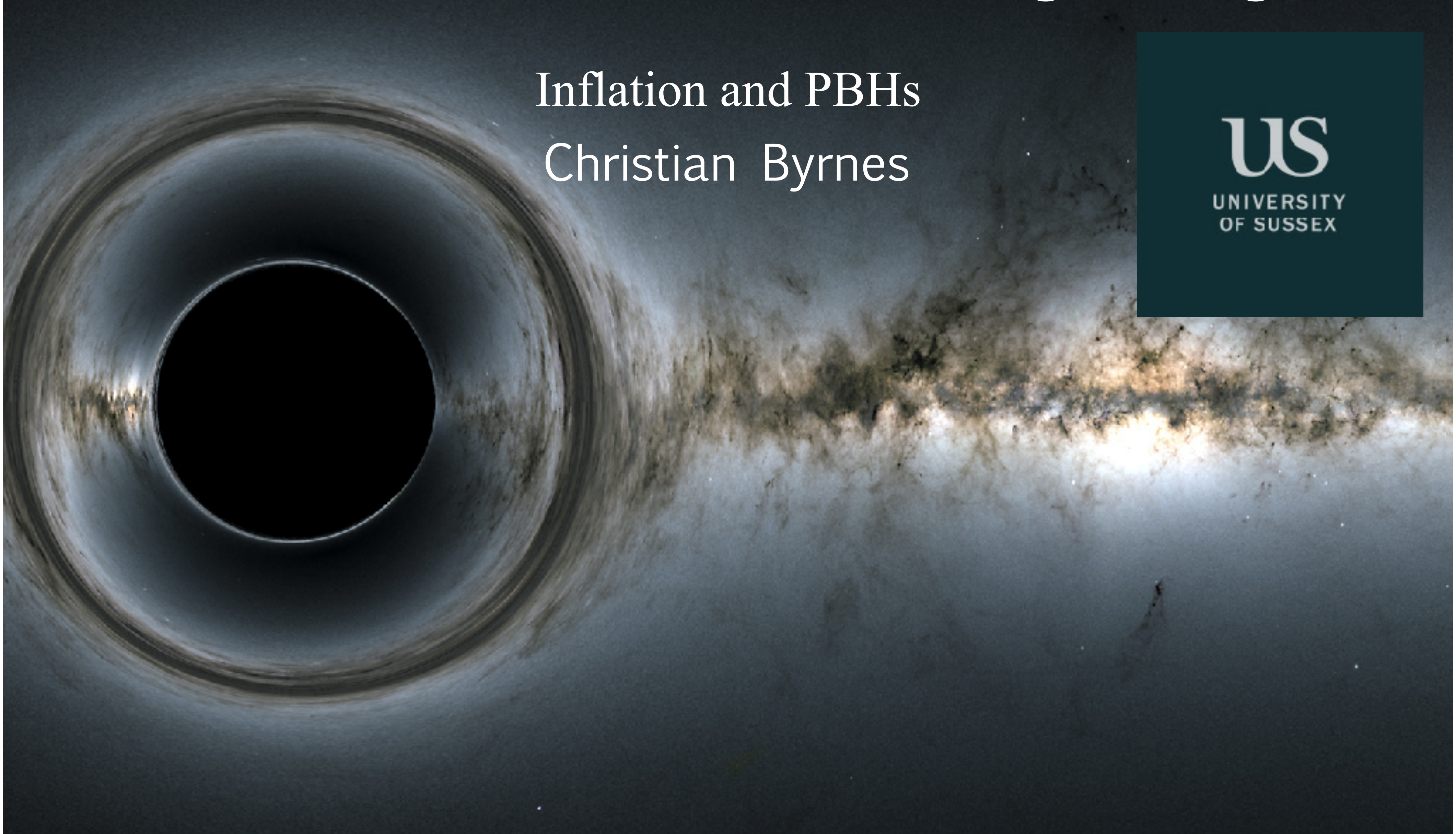
Black holes from the Big Bang

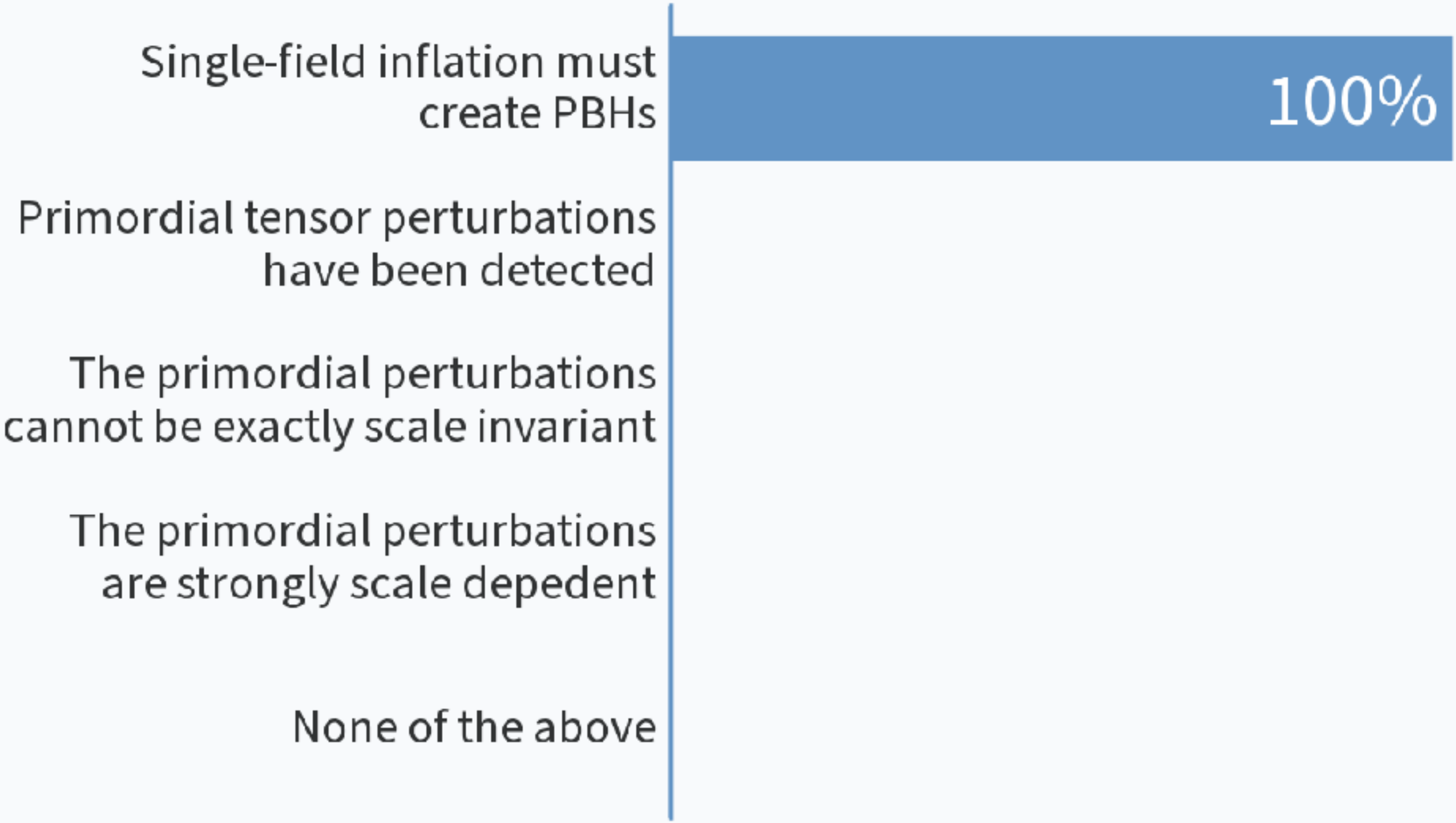
Inflation and PBHs

Christian Byrnes



GGI school - lecture 3 - 24 March 2021

SR inflation: Select the true statement



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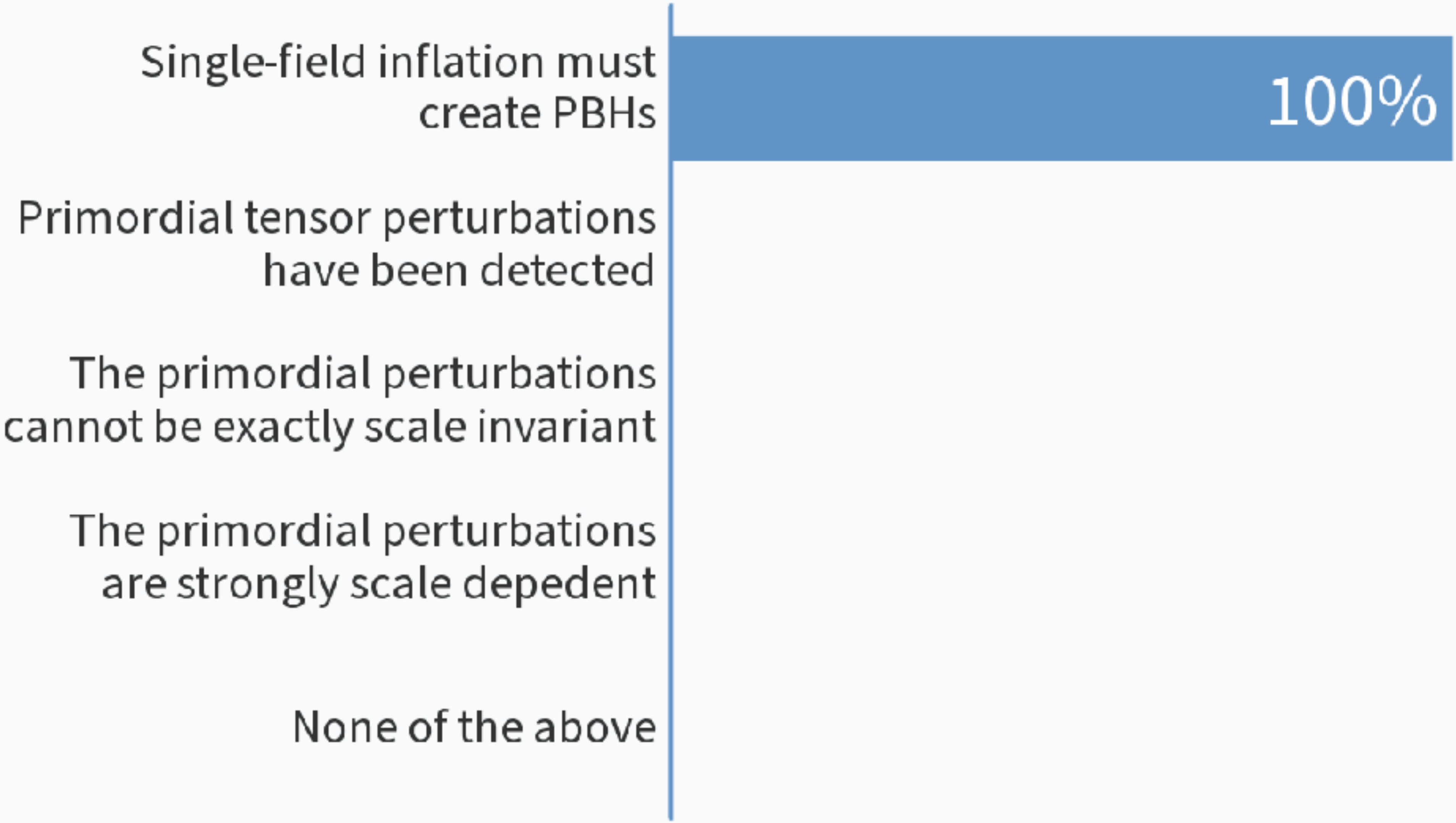

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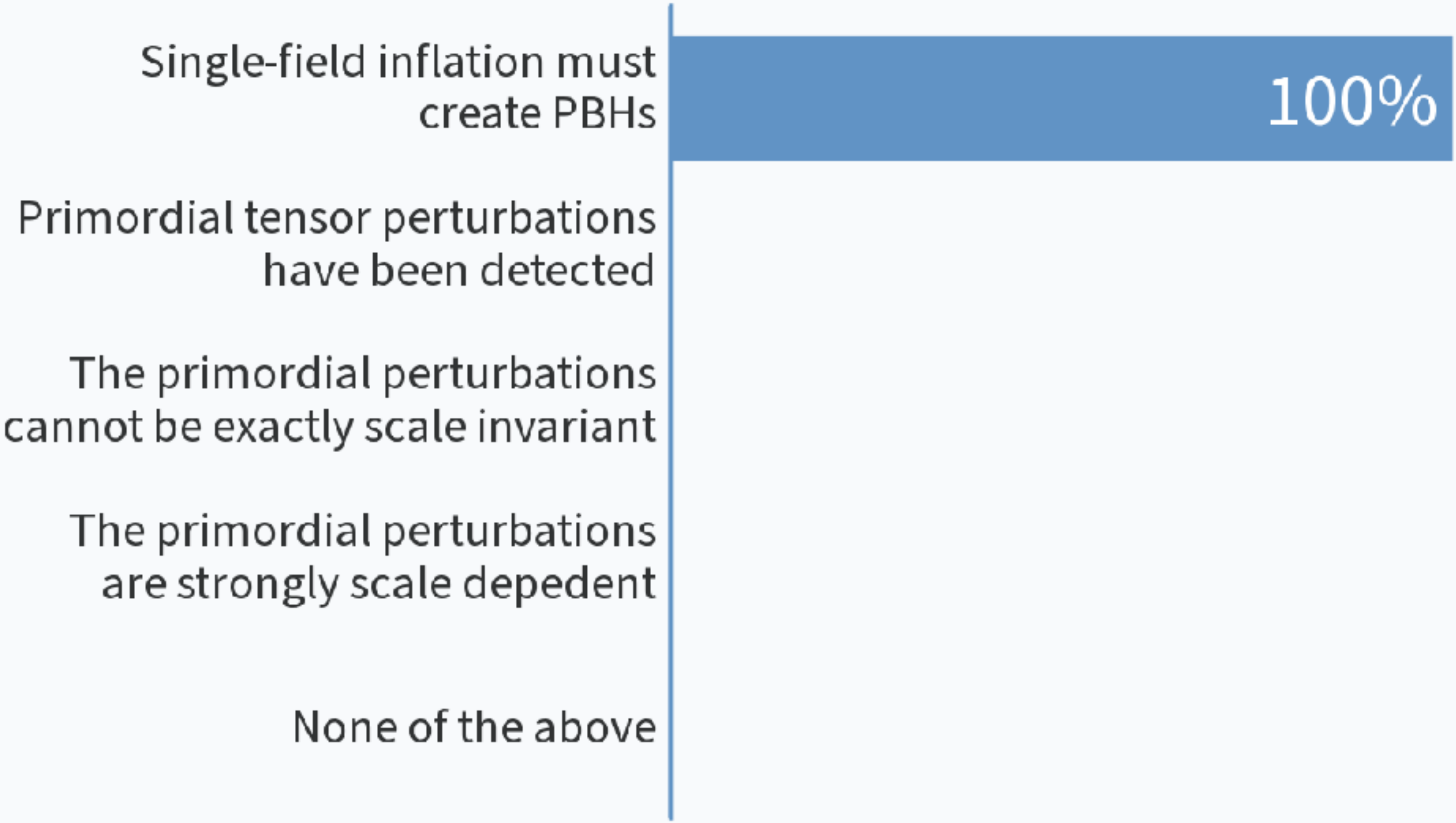

USR inflation: Which statement is true?

- About 1 efold of USR inflation leads to PBH production
- More than 2 efolds of USR inflation leads to eternal inflation
- An order unity primordial power spectrum implies eternal inflation
- You can evaluate the power spectrum at Hubble exit during USR inflation
- None of the above

When poll is active, respond at **pollev.com/byrnes**

Text **BYRNES** to **07480 781235** once to join

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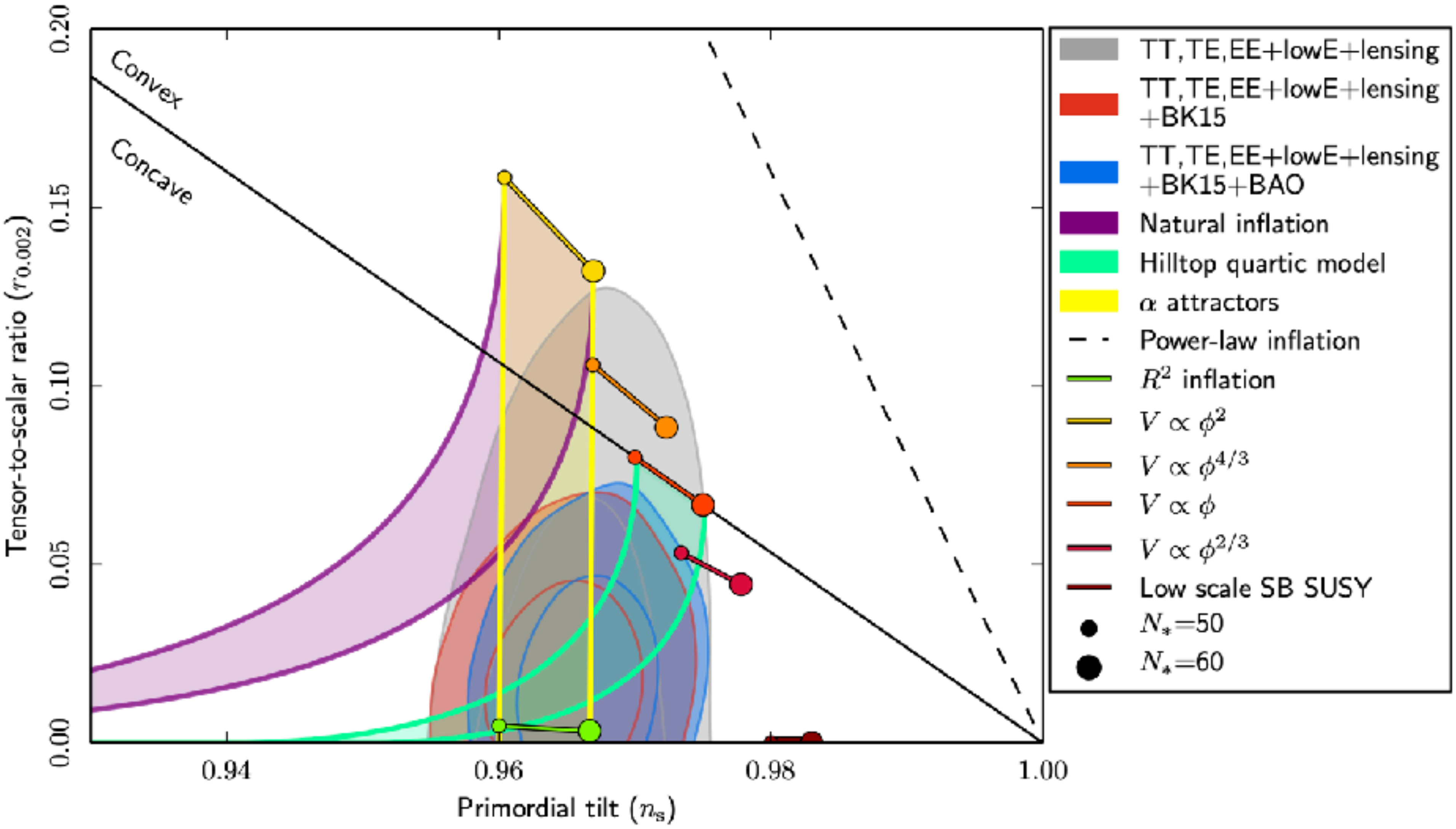
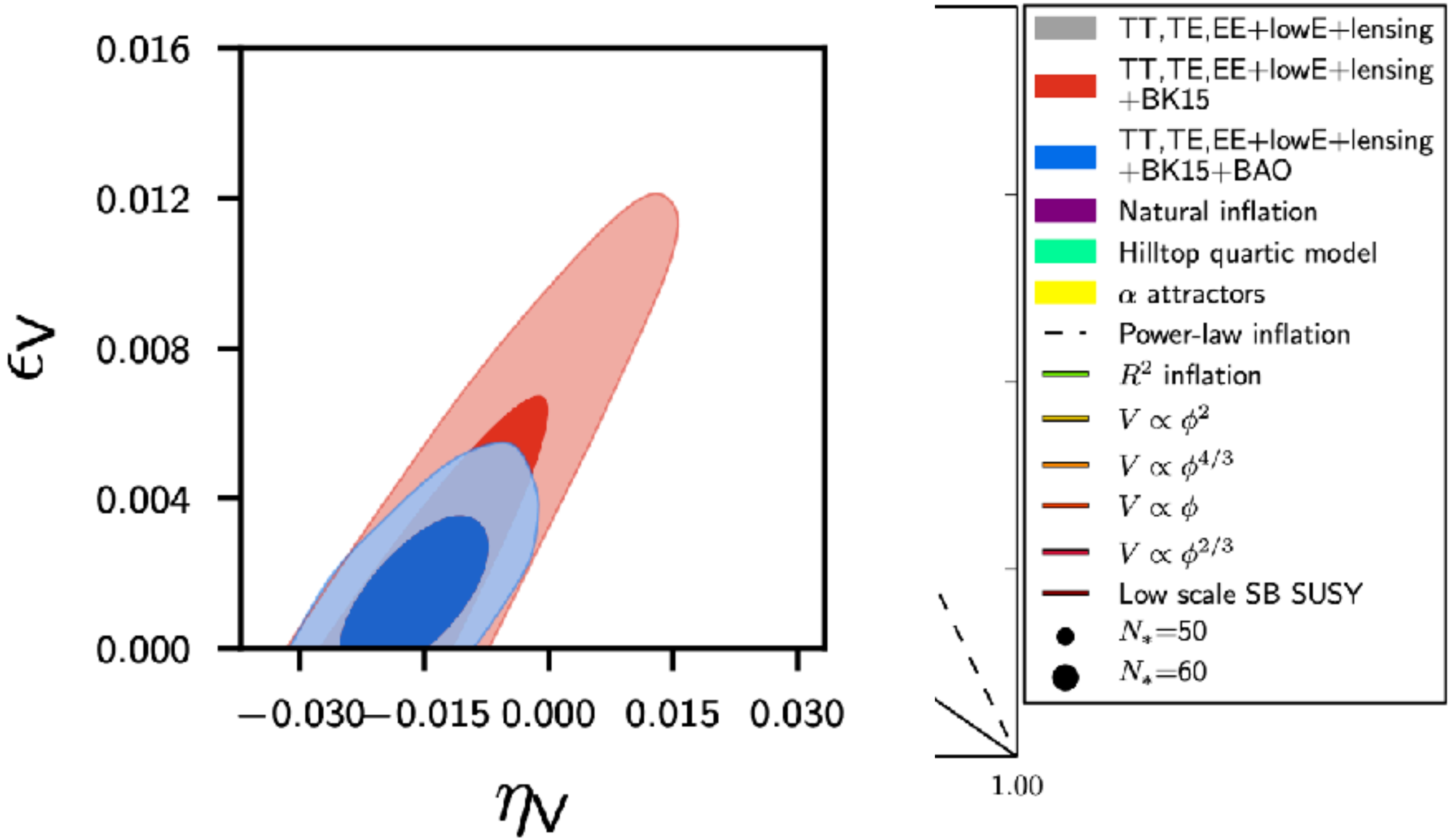


Fig. 8. Marginalized joint 68 % and 95 % CL regions for n_s and r at $k = 0.002\,\mathrm{Mpc}^{-1}$ from *Planck* alone and in combination with BK15 or BK15+BAO data, compared to the theoretical predictions of selected inflationary models. Note that the marginalized joint 68 % and 95 % CL regions assume $dn_s/d\ln k = 0$.

https://arxiv.org/pdf/1807.06211.pdf



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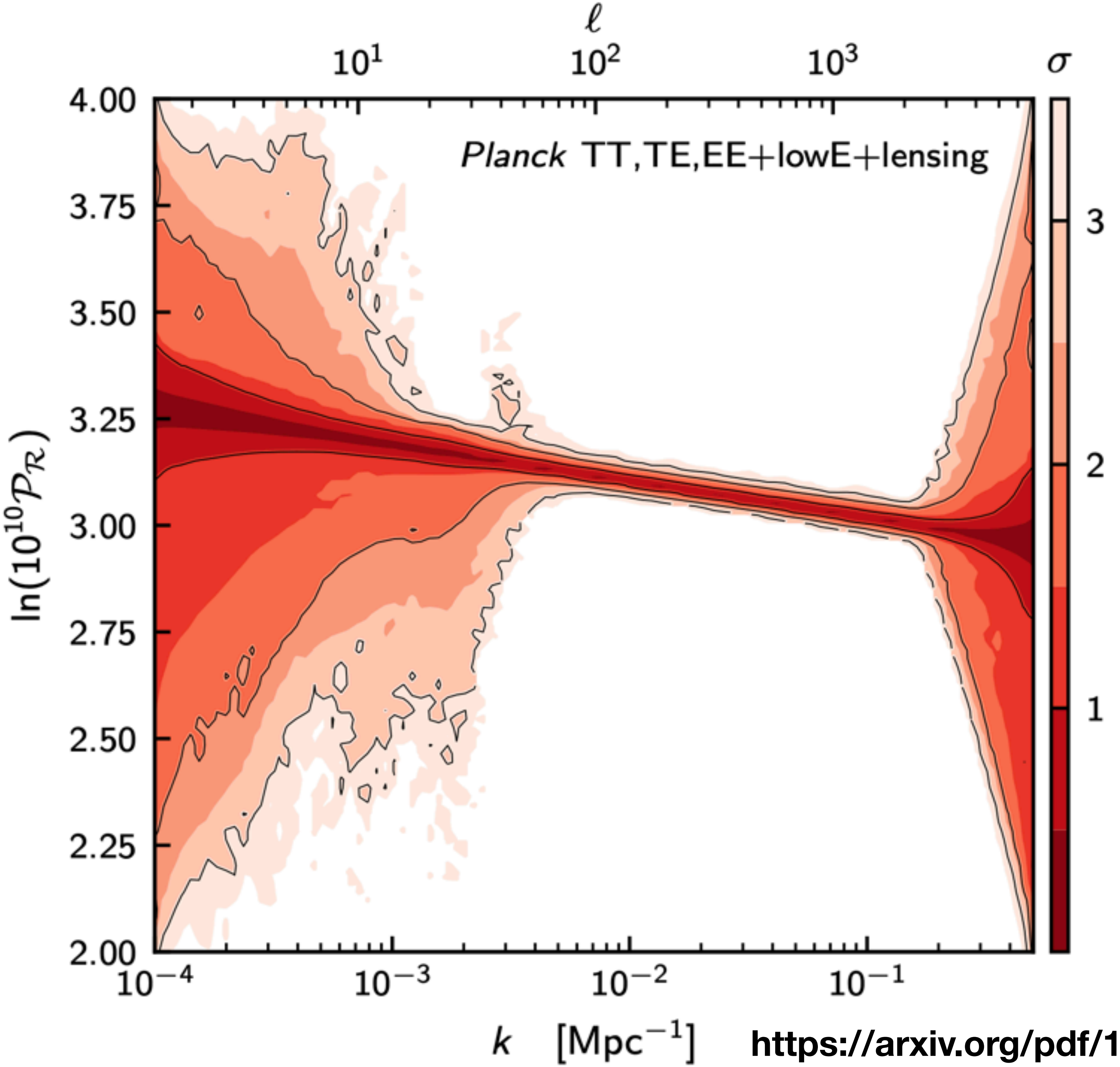

https://arxiv.org/pdf/1807.06211.pdf


What is the Universe made of?
By eye, we see stars
and a few planets

Observations of which of the following are compatible with DM being made of astrophysical black holes?

