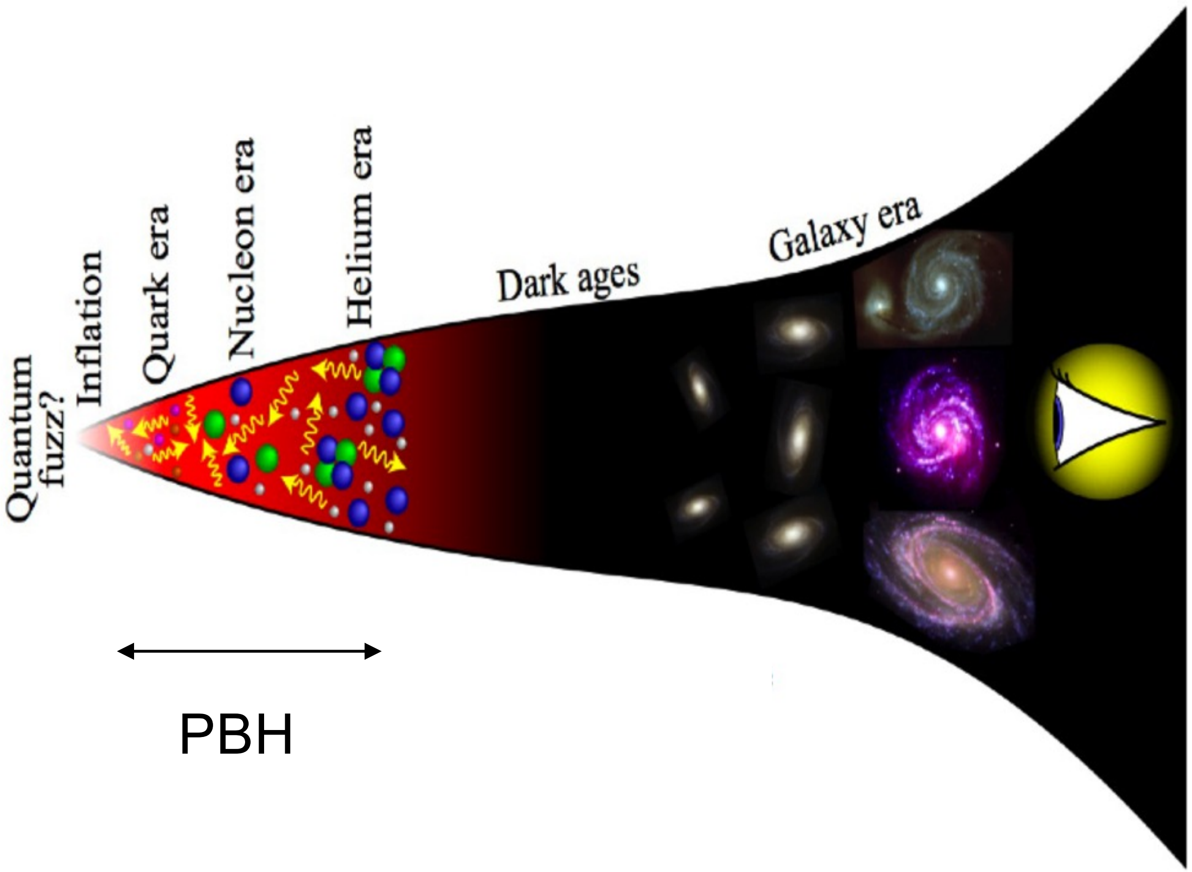
PRIMORDIAL BLACK HOLES: THE BRIGHT SIDE



Bernard Carr
Queen Mary University of London

PBH workshop, IPMU 13/11/2024

THE BRIGHT SIDE

Why Optimists Have The Power to Change The World

What do you see?

SUMIT PAUL-CHOUDHURY

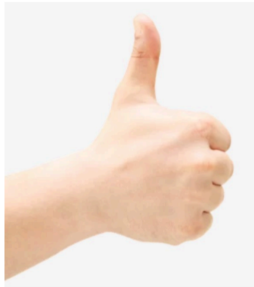
Observational Evidence for Primordial Black Holes: A Positivist Perspective

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

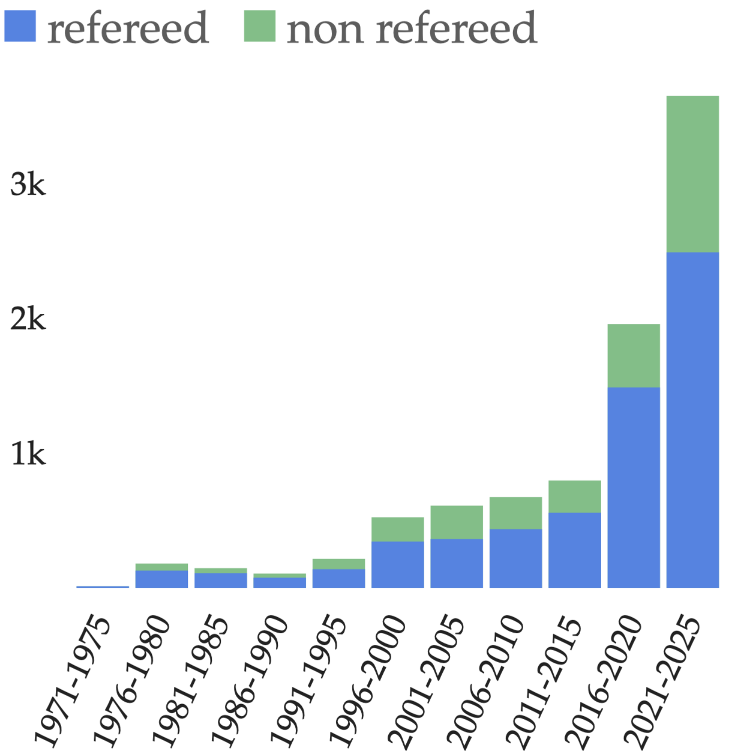
The History of Primordial Black Holes

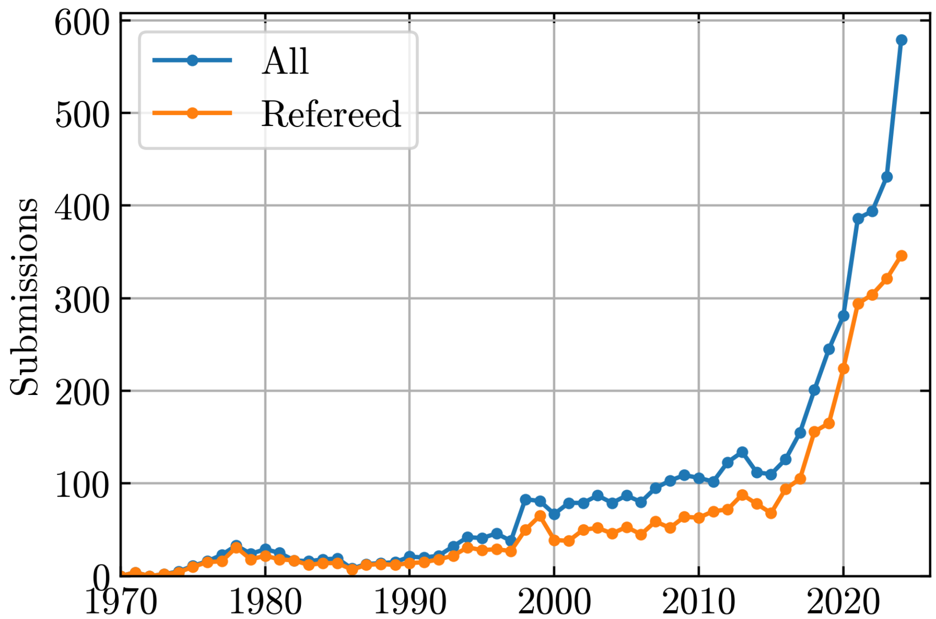
Bernard J. Carr [a] and Anne M. Green [b]

arXiv:24067.05736


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

PBH PUBLICATION RATE





Peaks due to

- Hawking radiation (1974)
- Microlensing (1995) Dark matter?
- LIGO/Virgo gravitational waves (2016)
- JWST Seeds for cosmic structure and SMBHs (2021)

PRIMORDIAL BLACK HOLES?

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

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

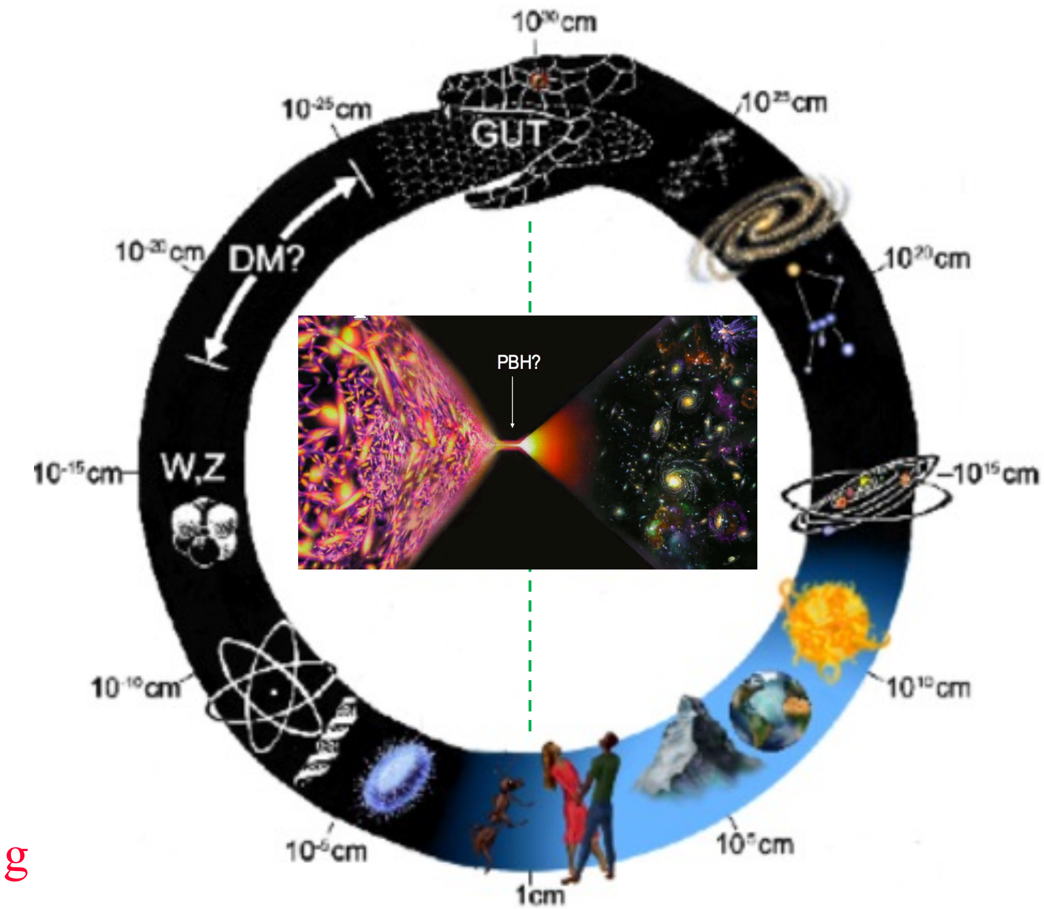
=> huge possible mass range

BLACK HOLES AS LINK BETWEEN MICRO AND MACRO PHYSICS

HIGHER DIMENSIONS

Planck 10^{-5}g

10^{22} M_O Universal



10^{12} M_O SLAB

exploding 10^{10}g

10^{9} M_O QSO

10^{6} M_O MW

evaporating 10^{15}g

10^{2} M_O IMBH

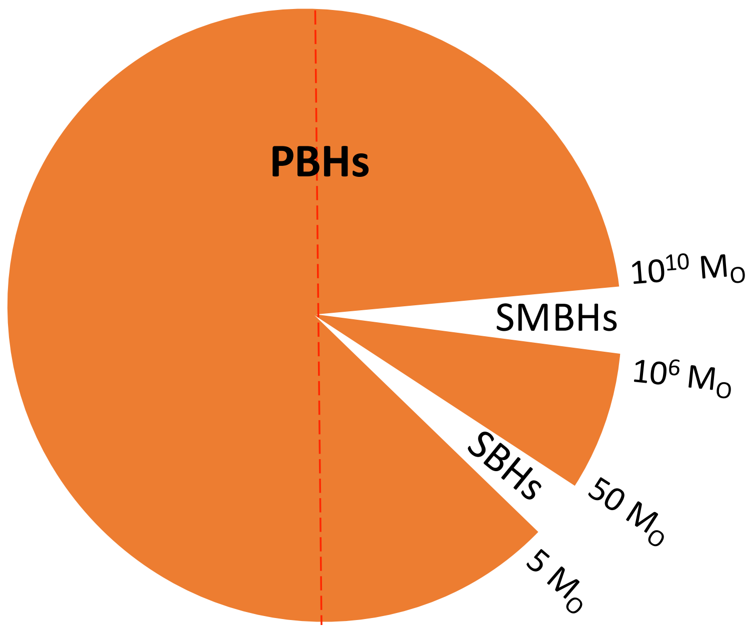
lunar 10^{21}g

1 M_O Stellar

terrestrial 10^{25}g

QUANTUM/CLASSICAL

ARE MOST BLACK HOLES PRIMORDIAL?



Does Nature populate whole Uroborus?

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.

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]

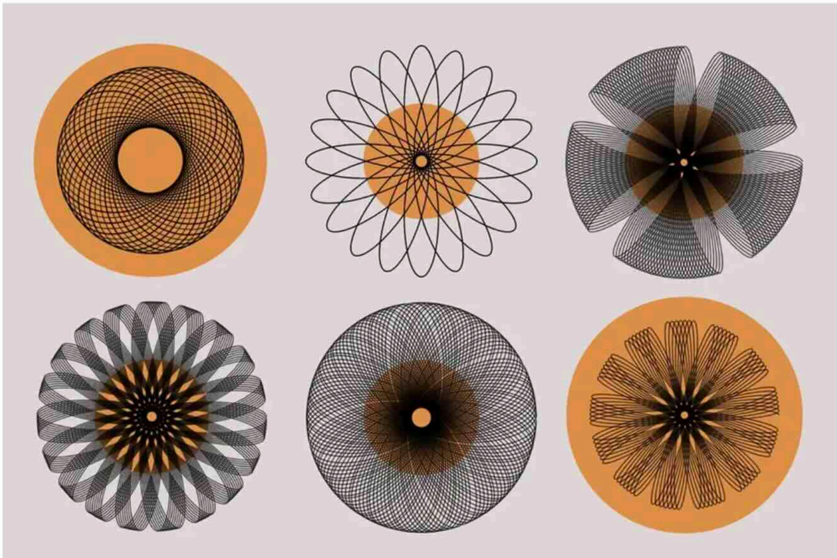
arXiv:2312.06782

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

By Leah Crane

24 May 2024



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

Vitorio A. De Lorenci

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

BLACK HOLES IN THE EARLY UNIVERSE

B. J. Carr and S. W. Hawking

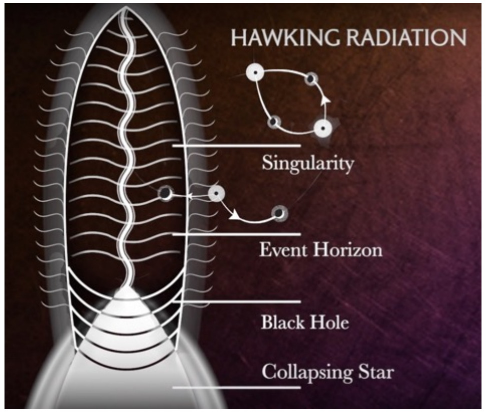
(Received 1974 February 25)

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

PBHs may be literally bright!



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

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

PBHs are important even if they never formed!

