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Université Libre de Bruxelles (ULB)

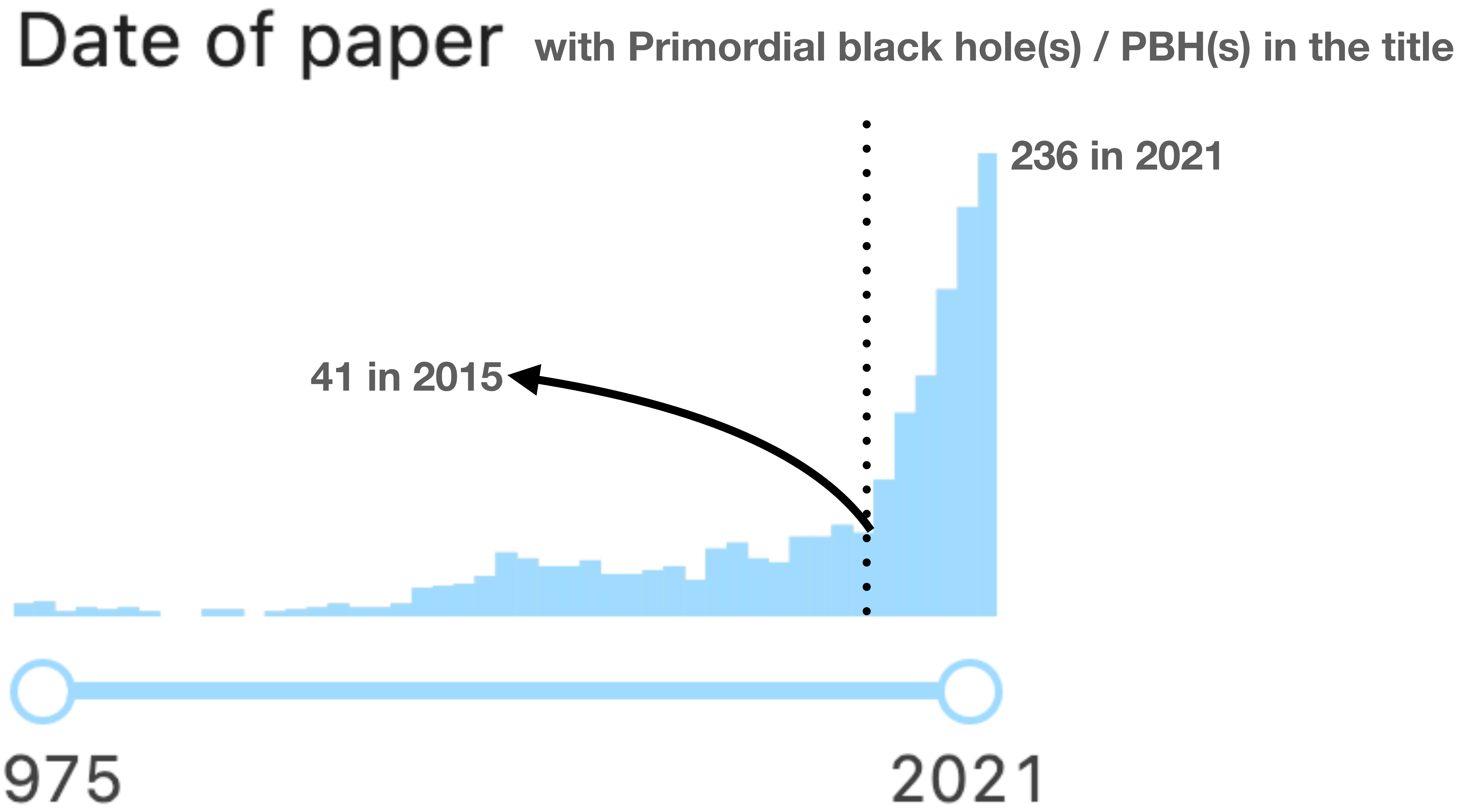
Primordial Black Holes

A (self) critical review

News From the Dark, LAPTh Annecy, November 22-24, 2021

A Hot topic !
From 1970 to 2021

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



source: InspireHEP

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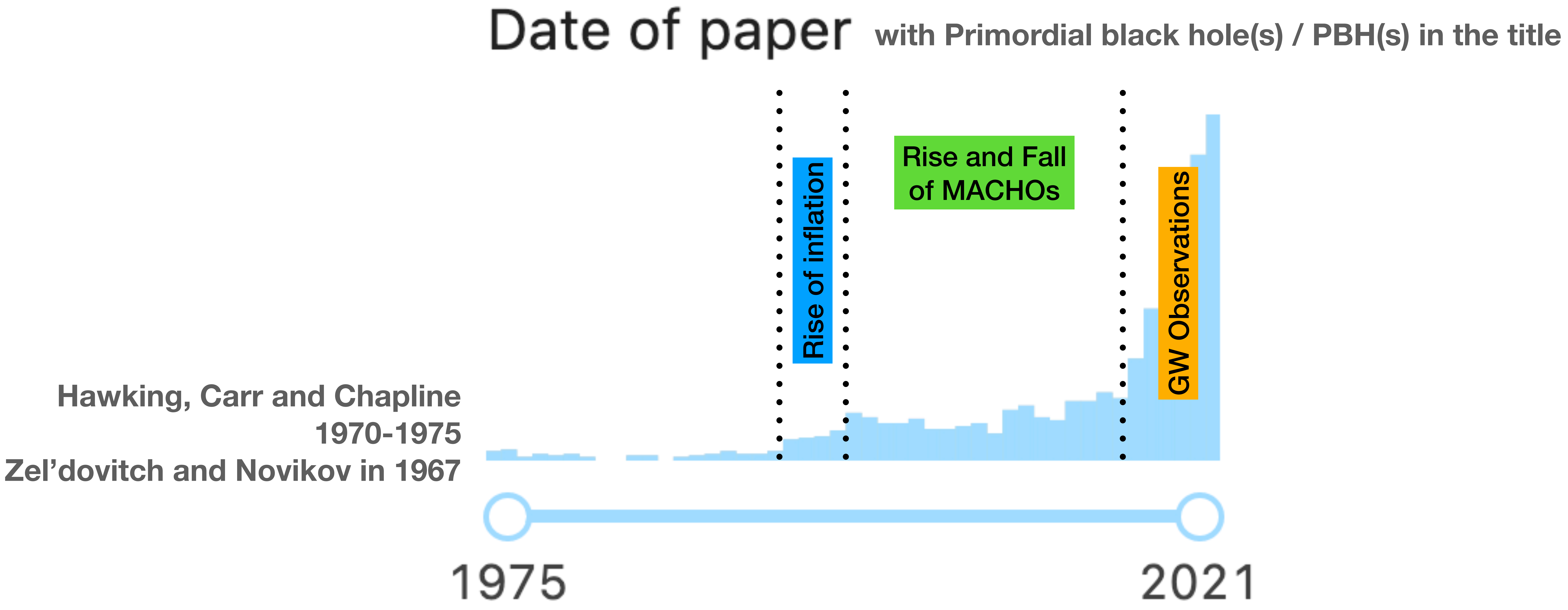

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Outline

A (self-critical) review of three fundamental questions:

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- How natural is PBH **formation** ?

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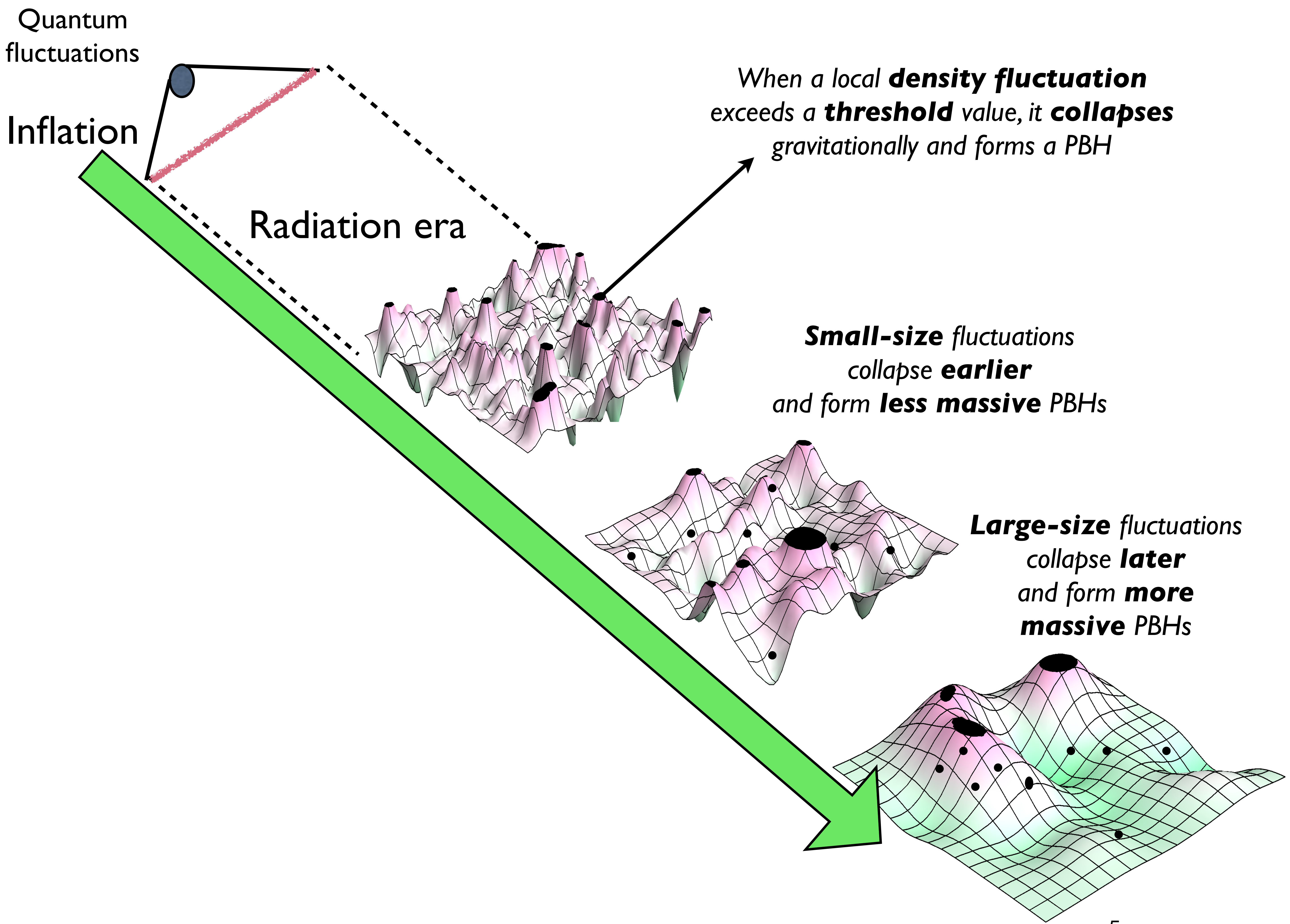
A (self-critical) review of three fundamental questions:

- How natural is PBH **formation** ?
- 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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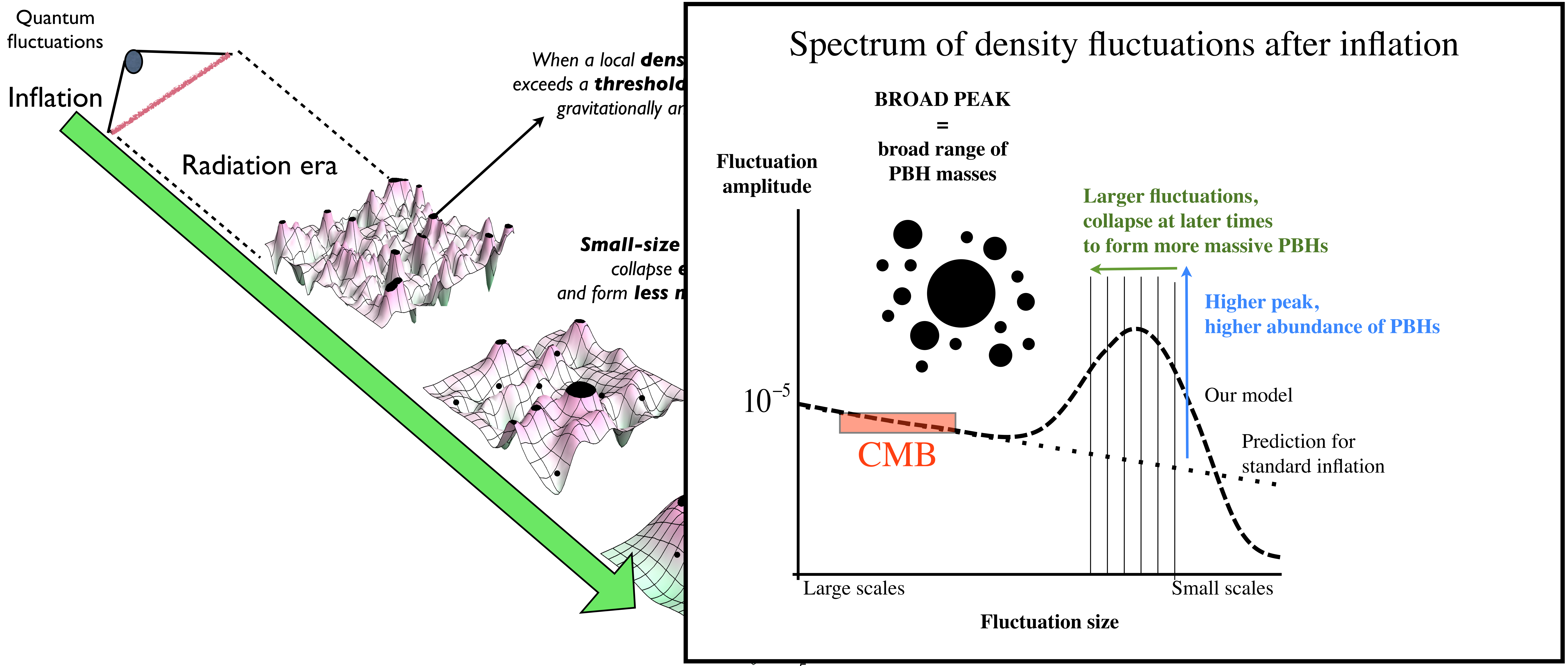

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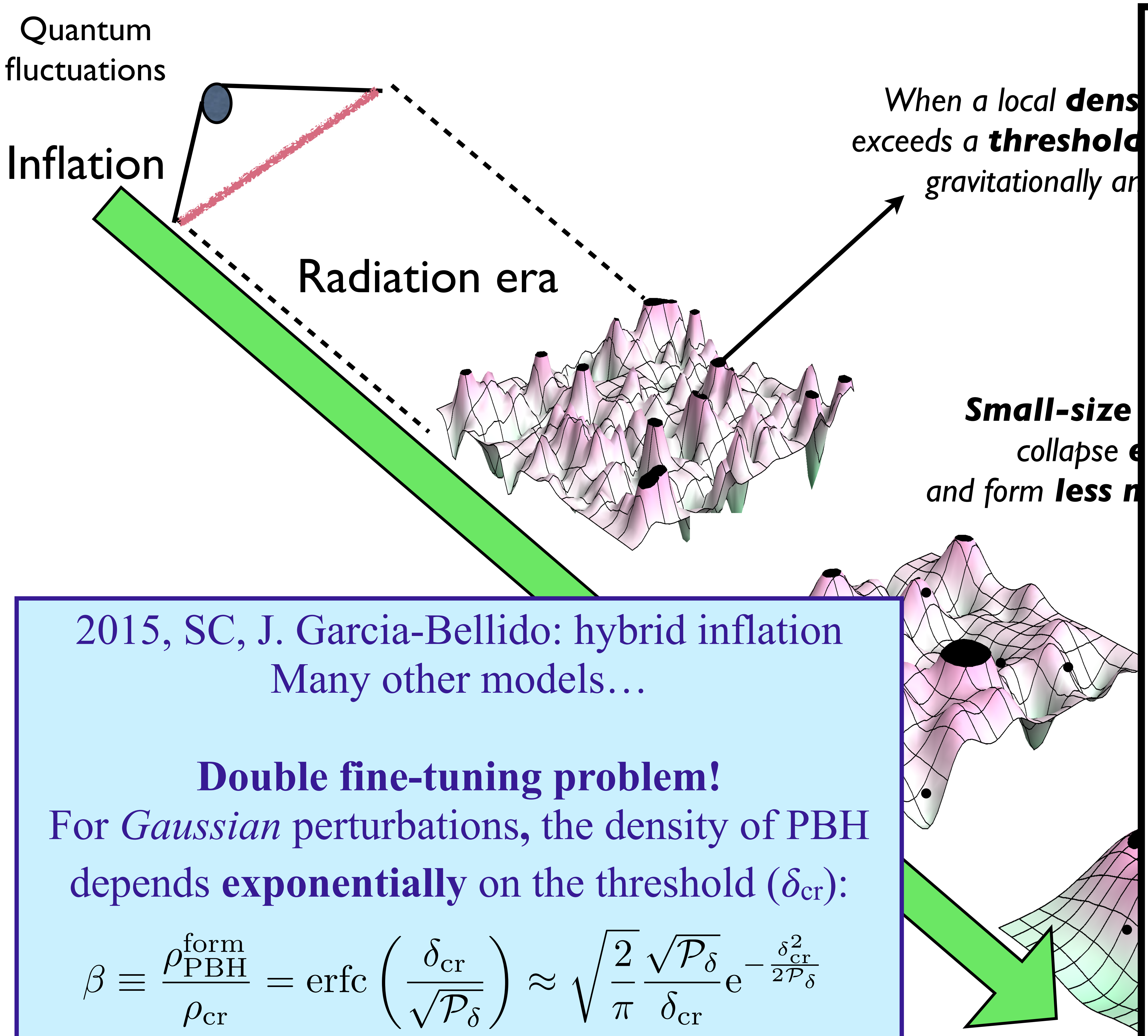
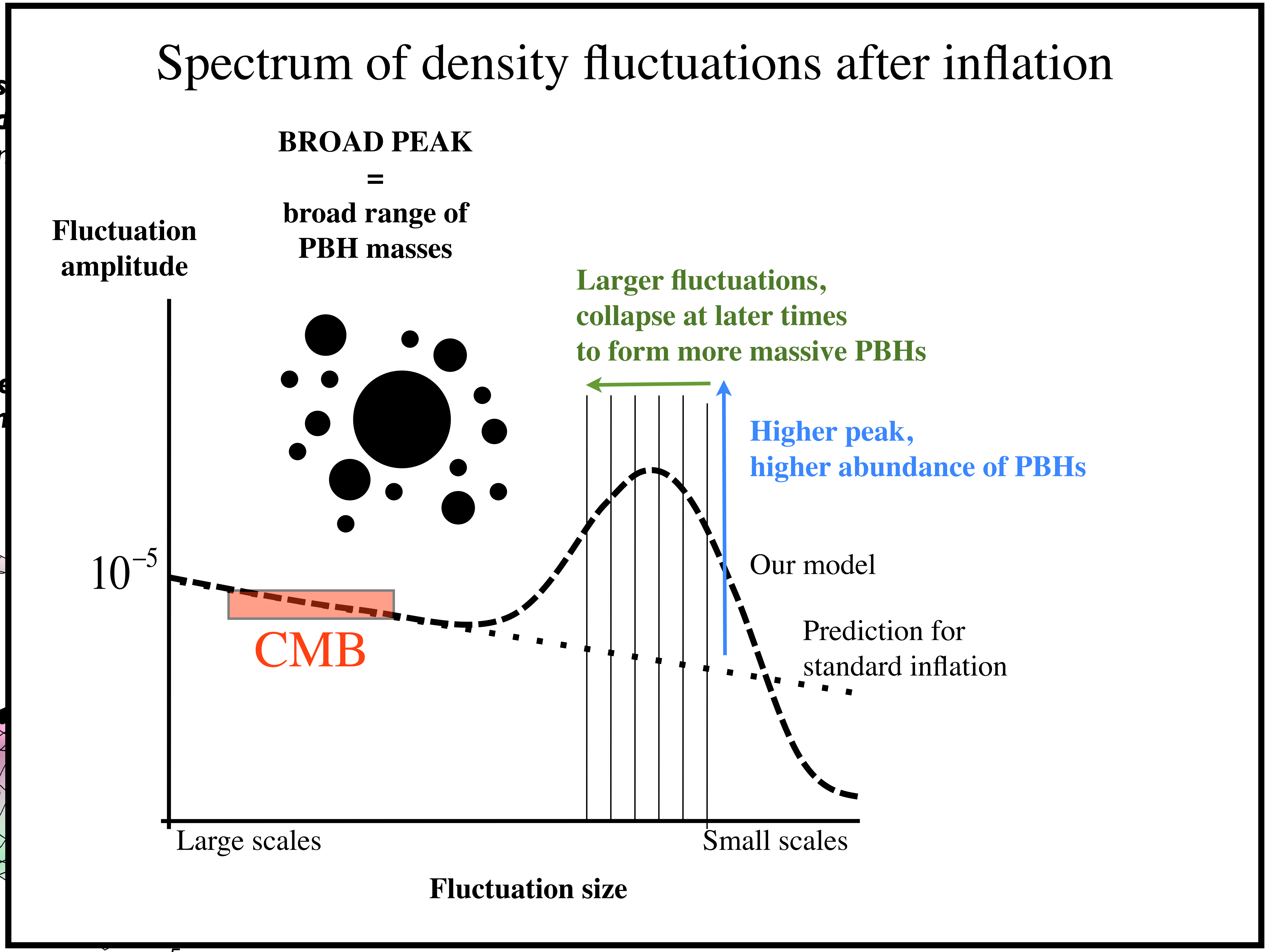


2015, SC, J. Garcia-Bellido: hybrid inflation
Many other models…

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

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



1. How natural is 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
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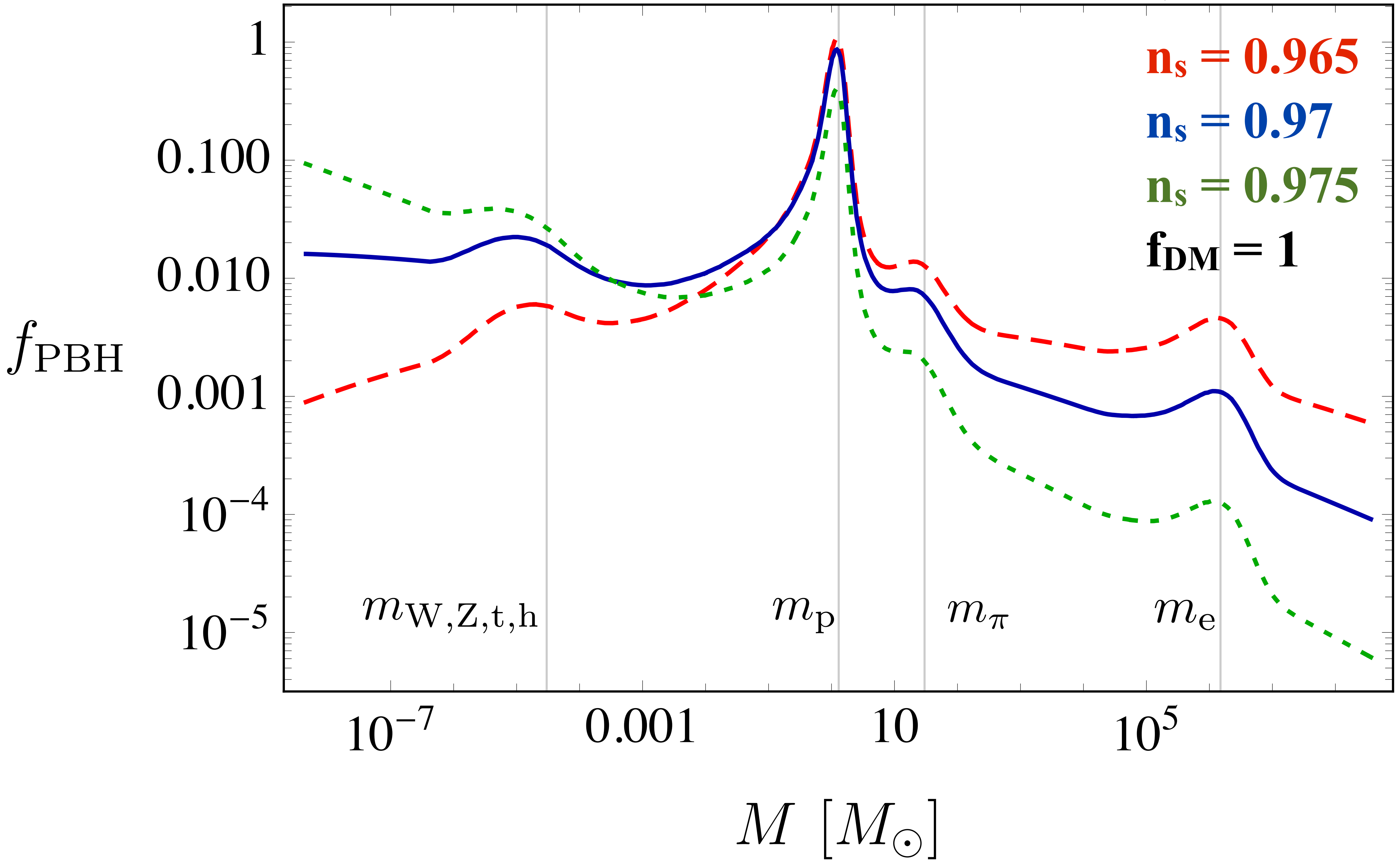

