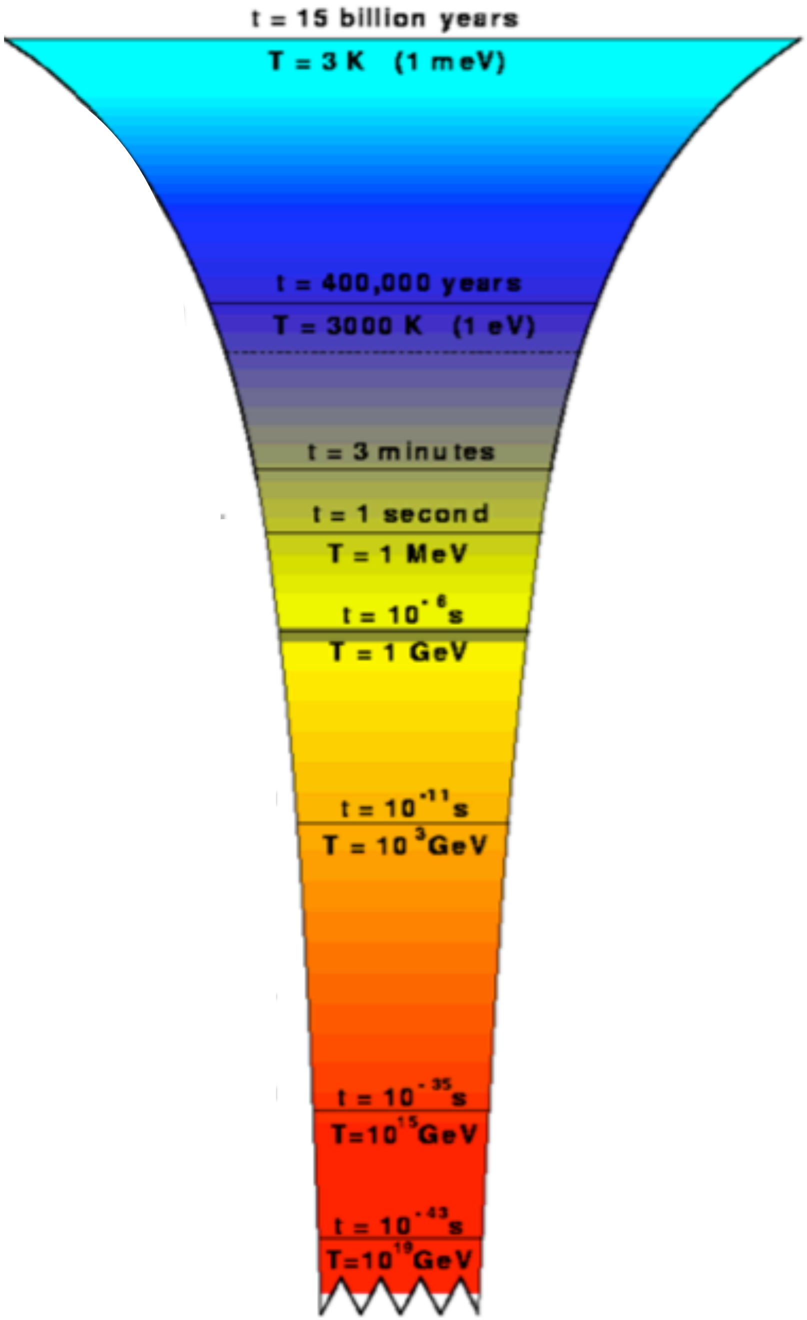


PRIMORDIAL BLACK HOLES AS A PROBE OF THE EARLY UNIVERSE

Bernard Carr
Queen Mary
University of London

APC 24/11/16

PLAN OF TALK

- Formation of primordial black holes
- Evaporation of primordial black holes
- Constraints on primordial black holes
- Primordial black holes as dark matter

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

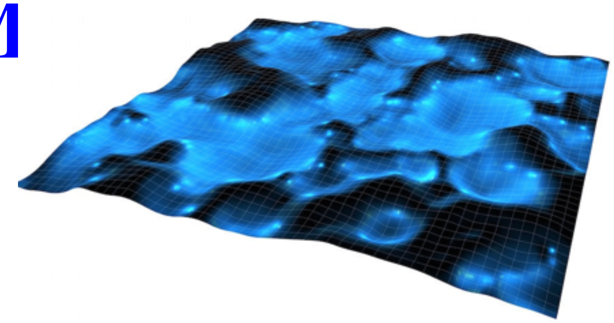
cf. cosmological density $\rho \sim 1/(Gt^2) \sim 10^6(t/s)^{-2}$g/cm^3

⇨ PBHs have horizon mass at formation

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

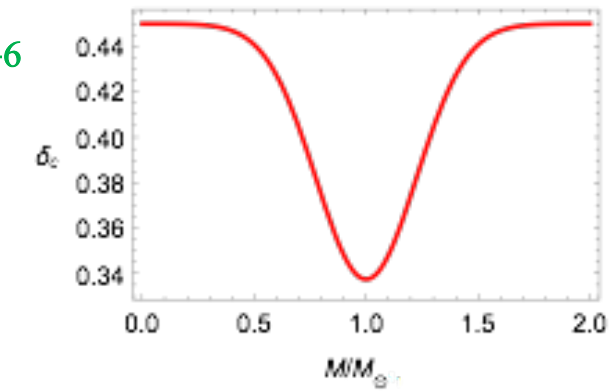
=> huge possible mass range

HOW PRIMORDIAL HOLES FORM

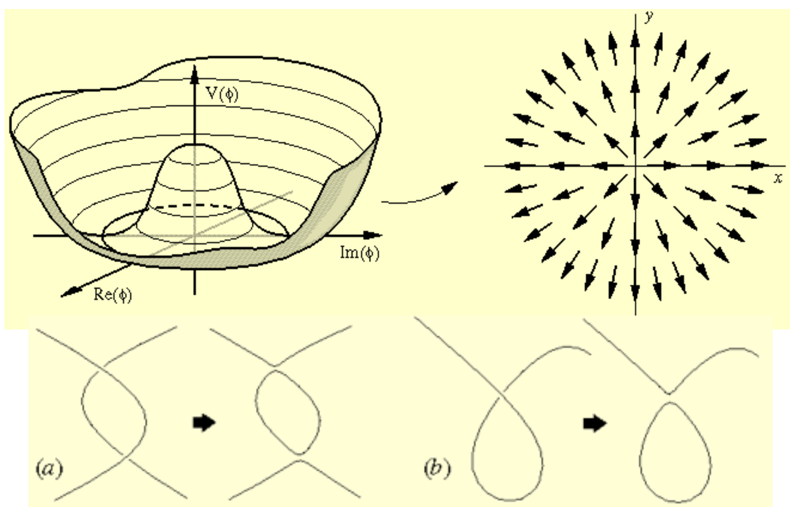


Primordial inhomogeneities Inflation

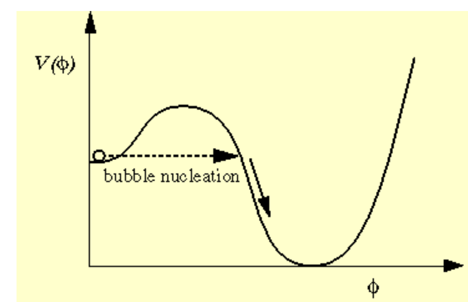
Pressure reduction Form more easily but need spherical symmetry



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



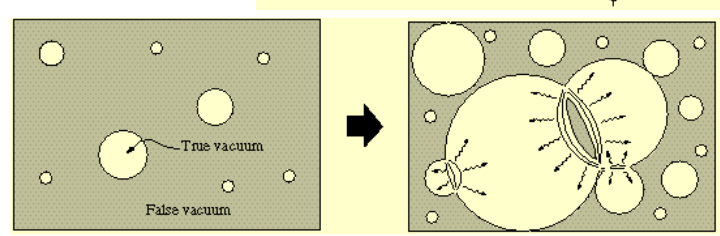
Oscillons?



Bubble collisions

Need fine-tuning of bubble formation rate

Khlopov



PBH EVAPORATION

Black holes radiate thermally with temperature

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

(Hawking 1974)

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

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

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

=> explosions undetectable in standard particle physics model

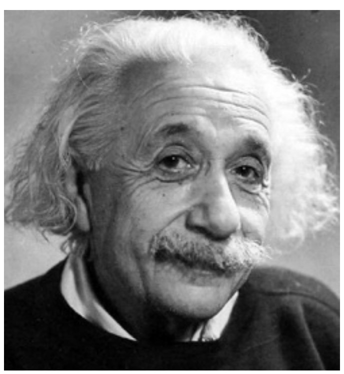
$T > T_{CMB}$=3K for M < 10^{26}g **=> "quantum" black holes**

PBHs are important even if they never formed!

