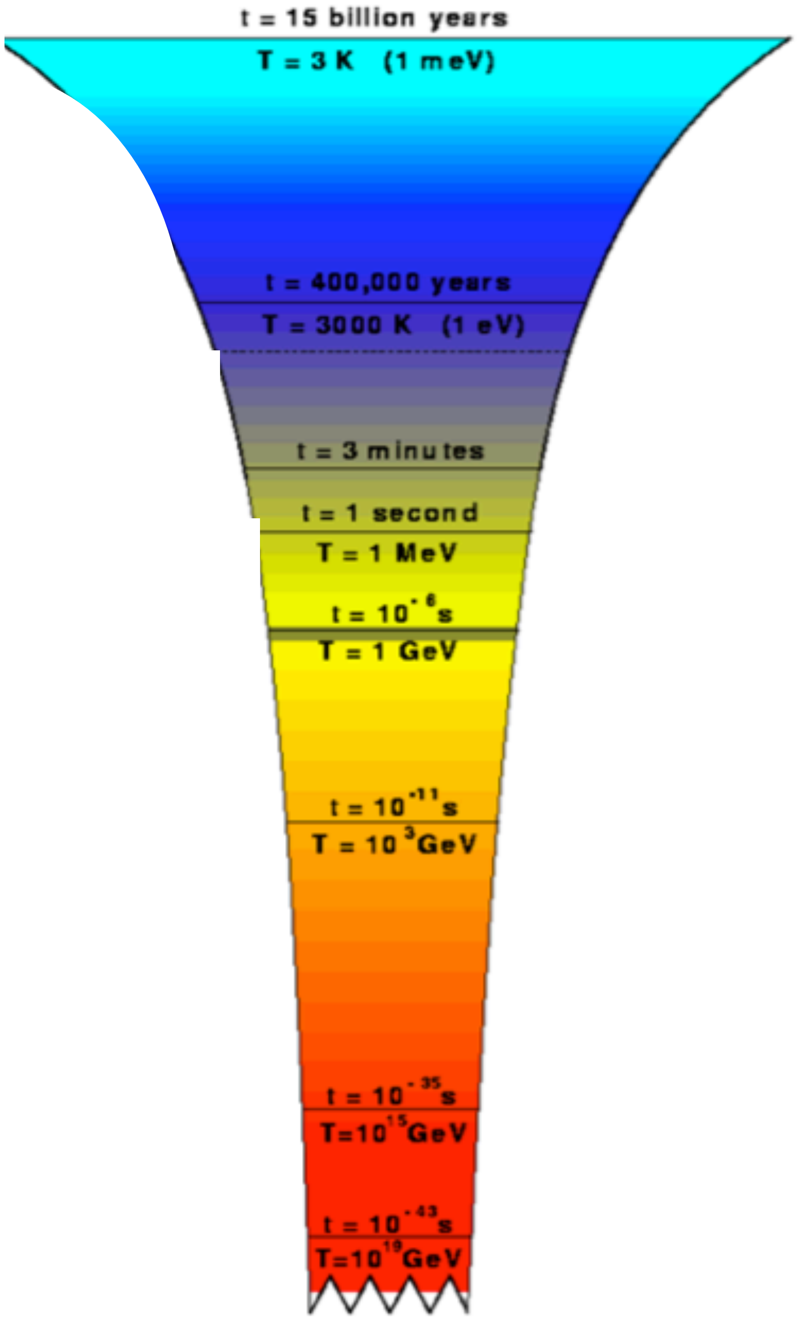


PRIMORDIAL BLACK HOLES: THEIR FORMATION AND COSMOLOGICAL CONSEQUENCES

Bernard Carr
Queen Mary
University of London

KEK 10/3/17

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

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

Small black holes can only form in early Universe

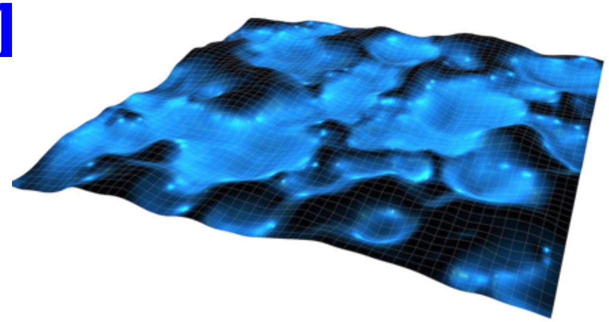
cf. cosmological density $\rho \sim 1/(Gt^2) \sim 10^6 (t/s)^{-2} \text{g/cm}^3$

⇨ PBHs have horizon mass at formation

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

=> huge possible mass range

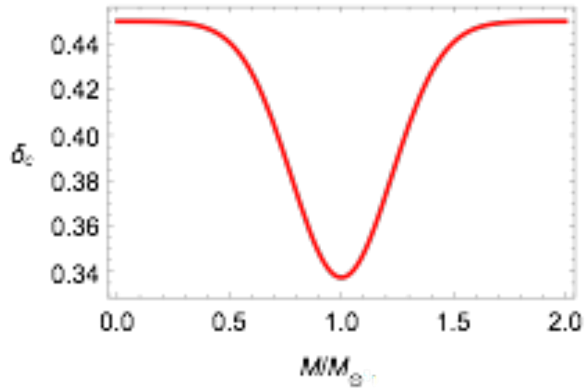
HOW PRIMORDIAL HOLES FORM

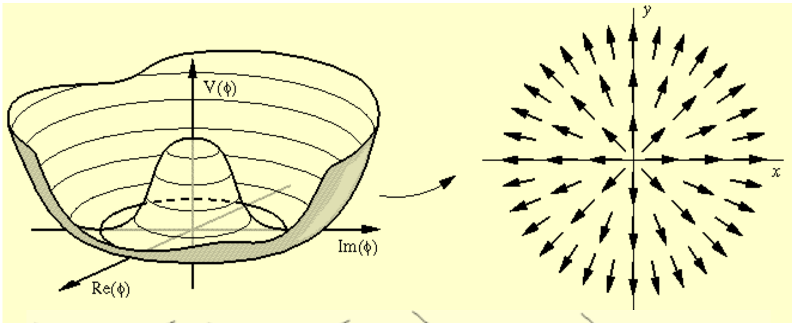


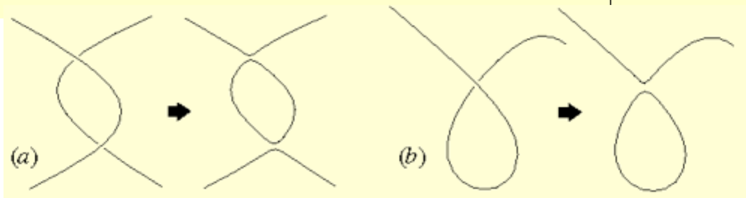
Primordial inhomogeneities Inflation

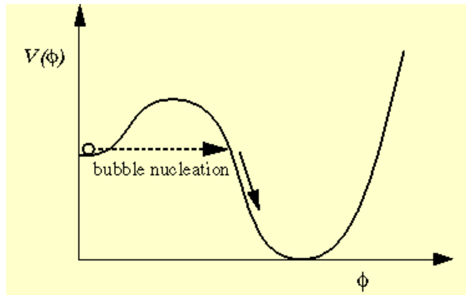
Pressure reduction Form more easily but need spherical symmetry

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





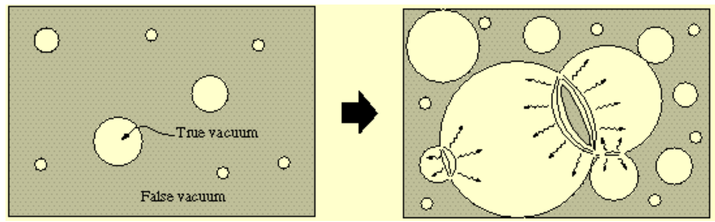




Bubble collisions

Need fine-tuning of bubble formation rate

Domain walls PBHs can be very large



PBH EVAPORATION

Black holes radiate thermally with temperature

$$T = \frac{hc^3}{8\pi GkM} \sim 10^{-7} \left[\frac{M}{M_0}\right]^{-1} \mathrm{K}$$ **(Hawking 1974)**

=> 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

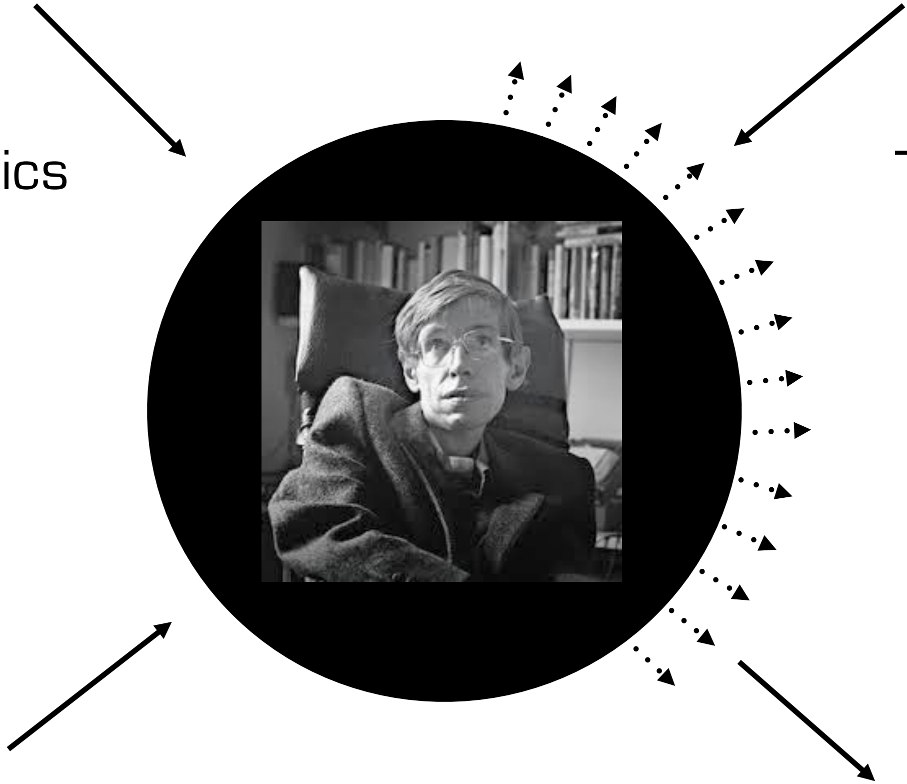
$T > T_{CMB}$=3K for $M < 10^{26}$g **=> "quantum" black holes**

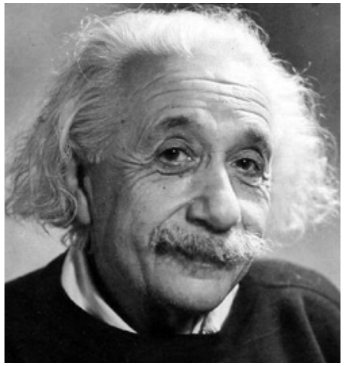
PBHs are important even if they never formed!

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

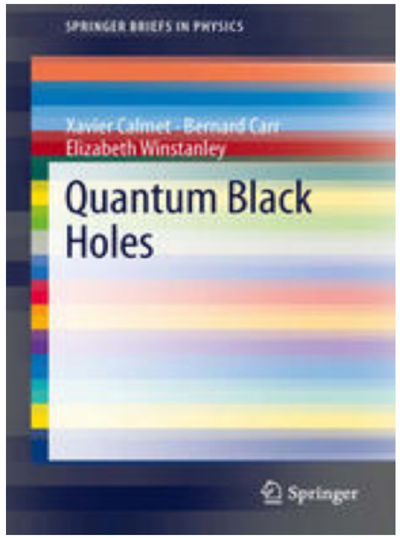
Quantum Mechanics

Thermodynamics





General Relativity



Calmet, BC, Winstanley

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

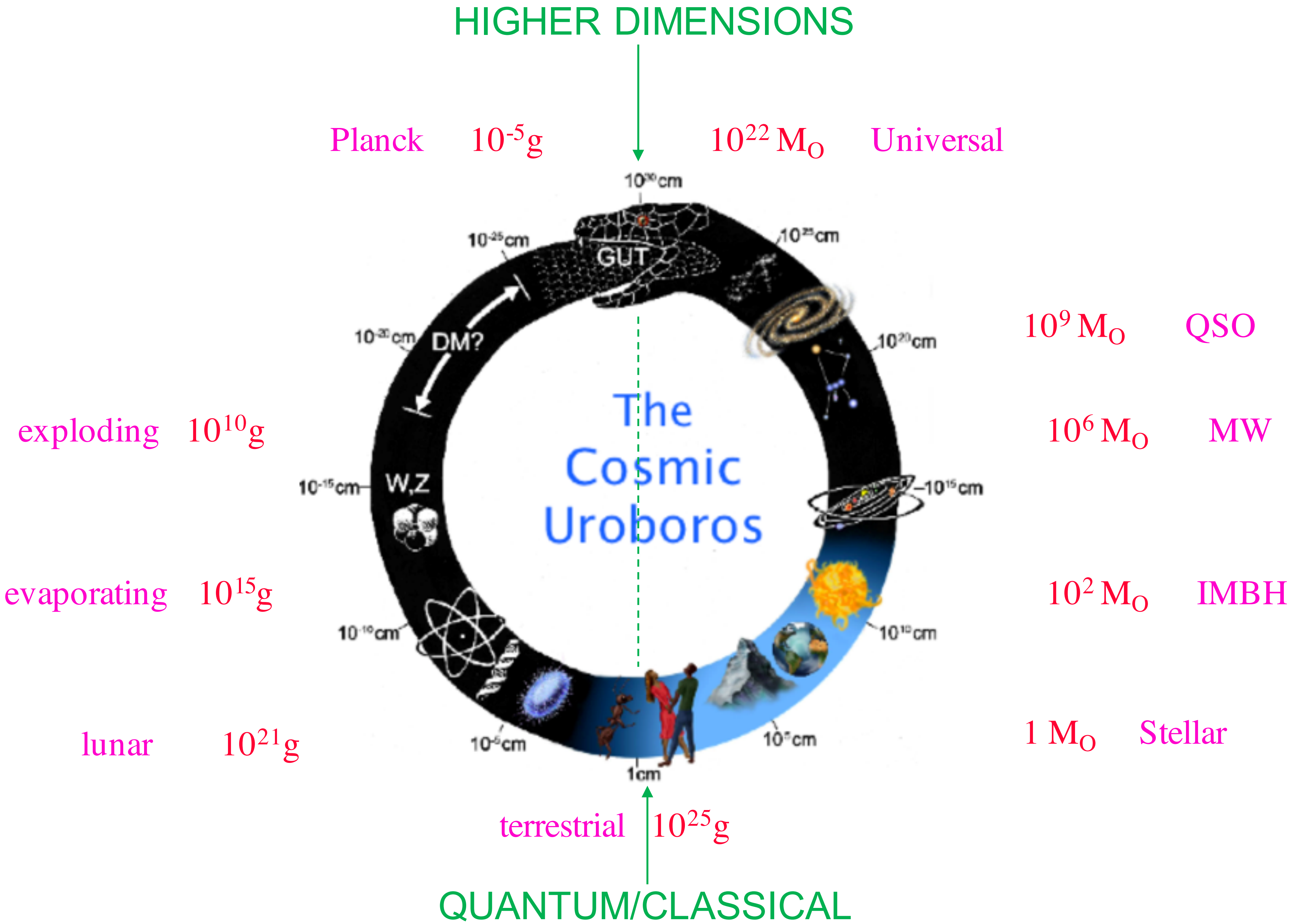
$M>10^{15}$g => Probe gravity and dark side

