PRIMORDIAL BLACK HOLES
AS SEEDS FOR COSMIC STRUCTURE

Bernard Carr
Queen Mary, University of London

Cumberland Lodge (9/4/19)

PERSONAL TRIBUTE TO OFER

I've known Ofer since we met in Cambridge in 1985. I was a postdoc and he was a new PhD student but he'd already written a paper on Population III stars.

Cooling of Population III objects in a pressure supported collapse

Ofer Lahav* *Physics Department, Ben-Gurion University, Beer-Sheva, Israel*

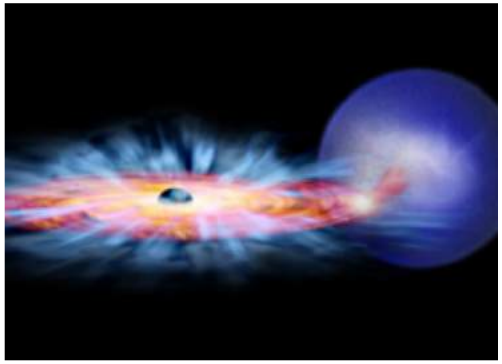
Mon. Not. R. astr. Soc. (1986) **220,** 259–269

This was one of my own research interests, so I regarded him as a natural ally. Although we never wrote any papers together, he once presented a talk on my behalf at a conference and people found my ideas much more plausible after that!

What we also have in common is that we both moved from Cambridge to London. Besides his huge contribution to London cosmology, this meant we could continue our friendship and we once spent Christmas together with my wife's family in Tokyo.

Nowadays I'm rather envious of Ofer since he studies objects which definitely exist, galaxies, while my focus is on more speculative objects, like primordial black holes. On the other hand, there's still a lot we don't understand about galaxies, whereas primordial black holes are understood rather well - even if they don't exist!

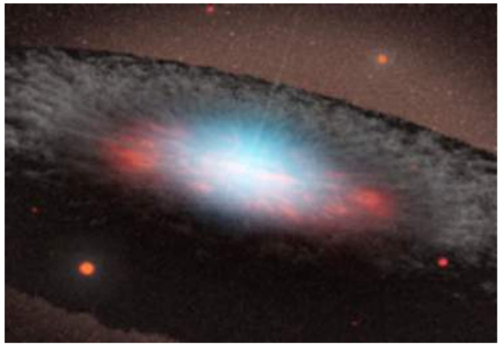
OVERWHELMING EVIDENCE FOR STELLAR BHS ($M \sim 10^{1-2} M_O$)



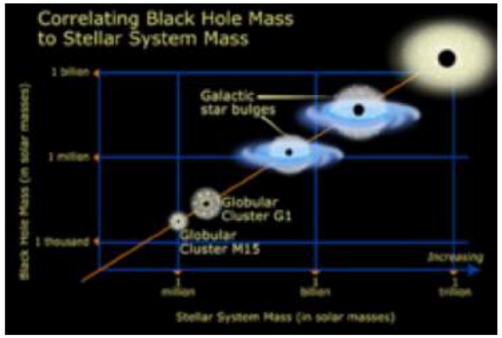
X-ray binaries
Cygnus X1

LIGO detects
gravity waves from
coalescing BHs

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



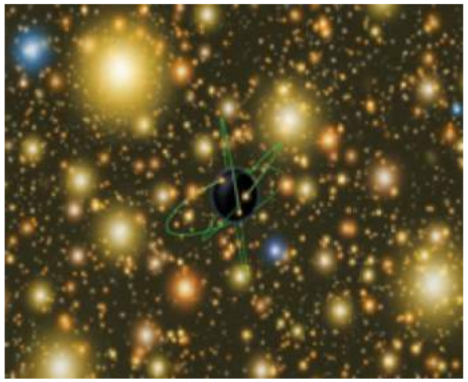
MW $4 \times 10^6 M_O$
QSO $10^8 M_O$
$1.4 \times 10^{10} M_O$
BH at z=6.3



BH mass
proportional
to stellar mass

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

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



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

PRIMORDIAL BLACK HOLE FORMATION

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

Small BHs can only form in early Universe

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

⇨ **primordial BHs with horizon mass at formation**

$M_{PBH} \sim c^3t/G =$

- 10^{-5}g at 10^{-43}s (minimum?)
- 10^{15}g at 10^{-23}s (evaporating now)
- $1M_O$ at 10^{-5}s (QCD transition)
- 10^5M_O at 1s (maximum?)

Mon. Not. R. astr. Soc. (1971) **152**, 75–78.

GRAVITATIONALLY COLLAPSED OBJECTS OF VERY LOW MASS

Stephen Hawking

(Communicated by M. J. Rees)

(Received 1970 November 9)

SUMMARY

It is suggested that there may be a large number of gravitationally collapsed objects of mass 10^{-5} g upwards which were formed as a result of fluctuations in the early Universe. They could carry an electric charge of up to ± 30 electron units. Such objects would produce distinctive tracks in bubble chambers and could form atoms with orbiting electrons or protons. A mass of 10^{17} g of such objects could have accumulated at the centre of a star like the Sun. If such a star later became a neutron star there would be a steady accretion of matter by a central collapsed object which could eventually swallow up the whole star in about ten million years.

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

BLACK HOLES IN THE EARLY UNIVERSE

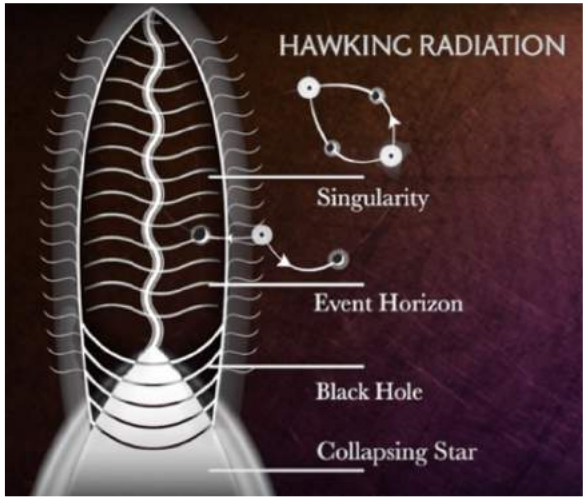
B. J. Carr and S. W. Hawking

(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?

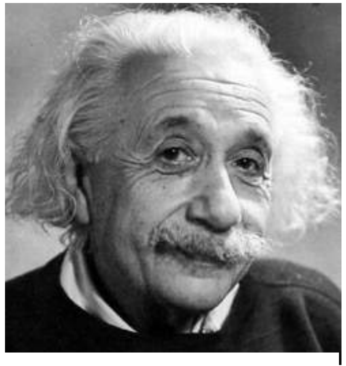
S. W. HAWKING

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

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

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

M ~ 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

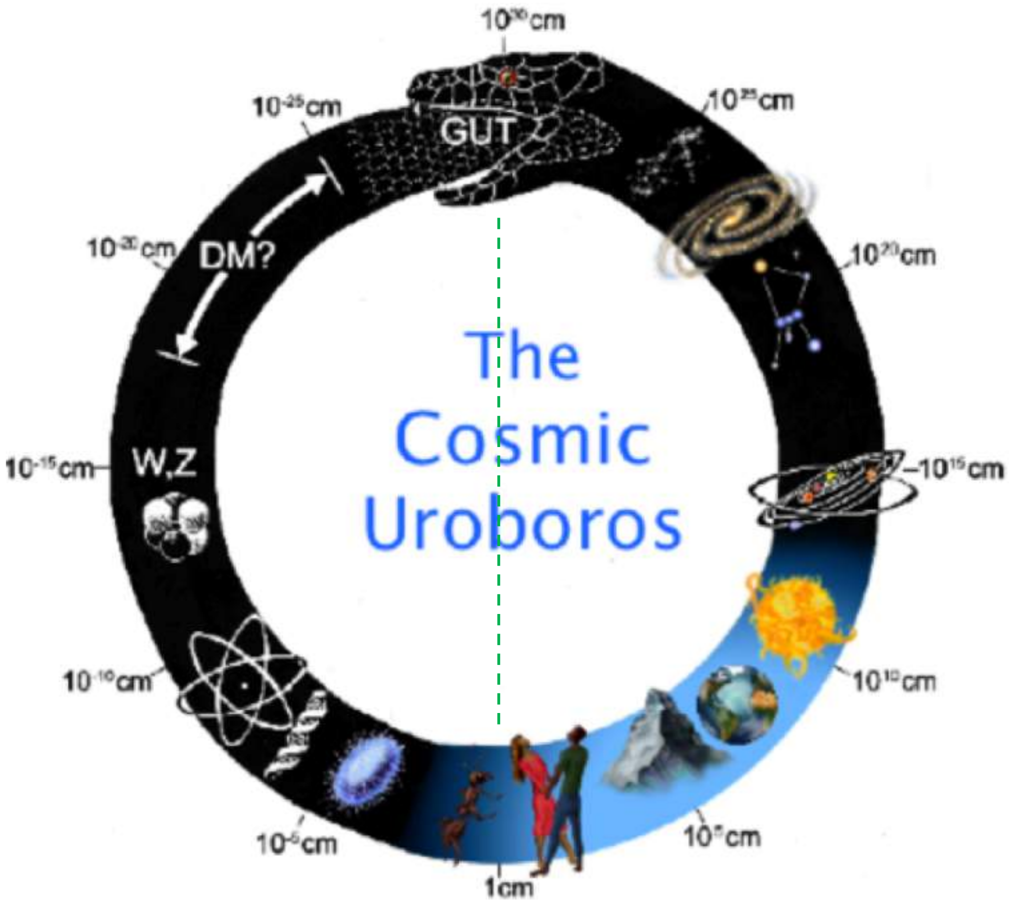
T > T_{CMB}=3K for M < 10^{26}g **=> "quantum" black holes**