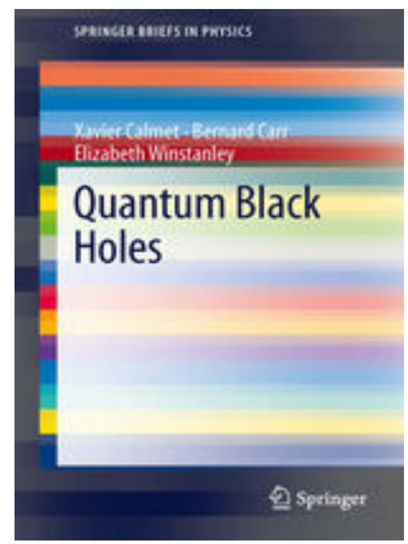
Quantum Mechanics

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

Thermodynamics



General Relativity



Calmet, BC, Winstanley

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

BLACK HOLES

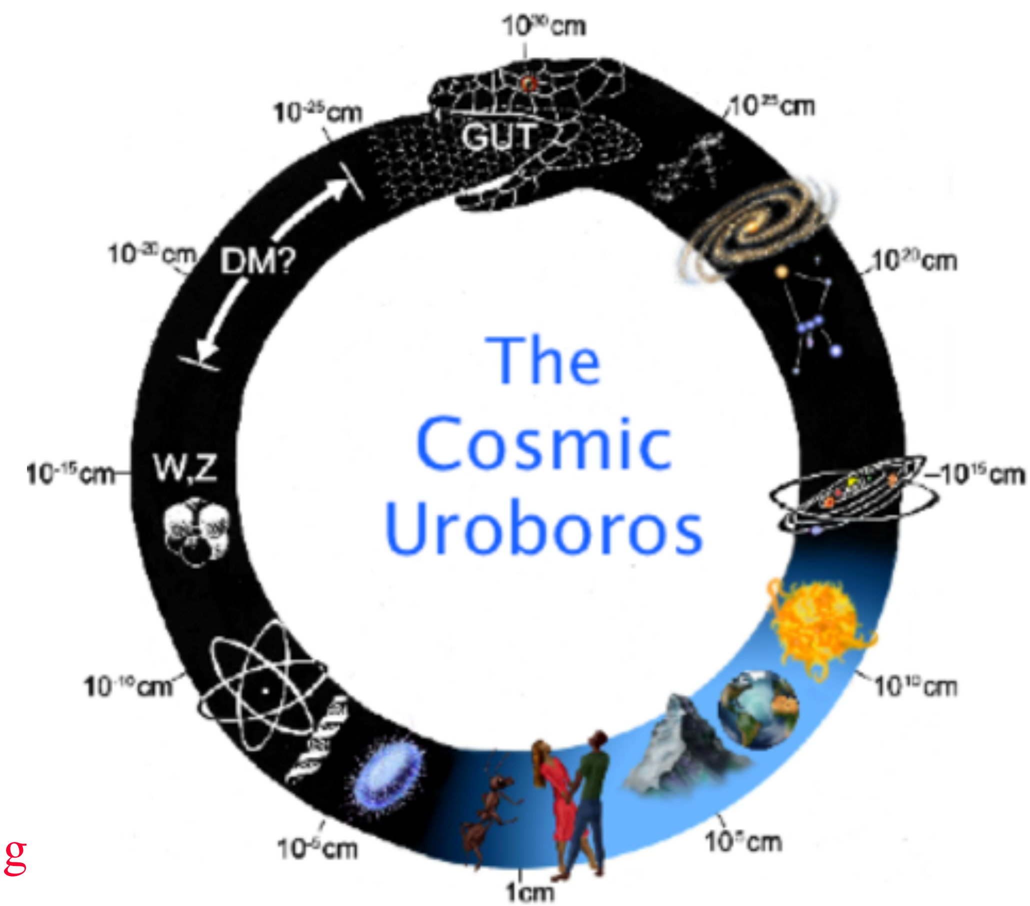
HIGHER DIMENSIONS

Planck 10^{-5}g | 10^{22} M_O Universal

10^{9} M_O QSO

exploding 10^{10}g

10^{6} M_O MW



evaporating 10^{15}g

10^{2} M_O IMBH

lunar 10^{21}g

1 M_O Stellar

terrestrial 10^{25}g

QUANTUM/CLASSICAL

Limit on fraction of Universe collapsing

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

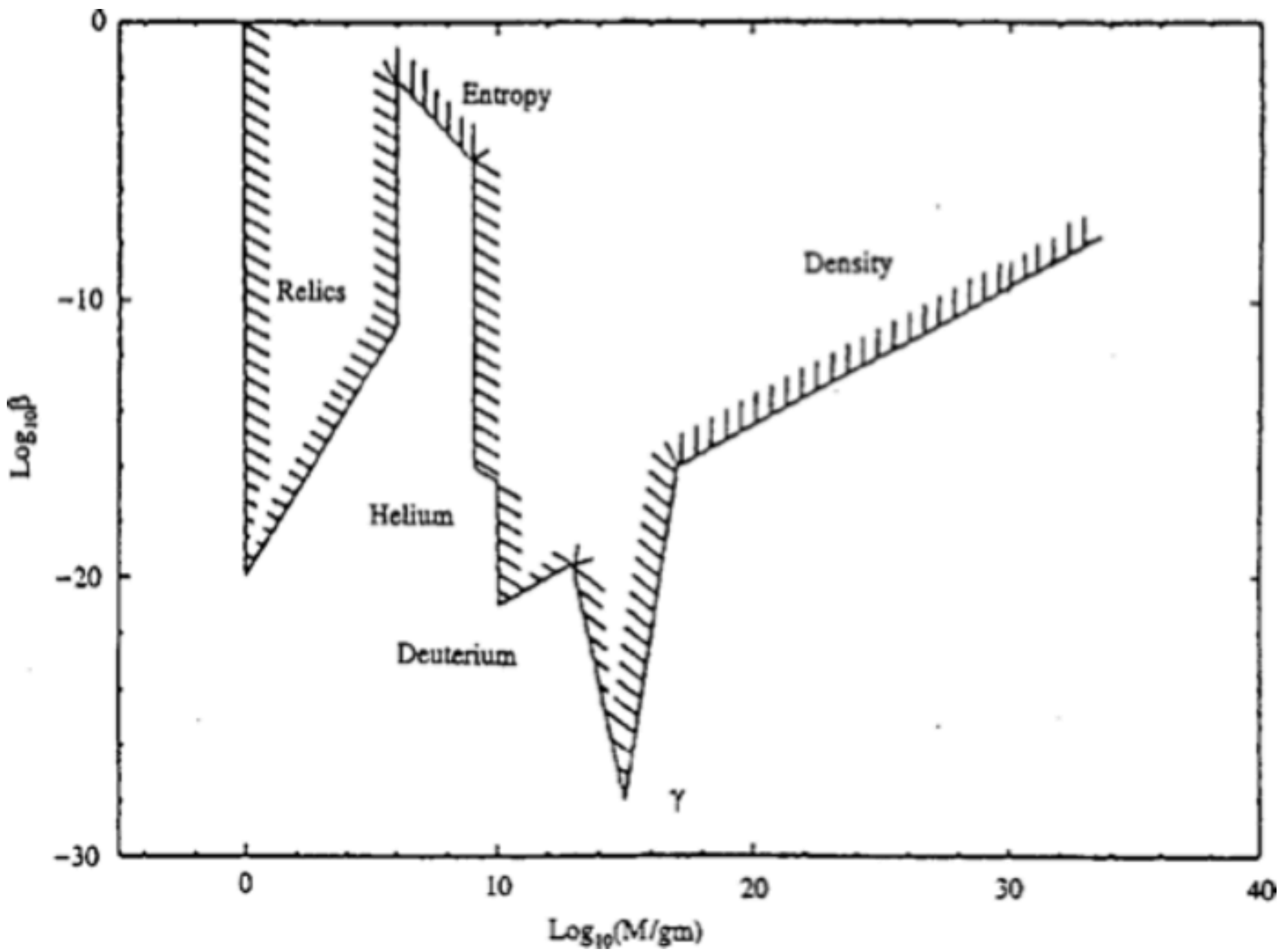
General limit

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

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

=> constraints from entropy, γ-background, BBNS

CONSTRAINTS ON FRACTION OF UNIVERSE IN PBHS



Carr, Gilbert & Lidsey (1994)

UPDATED CONSTRAINTS FOR EVAPORATING PBHS

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

Big bang nucleosynthesis

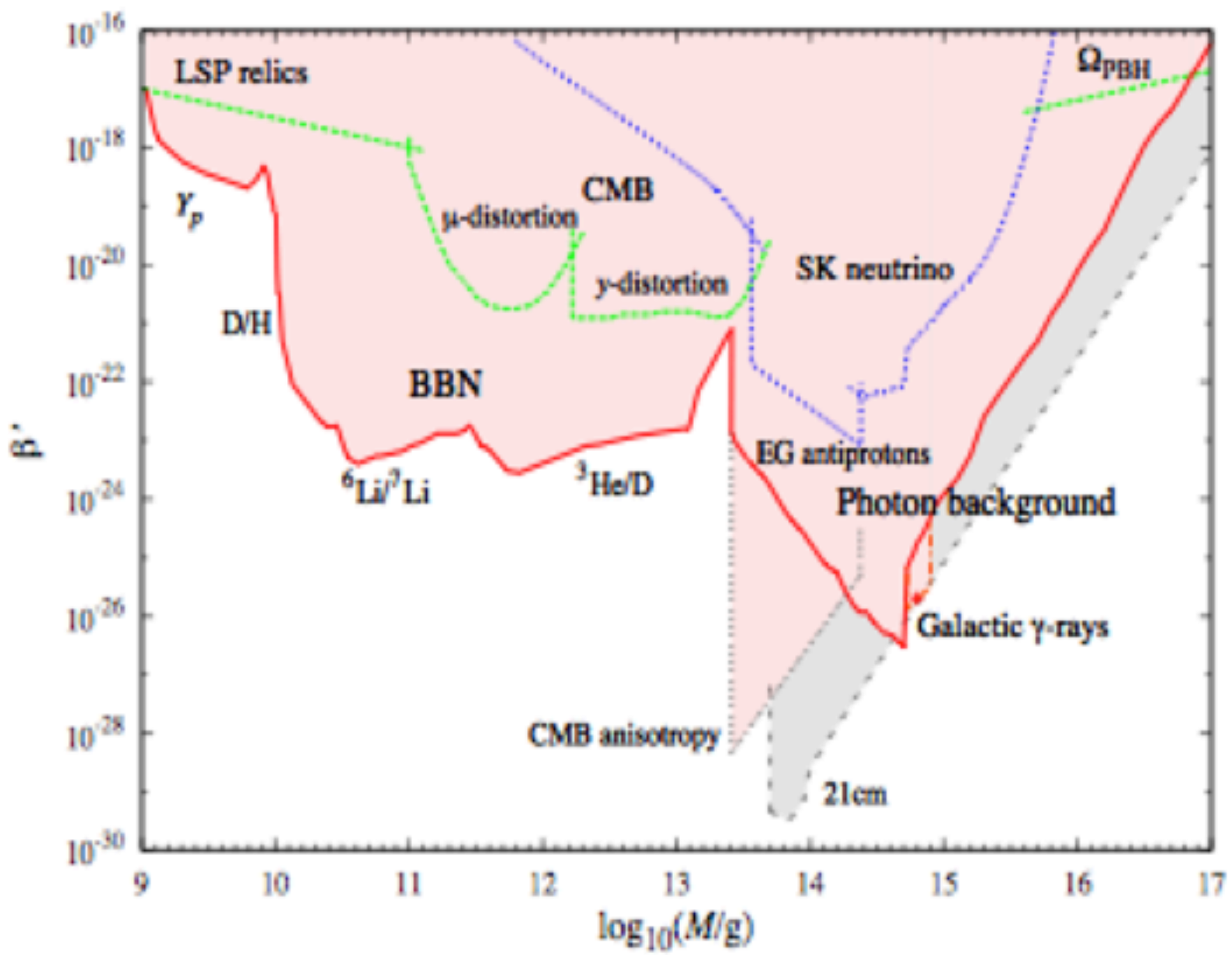
Gamma-ray background

Extragalactic cosmic rays

Neutrino relics

LSP relics

CMB distortions



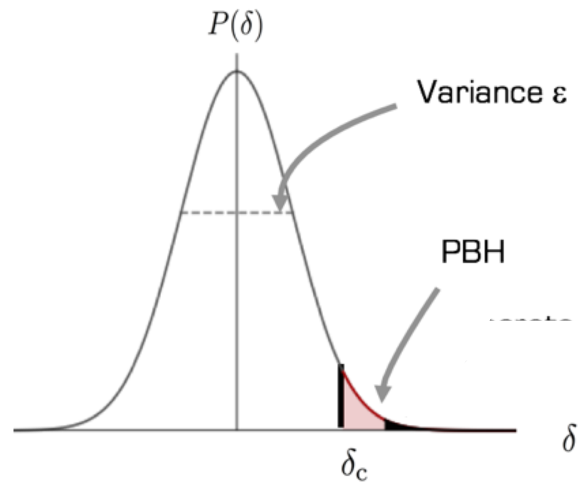
This assumes monochromatic mass function

