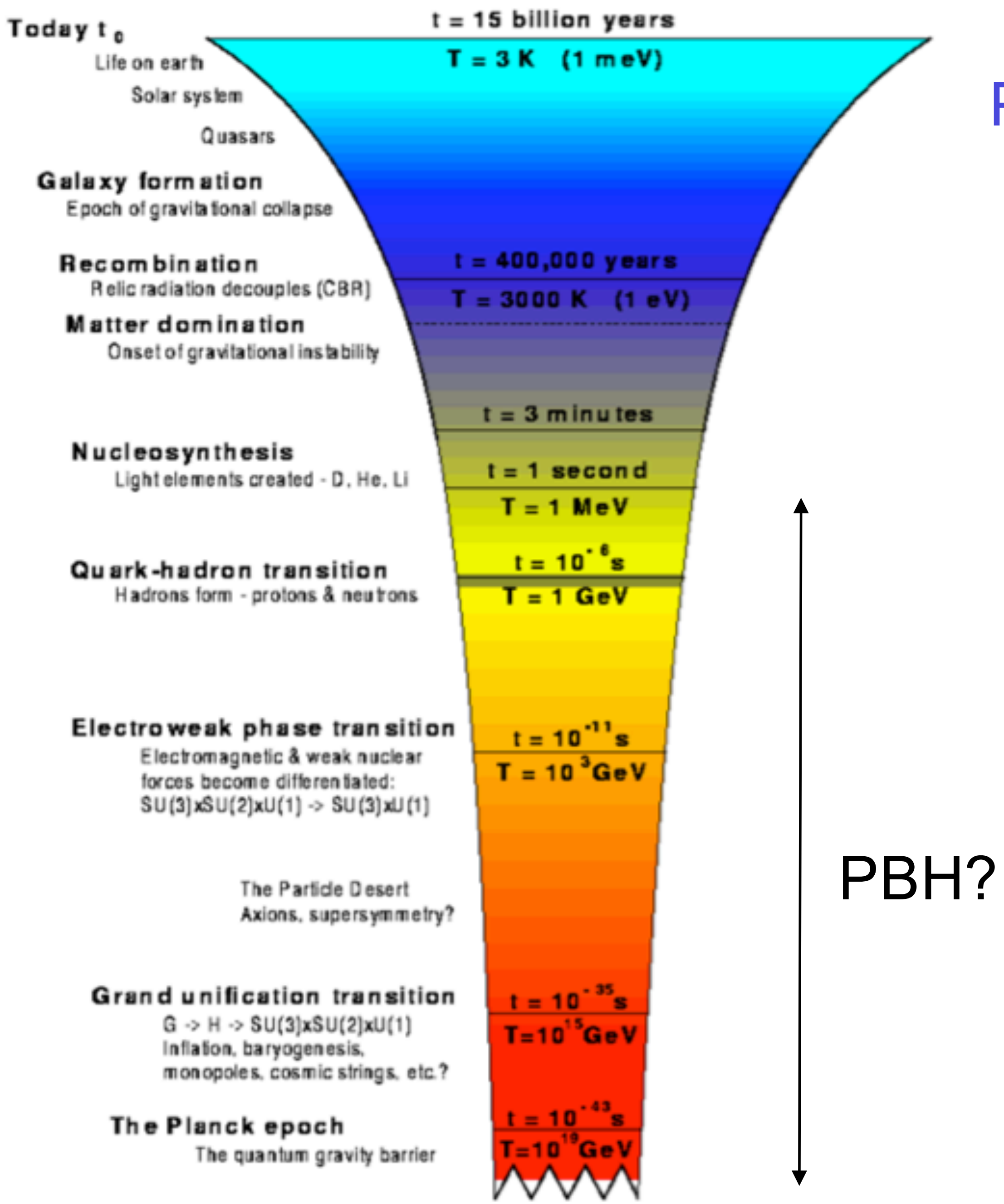
PRIMORDIAL BLACK HOLES AS THE SOLUTION OF MANY COSMOLOGICAL CONUNDRA

Bernard Carr, Queen Mary University of London

IPMU workshop (2/12/19)

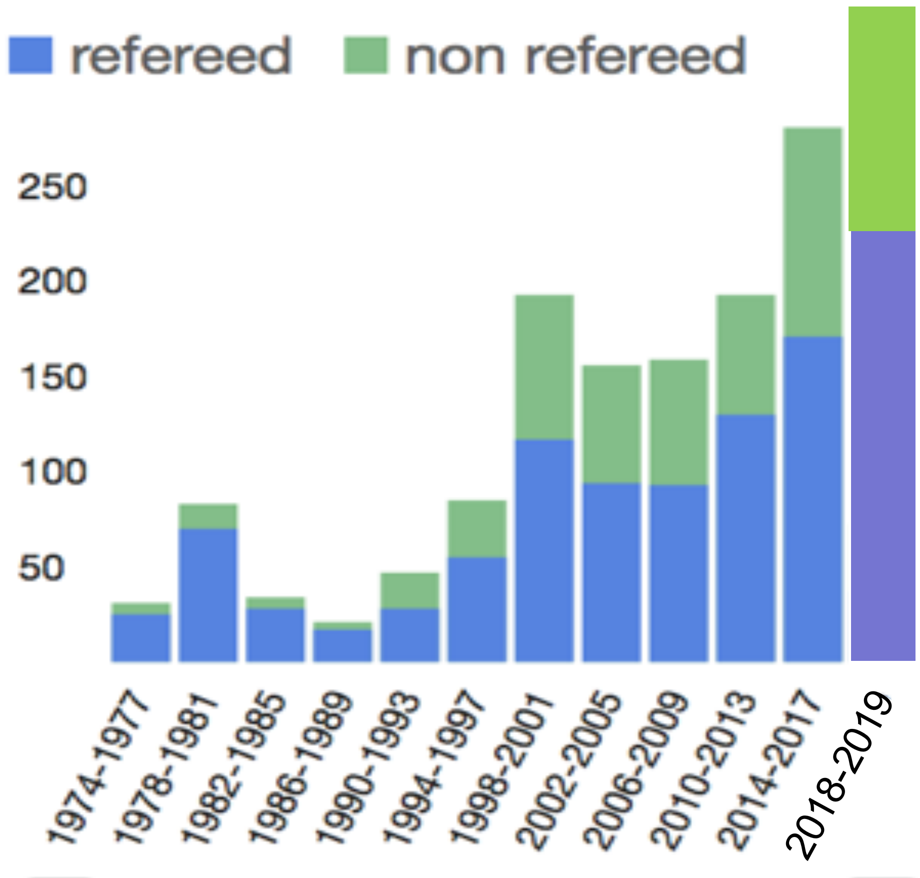
PRIMORDIAL BLACK HOLES AFTER 50 YEARS: A HISTORICAL OVERVIEW



Bernard Carr
Queen Mary
University of London

IPMU 13/11/17

PUBLICATION RATE OF PBH PAPERS



Impossible to keep up with literature!

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*

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Received 1975 January 31

ABSTRACT

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

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

New cosmological constraints on primordial black holes

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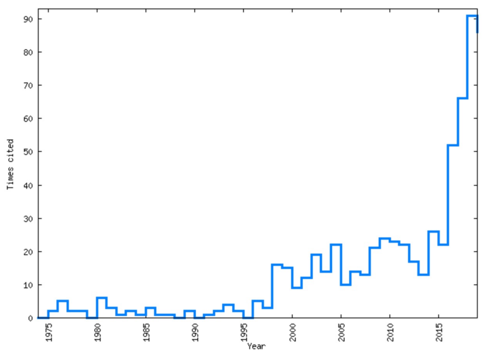
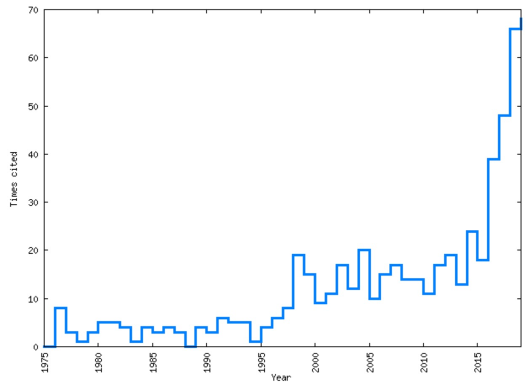
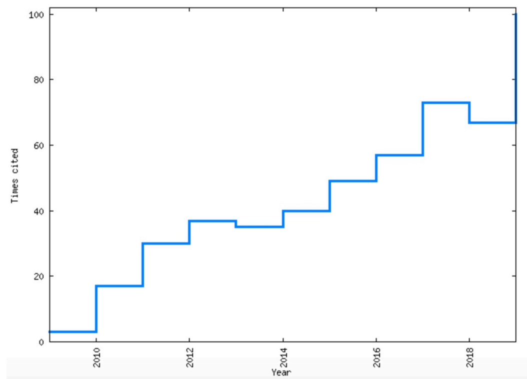
(Received 31 December 2009; published 10 May 2010)

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.







Career all downhill .....

until RESCEU!

PLAN OF TALK

- Formation and evaporation of PBHs
- Constraints on PBHs
- PBHs as dark matter dark
- PBHs as source of LIGO/Virgo events
- PBHs as generators of cosmic structure
- PBHs from QCD epoch and fine-tuning problem

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

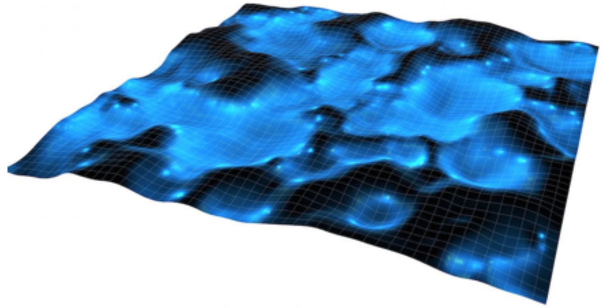
Small BHs can only form in early Universe

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

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

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

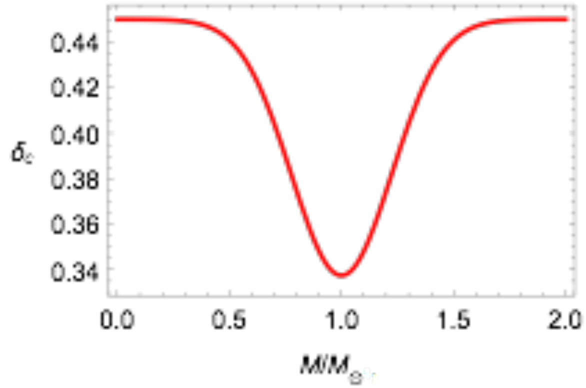
FORMATION MECHANISMS

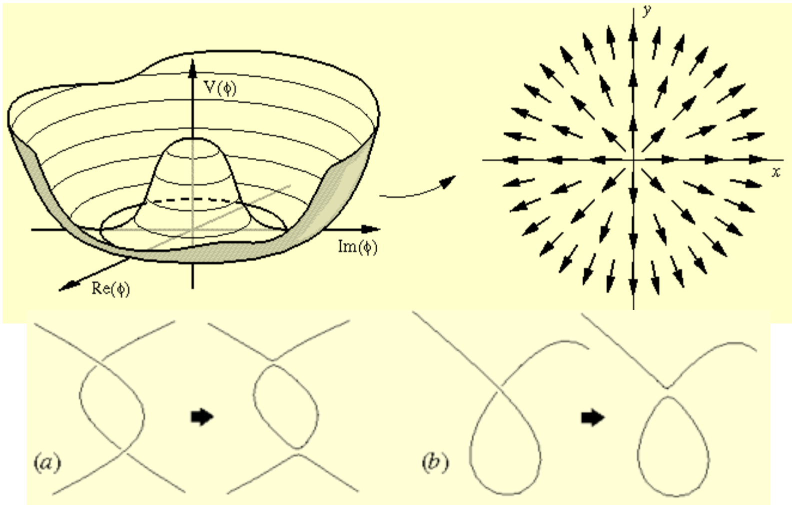


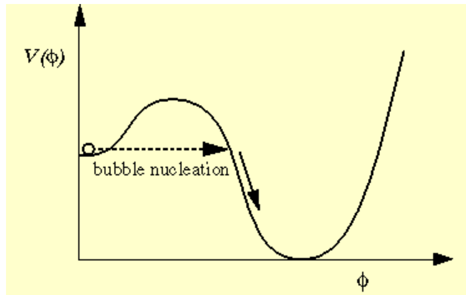
Primordial inhomogeneities   Inflation

Pressure reduction   Form more easily but need spherical symmetry

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

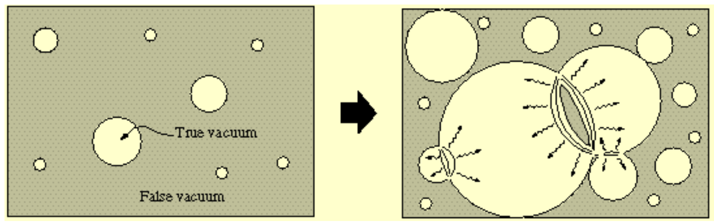






Bubble collisions

Need fine-tuning of bubble formation rate



Domain walls   PBHs can be very large

PBH EVAPORATION

Black holes radiate thermally with temperature

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

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

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

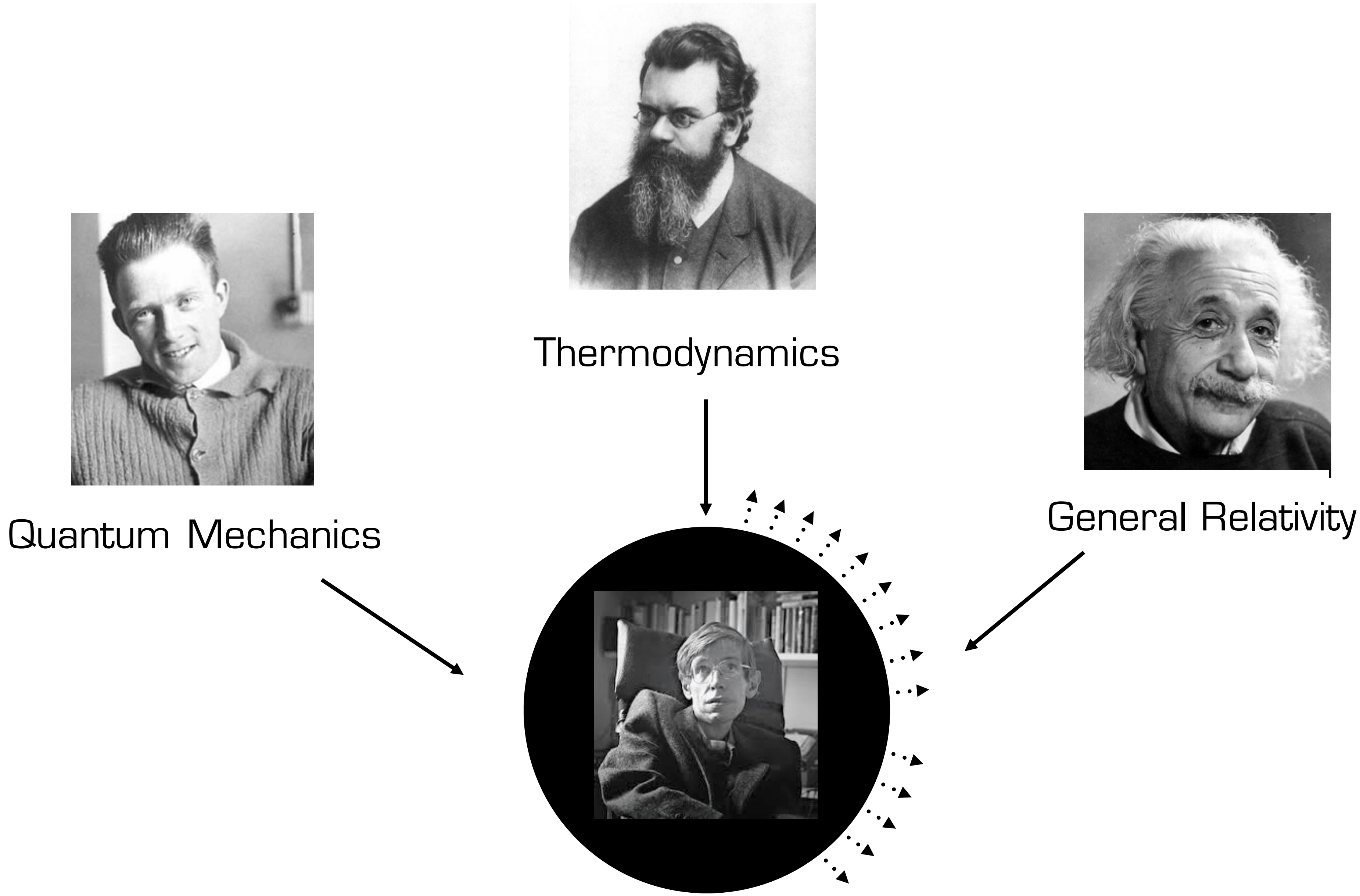
This can only be important for PBHs

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

=> explosions undetectable in standard particle physics model

Are some short γ-ray bursts PBH explosions (Cline et al.)

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



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

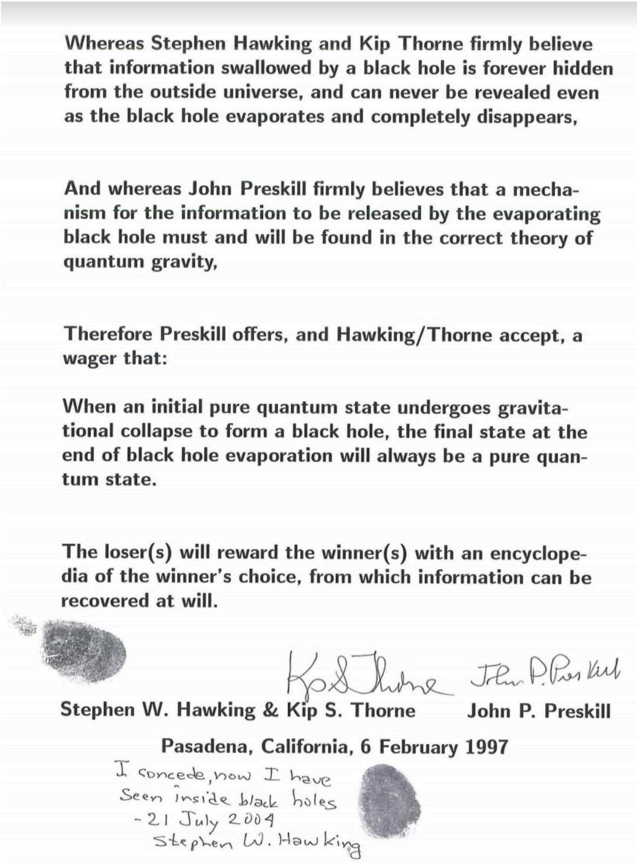
PBHs are important even if they never formed!

BLACK HOLE INFORMATION PARADOX

PHYSICAL REVIEW D VOLUME 14, NUMBER 10 15 NOVEMBER 1976

Breakdown of predictability in gravitational collapse*

S. W. Hawking†



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.

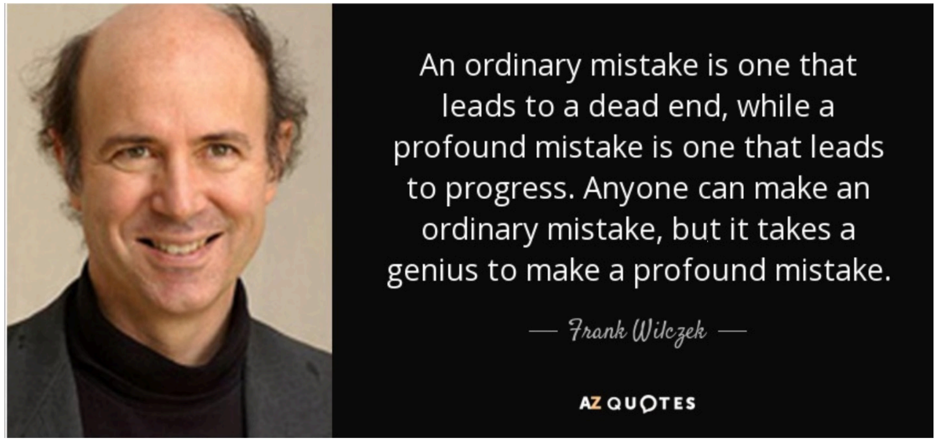
The loser(s) will reward the winner(s) with an encyclopedia of the winner's choice, from which information can be recovered at will.

