ASTROPHYSICAL AND COSMOLOGICAL CONSEQUENCES OF PRIMORDIAL BLACK HOLES

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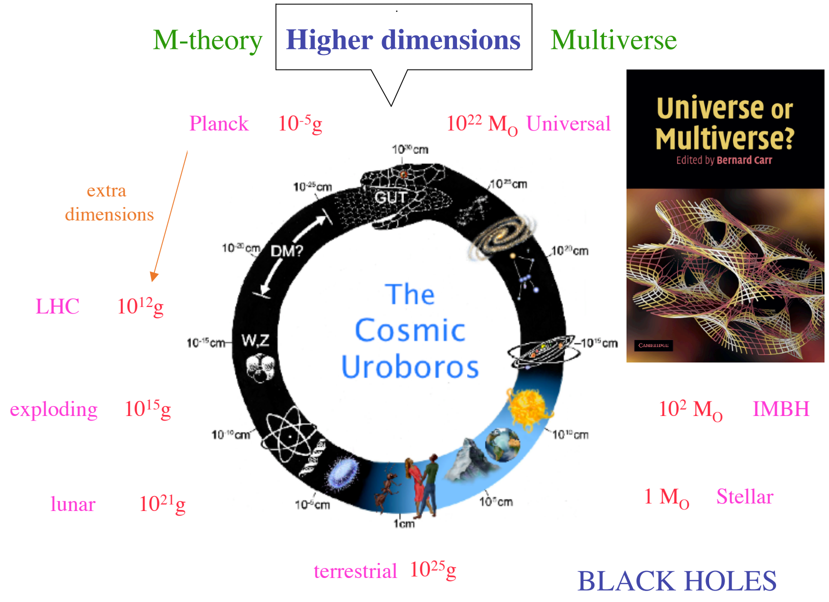
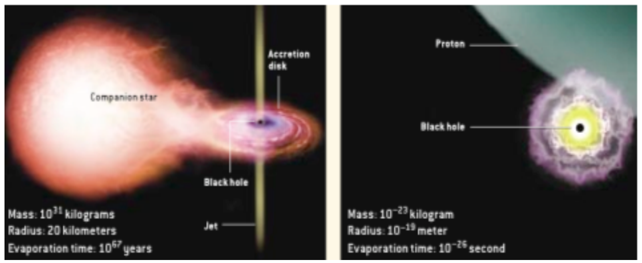
PBHs as probe of early Universe
inhomogeneities, phase transitions, inflation

PBHs as probe of high energy physics
PBH explosions, cosmic rays, TeV quantum gravity

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

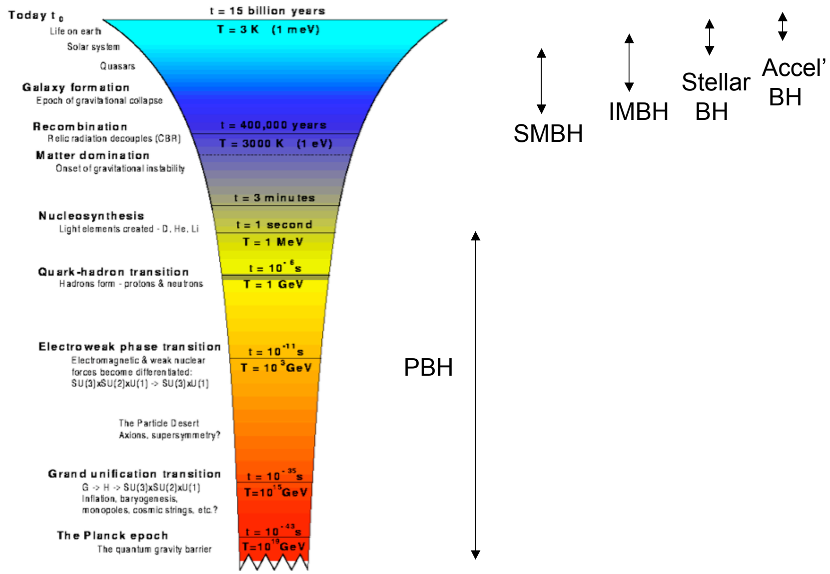


LARGE VERSUS SMALL BLACK HOLES

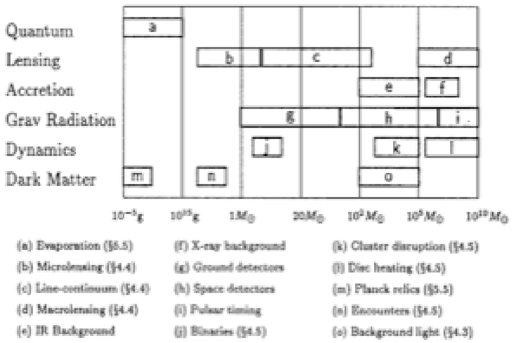


- Huge potential mass range of PBHs makes them a powerful probe of both macrophysics and microphysics.
- PBHs could provide unique information about higher dimensions, relevant to accelerator experiments and creation of Universe.

WHEN BLACK HOLES FORM



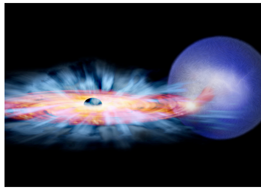
MODES OF BLACK HOLE DETECTION

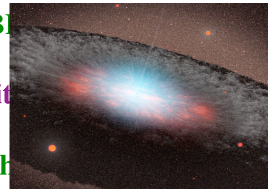


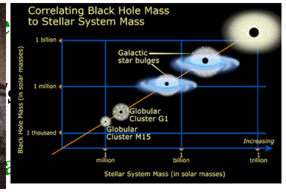
BLACK HOLE FORMATION

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

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







$$M_{PBH} \sim c^3 t/G = \begin{cases} 10^{-5}\text{g at } 10^{-43}\text{s} & \text{(minimum)} \\ 10^{15}\text{g at } 10^{-23}\text{s} & \text{(evaporating now)} \\ 1M_O \text{ at } 10^{-5}\text{s} & \text{(maximum)} \end{cases}$$

Higher dimensions => TeV quantum gravity => larger minimum?

… AND EVAPORATION

Black holes radiate thermally with temperature

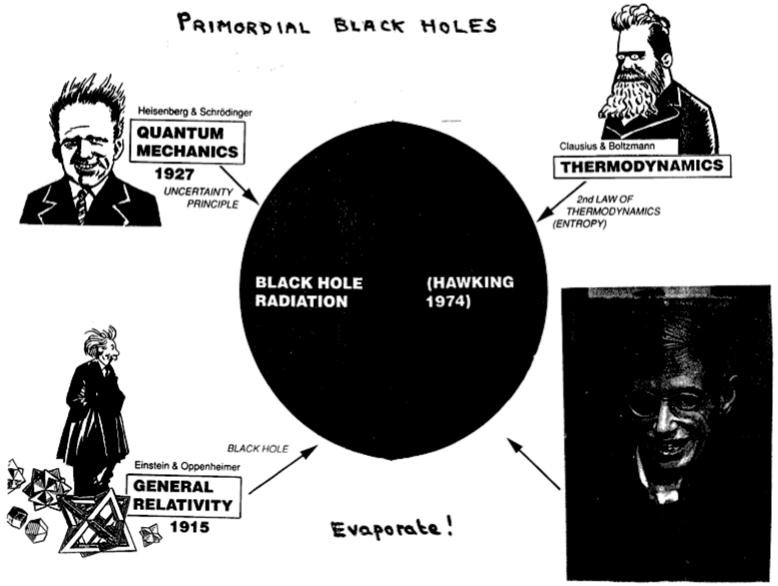
$$T = \frac{hc^3}{8\pi GkM} \sim 10^{-7}\left[\frac{M}{M_0}\right]^{-1} \text{K} \qquad \text{(Hawking 1974)}$$

=> 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)

γ-ray bgd at 100 MeV => $\Omega_{PBH}(10^{15}\text{g}) < 10^{-8}$
(Page & Hawking 1976)

=> explosions undetectable in standard particle physics model



PBHs important even if never formed!