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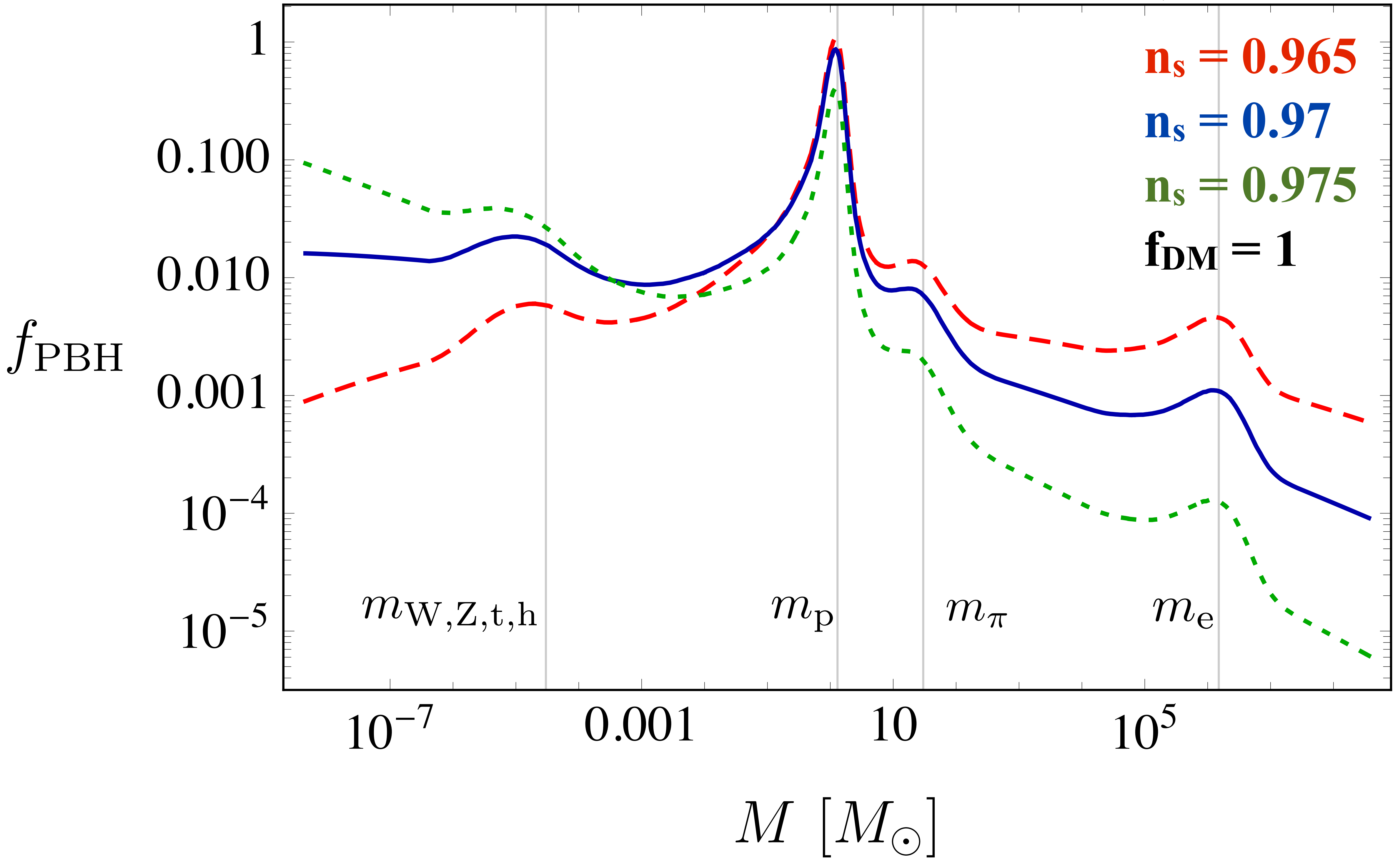

- **Nearly scale-invariant spectrum**
- **Spectral index: $n_s = 0.97$**
- **Peak at ~[2-3] $M_\odot$**
- **Second peak at ~30 $M_\odot$**
- **Two bumps at 10^{-6} and 10^{6} $M_\odot$**

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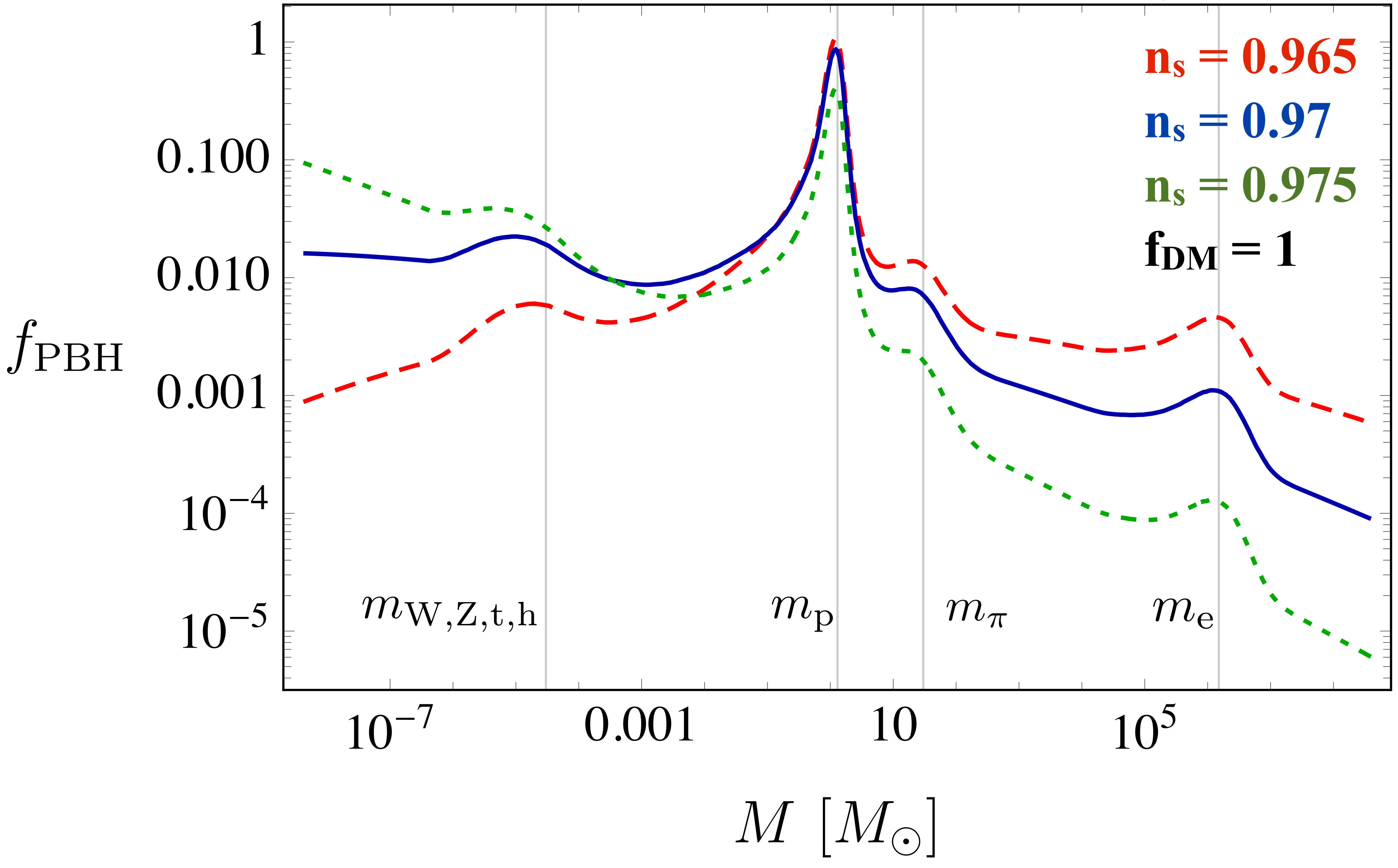
✓ **Inevitable**
✓ **Naturally** leads to **stellar-mass** PBHs
◉ But does **not solve the abundance/transition** problem

Carr+, 1906.08217



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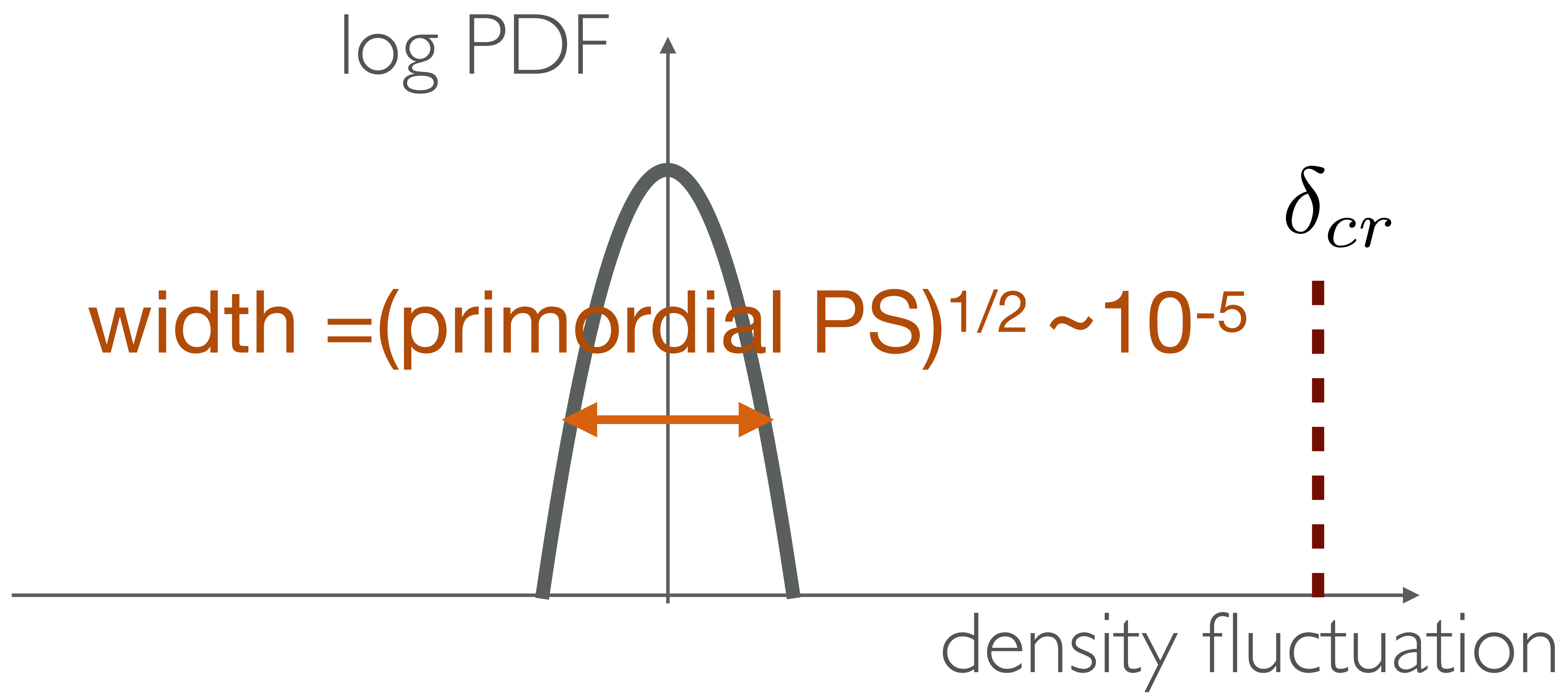
With non-Gaussian fluctuations

1) Gaussian case:

On CMB scales



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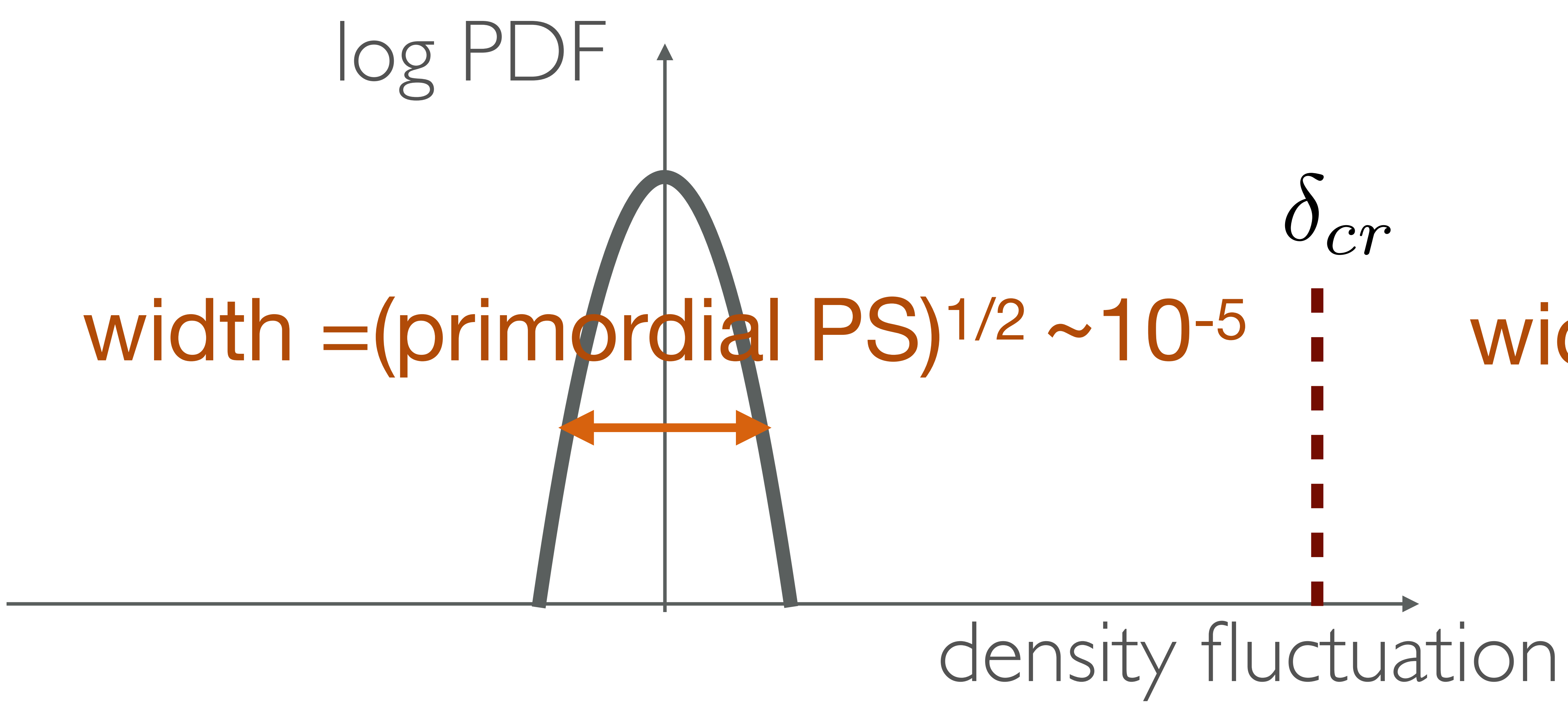

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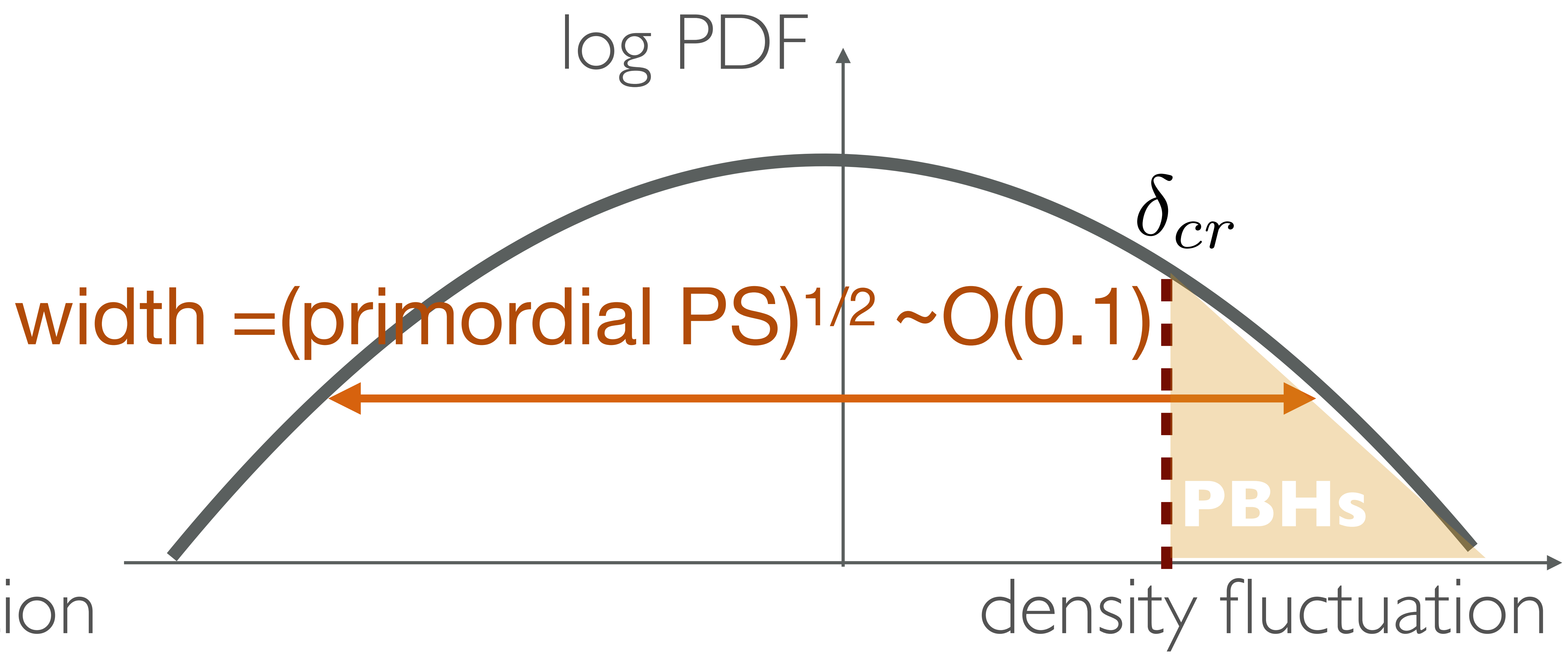

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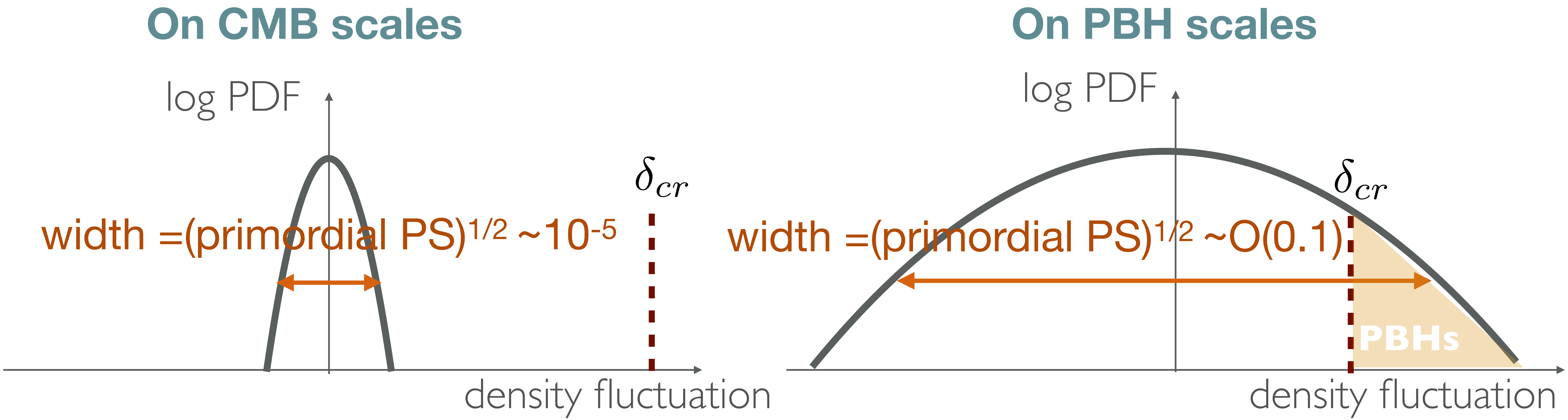

Need to tune the power spectrum (PS) amplitude and the transition from large to small scales…

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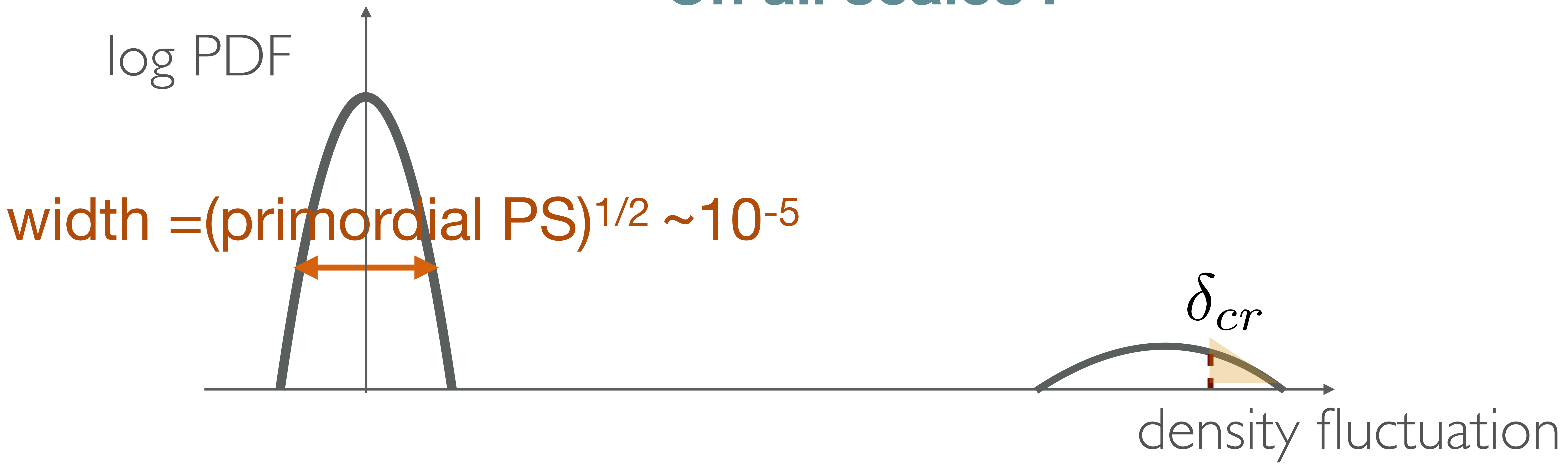
2) Non-Gaussian case:

On all scales !



