**Sébastien Clesse**
**Service de physique Théorique,**
**Université Libre de Bruxelles (ULB)**

# Popcorn in the sky

## How to distinguish the GW background from primordial black holes?

*Eleni Bagui, S.C., Federico De Lillo,*
*Alex Jenkins, Mairi Sakellariadou, in preparation*

**GW Orchestra workshop - September 8-9, 2022**
**Louvain-la-Neuve, Belgium**



*Background picture: artist view of GW190521 by Ingrid Bourgault*

# Outline

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- A quick **review** of **PBHs**

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- A boosted **gravitational-wave background** from PBHs with a broad mass distribution

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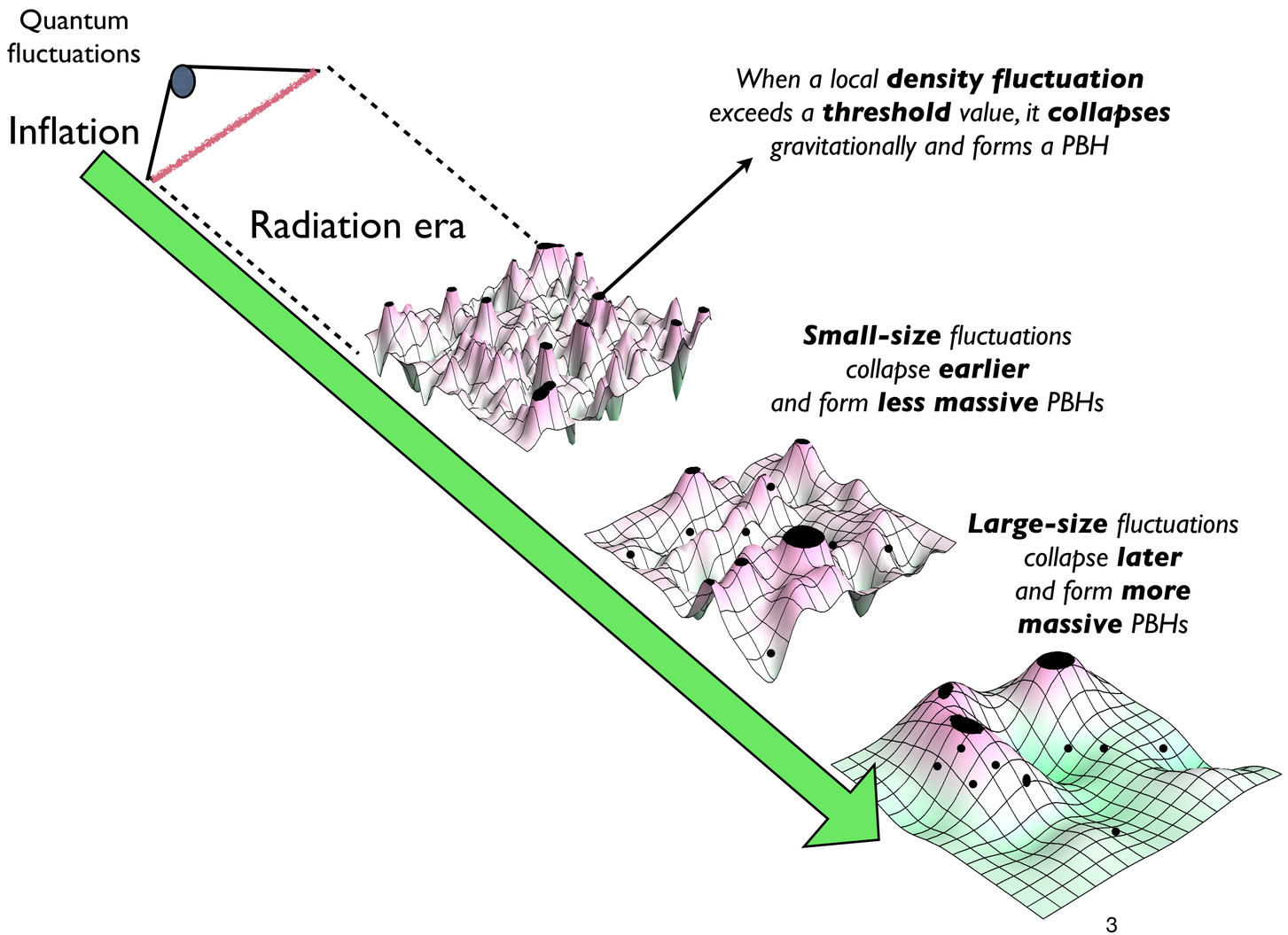
- A quick **review** of **PBHs**

- A boosted **gravitational-wave background** from PBHs with a broad mass distribution

- **Popcorn** vs continuous backgrounds: a possible way to **distinguish stellar vs primordial** black holes

# A quick review of PBHs

## PBH formation: a simple but fine-tuned process



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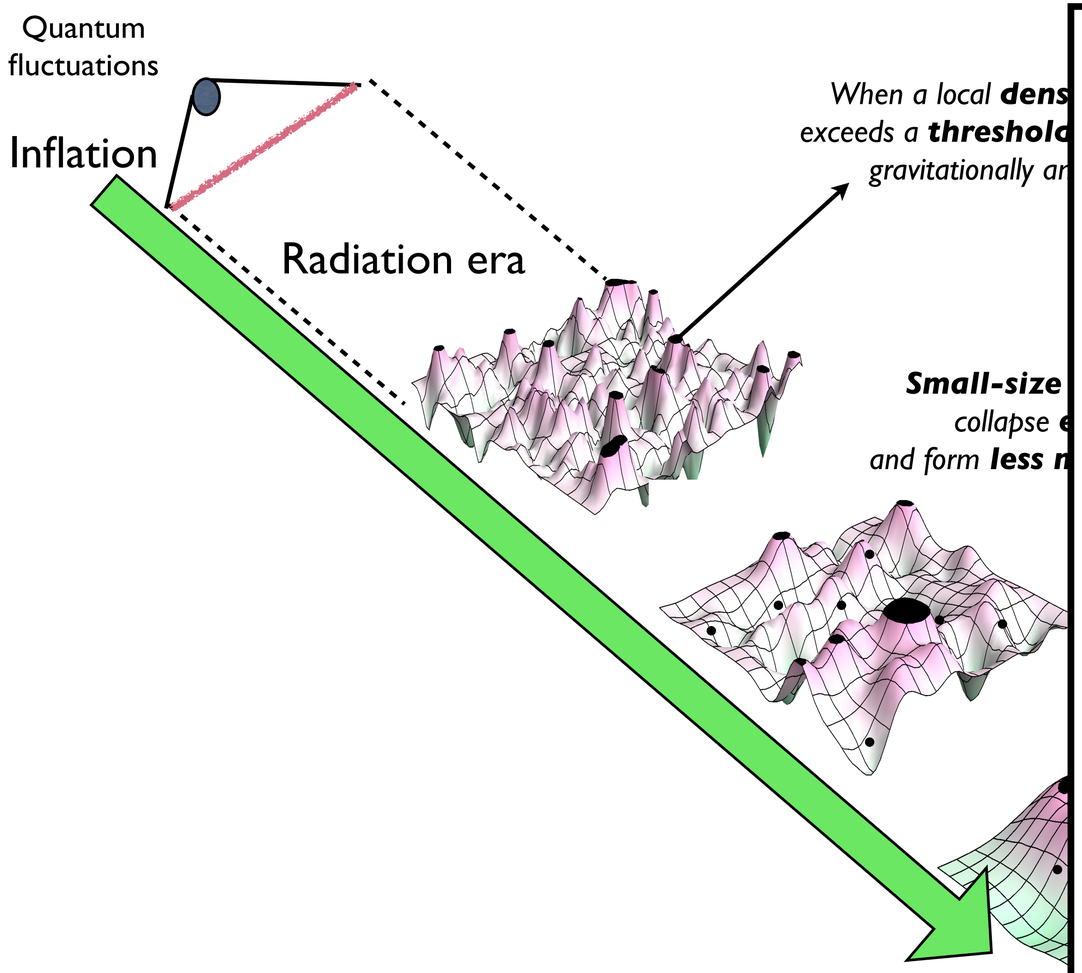