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

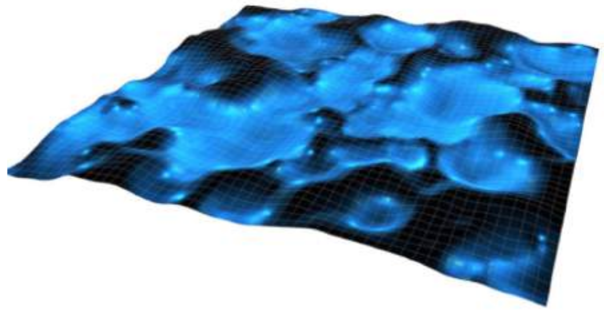
lunar 10^{21}g

1 M_O Stellar

terrestrial 10^{25}g

QUANTUM/CLASSICAL

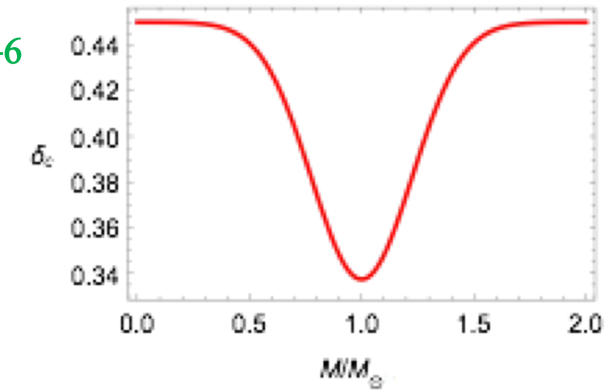
FORMATION MECHANISMS

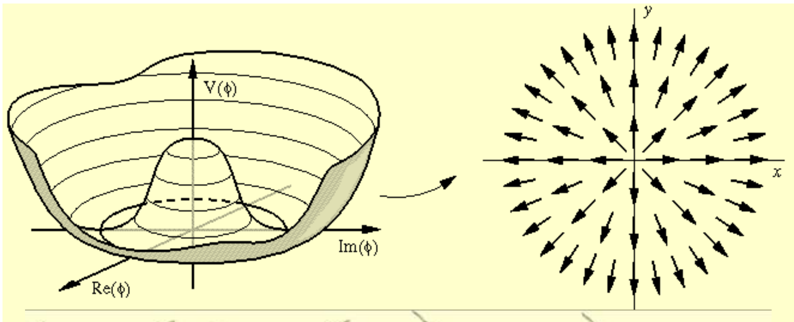


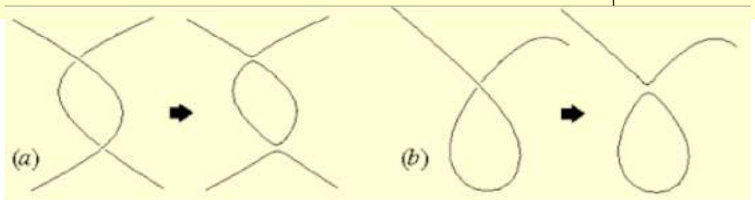
Primordial inhomogeneities Inflation

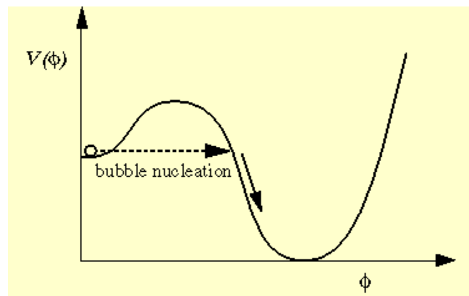
Pressure reduction Form more easily but need spherical symmetry

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



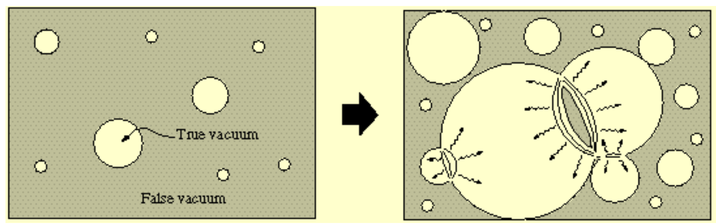






Bubble collisions

Need fine-tuning of bubble formation rate



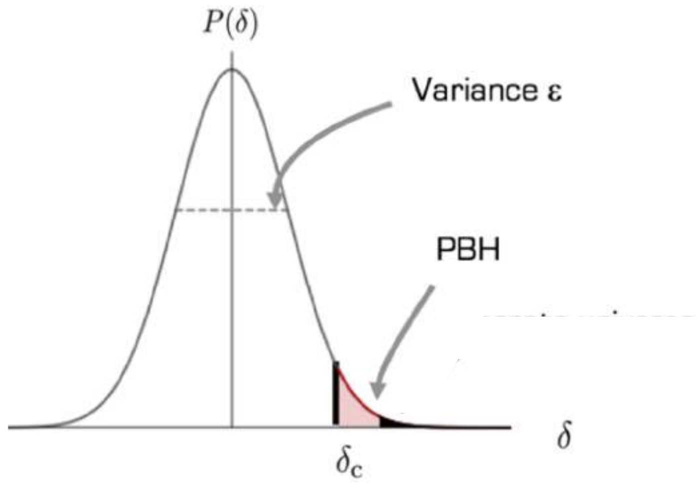
Domain walls PBHs can be very large

PBH FORMATION => LARGE INHOMOGENEITIES

To collapse against pressure, need (Carr 1975)

$$R > \sqrt{\alpha}\, ct \quad \text{when } \delta \sim 1 \;\Rightarrow\; \delta_H > \alpha \qquad (p=\alpha\rho c^2)$$

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



$\Rightarrow$ fraction of PBHs

tiny

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

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

no longer expected

Limit on fraction of Universe collapsing

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

General limit

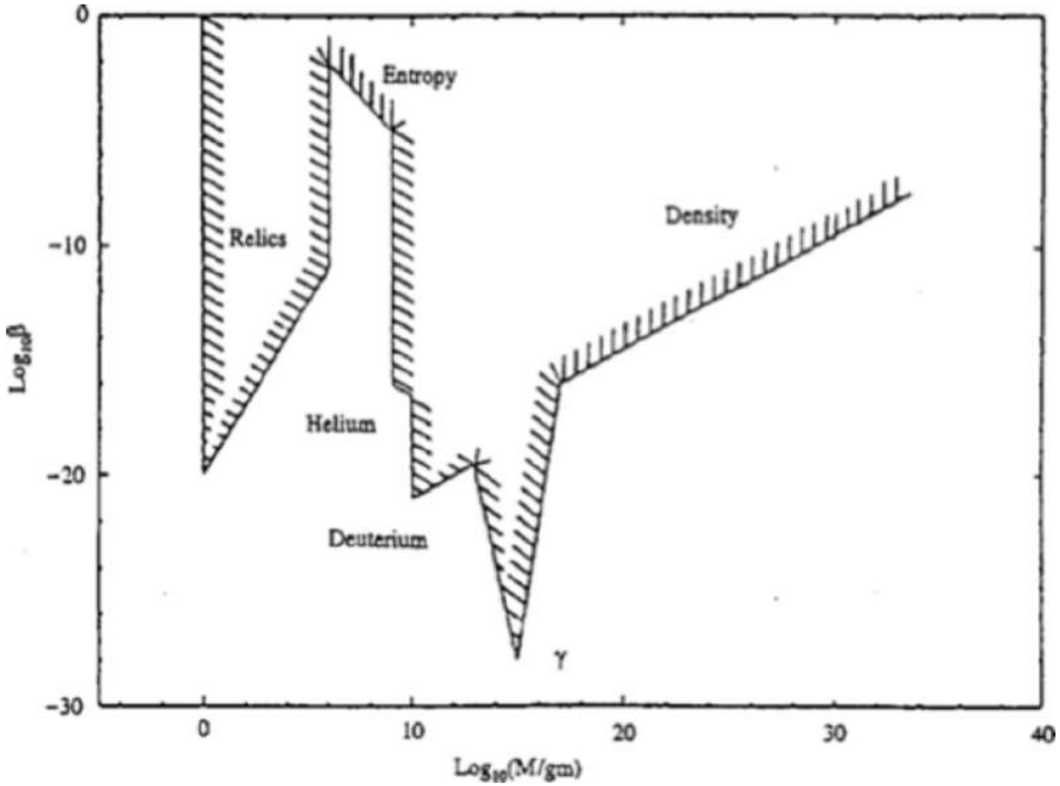
$$\frac{\rho_{PBH}}{\rho_{CBR}} \approx \frac{\Omega_{PBH}}{10^{-4}}\left[\frac{R}{R_0}\right] \Rightarrow \beta \sim 10^{-6}\,\Omega_{PBH}\left[\frac{t}{\sec}\right]^{1/2} \sim 10^{-18}\,\Omega_{PBH}\left[\frac{M}{10^{15}\,g}\right]^{1/2}$$

