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Université Libre de Bruxelles (ULB)

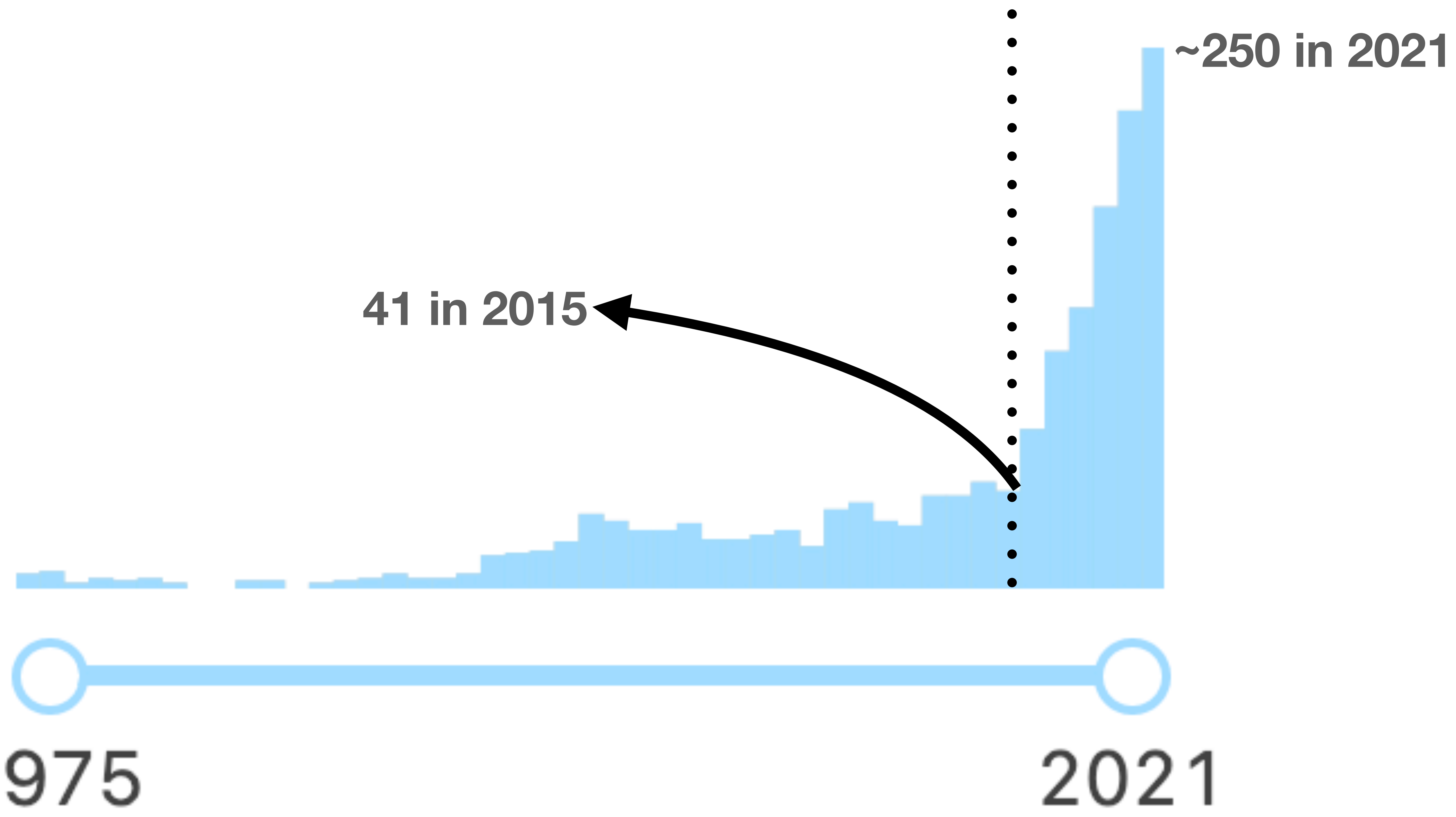
# Primordial Black Holes in the early Universe

*Second Chennai Symposium on Gravitation and Cosmology, February 2-5, 2022*

# A Hot topic !

## From 1970 to 2021

Date of paper with Primordial black hole(s) / PBH(s) in the title




Hawking, Carr and Chapline 1970-1975
Zel'dovitch and Novikov in 1967



*source: InspireHEP*

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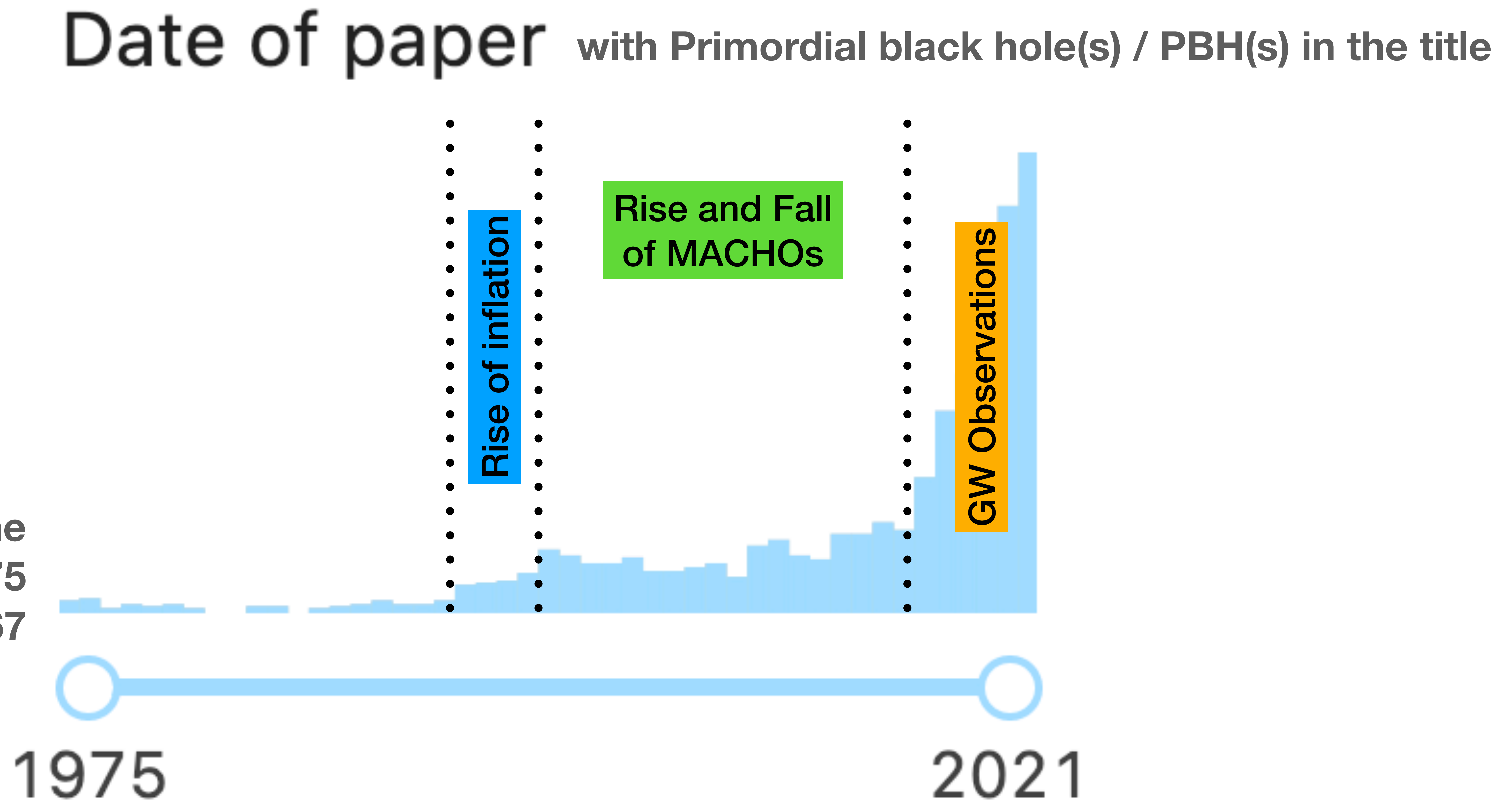


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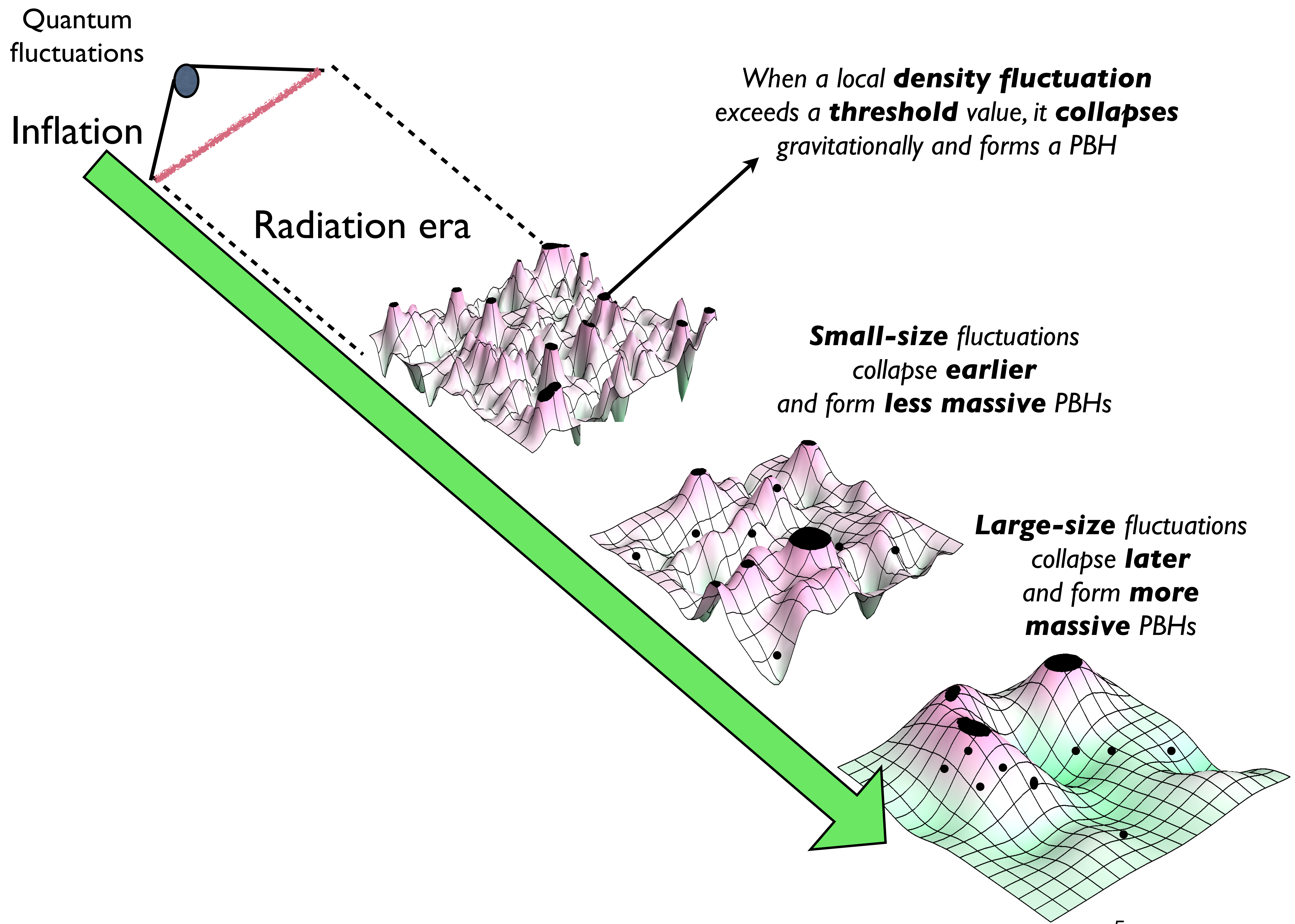
- Can (stellar-mass) PBHs be the **dark matter** ?

- Are **LIGO/Virgo** black holes primordial? How to distinguish stellar vs primordial black holes in **gravitational-wave** (GW) observations ?

# 1. How natural is PBH formation ?

## A simple but fine-tuned process



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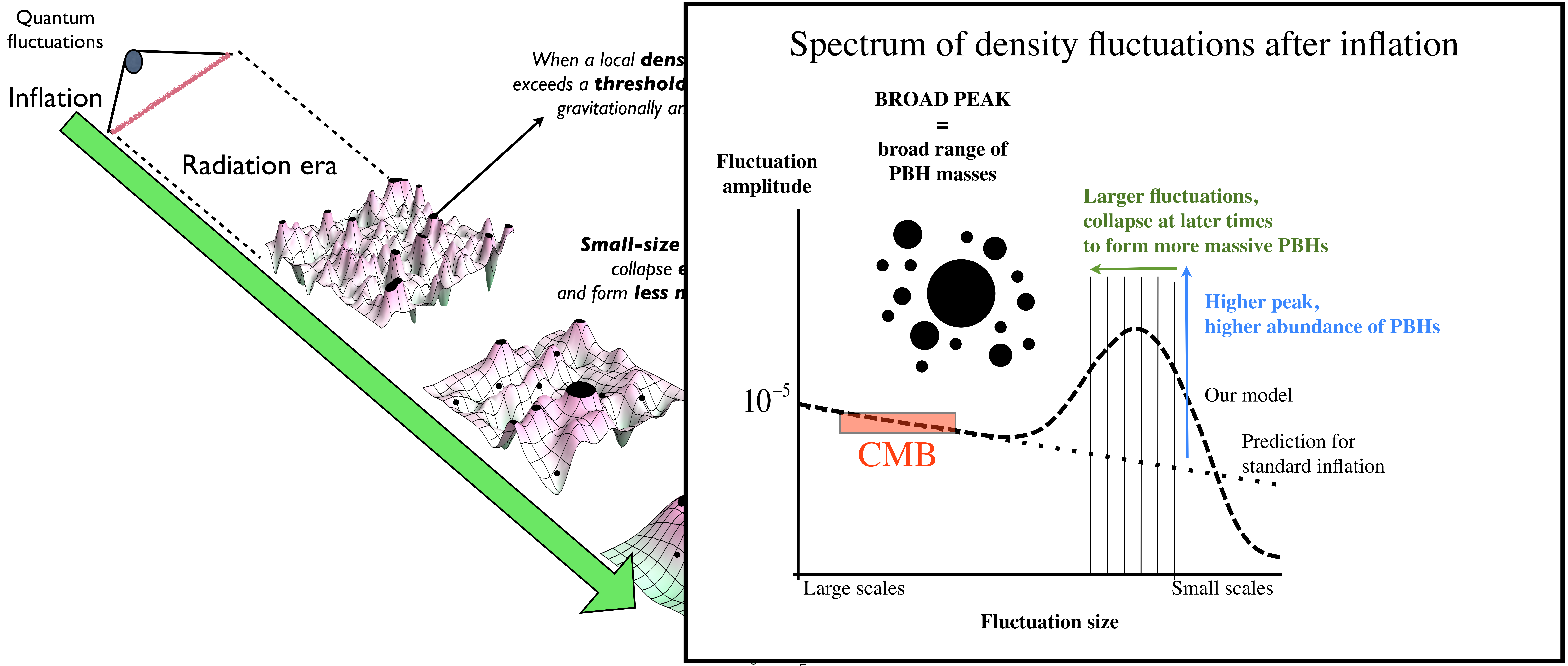

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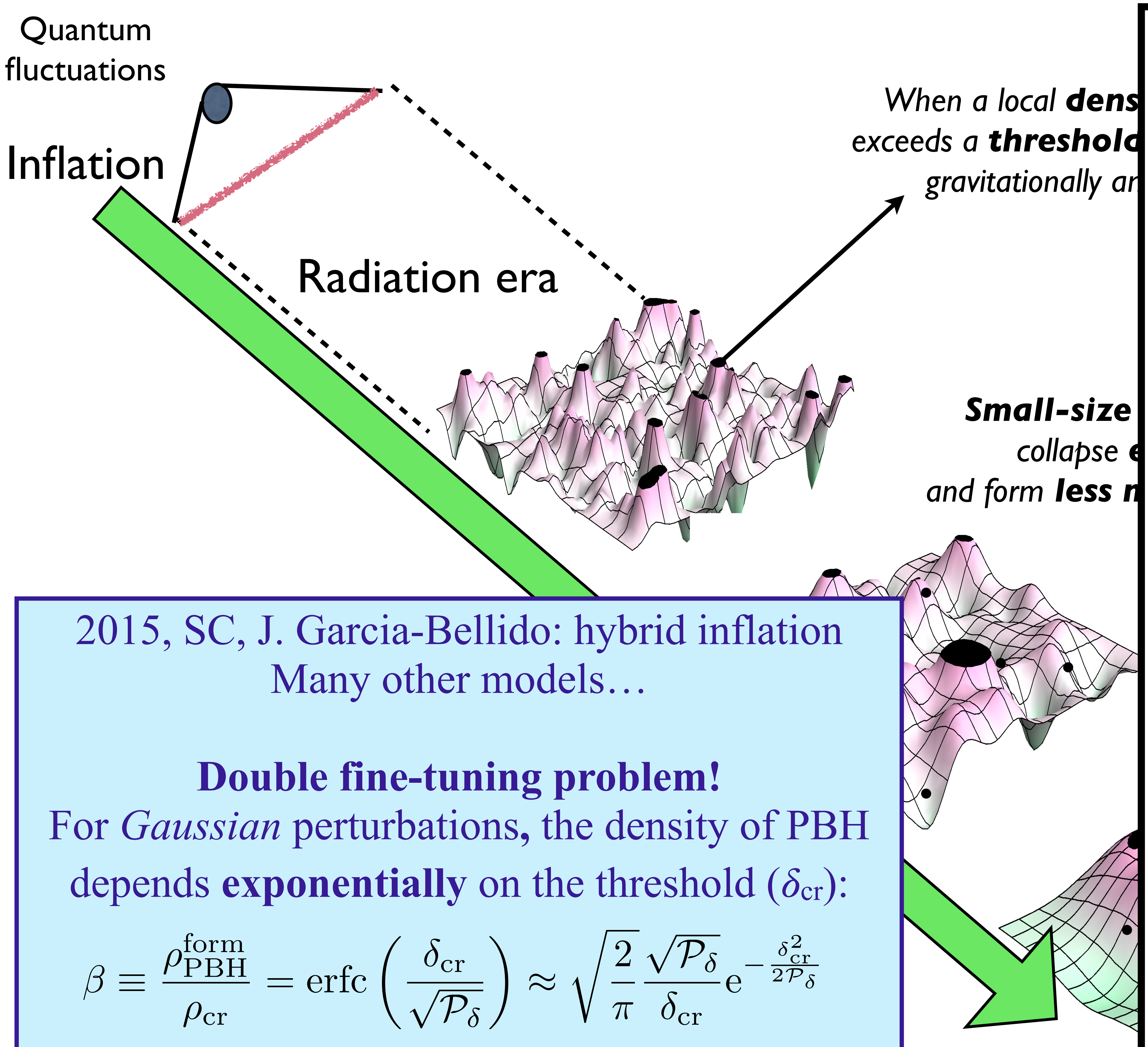
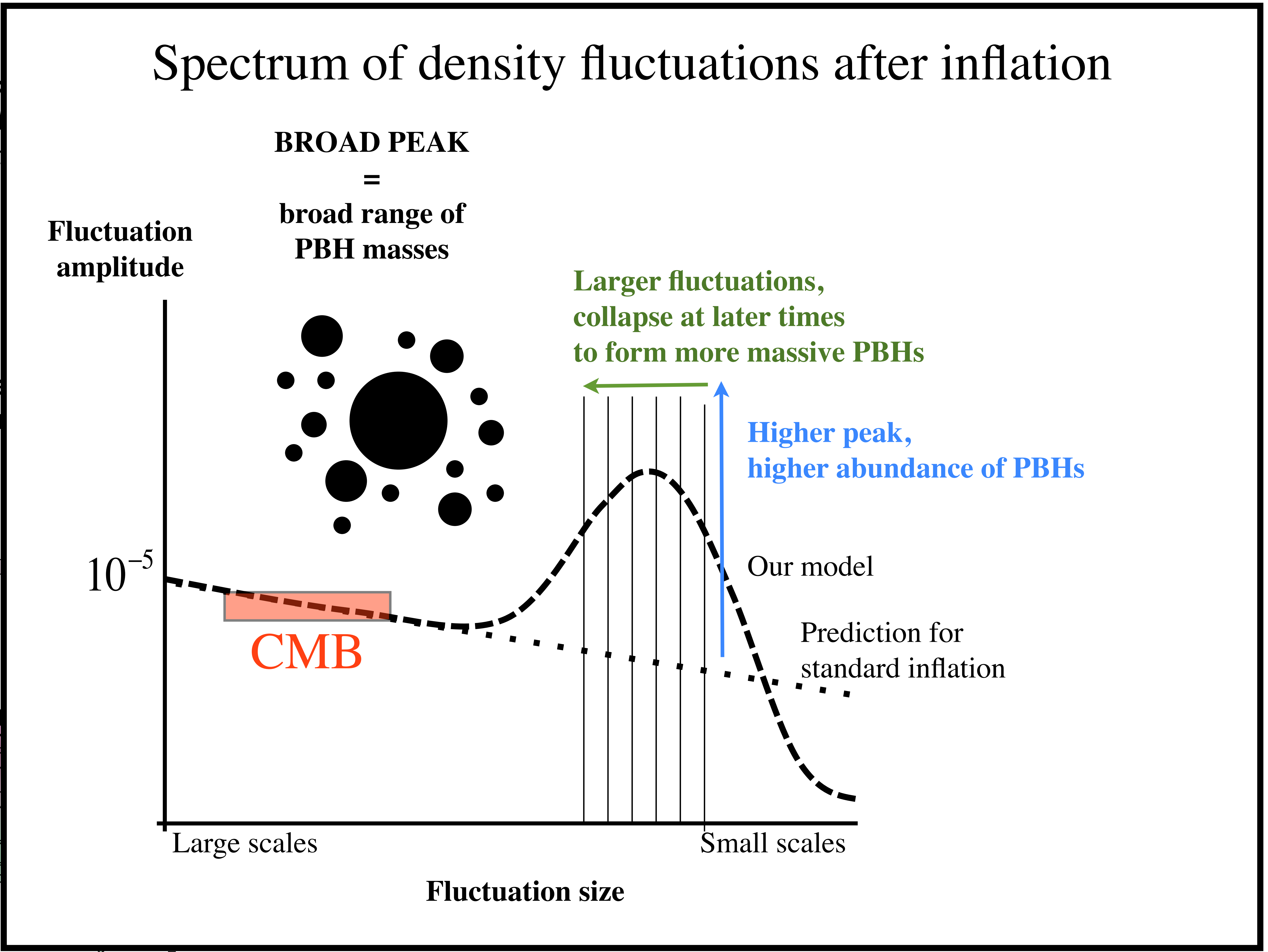



