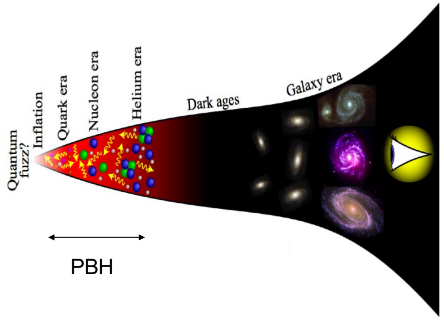
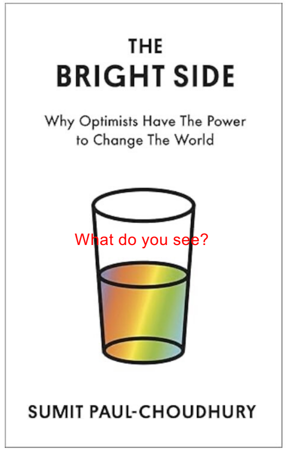
PRIMORDIAL BLACK HOLES AFTER 50 YEARS: THE BRIGHT SIDE



Bernard Carr
Queen Mary University of London

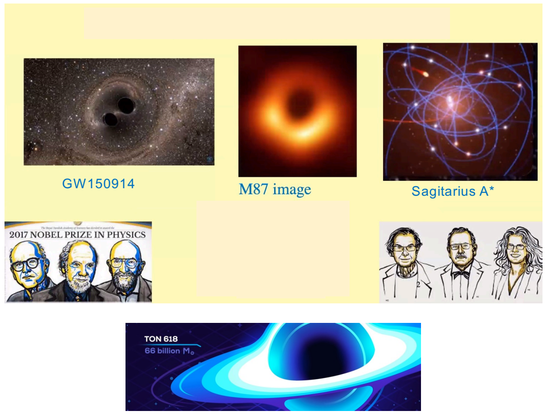
LMU Munich, 5/2/25

1



2

Irrefutable evidence for stellar and supermassive black holes



Plausible evidence for intermediate mass black holes

3

PRIMORDIAL BLACK HOLES?

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

Small black holes can only form in early Universe

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

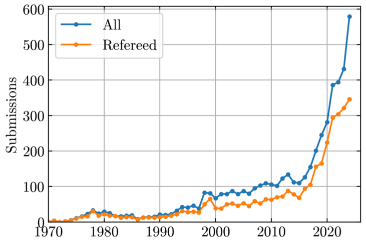
⇨ **PBHs have horizon mass at formation**

$$M_{PBH} \sim c^3t/G = \begin{cases} 10^{-5}\text{g at } 10^{-43}\text{s} & \text{(minimum)} \\ 10^{15}\text{g at } 10^{-23}\text{s} & \text{(evaporating now)} \\ 10^{6}M_O \text{ at } 10\text{ s} & \text{(maximum?)} \end{cases}$$

=> **huge possible mass range**

4

PBH PUBLICATION RATE



Peaks due to
- Hawking radiation (1974)
- Microlensing => dark matter (1995)
- LIGO/Virgo gravitational waves (2016)
- JWST => seeds for cosmic structure and SMBHs (2021)

5

Observational Evidence for Primordial Black Holes: A Positivist Perspective

B. J. Carr,[1,*] S. Clesse,[2,†] J. García-Bellido,[3,‡] M. R. S. Hawkins,[4,§] and F. Kühnel[5,¶]

arXiv:2306.03903

Physics Reports 1054 (2024) 1-67

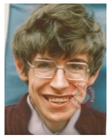
The History of Primordial Black Holes

Bernard J. Carr [a] and Anne M. Green [b]

arXiv:24067.05736

To appear "Primordial Black Holes", ed. Chris Byrnes, Gabriele Franciolini, Tomohiro Harada, Paolo Pani, Misao Sasaki; Springer (2024)

6



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.

7

Solar evolution models with a central black hole

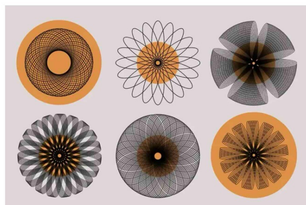
Earl P. Bellinger,[1,2,3] Matt E. Caplan,[4] Taeho Ryu,[1,5] Deepika Bollimpalli,[1] Warrick H. Ball,[6,7] Florian Kühnel,[8] R. Farmer,[1] S. E. de Mink,[1,9] and Jørgen Christensen-Dalsgaard[3]

arXiv:2312.06782

Tiny black holes hiding in the sun could trace out stunning patterns

If our solar system and even our sun contain tiny black holes formed just after the big bang, they should be orbiting in elaborate patterns

24 May 2024



Primordial black holes could take on intricate orbits inside the sun and similar stars

8

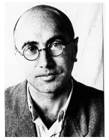
SOVIET ASTRONOMY – AJ VOL. 10, NO. 4 JANUARY-FEBRUARY, 1967

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.

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

BLACK HOLES IN THE EARLY UNIVERSE

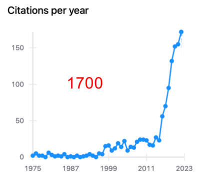
B. J. Carr and S. W. Hawking

(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.

MY MOST CITED PAPER



$\Rightarrow$ no observational evidence against them

Career downhill from start!

10

……with a resurgence towards the end!

PHYSICAL REVIEW D **81**, 104019 (2010)

New cosmological constraints on primordial black holes

B. J. Carr*
Astronomy Unit, Queen Mary University of London, Mile End Road, London E1 4NS, United Kingdom
Research Center for the Early Universe (RESCEU), Graduate School of Science, The University of Tokyo, Tokyo 113-0033, Japan
Canadian Institute for Theoretical Astrophysics, University of Toronto, 60 St. George Street, Toronto, Ontario M5S 1A1, Canada
Kazunori Kohri†
Department of Physics, Tohoku University, Sendai 980-8578, Japan
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Yuuiti Sendouda‡
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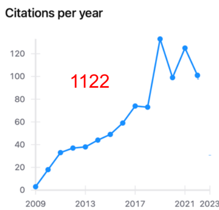
Department of Physics, Graduate School of Science, The University of Tokyo, Tokyo 113-0033, Japan
Jun'ichi Yokoyama§
Research Center for the Early Universe (RESCEU), Graduate School of Science, The University of Tokyo, Tokyo 113-0033, Japan
Institute for the Physics and Mathematics of the Universe (IPMU), The University of Tokyo, Kashiwa, Chiba 277-8568, Japan
(Received 31 December 2009; published 10 May 2010)

We update the constraints on the fraction of the Universe going into primordial black holes in the mass range 10^9–10^{17} g associated with the effects of their evaporations on big bang nucleosynthesis and the extragalactic photon background. We include for the first time all the effects of quark and gluon emission by black holes on these constraints and account for the latest observational developments. We then discuss the other constraints in this mass range and show that these are weaker than the nucleosynthesis and photon background limits, apart from a small range 10^{13}–10^{14} g, where the damping of cosmic microwave background anisotropies dominates. Finally we review the gravitational and astrophysical effects of nonevaporating primordial black holes, updating constraints over the broader mass range 1–10^{50} g.

