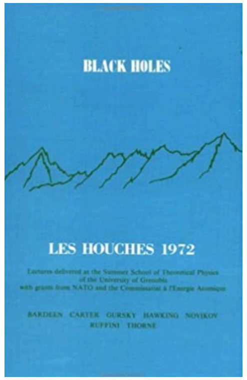
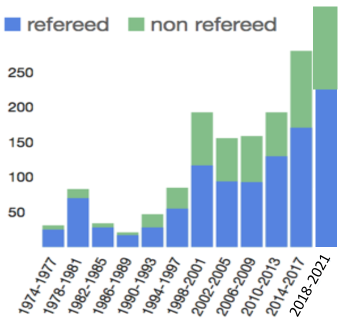
PRIMORDIAL BLACK HOLES
AS DARK MATTER CANDIDATES

Bernard Carr and Florian Kühnel

My first conference!

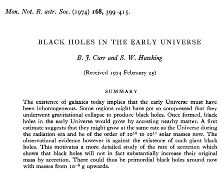


PUBLICATION RATE OF PBH PAPERS



Impossible to keep up with literature!

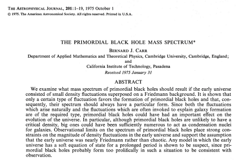
MY MOST CITED PAPERS!



BLACK HOLES IN THE EARLY UNIVERSE

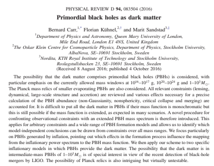
B. J. Carr and S. W. Hawking

SUMMARY

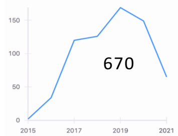


THE PRIMORDIAL BLACK HOLE MASS SPECTRUM

ABSTRACT



Primordial black holes as dark matter



Career all downhill from the start......

......with a resurgence at the end!

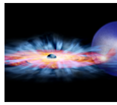
PLAN OF LECTURES

L1
- Overview of black holes
- Historical Introduction
- PBHs as link between macro and microphysics
- Formation of PBHs
- Constraints on PBHs

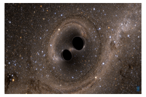
L2
- Constraints on PBHs (continued)
- PBHs as dark matter
- Natural scenario for PBHs as a solution to cosmic conundra
- PBH versus particle dark matter
- Final points

OVERVIEW AND HISTORICAL INTRODUCTION

OVERWHELMING EVIDENCE FOR STELLAR BHS ($M \sim 10^{1-2} M_{O}$)

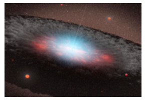


X-ray binaries Cygnus X1

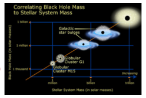


LIGO detects gravity waves from coalescing BHs

OVERWHELMING EVIDENCE FOR SMBH IN AGN ($M \sim 10^{6-11} M_{O}$)

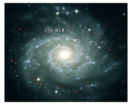


MW $4 \times 10^6 M_O$
QSO $10^8 M_O$
TON $7 \times 10^{10} M_O$

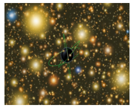


BH mass proportional to stellar mass

POSSIBLE EVIDENCE FOR IMBH ($M \sim 10^{3-5} M_{O}$)

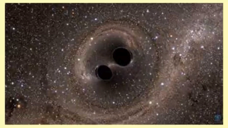


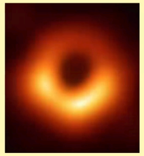
Ultralum' X-ray source NGC1313 has $500 M_O$ BH



Globular cluster Omega Cen has $4 \times 10^4 M_O$ BH

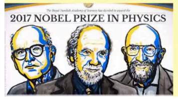
Black Holes Become Famous!

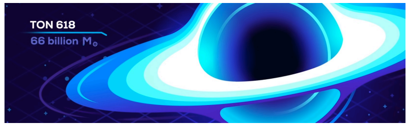




M87 image
Gamma Ray Bursts
300 EeV cosmic rays?
300 TeV γ-rays?
3 PeV neutrinos?

Penrose Symposium





(Blandford)

PRIMORDIAL BLACK HOLE FORMATION

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

Small BHs can only form in early Universe

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

⇨ **primordial BHs have horizon mass at formation**

$M_{PBH} \sim c^3t/G =$
- 10^{-5}g at 10^{-43}s (Planck minimum)
- 10^{15}g at 10^{-23}s (evaporating now)
- $1M_O$ at 10^{-5}s (QCD transition)
- 10^5M_O at 1s (maximum?)

Mon. Not. R. astr. Soc. (1971) **152**, 75–78.

GRAVITATIONALLY COLLAPSED OBJECTS OF VERY LOW MASS

Stephen Hawking

(Communicated by M. J. Rees)

(Received 1970 November 9)

SUMMARY

It is suggested that there may be a large number of gravitationally collapsed objects of mass 10^{-5} g upwards which were formed as a result of fluctuations in the early Universe. They could carry an electric charge of up to ±30 electron units. Such objects would produce distinctive tracks in bubble chambers and could form atoms with orbiting electrons or protons. A mass of 10^{17} g of such objects could have accumulated at the centre of a star like the Sun. If such a star later became a neutron star there would be a steady accretion of matter by a central collapsed object which could eventually swallow up the whole star in about ten million years.

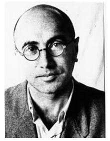
SOVIET ASTRONOMY – AJ VOL. 10, NO. 4 JANUARY-FEBRUARY, 1967

THE HYPOTHESIS OF CORES RETARDED DURING EXPANSION AND THE HOT COSMOLOGICAL MODEL

Ya. B. Zel'dovich and I. D. Novikov

Translated from Astronomicheskii Zhurnal, Vol. 43, No. 4, pp. 758–760, July–August, 1966
Original article submitted March 14, 1966

The existence of bodies with dimensions less than $R_g = 2GM/c^2$ at the early stages of expansion of the cosmological model leads to a strong accretion of radiation by these bodies. If further calculations confirm that accretion is catastrophically high, the hypothesis on cores retarded during expansion [3, 4] will conflict with observational data.



Newtonian argument for PBH accretion

- The Bondi accretion (spherically symmetric, quasi-stationary flow)

$$\frac{dM}{dt} = 4\pi\alpha R_A^2 v_s \rho_\infty,$$

where

$$R_A = GM/v_s^2, \quad \alpha = \text{const} = O(1), \quad v_s = \text{sound speed} = k^{1/2}$$

- Zeldovich & Novikov (1967) used the Friedmann density.

$$\rho_\infty = \frac{1}{6\pi G(1+k)^2 t^2}, \qquad p = k\rho$$

$$\frac{dM}{dt} = \frac{M^2}{\beta t^2}, \quad \beta = \frac{3k^{3/2}(1+k)^2}{2\alpha}\frac{c^3}{G}.$$

- M is integrated to (horizon mass ← βt)

$$M = \frac{\beta t}{1 + \frac{t}{t_f}\left(\frac{\beta t_f}{M_f} - 1\right)}, \sim \begin{cases} M_f & (M_f \ll \beta t_f) \\ \beta t & (M_f \sim \beta t_f) \end{cases}$$

Subhorizon PBH grows little but horizon-mass PBH grows like horizon.

But this neglects cosmological expansion.

Mon. Not. R. astr. Soc. (1974) **168,** 399–415.

BLACK HOLES IN THE EARLY UNIVERSE

B. J. Carr and S. W. Hawking

(Received 1974 February 25)

SUMMARY

The existence of galaxies today implies that the early Universe must have been inhomogeneous. Some regions might have got so compressed that they underwent gravitational collapse to produce black holes. Once formed, black holes in the early Universe would grow by accreting nearby matter. A first estimate suggests that they might grow at the same rate as the Universe during the radiation era and be of the order of 10^{15} to 10^{17} solar masses now. The observational evidence however is against the existence of such giant black holes. This motivates a more detailed study of the rate of accretion which shows ~~that black holes will not in fact substantially increase their original~~ mass by accretion. There could thus be primordial black holes around now with masses from 10^{-5} g upwards.

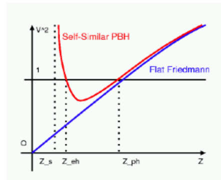
$\Rightarrow$ no observational evidence against them!

SPHERICALLY SYMMETRIC SELF-SIMILAR SOLUTIONS

Metric $ds^2 = -e^{2\Phi(z)}dt^2 + e^{2\psi(z)}dr^2 + r^2S^2(z)d\Omega^2$ Perfect fluid $p=k\rho$
Dimensionless quantities depend only on $z=r/t$

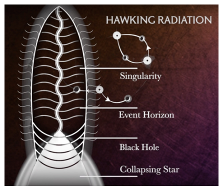
Speed of fluid relative to const z surface $V = |z|\, e^{\psi-\phi}$
$V = 1$ at event or particle horizon
$V = k^{1/2}$ at sonic point (discontinuity)

Carr & Hawking (1974): there is no SSSS solution with black hole interior attached to *exact* Friedmann exterior via sound-wave but 1-parameter family of such solutions if *asymptotically* Friedmann (k=1/3).



