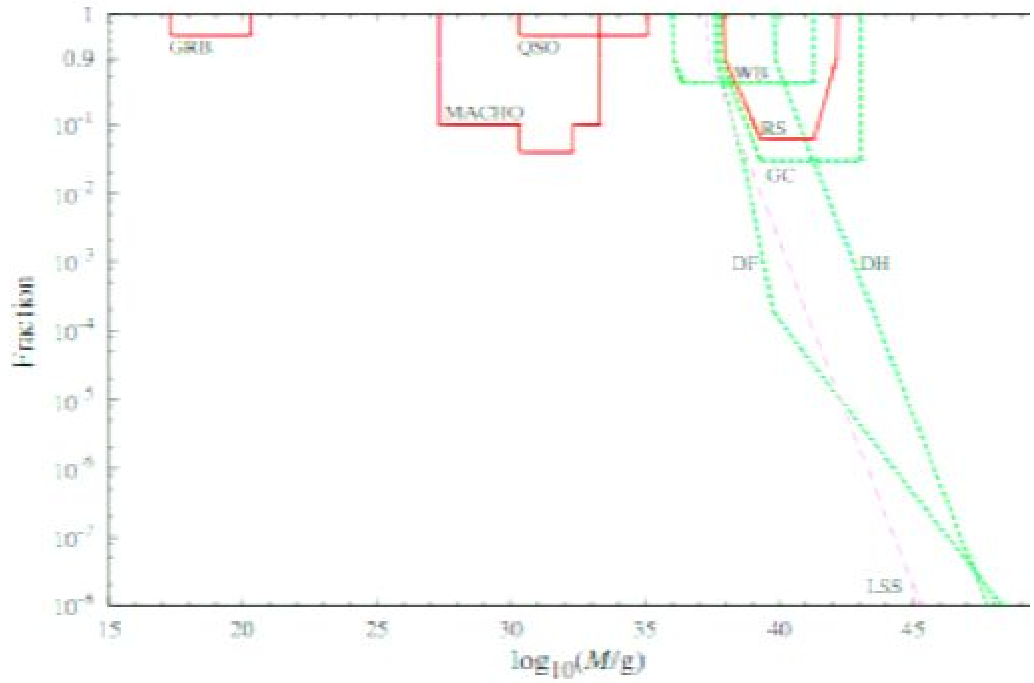


Binary disruption

$$f(M) < \begin{cases} (M/500M_\odot)^{-1} & (500M_\odot < M < 10^3 M_\odot) \\ 0.4 & (10^3 M_\odot < M < 10^8 M_\odot) \end{cases}$$

Globular cluster disruption

DYNAMICAL LIMITS



Binary disruption

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Globular cluster disruption

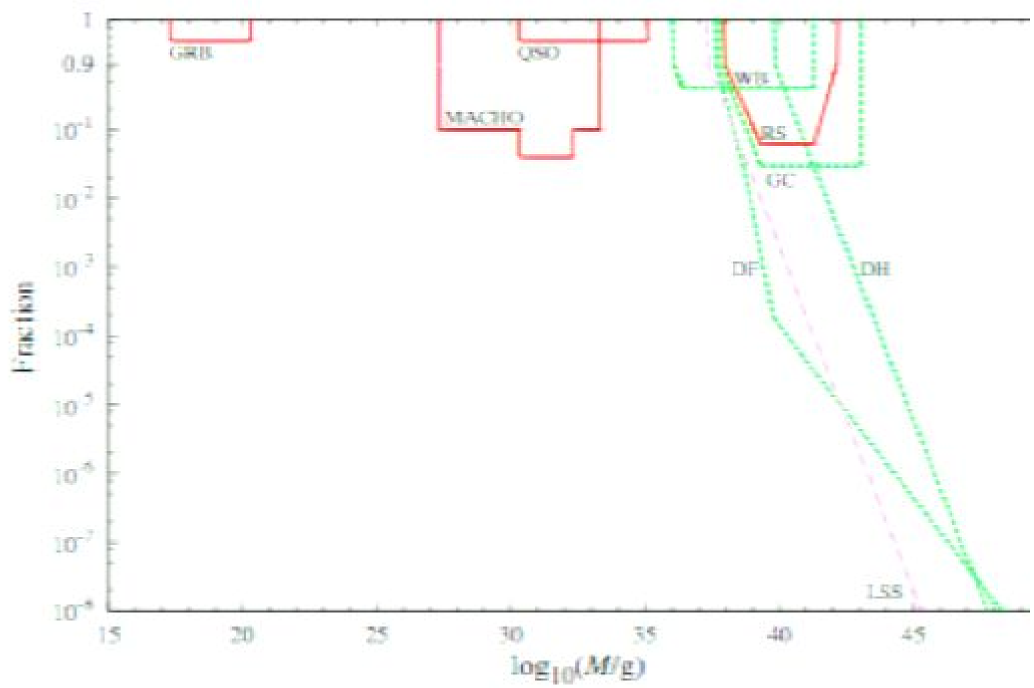
$$f(M) < \begin{cases} (M/3 \times 10^4 M_\odot)^{-1} & (3 \times 10^4 M_\odot < M < 10^6 M_\odot) \\ 0.03 & (10^6 M_\odot < M < 6 \times 10^9 M_\odot) \end{cases}$$