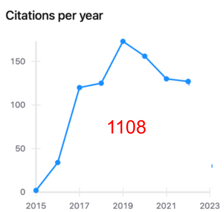


PHYSICAL REVIEW D **94**, 083504 (2016)

Primordial black holes as dark matter

Bernard Carr,[1,*] Florian Kühnel,[2,†] and Marit Sandstad[3,‡]
[1]*Department of Physics and Astronomy, Queen Mary University of London, Mile End Road, London E1 4NS, United Kingdom*
[2]*The Oskar Klein Centre for Cosmoparticle Physics, Department of Physics, Stockholm University, AlbaNova, SE–10691 Stockholm, Sweden*
[3]*Nordita, KTH Royal Institute of Technology and Stockholm University, Roslagstullsbacken 23, SE–10691 Stockholm, Sweden*
(Received 8 August 2016; published 4 October 2016)

The possibility that the dark matter comprises primordial black holes (PBHs) is considered, with particular emphasis on the currently allowed mass windows at 10^{16}–10^{17} g, 10^{20}–10^{24} g and 1–$10^3 M_\odot$. The Planck mass relics of smaller evaporating PBHs are also considered. All relevant constraints (lensing, dynamical, large-scale structure and accretion) are reviewed and various effects necessary for a precise calculation of the PBH abundance (non-Gaussianity, nonsphericity, critical collapse and merging) are accounted for. It is difficult to put all the dark matter in PBHs if their mass function is monochromatic but this is still possible if the mass function is extended, as expected in many scenarios. A novel procedure for confronting observational constraints with an extended PBH mass spectrum is therefore introduced. This applies for arbitrary constraints and a wide range of PBH formation models and allows us to identify which model-independent conclusions can be drawn from constraints over all mass ranges. We focus particularly on PBHs generated by inflation, pointing out which effects in the formation process influence the mapping from the inflationary power spectrum to the PBH mass function. We then apply our scheme to two specific inflationary models in which PBHs provide the dark matter. The possibility that the dark matter is in intermediate-mass PBHs of 1–$10^3 M_\odot$ is of special interest in view of the recent detection of black-hole mergers by LIGO. The possibility of Planck relics is also intriguing but virtually untestable.



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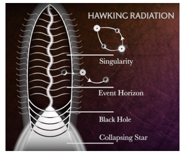
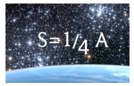
PBHs may be literally bright!

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.

PBHs led to Hawking radiation not vice versa!

Hawking	Received February 1974	Published March 1974
BC & Hawking	Received February 1974	Published August 1974

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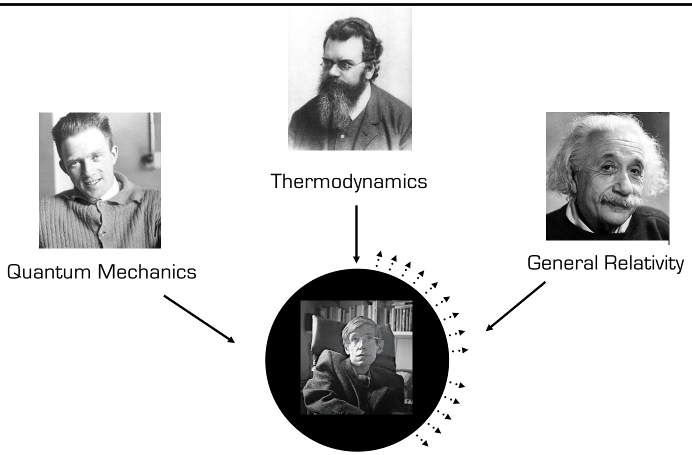

$$T_{BH}[\mathrm{K}] = 10^{-7}\,\frac{M_\odot}{M}$$

PBHs are important even if they never formed!

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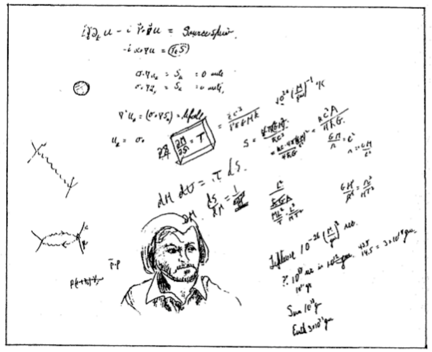
Feynman's envelope 1975



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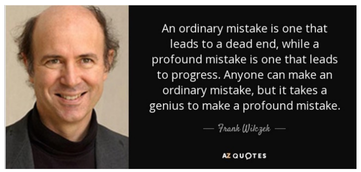
BLACK HOLE INFORMATION PARADOX

PHYSICAL REVIEW D VOLUME 14, NUMBER 10 15 NOVEMBER 1976

Breakdown of predictability in gravitational collapse*

S. W. Hawking†

Hawking, Perry & Strominger PRL 116 (2016) 231301, JHEP 1705 (2017)



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PBH EVAPORATION

Black holes radiate thermally with temperature

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

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

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

This can only be important for PBHs

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

=> explosions undetectable in standard particle physics model

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

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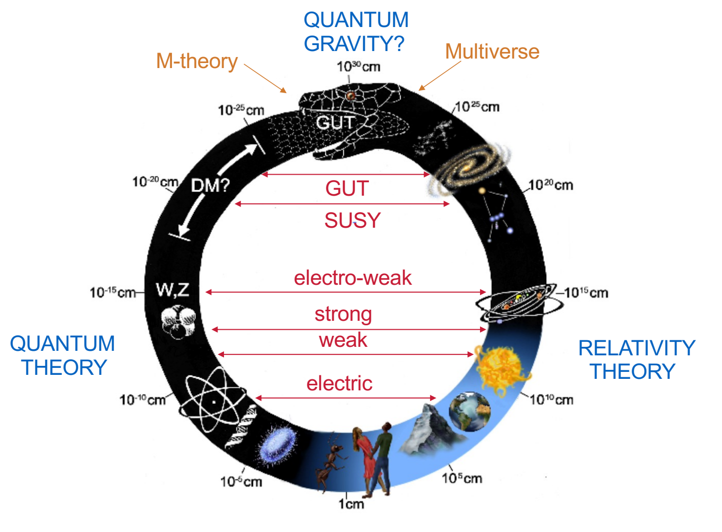

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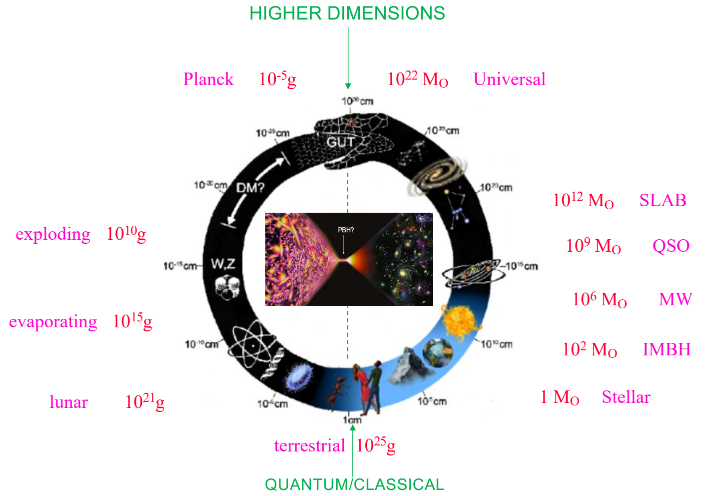
BLACK HOLES AS LINK BETWEEN MICRO AND MACRO PHYSICS



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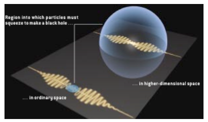
BLACK HOLES AS A PROBE OF HIGHER DIMENSIONS

Arkani-Hamed, Dimopoulos & Dvali,Phys.Lett.B.428,263(1998)

M-theory => extra compactified dimensions (n)

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

Large extra dimensions => $V_n >> M_P^{-n}$, $M_D << M_p$

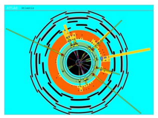


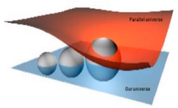
TeV quantum gravity?