dark matter, dark energy, dark dimensions

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

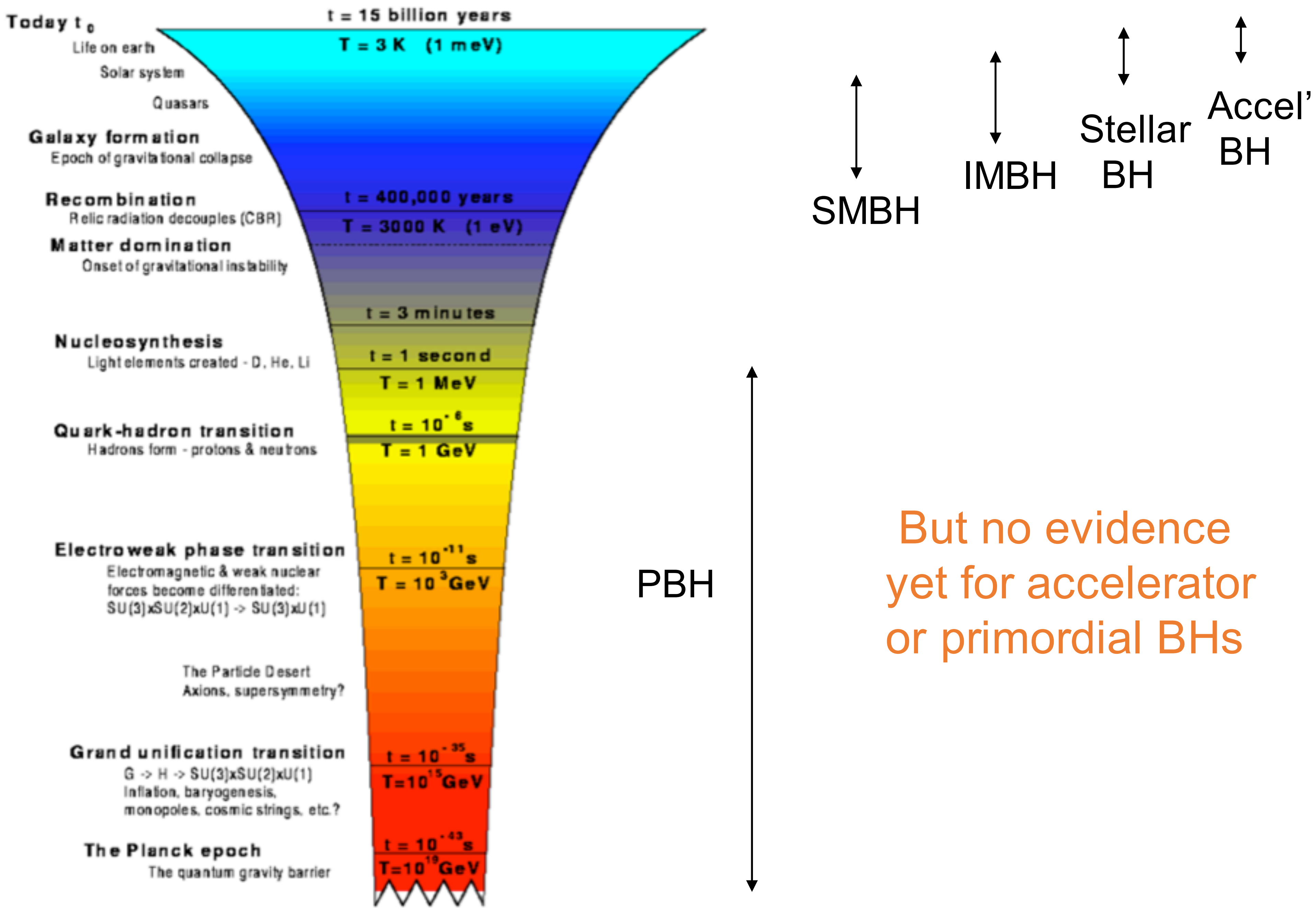
Planck mass relics, Generalized Uncertainty Principle

BLACK HOLES



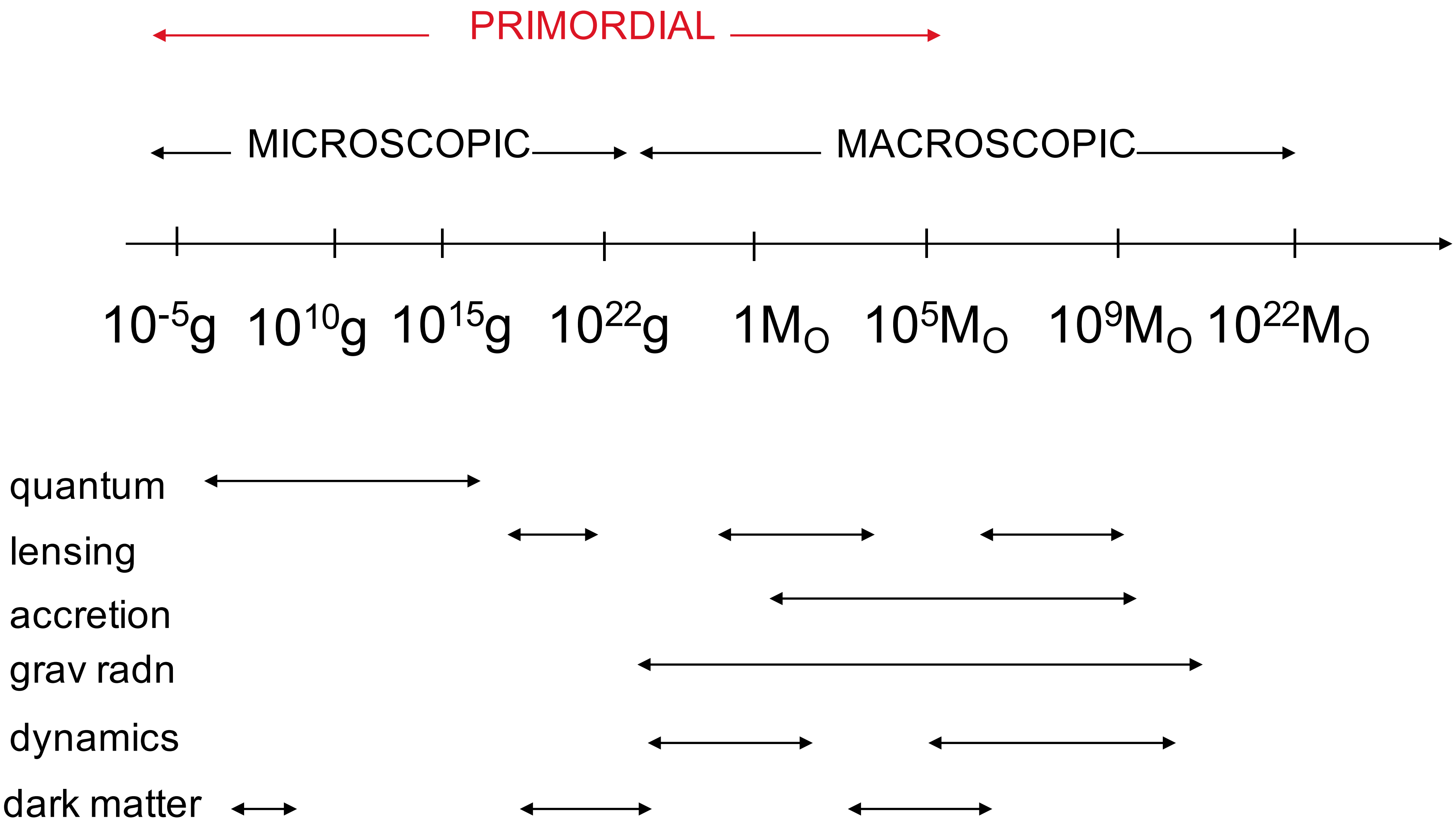
HIGHER DIMENSIONS
Planck 10^{-5}g
10^{22} M_O Universal
10^{9} M_O QSO
10^{6} M_O MW
10^{2} M_O IMBH
1 M_O Stellar
exploding 10^{10}g
evaporating 10^{15}g
lunar 10^{21}g
terrestrial 10^{25}g
QUANTUM/CLASSICAL
The Cosmic Uroboros
GUT
DM?
W,Z
1cm

WHEN BLACK HOLES FORM



But no evidence yet for accelerator or primordial BHs

QUANTUM & ASTROPHYSICAL EFFECTS OF BLACK HOLES



Limit on fraction of Universe collapsing

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

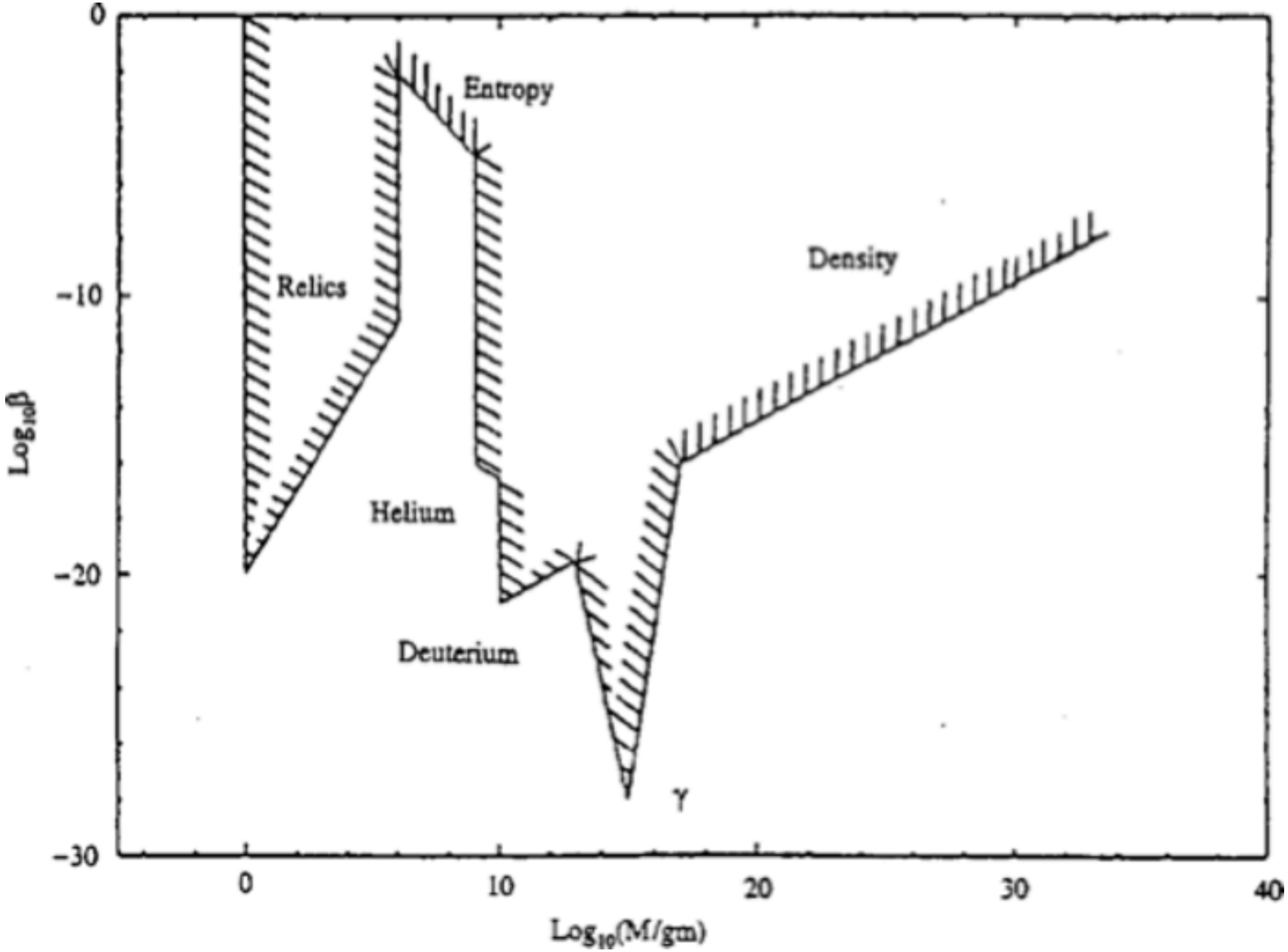
General limit

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

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



Carr, Gilbert & Lidsey (1994)

UPDATED CONSTRAINTS FOR EVAPORATING PBHS

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

Big bang nucleosynthesis

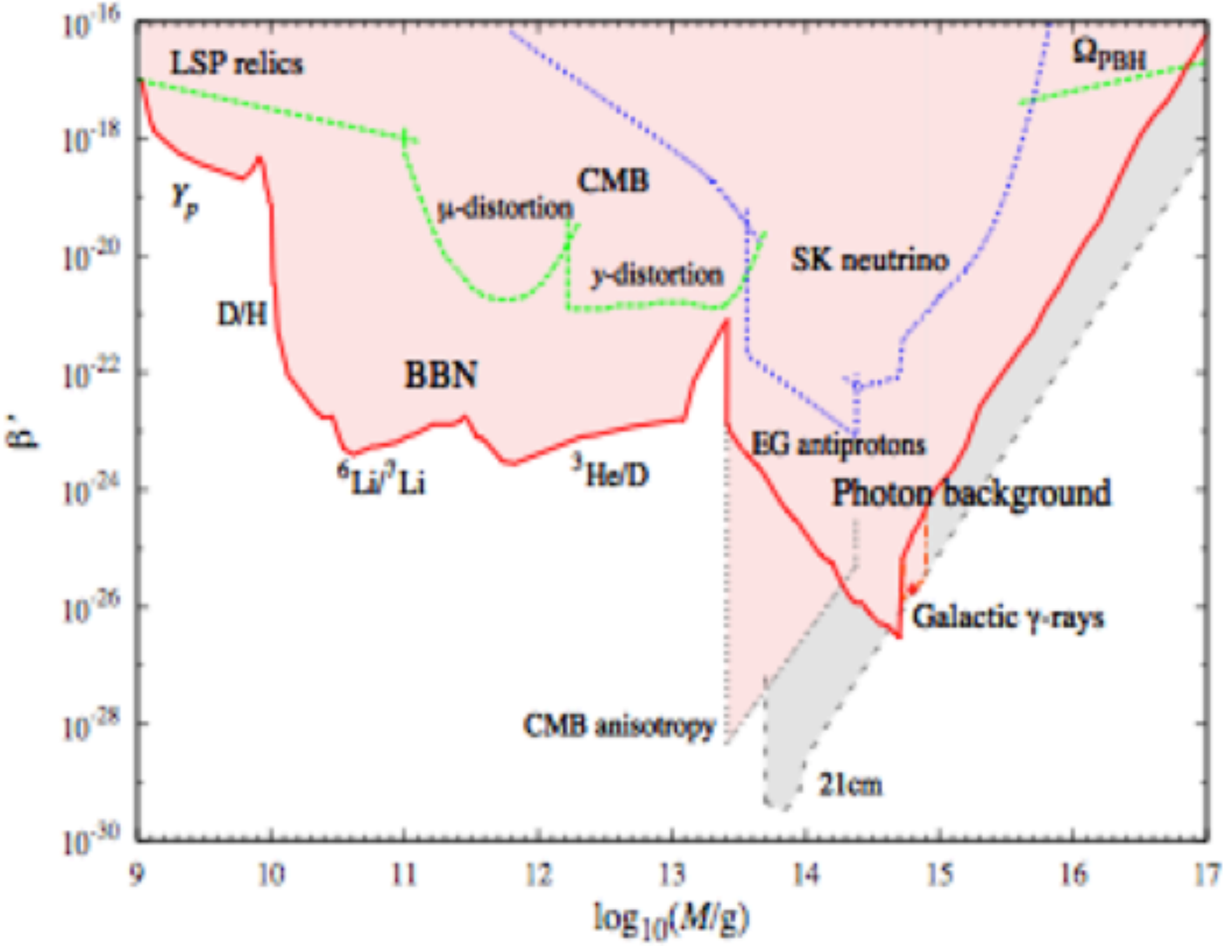
Gamma-ray background

Extragalactic cosmic rays

Neutrino relics

LSP relics

CMB distortions

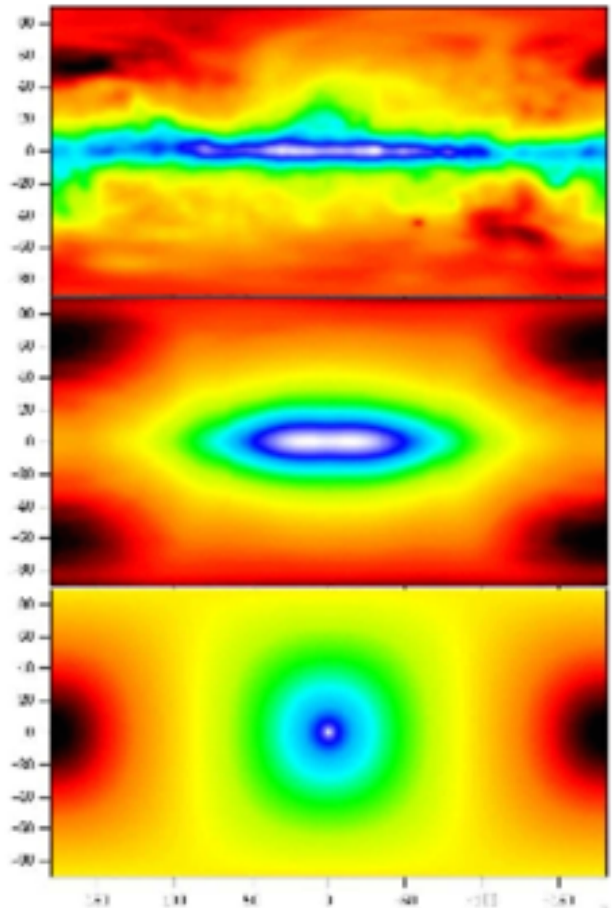


This assumes monochromatic mass function

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,§]