No need to modify the PS, no transition
Abundance could be fixed by anthropic selection
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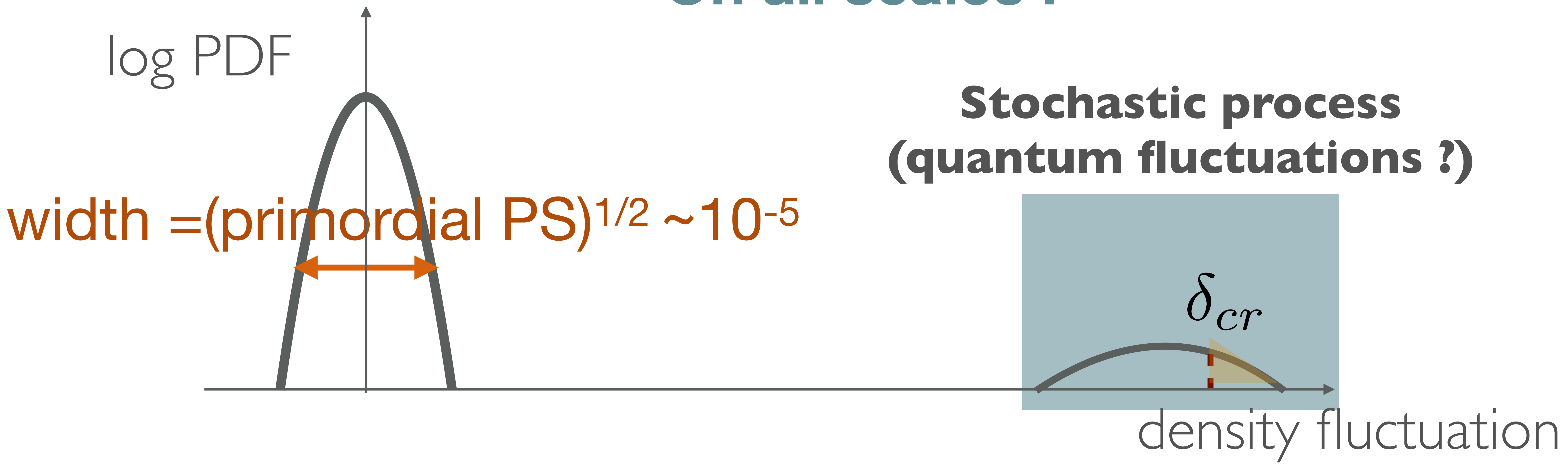

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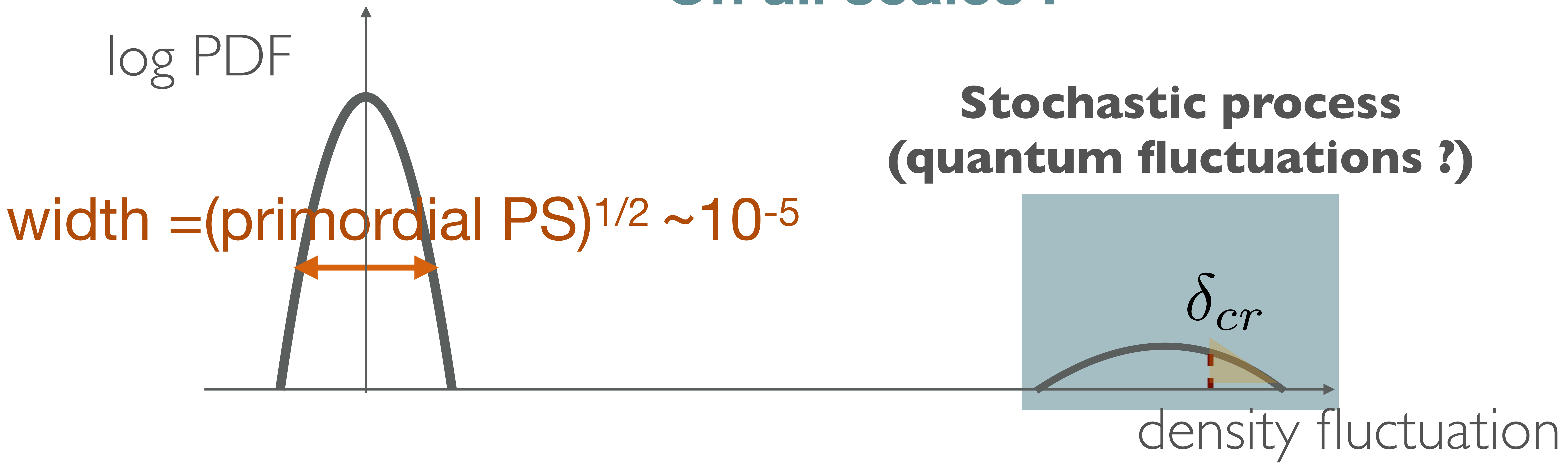

<u>Some realizations:</u>

- Light spectator field [Carr+2019]
- Ultra slow-roll inflaton (single field) [Vennin 20, Pattison+21]
- Critical Higgs inflation [Garcia-Bellido+]
- etc…

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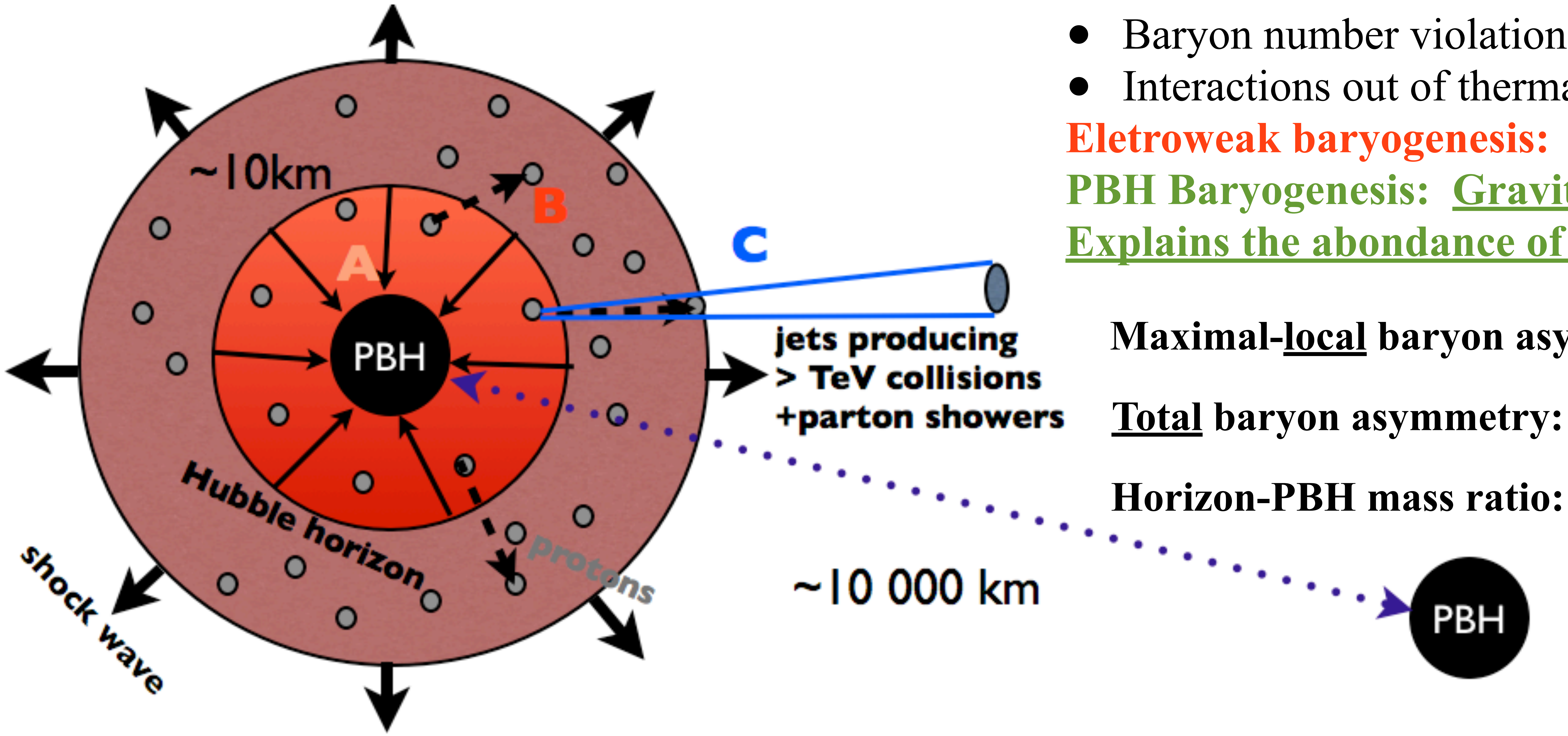
PBH baryogengesis



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: $\frac{\Omega_{\rm DM}}{\Omega_{\rm b}} \approx \frac{\gamma}{1-\gamma} \simeq 5$

B. Carr, S.C., J. Garcìa-Bellido, arXiv:1904.11482 and 1904.02129

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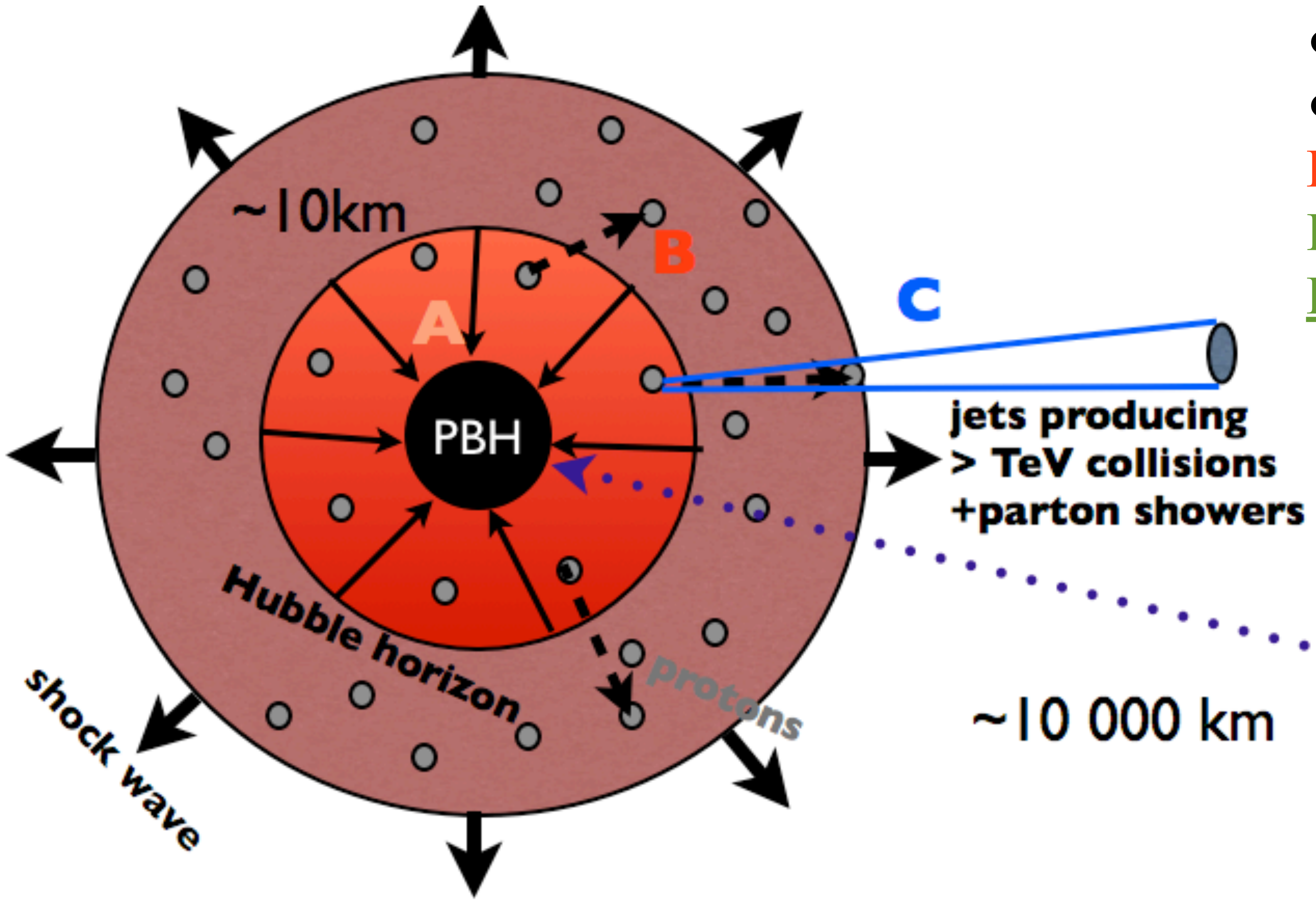

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✓ Missing ingredient for anthropic selection
✓ Resolves dark matter, baryogengesis, coincidences, fine-tunings problems

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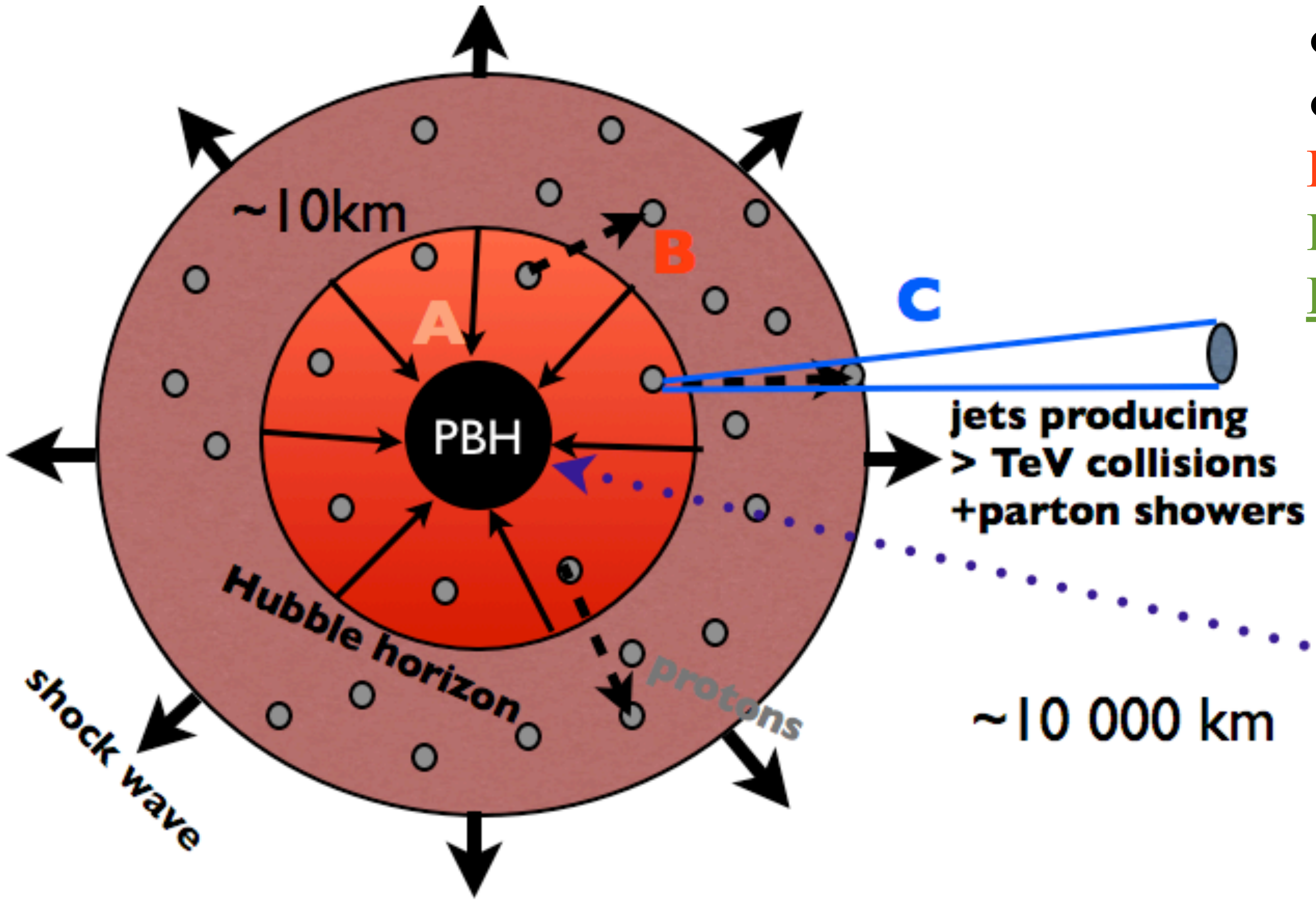

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◉ Existence of a shock wave ?
◉ Dilution before BBN ?
◉ Crude estimations

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1. How natural is PBH formation ?

Critical review of possible approaches

Atheists

- PBH models are not natural, twice fine-tuned or too specific
- Single-field slow-roll inflation works very well on cosmological scales
- Alternatives are specific and not convincing
- Realistically, PBHs should not exist
  - BUT: other DM models are often also tuned
  - BUT: maybe a natural formation scenario exists

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Naturalist

- Fine-tuning is a problem !
- Search for a natural scenario
- QCD transition naturally leads to stellar masses
  - But needs specific spectral index, PS transition
- PBH baryogengesis could explain the baryon/DM coincidence (and baryon-to-photon ratio)
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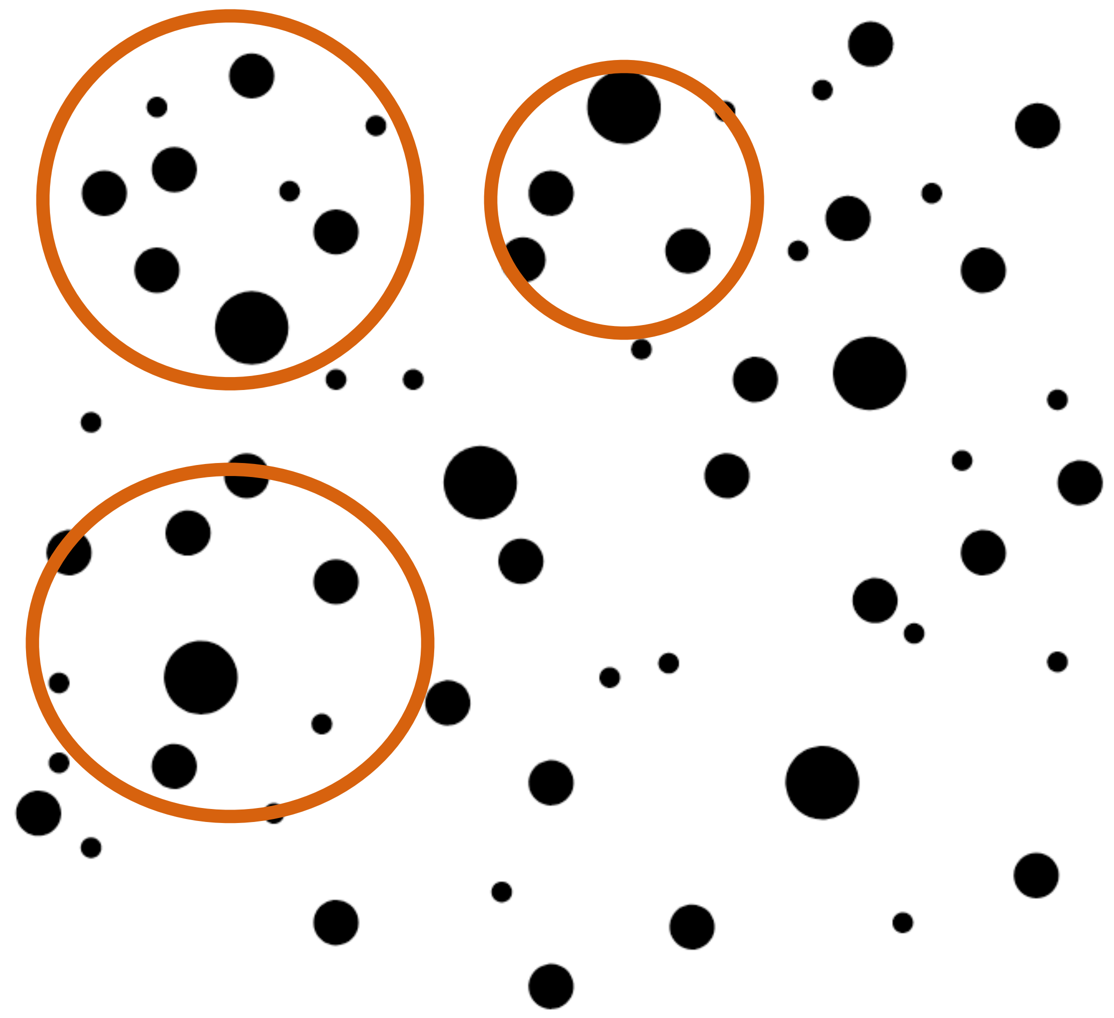
Believer

- Fine-tuning is not a problem (nature is what it is, with many other fine-tunings)
- Black holes exist
- Plenty of formation mechanisms
  - But: ultimately, any observation could be explained by PBHs
- $f_{PBH} < 1$ equally interesting

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]

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

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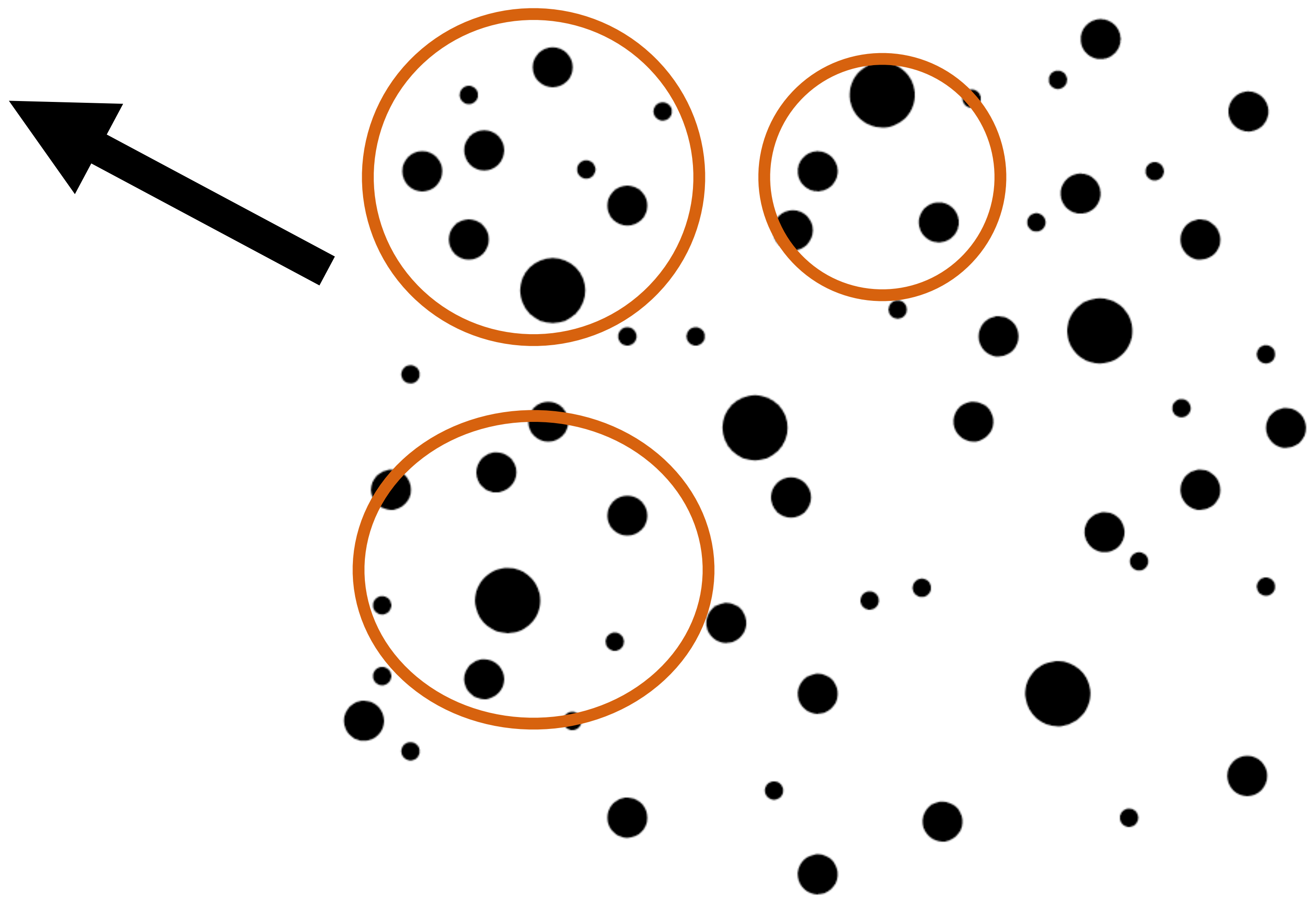

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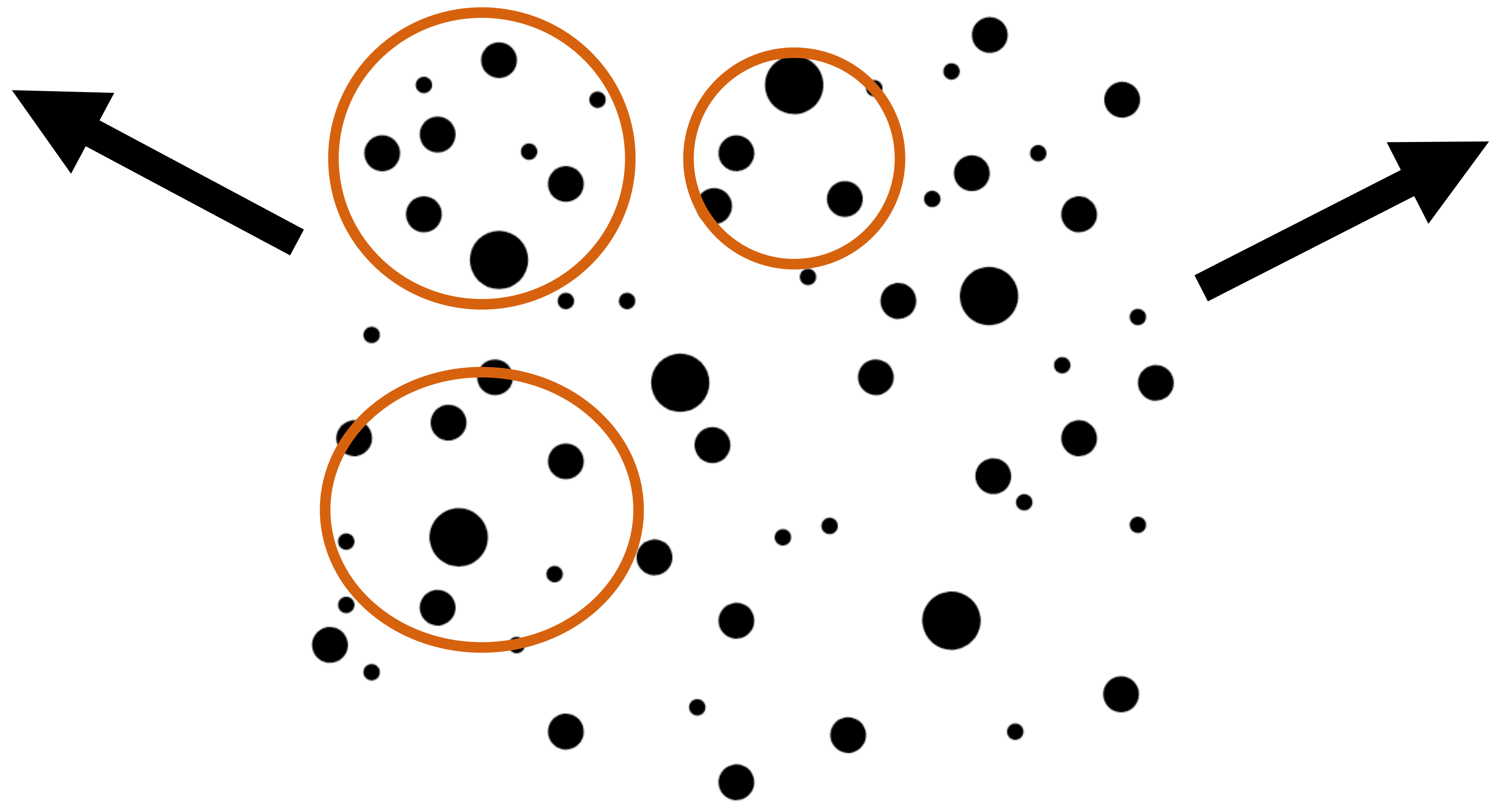

