PRIMORDIAL BLACK HOLES AS A PROBE OF DARK MATTER, DARK ENERGY & DARK DIMENSIONS

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Accelerating universe in the dark, 7/3/19

PLAN OF TALK

- Introduction
- PBHs as probe of dark energy

  PBHs formation from inflation

  Accretion of quintessence X
- PBHs as probe of dark matter

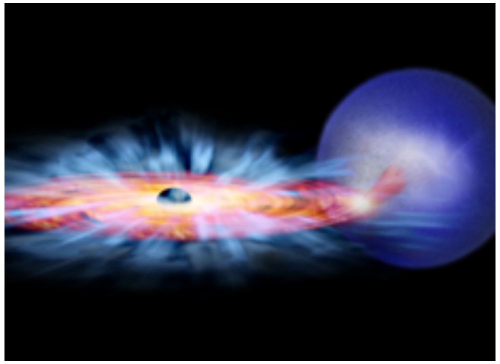
  PBHs as source of dark mattter

  PBHs as source of LIGO events

  PBHs as generators of cosmic structure
- PBHs as probe of dark dimensons

  PBHs in higher and lower dimensions X

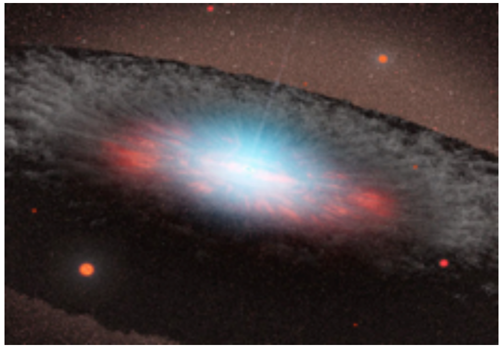
OVERWHELMING EVIDENCE FOR STELLAR BHS ($M \sim 10^{1\text{-}2} M_O$)



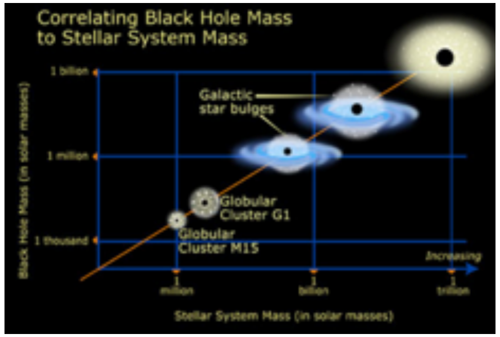
X-ray binary
Cygnus X1

LIGO detects
gravity waves from
coalescing BHs

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

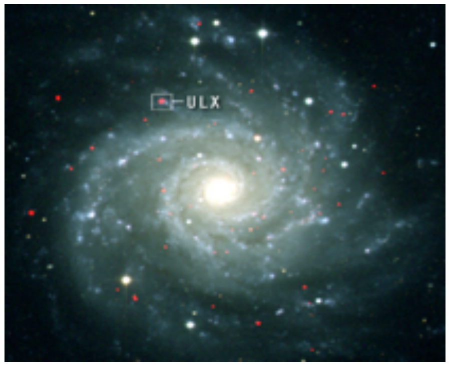


MW $4 \times 10^6 M_O$
QSO $10^8 M_O$
$1.4 \times 10^{10} M_O$
BH at z=6.3

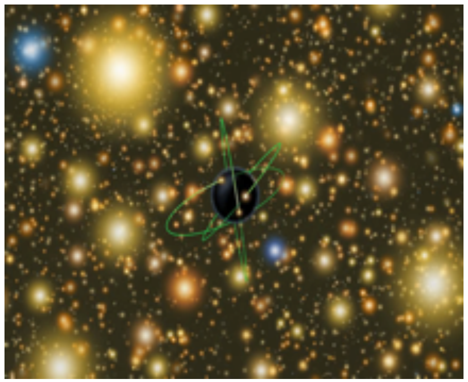


BH mass
proportional
to stellar mass

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



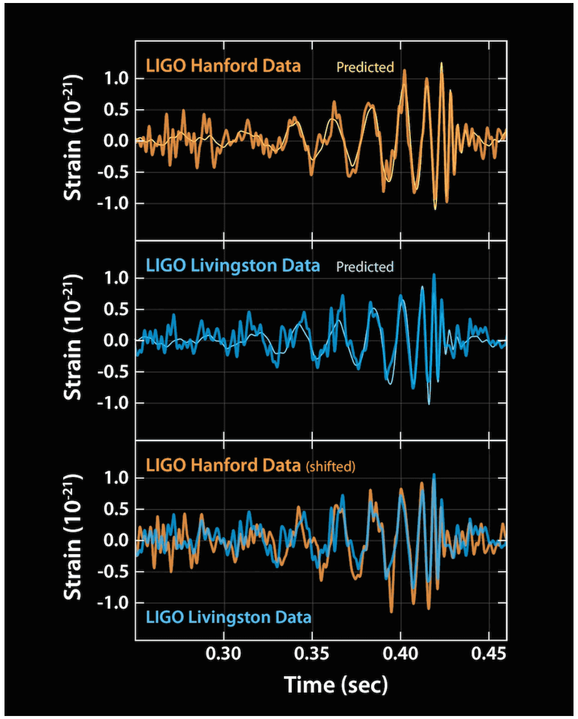
Ultraluminous
X-ray sources
NGC1313 may
have $500 M_O$ BH



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

Properties of the binary black hole merger GW150914

The LIGO Scientific Collaboration and The Virgo Collaboration



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

Largest is now 80 M_O which is nearly in IMBH range

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**

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

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.

Cosmological effects of primordial black holes

GEORGE F. CHAPLINE

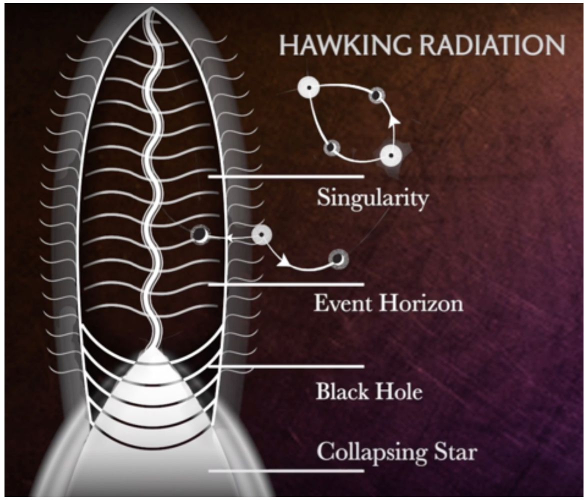
Nature **253**, 251–252 (24 January 1975)
doi:10.1038/253251a0
Download Citation

Received: 29 July 1974
Revised: 03 October 1974
Published online: 24 January 1975

Abstract

ALTHOUGH only black holes with masses $\gtrsim$; $1.5 M_{\odot}$ 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

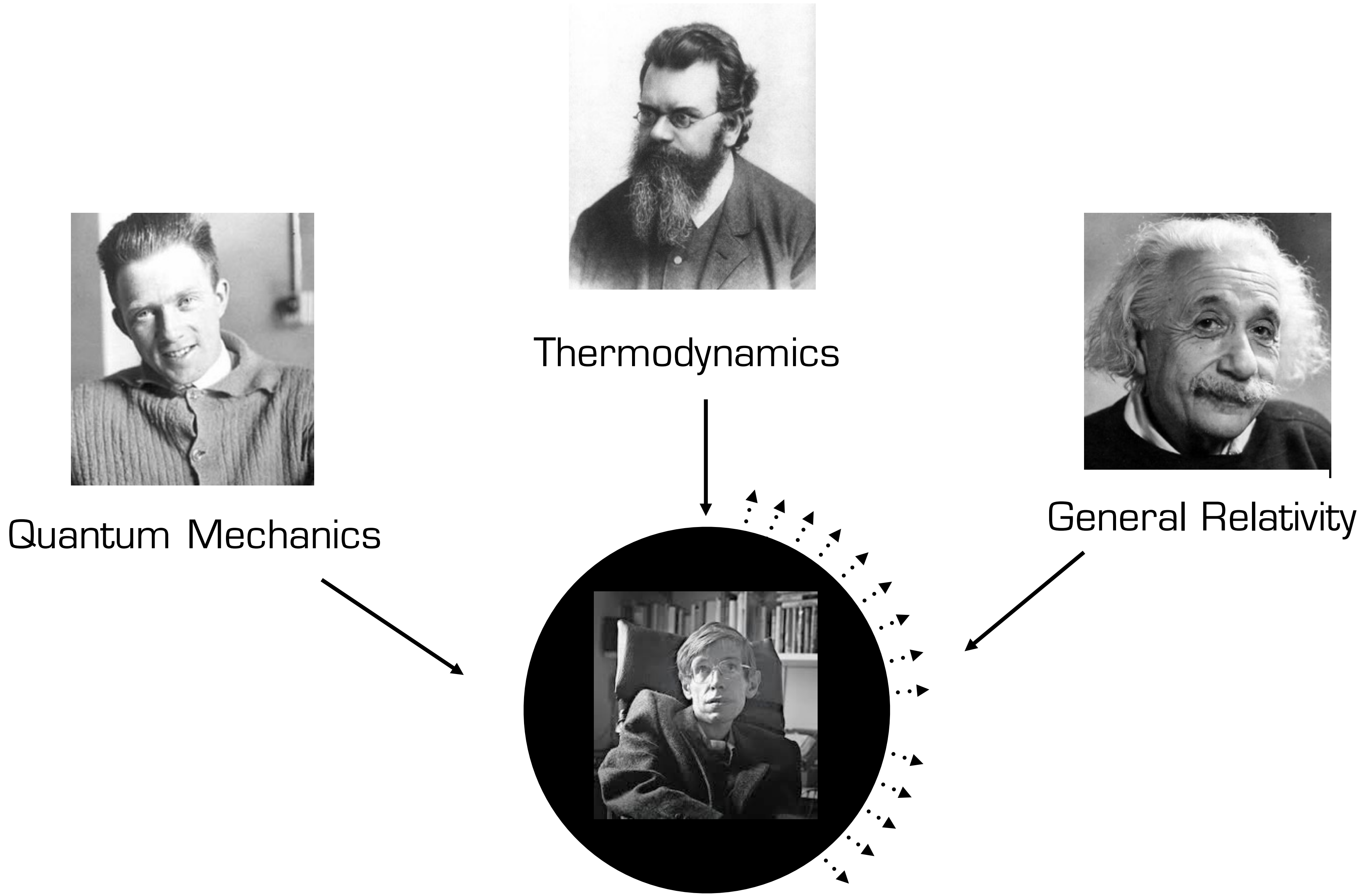
Nature **248**, 30 - 31 (01 March 1974); doi:10.1038/248030a0

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.



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

PBHs are important even if they never formed!

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)

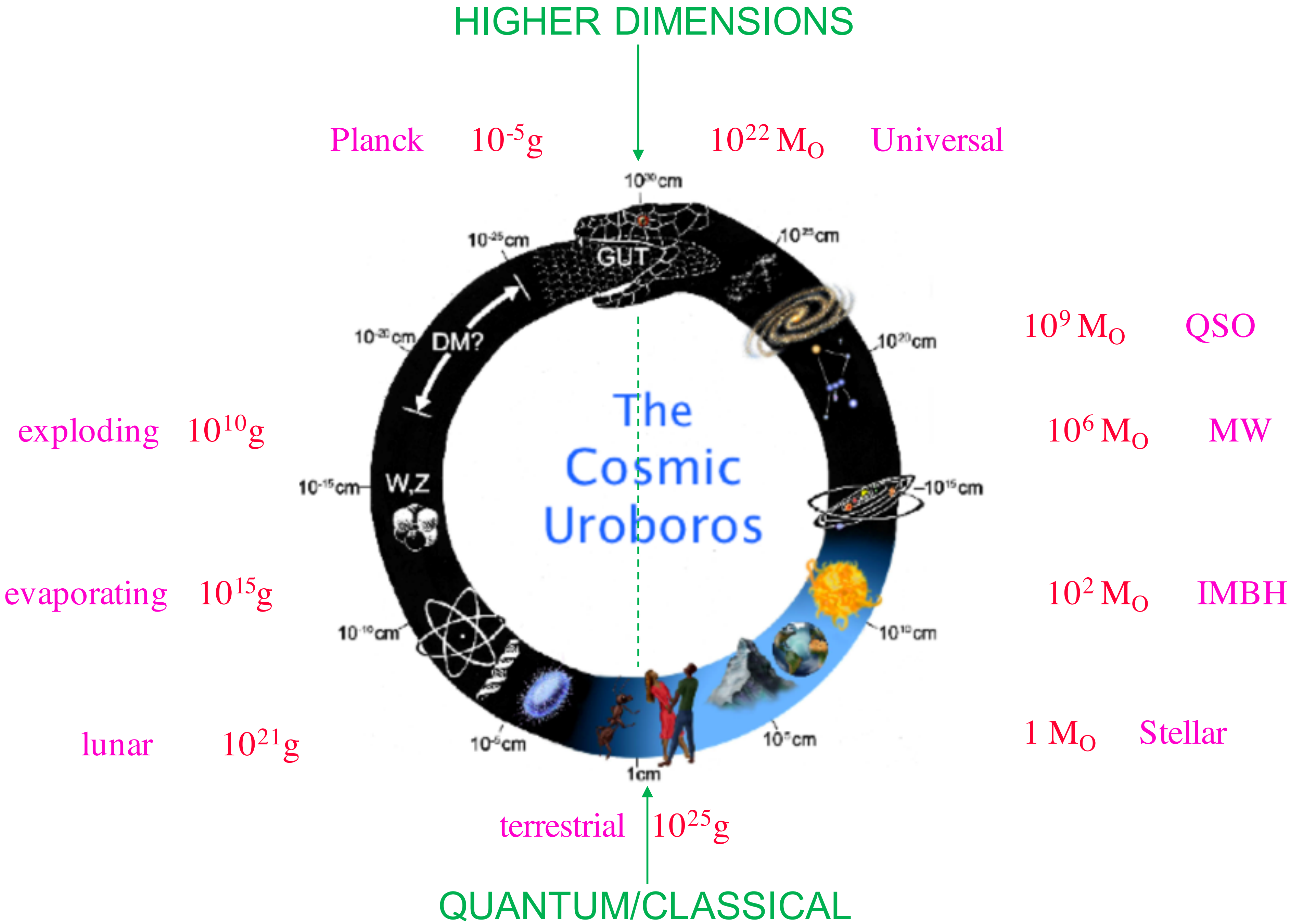
This can only be important for PBHs

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

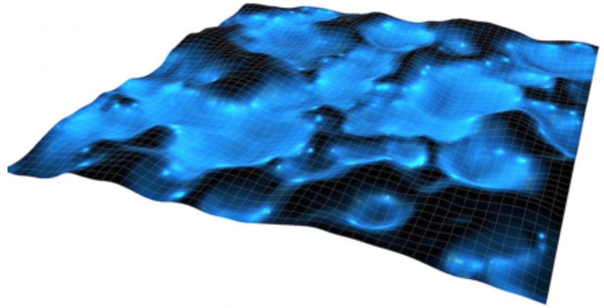
=> explosions undetectable in standard particle physics model

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

BLACK HOLES

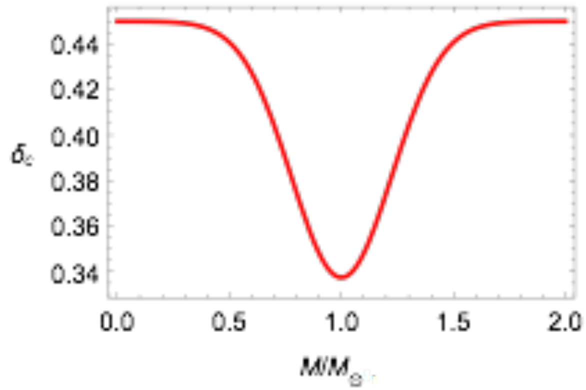

HIGHER DIMENSIONS
Planck 10^{-5}g
10^{22} M_O Universal
10^{30}cm
10^{-25}cm
GUT
10^{25}cm
10^{-20}cm
DM?
10^{20}cm
10^{9} M_O QSO
exploding 10^{10}g
The Cosmic Uroboros
10^{6} M_O MW
10^{-15}cm
W,Z
10^{15}cm
evaporating 10^{15}g
10^{2} M_O IMBH
10^{-10}cm
10^{10}cm
lunar 10^{21}g
10^{-5}cm
10^{5}cm
1 M_O Stellar
1cm
terrestrial 10^{25}g
QUANTUM/CLASSICAL

