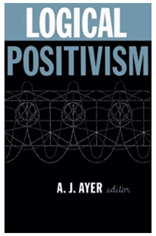
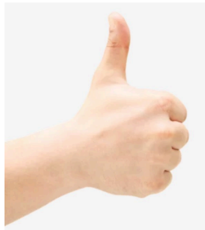
OBSERVATIONAL EVIDENCE FOR PRIMORDIAL BLACK HOLES: A POSITIVIST PERSPECTIVE *





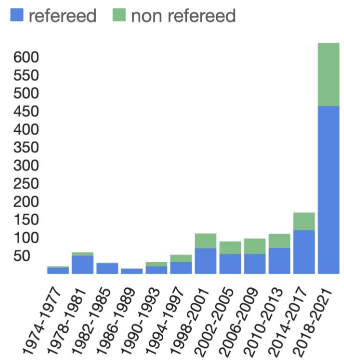
Bernard Carr, Queen Mary University of London

Leiden/Brussels webinar (3/10/22)

* with S.Clesse, J.Garcia-Bellido, M.Hawkins, F.Kuhnel

1

PUBLICATION RATE OF PBH PAPERS



Impossible to keep up with literature!

2

MY MOST CITED PAPERS!

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

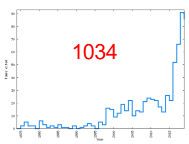
BLACK HOLES IN THE EARLY UNIVERSE

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.



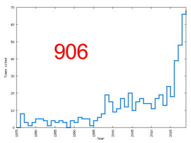
THE ASTROPHYSICAL JOURNAL, **201**:1–19, 1975 October 1
© 1975. The American Astronomical Society. All rights reserved. Printed in U.S.A.

THE PRIMORDIAL BLACK HOLE MASS SPECTRUM*

BERNARD J. CARR
Department of Applied Mathematics and Theoretical Physics, Cambridge University, Cambridge, England;
and
California Institute of Technology, Pasadena
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……

3

……with a resurgence at the end!

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

New cosmological constraints on primordial black holes

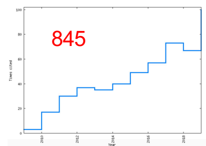
B. J. Carr*
Astronomy Unit, Queen Mary University of London, Mile End Road, London E1 4NS, United Kingdom
Research Center for the Early Universe (RESCEU), Graduate School of Science, The University of Tokyo, Tokyo 113-0033, Japan
Canadian Institute for Theoretical Astrophysics, University of Toronto, 60 St. George Street, Toronto, Ontario M5S 1A1, Canada

Kazunori Kohri†
Department of Physics, Tohoku University, Sendai 980-8578, Japan
Physics Department, Lancaster University, Lancaster LA1 4YB, United Kingdom
Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, Massachusetts 02138, USA

Yuuiti Sendouda‡
Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-8502, Japan
Department of Physics, Graduate School of Science, The University of Tokyo, Tokyo 113-0033, Japan

Jun'ichi Yokoyama§
Research Center for the Early Universe (RESCEU), Graduate School of Science, The University of Tokyo, Tokyo 113-0033, Japan
Institute for the Physics and Mathematics of the Universe (IPMU), The University of Tokyo, Kashiwa, Chiba 277-8568, Japan
(Received 31 December 2009; published 10 May 2010)

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



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

Primordial black holes as dark matter

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

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

4

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

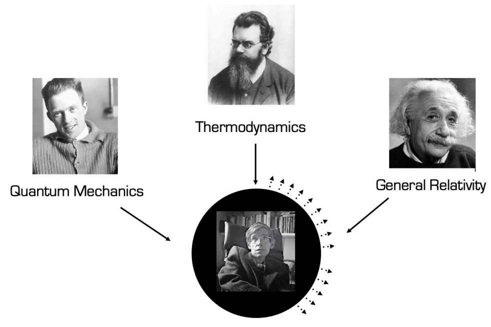
It is suggested that there may be a large number of gravitationally collapsed objects of mass 10^{-5} g upwards which were formed as a result of fluctuations in the early Universe. They could carry an electric charge of up to ± 30 electron units. Such objects would produce distinctive tracks in bubble 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.