High-z clusters: spatial correlations in IR and X-ray backgrounds
[Kashlinsky 16]

$$P_{\rm Poisson} \simeq 2 \times 10^{-3} \frac{f_{\rm PBH}}{g(z)^2} \left(\frac{M}{3 M_\odot} \right) {\rm Mpc}^3$$

Press-Schechter:
~100% probability to collapse
at **z > 20** for small perturbations
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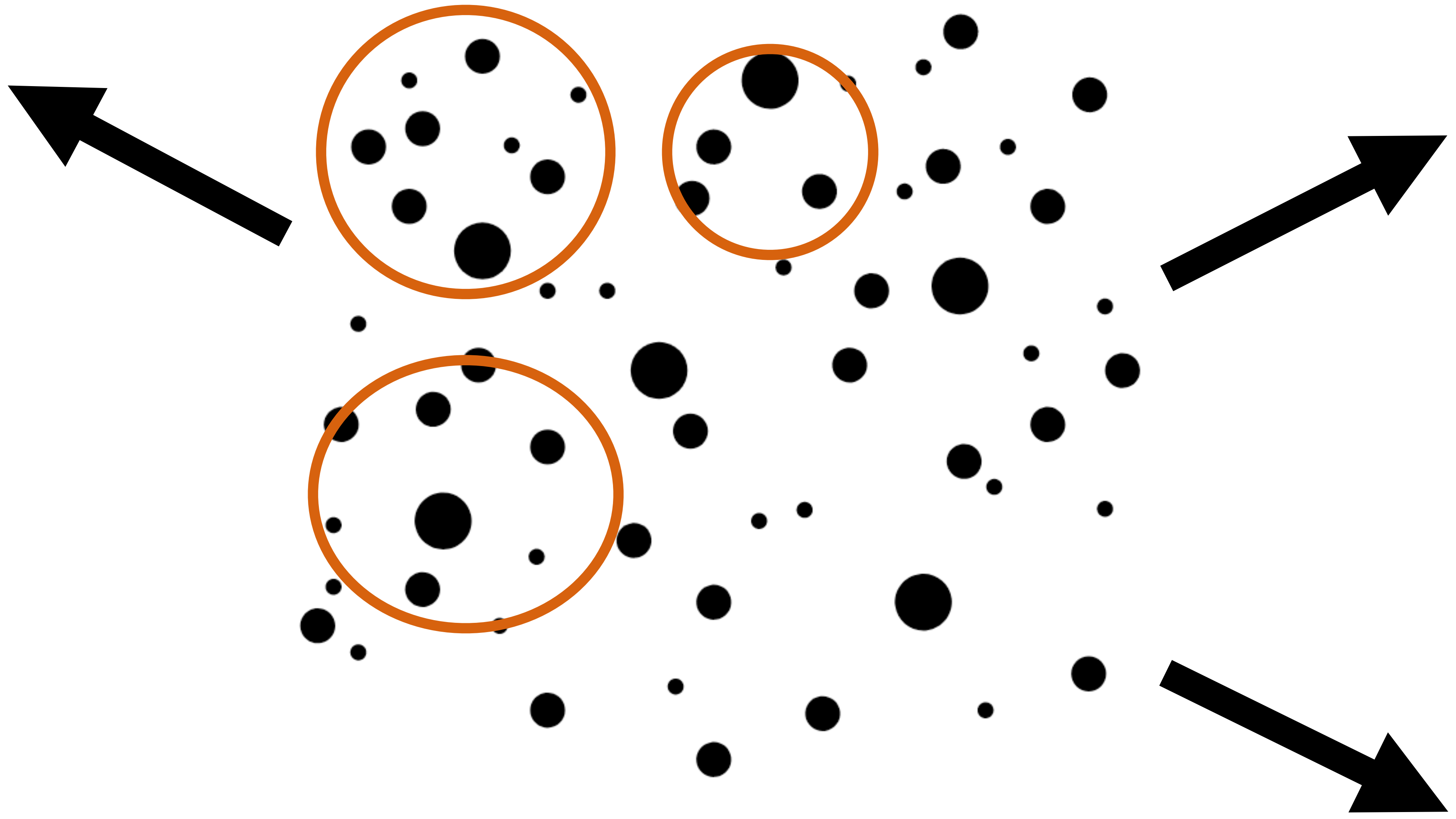

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Ultra-faint dwarf galaxies
with min radius ~20 pc and
large mass-to-light ratios
(dynamical heating + accretion)
[S.C.+17, S.C.+20]

$$\frac{{\rm d}\, r_{\rm halo}}{{\rm d}t} = \frac{4\sqrt{2}\, \pi\, G\, f_{\rm PBH}\, M \ln(M_{\rm halo}/2\, M)}{2\, \beta\, v_{\rm vir}\, r_{\rm halo}}$$

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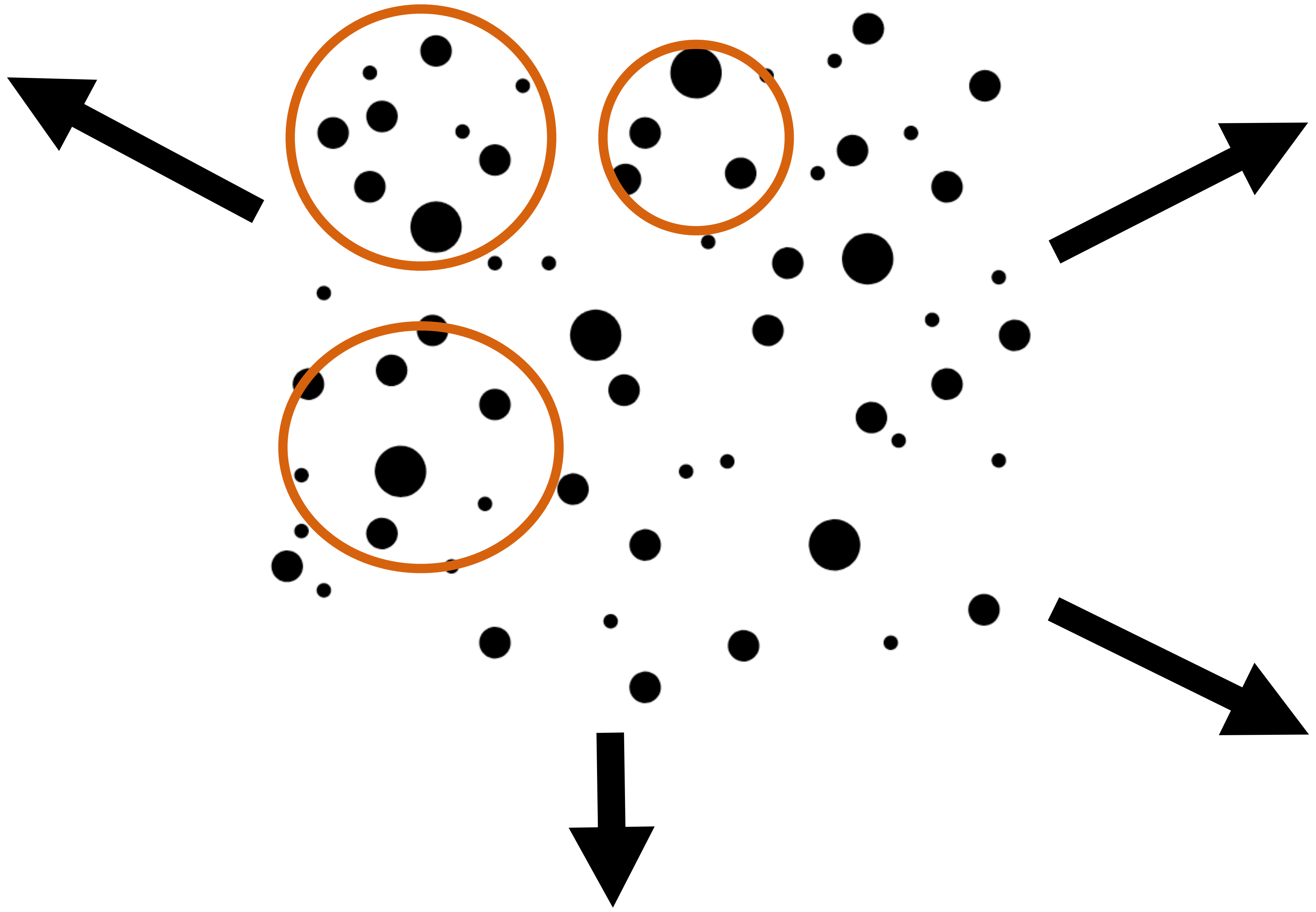

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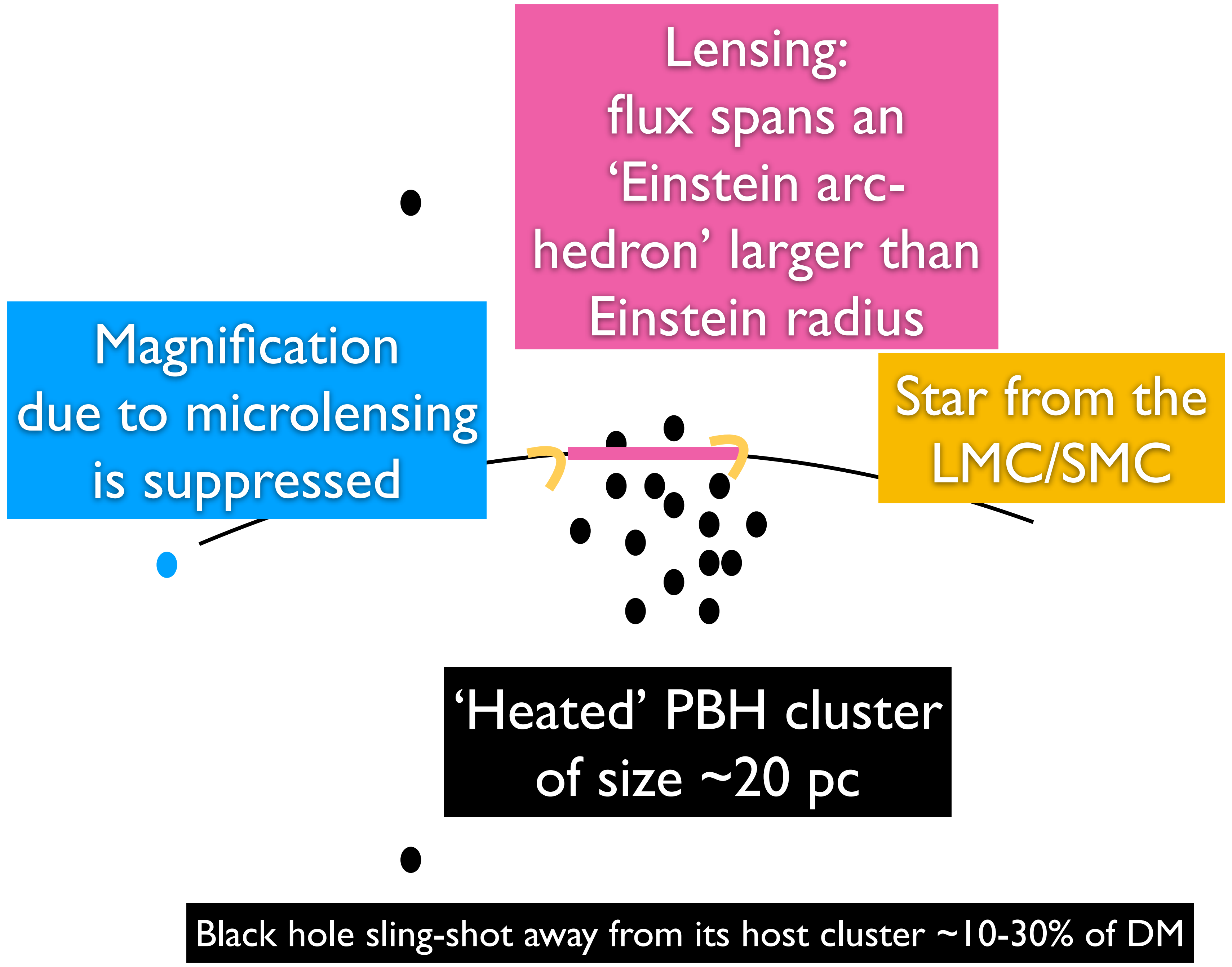
Evade micro-lensing limits [Carr+19]



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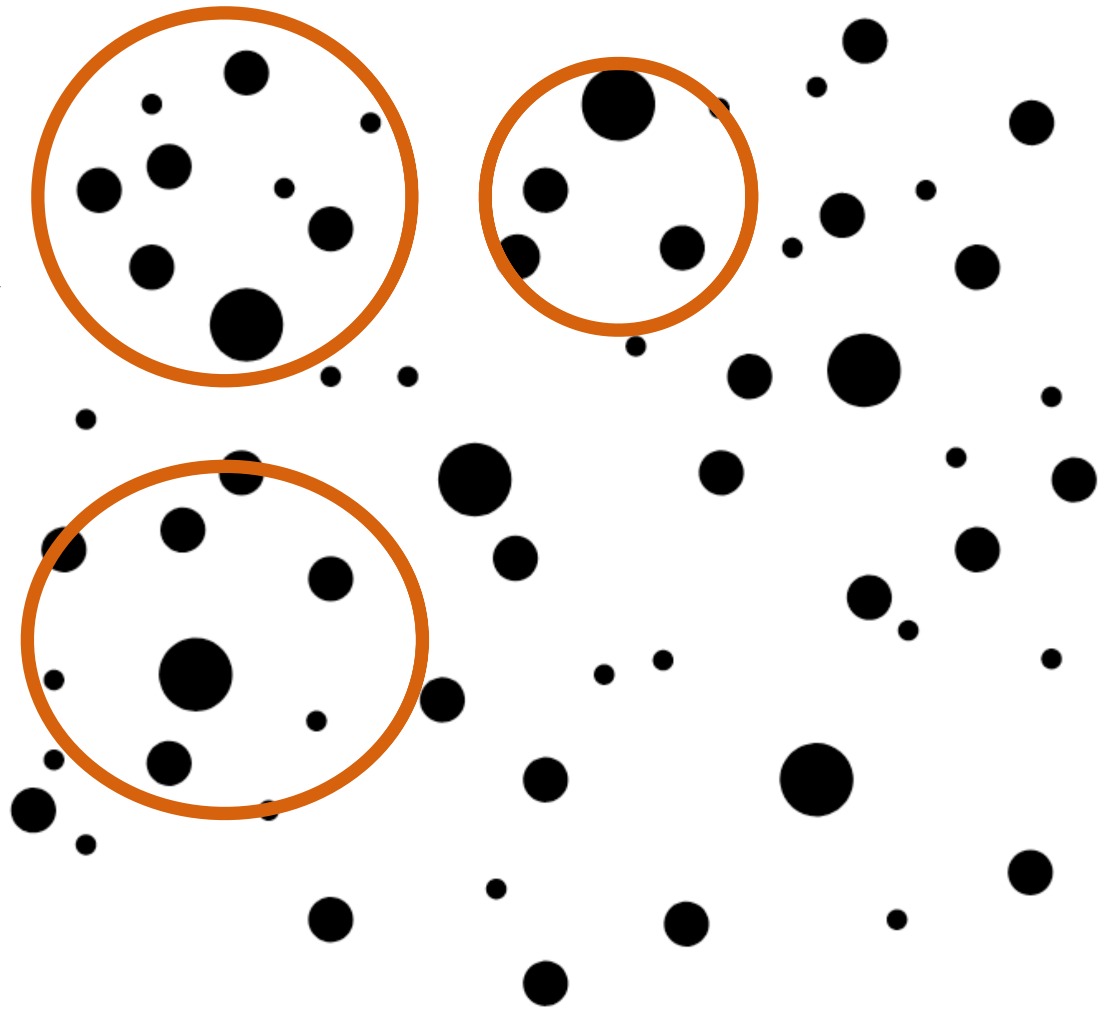

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N-body simulations by Inman & Ali-Haimoud, 1907.08129

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…

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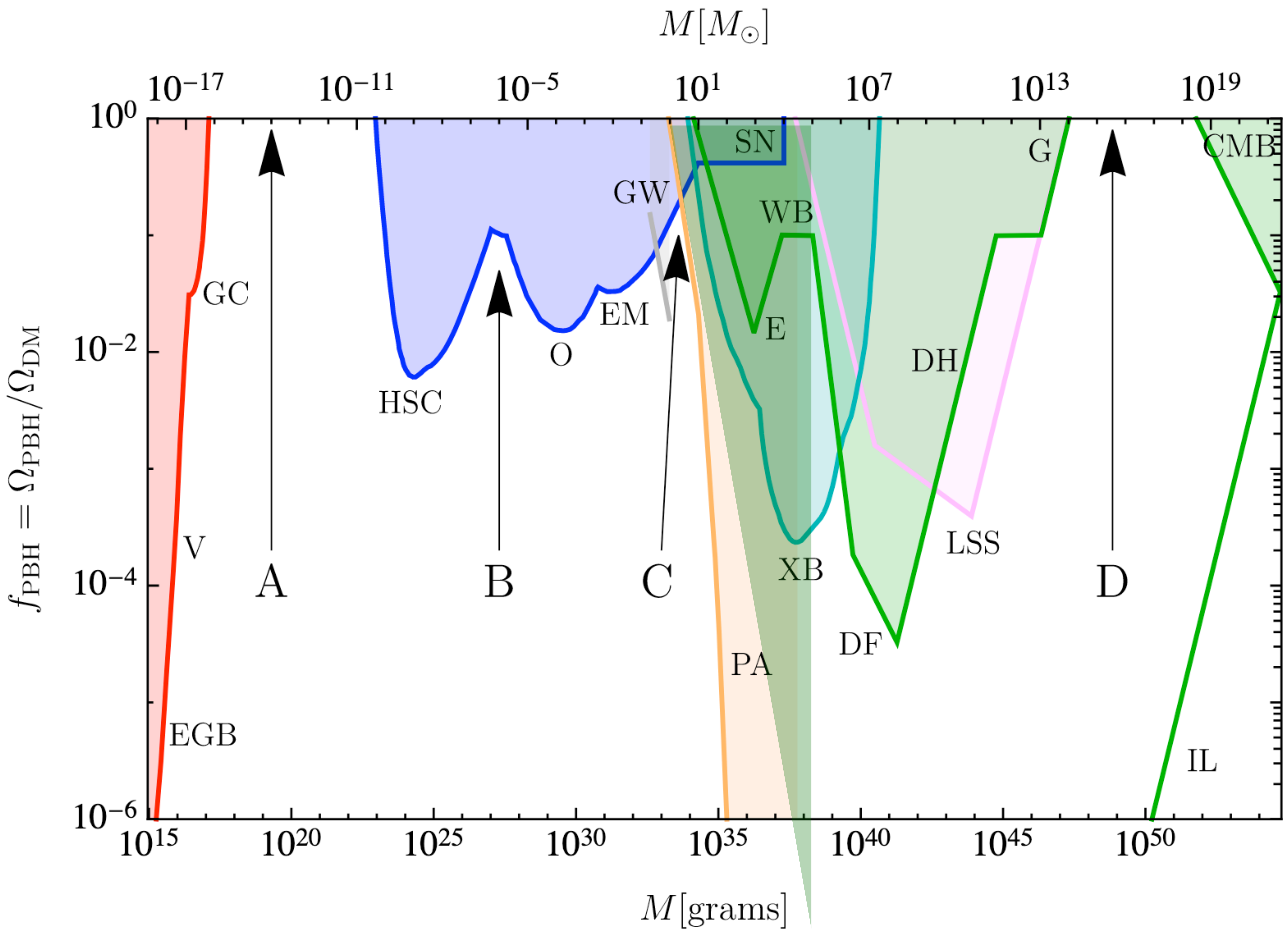
Limits vs clues: a question of point of view



Hawking radiation

Microlensing

LIGO-Virgo / PTAs

Dynamical effects

Accretion

Large scale structures

Carr & Kuhnel, 2006.02838

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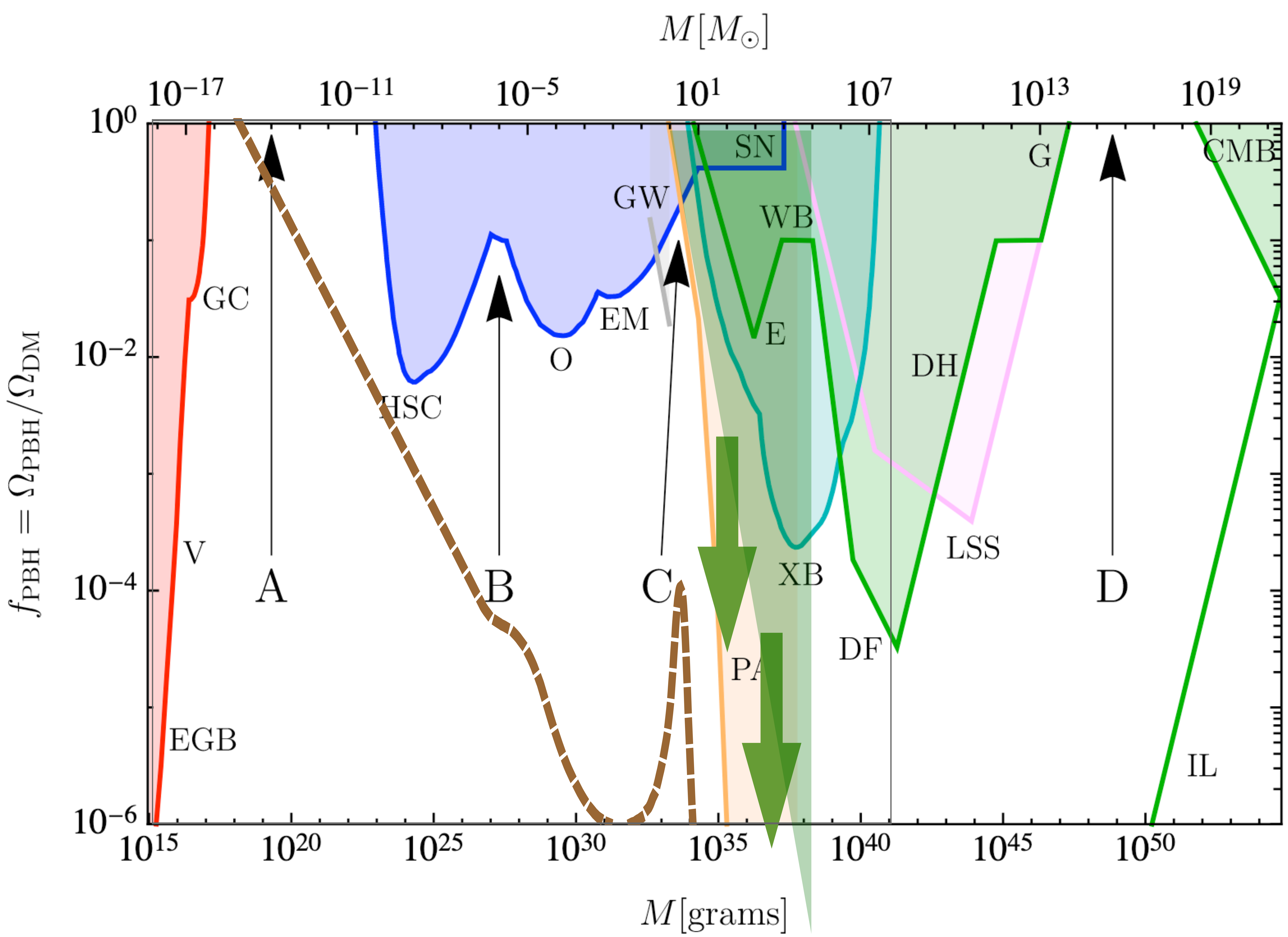

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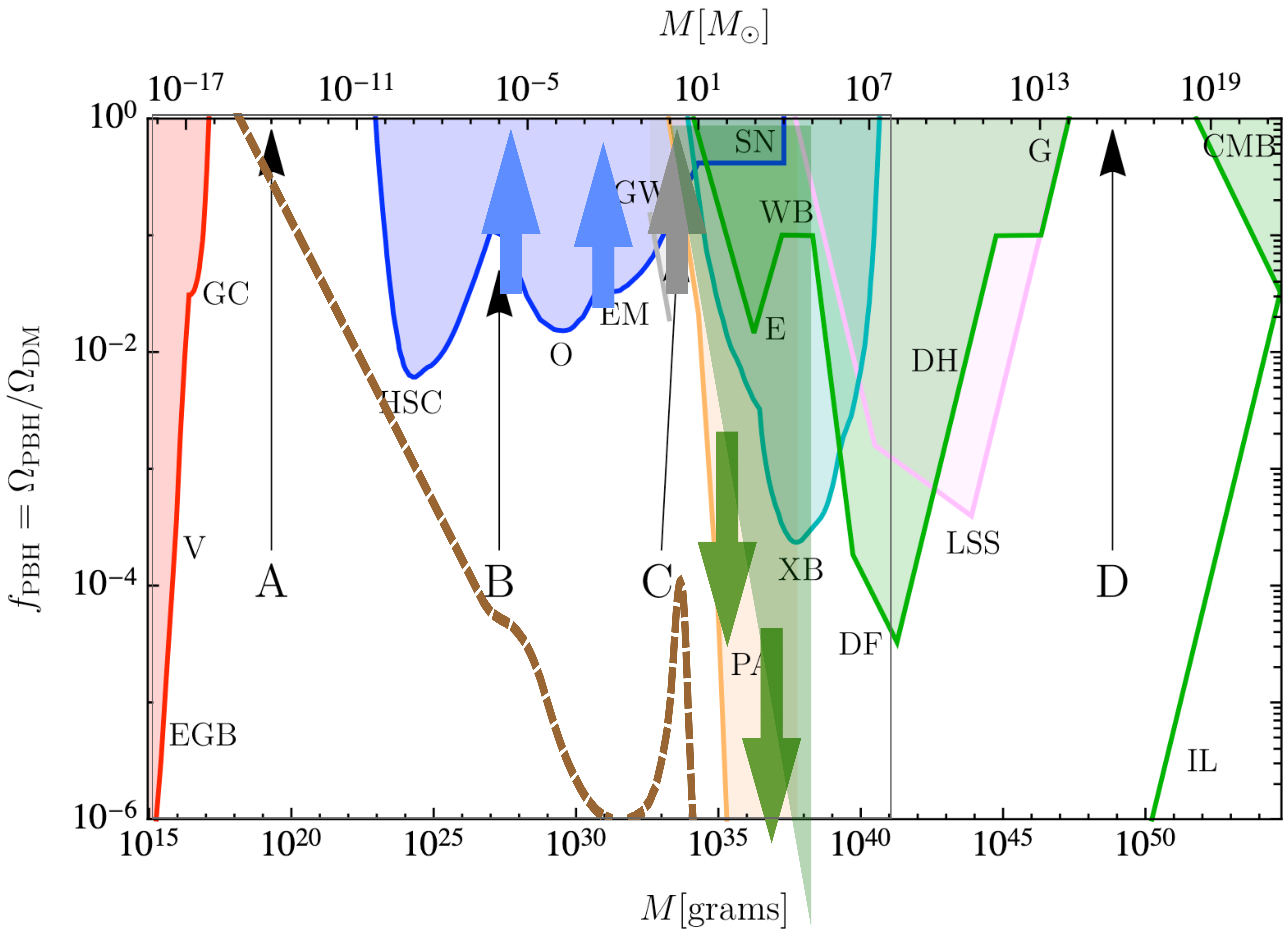
✓ Solar mass region exluded by several probes
✓ No limit on asteroid-masses
✓ If PBHs + WIMPs (or particle DM) => stronger limits
(e.g. Serpico+20, Carr+20, Byrnes+)

