# PRIMORDIAL BLACK HOLES AS DARK MATTER

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SUSY2018, Barcelona, 26/7/18

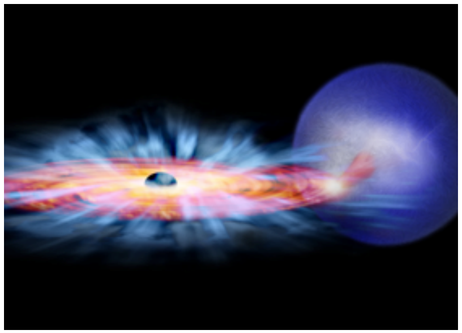
# PLAN OF TALK

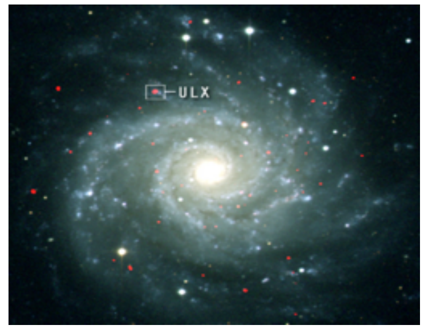
- Introduction and early history
- Formation of PBHs
- PBHs and dark matter
- PBHs and gravitational waves
- PBHs and large-scale structure

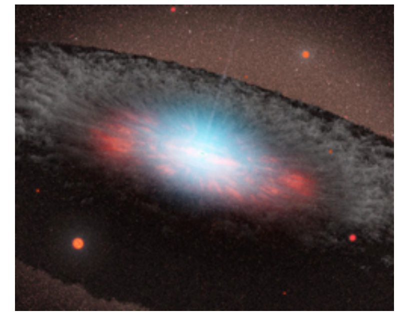
# BLACK HOLE FORMATION

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

**Stellar BH ($M \sim 10^{1-2} M_O$), IMBH ($M \sim 10^{3-5} M_O$), SMBH ($M \sim 10^{6-9} M_O$)**





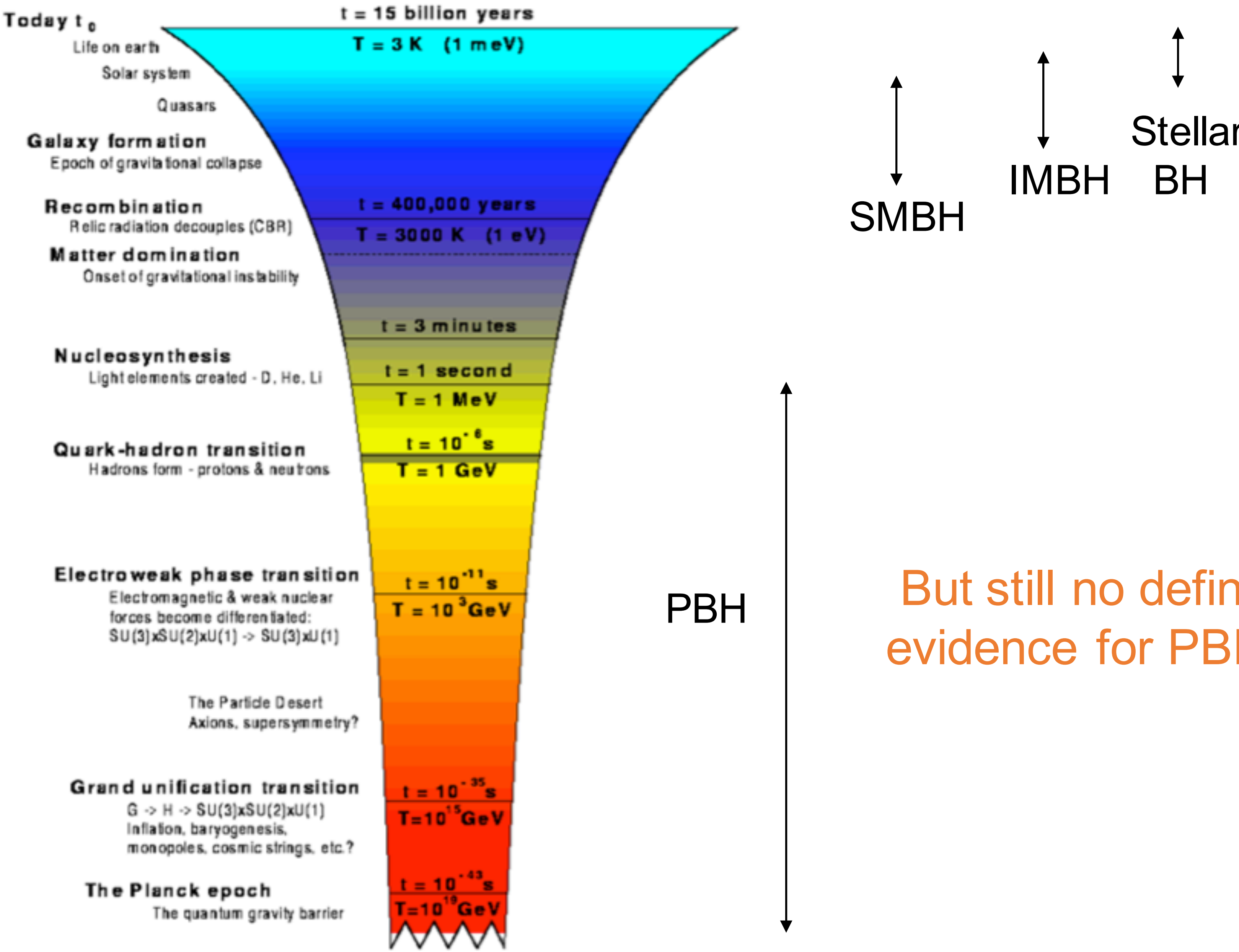



**Small "primordial" BHs can only form in early Universe**

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

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

# WHEN BLACK HOLES FORM




But still no definite evidence for PBHs

*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.

SOVIET ASTRONOMY — AJ VOL. 10, NO. 4 JANUARY-FEBRUARY, 1967

# 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.

*Mon. Not. R. astr. Soc.* (1974) **168**, 399–415.

# BLACK HOLES IN THE EARLY UNIVERSE

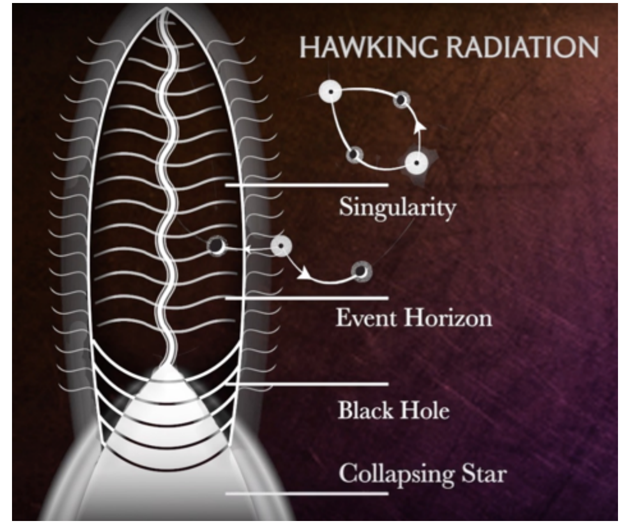
*B. J. Carr and S. W. Hawking*

(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.

$\Rightarrow$ no observational evidence against them!




letters to nature

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

# Black hole explosions?

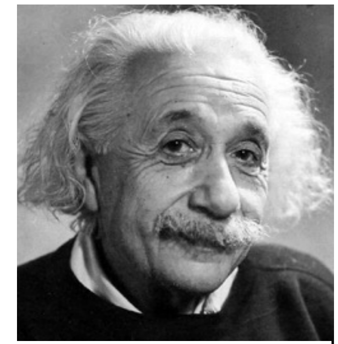
S. W. HAWKING

Department of Applied Mathematics and Theoretical Physics and Institute of Astronomy University of Cambridge

