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

Primordial black holes

A positivist review

SEWM conference - June 20-24
IPhT, Saclay - Université Paris VI, Paris

Francqui Foundation

Background picture: artist view of GW190521 by Ingrid Bourgault

Outline

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- How natural is PBH **formation** ?

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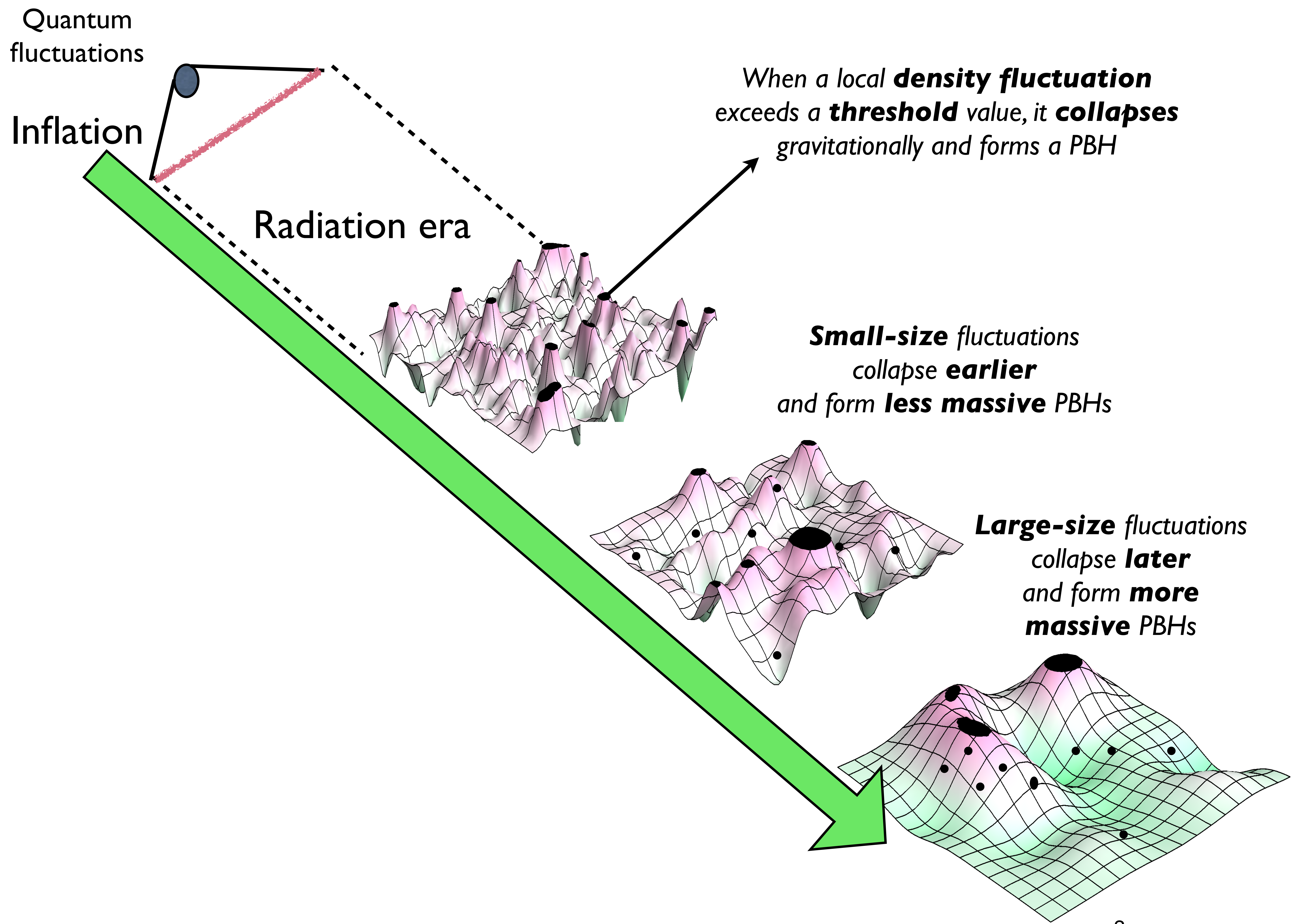
- Are **LIGO/Virgo** black holes primordial? How to distinguish stellar vs primordial black holes in **gravitational-wave** (GW) observations ?

1. How natural is PBH formation ?

A simple but fine-tuned process



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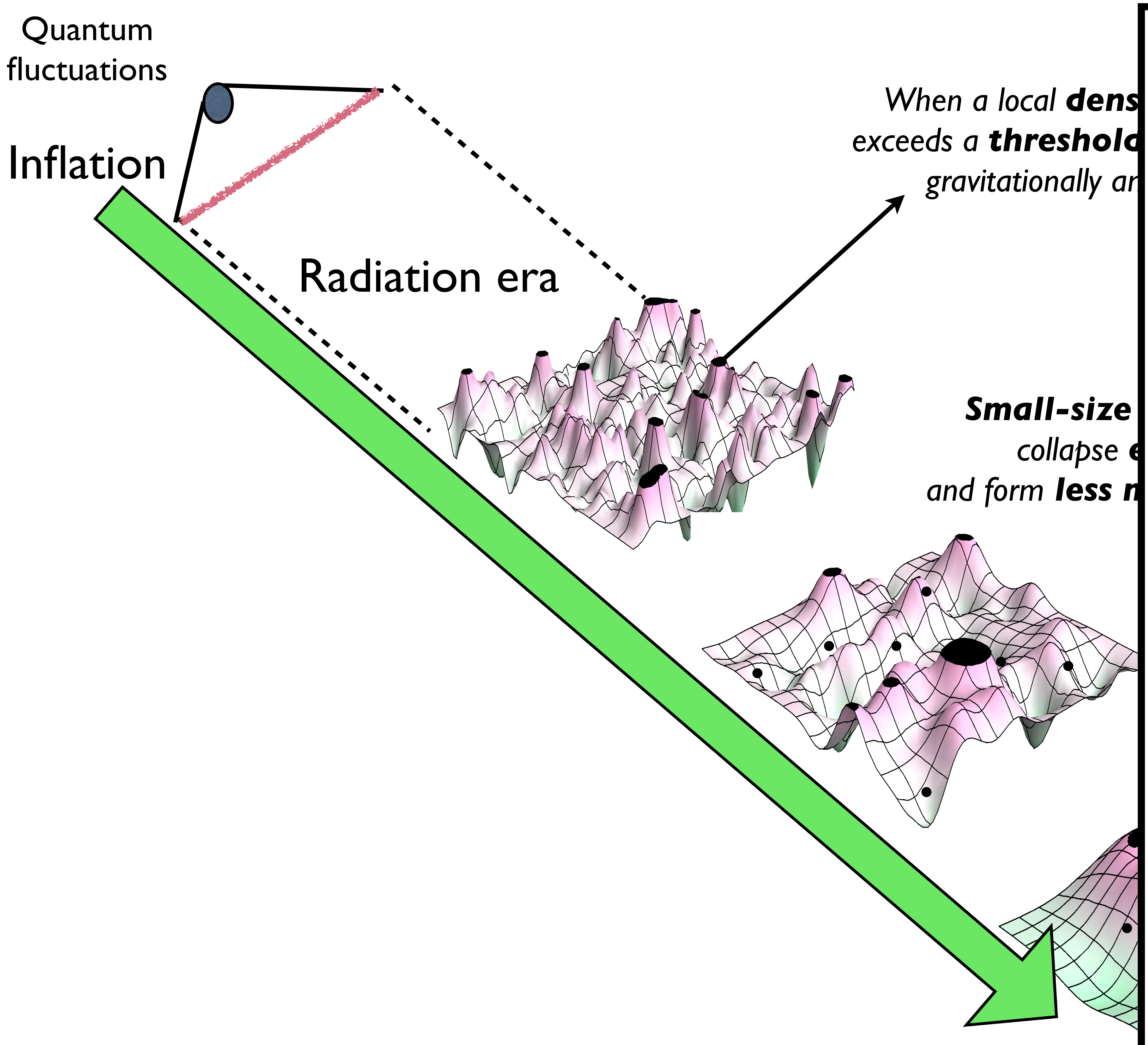

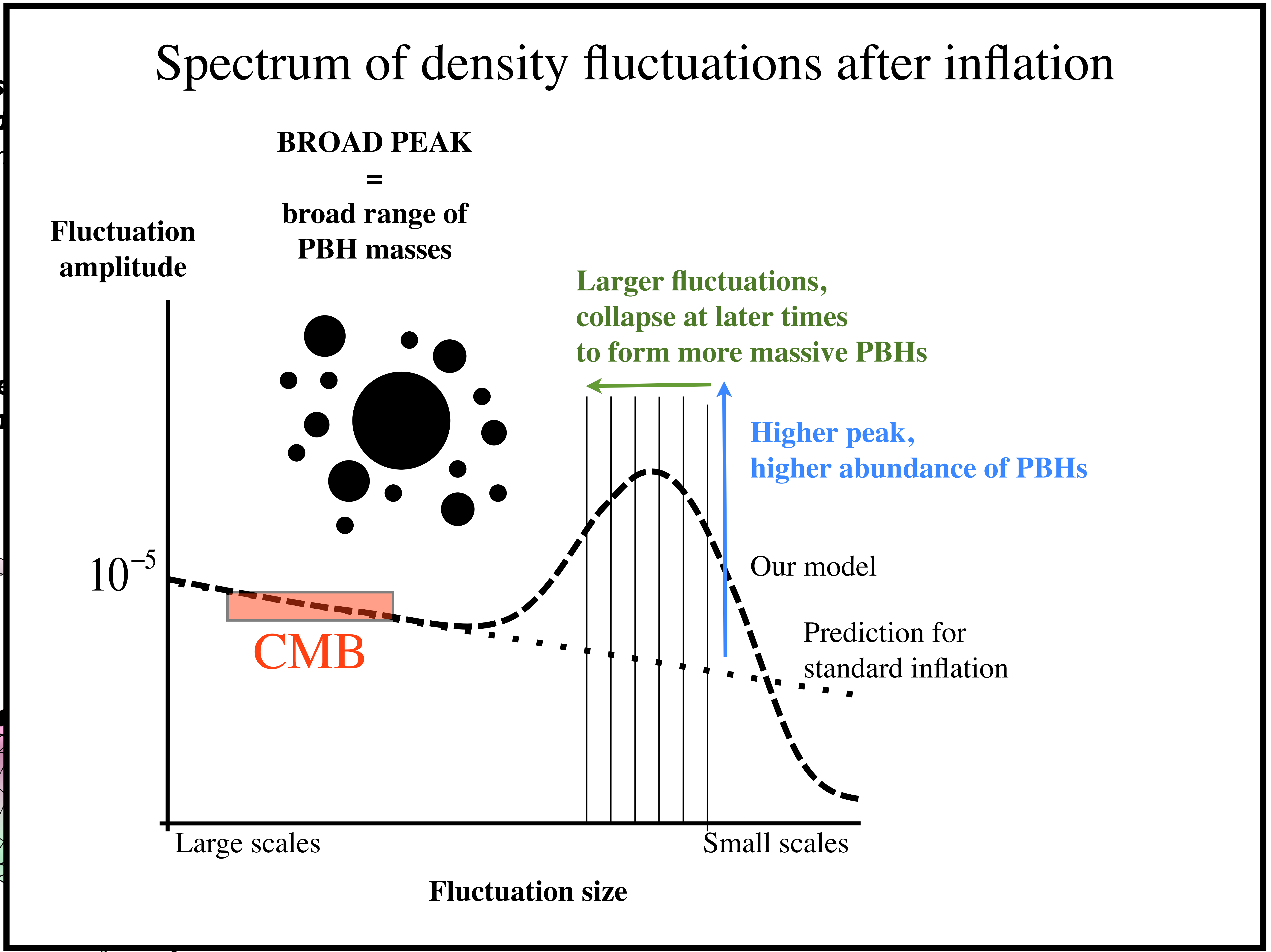

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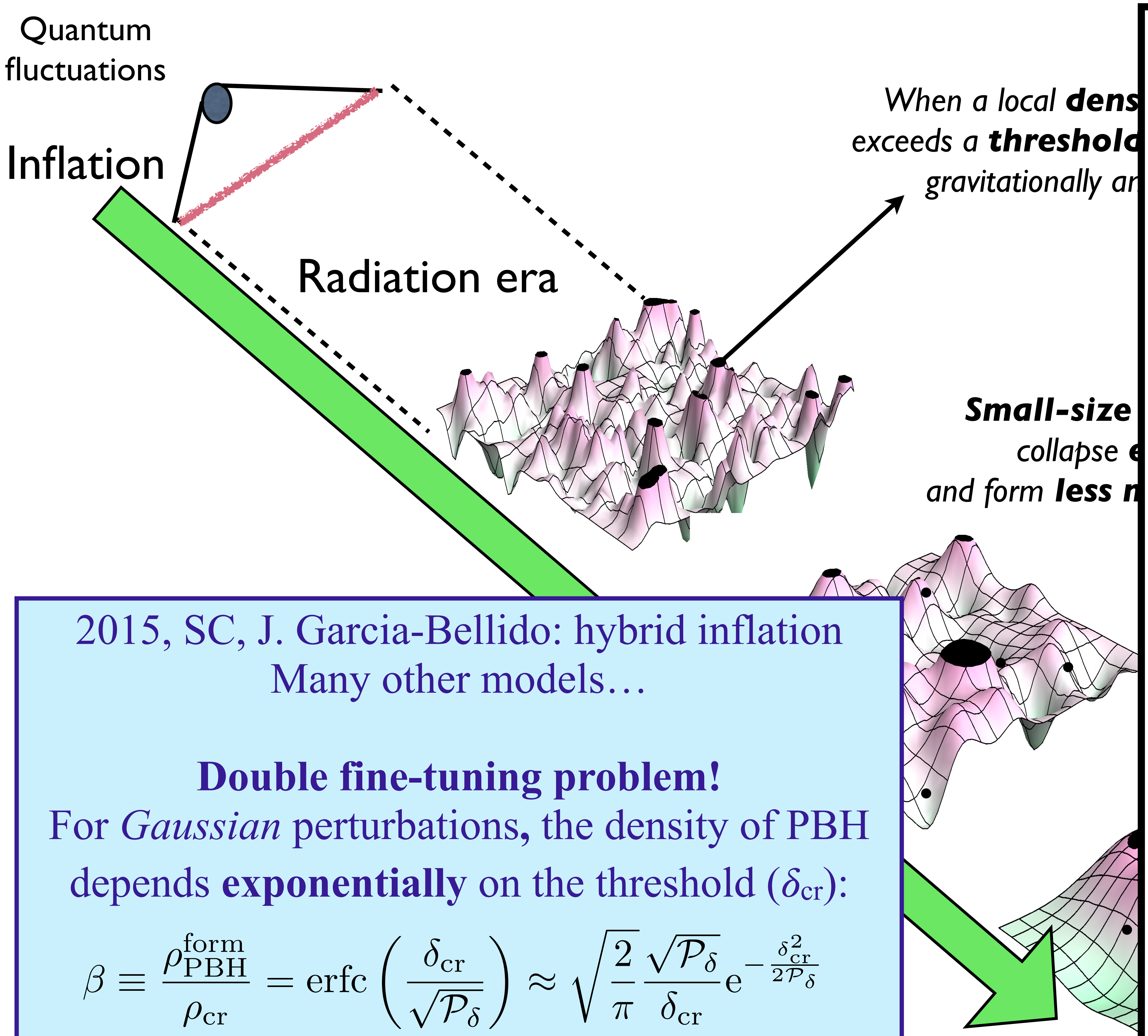
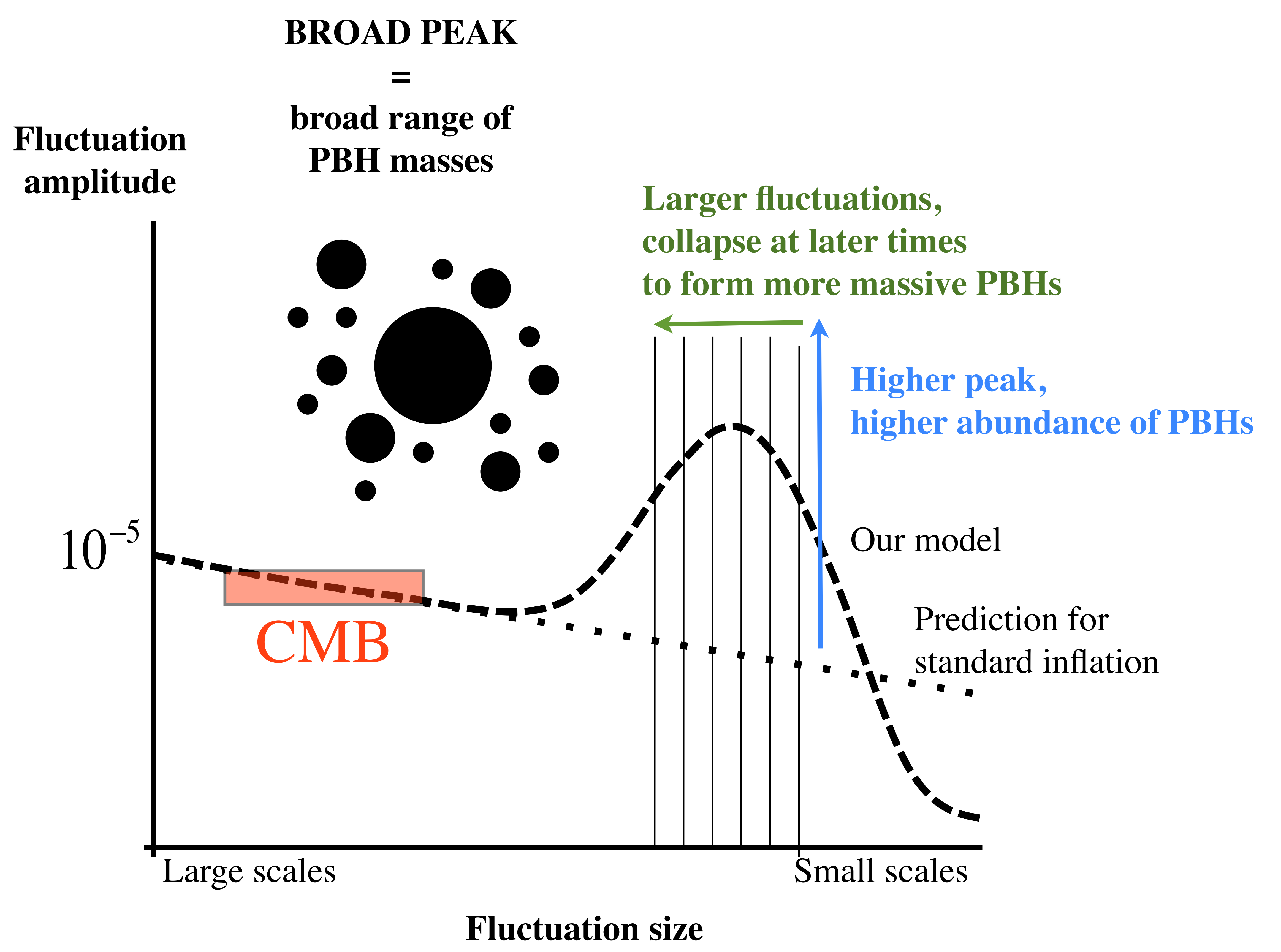


2015, SC, J. Garcia-Bellido: hybrid inflation
Many other models…

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

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

Spectrum of density fluctuations after inflation



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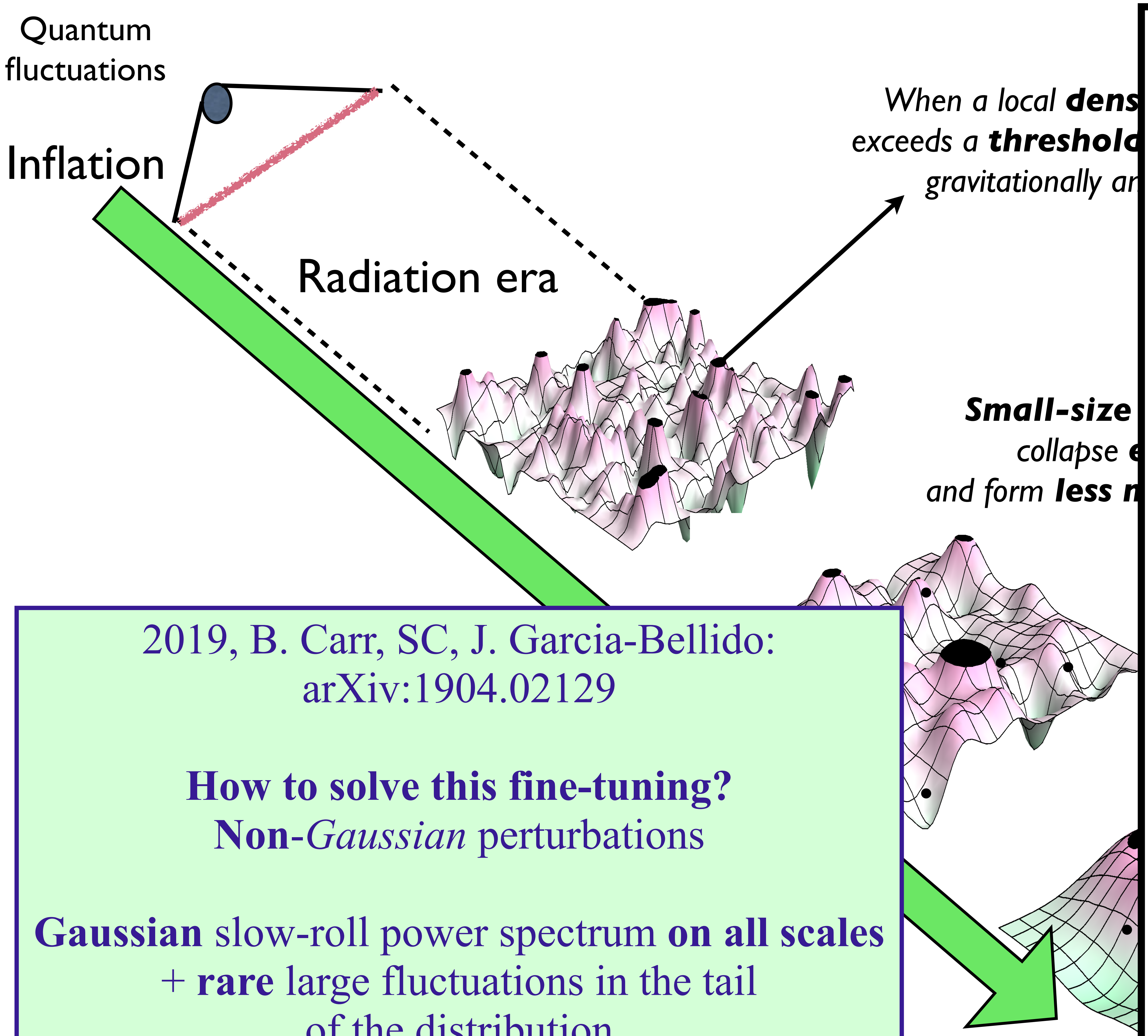
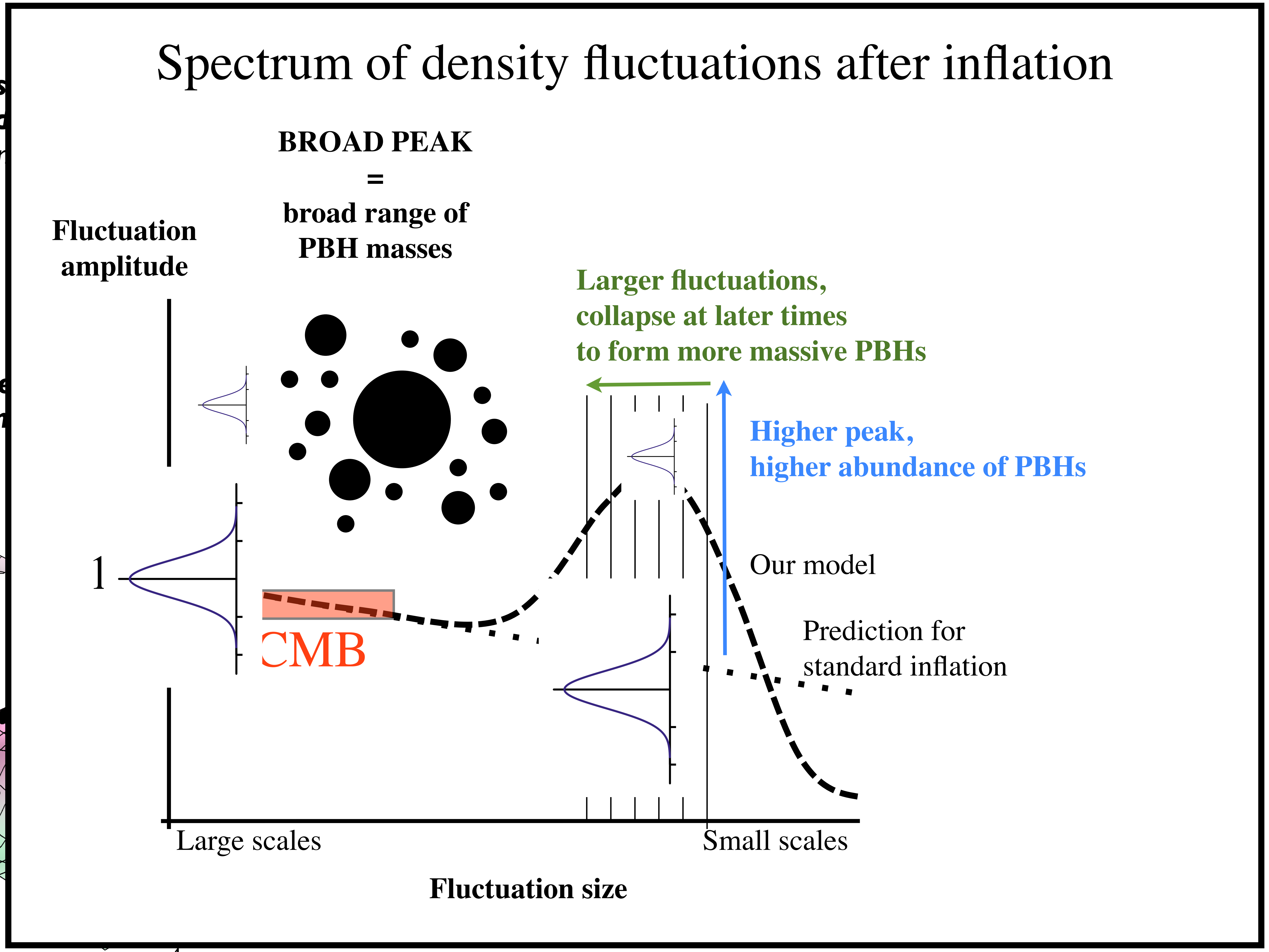


2019, B. Carr, SC, J. Garcia-Bellido:
arXiv:1904.02129

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**



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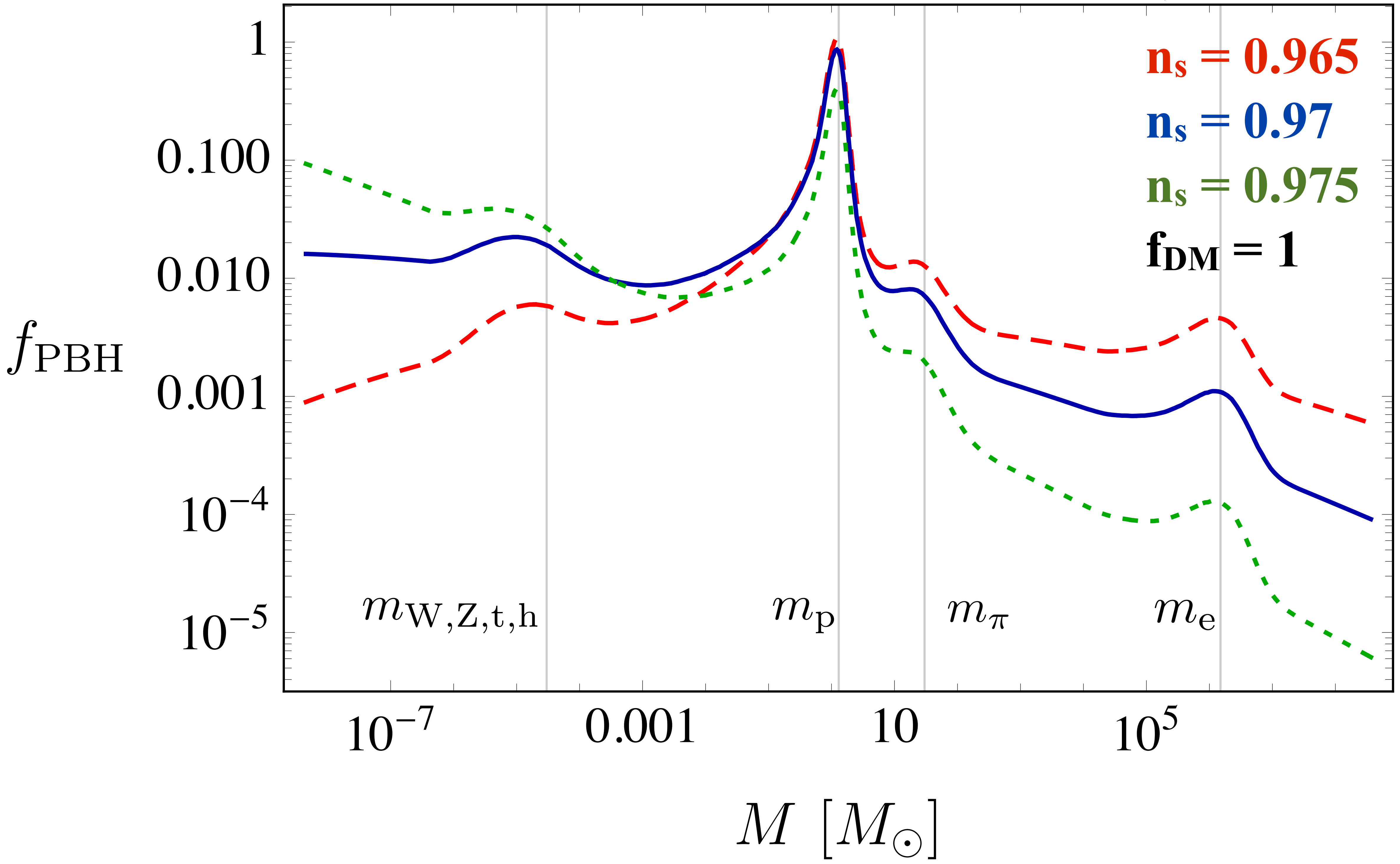
Carr+, 1906.08217