De Luca, Franciolini, Riotto et al., 2009.08268

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

Limits vs clues: a question of point of view



Carr & Kuhnel, 2006.02838

Hawking radiation

Microlensing

LIGO-Virgo / PTAs

Dynamical effects

Accretion

Large scale structures

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

- ◎ Asteroid-mass PBH dark matter => new fine-tuning
- ◎ Poisson clustering not included
- ◎ LIGO/Virgo limits less stringent
- ◎ Microlensing limits evaded if PBHs in clusters

De Luca, Franciolini, Riotto et al., 2009.08268

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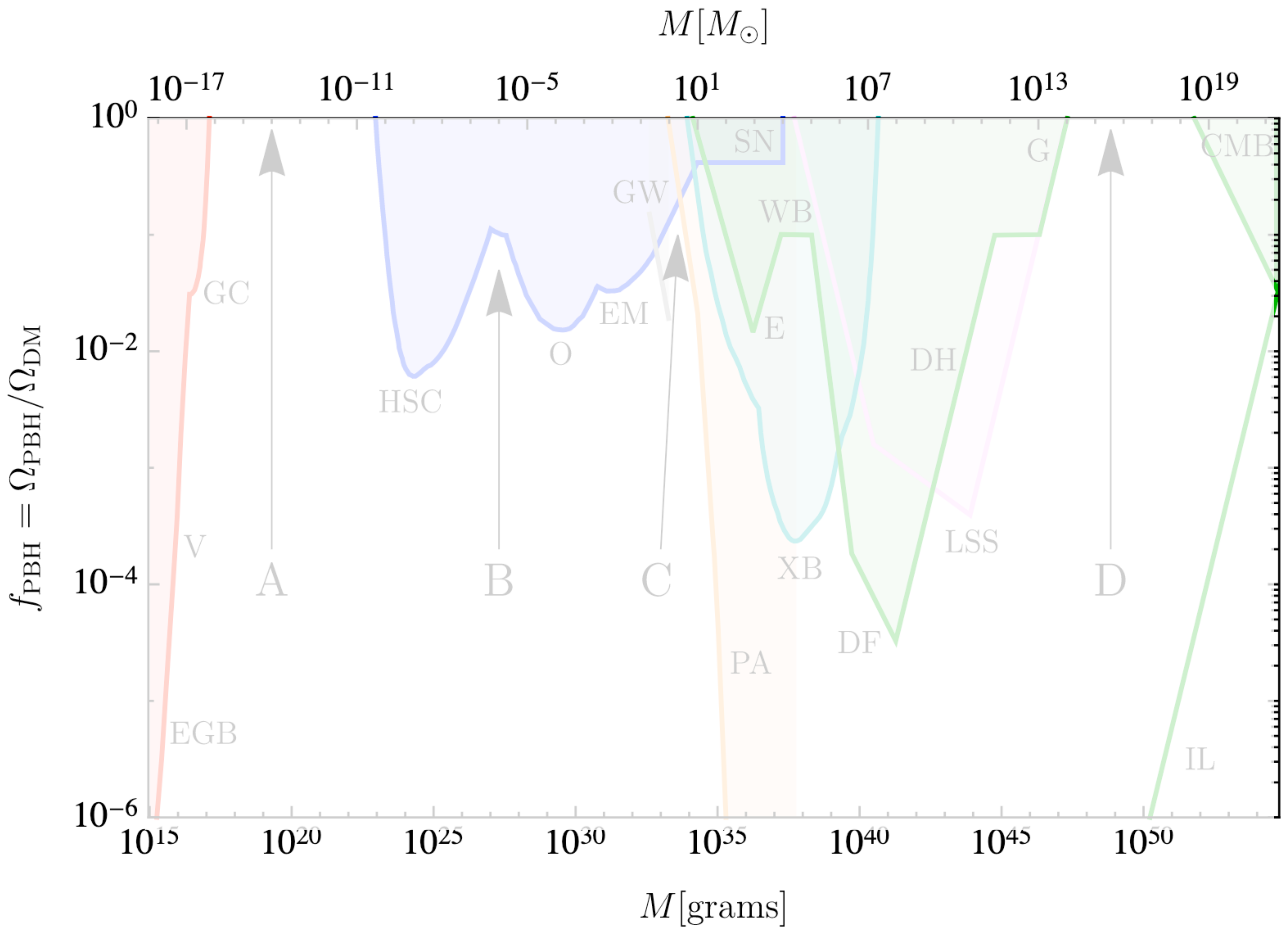

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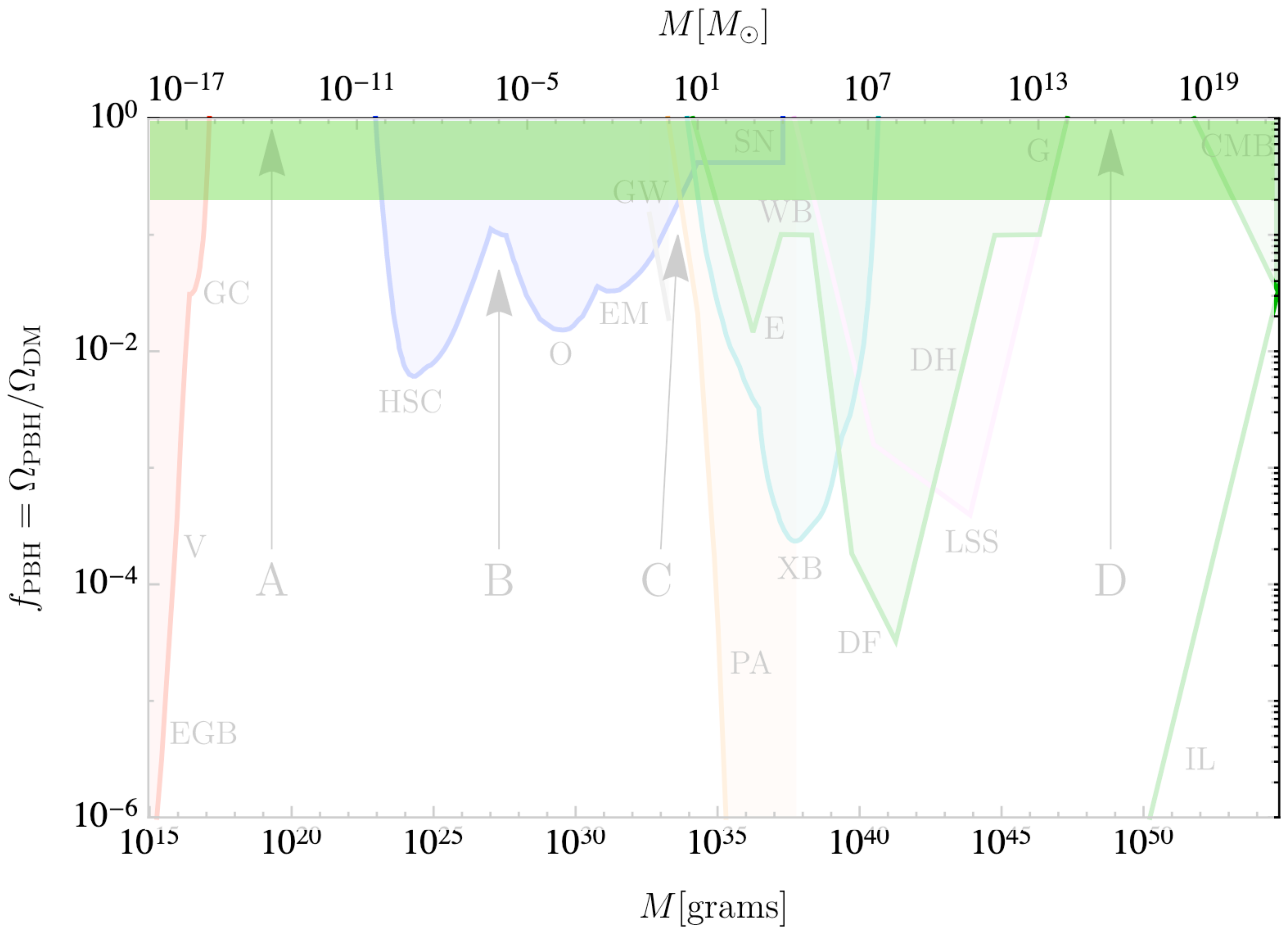

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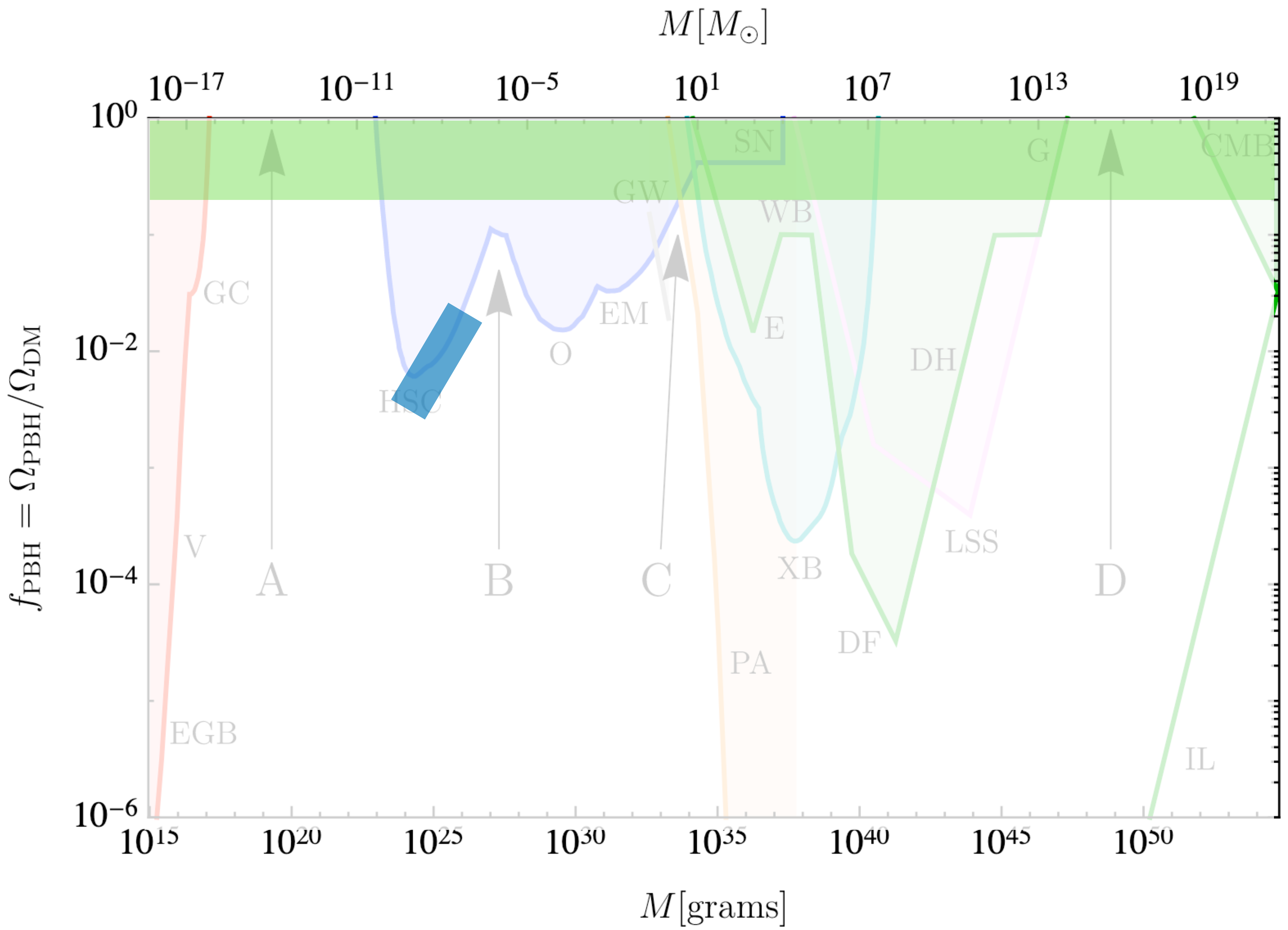

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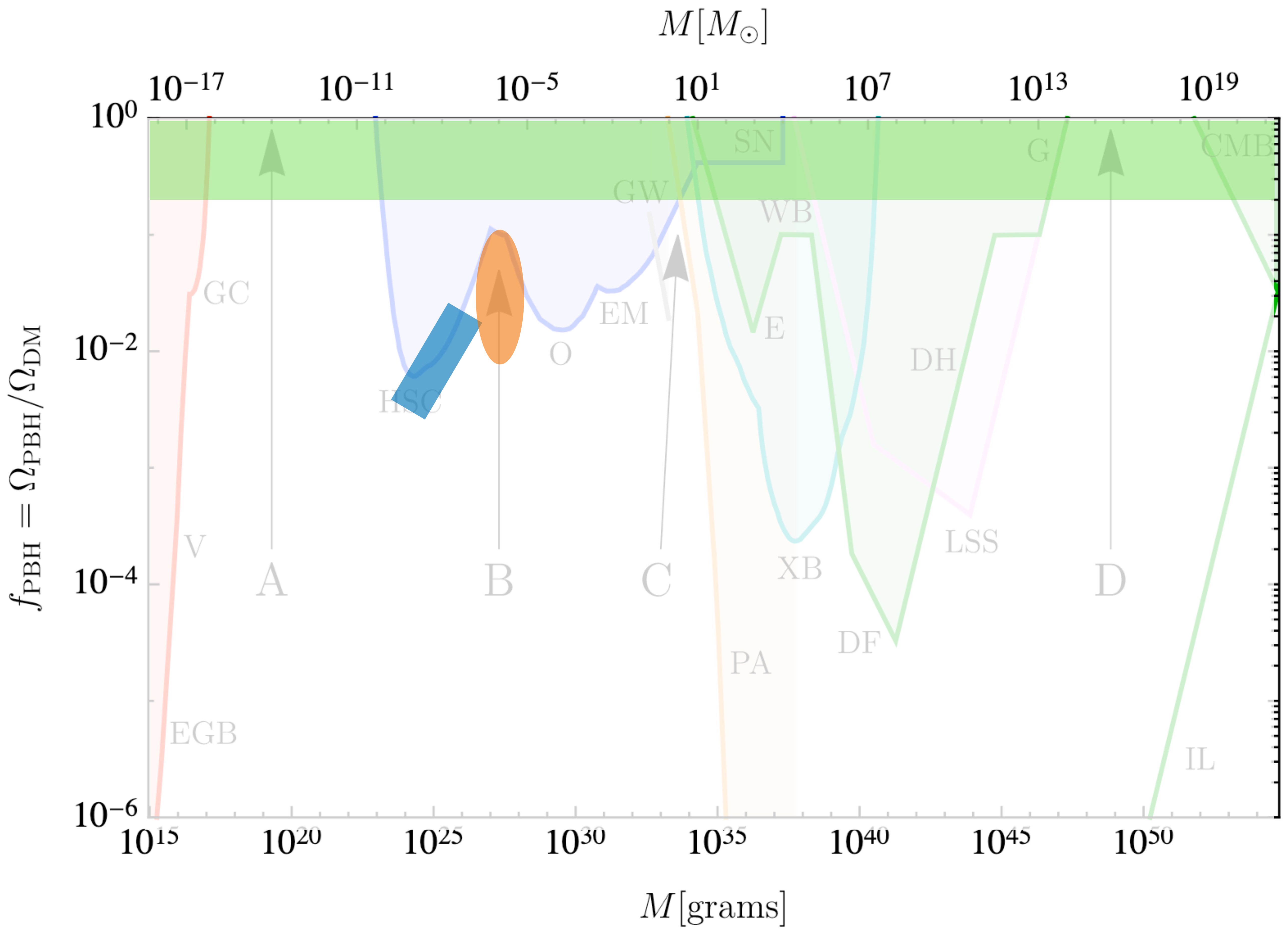

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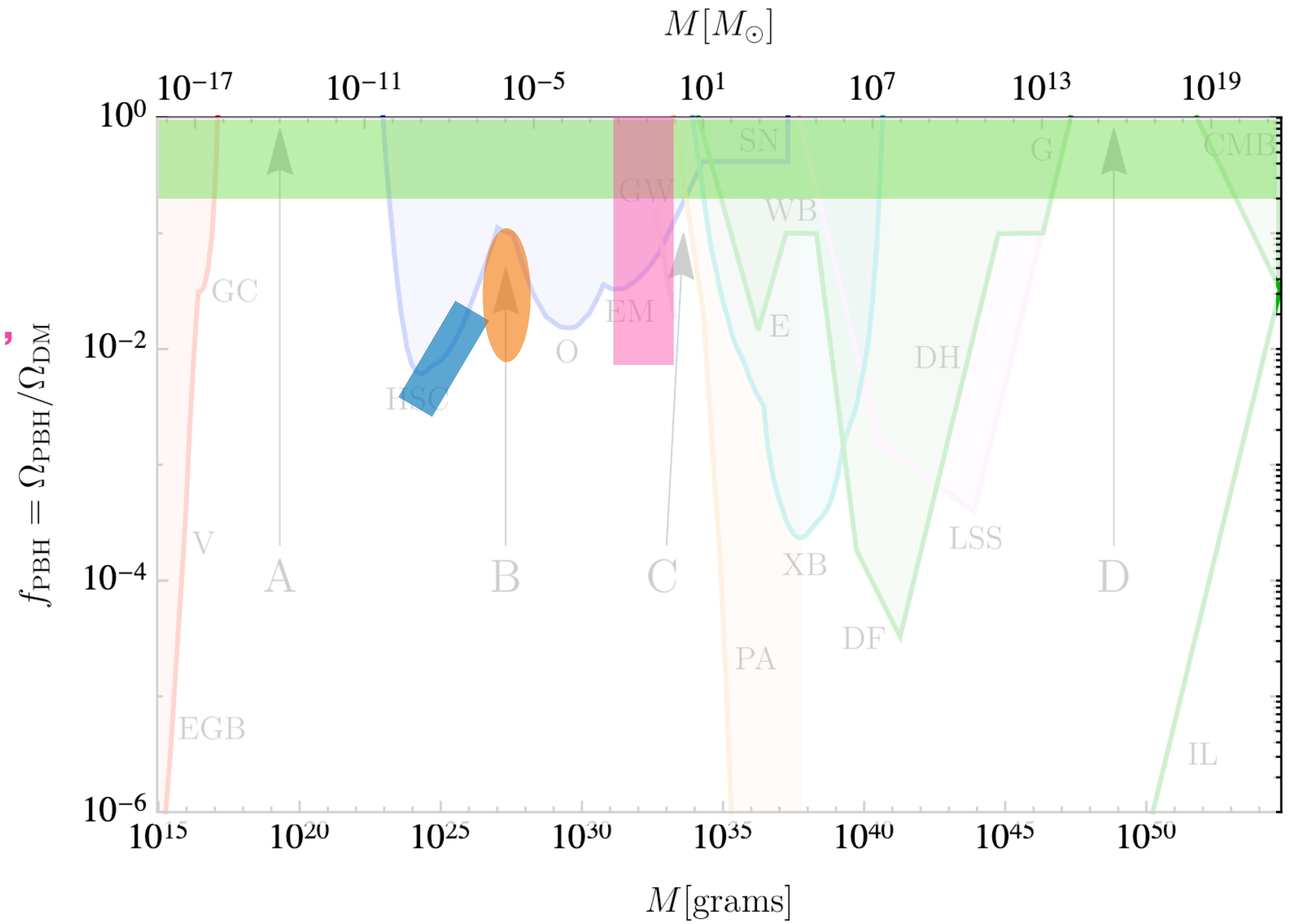

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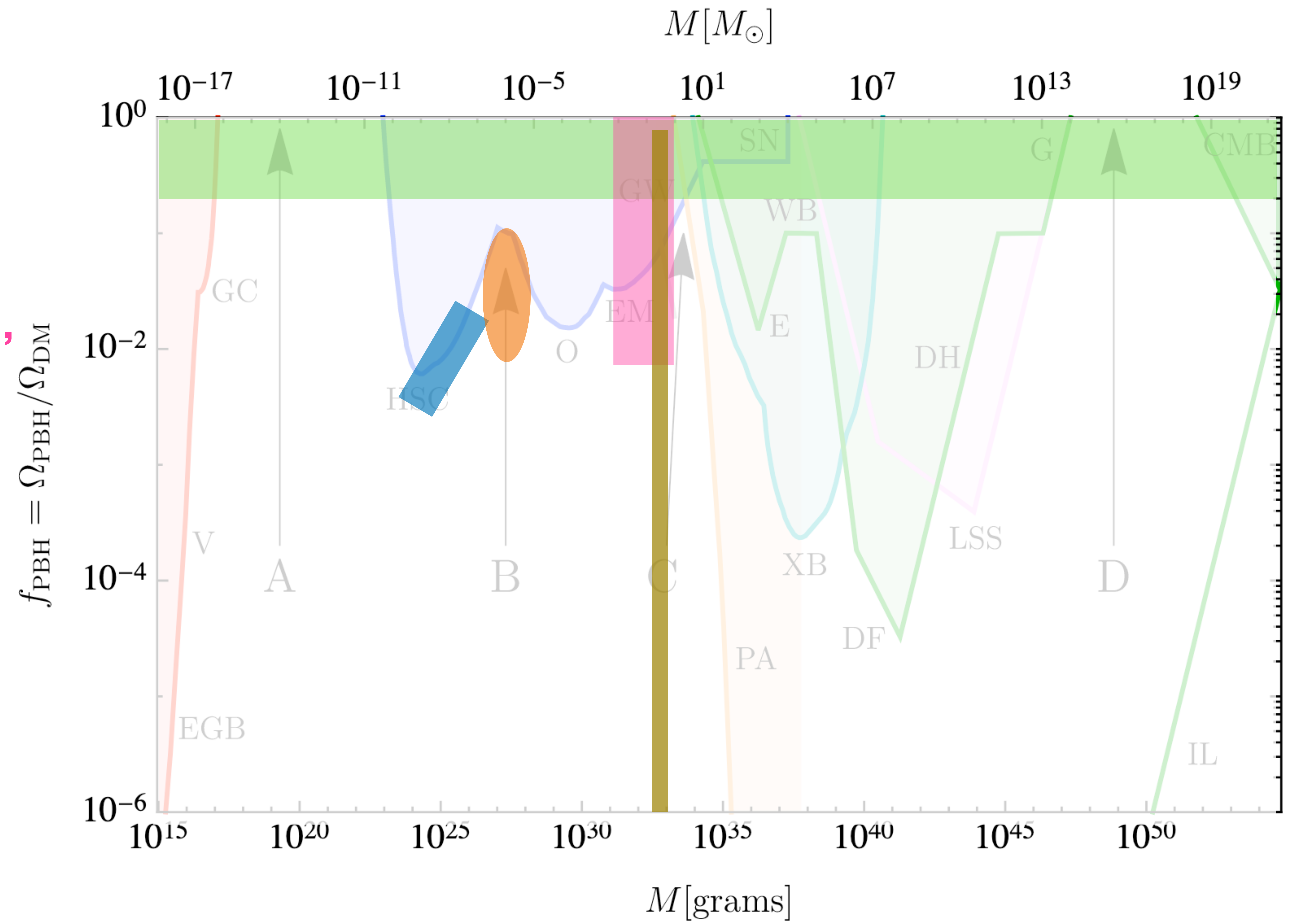