2015, SC, J. Garcia-Bellido: hybrid inflation
Many other models…

**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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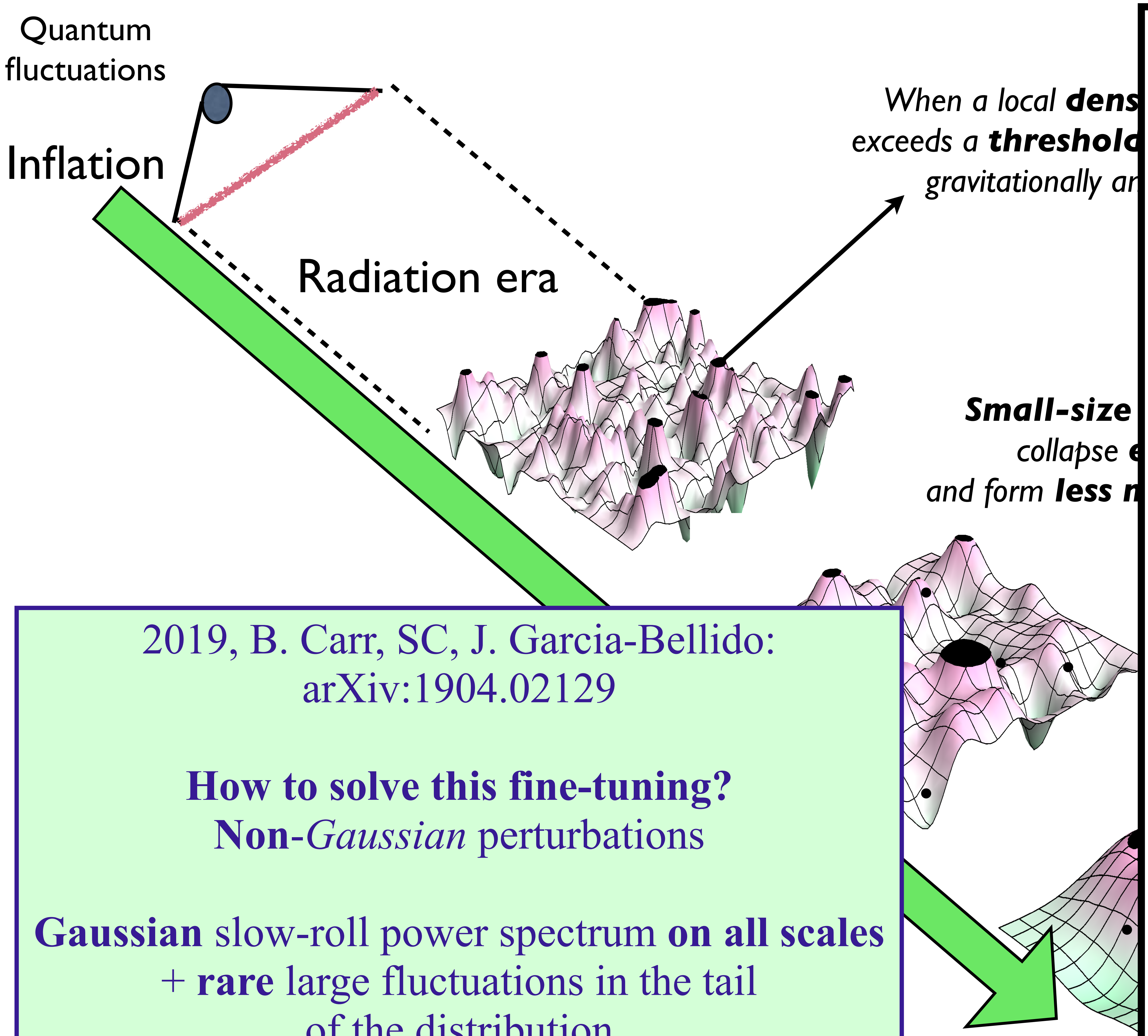
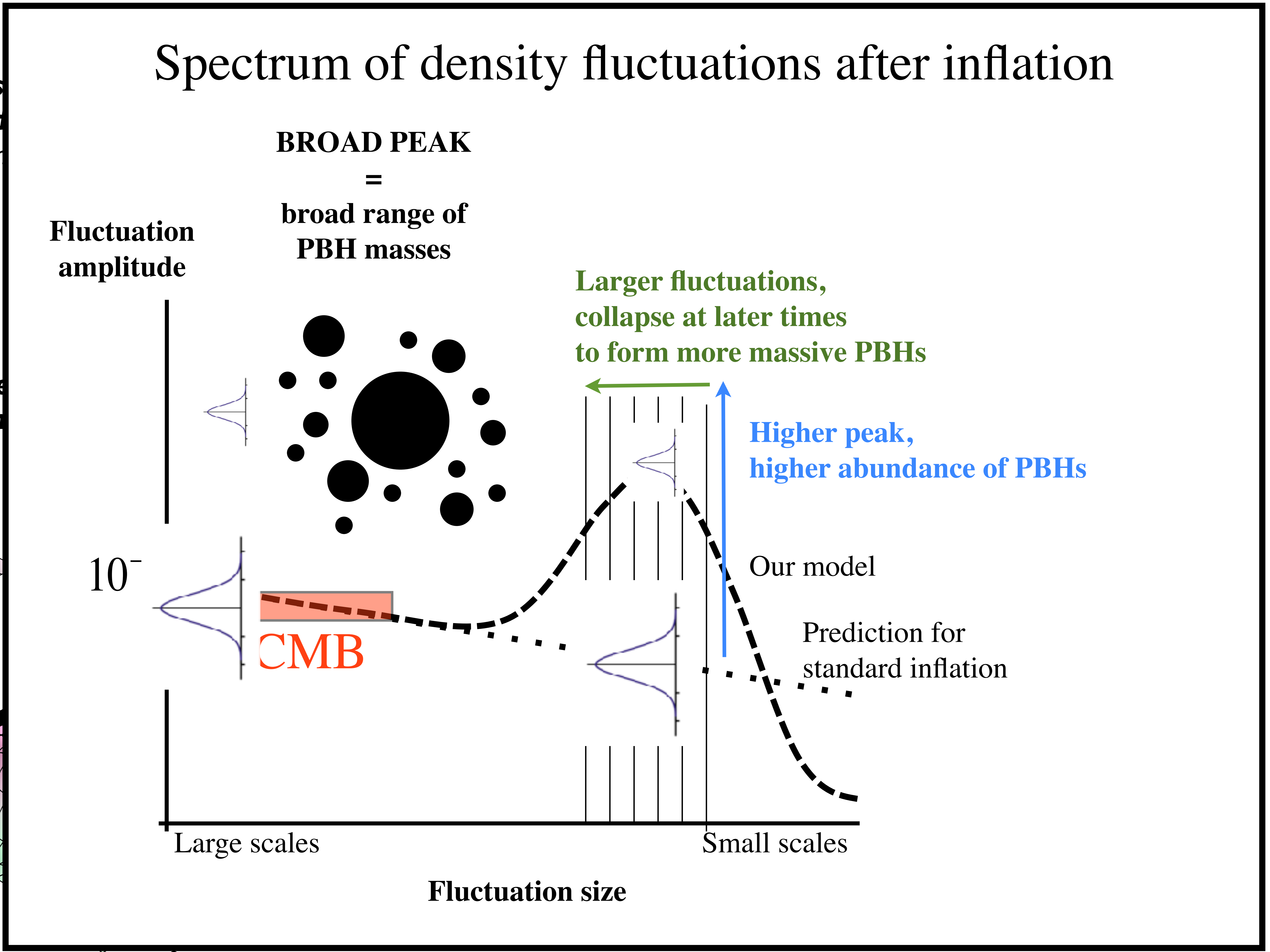



2019, B. Carr, SC, J. Garcia-Bellido:
arXiv:1904.02129

**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**



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## 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
De Luca, Franciolini, Riotto et al., 2009.08268
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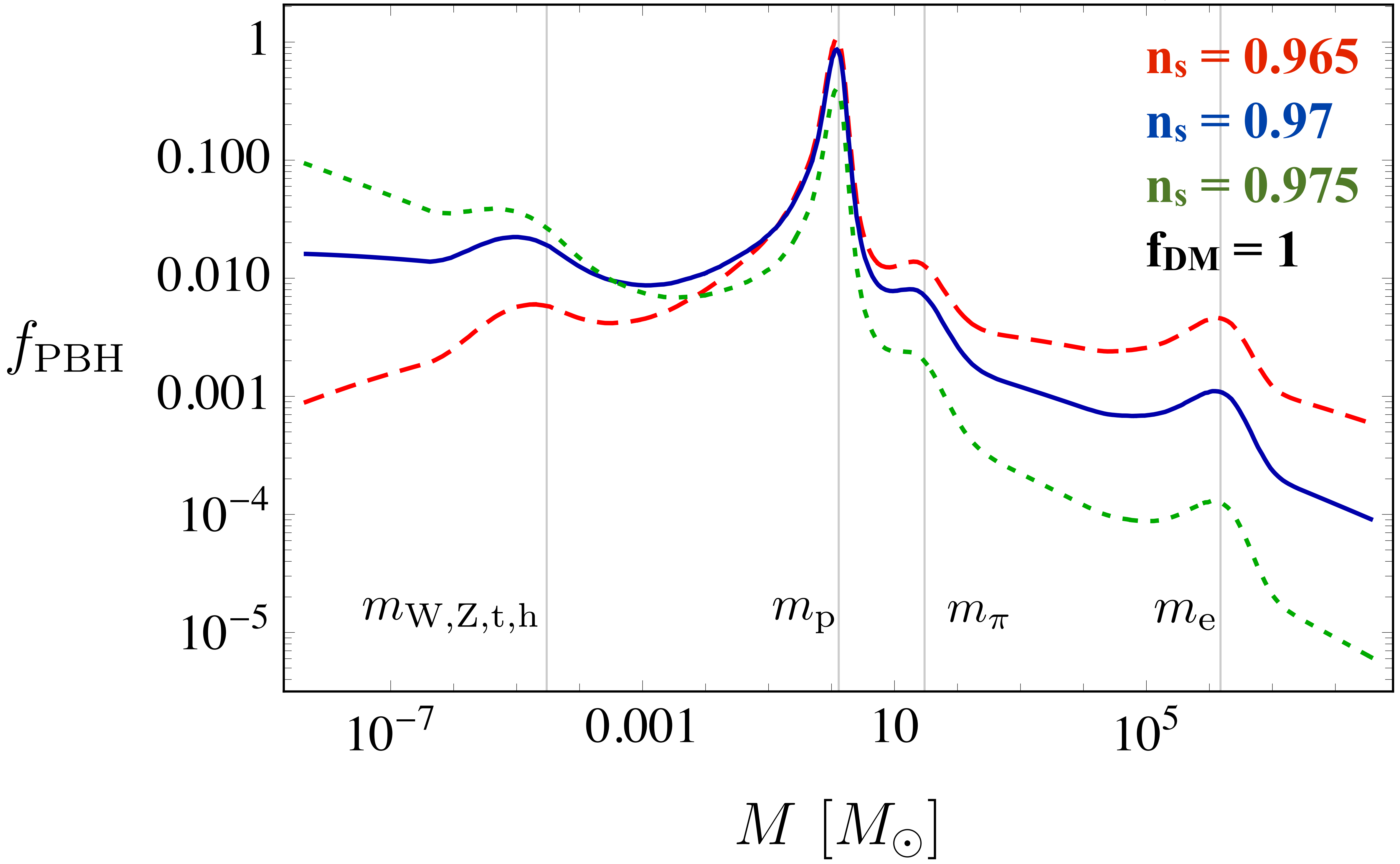

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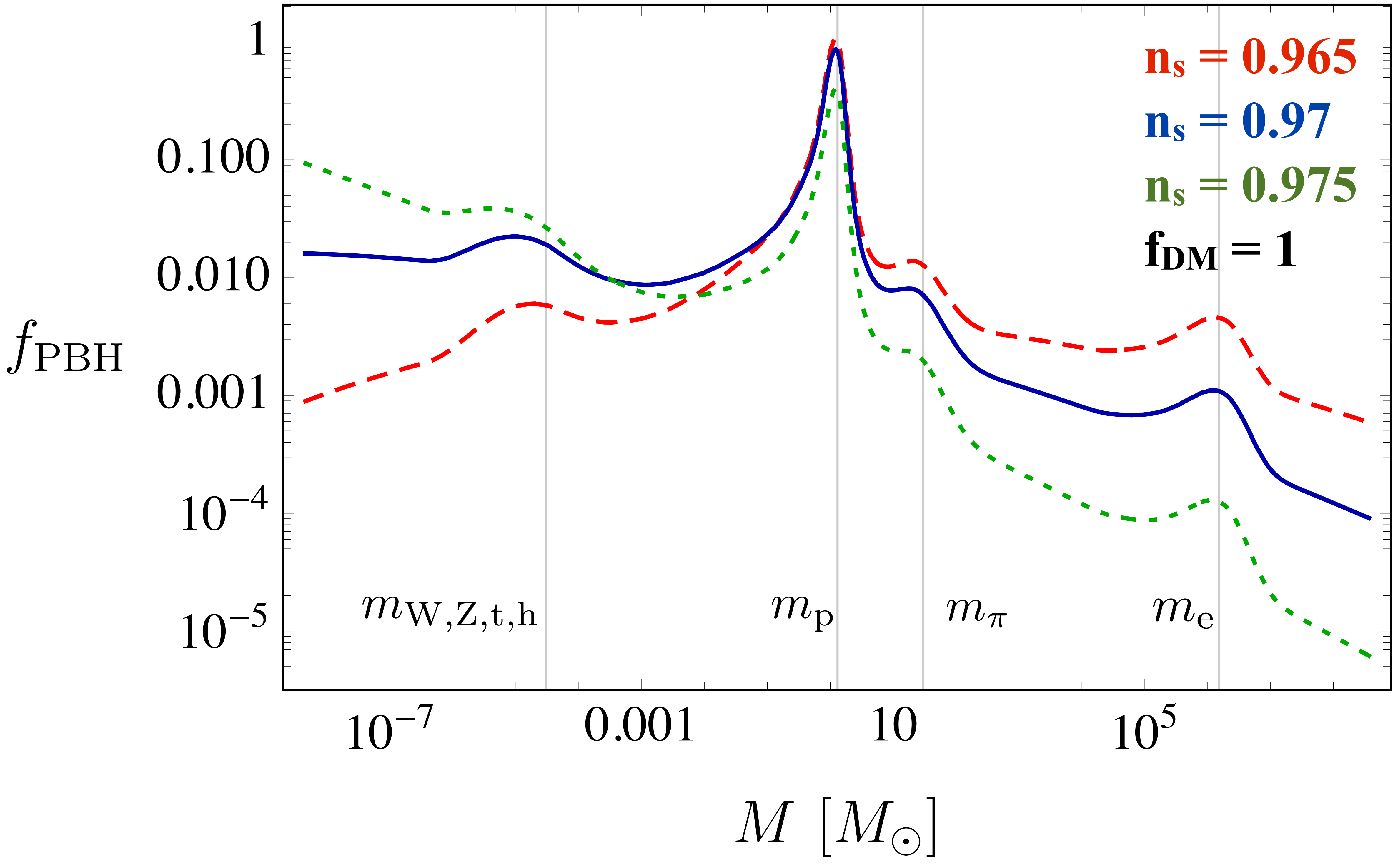


- **Nearly scale-invariant spectrum**
- **Spectral index: $n_s = 0.97$**
- **Peak at ~[2-3] $M_\odot$**
- **Second peak at ~30 $M_\odot$**
- **Two bumps at $10^{-6}$ and $10^{6}$ $M_\odot$**

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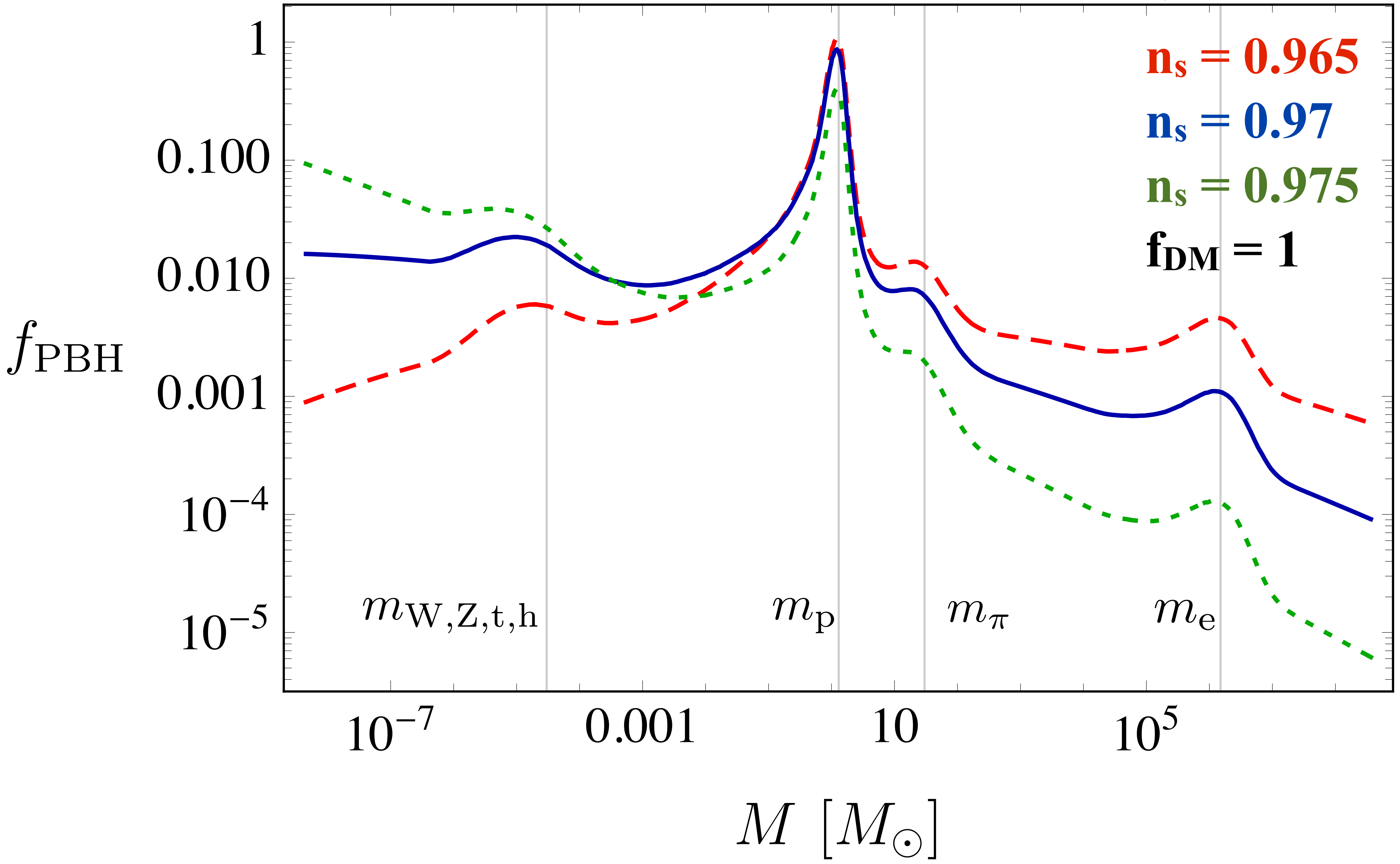
✓ **Inevitable**
✓ **Naturally** leads to **stellar-mass** PBHs
◉ But **does not solve** the **abundance/transition** problem

Carr+, 1906.08217

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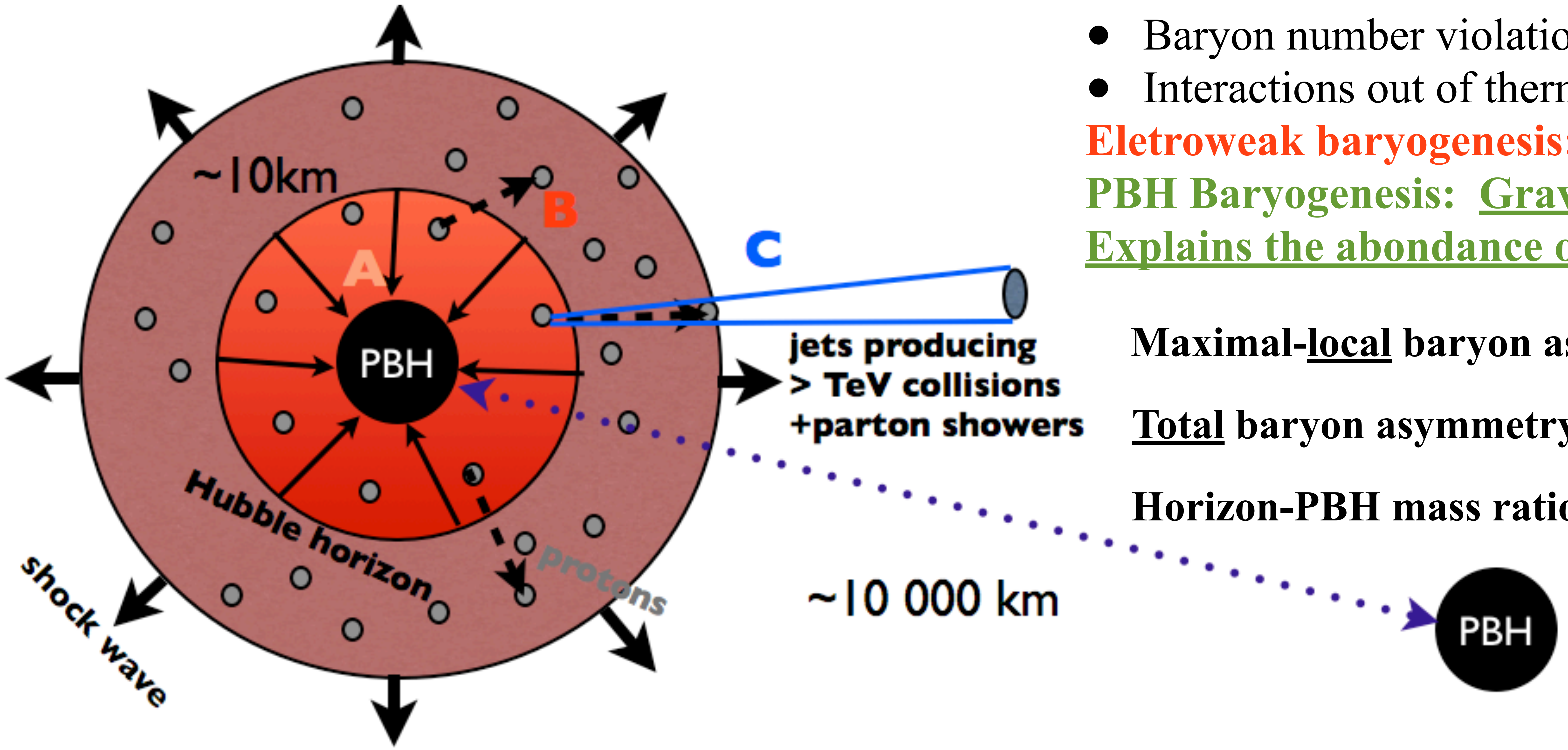


*Sakharov's Conditions:*

- C and CP violation: of the standard model
- Baryon number violation:  sphaleron transitions from >TeV collisions
- Interactions out of thermal equilibrium: PBH collapse/shock wave

**Eletroweak baryogenesis:  need of exotic physics.**

**PBH Baryogenesis:  Gravitation**

**Explains the abondance of DM/baryon and baryon/photon ratios!**

**Maximal-local baryon asymmetry:** $\eta \equiv n_{\rm b}/n_\gamma \sim \delta_{\rm CP}(T) \gg 1$

**Total baryon asymmetry:** $\beta \equiv \frac{\rho_{\rm PBH}^{\rm form}}{\rho_{\rm cr}} \approx 10^{-9} \approx \eta$

**Horizon-PBH mass ratio:** $\frac{\Omega_{\rm DM}}{\Omega_{\rm b}} \approx \frac{\gamma}{1-\gamma} \simeq 5$

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arXiv:1904.11482 and 1904.02129

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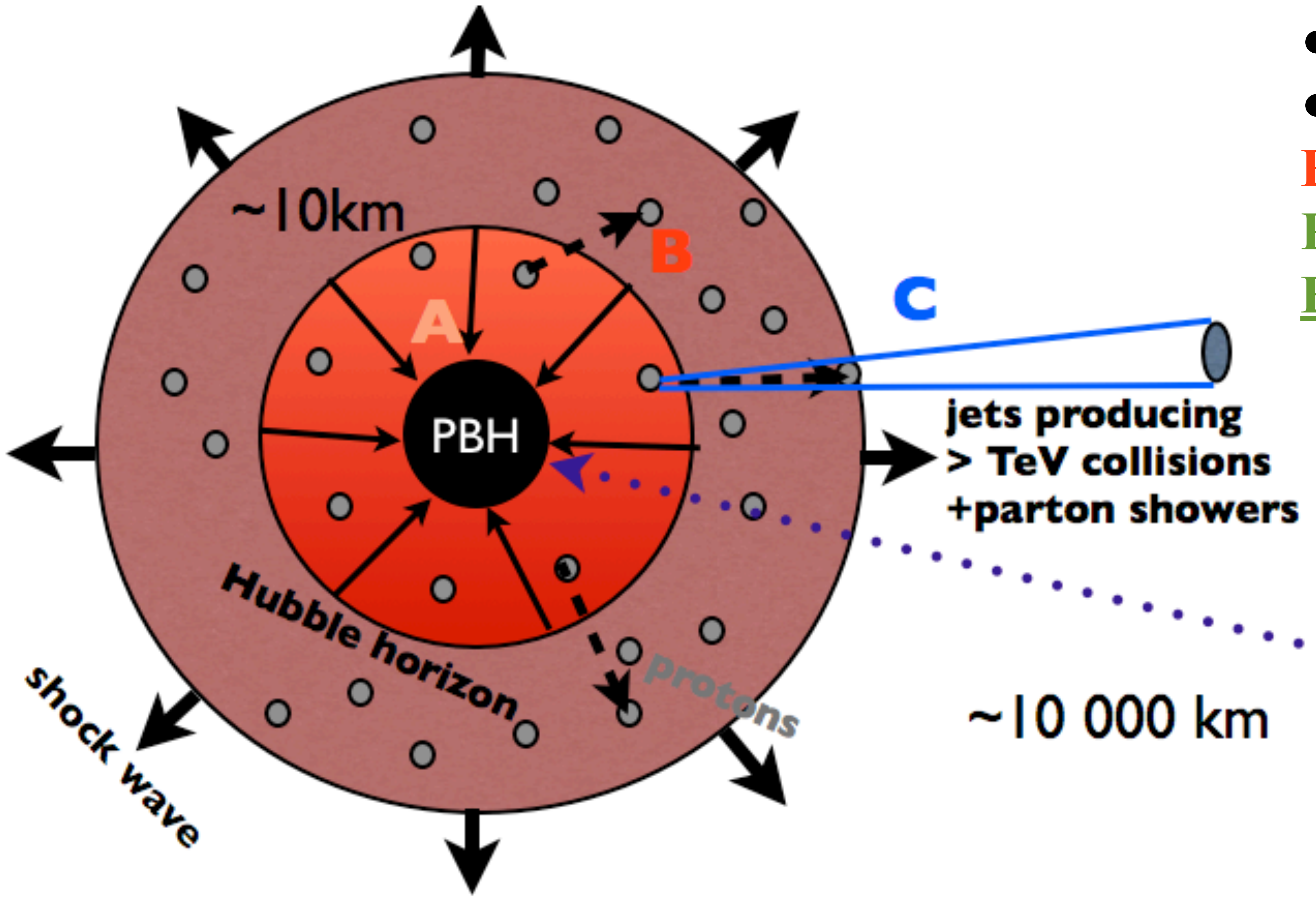


