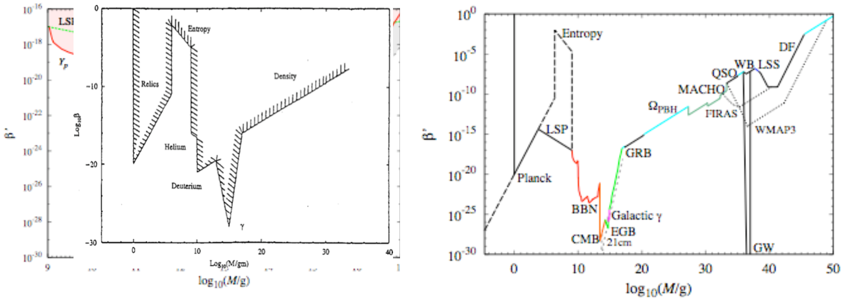
LECTURE II: CONSTRAINTS ON PBHS

B. Carr, K. Kohri, Y. Sendouda & J. Yokoyama
Phys. Rev. D. 81, 104019 (2010)



PBHS AS DARK MATTER?

PBHs are non-baryonic and behave like CDM $r \sim 10^{-8}\ \mathrm{cm}(m_{BH}/10^{20}g)$

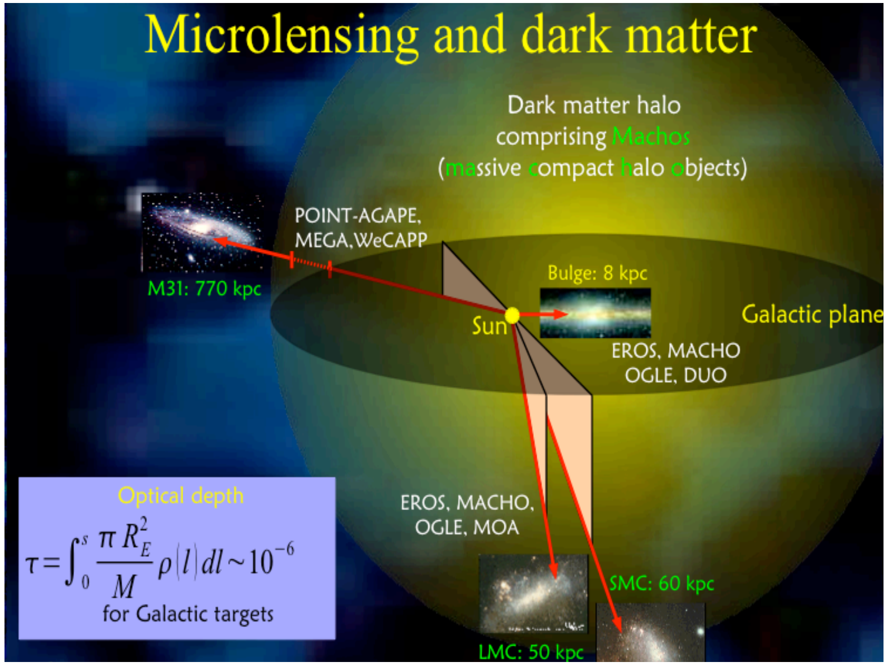
Early microlensing searches => MACHOs with 0.5 M_O
PBH formation at QCD transition?
Pressure reduction => PBH mass function peak at 0.5 M_O

Later microlensing => < 20% of DM can be in these objects

10^{26}-10^{34}g PBHs excluded by microlensing of LMC
10^{17}-10^{20}g PBHs excluded by femtolensing of GRBs
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^{34}g

Stable Planck-mass relics of evaporated BHs?

Microlensing and dark matter

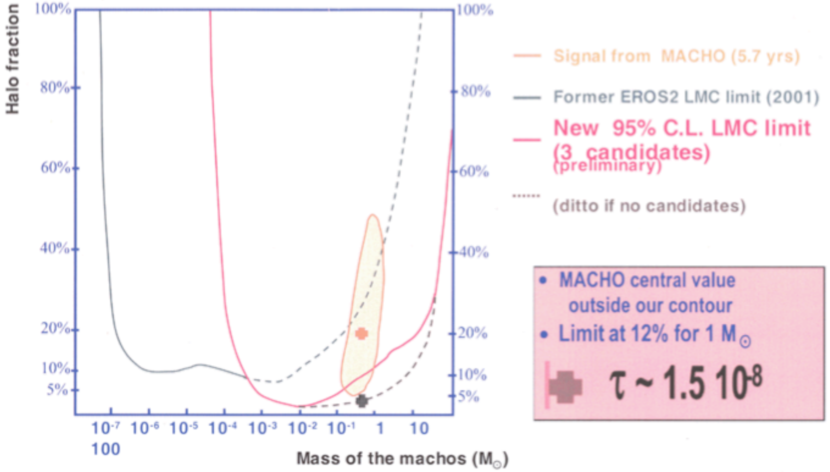


Optical depth

$$\tau = \int_0^s \frac{\pi R_E^2}{M} \rho(l)\, dl \sim 10^{-6}$$

for Galactic targets

Limits on macho content of the halo



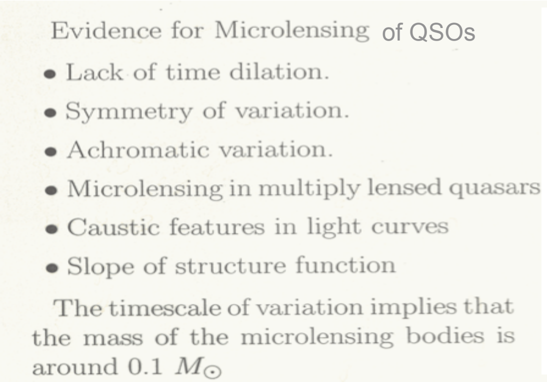
- MACHO central value outside our contour
- Limit at 12% for 1 $M_\odot$