5

Black hole explosions?

S. W. HAWKING

Nature **248**, 30 - 31 (01 March 1974)



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

PBHs are important even if they never formed!

6

PBH FORMATION .... AND EVAPORATION

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

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

⇨ primordial BHs with horizon mass at formation

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

Black holes radiate thermally with temperature

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

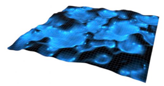
=> evaporate completely in time $t_{evap} \sim 10^{64}\left[\frac{M}{M_0}\right]^3$ y

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

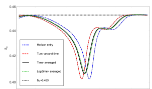
7

Formation Mechanisms of Primordial Black Holes

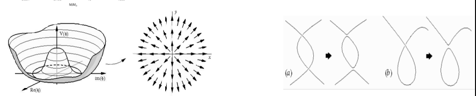
- Large density perturbations (inflation)



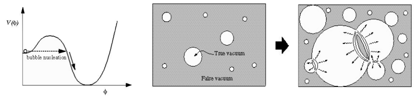
- Pressure reduction



- Cosmic string loops



- Bubble collisions



8

PBH FORMATION => LARGE INHOMOGENEITIES

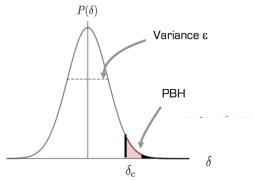
To collapse against pressure, need (Carr 1975)

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

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

⇒ fraction of PBHs

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



p=0 => need spherical symmetry => $\beta(M) \sim 0.06\, \varepsilon(M)^6$

(Khlopov & Polnarev 1982)

9

PBHS AND INFLATION

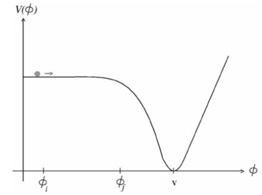
PBHs formed before reheat inflated away =>

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

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]

10

Fraction of Universe collapsing

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

General limit

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

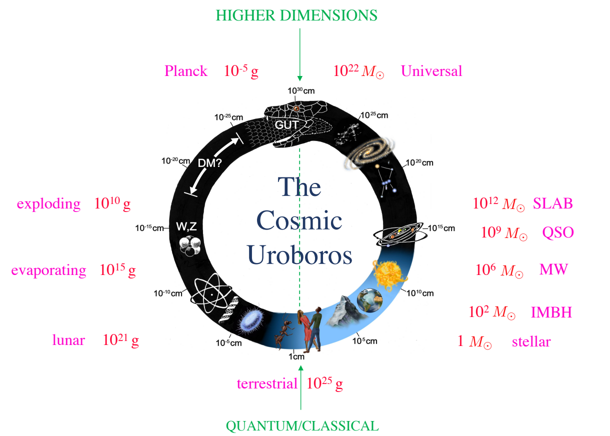
So both require and expect β(M) to be tiny

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

Fine-tuning problem!

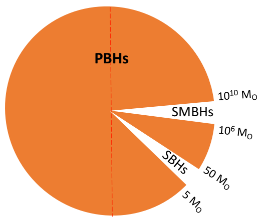
11

BLACK HOLES AS LINK BETWEEN MICRO AND MACRO PHYSICS



12

ARE MOST BLACK HOLES PRIMORDIAL?



God would be cruel not to populate whole Uroborus!

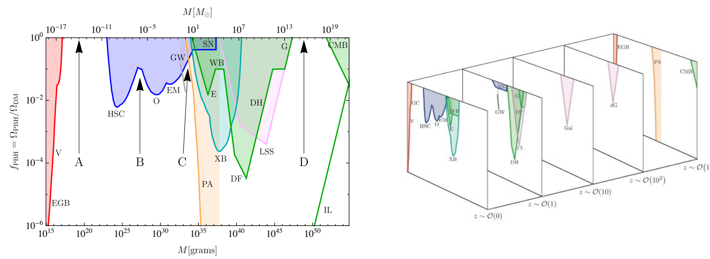
13

Primordial Black Holes as Dark Matter: Recent Developments

Bernard Carr[1,*] and Florian Kühnel[2,†]