FORMATION MECHANISMS

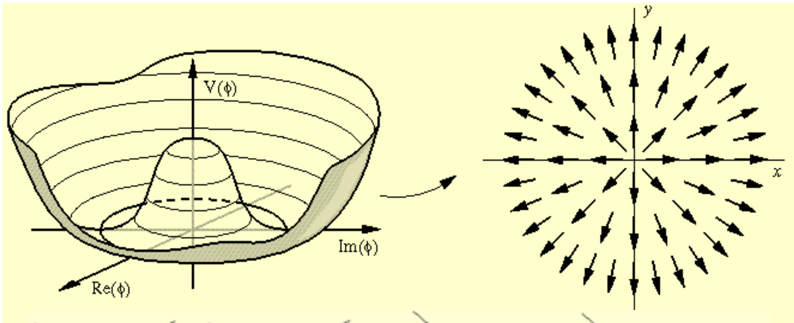


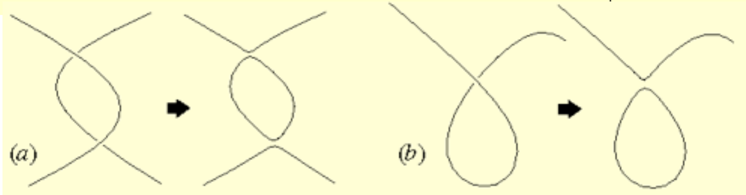
Primordial inhomogeneities Inflation

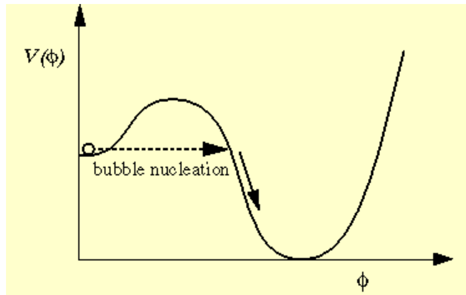
Pressure reduction Form more easily but need spherical symmetry



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

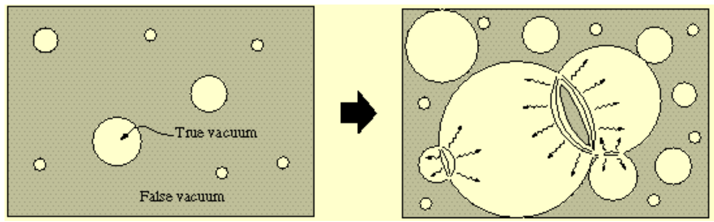






Bubble collisions

Need fine-tuning of bubble formation rate



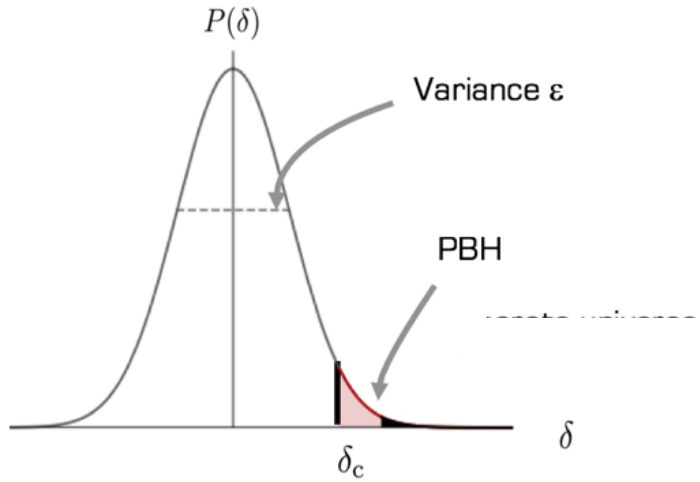
Domain walls PBHs can be very large

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**

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

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

$\varepsilon(M)$ decreases with M => exponential upper cut-off

Limit on 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 => fine-tuning

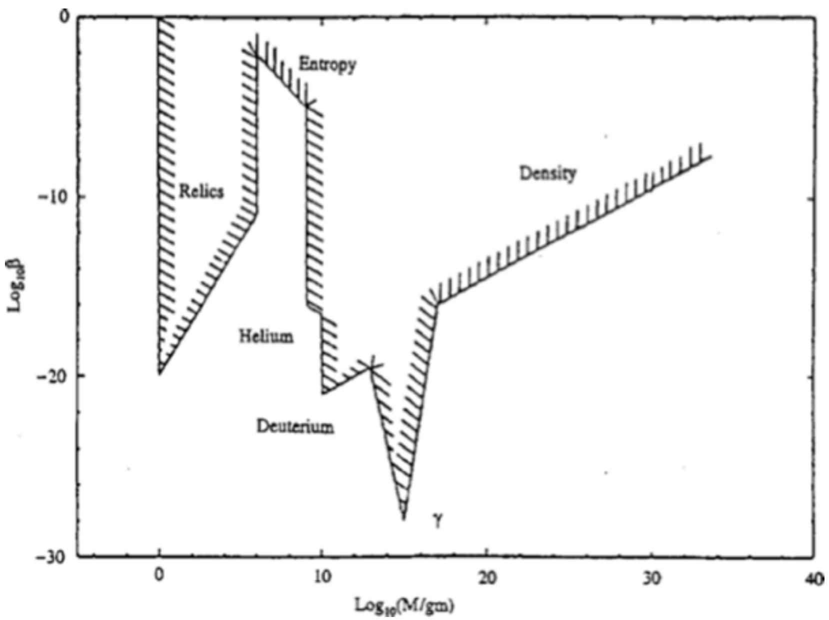
Unevaporated	**$M>10^{15}g \Rightarrow \Omega_{PBH} < 0.25$**	**(CDM)**
Evaporating now	**$M\sim10^{15}g \Rightarrow \Omega_{PBH} < 10^{-8}$**	**(GRB)**
Evaporated in past	**$M<10^{15}g$**	

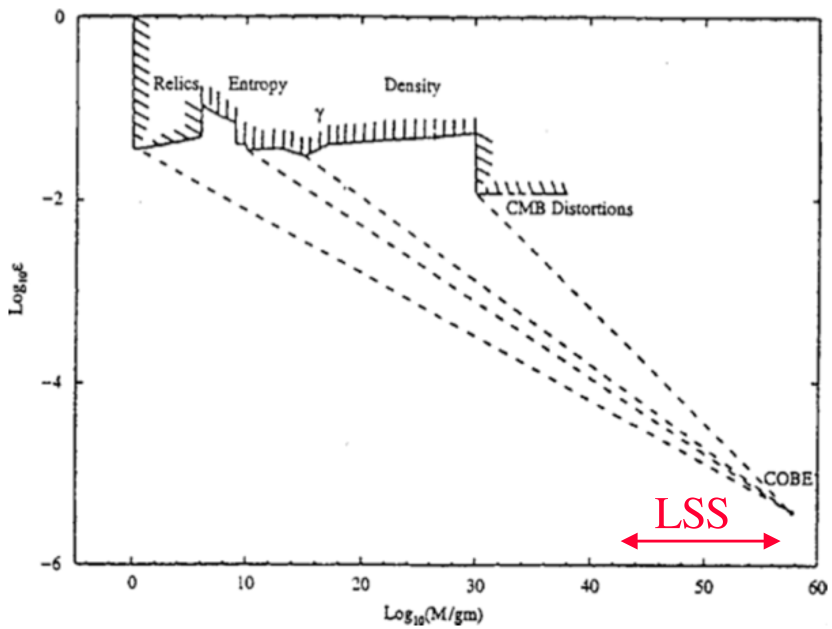
=> constraints from entropy, γ-background, BBNS

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.

CONSTRAINTS FOR EVAPORATING PBHS

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

Big bang nucleosynthesis

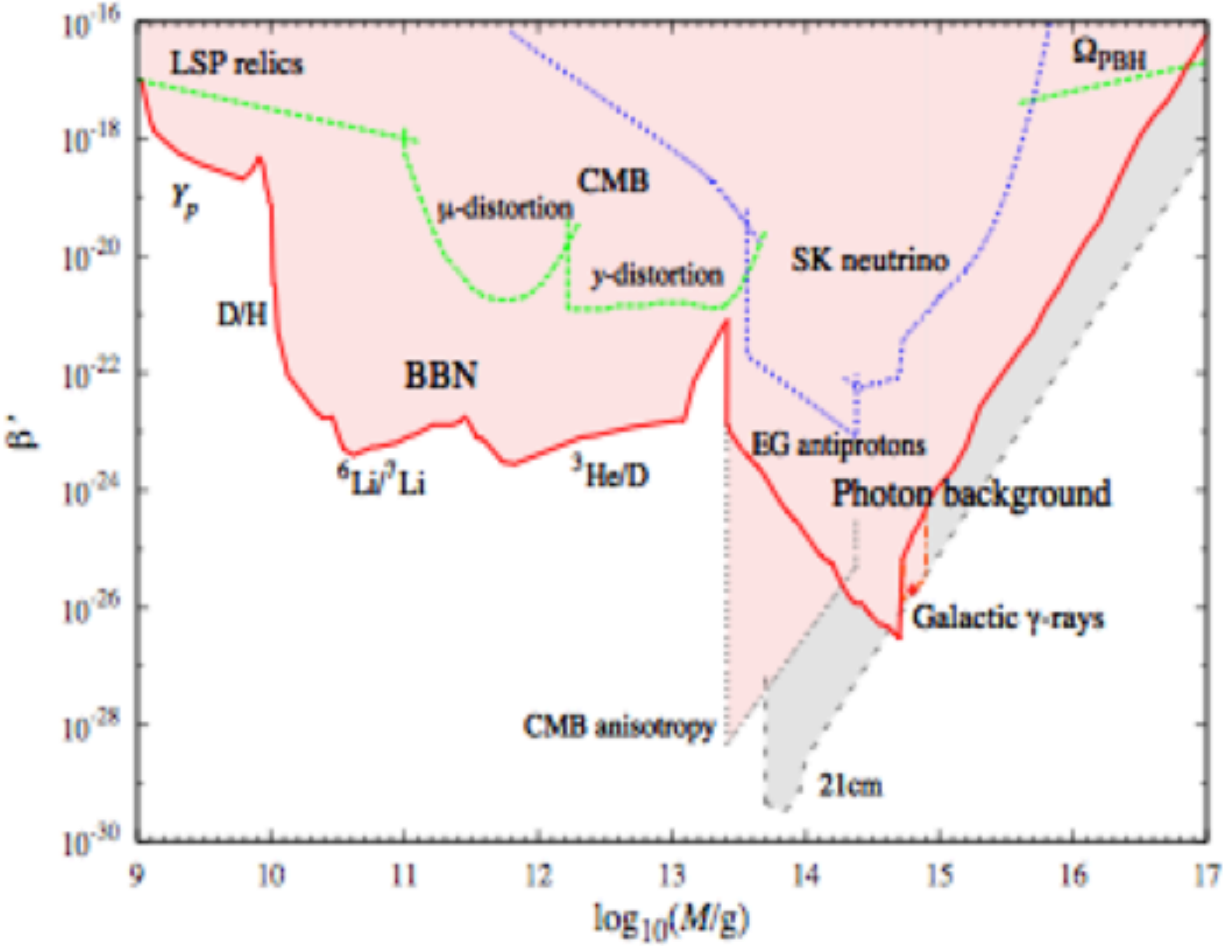
Gamma-ray background

Extragalactic cosmic rays

Neutrino relics

LSP relics

CMB distortions



PBHS FROM NEAR-CRITICAL COLLAPSE

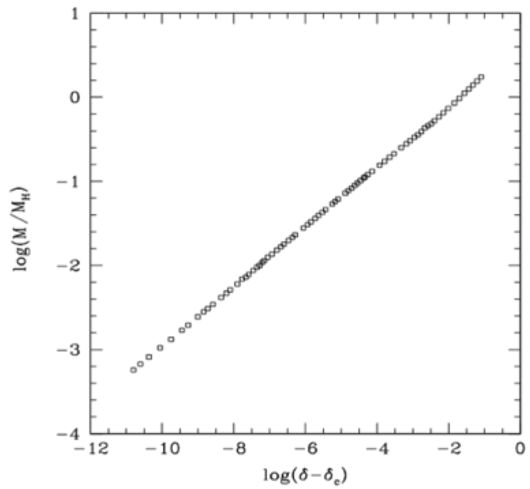
Critical phenomena => $M = k\, M_H(\delta-\delta_c)^{\gamma}$ (Niemeyer & Jedamzik 1999)

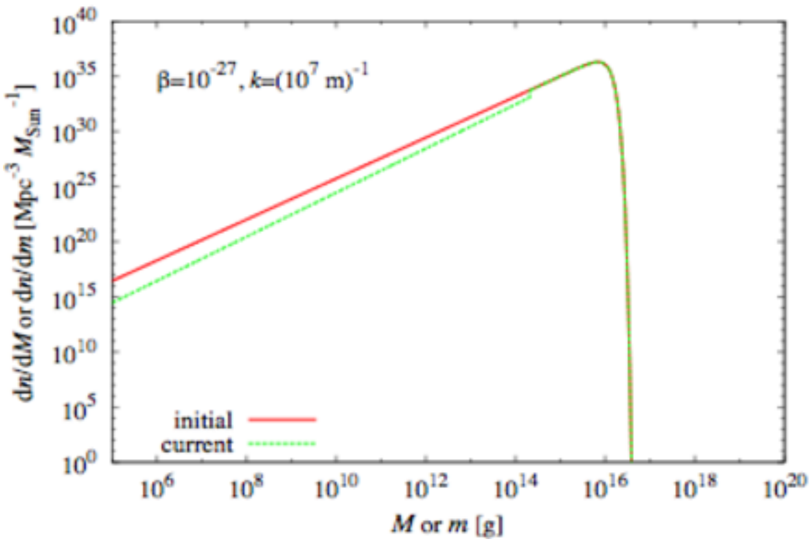
spectrum peaks at horizon mass with extended low mass tail

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

Later calculations and peak analysis =>

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





PBHS AND INFLATION

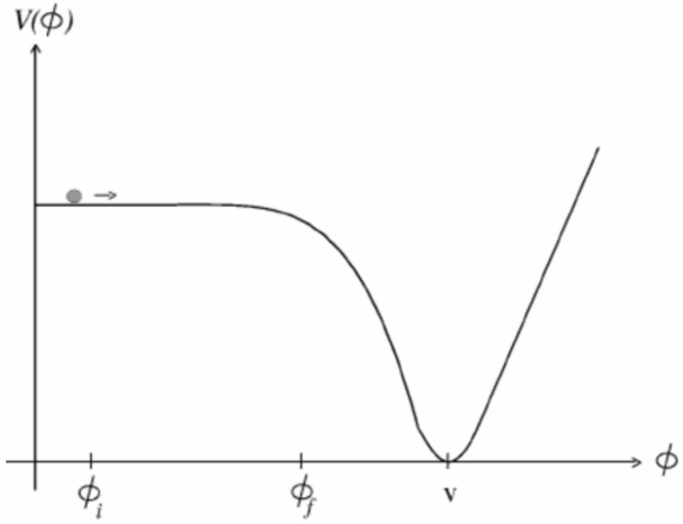
PBHs formed before reheat inflated away =>

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

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?

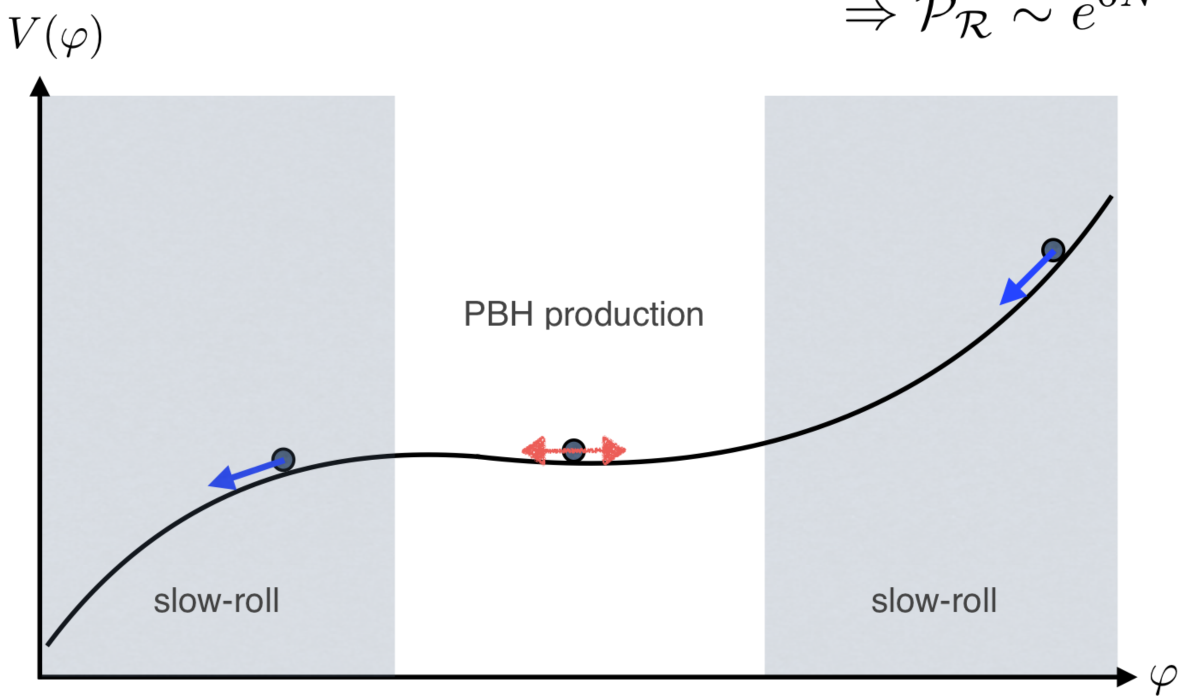
[HUGE NUMBER OF PAPERS ON THIS]