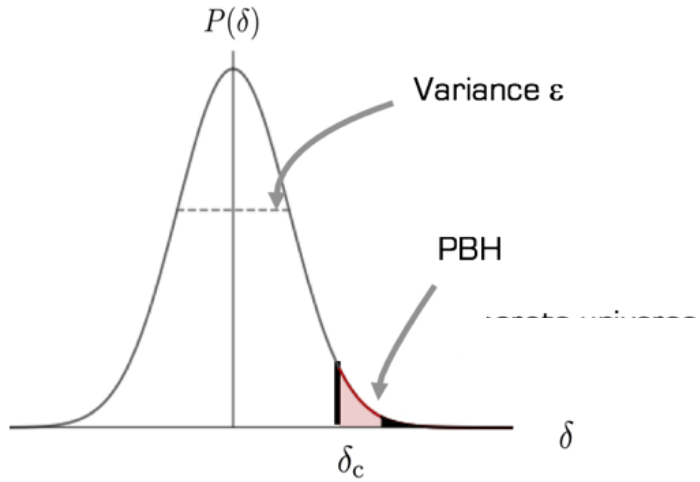


PBH FORMATION => LARGE INHOMOGENEITIES

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



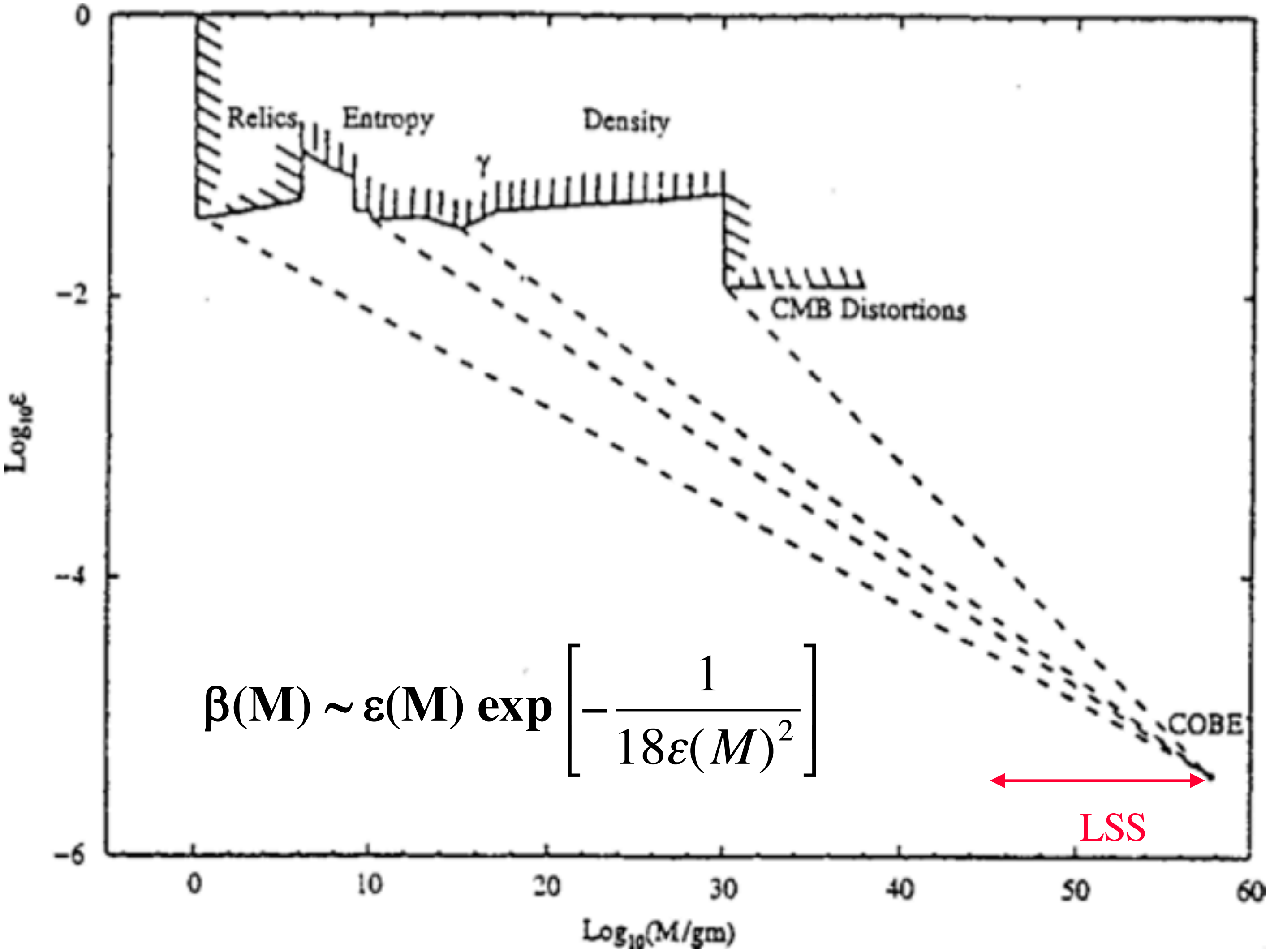
$\Rightarrow$ **fraction of PBHs**

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

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

p=0 => subhorizon holes but need spherical symmetry

Constraints on amplitude of density fluctuations at horizon epoch



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

Need blue spectrum or spectral feature for PBHs.
PBHs are unique probe of **ε** on small scales.

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)

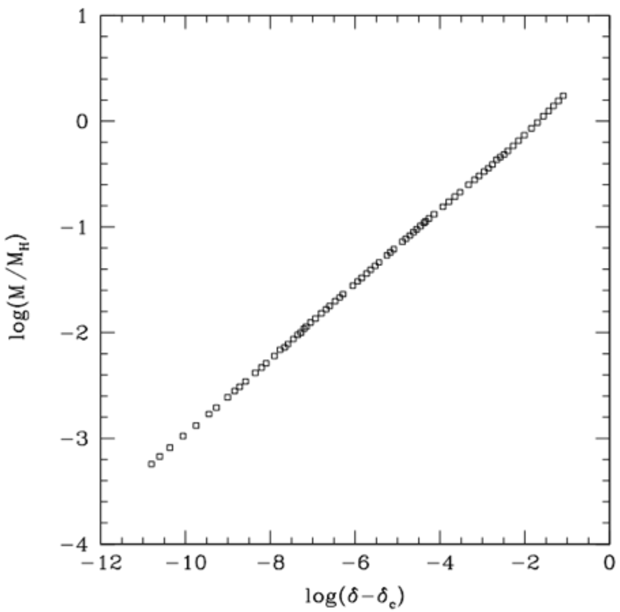
$\Rightarrow$ spectrum peaks at horizon mass with extended low mass tail

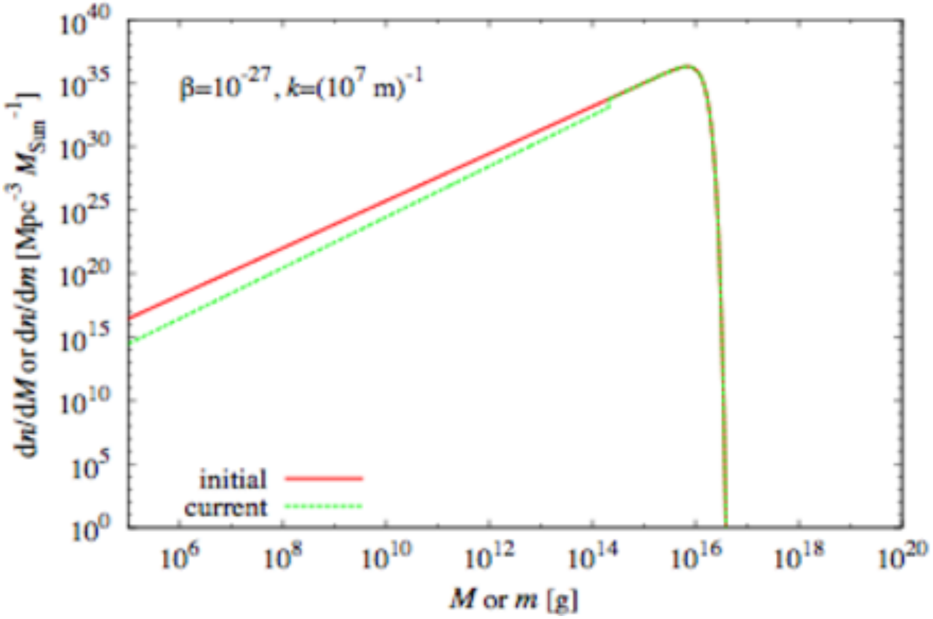
(Yokoyama 1998, Green 2000)

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

(Musco et al 2005, Green et al 2004)

PBHs from near-critical collapse





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

=> broad mass spectrum

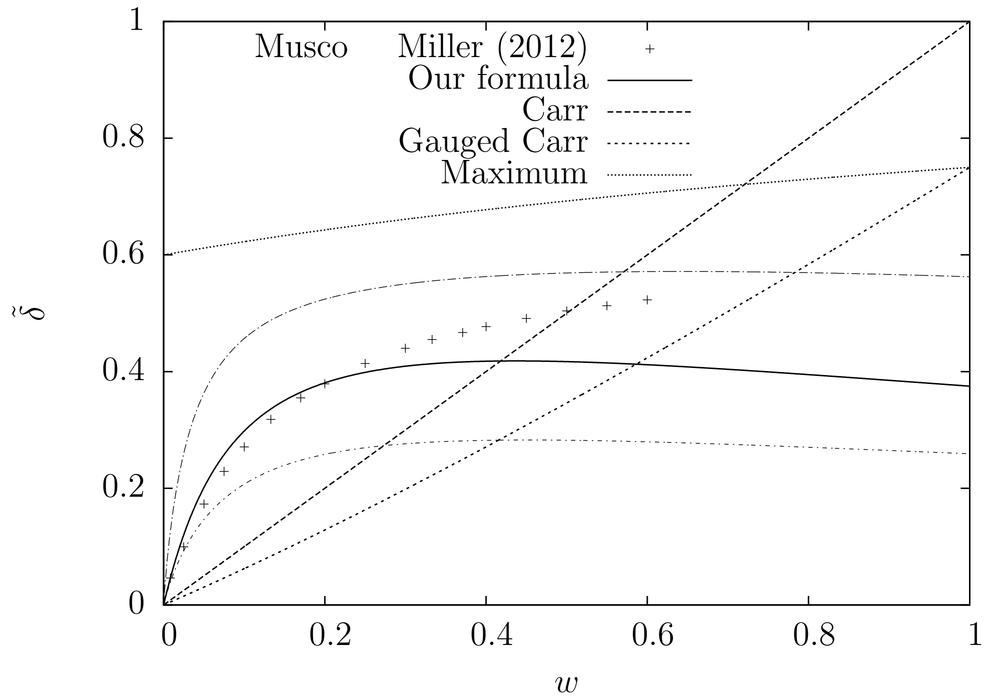
$$dN/dM \propto M^{1/\gamma - 1} \exp[-(M/M_f)^{1/\gamma}] \quad (\gamma = 0.35)$$ (Yokoyama 1998)

=> strong constraints even above 10^{15}g

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)

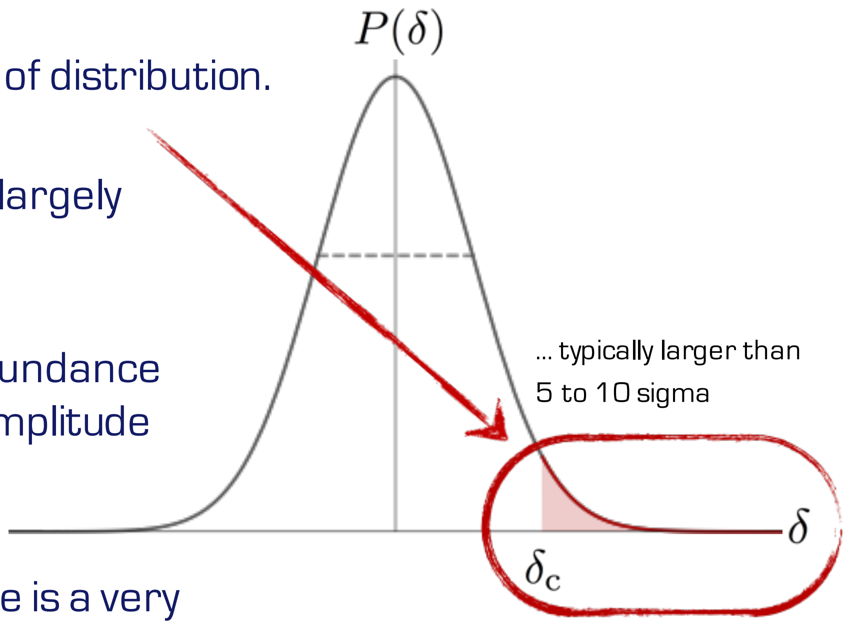
$$\delta_{Hc}^{\mathrm{UH}} = \sin^2\left(\frac{\pi\sqrt{w}}{1+3w}\right)$$

0.62 for radiation

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,†]

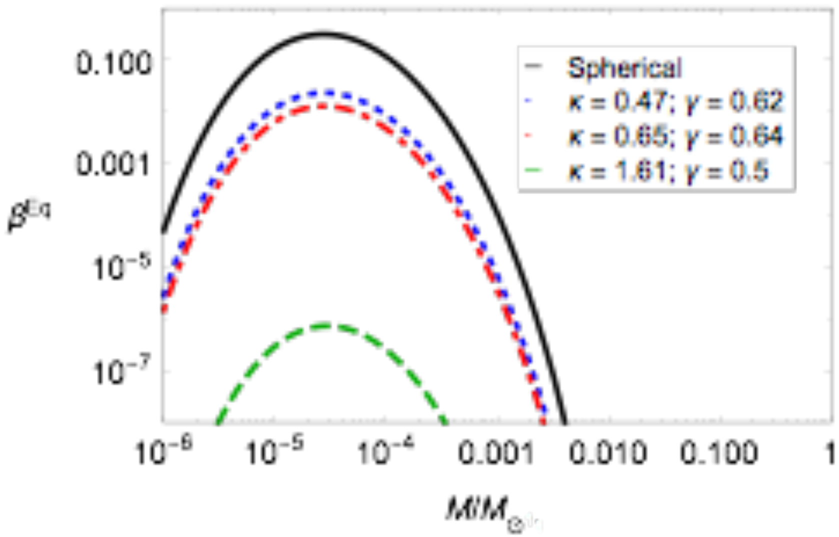
arXiv:1602:04815

★ 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



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

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

PBHS AND INFLATION

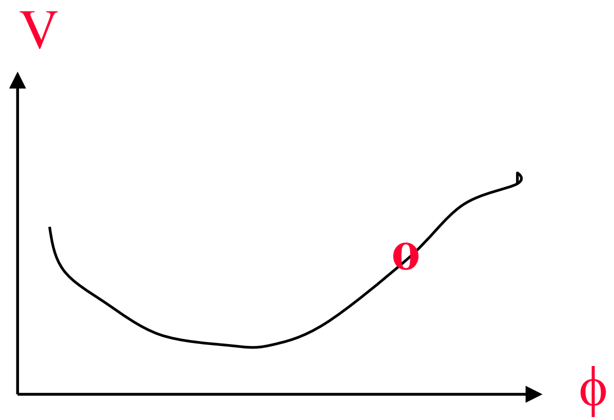
PBHs formed before reheat inflated away =>

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

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

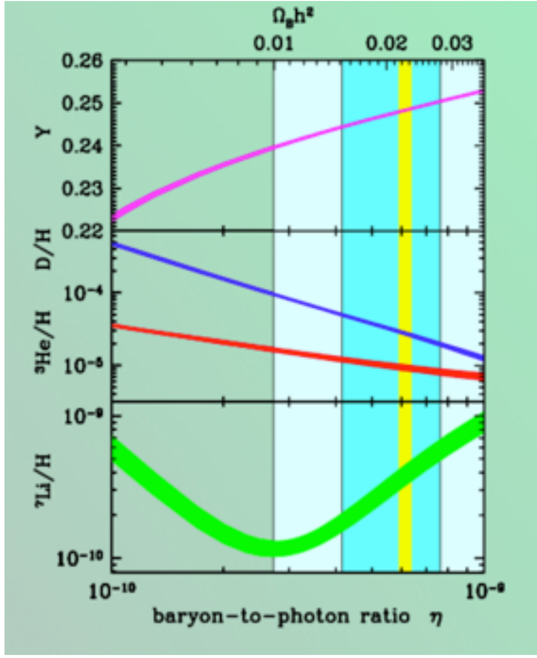
But inflation generates fluctuations

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



Can these generate PBHs?