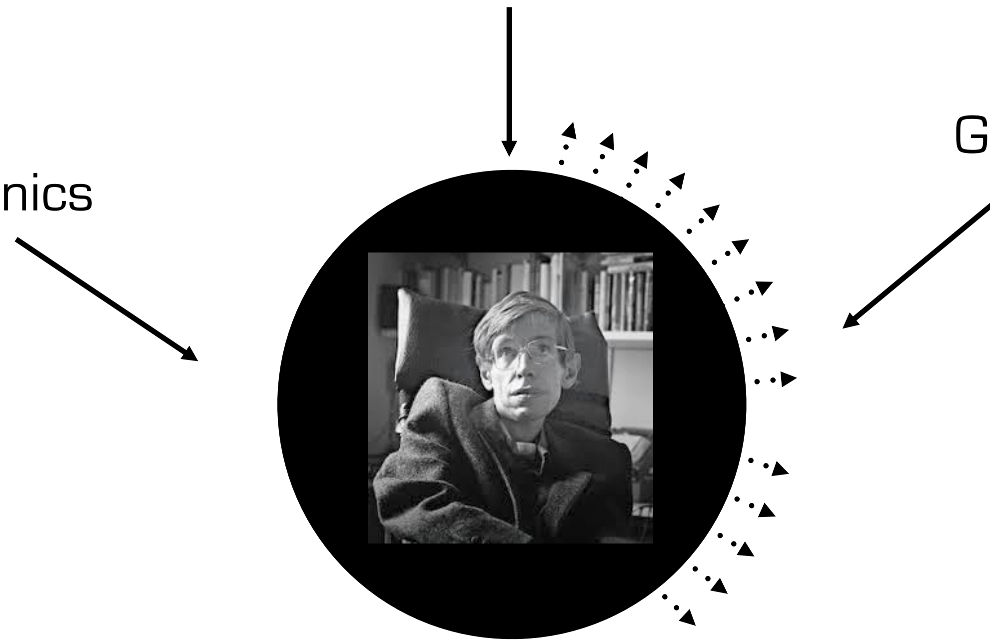
QUANTUM gravitational effects are usually ignored in calculations of the formation and evolution of black holes. The justification for this is that the radius of curvature of space-time outside the event horizon is very large compared to the Planck length $(G\hbar/c^3)^{1/2} \approx 10^{-33}$ cm, the length scale on which quantum fluctuations of the metric are expected to be of order unity. This means that the energy density of particles created by the gravitational field is small compared to the space-time curvature. Even though quantum effects may be small locally, they may still, however, add up to produce a significant effect over the lifetime of the Universe $\approx 10^{17}$ s which is very long compared to the Planck time $\approx 10^{-43}$ s. The purpose of this letter is to show that this indeed may be the case: it seems that any black hole will create and emit particles such as neutrinos or photons at just the rate that one would expect if the black hole was a body with a temperature of $(\varkappa/2\pi)(\hbar/2k) \approx 10^{-6} (M_\odot/M)K$ where $\varkappa$ is the surface gravity of the black hole[1]. As a black hole emits this thermal radiation one would expect it to lose mass. This in turn would increase the surface gravity and so increase the rate of emission. The black hole would therefore have a finite life of the order of $10^{71} (M_\odot/M)^{-3}$ s. For a black hole of solar mass this is much longer than the age of the Universe. There might, however, be much smaller black holes which were formed by fluctuations in the early Universe[2]. Any such black hole of mass less than $10^{15}$ g would have evaporated by now. Near the end of its life the rate of emission would be very high and about $10^{30}$ erg would be released in the last 0.1 s. This is a fairly small explosion by astronomical standards but it is equivalent to about 1 million 1 Mton hydrogen bombs.

Thermodynamics

Quantum Mechanics



General Relativity



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

PBHs are important even if they never formed!

# PBH EVAPORATION

**Black holes radiate thermally with temperature**

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

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

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

**$\gamma$-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**

# 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.

First paper on 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.

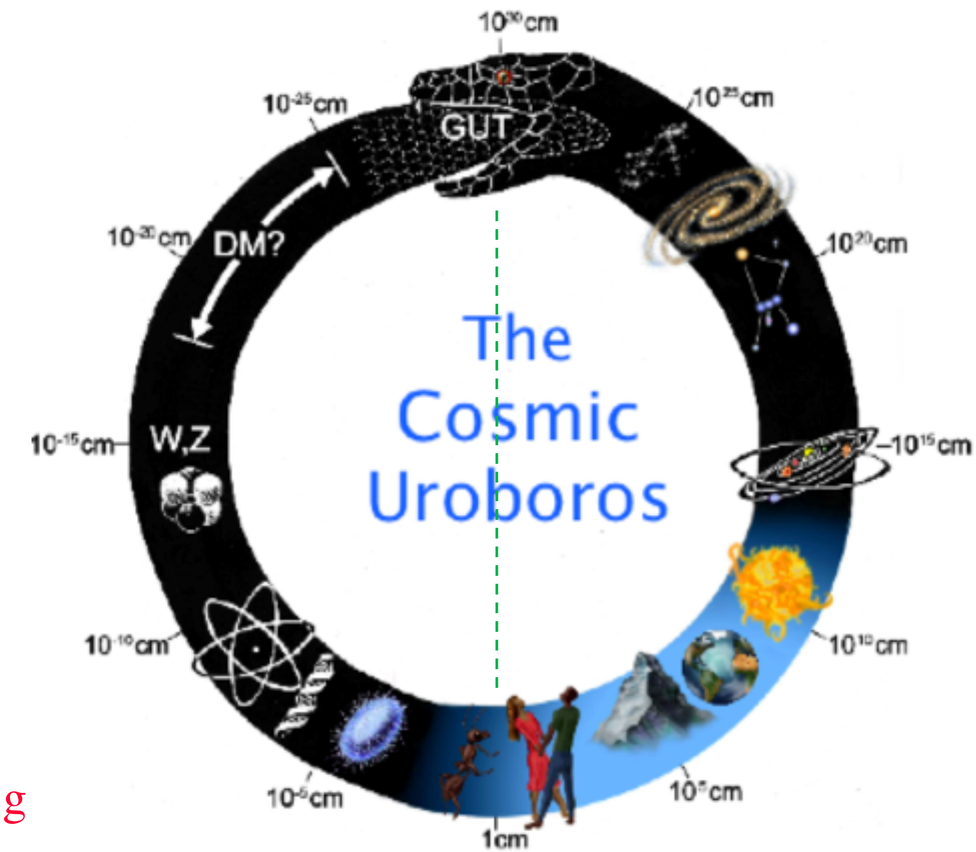
**Key words:** galaxy formation — primeval black holes — hidden mass — cosmology

