Determining the origin of LIGO’s black holes

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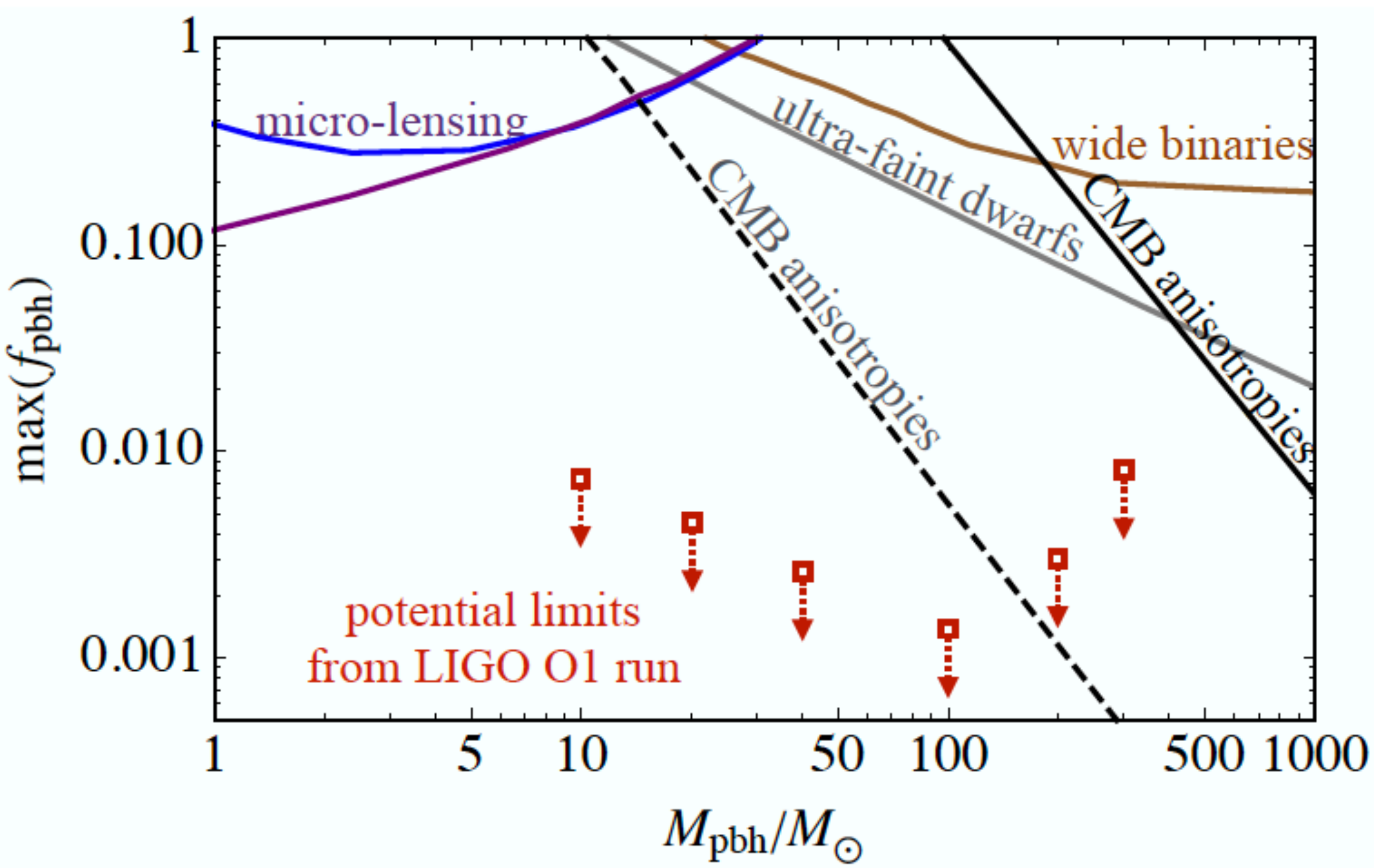
EXCELLENCE IN SCIENCE
THE ROYAL SOCIETY

PBH collaborators include: J. Adamek, N. Bellomo, P. Cole, E. Copeland, A. Gow, M. Gosenca, A. Green, A. Hall, M. Hawkins, S. Hotchkiss, M. Hindmarsh, I. Musco, S. Patil, J. Peacock, D. Regan, M. Sasaki, D. Seery, S. Young

Focus week on PBHs, IPMU, Tokyo, 4 December 19

The PBH merger rate and LIGO BHs



Haimoud et al 2017

Follows early-time clustering methodology of Nakamura et al '97

- The tightest observational constraint comes from the merger rate. 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*

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 halo formation around the BHs. Not a big effect overall *Kavanagh, Gaggero & Bertone '18*

Contents

- LIGO could be detecting PBHs
- The mass function and mass ratio as complementary probes
- PBH mass function constraints
- Non-Gaussianity: A blessing and a curse
- Future: We will find out if PBHs still exist*
  * T&C's apply

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?
  Mass
  Mass ratio
  (Spin, redshift distribution and location)

LIGO observables

- The merger rate and mass distribution are well studied
- LIGO also measure the mass ratio, which is close to 1
- Astrophysical black holes can form “dynamically”, i.e. the stellar binary forms first and exchanges gas such that the two masses become equal
- PBHs form before the binary does
- Hence, the PBH mass function must be broad enough to match the range of chirp/total masses seen by LIGO, but narrow enough to keep the mass ratio close to unity

Fresh from Monday

[24] arXiv:1911.12685 [pdf, other]

Primordial black hole merger rates: distributions for multiple LIGO observables

Andrew D. Gow, Christian T. Byrnes, Alex Hall, John A. Peacock

Comments: 23 pages + appendices, 17 figures

Subjects: **Cosmology and Nongalactic Astrophysics (astro-ph.CO)**; General Relativity and Quantum Cosmology (gr-qc)

We have calculated the detectable merger rate of primordial black holes, as a function of the redshift, as well as the binary's mass ratio, total mass and chirp mass (observables that have not previously been explored in great detail for PBHs). We consider both the current and design sensitivity of LIGO and five different primordial black hole mass functions, as well as showing a comparison to a predicted astrophysical black hole merger rate. We show that the empirical preference for nearly equal-mass binaries in current LIGO/Virgo data can be consistent with a PBH hypothesis once observational selection effects are taken into account. However, current data do exclude some PBH mass distributions, and future data may be able to rule out the possibility that all observed BH mergers had a primordial origin.

https://arxiv.org/abs/1911.12685

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

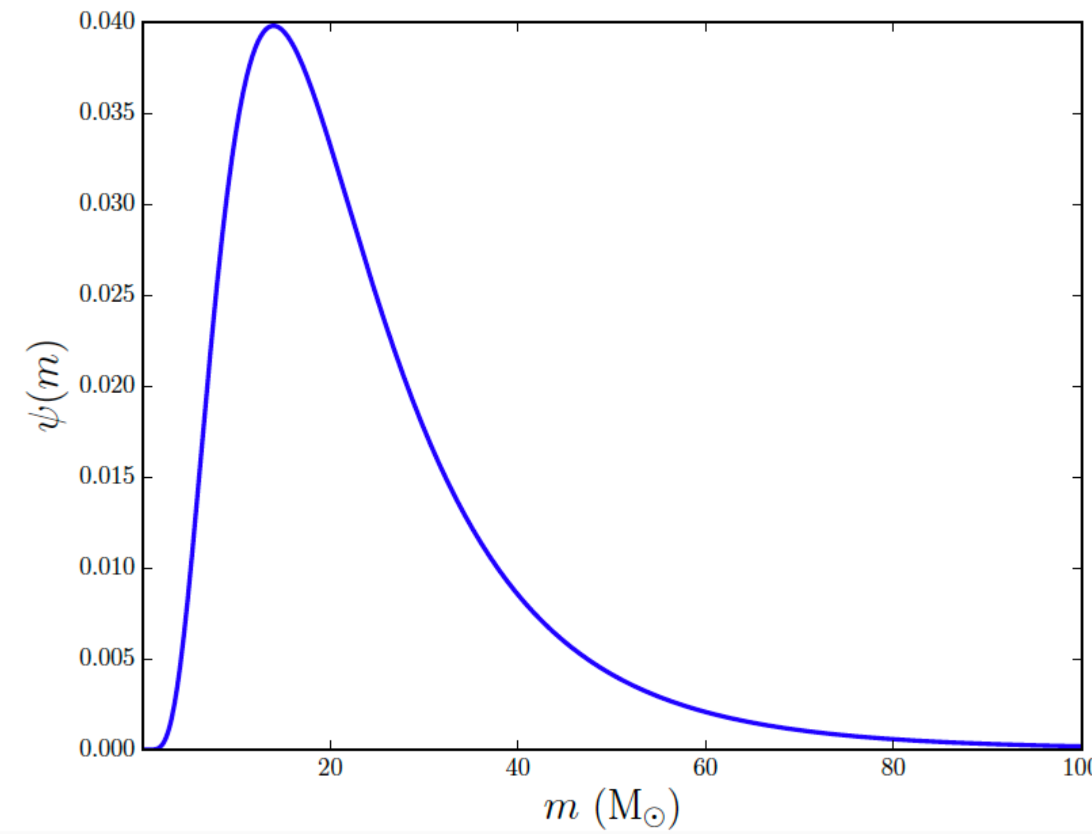
$$\psi(m) = \frac{1}{\sqrt{2\pi}\sigma m} \exp\left(-\frac{\ln^2(m/m_c)}{2\sigma^2}\right)$$

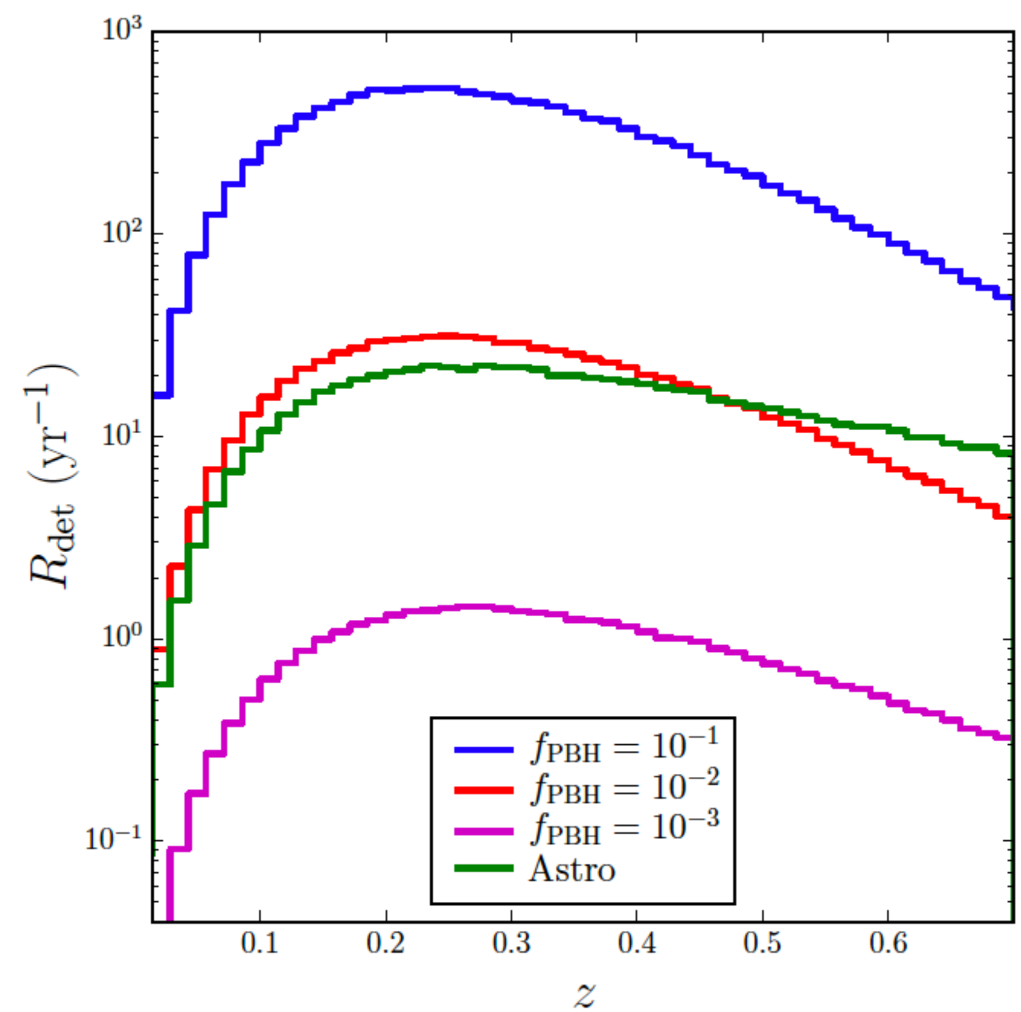
We match the expected astrophysical merger rate when about 1% of DM is in PBHs - for the assumed mass function.

The intrinsic merger rate estimated by LIGO assumes a mass function. To avoid doing so, one should calculate the observed merger rate

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 detection probability

z=0.2 **z=0.5**

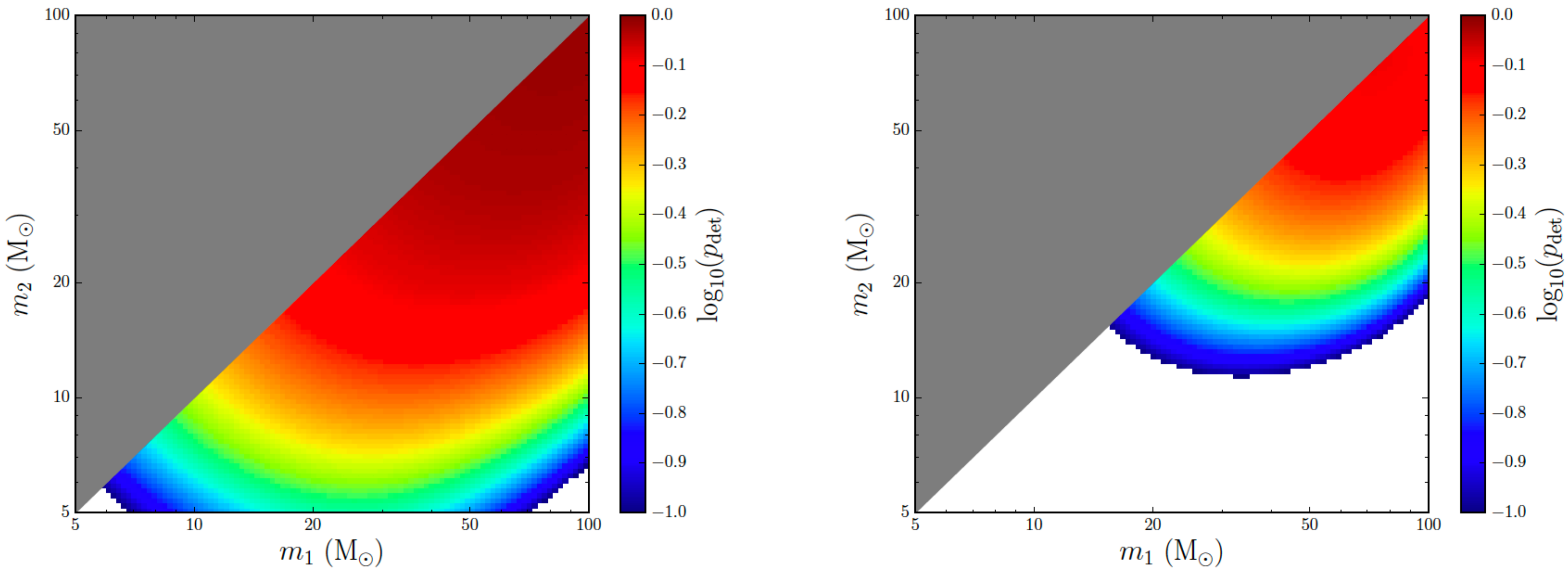


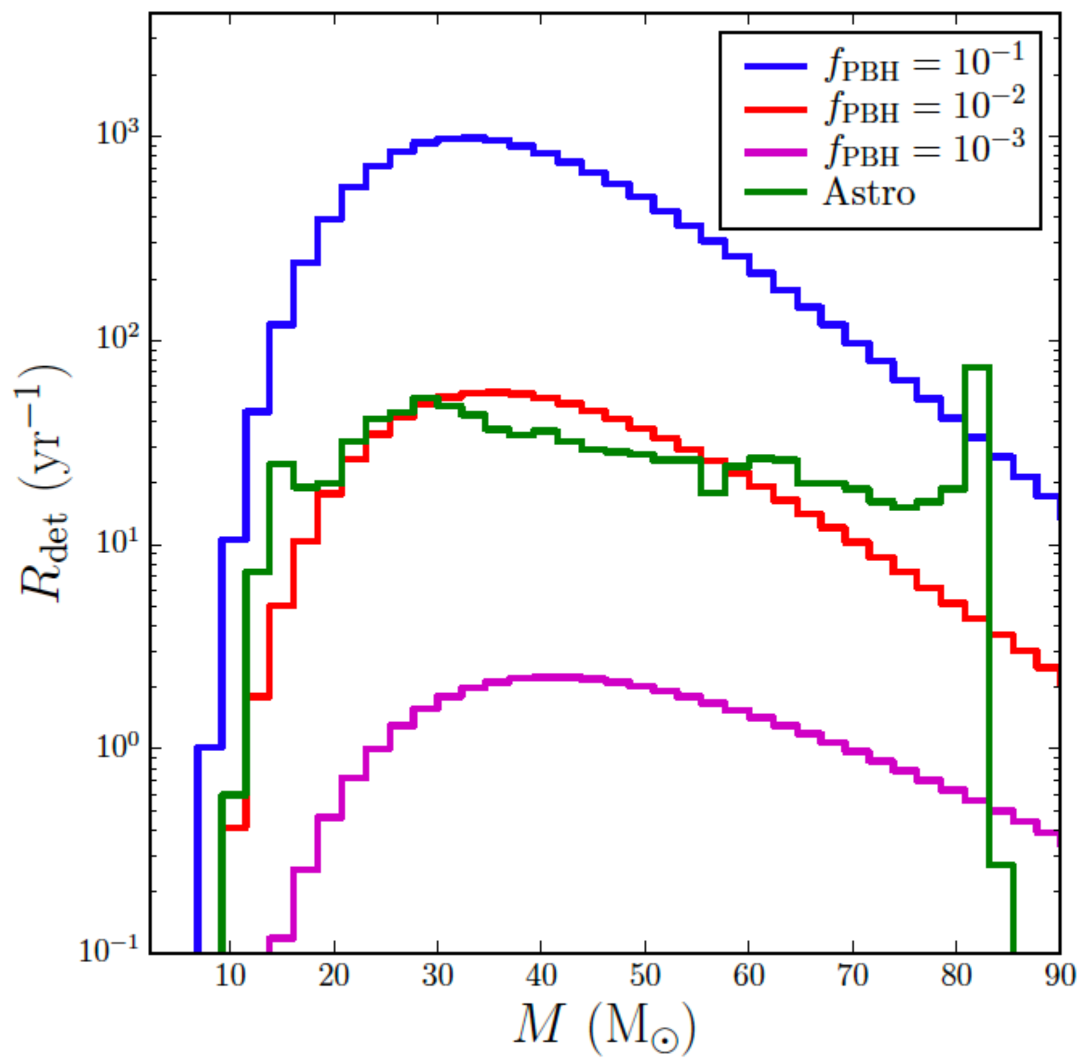
FIG. 2. Detection probability $p_{\rm det}(m1, m2)$ at $z = 0.2$ (left) and $z = 0.5$ (right). Note that all three scales are in log-space. The white area indicates $p_{\rm det} < 0.1$, and the grey triangle indicates the case $m_2 < m_1$, chosen by LIGO for their analysis.