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



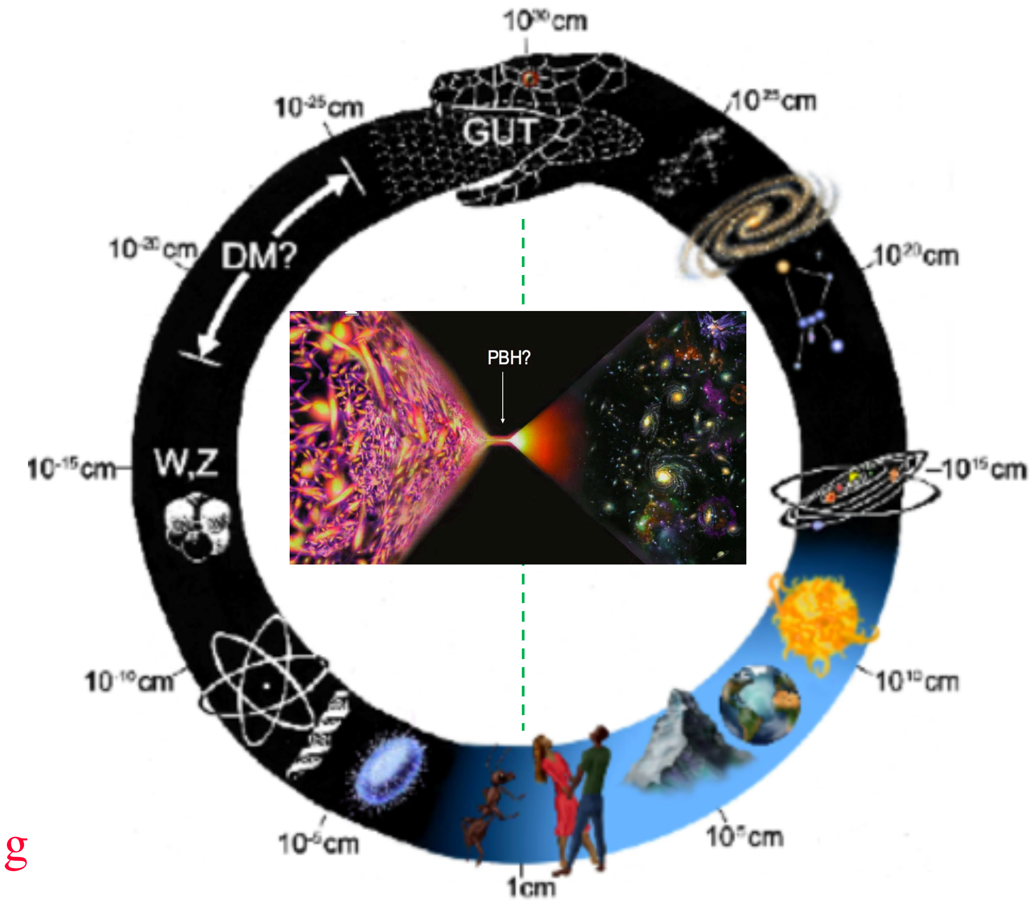
Hawking's bet

BLACK HOLES AS LINK BETWEEN MICRO AND MACRO PHYSICS

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

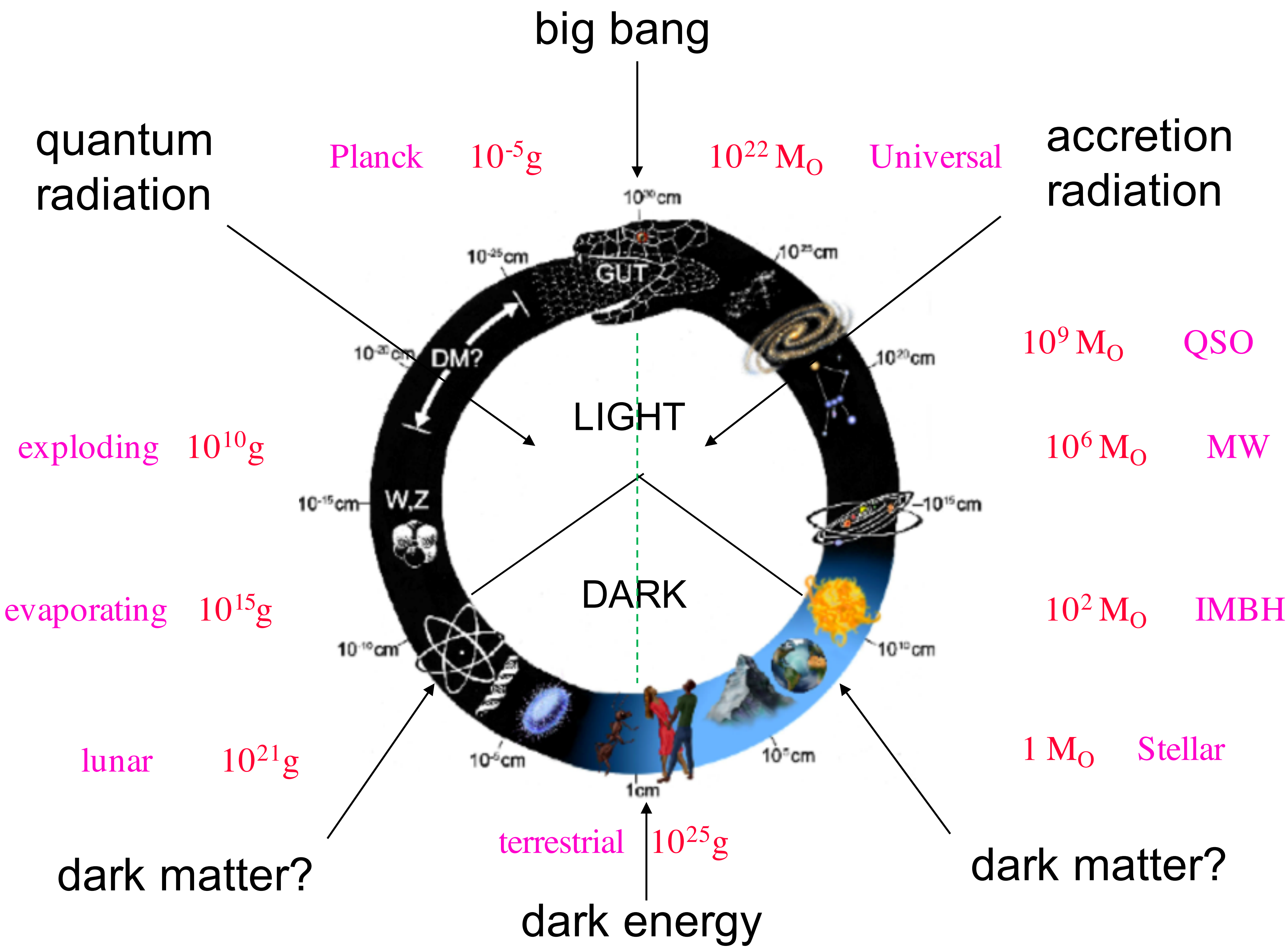
lunar 10^{21}g

$1\ M_O$ Stellar

terrestrial 10^{25}g

QUANTUM/CLASSICAL

BLACK HOLES AS LINK LIGHT AND DARK

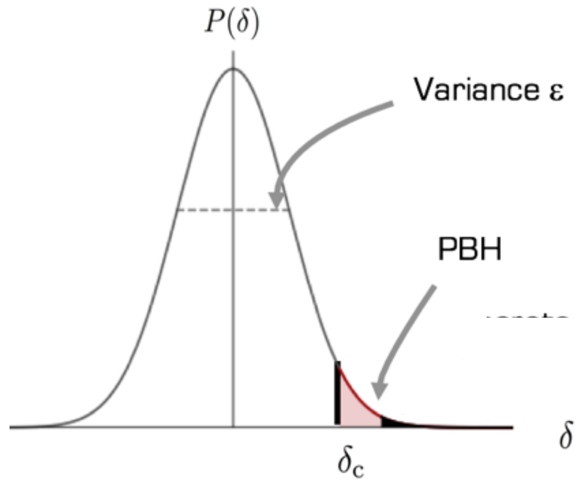


PBH FORMATION => LARGE INHOMOGENEITIES

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



$\Rightarrow$ **fraction of PBHs**

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

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

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

(Khlopov & Polnarev 1982)

Fraction of Universe collapsing

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

General limit

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

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

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

Fine-tuning problem!

β too large => PBHs overdominate => no galaxies

β too small => insufficient DM => no galaxies

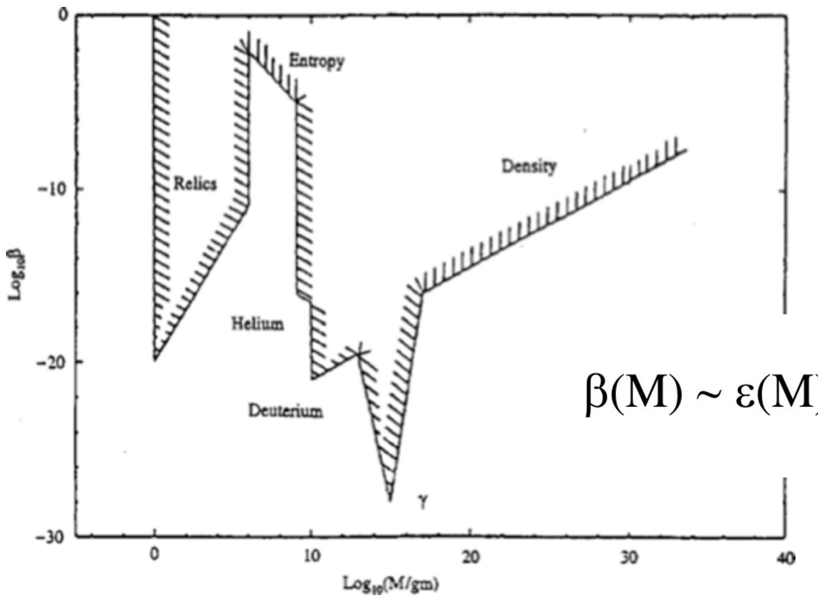
Limit on fraction of Universe collapsing

Unevaporated $M > 10^{15}$g => $\Omega_{PBH} < 0.25$ (CDM)

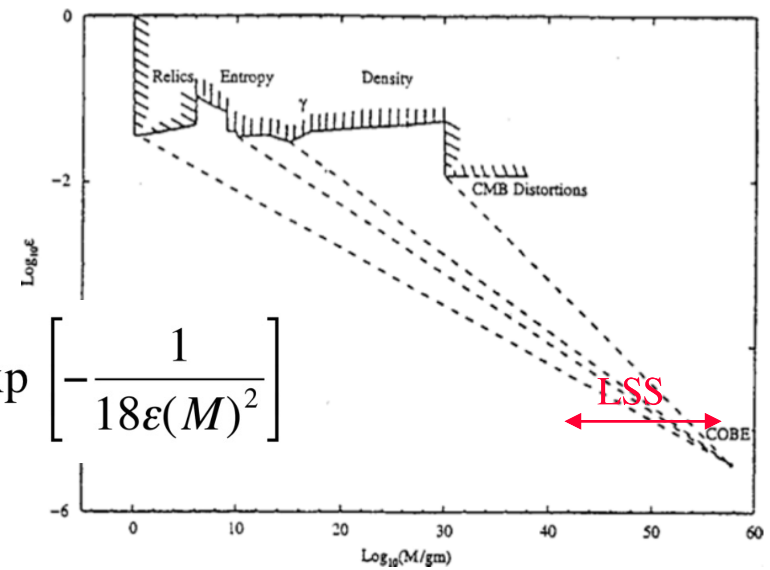
Evaporating now $M \sim 10^{15}$g => $\Omega_{PBH} < 10^{-8}$ (GRB)

Evaporated in past $M < 10^{15}$g

=> constraints from entropy, γ-background, BBNS



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



PBHs are unique probe of ε on small scales.

Need blue spectrum or spectral feature to produce them.

PBHS FROM NEAR-CRITICAL COLLAPSE

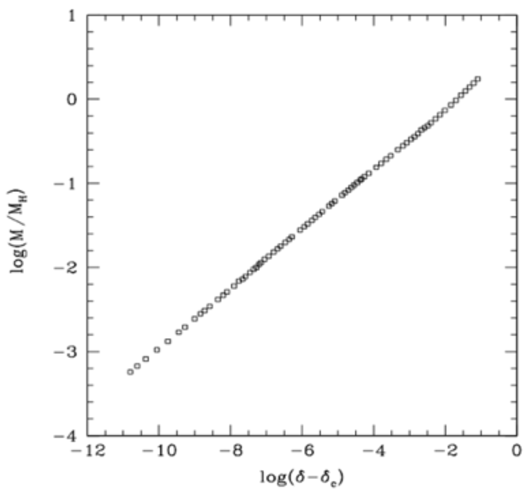
Critical phenomena => $M = k\, M_H(\delta-\delta_c)^\gamma$ (Niemeyer & Jedamzik 1999)

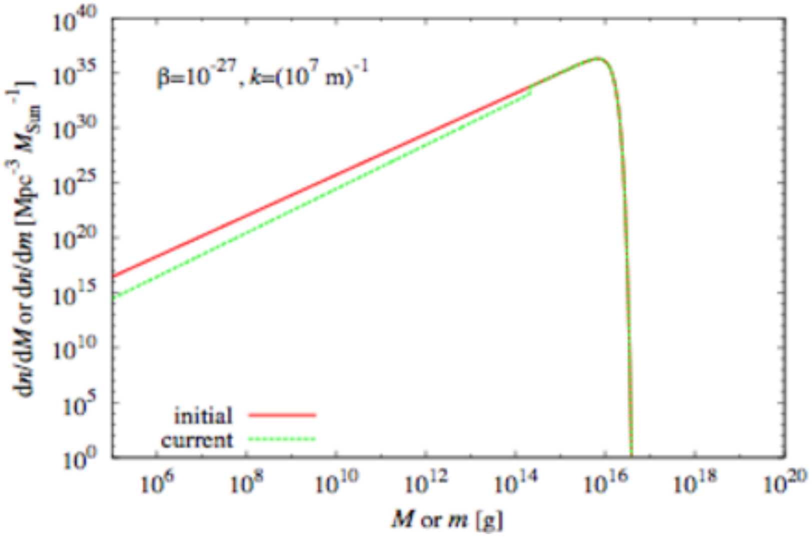
spectrum peaks at horizon mass with extended low mass tail

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

Later calculations and peak analysis =>

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



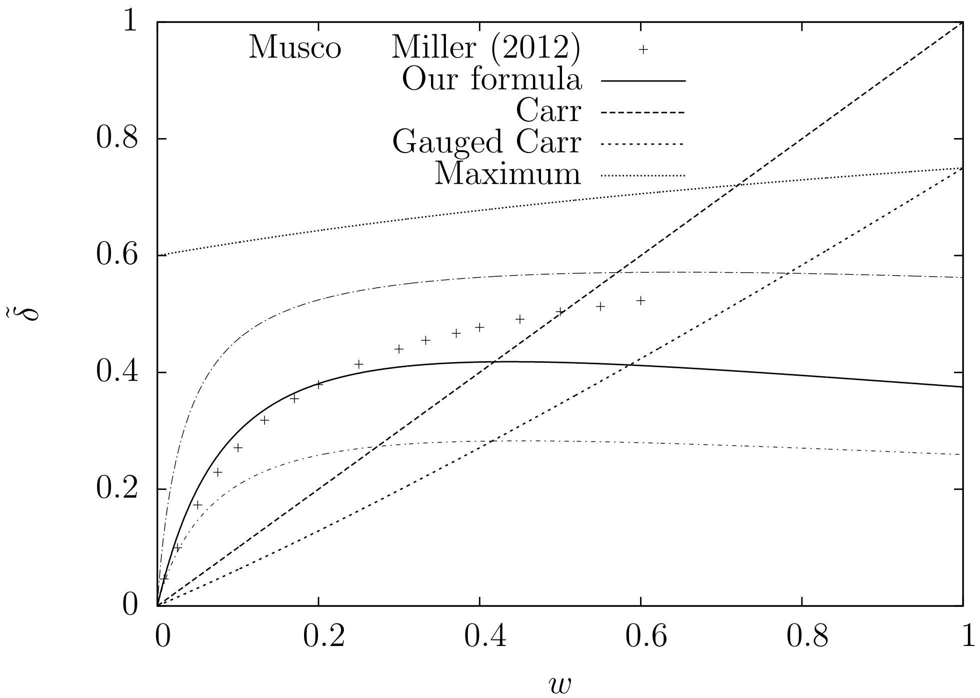


MORE PRECISE ESTIMATE OF δ_C

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

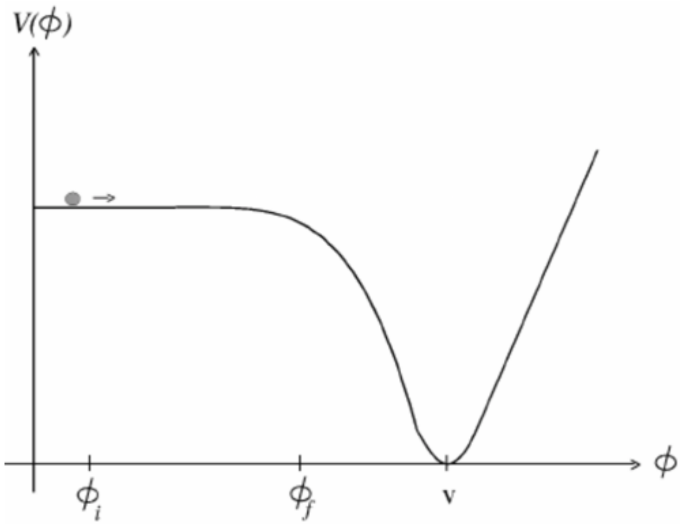
PBHs formed before reheat inflated away =>

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

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?

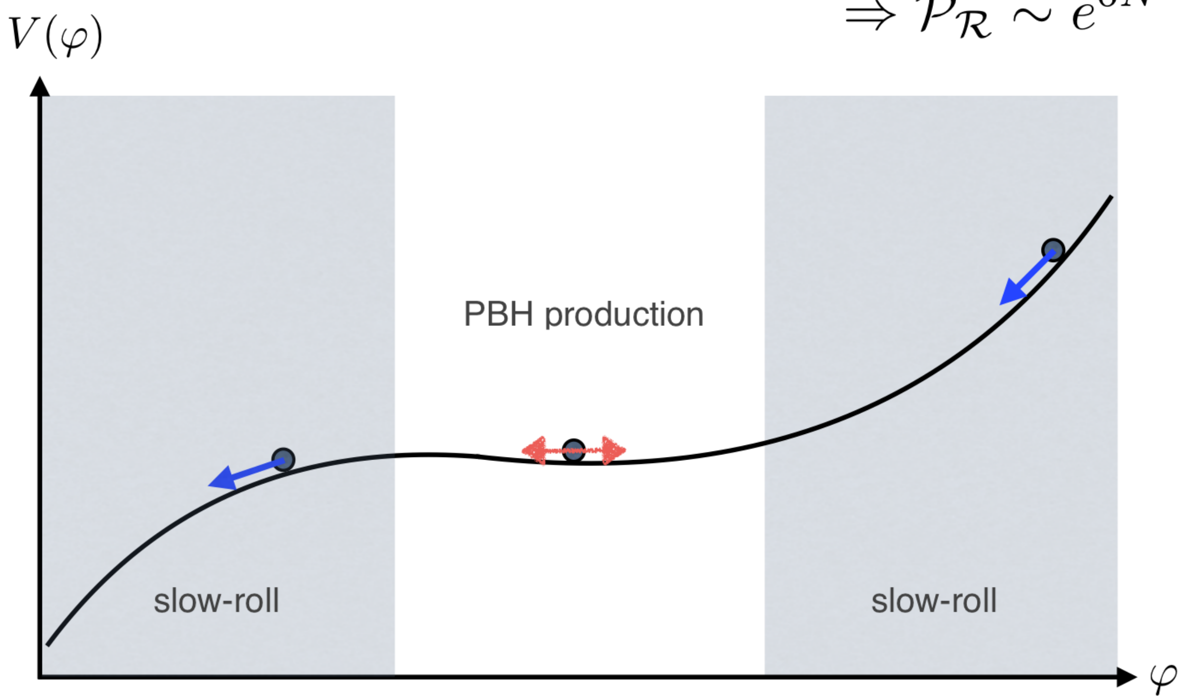
[HUGE NUMBER OF PAPERS ON THIS]

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

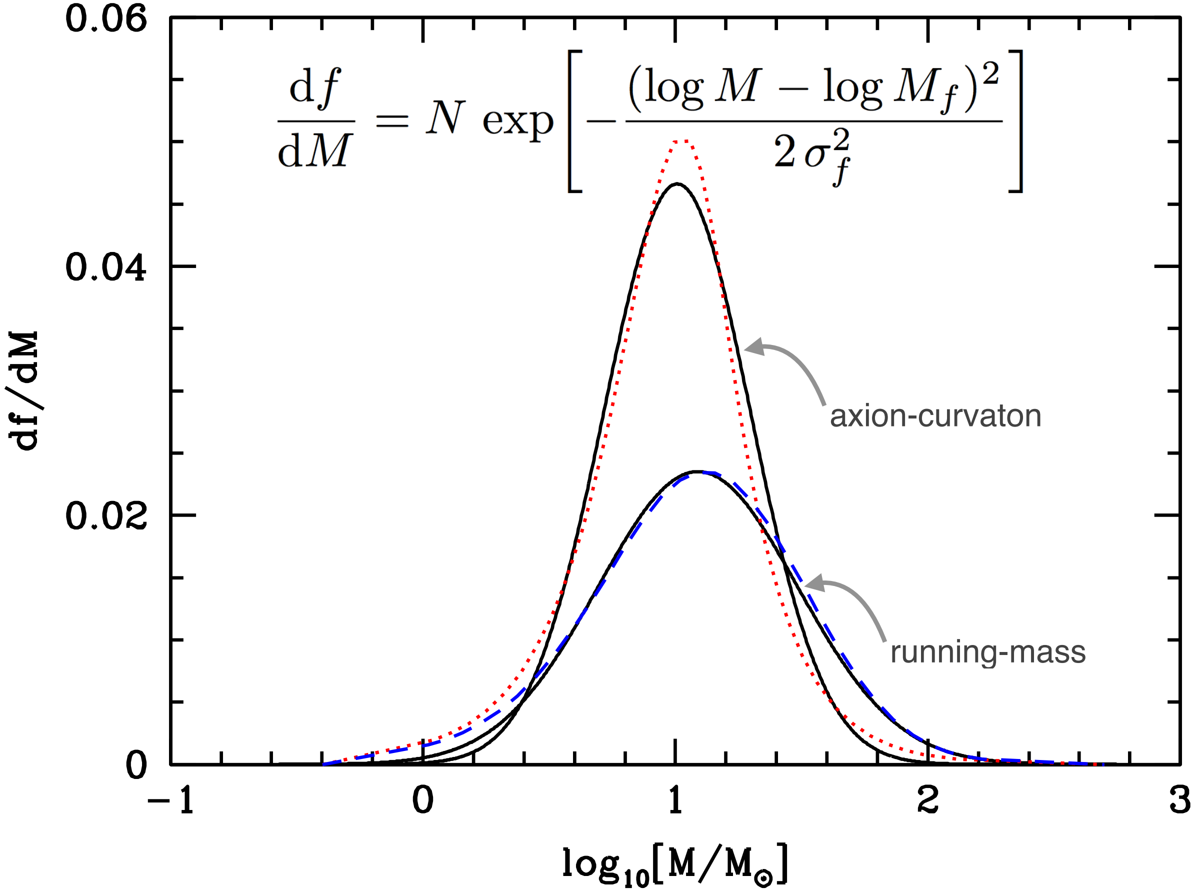
C Germani and T Prokopec

Primordial black holes from inflation and quantum diffusion

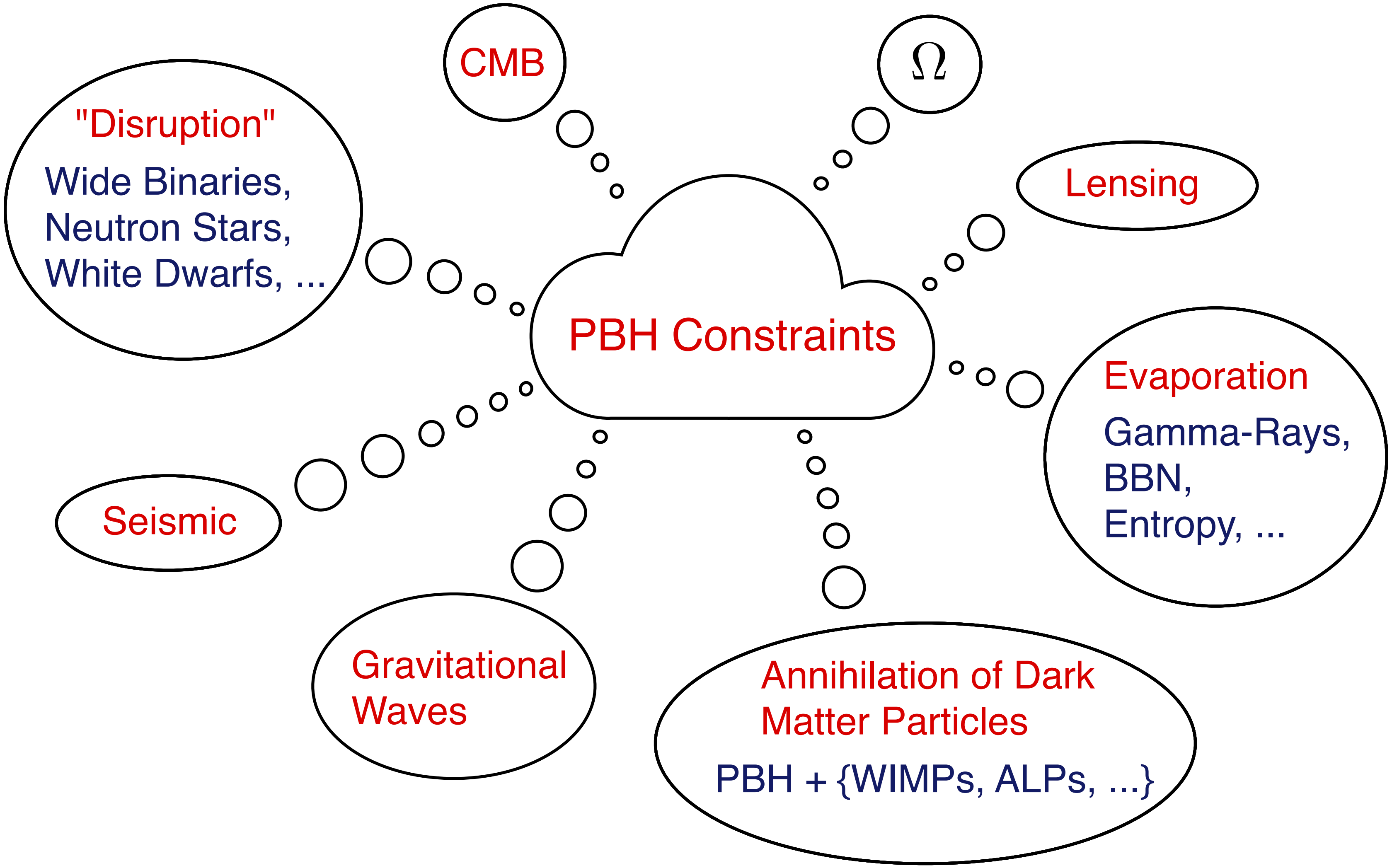
arXiv:1804.07124

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

Lognormal mass function is fairly generic



Dolgov & Silk (1993)


