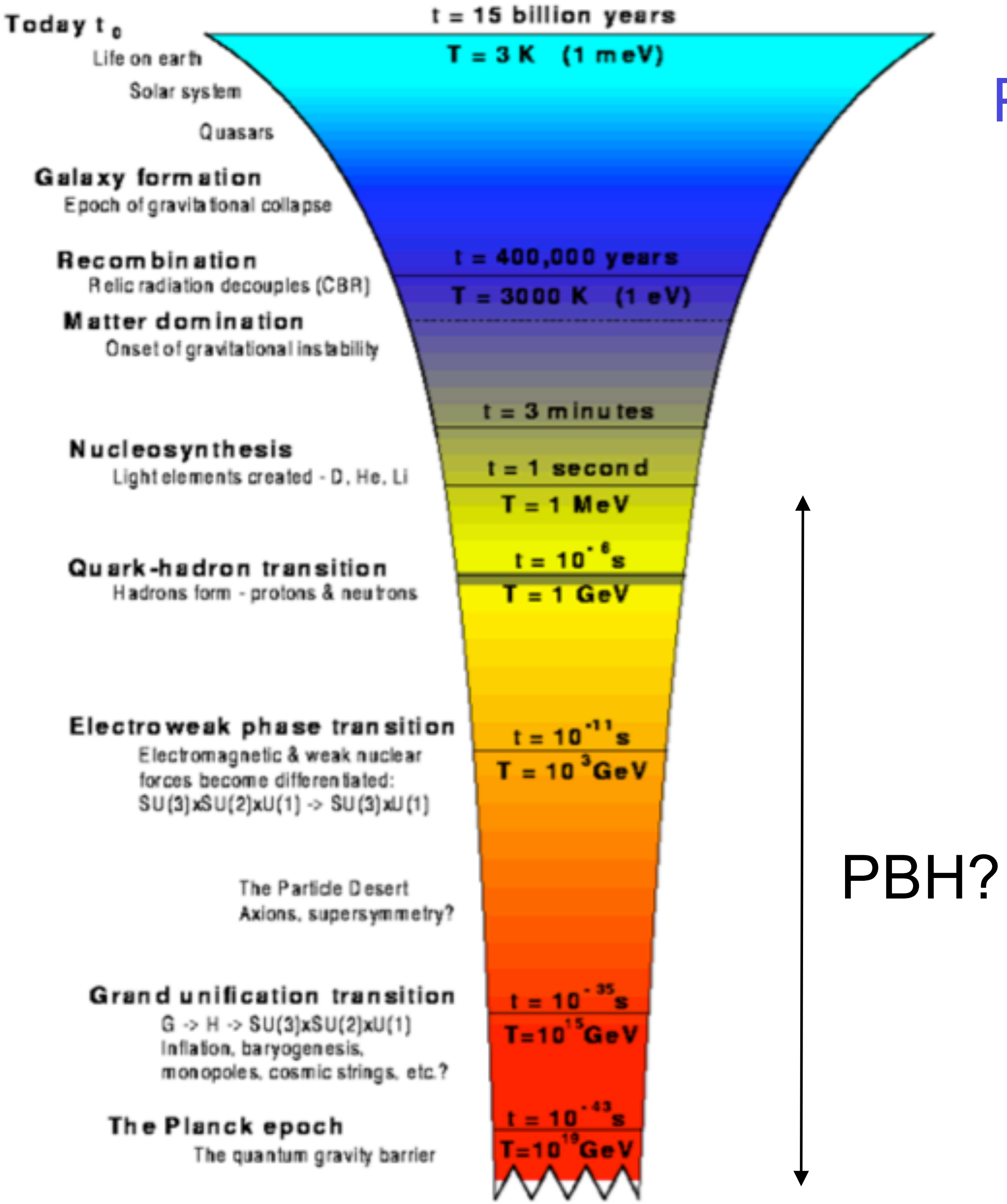



# PRIMORDIAL BLACK HOLES AFTER 50 YEARS: A HISTORICAL OVERVIEW


Bernard Carr
Queen Mary
University of London


IPMU 13/11/17

# PLAN OF TALK

- Introduction and early history
- Formation of PBHs Harada
- PBHs and inflation Mukaida
- Constraints on evaporating PBHs
- Constraints on PBHs as dark matter
- PBHs and large-scale structure
- PBHs and gravitational waves

(Last three items: Garcia-Bellido)

# PRIMORDIAL BLACK HOLES

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

**Small black holes can only form in early Universe**

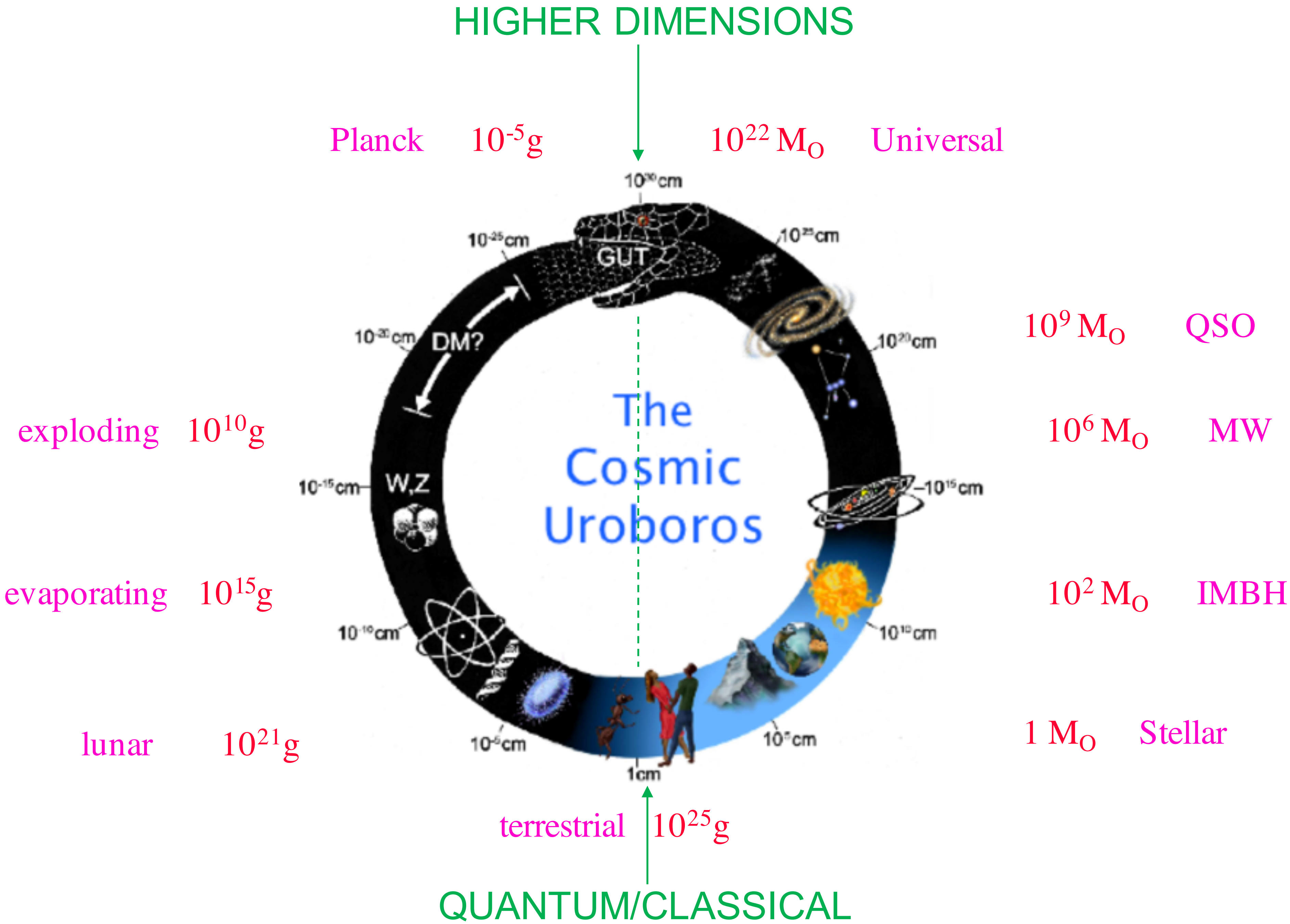
**cf. cosmological density** $\rho \sim 1/(Gt^2) \sim 10^6 (t/s)^{-2}$g/cm$^3$

⇨ **PBHs have horizon mass at formation**

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

**=> huge possible mass range**

# BLACK HOLES



HIGHER DIMENSIONS
Planck 10-5g
1022 MO Universal
109 MO QSO
106 MO MW
102 MO IMBH
1 MO Stellar
exploding 1010g
evaporating 1015g
lunar 1021g
terrestrial 1025g
QUANTUM/CLASSICAL
GUT
DM?
W,Z
The Cosmic Uroboros
1cm

# WHY PBHS ARE USEFUL

**$M<10^{15}$g =>** Probe early Universe

inhomogeneities, phase transitions, inflation

**$M\sim10^{15}$g =>** Probe high energy physics

PBH explosions, cosmic rays, gamma-ray background

**$M>10^{15}$g =>** Probe gravity and dark side

dark matter, dark energy, dark dimensions

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

Planck mass relics, Generalized Uncertainty Principle

*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 $\pm 30$ 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.

# Newtonian argument for PBH accretion

- The Bondi accretion (spherically symmetric, quasi-stationary flow)

$$\frac{dM}{dt} = 4\pi\alpha R_A^2 v_s \rho_\infty,$$

where

$$R_A = GM/v_s^2, \quad \alpha = \text{const} = O(1), \quad v_s = \text{sound speed}.$$

$k^{1/2}$

- Zeldovich & Novikov (1967) used the Friedmann density.

$$\rho_\infty = \frac{1}{6\pi G(1+k)^2 t^2},$$

p = kρ

$$\frac{dM}{dt} = \frac{M^2}{\beta t^2}, \quad \beta = \frac{3k^{3/2}(1+k)^2}{2\alpha}\frac{c^3}{G}.$$

- M is integrated to

$$M = \frac{\beta t}{1 + \frac{t}{t_f}\left(\frac{\beta t_f}{M_f} - 1\right)},$$

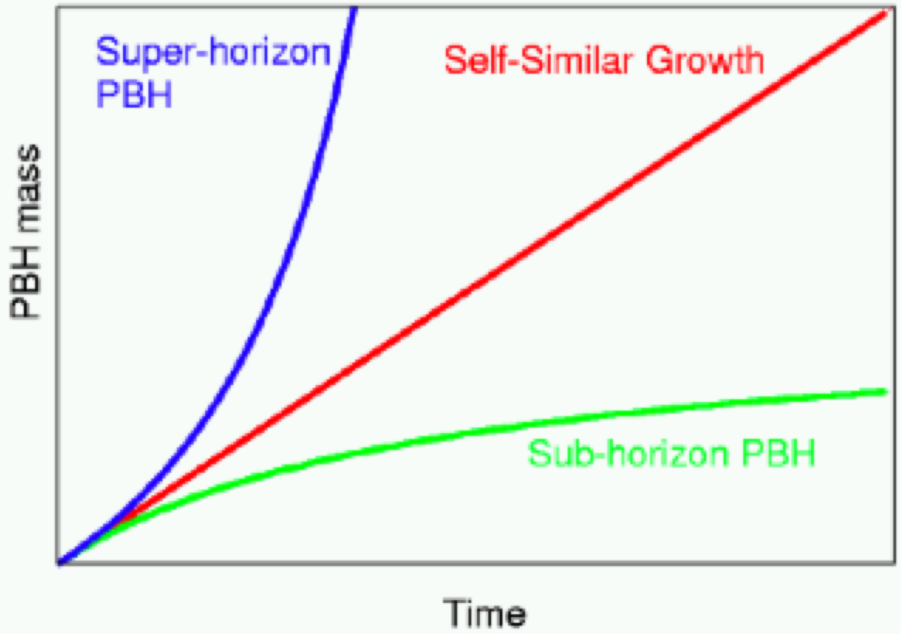
horizon mass

formation mass

Three classes of solutions

$$M \to \frac{M_f}{1-\xi} \quad \text{for} \quad \xi < 1,$$
$$M = \beta t \quad \text{for} \quad \xi = 1,$$
$$M \to \infty \quad \text{at} \quad t = t_d \quad \text{for} \quad \xi > 1,$$
$$\text{where} \quad \xi = \frac{M_f}{\beta t_f}.$$

horizon mass at formation




The growth of sub-horizon PBHs essentially stops in several Hubble times.
PBHs of horizon mass grow in proportion to time. Expected!
Super-horizon PBHs grow more rapidly and diverge in finite time.

The cosmological expansion is not considered at all.

*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.

# SPHERICALLY SYMMETRIC SELF-SIMILAR SOLUTIONS

Metric $ds^2 = -e^{2\Phi(z)}dt^2 + e^{2\psi(z)}dr^2 + r^2S^2(z)d\Omega^2$ Perfect fluid $p=k\rho$

Dimensionless quantities depend only on $z=r/t$

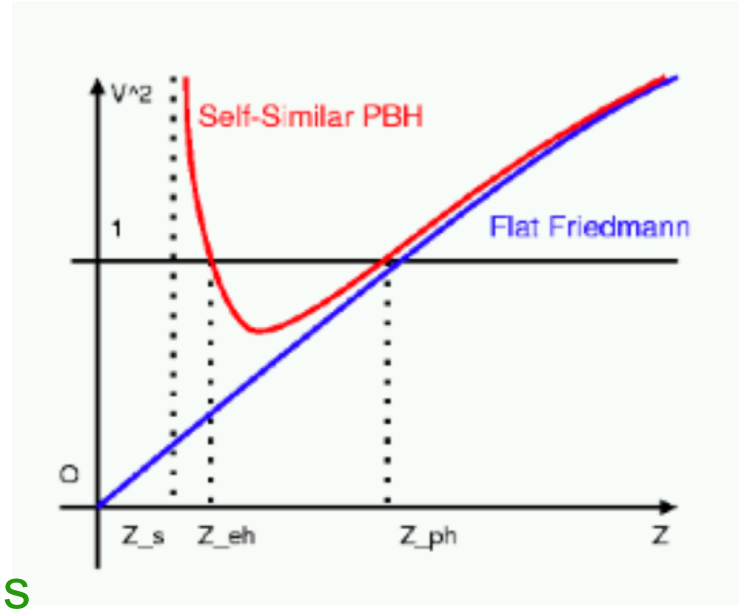
Speed of fluid relative to const z surface $V = |z|e^{\psi-\phi}$

$V = 1$ at event or particle horizon

$V = k^{1/2}$ at sonic point (discontinuity)

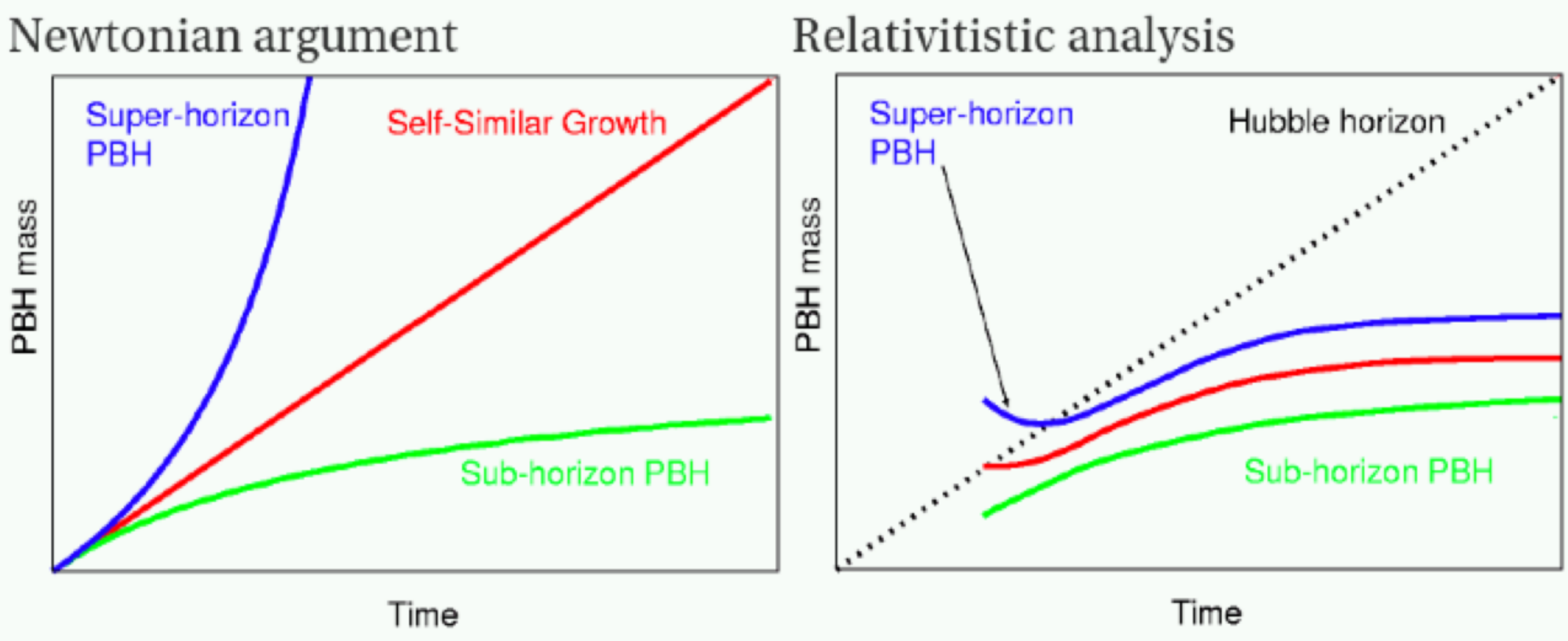
Carr & Hawking (1974): there is no SSSS solution with black hole interior attached to *exact* Friedmann exterior via sound-wave but 1-parameter family of such solutions if *asymptotically* Friedmann (k=0,1/3).

=> PBHs formed by *local* processes cannot grow very much but self-similar growth possible with special initial conditions




Carr (1976) and Bicknell & Henriksen (1978) extend result to $0 < k < 1$

Harada et al. (2002): solutions are only *quasi-asymptotically* Friedmann (angle deficit)




$\Rightarrow$ PBH does not grow very much at all

$\Rightarrow$ no observational evidence against them

=> need to consider quantum effects

*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

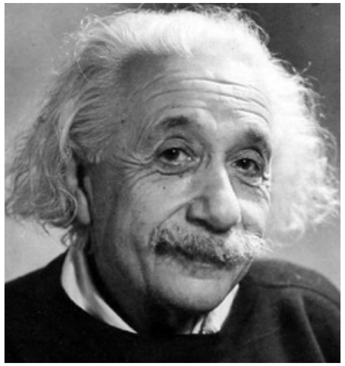
**QUANTUM gravitational effects are usually ignored in calculations of the formation and evolution of black holes. The justification for this is that the radius of curvature of space-time outside the event horizon is very large compared to the Planck length $(G\hbar/c^3)^{1/2} \approx 10^{-33}$ cm, the 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.**

# PBHs are important even if they never formed!

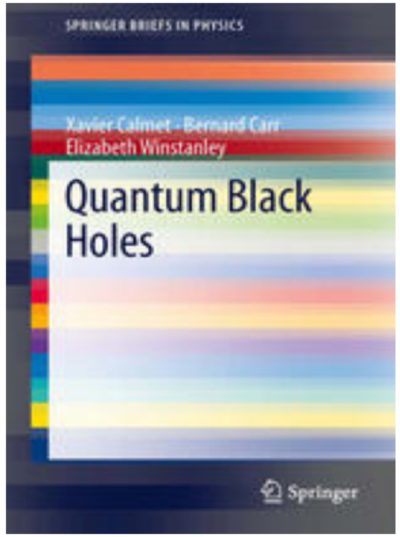
$$T_{BH}[\mathrm{K}] = 10^{-7}\,\frac{M_\odot}{M}$$

Quantum Mechanics

Thermodynamics

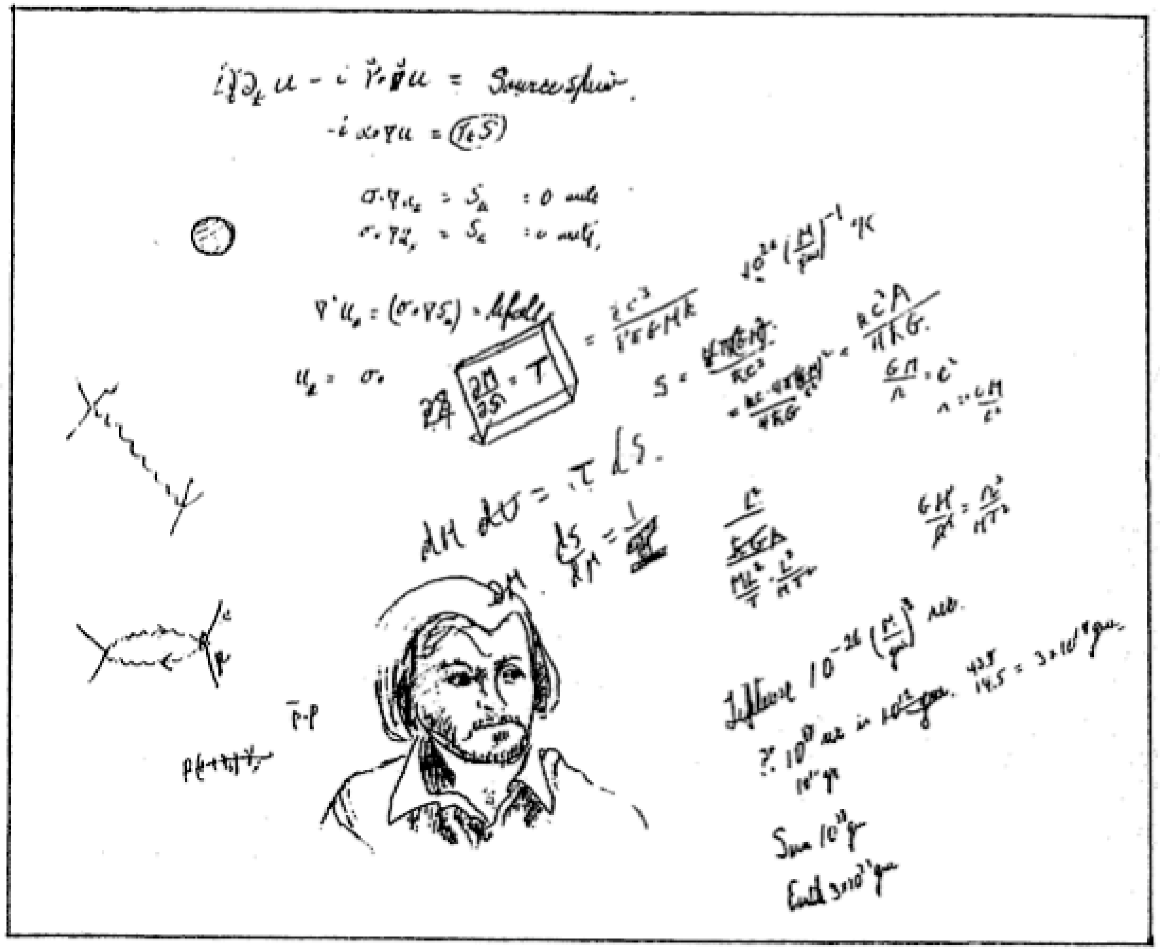


General Relativity




Calmet, BC, Winstanley

# Feynman’s envelope 1975



# PBH EVAPORATION

**Black holes radiate thermally with temperature**

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

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

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

**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**

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


# GAMMA RAYS FROM PRIMORDIAL BLACK HOLES*

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

## ABSTRACT

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

THE ASTROPHYSICAL JOURNAL, **206**: 8–25, 1976 May 15


# SOME COSMOLOGICAL CONSEQUENCES OF PRIMORDIAL BLACK-HOLE EVAPORATIONS

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Institute of Astronomy, Madingley Road, Cambridge, England;
and California Institute of Technology, Pasadena
*Received 1975 July 21; revised 1975 October 27*

## ABSTRACT

According to Hawking, primordial black holes of less than $10^{15}$ g would have evaporated by now. This paper examines the way in which small primordial black holes could thereby have contributed to the background density of photons, nucleons, neutrinos, electrons, and gravitons in the universe. Any photons emitted late enough should maintain their emission temperature apart from a redshift effect: it is shown that the biggest contribution should come from primordial black holes of about $10^{15}$ g, which evaporate in the present era, and it is argued that observations of the $\gamma$-ray background indicate that primordial black holes of this size must have a mean density less than $10^{-8}$ times the critical density. Photons which were emitted sufficiently early to be thermalized could, in principle, have generated the 3 K background in an initially cold universe, but only if the density fluctuations in the early universe had a particular form and did not extend up to a mass scale of $10^{15}$ g. Primordial black holes of less than $10^{14}$ g should emit nucleons: it is shown that such nucleons could not contribute appreciably to the cosmic-ray background. However, nucleon emission could have generated the observed number density of baryons in an initially baryon-symmetric universe, provided some *CP*-violating process operates in black hole evaporations such that more baryons are always produced than antibaryons. We predict the spectrum of neutrinos, electrons, and gravitons which should result from primordial black-hole evaporations and show that the observational limits on the background electron flux might place a stronger limitation on the number of $10^{15}$ g primordial black holes than the $\gamma$-ray observations. Finally, we examine the limits that various observations place on the strength of any long-range baryonic field whose existence might be hypothesized as a means of preserving baryon number in black-hole evaporations.