So both require and expect $\beta(M)$ to be tiny => fine-tuning

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

=> constraints from entropy, γ-background, BBNS

Constraints on $\beta(M)$



Carr, Gilbert & Lidsey (1994)

PBHS AND INFLATION

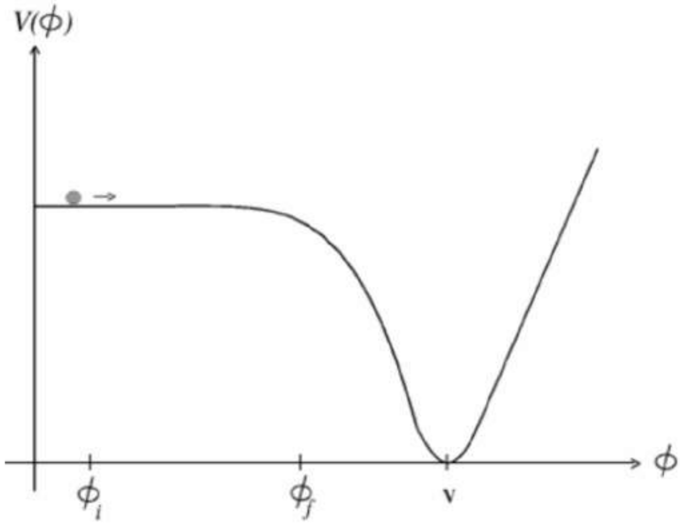
PBHs formed before reheat inflated away =>

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

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?

HUNDREDS OF PAPERS ON THIS!

PRIMORDIAL BLACK HOLES AS DARK MATTER

PRO

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

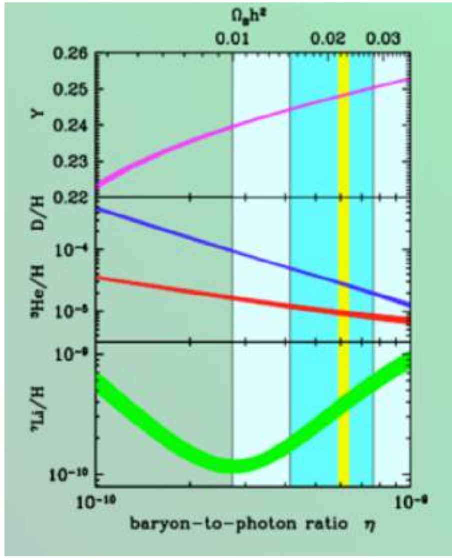
CON

* Requires fine-tuning

PBH can do it!