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

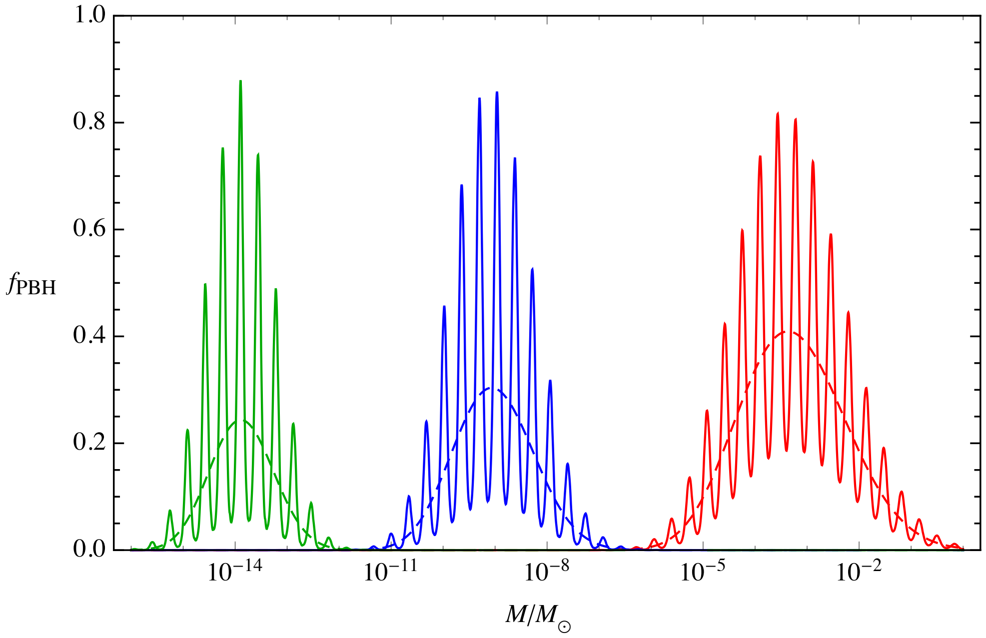
arXiv:1804.07124

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

Primordial Black Holes With Multi-Spike Mass Spectra

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

arXiv:1811.06532



cf. talk by Yuichiro Tada

PRIMORDIAL BLACK HOLES AS DARK MATTER

PRO

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

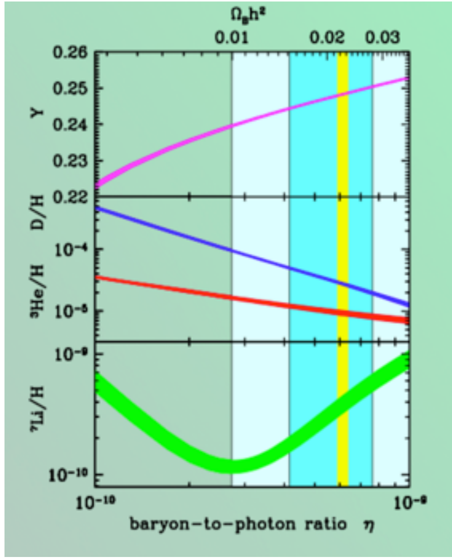
CON

* Requires fine-tuning

PBH can do it!

PRIMORDIAL BLACK HOLES AS DARK MATTER

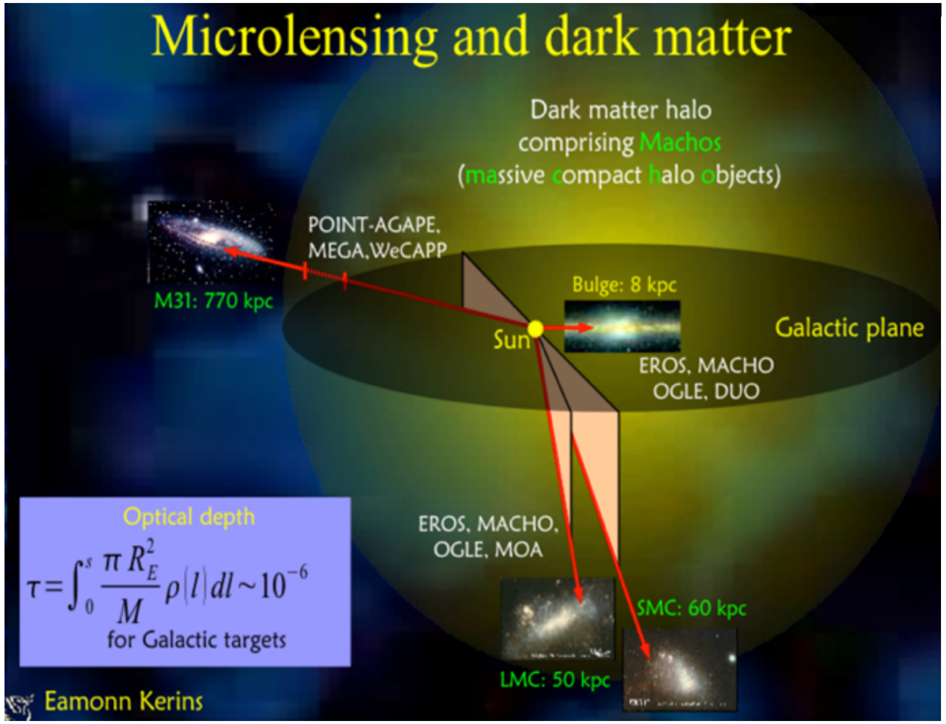
BBNS => $\Omega_{\rm baryon} = 0.05$



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

MACHOs WIMPs

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



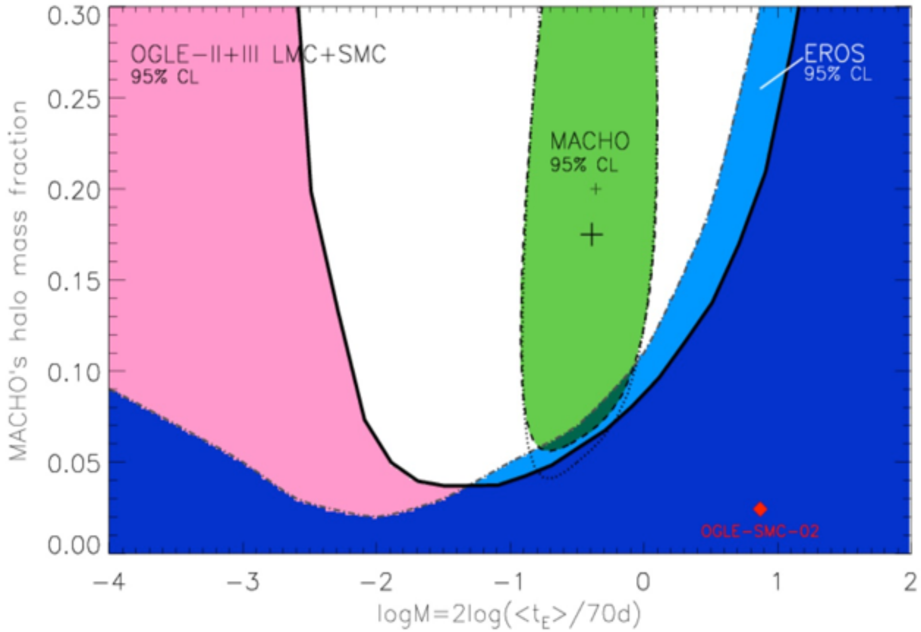


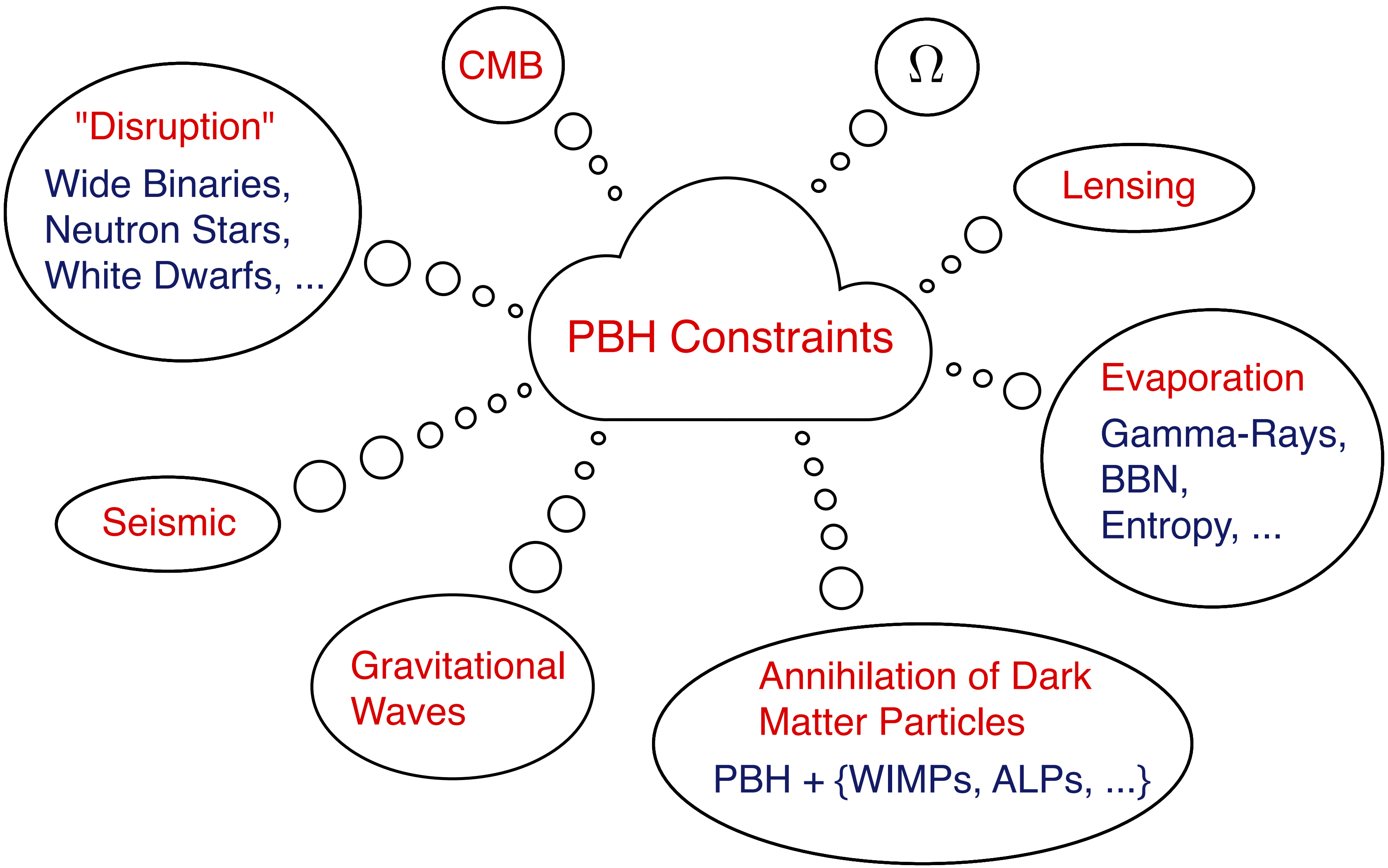
Image credit: Wyrzykowski et al., 2011, MNRAS, (astro-ph/1106.2925).

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

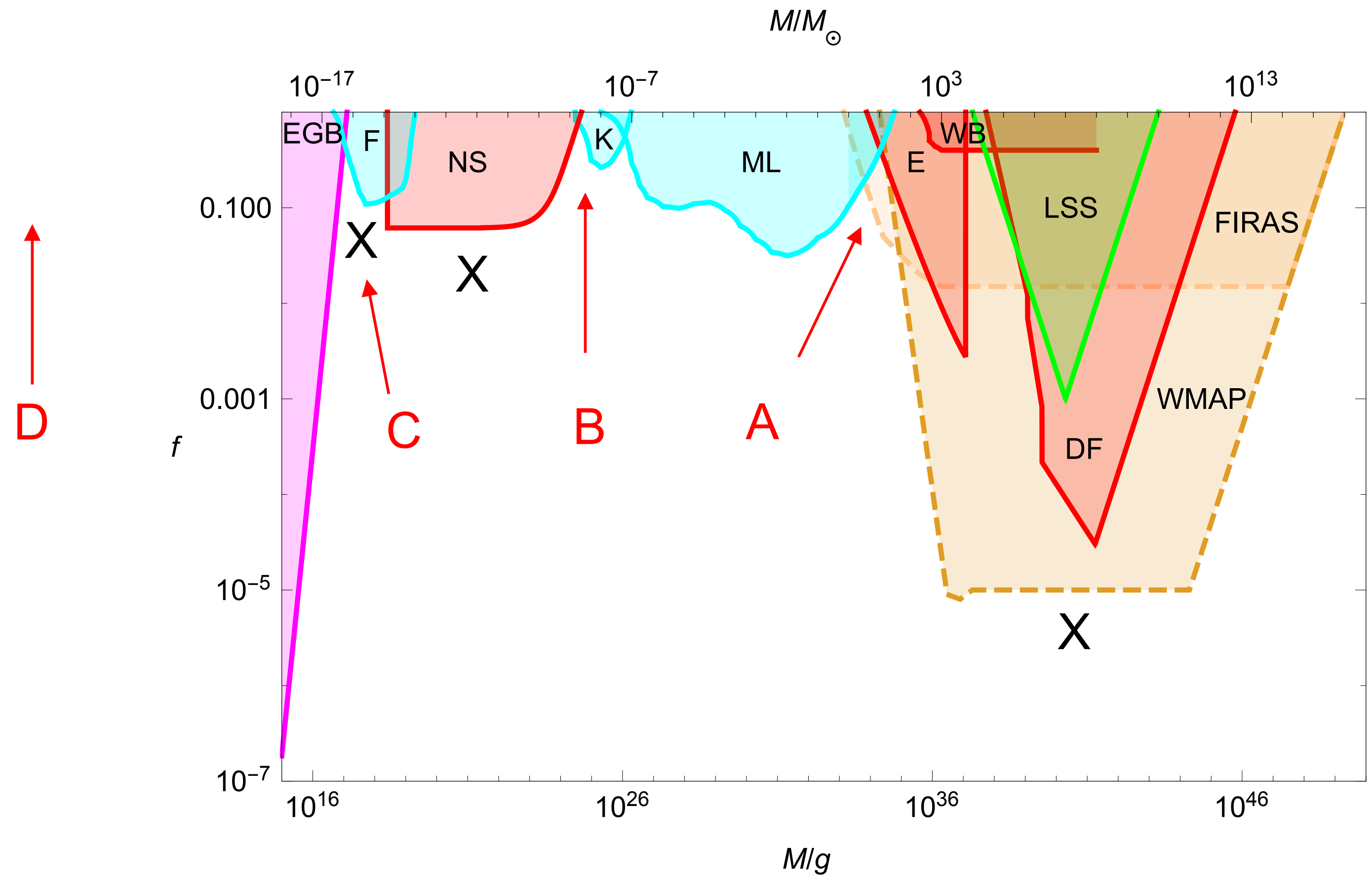
Later found that at most 20% of DM can be in these objects


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.

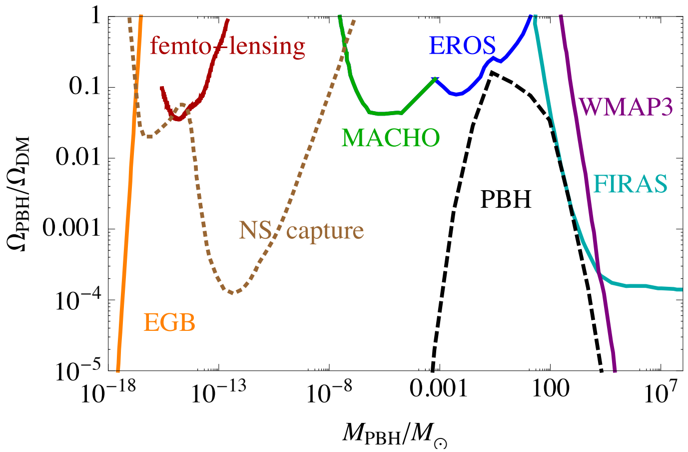
Also (D) Planck mass relics?

But some of these limits are now thought to be wrong

WHICH MASS WINDOW IS MOST PLAUSIBLE?