WHAT PRIMORDIAL BLACK HOLES DO

Probe fundamental physics ($M \sim 10^{-5}$g)

Planck-mass relics
Extra dimensions and higher dimensional BHs
TeV quantum gravity

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

Baryosynthesis/nucleosynthesis
Gravitino/neutrino/entropy production
Removing monopoles/domain walls

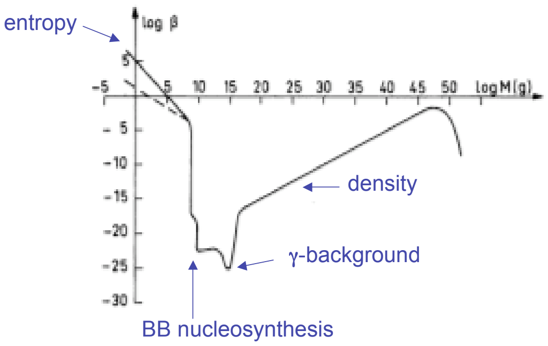
Probe high energy physics ($M \sim 10^{15}$g)

Cosmological and Galactic γ-rays
Cosmic ray antiprotons and positrons
PBH explosions and gamma-ray bursts

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

Non-baryonic cold dark matter candidate
Dynamical/lensing/gravitational-wave effects
Seed large-scale structure and SMBHs in galactic nuclei

Novikov et al. (1979)



Limit on fraction of Universe collapsing

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

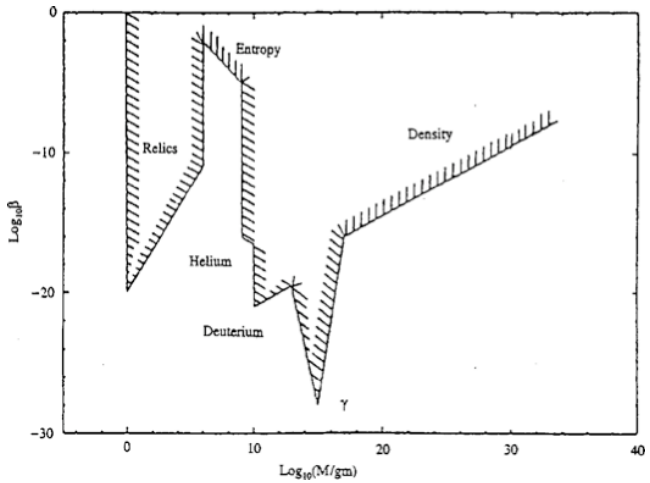
General limit

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

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

=> constraints from entropy, γ-background, BBNS

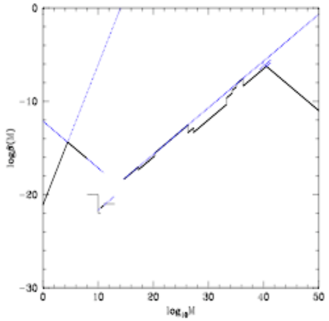
Carr, Gilbert & Lidsey (1994)



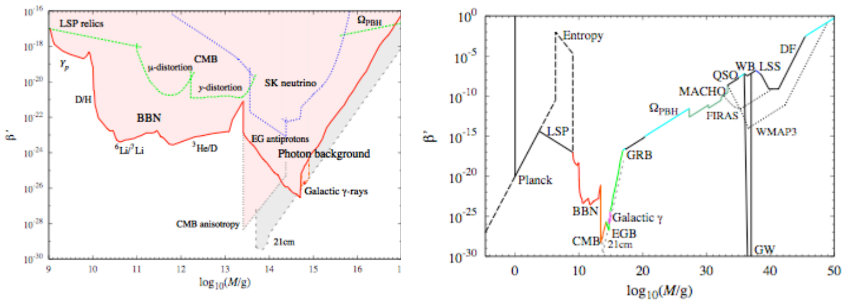
Josan, Green & Malik (2009)

TABLE I. Summary of constraints on the initial PBH abundance, $\beta(M_{PBH})$.

Description	Mass range	Constraint on $\beta(M_{PBH})$
	Gravitational constraints	
Present-day PBH density	$M_{PBH} > 5\times10^{14}$ g	$<2\times10^{-19}(\frac{M_{PBH}}{f_M 5\times10^{14}\ g})^{1/2}$
GRB femtolensing	$10^{-16}M_\odot < M_{PBH} < 10^{-13}M_\odot$	$<1\times10^{-19}(\frac{M_{PBH}}{f_M 5\times10^{14}\ g})^{1/2}$
Quasar microlensing	$0.001M_\odot < M_{PBH} < 60M_\odot$	$<1\times10^{-19}(\frac{M_{PBH}}{f_M 5\times10^{14}\ g})^{1/2}$
Radio source microlensing	$10^6M_\odot < M_{PBH} < 10^8M_\odot$	$<6\times10^{-20}(\frac{M_{PBH}}{f_M 5\times10^{14}\ g})^{1/2}$
	Halo density[a]	
LMC Microlensing	$10^{-7}M_\odot < M_{PBH} < 10^{-6}M_\odot$	$<3\times10^{-20}(\frac{M_{PBH}}{f_M 5\times10^{14}\ g})^{1/2}$
	$10^{-6}M_\odot < M_{PBH} < M_\odot$	$<1\times10^{-20}(\frac{M_{PBH}}{f_M 5\times10^{14}\ g})^{1/2}$
	$M_\odot < M_{PBH} < 10M_\odot$	$<5\times10^{-20}(\frac{M_{PBH}}{f_M 5\times10^{14}\ g})^{1/2}$
Wide binary disruption	$10^3M_\odot < M_{PBH} < 10^8M_\odot$	$<3\times10^{-20}(\frac{M_{PBH}}{f_M 5\times10^{14}\ g})^{1/2}$
Disk heating	$M_{PBH} > 3\times10^6M_\odot$	$<2\times10^{6}\frac{1}{f_M^{1/2}}(\frac{M_{PBH}}{5\times10^{14}\ g})^{-1/2}$
	Evaporation	
Diffuse gamma-ray background	2×10^{13} g $< M_{PBH} < 5\times10^{14}$ g	*depends on* PBH *mass function*
Cosmic-rays	similar to DGRB	*depends on* PBH *mass function*
Neutrinos	similar to DGRB	*depends on* PBH *mass function*
Hadron injection	10^8 g $< M_{PBH} < 10^{10}$ g	$<10^{-20}$
	10^{10} g $< M_{PBH} < 3\times10^{10}$ g	$<10^{-22}$
Photodissociation of deuterium	10^{10} g $< M_{PBH} < 10^{13}$ g	$<3\times10^{-22}(\frac{M_{PBH}}{f_M 10^{10}\ g})^{1/2}$
CMB distortion	10^{11} g $< M_{PBH} < 10^{13}$ g	$<10^{-21}$
(Quasi-)stable massive particles[b]	$M_{PBH} < 10^{11}$ g	$<\sim 10^{-18}(\frac{f_M M_{PBH}}{10^{11}\ g})^{-1/2}$
Present-day relic density[c]	$M_{PBH} < 5\times10^{14}$ g	$<4\frac{1}{f_M^{1/2} f_{rd}}(\frac{M_{PBH}}{5\times10^{14}\ g})^{3/2}$