# 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.

PBHs as dark matter?

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

# Primeval Black Holes and Galaxy Formation

P. Mészáros

Institute of Astronomy, University of Cambridge

Received September 4, revised October 14, 1974

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

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

Carr (1977) corrected some errors

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


# THE PRIMORDIAL BLACK HOLE MASS SPECTRUM*

BERNARD J. CARR
Department of Applied Mathematics and Theoretical Physics, Cambridge University, Cambridge, England;
and
California Institute of Technology, Pasadena
*Received 1975 January 31*

## ABSTRACT

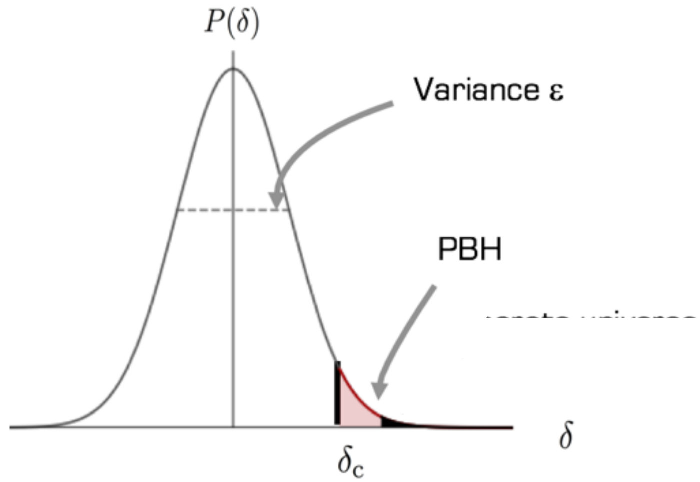
We examine what mass spectrum of primordial black holes should result if the early universe consisted of small density fluctuations superposed on a Friedmann background. It is shown that only a certain type of fluctuation favors the formation of primordial black holes and that, consequently, their spectrum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

# 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**

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

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

**ε(M) decreases with M => exponential upper cut-off**

**Separate universe for $\delta_H > 1$ but recently reinterprted**

# Limit on fraction of Universe collapsing

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

**General limit**

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

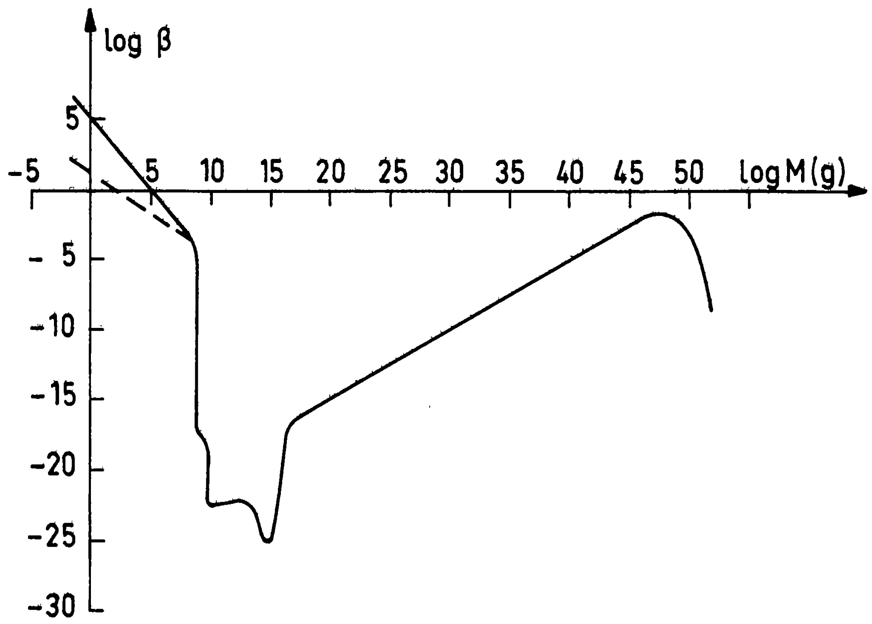
**Unevaporated** $M > 10^{15}g \Rightarrow \Omega_{PBH} < 0.25$ **(CDM)**

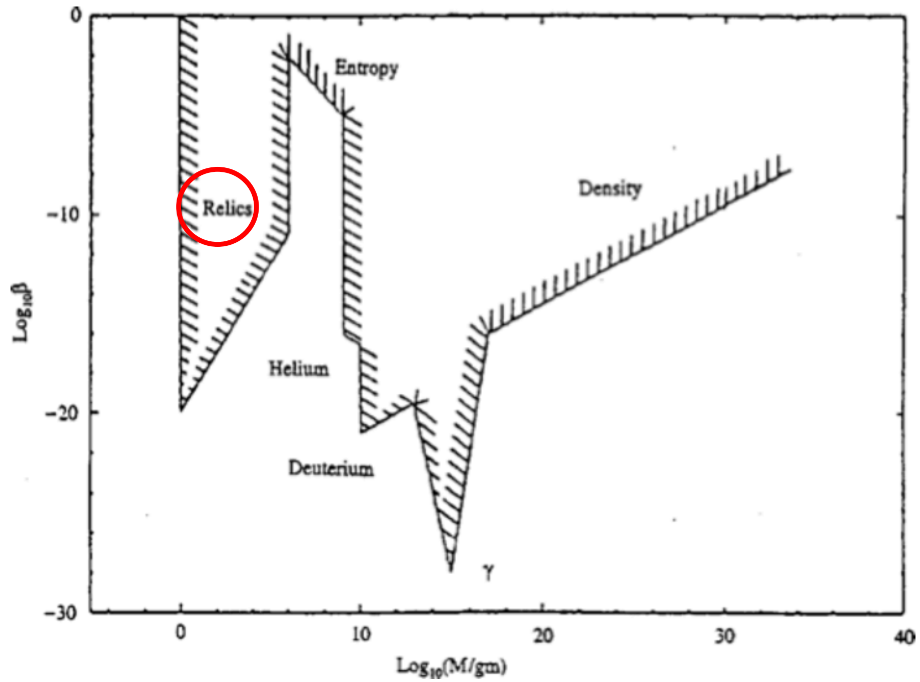
**Evaporating now** $M \sim 10^{15}g \Rightarrow \Omega_{PBH} < 10^{-8}$ **(GRB)**

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

**=> constraints from entropy, γ-background, BBNS**

# CONSTRAINTS ON FRACTION OF UNIVERSE IN PBHS

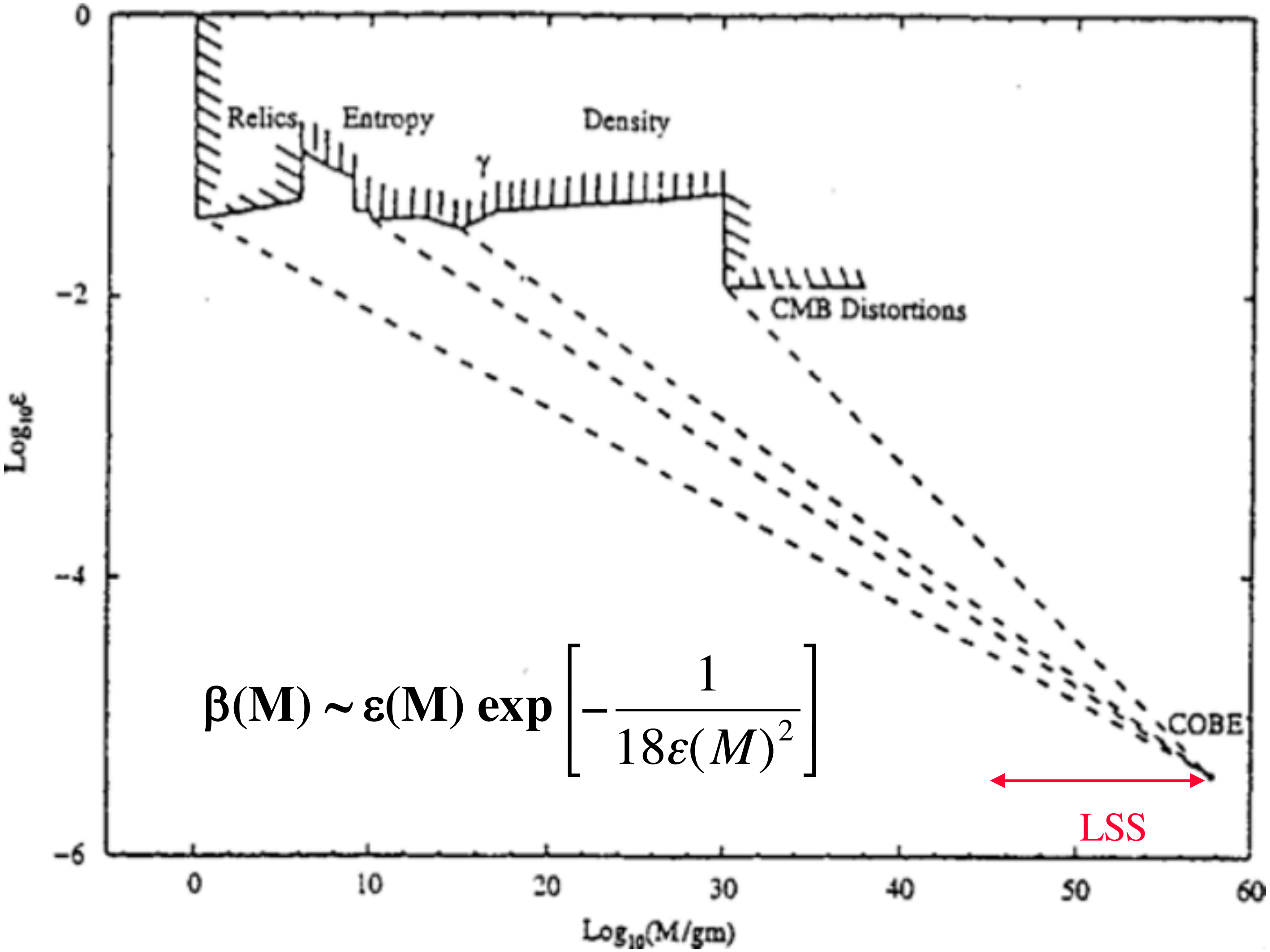



Novikov et al (1979)

Carr, Gilbert & Lidsey (1994)

# Constraints on amplitude of density fluctuations at horizon epoch




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

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

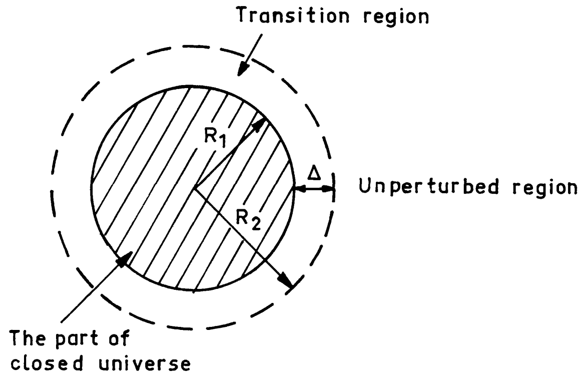
Need blue spectrum or spectral feature to produce them.

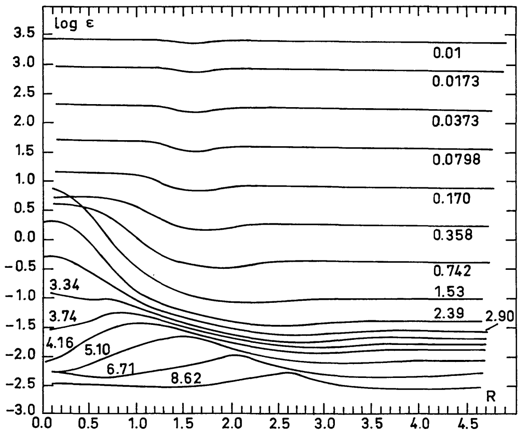
Astron. Astrophys. 80, 104–109 (1979)

# Primordial Black Holes

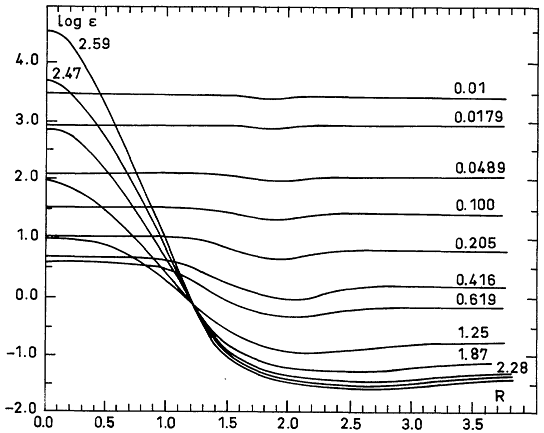
I. D. Novikov[1], A. G. Polnarev[1], A. A. Starobinsky[2], and Ya. B. Zeldovich[3]

**Summary.** The processes of primordial black hole formation and accretion of matter onto the primordial black holes already formed are investigated. We give the limits on the possible number of primordial black holes of various masses inferred from astrophysical observations.

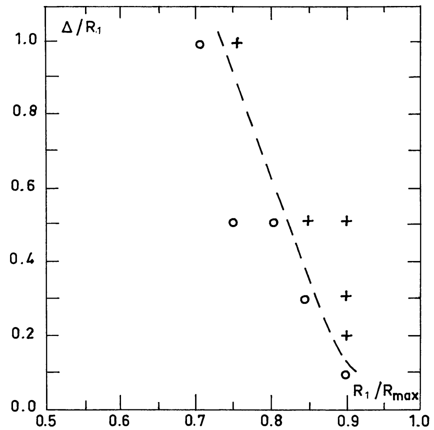



No PBH




PBH




+ yes o no

# MORE PRECISE ANALYSIS OF PBH FORMATION

**Analytic calculations imply need $\delta > 0.3$ for $\alpha = 1/3$ (Carr 1975)**

**Confirmed by first numerical studies (Nadezhin et al 1978)**

**but pressure gradient => PBHs smaller than horizon**

**Critical phenomena => $\delta > 0.7$** $M = k\, M_H(\delta-\delta_c)^\gamma$

**(Niemeyer & Jedamzik 1999, Shibata & Sasaki 1999)**

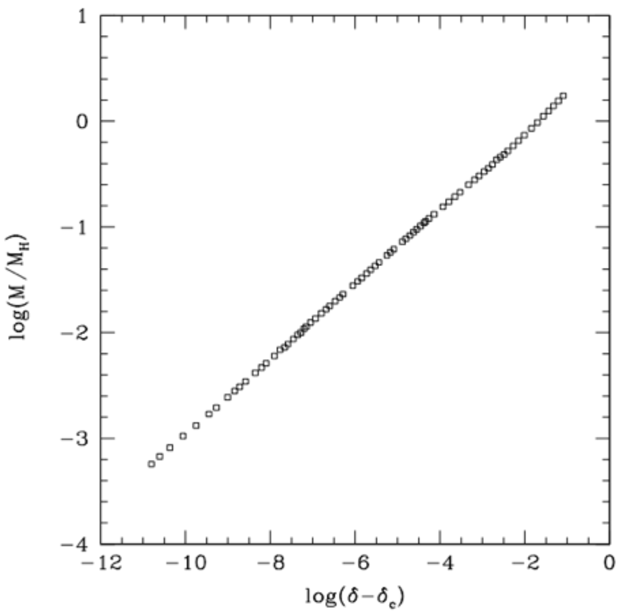
**$\Rightarrow$ spectrum peaks at horizon mass with extended low mass tail**

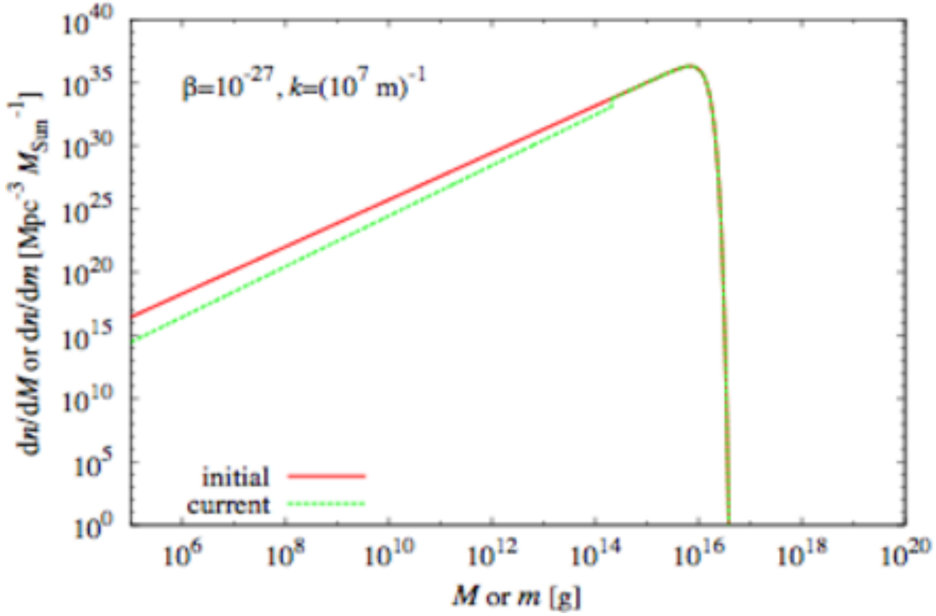
**(Yokoyama 1999, Green 2000)**

**Later calculations and peak analysis => $\delta > 0.4 - 0.5$**

**(Musco et al 2005, Green et al 2004)**

# PBHs from near-critical collapse




=> broad mass spectrum => strong constraints above $10^{14}$g

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

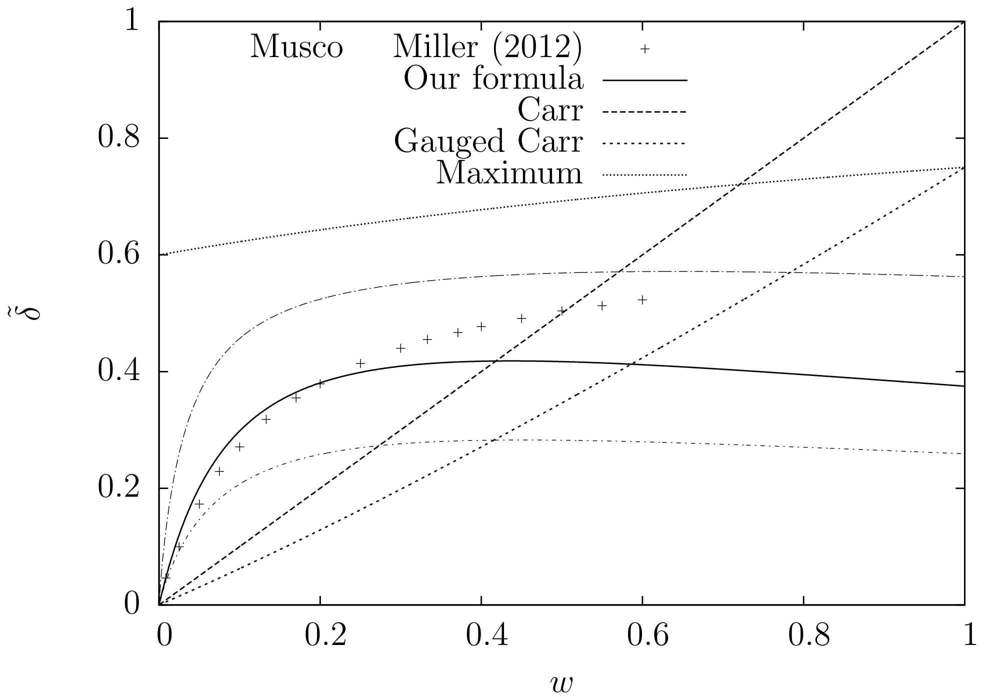
$\delta_C \sim 0.45$ and applies to $\delta - \delta_C \sim 10^{-10}$ (Musco & Miller 2013)

DM from $10^{16}$g PBHs without violating GRB constraints?

# MORE PRECISE ESTIMATE OF $\delta_C$

## 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 *

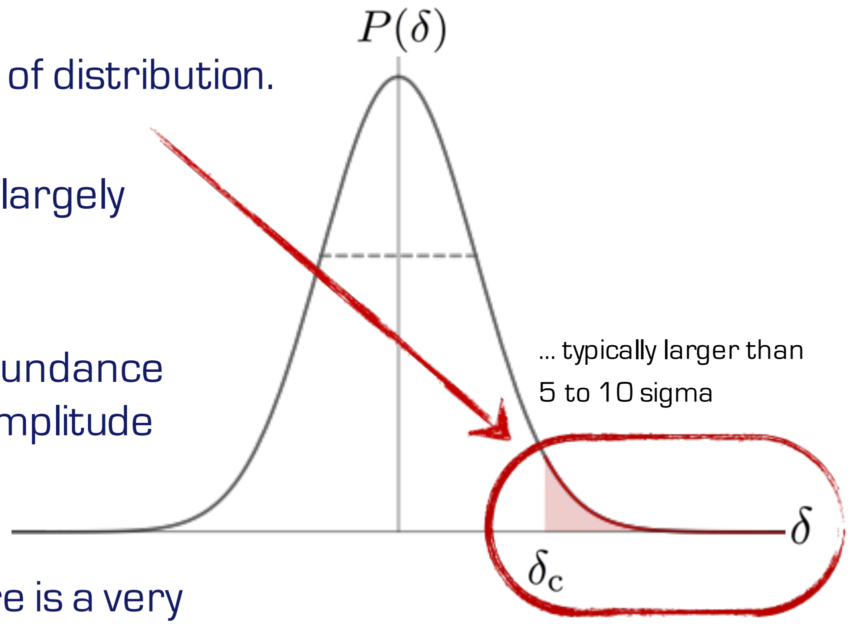
* For uniform-Hubble gauge but 0.4 for synchronous gauge

# NON-GAUSSIAN EFFECTS

Expected whenever fluctuations are large

Bullock & Primack 1997, Ivanov 1998, Hidalgo 2007, Young & Byres 2013, Byrnes et al 2014

PBH production is deep inside tail of distribution.




- This means, PBH production is largely sensitive to non-Gaussianity.
- ... even more so, as the PBH abundance depends exponentially on the amplitude of the perturbations.
- As shown by Byrnes et al., there is a very strong modal coupling between long- and short-wavelength modes.