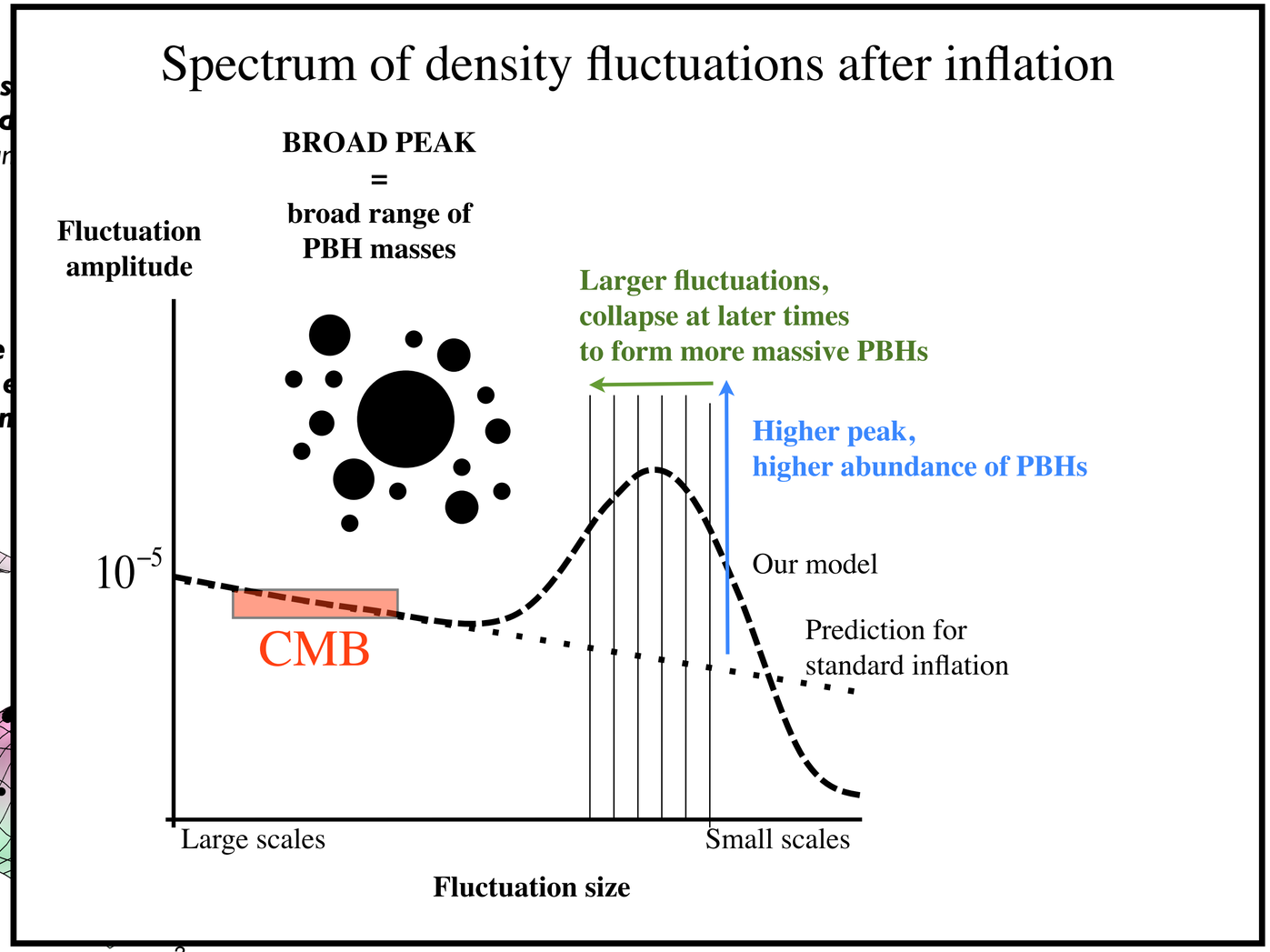

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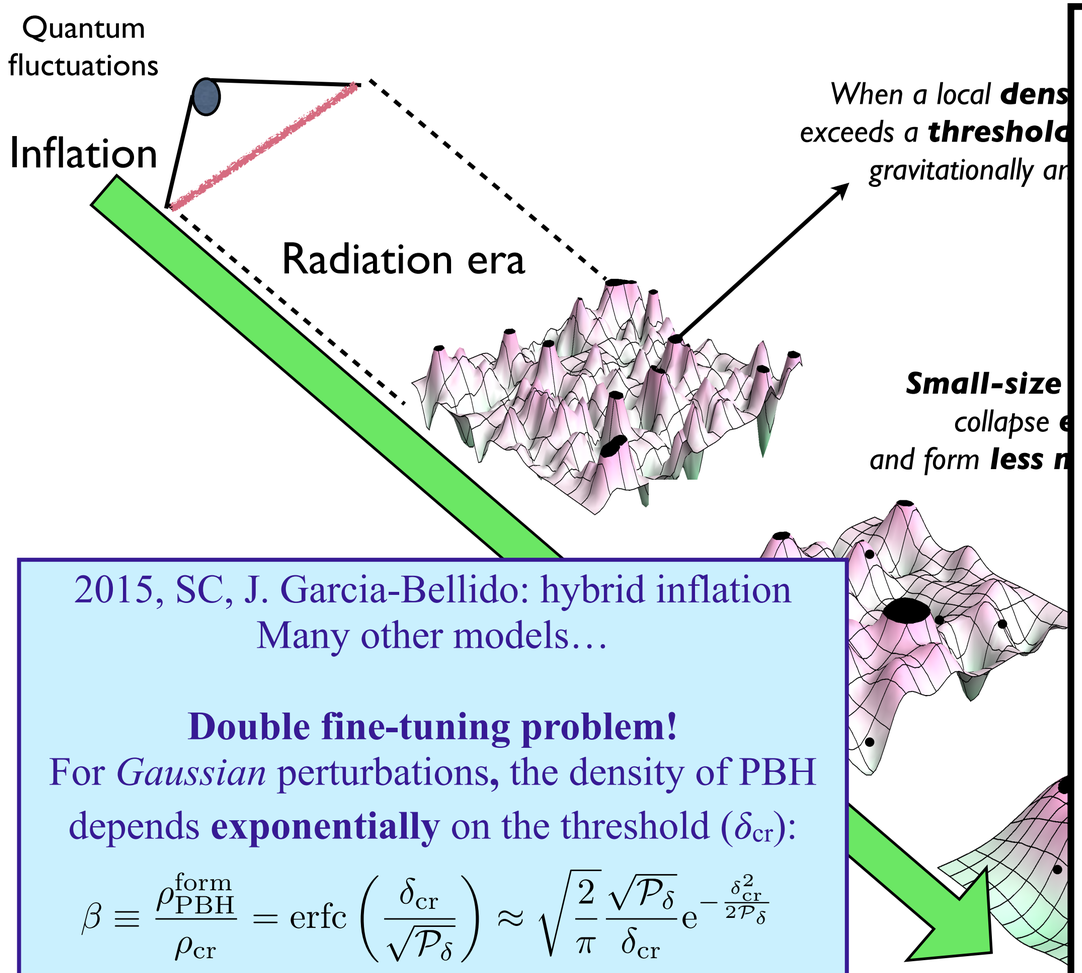
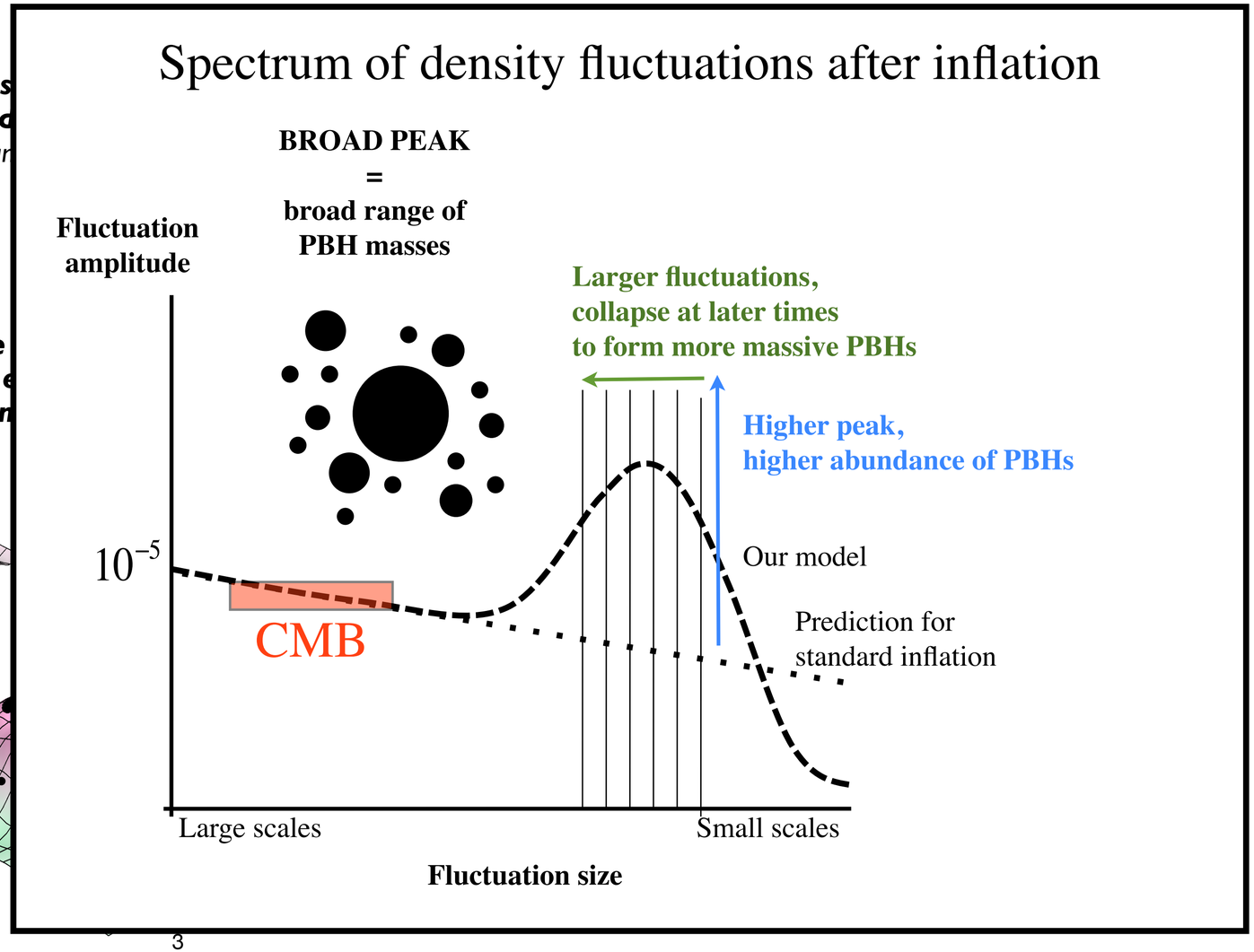



2015, SC, J. Garcia-Bellido: hybrid inflation
Many other models…

**Double fine-tuning problem!**
For *Gaussian* perturbations, the density of PBH depends **exponentially** on the threshold ($\delta_{\rm cr}$):

$$\beta \equiv \frac{\rho_{\rm PBH}^{\rm form}}{\rho_{\rm cr}} = {\rm erfc}\left(\frac{\delta_{\rm cr}}{\sqrt{\mathcal{P}_\delta}}\right) \approx \sqrt{\frac{2}{\pi}}\frac{\sqrt{\mathcal{P}_\delta}}{\delta_{\rm cr}}{\rm e}^{-\frac{\delta_{\rm cr}^2}{2\mathcal{P}_\delta}}$$



