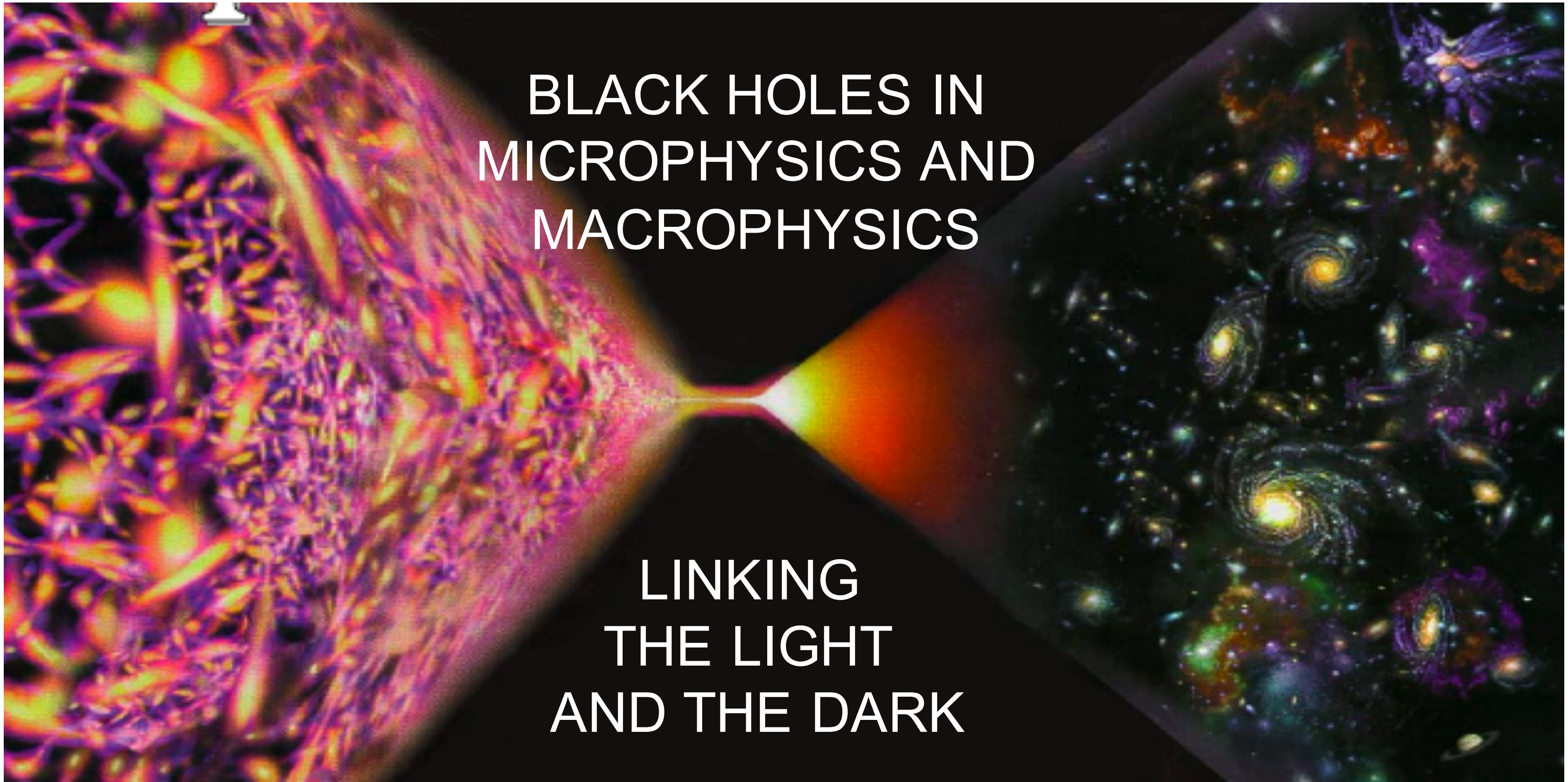
BLACK HOLES IN MICROPHYSICS AND MACROPHYSICS



LINKING THE LIGHT AND THE DARK

Bernard Carr, Queen Mary University of London

SOLVAY (3/4/19)

PLAN OF TALK

* Introduction to PBHs

  PBH formation

  PBH evaporation

- PBHs as a source of light

  Radiation from PBH evaporation

  Radiation from PBH accretion

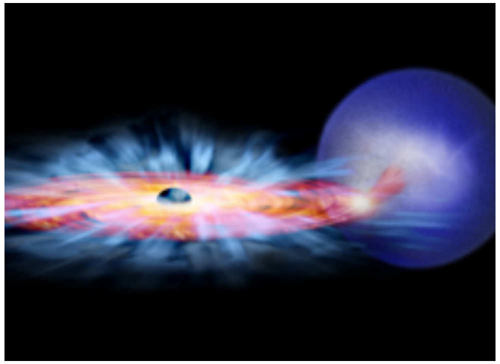
- PBHs as a source of dark

  PBHs and dark mattter

  PBHs and LIGO/Virgo events

- PBHs as generators of cosmic structure

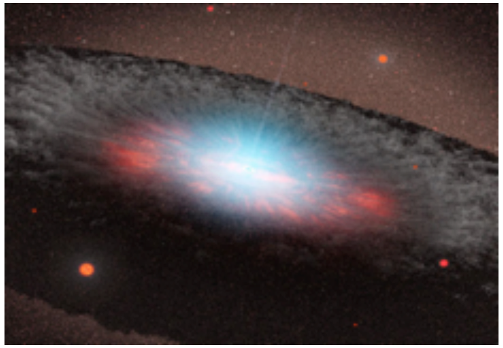
OVERWHELMING EVIDENCE FOR STELLAR BHS $(M \sim 10^{1-2} M_O)$



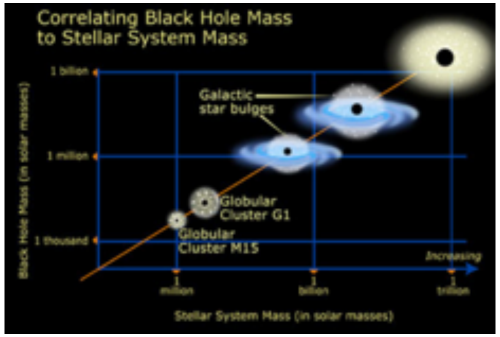
X-ray binaries
Cygnus X1

LIGO detects gravity waves from coalescing BHs

OVERWHELMING EVIDENCE FOR SMBH IN AGN $(M \sim 10^{6-9} M_O)$

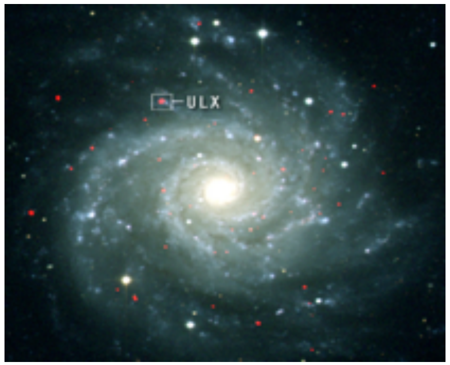


MW $4 \times 10^6 M_O$
QSO $10^8 M_O$
$1.4 \times 10^{10} M_O$
BH at z=6.3

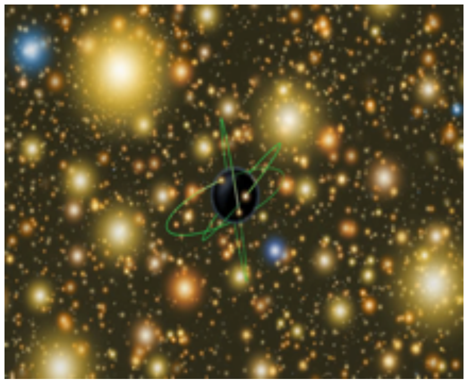


BH mass proportional to stellar mass

POSSIBLE EVIDENCE FOR IMBH $(M \sim 10^{3-5} M_O)$



Ultraluminous X-ray sources NGC1313 may have $500 M_O$ BH



Globular clusters Omega Cen may have $4 \times 10^4 M_O$ BH

PRIMORDIAL BLACK HOLE FORMATION

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

Small BHs can only form in early Universe

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

⇨ **primordial BHs with horizon mass at formation**

$$M_{PBH} \sim c^3 t/G = \begin{array}{ll} 10^{-5}\text{g at } 10^{-43}\text{s} & \text{(minimum?)} \\ 10^{15}\text{g at } 10^{-23}\text{s} & \text{(evaporating now)} \\ 1M_O \text{ at } 10^{-5}\text{s} & \text{(QCD transition)} \\ 10^5 M_O \text{ at 1s} & \text{(maximum?)} \end{array}$$

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

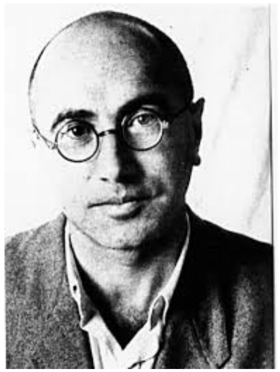
It is suggested that there may be a large number of gravitationally collapsed objects of mass 10^{-5} g upwards which were formed as a result of fluctuations in the early Universe. They could carry an electric charge of up to ± 30 electron units. Such objects would produce distinctive tracks in bubble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

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.



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

BLACK HOLES IN THE EARLY UNIVERSE

B. J. Carr and S. W. Hawking

(Received 1974 February 25)

SUMMARY

The existence of galaxies today implies that the early Universe must have been inhomogeneous. Some regions might have got so compressed that they underwent gravitational collapse to produce black holes. Once formed, black holes in the early Universe would grow by accreting nearby matter. A first estimate suggests that they might grow at the same rate as the Universe during the radiation era and be of the order of 10^{15} to 10^{17} solar masses now. The observational evidence however is against the existence of such giant black holes. This motivates a more detailed study of the rate of accretion which shows that black holes will not in fact substantially increase their original mass by accretion. There could thus be primordial black holes around now with masses from 10^{-5} g upwards.

$\Rightarrow$ no observational evidence against them

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

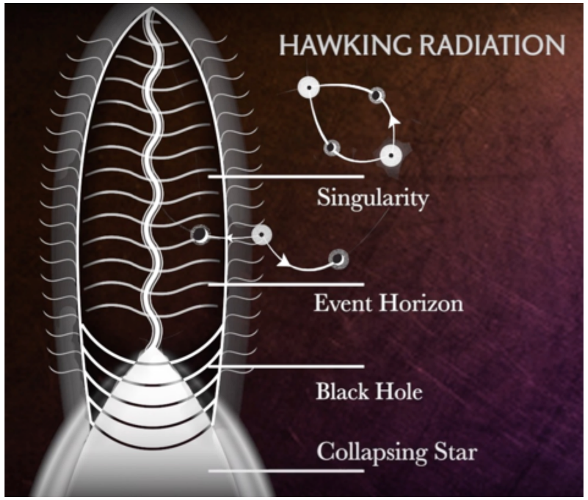
Abstract

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.

First paper on PBHs as dark matter

letters to nature

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



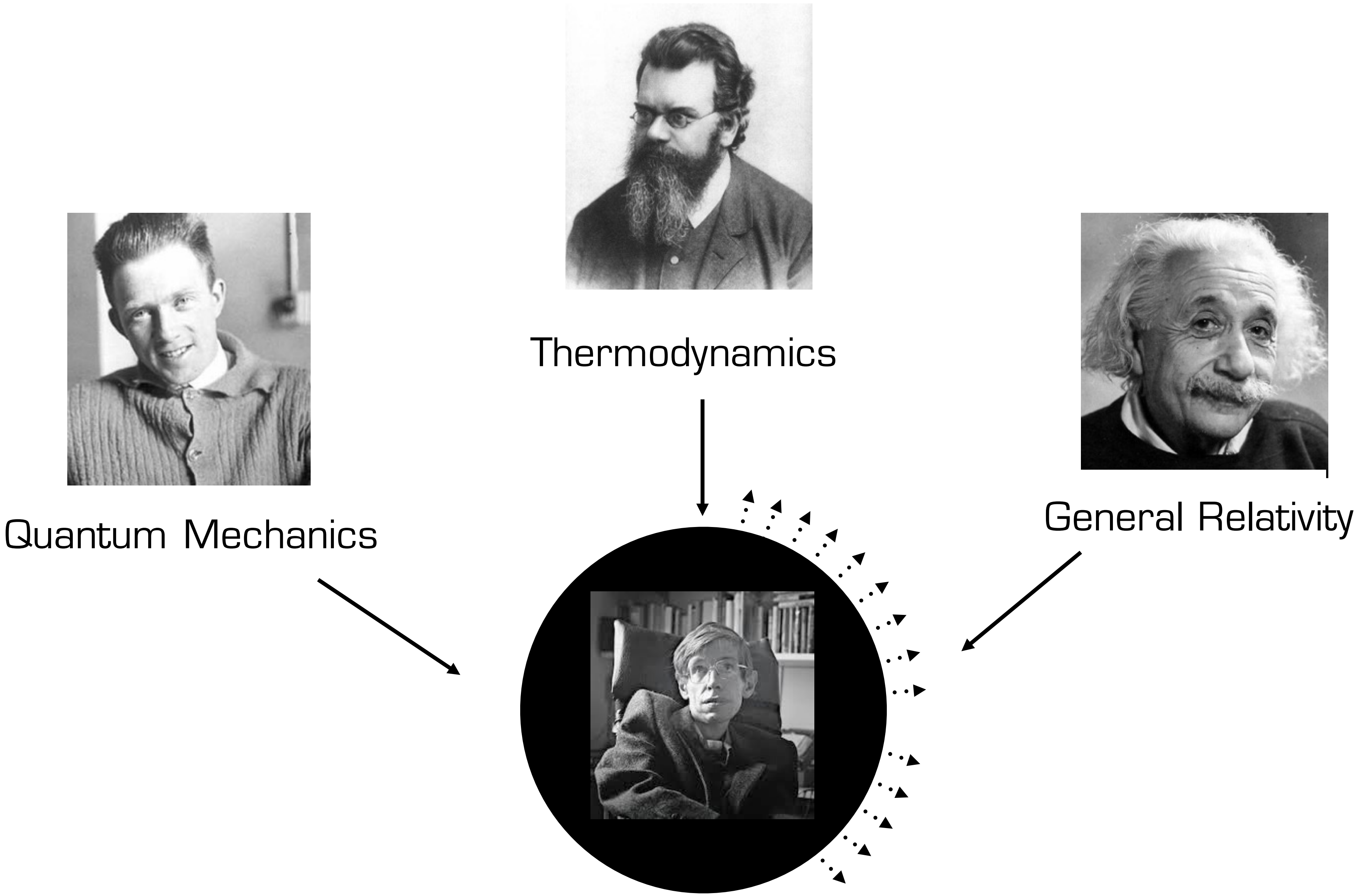
Black hole explosions?

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.

Black Hole = Dark + Light



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

PBHs are important even if they never formed!

BLACK HOLE INFORMATION PARADOX

PHYSICAL REVIEW D VOLUME 14, NUMBER 10 15 NOVEMBER 1976

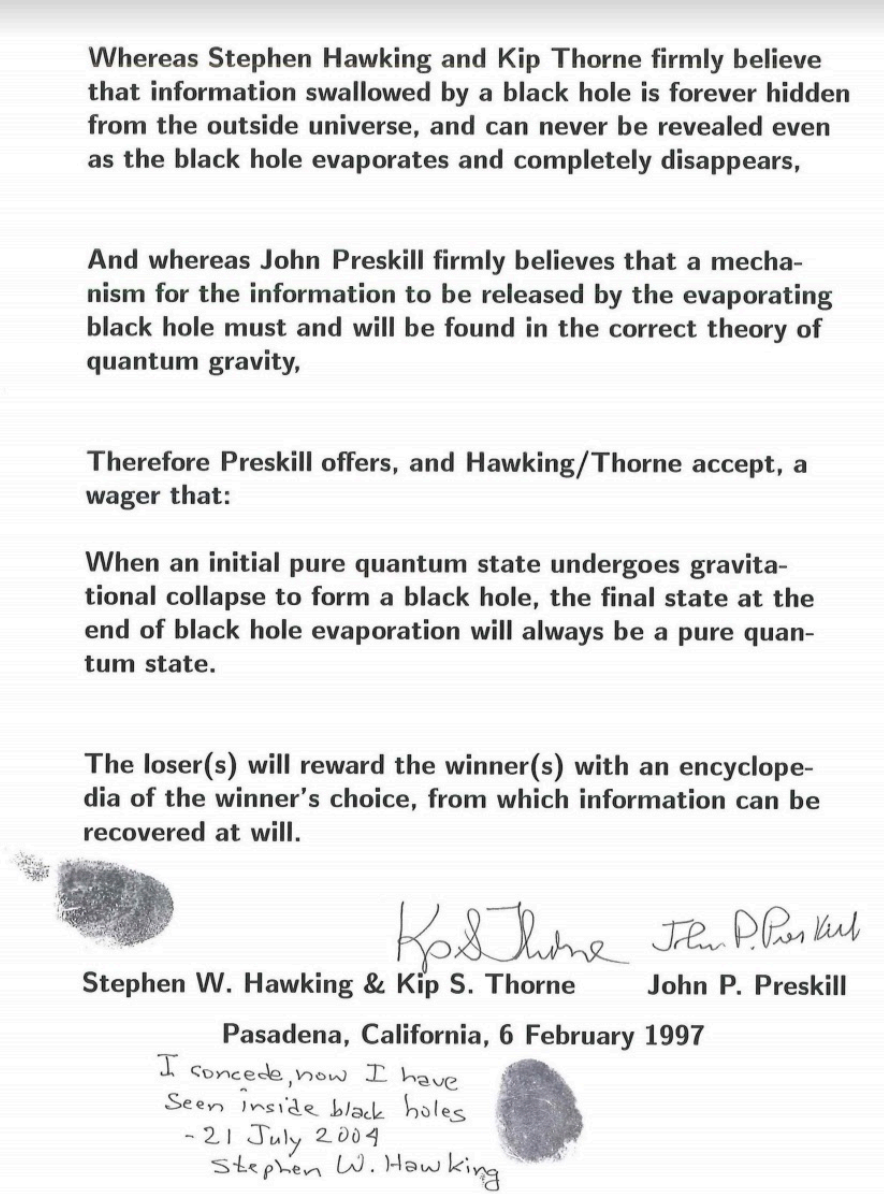
Breakdown of predictability in gravitational collapse*

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……..

STEPHEN'S BET



Whereas Stephen Hawking and Kip Thorne firmly believe that information swallowed by a black hole is forever hidden from the outside universe, and can never be revealed even as the black hole evaporates and completely disappears,

And whereas John Preskill firmly believes that a mechanism for the information to be released by the evaporating black hole must and will be found in the correct theory of quantum gravity,

Therefore Preskill offers, and Hawking/Thorne accept, a wager that:

When an initial pure quantum state undergoes gravitational collapse to form a black hole, the final state at the end of black hole evaporation will always be a pure quantum state.

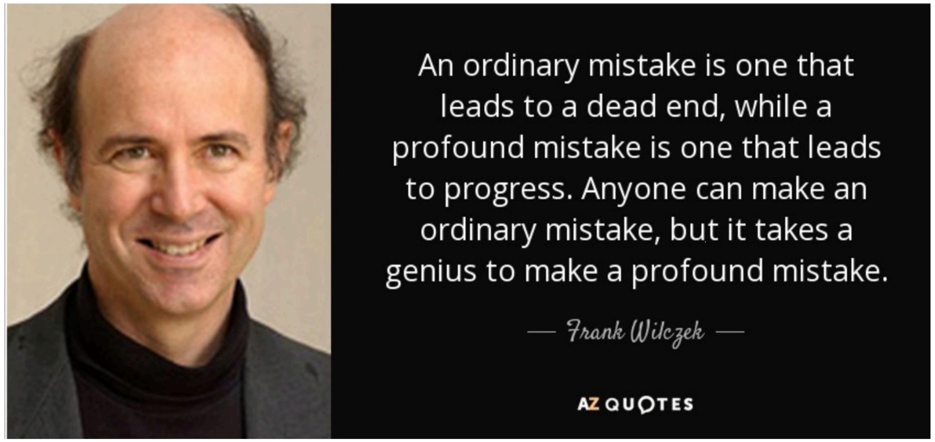
The loser(s) will reward the winner(s) with an encyclopedia of the winner's choice, from which information can be recovered at will.