PRIMORDIAL BLACK HOLES AS DARK MATTER

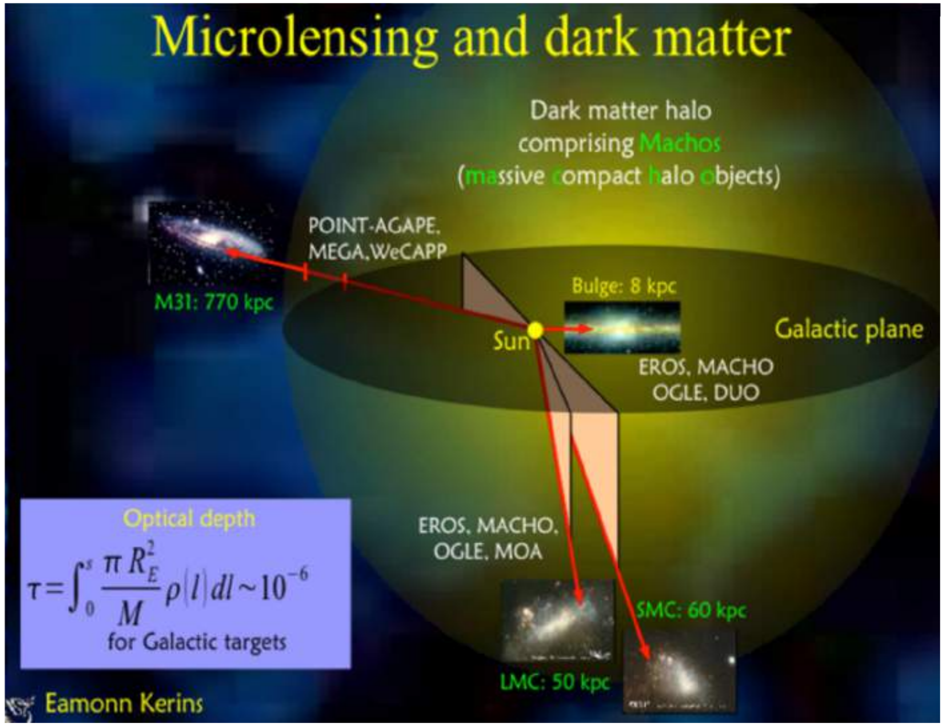
BBNS => $\Omega_{baryon} = 0.05$



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

MACHOs WIMPs

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



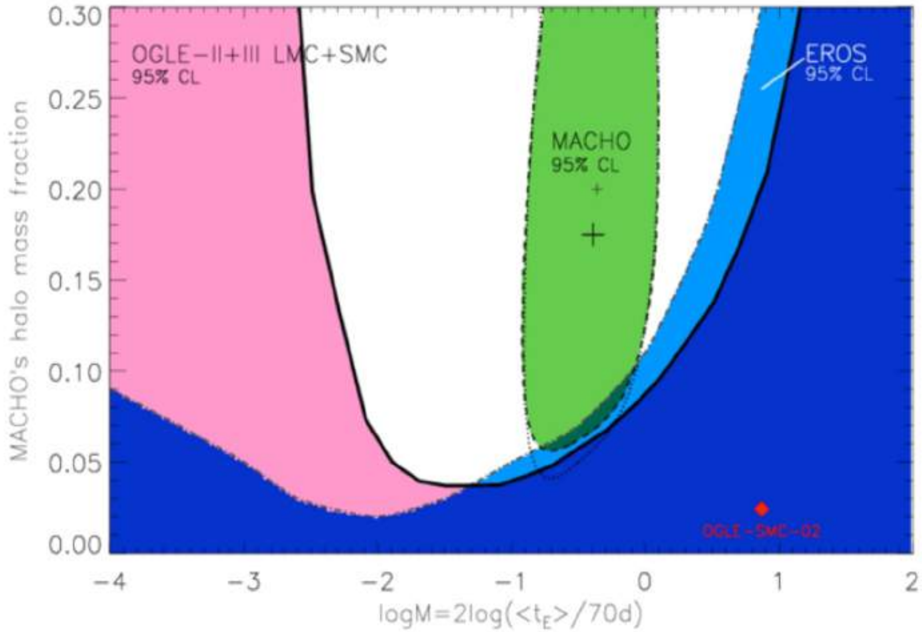


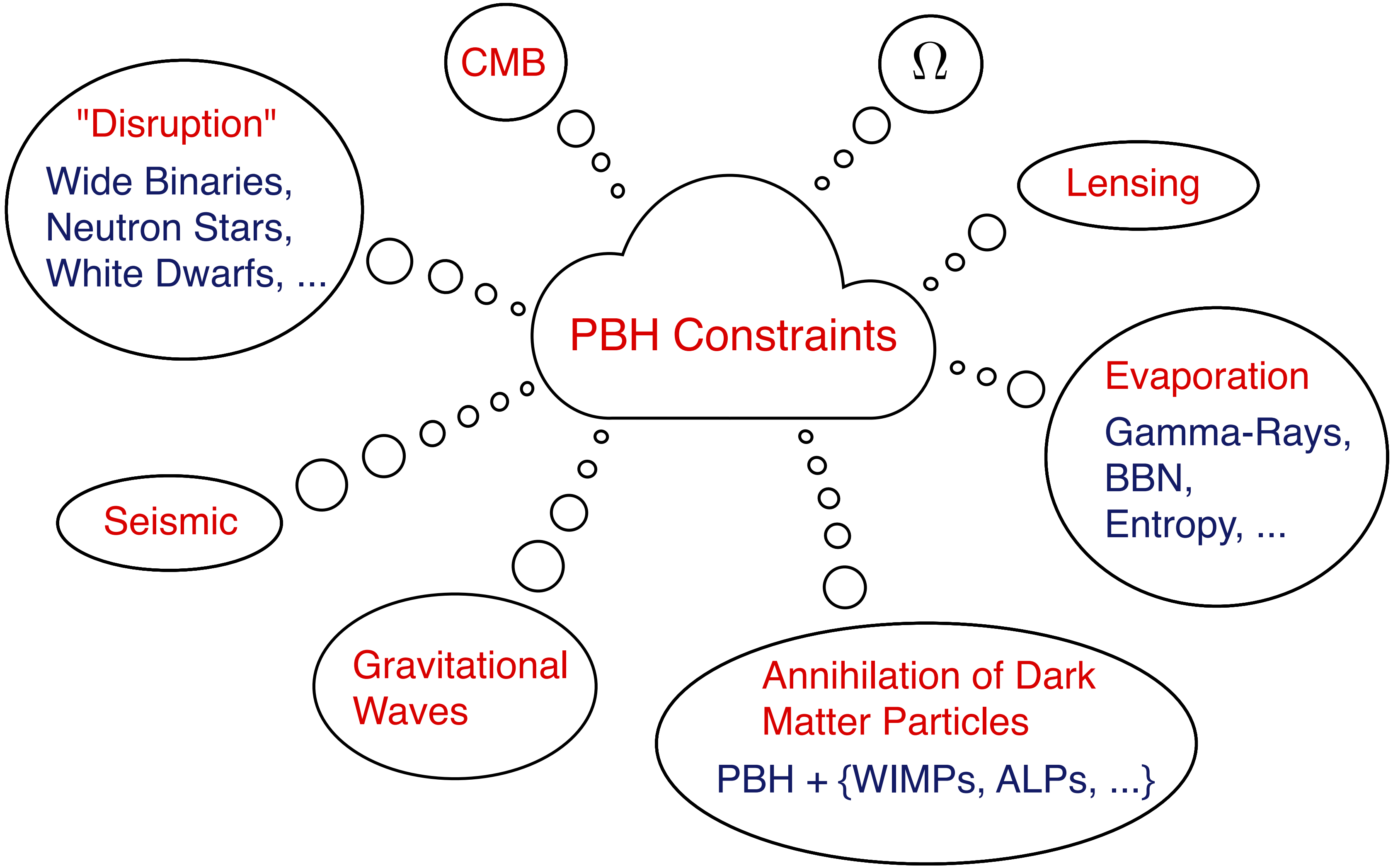
Image credit: Wyrzykowski et al., 2011, MNRAS, (astro-ph/1106.2925).

Early microlensing searches suggested MACHOs with 0.5 M_O

=> PBH formation at QCD transition?

Pressure reduction => PBH mass function peak at 0.5 M_O

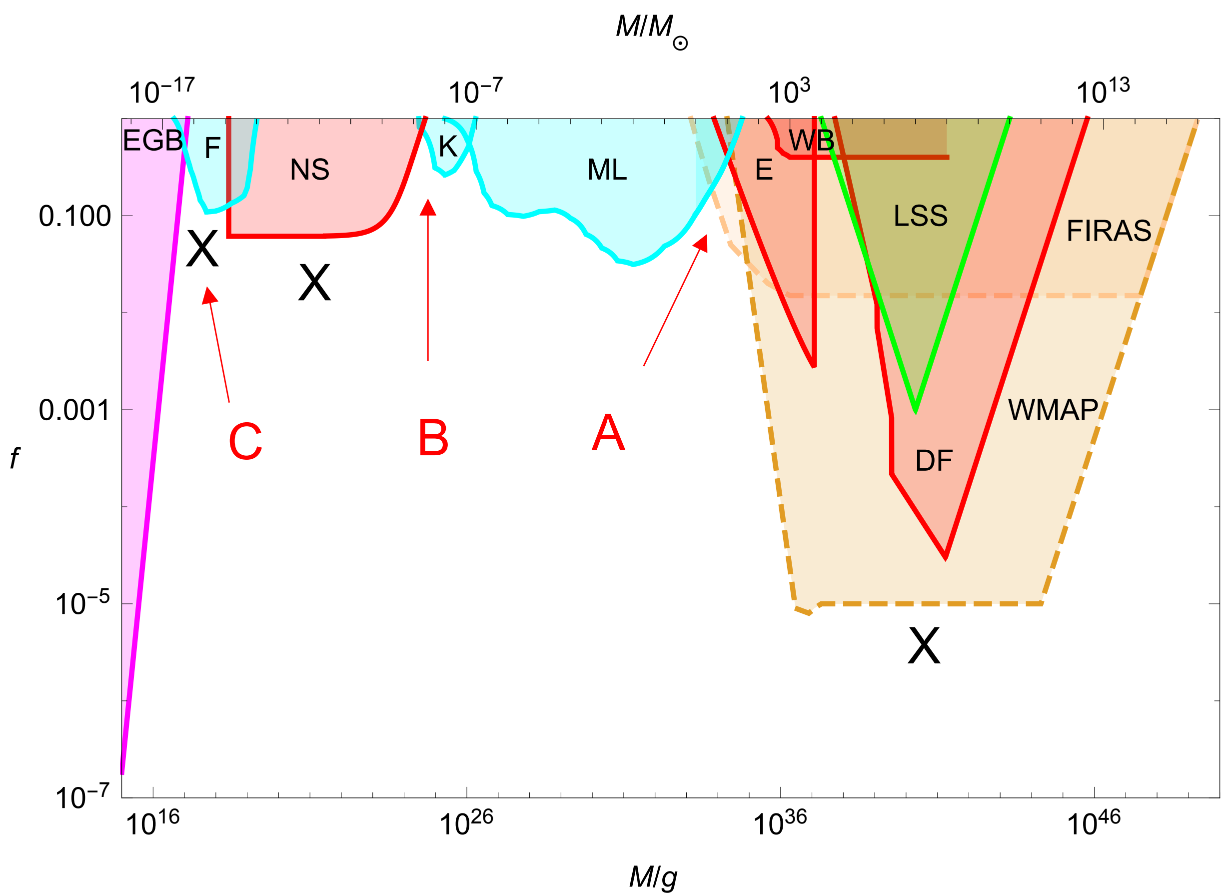
Later found that at most 20% of DM can be in these objects


CMB
Ω
"Disruption"
Wide Binaries,
Neutron Stars,
White Dwarfs, ...
Lensing
PBH Constraints
Evaporation
Gamma-Rays,
BBN,
Entropy, ...
Seismic
Gravitational
Waves
Annihilation of Dark
Matter Particles
PBH + {WIMPs, ALPs, ...}

PRIMORDIAL BLACK HOLES AS DARK MATTER

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

PRD 94, 083504, arXiv:1607.06077



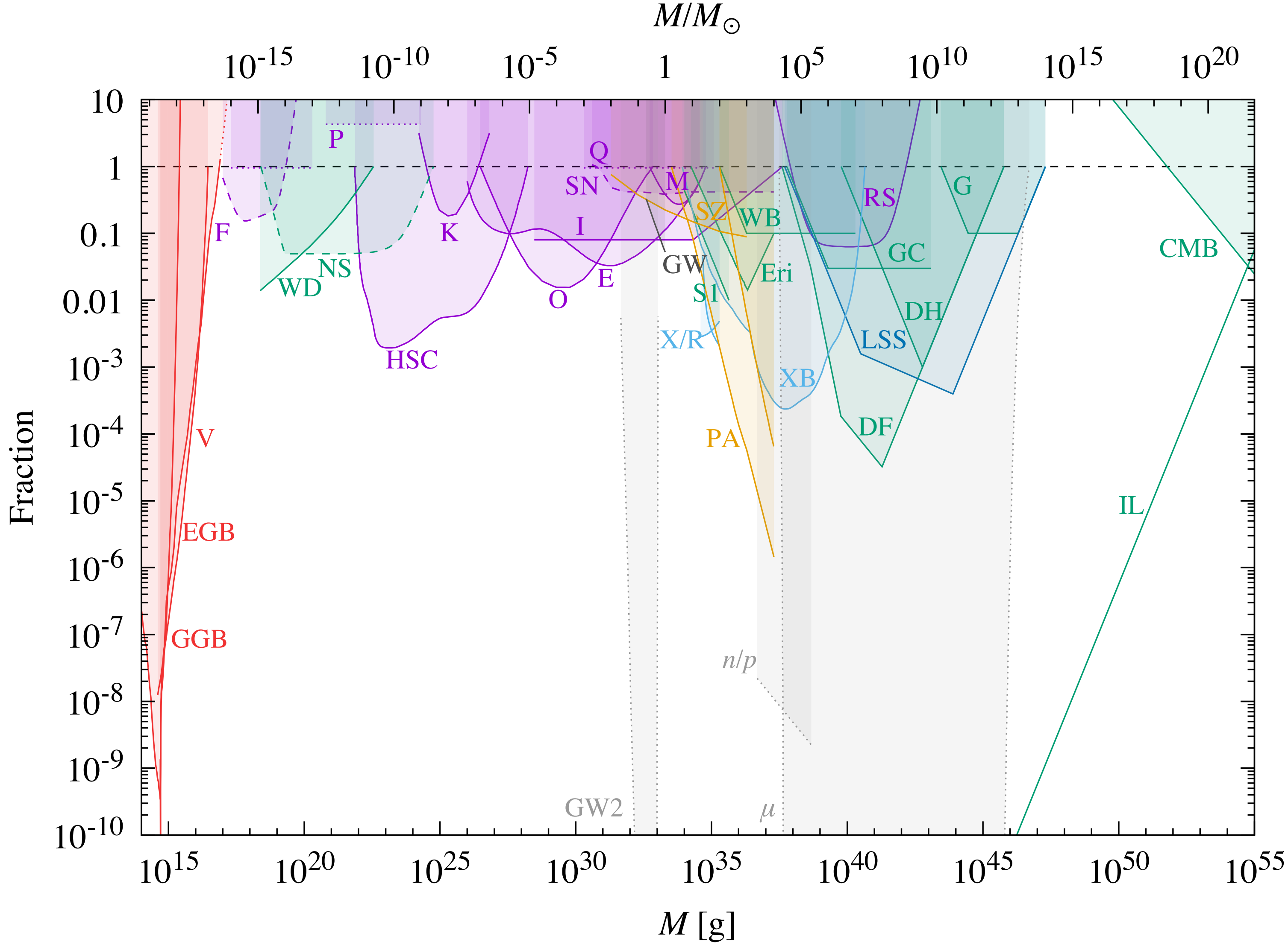
Three windows: (A) intermedate mass; (B) sublunar mass; (C) asteroid mass.