KAWASAKI TALK



BBNS => Ω_{baryon}= 0.05

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

MACHOs (→ baryonic) WIMPs (→ non-baryonic)

PBHs are non-baryonic with features of <u>both</u> 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 (10^{16}-10^{17}g) Sublunar (10^{20}-10^{24}g) Intermediate Mass (10^{33}-10^{36}g)

CAN PLANCK MASS RELICS PROVIDE DARK MATTER?

reheat

Natural outcome of inflation if fine-tune T_R

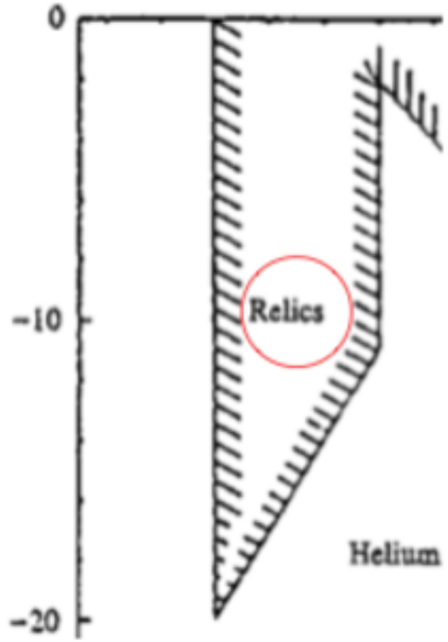
$$\Omega_{relic} < 0.25 \Rightarrow \beta(M) < 8\times10^{-28}\kappa^{-1}(M/M_P)^{3/2}$$

M_{relic} $/M_P$

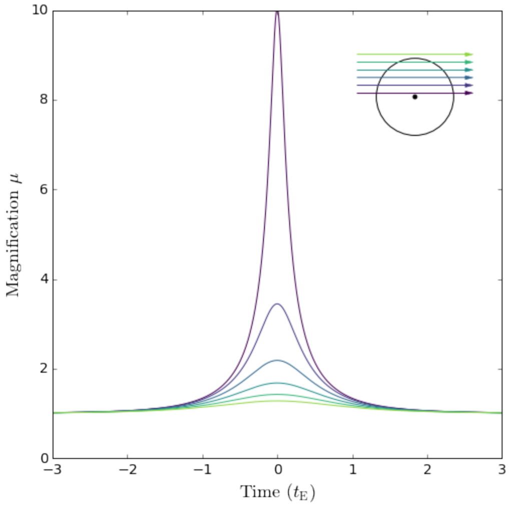
but only applies over limited mass range

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

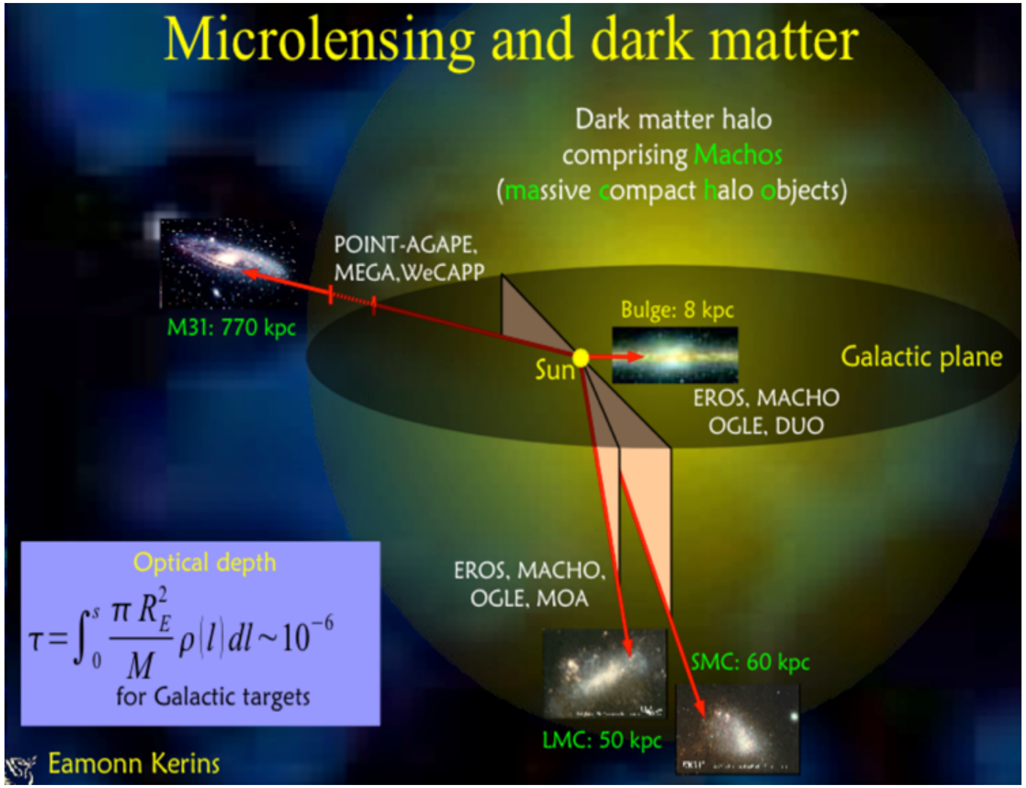
diluted by inflation PBHs dominate before evap'



These would be smallest objects in nature and undetectable!



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



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 IN 2010 (CKSY)

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

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

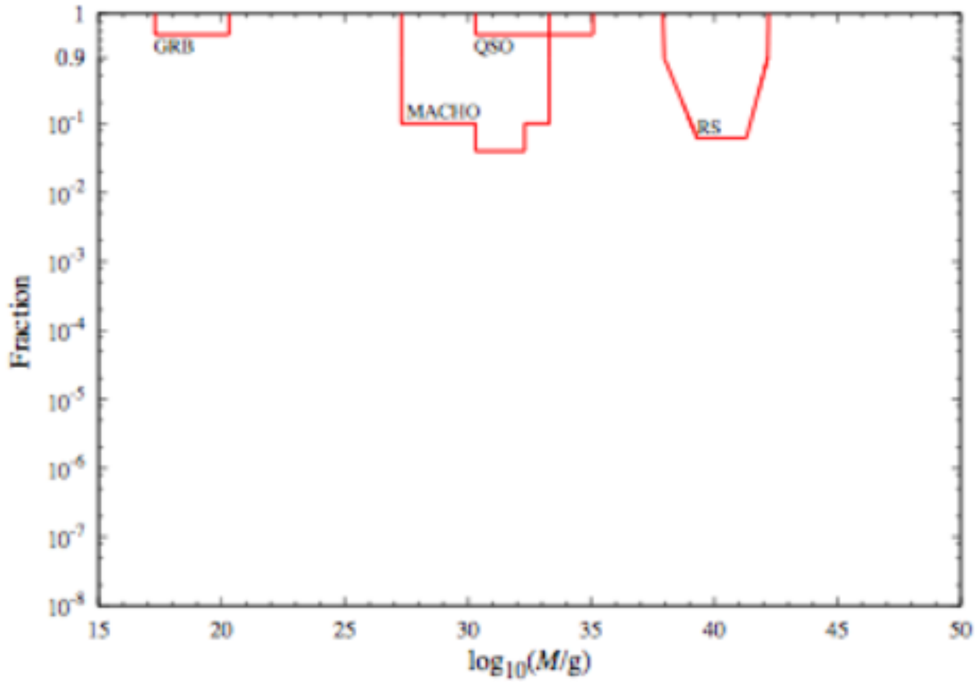
Microlensing QSOs

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

Millilensing Compact Radio Sources

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

LENSING LIMITS



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

DYNAMICAL LIMITS

Binary disruption

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

Globular cluster disruption

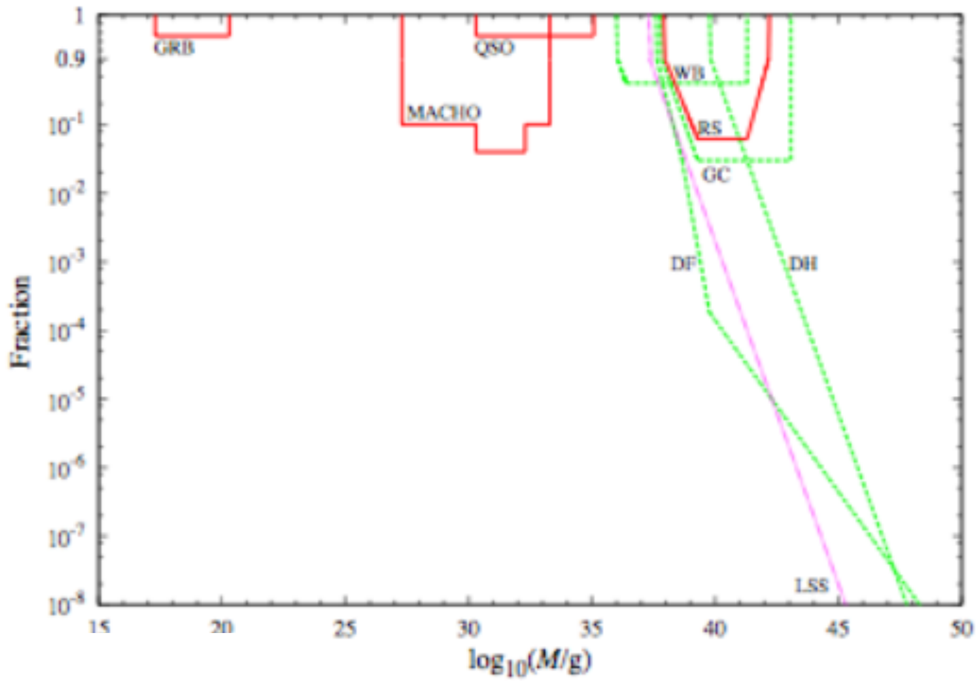
$$f(M) < \begin{cases} (M/3\times 10^4 M_\odot)^{-1} & (3\times 10^4 M_\odot < M < 10^6 M_\odot) \\ 0.03 & (10^6 M_\odot < M < 6\times 10^9 M_\odot) \end{cases}$$

Disk heating

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

Dynamical friction

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

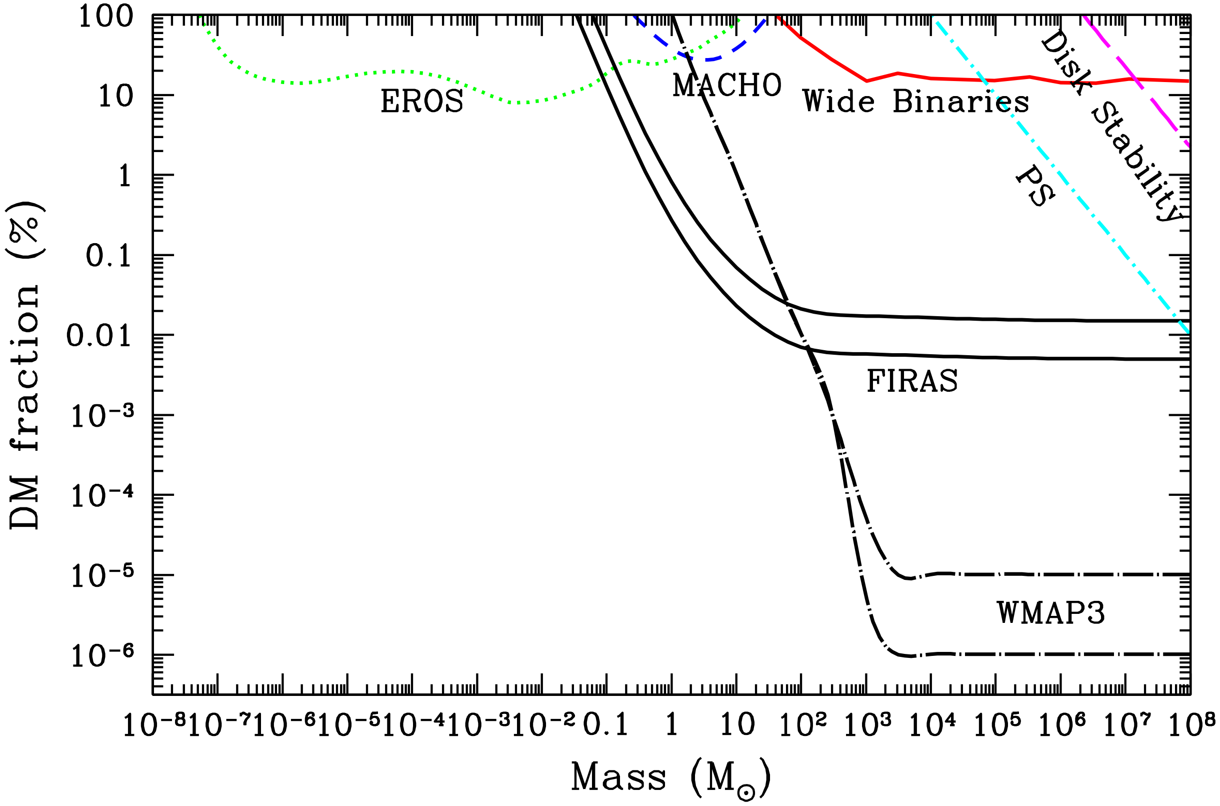


Some of these effects have been claimed as evidence for PBHs

ACCRETION CONSTRAINTS

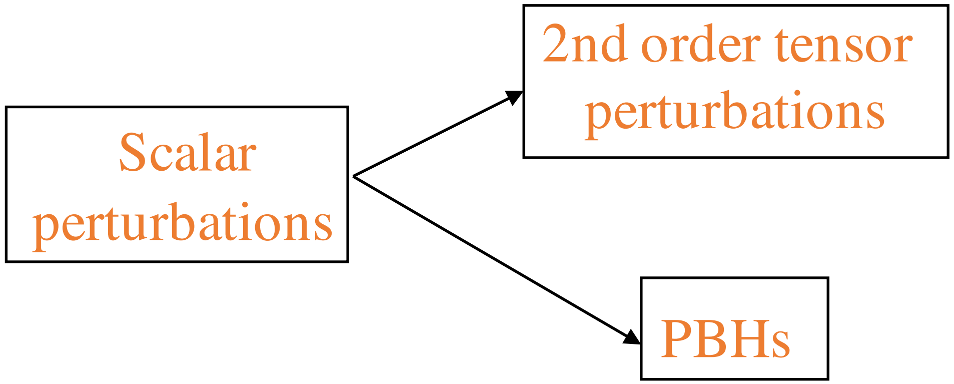
Ricotti, Ostriker & Mack (2008)