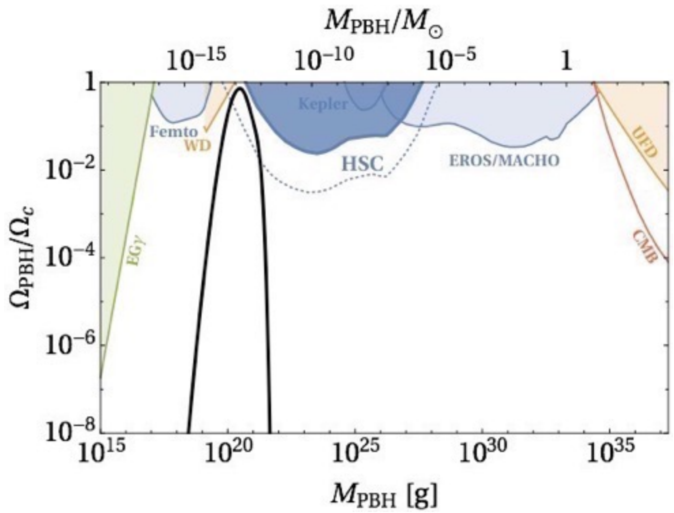
PBH dark matter @10 M_o from hybrid inflation

Clesse & Garcia-Bellido arXiv:1501.07565



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

Inomata et al arXiv:1701.02544

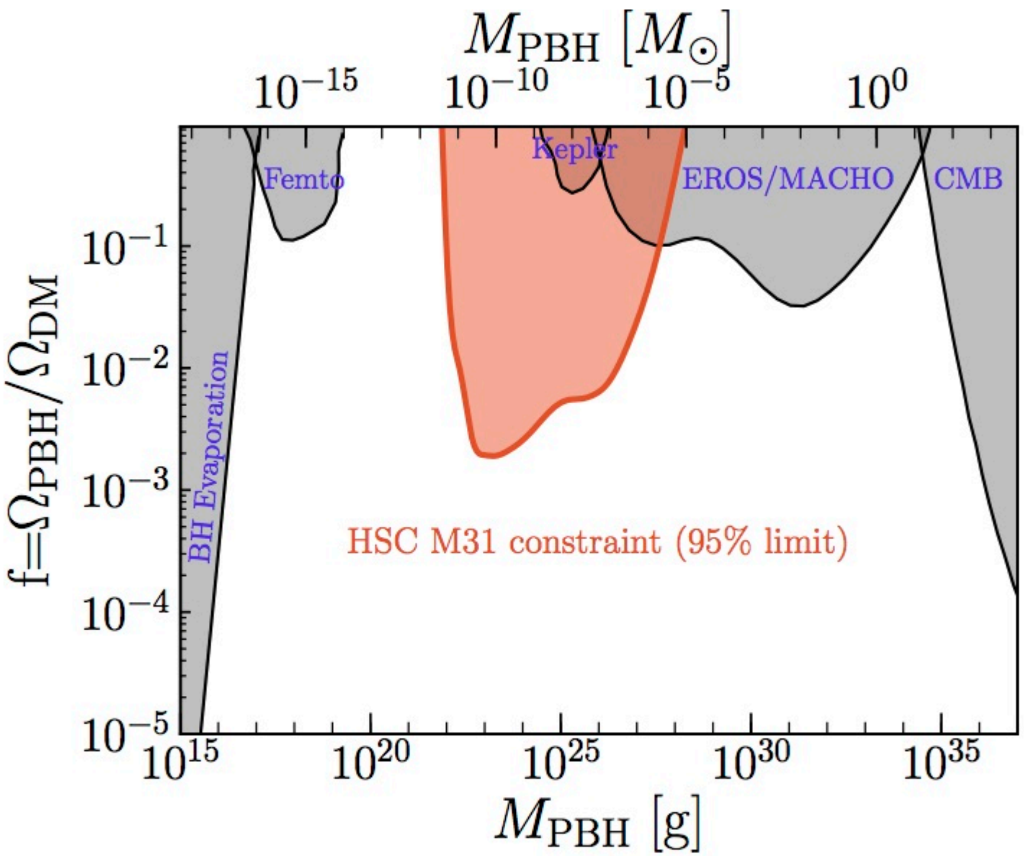


cf. light versus heavy dark matter particle

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]

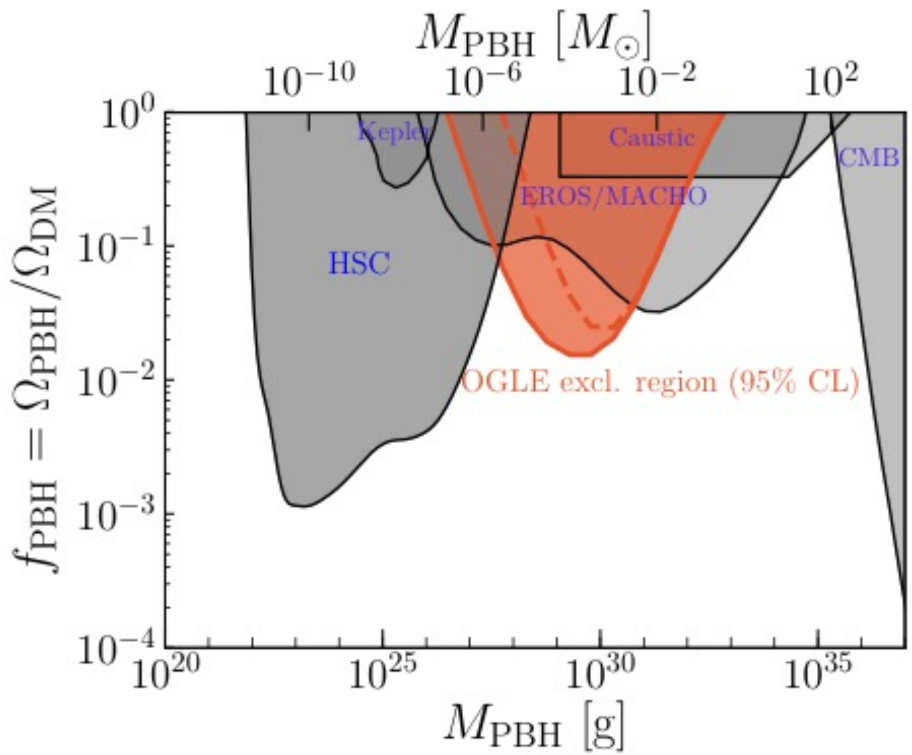
arXiv:1701.02151



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]

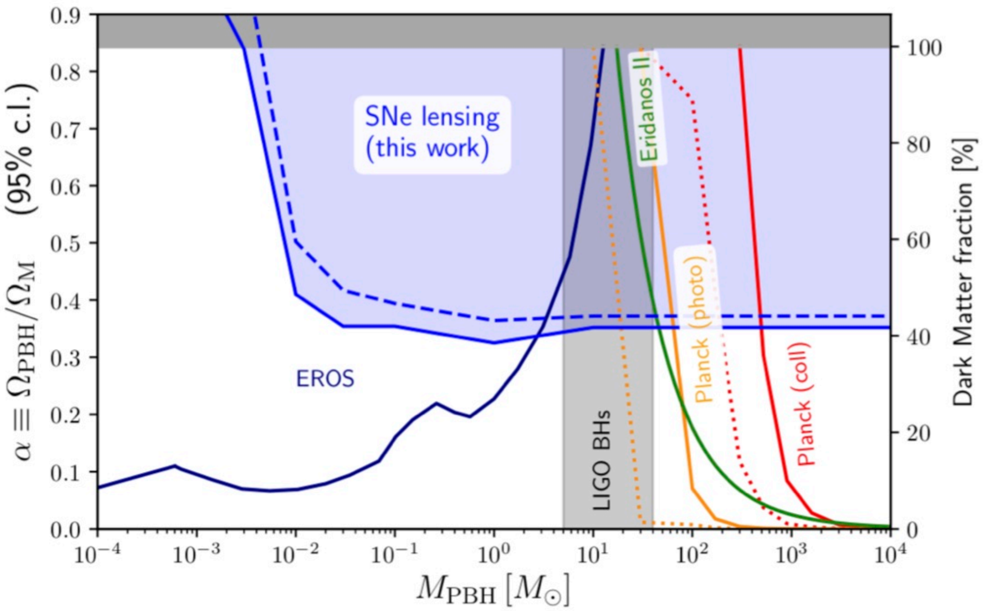
arXiv:1901.07120



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

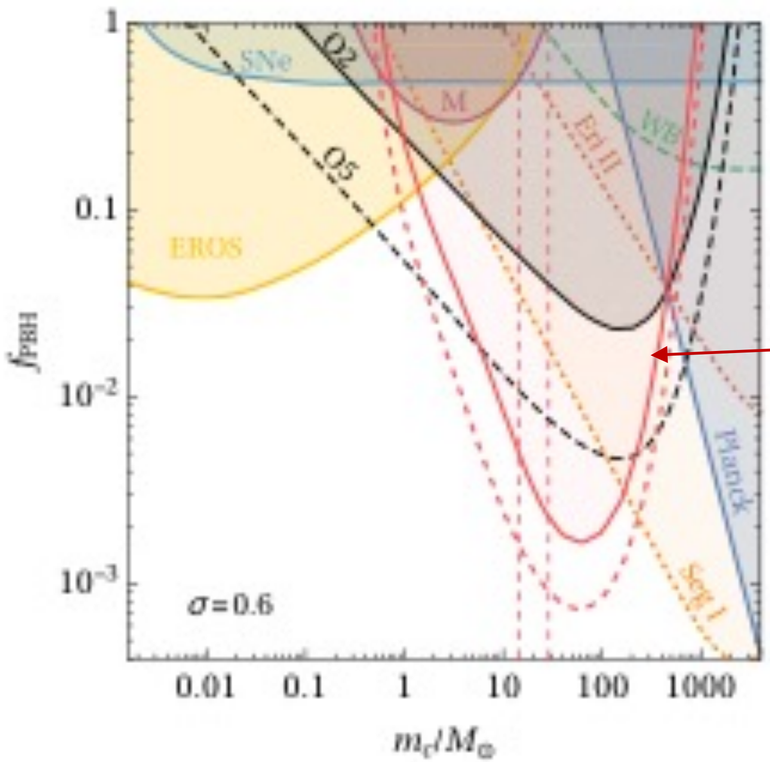


But PBHs can evade these limits Garcia-Bellido et al, arXiv:1712.06574

Formation and evolution of primordial black hole binaries in early universe

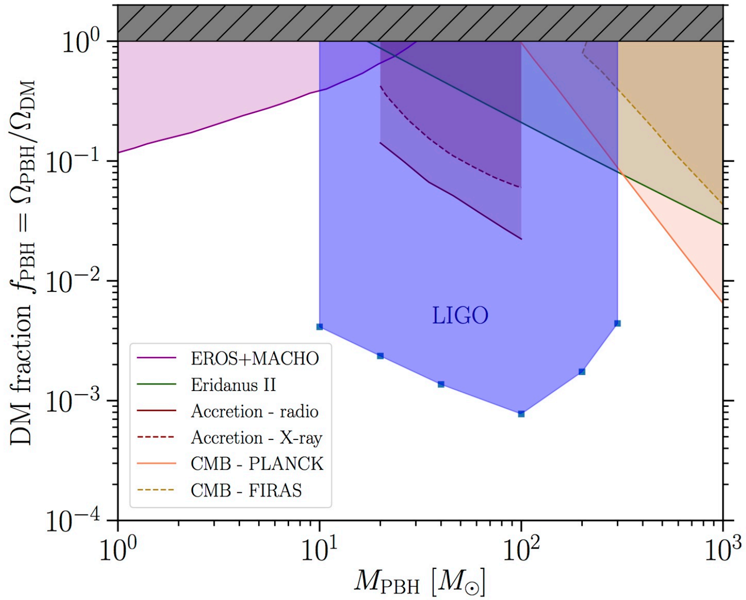
Raidal, Spethmann, Vaskonen, Veermae

arXiv:1812.01930



LIGO limit

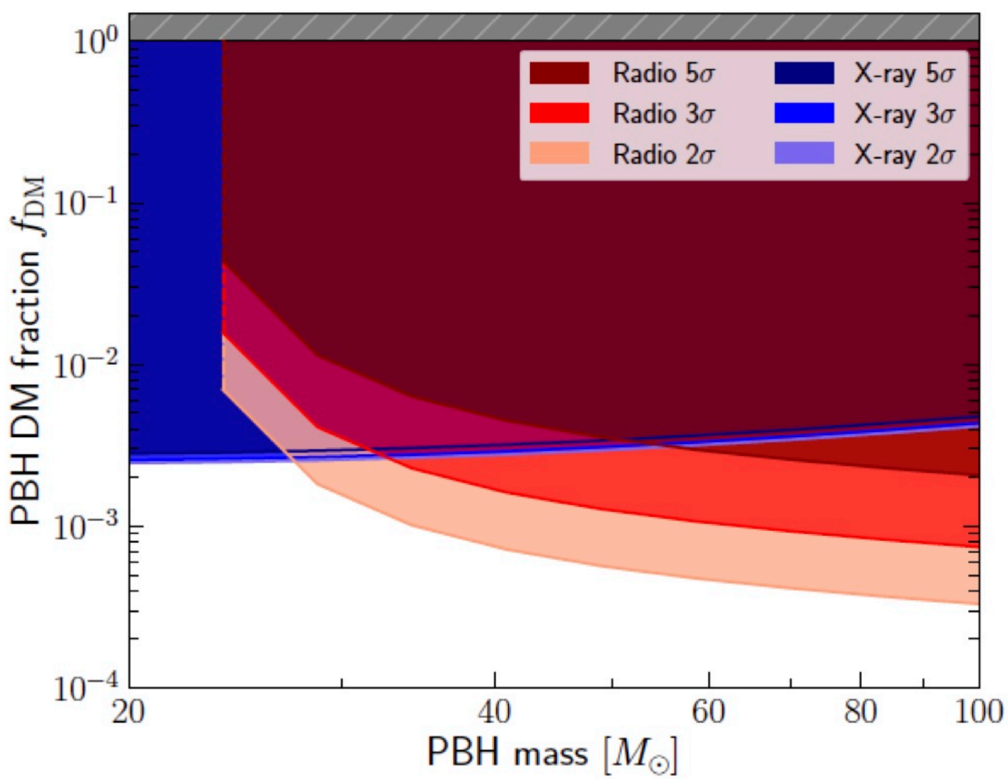
Kavanagh et al
arXiv:1805.09034



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]

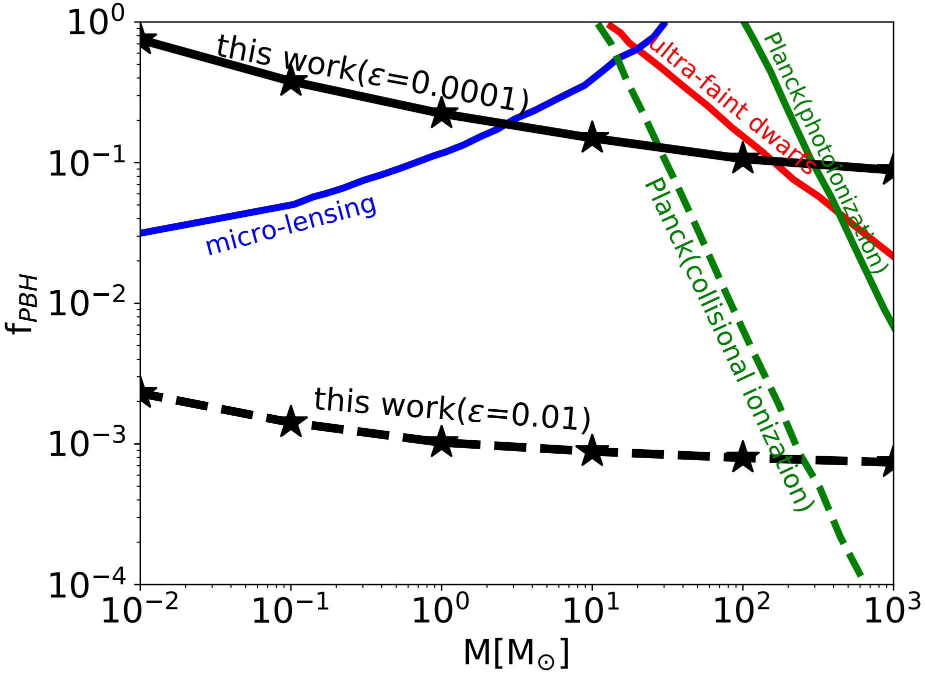
arXiv:1812.07967



Sunyaev-Zel'dovich anisotropy due to Primordial black holes

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

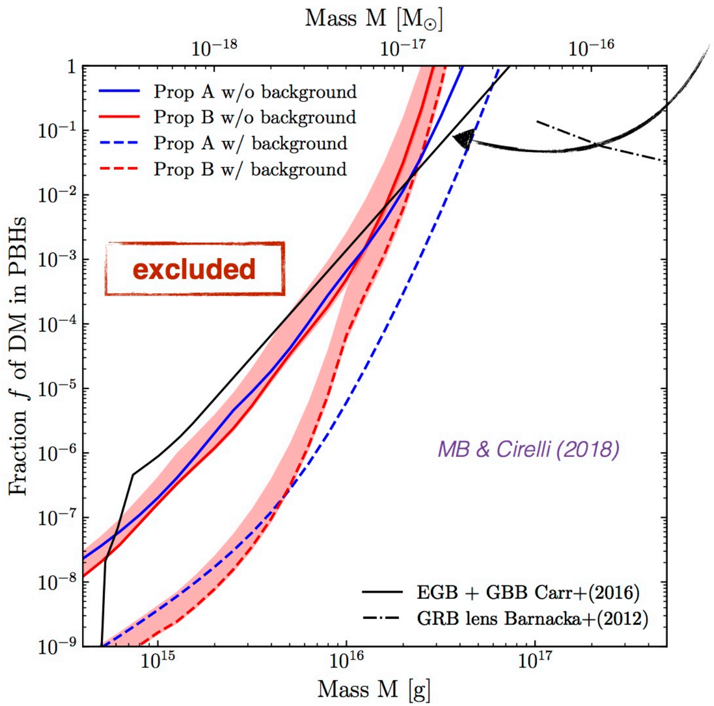
arXiv:1901.06809



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

Mathieu Boudaud[1] and Marco Cirelli[1]

