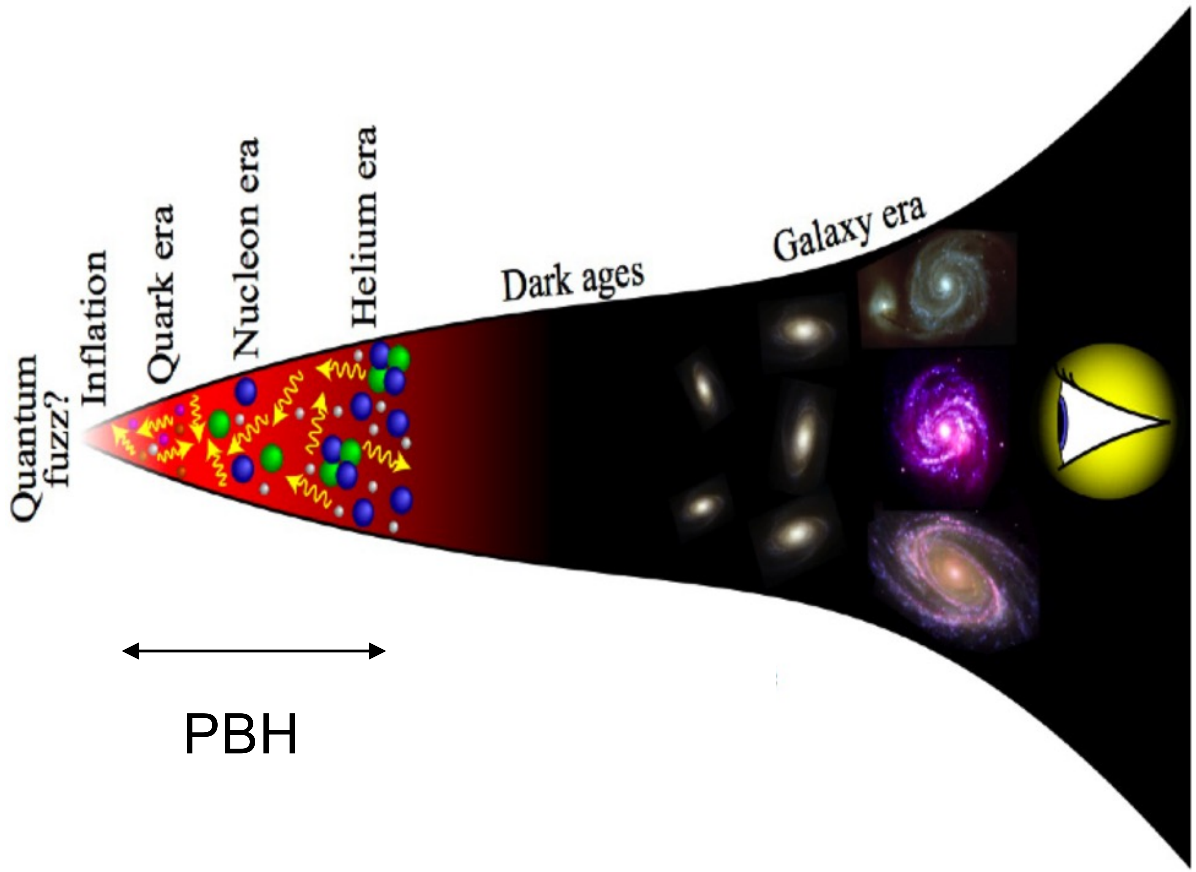
PRIMORDIAL BLACK HOLES AFTER 50 YEARS: A POSITIVE PERSPECTIVE



Bernard Carr
Queen Mary University of London

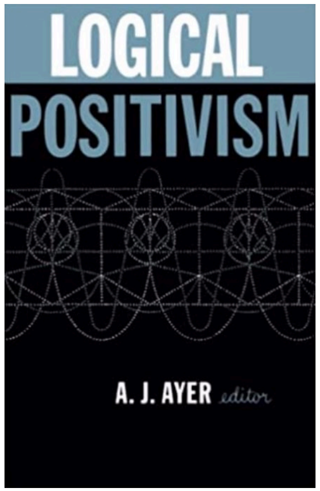
Paris-Saclay Astro-Particle Symposium 24/10/23

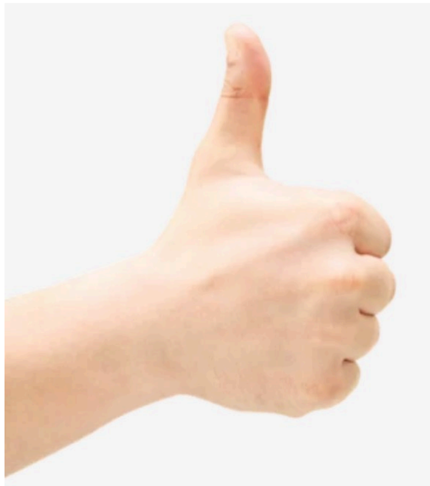
Observational Evidence for Primordial Black Holes: A Positivist Perspective

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

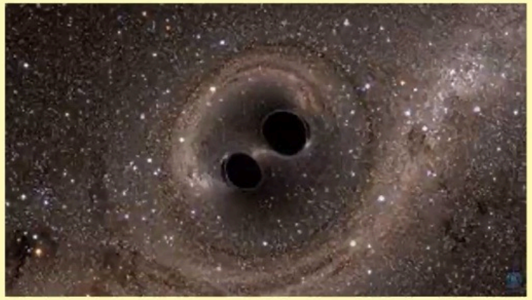
arXiv:2306.03903





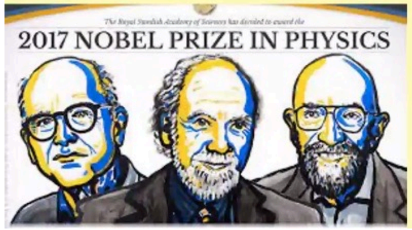
Irrefutable evidence for stellar and supermassive black holes

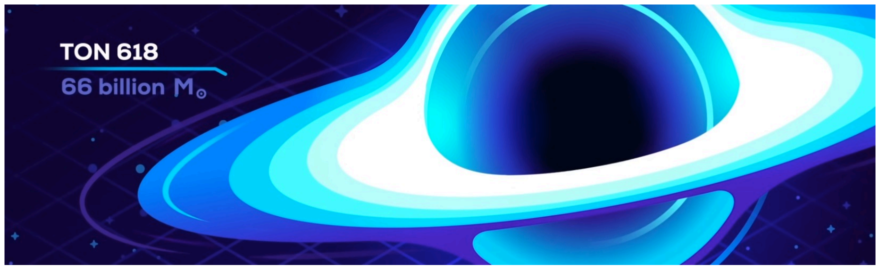


GW150914

M87 image

Sagitarius A*

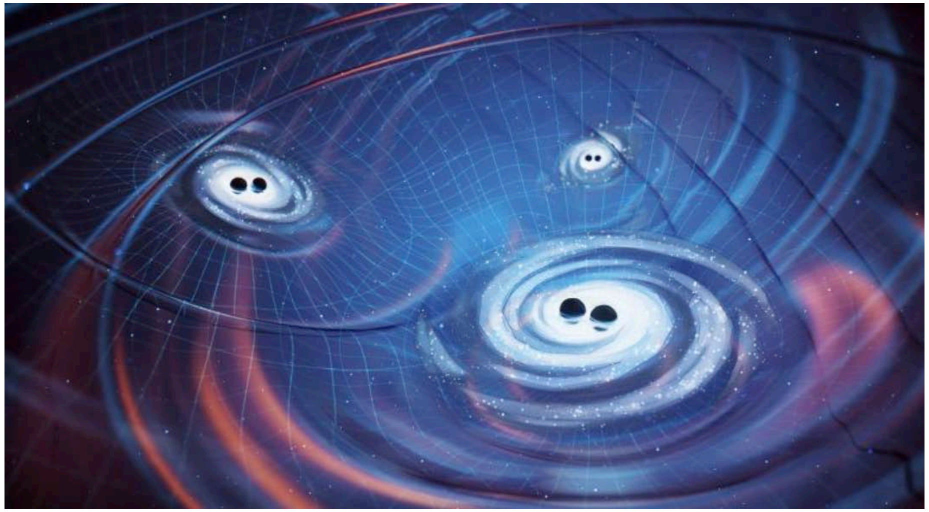




Plausible evidence for intermediate mass black holes

NANOGrav 15 yr Data Set:
Evidence for a Gravitational-wave Background

Agazie et al. Ap J Let 951, L8 (2023)



NANOGrav's most recent dataset offers compelling evidence for gravitational waves with oscillations of years to decades. These waves are thought to arise from orbiting pairs of the most massive black holes throughout the Universe: billions of times more massive than the Sun

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

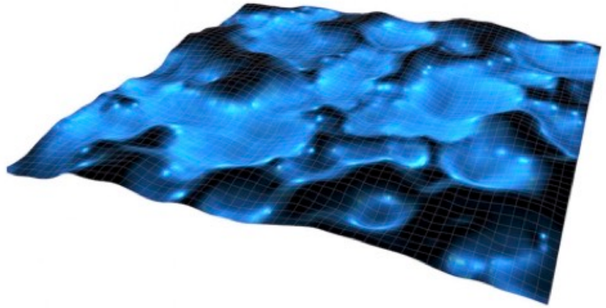
⇨ **PBHs have horizon mass at formation**

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

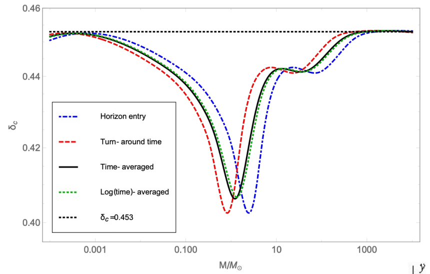
=> huge possible mass range

Formation Mechanisms of Primordial Black Holes

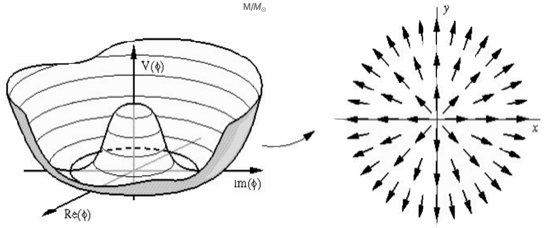
★ Large density perturbations (inflation)

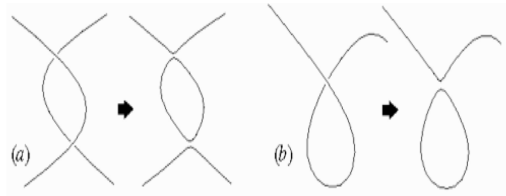


★ Pressure reduction

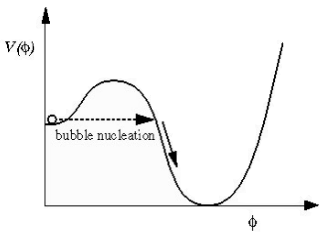


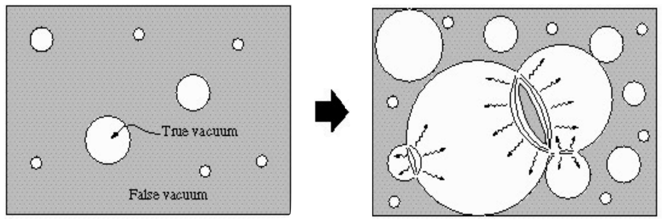
★ Cosmic string loops





★ Bubble collisions

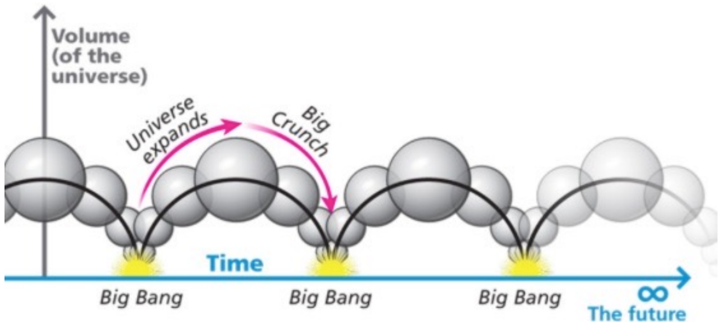




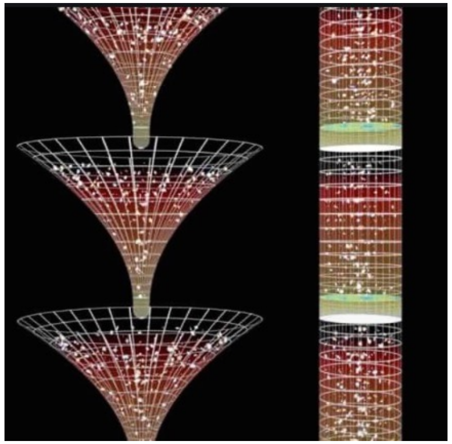
★ Scalar-field fragmentation, ...

BUT THEY MAY ALSO FORM IN LESS STANDARD MODELS

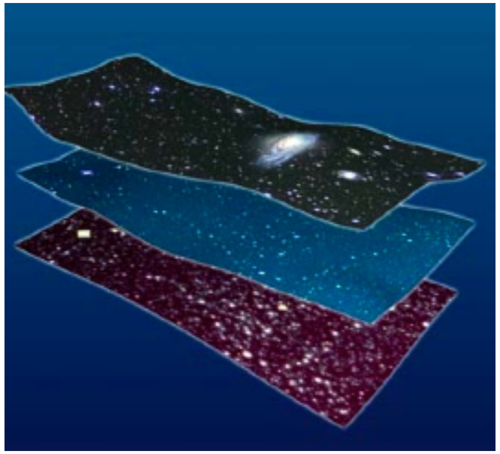
Cyclic Universe



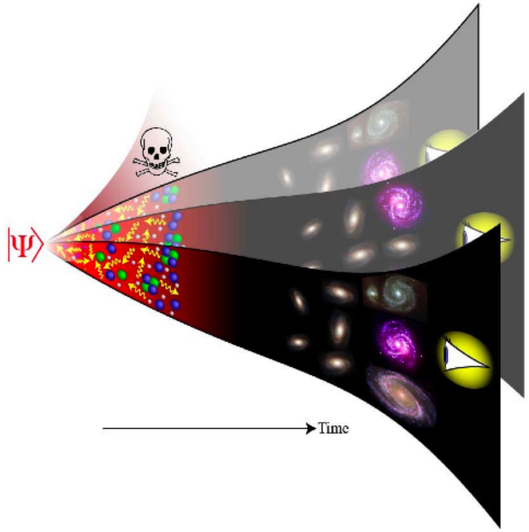
Conformal Cyclic Model



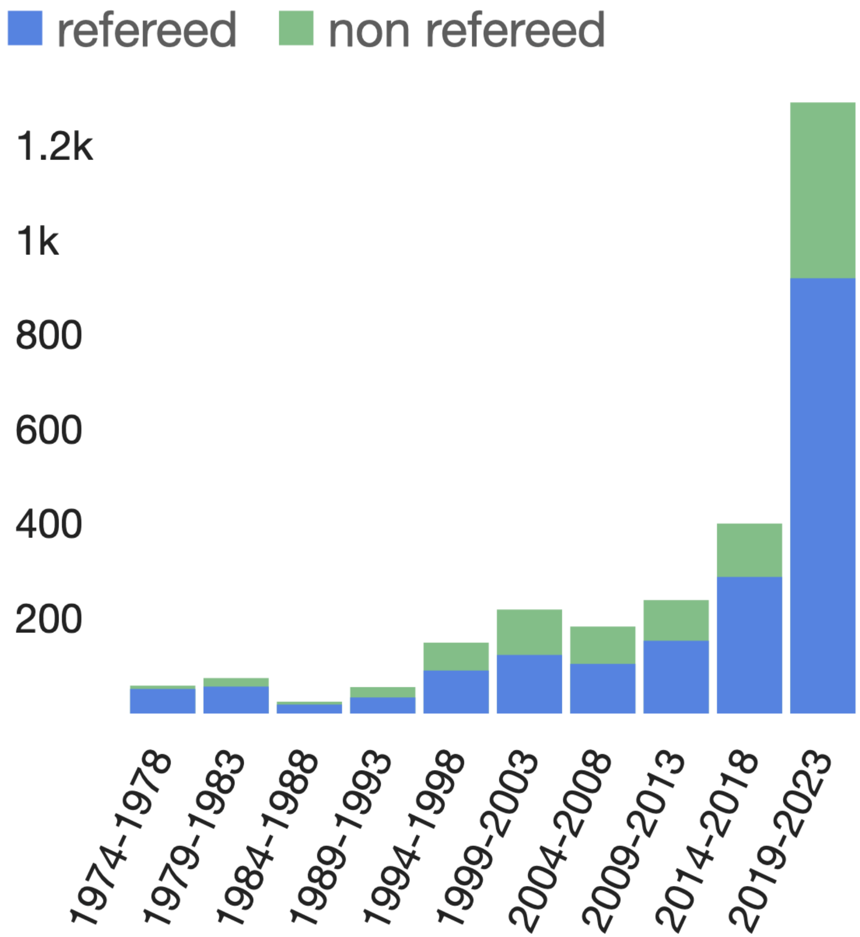
Ekpyrotic Model



Quantum Cosmology

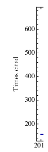


PBH PUBLICATION RATE



Impossible to keep up with literature!

MY MOST CITED PAPERS!



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.

THE ASTROPHYSICAL JOURNAL, **201**:1–19, 1975 October 1

THE PRIMORDIAL BLACK HOLE MASS SPECTRUM*

BERNARD J. CARR
Department of Applied Mathematics and Theoretical Physics, Cambridge University, Cambridge, England;
and
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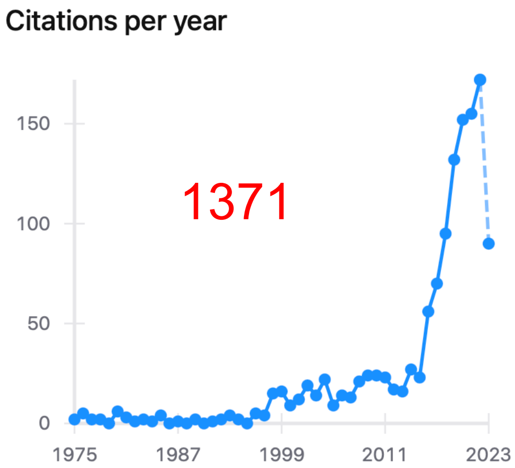
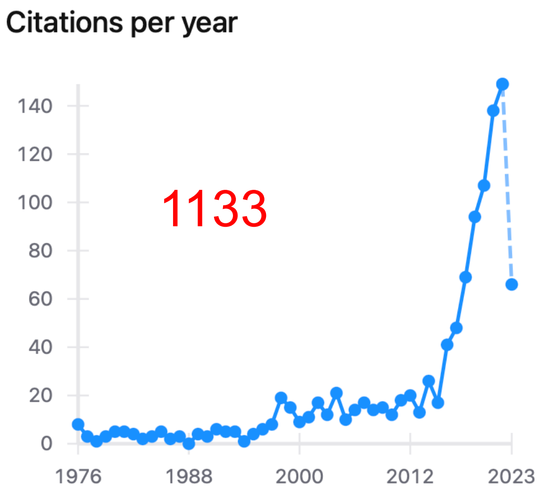
Received 1975 January 31

ABSTRACT

We examine what mass spectrum of primordial black holes should result if the early universe consisted of small density fluctuations superposed on a Friedmann background. It is shown that only a certain type of fluctuation favors the formation of primordial black holes and that, consequently, their spectrum should always have a particular form. Since both the fluctuations which arise naturally and the fluctuations which are often invoked to explain galaxy formation are of the required type, primordial black holes could have had an important effect on the evolution of the universe. In particular, although primordial black holes are unlikely to have a critical density, big ones could have been sufficiently numerous to act as condensation nuclei for galaxies. Observational limits on the spectrum of primordial black holes place strong constraints on the magnitude of density fluctuations in the early universe and support the assumption that the early universe was nearly Friedmann rather than chaotic. Any model in which the early universe has a soft equation of state for a prolonged period is shown to be suspect, since primordial black holes probably form too prolifically in such a situation to be consistent with observation.