- Galaxy cluster velocities
- Galaxy rotation curves
- The bullet cluster
- All of the above
- None of the above

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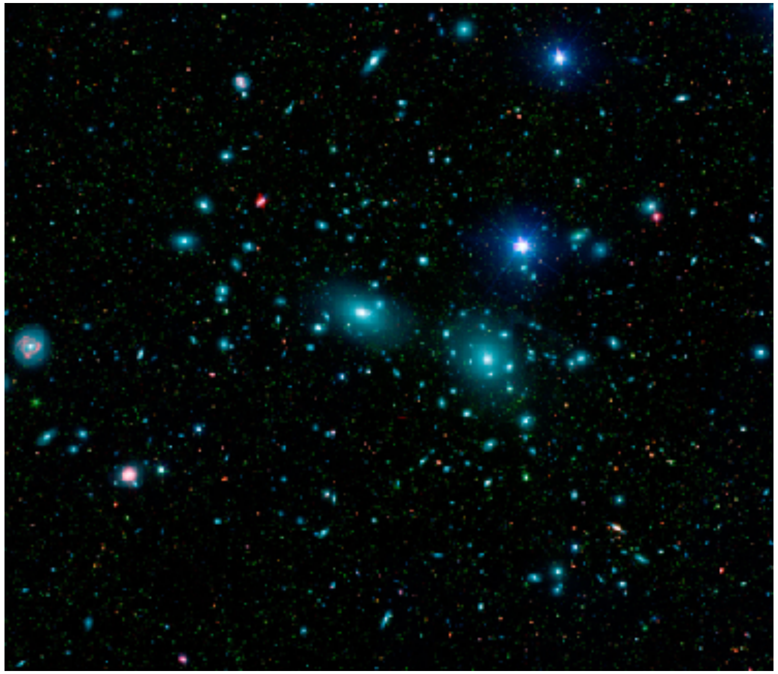
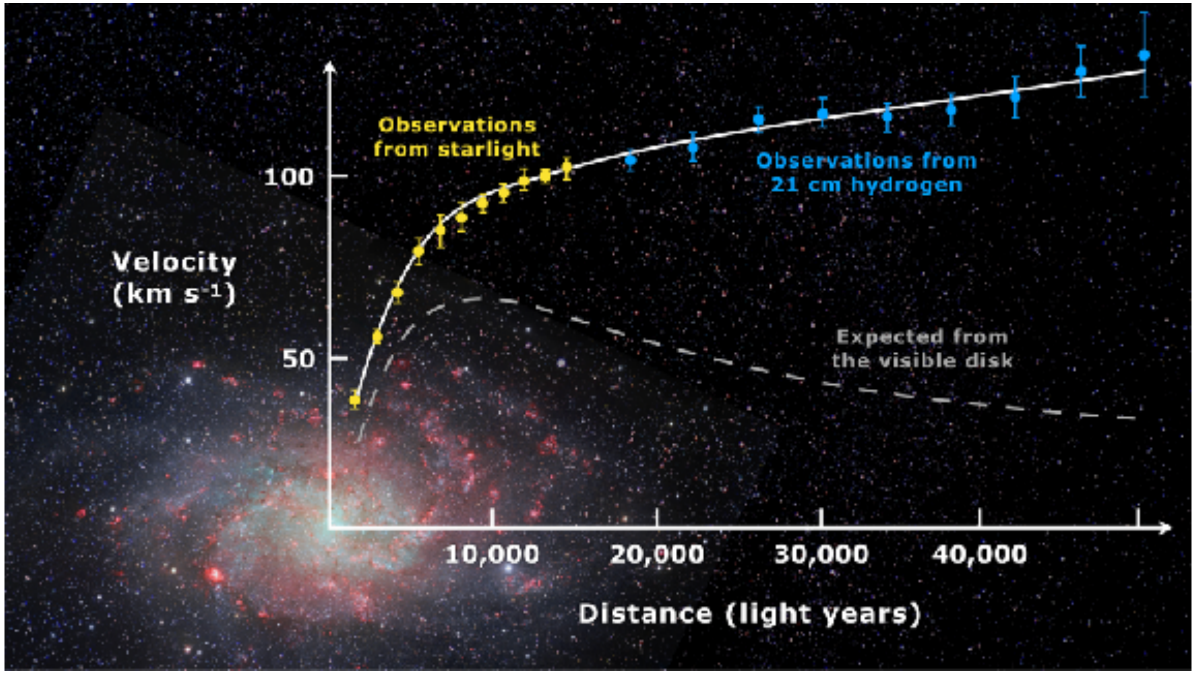


Coma galaxy cluster By NASA / JPL-Caltech



By Mario De Leo - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=74398525

Fritz Zwicky used galaxy clusters to postulate "dunkle materie" in 1933

Vera Rubin measured galaxy rotation curves from the 1960s

Cold dark matter

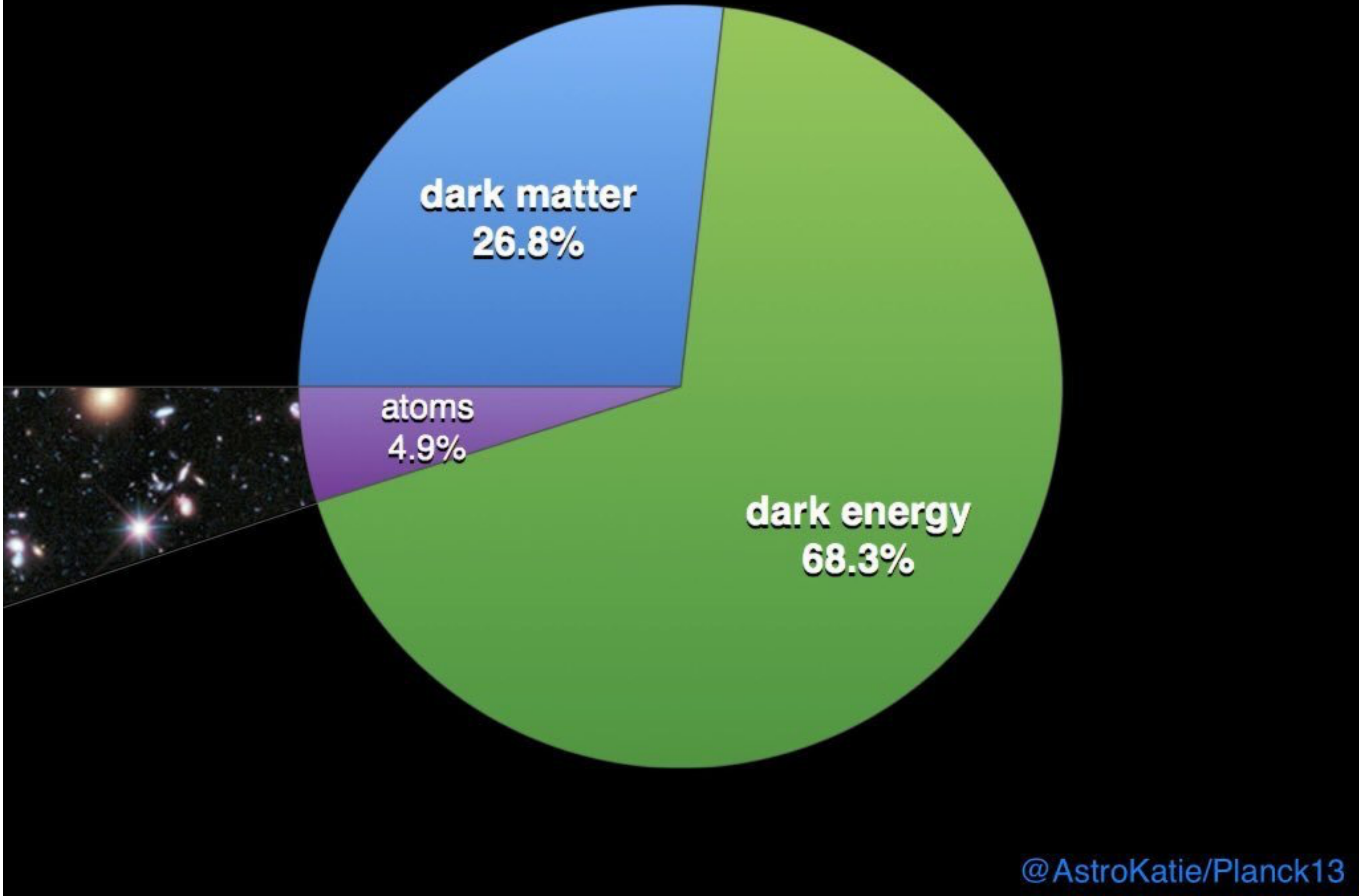
- The evidence includes galaxy rotation curves, galaxy cluster velocities and the bullet cluster

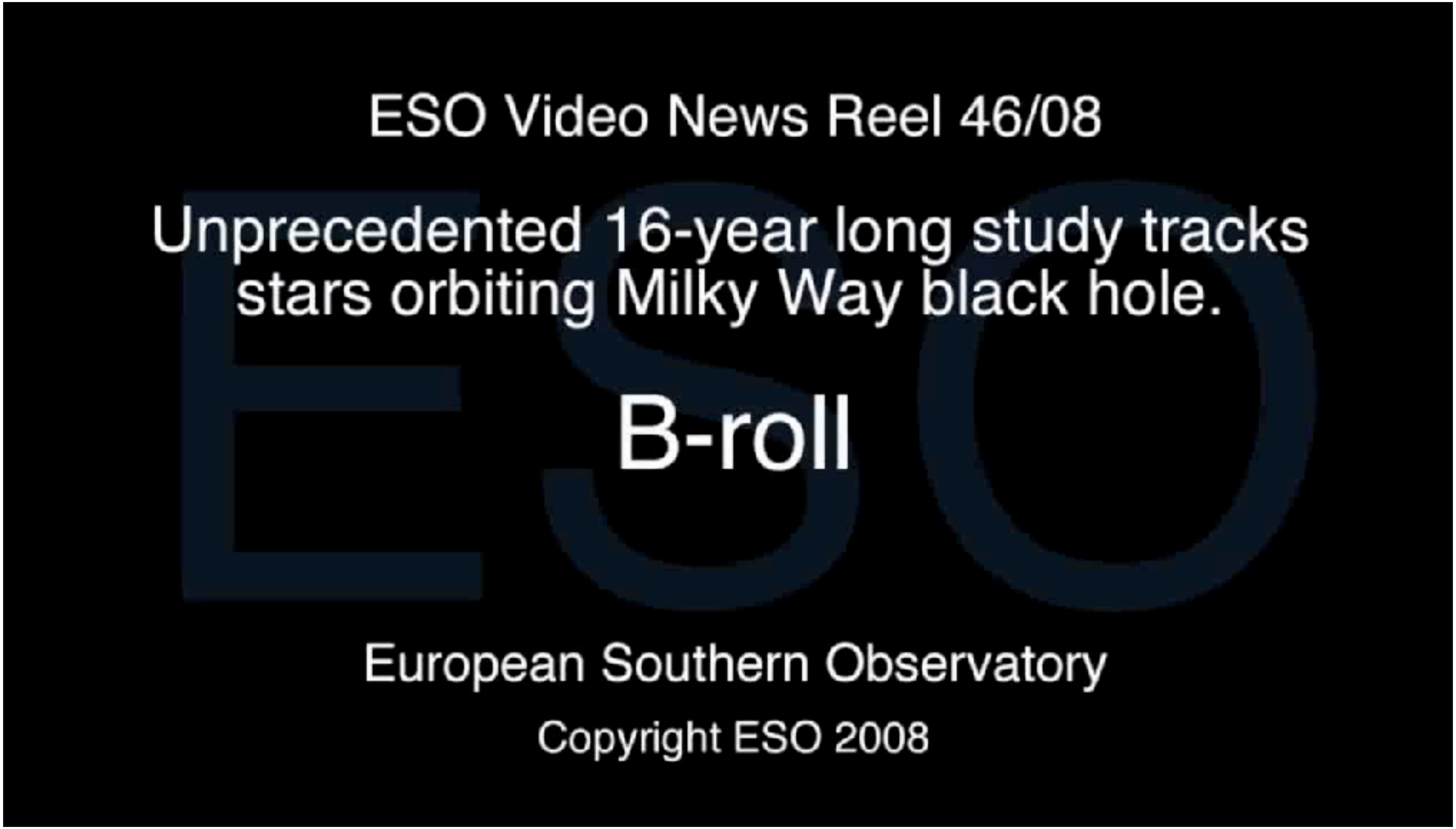
- Black holes are cold and dark

- However, the growth of structure from the CMB till today proves DM must have formed before the CMB. Does this rule out black holes as dark matter?

- Not if they are primordial!

By the 1980s nearly all cosmologists accepted the need for dark matter





Edited from the European Space Observatory 2008

The Nobel Prize in Physics 2020

© Nobel Media. Ill. Niklas Elmehed.

Roger Penrose

Prize share: 1/2

© Nobel Media. Ill. Niklas Elmehed.

Reinhard Genzel

Prize share: 1/4

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Andrea Ghez

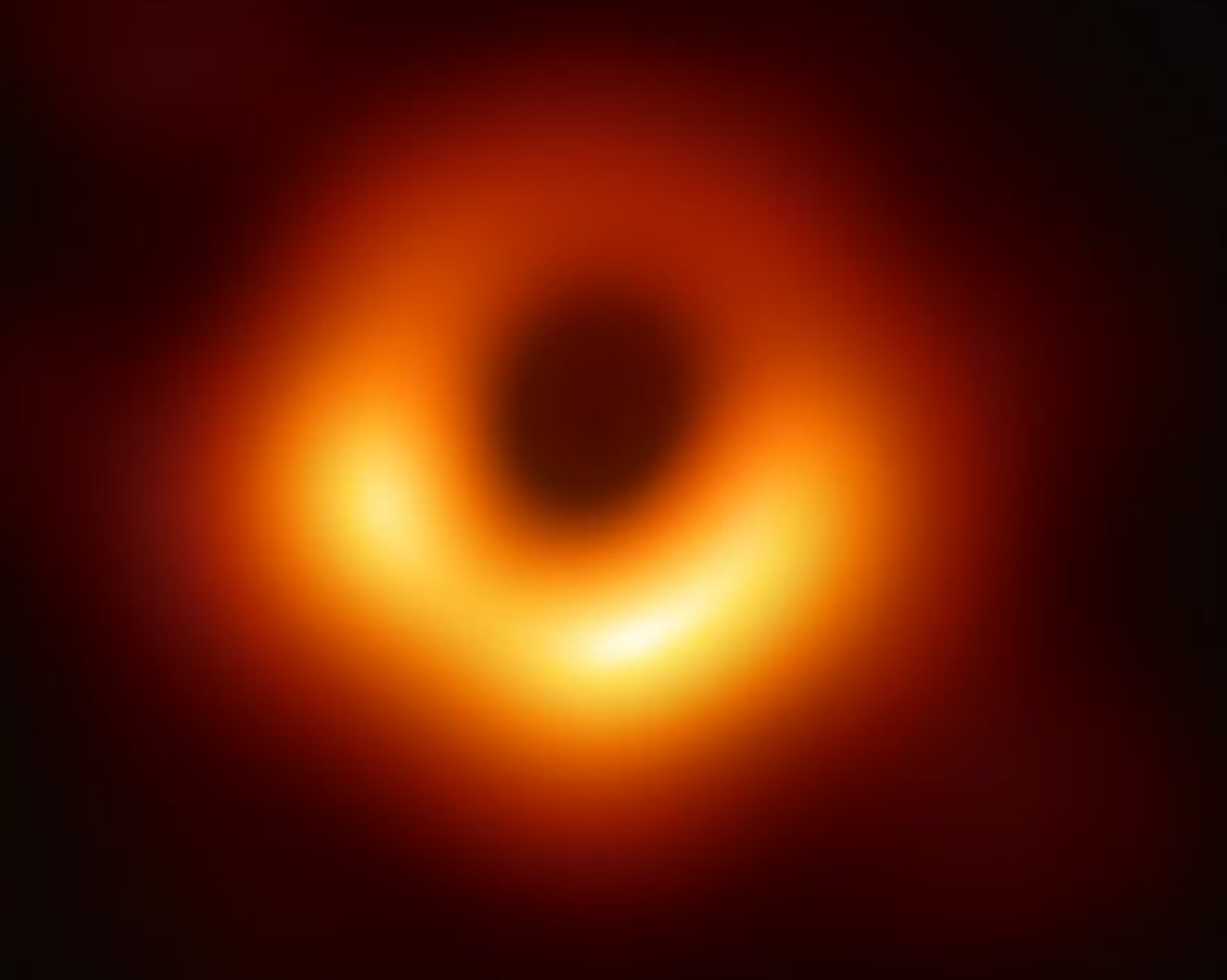
Prize share: 1/4

https://www.nobelprize.org/prizes/physics/2020/summary/

The Nobel Prize in Physics 2020 was divided, one half awarded to Roger Penrose "for the discovery that black hole formation is a robust prediction of the general theory of relativity", the other half jointly to Reinhard Genzel and Andrea Ghez "for the discovery of a supermassive compact object at the centre of our galaxy."

The event horizon telescope

A supermassive black hole in a nearby galaxy



https://www.space.com/event-horizon-telescope-black-hole-photos-future.html

Dark matter might not be a new particle

- The unique alternative in GR are primordial black holes (PBHs)

  Zel'dovich and Novikov 1967; Hawking 1974; Carr and Hawking 1974

- The existence of black holes which formed in the early universe requires special initial conditions but not new physics

- If detected, PBHs would teach us a lot about the early universe and inflation

- PBH reviews include: *Sasaki et al '18; Carr & Kuhnel '20; Green & Kavanagh '20*

Black holes

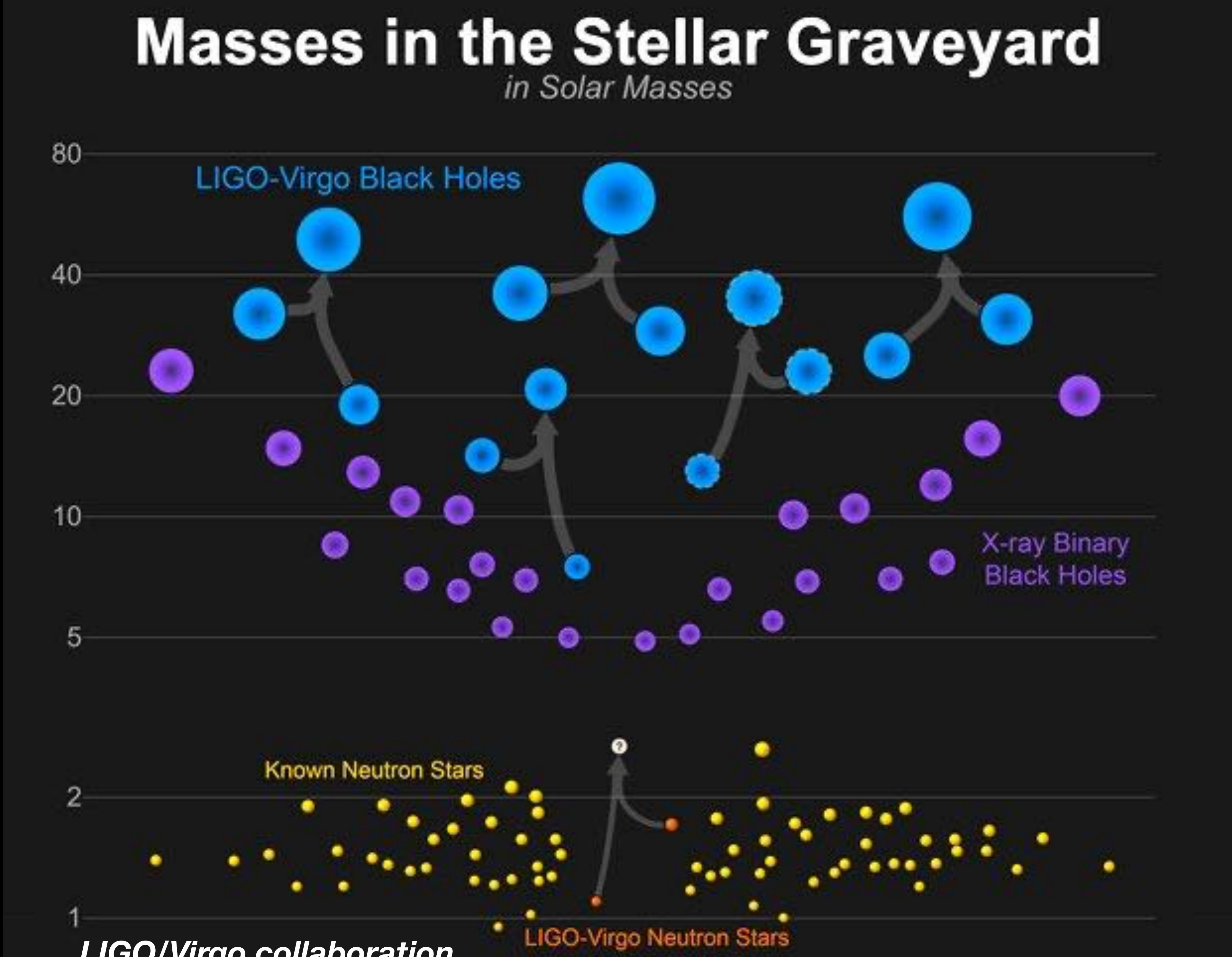
- Three populations have been observed
  1. "Light" BHs with 5-20 $M_\odot$ which formed via stellar collapse
  2. Supermassive BHs 10^6-10^{10} $M_\odot$ in galactic centres - formation process uncertain
  3. Intermediate mass BHs up to 40 $M_\odot$ detected by LIGO

- BHs can form in the "late" Universe via stellar or gas cloud collapse within certain mass ranges.

- Primordial Black Holes (PBHs) could have also formed in the early Universe (during the first second) and may have any mass whatsoever

- PBHs below the Tolman-Oppenheimer-Volkoff neutron star mass limit are of special interest (about 2 times the Chandrasekhar mass), since they would be a smoking gun for a primordial origin. Those below the Chandrasekhar mass would be an even clearer signature.

Bambi review 2017



LIGO/Virgo collaboration

[Submitted on 1 Mar 2016 (v1), last revised 30 May 2016 (this version, v2)]

Did LIGO detect dark matter?

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

We consider the possibility that the black-hole (BH) binary detected by LIGO may be a signature of dark matter. Interestingly enough, there remains a window for masses $20\,M_\odot \lesssim M_{\rm bh} \lesssim 100\,M_\odot$ where primordial black holes (PBHs) may constitute the dark matter. If two BHs in a galactic halo pass sufficiently close, they radiate enough energy in gravitational waves to become gravitationally bound. The bound BHs will rapidly spiral inward due to emission of gravitational radiation and ultimately merge. Uncertainties in the rate for such events arise from our imprecise knowledge of the phase-space structure of galactic halos on the smallest scales. Still, reasonable estimates span a range that overlaps the $2-53$ Gpc^{-3} yr^{-1} rate estimated from GW150914, thus raising the possibility that LIGO has detected PBH dark matter. PBH mergers are likely to be distributed spatially more like dark matter than luminous matter and have no optical nor neutrino counterparts. They may be distinguished from mergers of BHs from more traditional astrophysical sources through the observed mass spectrum, their high ellipticities, or their stochastic gravitational wave background. Next generation experiments will be invaluable in performing these tests.

Comments:	5 pages, 2 figures, updated to match version published in PRL
Subjects:	**Cosmology and Nongalactic Astrophysics (astro-ph.CO)**; High Energy Physics - Phenomenology (hep-ph)
Journal reference:	Phys. Rev. Lett. 116, 201301 (2016)
DOI:	10.1103/PhysRevLett.116.201301
Cite as:	arXiv:1603.00464 **[astro-ph.CO]**

The LIGO events

- It appears unlikely that more than 1% of the dark matter can be made out of LIGO mass PBHs

- But all of the LIGO BHs could be primordial

- Black holes have no hair, so how can we know?
  Total mass
  Mass ratio
  (Spin, redshift distribution and location)

LIGO/Virgo - gravitational wave hunters

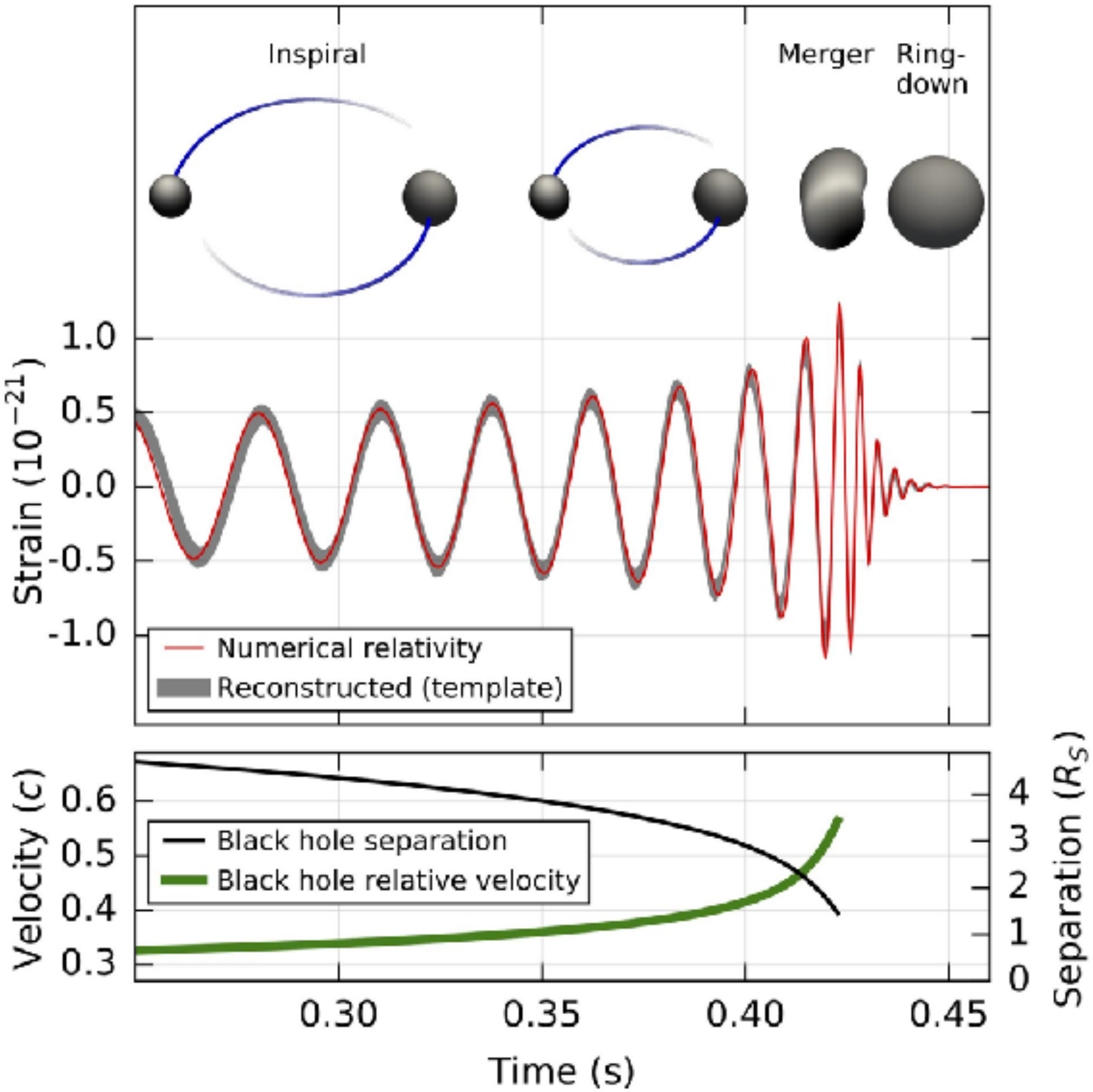
https://www.ligo.org/public.php

Gravitational waves - 2017 Nobel prize

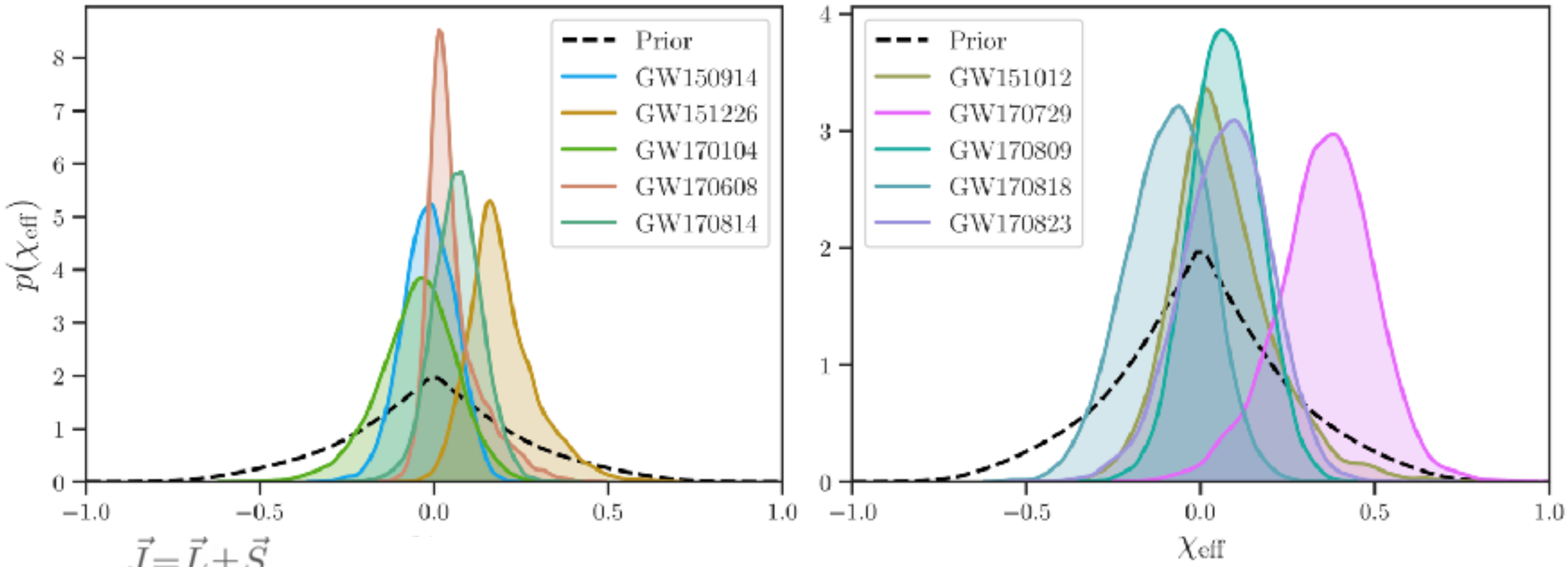
$$E = mc^2$$

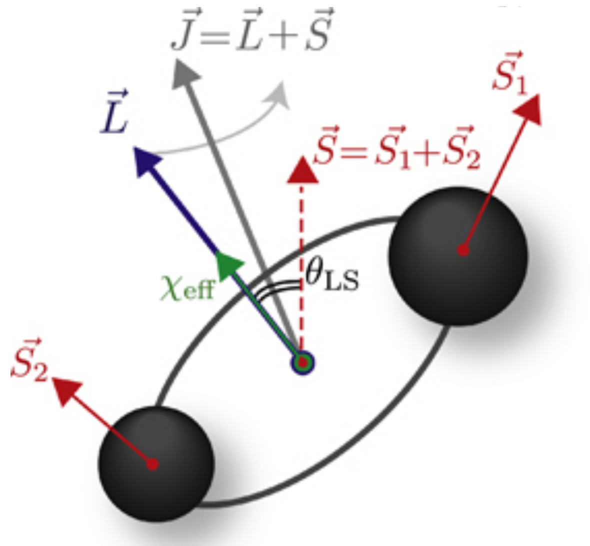
A new way to “see” the universe
Black holes and neutron stars have been seen merging

The three merger phases



Black hole spin - in isolation favours PBHs





$$\chi_{\rm eff} = \frac{c}{G(m_1+m_2)}\left(\frac{\vec{S}_1}{m_1}+\frac{\vec{S}_2}{m_2}\right)\cdot\vec{L} \qquad a_* = \frac{c\,|\,\vec{S}\,|}{Gm^2} \le 1$$

Model comparison based on spins
Fernandez & Profumo `19, Garcia-Bellido et al ’20, Wong et al 2020 (uses 03a data)
However, we find that by far the strongest constraining power comes from the masses

PBHs do not undergo much collapse before formation, small spin expected
Belczynski et al. `17; Mirbabyi et al `19; De Luca et al `19, Harada et al ’20 + many more

Has LIGO detected ~~DM~~ PBHs?