Annu. Rev. Nucl. Part. Sci. 2020. 70:14.1–14.40

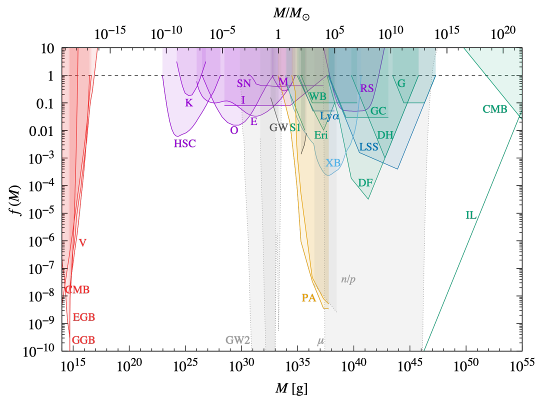
arXiv:2006.02838



Five windows where f_{PBH} can be appreciable: (A) asteroid mass; (B) sublunar mass; (C) intermediate mass; (D) stupendously massive; (E) Planck mass evaporation relics.

14

More Detailed Constraints on PBH Dark Matter Fraction

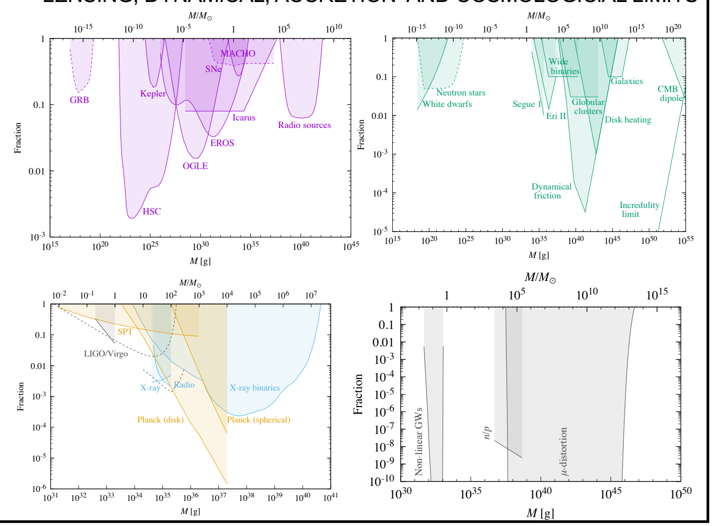


B. Carr, K. Kohri, Y. Sendouda & J. Yokoyama

Progress Theoretical Physics (2020), arXiv:2002.12778

15

LENSING, DYNAMICAL, ACCRETION AND COSMOLOGICIAL LIMITS



16

EXTENDED MASS FUNCTION

Most constraints assume monochromatic PBH mass function

Can we evade standard limits with extended mass spectrum?

But this is two-edged sword!

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

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

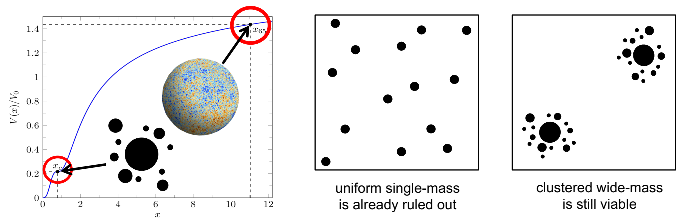
PBH CONSTRAINTS FOR EXTENDED MASS FUNCTIONS
Carr, Raidal, Tenkanen, Vaskonen & Veermae (arXiv:1705.05567)

17

Clustering

★ Many inflationary scenarios yield a lognormal PBH mass distribution.

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



Trashorras et al. arXiv:2006.15018

★ Always expect Poisson clustering (many recent papers)

18

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.

19

PRIMORDIAL BLACK HOLES AS DARK MATTER

PRO

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

CON

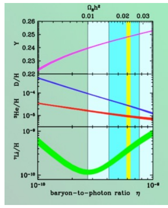
* Requires fine-tuning

PBH can do it!

