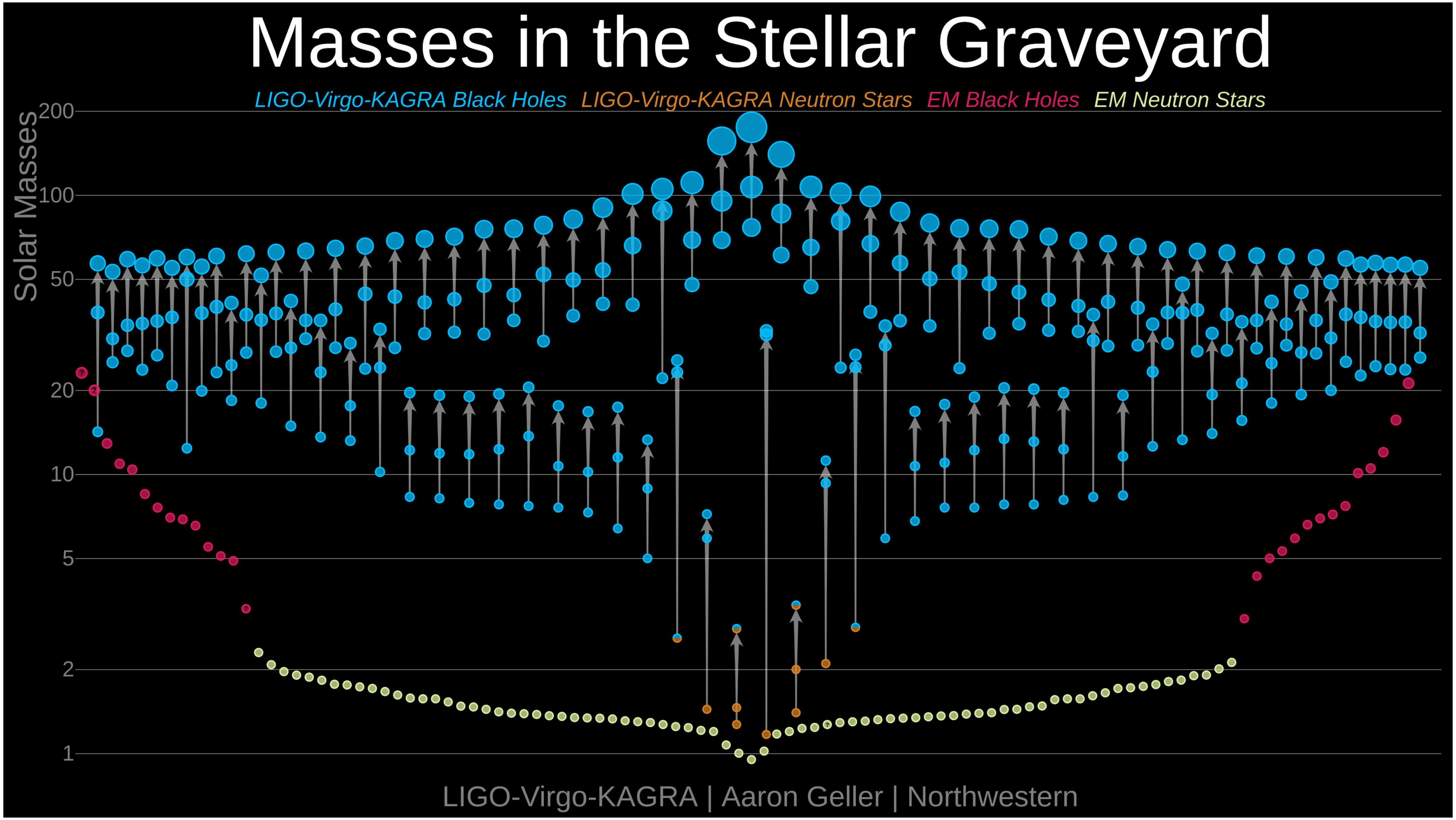
QCD phase transition behind a PBH origin of LIGO/Virgo events?



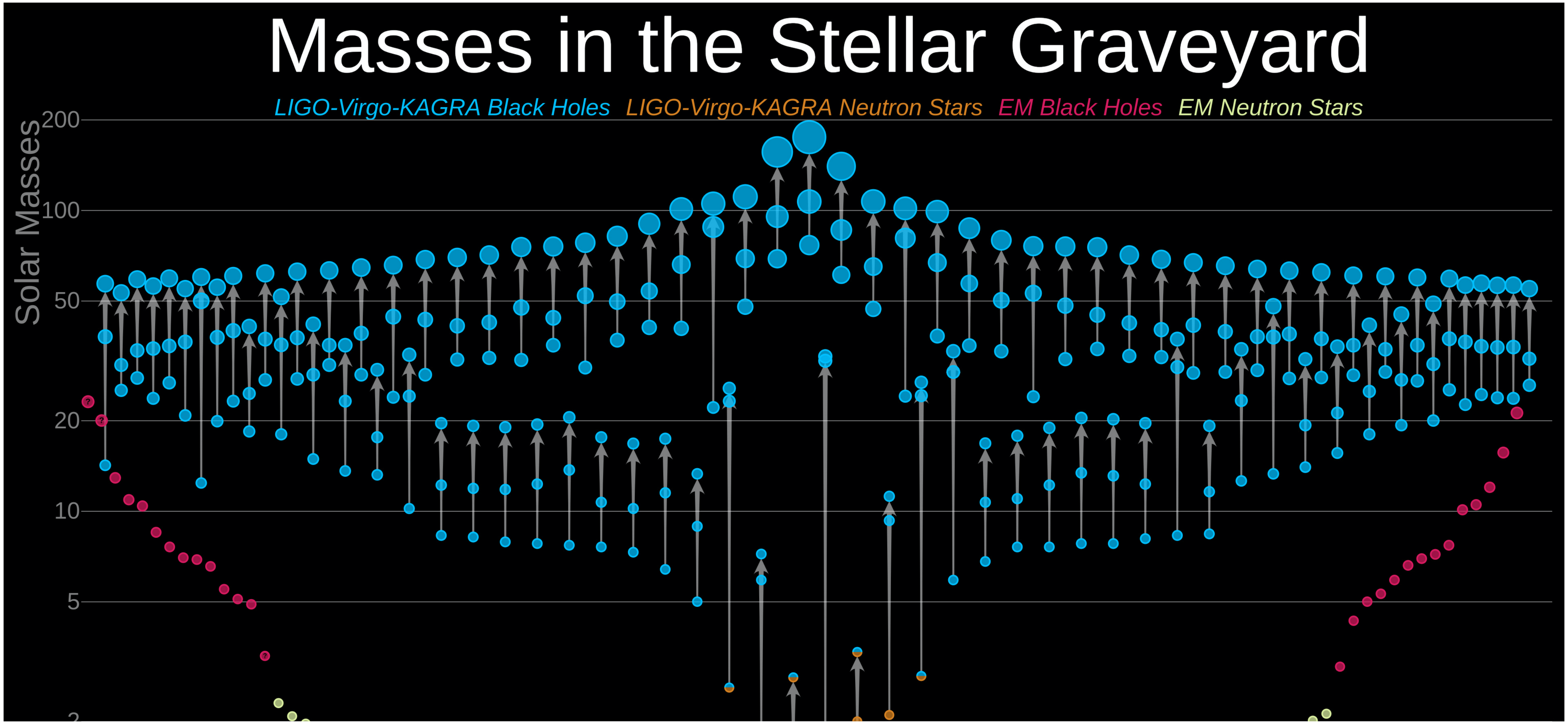
Corfu, 28/08/2023

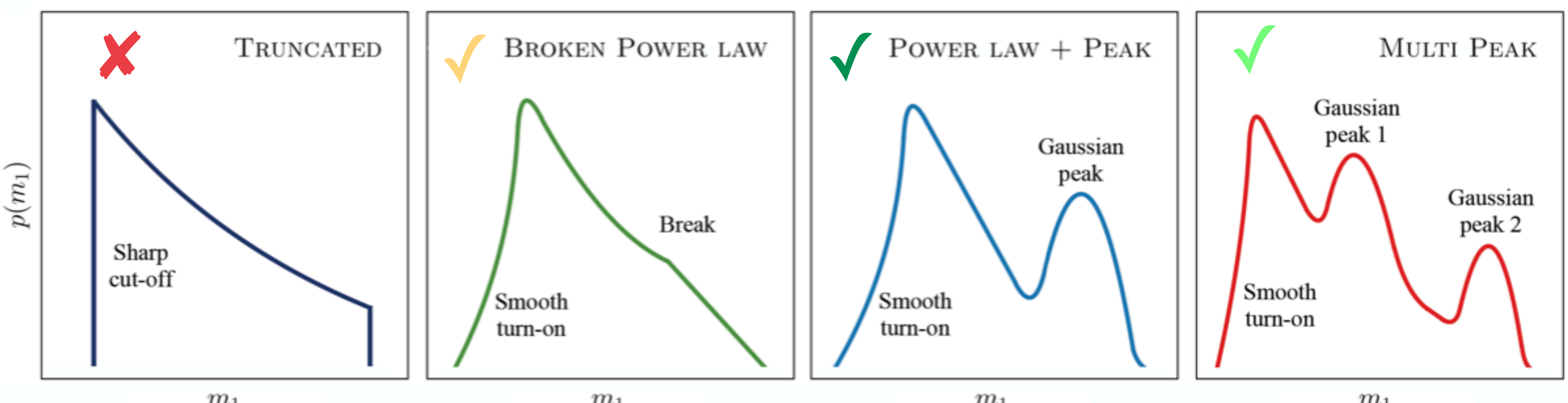
Pasquale Dario Serpico (LAPTh - Annecy, France)

mostly based on J. I. Juan, P.D.S. and G. Franco Abellán, JCAP (2022) 07, 009

Outline

- Intriguing mass function in the LIGO/Virgo(/KAGRA) BH-BH events
- A primordial black hole (PBH) component?
- QCD epoch as a ‘natural’ shaper of the PBH mass function
- Testing the “QCD hypothesis” against pheno constraints (& loopholes?)
- Conclusions





R. Abbott et al. "Population Properties of Compact Objects from the Second LIGO-Virgo Gravitational-Wave Transient Catalog," Astrophys. J. Lett. 913 (2021) no.1, L7 [arXiv:2010.4533]

$$p(m_2/m_1) \propto (m_2/m_1)^{\beta}$$

$\beta \approx 1$ $[0<\beta<3]$

What's the problem with heavy BH? Pair-instability gap

Stellar evolution theory predicts a *gap* in the BH birth mass caused by the pair instability: Presupernovae with core mass below $M_L \sim 50\ M_\odot$ collapse to BH, whereas more massive ones, up to some limiting value, $M_H \sim 130\ M_\odot$ explode completely as pair-instability SNae.

S. E. Woosley and A. Heger, arXiv:2103.07933

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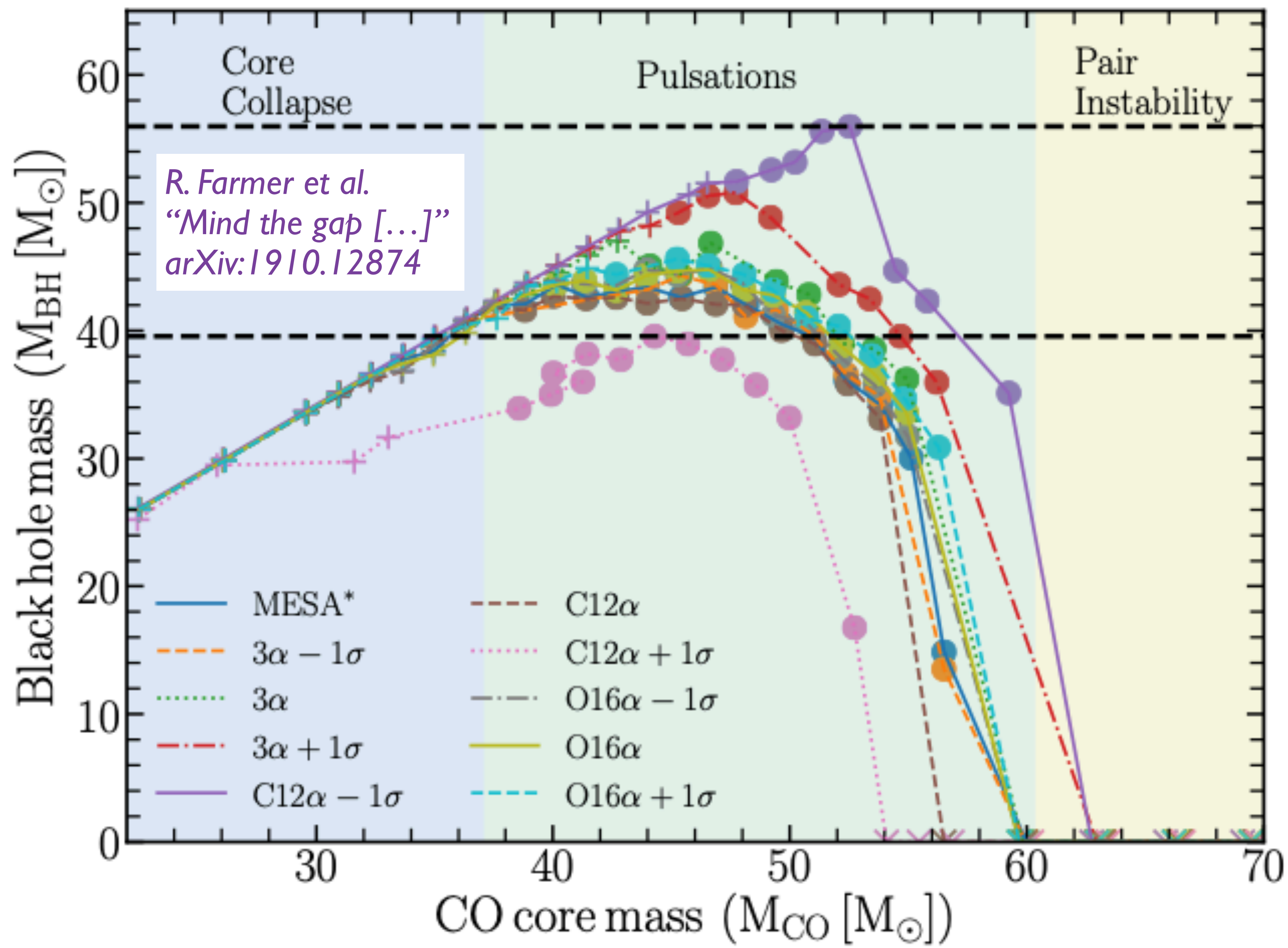
- *Possibility of hierarchical mergers*
- *Perhaps primordial BH?*



(d) Nuclear reaction rates

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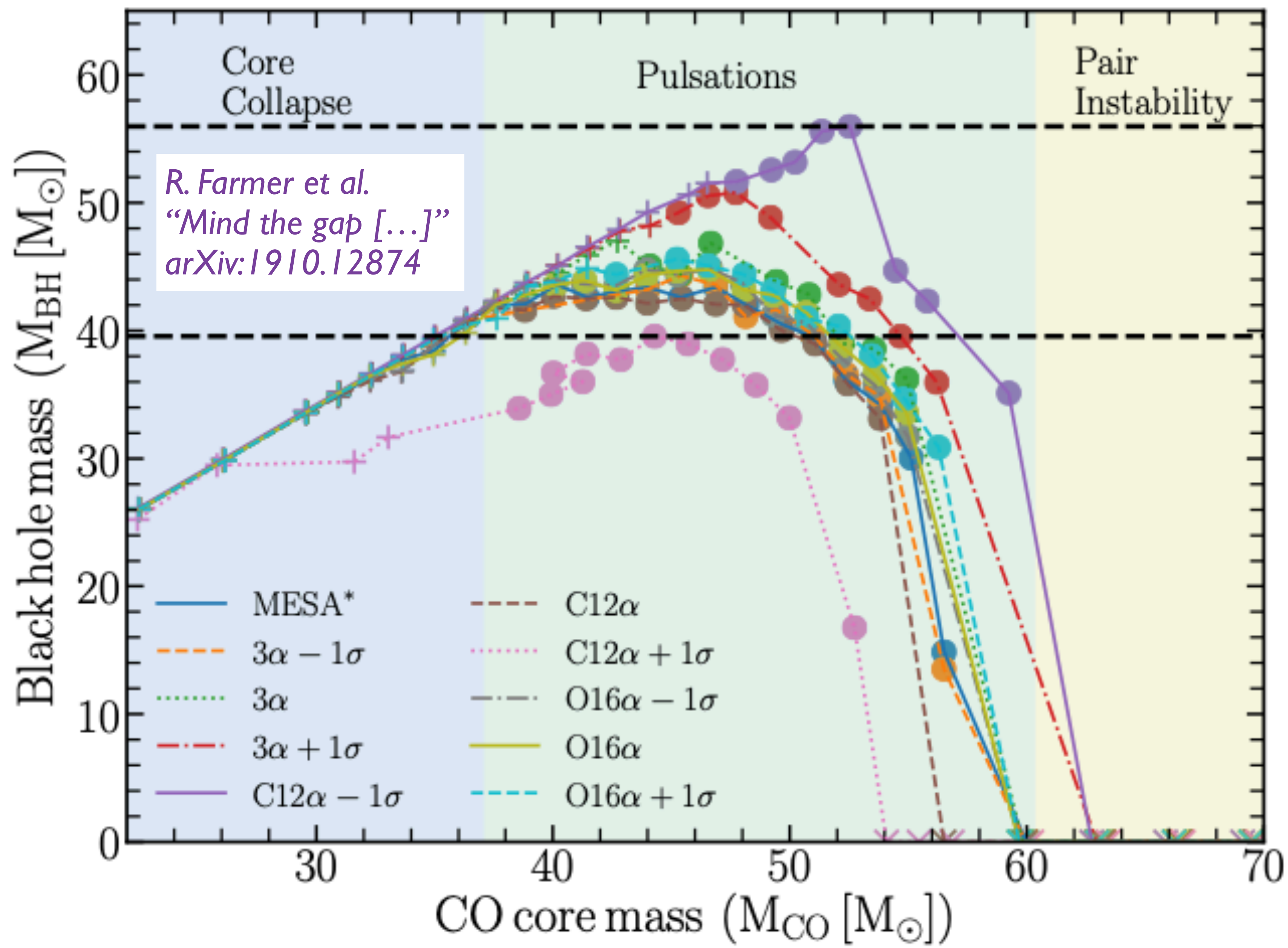

(d) Nuclear reaction rates

PBH

Notions on the concept and formation of PBHs

PBH from gravitational collapse of sufficiently large density fluctuations,
at scales much smaller than the CMB ones (*Zeldovich & Novikov 67, Carr & Hawking 74, Carr 75…*)

Associated to non-trivial inflationary dynamics, phase transitions, defects…
(change of EOS, bubble collisions, string loops…) *A. M. Green, arXiv:1403.1198*

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Simple argument:
Forms when overdense region of Hubble size collapses faster than pressure counterbalance timescale

$$\tau_{\rm fall} < \tau_{\rm press} \Leftrightarrow \frac{\delta\rho}{\rho} \gtrsim \mathcal{O}(1) c_s^2 \simeq \frac{1}{3}\,({\rm RD})$$

Requires density contrast >> CMB-level ones!
(early matter phase would help, too!)

where

$$\tau_{\rm fall} \simeq (4\pi G\delta\rho)^{-1/2}$$

gravitational instability time

$$\tau_{\rm press} \simeq \frac{R_H}{c_s} \simeq \frac{\sqrt{3}}{c_s\sqrt{8\pi G\rho}}$$

timescale for pressure support over Hubble patch

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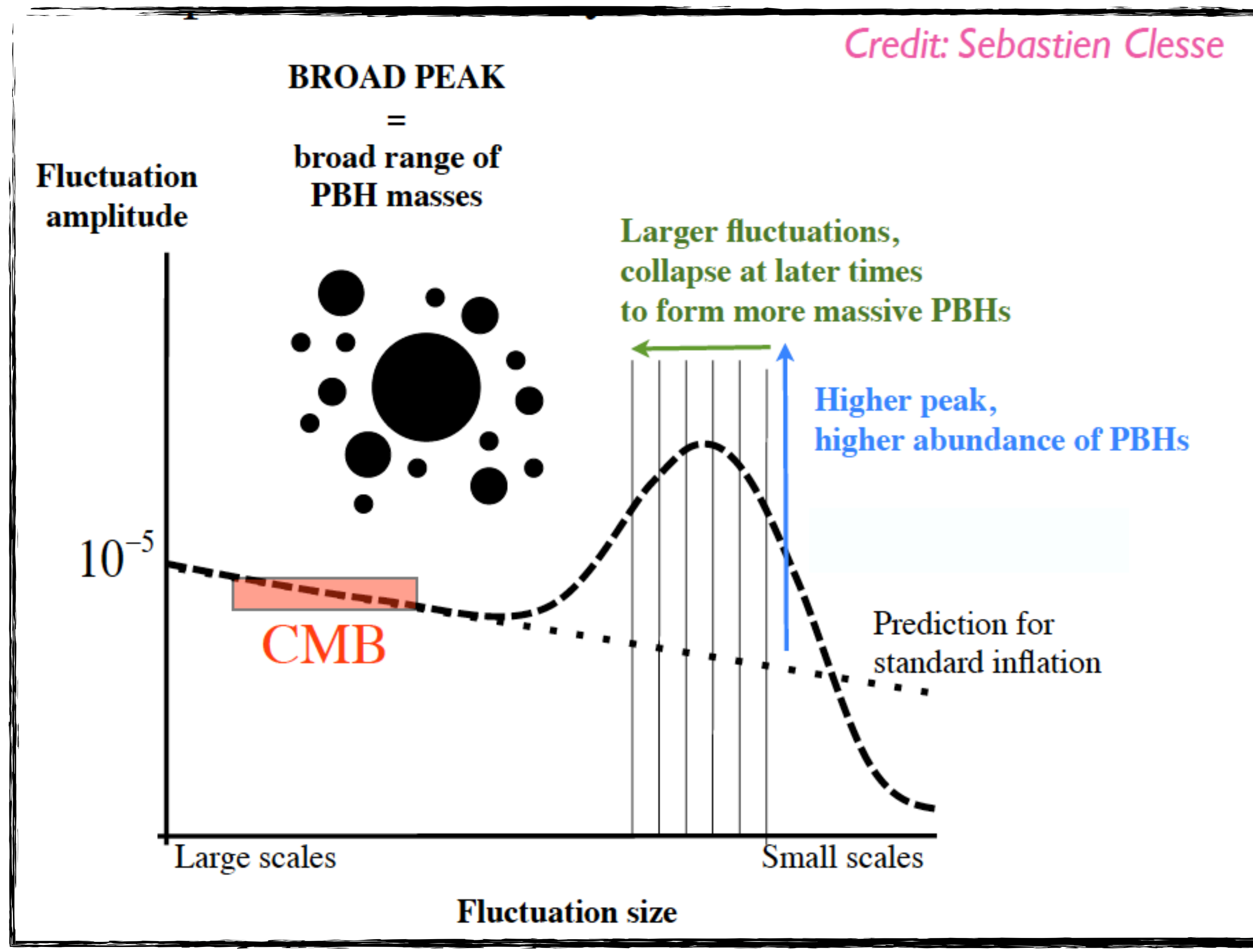
Mass of the order of the size of the causally connected universe at time of collapse