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

CONSTRAINTS FOR EVAPORATING PBHS

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

Big bang nucleosynthesis

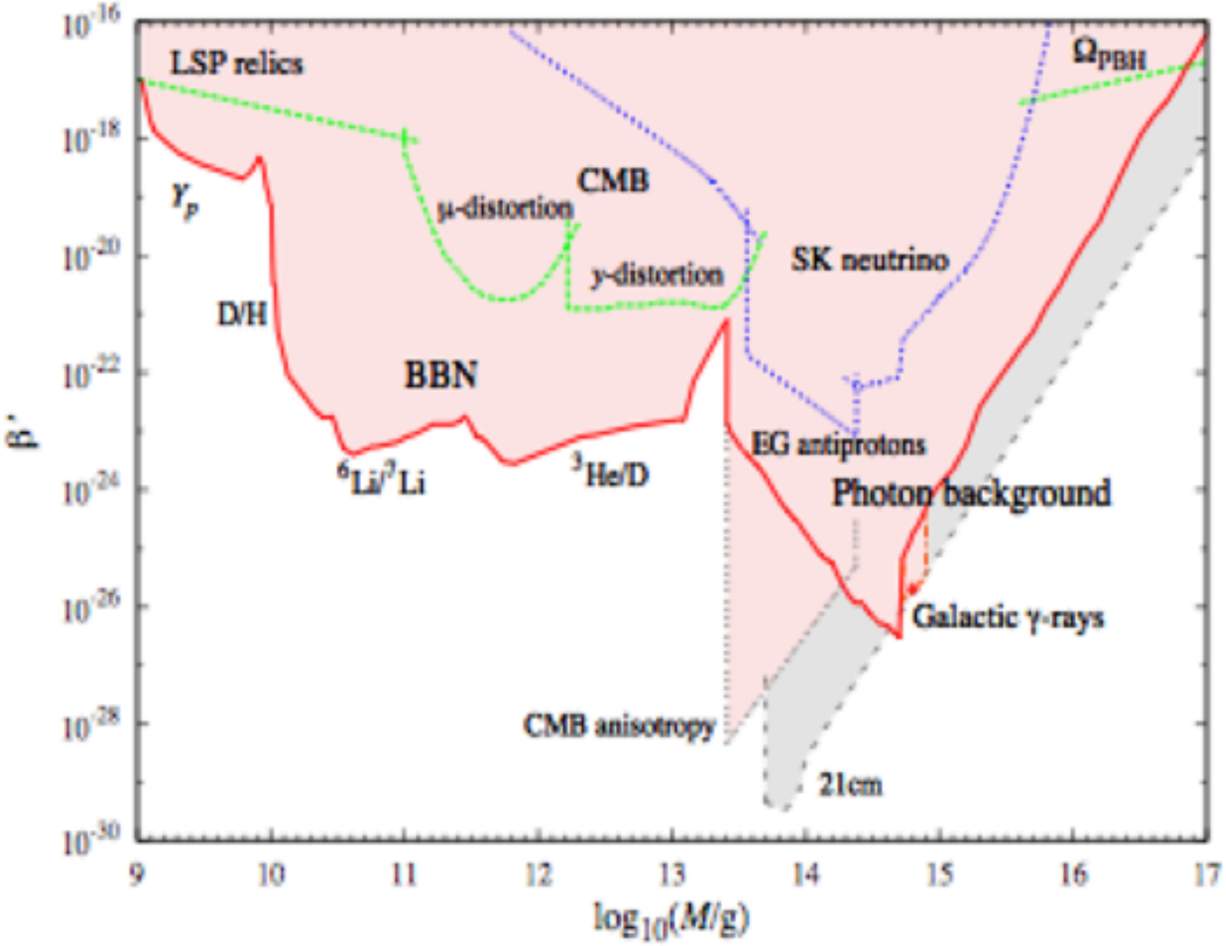
Gamma-ray background

Extragalactic cosmic rays

Neutrino relics

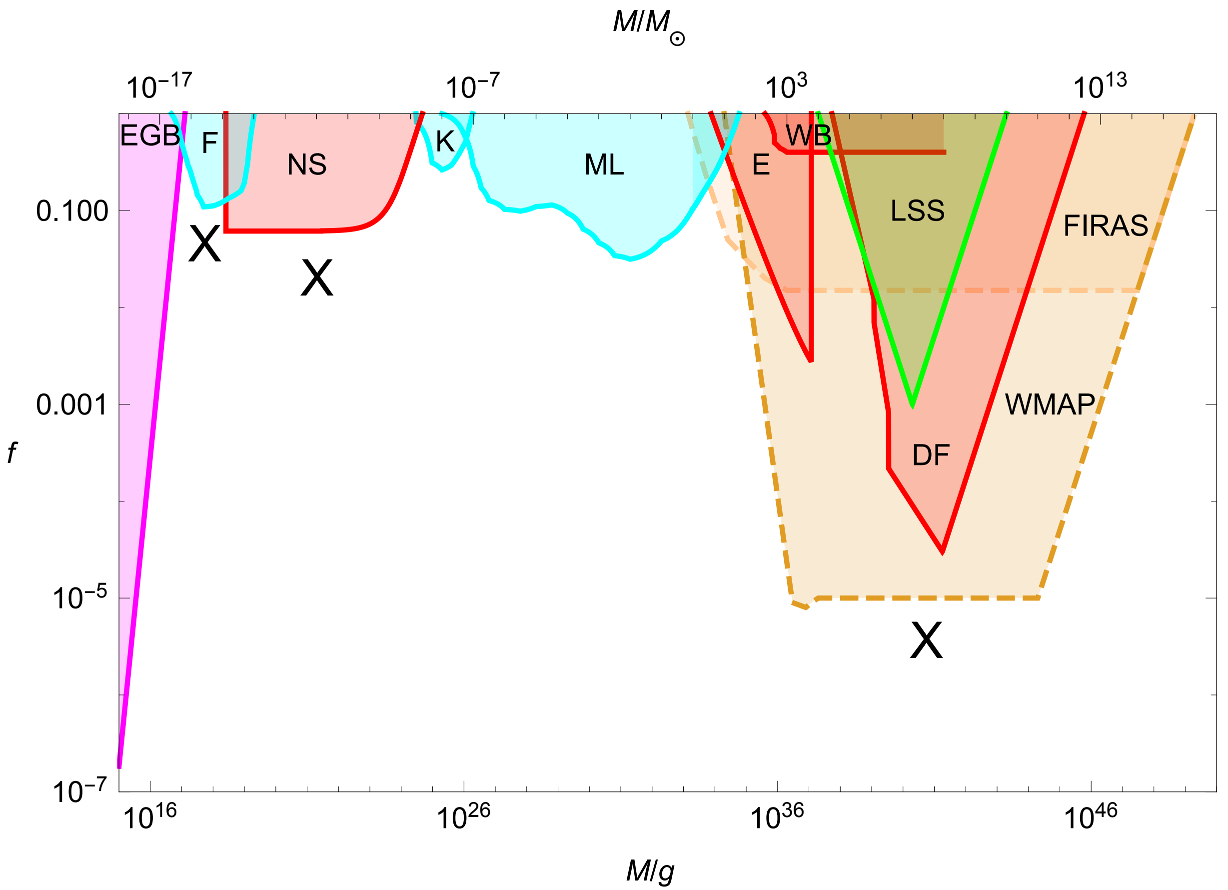
LSP relics

CMB distortions



CONSTRAINTS ON NON-EVAPORATED PBHS

Carr, Kuhnel & Sandstad, arXiv:1607.06077



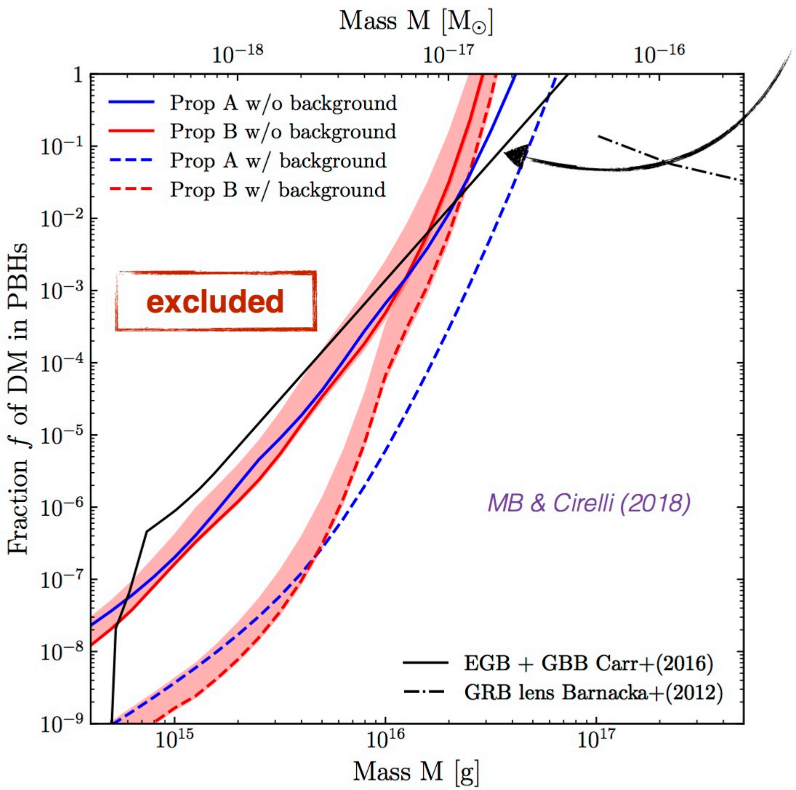
But some of these limits are now thought to be wrong

SOME NEW RECENT CONSTRAINTS

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

Mathieu Boudaud[1] and Marco Cirelli[1]

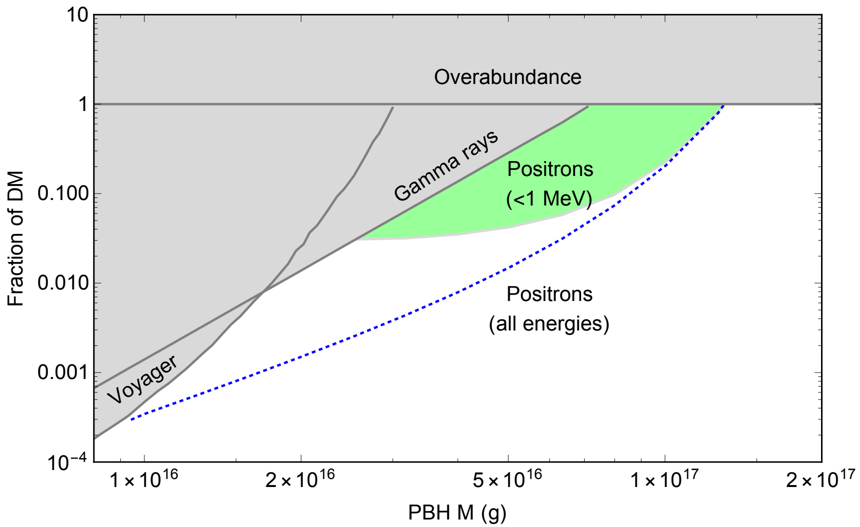
arXiv:1807.03075



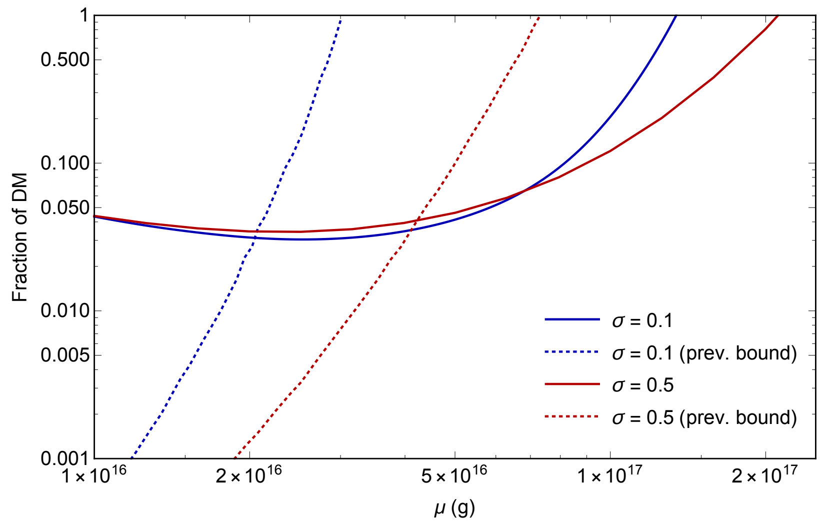
Constraining PBH abundance with the Galactic 511 keV line

William DeRocco1 and Peter W. Graham

arXiv:1906.07740



monochromatic

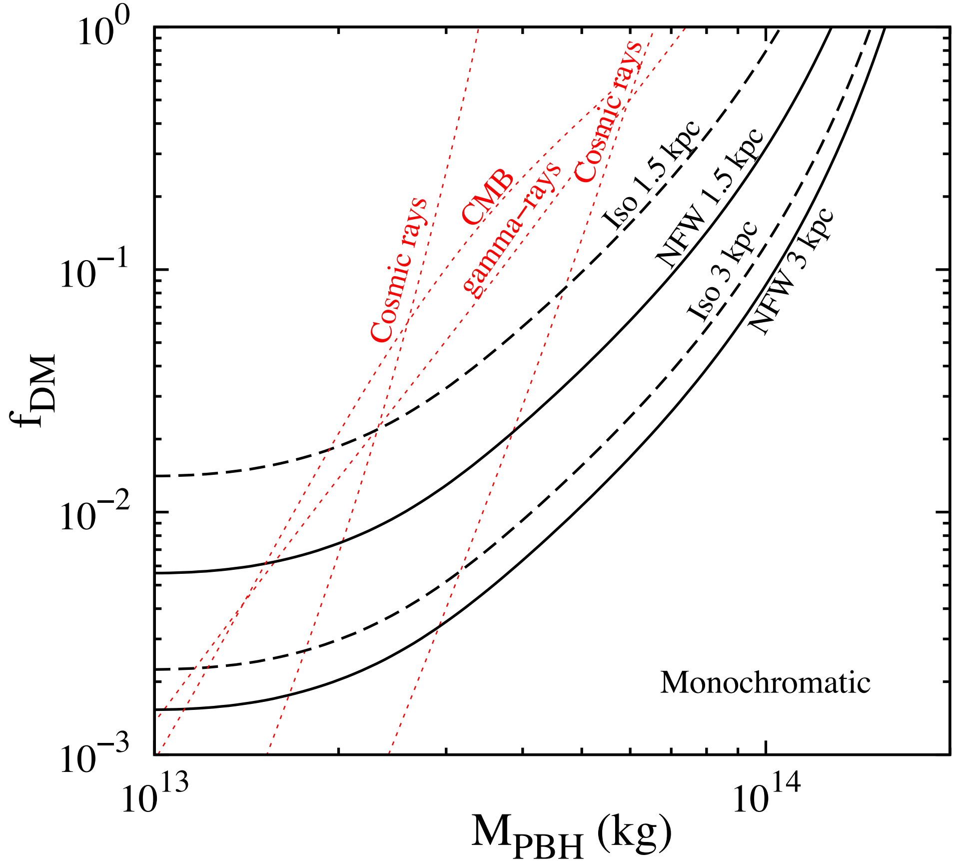


lognormal

PBHs as dark matter candidate are severely constrained by the Galactic Center 511 keV gamma-ray line

Laha

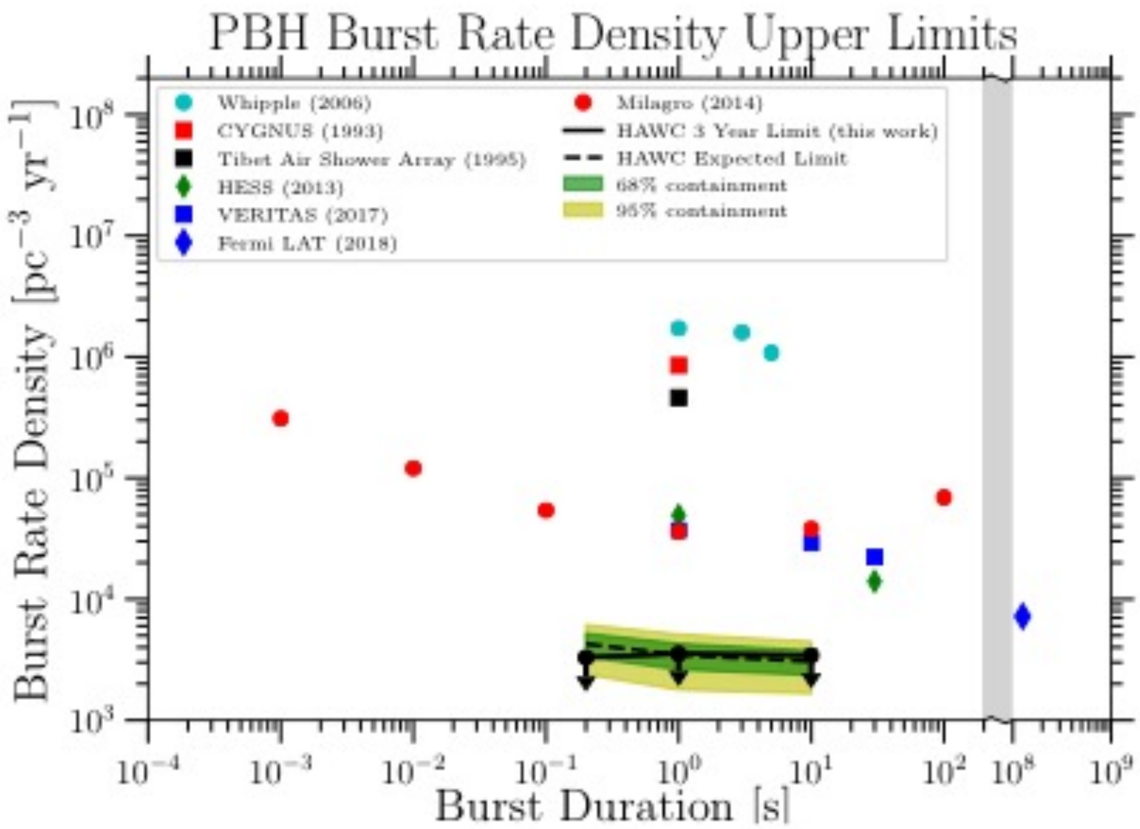
arXiv:1906.09994



Constraining the Local Burst Rate Density of PBHs with HAWC

Albert et al.

arXiv:1911.04356

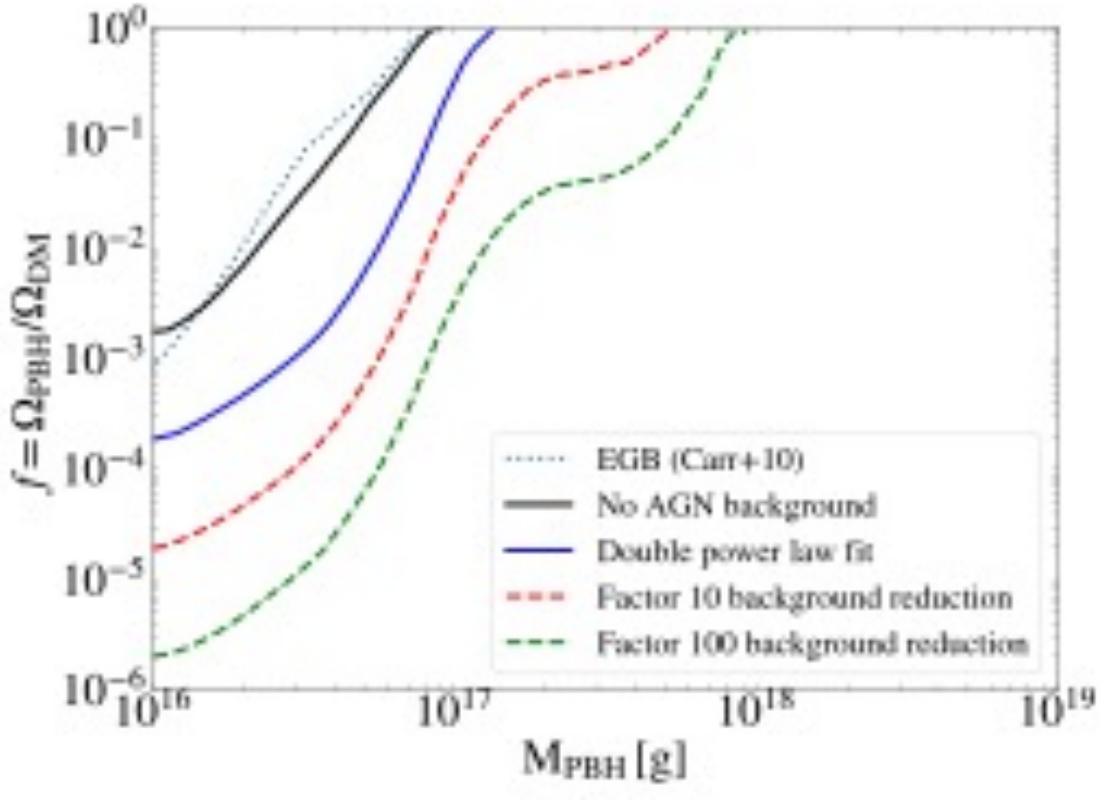


$$\dot{\rho} < 3400^{+400}_{-100}\ \mathrm{pc}^{-3}\mathrm{yr}^{-1}$$

X-ray and gamma-ray limits on the primordial black hole abundance from Hawking radiation