B. Carr, K. Kohri, Y. Sendouda & J. Yokoyama (2010)



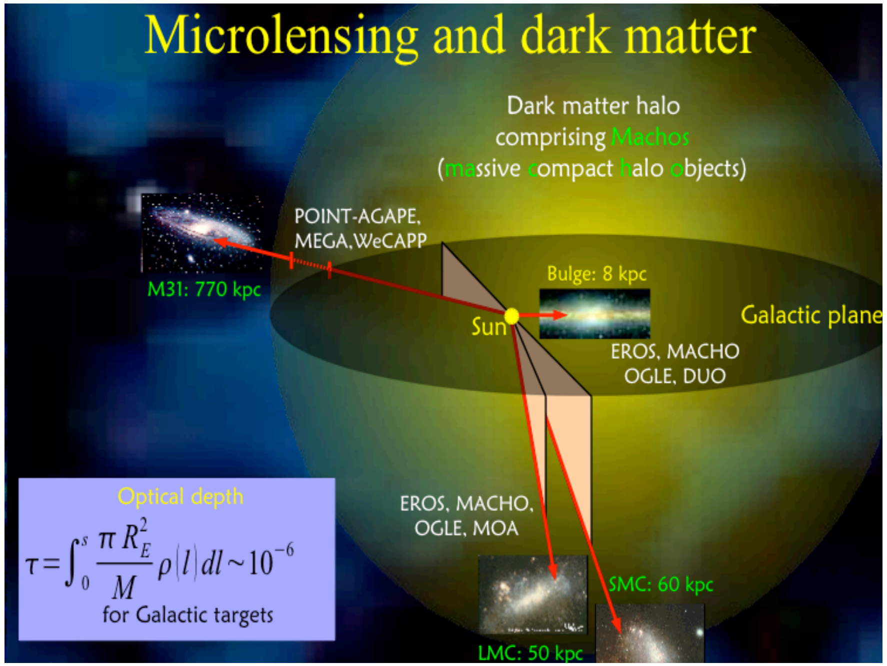
Microlensing searches => MACHOs with 0.5 M_O

⇒ PBH formation at QCD transition?

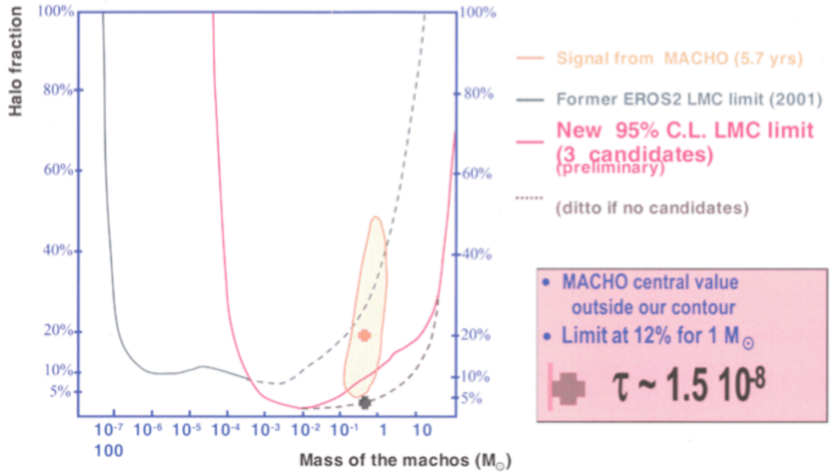
Pressure reduction => PBH mass function peak at 0.5 M_O

(Jedamzik 1997, Yokoyama 1997, Widerin & Schmid 1998,
Kawasaki 1998, Jedamzik & Niemeyer 1999, Fuller et al 2000)

However, it now seems that at most 20% of DM can be in these objects



Limits on macho content of the halo



Evidence for dark matter in the form of compact bodies

1993

Michael Hawkins
University of Edinburgh

Evidence for Microlensing

- Lack of time dilation.
- Symmetry of variation.
- Achromatic variation.
- Microlensing in multiply lensed quasars
- Caustic features in light curves
- Slope of structure function

The timescale of variation implies that the mass of the microlensing bodies is around 0.1 $M_\odot$

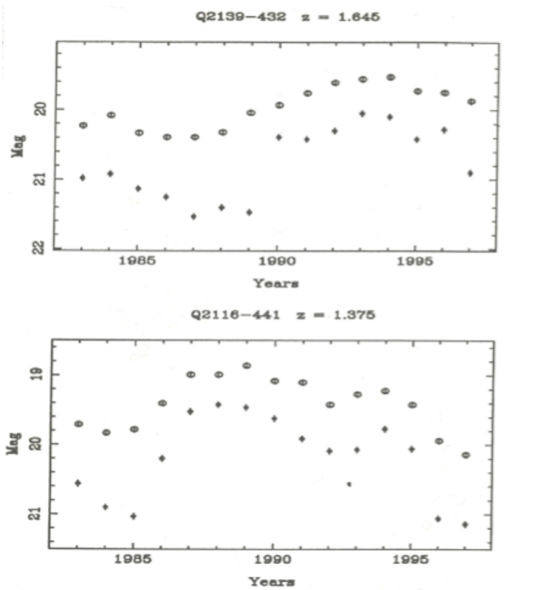


Fig. 3. Light curves for two quasars showing all the characteristics expected of caustic crossing events. Symbols as for Fig. 1.

DETECTION OF 10^{17}G PBHS BY FEMTOLENSING?

Will measurements of gamma-ray bursts, like the one shown sterilizing a planet in this artist's rendering, reveal the existence of tiny black holes? We may know soon.

Marani et al. (1999)

LENSING LIMITS

MACHO microlensing

$$f(M) < \begin{cases} 1 & (6\times10^{-8}M_\odot < M < 30M_\odot) \\ 0.1 & (10^{-6}M_\odot < M < M_\odot) \\ 0.04 & (10^{-3}M_\odot < M < 0.1M_\odot). \end{cases}$$

Femtolensing GRBs

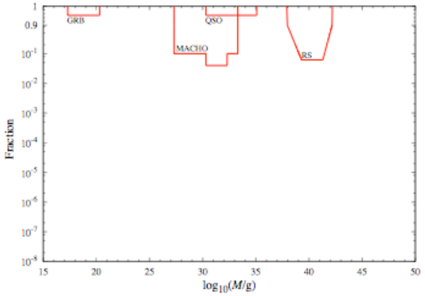
$$f < 1 \text{ for } 10^{-16}M_\odot < M < 10^{-13}M_\odot$$

Microlensing QSOs

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

Millilensing Compact Radio Sources

$$f < 0.06 \text{ for } 10^{6}M_\odot < M < 10^{8}M_\odot$$



$$f \equiv \frac{\Omega_{\rm PBH}}{\Omega_{\rm CDM}} \approx 4.8\,\Omega_{\rm PBH} = 4.11\times10^{8}\beta'(M)\left(\frac{M}{M_\odot}\right)^{-1/2}$$

DYNAMICAL LIMITS

Binary disruption

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

Globular cluster disruption

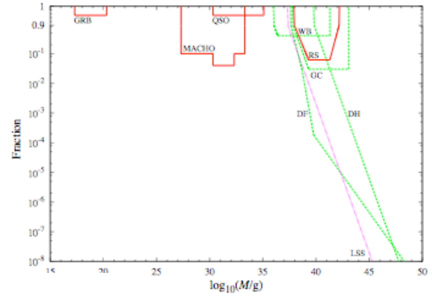
$$f(M) < \begin{cases} (M/3\times10^4M_\odot)^{-1} & (3\times10^4M_\odot < M < 10^6M_\odot) \\ 0.03 & (10^6M_\odot < M < 6\times10^9M_\odot) \end{cases}$$

Disk heating

$$f(M) < (M/3\times10^6M_\odot)^{-1}$$

Dynamical friction

$$f(M) < \begin{cases} (M/2\times10^4M_\odot)^{-10/7}(r_c/2\mathrm{kpc})^2 & (M < 6\times10^5M_\odot) \\ (M/4\times10^4M_\odot)^{-2}(r_c/2\mathrm{kpc})^2 & (6\times10^5M_\odot < M < 3\times10^6[r_c/2\mathrm{kpc}]^2M_\odot) \\ (M/0.1M_\odot)^{-1/2} & (M > 3\times10^6[r_c/2\mathrm{kpc}]^2M_\odot). \end{cases}$$



Some of these effects have been claimed as evidence for PBHs

CAN PBHS GENERATE LARGE-SCALE STRUCTURE?