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





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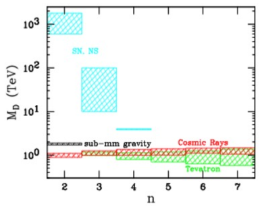
DETECTABLE AT LHC?

$M_D \sim TeV \Rightarrow R_C \sim 10^{(32/n)-17}\,cm \sim$

10^{16} cm (n=1) excluded
10^{-1} cm (n=2)
10^{-6} cm (n=3)
10^{-13} cm (n=7)



No evidence from LHC so far

Probing Large Extra Dimensions with Neutrinos

Gia Dvali[1,2] and Alexei Yu. Smirnov[2,3]

arXiv:hep-ph/9904211

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Dark dimension, the swampland, and the dark matter fraction composed of primordial near-extremal black holes

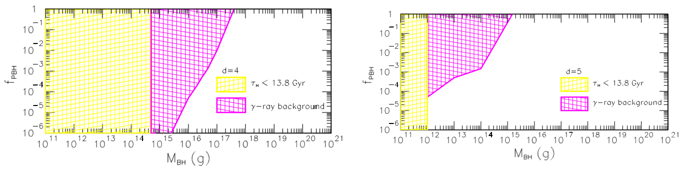
Luis A. Anchordoqui,[1,2] Ignatios Antoniadis,[3,4,5] and Dieter Lüst[6,7]

arXiv:2206.07071

More on black holes perceiving the dark dimension

Luis A. Anchordoqui,[1,2,3] Ignatios Antoniadis,[4,5] and Dieter Lüst[6,7]

arXiv:2403.19604



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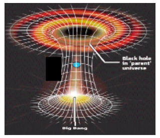
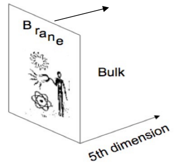
IS UNIVERSE A PRIMORDIAL BLACK HOLE?

Collapse to black hole may generate 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)

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WHY PBHS ARE USEFUL

M~10^{-5}g => Probe quantum gravity
Planck mass relics, higher dimensions

M<10^{15}g => Probe early Universe
inhomogeneities, phase transitions, inflation

M~10^{15}g => Probe high energy physics
PBH explosions, cosmic rays, gamma-ray background

M>10^{15}g => Probe gravity and dark side
critical collapse, dark matter, dark energy

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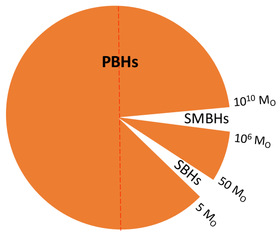
ARE MOST BLACK HOLES PRIMORDIAL?



Does Nature populate whole Uroborus?

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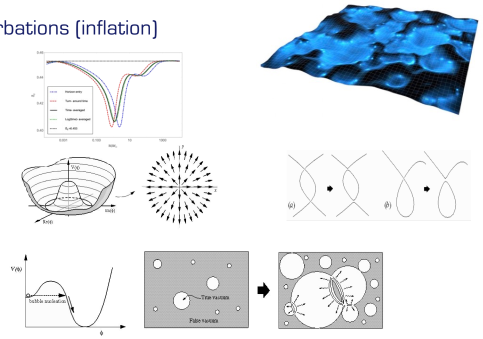
Formation Mechanisms of Primordial Black Holes

- Large density perturbations (inflation)
- Pressure reduction
- Cosmic string loops
- Bubble collisions



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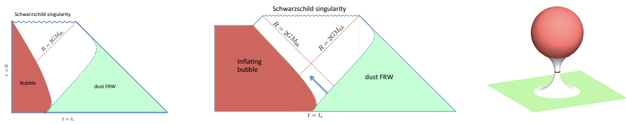
Black holes and the multiverse

Jaume Garriga[a,b], Alexander Vilenkin[b] and Jun Zhang[b]

JCAP 02 (2016) 064

Collapse of spherical domain wall or bubble of broken symmetry gives PBH if small but wormhole and baby universe if large



$\Rightarrow$ specific PBH mass function + evidence for multiverse

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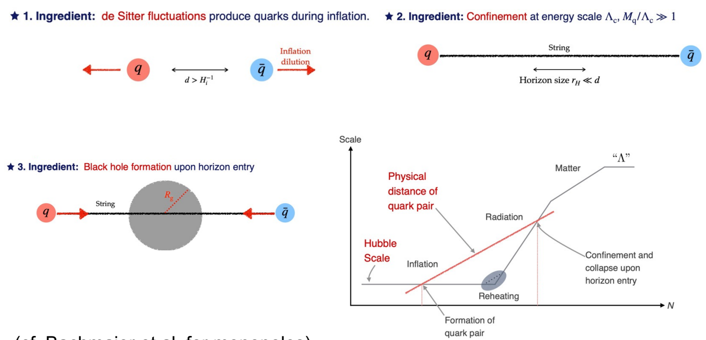
Primordial black holes from confinement

Gia Dvali,[1,2] Florian Kühnel,[1,*] and Michael Zantedeschi[1,2,†]



(cf. Bachmaier et al. for monopoles)

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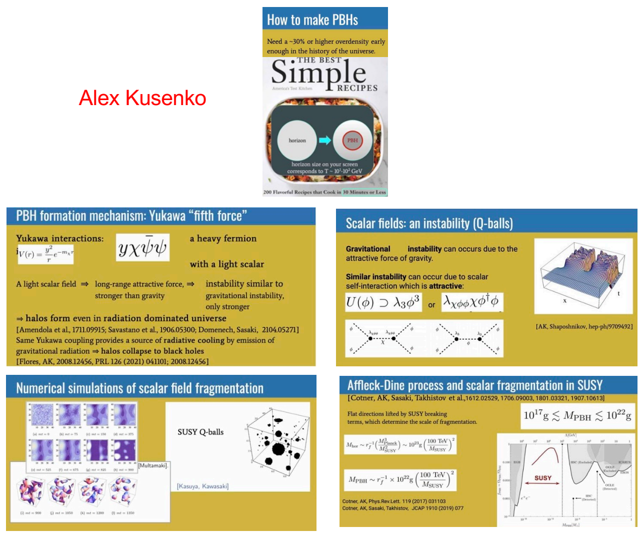
Alex Kusenko



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Fraction of Universe collapsing

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

General limit

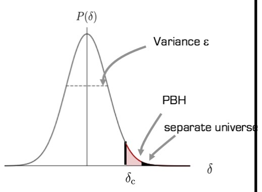
$$\frac{\rho_{PBH}}{\rho_{CBR}} \approx \frac{\Omega_{PBH}}{10^{-4}}\left[\frac{R}{R_0}\right] \Rightarrow \beta \sim 10^{-6}\,\Omega_{PBH}\left[\frac{t}{\sec}\right]^{1/2} \sim 10^{-18}\,\Omega_{PBH}\left[\frac{M}{10^{15}g}\right]^{1/2}$$

To collapse against pressure, need $\delta_H > \alpha$ $(p=\alpha\rho c^2)$

Gaussian fluctn's with $\langle\delta_H^2\rangle^{1/2} = \varepsilon(M)$

$$\Rightarrow \beta(M) \sim \varepsilon(M)\exp\left[-\frac{\alpha^2}{2\varepsilon(M)^2}\right]$$ (BC1975)

So both expect and require $\beta(M)$ to be tiny



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PBHs: Critical Collapse

VOLUME 70, NUMBER 1 PHYSICAL REVIEW LETTERS 4 JANUARY 1993

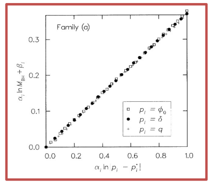
Universality and Scaling in Gravitational Collapse of a Massless Scalar Field

Matthew W. Choptuik

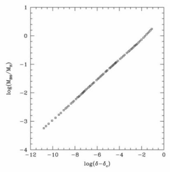
Center for Relativity, University of Texas at Austin, Austin, Texas 78712-1081

(Received 22 September 1992)

I summarize results from a numerical study of spherically symmetric collapse of a massless scalar field. I consider families of solutions, $S[p]$, with the property that a critical parameter value, p^*, separates solutions containing black holes from those which do not. I present evidence in support of conjectures that (1) the strong-field evolution in the $p \to p^*$ limit is universal and generates structure on arbitrarily small spatiotemporal scales and (2) the masses of black holes which form satisfy a power law $M_{BH} \propto |p-p^*|^\gamma$, where $\gamma \approx 0.37$ is a universal exponent.