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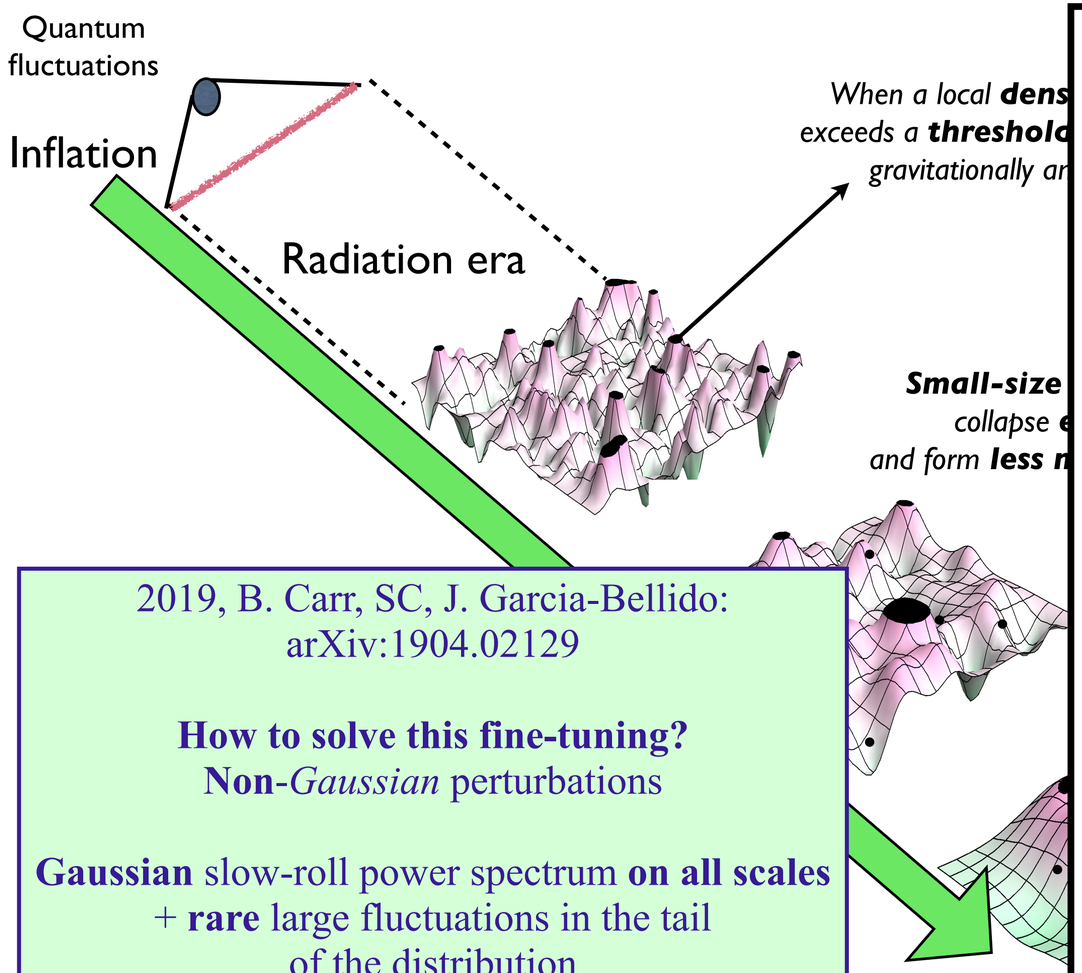
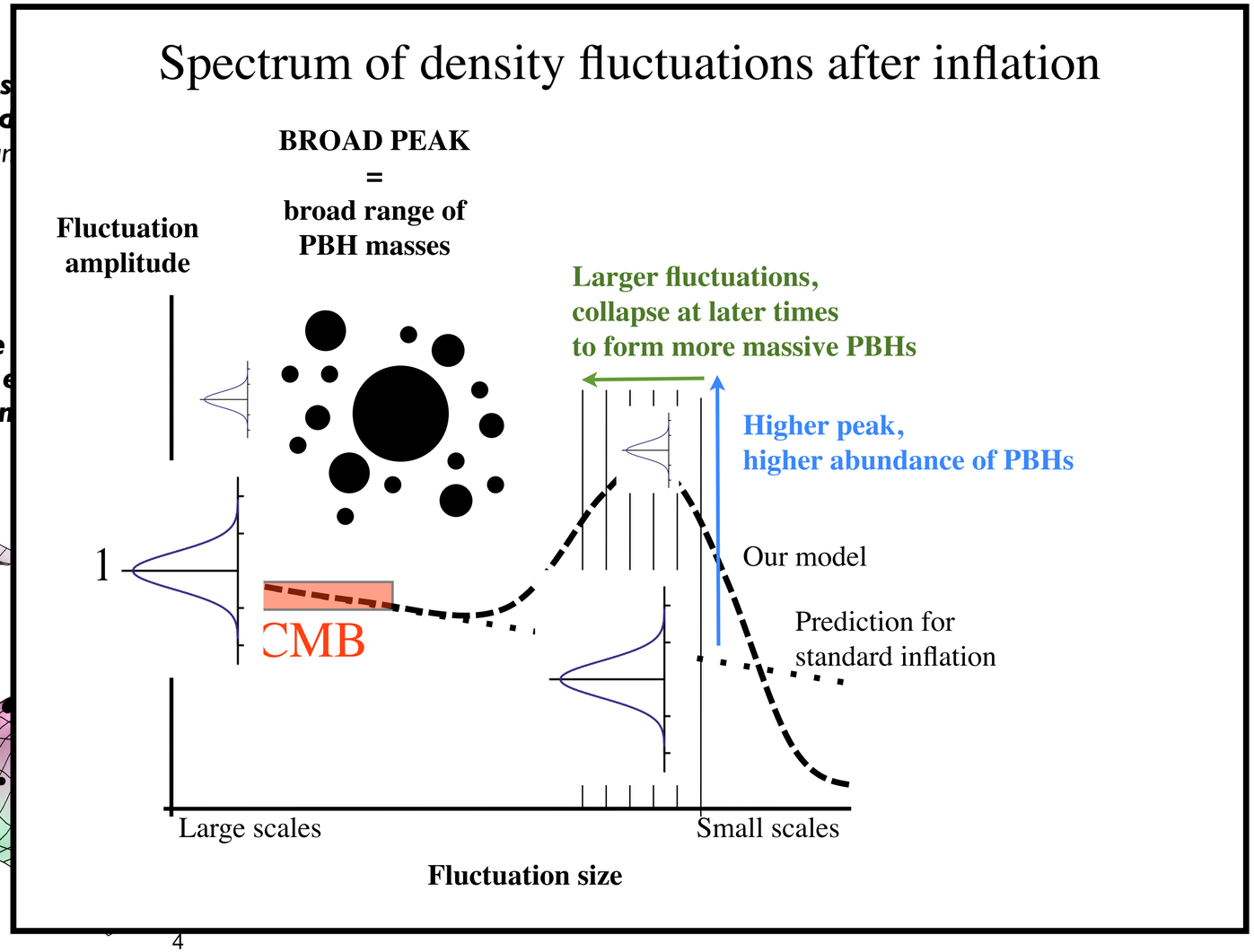



2019, B. Carr, SC, J. Garcia-Bellido:
arXiv:1904.02129

**How to solve this fine-tuning?**
**Non-*Gaussian*** perturbations

**Gaussian** slow-roll power spectrum **on all scales**
+ **rare** large fluctuations in the tail
of the distribution
from a **stochastic spectator field**



# A quick review of PBHs

## PBH formation at the QCD transition

From *known* thermal history:

- Change in the **number of relativistic degrees of freedom**
- **Equation of state** reduction, particularly at the QCD transition
- **Critical threshold** is **reduced**
- **Boosted PBH formation**, resulting in a bumpy mass function