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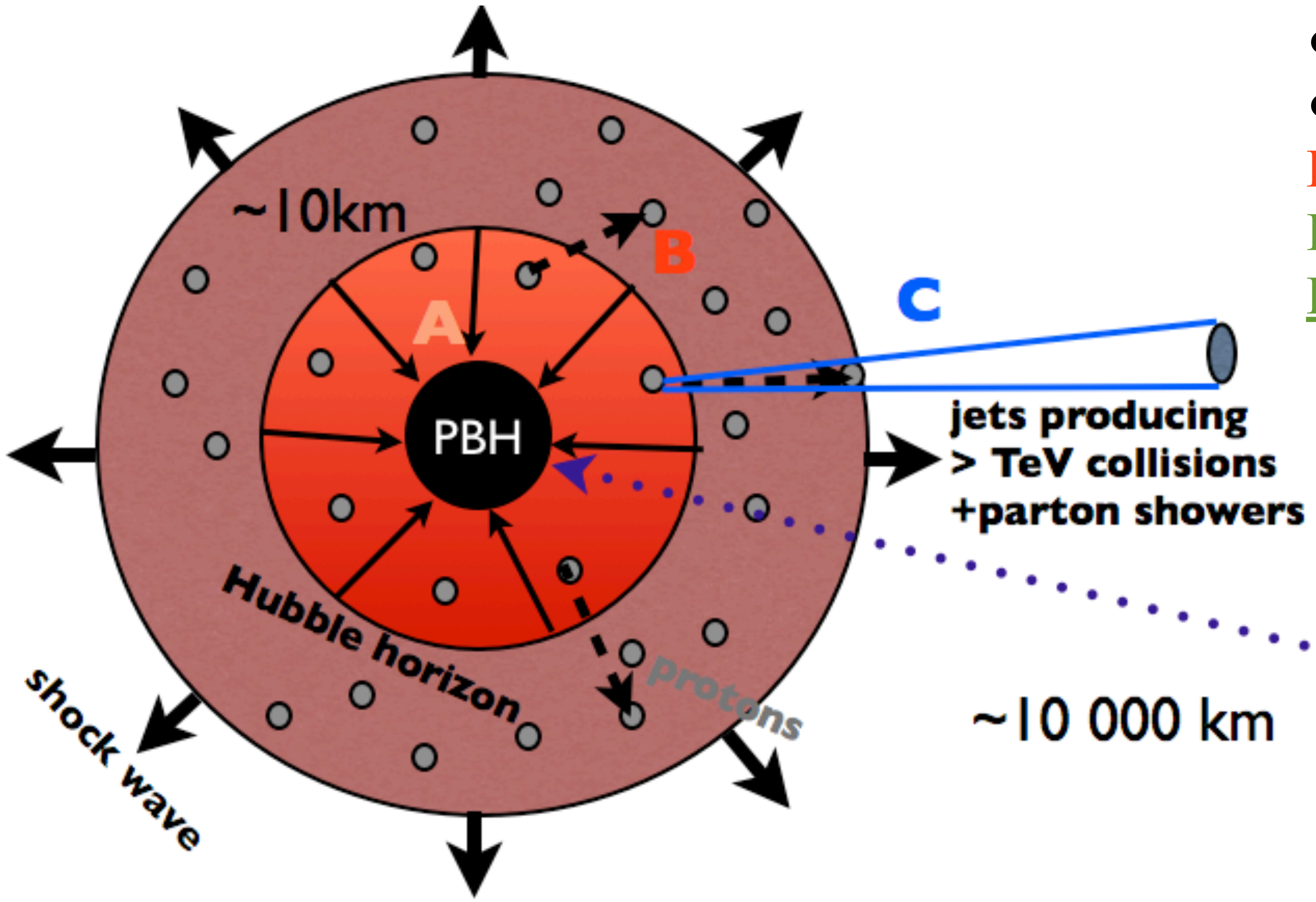


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◉ Existence of a shock wave ?
◉ Dilution before BBN ?
◉ Crude estimations

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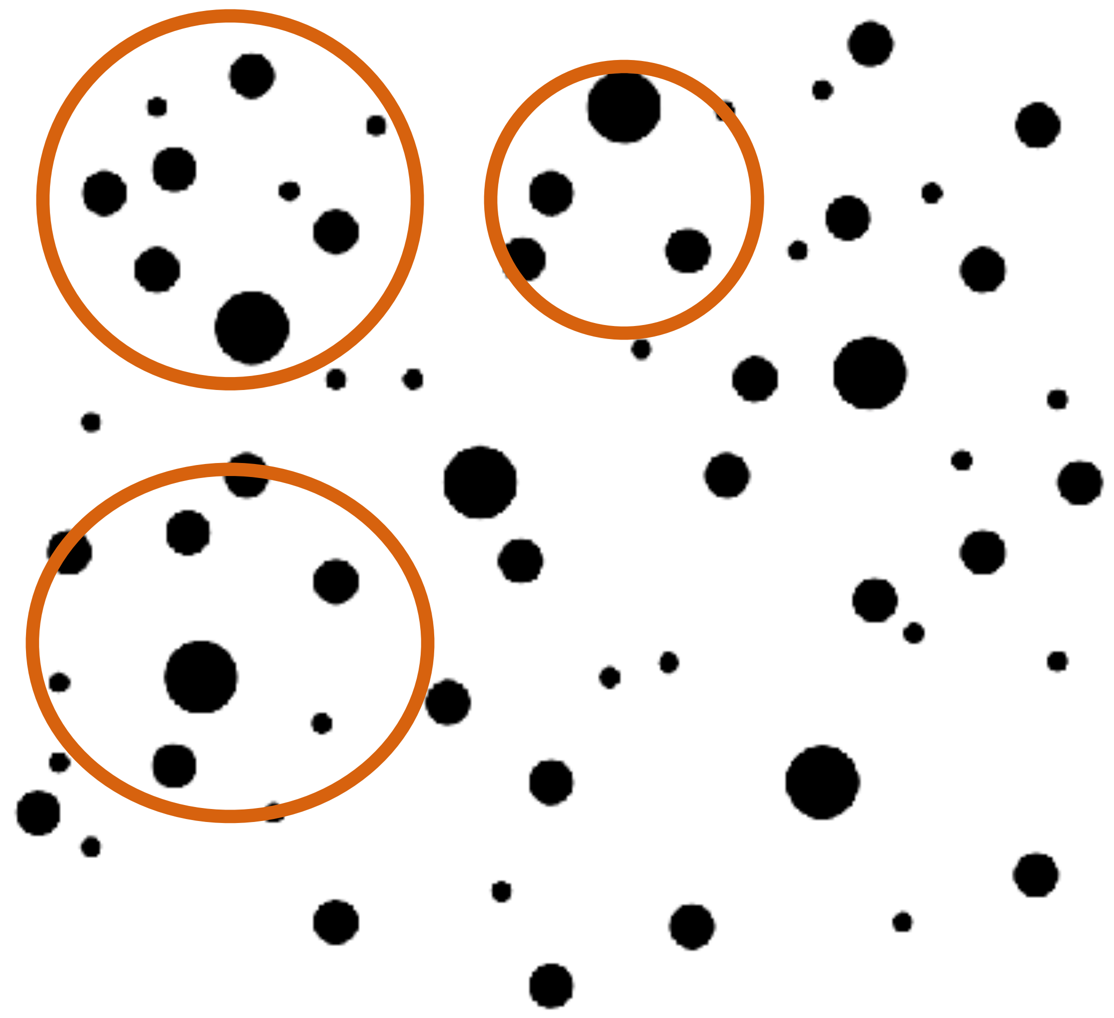
# 2. Can (stellar-mass) PBHs be the dark matter?

## Poisson in a PBH sea…

Ali-Haimoud 1805.05912



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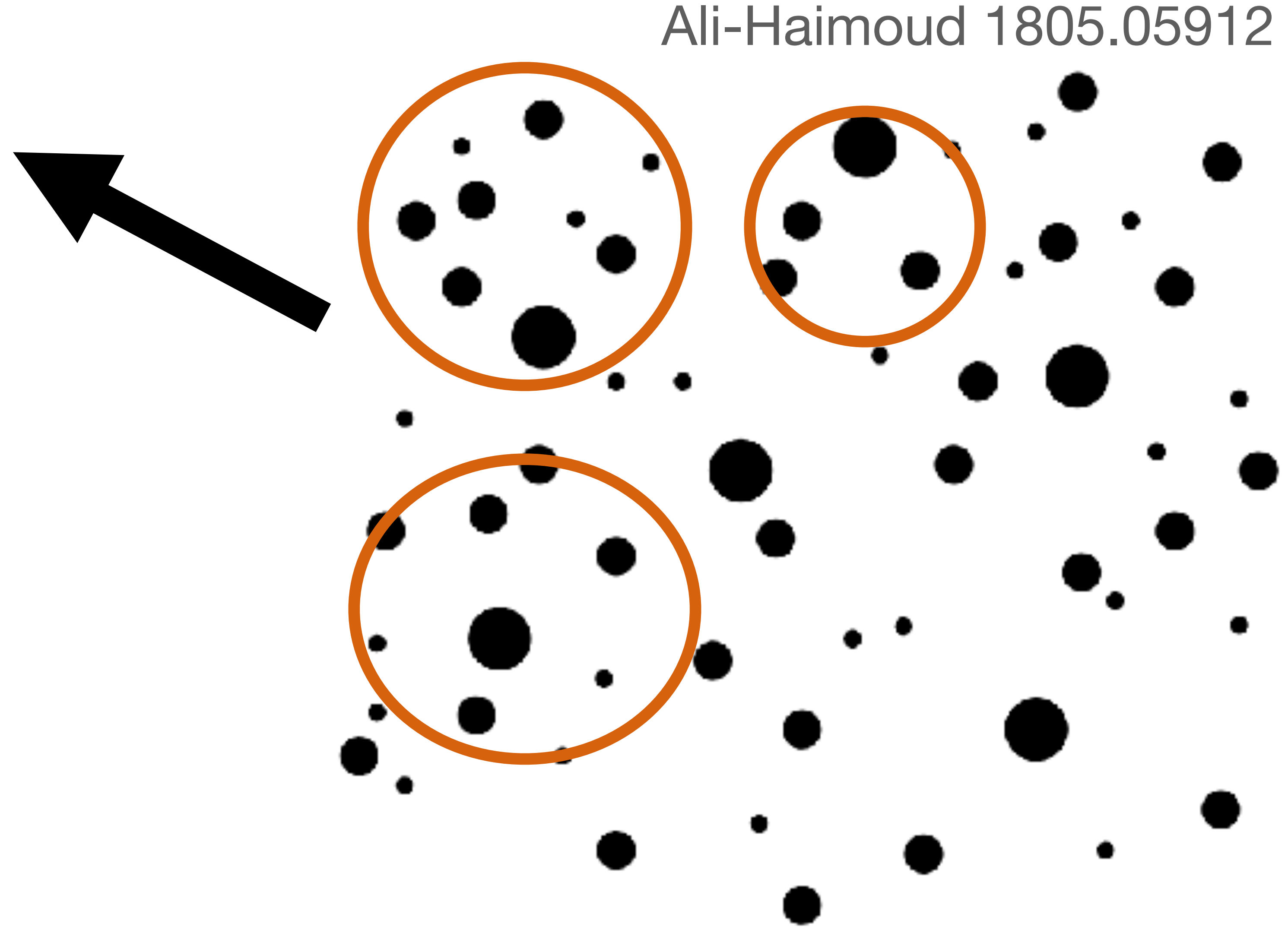
**Merging rate suppression for early binaries**
down to LIGO/Virgo merging rates
due to disruption in or by early clusters
[Raidal+18]

$$f_{\rm sup} \approx 0.002$$



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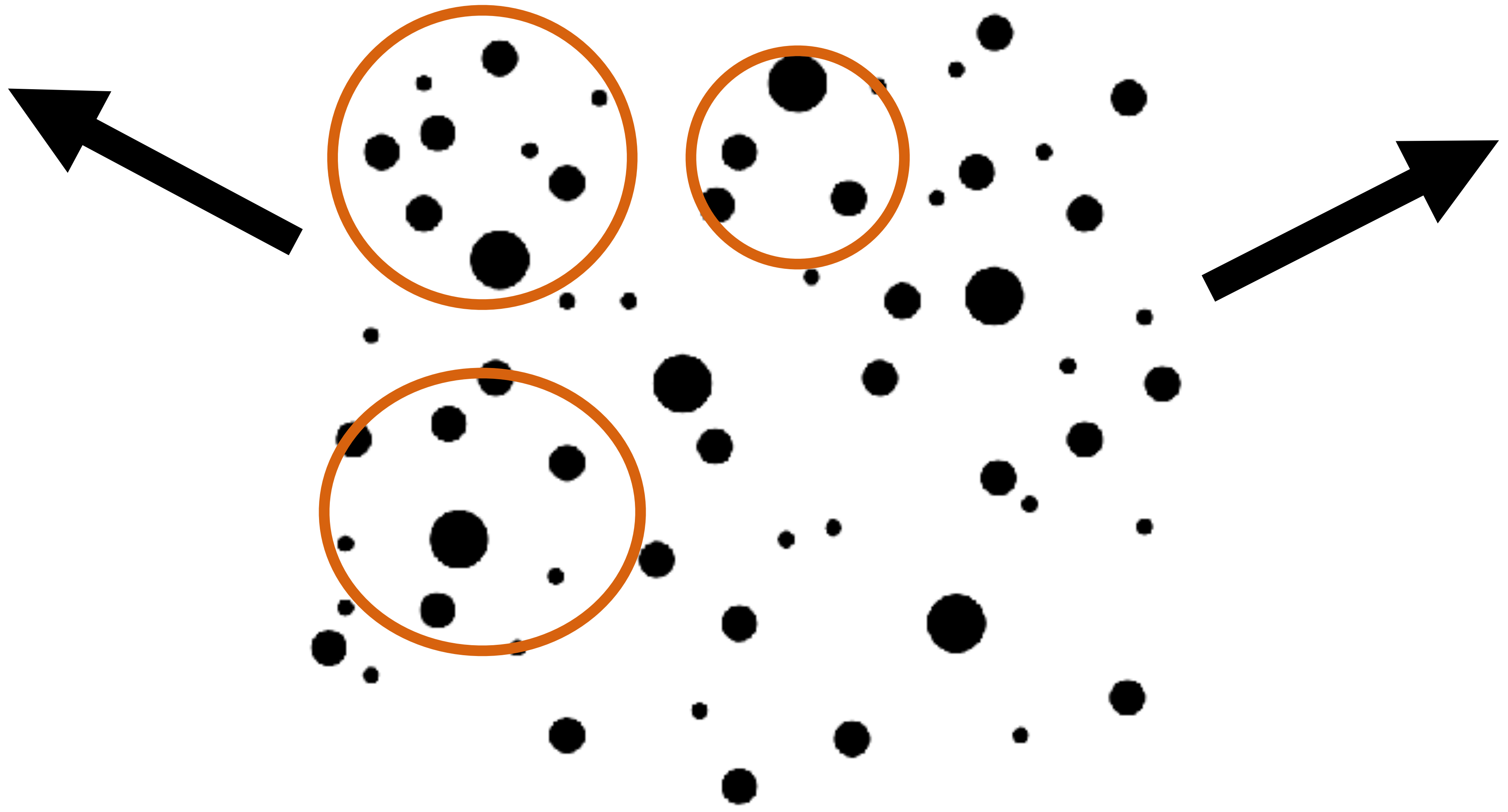

**High-z clusters: spatial correlations in IR and X-ray backgrounds**
[Kashlinsky 16]

$$\delta^2_{\rm Poisson} \propto (f_{\rm PBH} m_{\rm PBH}) \times k^3$$

Press-Schechter:
**~100% probability to collapse**
at **z > 20** for small perturbations
$M_\odot$ PBHs: halos up to $10^6$ - $10^7$ $M_\odot$

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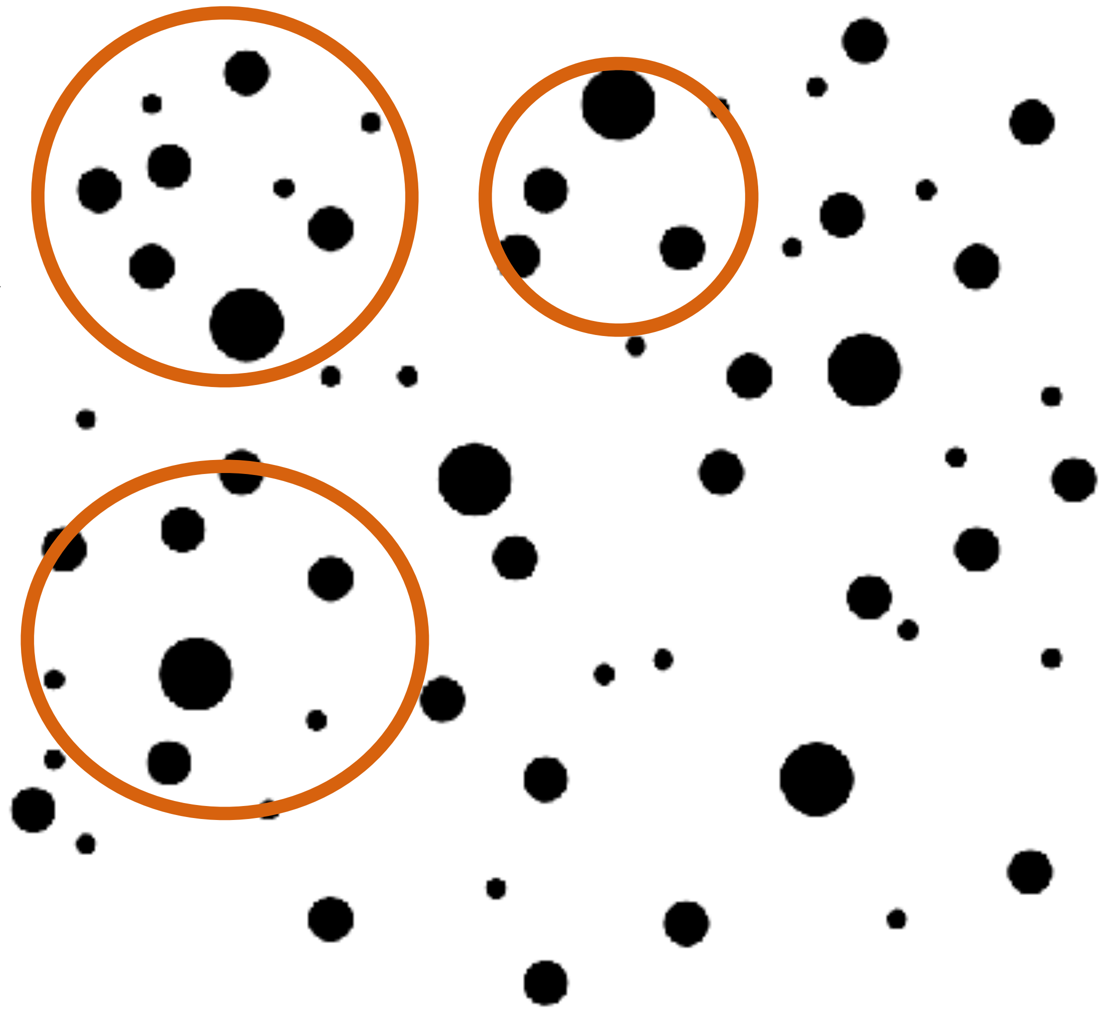

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min radius ~20 pc and
large mass-to-light ratios
(dynamical heating + accretion)
[S.C.+17, S.C.+20]

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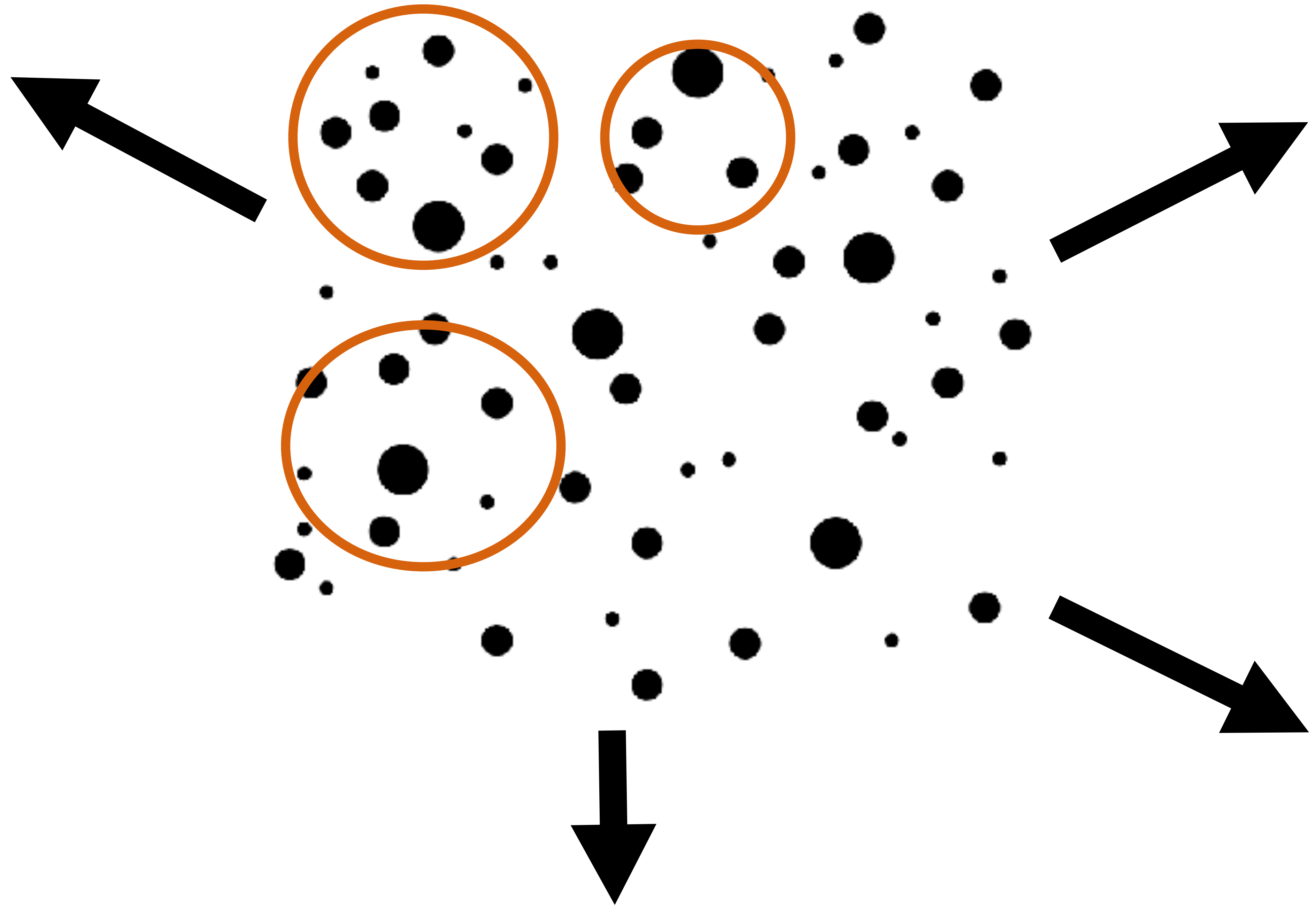