arXiv:1807.03075

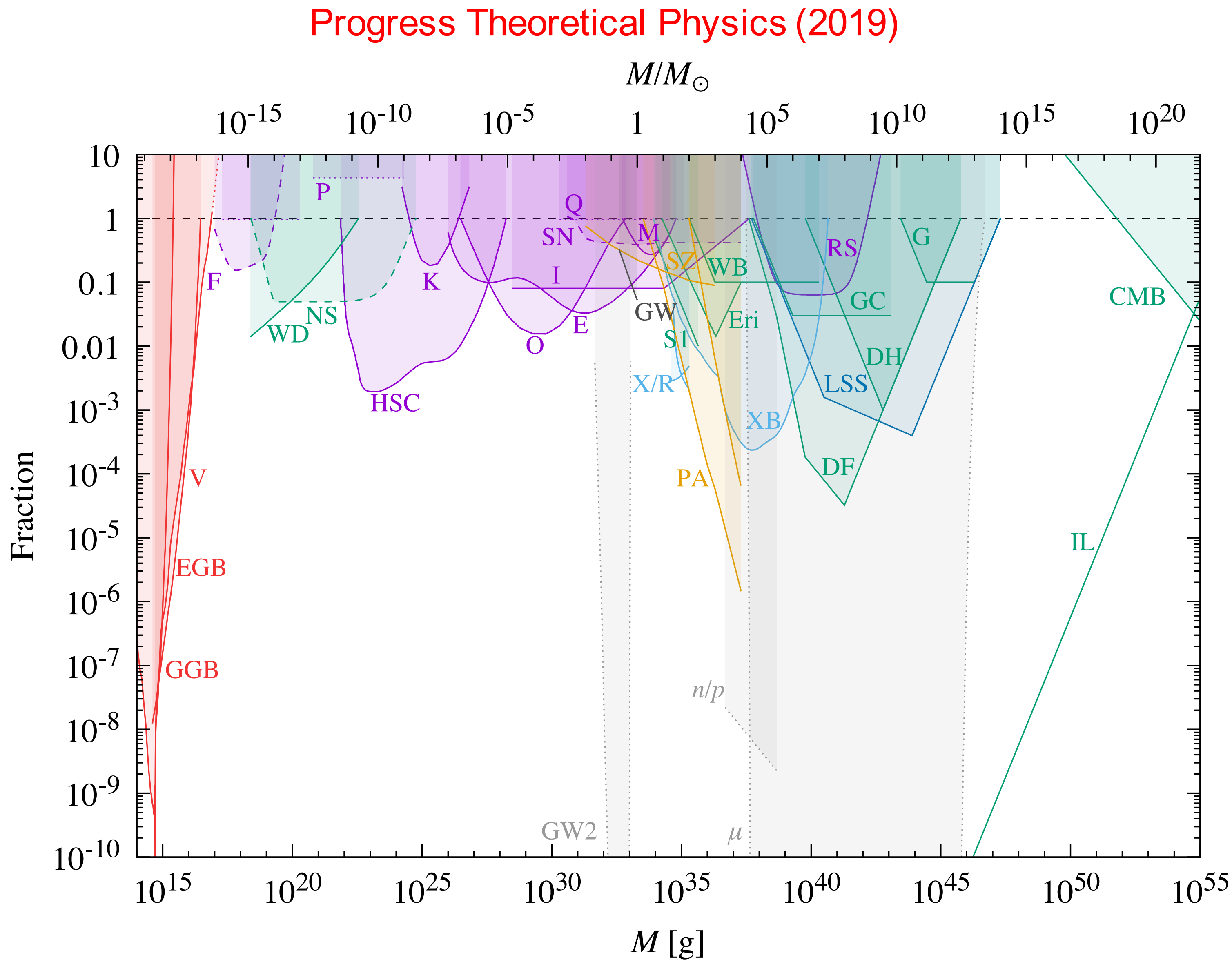


- EGB limits (Fermi-LAT) *Carr+(2010)*
- red band: propagation uncertainty (magnetic halo size) $4 < L < 20$ kpc *Reinert & Winkler(2018)*
- even better assuming a background for Voyager-1 data (SNRs e^-)

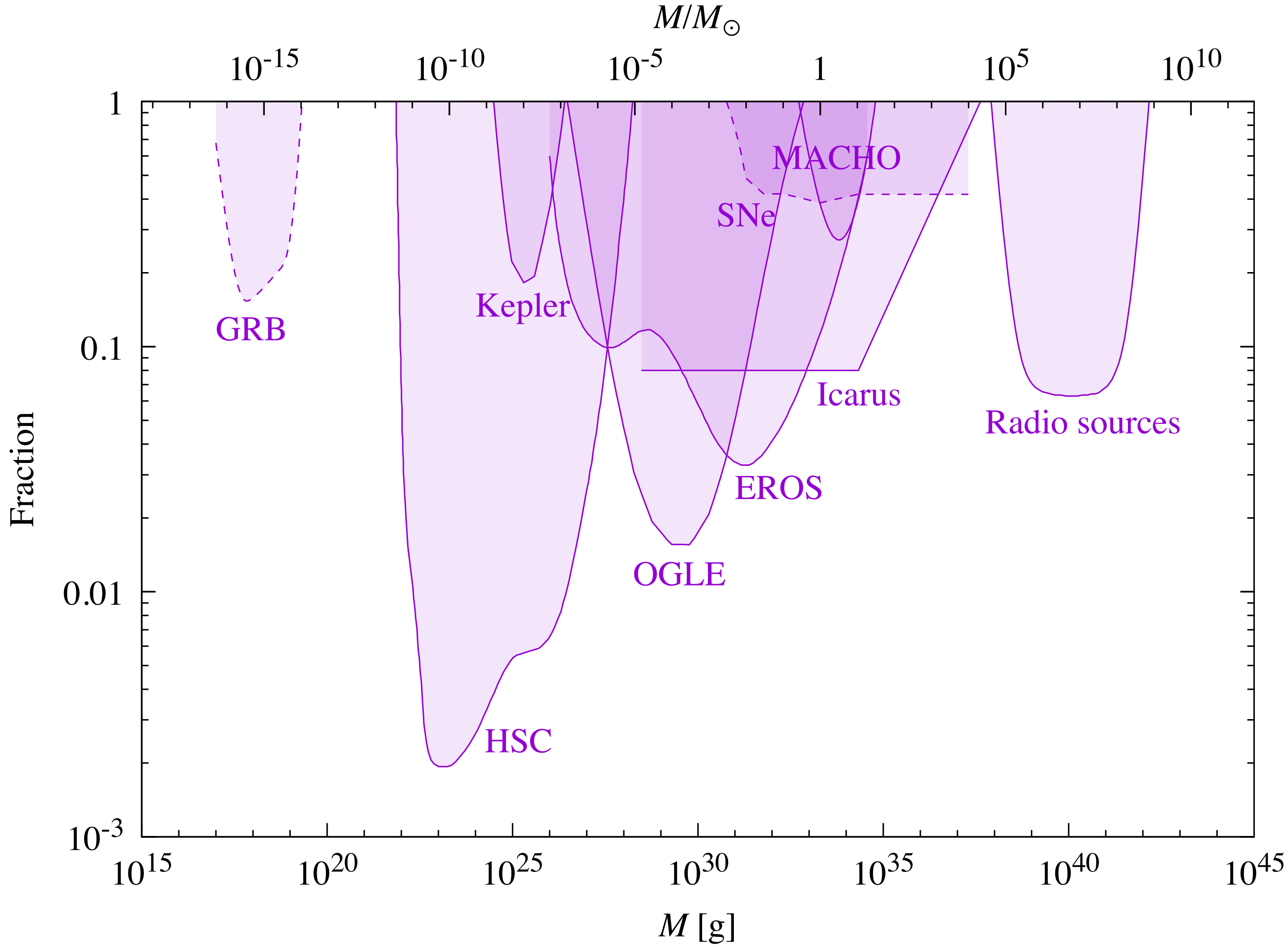
$$\Phi_{e^-}(E) \propto E^{-1.3}$$

CONSTRAINTS ON PRIMORDIAL BLACK HOLES

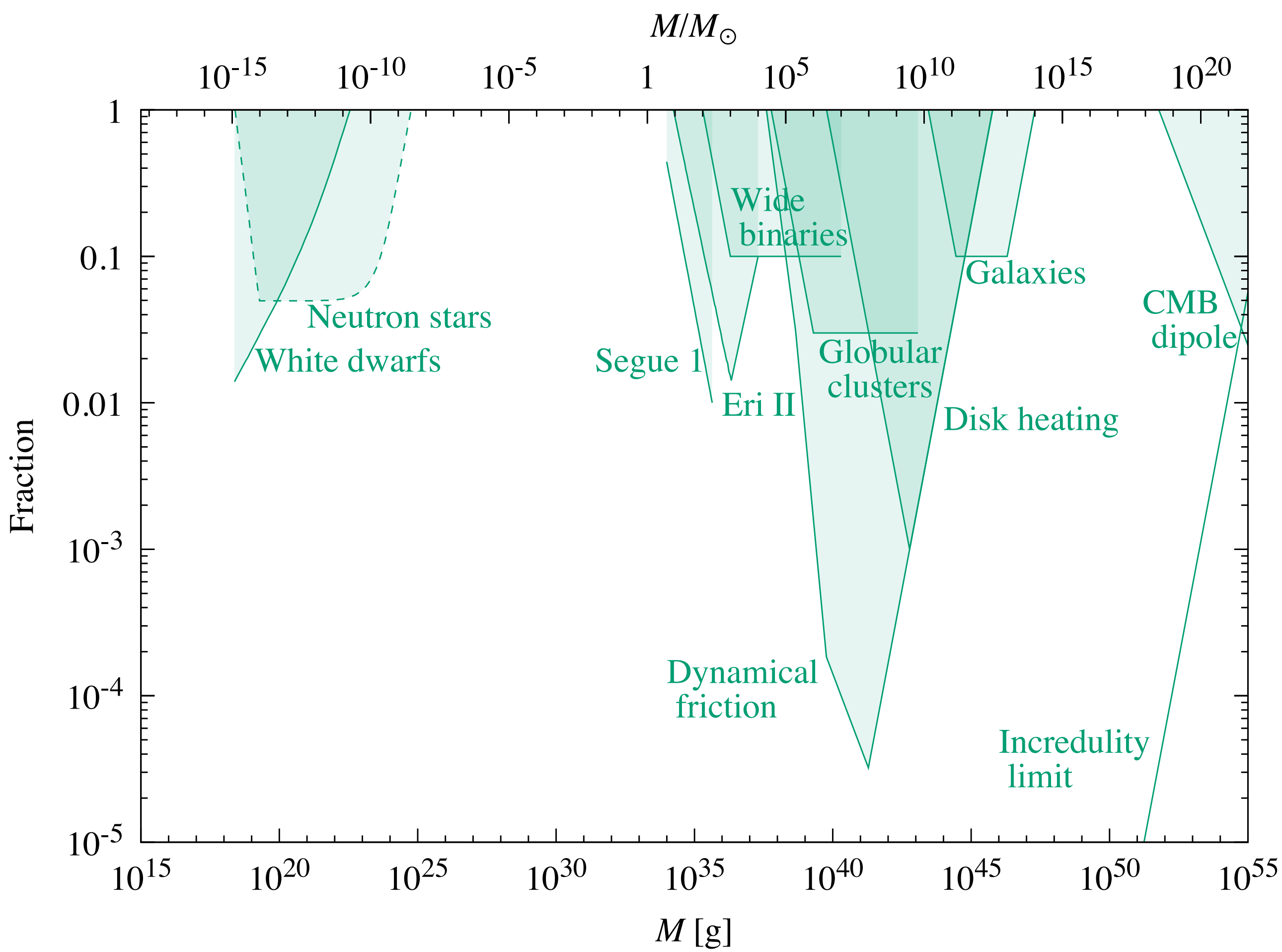
Bernard Carr,[1,2,*] Kazunori Kohri,[3,†] Yuuiti Sendouda,[4,‡] and Jun'ichi Yokoyama[2,5,§]