Ballesteros, Coronado-Blazquez and Gaggero

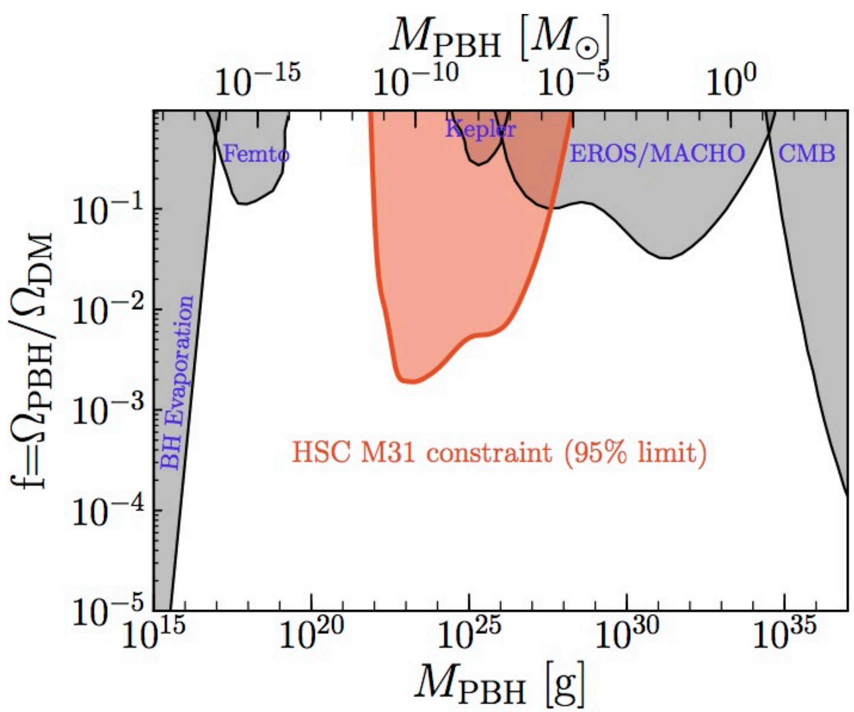
arXiv:1906.10113



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]

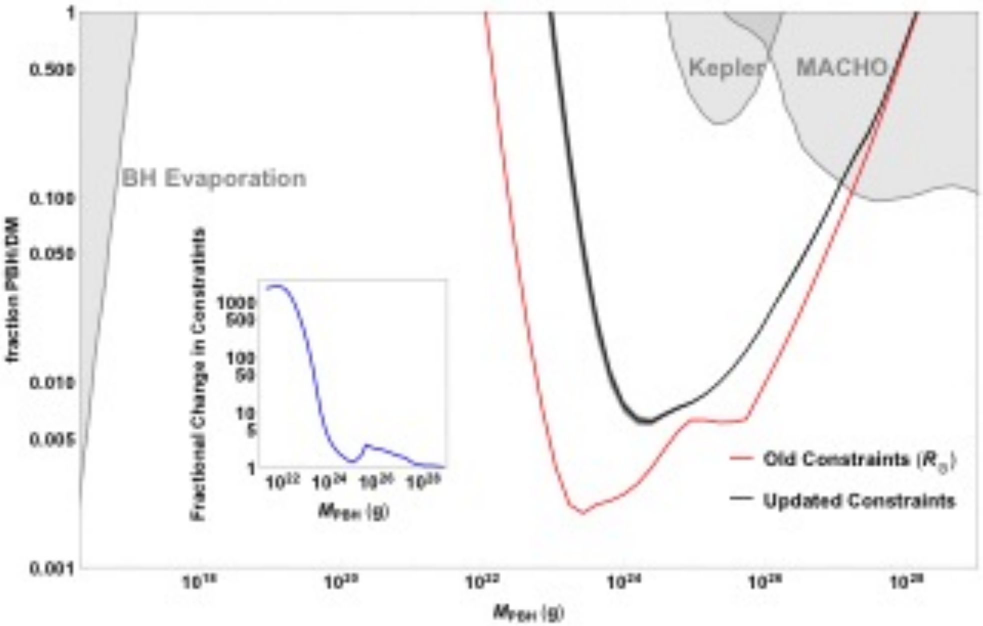
Nature Astronomy 3, 524 (2019),



Updated Constraints on Asteroid-Mass PBHs as Dark Matter

Smyth et al

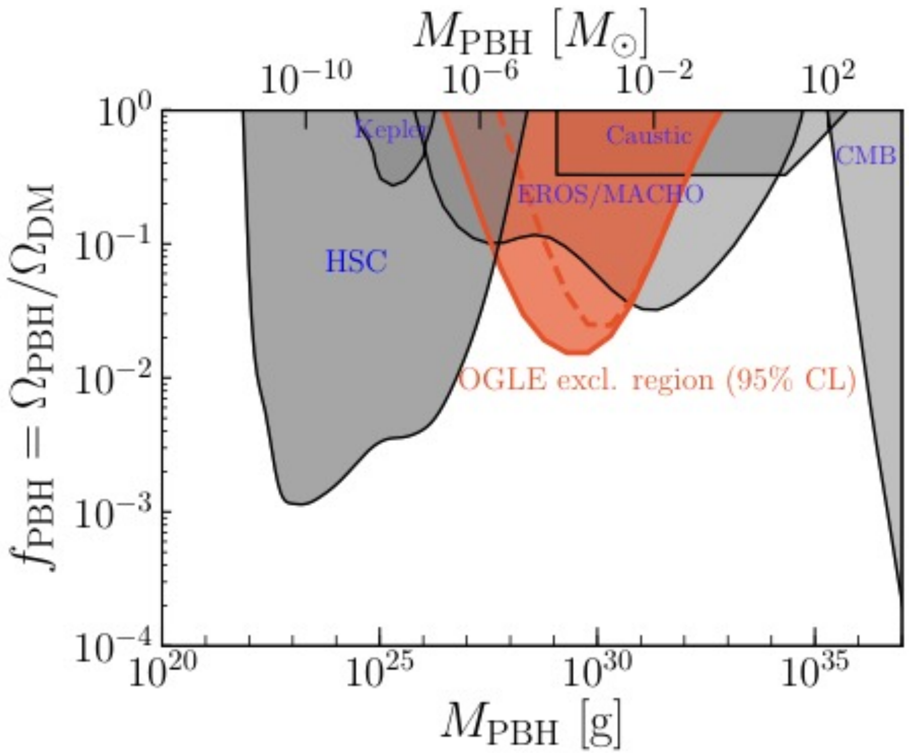
arXiv:1910.01285

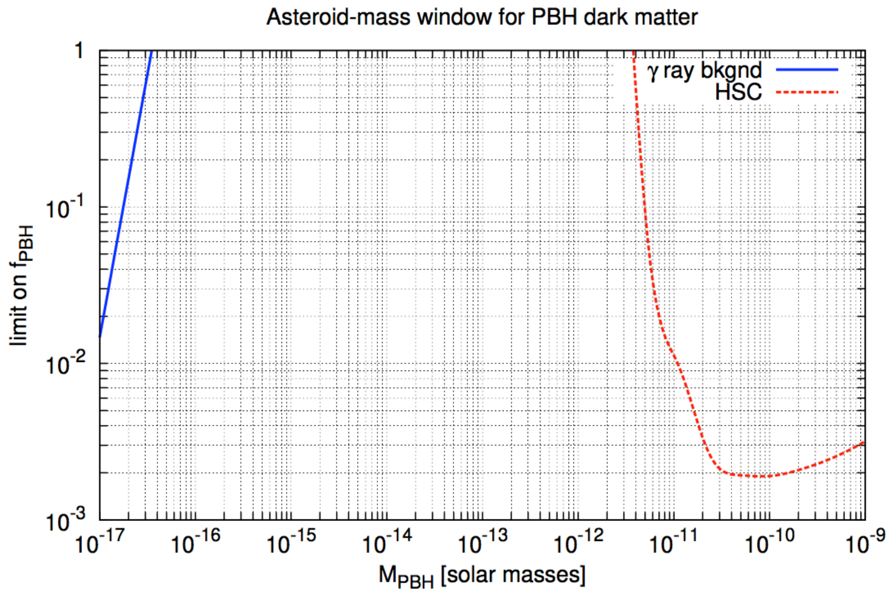


Earth-mass black holes? – Constraints on primordial black holes with 5-years OGLE microlensing events

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

arXiv:1901.07120





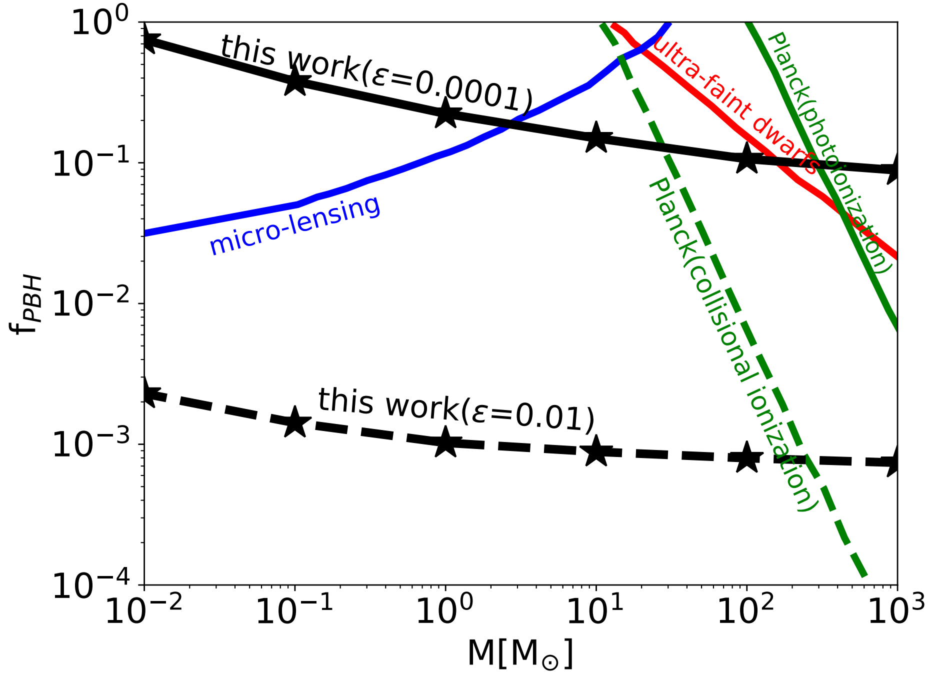
Revisiting constraints on asteroid-mass PBHs as DM candidates

Paulo Montero-Camacho arXiv:1906.05950

Sunyaev-Zel'dovich anisotropy due to Primordial black holes

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

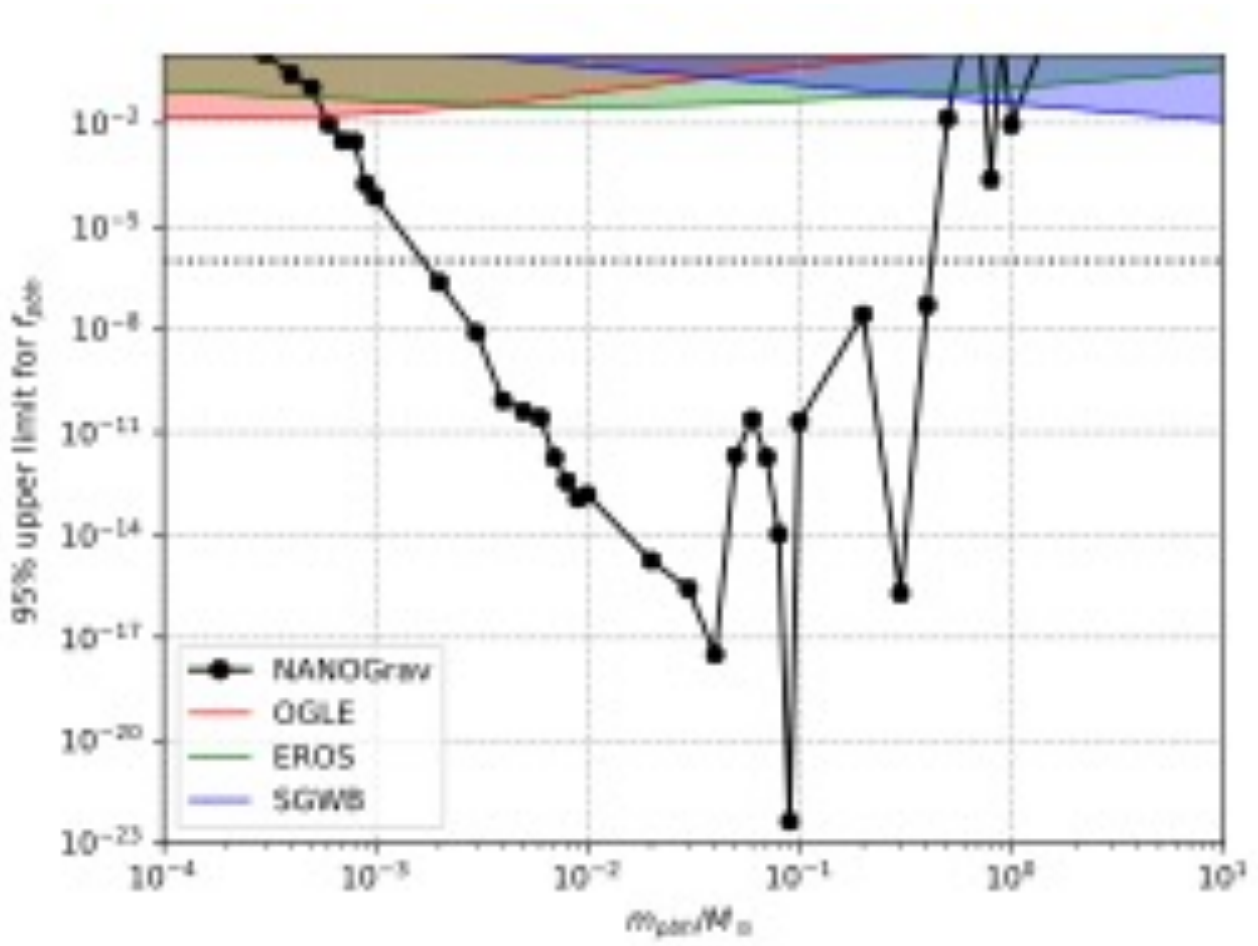
arXiv:1901.06809



Pulsar Timing Array Constraints on PBHs with NANOGrav...

Zu-Cheng Chen,1Chen Yuan and Qing-Guo Huang1

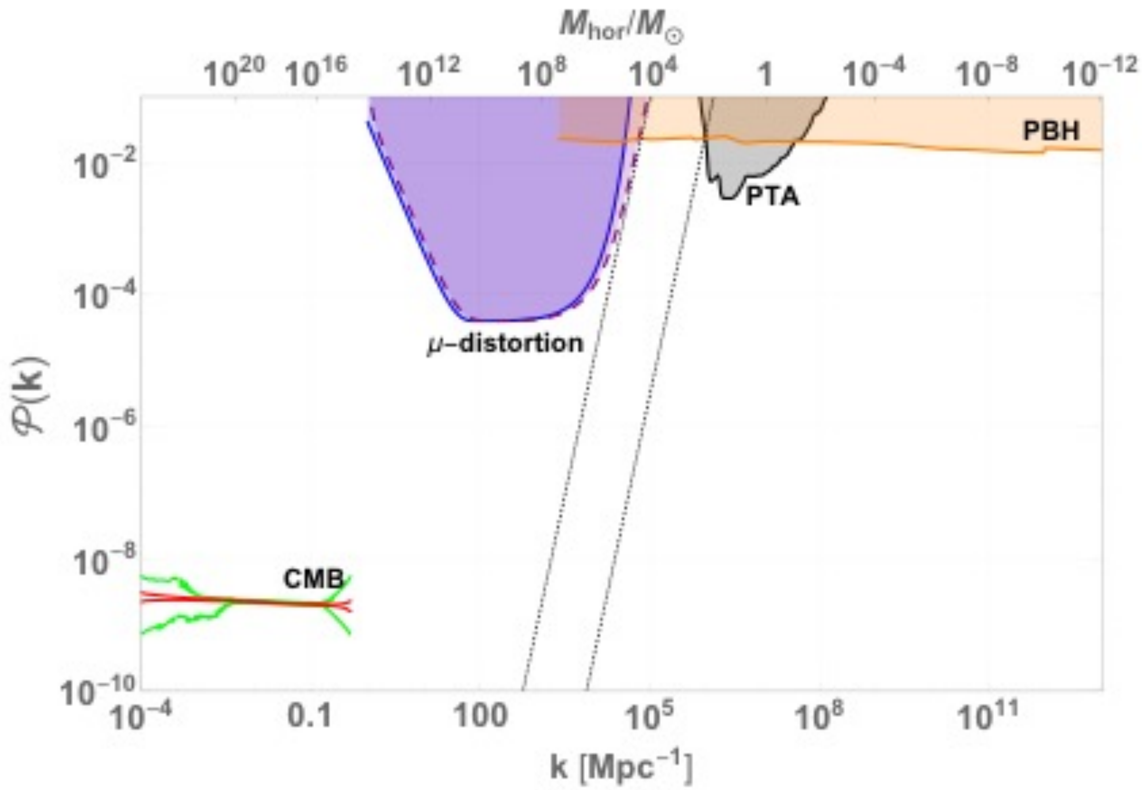
arXiv:1910.12239



Steepest growth of the power spectrum and PBHs

Byrnes, Cole and Patil

arXiv:1811.11158



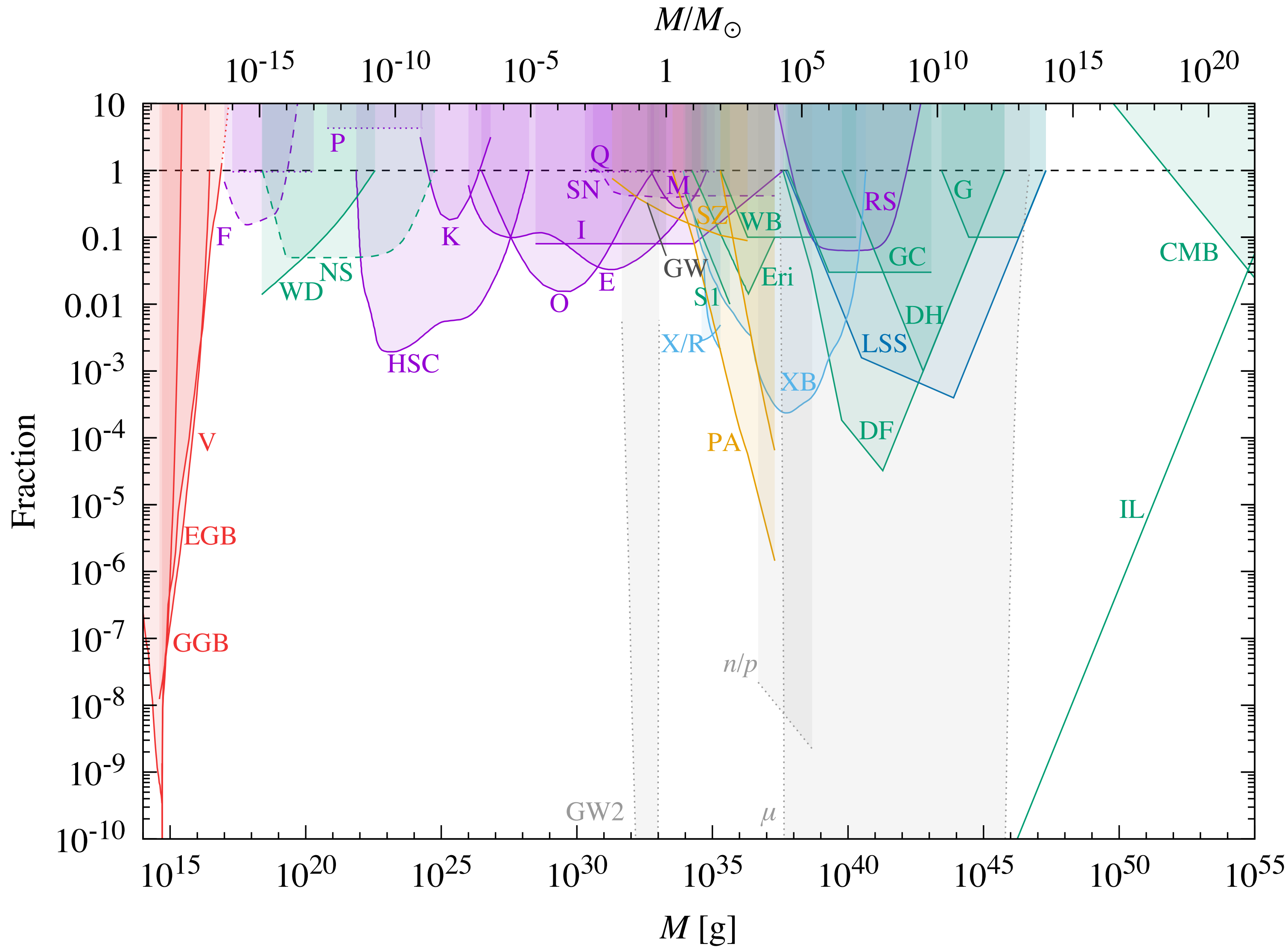
Dissecting the growth of the power spectrum for PBHs

