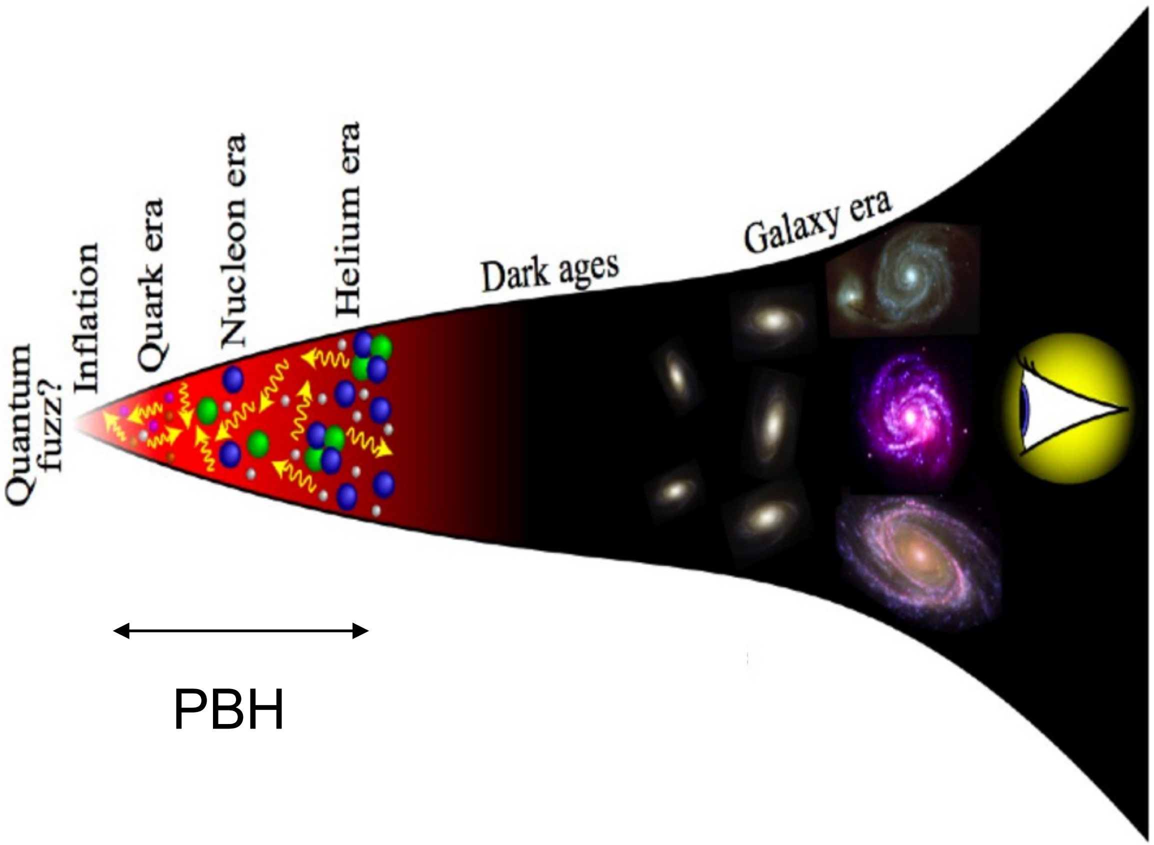
PRIMORDIAL BLACK HOLES: 50 YEARS ON



Bernard Carr
Queen Mary University of London

Naples 19/6/23

Florian talk at 17:40

Observational Evidence for Primordial Black Holes: A Positivist Perspective

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

arXiv:2306.03903

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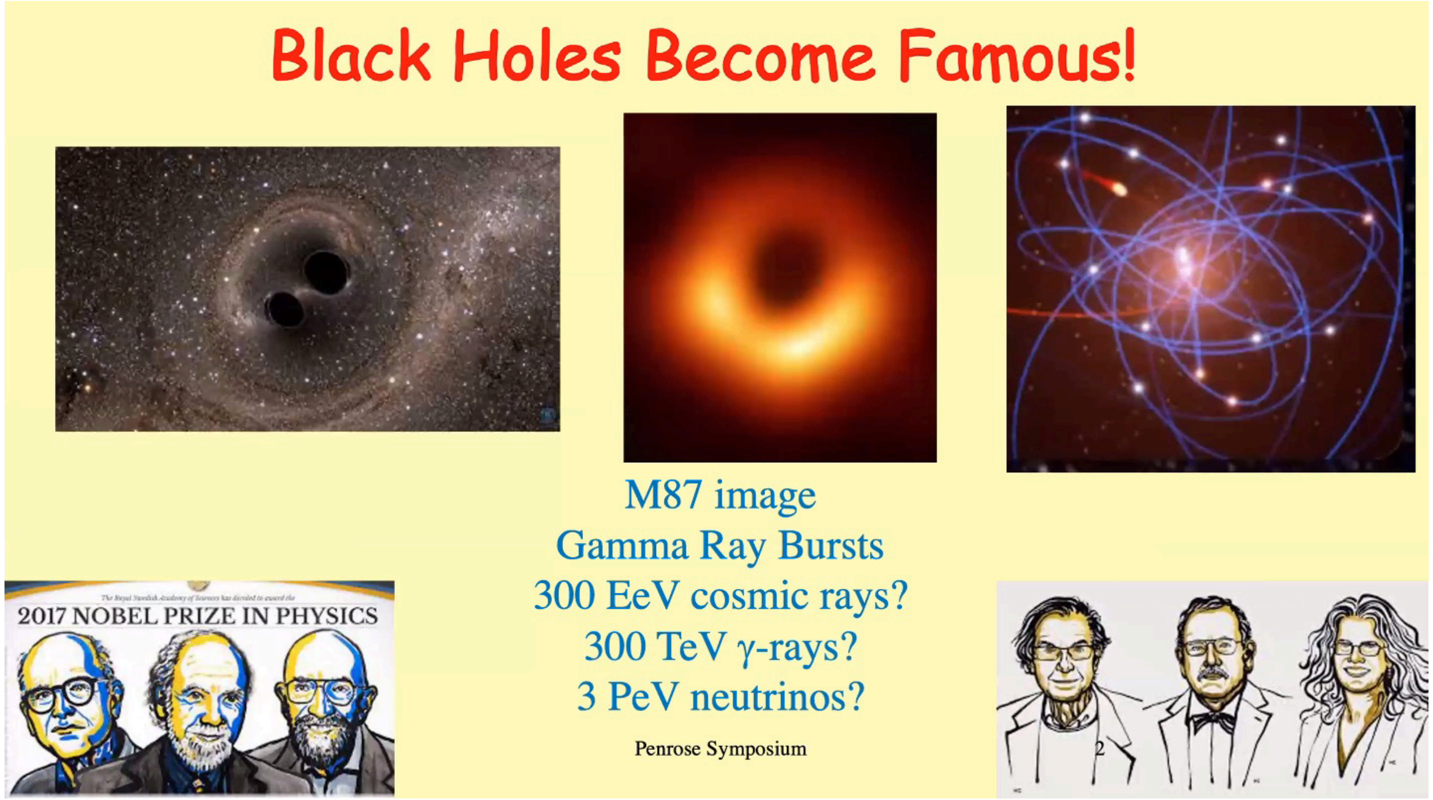
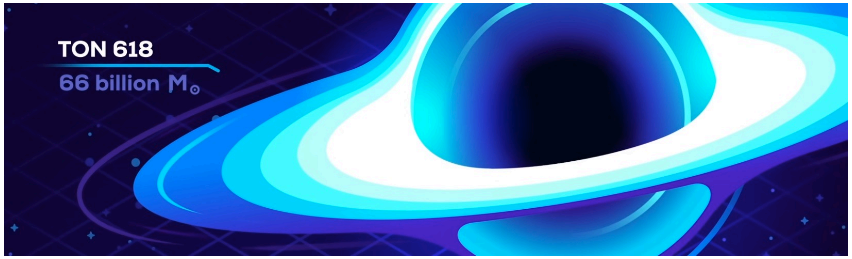




Irrefutable evidence for stellar ($10^{1-2}M_O$), intermediate ($10^{3-5}M_O$) and supermassive ($10^{6-10}M_O$) black holes

PRIMORDIAL BLACK HOLES

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

Small black holes can only form in early Universe

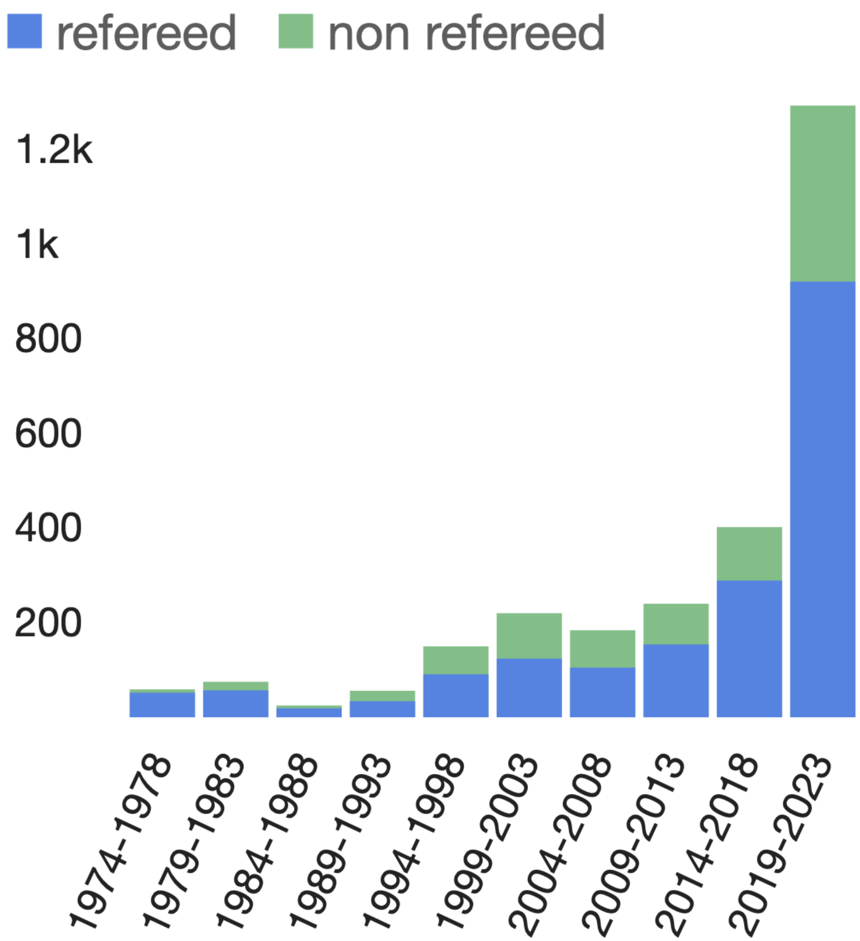
cf. cosmological density $\rho \sim 1/(Gt^2) \sim 10^6 (t/s)^{-2} \mathrm{g/cm^3}$

⇨ **PBHs have horizon mass at formation**

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

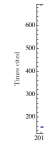
=> huge possible mass range

PUBLICATION RATE OF PBH PAPERS



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

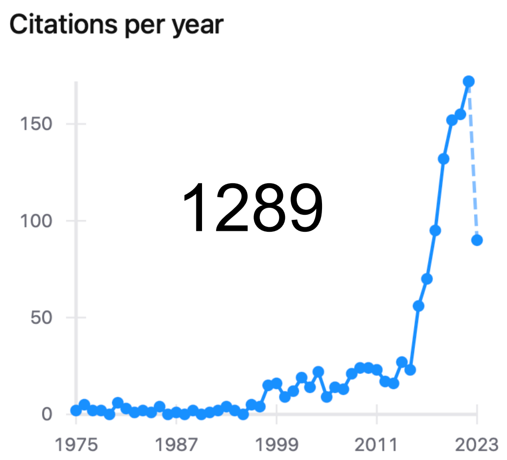
THE PRIMORDIAL BLACK HOLE MASS SPECTRUM*

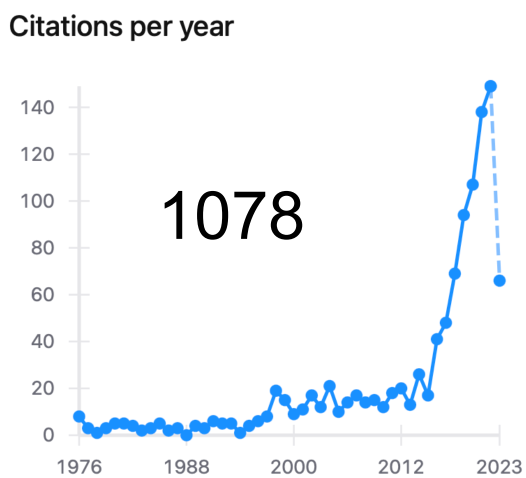
BERNARD J. CARR
Department of Applied Mathematics and Theoretical Physics, Cambridge University, Cambridge, England;
and
California Institute of Technology, Pasadena

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……

……with a resurgence towards the end!