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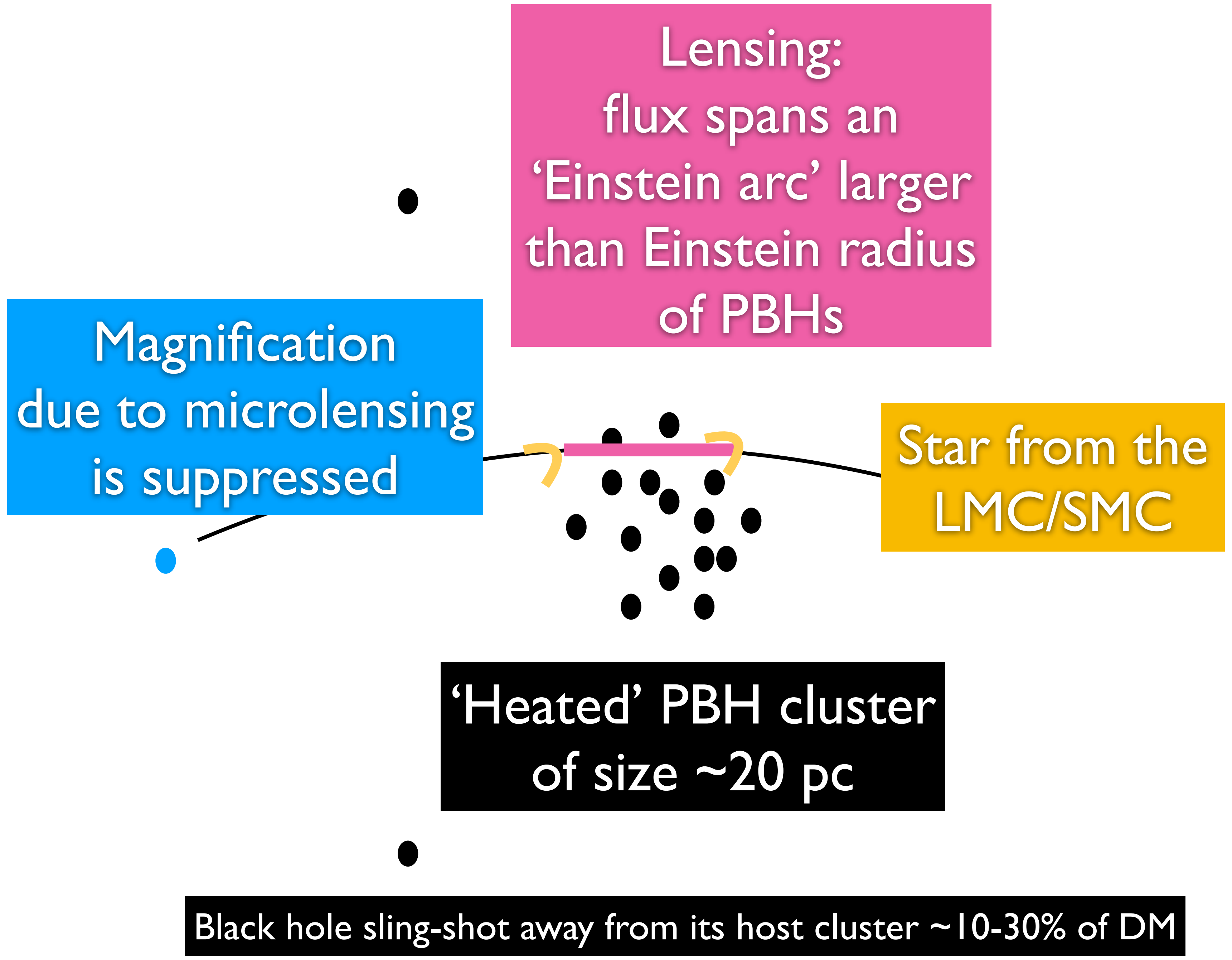
**Evade micro-lensing limits [Carr+19]**

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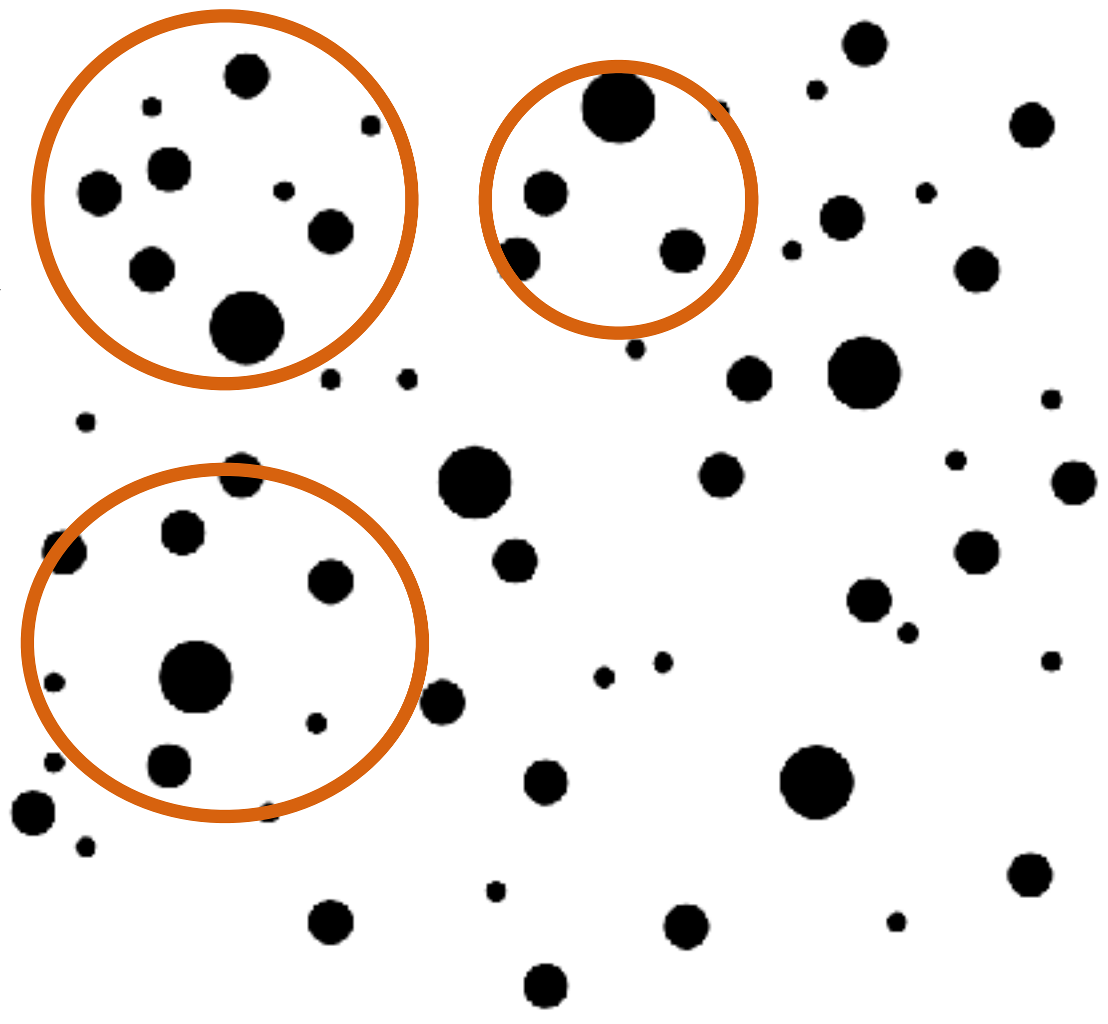

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**N-body simulations** by Inman & Ali-Haimoud, 1907.08129

$m_{PBH}$= 30 $M_\odot$, snapshots at z=99


**Halos of $10^6$ - $10^7$** $M_\odot$

**On small scales, completely different than particle-CDM !**

**Potential implications for 21cm, recombination, etc…** [Hasinger+20]

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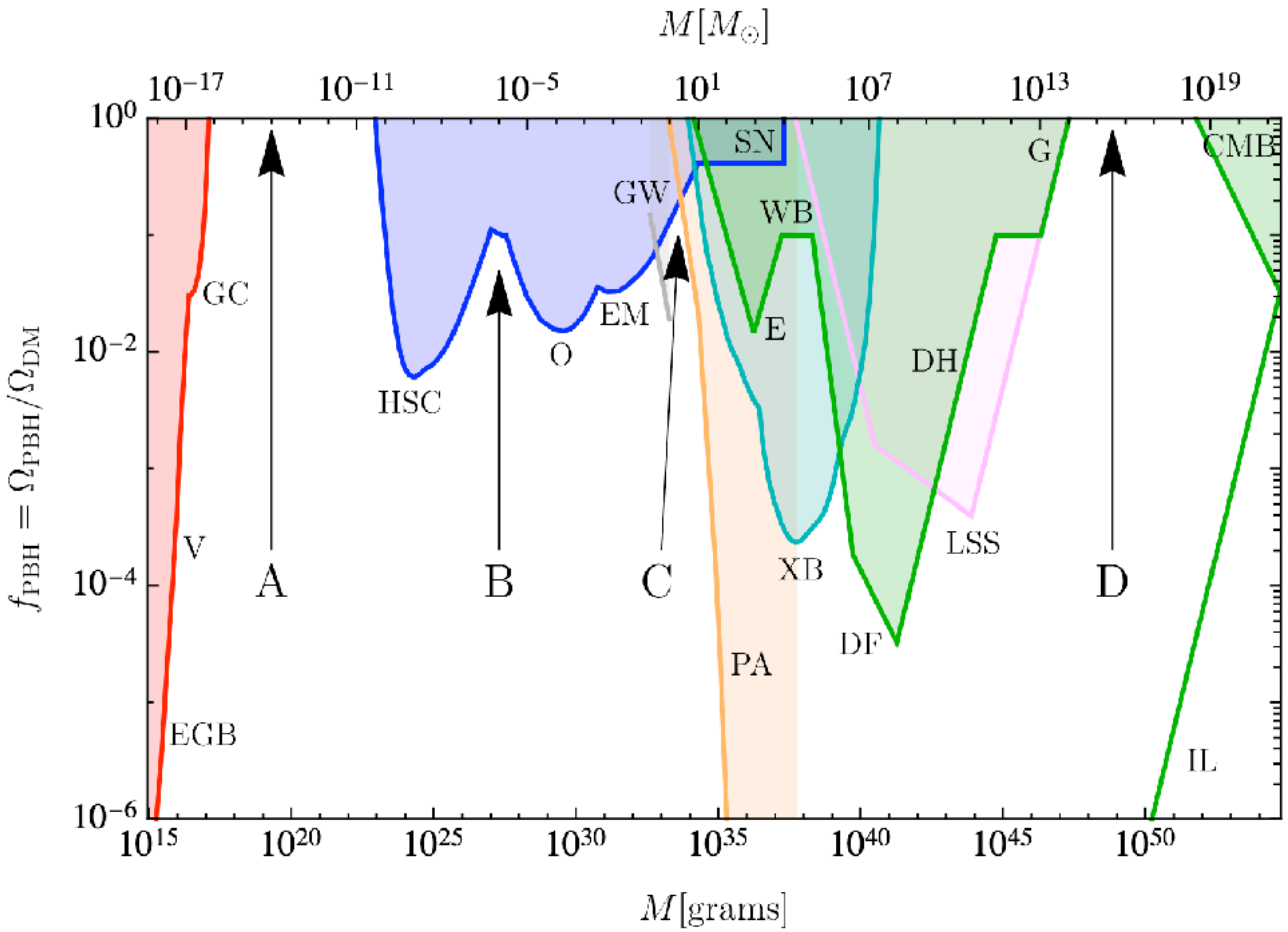
## Limits vs clues: a question of point of view




Carr & Kuhnel, 2006.02838

Hawking radiation

Microlensing

LIGO-Virgo

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Dynamical effects

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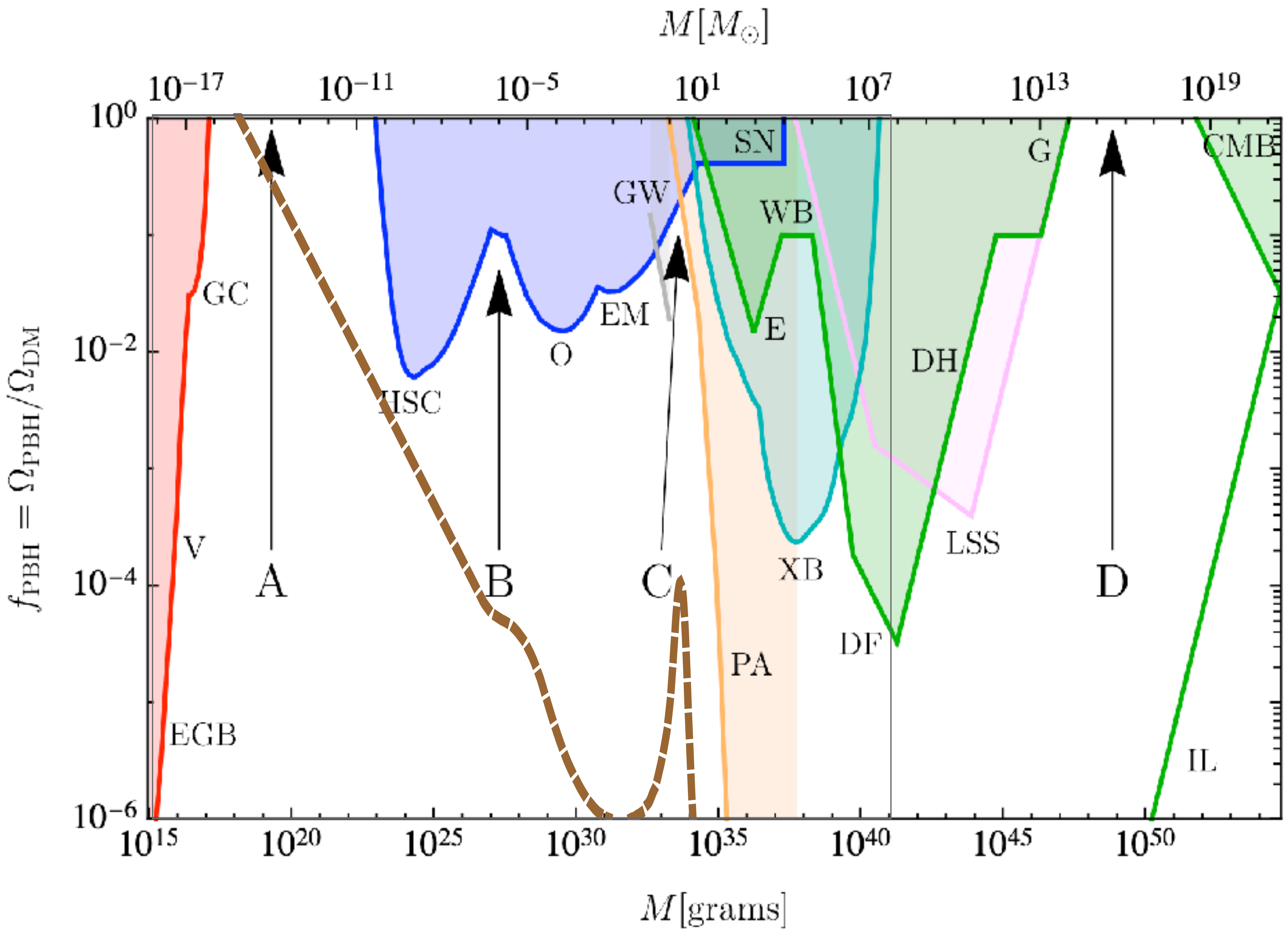


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✓ Solar mass region excluded by several probes
✓ No limit on asteroid-masses
✓ If PBHs + WIMPs (or particle DM) => stronger limits
(e.g. [Serpico+20] [Carr+20] [Byrnes+] [Boudaud+21])

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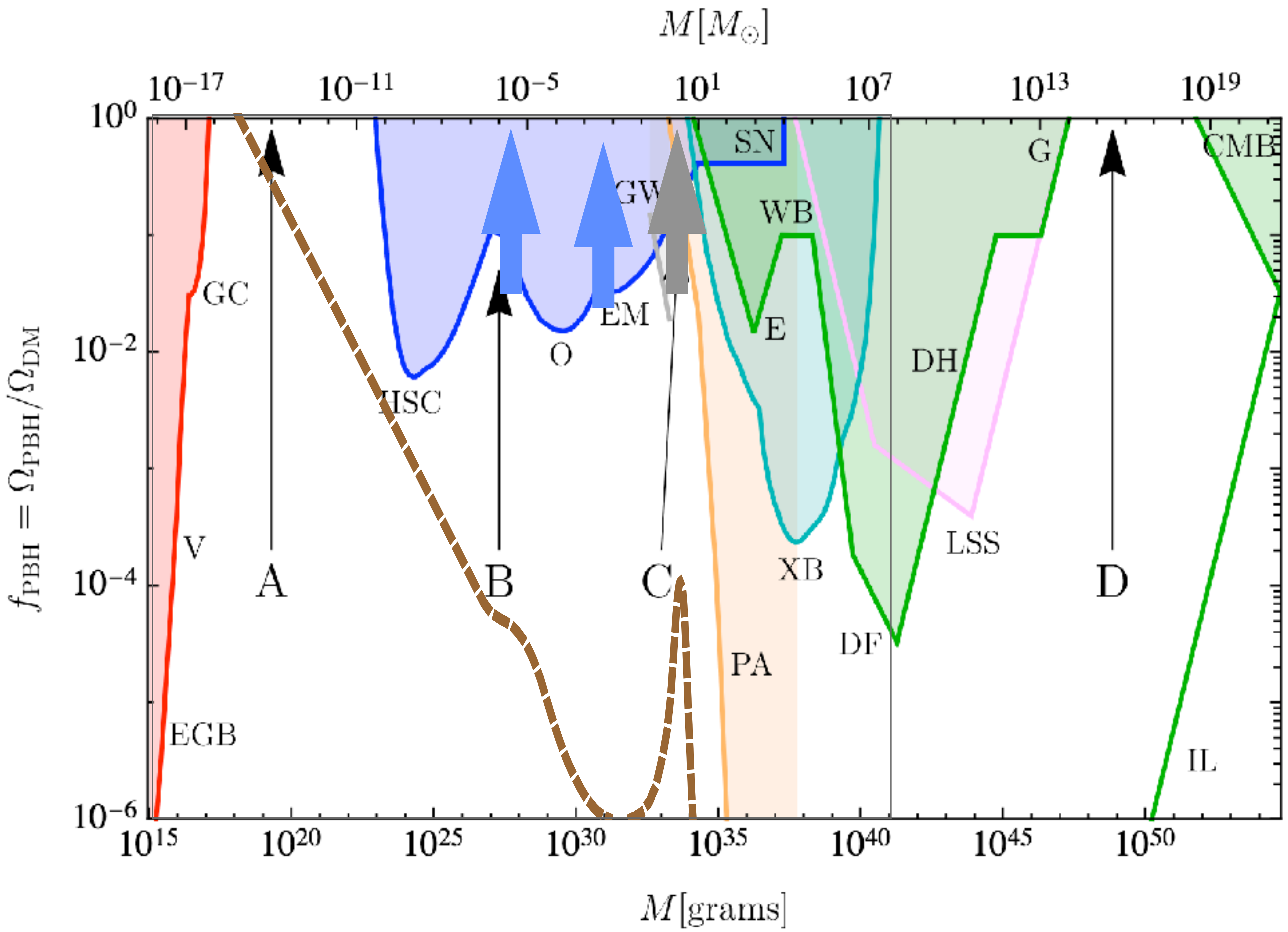


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◉ Asteroid-mass PBH dark matter => new fine-tuning
◉ Poisson clustering often not included in limits
◉ LIGO/Virgo limits less stringent
◉ Microlensing limits evaded if PBHs in clusters
◉ Backreactions for wide mass distributions

De Luca, Franciolini, Riotto et al., 2009.08268

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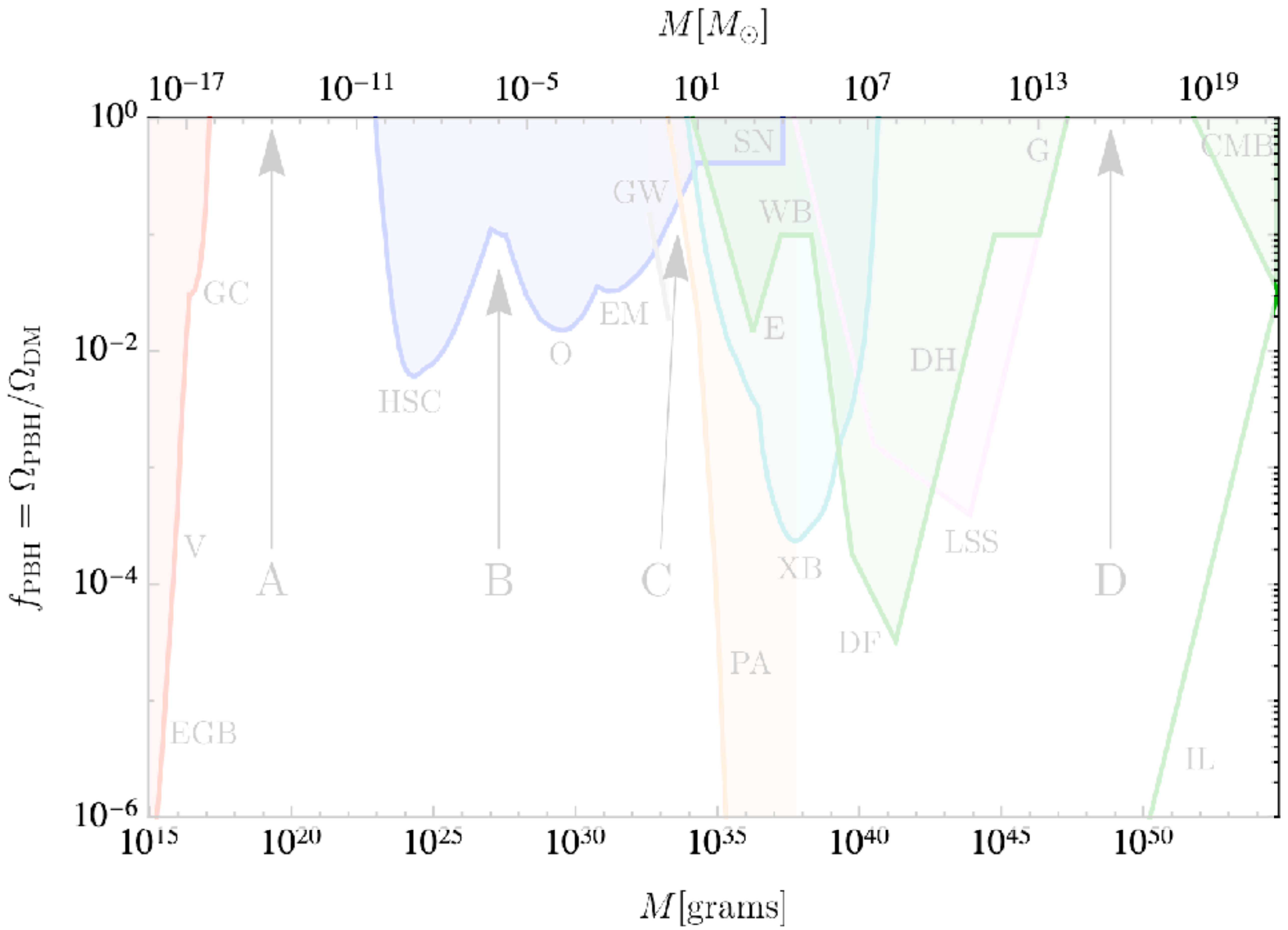