Career all downhill from the start……

……with a resurgence towards the end!

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

New cosmological constraints on primordial black holes

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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
Physics Department, Lancaster University, Lancaster LA1 4YB, United Kingdom
Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, Massachusetts 02138, USA

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
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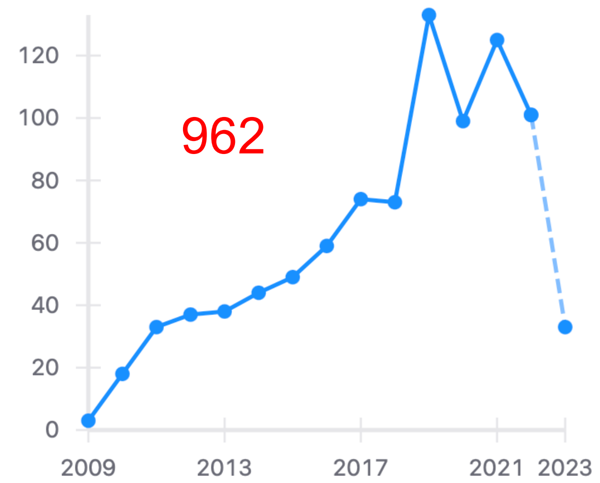
(Received 31 December 2009; published 10 May 2010)

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.

Citations per year



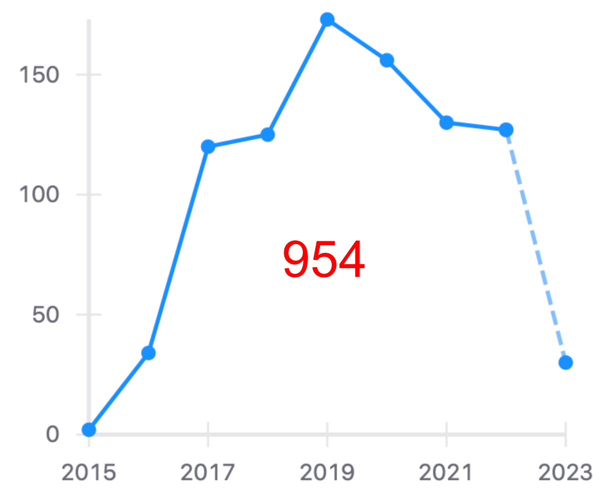
PHYSICAL REVIEW D **94,** 083504 (2016)

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.

Citations per year



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

GRAVITATIONALLY COLLAPSED OBJECTS OF VERY LOW MASS

Stephen Hawking

(Communicated by M. J. Rees)

(Received 1970 November 9)

SUMMARY

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

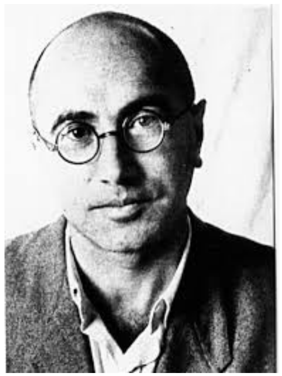
SOVIET ASTRONOMY — AJ VOL. 10, NO. 4 JANUARY-FEBRUARY, 1967

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

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

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

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



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(Received 1974 February 25)

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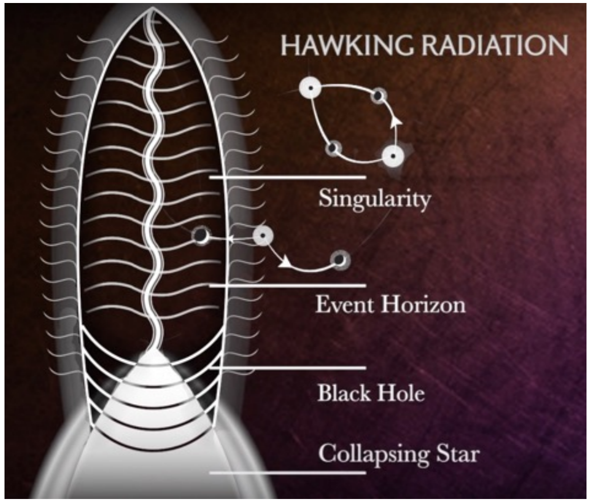
⇒ no observational evidence against them

Warsaw meeting 1973!



letters to nature

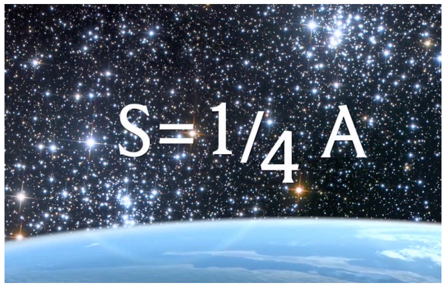
Nature **248**, 30 - 31 (01 March 1974); doi:10.1038/248030a0

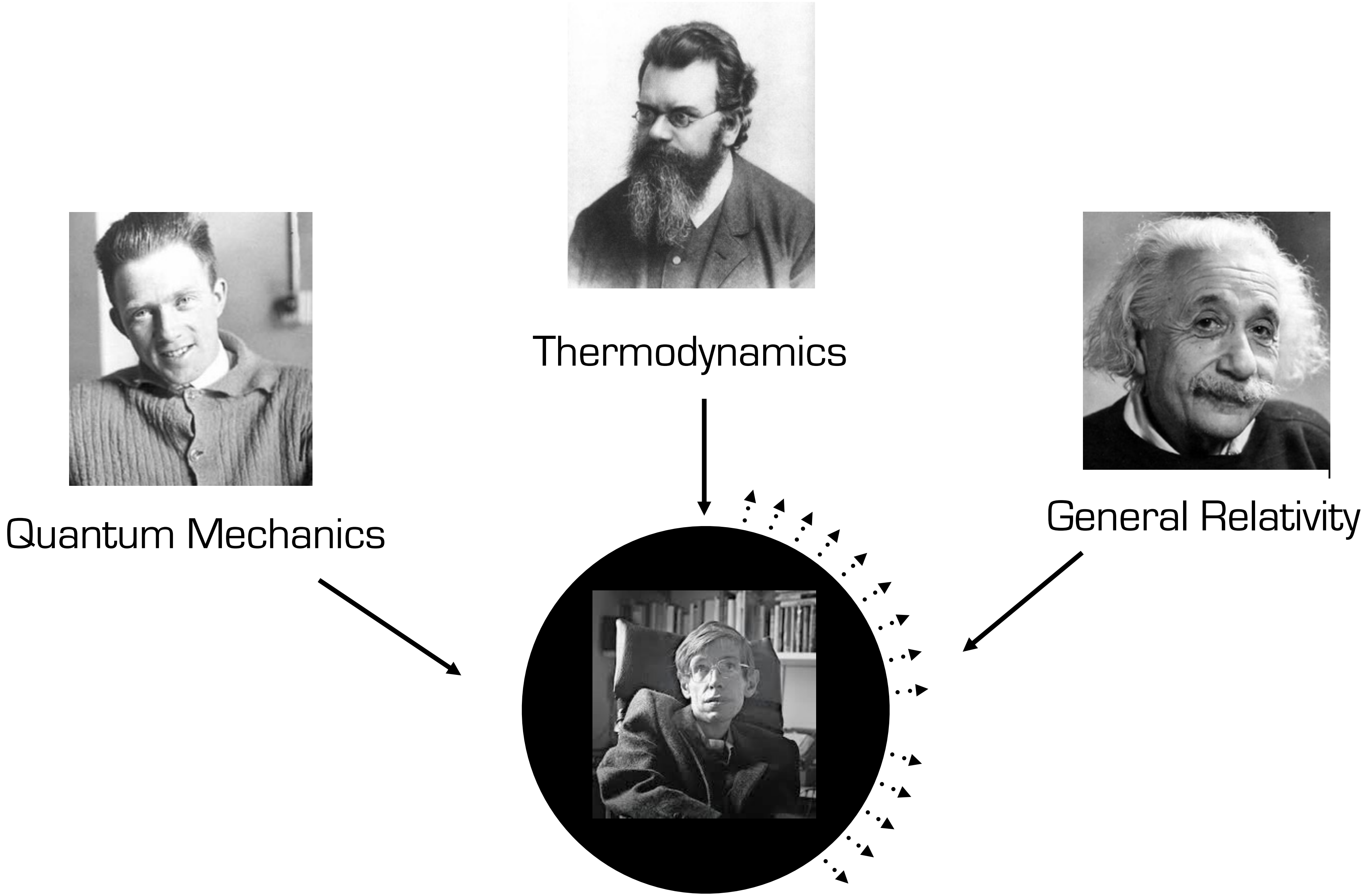
Black hole explosions?

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.

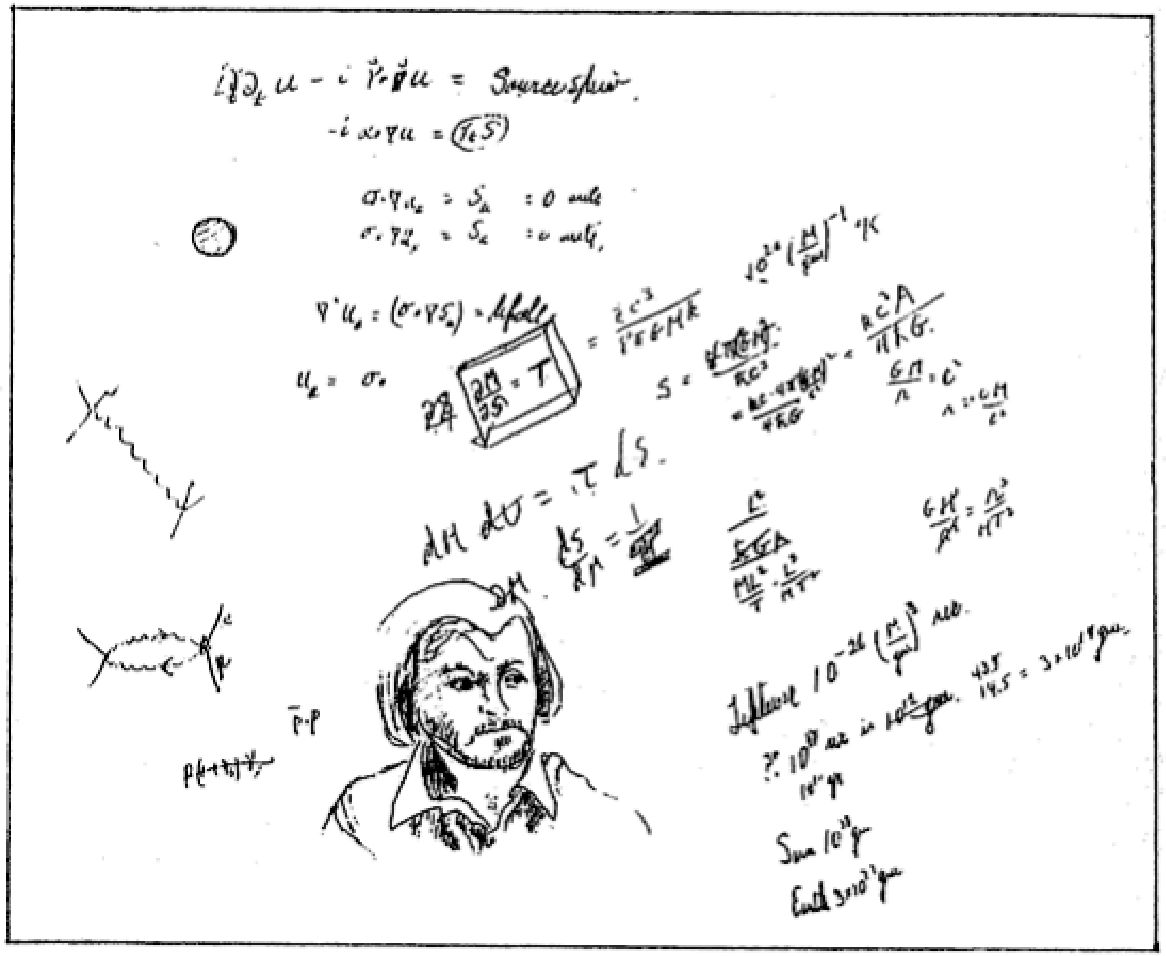




$$T_{BH}[\mathrm{K}] = 10^{-7}\,\frac{M_\odot}{M}$$

PBHs are important even if they never formed!

Feynman's envelope 1975



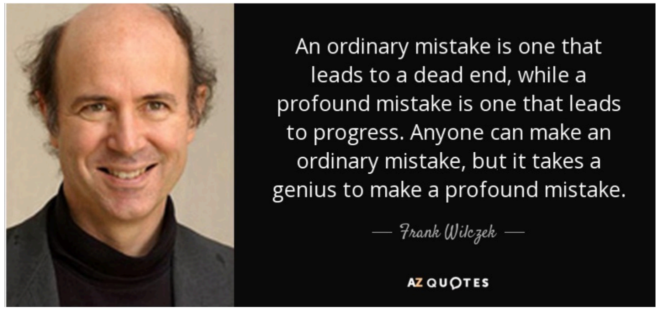
BLACK HOLE INFORMATION PARADOX

PHYSICAL REVIEW D VOLUME 14, NUMBER 10 15 NOVEMBER 1976

Breakdown of predictability in gravitational collapse*

S. W. Hawking†
Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Cambridge, England and California Institute of Technology, Pasadena, California 91125
(Received 25 August 1975)

The principle of equivalence, which says that gravity couples to the energy-momentum tensor of matter, and the quantum-mechanical requirement that energy should be positive imply that gravity is always attractive. This leads to singularities in any reasonable theory of gravitation. A singularity is a place where the classical concepts of space and time break down as do all the known laws of physics because they are all formulated on a classical space-time background. In this paper it is claimed that this breakdown is not merely a result of our ignorance of the correct theory but that it represents a fundamental limitation to our ability to predict the future, a limitation that is analogous but additional to the limitation imposed by the normal quantum-mechanical uncertainty principle. The new limitation arises because general relativity allows the causal structure of space-time to be very different from that of Minkowski space. The interaction region can be bounded not only by an initial surface on which data are given and a final surface on which measurements are made but also a "hidden surface" about which the observer has only limited information such as the mass, angular momentum, and charge. Concerning this hidden surface one has a "principle of ignorance": The surface emits with equal probability all configurations of particles compatible with the observers limited knowledge. It is shown that the ignorance principle holds for the quantum-mechanical evaporation of black holes: The black hole creates particles in pairs, with one particle always falling into the hole and the other possibly escaping to infinity. Because part of the information about the state of the system is lost down the hole, the final situation is represented by a density matrix rather than a pure quantum state. This means there is no S matrix for the process of black-hole formation and evaporation. Instead one has to introduce a new operator, called the superscattering operator, which maps density matrices describing the initial situation to density matrices describing the final situation.



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

PBH EVAPORATION

Black holes radiate thermally with temperature

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

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

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

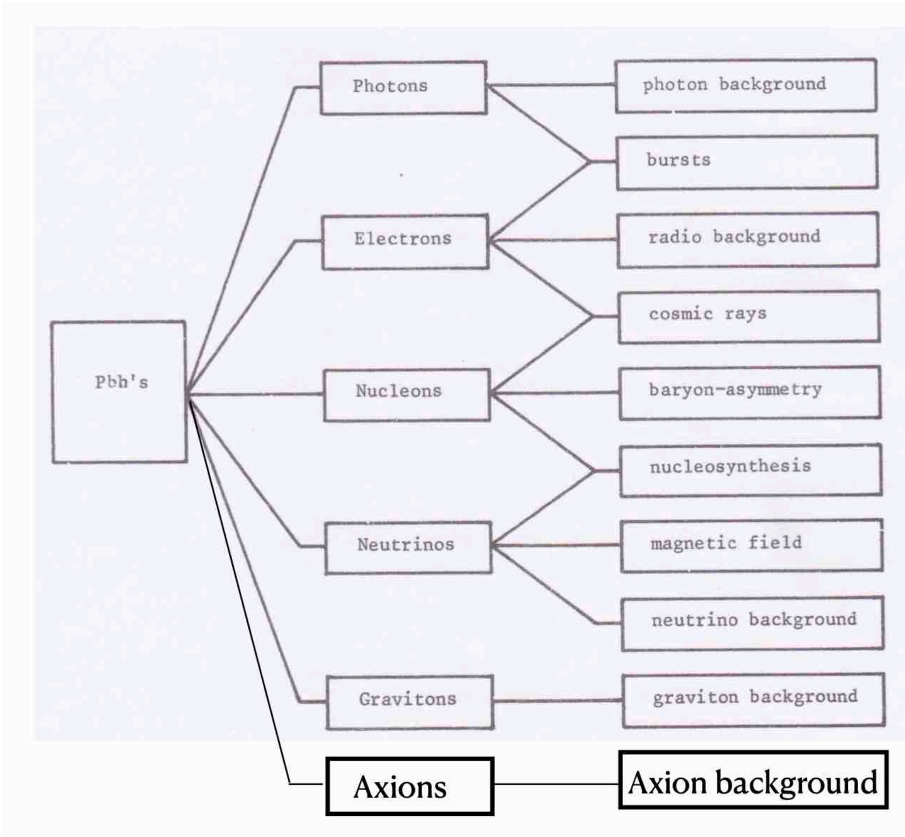
This can only be important for PBHs

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

=> explosions undetectable in standard particle physics model

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

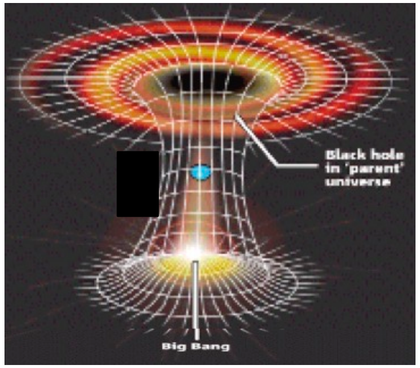
Black Hole Evaporations and their Cosmological Consequences

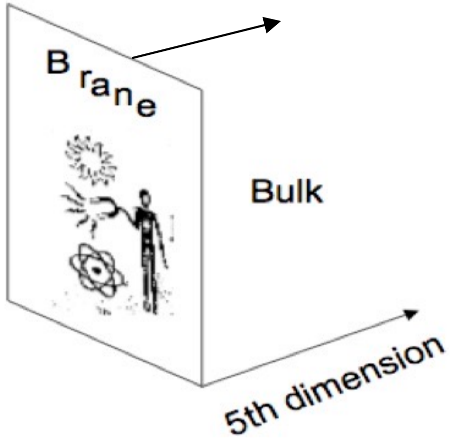


Talk by Lucien Heurtier for more recent work of PBH evaporations and dark matter

IS UNIVERSE A PRIMORDIAL BLACK HOLE?