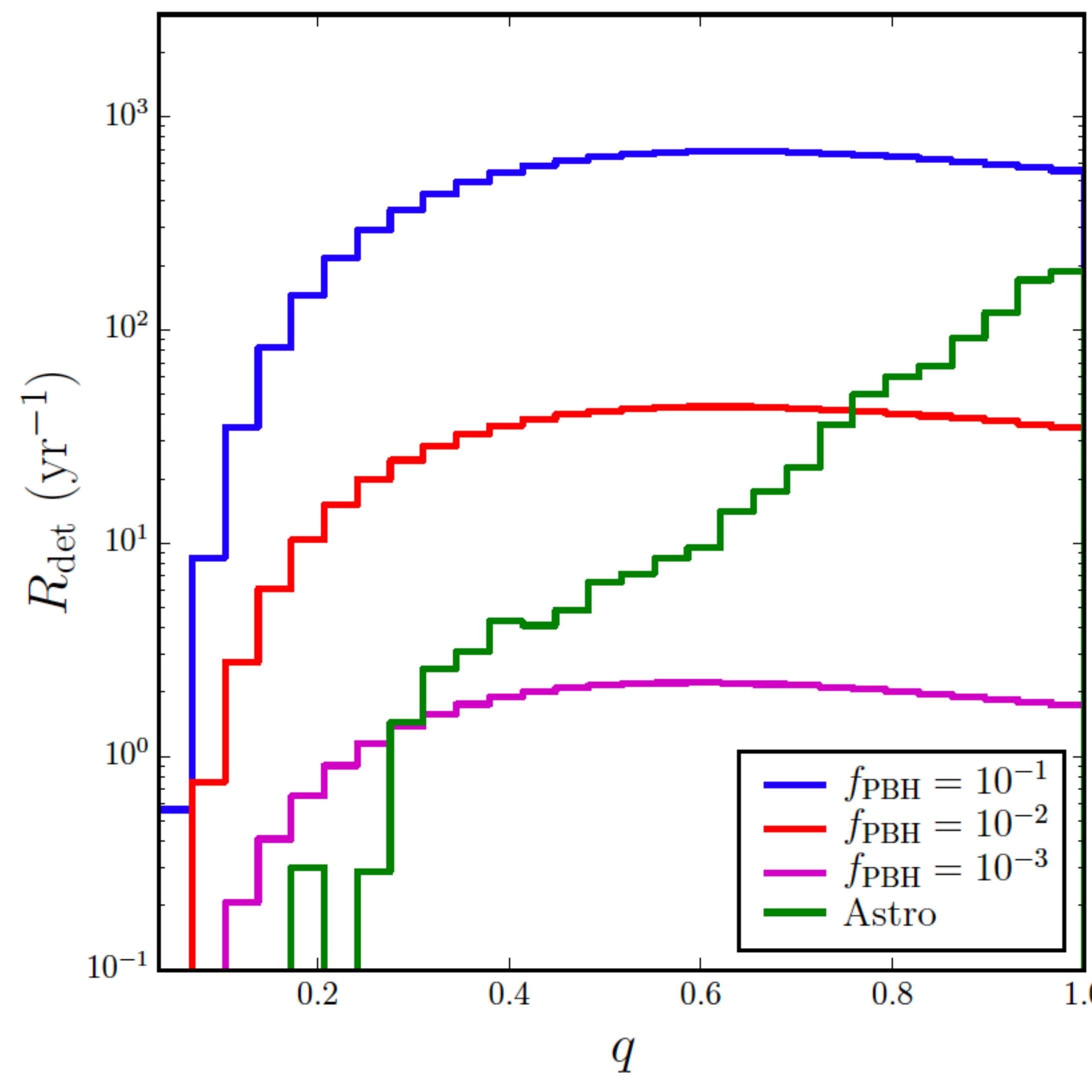
Gow, CB, Hall, Peacock 2019

For LIGO design (not current) sensitivity, and neglecting spin

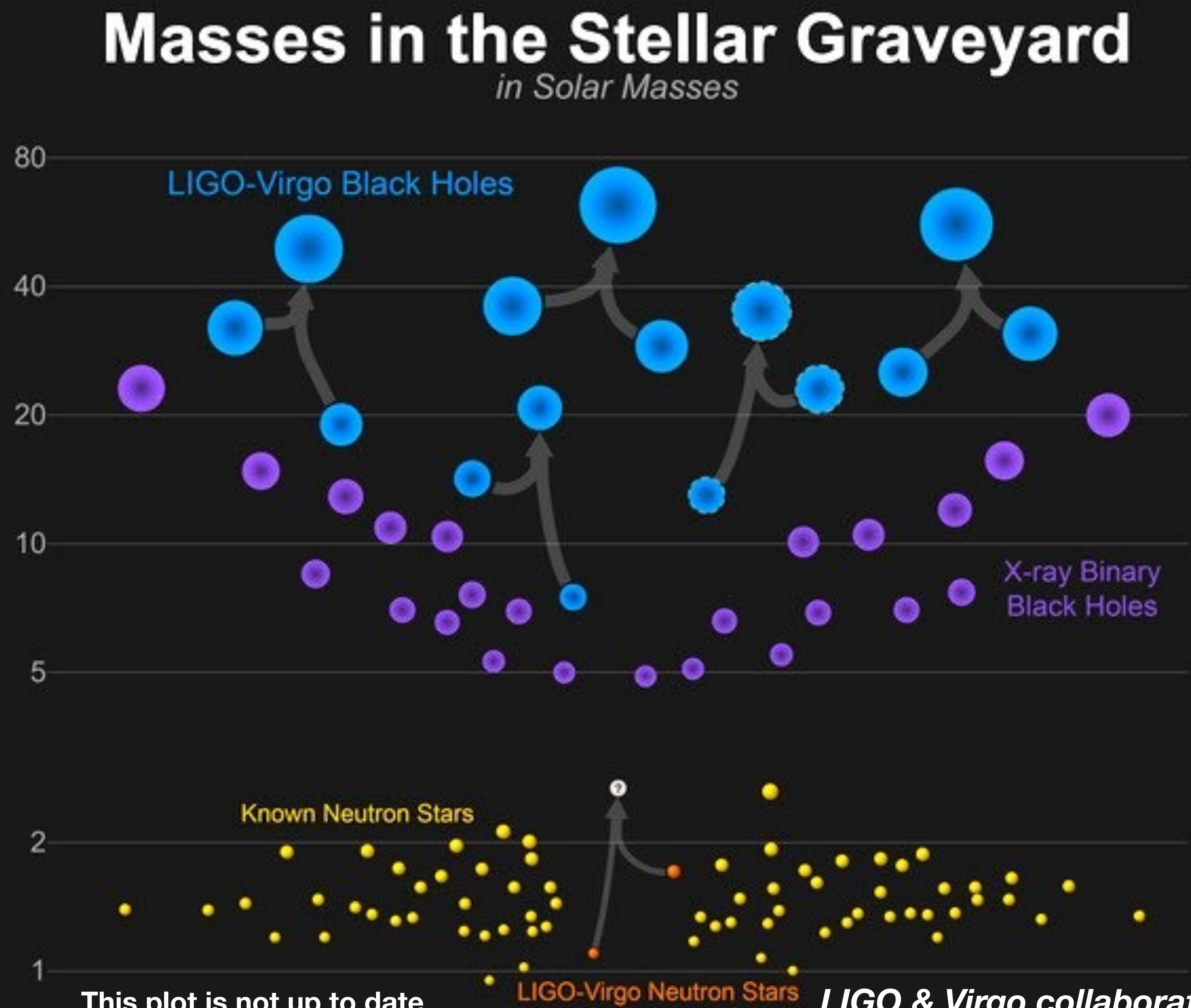
Calculated using the gwdet code by Gerosa https://zenodo.org/record/889966#.XeQ_ni17HfY

The total mass and mass ratio





Notice how astrophysical black holes have an expected maximum (and minimum) mass
The mass ratio looks like a more promising discriminant between the two scenarios
However, q is also harder to measure

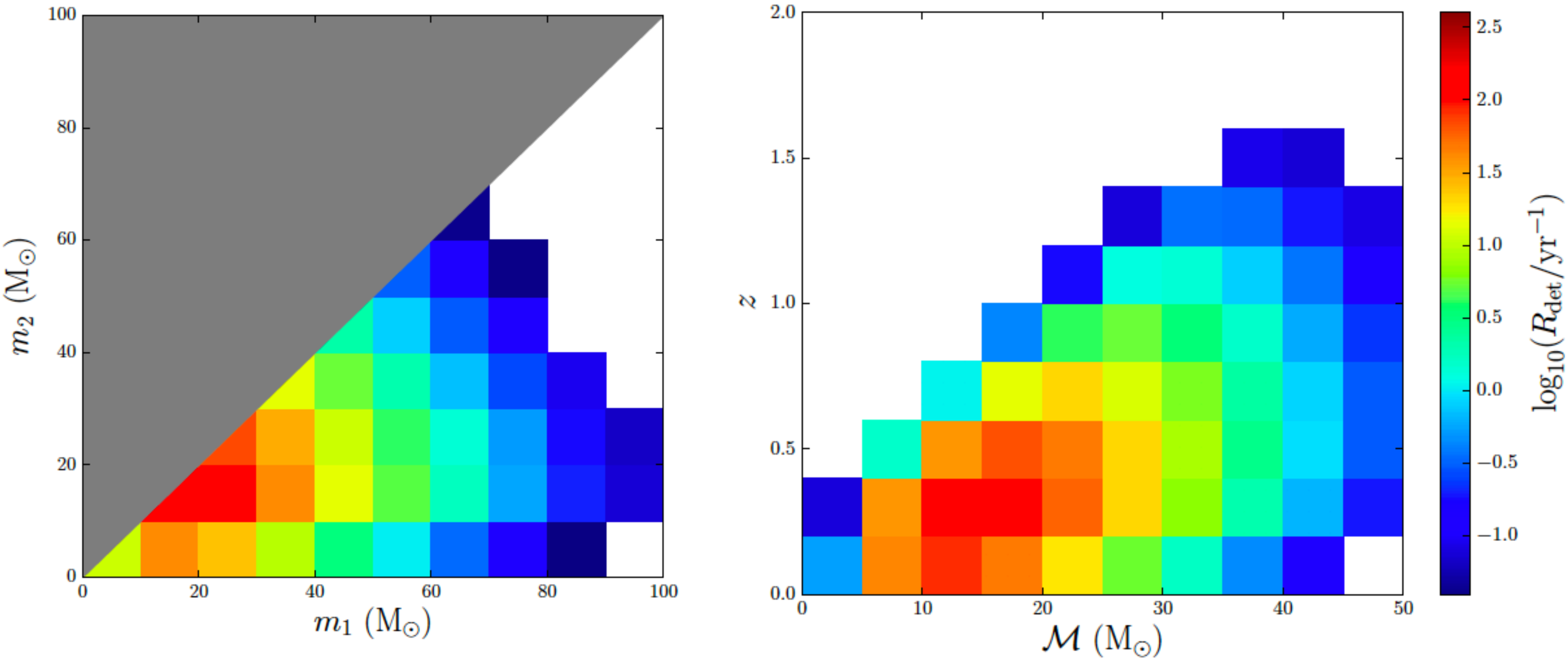


This plot is not up to date

LIGO & Virgo collaboration

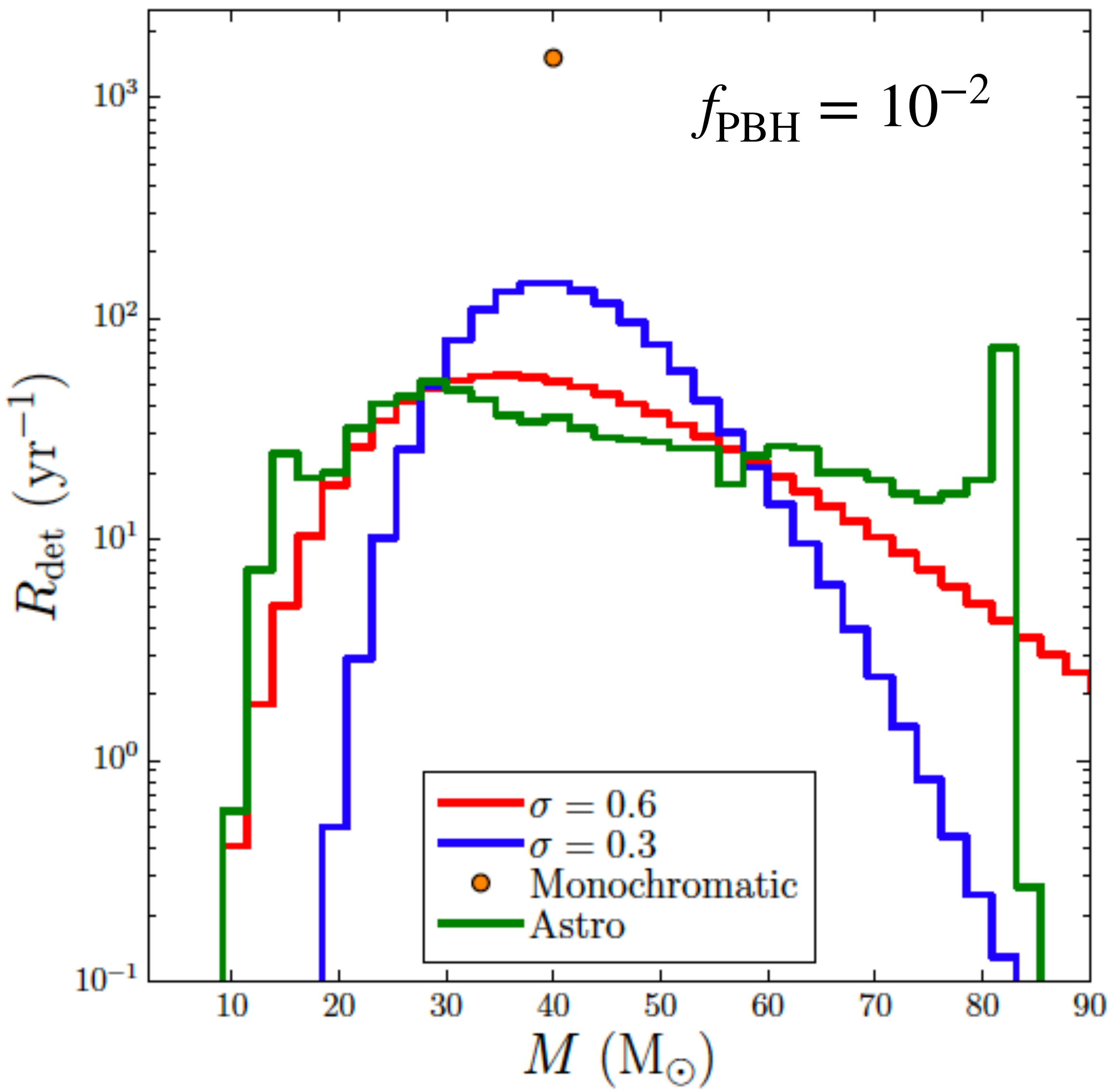
The component masses and chirp mass vs z