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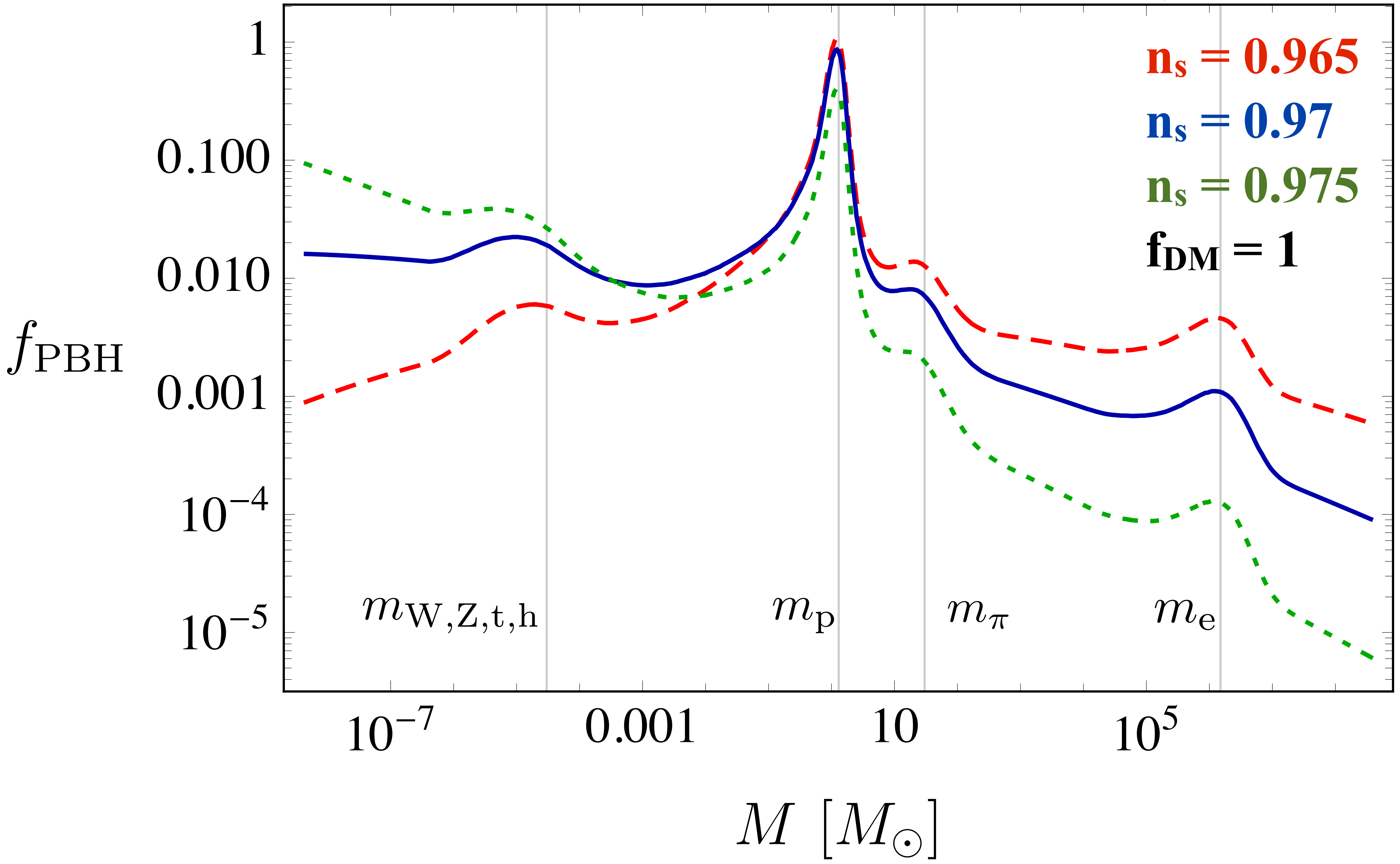

- **Nearly scale-invariant spectrum**
- **Spectral index: $n_s = 0.97$**
- **Peak at ~[2-3] $M_\odot$**
- **Second peak at ~30 $M_\odot$**
- **Two bumps at 10^{-6} and 10^6 $M_\odot$**

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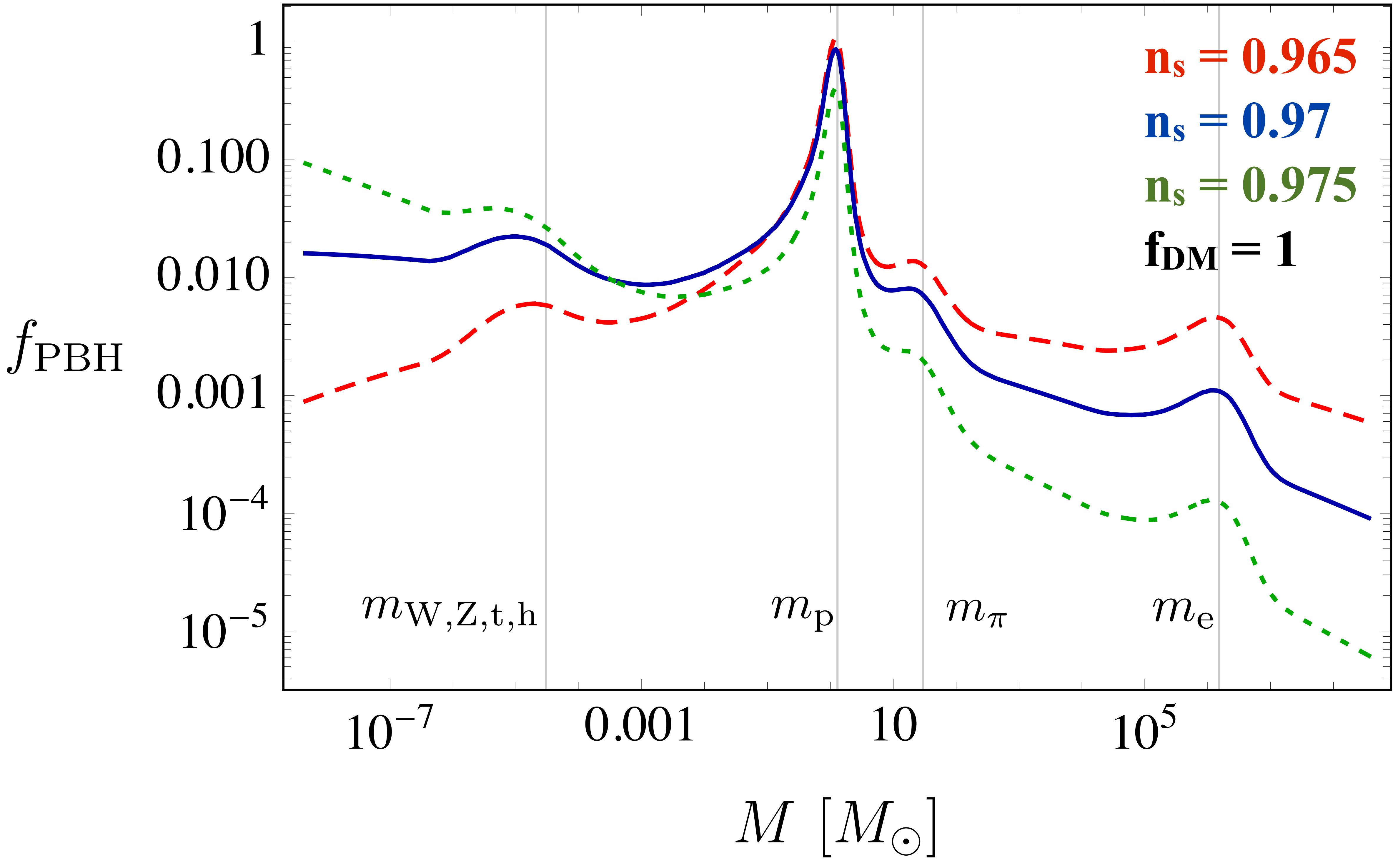
✓ **Inevitable**
✓ **Naturally** leads to **stellar-mass** PBHs
◉ But **does not solve the abundance/transition** problem

Carr+, 1906.08217



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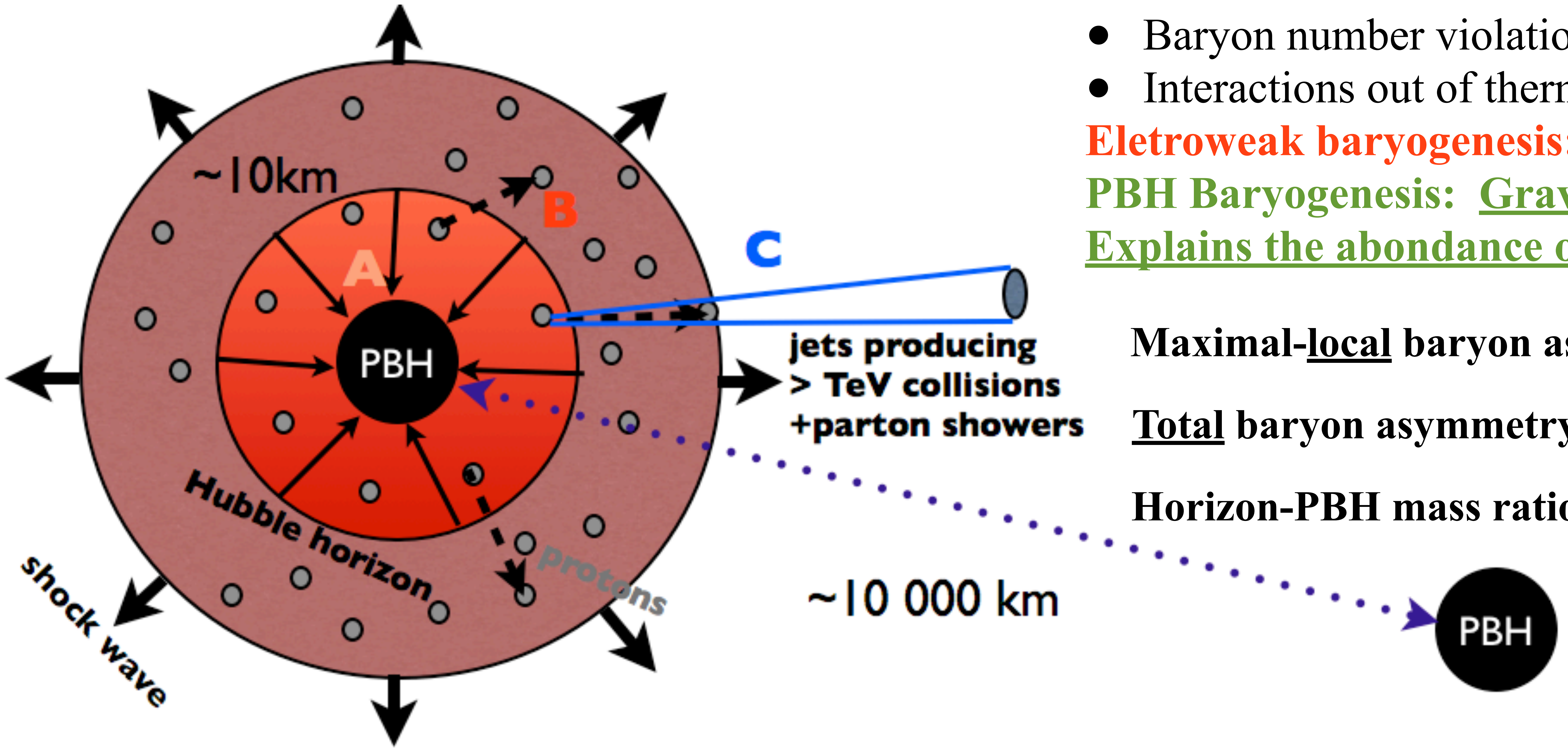
PBH baryogengesis



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: $\eta \equiv n_\mathrm{b}/n_\gamma \sim \delta_\mathrm{CP}(T) \gg 1$

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

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

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

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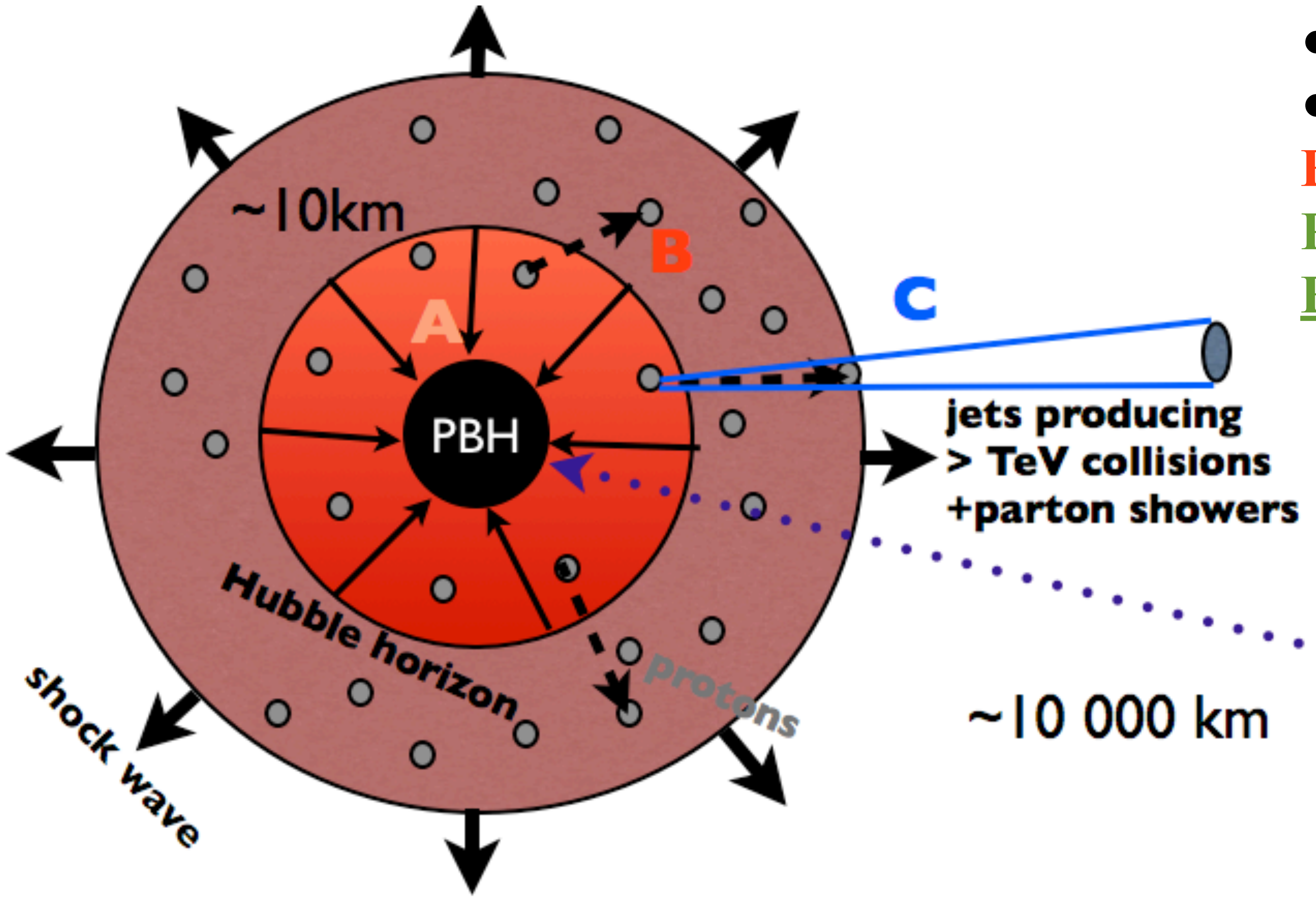

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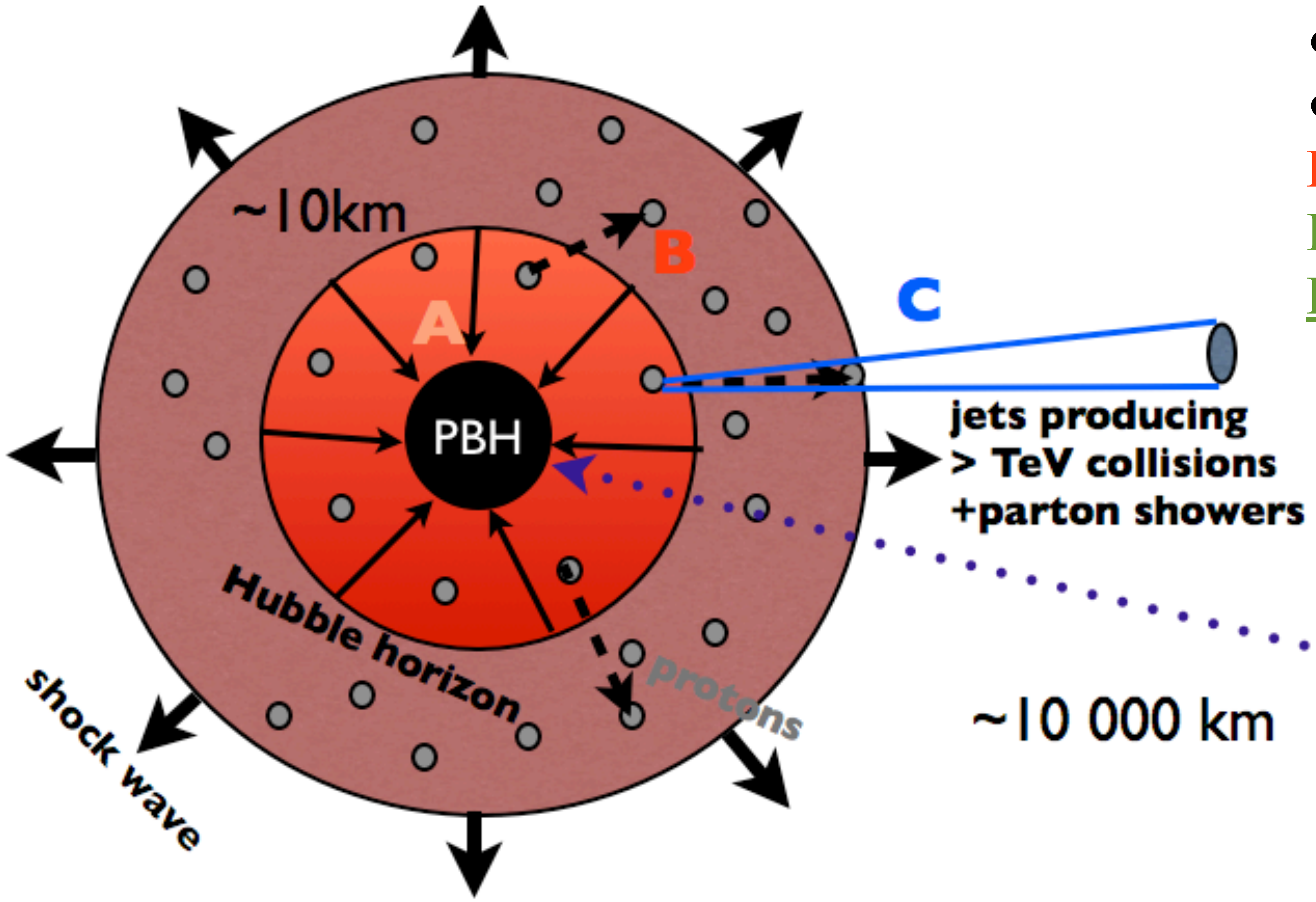

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◉ Existence of a shock wave ?
◉ Dilution before BBN ?
◉ Crude estimations

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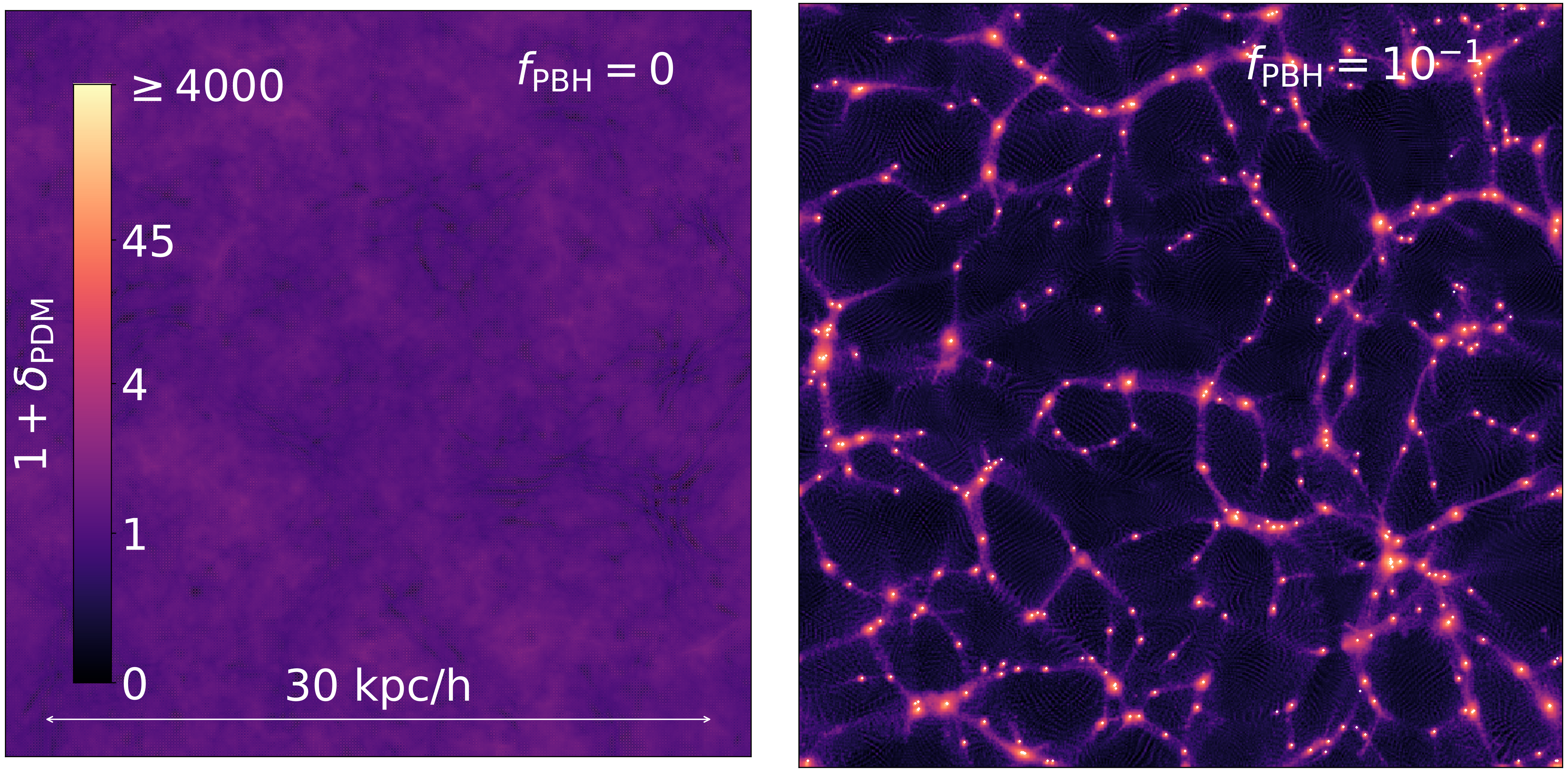
2. Can (stellar-mass) PBHs be the dark matter?

Poisson in a PBH sea…

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

f_{PBH} m_{PBH}= 3 $M_{\odot}$, snapshots at z=99



On small scales, completely different than particle-CDM !

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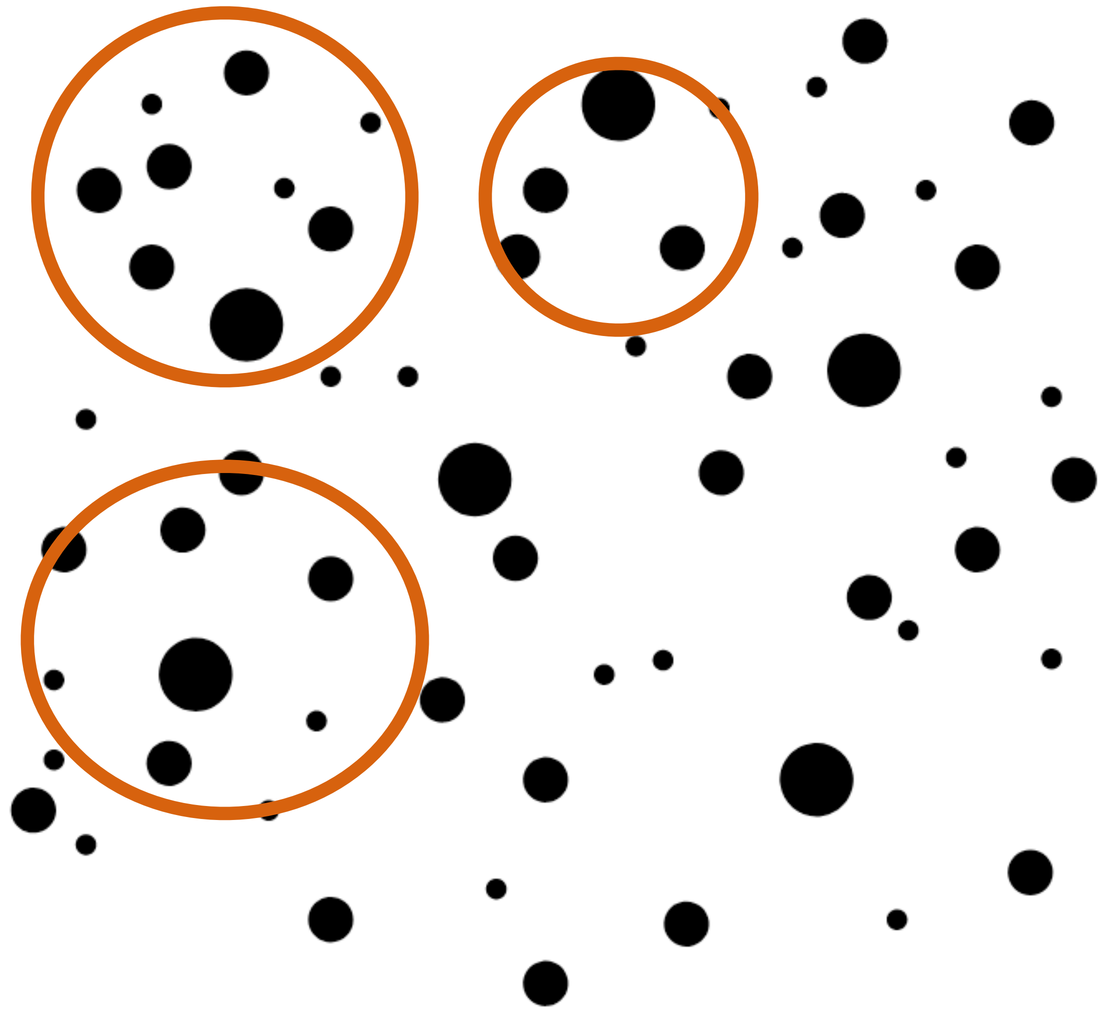
$$\delta = \frac{1}{\sqrt{N}} \times \left(\frac{1+z_{\rm eq}}{1+z}\right)$$

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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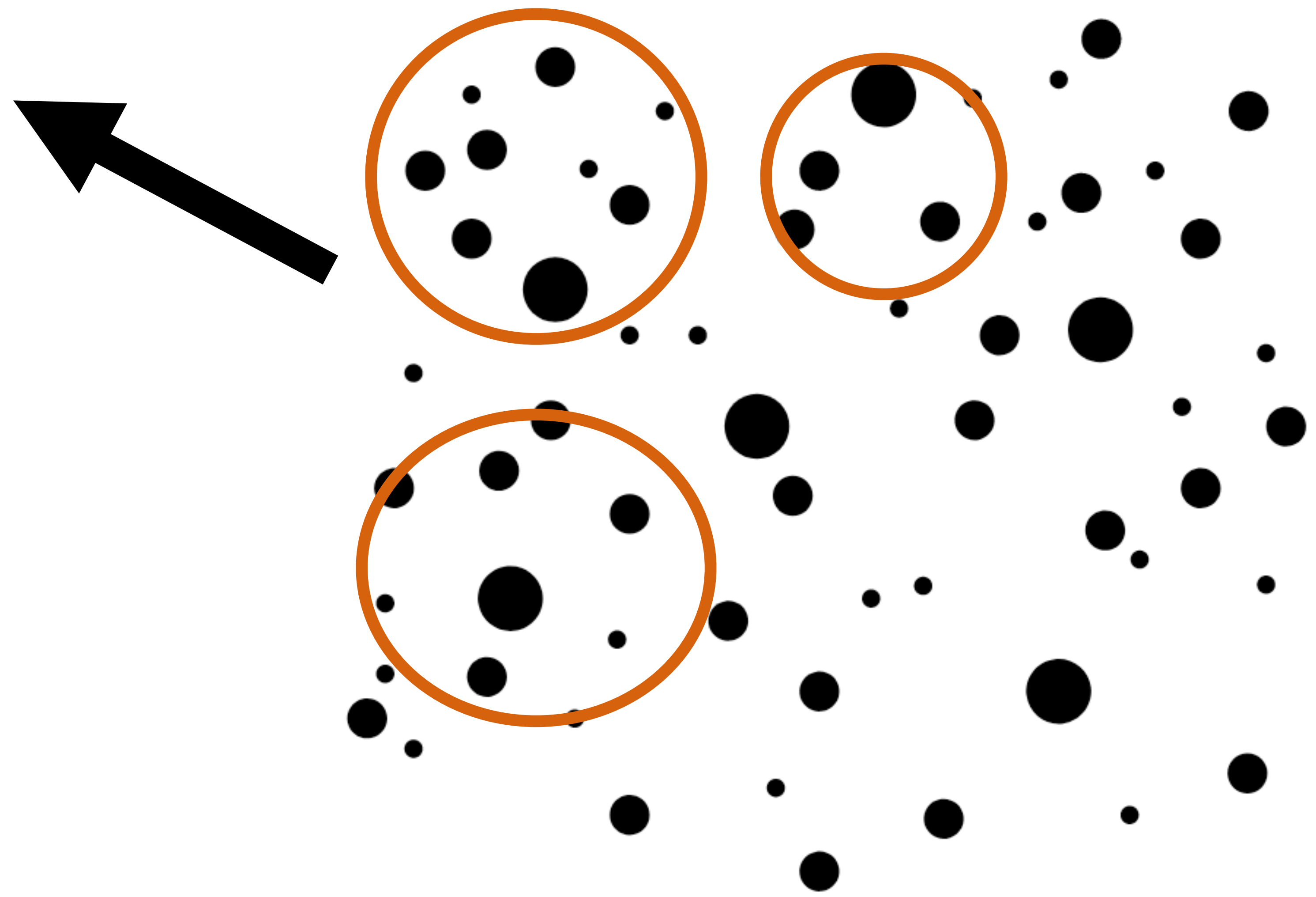