But some of these limits are now thought to be wrong

CONSTRAINTS ON PRIMORDIAL BLACK HOLES

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

Progress Theoretical Physics (2019)



These constraints are not just nails in a coffin!

PBHs are interesting even if $f << 1$

Each constraint is a potential signature

EXTENDED MASS FUNCTION?

Most constraints assume monochromatic PBH mass function

So can we evade standard limits with extended mass spectrum?

But this is two-edged sword!

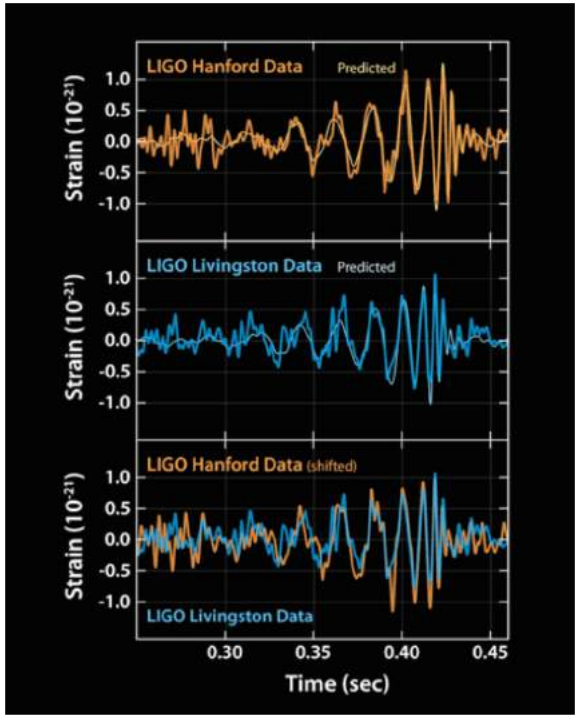
PBHs may be dark matter even if fraction is low at each scale

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

Carr, Raidal, Tenkanen, Vaskonen & Veermae (arXiv:1705.05567)

Properties of the binary black hole merger GW150914

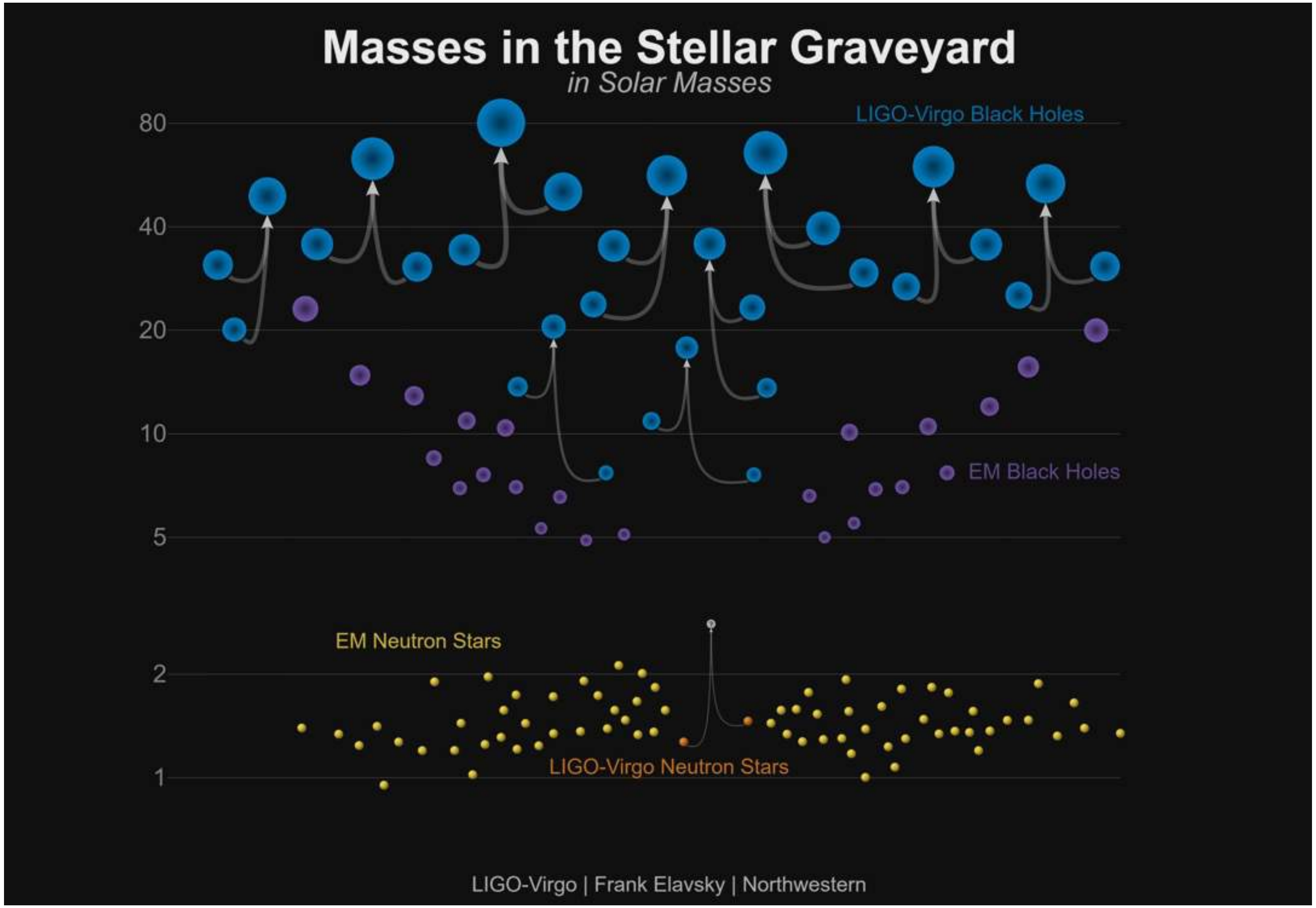
The LIGO Scientific Collaboration and The Virgo Collaboration



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

Largest is now 80 M_O which is nearly in IMBH range

PBHS AND LIGO/Virgo



Do we need Population III or primordial BHs?

Did LIGO detect dark matter?

Simeon Bird,* Ilias Cholis, Julian B. Muñoz, Yacine Ali-Haïmoud, Marc Kamionkowski, Ely D. Kovetz, Alvise Raccanelli, and Adam G. Riess[1]

arXiv:1603.00464

Dark matter in 20-100 $M_{\odot}$ binaries may provide observed rate of 2-53 $Gpc^{-1} yr^{-1}$