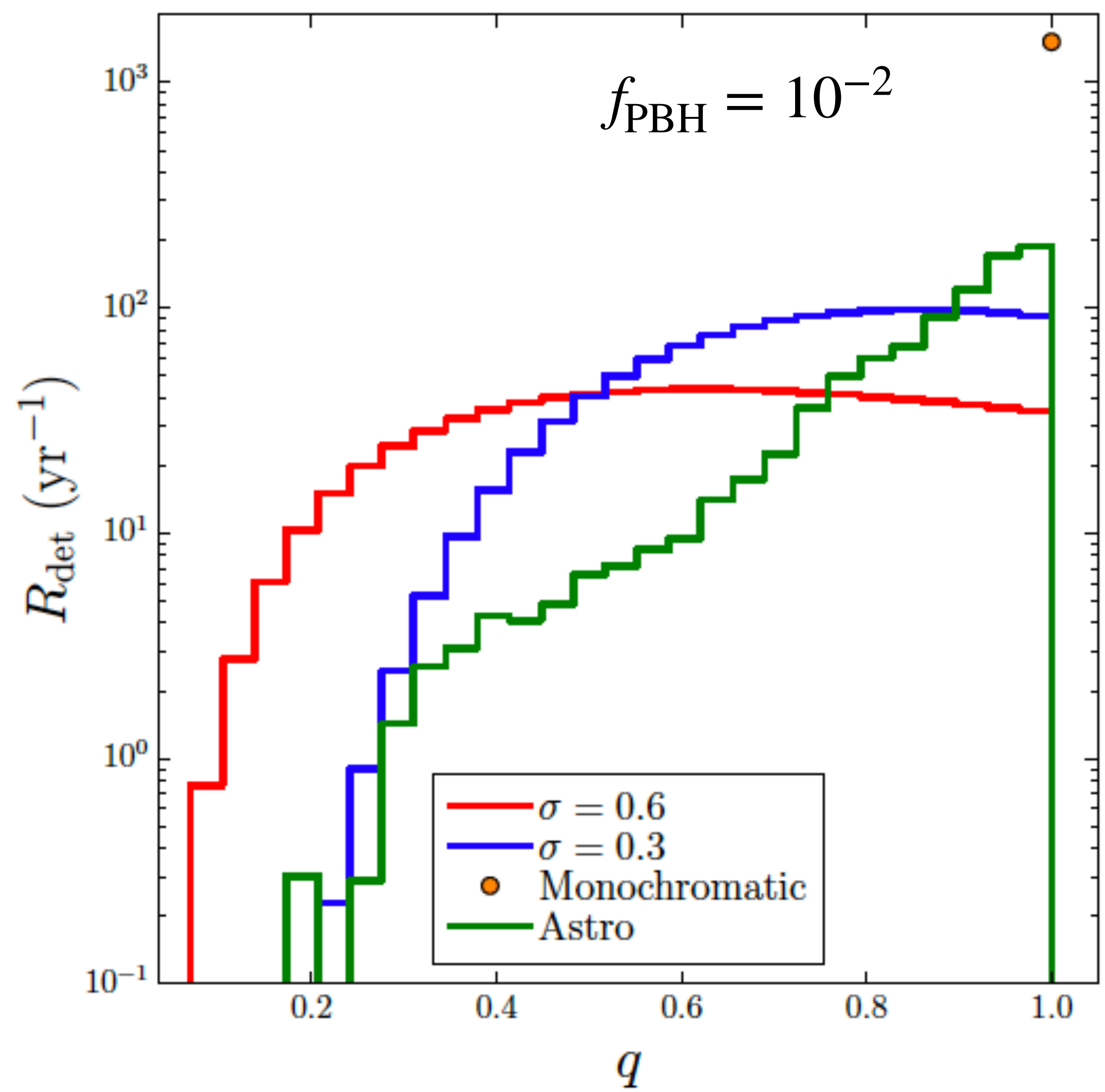
$f_{\rm PBH} = 10^{-2}$



Gow, CB, Hall, Peacock 2019

Varying the PBH mass function width

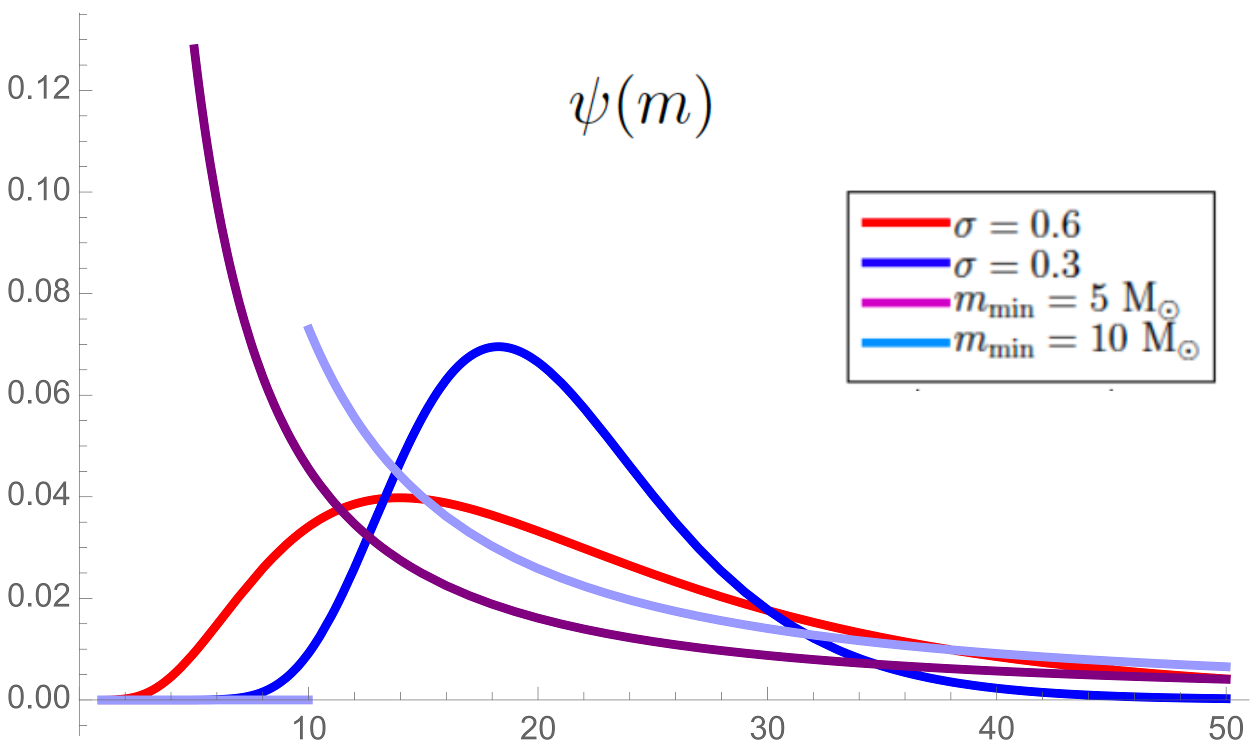


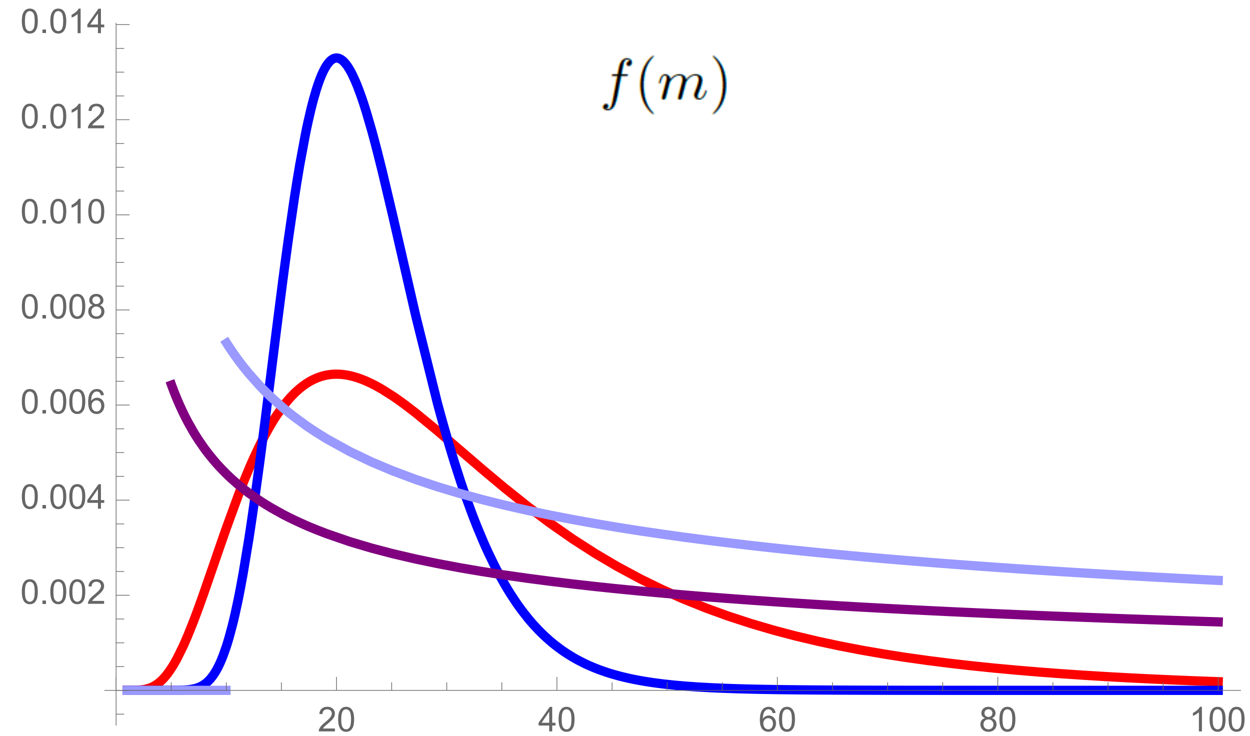


The "astro" distribution covers a broader range of total masses than sigma=0.3, but it still prefers the mass ratio q~1. A monochromatic mass function is completely ruled out.

A power law mass function: $m^{-\alpha}$

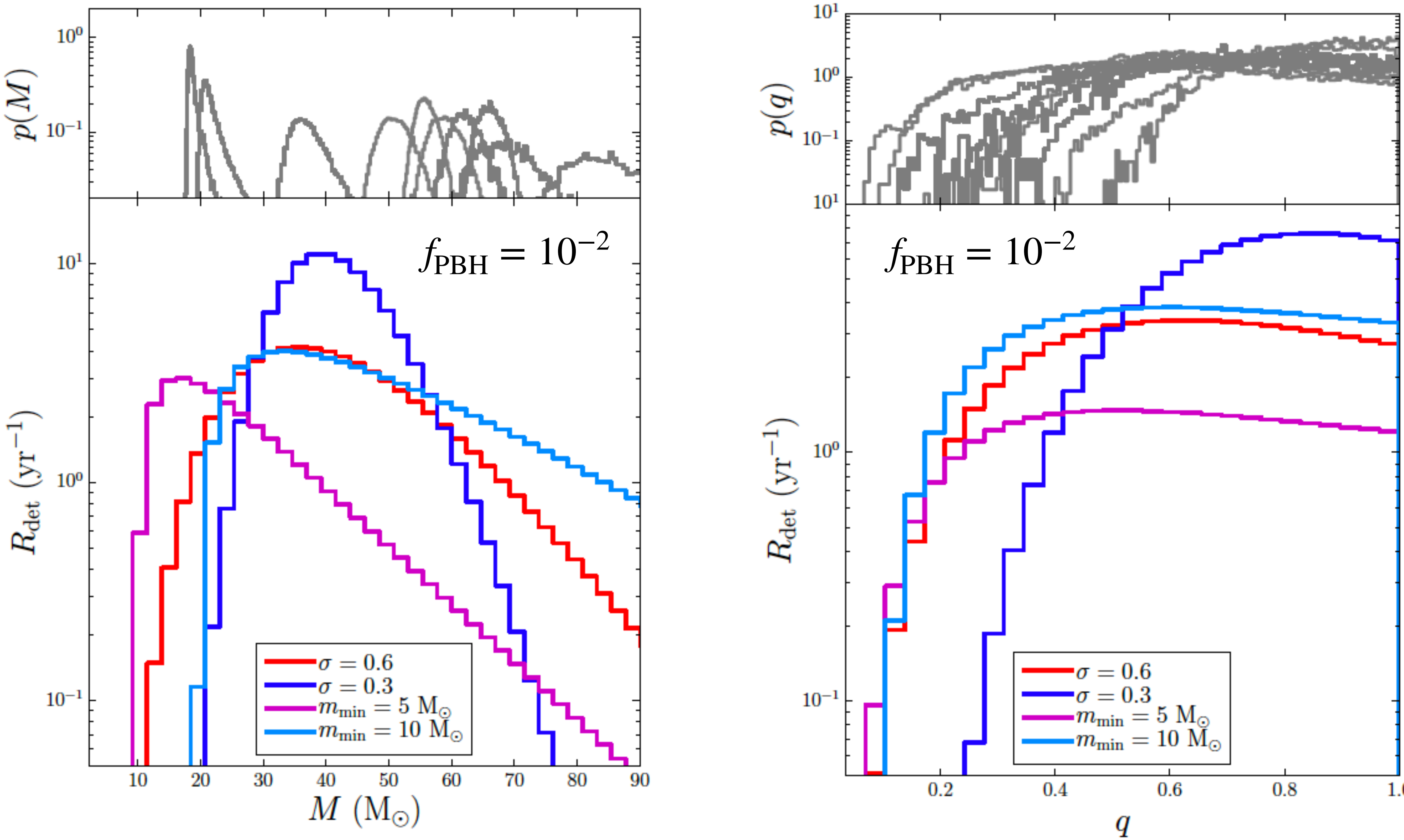
$$\int_0^\infty \psi(m) dm = 1 \qquad \psi(m) = \frac{1}{f_{\rm PBH}} \frac{f(m)}{m} \qquad \int \mathrm{d}\ln(m)\ f(m) = f_{\rm PBH}$$





$\alpha = 3/2$ if the power law is created by a scale-invariant power spectrum.
A lower mass cut off is required. We consider 5 and 10 $M_\odot$.
The power-law mass functions are heavily weighted towards lower masses

Comparing to current data



We use the LIGO 0102 sensitivity curves. 1/2 a year of data for 10 events.

Goodness of fit to the total event rate

Test	N			
f_{PBH}	10^{-2}		10^{-3}	
Model	Expected number	Probability	Expected number	Probability
Lognormal ($m_c = 20\ \mathrm{M}_\odot$, $\sigma = 0.6$)	31	1.2×10^{-5}	1.6	1.3×10^{-6}
Lognormal ($m_c = 20\ \mathrm{M}_\odot$, $\sigma = 0.3$)	47	6.4×10^{-11}	1.9	4.1×10^{-6}
Power-law ($m_{\mathrm{min}} = 5\ \mathrm{M}_\odot$, $\alpha = 3/2$)	15	0.12	0.96	6.3×10^{-9}
Power-law ($m_{\mathrm{min}} = 10\ \mathrm{M}_\odot$, $\alpha = 3/2$)	37	1.5×10^{-7}	2.0	9.3×10^{-6}

The observed merger rate depends significantly on the mass function. Unless you use the same mass functions as LIGO did, you need to calculate the detected merger rate, not the intrinsic merger rate.

The mass functions require f_{PBH} = few * 10^{-3}

Caveat: The formula from *Raidal et al 2019* (the “best” formula to date we are aware of) assumes that PBHs form binary pairs with their nearest neighbour. When the mass function is sufficiently broad, light PBHs dominate the number density and artificially suppress the merger rate of heavier PBHs. This probably explains the difference in the 2 power law results. We can’t fit the QCD mass function.