Quantum field theory => n-point correlation function
Slow-roll correction using inflation 3-point correlator

$$P(\delta) = \frac{1}{\sqrt{2\pi}\Sigma}\left[1 - \left(\frac{\delta^3}{\Sigma^6} - \frac{3\delta}{\Sigma^4}\right)\right]\exp\left[-\frac{\delta^2}{2\Sigma^2}\right]$$

Seery & Hidalgo 2006

# NON-SPHERICITY EFFECTS

## On Ellipsoidal Collapse and Primordial Black-Hole Formation

Florian Kühnel[1,*] and Marit Sandstad[2,†]

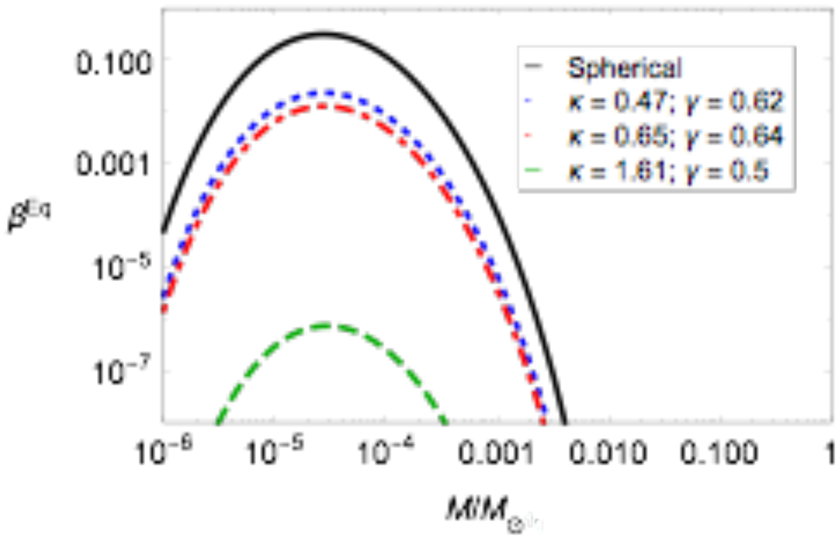
arXiv:1602:04815

★ Non-Sphericity

ellipsoidal threshold

$$\frac{\delta_{\rm ec}}{\delta_{\rm c}} \simeq 1 + \kappa \left( \frac{\sigma^2}{\delta_{\rm c}^2} \right)^{\gamma}$$

spherical threshold




★ Simple estimate: → consider collapse of largest enclosed sphere (green curve):

$$\frac{\delta_{\rm ec}}{\delta_{\rm c}} \simeq (1 + 3\,e) = 1 + \frac{9}{\sqrt{10\,\pi}} \left( \frac{\sigma^2}{\delta_{\rm c}^2} \right)^{1/2}$$

# COLLAPSE FROM INHOMOGENEITIES

*Spherical collapse*

Carr 1975
Nadezhin et al 1978
Green et al. 2004
Harada et al. 2013
Young, Byrnes & Sasaki 2014

*Non-Gaussian collapse*

Bullock & Primack 1997
Ivanov 1998
Hidalgo 2009/16
Young & Byrnes 2013
Bugaev 2013
Toda & Yokoyama 2015

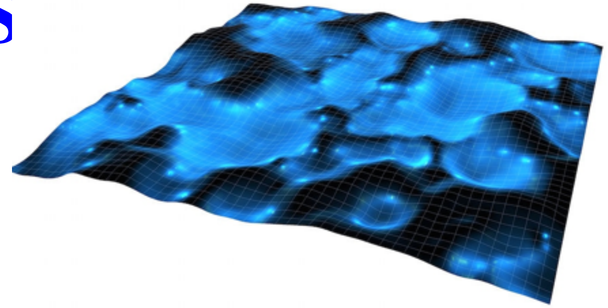
*Non-spherical collapse*

Doroshkevich 1970
Bond & Myers 1996
Sheth et al 2001
Kuhnel & Sandstat 2016

*Critical collapse*

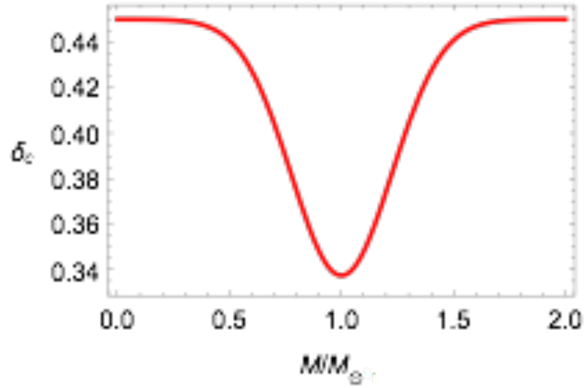
Koike et al 1995
Niemeyer & Jedamzik 1998/9
Yokoyama 1998
Shibata & Sasaki 1999
Green & Liddle 1999
Musco, Miller & Renzolla 2005
Musco & Miller 2013
Harada et al 2013
Kuhnel et al. 2016

# OTHER FORMATION MECHANISMS

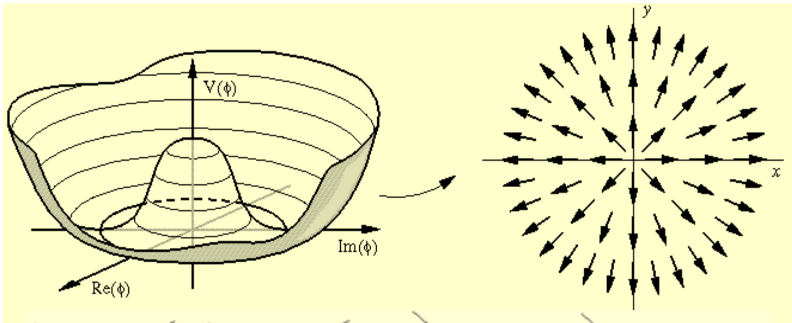


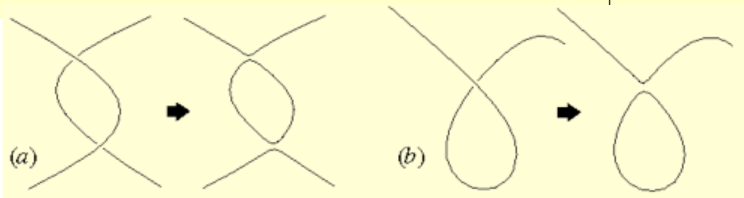
Inflation Generates inhomogeneities

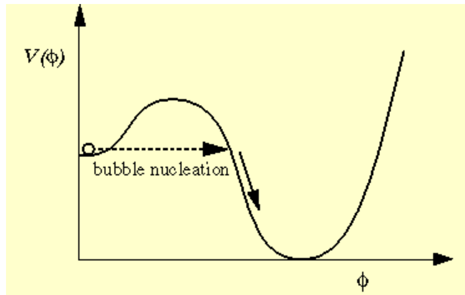
Pressure reduction Form more easily but need spherical symmetry




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

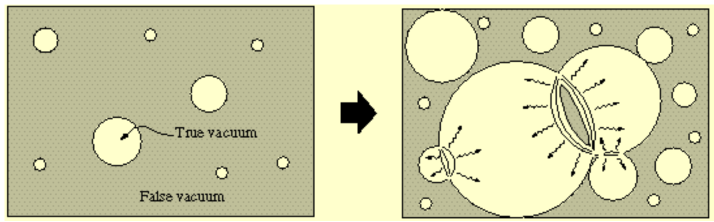



Bubble collisions

Need fine-tuning of bubble formation rate




Domain walls PBHs can be very large

# PBH FORMATION FROM PHASE TRANSITONS

*Matter-dominated era*

Khlopov & Polnarev 1980
Polnarev & Khlopov 1985
Khlopv et al. 1985
Jedamzik & Nemeyer 1999
Harada et al. 2016
Carr, Tenkanen & Vaskonen 2017
Georg et al 2016

*Cosmic strings*

Hogan 1984
Hawking 1989
Polnarev & Zemboricz 1991
Garriga & Sakellariadou 1993
Caldwell & Casper 1996
MacGibbon et al 1998
Hansen et al 2000
Nagasawa 2005

*Bubble collisions*

Crawford & Schramm 1982
Hawking, Moss & Stewart 1982
Kodama et al. 1982
La & Steinhardt 1989
Moss 1994
Konoplich 1998/99
Jedamzik 1996

*Domain walls*

Caldwell, Chamblin & Gibbons 1996
Khlopov et al. 2000
Rubin, Sakharov & Khlopov.2000/1
Dokuchaev et al 2005

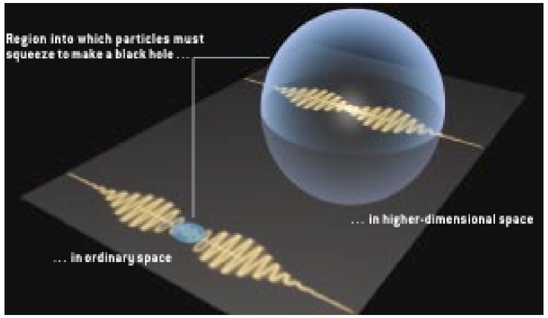
*Other mechansms*

Matsuda 2006
Lake, Thomas & Ward 2009
Garriga et al 2015
Cotner 2016

# BLACK HOLES AS A PROBE OF HIGHER DIMENSIONS

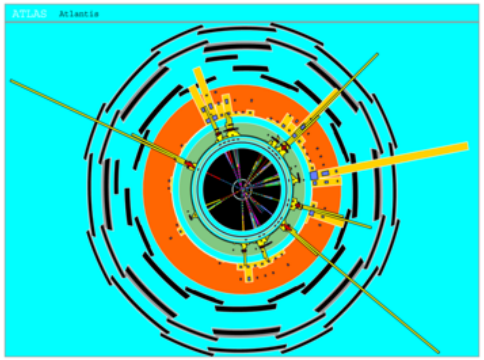
M-theory => extra compactified dimensions (n)

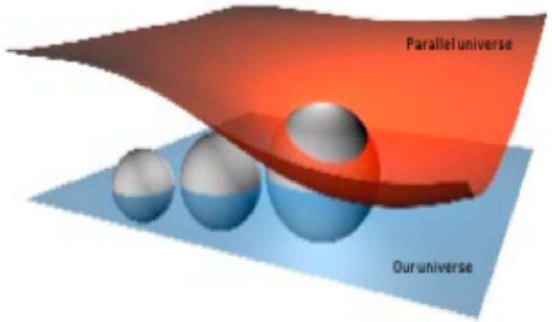
Standard model => $V_n \sim M_P^{-n}$, $M_D \sim M_p$,
Large extra dimensions => $V_n >> M_P^{-n}$, $M_D << M_p$




TeV quantum gravity?

Schwarzschild radius $r_S = M_P^{-1}(M_{BH}/M_P)^{1/(1+n)}$
Temperature $T_{BH} = (n+1)/r_S$ < 4D case
Lifetime $\tau_{BH} = M_P^{-1}(M_{BH}/M_P)^{(n+3)/(1+n)}$ > 4D case

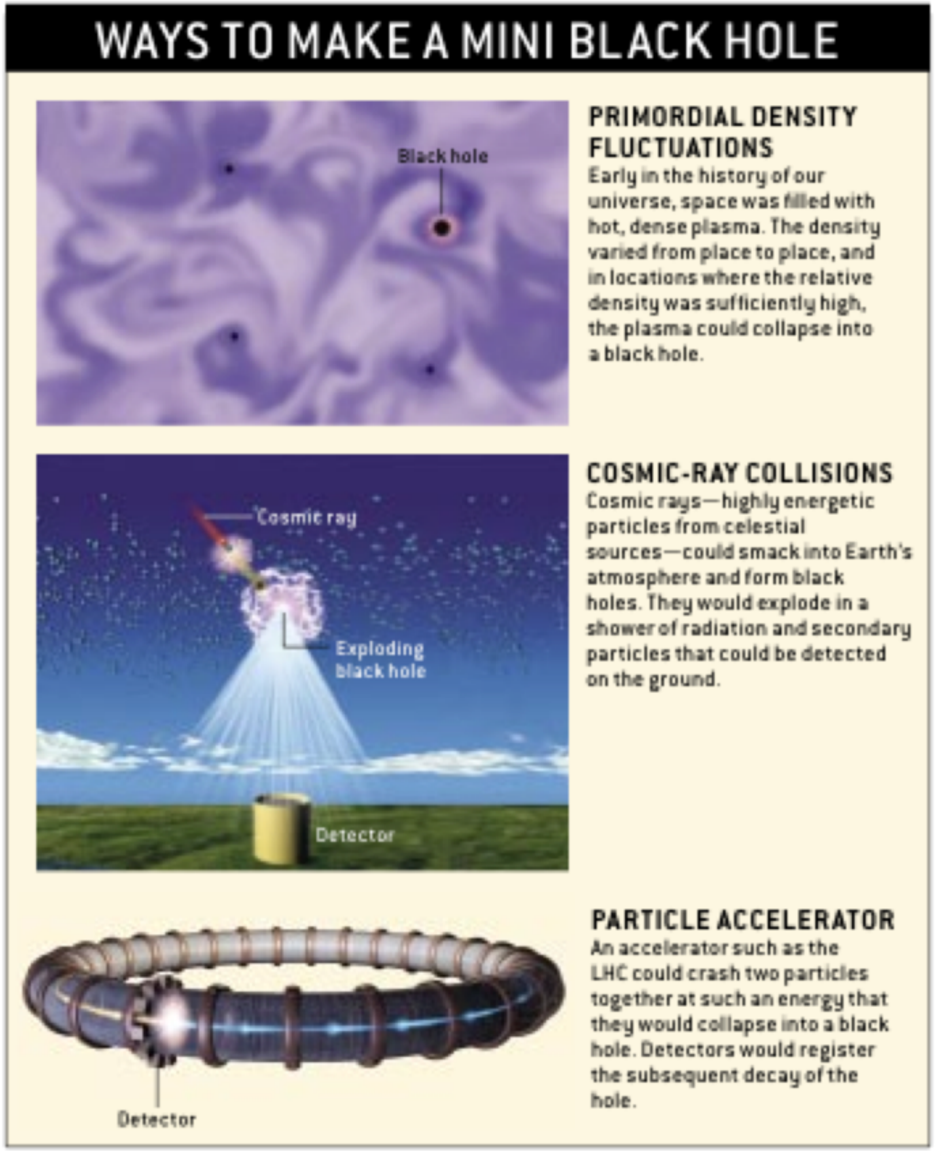




**Scientific American**

May 2005

Carr and Giddings



# ブラックホールを製造する

粒子加速器を使って地上に小さなブラックホールを作り出そう——
理論物理学の研究から，びっくりするような構想が生まれてきた
「隠れた次元」の存在など，時空の謎に迫る壮大な実験だ

Translated into Japanese
by Tetsuya Shiromizu!

B. J. カー（ロンドン大学クイーンメアリー校）／S. B. ギディングズ（カリフォルニア大学サンタバーバラ校）

原子を分裂させたり，元素を別の元素に変えたり，反物質を作ったり，自然界で観測されたことのない新粒子を作り出したり——粒子加速器の発明以来かれこれ80年，物理学者はそんな風変わりな仕事にこの装置を利用してきた。しかし，うまくすると，間もなく別の使い道が開けそうだ。そうなれば，過去の成果などまるで陳腐に思えてくるに違いない。加速器を使って，宇宙で最も謎めいた天体，ブラックホールを作り出せるかもしれないのだ。

ブラックホールといえば，宇宙船から星に至るまであらゆるものをのみ込んでしまう巨大な怪物を思い浮かべるのが普通だろう。しかし，高エネルギーの加速器で作り出せそうなのは，そんな天体物理学の巨獣とはまるで違って，素粒子ほどの微小なブラックホールだ。早ければ2007年ころ，ジュネーブ近郊にある欧州合同原子核研究機構（CERN）で大型ハドロン衝突型加速器（LHC）が始動すると，ブラックホール作りの実験が可能になる。

微小ブラックホールは星を引き裂くことも銀河に君臨することもなく，私たちの地球を脅かすこともない。しかしその特性は，ある意味で巨大なブラックホールよりも劇的だ。量子効果によって，微小ブラックホールは生まれたそばから蒸発し，クリスマスツリーの電飾のように検出器に光をともす。これによって，時空がどのように織り成されているのか，私たちの目には見えない次元が存在するのかといった謎を解く手がかりが得られる。

## ブラックホールができるには

ブラックホールの概念はアインシュタインの一般相対性理論から生まれた。一般相対性理論では，物質が十分に圧縮されると非常に強い重力を発揮して空間の一部を切り開き，どんな物質もその領域から逃れられなくなる。この領域の外縁がブラックホールの「事象の地平」で，物体はその中に落ち込むことはできても，決して外には出てこられない。

最も単純な場合には（空間に未知の次元が存在しないか，存在してもブラックホールより小さい場合），ブラックホールの大きさは質量に正比例する。太陽を半径3km，現在の大きさのおよそ100万分の4にまで圧縮すると，ブラックホールになるだろう。地球に同じ運命をたどらせるには，現在の大きさの約10億分の1，半径9mmに押しつぶす必要がある。

このように，小さなブラックホールほど，それを作り出すのに必要な圧縮の度合いは大きくなる。物質がブラックホールになる密度は質量の2乗に反比例して小さくなるからだ。太陽と同じ質量のブラックホールの場合，この密度は$10^{19}$kg/m$^3$で，原子核の密度よりも大きい。現在の宇宙で，重力崩壊によって作り出せる密度はこのあたりが限界となる。太陽よりも軽い天体は重力崩壊を起こさない。原子を構成する小さな粒子の間に量子的な反発力が働いて，安定な状態を保つからだ。これまでに見つかった最も軽いと思われるブラックホールでも，太陽の6倍程度の質量がある。

しかし，ブラックホールを作り出すのは星の重力崩壊だけではない。1970年代初頭，英ケンブリッジ大学のホーキング（Stephen W. Hawking）と私たち著者の1人であるカーは，ビッグバン直後の初期宇宙にブラックホールが生じていた可能性があると考え，そのメカニズムを研究した。これらのブラックホールは「原始ブラックホール」と呼ばれる。

空間が膨張すると，物質の平均密度は下がる。だから，かつての宇宙は現在よりもずっと高密度で，ビッグバン後の数マイクロ秒は原子核の密度を超えていた。既知の物理法則によると，物質の密度には上限がある。「プランク密度」と呼ばれる値で，$10^{97}$kg/m$^3$だ。この値では重力が極めて強くなり，量子力学的な揺らぎによって時空の構造が壊れてしまう。これほどの高密度なら，直径わずか$10^{-35}$m，質量$10^{-8}$kg

**蒸発するブラックホール**　どんなブラックホールも徐々にエネルギーを放射し，ついには消えてしまう（イメージ図）。

# PBHS AND INFLATION

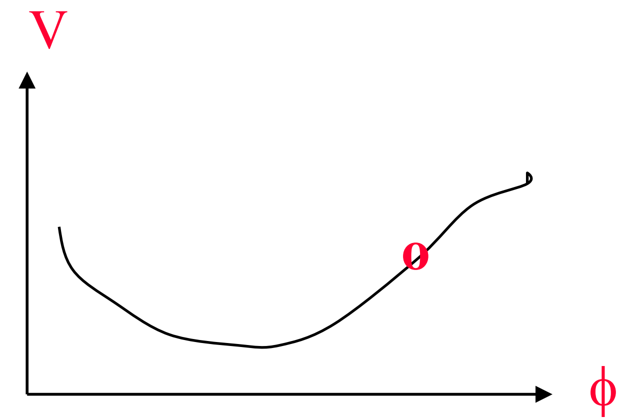
**PBHs formed before reheat inflated away =>**

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

**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?**

**Slow roll plus friction-domination** Carr & Lidsey 1993

$$\xi = (M_{Pl} V'/V)^2 << 1, \quad \eta = M_{Pl} V''/V << 1$$

**=> nearly scale-invariant fluctuations**

$$|\delta_k^2| \sim k^n, \; \delta_H \sim M^{(1-n)/4} \text{ with } n = 1 - 3\xi + 2\eta \sim 1$$

**CMB => $\delta_H \sim 10^{-5}$ => $n > 1$ for PBHs =>** $V''V/V'^2 > 3/2.$

**Observe n < 1 on horizon scale => need running index for PBHs.**

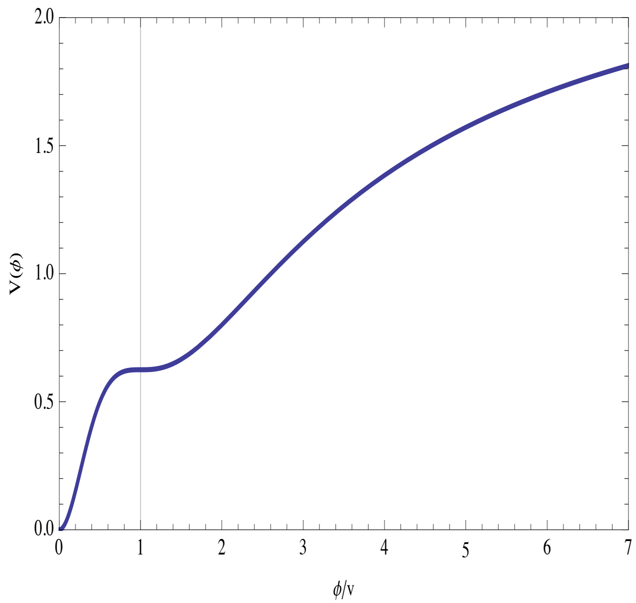
**Planck gives** $\frac{d \ln n}{dk} \approx -0.02 \pm 0.01$ **(wrong sign!)**

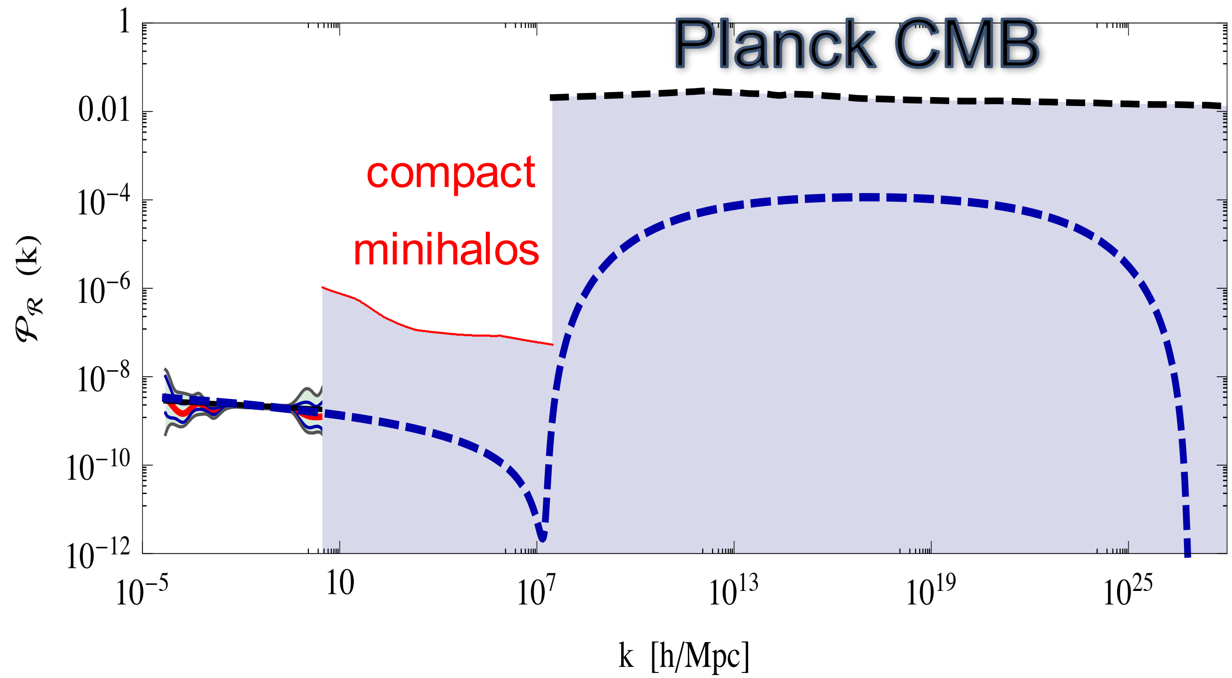
**Can reasonable inflation model allow n > 1 at large k?**

**Flattening of V(ϕ) => PBH production on particular scale**
Ivanov, Naselsy & Novikov 1994

# PBHs from single field with bump in inflationary potential

García-Bellido & Morales arXiv:1702.03901




Many other models PBH generation through inflation (Mukaida)

# PBH FORMATION FROM INFLATION

*Chaotic inflation*

Carr & Lidsey 1993
Carr et al 1994
Green & Liddle 1997
Bringmann et al 2001
Lyth et al 2006
Zaballa et al 2007

*Designer inflation*

Ivanov et al. 1994
Yokoyama 1999
Blais et al 2003
Garcia-Bellido & Morales 2016

*Hybrid inflation*

Garcia-Bellido et al 1996
Yokoyama 1997
Randall et al 1998
Kanazawa et al 2000
Frampton et al 2010
Bugaev & Klimai 2011
Kawasaki & Tada 2015
Clesse & Garcia-Bellido 2015

*Running index*

Stewart 1997
Leach et al 2000
Kawasaki et al 2007
Kawaguchi et al 2008
Bugaev & Klimai 2009
Kohri et al 2009
Josan & Green 2010
Drees & Erfani 2011
Clesse et al 2011
Kodama et al 2011
Kawasaki et al 2013
Belotsky et al 2014
Kuhnel et al. 2016
Carr et al 2017

*Preheating*

Khlopv et al. 1985
Taruya 1999
Easther & Parry 2000
Green & Malik 2000
Bassett & Tsukikawa 2001
Khlopov et al 2006

# CONSTRAINTS FOR EVAPORATING PBHS

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

Big bang nucleosynthesis

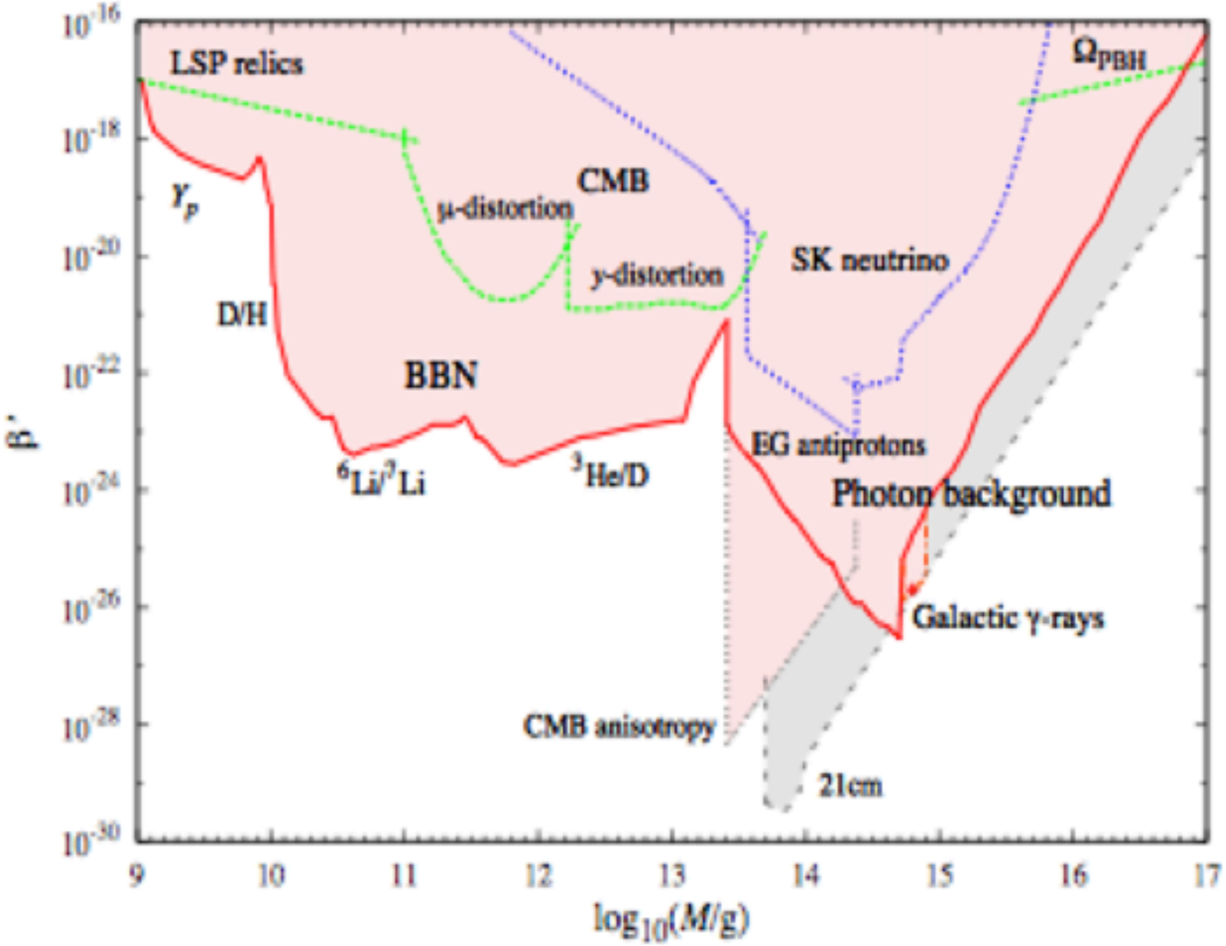
Gamma-ray background

Extragalactic cosmic rays

Neutrino relics

LSP relics

CMB distortions




This assumes monochromatic mass function

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

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

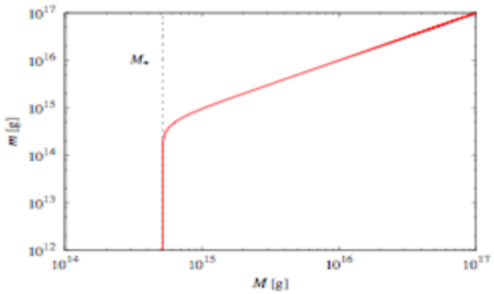
B. J. Carr,[1,2,*] Kazunori Kohri,[3,†] Yuuiti Sendouda,[4,‡] and Jun'ichi Yokoyama[2,5,6,§]