Carrilho, Malik and Mulryne arXiv:1907.05237

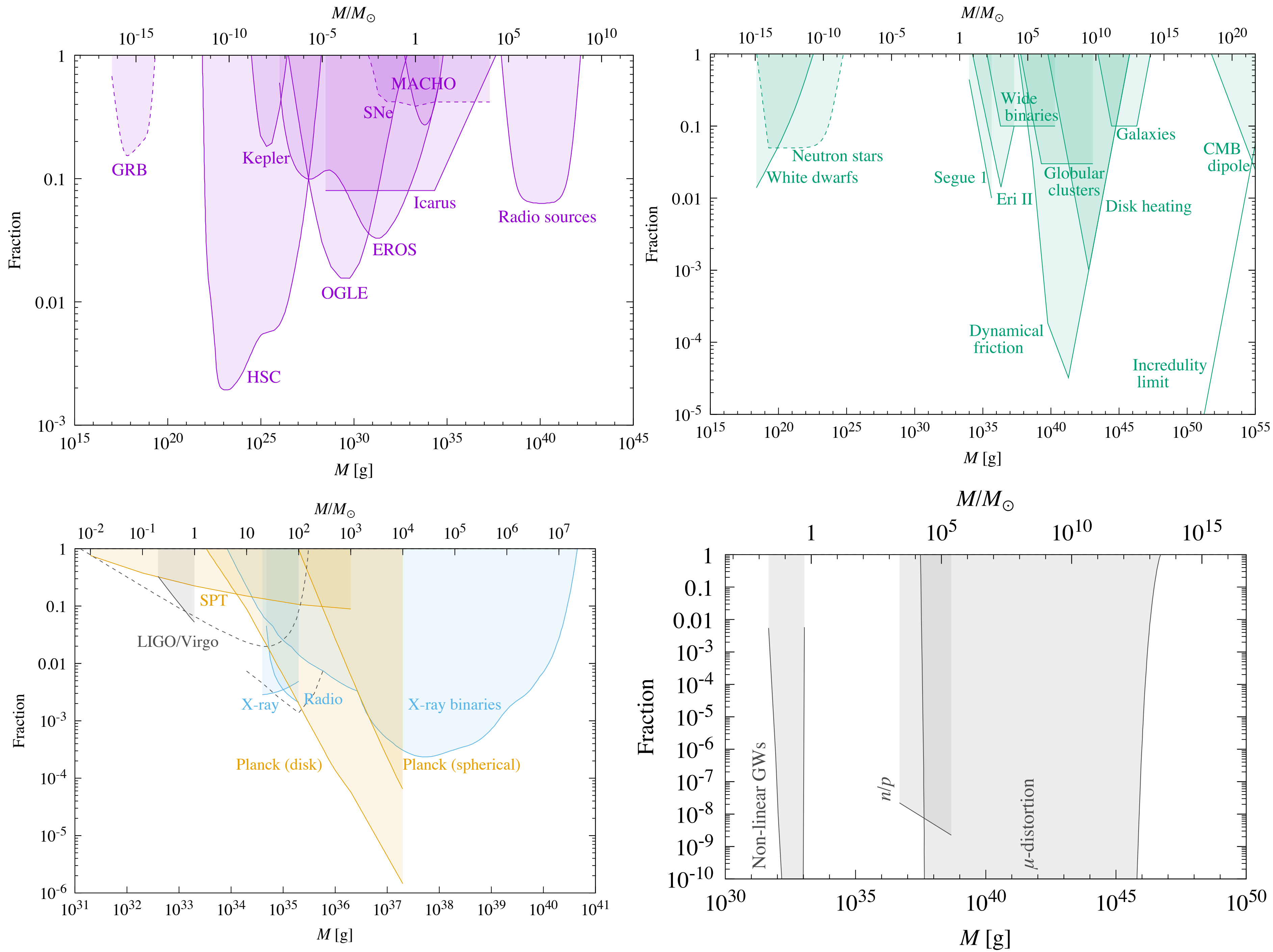
CONSTRAINTS ON PRIMORDIAL BLACK HOLES

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

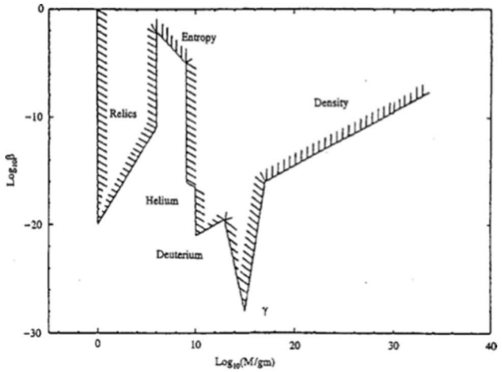
Progress Theoretical Physics (2019)

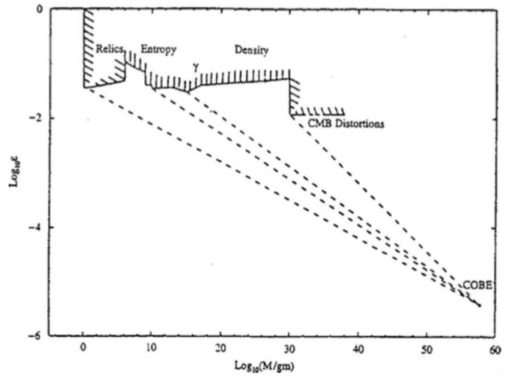


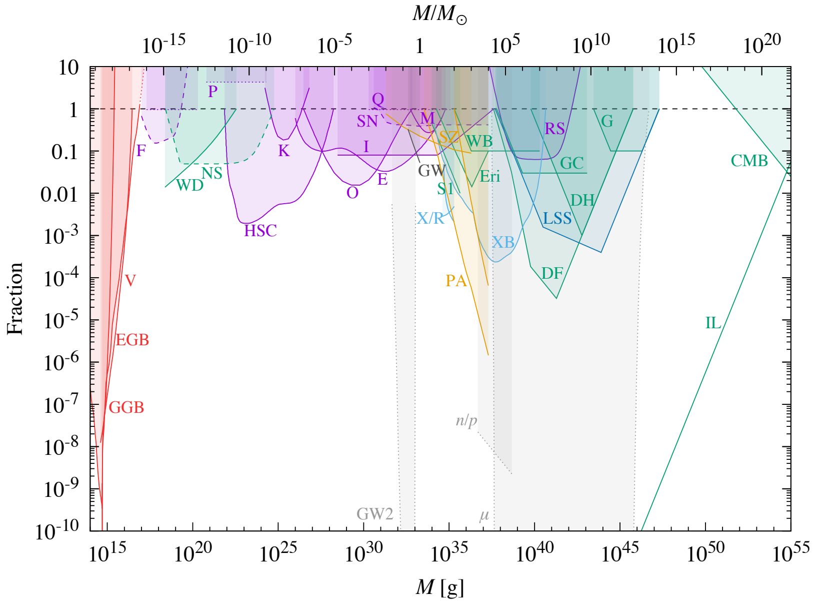
LENSING, DYNAMICAL, ACCRETION AND COSMOLOGICIAL LIMITS

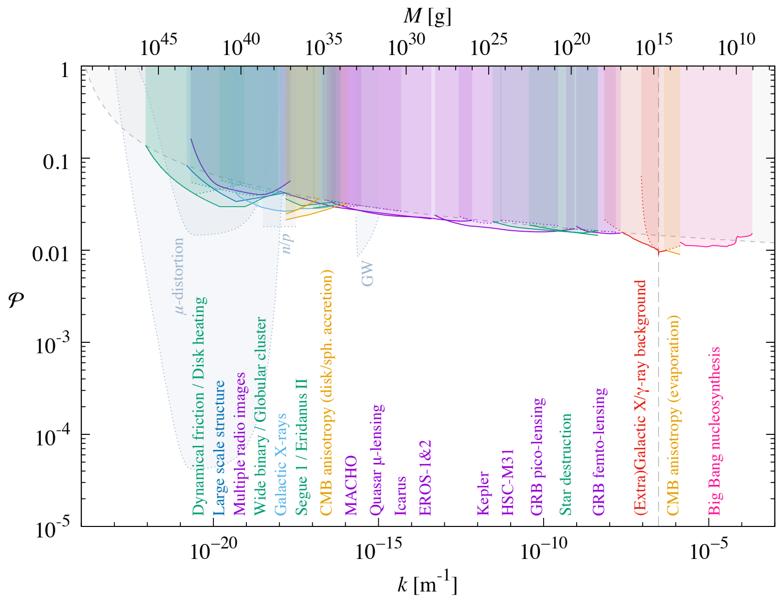


CONSTRAINTS ON POWER SPECTRUM









From PBH Abundance to Primordial Curvature Power Spectrum

Kalaja et al arXiv: 1908.03596

Constraints on the primordial curvature power spectrum from PBHs

Sato-Polito, Kovetz and Kamionkowski arXiv:1904.10971

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

Alex Kusenko

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

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

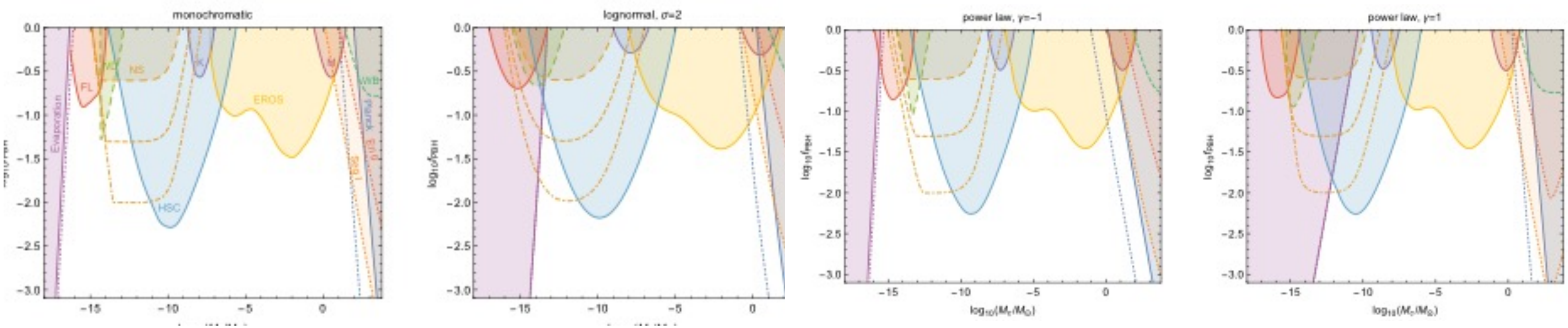
2 parameters (M_c,σ)

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

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

f(M) limits themselves depend on PBH mass function

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



PRIMORDIAL BLACK HOLES AS DARK MATTER

PRO

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

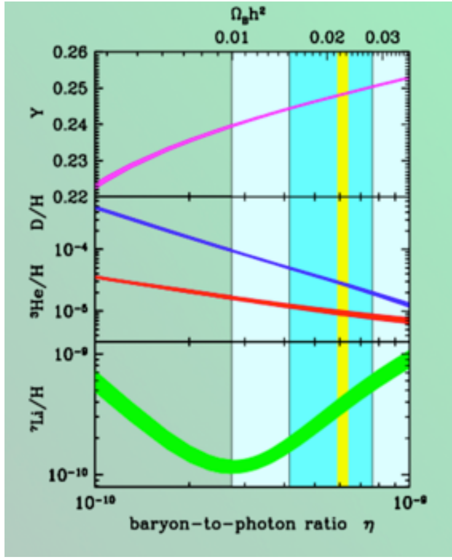
CON

* 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

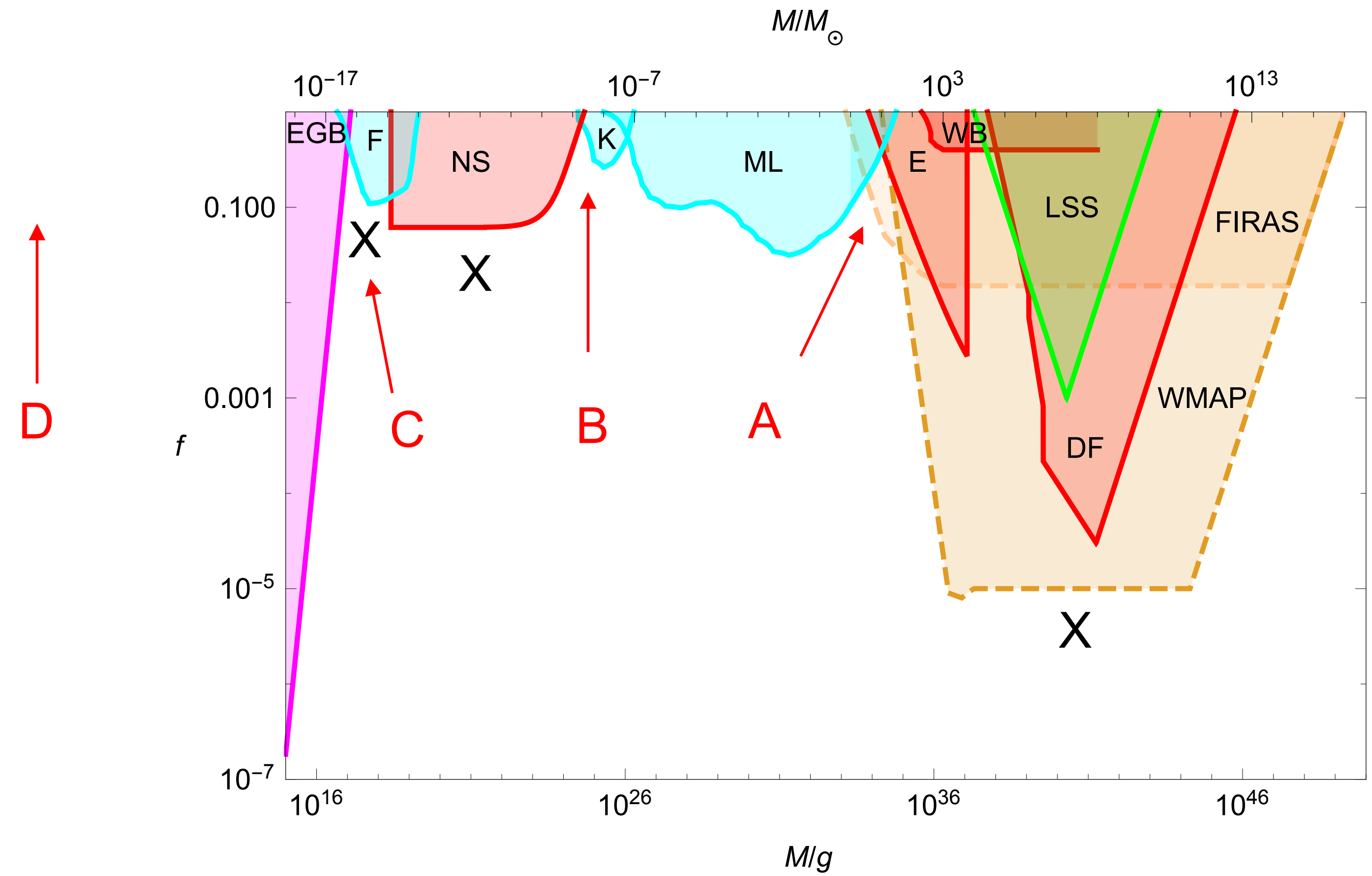
MACHOs WIMPs

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

PRIMORDIAL BLACK HOLES AS DARK MATTER

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

PRD 94, 083504, arXiv:1607.06077



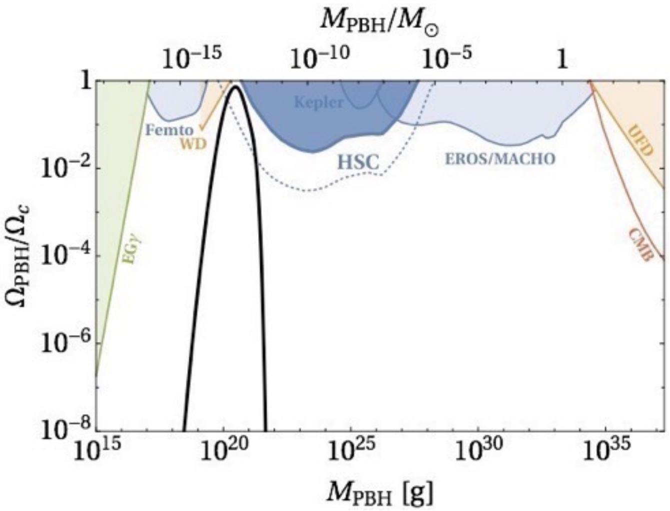
Three windows: (A) intermedate mass; (B) sublunar mass; (C) asteroid mass.

Also (D) Planck mass relics?

WHICH MASS WINDOW IS MOST PLAUSIBLE?

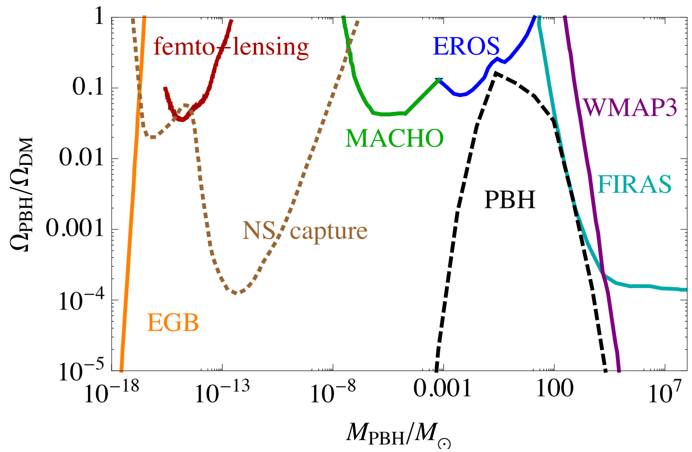
PBH dark matter @10^{20}g
from double inflation

Inomata et al
arXiv:1701.02544

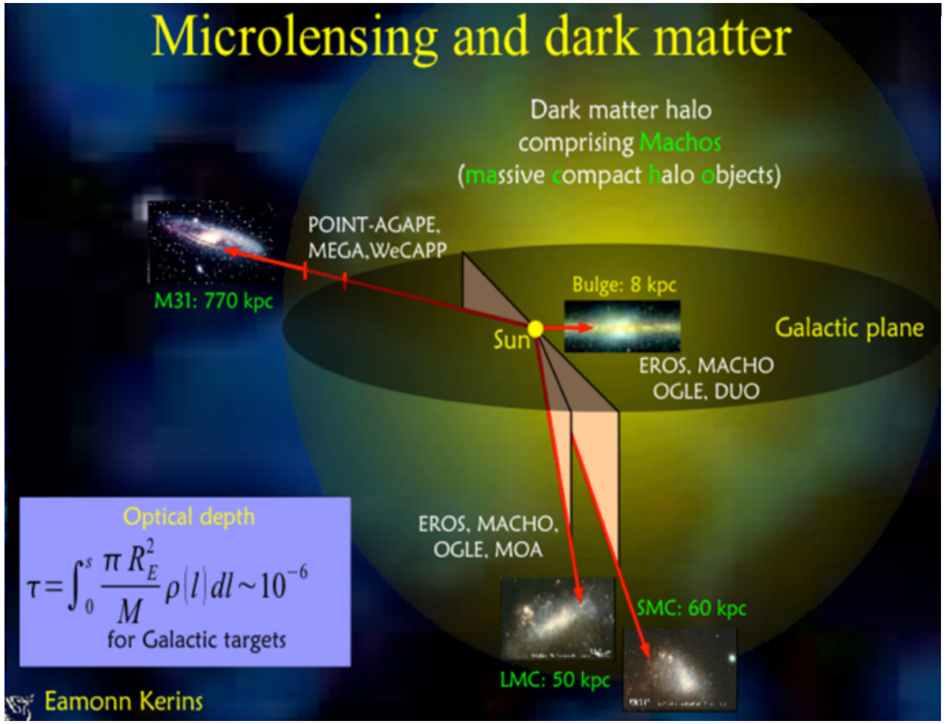


PBH dark matter @10 M_o
from hybrid inflation

Clesse & Garcia-Bellido
arXiv:1501.07565



cf. light versus heavy dark matter particle



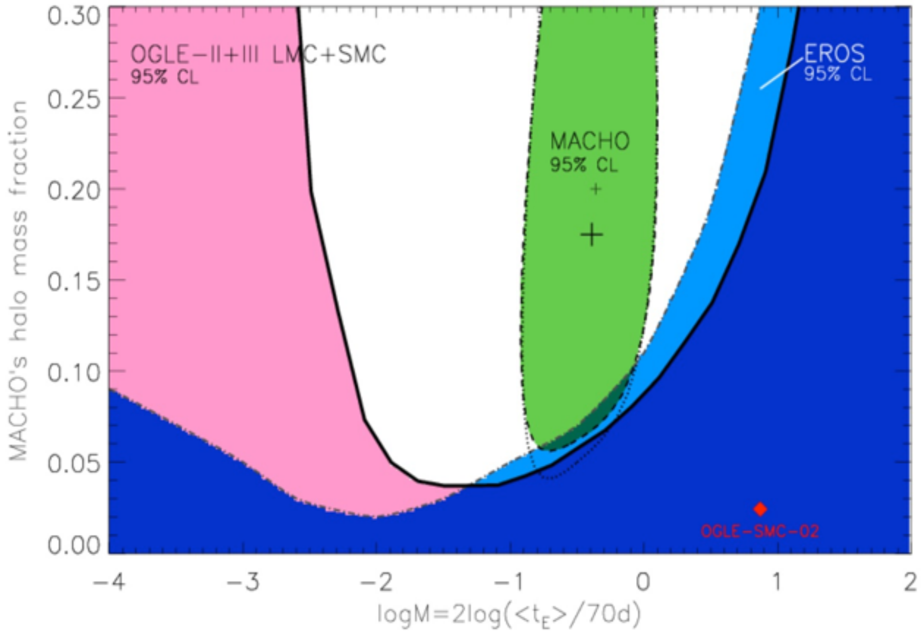


Image credit: Wyrzykowski et al., 2011, MNRAS, (astro-ph/1106.2925).