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

New cosmological constraints on primordial black holes

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Research Center for the Early Universe (RESCEU), Graduate School of Science, The University of Tokyo, Tokyo 113-0033, Japan
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Kazunori Kohri†
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Department of Physics, Graduate School of Science, The University of Tokyo, Tokyo 113-0033, Japan

Jun'ichi Yokoyama§
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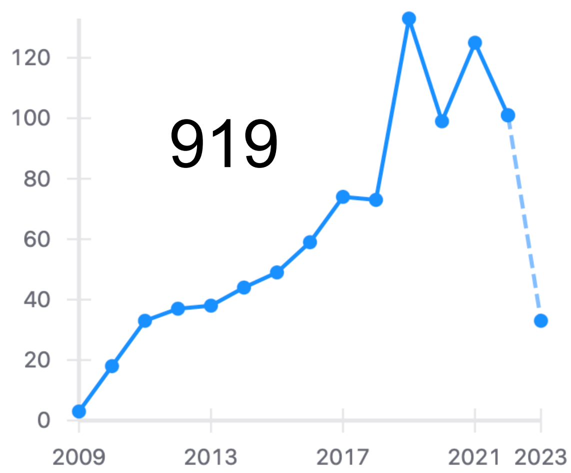
(Received 31 December 2009; published 10 May 2010)

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,‡]
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[2]*The Oskar Klein Centre for Cosmoparticle Physics, Department of Physics, Stockholm University, AlbaNova, SE–10691 Stockholm, Sweden*
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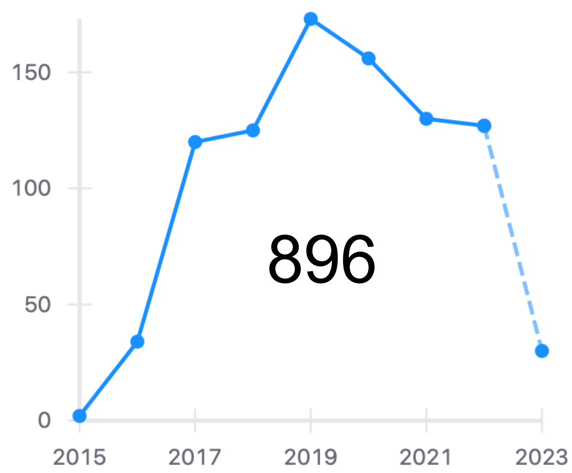
(Received 8 August 2016; published 4 October 2016)

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.

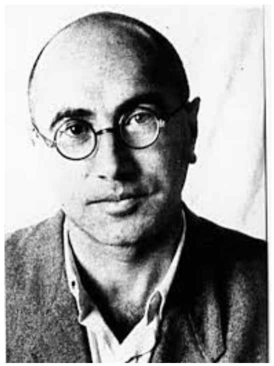
SOVIET ASTRONOMY — AJ VOL. 10, NO. 4 JANUARY-FEBRUARY, 1967

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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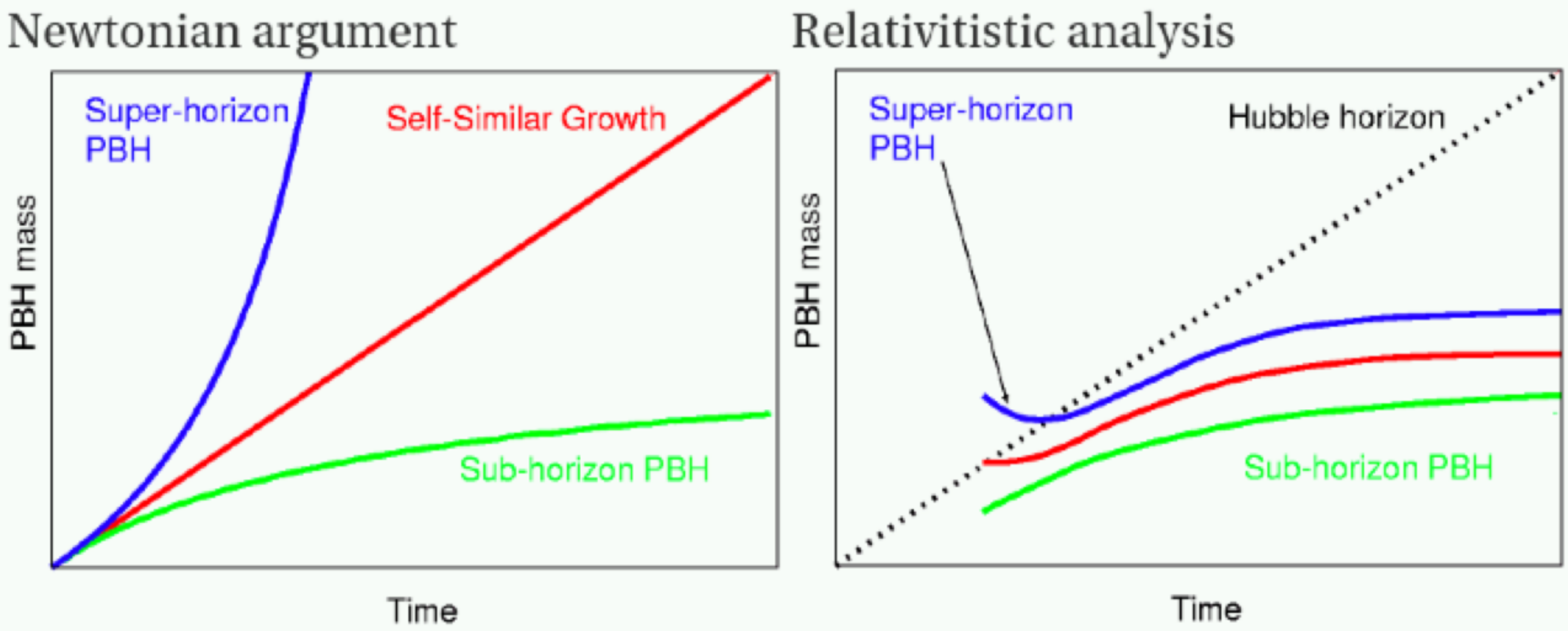
$\Rightarrow$ no observational evidence against them

Warsaw meeting 1973!

Newton vs Einstein



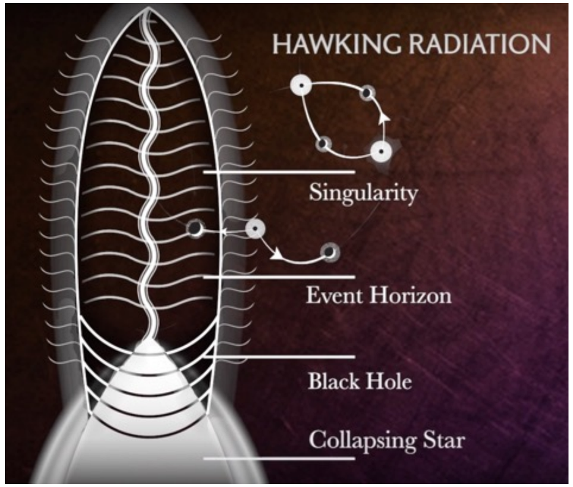
horizon mass

Bondi => $\dfrac{dM}{dt} = \dfrac{M^2}{\beta t^2}$ => $M = \dfrac{\beta t}{1 + \frac{t}{t_f}\left(\frac{\beta t_f}{M_f} - 1\right)}$

formation mass

This suggests PBH grows as horizon if initially has horizon mass

But GR analysis implies PBH does not grow very much at all



letters to nature

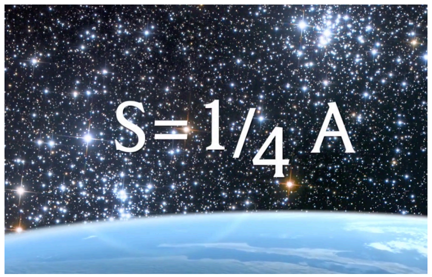
Nature **248**, 30 - 31 (01 March 1974); doi:10.1038/248030a0

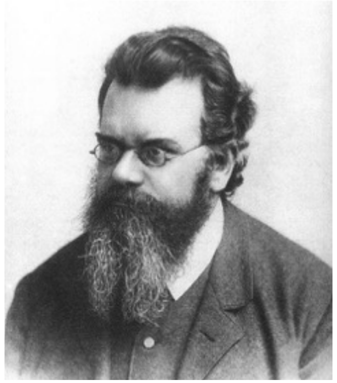
Black hole explosions?