Disk heating

$$f(M) < (M/3 \times 10^6 M_\odot)^{-1}$$

Dynamical friction

DYNAMICAL LIMITS



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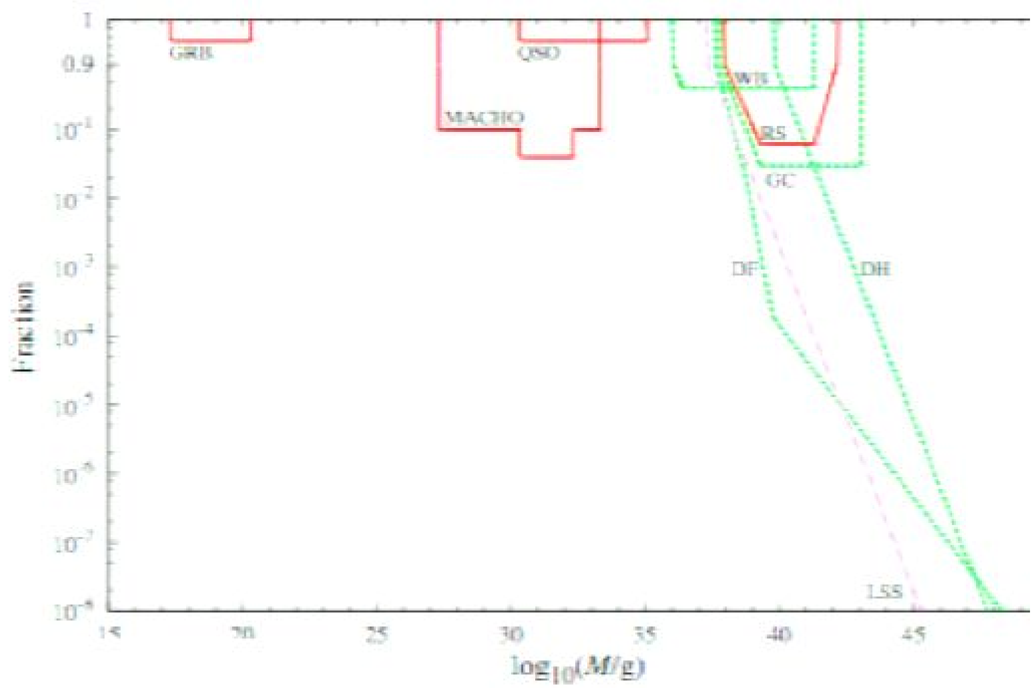
DYNAMICAL LIMITS



Globular cluster disruption

$$f(M) < \begin{cases} (M/3\times 10^4 M_\odot)^{-1} & (3\times 10^4 M_\odot < M < 10^6 M_\odot) \\ 0.03 & (10^6 M_\odot < M < 6\times 10^9 M_\odot) \end{cases}$$