Numerical Results: Scaling Law / Critical collapse



$$M_{PBH} = \mathcal{K}(\delta-\delta_c)^\gamma M_H$$

M_H – cosmological horizon mass

$\mathcal{K}, \delta_c$ – shape dependent

$\gamma \simeq 0.36$

Niemeyer , Jedamzik - (1999) *IM, Miller, Polnarev* - CQG (2009, 2013)

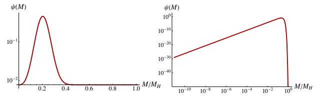
PBH Mass Distribution

$$\psi(M) \equiv \frac{M}{\rho_{pbh}(t_c)}\frac{dn_{pbh}(M,t_c)}{dM} \sim \left(\frac{M}{\bar{M}}\right)^{1/\nu}$$ $\nu = 0.36$ for collapse within RD fluid

Critical collapse yields a mass distribution that is ***strongly peaked*** near

$$\bar{M}(t_c) = \gamma\, M_H(t_c) \qquad \gamma \simeq 0.2$$ (Carr's estimate from 1975!)

but with a ***long tail*** for masses $M << \bar{M}$, governed by the same ***universal scaling exponent*** ν.



The distribution $\psi(M)$ depends on details of how the compaction C relates to $\delta\rho/\rho$ and is sensitive to non-Gaussian features of $\mathcal{P}_\mathcal{R}(k)$. But the **long tail** for $M < \bar{M}$ is **generic**.

Niemeyer and Jedamzik (1997); Green and Liddle (1999). *Many* papers since 2010: Musco, Kühnel, Riotto, Cole, Byrnes, Vennin, Escrivà ...

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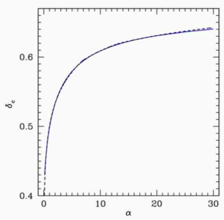
PBH threshold

- *Escrivá, Germani, Sheth* - PRD (2020)

$$\bar{\mathcal{C}}(r_m) \simeq 0.4 \quad \text{(shape independent)}$$

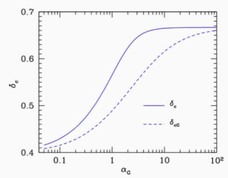
$$\delta_c \simeq \frac{4}{15}e^{-\frac{1}{\alpha}}\frac{\alpha^{1-5/2\alpha}}{\Gamma\left(\frac{5}{2\alpha}\right)-\Gamma\left(\frac{5}{2\alpha},\frac{1}{\alpha}\right)}$$



- *IM, De Luca, Franciolini, Riotto* - PRD (2021)

$$\delta_c \simeq \begin{cases} 0.13\alpha + 0.41 & \alpha \lesssim 0.25 \\ \alpha^{0.045} - 0.50 & 0.25 \lesssim \alpha \lesssim 7 \\ \alpha^{0.035} - 0.475 & 7 \lesssim \alpha \lesssim 13 \\ \alpha^{0.026} - 0.45 & 13 \lesssim \alpha \lesssim 30 \end{cases}$$

$$\delta_m = \frac{4}{3}\Phi_m\left(1-\frac{1}{2}\Phi_m\right) = \delta_G\left(1-\frac{3}{8}\delta_G\right)$$



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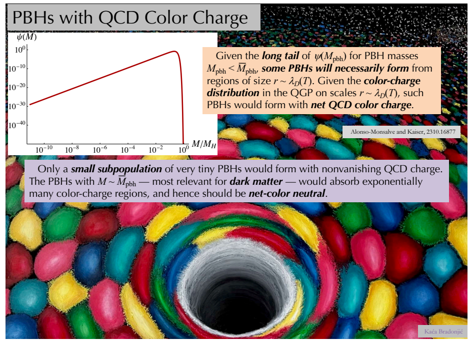
Primordial Black Holes with QCD Color Charge

Elba Alonso-Monsalve* and David I. Kaiser†

arXiv:2310.16877



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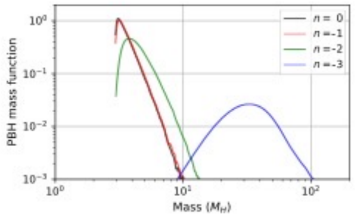
Aspects of Spatially-Correlated Random Fields: Extreme-Value Statistics and Clustering Properties

Ka Hei Choi [1] James Creswell,[1] Florian Kühnel [1,2] and Dominik J. Schwarz [3]

arXiv:2501.17936

Rare events of large-scale spatially-correlated exponential random fields are studied. The influence of spatial correlations on clustering and non-sphericity is investigated. The size of the performed simulations permits to study beyond-7.5-sigma events (1 in 10^{13}). As an application, this allows to resolve individual Hubble patches which fulfill the condition for primordial black hole formation. It is argued that their mass spectrum is drastically altered due to co-collapse of clustered overdensities as well as the mutual threshold-lowering through the latter. Furthermore, the corresponding non-sphericities imply possibly large changes in the initial black hole spin distribution.



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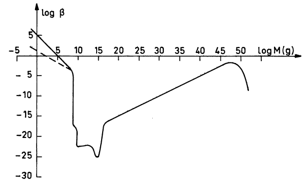
Primordial Black Holes

I. D. Novikov[1], A. G. Polnarev[1], A. A. Starobinsky[2], and Ya. B. Zeldovich[3]

Astron. Astrophys. 80, 104–109 (1979)

Summary. The processes of primordial black hole formation and accretion of matter onto the primordial black holes already formed are investigated. We give the limits on the possible number of primordial black holes of various masses inferred from astrophysical observations.