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



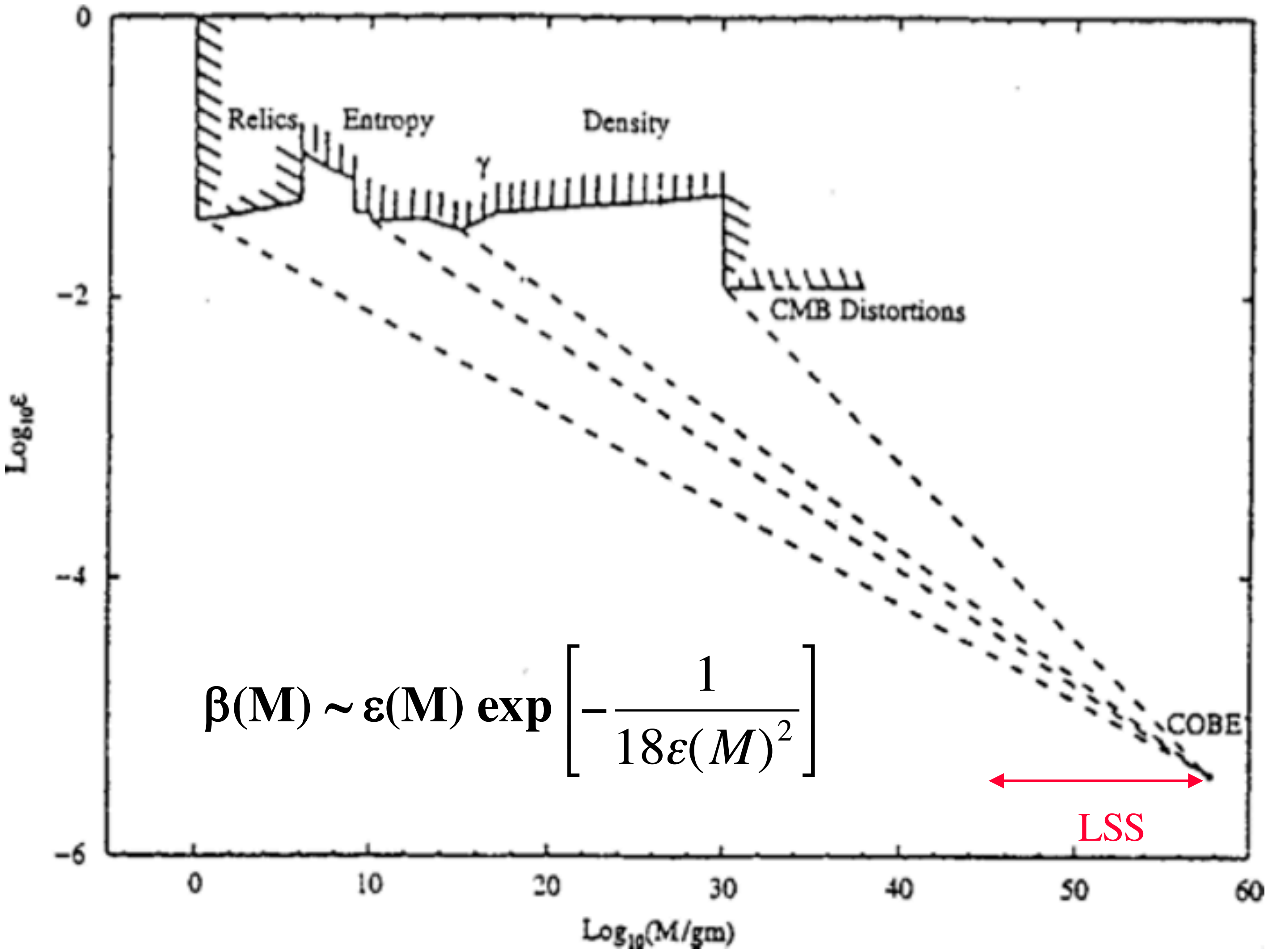
$\Rightarrow$ fraction of PBHs

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

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

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.

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)

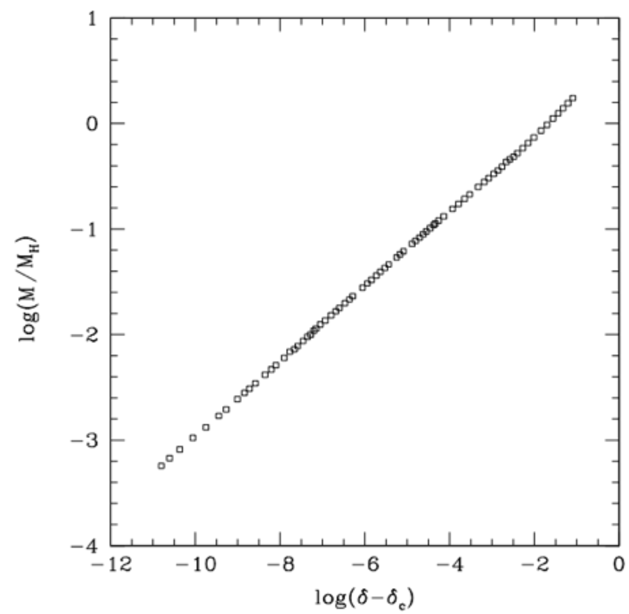
$\Rightarrow$ spectrum peaks at horizon mass with extended low mass tail

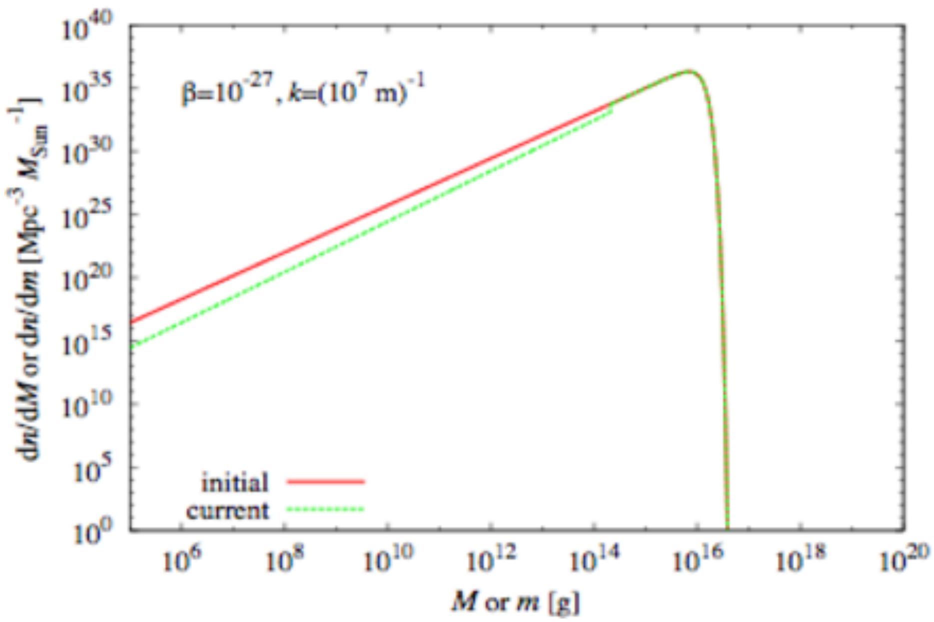
(Yokoyama 1998, Kribs 1999, Green 2000)

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

(Musco et al 2005, Green et al 2004)

PBHs from near-critical collapse





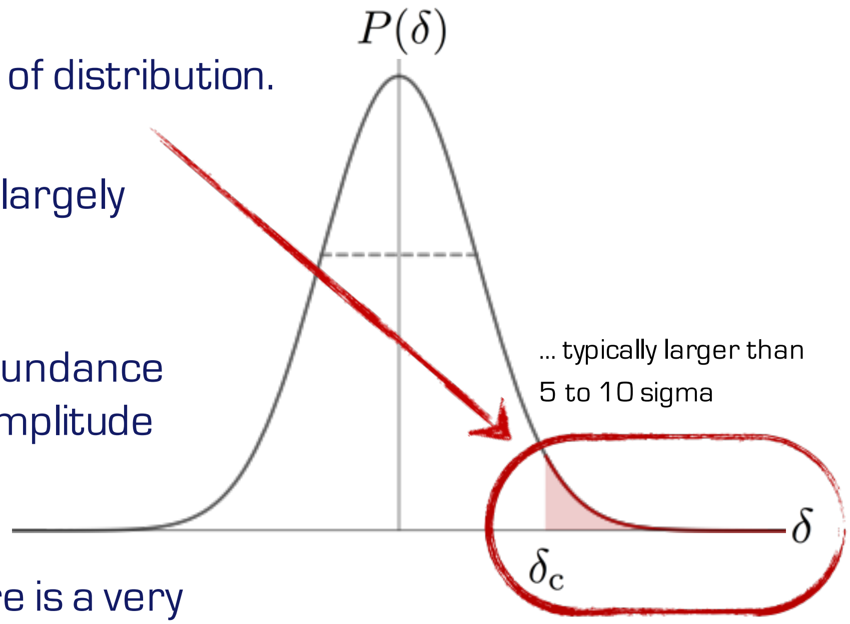
=> broad mass spectrum => strong constraints above 10^{14}g

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

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

NON-GAUSSIAN EFFECTS

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.

[Byrnes et al. 2014]

→ This generates isocurvature perturbations, and basically rules out all multi-field models with significant non-Gaussianity.