Kip S. Thorne   John P. Preskill

Stephen W. Hawking & Kip S. Thorne   John P. Preskill

Pasadena, California, 6 February 1997

I concede, now I have
Seen inside black holes
- 21 July 2004
Stephen W. Hawking



PBH EVAPORATION

Black holes radiate thermally with temperature

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

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

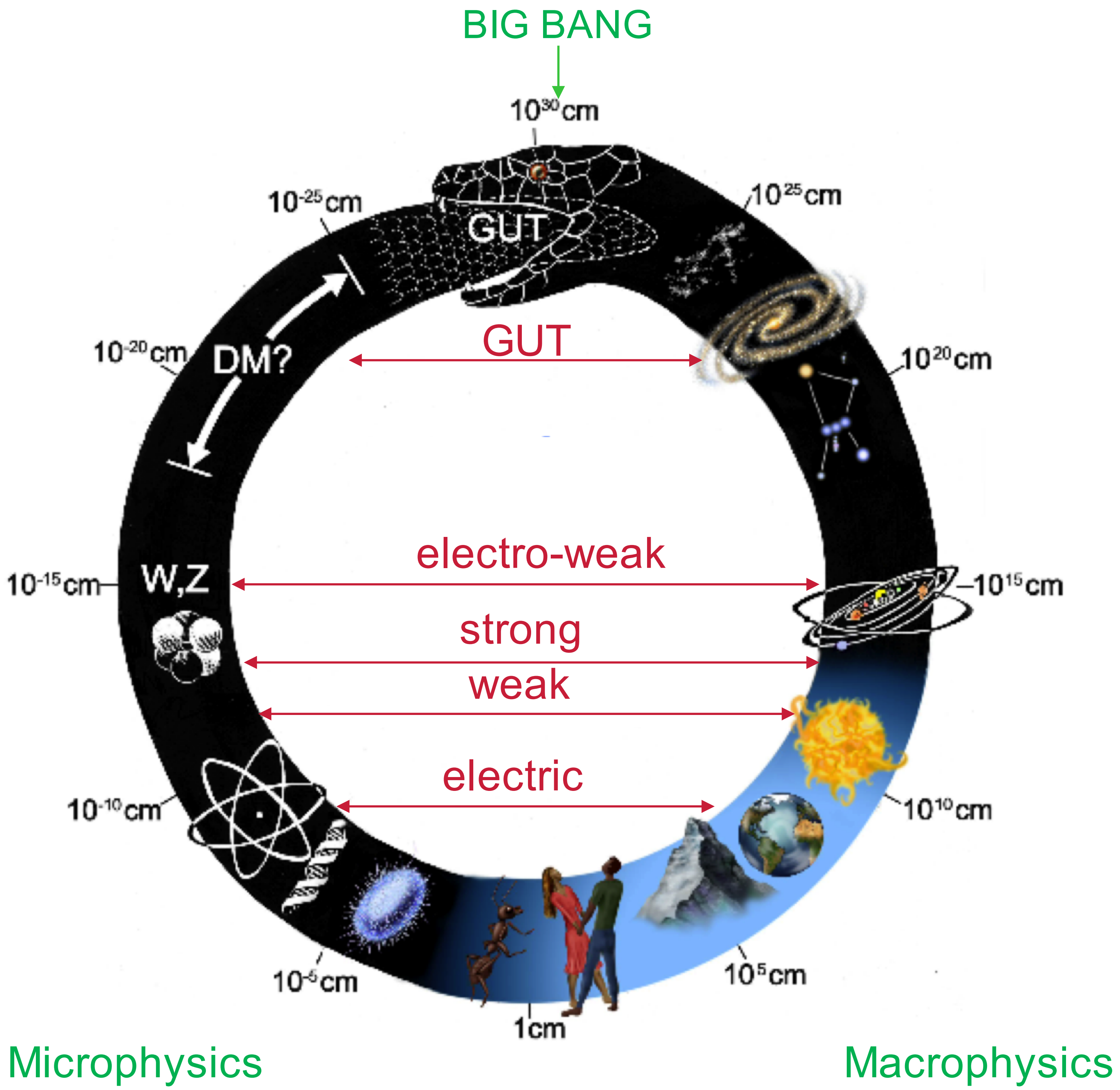
$M \sim 10^{15}$g => final explosion phase today (10^{30} ergs)

This can only be important for PBHs

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

=> explosions undetectable in standard particle physics model

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



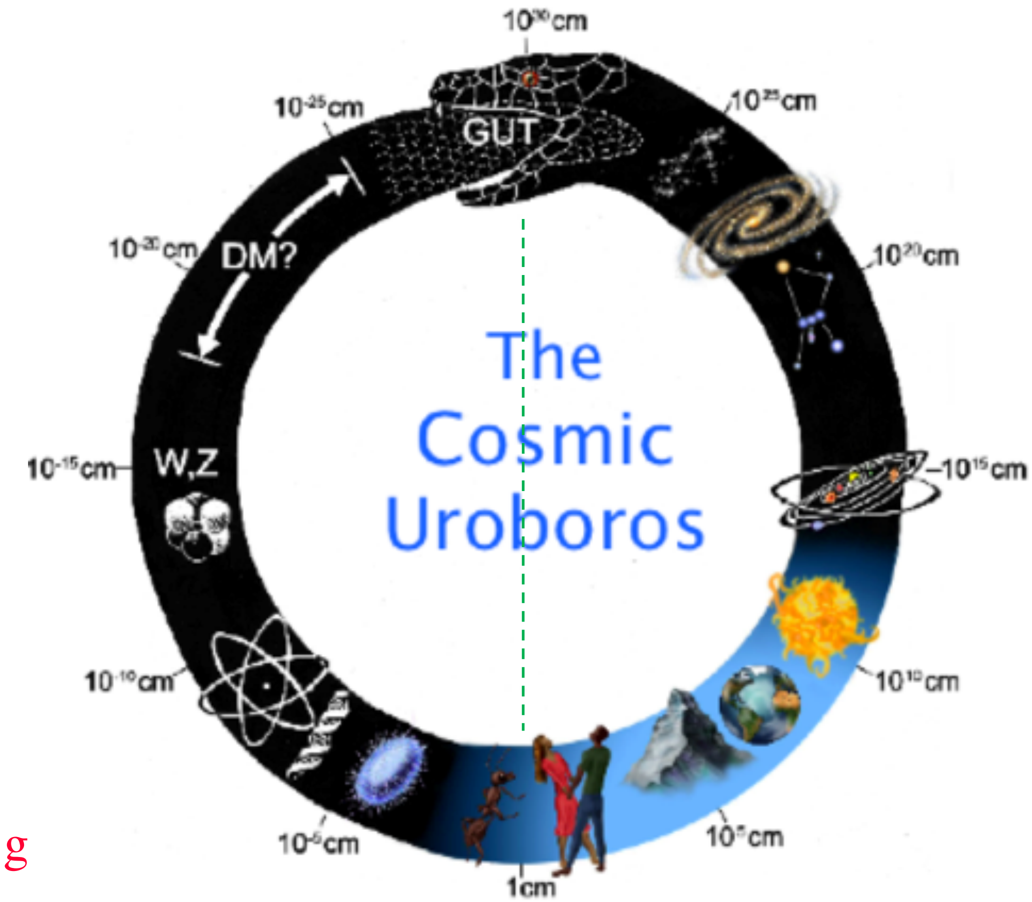
BIG BANG
10^30 cm
10^25 cm
10^-25 cm
GUT
GUT
10^-20 cm
DM?
10^20 cm
10^-15 cm
W,Z
electro-weak
10^15 cm
strong
weak
electric
10^-10 cm
10^10 cm
10^-5 cm
10^5 cm
1cm
Microphysics
Macrophysics

BLACK HOLES

HIGHER DIMENSIONS

Planck 10^{-5}g

$10^{22}\, M_O$ Universal



$10^{9}\, M_O$ QSO

exploding 10^{10}g

$10^{6}\, M_O$ MW

evaporating 10^{15}g

$10^{2}\, M_O$ IMBH

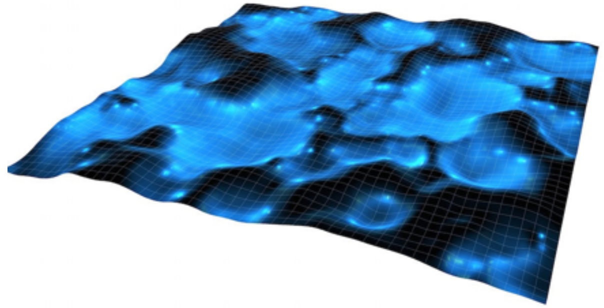
lunar 10^{21}g

$1\, M_O$ Stellar

terrestrial 10^{25}g

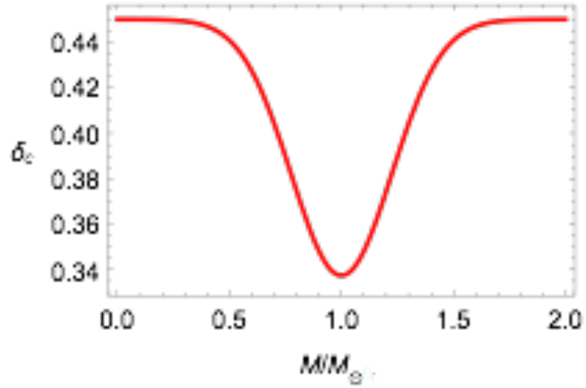
QUANTUM/CLASSICAL

FORMATION MECHANISMS

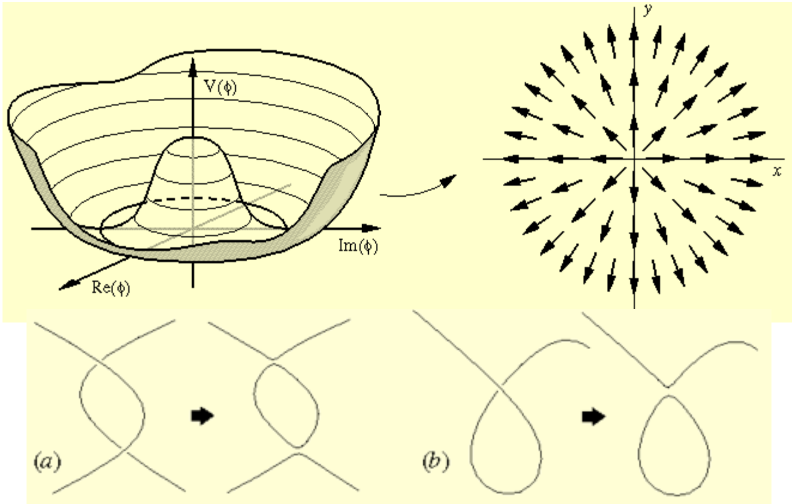


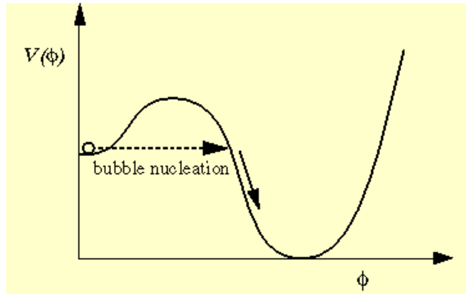
Primordial inhomogeneities Inflation

Pressure reduction Form more easily but need spherical symmetry



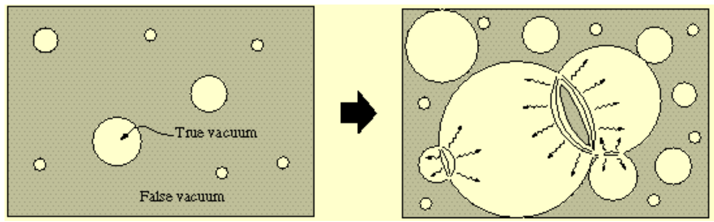
Cosmic strings PBH constraints => $G\mu < 10^{-6}$





Bubble collisions

Need fine-tuning of bubble formation rate



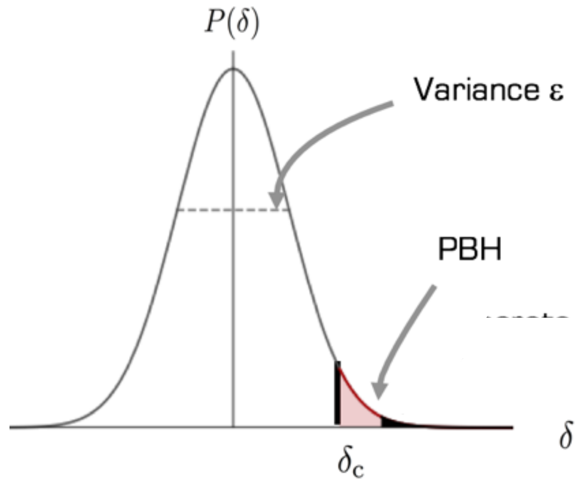
Domain walls PBHs can be very large

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 fluctns with $\langle \delta_H^2 \rangle^{1/2} = \varepsilon(M)$



$\Rightarrow$ fraction of PBHs

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

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

(Khlopov & Polnarev 1982)

Claim of separate Universe for $\delta_H > 1$ is misleading!

(Kopp et al. 2011, Carr & Harada 2015)

Limit on fraction of Universe collapsing

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

General limit

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

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

So both require and expect β(M) to be tiny => fine-tuning

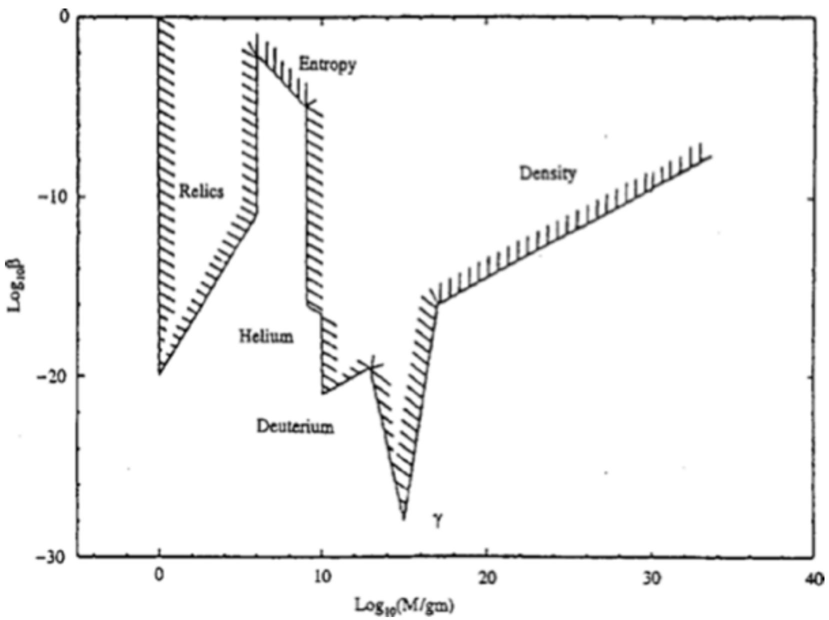
Unevaporated	$M>10^{15}$g => $\Omega_{PBH} < 0.25$	(CDM)
Evaporating now	$M\sim10^{15}$g => $\Omega_{PBH} < 10^{-8}$	(GRB)
Evaporated in past	$M<10^{15}$g	

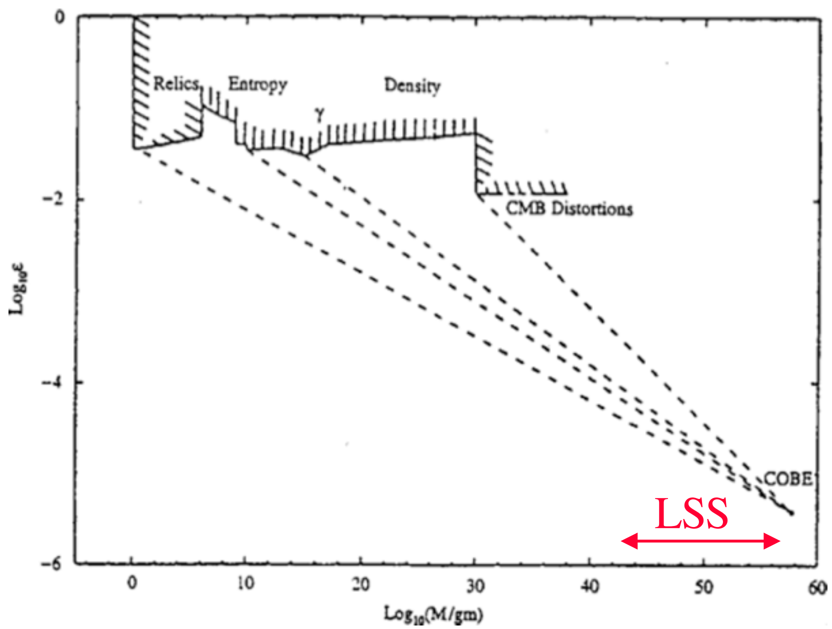
=> constraints from entropy, γ-background, BBNS

PBHS AS PROBE OF PRIMORDIAL FLUCTUATIONS

Constraints on β(M) => Constraints on ε(M)

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





PBHs are unique probe of **ε** on small scales.

Need blue spectrum or spectral feature to produce them.

PBHS FROM NEAR-CRITICAL COLLAPSE

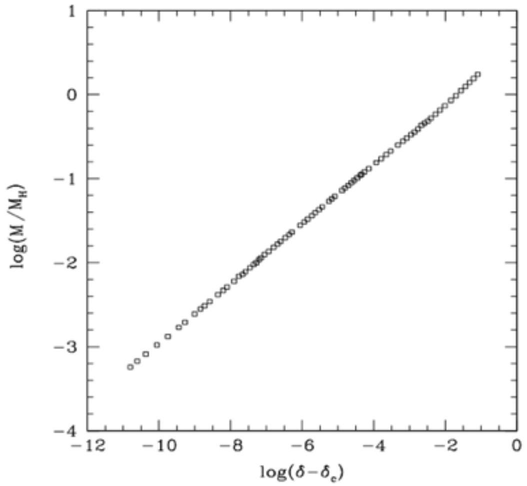
Critical phenomena => $M = k\, M_H(\delta-\delta_c)^\gamma$ (Niemeyer & Jedamzik 1999)

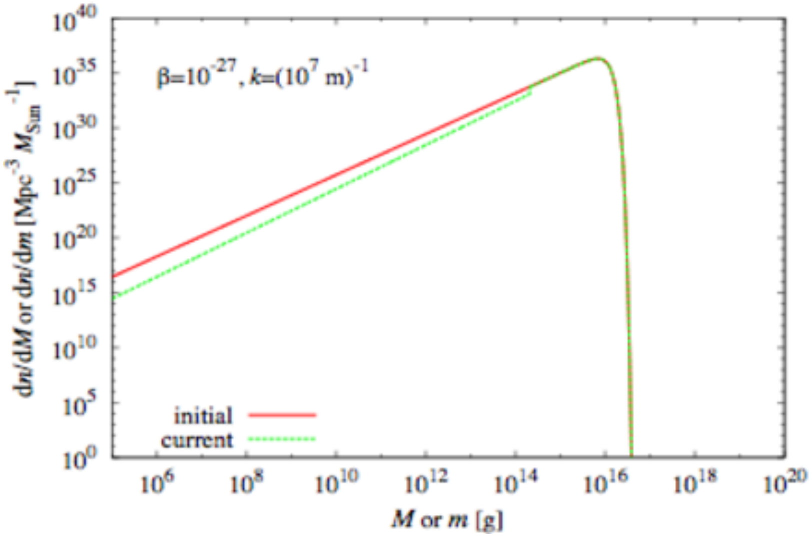
spectrum peaks at horizon mass with extended low mass tail

$$dN/dM \propto M^{1/\gamma-1}\exp[-(M/M_f)^{1/\gamma}] \quad (\gamma = 0.35)$$ (Yokoyama 1998)

Later calculations and peak analysis =>

$\delta_C \sim 0.45$ and applies to $\delta - \delta_C \sim 10^{-10}$ (Musco & Miller 2013)



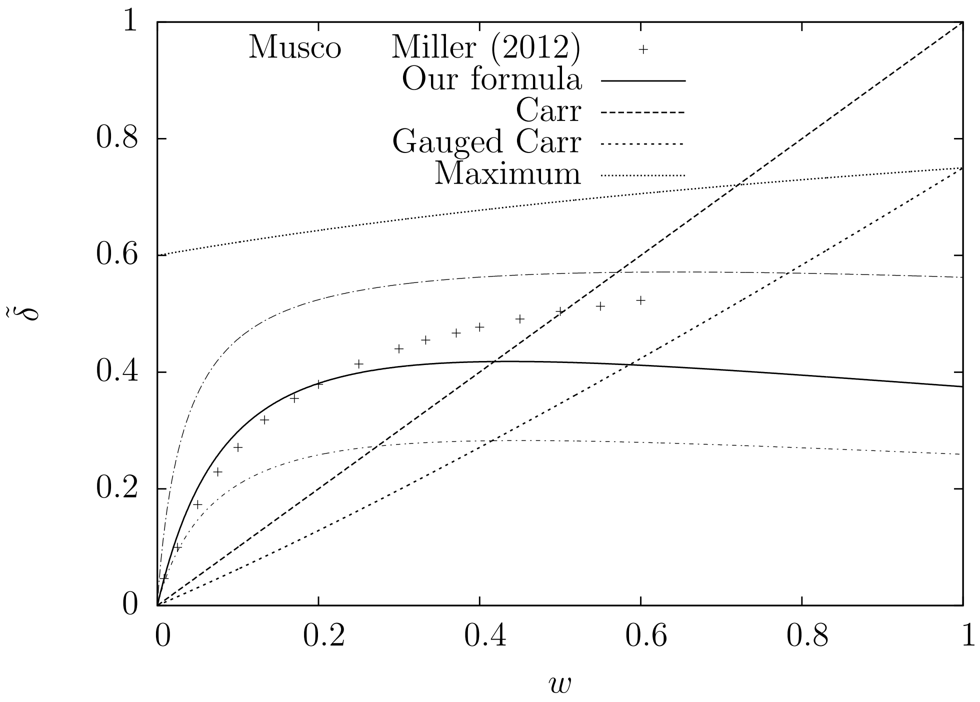


MORE PRECISE ESTIMATE OF δ_C

Threshold of primordial black hole formation

[1]Tomohiro Harada,* [2]Chul-Moon Yoo, and [3,4]Kazunori Kohri

PRD 88 084051 (2013)



$$\delta_{Hc}^{\mathrm{UH}} = \sin^2\left(\frac{\pi\sqrt{w}}{1+3w}\right)$$

0.62 for radiation

PBHS AND INFLATION

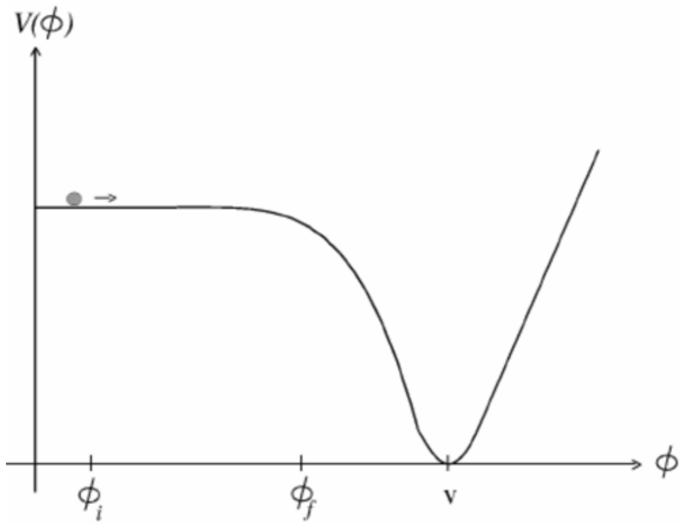
PBHs formed before reheat inflated away =>

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

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]

Inflation and primordial black holes as dark matter

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

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

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.