20

BLACK HOLES COULD BE DARK MATTER ONLY IF PRIMORDIAL

BBNS => Ω_{baryon} = 0.05



Ω_{vis} = 0.01, Ω_{dm} = 0.25 ⇒ need baryonic and non-baryonic DM

MACHOs   WIMPs

PBHs are non-baryonic with features of <u>both</u> WIMPs and MACHOs

21

Cosmological effects of primordial black holes

GEORGE F. CHAPLINE

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

Abstract

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

First paper on PBHs as dark matter

22

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

Primeval Black Holes and Galaxy Formation

P. Mészáros
Institute of Astronomy, University of Cambridge

Received September 4, revised October 14, 1974

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

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

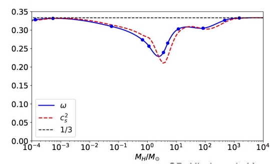
PBHs relevant to galaxy formation if dark matter

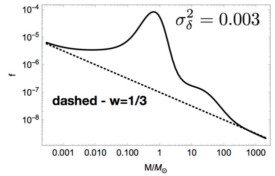
23

Primordial black holes with an accurate QCD equation of state

Christian T. Byrnes,[1,*] Mark Hindmarsh,[1,2,†] Sam Young,[1,‡] and Michael R. S. Hawkins[3,§]

arXiv:1801.06138





Jedamzik (1996)

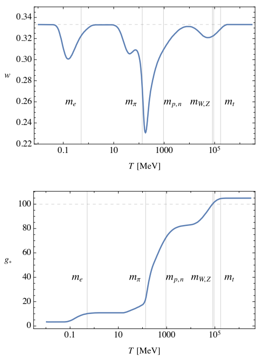
24

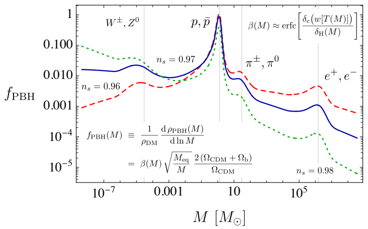
Cosmic Conundra Explained by Thermal History and Primordial Black Holes

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

arXiv:1906.08217

Extend this to include other stages in thermal history

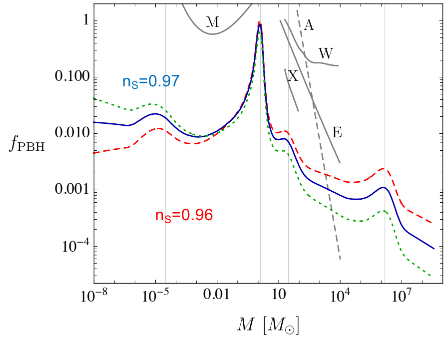




- Nearly scale-invariant PS
- Spectral index: $n_s = 0.97$
- Peak at ~2 M⊙
- Second peak at ~30 M⊙
- Two bumps at 10^{-6} and 10^{6} M⊙

25

CONSTRAINTS

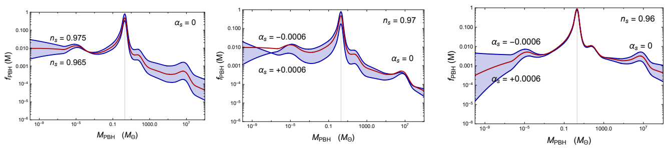


Overproduce light PBHs for $n_S > 0.975$

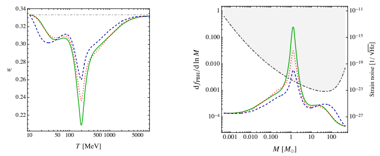
Overproduce heavy PBHs for $n_S < 0.965$