Carr (1977) corrected some errors

# 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

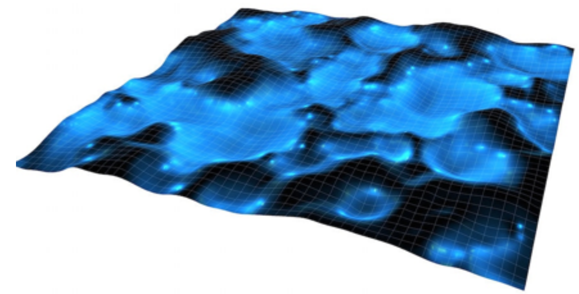
1 $M_O$ Stellar

terrestrial $10^{25}$g

QUANTUM/CLASSICAL

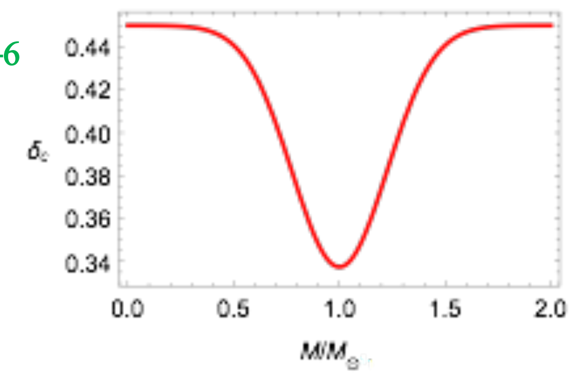
# FORMATION MECHANISMS

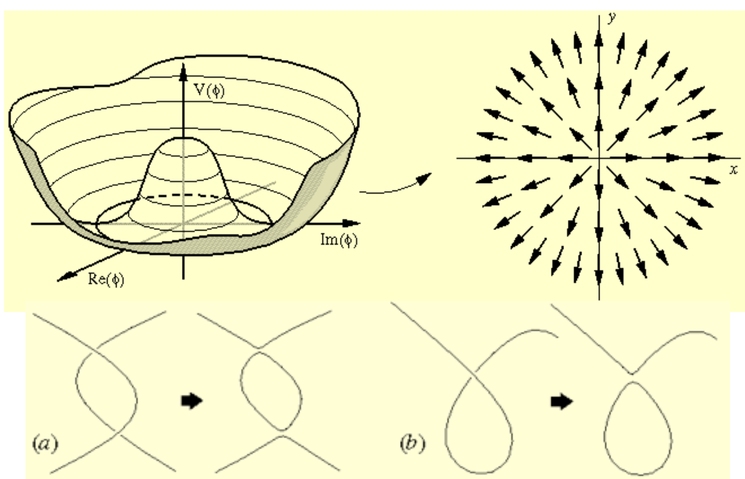
Primordial inhomogeneities Inflation

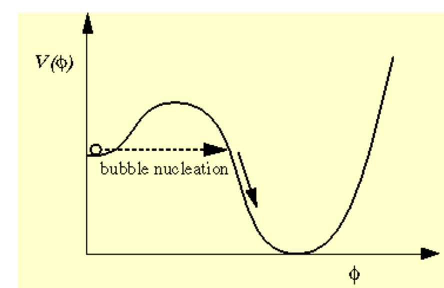


Pressure reduction Form more easily but need spherical symmetry

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



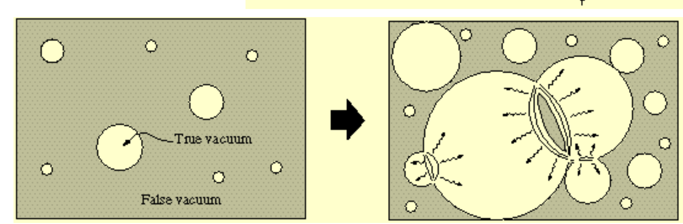




Bubble collisions

Need fine-tuning of bubble formation rate

Domain walls PBHs can be very large

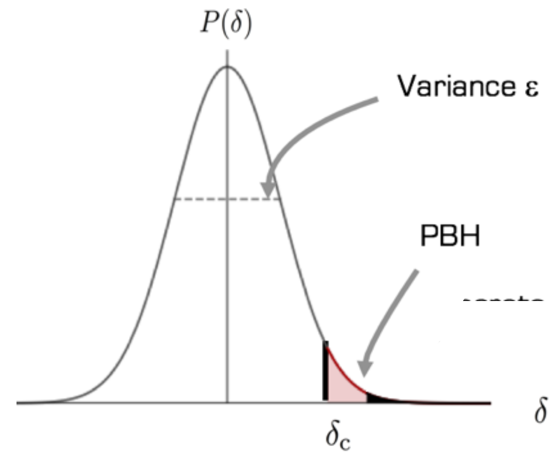


# PBH FORMATION => LARGE INHOMOGENEITIES

**To collapse against pressure, need** **(Carr 1975)**

$R > \sqrt{\alpha}\, ct$ **when $\delta \sim 1$ => $\delta_H > \alpha$** $(p = \alpha \rho c^2)$

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




**$\Rightarrow$ fraction of PBHs**

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

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

**p=0 => subhorizon holes but need spherical symmetry**

**=> $\beta(M) \sim 0.06\, \varepsilon(M)^6$** **(Khlopov & Polnarev 1982 )**

# Limit on fraction of Universe collapsing

**β(M)** **fraction of density in PBHs of mass M at formation**

**General limit**

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

**So both require and expect β(M) to be tiny => fine-tuning**

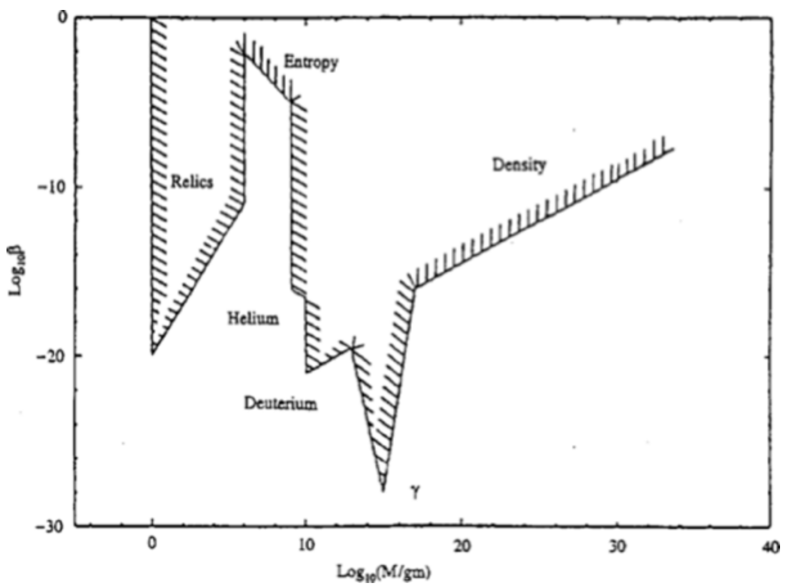
| | | |
|---|---|---|
| **Unevaporated** | $M > 10^{15}g \Rightarrow \Omega_{PBH} < 0.25$ | **(CDM)** |
| **Evaporating now** | $M \sim 10^{15}g \Rightarrow \Omega_{PBH} < 10^{-8}$ | **(GRB)** |
| **Evaporated in past** | $M < 10^{15}g$ | |

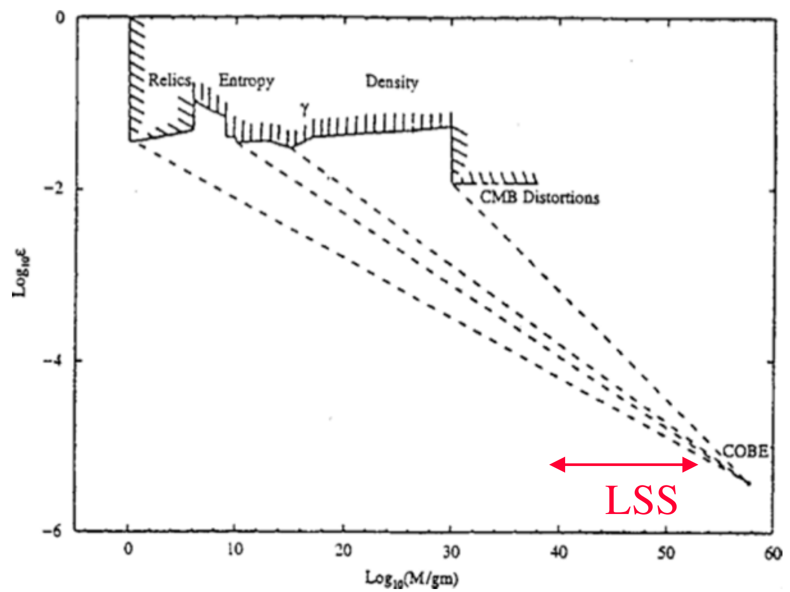
**=> constraints from entropy, γ-background, BBNS**

# PBHS AS PROBE OF PRIMORDIAL FLUCUTUATIONS

Constraints on β(M) => Constraints on ε(M)

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




Need blue spectrum or spectral feature to produce them.