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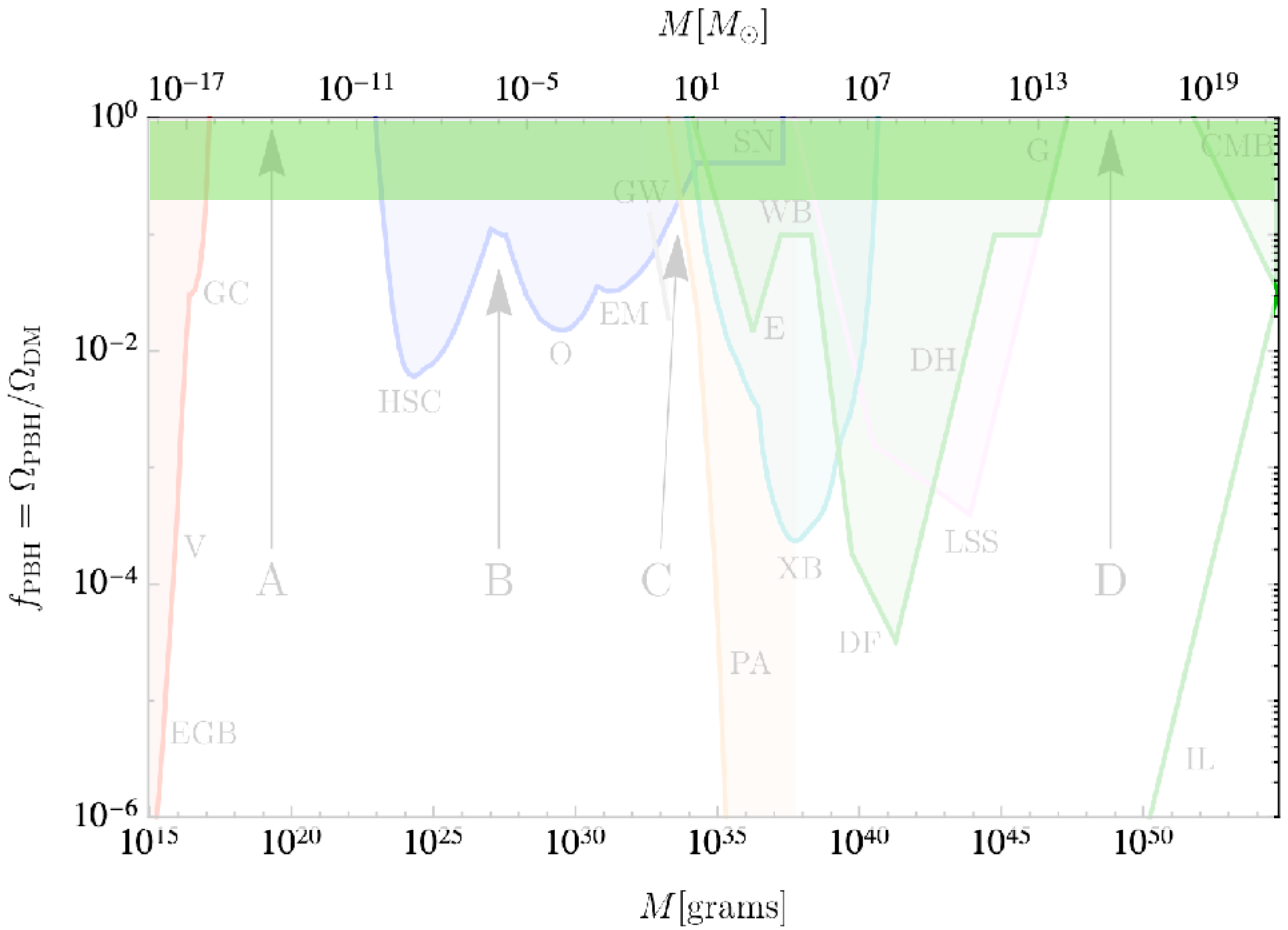

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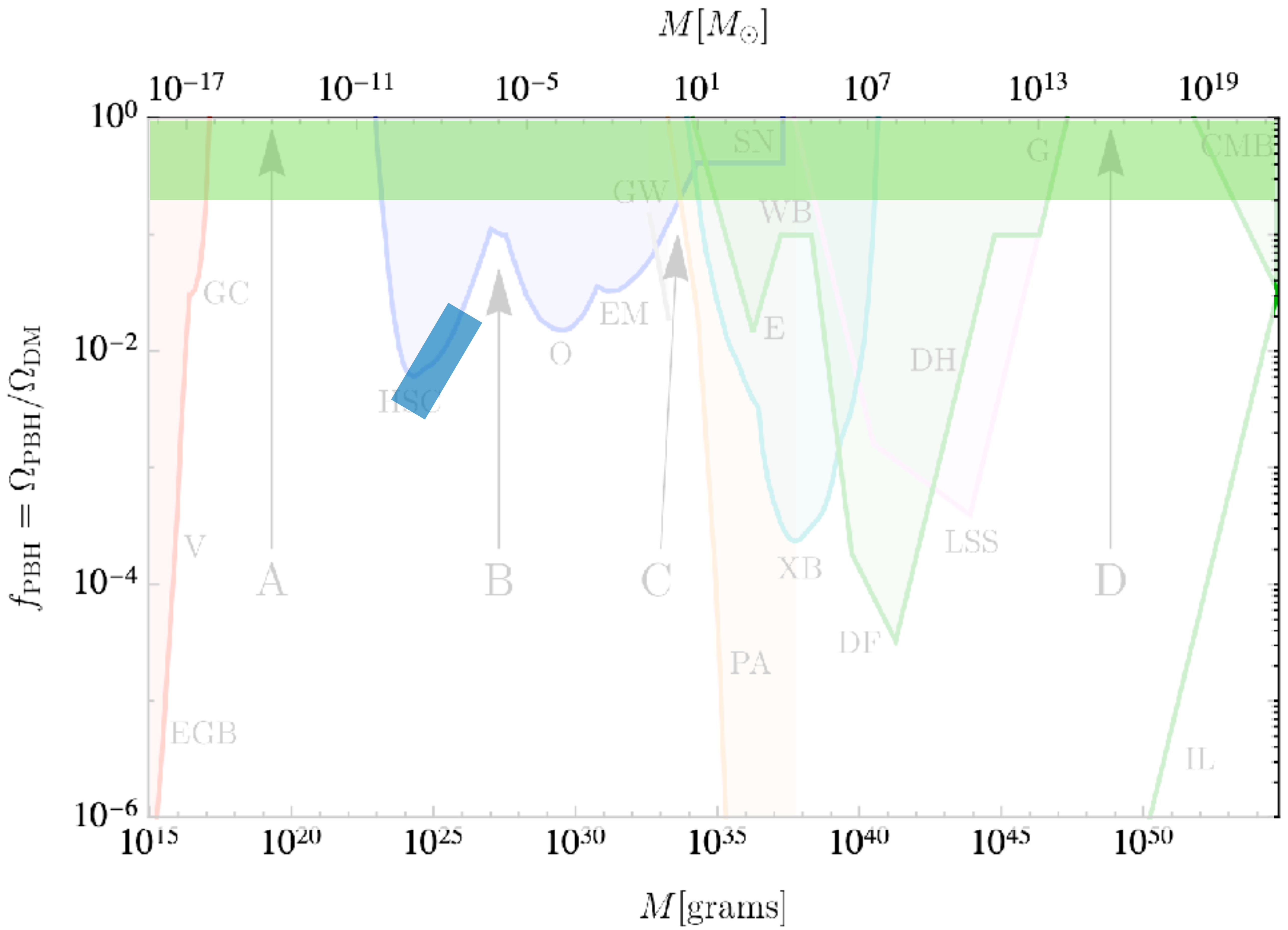

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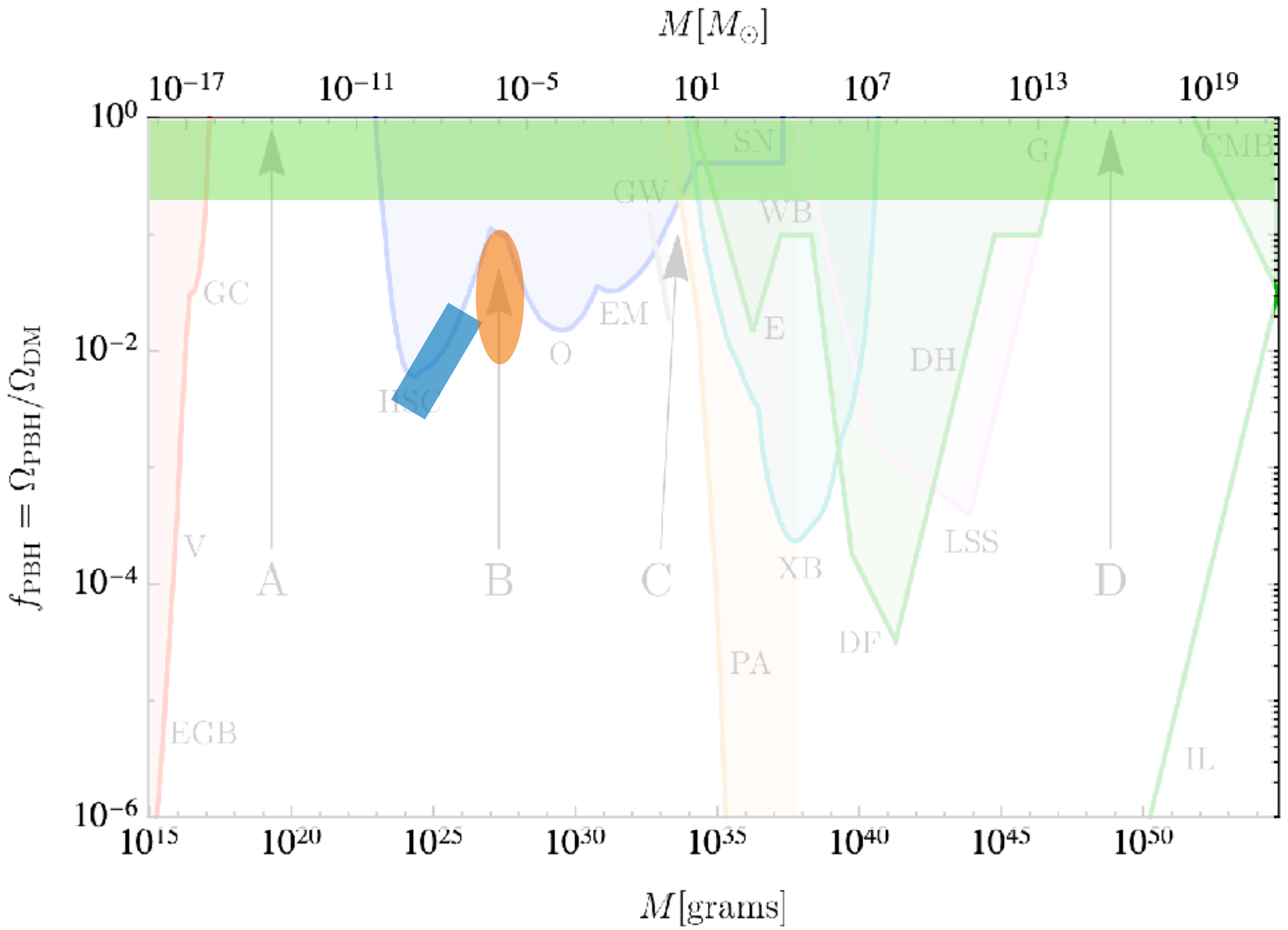

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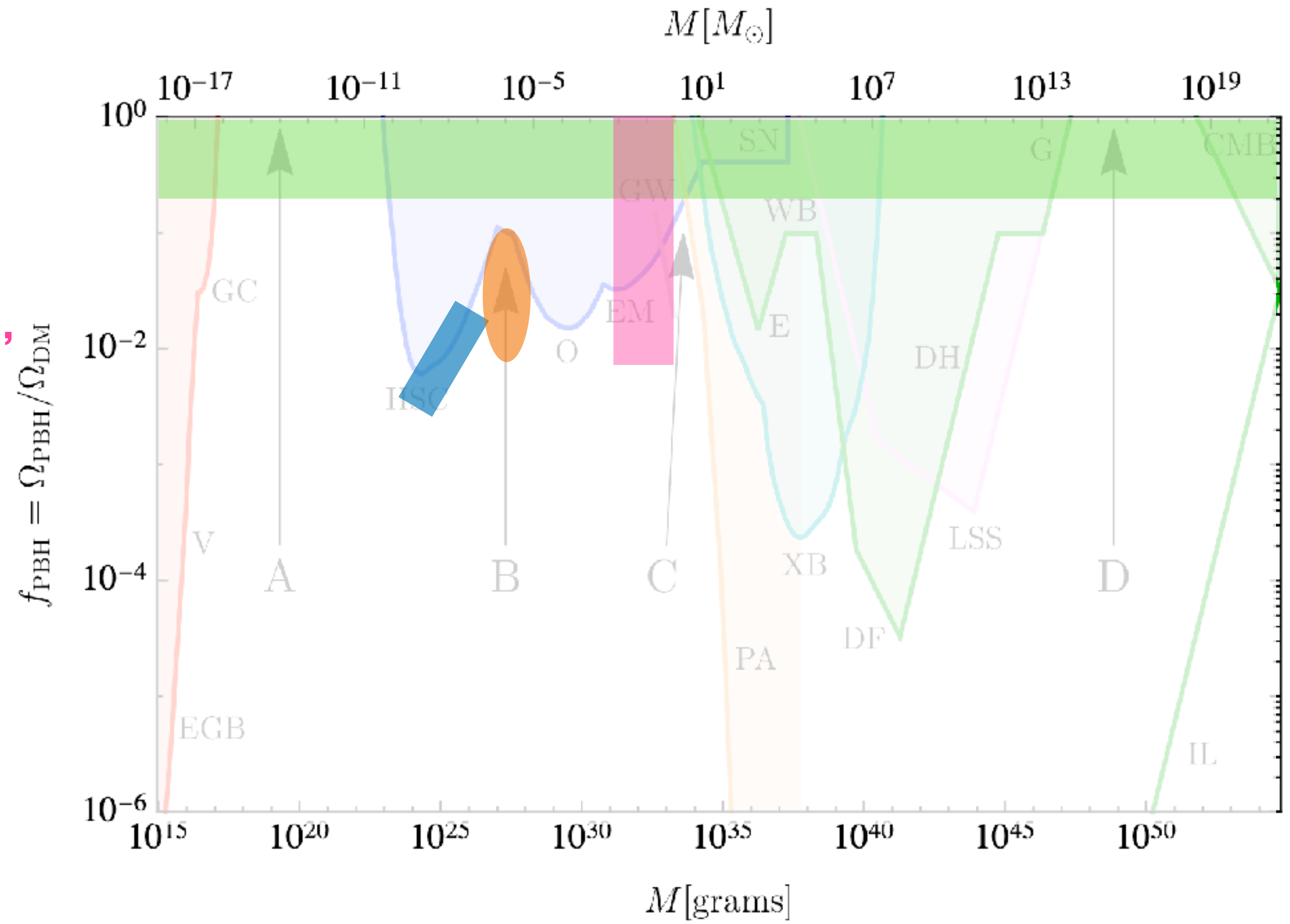

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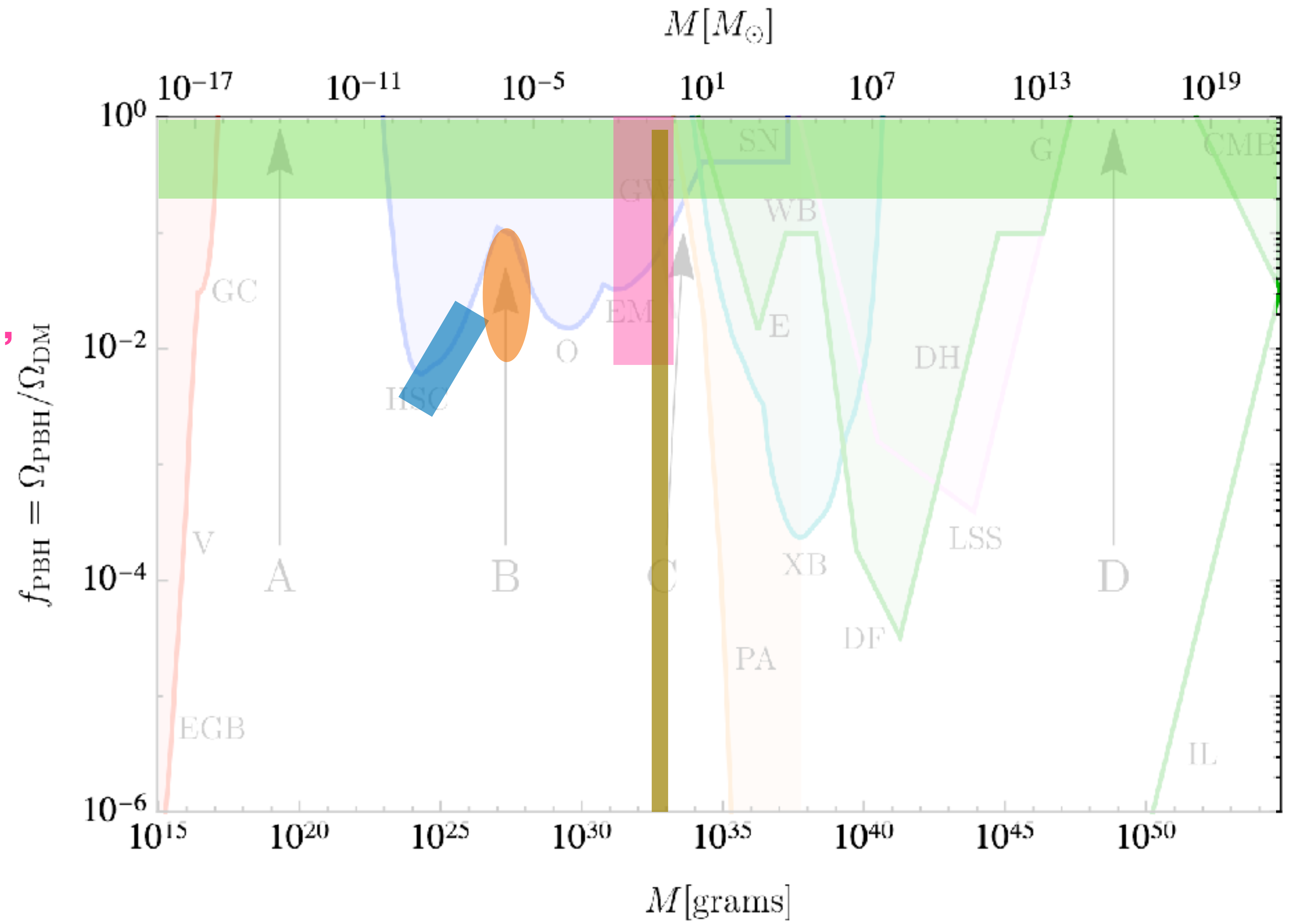
- OGLE+Gaia: BHs in the low mass gap, towards the galactic center) [Wyrzykowski+19]



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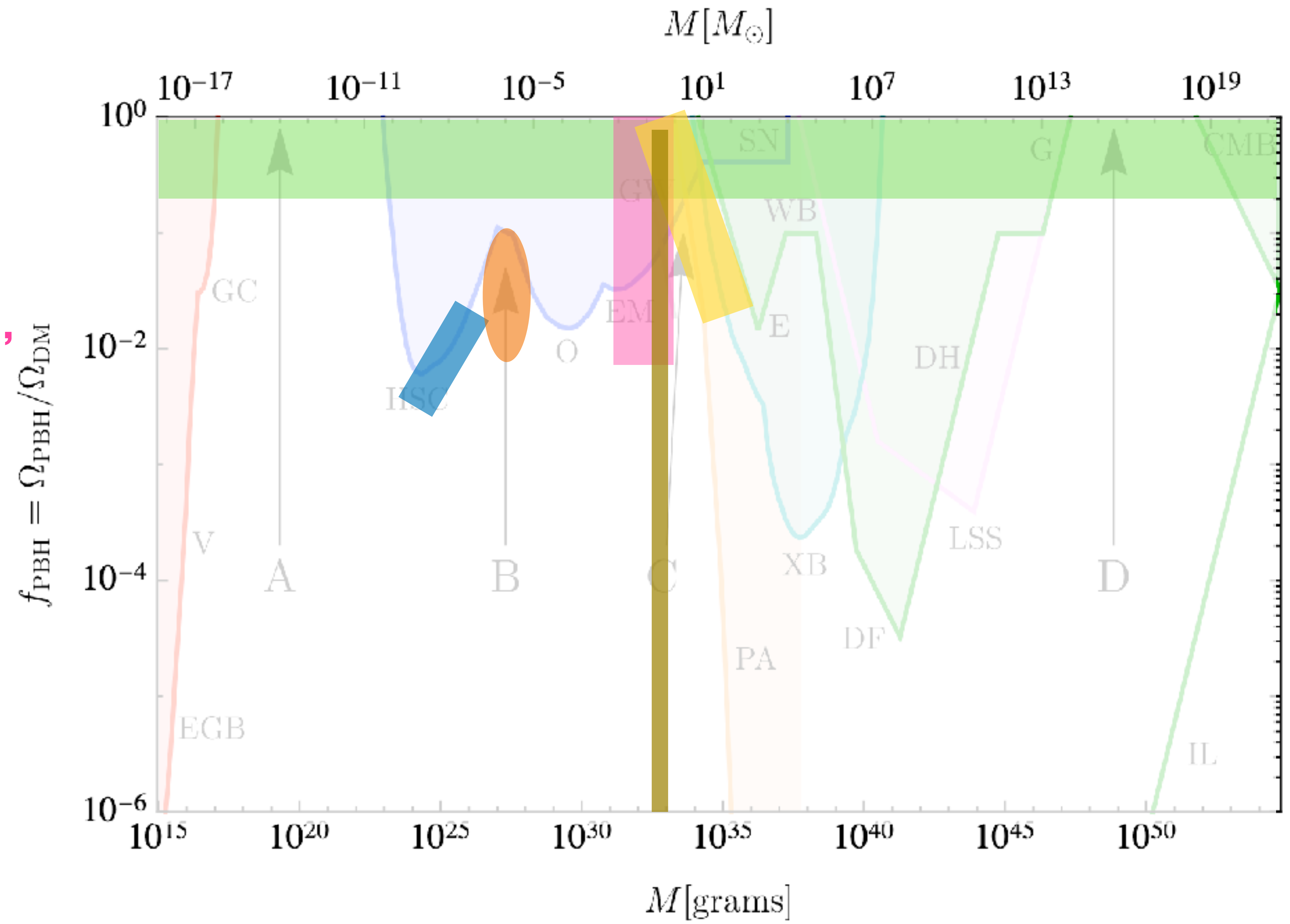

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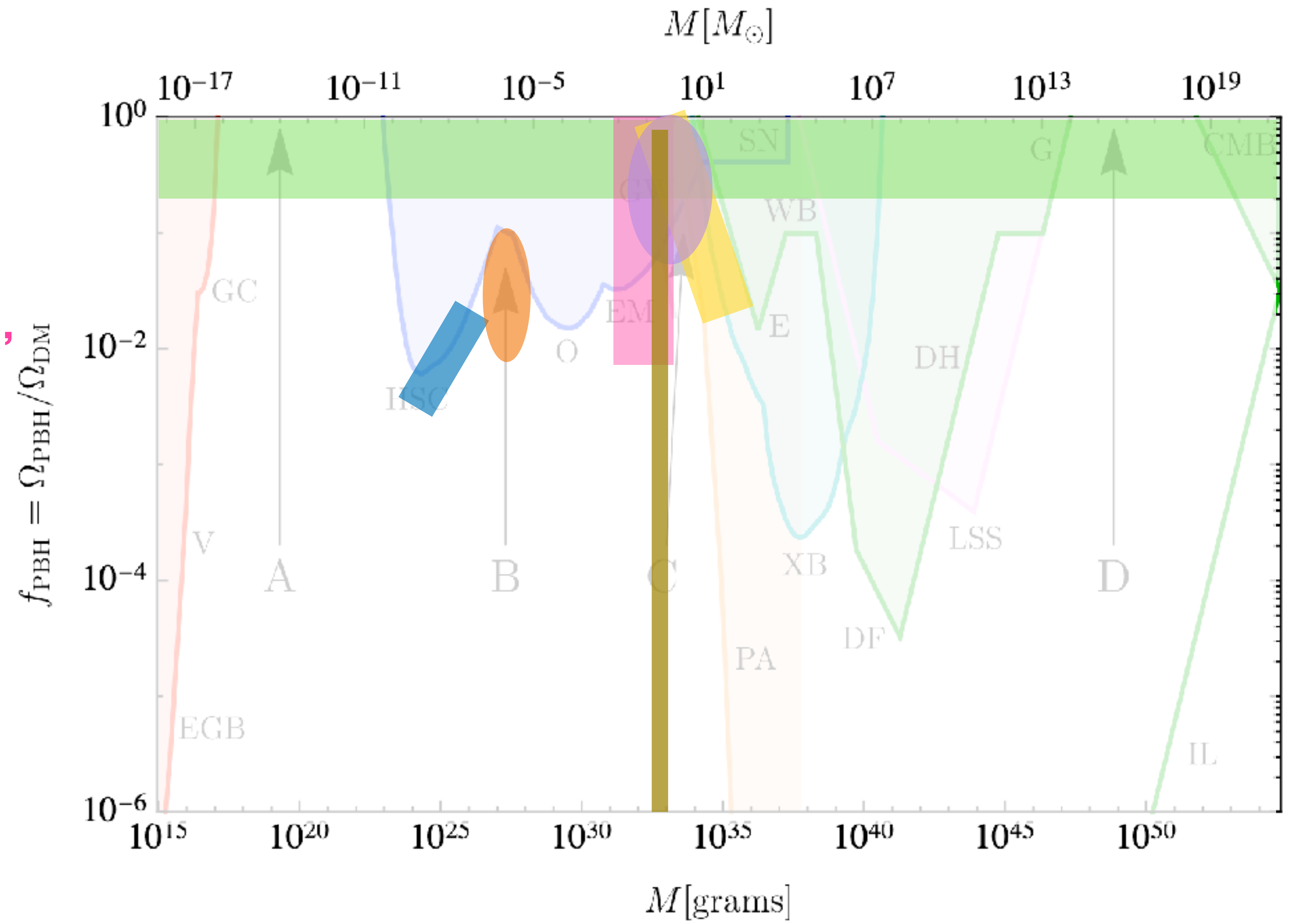