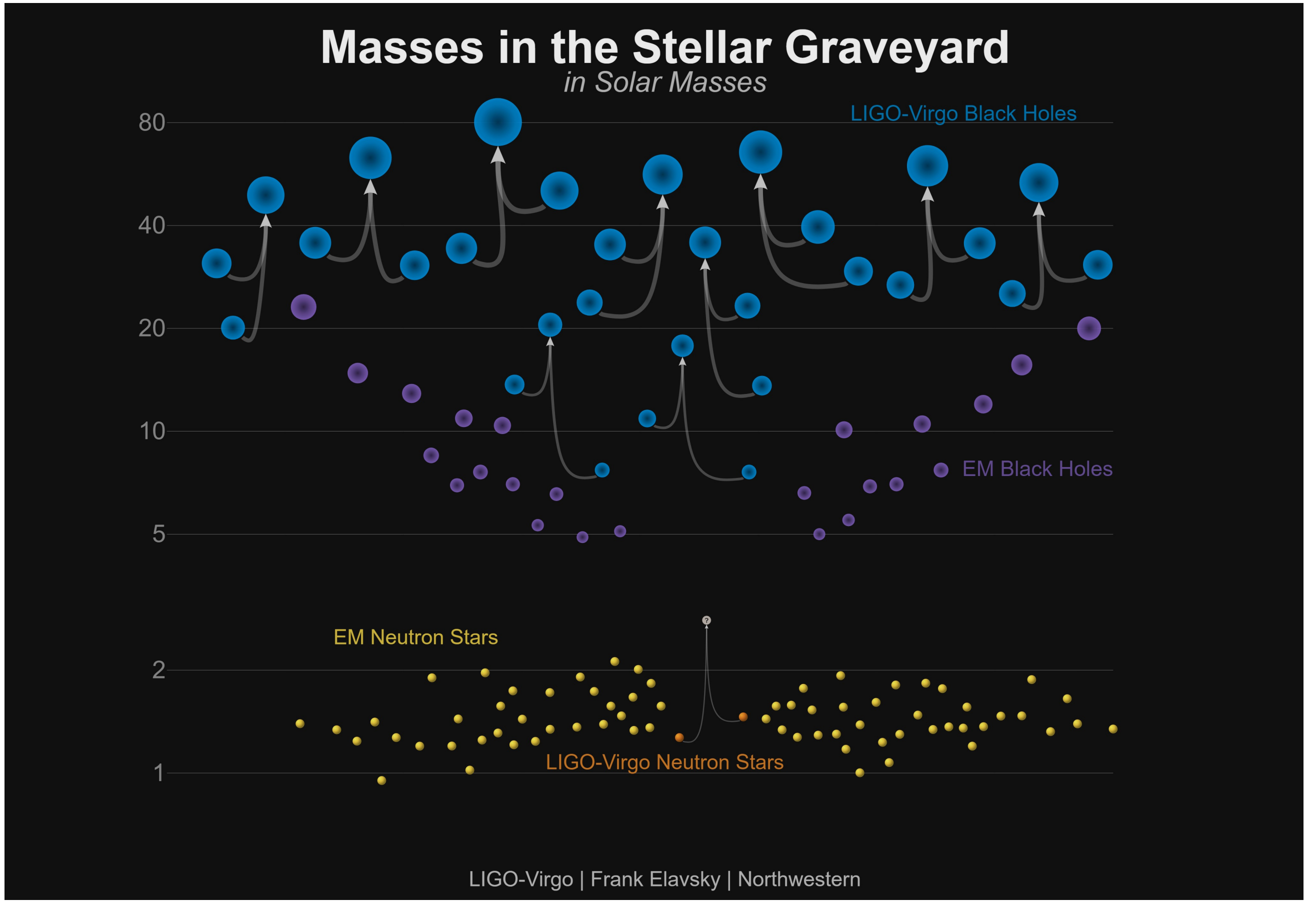
Early microlensing searches suggested MACHOs with 0.5 M_O

=> 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

PBHS AND LIGO/Virgo



Do we need Population III or primordial BHs?

Prescience of Japanese!

GRAVITATIONAL WAVES FROM COALESCING BLACK HOLE MACHO BINARIES

Takashi Nakamura, Misao Sasaki, Takahiro Tanaka and Kip Thorne

THE ASTROPHYSICAL JOURNAL, 487:L139–L142, 1997

If MACHOs are black holes of mass ~0.5 $M_{\odot}$, they must have been formed in the early universe when the temperature was ~1 GeV. We estimate that in this case in our Galaxy's halo out to ~ 50 kpc there exist ~5 × 10^{8} black hole binaries the coalescence times of which are comparable to the age of the universe, so that the coalescence rate will be ~5 × 10^{-2} events yr^{-1} per galaxy. This suggests that we can expect a few events per year within 15 Mpc. The gravitational waves from such coalescing black hole MACHOs can be detected by the first generation of interferometers in the LIGO/VIRGO/TAMA/GEO network. Therefore, the existence of black hole MACHOs can be tested within the next 5 yr by gravitational waves.

POSSIBLE INDIRECT CONFIRMATION OF THE EXISTENCE OF POP III MASSIVE STARS BY GRAVITATIONAL WAVES

Tomaya Kinagawa, Kohei Inayoshi, Kenta Hotokezaka, Daisuka Nakauchi and Tahashi Nakamura

MNRAS **442,** 2963–2992 (2014

We perform population synthesis simulations for Population III (Pop III) coalescing compact binary which merges within the age of the Universe. We found that the typical mass of Pop III binary black holes (BH–BHs) is $\sim 30\,M_{\odot}$ so that the inspiral chirp signal of gravitational waves can be detected up to $z = 0.28$ by KAGRA, Adv. LIGO, Adv. Virgo and GEO

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 $M_{\odot}$ binaries may provide observed rate of 2-53 $Gpc^{-1} yr^{-1}$

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

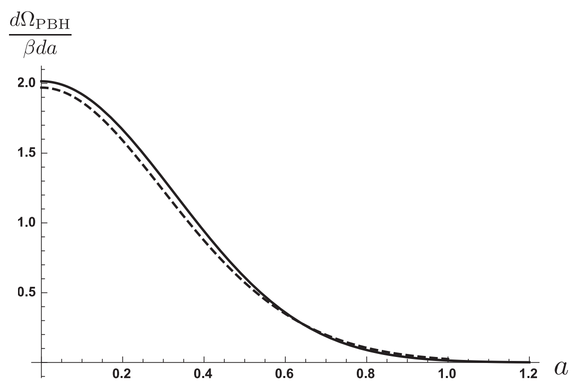
Spin Distribution of Primordial Black Holes

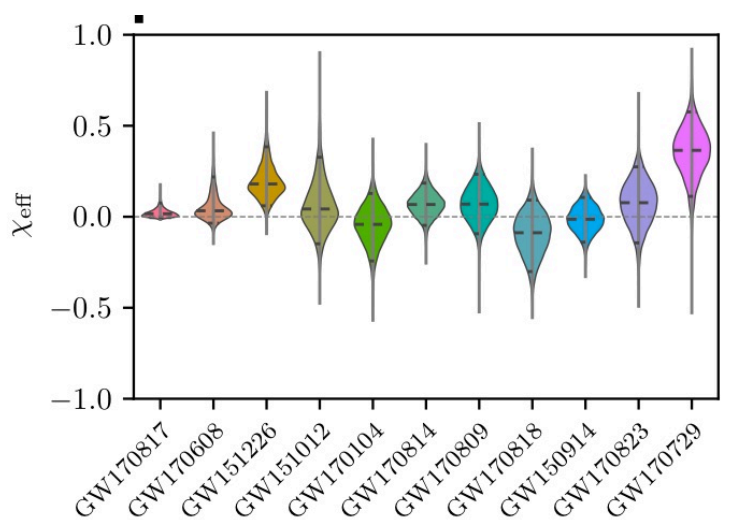
Takeshi Chiba[1] and Shuichiro Yokoyama[2]

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.





Unraveling origin of BHs from effective spin measurements with LIGO-Virgo

Fernandez and Profumo arXiv:1905.13019

RECENT PAPERS

Merger rates in primordial black hole clusters without initial binaries
Korol et al. arXiv:1911.033483

Search for sub-solar mass ultracompact binaries in Advanced LIGO…
LIGO/Virgo collaboration arXiv:1904.08976

Constraining the abundance of PBHs with gravitational lensing of gravitational waves at LIGO frequencies
Jose M. Diego arXiv:1911.05736

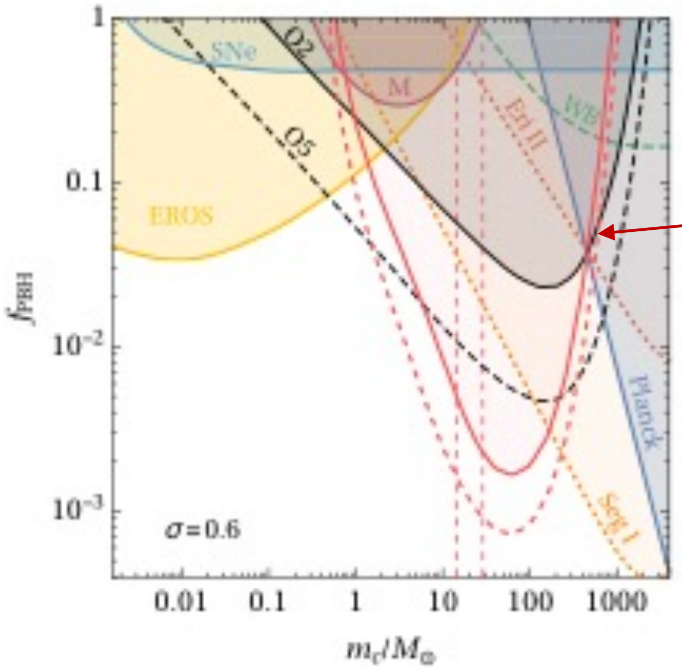
Merger rates in primordial black hole clusters without initial binaries
Korol et al. arXiv:1911.033483

Search for sub-solar mass ultracompact binaries in Advanced LIGO…
LIGO/Virgo collaboration arXiv:1904.08976

Constraining the abundance of PBHs with gravitational lensing of gravitational waves at LIGO frequencies
Jose M. Diego arXiv:1911.05736

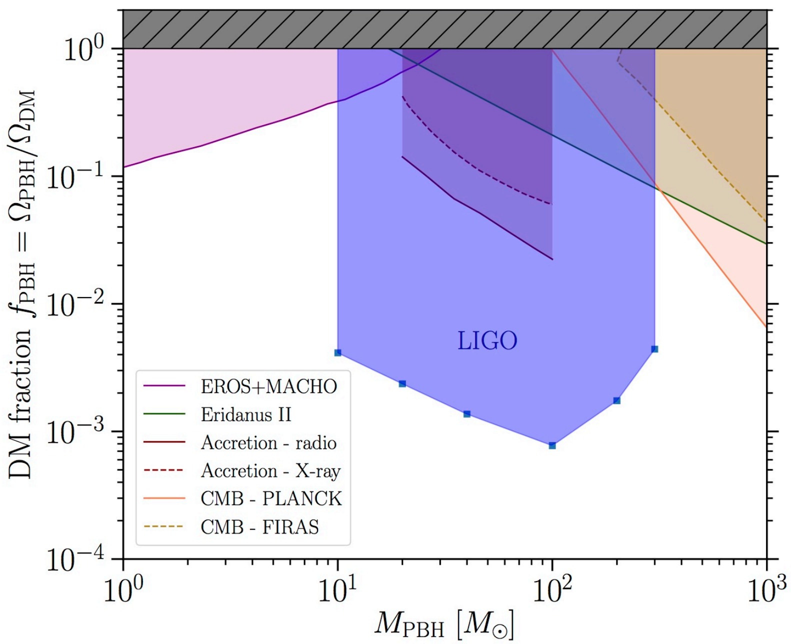
LIGO/VIRGO PBH CONSTRAINTS

Raidal et al.
arXiv:1812.01930



LIGO
limit

Kavanagh et al
arXiv:1805.09034



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 $(M/10^4 M_o)^{-1}$

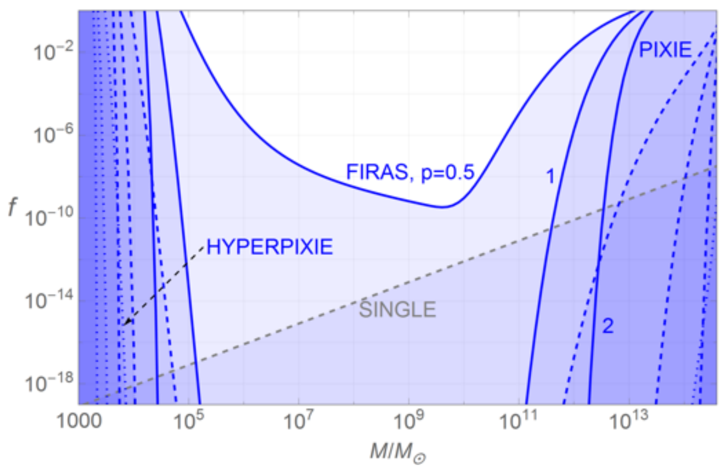
Dolgov talk

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.



ADDRESSING FINE-TUNING PROBLEM

Primordial black holes, dark matter and hot-spot electroweak baryogenesis at the quark-hadron epoch

Bernard Carr[a,b], Sebastien Clesse[c,d], Juan García-Bellido[e*]

arXiv:1904.02129

A common origin of baryons and dark matter via the gravitational collapse of black holes in the early universe

Juan García-Bellido[a],[*] Bernard Carr[b,c],[†] and Sébastien Clesse[d,e‡]

arXiv:1904.11482

Cosmic Conundra Explained by Thermal History and Primordial Black Holes

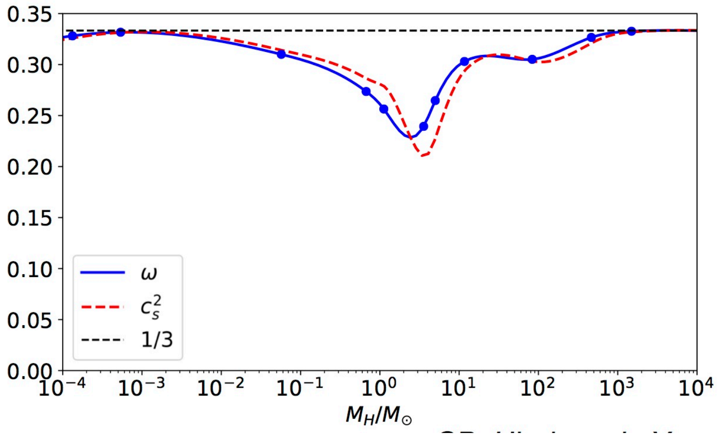
Bernard Carr,[1, 2, *] Sébastien Clesse,[3, 4, †] Juan García-Bellido,[5, ‡] and Florian Kühnel[6, §]

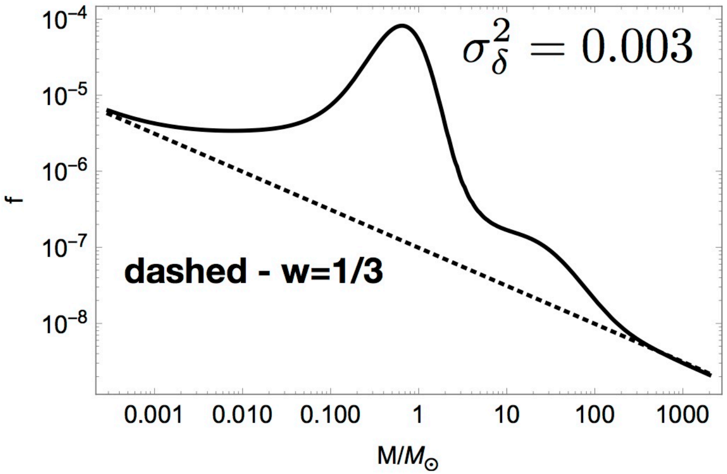
arXiv:1906.08217

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), Cardal & Fuller (1998)

ADDRESSING FINE-TUNING PROBLEM AT QCD EPOCH

PBHs forming at time t have mass and collapse fraction

$$M \sim 10^5 (t/s)\, M_O, \quad \beta(M) \sim 10^{-9} f(M)\, (M/M_O)^{1/2}$$

So β appears fine-tuned and we must also explain why

$$\chi = \rho_{PBH}/\rho_B = f\, \rho_{DM}/\rho_B = 6 f \text{ is } O(1).$$

$\chi >> 1$ => $t_{eq} << t_{dec}$ => 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

$M_C \sim \alpha_G^{-3/2} m_P \sim 1 M_O$ is Chandra' mass ($\alpha_G \sim 10^{-38}$) and all stars have mass in range (0.1–10) M_C

ANTHROPIC CONSTRAINTS ON χ AND η

$$t_{\rm dec} \sim 10\,(1+\chi)^{-1/2}\eta^{-1/2}\alpha_{\rm G}^{-1/2}\alpha^{-6}t_{\rm p} \sim 10^{13}\,(1+\chi)^{-1/2}{\rm s}$$

$$t_{\rm eq} \sim (1+\chi)^{-2}\eta^{-2}\alpha_{\rm G}^{-1/2}t_{\rm p} \sim 10^{12}\,(1+\chi)^{-2}{\rm s}\,.$$

where

$$\alpha \equiv e^2/(\hbar\, c) \sim 10^{-2} \qquad \alpha_{\rm G} \equiv G m_{\rm p}^2/(\hbar c) = m_{\rm p}^2/M_{\rm P}^2 \approx 6\times 10^{-39}$$

$\chi = 6$ $$\eta \equiv n_{\rm b}/n_\gamma = 2.8\times 10^{-8}\Omega_{\rm b}h^2 = 6.1\times 10^{-10}$$

Formation of galaxies requires

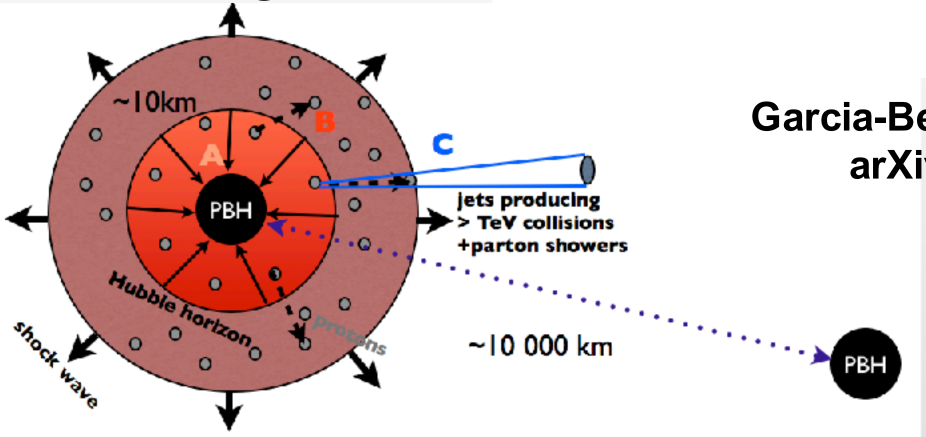
$$t_{\rm eq} \sim t_{\rm dec} \quad \textbf{=>} \quad \eta \sim 0.1\,(1+\chi)^{-1}\alpha^4 \sim 10^{-9}(1+\chi)^{-1}$$

Lifetime of star exceeds t_{eq} for

$$\eta > (1+\chi)^{-1}\alpha_G^{1/4} \sim 10^{-10}$$

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)

$$\Delta K \simeq \left(\frac{1}{\gamma} - 1\right) M_{\rm H} \qquad E_0 = \frac{\Delta K}{n_{\rm p}\,\Delta V} \qquad k_{\rm B}T_{\rm eff} = \frac{2}{3}E_0 \simeq 5\,{\rm TeV}$$

$$\delta_{\rm CP}(T) = 3\times 10^{-5}\,(20.4\,{\rm GeV}/T)^{12}$$ above sphaleron barrier

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

Baryogenesis scenario

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 $\chi \sim 1$

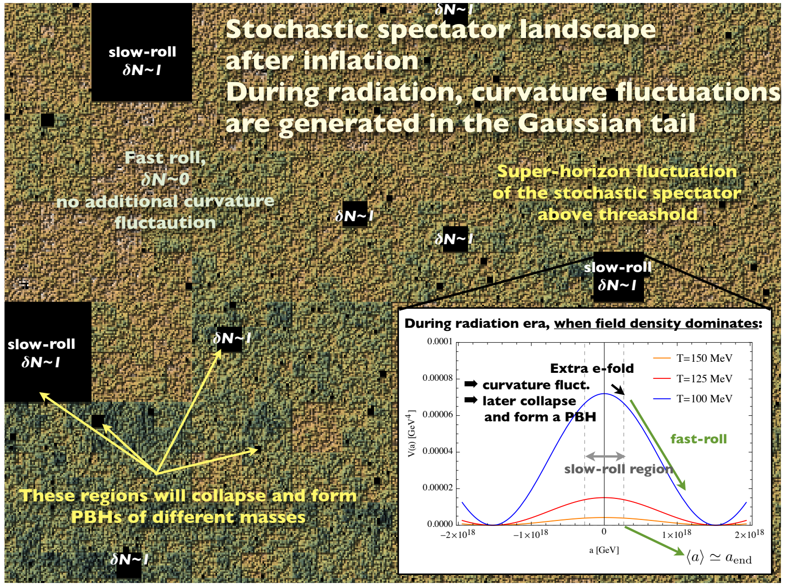
Curvature perturbation scenario

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.

Primordial Black Holes

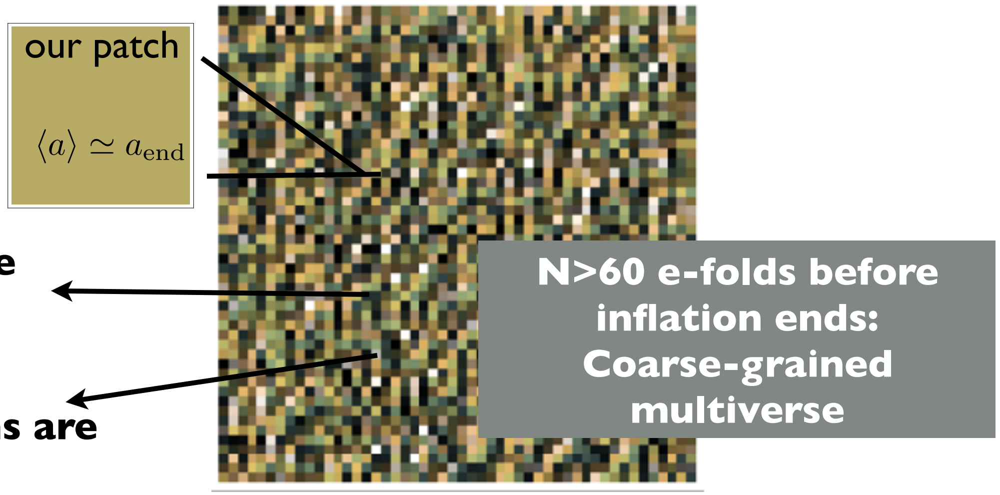
without parameter fine-tuning



- Light **stochastic spectator** field during inflation (e.g. QCD axion)
- Plateau or small-field potential
- Domination before QCD epoch
- **No parameter tuning**

In the stochastic spectator scenario: no parameter tuning,
but unavoidable **anthropic selection** due to the field **stochasticity**

These regions exist!
quantum fluctuations
cannot be avoided...



radiation dominated Universe

Shorter Silk damping scale,
overabundance of
DM subhaloes, all the baryons are
accreted by PBH

PBH mass function

- 'Standard' PBH formation scenario: $\beta = \mathrm{erfc}(\zeta_{\rm tr}/\sqrt{2\sigma^2})$.
- Light Stochastic Spectator: $m_\psi \ll H_{\rm inf}$ and $\Delta\psi^{\rm stoch} \sim H/2\pi$

$$\langle\delta\psi^2\rangle \simeq \int_0^N \frac{H(N')^2}{4\pi^2}\mathrm{d}N' \simeq \frac{H^2_{\rm CMB}}{8\pi^2\epsilon_1}\left(1-\mathrm{e}^{-2\epsilon_1 N}\right) \qquad P(\psi,N) = \frac{1}{\sqrt{2\pi\langle\delta\psi^2\rangle}}\exp\left[-\frac{(\psi-\langle\psi\rangle)^2}{2\langle\delta\psi^2\rangle}\right]$$

Probability of a local field fluctuation: $P(\Delta\psi,N) = \frac{1}{\sqrt{2\pi(H(N)^2/4\pi^2)}}\exp\left[-\frac{\Delta\psi^2}{2(H(N)^2/4\pi^2)}\right]$.