The Bayesian evidence ratio

$$\frac{Z_A}{Z_B} \equiv \frac{p(M_A|\mathbf{d})}{p(M_B|\mathbf{d})} = \frac{p(M_A)}{p(M_B)} \frac{\int p(\mathbf{d}|\boldsymbol{\theta}, M_A) p(\boldsymbol{\theta}|M_A) \mathrm{d}\boldsymbol{\theta}}{\int p(\mathbf{d}|\boldsymbol{\theta}', M_B) p(\boldsymbol{\theta}'|M_B) \mathrm{d}\boldsymbol{\theta}'}$$

Population parameters, i.e. mass function parameters, PBH abundance etc.

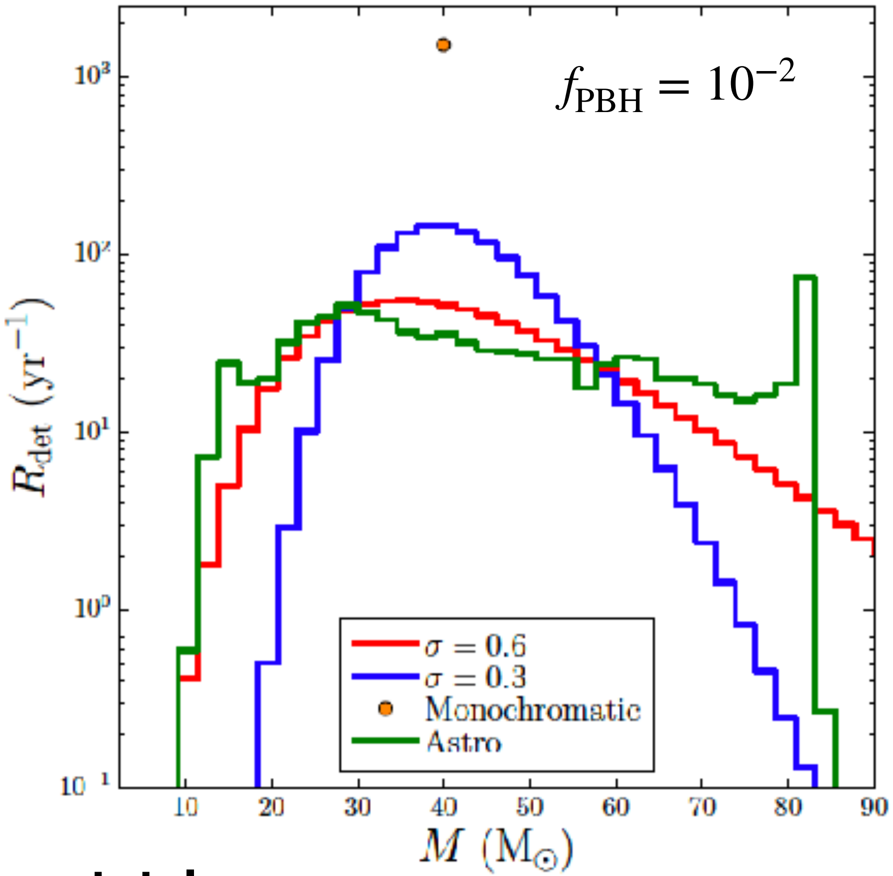
Hall, Gow, CB, 2020: Bayesian comparison

Key ingredients

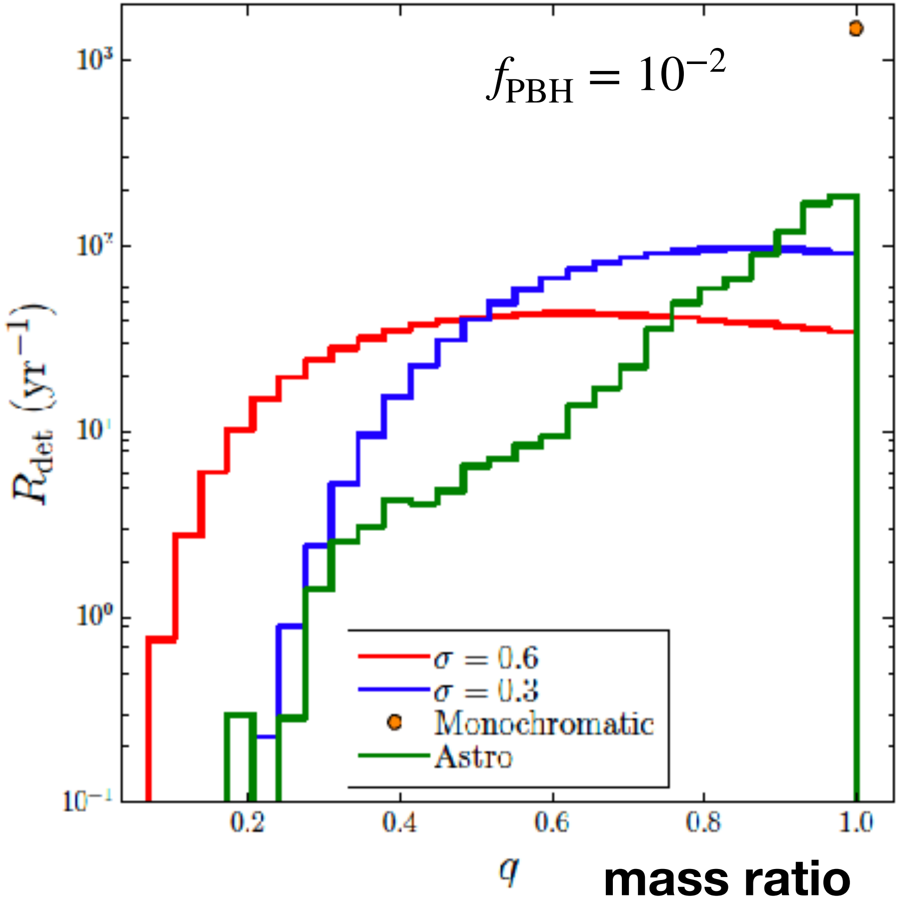
- We perform a Bayesian model comparison, where the two models are either all black holes are astrophysical or all are primordial
- We marginalise over the PBH merger rate, by assuming a functional form of the PBH mass function and then fit the free parameters to the data
- This typically means fitting a peak mass, a width, and an amplitude (f_{PBH})
- We take broad priors on all parameters
- For the astrophysical model we take the empirical models A and B from LIGO-Virgo 02 results, which captures some key physics such as the lower and upper mass cut offs and power law dependence on the upper mass and the mass ratio

Varying the PBH mass function width (sigma)

Wide enough to fit the masses, yet not so wide to stop q~1



total mass



mass ratio

The "astro" distribution covers a broader range of total masses than sigma=0.3, but it still prefers the mass ratio q~1. A monochromatic mass function is ruled out.

Gow, CB, Hall, Peacock 2019

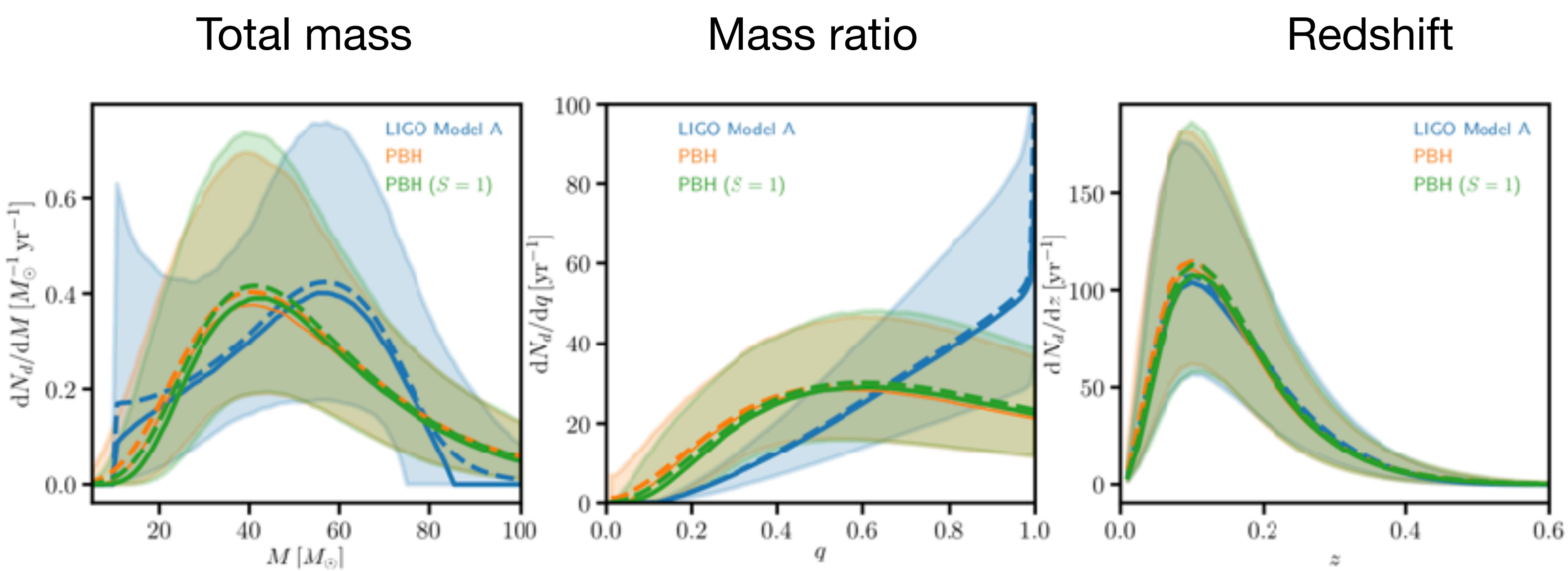
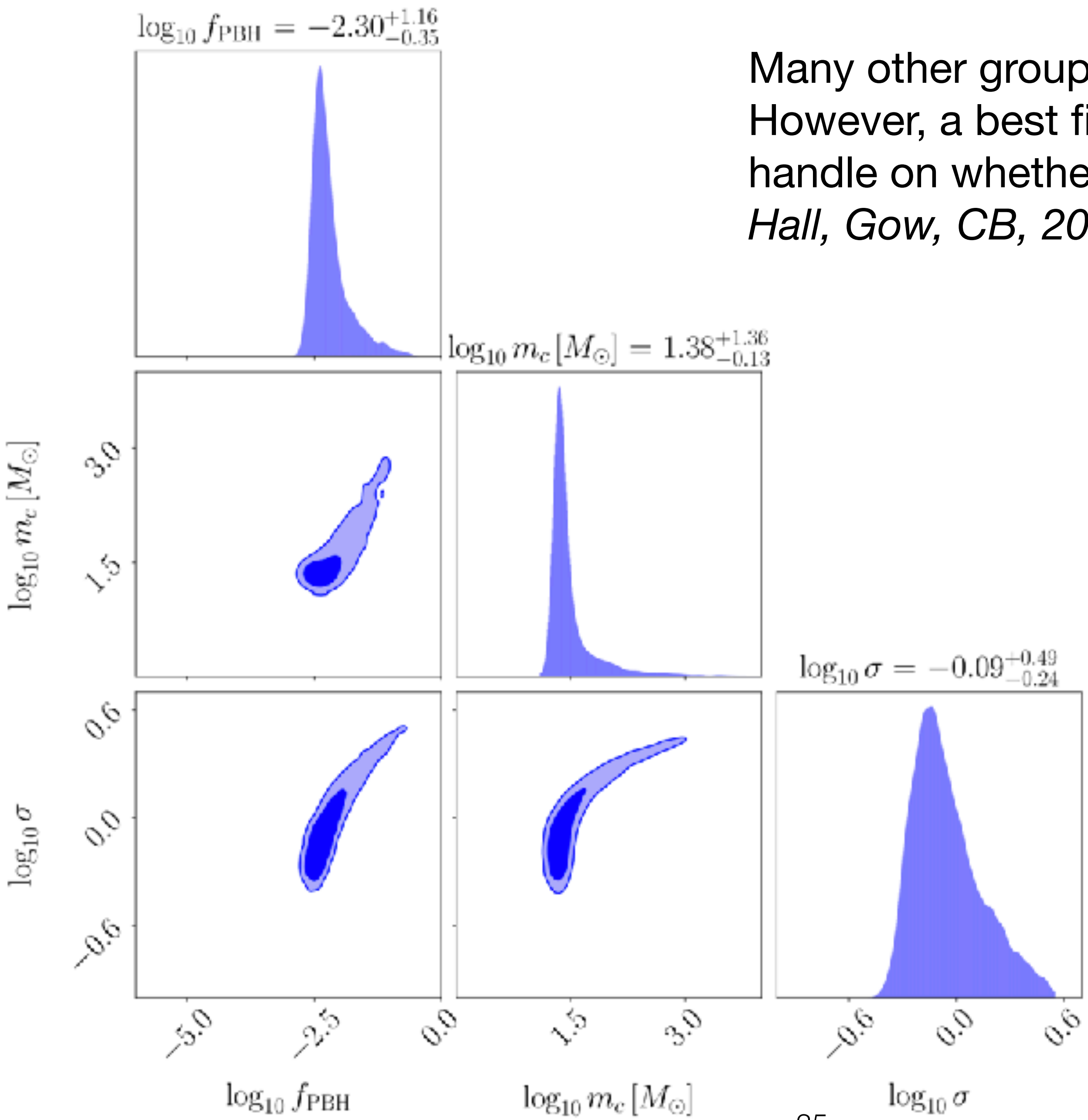


FIG. 11: Differential detector-frame merger rates with respect to total mass (left panel), mass ratio (middle panel) and redshift (right panel) for LIGO Model A (blue), the lognormal PBH model (orange) and the lognormal PBH model with suppression factor set to unity (green). In each case we plot the median and 90% quantiles over the posterior samples for each model given the GWTC-1 data (solid lines and shaded bands), and the (weighted) mean over the samples (dashed lines).

Hall, Gow, CB, 2020: Bayesian comparison

PBHs are better are explaining events with a small mass ratio, but don't naturally explain the upper and lower mass gaps predicted by stellar models
PBHs are more flexible at explaining individual events

Fitting a lognormal mass function



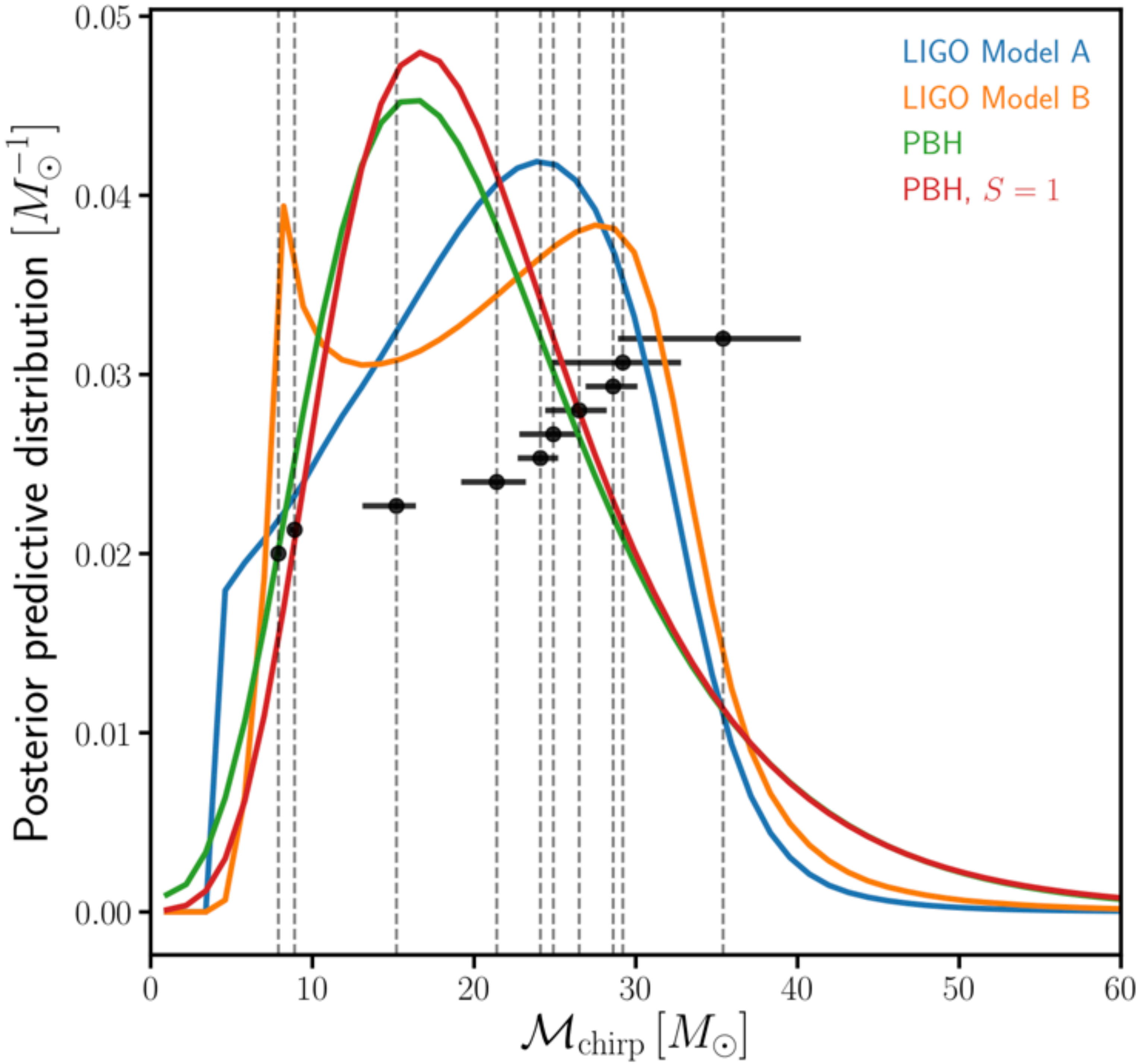
Many other groups have made similar fits
However, a best fit analysis does not give any handle on whether the best fit is also a good fit
Hall, Gow, CB, 2020

Bayesian results

- Our models are: All mergers are due to PBHs vs all due to stellar BHs
- We use 01/02 data only and carefully use the LIGO sensitivity curve.
- The Bayesian evidence can be approximated as the likelihood of the best fit model * the Occam factor
- Both are important but the Occam factor is prior dependent and more controversial
- PBHs are disfavoured by both terms - assuming the “normal” lognormal mass function

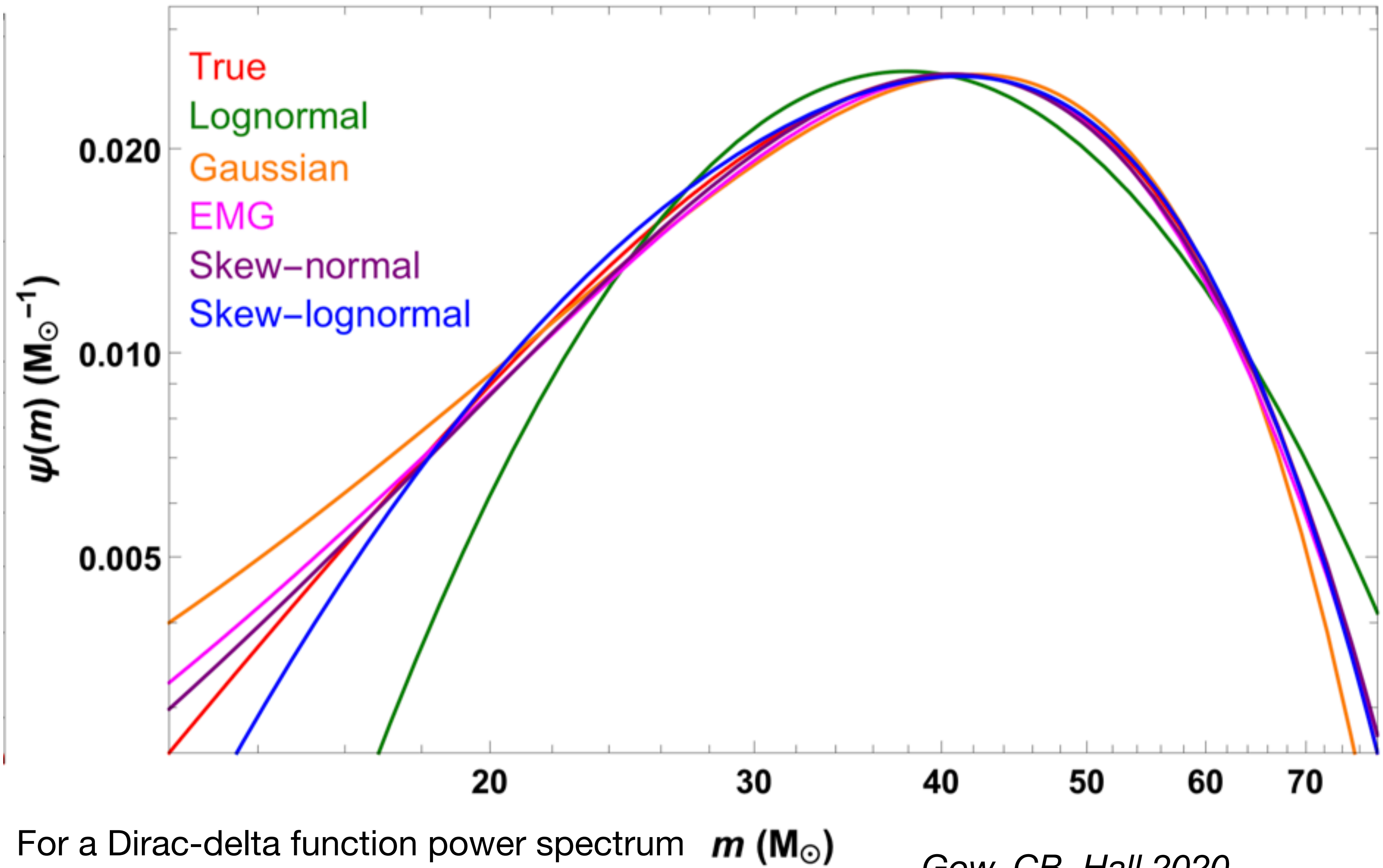
PBH models are disfavoured decisively

$$\ln Z_{\mathrm{PBH}}/Z_{\mathrm{stellar}} = -7.35 \pm 0.23$$



Hall, Gow, CB, 2020: Bayesian comparison

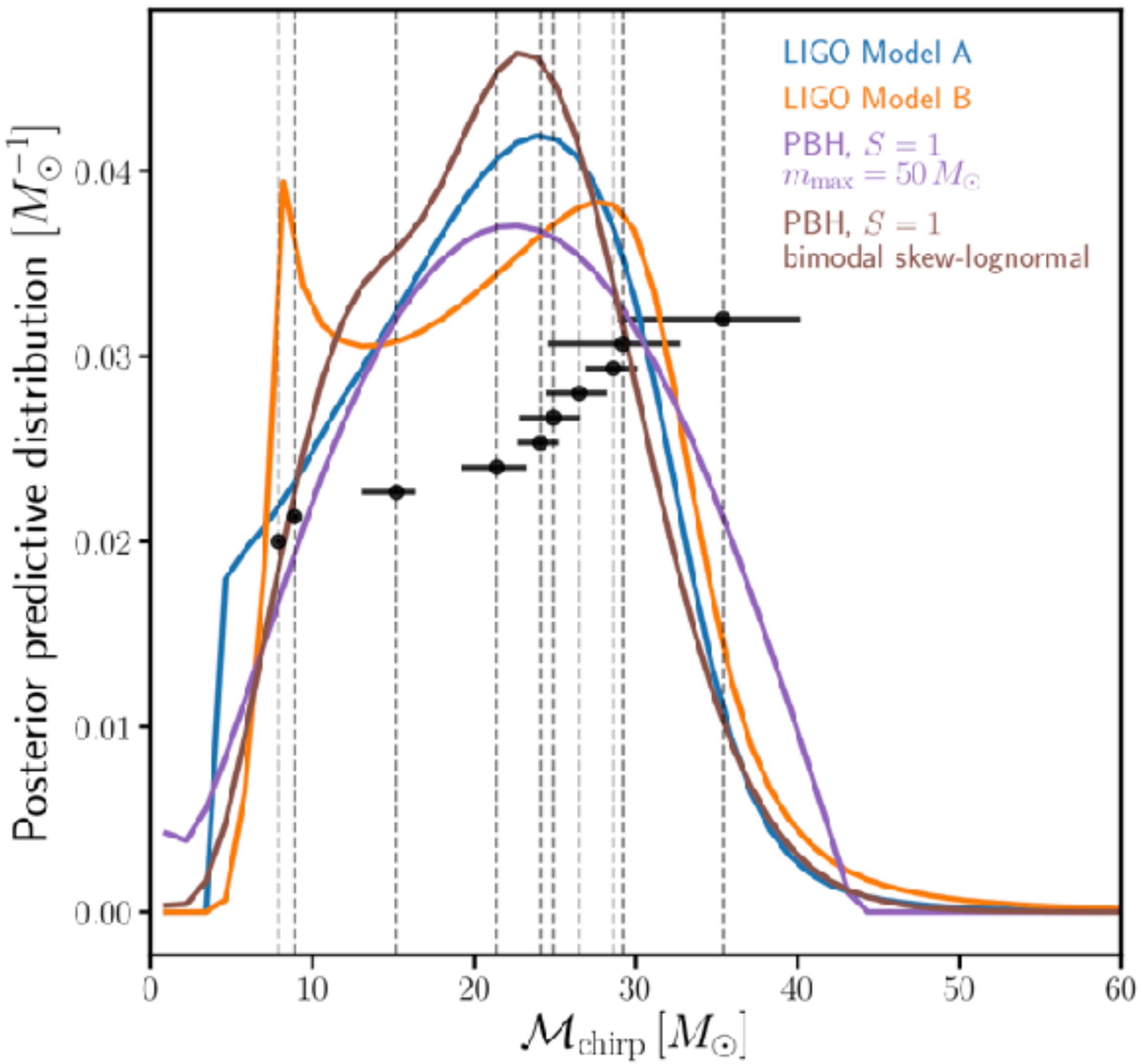
Is the lognormal mass function correct?