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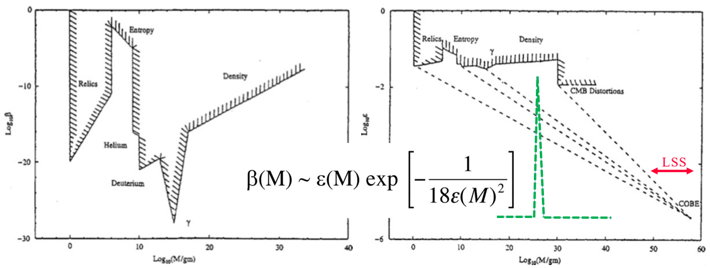
PBHs as a Unique Probe Small Scales



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

[BC, Gilbert, Lidsey 1994]

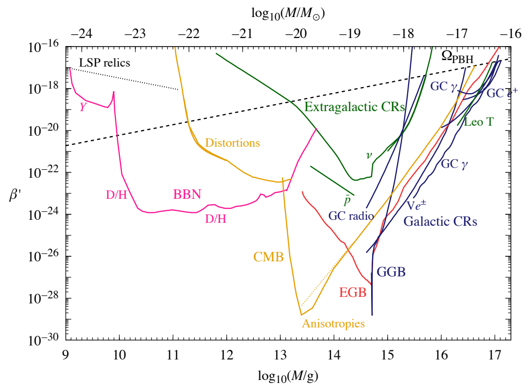
- ★ PBHs are a unique probe of ε on small scales.
- ★ They need either blue spectrum or spectral feature or pressure reduction

35

Evaporation Constraints

B. Carr, K. Kohri, Y. Sendouda & J. Yokoyama

Progress Theoretical Physics 84 (2021) 116902, arXiv:2002.12778



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MEMORY BURDEN EFFECT

- ★ Black hole evaporation *leaves the semi-classical regime* ***at latest at half-mass***, possibly much earlier.
  [Dvali 2021]
- ★ Evaporation rate Γ becomes *entropy suppressed*
  [Dvali *et al.* 2020]

$$\Gamma \longrightarrow \frac{1}{S^k}\Gamma\,, \qquad k \geq 1, k \in \mathbb{N}$$

S is huge: $S \sim 10^{30}\left(\frac{M}{10\,\mathrm{g}}\right)^2$

- ★ This opens up a large mass range for *ultra-light PBHs* as (quasi-)remnants!

Black Hole Metamorphosis and Stabilization by Memory Burden

Gia Dvali,[1,2,*] Lukas Eisemann,[1,2,†] Marco Michel,[1,2,‡] and Sebastian Zell[3,1,2,§]

arXiv:2006.000011

New Mass Window for Primordial Black Holes as Dark Matter from Memory Burden Effect

Ana Alexandre,[1,2,*] Gia Dvali,[1,2] and Emmanouil Koutsangelas[1,2,†]

arXiv:2402.14069

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Memory burden effect in black holes and solitons: Implications for PBH

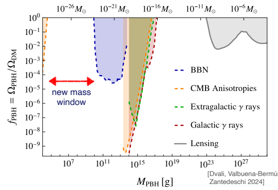
Gia Dvali,[1,2] Juan Sebastián Valbuena-Bermúdez,[3,*] and Michael Zantedeschi[4,5,†]

arXiv:2405.13117

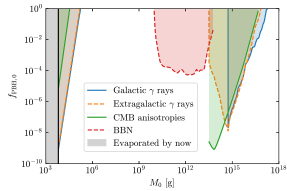
Breakdown of hawking evaporation opens new mass window for primordial black holes as dark matter candidate

Valentin Thoss,[1,2,3★] Andreas Burkert[1,2,3] and Kazunori Kohri[4,5,6]

arXiv:2402.17823



[Dvali, Valbuena-Bermúdez, Zantedeschi 2024]



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PBHS AND INFLATION

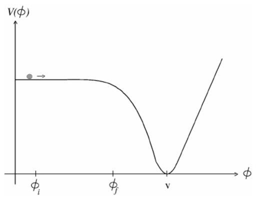
PBHs formed before reheat inflated away =>

$$M > M_{min} = M_{Pl}(T_{reheat} / T_{Pl})^{-2} > 1\ \mathrm{gm}$$

CMB quadrupole => $T_{reheat} < 10^{16}$GeV

But inflation generates fluctuations

$$\frac{\delta\rho}{\rho} \sim \left[\frac{V^{3/2}}{M_{Pl}^{\ 3}V'}\right]_H$$



Can these generate PBHs?

[HUGE NUMBER OF PAPERS ON THIS]

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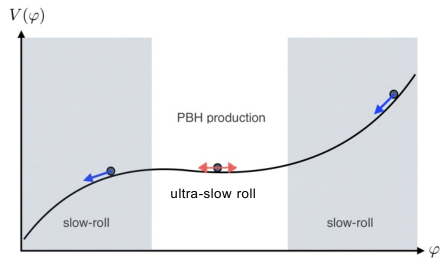
QUANTUM DIFFUSION

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

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



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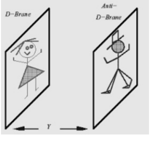
D-BRANE INFLATION

Dvali & Tye (1998) arXiv: hep-ph/9812483

Abstract

We present a novel inflationary scenario in theories with low scale (TeV) quantum gravity, in which the standard model particles are localized on the branes whereas gravity propagates in the bulk of large extra dimensions. This inflationary scenario is natural in the brane world picture. In the lowest energy state, a number of branes sit on top of each other (or at an orientifold plane), so the vacuum energy cancels out. In the cosmological setting, some of the branes "start out" relatively displaced in the extra dimensions and the resulting vacuum energy triggers the exponential growth of the 3 non-compact dimensions. The number of e-foldings can be very large due to the very weak brane-brane interaction at large distances. In the effective four-dimensional field theory, the brane motion is described by a slowly rolling scalar field with an extremely flat plateau potential. When branes approach each other to a critical distance, the potential becomes steep and inflation ends rapidly. Then the branes "collide" and oscillate about the equilibrium point, releasing energy mostly into radiation on the branes.



Only form of inflation in string theory and generically produces PBHs

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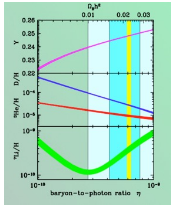
THE DARK SIDE

BLACK HOLES COULD BE DARK MATTER ONLY IF PRIMORDIAL

BBNS => Ω_{baryon}= 0.05



Ω_{dm}= 0.25 ⇒ need non-baryonic DM => WIMPs or PBHs

No evidence yet for WIMPs!

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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 ≳ 1.5$M_\odot$ 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.

Early paper on PBHs as dark matter

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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

Early paper on generation of galaxies by PBHs

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Inflation and primordial black holes as dark matter

P. Ivanov, P. Naselsky, and I. Novikov

Phys. Rev. D **50**, 7173 - 7178 (1994)

Massive Primordial Black Holes from Hybrid Inflation as Dark Matter and the seeds of Galaxies

Sébastien Clesse[1,*] and Juan García-Bellido[2,†]

arXiv:1501.7565

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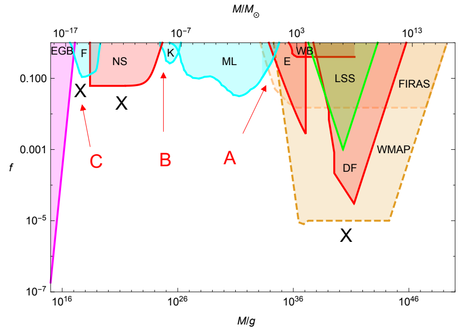
PRIMORDIAL BLACK HOLES AS DARK MATTER

Bernard Carr,[1,*] Florian Kühnel,[2,†] and Marit Sandstad[3,‡]

PRD 94, 083504, arXiv:1607.06077



Three windows: (A) intermedate mass; (B) sublunar mass; (C) asteroid mass.