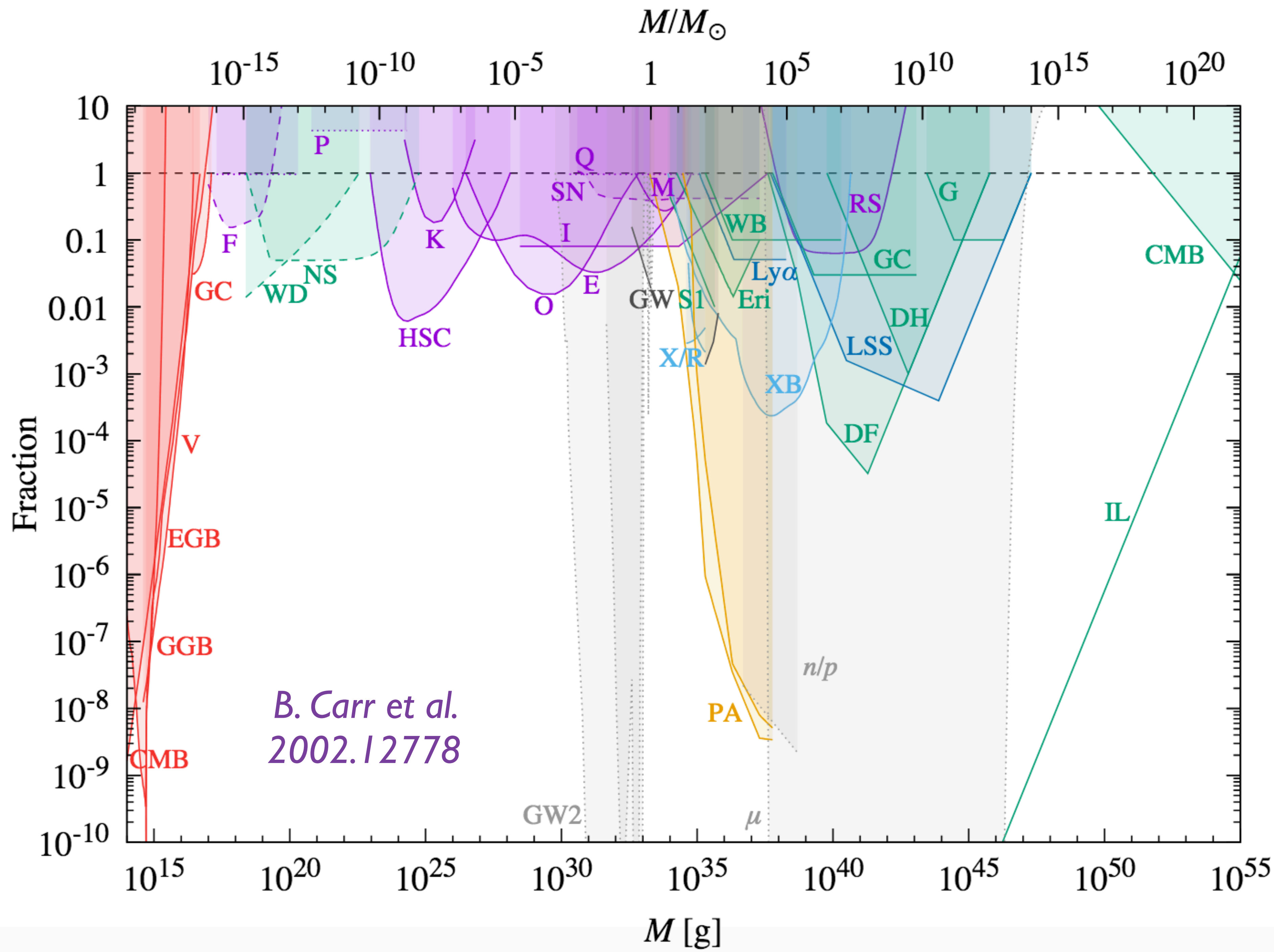
$$M_{\rm PBH} \sim M_H\Big|_{\rm cross} \sim \rho\, H^{-3}\Big|_{\rm cross} \propto H^{-1}\Big|_{\rm cross} \propto k_{\rm peak}^{-2}$$

Significant departure from current inflationary models, new physics needed!



Overall bounds

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



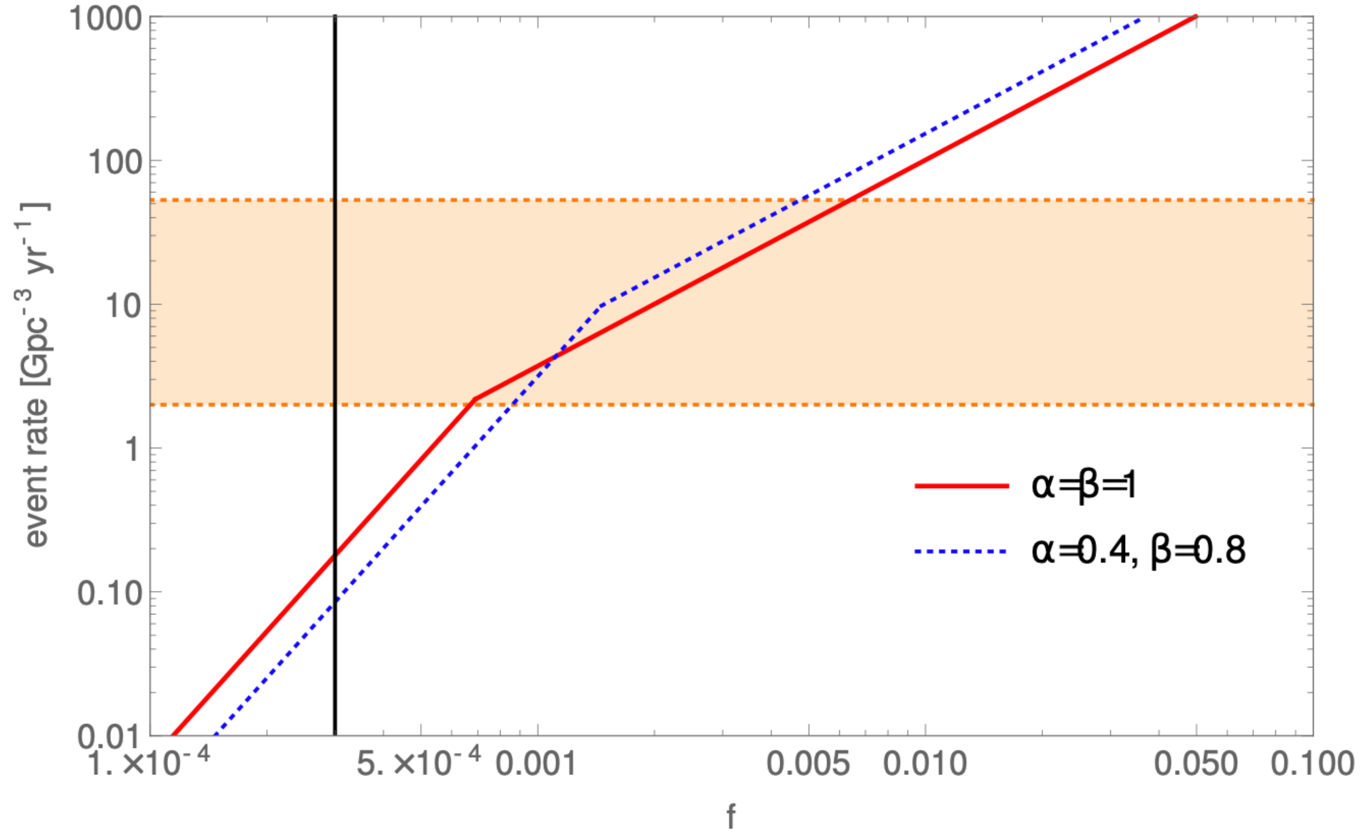
Constraints on f(M) from evaporation (red), lensing (magenta), dynamical effects (green), accretion (light blue), CMB distortions (orange), large-scale structure (dark blue) and background effects (grey). Evaporation limits come from the extragalactic gamma-ray background (EGB), the Galactic gamma-ray background (GGB) and Voyager e± limits (V). Lensing effects come from femtolensing (F) and picolensing (P) of gamma-ray bursts, microlensing of stars in M31 by Subaru (HSC),in the Magellanic Clouds by MACHO (M) and EROS (E), in the local neighbourhood by Kepler (K), in the Galactic bulge by OGLE (O) and the Icarus event in a cluster of galaxies (I), microlensing of supernova (SN) and quasars (Q), and millilensing of compact radio sources (RS). Dynamical limits come from disruption of wide binaries (WB) and globular clusters (GC), heating of stars in the Galactic disk (DH), survival of star clusters in Eridanus II (Eri) and Segue 1 (S1), infalling of halo objects due to dynamical friction (DF), tidal disruption of galaxies (G), and the CMB dipole (CMB). Accretion limits come from X-ray and radio (X/R) observations, CMB anisotropies measured by Planck (PA) and gravitational waves from binary coalescences (GW). Background constraints come from CMB spectral distortion (μ), 2nd order gravitational waves (GW2) and the neutron-to-proton ratio (n/p). The incredulity limit (IL) corresponds to one hole per Hubble volume.

PBH events in the ballpark of LIGO/Virgo rates?

Yes for f_{PBH}~10^{-3}

Dominated by 'primordial' binaries forming at z~$O(z_{eq})$~3000

M. Sasaki, T. Suyama, T. Tanaka and S. Yokoyama, PRL 117 (2016) 061101 [erratum: PRL 121 (2018) 059901] [arXiv:1603.08338]



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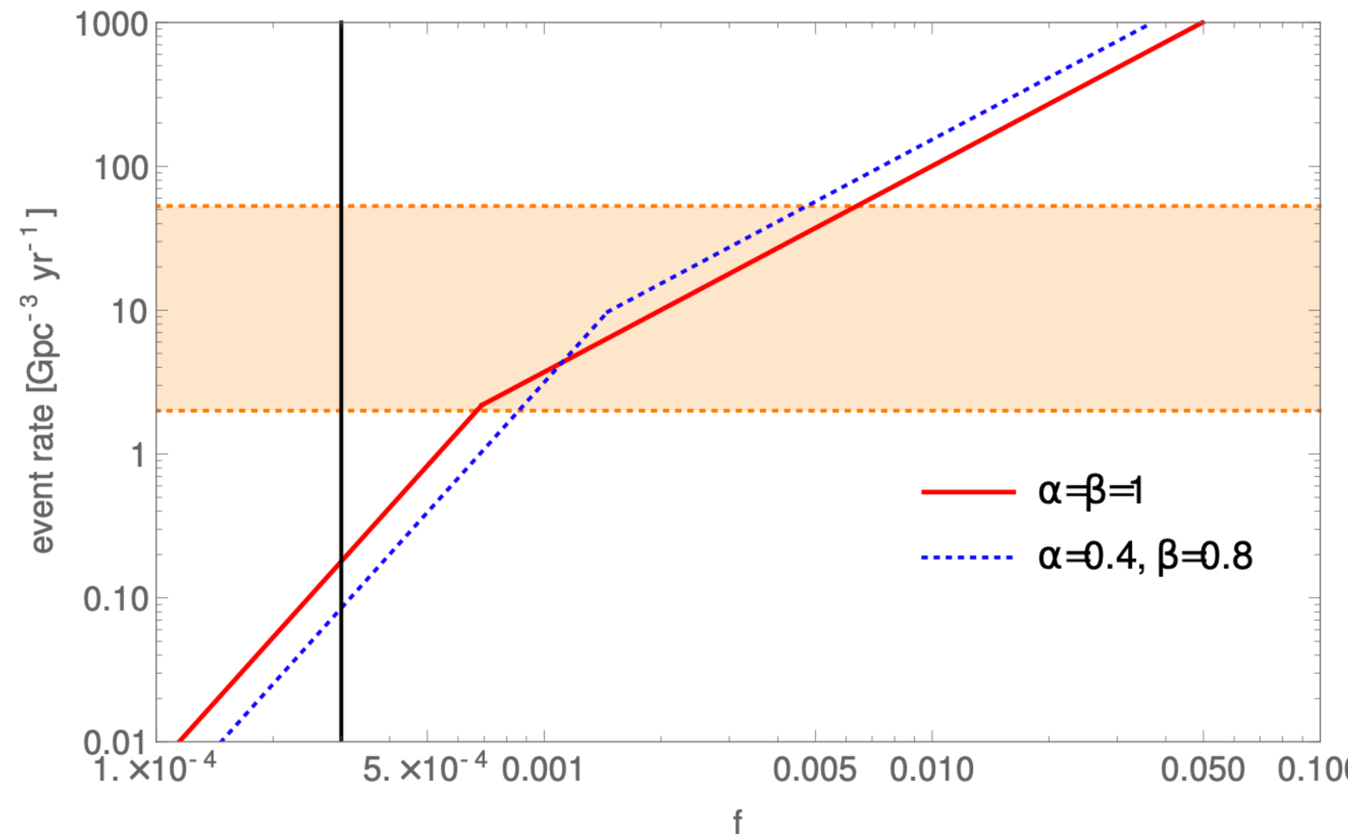
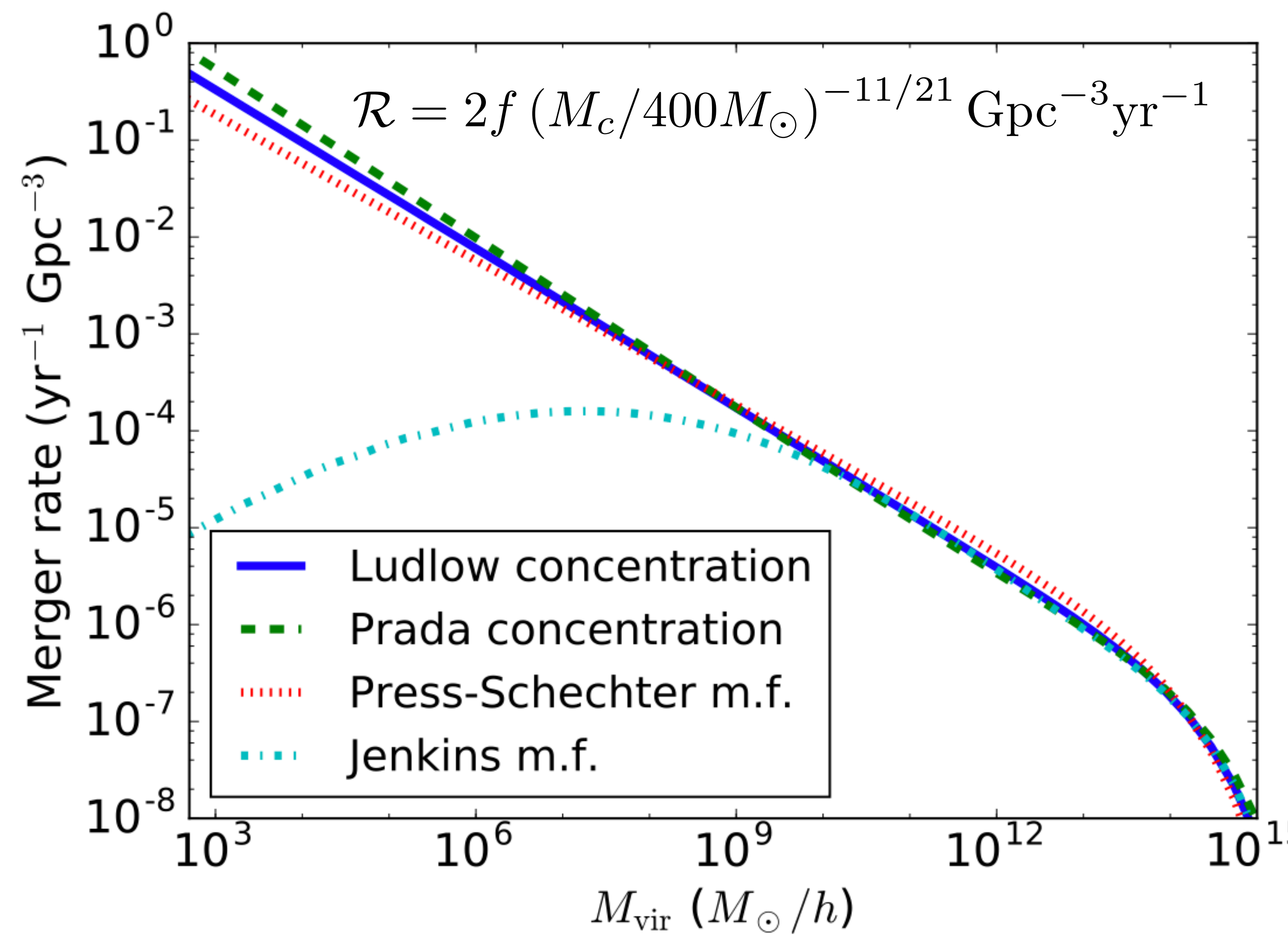


Alternative idea: For f_{PBH}~1

S. Bird et al. PRL 116 (2016) 201301 [arXiv:1603.00464]

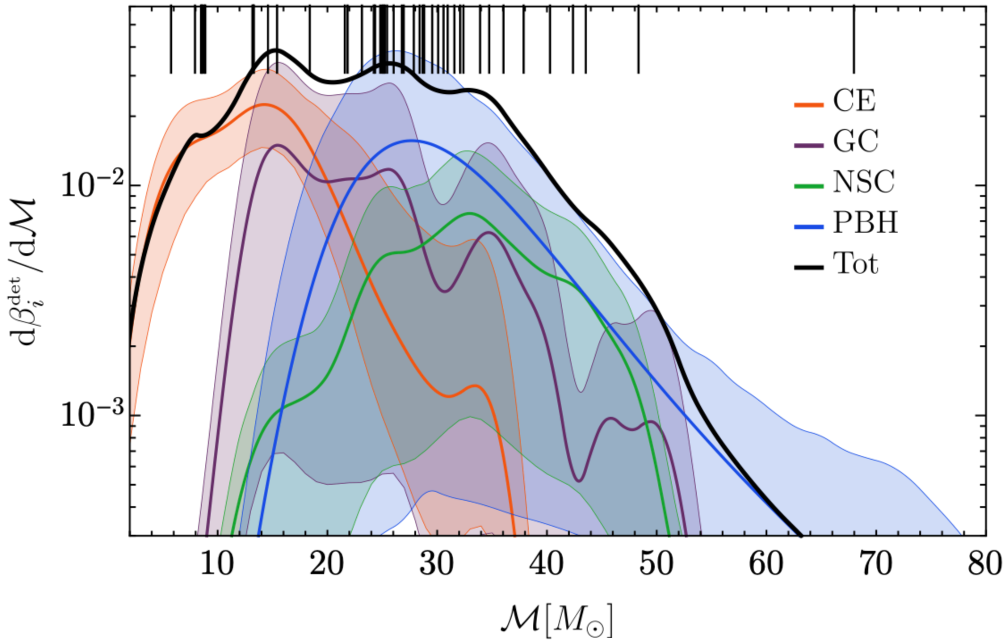
Capture in light halos via hyperbolic encouters+GW emission

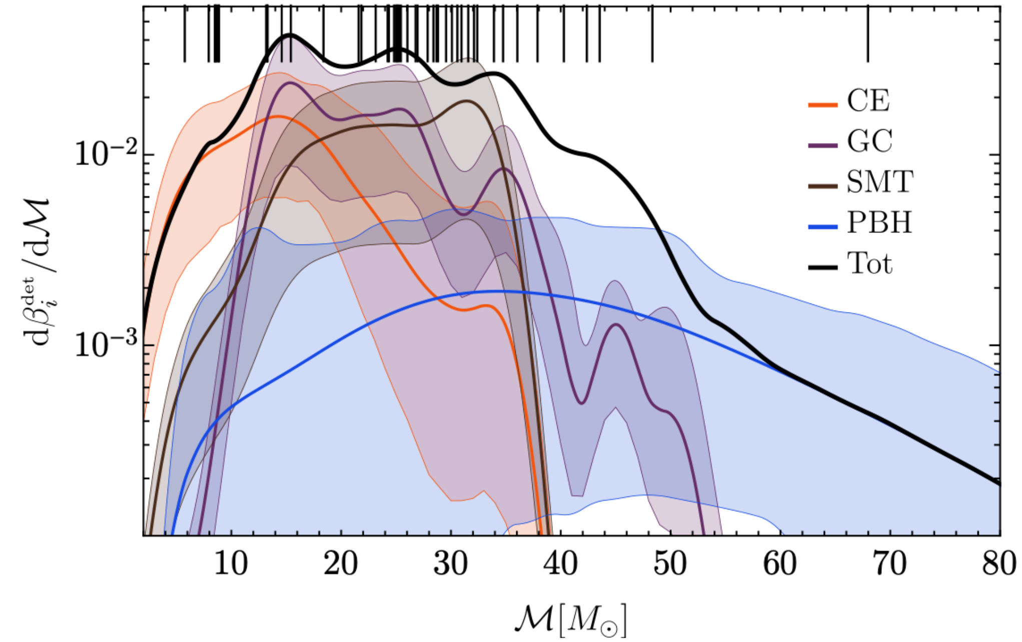


Currently untenable:

Too high merger rate from primordial binaries + excluded by several independent constraints