For a Dirac-delta function power spectrum

Gow, CB, Hall 2020

Trying hard to fit the data - cutoff or bimodal mass function



Hall, Gow, CB, 2020

These alternatives are a better fit, but still not a good fit compared to the stellar models
The late time PBH capture and merger is also a bad fit
Accretion broadens the mass function at large masses (*de Luca et al '20):* => worse fit

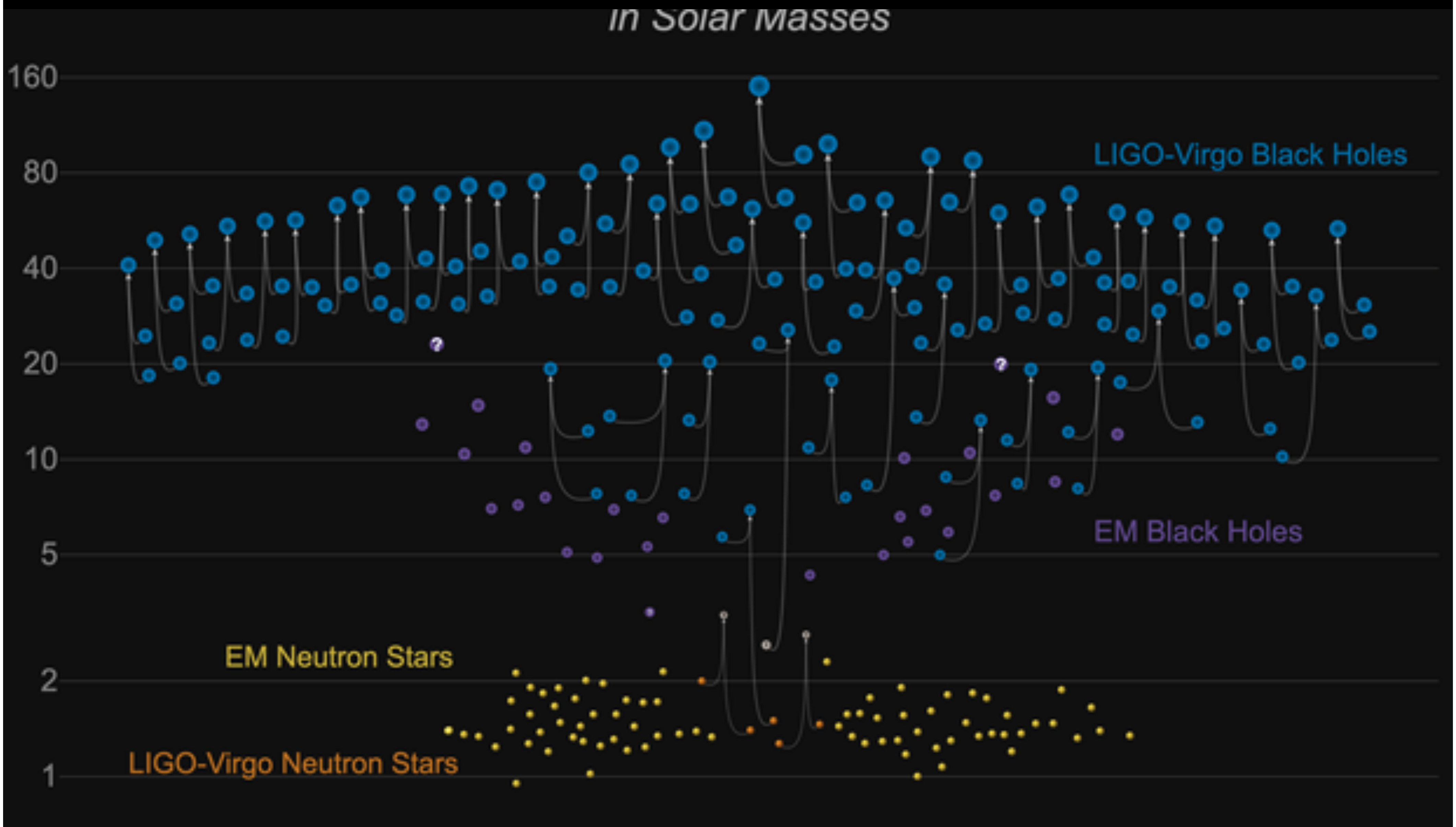
LIGO-Virgo conclusion

- Now a consensus that LIGO-Virgo is exclusively or primarily seeing astrophysical black holes: Mixed astrophysical + PBH models also studied - *Bhagwat et al 2020, Hütsi et al 2020*

- The BH properties are somewhat unexpected but modelling stellar collapse is hard

- Mixed astrophysical + PBH models remain possible

- A sub Chandrasekhar mass compact object would be the best evidence and could be seen with the current experiments

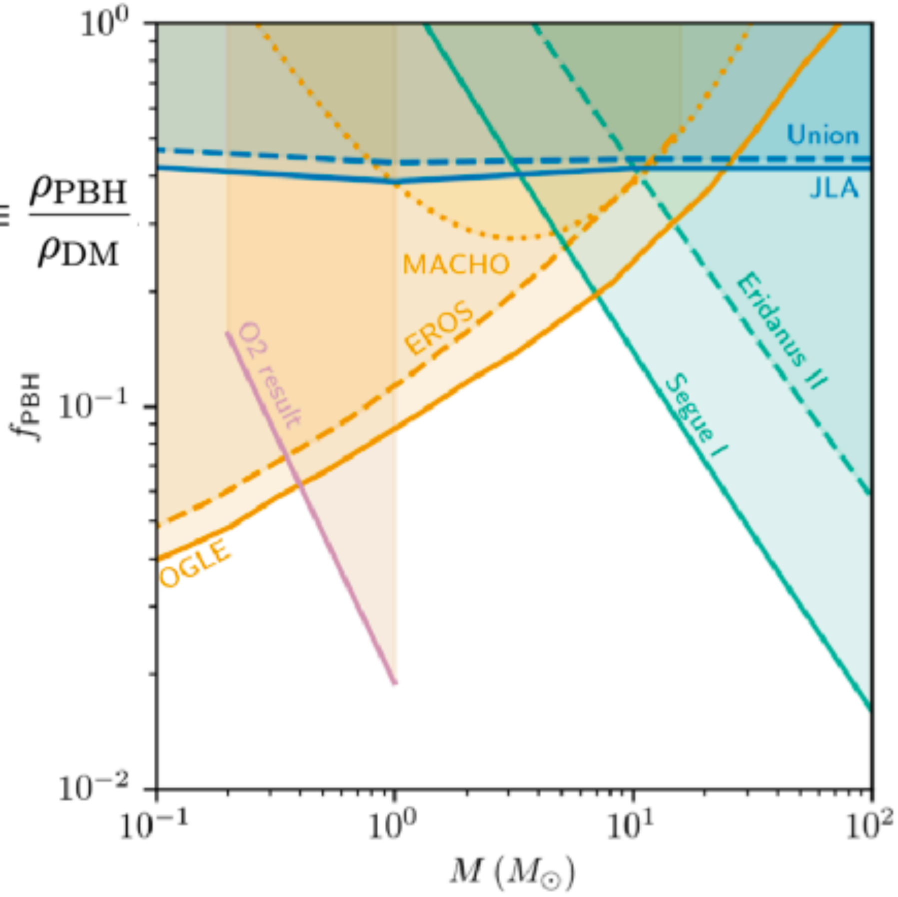


LIGO & Virgo collaboration

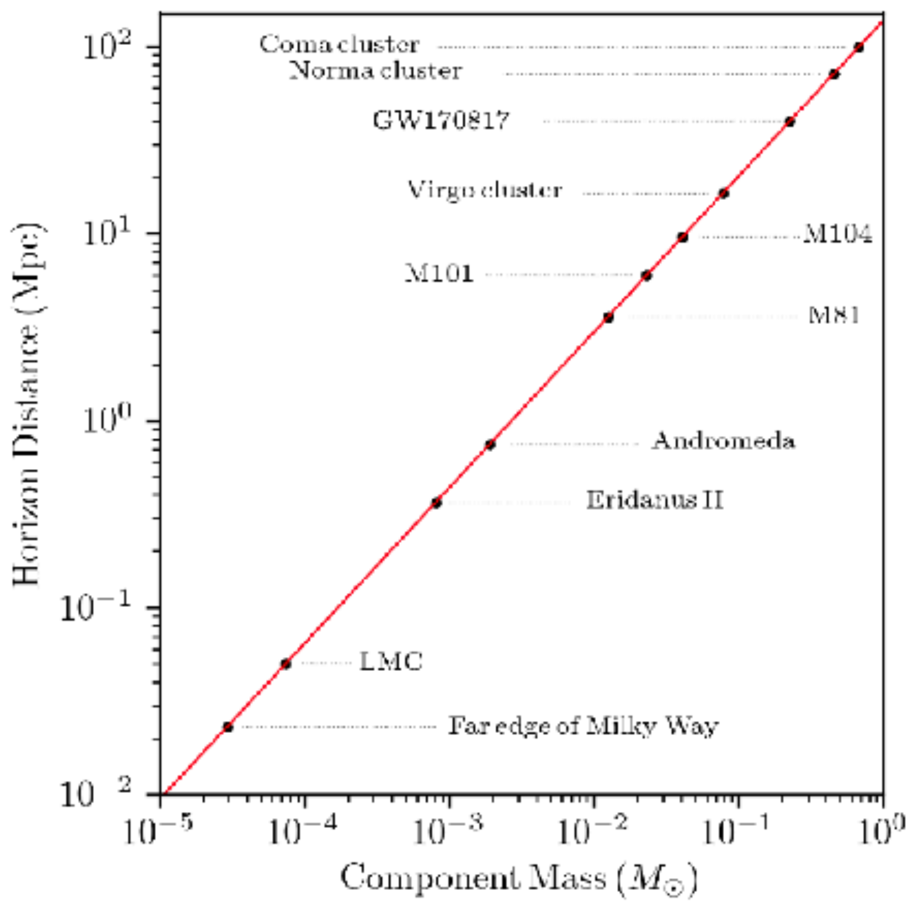
Sub-solar mass GW searches

GW searches have been made, with no detections so far.
The right hand figure shows the distance to which an equal mass merger could be detected.

$$f_{\rm PBH} \equiv \frac{\rho_{\rm PBH}}{\rho_{\rm DM}}$$



LIGO & Virgo collaboration 2019



Magee et al 2018

LIGO-Virgo PBH connection?

Advocates of the primordial black hole hypothesis still have a lot of convincing to do. Most physicists still believe that dark matter is made of some kind of elementary particle, one that's devilishly hard to detect. Moreover, the LIGO black holes aren't too different from what we would expect if they came from ordinary stars. "It sort of fills a hole in the theory that isn't actually there," said Carl Rodriguez, an astrophysicist at Carnegie Mellon University. "There are things that are weird about some of the LIGO sources, but we can explain everything that we've seen so far through normal stellar evolutionary process."

https://www.quantamagazine.org/black-holes-from-the-big-bang-could-be-the-dark-matter-20200923/?fbclid=IwAR2GgveIVyYAEkvZTfitIVjAEgwnvTwpgp6TNHfNrtS1SHin6hX6Gy7L5BY

PBH formation and QCD transition

PBH formation

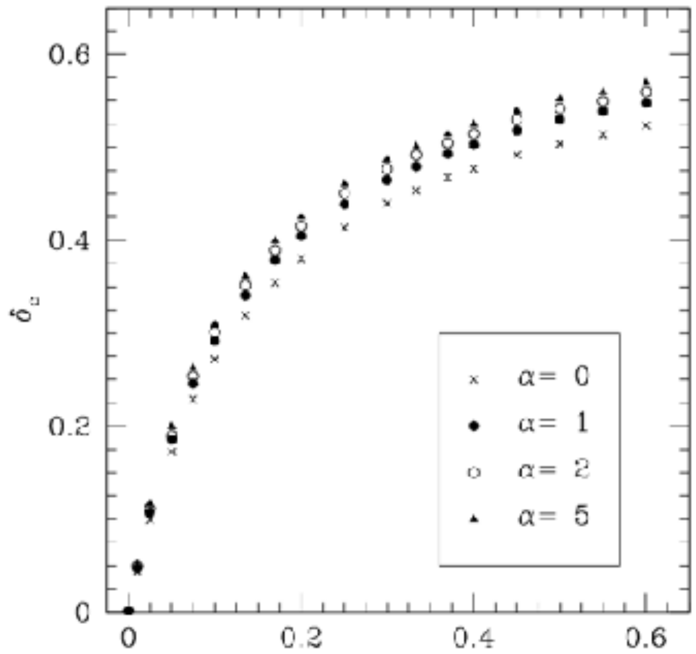
1. They could form from large amplitude density perturbations shortly after horizon entry

2. Causality prevents collapse before horizon entry

3. Approximate 1-to-1 relation between horizon entry time, horizon length and PBH mass

Collapse threshold

$$\delta \equiv \frac{\delta\rho}{\rho}|_{k=aH} > \delta_c$$

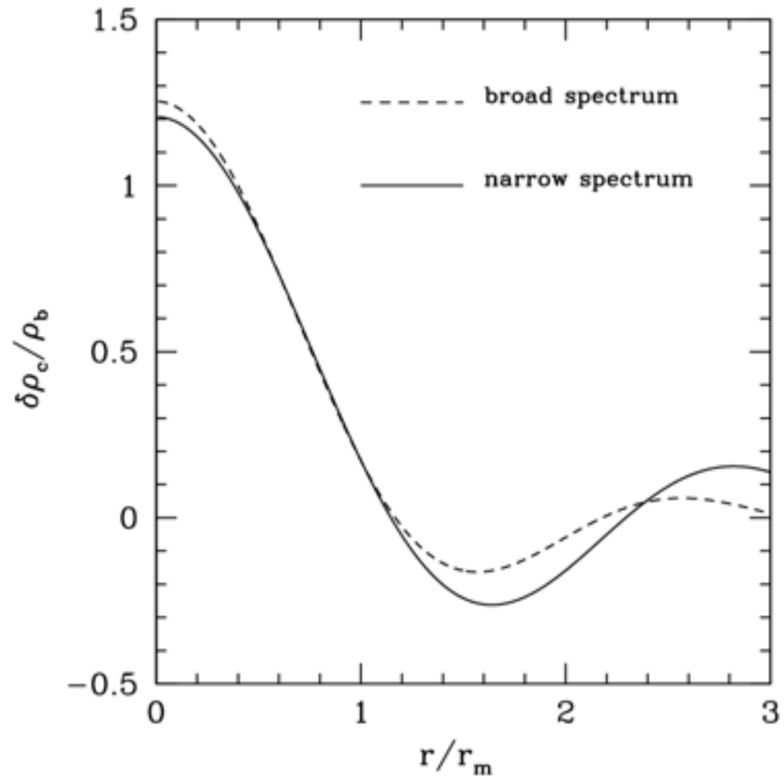


equation of state

Musco and Miller 2013

The density profiles are related to the power spectrum shape

The 2-point correlation function of the density "predicts" the density near peaks and shows that spherical symmetry is a good approximation (*BBKS 1986* classic paper, non-spherical effects *Kühnel & Sandstad 2016*)
The density profile does not change strongly assuming a smooth peak in the primordial power spectrum, independently of the width



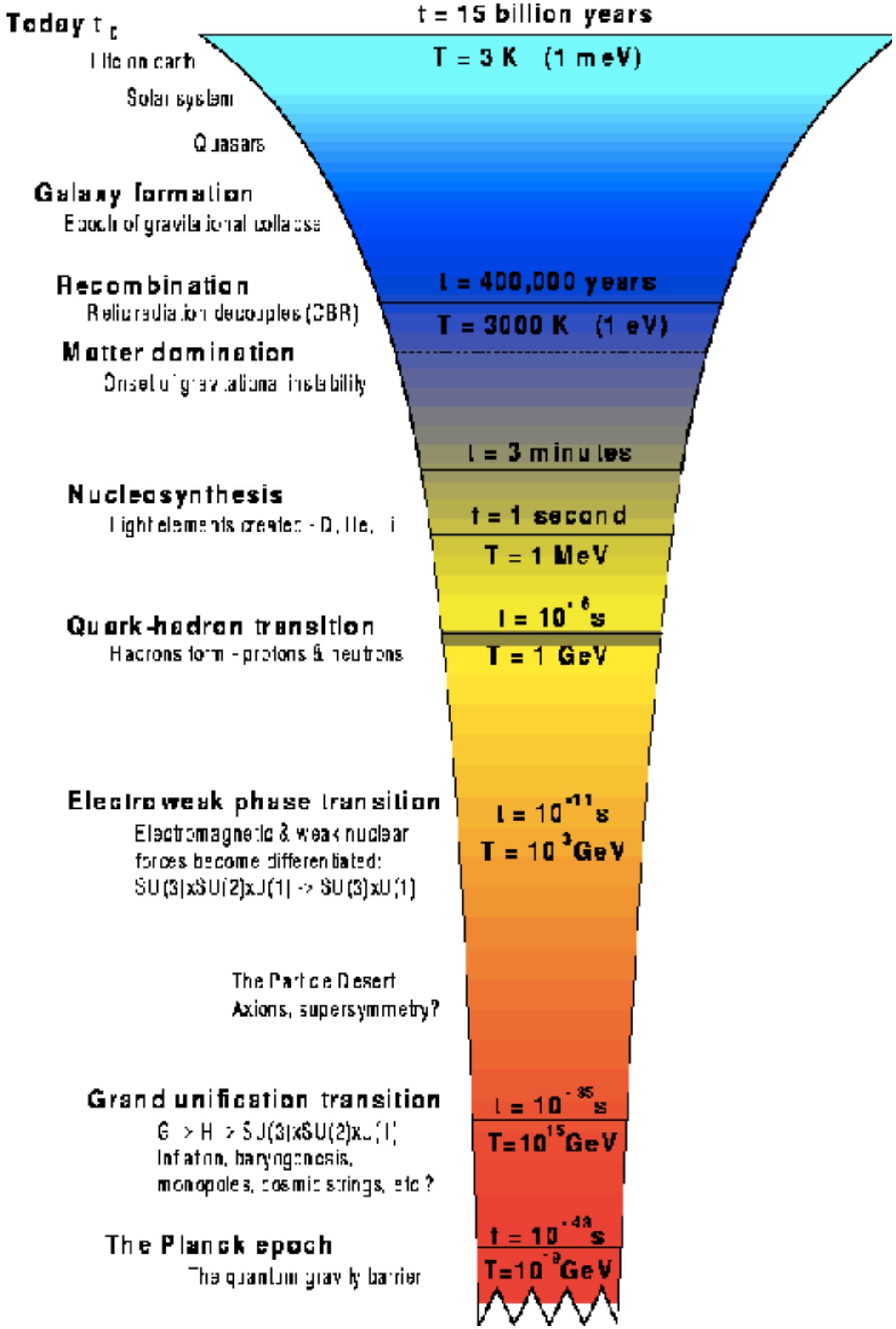
Germani & Musco 2018

A cosmological coincidence

- PBHs form quickly due to gravitational collapse as soon as the relevant scale enters the horizon (becomes causal)

- For every given mass, there is a corresponding scale and temperature during the early Universe. QCD transition: t~10^{-6}s, T~200MeV, M~1 $M_\odot$, k~10^7 Mpc^{-1}

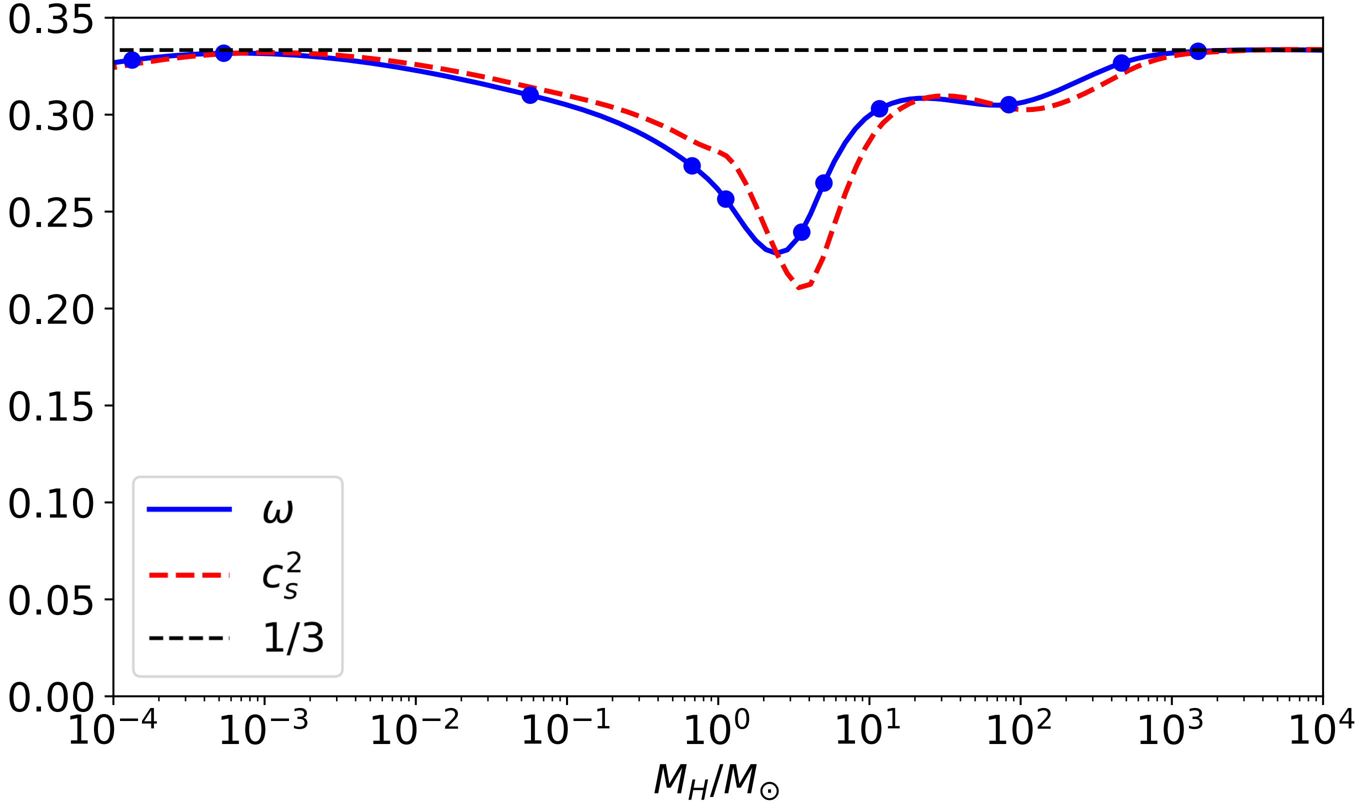
- The horizon mass has grown by about 50 orders of magnitude since the end of inflation. The QCD phase transition occurs during the time when LIGO mass PBHs formed.



The QCD transition

Strong interactions confine quarks into hadrons and the equation-of-state parameter w decreases. *Crawford & Schramm `82, Jedamzik `98*

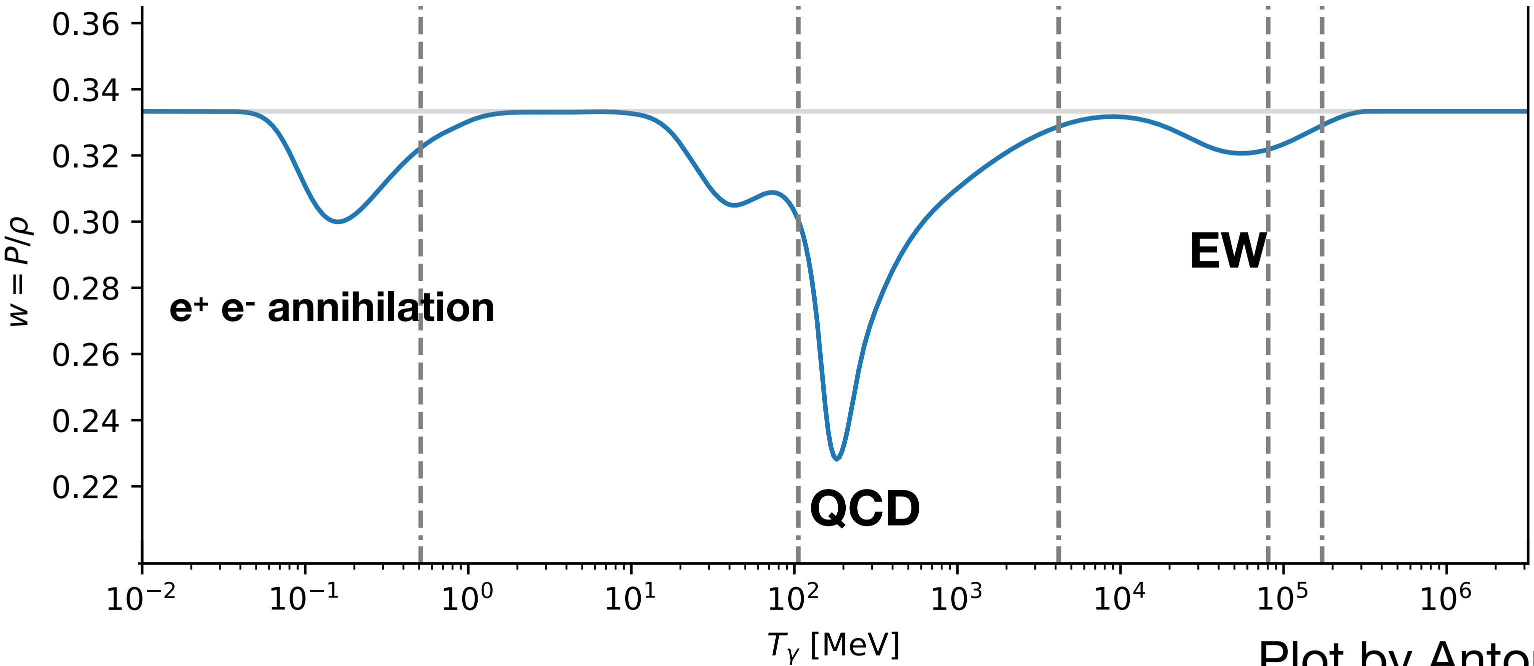
QCD transition: t~10^{-6} s, T~200 MeV, M~1 $M_\odot$, k~10^7 Mpc^{-1}