=> PBHs formed by *local* processes cannot grow much at all

letters to nature
Nature **248**, 30 - 31 (01 March 1974); doi:10.1038/248030a0



Black hole explosions?

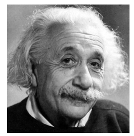
S. W. HAWKING

Department of Applied Mathematics and Theoretical Physics and Institute of Astronomy University of Cambridge

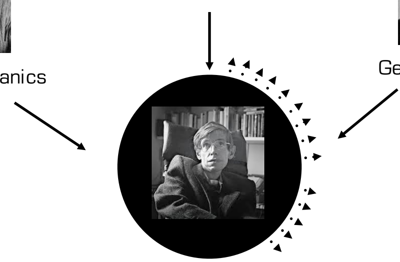
QUANTUM gravitational effects are usually ignored in calculations of the formation and evolution of black holes. The justification for this is that the radius of curvature of space-time outside the event horizon is very large compared to the Planck length $(G\hbar/c^3)^{1/2} \approx 10^{-33}$ cm, the length scale on which quantum fluctuations of the metric are expected to be of order unity. This means that the energy density of particles created by the gravitational field is small compared to the space-time curvature. Even though quantum effects may be small locally, they may still, however, add up to produce a significant effect over the lifetime of the Universe $\approx 10^{17}$ s which is very long compared to the Planck time $\approx 10^{-43}$ s. The purpose of this letter is to show that this indeed may be the case: it seems that any black hole will create and emit particles such as neutrinos or photons at just the rate that one would expect if the black hole was a body with a temperature of $(\varkappa/2\pi)(\hbar/2k) \approx 10^{-6}(M_\odot/M)K$ where $\varkappa$ is the surface gravity of the black hole[1]. As a black hole emits this thermal radiation one would expect it to lose mass. This in turn would increase the surface gravity and so increase the rate of emission. The black hole would therefore have a finite life of the order of $10^{71}(M_\odot/M)^{-3}$ s. For a black hole of solar mass this is much longer than the age of the Universe. There might, however, be much smaller black holes which were formed by fluctuations in the early Universe[2]. Any such black hole of mass less than 10^{15} g would have evaporated by now. Near the end of its life the rate of emission would be very high and about 10^{30} erg would be released in the last 0.1 s. This is a fairly small explosion by astronomical standards but it is equivalent to about 1 million 1 Mton hydrogen bombs.

Thermodynamics

Quantum Mechanics



General Relativity



$$T_{BH}[\mathrm{K}] = 10^{-7}\,\frac{M_\odot}{M}$$

PBHs are important even if they never formed!

PBH EVAPORATION

Black holes radiate thermally with temperature

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

=> 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)

This can only be important for PBHs

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

=> explosions undetectable in standard particle physics model

Are some short γ-ray bursts PBH explosions (D.Cline et al.)

$T > T_{CMB}$=3K for M < 10^{26}g => "quantum" black holes

PBHS PROBE HUGE RANGE OF SCALES

$M \sim 10^{-5}$g	Quantum Gravity	Planck relics, Extra dimensions and higher-dimensional black holes, ...
$M \lesssim 10^{15}$g	Early Universe	Nucleosynthesis, Reionisation, ...
$M \sim 10^{15}$g	High-Energy Physics	Cosmological and galactic gamma-rays
$M \gtrsim 10^{15}$g	Gravity	Critical phenomena, Cold dark matter, Dynamical effects, Lensing effects, Gravitational waves, Black holes in galactic nuclei, ...

PBHS AS DARK MATTER

PRIMORDIAL BLACK HOLES AS DARK MATTER

PRO

* Black holes exist
* No new physics needed
* LIGO results

CON

* Requires fine-tuning

PBH can do it!

Cosmological effects of primordial black holes

GEORGE F. CHAPLINE

Nature **253**, 251–252 (24 January 1975)
doi:10.1038/253251a0
Download Citation
Received: 29 July 1974
Revised: 03 October 1974
Published online: 24 January 1975

Abstract

ALTHOUGH only black holes with masses $\gtrsim$; $1.5M_\odot$ are expected to result from stellar evolution[1] black holes with much smaller masses may be present throughout the Universe[2]. These small black holes are the result of density fluctuations in the very early Universe. Density fluctuations on very large mass scales were certainly present in the early universe as is evident from the irregular distribution of galaxies in the sky[3]. Evidence of density fluctuations on scales smaller than the size of galaxies is generally thought to have been destroyed during the era of radiation recombination[4]. But fluctuations in the metric of order unity may be fossilised in the form of black holes. Observation of black holes, particularly those with masses $M < M_\odot$, could thus provide information concerning conditions in the very early Universe.

First paper on PBHs as dark matter

Astron. & Astrophys. 38, 5 – 13 (1975)

Primeval Black Holes and Galaxy Formation

P. Mészáros
Institute of Astronomy, University of Cambridge

Received September 4, revised October 14, 1974

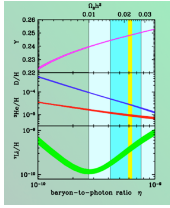
Summary. We present a scheme of galaxy formation, based on the hypothesis that a certain fraction of the mass of the early universe is in the form of black holes. It is argued that the black hole mass should be $\sim 1\, M_\odot$, and it is shown that random statistical fluctuations in their number cause density fluctuations which grow in time. The advantage over the usual baryon fluctuations are twofold: $\delta N/N$ is much larger for black holes than for baryons, and the black holes are not electromagnetically coupled to the radiation field, as the baryons are. One is thus able to achieve galaxy and cluster formation at the right redshifts, and at the same time the black holes would account for the recently proposed massive halos of galaxies, and for the hidden mass in clusters required by virial theorem arguments. The number of free parameters in this theory is less than, or at most equal to, that in the current "primeval fluctuations" theory, while the physical picture that is achieved seems more satisfactory, from a self-consistency point of view.

Key words: galaxy formation — primeval black holes — hidden mass — cosmology

PBHs relevant to galaxy formation if dark matter

BLACK HOLES COULD BE DARK MATTER ONLY IF PRIMORDIAL

BBNS $\Rightarrow$ $\Omega_{baryon} = 0.05$

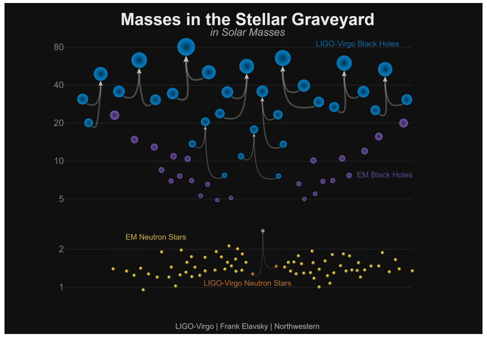


$\Omega_{vis} = 0.01$, $\Omega_{dm} = 0.25$ $\Rightarrow$ need baryonic and non-baryonic DM

MACHOs WIMPs

PBHs are non-baryonic with features of both WIMPs and MACHOs

PBHS AND LIGO/Virgo



Do we need Population III or PBHs?

Fraction of Universe collapsing

$\beta(M)$ fraction of density in PBHs of mass M at formation

General limit

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

So collapse fraction must be tiny

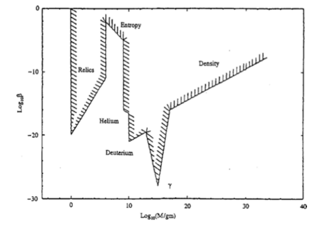
Fraction of dark matter $f_{DM} \sim (\beta / 10^{-9})\,(M/M_o)^{-1/2}$

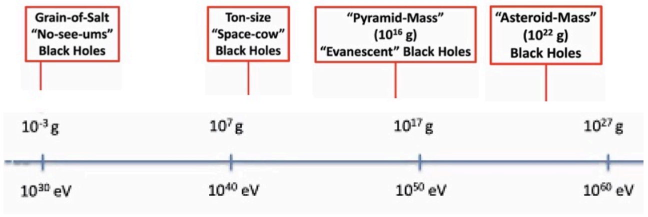
Fine-tuning problem!

Limit on fraction of Universe collapsing

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





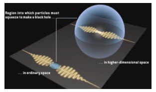
(Profumo)

BLACK HOLES AS A PROBE OF HIGHER DIMENSIONS

M-theory => n extra compactified dimensions

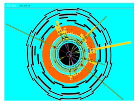
D-dim' Planck

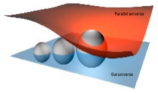
Standard model => $V_n \sim M_P^{-n}$, $M_D \sim M_P$,
Large extra dimensions => $V_n >> M_P^{-n}$, $M_D << M_P$



TeV quantum gravity?

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



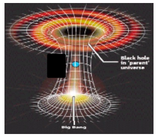


LHC?

IS THE UNIVERSE A PRIMORDIAL BLACK HOLE?