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



=> PBHs larger than 1 M_o excluded

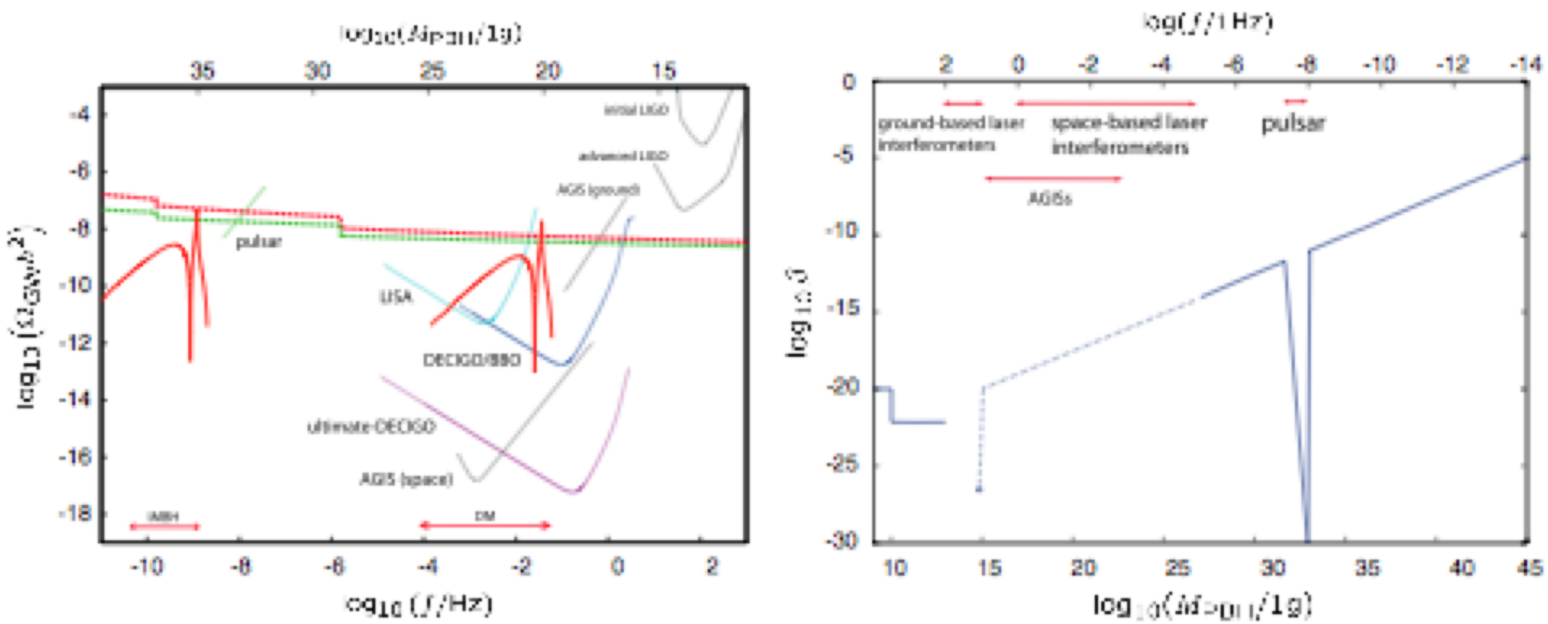
GRAVITY WAVES FROM PBHS



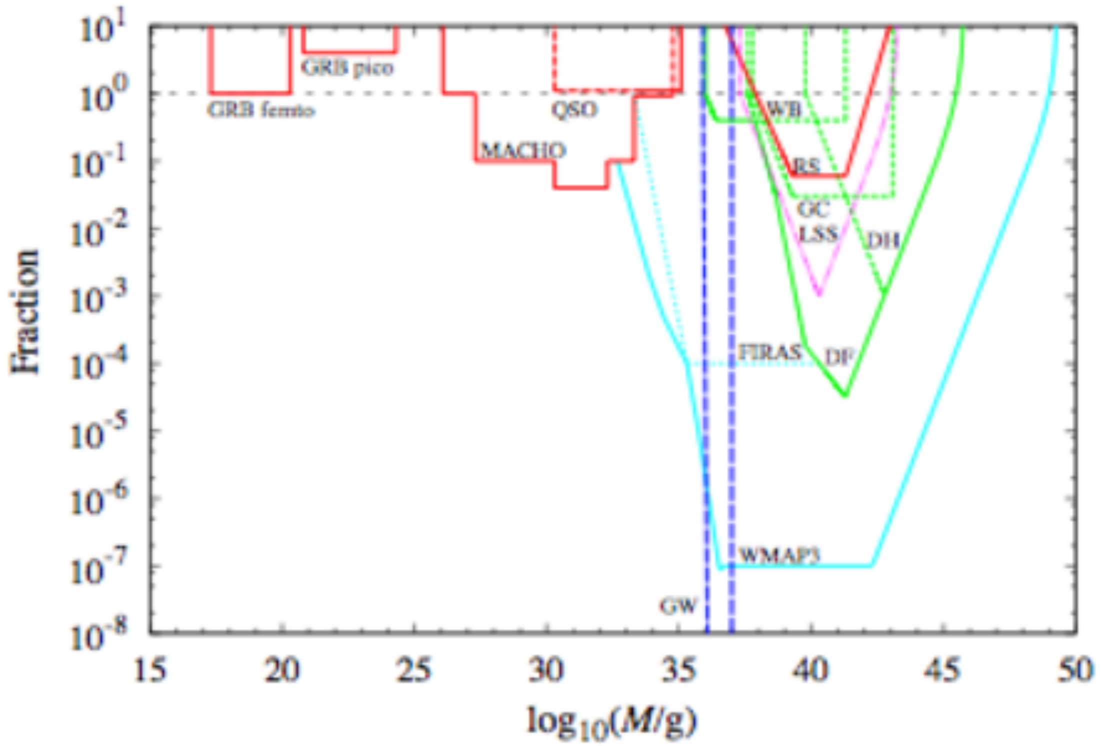
Saito & Yokoyama (2009)
Assadullahi & Wands (2009)
Bugaev & Klimai (2010)

$$f_{\mathrm{GW}} = 4 \times 10^{-10}\ \mathrm{Hz}\left(\frac{M_{\mathrm{PBH}}}{10^{36}\ \mathrm{g}}\right)^{-1/2}$$

Saito & Yokoyama PRL 107, 169901 (2011)



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



But many extra constraints since 2010!

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

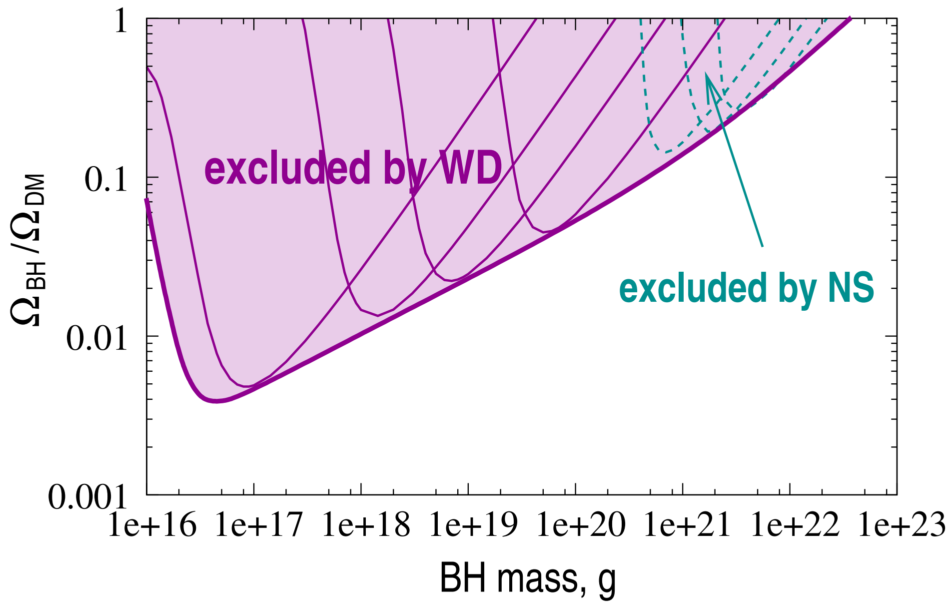
Fabio Capela,[1,*] Maxim Pshirkov,[2,3,4,†] and Peter Tinyakov[1,‡]

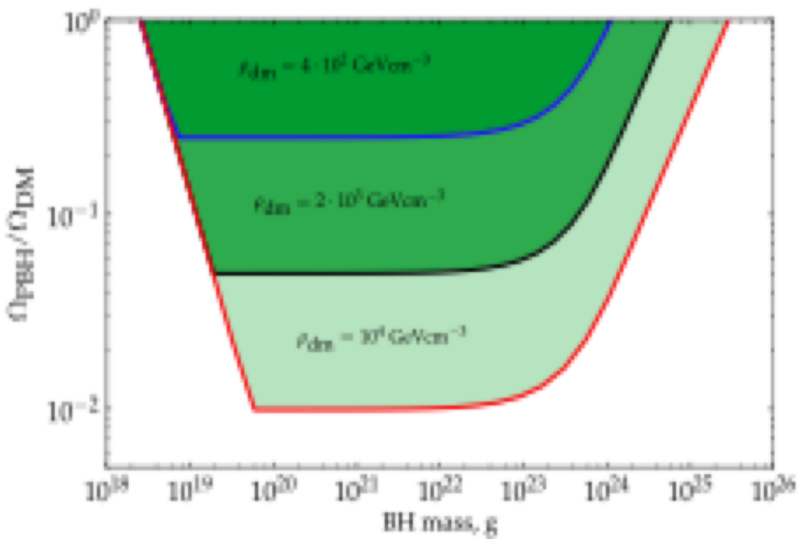
arXiv:1209.6021 PRD 87 023507 (2013)

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

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)

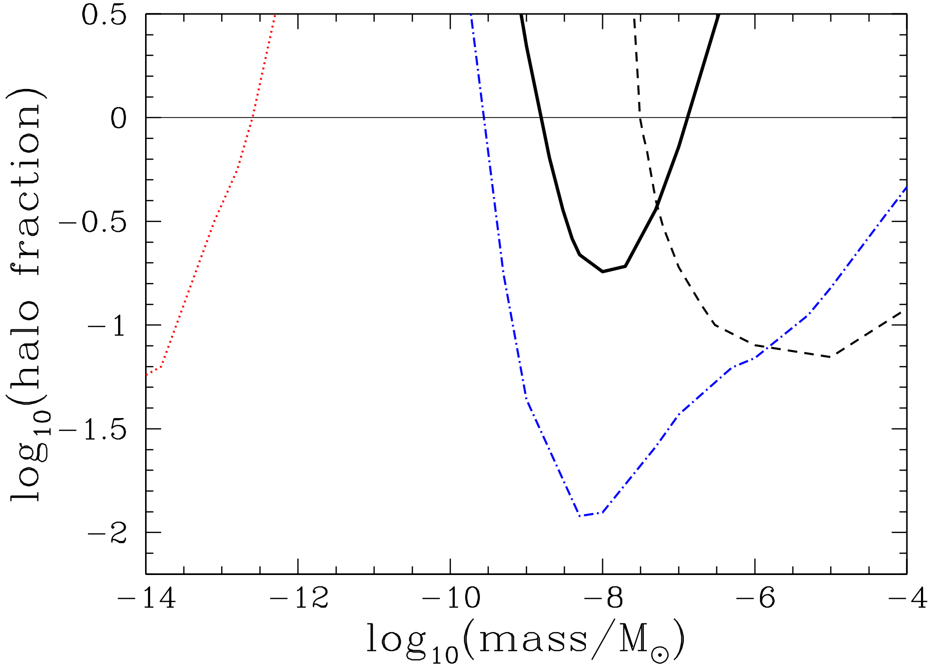
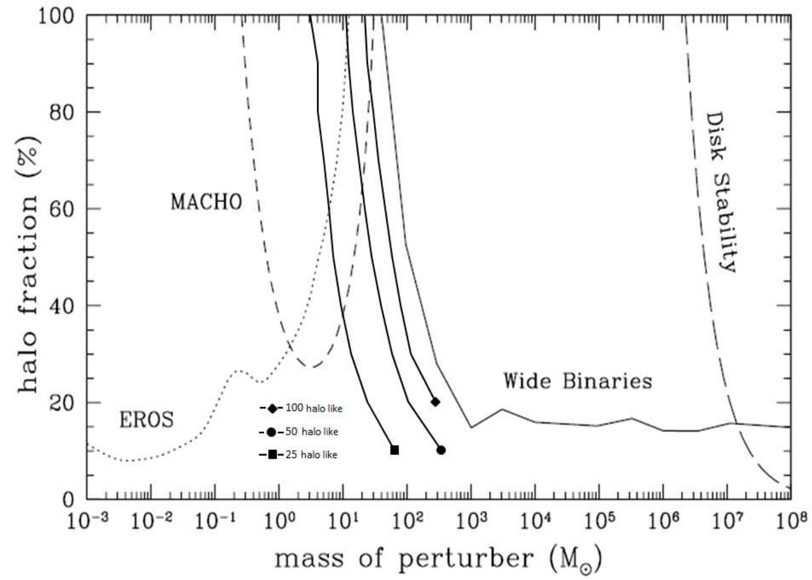


Figure 6. Upper limits (95% C.L.) on PBH DM from nonobservation of PBH microlensing in two yr of *Kepler* data. The solid black line is our new limit, the dashed black line is the previous best limit (Alcock et al. 1998), the blue dot–dashed line is the theoretical limit from Paper II, and the red dotted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

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): $21 - 68$ $M_\odot$.

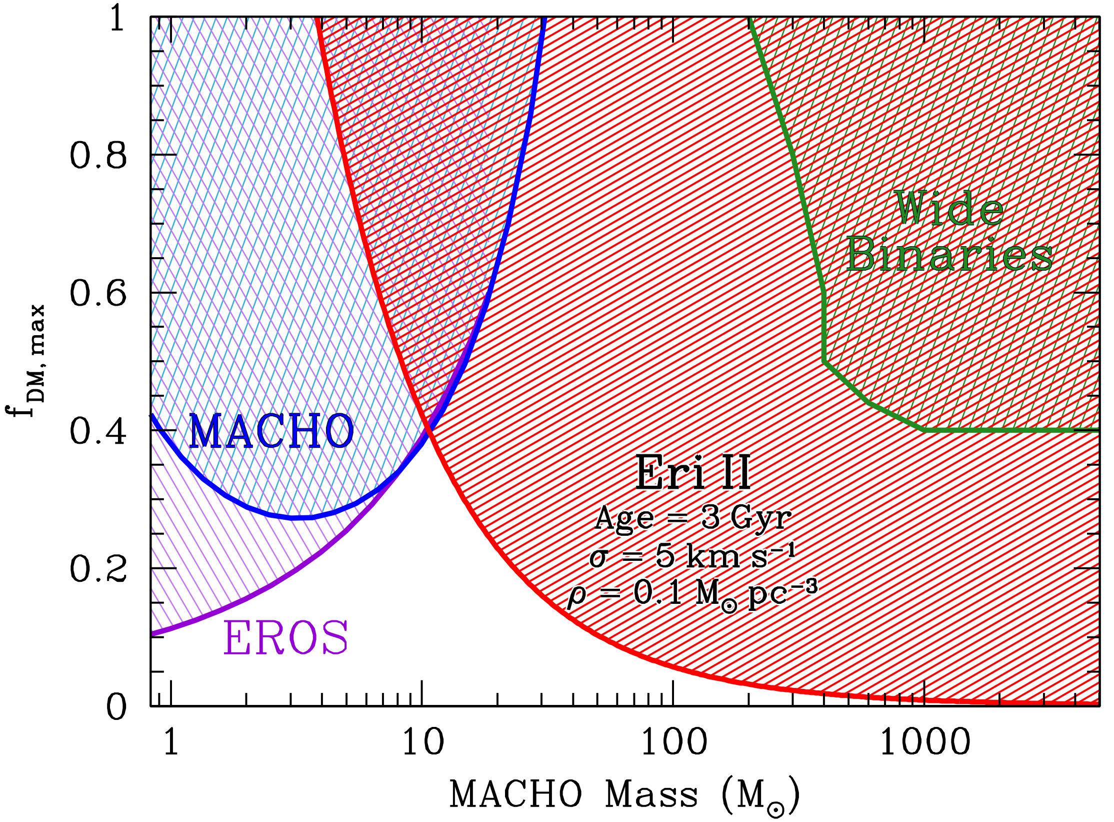
From the same 100 binaries, but taking into account the non-uniform halo density: $28-78$ $M_\odot$.