CB, Hindmarsh, Young & Hawkins 2018 using Borsanyi et al 2016

Thermal history

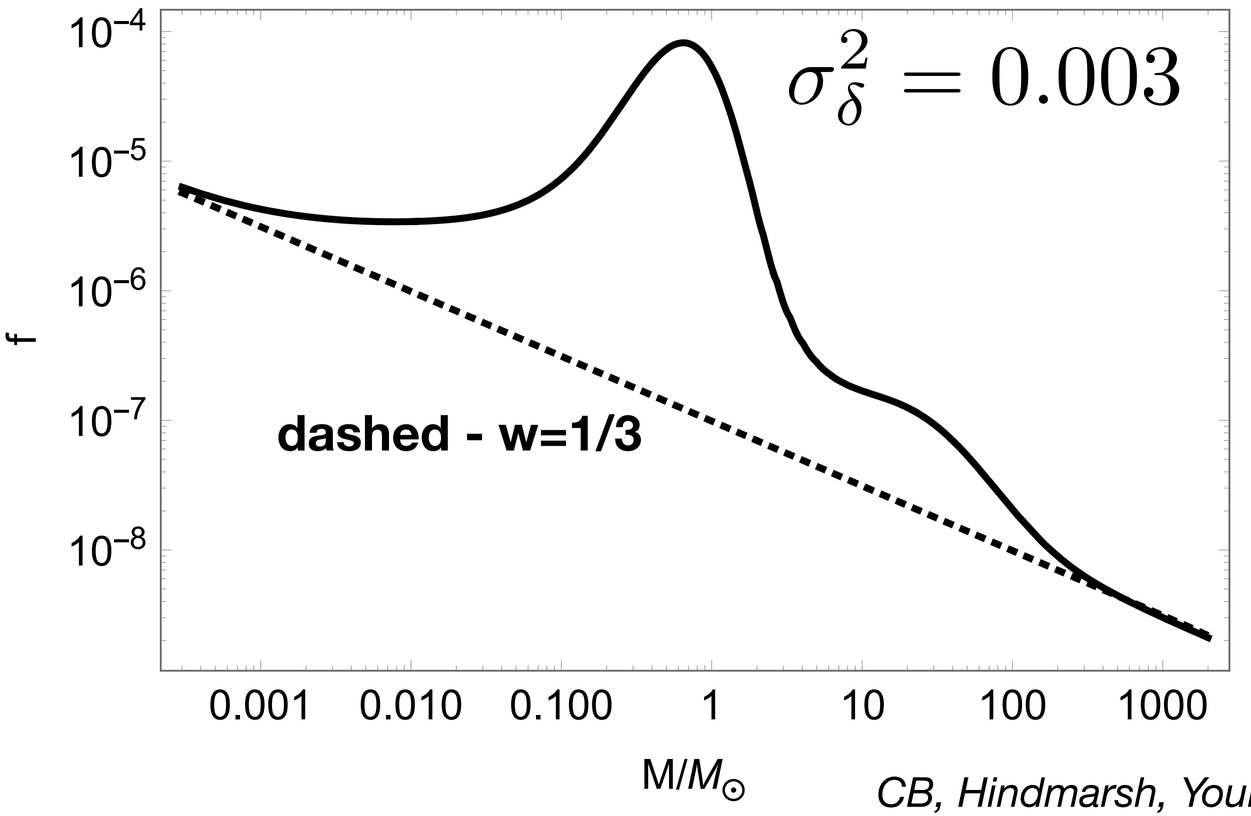
In terms of PBH production, the QCD transition is the most important in standard model physics



Plot by Antony Lewis

The resultant PBH-QCD mass function

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



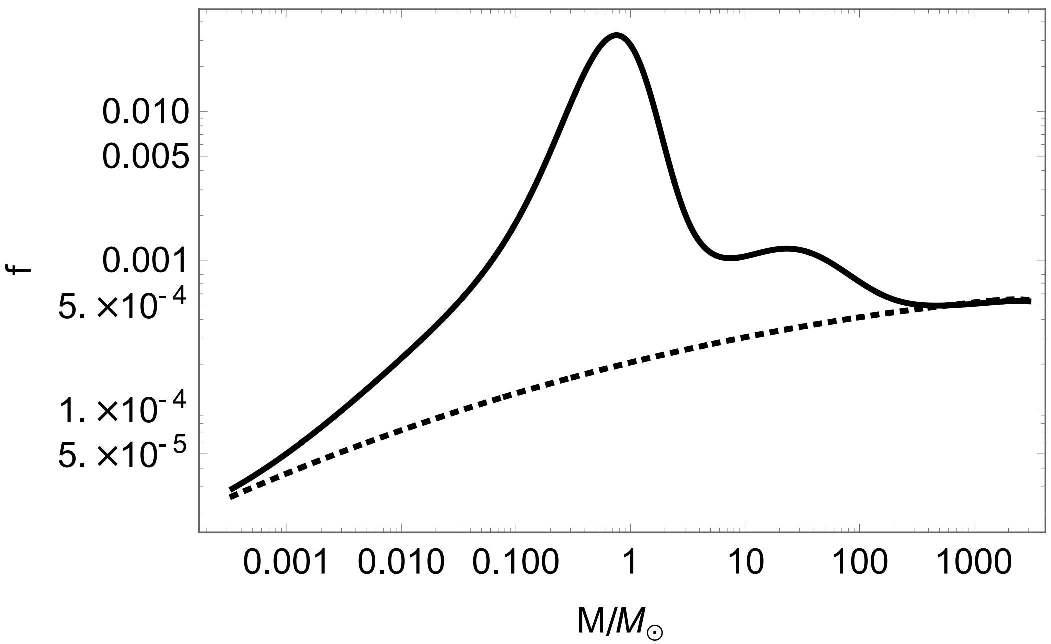
CB, Hindmarsh, Young & Hawkins 2018

The QCD phase transition took place during the time when LIGO mass PBHs would have formed. It boosts the formation rate of solar mass PBHs by 2 orders of magnitude
These are below the Chandrasekhar mass - potential proof of PBHs
No detection: *LIGO & Virgo collaboration 2019, Magee et al 2019*

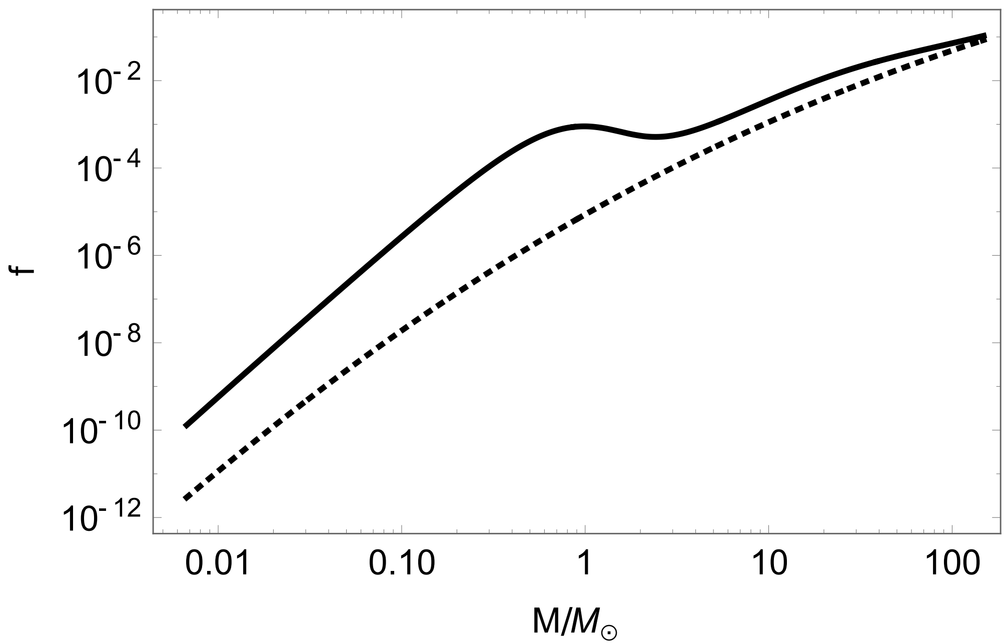
Varying the primordial perturbations

If the primordial power spectrum is not scale invariant on the relevant scales then the mass function changes, but a peak remains

$n_s - 1 = -0.05$



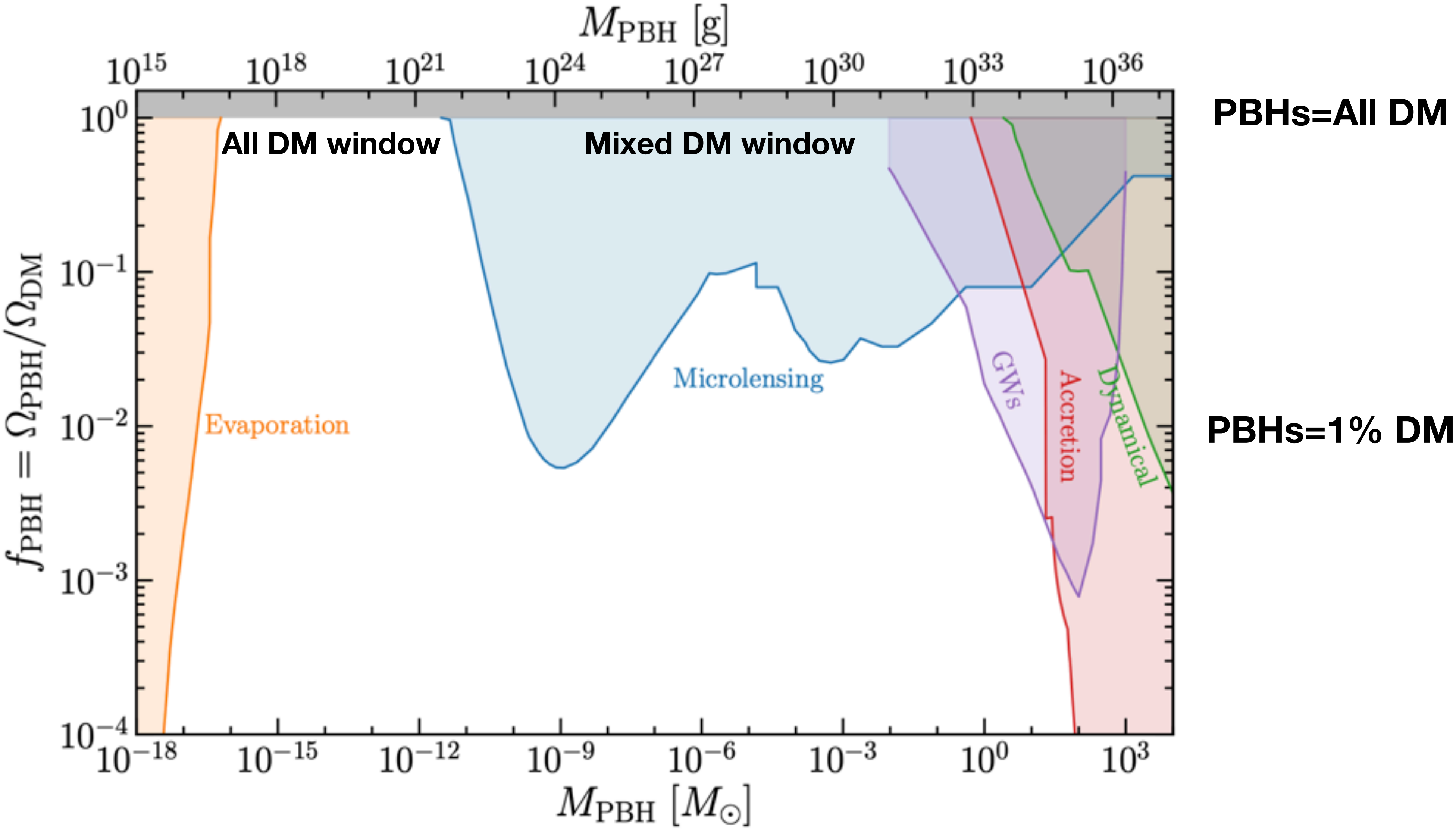
$n_s - 1 = -0.2$



Observational constraints

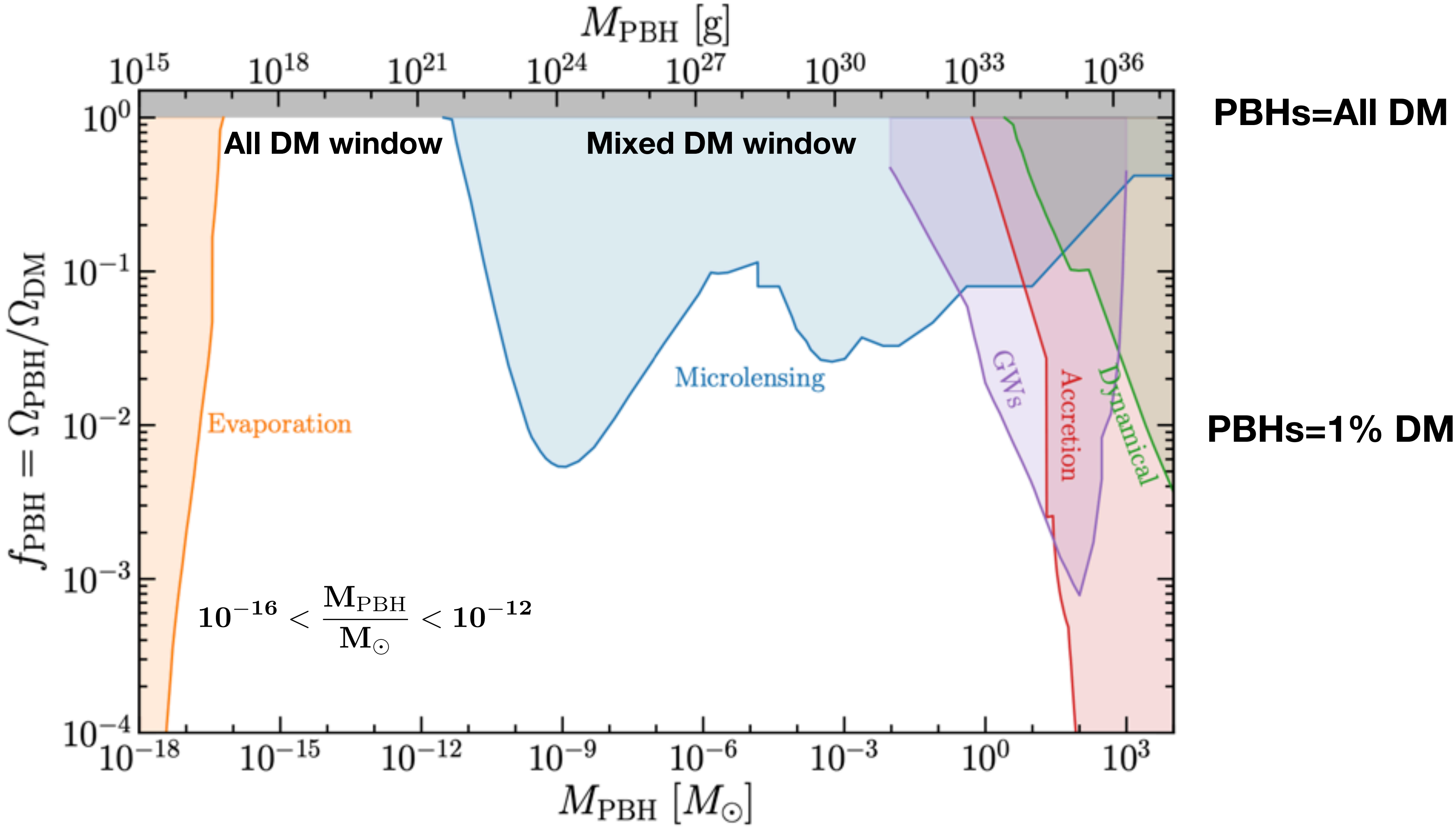
To be discussed on Friday

Observational constraints



Green and Kavanagh https://arxiv.org/pdf/2007.10722.pdf

The uncontroversial PBH=DM window “Asteroid” or “LISA” mass range



Green and Kavanagh https://arxiv.org/pdf/2007.10722.pdf

Redshift dependent constraints

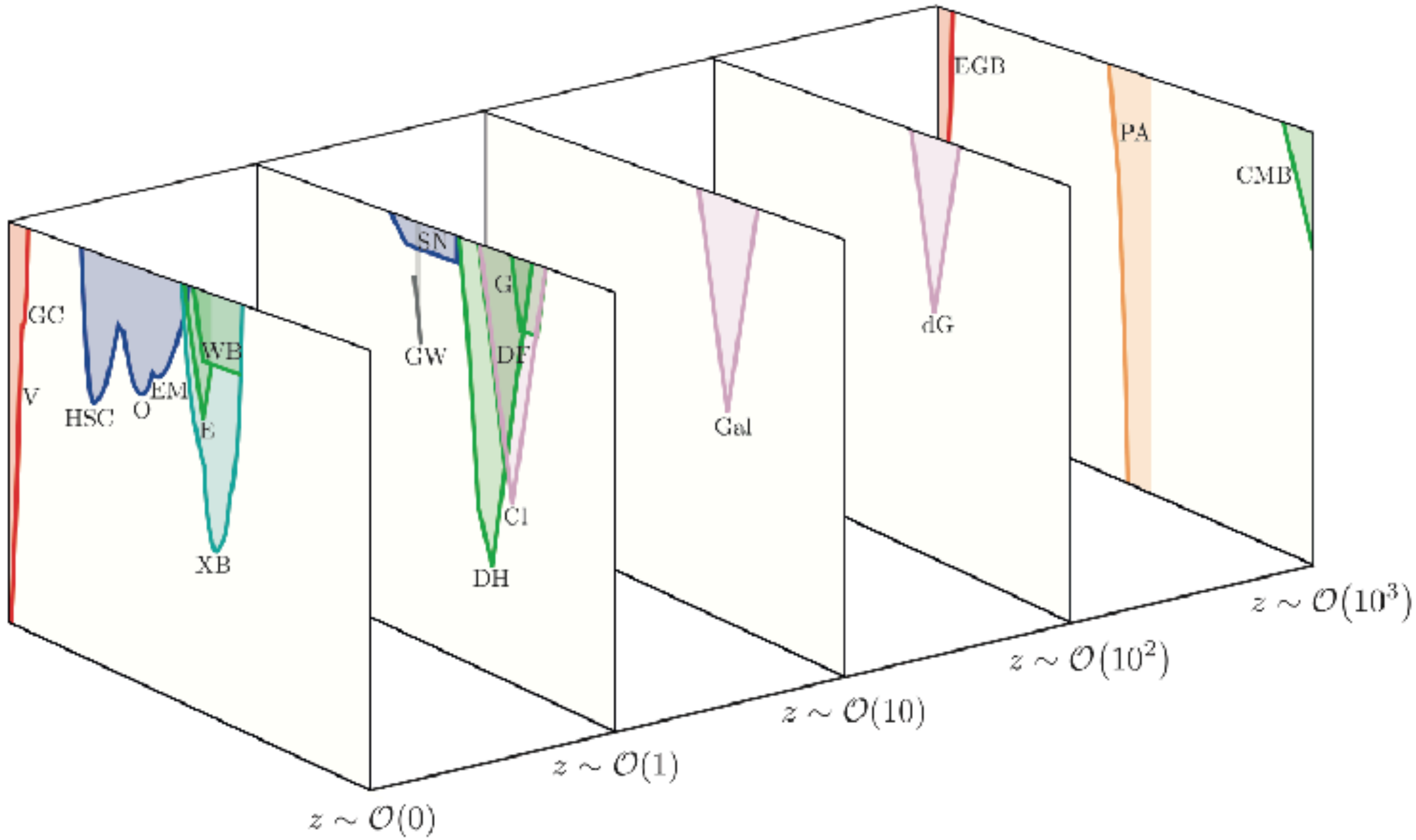
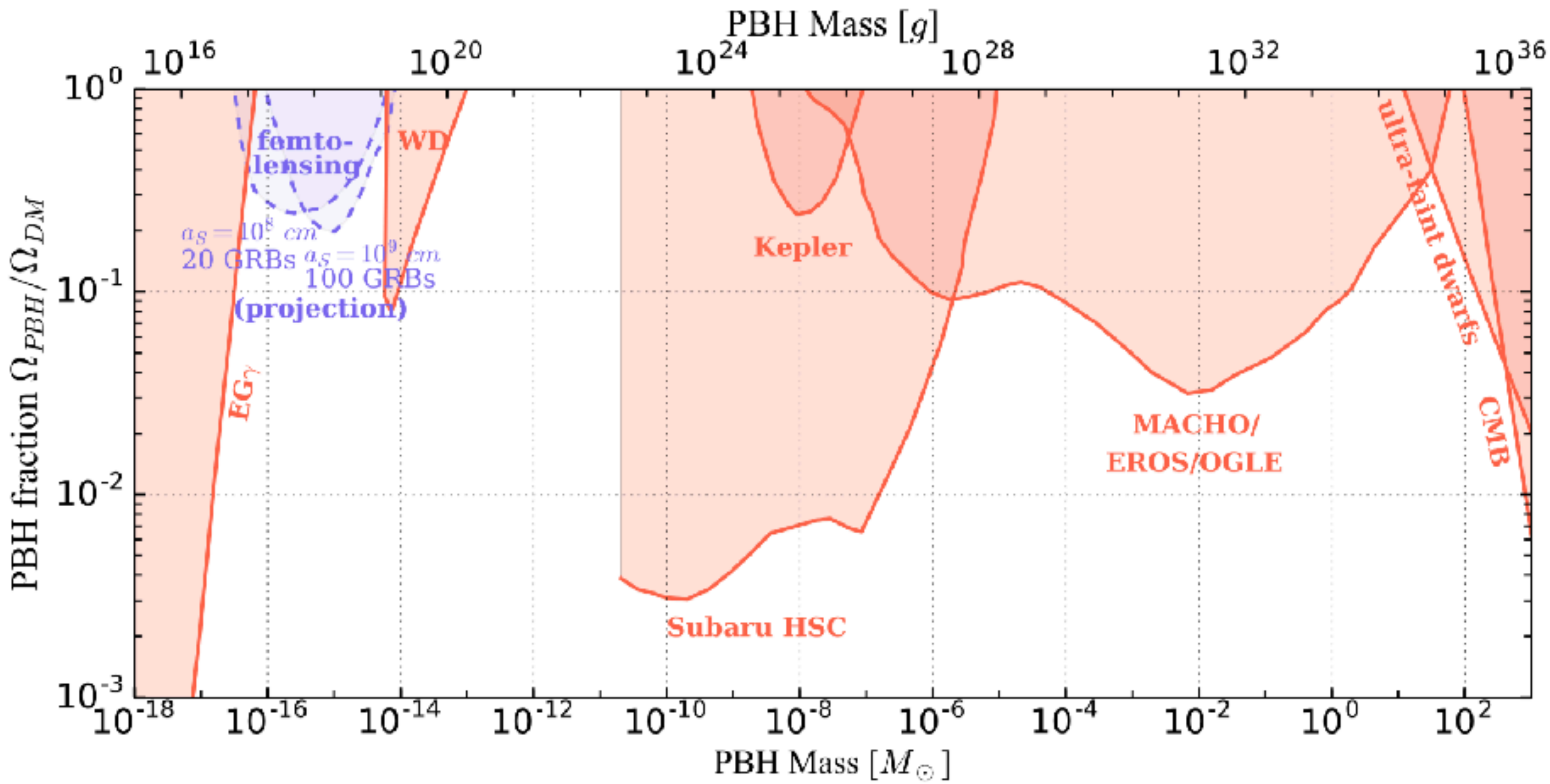


FIG. 2. Sketch of the limits shown in Figure 1 for different redshifts. Here, we break down the large-scale structure limit into its individual components from clusters (Cl), Milky Way galaxies (Gal) and dwarf galaxies (dG), as these originate from different redshifts (cf. Reference [145]). Further abbreviations are defined in the caption of Figure 1.

Carr & Kuhnel 2020

“Time dependent” constraints



Katz et al 2018 “Femtolensing revisited”; see also Sasaki et al 2017 Review

The constraints have shifted and some have disappeared over time *Niikura et al `18*
Potential NS destruction constraints via PBH capture was discussed already

This bound was eliminated in 6 days

[Submitted on 8 Mar 2021 (v1), last revised 14 Mar 2021 (this version, v2)]

Eliminating the Remaining Window for Primordial Black Holes as Dark Matter from the Dynamics of the Cold Kuiper Belt

Amir Siraj, Abraham Loeb

The nature of dark matter (DM) is unknown. One compelling possibility is DM being composed of primordial black holes (PBHs), given the tight limits on some types of elementary particles as DM. There is only one remaining window of masses available for PBHs to constitute the entire DM density, $10^{17} - 10^{23}$ g. Here, we show that the kernel population in the cold Kuiper belt rules out this window, arguing in favor of a particle nature for DM.

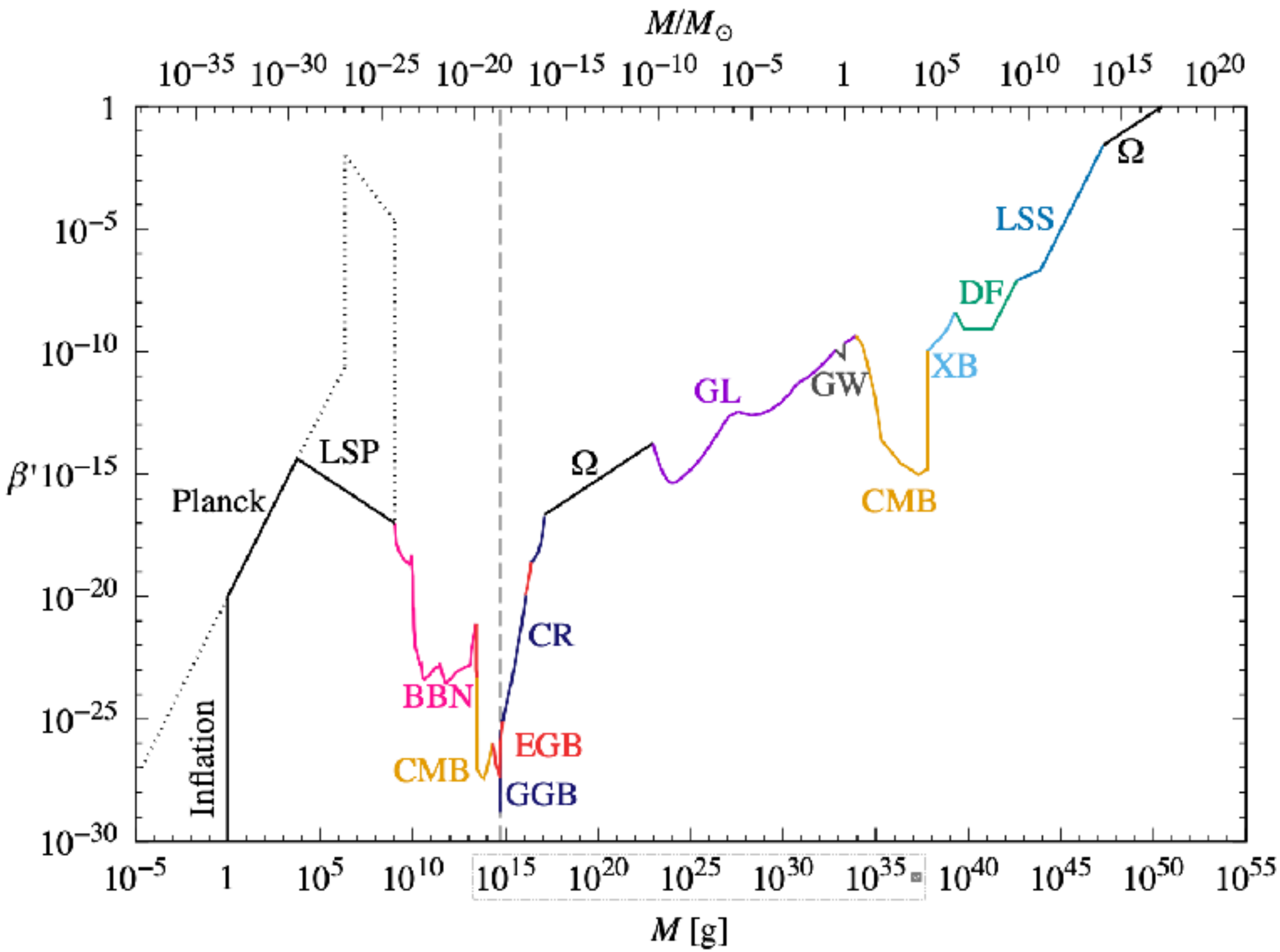
Comments: KBO limit had to be modified to the diffusion regime which weakened significantly the constraints

Subjects: **Cosmology and Nongalactic Astrophysics (astro-ph.CO)**

Cite as: arXiv:2103.04995 **[astro-ph.CO]**

(or arXiv:2103.04995v2 **[astro-ph.CO]** for this version)

Constraints on the initial PBH mass fraction



$$f_{\rm PBH} = \frac{\rho_{\rm PBH}}{\rho_{\rm DM}}|_0 \simeq \frac{\rho_{\rm PBH}}{\rho_{\rm tot}}|_{\rm eq} \simeq \frac{a_{\rm eq}}{a_{\rm form}}\beta.$$

https://arxiv.org/pdf/2002.12778.pdf

The initial conditions of the universe

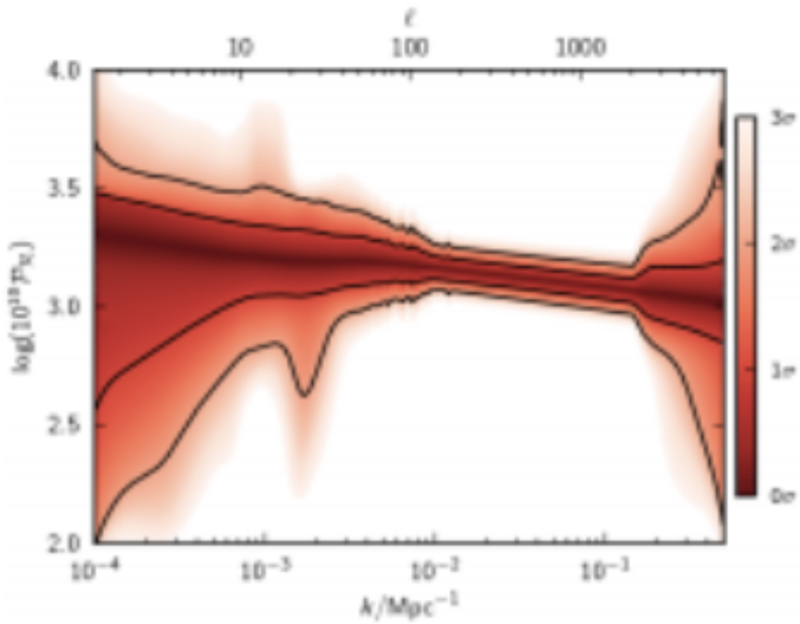
From very large to very small scales

- We have the “precision era” measurements on CMB and LSS scales
- These span approximately the largest 5-10 efoldings which are inside the Hubble scale today
- Lyman alpha, 21cm and spectral mu distortions in the CMB may add a similar range of scales in the (farish) future
- But inflation is believed to have lasted at least 50-60 efoldings
- So we only observe a small fraction of all scales
- Limits our ability to constrain the early universe

Why can’t we observe small scales?