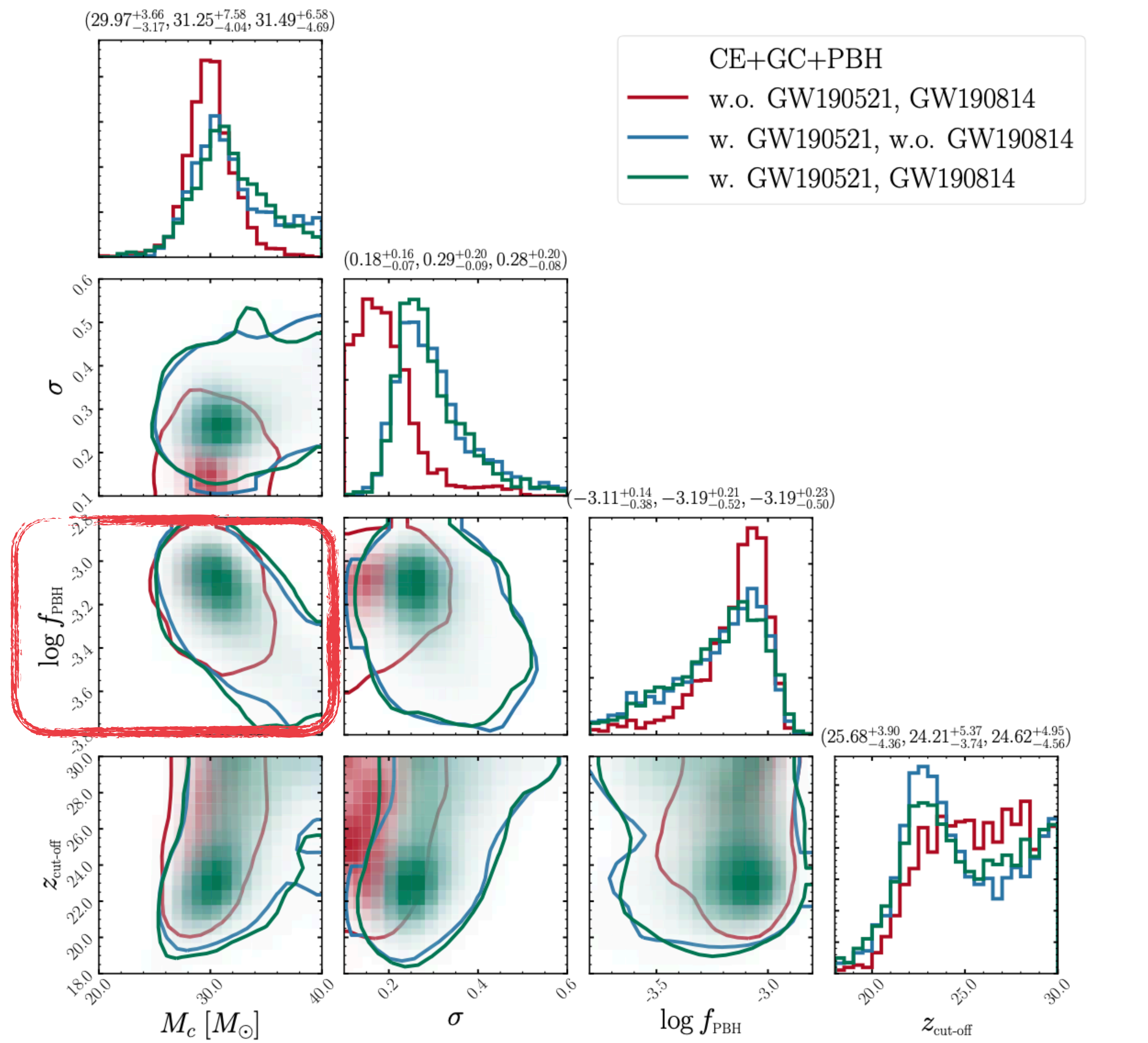
Confirmed in recent fits





CE=common envelope
SMT= stable mass transfer
GC=globular clusters
NSC=nuclear star cluster

G. Franciolini et al.
PRD 105 (2022) 083526 [arXiv:2105.03349]



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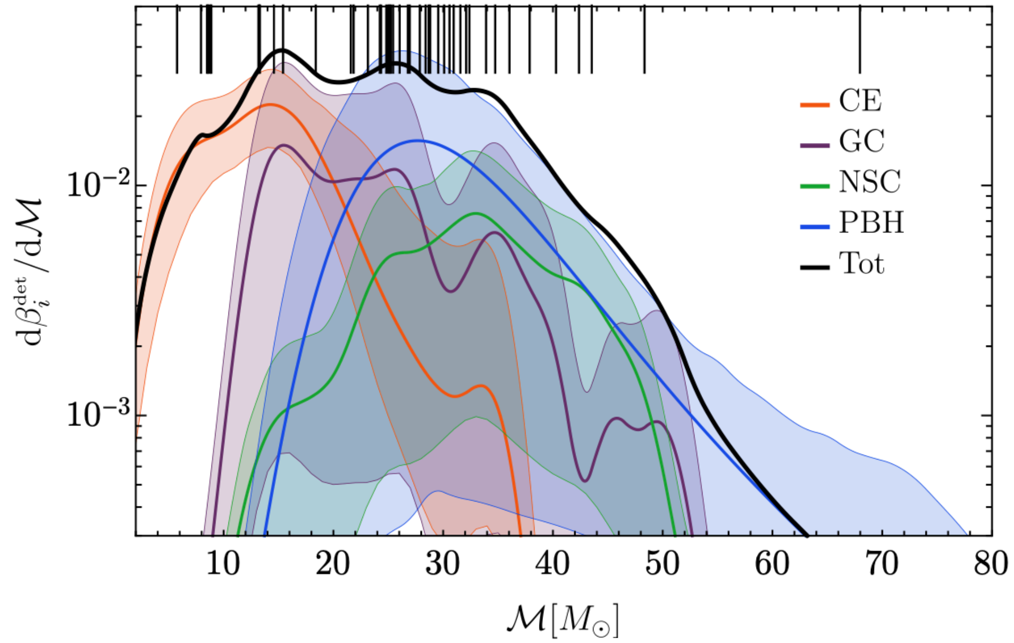

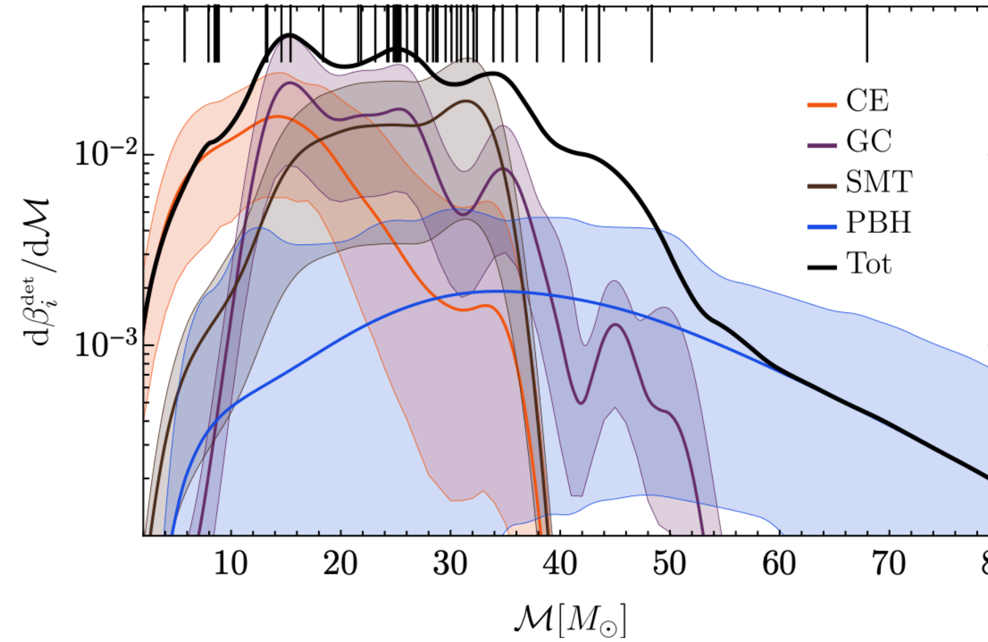

G. Franciolini et al.
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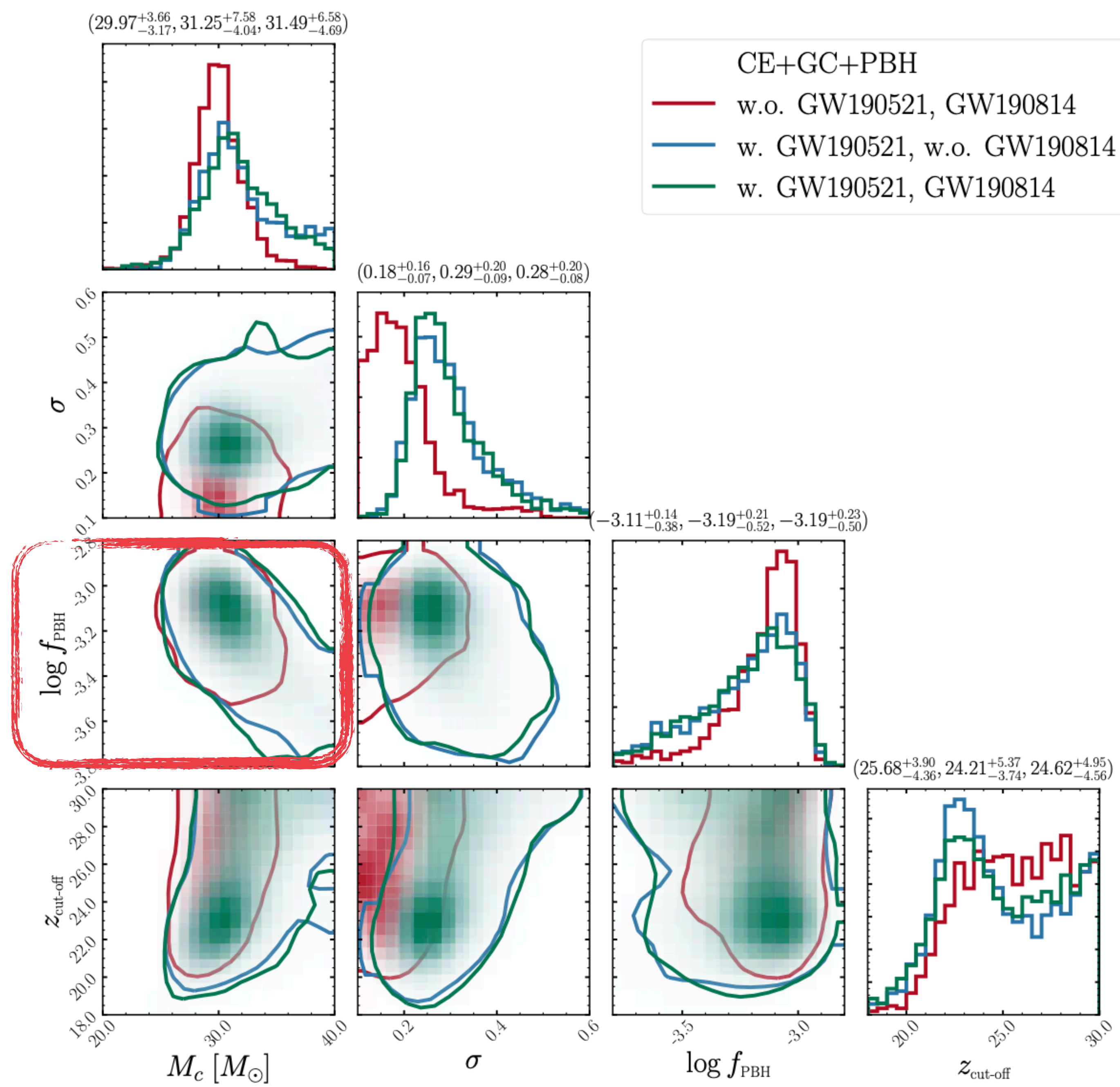
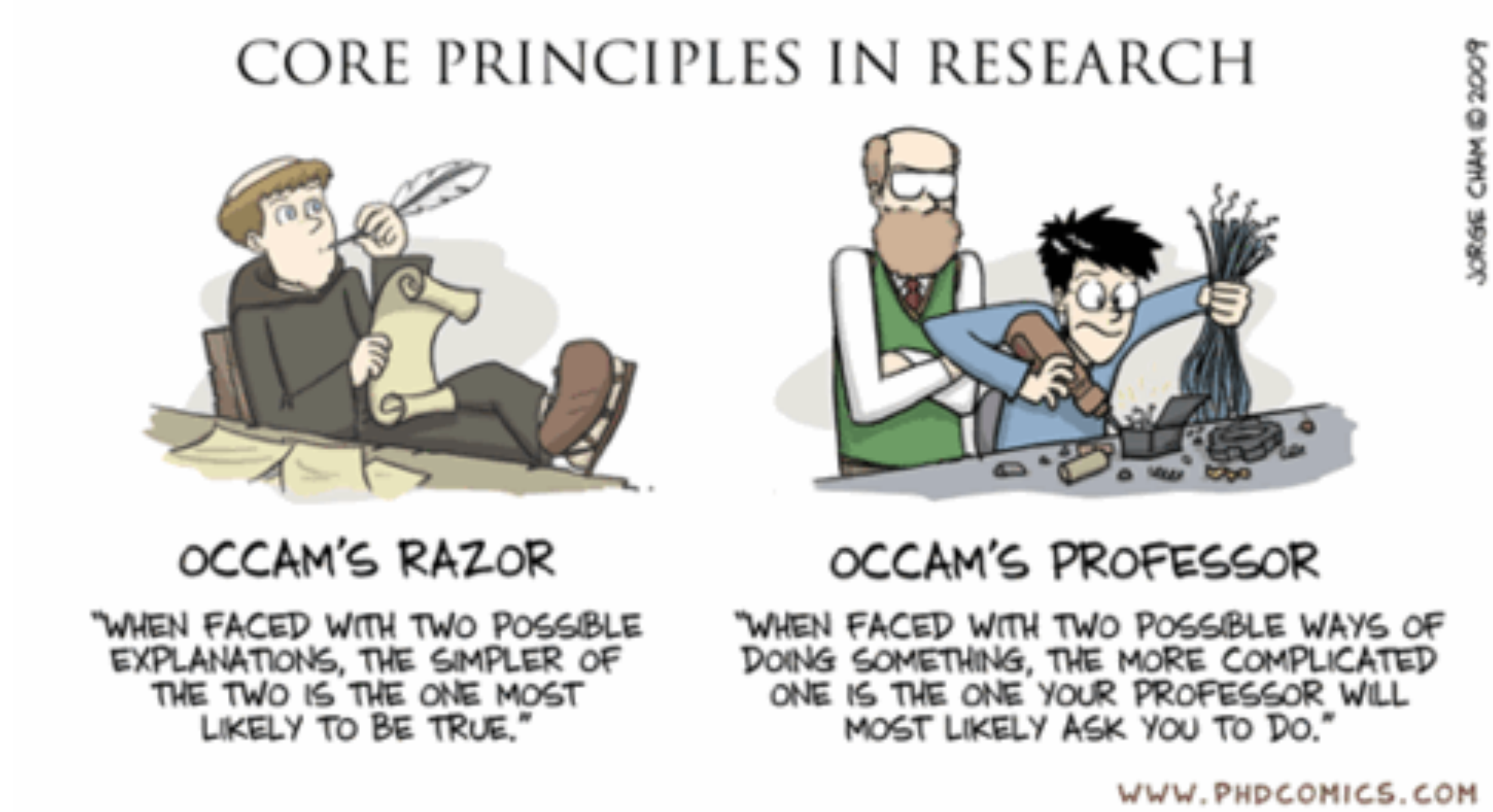
the fraction of a putative subpopulation of PBHs in the data […] depends significantly on the set of assumed astrophysical models […] The tantalizing possibility that black holes formed after inflation are contributing to LIGO-Virgo observations could only be verified by further reducing uncertainties in astrophysical and primordial formation models, and it may ultimately be confirmed by third-generation interferometers.



Disclaimer: One **can** account for that if reverse-engineering the model, see *Franciolini et al. 2207.10056, 2209.05959*
(Not concerned by following discussion!)

A predictive scenario?

Currently degenerate
with astrophysics



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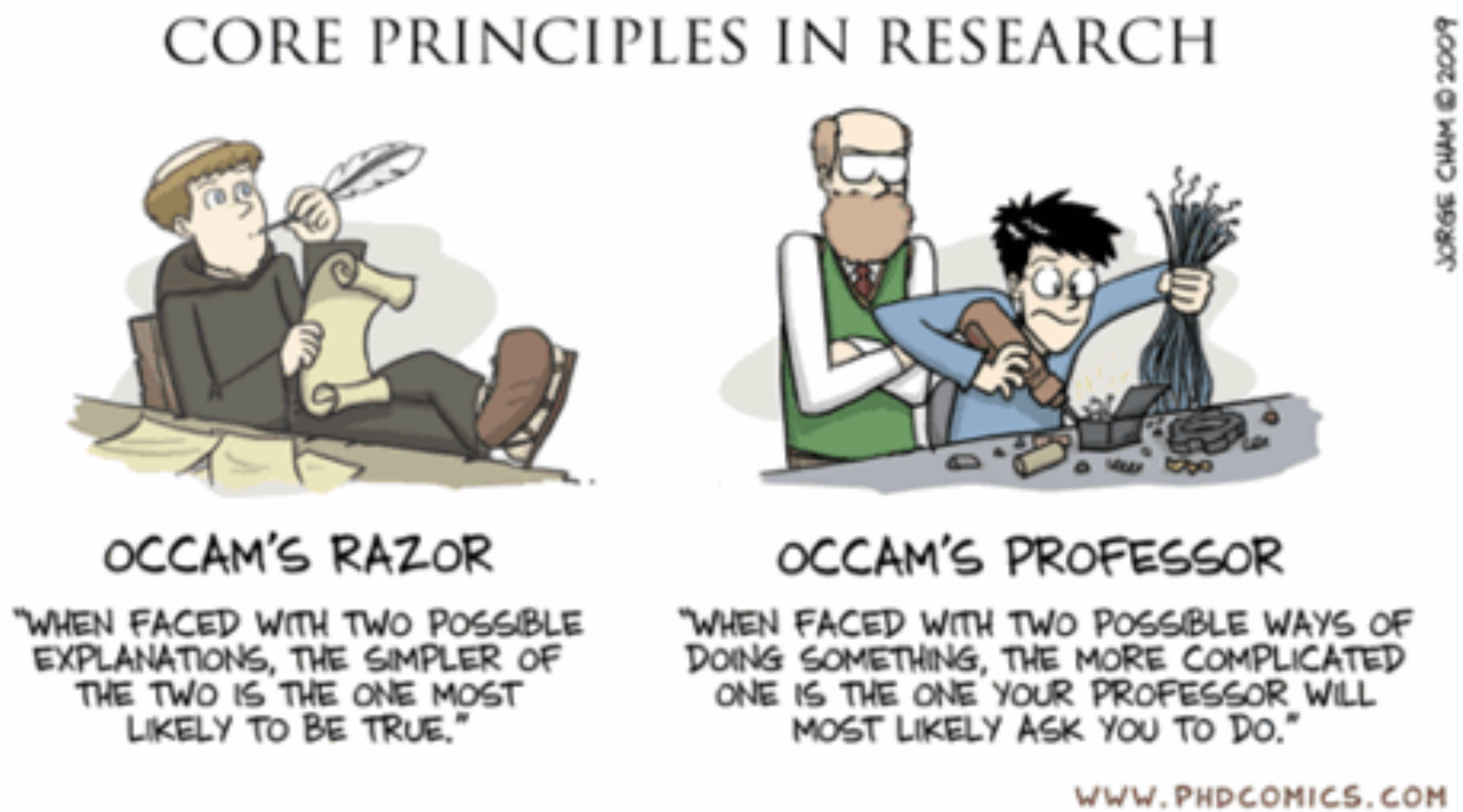


Could be tested if a production scenario is specified… How?

Almost impossible via f_{PBH} → Mass function or z≫10 effects

fraction of the Universe E-density collapsing into PBHs

$$f_{\rm PBH} = \int \psi_p(M) {\rm d}M \equiv \int F(M) \frac{{\rm d}M}{M} = \int \left(\frac{M}{M_{\rm eq}}\right)^{-1/2} \frac{\beta(M)}{\Omega_{\rm DM}} \frac{{\rm d}M}{M}$$

Is this scenario predictive? (Continued)

Almost impossible via f_{PBH} : exponentially sensitive to the parameters

$$\beta = 2\int_{\delta_c}^{\infty} \mathrm{d}\delta \frac{M}{M_H} P(\delta) \simeq \mathrm{erfc}\left(\frac{\delta_c}{\sqrt{2\sigma^2}}\right)$$

probability density function of the density contrast (here assumed Gaussian)

Threshold density contrast to form BH

Curvature power spectrum

$$\sigma^2 = \int_0^{\infty} W(kR)^2 \mathcal{P}_\delta(k) \frac{\mathrm{d}k}{k} = \int_0^{\infty} W(kR)^2 \frac{16}{81} (kR)^4 \mathcal{P}_\zeta(k) \frac{\mathrm{d}k}{k}$$

$$M_H = 17 \left(\frac{g}{10.75}\right)^{-1/6} R_{\mathrm{pc}}^2 \, M_\odot$$ *Mass-R relation*

Mass dependence much more promising than ‘normalisations’!

QCD & friends enter the scene

What’s so special about the QCD scale?