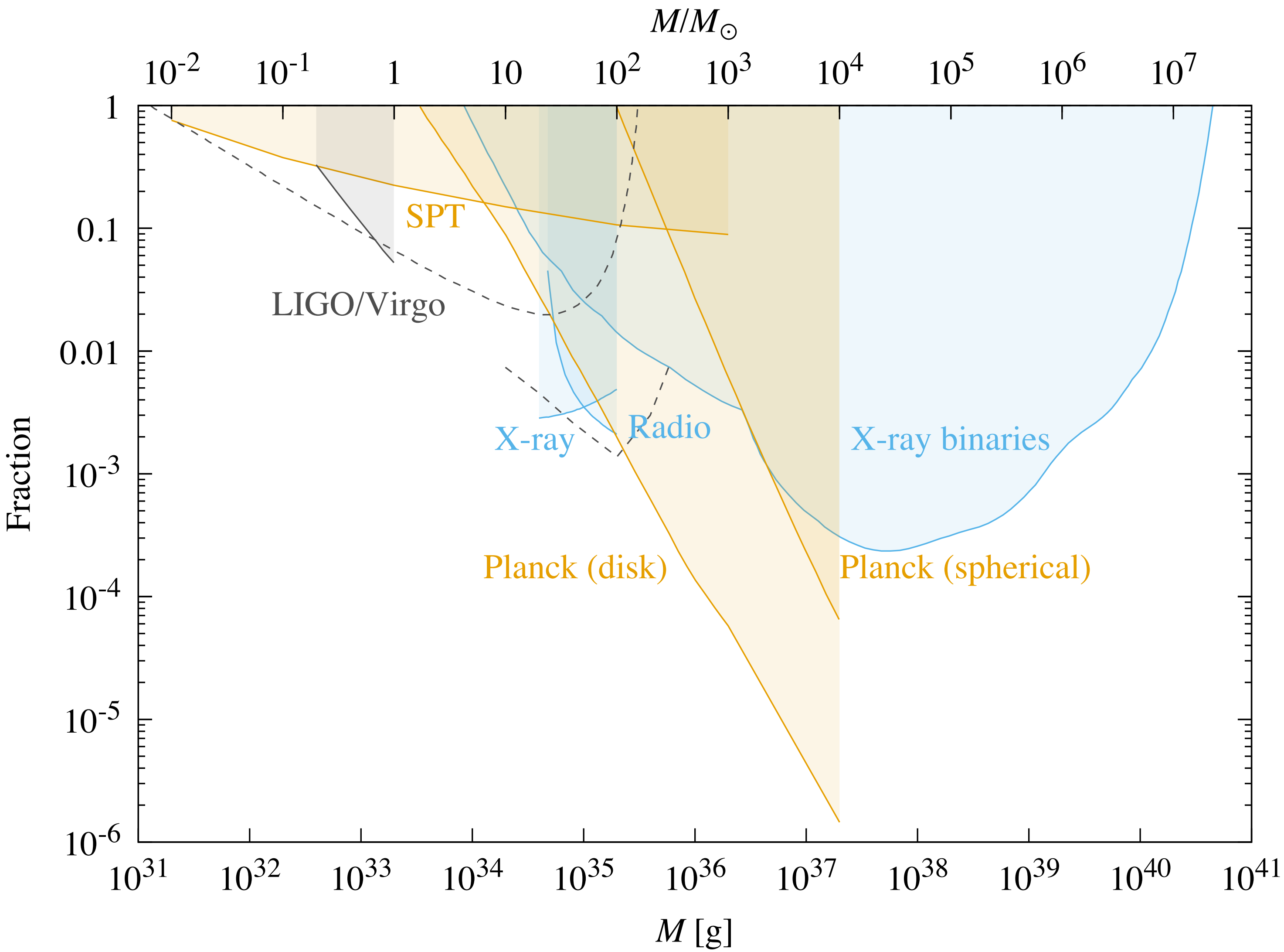
LENSING LIMITS



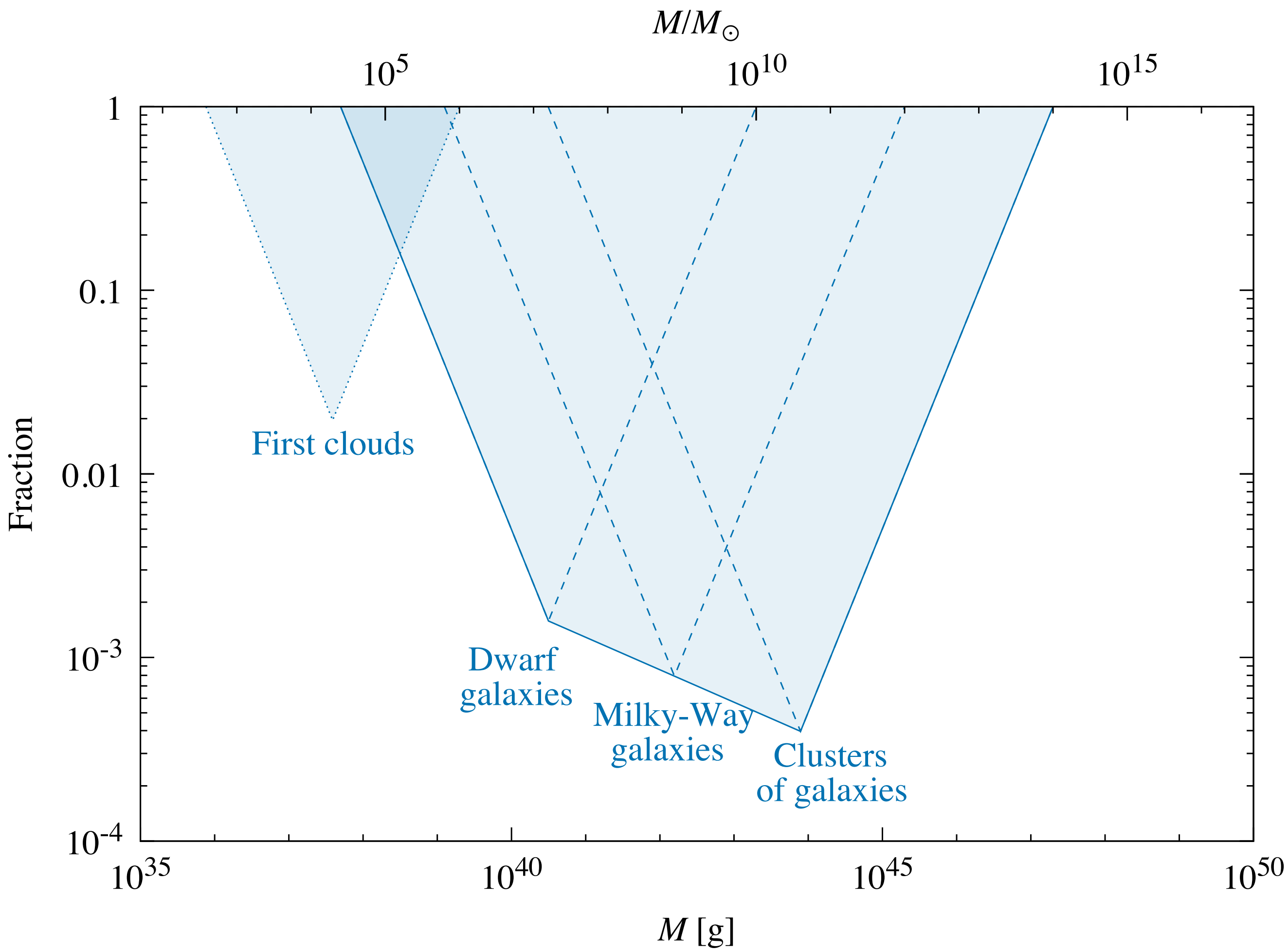
DYNAMICAL LIMITS



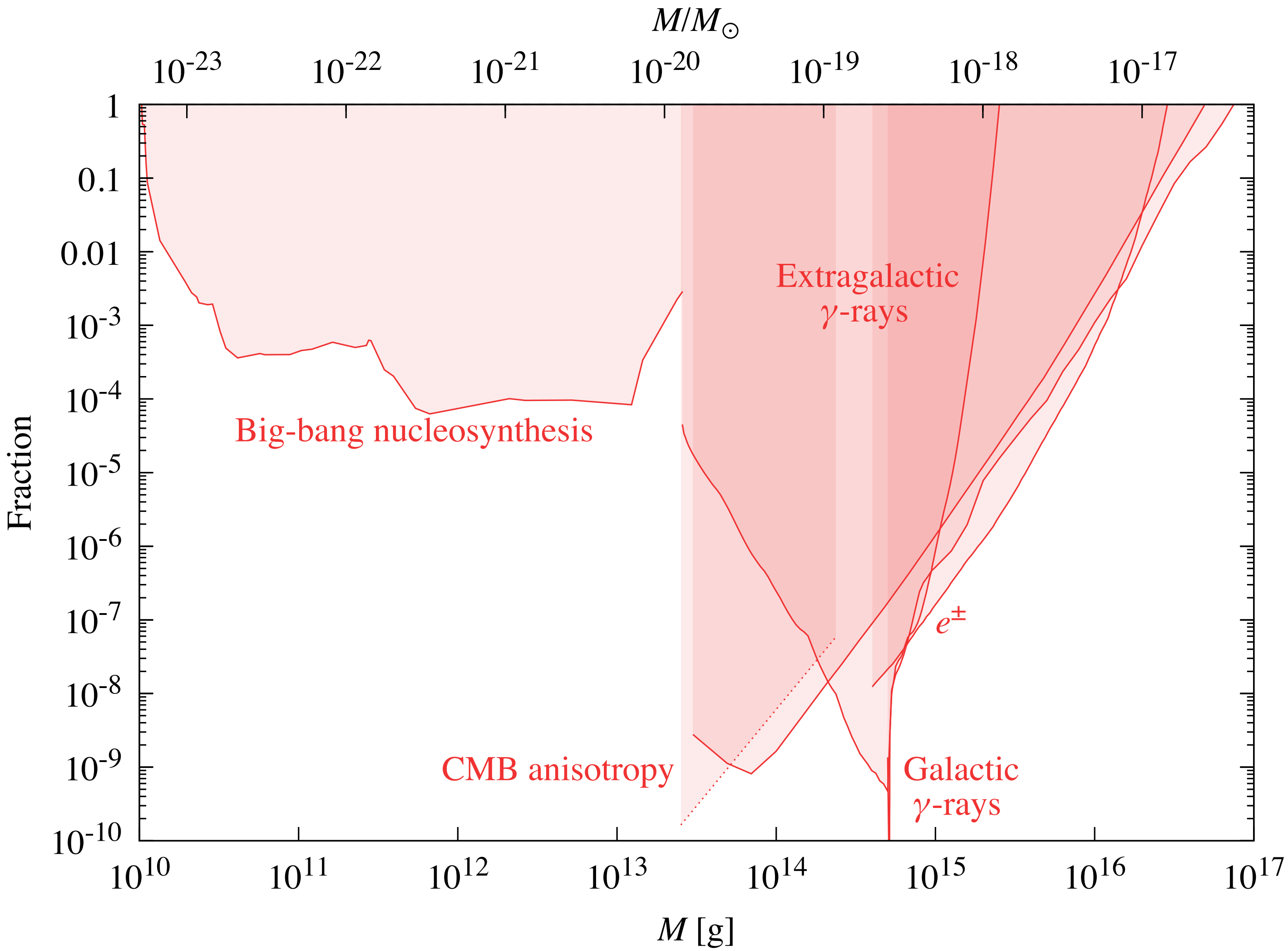
ACCRETION AND LIGO LIMITS



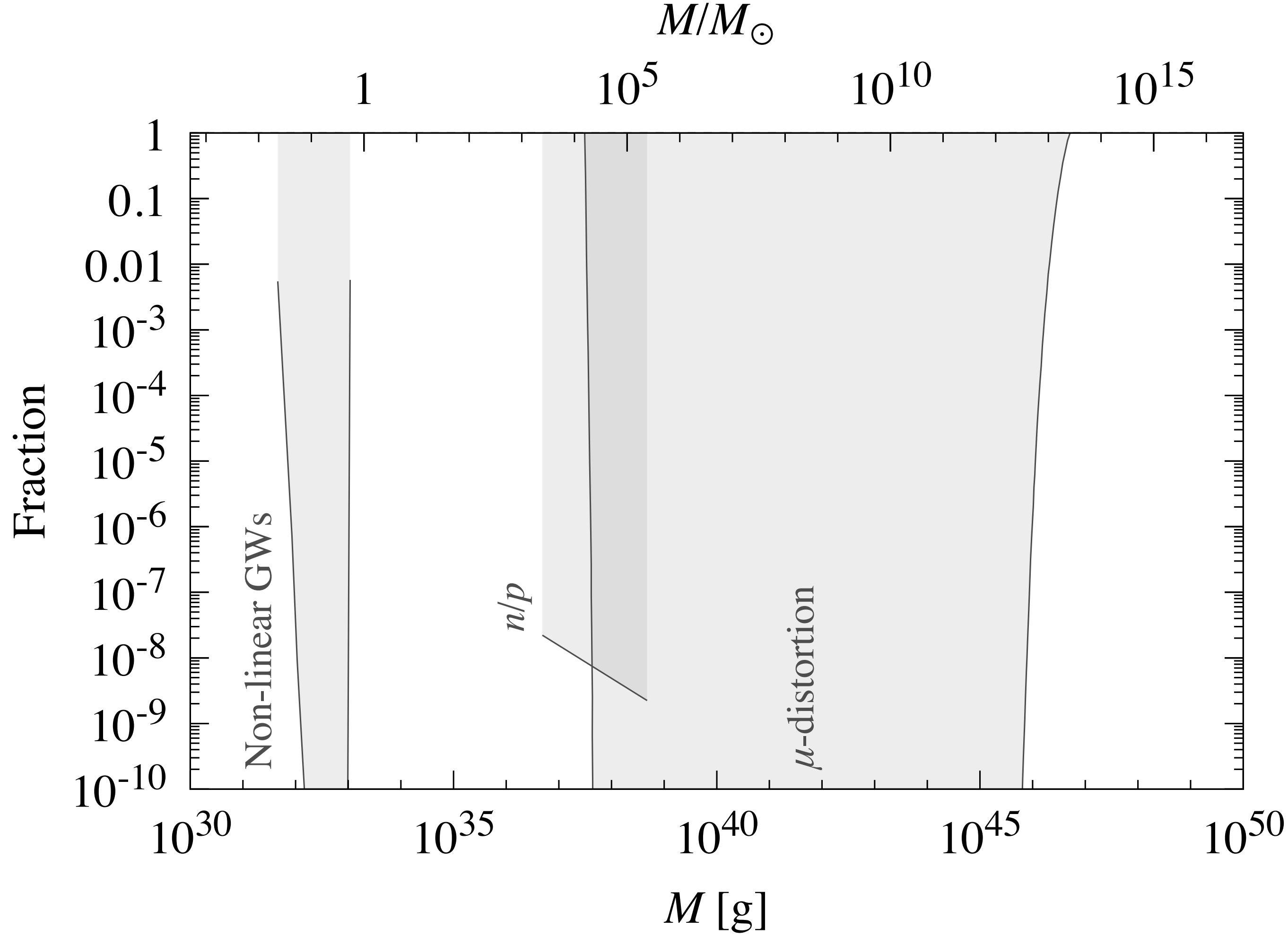
LARGE-SCALE STRUCTURE LIMITS



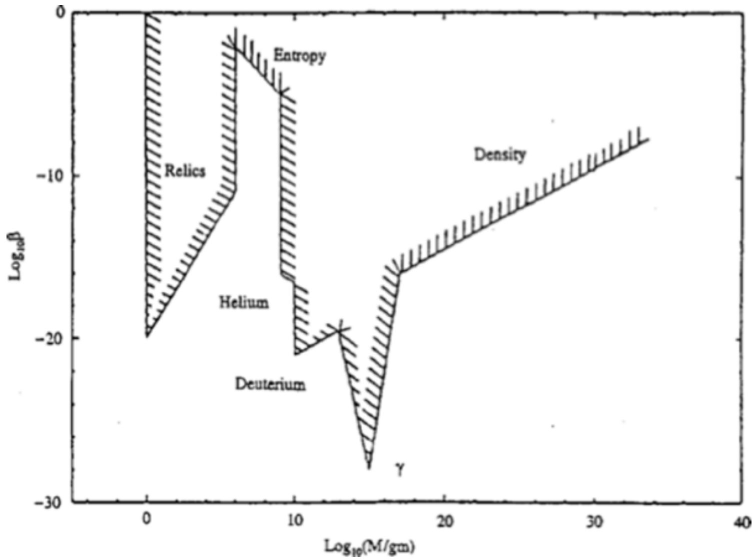
EVAPORATION LIMITS



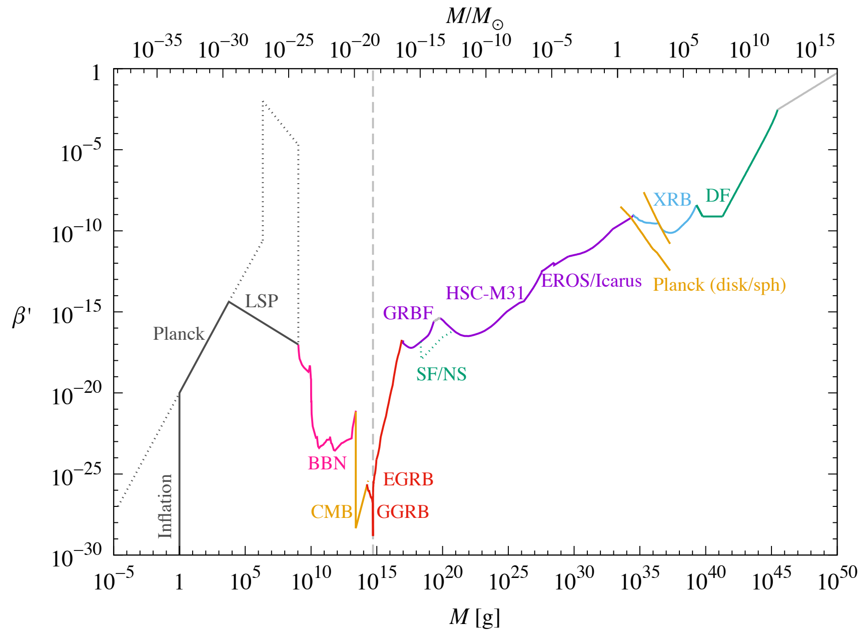
COSMOLOGICAL LIMITS



EVOLUTION OF CONSTRAINTS ON COLLAPSE FRACTION

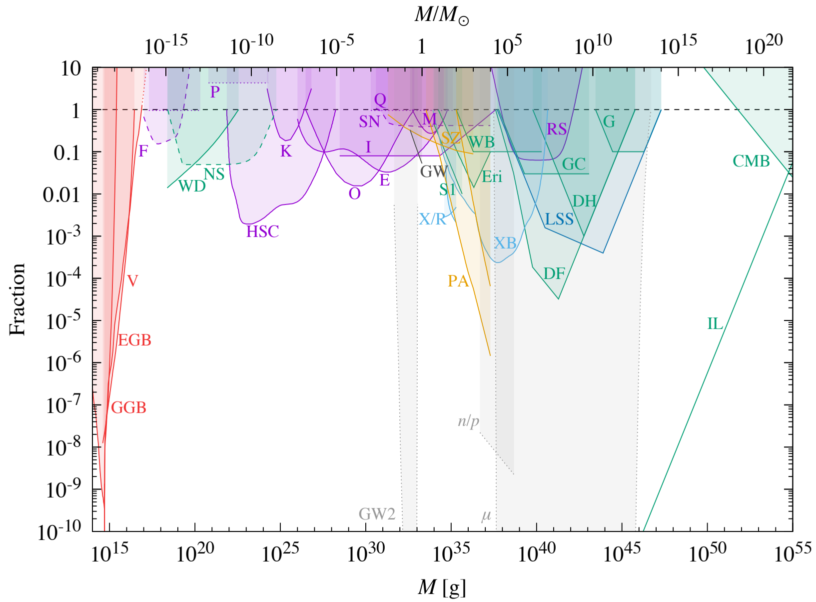


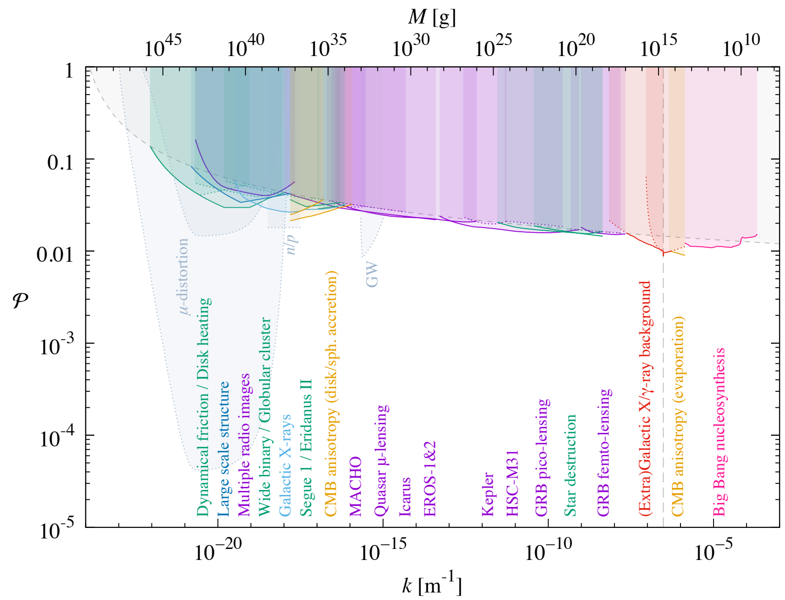
1994



2019

CONSTRAINTS ON POWER SPCTRUM





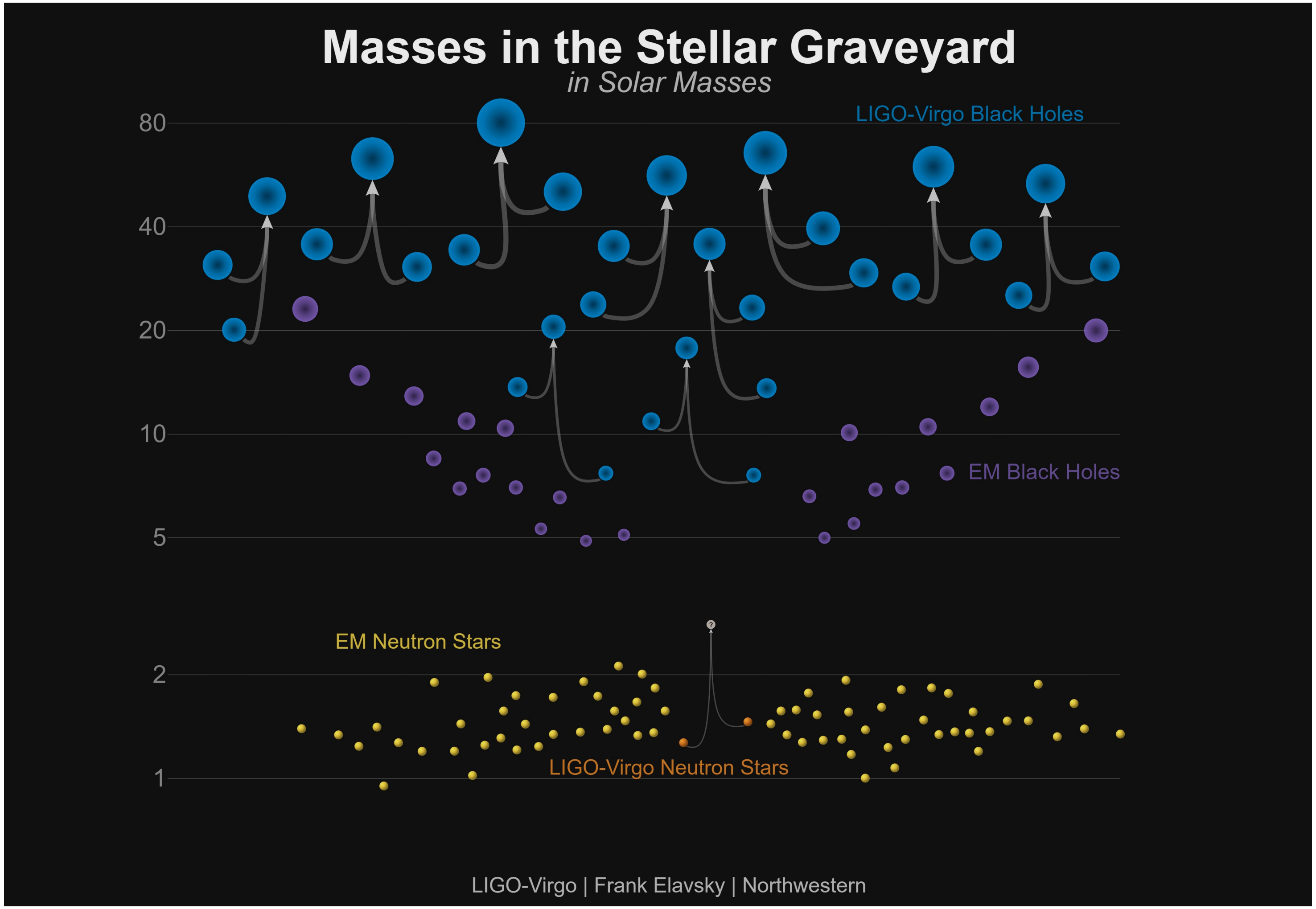
These constraints are not just nails in a coffin!

All constraints have caveats and may change

Each constraint is a potential signature

PBHs are interesting even if f << 1

PBHS AND LIGO



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 $\sim 0.5\ M_\odot$, 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 $\sim 5 \times 10^8$ black hole binaries the coalescence times of which are comparable to the age of the universe, so that the coalescence rate will be $\sim 5 \times 10^{-2}$ 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 $\sim 30\,\mathrm{M}_\odot$ 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]

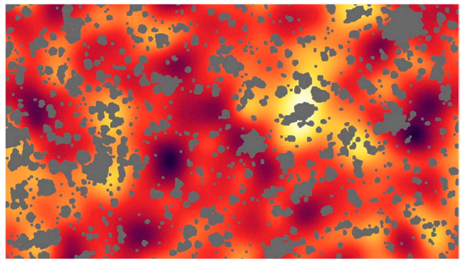
arXiv:1603.08338

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 generate early structure and infrared background

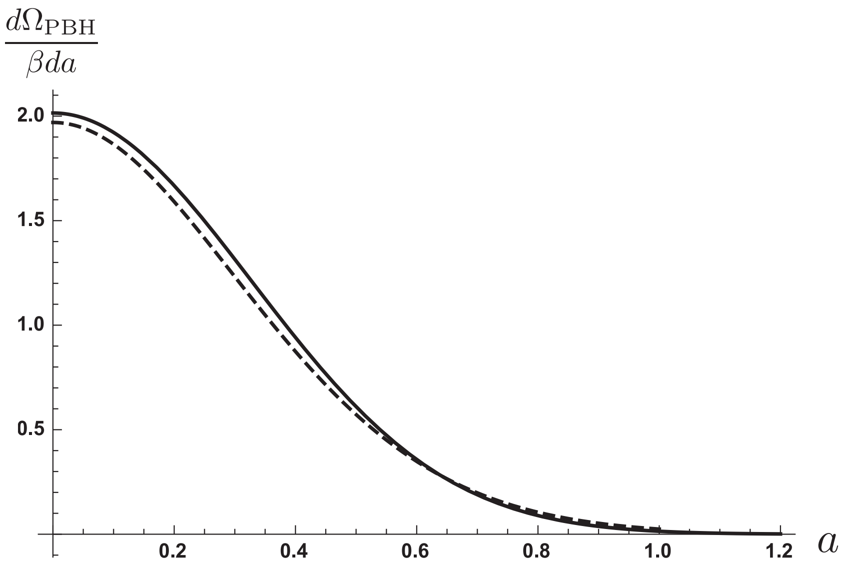
Spin Distribution of Primordial Black Holes

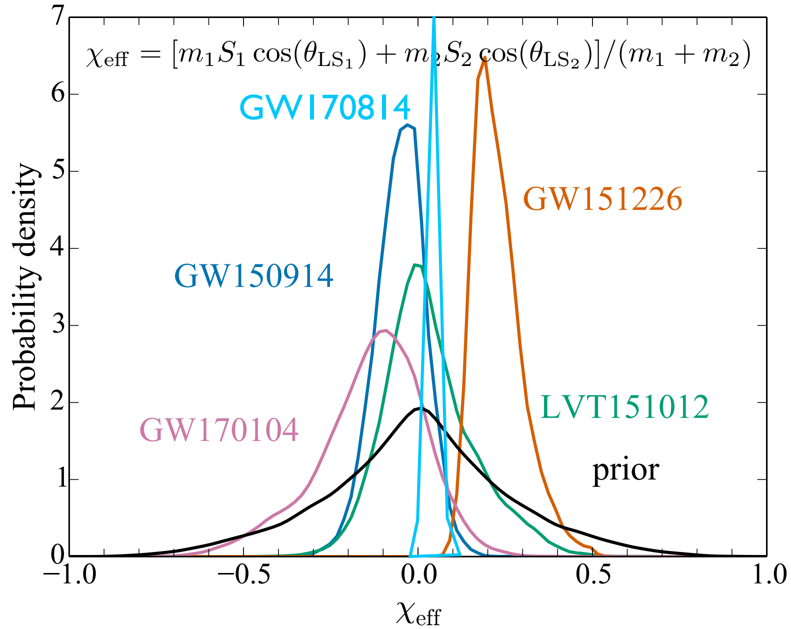
Takeshi Chiba[1] and Shuichiro Yokoyama[2]

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.

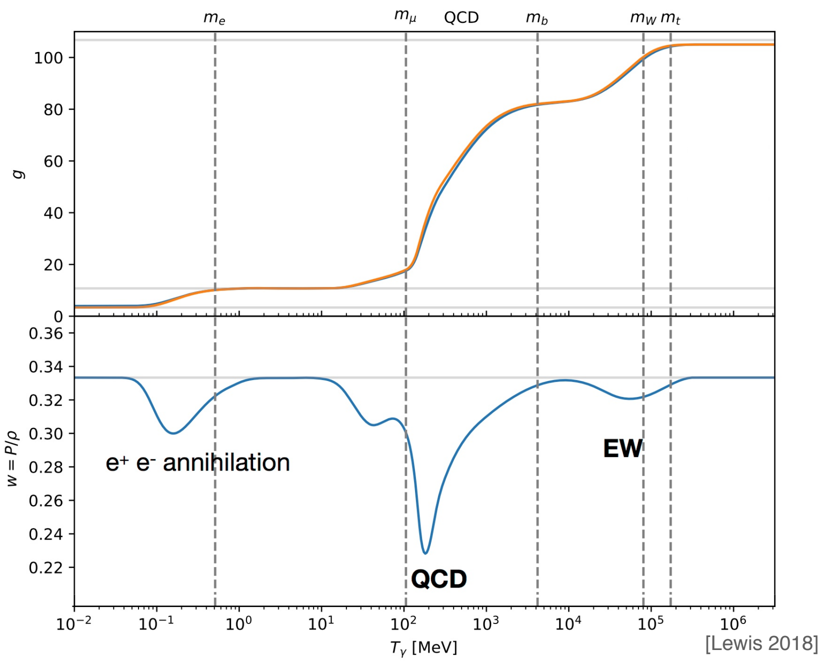