Primordial Black Hole Scenario for the Gravitational-Wave Event GW150914

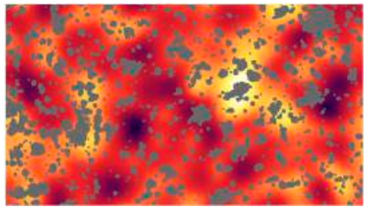
Misao Sasaki,[1] Teruaki Suyama,[2] Takahiro Tanaka,[3,1] and Shuichiro Yokoyama[4]

arXiv:1603.08338

Only need small f and comparable to limits from CMB distortion

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

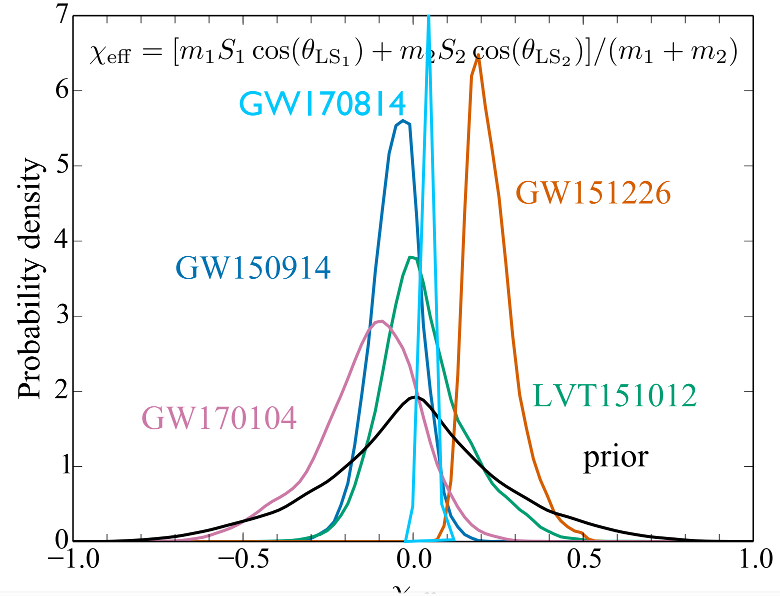
A. Kashlinsky[1],

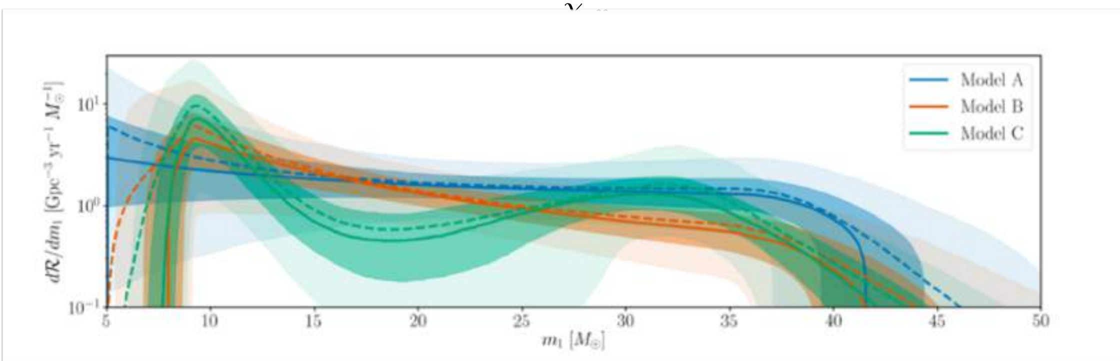


arXiv:1605.04023

PBHs may generate early structure and infrared background

Hint from spin of LIGO black holes and mass function?

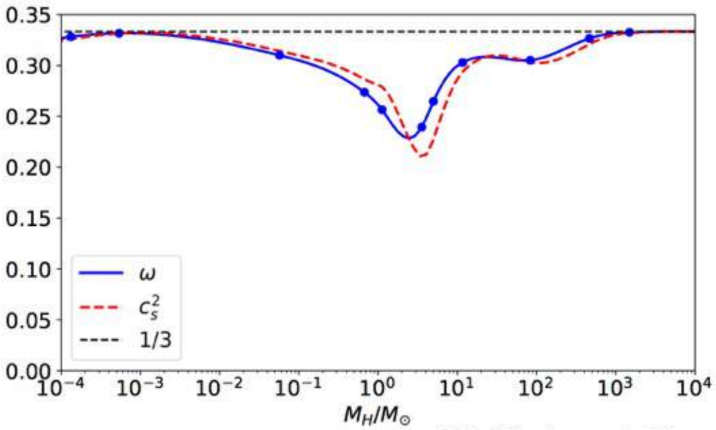


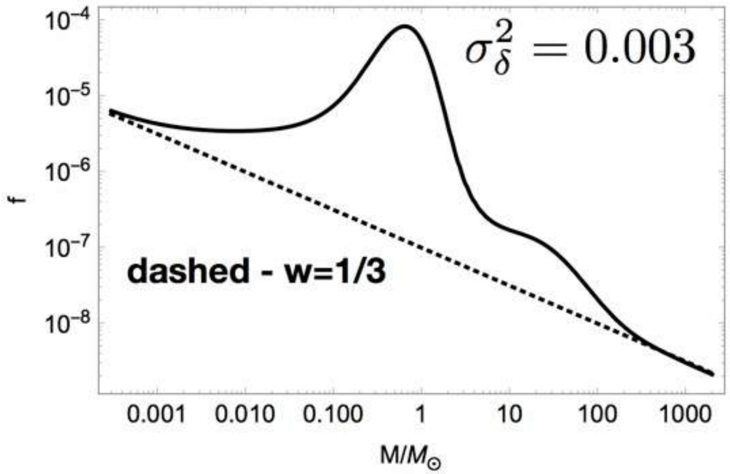


Primordial black holes with an accurate QCD equation of state

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

arXiv:1801.06138





PBHS, DARK MATTER AND ELECTROWEAK BARYOGENESIS AT THE QUARK HADRON EPOCH

Carr, Clesse & Garcia-Bellido
arXiv:1904.02129

Stars have a mass in range (0.1 – 10) M_C where
$M_C \sim \alpha_G^{-3/2}\, m_P \sim 1\, M_O$ and $\alpha_G \sim G m_P^2/hc \sim 10^{-38}$

PBHs forming at time t have mass and collapse fraction

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

So β appears fine-tuned and we must also explain why

$$\chi = \rho_{PBH}/\rho_B = f\, \rho_{DM}/\rho_B = 6 f \quad \text{is } O(1).$$

QCD epoch => $M \sim M_C$, $\beta(M) \sim \eta = n_B/n_\gamma \sim 10^{-9}$

=> dark matter and visible baryons have similar mass

=> PBHs may *generate* baryon asymmetry

Baryogenesis scenario

EW baryogenesis at QCD epoch

Baryon violation via sphaleron transitions and B+L chiral anomaly

PBH form'n => large curvature perturb'n => huge entropy prod'n => out-of-equilibrium condition => baryogenesis with $\eta_{loc} \sim 1$

Diffusion of baryon asymmetry => $\eta \sim \beta$ and $\chi \sim 1$

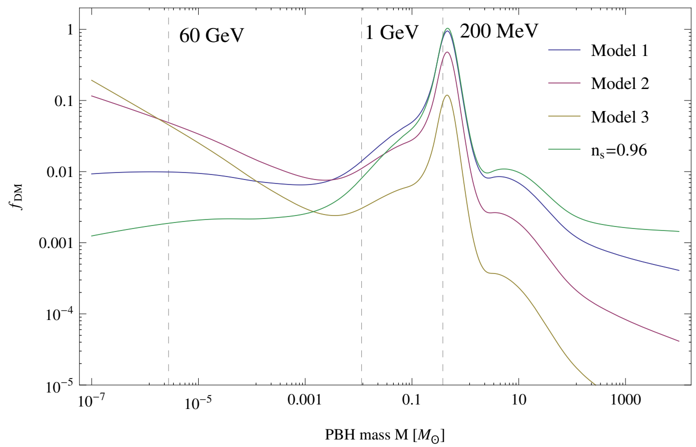
Curvature perturbation scenario

Stochastic fluct'ns in spectator field during inflation (QCD axion)

$\Rightarrow$ different values in different patches

$\Rightarrow$ 2nd inflation phase within some regions

$\Rightarrow$ non-linear curv'pert'ns => PBHs.



1st peak at $1M_O$ for DM plus 2nd peak at 10-20 M_O for LIGO events

Primordial black holes as generators of cosmic structures

Bernard Carr[1,2★] and Joseph Silk[3,4]

MNRAS 478 (2018) 3756; arXiv:1801.00672

What is maximum mass of PBH?

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

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

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

Hoyle & Narlikar 1966, Meszaros 1975, Carr & Silk 1983, Carr & Rees 1984

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

Nakama, Carr & Silk, arXiv:1710.0604

SEED AND POISSON FLUCTUATIONS

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

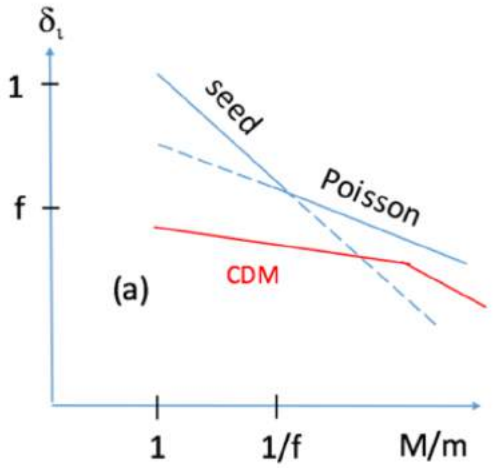
If region of mass M contains PBHs of mass m, initial fluctuation is

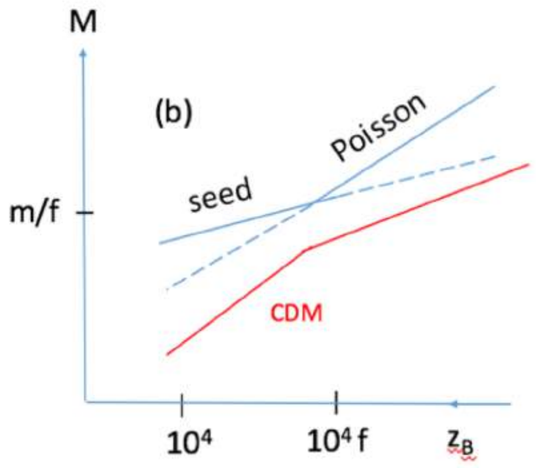
$$\delta_i \sim \begin{cases} m/M & \text{(seed)} \\ (fm/M)^{1/2} & \text{(Poisson)} \end{cases}$$