See also Dolgov & Silk, Phys. Rev. D, 47, 4244 (1993)

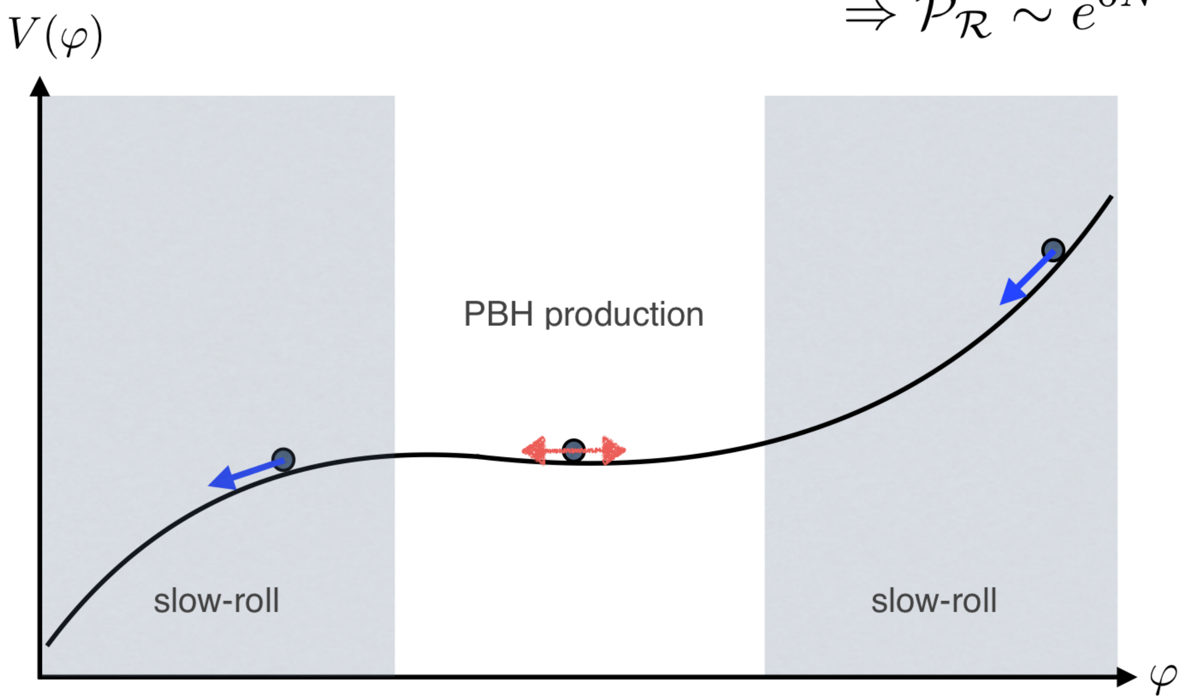
(Kuhnel)

QUANTUM DIFFUSION

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

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

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



QUANTUM DIFFUSION: CURRENT HOT TOPIC

Quantum diffusion during inflation and primordial black holes

arXiv:1705.04861

Chris Pattison,[a] Vincent Vennin,[b,a] Hooshyar Assadullahi,[a,c] and David Wands[a]

Quantum diffusion beyond slow-roll: implications for primordial black-hole production

arXiv:1805.06731

Jose María Ezquiaga[a,b] and Juan García-Bellido[a,b]

Single Field Double Inflation and Primordial Black Holes

arXiv:1705.06225

K. Kannike,[a] L. Marzola,[a,b] M. Raidal,[a] and H. Veermäe[a]

Primordial black hole production in critical Higgs inflation

arXiv:1705.04861

J Ezquiaga, J Garcia-Bellido, E Morales

Primordial black holes from an inflexion point

arXiv:1706.042261

C Germani and T Prokopec

Primordial black holes from inflation and quantum diffusion

arXiv:1804.07124

M. Biagetti,[a] G. Franciolini,[b] A. Kehagias[c] and A. Riotto[b]

Primordial black holes from inflaton and spectator field perturbations in a matter-dominated era

Bernard Carr,[1,*] Tommi Tenkanen,[1,†] and Ville Vaskonen[2,‡]

Phys Rev D 96, 063507 (2017)

Primordial Black Hole Formation During Slow Reheating After Inflation

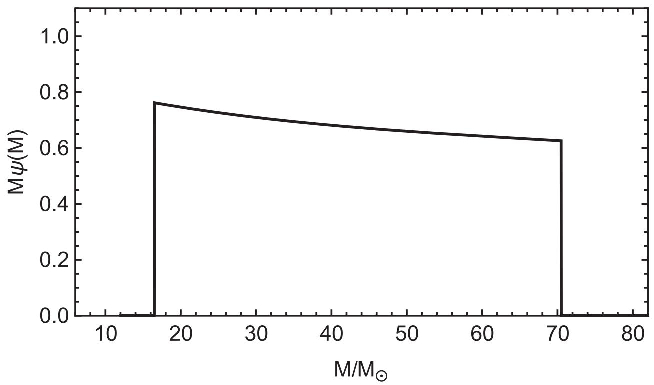
Bernard Carr,[1,*] Konstantinos Dimopoulos,[2,†] Charlotte Owen,[2,‡] and Tommi Tenkanen[1,§]

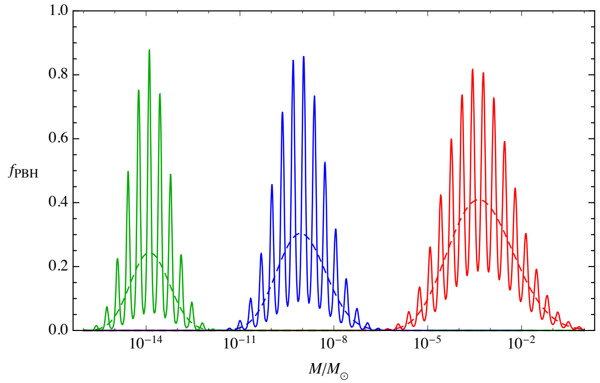
arXiv:1804.08639

Primordial Black Holes With Multi-Spike Mass Spectra

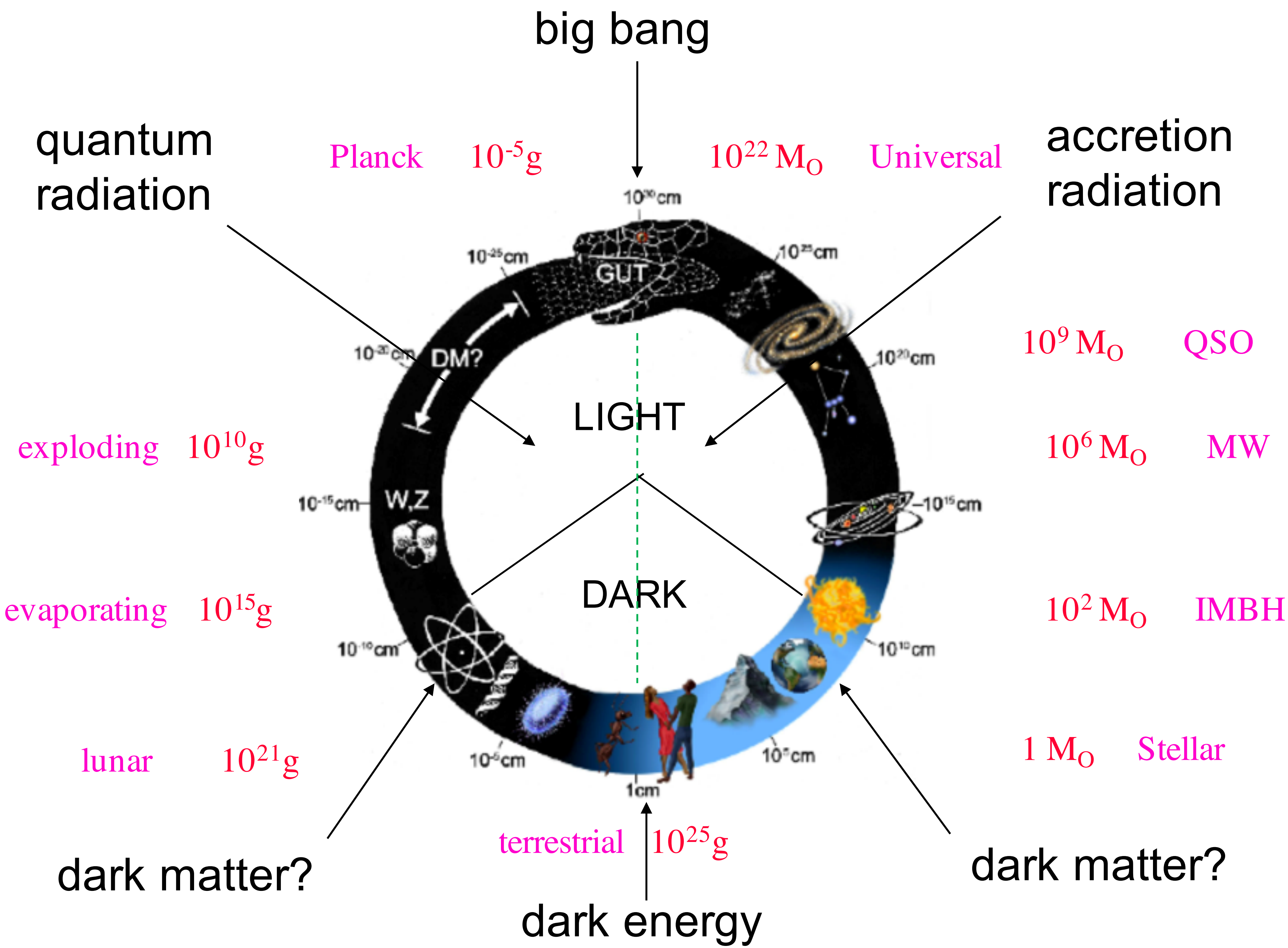
Bernard Carr[1,*] and Florian Kühnel[2,3,†]

arXiv:1811.06532





LINKING LIGHT AND DARK



CONSTRAINTS FOR EVAPORATING PBHS

B. Carr, K. Kohri, Y. Sendouda & J. Yokoyama PRD 81(2010) 104019

Big bang nucleosynthesis

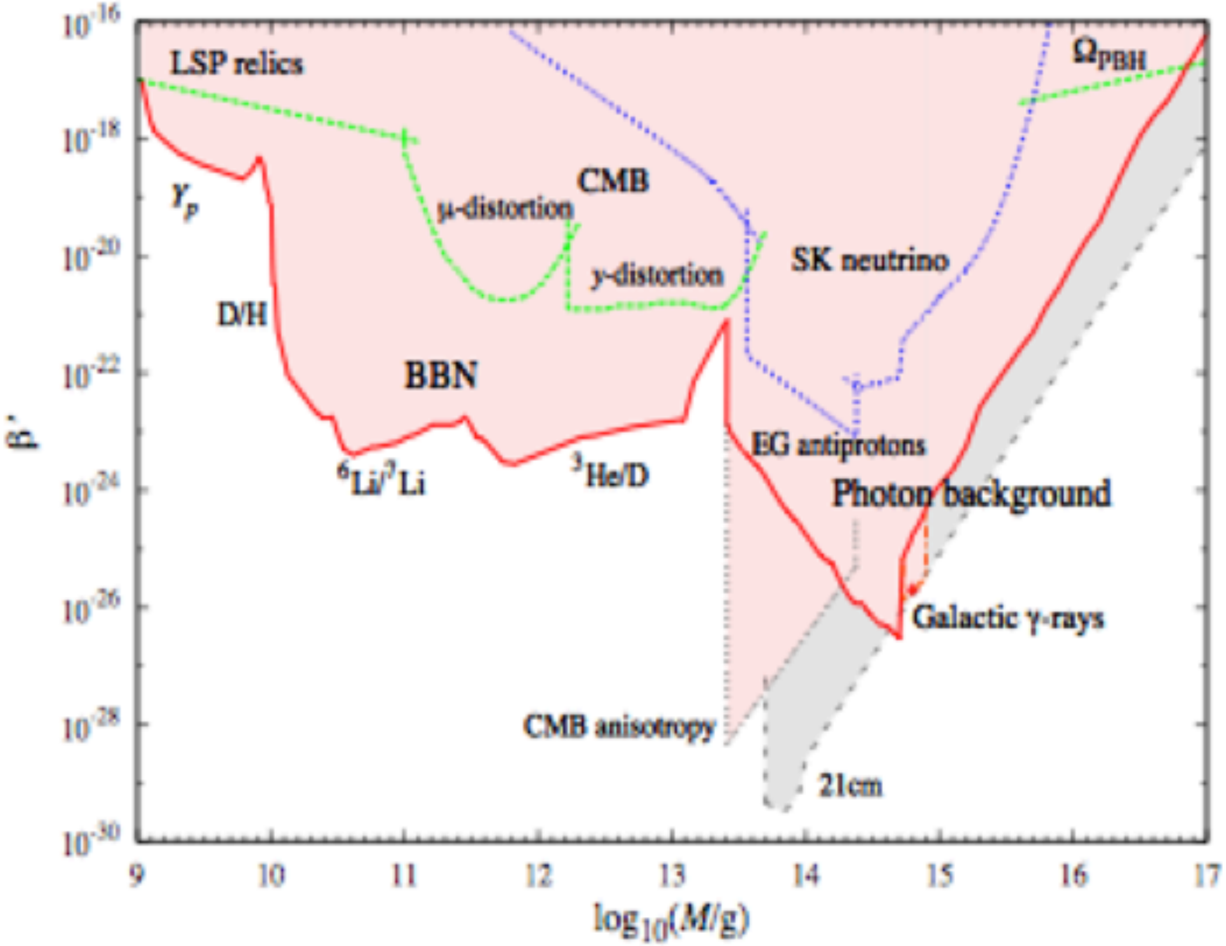
Gamma-ray background

Extragalactic cosmic rays

Neutrino relics

LSP relics

CMB distortions

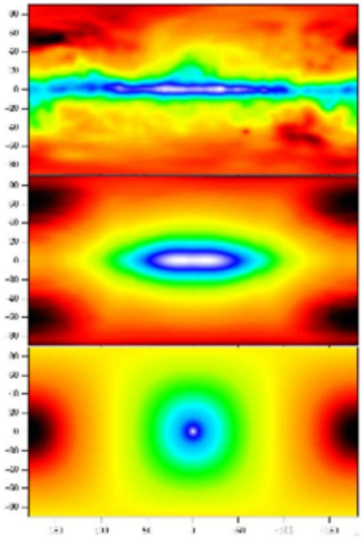


PHYSICAL REVIEW D **94,** 044029 (2016)

Constraints on primordial black holes from the Galactic gamma-ray background

B. J. Carr,[1,2,*] Kazunori Kohri,[3,†] Yuuiti Sendouda,[4,‡] and Jun'ichi Yokoyama[2,5]

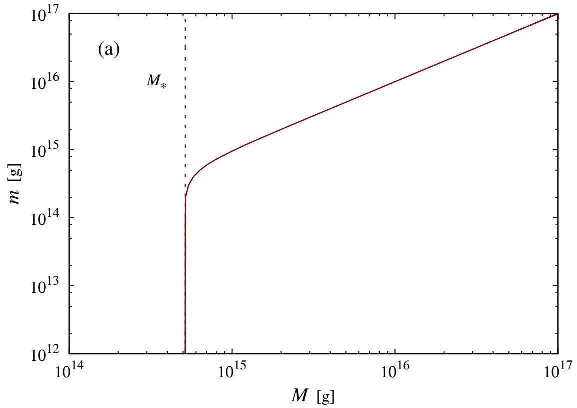
arXiv: 1604.05349



- Must distinguish between initial mass M and current mass m

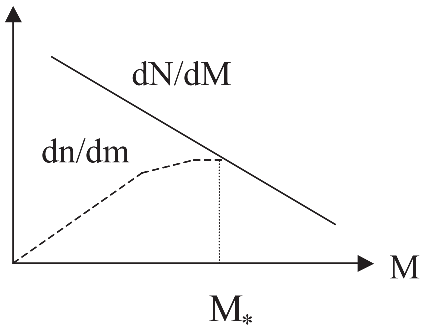
$$M = M_* \, (1+\mu) \,, \qquad q \equiv M_{\rm q}/M_* = 0.3 \qquad q^3/(3\,\alpha) = 0.005$$

$$m = \begin{cases} \left[(\mu+1)^3 - 1 + (1-\alpha^{-1})\, q^3\right]^{1/3} M_* & (\mu \geq \mu_{\rm c}) \\ (3\,\alpha\,\mu)^{1/3}\,(1+\mu+\mu^2/3)^{1/3}\, M_* & (0 \leq \mu \leq \mu_{\rm c}) \end{cases}$$



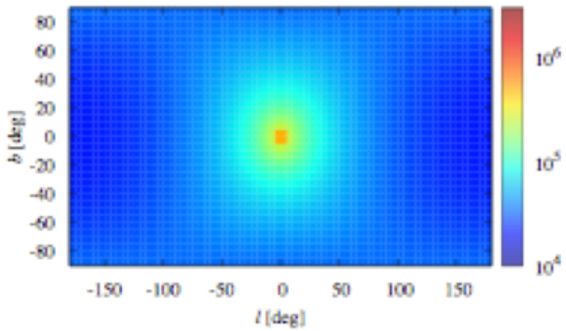
- Must distinguish between initial and current mass function

$$\frac{{\rm d}n}{{\rm d}m} = \begin{cases} \frac{1}{\alpha}\left(\frac{m}{M_*}\right)^2 \left(\frac{{\rm d}n}{{\rm d}M}\right)_* & (m < M_{\rm q}) \\ \left(\frac{m}{M_*}\right)^2 \left(\frac{{\rm d}n}{{\rm d}M}\right)_* & (M_{\rm q} < m < M_*) \\ \frac{{\rm d}n}{{\rm d}M} & (m > M_*)\,. \end{cases}$$



Main GRB contribution from dn/dm ~ m^2 low mass tail

- Must specific density profile of halo and direction of observation

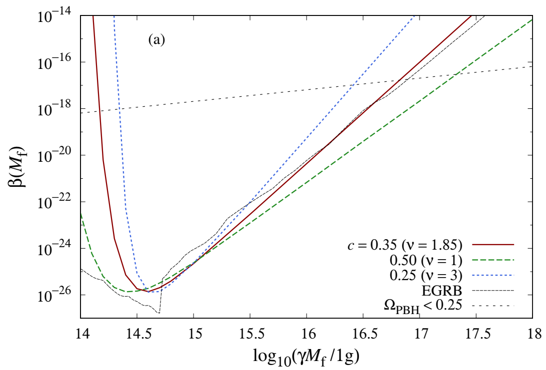


$$\rho_{\rm PBH}(R) = \frac{f\,\rho_{\rm s}}{(R/R_{\rm s})^{\gamma}\,[1+(R/R_{\rm s})^{\alpha}]^{(\beta-\alpha)/\alpha}}$$

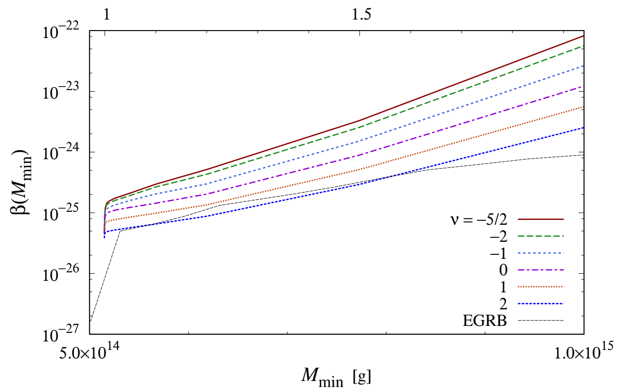
$$g(\boldsymbol{n}) = \frac{1}{r_{\rm gal}}\int_0^{r_{\rm gal}} {\rm d}r\,\frac{\rho_{\rm PBH}(R(\boldsymbol{n},r))}{\bar{\rho}_{\rm PBH}}$$