S. W. HAWKING

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

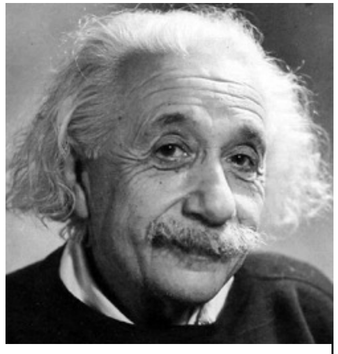
QUANTUM gravitational effects are usually ignored in calculations of the formation and evolution of black holes. The justification for this is that the radius of curvature of space-time outside the event horizon is very large compared to the Planck length $(G\hbar/c^3)^{1/2} \approx 10^{-33}$ cm, the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





Thermodynamics

Quantum Mechanics

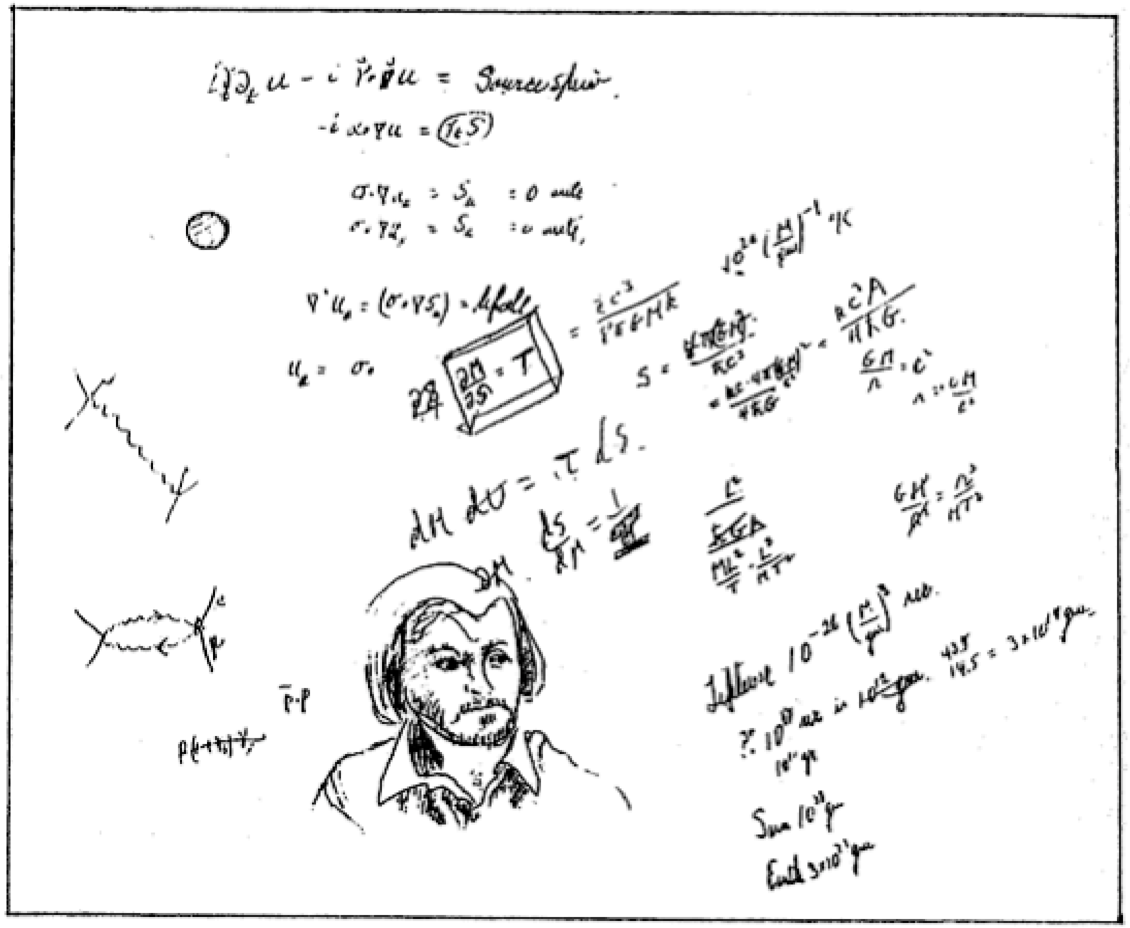


General Relativity

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

PBHs are important even if they never formed!

Feynman’s envelope 1975



BLACK HOLE INFORMATION PARADOX

PHYSICAL REVIEW D VOLUME 14, NUMBER 10 15 NOVEMBER 1976

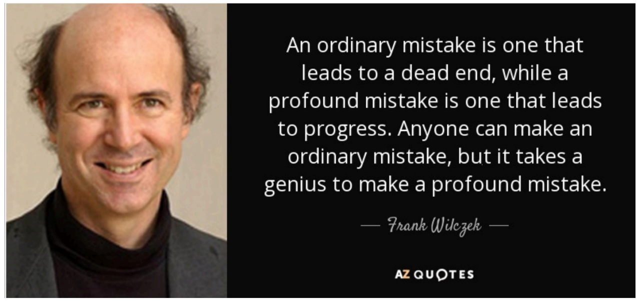
Breakdown of predictability in gravitational collapse*

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

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

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

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

This can only be important for PBHs

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

=> explosions undetectable in standard particle physics model

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

THE ASTROPHYSICAL JOURNAL, **206**: 1–7, 1976 May 15

GAMMA RAYS FROM PRIMORDIAL BLACK HOLES*

DON N. PAGE†
California Institute of Technology

AND

S. W. HAWKING‡
California Institute of Technology; and Department of Applied Mathematics and Theoretical Physics, University of Cambridge
Received 1975 October 7

ABSTRACT

This paper examines the possibilities of detecting hard γ-rays produced by the quantum-mechanical decay of small black holes created by inhomogeneities in the early universe. Observations of the isotropic γ-ray background around 100 MeV place an upper limit of 10^4 pc^{-3} on the average number density of primordial black holes with initial masses around 10^{15} g. The local number density could be greater than this by a factor of up to 10^6 if the black holes were clustered in the halos of galaxies. The best prospect for detecting a primordial black hole seems to be to look for the burst of hard γ-rays that would be expected in the final stages of the evaporation of the black hole. Such observations would be a great confirmation of general relativity and quantum theory and would provide information about the early universe and about strong-interaction physics.

ARE SOME SHORT (100 msec) GRBS PBH EXPLOSIONS?

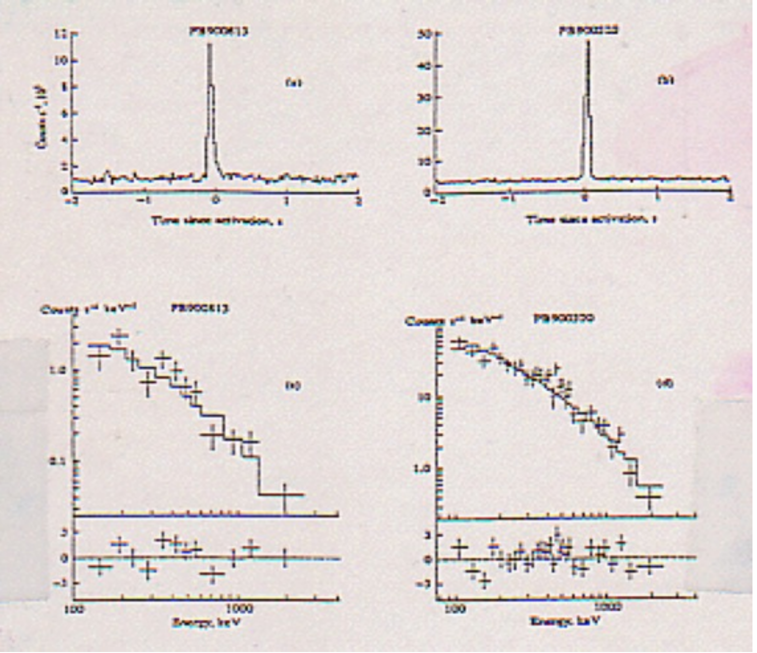
GRB => $dn/dt < 10^{-6}\ pc^{-3}y^{-1}$ (if uniform) or $< 1\ pc^{-3}y^{-1}$ (if in halo)

Observational limit depends on details of final explosive phase

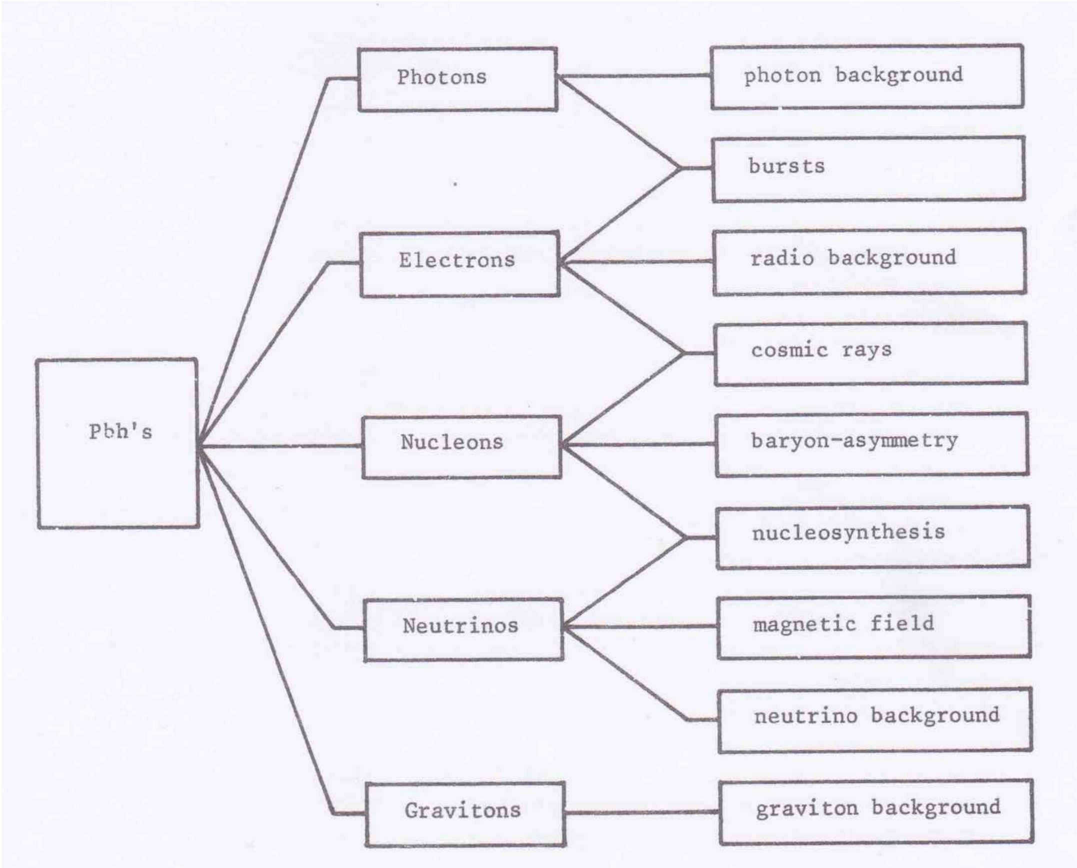
$$dn/dt < \begin{cases} 10^{6}\ pc^{-3}y^{-1} & \text{(standard model)} \\ 0.1\ pc^{-3}y^{-1} & \text{(QCD fireball)} \end{cases}$$

Cline et al (2003) => 42 BATSE events
Cline et al (2005) => Konus events
Cline et al (2007) => 8 Swift events

Local => Euclidean dbn, V/V_{max} test



Black Hole Evaporations and their Cosmological Consequences



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

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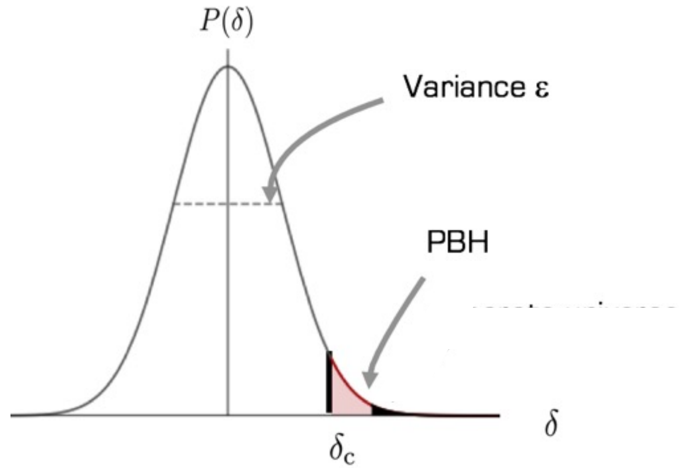
First use of acronym PBH!