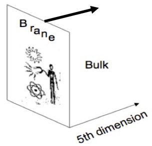
Collapse to black hole generates a baby Universe

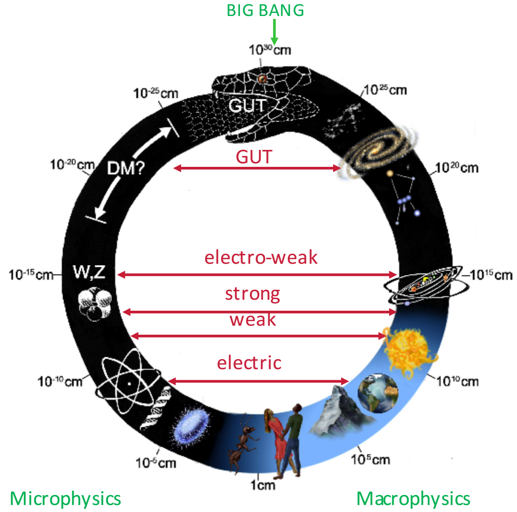
Smolin (1997)



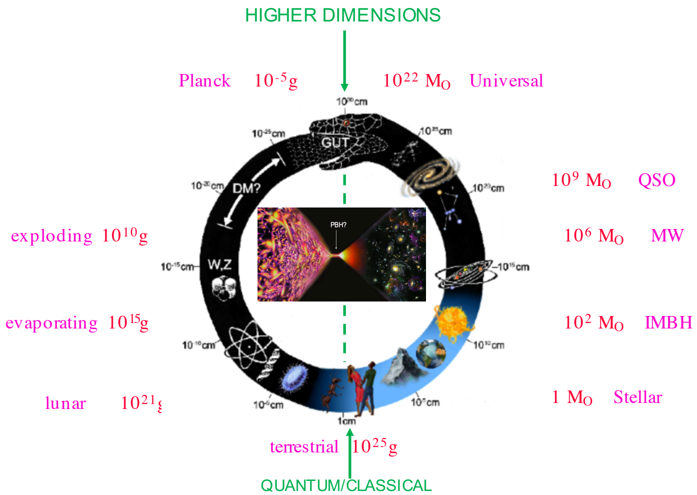
Brane cosmology => 5D Schwarzschild de Sitter model
=> Universe emerges out of 5D black hole

Bowcock et al. (2000), Mukhoyama et al. (2000)

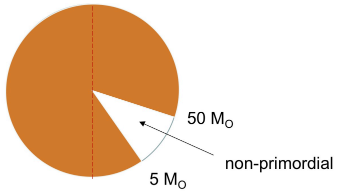




BLACK HOLES AS LINK BETWEEN MICRO AND MACRO PHYSICS



ARE MOST BLACK HOLES PRIMORDIAL?

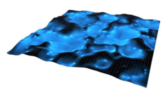


God would be cruel not to populate whole Uroborus!

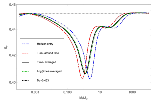
FORMATION

Formation Mechnisms of Primordial Black Holes

- ★ Large density perturbations (inflation)

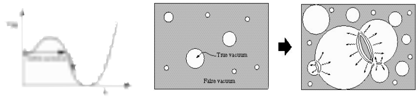


- ★ Pressure reduction

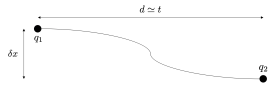


- ★ Cosmic string loops

- ★ Bubble collisions



- ★ Quark confinement



[Dvali, FK, Zantedeschi 2021]

PBH Formation from Large Inhomgeneities

- ★ To collapse against pressure, need [BC 1975]

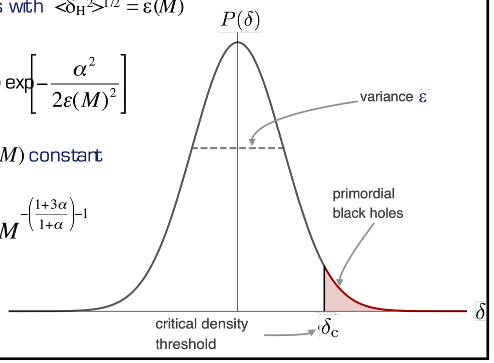
$R > \sqrt{\alpha}\, ct$ when $\delta \sim 1$ => $\delta_H > \alpha$ $(p = \alpha\rho c^2)$

- ★ Gaußian fluctuations with $<\delta_H^2>^{1/2} = \varepsilon(M)$

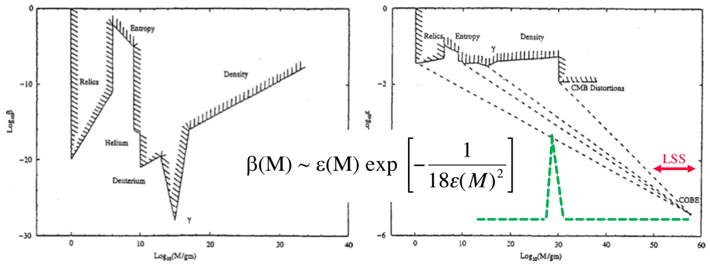
=> $\beta(M) \sim \varepsilon(M) \exp\left[-\dfrac{\alpha^2}{2\varepsilon(M)^2}\right]$

- ★ $\varepsilon(M)$ constant => $\beta(M)$ constant

=> $dN/dM \propto M^{-\left(\frac{1+3\alpha}{1+\alpha}\right)-1}$



PBHs as a Unique Probe Small Scales

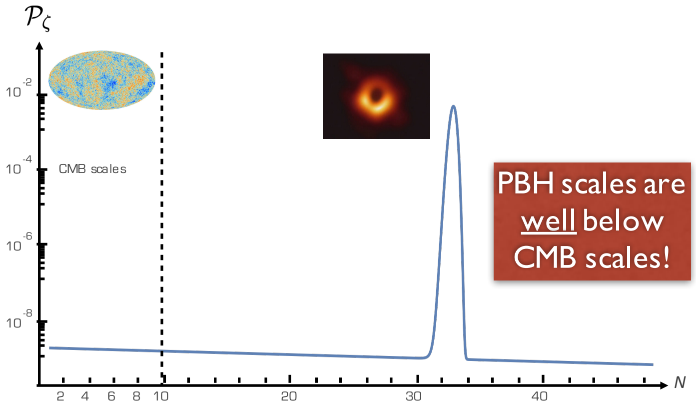


$\beta(M) \sim \varepsilon(M) \exp\left[-\dfrac{1}{18\varepsilon(M)^2}\right]$

[BC, Gilbert, Lidsey 1994]

- ★ PBHs are a unique probe of ε on small scales.
- ★ Need either blue spectrum or spectral feature to produce them.

Scales of PBH Formation



PBH scales are <u>well</u> below CMB scales!

More Precise Analysis of PBH Formation

- Analytic calculations imply need $\delta > 0.3$ for $\alpha = 1/3$ [BC 1975]
- Confirmed by first numerical studies [Nadezhin *et al.* 1978]
  - → but pressure gradient => PBHs smaller than horizon
- Critical phenomena => $\delta > 0.7$ [Niemeyer & Jedamzik 1999], [Shibata & Sasaki 1999]
  - → spectrum peaks at horizon mass with extended low mass tail [Yokoyama 1999], [Green 2000]
- Later calculations => $\delta > 0.45$ [Musco *et al.* 2008], [Musco & Miller 2013]
- Confirmed by latest work, incorporation of different shapes and statistics [Musco *et al.* 2020]

PBHs from Near-Critical Collapse

- Usually: Assume

$$M_{BH} \propto M_H$$

horizon mass

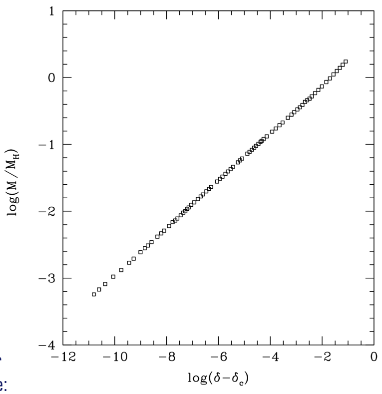
- Critical Scaling [Choptuik '93]

$$M_{BH} = k\, M_H (\delta - \delta_c)^\gamma$$

density contrast

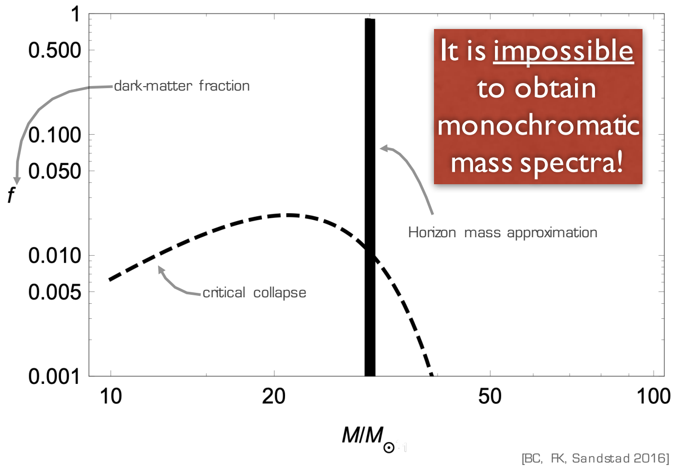
- Radiation domination and for spherical Mexican-hat profile:

$$k \approx 3.3\,, \quad \delta_c \approx 0.45\,, \quad \gamma \approx 0.36$$



[Musco, Miller, Polnarev 2008]

How would this look for monochromatic mass function?