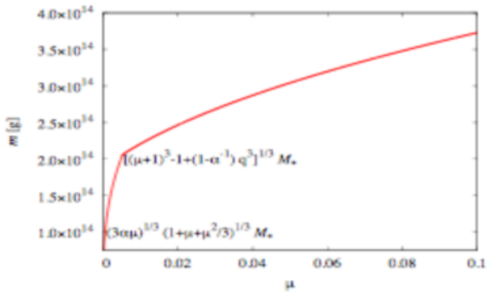
arXiv: 1604.05349

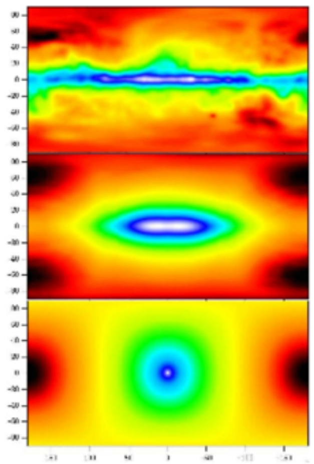
$q^3/(3\,\alpha) = 0.005$ , α=3

- Must distinguish between initial mass M and current mass m

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



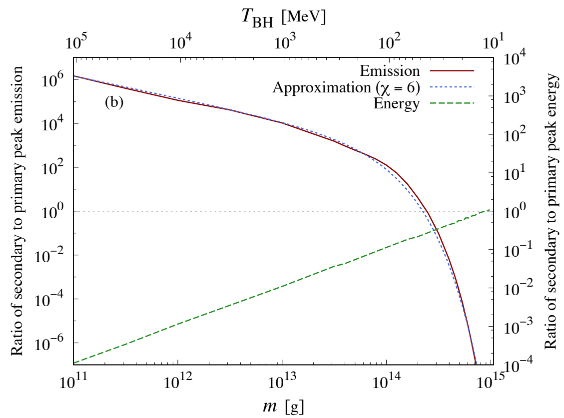



- Must distinguish between primary and secondary emission

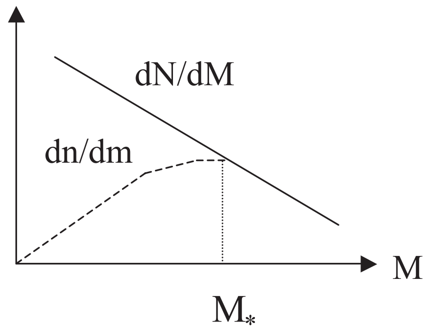
$$\frac{\bar{E}^{\rm S}}{\bar{E}^{\rm P}} \approx (68\,{\rm MeV})/(600\,m_{14}^{-1}\,{\rm MeV}) \approx 0.6\,(m/M_*)$$

$$\left(\frac{{\rm d}\dot{N}^{\rm S}}{{\rm d}E}\right)_{\bar{E}^{\rm S}} \Big/ \left(\frac{{\rm d}\dot{N}^{\rm P}}{{\rm d}E}\right)_{\bar{E}^{\rm P}} \approx 1.4\left(\frac{m}{M_*}\right)^{-1} {\rm e}^{-\chi\,m/M_{\rm q}}$$



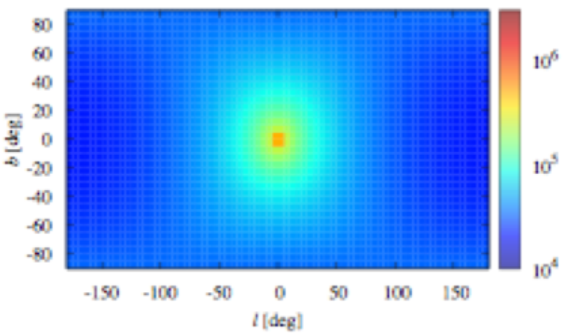
• Must distinguish between initial and current mass function

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




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

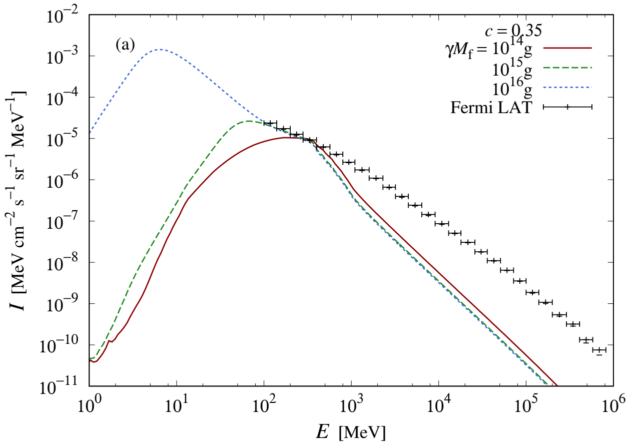
• Must specify density profile of halo and direction of observation

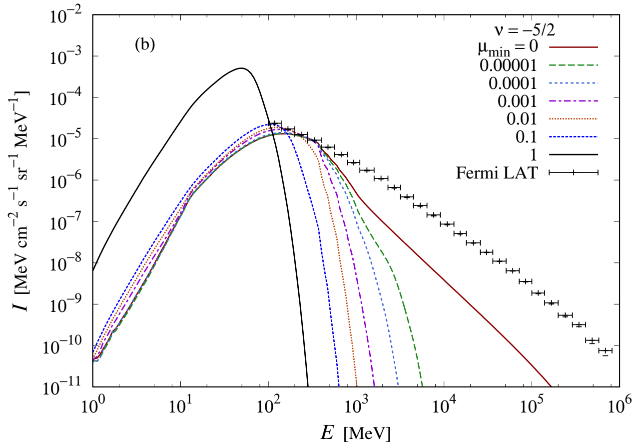



$$\rho_\mathrm{PBH}(R) = \frac{f\,\rho_\mathrm{s}}{(R/R_\mathrm{s})^\gamma\,[1 + (R/R_\mathrm{s})^\alpha]^{(\beta-\alpha)/\alpha}}$$

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

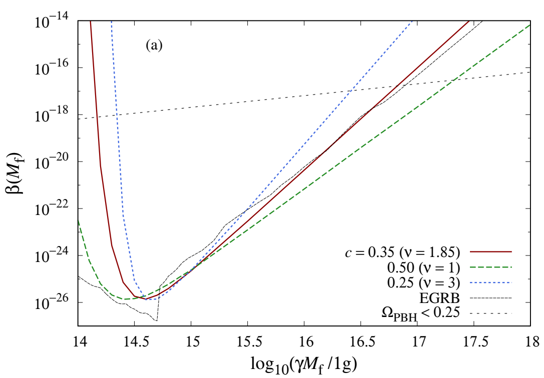
- Then compare predicted intensity with FermiLAT observations



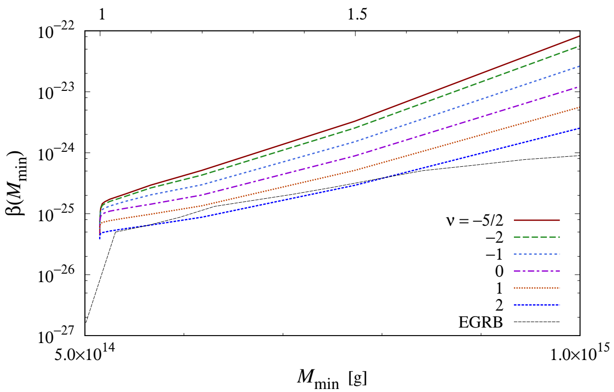




- Then obtain constraints on $\beta(M)$ and $n_{PBH}(M)$ or values required to explain background

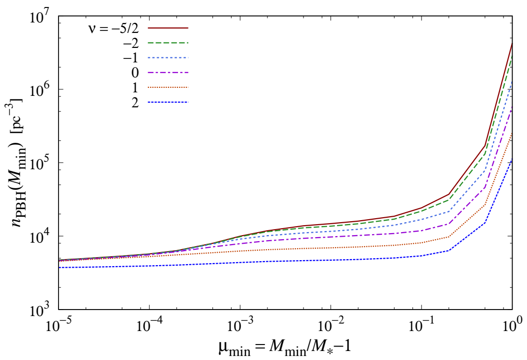
## Critical IMF




## Extended IMF




## Extended IMP



# PBH EVAPORATION CONSTRAINTS

*Extragalactic gamma-rays*

Page & Hawking 1976 Carr 1976
Rees 1977
MacGibbon & Carr 1991
Barrau et al 2003
Carr et al 2010

*BBNS*

Vainer & Nasleksii 1978 (BBNS)
Miyama & Sato 1978
Zeldovich et al. 1977
Vainer et al. 1978
Lindley 1980
Kohri & Yokoyama 1999
Carr et al 2010

*LSP relics*

Green 1999
Lemoine 2010

*Annihilation line*

Okeke & Rees 1980
Adriani et al 2008
Bambi et al 2009

*Cosmic rays*

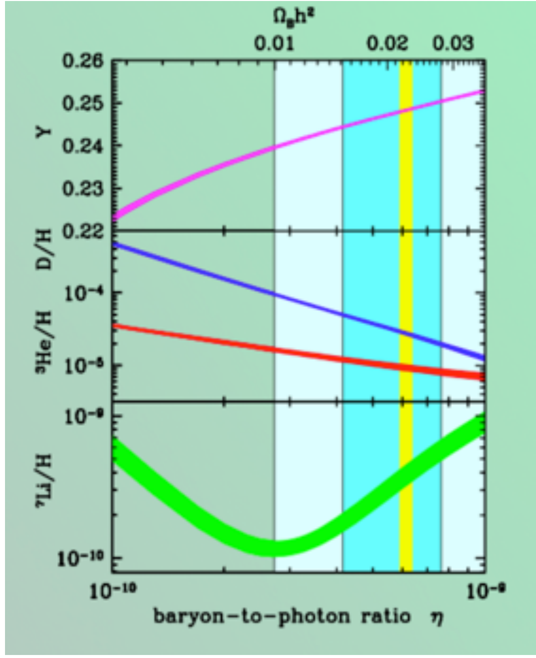
MacGibbon & Carr 1991
Maki et al 1997
Barrau et al 2003
Adriani et al 2008
Belotsky 2015

*Galactic gamma-rays*

Wright 1996
Lehoucq et al. 2009
Carr et al. 2016

*CMB distortion*

Zeldovich et al 1977
Tashiro & Sugiyama 2008
Carr et al 2010


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

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

MACHOs WIMPs

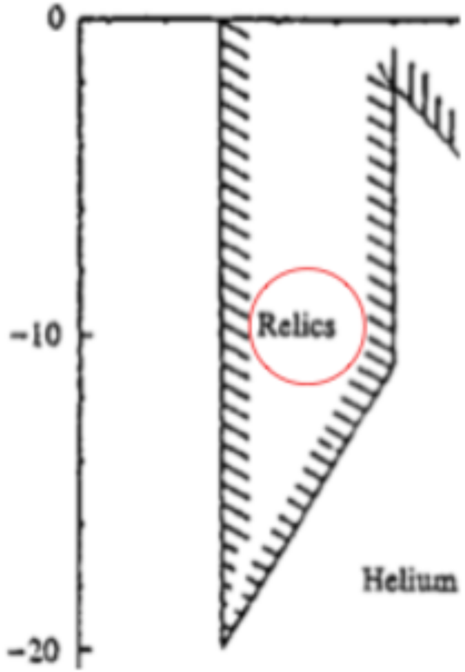
PBHs are non-baryonic with features of both WIMPs and MACHOs

$10^{17}$-$10^{20}$g PBHs excluded by femtolensing of GRBs
$10^{26}$-$10^{33}$g PBHs excluded by microlensing of LMC (2010)
Above $10^3 M_0$ excluded by dynamical effects

=> windows at $10^{16}$-$10^{17}$g or $10^{20}$-$10^{24}$g or $10^{33}$-$10^{36}$g for dark matter

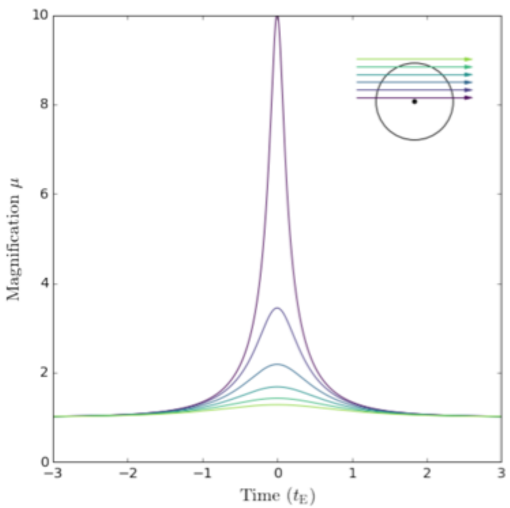
Atomic Sublunar Intermediate Mass

# CAN PLANCK MASS RELICS PROVIDE DARK MATTER?

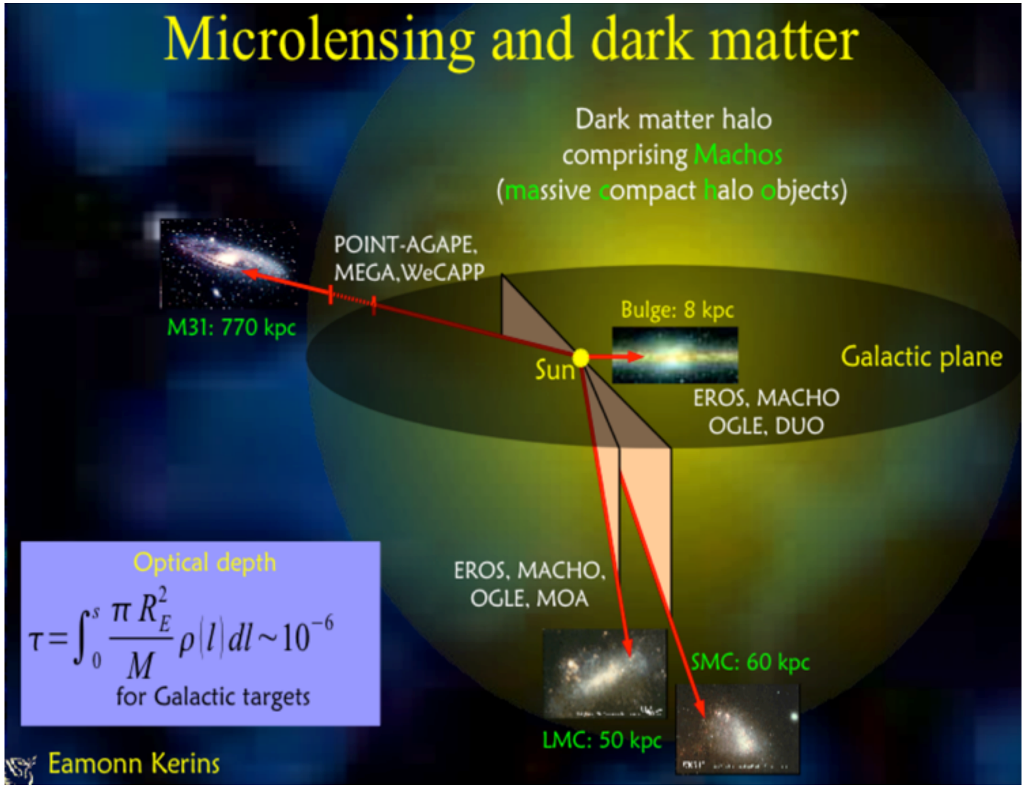



These would be smallest objects in nature and undetectable!

MacGibbon 1987, Barrow et al 1992, Carr et al 1994, Alexeev et al 2002




$$\hat{t} = 0.2yrs \left(\frac{M_{PBH}}{M_\odot}\right)^{\frac{1}{2}}$$



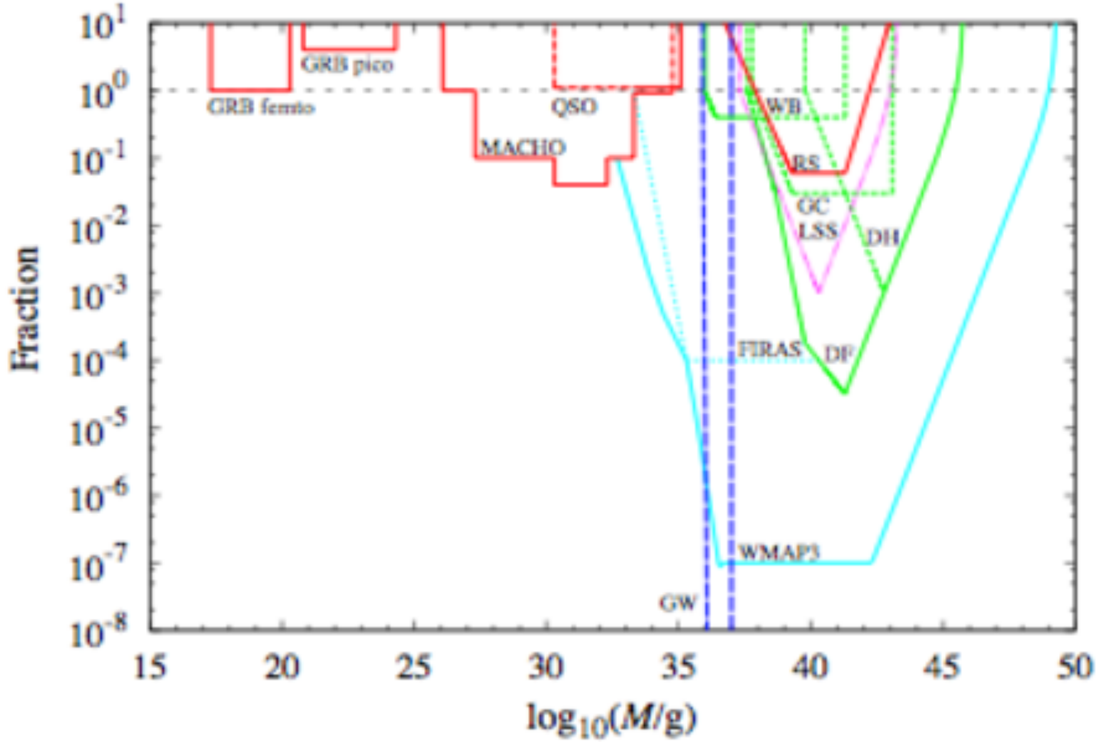

Early microlensing searches suggested MACHOs with 0.5 $M_O$

=> 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

# CONSTRAINTS ON NON-EVAPORATING PBHS (CKSY (2010))




$$f \equiv \frac{\Omega_{\rm PBH}}{\Omega_{\rm CDM}} \approx 4.8\,\Omega_{\rm PBH} = 4.11 \times 10^{8} \beta'(M) \left(\frac{M}{M_{\odot}}\right)^{-1/2}$$

# LENSING LIMITS (2010)

## MACHO microlensing

$$f(M) < \begin{cases} 1 & (6 \times 10^{-8} M_\odot < M < 30 M_\odot) \\ 0.1 & (10^{-6} M_\odot < M < M_\odot) \\ 0.04 & (10^{-3} M_\odot < M < 0.1 M_\odot). \end{cases}$$

## Femtolensing GRBs

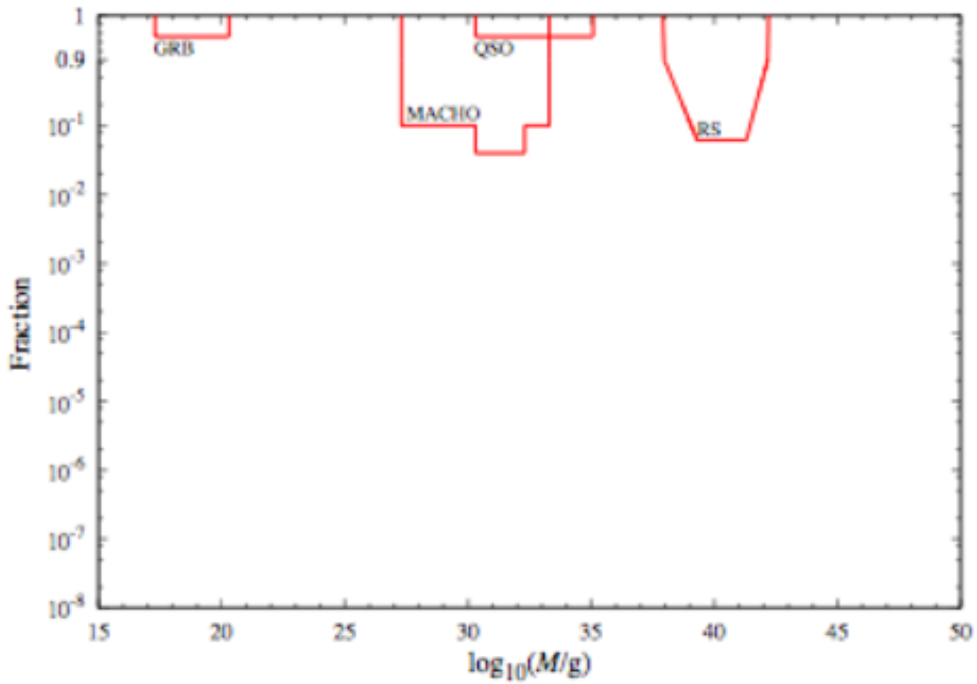
$$f < 1 \text{ for } 10^{-16} M_\odot < M < 10^{-13} M_\odot$$

## Microlensing QSOs

$$f < 1 \text{ for } 10^{-3} M_\odot < M < 60 M_\odot$$

## Millilensing Compact Radio Sources

$$f < 0.06 \text{ for } 10^{6} M_\odot < M < 10^{8} M_\odot$$



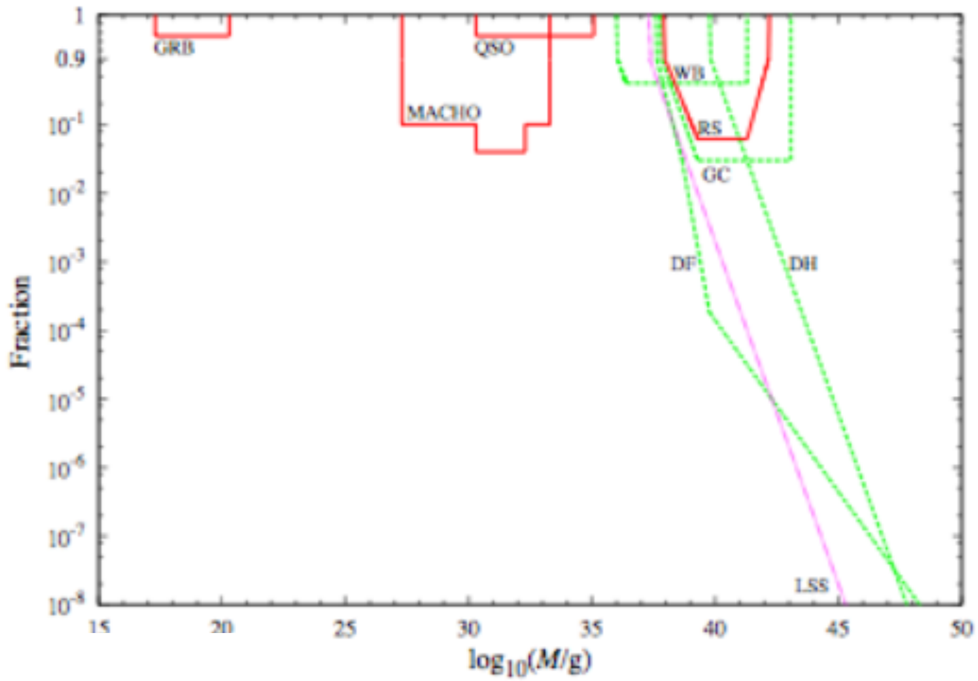
## Binary disruption

$$f(M) < \begin{cases} (M/500M_\odot)^{-1} & (500M_\odot < M < 10^3 M_\odot) \\ 0.4 & (10^3 M_\odot < M < 10^8 M_\odot) \end{cases}$$