PBH FORMATION FROM LARGE INHOMOGENEITIES

To collapse against pressure, need

$R > \sqrt{\alpha}\ \mathrm{ct}$ **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**

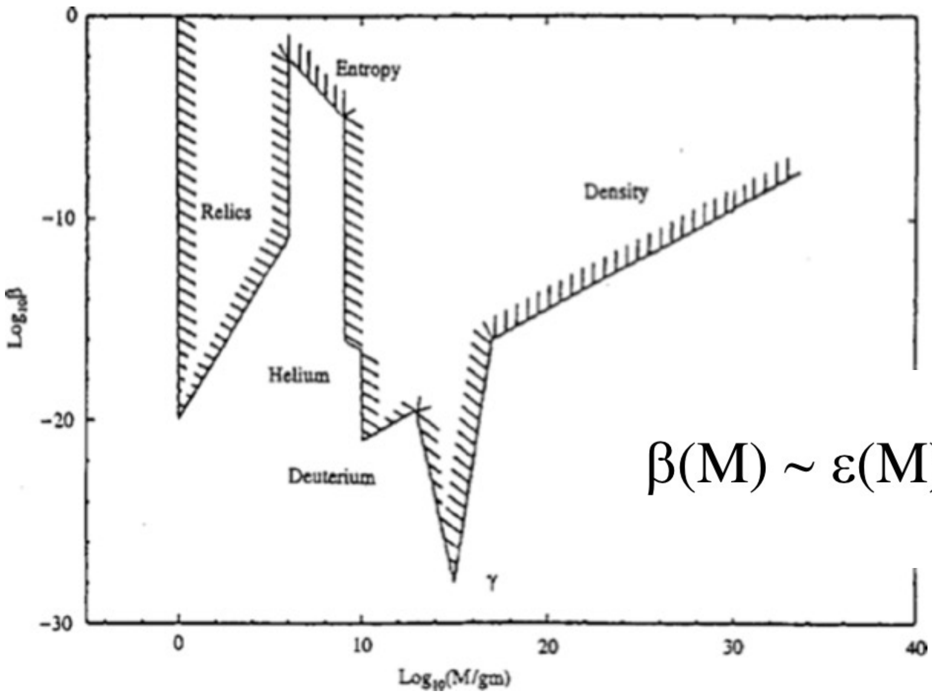
General limit

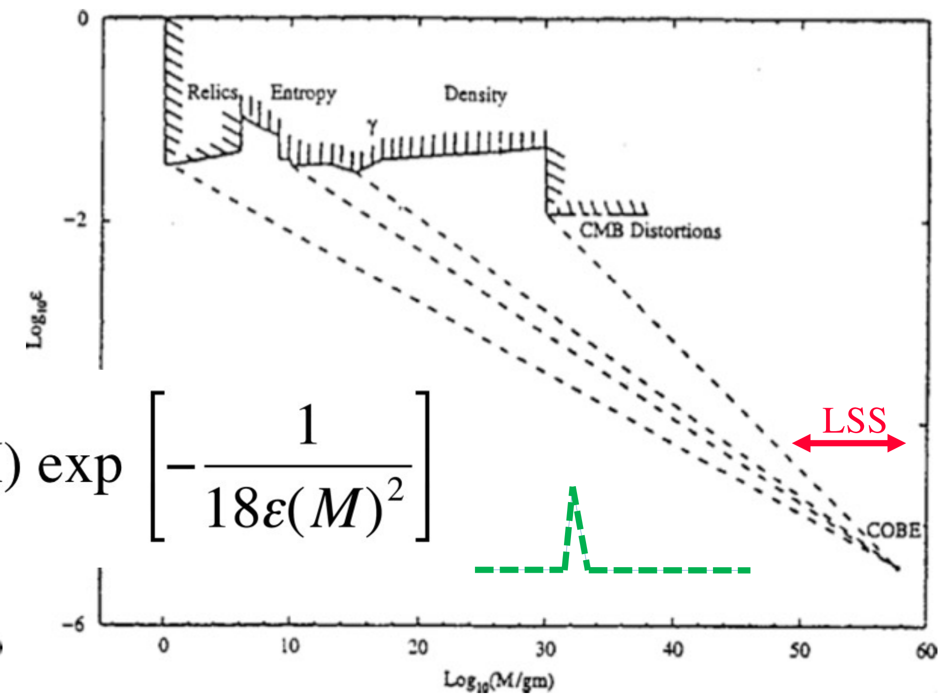
$$\frac{\rho_{PBH}}{\rho_{CBR}} \approx \frac{\Omega_{PBH}}{10^{-4}}\left[\frac{R}{R_0}\right] \Rightarrow \beta \sim 10^{-6}\,\Omega_{\mathrm{PBH}}\left[\frac{t}{\sec}\right]^{1/2} \sim 10^{-18}\,\Omega_{\mathrm{PBH}}\left[\frac{M}{10^{15}\,g}\right]^{1/2}$$

So both require and expect collapse fraction to be tiny

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

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

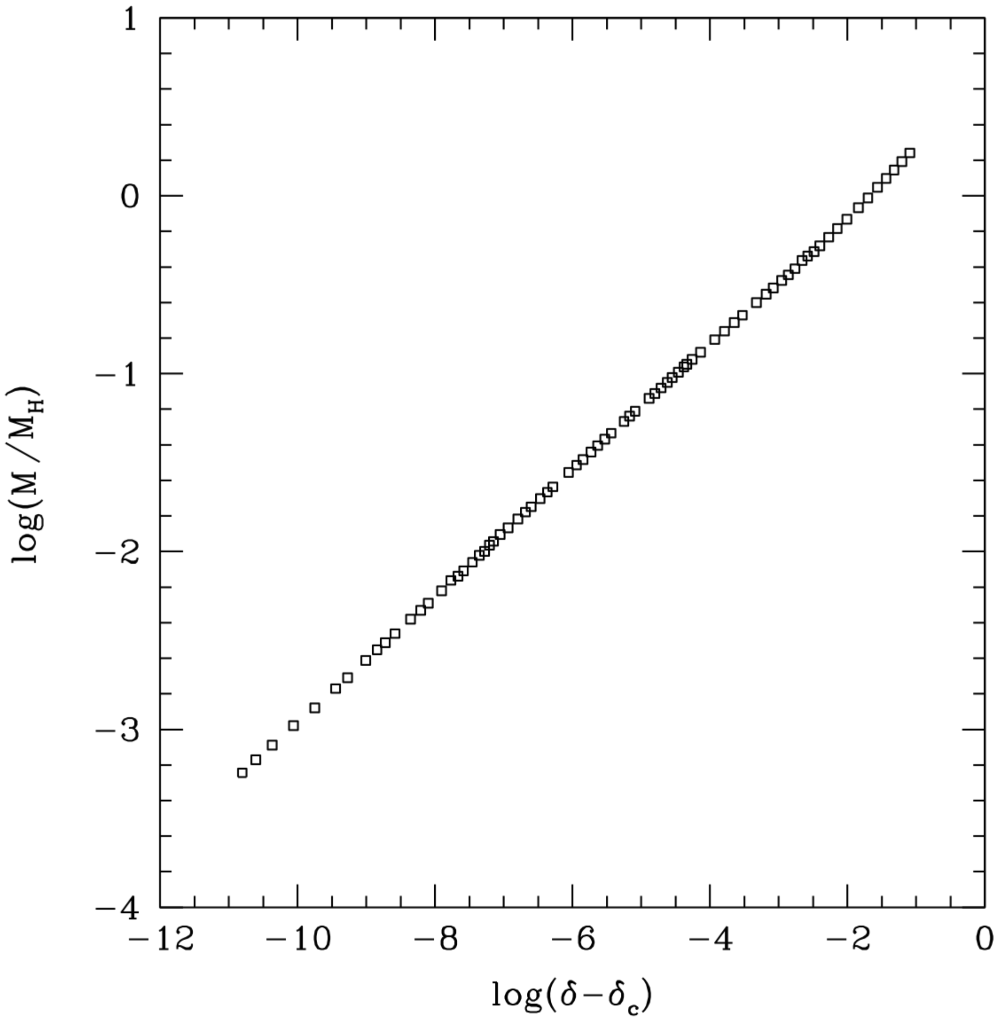
[Choptuik '93]

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

density contrast

★ Radiation domination and for spherical Mexican-hat profile:

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



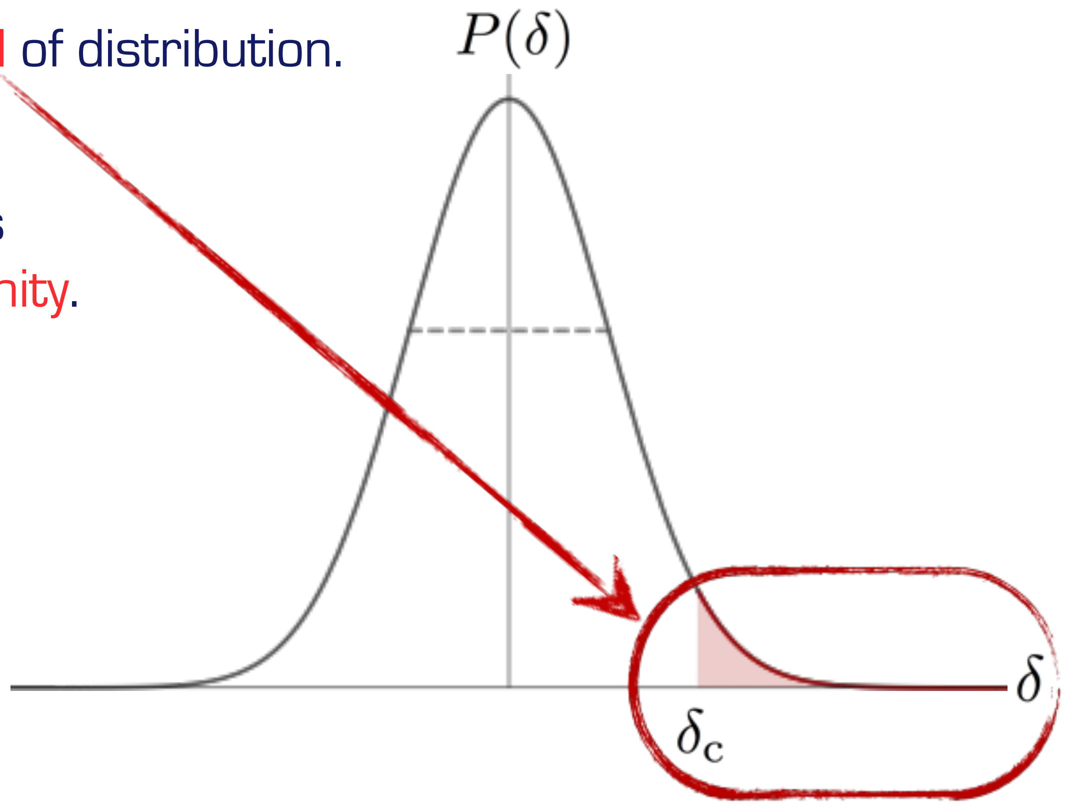
[Musco, Miller, Polnarev 2008]

Non-Gaußianities

★ PBH fluctuations are extremely rare.

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

★ PBH production is deep inside tail of distribution.



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

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

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

PBHS AND INFLATION

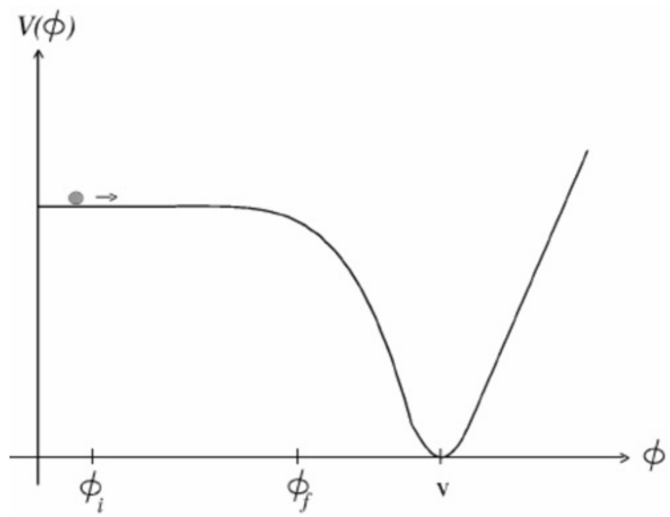
PBHs formed before reheat inflated away =>

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

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?