Collapse to black hole generates a baby Universe Smolin (1997)

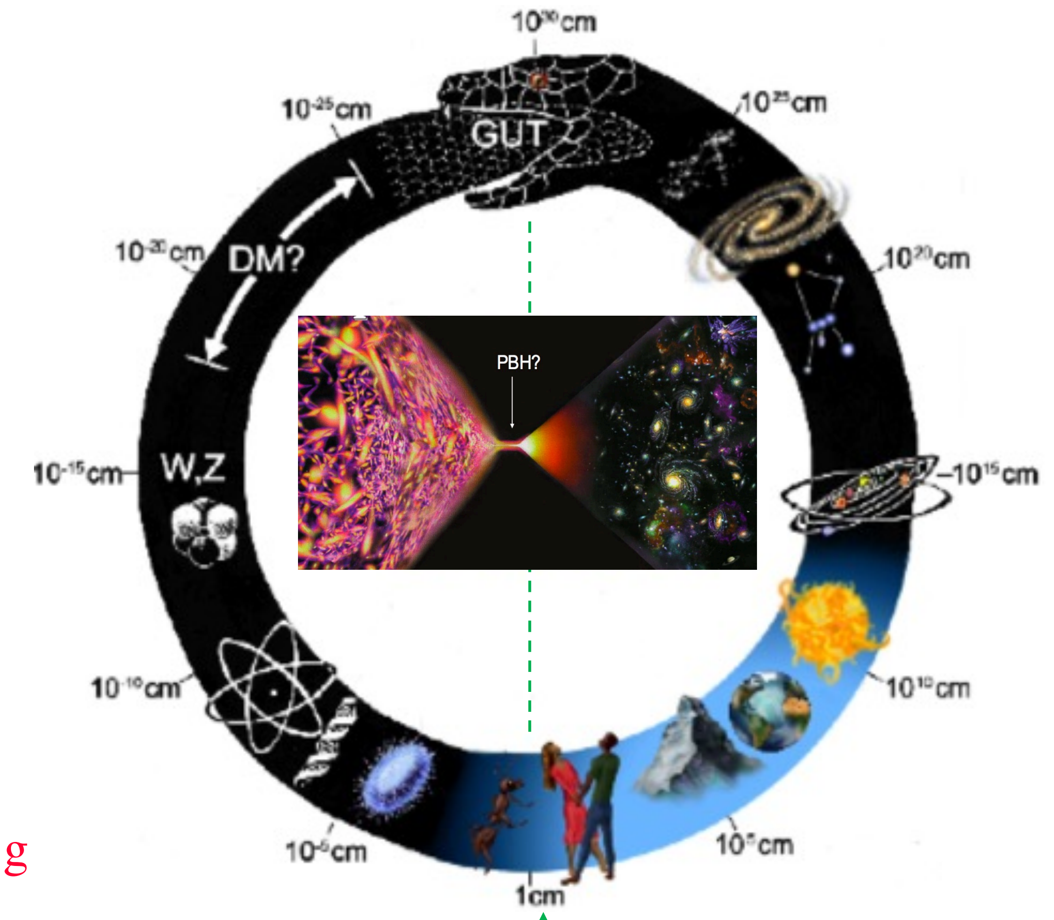




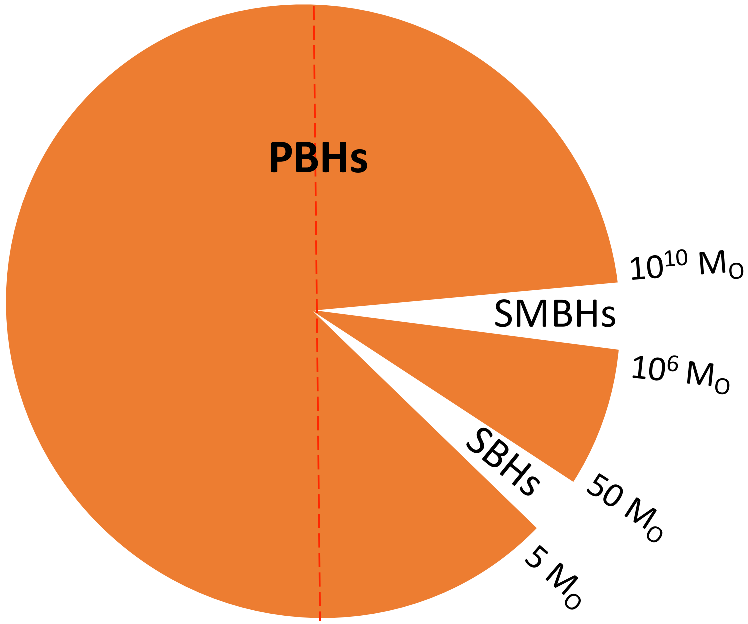
Brane cosmology => 5D Schwarzschild de Sitter model
=> Universe emerges out of 5D black hole

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

BLACK HOLES AS LINK BETWEEN MICRO AND MACRO PHYSICS



ARE MOST BLACK HOLES PRIMORDIAL?



God would be cruel not to populate whole Uroborus!

WHY PBHS ARE USEFUL

$M<10^{15}$g => Probe early Universe

inhomogeneities, phase transitions, inflation

$M\sim10^{15}$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

$M\sim10^{-5}$g => Probe quantum gravity

Planck mass relics, higher dimensions

THE ASTROPHYSICAL JOURNAL, **201**: 1–19, 1975 October 1

THE PRIMORDIAL BLACK HOLE MASS SPECTRUM*

BERNARD J. CARR
Department of Applied Mathematics and Theoretical Physics, Cambridge University, Cambridge, England;
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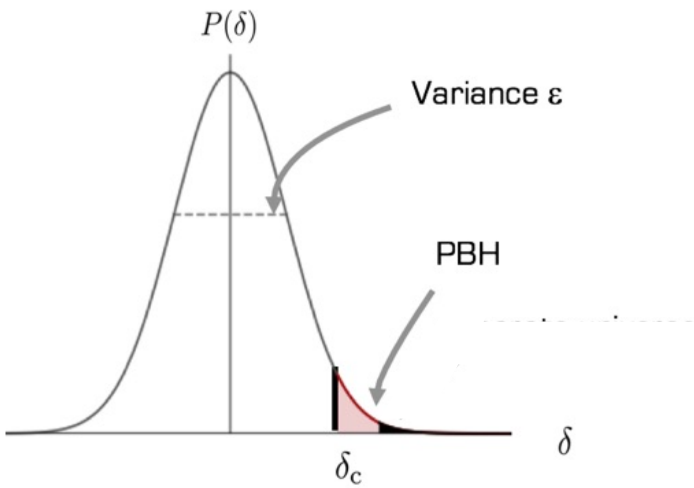
PBH FORMATION FROM LARGE INHOMOGENEITIES

To collapse against pressure, need

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

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



$\Rightarrow$ **fraction of PBHs**

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

So expect collapse fraction to be tiny

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

Fraction of Universe collapsing

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

General limit

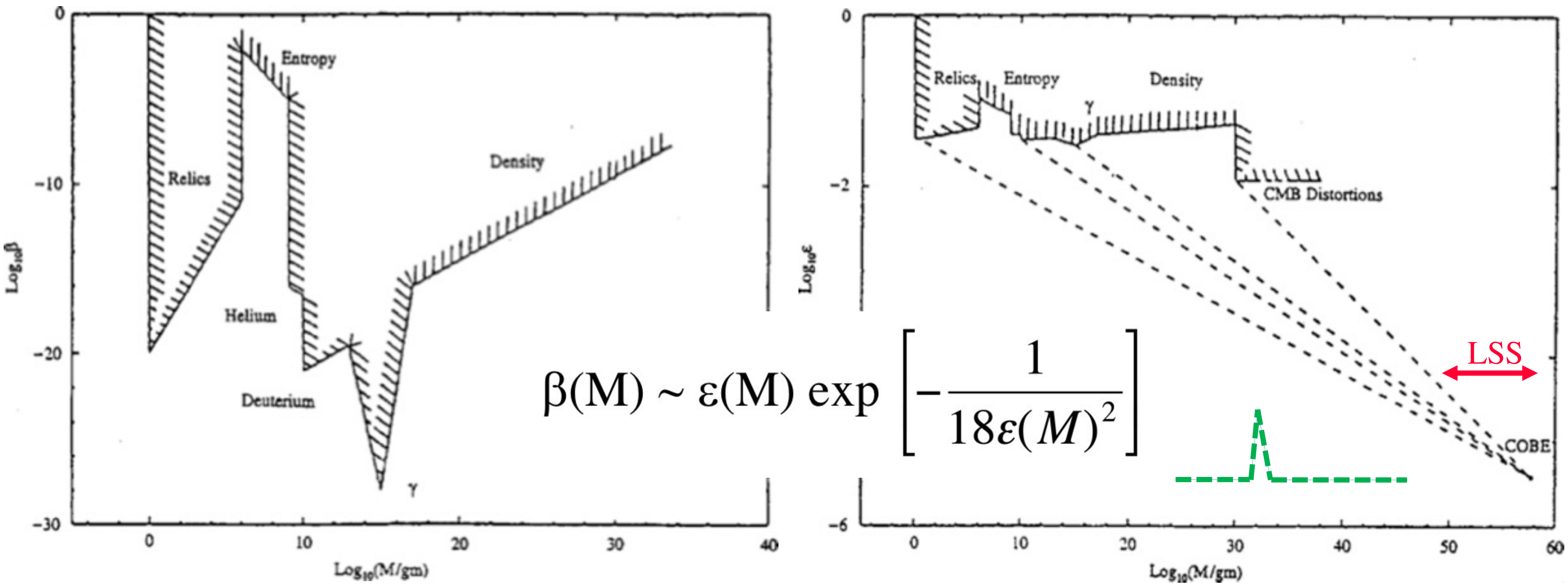
$$\frac{\rho_{PBH}}{\rho_{CBR}} \approx \frac{\Omega_{PBH}}{10^{-4}} \left[\frac{R}{R_0}\right] \Rightarrow \beta \sim 10^{-6}\,\Omega_{PBH}\left[\frac{t}{\sec}\right]^{1/2} \sim 10^{-18}\,\Omega_{PBH}\left[\frac{M}{10^{15}g}\right]^{1/2}$$

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

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

Fine-tuning problem!

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.
- ★ Need either blue spectrum or spectral feature to produce them.

More Precise Analysis of PBH Formation

★ Analytic calculations imply need $\delta > 0.3$ for $\alpha = 1/3$

[BC 1975]

★ Confirmed by first numerical studies

[Nadezhin *et al.* 1978]

→ but pressure gradient => PBHs smaller than horizon

★ Critical phenomena => $\delta > 0.7$

[Niemeyer & Jedamzik 1999], [Shibata & Sasaki 1999]

→ spectrum peaks at horizon mass with extended low mass tail

[Yokoyama 1999], [Green 2000]

★ Later calculations => $\delta > 0.45$

[Musco *et al.* 2008], [Musco & Miller 2013]

★ Confirmed by latest work; incorporation of different shapes and statistics

[Musco *et al.* 2020]

PBHs from Near-Critical Collapse

★ Usually: Assume

$$M_{BH} \propto M_H$$

horizon mass

★ Critical Scaling

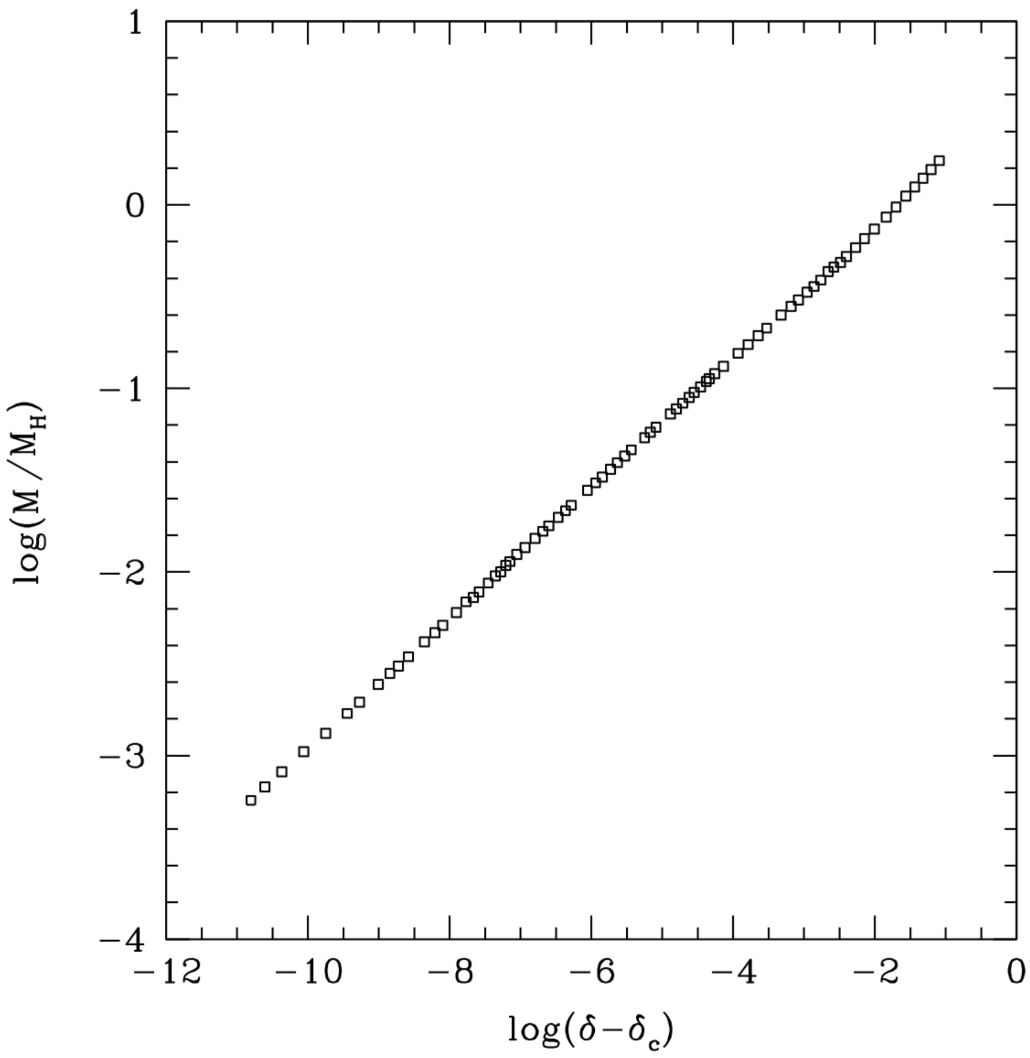
[Choptuik '93]

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

density contrast

★ Radiation domination and for spherical Mexican-hat profile:

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



[Musco, Miller, Polnarev 2008]

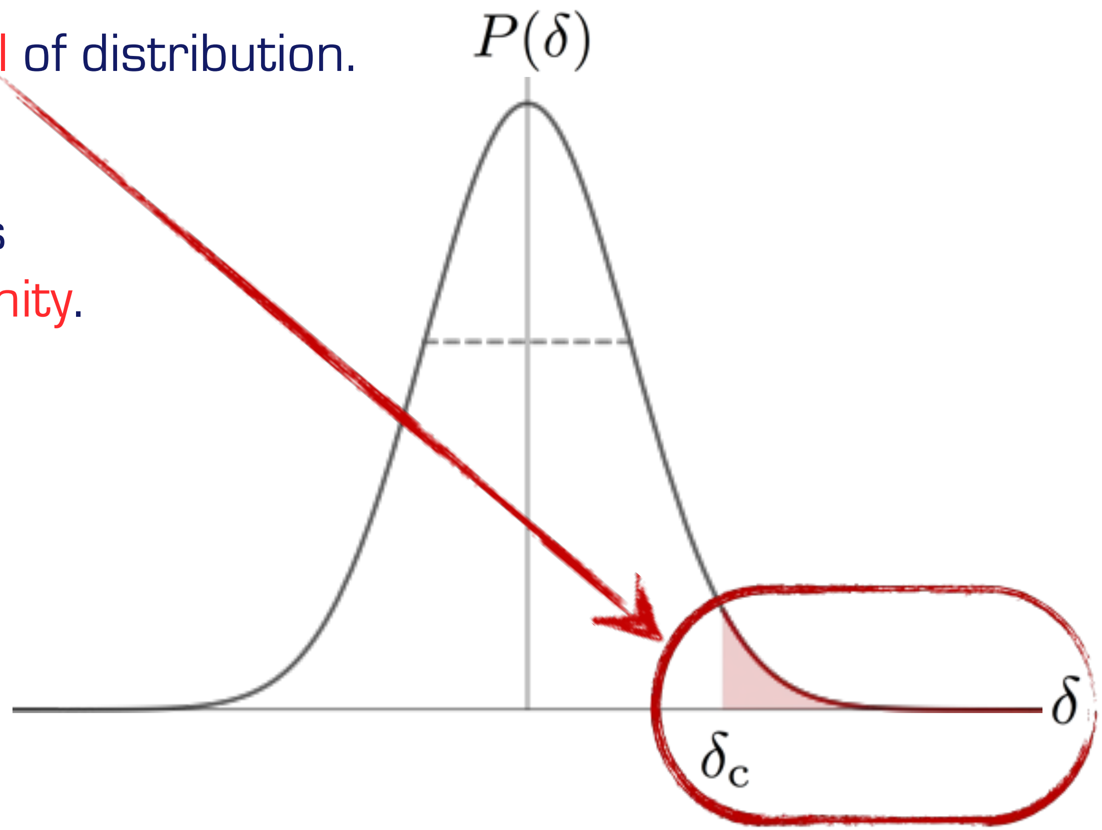
Non-Gaußianities

Vennin

★ PBH fluctuations are extremely rare.

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

★ PBH production is deep inside tail of distribution.