Disk heating

$$f(M) < (M/3\times 10^6 M_\odot)^{-1}$$

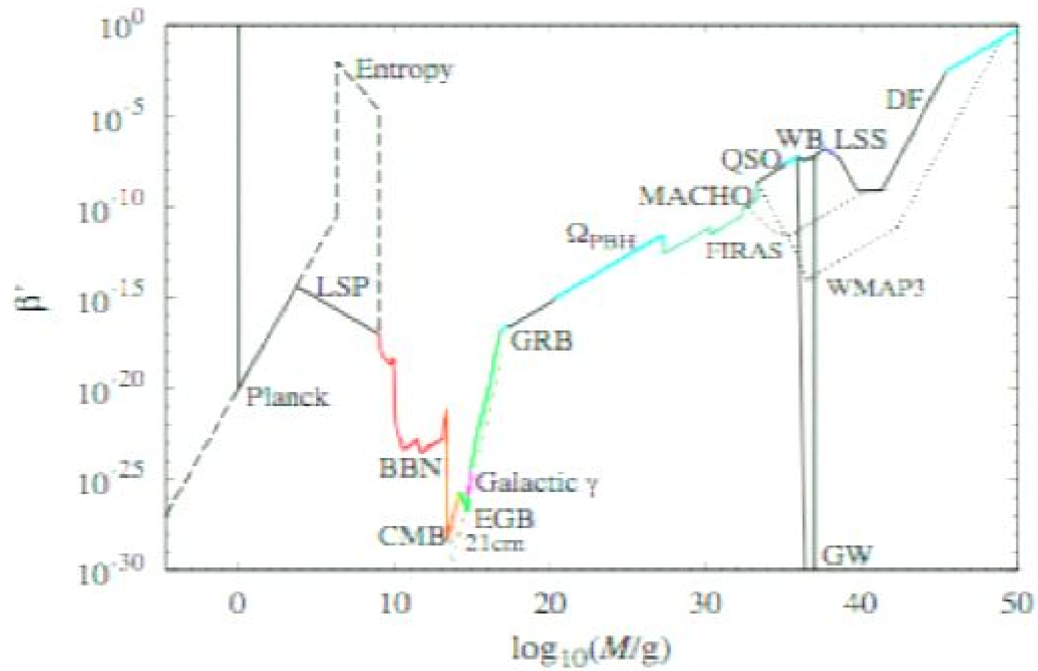
Dynamical friction

$$f(M) < \begin{cases} (M/2\times 10^4 M_\odot)^{-10/7}(r_c/2\mathrm{kpc})^2 & (M < 6\times 10^5 M_\odot) \\ (M/4\times 10^4 M_\odot)^{-2}(r_c/2\mathrm{kpc})^2 & (6\times 10^5 M_\odot < M < 3\times 10^6 [r_c/2\mathrm{kpc}]^2 M_\odot) \\ (M/0.1M_\odot)^{-1/2} & (M > 3\times 10^6 [r_c/2\mathrm{kpc}]^2 M_\odot). \end{cases}$$