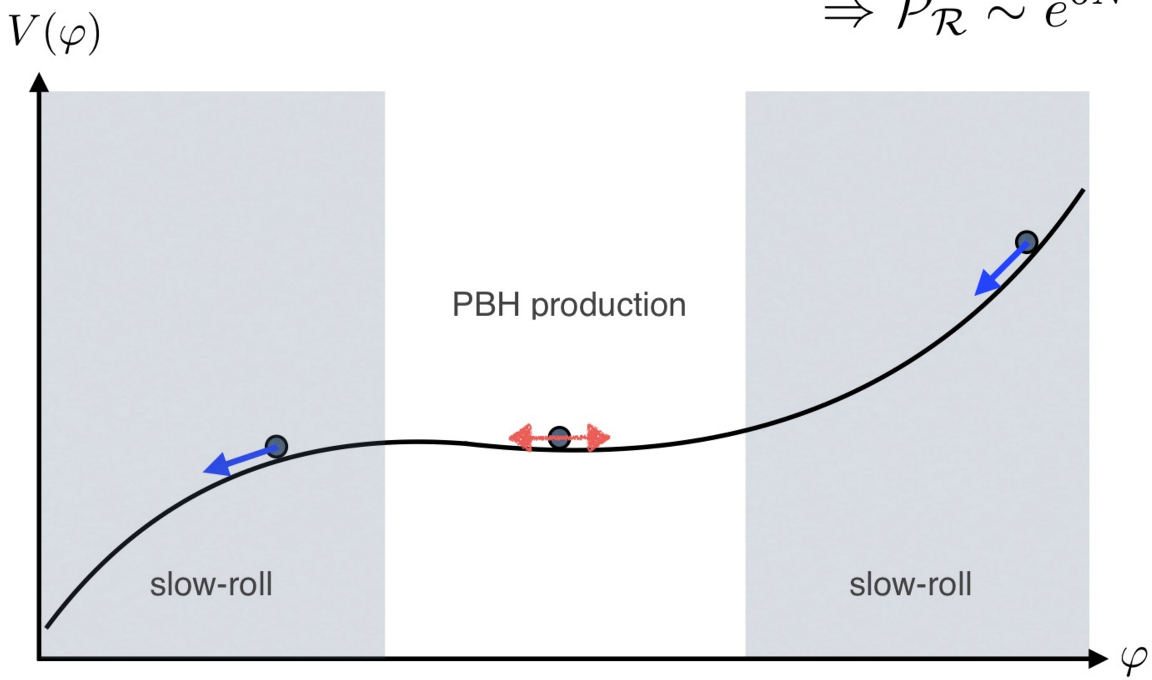
[HUGE NUMBER OF PAPERS ON THIS]

QUANTUM DIFFUSION

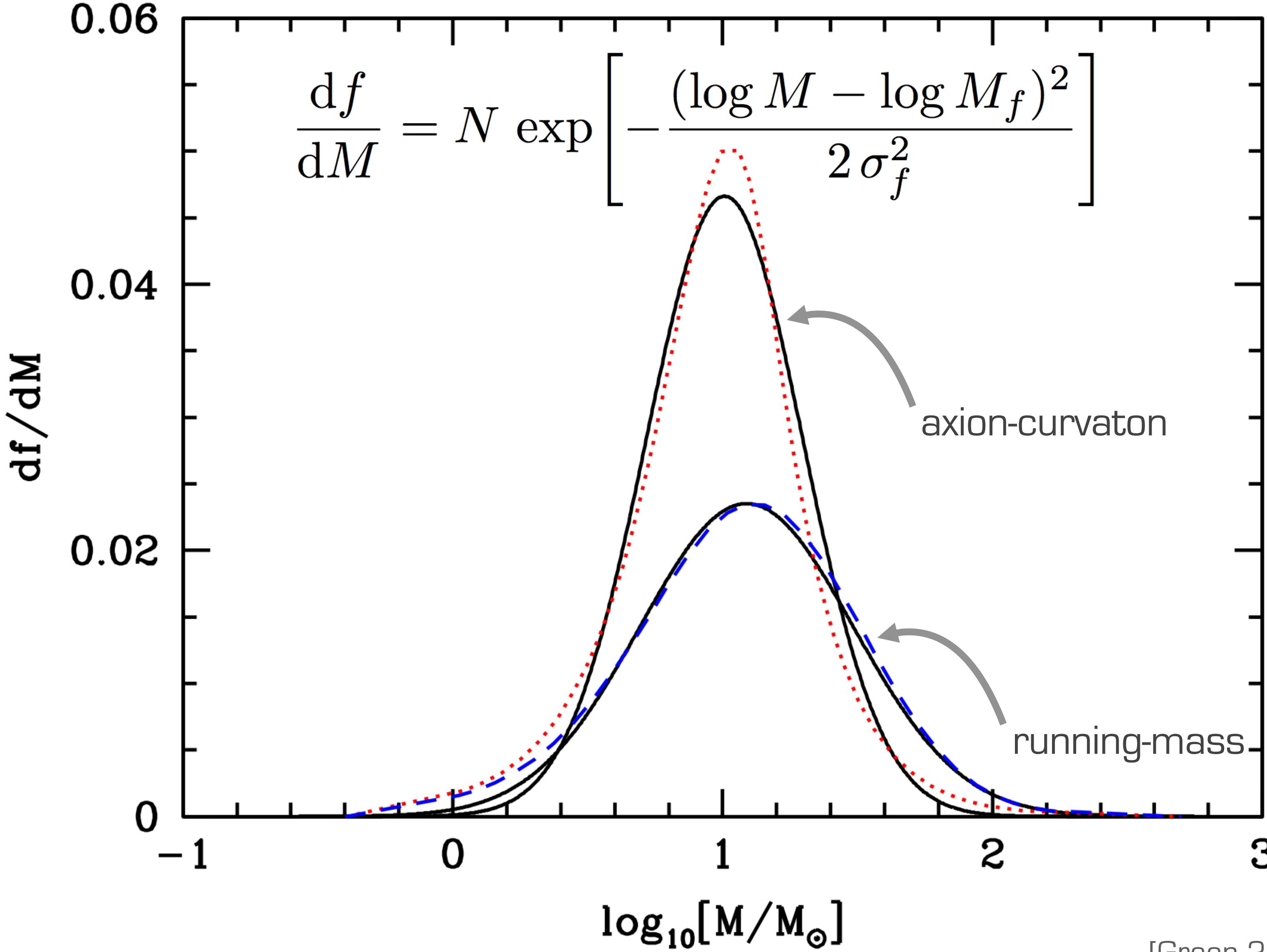
★ Consider the possibility of a plateau in the inflaton potential:

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

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



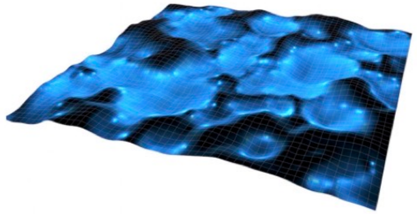
Generic Mass Functions – The Lognormal Case



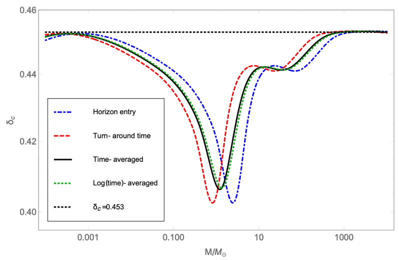
[Green 2016]

Other formation mechanisms in standard model

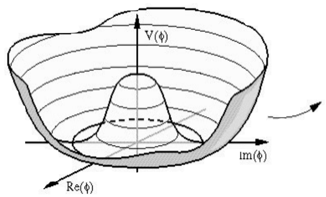
★ Large density perturbations (inflation)