$\tau \sim 1.5\ 10^{8}$

Evidence for dark matter in the form of compact bodies

1993

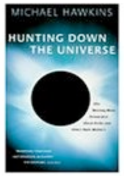
Michael Hawkins
University of Edinburgh



Evidence for Microlensing of QSOs

- 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 $M_\odot$



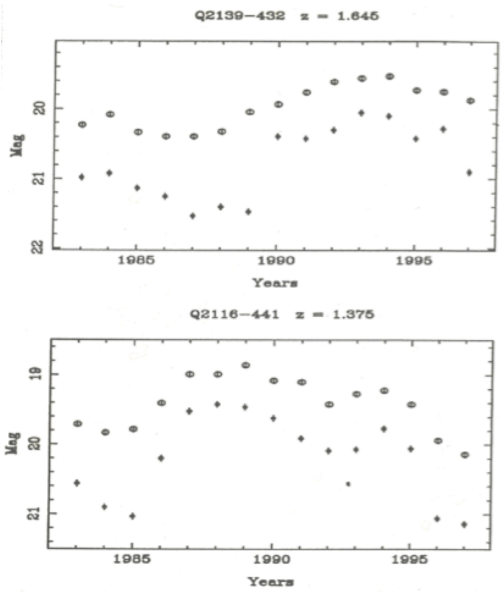
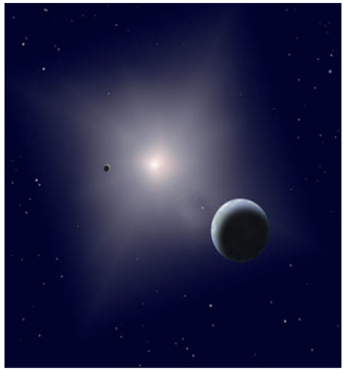


Fig. 3. Light curves for two quasars showing all the characteristics expected of caustic crossing events. Symbols as for Fig. 1.

DETECTION OF 10^{17}G PBHS BY FEMTOLENSING

Femtolensing (10^{-15} arcsec) =>
interferometry pattern in lensed object spectrum (Gould 1992)
Constrains PBHs and axion clusters



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 (2010)

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

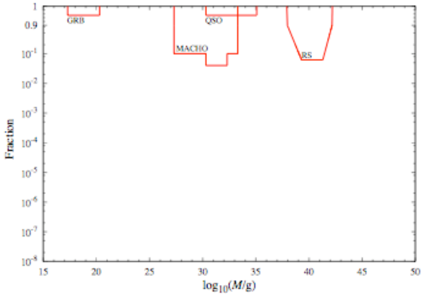
$$f < 1 \text{ for } 10^{-16} M_\odot < M < 10^{-13} M_\odot$$

Microlensing QSOs

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

Millilensing Compact Radio Sources

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



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

RECENT DEVELOPMENTS

PHYSICAL REVIEW D 86, 043001 (2012)

New constraints on primordial black holes abundance from femtolensing of gamma-ray bursts

A. Barnacka,[1,2,*] J.-F. Glicenstein,[2,†] and R. Moderski[1]

Detectable when fringe period between detector energy resolution and energy range

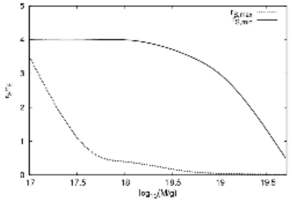
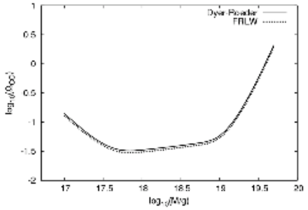


FIG. 5. Minimum and maximum detectable r_S/r_E as a function of lens mass for GRB 090424592.

Fermi data => no femtolensing in GRBs => PBHs excluded as DM for 10^{17}-10^{20}g



PRL 111, 181302 (2013)

New Limits on Primordial Black Hole Dark Matter from an Analysis of Kepler Source Microlensing Data

Kim Griest,[1,*] Agnieszka M. Cieplak,[1,4,†] and Matthew J. Lehner[2,3,‡]

150,000 stars within 1kpc over 2 years

High precision photometry => more sensitive than previous searches for 2×10^{-10}-$2\times10^{-6}M_O$

100 initial candidates but mostly stellar flares
⇒ 17 candidates but probably due to comets
⇒ no ML candidates!

PBHs excluded for 2×10^{-9}-$3\times10^{-8}M_O$
but still allowed for 3×10^{-13}-$2\times10^{-9}M_O$

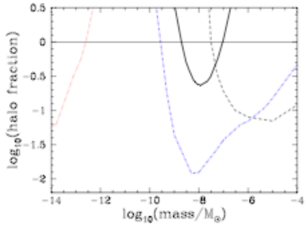


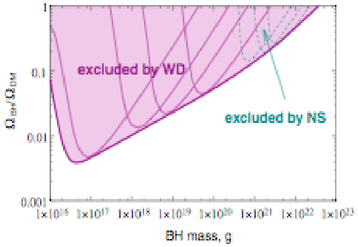
FIG. 2 (color online). Upper limits (95% C.L.) on PBH DM from nonobservation of PBH microlensing in two years of Kepler data. The solid black line is our new limit, the dashed black line is the previous best limit (Ref. [11]), the blue dot-dash line is the theoretical limit from Paper II, and the red dotted line is the femtolensing limit from Ref. [32]. The black horizontal line indicates a halo density of 0.3 GeV cm^{-3}.