NON-SPHERICITY EFFECTS

On Ellipsoidal Collapse and Primordial Black-Hole Formation

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

arXiv:1602:04815

★ Non-Sphericity

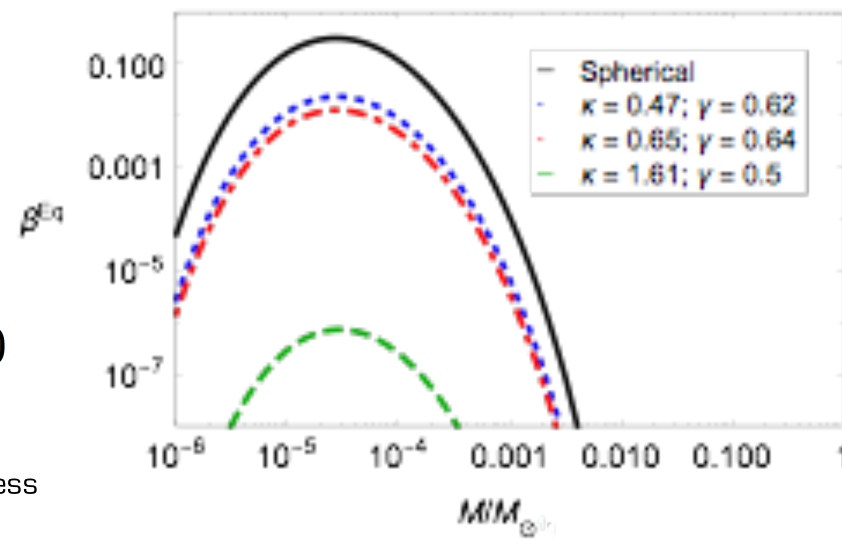
ellipsoidal threshold

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

spherical threshold

$$\langle e \rangle = \frac{3\,\sigma}{\sqrt{10\pi}\;\delta}\,, \qquad \langle p \rangle = 0$$

ellipticity   prolateness



★ Simple estimate: As the collapse starts along shortest axis first,

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

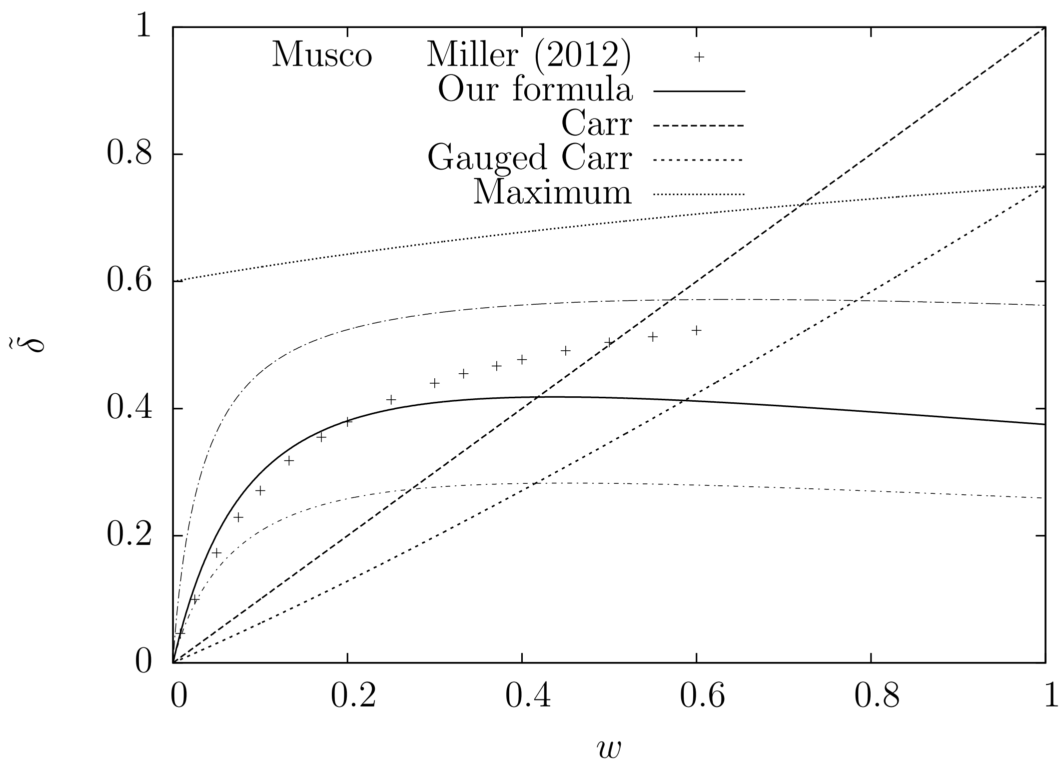
$$\frac{\delta_{\rm ec}}{\delta_{\rm c}} \simeq (1 + 3\,e) = 1 + \frac{9}{\sqrt{10\,\pi}} \left(\frac{\sigma^2}{\delta_{\rm c}^2} \right)^{1/2}$$

MORE PRECISE ESTIMATE OF δ_C

Threshold of primordial black hole formation

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

PRD 88 084051 (2013)



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

0.62 for radiation

PBHS AND INFLATION

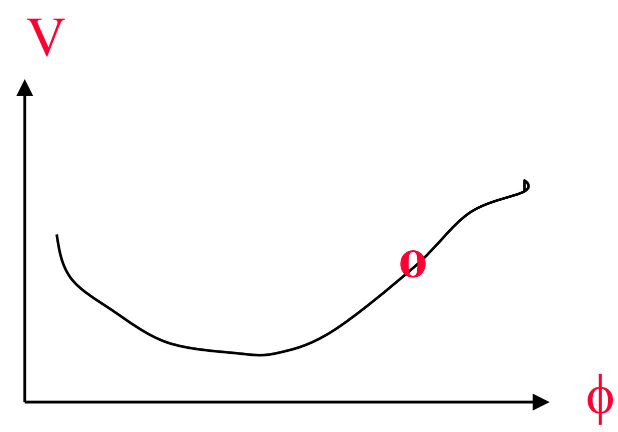
PBHs formed before reheat inflated away =>

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

CMB quadrupole => $T_{reheat} < 10^{16}$GeV

But inflation generates fluctuations

$$\frac{\delta\rho}{\rho} \sim \left[\frac{V^{3/2}}{M_{Pl}{}^{3}V'}\right]_H$$



Can these generate PBHs?

Slow roll plus friction-domination

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

=> 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.

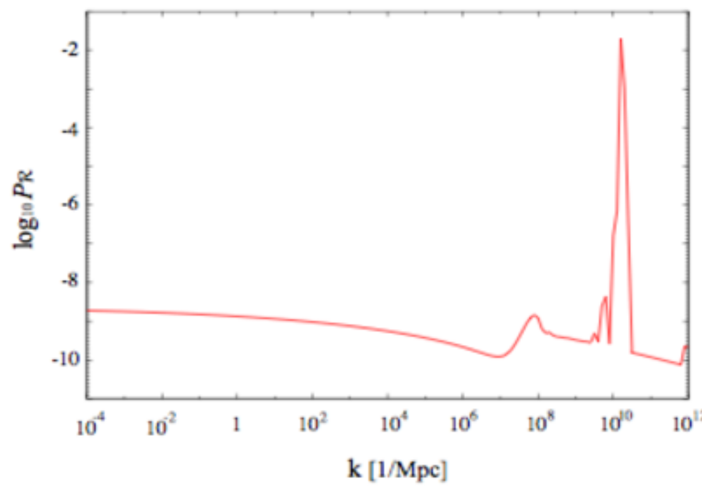
Planck gives $\dfrac{d\ln n}{dk} \approx -0.02 \pm 0.01$ **(wrong sign!)**

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

Feature in V(φ) => discrete PBH mass spectrum on any scale

INTERMEDIATE MASS PBHS?

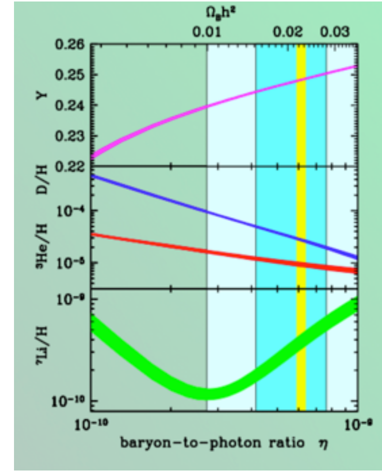
Second inflationary phase
=> PBHs in any mass range
P Frampton et al. JCAP 04 (2010) 023



Curvature perturbation spectra from waterfall transition, black hole constraints and non-Gaussianity
E Bugaev and P Klimai JCAP 11 (2011) 028

Can massive primordial black holes be produced in mild waterfall hybrid inflation?
M Kawasaki and Y Tada arXiv:1512.03515

Massive black holes from hybrid inflation as dark matter and seeds of galaxies
S Cleese and J Garcia-Bellido arXiv:1501.07565



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

MACHOs WIMPs

$\Omega_{vis} = 0.01$, $\Omega_{dm} = 0.3$ $\Rightarrow$ need baryonic and non-baryonic DM

PBHs 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

Above $10^{3} M_0$ excluded by dynamical effects

But windows at 10^{16}-10^{17}g or 10^{20}-10^{24}g or 10^{33}-10^{36}g

Atomic Sublunar IMBHs

CAN PLANCK MASS RELICS PROVIDE DARK MATTER?

reheat

Natural outcome of inflation if fine-tune T_R

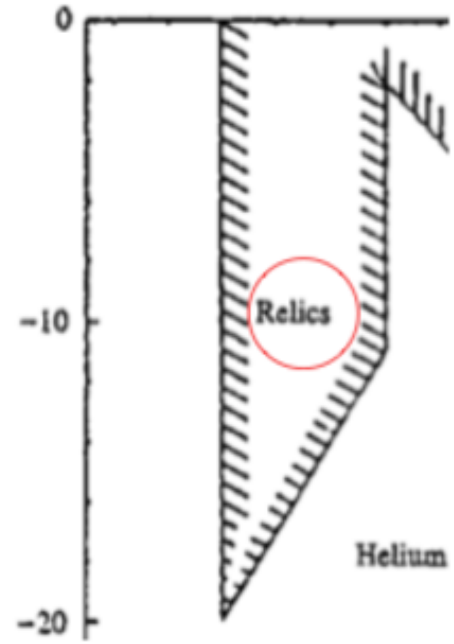
$\Omega_{relic} < 0.25 \Rightarrow \beta(M) < 8\times10^{-28}\kappa^{-1}(M/M_P)^{3/2}$

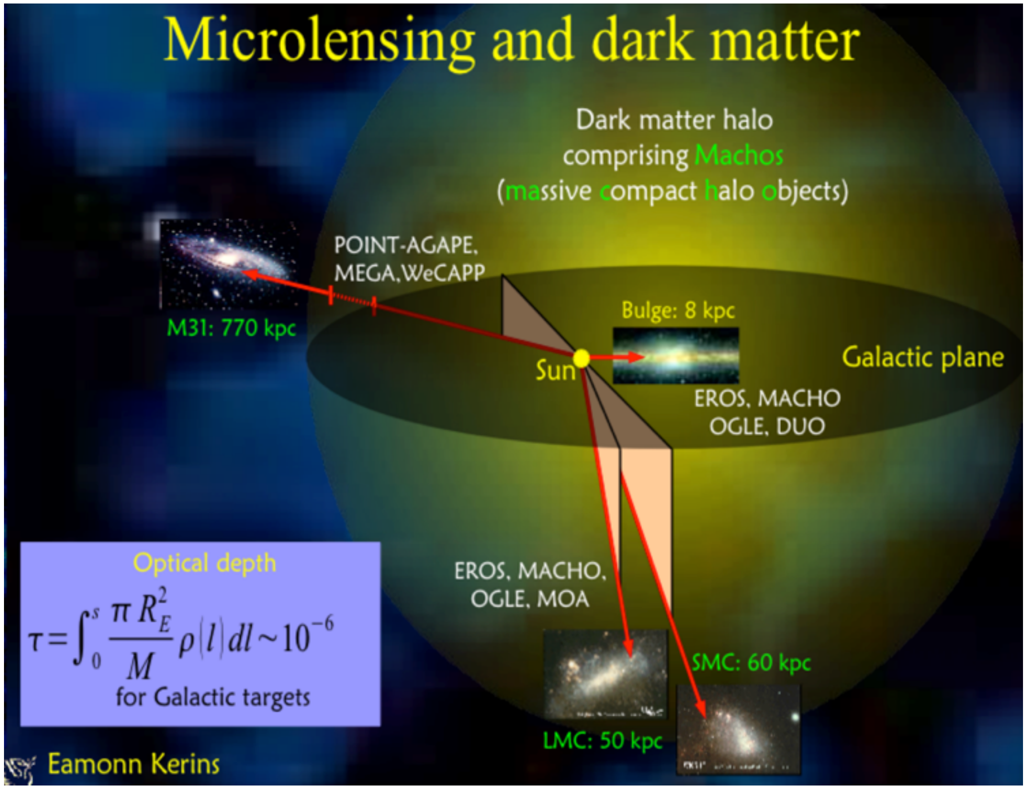
$M_{relic}\ /M_P$

but only applies over limited mass range

$(T_R/T_P)^{-2} < M/M_P < 10^{11}\kappa^{2/5}$

diluted by inflation   PBHs dominate before evap'





Early microlensing searches suggested MACHOs with 0.5 M_O

=> PBH formation at QCD transition?