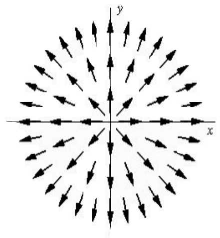


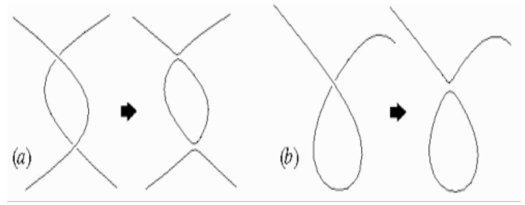
★ Pressure reduction



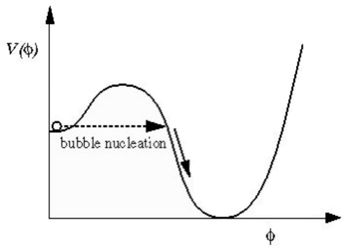
★ Cosmic string loops

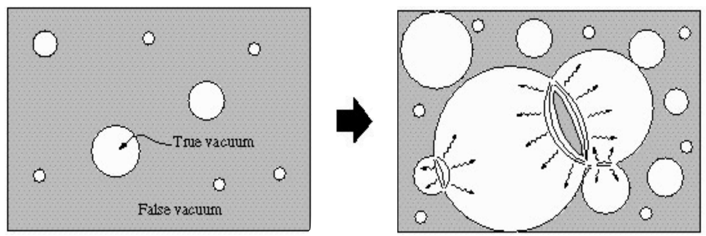




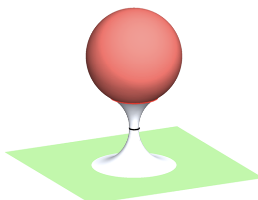


★ Bubble collisions



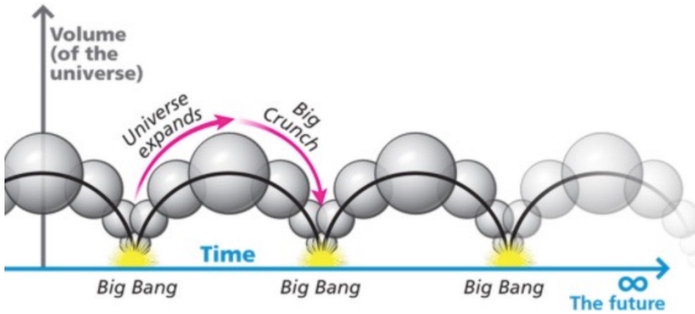


★ Collapse of domain walls or bubble of broken symmetry

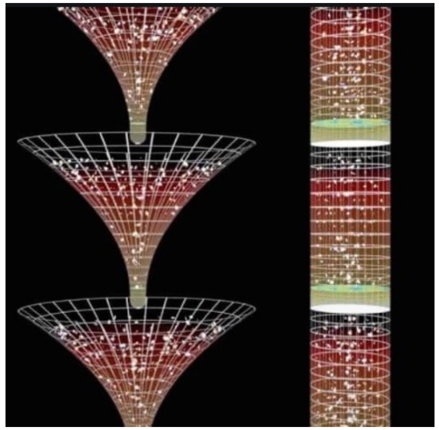


BUT THEY MAY ALSO FORM IN LESS STANDARD MODELS

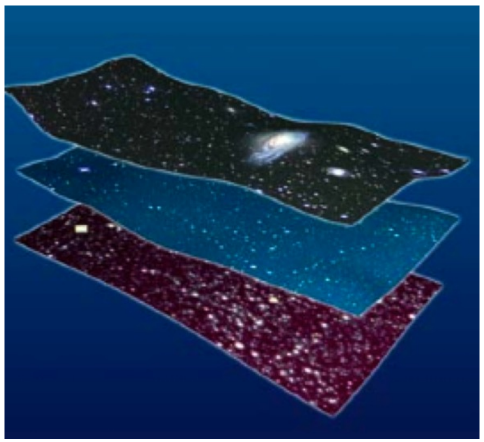
Cyclic Universe



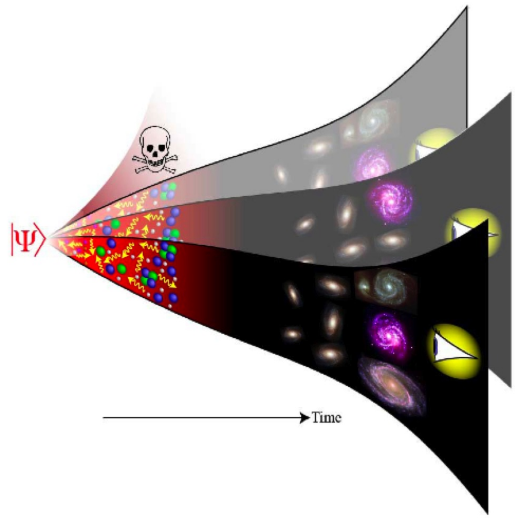
Conformal Cyclic Model



Ekpyrotic Model

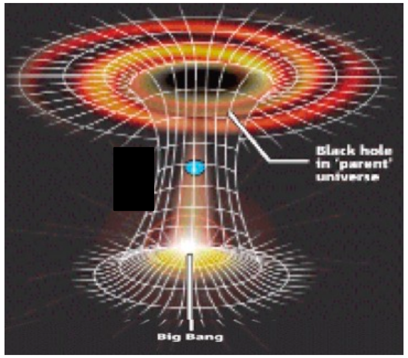


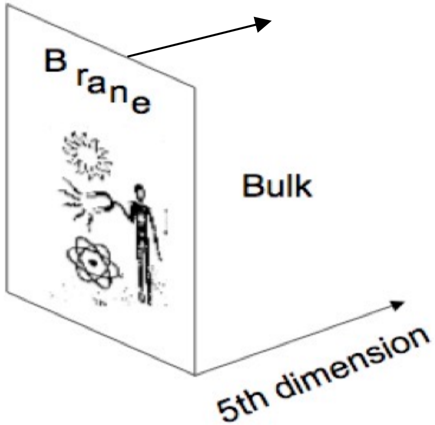
Quantum Cosmology



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

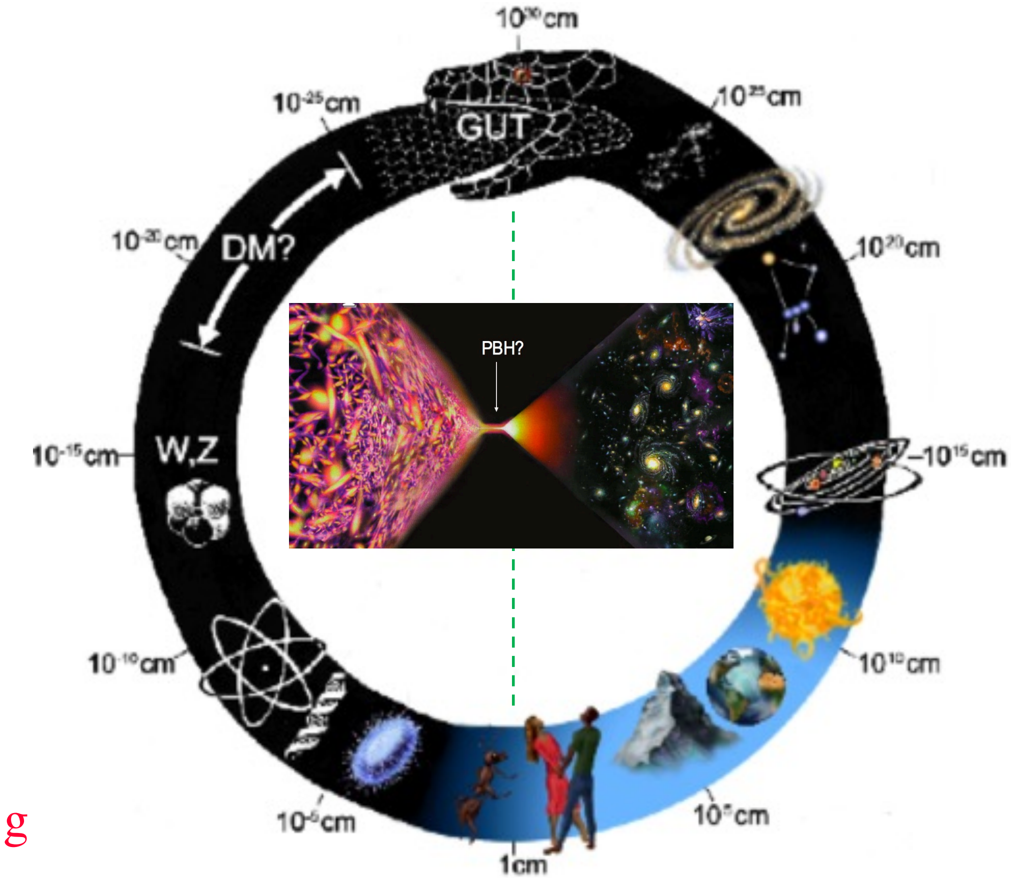
Bowcock et al. (2000), Mukhoyama et al. (2000)

BLACK HOLES AS LINK BETWEEN MICRO AND MACRO PHYSICS

HIGHER DIMENSIONS

Planck 10^{-5}g

10^{22} M_O Universal



exploding 10^{10}g

evaporating 10^{15}g

lunar 10^{21}g

10^{12} M_O SLAB

10^{9} M_O QSO

10^{6} M_O MW

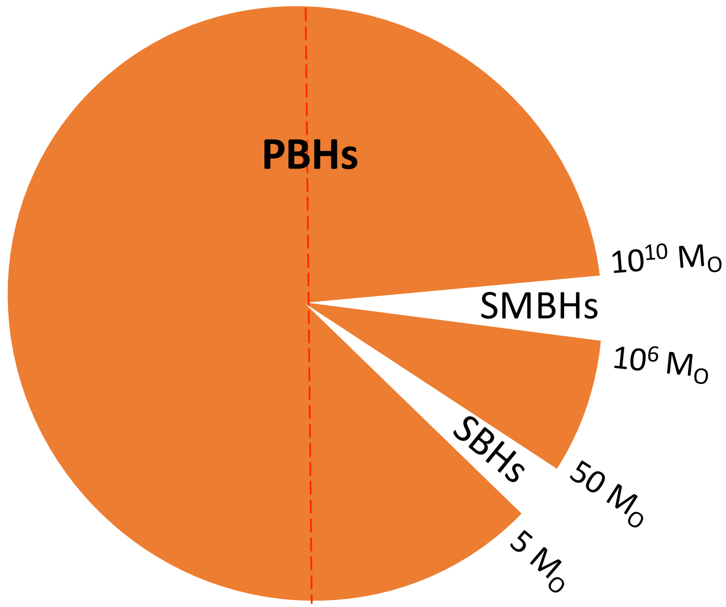
10^{2} M_O IMBH

1 M_O Stellar

terrestrial 10^{25}g

QUANTUM/CLASSICAL

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

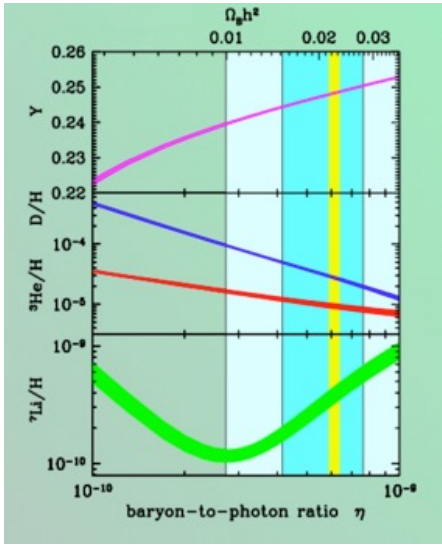
critical collapse, dark matter, dark energy

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

Planck mass relics, higher dimensions

BLACK HOLES COULD BE DARK MATTER ONLY IF PRIMORDIAL

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



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

No evidence yet for WIMPs!

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

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

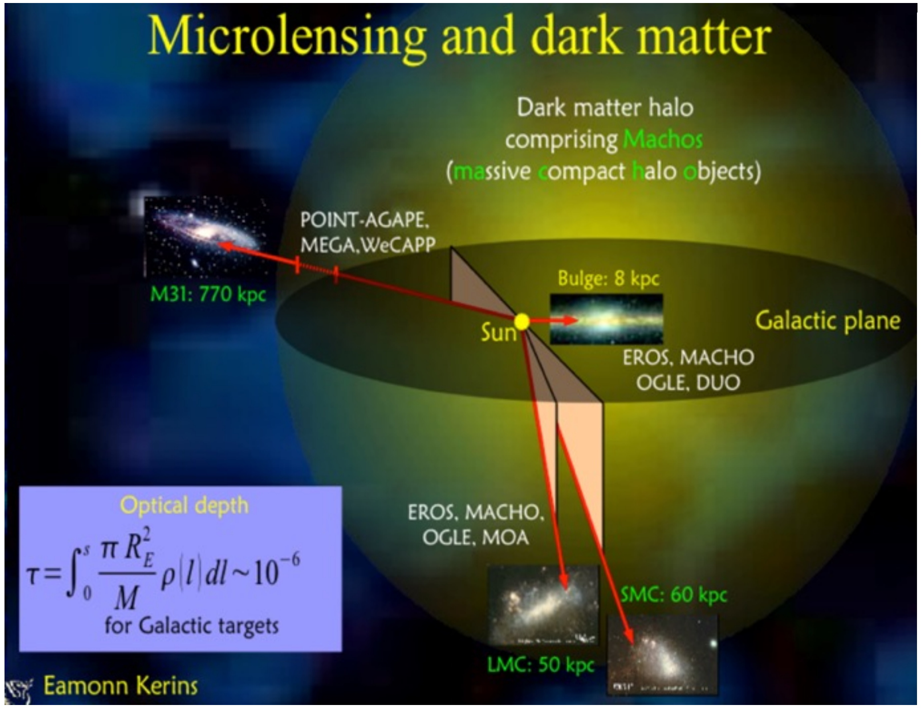
Received September 4, revised October 14, 1974