- Obtain constraints on β(M) required by Galactic background

Critical IMF



Extended IMF

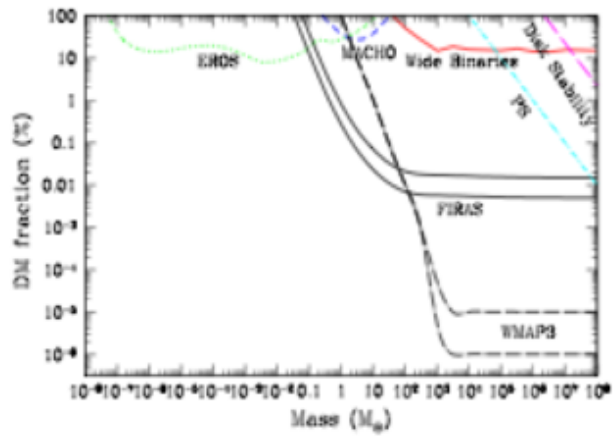


See also earlier calculations of Wright (1996),and Lehoucq et al. (2009)

ACCRETION CONSTRAINTS ON LARGE PBHS

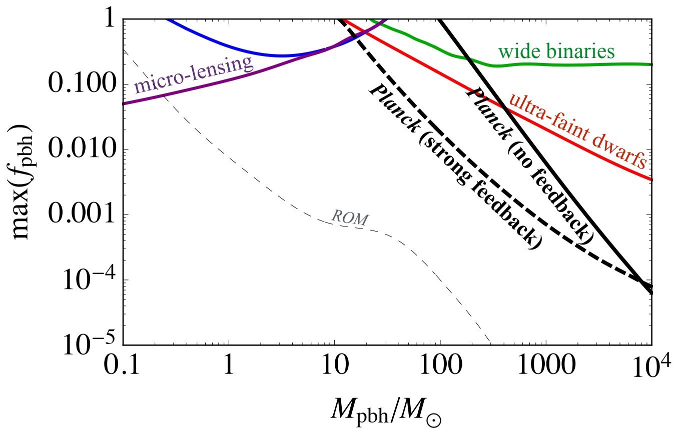
Ricotti et al. (2008)

PBH accretion => X-rays
=> CMB spectrum/anisotropies
=> FIRAS/WMAP limits



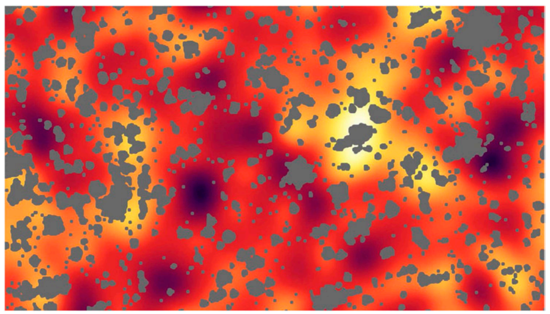
Ali-Haimoud & Kamionkowski
arXiv:1612.05644

Only exclude PBHs
larger than 100 M_{O}



Kashlinsky
arXiv:1605.04023

PBHs generate early structure
and infrared background



“EM probes PBHs as dark matter” (white paper) arXiv:1903.04424

PRIMORDIAL BLACK HOLES AS DARK MATTER

PRO

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

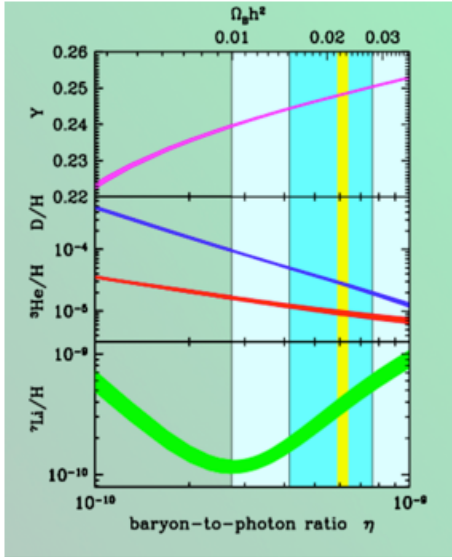
CON

* Requires fine-tuning

PBH can do it!

PRIMORDIAL BLACK HOLES AS DARK MATTER

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



$\Omega_{vis} = 0.01, \Omega_{dm} = 0.25 \Rightarrow$ need baryonic and non-baryonic DM

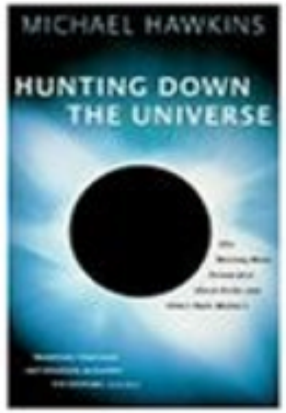
MACHOs WIMPs

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

Evidence for dark matter in the form of compact bodies

Michael Hawkins
University of Edinburgh

1993



Evidence for Microlensing of QSOs

- Lack of time dilation.
- Symmetry of variation.
- Achromatic variation.
- Microlensing in multiply lensed quasars
- Caustic features in light curves
- Slope of structure function

The timescale of variation implies that the mass of the microlensing bodies is around 0.1 $M_\odot$

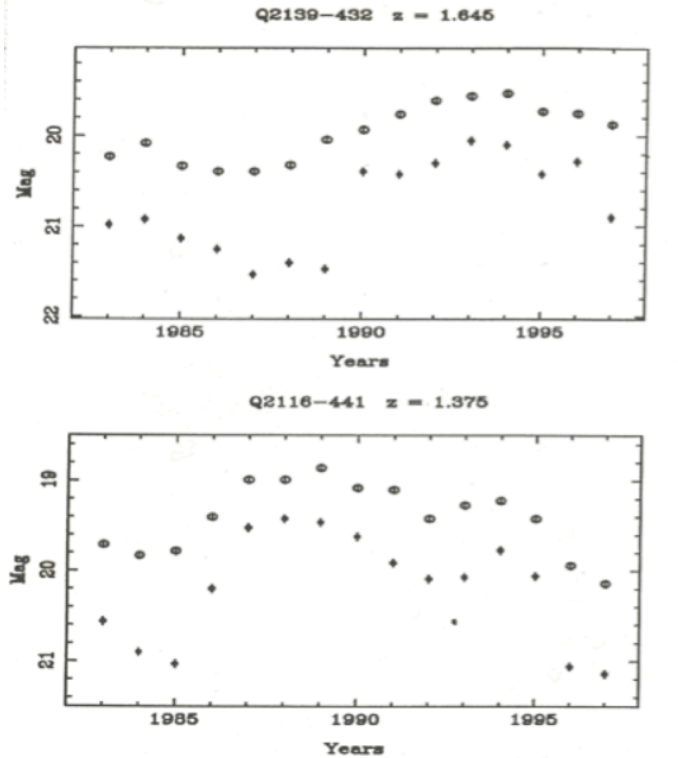
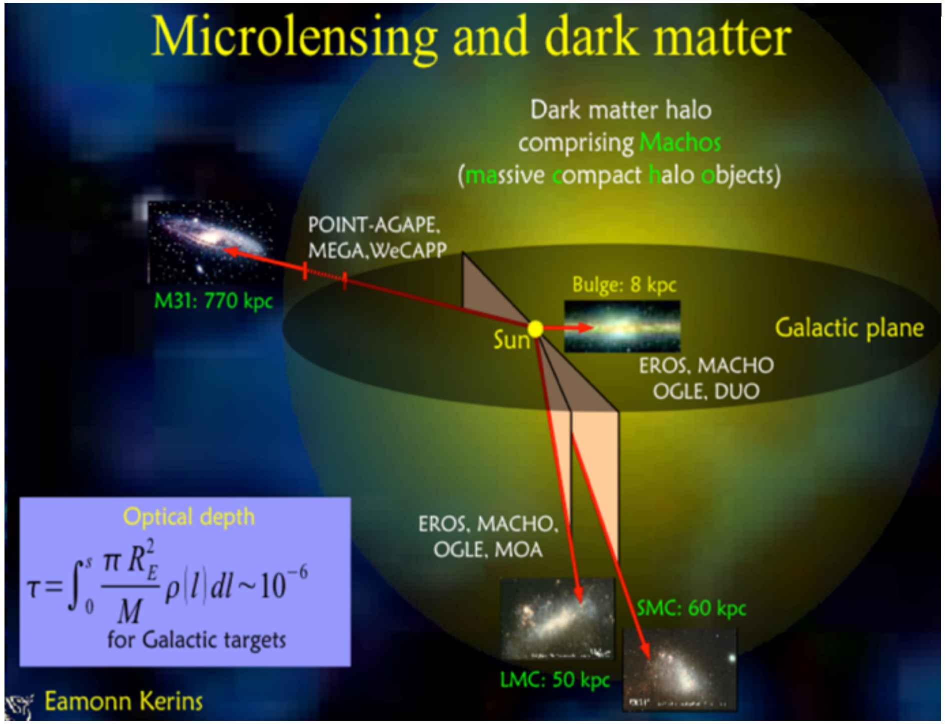


Fig. 3. Light curves for two quasars showing all the characteris expected of caustic crossing events. Symbols as for Fig. 1.

Hawkins now gives mass as 1 M_O



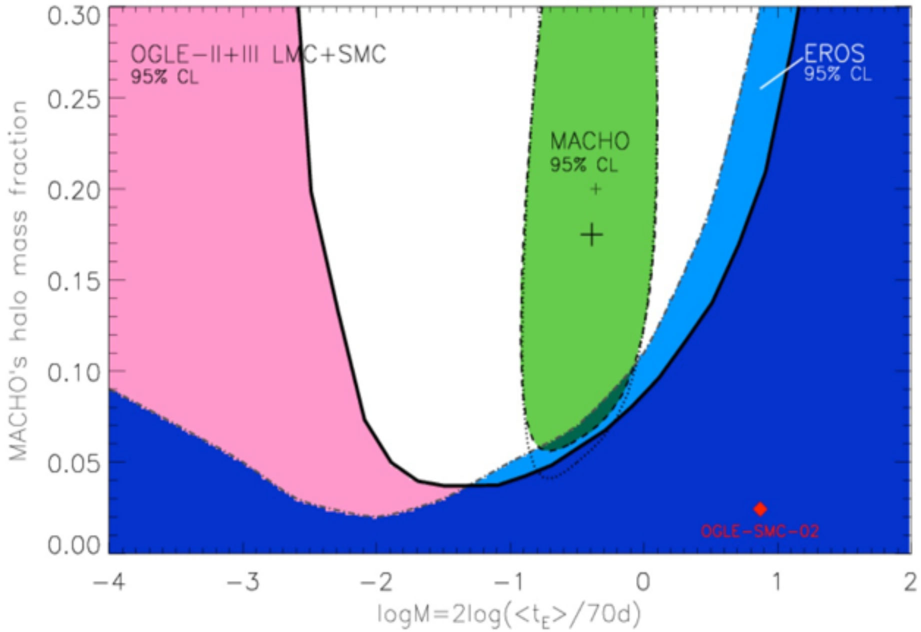


Image credit: Wyrzykowski et al., 2011, MNRAS, (astro-ph/1106.2925).

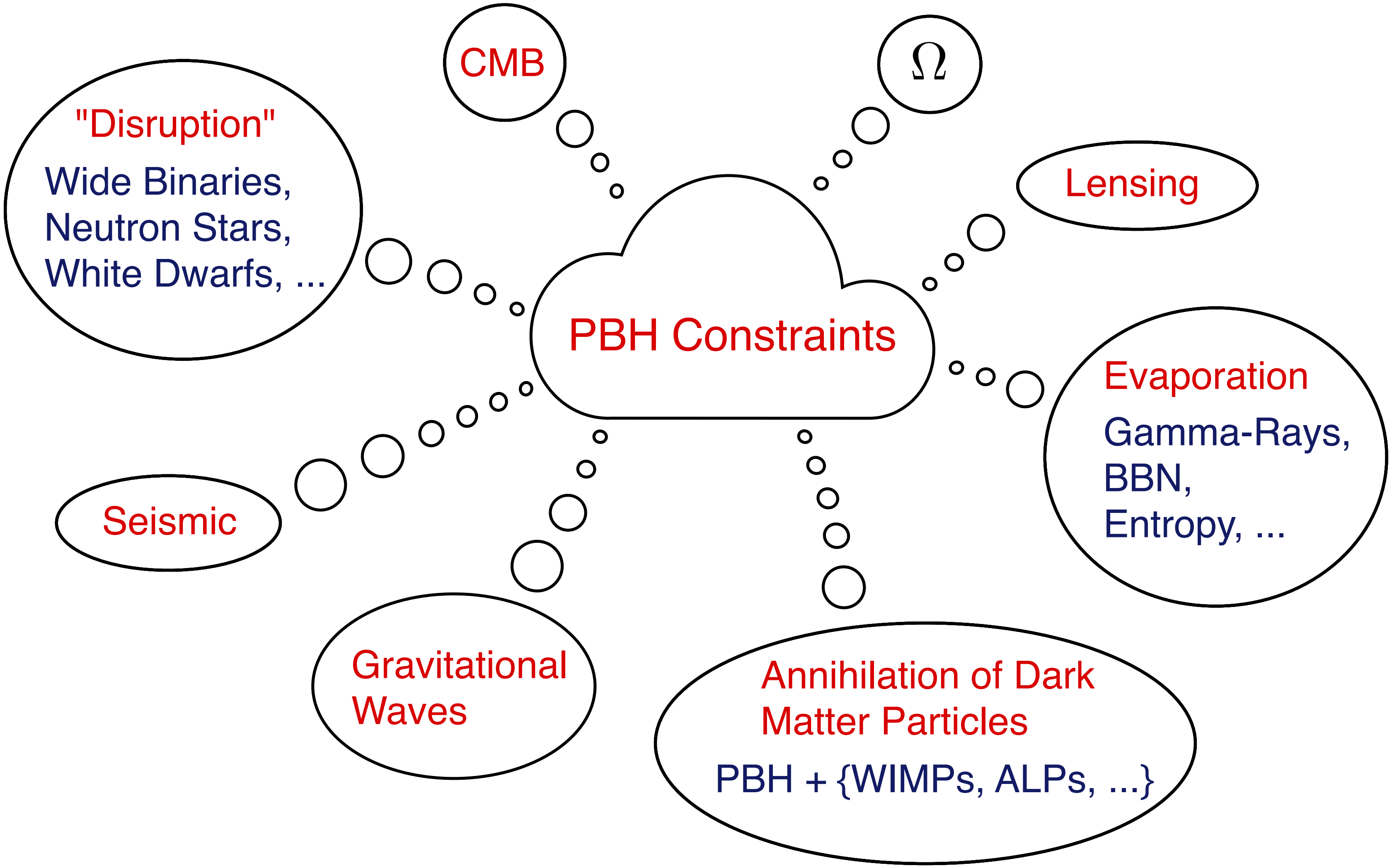
Early microlensing searches suggested MACHOs with 0.5 M_O

=> 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

(Kuhnel)

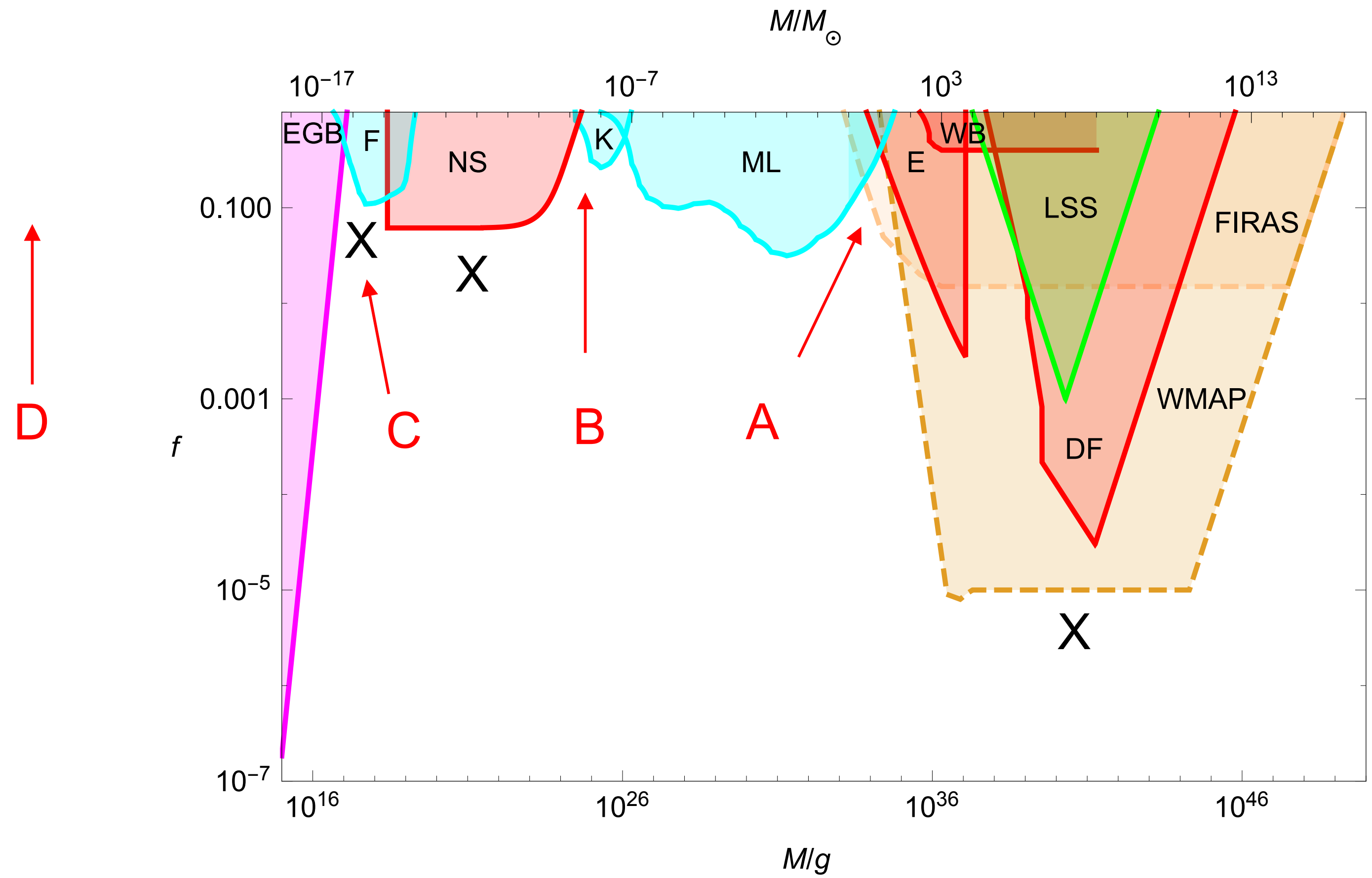


CMB
Ω
"Disruption"
Wide Binaries,
Neutron Stars,
White Dwarfs, ...
Lensing
PBH Constraints
Evaporation
Gamma-Rays,
BBN,
Entropy, ...
Seismic
Gravitational
Waves
Annihilation of Dark
Matter Particles
PBH + {WIMPs, ALPs, ...}

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) intermedate mass; (B) sublunar mass; (C) asteroid mass.

Also (D) Planck mass relics?

But some of these limits are now thought to be wrong

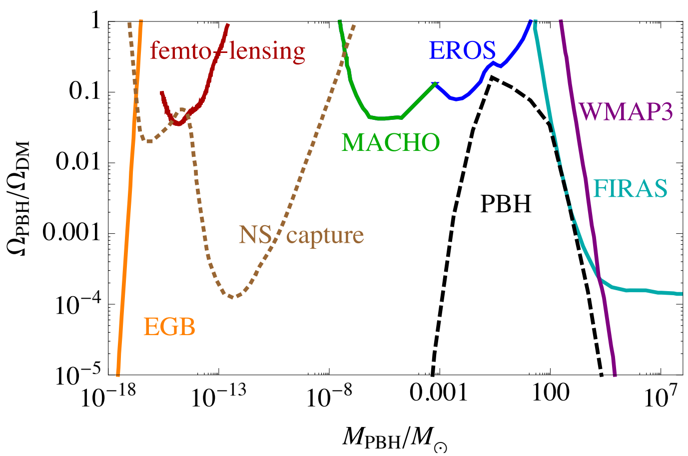
WHICH MASS WINDOW IS MOST PLAUSIBLE?