**Jedamzik, astro-ph/9605152**
Cardal & Fuller, astro-ph/9801103
Jedamzik & Niemeyer, astro-ph/9901293
**Byrnes, Hindmarsh, Young, Hawkins, 1801.06138**
Carr, S.C., Garcìa-Bellido, Kühnel, 1906.08217
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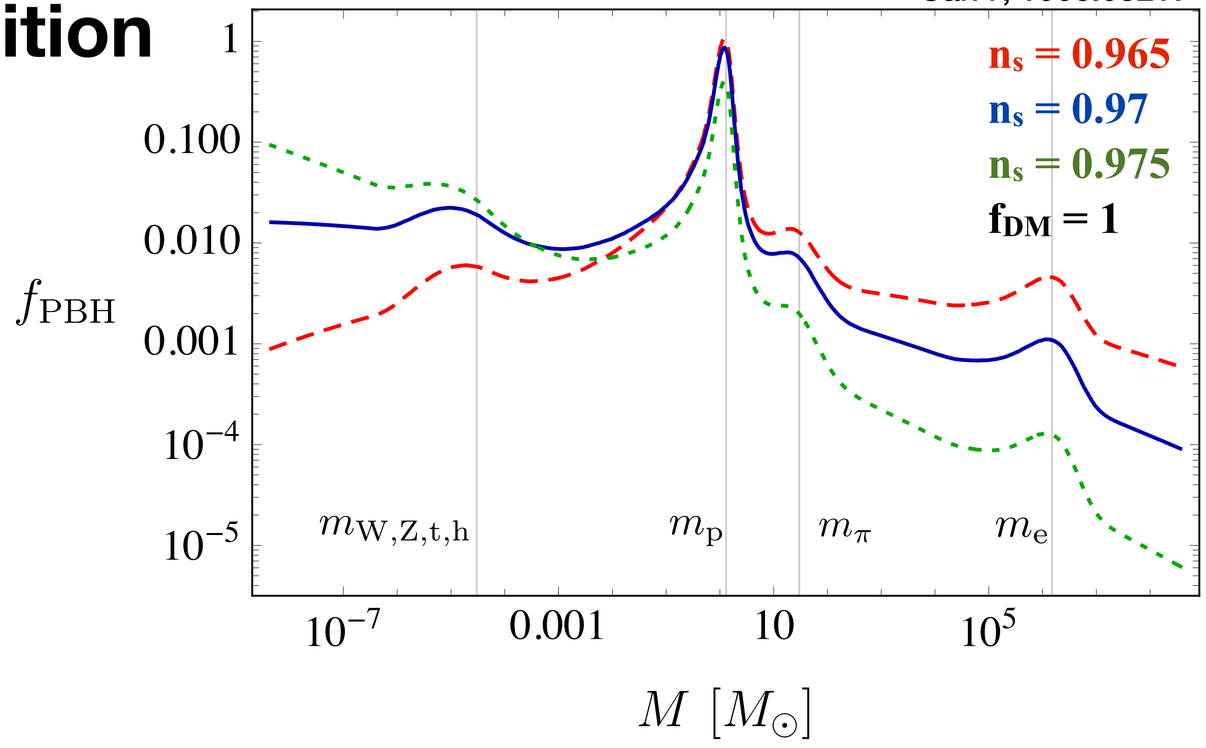
Carr+, 1906.08217



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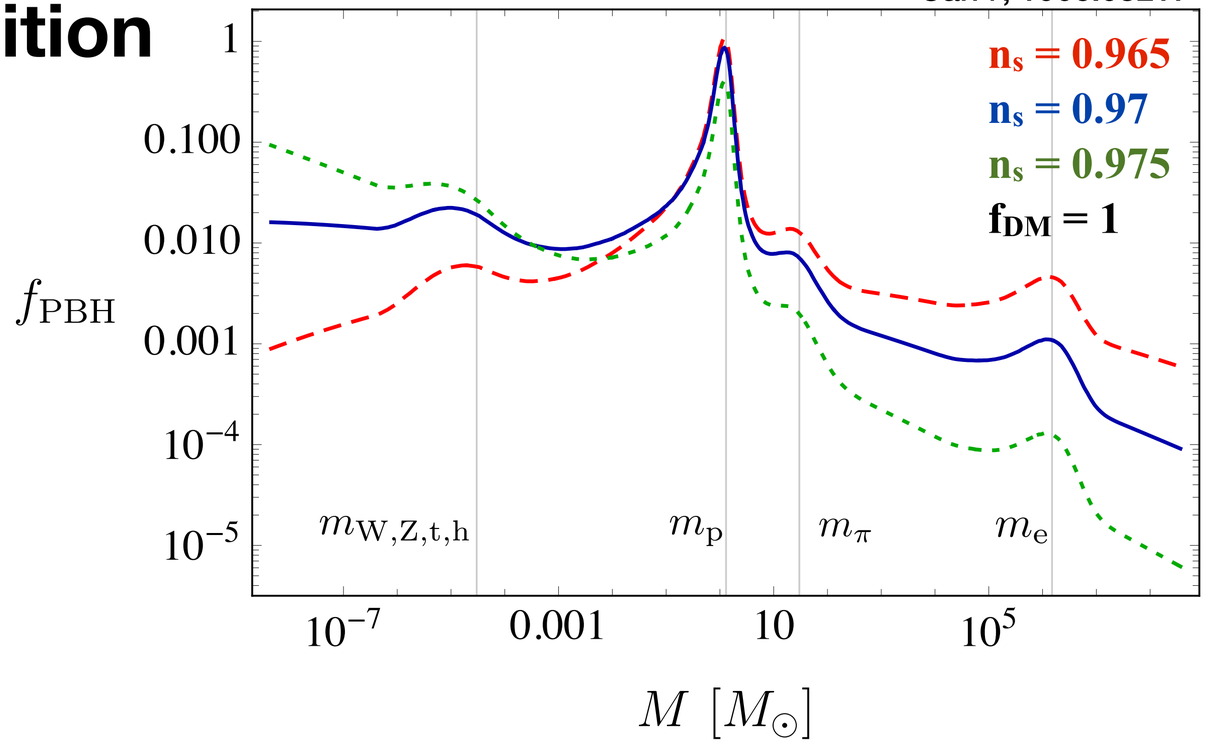


- **Nearly scale-invariant spectrum**
- **Spectral index: $n_s = 0.97$**
- **Peak at ~[2-3] $M_\odot$**
- **Second peak at ~30 $M_\odot$**
- **Two bumps at $10^{-6}$ and $10^6$ $M_\odot$**

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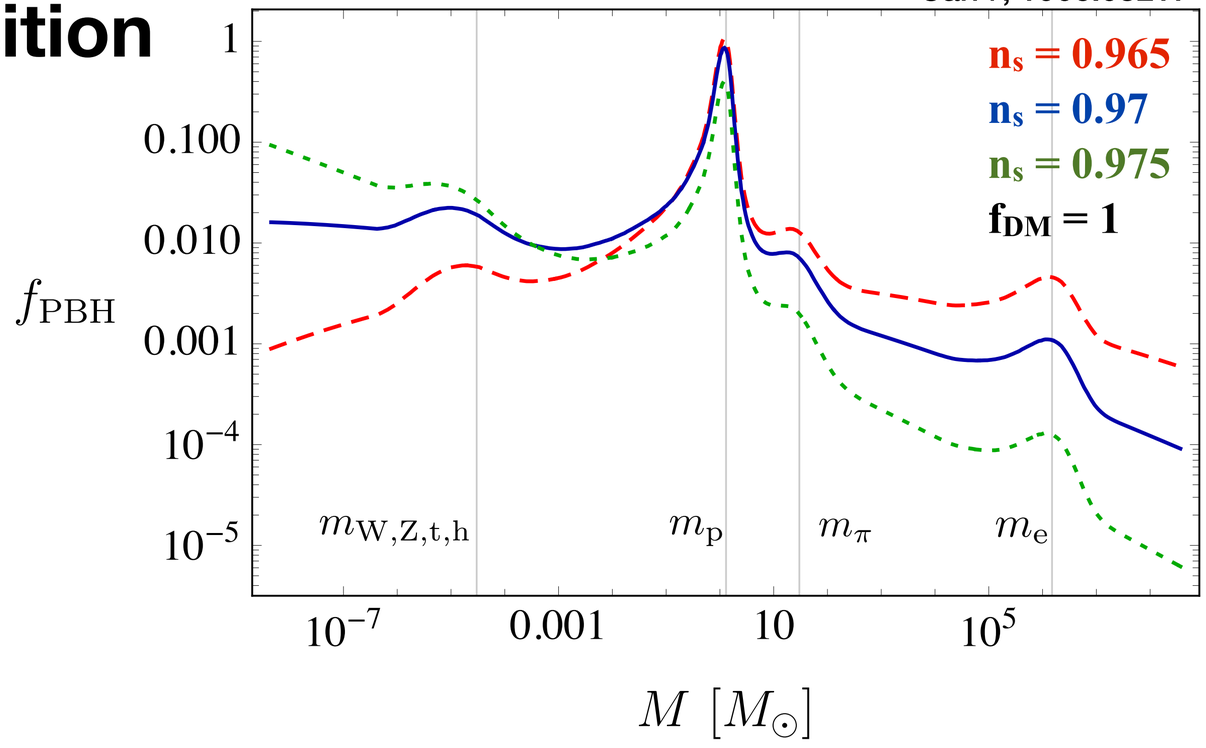
✓ **Inevitable**
✓ **Naturally** leads to **stellar-mass** PBHs