Case 1:
$\Delta\psi^{\rm sr} \gg \Delta\psi^{\rm stoch}$
Plateau pot.

Proba. that the field lies in the slow-roll region

$$P_{\rm PBH} = \frac{\mathrm{d}\beta(t)}{\mathrm{d}\ln M} = \frac{1}{4}\mathrm{erfc}\left[\frac{\boxed{\psi_{\rm cr}} - \langle\psi\rangle}{\sqrt{2\langle\delta\psi^2\rangle}}\right]\mathrm{erfc}\left[\frac{\boxed{\Delta\psi_{\rm tr}}}{\sqrt{2}H(N)/(2\pi)}\right]$$

Proba. of fluctuation leading to extra N~(1)

Potential dependent, fixed by field dynamics

Case 2
$\Delta\psi^{\rm sr} \ll \Delta\psi^{\rm stoch}$
Small field pot.

Symmetric potential (for simplicity):

$$P_{\rm PBH} = \sqrt{\frac{2}{\pi}}\frac{\boxed{\Delta\psi^{\rm sr}}}{\sqrt{H_N^2/(4\pi^2)+\langle\delta\psi^2\rangle_{N-1}}}\exp\left[-\frac{\langle\psi\rangle^2}{2(H_N^2/4\pi^2+\langle\delta\psi^2\rangle_{N-1})}\right]$$

Proba. to get a field value leading to extra N~(1)

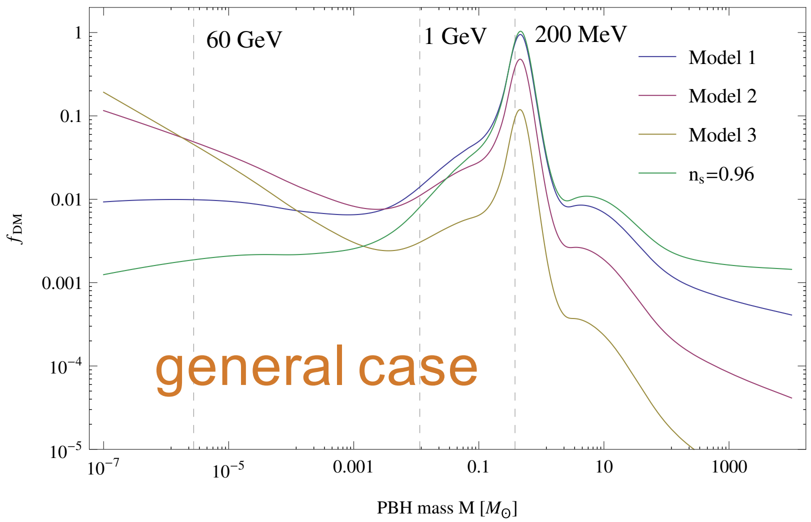
In both cases, the PBH mass function 'mimics' the standard scenario.

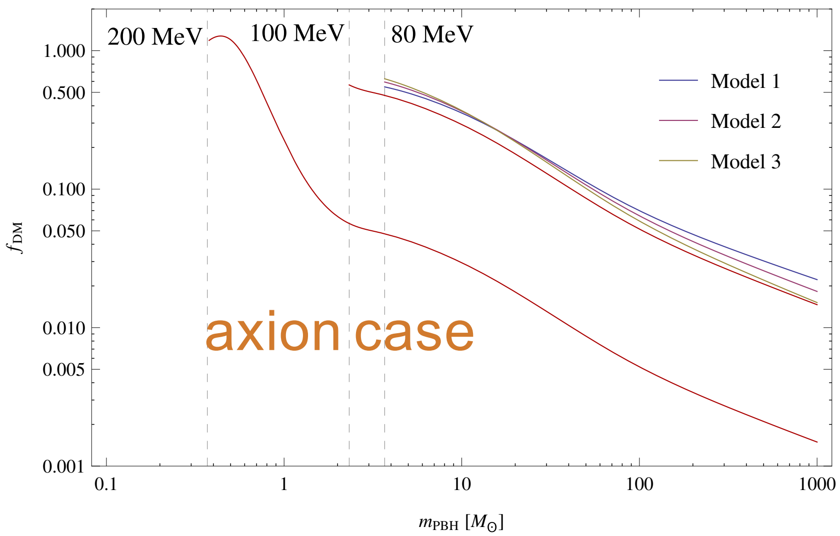
With anthropic selection of $\langle\psi\rangle$ one gets PBH-DM with $A_{\rm s} = 2.1\times10^{-9} \simeq \frac{H_*^2}{8\pi\epsilon_{1*}M_{\rm P}^2}$

PBH MASS FUNCTION

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

.



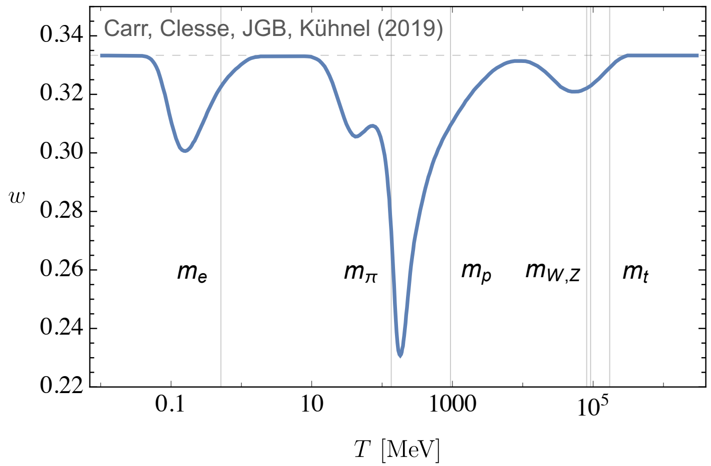


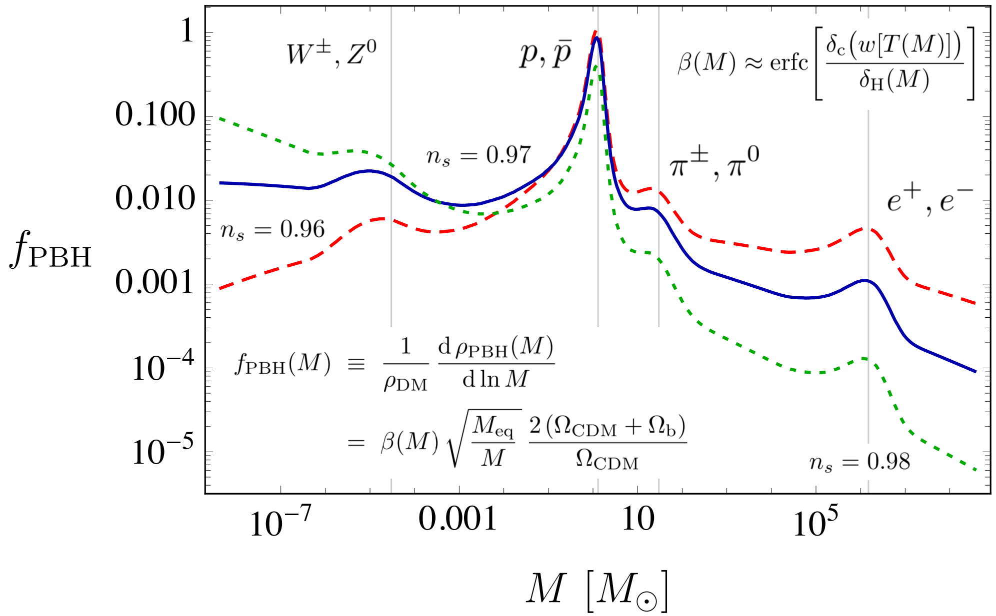
1st peak at $1 M_O$ for DM plus 2nd peak at 10-20 M_O for LIGO events

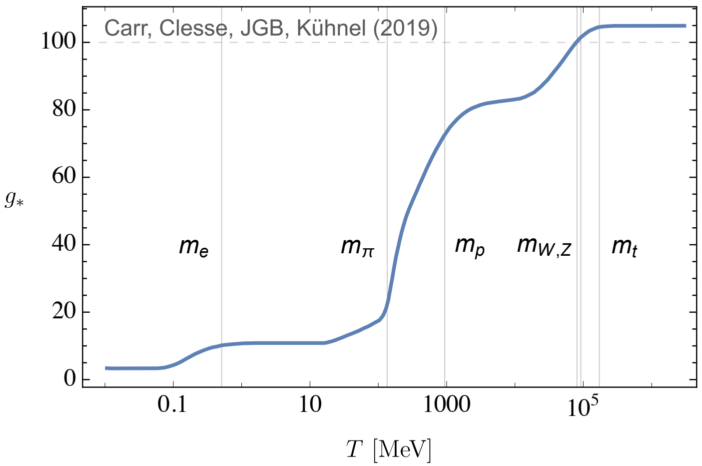
Cosmic Conundra Explained by Thermal History and Primordial Black Holes

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

Extend this to include other stages in thermal history

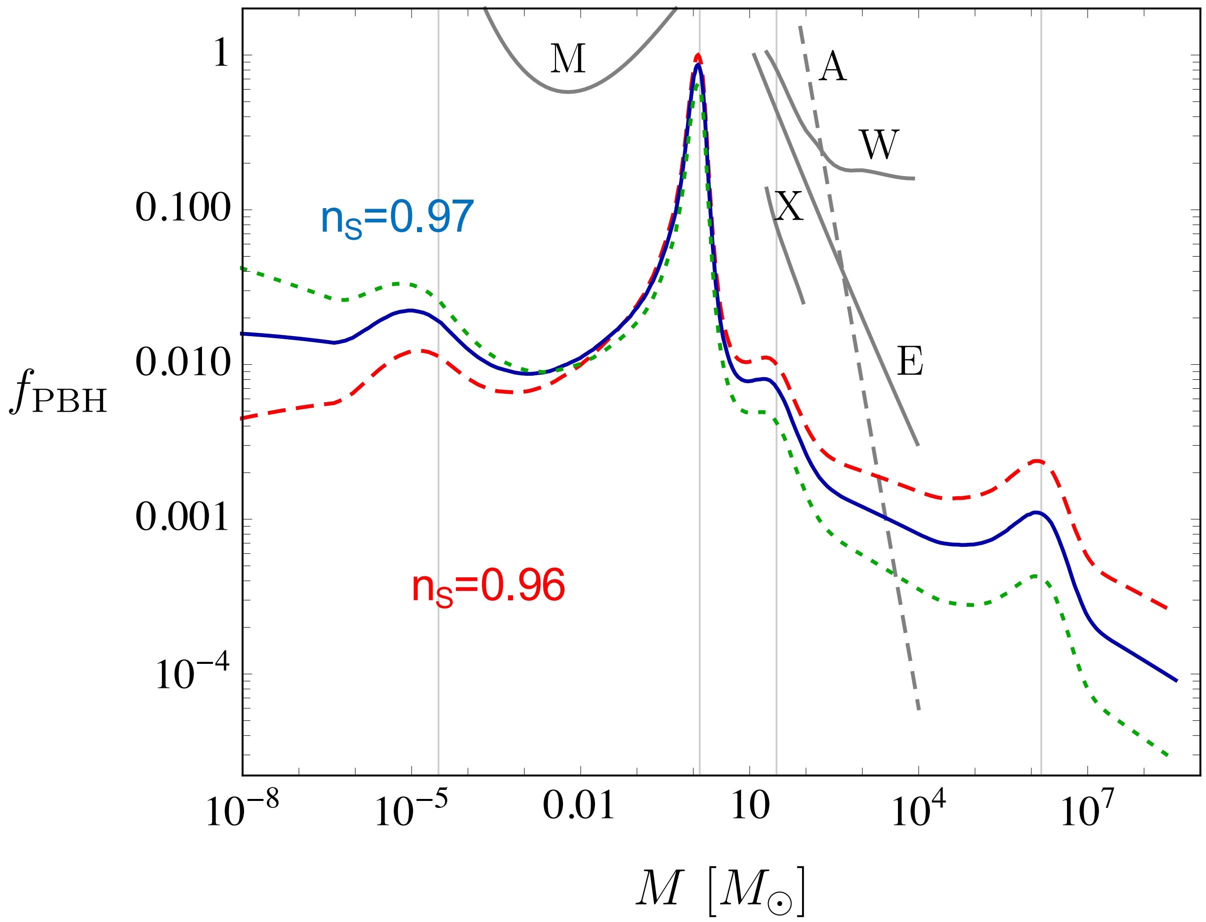






- **Nearly scale-invariant PS**
- **Spectral index: $n_s = 0.97$**
- **Peak at ~2 $M_\odot$**
- **Second peak at ~30 $M_\odot$**
- **Two bumps at 10^{-6} and 10^6 $M_\odot$**

CONSTRAINTS



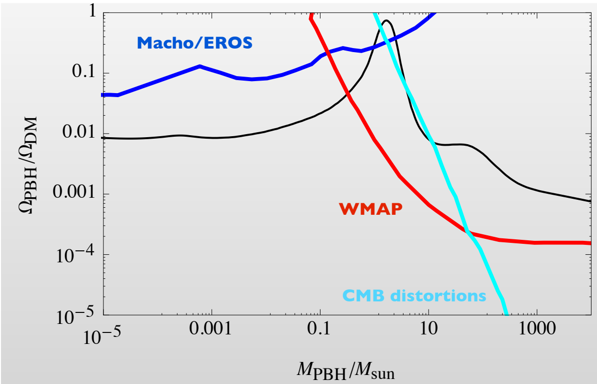
$$\delta_{\rm rms}(M) = A\left(\frac{M}{M_\odot}\right)^{(1-n_{\rm s})/4}$$

Overproduce light PBHs for $n_S > 0.975$

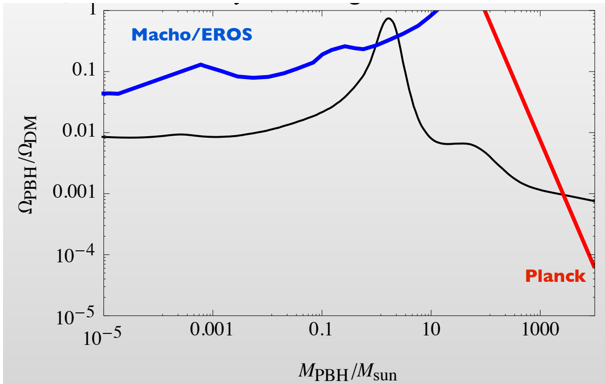
Overproduce heavy PBHs for $n_S < 0.965$

IS PREDICTED MASS FUNCTION ALLOWED BY PBH LIMITS?

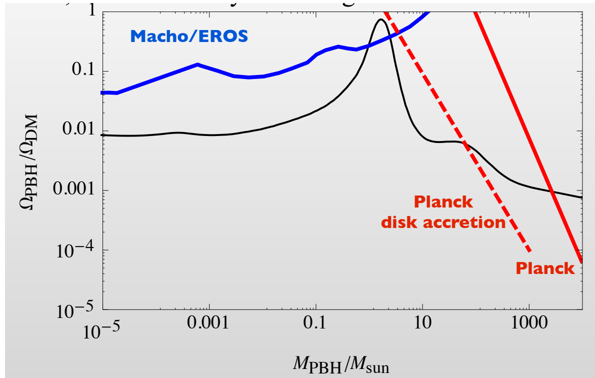
(monochromatic case)



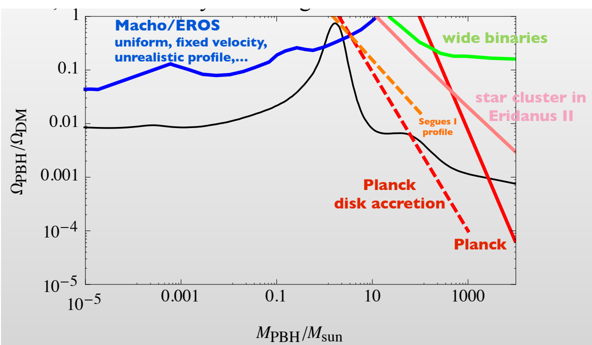
Pre 2016

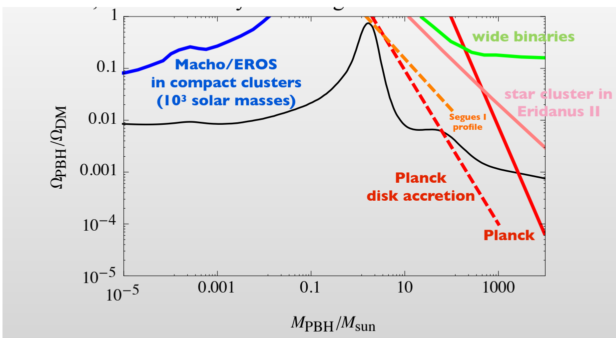


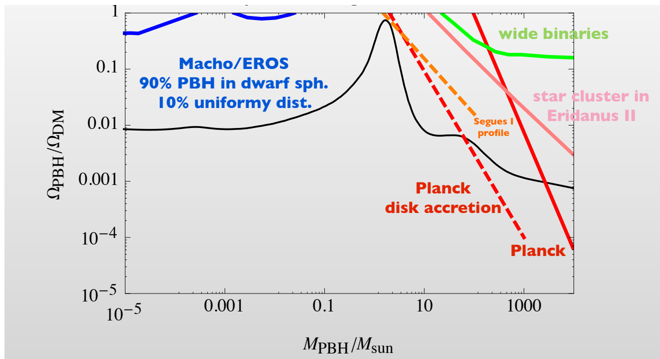
Ali-Hamoud & Kamionkowski
arXiv:1612.05644



Poulin, Serpico, Clesse & Kohri
arXiv:1707.04206





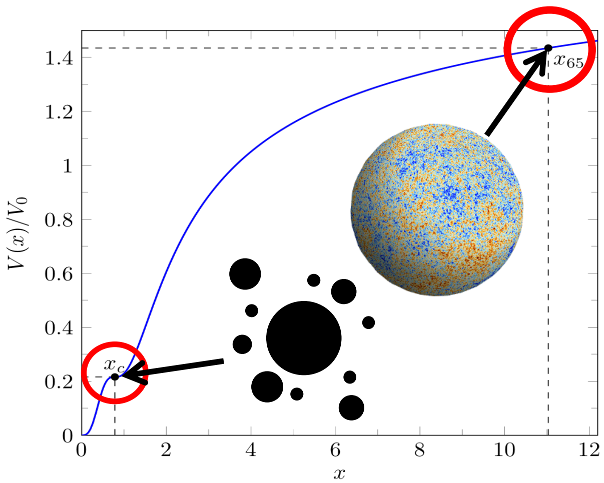


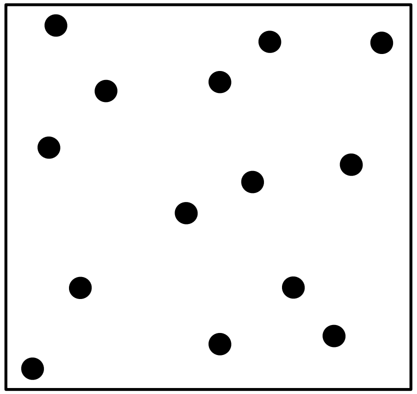
Green
arXiv:1705.10818,1707.04206

ARE PBHS CLUSTERED?

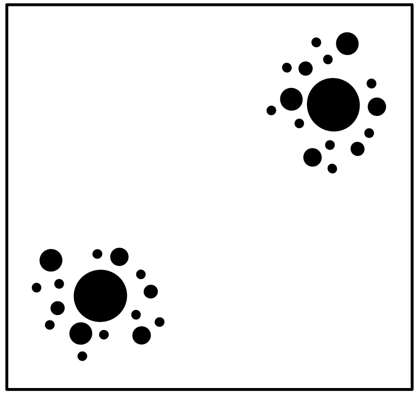
Inflation =>

- Lognormal wide-mass distribution   JGB & Clesse (2017)
- Clusters of PBH: N_{cl} ~100-1000 , comoving size ~1mpc





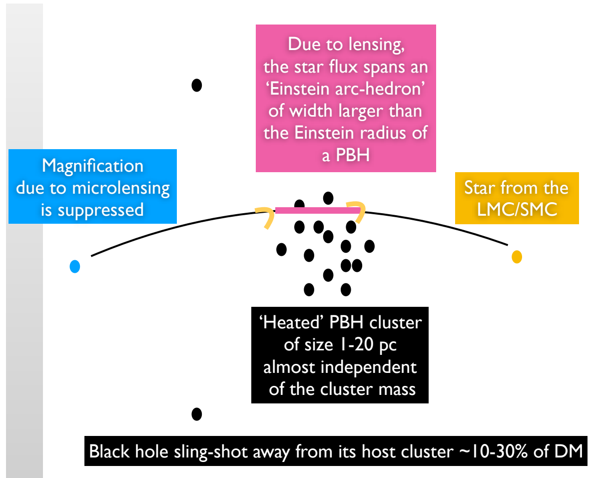
uniform single-mass
is already ruled out



clustered wide-mass
is still viable

Towards closing the window of PBHs as DM: the case of large clustering
Bringmann et al.   arXiv:1808.05910

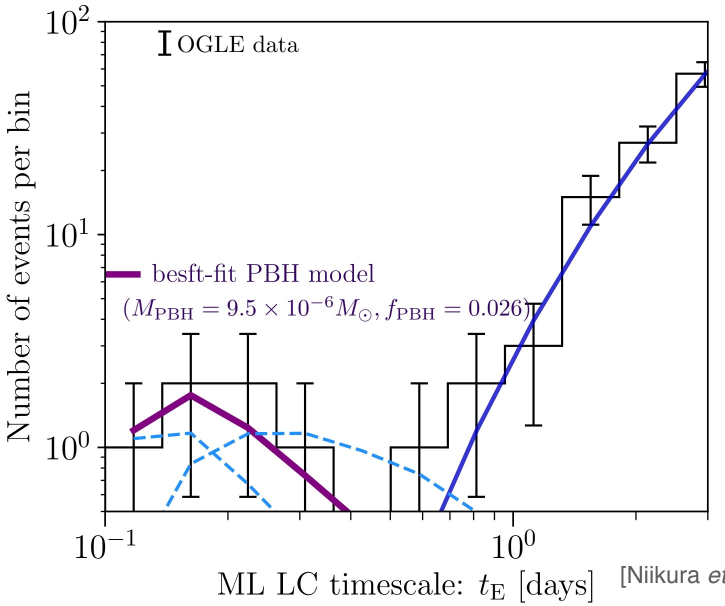
Initial clustering and the PBH merger rate
Young and Byrnes   arXiv:1910.06077



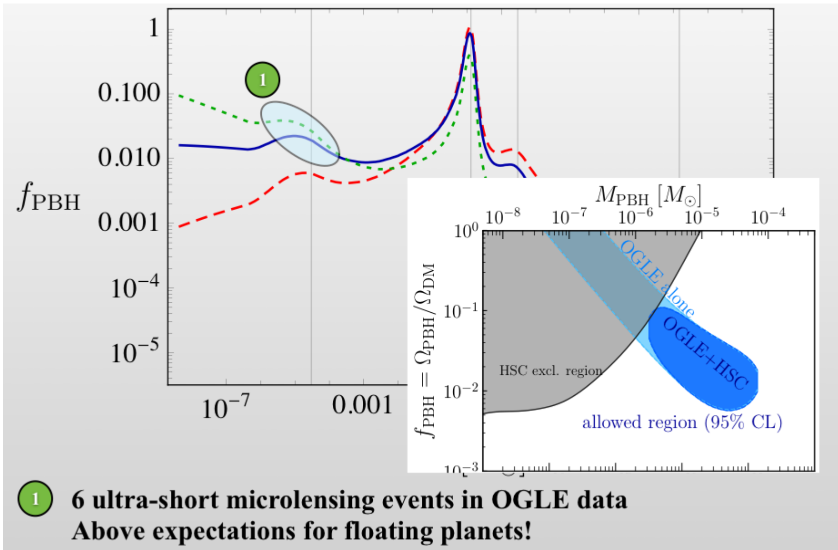
Planetary-mass microlenses

OGLE detected microlenses on 0.1-0.3 day timescale of unknown origin – free-floating planets of PBHs?