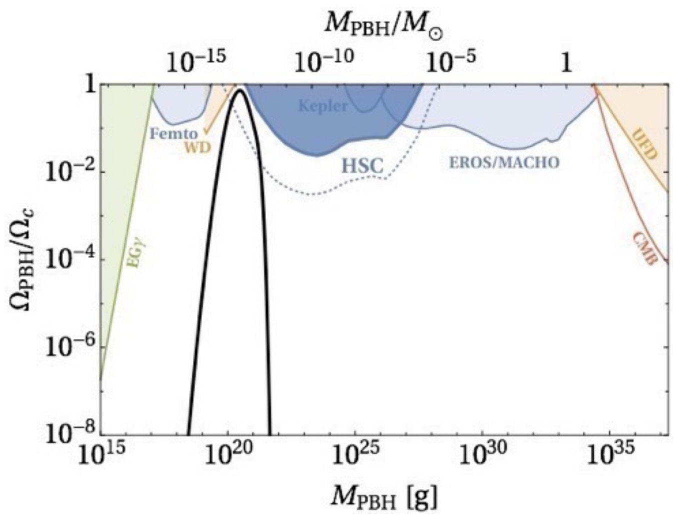
PBH dark matter @10 M_o
from hybrid inflation

Clesse & Garcia-Bellido
arXiv:1501.07565

PBH dark matter @10^{20}g
from double inflation

Inomata et al
arXiv:1701.02544





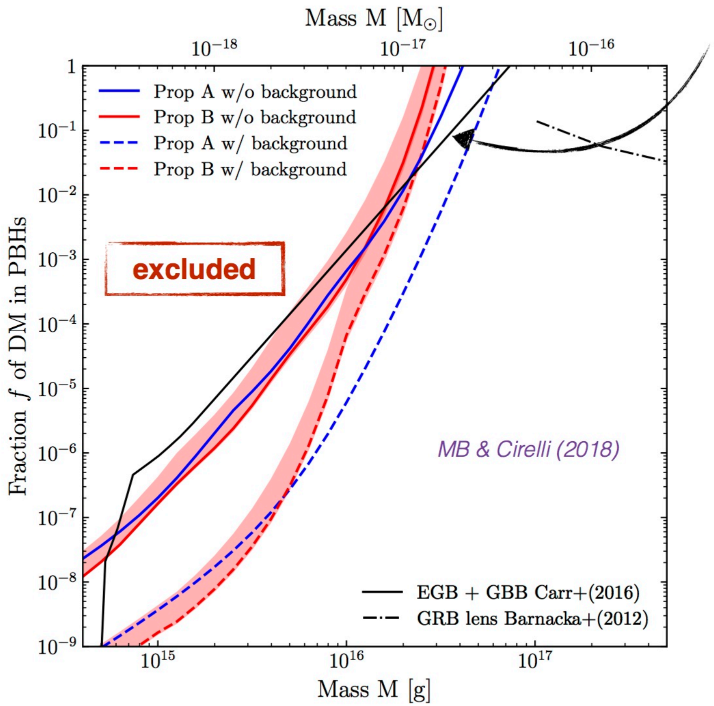
cf. light versus heavy dark matter particle

SOME NEW RECENT CONSTRAINTS

VOYAGER-1 $e^{\pm}$ further constrain Primordial Black Holes as Dark Matter

Mathieu Boudaud[1] and Marco Cirelli[1]

arXiv:1807.03075



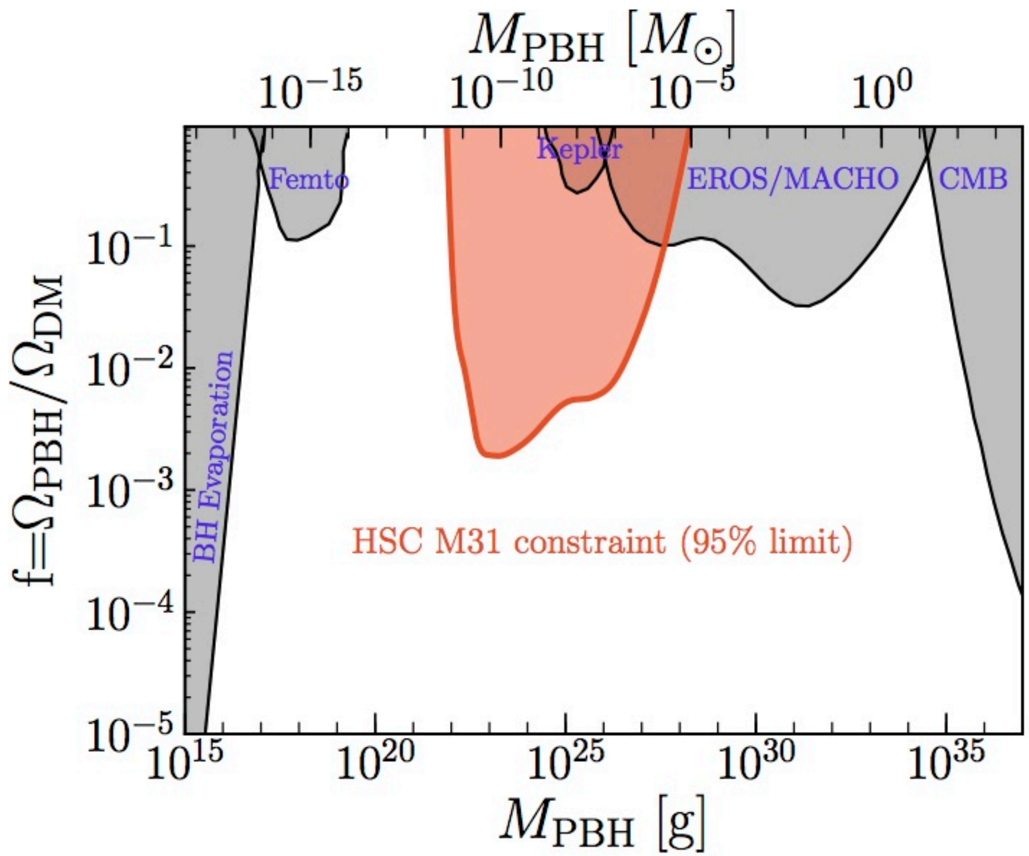
- EGB limits (Fermi-LAT) *Carr+(2010)*
- red band: propagation uncertainty (magnetic halo size) $4 < L < 20$ kpc *Reinert & Winkler(2018)*
- even better assuming a background for Voyager-1 data (SNRs e^-)

$$\Phi_{e^-}(E) \propto E^{-1.3}$$

Microlensing constraints on primordial black holes with the Subaru/HSC Andromeda observation

Hiroko Niikura[1,2], Masahiro Takada[1], Naoki Yasuda[1], Robert H. Lupton[3], Takahiro Sumi[4], Surhud More[1,5], Toshiki Kurita[1,2], Sunao Sugiyama[1,2], Anupreeta More[1], Masamune Oguri[1,2,6], Masashi Chiba[7]

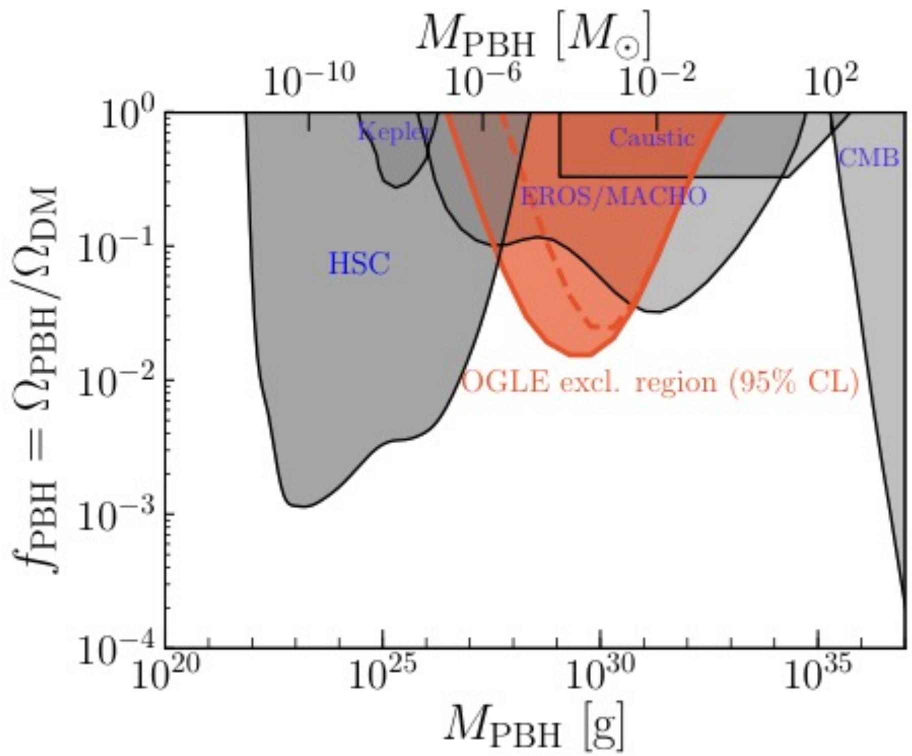
arXiv:1701.02151



Earth-mass black holes? – Constraints on primordial black holes with 5-years OGLE microlensing events

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

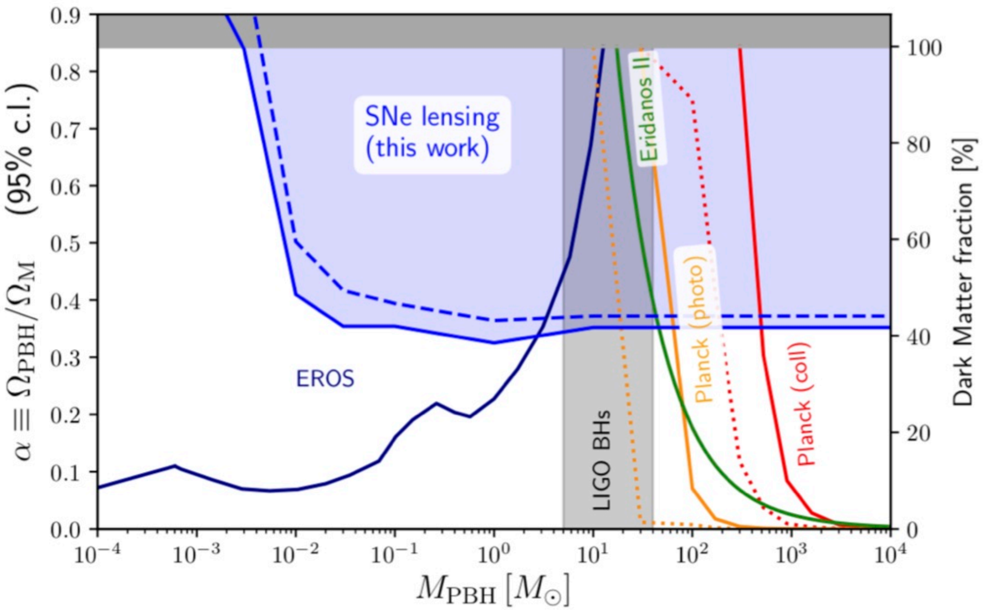
arXiv:1901.07120



Limits on stellar-mass compact objects as dark matter from gravitational lensing of type Ia supernovae

Miguel Zumalacárregui[1, 2, 3, *] and Uroš Seljak[1, 4, †]

arXiv:1712.02240

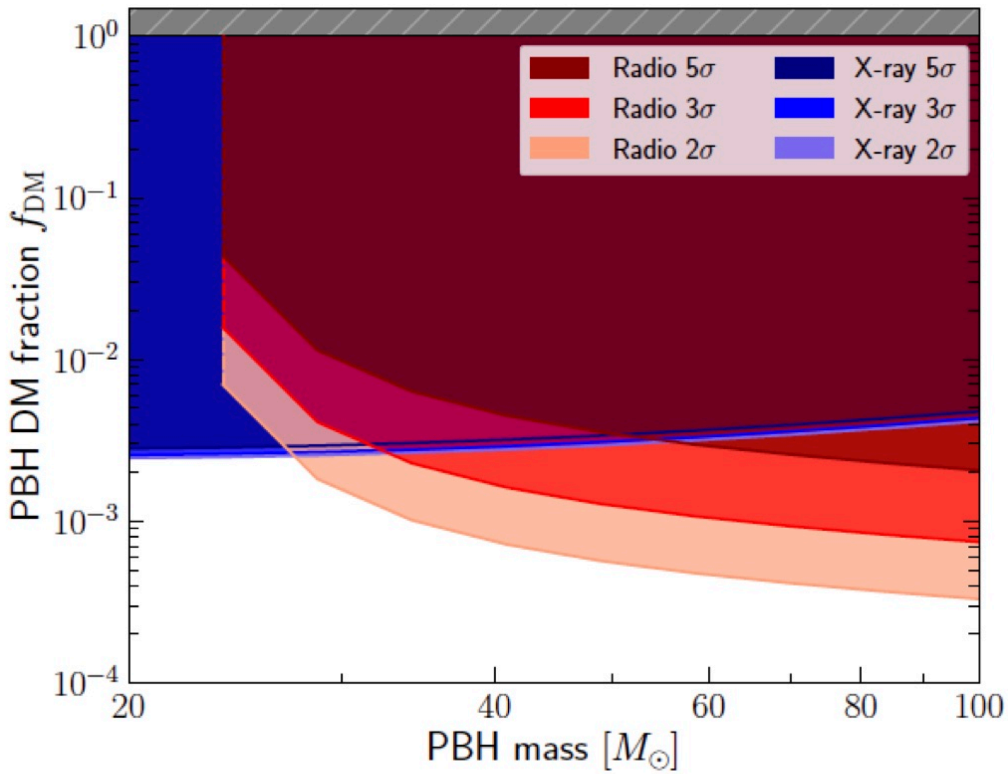


But PBHs can evade these limits   Garcia-Bellido et al, arXiv:1712.06574

Multi-wavelength astronomical searches for primordial black holes

Julien Manshanden[a,b] Daniele Gaggero[a,c] Gianfranco Bertone[a]
Riley M. T. Connors[d] Massimo Ricotti[e]

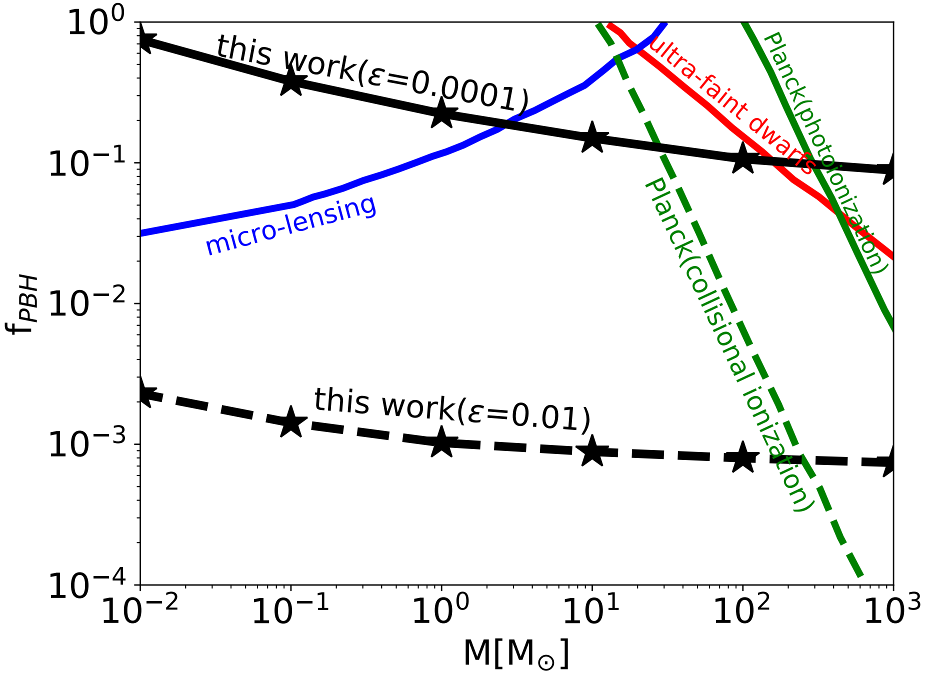
arXiv:1812.07967



Sunyaev-Zel'dovich anisotropy due to Primordial black holes

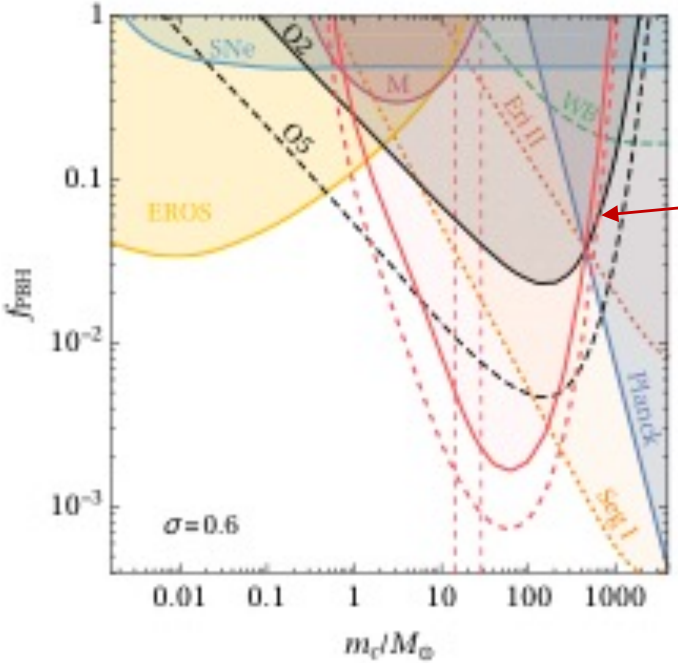
Katsuya T. Abe,* Hiroyuki Tashiro, and Toshiyuki Tanaka