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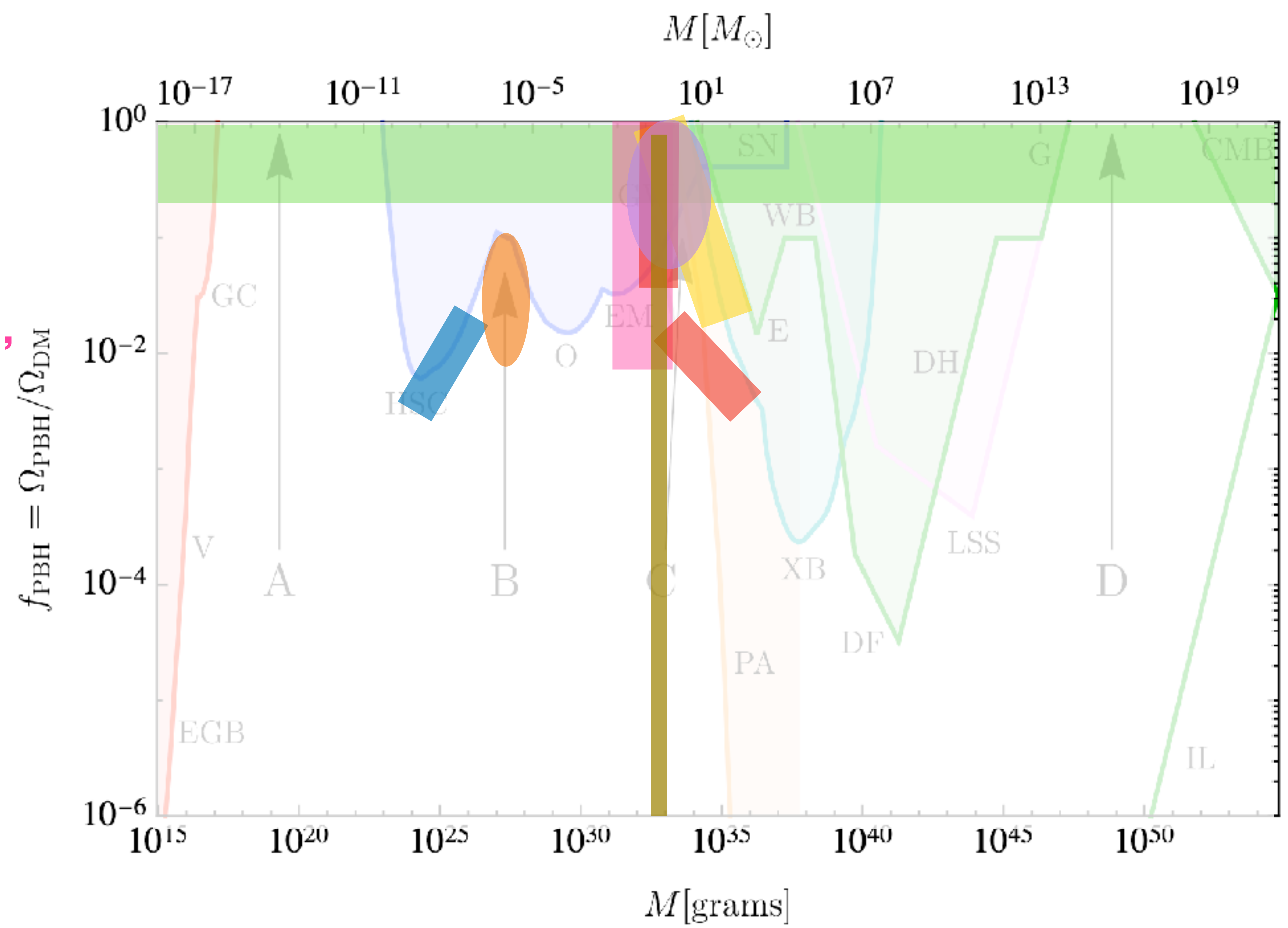

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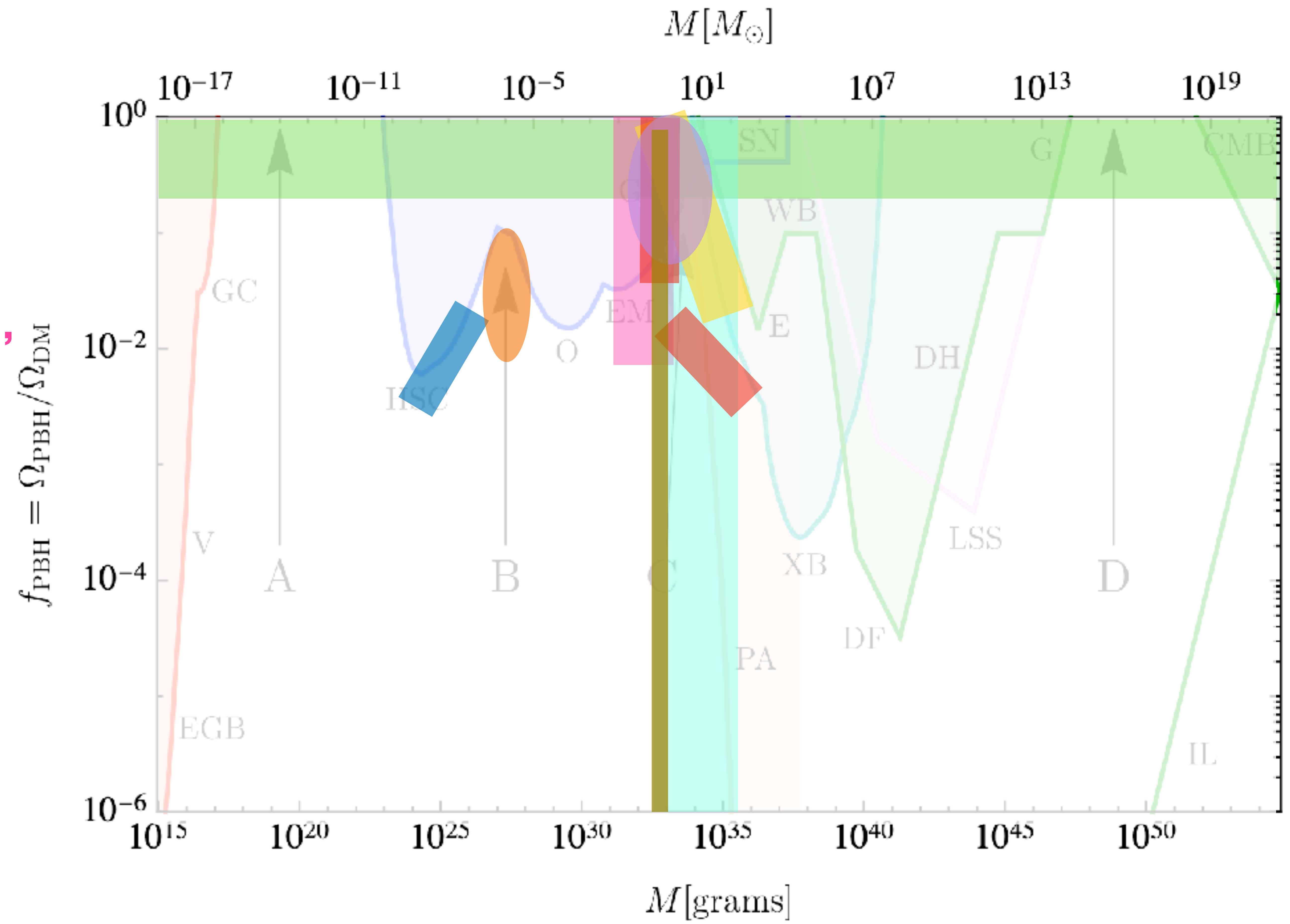

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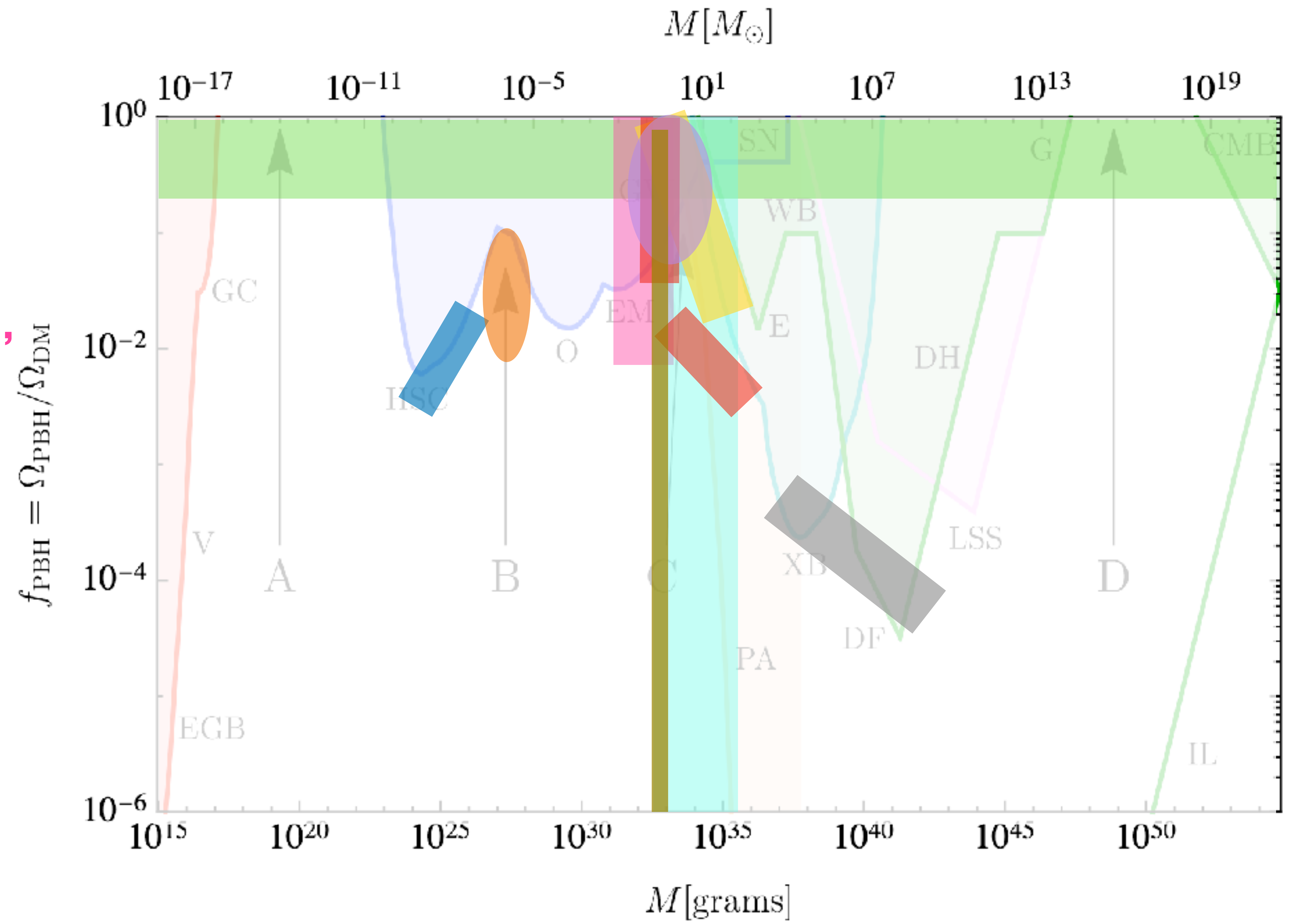

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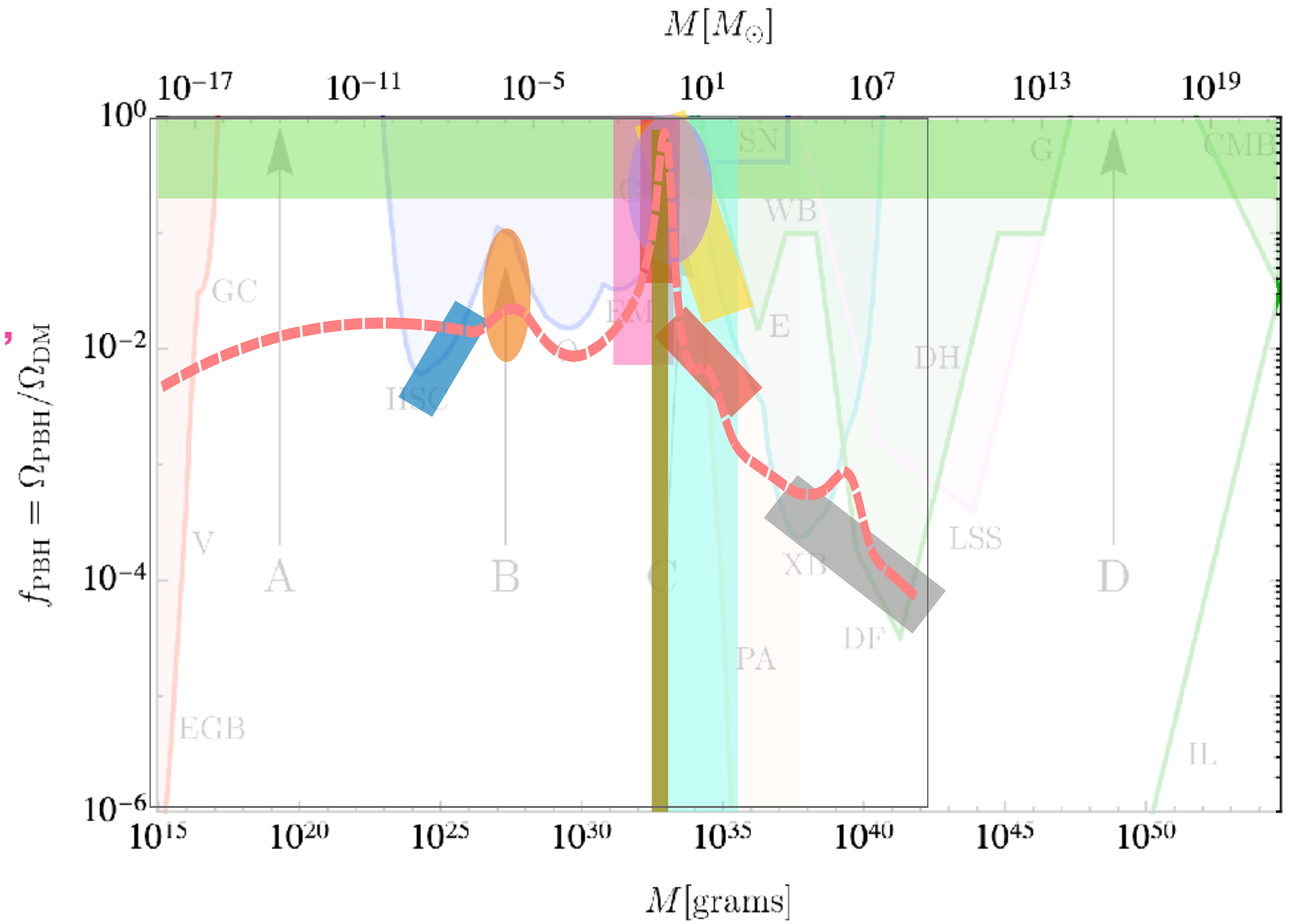

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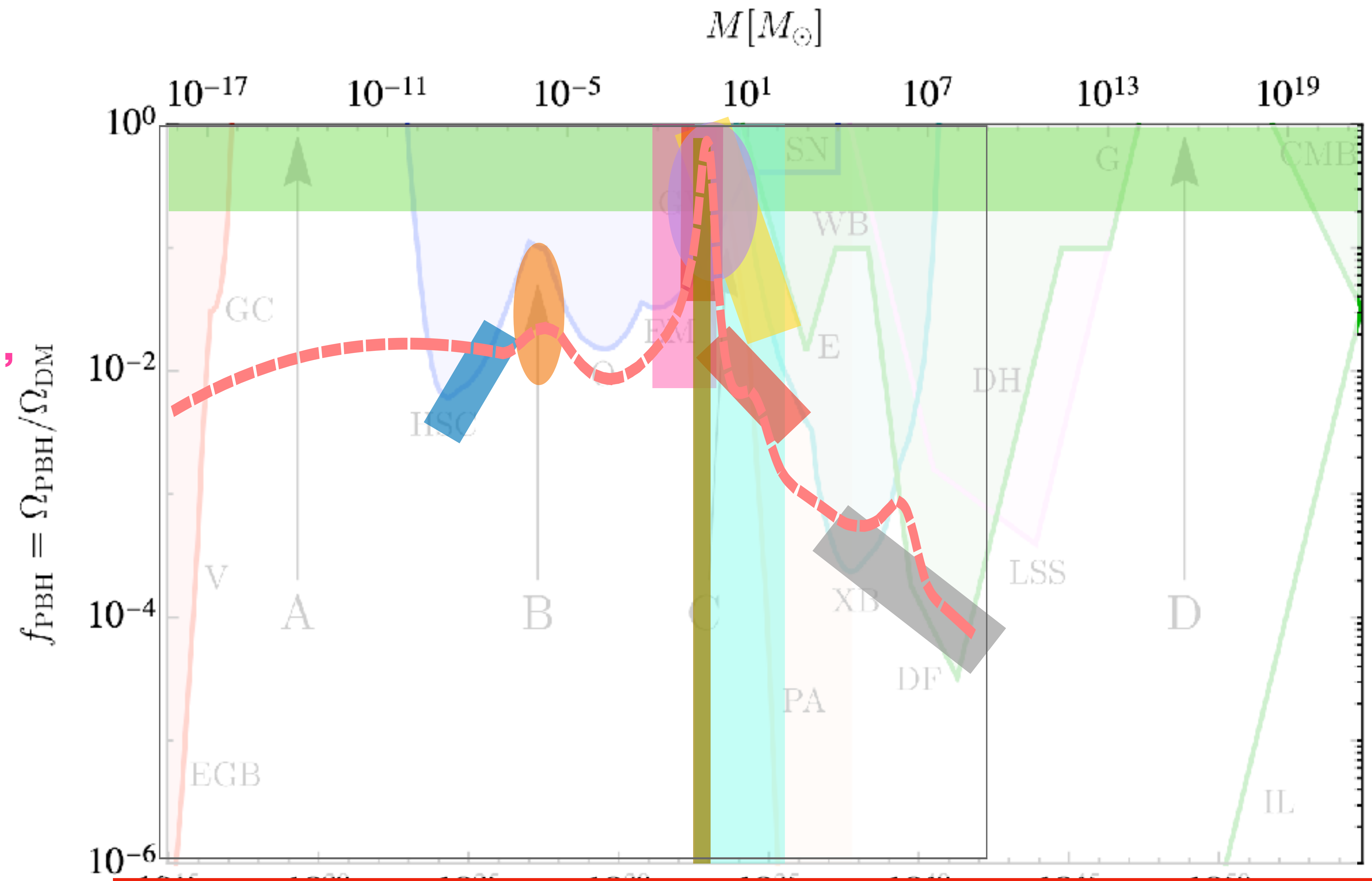


- ◉ How to avoid sub-asteroid masses ?
- ◉ Tension with Segues 1 limit
- ◉ Excluded by CMB limits (but do not include clustering)
- ◉ SMBHs excluded by CMB distortions (for Gaussian fluct).

# 3. Are LIGO/Virgo black holes primordial ?

## Merging rates

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**Early binaries**

$$R^{\rm early} = \frac{1.6 \times 10^6}{\rm Gpc^3\, yr} f_{\rm sup}(m_1, m_2, z)\, f_{\rm PBH}^{53/37}\, f(m_1)\, f(m_2) \left[\frac{t(z)}{t_0}\right]^{-34/37} \times \left(\frac{m_1 + m_2}{M_\odot}\right)^{-32/37} \left[\frac{m_1 m_2}{(m_1 + m_2)^2}\right]^{-34/37} .$$

03/2016: Sasaki et al (**$f_{sup}$=1**): **$f_{PBH}$ < 0.01 for $m_{PBH}$ = 30 $M_\odot$**

2018-2020: Raidal et al., Hutsi et al.: **$f_{sup}$ = 0.002** if $f_{PBH}$ = 1:

**In LIGO/Virgo range for 30 $M_\odot$ PBHs if $f_{PBH}$ ~ 0.001 - 0.01 [Riotto+], [Jedamzik 20], [Raidal+], etc…**

**In the LIGO/Virgo range for solar-mass PBHs $f_{PBH}$ = 1 (e.g. GW190425)** [Carr+19] [SC+20] [Jedamzik 20]

But: Issue with the rate of disrupted binaries ! (for monochromatic) slightly above LIGO/Virgo at ~solar-mass [Vaskonnen+19 ]

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**Late Binaries**

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

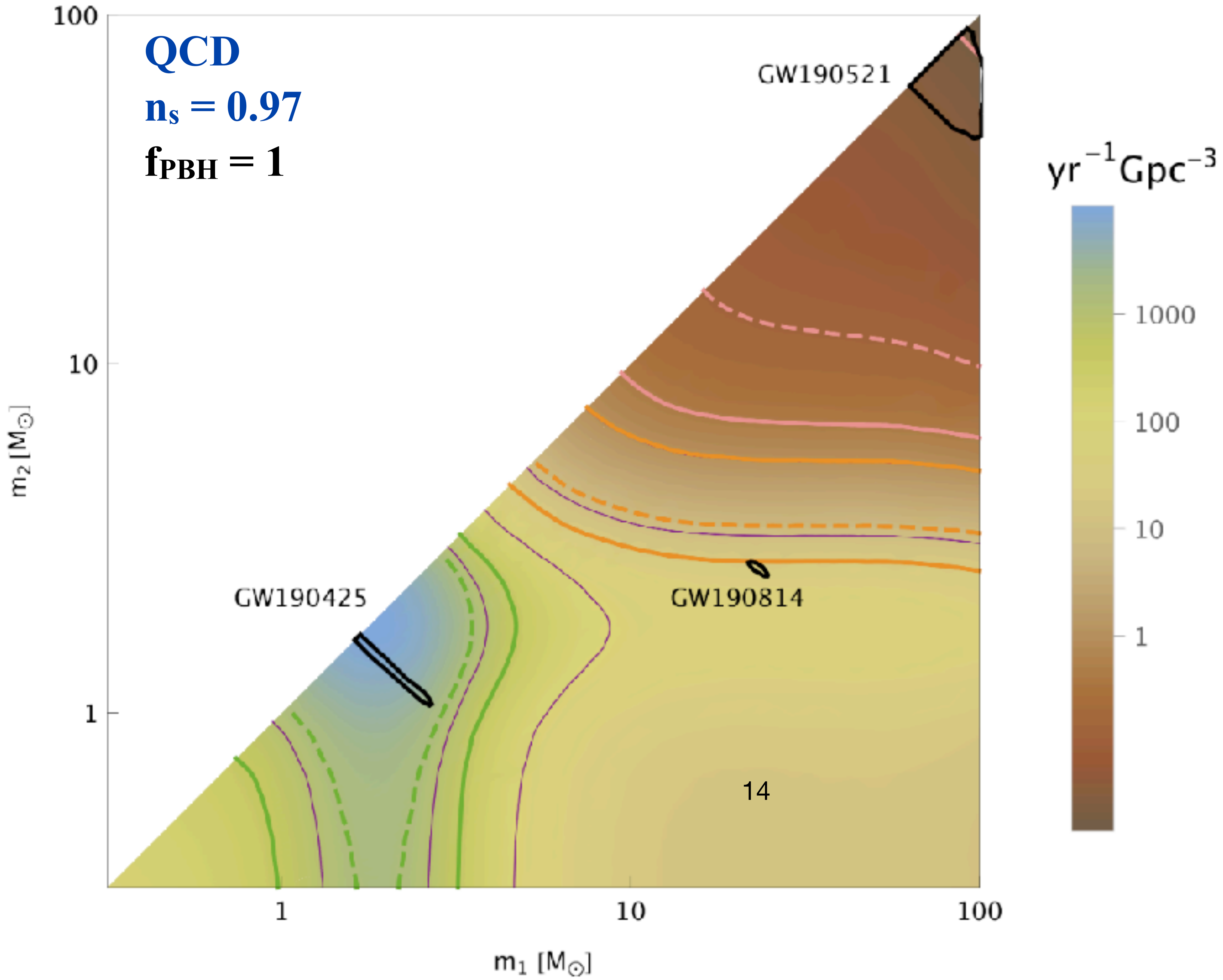
03/2016: Bird et al.
**standard halo mass function** (no Poisson clustering):
$R_{clust}$ = 1-10
**$f_{PBH}$ = 1** possible for **$m_{PBH}$ = 30 sun**
**After GTC3: below LIGO/Virgo rates**