# DYNAMICAL LIMITS (2010)

## Globular cluster disruption

$$f(M) < \begin{cases} (M/3\times 10^4 M_\odot)^{-1} & (3\times 10^4 M_\odot < M < 10^6 M_\odot) \\ 0.03 & (10^6 M_\odot < M < 6\times 10^9 M_\odot) \end{cases}$$




## Disk heating

$$f(M) < (M/3\times 10^6 M_\odot)^{-1}$$

## Dynamical friction

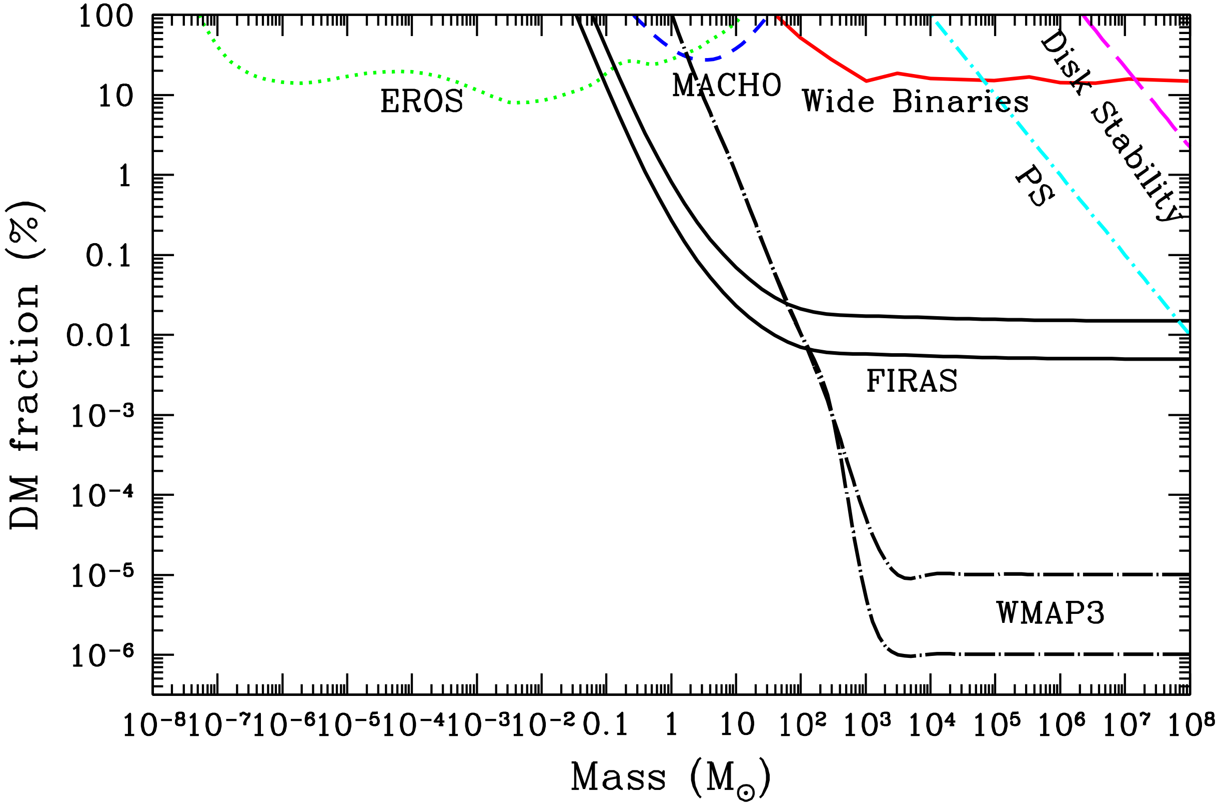
$$f(M) < \begin{cases} (M/2\times 10^4 M_\odot)^{-10/7}(r_c/2\text{kpc})^2 & (M < 6\times 10^5 M_\odot) \\ (M/4\times 10^4 M_\odot)^{-2}(r_c/2\text{kpc})^2 & (6\times 10^5 M_\odot < M < 3\times 10^6 [r_c/2\text{kpc}]^2 M_\odot) \\ (M/0.1 M_\odot)^{-1/2} & (M > 3\times 10^6 [r_c/2\text{kpc}]^2 M_\odot). \end{cases}$$

Some of these effects have been claimed as evidence for PBHs

# ACCRETION LIMITS (2010)

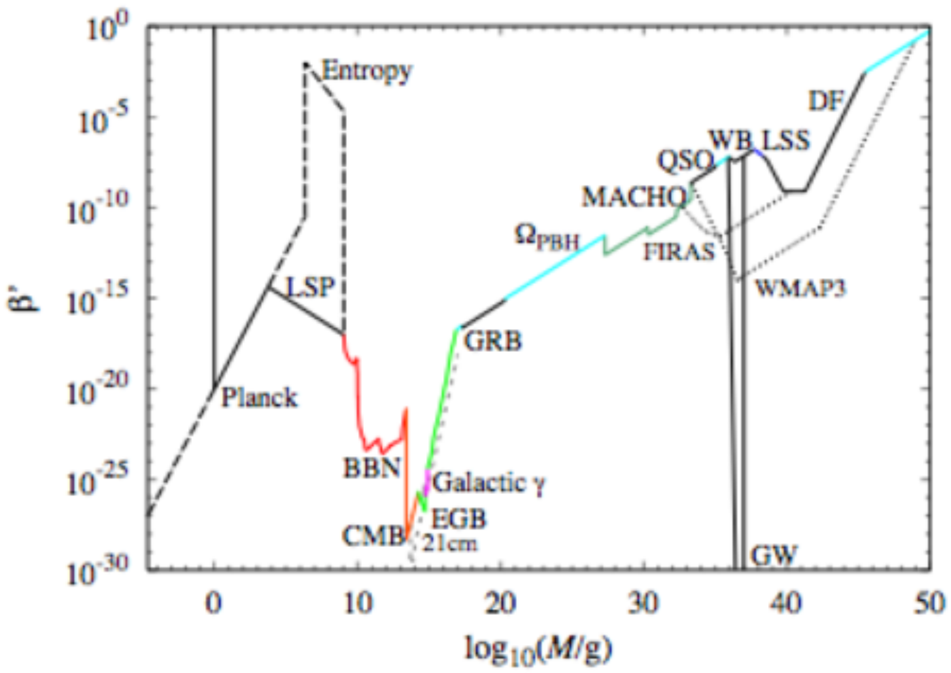
Ricotti, Ostriker & Mack (2008)

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




=> PBHs larger than 1 $M_o$ excluded (but error)

# CKSY 2010




There is still no definite evidence for PBHs but a large variety of constraints over 60 mass decades provide a unique probe of the various formation scenarios. The best dark matter candidates would be relics of evaporating PBHs or intermediate mass PBHs.

But many extra constraints since 2010

# EXPERIMENTAL LIMITS ON PRIMORDIAL BLACK HOLE DARK MATTER FROM THE FIRST 2 YR OF *KEPLER* DATA

Kim Griest[1], Agnieszka M. Cieplak[1,2], and Matthew J. Lehner[3,4]

Ap. J. 786, 158 (2014)

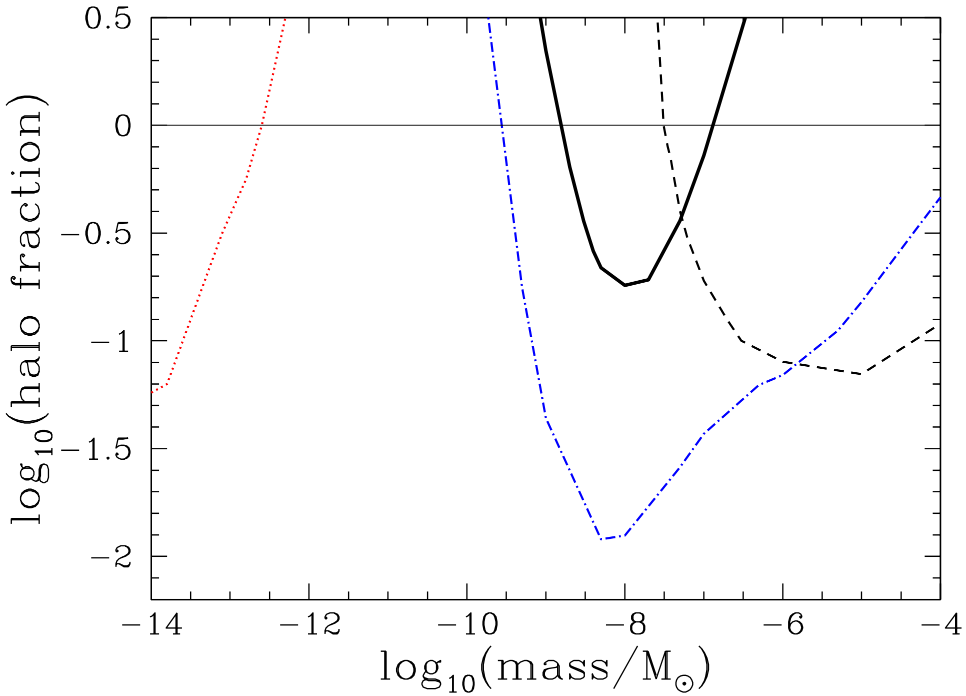
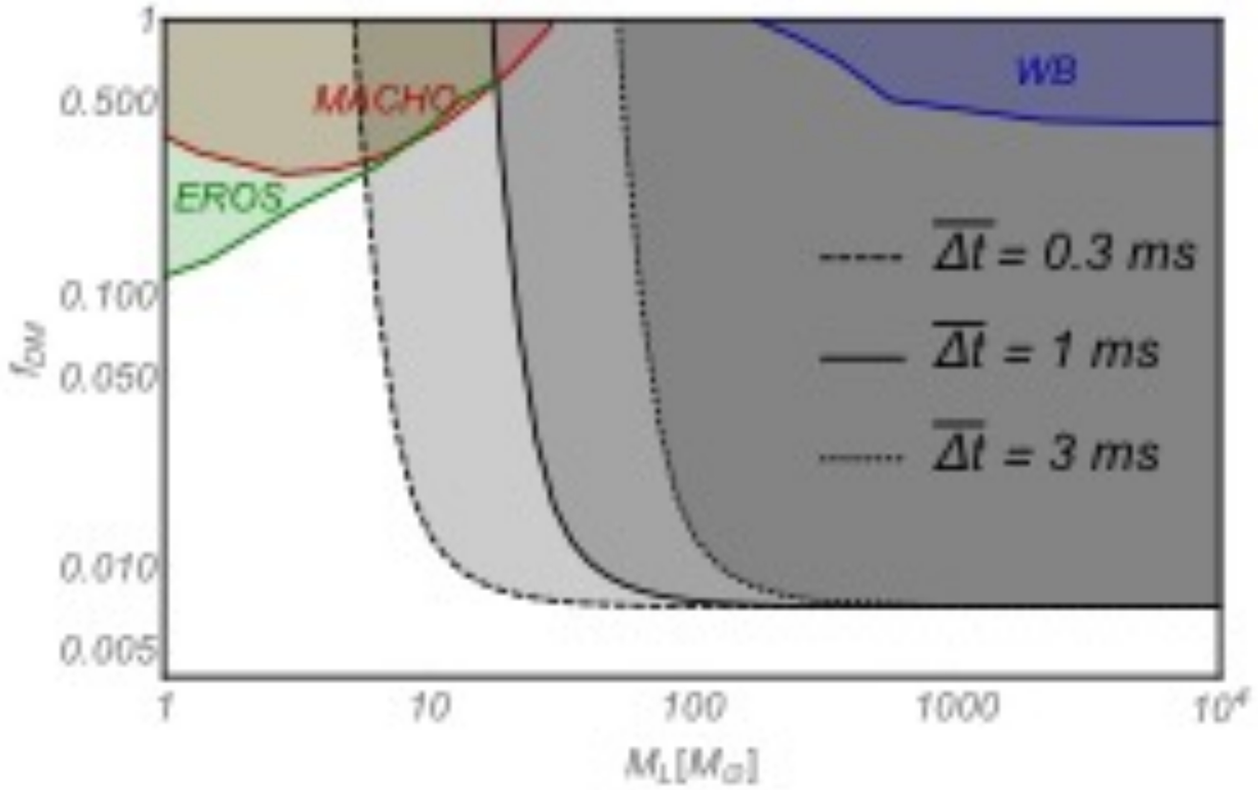



**Figure 6.** Upper limits (95% C.L.) on PBH DM from nonobservation of PBH microlensing in two yr of *Kepler* data. The solid black line is our new limit, the dashed black line is the previous best limit (Alcock et al. 1998), the blue dot–dashed line is the theoretical limit from Paper II, and the red dotted line is the femtolensing limit from Barnacka et al. (2012). The black horizontal line indicates a halo density of 0.3 GeV $cm^{-3}$.

# Lensing of Fast Radio Bursts as a Probe of Compact Dark Matter

Julian B. Muñoz,[1] Ely D. Kovetz,[1] Liang Dai,[2] and Marc Kamionkowski[1]

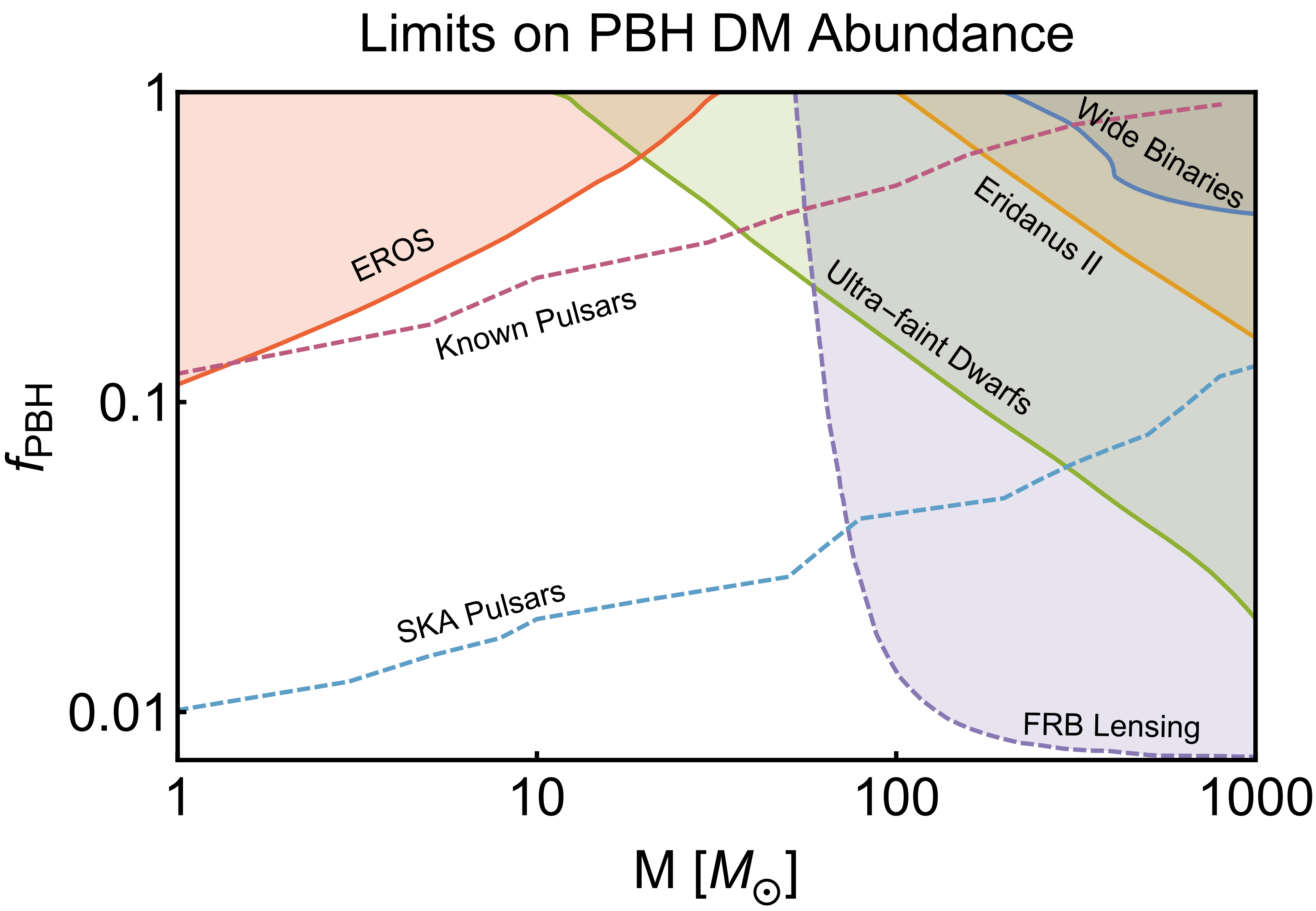
arXiv:1605.00008




CHIME gives $10^4$ FRB per year => 10-100 repeats

# PULSAR TIMING CONSTRAINTS

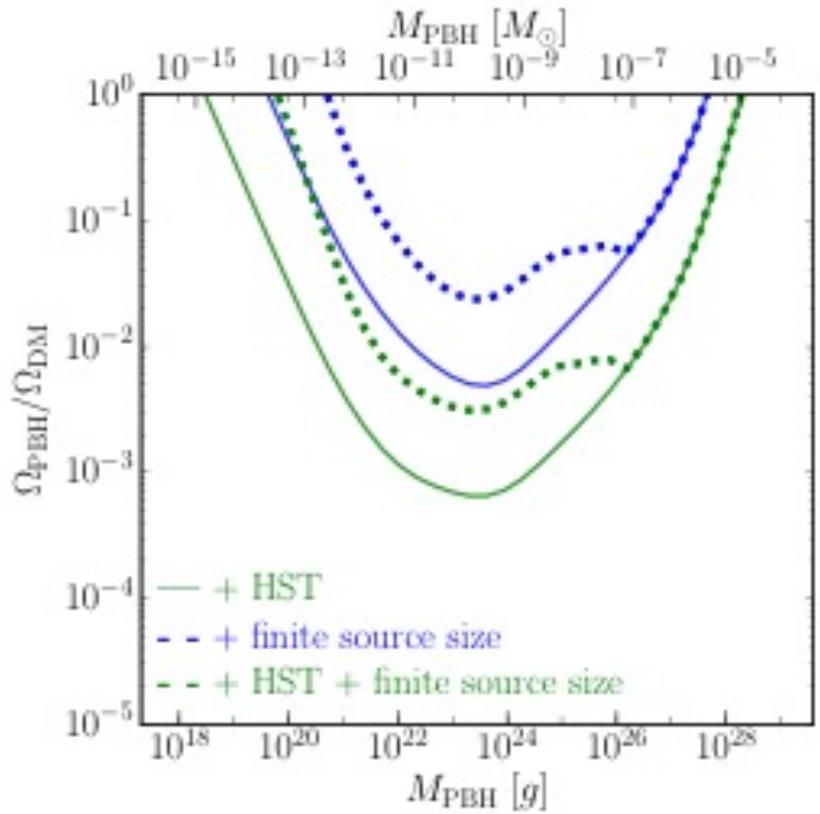
Schultz & Liu arXiv:1610.04234




SKA => f < 0.01 for 1 < $M/M_O$ < 30 (potential)

# MICROLENSING CONSTRAINTS FROM SUBARU HSC

Niikura et al. arXiv:1701.02151




Excludes PBHs with $10^{20}$g < M < $10^{26}$g

# LENSING CONSTRAINTS

*Femtolensing of GRBs*

Marani et al 1999
Nemirof et al 2001
Barnacka et al 2012

*Microlensing of quasars*

Hawkins 1993
Dalcanton et al 1994
Mediavilla et al 2009

*Millilensing of radio sources*

Wilkinson 2001
Vedantham et al. 2017
Minoz et al 2016

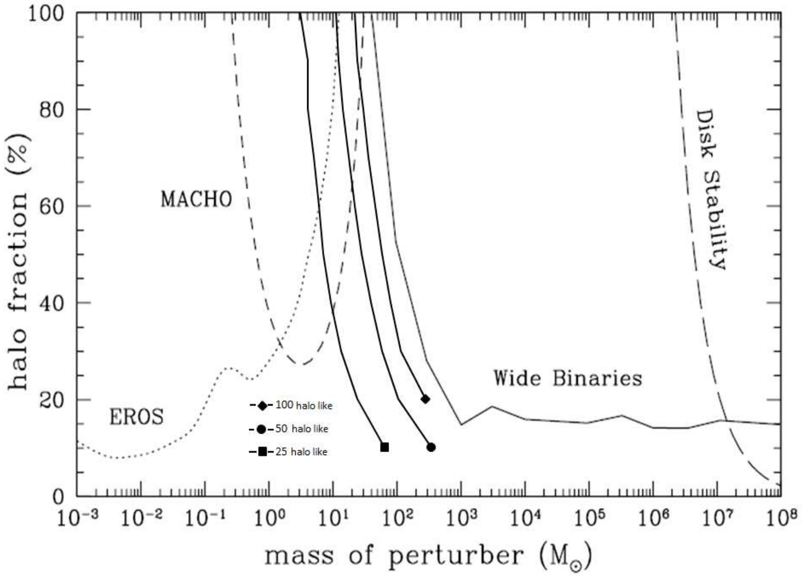
*Microlensing of stars*

Alcock et al 1998/2000/2001 (MACHO)
Allsman et al 2001
Tisserand et al 2007 (EROS)
Dong et al 2007
Wyrzykowski 2010/11 (OGLE)
Calchi-Novati et al 2013 (EROS-OGLE)
Karami et al 2016
Griest et al. 2013/4 (Kepler)
Calchi-Novati et al 2006 (M31)
Niikura et al 2017 (SUBARU)

# The end of the MACHO era- revisited: new limits on MACHO masses from halo wide binaries

Miguel A. Monroy-Rodríguez [1] & Christine Allen[1]

arXiv:1406.5169




From 211 systems likely to be halo binaries: 112 $M_\odot$.

From 150 halo binaries with computed galactic orbits: 85 $M_\odot$.

From 100 binaries that spend the smallest times within the disk (on average, half their lifetimes): $21 - 68$ $M_\odot$.

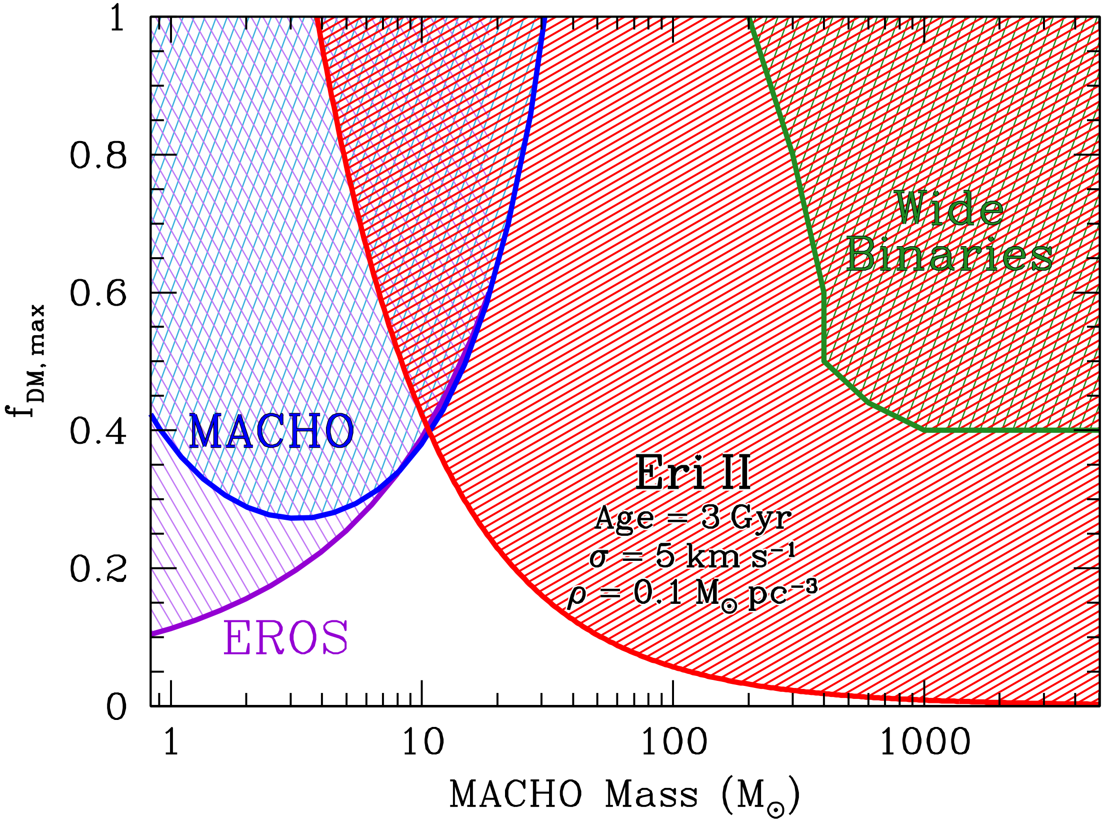
From the same 100 binaries, but taking into account the non-uniform halo density: $28-78$ $M_\odot$.

From the 25 most halo like binaries (those that spend on average 0.08 of their lifetimes within the disk): $3 - 12$ $M_\odot$.