arXiv:1901.06809



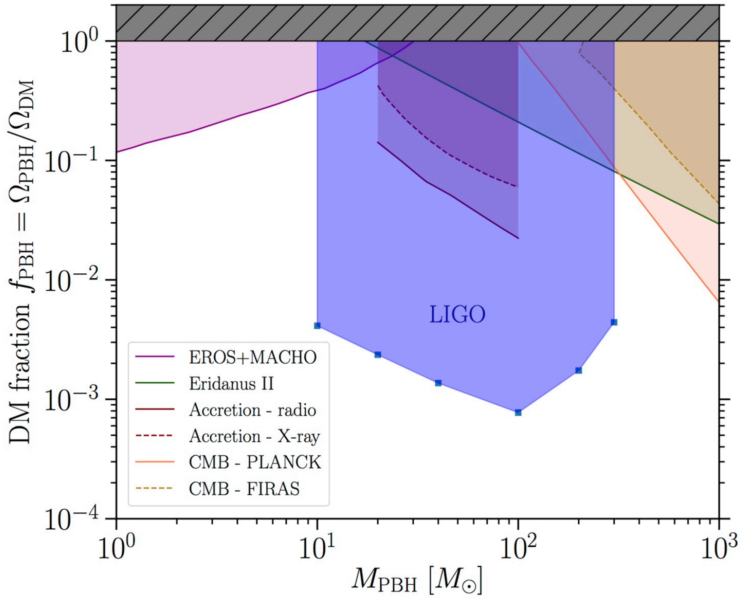
LIGO CONSTRAINTS

Raidal et al.
arXiv:1812.01930

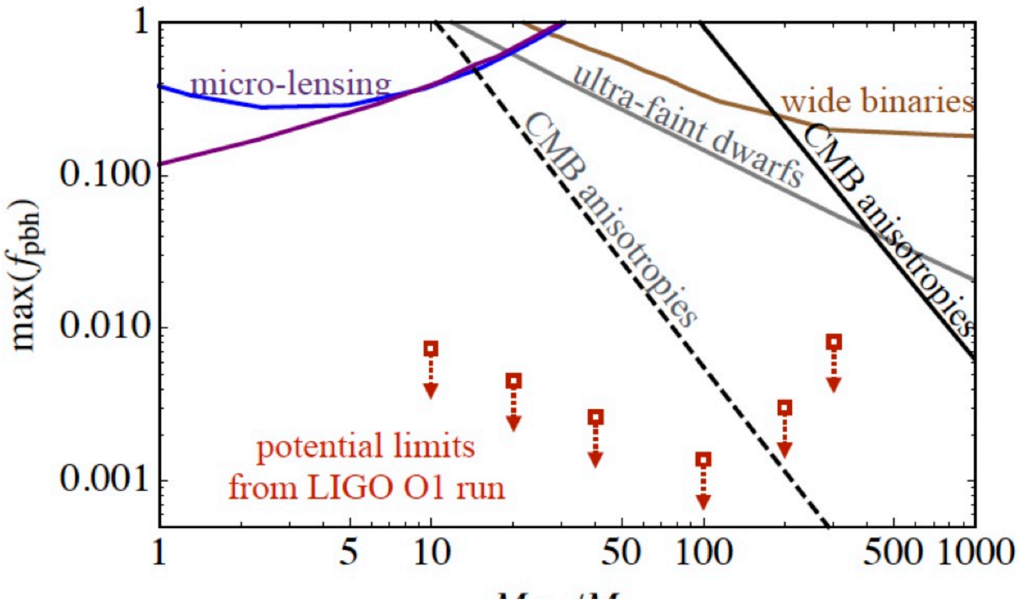


LIGO
limit

Kavanagh et al
arXiv:1805.09034



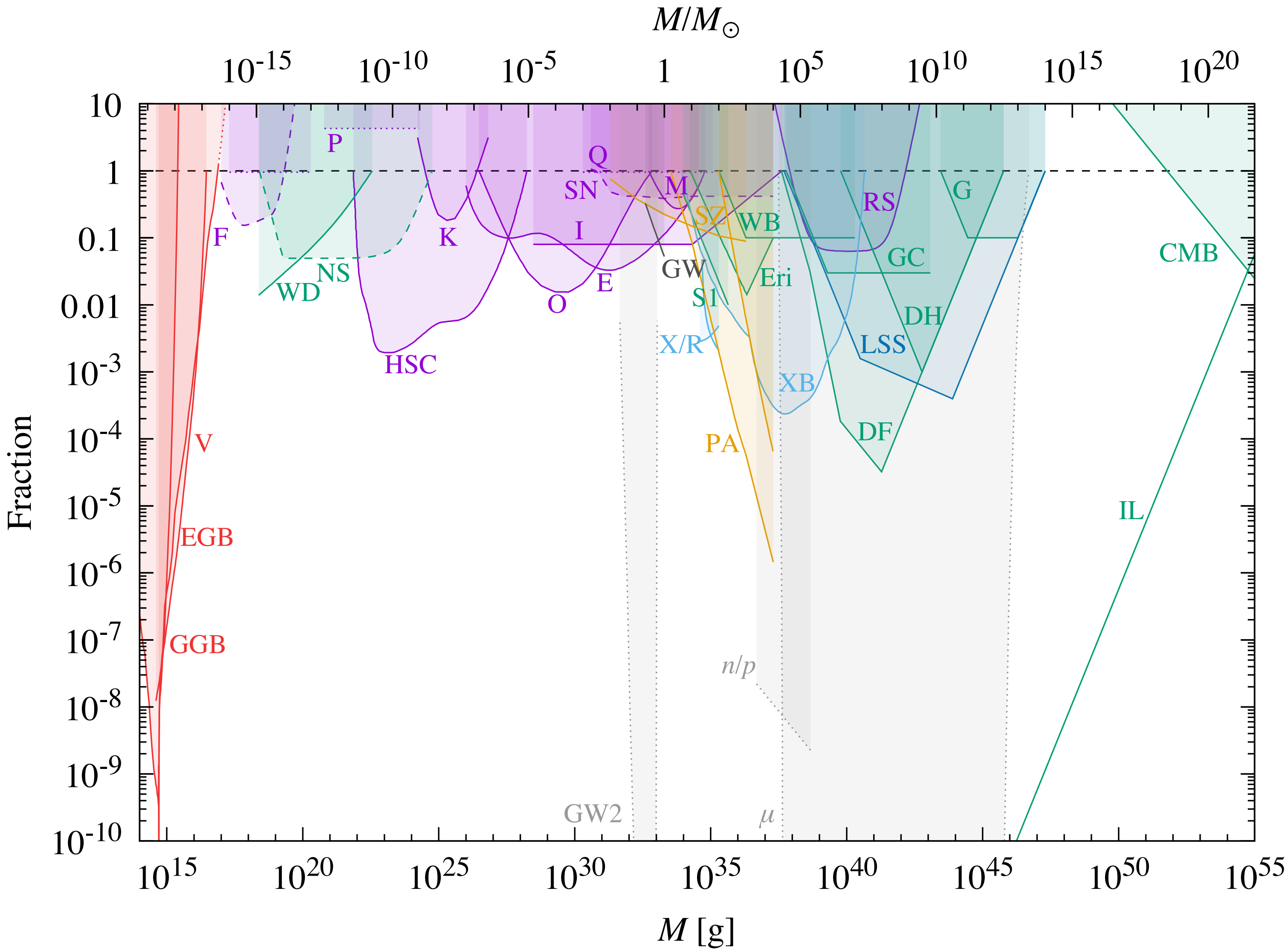
Ali-Haimoud et al.
arXiv:1609.06576



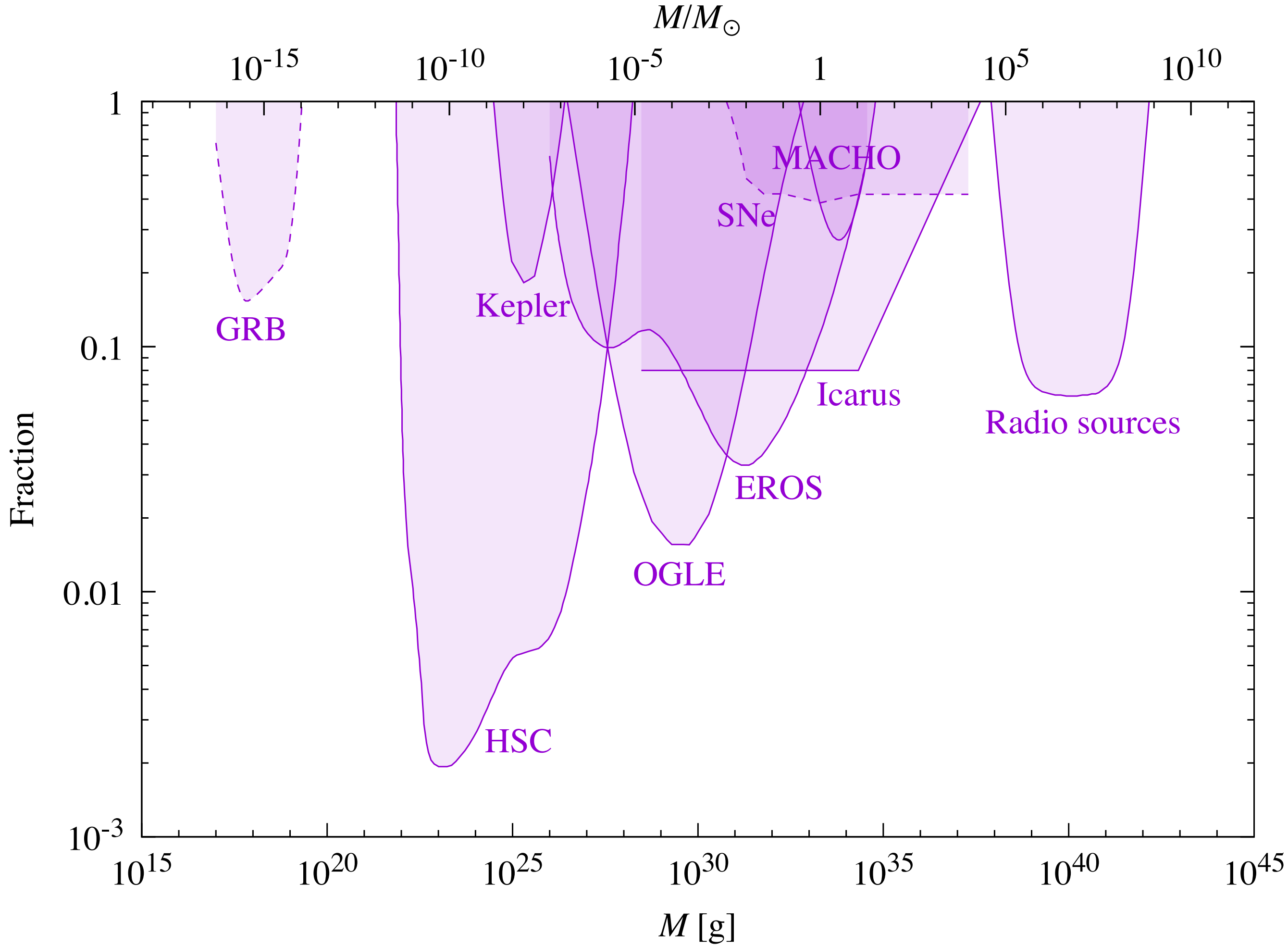
CONSTRAINTS ON PRIMORDIAL BLACK HOLES

Bernard Carr,[1,2,*] Kazunori Kohri,[3,†] Yuuiti Sendouda,[4,‡] and Jun'ichi Yokoyama[2,5,§]

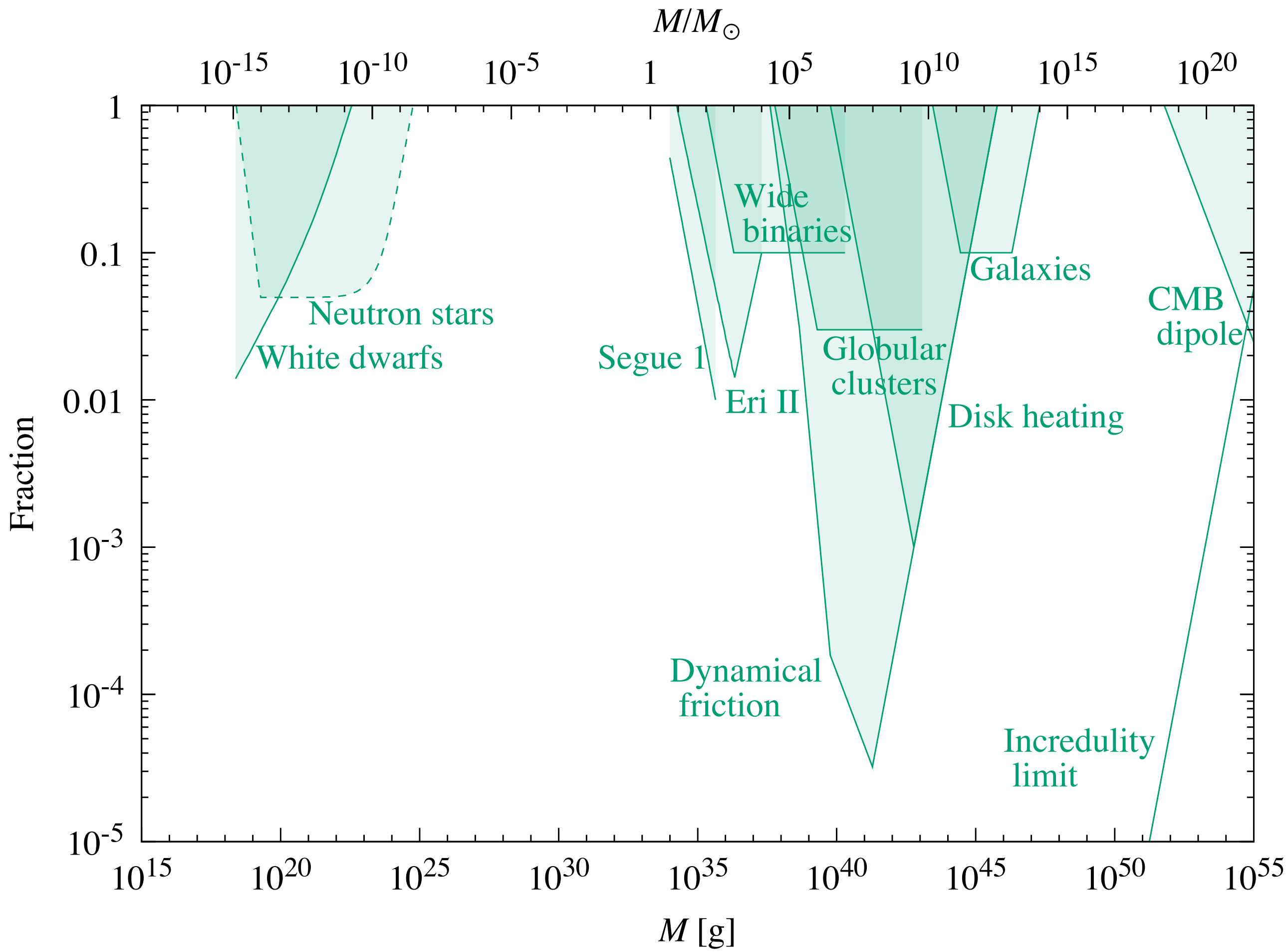
Progress Theoretical Physics (2019)