PHYSICAL REVIEW D 87, 023507 (2013)

Constraints on primordial black holes as dark matter candidates from star formation

Fabio Capela,[1] Maxim Pshirkov,[2,3,4] and Peter Tinyakov[1]

By considering adiabatic contraction of the dark matter (DM) during star formation, we estimate the amount of DM trapped in stars at their birth. If the DM consists partly of primordial black holes (PBHs), they will be trapped together with the rest of the DM and will be finally inherited by a star compact remnant—a white dwarf (WD) or a neutron star (NS), which they will destroy in a short time. Observations of WDs and NSs thus impose constraints on the abundance of PBH. We show that the best constraints come from WDs and NSs in globular clusters which exclude the DM consisting entirely of PBH in the mass range $10^{16} - 3\times10^{22}$ g, with the strongest constraint on the fraction $\Omega_{\rm PBH}/\Omega_{\rm DM} \lesssim 10^{-2}$ being in the range of PBH masses 10^{17}–10^{18} g.



$$m_{\rm trans} \sim 4\times10^{17}\,{\rm g}\left(\frac{t_*}{10\,{\rm Gyr}}\right)^{-1}\left(\frac{M_*}{M_\odot}\right)^{1/2}\left(\frac{R_*}{R_\odot}\right)^{3/2}$$

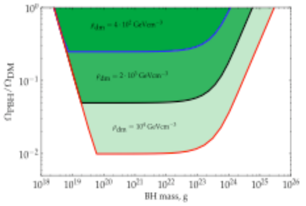
Excludes 10^{16} - 3×10^{22} g

PHYSICAL REVIEW D 87, 123524 (2013)

Constraints on primordial black holes as dark matter candidates from capture by neutron stars

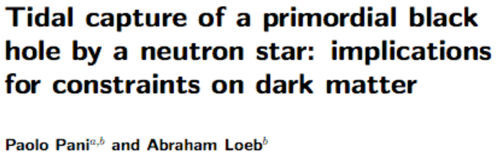
Fabio Capela,[1,*] Maxim Pshirkov,[2,3,4,†] and Peter Tinyakov[1,‡]

We investigate constraints on primordial black holes (PBHs) as dark matter candidates that arise from their capture by neutron stars (NSs). If a PBH is captured by a NS, the star is accreted onto the PBH and gets destroyed in a very short time. Thus, mere observations of NSs put limits on the abundance of PBHs. High DM densities and low velocities are required to constrain the fraction of PBHs in DM. Such conditions may be realized in the cores of globular clusters if the latter are of a primordial origin. Assuming that cores of globular clusters possess the DM densities exceeding several hundred GeV/cm^3 would imply that PBHs are excluded as comprising all of the dark matter in the mass range $3\times10^{18} \lesssim m_{\rm BH} \lesssim 10^{24}$ g. At the DM density of 2×10^3 GeV/cm^3 that has been found in simulations in the corresponding models, less than 5% of the DM may consist of PBH for these PBH masses.



Excludes 3×10^{18} - 10^{24} g => just small window around 10^{25}g for DM

JCAP 06 (2014) 026



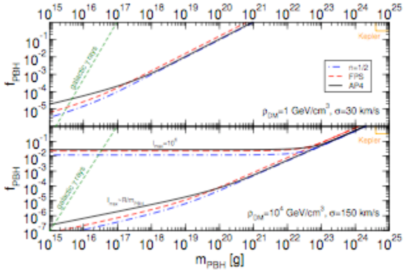
Tidal capture of a primordial black hole by a neutron star: implications for constraints on dark matter

Paolo Pani[a,b] and Abraham Loeb[b]

PBHs tidally captured by NS because deposits energy into nonradial stellar modes => destroys NS by accretion.

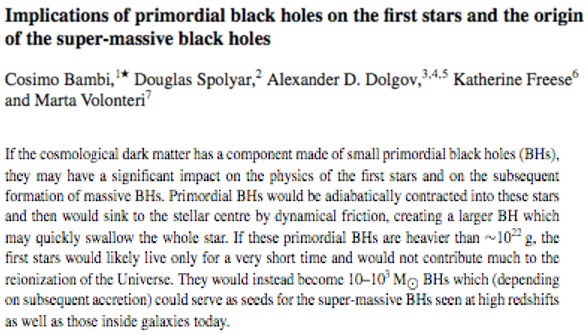
$$m_{\rm PBH} \gtrsim 10^{16}\left(\frac{10^6}{l_{\rm max}}\right)^{1/2}\left(\frac{M}{1.4M_\odot}\right)^{2/3}\left(\frac{R}{12\,{\rm km}}\right)\,{\rm g}$$

Constrains PBHs in range 10^{17}-10^{24}g



Capella et al. (2014) criticize this argument!