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

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

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

PBHS AND INFLATION

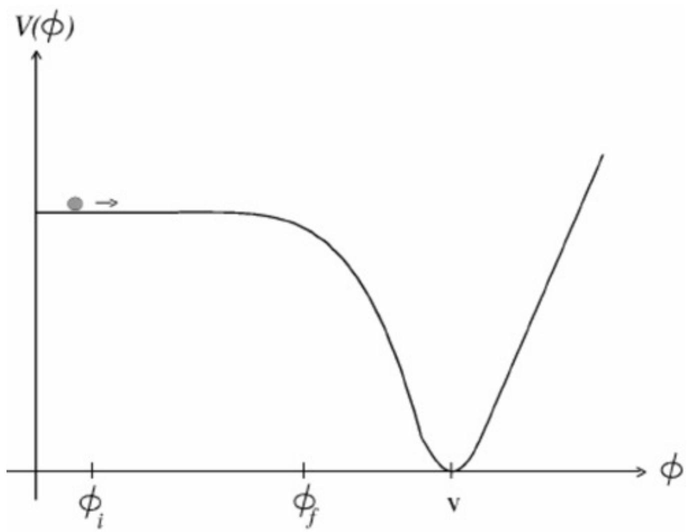
PBHs formed before reheat inflated away =>

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

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

But inflation generates fluctuations

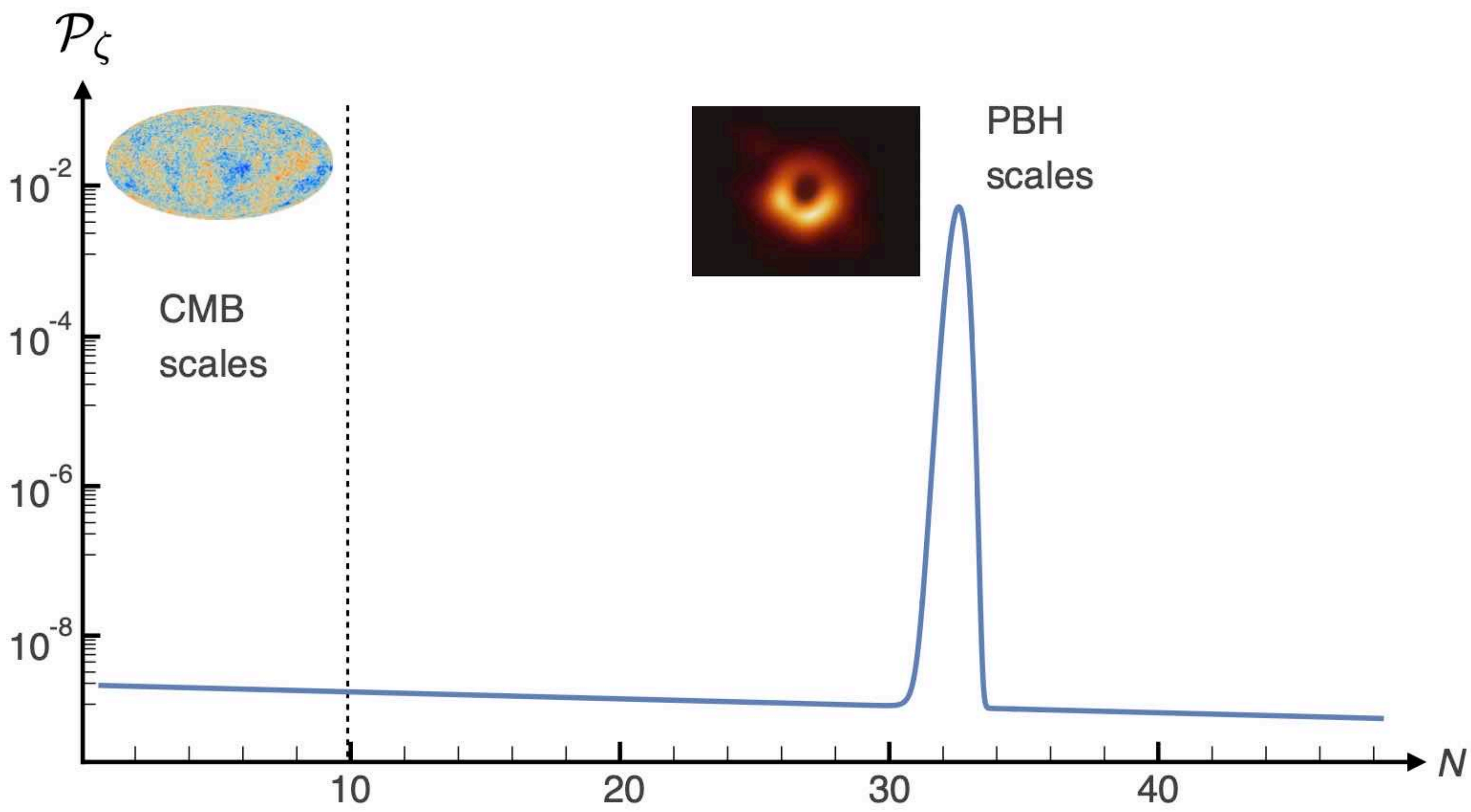
$$\frac{\delta\rho}{\rho} \sim \left[\frac{V^{3/2}}{M_{Pl}{}^{3}V'}\right]_H$$



Can these generate PBHs?

[HUGE NUMBER OF PAPERS ON THIS]

PBH Formation — Scales

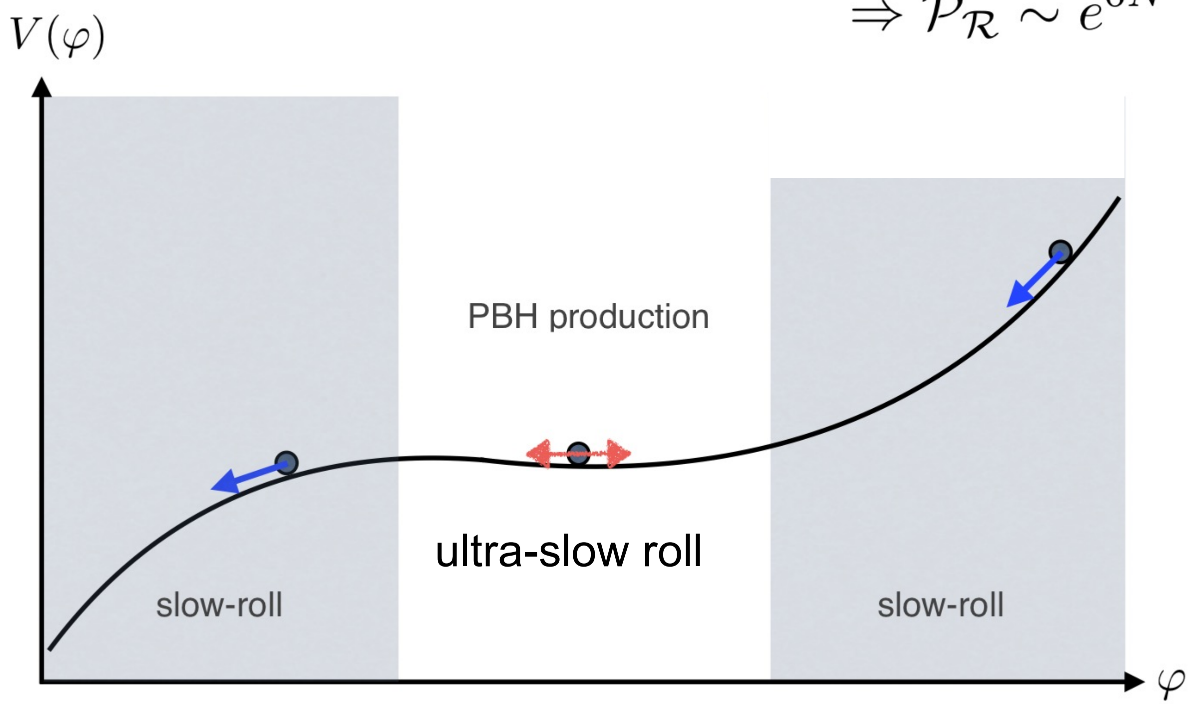


QUANTUM DIFFUSION

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

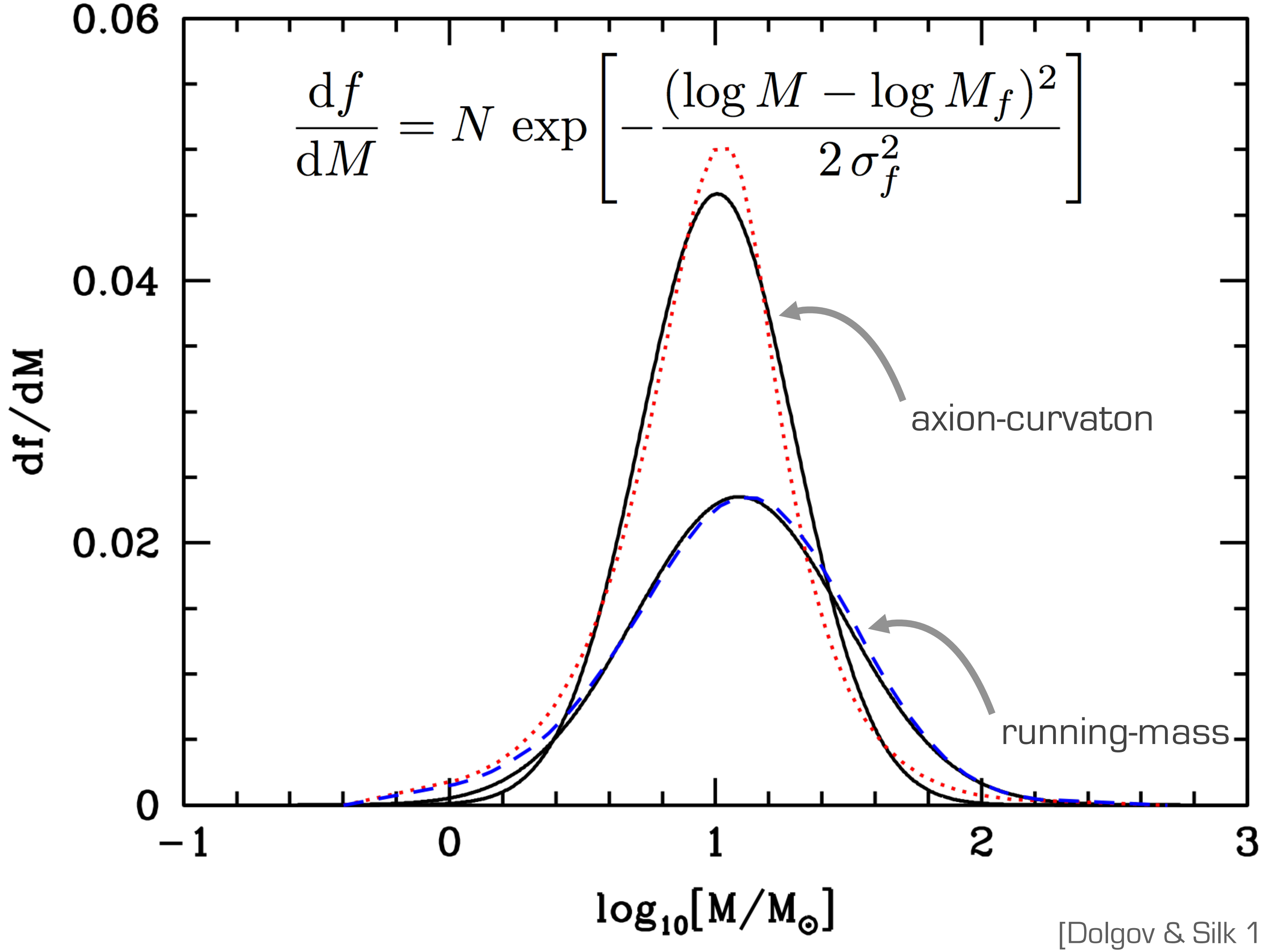
$$\mathcal{P}_\mathcal{R} = \left(\frac{H}{2\pi\varphi'}\right)^2 \,, \quad \varphi' \equiv \frac{\mathrm{d}\varphi}{\mathrm{d}N} \,, \quad \varphi'' + 3\varphi' + \frac{V_{,\varphi}}{H^2} \simeq \varphi'' + 3\varphi' = 0$$

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



Talk by Vincent Vennin for more recent work of PBHs and inflation

Generic Mass Functions – The Lognormal Case



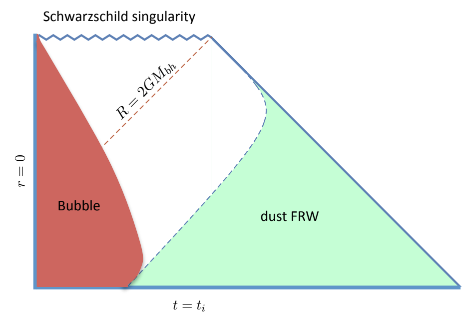
[Dolgov & Silk 1992]

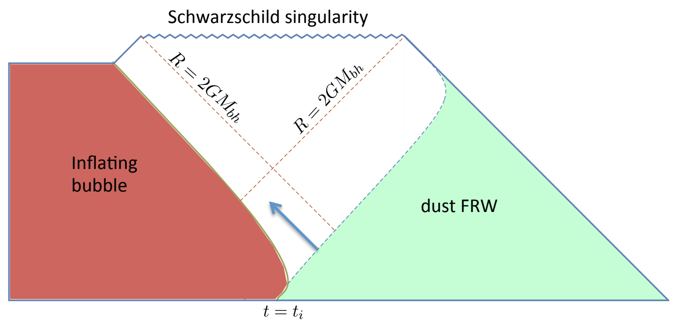
Black holes and the multiverse

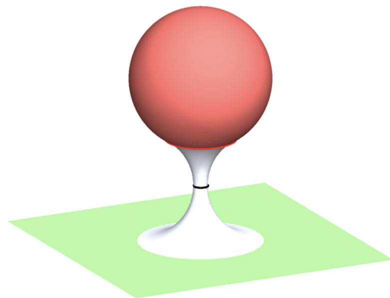
Jaume Garriga[a,b], Alexander Vilenkin[b] and Jun Zhang[b]

arXiv:1JCAP 02 (2016) 064

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

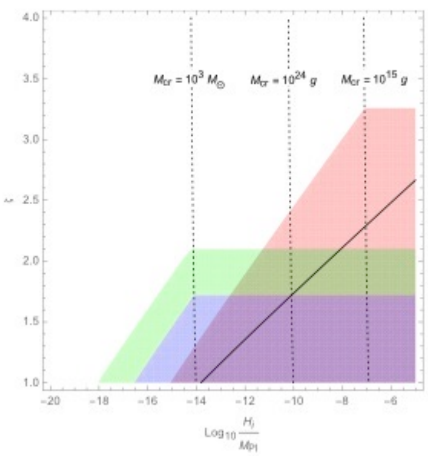






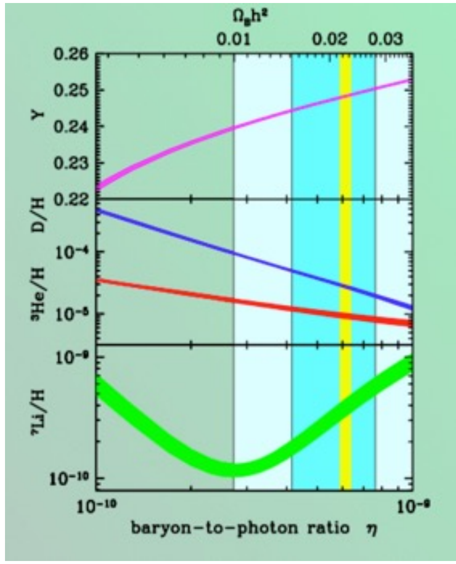
$\Rightarrow$ specific PBH mass function

=> evidence for multiverse?



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

Inflation and primordial black holes as dark matter

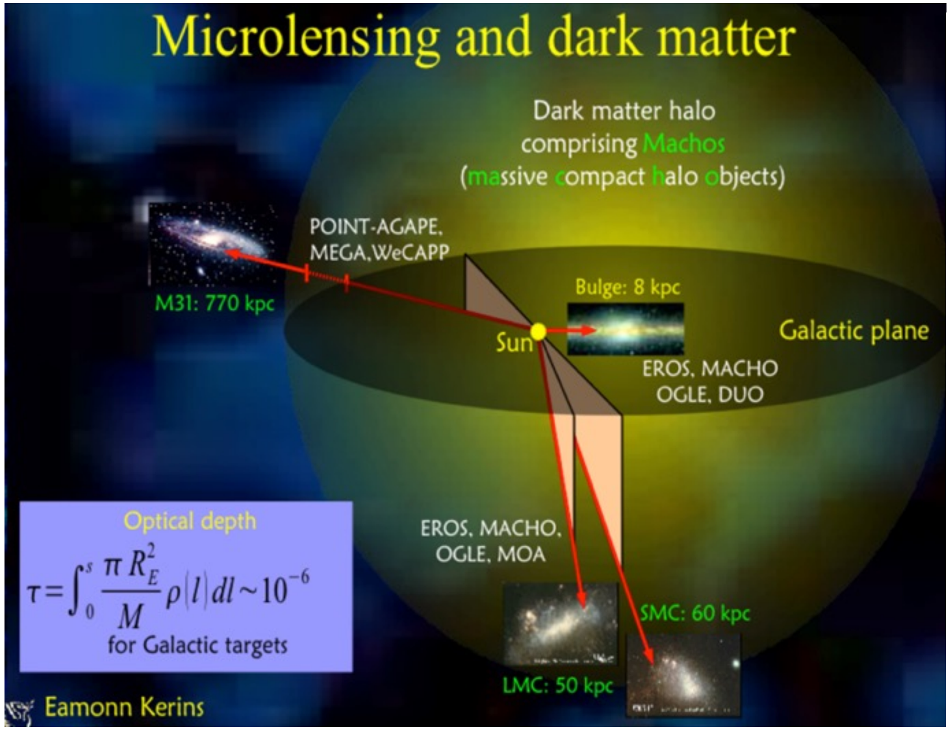
P. Ivanov, P. Naselsky, and I. Novikov

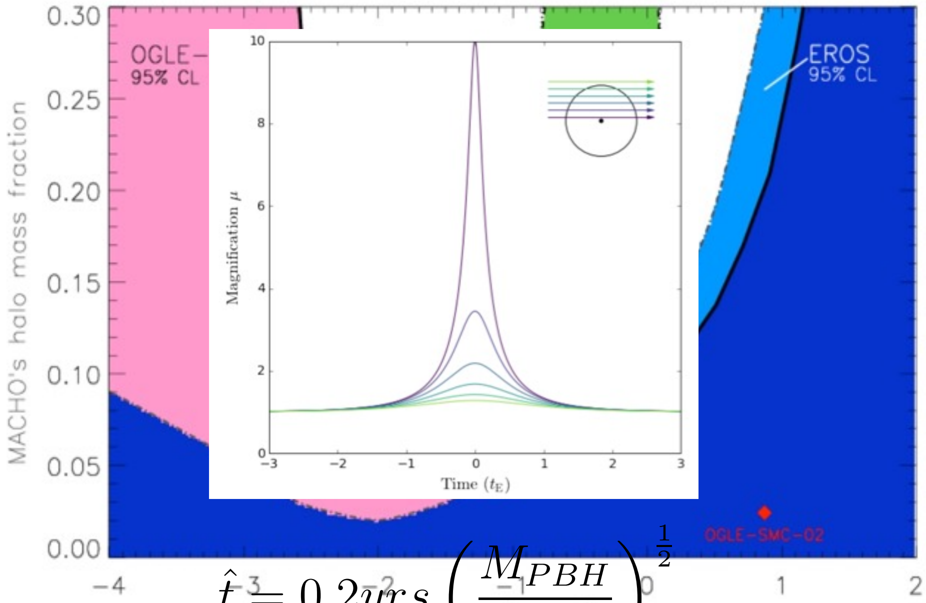
Phys. Rev. D **50**, 7173 -

ABSTRACT

We discuss the hypothesis that a large (or even a major) fraction of dark matter in the Universe consists of primordial black holes (PBH's). PBH's may arise from adiabatic quantum fluctuations appearing during inflation. We demonstrate that the inflation potential *V*(*cphi*) leading to the formation of a great number of PBH's should have a feature of the “plateau”-type in some range $cphi_1 < cphi < cphi_2$ of the inflation field *cphi*. The mass spectrum of PBH's for such a potential is calculated.