PBH formation => Poisson fluctuations which can grow large

Meszaros 1975, Carr 1977, Frees et al 1983, Carr & Silk 1983

Ly-α clouds => upper limit of $10^4 M_O$ Afshordi et al. 2003

$$\delta(M) \sim f(M)\left(\frac{f(M)M_{Ly\alpha}}{M}\right)^{-1/2} \sim 10^{-5}f(M)^{1/2}\left(\frac{M}{M_\odot}\right)^{1/2}\left(\frac{M_{Ly\alpha}}{10^{10}M_\odot}\right)^{-1/2} \Rightarrow f(M) < (M/10^4M_\odot)^{-1}$$

Similar effect can lead to SMBHs in galactic nuclei

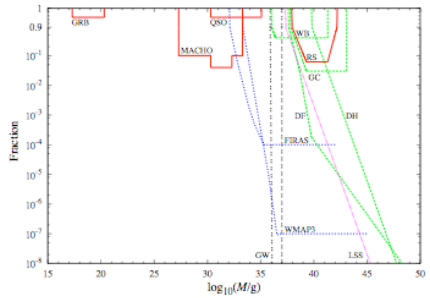
Duchting 2004, Khlopov et al. 2005, Chisholm 2006

Accretion of quintessence by $10^2 M_O$ PBHs might also generate SMBHs but simple accretion analysis is wrong

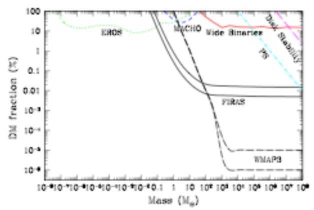
Bean & Magueijo 2002, Carr, Harada & Meada 2010

ASTROPHYSICAL CONSTRAINTS ON LARGE PBHS

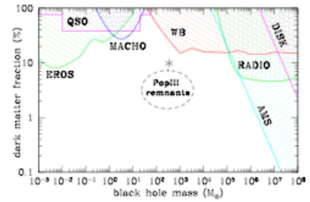
PBH accretion => X-rays
=> CMB spectrum/anisotropies
=> FIRAS/WMAP limits



Ricotti et al. (2008)



Mack et al. (2008)



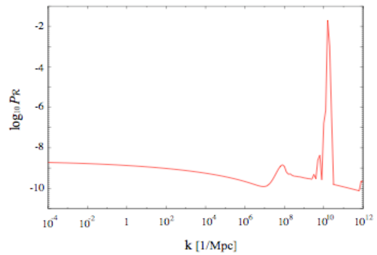
COULD COLD DARK MATTER BE PBHS?

Blais, Kiefer & Polarski (2002)

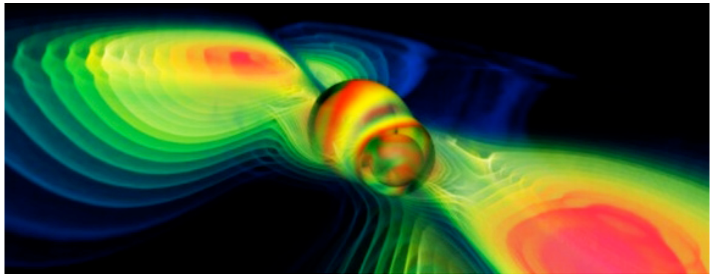
10^{17}-10^{20}g PBHs excluded by femtolensing of GRBs
10^{26}-10^{30}g PBHs excluded by microlensing of LMC
Above $10^5 M_0$ excluded by dynamical effects
But no constraints for 10^{16}-10^{17}g or 10^{20}-10^{26}g or above 10^{30}g

Micro Sublunar IMBHs

Frampton et al. (2010)
Double inflation model
=> peak in spectrum
=> PBHs with 10^{-8}-$10^5 M_O$

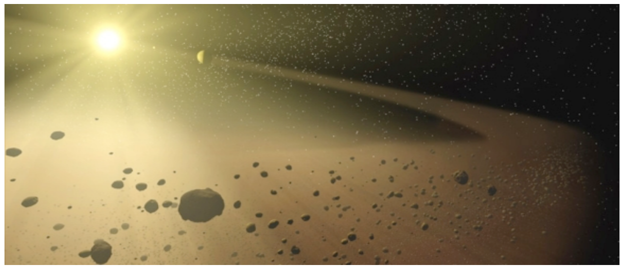


What Would Happen if a Small Black Hole Hit the Earth?
by IAN O'NEILL *on* FEBRUARY 17, 2008



Khriplovich et al. (2008)
Long tube of radiatively damaged material recognisable for geological time

Could Primordial Black Holes Deflect Asteriods on a Collision Course with Earth?
by IAN O'NEILL *on* FEBRUARY 22, 2008



Shatskiy (2008)
Earth-mass PBHs could deflect asteroids onto Earth every 190M years

CAN PLANCK MASS RELICS PROVIDE DARK MATTER?

(MacGibbon 1987, Barrow et al 1992, Carr et al 1997)

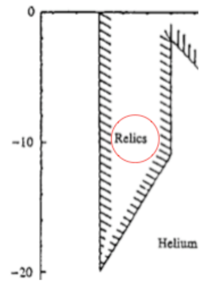
Natural outcome of inflation if fine-tune T_R (reheat)

$\Omega_{relic} < 0.25 \Rightarrow \beta(M) < 8\times10^{-28}\kappa^{-1}(M/M_P)^{3/2}$ (M_{relic}/M_P)

but only applies over limited mass range

$(T_R/T_P)^{-2} < M/M_P < 10^{11}\kappa^{2/5}$

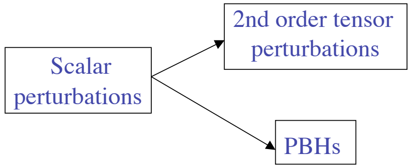
diluted by inf' PBHs dominate before evap'



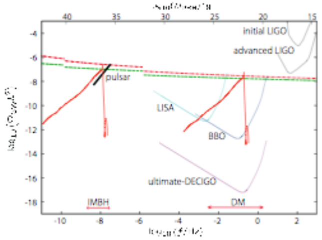
Above upper limit baryon asymmetry from evaporations determines final photon-to-baryon ratio => $M \sim 10^6$g, $t \sim 10^{-23}$ s
(Alexeyev et al 2002, Chen & Adler 2003, Barrau et al 2004, Alexander & Meszaros 2007)

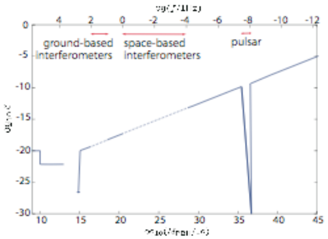
GRAVITY WAVES FROM PBHS

Saito & Yokoyama (2009)
Assadullahi & Wands (2009)
Bugaev & Klimai (2010)



Frequency ~ $10^{-8}(M/10^3 M_\odot)$ Hz





HAWKING RADIATION IN MORE DETAIL

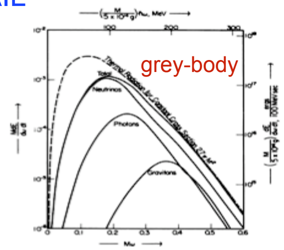
PBH temperature $T_{\rm BH} = \frac{1}{8\pi G M} \approx 1.06\, M_{10}^{-1}\,\text{TeV}$

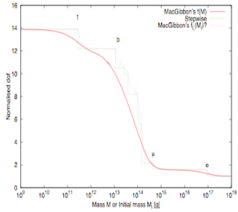
Peak in flux $E_{s=1/2} = 4.02T_{bh}$, $E_{s=1} = 5.77T_{bh}$, $E_{s=0} \approx 2.81T_{bh}$.