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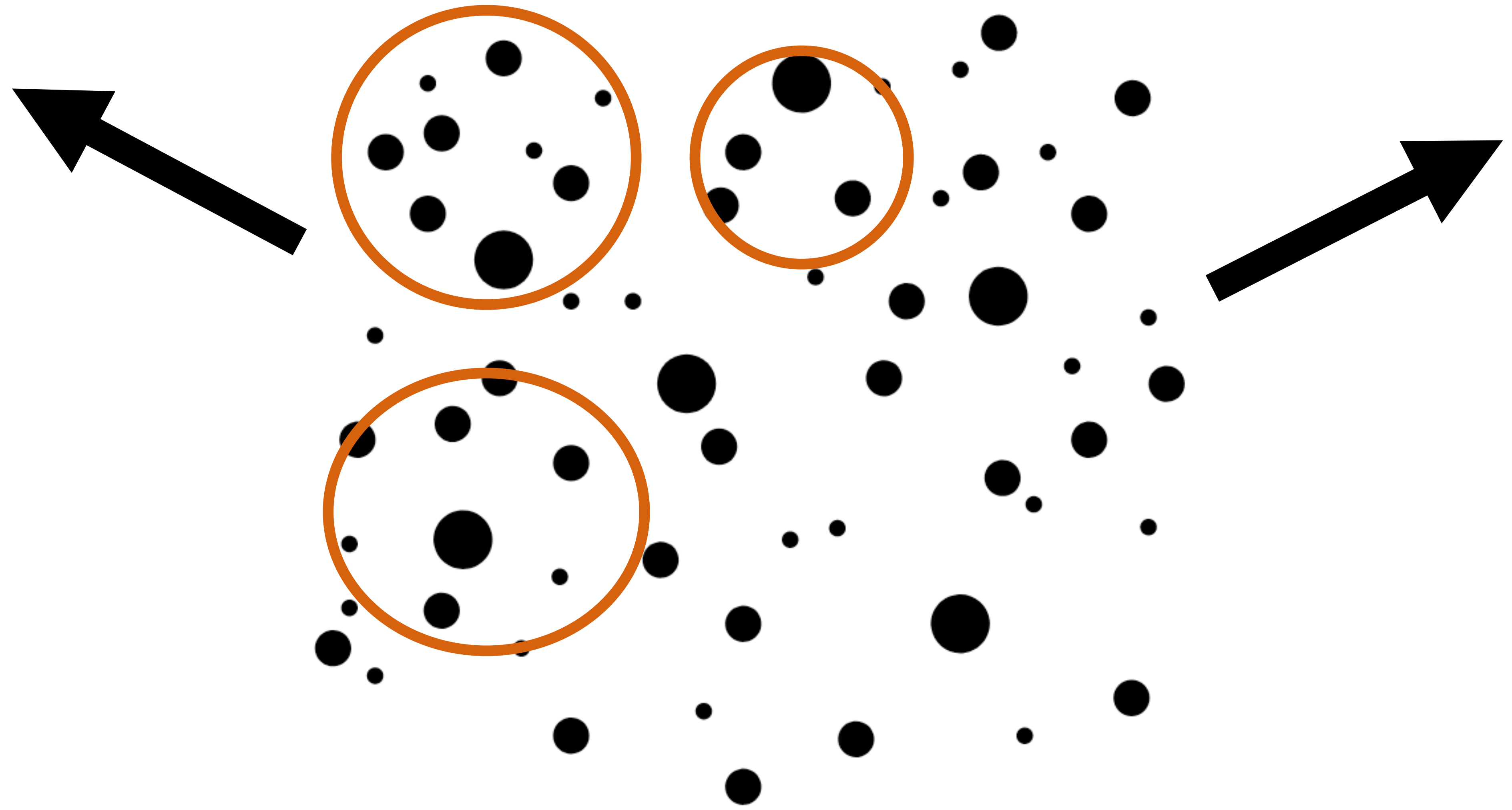

High-z clusters: spatial correlations in IR and X-ray backgrounds
[Kashlinsky 16]

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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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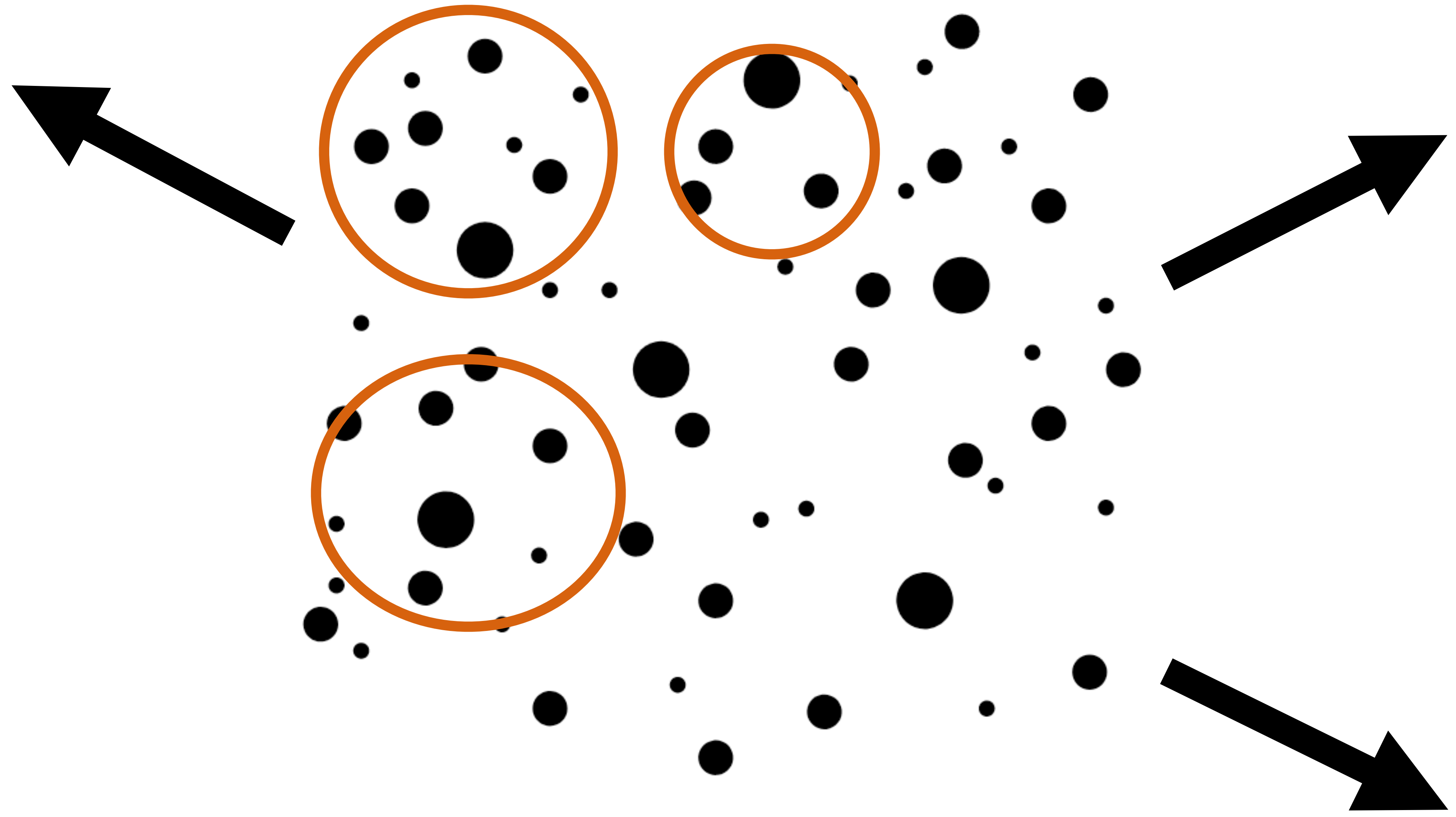

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Ultra-faint dwarf galaxies
min radius ~20 pc and
large mass-to-light ratios
(dynamical heating + accretion)
[S.C.+17, S.C.+20]

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

subhalos diluted in larger halos

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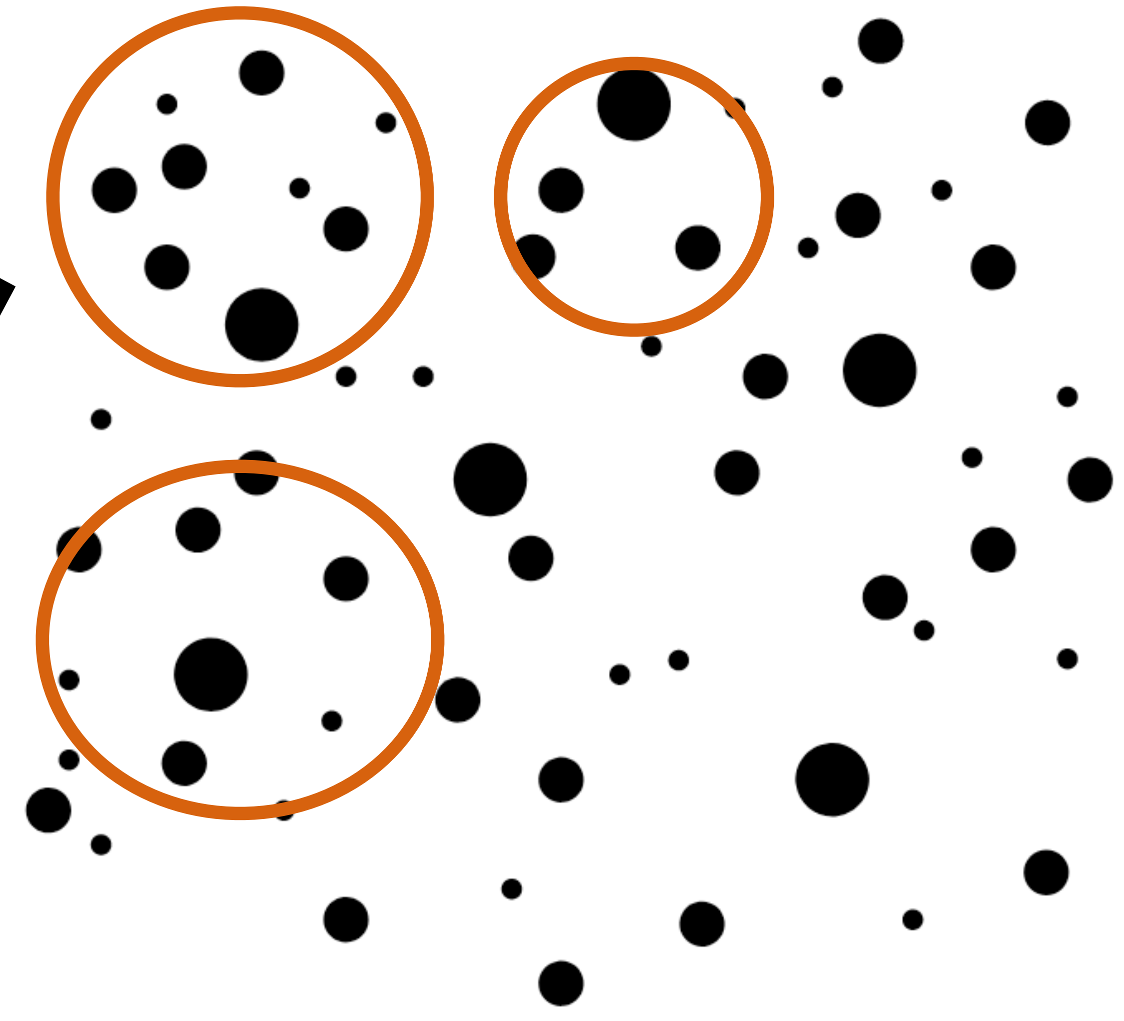

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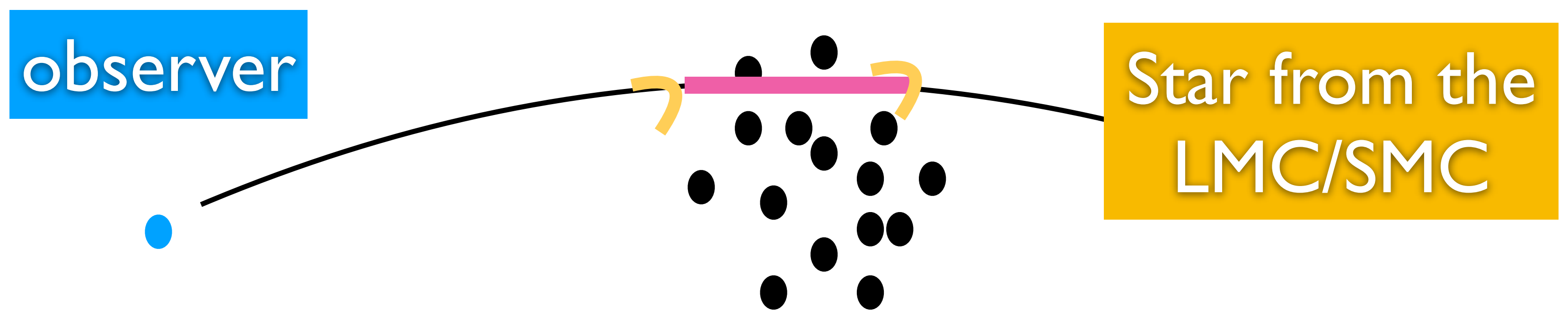
Evade micro-lensing limits [Carr+19]

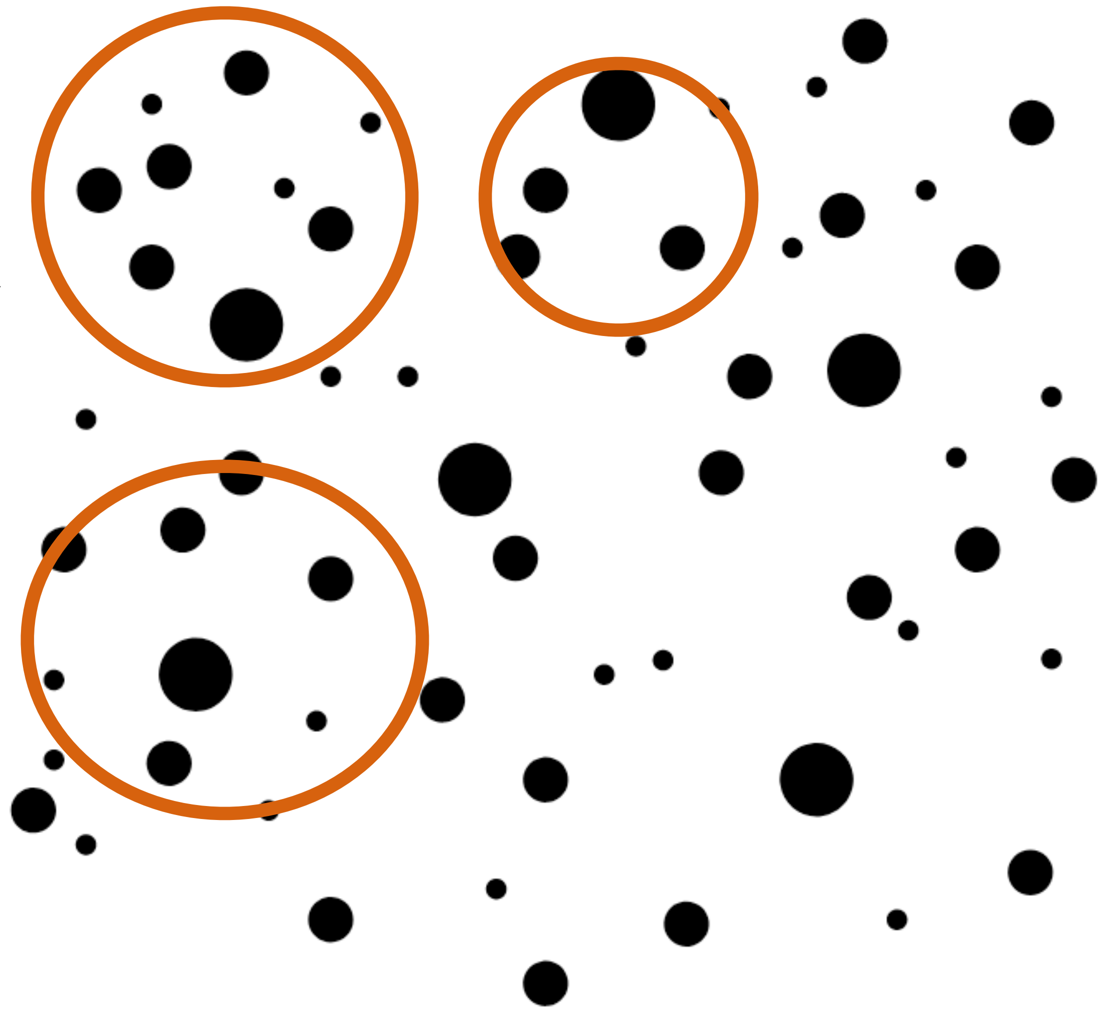
- lensing + microlensing
- cluster microlensing
- probability of finding a cluster



'Heated' PBH cluster

Black hole sling-shot away from its host cluster ~10-30% of DM

Ali-Haimoud 1805.05912



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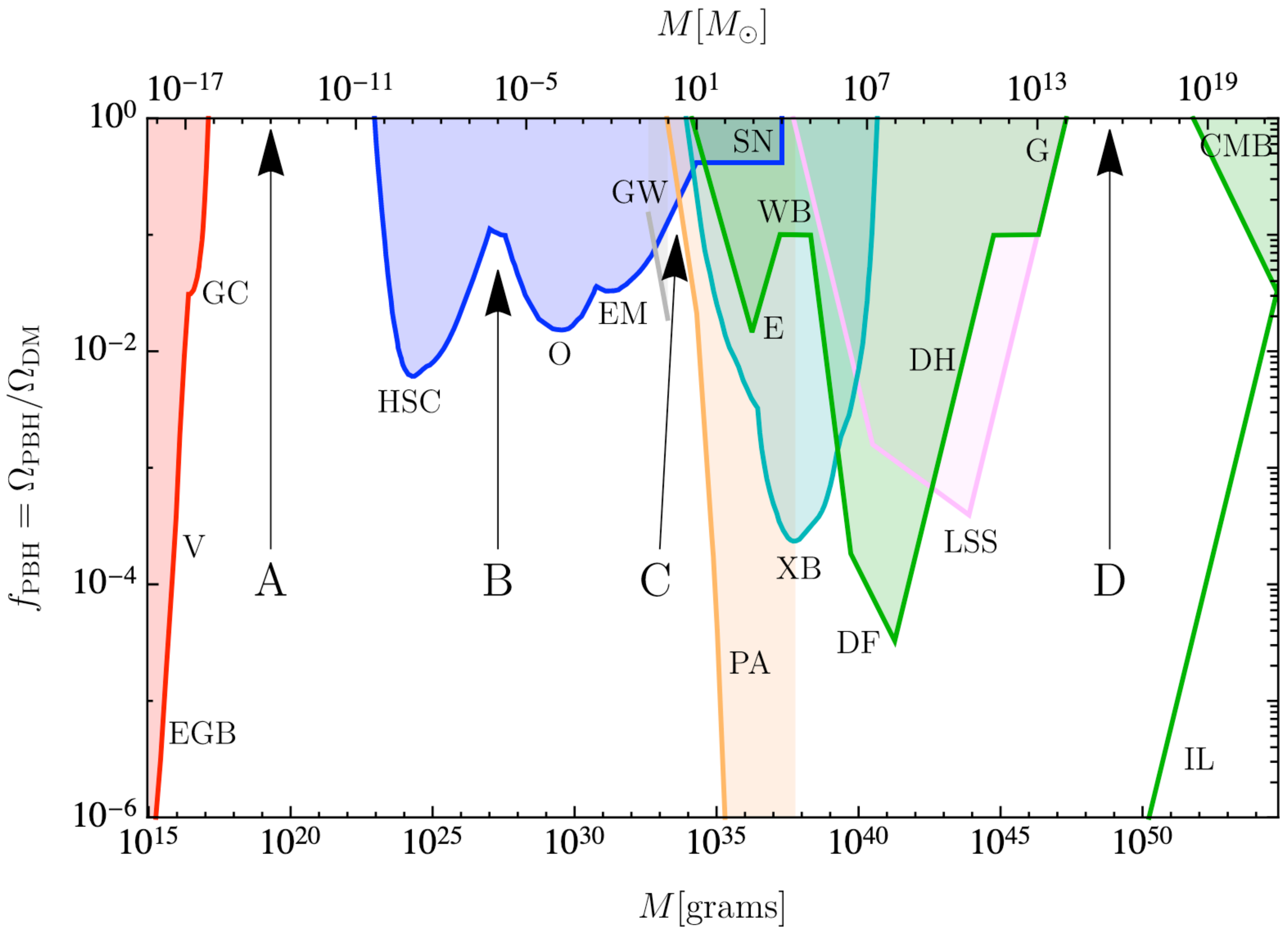

Carr & Kuhnel, 2006.02838

Hawking radiation

Microlensing

LIGO-Virgo

CMB

Dynamical effects

Accretion

Large scale structures

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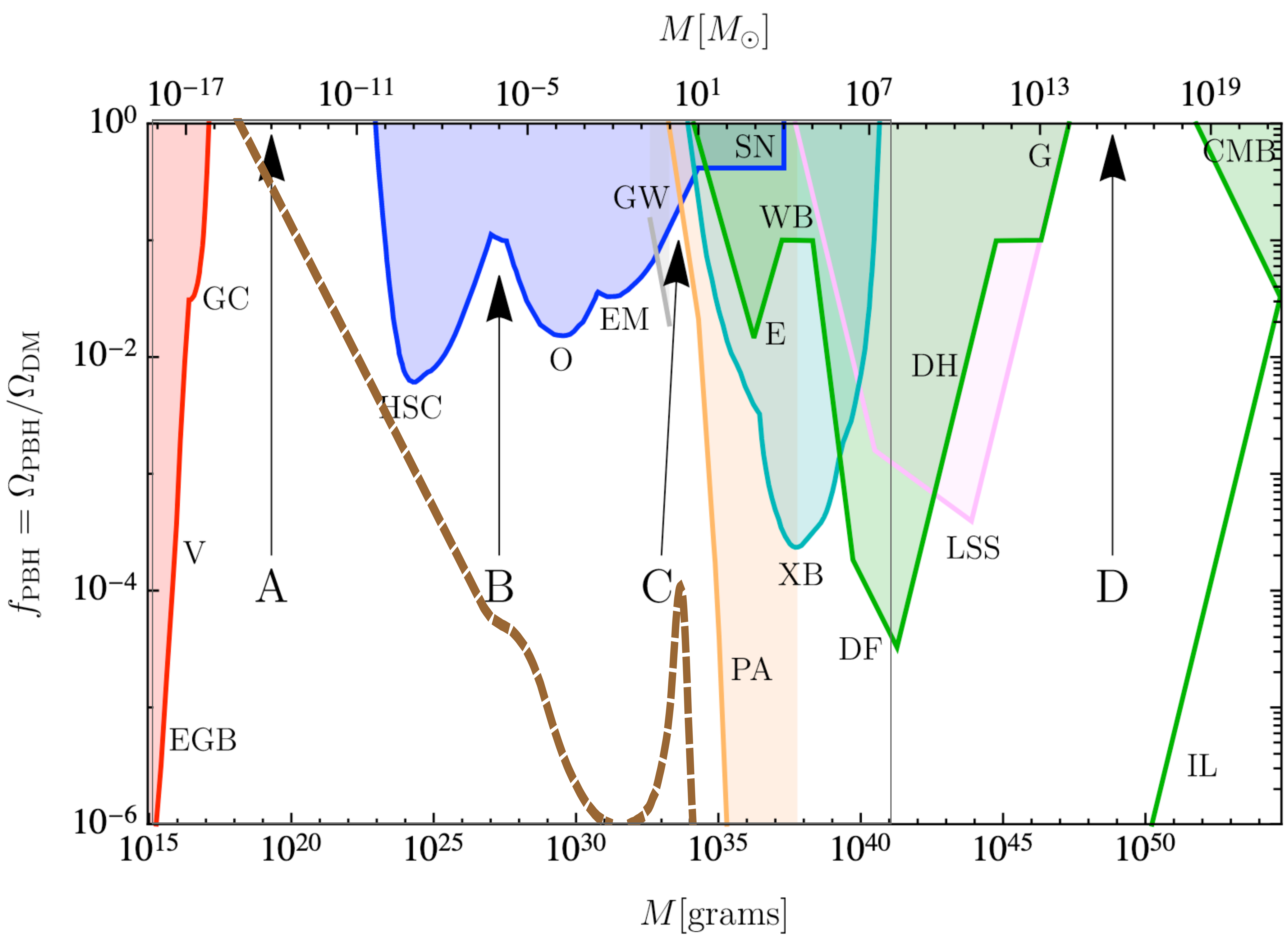

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✓ Solar mass region excluded by several probes
✓ No limit on asteroid-masses
✓ If PBHs + WIMPs (or particle DM) => stronger limits
(e.g. [Serpico+20] [Carr+20] [Byrnes+] [Boudaud+21])

De Luca, Franciolini, Riotto et al., 2009.08268

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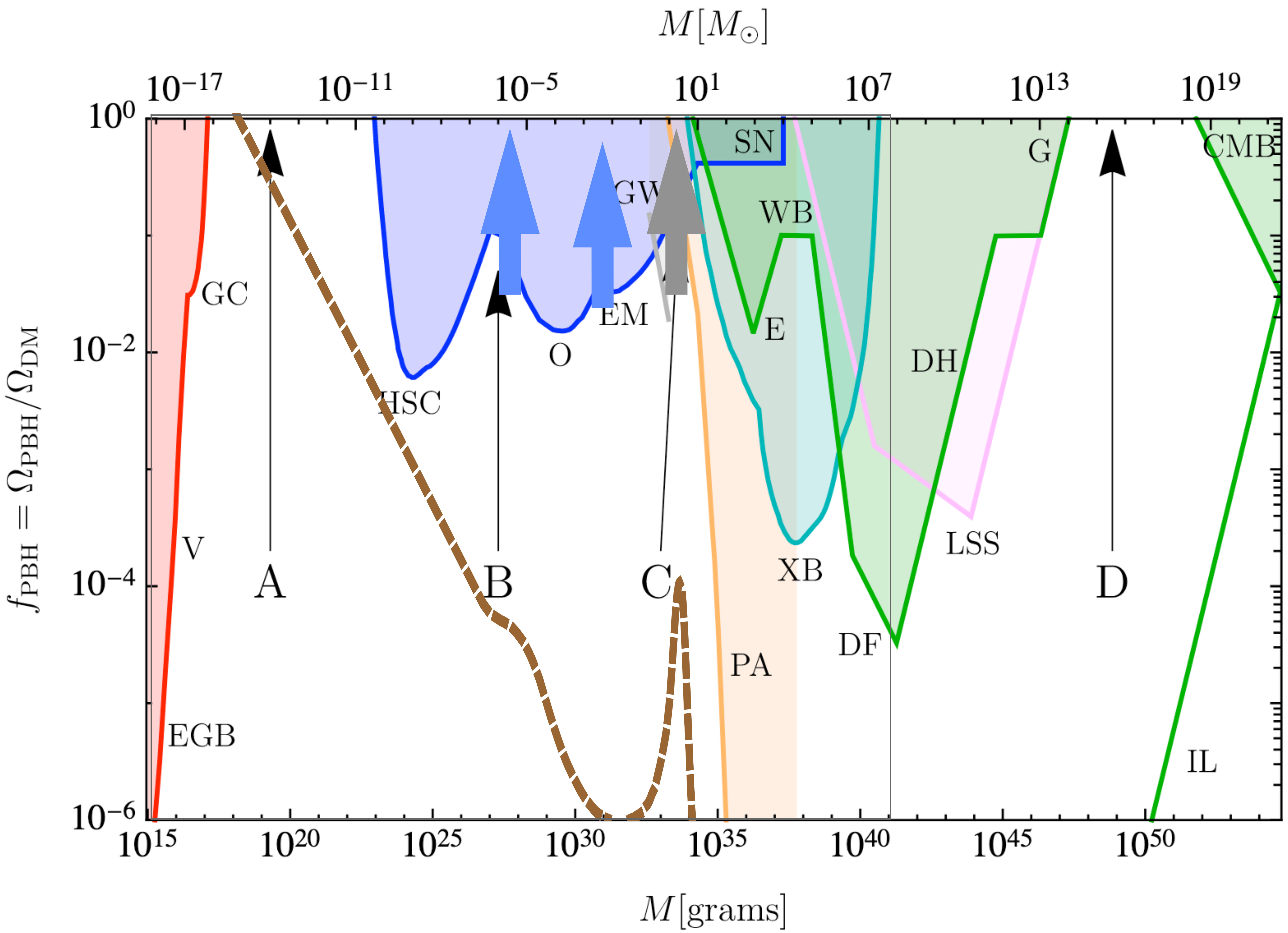

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◉ Asteroid-mass PBH dark matter => new fine-tuning
◉ Lot of uncertainties (e.g. clustering)
◉ LIGO/Virgo limits less stringent
◉ Microlensing limits evaded?
◉ Backreactions for wide mass distributions