EXCITING DEVELOPMENT IN 1996: MICROLENSING





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

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

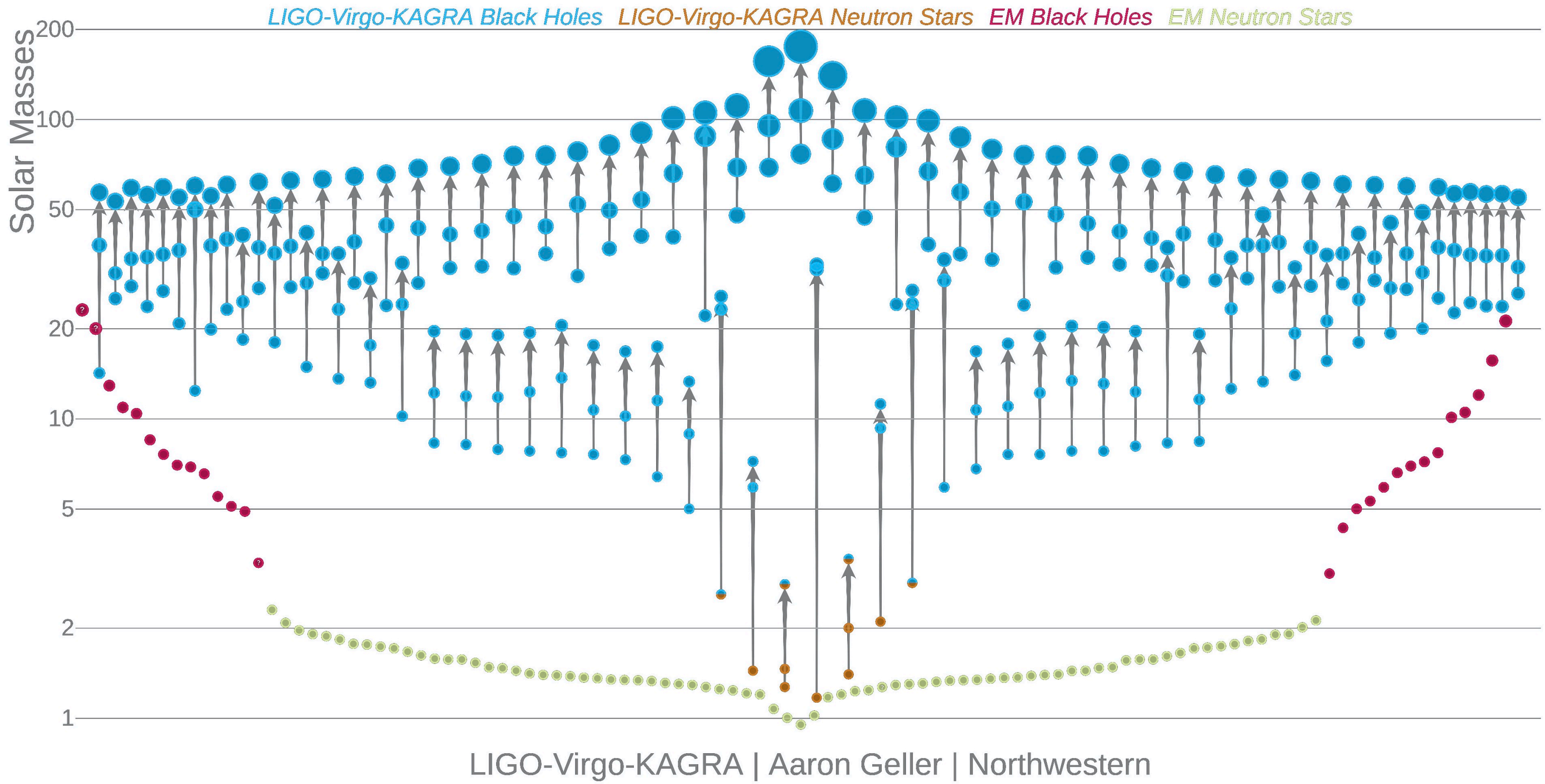
Early microlensing searches suggested MACHOs with 0.5 M_O

=> PBH formation at QCD transition?

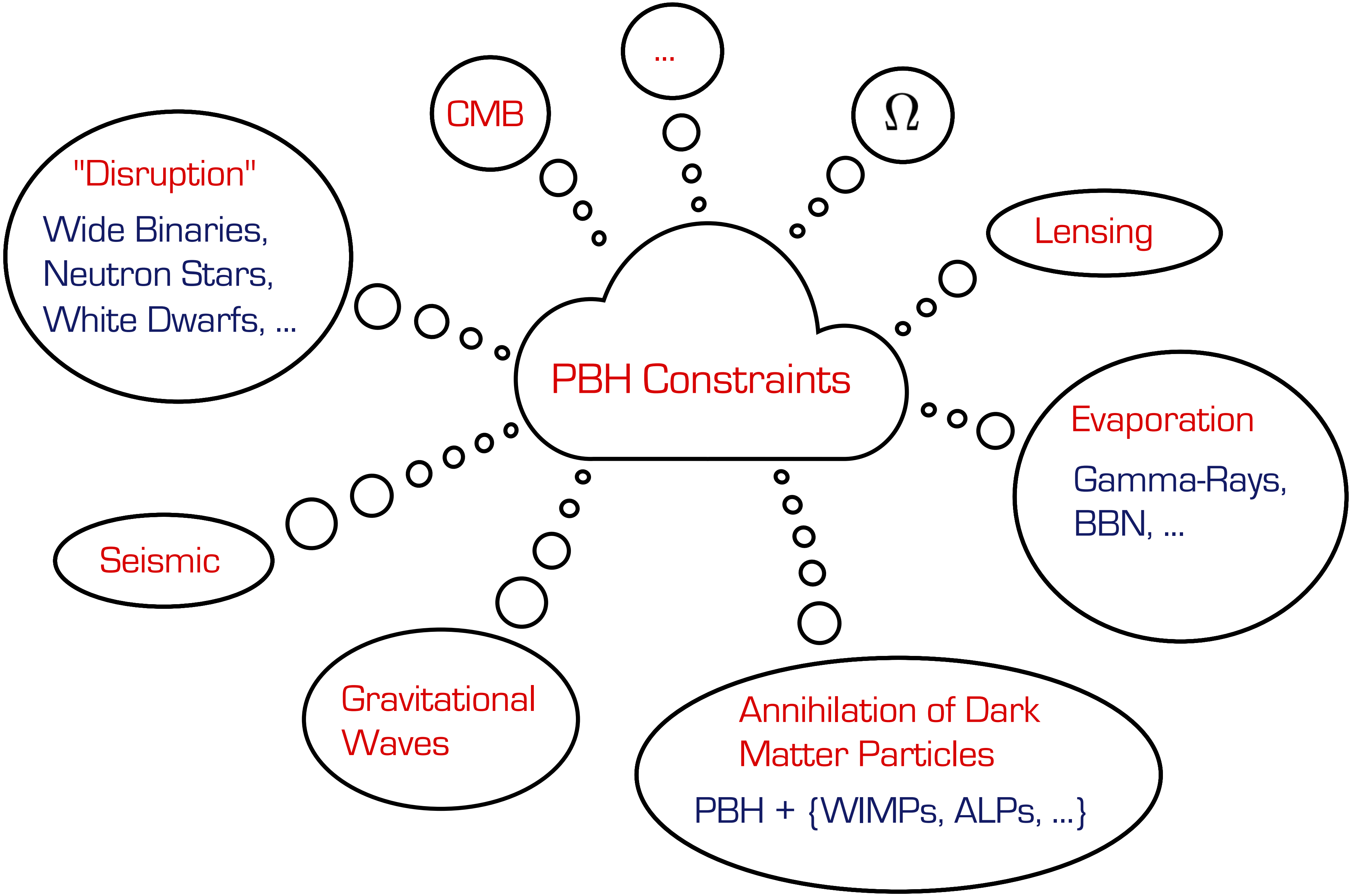
Pressure reduction => PBH mass function peak at 0.5 M_O

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

EXCITING DEVELOPMENT IN 2016:
LIGO DETECTION OF GRAVITY WAVES



Do we need PBHs?

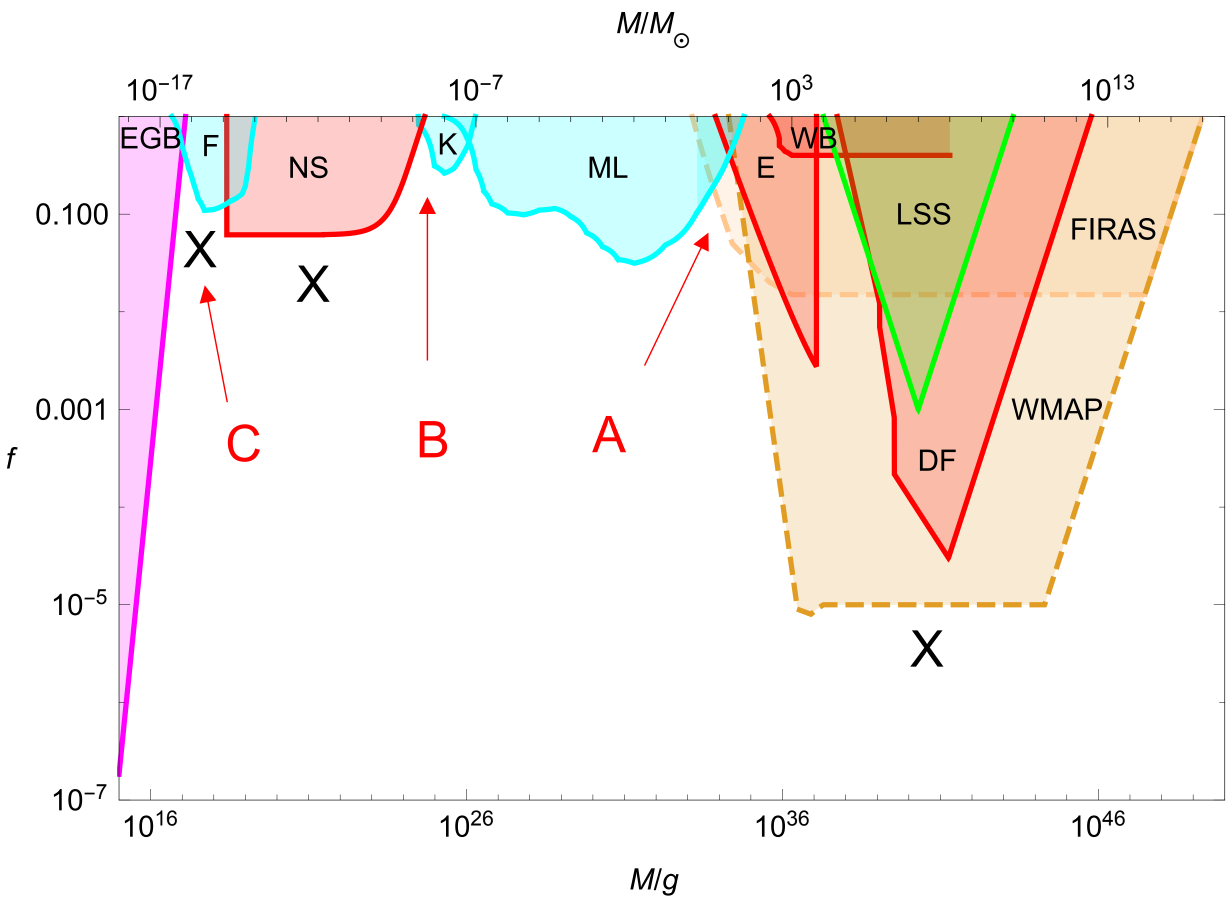


...
CMB
Ω
"Disruption"
Wide Binaries,
Neutron Stars,
White Dwarfs, ...
Lensing
PBH Constraints
Evaporation
Gamma-Rays,
BBN, ...
Seismic
Gravitational
Waves
Annihilation of Dark
Matter Particles
PBH + {WIMPs, ALPs, ...}

PRIMORDIAL BLACK HOLES AS DARK MATTER

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

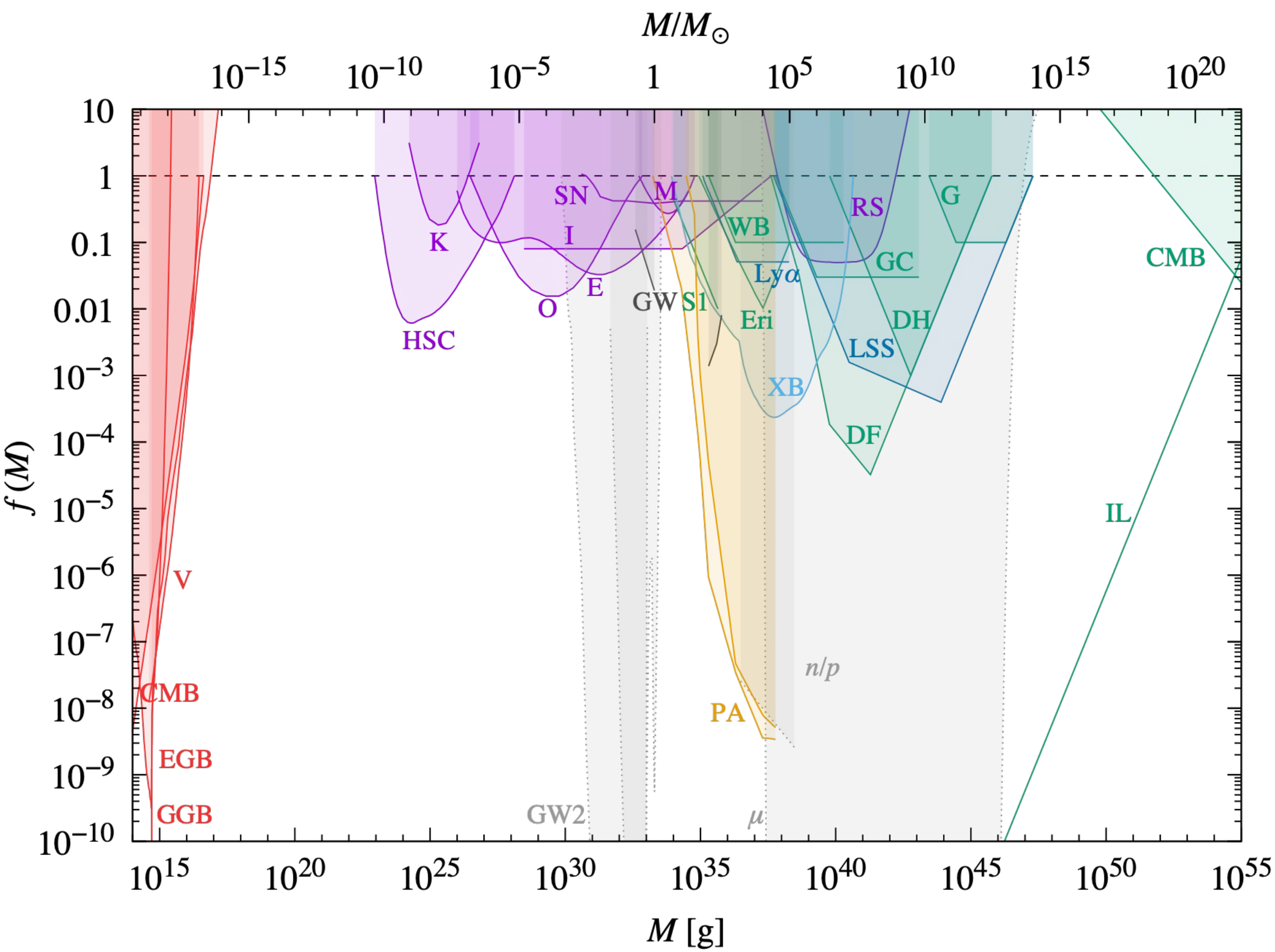
PRD 94, 083504, arXiv:1607.06077



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

But some of these limits are now thought to be wrong

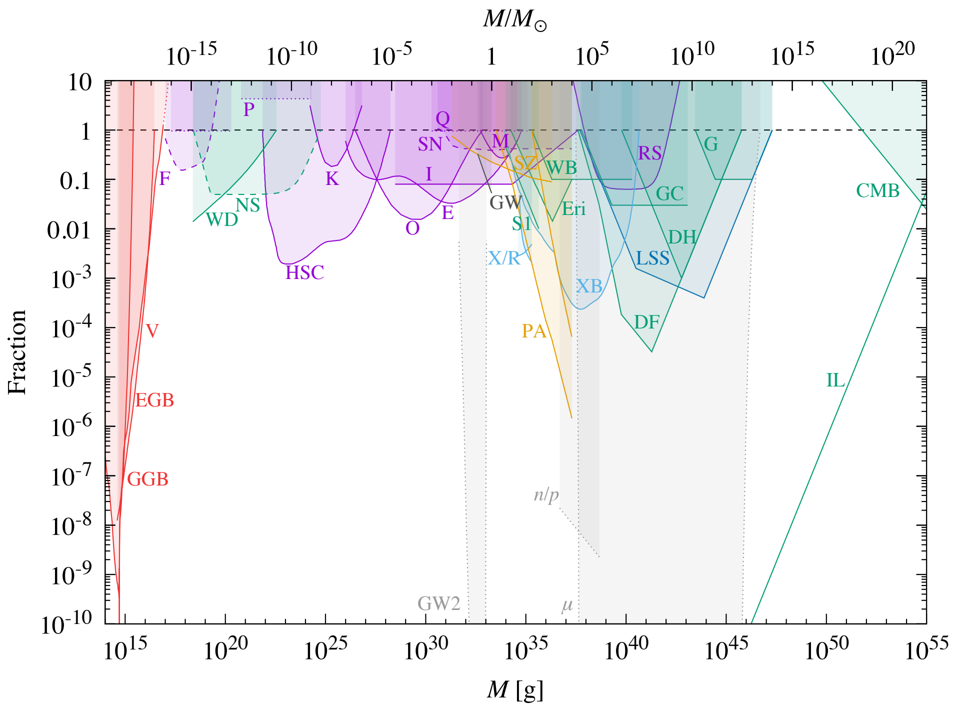
More Detailed Constraints on PBH Dark Matter Fraction