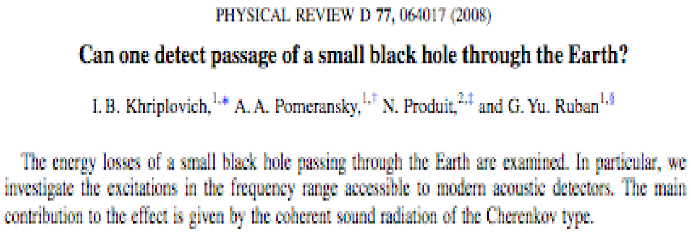
MNRAS 399, 1347 (2009)



Implications of primordial black holes on the first stars and the origin of the super-massive black holes

Cosimo Bambi,[1★] Douglas Spolyar,[2] Alexander D. Dolgov,[3,4,5] Katherine Freese[6] and Marta Volonteri[7]

If the cosmological dark matter has a component made of small primordial black holes (BHs), they may have a significant impact on the physics of the first stars and on the subsequent formation of massive BHs. Primordial BHs would be adiabatically contracted into these stars and then would sink to the stellar centre by dynamical friction, creating a larger BH which may quickly swallow the whole star. If these primordial BHs are heavier than $\sim 10^{22}$ g, the first stars would likely live only for a very short time and would not contribute much to the reionization of the Universe. They would instead become 10–10^3 $M_\odot$ BHs which (depending on subsequent accretion) could serve as seeds for the super-massive BHs seen at high redshifts as well as those inside galaxies today.

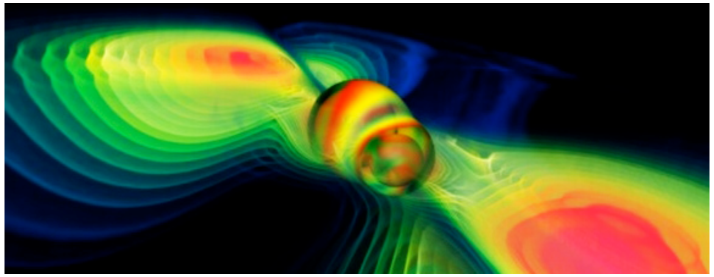


PHYSICAL REVIEW D 77, 064017 (2008)

Can one detect passage of a small black hole through the Earth?

I. B. Khriplovich,[1,*] A. A. Pomeransky,[1,†] N. Produit,[2,‡] and G. Yu. Ruban[1,§]

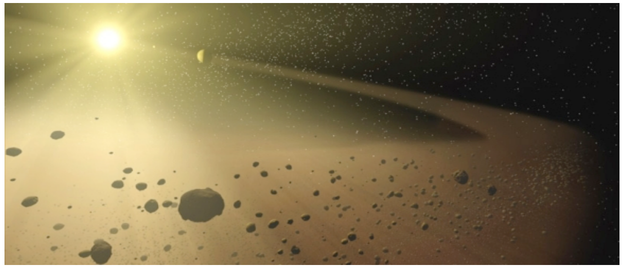
The energy losses of a small black hole passing through the Earth are examined. In particular, we investigate the excitations in the frequency range accessible to modern acoustic detectors. The main contribution to the effect is given by the coherent sound radiation of the Cherenkov type.



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 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

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

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

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

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

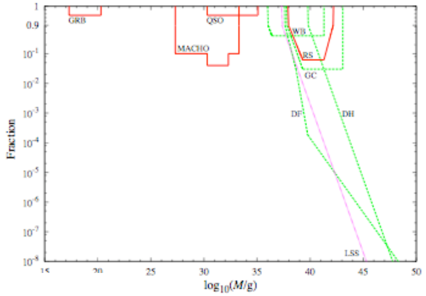
Disk heating

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

Dynamical friction

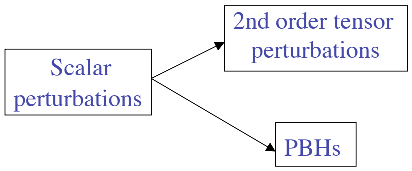
$$f(M) < \begin{cases} (M/2\times10^4 M_\odot)^{-10/7}(r_c/2\mathrm{kpc})^2 & (M < 6\times10^5 M_\odot) \\ (M/4\times10^4 M_\odot)^{-2}(r_c/2\mathrm{kpc})^2 & (6\times10^5 M_\odot < M < 3\times10^6[r_c/2\mathrm{kpc}]^2 M_\odot) \\ (M/0.1M_\odot)^{-1/2} & (M > 3\times10^6[r_c/2\mathrm{kpc}]^2 M_\odot).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

DYNAMICAL LIMITS (2010)



Some of these effects have been claimed as evidence for PBHs

GRAVITY WAVES FROM PBHS



Scalar perturbations

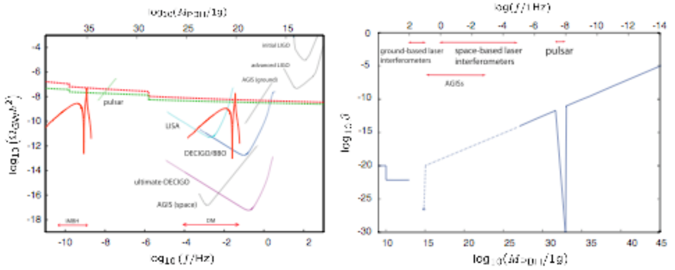
2nd order tensor perturbations

PBHs

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

$$f_{GW} = 4\times10^{-10}\,\mathrm{Hz}\left(\frac{M_{PBH}}{10^{36}\,\mathrm{g}}\right)^{-1/2}$$

Saito & Yokoyama PRL 107, 169901 (2011)



CAN PLANCK MASS RELICS PROVIDE DARK MATTER?