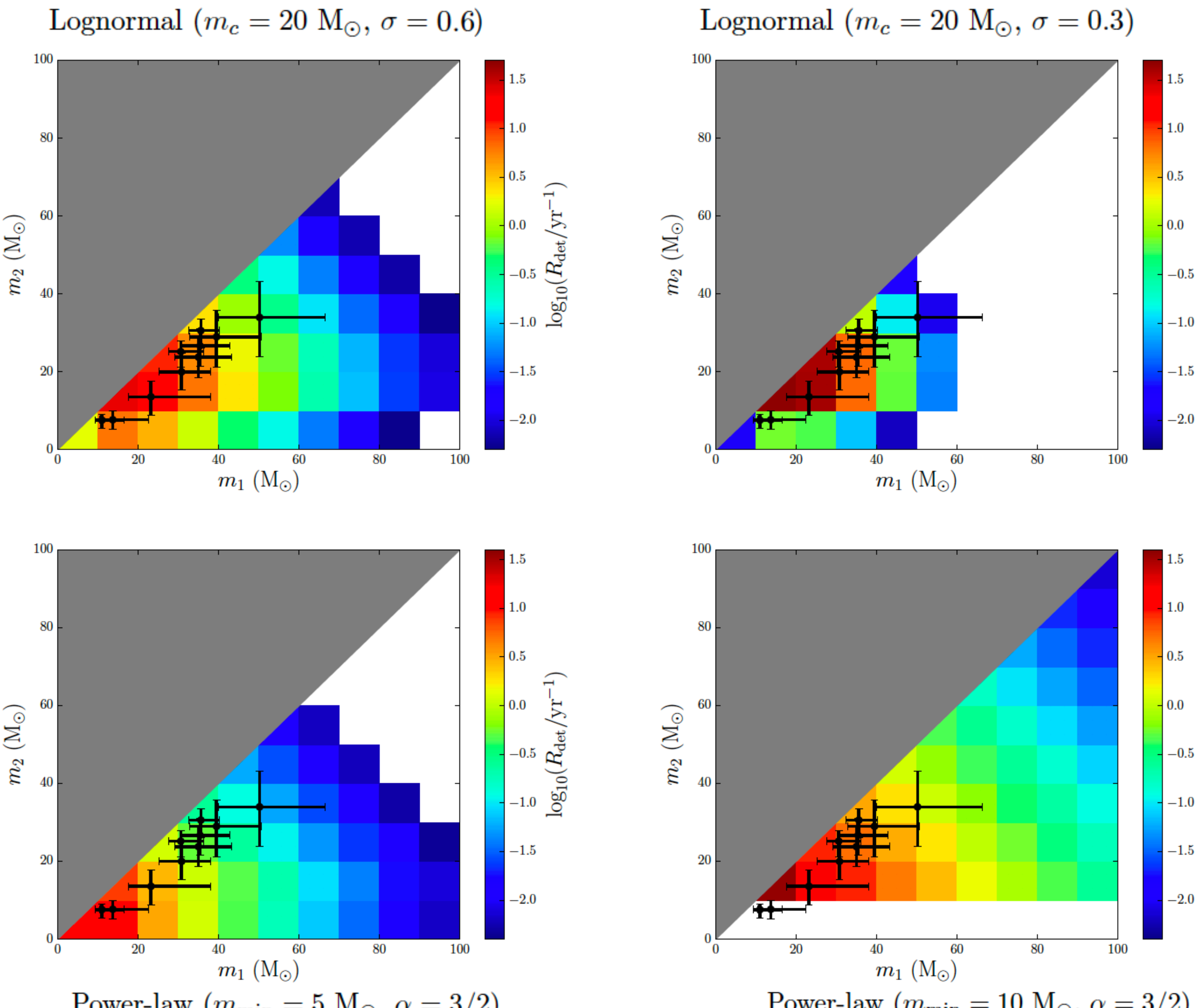
Goodness of fit to the mass distribution

Test		m_1-m_2	
f_{PBH}		10^{-2}	10^{-3}
Model	Expe	Probability	Probability
Lognormal ($m_c = 20$ M$_\odot$, $\sigma = 0.6$)		0.15	0.37
Lognormal ($m_c = 20$ M$_\odot$, $\sigma = 0.3$)		$\lesssim 10^{-4}$	5×10^{-4}
Power-law ($m_{\mathrm{min}} = 5$ M$_\odot$, $\alpha = 3/2$)		2×10^{-4}	0.30
Power-law ($m_{\mathrm{min}} = 10$ M$_\odot$, $\alpha = 3/2$)		0.15	0.45

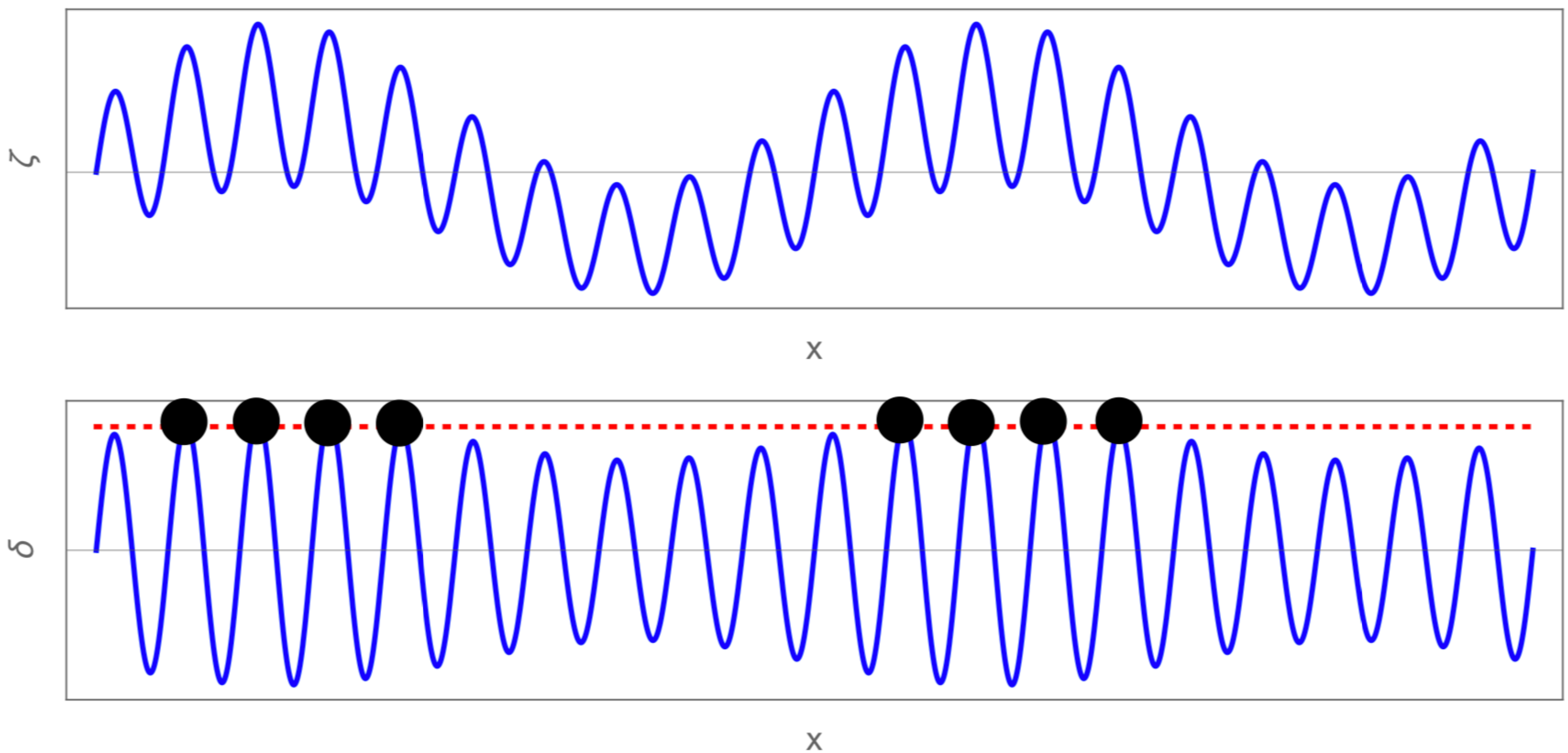
We crudely include the LIGO error bars by smoothing the detected masses

The lognormal with sigma=0.3 is too narrow and completely ruled out.

Edoardo Vitagliano talk: A flat spectrum in f would probably overproduce heavy BHs

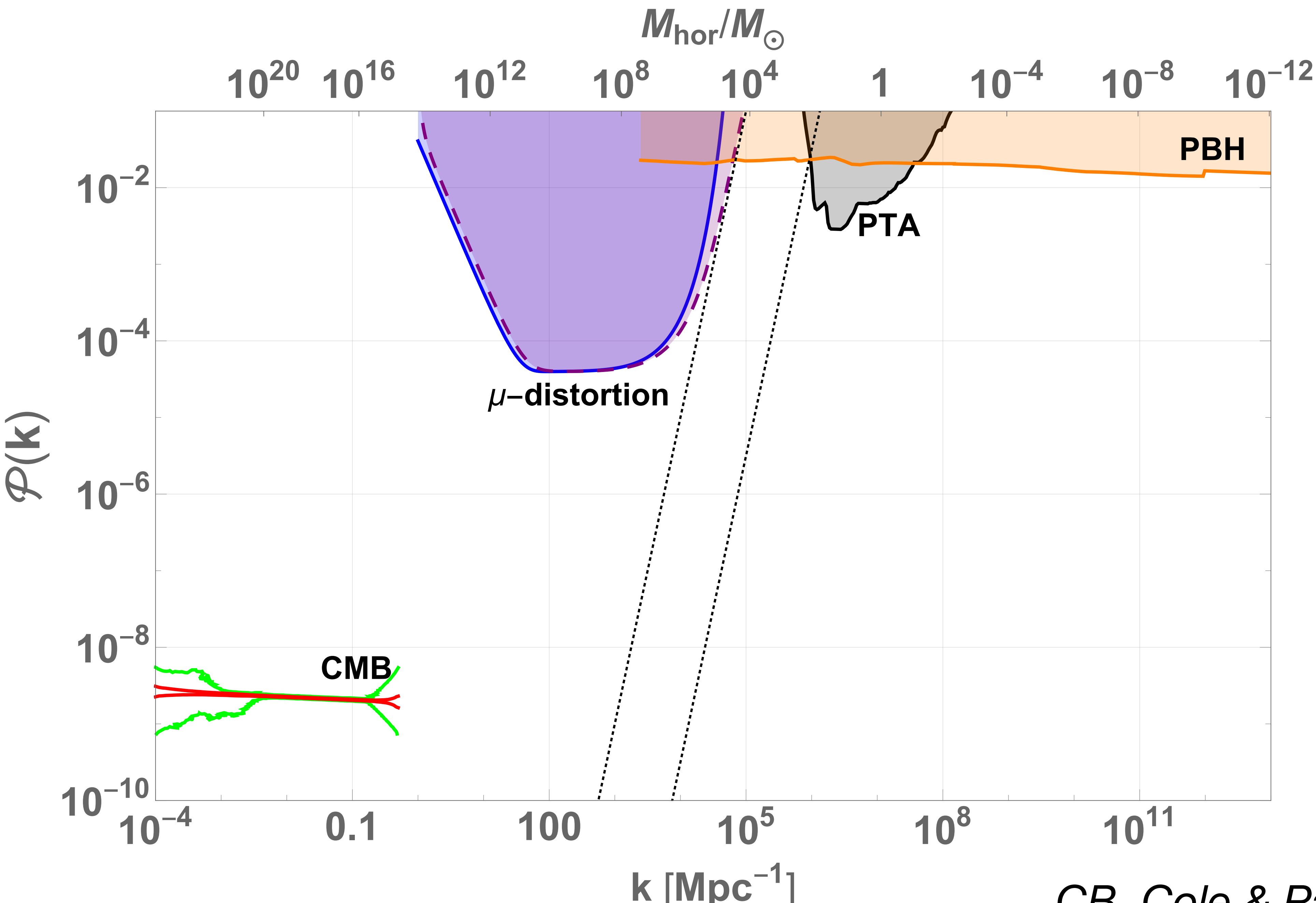

Lognormal ($m_c = 20$ M$_\odot$, $\sigma = 0.6$)
Lognormal ($m_c = 20$ M$_\odot$, $\sigma = 0.3$)
Power-law ($m_{\min} = 5$ M$_\odot$, $\alpha = 3/2$)
Power-law ($m_{\min} = 10$ M$_\odot$, $\alpha = 3/2$)
m_1 (M$_\odot$)
m_2 (M$_\odot$)
$\log_{10}(R_{\rm det}/{\rm yr}^{-1})$
0
20
40
60
80
100
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0

The impact of non-Gaussianity



Local non-Gaussianity boosts the PBH fraction and creates an initial spatial clustering
Suyama & Yokoyama 2019
This (probably) increases the merger rate
It may also rule out the PBH scenario entirely, by generating a large DM-photon isocurvature perturbation - *Tada & Yokoyama 2015, Young & CB 2015*

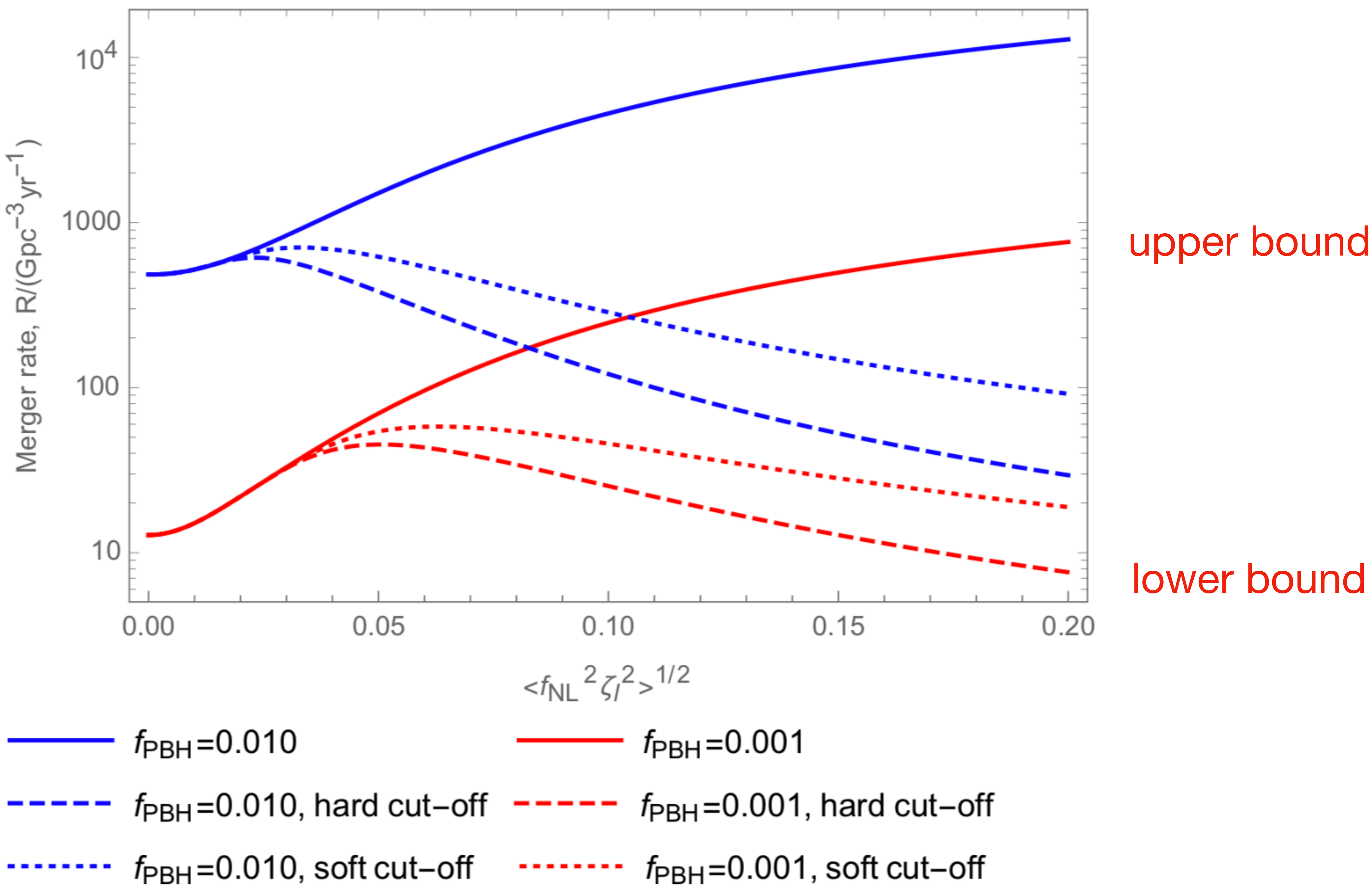
Current power spectrum constraints



CB, Cole & Patil `18

PTA constraints may rule out LIGO mass PBHs, but order one uncertainties are crucial. Chulmoon Yoo and Cris Germani's talks. If zero PBHs exist (Ruth Gregory's talk), the PBH constraint only improves by a factor of ~ 3 *Cole & CB '17*

Clustering and the merger rate



With non-Gaussianity, the spatial clustering quickly leads to large local PBH densities
We don't know the merger rate in such cases - binaries are likely to be disrupted
In principle, one millionth of DM in PBHs could be large enough to explain the LIGO events

Non-Gaussianity take-away message

- Beware of invoking non-Gaussianity to “evade” constraints, since it introduces new challenges

- The PBH abundance, initial clustering, merger rate and isocurvature fraction are all very sensitive to non-Gaussianity

- Even slow-roll suppressed values of f_{NL} and tau_{NL} can rule out PBHs being the dark matter

Smoking gun PBH signatures

- A very high redshift merger would have to be primordial
  Koushiappas & Loeb 2017

- If LIGO detects PBHs then early-time mergers will create a stochastic GW background also detectable by LIGO
  Raidal et al 2018