De Luca, Franciolini, Riotto et al., 2009.08268

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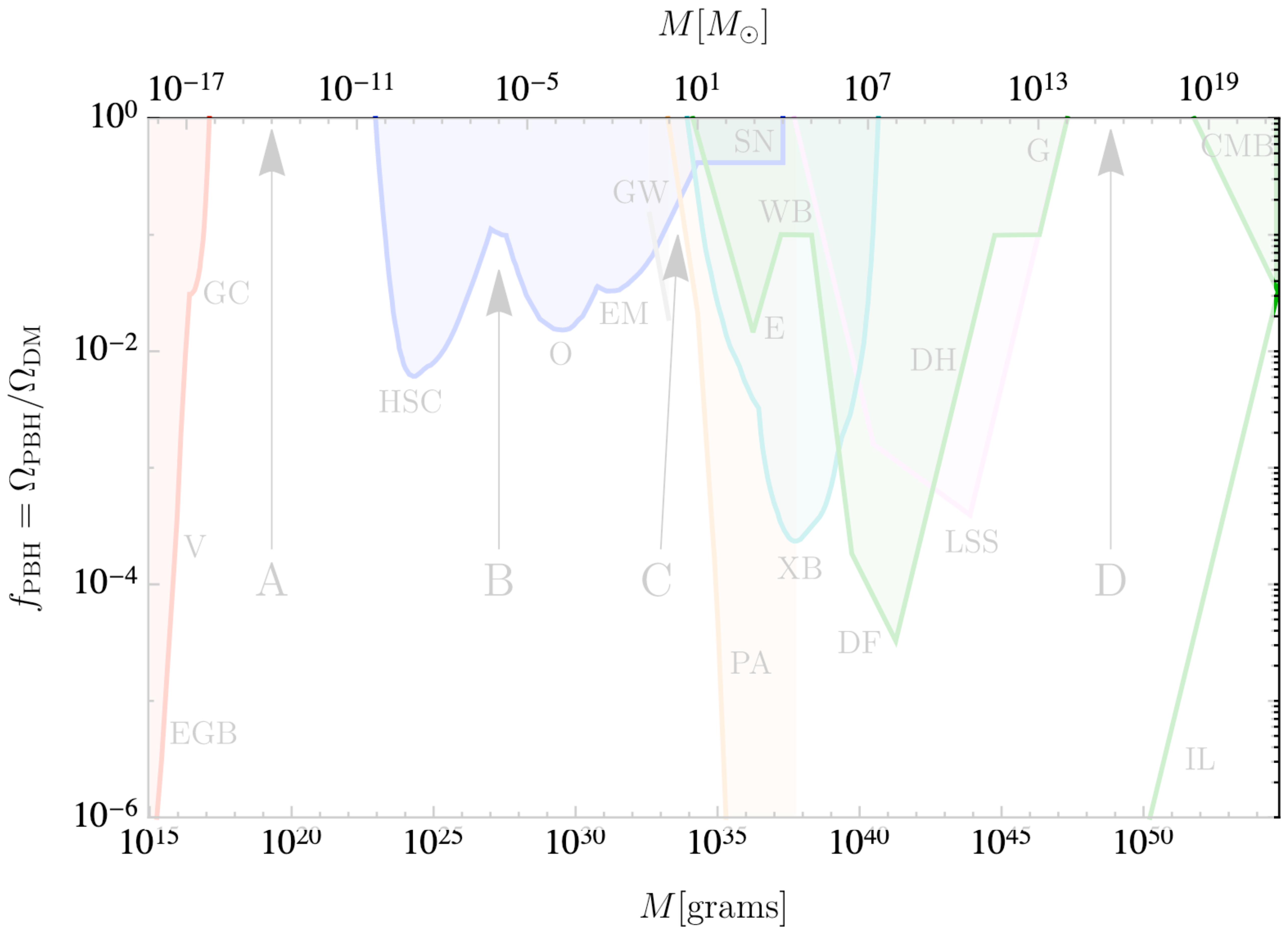

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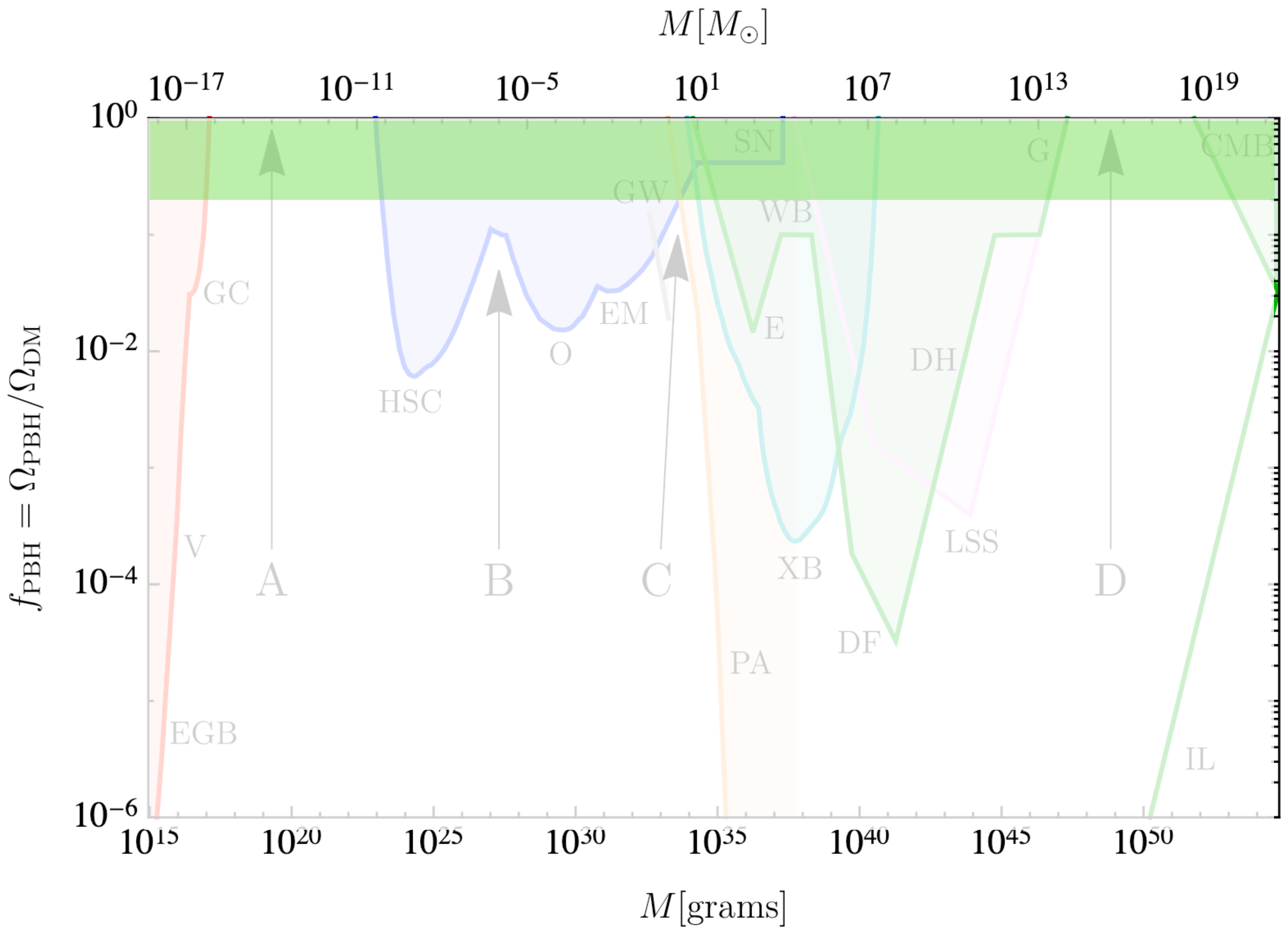

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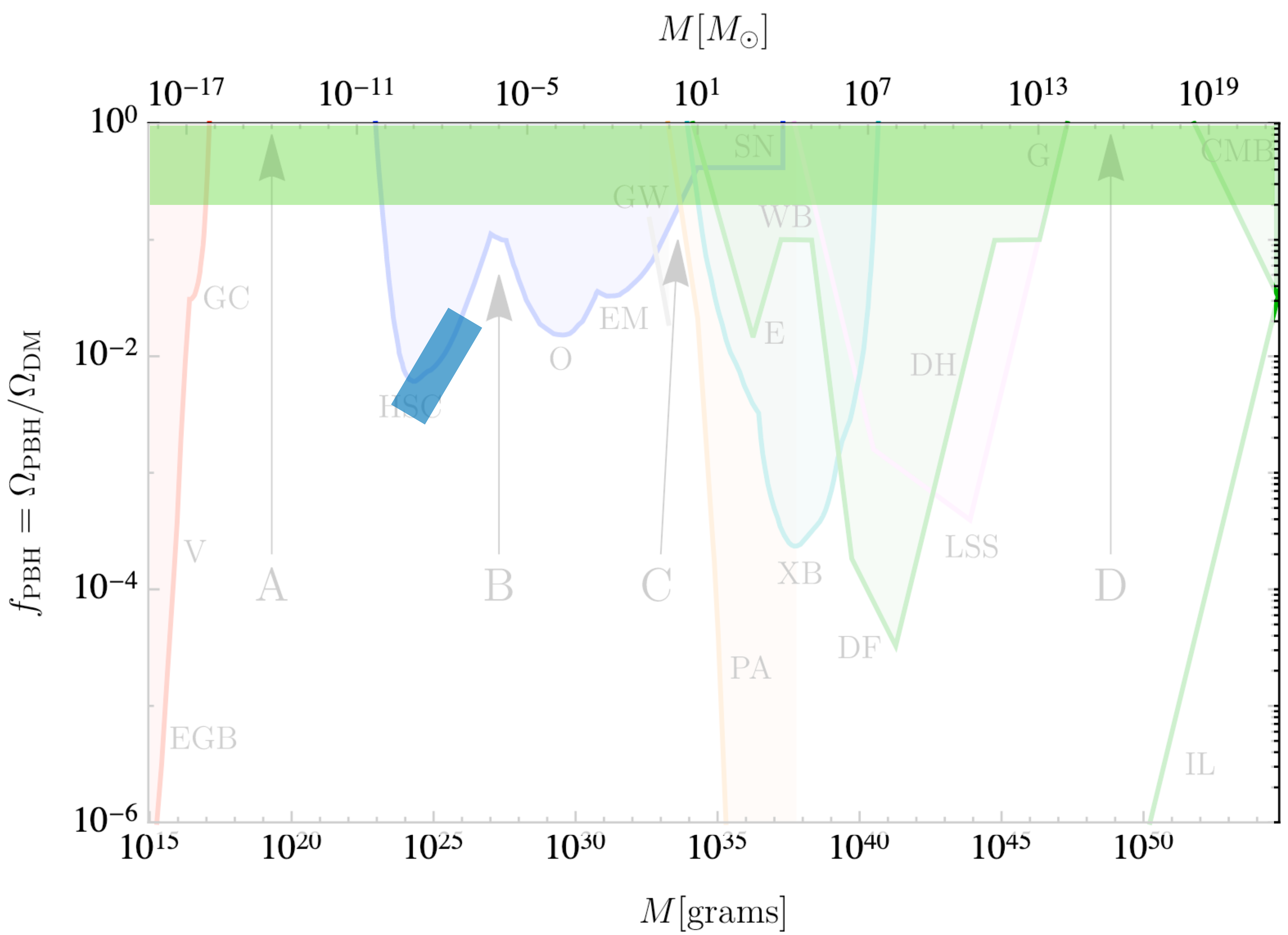

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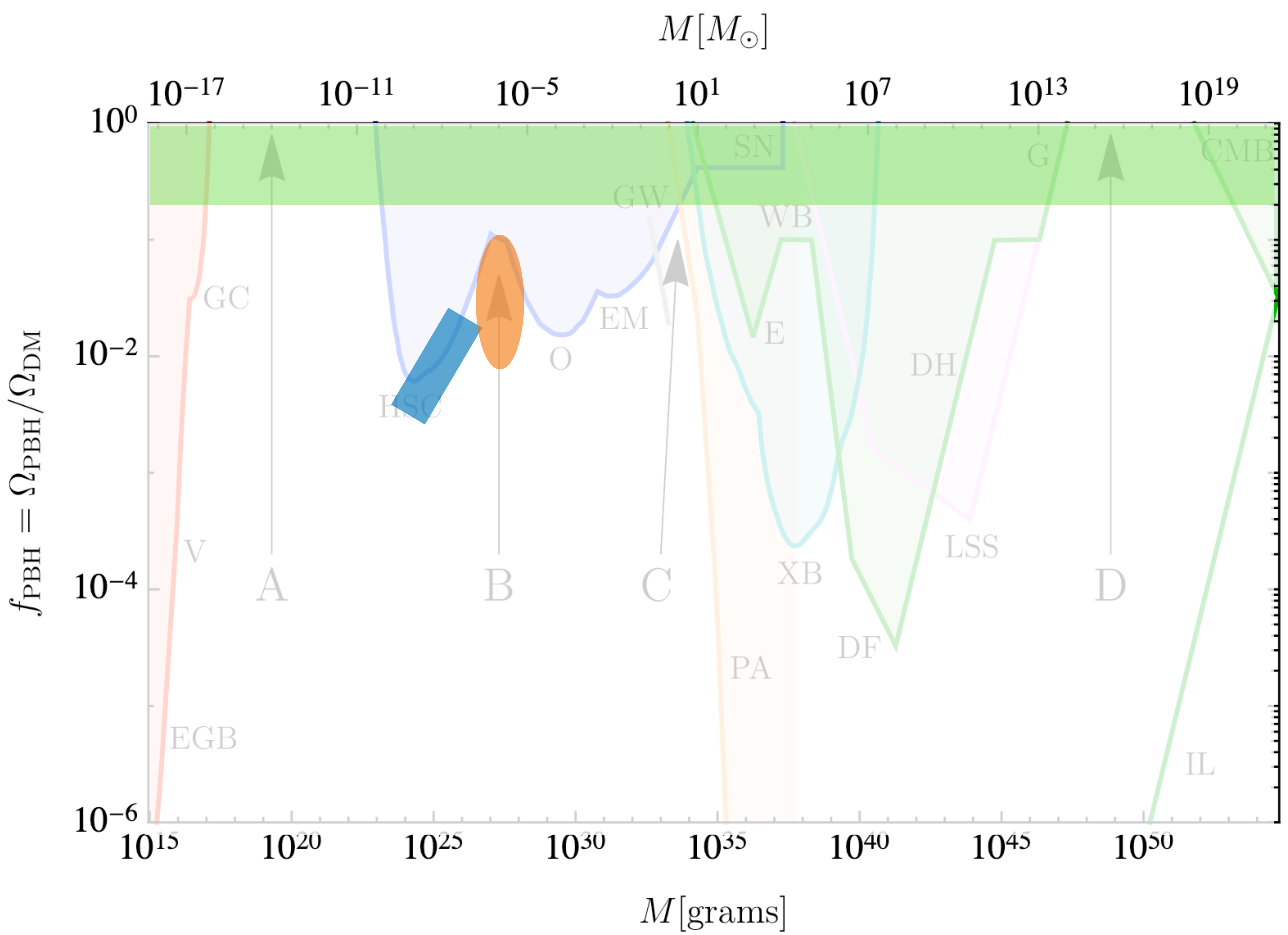

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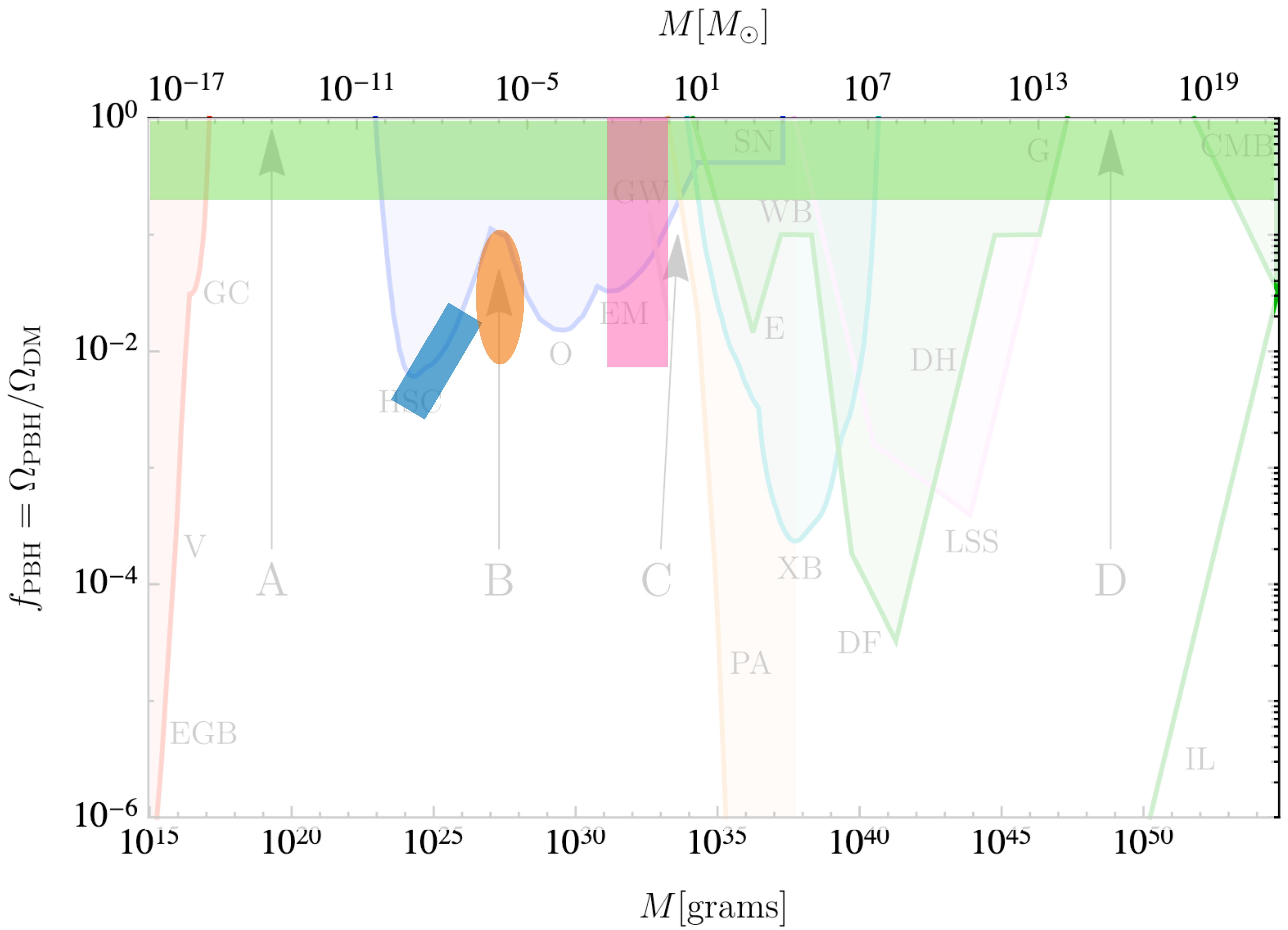

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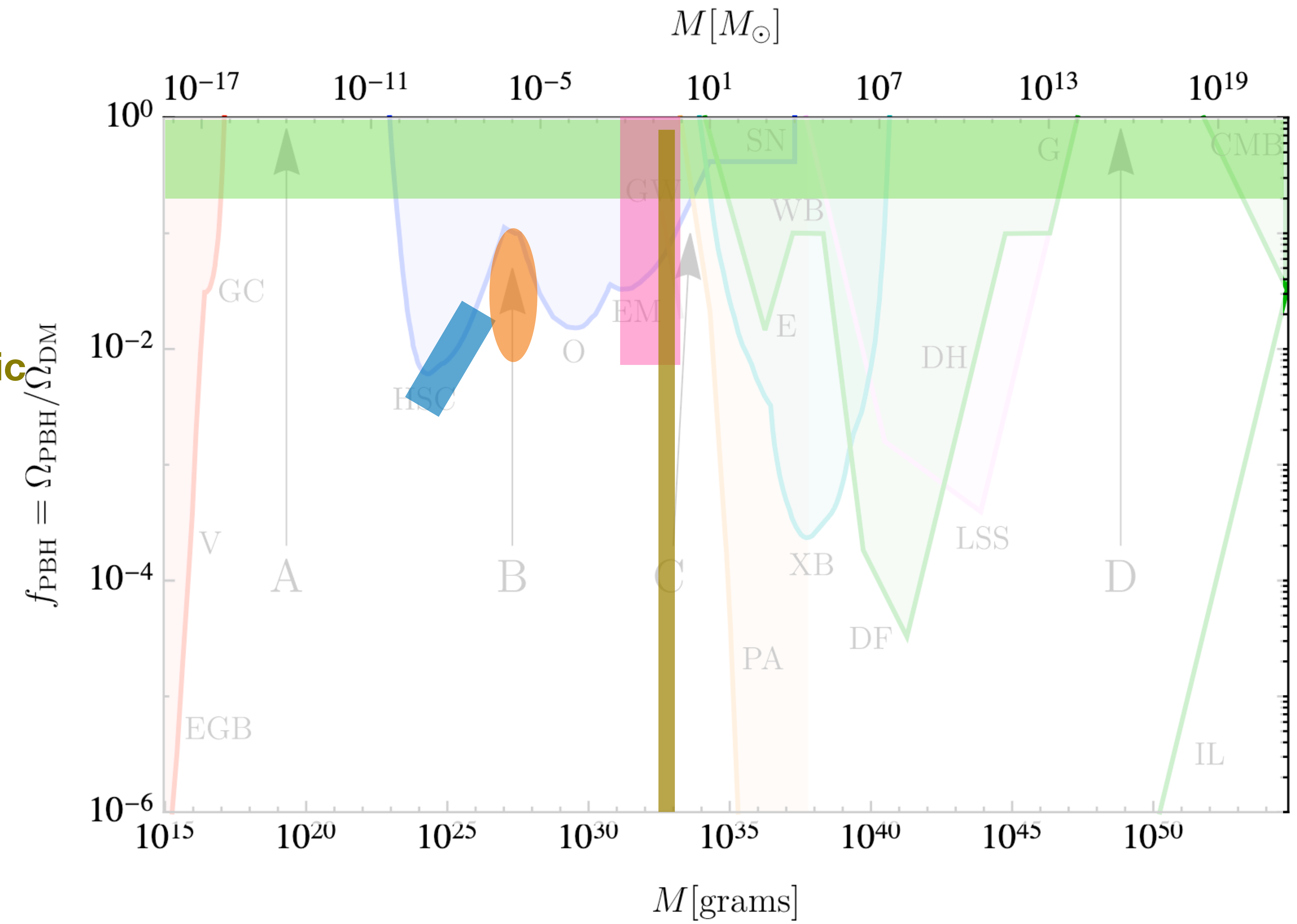

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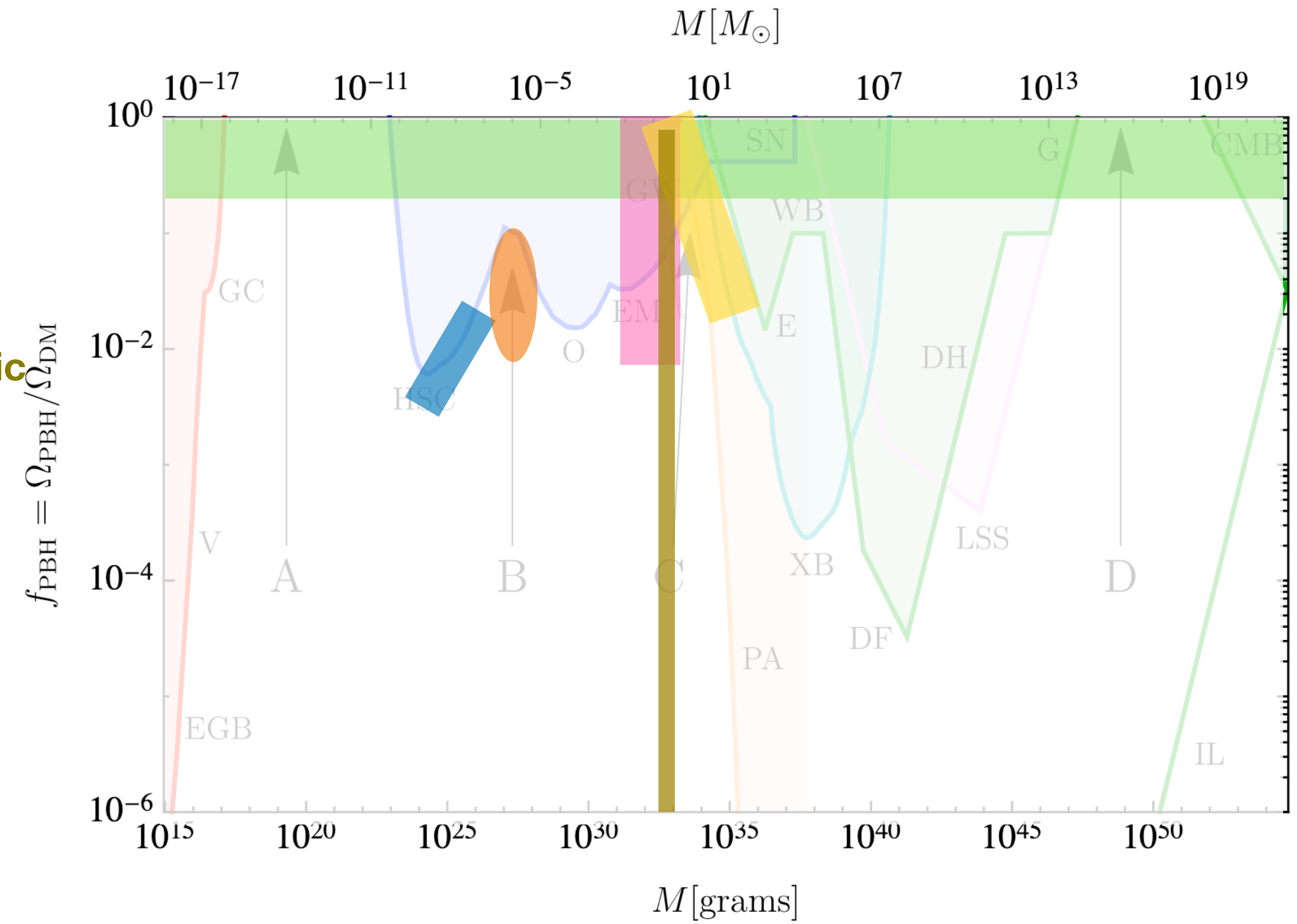

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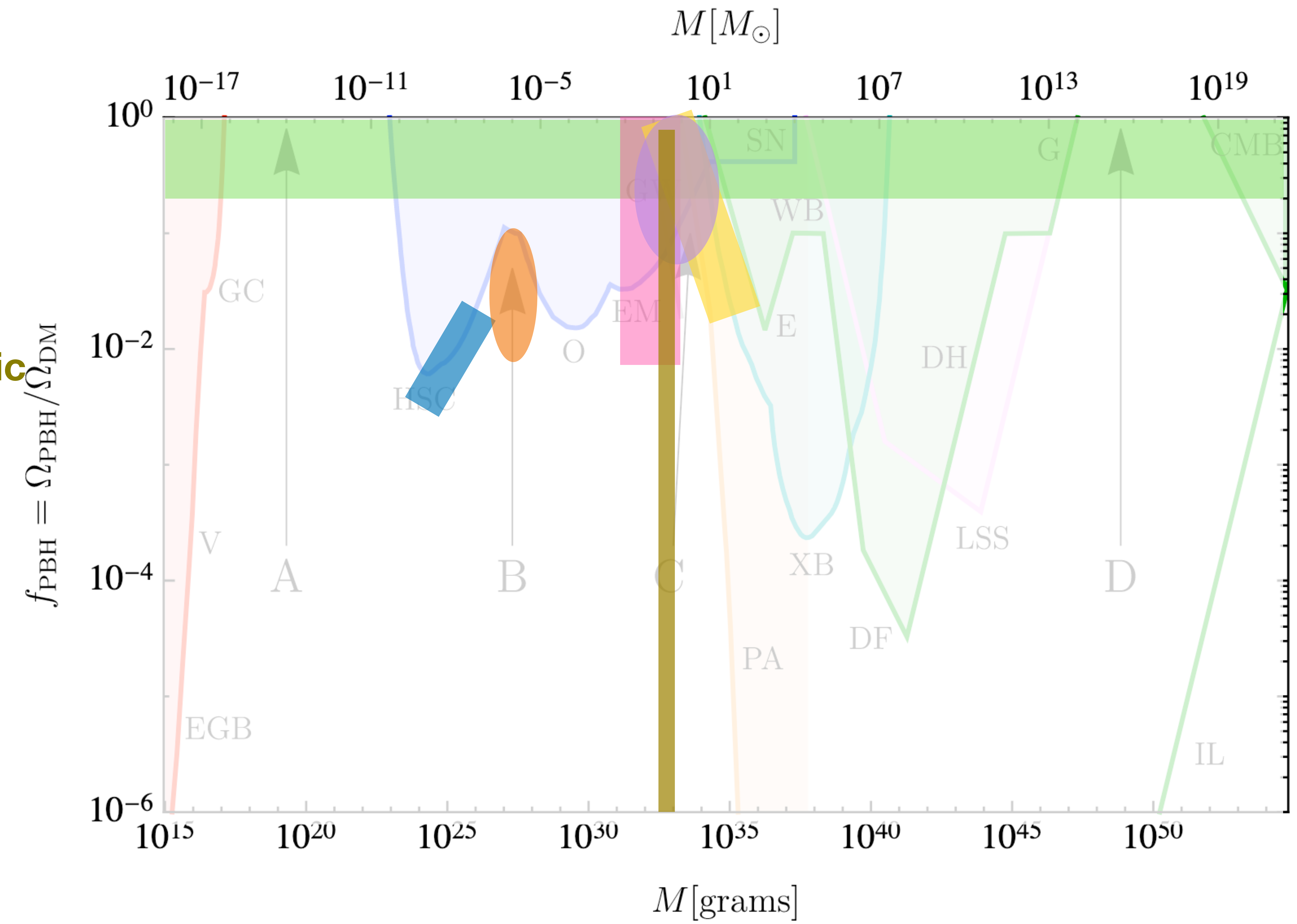