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

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

SEED VERSUS POISSON





cf. CDM fluctuations

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

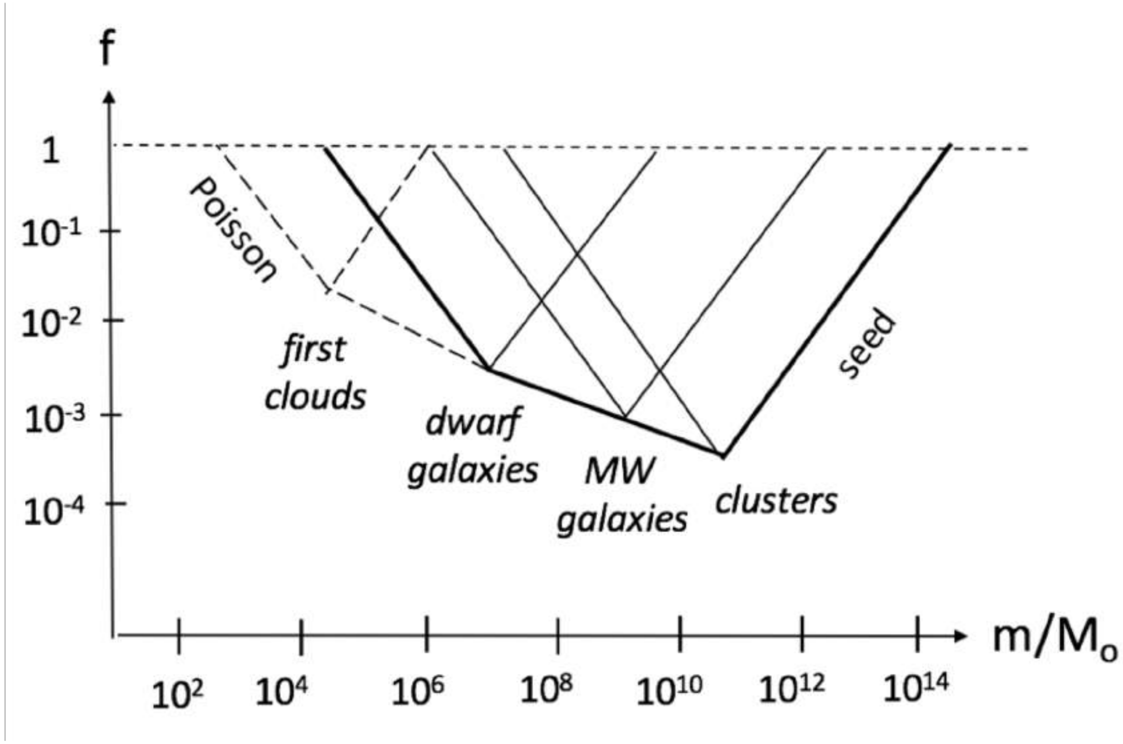
f = 1 => m < $10^3\, M_O$ => M < $10^{11} z_B^{-2}\, M_O$ < M_{gal} (Poisson)

=> can generate dwarf galaxies

f << 1 => M can be larger

=> PBHs can be seeds for galaxies

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



First clouds bind earlier than in standard model

Joe Silk

What IMBH can do for dwarf galaxies

motivation: something new may be needed

mostly passive today but active in gas-rich past

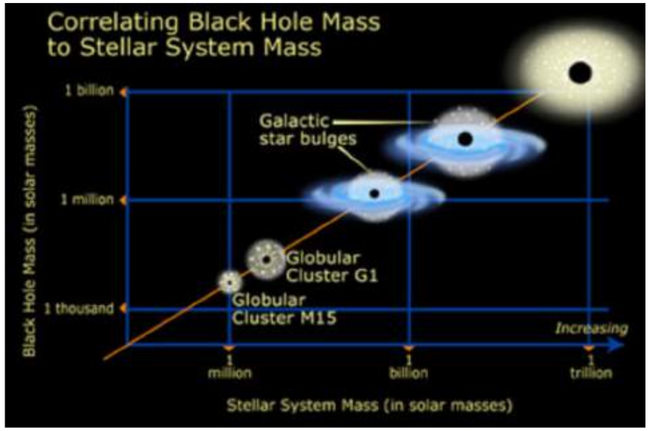
- 1.Suppress number of luminous dwarfs
- 2. Generate cores in dwarfs by dynamical heating
- 3 Resolve the “too big to fail” problem
- 4. Create bulgeless disks
- 5. Form ultrafaint dwarfs & ultradiffuse galaxies
- 6. Reduce baryon fraction in MWG-mass galaxies
- 7. Seeds for SMBH at high z
- 8. ULXs in outskirts of galaxies: relics of dwarfs
- 9. AGN triggering of star formation in dwarfs
- 10. Early galaxy formation

Predictions: 21cm, LISA, TDEs, μ-lensing

SUPERMASSIVE PBHS AS SEEDS FOR GALAXIES

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

Effect of mergers an accretion?



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

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

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

Bondi accretion => $m \approx m_i/(1 - m_i \eta t)$, $\qquad M_{eq}\sim 10^{15} M_O$

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

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

Signatures of primordial black holes as seeds of supermassive black holes

José Luis Bernal[1,2], Alvise Raccanelli[⋆,1], Licia Verde[1,3], Joseph Silk[4,5,6]

arXiv:1712.01311

It has been suggested that primordial black holes (PBHs) of masses $\gtrsim 10^2 M_\odot$ may provide such seeds, which would grow to become SMBHs. We suggest an observational test to constrain this hypothesis: gas accretion around PBHs during the cosmic dark ages powers the emission of high energy photons which would modify the spin temperature as measured by 21cm Intensity Mapping

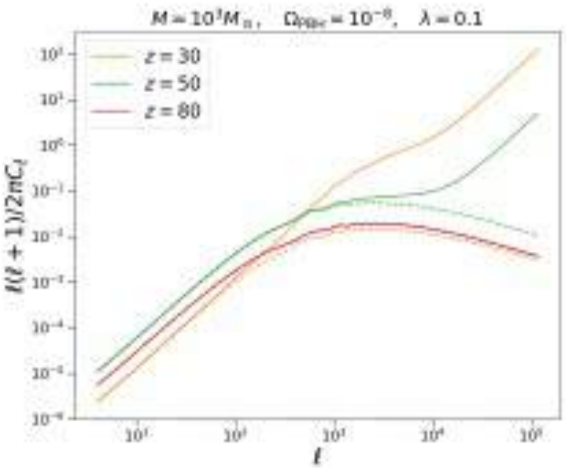


FIG. 10: Angular power spectrum comparing the total signal in 21 cm IM (solid lines) with the case where there are no PBHs (dashed lines) for $M = 10^3 M_\odot$, $\Omega_{\rm PBH} = 10^{-8}$, $\lambda = 0.1$ and $\Delta\nu = 1$ MHz at different redshifts.

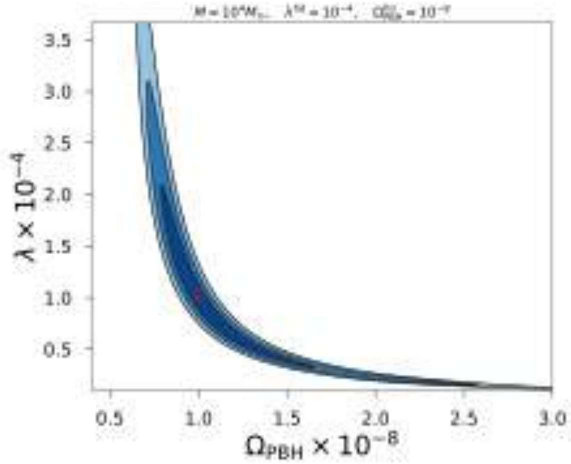


FIG. 11: 1σ, 2σ and 3σ confidence level forecasted constraints in the $\Omega_{\rm PBH}$-λ plane from theoretical $\Delta\chi^2$ values for the fiducial cases of $M^{\rm fid} = 10^4 M_\odot$, $\Omega^{\rm fid}_{\rm PBH} = 10^8$ and $\lambda^{\rm fid} = 0.1$ (top) and $\lambda^{\rm fid} = 10^{-4}$ (bottom), considering SKA$_{\rm Adv}$ in both cases. The fiducial case is marked with a red dot.