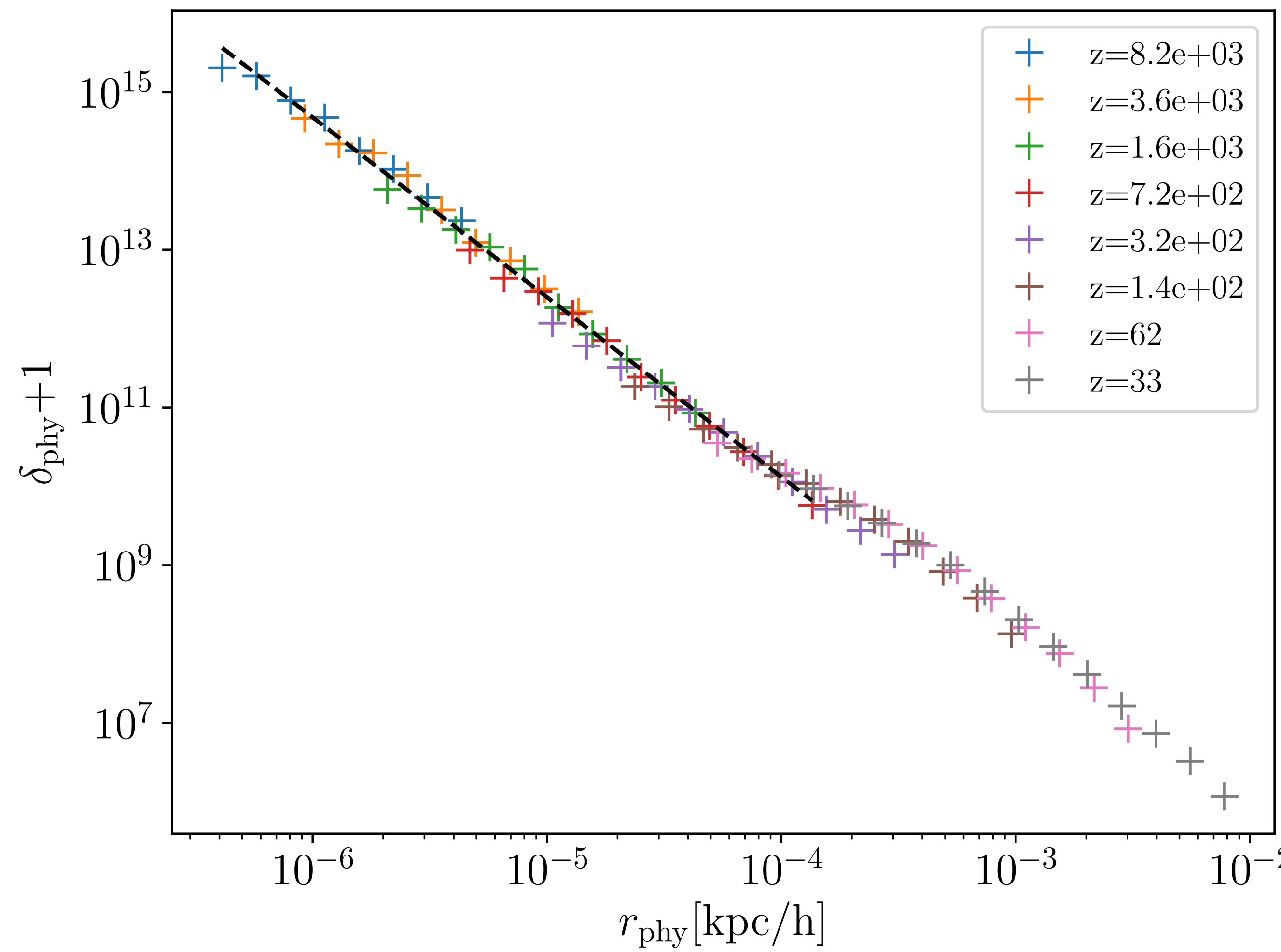
- A sub Chandrasekhar mass compact object. This is motivated by the QCD transition, which boosts the production of PBHs by 1-2 orders of magnitude
  Bernard Carr's talk, *CB, Hindmarsh, Young & Hawkins 2018*

- The low spin may also be a hint - Minxi He and Kaz Kohri talks

What if one PBH was detected?

- Assuming WIMPs have the standard, velocity independent cross section which gets the right abundance, and $M_{PBH}>10^{-6}$ M_{sun}. And annihilation channel into gamma rays.
- 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 in them.
- In contrast to ultracompact minihalos without a PBH seed. *Gosenca et al '17, Delos et al '17*

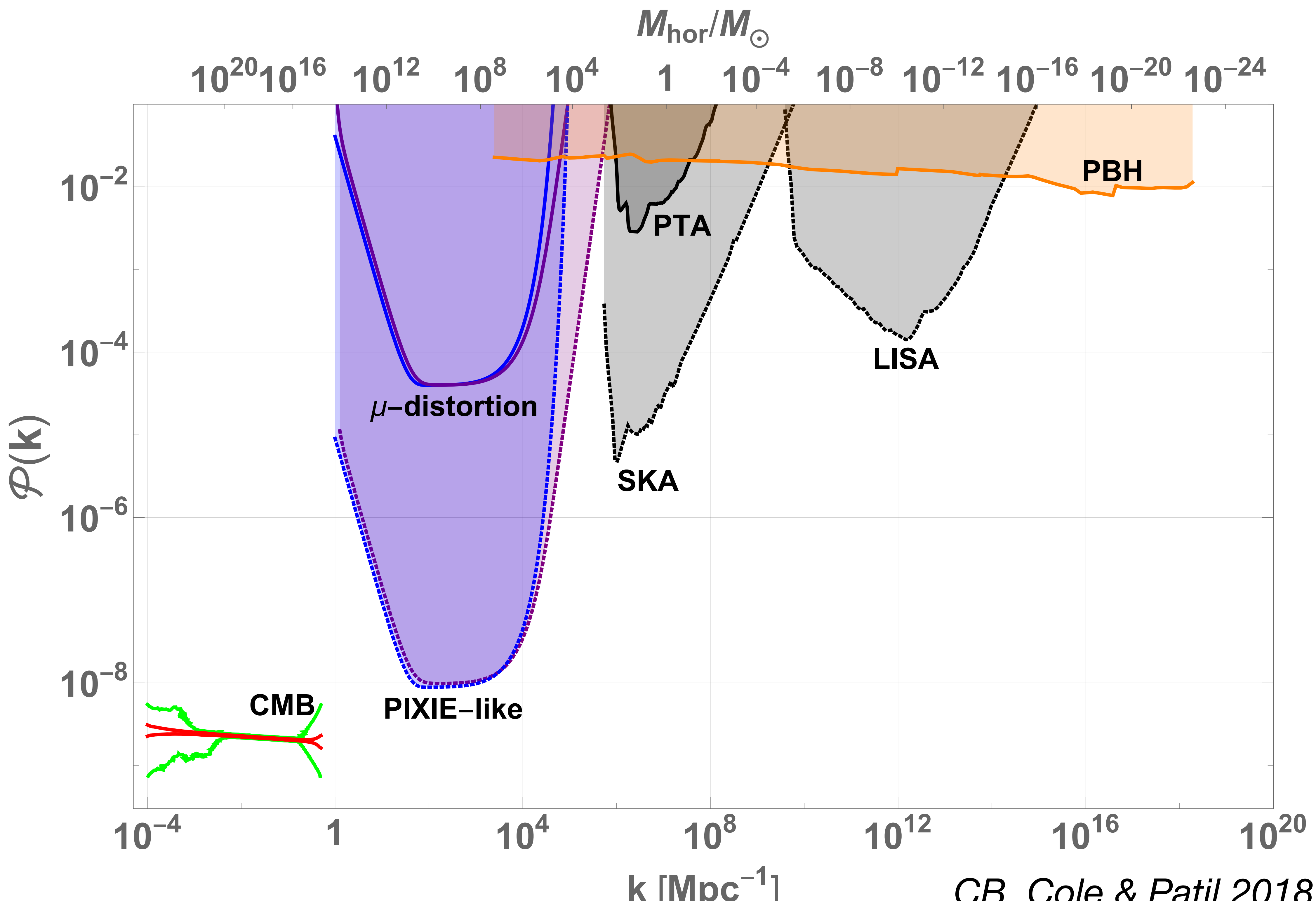
- A detection of WIMPs or PBHs may effectively rule out the existence of the other



Adamek, CB, Gosenca & Hotchkiss 2019;

Lacki & Beacom 2010; Eroshenko 2016; Boucenna, Kühnel, Ohlsson & Visinelli 2017
The 3 papers above all find different profiles. We agree with Eroshenko and derive the profile analytically and with the first 3D simulations

Future constraints



CB, Cole & Patil 2018

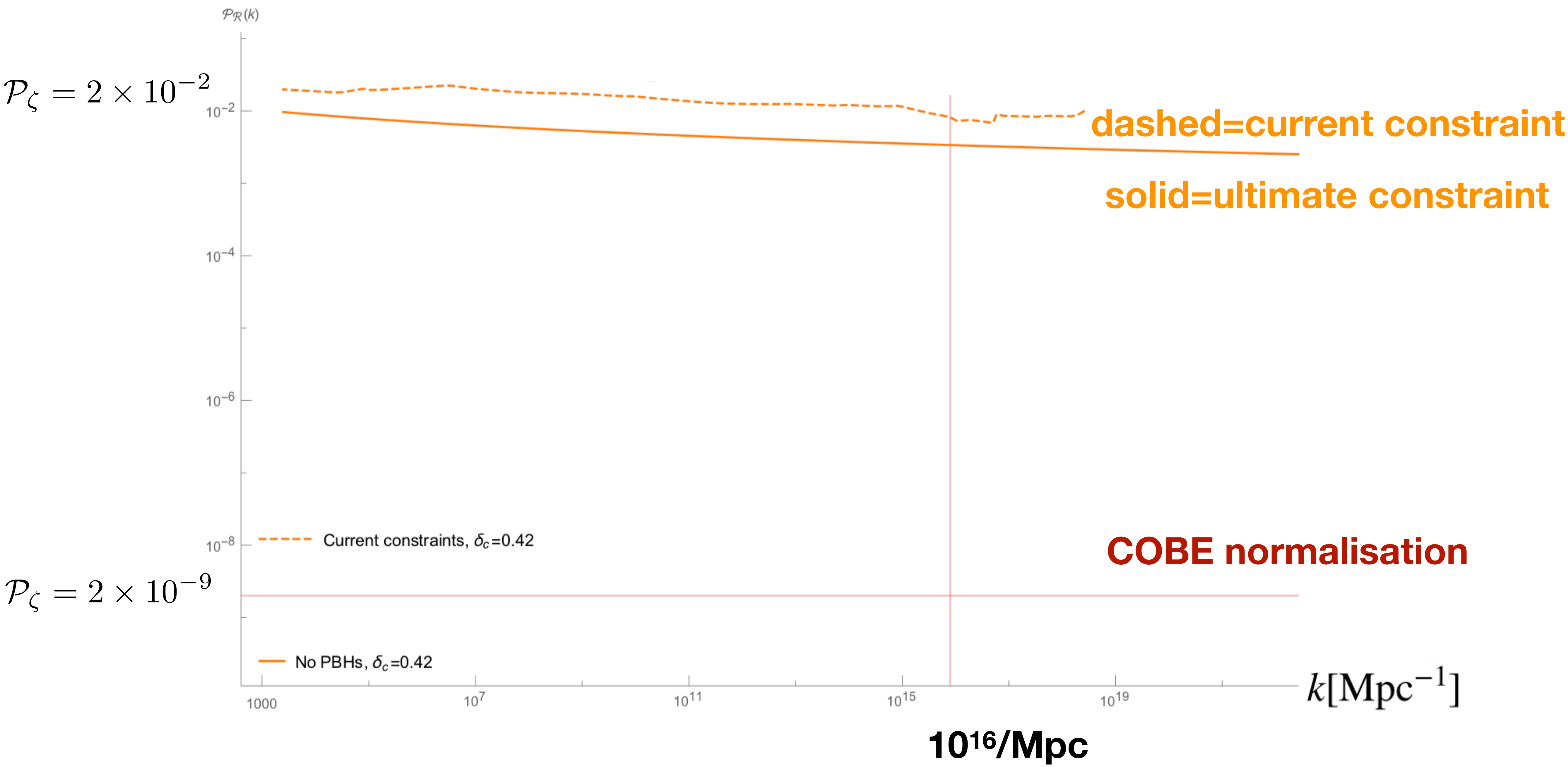
If PBHs form from large amplitude perturbations, we will either detect PBHs, or else (almost) rule out their existence at late times

Summary

- It remains possible that all the LIGO black holes were primordial
- There are many ways to test this.
- The PBH mass function cannot be too broad or too narrow. We will carry out a full likelihood fit to the LIGO data.
- The merger rate is highly sensitive to non-Gaussianity
- Results cannot be trusted in the case of a (locally) large PBH mass fraction and/or a very broad mass function
- Be wary of invoking non-Gaussianity to evade constraints
- Providing PBHs formed from large primordial overdensities, in ~ 20 years we should be able to rule in or out the present existence of PBHs