- We do accurately observe small scales, such as our solar system
- However, radiation pressure/chaotic solutions of gravitational collapse mean that the memory of initial conditions on small scales is erased
- We can measure the primordial perturbations only on scales which remain linear today (> 1 Mpc)

Current power spectrum constraints



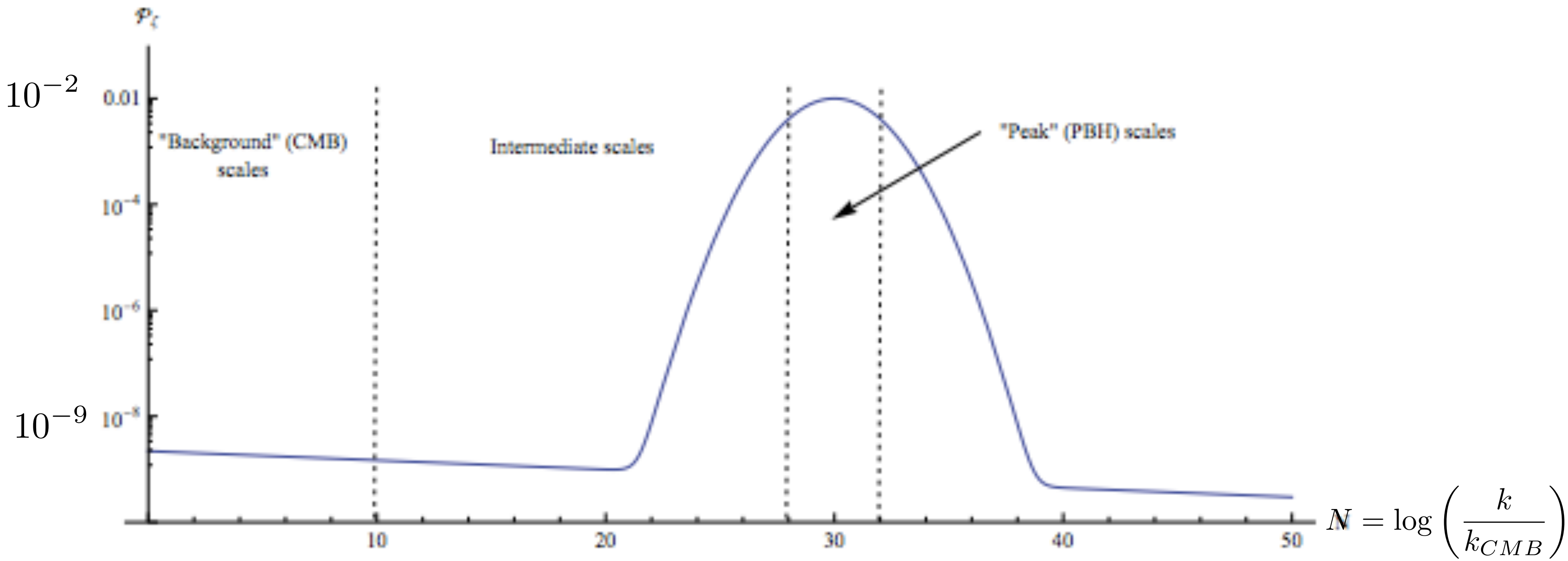
Planck 2015
constraints on inflation

Fig. 26. Bayesian reconstruction of the primordial power spectrum averaged over different values of N_{int} (as shown in Fig. 24), weighted according to the Bayesian evidence. The region $30 < \ell < 2300$ is highly constrained, but the resolution is lacking to say anything precise about higher ℓ. At lower ℓ, cosmic variance reduces our knowledge of $\mathcal{P}_{\mathcal{R}}(k)$. The weights assigned to the lower N_{int} models outweigh those of the higher models, so no oscillatory features are visible here.

- Featureless power law over 1 decade in scales (or log(2300/30)=4.3 efolds)

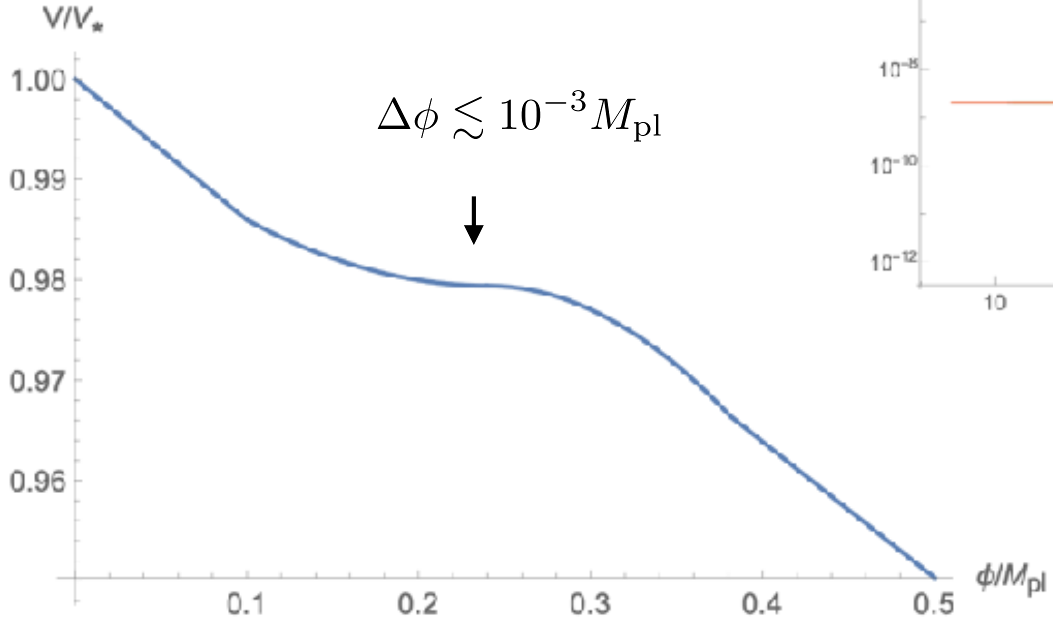
A boosted power spectrum

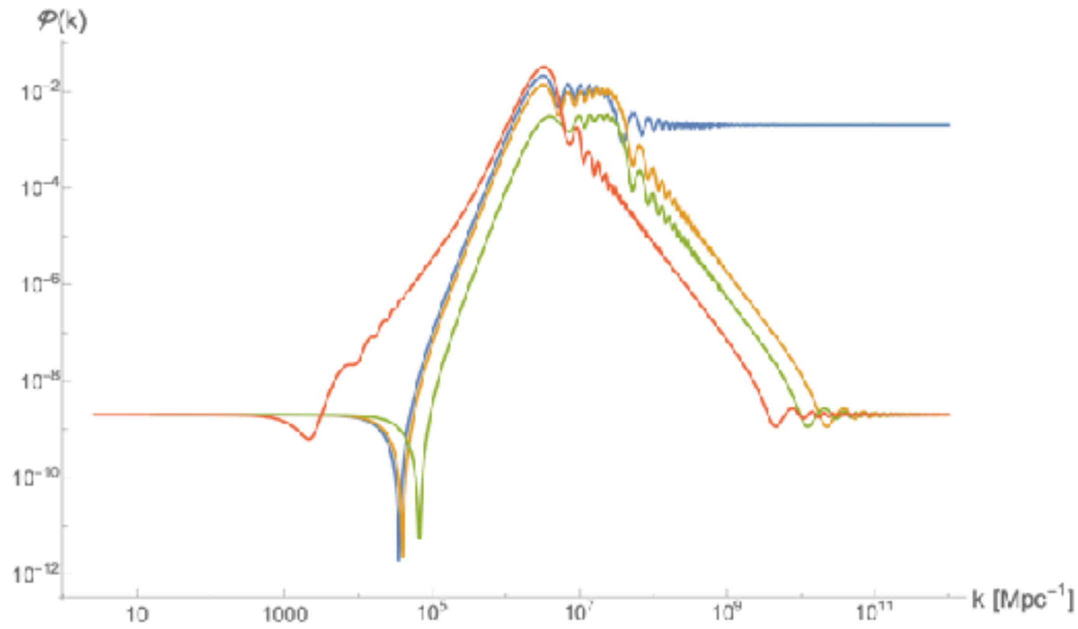
In order for such compact objects to form, the primordial power spectrum needs to be boosted by 5 - 7 orders of magnitude above the value observed on large scales. Exactly how much depends on the equation of state and whether the perturbations are Gaussian



Young and CB 2015

Ultra-slow-roll inflation (inflection point)



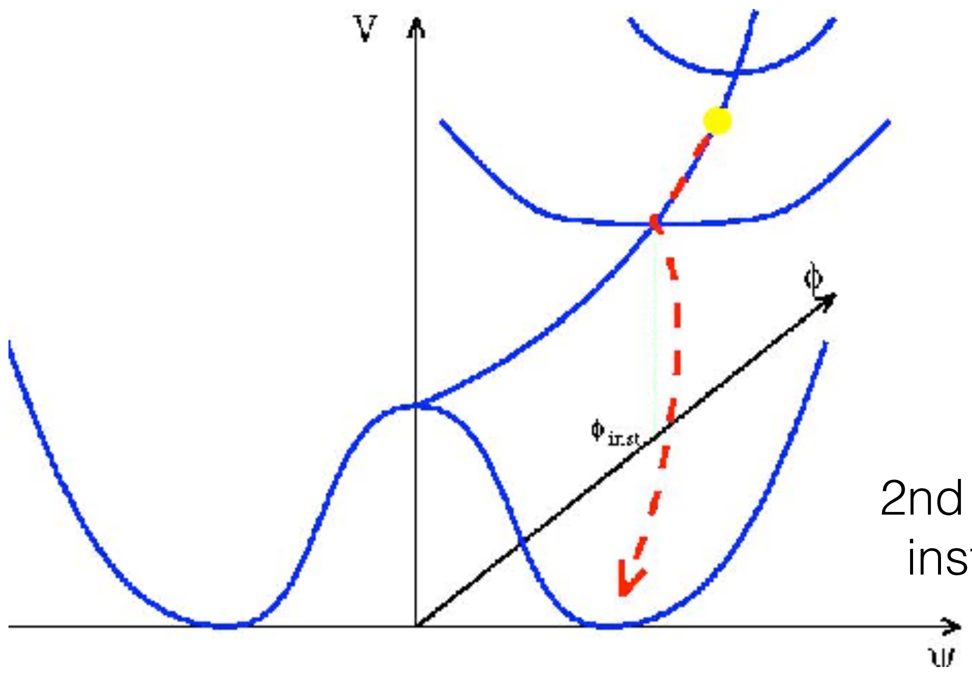


CB, Cole & Patil 2018

Canonical single-field slow-roll inflation cannot produce any PBHs
Lots of activity on calculating PBH production from ultra-slow-roll inflation
All such models require two fine tunings: The duration of the inflection point and the exponential dependence of f_{PBH} on the resulting amplitude

Hybrid inflation

- Hybrid inflation: popular model in which a second stage generates much larger small scale perturbations (also highly non-Gaussian)

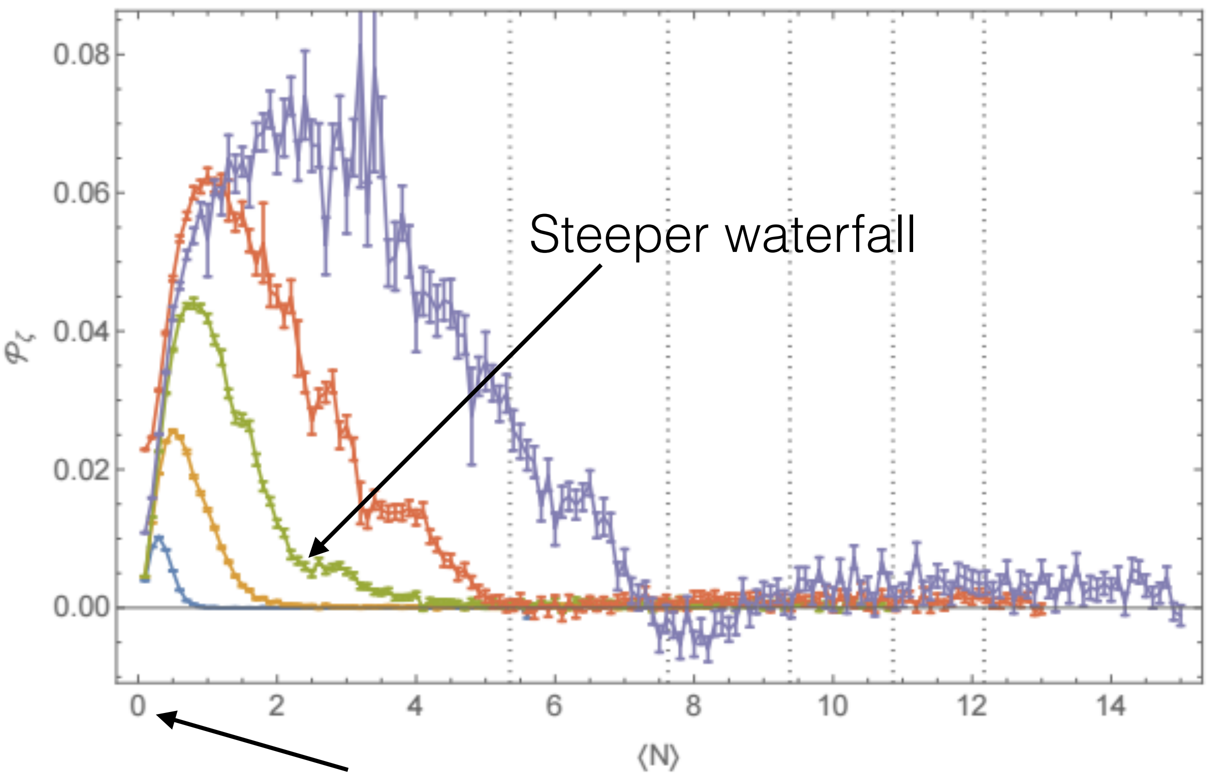


1st stage from inflaton field, Gaussian perturbations

2nd stage from waterfall field - tachyonic instability, non-Gaussian perturbations

Growth of perturbations

- Sensitive to steepness of waterfall phase
- The steeper it is, the quicker inflation ends
- PBHs constrain the waterfall phase to last less than ~5 efolds of the 50 required

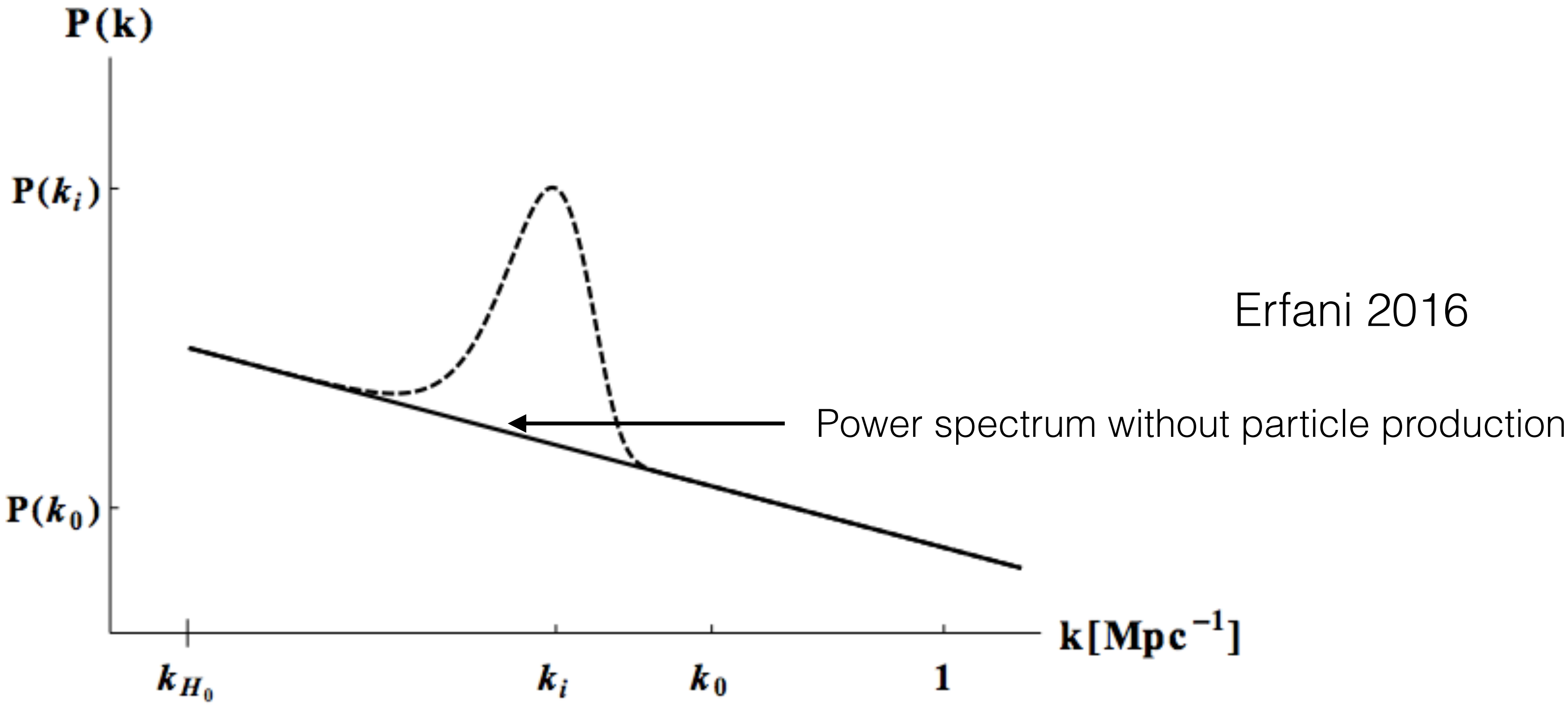


Kawasaki and Tada 2015

End of inflation and the smallest scales

Observable scales

Particle production during inflation



Erfani 2016

This can produce a spike instead, and be tuned to occur at any mass/scale range

Generic model building thoughts

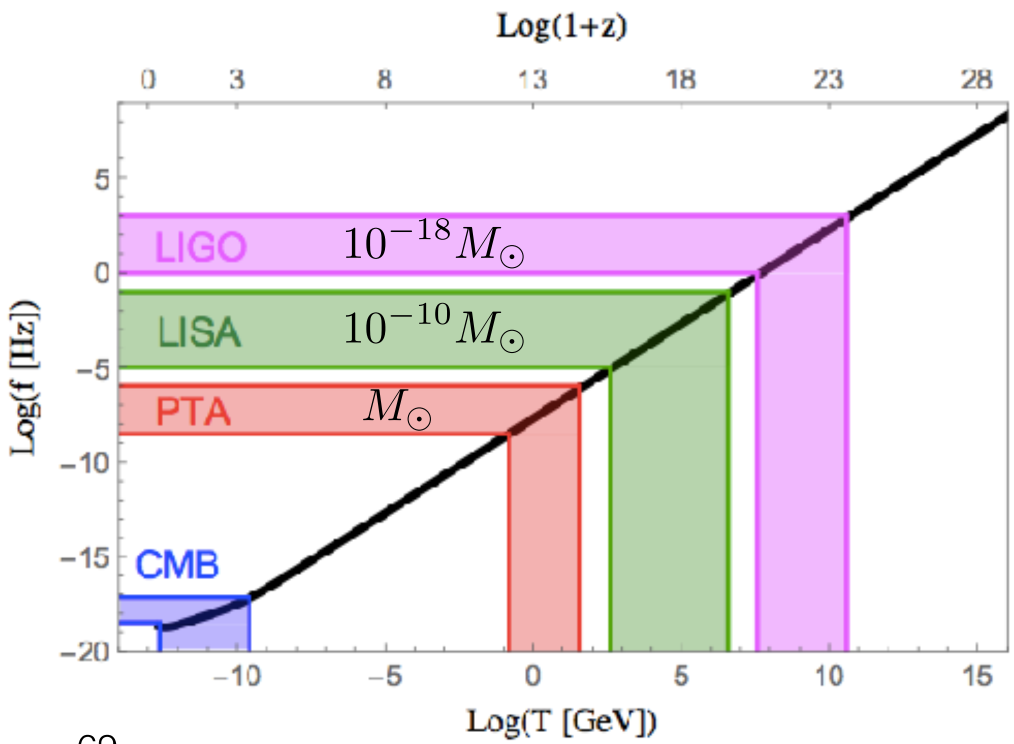
- To produce any PBHs, we need to power spectrum to grow by ~ 7 orders of magnitude
- If that happens, we should not use the usual spectral index (+ running etc) parametrisations of power spectrum
- If the spectrum turns blue, we expect the smallest scales to form the most PBHs
- To have a DM candidate other than relics, we instead need a localised peak, e.g. transition between two phases of inflation, an inflection point, particle production or a phase transition

Gravitational wave constraints

- GWs are a potential relic
- At linear order in perturbation theory; scalar, vector and tensor modes decouple
- Second-order tensor perturbations are sourced by scalar perturbations squared
- A large scalar power spectrum will induce GWs

$$f = \frac{c_s k}{2\pi} \qquad \Omega_{GW}(k) \simeq 30 \Omega_{\rm rad} \mathcal{P}_\zeta(k)^2$$

$$M_{\rm PBH} \simeq 0.1 \left(\frac{\rm GeV}{T}\right)^2 M_\odot$$

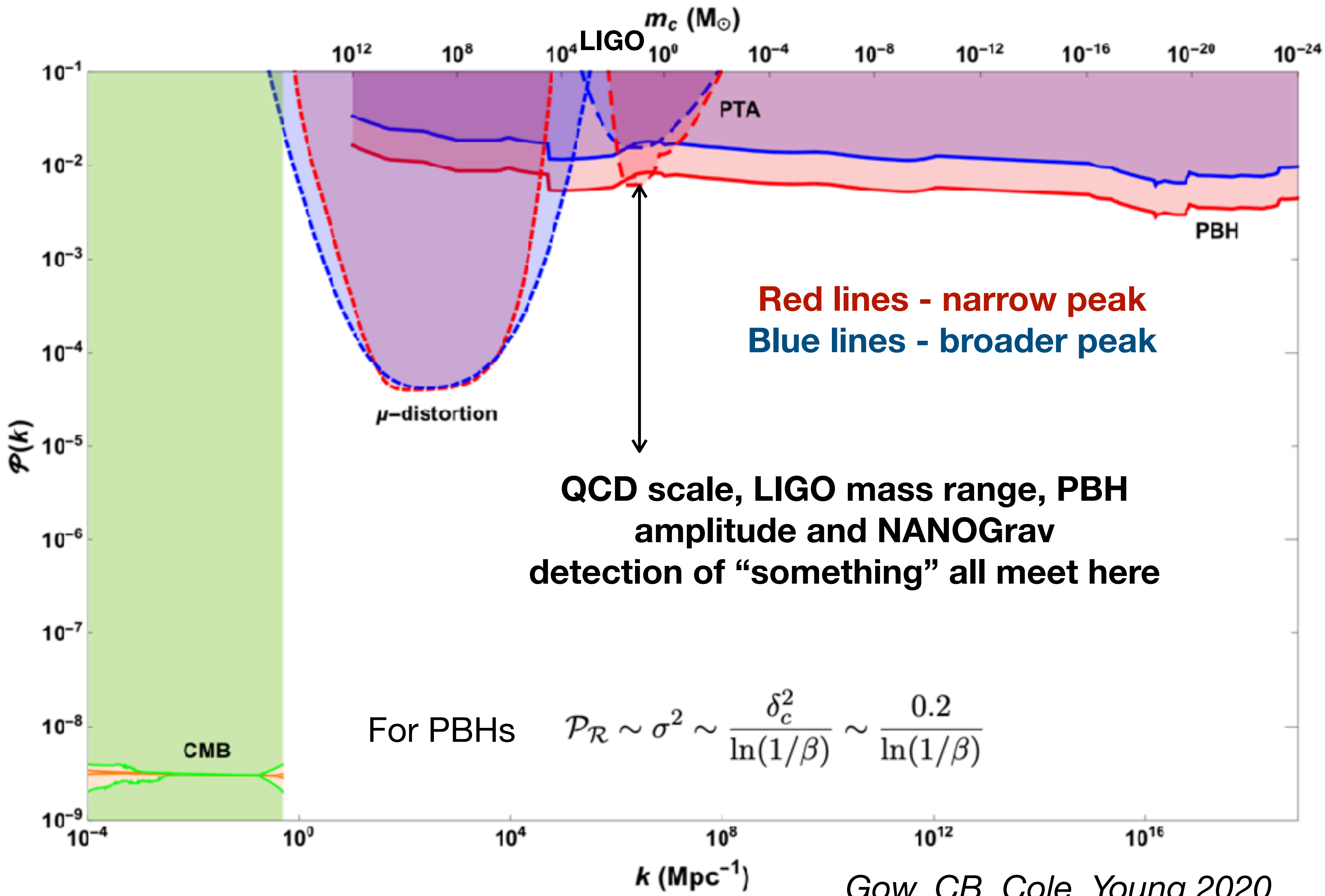


Review: Caprini and Figueroa 2018

CMB spectral distortions

- COBE (FIRAS) showed that the CMB is extremely close to being a black body with no chemical potential
- But it can't be exactly so, must be some deviations on smaller scales, eg from energy release into plasma (matter-photon interactions)
- Latter is silk damping, effective at small scales
- Pixie (NASA) or Prism (L class, ESA) are proposed missions to measure these distortions
- Could open up another 7 efolds of inflation to be visible, though with nothing like the current CMB precision