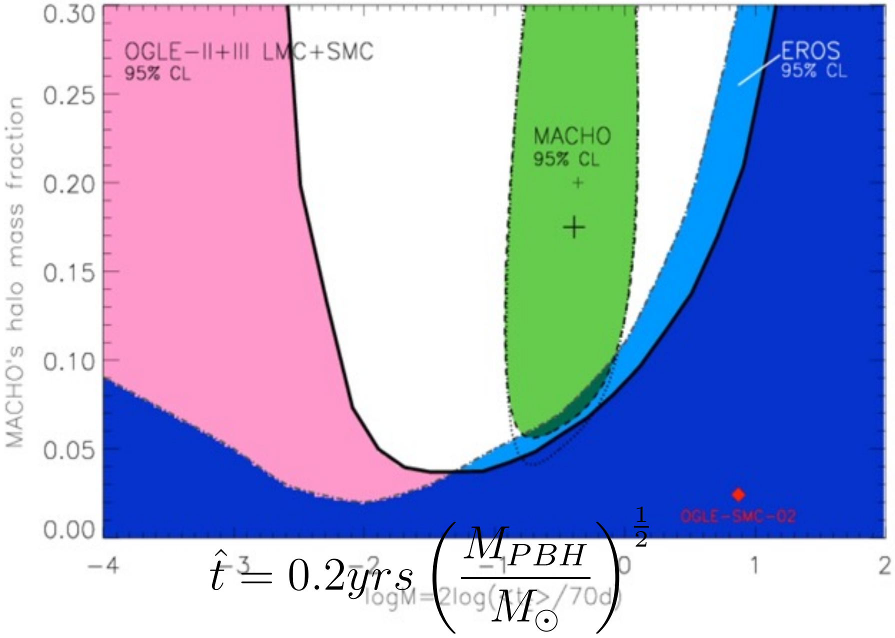
Summary. We present a scheme of galaxy formation, based on the hypothesis that a certain fraction of the mass of the early universe is in the form of black holes. It is argued that the black hole mass should be $\sim 1\, M_\odot$, and it is shown that random statistical fluctuations in their number cause 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

EXCITING DEVELOPMENT IN 1996: 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 microlensing searches suggested MACHOs with 0.5 M_O

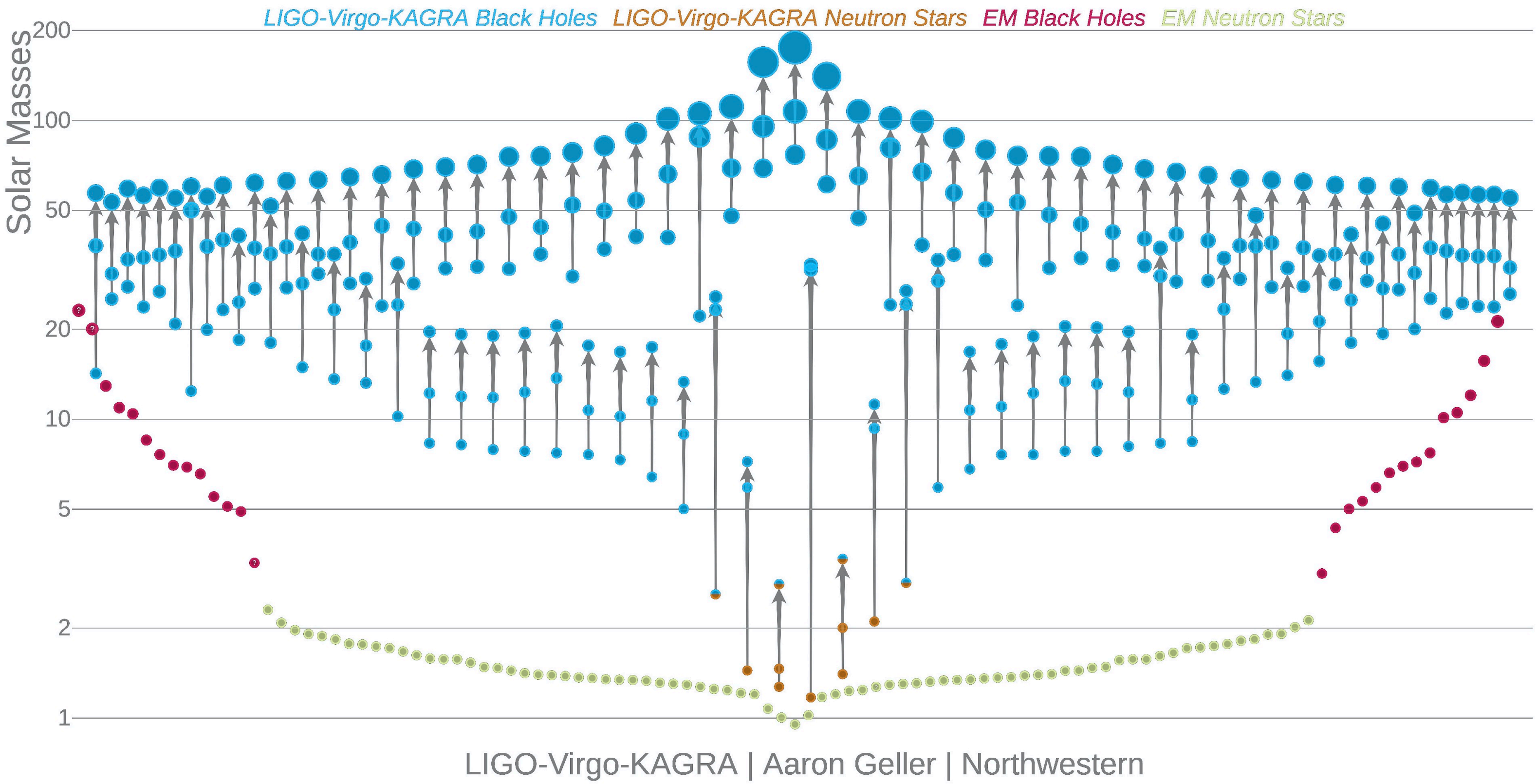
=> PBH formation at QCD transition?

Pressure reduction => PBH mass function peak at 0.5 M_O

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

But Galactic rotation curve and extended mass function allow

EXCITING DEVELOPMENT IN 2016:
LIGO DETECTION OF GRAVITY WAVES



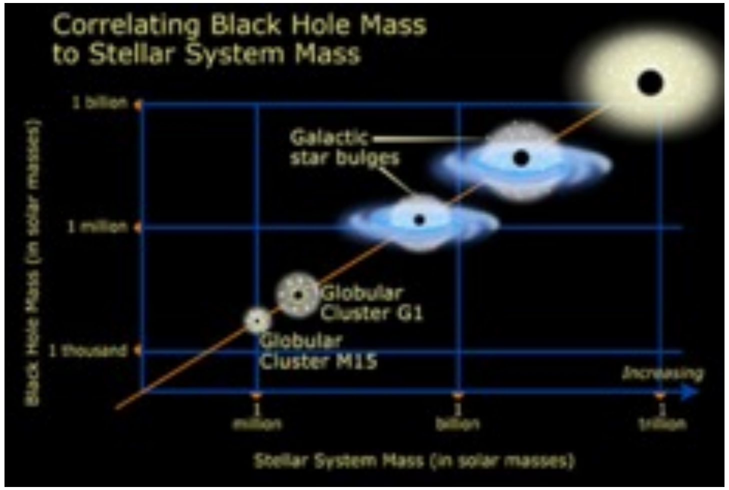
Do we need PBHs? [Riotto talk]

PBHS AS SEEDS FOR COSMIC STRUCTURE?

arXiv:1801.00672

What is maximum mass of PBH?

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



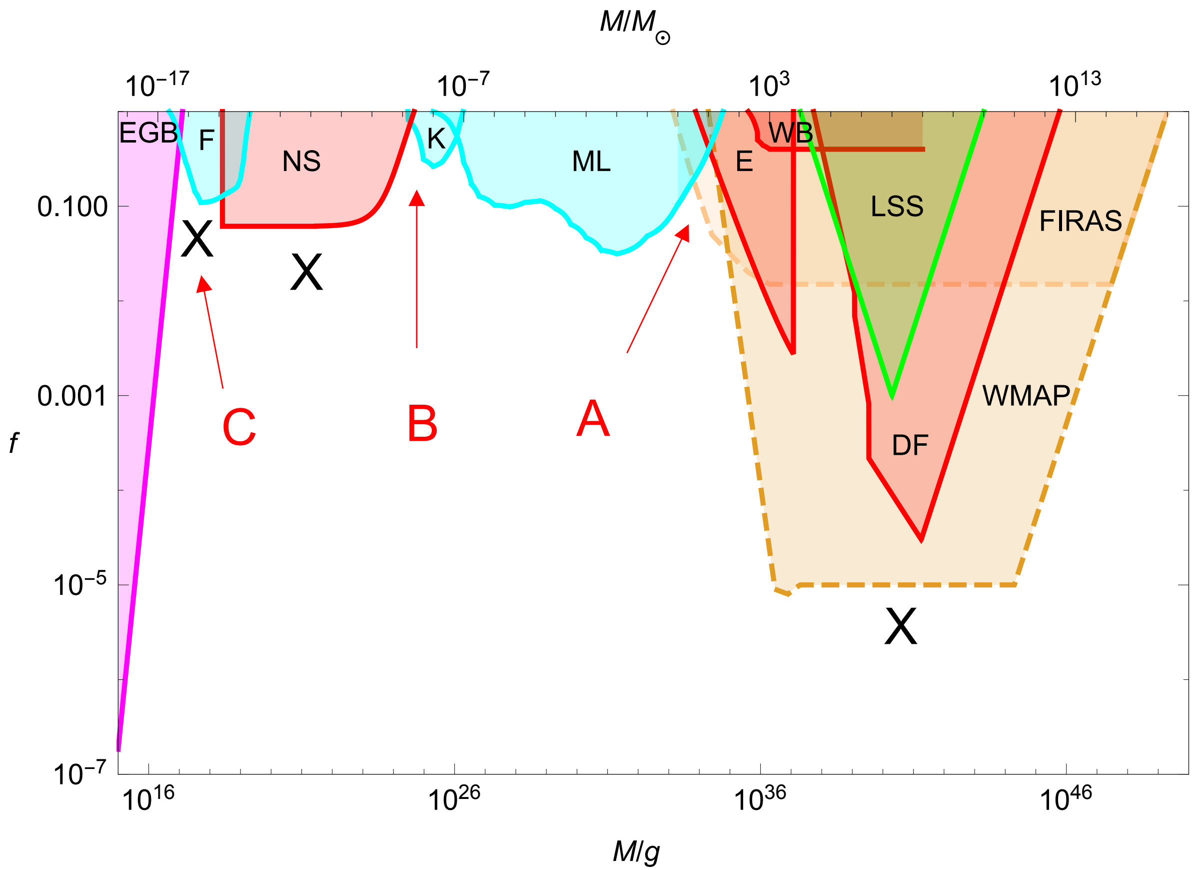
BH mass
proportional
to stellar mass

Upper limit on μ distortion of CMB excludes $10^4 < M/M_O < 10^{13}$
but non-Gaussian model evade limits.