But some of these limits are now thought to be wrong

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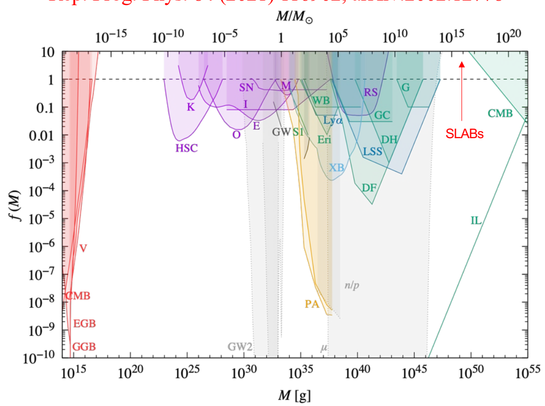
More Detailed Constraints on PBH Dark Matter

B. Carr, K. Kohri, Y. Sendouda & J. Yokoyama

Rep. Prog. Phys. 84 (2021) 116902, arXiv:2002.12778



Stupendously Large Black Holes (SLABs) BC, Kuhnel & Visinelli 2021

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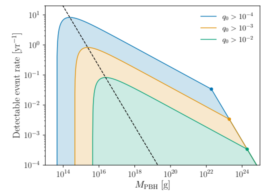
Close encounters of the primordial kind: a new observable for primordial black holes as dark matter

Tung X. Tran,[1,*] Sarah R. Geller,[1,2,3,†] Benjamin V. Lehmann,[1,‡] and David I. Kaiser[1,§]

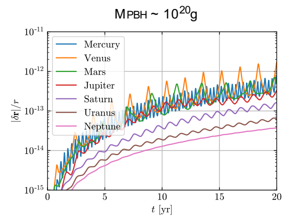
arXiv:2312.1727

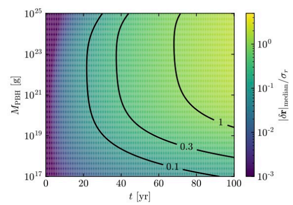


Primordial Black Holes in the Solar System

Valentin Thoss[1,2,3] and Andreas Burkert[1,2,3]

arXiv:2409.04518





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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.

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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.

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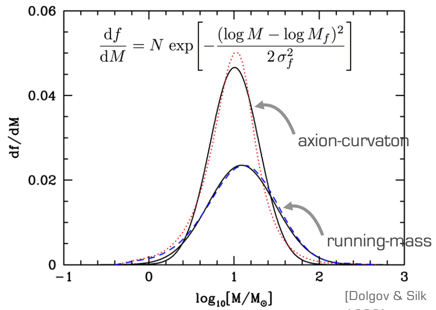
Generic Mass Function – The Lognormal Case



[Dolgov & Silk 1992]

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Seven Hints for Primordial Black Hole Dark Matter

Sébastien Clesse[1,2,*] and Juan García-Bellido[3,4,†]

arXiv:1711.10458

Cosmic Conundra Explained by Thermal History and Primordial Black Holes

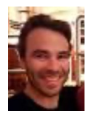
Bernard Carr,[1,2,*] Sébastien Clesse,[3,4,†] Juan García-Bellido,[5,‡] and Florian Kühnel[6,§]

arXiv:1906.08217

Observational Evidence for Primordial Black Holes: A Positivist Perspective

B. J. Carr,[1,*] S. Clesse,[2,†] J. García-Bellido,[3,‡] M. R. S. Hawkins,[4,§] and F. Kühnel[5,¶]

arXiv:2306.03903



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Observational evidence for primordial black holes

- Microlensing of Quasars + M31
- LVK - GWTC-3 - (mass+spin+merger rates)
- Core-cusp in dwarf spheroidals
- CIB - XRB source-subtracted correlations
- UFDG min size
- UFDG mass-to-light ratio
- Chandra Deep Field (IMBH)
- OGLE+Gaia (solar-mass)
- OGLE+HSC (planetary-mass)
- SMBH + IMBH accretion (Chandra)
- MW ultra-high-velocity stars (Gaia DR2)
- MACHO events to LMC (Gaia DR3)
- SSM black hole candidates (LVK)
- high-z galaxies + SMBH (JWST)
- Radio background
- exploding white dwarfs SN
- MW Disk heating
- MW tidal stream's perturbations
- PTAs – ISGW (Nanograv-IPTA)
- Dark Matter halos - rotation curves

Seven Hints
Clesse & Garcia-Bellido (2018)

Conundra
Carr, Clesse, Garcia-Bellido & Kuhnel (2021)

Evidence
Carr, Clesse, Garcia-Bellido, Hawkins & Kuhnel (2024)

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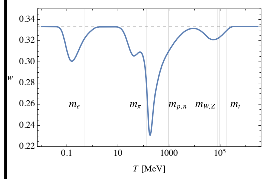
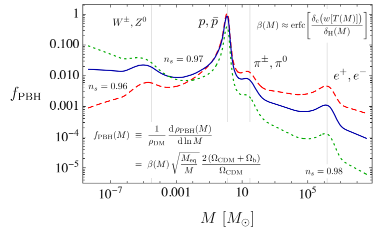
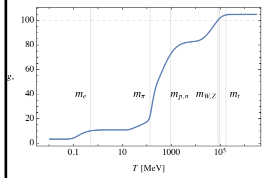
Cosmic Conundra Explained by Thermal History and Primordial Black Holes

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

arXiv:1906.08217

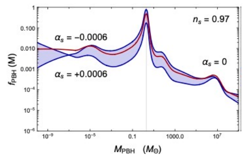






- Nearly scale-invariant PS
- Spectral index: $n_s = 0.97$
- Peak at ~2 M⊙
- Second peak at ~30 M⊙
- Two bumps at 10^{-6} and 10^{6} M⊙

Running α_s?



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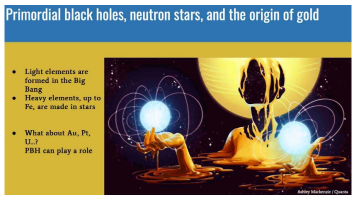
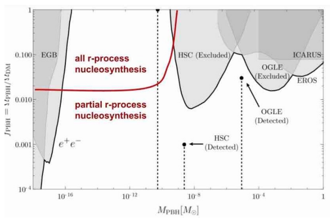
R-process elements

Fuller et al. PRL 119 (2017) 061101





Affleck-Dine process and scalar fragmentation in SUSY

[Cotner, AK, Sasaki, Takhistov et al.,1612.02529, 1706.09003, 1801.03321, 1907.10613]

Flat directions lifted by SUSY breaking terms, which determine the scale of fragmentation.

$$10^{17}\mathrm{g} \lesssim M_{\rm PBH} \lesssim 10^{22}\mathrm{g}$$

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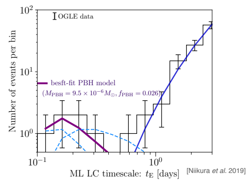
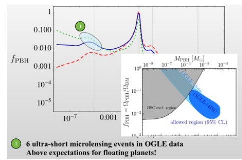
Planetary-mass microlenses

Niikura et al. arXiv:1901.07120

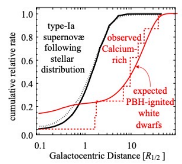
OGLE detected microlenses on 0.1-0.3 day timescale of unknown origin

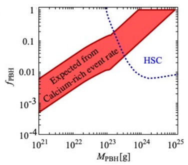




Exploding white dwarfs

Smirnov et al. arXiv:2211.00013





10^{21} g < M < 10^{24} g with 10^{-3}< $f_{\rm PBH}$ < 0.1

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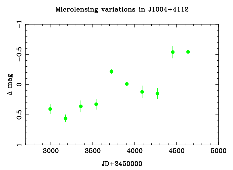
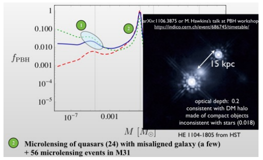
Quasar microlensing



Caustic crossing



Hawkins arXiv:2010.15007

The most plausible micolenses are PBHs in galactic halos or along line of sight to quasar

Evidence for microlensing by primordial black holes in quasar broad emission lines

M. R. S. Hawkins★

MNRAS 527, 2393 (2024)

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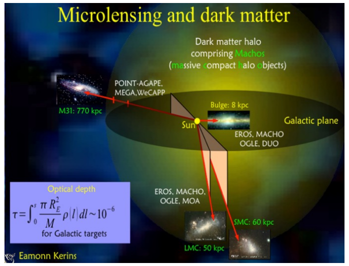
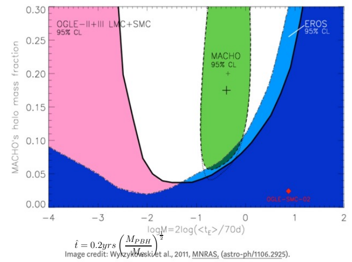
LMC/SMC microlensing



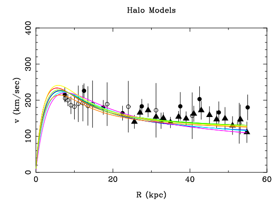


Early searches => MACHOs with 0.5 M_O

=> PBH formation at QCD transition?