Fraction of Universe collapsing

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

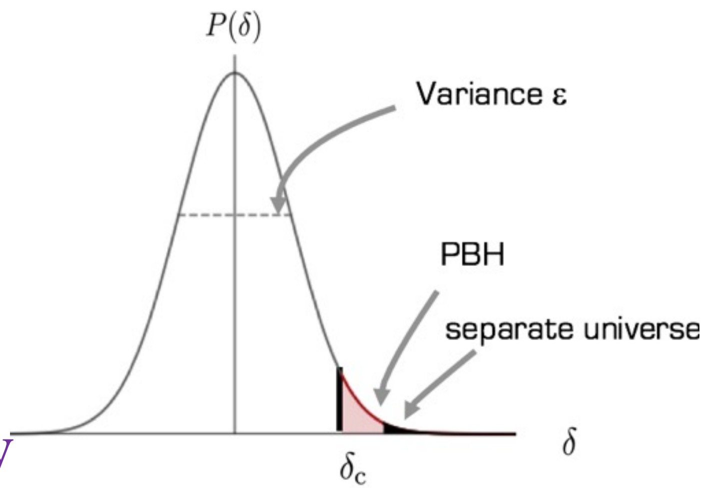
General limit

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

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

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

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



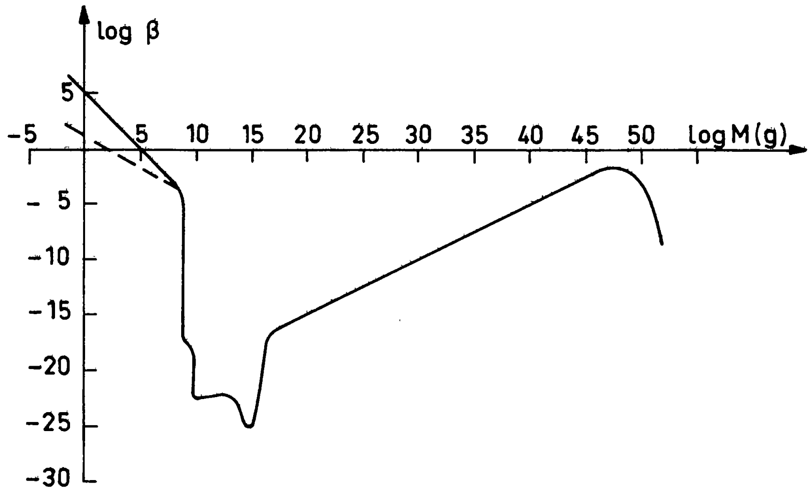
So both <u>expect</u> and <u>require</u> β(M) **to be tiny**

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)

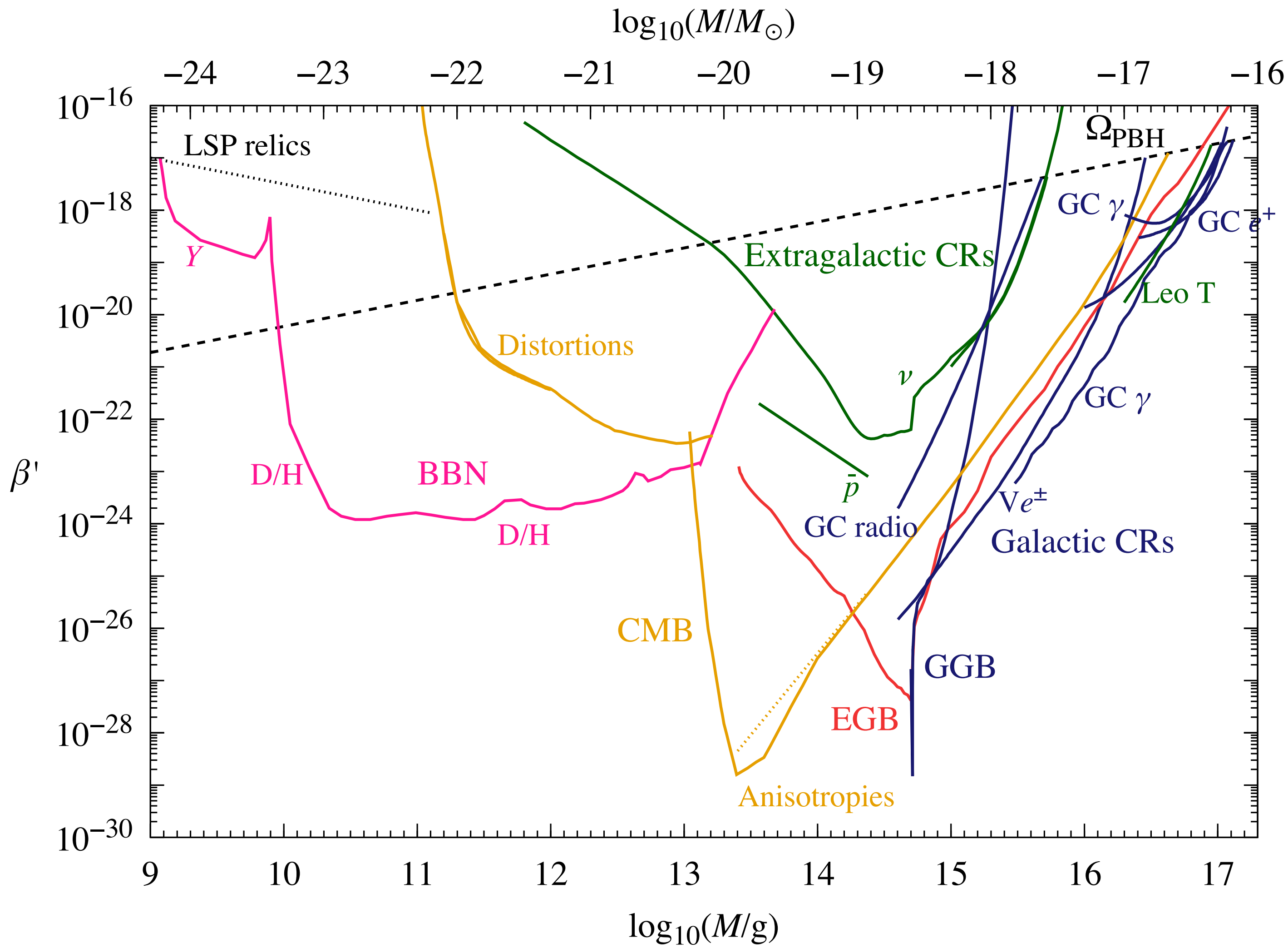
Summary. The processes of primordial black hole formation and accretion of matter onto the primordial black holes already formed are investigated. We give the limits on the possible number of primordial black holes of various masses inferred from astrophysical observations.



Evaporation Constraints

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

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



MEMORY BURDEN EFFECT?

KUHNEL TALK

Black Hole Metamorphosis and Stabilization by Memory Burden

arXiv:2006.000011

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

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

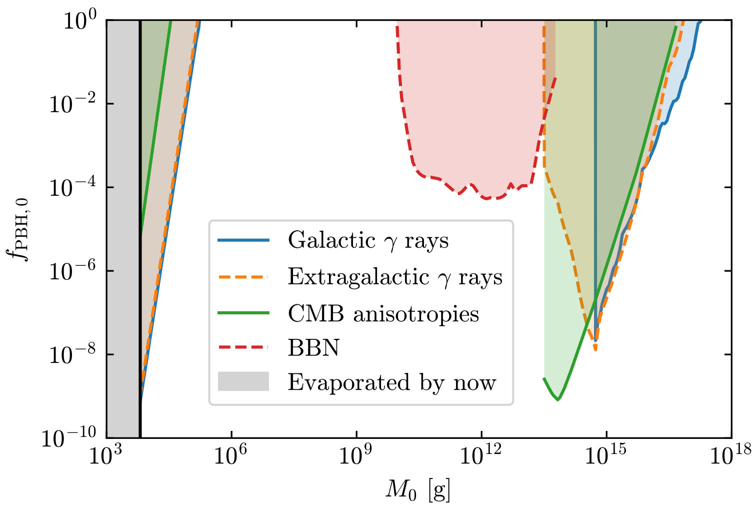
arXiv:2402.14069

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

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

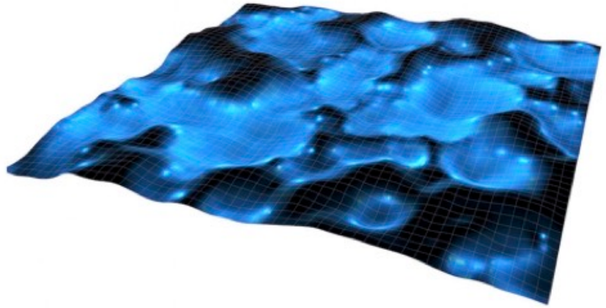
arXiv:2402.17823

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

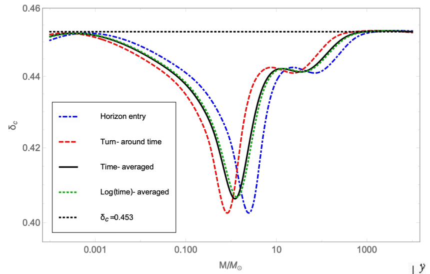


Formation Mechanisms of Primordial Black Holes

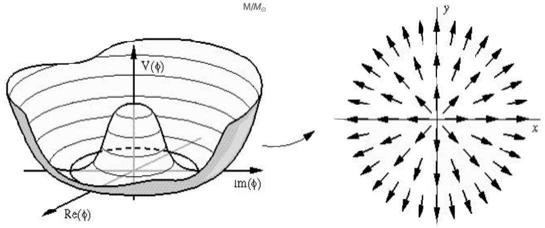
- Large density perturbations (inflation)

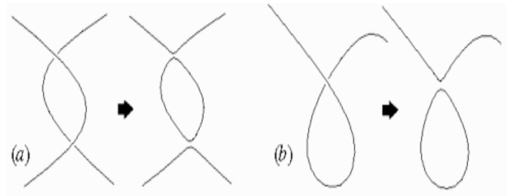


- Pressure reduction

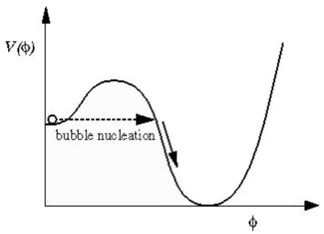


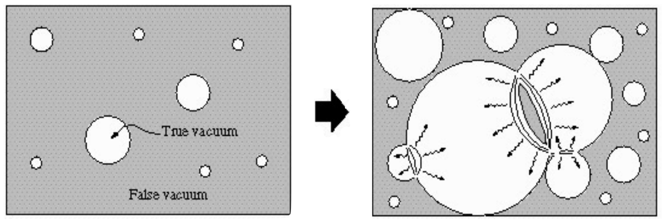
- Cosmic string loops



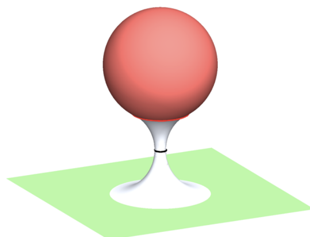


- Bubble collisions





- Collapse of domain walls or bubble of broken symmetry



ALEX KUSENKO

How to make PBHs

Need a ~30% or higher overdensity early enough in the history of the universe.

PBH formation mechanism: Yukawa "fifth force"

Yukawa interactions: $y\chi\bar{\psi}\psi$ — a heavy fermion with a light scalar

$$V(r) = \frac{y^2}{r} e^{-m_\chi r}$$

A light scalar field ⇒ long-range attractive force, stronger than gravity ⇒ instability similar to gravitational instability, only stronger

⇒ **halos form even in radiation dominated universe**

[Amendola et al., 1711.09915; Savastano et al., 1906.05300; Domenech, Sasaki, 2104.05271]

Same Yukawa coupling provides a source of **radiative cooling** by emission of gravitational radiation ⇒ **halos collapse to black holes**

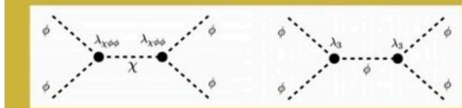
[Flores, AK, 2008.12456, PRL 126 (2021) 041101; 2008.12456]

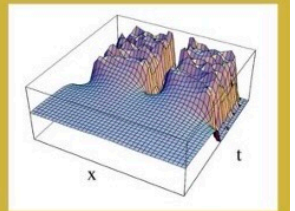
Scalar fields: an instability (Q-balls)

Gravitational instability can occurs due to the attractive force of gravity.

Similar instability can occur due to scalar self-interaction which is **attractive**:

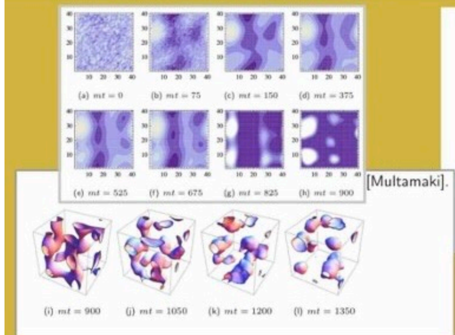
$$U(\phi) \supset \lambda_3 \phi^3 \quad \text{or} \quad \lambda_{\chi\phi\phi}\chi\phi^\dagger\phi$$





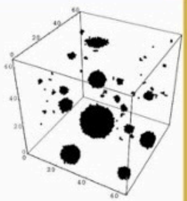
[AK, Shaposhnikov, hep-ph/9709492]

Numerical simulations of scalar field fragmentation



[Multamaki].

SUSY Q-balls



[Kasuya, Kawasaki]

Affleck-Dine process and scalar fragmentation in SUSY

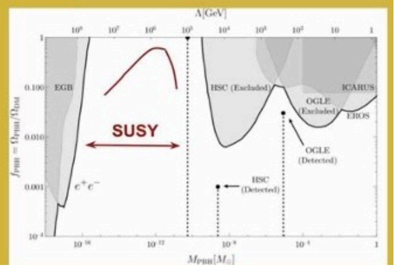
[Cotner, AK, Sasaki, Takhistov et al.,1612.02529, 1706.09003, 1801.03321, 1907.10613]

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

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

$$M_{\rm hor} \sim r_f^{-1}\left(\frac{M^3_{\rm Planck}}{M^2_{\rm SUSY}}\right) \sim 10^{23}\mathrm{g}\left(\frac{100\ \mathrm{TeV}}{M_{\rm SUSY}}\right)^2$$

$$M_{\rm PBH} \sim r_f^{-1} \times 10^{22}\mathrm{g}\left(\frac{100\ \mathrm{TeV}}{M_{\rm SUSY}}\right)^2$$



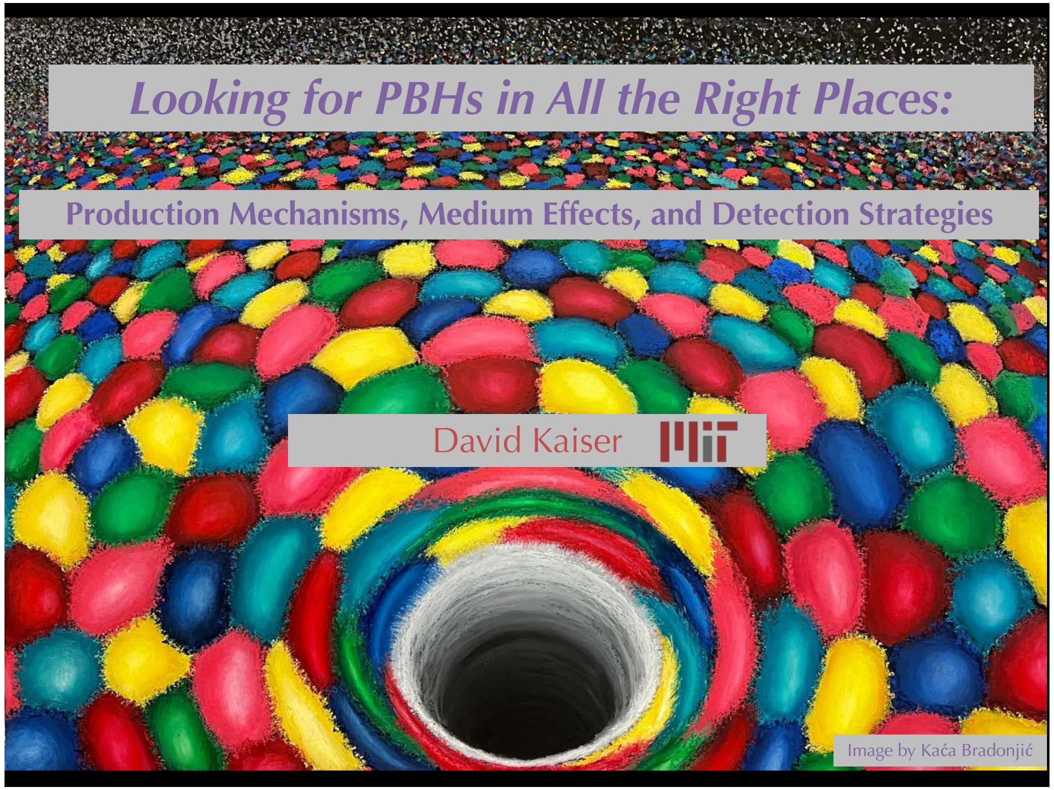
Cotner, AK, Phys.Rev.Lett. 119 (2017) 031103
Cotner, AK, Sasaki, Takhistov, JCAP 1910 (2019) 077

Primordial Black Holes with QCD Color Charge

Elba Alonso-Monsalve* and David I. Kaiser†

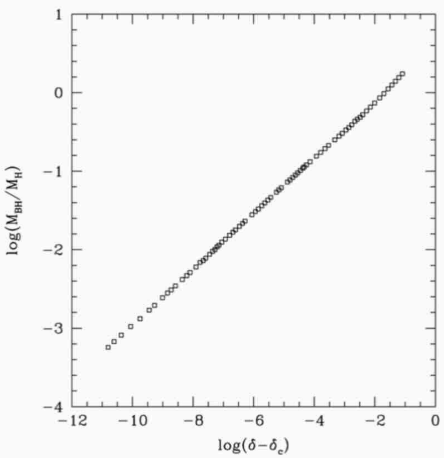
We describe a realistic mechanism whereby black holes with significant QCD color charge could have formed during the early universe. Primordial black holes (PBHs) could make up a significant fraction of the dark matter if they formed well before the QCD confinement transition. Such PBHs would form by absorbing unconfined quarks and gluons, and hence could acquire a net color charge. We estimate the number of PBHs per Hubble volume with near-extremal color charge for various scenarios, and discuss possible phenomenological implications.

arXiv:2310.16877



ILIA MUSCO (NUMERICAL SIMULATIONS)

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

$\gamma \simeq 0.36$

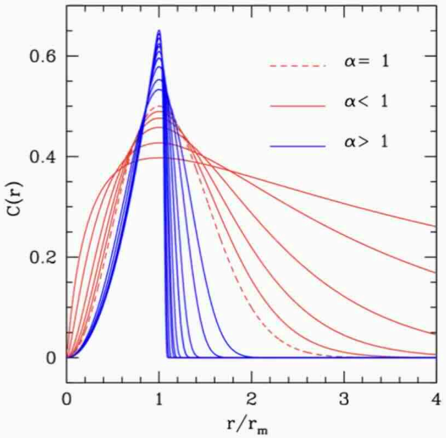
Niemeyer , Jedamzik - (1999)

IM, Miller, Polnarev - CQG (2009, 2013)