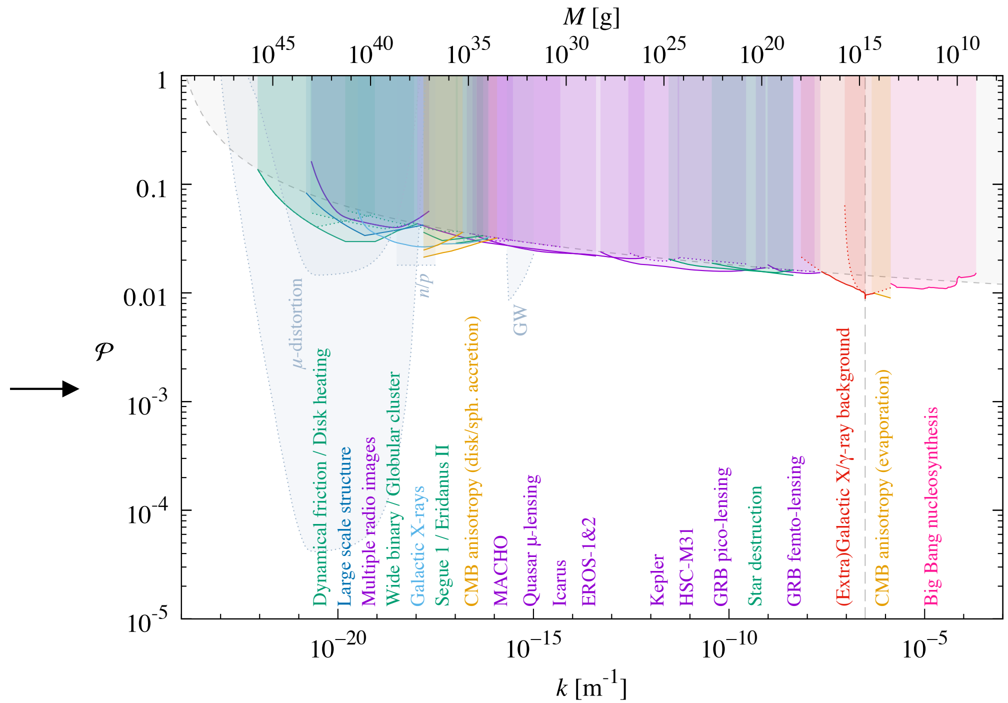


B. Carr, K. Kohri, Y. Sendouda & J. Yokoyama

Progress Theoretical Physics (2020), arXiv:2002.12778

Constraints on the Power Spectrum





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

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.

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.

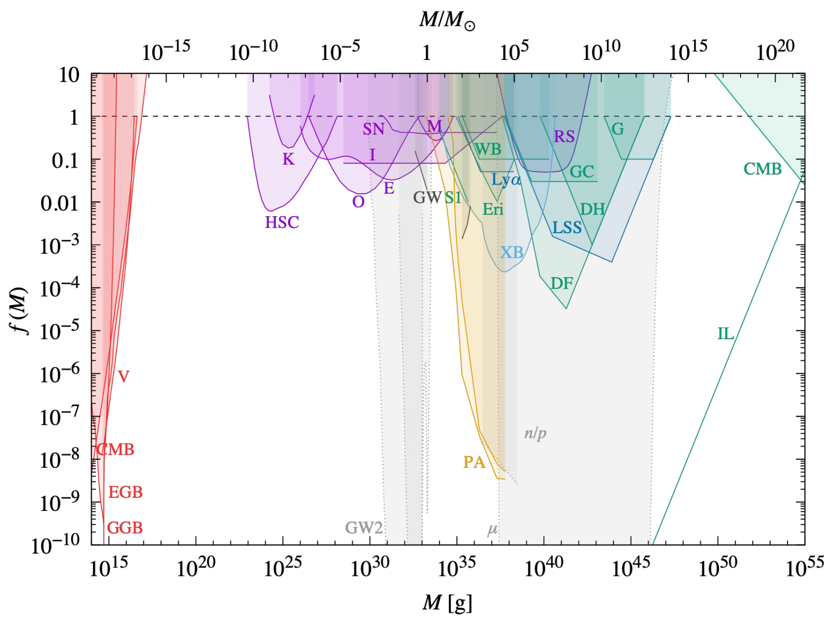
★ f(M) limits themselves depend on PBH mass function $\psi(M) \propto M \frac{\mathrm{d}n}{\mathrm{d}M}$

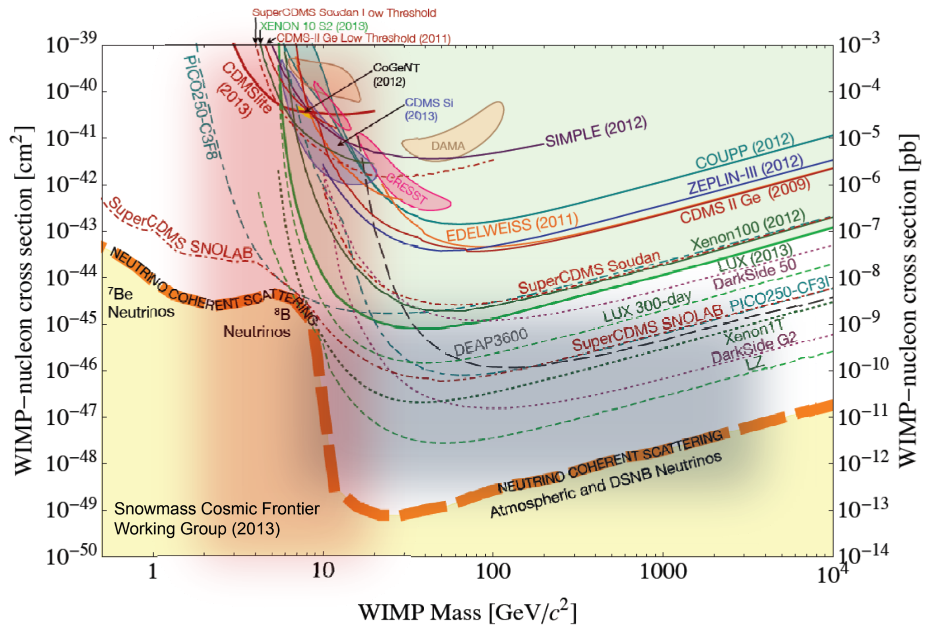
$$\int \mathrm{d}M \frac{\psi(M)}{f_{\max}(M)} \leq 1 \quad + \ \psi(M; f_{\mathrm{PBH}}, M_c, \sigma) \ \Rightarrow \ f_{PBH}(M_c, \sigma)$$

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

PBHS or WIMPS?

Historical Perspective





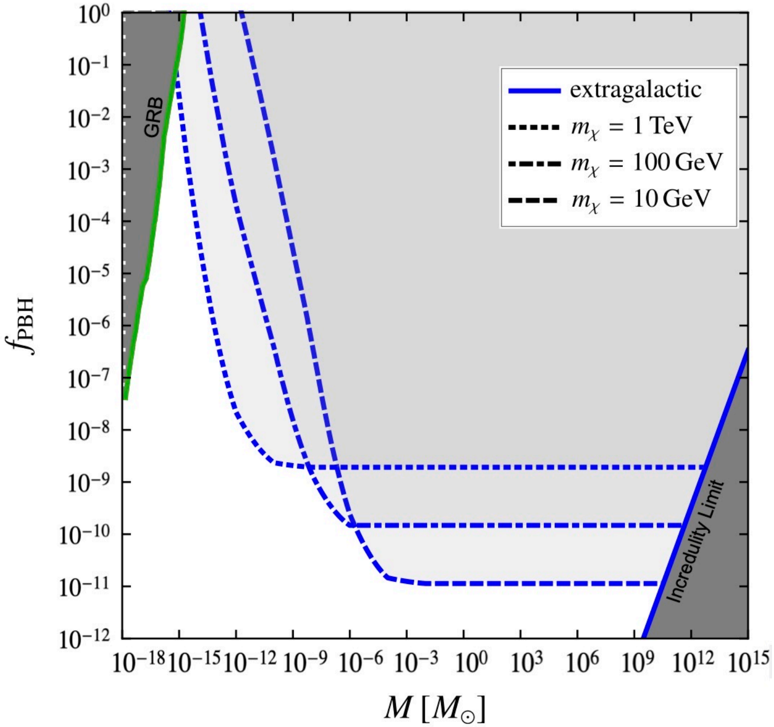
Light versus heavy candidates

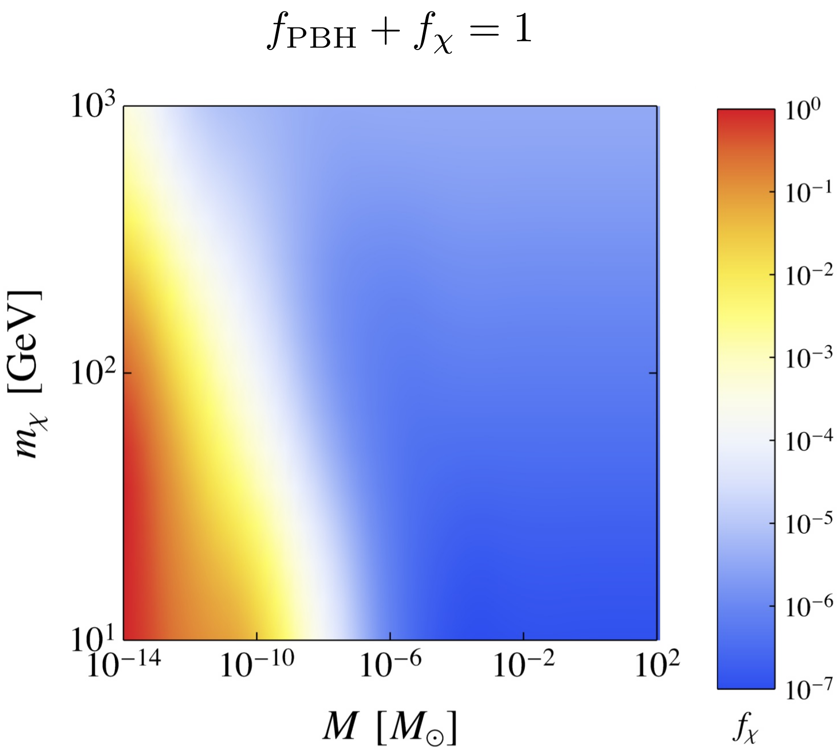
Both can be important even if not dark matter

PBHs & WIMPs?

Carr, Kuhnel & Visinelli
arXiv:2011.01930

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





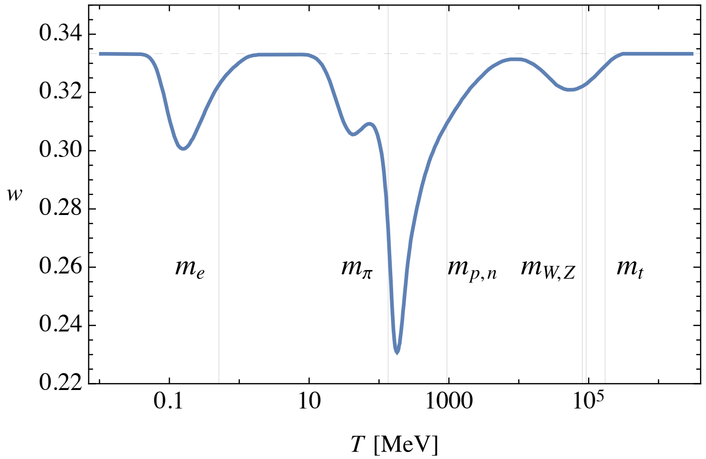
- ★ If WIMPs provide dark matter, then f_{PBH} is tiny
- ★ If 1-10 M_o PBHs provide dark matter, then f_χ is tiny
- ★ Even small values of f_{PBH} strongly constrain f_χ

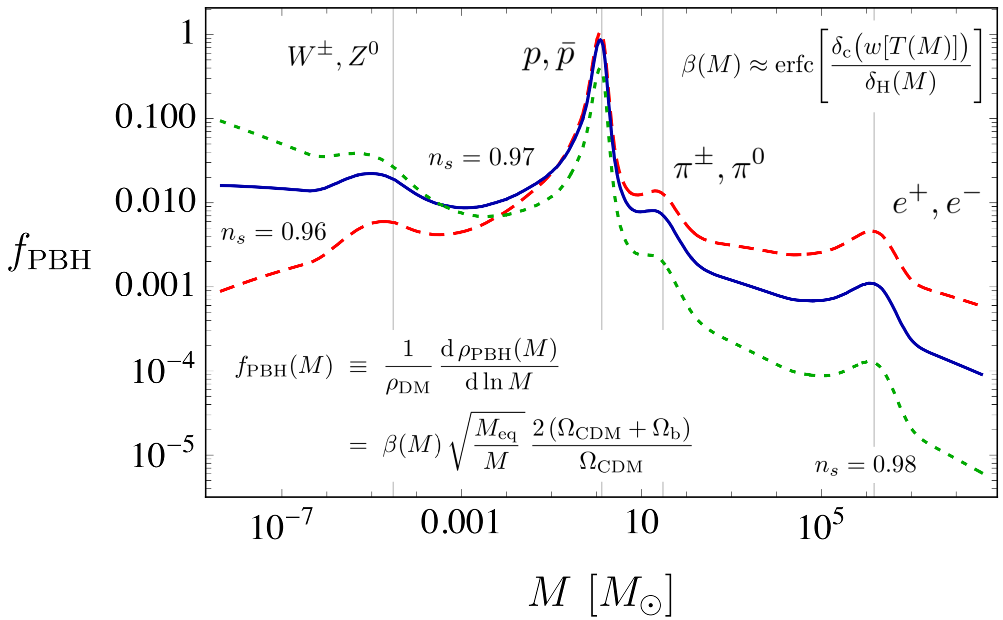
If the LIGO/Virgo black holes are primordial, this would rule out any standard WIMP scenario!

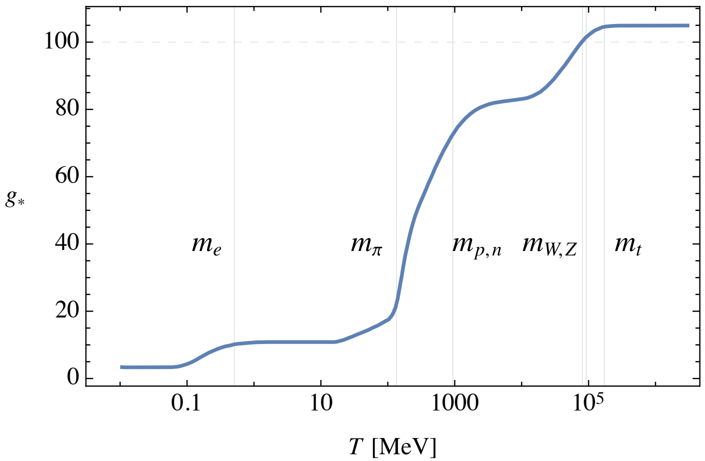
Cosmic Conundra Explained by Thermal History and Primordial Black Holes

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

arXiv:1906.08217

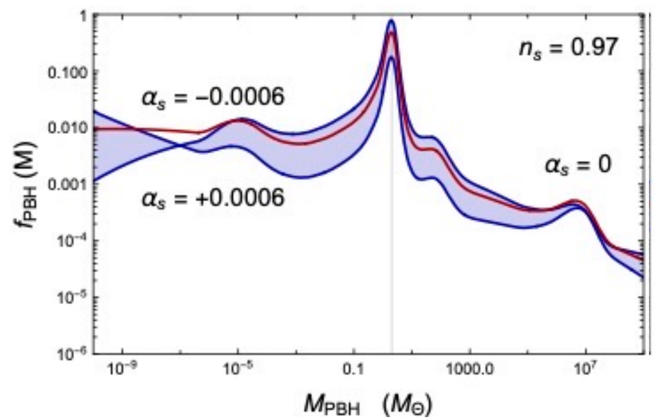






- **Nearly scale-invariant PS**
- **Spectral index: $n_s = 0.97$**
- **Peak at ~2 M⊙**
- **Second peak at ~30 M⊙**
- **Two bumps at 10^{-6} and 10^6 M⊙**

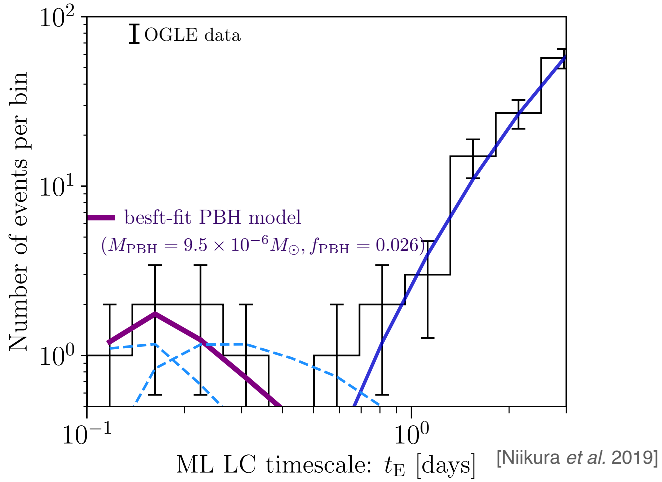
Running α_s?