The initial conditions of the universe



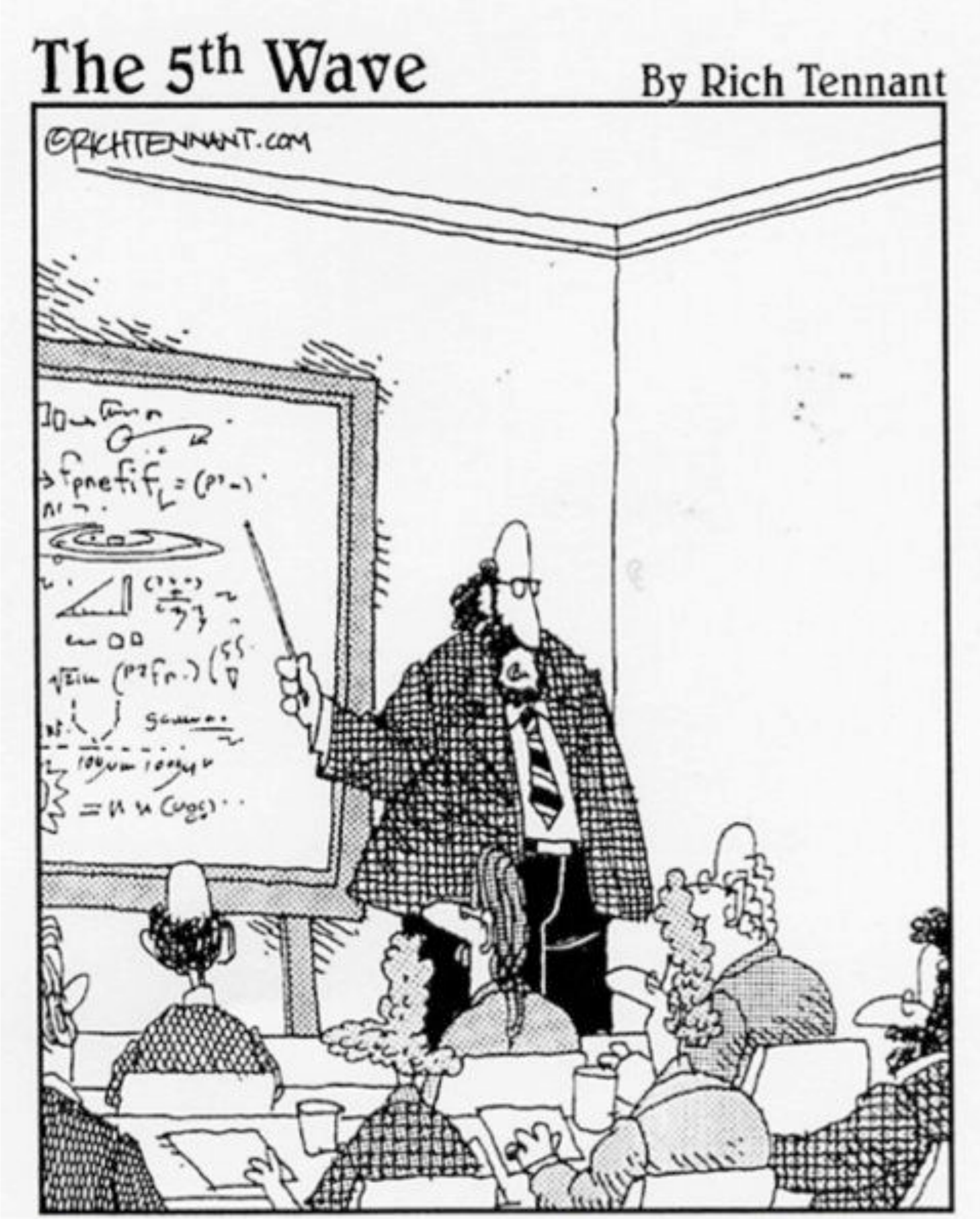
Red lines - narrow peak
Blue lines - broader peak

QCD scale, LIGO mass range, PBH amplitude and NANOGrav detection of "something" all meet here

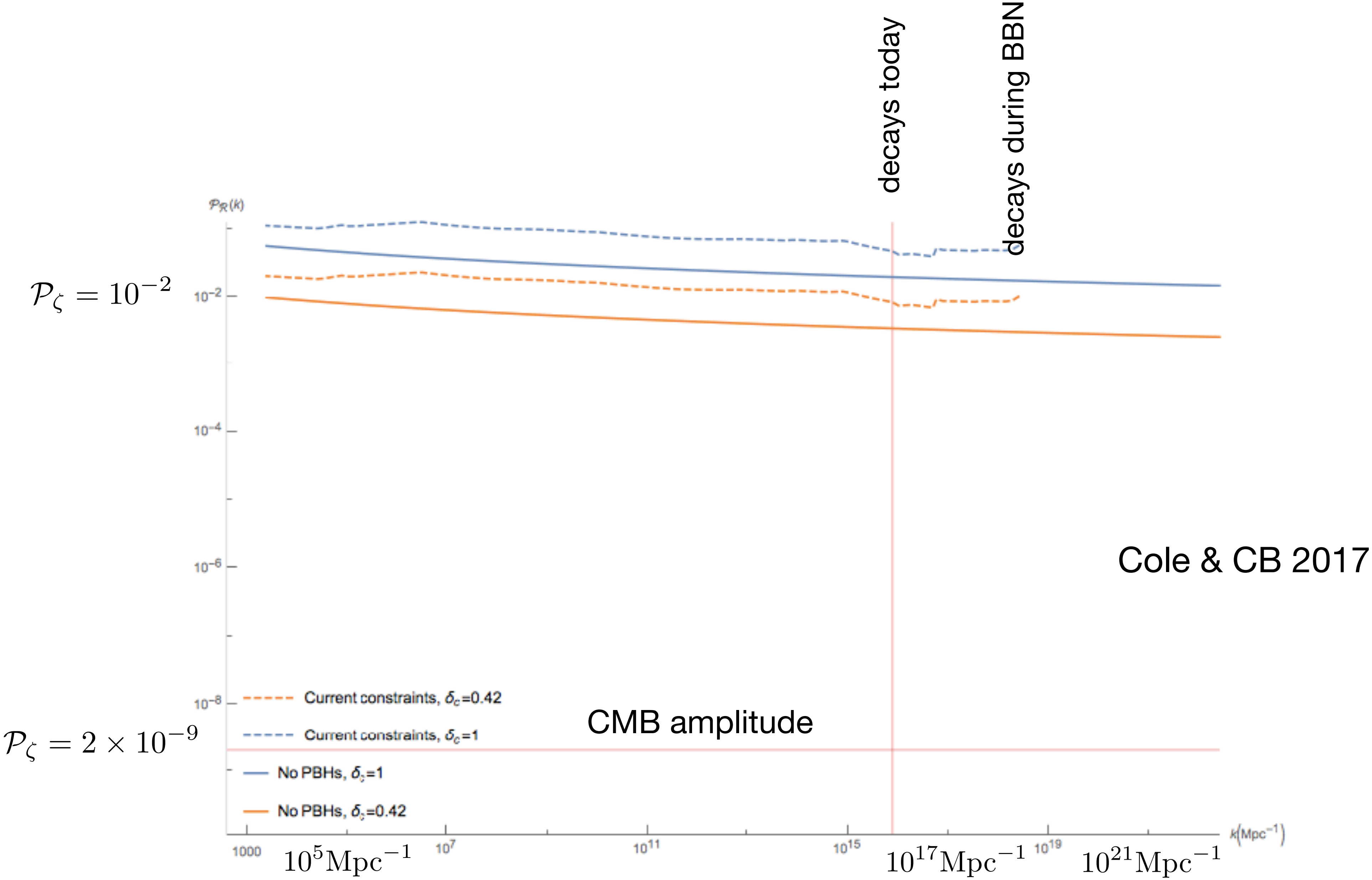
For PBHs $\quad \mathcal{P}_\mathcal{R} \sim \sigma^2 \sim \dfrac{\delta_c^2}{\ln(1/\beta)} \sim \dfrac{0.2}{\ln(1/\beta)}$

Gow, CB, Cole, Young 2020

Even things which might not exist can matter!



"After the discovery of 'antimatter' and 'dark matter', we have just confirmed the existence of 'doesn't matter', which does not have any influence on the Universe whatsoever."



The dashed lines shows the current constraints, the solid lines show the “ideal” constraint of zero PBHs inside the observable universe

Relics: a nightmare scenario?

- PBHs decaying today would emit Hawking radiation, those decaying before BBN are invisible
- Without a theory of quantum gravity we don’t know if they evaporate to nothing or leave a Planck mass relic (solves information paradox?)
- Arguably this is the most likely PBH DM scenario, since it’s “easier” to make the smallest scales amplitude larger and these form the lightest PBHs - *MacGibbon 1987*
- May be detectable if charged - *Lehmann et al 2019*

Hawking-Radiation Recoil of Microscopic Black Holes

Samuel Kováčik [1]

[1] *Faculty of Mathematics, Physics and Informatics, Comenius University of Bratislava, Bratislava, Slovakia*
[1] *Department of Theoretical Physics and Astrophysics, Faculty of Science, Masaryk University, Brno, Czech Republic*

Abstract

The Hawking radiation would make microscopic black holes evaporate rapidly which excludes them from many astrophysical considerations. However, it has been argued that the quantum nature of space would alter this behaviour: the temperature of a Planck-size black hole vanishes and what is left behind is a Planck-mass remnant with a cross-section on the order of $10^{-70}m^2$ which makes direct detection nearly impossible. Such black hole remnants have been identified as possible dark matter candidates. Here we argue that the final stage of the evaporation has a recoil effect which would give the microscopic black hole velocity on the order of $10^{-1}c$ which is in disagreement with the cold dark matter cosmological model.

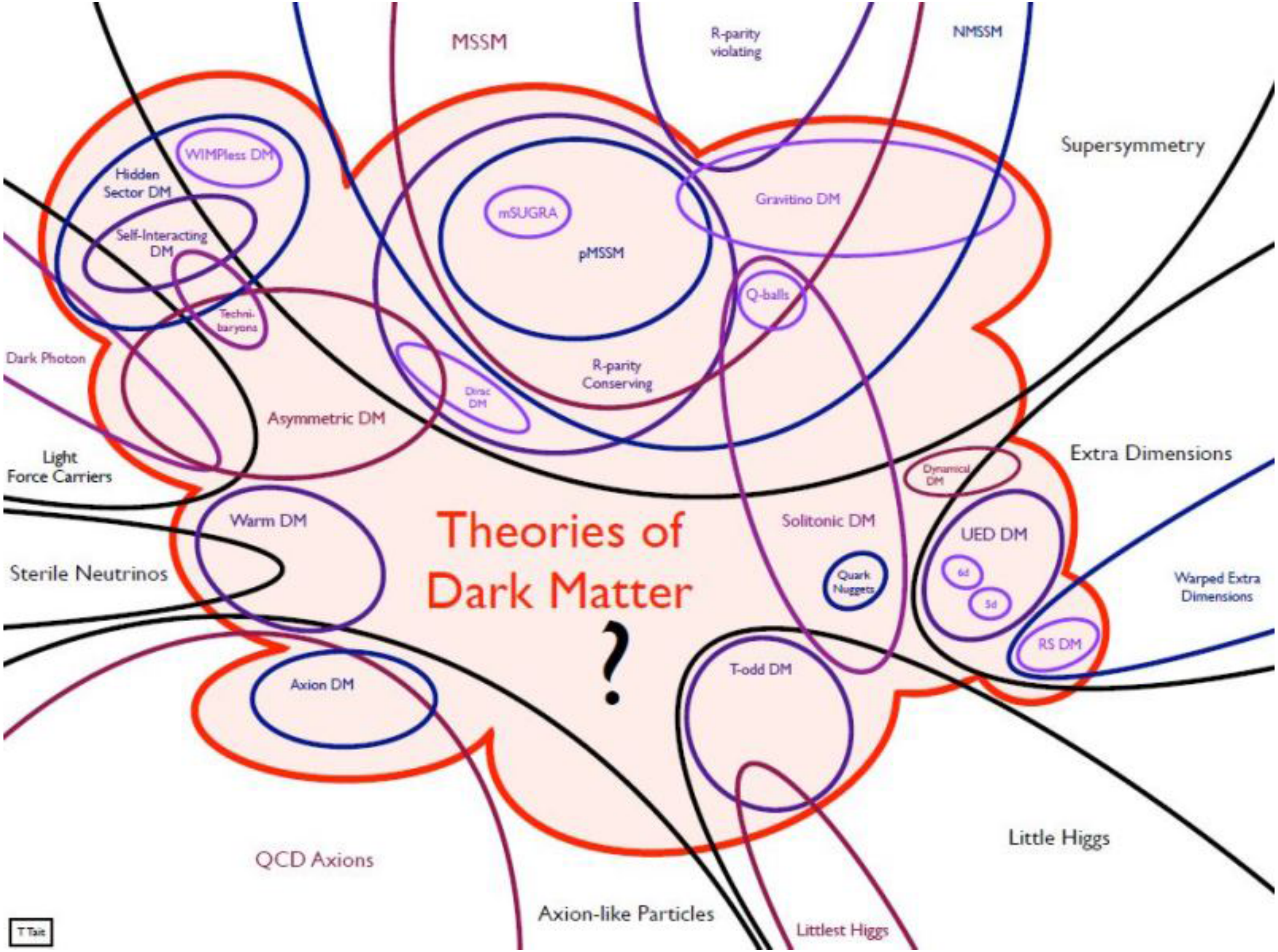
1 Introduction

Quantum theory of gravity is not known at the moment, yet we can assume some of its properties. One of them is that space has a structure that becomes evident at the Planck scale. This idea is not new and has been explored from various angles [1, 2, 3, 4, 5, 6, 7].

A general feature of theories of quantum space is the impossibility of distinguishing points with sep- as a mathematical tool or as an approximation. Yet there is one prominent example where it is taken to describe physical reality: the matter distribution of a black hole is zero everywhere but at one point. Theories of quantum space often lack the notion of exact point localisation and any matter distribution is rendered nonsingular; regular black holes have been studied before, for example in [8]. This affects behaviour of black holes size of which is comparable to the fundamental length scale. One of the striking difference compared to the ordinary black hole theory is that the Hawking temperature [9] defined to be proportional to the surface gravity at the horizon does not grow indefinitely but instead drops to zero at small but positive mass, resulting in a microscopic black hole remnant.

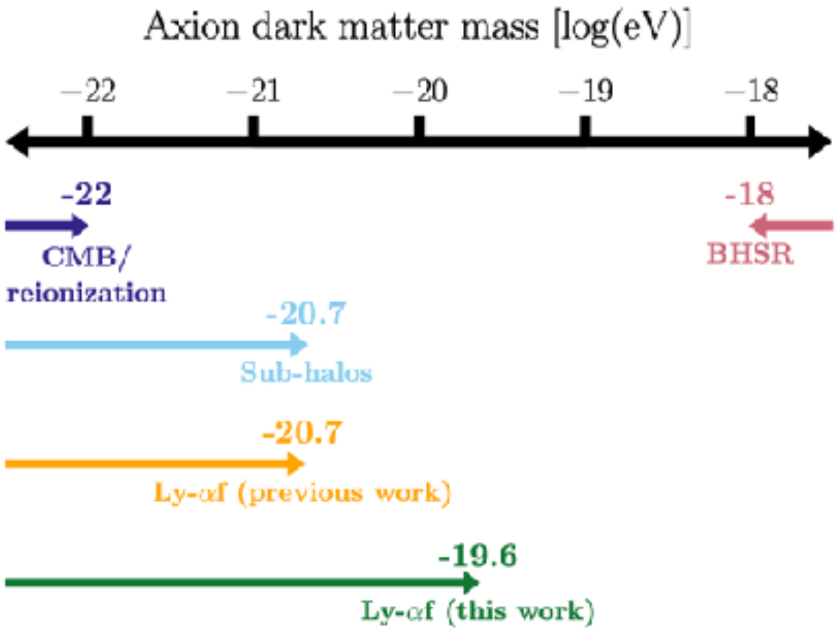
Black holes remnants have been considered as possible dark matter constituents [10]. In the ordinary space, small black holes evaporate rapidly. In quantum space, they can be eternal and are very difficult to detect due to their miniscule cross-section. If they contributed significantly to the overall dark matter density, proving it would be difficult as direct detection seems to be impossible.

Gravitational collapse leading to black hole formation or merger of two black holes can produce gravitational waves carrying a significant momentum in a single direction, recoiling the resulting

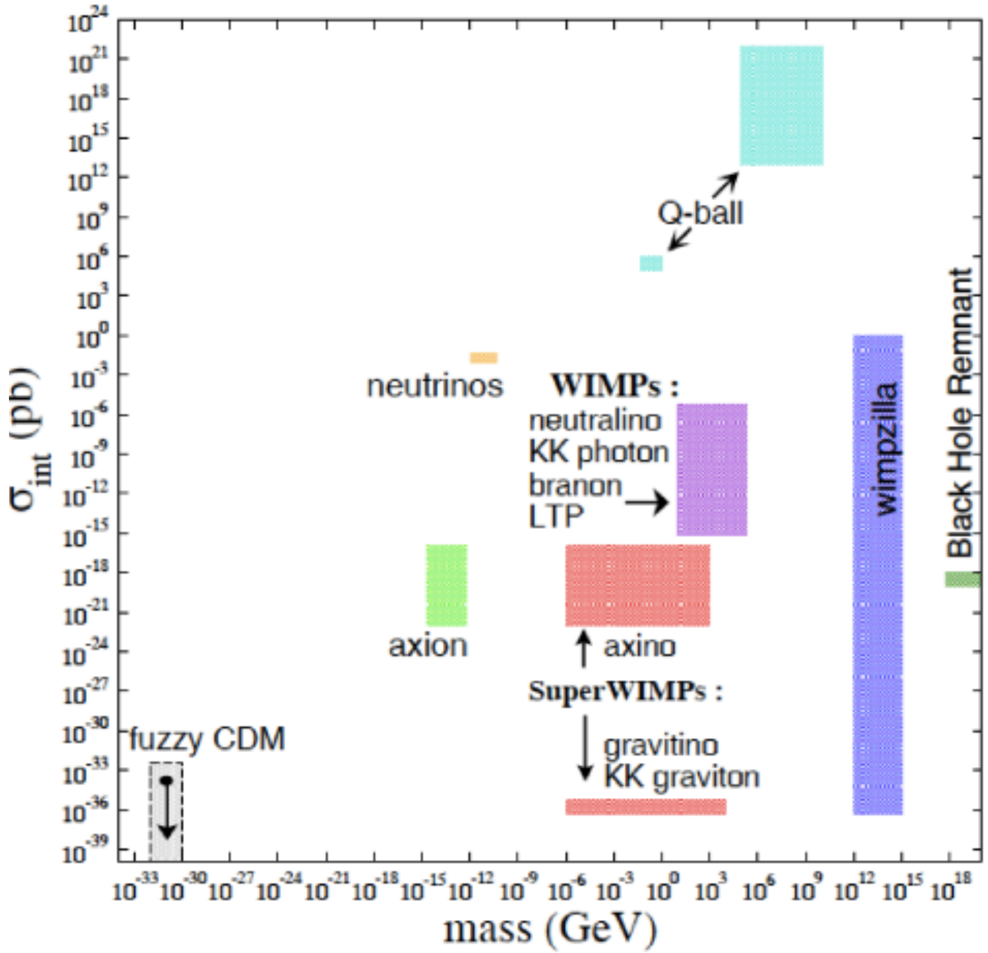


https://physics.aps.org/articles/v11/48

We search under the spotlight
- no reason to ever expect a DM detection?



Rogers & Peiris 2020



https://www.groundai.com/project/dark-matter-studies-entrain-nuclear-physics/1

PBHs are a unique candidate in several ways, so worth detecting/excluding
We can at least improve the DM upper mass bound

IPPP/19/73

What if Planet 9 is a Primordial Black Hole?

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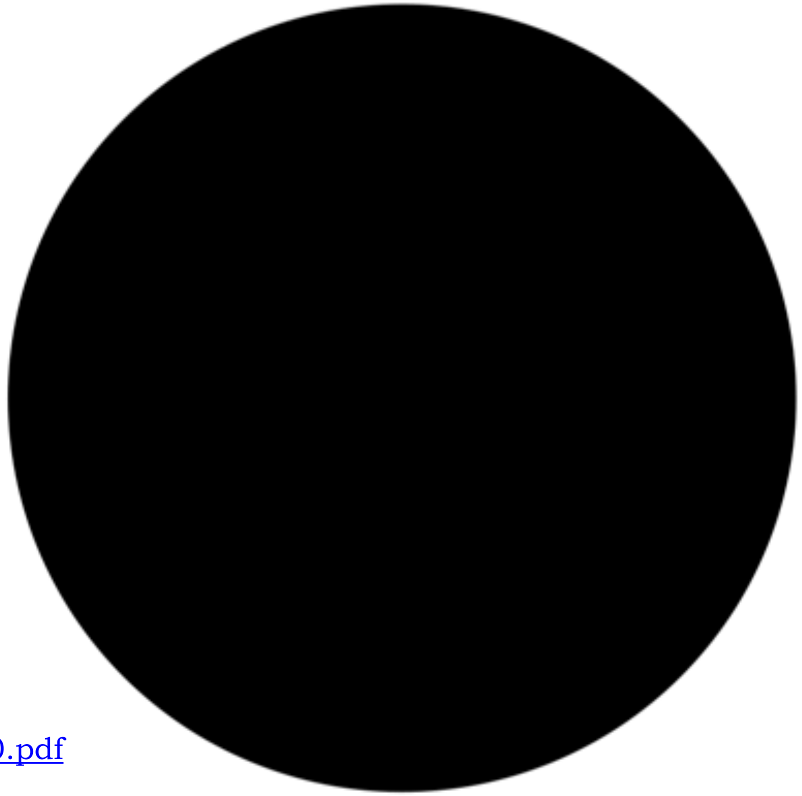
We highlight that the anomalous orbits of Trans-Neptunian Objects (TNOs) and an excess in microlensing events in the 5-year OGLE dataset can be simultaneously explained by a new population of astrophysical bodies with mass several times that of Earth ($M_\oplus$). We take these objects to be primordial black holes (PBHs) and point out the orbits of TNOs would be altered if one of these PBHs was captured by the Solar System, inline with the Planet 9 hypothesis. Capture of a free floating planet is a leading explanation for the origin of Planet 9 and we show that the probability of capturing a PBH instead is comparable. The observational constraints on a PBH in the outer Solar System significantly differ from the case of a new ninth planet. This scenario could be confirmed through annihilation signals from the dark matter microhalo around the PBH.

1. Introduction. As of this year, two gravitational anomalies of similar mass but very different origins remain to be explained. First, there is a growing body

2. Two Anomalies. While the structure of the Solar System to semi-major axis $a \sim 100$ AU is well explained, for $a > 250$ AU there are TNO populations whose orbits



https://arxiv.org/pdf/1909.11090.pdf

FIG. 1. Exact scale (1:1) illustration of a $5M_\oplus$ PBH. Note that a $10M_\oplus$ PBH is roughly the size of a ten pin bowling ball.

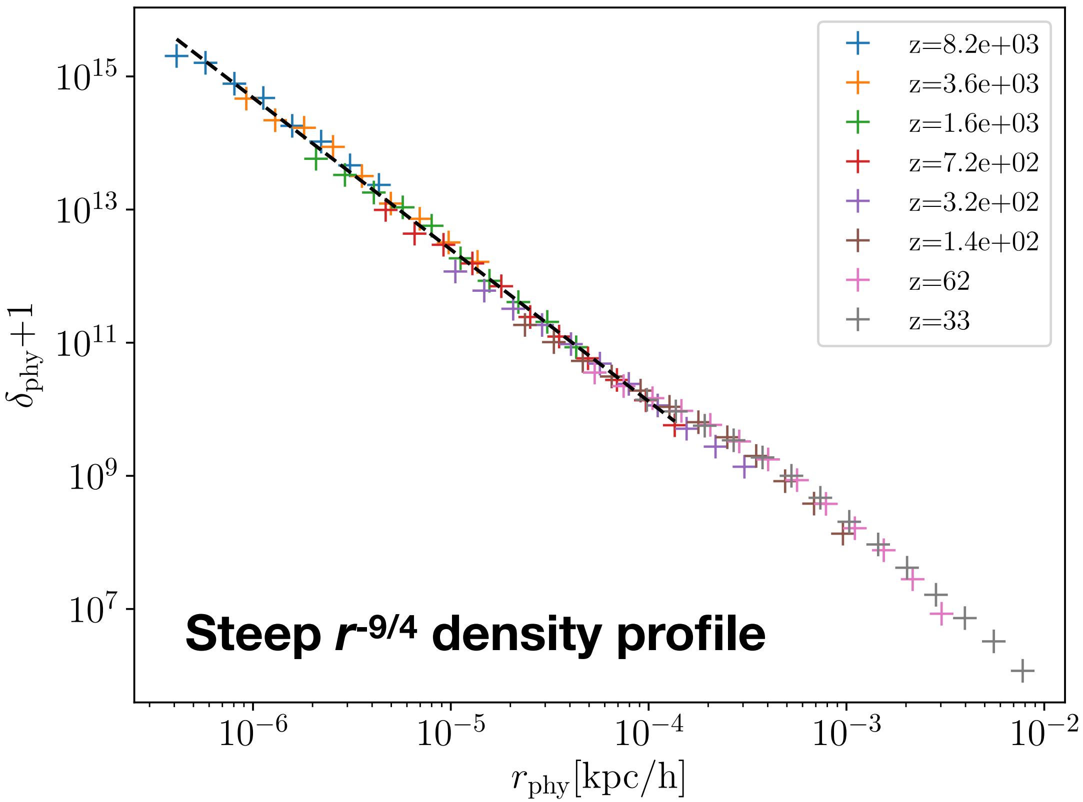
What if one PBH was detected?