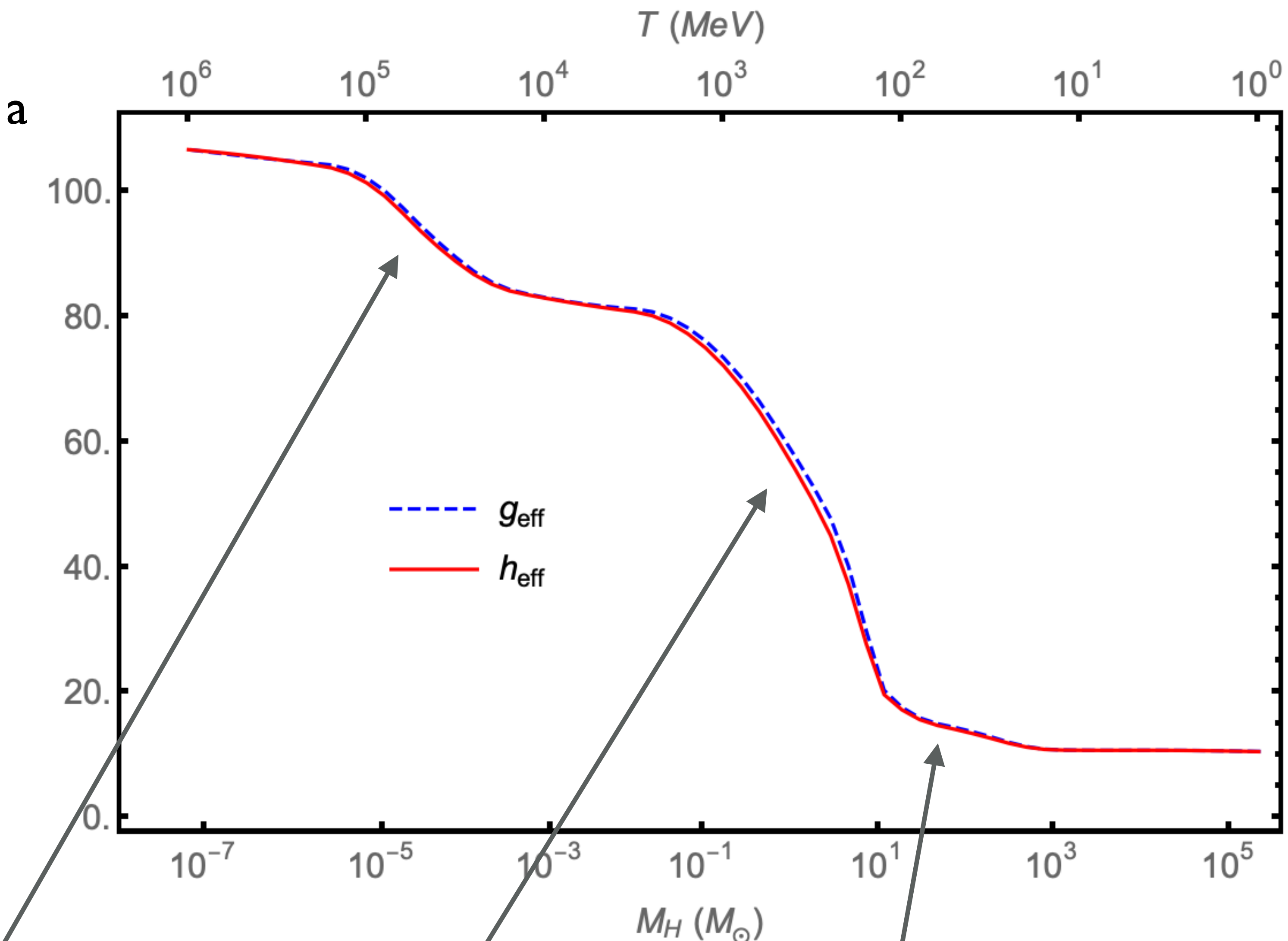
1. **Varying entropy (s) and energy (ρ) density**
2. **Mass of causally connected patch ~ solar mass**

At the EW but above all at the QCD PT (actually, a cross-over) energy and entropy density varying non-trivially vs. T due to varying # dofs

$$g_{\rm eff}(T) \equiv \frac{30\rho}{\pi^2 T^4}$$

$$h_{\rm eff}(T) \equiv \frac{45s}{2\pi^2 T^3}$$

milder variations present in association with annihilation phase of π’s, μ’s and eventually e’s



EW phase transition, $t, H, Z, W\ldots$ annihilate out of thermal plasma

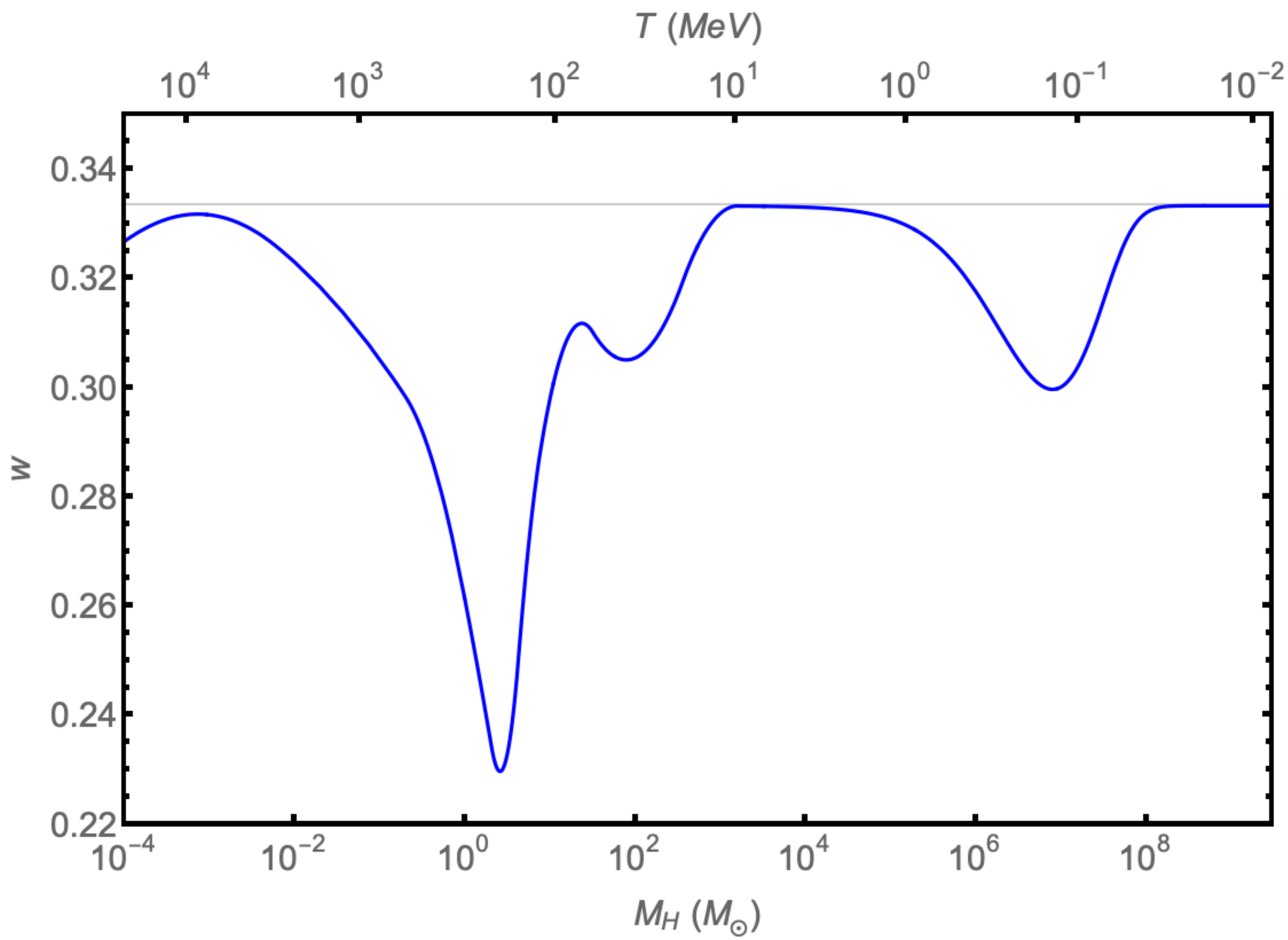
Quarks and gluons confined in hadrons

annihilation phase of π’s, μ’s

Associated changes in the equation of state (EOS)

$$w(T) \equiv \frac{P}{\rho} = \frac{4h_{\rm eff}(T)}{3g_{\rm eff}(T)} - 1$$

Major change at M_H~O(3) $M_\odot$, milder change during annihilation phase of π's, μ's and eventually e's



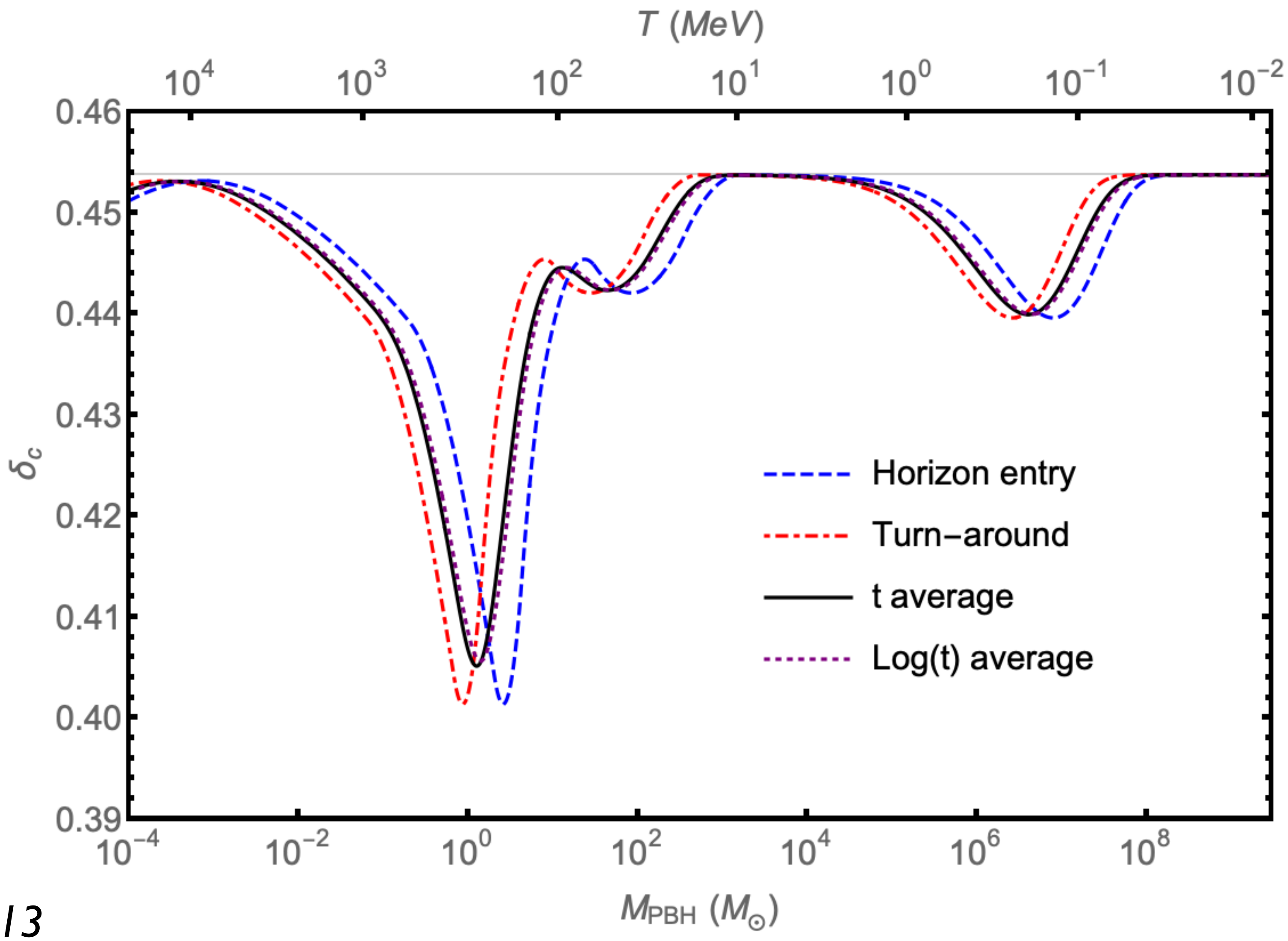
Critical density for collapse into PBH

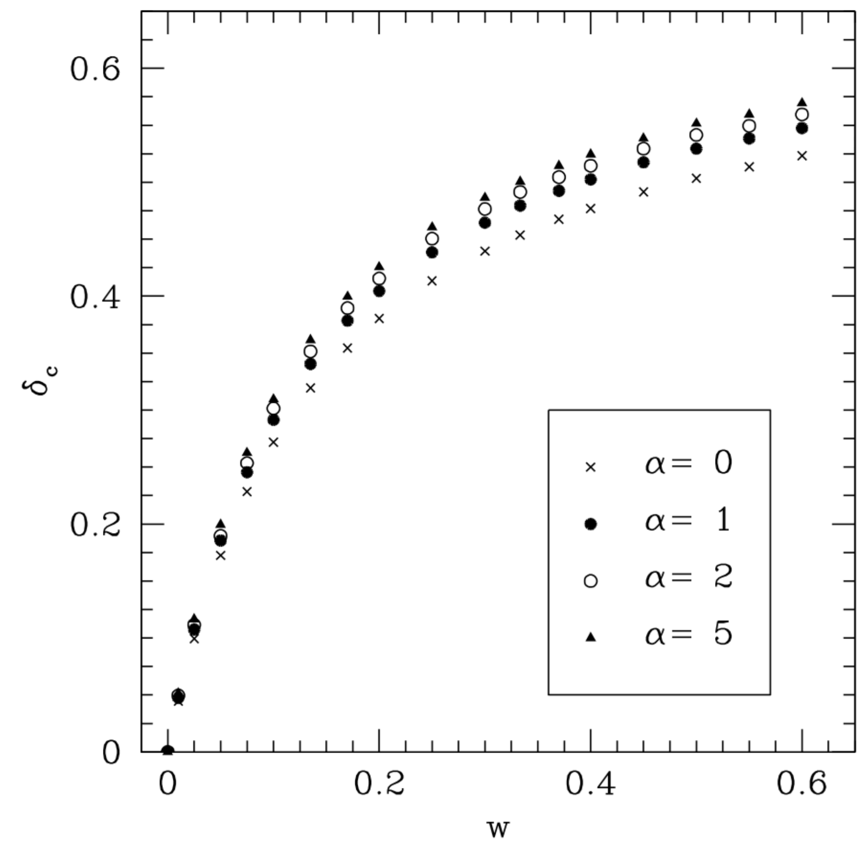
Lower pressure to counteract collapse = easier to form PBH (lower threshold δ_c)

We rely on the numerical calculations of

I. Musco and J. C. Miller, "Primordial black hole formation in the early universe: critical behaviour and self-similarity," Class. Quant. Grav. 30 (2013), 145009 [arXiv:1201.2379]

to deduce the δ_c-w relation





Some uncertainty of ~factor 2 remains due to the non-instantaneous PBH formation process

Intriguing hint noted in the past

"Stellar mass scale" for PBH from particle physics and cosmology!

K. Jedamzik, "Could MACHOS be primordial black holes formed during the QCD epoch?," Phys. Rept. 307 (1998), 155-162 [astro-ph/9805147]

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Scenarios where PBHs form during the QCD epoch have essentially only one free parameter f_{PBH} […] Everything else is simply dictated by known physics. In this highly constrained setting, PBHs formed during the QCD epoch can (pre-) post-dict, the mass scale of ~ 30 $M_\odot$ for PBHs observed by LIGO/Virgo […]

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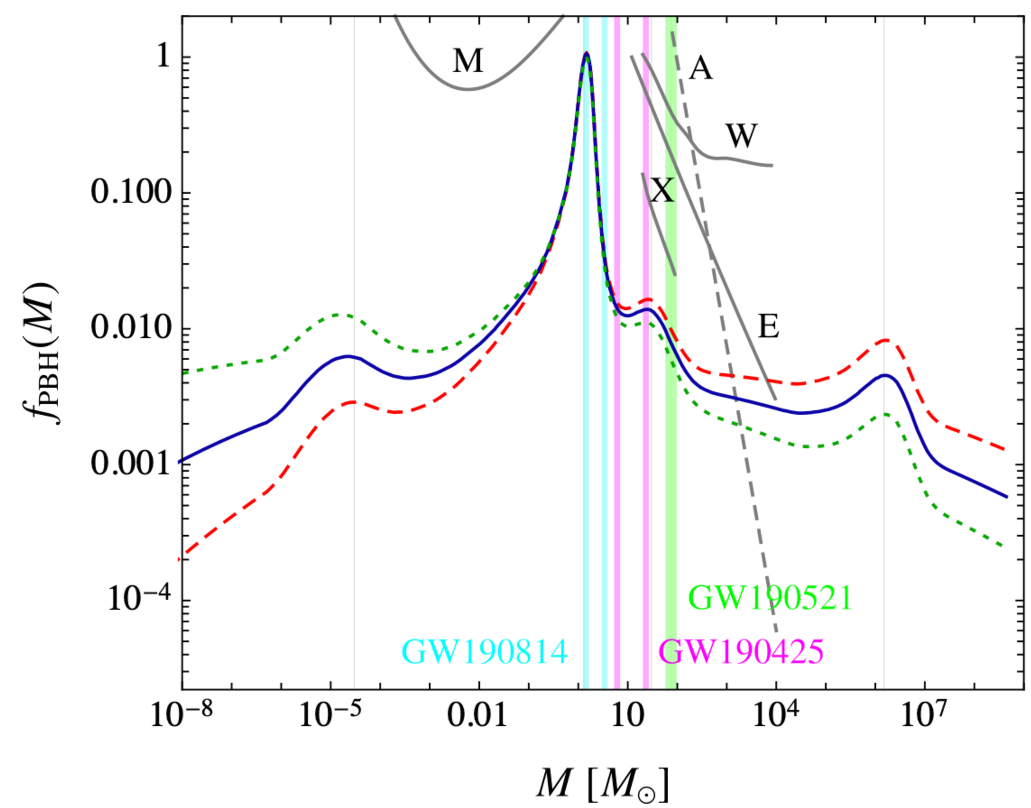
Maybe linked to other phenomena, too?

B. Carr, S. Clesse, J. Garcìa-Bellido and F. Kühnel, "Cosmic conundra explained by thermal history and primordial black holes," Phys. Dark Univ. 31 (2021), 100755 [arXiv:1906.08217]

The sudden drop in the pressure of relativistic matter at $W^{\pm}/Z^0$ decoupling, the quark–hadron transition and e^+e^- annihilation enhances the probability of PBH formation in the early Universe. Assuming the amplitude of the primordial curvature fluctuations is approximately scale-invariant, this implies a multi-modal PBH mass spectrum […] This suggests a unified PBH scenario which naturally explains the dark matter and recent microlensing observations, the LIGO/Virgo black hole mergers, the correlations in the cosmic infrared and X-ray backgrounds, and the origin of the supermassive black holes in galactic nuclei at high-z.



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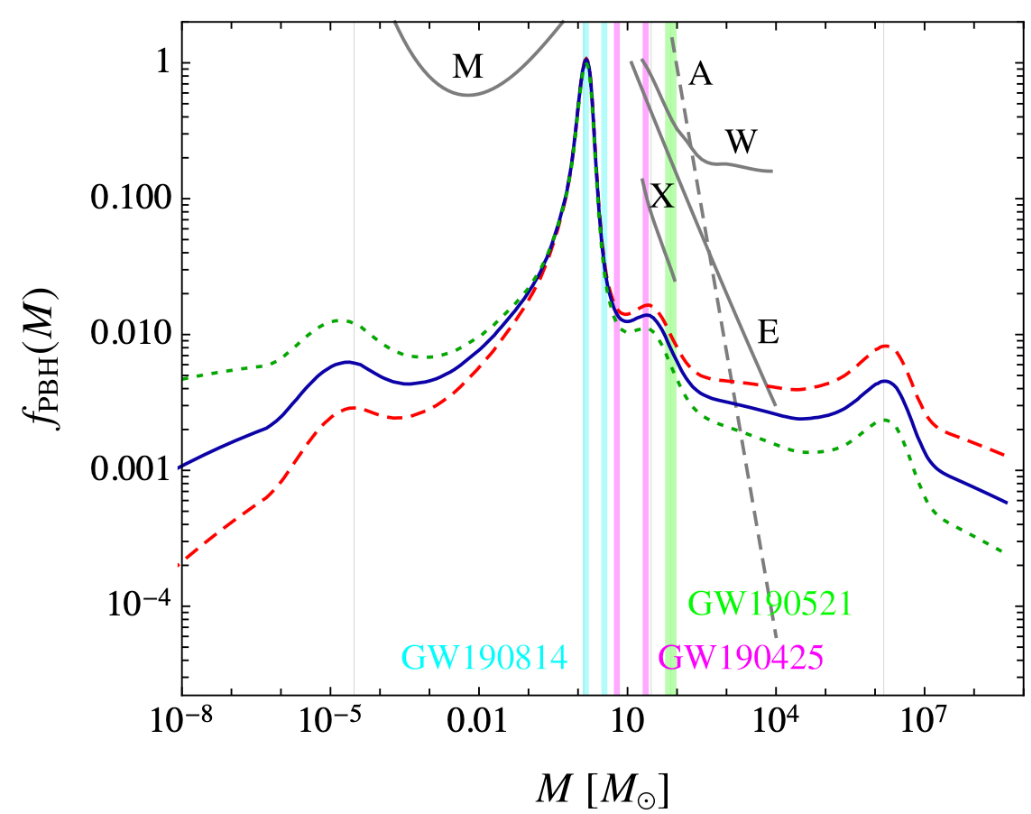
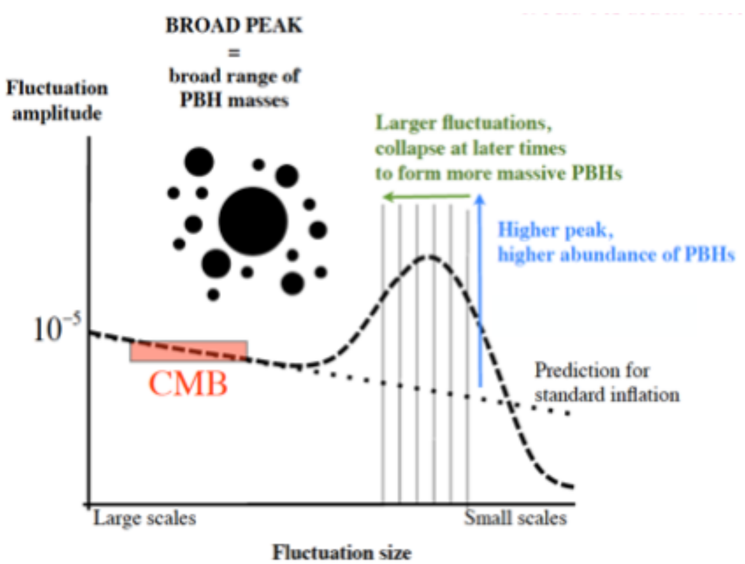


Technical point: Still enhanced PS at 'small scales' needed

But apart for that, matched to $f_{\rm PBH}$, no further scale set by hand. We parameterise

$$\mathcal{P}_\zeta(k) = \mathcal{P}_{\rm CMB}(k) + \frac{\Delta}{1+\exp\left(\frac{k_\bullet - k}{\rm Mpc^{-1}}\right)}$$

$$k_{\rm QCD} \gg k_\bullet \gg k_{\rm CMB}$$



Needed to avoid overshooting CMB/LSS

$k_\bullet$ equivalent to $M_{\rm cut} = \left[\frac{k_\bullet}{10^6{\rm Mpc}^{-1}}\left(\frac{g_*}{10.75}\right)^{1/12} 17^{-1/2}\right]^{-2} M_\odot$

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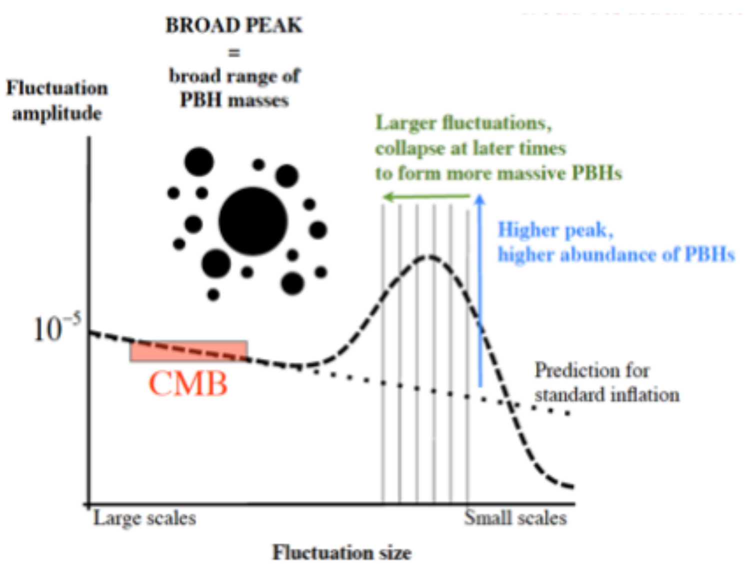

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Allowing for a small scale-dependence (as the one inferred from CMB) does not change qualitative conclusions.