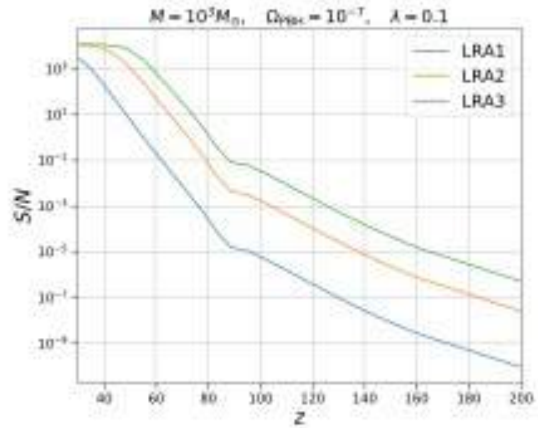
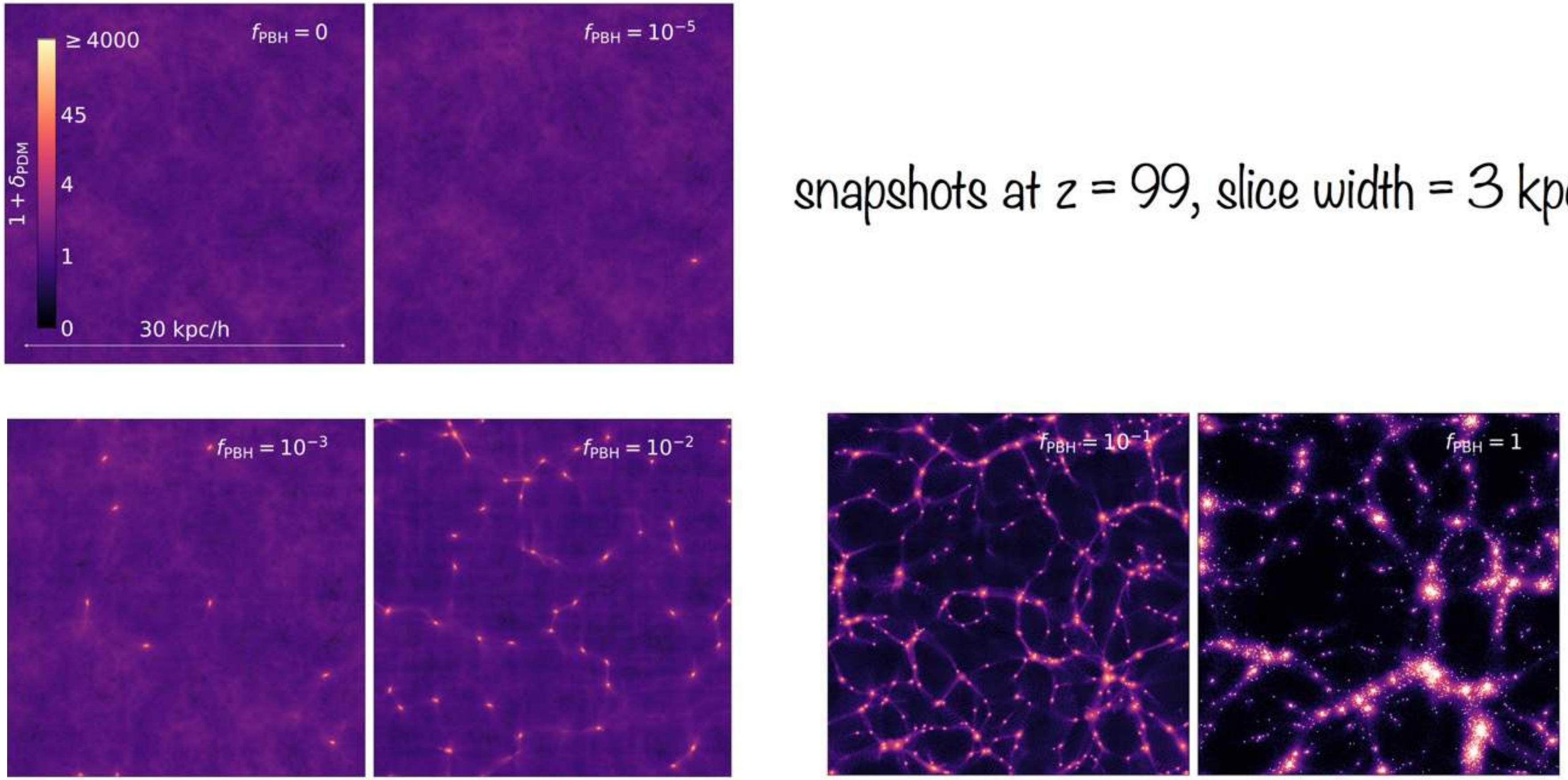


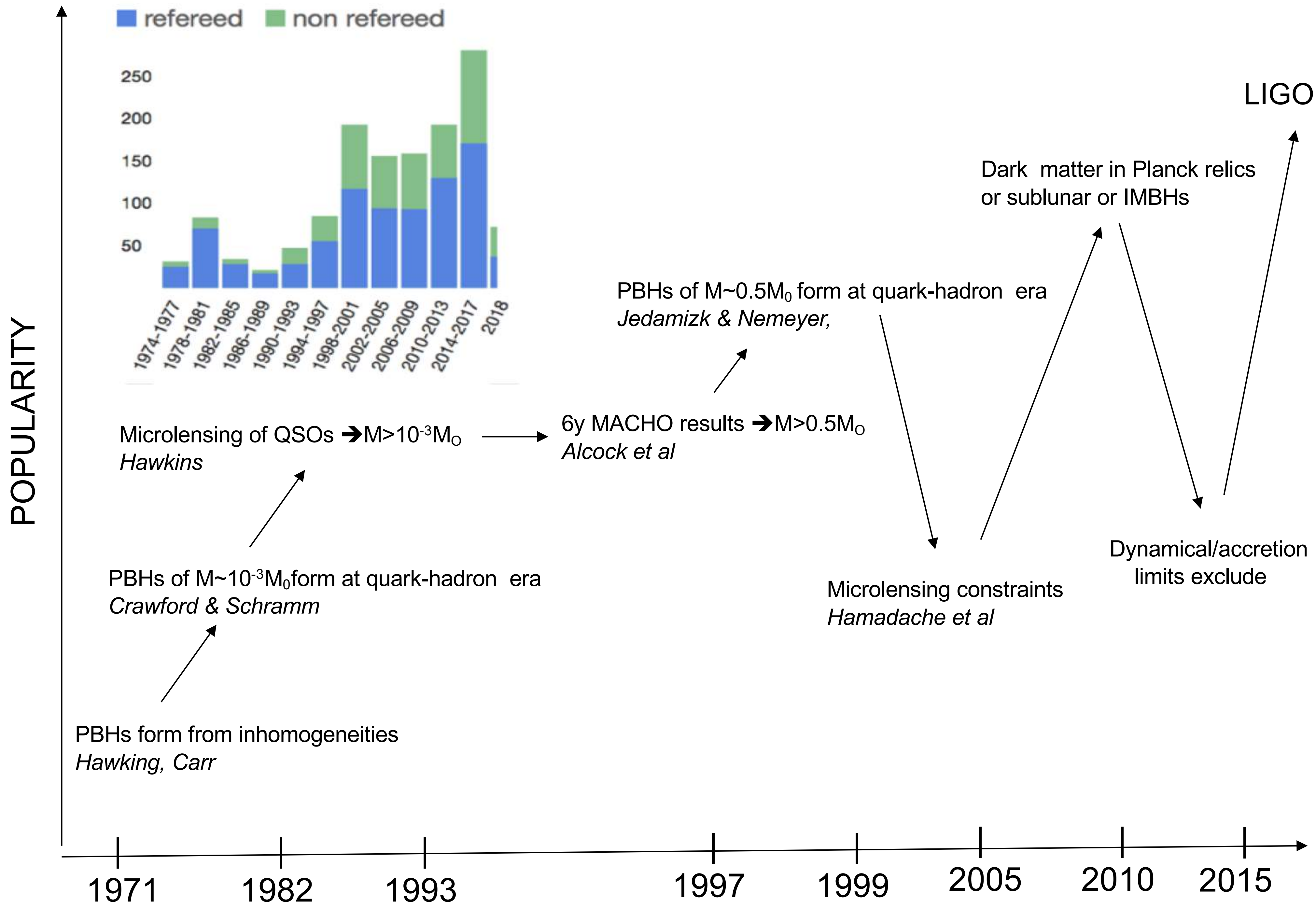
FIG. 12: Evolution of the signal-to-noise ratio between the power spectrum accounting for the PBH contribution and the standard one with respect to redshift. We consider $M = 10^3 M_\odot$, $\Omega_{\rm PBH} = 10^{-7}$ and $\lambda = 0.1$, and show the results for the three realizations of the LRA.

$\lambda = L/L_{ED}$

Inman & Ali-Haïmoud, in preparation



snapshots at $z = 99$, slice width = 3 kpc


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 $M\sim0.5M_0$ form at quark-hadron era
Jedamizk & Nemeyer,
Microlensing of QSOs ➔$M>10^{-3}M_O$
Hawkins
6y MACHO results ➔$M>0.5M_O$
Alcock et al
Dynamical/accretion
limits exclude
Microlensing constraints
Hamadache et al
PBHs of $M\sim10^{-3}M_0$form at quark-hadron era
Crawford & Schramm
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 PBHs with extended mass function could play all!

HAPPY 60TH BIRTHDAY