Niikura et al. (2019)



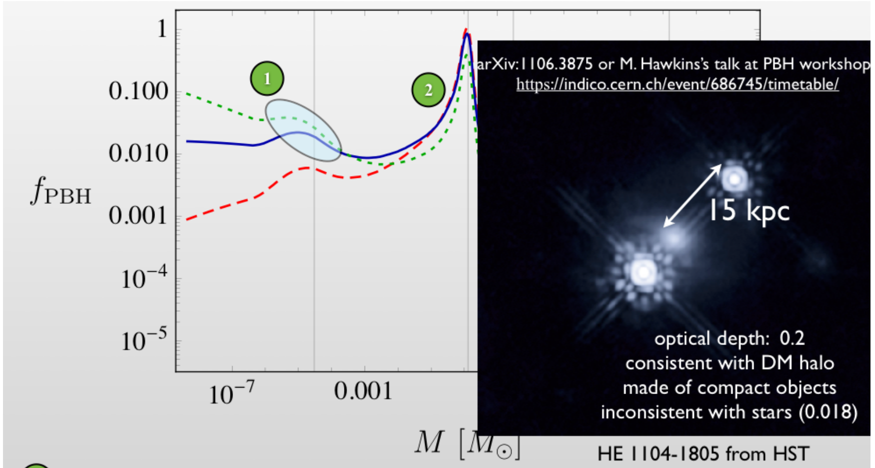
[Niikura *et al.* 2019]



What if Planet 9 is a Primordial Black Hole?

Scholtz and Unwin arXiv:1909.11090

Quasar microlensing



2 Microlensing of quasars (24) with misaligned galaxy (a few)
+ 56 microlensing events in M31

Evidence for dark matter in the form of compact bodies

Michael Hawkins
University of Edinburgh

Evidence for Microlensing

- 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 $M_\odot$

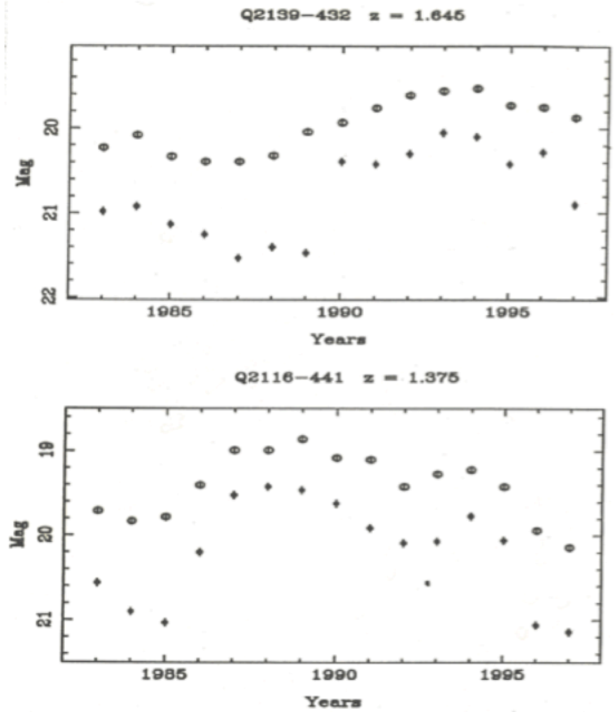
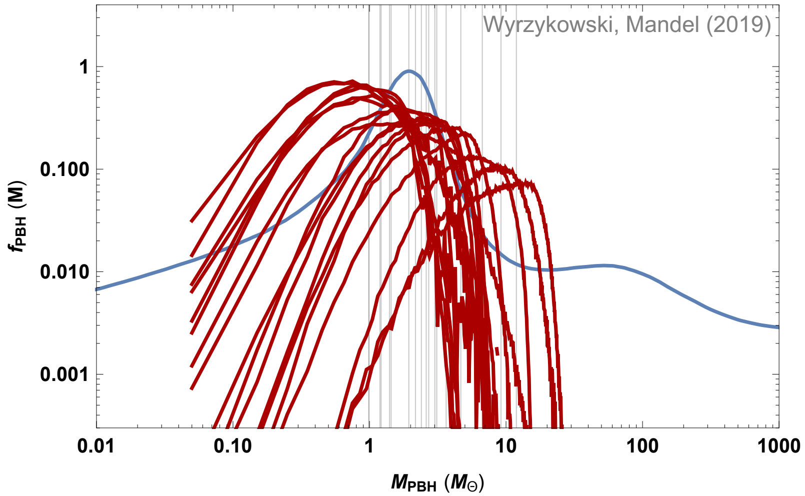
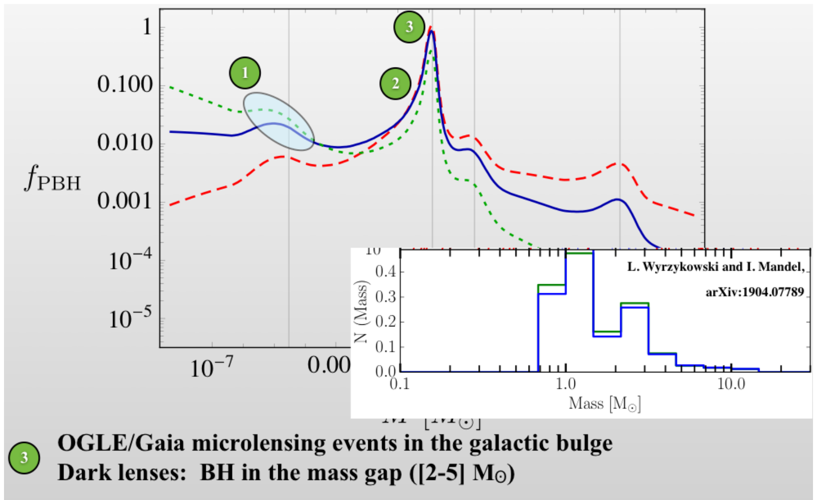


Fig. 3. Light curves for two quasars showing all the characteristics expected of caustic crossing events. Symbols as for Fig. 1.

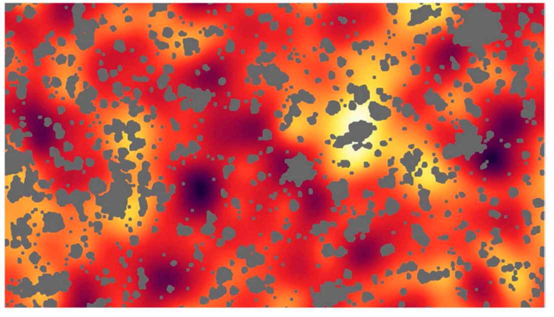
OGLE/GAIA excess of lenses in Galactic bulge



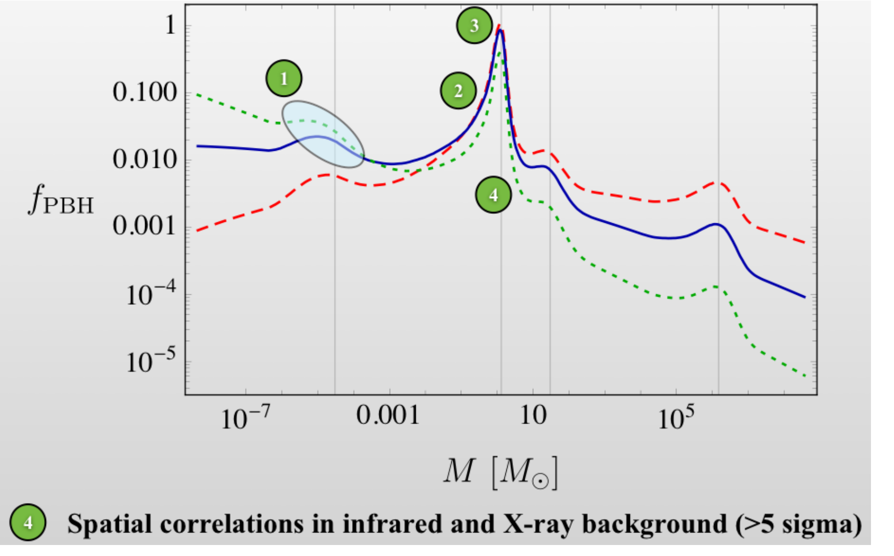


Cosmic infrared/X-ray backgrounds

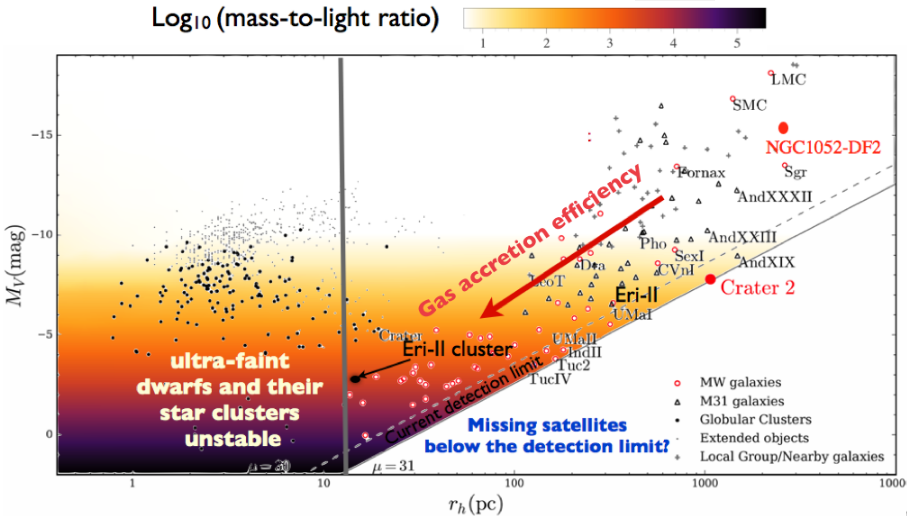
PBHs generate early structure
and infrared background

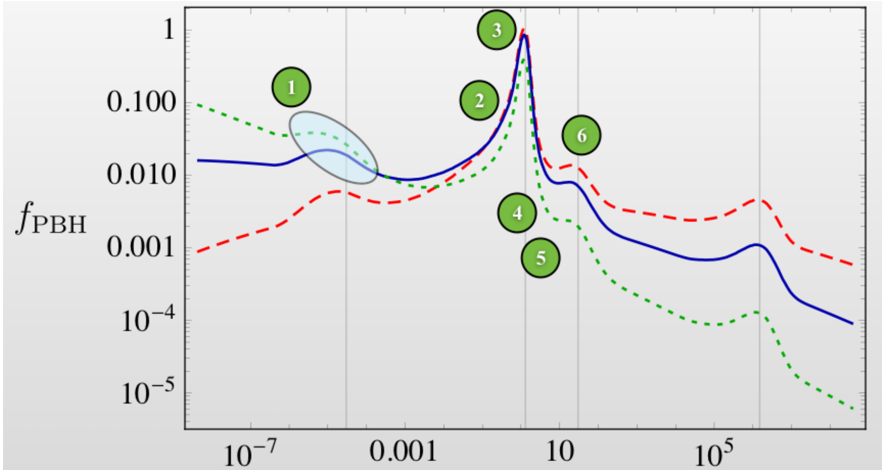


Kashlinsky
arXiv:1605.04023



Ultra-faint dwarf galaxies





5 Minimum radius of (ultra-faint) dwarf galaxies and cored DM profiles

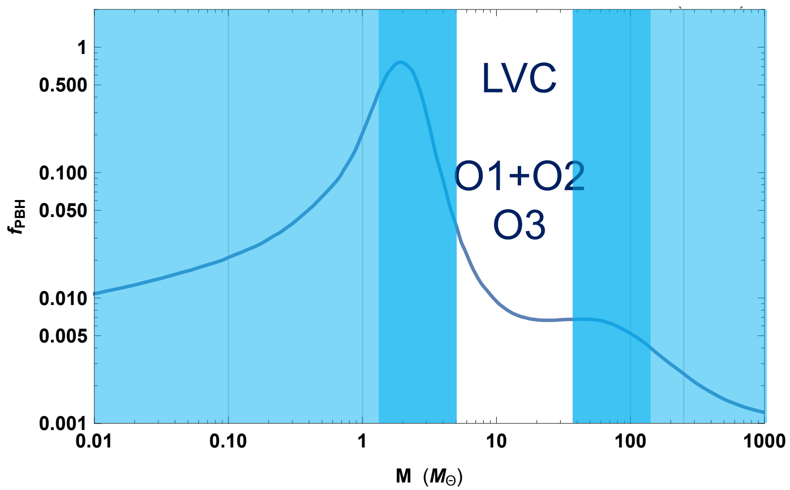
Improved constraints from ultra-faint dwarf galaxies on PBHs as DM

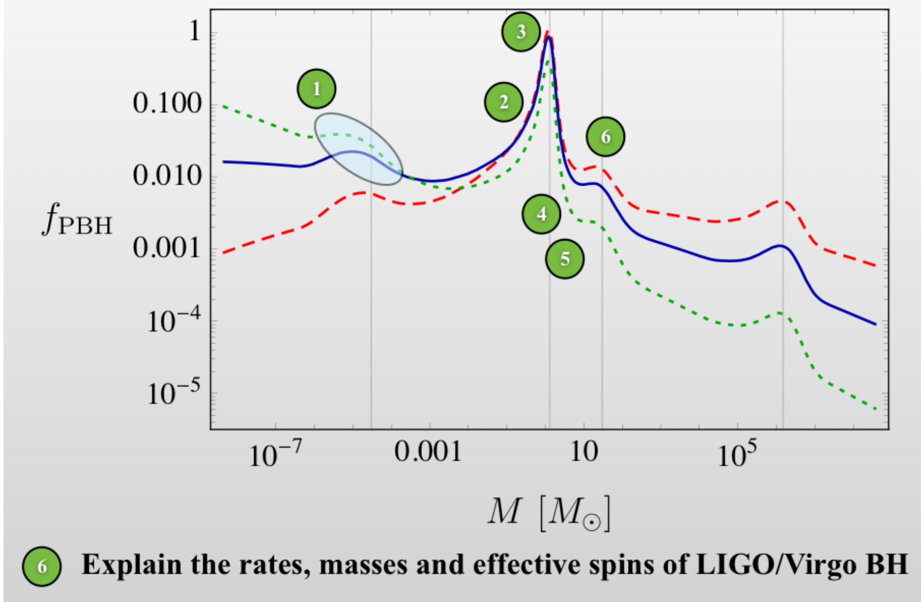
Stegmann et al arXiv:1910.04793

PBHs as dark matter: cusp-to-core transition in low-mass dwarf galaxies

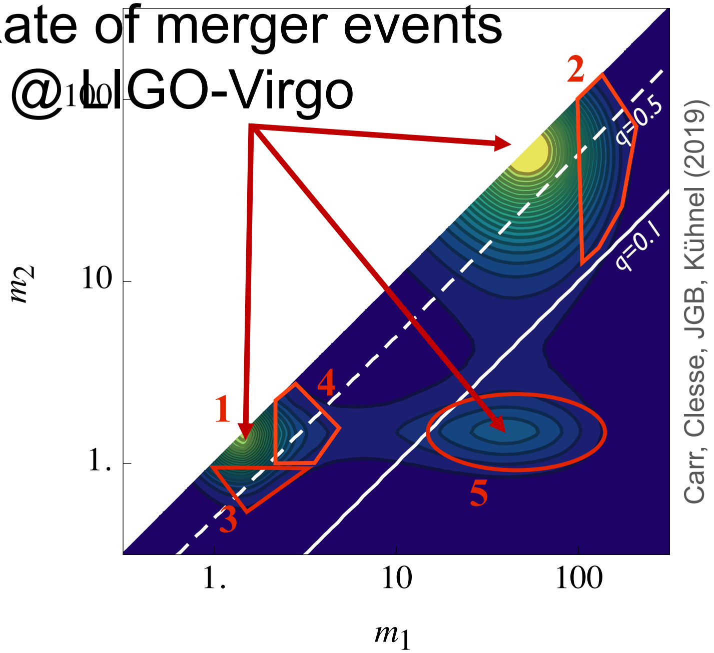
Boldrini et al. arXiv:1909.07395

LIGO/Virgo black holes

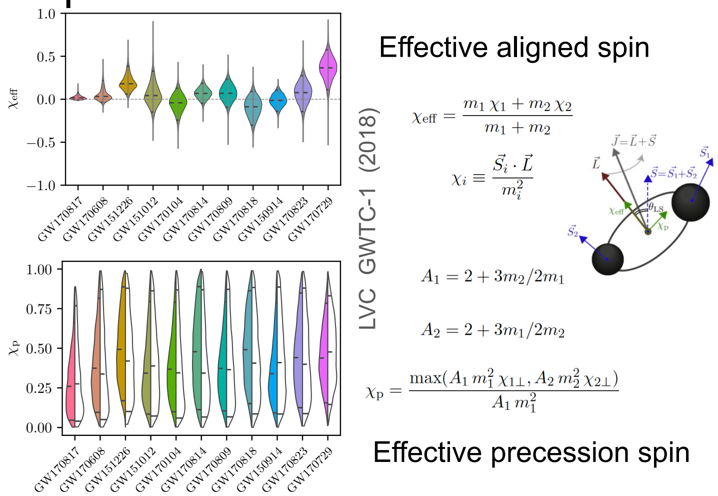




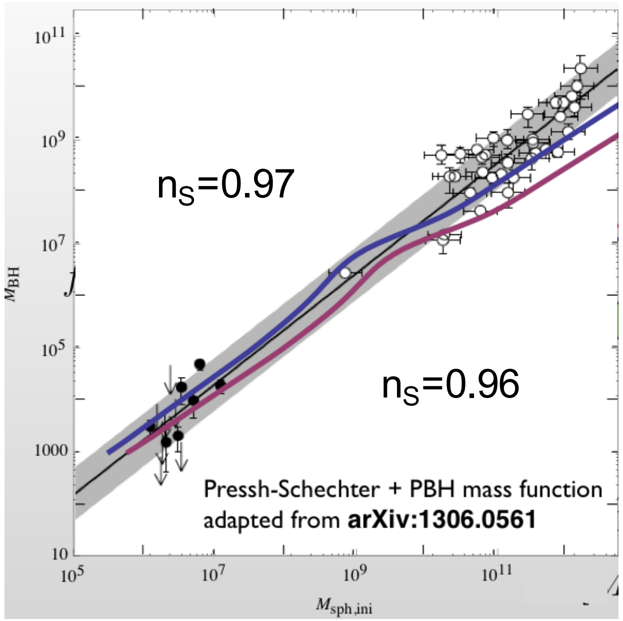
Rate of merger events @LIGO-Virgo

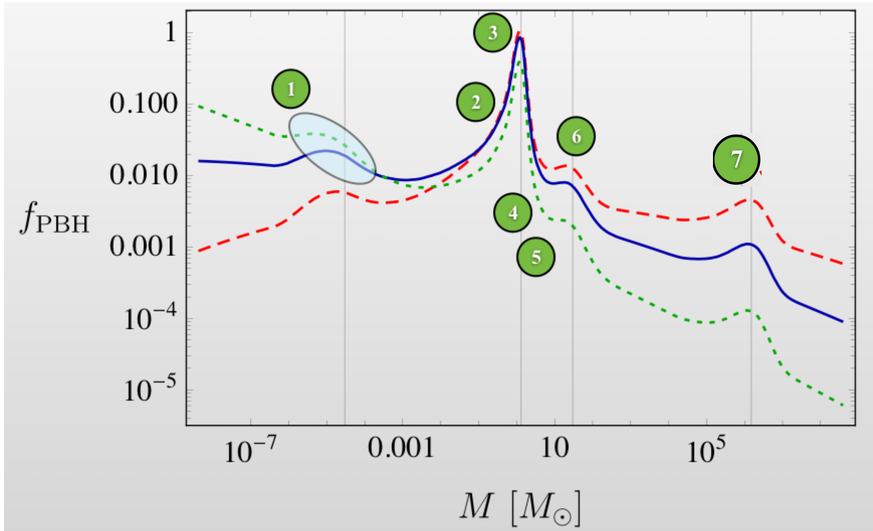


Spin distribution of GWTC-1 BBH



Intermediate and supermassive black holes





7 **Right number of intermediate and supermassive black holes**

n_S = 0.97 => observed relation between BH and halo mass only if f_{PBH} ~ 1. We predict one $10^8 M_O$ PBHs per halo with smaller ones seeding dwarf galaxies.

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 to explain numerous cosmological conundra:

Cosmic rays | Dark matter | LIGO/Virgo | Cosmic structure

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

PBHs naturally form at QCD epoch and could thereby explain both dark matter and baryon asymmetry.