$$\sigma^2 = 0.0033\left(\frac{M}{10M_\odot}\right)^{n_M}$$

Much larger scale dependences inconsistent with Ansatz that no other scale put by hand

$$|n_M| \sim \mathcal{O}(|n_s - 1|)$$

(Almost) parameter-free predictions: Ready to test

Caveat

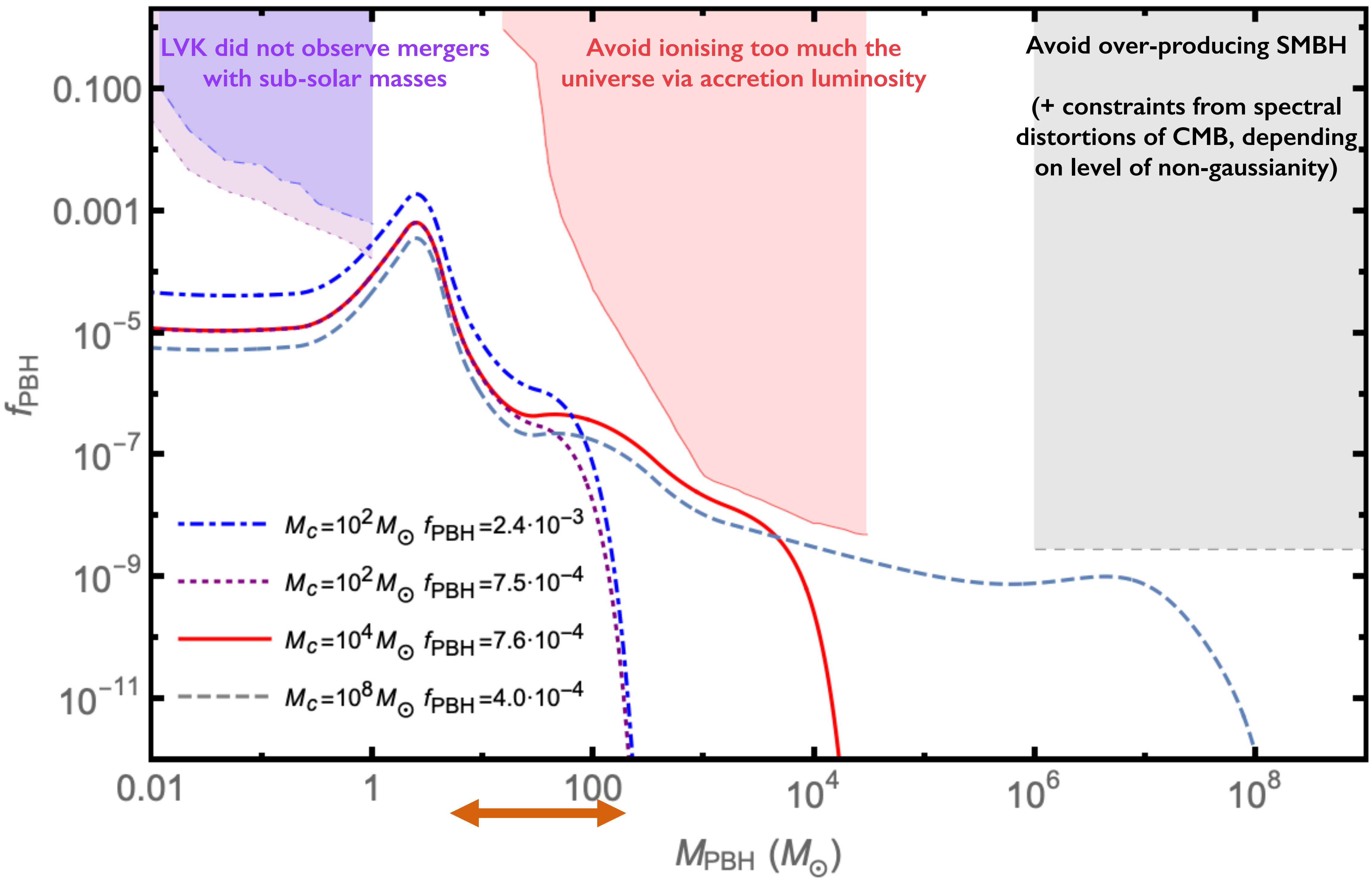
Very broad mass functions!
Mass-integrated f_{PBH} not equivalent to PBH impact on LIGO/VIRGO

We thus introduce also

$$f_{\rm GW} \equiv \int_{5M_\odot}^{160\,M_\odot} \psi_p(M)\mathrm{d}M \sim \mathcal{O}(0.01) f_{\rm PBH}$$

Need f_{GW}~10^{-3} (hence f_{PBH}~10^{-1}) for a sizeable impact on LIGO/Virgo mergers

Money Plot: some mass function* barely allowed



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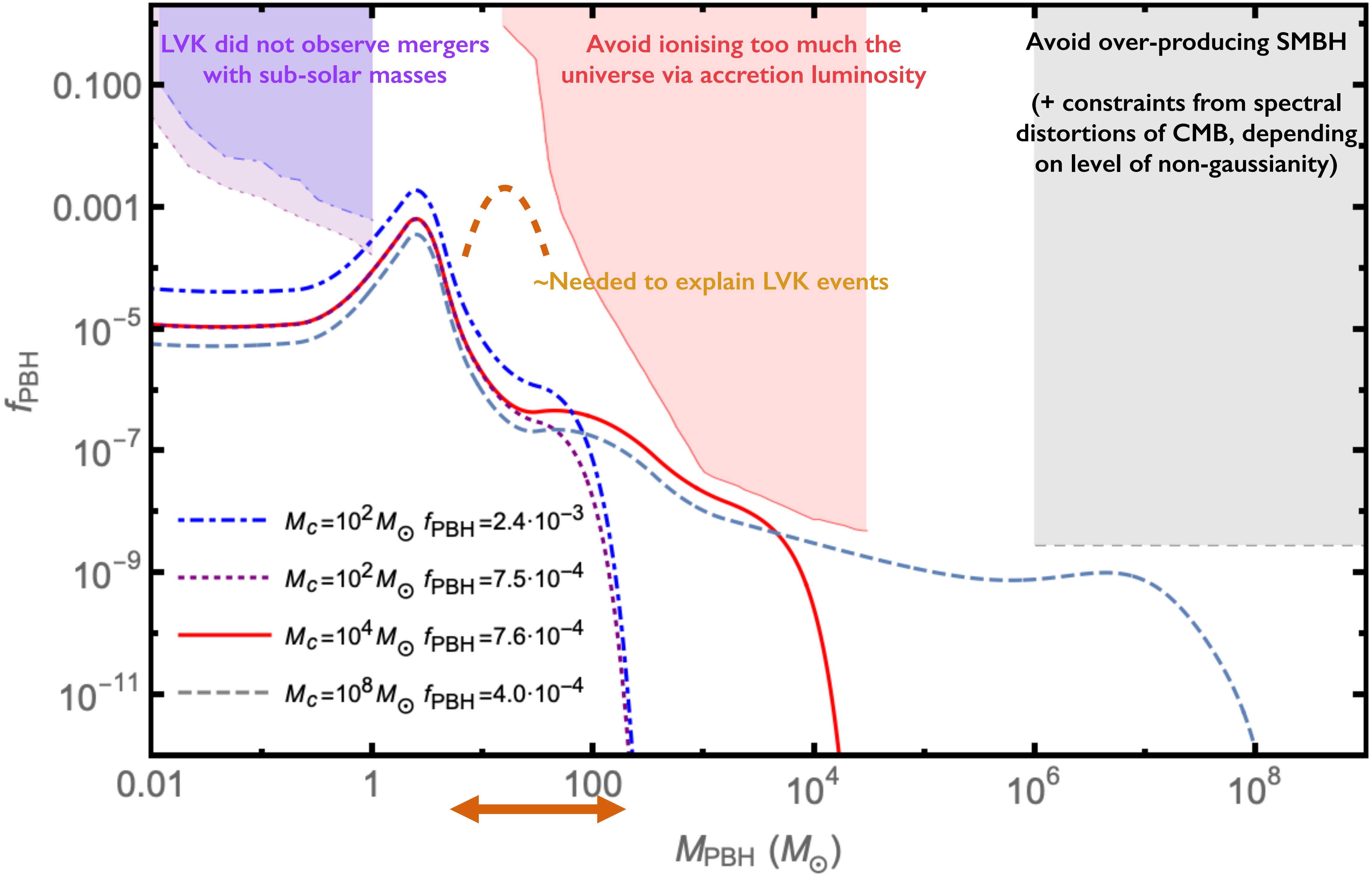

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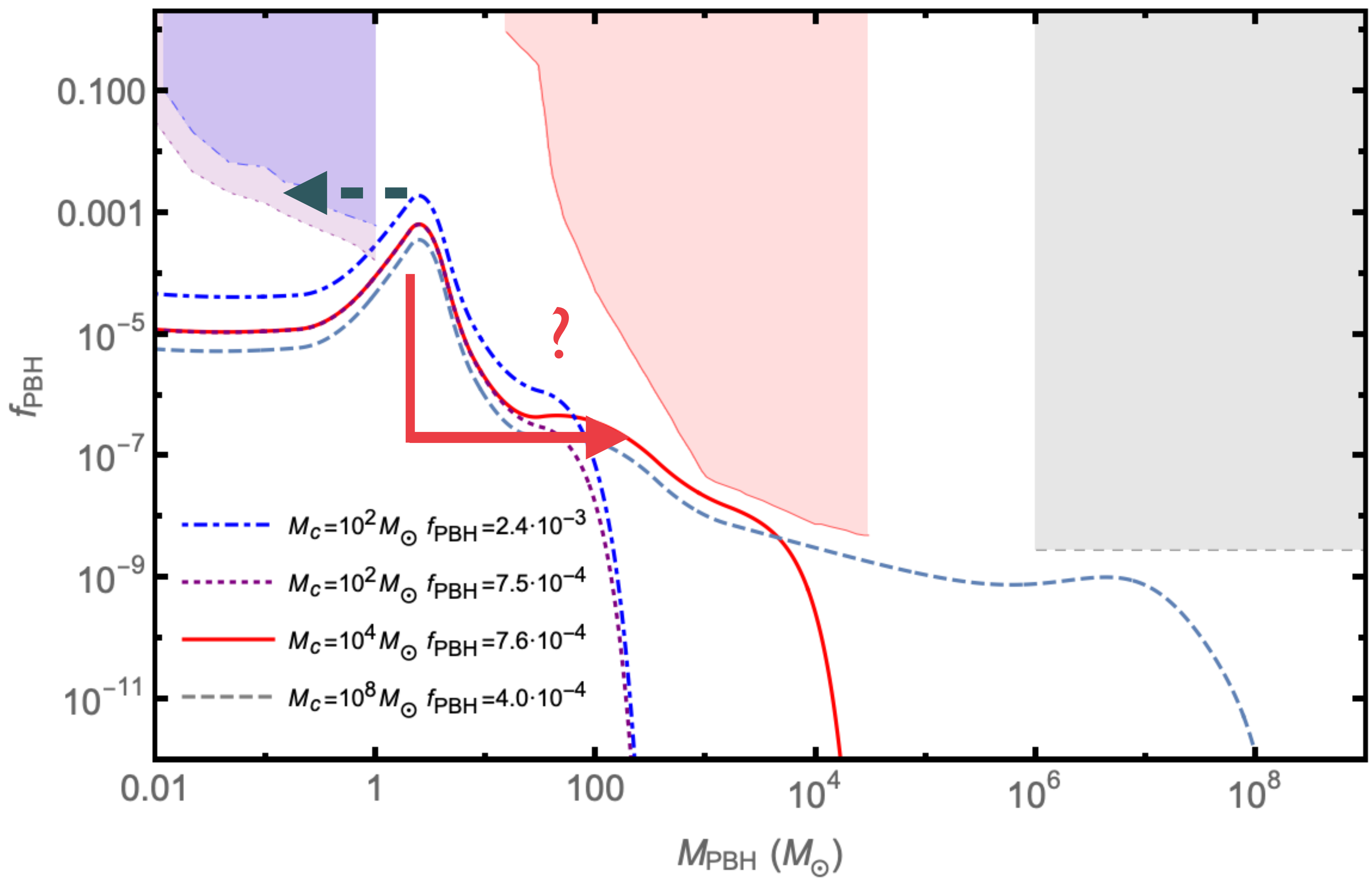
Loopholes?

Strong causality bound: Reducing fraction of Hubble volume mass engulfed into PBH worsens the absence of light PBH mergers & makes harder to explain LIGO/Virgo O3

Can the PBH mass function undergo a significant evolution of its bulk properties?



We argue it's impossible (e.g. overshoots GW background in case of mergers) or violate "QCD-shaped" Ansatz

Conclusions

- Heavy BH mergers among the LIGO/Virgo(/KAGRA) events revamped the idea that there is perhaps a PBH component.

- Currently hard to test and of little explanatory power if both PBH abundance and mass-function are engineered to fit the data.

- Thermodynamics in the early universe, notably at/around QCD epoch, considered most natural mechanism to generate "appropriate" mass function via EOS alteration.

- We tested this hypothesis with a number of probes, and all suggest that the idea is excluded (by wide margins, typically factor ~100)

- While uncertainties exist and factor~2 wiggle room possible (although usually in the direction of tightening constraints!), the idea does not seem viable unless 'reverse-engineering', i.e. dropping its rationale

- *Interesting to keep looking for light BH mergers, those might be possibly linked to origin of SMBH… if spectral distortions constraints can be avoided (e.g. Hooper et al. 2308.00756, for a recent attempt)*

Extras

Pheno consequence nr. 1 : Super-massive-black holes (SMBH) associated to e^+e^- annihilation era

SMBH

- Supermassive BH with $M \lesssim 10^9\, M_\odot$ have been inferred at $z \gtrsim 6$ (linked to QUASARs)
- **Can they form from stellar BH** ($M \lesssim 10^2\, M_\odot$) **seeded at z~15** (PopIII star collapse)?

PBH mass (growing via accretion) obeys the bound

$$M(t) \lesssim M_i \times \exp\left(\frac{1-\epsilon}{\epsilon}\frac{t-t_i}{\tau_E}\right) \qquad \tau_E = \frac{c^2 M}{L_E} = 0.4\,\mathrm{Gyr}$$

Barely so if accreting at Eddington luminosity for a benchmark ϵ=0.1

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Barely so if accreting at Eddington luminosity for a benchmark ϵ=0.1

Several hypotheses around:

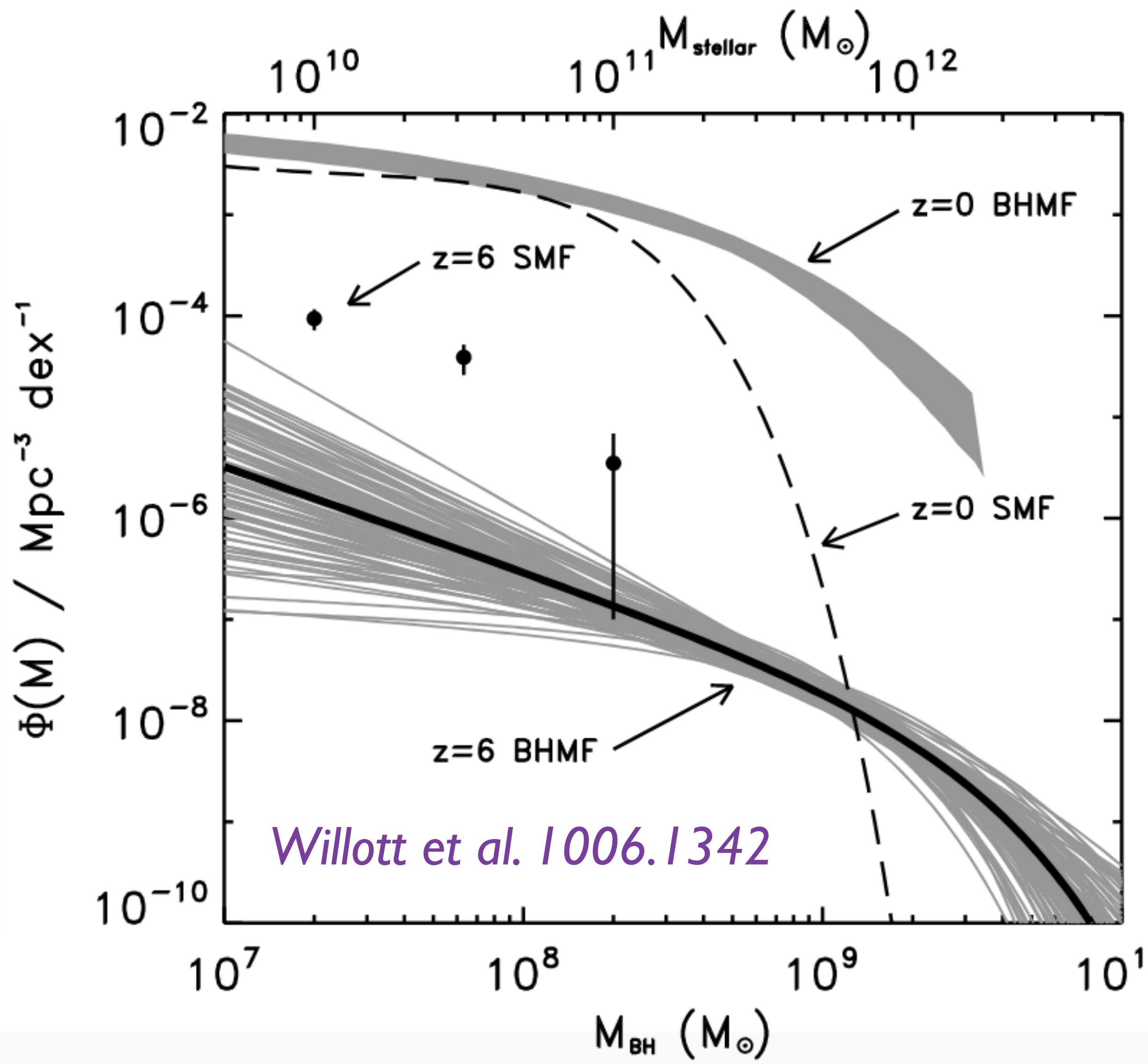
- Super-Eddington accretion?
- (close to) Eddington luminosity with a very small ϵ?
- Important role of mergers?
- Direct collapse of very massive clouds (rather than seeded via stellar BH)?
- Primordial origin?
- …

For a review, see e.g. M.Volonteri, 1003.4404

How many SMBH allowed in the early universe?

- SMBH *<u>currently</u>* account for ~10^{-5} of the DM density.
- Observations suggest SMBH having undergone significant evolution between z~6 and z~0, cumulatively growing in mass by a factor ~$10^{3.5}$ *(much more than stars!)*
- Even if SMBH underwent no mass growth before z~6, their initial abundance must fulfill:

$$f_{\rm PBH}(M \geq 10^6\, M_\odot) \lesssim 3 \times 10^{-9}$$



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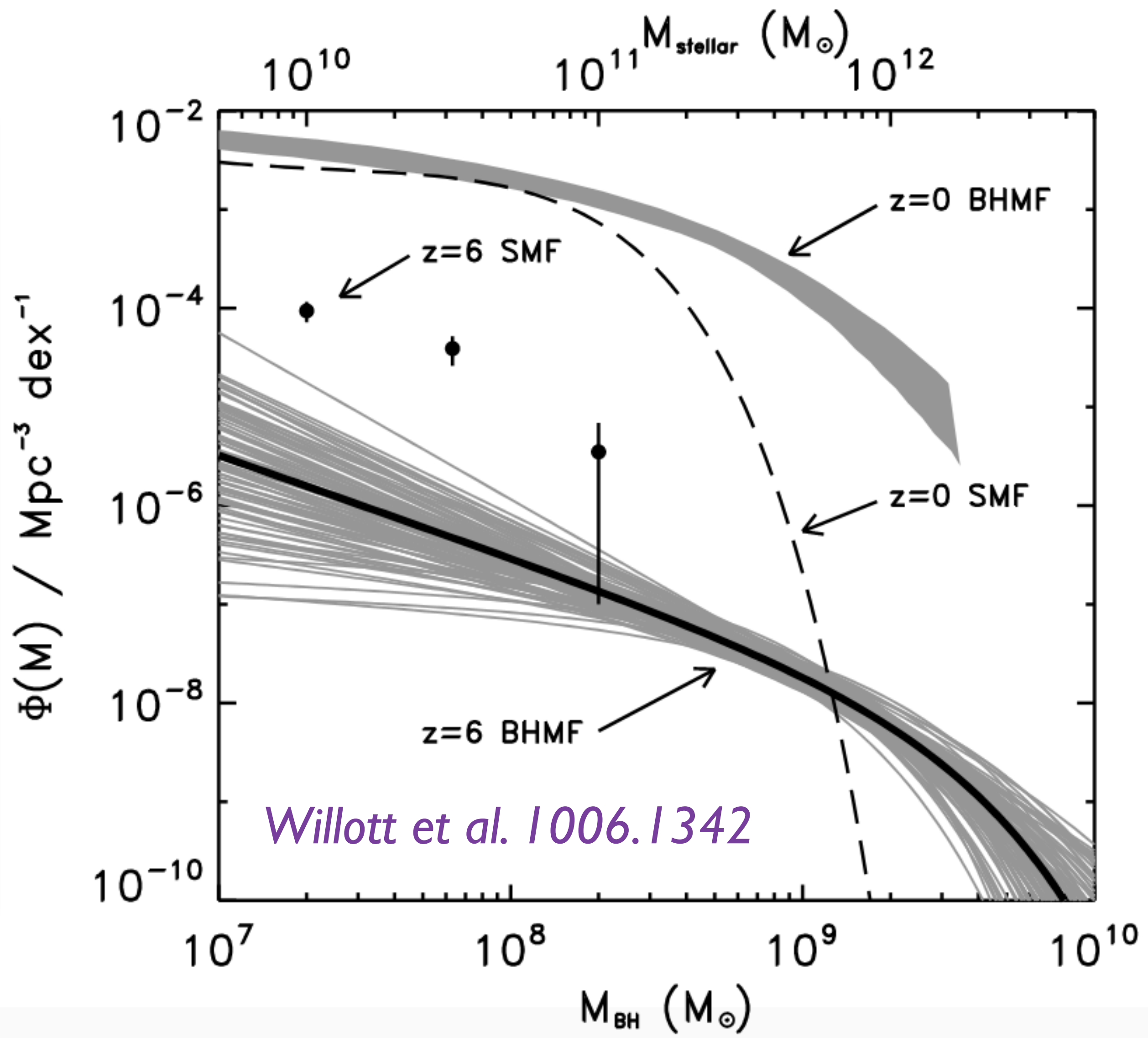
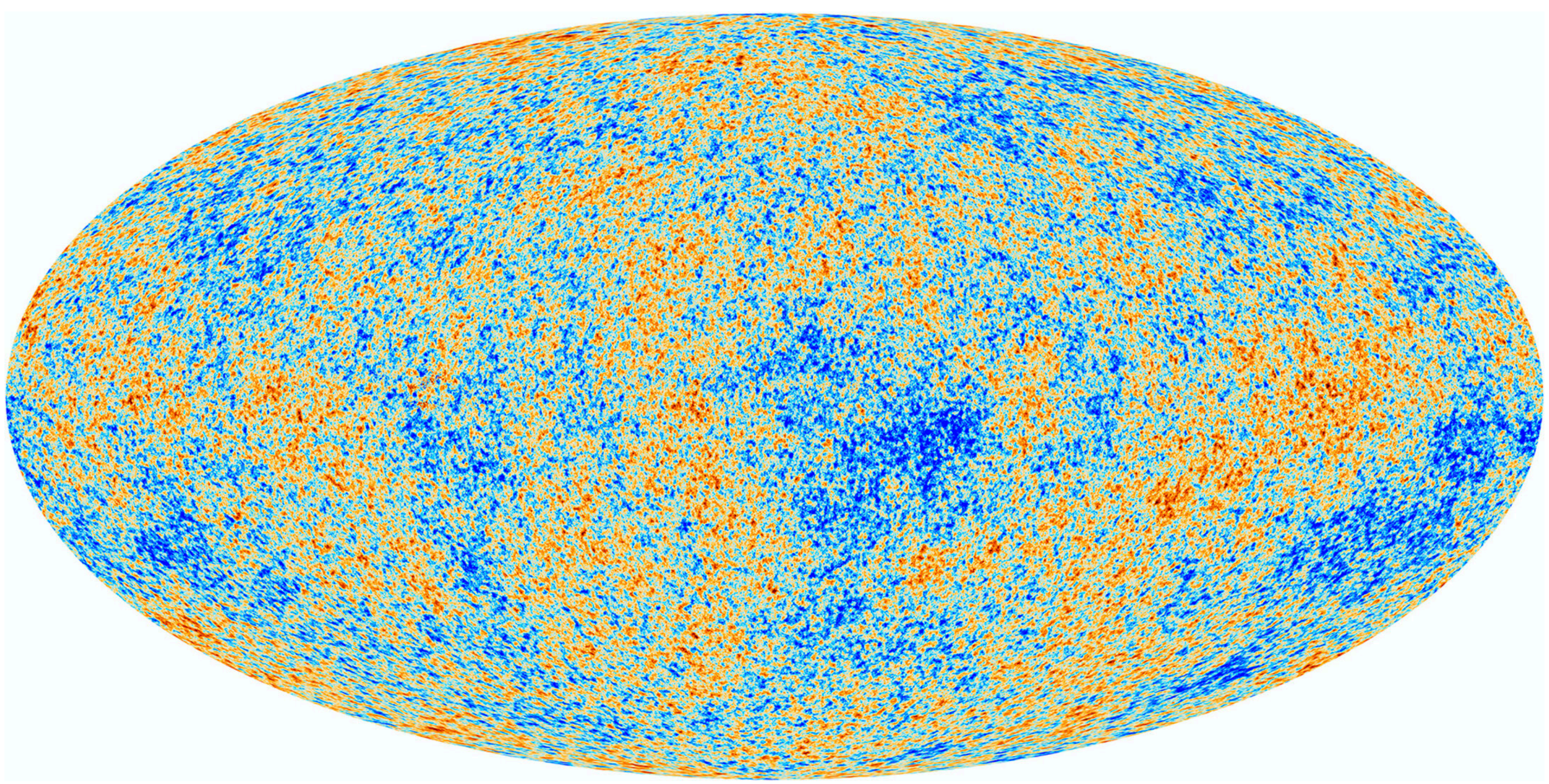