PRIMORDIAL BLACK HOLES AS DARK MATTER

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

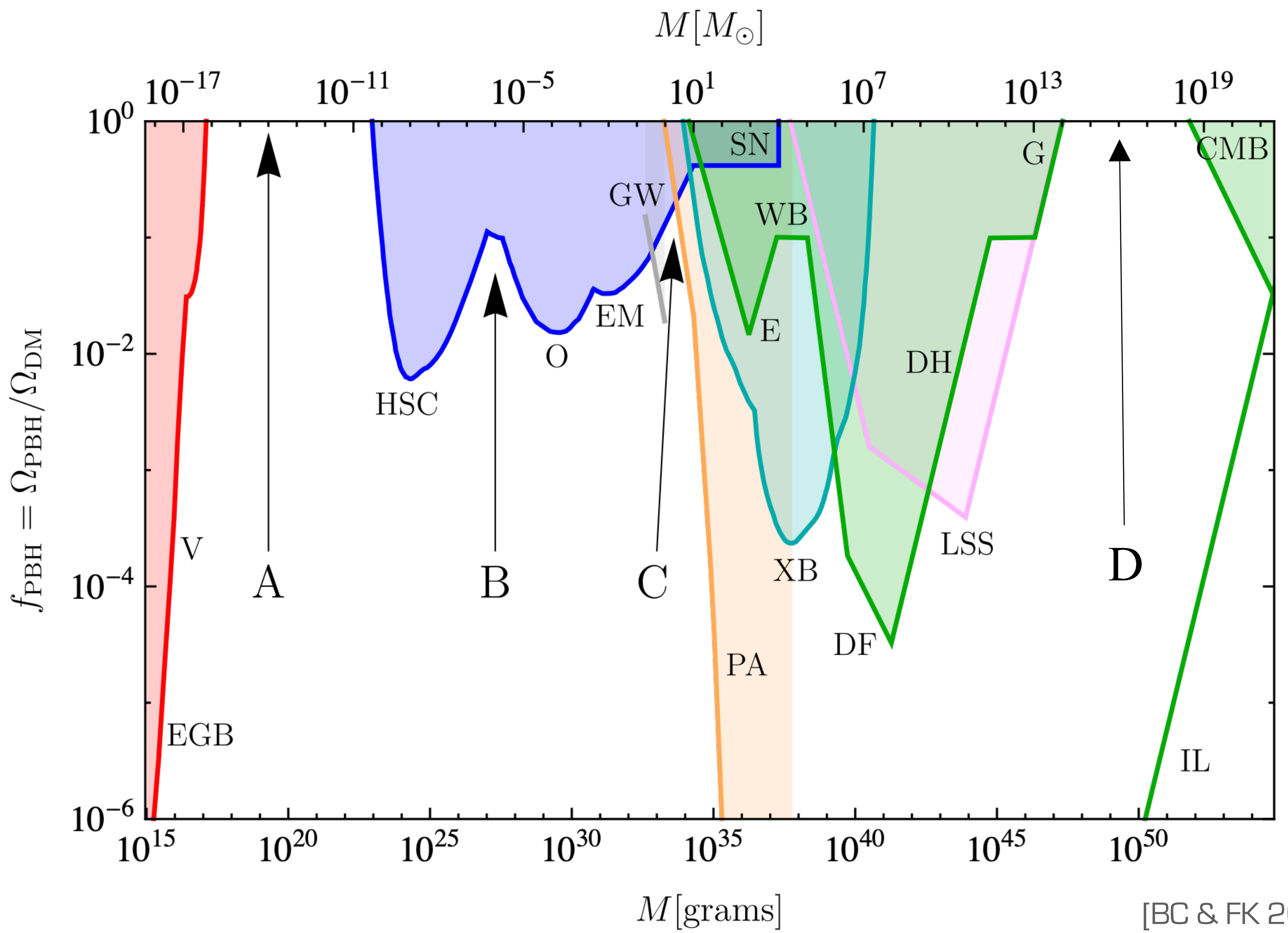
PRD 94, 083504, arXiv:1607.06077



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

But some of these limits are now thought to be wrong

Updated PBH Constraints — Possible Windows



[BC & FK 2020]

★ D = Stupendously Large Black Hole (SLAB) window! [BC, FK, Visinelli 2021]

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.

CKS 2016

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

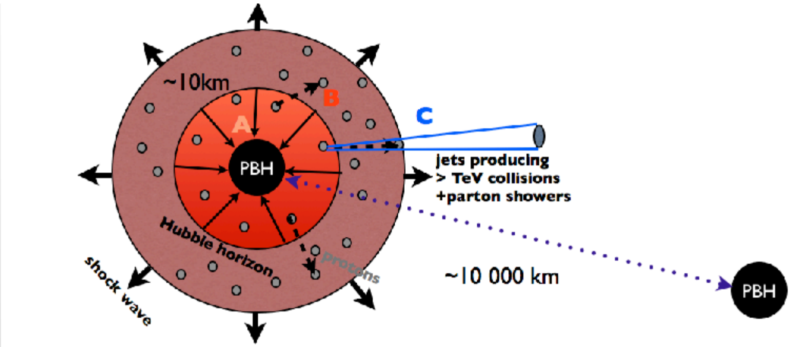
Amplitude of horizon-scale fluctuations $\beta(M) \sim \varepsilon(M) \exp\left[-\frac{\alpha^2}{2\varepsilon(M)^2}\right]$

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)

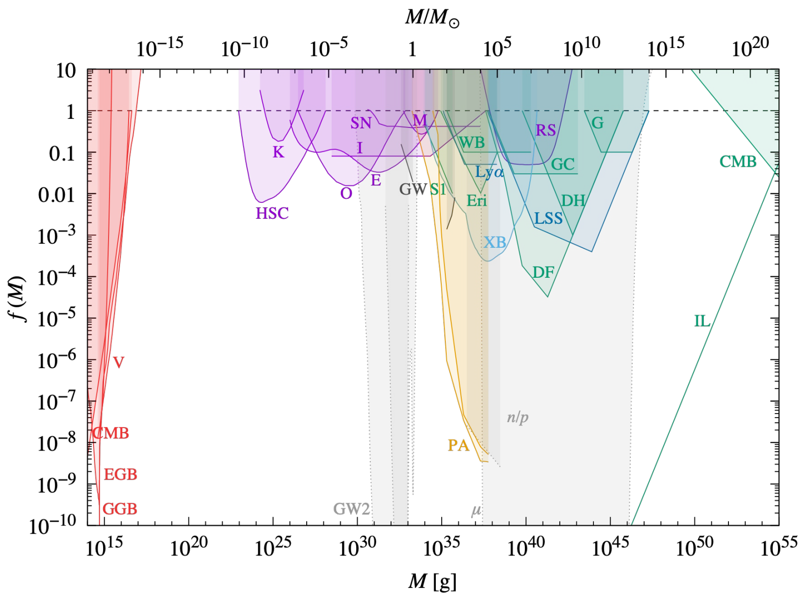
$\eta_{loc} \sim 1 \Rightarrow \eta \sim \beta$ after diffusion

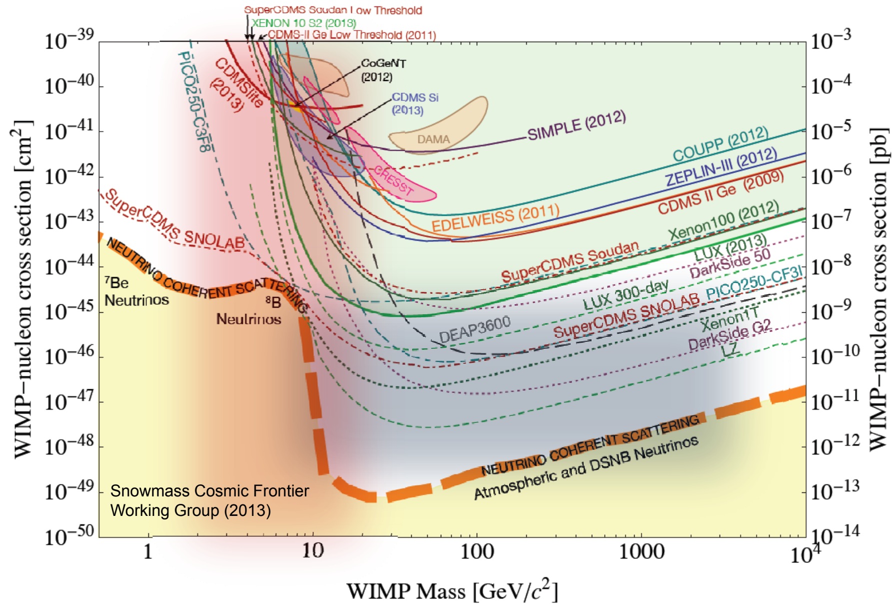
$\chi \approx \gamma/(1-\gamma) \approx 5$ if $\gamma \approx 0.8$

$$\left.\begin{array}{l}\beta \text{ too small} \Rightarrow \text{too little DM} \\ \beta \text{ too large} \Rightarrow \text{too much DM}\end{array}\right\} \Rightarrow \text{no gals}$$

PBHS or WIMPS?

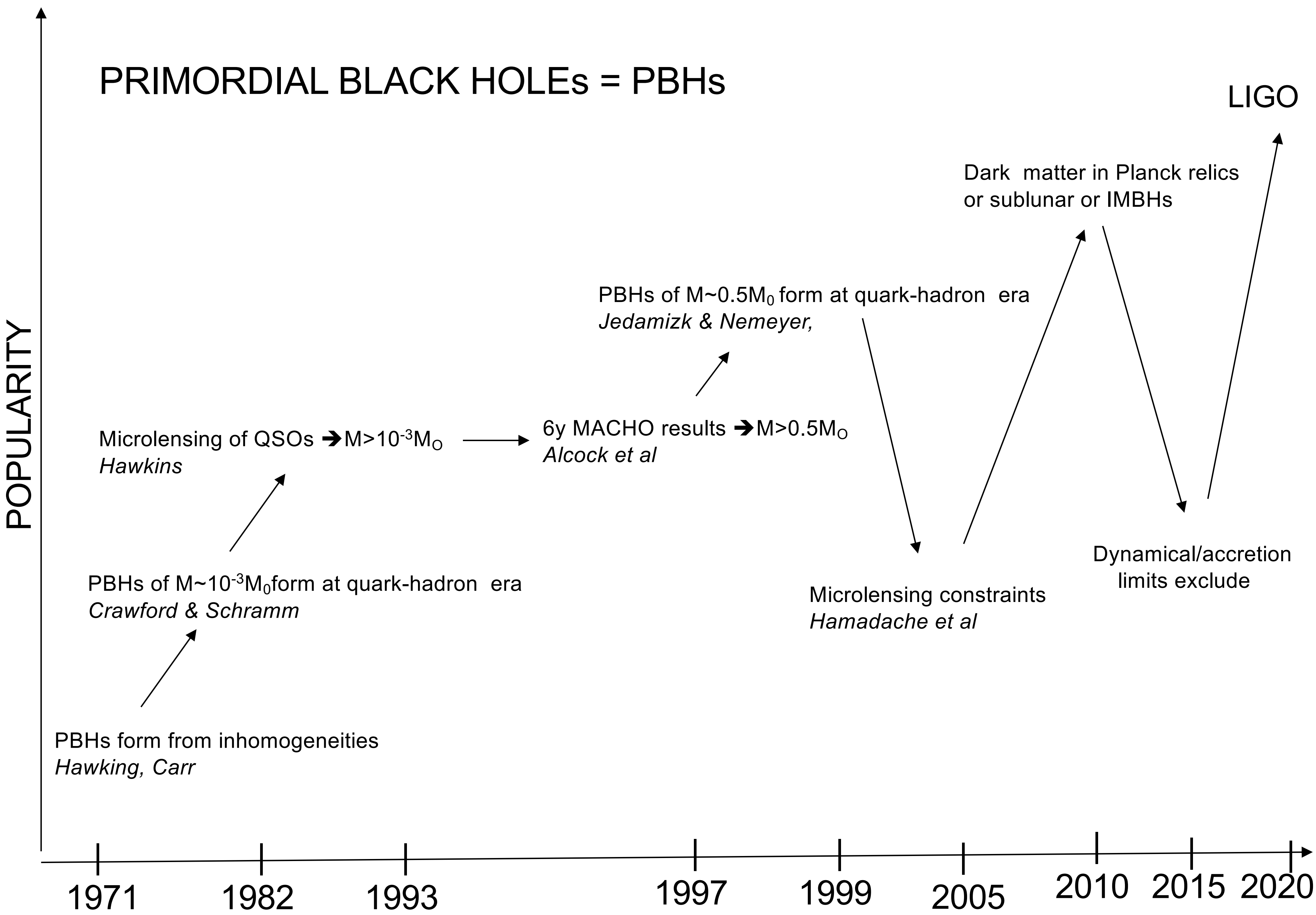
Historical Perspective





Light versus heavy candidates

Both can be important even if not dark matter


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