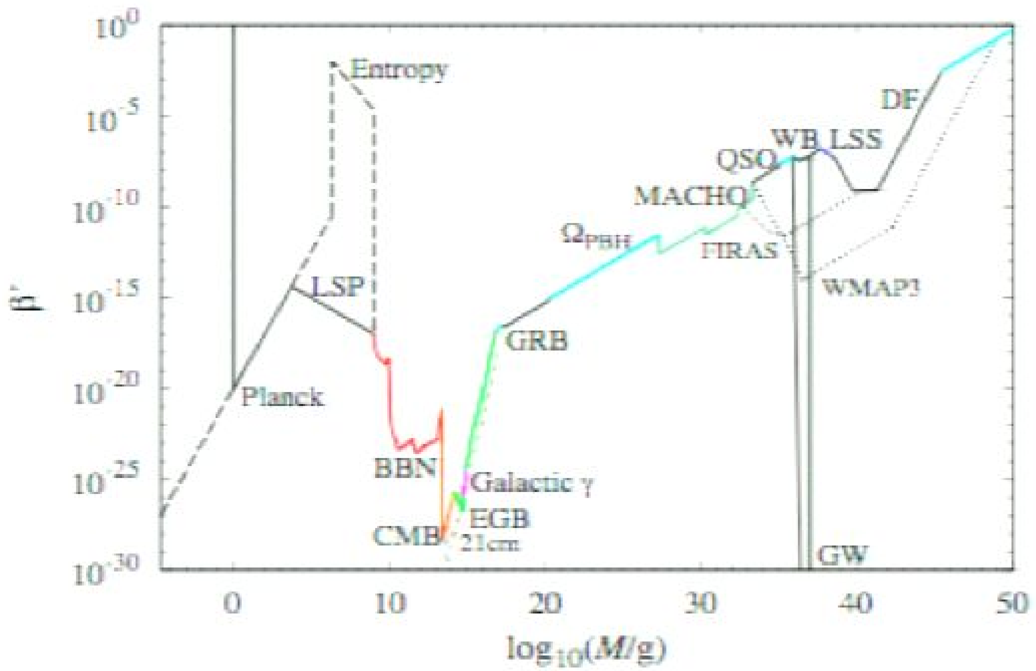
Large-scale structure

Afshordi et al (2008)

CONCLUSIONS



CONCLUSIONS



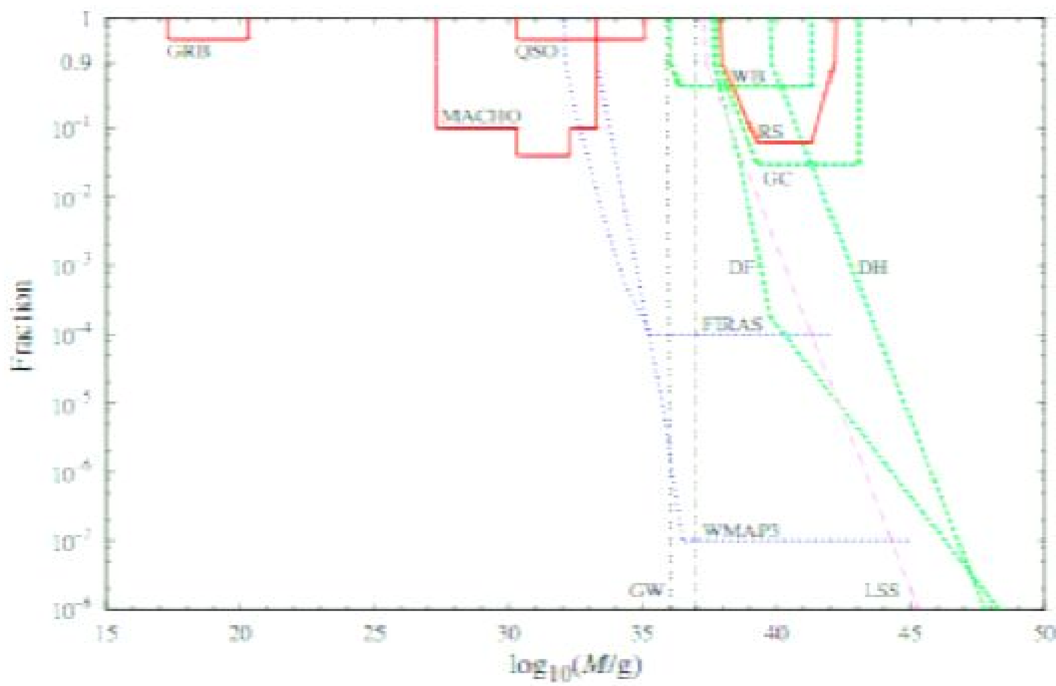
ЗH constraints over 60 mass decades provide unique probe of

lation, dust phase, cosmic strings, domain walls, primordial
homogeneities, non-Gaussianity, extra dimensions, variable G.

ACCRETION AND GRAVITY WAVE CONSTRAINTS

Ricotti et al. (2008)

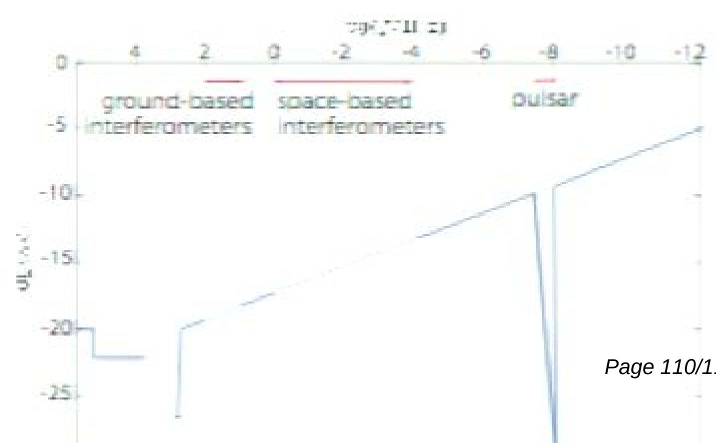
PBH accretion => X-rays
=> CMB spectrum/anisotropies
=> FIRAS/WMAP limits