# CONSTRAINTS ON MACHO DARK MATTER FROM THE STAR CLUSTER IN THE DWARF GALAXY ERIDANUS II

Timothy D. Brandt[1,2]

arXiv: 1605.03665



## Constraints on primordial black holes as dark matter candidates from star formation

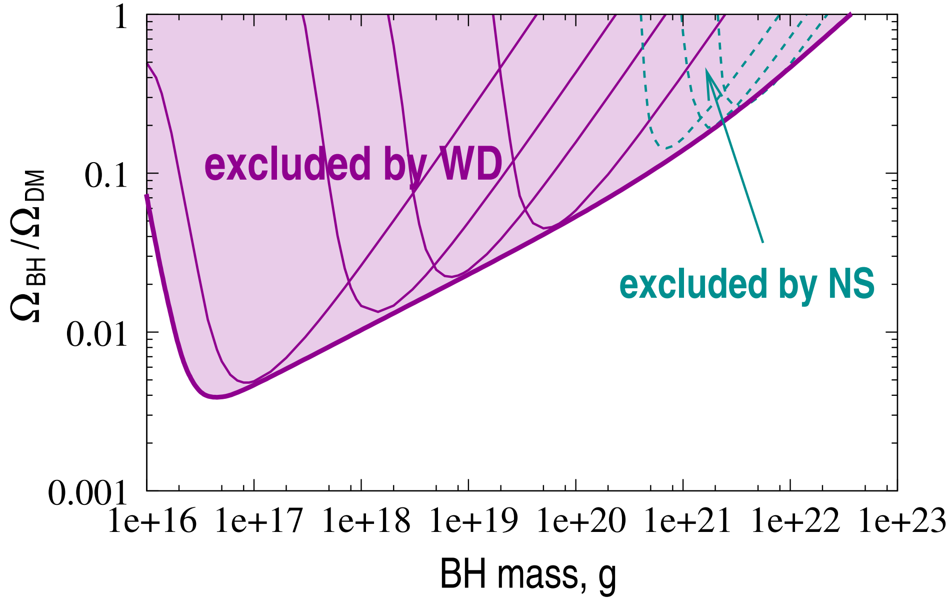
Fabio Capela,[1,*] Maxim Pshirkov,[2,3,4,†] and Peter Tinyakov[1,‡]

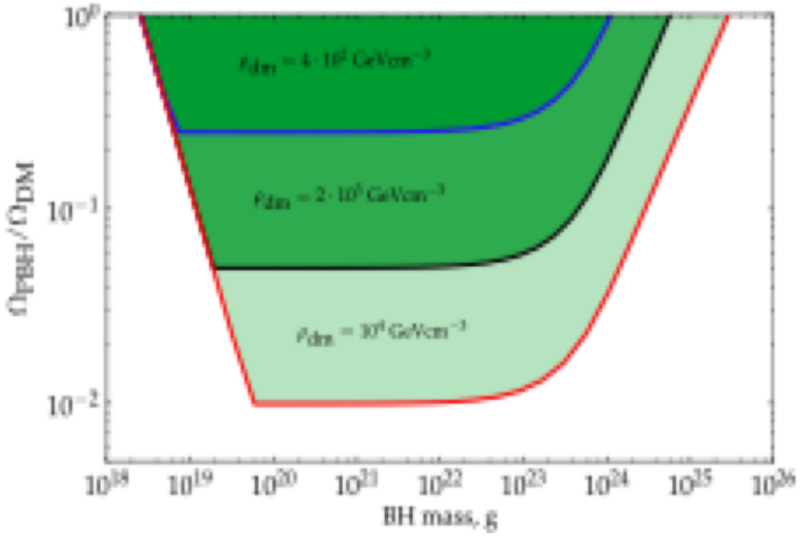
arXiv:1209.6021 PRD 87 023507 (2013)

## Constraints on primordial black holes as dark matter candidates from capture by neutron stars

Fabio Capela,[1,*] Maxim Pshirkov,[2,3,4,†] and Peter Tinyakov[1,‡]

arXiv:1301.4984



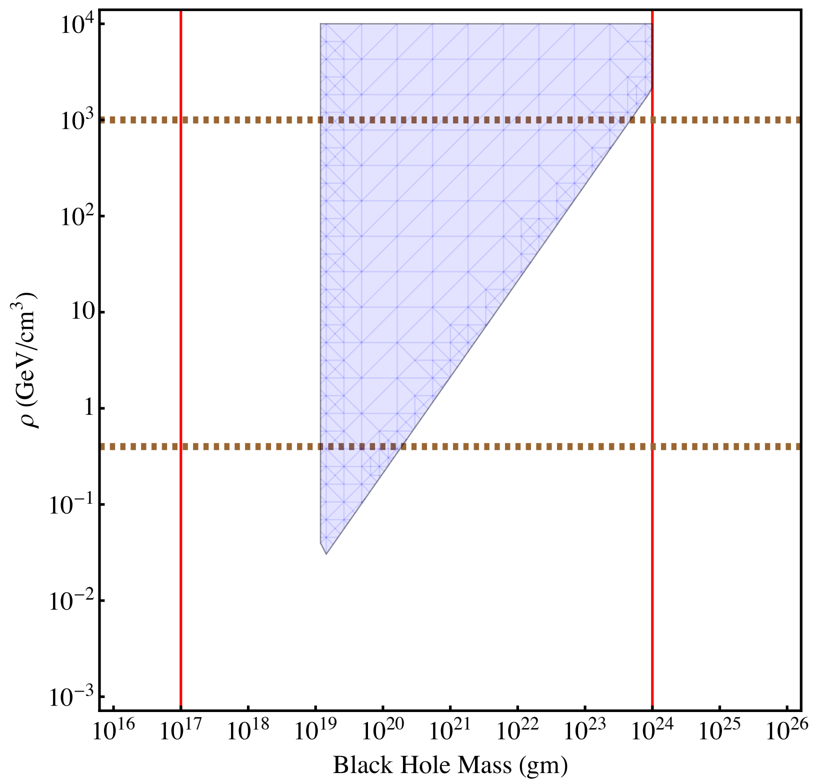




< 5% of DM in range 3 x $10^{18}$ g – $10^{24}$ g

# Dark Matter Triggers of Supernovae

Peter W. Graham,[1] Surjeet Rajendran,[2] and Jaime Varela[2]

arXiv:1505.044444



# DYNAMICAL CONSTRAINTS

*Collisions*

Jackson & Ryan 1973
Khriplovich et al 2008
Zhilyaev 2007
Adams & Bloom 2004 (eLISA)
Seto & Cooray 2004

*Captures*

Roncadelli et al 2009 (stars)
Capella et al 2013 (WD and NS)
Pani & Loeb 2014
Ibata et al.2013
Graham et al 2015 (WD -> SN)

*Dynamical friction*

Carr & Sakellariadou 1999

*Disruptions*

Yoo et al 2004 (wide binaries)
Quinn et al 2009
Monroy-Rodrigues & Allen 2014
Carr & Sakellariadou 1999 (glob clust)
Moore 1993

*Heating*

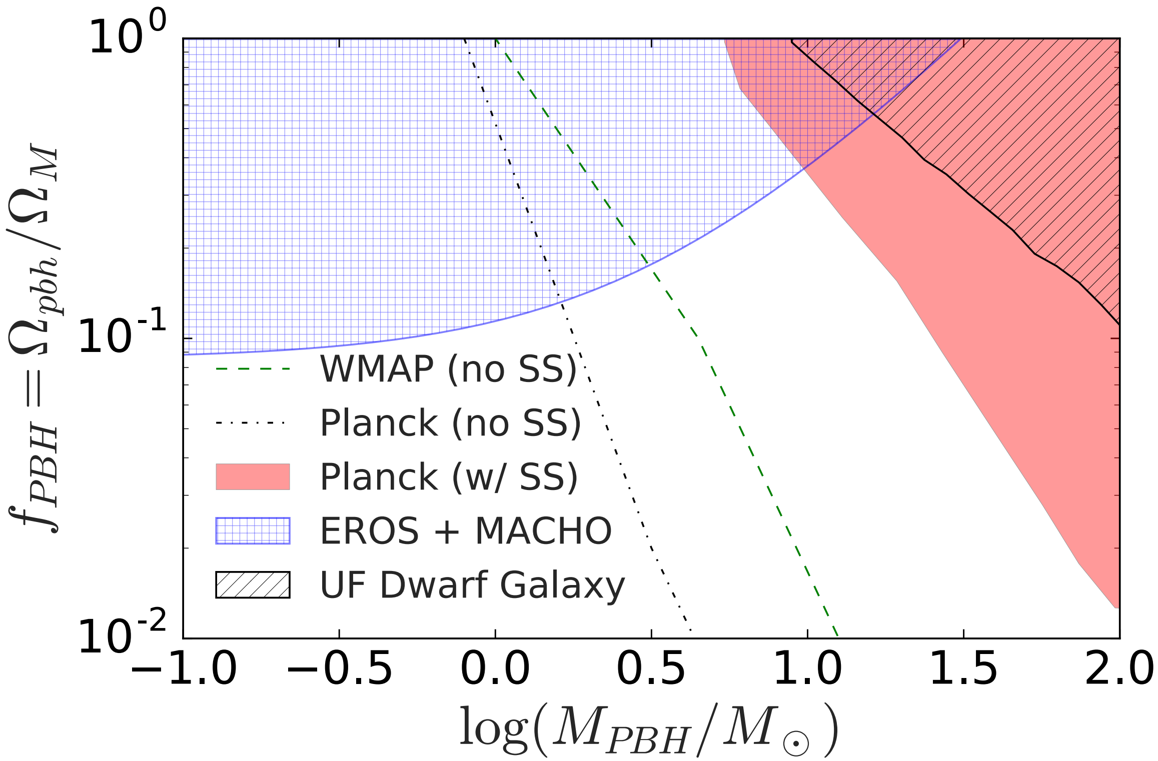
Lacy & Ostriker 1985 (discs)
Totani 2010
Brandt 2016 (Eridanus)
Koushippas & Loen 2017 (Segue 1)

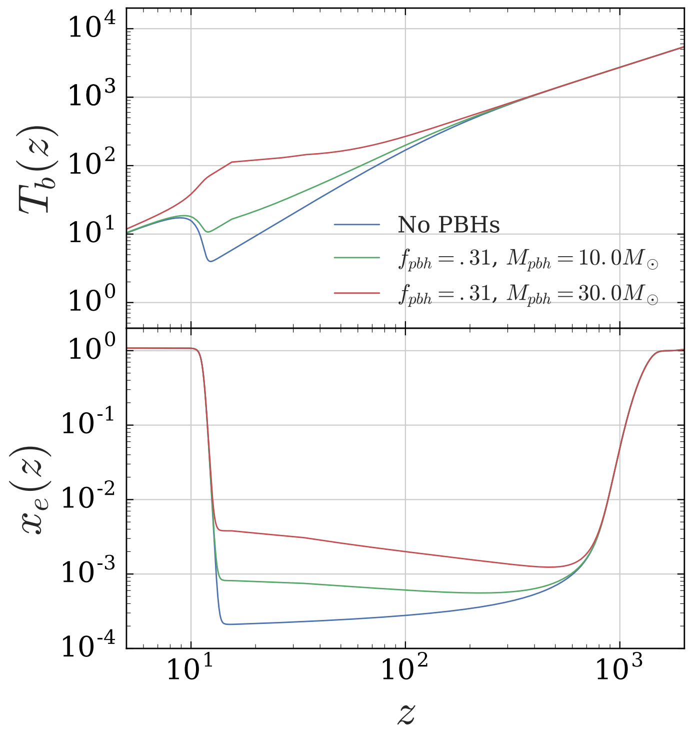
*PBH Clusters*

Carr & Lacey 1986
Chisholm 2007
Belotsky et al 2015

# REASSESING THE “ROM” CONSTRAINT

Horowitz arXiv:1612.07264v

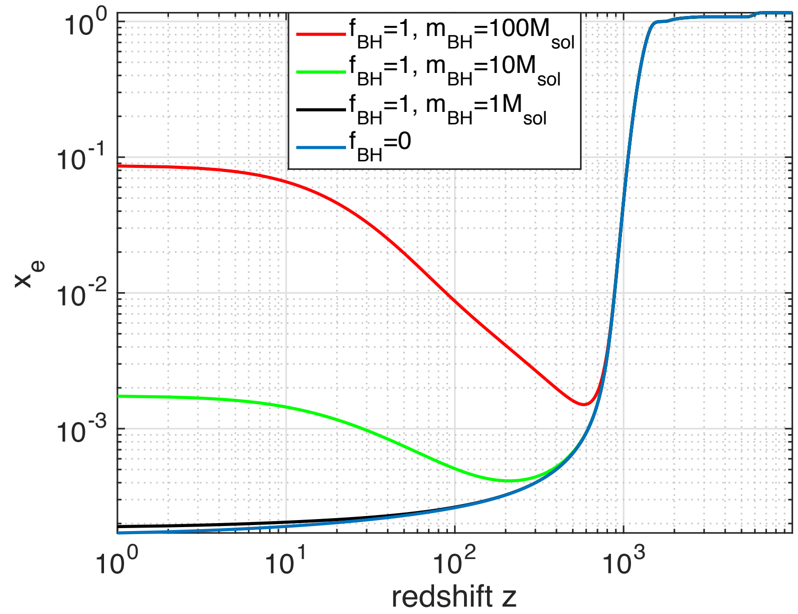


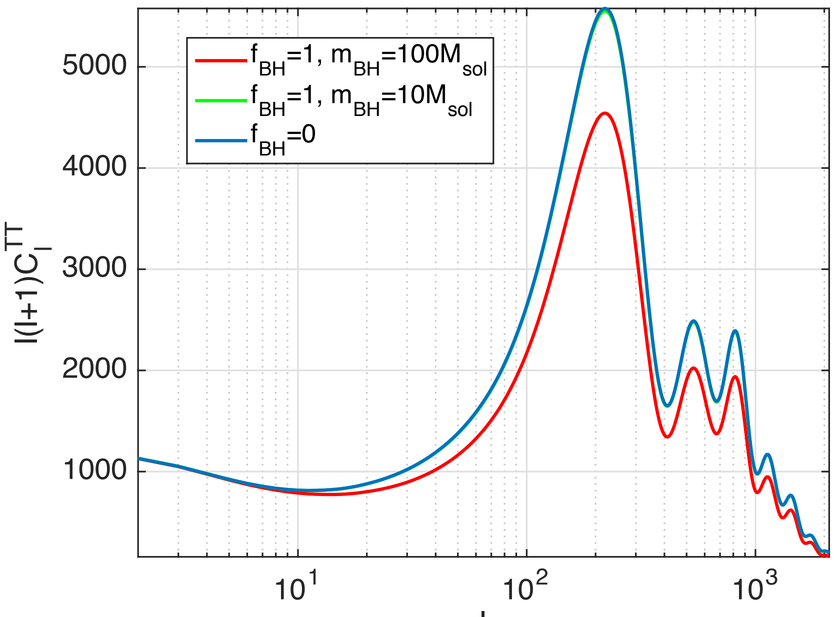

Only exclude PBHs larger than 30 $M_O$

Aloni, Blum & Flauger
arXiv:1612.06811

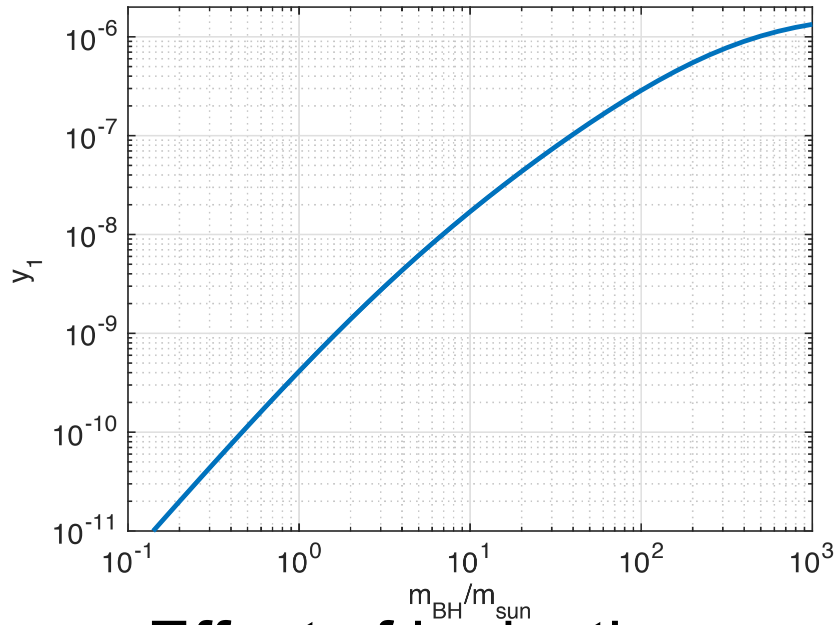
Exclude PBHs larger than 30 $M_O$




Fractional Ionization $X_e$

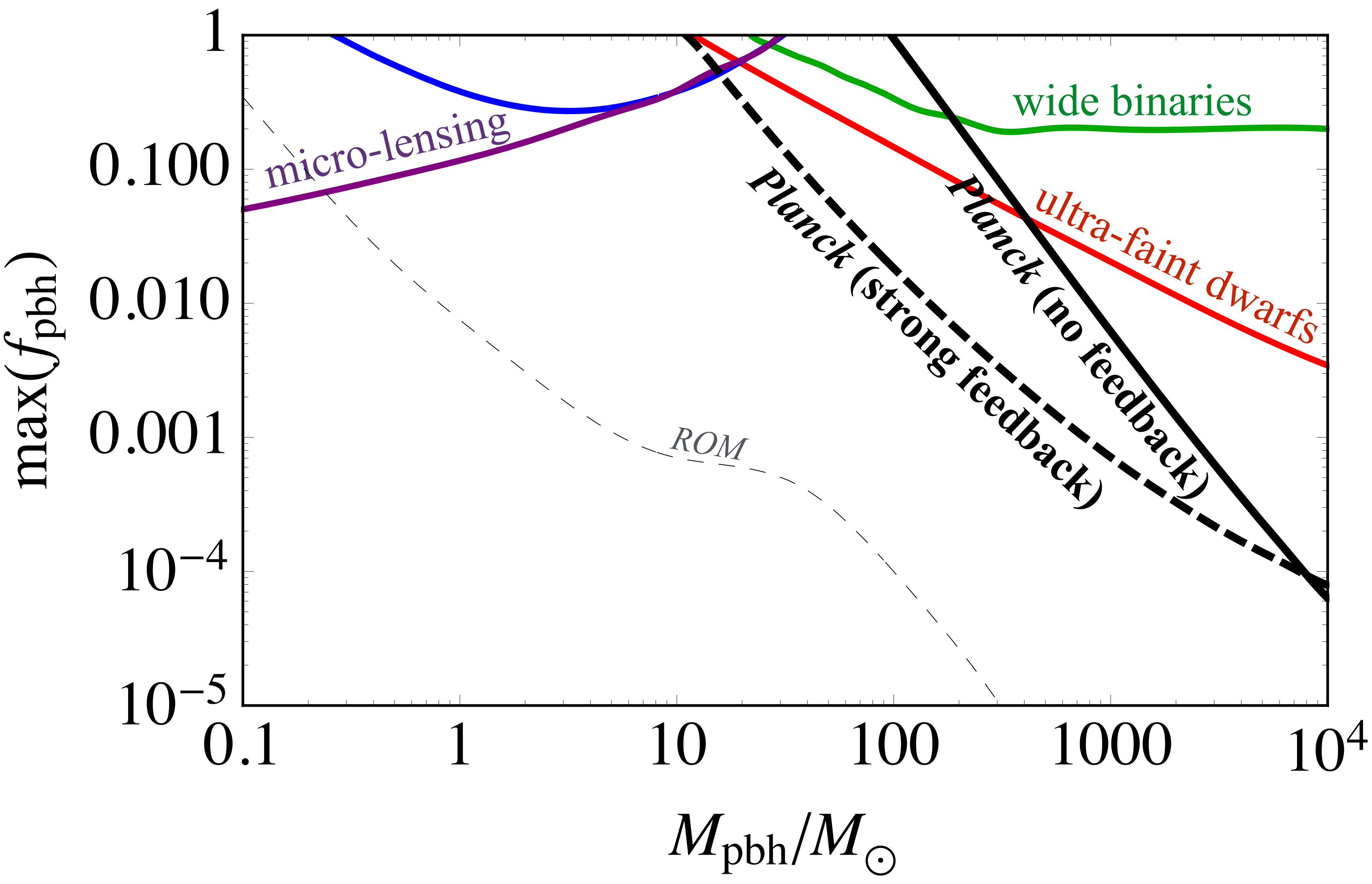



Effect of ionization on $C_l$




Effect of ionization on y

Ali-Haimoud & Kamionkowski arXiv:1612.05644



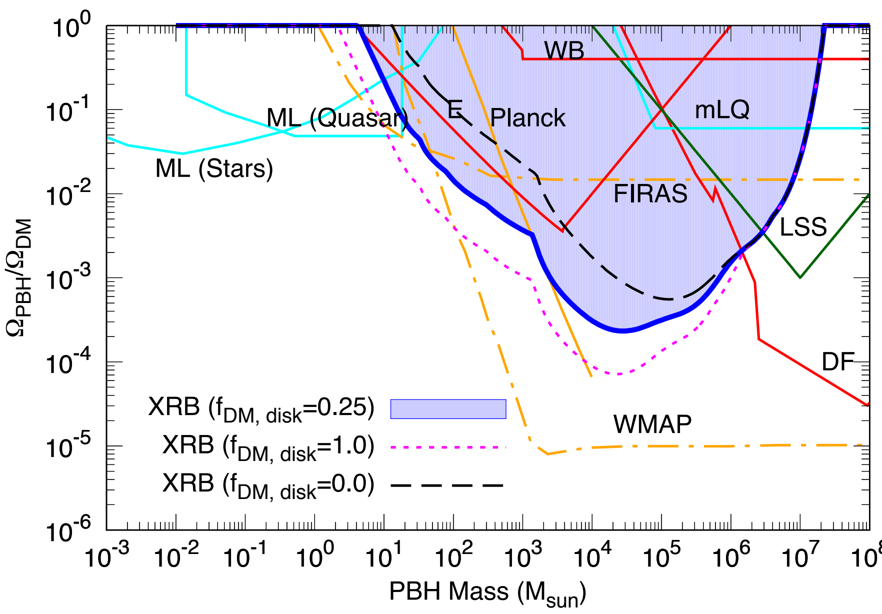

Only exclude PBHs larger than 100 $M_O$

# A new X-ray bound on primordial black holes density

Yoshiyuki Inoue*
*Institute of Space and Astronautical Science JAXA,*
*3-1-1 Yoshinodai, Chuo-ku, Sagamihara, Kanagawa 252-5210, Japan*

Alexander Kusenko†
*Department of Physics and Astronomy, University of California, Los Angeles, CA 90095-1547, USA*
*Kavli IPMU (WPI), University of Tokyo, Kashiwa, Chiba 277-8568, Japan*
(Dated: May 3, 2017)

We set a new upper limit on the abundance of primordial black holes (PBH) based on existing X-ray data. PBH interactions with interstellar medium should result in significant fluxes of X-ray photons, which would contribute to the observed number density of compact X-ray objects in galaxies. The data constrain PBH number density in the mass range from a few $M_\odot$ to $2 \times 10^7 M_\odot$. PBH density needed to account for the origin of black holes detected by LIGO is marginally allowed.