Carr+, 1906.08217

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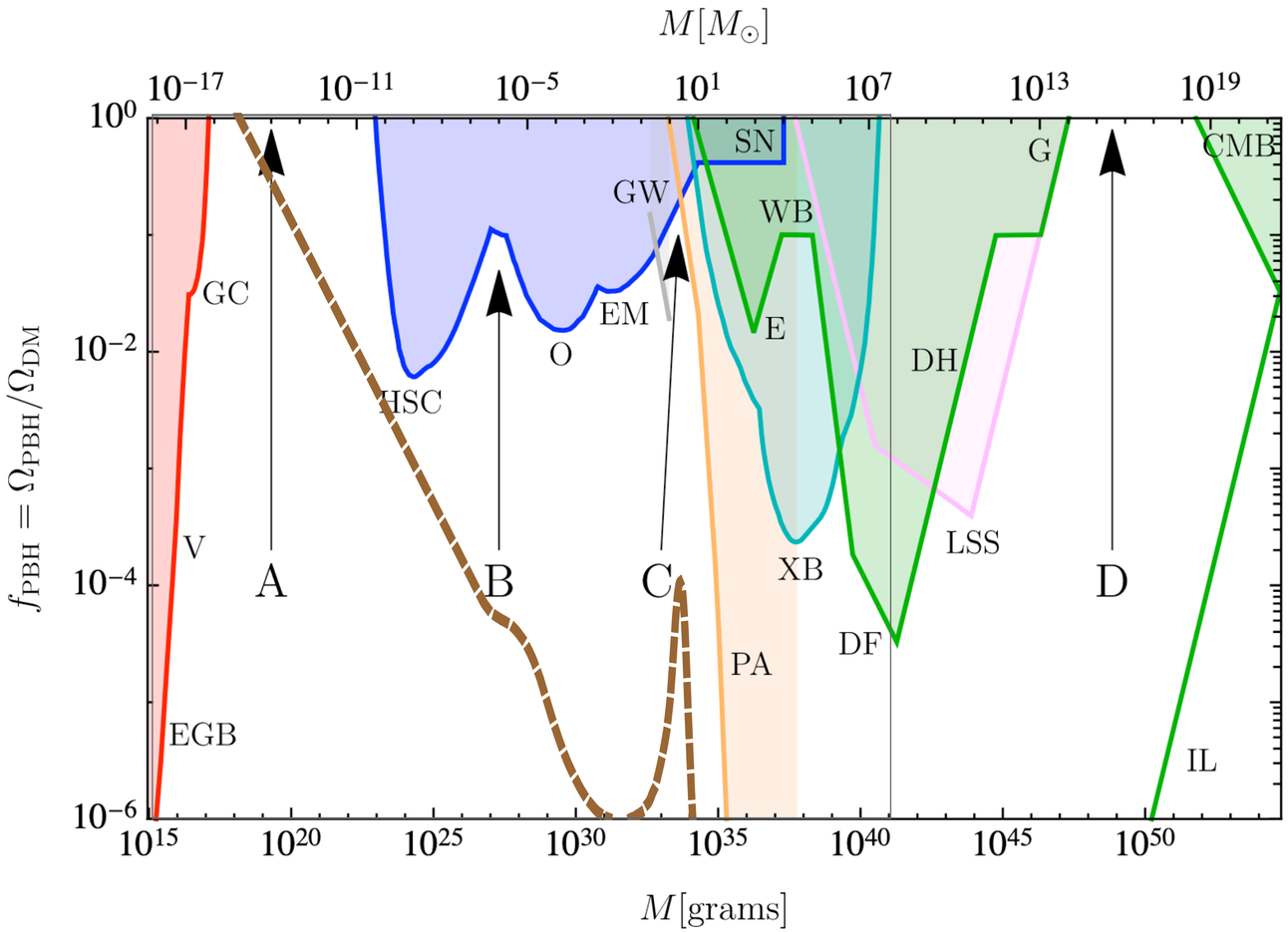
# A quick review of PBHs

## Limits vs clues: a question of point of view




Carr & Kuhnel, 2006.02838

Hawking radiation

Microlensing

LIGO-Virgo

CMB

Dynamical effects

Accretion

Large scale structures

✔ Solar mass region excluded by several probes
✔ No limit on asteroid-masses
✔ If PBHs + WIMPs (or particle DM) => stronger limits (e.g. [Serpico+20] [Carr+20] [Byrnes+] [Boudaud+21])

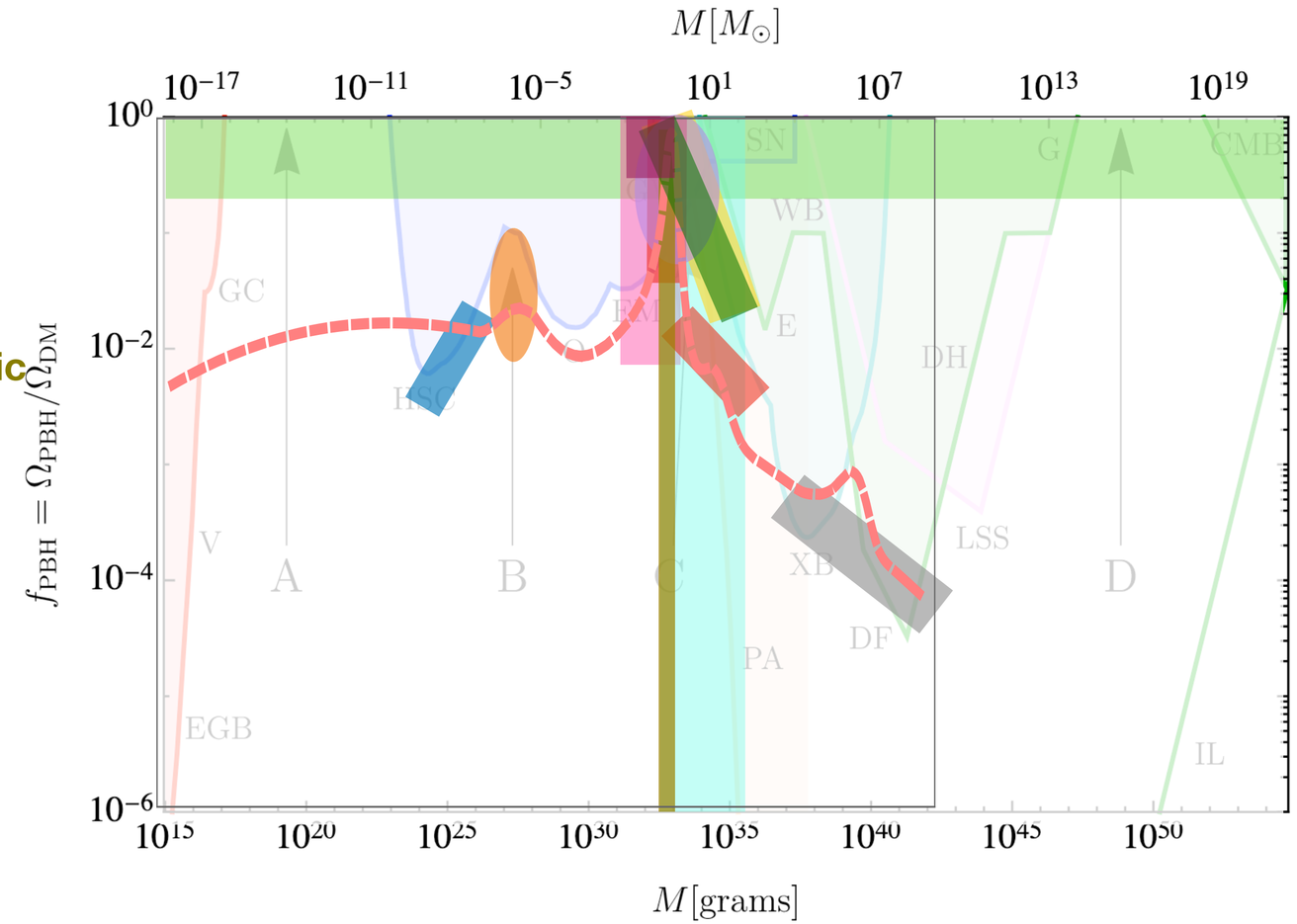
◉ Lot of uncertainties: simple assumptions (e.g. clustering, accretion), model dependences…

De Luca, Franciolini, Riotto et al., 2009.08268

# A quick review of PBHs

## Limits vs clues: a question of point of view

- Dark Matter [Chapline 75, Carr+Hawking 75]
- HSC: short microlensing event [Niikura+17]
- OGLE: microlensing in galactic center [Mros+17]
- Quasar micrrolensing in non-aligned galaxies [Hawkins], (+microlensing in M31 and SMC/LMC)
- OGLE+Gaia: BHs in the low mass gap, towards the galactic center) [Wyrzykowski+19]
- Critical radius of ultra-faint dwarf galaxies [SC+17]
- Core-cusp problem [SC+17, Boldrini+19]
- LIGO/Virgo (solar-mass and 20-100 solar mass)
- GW background from pulsar timing arrays [De Luca+19]
- Subsolar triggers in LIGO-O2 (Phukon+21)
- X-ray / infrared correlations (Kashlinsky 16)
- Intermediate-mass and supermassive black holes (one per halo and BH-halo mass relation) [Carr+19]




◉ Problem microlensing limits ?
◉ Problem with CMB limits (Serpico+22) ?

# A quick review of PBHs

## Merger rates

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## Merger rates

**Early binaries**

$$R^{\rm early} = \frac{1.6\times 10^6}{{\rm Gpc}^3\,{\rm yr}}\, f_{\rm sup}(m_1, m_2, z)\, f_{\rm PBH}^{53/37}\, f(m_1)\, f(m_2) \left[\frac{t(z)}{t_0}\right]^{-34/37}$$

$$\times \left(\frac{m_1+m_2}{M_\odot}\right)^{-32/37} \left[\frac{m_1\, m_2}{(m_1+m_2)^2}\right]^{-34/37} .$$

2018-2020: Raidal et al., Hutsi et al.: **$f_{sup}$ = 0.0024** if $f_{PBH}$ = 1:

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## Merger rates

### Early binaries

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2018-2020: Raidal et al., Hutsi et al.: **$f_{sup}$ = 0.0024** if $f_{PBH}$ = 1:

### Late Binaries

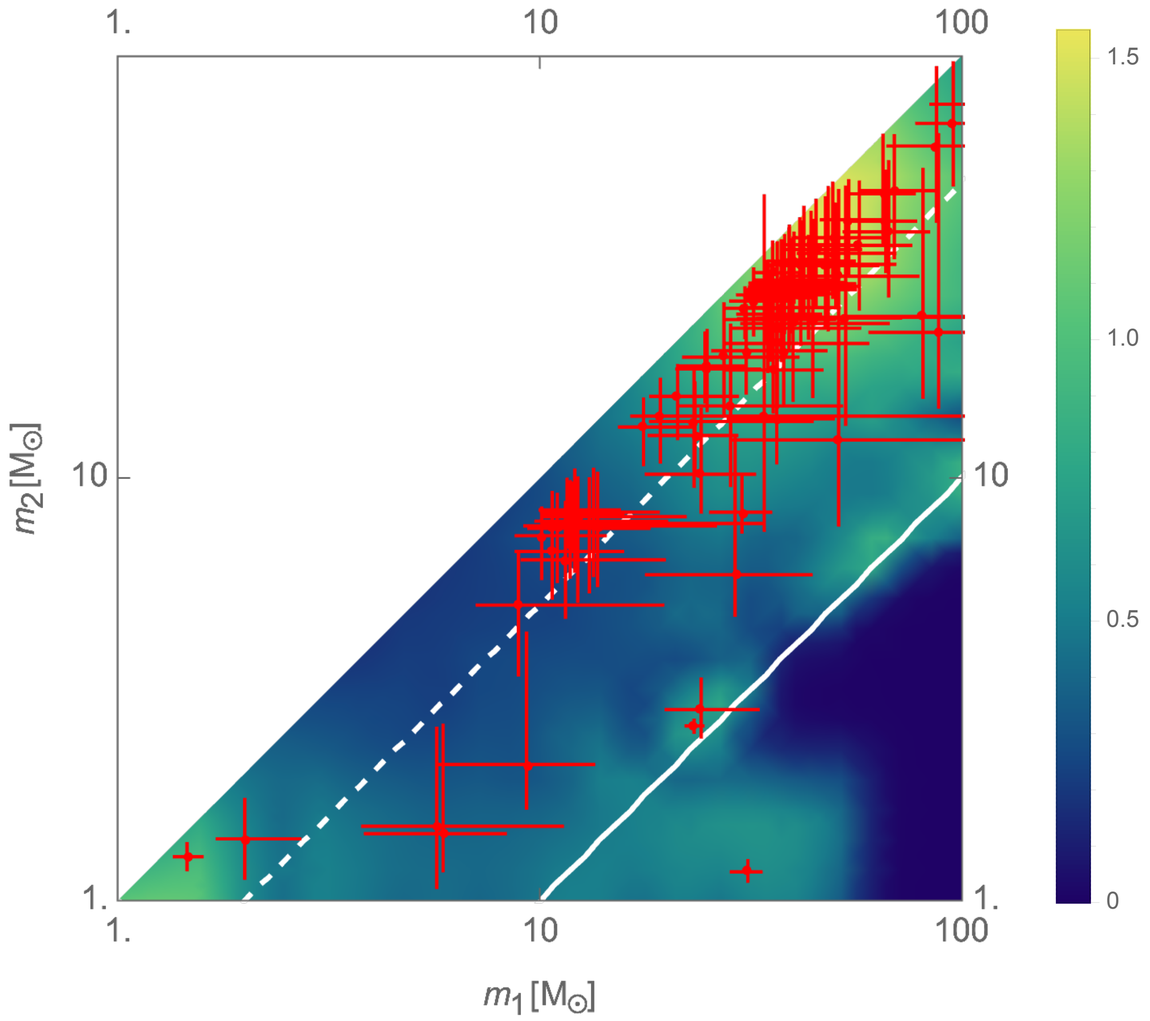
$$R^{\rm late}(m_1, m_2) = R_{\rm clust}\, f(m_1)\, f(m_2)\, \frac{(m_1+m_2)^{10/7}}{(m_1\, m_2)^{5/7}}\ {\rm yr}^{-1}\,{\rm Gpc}^{-3}$$

**Standard halo mass function:**
$R_{clust}$ = 1-10

**Poisson clustering** [SC,Garcia-Bellido 20]:
$R_{clust}$ = 100-700

# A quick review of PBHs

## Expected distribution GW detections



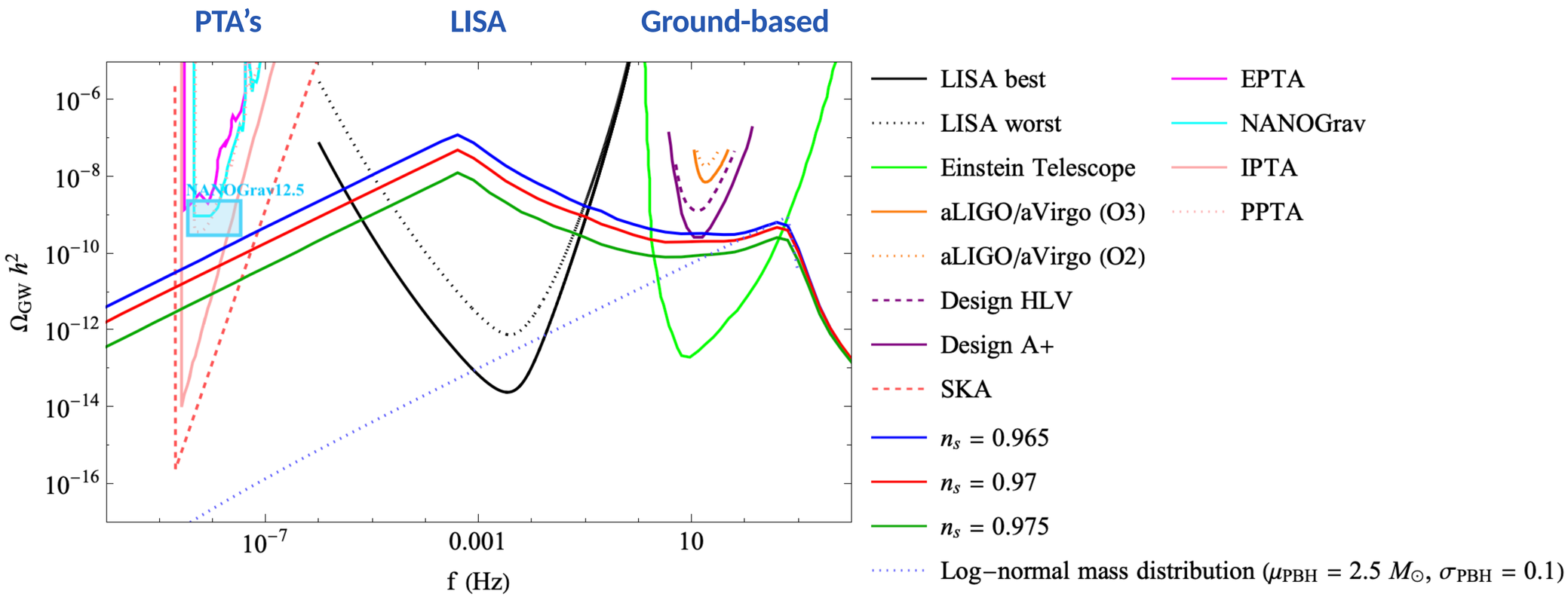

- Expected normalized distribution of BBH merger detections
- *Preliminary results: Albert Escrivà, Eleni Bagui, SC, arXiv release planned next week*
- More accurate simulations/calculations of PBH mass function
- **LIGO/Virgo O3** volume sensitivity
- PBHs can explain BH binaries, **except around 10 solar masses => astrophysical BHs ?**
- Need of population MCMC analysis to explore the entire parameter space

# A boosted GW background

## from PBHs with broad mass distributions

[E. Bagui, SC, 2021]

Gravitational-wave background from late PBH binaries in clusters:




Well **above monochromatic/lognormal** models due to **IMBH + solar mass** binaries
Could explain a detection by **NANOGrav ?** **Alternative: from 2nd order perturbations**