- We would know what some of the DM was (and what it is not - next slide)
- It would be the oldest relic detected, predating the primordial element abundance generated by BBN
- Other potential relics include: gravitational waves, topological defects such as cosmic strings, CMB spectral distortions, ultracompact minihalos
- Requires non-trivial inflationary dynamics, perhaps with an early-matter-dominated phase and/or topological defects. *PBH review article: Green 2015*

WIMPs and PBHs are incompatible

- Assuming WIMPs have the standard, velocity independent cross section which gets the right abundance, and $M_{PBH}>10^{-6}\ M_{sun}$.
- If $f_{PBH}<1$, then another DM component is inevitable
- Steep and high density profiles form around PBHs (density~ $r^{-9/4}$). WIMPs would rapidly annihilate to gamma rays.
- In contrast to ultracompact minihalos without a PBH seed. *Gosenca et al '17, Delos et al '17*

- A detection of WIMPs or PBHs may effectively rule out the existence of the other



Adamek, CB, Gosenca & Hotchkiss 2019;

Lacki & Beacom 2010; Eroshenko 2016; Boucenna, Kühnel, Ohlsson & Visinelli 2017

The 3 papers above all find different profiles. We made the first simulations of this scenario

Looking forwards

- LIGO/Virgo have many more events to come

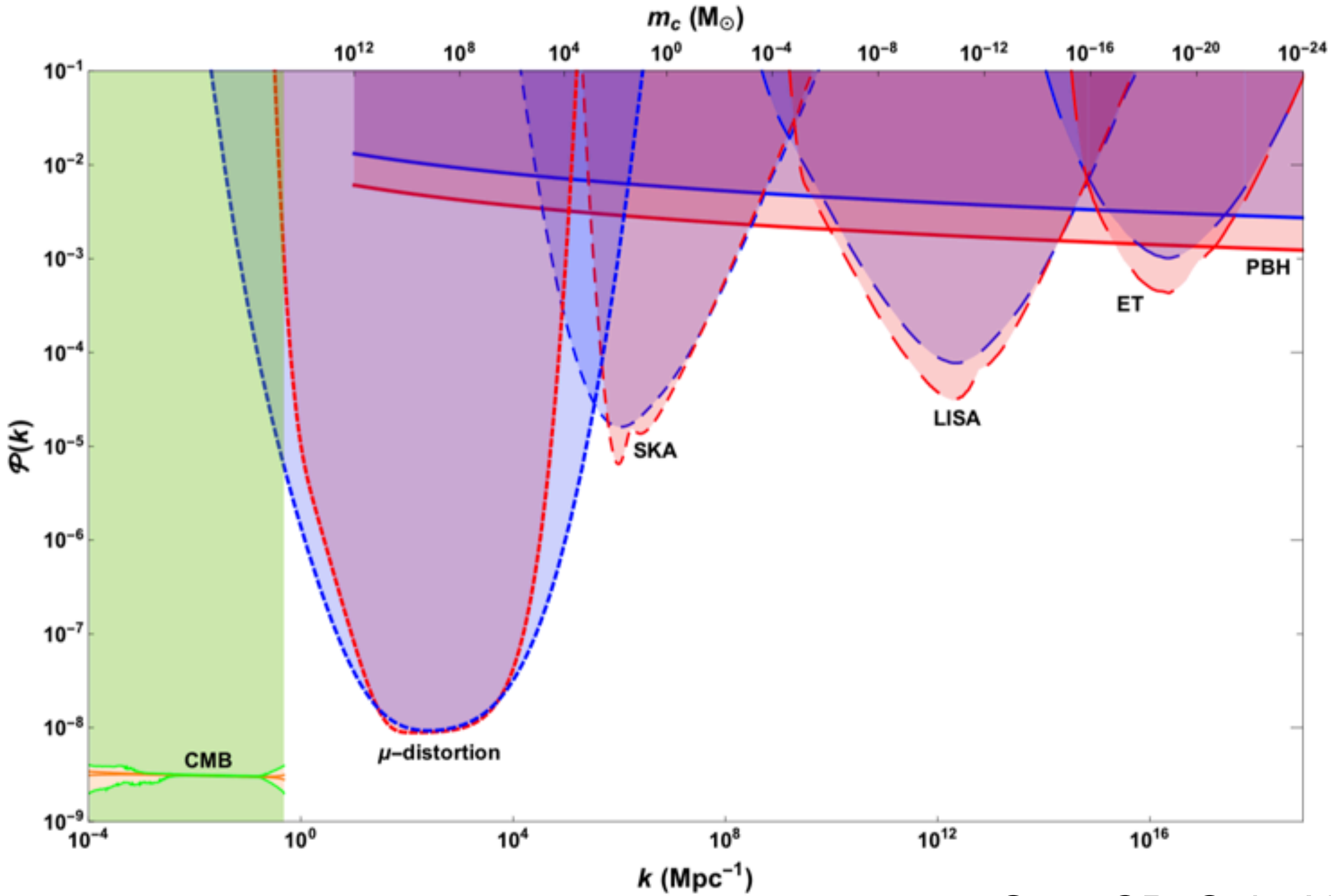
- The pulsar timing array (PTA) collaborations will firm up the "detection" or reach a sensitivity which rules out PBH generation from large amplitude scalar perturbations on LIGO related mass scales

- LISA and future ground based detectors will be sensitive to very high redshift mergers + better probe of the spins, mass ratio, etc

- Theoretical and numerical work, especially on the merger rate and accretion, is required

- The detection of a sub Chandrasekhar mass object is what I hope for

Future constraints



The PBH lines correspond to zero PBHs
Cole & CB '17

Gow, CB, Cole, Young 2020

Summary

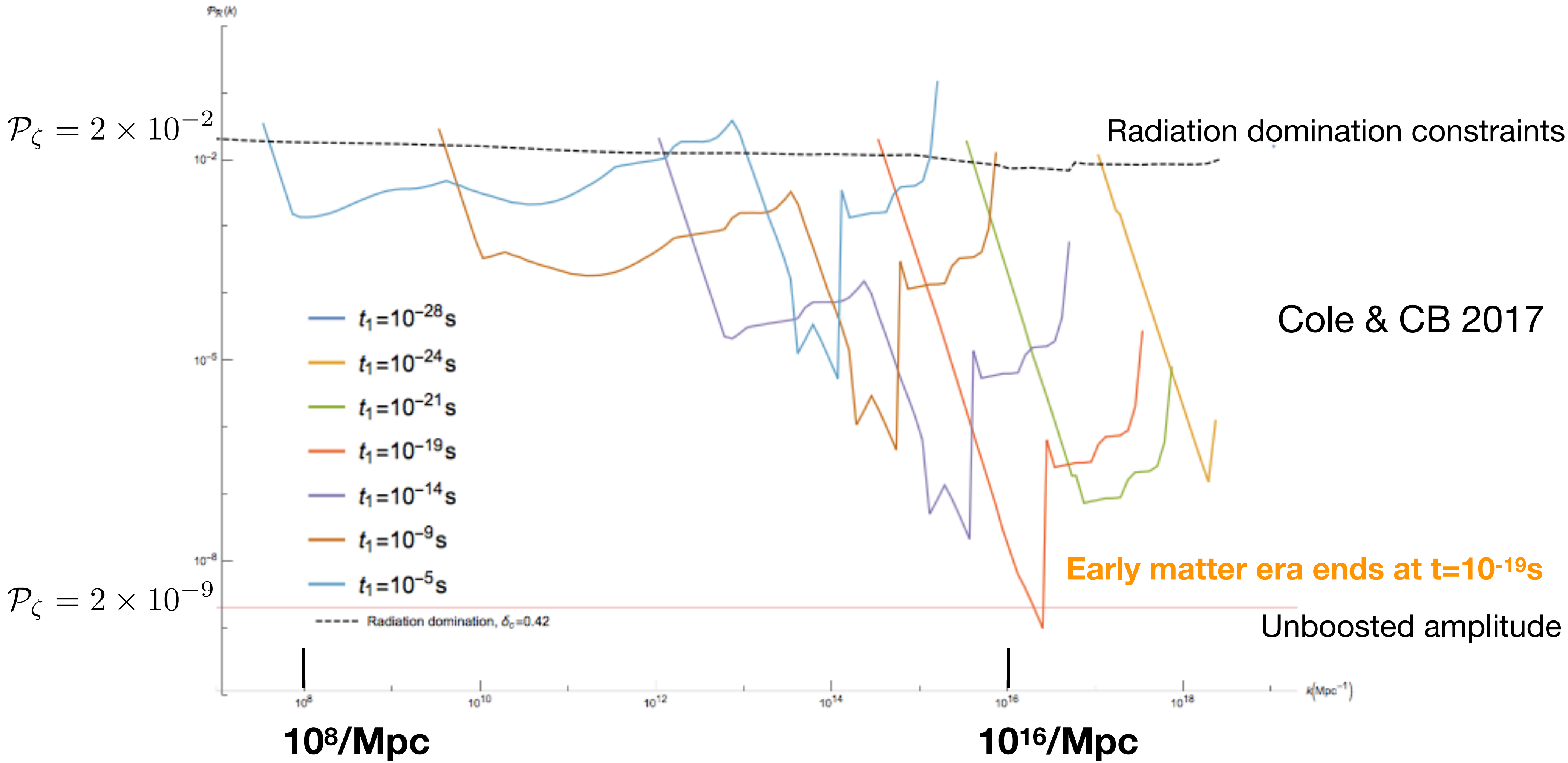
- PBHs could still form all of the DM, at least in the asteroid mass range
- Mixed DM models are also interesting. Some combinations are ruled out.
- It remains possible that some - but not all - of the LIGO Virgo black holes were primordial
- Whether or not PBHs exist, the search has taught us about the early universe and inflation

> Finding just one black hole of sub-solar mass — which should be common, according to the primordial black hole scenario, and which can't form from stars — would transform this entire debate. And with

Quanta magazine

Backup slides

PBHs without boosting the power spectrum



Without boosting the power spectrum amplitude (or other new physics) the formation of a detectable fraction of PBHs decaying during CMB formation may be possible if there was an extended **early matter dominated era**, but typically not more massive PBHs

See also Harada et al 2016, Georg & Watson 2017, Carr, Tenkanen & Vaskonen 2017 ++

Parameter	Model					
	PBH	PBH, $S=1$	Model A	Model B	PBH, S=1, $m_{\rm max}=50\,M_\odot$	PBH, S=1, skew-bimodal
$\log_{10} f_{\rm PBH}$	$-2.30^{+1.16}_{-0.35}$	$-2.76^{+0.25}_{-0.24}$	–	–	$-2.72^{+0.25}_{-0.25}$	$-2.74^{+0.23}_{-0.23}$
$\log_{10} m_c\,[M_\odot]$	$1.38^{+1.36}_{-0.13}$	$1.26^{+0.12}_{-0.22}$	–	–	$1.91^{+1.91}_{-0.76}$	–
$\log_{10}\sigma$	$-0.09^{+0.49}_{-0.24}$	$-0.21^{+0.24}_{-0.16}$	–	–	$0.27^{+0.23}_{-0.47}$	–
$m_c\,[M_\odot]$	$24.23^{+528.62}_{-6.31}$	$18.06^{+5.72}_{-7.10}$	–	–	$81.28^{+6525.7}_{-67.15}$	–
σ	$0.82^{+1.71}_{-0.35}$	$0.61^{+0.45}_{-0.19}$	–	–	$1.86^{+1.30}_{-1.23}$	–
$\log_{10} R_0$	–	–	$1.63^{+0.50}_{-0.45}$	$1.55^{+0.41}_{-0.43}$	–	–
$m_{\rm max}\,[M_\odot]$	–	–	$42.65^{+18.96}_{-5.99}$	$42.73^{+35.11}_{-6.31}$	50.0	–
$m_{\rm min}\,[M_\odot]$	–	–	5.00	$7.88^{+1.30}_{-2.64}$	–	–
α	–	–	$0.94^{+1.59}_{-2.38}$	$1.93^{+1.70}_{-1.96}$	–	–
β_q	–	–	0.00	$6.62^{+5.04}_{-6.62}$	–	–
λ	–	–	–	–	–	$0.35^{+0.14}_{-0.27}$
$\log_{10} m_{c,1}\,[M_\odot]$	–	–	–	–	–	$1.08^{+0.57}_{-0.38}$
$\log_{10} m_{c,2}\,[M_\odot]$	–	–	–	–	–	$1.57^{+0.08}_{-0.62}$
$m_{c,1}\,[M_\odot]$	–	–	–	–	–	$12.02^{+32.65}_{-10.82}$
$m_{c,2}\,[M_\odot]$	–	–	–	–	–	$37.15^{+7.52}_{-28.24}$
$\ln L^*/L^*_{\rm B}$	-6.99	-7.14	-2.51	0.00	-5.44	-3.53
$\ln$ Occam	-6.13	-8.21	-5.71	-6.74	-5.46	-7.73
$\ln Z_{\rm Lap}/Z_{NS}$	$1.60^{+0.16}_{-0.16}$	$0.26^{+0.17}_{-0.17}$	$0.77^{+0.15}_{-0.15}$	$0.63^{+0.16}_{-0.16}$	$0.54^{+0.13}_{-0.13}$	$1.92^{+0.18}_{-0.18}$
$\ln Z_{NS}/Z_{NS,\rm B}$	$-7.35^{+0.23}_{-0.23}$	$-8.25^{+0.23}_{-0.23}$	$-1.62^{+0.22}_{-0.22}$	0.00	$-4.01^{+0.21}_{-0.21}$	$-5.79^{+0.24}_{-0.24}$

TABLE II: Median and 95% credible intervals for the parameters of each model considered. The bottom four rows display difference in best-fit log-likelihood between each model and LIGO Model B, the log of the Occam factor defined in the text, the difference in log-evidence between the DYNESTY nested sampling estimate and the Laplace approximation defined in the text, and the Bayesian evidence ratios computed from nested sampling along with uncertainties.

https://arxiv.org/pdf/2008.13704.pdf

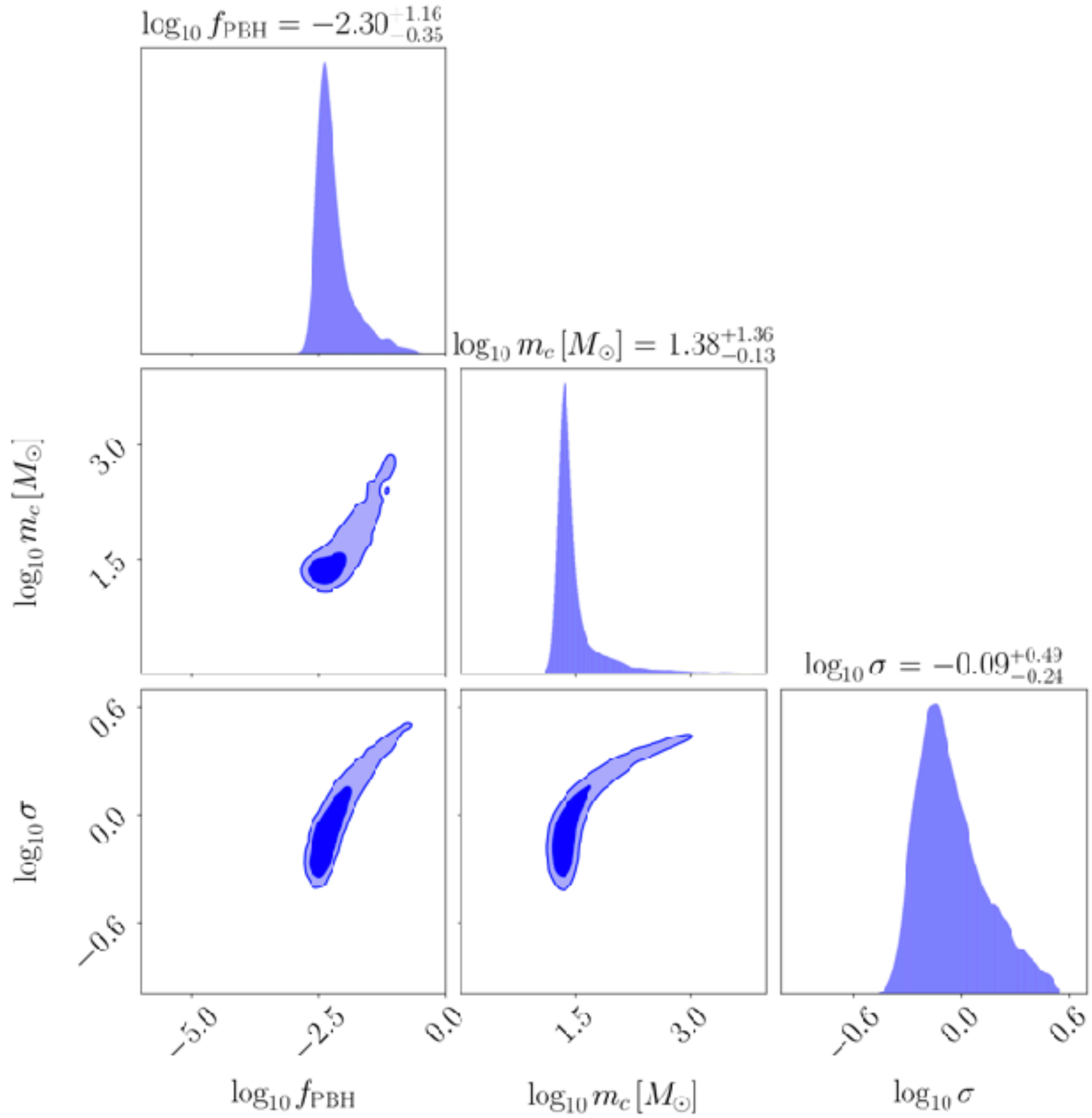


FIG. 8: *Off-diagonal panels*: Two-dimensional 68% and 95% marginal posterior quantiles for the parameters of the lognormal PBH model including the 3-body suppression factor, given the GWTC-1 data. The plot boundaries correspond to the extent of the (uniform) priors on the parameters shown. *Diagonal panels*: One-dimensional marginal posterior densities for the parameters. Above each panel are the marginalised posterior median and 95% posterior quantiles for each parameter.

The merger rate

The merger time of a binary

$$\tau = \frac{3}{85}\frac{r_a^4}{\eta M^3} j^7$$

$$e = \sqrt{1 - j^2} \qquad \eta \equiv \mu/M \qquad M \equiv m_1 + m_2 \text{ and } \mu \equiv m_1 m_2/M$$

The differential merger rate

$$\mathrm{d}R = S \times \mathrm{d}R_0$$

S is a suppression factor

$$\mathrm{d}R_0 = \frac{0.65}{\tau}\left(\frac{\tau\eta M^{14}}{f_{\mathrm{PBH}}^7 c_j^7 c_a^4 \rho_M^{11}}\right)^{\frac{3}{37}} \mathrm{d}n(m_1)\mathrm{d}n(m_2)$$

$$\approx \frac{1.6\times 10^6}{\mathrm{Gpc}^3\mathrm{yr}} f_{\mathrm{PBH}}^{\frac{53}{37}} \eta^{-\frac{34}{37}} \left(\frac{M}{M_\odot}\right)^{-\frac{32}{37}} \left(\frac{\tau}{t_0}\right)^{-\frac{34}{37}} \psi(m_1)\psi(m_2)\,\mathrm{d}m_1\mathrm{d}m_2$$

Raidal et al https://arxiv.org/pdf/1812.01930.pdf

PBH formation comments

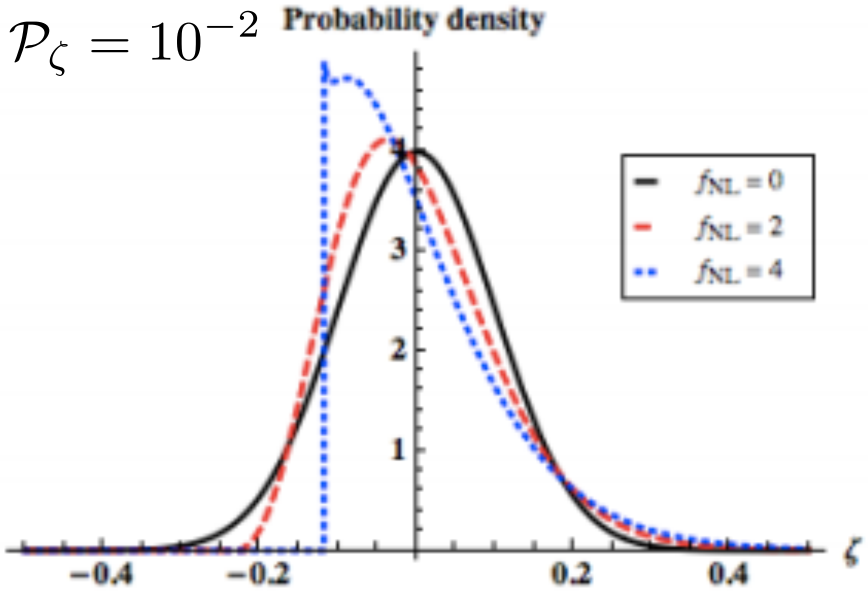
- The formation rate is exponentially sensitive to the amplitude of the power spectrum, and the collapse threshold
- Inflationary models posit an inflection point (ultra-slow-roll inflation) or other feature
- The power spectrum can't grow faster than about k4 (in canonical single-field inflation), impacts the constraints. *Byrnes, Cole & Patil '18; Carrilho, Malik & Mulryne '19*
- PBHs are very rare - very sensitive to non-Gaussianity
- The formation criteria depends on the density profile. Many spherically symmetric simulations exist, e.g. *Niemeyer & Jedamjik, Musco & Miller, Harada ++, Nakama ++…*
- Extensive recent analytic work has been done to relate the power spectrum to PBH formation rate at, but (at least) an order unity uncertainty remains (= tens of orders of magnitude in terms of the formation rate). *Germani & Musco '17, Yoo et al '17, Kawasaki & Nakatsuka '19, de Luca et al '19, Young et al '19, Young '19, Kalaja et al '19*

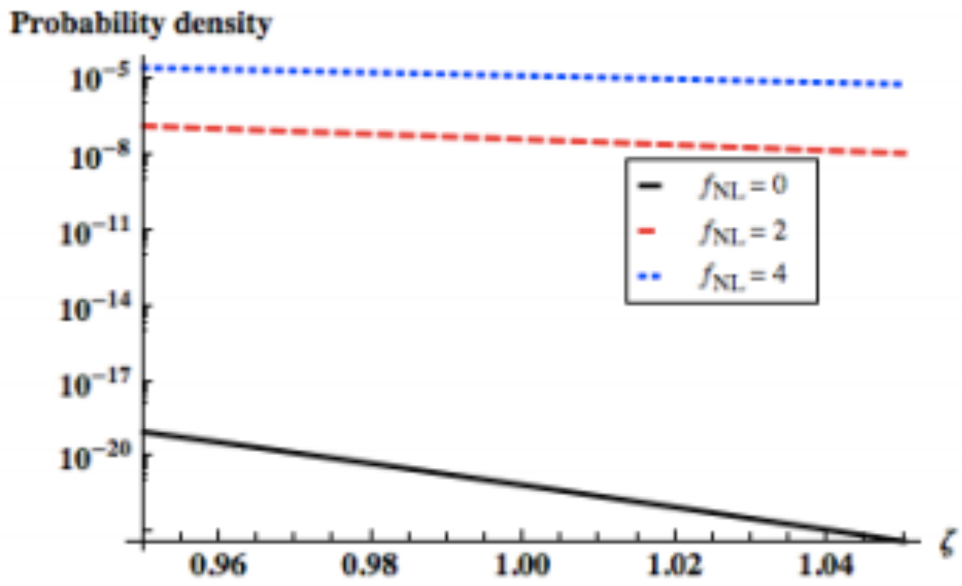
PBH abundance is exponentially sensitive to non-Gaussianity

Local non-Gaussianity

$$\zeta = \zeta_g + \frac{3}{5} f_{NL} \left(\zeta_g^2 - \sigma^2 \right)$$

$\mathcal{P}_\zeta = 10^{-2}$

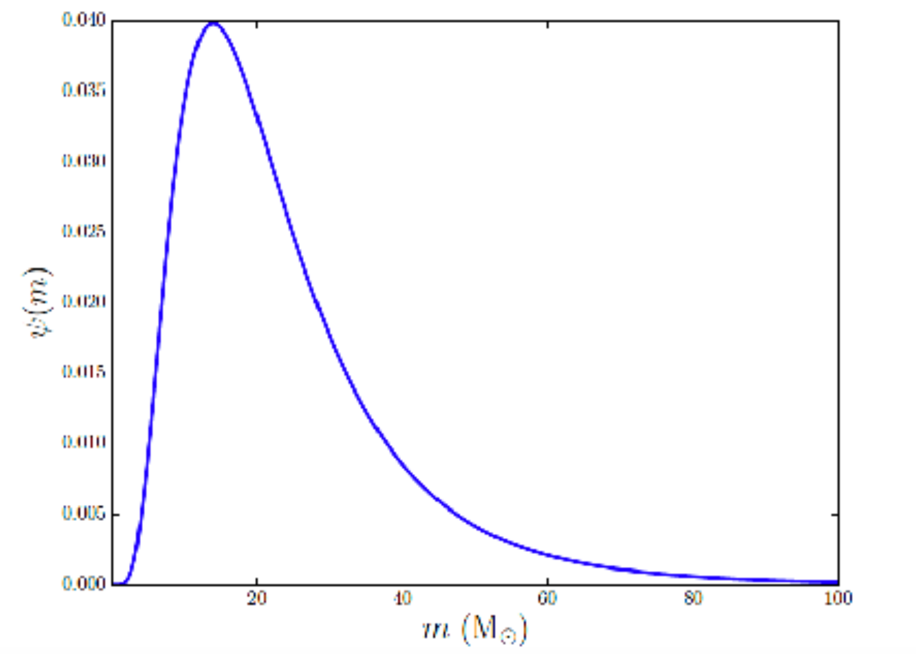




Young & CB 2013

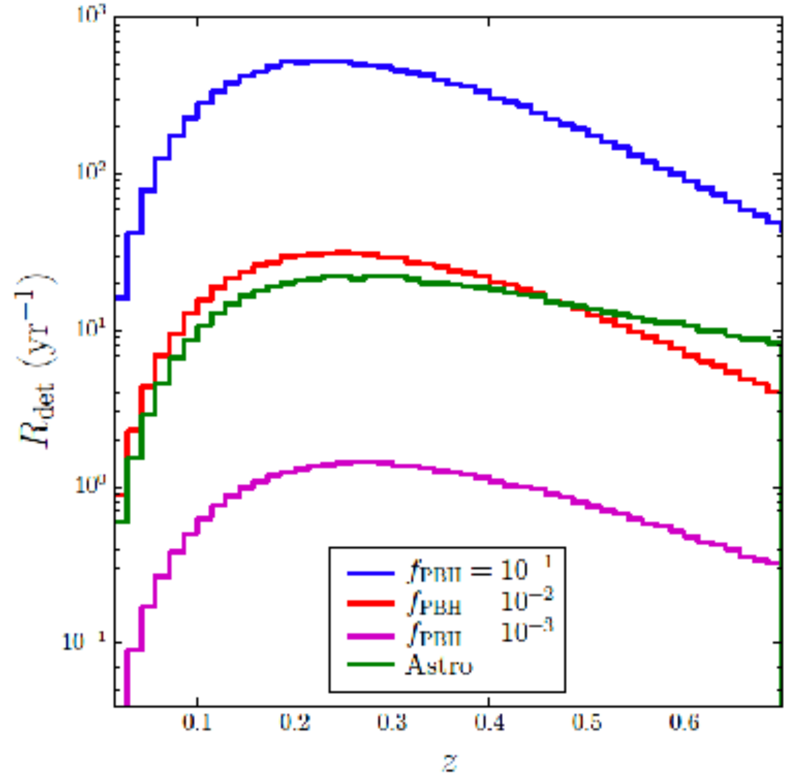
Following *Raidal et al 2019* we consider a log-normal mass function with "central mass" m_c=20 $M_\odot$ and sigma=0.6

$$\psi(m) = \frac{1}{\sqrt{2\pi}\sigma m} \exp\left(-\frac{\ln^2(m/m_c)}{2\sigma^2}\right)$$



We match the expected astrophysical merger rate when about 1% of DM is in PBHs

The intrinsic BH merger rate estimated by LIGO assumes a mass function. We calculate the observed merger rate in order to avoid this assumption

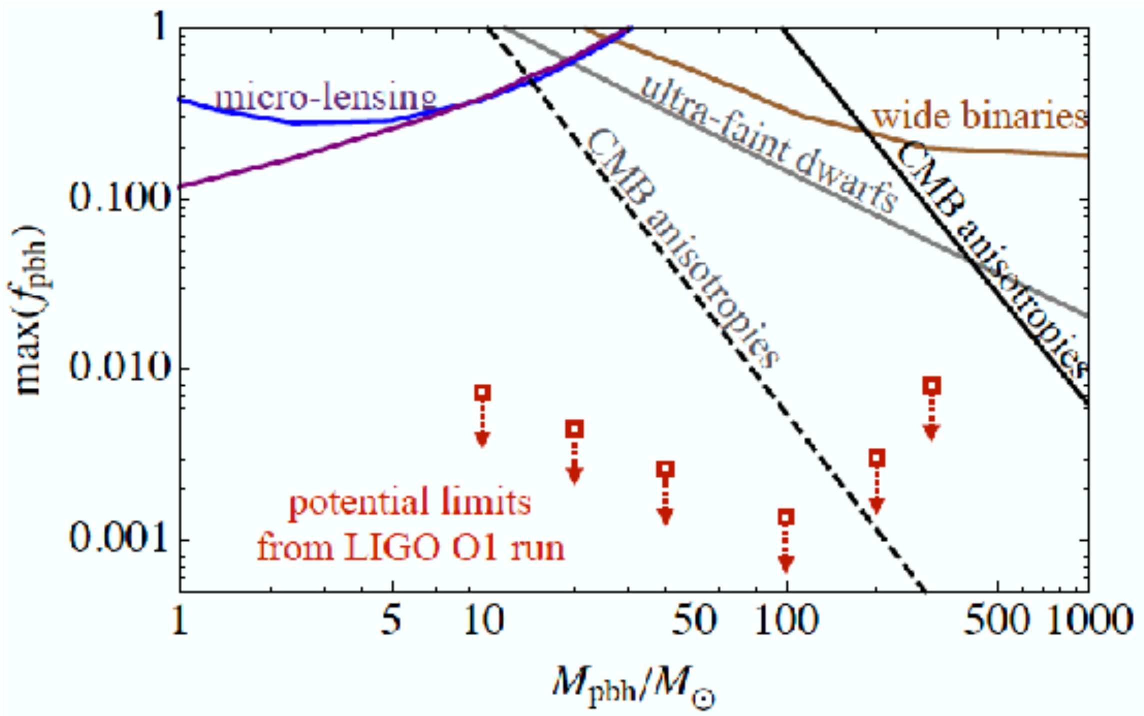


Despite knowing the number density of binary stars, the "astro" prediction is very uncertain

The astrophysical line in the plots is always based on *Gerosa et al 2019*

Gow, CB, Hall, Peacock 2019

The PBH merger rate places the tightest constraint



Haimoud et al 2017

- Caveats:

1. Assumes a monochromatic mass spectrum. Extended by *Chen & Huang '18, Raidal et al '18* ++
2. Assumes PBHs are randomly placed initially, true if Gaussian initial conditions. Clustering does not help *Bringmann et al '18, Young & CB '19*
3. Assumes BH binaries are not disrupted. Recently tested to z~1000 by simulations (*Raidal et al '18)* and even disrupted PBHs can merge *Vaskonen & Veermäe '19*
4. Neglects DM halo formation around the BHs. Not a big effect overall *Kavanagh, Gaggero & Bertone '18*