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

# CONSTRAINTS FOR EVAPORATING PBHS

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

Big bang nucleosynthesis

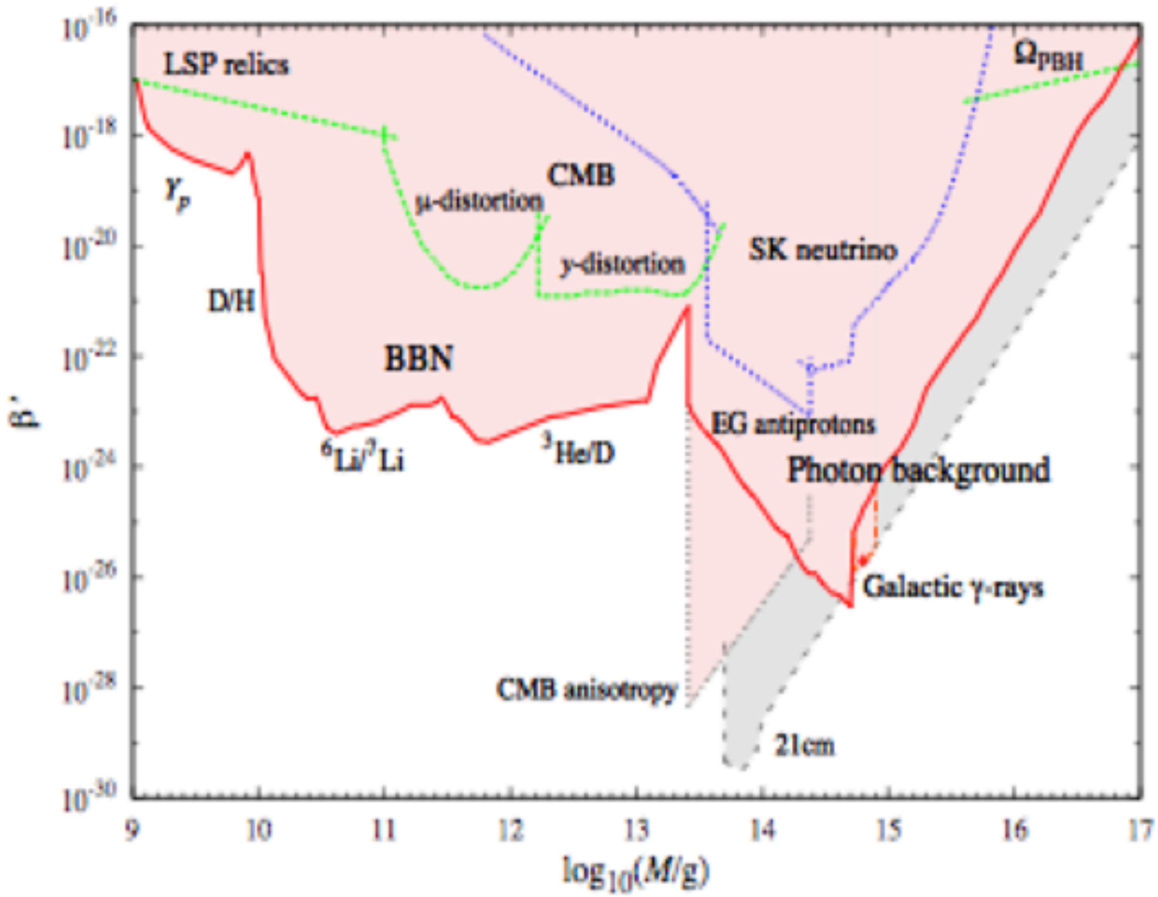
Gamma-ray background

Extragalactic cosmic rays

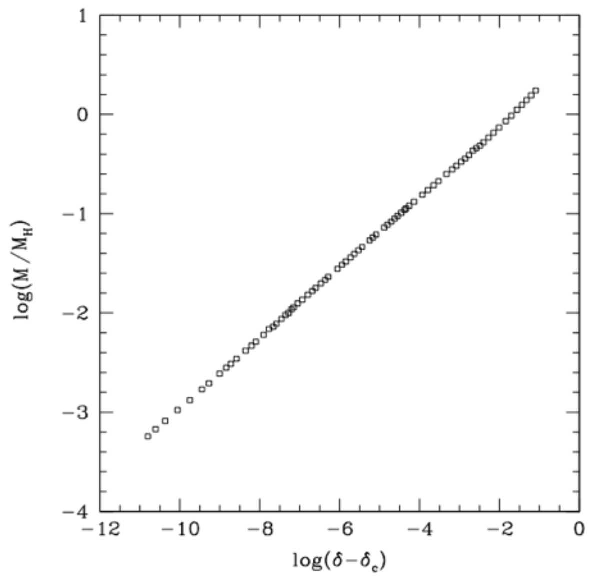
Neutrino relics

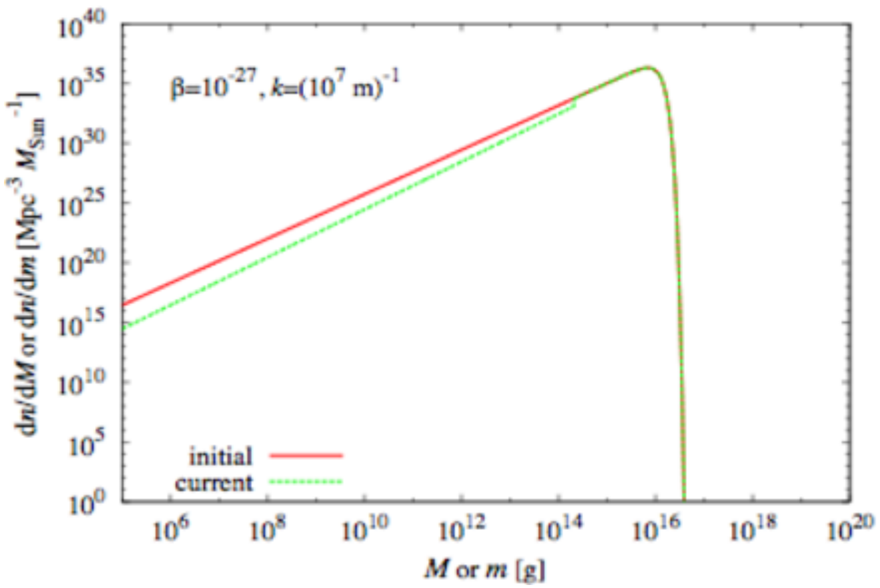
LSP relics

CMB distortions



# PBHs from near-critical collapse




=> 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?

# PBHS AND INFLATION

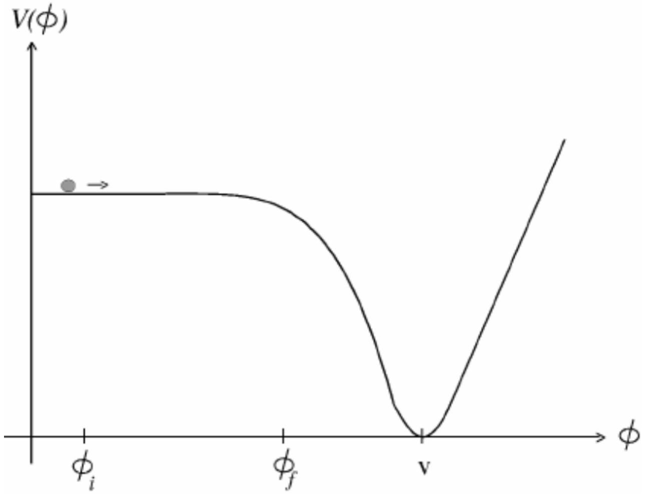
**PBHs formed before reheat inflated away =>**

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

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

**But inflation generates fluctuations**

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




**Can these generate PBHs?**

[HUGE NUMBER OF PAPERS ON THIS]

# PRIMORDIAL BLACK HOLES AS DARK MATTER

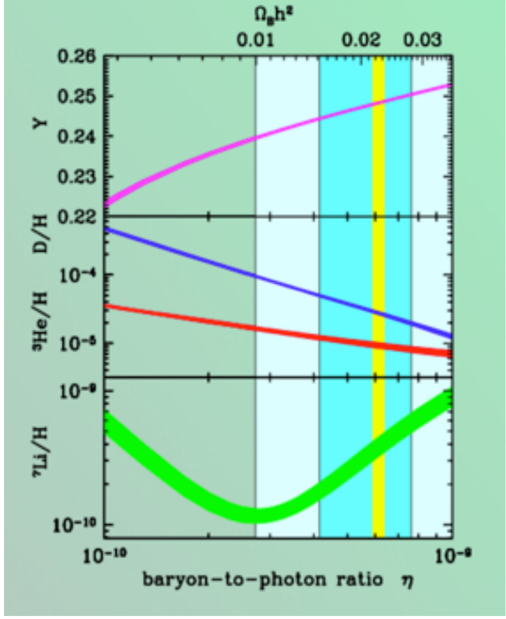
PRO

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

CON

* Requires fine-tuning

**PBH can do it!**


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

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

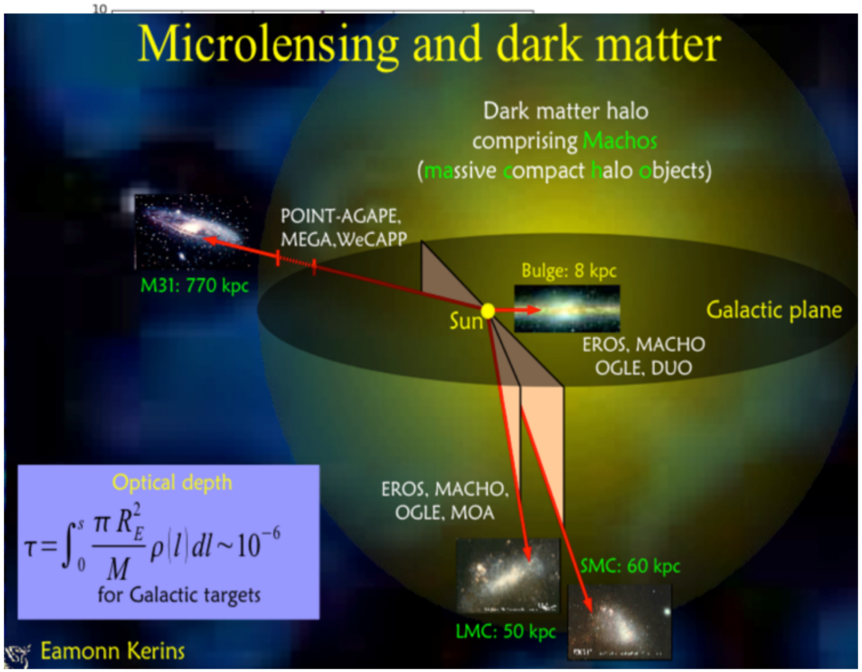
MACHOs WIMPs

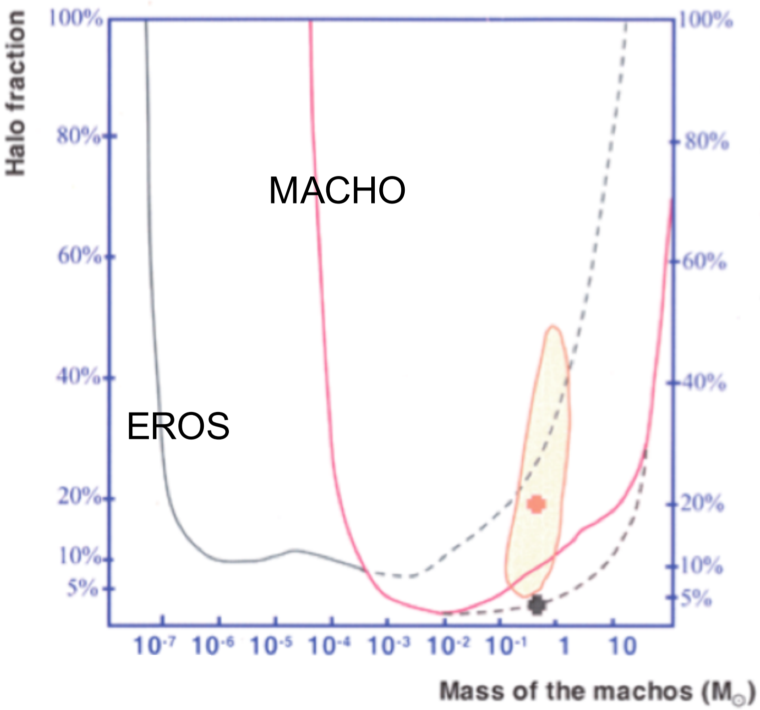
PBHs are non-baryonic with features of both WIMPs and MACHOs

$10^{17}$-$10^{20}$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

Asteroid Sublunar Intermediate Mass




Early microlensing searches suggested MACHOs with 0.5 $M_O$

=> PBH formation at QCD transition?