# A boosted GW background

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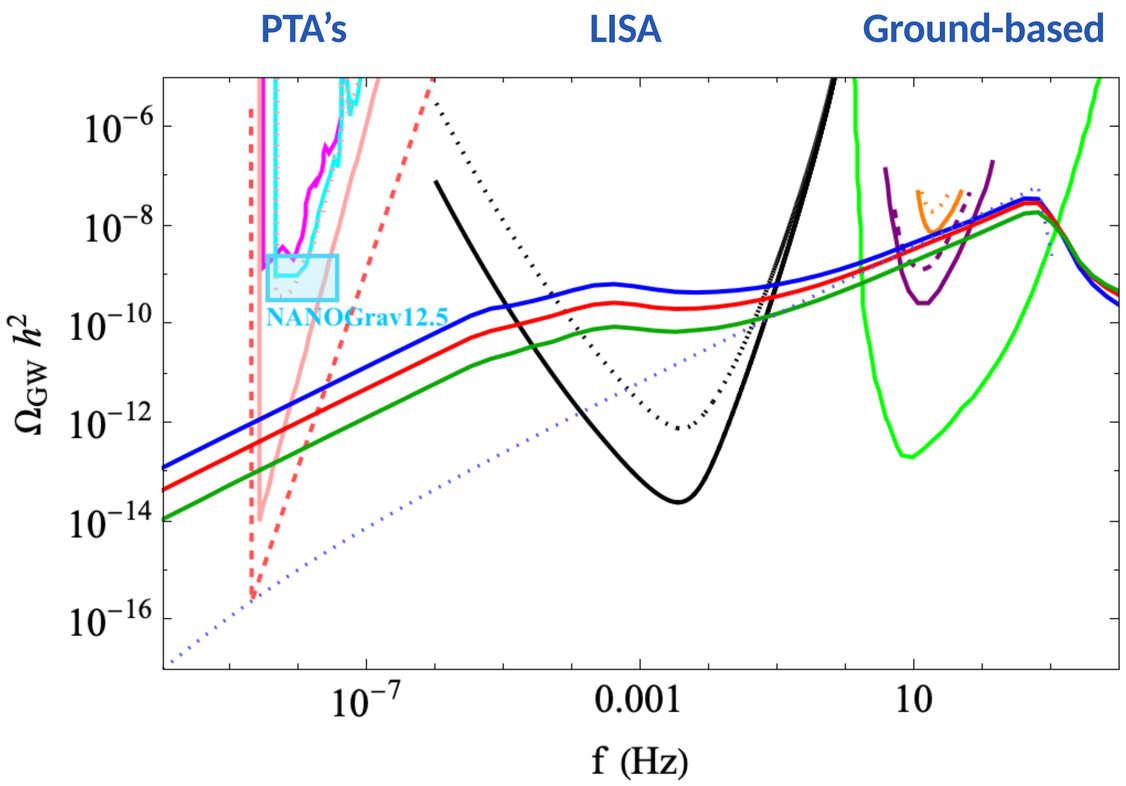
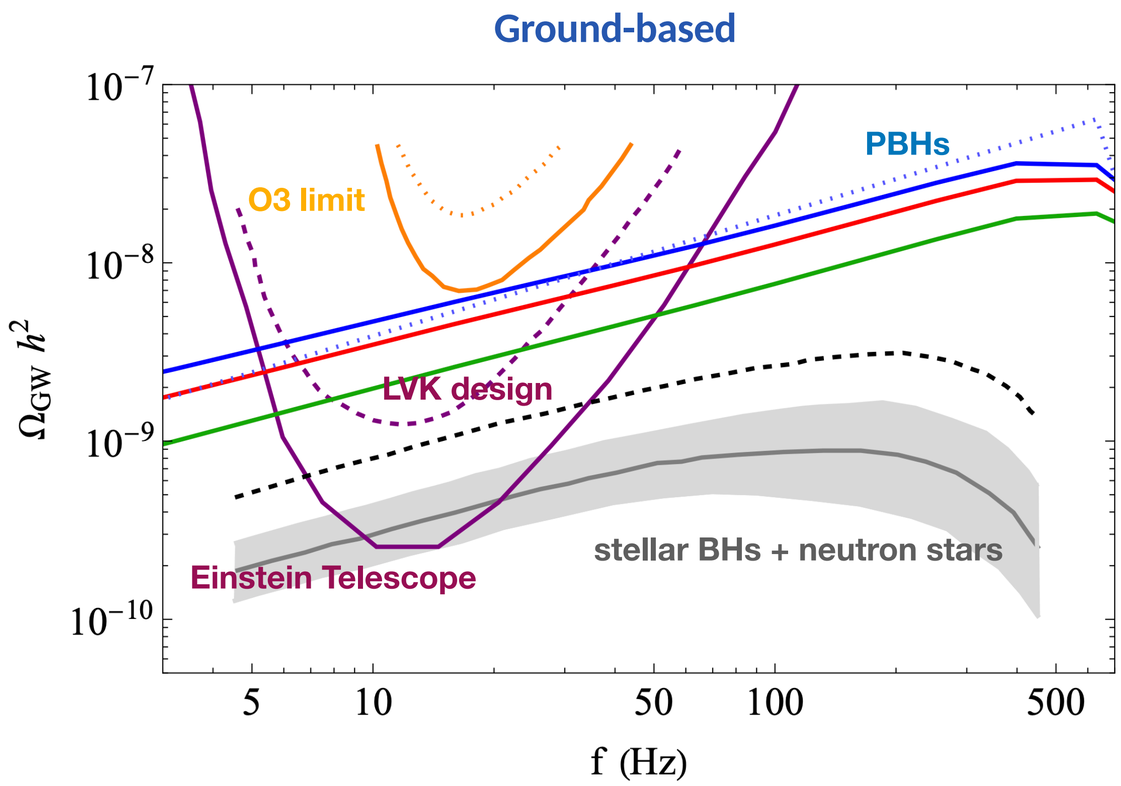
[E. Bagui, SC, 2021]

Gravitational-wave background from early PBH binaries:




Well **above stellar BH predictions** due to **solar-mass + planetary-mass** binaries

**At the limit of being detected by LIGO/Virgo !**

# Popcorn vs continuous background

## How to distinguish primordial and stellar black holes?

**Duty cycle**: average number of events overlapping at a given time. This quantity, in the observer frame, is defined as the ratio of the typical duration of an event, to the average time interval between two successive events

$$\Delta(z) = \int_0^z \Delta T(z') \frac{dR^o(z')}{dz'} dz'$$

**Duration of a GW signal**

**Coalescence rate per unit of redshift**

# Popcorn vs continuous background

## How to distinguish primordial and stellar black holes?

Based on the magnitude of the duty cycle, three different regimes can be defined:

- $\Delta >> 1$, where the overlap of the signals generates a continuous, **Gaussian**, background.
- $\Delta << 1$, where long periods of silence separate two signals, resulting in a **shot-noise** background.
- $\Delta \simeq 1$, where the signals may overlap, but their statistics is no longer Gaussian and the amplitude at a given time at a detector is not predictable, turning into a **popcorn-noise** background.

# Popcorn vs continuous background

## How to distinguish primordial and stellar black holes?

$$\Delta(z) = \int_0^z \mathrm{d}z' \frac{5c^5}{256\pi^{8/3}(GM_c(1+z'))^{5/3}} \left[ \left(\frac{f}{e}\right)^{-8/3} - f^{-8/3} \right] \tau_{\mathrm{merg}}(m_1, m_2) \frac{\mathrm{d}V}{\mathrm{d}z'}$$

$$(f_{\mathrm{min,det}})^{-8/3} - (f_{\mathrm{max}})^{-8/3}$$

$$f_{\mathrm{max}} = \mathrm{Max}[f_{\mathrm{min,det}}, \mathrm{Min}[f_{\mathrm{ISCO}}, f_{\mathrm{max,det}}]]$$

$$\frac{\mathrm{d}V}{\mathrm{d}z'} = 4\pi \left( \int_0^z \frac{c\mathrm{d}z'}{H(z')} \right)^2 \left( \frac{c}{H(z)} \right)$$

$$\tau_{\mathrm{merg}}(m_1, m_2) \propto \frac{(m_1+m_2)^{10/7}}{(m_1 m_2)^{5/7}} \mathrm{yr}^{-1}\mathrm{Gpc}^{-3}$$

$$h_c^2(f) = \frac{4\,G^{5/3}}{3\pi^{1/3}\,c^2} f^{-4/3} \int_0^{\infty} \frac{\mathrm{d}z}{(1+z)^{4/3}H(z)} \times \int\int \mathrm{d}\ln m_1\, \mathrm{d}\ln m_2\, \tau_{\mathrm{merg}}(m_1, m_2)\, M_c^{5/3}$$

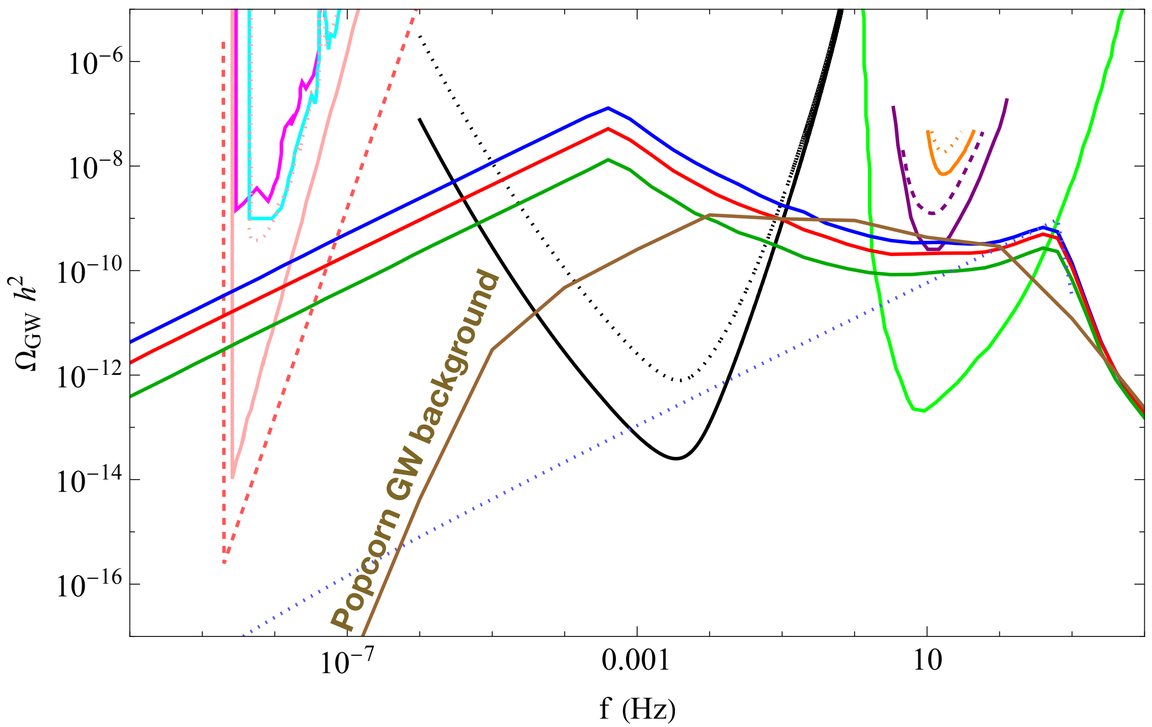
$z_{\mathrm{max}}$ such that $\Delta(z_{\mathrm{max}}) = 1$