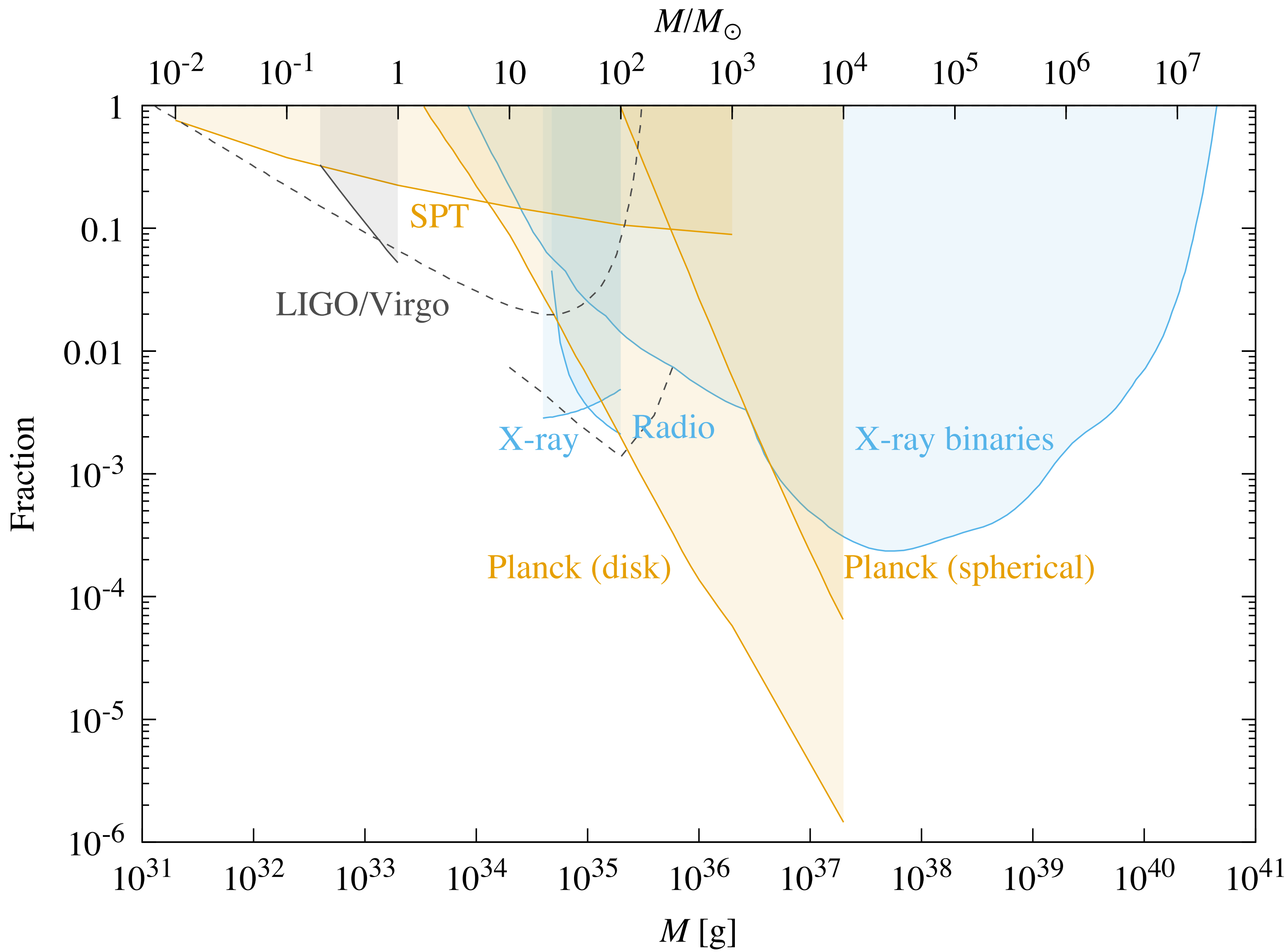
LENSING LIMITS



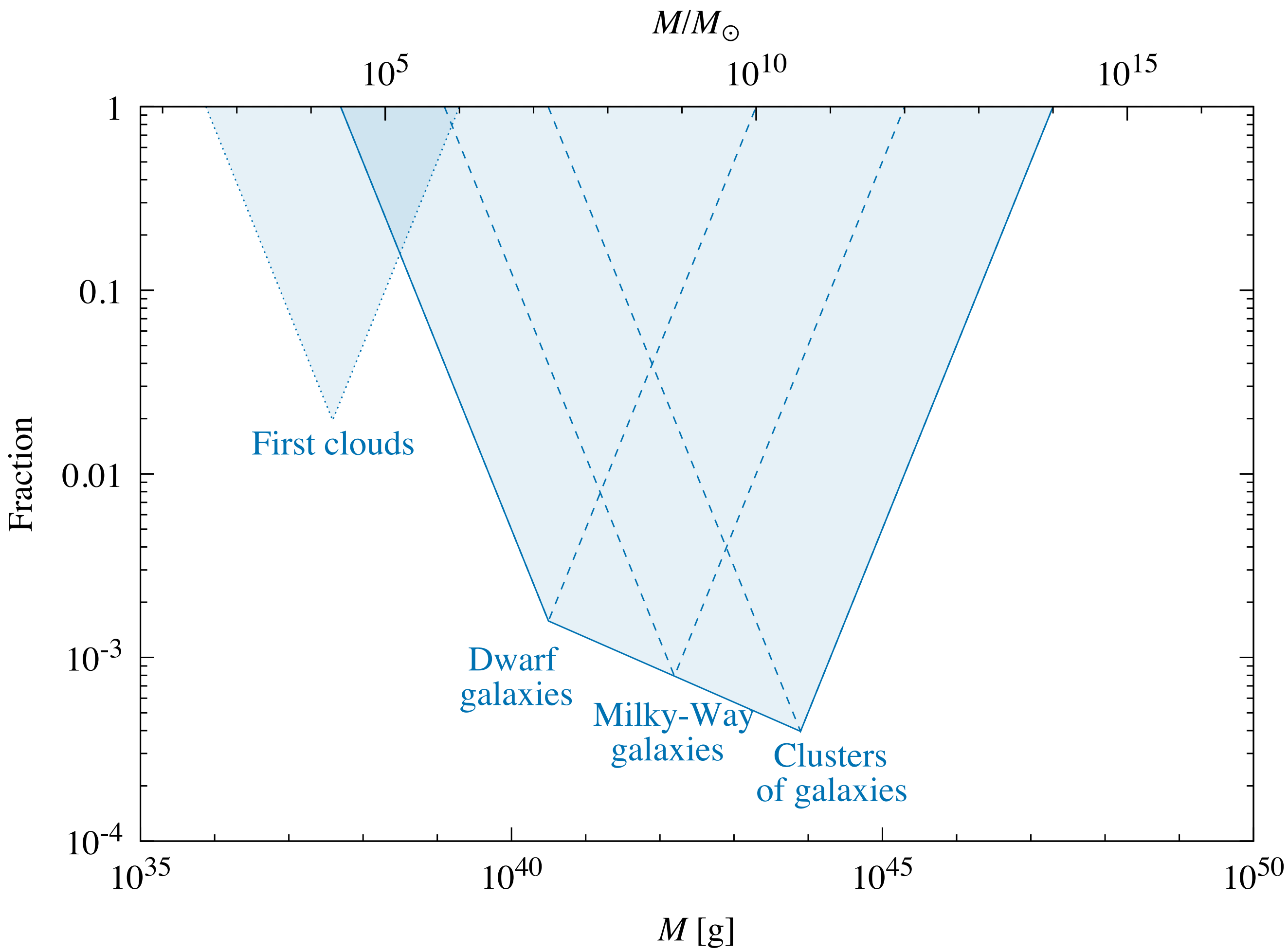
DYNAMICAL LIMITS



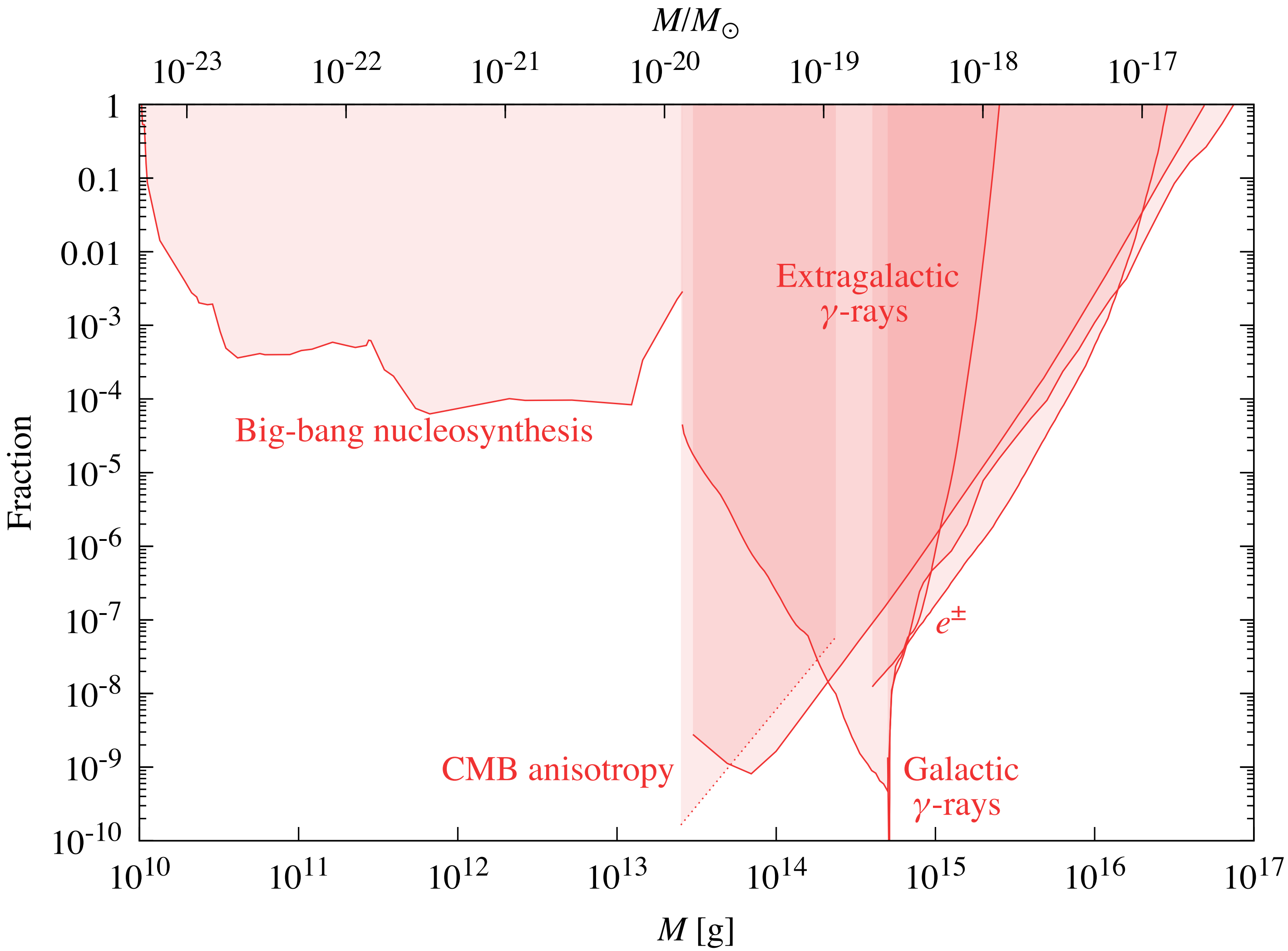
ACCRETION AND LIGO LIMITS



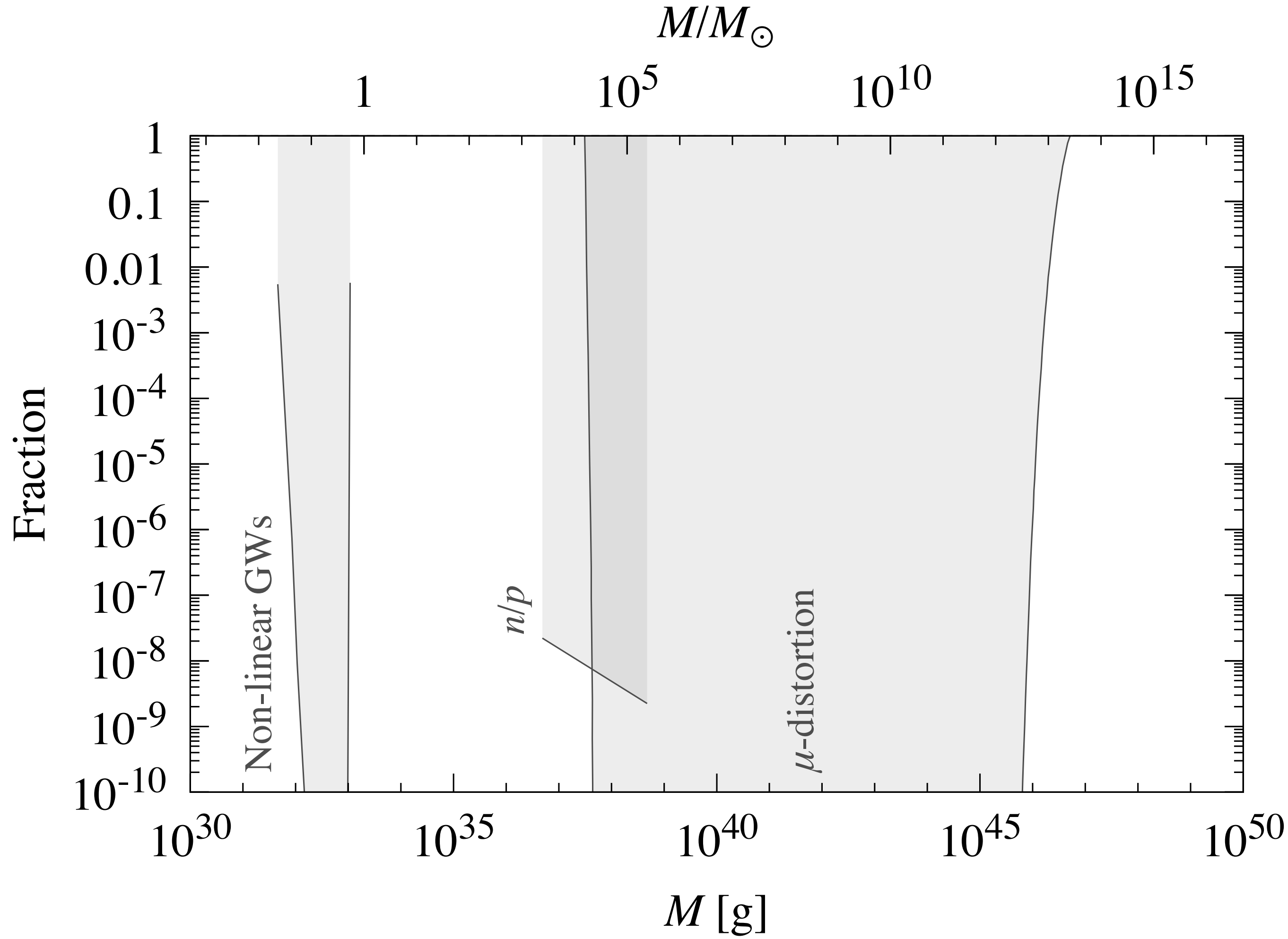
LARGE-SCALE STRUCTURE LIMITS



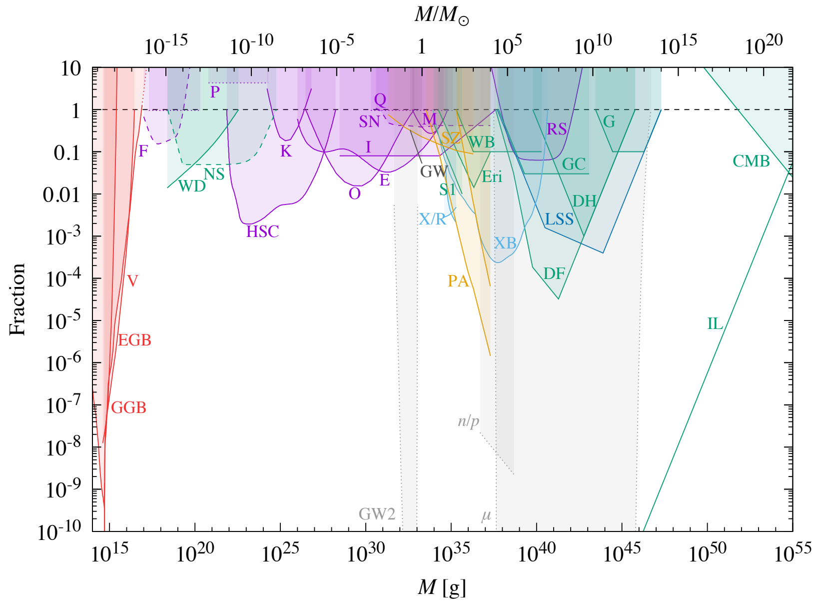
EVAPORATION LIMITS

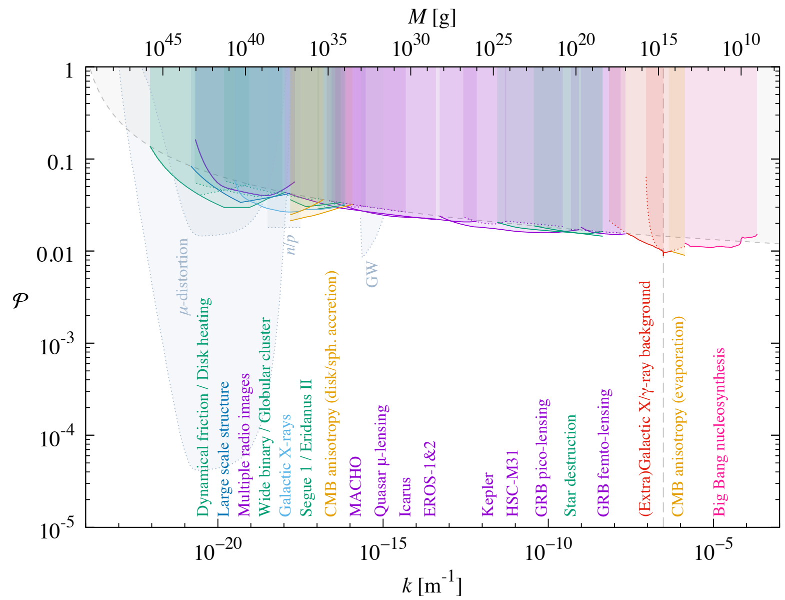


COSMOLOGICAL LIMITS



CONSTRAINTS ON POWER SPCTRUM





These constraints are not just nails in a coffin!

All constraints have caveats and may change

Each constraint is a potential signature

PBHs are interesting even if $f << 1$

CKS 2016

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)

Possible PBH mass functions $\psi(M) \propto M \frac{\mathrm{d}n}{\mathrm{d}M}$ => $\frac{\Omega_{\mathrm{PBH}}}{\Omega_{\mathrm{DM}}} = \int \mathrm{d}M\, \psi(M)$

lognormal $\psi(M) = \frac{f_{\mathrm{PBH}}}{\sqrt{2\pi}\sigma M} \exp\left(-\frac{\log^2(M/M_c)}{2\sigma^2}\right)$

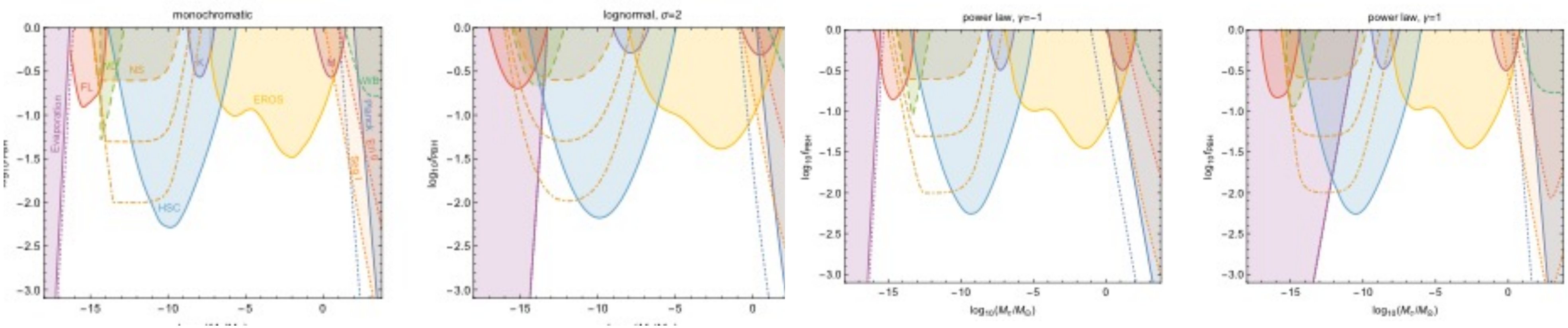
2 parameters (M_c,σ)

power-law $\psi(M) \propto M^{\gamma-1} \quad (M_{\min} < M < M_{\max})$

critical collapse $\psi(M) \propto M^{2.85} \exp(-(M/M_f)^{2.85})$

f(M) limits themselves depend on PBH mass function

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



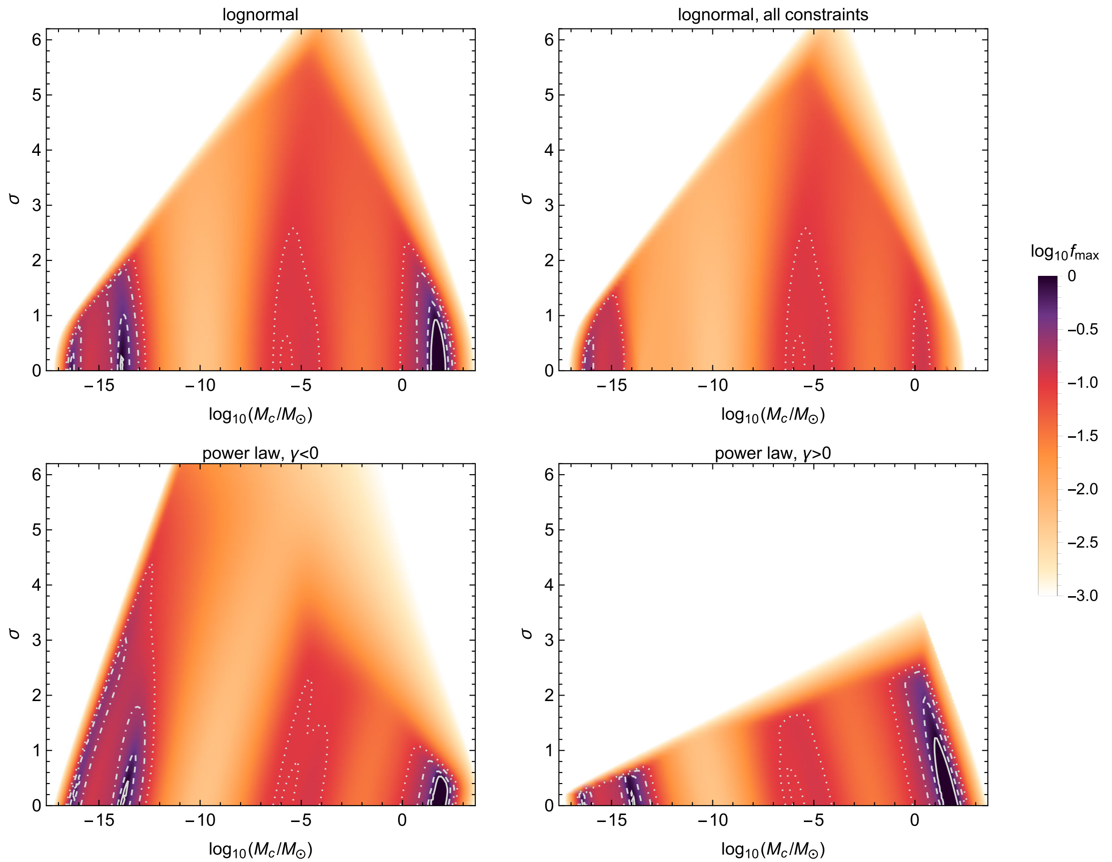
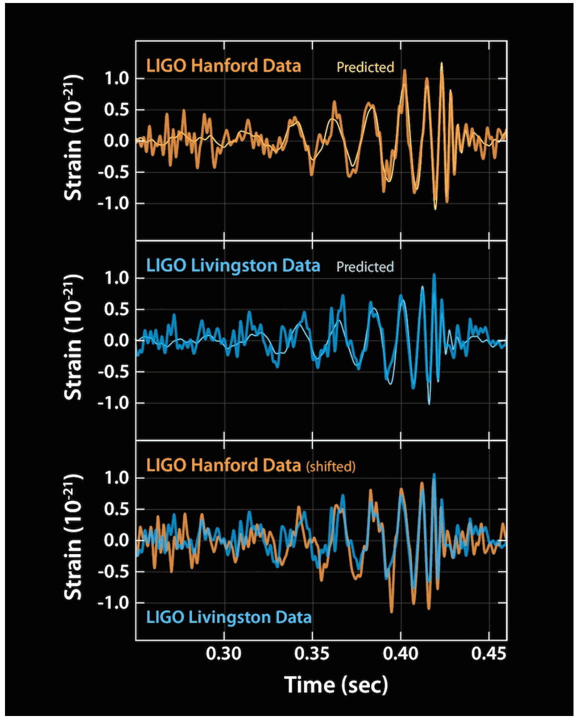


FIG. 2. Upper panels: Combined observational constraints on M_c and σ for a lognormal PBH mass function. The color coding shows the maximum allowed fraction of PBH DM. In the white region $\log_{10} f_{\max} < -3$, while the solid, dashed, dot-dashed, and dotted contours correspond to $f_{\max} = 1$, $f_{\max} = 0.5$, $f_{\max} = 0.2$, and $f_{\max} = 0.1$, respectively. In the left panel only the constraints depicted by the solid lines in Fig. 1 are included, whereas the right panel includes all the constraints. Lower panels: Same as the upper left panel but for a power-law mass function with $\gamma < 0$ (left) and $\gamma > 0$ (right).

cf. Green (2016), Kuhnel & Freese (2017)

Properties of the binary black hole merger GW150914

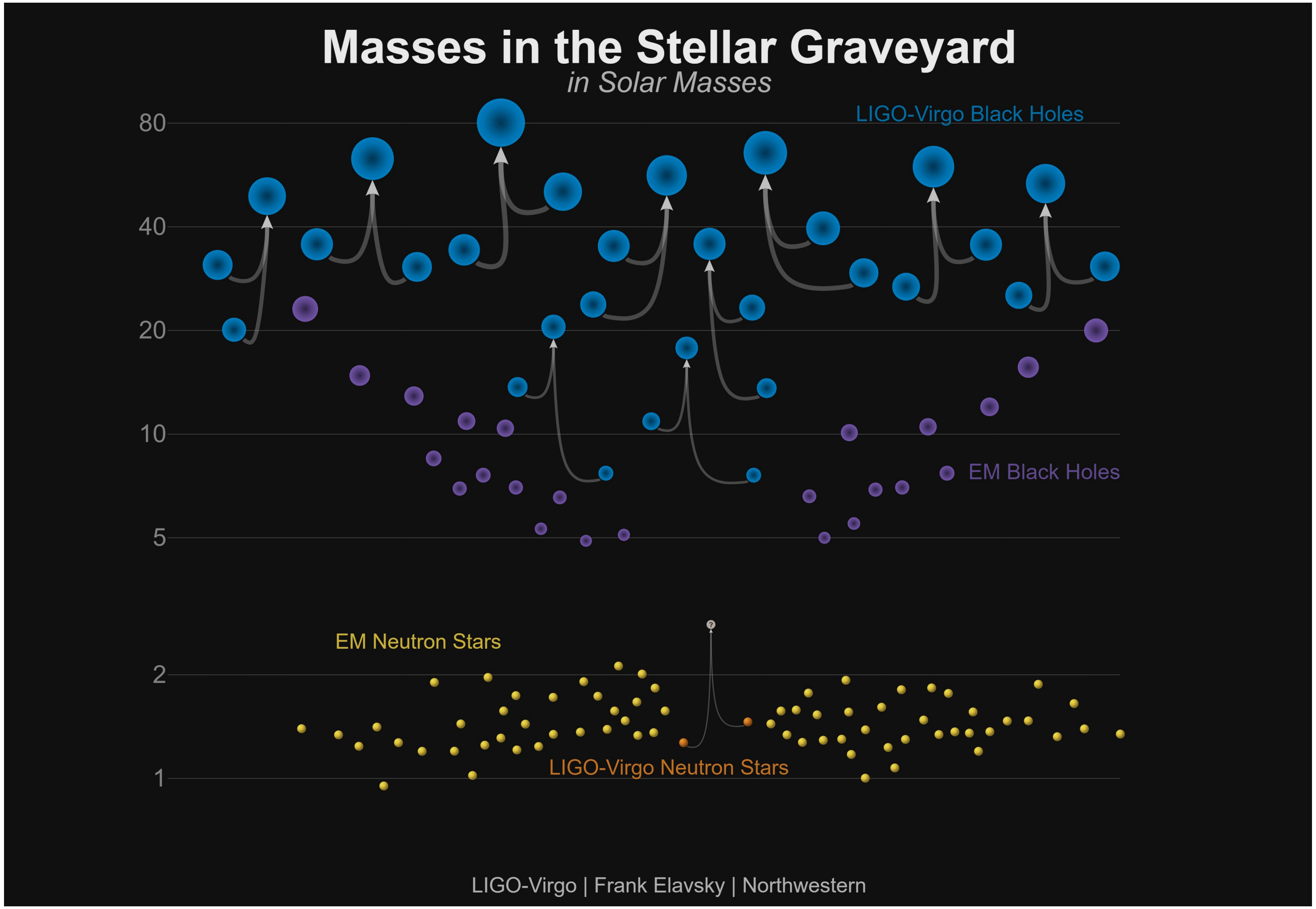
The LIGO Scientific Collaboration and The Virgo Collaboration



$$36^{+5}_{-4}\ \mathrm{M}_\odot + 29^{+4}_{-4}\ \mathrm{M}_\odot \longrightarrow 62^{+4}_{-4}\ \mathrm{M}_\odot$$

Largest is now 80 $M_\odot$ which is nearly in IMBH range

PBHS AND LIGO/Virgo



Do we need Population III or primordial BHs?

Did LIGO detect dark matter?

Simeon Bird,* Ilias Cholis, Julian B. Muñoz, Yacine Ali-Haïmoud, Marc Kamionkowski, Ely D. Kovetz, Alvise Raccanelli, and Adam G. Riess[1]

arXiv:1603.00464

Dark matter in 20-100 M_O binaries may provide observed rate of 2-53 $Gpc^{-1}yr^{-1}$

The clustering of massive PBHs as dark matter…….