reheat

Natural outcome of inflation if fine-tune T_R

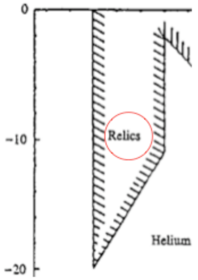
$\Omega_{relic} < 0.25 \Rightarrow \beta(M) < 8\times10^{-28}\kappa^{-1}(M/M_P)^{3/2}$

M_{relic}/M_P

but only applies over limited mass range

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

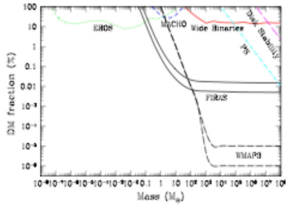
diluted by inf’ PBHs dominate before evap’



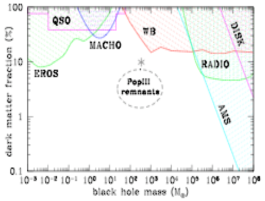
ASTROPHYSICAL CONSTRAINTS ON LARGE PBHS

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

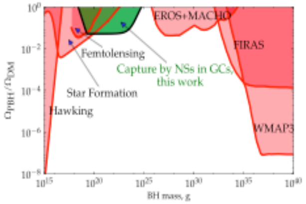
Ricotti et al. (2008)



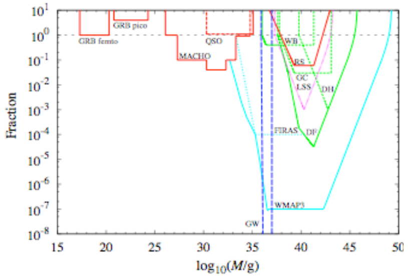
Mack et al. (2008)

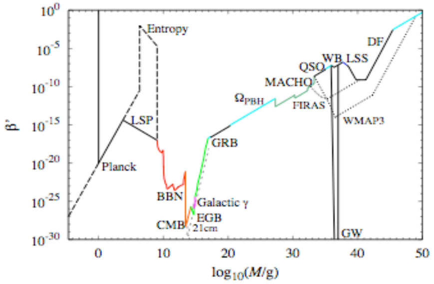


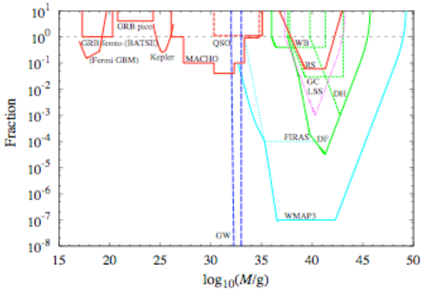
Capela et al. (2013)



Constraints on non-evaporating PBHs (CKSY 2010)



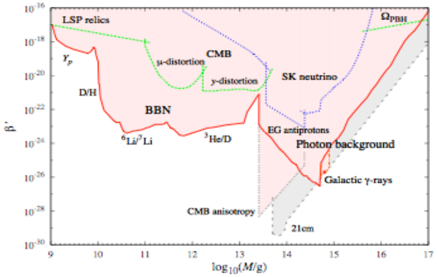




Updated (CKSY 2014)

CONSTRAINTS ON EVAPORATING PBHS

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



HAWKING RADIATION IN MORE DETAIL

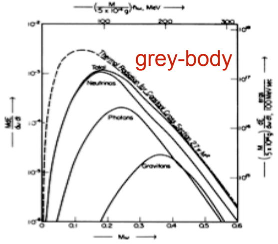
PBH temperature $T_{\rm BH} = \dfrac{1}{8\pi G M} \approx 1.06\, M_{10}^{-1}\,{\rm TeV}$

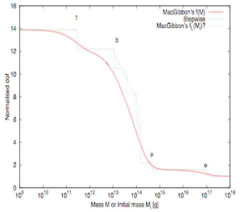
Peak in flux $E_{s=1/2} = 4.02 T_{bh},\ E_{s=1} = 5.77 T_{bh},\ E_{s=0} \approx 2.81 T_{bh}.$

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

effective no.species emitted (1 for massless)

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





Quark and gluon jet emission

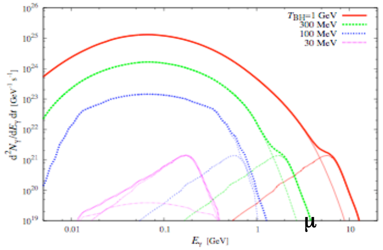
$T_{BH} > \Lambda_{QCD}$ = 250-300 MeV => big f increase

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

TeV BHs

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

CSKY



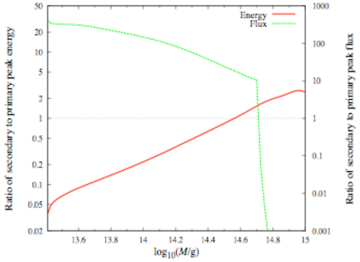
PYTHIA CODE

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

fraction of jet energy going into pions

1.6 x 10^{-3}

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



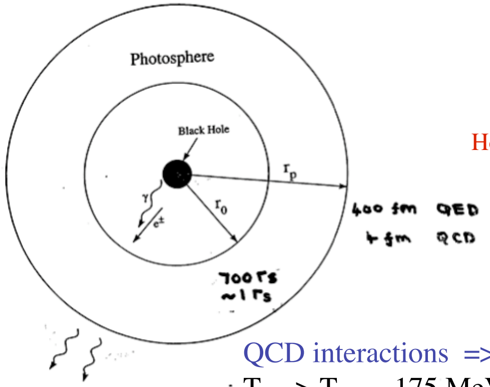
Secondary emission below $M_q = 0.4M_*$

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

so time-integrated emission drops off rapidly above M_*

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



Heckler (1997, 1998)