Shape parameter

$$\mathcal{C}'(r_m) = 0, \quad \Phi_m \equiv -r_m \zeta'(r_m)$$

$$\delta(r_m, t_H) = 3\frac{\delta\rho}{\rho_b}(r_m, t_H)$$



$$\tilde{r} = r e^{\zeta(r)}$$

$$\alpha \equiv -\frac{\mathcal{C}''(\tilde{r}_m)\tilde{r}_m^2}{4\mathcal{C}(\tilde{r}_m)} = \frac{\alpha_G}{\left(1 - \frac{1}{2}\Phi_m\right)\left(1 - \Phi_m\right)}$$

$$0.4 \leq \delta_c(\alpha) \leq \frac{2}{3}$$

- *I. Musco* - PRD (2019)
- *Escrivá, Germani, Sheth* - PRD (2020)

PBH threshold

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

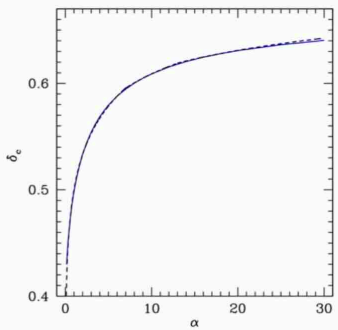
$\bar{\mathcal{C}}(r_m) \simeq 0.4$ (shape independent)

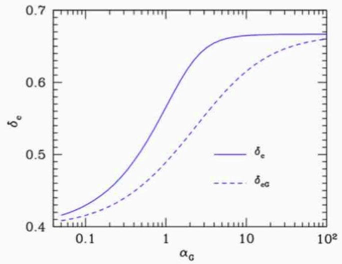
$$\delta_c \simeq \frac{4}{15} e^{-\frac{1}{\alpha}} \frac{\alpha^{1-5/2\alpha}}{\Gamma\left(\frac{5}{2\alpha}\right) - \Gamma\left(\frac{5}{2\alpha}, \frac{1}{\alpha}\right)}$$

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

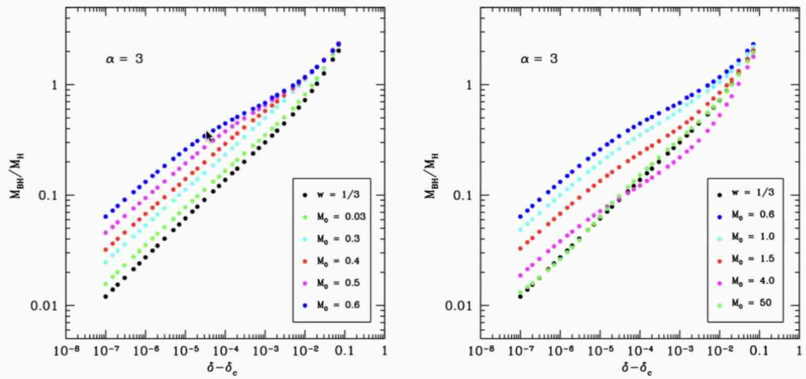
$$\delta_c \simeq \begin{cases} 0.13\alpha + 0.41 & \alpha \lesssim 0.25 \\ \alpha^{0.045} - 0.50 & 0.25 \lesssim \alpha \lesssim 7 \\ \alpha^{0.035} - 0.475 & 7 \lesssim \alpha \lesssim 13 \\ \alpha^{0.026} - 0.45 & 13 \lesssim \alpha \lesssim 30 \end{cases}$$

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





PBH scaling law during the QCD



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

IM, K. Jedamzik, Sam Young - PRD (2024)

PBHS AND INFLATION

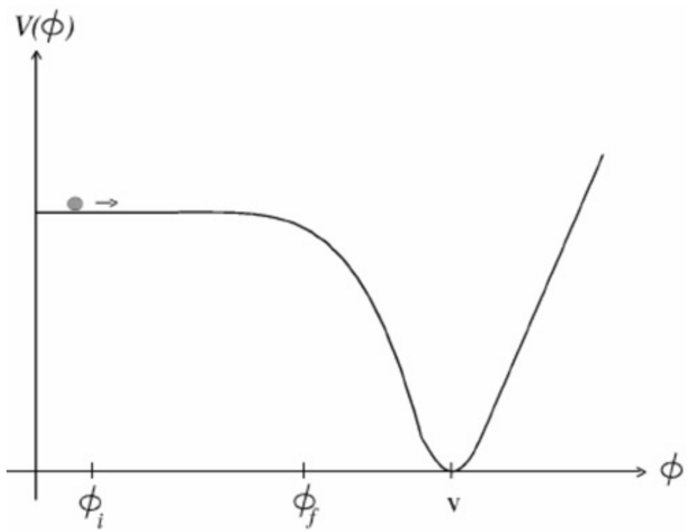
PBHs formed before reheat inflated away =>

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

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

But inflation generates fluctuations

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



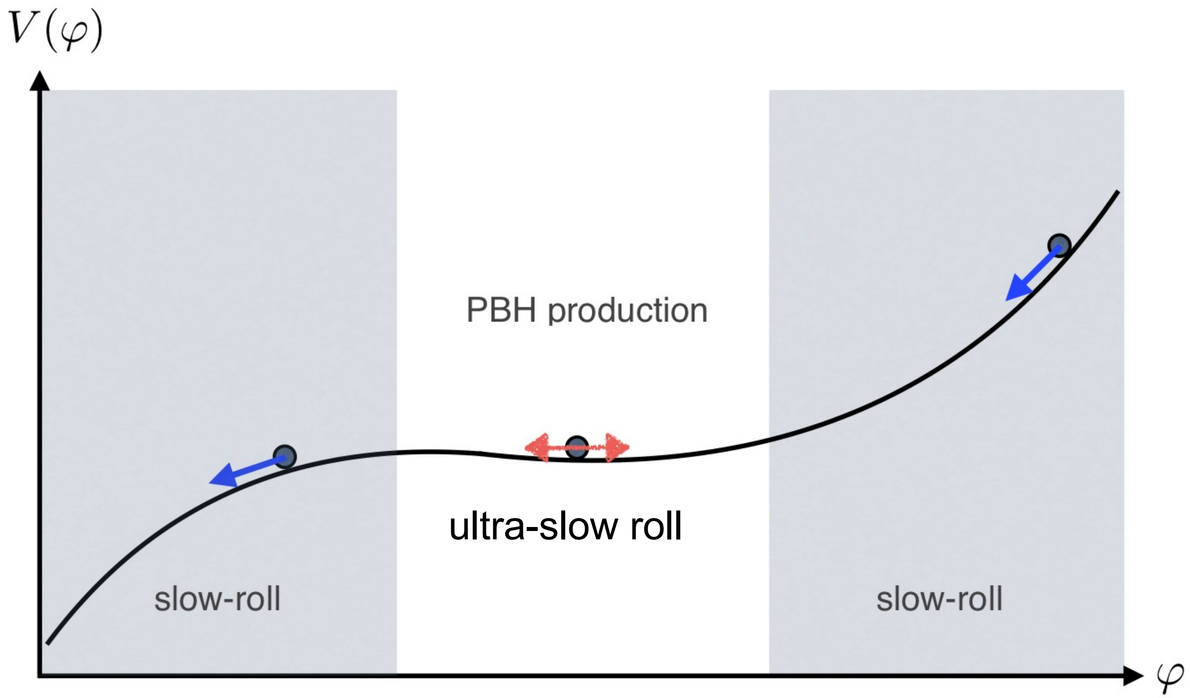
Can these generate PBHs?

[HUGE NUMBER OF PAPERS ON THIS]

QUANTUM DIFFUSION

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

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



"Looping in the Primordial Universe", October 28 - November 1, CERN

Constraining Primordial Black Hole Formation from Single-Field Inflation

Jason Kristiano, Jun'ichi Yokoyama

Phys.Rev.Lett. 132 (2024) 22, 221003,

arXiv:2211.03395

Comparing sharp and smooth transitions of the second slow-roll parameter in single-field inflation

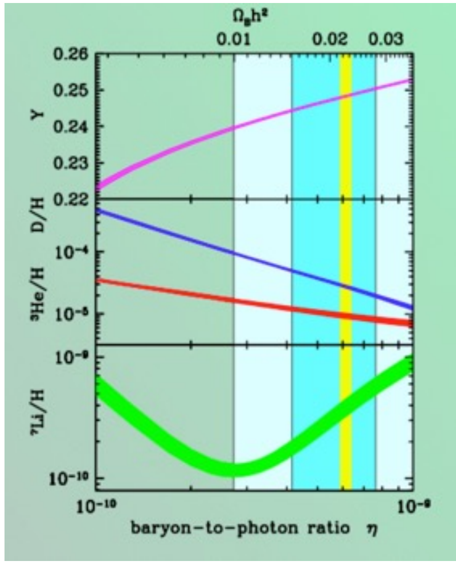
Jason Kristiano, Jun'ichi Yokoyama

arXiv:2405.12149

THE DARK SIDE

BLACK HOLES COULD BE DARK MATTER ONLY IF PRIMORDIAL

BBNS => Ω_{baryon}= 0.05



Ω_{dm}= 0.25 $\Rightarrow$ need non-baryonic DM => WIMPs or PBHs

No evidence yet for WIMPs!

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.

Early 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.

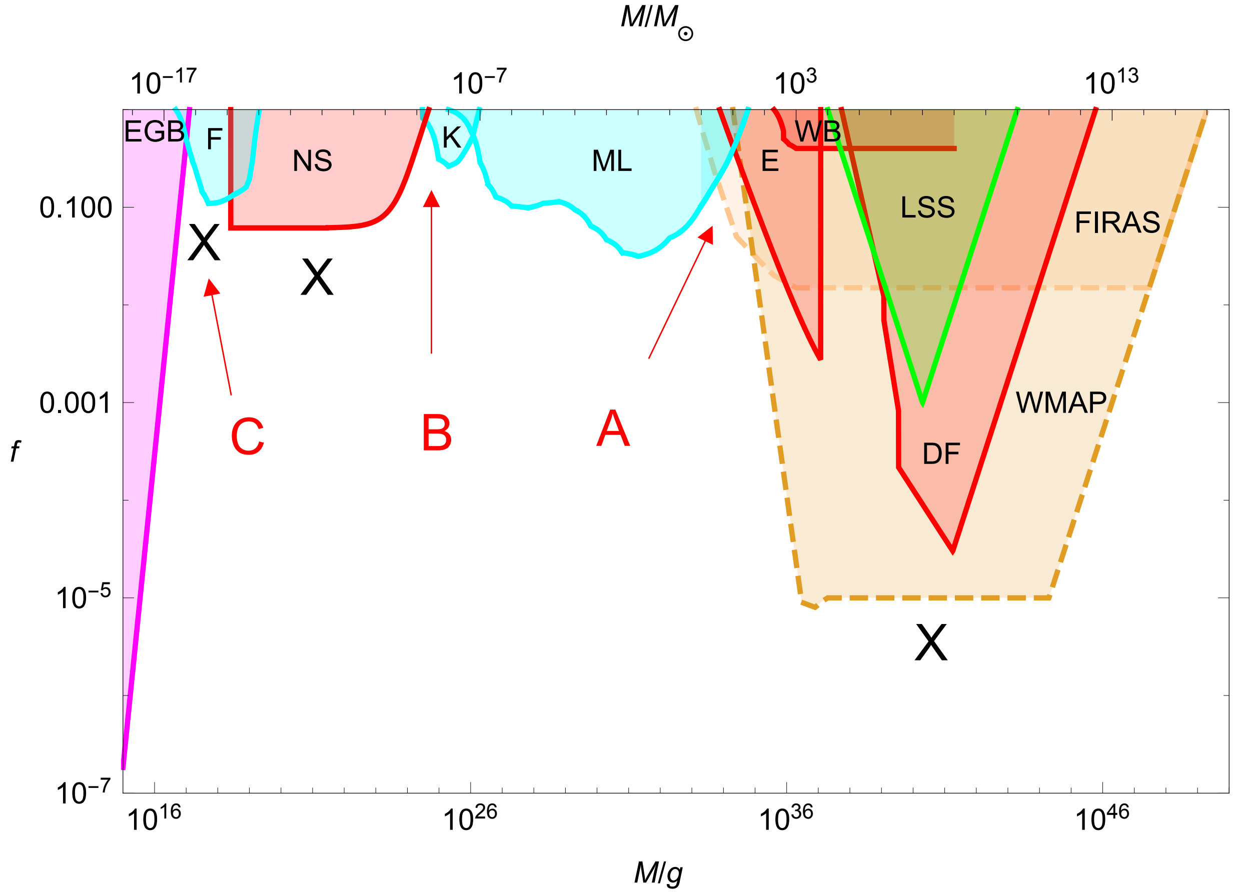
Key words: galaxy formation — primeval black holes — hidden mass — cosmology

Early paper on generation of galaxies by PBHs

PRIMORDIAL BLACK HOLES AS DARK MATTER

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

PRD 94, 083504, arXiv:1607.06077



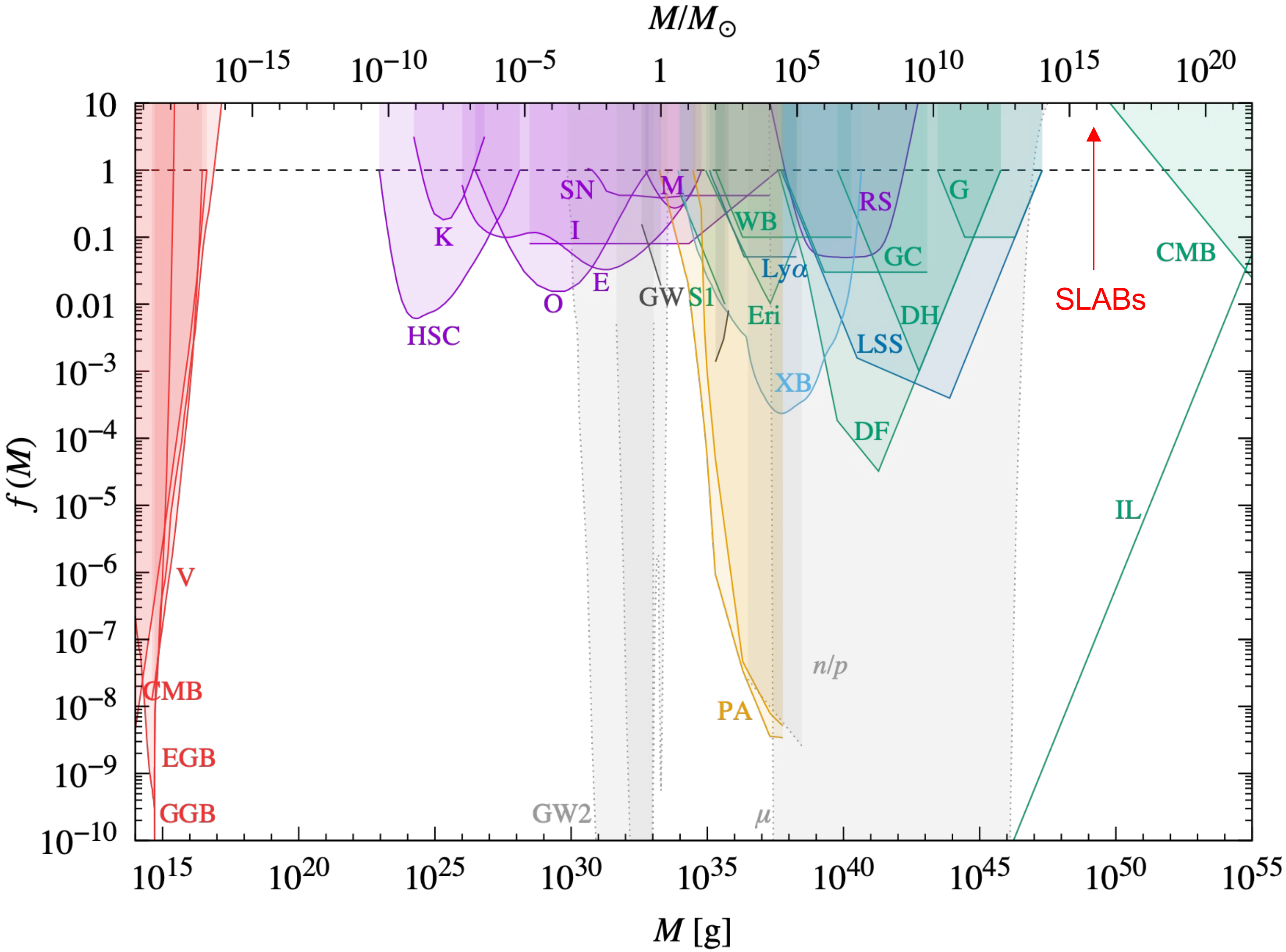
Three windows: (A) intermediate mass; (B) sublunar mass; (C) asteroid mass.