Mass loss $\frac{dM_{10}}{dt} = -5.34\times10^{-5}\, f(M)\, M_{10}^{-2}\,\text{s}^{-1}$

effective no.species emitted, 1 for massless

$f_{s=0} = 0.267$, $f_{s=1} = 0.060$, $f_{s=3/2} = 0.020$, $f_{s=2} = 0.007$,
$f_{s=1/2} = 0.147$ (neutral), $f_{s=1/2} = 0.142$ (charge $\pm e$).





Quark and gluon jet emission

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

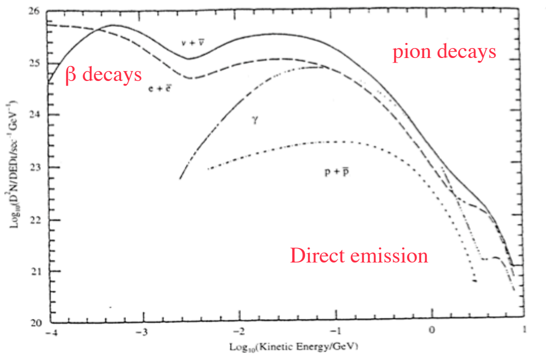
PBH lifetime $\tau \approx 407 \left(\frac{f(M)}{15.35}\right)^{-1} M_{10}^3\,\text{s}$

TeV BHs

Mass evaporating today $M_* \approx 1.02\times10^{15}\left(\frac{f_*}{15.35}\right)^{1/3}\text{g} \approx 5.1\times10^{14}\,\text{g}$ (f_*=1.9, T_*=21MeV)

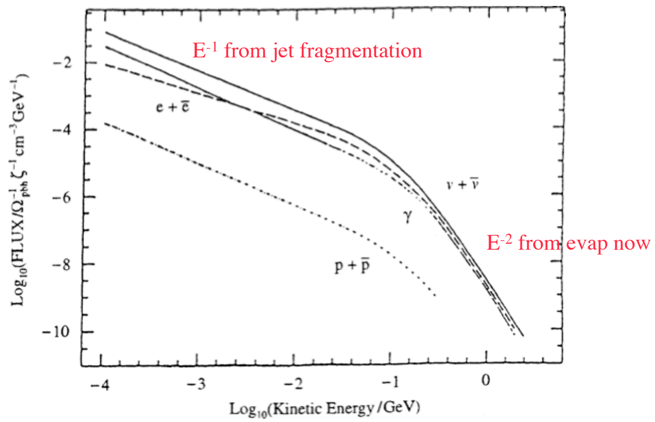
MacGibbon and Webber (1990)

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

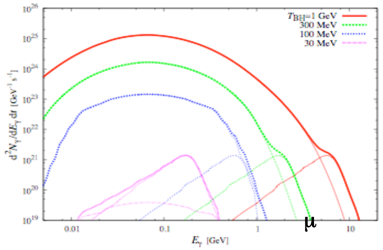


Instantaneous emission from 1GeV black hole

Time integrated emission from all PBHs



CSKY



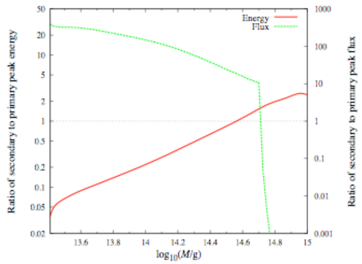
PYTHIA CODE

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

fraction of jet energy going into pions

1.6 x 10^{-3}

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



Secondary emission below $M_q = 0.4M_*$

$M = M_*(1+\mu)$
=> $M(t_o) = (3\mu)^{1/3}M_* > M_q$ for $\mu < 0.02$

so time-integrated emission drops off rapidly above M_*

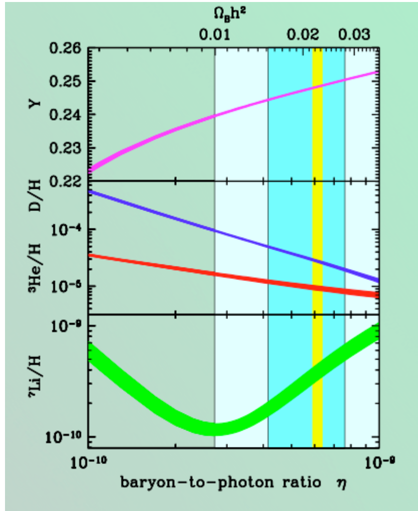
PBH CONSTRAINTS FROM BIG BANG NUCLEOSYNTHESIS

BBNS =>

Ω_{baryon}= 0.04

WMAP, SDSS, BAO confirm

⇒ non-baryonic dark matter



$\tau < 10^{-2}$s => $M<10^9$g
=> no trace

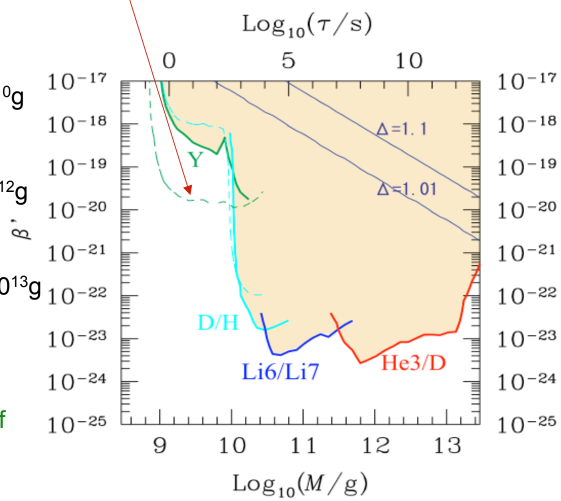
$\tau = 10^{-2}$-10^2s => $M=10^9$-10^{10}g
=> increase $(n/p)_F$ and Y

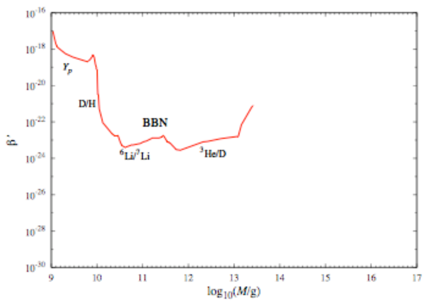
$\tau = 10^2$-10^7s => $M=10^{10}$-10^{12}g
=> increase D and ^{6}Li

$\tau = 10^7$-10^{12} s => $M=10^{12}$-10^{13}g
=> increase D and ^{3}He

$\tau > 10^{12}$s => $M<10^{13}$g
⇒ no effect but $M^{7/2}$ cut-off from low-mass tail

Kohri & Yokoyama (2000)