It is <u>impossible</u> to obtain monochromatic mass spectra!

[BC, FK, Sandstad 2016]

PBHs and Inflation

★ PBHs formed before reheating are inflated away.

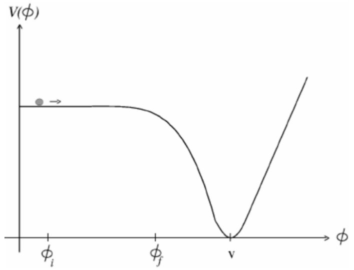
$$\Rightarrow M > M_{\min} = \left(\frac{T_{\rm reheat}}{T_{\rm Pl}}\right)^{-2} M_{\rm Pl} > 1\,{\rm g},$$

since $T_{\rm reheat} < 10^{16}\,{\rm GeV}$ from CMB quadrupole.

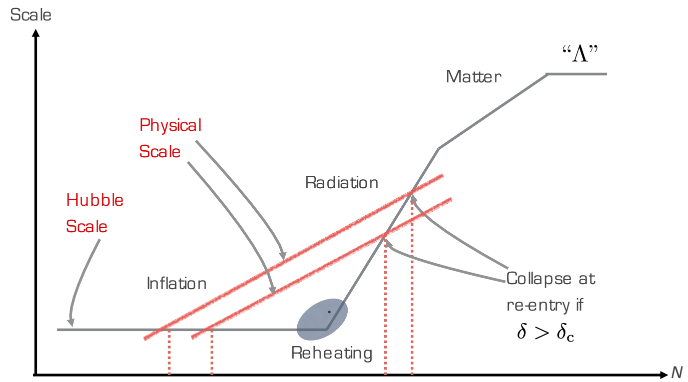
★ Fluctuations from inflation

$$\frac{\delta\rho}{\rho} \sim \frac{V^{3/2}}{M_{\rm Pl}\,V'}\Bigg|_{\rm H}$$

→ Can these generate PBHs?



Scales of PBH Formation



PBHs and Inflation

★ Slow-roll plus friction-domination [BC & Lidsey 1993]

$$\xi = (M_{Pl}V'/V)^2 << 1, \quad \eta = M_{Pl}V''/V << 1$$

=> nearly scale-invariant fluctuations

$|\delta_k^2| \sim k^n$, $\delta_H \sim M^{(1-n)/4}$ with $n = 1 - 3\xi + 2\eta \sim 1$

★ CMB => $\delta_H \sim 10^{-5}$ => need $n > 1$ for PBHs

★ Observe $n < 1$ on horizon scale ⇒ need running index for PBHs.

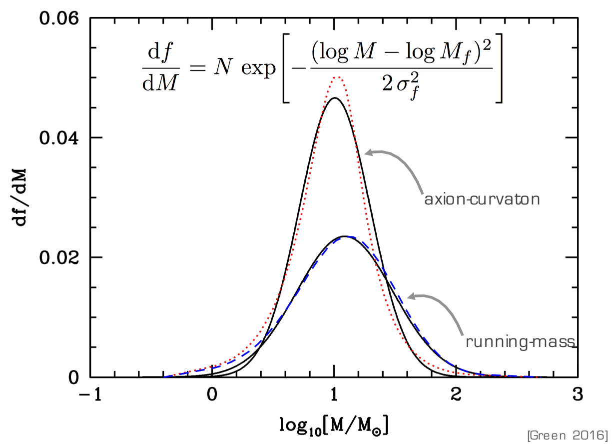
→ Planck gives $\frac{d\ln n}{dk} \approx -0.02 \pm 0.01$ (wrong sign!)

★ Need $n > 1$ at large k or some feature in $V(\phi)$ at some k.

★ E.g. flattening of $V(\phi)$ ⇒ PBH production on particular scale [Ivanov *et al.* 1994]

★ Numerous other inflation scenarios: hybrid, multifield, running index, designer, preheating, axion-curvaton...

Generic Mass Functions – The Lognormal Case



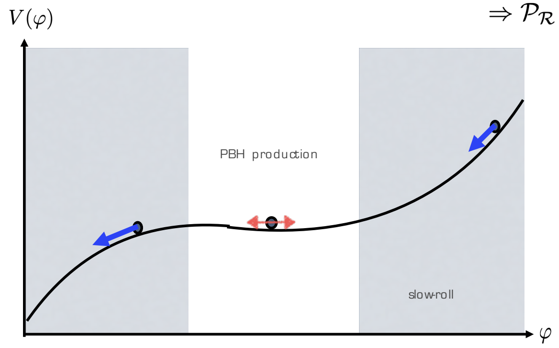
[Green 2016]

Quantum Diffusion

★ Consider the possibility of a plateau in the inflaton potential:

$$\mathcal{P}_\mathcal{R} = \left(\frac{H}{2\pi\varphi'}\right)^2 , \quad \varphi' \equiv \frac{\mathrm{d}\varphi}{\mathrm{d}N} , \quad \varphi'' + 3\varphi' + \frac{V_{,\varphi}}{H^2} \simeq \varphi'' + 3\varphi' = 0$$

$$\Rightarrow \mathcal{P}_\mathcal{R} \sim e^{6N}$$



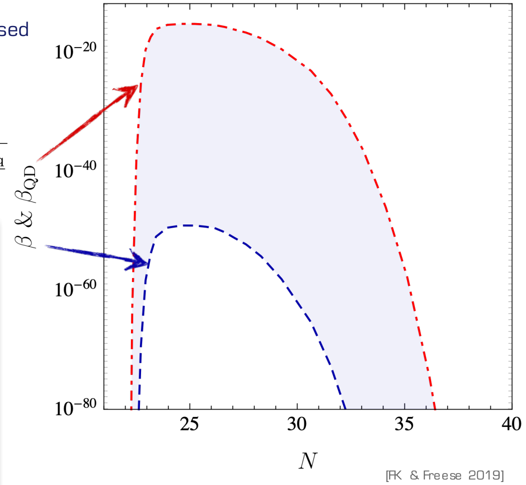
Quantum Diffusion

★ Fraction of collapsed horizon patches:

$$\beta \sim \mathrm{erfc}\left(\frac{\delta_c}{2\,\sigma}\right)$$

$$f_\mathrm{PBH} \approx 2.4\,\beta\,\sqrt{\frac{M_\mathrm{eq}}{M}}$$

Quantum diffusion leads to strongly enhanced PBH production.



[FK & Freese 2019]

PBH Scenarios

★ Collapse from Bubble Collision

Bubble-formation rate per Hubble volume ξ) must be finely tuned:

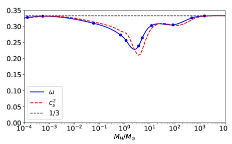
ξ >> 1 => entire Universe undergoes the phase transition immediately => no PBHs

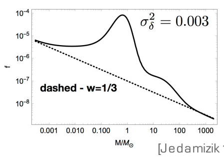
ξ << 1 => bubbles very rare and never collide => no PBHs

PBHs have horizon mass at transition => 10^3 g at GUT epoch; 10^{28} g at EW epoch; $M_\odot$ at QCD epoch

★ Collapse at QCD epoch (2nd order)

10% dip in sound-speed at 10^{-5}s => natural enhancement at Chandrasekhar mass





$$M \approx 0.9 \left(\frac{\gamma}{0.2}\right)\left(\frac{\xi}{5}\right)^2 M_\odot$$

$$\xi \equiv \frac{m_\mathrm{Pl}}{k_\mathrm{B}T} \approx 5$$

[Jedamzik 1997][Byrnes *et al.* 2018]

1st order => collapse from bubble collisions

PBH Scenarios

★ Collapse in the Matter-Dominated Era

★ Collapse prevented by deviations from spherical symmetry

=> $\beta(M) = 0.02\,\delta_\mathrm{H}(M)^5$

★ If matter-dominated phase from t_1 to t_2, PBH formation is enhanced for

$$M_\mathrm{min} \sim M_\mathrm{H}(t_1) < M < M_\mathrm{max} \sim M_\mathrm{H}(t_2)\,\delta_\mathrm{H}(M_\mathrm{max})^{3/2}$$

★ Collapse from Cosmic Strings

★ Typical loop larger than its Schwarzschild radius by $(G\mu)^{-1}$ => $\beta \sim (G\mu)^{2x-4}$

$x \equiv L/s$ is the ratio of the string length to the correlation scale

★ Epoch independent

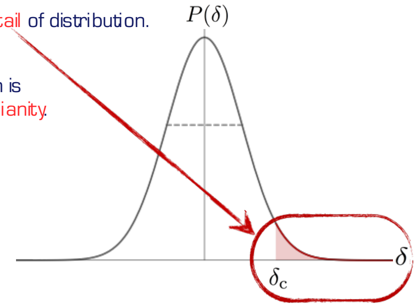
=> $\frac{\mathrm{d}n}{\mathrm{d}M} \propto M^{-\alpha}$ with $\alpha = \frac{2\,(1+2\,w)}{1+w}$ => $f(M) \approx f_\mathrm{DM}\left(\frac{M_\mathrm{DM}}{M}\right)^{\alpha-2}$

Non-Gaußianities

★ PBH fluctuations are extremely rare.