But some of these limits are now thought to be wrong

More Detailed Constraints on PBH Dark Matter

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

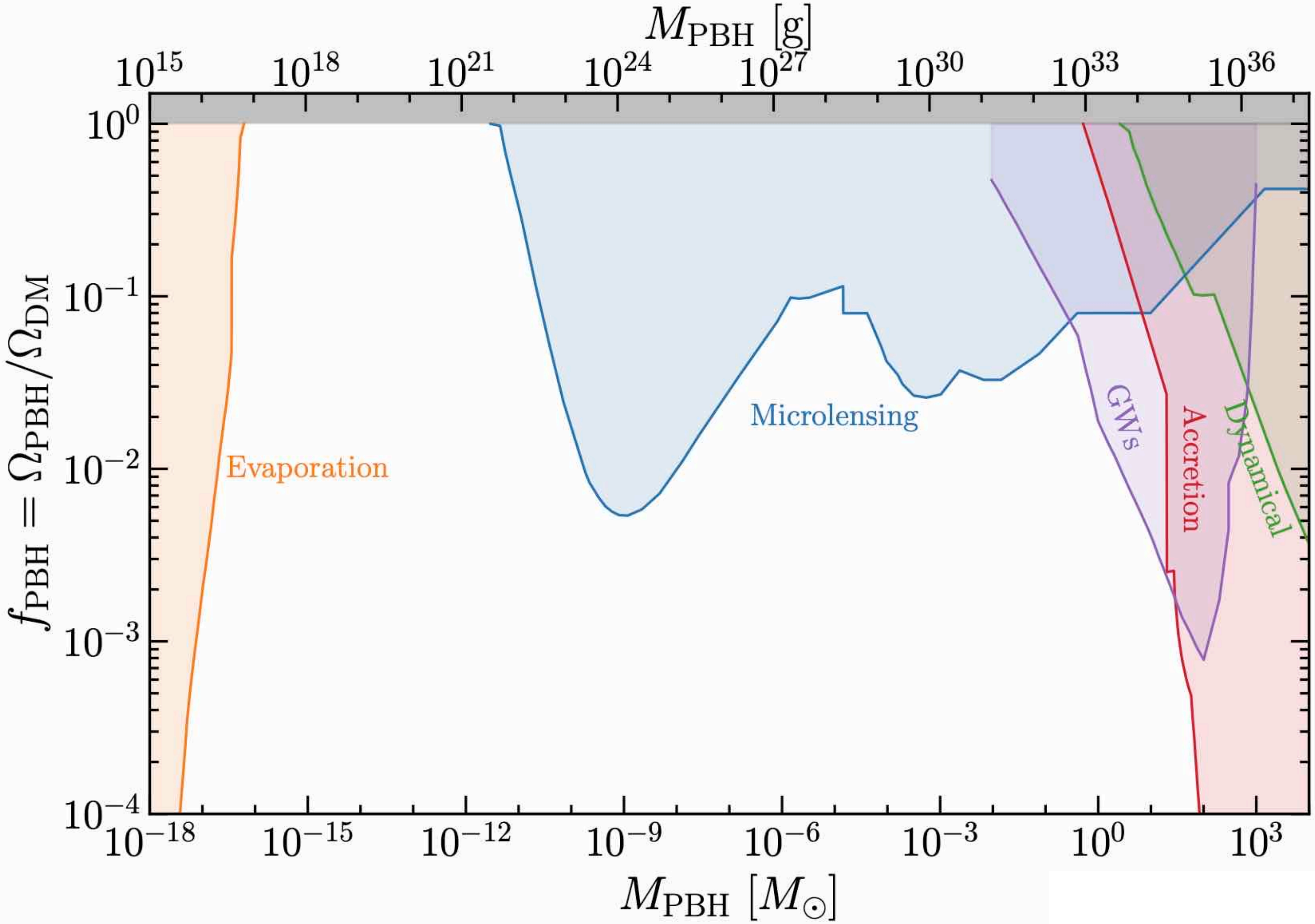
Rep. Prog. Phys. 84 (2021) 116902, arXiv:2002.12778



Stupendously Large Black Holes (SLABs) BC, FK, Visinelli 2021

PBH Constraints

[Code online: github.com/bradkav/PBHbounds]



Green & Kavanagh, arXiv:2007.10722

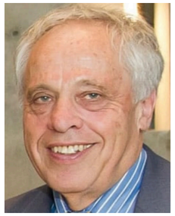
Extended Mass Functions

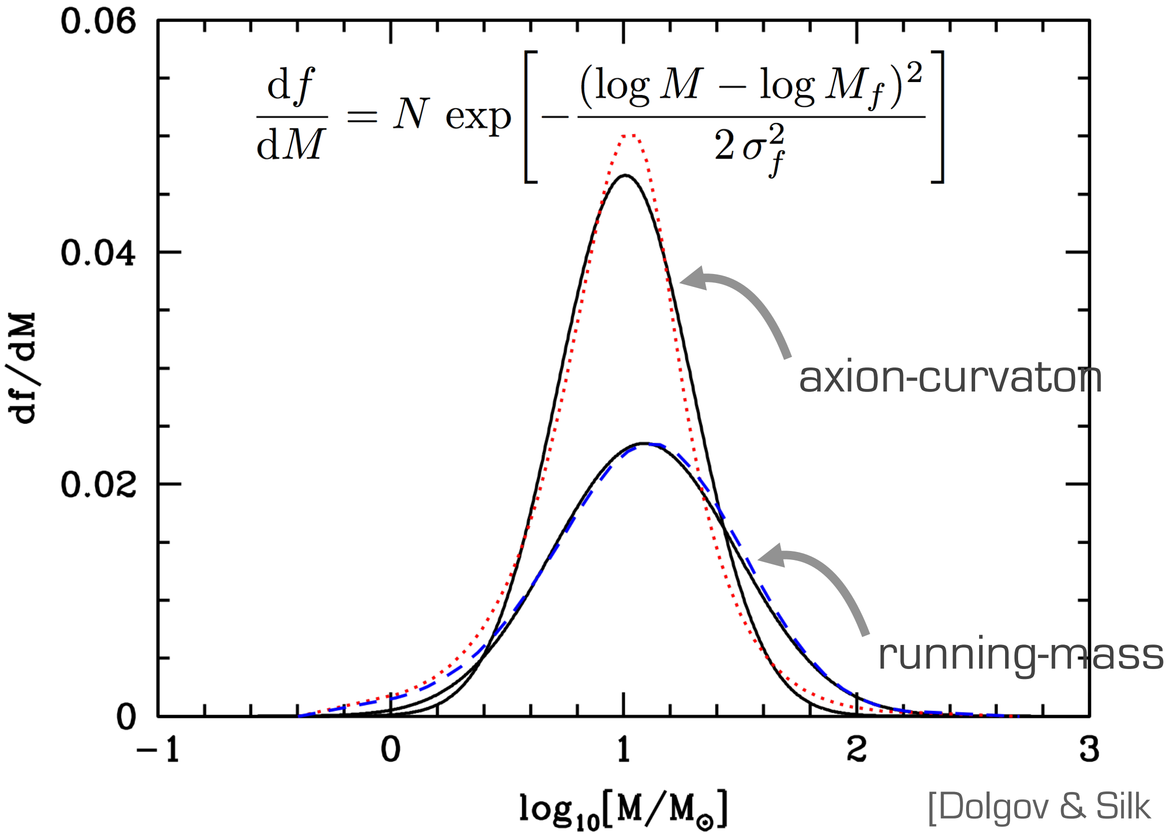
- Most constraints assume monochromatic PBH mass function.
- Can we evade standard limits with extended mass spectrum?

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.

Generic Mass Function – The Lognormal Case





[Dolgov & Silk 1992]

A. D. Gow, C. T. Byrnes and A. Hall, arXiv:2009.03204

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.

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,¶]

Physics Reports 1054 (2024) 1-67, arXiv:2306.03903

We review numerous arguments for primordial black holes (PBHs) based on observational evidence from a variety of lensing, dynamical, accretion and gravitational-wave effects. This represents a shift from the usual emphasis on PBH constraints and provides what we term a positivist perspective. Microlensing observations of stars and quasars suggest that PBHs of around $1\,M_\odot$ could provide much of the dark matter in galactic halos, this being allowed by the Large Magellanic Cloud microlensing observations if the PBHs have an extended mass function. More generally, providing the mass and dark matter fraction of the PBHs is large enough, the associated Poisson fluctuations could generate the first bound objects at a much earlier epoch than in the standard cosmological scenario. This simultaneously explains the recent detection of high-redshift dwarf galaxies, puzzling correlations of the source-subtracted infrared and X-ray cosmic backgrounds, the size and the mass-to-light ratios of ultra-faint-dwarf galaxies, the dynamical heating of the Galactic disk, and the binary coalescences observed by LIGO/Virgo/KAGRA in a mass range not usually associated with stellar remnants. Even if PBHs provide only a small fraction of the dark matter, they could explain various other observational conundra, and sufficiently large ones could seed the supermassive black holes in galactic nuclei or even early galaxies themselves. We argue that PBHs would naturally have formed around the electroweak, quantum chromodynamics and electron-positron annihilation epochs, when the sound-speed inevitably dips. This leads to an extended PBH mass function with a number of distinct bumps, the most prominent one being at around $1\,M_\odot$, and this would allow PBHs to explain many of the observations in a unified way.




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)

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

Detecting the gravitational wave background from primordial black hole dark matter

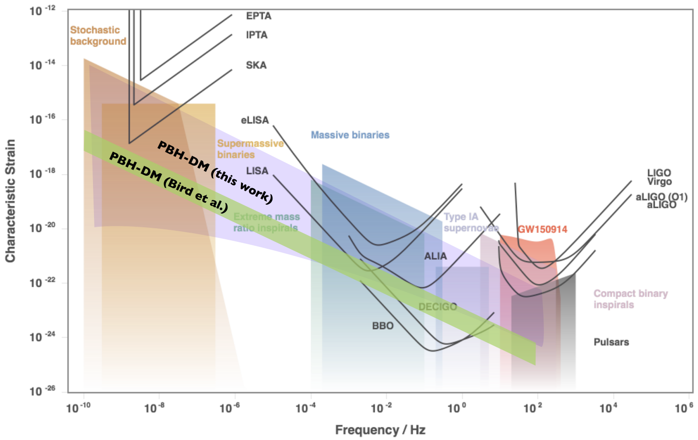
Sébastien Clesse[1,*] and Juan García-Bellido[2,†]

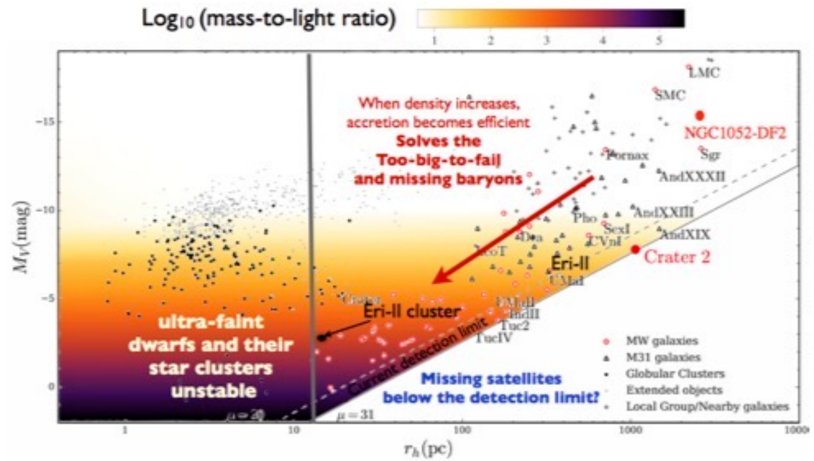
arXiv:1610.08479

Seven Hints for Primordial Black Hole Dark Matter

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

arXiv:1711.10458

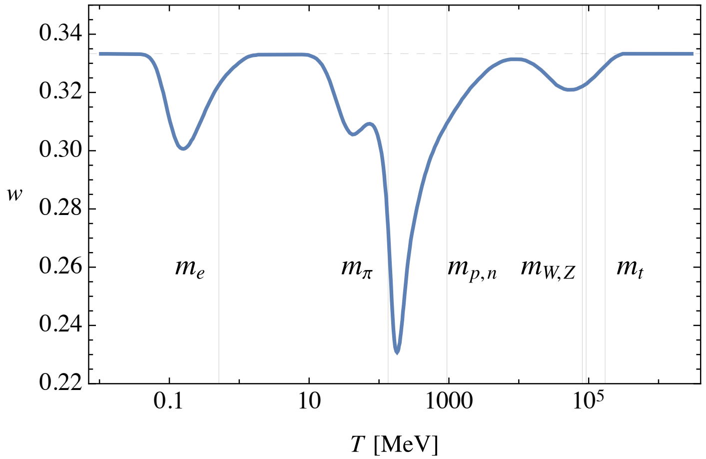


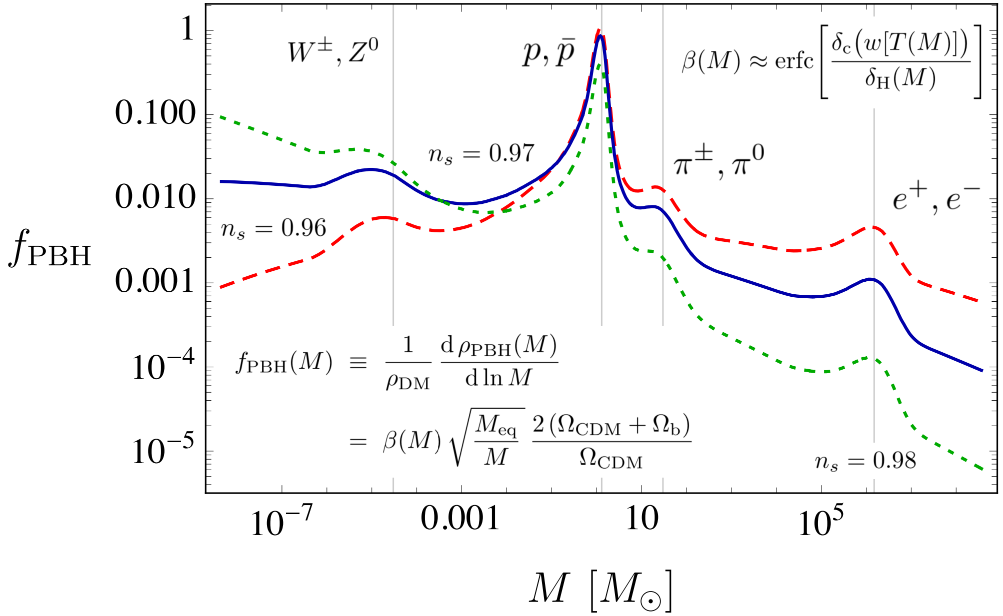


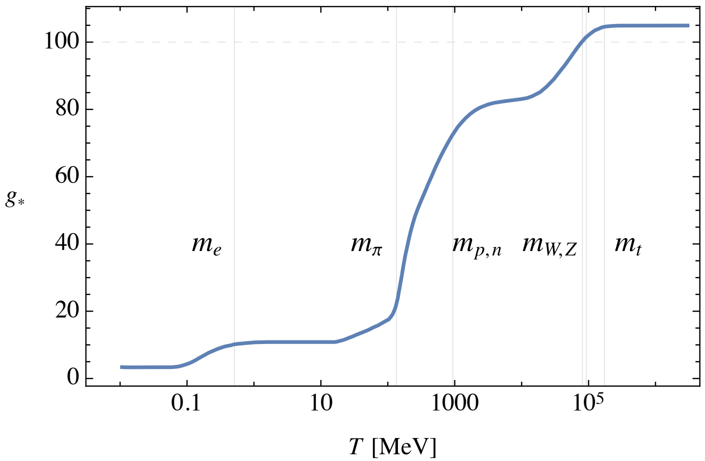
Cosmic Conundra Explained by Thermal History and Primordial Black Holes

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

arXiv:1906.08217

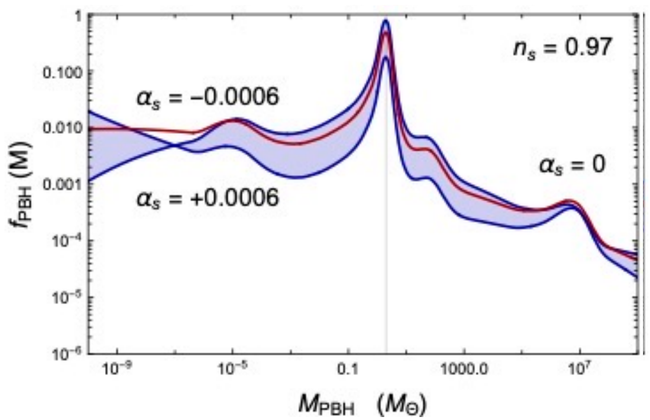






- **Nearly scale-invariant PS**
- **Spectral index: $n_s = 0.97$**
- **Peak at ~2 M⊙**
- **Second peak at ~30 M⊙**
- **Two bumps at 10^{-6} and 10^6 M⊙**

Running α_s?