26

Effect of spectral tilt CCGHK



Effect of lepton flavour asymmetries Bodeker et al. PRD 103, 063506

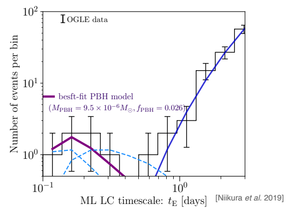


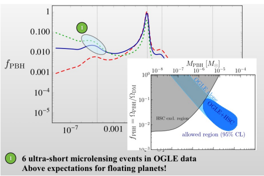
27

Planetary-mass microlenses

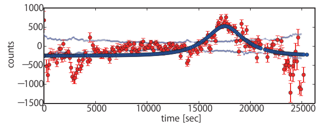
OGLE detected microlenses on 0.1-0.3 day timescale of unknown origin

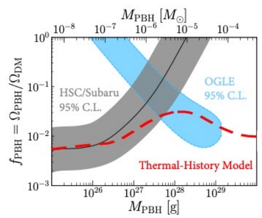
Niikura et al. arXiv:1901.07120





Niikura et al. arXiv:1701.02151



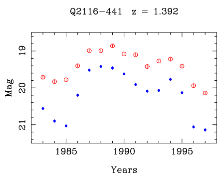


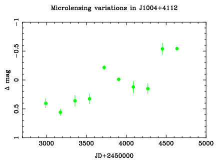
28

Quasar Lensing

Caustic crossing

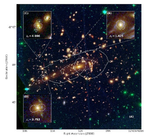
Multiply lensed quasar



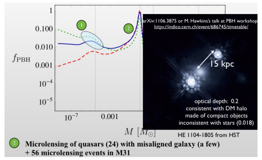


=> cos' distrib'n of $1M_\odot$ PBHs

Galaxy-galaxy strong lensing

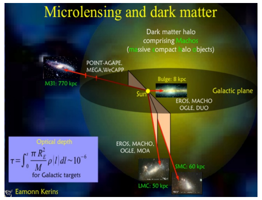


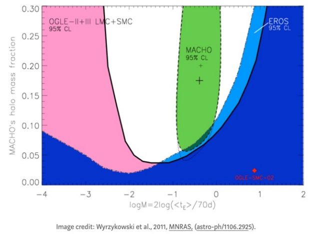
MACSJ1206
⇒ more DM substructure than expected in CDM
Meneghetti et al. (2020)



29

HALO MICROLENSING EVIDENCE



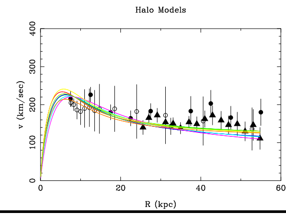


Early microlensing searches suggested MACHOs with 0.5 $M_\odot$

=> PBH formation at QCD transition?

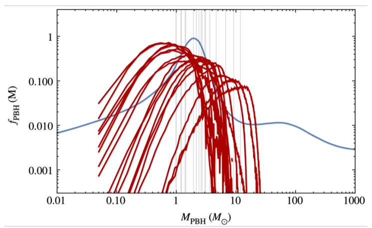
Later found that at most 20% of DM

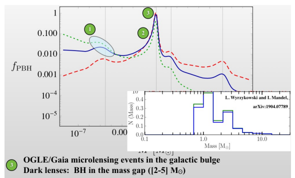
But this assume flat rotation curves and more recent models allow 100%



30

OGLE/GAIA Excess of Lenses in Galactic Bulge



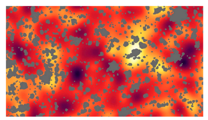


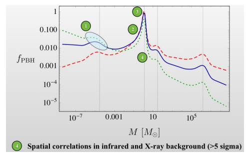
31

Cosmic infrared/X-ray backgrounds

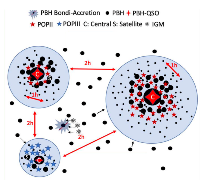
Spatial coherence of X and IR source-subtracted backgrounds
=> overabundance of high-z halos => PBH Poisson effect