★ Example: Even for 100% of PBH dark matter, at (say) 10^{20} g only one in 10^{15} horizon patches undergoes a collapse!

★ PBH production is deep inside tail of distribution.



★ This means, PBH production is largely sensitive to non-Gaußianity.

★ There is a very strong modal coupling between long- and short-wavelengths.

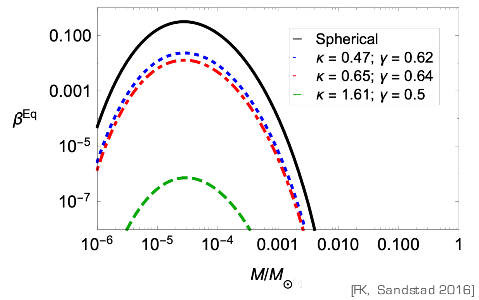
★ Recent calculations from quantum diffusion as well as refined statistical analyses find an approximate exponential tail (as opposed to a Gaußian).

Non-Sphericity

ellipsoidal threshold

$$\frac{\delta_{ec}}{\delta_c} \simeq 1 + \kappa \left(\frac{\sigma^2}{\delta_c^2} \right)^{\gamma}$$

spherical threshold



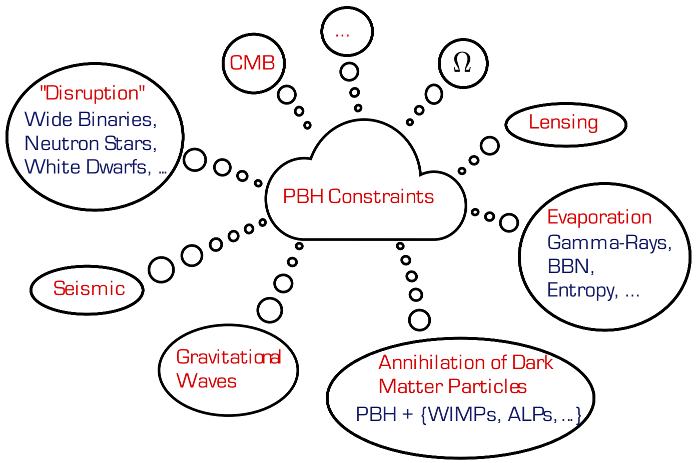
[FK, Sandstad 2016]

★ Simple estimate: As the collapse starts along shortest axis first, consider collapse of largest enclosed sphere (green curve):

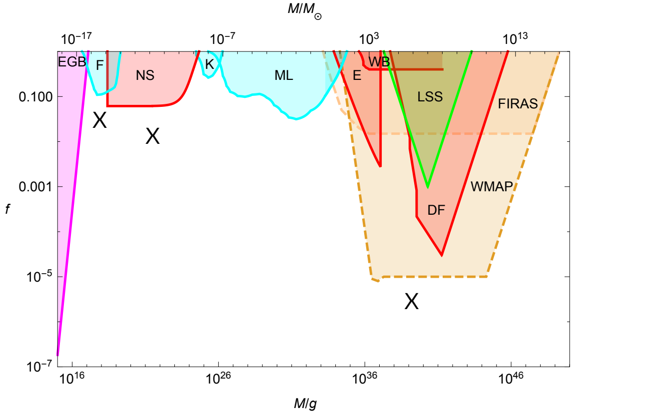
$$\rightarrow \frac{\delta_{ec}}{\delta_c} \simeq (1 + 3\,e) = 1 + \frac{9}{\sqrt{10\,\pi}} \left(\frac{\sigma^2}{\delta_c^2} \right)^{1/2}$$

CONSTRAINTS

PBH Constraints — Overview



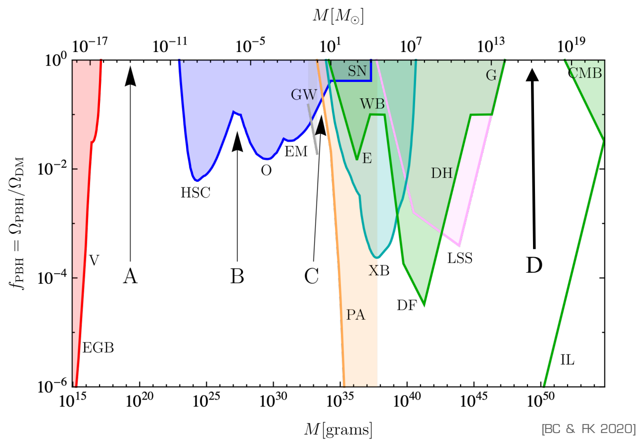
Constraints Non-Evaporating PBHs



[BC, FK, Sandstad 2016]

➔ But some of these limits are now thought to be wrong.

Updated PBH Constraints — Possible Windows

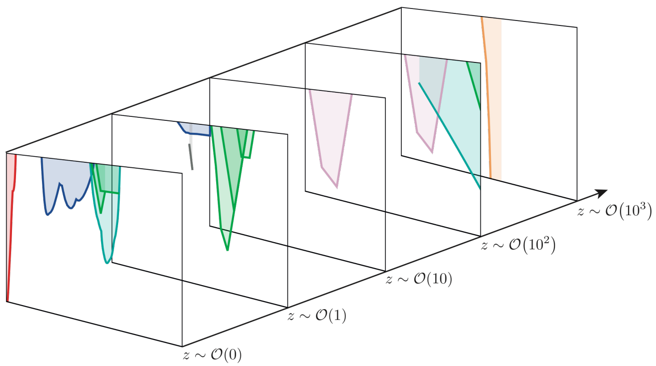


[BC & FK 2020]

★ D = Stupendously Large Black Hole (SLAB) window!

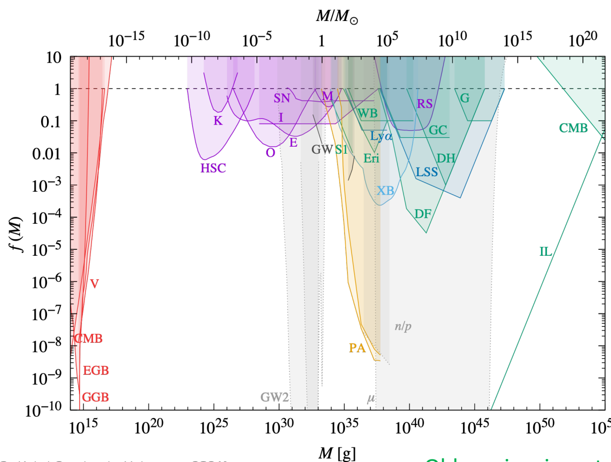
[BC, FK, Visinelli 2021]

PBH Constraints — Redshift Dependence



[BC & FK 2020]

More Detailed Constraints on PBH Dark Matter Fraction



[BC, Kohri, Sendouda, Yokoyama, 2021]

Old version in notes!

Lensing Limits

GRB: Femtolensing of gamma-ray bursts (10^{-16}-10^{-14}Mo)

HSC (Subaru): microlensing of M31 stars (10^{-10}-10^{-5}Mo)

Kepler: microlensing of Galactic stars (10^{-9}-10^{-3}Mo)

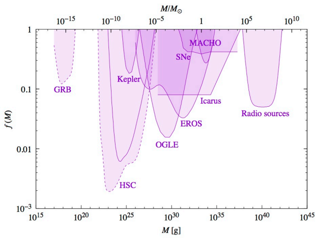
OGLE: microlensing of Galactic bulge stars (10^{-3}-10^{-1}Mo)

EROS: microlensing of LMC stars (10^{-7}-15 Mo)

MACHO: microlensing of LMC stars (0.1 x 30 Mo)

SNe: microlensing of supernovae (10^{-2}-10^{4}Mo)

Radio sources: millensing of compact radio sources (10^{5}-10^{8}Mo)



Dynamical Limits

NS and WDs: destroyed by captured PBHs (10^{-15}-10^{-8}Mo)

Supernovae: transit of PBH through white dwarf (10^{-15}-10^{13}Mo)

Wide binaries: destroyed by PBH tidal effects (10^{2}-10^{7}Mo)

Globular clusters: destroyed by PBHs tidal effects (10^{4}-10^{10}Mo)