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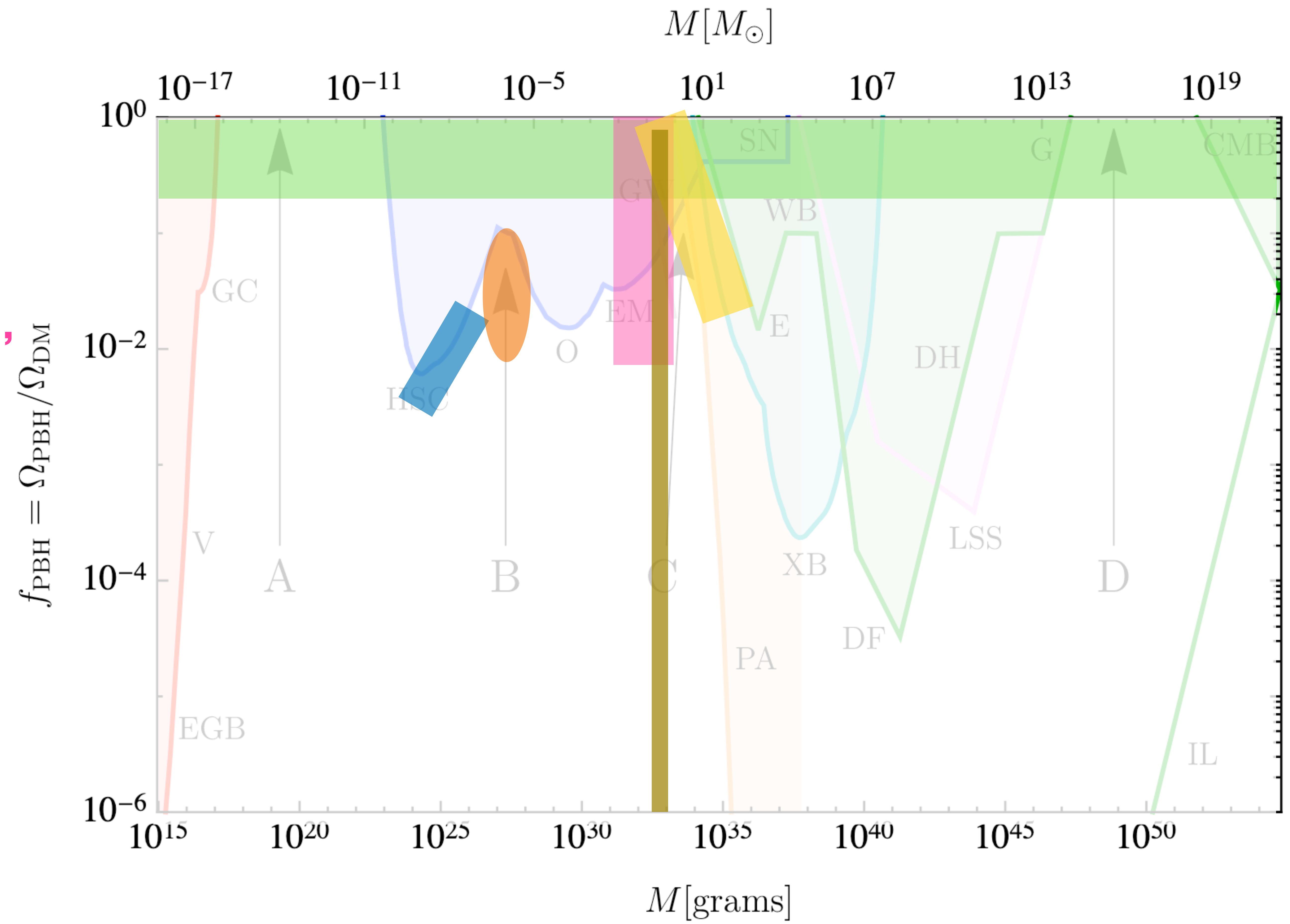

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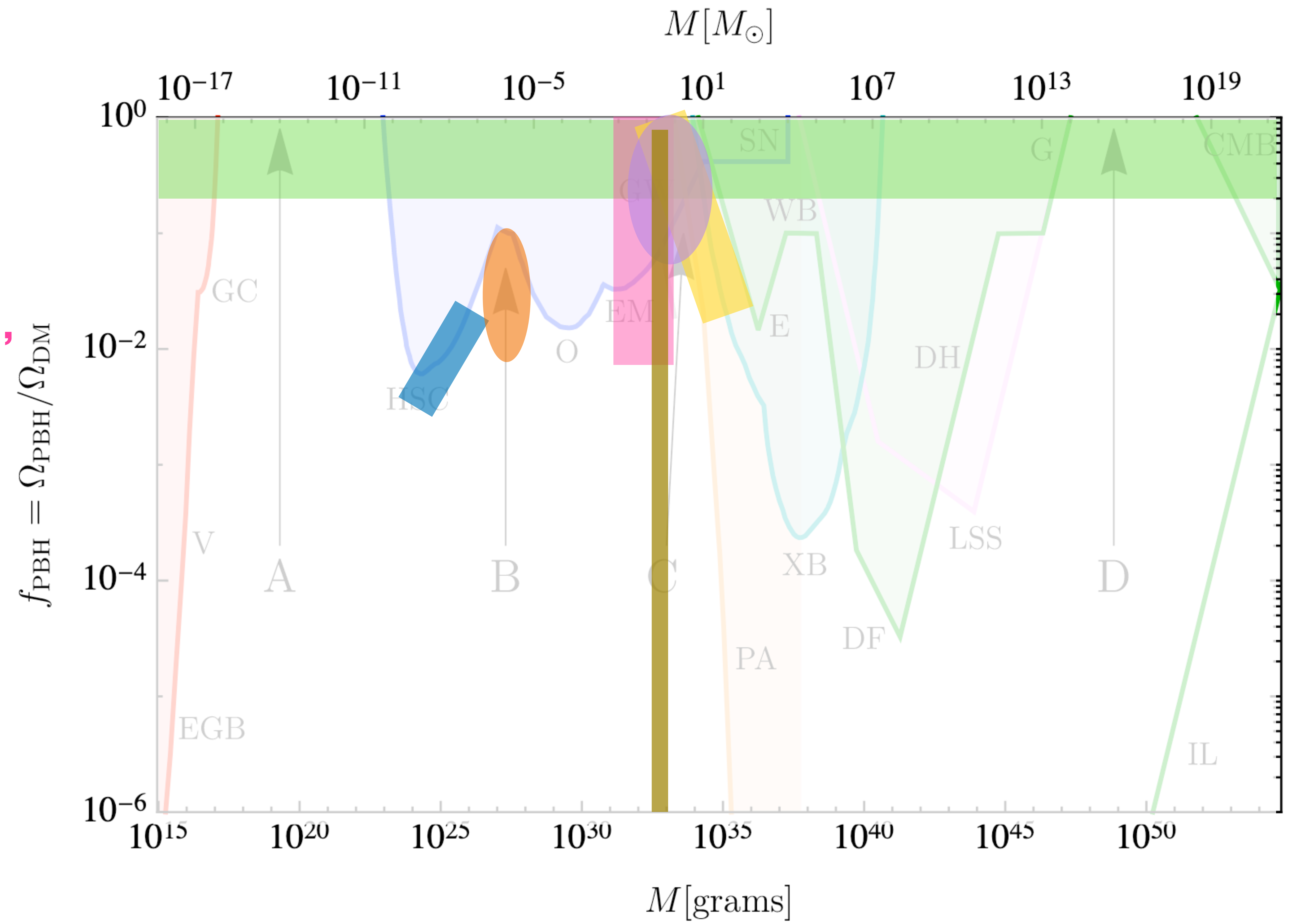

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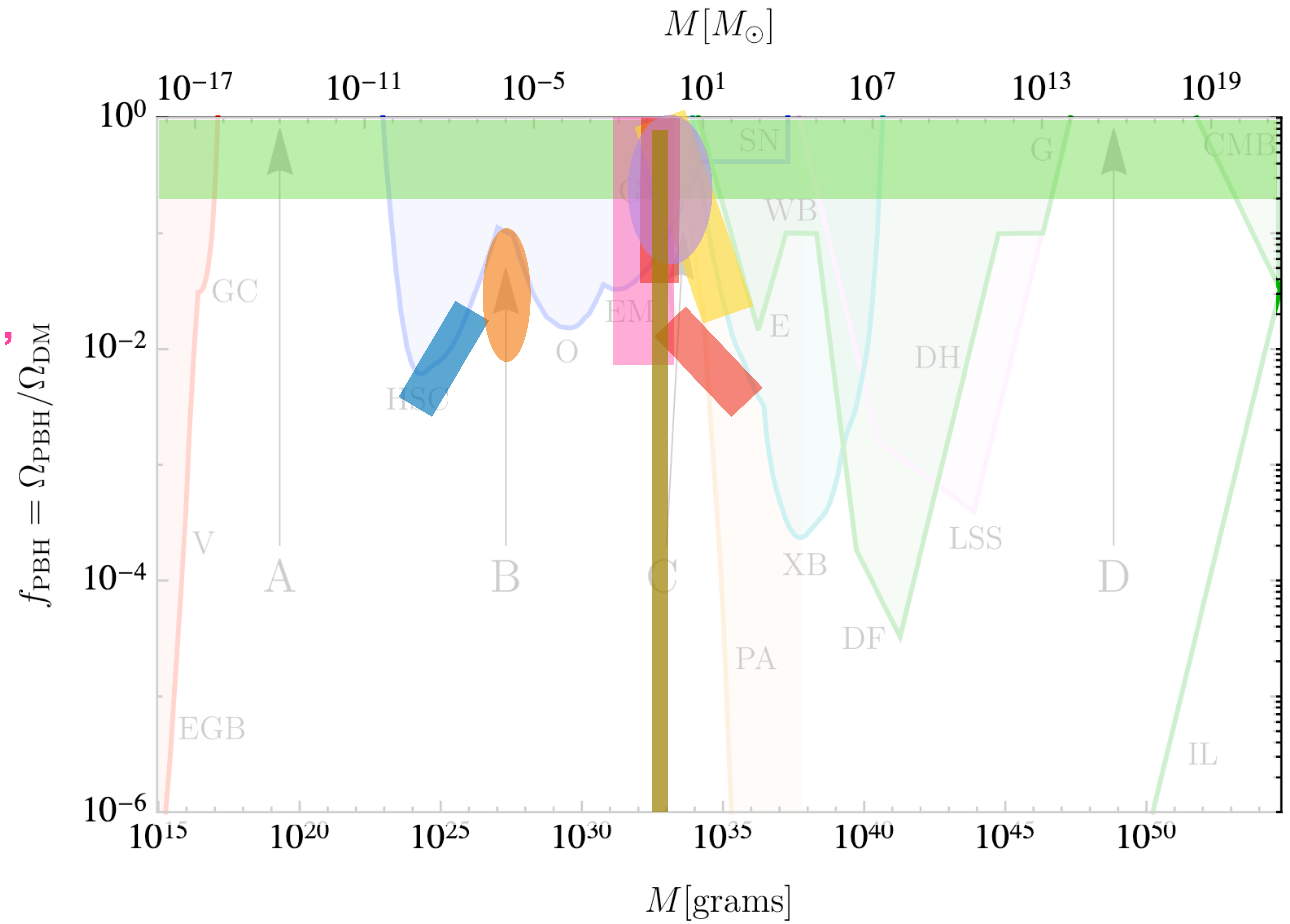

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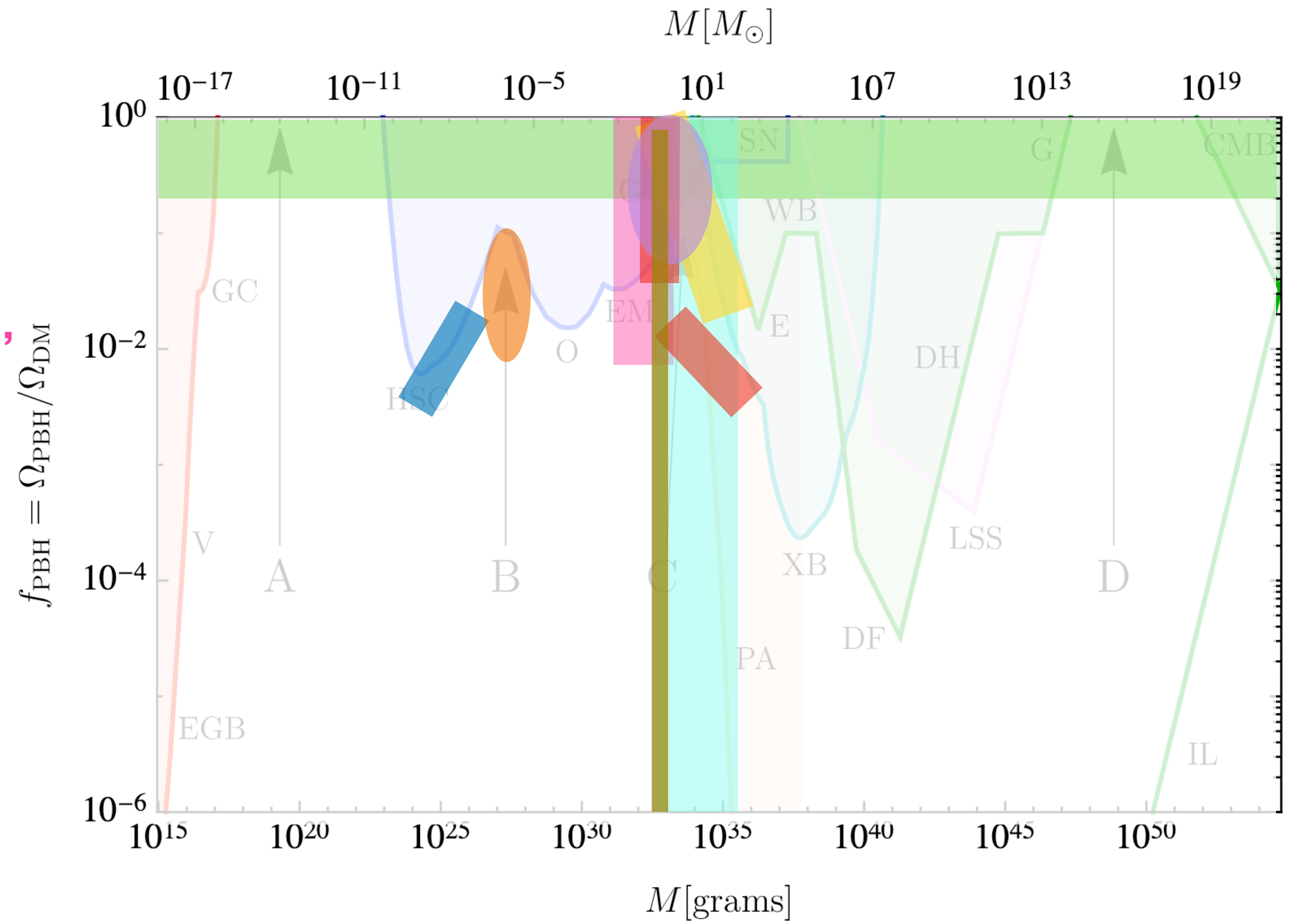

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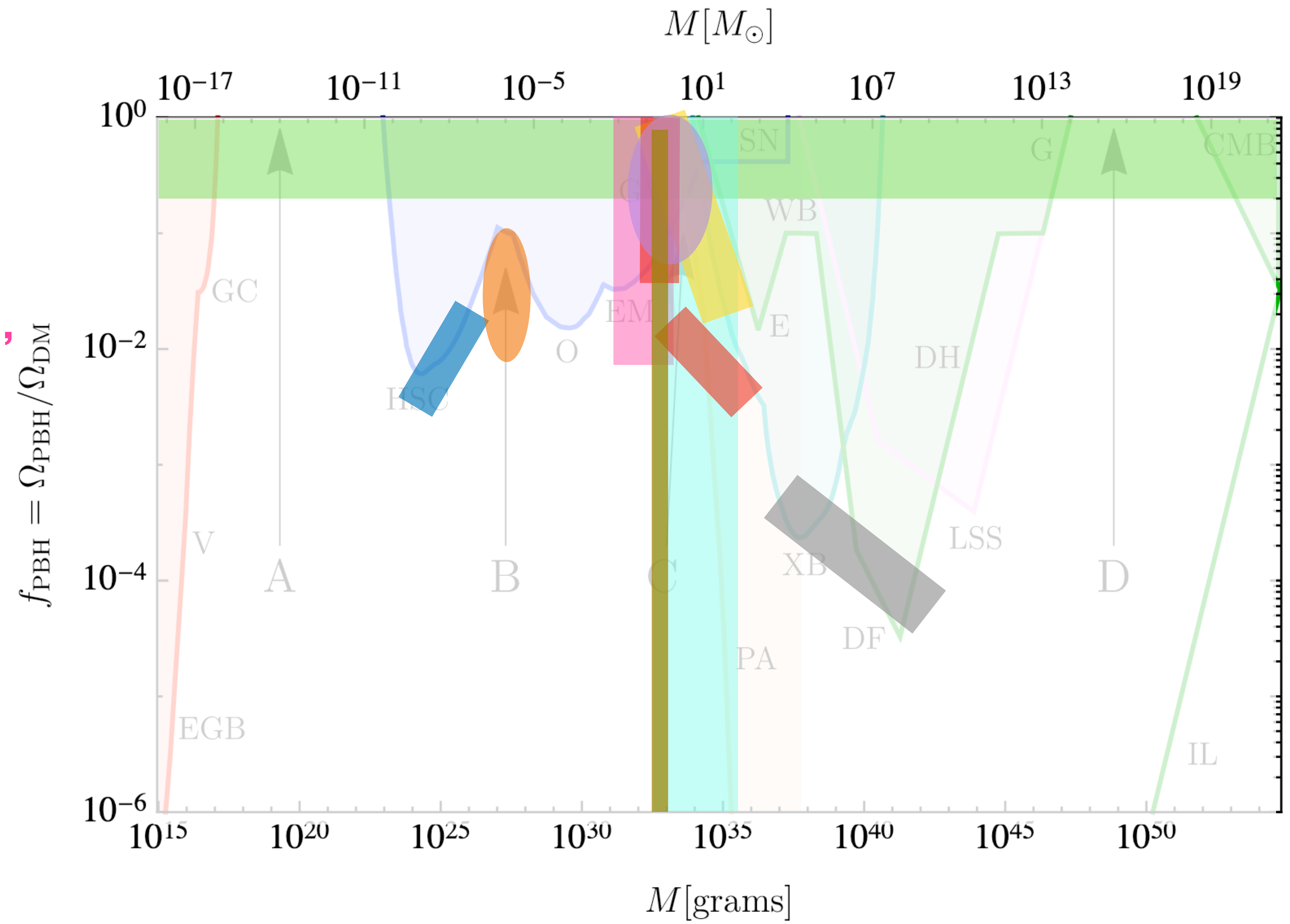

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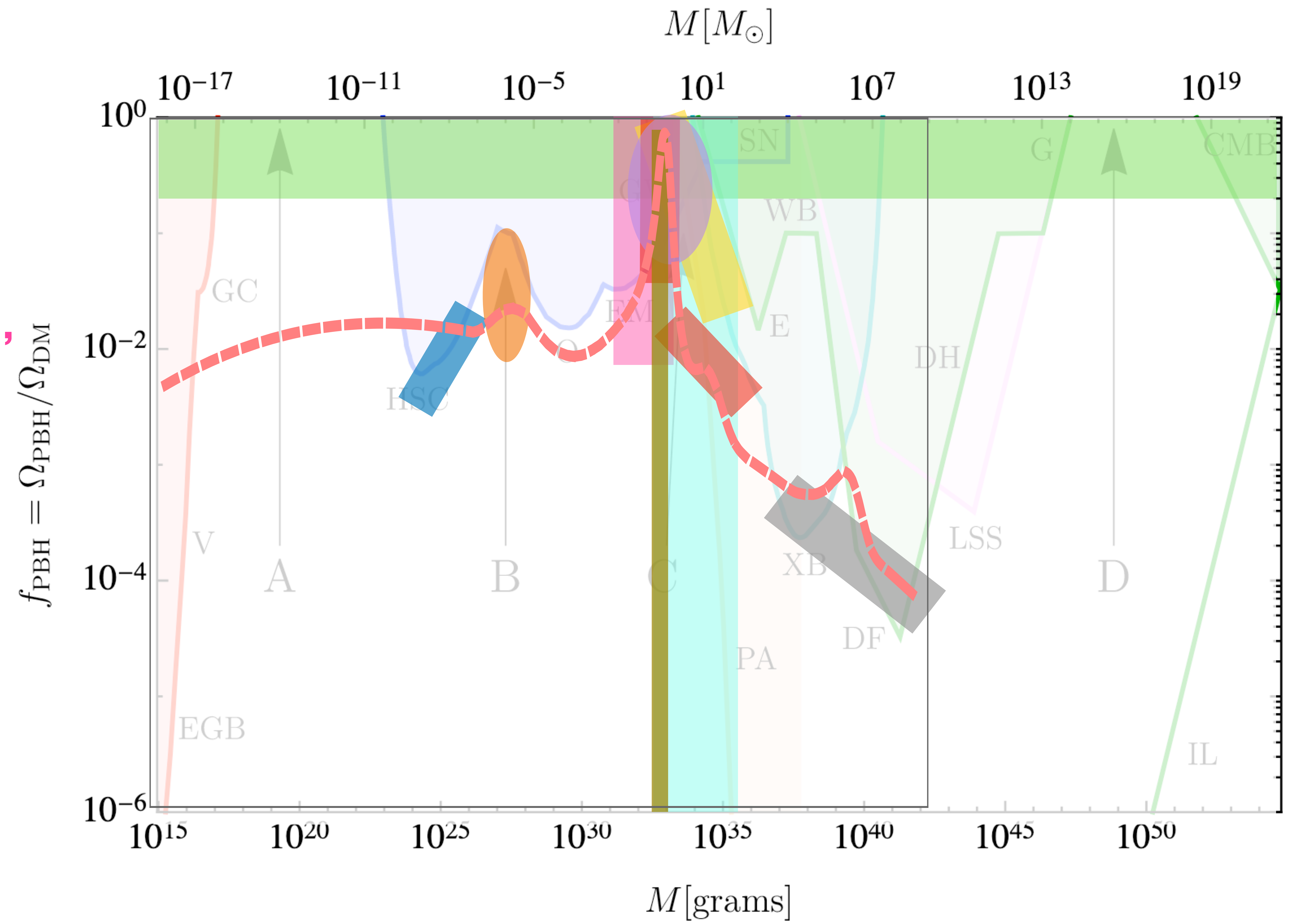

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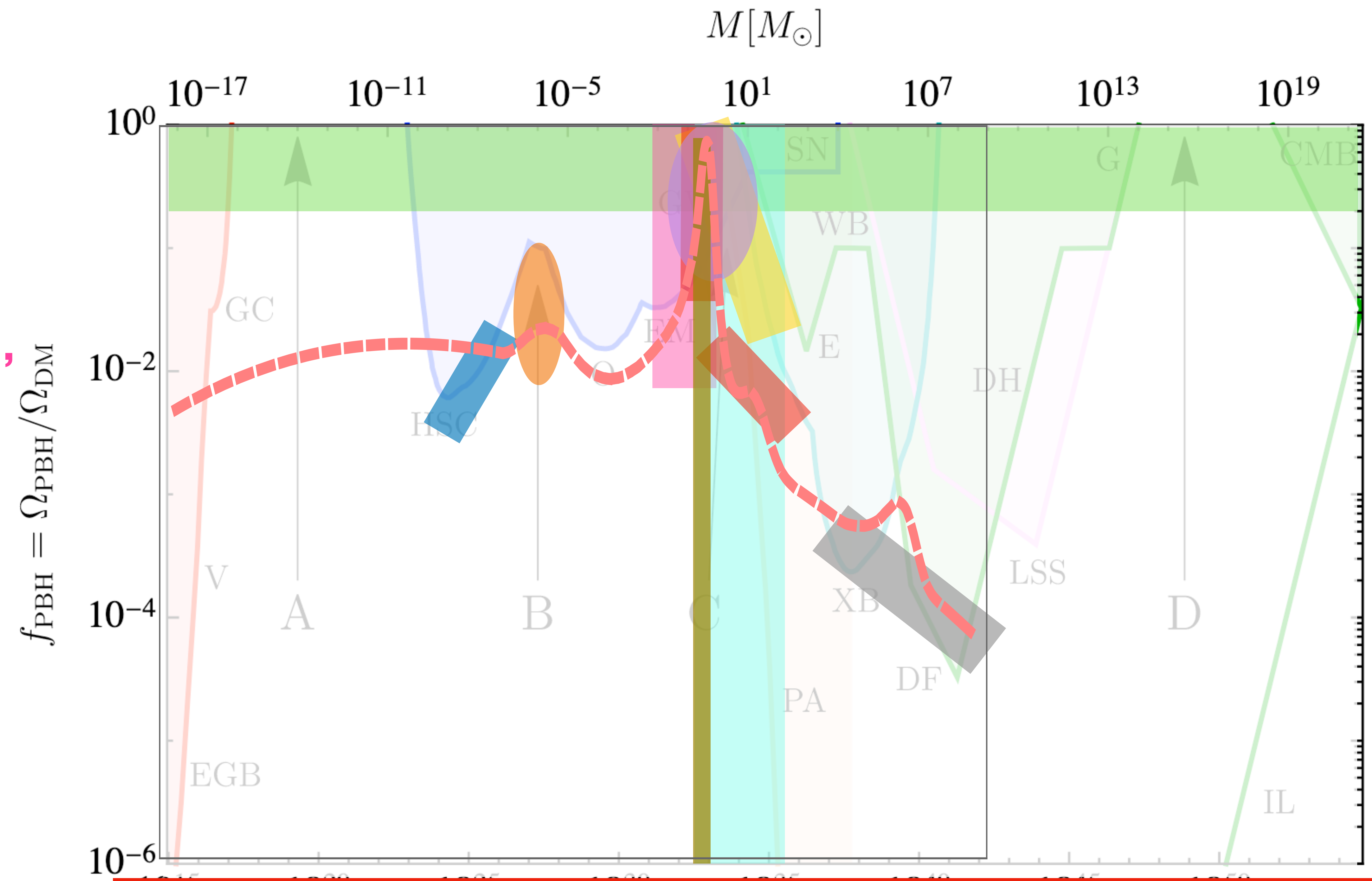

- How to avoid sub-asteroid masses ?
- Tension with Segues 1 limit
- Excluded by CMB limits (but do not include clustering)
- SMBHs excluded by CMB distortions (for Gaussian fluct).