Primordial black hole formation during the QCD phase transition: threshold, mass distribution and abundance

Ilia Musco,[1] Karsten Jedamzik,[2] and Sam Young[3]

arXiv:2303.07980

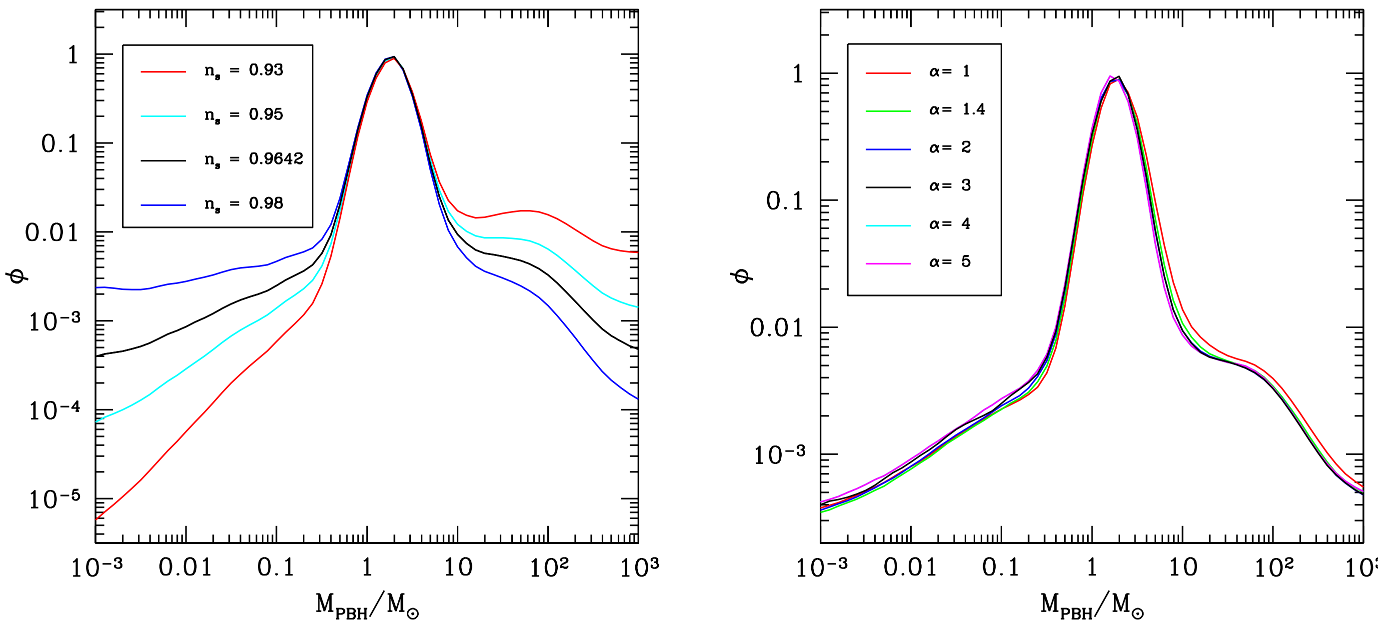


FIG. 9: **The effect of the spectral index and the shape profile on the mass function.** The mass function $\phi(M_{\rm PBH})$ is shown for different values of n_s with $\alpha = 3$ (left panel), and different values of α with $n_s = 0.9642$, the same value used in Figure 8 (right panel). The amplitude of the power spectrum is fixed in each case to give $f_{\rm PBH} = 1$. On the left panel the logarithmic axes allow to show the significant changes to the tail of the distribution, while the peak is almost the same. In the right panel we can appreciate the minor effect of the shape on the whole profile of the mass function.

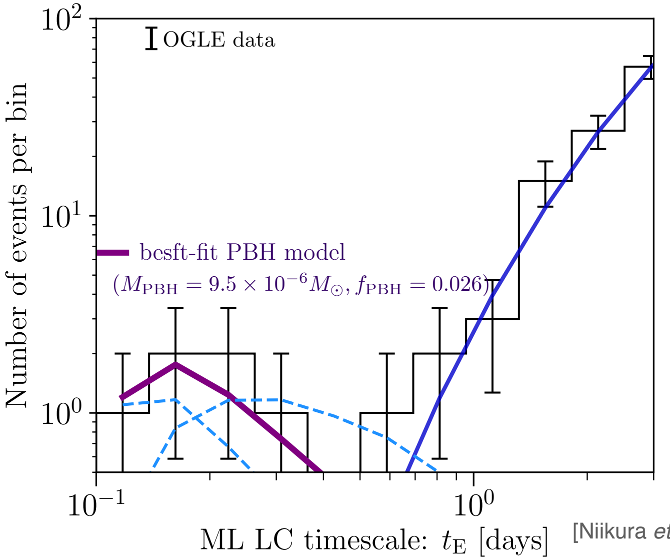
Planetary-mass microlenses

Constraints on Earth-mass primordial black holes from OGLE 5-year microlensing events

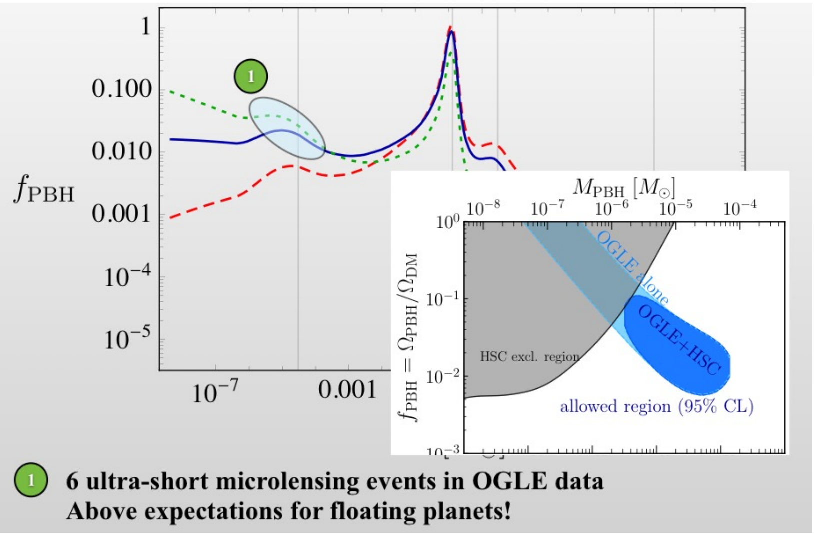
Hiroko Niikura,[1,2,*] Masahiro Takada,[2,†] Shuichiro Yokoyama,[3,2] Takahiro Sumi,[4] and Shogo Masaki[5]

PRD 99 (2019) 083503, arXiv:1901.07120

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



[Niikura *et al.* 2019]

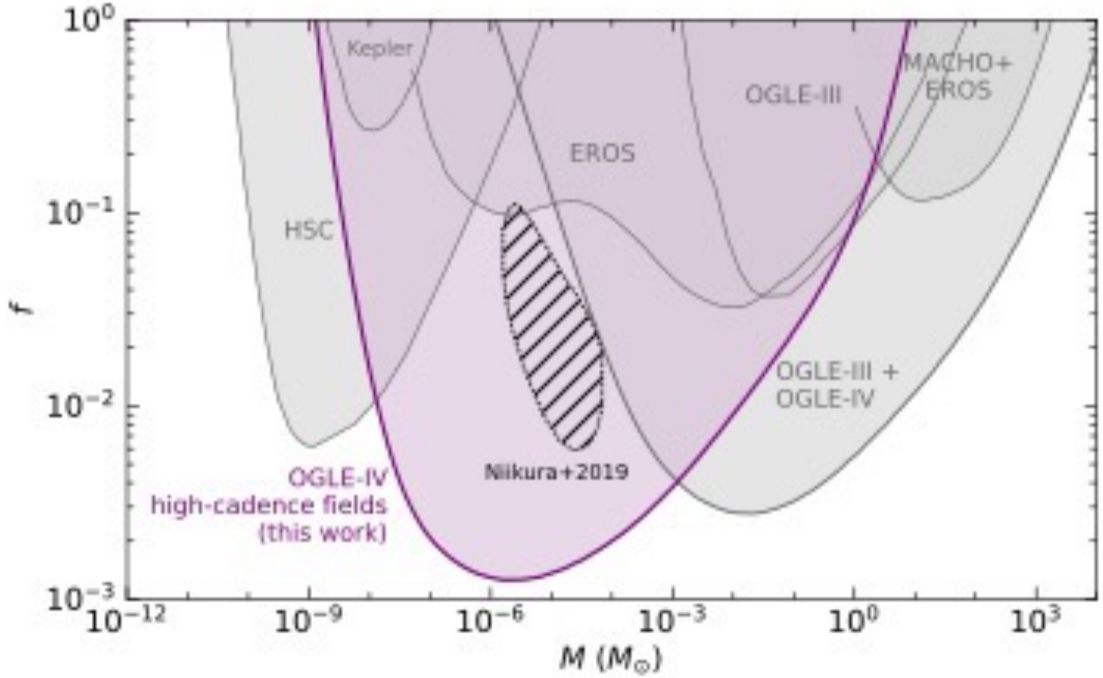


However….

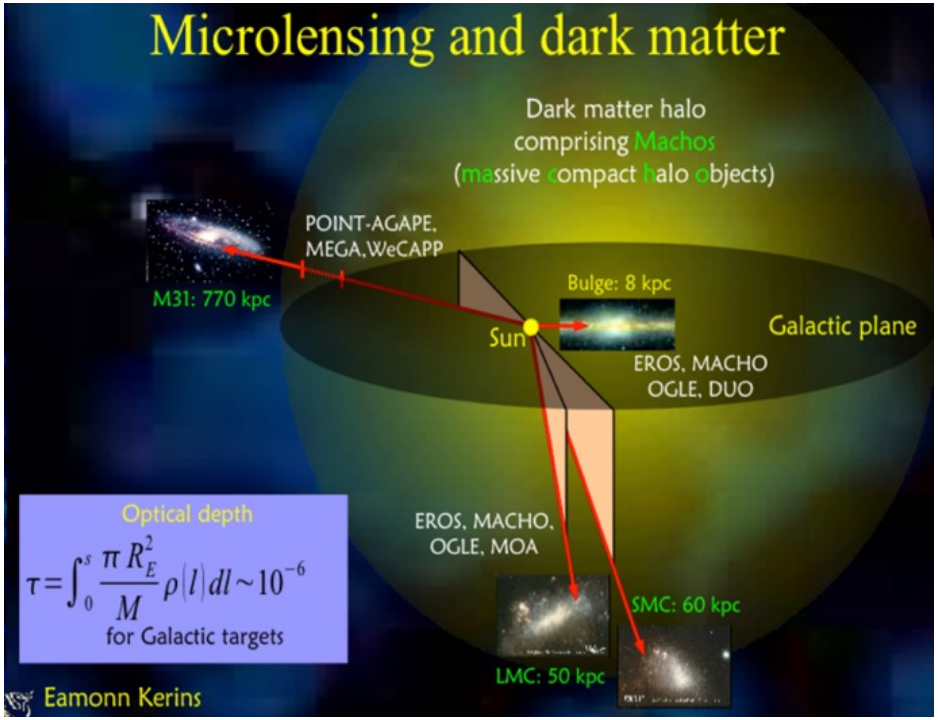
Limits on planetary-mass primordial black holes from the OGLE high-cadence survey of the Magellanic Clouds

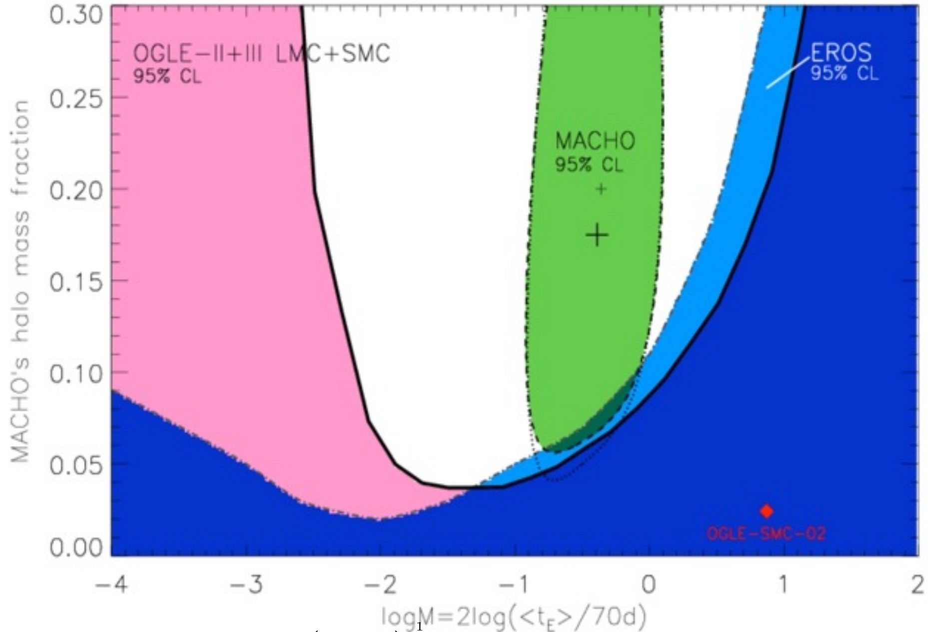
Przemek Mróz,[1] Andrzej Udalski,[1] Michał K. Szymański,[1] Igor Soszyński,[1] Paweł Pietrukowicz,[1] Szymon Kozłowski,[1] Radosław Poleski,[1] Jan Skowron,[1] Krzysztof Ulaczyk,[2,1] Mariusz Gromadzki,[1] Krzysztof Rybicki,[3,1] Patryk Iwanek,[1] Marcin Wrona,[4,1] and Mateusz J. Mróz[1]

arXiv:2410.06251



LMC/SMC microlensing



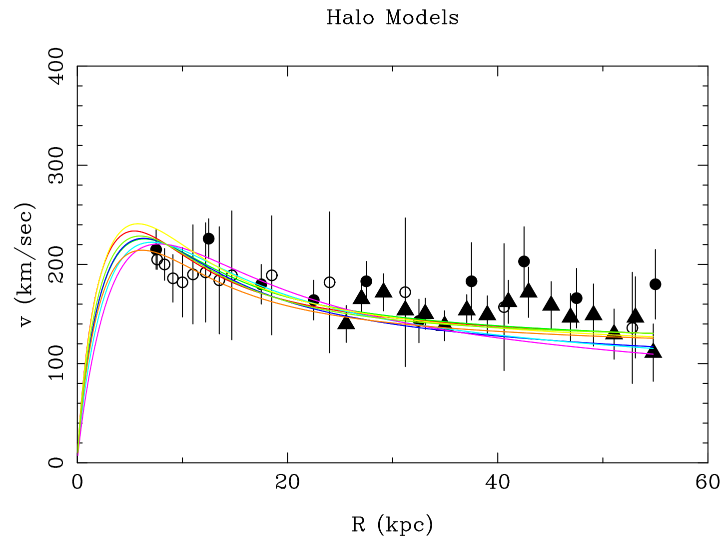


$\hat{t} = 0.2yrs\left(\frac{M_{PBH}}{M_\odot}\right)^{\frac{1}{2}}$

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

Early searches => MACHOs with 0.5 M_O

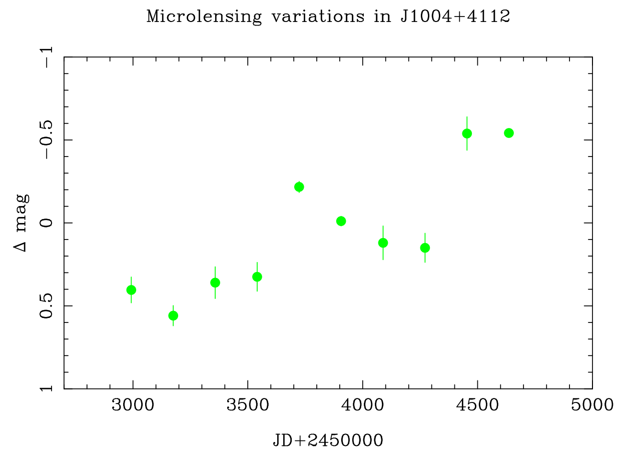
=> PBH formation at QCD transition?



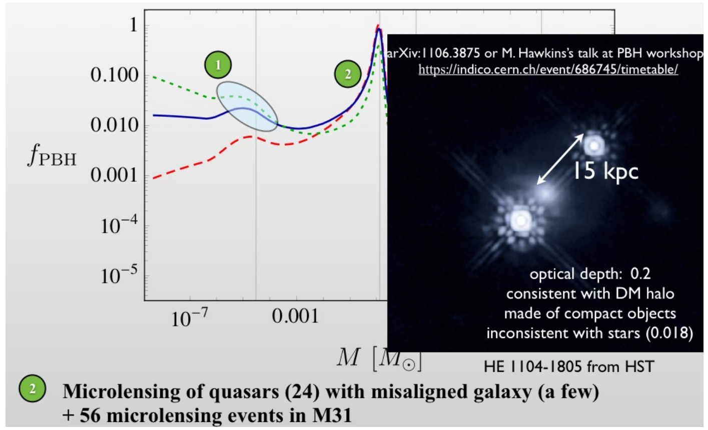
Later found they provide at most 20% of DM

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

Quasar microlensing



Caustic crossing



Hawkins arXiv:2010.15007

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

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

M. R. S. Hawkins★

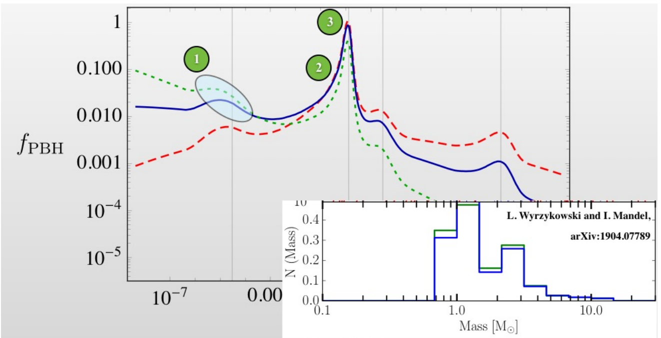
MNRAS 527, 2393 (2024)

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/Gaia microlensing events in the galactic bulge
Dark lenses: BH in the mass gap ([2-5] M⊙)

- ★ 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…

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

ABSTRACT

Measurements of the microlensing optical depth and event rate toward the Large Magellanic Cloud (LMC) can be used to probe the distribution and mass function of compact objects in the direction toward that galaxy – in the Milky Way disk, Milky Way dark matter halo, and the LMC itself. The previous measurements, based on small statistical samples of events, found that the optical depth is an order of magnitude smaller than that expected from the entire dark matter halo in the form of compact objects. However, these previous studies were not sensitive to long-duration events with Einstein timescales longer than 2.5–3 years, which are expected from massive ($10 - 100\,M_\odot$) and intermediate-mass ($10^2 - 10^5\,M_\odot$) black holes. Such events would have been missed by the previous studies and would not have been taken into account in calculations of the optical depth. 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 describe the observing setup, the construction of the 20-year OGLE dataset, the methods used for searching for microlensing events in the light curve data, and the calculation of the event detection efficiency. In total, we find 16 microlensing events (thirteen using an automated pipeline and three with manual searches), all of which have timescales shorter than 1 yr. We use a sample of thirteen events to measure the microlensing optical depth toward the LMC $\tau = (0.121 \pm 0.037) \times 10^{-7}$ and the event rate $\Gamma = (0.74 \pm 0.25) \times 10^{-7}\,\mathrm{yr}^{-1}\,\mathrm{star}^{-1}$. These numbers are consistent with lensing by stars in the Milky Way disk and the LMC itself, and demonstrate that massive and intermediate-mass black holes cannot comprise a significant fraction of dark matter.