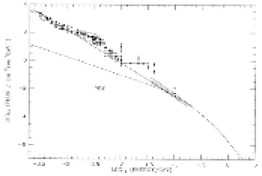




CONSTRAINTS ON PBHS FROM γ-RAY BACKGROUND

Page & Hawking (1976) => $\Omega_{PBH}(M_*) < 10^{-8}$ (Fichtel et al)

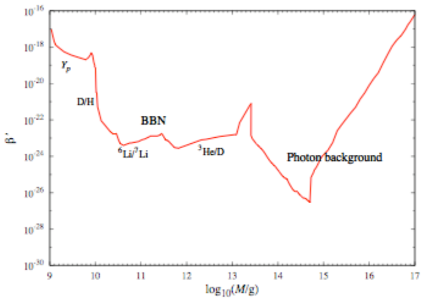
Carr & MacGibbon (1998) => $\Omega_{PBH}(M_*) < 5.1 + 2.6 \times 10^{-9}$ (EGRET, jets)

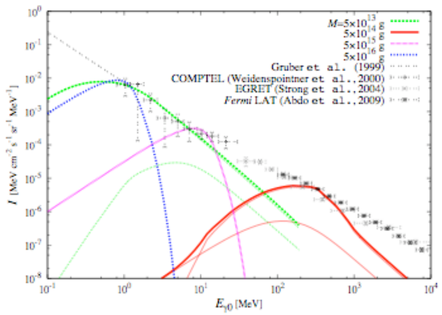


Barrau et al. (2003) => $\Omega_{PBH}(M_*) < 3.3 \times 10^{-9}$ (subtracting blazars)

Cannot explain the γ-ray background but can place limits on $\beta(M_*)$

For monochromatic mass function, limits are strongest at M_*
CKSY (2010) => $\Omega_{PBH}(M_*) < 5 \times 10^{-10}$ (FermiLAT)





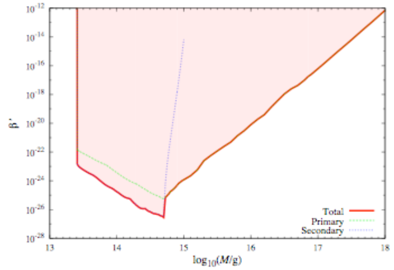
Diffuse γ-ray background

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

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

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

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



Constraints on β(M)

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

$$\beta'(M) \lesssim 4 \times 10^{-26} \left(\frac{M}{M_*}\right)^{7/2+\epsilon} \quad (M > M_*)$$

GALACTIC γ-BACKGROUND

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

Galactic γ-background (Wright 1996)
=> explosion rate $dn/dt < 0.07 - 0.42\ pc^{-3}y^{-1}$
=> Galactic halo concentration $\xi = (2\text{-}12) \times 10^5 h^{-1}$

More recent analysis (Lehoucq et al. 2009)
=> explosion rate $dn/dt < 0.06\ pc^{-3}y^{-1}$
⇒ limit $\Omega_{PBH}(M_*) < 2.6 \times 10^{-9}$ and $\beta(M_*) < 2 \times 10^{-26}$

4 x weaker than EG limit

Lehoucq et al. (2009)

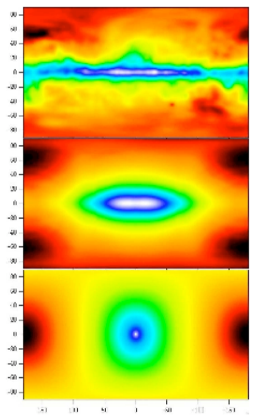


Fig. 4. Predicted photon counts in the merged 70 to 150 MeV energy band originating from π^0-decay and bremsstrahlung radiation in the HI and H_2 gas (top), inverse Compton scattering of the interstellar radiation field (middle), and PBH emission from the Moore dark matter distribution (bottom). All maps are displayed in Galactic coordinates with different logarithmic scales to easily compare the radial profiles.

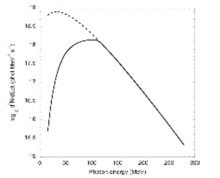


Fig. 1. Instantaneous γ-ray photon emission rate from a kT = 20 MeV black hole (McGibbon & Webber 1990) compared to the black-body emission at the same temperature (dashed line).

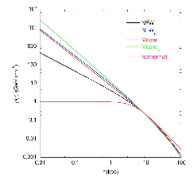


Fig. 2. Dark matter density profiles following NFW (1997), Moore et al. (1999) without and with adiabatic compression (NFW_c and $Moore_c$ respectively, Mambrini et al. 2006). An isothermal profile is also added for comparison. All these distributions are normalized to 0.3 GeV/cm^3 in the solar neighbourhood.

Table 1. Constraints on PBHs of mass M_* for different dark matter distributions[a].

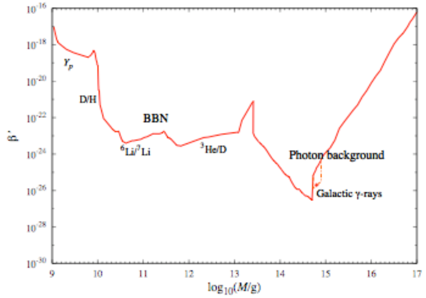
DM distribution	$f(M_*)$	$\Omega_{PBH}(M_*)$	$\beta(M_*)$
Moore	$6.04 \pm 0.05\ 10^{-9}$	$1.38\ 10^{-9}$	$0.98\ 10^{-27}$
$Moore_c$	$1.07 \pm 0.07\ 10^{-9}$	$0.24\ 10^{-9}$	$0.17\ 10^{-27}$
NFW	$6.70 \pm 0.05\ 10^{-9}$	$1.53\ 10^{-9}$	$1.08\ 10^{-27}$
NFW_c	$1.93 \pm 0.08\ 10^{-9}$	$0.44\ 10^{-9}$	$0.31\ 10^{-27}$
isothermal	$11.62 \pm 0.04\ 10^{-9}$	$2.65\ 10^{-9}$	$1.87\ 10^{-27}$

CKSY analysis of Galactic γ-background

$M_i = M_*(1+\mu) \Rightarrow M(t_o) = (30\mu)^{1/3} M_*$

$\Rightarrow E_{peak} = 100\ (30\mu)^{-1/3}$ in 80-160 MeV for $0.7 > \mu > 0.08$

$\Rightarrow$ limit on $\beta(M)$ strongest at $1.08 M_*$ and scales as $\mu^{1/3}$



ANTIPROTONS MacGibbon & Carr (1991)

$n_{p^-}/n_p = 10^{-4}$ for $0.1 < (E/GeV) < 10 \Rightarrow$ some p^- from PBHs?

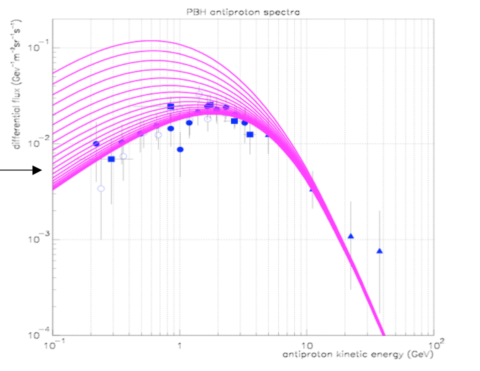
Small excess at low energy => possible primary contribution

Antiprotons => $T >> T(M_*)$ => local PBHs in explosive phase

Maki et al. (1996)
=> $dn/dt < 0.017\ pc^{-3}y^{-1}$

Barrau et al. (2003)
=> $\beta(M_*) < 2 \times 10^{-28}$ →
(0.1 x GRB limit)

but model-dependent
(solar modulation,
diffusion radius etc)



CAN PBHS GENERATE PRIMARY POSITRONS?