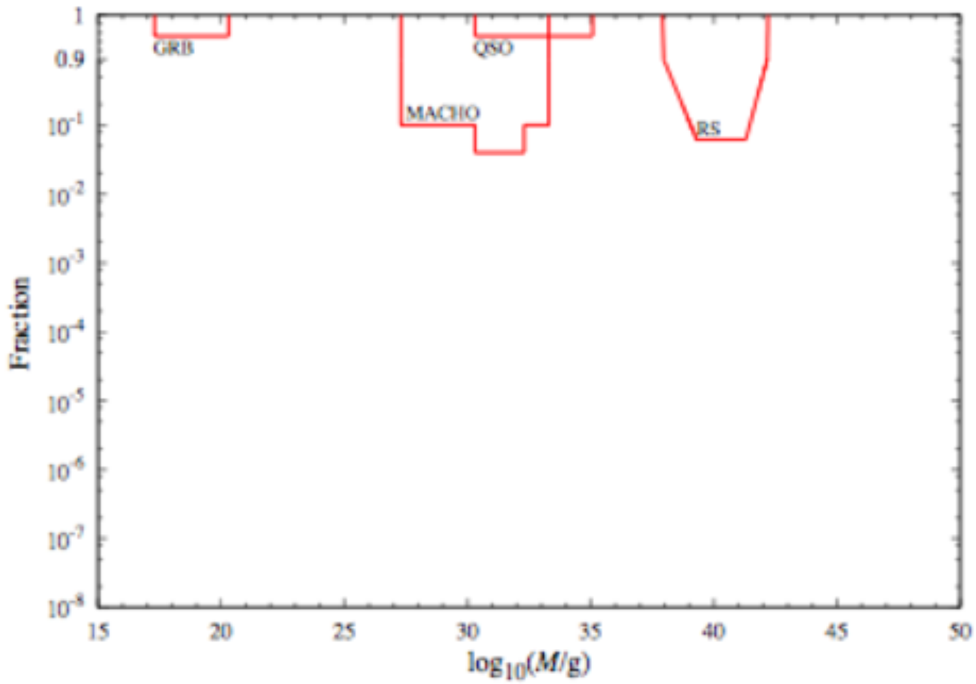
Pressure reduction => PBH mass function peak at 0.5 M_O

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

LENSING LIMITS

MACHO microlensing

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



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

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

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

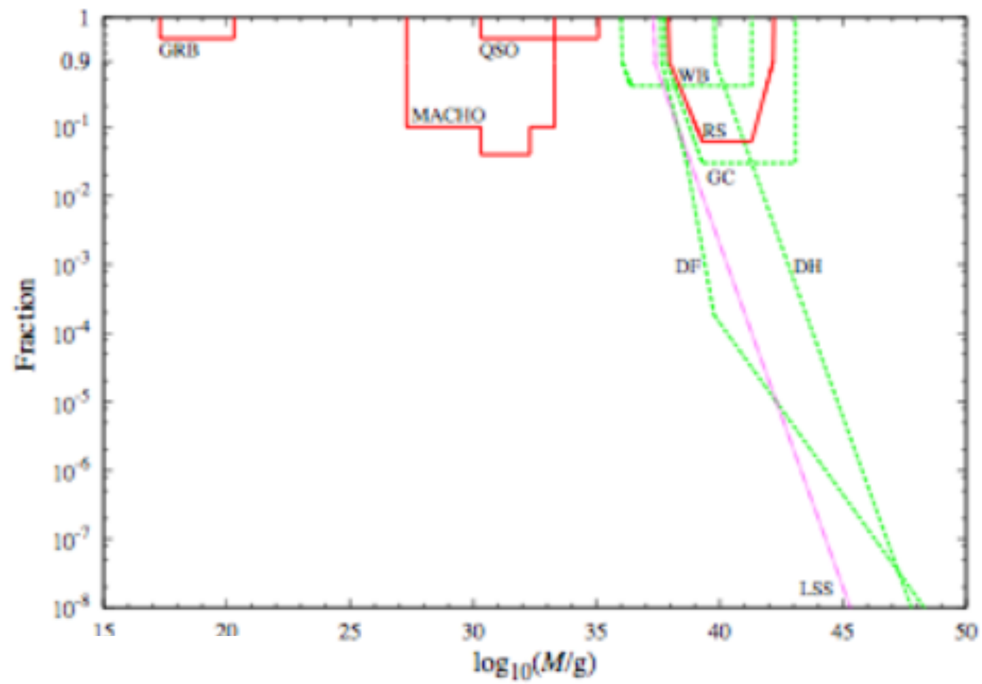
Binary disruption

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

DYNAMICAL LIMITS

Globular cluster disruption

$$f(M) < \begin{cases} (M/3\times10^4M_\odot)^{-1} & (3\times10^4M_\odot < M < 10^6M_\odot) \\ 0.03 & (10^6M_\odot < M < 6\times10^9M_\odot) \end{cases}$$



Disk heating

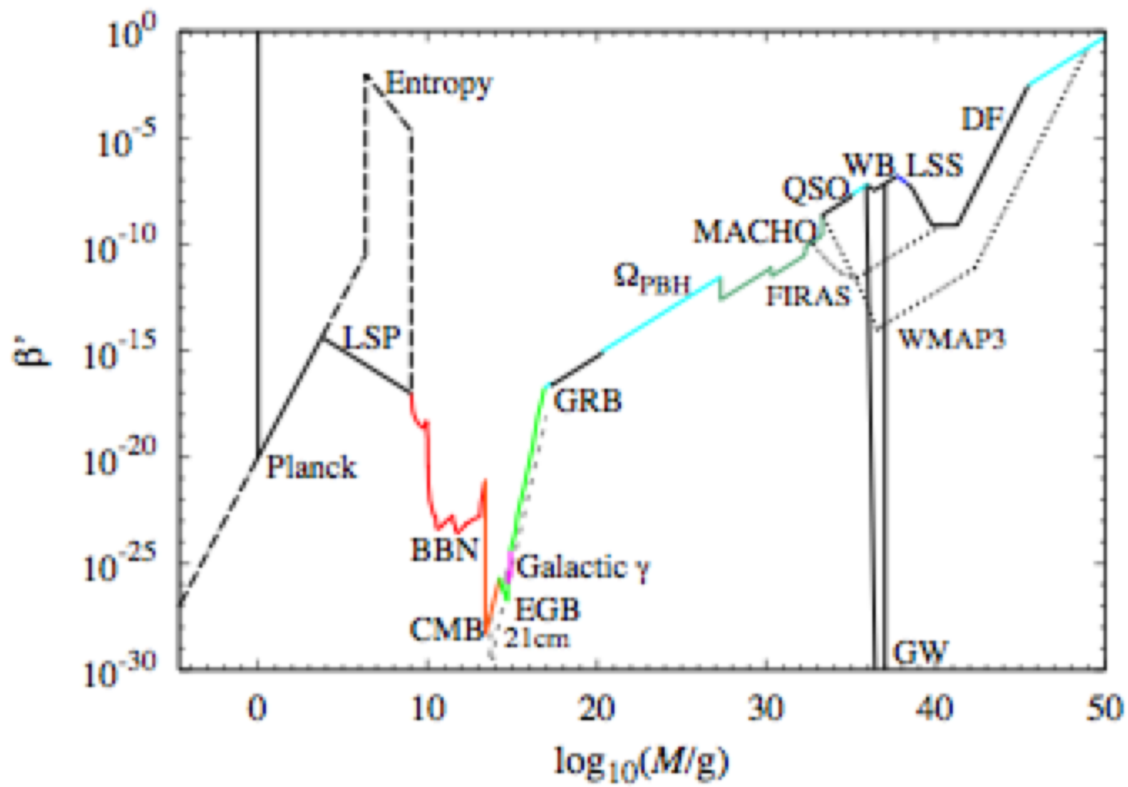
$$f(M) < (M/3\times10^6M_\odot)^{-1}$$

Dynamical friction

$$f(M) < \begin{cases} (M/2\times10^4M_\odot)^{-10/7}(r_c/2\text{kpc})^2 & (M < 6\times10^5M_\odot) \\ (M/4\times10^4M_\odot)^{-2}(r_c/2\text{kpc})^2 & (6\times10^5M_\odot < M < 3\times10^6[r_c/2\text{kpc}]^2M_\odot) \\ (M/0.1M_\odot)^{-1/2} & (M > 3\times10^6[r_c/2\text{kpc}]^2M_\odot). \end{cases}$$

Some of these effects have been claimed as evidence for PBHs

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



DETECTION OF 10^{17}G PBHS BY FEMTOLENSING?

Will measurements of gamma-ray bursts, like the one shown sterilizing a planet in this artist's rendering, reveal the existence of tiny black holes? We may know soon.