Can combination of extended mass function, clustering and falling rotation curve avoid this?

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

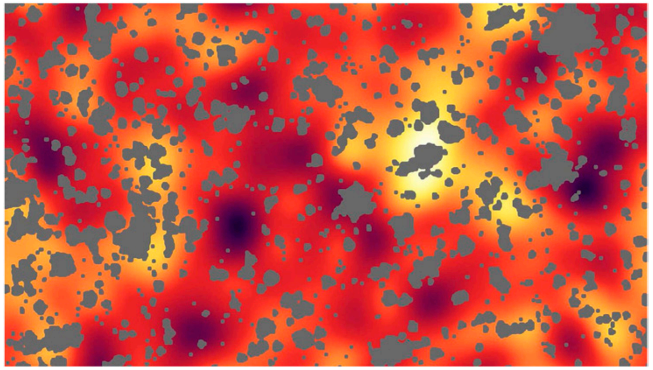
Anne Green's talk

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

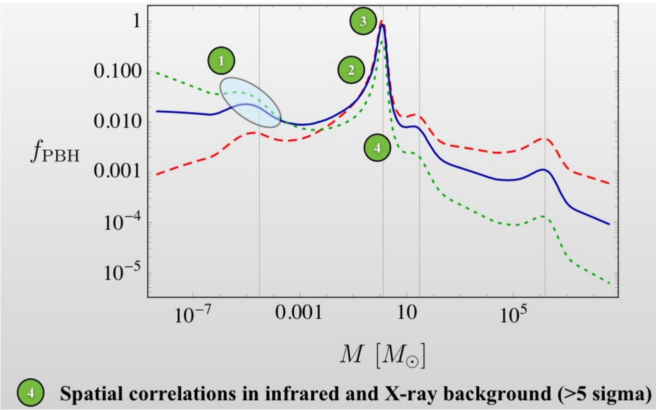
arXiv:2402.00212

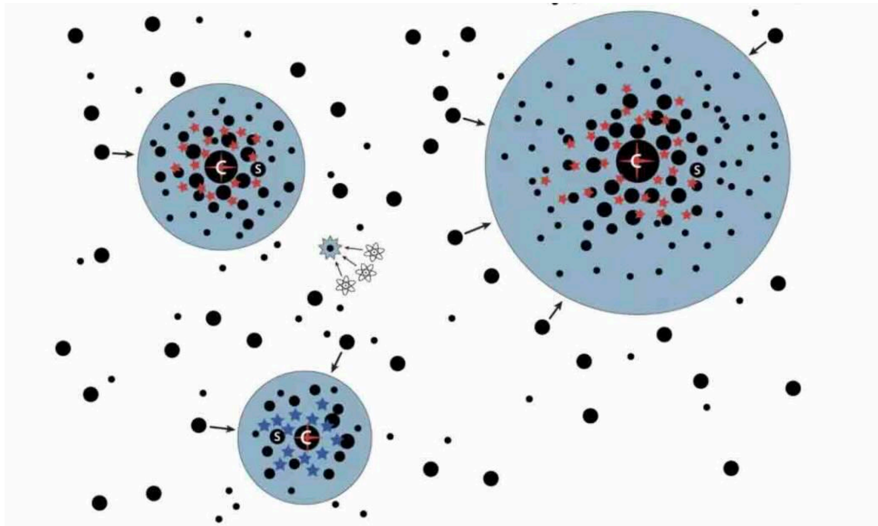
Cosmic infrared/X-ray backgrounds

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



Kashlinsky arXiv:1605.04023

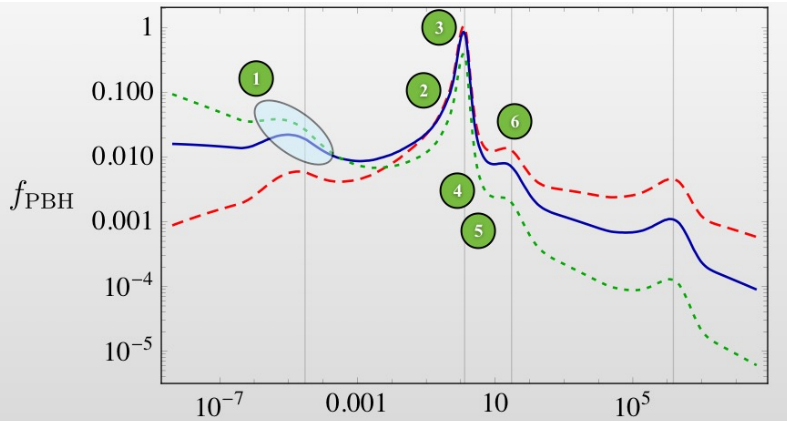


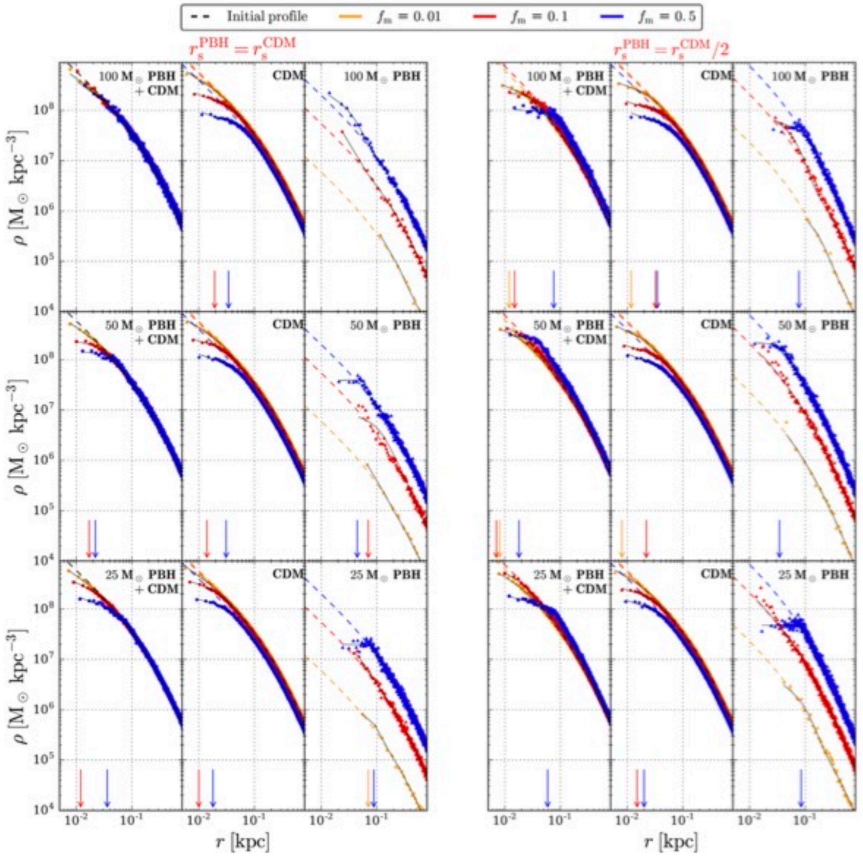


Cappelluti, Hasinger, Natarajan
arXiv:2109.08701

Minimum radius of ultra-faint dwarf galaxies and DM cores

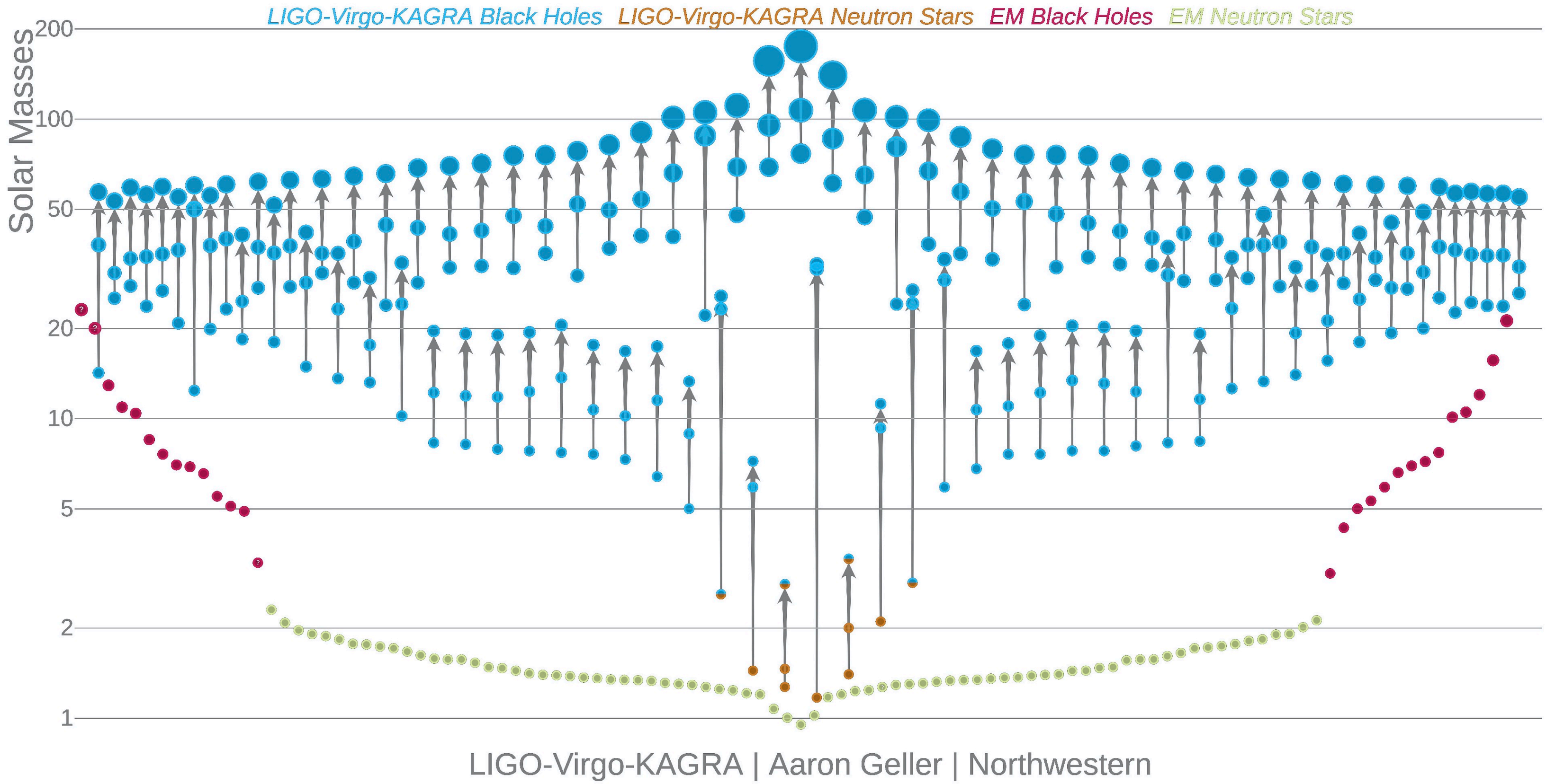
Boldrini et al. arXiv:1909.07395





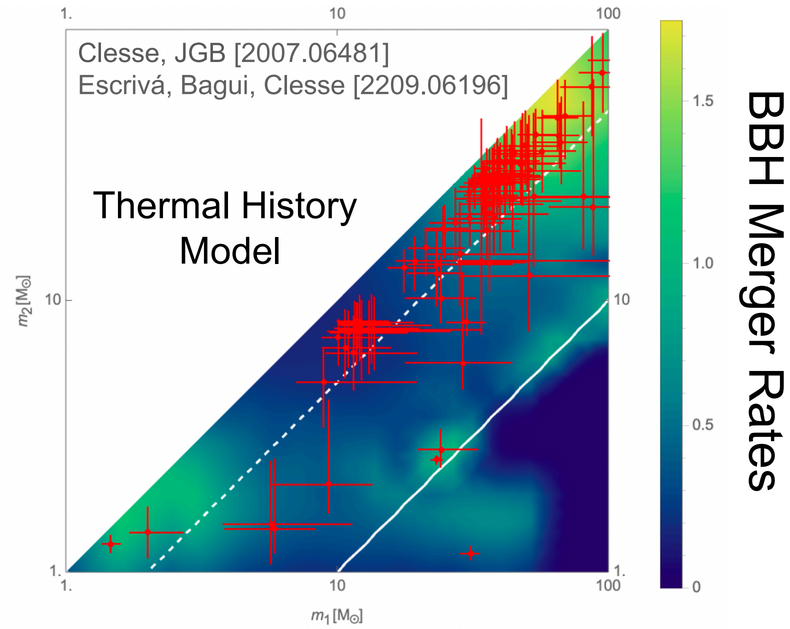
- ★ Non-detection of dwarf galaxies smaller than ~ 10 – 20 pc
- ★ Ultra-faint dwarf galaxies are dynamically unstable below some critical radius in the presence of PBH CDM!
- ★ This works with a few percent of PBH DM of 25 – 100 $M_\odot$.

LIGO DETECTION OF GRAVITY WAVES (2016)

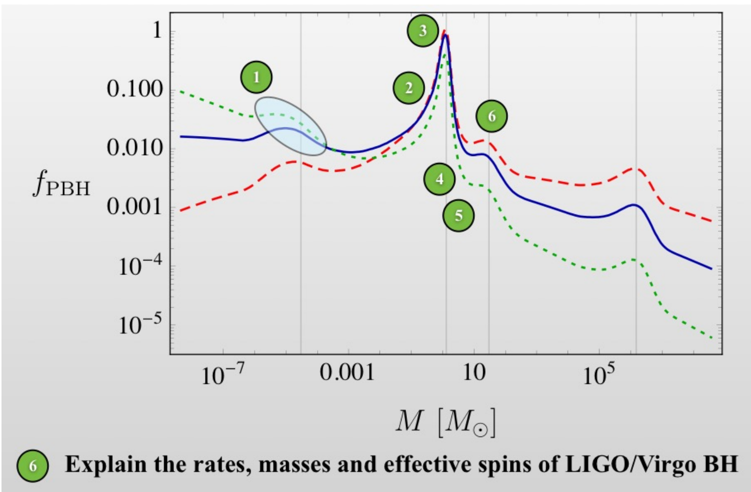


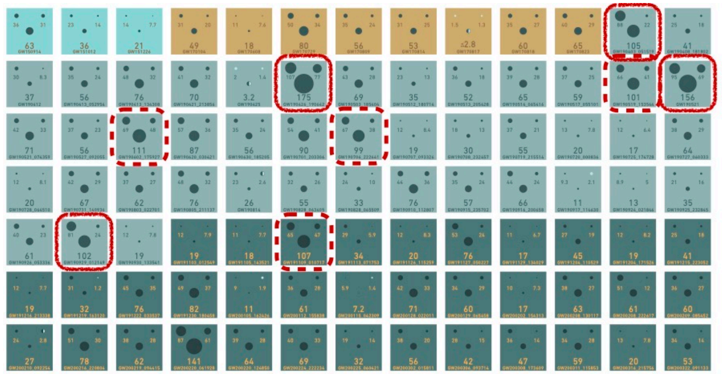
Do we need PBHs?

LIGO/Virgo/KAGRA black holes

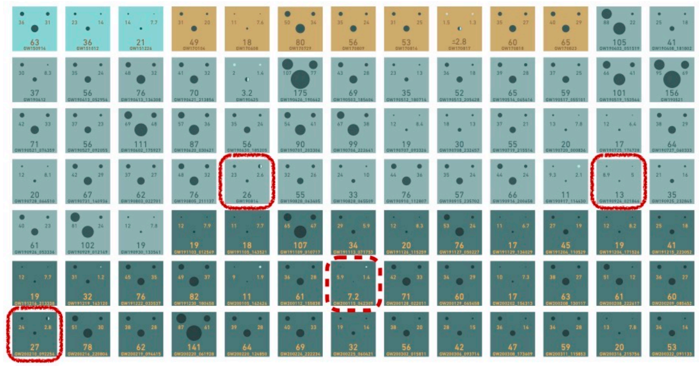


n_s=0.975, α = 0, q = 0.5,0.1

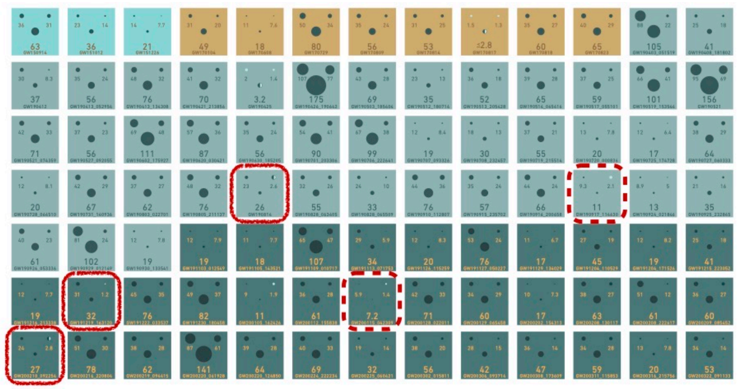




★ Black hole progenitors in the pair-instability mass gap (i.e. above ~ 60 $M_\odot$)



★ Black hole progenitors in the lower mass gap (i.e. between 2 and 5 $M_\odot$)



★ Asymmetric black hole progenitors (mass ratio q < 0.25)

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

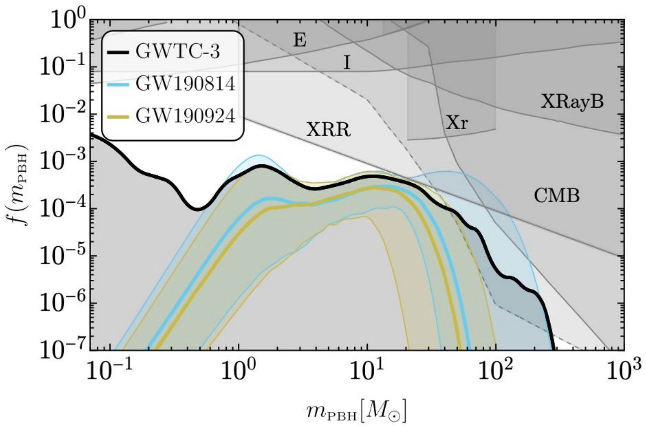
subsolar candidates?