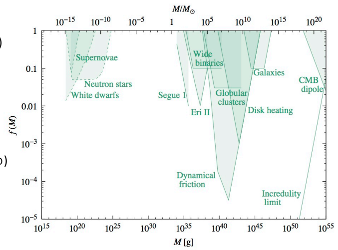
Eri II: survival of star cluster in centre of dwarf galaxy (10^{2}-10^{6}Mo)

Disk heating: destroyed by PBHs tidal effects (10^{6}-10^{12}Mo)

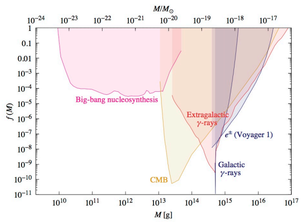
Dynamical friction: drag of halo stars (10^{4}-10^{12}Mo)

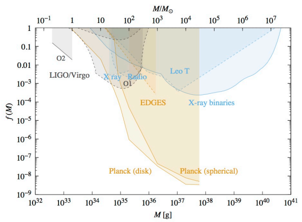
Galaxies in clusters: tidal distortion by giant PBHs tidal effects (10^{10}-10^{14}Mo)

CMB dipole: peculiar velocity from nearest PBH (10^{18}-10^{21}Mo)



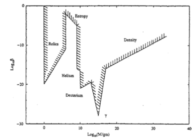
Evaporation and Accretion Limits



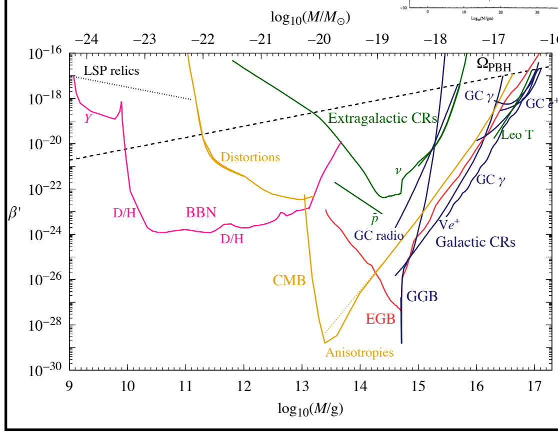


Evaporation Constraints

[BC, Kohri, Sendouda, Yokoyama, 2021]



1994



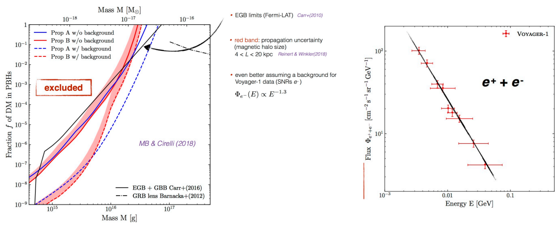
2021

IMPORTANT EVAPORATION CONSTRAINT

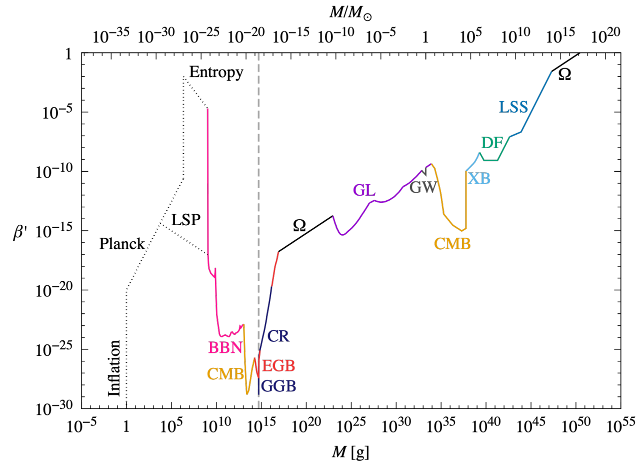
VOYAGER-1 $e^{\pm}$ **further constrain Primordial Black Holes as Dark Matter**

Mathieu Boudaud[1] and Marco Cirelli[1]

arXiv:1807.03075

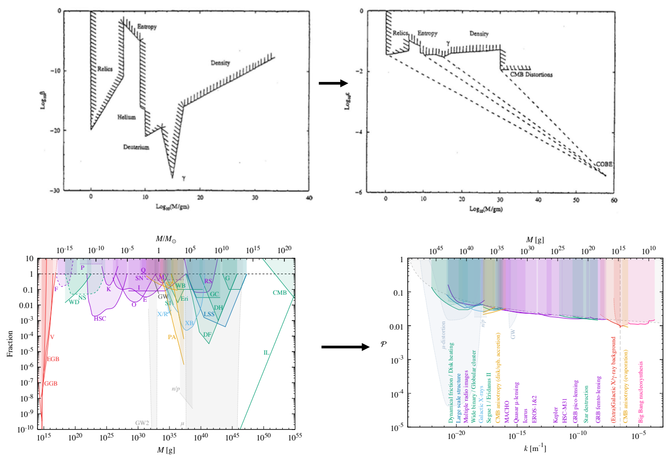


PBH Constraints at Formation



[BC, Kohri, Sendouda, Yokoyama, 2021]

Constraints on the Power Spectrum



PBH Constraints — Comments

★ These constraints are not just nails in a coffin!

★ All constraints have caveats and may change.

★ PBHs are interesting even for $f_{\rm PBH} \ll 1$.

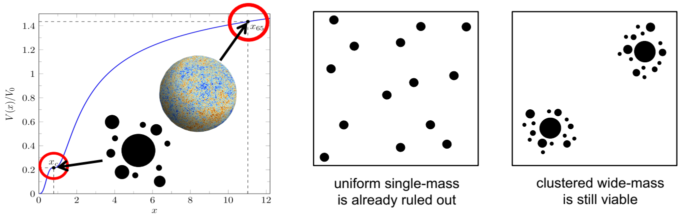
★ Each constraint is a potential signature.

★ PBHs generically have an extended mass function.

Clustering

★ Many inflationary scenarios yield a lognormal PBH mass distribution.

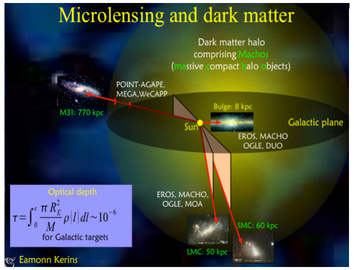
→ This leads to clusters of 100 – 1000 PBHs with extend ~ 1 Mpc.



uniform single-mass is already ruled out

clustered wide-mass is still viable

The clustering dynamics of primordial black boles in N-body simulations
Manuel Trashorras, Juan García-Bellido, Savvas Nesseris (Jun 26, 2020)
Published in: Universe 7 (2021) 1, 18 • e-Print: 2006.15018 [astro-ph.CO]



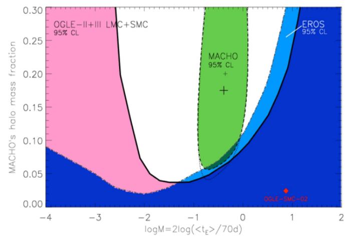


Image credit: Wyrzykowski et al., 2011, MNRAS, (astro-ph/1106.2925).

Early microlensing searches suggested MACHOs with 0.5 $M_\odot$

=> PBH formation at QCD transition?

Pressure reduction => PBH mass function peak at 0.5 $M_\odot$

Later found that at most 20% of DM can be in these objects

Evidence for dark matter in the form of compact bodies

Michael Hawkins
University of Edinburgh

1993

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 $M_\odot$

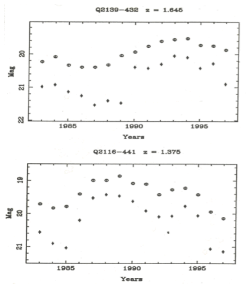


Fig. 3. Light curves for two quasars showing all the character... expected of caustic crossing events. Symbols as for Fig. 1.

Hawkins now gives mass as 1 $M_\odot$

Extended Mass Functions

★ Most constraints assume monochromatic PBH mass function.

★ Can we evade standard limits with extended mass spectrum?

But this is two-edged sword!

★ PBHs may be dark matter even if fraction is low at each scale.

★ PBHs giving dark matter at one scale may violate limits at others.