Barnacka et al. (2012) => $f_{DM}<1$ for 10^{17}g < M < 10^{20}g

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

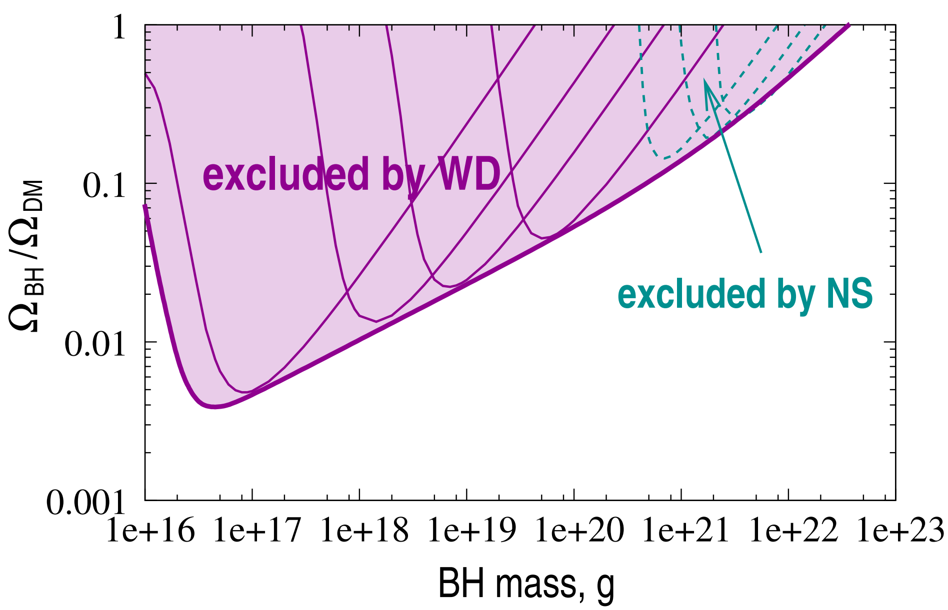
Fabio Capela,[1,*] Maxim Pshirkov,[2,3,4,†] and Peter Tinyakov[1,‡]

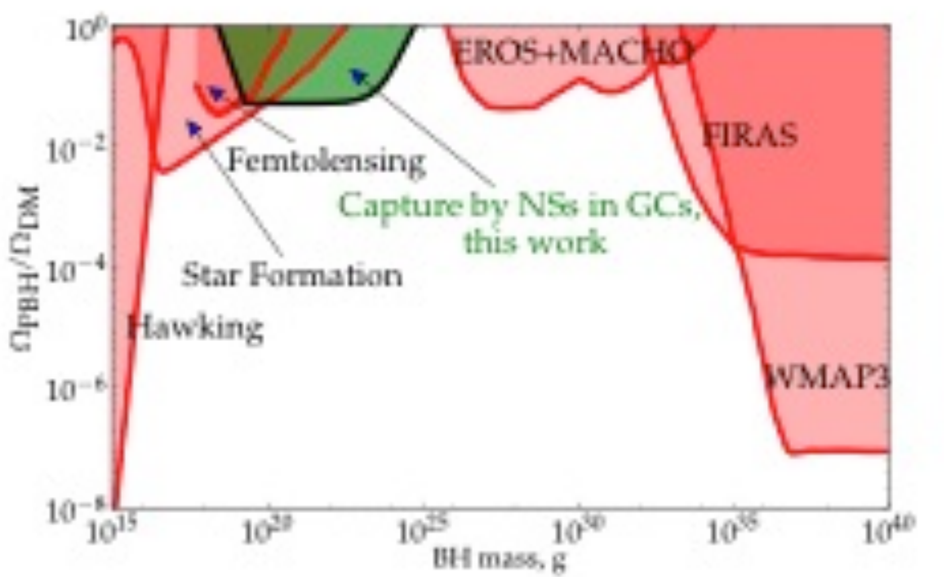
arXiv:1209.6021 PRD 87 023507 (2013)

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



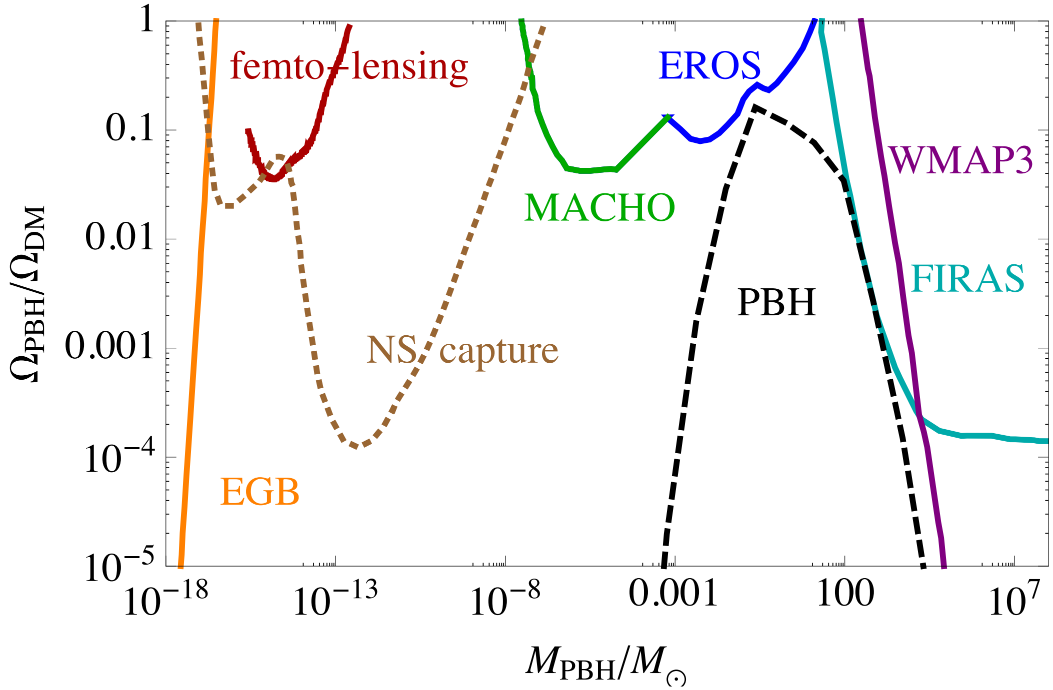


< 5% of DM in range 3 x 10^{18} g – 10^{24} g

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

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

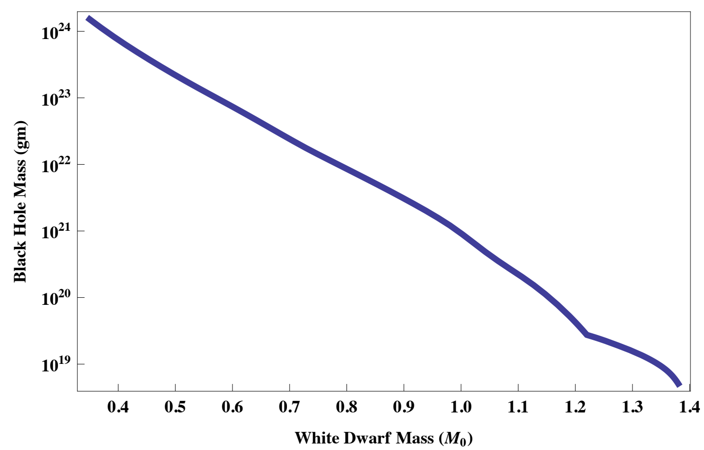
arXiv:1501.07565



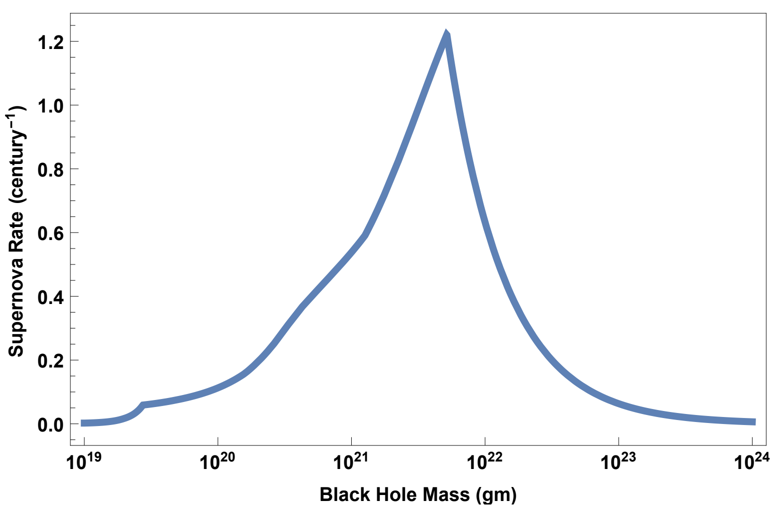
arXiv:1505.044444

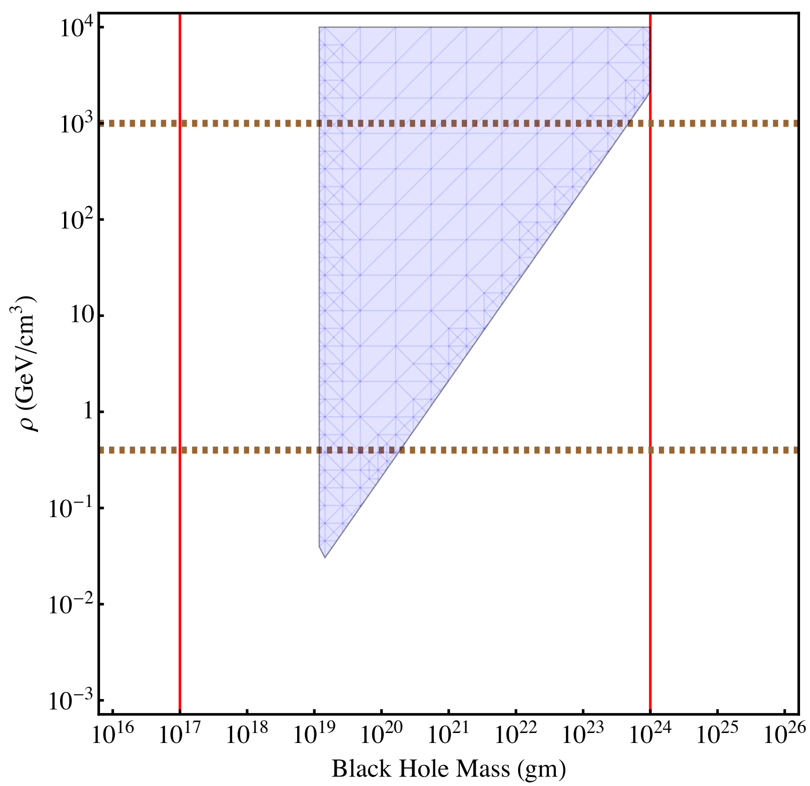
Dark Matter Triggers of Supernovae

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



The minimum mass of a black hole whose transit can destroy a carbon white dwarf

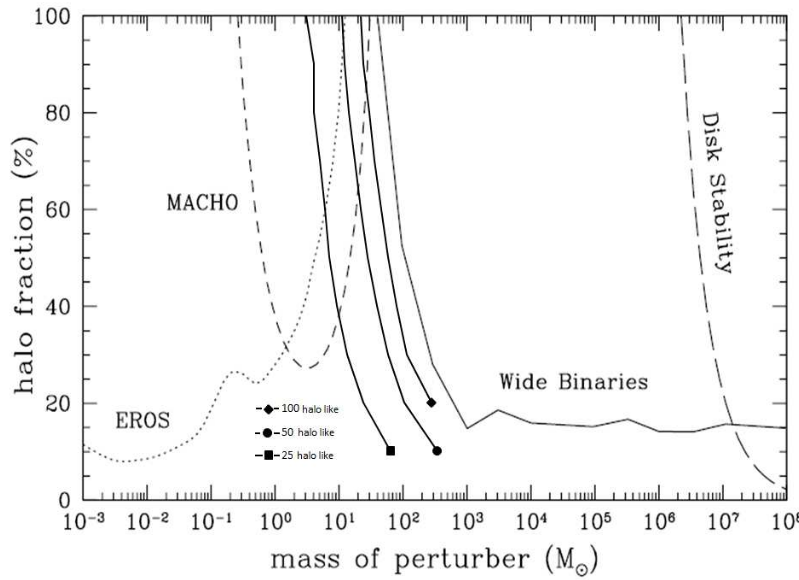




arXiv:1406.5169

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

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



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 $M_\odot$.