QCD interactions => quark-gluon photosphere
$T_{BH} > T_{crit} \sim 175$ MeV => $M_{BH} < 5 \times 10^{14}$g

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

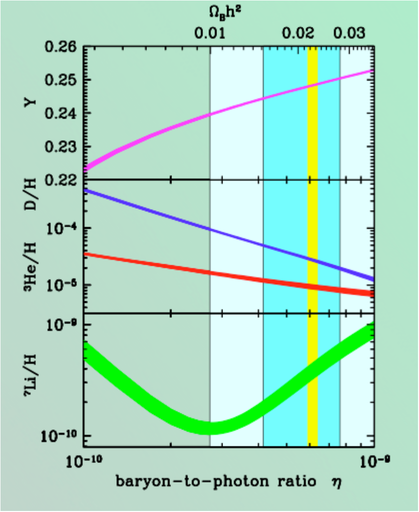
PBH CONSTRAINTS FROM BIG BANG NUCLEOSYNTHESIS

BBNS =>

$\Omega_{\rm baryon} = 0.04$

⇒ non-baryonic dark matter

PBHs evaporating at 10^3s could mar this



PREVIOUS BIG BANG NUCLEOSYNTHESIS CONSTRAINTS

Injection of neutrinos (Vainer & Naselskii 1978)

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

Injection of photons (Miyama & Sato 1978)

$$\beta'(M) < 10^{-15}\, M_{10}^{-5/2} \quad (M = 10^9\text{–}10^{13}\,{\rm g})\,.$$

Injection of nucleons (Zeldovich 1977)

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

Injection of deuterons (Lindley 1980)

$$\beta'(M) < 3 \times 10^{-20}\, M_{10}^{1/2} \quad (M > 10^{10}\,{\rm g})$$

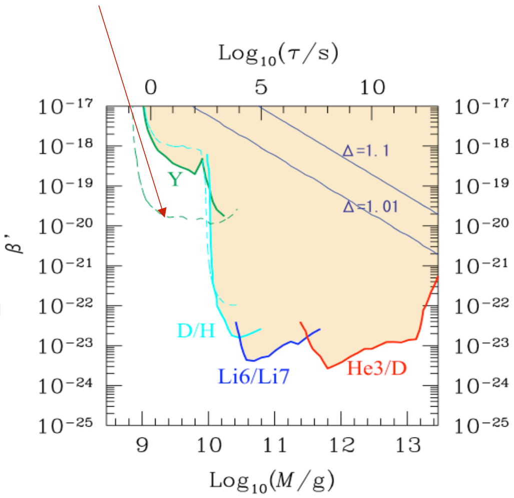
$\tau < 10^{-2}$s => $M<10^9$g
=> no trace

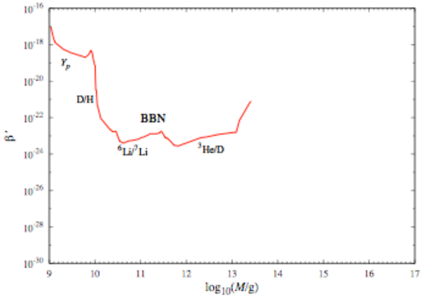
$\tau = 10^{-2}$-10^2s => $M=10^9$-10^{10}g
⇒ emitted mesons
increase $(n/p)_F$ and Y

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

$\tau = 10^7$-10^{12} s => $M=10^{12}$-10^{13}g
⇒ photoionizations
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

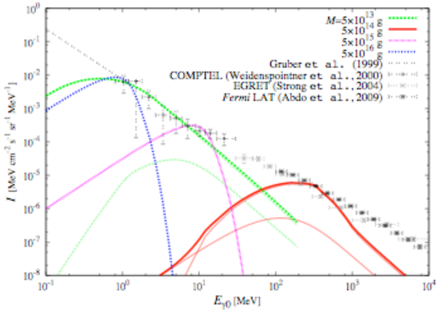
Page & Hawking (1976) => $\Omega_{PBH}(M_*) < 10^{-8}$ (Fichtel et al)

Carr & MacGibbon (1998) => $\Omega_{PBH}(M_*) < 7.6 \times 10^{-9}$ (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)



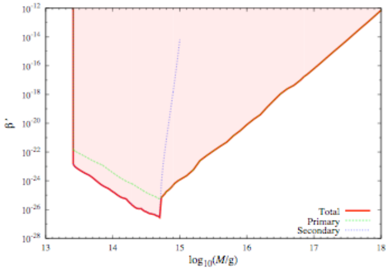
Diffuse γ-ray background

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

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

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

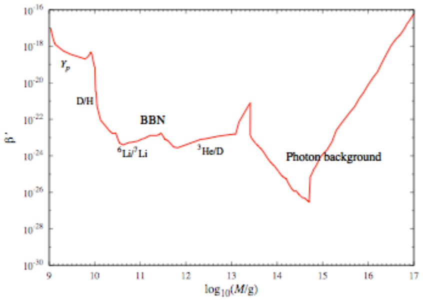
$$I \equiv \frac{c}{4\pi} n_{\gamma 0} \qquad I^{\mathrm{obs}} \propto E_{\gamma 0}^{-(1+\epsilon)} \qquad \epsilon \approx 0.2\text{–}0.3$$



Constraints on β(M)