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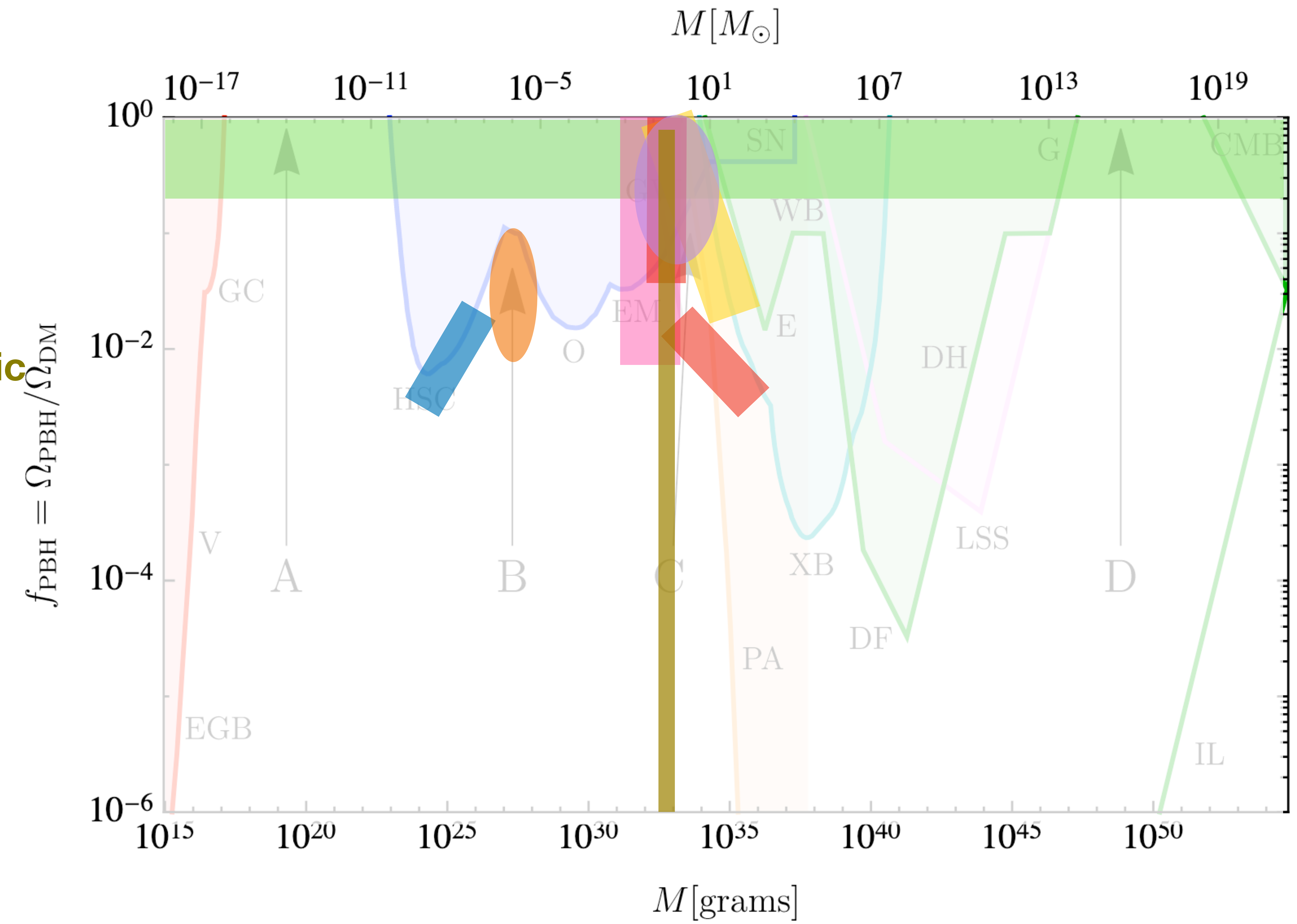

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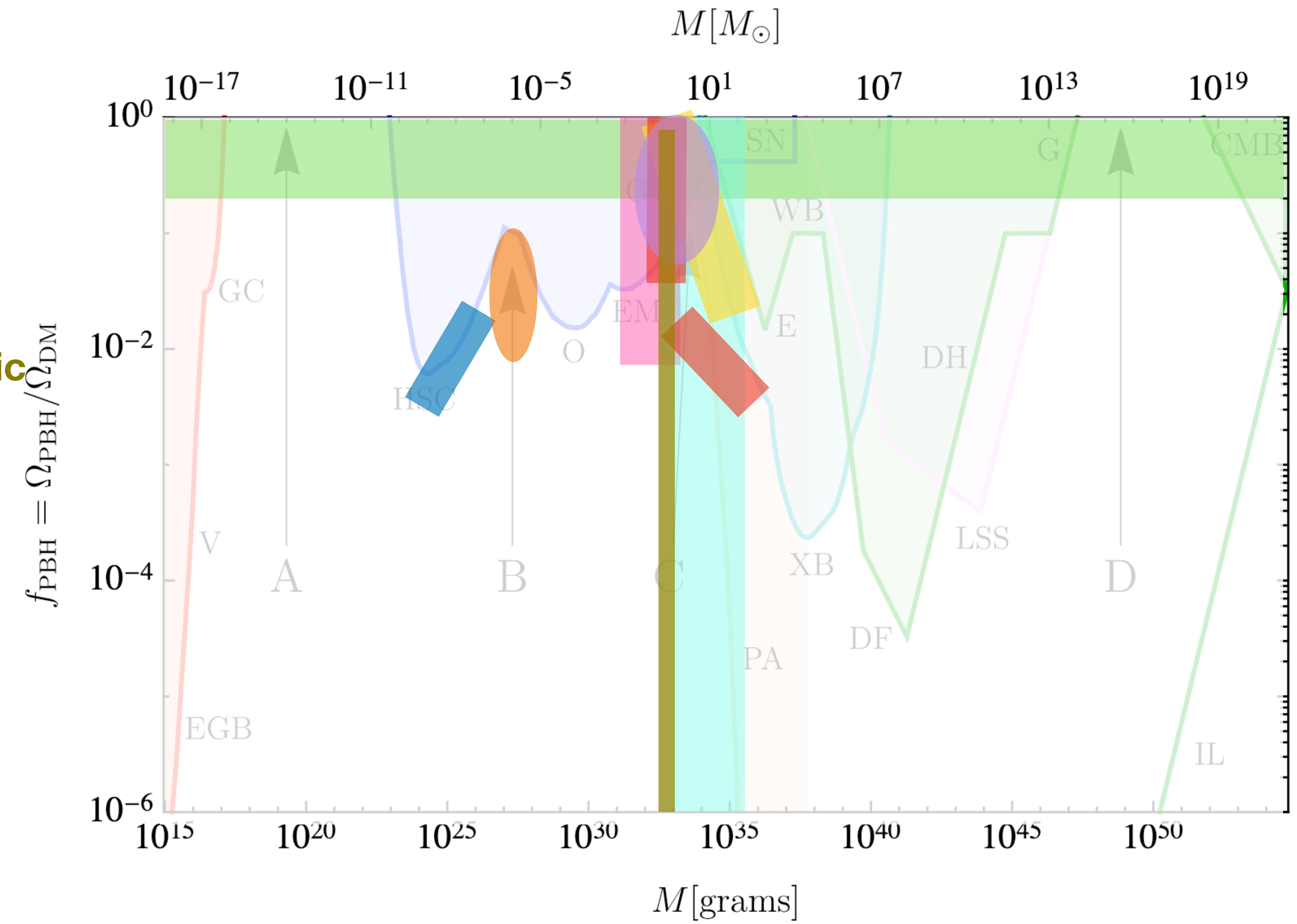

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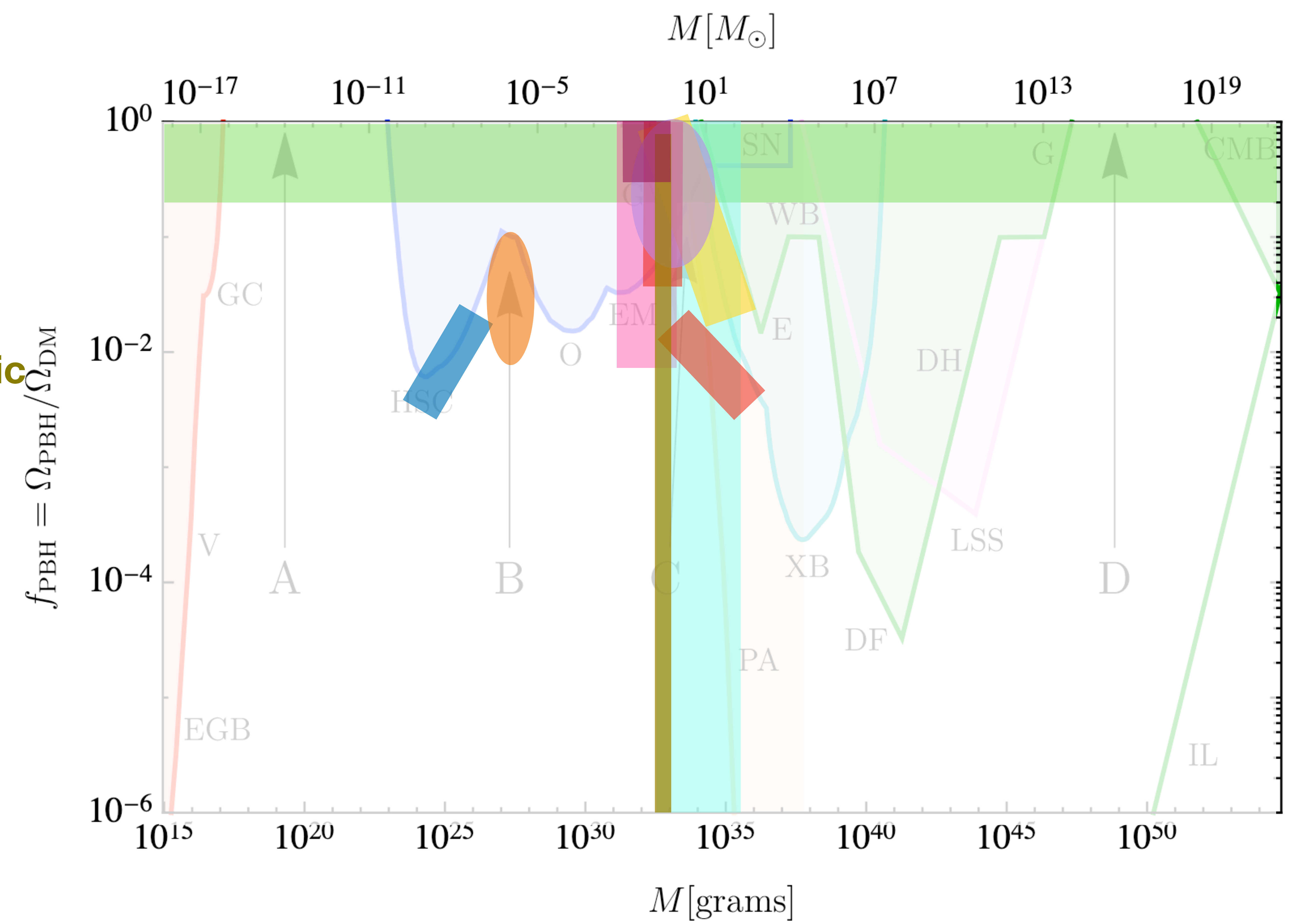

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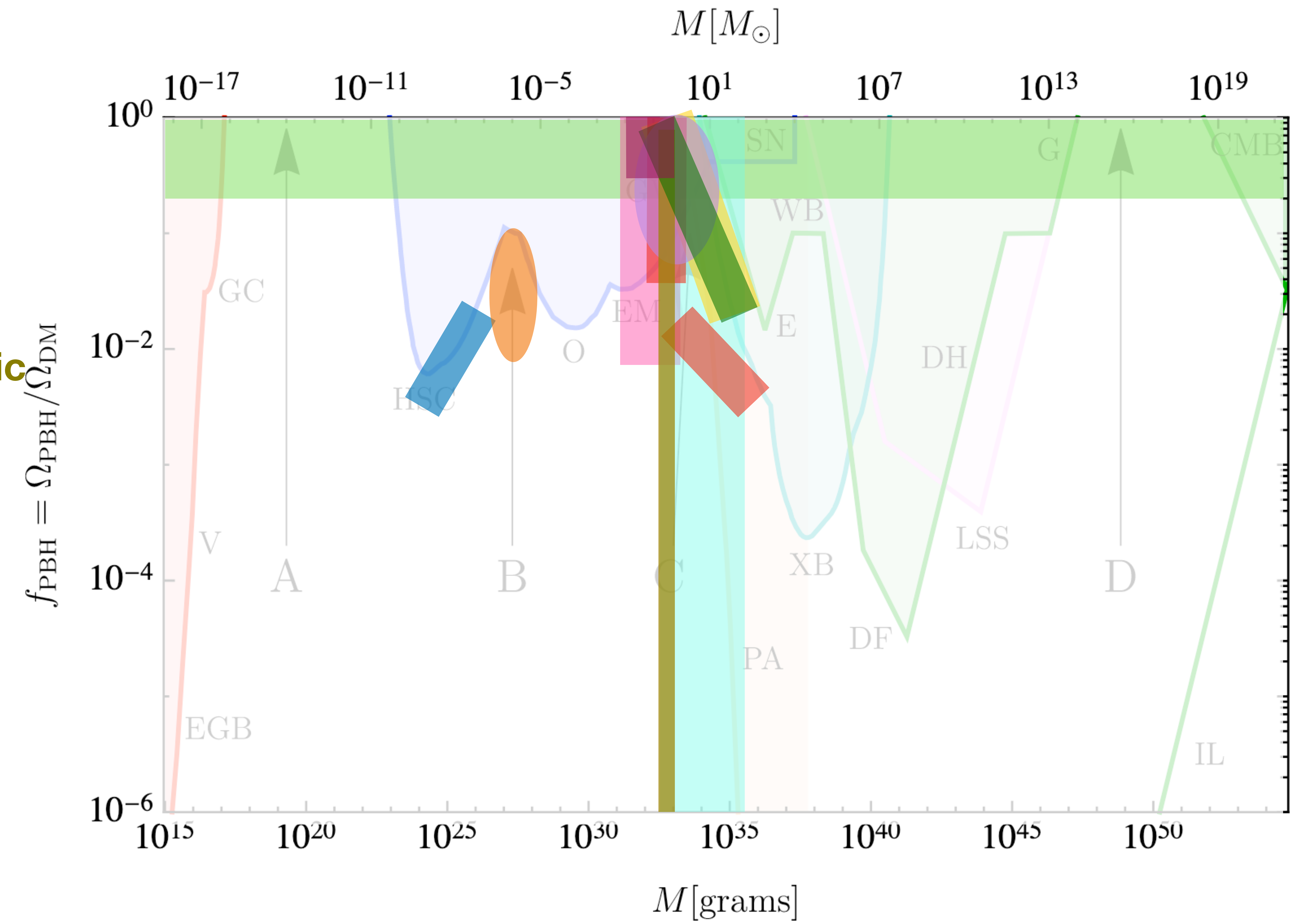

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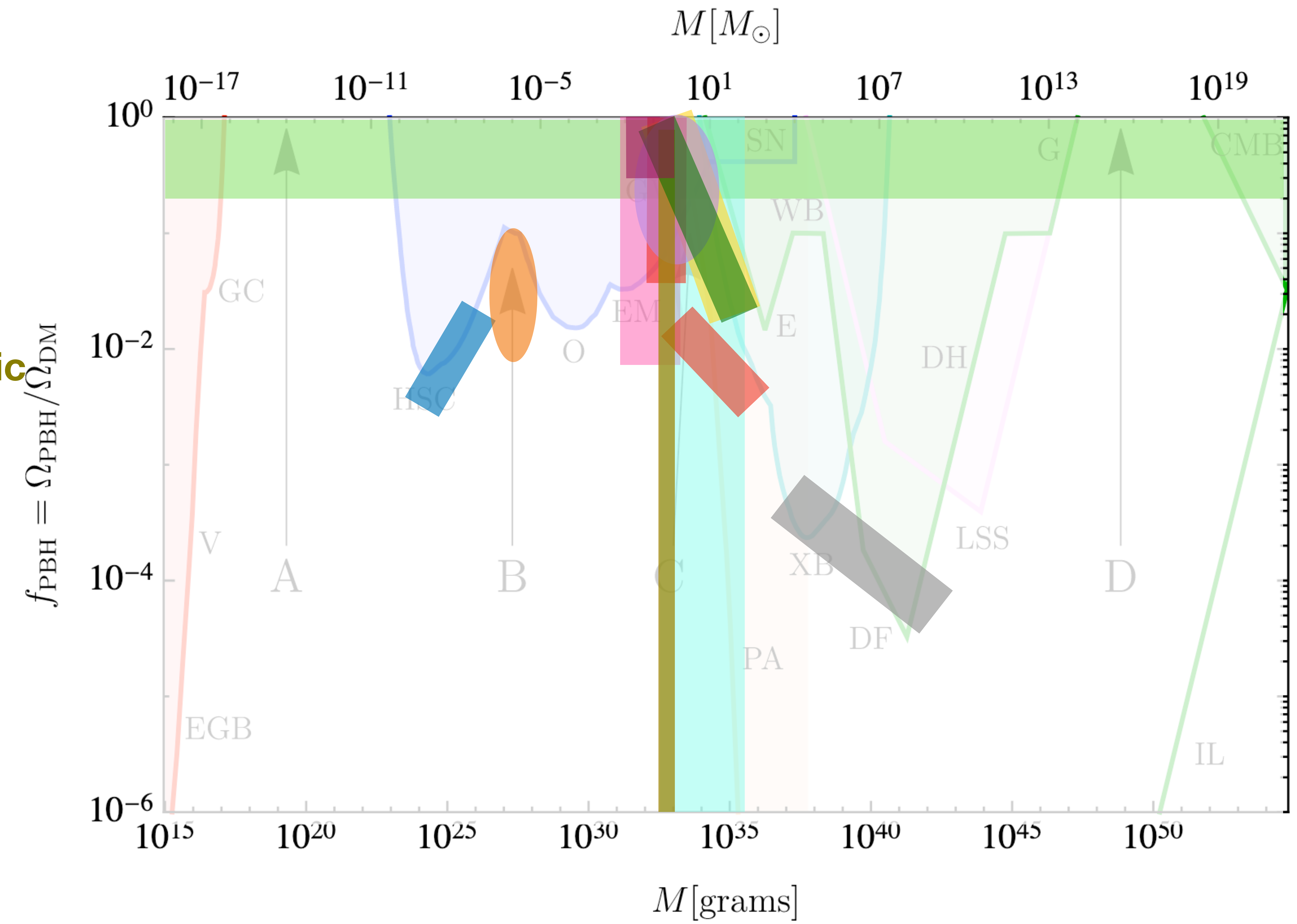

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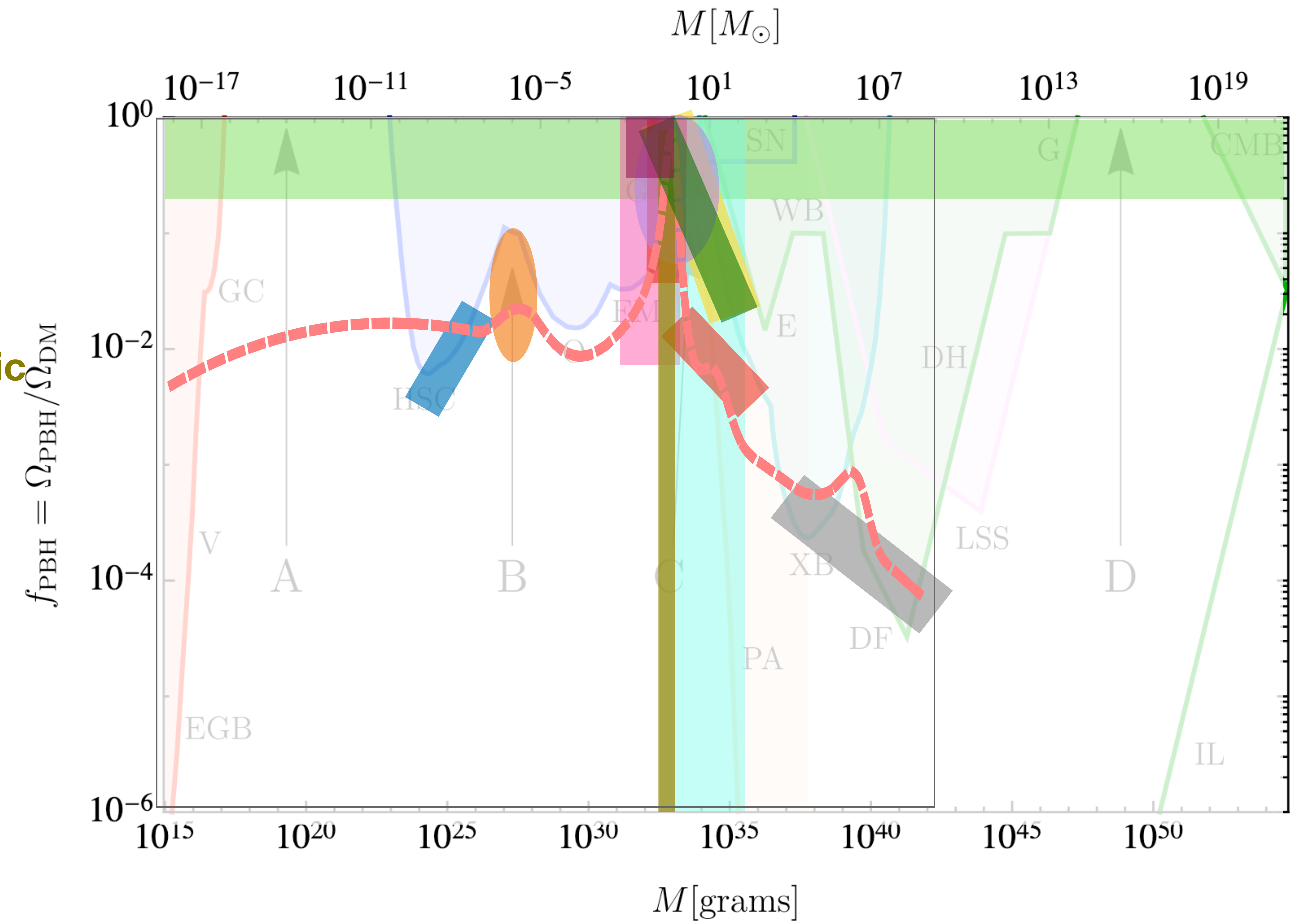

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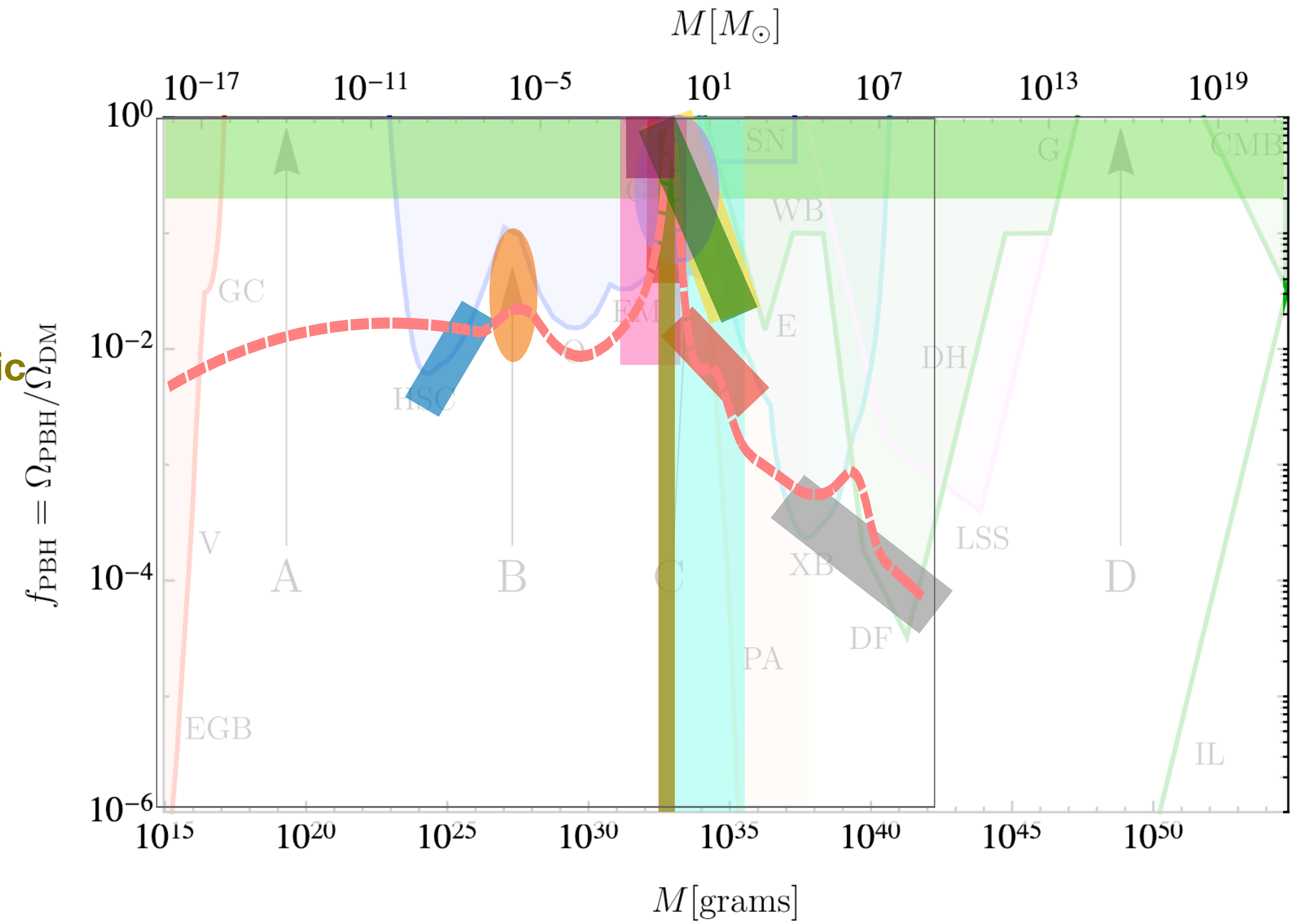

◎ Tension with Segues 1 limit ?
◎ Problem with CMB limits ?

Outline

- 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 ?**

3. Are LIGO/Virgo black holes primordial ?

Merging rates

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Merging rates

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 ?

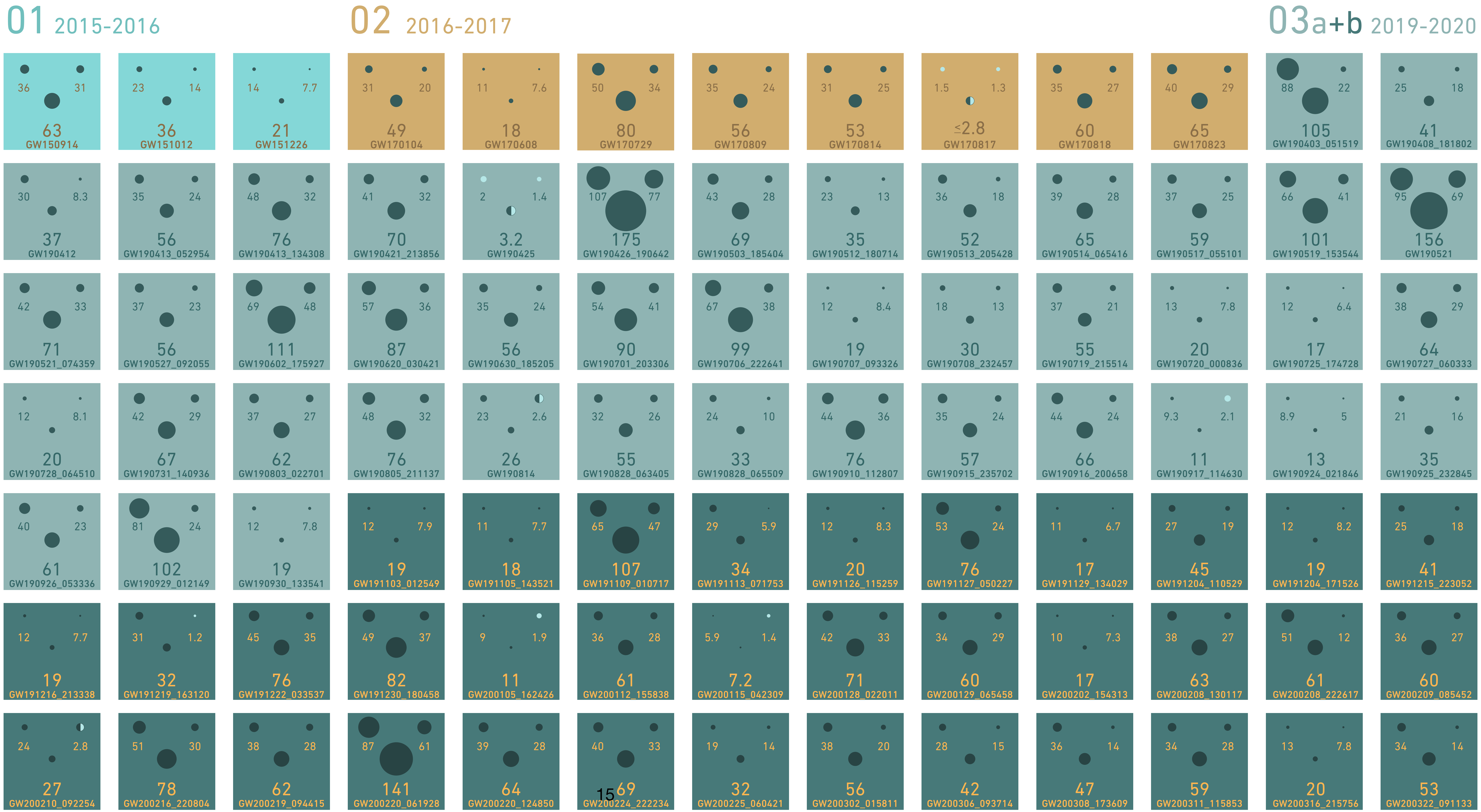
Merging rates

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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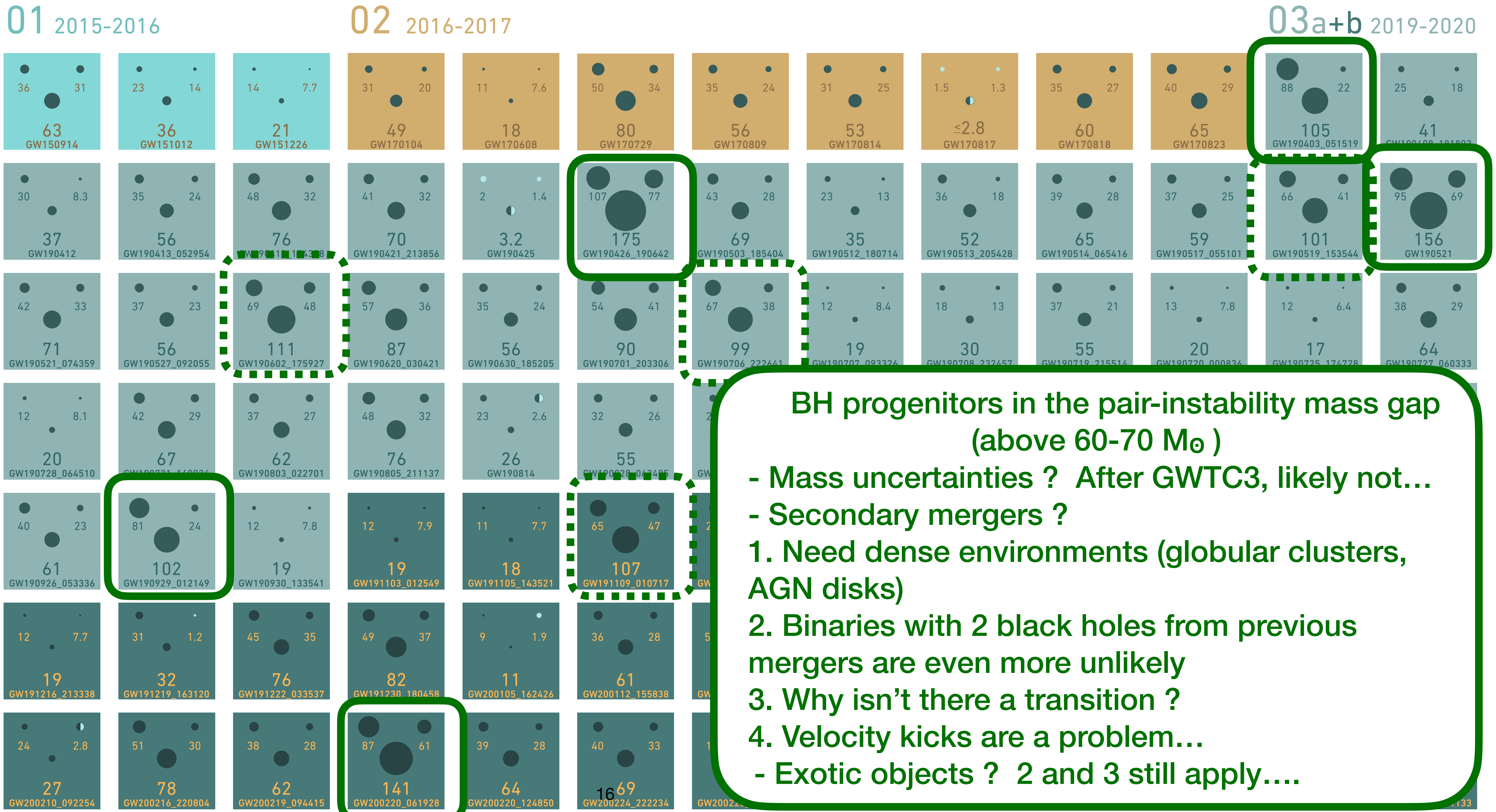