Saito & Yokoyama (2009)
Assadullahi & Wands (2009)

Scalar perturbations → 2nd order tensor perturbations

Scalar perturbations → PBHs



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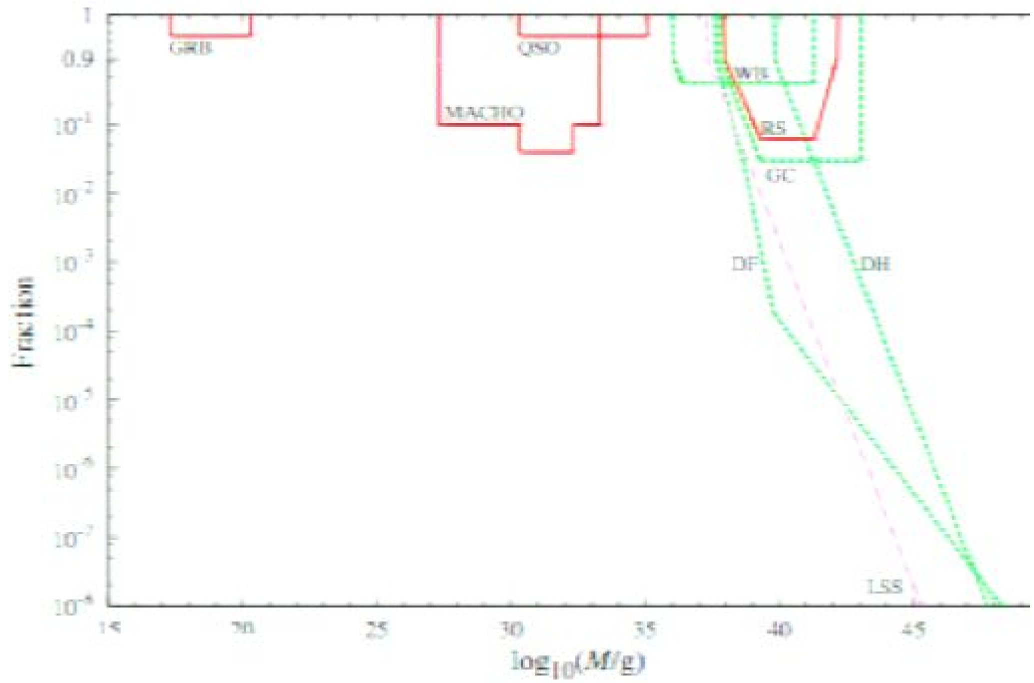
DYNAMICAL LIMITS



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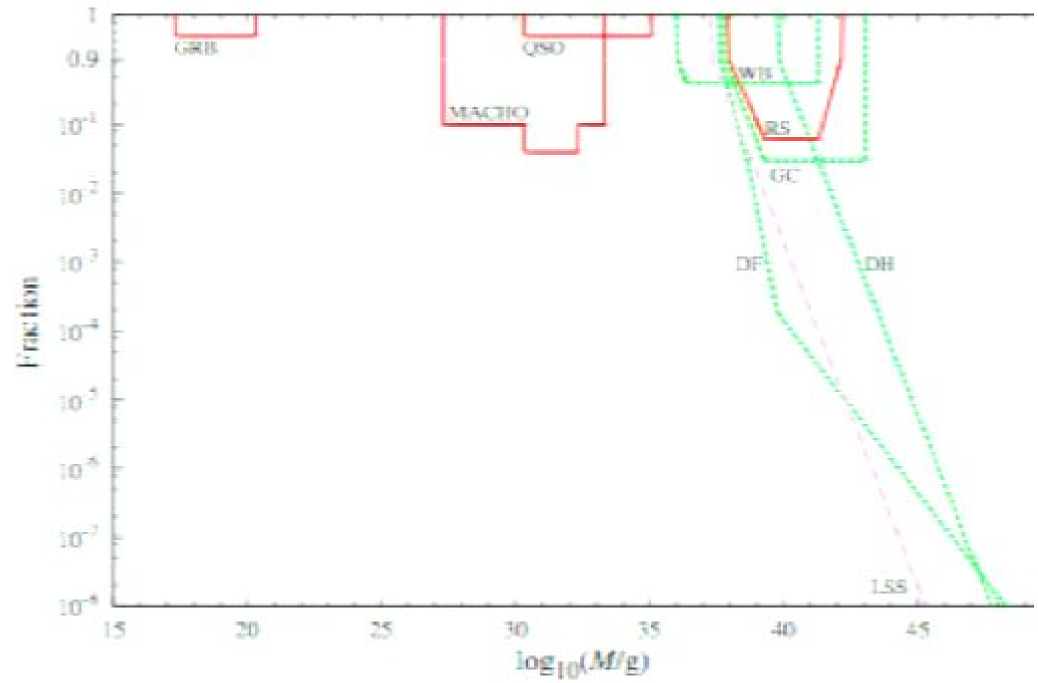