This argument implies that f_{PBH}<4 x 10^{-4} (f_{GW}<4 x 10^{-6}) if setting M_c=10^8 $M_\odot$

Either explain SMBH and kill its relevance for LIGO/Virgo events, or give-up idea to explain SMBH, imposing $M_c \ll 10^8\, M_\odot$

Pheno consequence nr. 2 : CMB anisotropies



CMB PBH accretion bounds: Key notions

- Like ordinary BH, PBH can accrete matter & heat it up → radiation (Note peculiar environmental conditions: quasi-homogeneity, high photon density…)

- The associated photon emission can be detected indirectly via alterations to CMB anisotropies

Key point

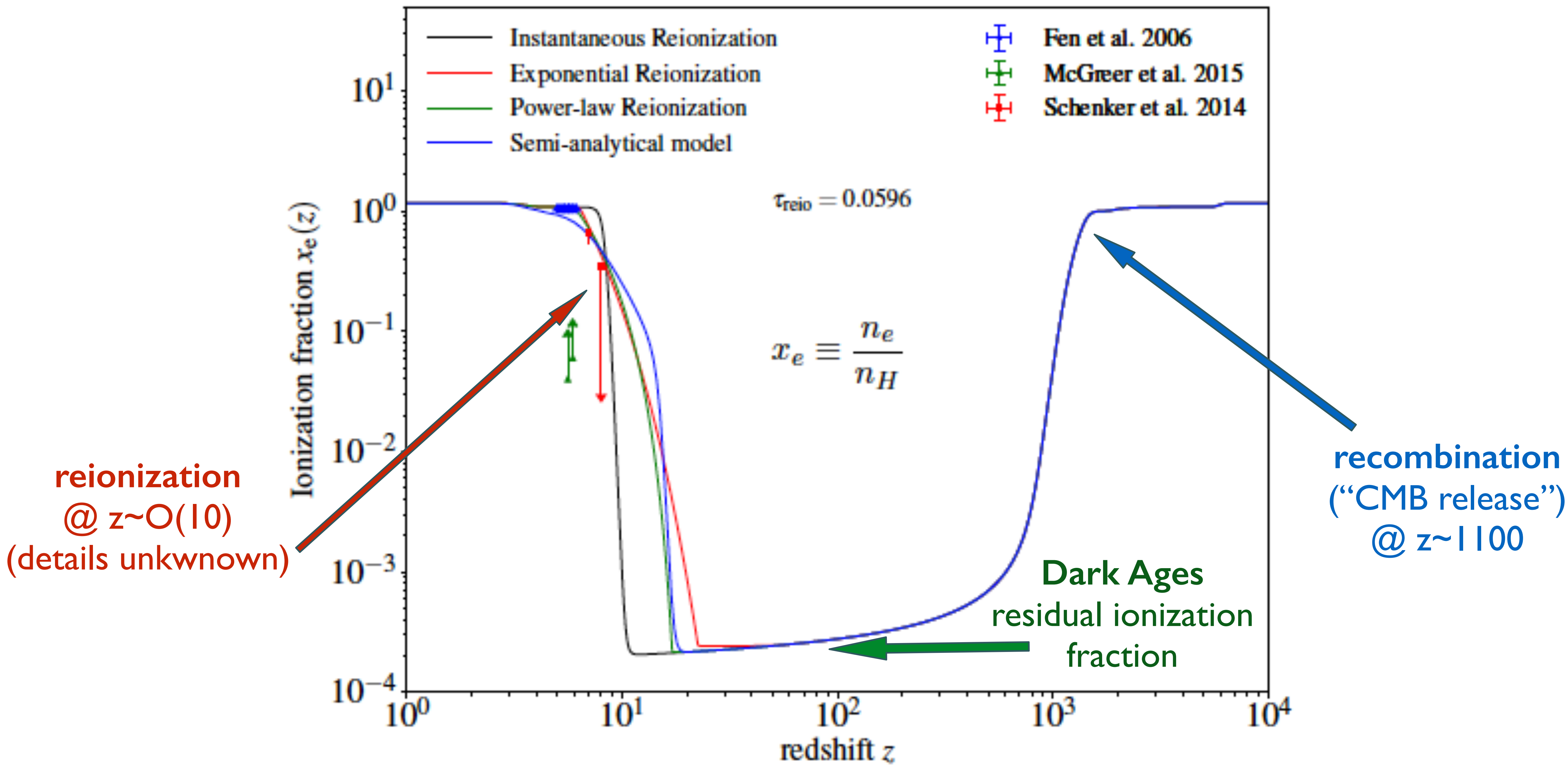
Energy density of injected energetic photons, even if negligible wrt ρ_{CMB}, **not negligible wrt baryonic gas kinetic energy.**
These photons can **heat up** (alter T_M) and especially **ionize the gas** (alter x_e)

→ **CMB anisotropies are very sensitive to that!**
(Technically, via alterations to optical depth and its time dependence/visibility function)

M. Ricotti, J. P. Ostriker and K. J. Mack, ApJ 680 (2008) 829[arXiv:0709.0524]
Ali-Haïmoud & Kamionkowski, PRD95 (2017), 043534
V. Poulin et al. Phys. Rev. D 96, 083524 (2017)
PDS, V. Poulin, D. Inman and K. Kohri, Phys.Rev.Res. 2 (2020), 023204

The three epochs affected

Have a look at the standard **ionization** and gas temperature evolution



optical depth

$$\kappa(z) = \sigma_T n_{e,0} \int_0^z dz' \frac{dt}{dz'} (1+z')^3 x_e(z')$$

E-deposition module interfaced via Boltzmann CMB solver dealt with via ExoCLASS *see 1801.01871*

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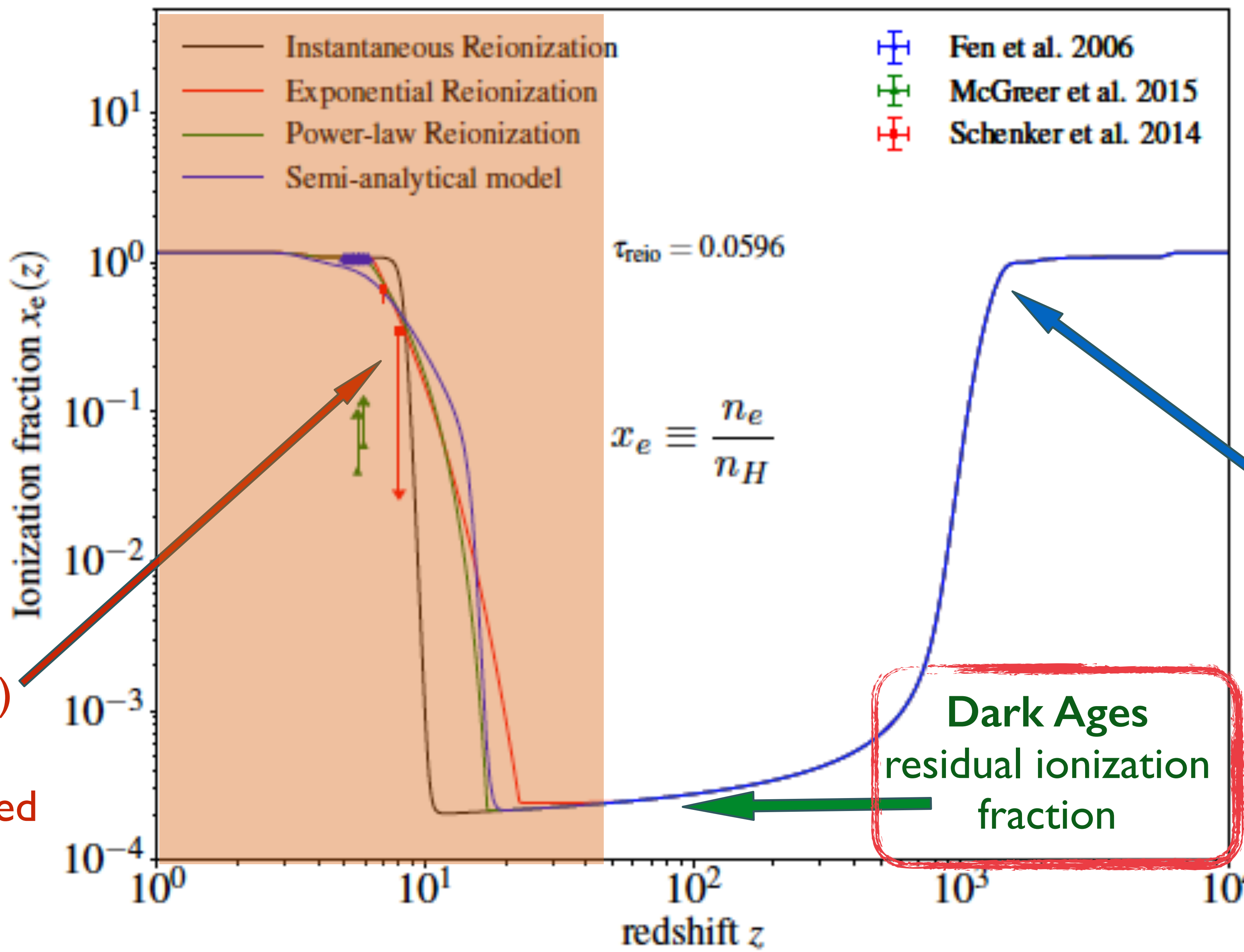


reionization
@ z~O(10)
(details unkwnown)

PBH effects
conservatively ignored
in the following

recombination
("CMB release")
@ z~1100

optical depth

$$\kappa(z) = \sigma_T n_{e,0} \int_0^z \mathrm{d}z' \frac{\mathrm{d}t}{\mathrm{d}z'} (1+z')^3 x_e(z')$$

E-deposition module interfaced via Boltzmann CMB solver dealt with via ExoCLASS *see 1801.01871*

Dominant uncertainty: Luminosity; two benchmarks

1. Collisional ionization for spherical case at $v \sim c_s$ *(relatively high $\dot{M}$, low L)*

2. ADAF model with suppressed accretion & two-temperature disk

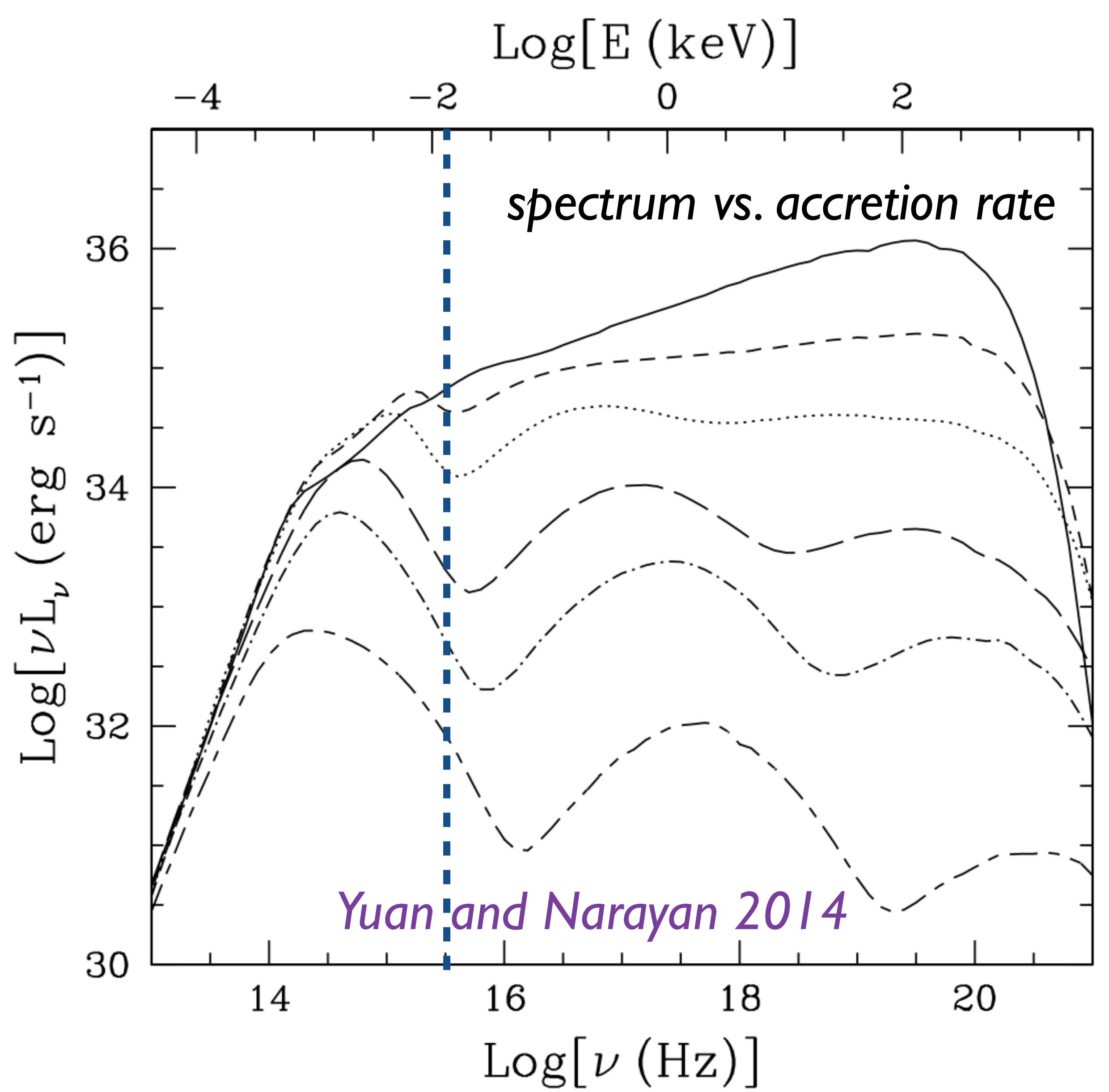
Loosely, speaking, conservative bracketing models (while remaining physically and pheno viable)

Disk spectrum parameterized as

$$L_\omega \propto \Theta(\omega - \omega_{\min})\omega^{-a} \exp(-\omega/T_s)$$

$a \sim 0\text{-}0.5$ *$T_s \sim O(m_e)$*

ω_{min} accounts for 'useful fraction of the spectrum', $\omega_{min} \sim O(10)$ eV

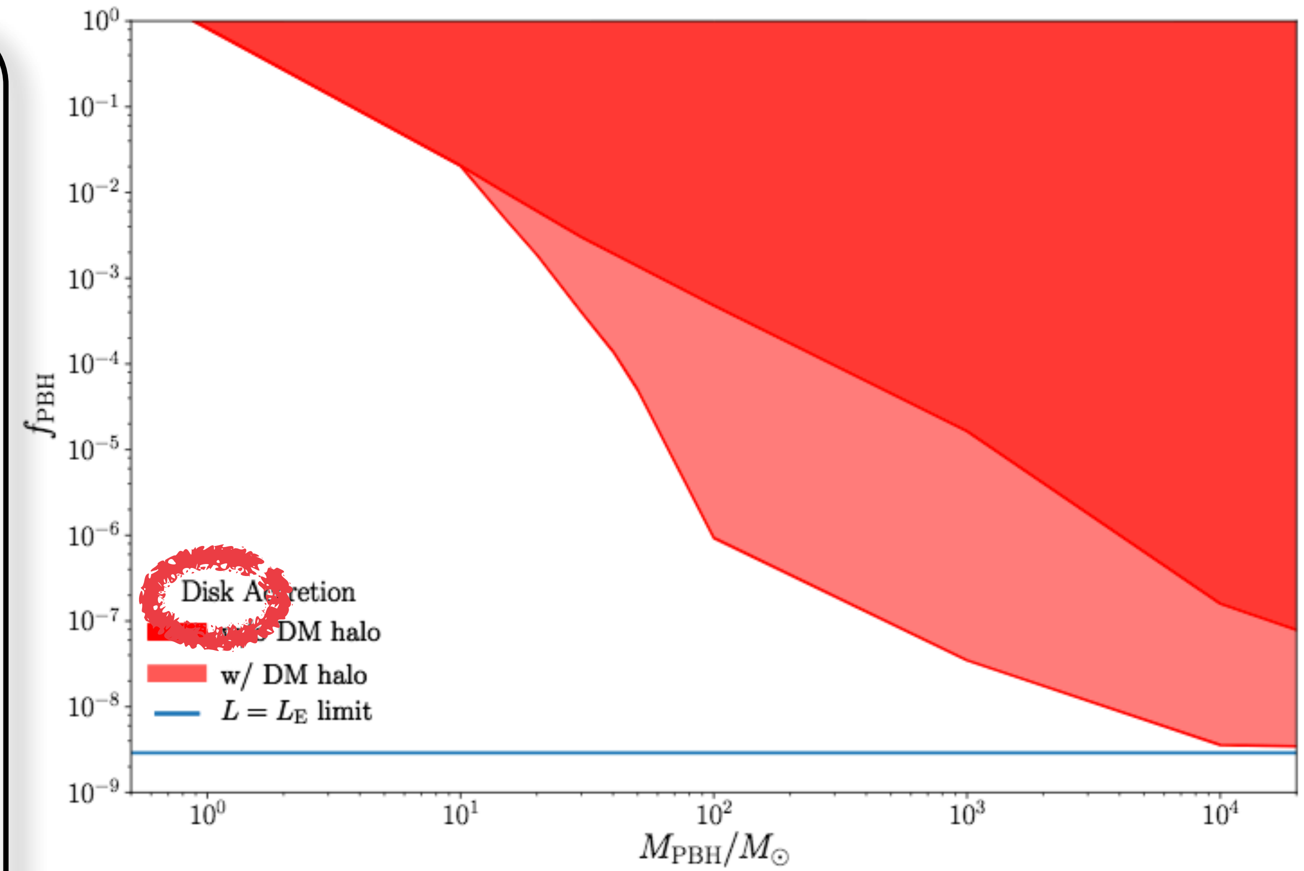


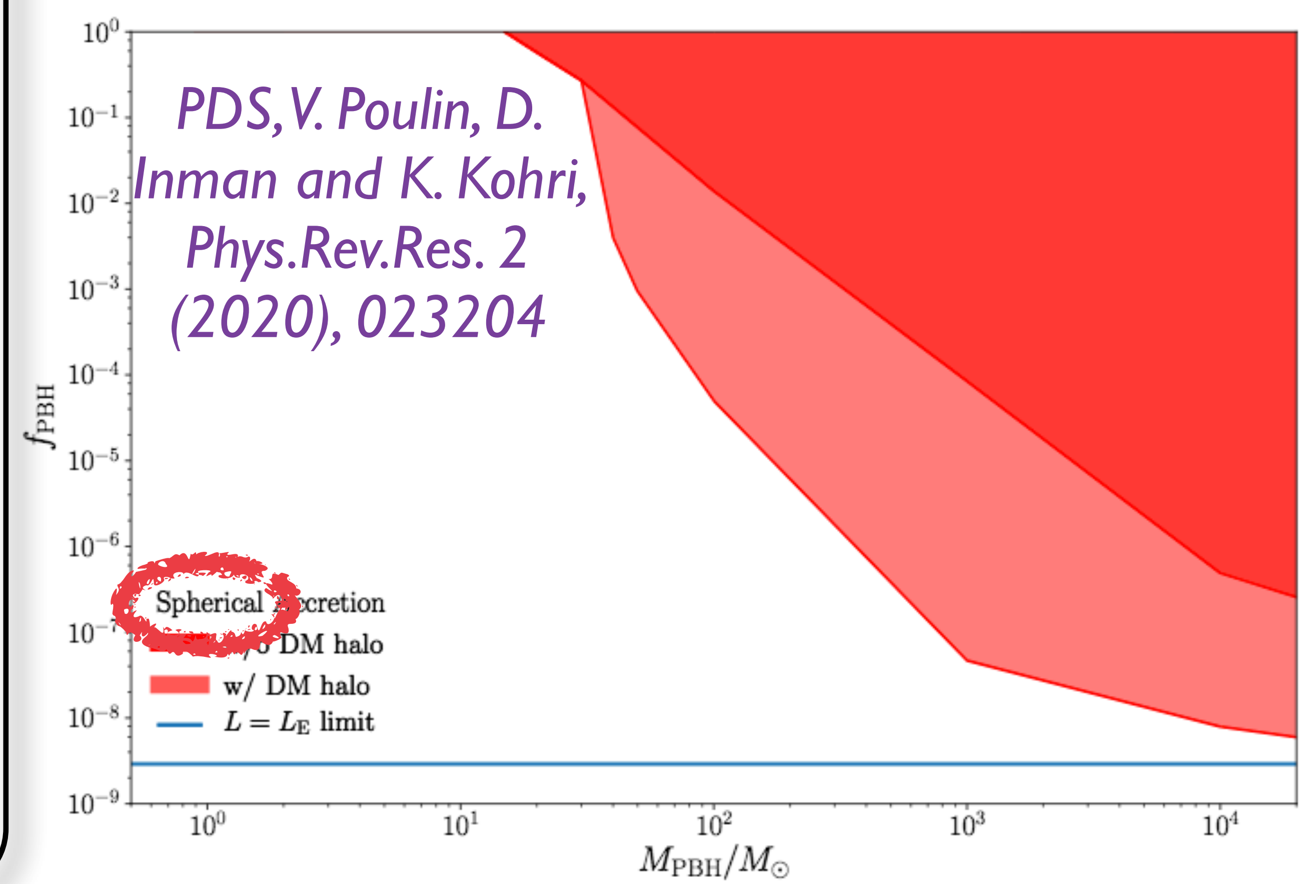
Effects on the CMB almost 'bolometric', minor dependence on E-distribution (factor ~2)