BH progenitors in the pair-instability mass gap (above 60-70 $M_\odot$)

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

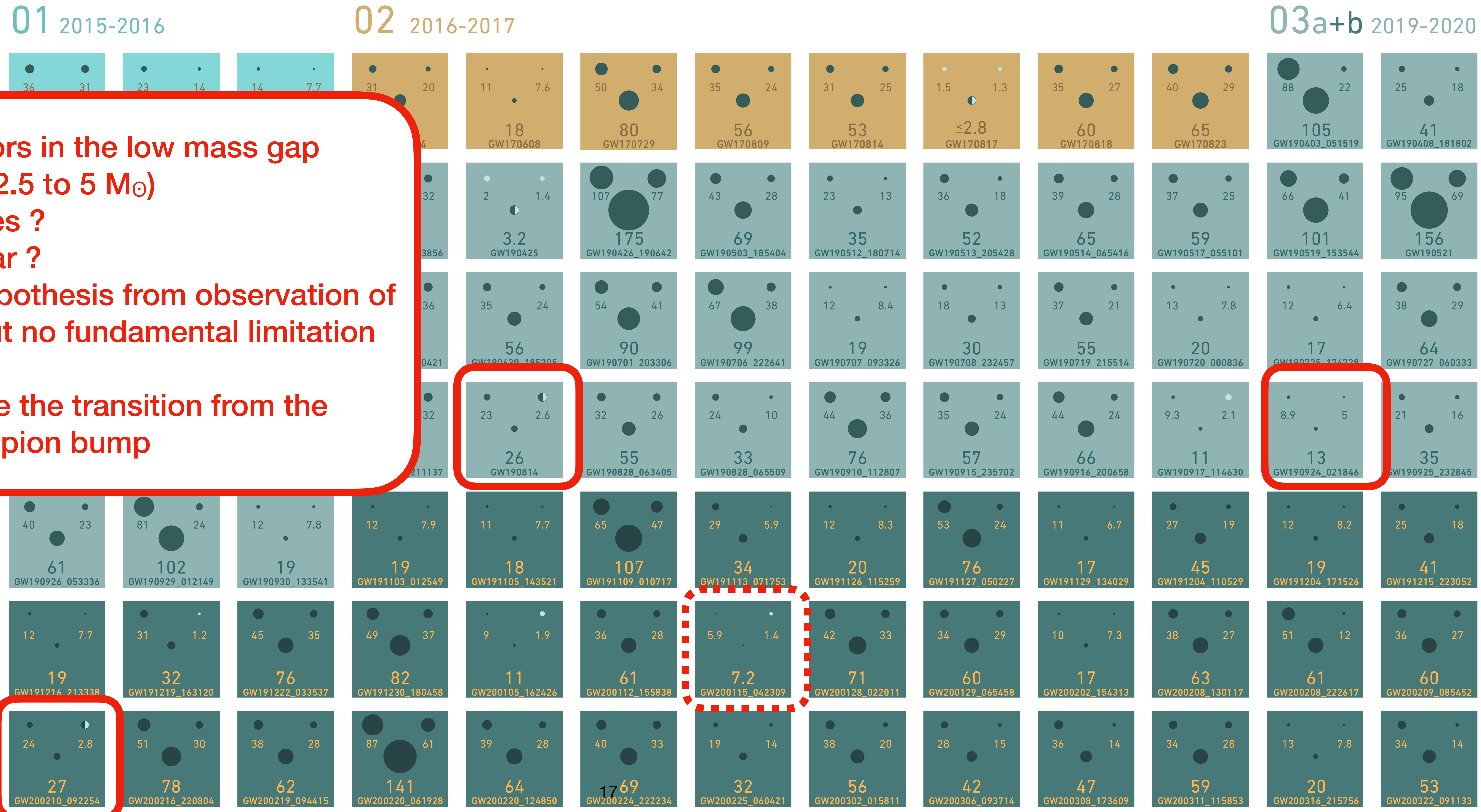
1. Need dense environments (globular clusters, AGN disks)
2. Binaries with 2 black holes from previous mergers are even more unlikely
3. Why isn't there a transition ?
4. Velocity kicks are a problem…

- 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☉)

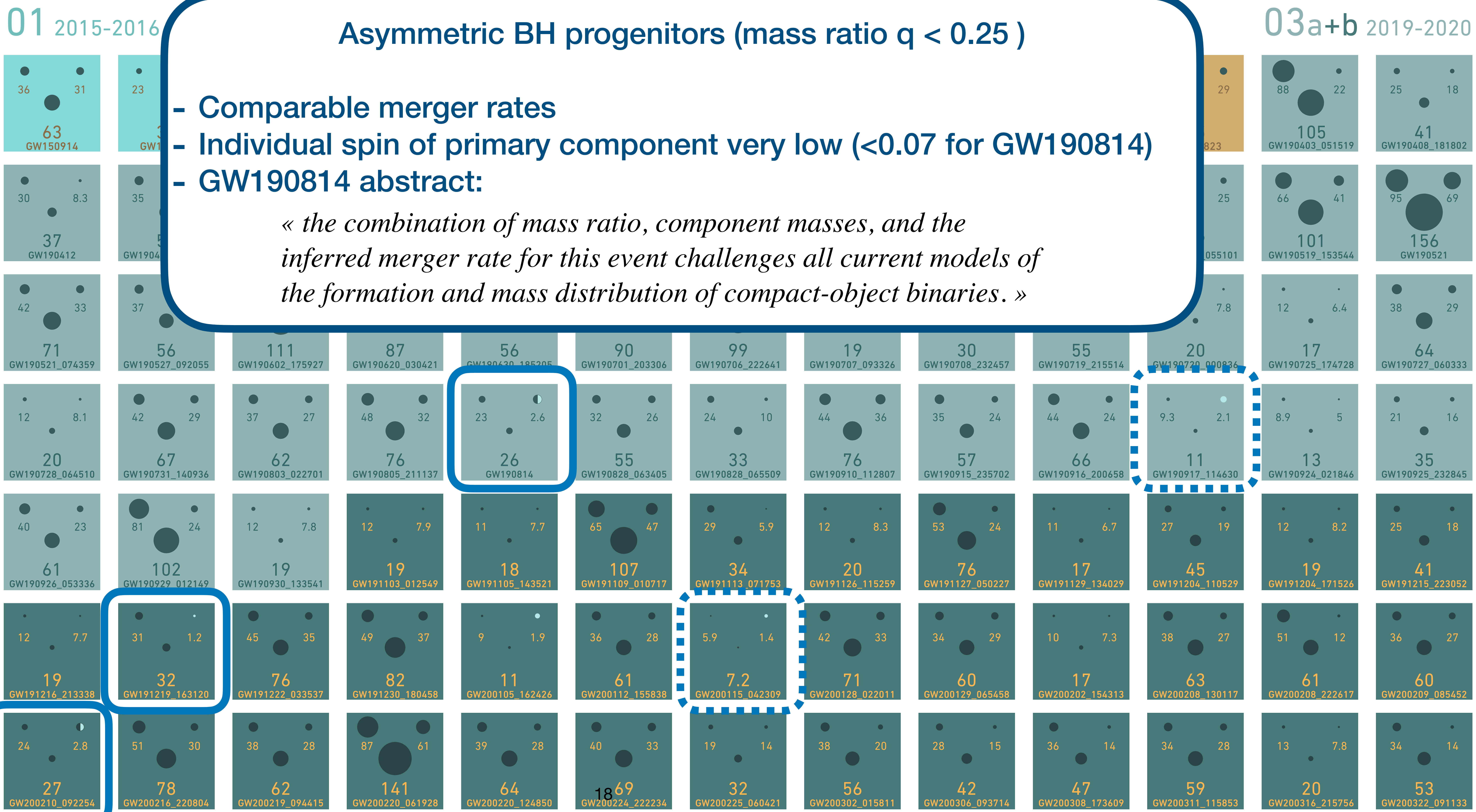
- Mass uncertainties ?
- BH vs neutron star ?
- The mass gap hypothesis from observation of X-ray binaries, but no fundamental limitation

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

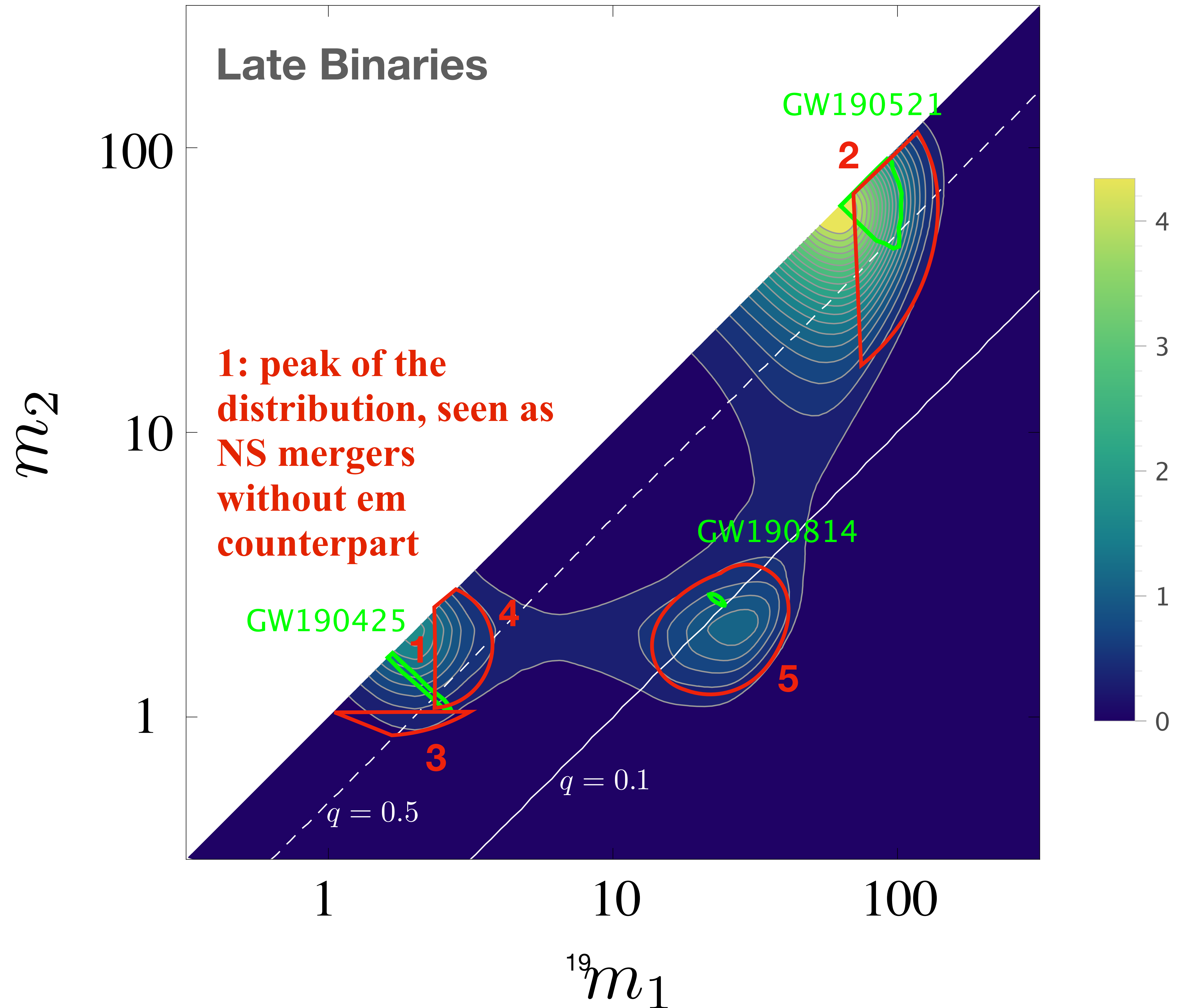
Astrophysical range:

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

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



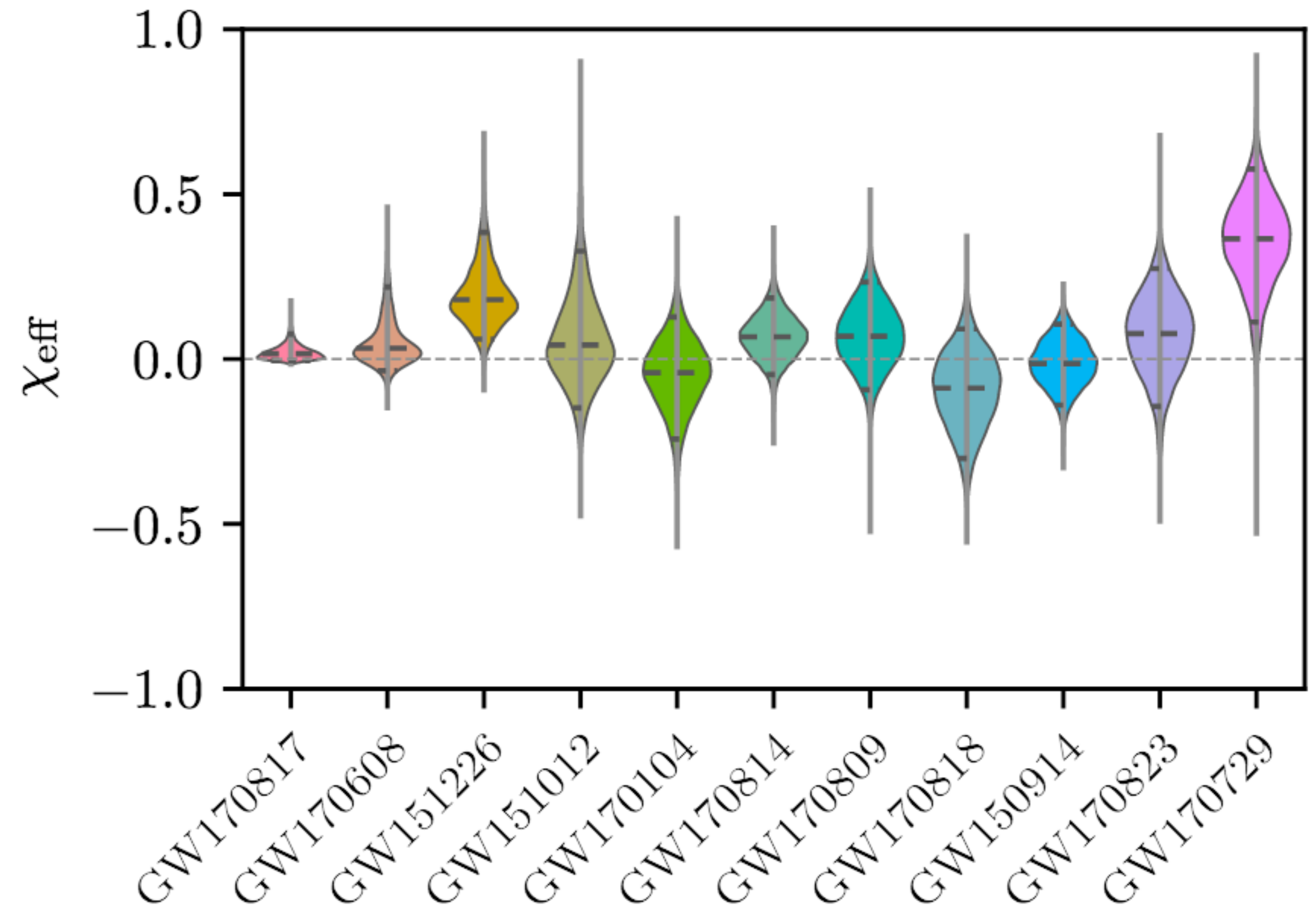
BUT: Observation of mergers in central blue region

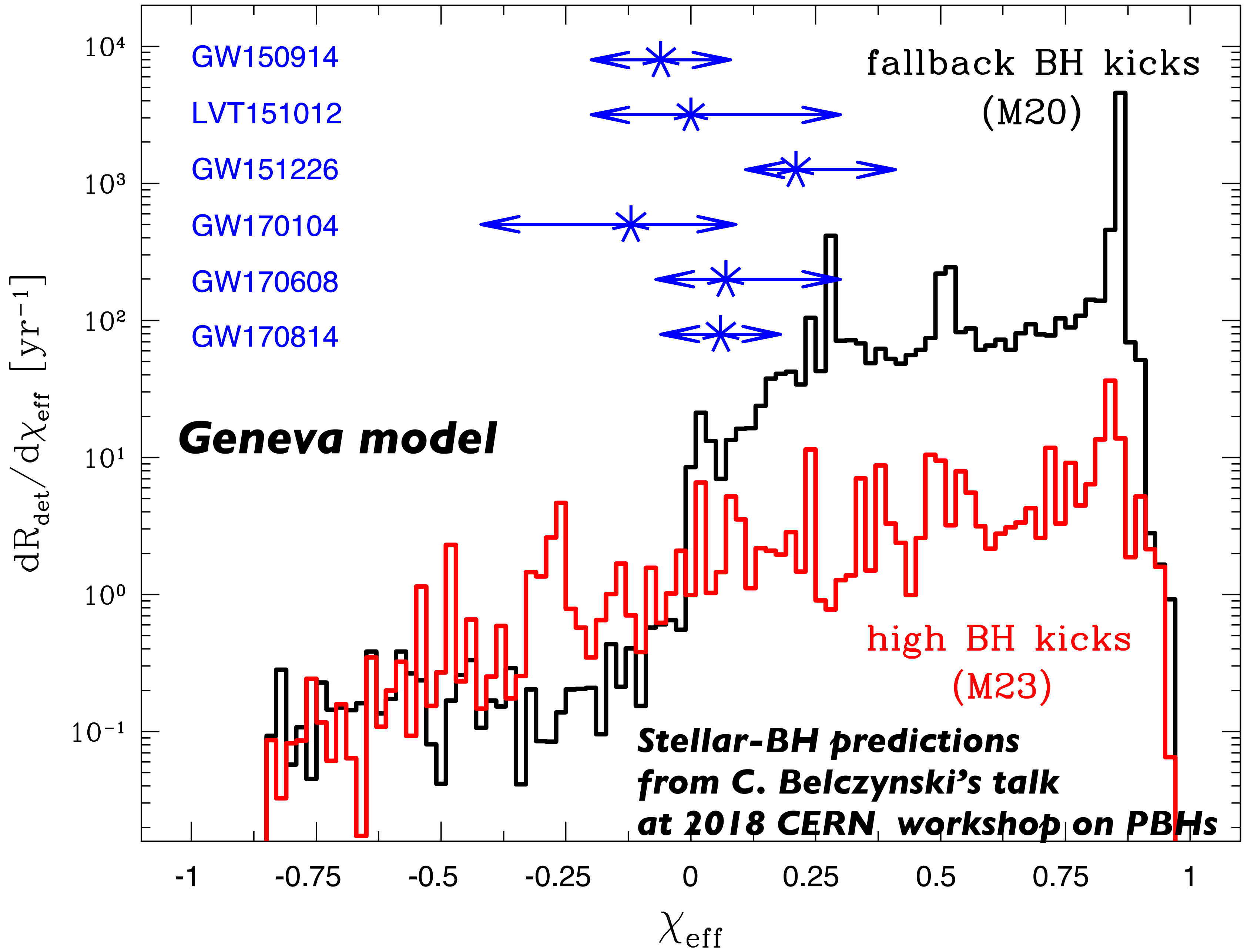
Next: Bayesian analysis for GWTC3

3. Are LIGO/Virgo black holes primordial ?

Effective spins

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





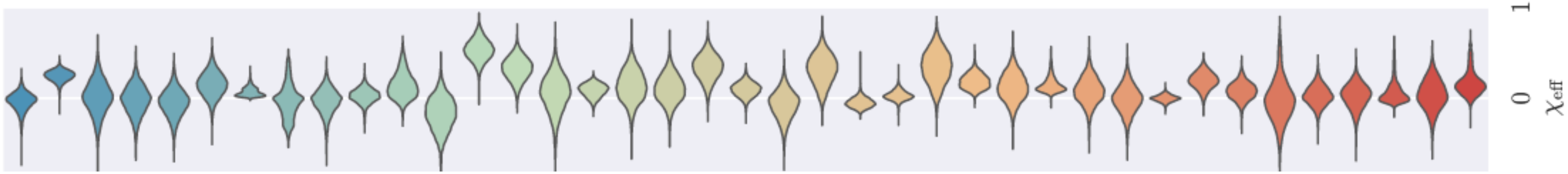
Spin of primary component for asymmetric mergers:

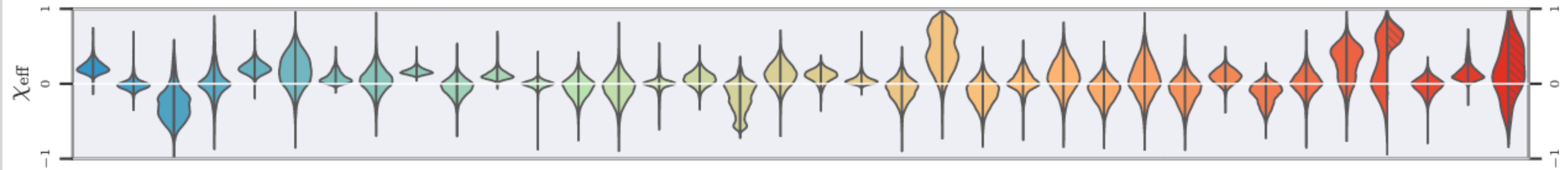
GW190814: < 0.07

GW191219…: <0.2

GW200210…: <0.4

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



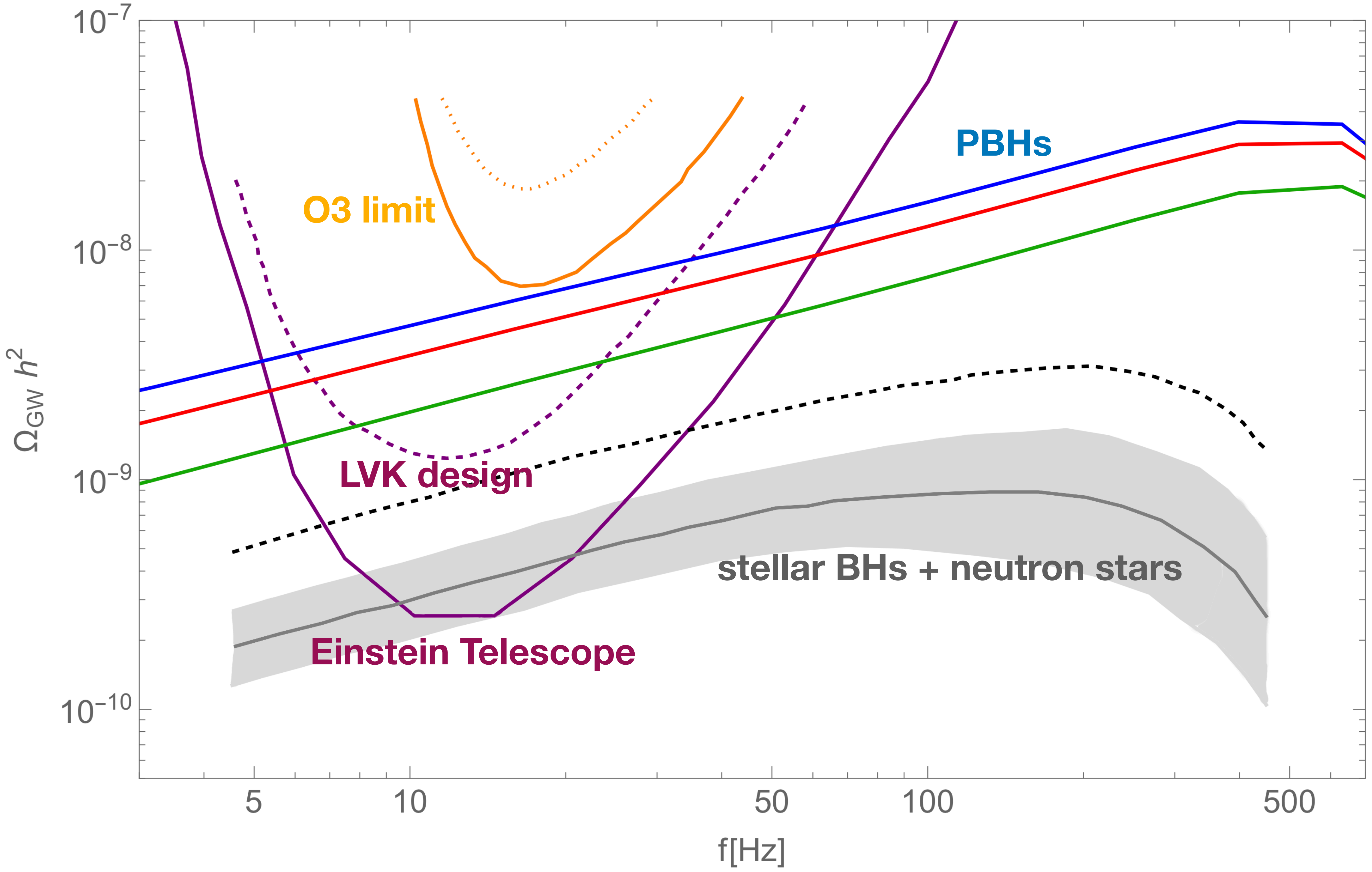


PBHs have zero spin initially but can acquire a low spin due to accretion/mergers [De Luca+20]

3. How to distinguish primordial vs stellar BHs?

GW backgrounds [Bagui, SC, 2021]

Early binaries



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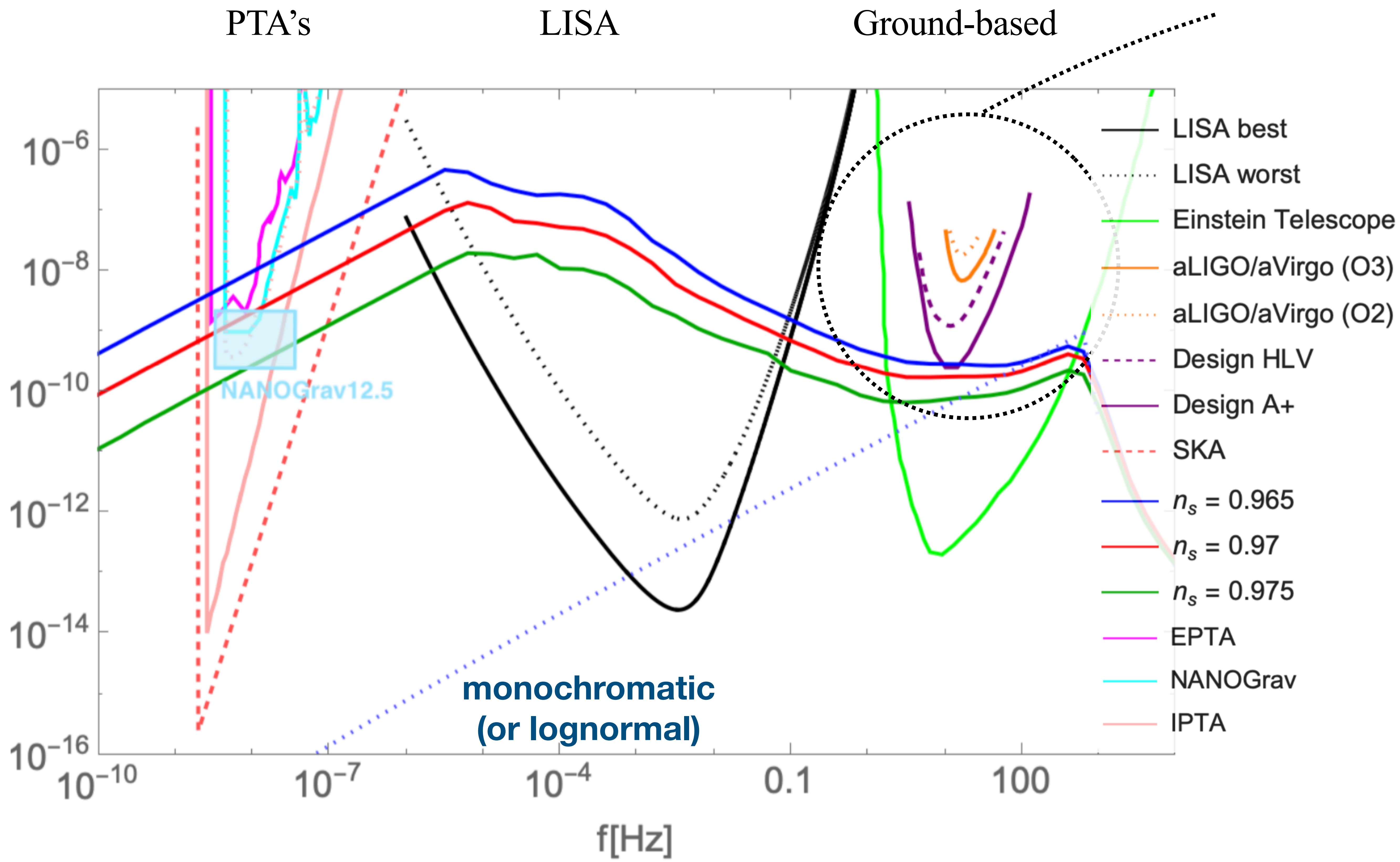