# ACCRETION AND THERMAL CONSTRANTS

*Self-similar growth*

Zeldovich & Novikov 1967
Carr & Hawking 1974
Bicknell & Henriksen 1978
Bean & Magueijo 2002
Harada, Maeda & Carr 2008
Carr, Harada and Maeda 2010

*Thermal history*

Carr 1981
Mack, Ostriker & Ricotti 2007
Ricotti, Ostriker & Mack 2008
Horowitz et al. 2016
Aloni et al 2016
Ali-Haimoud & Kamionkoski 2017

*Accretion*

Carr 1979
Kawaguchi et al 2008
Gaggero et al 2016
Inoue & Kusenko 2017
Poulin et al 2017

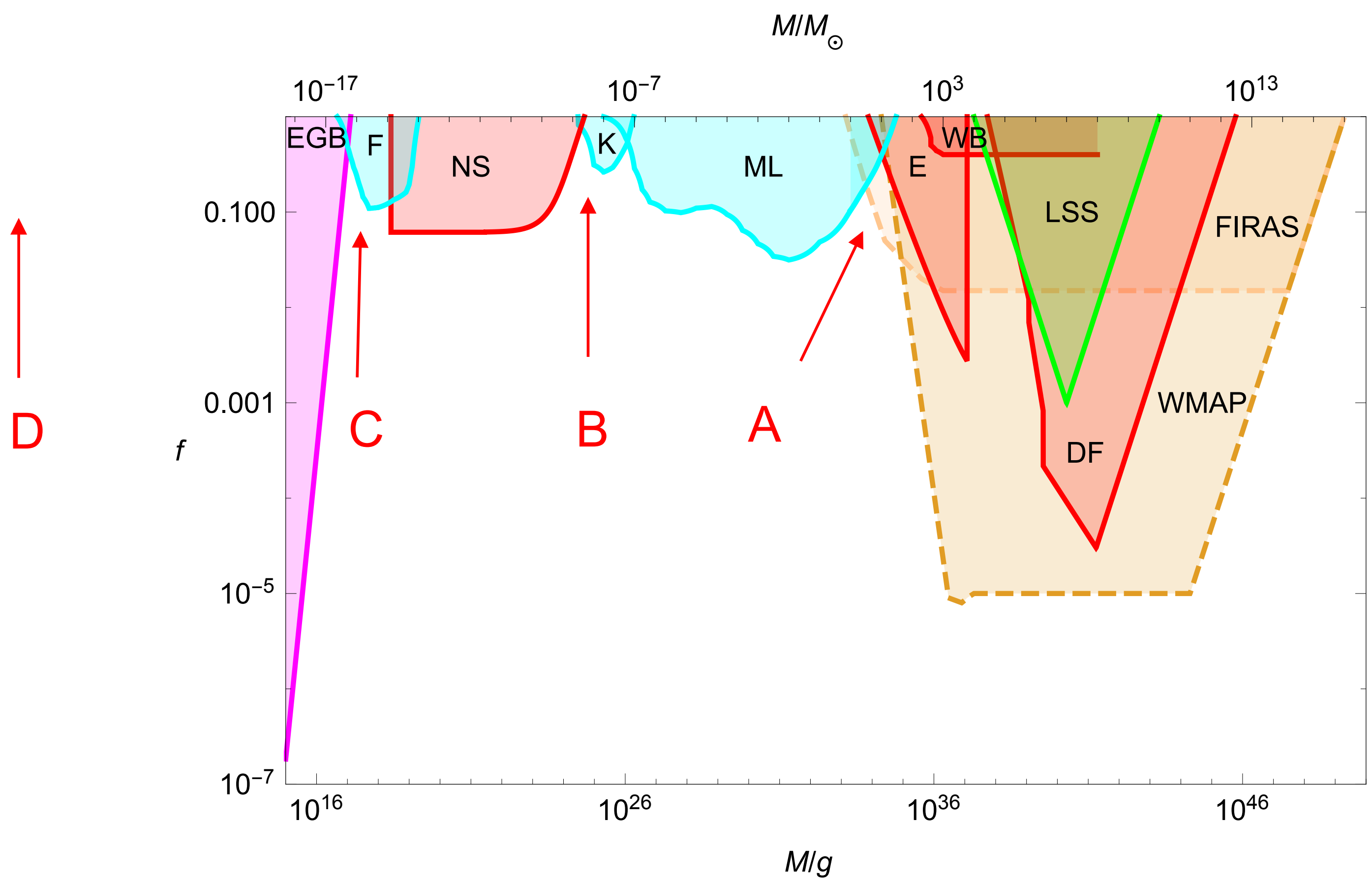
*r-process elements*

Fuller, Kosenk & Takhistov 2017

# 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) atomic size.

Also (D) Planck mass relics

CKS 2016

# EXTENDED MASS FUNCTION?

Most constraints assume monochromatic PBH mass function

Can we evade standard limits with extended mass spectrum?

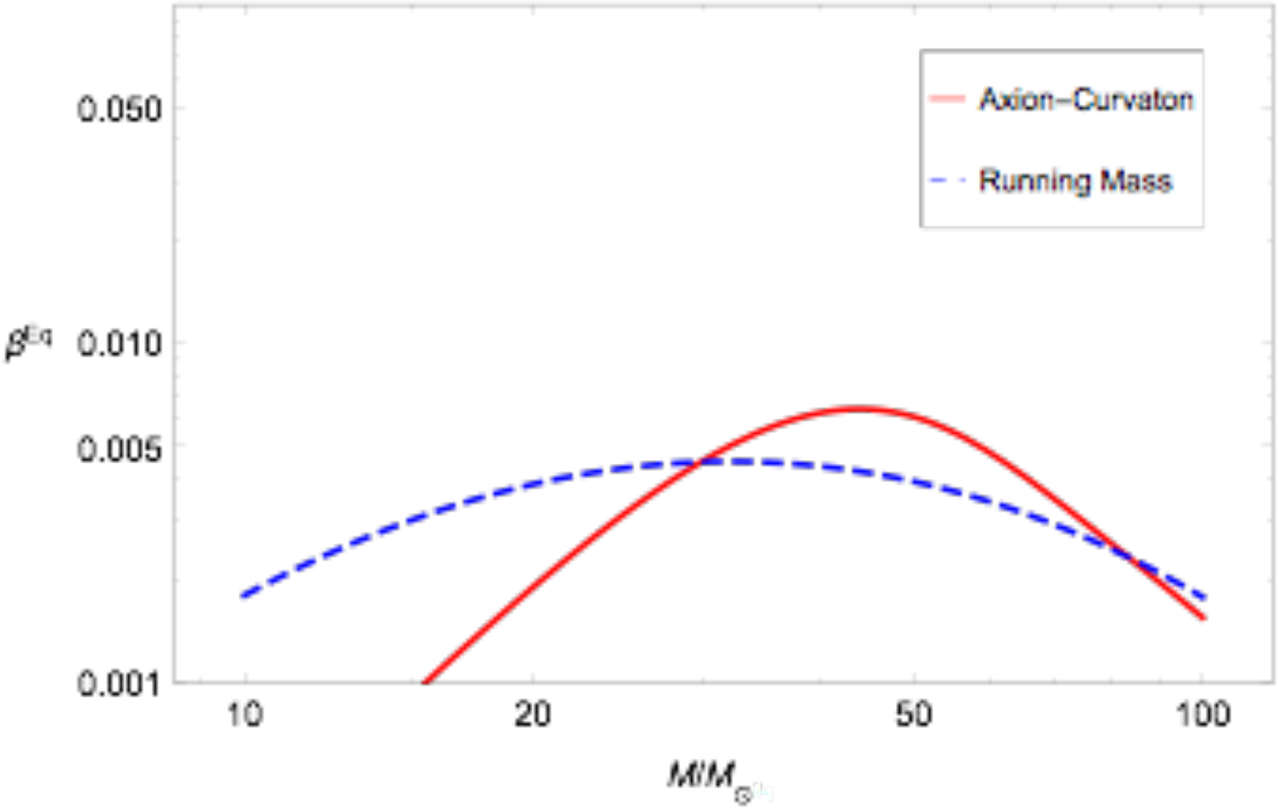
But this is two-edged sword!

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

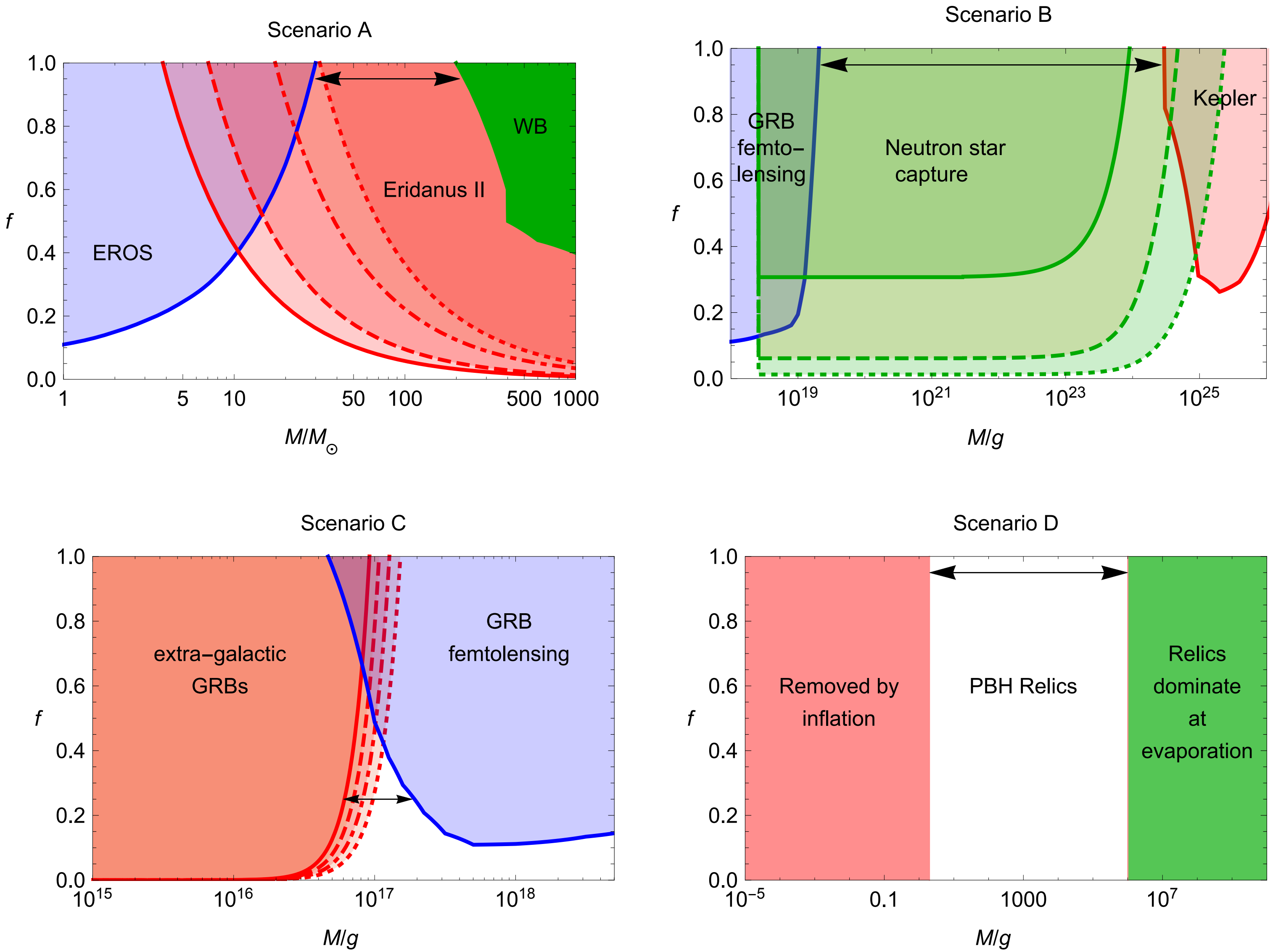
PBHs giving dark matter at one scale may violate limits at others

# Extended mass function expected in many inflation models

★ LIGO mass range:




But precise form subject to various uncertainties….



Scenario A
1.0
0.8
0.6
0.4
0.2
0.0
f
1
5
10
50
100
500
1000
M/M⊙
EROS
Eridanus II
WB
Scenario B
1.0
0.8
0.6
0.4
0.2
0.0
f
10^19
10^21
10^23
10^25
M/g
GRB
femto-
lensing
Neutron star
capture
Kepler
Scenario C
1.0
0.8
0.6
0.4
0.2
0.0
f
10^15
10^16
10^17
10^18
M/g
extra-galactic
GRBs
GRB
femtolensing
Scenario D
1.0
0.8
0.6
0.4
0.2
0.0
f
10^−5
0.1
1000
10^7
M/g
Removed by
inflation
PBH Relics
Relics
dominate
at
evaporation

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

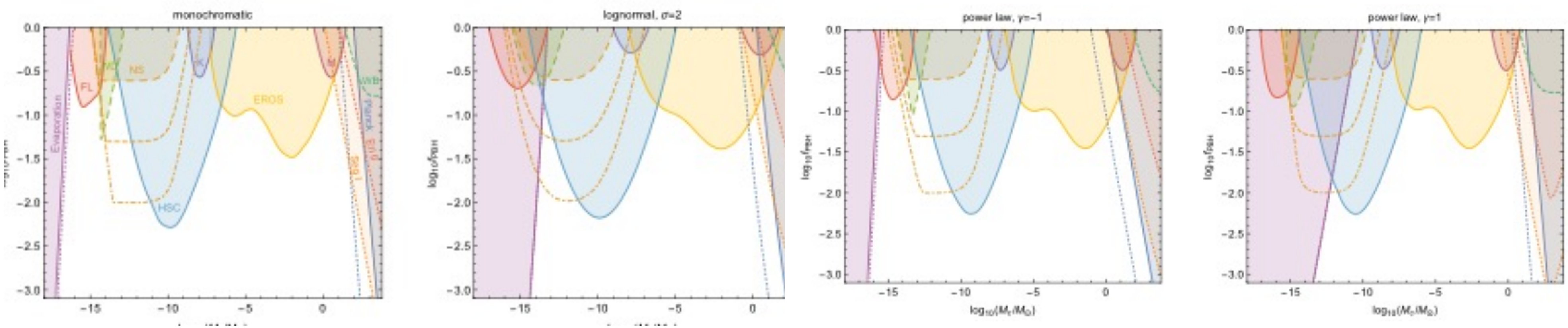
2 parameters ($M_c$,σ)

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

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

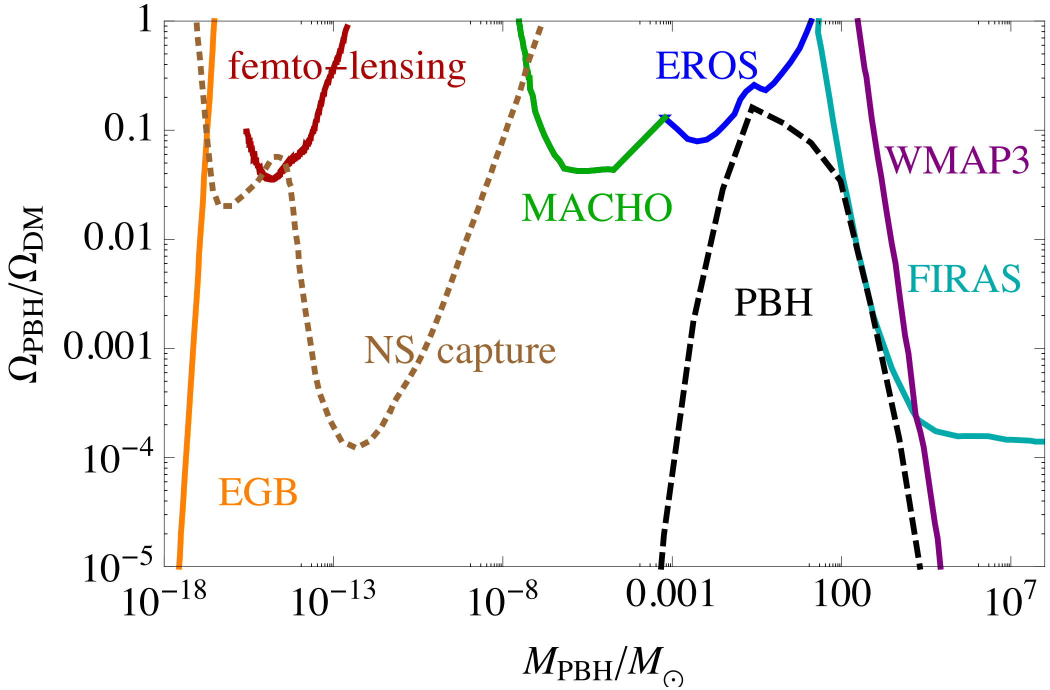


# WHICH MASS WINDOW IS MOST PLAUSIBLE?

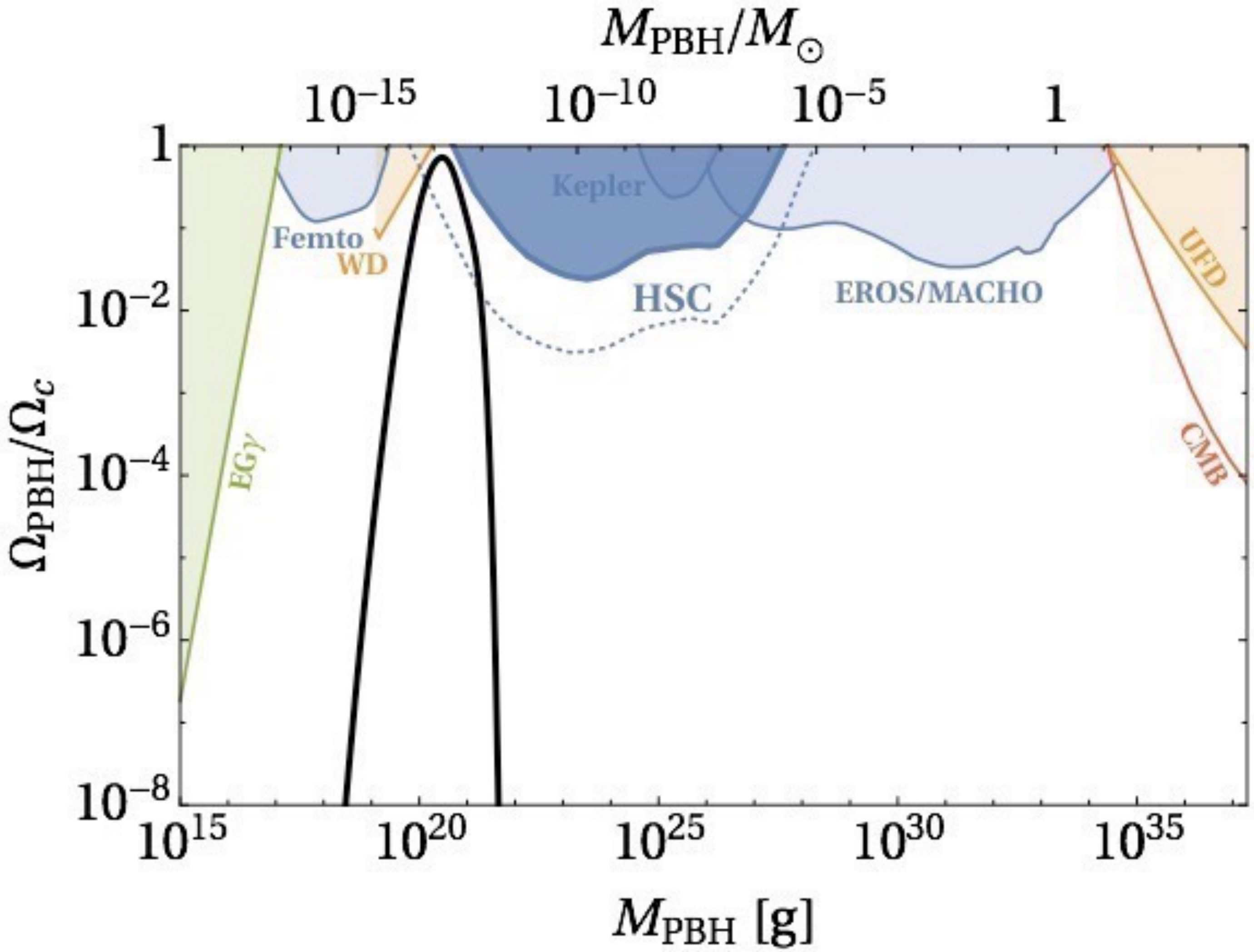
**Massive Primordial Black Holes from Hybrid Inflation as Dark Matter and the seeds of Galaxies**

Sébastien Clesse[1,*] and Juan García-Bellido[2,†]

arXiv:1501.07565

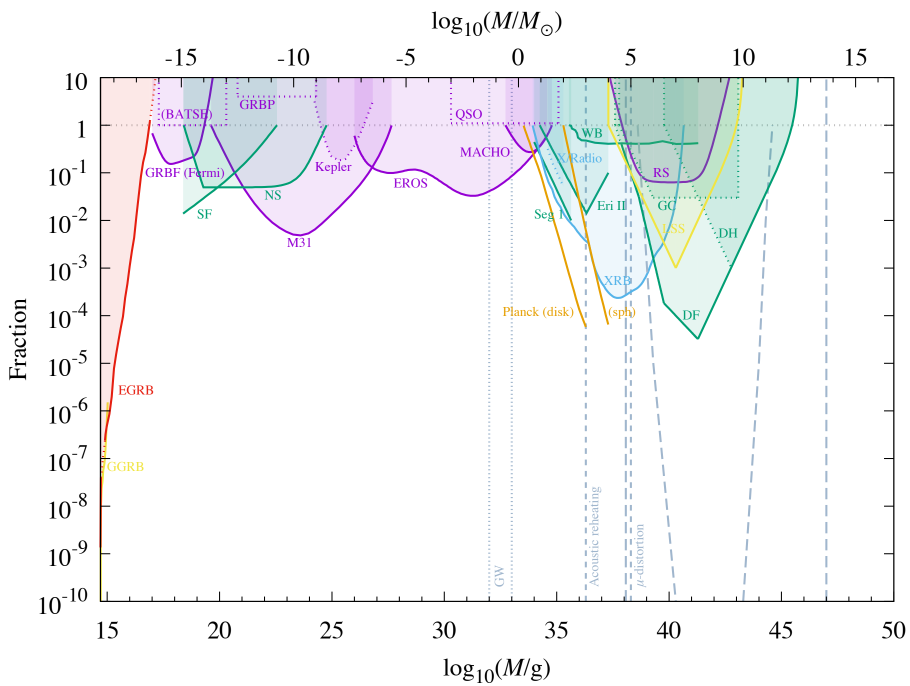


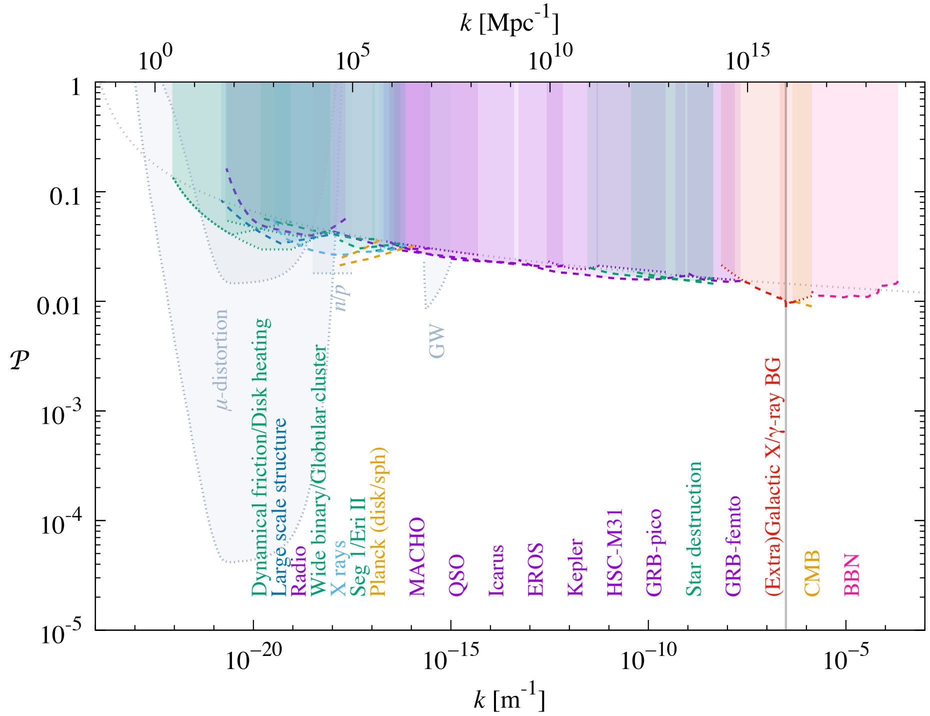
# PBH dark matter with M = $10^{20}$g from double inflation




Inomata, Kawasaki, Mukaida &. Yanagida arXiv:1701.02544

# Carr, Kohri, Sendouda & Yokoyama 2017



# PBHS AS SEEDS FOR COSMIC STRUCTURE

Carr & Silk (2017)

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 $\beta < 10^{-6} (t/s)^{1/2}$

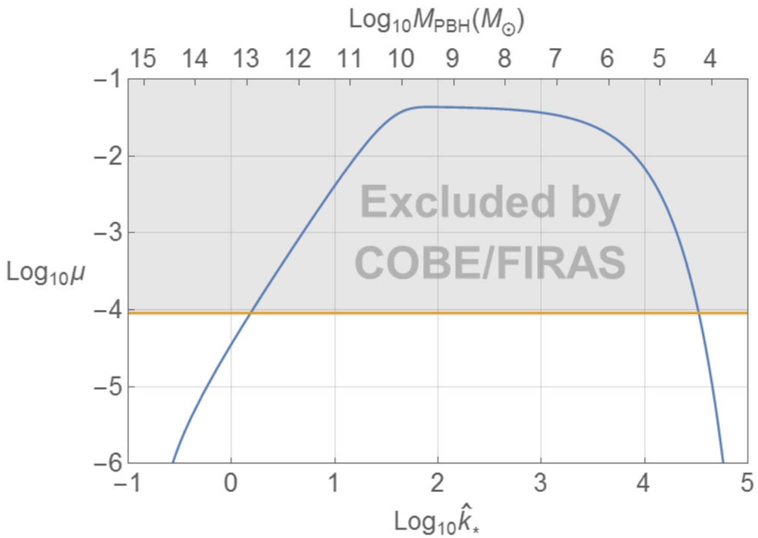
Upper limit on $\mu$ distortion of CMB excludes $10^4 < M/M_O < 10^{13}$ for Gaussian fluctuations (Kohri et al. 2014) but non-Gaussian model evade these limits (Nakama et al 2016/2017)

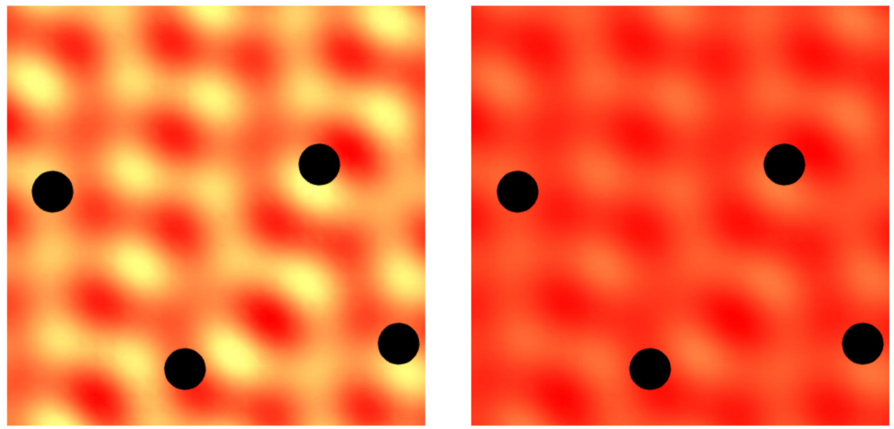
[Garcia-Bellido]