Results for monochromatic mass function, circa 2020

- PBH excluded as totality of DM if $M > 15\ M_\odot$ even for spherical accretion under most conservative case of collisional ionization
- Compared to our results in 2017, factor ~4 improvement due to new & better cosmo data (notably Planck 2018 release with low-ℓ polarization) & better account of t-dependence of E-release/absorption (via ExoCLASS)
- The DM halos tighten the bound up to ~3 oom.
- Caveat for $0.01 \lesssim f_{PBH} \lesssim 0.1$ (unaccounted modifications of halo profile due to neighboring PBH)
- Spherical and disk case not so different especially at high-M, due to the lower velocity required for spherical case consistency
- Bounds flatten at $M \gtrsim 10^4\ M_\odot$ since approaching Eddington limit (at which we cap luminosity) for most of the cosmo relevant time

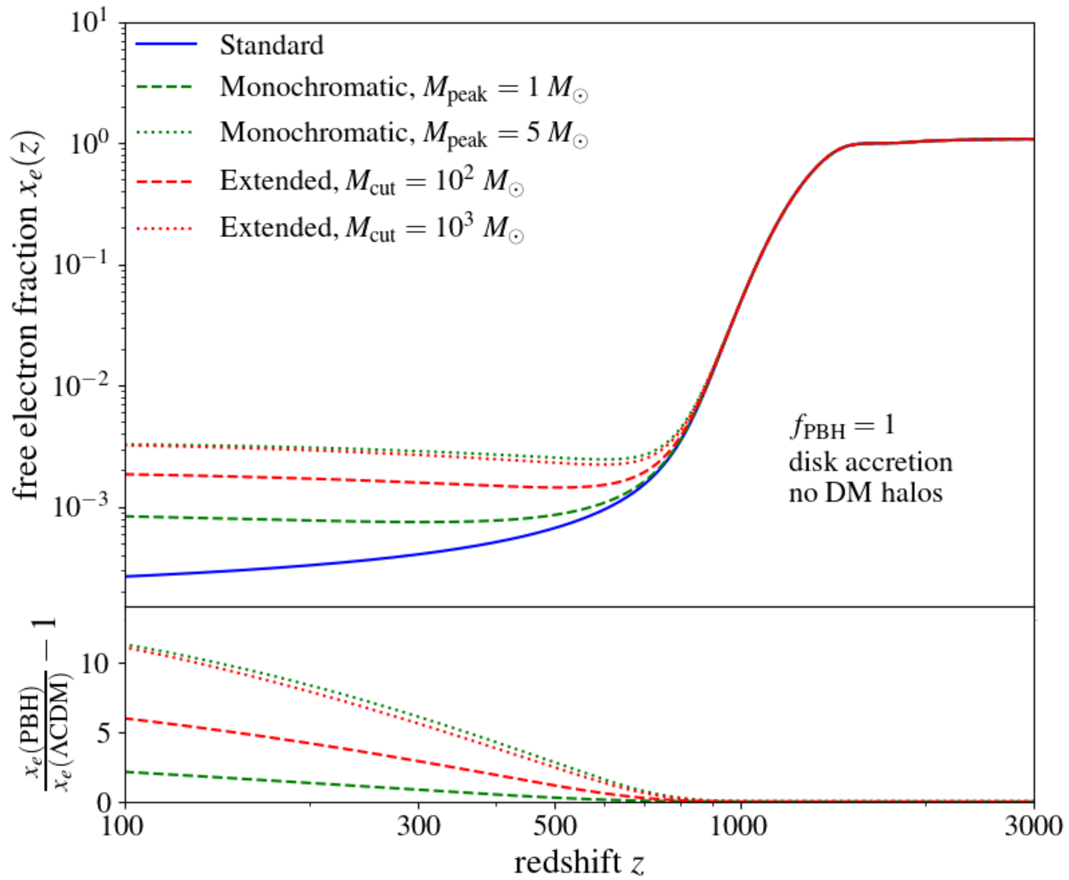
$$f_{\rm PBH} < 2.9 \times 10^{-9} \quad (L_{\rm acc} = L_E)$$

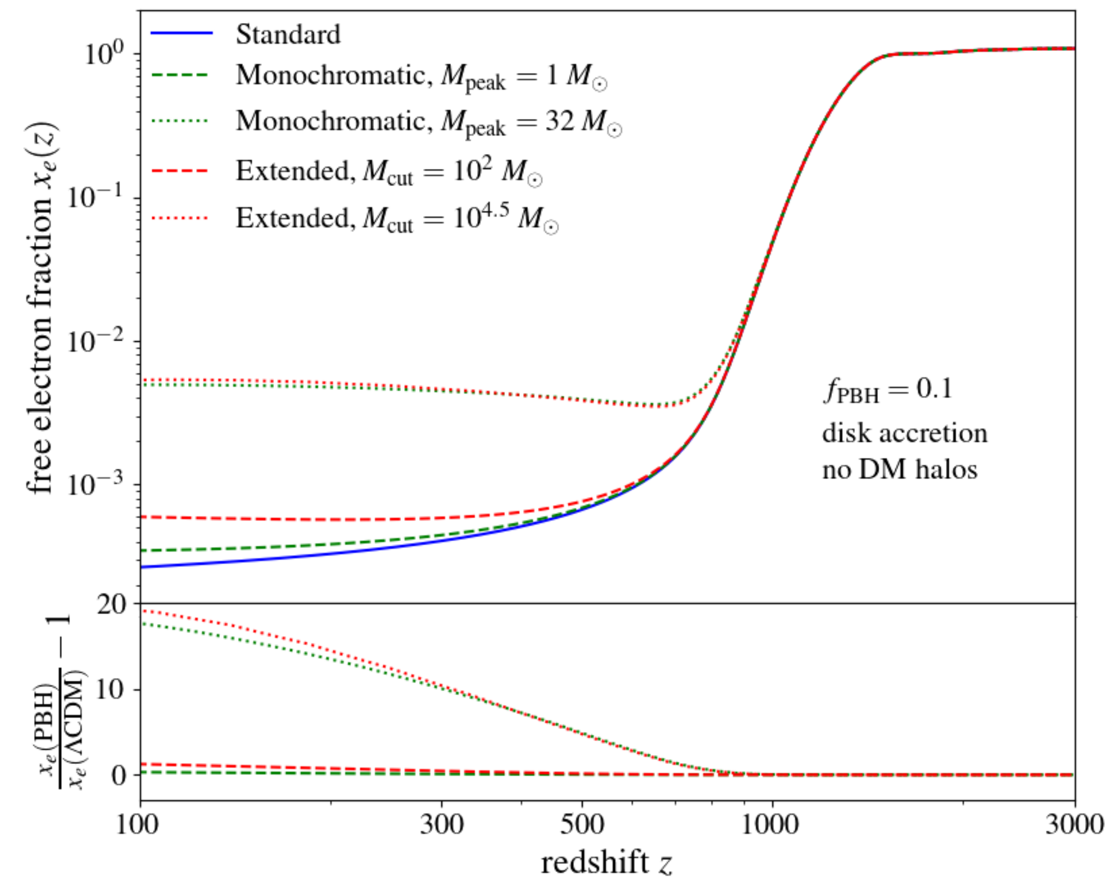


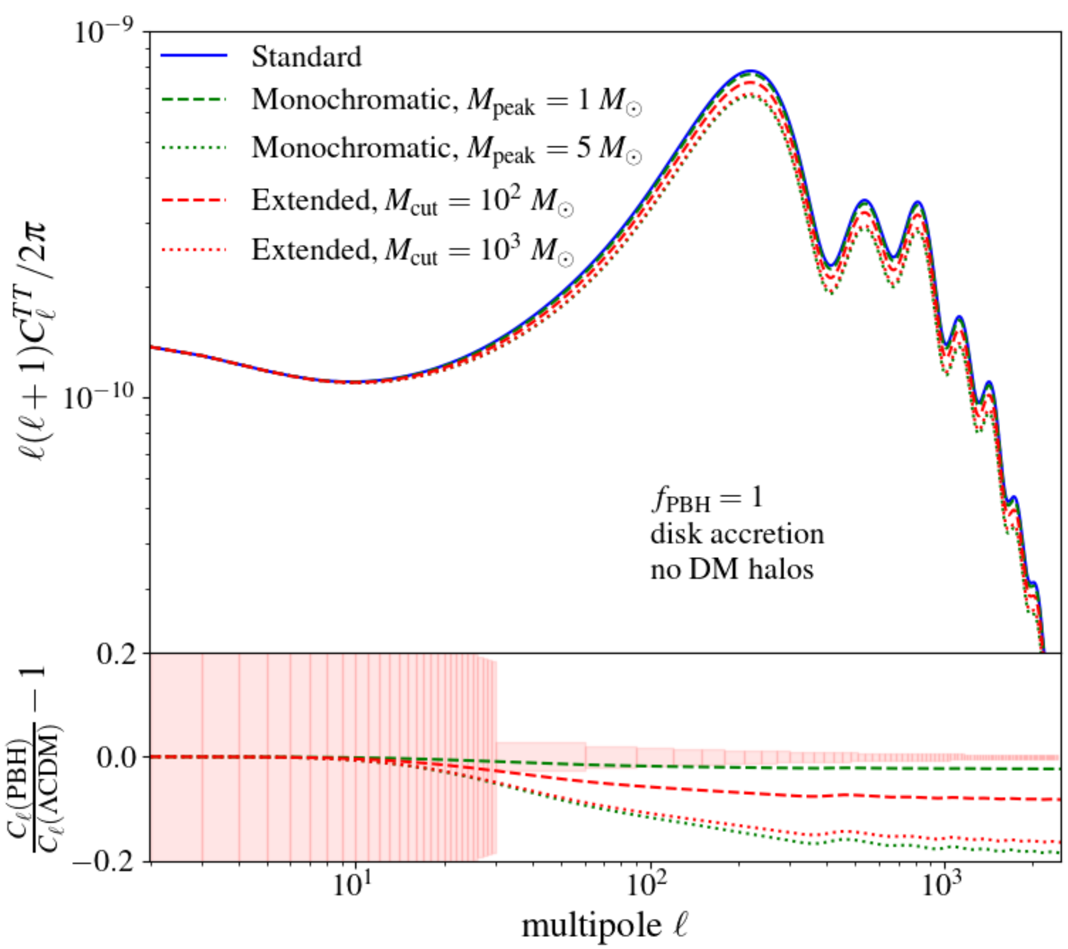


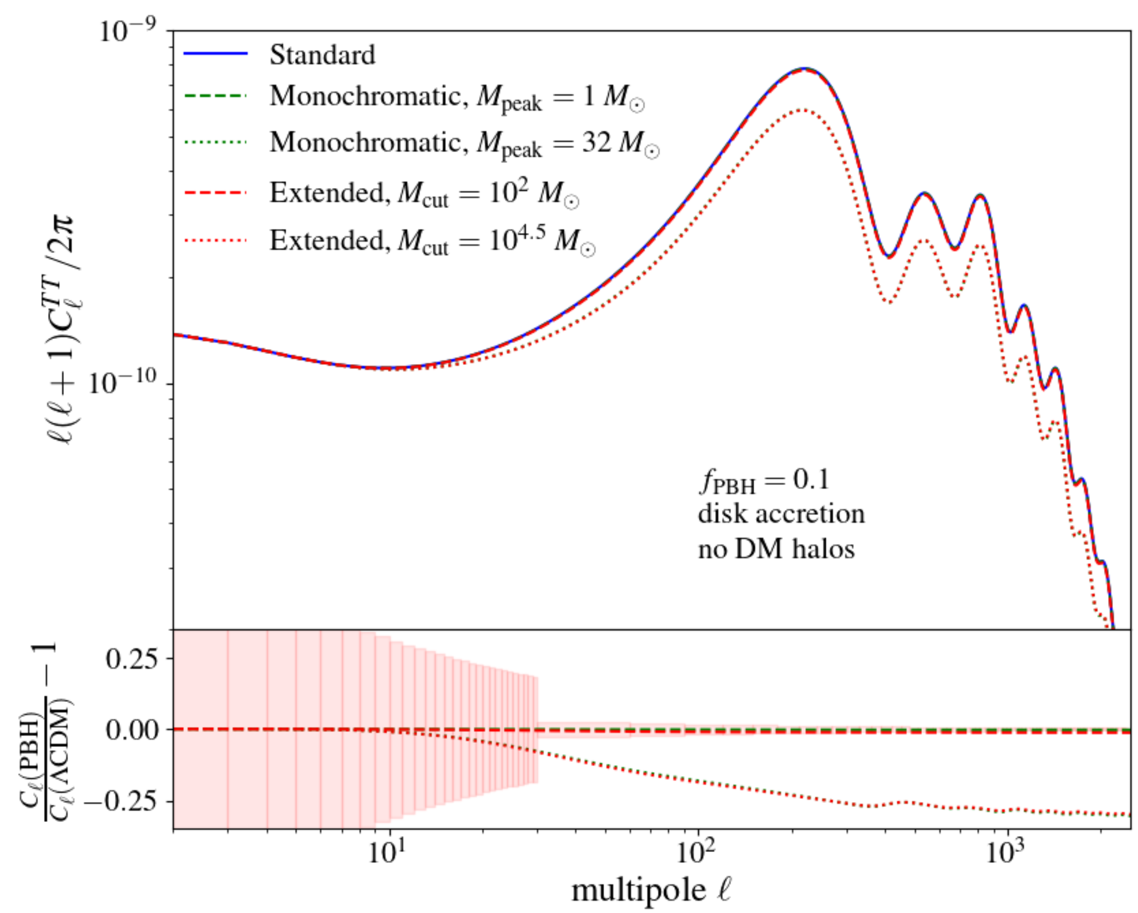
PDS, V. Poulin, D. Inman and K. Kohri, Phys.Rev.Res. 2 (2020), 023204

Importance of extended mass function









Linear vs. nonlinear treatment of extended MF for CMB

Much slower to run CMB bounds on very extended mass functions.
For plots, bounds we used results of the monochromatic case + linear approach

B. Carr, M. Raidal, T. Tenkanen, V. Vaskonen and H. Veermäe, Phys. Rev. D 96 (2017) no.2, 023514 [arXiv:1705.05567].

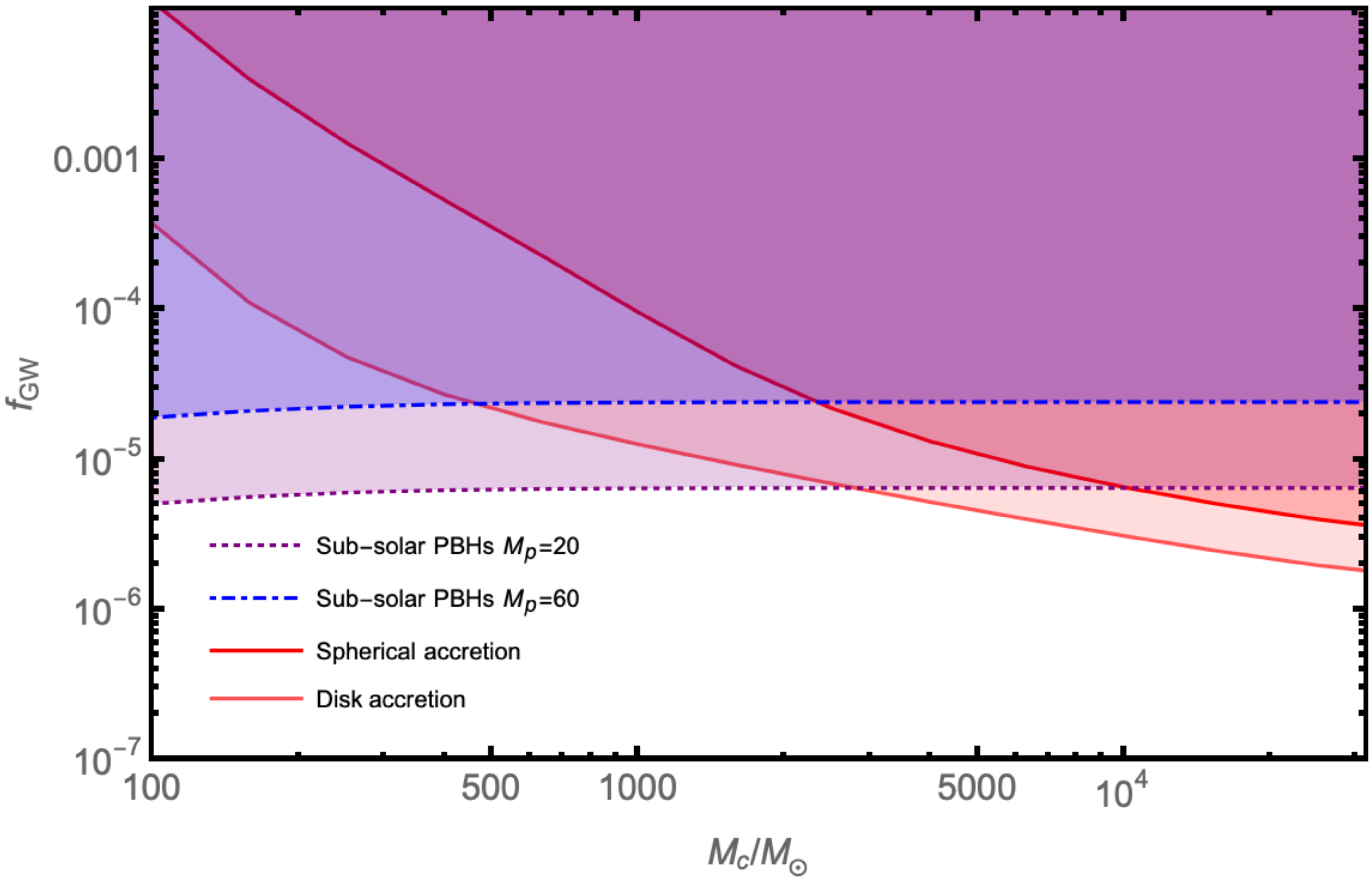
Boiling down to this formula:

$$\int_{M_{\rm min}}^{M_{\rm max}} {\rm d}M \, \frac{\psi_p(M)}{f_{\rm mono}^{\rm max}(M)} = 1$$

Is this robust? Actually turns out to be ~50% more conservative

		$f_{\rm PBH}^{\rm max}$	$f_{\rm GW}^{\rm max}$
$M_{\rm cut} = 10^2 \ M_\odot$	Full	0.129	2.83×10^{-3}
	Approx	0.177	3.88×10^{-3}
$M_{\rm cut} = 10^{4.5} \ M_\odot$	Full	1.99×10^{-3}	4.87×10^{-5}
	Approx	3.09×10^{-3}	7.54×10^{-5}

CMB bounds



This argument implies that f_{PBH}<3-8 x 10^{-4} (f_{GW}≲3-8 x 10^{-6}) if setting $M_c=10^4\,M_\odot$

Can get rid of the bound if choosing $M_c \ll 10^2\,M_\odot$

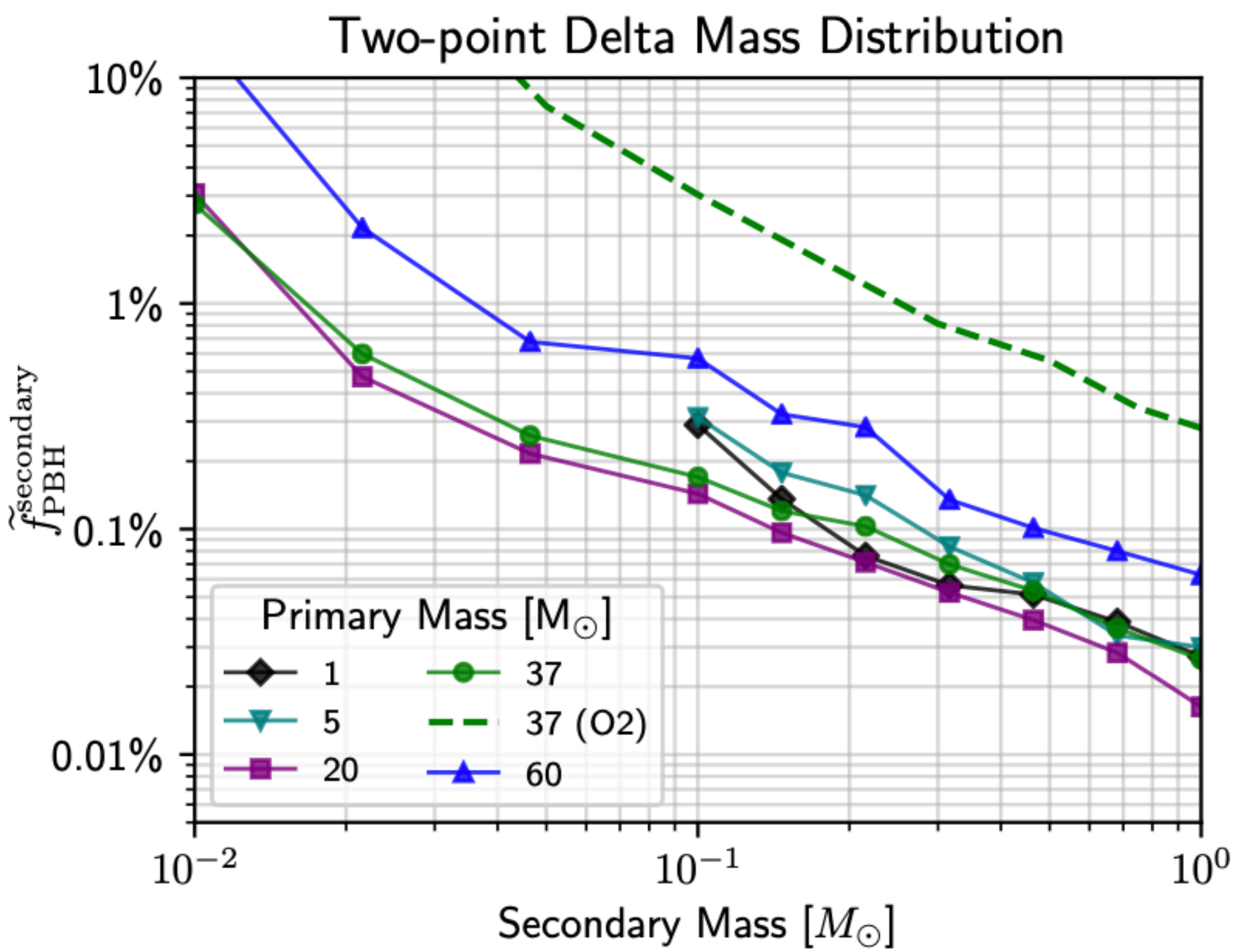
... but tension/fine-tuning with the very scales you need to explain!