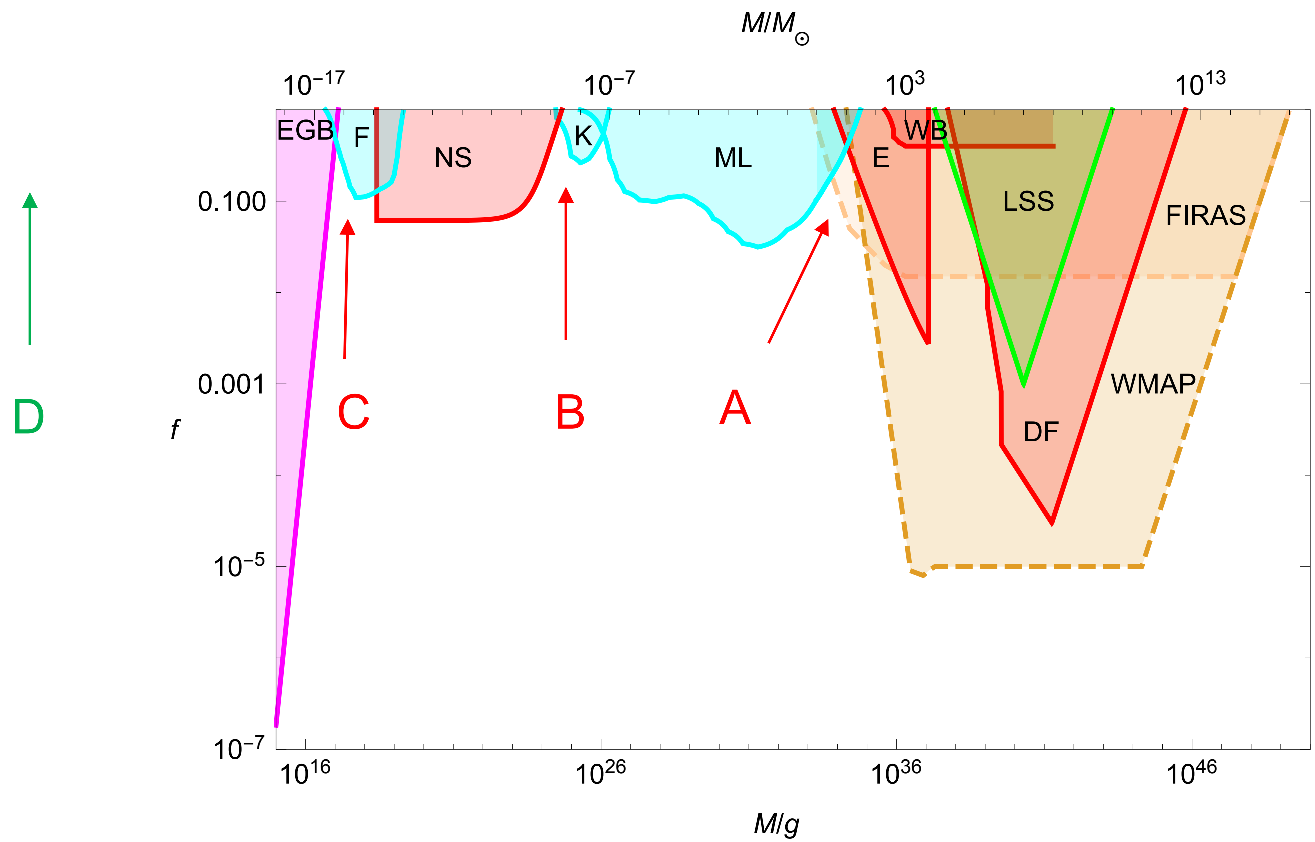
Pressure reduction => PBH mass function peak at 0.5 $M_O$

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

# PRIMORDIAL BLACK HOLES AS DARK MATTER

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

PRD 94, 083504, arXiv:1607.06077



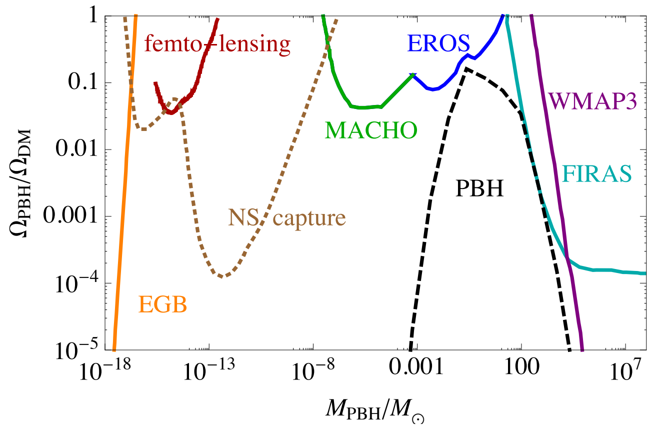

Three windows: (A) intermedate mass; (B) sublunar mass; (C) asteroid mass.

Also (D) Planck mass relics?

# WHICH MASS WINDOW IS MOST PLAUSIBLE?

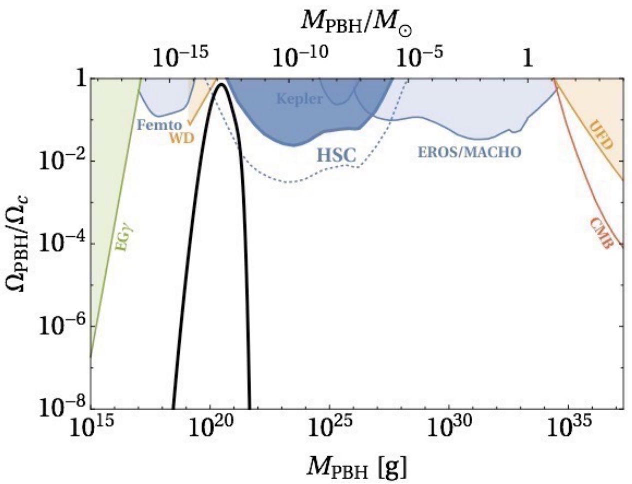
PBH dark matter @10 $M_o$
from hybrid inflation