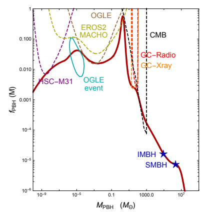
Kashlinsky arXiv:1605.04023





Cappelluti et al. arXiv:2109.08701

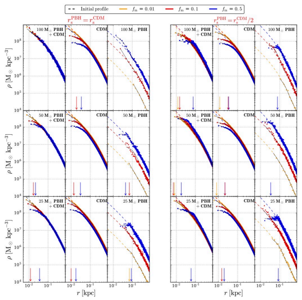


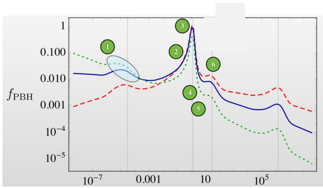


32

Ultra-Faint Dwarf Galaxies

PBH dark matter => UFDGs unstable below some radius
Non-detection of galaxies smaller than 10-20pc => PBHs?





Improved constraints from ultra-faint dwarf galaxies on PBHs as DM
Stegmann et al arXiv:1910.04793

33

CUSP/CORE PROBLEM

CDM => cuspy DM halos => stellar feedback or WIMP self-interaction

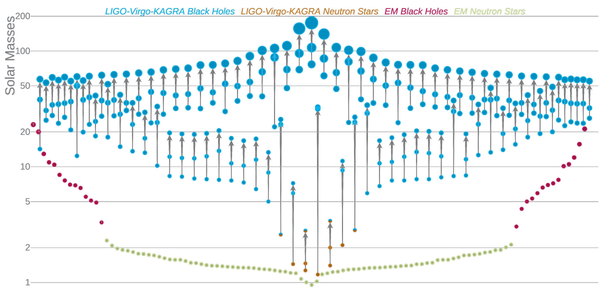
$10^7 M_O$ dwarf galaxies + 1% DM in 25-100 M_O PBHs resolves problem

PBHs => cusp-to-core transition in low-mass dwarf galaxies
Boldrini et al. arXiv:1909.07395

Break in distribution of halo wide binaries => M>10M_o (Tien)

34

PBHS AND LIGO/Virgo/KAGRA



LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

Do we need PBHs?

35

Merger at early or late times?

Bird et al. arXiv:1603.00464 Sasaki et al. arXiv:1603.08338

Poisson clustering boosts merging rate at late times

PBHs of 30 M_O can only provide 0.1-1% of DM

PBHs of 1 M_O can only provide 100% of DM
=> late ~ early ~ neutron star => could be PBHs

BHs in pair-instability and low mass gaps

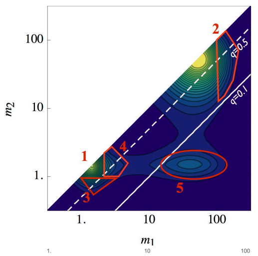
Extended mass function => asymmetric masses challenging astrophysical models

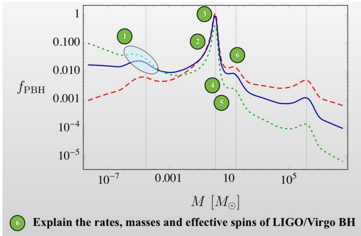
Subsolar candidates?

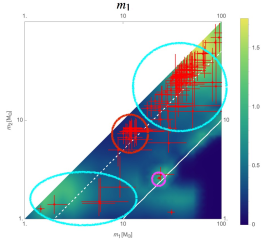
Mass, spin and redshift distribution will determine

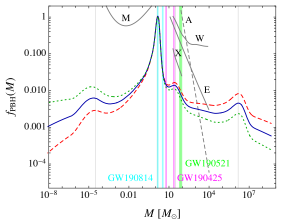
36

LIGO/Virgo Black Holes







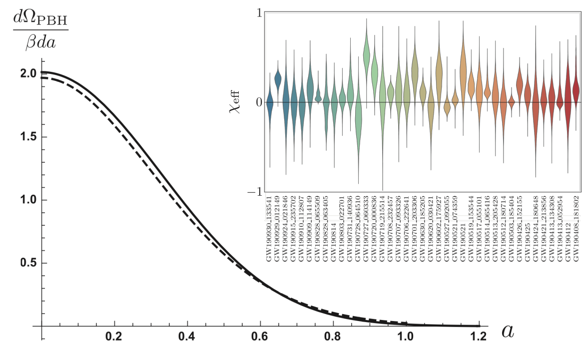


37

Spin Distribution

★ Gravitational-wave emission from black-hole binaries

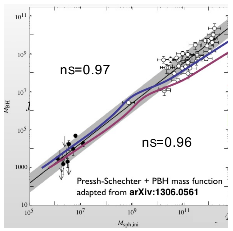
☆ For PBH (produced in RD) we expect close to zero spin.