Adriani et al (2008)

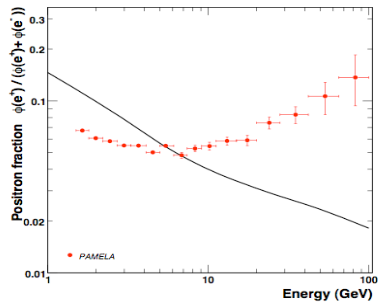


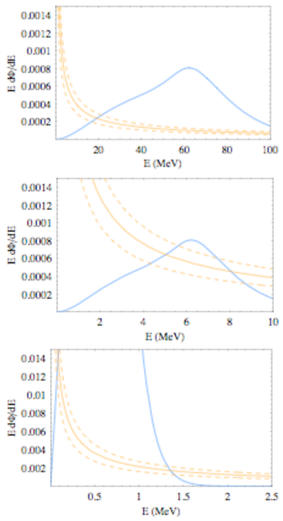
FIG. 4: **PAMELA positron fraction with theoretical models.** The PAMELA positron fraction compared with theoretical model. The solid line shows a calculation by Moskalenko & Strong [39] for pure secondary production of positrons during the propagation of cosmic-rays in the galaxy. One standard deviation error bars are shown. If not visible, they lie inside the data points.

More likely from WIMP annihilations in UCMHs than PBHs

CAN PBHS GENERATE ANNIHILATION RADIATION FROM GALACTIC CENTRE?

511 keV line => 3×10^{43} ann/sec

Bambi et al. (2008)
10^{16}g PBHs could explain this and dark matter without exceeding γ-ray background



CAN PBH EXPLOSIONS GENERATE g-RAY BURSTS?

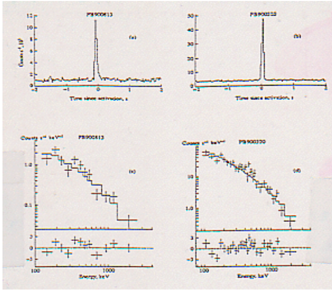
GRB => $dn/dt < 10^{-6}\ pc^{-3}y^{-1}$ (if uniform) or $< 1\ pc^{-3}y^{-1}$ (if in halo)
Galactic γ-halo => $dn/dt = 0.06\ pc^{-3}y^{-1}$ Lehoucq et al (2009)
Cosmic rays => $dn/dt = 0.02\ pc^{-3}y^{-1}$ Maki et al (1996)

Observational limit depends on details of final explosive phase

	$10^6\ pc^{-3}y^{-1}$ (standard)	Semikoz (1994)
dn/dt <	$0.05\ pc^{-3}y^{-1}$ (Hagedorn)	Fichtel et al (1993)
	$0.1\ pc^{-3}y^{-1}$ (QCD fireball)	Cline & Hong (1992)

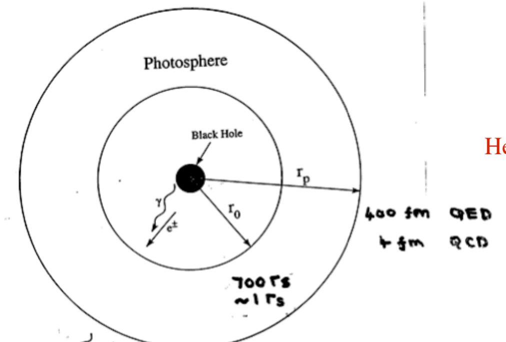
Can some short (100msec) γ-ray bursts be PBH explosions?

Cline et al (2003) => 42 BATSE events
Cline et al (2005) => ? KONUS events
Cline et al (2007) => 8 Swift events
Local => Euclidean dbn, V/V_{max} test



DO EVAPORATING PBHS FORM PHOTOSPHERES?

QED interactions => $e^+e^-\gamma$ photosphere
$T_{BH} > T_{crit} \sim 45$GeV => $M_{BH} < 2\times10^{12}$g



Heckler (1997, 1998)

QCD interactions => quark-gluon photosphere
$T_{BH} > T_{crit} \sim 175$ MeV => $M_{BH} < 5\times10^{14}$g

More careful calculation => <u>no</u> photosphere! MacGibbon, Carr & Page (2008)

OTHER CONSTRAINTS ON EVAPORATING PBHS

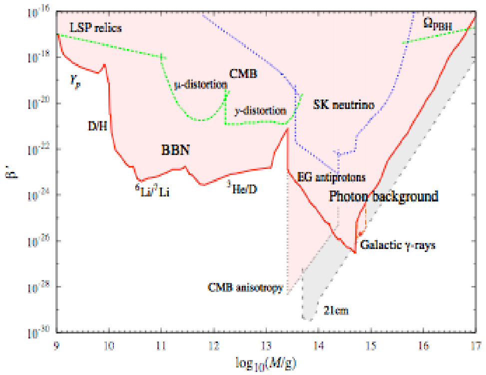
Extragalactic cosmic rays

Neutrino relics

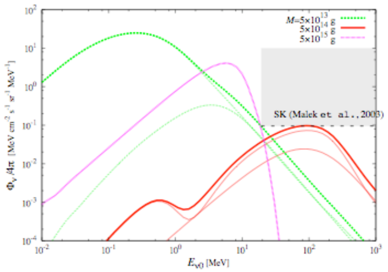
LSP relics

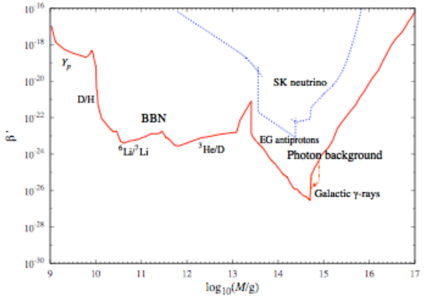
CMB distortions

Reionization and 21cm



NEUTRINO BACKGROUND LIMIT

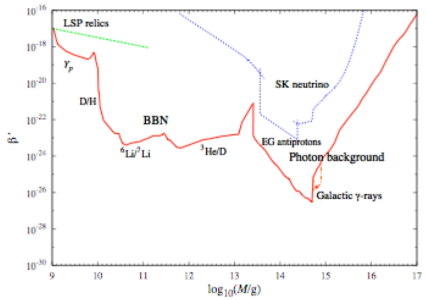




(cf. Bugaev & Konishchev 2002, Bugaev & Klimai 2009, CKSY)

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

(Green 1999, Lemoine 2000)



CMB DISTORTIONS

Thermalization for t <10 s => photon-to-baryon increase for M > 10^9g =>

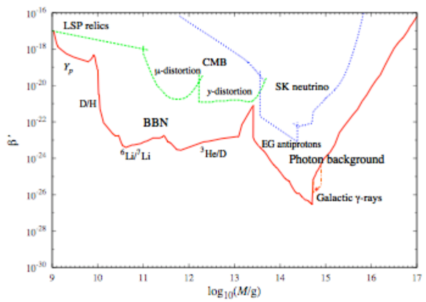
$\beta'(M) < 10^9 (M/M_{Pl})^{-1} \approx 10^{-5}(M/10^9\,\mathrm{g})^{-1} \quad (M < 10^9\,\mathrm{g})$ (Zeldovich &Starobinsky 1977)

Evaporate after freeze-out of double Compton scattering for t >7x10^6s
⇒ μ distortion in CMB for M > 10^{11}g

Evaporate after freeze-out of single Compton scattering for t >3x10^9s
⇒ y distortion in CMB for M > 10^{12}g