Clesse & Garcia-Bellido
arXiv:1501.07565




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

Inomata et al
arXiv:1701.02544

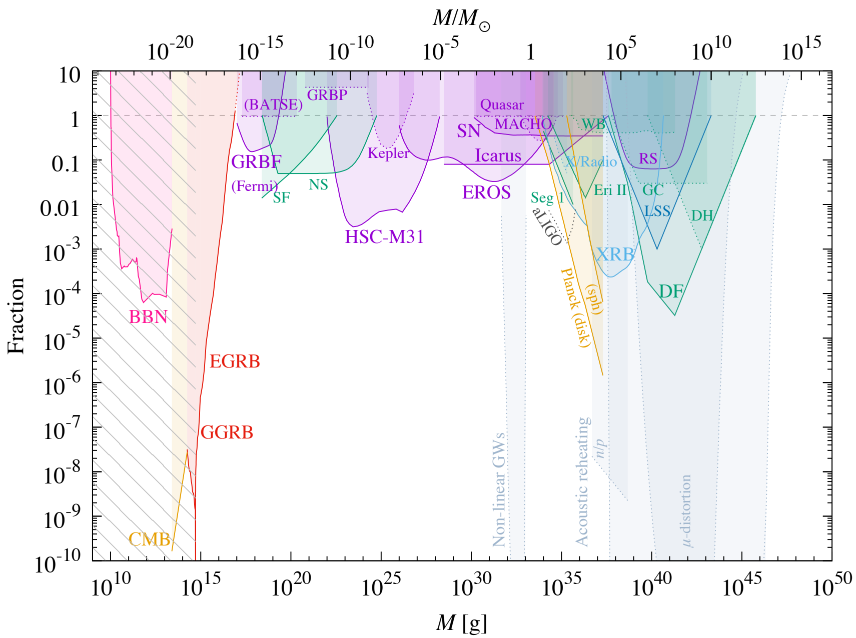


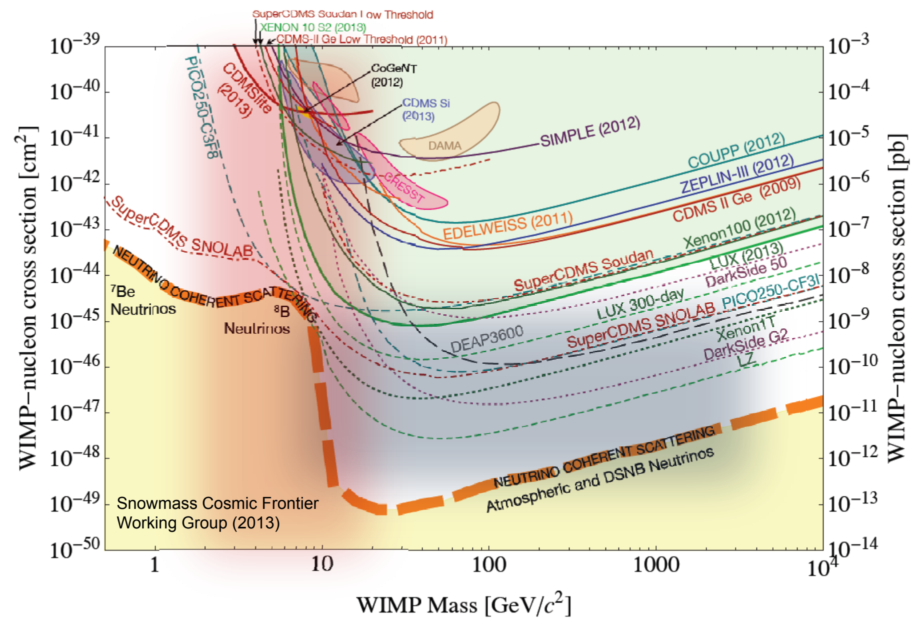

cf. heavy versus light dark matter particle

# CONSTRAINTS ON PRIMORDIAL BLACK HOLES

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

Progress Theoretical Physics (2018)




Each constraint comes with caveats and may improve or go away.

Still no definite evidence, although some affects claimed to be PBH signature.

cf. constraints on particle dark matter

CKS 2016

## EXTENDED MASS FUNCTION?

Most constraints assume monochromatic PBH mass function

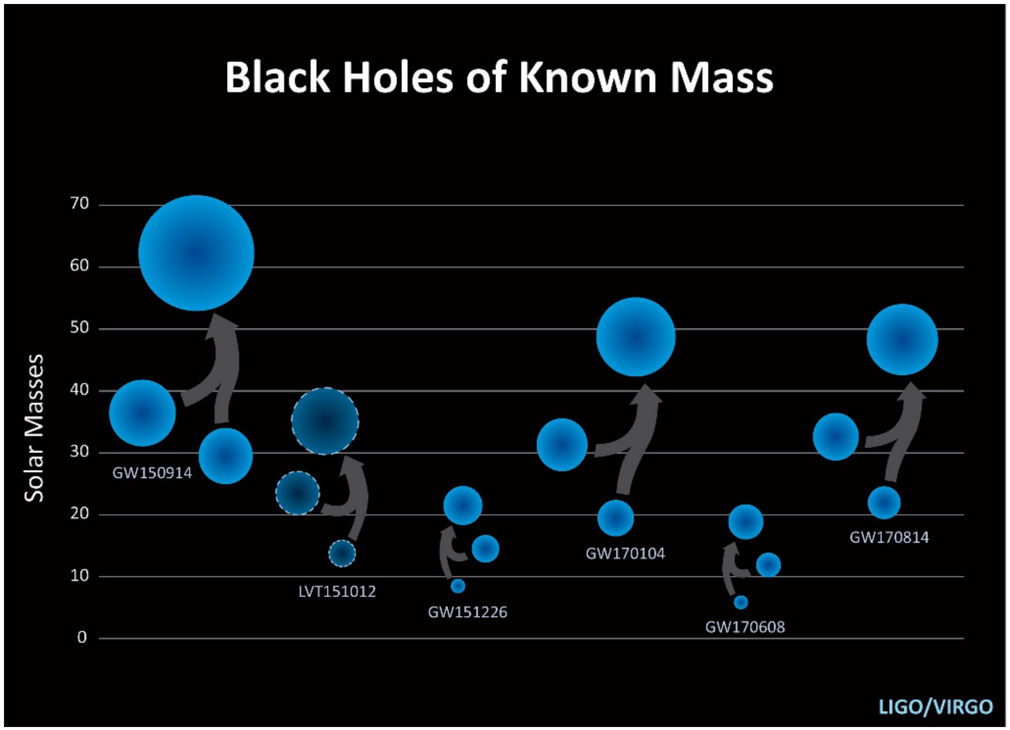
Can we evade standard limits with extended mass spectrum?

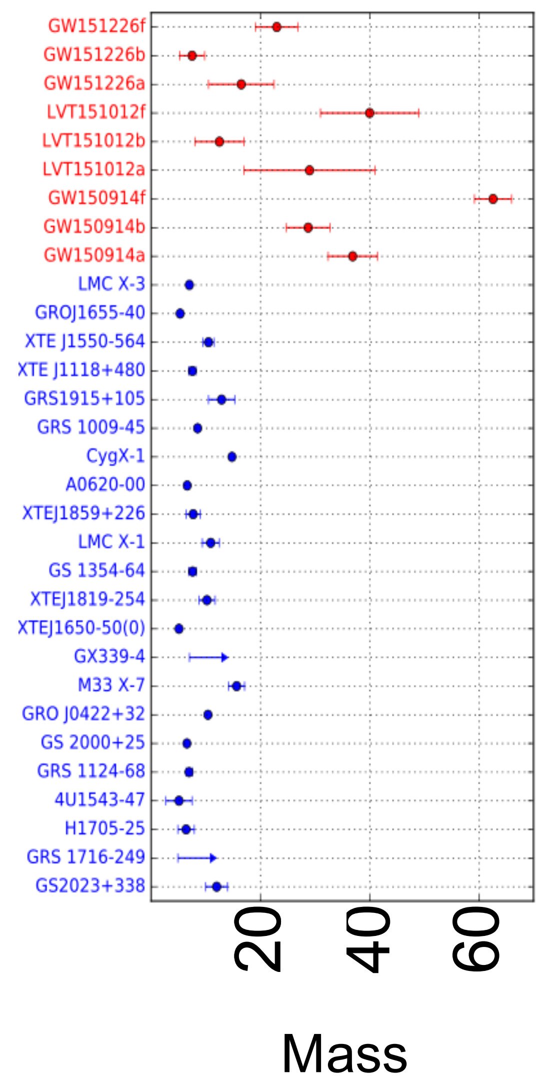
But this is two-edged sword!

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

# PBHS AND LIGO




Courtesy: Salvatore Vitale (MIT)

Do we need Pop III or primordial BHs?

THE ASTROPHYSICAL JOURNAL, 487:L139–L142, 1997

# GRAVITATIONAL WAVES FROM COALESCING BLACK HOLE MACHO BINARIES

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*Received 1997 April 11; accepted 1997 July 23; published 1997 September 2*

## ABSTRACT

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

# Possible indirect confirmation of the existence of Pop III massive stars by gravitational wave

Tomoya Kinugawa,* Kohei Inayoshi, Kenta Hotokezaka, Daisuke Nakauchi and Takashi Nakamura

MNRAS **442,** 2963–2992 (2014)

We perform population synthesis simulations for Population III (Pop III) coalescing compact binary which merges within the age of the Universe. We found that the typical mass of Pop III binary black holes (BH–BHs) is $\sim 30\,M_\odot$ so that the inspiral chirp signal of gravitational waves can be detected up to $z = 0.28$ by KAGRA, Adv. LIGO, Adv. Virgo and GEO network. Our simulations suggest that the detection rate of the coalescing Pop III BH–BHs is 140(68) events $yr^{-1}$ $(SFR_p/(10^{-2.5}\,M_\odot\,yr^{-1}\,Mpc^{-3})) \cdot Err_{sys}$ for the flat (Salpeter) initial mass function, respectively, where $SFR_p$ and $Err_{sys}$ are the peak value of the Pop III star formation rate and the possible systematic errors due to the assumptions in Pop III population synthesis, respectively. $Err_{sys} = 1$ corresponds to conventional parameters for Pop I stars. From the observation of the chirp signal of the coalescing Pop III BH–BHs, we can determine both the mass and the redshift of the binary for the cosmological parameters determined by the *Planck* satellite. Our simulations suggest that the cumulative redshift distribution of the coalescing Pop III BH–BHs depends almost only on the cosmological parameters. We might be able to confirm the existence of Pop III massive stars of mass $\sim 30\,M_\odot$ by the detections of gravitational waves if the merger rate of the Pop III massive BH–BHs dominates that of Pop I BH–BHs.