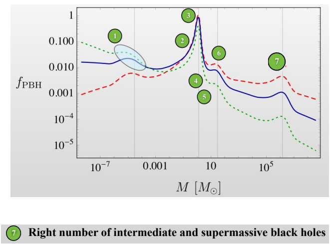


[Chiba & Yokoyama 2017]

38

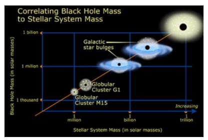
Intermediate and supermassive black holes





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

But accretion important



39

OTHER COSMIC PROBLEMS

* Fast radio bursts
* Missing pulsar problem
* Hubble tension
* Non-flat rotation curves at high redshift
* High velocity stars
* Low mass X-ray binaries

40

ADDRESSING FINE-TUNING PROBLEM AT QCD EPOCH

Carr, Clesse & Garcia-Bellido, arXiv:1904.02129

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

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

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

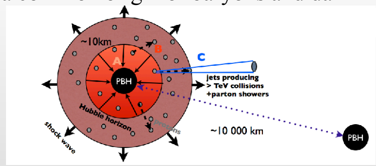
QCD epoch => $M \sim M_C$, $\beta(M) \sim \eta = n_B/n_\gamma \sim 10^{-9}$ anthropic selection?

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

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

41

Primordial Black Holes
as a common origin of baryons and dark matter



Garcia-Bellido,Carr, Clesse
arXiv:1904.114827

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

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

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

42

PBH + Particle DM

★ Always when $f_{\rm PBH} < 1$ there must be another DM component!

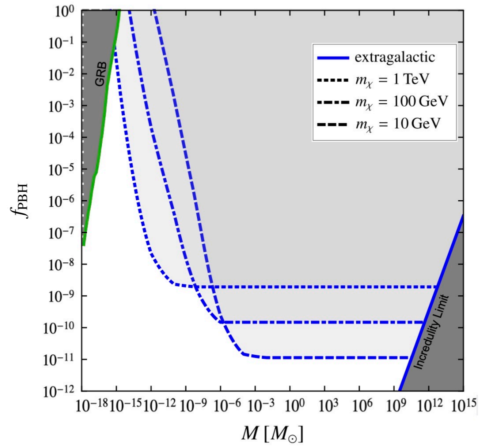
★ Study a combined scenario: DM = PBHs + Particles

- The latter will be accreted by the former; formation of halos.
- Study WIMP annihilations in PBH halos:
  - ★ The annihilation rate $\Gamma \propto n^2$.
  - ★ Halo profile => enhancement of Γ in density spikes.
    1) Derive the density profile of the captured WIMPs;
    2) calculate the annihilation rate;
    3) and compare to extragalactic gamma-ray background.

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

43

PBHs & WIMPs - Constraints

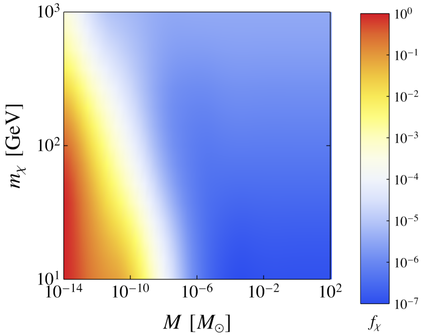


If the LIGO/Virgo black holes are primordial, this would rule out any standard WIMP scenario!

[BC, FK, Visinelli 2021]

44

PBHs & WIMPs - Constraints



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

[Carr, Kühnel, Visinelli 2021]

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

→ Motivates a third dark-matter candidate?

45

CONCLUSIONS

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

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

Dark matter	LIGO/Virgo	SMBH seeds

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

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

46