PHYSICAL REVIEW D **94,** 103522 (2016)

# Supermassive black holes formed by direct collapse of inflationary perturbations

Tomohiro Nakama,[1] Teruaki Suyama,[2] and Jun'ichi Yokoyama[2,3,4]

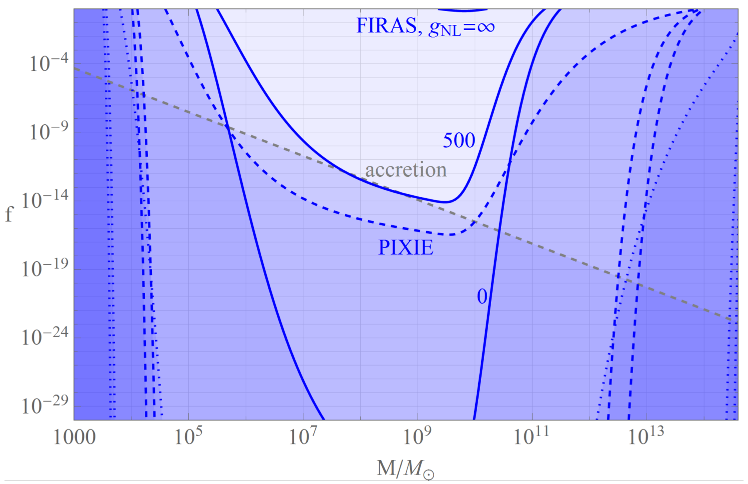


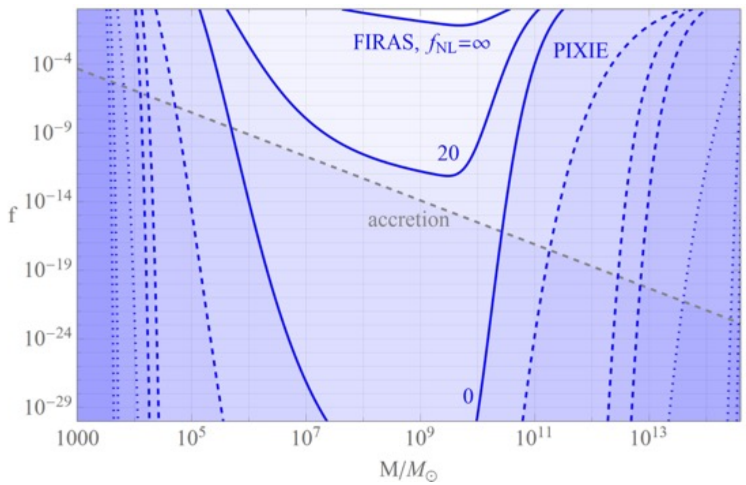



# Limits on primordial black holes from $\mu$ distortions in cosmic microwave background

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

If primordial black holes (PBHs) form directly from inhomogeneities in the early universe, then the number in the mass range $10^6 - 10^9 M_\odot$ is severely constrained by upper limits to the $\mu$-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-$\sigma$ tail, as in the simplest scenarios, then the $\mu$ 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.




arXiv:1710.06945

# 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.

For region of mass M containing PBHs of mass m, initial fluctuatior

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

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

$$M \sim \begin{cases} 10^4 m z_B^{-1} & \text{(seed)} \\ 10^8 f m z_B^{-2} & \text{(Poisson)} \end{cases}$$

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

LYMAN-ALPHA FOREST (Afshordi et al 2003)

$M_B \sim 10^{10} M_O$ at $z_B \sim 10$ for $m \sim 10^4 M_O$

To avoid Ly-$\alpha$ forest forming too early, we require

$$f < \max[(m/10^4 M_\odot)^{-1}, (m/10^{10} M_\odot)]$$

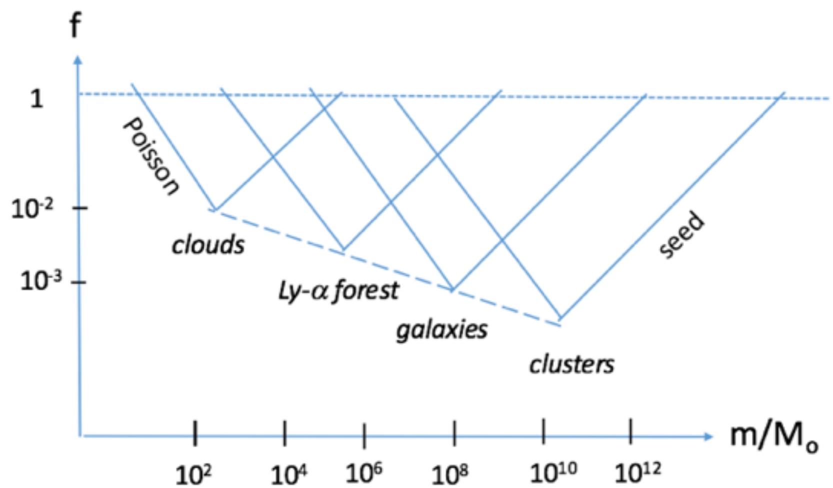
Seed effect wins for $f < m/M$ and requires $m < 10^7 M_O$

FIRST CLOUDS ($M \sim 10^6 M_O$)

Poisson => these bind earlier than in standard LCDM at

$$z \sim 100(f_{0.01} m_{100}/M_{J,6})^{1/2}$$

(Kashlinksy 2016)




Carr & Silk 2017)

# SUPERMASSIVE PBHS AS SEEDS FOR GALAXIES

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

Also predict mass function of galaxies (Press-Schechter)

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

For extended mass function, predict

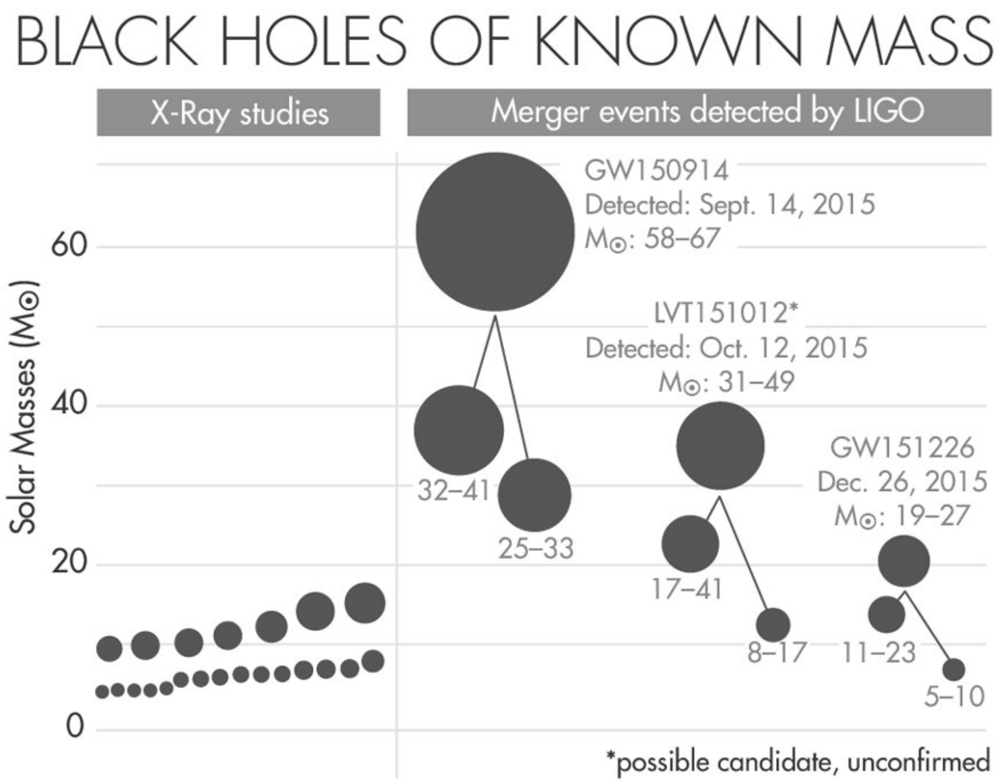
$$t_B(M) \sim t_{eq} \left[\frac{M}{m_{seed}(M)}\right]^{3/2} \propto \left(\frac{M}{m_{dm}}\right)^{3(\alpha-2)/2(\alpha-1)}$$

Bondi accretion => $m \approx m_i/(1 - m_i \eta t)\,,$

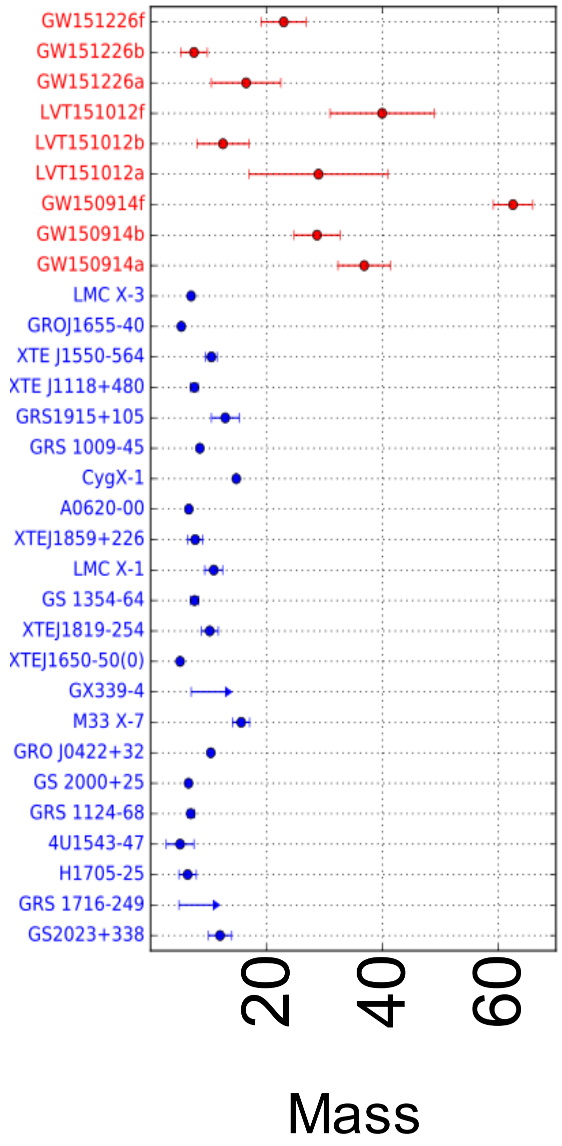
=> diverges at $\tau = 1/(\eta m_i) \sim (M_{eq}/m_i)(c_{eq}/c)^3 t_{eq}$

=> upper limit $m_i > M_{eq}(t_{eq}/t_o) \sim 10^9 M_\odot$

# PBHS AND LIGO




Do we need Pop III or primordial BHs?

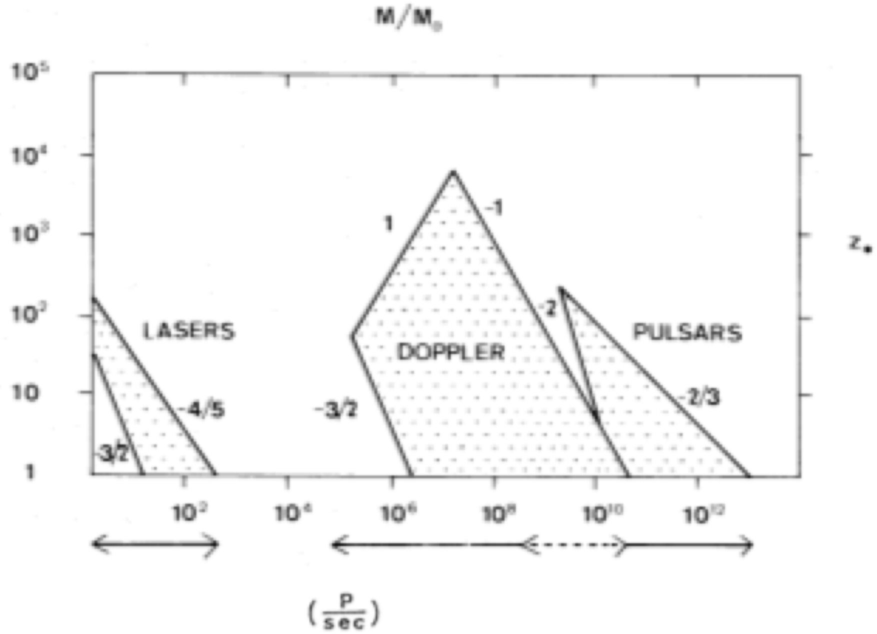



Courtesy: Salvatore Vitale (MIT)

# Gravitational waves from a population of binary black holes

MNRAS 207, 585 (1984)

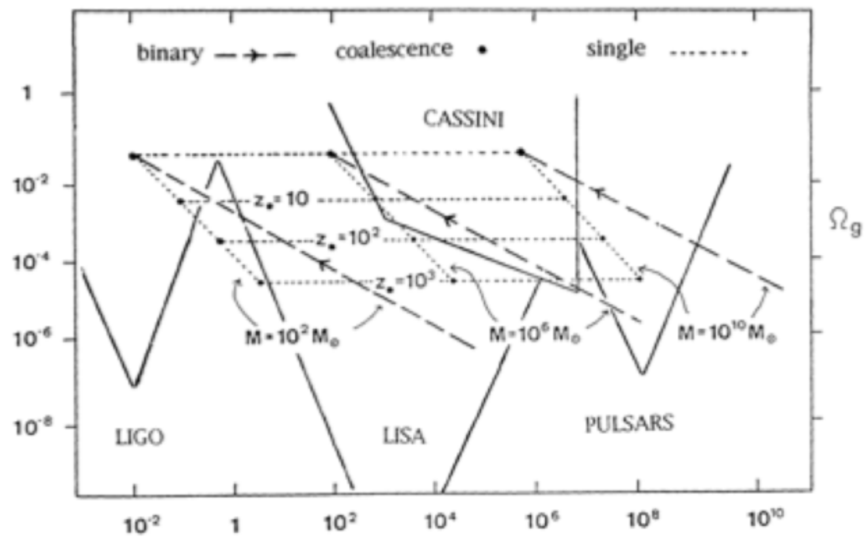
**J. R. Bond** *Institute of Astronomy, Madingley Road, Cambridge and Department of Physics, Stanford University, California, USA*
**B. J. Carr** *Institute of Astronomy, Madingley Road, Cambridge and Research Institute for Fundamental Physics, Kyoto University, Kyoto 606, Jap*




GW background from formation of VMO BHs

$$P_\circ \approx 10GM\frac{(1+z_B)}{c^3} \approx 10^{-2}\left(\frac{M}{10^2 M_\odot}\right)(1+z_B)\ \mathrm{s}.$$

$$t_{\rm burst} = 10\left(\frac{M}{10^2 M_\odot}\right) f_{\rm crit}^{-1} h^{-1}\,\mathrm{y}, \quad h_{\rm burst} = 7\times 10^{-17}\left(\frac{M}{10^2 M_\odot}\right)$$




GWs generated by VMO coalescences

Detectable by various methods

# PBHS AND GRAVITATIONAL WAVES

*Stochastic PBH background*

Carr 1980
Clesse & Garcia-Bellido 2015

*Binary background*

Bond & Carr 1984
Nakamura et al. 1997
Ioka et al. 1999
Inoue & Tanaka 2003

*Induced GWs*

Saito & Yokoyama 2009/10
Assadullahi & Wands 2010
Bugaev & Klimai 2011
Nakama & Suyama 2015/6
Pen & Turok 2015

*LIGO*

Bird et al. 2016
Clesse & Garcia-Bellido 2016
Ereshenko 2016
Sasaki et al. 2016
Raccanelli et al 2016
Dai et al 2016
Seto 2016
Nishizawa et al 2016
Kawamura et al. 2016
Nakamura et al. 2016
Cholis et al 2016

# CLESSE & GARCIA-BELLIDO

## Our model of Primordial Black Holes Dark Matter in a sketch...

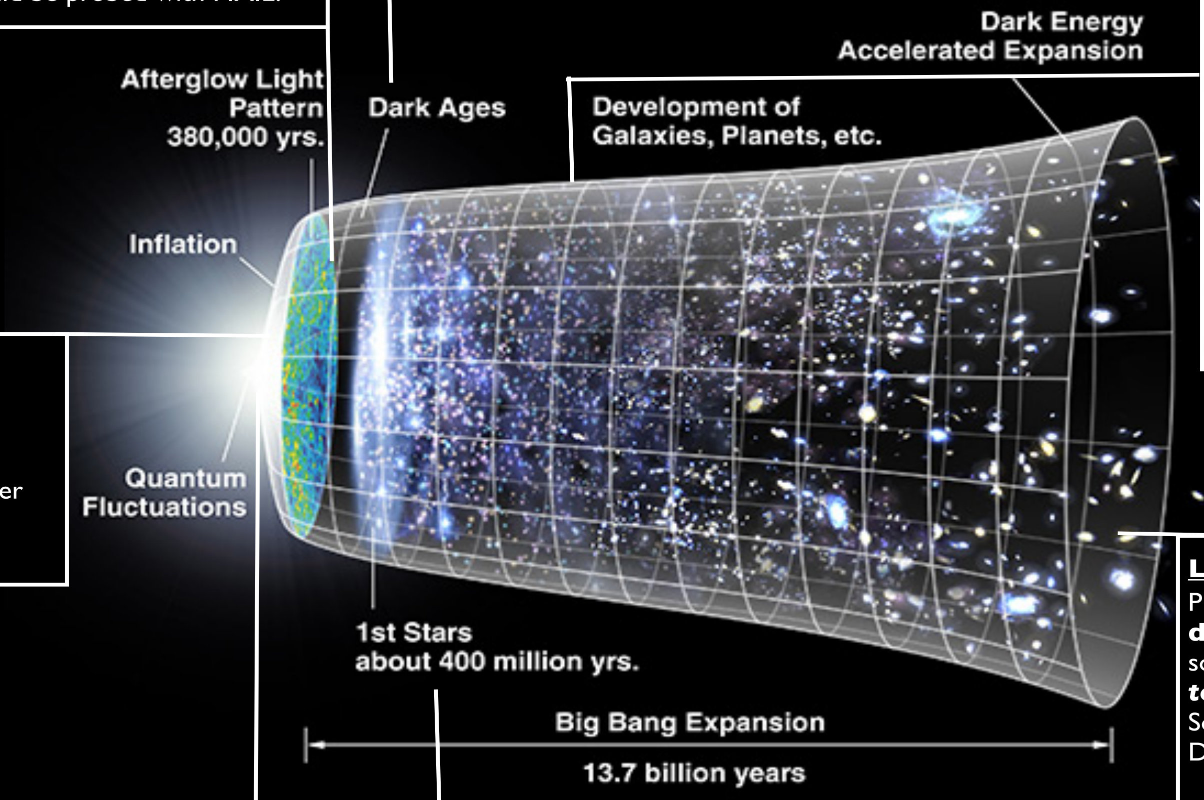
**Cosmic Microwave Background:**
Massive primordial black holes induce **distortions of the CMB**,. These could be probed with PIXIE.

**21cm signal** ***about 500 million years...***
**X-rays** emitted by **accreting matter** onto PBHs **ionize** the environment, leading to **detectable signatures in the 21cm signal.**

**Over the cosmic evolution...**

**Binaries can form** when PBH trajectories cross. After a spiraling phase, the two **PBH merge** and emit **gravitational waves**, such as the ones detected by **aLIGO/VIRGO**. PBH binaries also produce a **background of gravitational waves**, that will be probed by **eLISA**.

Halos of PBH induce **correlated anomalies** in the **Cosmic Infrared Background** (CIB) and **X-ray background.**




**Hybrid Inflation :**

**Mild-waterfall**

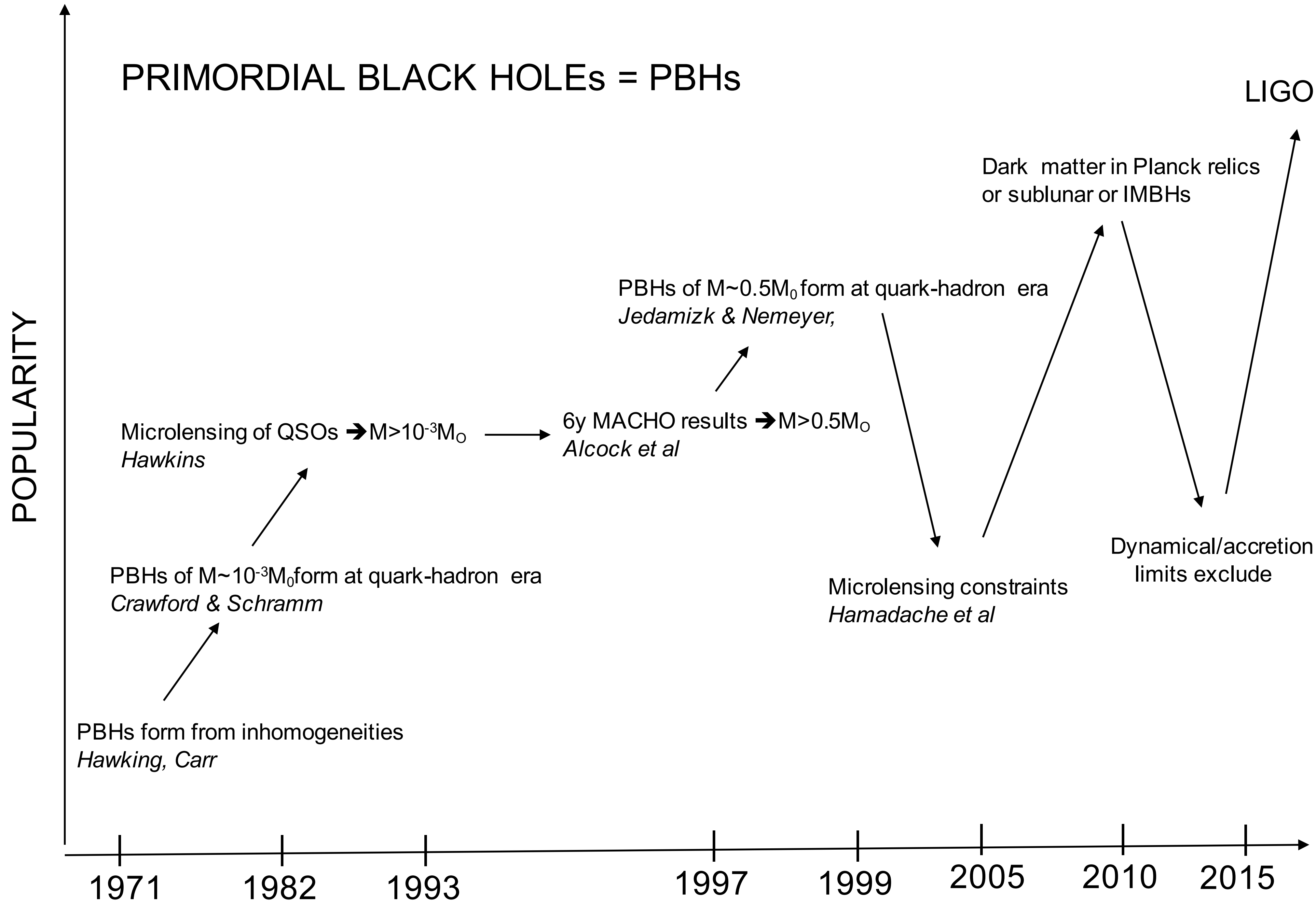
**Broad peak** in the power spectrum of density perturbations

**Local Universe:**
PBH are **regrouped in ultra-faint dwarf galaxies**. Their existence could solve the ***missing satellite*** and ***too-big-to-fail*** **problems.**
Some of them have been detected by the DES experiment.

**In the Milky-Way:**
The presence of PBH should induce **tiny variations in the position and velocity of stars** that are being monitored by **GAIA**.

**Formation of primordial black holes (PBH) :**
***less than one second after the end of inflation...***
Large inhomogeneities collapse gravitationally and **form massive primordial black holes,** which could be already **regrouped in dense halos.**

**The seeds of supermassive black holes :**
***during the first billion years...***
A **subdominant fraction** of very massive PBH could be the **seeds of SMBH**, then growing by successive merging and matter accretion.



PRIMORDIAL BLACK HOLEs = PBHs
POPULARITY
PBHs form from inhomogeneities
*Hawking, Carr*
PBHs of M~10$^{-3}$M$_0$form at quark-hadron era
*Crawford & Schramm*
Microlensing of QSOs ➔M>10$^{-3}$M$_O$
*Hawkins*
6y MACHO results ➔M>0.5M$_O$
*Alcock et al*
PBHs of M~0.5M$_0$ form at quark-hadron era
*Jedamizk & Nemeyer,*
Microlensing constraints
*Hamadache et al*
Dark matter in Planck relics
or sublunar or IMBHs
Dynamical/accretion
limits exclude
LIGO
1971
1982
1993
1997
1999
2005
2010
2015