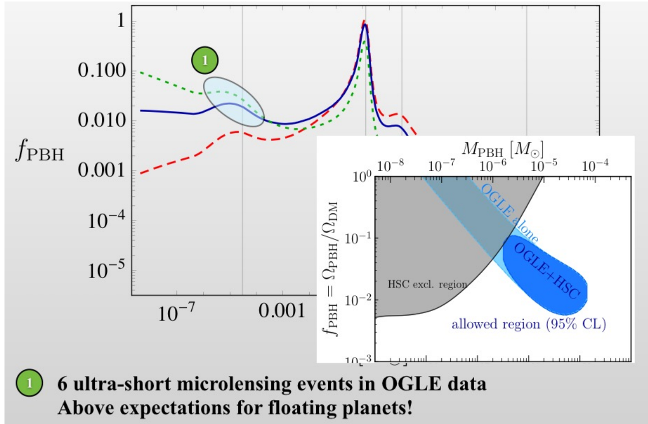


Planetary-mass microlenses

Niikura et al. arXiv:1901.07120

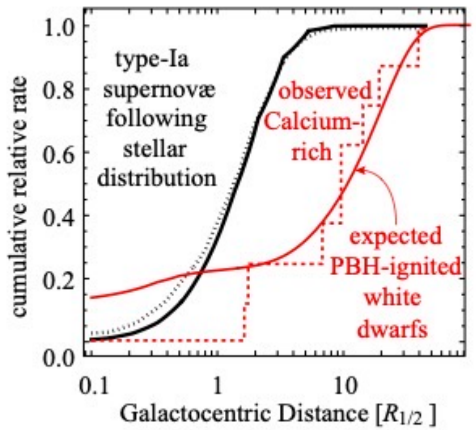
OGLE detected microlenses on 0.1-0.3 day timescale of unknown origin

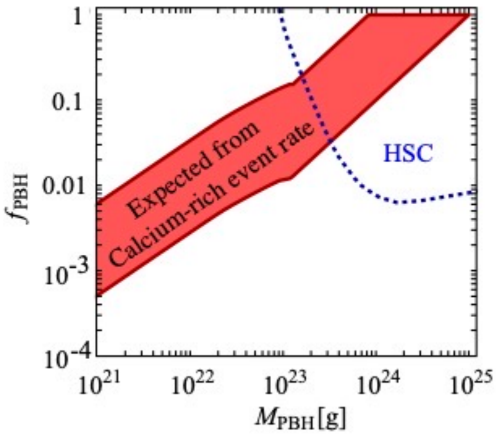




Exploding white dwarfs

Smirnov et al. arXiv:2211.00013





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

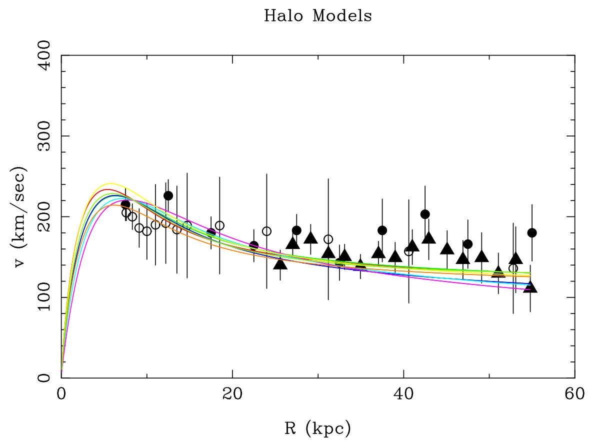
LMC/SMC microlensing

Early searches => MACHOs with 0.5 M_O

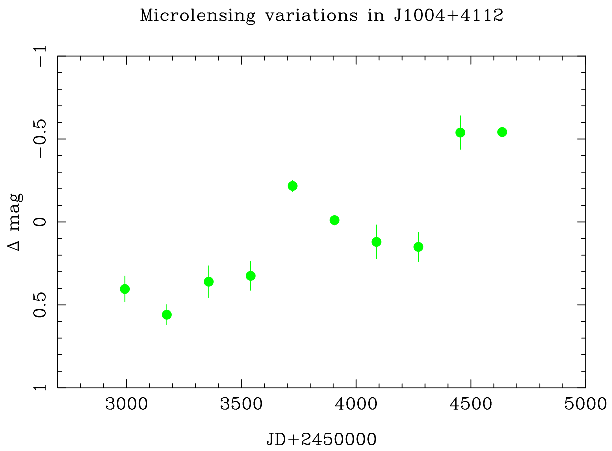
Later found they provide at most 20% of DM

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

Hawkins arXiv:1503.01935

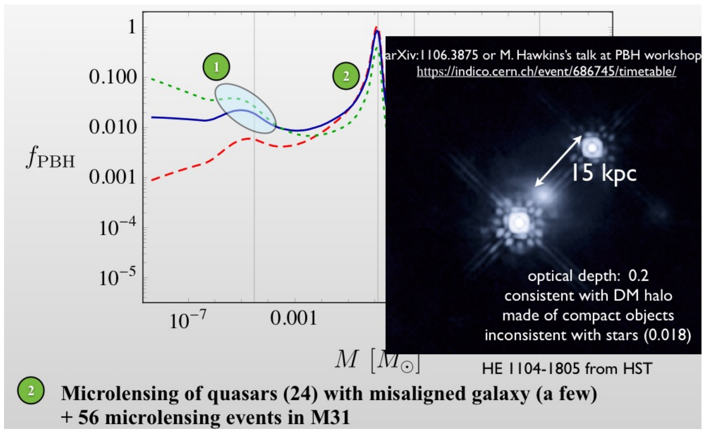


Quasar microlensing



Hawkins arXiv:2010.15007

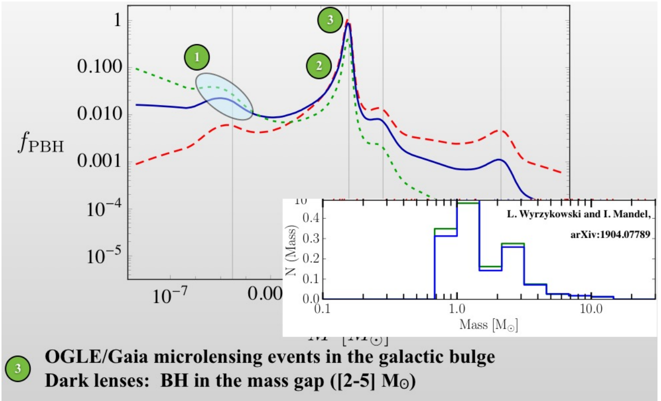
Caustic crossing



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

Excess of lenses in Galactic Bulge

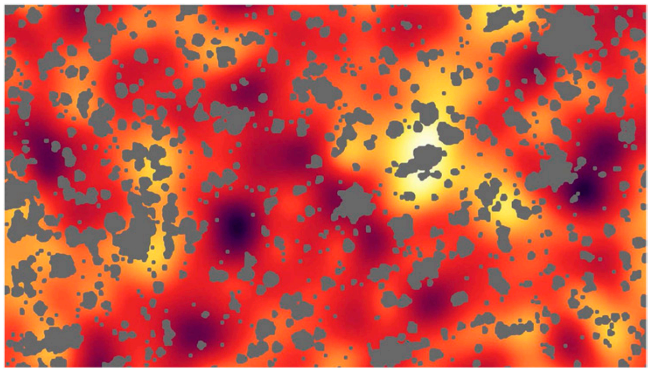
Wyrzykowski & Mandel 2020



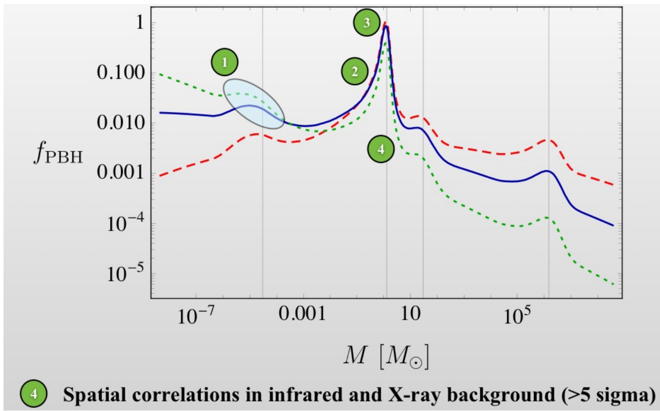
- ★ OGLE has detected 58 long-duration microlensing events in the Galactic bulge.
- ★ 18 of these cannot be main-sequence stars and are very likely black holes.
- ★ Their mass function overlaps the low mass gap from 2 to 5 $M_\odot$.
- ★ These are not expected to form as the endpoint of stellar evolution.

Cosmic infrared/X-ray backgrounds

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



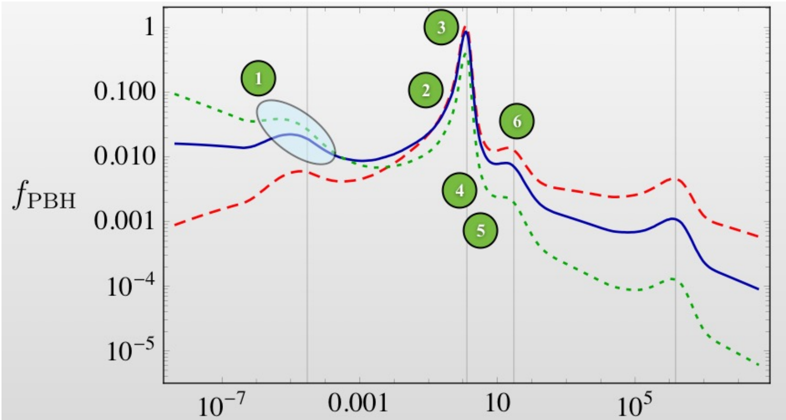
Kashlinsky arXiv:1605.04023

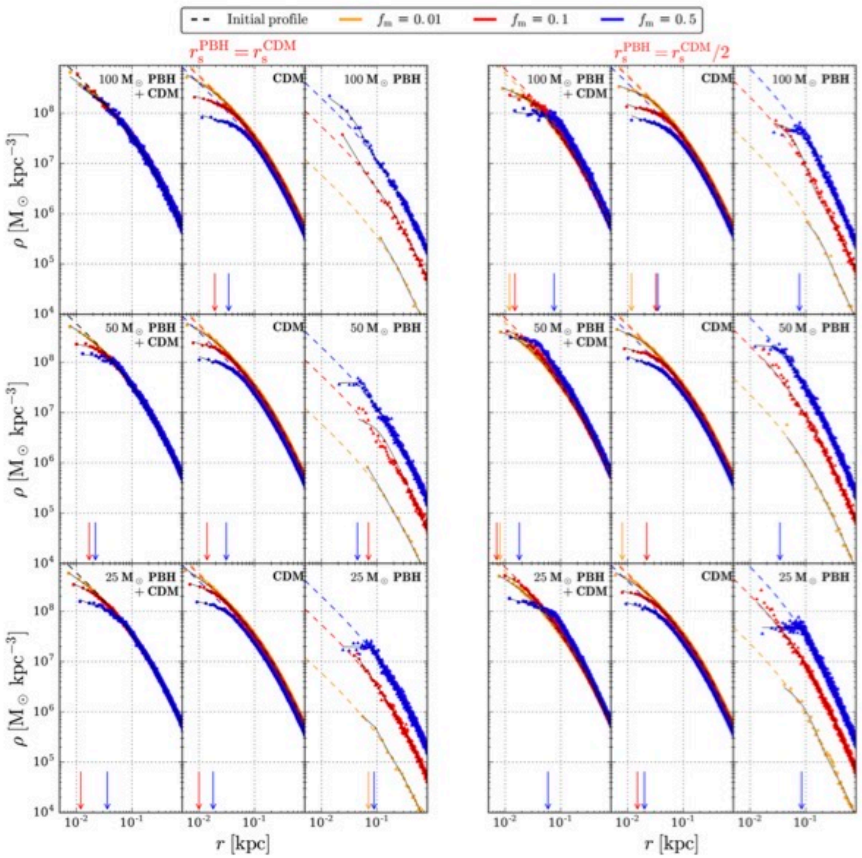


Cappelluti et al. arXiv:2109.08701

Minimum radius of ultra-faint dwarf galaxies and DM cores

Boldrini et al. arXiv:1909.07395





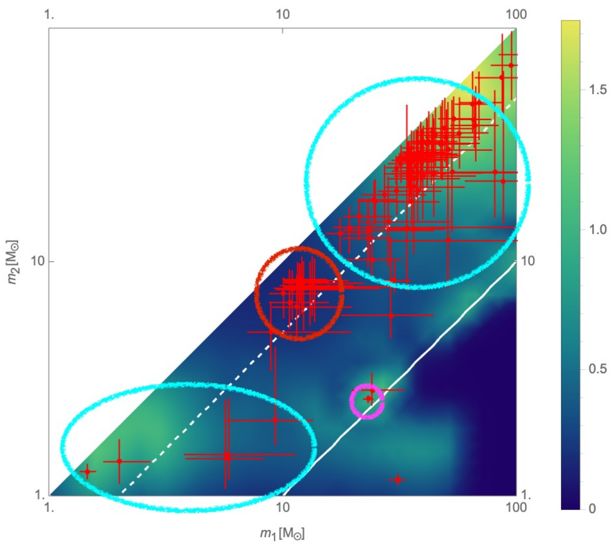
★ Non-detection of dwarf galaxies smaller than ~ 10 – 20 pc

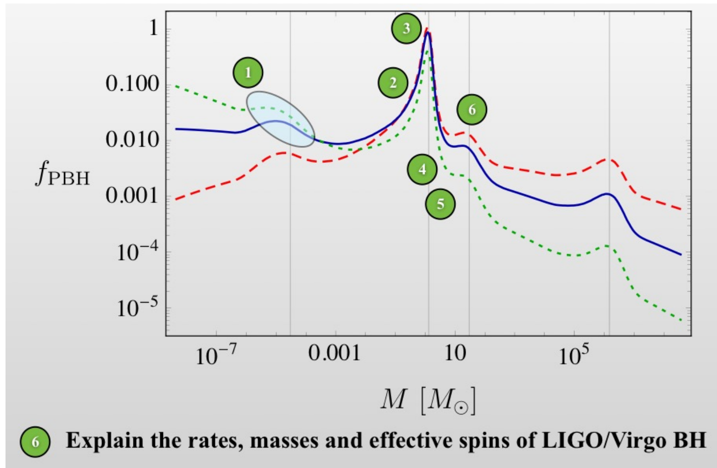
★ Ultra-faint dwarf galaxies are dynamically unstable below some critical radius in the presence of PBH CDM!

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

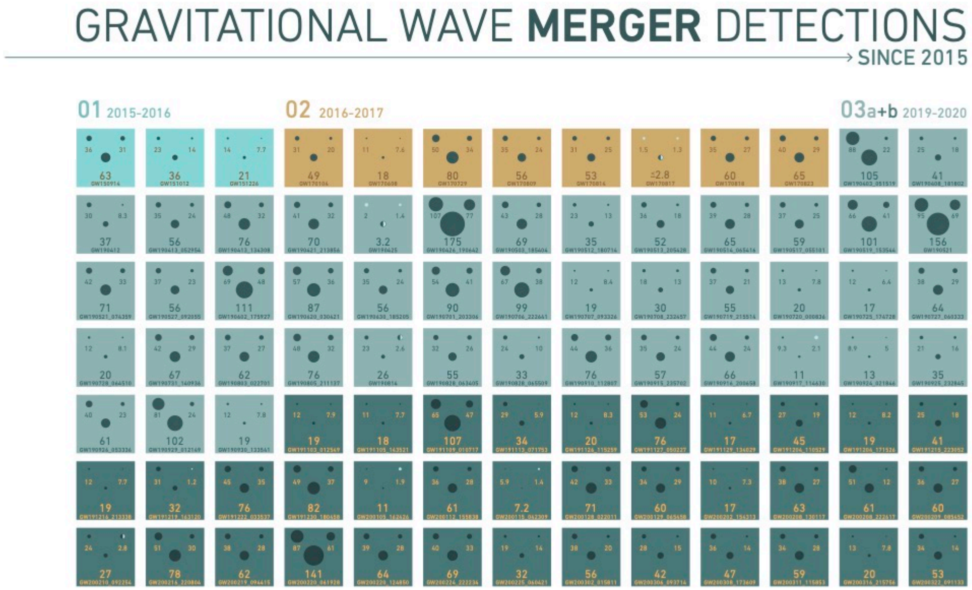
LIGO/Virgo/KAGRA black holes

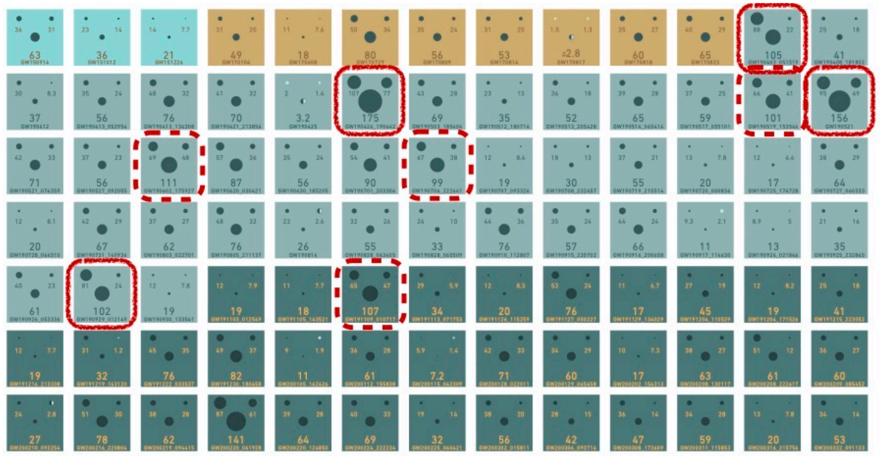
$n_s = 0.975$
α = 0.7
q = 0.5,0.1



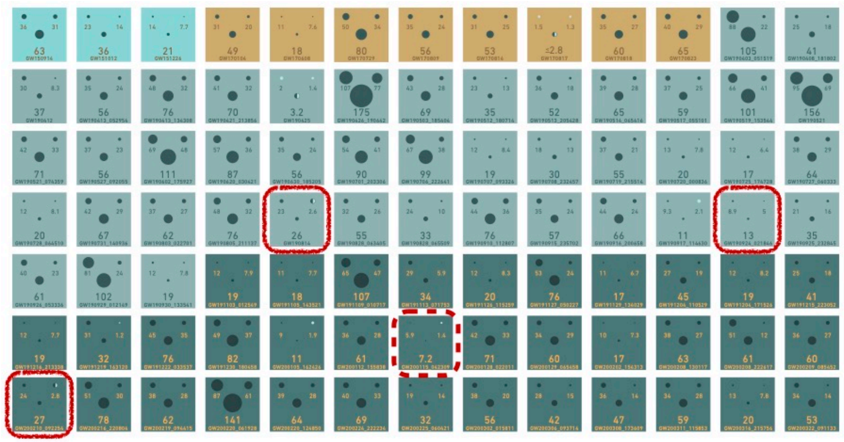


Escriva, Bagui & Clesse, arXiv:2209.06196

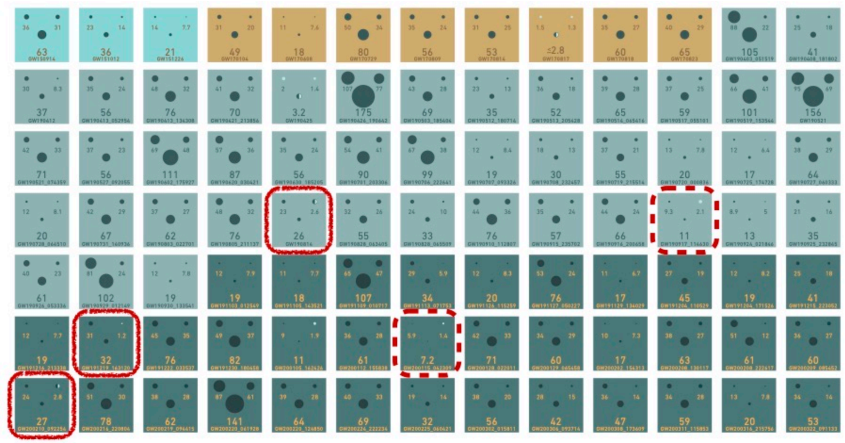




★ Black hole progenitors in the pair-instability mass gap (i.e. above ~ 60 $M_{\odot}$)



★ 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.