Limits around $\beta(M) < 10^{-21}$
in mass range 10^{11}-10^{13}g

(Tashiro & Sugiyama 2008)



DAMPING OF SMALL-SCALE CMB ANISOTROPIES

CKSY

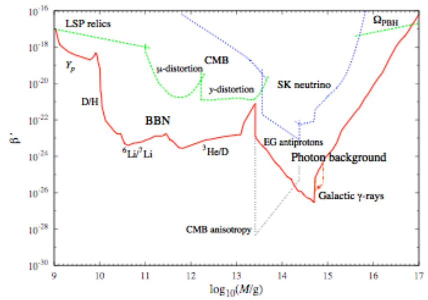
Similar effect to that of decaying particles (Zhang et al 2007)

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

decay rate

CDM fraction
in PBHs

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



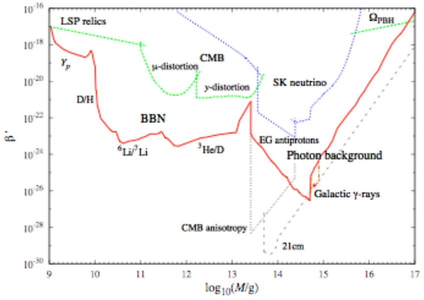
21 CM ABSORPTION

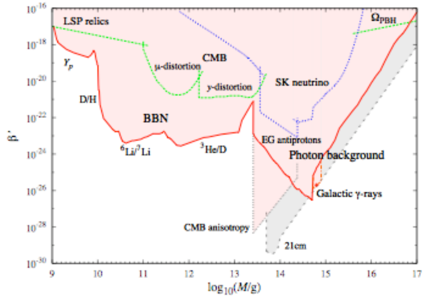
(Mack & Wesley (2008))

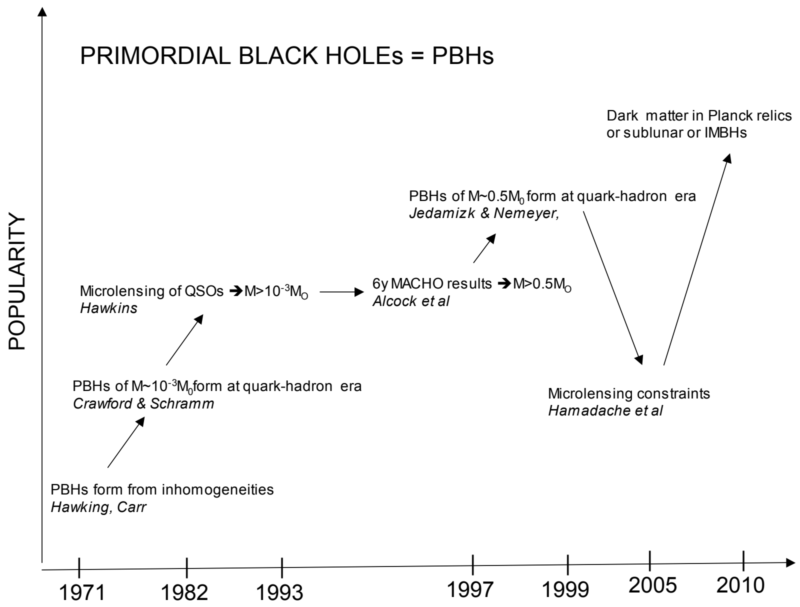
PBHs with 5×10^{13}g < M < 10^{14}g heat IGM in 30<z<90
=> raise 21cm brightness temp => reduced absorption against CMB

PBHs with M ~10^{14}g raise spin temp above CMB
=> 21cm seen in emission against CMB

PBHs with 10^{13}g < M < 10^{17}g => less pronounced effect

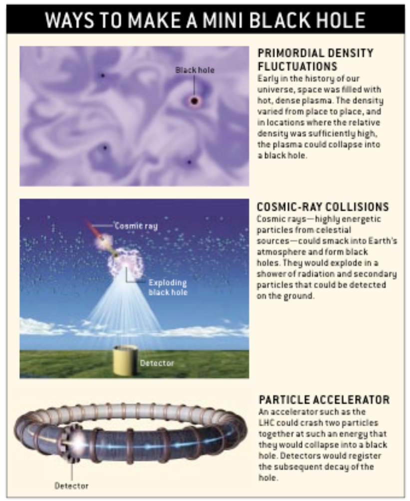






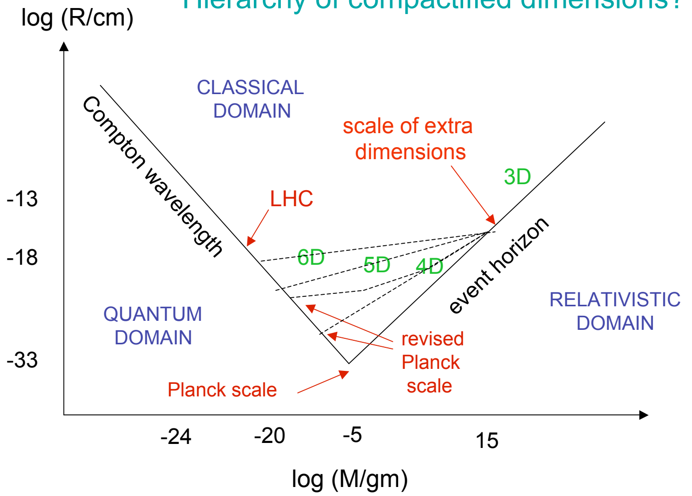
BLACK HOLES AS A PROBE OF HIGHER DIMENSIONS

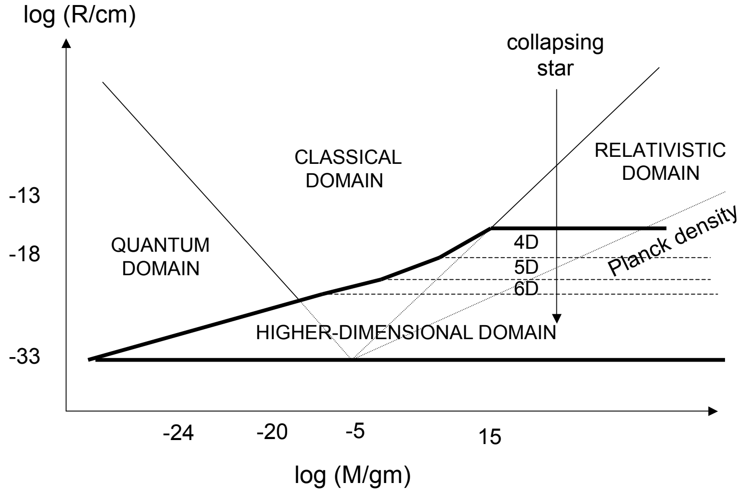
Scientific American
May 2005
Carr and Giddings



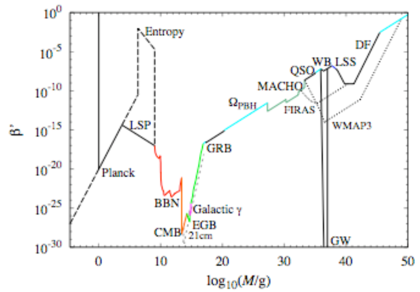
Black hole radius $R_S = M_P^{-1}(M_{BH}/M_P)^{1/(1+n)}$

Hierarchy of compactified dimensions?





SUMMARY



PBHs have been proposed for numerous astrophysical and cosmological purposes. There is still no definite evidence for them but a large variety of constraints over 60 mass decades provide a unique probe of the various formation scenarios to be discussed by ANNE GREEN