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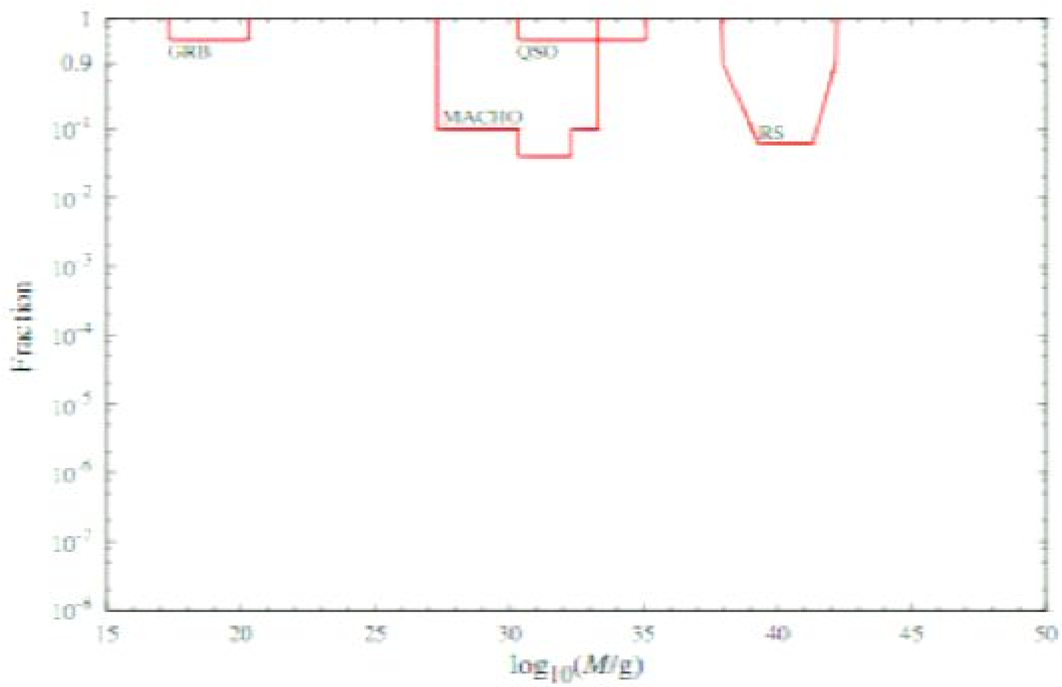