Well **above stellar BH predictions**
due to solar-mass-planetary-mass binaries
At the limit of being detected by LIGO/Virgo !
Next: pop-corn vs continuous regimes…

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 [yr^{-1}]	$\ln\mathcal{L}$	UTC time	mass 1 [$M_\odot$]	mass 2 [$M_\odot$]	spin1z	spin2z	Network SNR	H1 SNR	L1 SNR
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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	-0.03655	-0.04473	8.535	6.321	5.736

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

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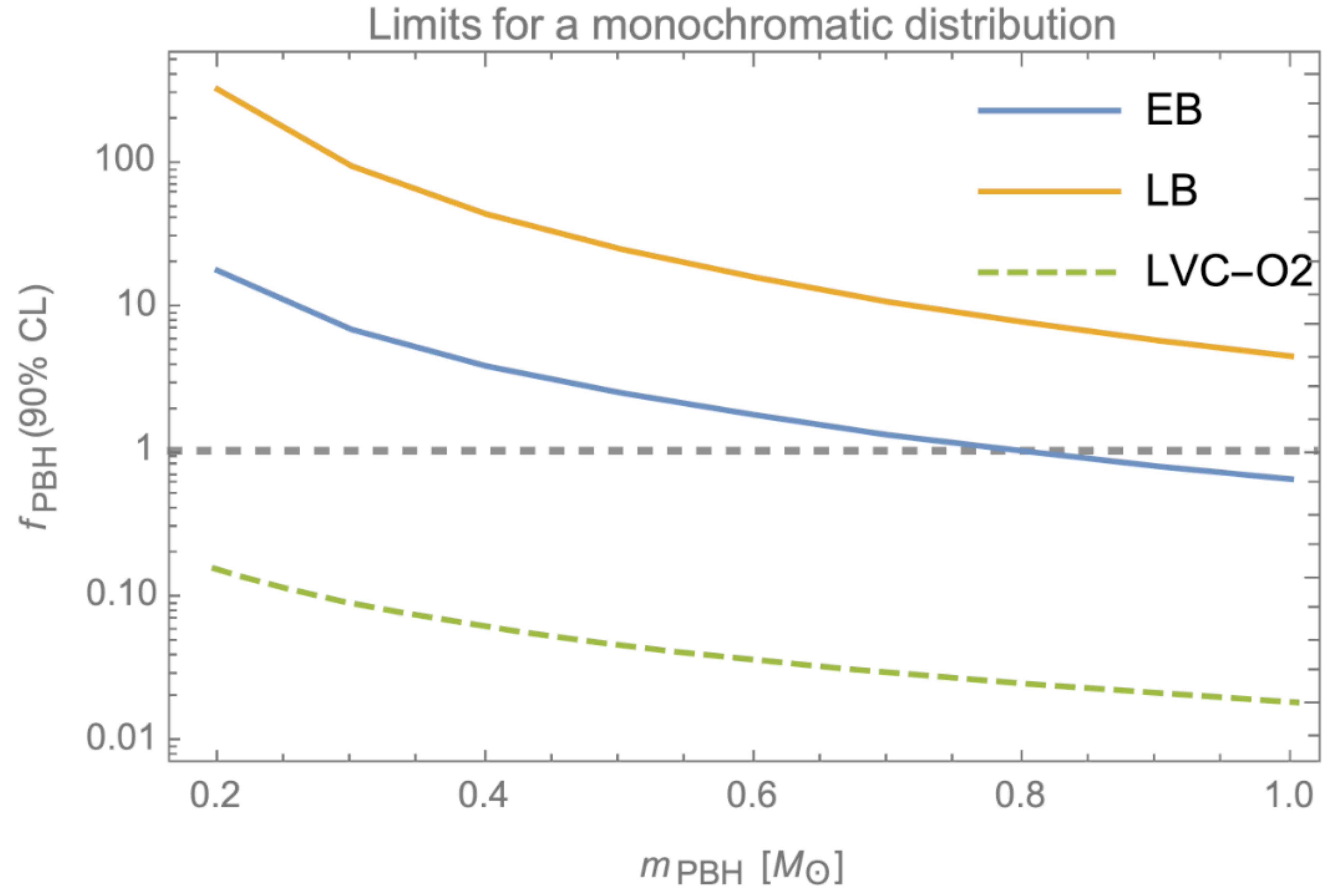

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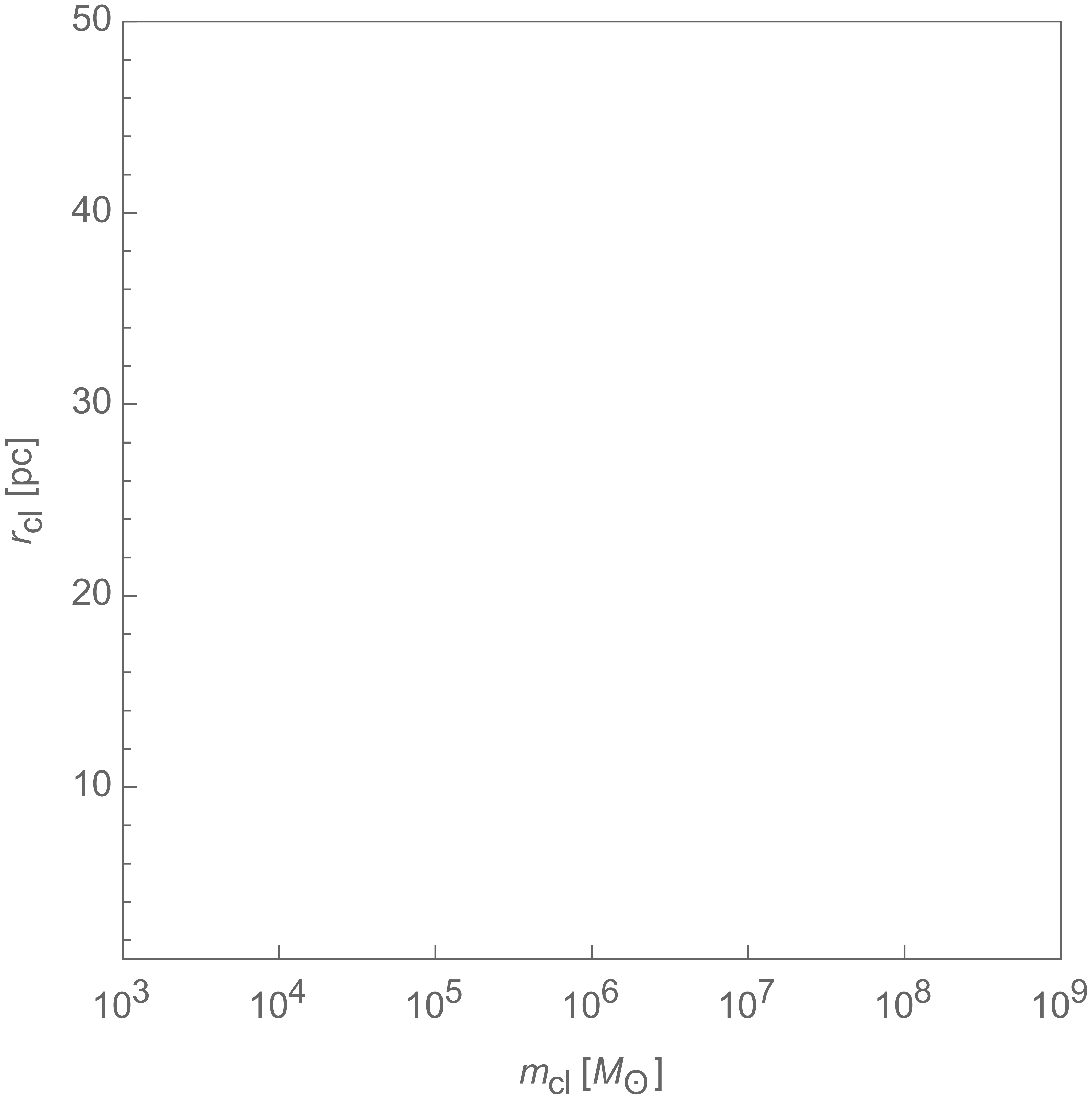
- **Complex phenomenology**: formation, clustering, accretion, mergers, etc… **Strong statements are still premature**
- Common agreement: finding **subsolar black holes** is the best way to **prove the existence of PBHs**… 4 candidates already found. Stay tuned!

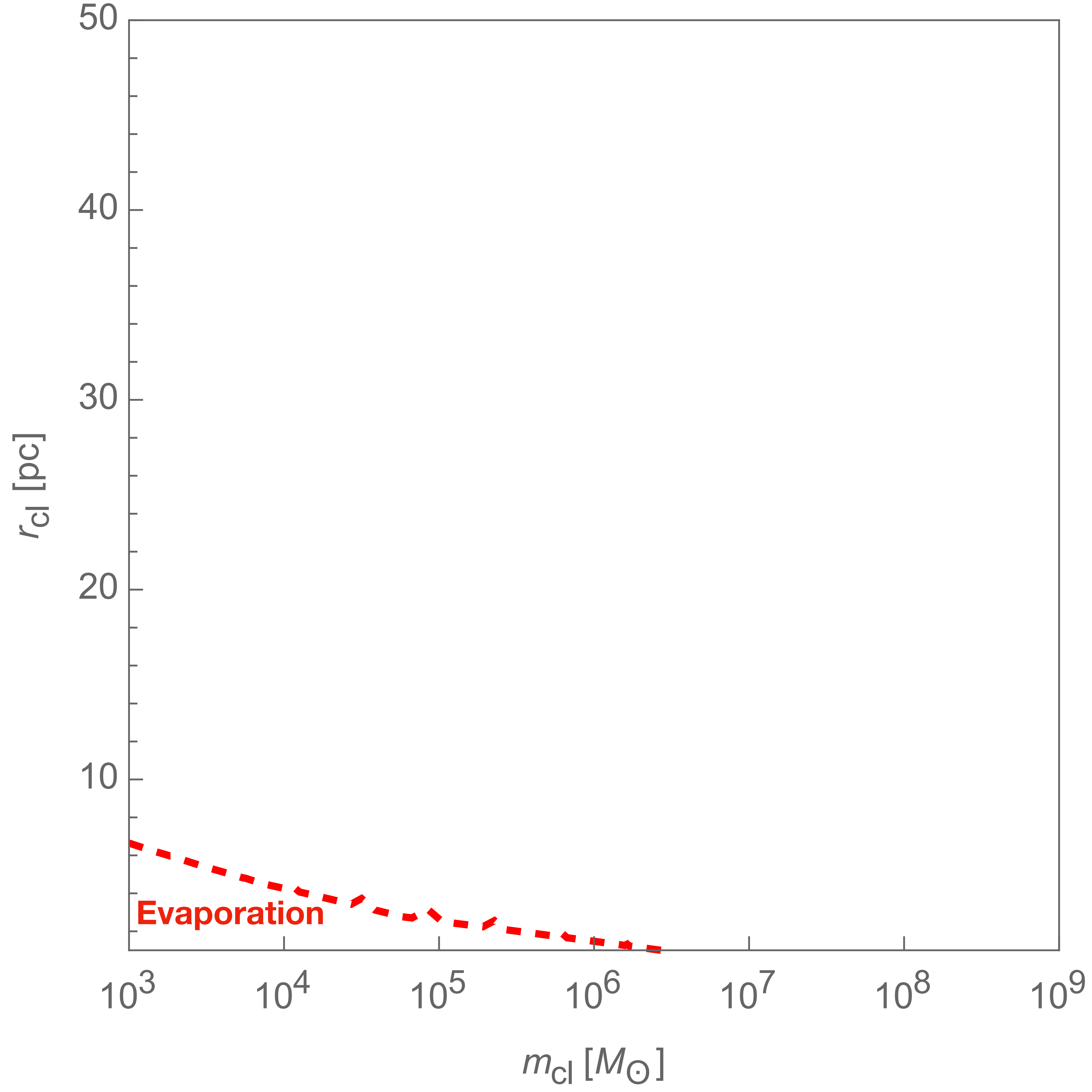
4. Our playground

PBH cluster size-mass relation



4. Our playground

PBH cluster evaporation

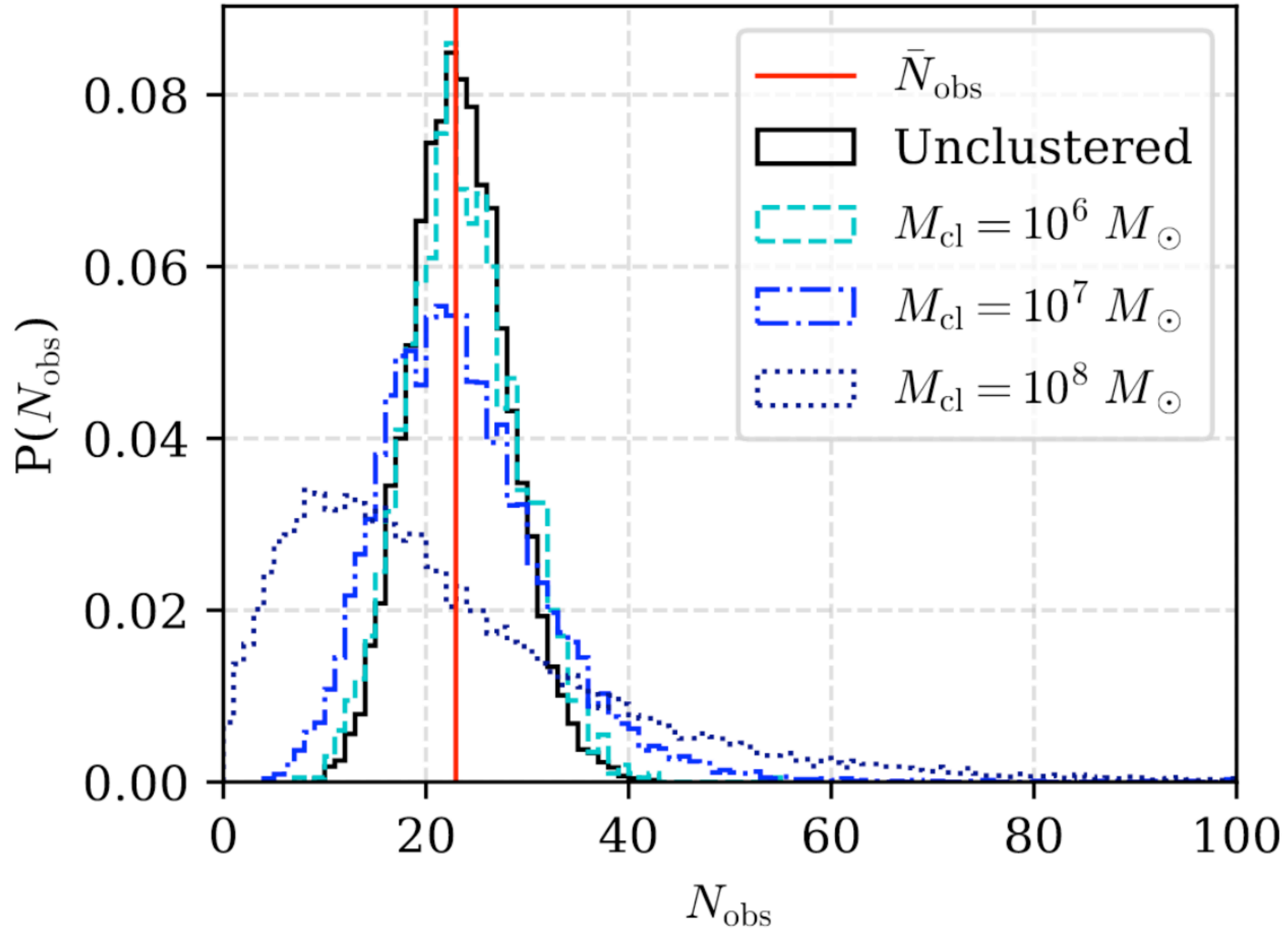


Compact clusters evaporate and are not single lenses: Petac, Lavalle, Jedamzik, 2201.02521

Evaporation time: $t_{\mathrm{evap}} \sim 140\, t_{\mathrm{relax}} \sim \dfrac{14\, N_{\mathrm{pbh}}}{\log N_{\mathrm{pbh}}}\, t_{\mathrm{cross}}$

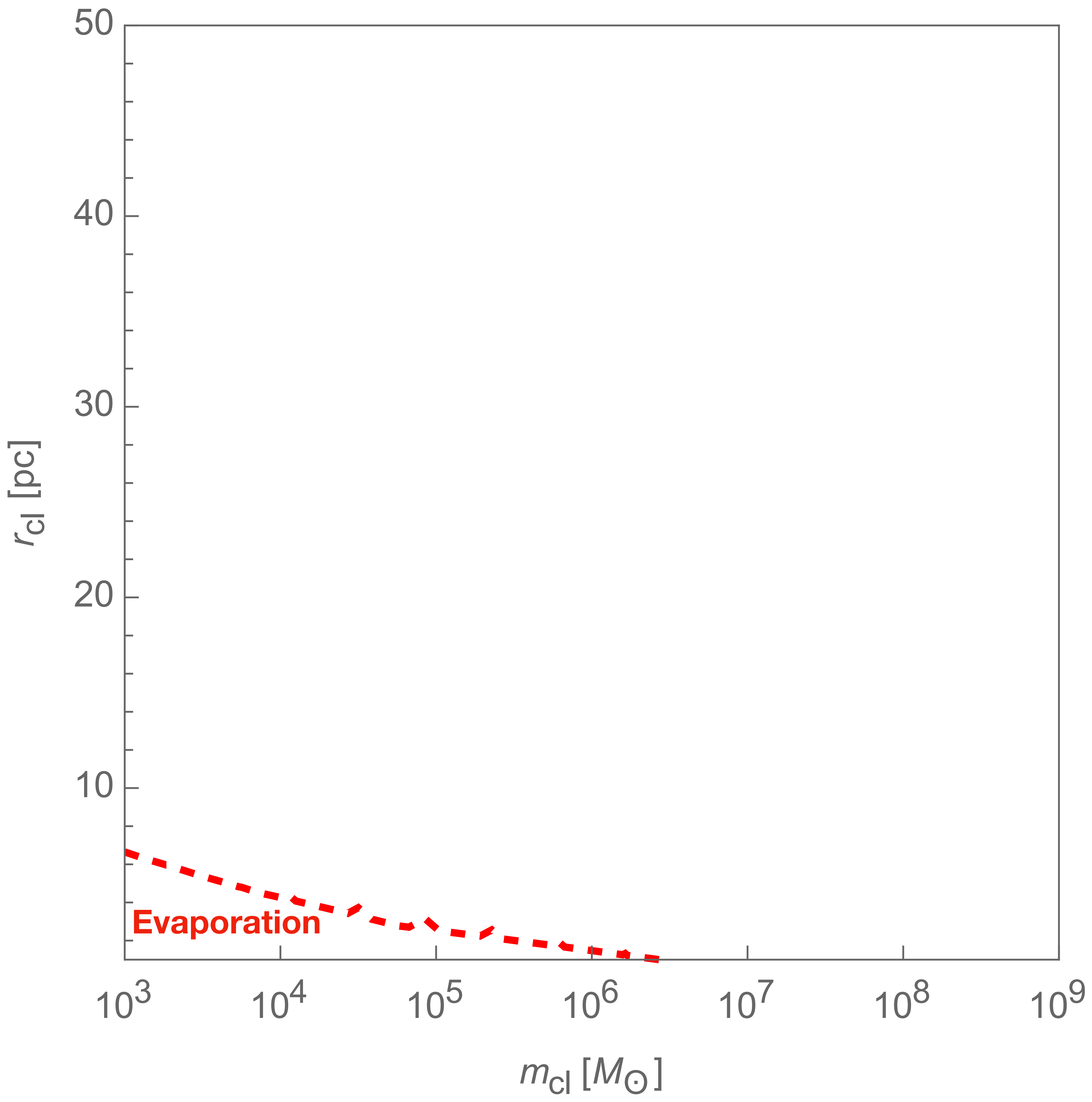
Crossing time: $t_{\mathrm{cross}} \sim r_{\mathrm{cl}}/v_{\mathrm{cl}}$

Monte-Carlo simulations: **microlensing limits are solid!**



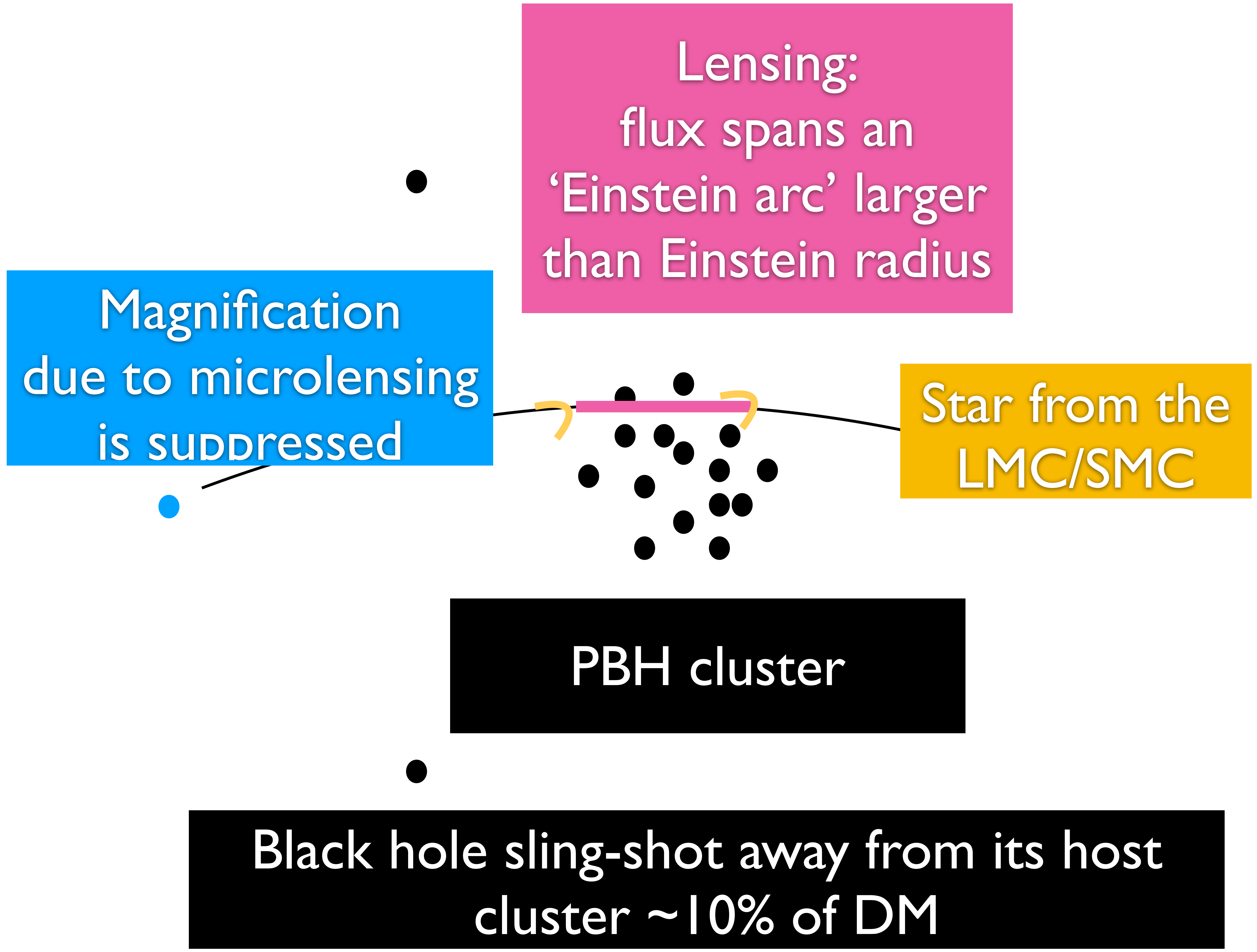
4. Our playground

Lensing + microlensing effect



Compact clusters act as lenses and suppress the magnitude of superimposed microlensing:

Carr, Clesse, Garcia-Bellido, Kühnel, 1906.08217
Gorton & Green, 2203.04209



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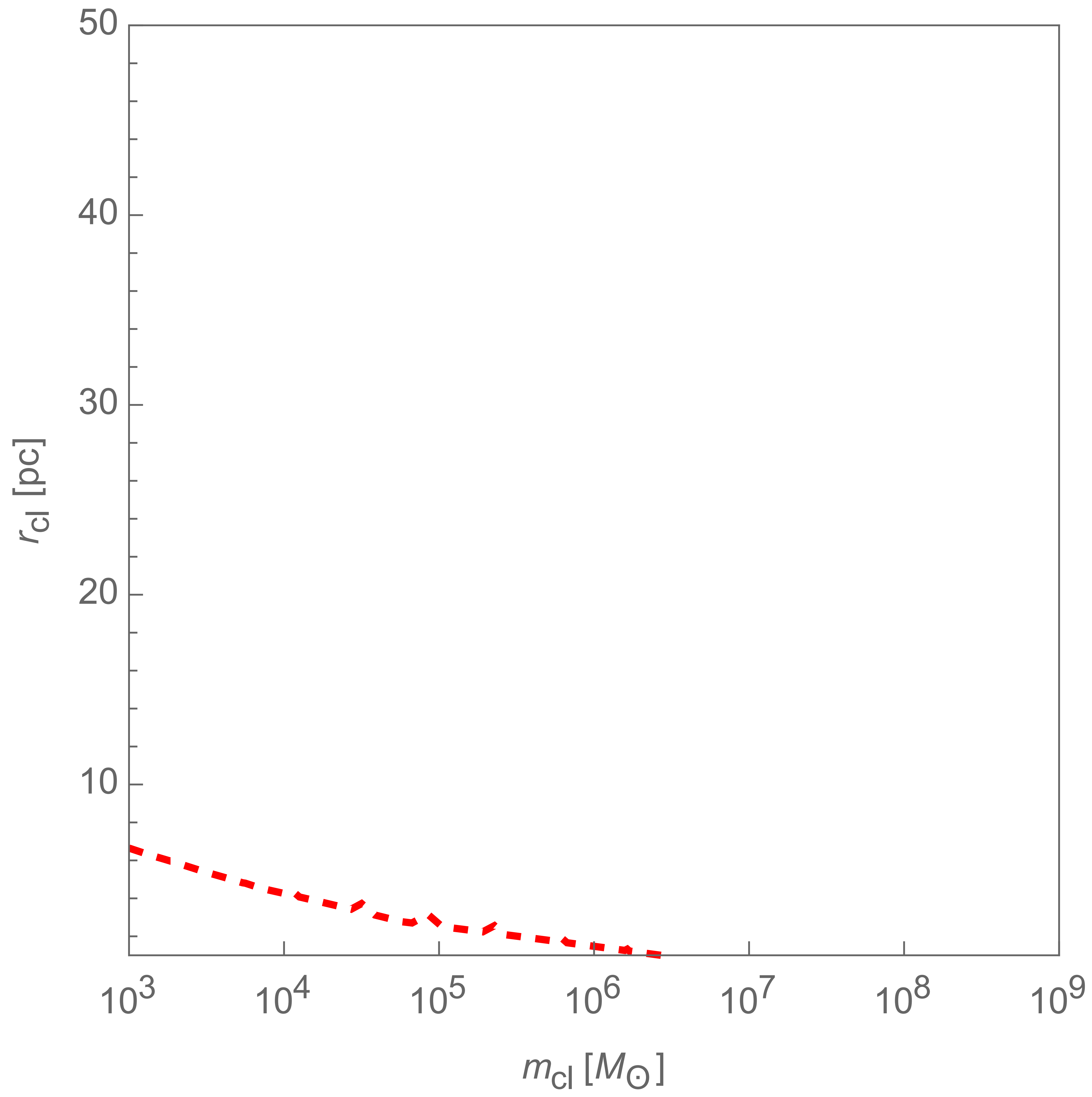

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Deflection angle:

$$\alpha(\zeta) = \frac{4\,GM(\zeta)}{c^2\,\zeta} \approx 2\times 10^{-13}\left(\frac{M_{\rm cl}}{M_\odot}\right)\left(\frac{\rm pc}{R_{\rm cl}}\right)$$

Distance point source -> Einstein arc $L_{\rm arc} \sim \alpha D_{\rm cl}$

Einstein radius of the (micro-)lens:

$$R_{\rm E} = 2\sqrt{G\,m_{\rm PBH}\,x\,(1-x)\,\frac{D_{\rm cl}}{c^2}}$$

$$\sim 10^{-5}\,{\rm pc}\left(\frac{m_{\rm PBH}}{M_\odot}\,\frac{D_{\rm cl}}{\rm kpc}\right)^{1/2}$$