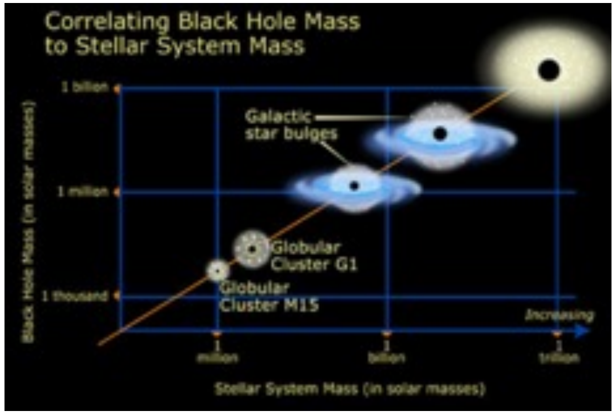
★ Recent reanalysis of LIGO data updated merger rates and low mass ratios:

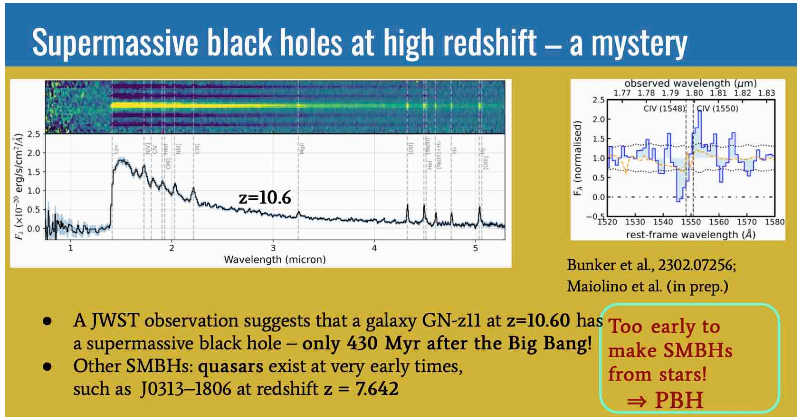
Date	FAR [yr^{-1}]	$m_1 [M_\odot]$	$m_2 [M_\odot]$	spin-1-z	spin-2-z	H SNR	L SNR	V SNR	Network SNR
2017-04-01	0.41	4.90	0.78	−0.05	−0.05	6.32	5.94	–	8.67
2017-03-08	1.21	2.26	0.70	−0.04	−0.04	6.32	5.74	–	8.54
2020-03-08	0.20	0.78	0.23	0.57	0.02	6.31	6.28	-	8.90
2019-11-30	1.37	0.40	0.24	0.10	−0.05	6.57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

PBHs as seeds for SMBHs

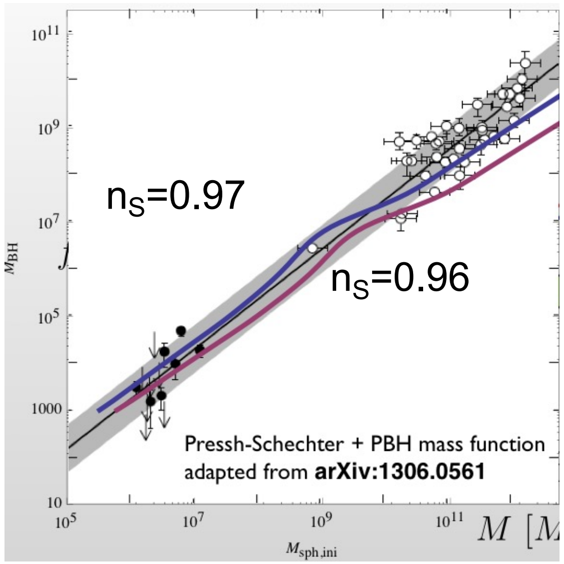
Could 10^6-10^{10} M_O black holes in galactic nuclei be primordial?

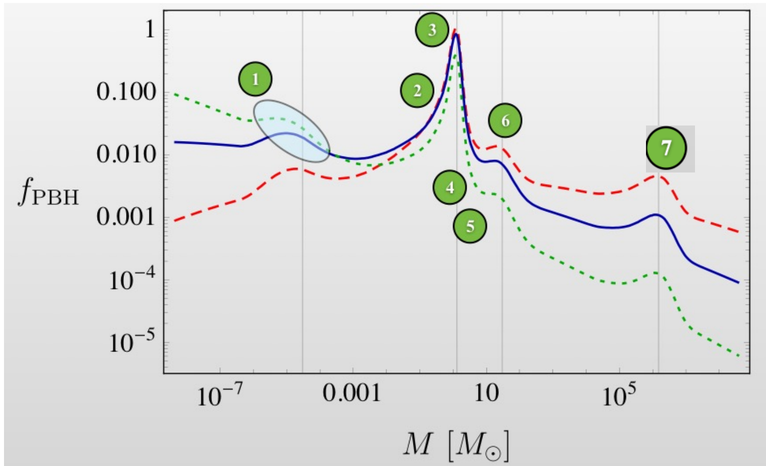




BH mass prop' to stellar mass

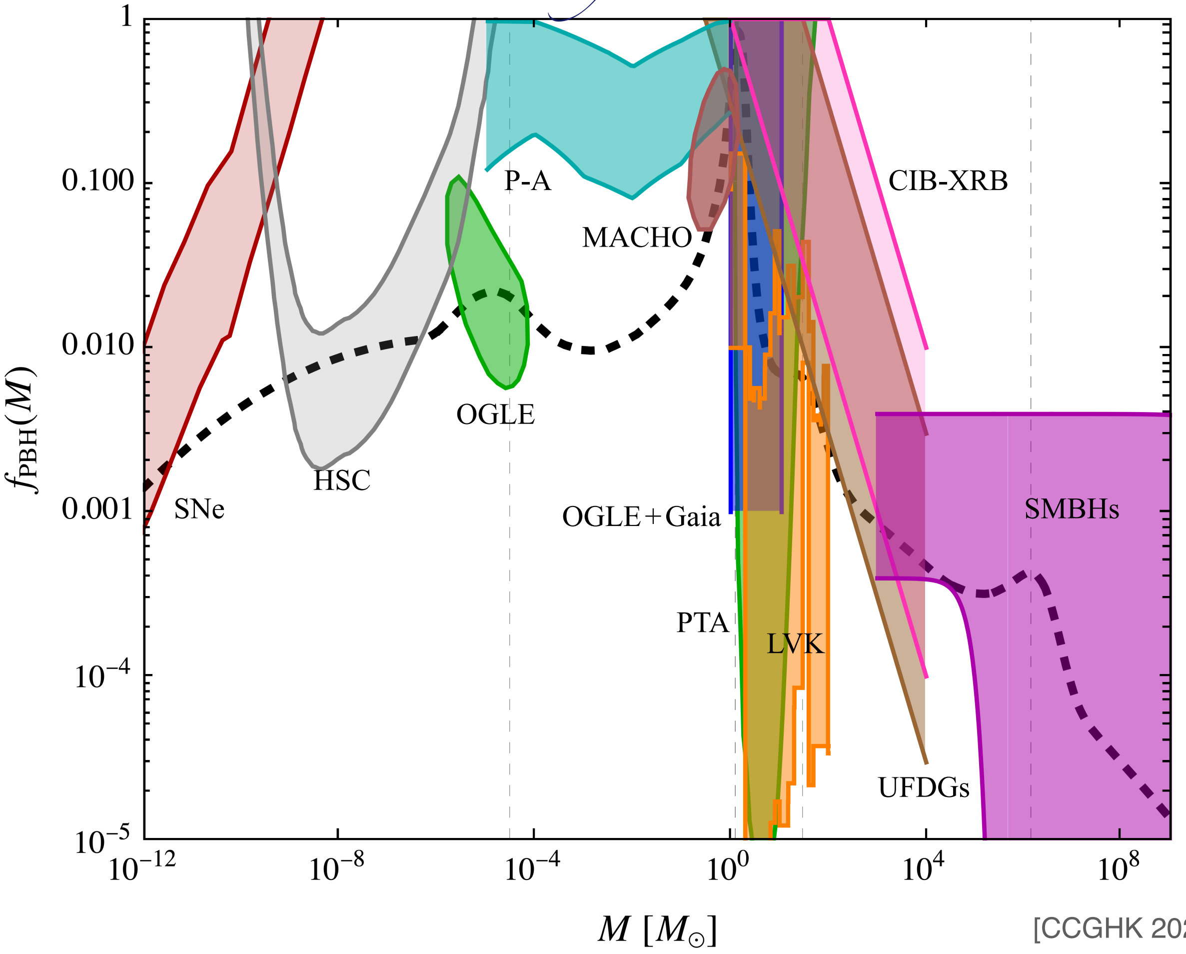
Kusenko





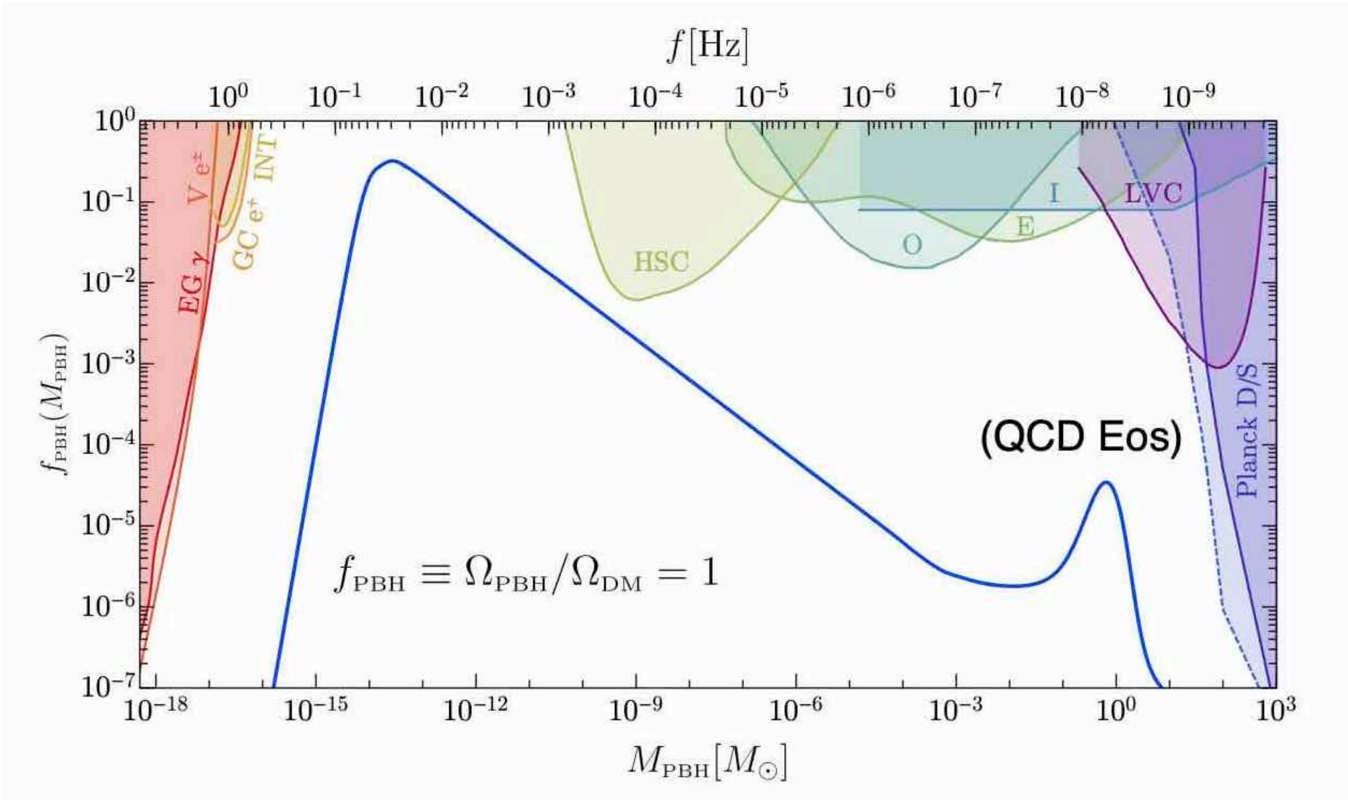
n_S = 0.97 => observed ratio of BH and halo mass if f_{PBH} ~ 1.

PBH Mass Function — Confronted with Observations



[CCGHK 2023]

Others prefer asteroidal PBHs to provide DM



Franciolini et al. 2022

Fine-tuning problem 1

Fraction of density in PBHs of mass M at formation $\beta \sim 10^{-18}\,\Omega_{PBH}\left[\frac{M}{10^{15}\,g}\right]^{1/2}$

Fine-tuning problem 2

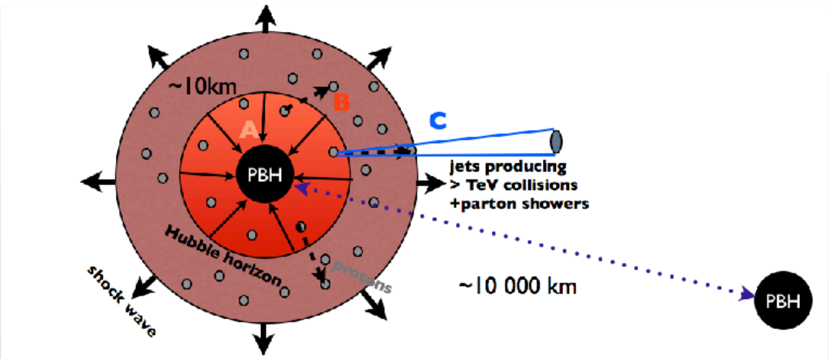
Amplitude of horizon-scale fluctuations $\beta(M) \sim \varepsilon(M)\,\exp\left[-\frac{\alpha^2}{2\varepsilon(M)^2}\right]$

Fine-tuning problem 3

Ratio of dark matter to baryonic density $\chi \sim 5$

Garcia-Bellido, Carr, Clesse
arXiv:1904.114827

PBHs as origin of baryons and dark matter

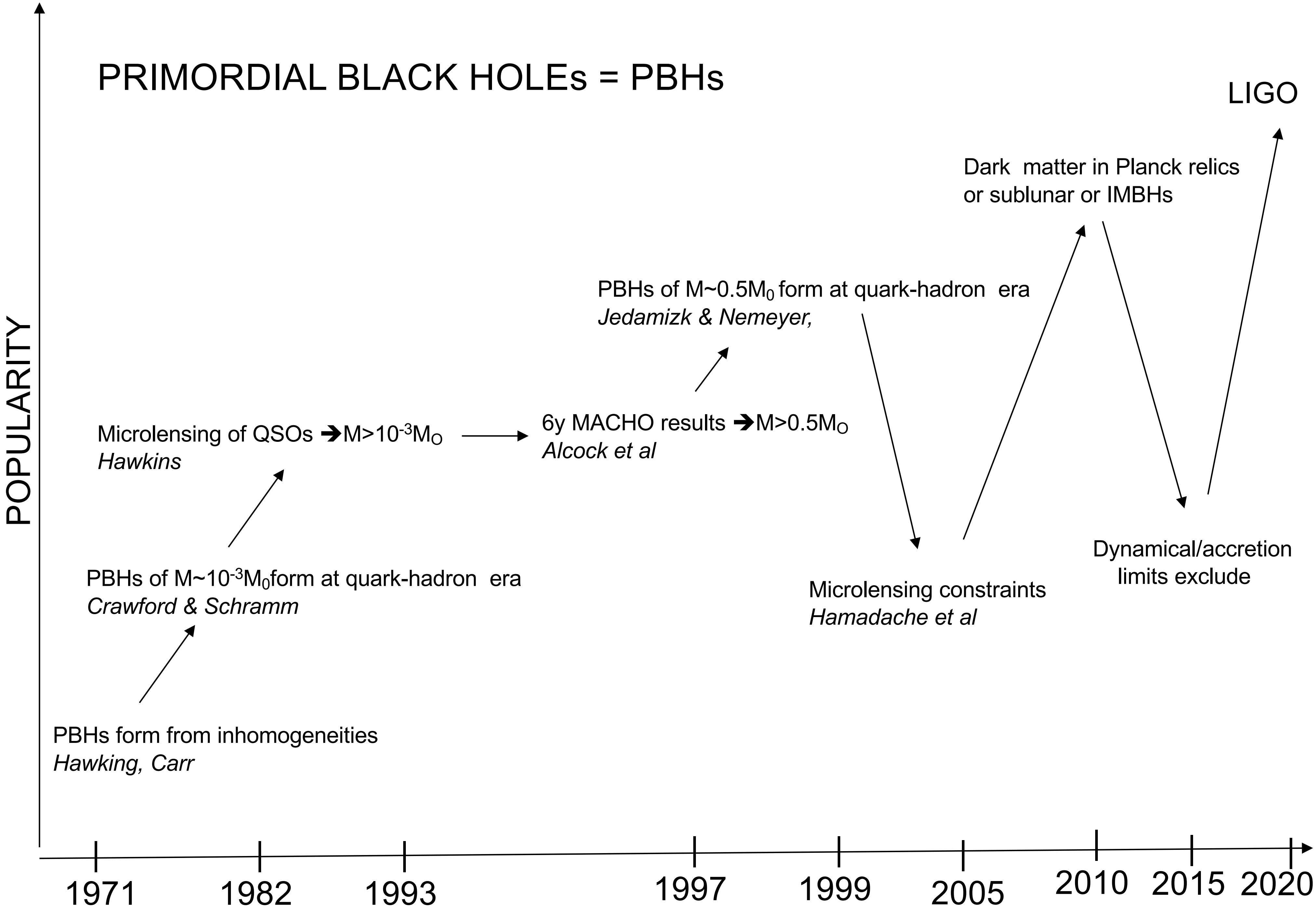


- C and CP violation of the standard model (CKM matrix)
- Baryon number violation: sphaleron transitions from >TeV collisions
- Out of thermal equilibrium (PBH collapse)

$\eta_{loc} \sim 1 \Rightarrow \eta \sim \beta$ after diffusion

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

β too small => too little DM
β too large => too much DM
} => no gals



PRIMORDIAL BLACK HOLEs = PBHs
POPULARITY
PBHs form from inhomogeneities
Hawking, Carr
PBHs of M~10^-3M0form at quark-hadron era
Crawford & Schramm
Microlensing of QSOs ➔M>10^-3MO
Hawkins
6y MACHO results ➔M>0.5MO
Alcock et al
PBHs of M~0.5M0 form at quark-hadron era
Jedamizk & Nemeyer,
Microlensing constraints
Hamadache et al
Dark matter in Planck relics
or sublunar or IMBHs
Dynamical/accretion
limits exclude
LIGO
1971
1982
1993
1997
1999
2005
2010
2015
2020