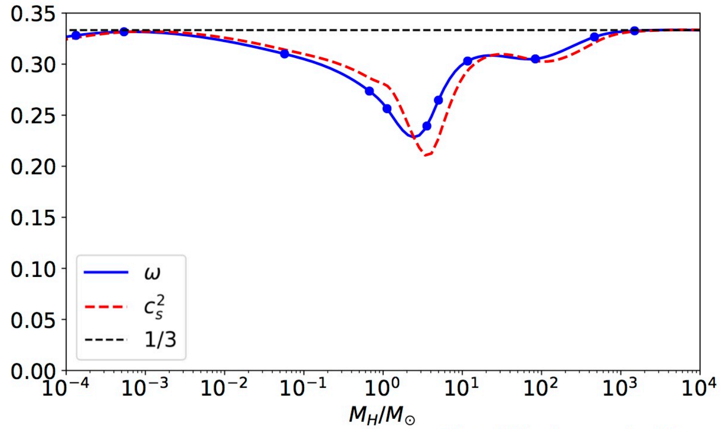


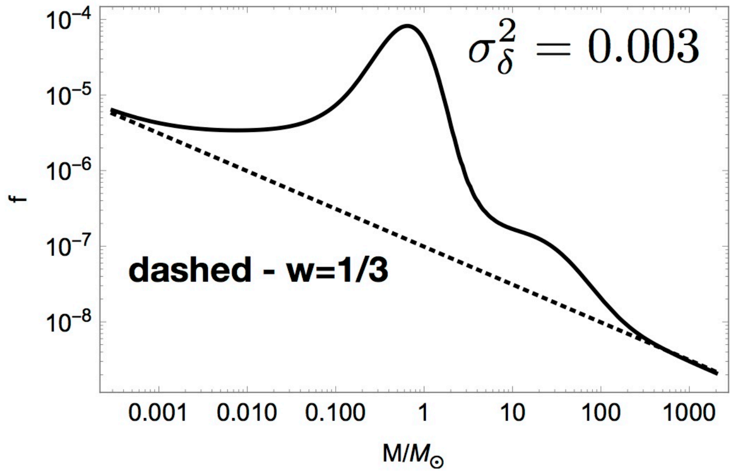
Primordial black holes with an accurate QCD equation of state

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

arXiv:1801.06138







PBHS, DARK MATTER AND BARYOGENESIS AT THE QUARK HADRON EPOCH: ADDRESSING THE FINE-TUNINGS

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

So β must be 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

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

$\chi << 1$ => $t_{deq} >> t_{dec}$ => fluctuations too small to make galaxies

Baryogenesis scenario

EW baryogenesis a 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 formation => large curvature perturbations => huge entropy production => out-of-equilibrium condition => baryogenesis

$\eta_{loc} \sim \dfrac{\Gamma_{\rm sph}(T_{\rm eff})}{T_{\rm eff}\, T_{\rm rh}^3}\, \delta_{\rm CP}(T_{\rm rh})\, \Delta\theta$ ~ O(1) for T_{eff} ~ 60 GeV, T_{rh}~200 MeV, $\Delta\theta \sim 1$

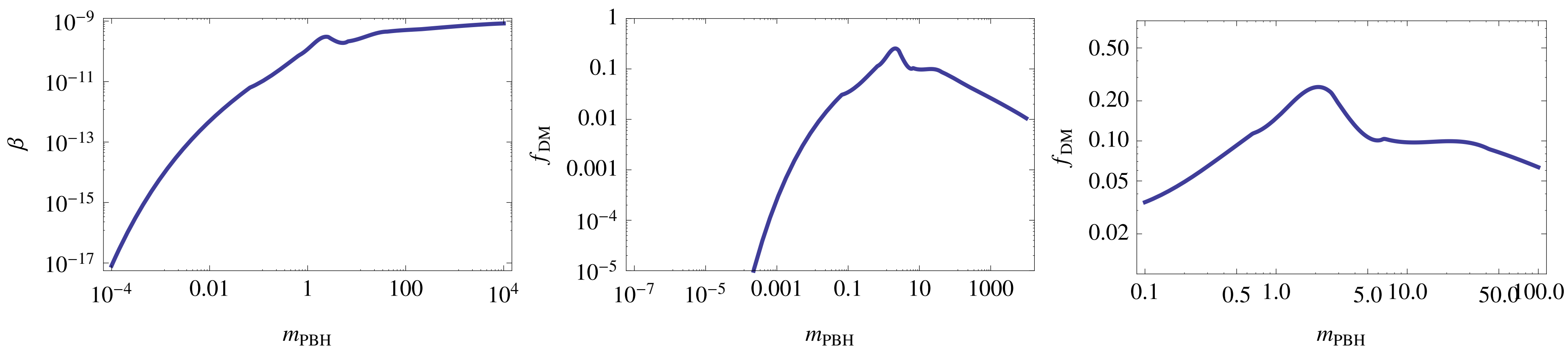
Diffusion of baryon asymmetry => $\eta \sim \beta\, \eta_{loc}$

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 PE dominates density long after inflation
$\Rightarrow$ 2nd 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.



1st peak at $1M_O$ for DM plus 2nd 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

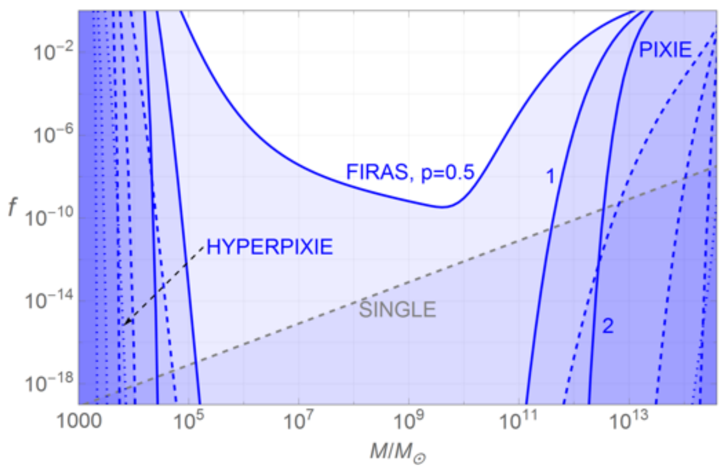
Upper limit on μ distortion of CMB excludes $10^4 < M/M_O < 10^{12}$ for Gaussian fluctuations but some models evades these limits. Otherwise need accretion factor of $(M/10^4 M_o)^{-1}$

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.