# Popcorn vs continuous background

*Preliminary!*

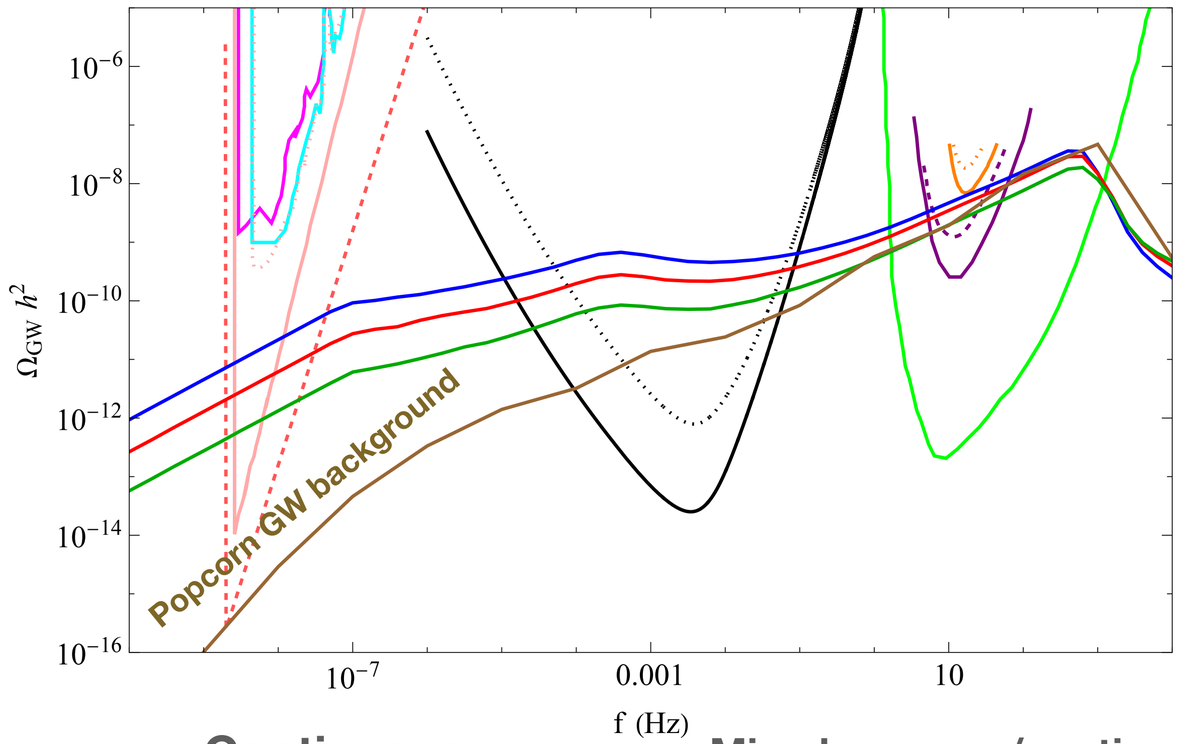
## How to distinguish primordial and stellar black holes?

### Late binaries




Continuous Popcorn Continuous

### Early binaries




Continuous Mixed popcorn/continuous

**The popcorn/continuous ratio increases with frequency !**
**Origin: binaries with low mass ratios and subsolar PBHs**

# Popcorn vs continuous background

## How to distinguish primordial and stellar black holes?

*GW background for late binaries and different models (Braglia et al, 2022) with detector-dependence of duty cycle (threshold SNR=8)*

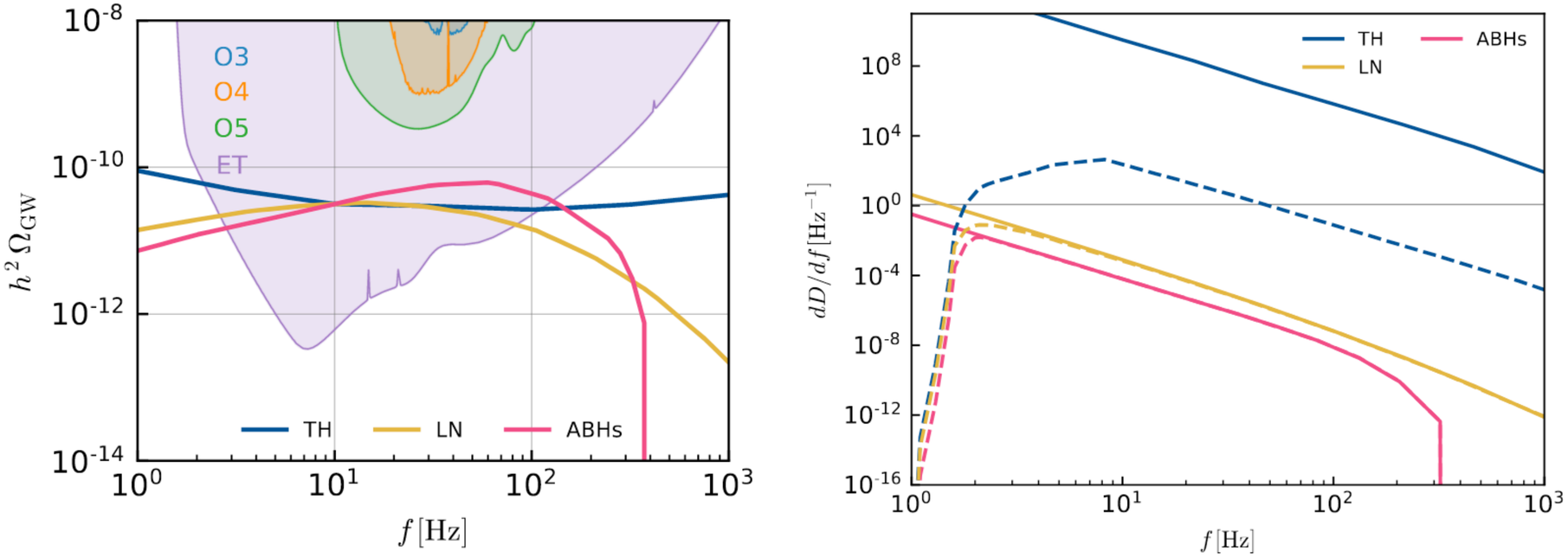



**Figure 7.** [Left] $\Omega_{GW}$ normalized to the same amplitude. [Right] Detector-independent (solid) and dependent (dashed) duty-cycle corresponding to the backgrounds shown in the left panel.

*Detector dependent effects for early binaries ?  Work in progress….*

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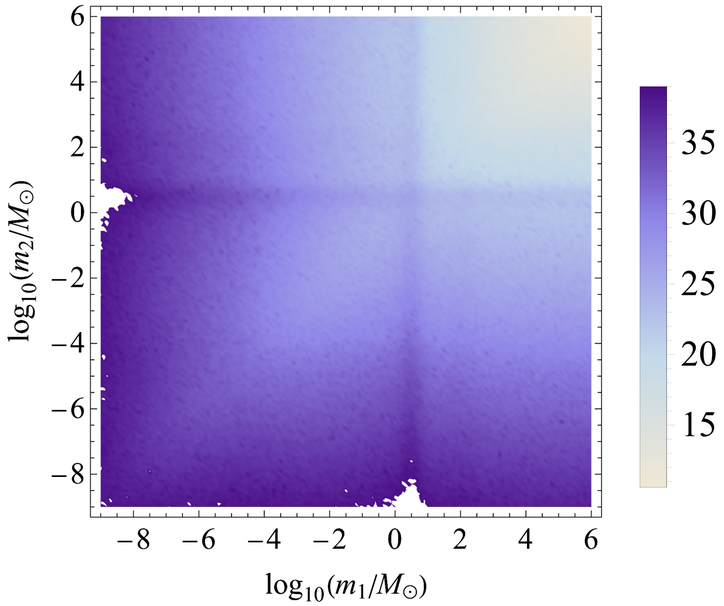
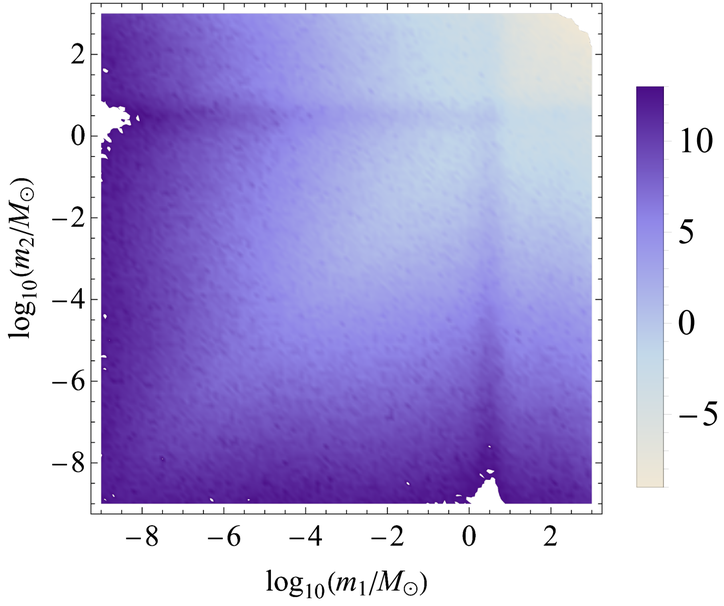
- Need to develop methods to extract the duty cycle **as a function of frequency**

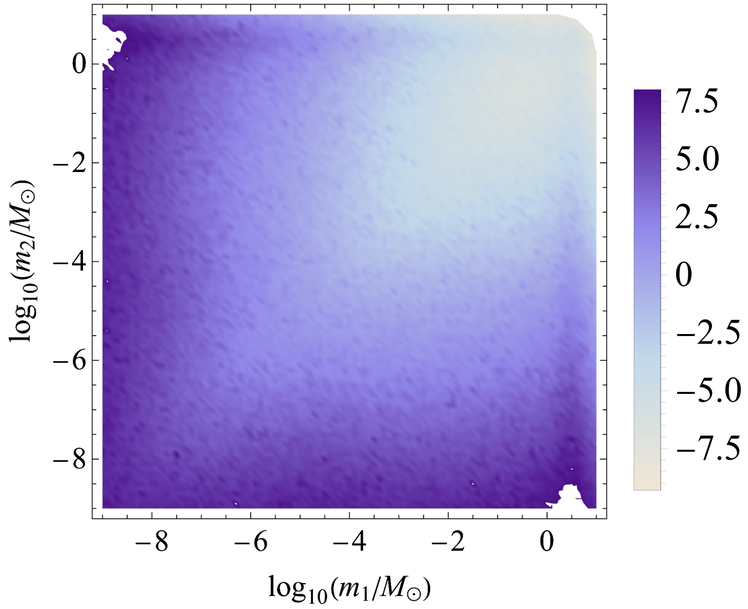
# Duty cycle as a function of the PBH masses

$f$ = $10^{-9}$ Hz




$f$ = 10 Hz




$f$ = 1000 Hz