Later found they provide at most 20% of DM

This assumes flat rotation curves and spherical halos and more recent models allow 100%



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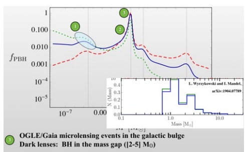
Excess of lenses in Galactic Bulge

Constraining the masses of microlensing black holes and the mass gap with *Gaia* DR2

Łukasz Wyrzykowski[1] and Ilya Mandel[2,3,4]

A&A 636, A20 (2020)



- ★ OGLE has detected 58 long-duration microlensing events in the Galactic bulge.
- ★ 18 of these cannot be main-sequence stars and are very likely black holes.
- ★ Their mass function overlaps the low mass gap from 2 to 5 $M_\odot$.
- ★ These are not expected to form as the endpoint of stellar evolution.

However…

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Microlensing optical depth and event rate toward the Large Magellanic Cloud based on 20 years of OGLE observations

Przemek Mróz,[1] Andrzej Udalski,[1] Michał K. Szymański,[1] Mateusz Kapusta,[1] Igor Soszyński,[1] Łukasz Wyrzykowski,[1] Paweł Pietrukowicz,[1] Szymon Kozłowski,[1] Radosław Poleski,[1] Jan Skowron,[1] Dorota Skowron,[1] Krzysztof Ulaczyk,[2,1] Mariusz Gromadzki,[1] Krzysztof Rybicki,[3,1] Patryk Iwanek,[1] Marcin Wrona,[1] and Milena Ratajczak[1]

arXiv:2403.02398

....Previous studies were not sensitive to long-duration events with Einstein timescales longer than 2.5-3 yr, which are expected from massive (10–100$M_\odot$) and intermediate-mass (10^2–$10^5 M_\odot$) black holes. Here, we present the analysis of nearly 20-year-long photometric monitoring of 78.7 million stars in the LMC by the Optical Gravitational Lensing Experiment (OGLE) from 2001 through 2020.....We use a sample of thirteen events to measure the microlensing optical depth toward the LMC $\tau=(0.121\pm0.037)\times10^{-7}$ and the event rate $\Gamma=(0.74\pm0.25)\times10^{-7}\ \mathrm{yr^{-1}star^{-1}}$. These numbers are consistent with lensing by stars in the Milky Way disk and the LMC itself, and they demonstrate that massive and intermediate-mass black holes cannot comprise a significant fraction of the dark matter.

But combination of extended mass function, clustering and falling rotation curve get around this.

Reanalysis of the MACHO constraints on PBH in the light of Gaia DR3 data

Juan García-Bellido[1*] and Michael Hawkins[2†]

arXiv:2402.00212

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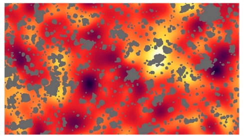
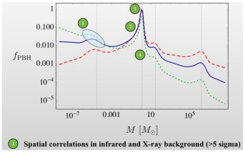
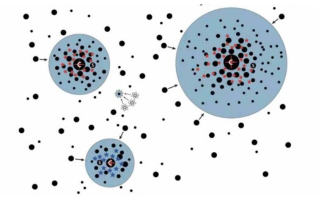
Cosmic infrared/X-ray backgrounds

Spatial coherence of X and IR source-subtracted backgrounds
=> overabundance of high-z halos => PBH Poisson effect



Kashlinsky arXiv:1605.04023





Cappelluti, Hasinger, Natarajan
arXiv:2109.08701

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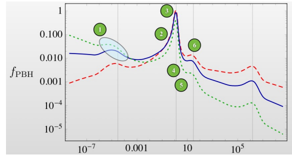
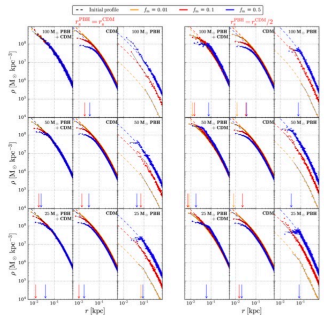
Minimum radius of ultra-faint dwarf galaxies and DM cores

Boldrini et al. arXiv:1909.07395





★ Non-detection of dwarf galaxies smaller than ~ 10 – 20 pc

★ Ultra-faint dwarf galaxies are dynamically unstable below some critical radius in the presence of PBH CDM!

★ This works with a few percent of PBH DM of 25 – 100 $M_\odot$.

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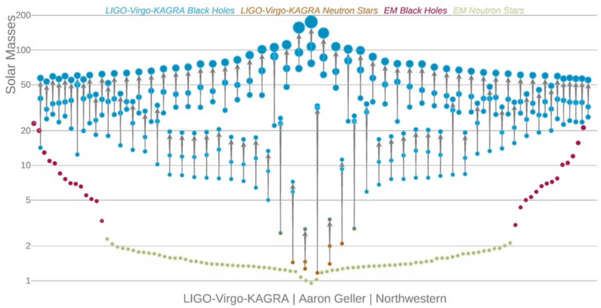
LIGO DETECTION OF GRAVITY WAVES (2016)



Do we need PBHs?

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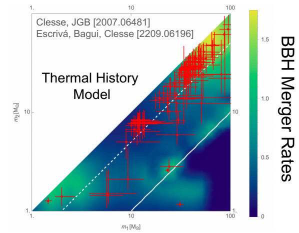
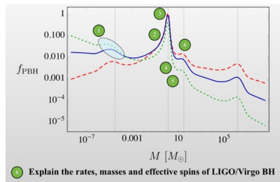
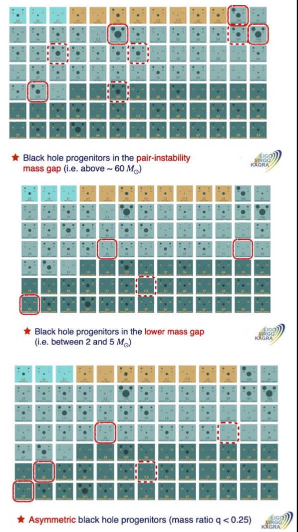
LIGO/Virgo/KAGRA black holes



n_s=0.975, α = 0, q = 0.5,0.1





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GW190814: Gravitational Waves from the Coalescence of a 23 Solar Mass Black Hole with a 2.6 Solar Mass Compact Object

R. Abbott[1], [...]

Abstract

We report the observation of a compact binary coalescence involving a 22.2–24.3 $M_\odot$ black hole and a compact object with a mass of 2.50–2.67 $M_\odot$ [...] the combination of mass ratio, component masses, and the inferred merger rate for this event challenges all current models of the formation and mass distribution of compact-object binaries.