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]

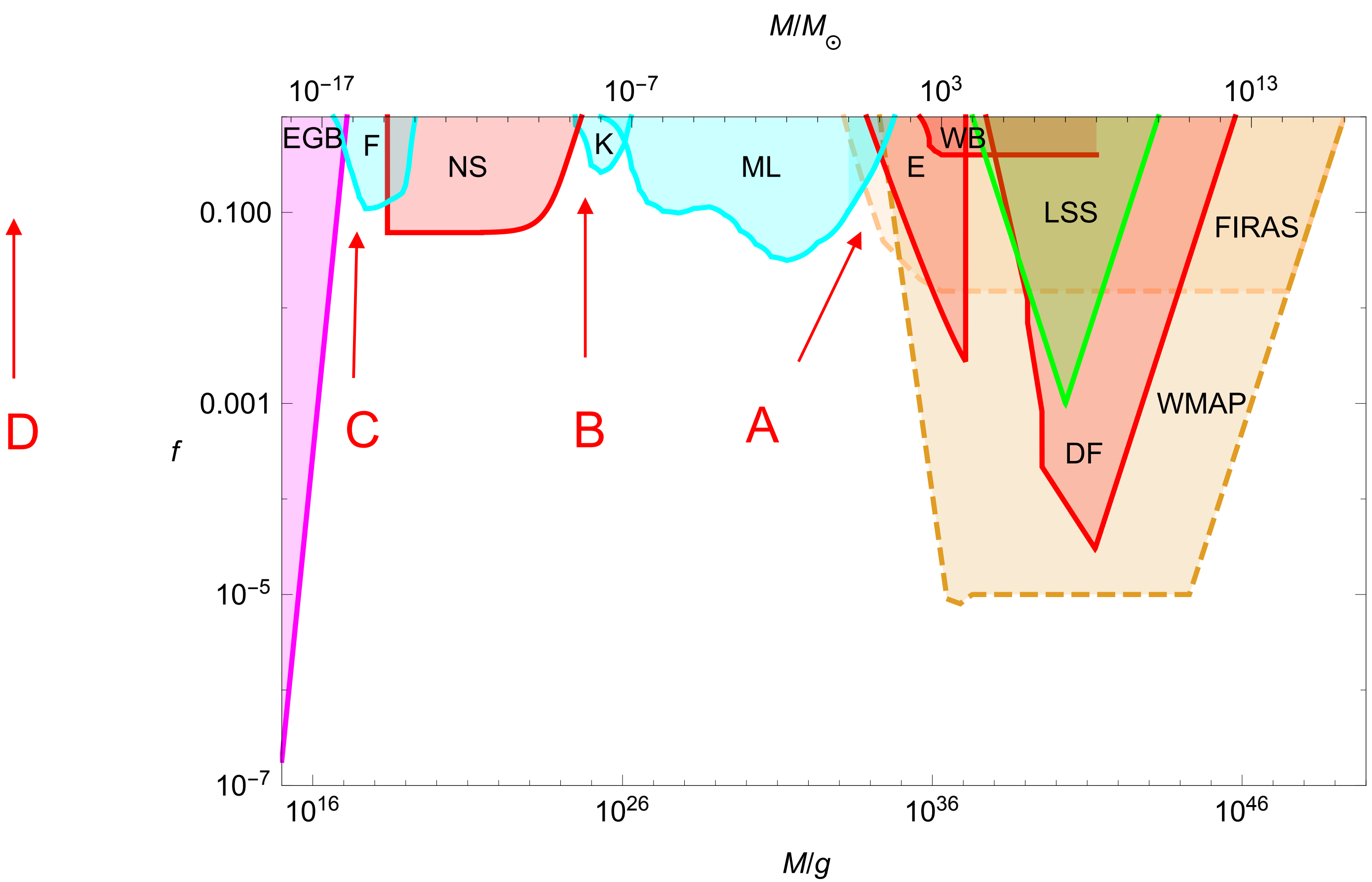
arXiv: 1605.03665



PRIMORDIAL BLACK HOLES AS DARK MATTER

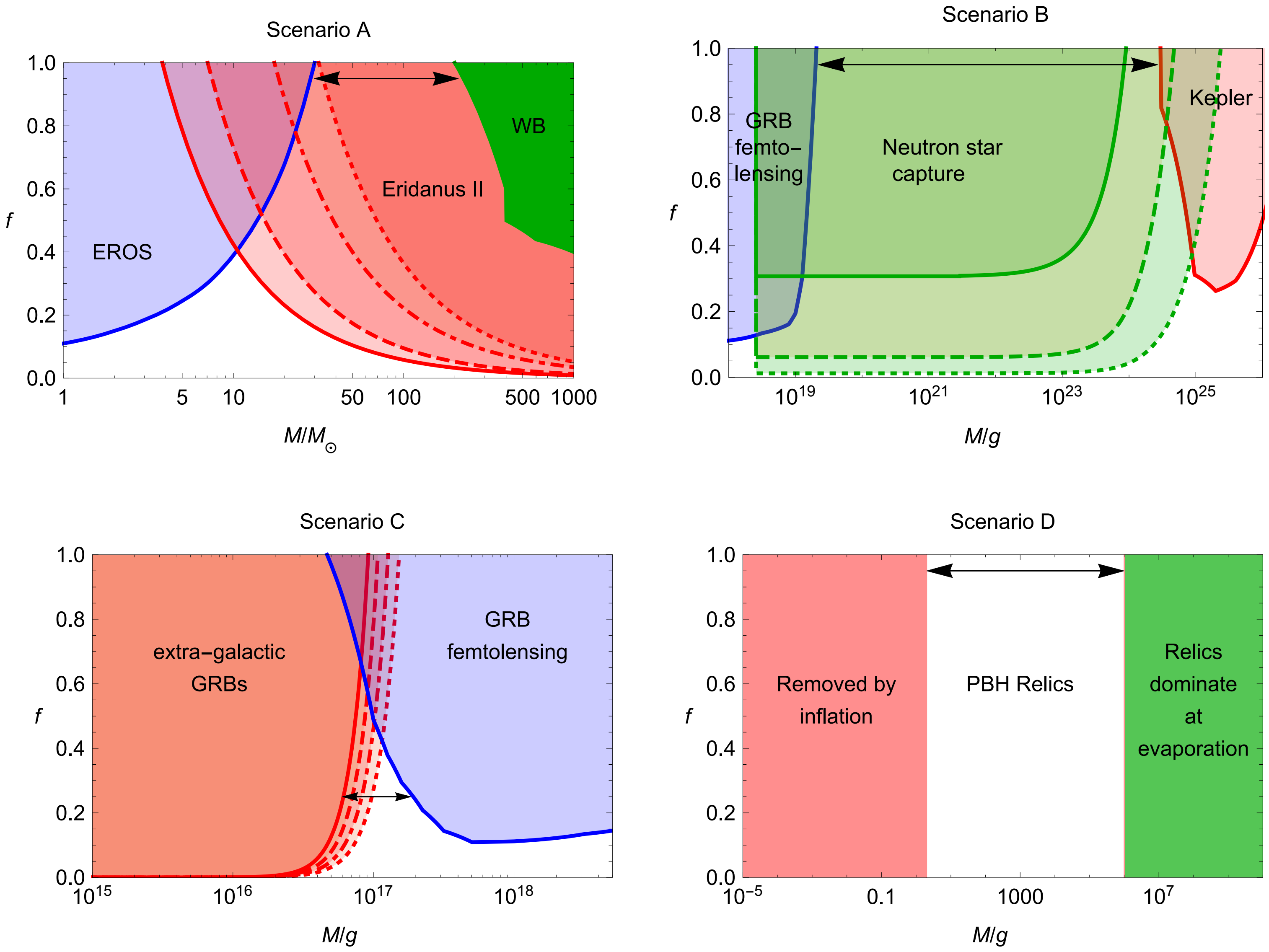
Bernard Carr,[1,*] Florian Kühnel,[2,†] and Marit Sandstad[3,‡]

PRD 94, 083504, arXiv:1607.06077



Three windows: (A) intermediate mass; (B) sublunar mass; (C) atomic size.

Also (D) Planck mass relics


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

CKS 2016

EXTENDED MASS FUNCTION?

Most constraints assume monochromatic PBH mass function

Can we evade standard limits with extended mass spectrum?

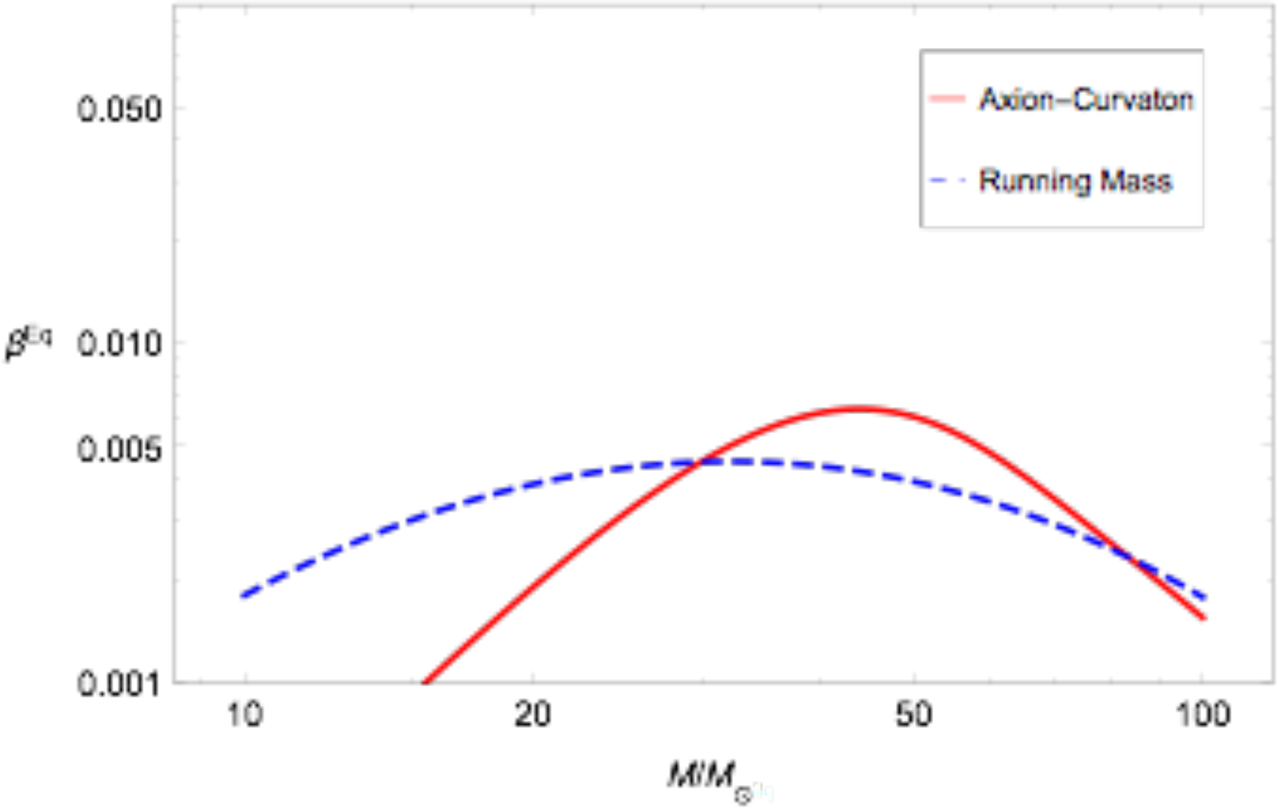
But this is two-edged sword!

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 <u>expected</u> in many inflation models

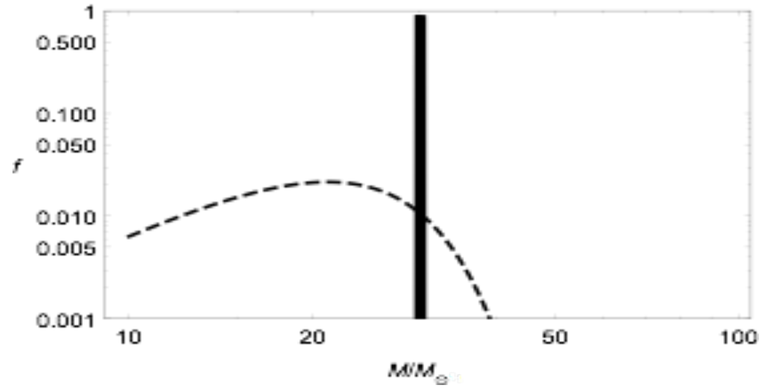
★ LIGO mass range:



But precise form subject to various uncertainties….

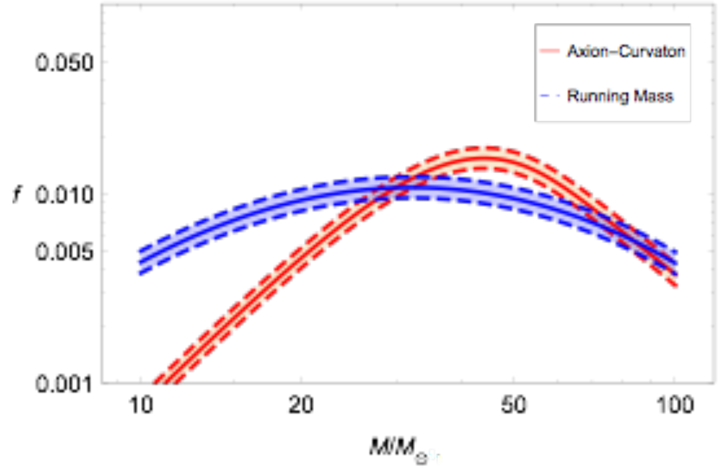
★ Critical collapse

Monochromatic mass
extends to very low masses



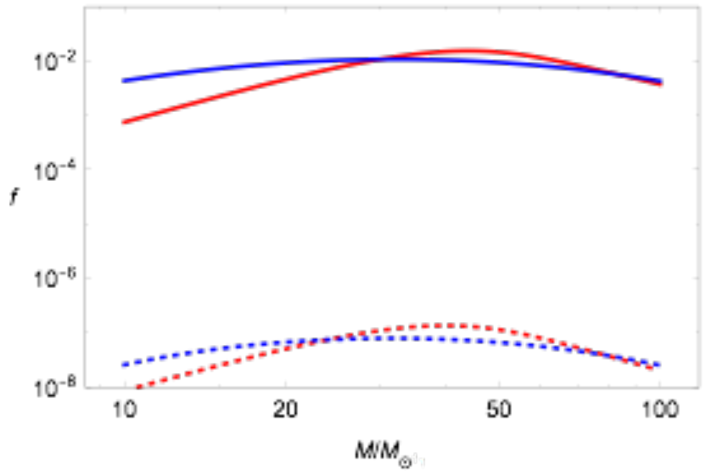
★ Non-Gaussianity

PBH production is
largely sensitive to
non-Gaussianity.

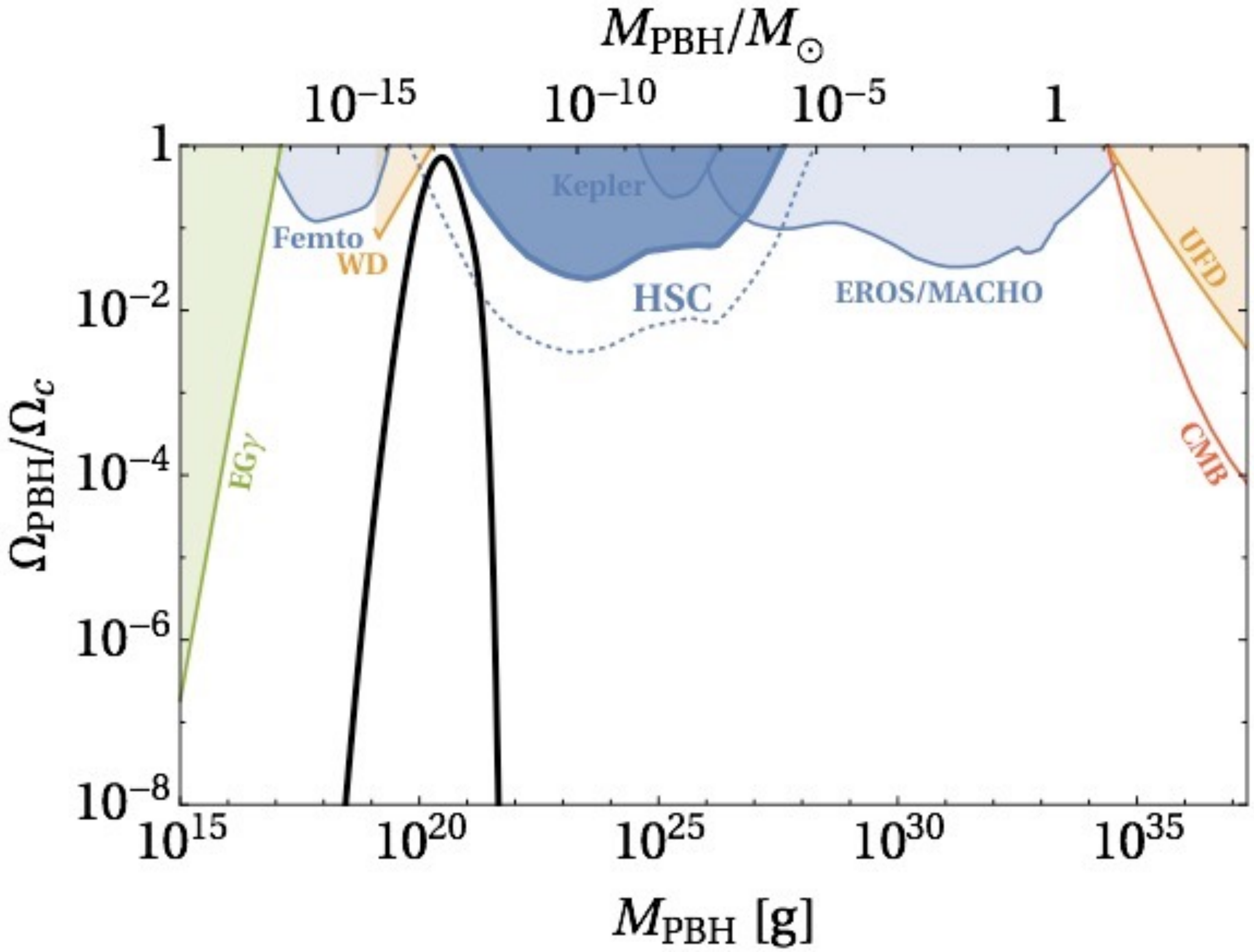


★ Non-Sphericity

Increases the threshold:



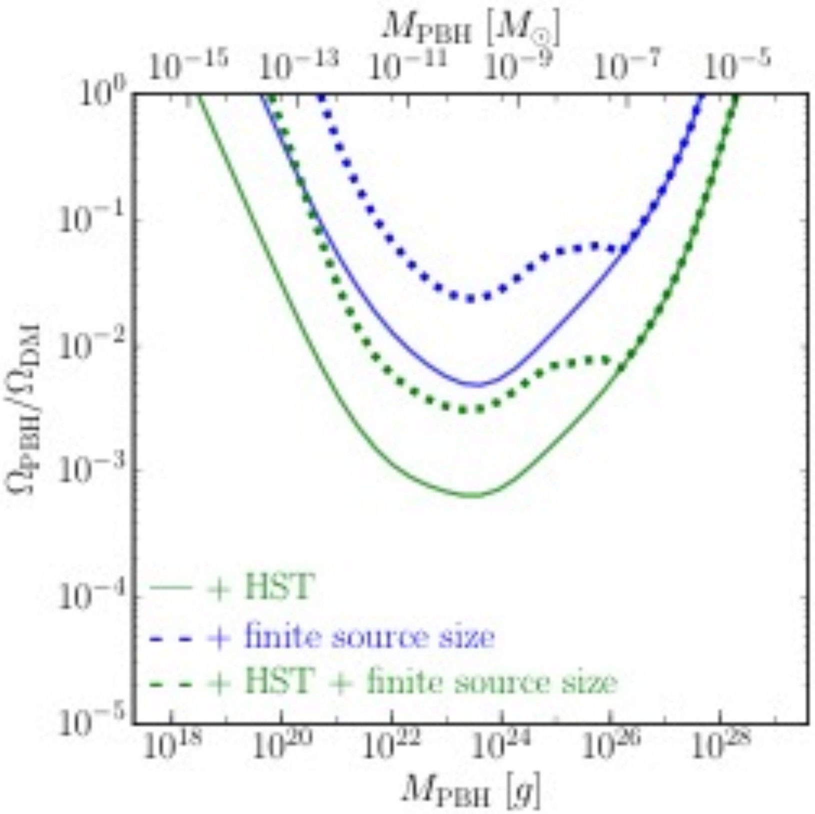
PBH dark matter with M = 10^{20}g from double inflation

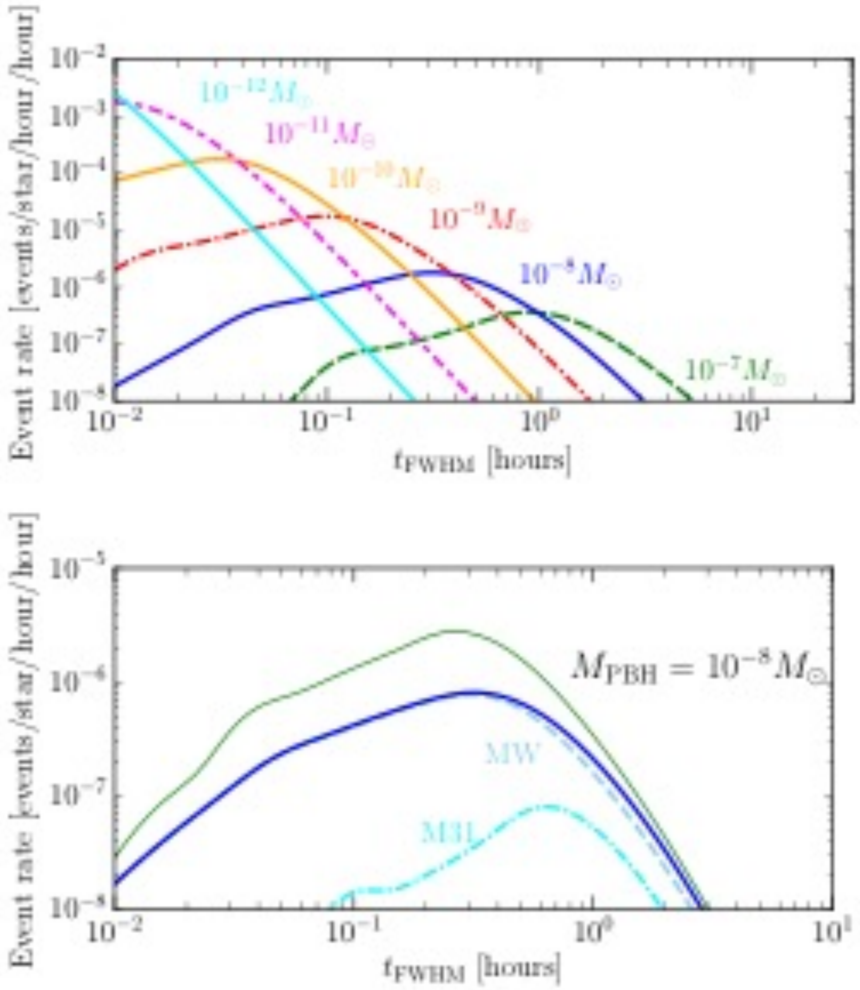


Inomata, Kawasaki, Mukaida &. Yanagida arXiv:1701.02544

MICROLENSING CONSTRAINTS FROM SUBARU HSC

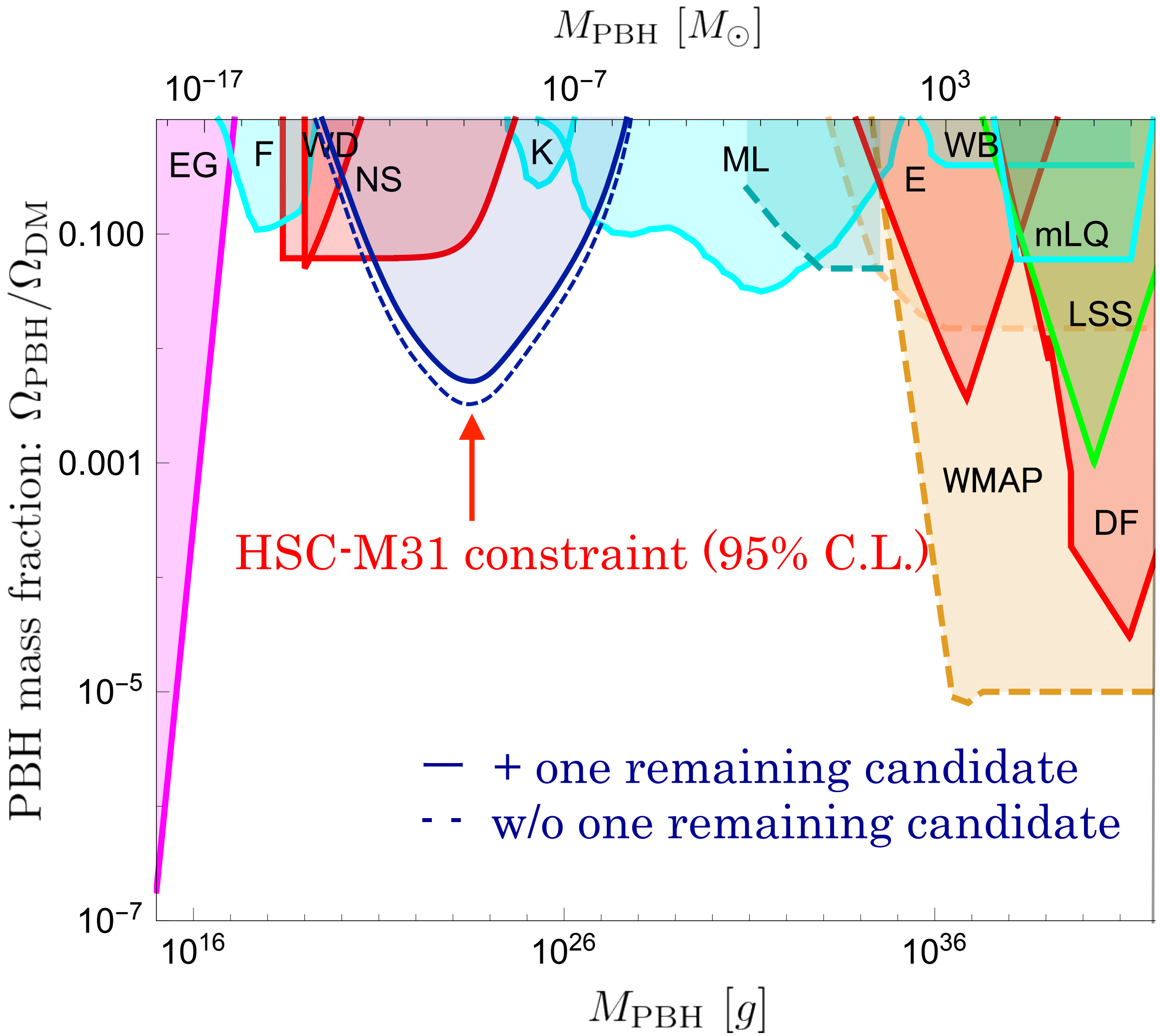
Niikura et al. arXiv:1701.02151





Excludes PBHs with

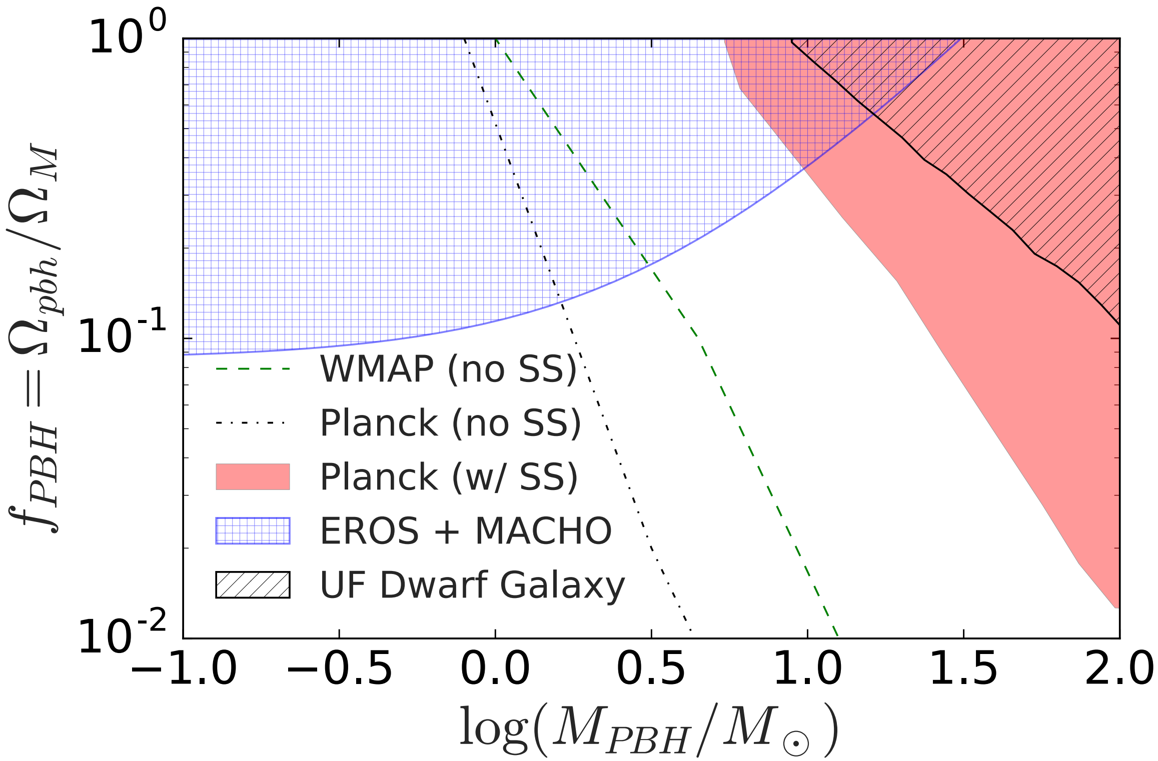
10^{20}g < M < 10^{26}g

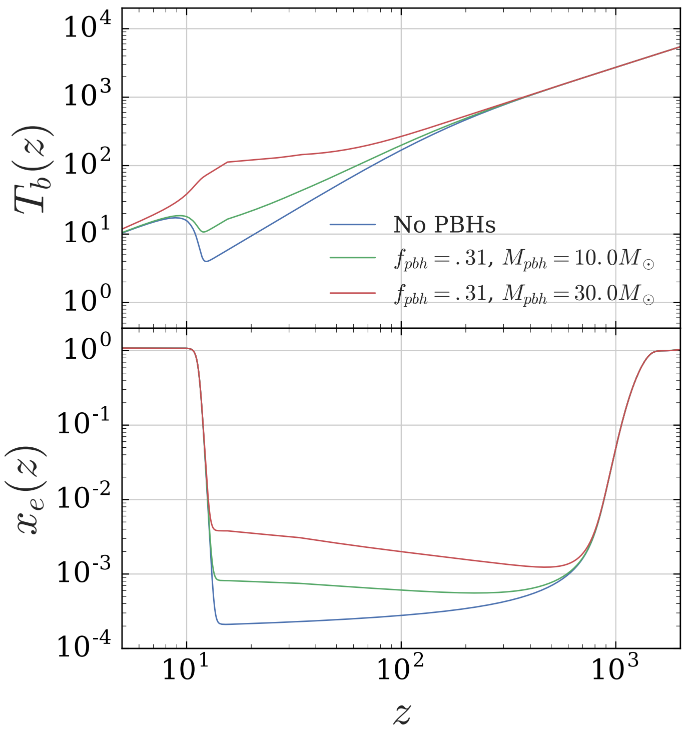


$M_{\rm PBH}\ [M_\odot]$
10^{-17}
10^{-7}
10^{3}
EG
F
WD
NS
K
ML
E
WB
mLQ
LSS
WMAP
DF
HSC-M31 constraint (95% C.L.)
+ one remaining candidate
w/o one remaining candidate
PBH mass fraction: $\Omega_{\rm PBH}/\Omega_{\rm DM}$
0.100
0.001
10^{-5}
10^{-7}
10^{16}
10^{26}
10^{36}
$M_{\rm PBH}\ [g]$

REASSESING THE “ROM” CONSTRAINT

Horowitz arXiv:1612.07264v



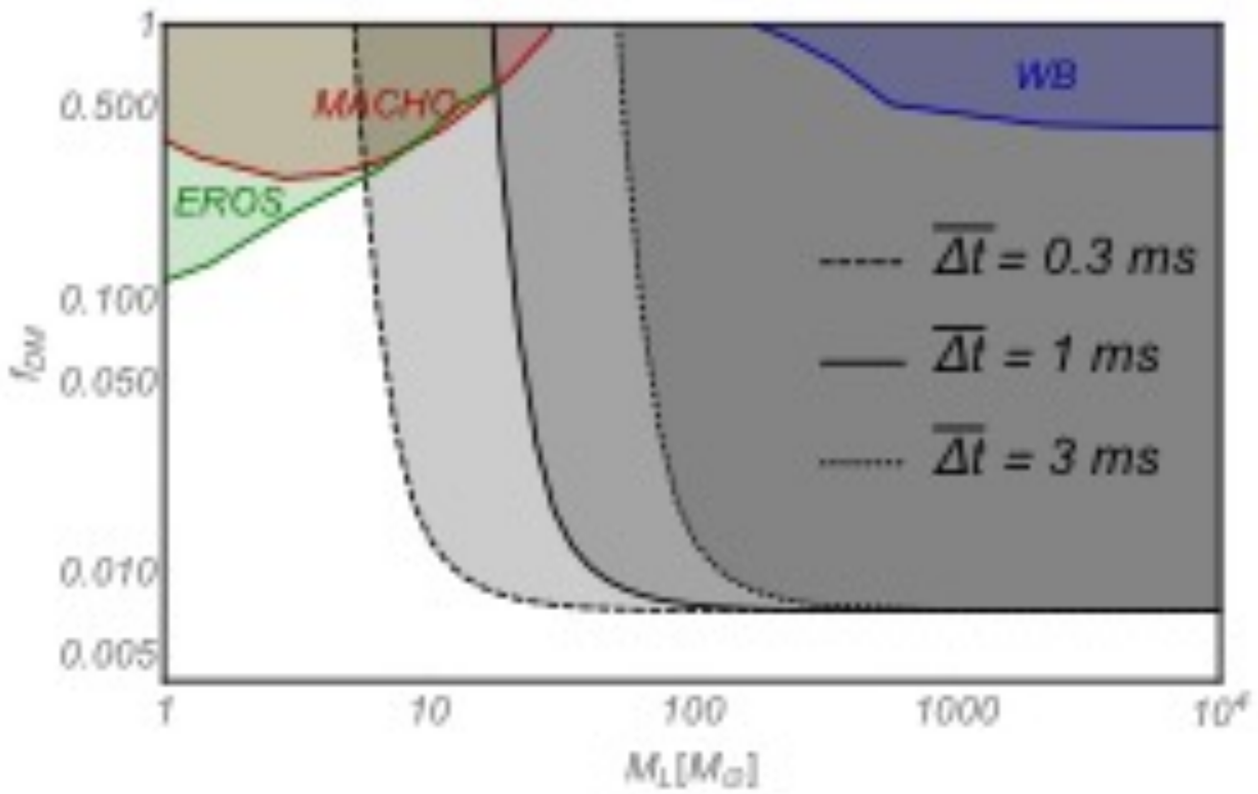


Only exclude PBHs larger than 30 M_O

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]