S. Clesse and J. Garćıa-Bellido,

arXiv:1603.05234

Measuring the PBH mass distribution with advanced LIGO

Primordial Black Hole Scenario for the Gravitational-Wave Event GW150914

Misao Sasaki,[1] Teruaki Suyama,[2] Takahiro Tanaka,[3,1] and Shuichiro Yokoyama[4]

arXiv:1603.08338

Only need small f and comparable to limits from CMB distortion

LIGO gravitational wave detection, primordial black holes and the near-IR cosmic infrared background anisotropies

A. Kashlinsky[1],

arXiv:1605.04023

PBHs may generate early structure and infrared background

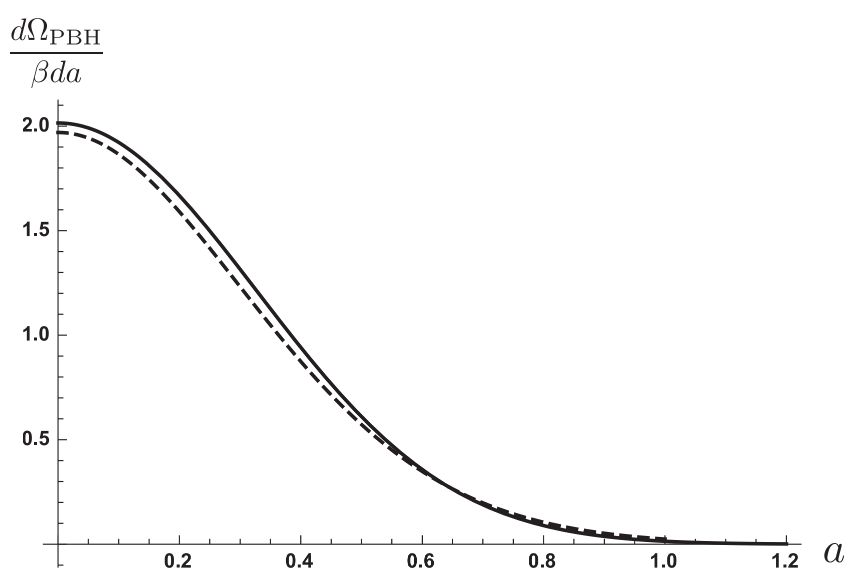
Spin Distribution of Primordial Black Holes

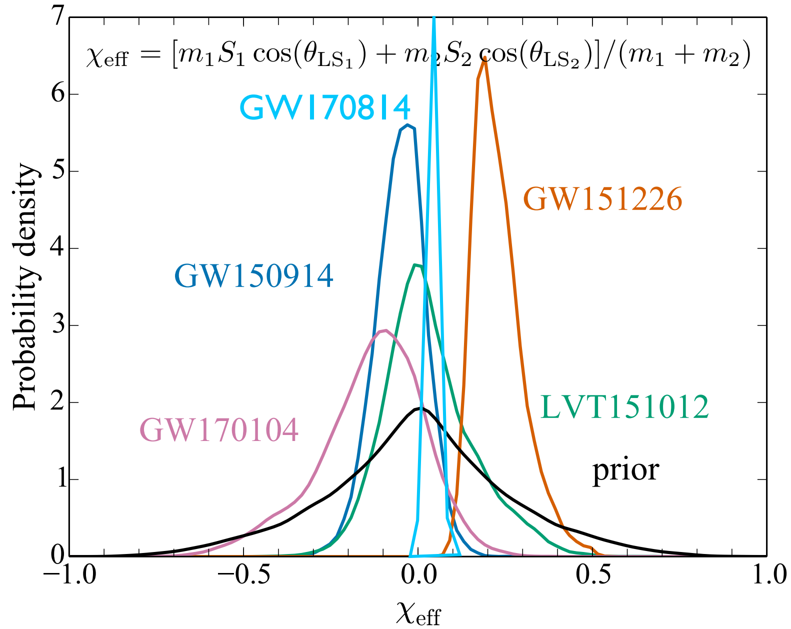
Takeshi Chiba[1] and Shuichiro Yokoyama[2]

arXiv:1704.06573

Abstract

We estimate the spin distribution of primordial black holes based on the recent study of the critical phenomena in the gravitational collapse of a rotating radiation fluid. We find that primordial black holes are mostly slowly rotating.

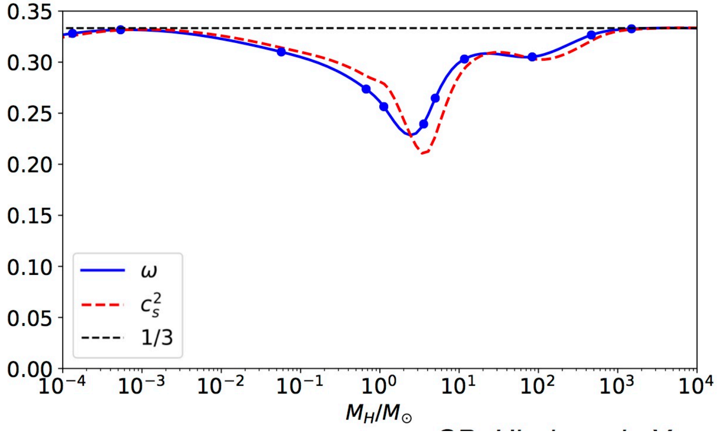


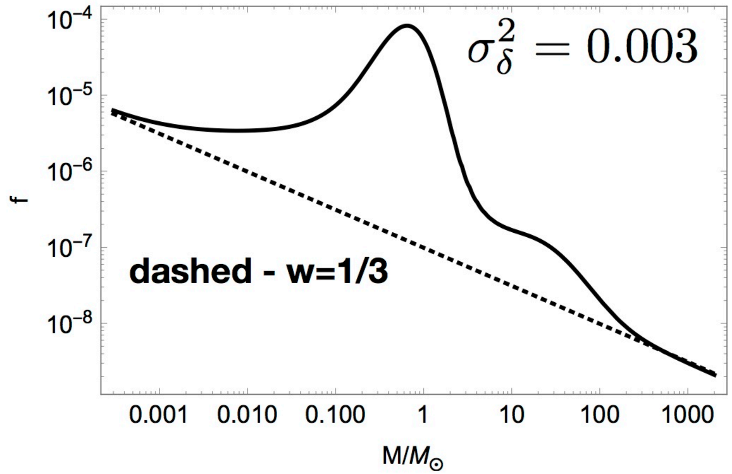


Primordial black holes with an accurate QCD equation of state

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

arXiv:1801.06138





PBHS, DARK MATTER AND ELECTROWEAK BARYOGENESIS AT THE QUARK HADRON EPOCH

BC, Sebastien Clesse & Juan Garcia-Bellido (2019)

Stars have a mass in range (0.1 – 10) M_C where
$M_C \sim \alpha_G^{-3/2}\, m_P \sim 1\, M_O$ and $\alpha_G \sim G m_P^2/hc \sim 10^{-38}$

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).

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

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

Baryogenesis scenario (Garcia-Bellido talk)

EW baryogenesis at QCD epoch

Baryon violation via sphaleron transitions and B+L chiral anomaly

CP violation via CKM matrix

Equilibrium violation via supercooling near QCD scale

PBH form'n => large curvature perturb'n => huge entropy prod'n => out-of-equilibrium condition => baryogenesis with $\eta_{loc} \sim 1$

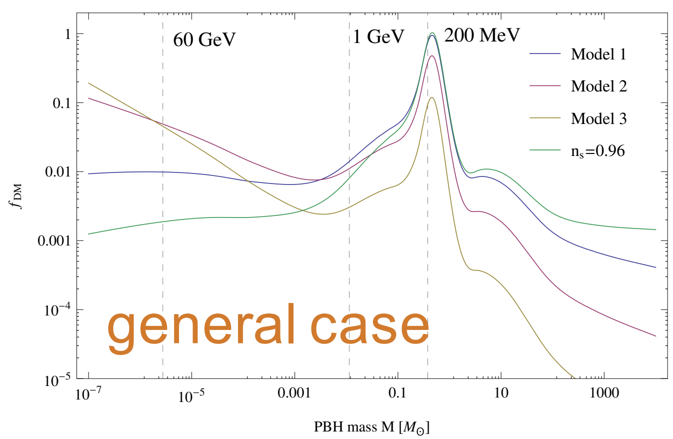
Diffusion of baryon asymmetry => $\eta \sim \beta$ and $\chi \sim 1$

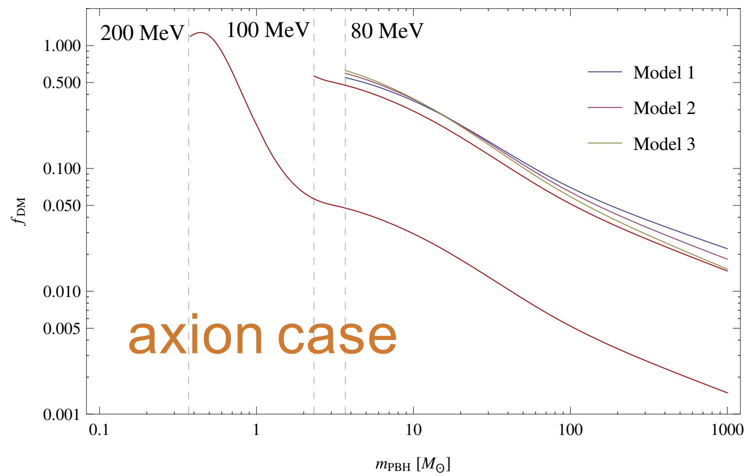
Curvature perturbation scenario (Clesse talk)

Natural peak in PBH mass function but need to fine-tune pert' amp'

Stochastic fluct'ns in spectator field during inflation (QCD axion)
$\Rightarrow$ different values in different patches
$\Rightarrow$ frozen until pot' energy dominates density long after inflation
$\Rightarrow$ 2^{nd} inflation phase within region (few e-folds)
$\Rightarrow$ non-linear perturbations => PBHs.

Axion field fluct' => $\Delta N \sim O(1)$ => O(1) curv' fluct' if $f_a \sim 0.2\ M_{Pl}$
=> PQ breaking at GUT epoch => axions dominate at QCD epoch.





1^{st} peak at $1M_O$ for DM plus 2^{nd} peak at 10-20 M_O for LIGO events

PBHS AS GENERATORS OF COSMIC STRUCTURES

B.J. Carr & J. Silk

MNRAS 478 (2018) 3756; arXiv:1801.00672

What is maximum mass of PBH?

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

BBNS => t < 1 s => M < $10^5 M_O$ .....but $\beta < 10^{-6} (t/s)^{1/2}$

Supermassive PBHs could also generate cosmic structures on larger scale through 'seed' or 'Poisson' effect

Upper limit on μ distortion of CMB excludes $10^4 < M/M_O < 10^{12}$ for Gaussian fluctuations but some models evades these limits. Otherwise need accretion factor of $(M/10^4 M_o)^{-1}$

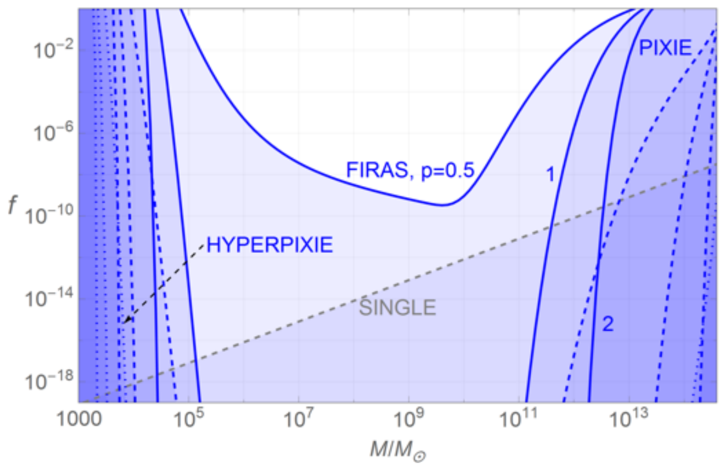
Dolgov (2016)

Limits on primordial black holes from μ distortions in cosmic microwave background

Tomohiro Nakama,[1] Bernard Carr,[2,3] and Joseph Silk[1,4,5]

PHYSICAL REVIEW D **97,** 043525 (2018)

If primordial black holes (PBHs) form directly from inhomogeneities in the early Universe, then the number in the mass range $10^5 - 10^{12}\ M_\odot$ is severely constrained by upper limits to the μ distortion in the cosmic microwave background (CMB). This is because inhomogeneities on these scales will be dissipated by Silk damping in the redshift interval $5 \times 10^4 \lesssim z \lesssim 2 \times 10^6$. If the primordial fluctuations on a given mass scale have a Gaussian distribution and PBHs form on the high-σ tail, as in the simplest scenarios, then the μ constraints exclude PBHs in this mass range from playing any interesting cosmological role. Only if the fluctuations are highly non-Gaussian, or form through some mechanism unrelated to the primordial fluctuations, can this conclusion be obviated.



SEED AND POISSON FLUCTUATIONS

PBHs larger than $10^2 M_O$ cannot provide dark matter but can affect large-scale structure through seed effect on small scales or Poisson effect on large scales even if f small.

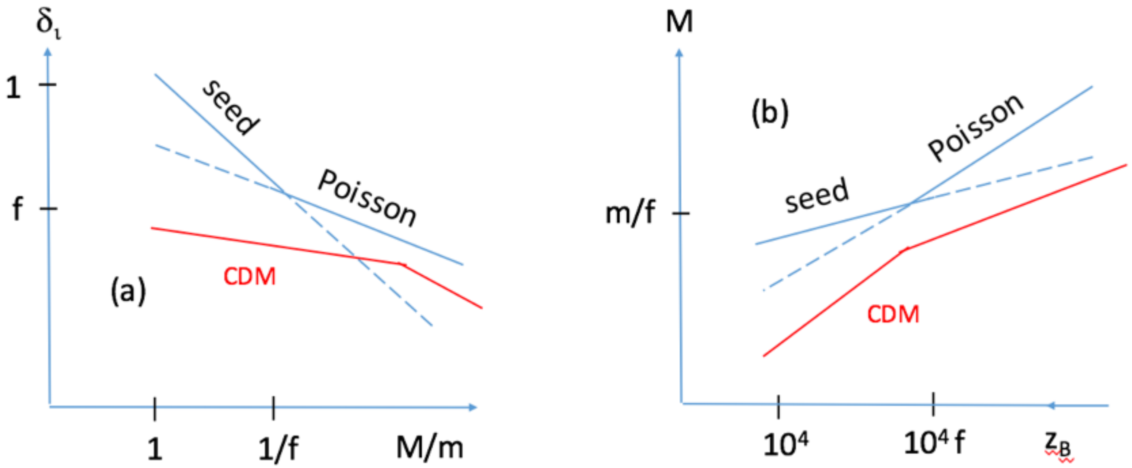
If region of mass M contains PBHs of mass m, initial fluctuation is

$$\delta_i \sim \begin{cases} m/M & \text{(seed)} \\ (fm/M)^{1/2} & \text{(Poisson)} \end{cases}$$

f = 1 => Poisson dominates; f <<1 => seed dominates for M < m/f. Fluctuation grows as z^{-1} from $z_{eq} \sim 10^4$, so mass binding at z_B is

$$M \approx \begin{cases} 4000\, m z_B^{-1} & \text{(seed)} \\ 10^7 f m z_B^{-2} & \text{(Poisson)} \end{cases}$$

SEED VERSUS POISSON



cf. CDM fluctuations

$$\delta_{eq} \propto \begin{cases} M^{-1/3} & (M < M_{eq}) \\ M^{-2/3} & (M > M_{eq}) \end{cases}$$

$f = 1 \Rightarrow m < 10^3\, M_O \Rightarrow M < 10^{11} z_B^{-2}\, M_O < M_{gal}$ (Poisson)

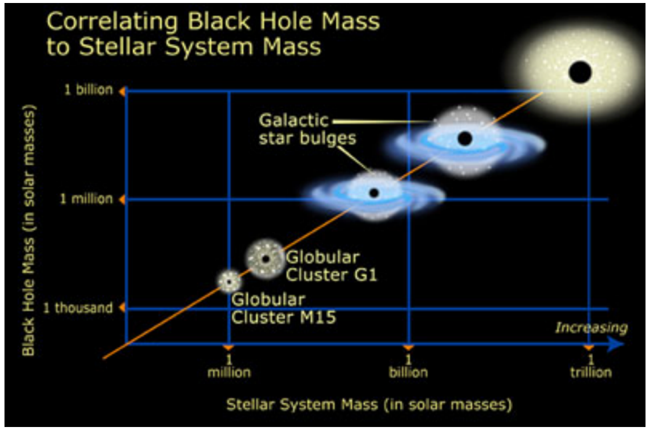
=> can generate dwarf galaxies

$f << 1 \Rightarrow M$ can be larger

=> PBHs can be seeds for galaxies

SUPERMASSIVE PBHS AS SEEDS FOR GALAXIES

Seed effect => $M_B \sim 10^3$ m (z_B/10)
$\Rightarrow$ naturally explain M_{BH}/M_{bulge} relation



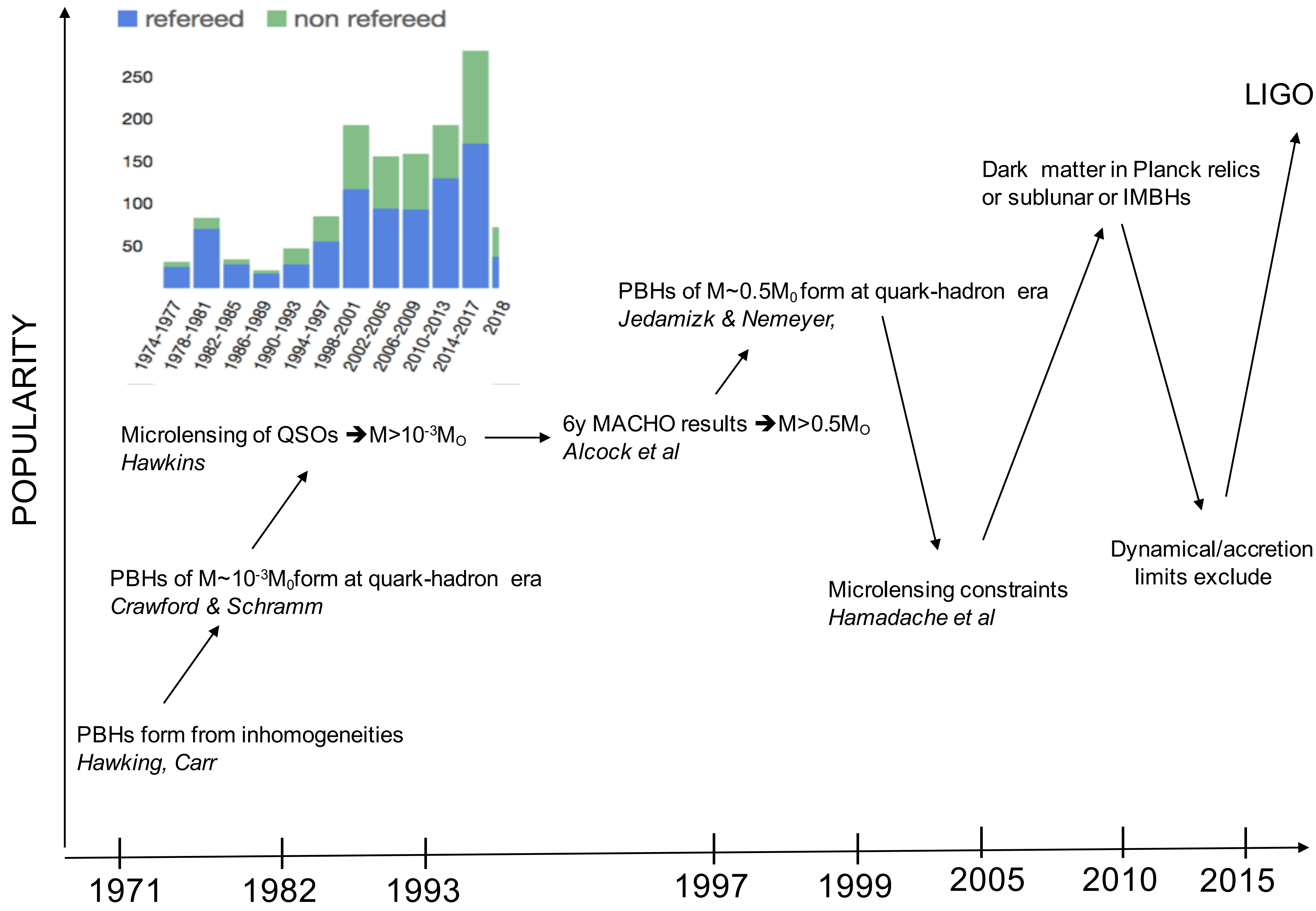
Effect of mergers and accretion?

Also predict mass function of galaxies (cf. Press-Schechter)

$$dN_g/dM \propto M^{-2} \exp(-M/M_*) \qquad M_* \sim 10^{12} M_\odot$$

If M exceeds $10^{10} M_O$, black hole accretes whole galaxy

cf. Dolgov (2016)



refereed
non refereed
250
200
150
100
50
1974-1977
1978-1981
1982-1985
1986-1989
1990-1993
1994-1997
1998-2001
2002-2005
2006-2009
2010-2013
2014-2017
2018
POPULARITY
LIGO
Dark matter in Planck relics
or sublunar or IMBHs
PBHs of M~0.5M0 form at quark-hadron era
Jedamizk & Nemeyer,
6y MACHO results → M>0.5MO
Alcock et al
Microlensing of QSOs → M>10-3MO
Hawkins
PBHs of M~10-3M0 form at quark-hadron era
Crawford & Schramm
Microlensing constraints
Hamadache et al
Dynamical/accretion
limits exclude
PBHs form from inhomogeneities
Hawking, Carr
1971
1982
1993
1997
1999
2005
2010
2015

CONCLUSIONS

PBHs have been invoked for four roles:

Cosmic rays	Dark matter	LIGO/Virgo	Cosmic structure

These are distinct roles but PBHs with extended mass function could play all!

This talk is dedicated to the memory of Stephen Hawking. He wrote the first paper on primordial black holes in 1971. If they play any of the roles discussed here, this may have been his most prescient and important work