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

Critical review of possible approaches

Model-killer

- Observations progressively reduce the allowed region in f_{PBH} vs m_{PBH} plane
- Asteroid-mass range still allowed
- For stellar-mass PBHs, $f_{PBH} = 1$ already excluded by multiple probes
  - BUT: not for wide-mass and clustered PBHs
    - BUT: clusters = very specific models
      - BUT: Poisson is inevitable
        - BUT: predictions become less clear…
    - BUT: wide-mass still excluded if limits are convolved
      - BUT: non-linear « backreactions » ?
- Additional limits if DM is considered

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Positivist

- Series of observations could be explained by PBHs, especially if $f_{PBH} \sim 1$ at solar-mass scale
- This scale coincides with the QCD transition
  - BUT: limits exclude this region (microlensing, Seigues 1,…)
    - BUT: Evaded if PBHs are in clusters, e.g. due to Poisson clustering
      - BUT: Then 90% of PBHs must be in clusters! Realistic ?
- Clues suggest a wide mass distribution
  - BUT: CMB limits
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  - BUT: Transition in power spectrum limited by CMB distortions, etc
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      - BUT: specific models
        - BUT: specific but natural…

3. Are LIGO/Virgo black holes primordial ?

Merging rates

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Merging rates

Early binaries

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

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:

Above LIGO/Virgo for 30 $M_\odot$ PBHs
[Riotto+], [Jedamzik 20], [Raidal+], etc…

In the LIGO/Virgo range for solar-mass PBHs (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

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

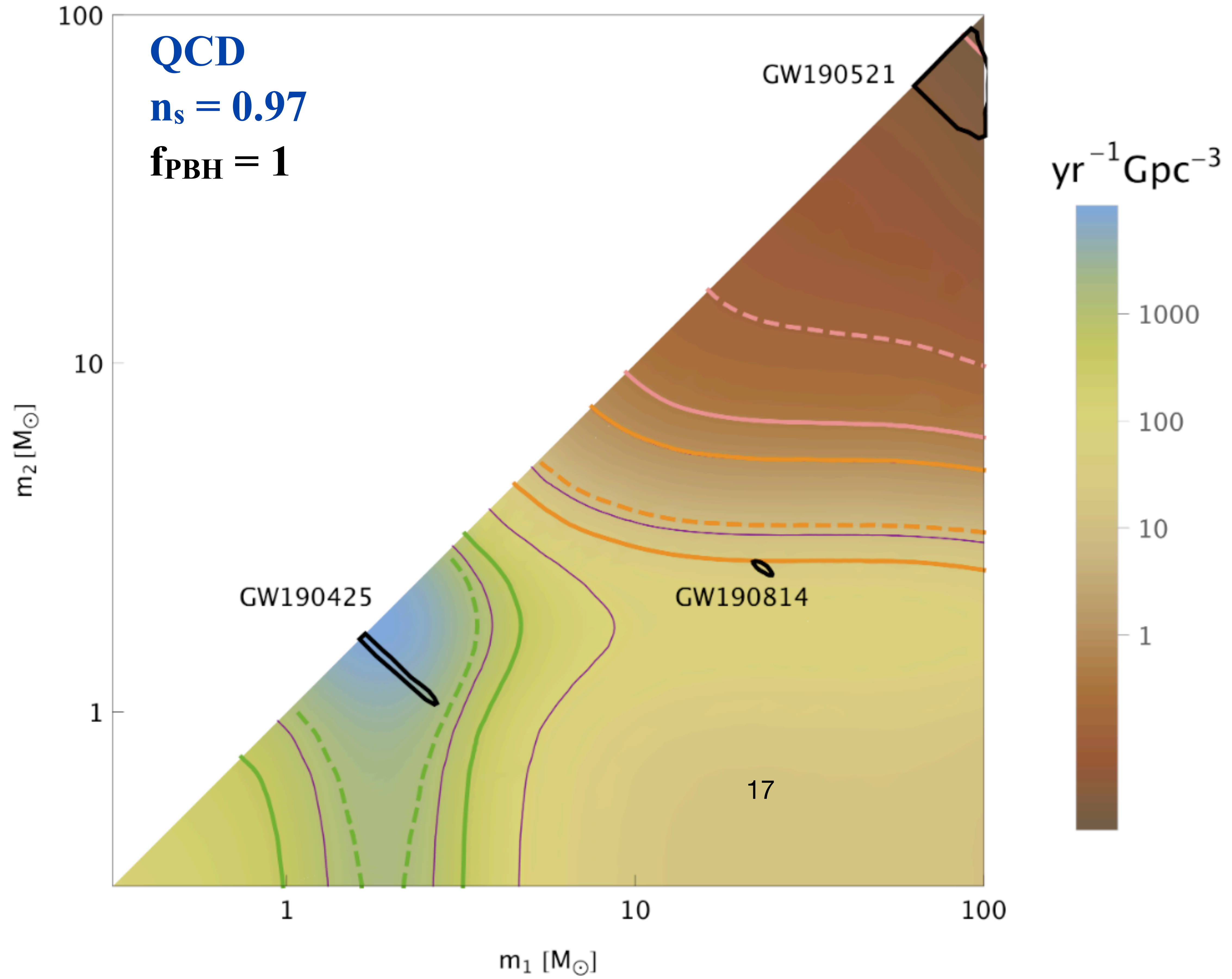
03/2016: Bird et al.
standard halo mass function (no Poisson clustering):
R_{clust} = 1-10
f_{PBH} = 1 possible for **m_{PBH} = 30 sun**
After GTC3: below LIGO/Virgo rates

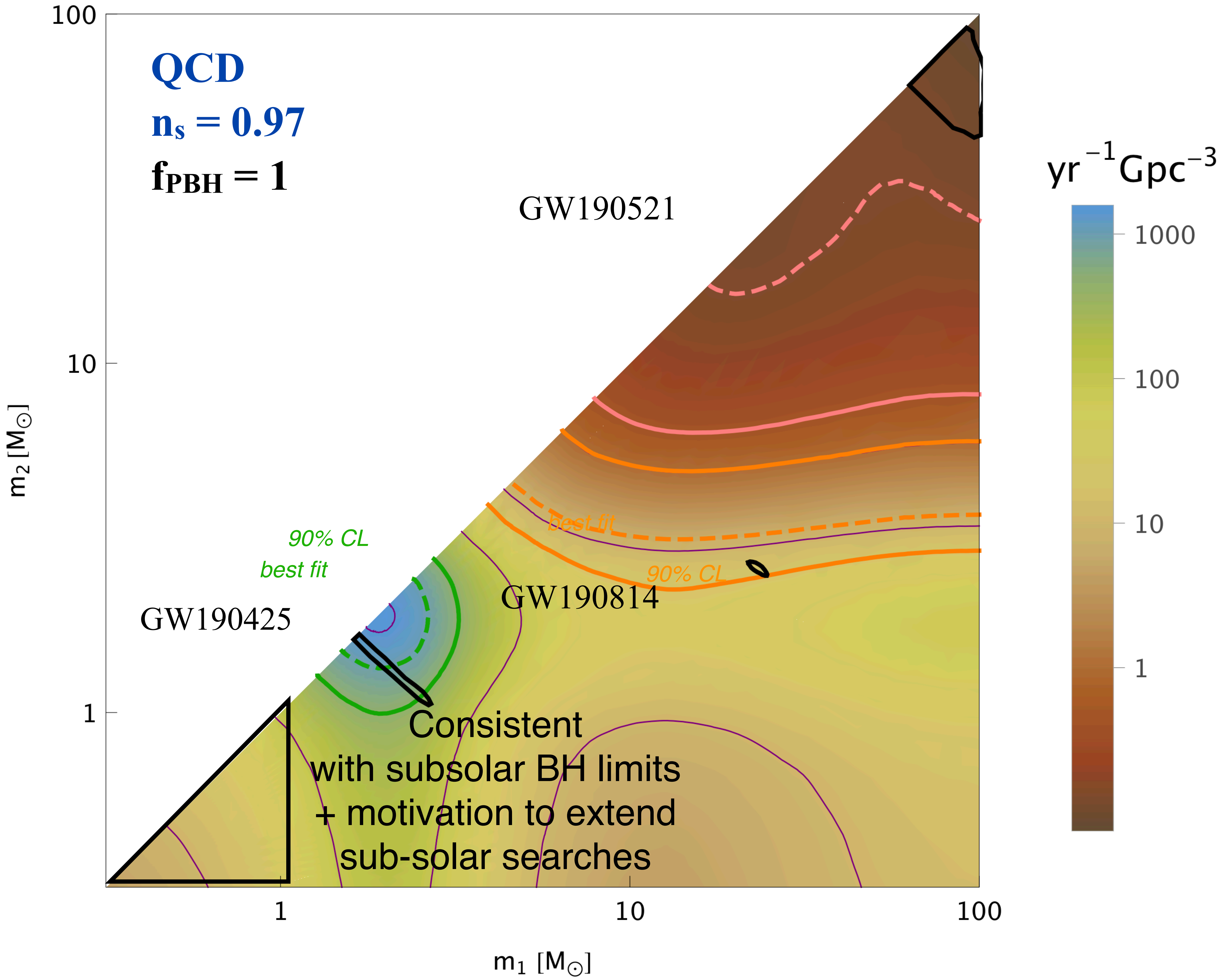
03/2016: S.C + Garcia-Bellido
Enhanced clustering (UFDG):
f_{PBH} = 1 possible for **m_{PBH} = 30 $M_\odot$**
2020: **Poisson clustering:**
R_{clust} = 100-700
f_{PBH} = 1 leads to LIGO/Virgo rates at solar-mass scale
only allows f_{PBH} ~0.01 at 30 $M_\odot$

3. Are LIGO/Virgo black holes primordial ?

Merging rates

Early binaries	Late Binaries





3. Are LIGO/Virgo black holes primordial ?

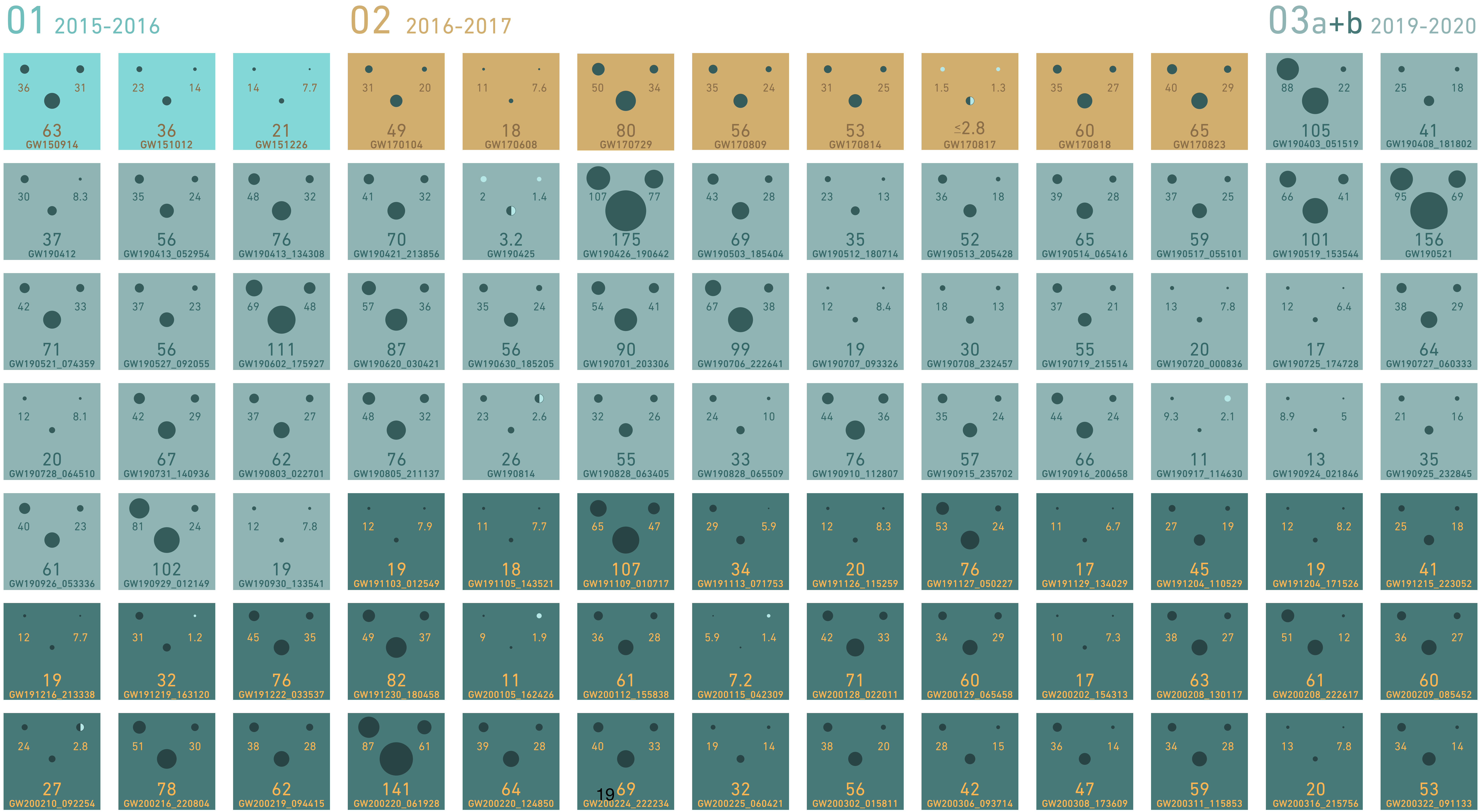
Merging rates

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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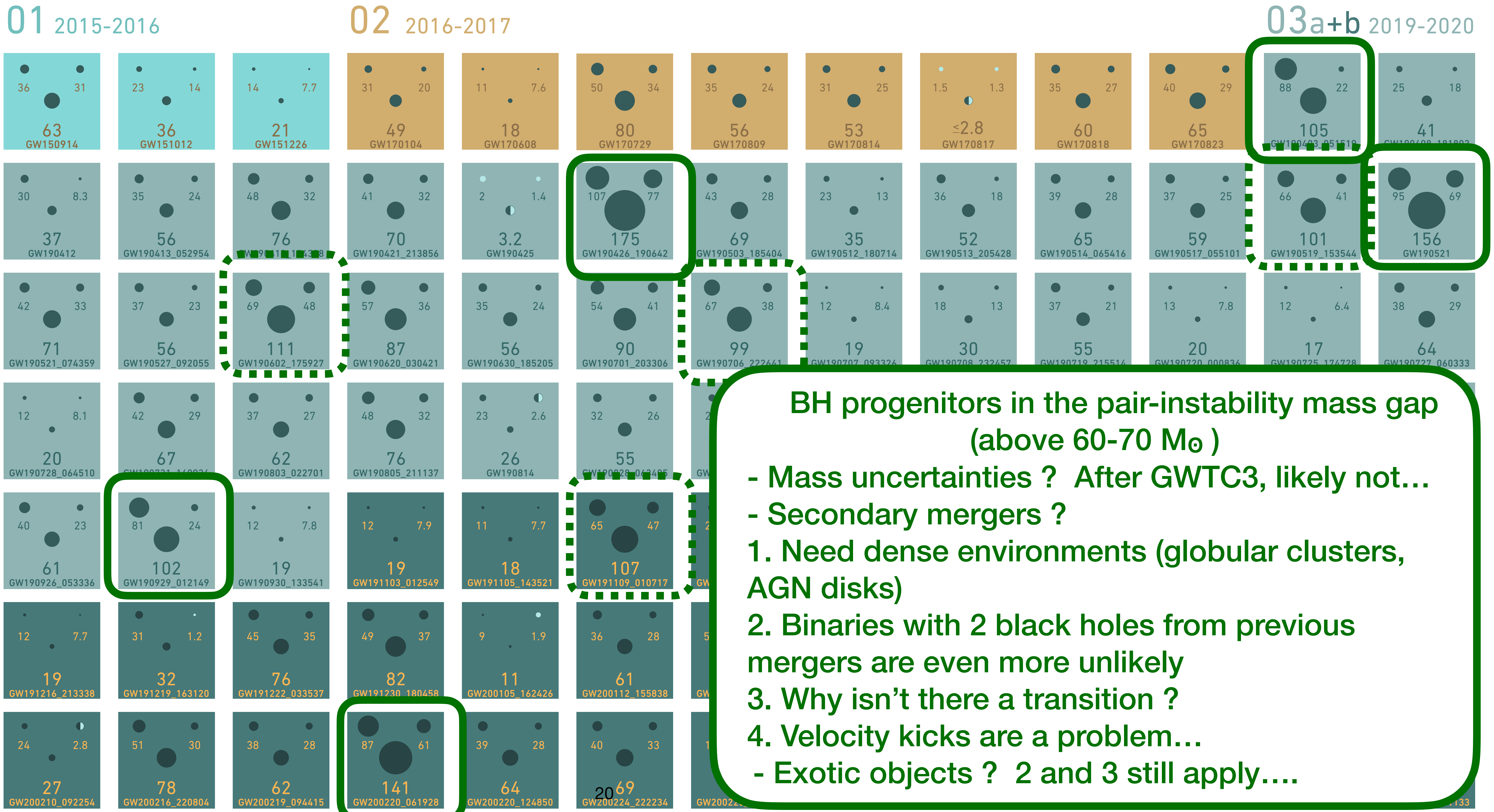


BH progenitors in the pair-instability mass gap (above 60-70 $M_\odot$)

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

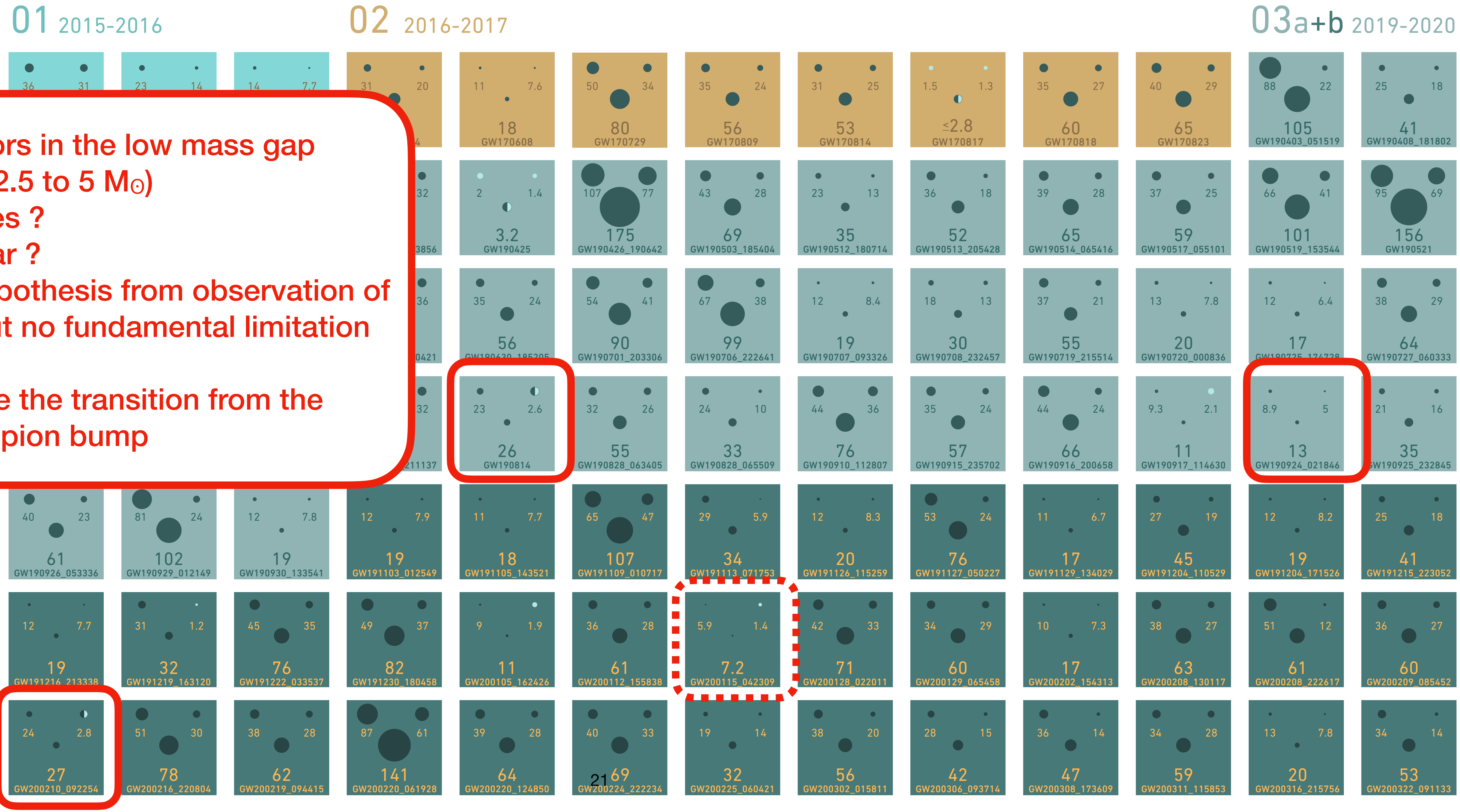
1. Need dense environments (globular clusters, AGN disks)
2. Binaries with 2 black holes from previous mergers are even more unlikely
3. Why isn't there a transition ?
4. Velocity kicks are a problem…

- 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

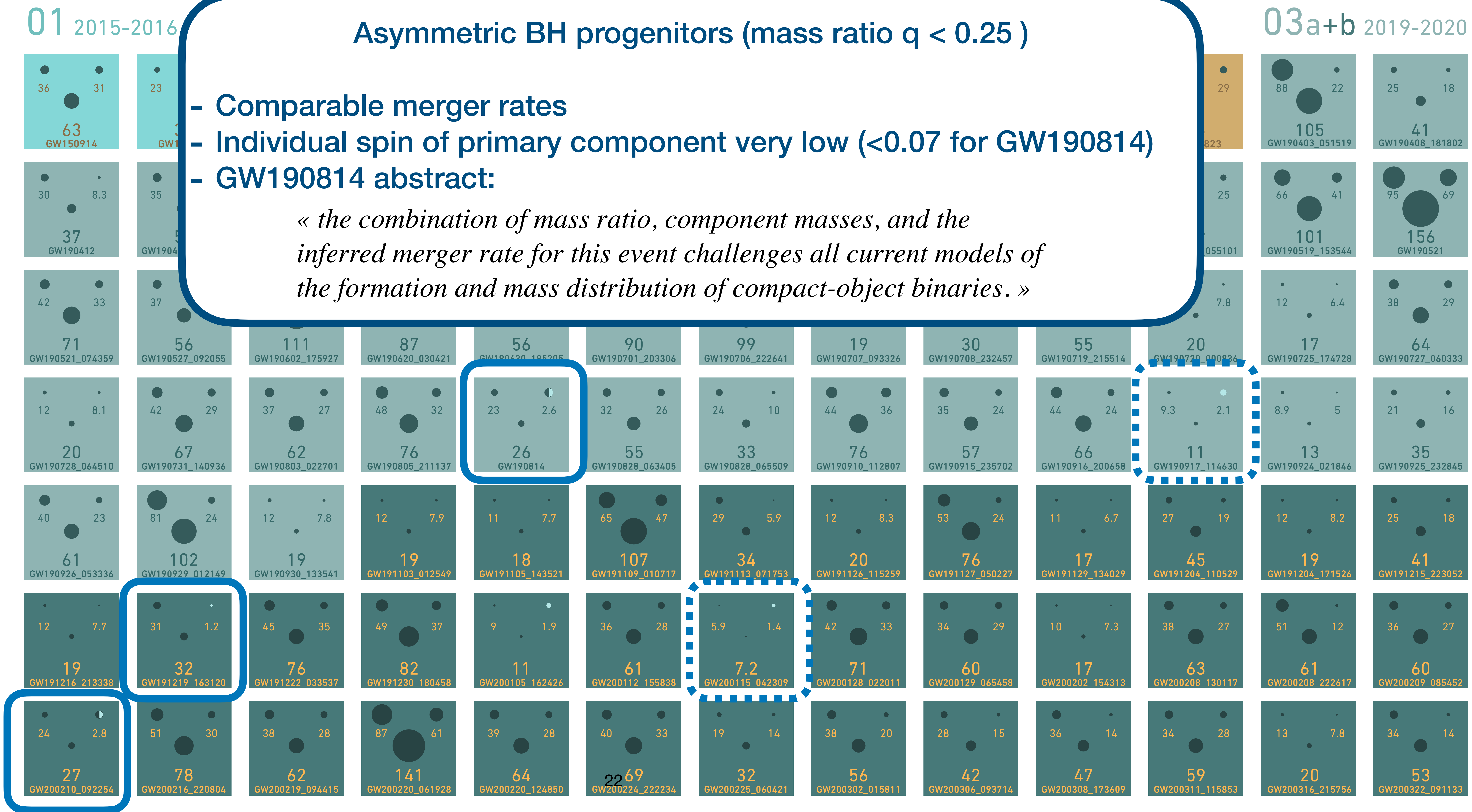
3. Are LIGO/Virgo black holes primordial ?

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 ?