Backup slides

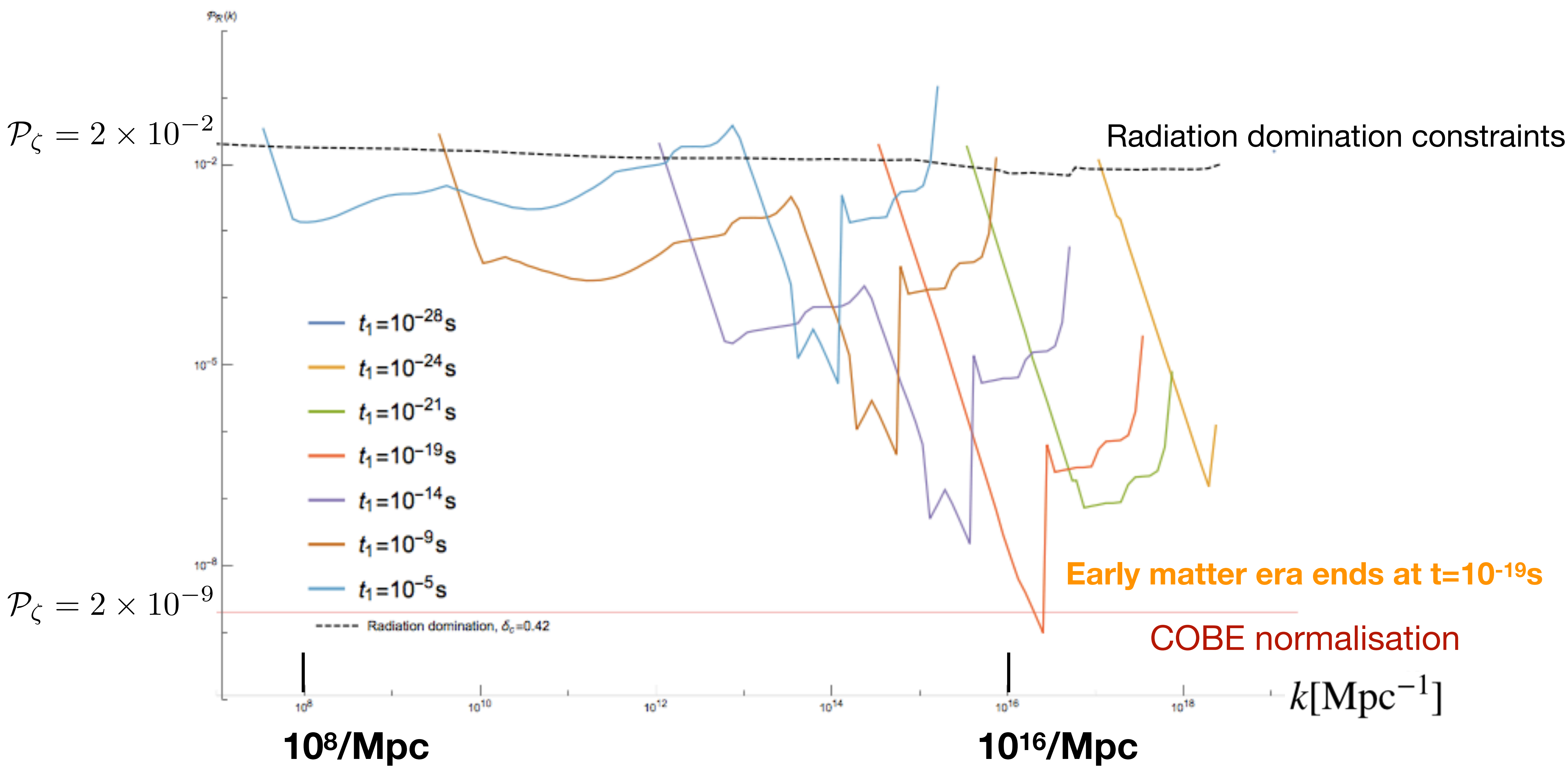
Ultimate constraints from PBHs



$$\beta' = e^{-\frac{\delta_c^2}{2\mathscr{P}_\delta}}$$

Cole & CB '17

Early matter domination dramatically tightens constraints



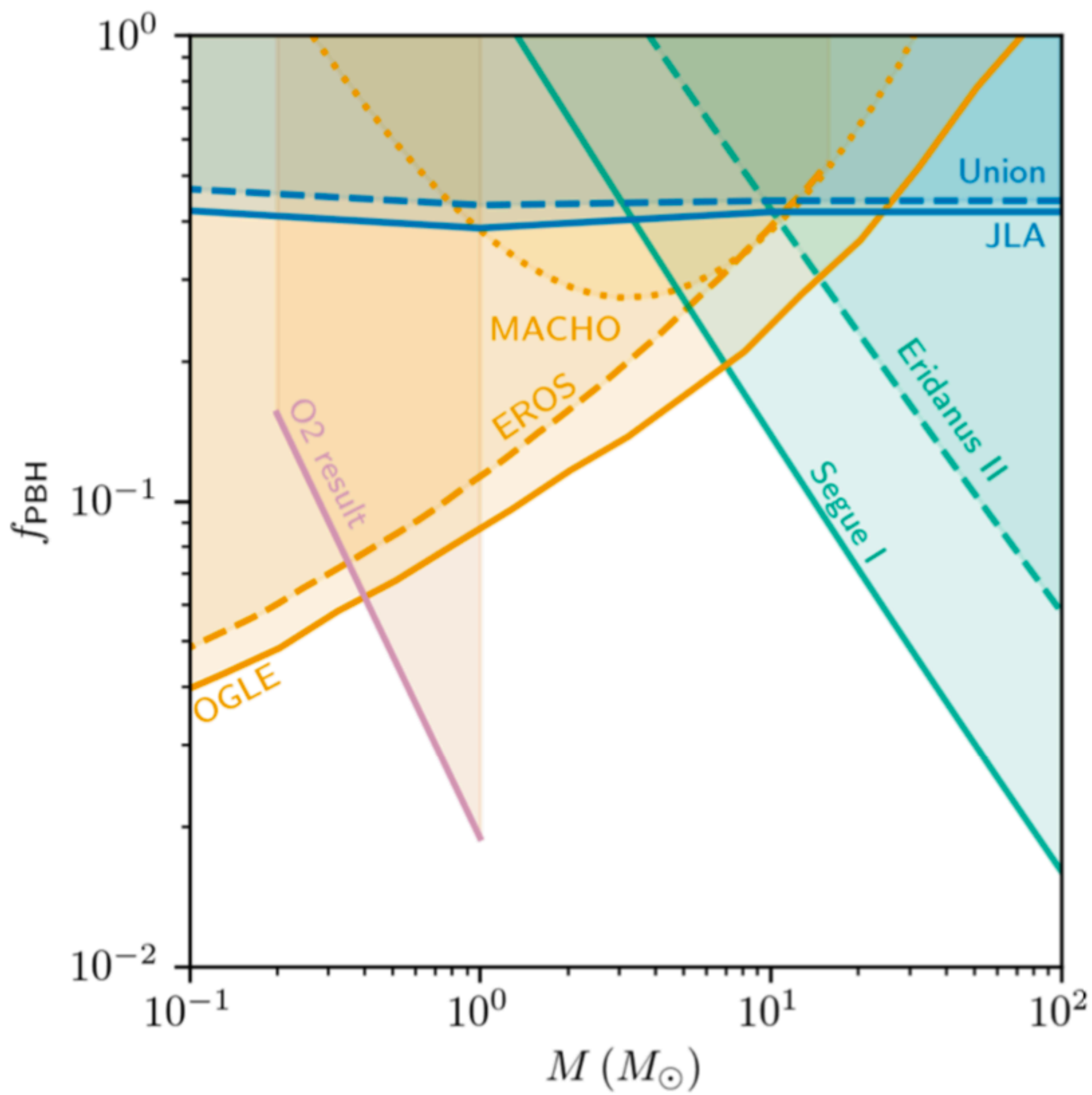
Cole & CB '17

PBH formation comments

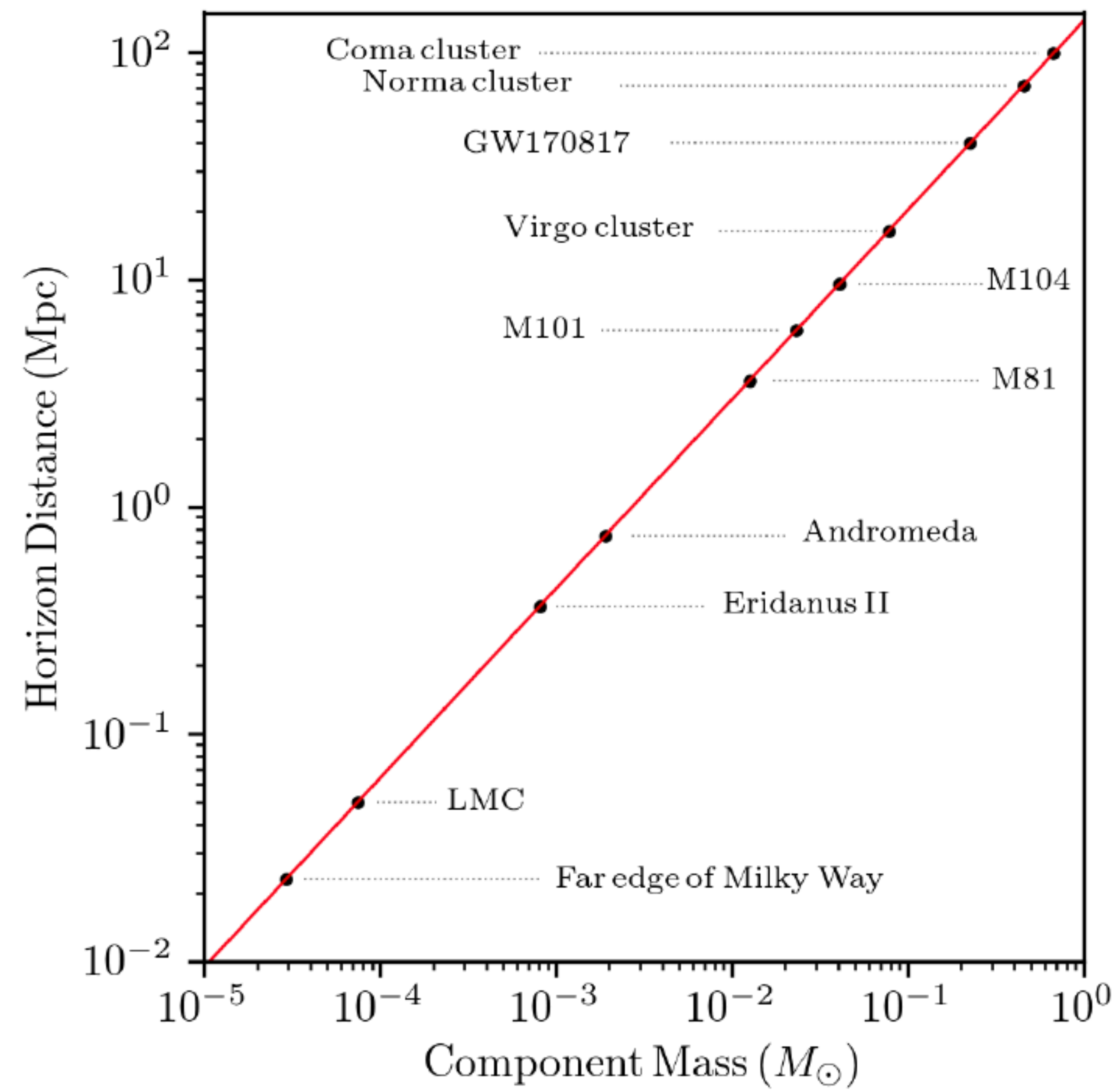
- The formation rate is exponentially sensitive to the amplitude of the power spectrum, and the collapse threshold
- Inflationary models posit an inflection point (ultra-slow-roll inflation) or other feature
- The power spectrum can't grow faster than about k4 (in canonical single-field inflation), impacts 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*

Sub-solar mass GW searches

GW searches have been made, with no detections so far
These are below the Chandrasekhar mass, hence potential proof of a primordial origin

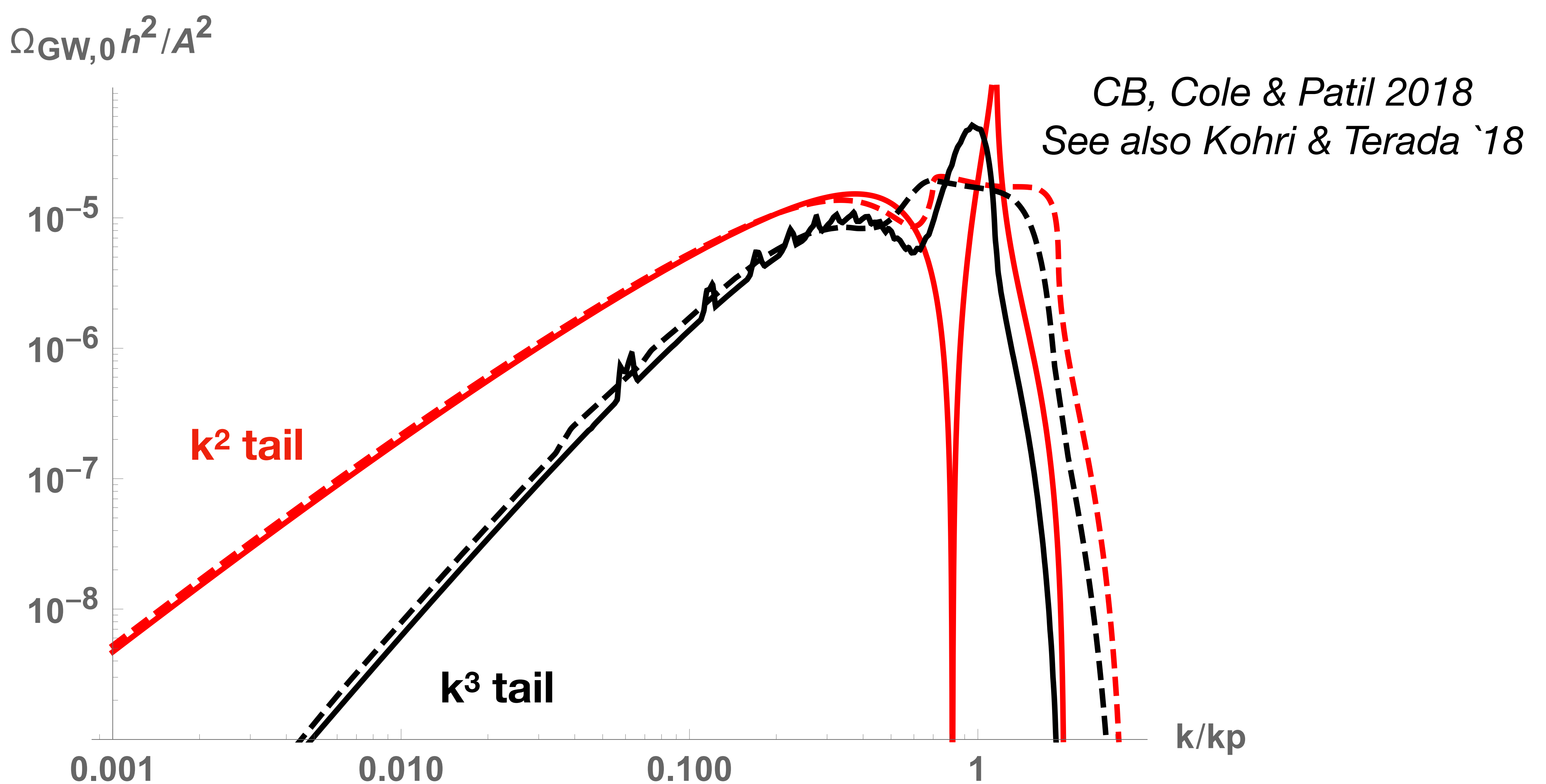


LIGO & Virgo collaboration 2019



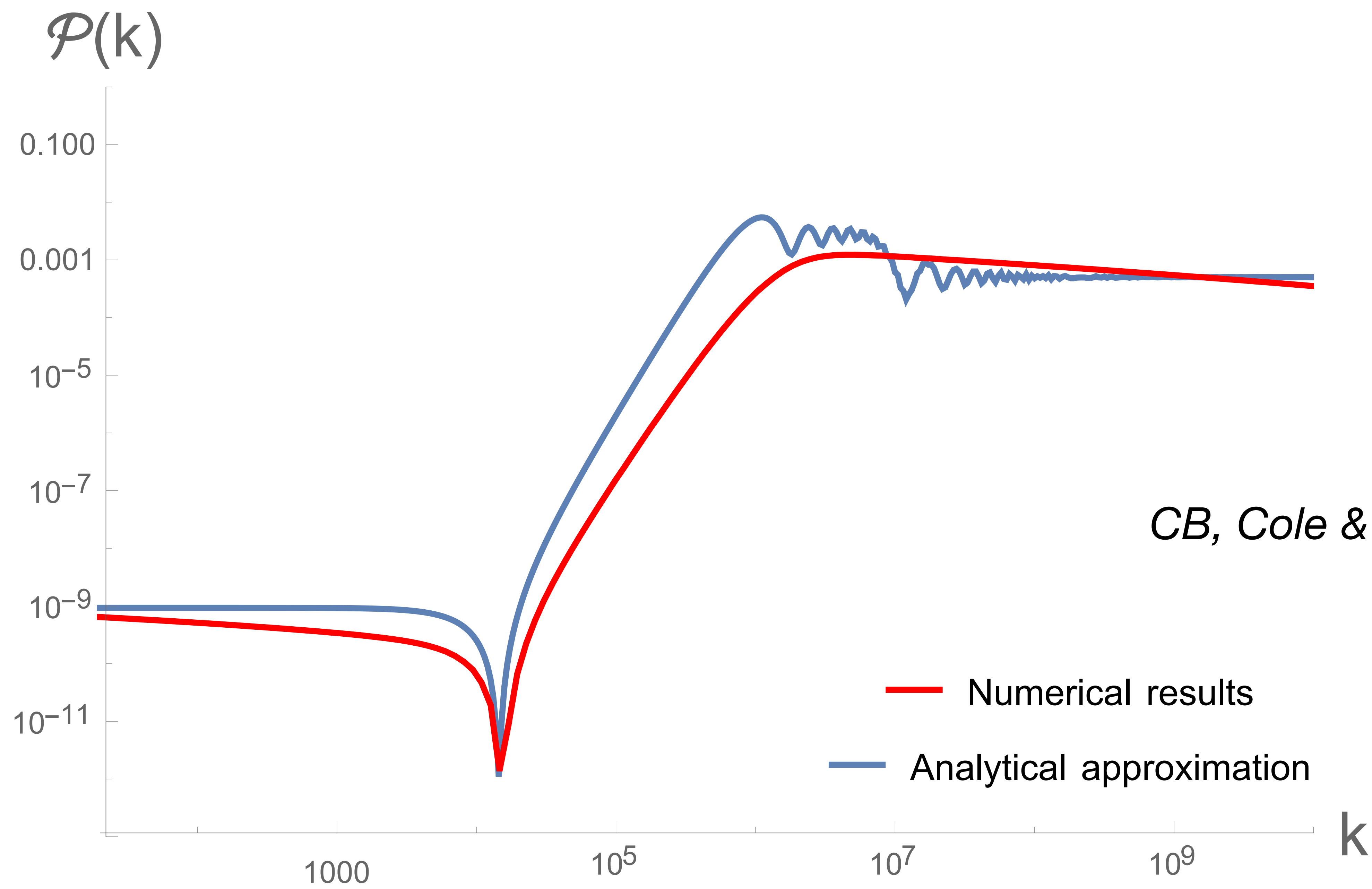
Magee et al 2018

GW spectrum



Red line - delta function scalar power spectrum
Black line - k^4 scalar power spectrum with cut off
Surprisingly, the delta function scalar power spectrum has a broader GW spectrum
This is unphysical and a warning against using delta function power spectra