03/2016: S.C + Garcia-Bellido
**Enhanced clustering (UFDG):**
**$f_{PBH}$ = 1** possible for **$m_{PBH}$ = 30 $M_\odot$**
2020: **Poisson clustering:**
$R_{clust}$ = 100-700
**$f_{PBH}$ = 1 leads to LIGO/Virgo rates at solar-mass scale**
only allows $f_{PBH}$ ~0.01 at 30 $M_\odot$

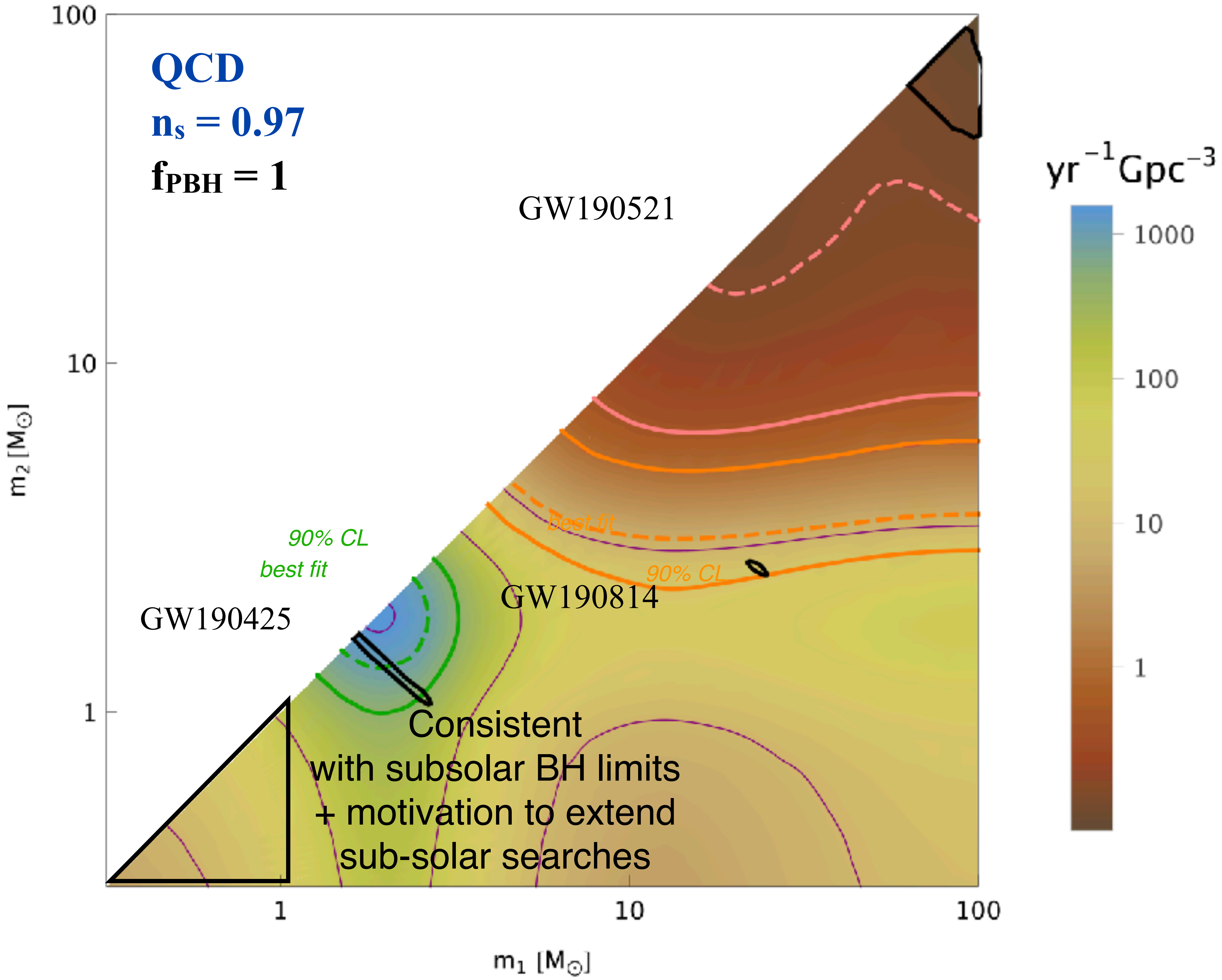
# 3. Are LIGO/Virgo black holes primordial ?

## Merging rates

**Early binaries**




**Late Binaries**



# 3. Are LIGO/Virgo black holes primordial ?

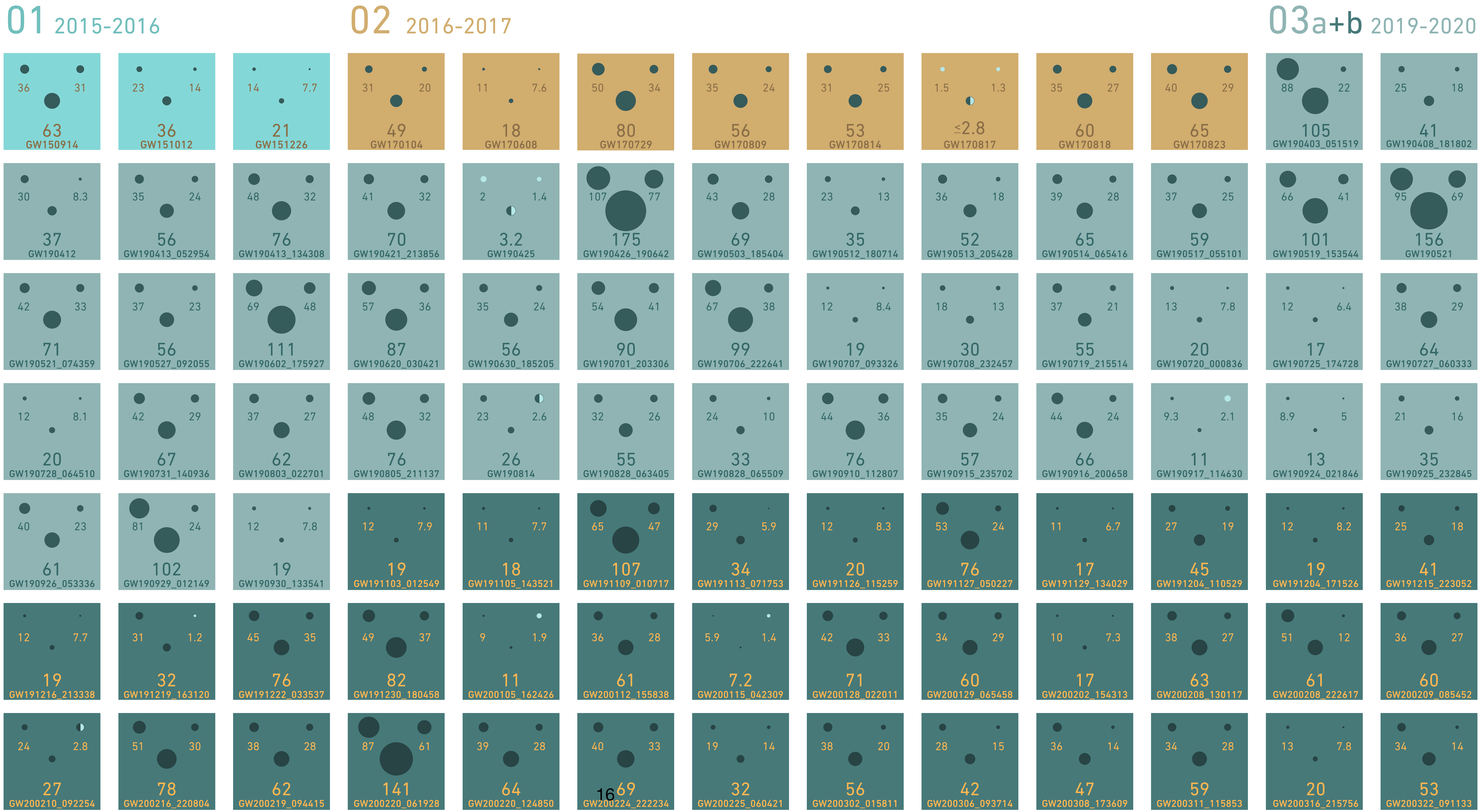
## Merging rates

Summary and current status:

- **Early** and **late** binaries **compete** at similar level, due to **Poisson clustering**
- At 30 $M_\odot$: **$f_{PBH}$ = 1 excluded** by LIGO/Virgo (and other limits), but **$f_{PBH}$ ~ 0.01 - 0.1 plausible** (as expected for a QCD transition)
- At 2-3 $M_\odot$: **$f_{PBH}$ = 1 possible**, both for **early** and **late** binaries, but the rate of **disrupted binaries** must be **suppressed** wrt [Vaskonen+19]

# 3. Are LIGO/Virgo black holes primordial ?

## Masses




**GWTC3 catalog**
**11/2021**

# 3. Are LIGO/Virgo black holes primordial ?

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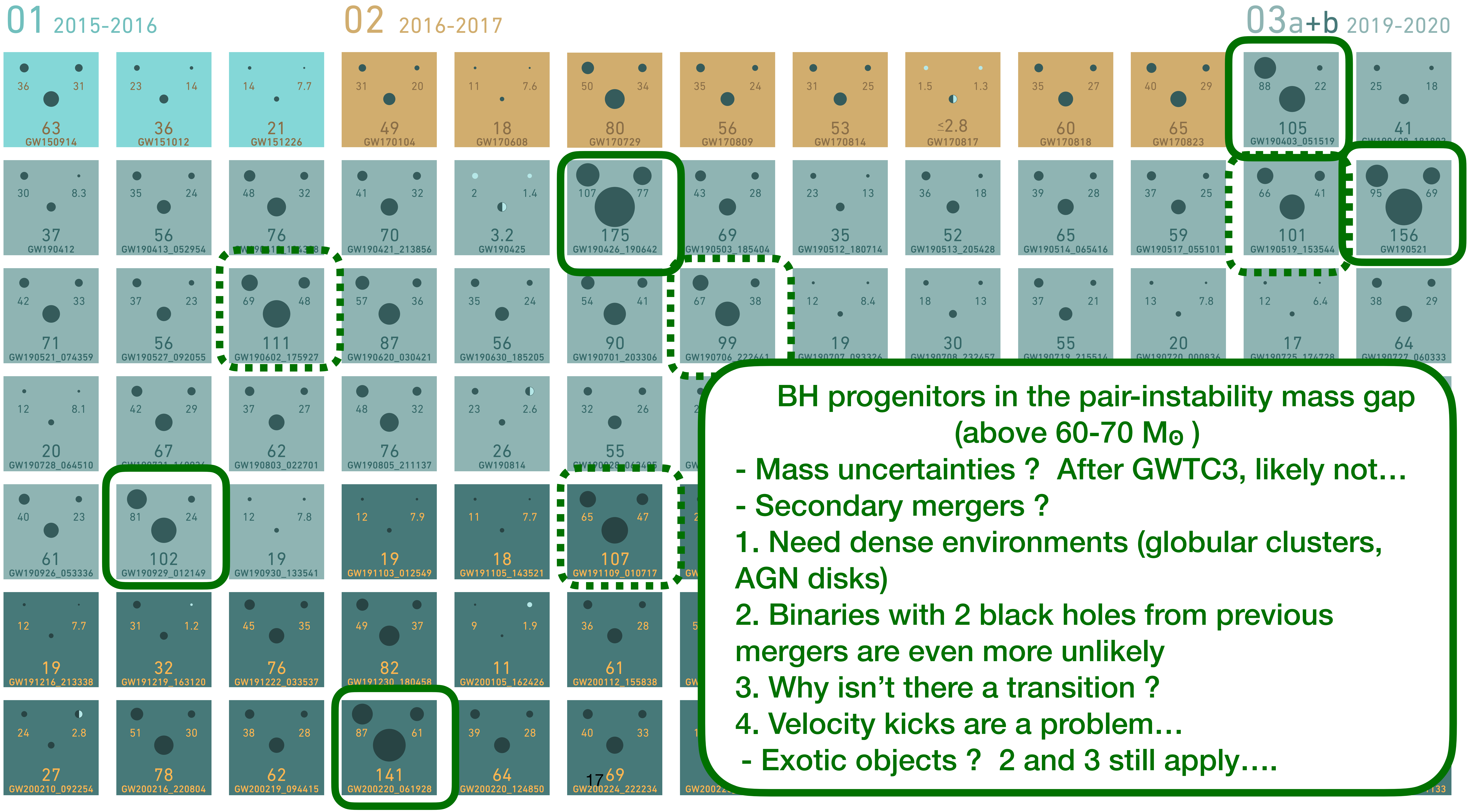



BH progenitors in the pair-instability mass gap (above 60-70 $M_\odot$ )

- Mass uncertainties ?  After GWTC3, likely not…
- Secondary mergers ?

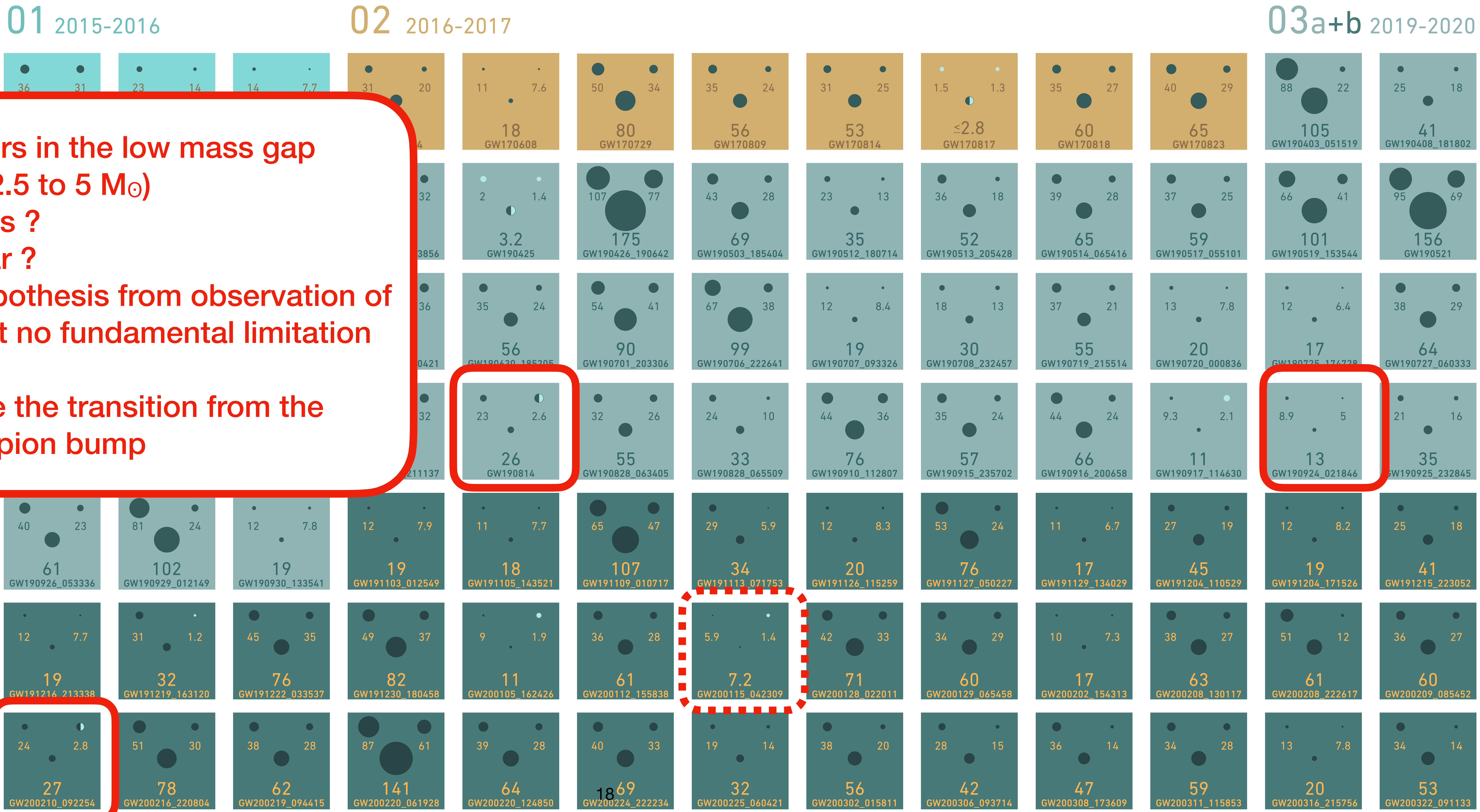
1. Need dense environments (globular clusters, AGN disks)
2. Binaries with 2 black holes from previous mergers are even more unlikely
3. Why isn't there a transition ?
4. Velocity kicks are a problem…

- Exotic objects ?  2 and 3 still apply….

GWTC3 catalog
11/2021

# 3. Are LIGO/Virgo black holes primordial ?

## Masses




BH progenitors in the low mass gap
(2.5 to 5 M☉)

- Mass uncertainties ?
- BH vs neutron star ?
- The mass gap hypothesis from observation of X-ray binaries, but no fundamental limitation

For PBHs: could be the transition from the proton peak to the pion bump

GWTC3 catalog
11/2021

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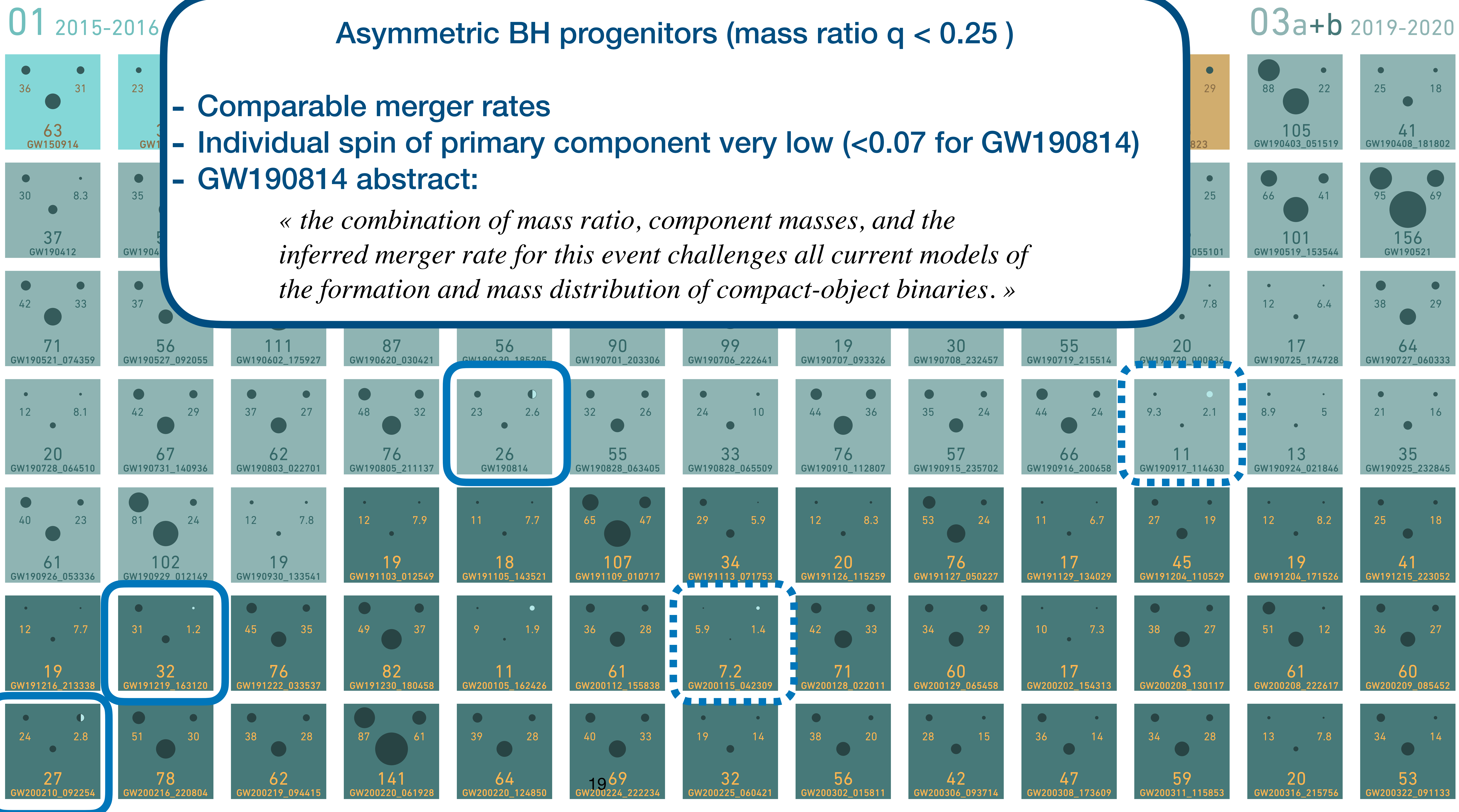
## Masses




**Asymmetric BH progenitors (mass ratio q < 0.25 )**

- Comparable merger rates
- Individual spin of primary component very low (<0.07 for GW190814)
- GW190814 abstract:

*« the combination of mass ratio, component masses, and the inferred merger rate for this event challenges all current models of the formation and mass distribution of compact-object binaries. »*

**GWTC3 catalog 11/2021**

# 3. Are LIGO/Virgo black holes primordial ?

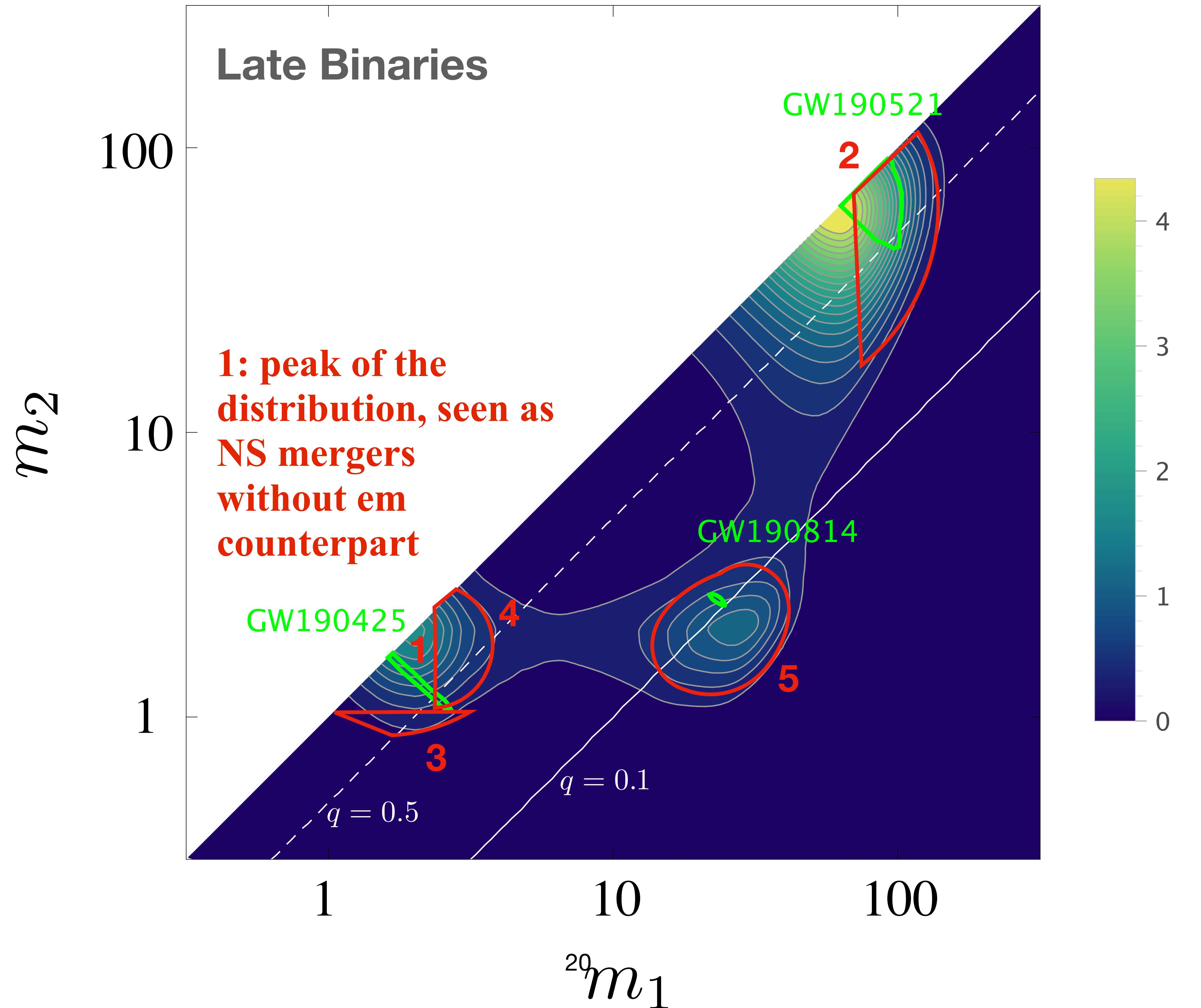
## Masses

**Astrophysical range:** $$R_{\rm det} = \frac{\sqrt{5}}{24}\frac{(G\mathcal{M}c^3)^{5/6}}{\pi^{2/3}} \times \frac{1}{2.26}\left[\int_{f_{\rm min}}^{f_{\rm max}} {\rm d}f\, \frac{f^{-\alpha}}{S_h(f)}\right]^{1/2}$$