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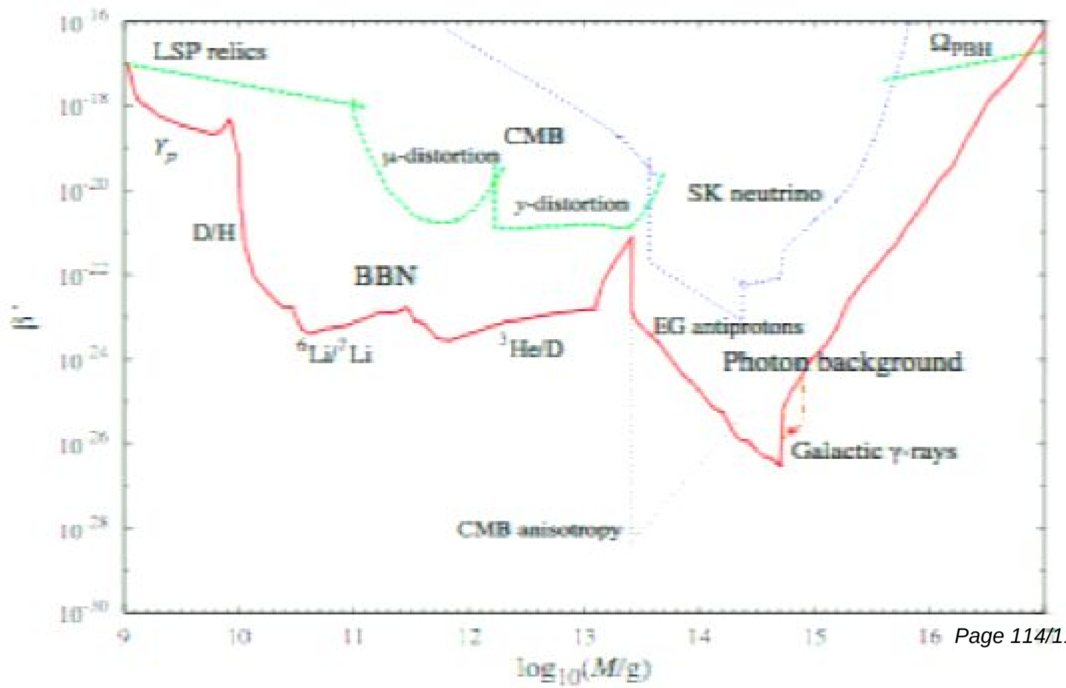

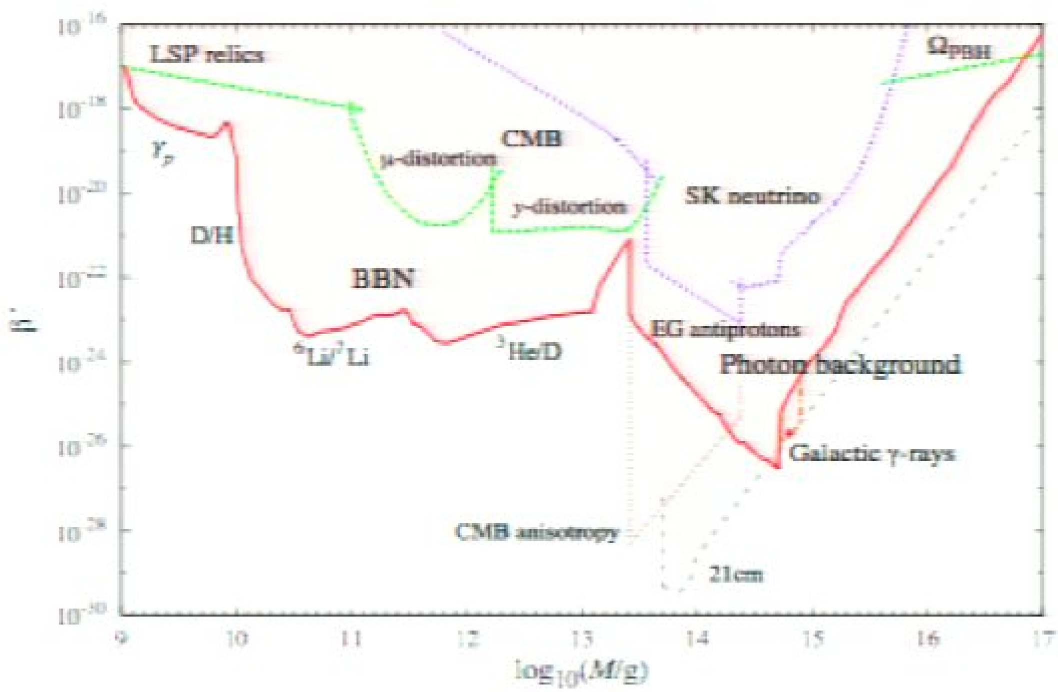
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