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

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



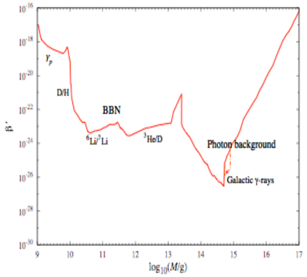
GALACTIC γ-BACKGROUND

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

Galactic γ-background (Wright 1996)
=> explosion rate $dn/dt < 0.07 - 0.42\ pc^{-3}y^{-1}$

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 $\beta(M_*) < 2 \times 10^{-26}$

CKSY analysis of Galactic γ-background
$M_i = M_*(1+\mu) \Rightarrow M(t_o) = (30\mu)^{1/3} M_*$
⇒ $E_{peak} = 100\ (30\mu)^{-1/3}$
⇒ limit on $\beta(M)$ strongest at $1.08 M_*$
and scales as $\mu^{1/3}$



CKSY (2014) updates this

ANTIPROTONS MacGibbon & Carr (1991)

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

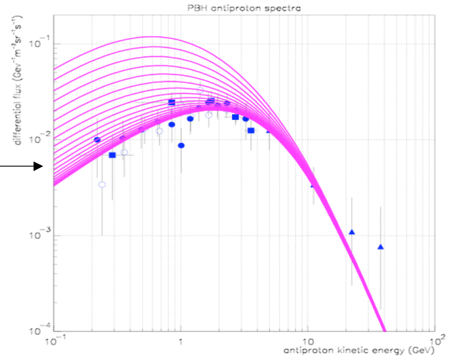
Small excess at low energy => possible primary contribution

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)

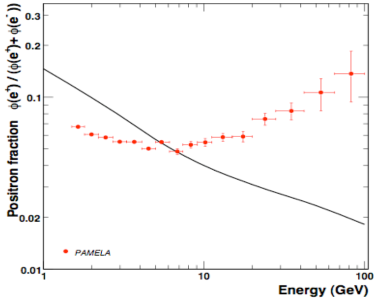
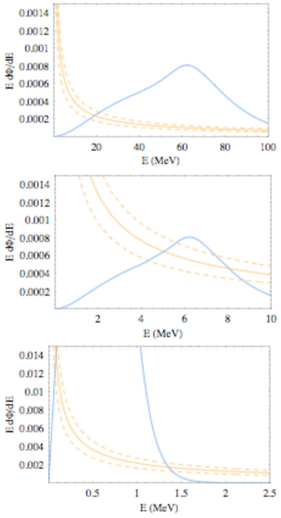


FIG. 4: **PAMELA positron fraction with theoretical models.** The PAMELA positron fraction compared with theoretical model. The solid line shows a calculation by Moskalenko & Strong[39] for pure secondary production of positrons during the propagation of cosmic-rays in the galaxy. One standard deviation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

More likely from WIMP annihilations in UCMHs than PBHs

Adriani et al (2008)

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

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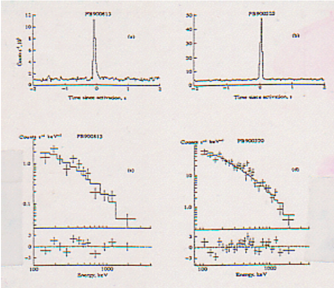
CAN PBH EXPLOSIONS GENERATE g-RAY BURSTS?

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

OTHER CONSTRAINTS ON EVAPORATING PBHS

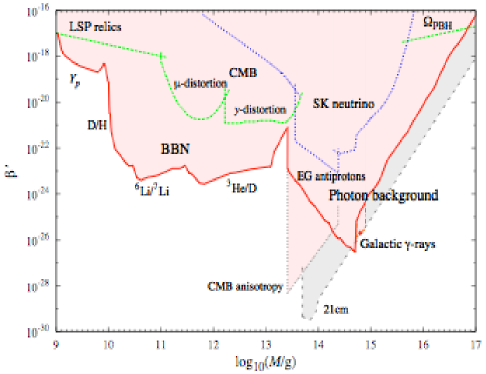
Extragalactic cosmic rays

Neutrino relics

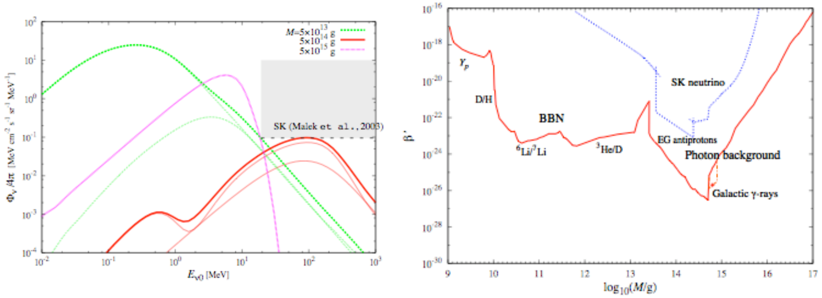
LSP relics

CMB distortions

CMB anisotropy



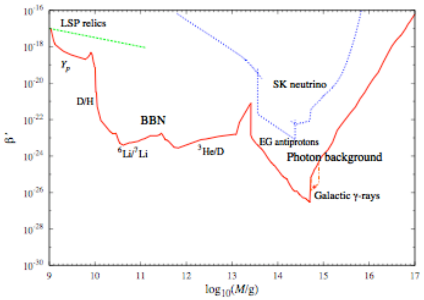
NEUTRINO BACKGROUND LIMIT



(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

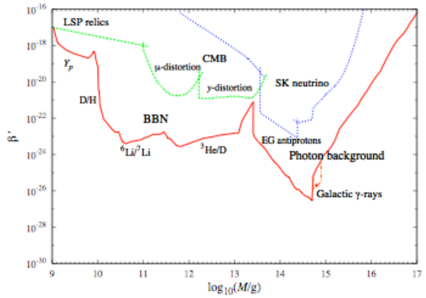
Thermalization for t <10 s => photon-to-baryon increase for M > 10^9g
=> $\beta'(M) < 10^9 (M/M_{Pl})^{-1} \approx 10^{-5}(M/10^9\,\mathrm{g})^{-1} \quad (M < 10^9\,\mathrm{g})$ (Zeldovich &Starobinsky 1977)