Prediction <u>before</u> LIGO discovery

## 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 $M_O$ binaries may provide observed rate of 2-53 $Gpc^{-1}yr^{-1}$

## Primordial Black Hole Scenario for the Gravitational-Wave Event GW150914

Misao Sasaki,[1] Teruaki Suyama,[2] Takahiro Tanaka,[3,1] and Shuichiro Yokoyama[4]

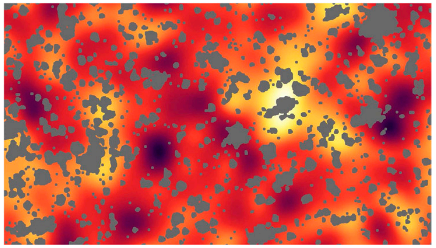
arXiv:1603.08338

Only need small f and comparable to limits from CMB distortion

## LIGO gravitational wave detection, primordial black holes and the near-IR cosmic infrared background anisotropies

A. Kashlinsky[1],

arXiv:1605.04023



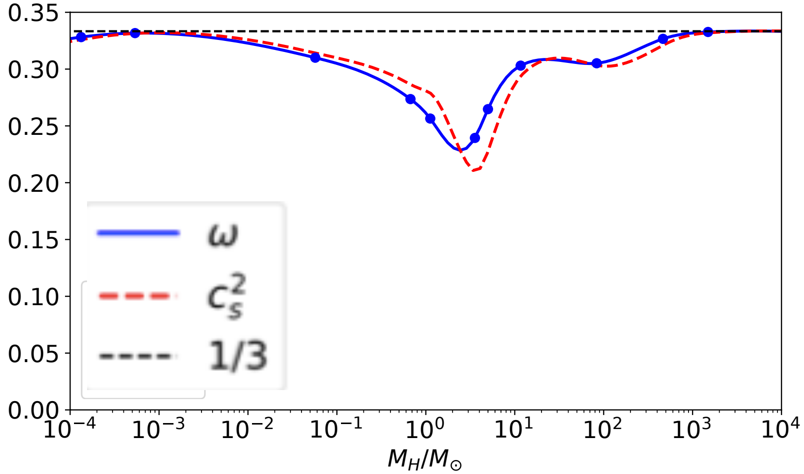
PBHs generate early structure => infrared background

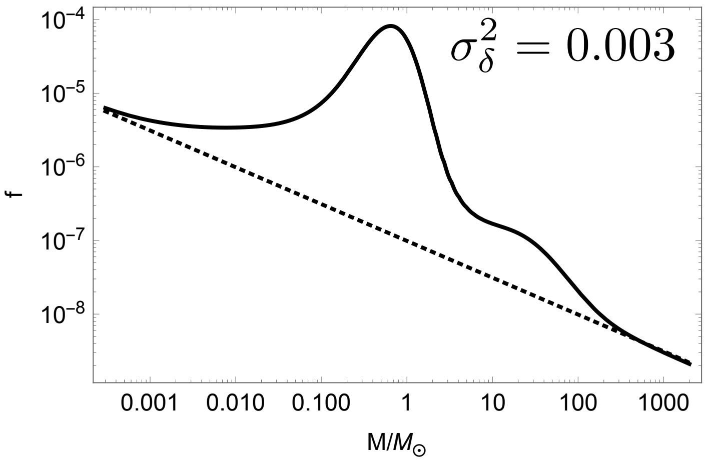
## Primordial black holes with an accurate QCD equation of state

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

arXiv:1801.06138

$$f(M) \propto M^{-1/2} e^{-\frac{\delta_c^2}{2\sigma_\delta^2}}$$




Explains why $M_{PBH} \sim M_C \sim 1\ M_o$ but also need $\beta \sim S^{-1}$

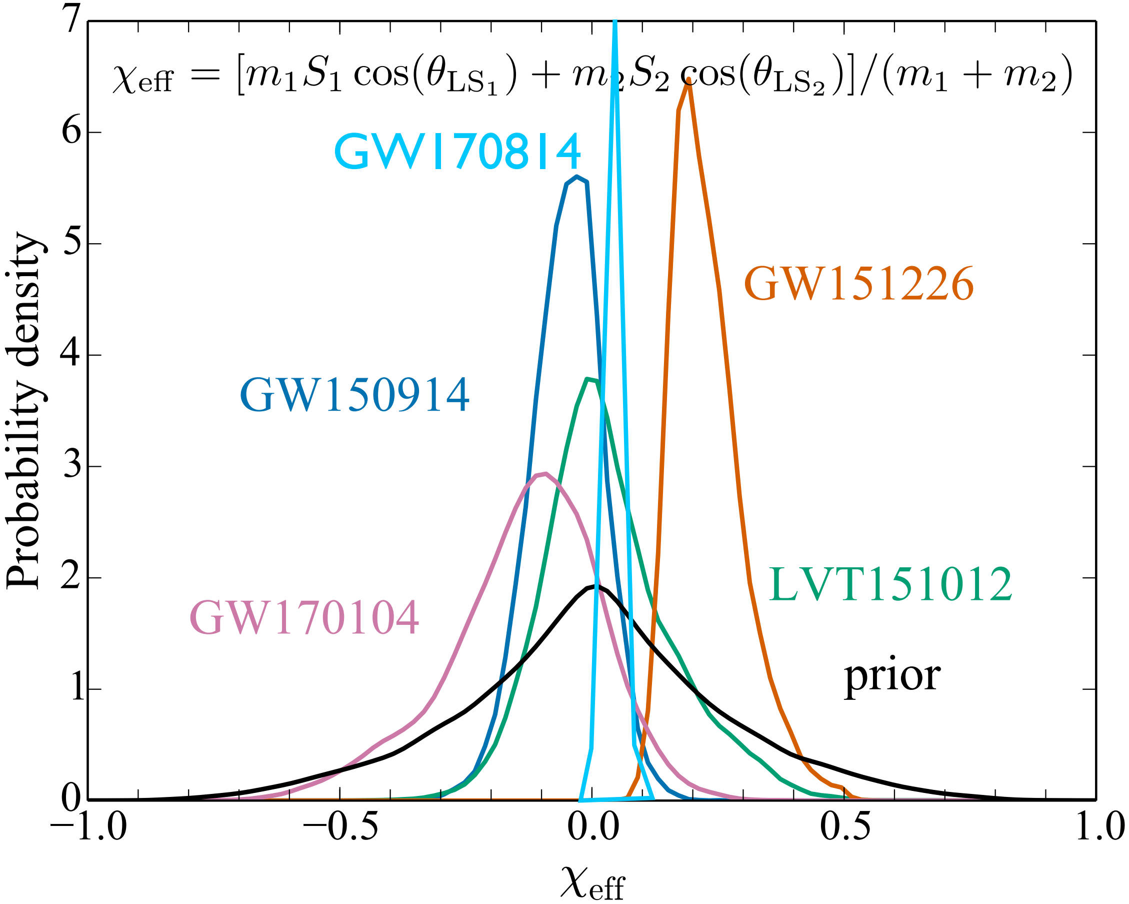
# Primordial black holes in the axion-like curvature model and the LIGO events

K Ando, K Inomata, M Kawasaki, K Mukaida, T Yanagida

For a realistic scenario of inflationary primordial black holes (PBHs), a highly blue-tilted power spectrum of primordial perturbations is required. In the axion-like curvaton model, which is base on the supersymmetric axion model, such a spectrum is achieved. I will show that PBHs formed in this model can explain the massive black holes implied by the LIGO gravitational wave (GW) events. Large scalar curvature perturbations induce primordial GWs via the second-order effects, and they are compared with the constraints from the pulsar timing array experiments. In calculating the secondary GWs, it is important to take into account the effect of non-Gaussianity that a fixed amount of PBHs can be produced by a smaller power spectrum.

THIS MEETING

# Hint from spin of LIGO black holes?



# PBHS AS GENERATORS OF COSMIC STRUCTURES

B.J. Carr & J. Silk

arXiv:1801.00672

What is maximum mass of PBH?

Could $10^6$ -$10^{10}$ $M_O$ black holes in galactic nuclei be primordial?

BBNS => $t < 1$ s => $M < 10^5 M_O$ .....but $\beta < 10^{-6} (t/s)^{1/2}$

Supermassive PBHs could also generate cosmic structures on larger scale through 'seed' or 'Poisson' effect

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

# SEED AND POISSON FLUCTUATIONS

PBHs larger than $10^2 M_O$ cannot provide dark matter but can affect large-scale structure through seed effect on small scales or Poisson effect on large scales even if f small.