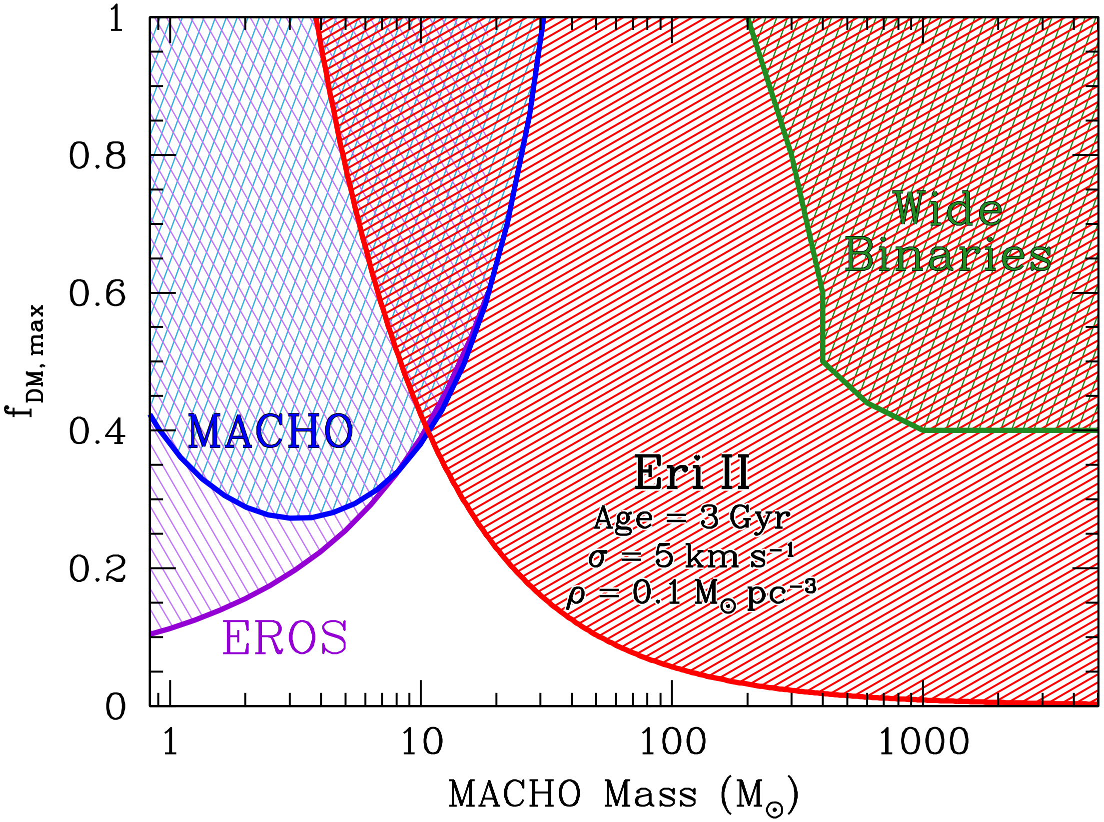
From the same 100 binaries, but taking into account the non-uniform halo density: 28–78 $M_\odot$.

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]

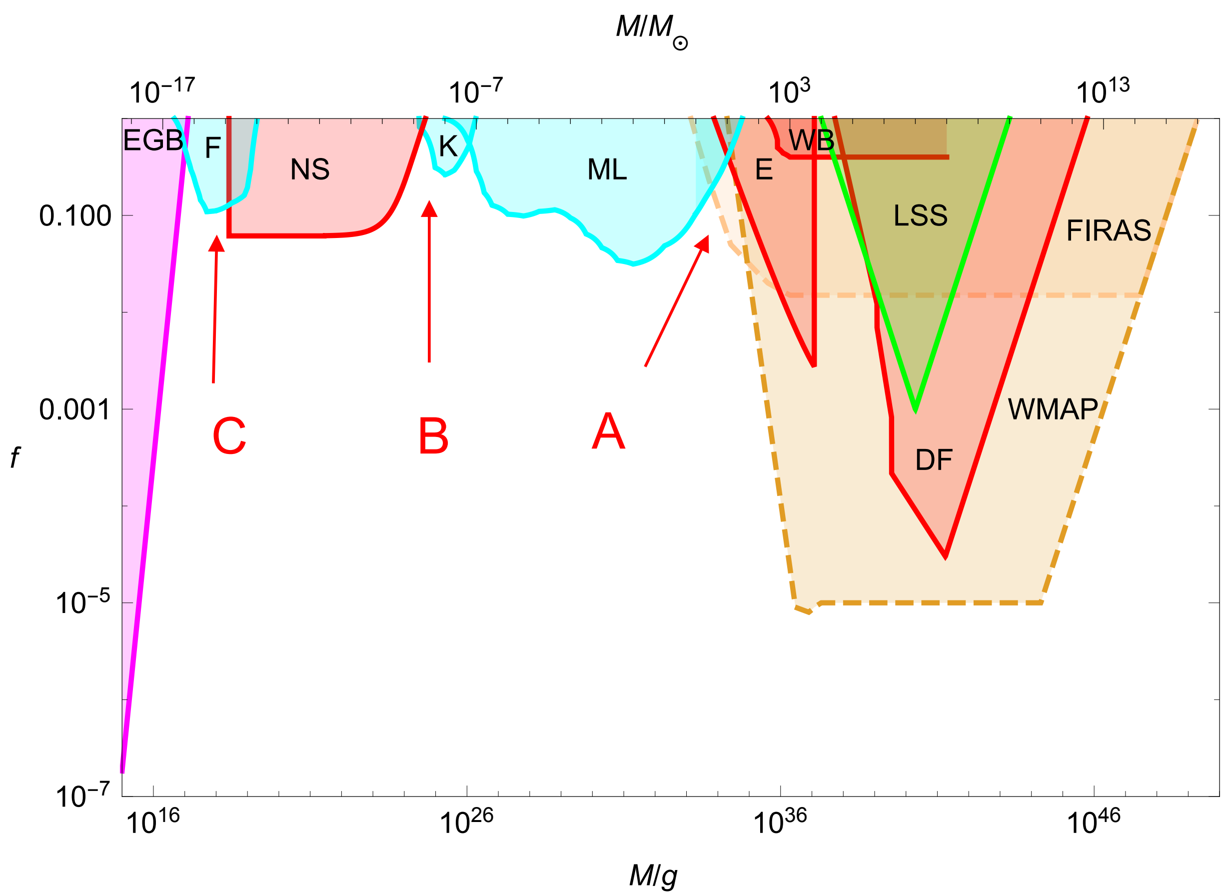
arXiv: 1605.03665



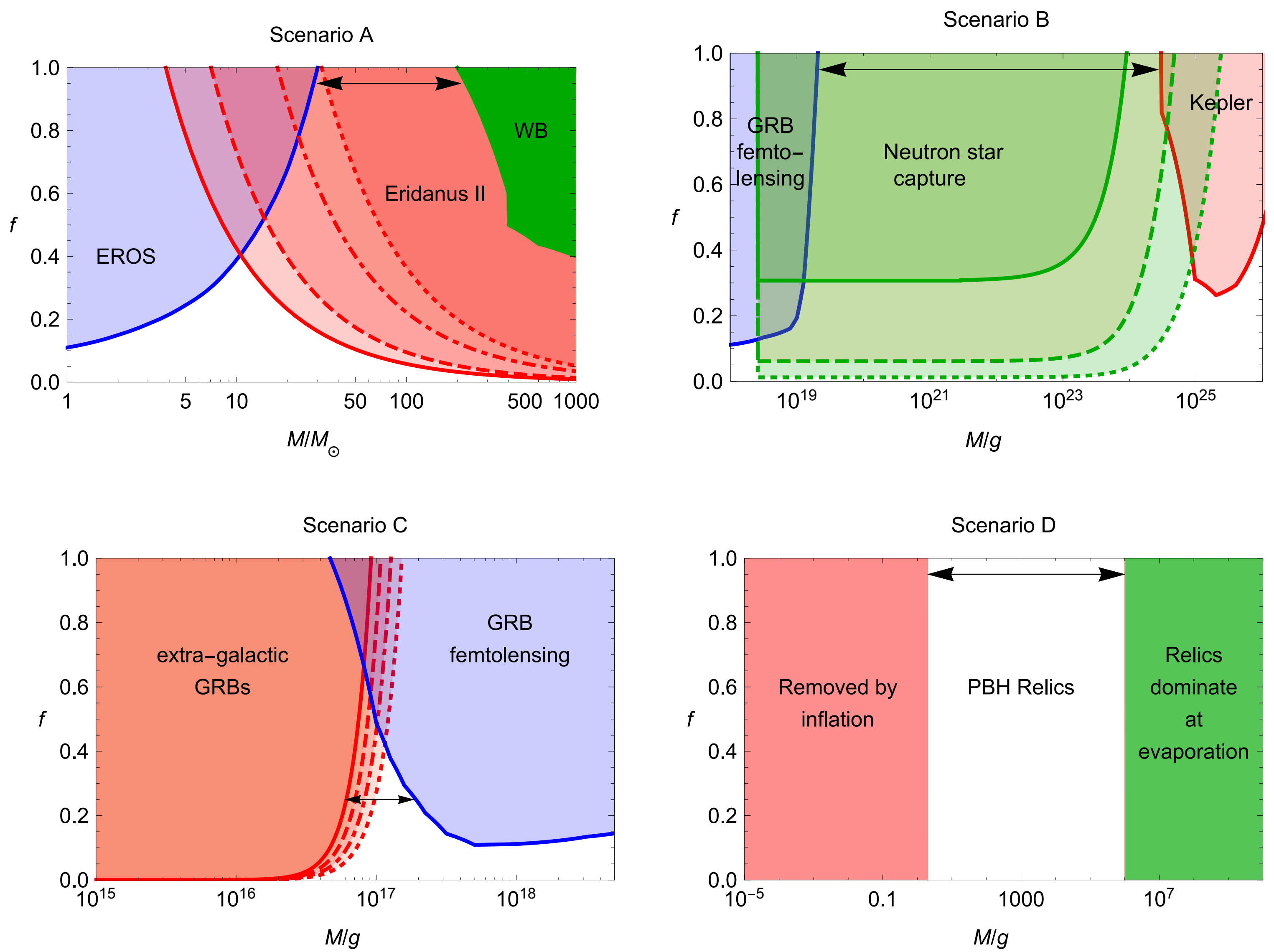
PRIMORDIAL BLACK HOLES AS DARK MATTER

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.