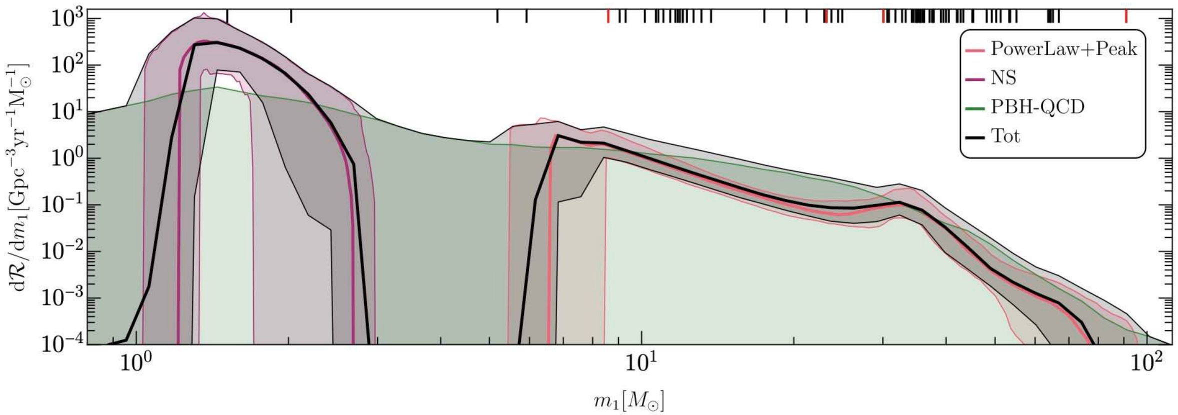
However…

From inflation to black hole mergers and back again: Gravitational-wave data-driven constraints on inflationary scenarios with a first-principle model of primordial black holes across the QCD epoch

Gabriele Franciolini,[1,2] Ilia Musco,[2] Paolo Pani,[1,2] and Alfredo Urbano[1,2]

arXiv:2209.05959





Constraints on primordial black holes from LIGO-Virgo-KAGRA O3 events

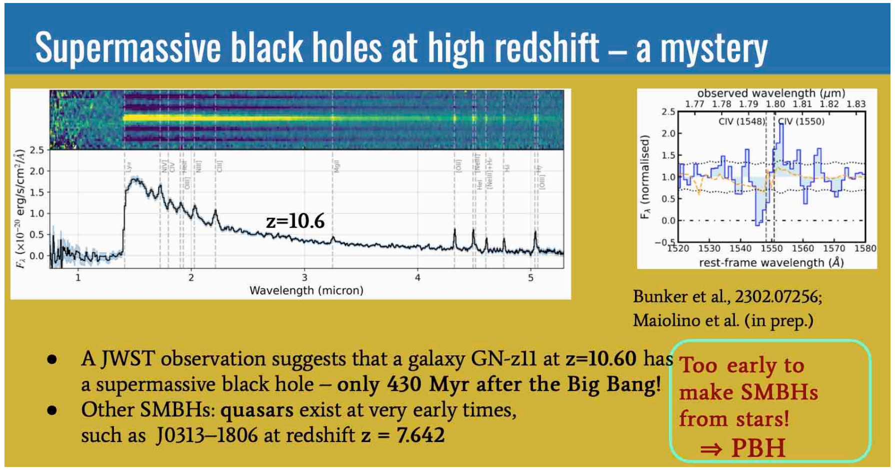
M. Andrés-Carcasona,[1,*] A.J. Iovino,[2,3,4,†] V. Vaskonen,[5,6,7,‡] H. Veermäe,[5,§] M. Martínez,[1,8] O. Pujolàs,[1] and Ll.M. Mir[1]

arXiv:2405.05732

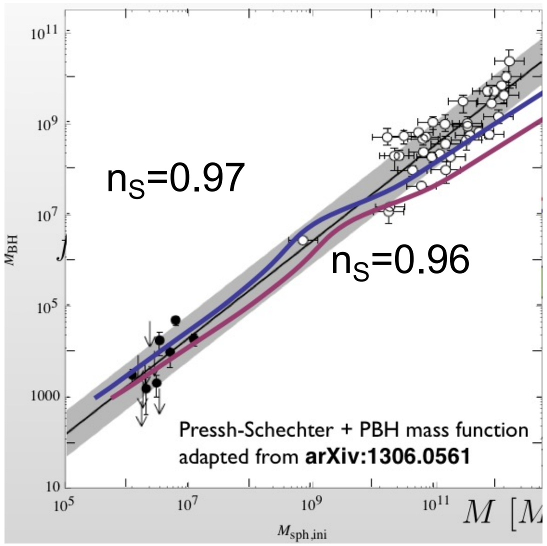
$f_{PBH} < 10^{-3}$ for $1 < M/M_O < 200$

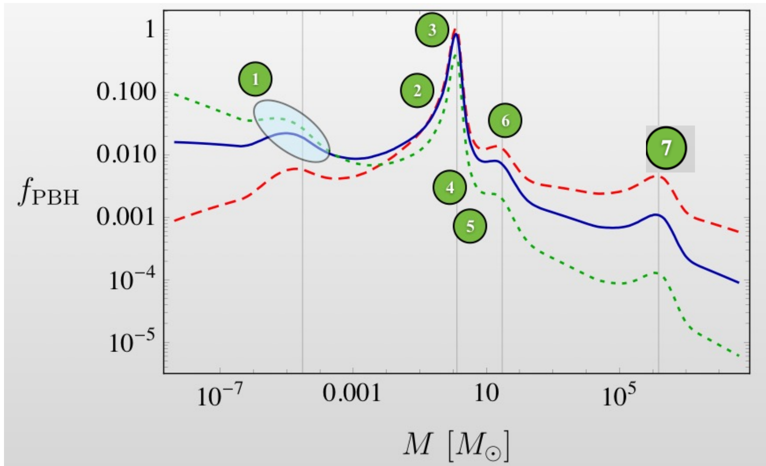
PBHs as seeds for SMBHs

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



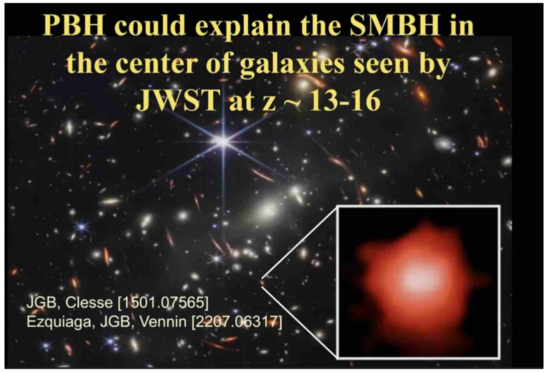
Kusenko





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

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

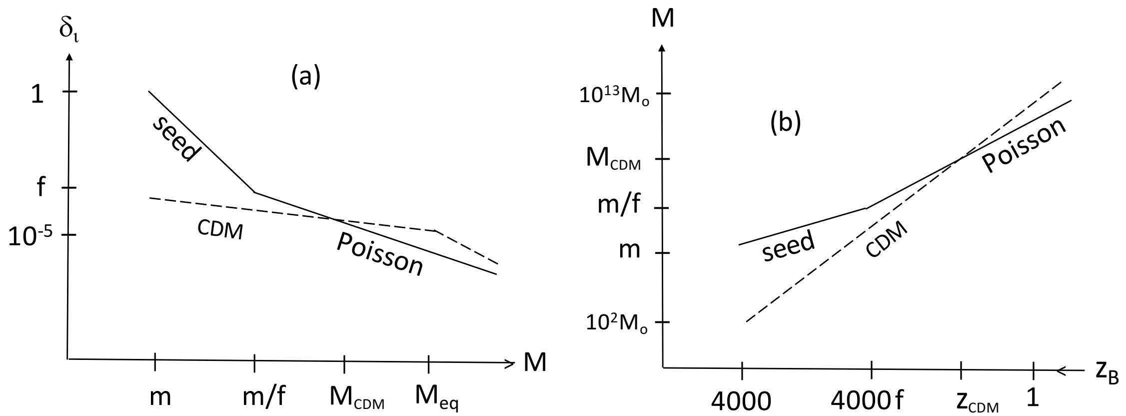
Supermassive primordial black holes for the GHZ9 and UHZ1 observed by the JWST

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

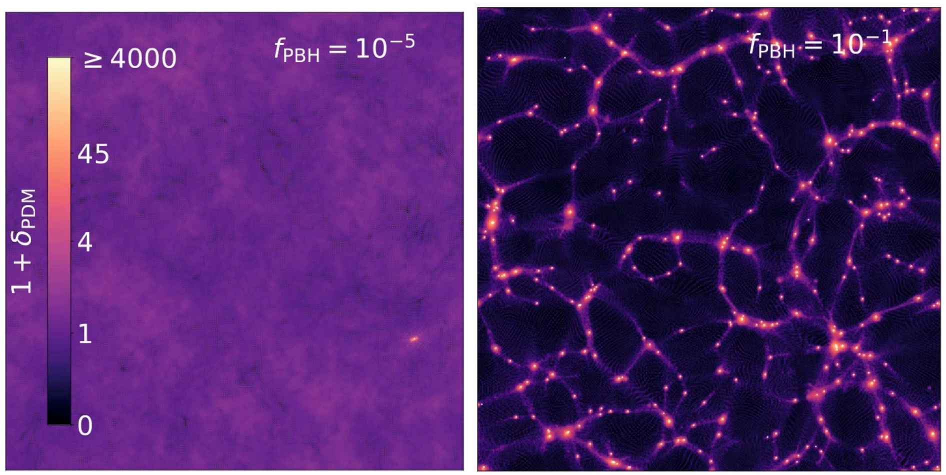
arXiv:2410.05891

SEED AND POISSON EFFECT OF PBHS ON LARGE-SCALE STRUCTURE

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



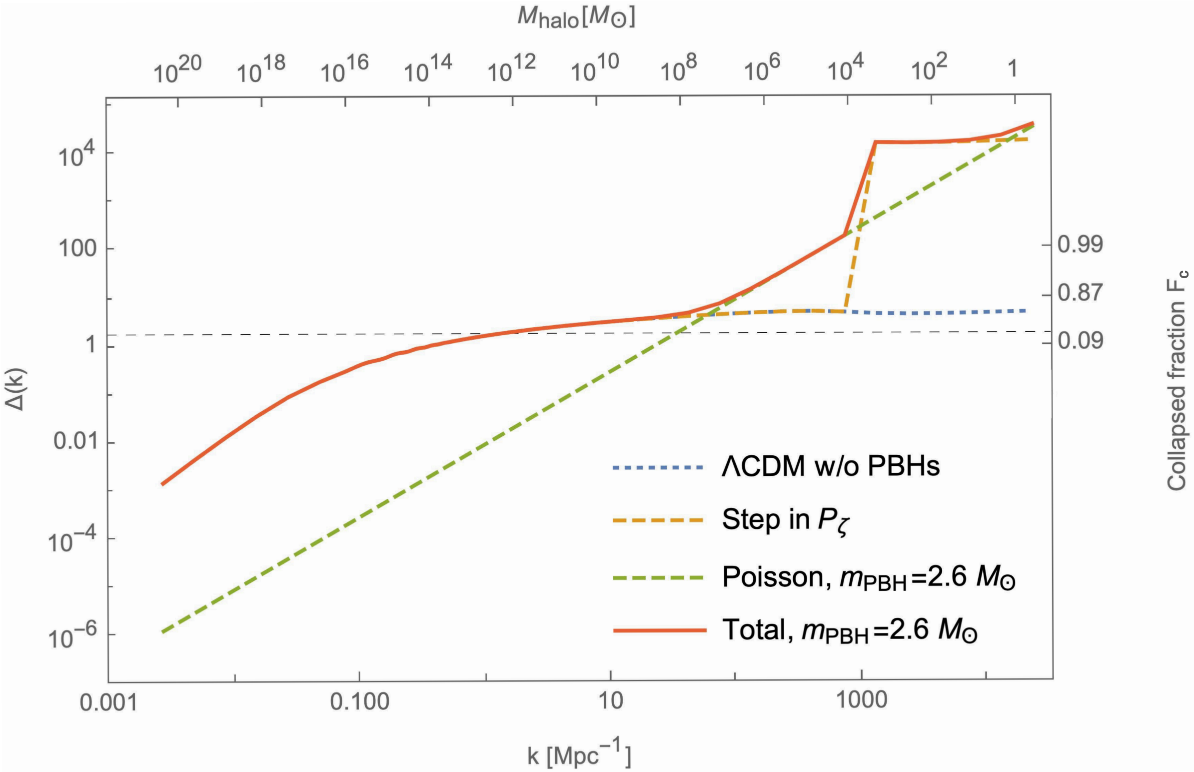
Carr & Silk
arXiv:1801.00672



Inman & Ali-Hamoud
arXiv:1907.08129

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

Analysis of CCGHK



$$P_{\rm Poisson} \simeq 2\times 10^{-3}\,\frac{f_{\rm PBH}}{g(z)^2}\left(\frac{m}{3M_\odot}\right)\,{\rm Mpc}^3$$

=> $$z_{\rm c}+1 \simeq 39\times\left[\frac{10^6\,m\,f_{\rm PBH}}{M_{\rm c}}\right]^{1/2} \quad , \quad r_{\rm c}\simeq 135\,{\rm pc}\left(\frac{m\,f_{\rm PBH}}{M_\odot}\right)^{-1/2}\left(\frac{M_{\rm c}}{10^6\,M_\odot}\right)^{5/6}$$

$$F_{\rm c}(M_{\rm c},\,z_{\rm c}) = {\rm erfc}\left[\frac{\delta_{\rm c}}{\sqrt{2}\,\sigma(M_{\rm c},z_{\rm c})}\right]$$

Dynamical relaxation on timescale

$$t_{\rm rel} \simeq 2.1 \times 10^6\,{\rm yr}\,\frac{(M_{\rm c}/M_\odot)^{1/2}}{(m/M_\odot)\ln[0.14\,M_{\rm c}/m]}\left(\frac{r_{\rm c}}{\rm pc}\right)^{3/2}$$

Cluster has now expanded to radius

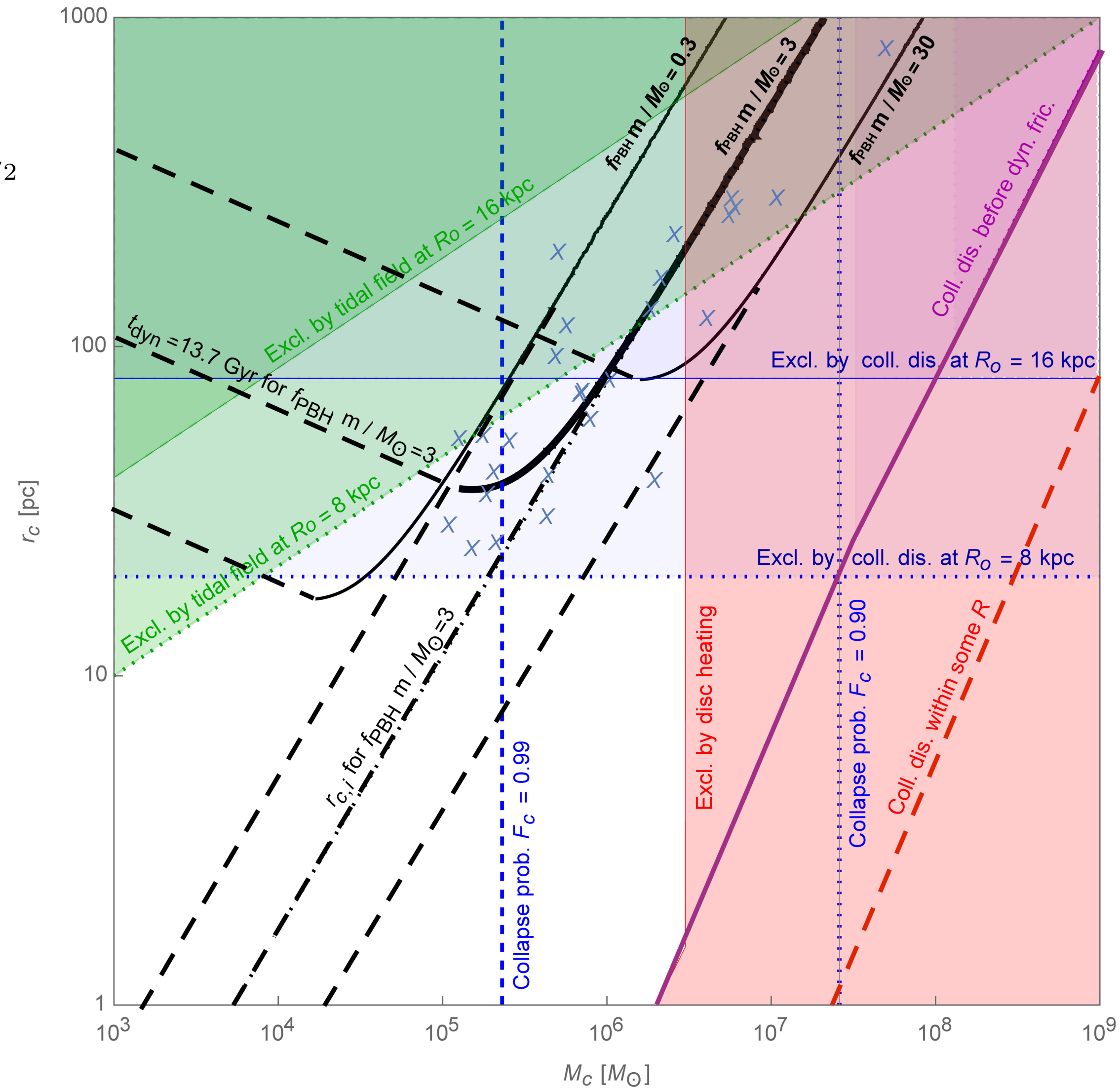
$$r_{\rm c}(t_0) \simeq 400\,\beta^{-2/3}\left(\frac{M_{\rm c}}{M_\odot}\right)^{-1/3}\left(\frac{m}{M_\odot}\right)^{2/3}\ln\left[\frac{M_{\rm c}}{2\,m}\right]$$