Pheno consequence nr. 3 : coalescence of light PBH

Light BH mergers

No merger of compact objects with mass < 1 $M_\odot$ observed by LIGO/Virgo O3,
Sizeable number expected based on predicted mass functions!

A. H. Nitz and Y. F. Wang, "Broad search for gravitational waves from subsolar-mass binaries through LIGO and Virgo's third observing run," arXiv:2202.11024



This argument implies that $f_{GW} \lesssim 10^{-5}$ ($f_{PBH} \lesssim 10^{-3}$)

Some model-dependence on these calculations, but most uncertainties affect equally the normalisation to fit LIGO/Virgo

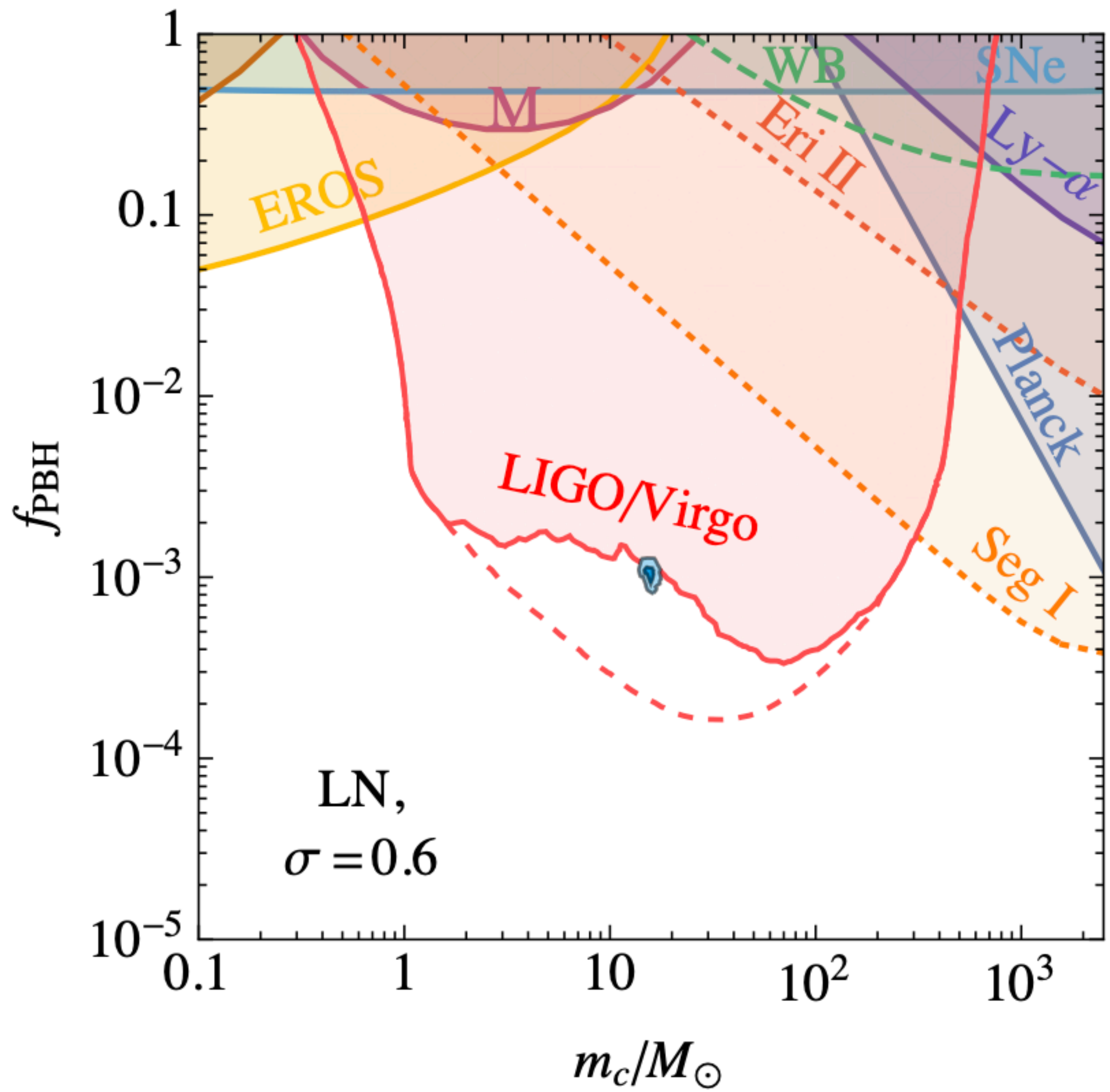
Lack of *even heavier* PBH mergers (200-300 $M_\odot$)

Similar conclusion as CMB: fine-tuned sharp cutoff in mass function just above LIGO/Virgo

Constraints for log-normal PBH mass function with σ = 0.6. The red dashed curve shows the 2σ CL constraint from LIGO-Virgo obtained assuming that all observed events are astrophysical

the solid red curve presents the 2σ CL constraint when the observed events are taken into account.

The blue region right below the solid red curve indicates the PBH fit to all observed events



G. Hütsi, M. Raidal, V. Vaskonen and H. Veermäe, JCAP 03 (2021), 068 [arXiv:2012.02786]

Loopholes?

1. Mergers

Can the MF be changed via hierarchical mergers (HM) in the dark ages?

1. Altering the bulk of the MF via HM is **way** above what theoretical expected
2. Even a **single** merger on average exceeds the stochastic GW background bound

E. S. Phinney, "A Practical theorem on gravitational wave backgrounds," [astro-ph/0108028]

$$\Omega_{\mathrm{GW}}(\nu) = \frac{\nu}{\rho_c} \int_0^{\nu_{\mathrm{cut}}} \frac{N(z)}{1+z} \left(f_r \frac{\mathrm{d}E_{\mathrm{GW}}}{\mathrm{d}f_r} \right) \mathrm{d}z$$

$f_r = f(1+z)$

Pheno parameterisation of a 'Gaussian bump' around $z = z_p$

$$N_{\mathrm{bump}}(z) = \frac{f_{\mathrm{PBH}} \Omega_{\mathrm{DM}} \rho_c}{M_{\mathrm{PBH}} \sqrt{2\pi\sigma^2}} \exp\left[-\frac{(z - z_p)^2}{2\sigma^2} \right]$$

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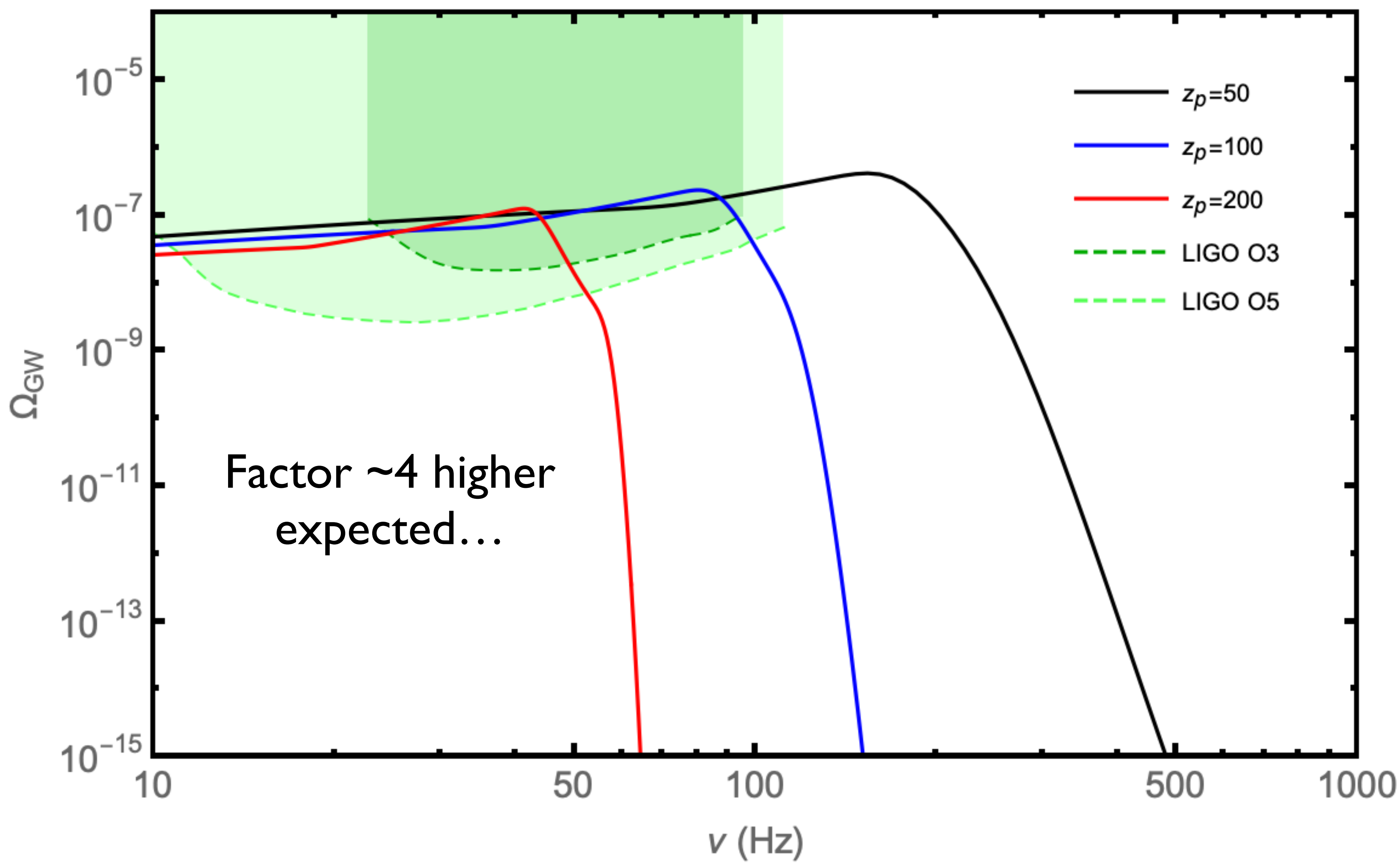


2. Accretion

To avoid problems with CMB, should not take place at z≫10
(and at z≫10, irrelevant even for $L \sim L_{Eddington}$)

Hence, significant accretion should take place when cosmo structures far from linear, halos form: no reliable calculations exist!

Can the mass growth be of 2 orders of magnitude @ z≲O(10)?

2. Accretion

To avoid problems with CMB, should not take place at $z \gg 10$
(and at $z \gg 10$, irrelevant even for $L \sim L_{Eddington}$)

Hence, significant accretion should take place when cosmo structures far from linear, halos form: no reliable calculations exist!

Can the mass growth be of 2 orders of magnitude @ $z \lesssim O(10)$?

No 'no go' theorem, but:

- Would require 0.5% of the total baryonic matter of the universe involved in accretion phenomena in the dark ages (about 10% of the whole stellar production ever!)
- Would violate our hypothesis: The mass function seen by LIGO/Virgo would be determined by unknown astrophysics rather than by QCD physics
- Would naturally offer another, more obvious astrophysical solution to the 'problem' of heavy BH seen by LIGO/Virgo: The same putative accretion acting on astro BH…

Spectral distortions

CMB spectral distortions

A *spectral distortion* of the CMB expected due to enhanced small-scale fluctuations (think of superposition of blackbodies at different temperatures, which is not a blackbody…)

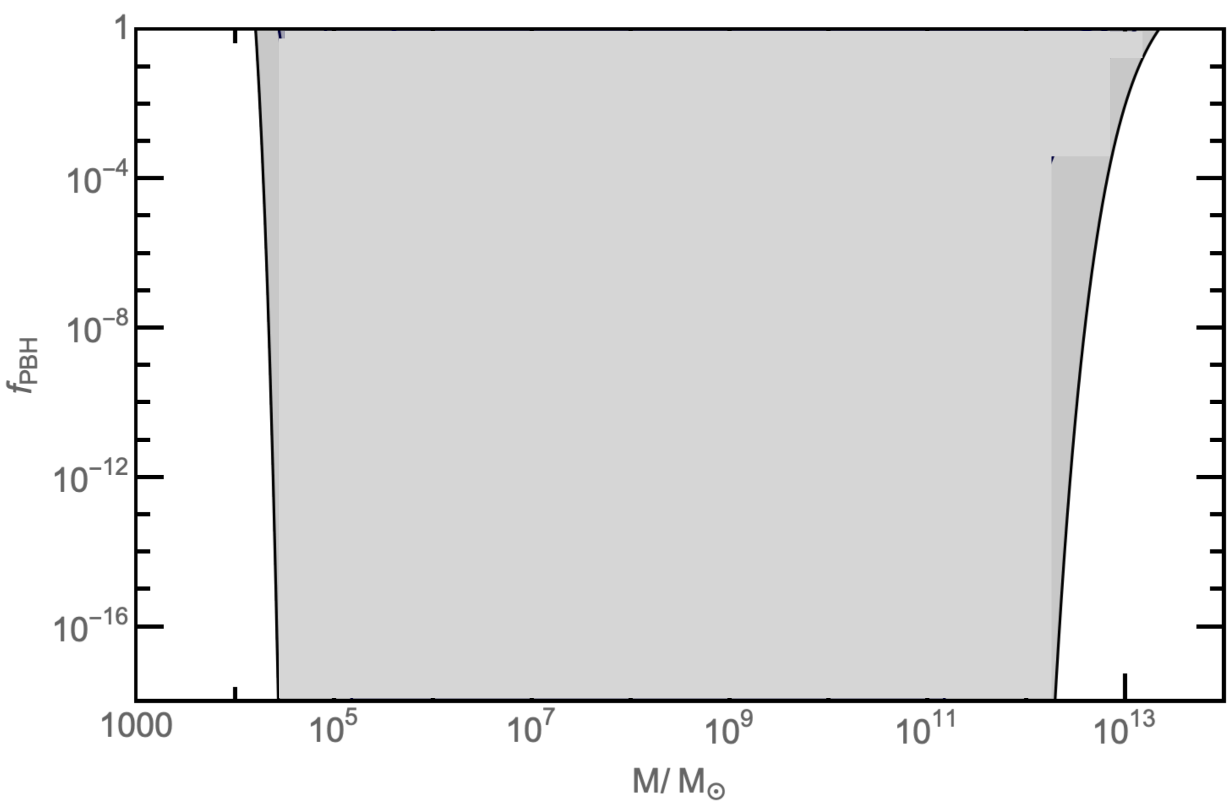
Large small-scale fluctuations required to generate PBH should give rise to spectral distortions of the CMB

Details e.g. in *J. Chluba, A.L. Erickcek and I. Ben-Dayan, Astrophys. J. 758 (2012), 76 [arXiv:1203.2681]*

$$\mu \simeq 1.4\frac{\Delta\rho_\gamma}{\rho_\gamma} = 1.4\int_{5\times10^4}^{\infty} \mathcal{J}_{bb}(z)\frac{1}{\rho_\gamma}\frac{\mathrm{d}Q_{ac}}{\mathrm{d}z}\mathrm{d}z$$

$$\frac{1}{\rho_\gamma}\frac{\mathrm{d}Q_{\rm ac}}{\mathrm{d}z} \approx 9.4a\int \frac{k\;\mathrm{d}k}{k_{\rm D}^2}\mathcal{P}_\zeta(k)2\sin^2\left(kr_{\rm s}\right)e^{-2k^2/k_{\rm D}^2}$$

COBE-FIRAS bound $\mu \lesssim 9\times10^{-5}$



Window of masses excluded
(scales controlled by photon mfp and epoch at which double Compton scattering becomes ineffective)

For small, gaussian temperature perturbations

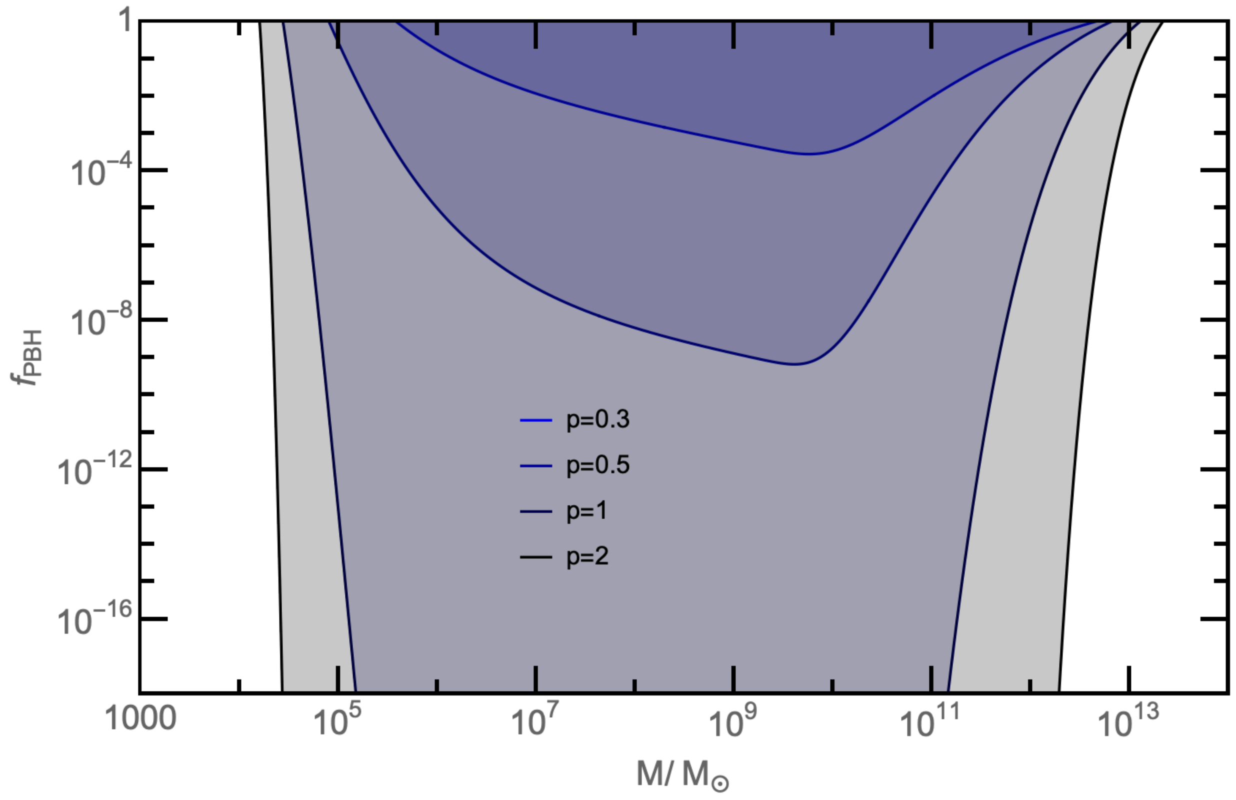
$$\mu \simeq 2.8\langle\theta^2\rangle \qquad \theta = (\delta T/T)$$

CMB spectral distortions - evaded with non-gaussianities?

Proposed that going to (very) NG pdf's, these bounds can be 'evaded'.

$$P(\zeta) = \frac{1}{2\sqrt{2}\tilde{\sigma}\Gamma(1+1/p)} \exp\left[-\left(\frac{|\zeta|}{\sqrt{2}\tilde{\sigma}}\right)^p\right]$$

T. Nakama, T. Suyama and J. Yokoyama, PRD 94 (2016) 103522 [arXiv:1609.02245]
T. Nakama, B. Carr and J. Silk, PRD 97 (2018) 043525 [arXiv:1710.06945]



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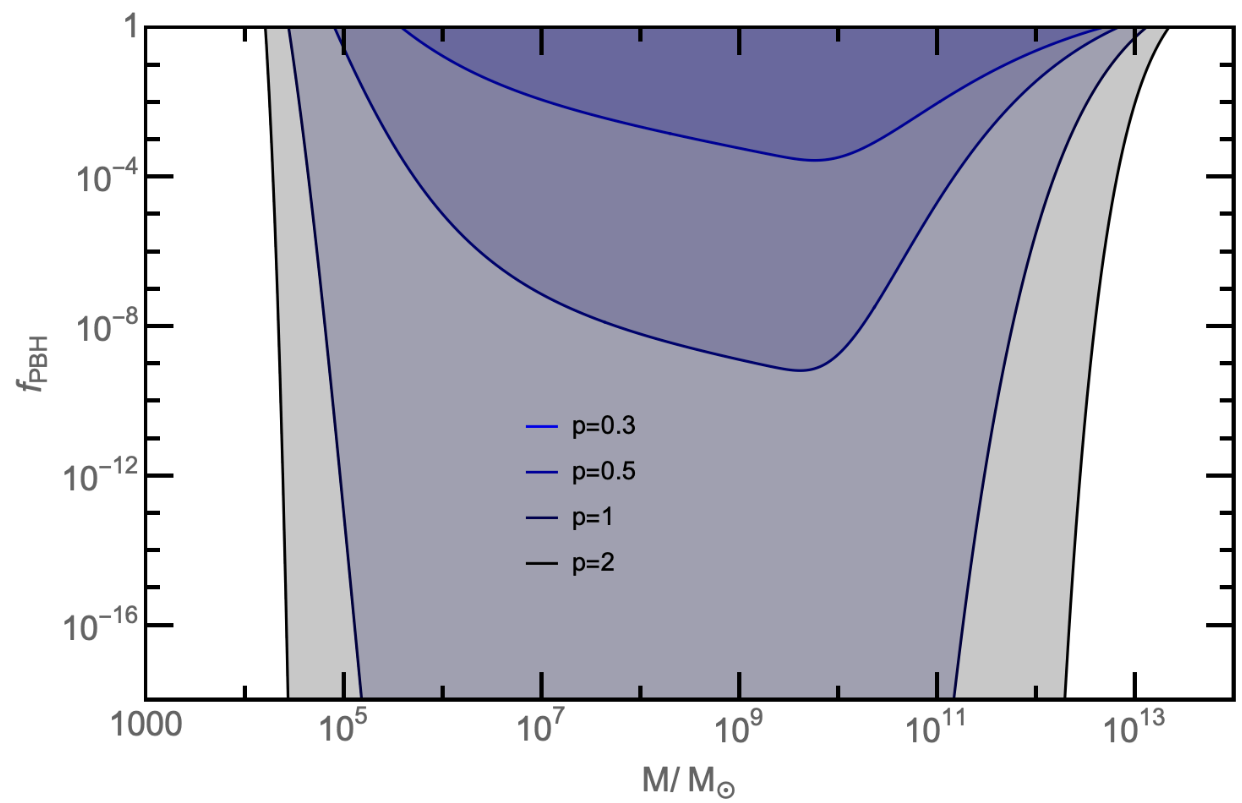

There is a limit to this argument, in the sense that non-linearities and non-gaussianities eventually matter!

$$\mu = 1.4\left(\left[1+6\langle\theta^2\rangle+4\langle\theta^3\rangle+\langle\theta^4\rangle\right]-\left[1+3\langle\theta^2\rangle+\langle\theta^3\rangle\right]^{4/3}\right)$$

The 'Gaussian' relations

$$\langle\theta^{2n+1}\rangle = 0\,,\, \langle\theta^{2n}\rangle \sim \left(\langle\theta^2\rangle\right)^n$$

may not hold