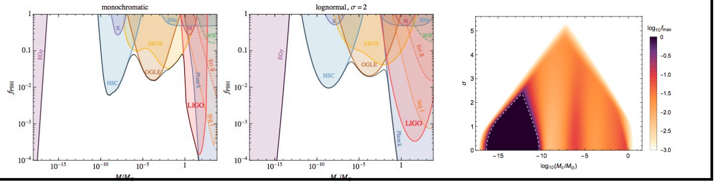
PBH Constraints for Extended Mass Functions

★ Possible PBH mass functions $\psi(M) \propto M \frac{\mathrm{d}n}{\mathrm{d}M}$ => $\frac{\Omega_{\rm PBH}}{\Omega_{\rm DM}} = \int \mathrm{d}M\, \psi(M)$

- ★ lognormal $\psi(M) = \frac{f_{\rm PBH}}{\sqrt{2\pi}\sigma M} \exp\left(-\frac{\log^2(M/M_c)}{2\sigma^2}\right)$
- ★ power-law $\psi(M) \propto M^{\gamma-1} \quad (M_{\rm min} < M < M_{\rm max})$
- ★ critical collapse $\psi(M) \propto M^{2.85} \exp(-(M/M_f)^{2.85})$
- ★ f(M) limits themselves depend on PBH mass function

$\int \mathrm{d}M \frac{\psi(M)}{f_{\rm max}(M)} \leq 1$ + $\psi(M; f_{\rm PBH}, M_c, \sigma)$ => $f_{\rm PBH}(M_c,\sigma)$

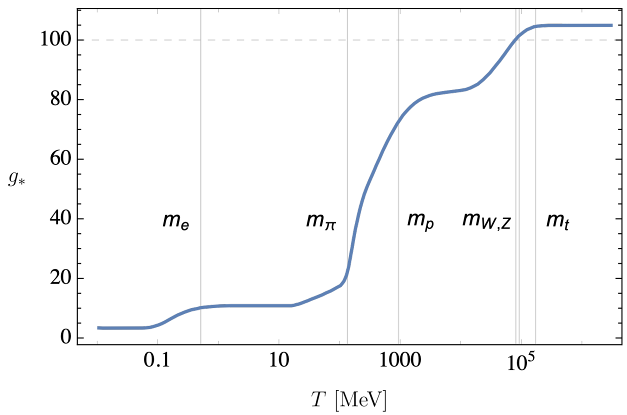
[BC, Raidal, Tenkanen, Vaskonen, Veermae 2017]



Natural scenario for PBHs as solution to cosmic conundra

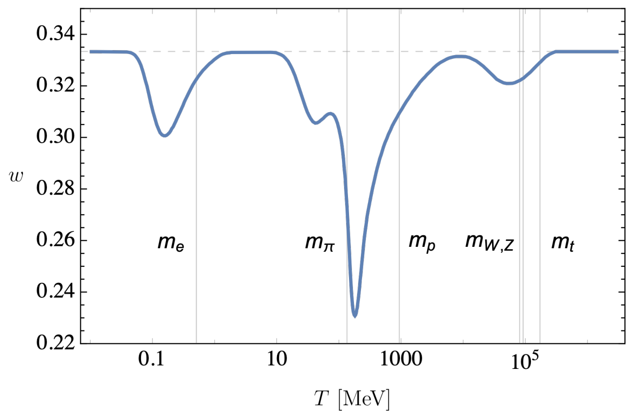
Thermal History of the Universe

★ Changes in the relativistic degrees of freedom:



Thermal History of the Universe

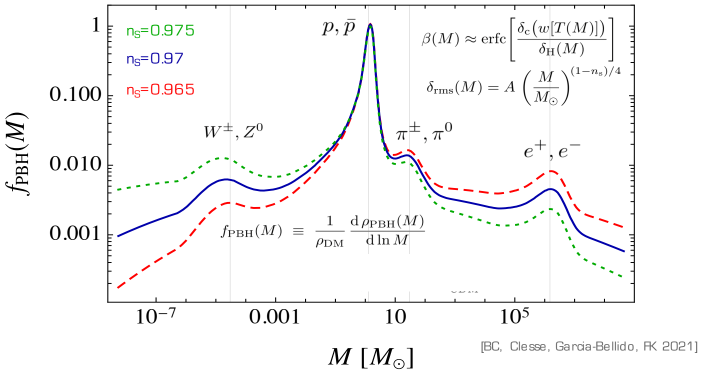
★ Changes in the equation-of-state parameter $w = p/\rho$:



Cosmic Conundra Explained by Thermal History and Primordial Black Holes

Bernard Carr,[1,2,*] Sébastien Clesse,[3,4,†] Juan García-Bellido,[5,‡] and Florian Kühnel[6,§]

arXiv:1906.08217

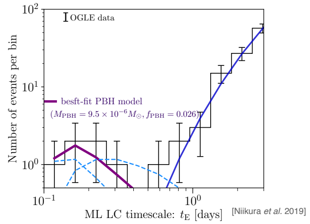


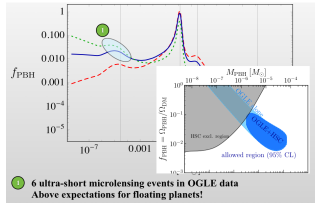
Overproduce light PBHs for $n_s > 0.975$ Overproduce heavy PBHs for $n_s < 0.965$

Planetary-mass microlenses

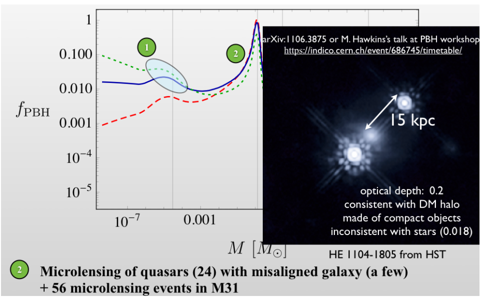
OGLE detected microlenses on 0.1-0.3 day timescale of unknown origin – free-floating planets of PBHs?

Niikura et al. (2019)

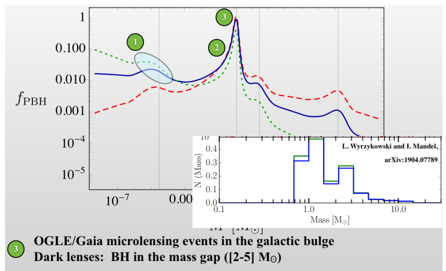




Quasar Microlensing

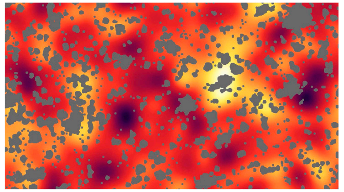


OGLE/GAIA Excess of Lenses in Galactic Bulge

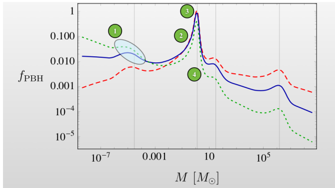


Cosmic Infrared/X-Ray Backgrounds

★ PBHs generate early structure and infrared background



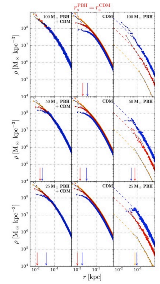
Kashlinsky
arXiv:1605.04023

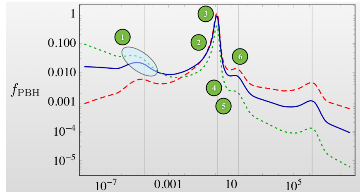


④ Spatial correlations in infrared and X-ray background (>5 sigma)

Ultra-Faint Dwarf Galaxies

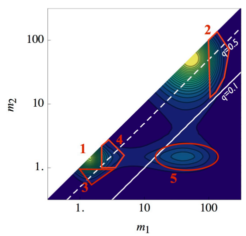
★ ⑤ **Minimum radius of (ultra-faint) dwarf galaxies and cored DM profiles**

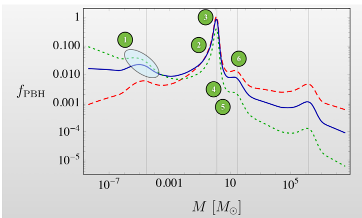




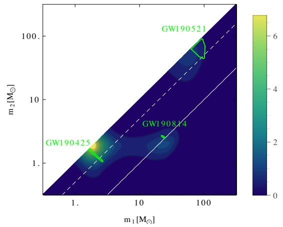
★ Improved constraints from ultra-faint dwarf galaxies on PBHs as DM
[Stegmann *et al.* 2020]

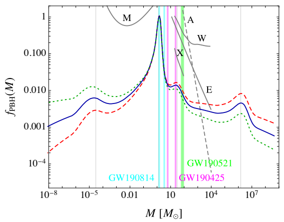
LIGO/Virgo Black Holes





⑥ **Explain the rates, masses and effective spins of LIGO/Virgo BH**

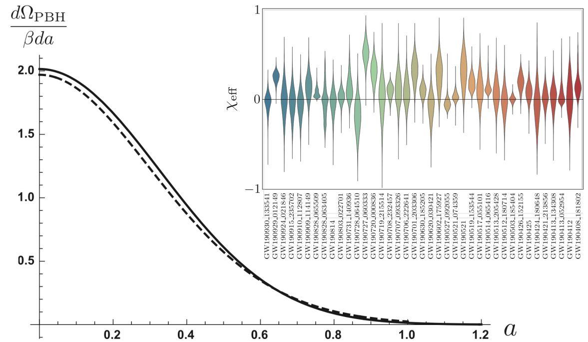




Spin Distribution

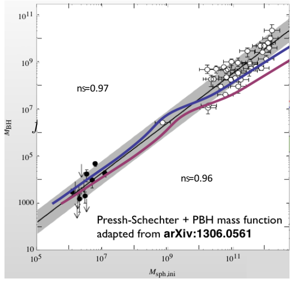
★ Gravitational-wave emission from black-hole binaries

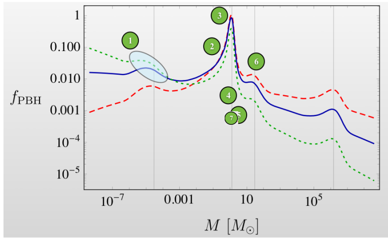
★ For PBH (produced in RD) we expect close to zero spin.