★ Recent reanalysis of LIGO data updated merger rates and low mass ratios:

Date	FAR [yr^{-1}]	$m_1[M_\odot]$	$m_2[M_\odot]$	spin-1-z	spin-2-z	H SNR	L SNR	V SNR	Network SNR
2017-04-01	0.41	4.90	0.78	−0.05	−0.05	6.32	5.94	–	8.67
2017-03-08	1.21	2.26	0.70	−0.04	−0.04	6.32	5.74	–	8.54
2020-03-08	0.20	0.78	0.23	0.57	0.02	6.31	6.28	-	8.90
2019-11-30	1.37	0.40	0.24	0.10	−0.05	6.57	5.31	5.81	10.25
2020-02-03	1.56	1.52	0.37	0.49	0.10	6.74	6.10	-	9.10

subsolar candidates?

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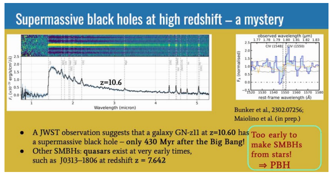
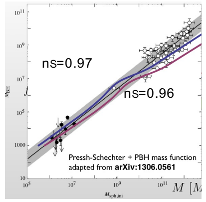
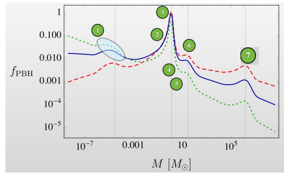
PBHs as seeds for SMBHs

Could 10^6 -10^{10} M_O black holes in galactic nuclei be primordial?



Kusenko





n_S = 0.97 => observed ratio of BH and halo mass if f_{PBH} ~ 1.

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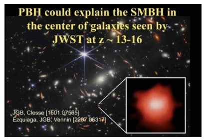
EVIDENCE FROM JWST?



Exploring a primordial solution for early black holes detected with the JWST

Pratika Dayal[1]

arXiv:2407.07162

High-redshift JWST massive galaxies and the initial clustering of supermassive primordial black holes

Hai-Long Huang[1,2] Jun-Qian Jiang[2] and Yun-Song Piao[1,2,3,4]

arXiv:2407.15781

Supermassive primordial black holes for the GHZ9 and UHZ1 observed by the JWST

Hai-Long Huang[1,2] Yu-Tong Wang,[1,2] and Yun-Song Piao[1,2,3,4]

arXiv:2410.05891

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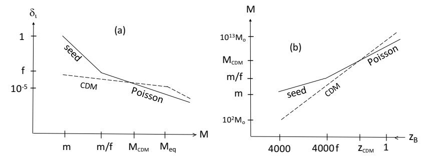
SEED AND POISSON EFFECT OF PBHS ON LARGE-SCALE STRUCTURE

$$\delta_i \approx \begin{cases} m/M & \text{(seed)} \\ (f_{\rm PBH}\, m/M)^{1/2} & \text{(Poisson)} \end{cases} \quad \Rightarrow \quad M_c \approx \begin{cases} 4000\, m\,(1+z_c)^{-1} & \text{(seed)} \\ 10^7 f_{\rm PBH}\, m\,(1+z_c)^{-2} & \text{(Poisson)} \end{cases}$$



Carr & Silk
arXiv:1801.00672

Inman & Ali-Hamoud
arXiv:1907.08129

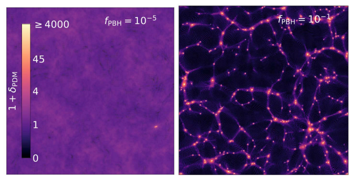


Figure 3. Expected dark matter density distribution over a scale of $2h^{-1}$ kpc at redshift $z = 100$ obtained from the N-body simulations of Ref. [49] for $m = 30\,M_\odot$ and $f_{PBH} = 10^{-5}$ (left) or $f_{PBH} = 0.1$ (right).

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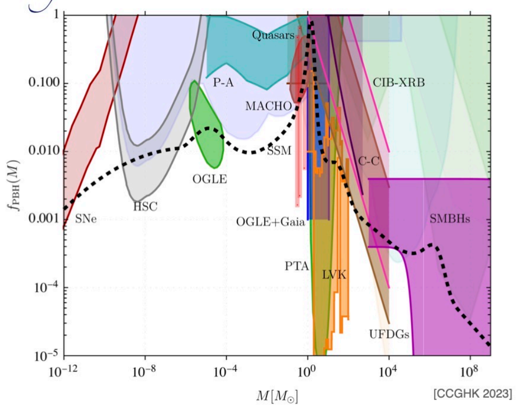
Connecting all Positive Evidences!



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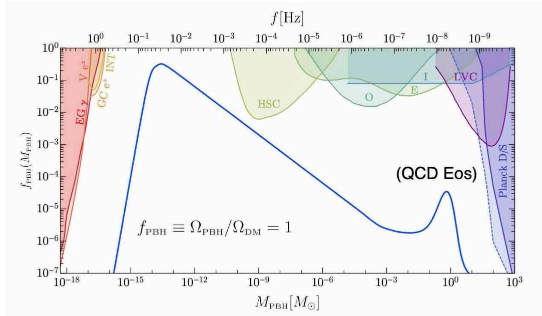
DARK MATTER IN ASTEROIDAL MASS RANGE?



Primordial black hole dark matter from inflation: the reverse engineering approach

Gabriele Franciolini[1,2,*] and Alfredo Urbano[1,2,†]

arXiv:2207.10056

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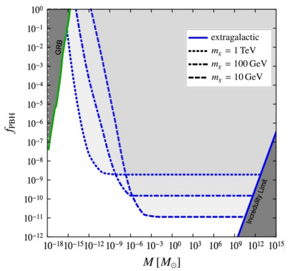
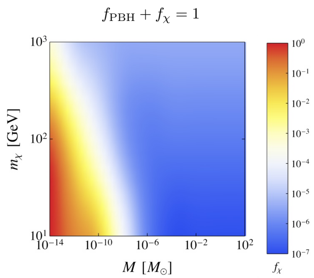
PBHs & WIMPs?

Boucenna et al. arXiv:1712.06383, Adamek et al. arXiv:1901.08528, Boudad et al. arXiv:2106.07480, Gines et al. arXiv:2207.09481, Oguri et al. arXiv:2208.05957, Chanda et al. arXiv:2209.07541, Cole et al. arXiv:2207.07576, Carr, Kuhnel & Visinelli, arXiv:2011.01930





- ★ If WIMPs provide dark matter, then f_{PBH} is tiny
- ★ If 1-10 M_o PBHs provide dark matter, then f_χ is tiny
- ★ Even small values of f_{PBH} strongly constrain f_χ

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

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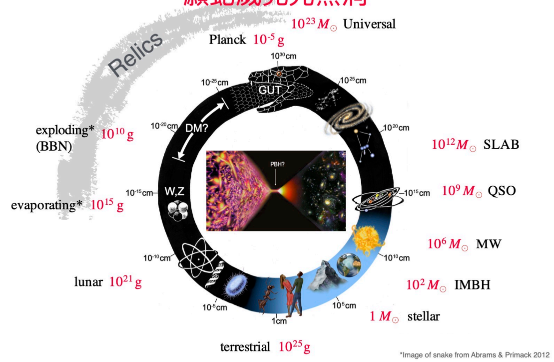
Black Holes as a Link between Micro and Macro Physics

願蛇歲見元黑洞



Ka Hei Choi "May the year of the snake be the year of primordial black hole discovery"

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