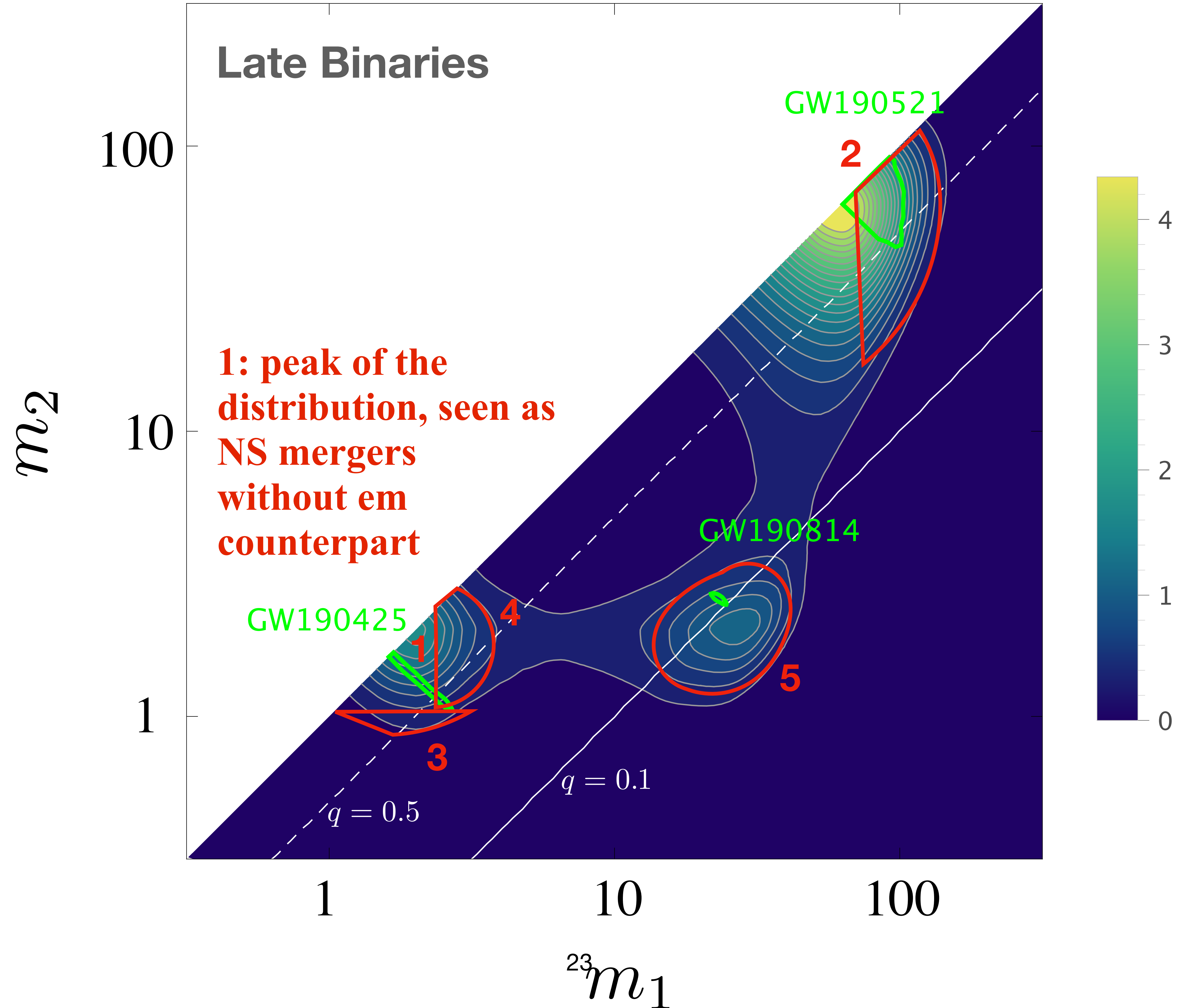
Masses

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



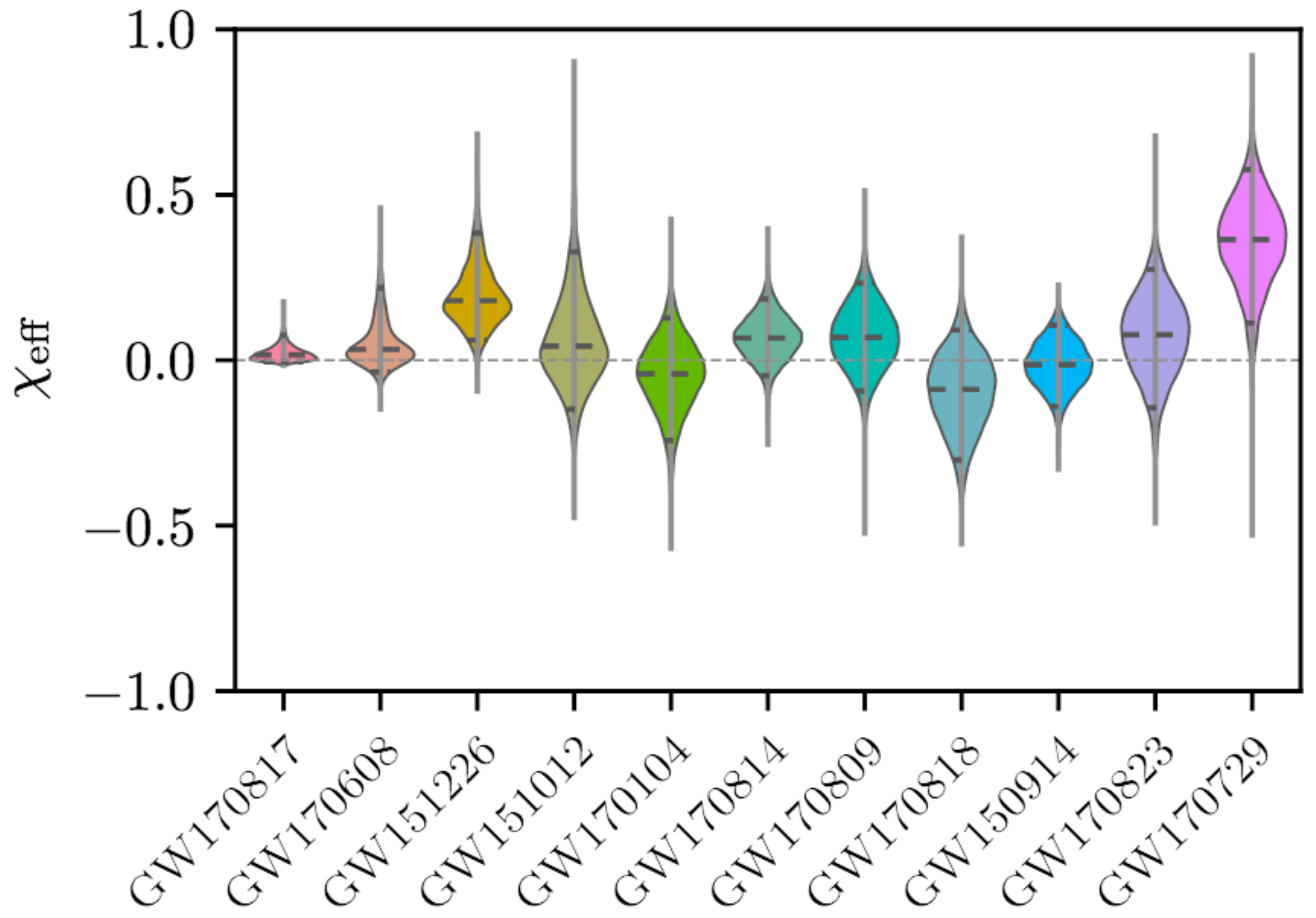
BUT: Observation of mergers in central blue region

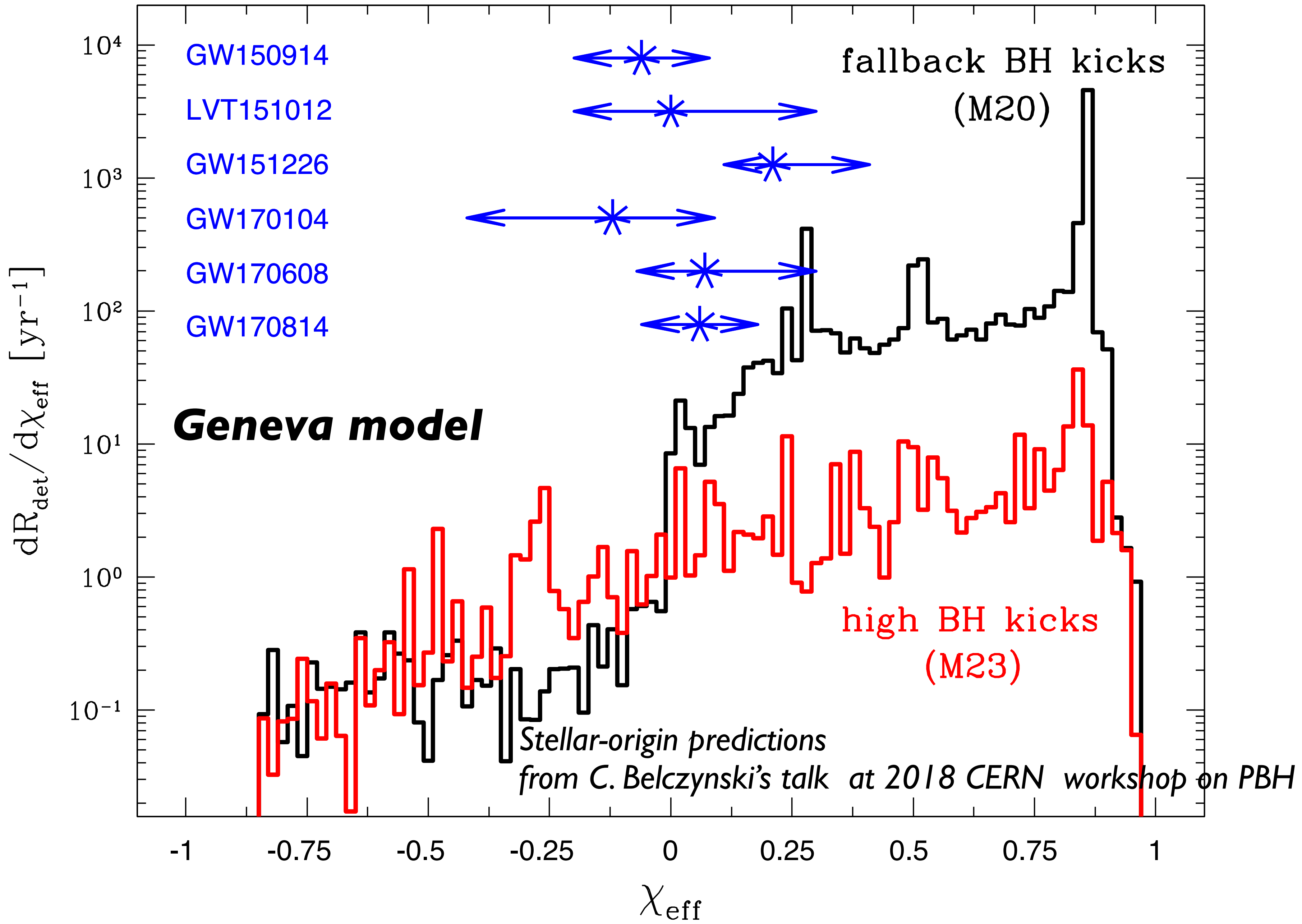
Next: Bayesian analysis for GWTC3

3. Are LIGO/Virgo black holes primordial ?

Effective spins

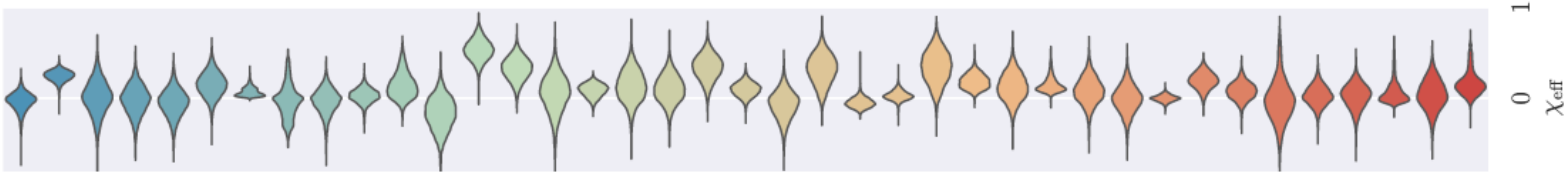
$$\chi_{\rm eff} = [m_1 S_1 \cos(\theta_{\rm LS_1}) + m_2 S_2 \cos(\theta_{\rm LS_2})]/(m_1 + m_2)$$





Spin of primary component for asymmetric mergers:

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

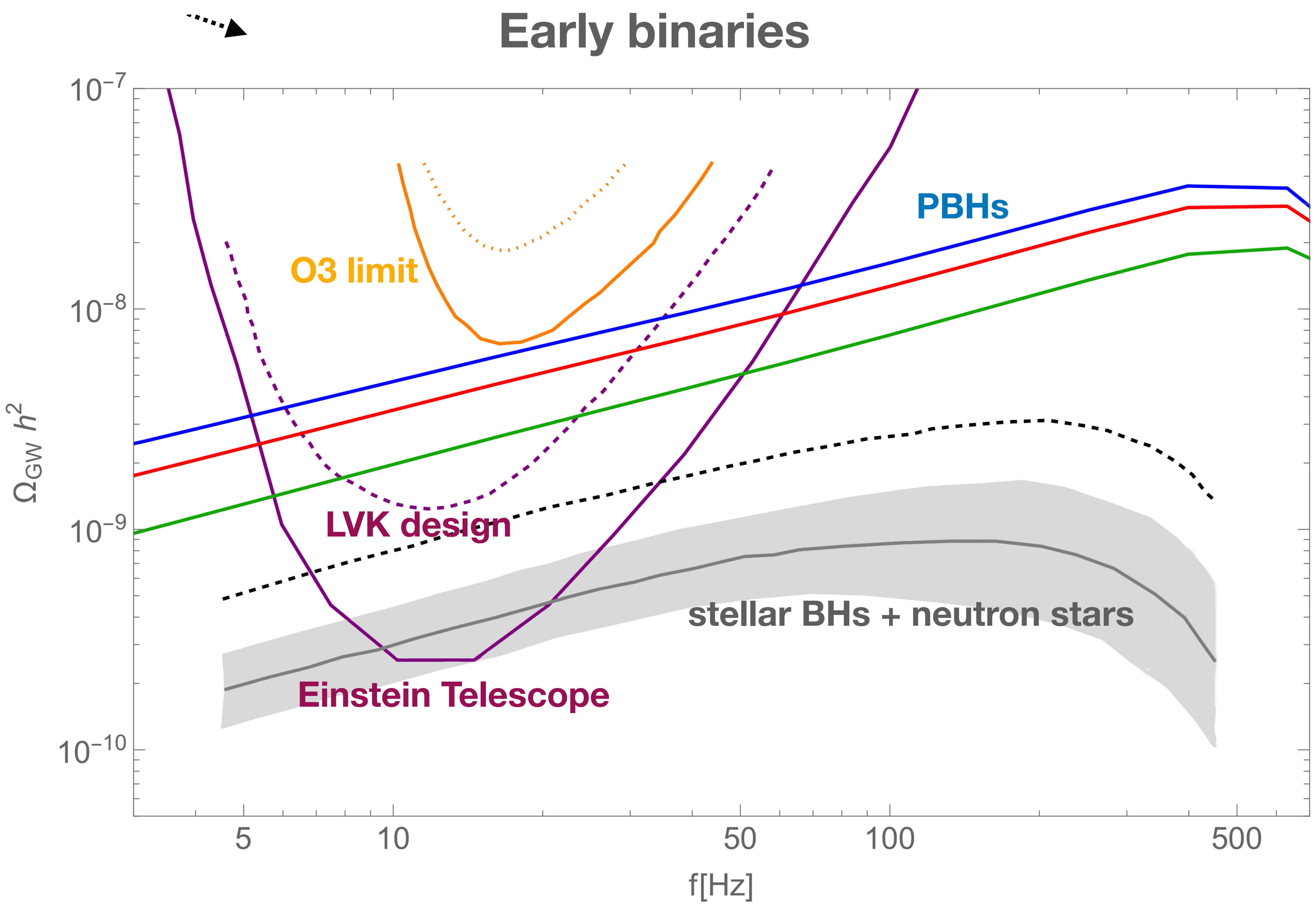


A few: evidence for effective spin > 0

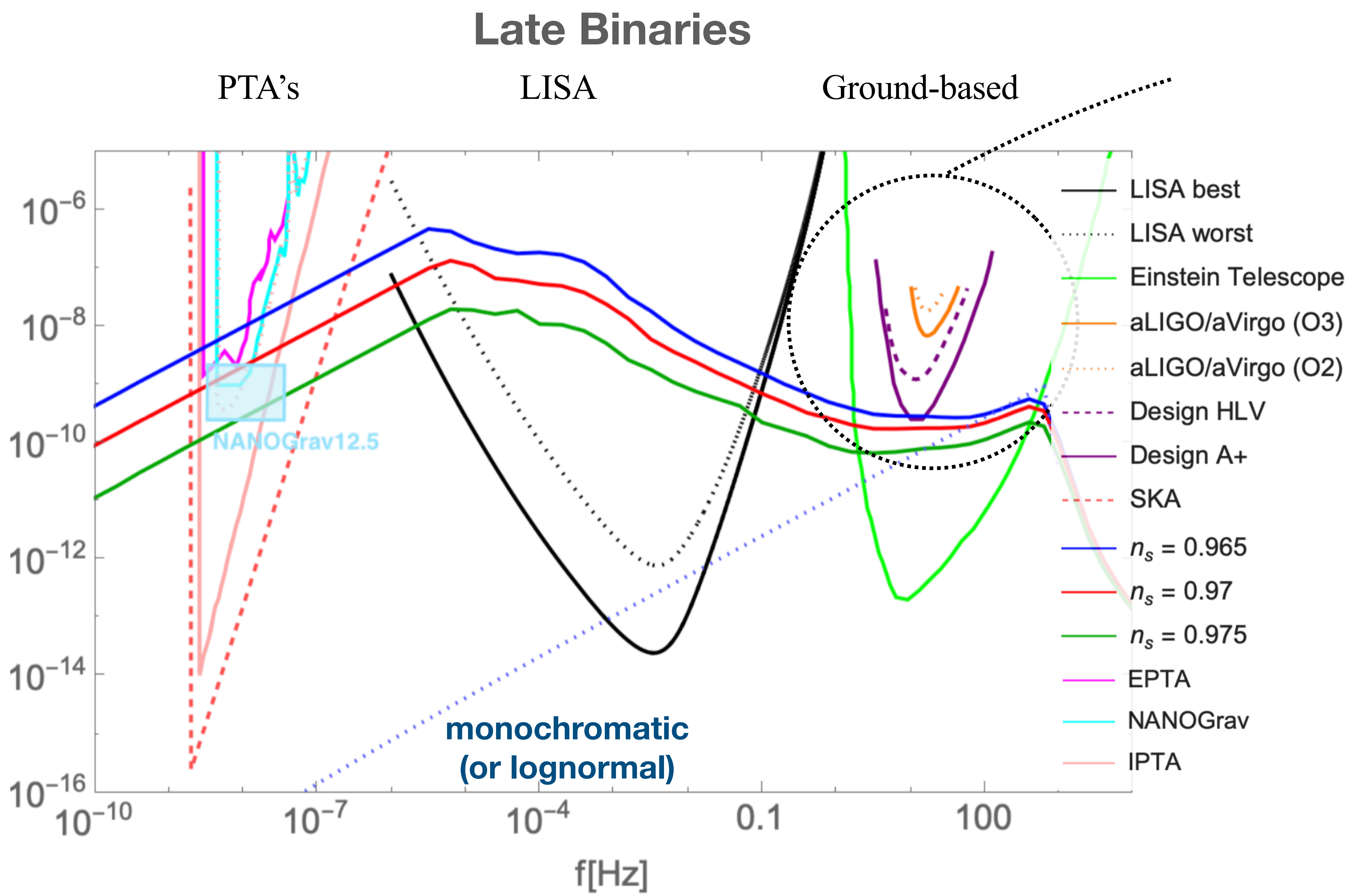
PBHs have zero spin initially but can acquire a low spin due to accretion/mergers [De Luca+20]

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

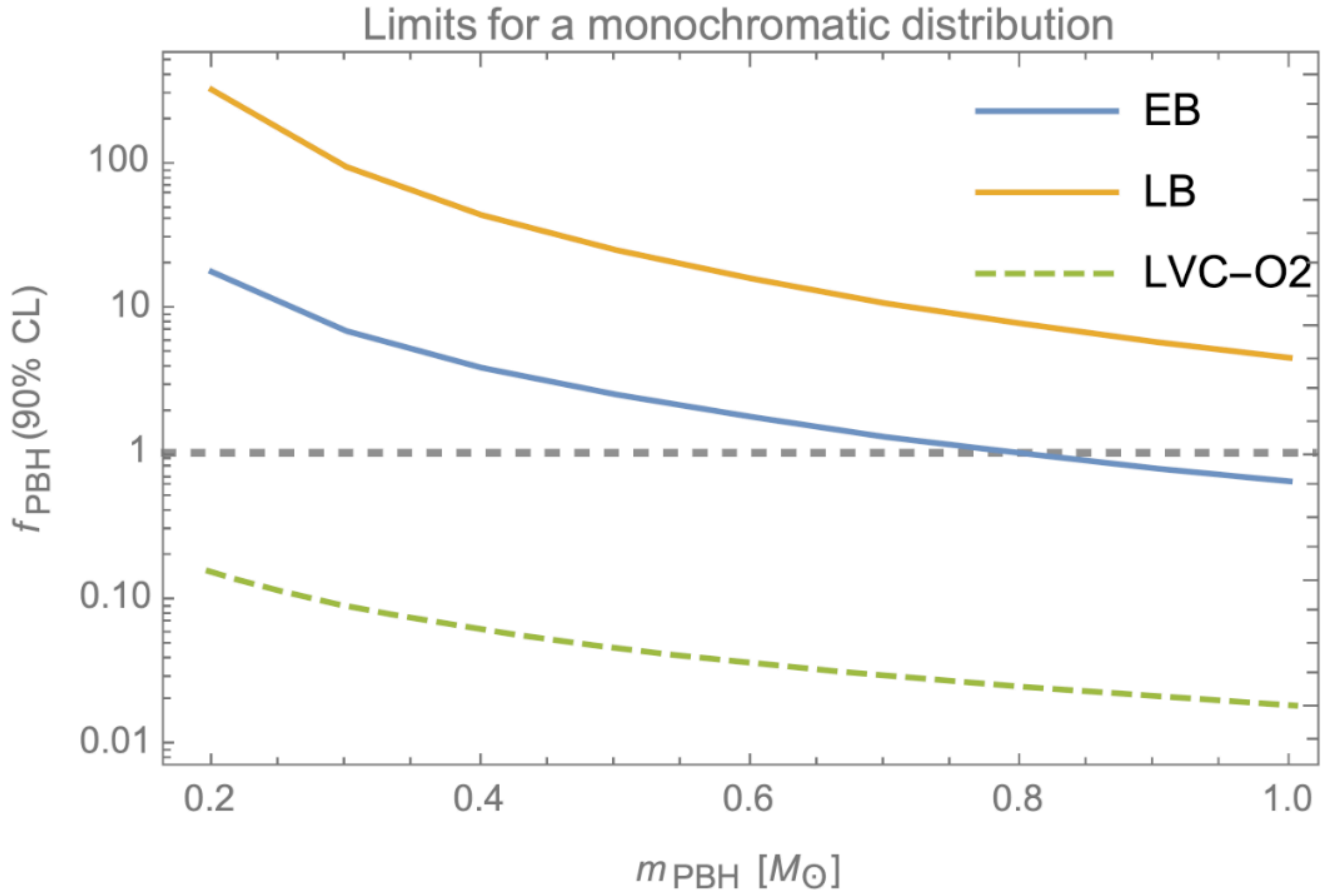
TABLE I. The candidates of the search with a SNR > 8 and a FAR $< 2\,\mathrm{yr}^{-1}$. We report here the FAR, $\ln \mathcal{L}$, the UCT time of the event (date and hours), template parameters that pick the events and the associated SNRs.

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



3. Are LIGO/Virgo black holes primordial ?

Critical review of possible approaches

Reductionist

- Each observation, taken individually, can still be explained by stellar models
  - Really difficult for the rate of GW190814
  - GWTC3 favors the absence of mass gaps
- Different processes are at play (low metallicity environments, secondary mergers in dense environments,...)
  - BUT: the scenario of secondary mergers is not natural
  - BUT: PBHs explain the observations with a single, natural model
- PBHs could explain a fraction of events, likely not all

Holistic

- Wide mass function -> PBH distribution imprinted by thermal history
- Merger rates in agreement with LIGO
- Mass distribution (qualitatively) in agreement
  - BUT: not between 10 and 20 Msun
- PBHs: no spin at formation => low effective spins
  - BUT: some mergers have an effective spin
    - BUT: PBHs can acquire spin through accretion (or mergers)
- Possible observation of a GW background at nanoHertz: from 2nd order perturbations or late binaries with asymmetric masses
  - BUT: GW nature of the signal not confirmed
- Subsolar candidates in O2
  - BUT: not in O3a, no parameter estimation (yet)

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- **Lot of BUTs,** BUTs to BUTs, BUTs to BUTs to BUTs: strong statements are still premature
- **Complex phenomenology**: formation, clustering, accretion, mergers, etc…
- Common agreement: finding **subsolar black holes** is the best way to **prove the existence of PBHs**… Stay tuned!