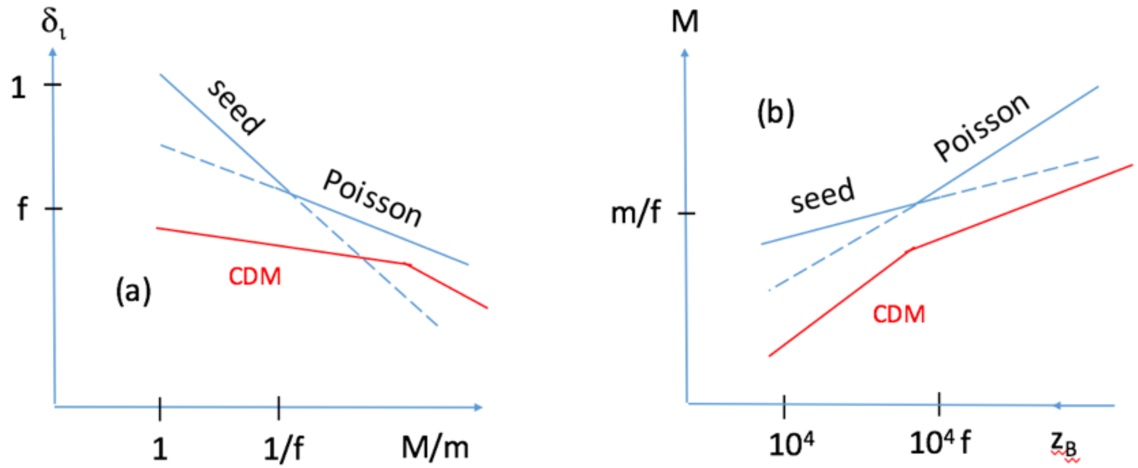
If region of mass M contains PBHs of mass m, initial fluctuation is

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

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

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

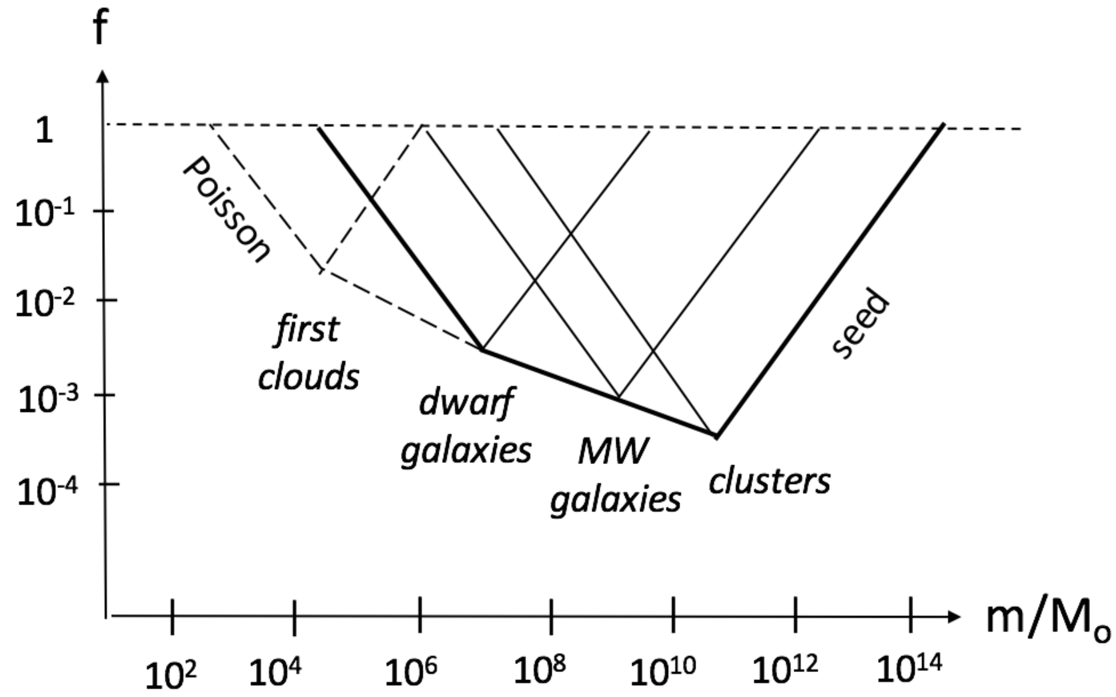
f = 1 => m < 10^3 M_O => M <$10^{11} z_B^{-2}$ M_O < M_{gal} (Poisson)

=> can generate dwarf galaxies

f << 1 => M can be larger

=> PBHs can be seeds for galaxies

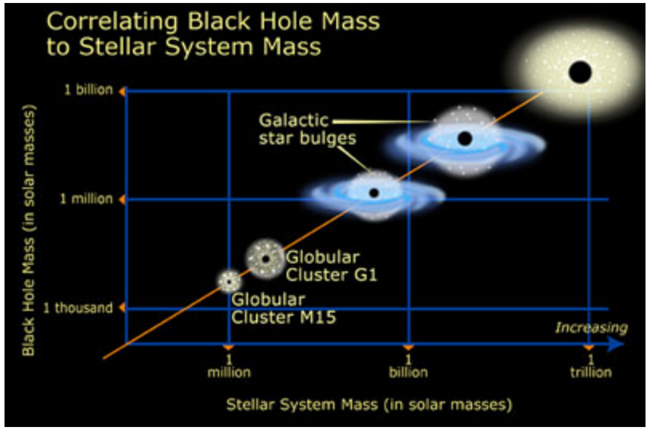
Can constrain PBH scenarios by requiring that various cosmic structures do not form too early



First clouds bind earlier than in standard model

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

PRIMORDIAL BLACK HOLES IN A DIMENSIONALLY REDUCED UNIVERSE

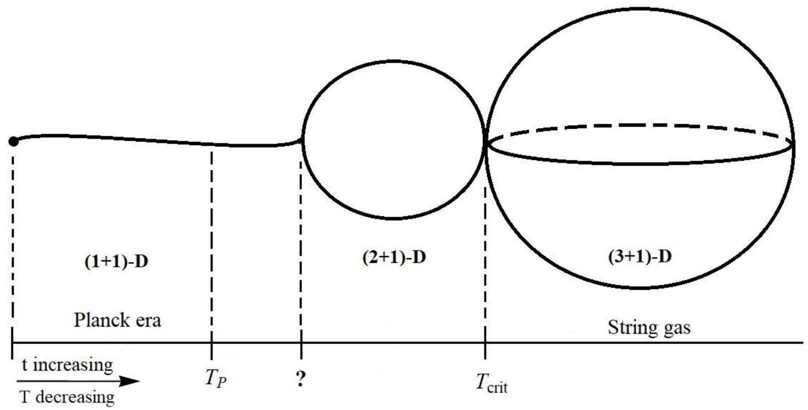
A. Tzikas, P. Nicolini, J. Mureika and B. Carr

JCAP 1812(2018), 033; arXiv:1811.09518

Abstract

We investigate the spontaneous creation of primordial black holes in a lower-dimensional expanding early universe. We use the no-boundary proposal to construct instanton solutions for both the background and a black hole nucleated inside this background. The resulting creation rate could lead to a significant population of primordial black holes during the lower dimensional phase. We also consider the subsequent evaporation of these dimensionally reduced black holes and find that their temperature increases with mass, whereas it decreases with mass for 4-dimensional black holes. This means that they could leave stable sub-Planckian relics, which might in principle provide the dark matter.

Universe may have been (1+1)-dimensional at early times



(t'Hooft)

=> PBH production through gravitational instanton effects

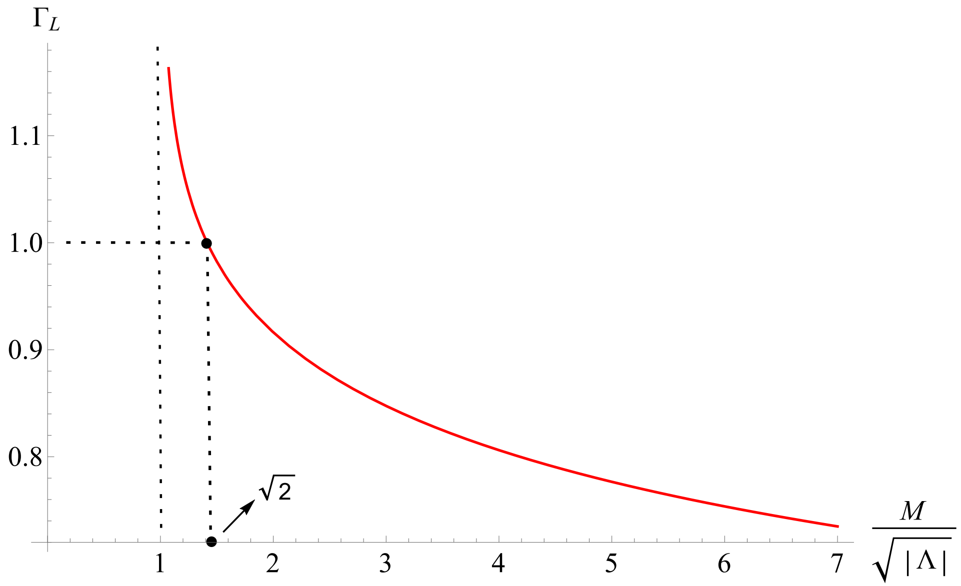
In 3+1 case $\Gamma \sim \exp(-\pi/\Lambda) << 1$ now (Bousso & Hawking 1996)

In 1+1 case:

$$\Gamma_{\rm L} = \left[\frac{\Lambda^2}{(M^2 - |\Lambda|)^2}\right]^{\frac{1}{4G_{(2)}}} \quad M > \sqrt{|\Lambda|}$$

$$\Gamma_{\rm N} = \left(\frac{\mu_0^2}{|\Lambda|}\right)^{\frac{1}{2G_{(2)}}} \quad M = \sqrt{|\Lambda|}.$$

Nariai



PBH PRODUCTION RATE

$$M \ll \sqrt{|\Lambda|} \quad \textbf{=>} \quad T \approx M/(2\pi), \quad \Gamma_{\rm L} \approx (\Lambda/M^2)^{1/2} \ll 1$$

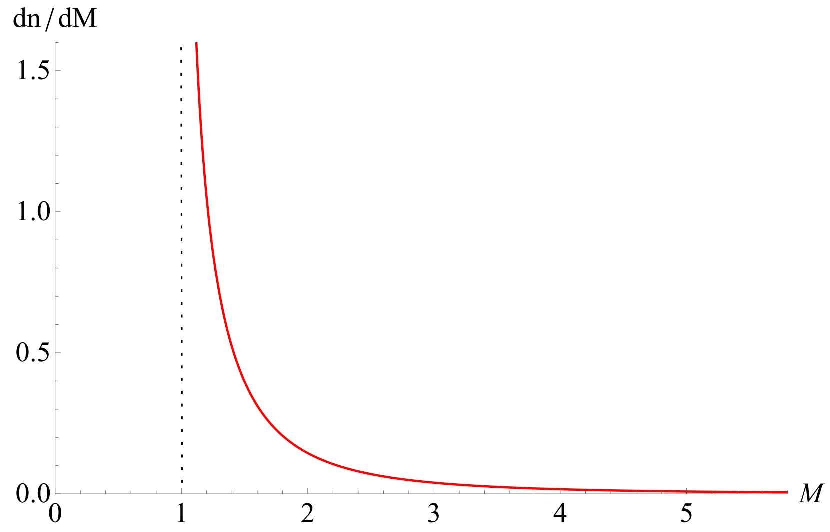
$$\sqrt{|\Lambda|} < M < \sqrt{2|\Lambda|} \quad \textbf{=>} \quad T \approx \sqrt{|\Lambda|}/(2\pi), \quad \Gamma_{\rm L} \approx 1$$

$$M = \sqrt{|\Lambda|}(1+\epsilon) \quad \textbf{=>} \quad T \approx \sqrt{\epsilon|\Lambda|}/(\sqrt{2}\pi) \ll \sqrt{|\Lambda|}, \quad \Gamma_{\rm L} \approx \epsilon^{-1/2} \gg 1$$

$$M = \sqrt{|\Lambda|} \quad \textbf{=>} \quad T = 0, \quad \Gamma_{\rm N} = (\mu_0/\sqrt{|\Lambda|})$$ (Nariai)

PBH MASS FUNCTION

$$\frac{dn}{dM} \sim \frac{\beta(M)}{M^2} \sim \frac{\Gamma(M)}{M^2}$$



PBH EVAPORATION

$$\beta = T^{-1} = \left(\frac{1}{2\pi}\sqrt{M^2 - |\Lambda|}\right)^{-1}$$

$M \gg \sqrt{|\Lambda|}$ => $R_\mathrm{S} \approx \frac{1}{2M}, \quad T \approx \frac{M}{2\pi}$ => $L \sim R_\mathrm{S}^2 T^4 \sim \gamma M^2$

=> $M = \frac{M_\mathrm{i}}{1+\gamma M_\mathrm{i}(t_o - t_\mathrm{i})} \approx \frac{M_\mathrm{i}}{1 + M_\mathrm{i}/M_*}$ with $M_* \sim 1/(\gamma t_0) \sim \hbar/(c^2 t_0) \sim 10^{-65}\ \mathrm{g}$

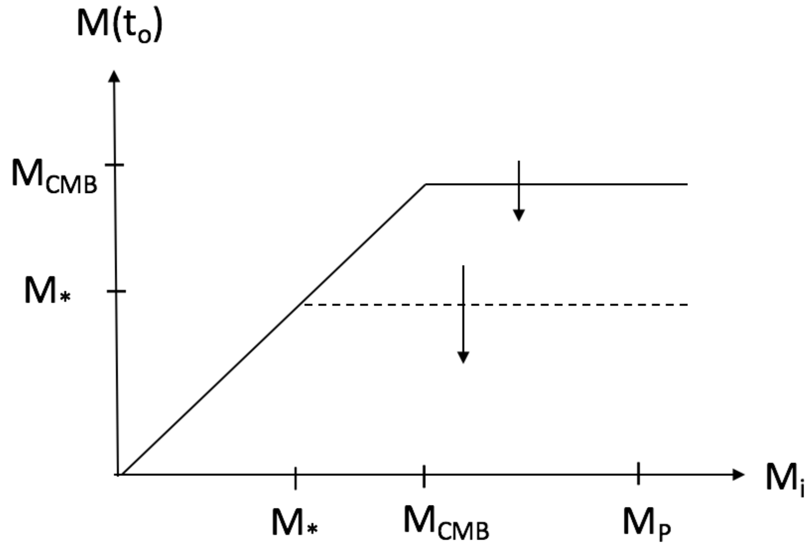
But CMB suppresses evaporation above

$$M_\mathrm{CMB} = 10^{-36}(T_\mathrm{CMB}/3K)\,\mathrm{g}$$

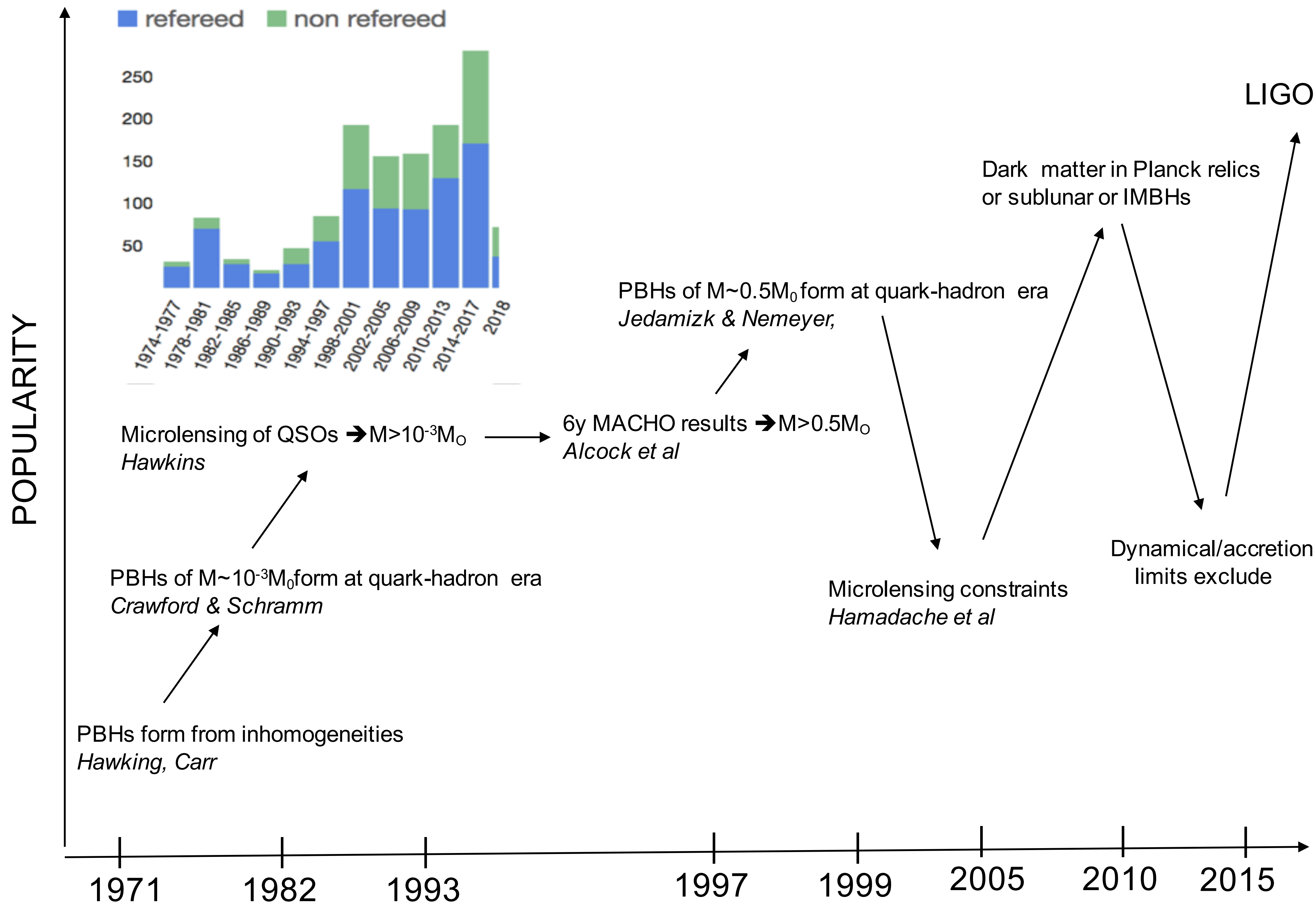
Non-evaporating Nariai PBHs have

$$\rho_N(\Lambda_i) \sim M^2\,\frac{dn_N}{dM} \sim \Gamma(\Lambda_i) \sim \frac{\mu_0}{\sqrt{\Lambda_i}}$$

and could provide dark matter



Transition to 3+1 may generate Λ with density comparable to DM


refereed
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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,
Microlensing of QSOs → M>10-3MO
Hawkins
6y MACHO results → M>0.5MO
Alcock et al
Dynamical/accretion limits exclude
PBHs of M~10-3M0 form at quark-hadron era
Crawford & Schramm
Microlensing constraints
Hamadache et al
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 events	Cosmic structure

These are distinct roles but with extended mass function PBHs could fulfill 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