Scenario A
EROS
Eridanus II
WB
f
M/M☉
Scenario B
GRB femto-lensing
Neutron star capture
Kepler
f
M/g
Scenario C
extra-galactic GRBs
GRB femtolensing
f
M/g
Scenario D
Removed by inflation
PBH Relics
Relics dominate at evaporation
f
M/g

EXTENDED MASS FUNCTION

Most constraints assume monochromatic PBH mass function

Can we evade standard limits with extended mass spectrum?

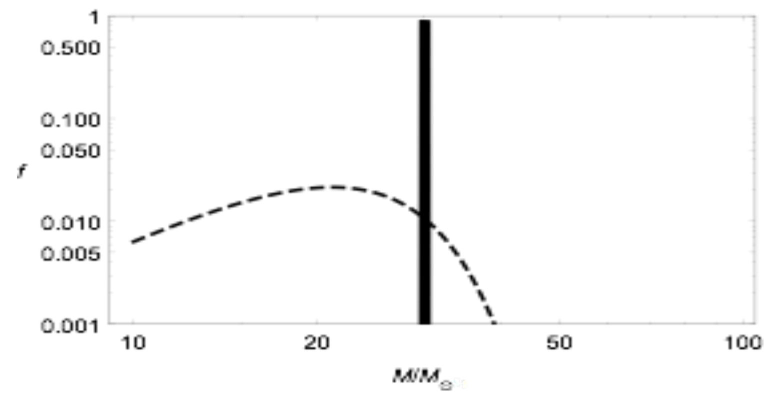
But this is two-edged sword!

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

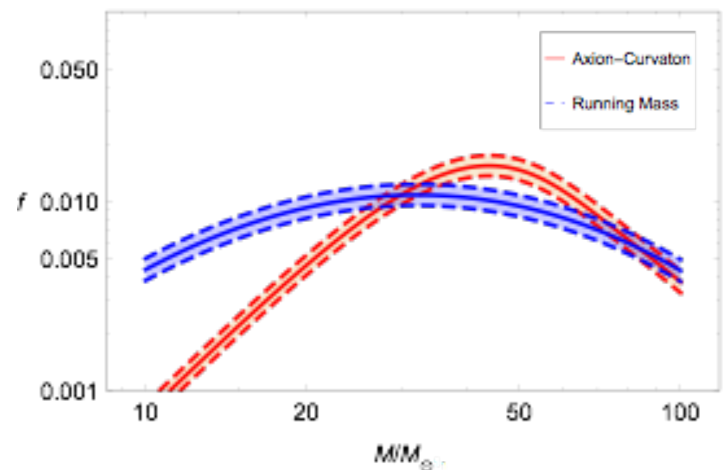
★ Critical collapse

Monochromatic mass extends to very low masses



★ Non-Gaussianity

PBH production is largely sensitive to non-Gaussianity.



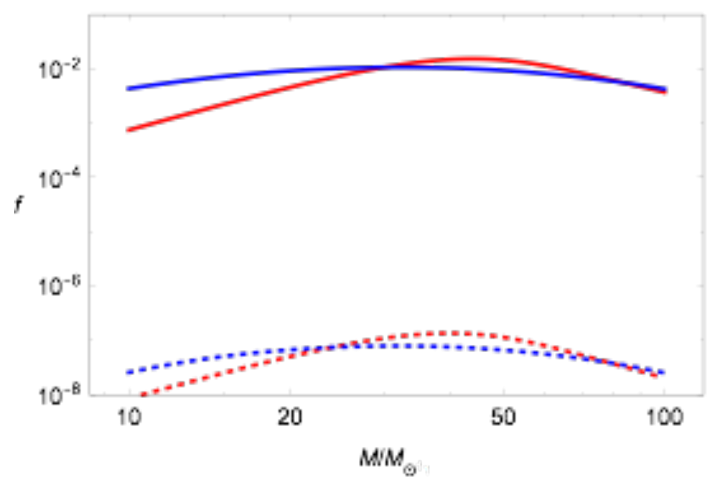
★ Non-Sphericity

Increases the threshold:

ellipsoidal threshold

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

spherical threshold



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 $Gpc^{-1}yr^{-1}$

The clustering of massive Primordial Black Holes as Dark Matter: measuring their mass distribution with Advanced LIGO

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

arXiv:1603.05234

Dark matter in 5-200 $M_{\odot}$ binaries may provide observed rate up to 2-200 $Gpc^{-1}yr^{-1}$

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

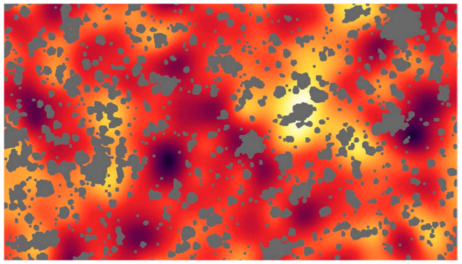
Similar f constraint and comparable to limits from CMB distortion

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 => infrared background

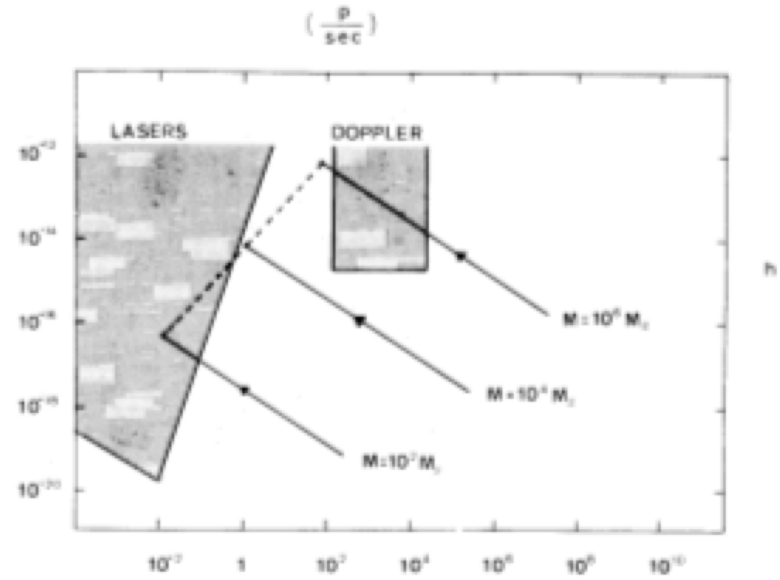


Gravitational waves from a population of binary black holes

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, Japan*

GWs generated by VMO coalescences

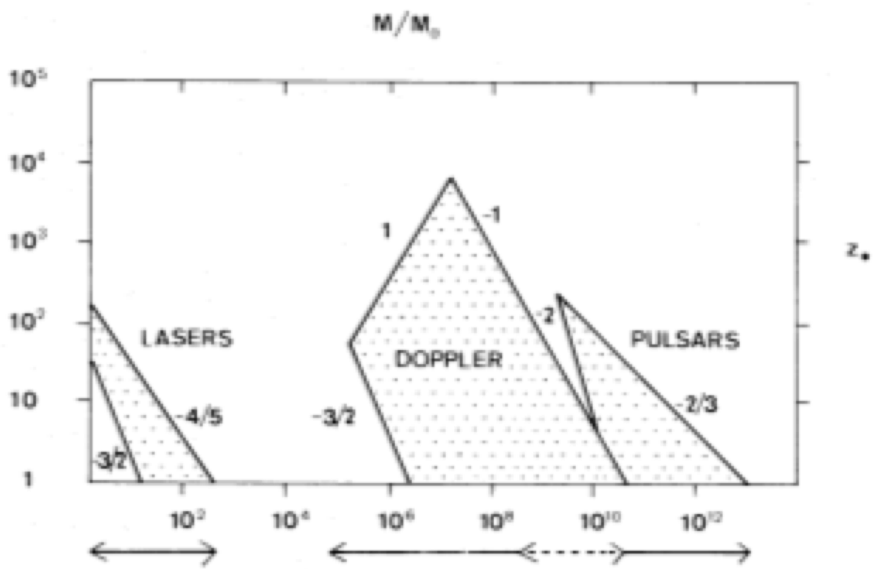


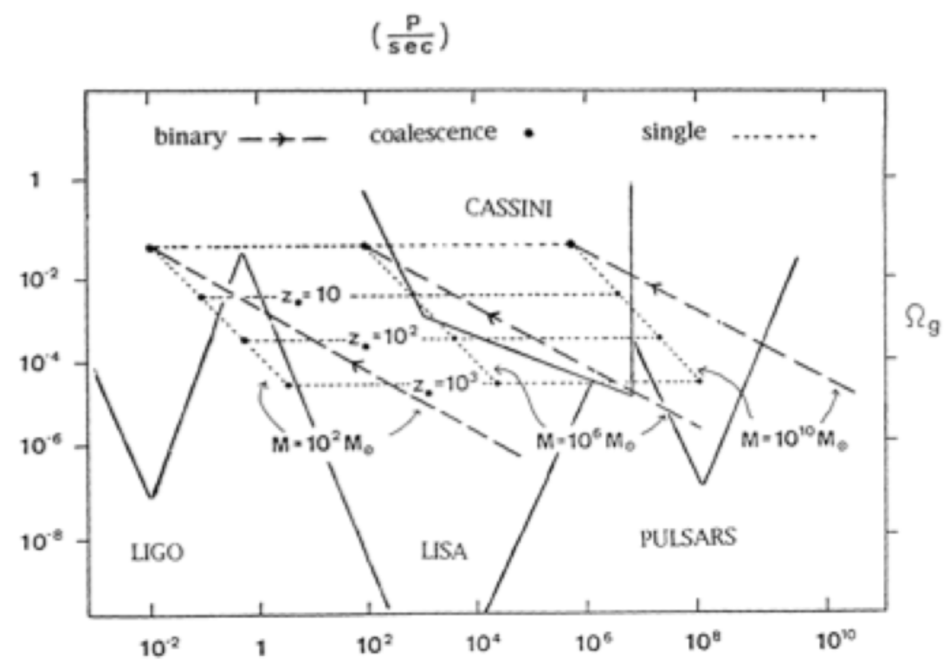
GW background generated by VMO BHs

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

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

Detectability by various methods





CONCLUSIONS

- PBHs are unique probes of early universe and various cosmological parameters associated with their formation mechanism.

- There are four mass windows where PBHs could comprise a significant fraction of dark matter. The intermediate-mass one is most topical because of LIGO but Planck-mass relics are also intriguing.

- Extended mass spectra are expected and special care is required when comparing to constraints. A detailed understanding of PBH formation is crucial.