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 β(M) < 10^{-21}
in mass range 10^{11}-10^{13}g

(Tashiro & Sugiyama 2008)



DAMPING OF SMALL-SCALE CMB ANISOTROPIES

CKSY

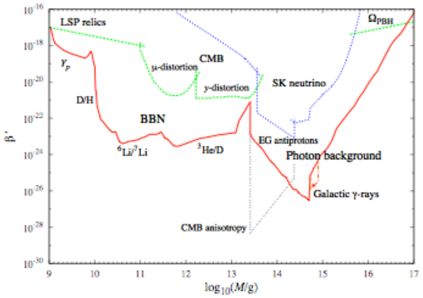
Similar effect to that of decaying particles (Zhang et al 2007)

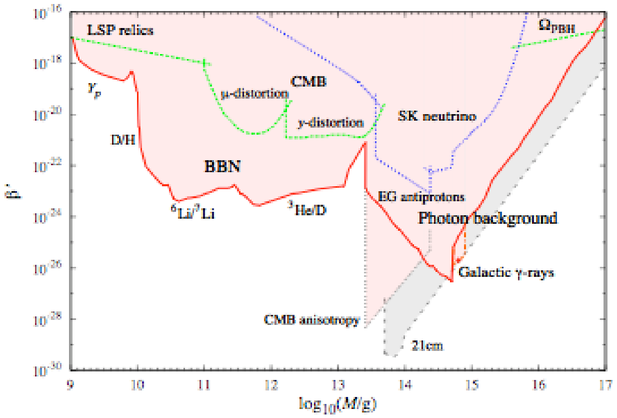
$\log_{10}\zeta < -10.8 - 0.50x + 0.085x^2 + 0.0045x^3, \quad x \equiv \log_{10}(\Gamma/10^{-13}\,\mathrm{s}^{-1})$

decay rate

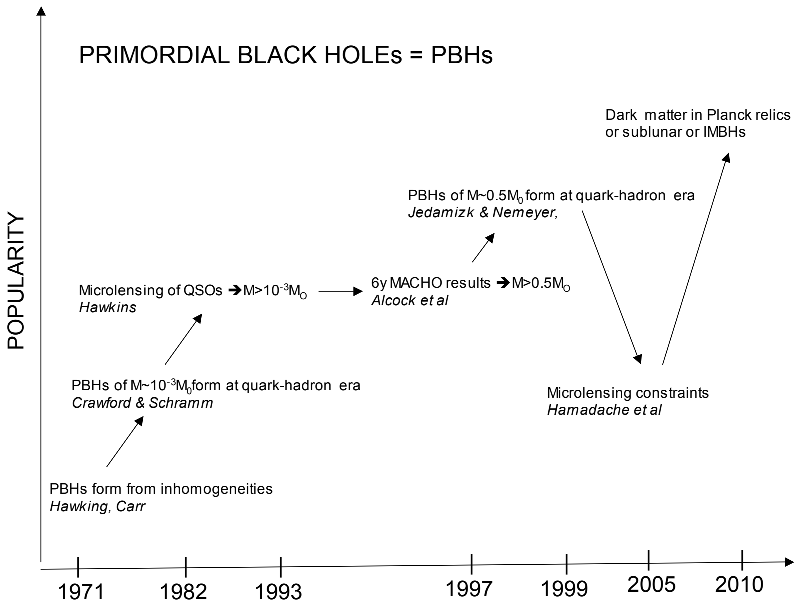
CDM fraction
in PBHs

=> $\beta'(M) < 3\times10^{-30}(f_H/0.1)^{-1}(M/10^{13}\mathrm{g})^{3.1} \quad (2.5\times10^{13}\mathrm{g} \lesssim M \lesssim 2.4\times10^{14}\mathrm{g})$





PRIMORDIAL BLACK HOLEs = PBHs



PBHs form from inhomogeneities
Hawking, Carr

PBHs of $M{\sim}10^{-3}M_0$ form at quark-hadron era
Crawford & Schramm

Microlensing of QSOs ➔ $M>10^{-3}M_O$
Hawkins

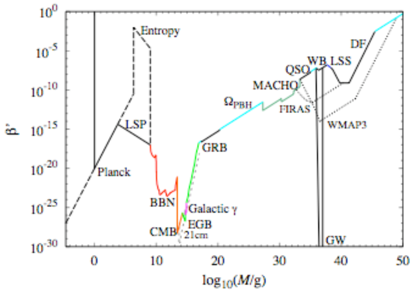
6y MACHO results ➔ $M>0.5M_O$
Alcock et al

PBHs of $M{\sim}0.5M_0$ form at quark-hadron era
Jedamizk & Nemeyer,

Microlensing constraints
Hamadache et al

Dark matter in Planck relics
or sublunar or IMBHs

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.