“Realistic” model with a smooth potential

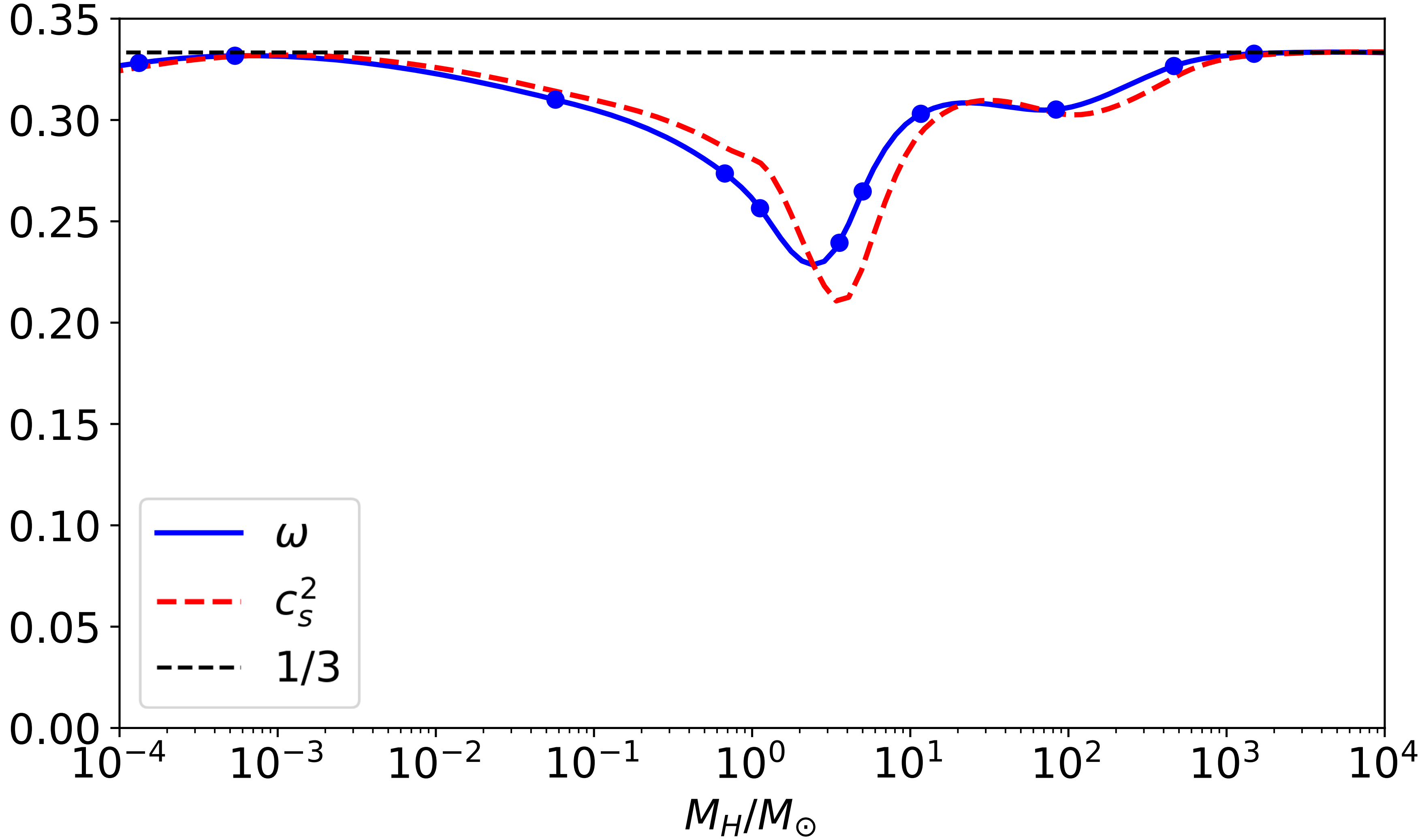


CB, Cole & Patil 2018

The red line is a full result from a smooth potential (*Germani & Prokopec* `17), while the red line is based on a piecewise analytic calculation.
Calculated using CPPTransport created by *David Seery 2016*

The QCD transition

As the Universe cools below 1 GeV (t~10^{-6} s), strong interactions confine quarks into hadrons and the equation-of-state parameter w decreases. *Crawford & Schramm `82, Jedamzik `98*

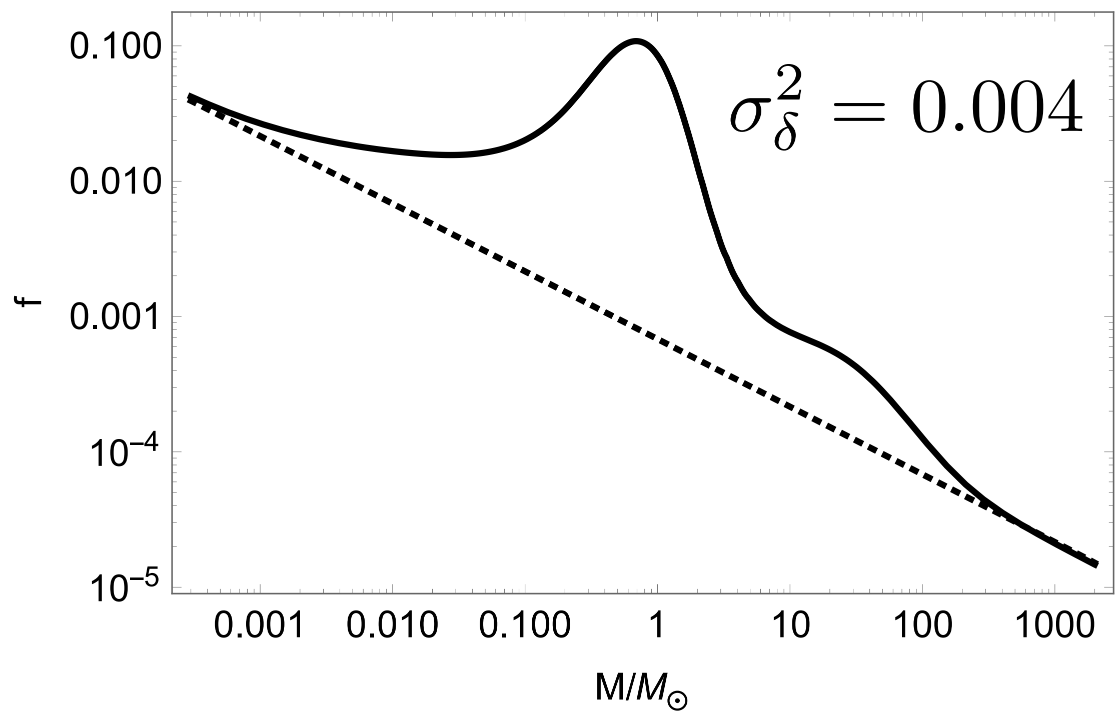


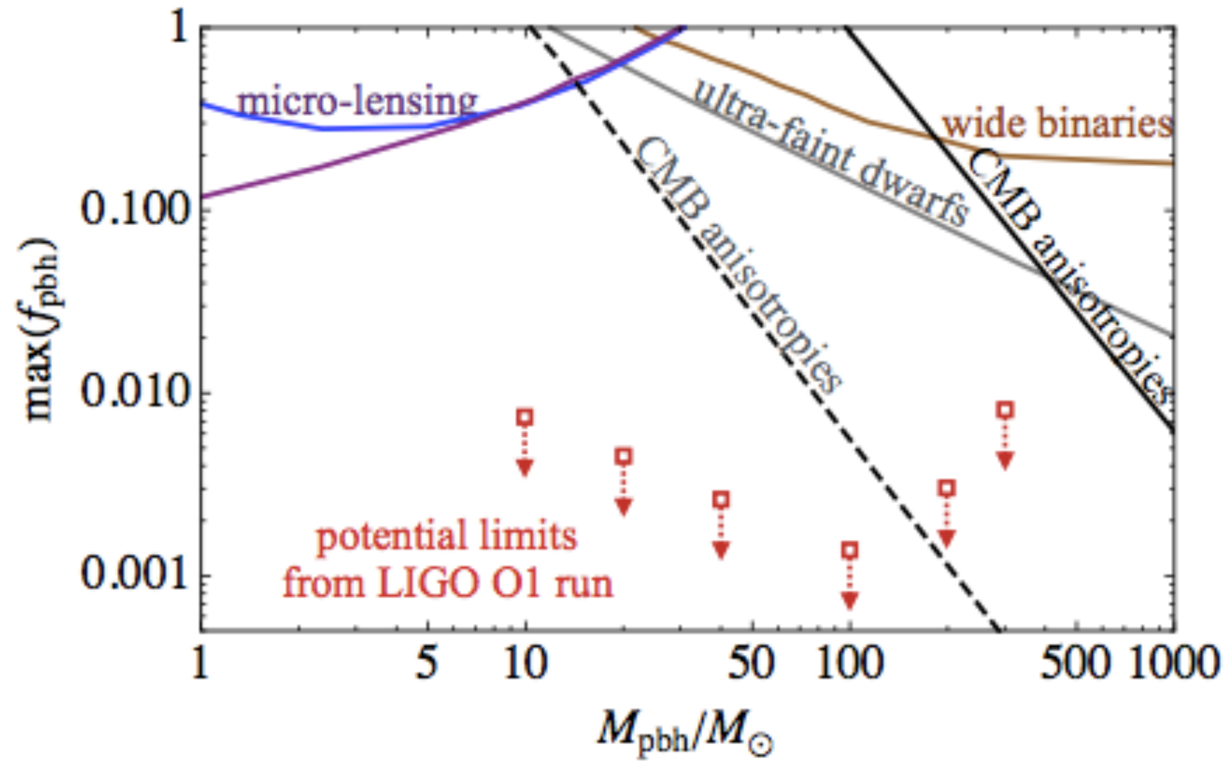
CB, Hindmarsh, Young & Hawkins 2018 using Borsanyi et al 2016

The resultant PBH mass function

$$f(M) = \frac{1}{\Omega_{\rm CDM}} \frac{d\Omega_{\rm PBH}}{d\ln M_{\rm H}}$$

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





CB, Hindmarsh, Young & Hawkins 2018

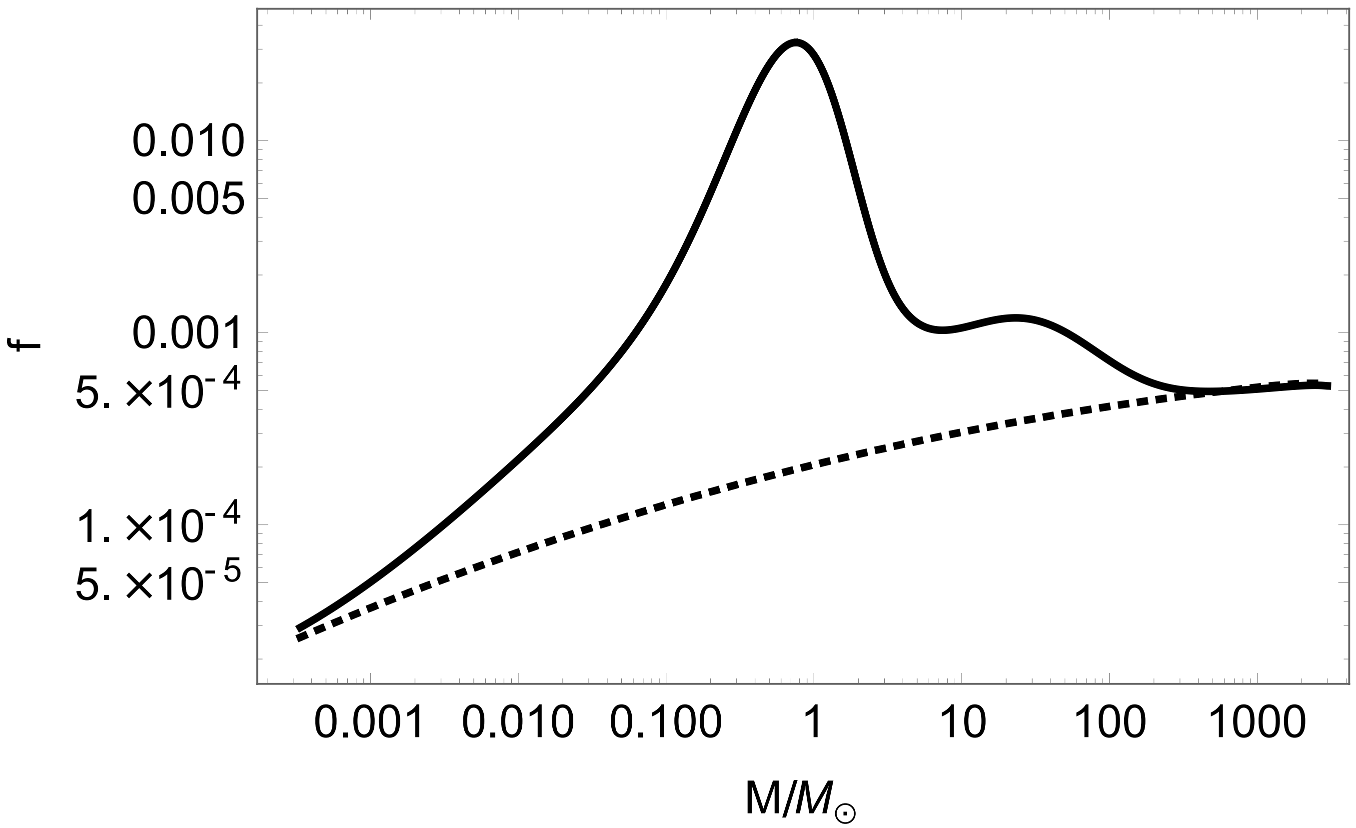
Haimoud et al 2017

For the left plot, approx 10% of DM is made up of ~ solar mass PBHs and 0.1% lies in the LIGO mass range - enough to get the merger rate LIGO detects
Sasaki et al + Haimoud et al + Chen & Huang + Raidal et al + many more

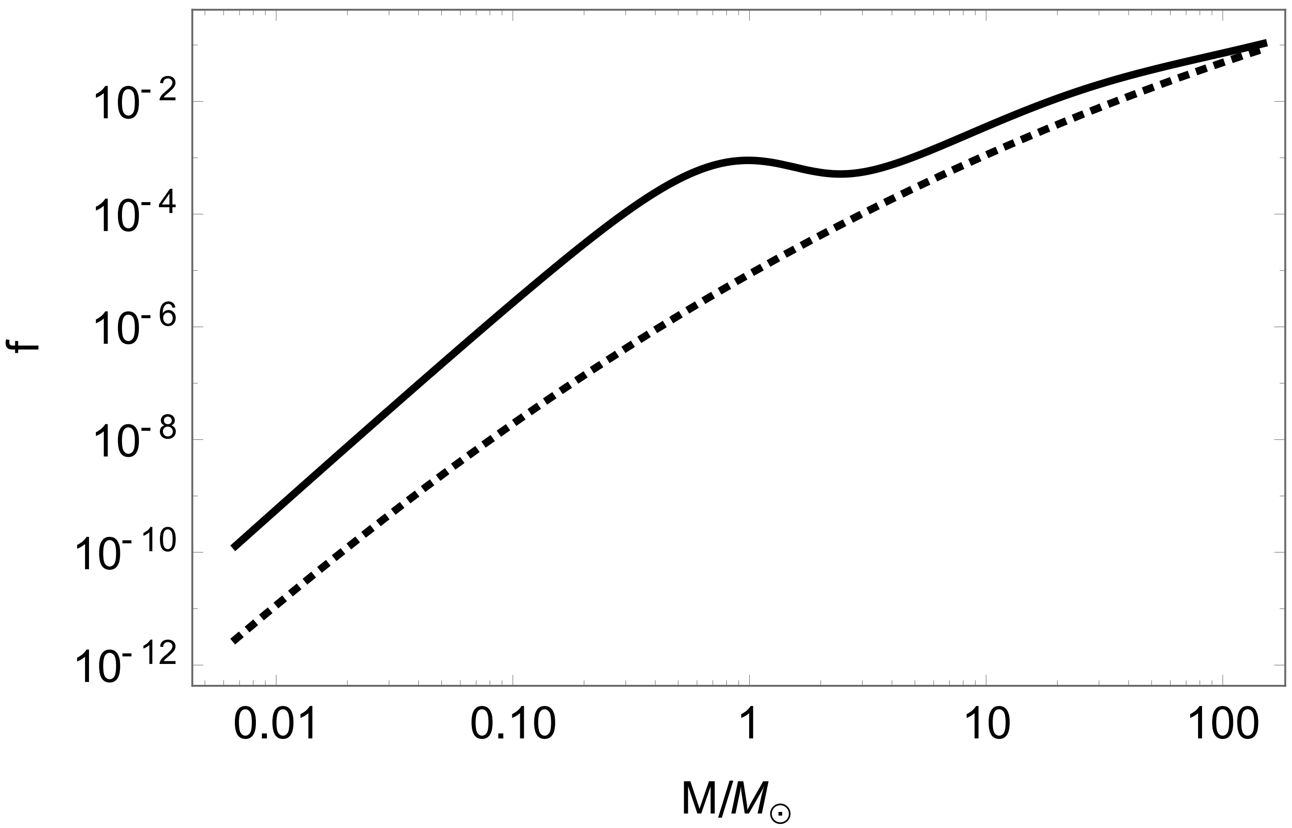
Varying the primordial perturbations

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

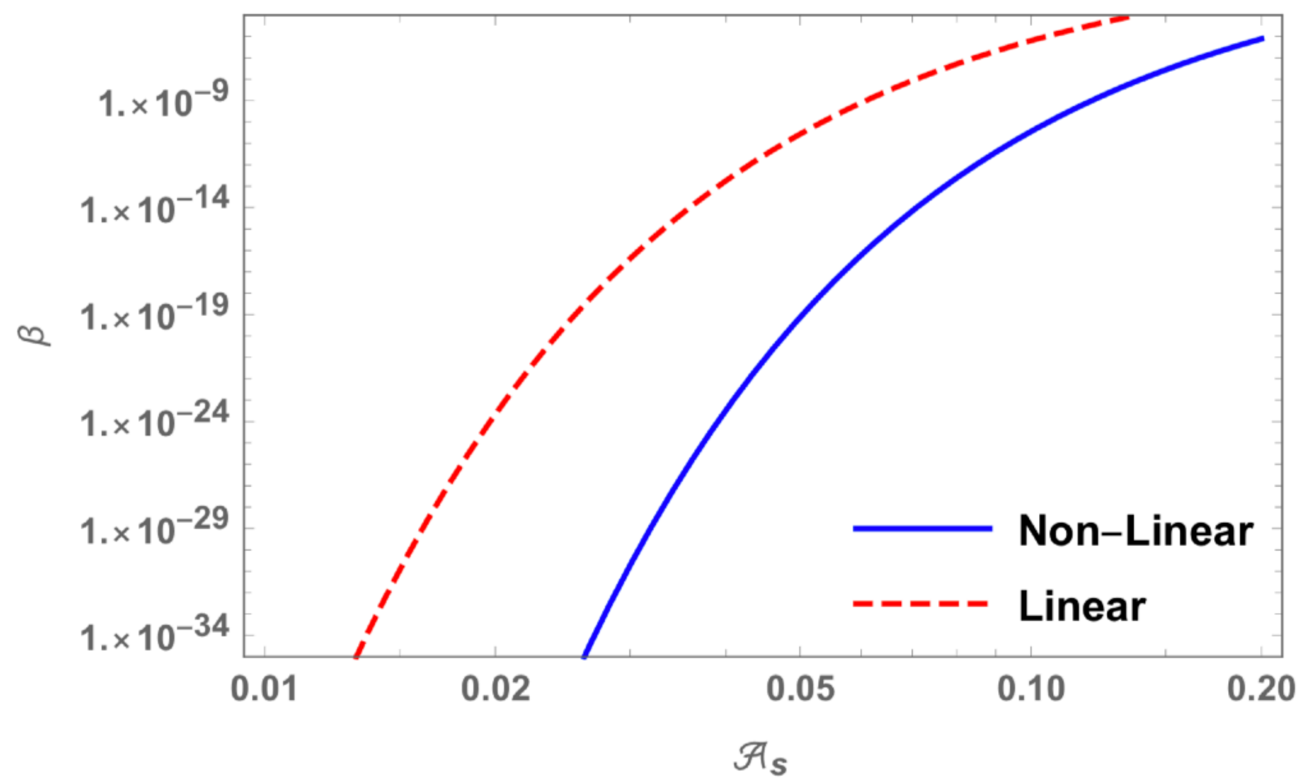
$$n_s - 1 = -0.05$$



$$n_s - 1 = -0.2$$



Power spectrum constraints are weakened by a factor ~ 2



Delta function power spectrum
Young, Musco, CB `19

In order to generate the same number of PBHs when taking the non-linear (NL) relation into account, compared to the normal/wrong case that you use the linear relation, the power spectrum amplitude needs to increase by the ratio

$$1.5 \lesssim \frac{\mathscr{A}_{NL}}{\mathscr{A}_L} = \frac{16\left(1 - \sqrt{\frac{2-3\delta_c}{2}}\right)^2}{9\delta_c^2} \lesssim 4$$