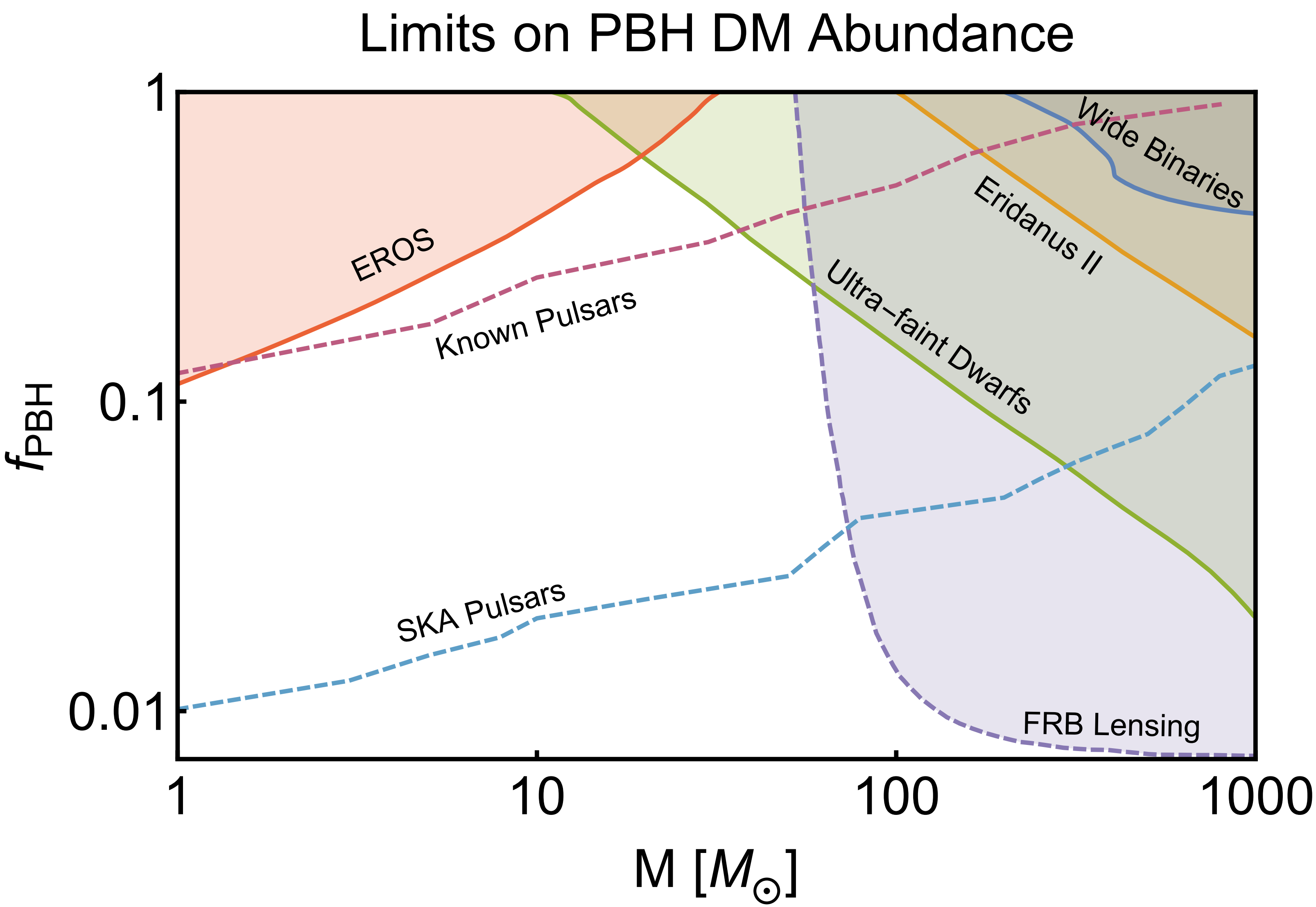
arXiv:1605.00008



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)

PBHS AS SEEDS FOR COSMIC STRUCTURE

B.J. Carr & J. Silk

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

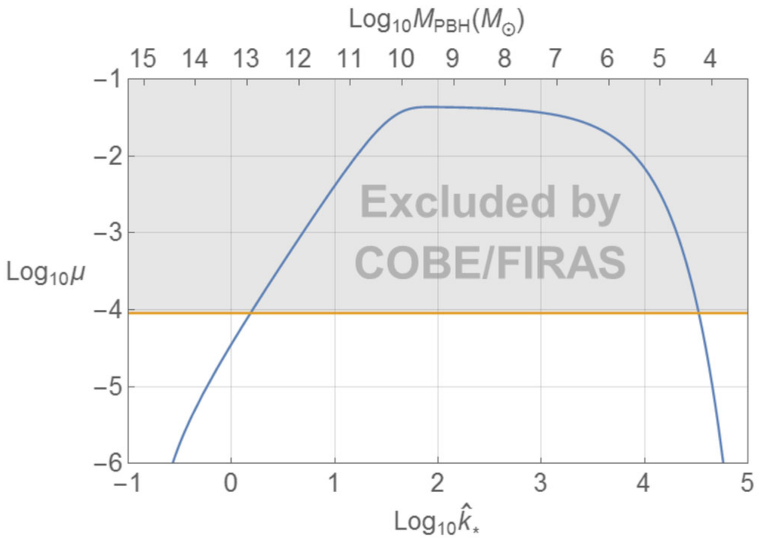
Upper limit on μ distortion of CMB excludes $10^4 < M/M_O < 10^{13}$ for Gaussian fluctuations (Kohri et al. 2014)

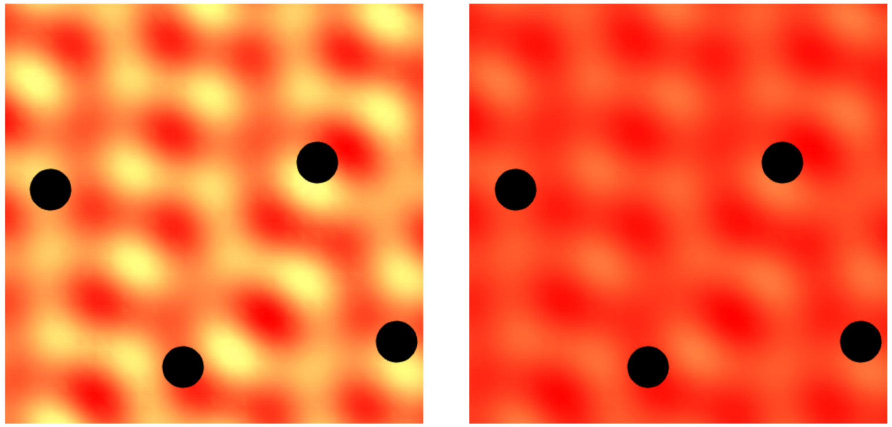
But patch model evades these limits (Nakama et al 2016)

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]





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, $m < 10^3 M_O \Rightarrow M < 10^{11} z_B^{-2} M_O < M_{gal}$

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)

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

and core density profile $\rho(r) \propto r^{-9/4}$

For extended mass function, predict

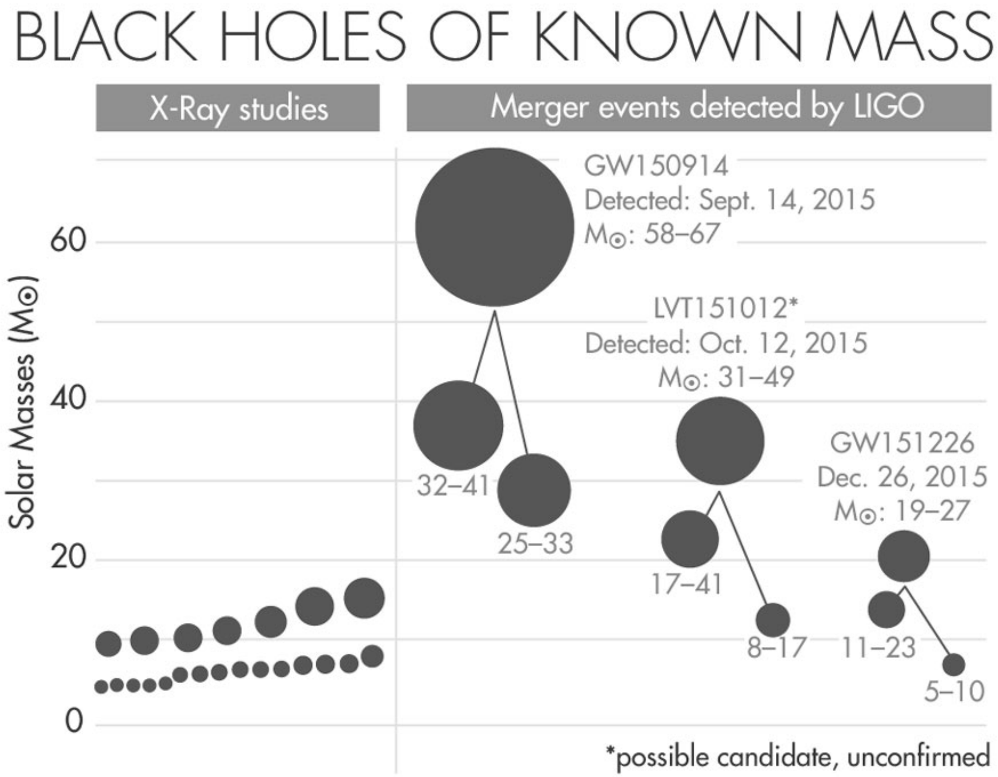
$$t_B(M) \sim t_{eq} \left[\frac{M}{m_{seed}(M)}\right]^{3/2} \propto \left(\frac{M}{m_{dm}}\right)^{3(\alpha-2)/2(\alpha-1)}$$

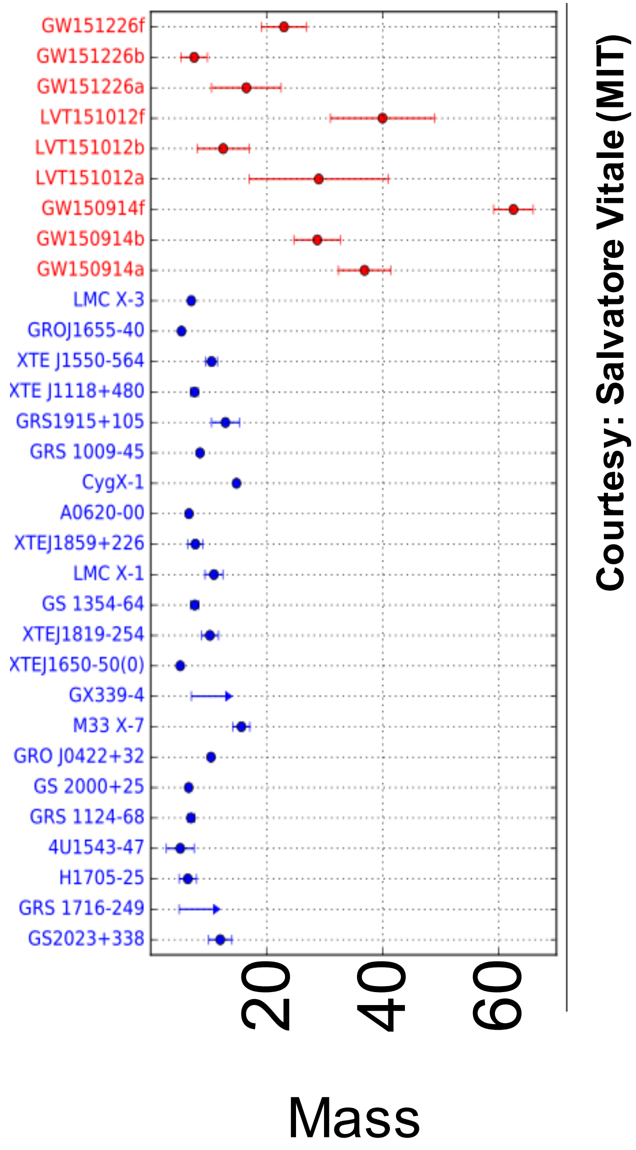
Massive Primordial Black Holes from Hybrid Inflation as Dark Matter and the seeds of Galaxies

Sébastien Clesse[1,*] and Juan García-Bellido[2,†] arXiv:1501.07565

PBHS AND LIGO

(Smoot slide)





Do we need Pop III or primordial BHs?

IOKA TALK

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

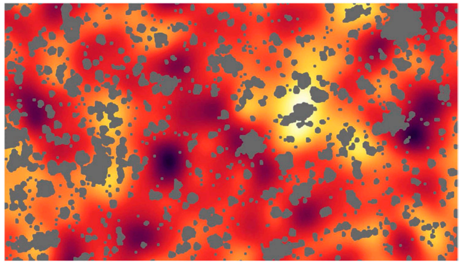
Similar f constraint and comparable to limits from CMB distortion

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



SEBASTIEN CLESSE

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

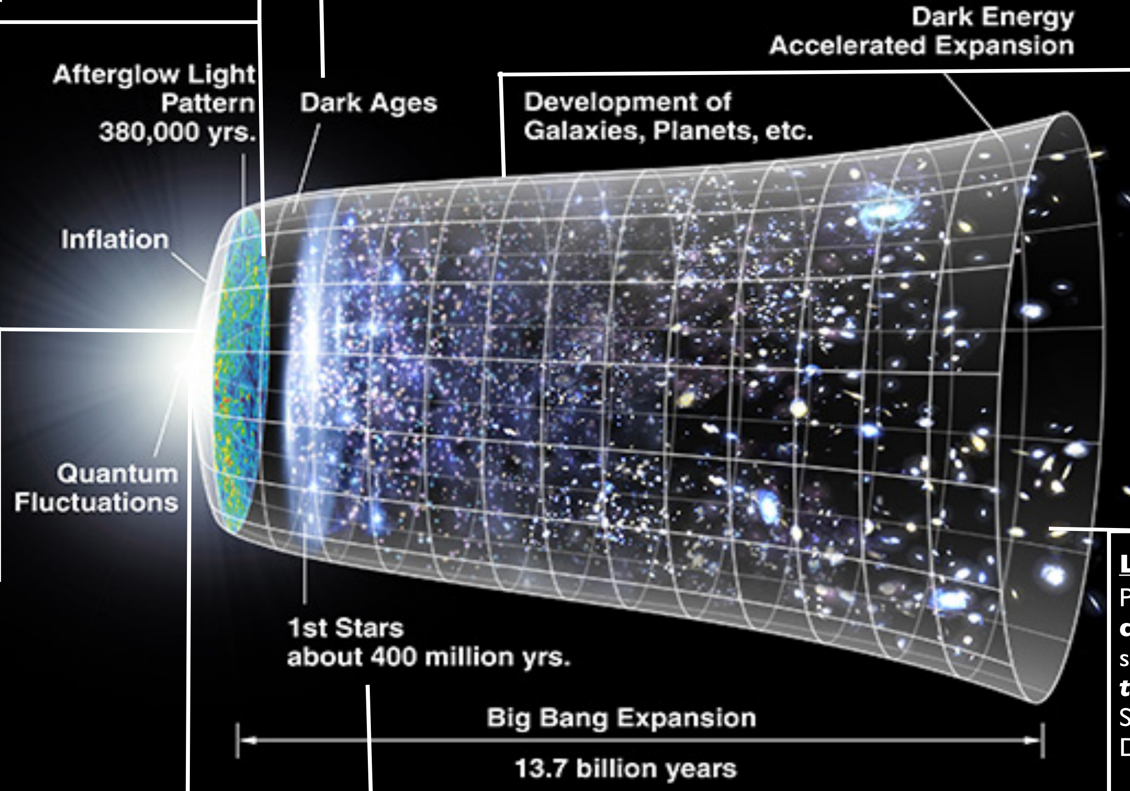
Cosmic Microwave Background:
Massive primordial black holes induce **distortions of the CMB**,. These could be probed with PIXIE.

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.