Destroyed by Galactic tidal field unless

$$r_{\rm c} < 100\,(M_{\rm c}/10^6\,M_\odot)^{1/3}(R_{\rm o}/8\,{\rm kpc})^2\,{\rm pc}$$

Survive collisions providing

$$r_{\rm c} < 20\,f_{\rm h}^{-1}(R_{\rm o}/8\,{\rm kpc})^2\,{\rm pc}$$

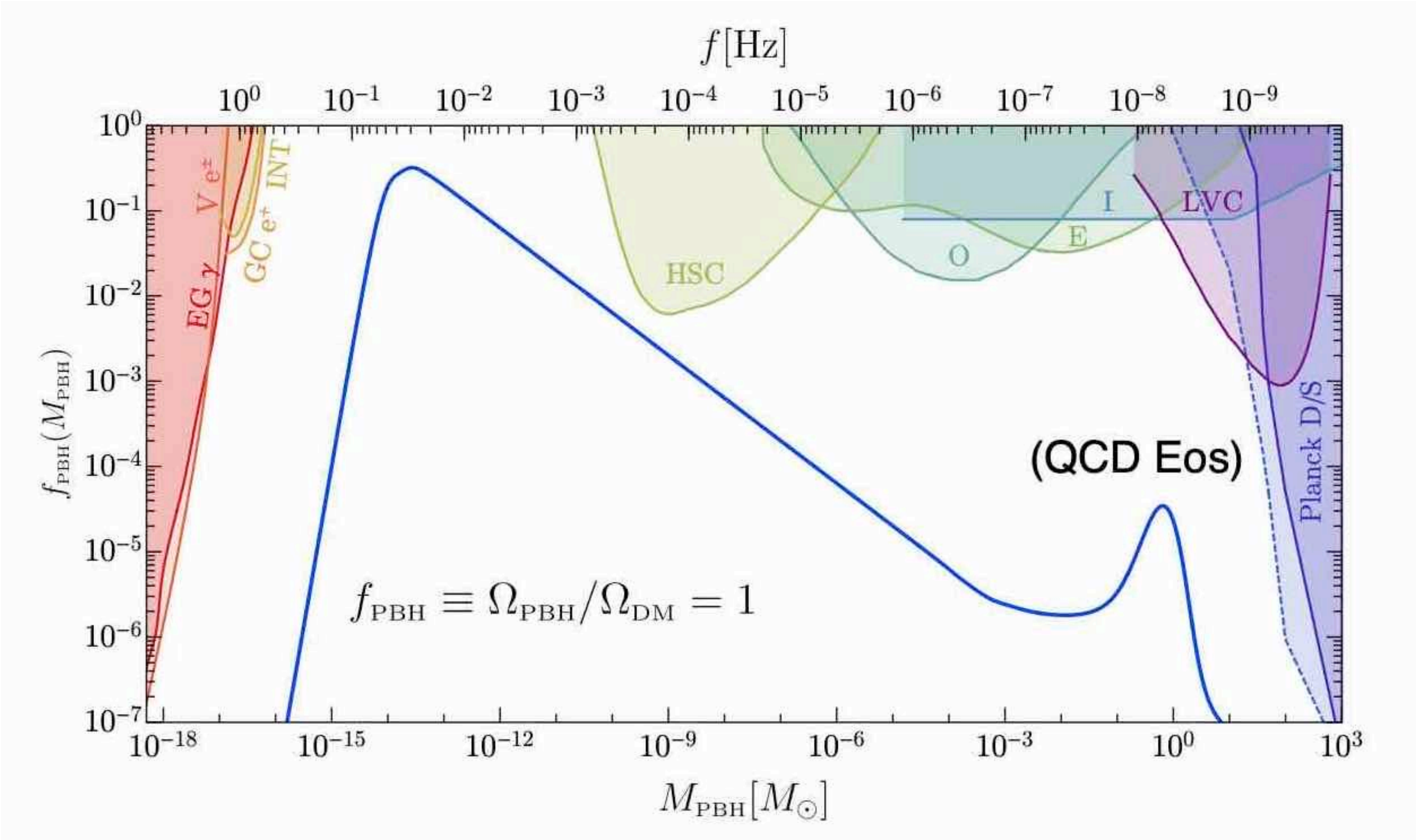


Destroyed by collisions before dynamical friction providing

$$r_{\rm c} > \begin{cases} 0.5\,f_{\rm h}^{-1}\left(\frac{M_{\rm c}}{10^6\,M_\odot}\right)^{4/3}{\rm pc} & (M_{\rm c} < M_2) \\ 0.8\,f_{\rm h}^{-1}\left(\frac{M_{\rm c}}{10^6\,M_\odot}\right){\rm pc} & (M_{\rm c} > M_2) \end{cases}$$

X Ultra-Faint Dwarf Galaxies

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,†]

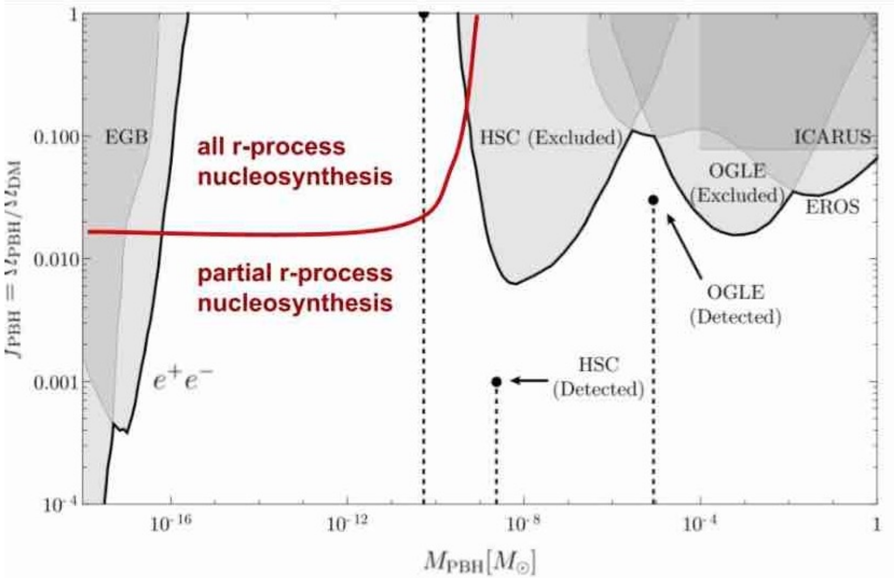
arXiv:2207.10056

R-process elements

Fuller et al. PRL 119 (2017) 061101

Primordial black holes, neutron stars, and the origin of gold

- Light elements are formed in the Big Bang
- Heavy elements, up to Fe, are made in stars
- What about Au, Pt, U...?
  PBH can play a role



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.

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

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:2312.17217

Primordial black holes (PBHs) remain a viable dark matter candidate in the asteroid-mass range. We point out that in this scenario, the PBH abundance would be large enough for at least one object to cross through the inner Solar System per decade. Since Solar System ephemerides are modeled and measured to extremely high precision, such close encounters could produce detectable perturbations to orbital trajectories with characteristic features. We evaluate this possibility with a suite of simple Solar System simulations, and we argue that the abundance of asteroid-mass PBHs can plausibly be probed by existing and near-future data.

How open is the asteroid-mass primordial black hole window?

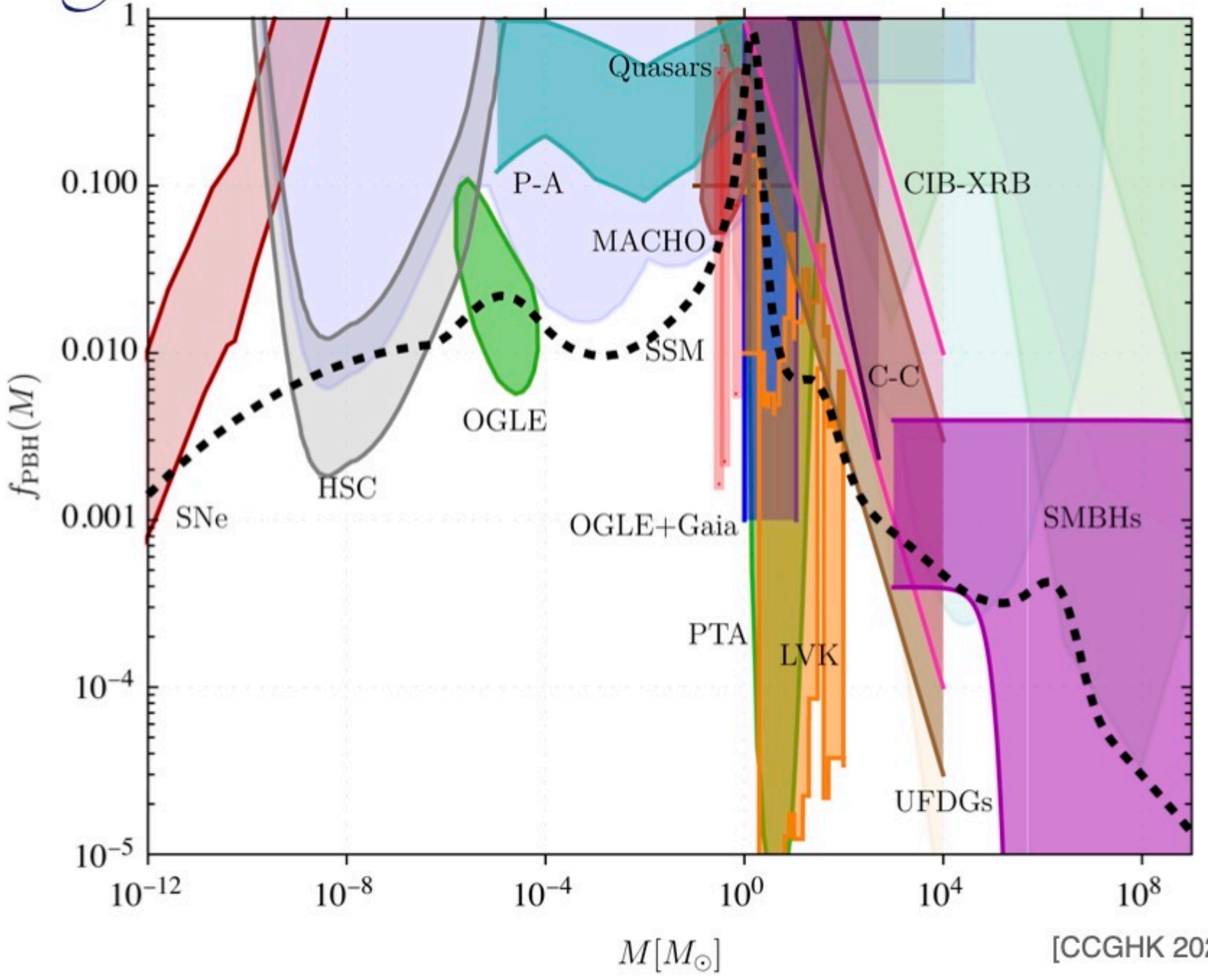
Matthew Gorton* and Anne M. Green†

arXiv:2403.03839

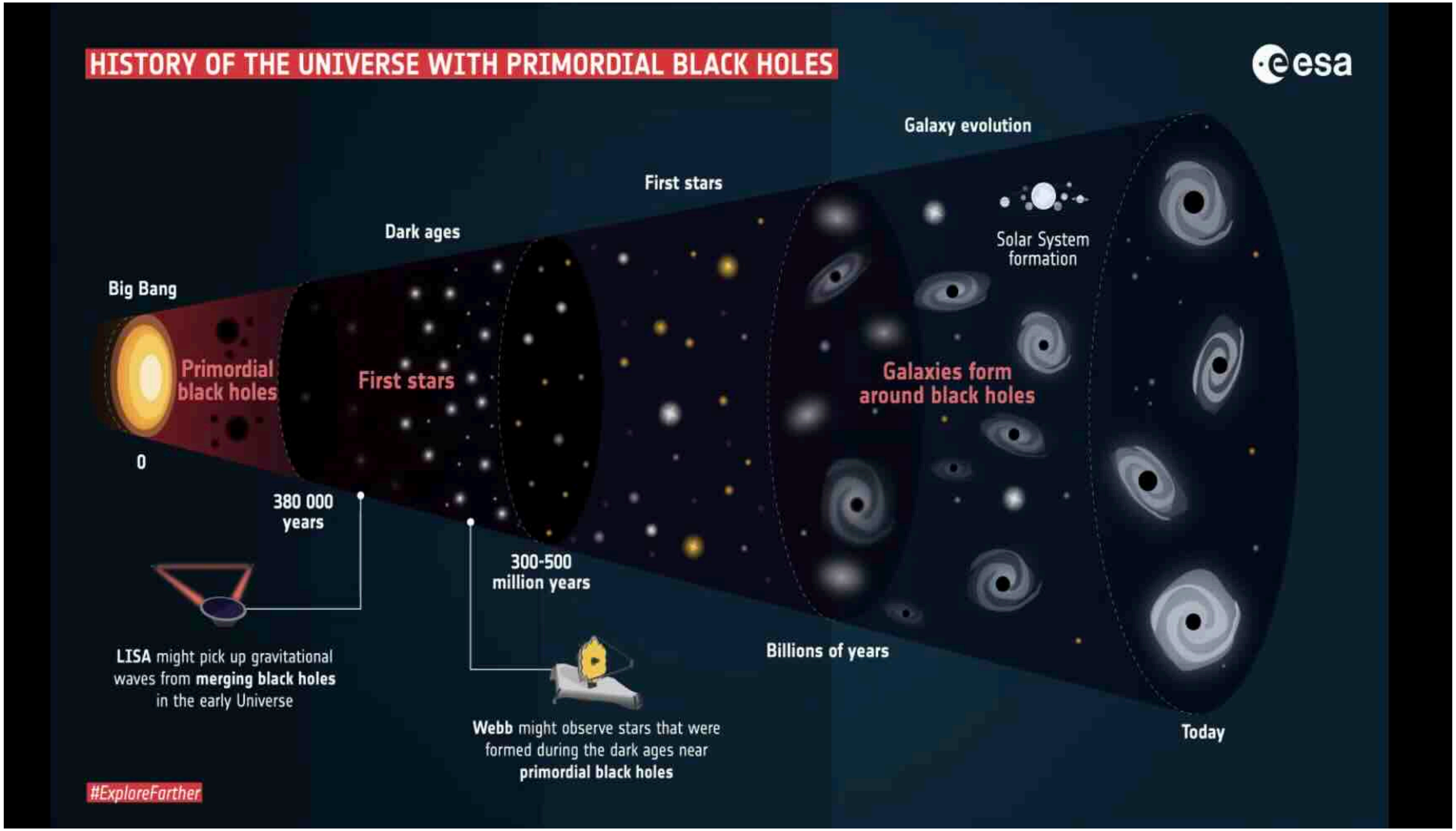
Abstract

Primordial black holes (PBHs) can make up all of the dark matter (DM) if their mass, m, is in the so-called 'asteroid-mass window', $10^{17}\,\mathrm{g} \lesssim m \lesssim 10^{22}\,\mathrm{g}$. Observational constraints on the abundance of PBHs are usually calculated assuming they all have the same mass, however this is unlikely to be a good approximation. PBHs formed from the collapse of large density perturbations during radiation domination are expected to have an extended mass function (MF), due to the effects of critical collapse. The PBH MF is often assumed to be lognormal, however it has recently been shown that other functions are a better fit to numerically calculated MFs. We recalculate both current and potential future constraints for these improved fitting functions. We find that for current constraints the asteroid-mass window narrows, but remains open (i.e. all of the DM can be in the form of PBHs) unless the PBH MF is wider than expected. Future evaporation and microlensing constraints may together exclude all of the DM being in PBHs, depending on the width of the PBH MF and also the shape of its low and high mass tails.

Connecting all Positive Evidences!



[CCGHK 2023]


HISTORY OF THE UNIVERSE WITH PRIMORDIAL BLACK HOLES
esa
Galaxy evolution
First stars
Dark ages
Solar System formation
Big Bang
Primordial black holes
First stars
Galaxies form around black holes
0
380 000 years
300-500 million years
Billions of years
Today
LISA might pick up gravitational waves from merging black holes in the early Universe
Webb might observe stars that were formed during the dark ages near primordial black holes
#ExploreFarther

PBHS AS LINK BETWEEN BRIGHT AND DARK