For the typical value of delta_c~0.55, power spectrum constraints are weakened by a factor of 2

Hints for PBHs

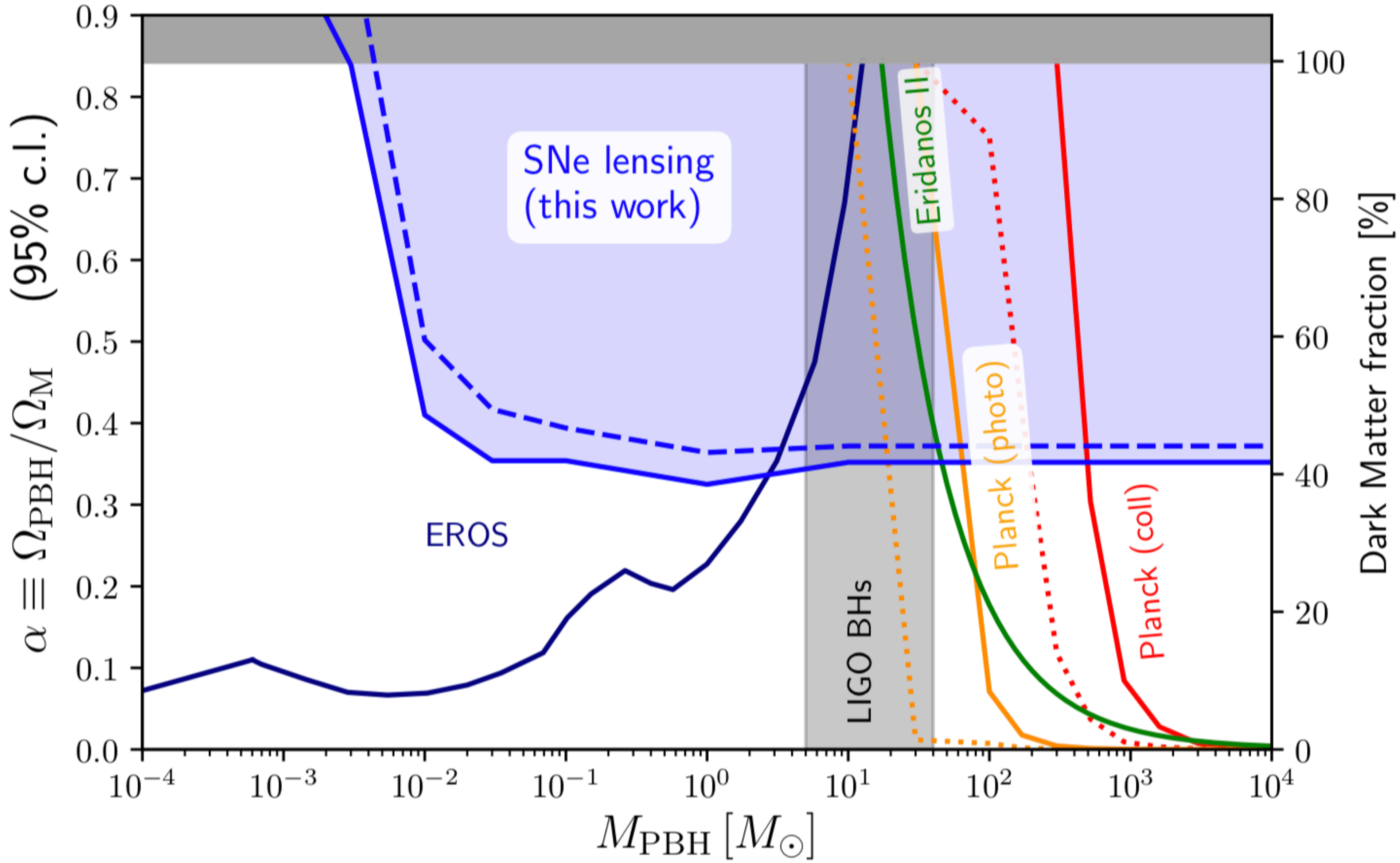
- PBHs might not exist, but there are some hints
  Clesse & Garcia-Bellido 2017

- The “unexpected” masses and low spins of those LIGO/Virgo detected created an explosion of interest.
  “Did LIGO detect dark matter” Bird et al;
  see also Clesse & Garcia-Bellido; Sasaki et al; all 2016

- The existence of supermassive black holes in almost all galaxies, with unknown formation process. However, creating a heavy PBH seed requires non-Gaussian initial conditions to evade CMB mu-distortion constraints. *Carr, Nakama & Silk 2017*

- Correlation between the cosmic infrared background and unresolved cosmic X-ray background. *Kashlinsky et al Astro2020 white paper*

Constraints on the LIGO mass range



Zumalacárregui and Seljak 2018

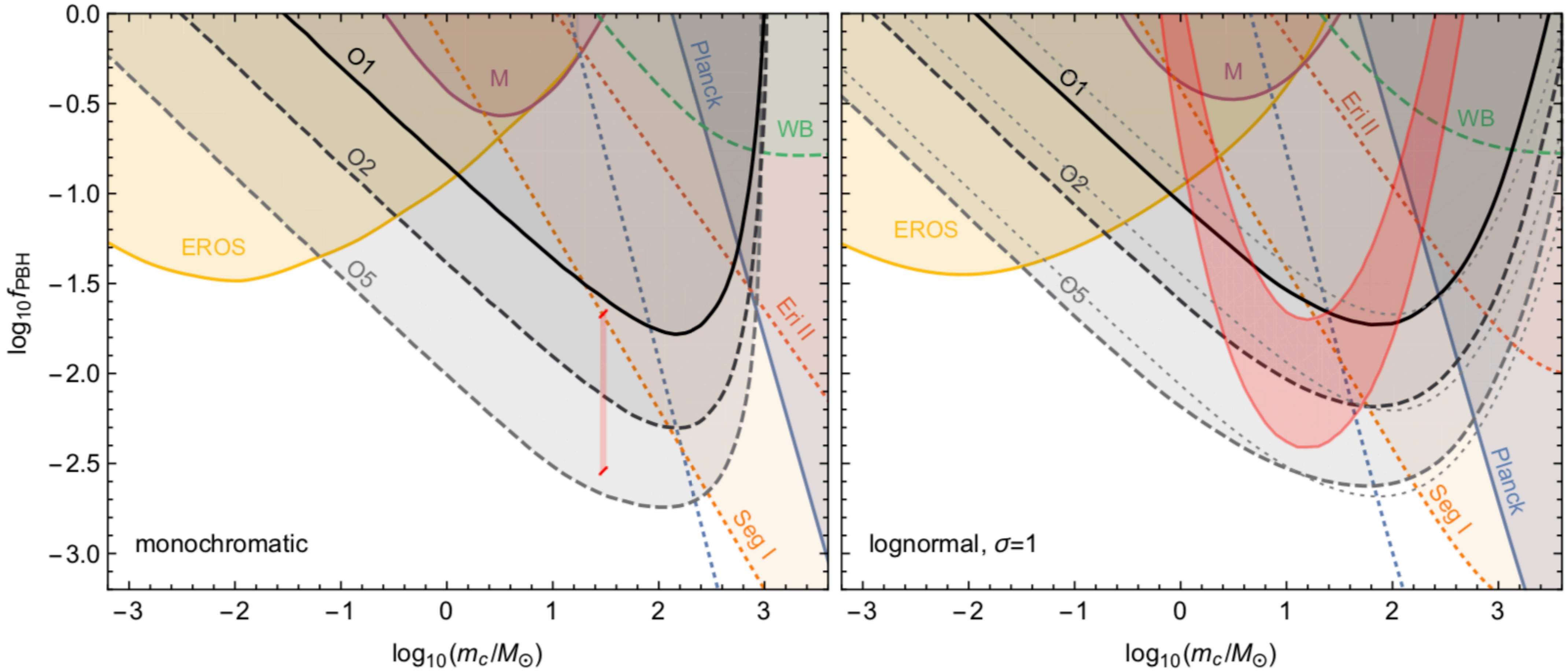
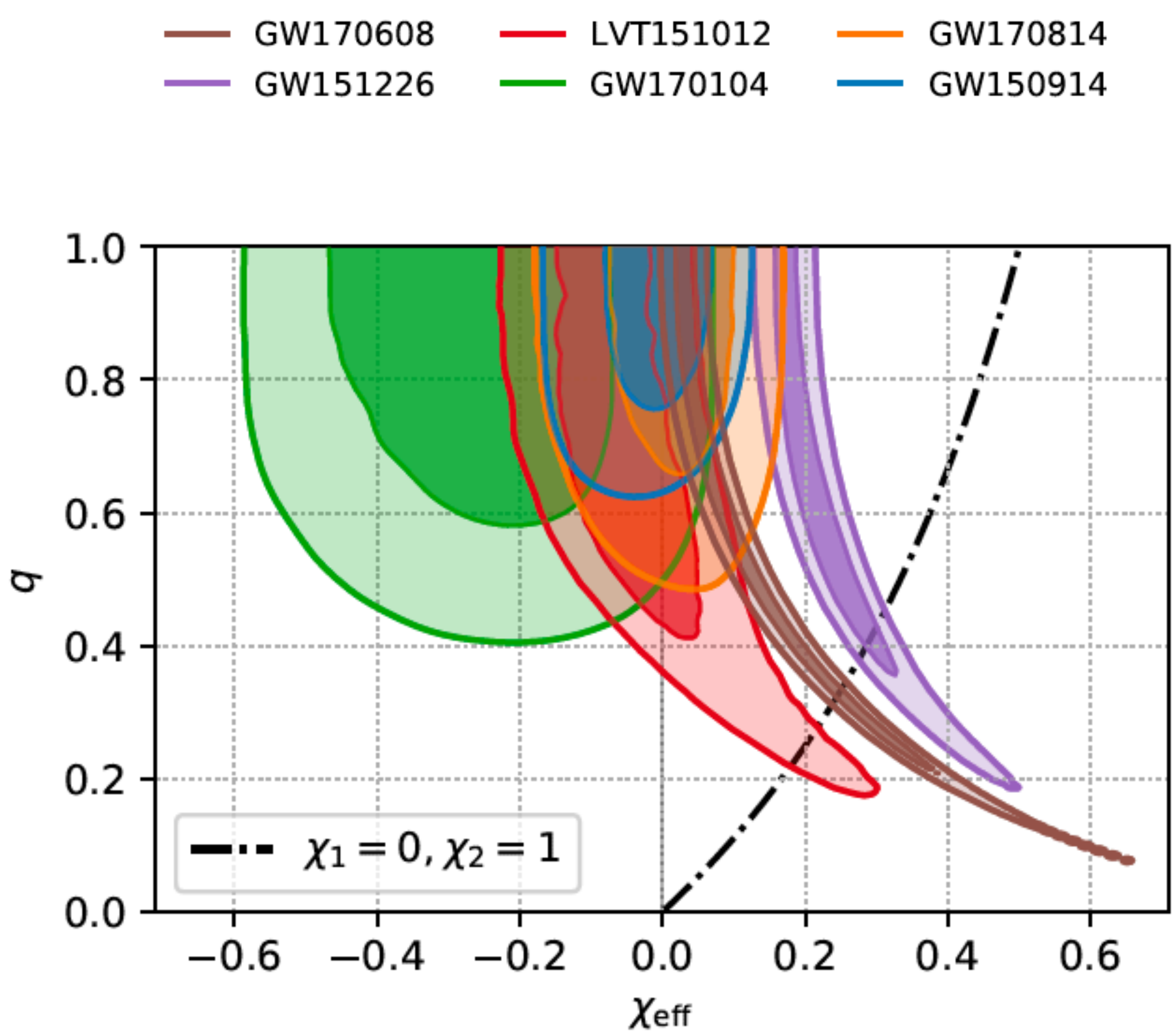
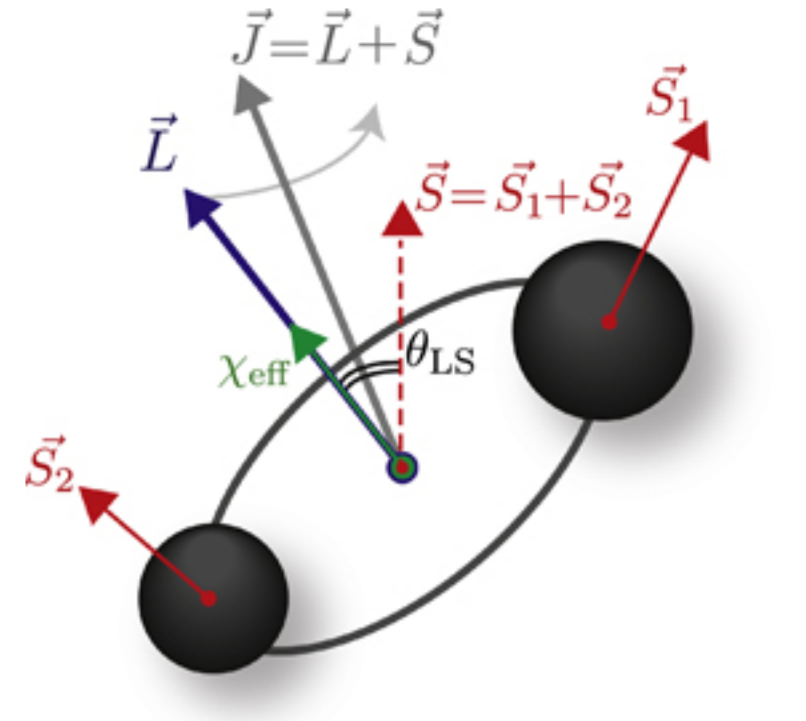


Figure 3. The constraints on the fraction of DM in PBHs, $f_{\rm PBH}$, from non-observation of the stochastic GW background for the monochromatic (left panel) and lognormal (right panel) PBH mass functions. The black solid line (O1) shows the constraint from the first LIGO observing run and the grey dashed lines (O2, O5) present the projected sensitivities of next phases of LIGO. The yellow and purple regions are excluded by the microlensing results from EROS [71] and MACHO (M) [72], respectively. The dark blue, orange, red and green regions on the right are excluded by Planck data [73], survival of stars in Segue I (Seg I) [74] and Eridanus II (Eri II) [75], and the distribution of wide binaries (WB) [56], respectively. On the right panel the thin dotted lines show, for comparison, the constraints calculated for the lognormal mass function from the ones in the monochromatic case by the method of Ref. [15] which has been used for all other constraints. The red lines show the values of $f_{\rm PBH}$ for which the merger rate in the LIGO sensitivity range today is $12\,{\rm Gpc}^{-3}{\rm yr}^{-1}$ (lower) and $213\,{\rm Gpc}^{-3}{\rm yr}^{-1}$ (upper).

Raidal et al 2018

Black hole spin





$$\chi_{\rm eff} = \frac{c}{G(m_1 + m_2)} \left(\frac{\vec{S}_1}{m_1} + \frac{\vec{S}_2}{m_2} \right) \cdot \vec{L}$$

$$a_* = \frac{c\,|\,\vec{S}\,|}{Gm^2} \leq 1$$

Negligible spin is expected for PBHs formed during radiation domination.
Unlike astrophysical BHs, PBHs do not undergo much collapse before formation.
Chiba & Yokoyama 2017; Belczynski et al. 2017; Mirbabyi et al 2019; De Luca et al 2019; Fernandez & Profumo 2019; He & Suyama 2019