[Chiba & Yokoyama 2017]

Intermediate and Supermassive Black Holes





7 Right number of intermediate and supermassive black holes

- ★ n_S = 0.97 => observed ratio of black hole and halo mass if f_{PBH} ~ 1.

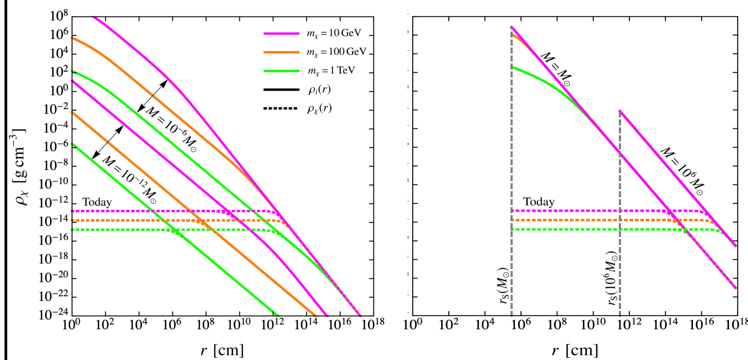
PBH versus Particle Dark Matter

PBH + Particle DM

- ★ Always when $f_{\rm PBH} < 1$ there must be another DM component!
- ★ Study a combined scenario: DM = PBHs + Particles
  - ★ The latter will be accreted by the former; formation of halos.
  - ★ Study WIMP annihilations in PBH halos:
    - ★ The annihilation rate $\Gamma \propto n^2$.
    - ★ Halo profile => enhancement of Γ in density spikes.
      1) Derive the density profile of the captured WIMPs;
      2) calculate the annihilation rate;
      3) and compare to extragalactic gamma-ray background.

[Eroshenko 2016, Boucenna *et al.* 2017, Adamek *et al.* 2019, BC, FK, Visinelli 2020 & 2021]

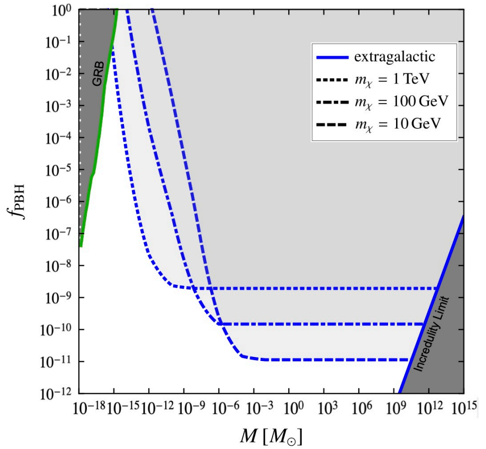
PBHs & WIMPs - Halo Profiles



[Carr, Kühnel, Visinelli 2021]

- ★ Annihilations lead to plateaux in the present-day halos.
- ★ Three different shapes: $\rho_{\chi,\,\rm spike}(r) \propto \begin{cases} r^{-3/4} & \text{(innermost)} \\ r^{-3/2} & \text{(intermediate)} \\ r^{-9/4} & \text{(outermost)} \end{cases}$

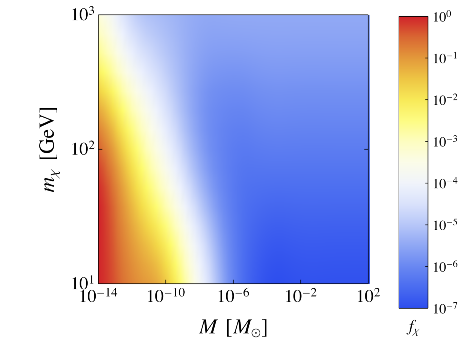
PBHs & WIMPs - Constraints



[BC, FK, Visinelli 2021]

If the LIGO/Virgo black holes are primordial, this would rule out any standard WIMP scenario!

PBHs & WIMPs - Constraints



$f_{\rm PBH} + f_\chi = 1$

[Carr, Kühnel, Visinelli 2021]

- ★ Even for small values of $f_{\rm PBH}$, f_χ is heavily constrained.
- ★ For $M_{\rm PBH} \gtrsim 10^{-11}\, M_\odot$ and $m_\chi \lesssim 100$ GeV, both the WIMP and PBH fractions are $\mathcal{O}(10\%)$.

→ Motivates a third dark-matter candidate?

Some final points

ADDRESSING FINE-TUNING PROBLEM AT QCD EPOCH

arXiv:1904.02129

PBHs forming at time t have mass and collapse fraction
$M \sim 10^5 (t/s)\, M_O$, $\beta(M) \sim 10^{-9} f(M)\, (M/M_O)^{1/2}$

So β appears fine-tuned and we must also explain why
$\chi = \rho_{PBH}/\rho_B = f\, \rho_{DM}/\rho_B = 6\, f$ is O(1).

$\chi >> 1$ => $t_{eq} << t_{dec}$ => not enough baryons to make galaxies

$\chi << 1$ => $t_{deq} >> t_{dec}$ => fluctuations too small to make galaxies

QCD epoch => $M \sim M_C$, $\beta(M) \sim \eta = n_B/n_\gamma \sim 10^{-9}$ anthropic selection?

=> dark matter and visible baryons have similar mass
PBHs may *generate* baryon asymmetry

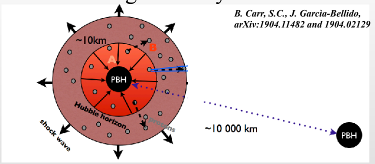
$M_C \sim \alpha_G^{-3/2} m_P \sim 1 M_O$ and all stars have mass in range (0.1–10) M_C

arXiv:1904.114827

Primordial Black Holes

as a common origin of baryons and dark matter

B. Carr, S.C., J. Garcia-Bellido, arXiv:1904.11482 and 1904.02129

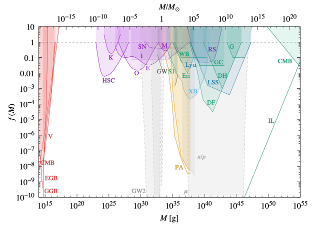


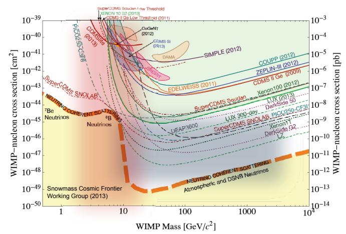
- C and CP violation of the standard model (CKM matrix)
- Baryon number violation: sphaleron transitions from >TeV collisions
- Out of thermal equilibrium (PBH collapse)

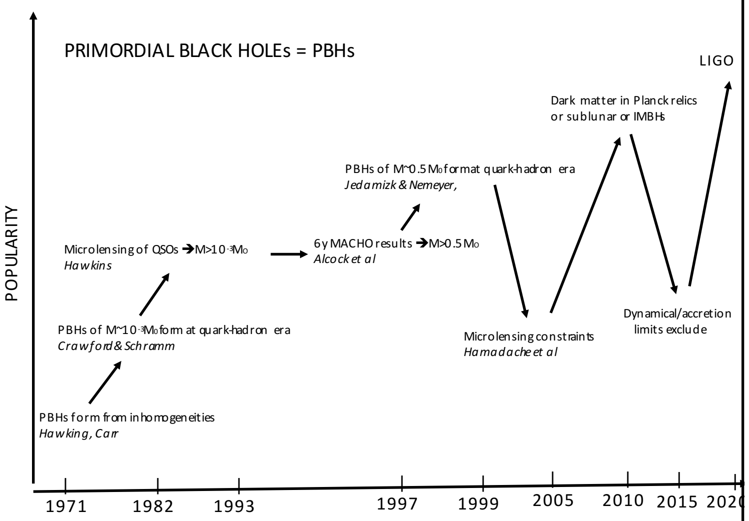
$$\chi \approx \gamma/(1-\gamma) \approx 5 \text{ if } \gamma \approx 0.8$$

η_{loc} ~ 1 => $\eta \sim \beta$ and $\chi \sim 1$ after diffusion of baryon asymmetry

PBHS or WIMPS: HISTORICAL PERSPECTIVE?







CONCLUSIONS

PBH studies have already led to profound insights into cosmology and fundamental physics, even if they never formed.

Until recently most work focused on PBH constraints but now they have been invoked for numerous cosmological purposes:

Dark matter	LIGO/Virgo	Other Conundra

These are distinct roles but PBHs with extended mass function could play all of them with fine-tuning of collapse fraction.

PBHs naturally form at QCD epoch and could explain both dark matter and baryon asymmetry with anthropic fine-tuning.