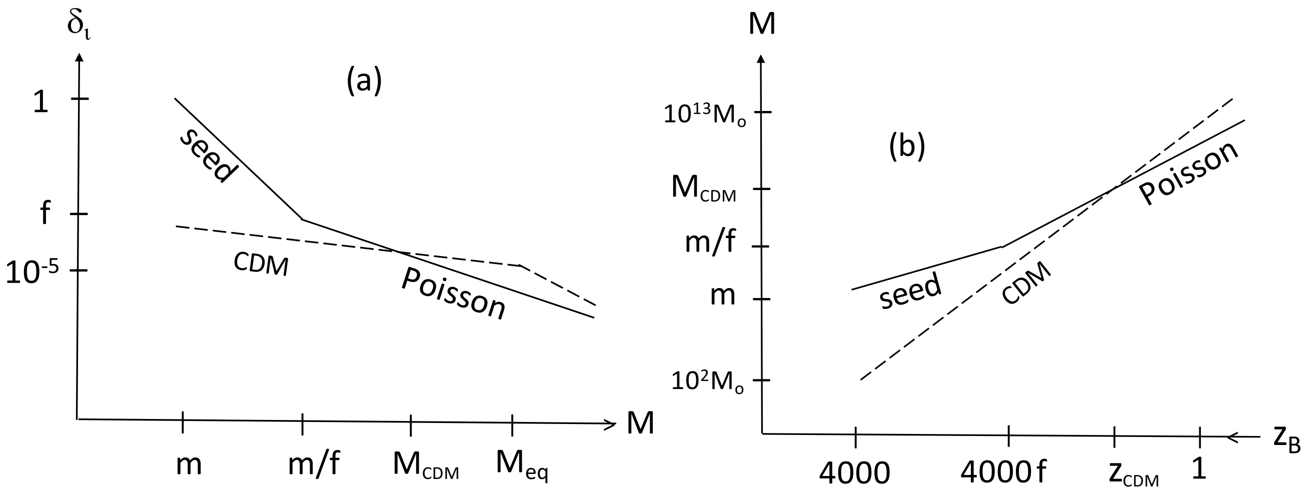
If region of mass M contains PBHs of mass m, initial fluctuation is

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

f = 1 => Poisson dominates; f <<1 => seed dominates for M < m/f.
Fluctuation grows as $z^{-1}$ from $z_{eq} \sim 10^4$, so mass binding at $z_B$ is

$$M \approx \begin{cases} 4000\, m z_B^{-1} & \text{(seed)} \\ 10^7 f m z_B^{-2} & \text{(Poisson)} \end{cases}$$

# SEED VERSUS POISSON




cf. CDM fluctuations

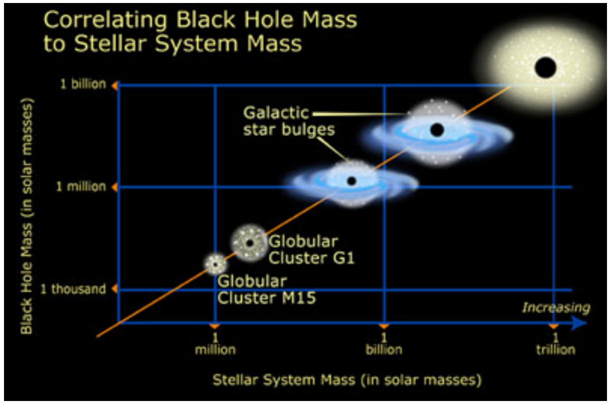
$$\delta_{eq} \propto \begin{cases} M^{-1/3} & (M < M_{eq}) \\ M^{-2/3} & (M > M_{eq}) \end{cases}$$

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

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

Extended PBH mass function => DM <u>and</u> cosmic structures

# SUPERMASSIVE PBHS AS SEEDS FOR GALAXIES




Seed effect => $M_B \sim 10^3$ m $(z_B/10)$

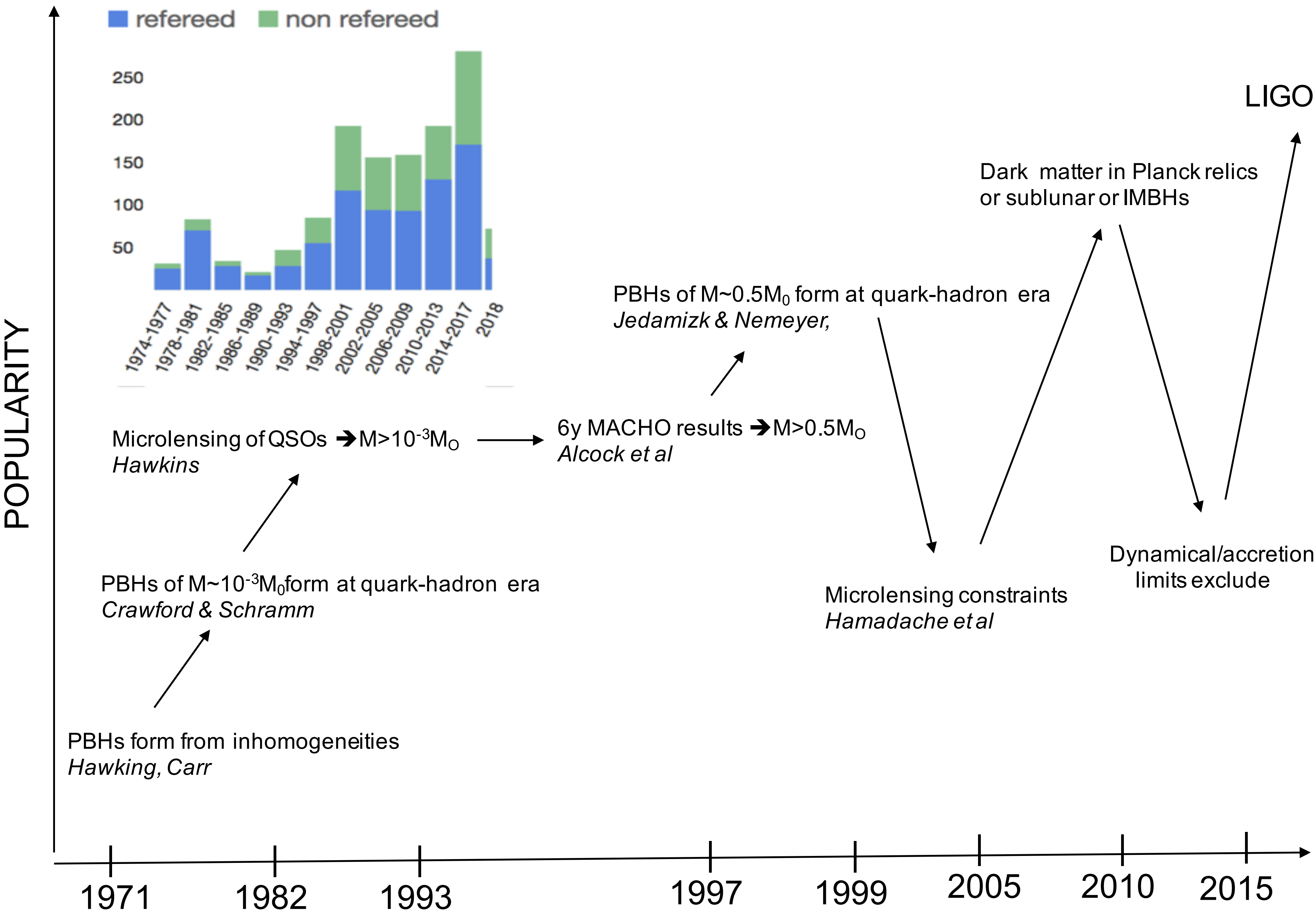
$\Rightarrow$ naturally explain $M_{BH}/M_{bulge}$ relation

Also predict mass function of galaxies (cf. Press-Schechter)

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

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

=> diverges by now for $m_i > M_{eq}(t_{eq}/t_o) \sim 10^{10} M_\odot$



refereed
non refereed
250
200
150
100
50
1974-1977
1978-1981
1982-1985
1986-1989
1990-1993
1994-1997
1998-2001
2002-2005
2006-2009
2010-2013
2014-2017
2018
POPULARITY
LIGO
Dark matter in Planck relics or sublunar or IMBHs
PBHs of $M \sim 0.5 M_0$ form at quark-hadron era
*Jedamizk & Nemeyer,*
6y MACHO results ➔ $M > 0.5 M_O$
*Alcock et al*
Microlensing of QSOs ➔ $M > 10^{-3} M_O$
*Hawkins*
PBHs of $M \sim 10^{-3} M_0$ form at quark-hadron era
*Crawford & Schramm*
Microlensing constraints
*Hamadache et al*
Dynamical/accretion limits exclude
PBHs form from inhomogeneities
*Hawking, Carr*
1971
1982
1993
1997
1999
2005
2010
2015

# CONCLUSIONS

PBHs have been invoked for three roles

| Dark matter | LIGO events | Cosmic structure |
|---|---|---|

These are distinct roles but with an extended mass function PBHs could possibly fulfill all three.

This talk is dedicated to the memory of Stephen Hawking, He was a pioneer of primordial black holes. If they play any of the roles discussed in this talk, this may have been his most prescient and important work