**Expected** distribution of GW **observations** with **O2** LIGO (L1) sensitivity

B. Carr, S.C., J. Garcia-Bellido, F. Kühnel, 19'

*Similar distributions for primordial binaries, but less mergers above ~20 solar masses*



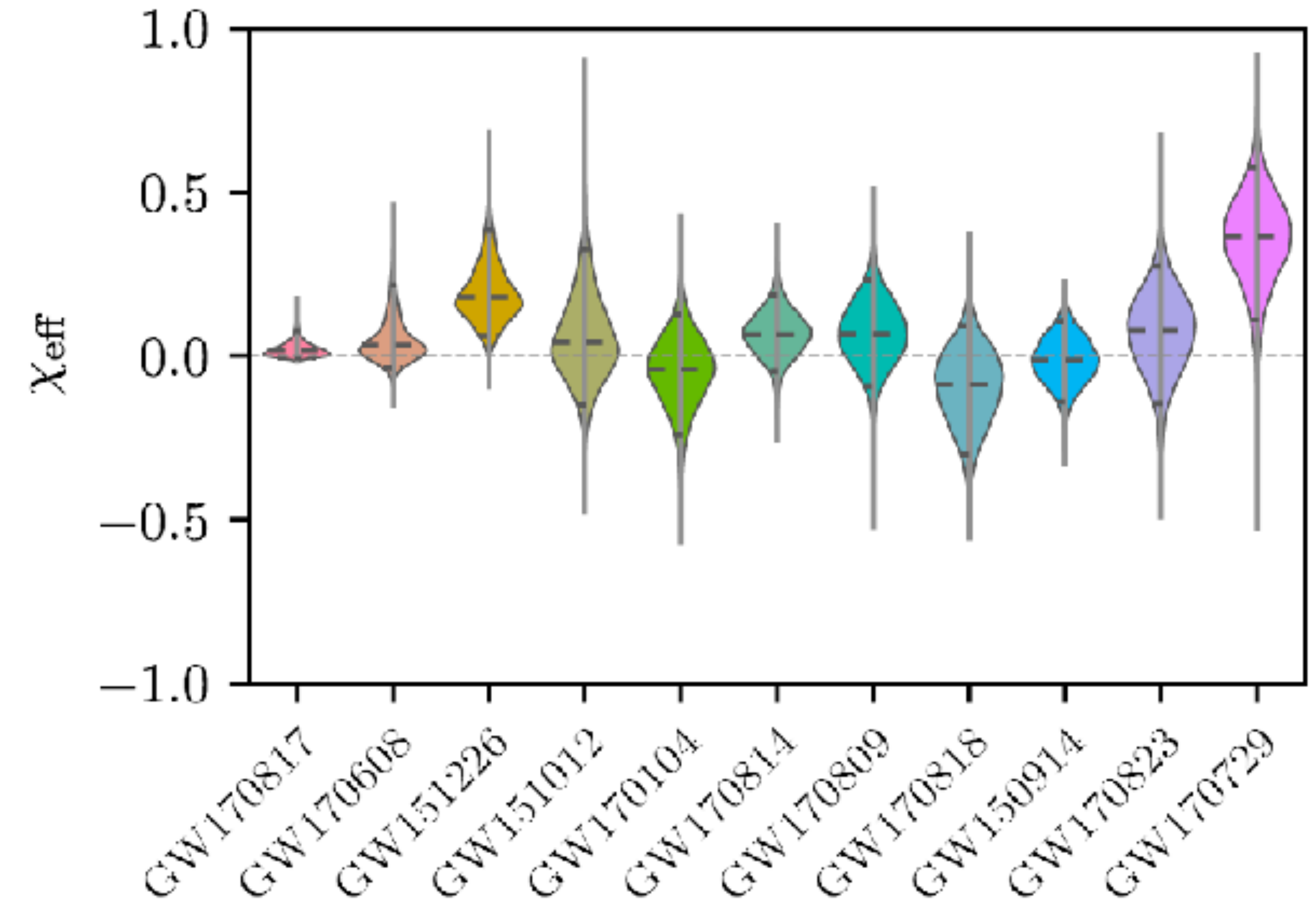

BUT: Observation of mergers in central blue region

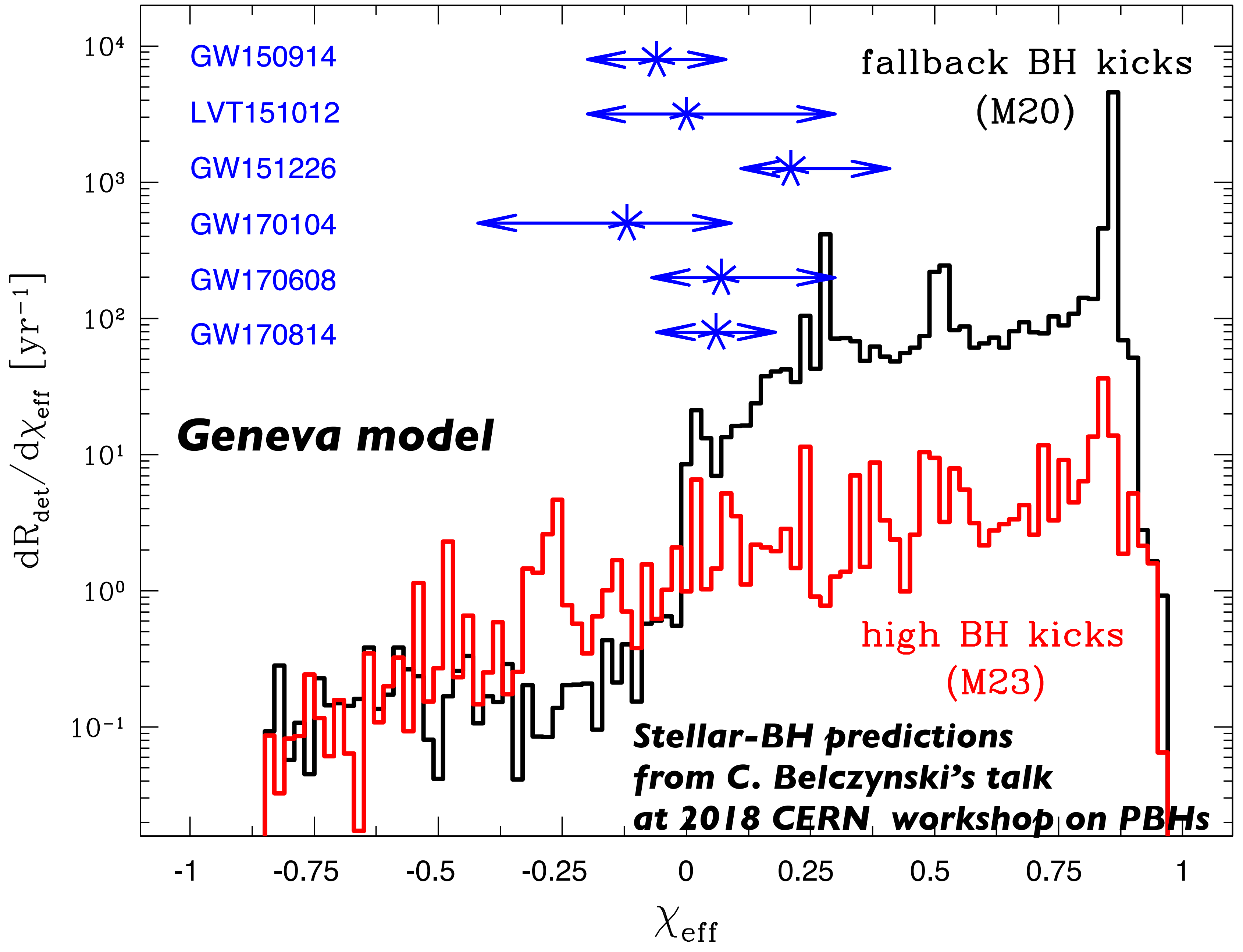
Next: Bayesian analysis for GWTC3

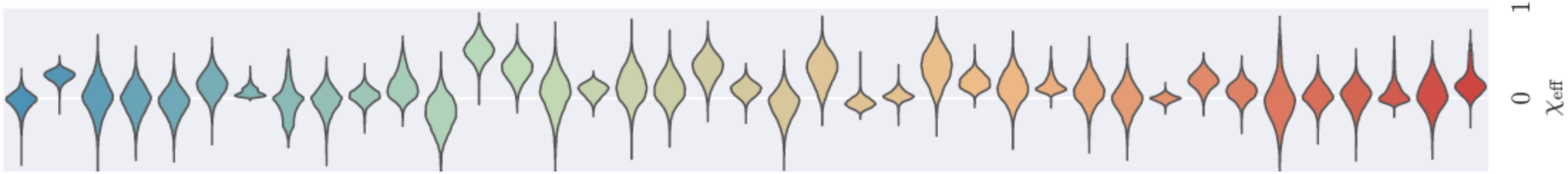
# 3. Are LIGO/Virgo black holes primordial ?

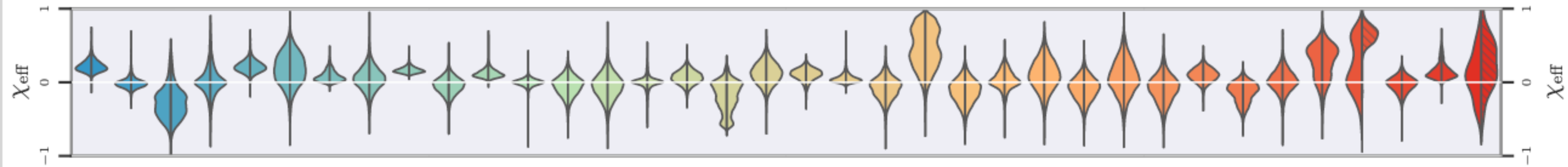
## Effective spins

$$\chi_{\rm eff} = [m_1 S_1 \cos(\theta_{{\rm LS}_1}) + m_2 S_2 \cos(\theta_{{\rm LS}_2})]/(m_1 + m_2)$$




**Spin of primary component for asymmetric mergers:**

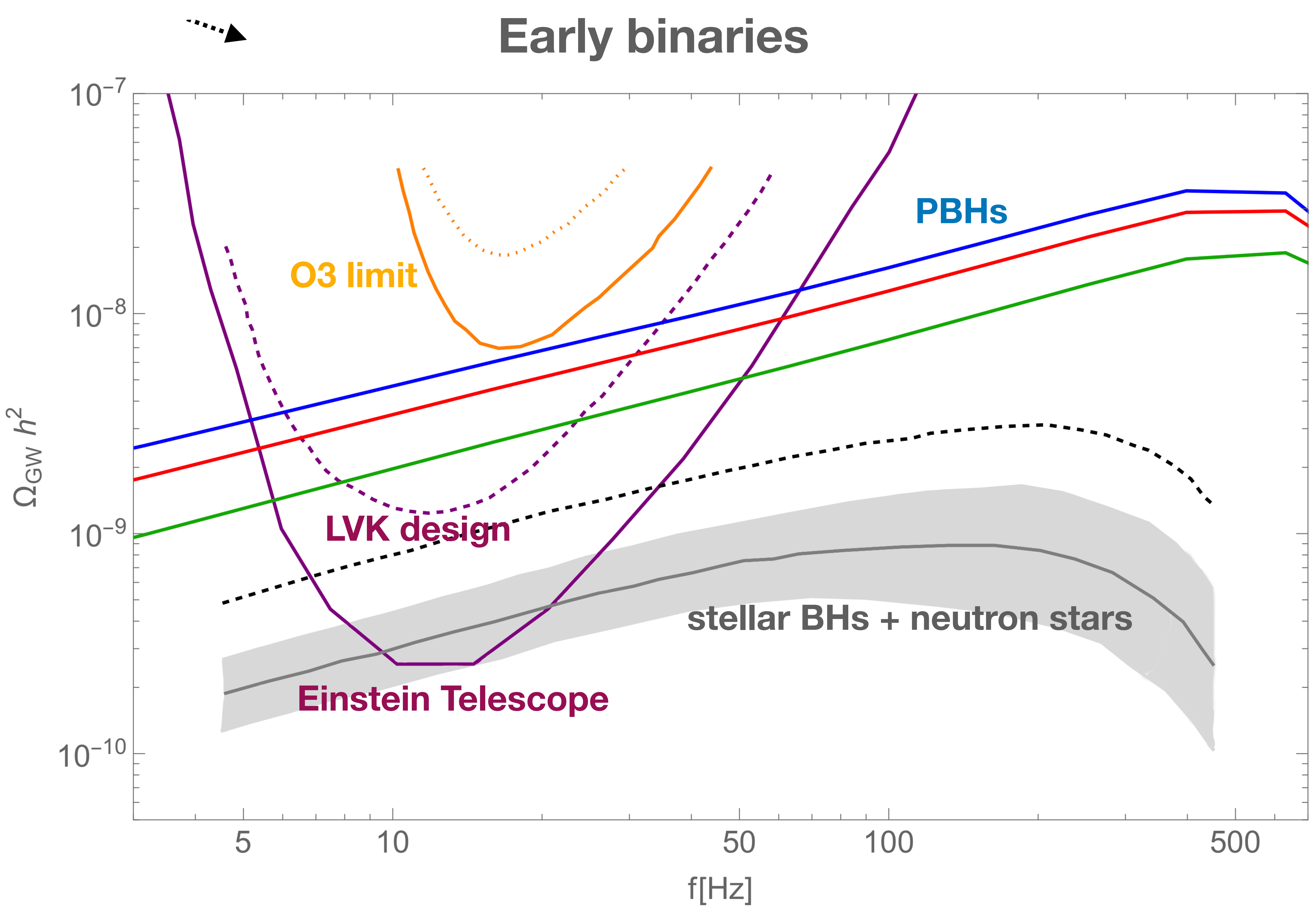
**GW190814: < 0.07**
GW191219…: <0.2
GW200210…: <0.4

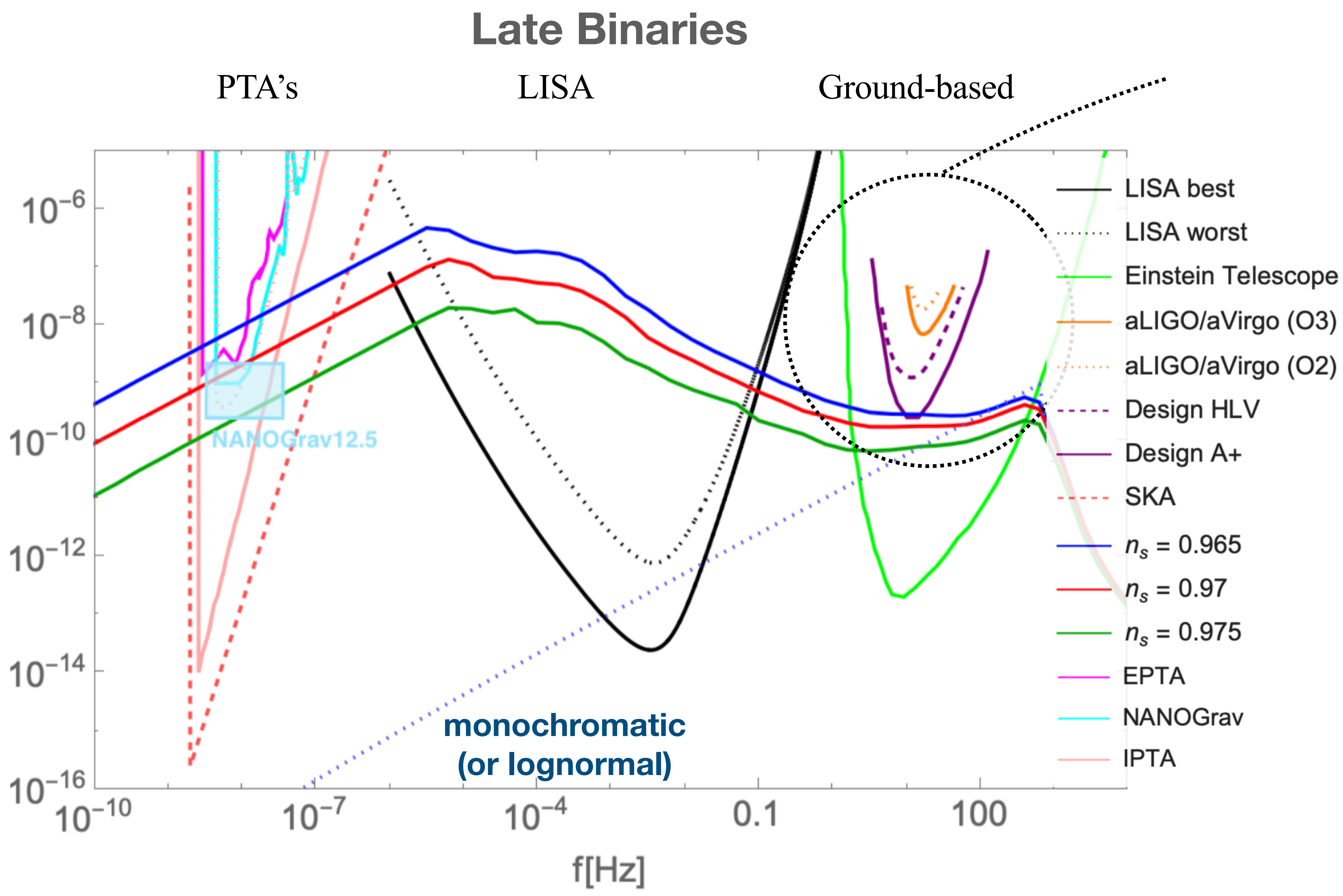
A few: in some cases evidence for a non-zero effective spin

PBHs have zero spin initially but can acquire a low spin due to accretion/mergers [De Luca+20]

# 3. How to distinguish primordial vs stellar BHs?

## GW backgrounds [Bagui, SC, 2021]




Well **above stellar BH predictions**
due to solar-mass-planetary-mass binaries
**At the limit of being detected by LIGO/Virgo !**
Next: pop-corn vs continuous regimes…

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

# 3. How to distinguish primordial vs stellar BHs?

## Subsolar black holes

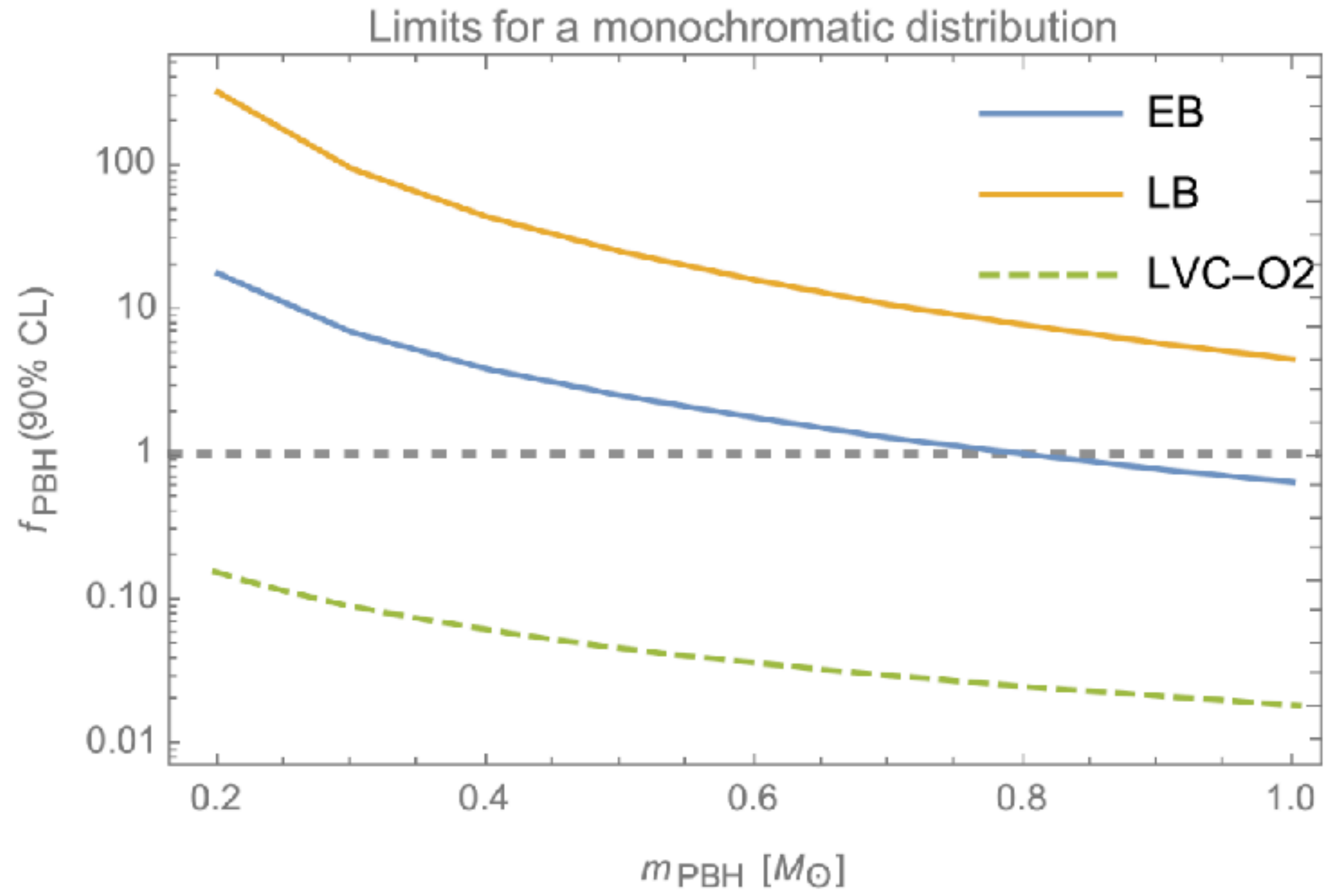
TABLE I. The candidates of the search with a SNR > 8 and a FAR < 2 $\mathrm{yr}^{-1}$. We report here the FAR, $\ln \mathcal{L}$, the UCT time of the event (date and hours), template parameters that pick the events and the associated SNRs.

| FAR [$\mathrm{yr}^{-1}$] | $\ln \mathcal{L}$ | UTC time | mass 1 [$M_\odot$] | mass 2 [$M_\odot$] | spin1z | spin2z | Network SNR | H1 SNR | L1 SNR |
|---|---|---|---|---|---|---|---|---|---|
| 0.1674 | 8.457 | 2017-03-15 15:51:30 | 3.062 | 0.9281 | 0.08254 | -0.09841 | 8.527 | 8.527 | - |
| 0.2193 | 8.2 | 2017-07-10 17:52:43 | 2.106 | 0.2759 | 0.08703 | 0.0753 | 8.157 | - | 8.157 |
| 0.4134 | 7.585 | 2017-04-01 01:43:34 | 4.897 | 0.7795 | -0.05488 | -0.04856 | 8.672 | 6.319 | 5.939 |
| 1.2148 | 6.589 | 2017-03-08 07:07:18 | 2.257 | 0.6997 | -0.[illegible] | [illegible] | [illegible] | [illegible] | [illegible] |

**Reanalysis of O2 data in 2105.11449**
**with updated merger rates and low mass ratios**

**A follow-up is ongoing with parameter estimations**

**$f_{PBH}$ = 1 still allowed by subsolar searches**



# Conclusion

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- **GW observations** (rate, masses, spins, background) are **very intriguing**, but not (yet?) fully convincing
- **Complex phenomenology**: formation, clustering, accretion, mergers, etc… **Strong statements are still premature**
- Common agreement: finding **subsolar black holes** is the best way to **prove the existence of PBHs**… 4 candidates already found. Stay tuned!