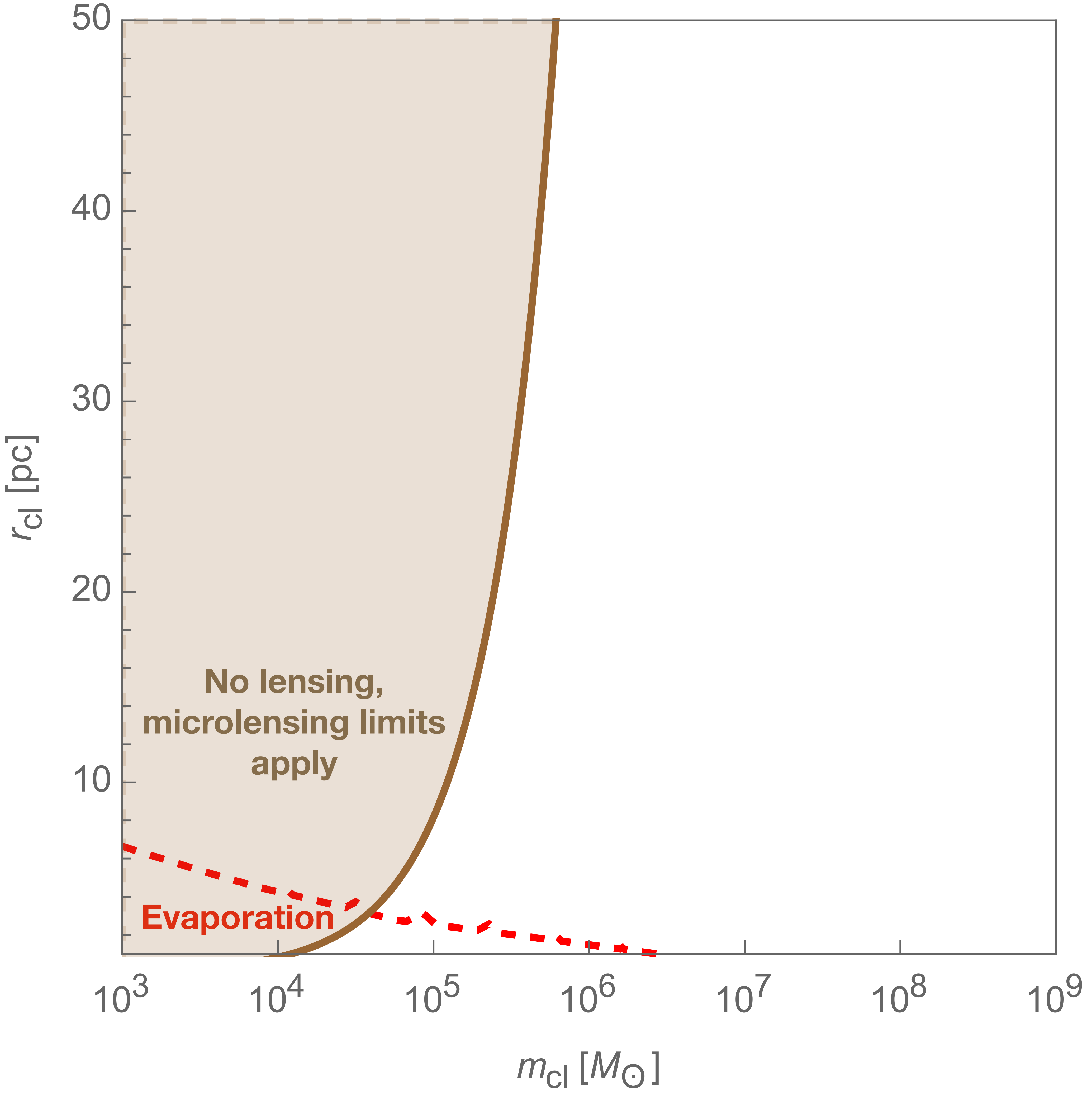
Magnitude of the microlensing event suppressed if

$$L_{\rm arc} > R_{\rm E}$$

Microlensing limits apply to Poisson clusters up to 10^6 solar masses

4. Our playground

Lensing + microlensing effect



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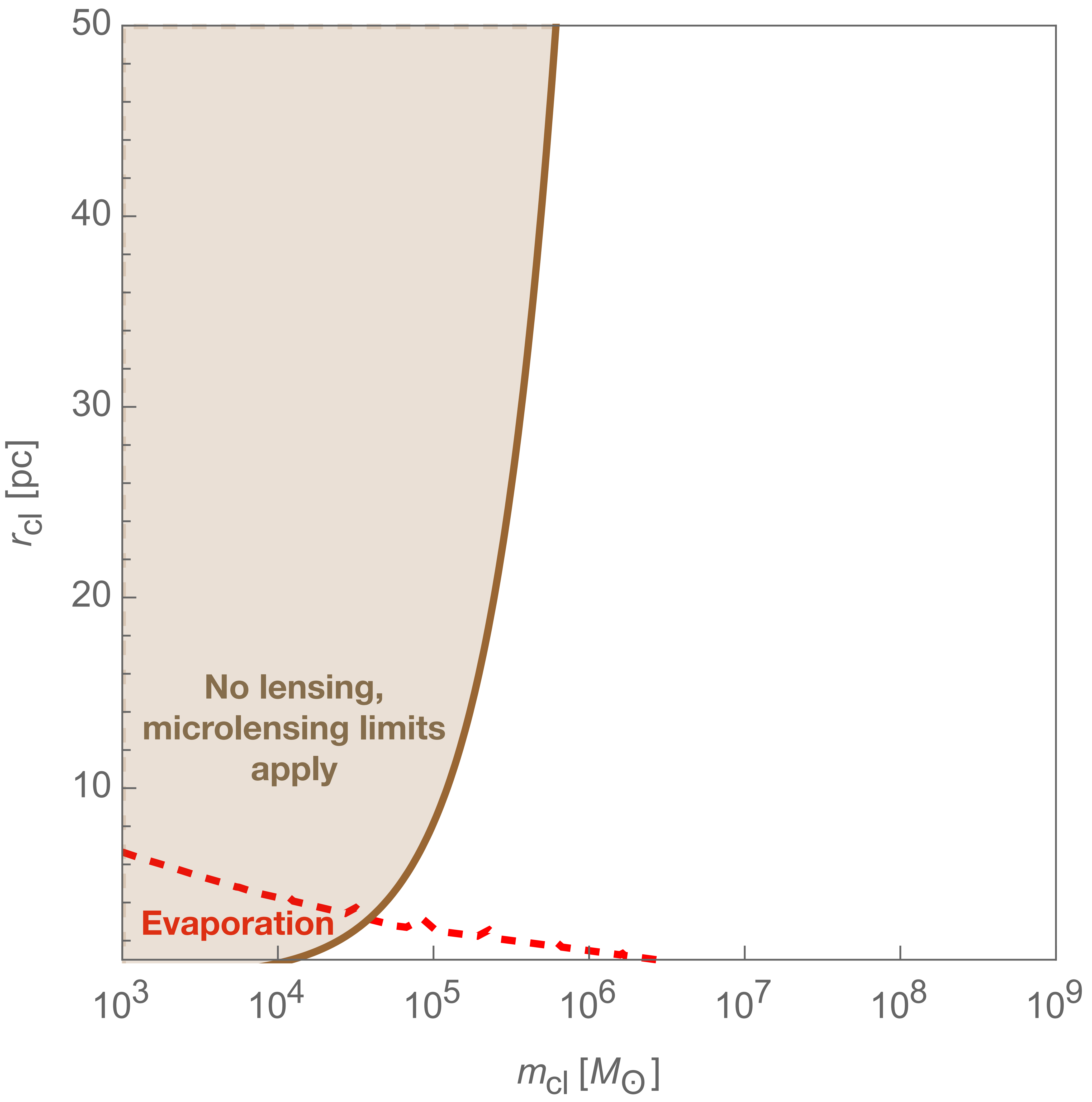
4. Our playground

Dynamical heating



Compact clusters are dynamically heated

Brandt, 1605.03665
Green, 1609.01143
S.C, Garcia-Bellido, 1711.10458

Increase of the cluster radius with time:

$$\frac{{\rm d}\, r_{\rm cl}}{{\rm d}t} = \frac{4\sqrt{2}\,\pi\, G\, f_{\rm PBH}\, m_{\rm PBH}\, \ln\left(\frac{m_{\rm cl}}{2\, m_{\rm PBH}}\right)}{2\,\beta\, v_{\rm vir}\, r_{\rm cl}}$$

Poisson fluctuation = isocurvature fluctuation

$$\delta = \frac{1}{\sqrt{N}} \times \left(\frac{1+z_{\rm eq}}{1+z}\right)$$

Redshift of formation, when $\delta \approx \delta_{\rm cr} \approx 1.68$:

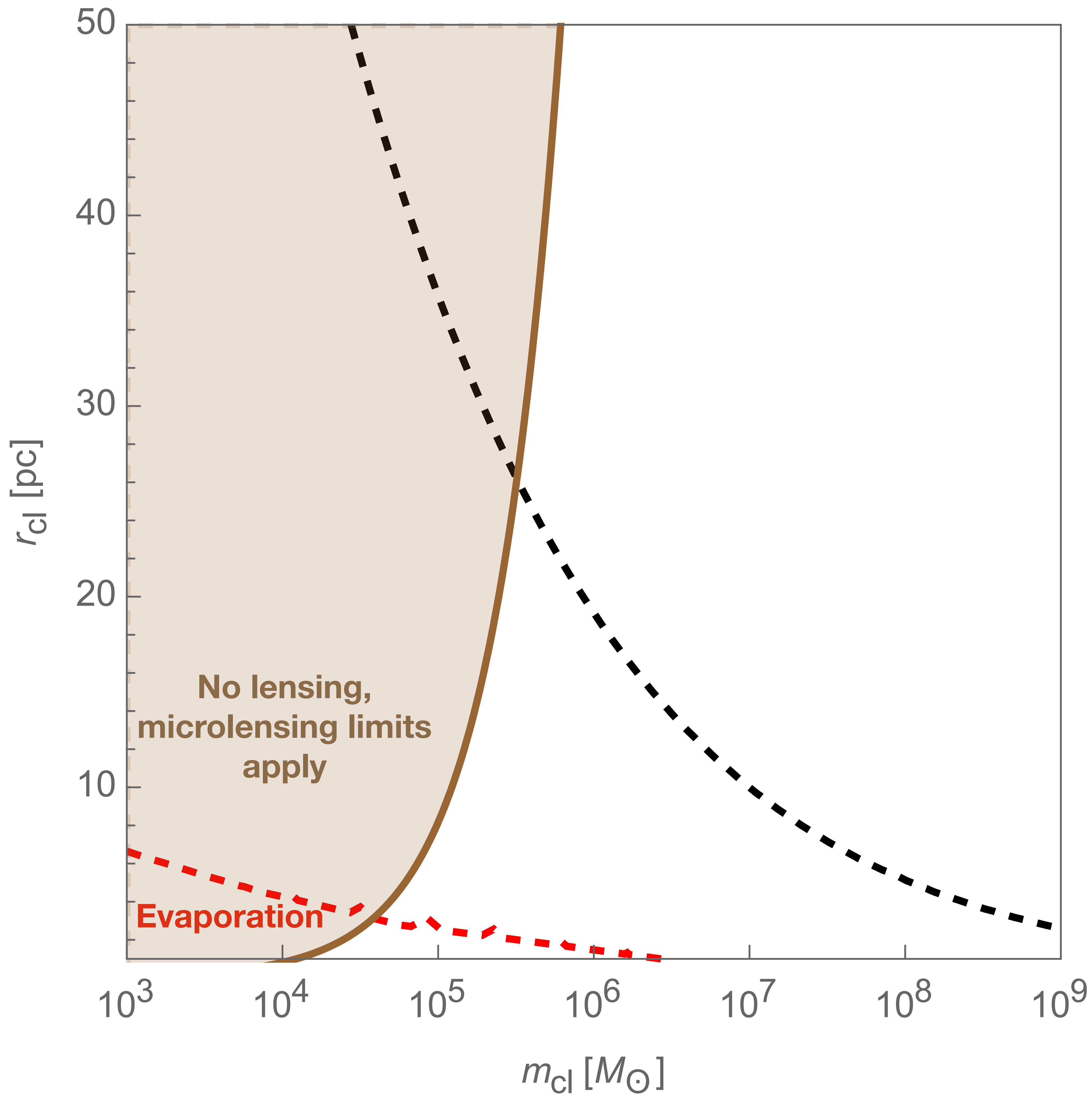
$$z_{\rm form} + 1 \simeq 3.7 \times 10^{-3} k^{-3/2} \left(\frac{m_{\rm PBH}}{M_\odot}\right)^{-1/2}$$

$$\simeq 24 \times \left[\frac{10^6 m_{\rm PBH}}{m_{\rm cl}}\right]^{1/2} .$$

Very early (cf. N-body simulation)

4. Our playground

Dynamical heating



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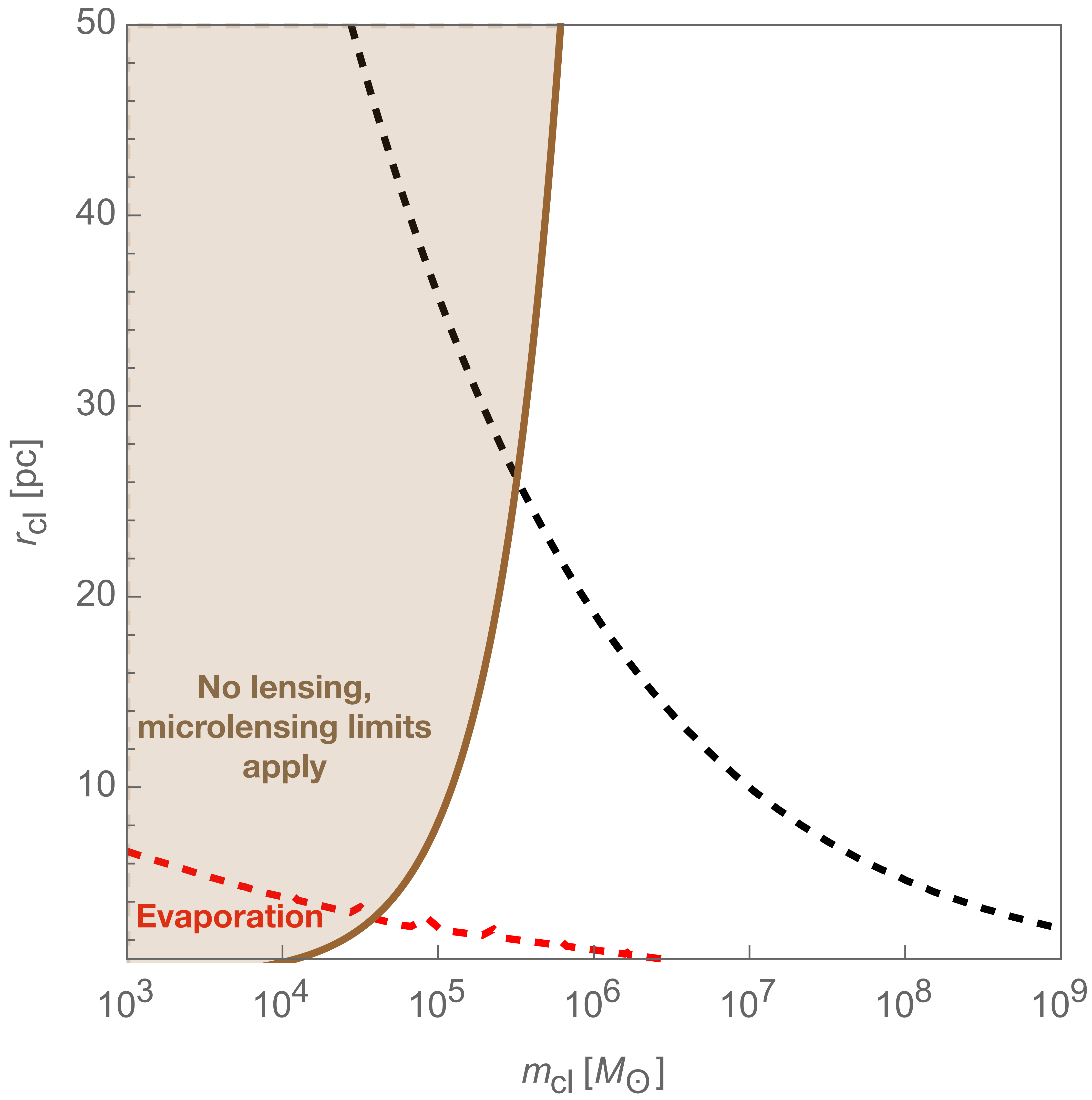
4. Our playground

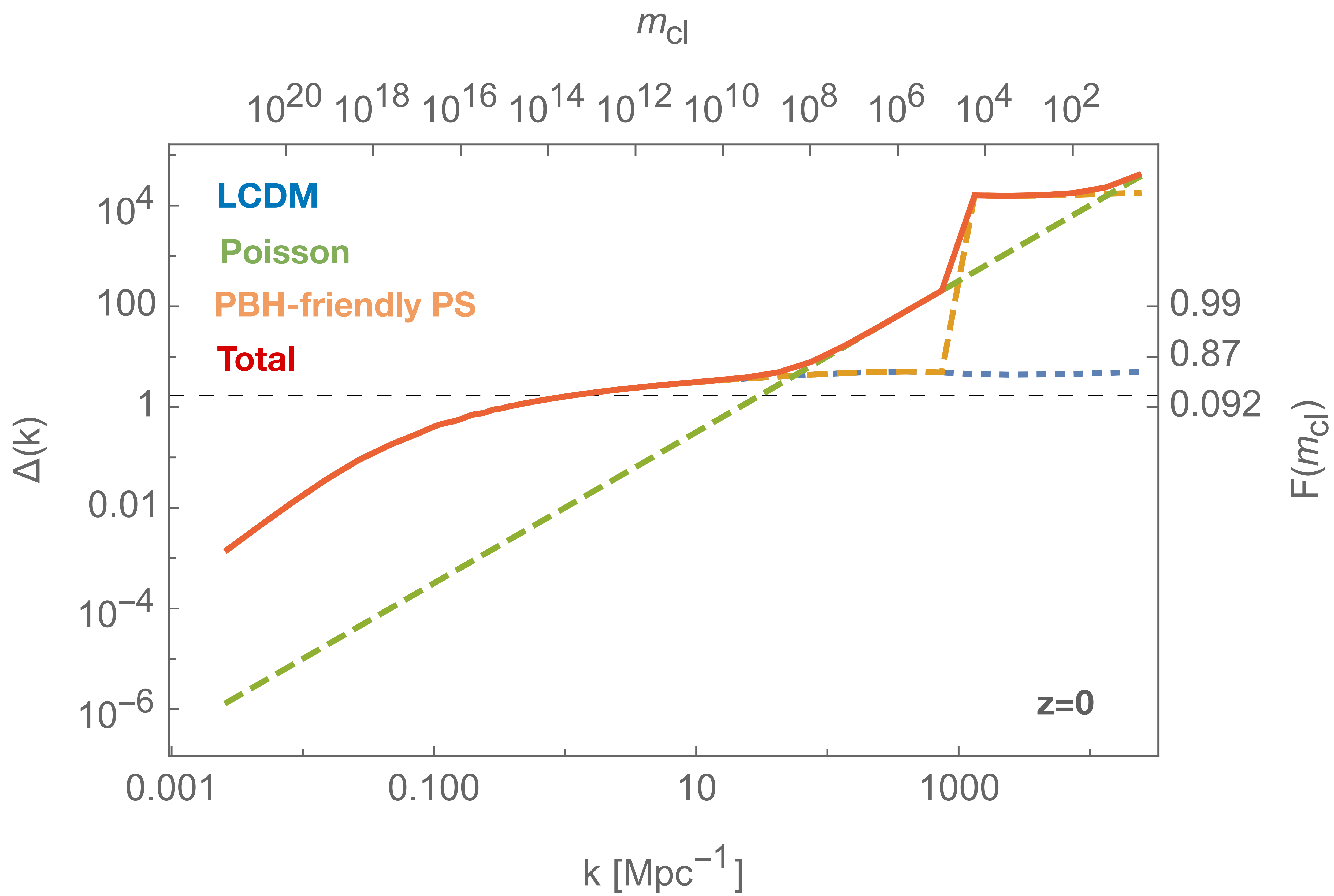
Probability of collapse



Almost 100% of fluctuations collapse up to 10^7 M$_\odot$
Sub-sub halos diluted in their sub halo
Natural clustering scale around 10^7 M$_\odot$
S.C, Garcia-Bellido, 2007.06481

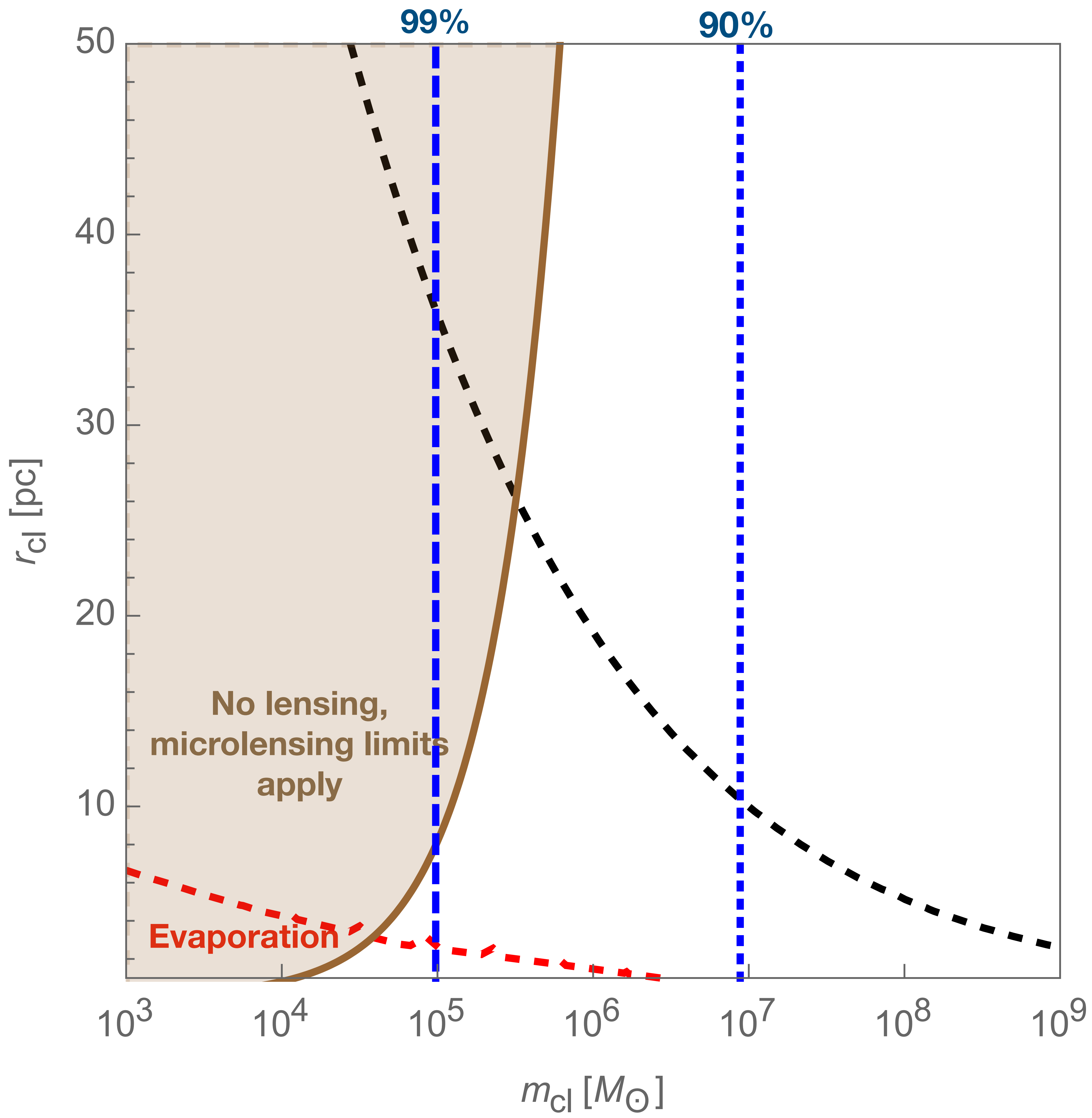
Fraction of (Poisson) fluctuations that collapse, in the Press-Schechter formalism:

$$F(m_{\rm cl}) \approx {\rm erfc}\left[\frac{\delta_{\rm cr}}{\sqrt{2}\delta_{\rm Poisson}}\right]$$



4. Our playground

Probability of collapse



Almost 100% of fluctuations collapse up to 10^7 M⊙
Sub-sub halos diluted in their sub halo
Natural clustering scale above 10^7 M⊙
S.C, Garcia-Bellido, 2007.06481

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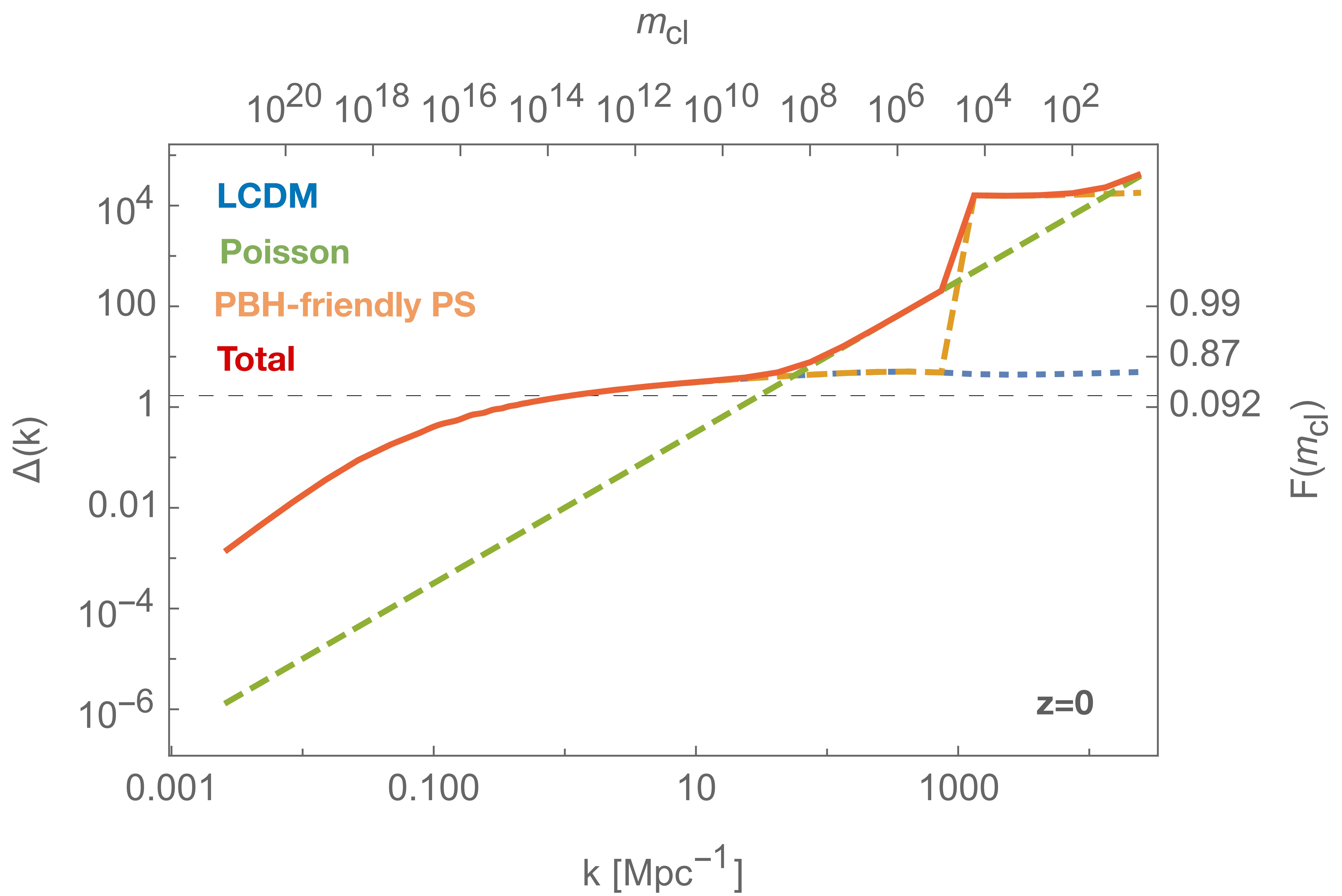
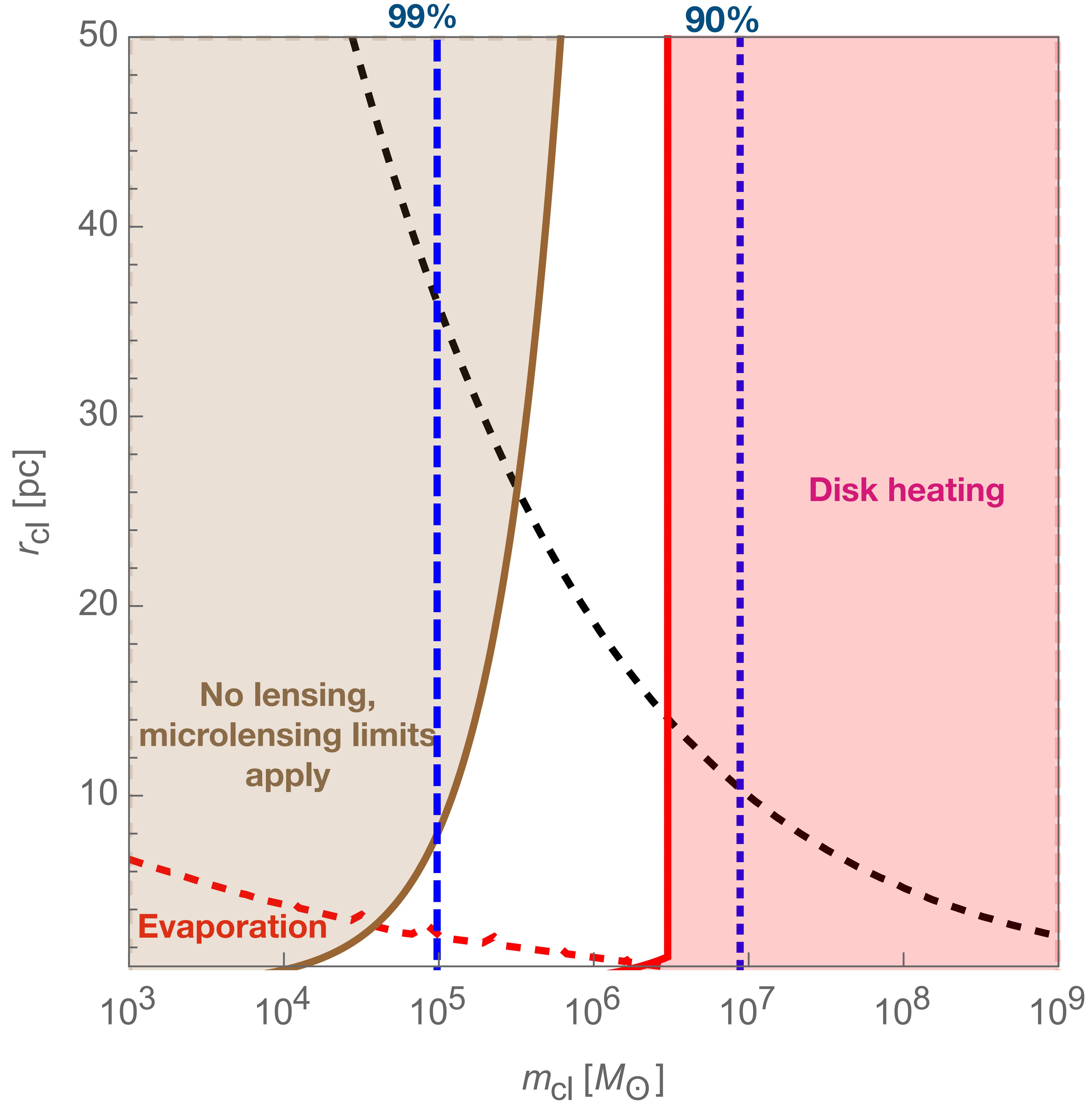


4. Our playground

Heating of the galactic disk



Clusters dynamically heat the galactic disk
Clue or limit ?

Carr & Lacey, 1987

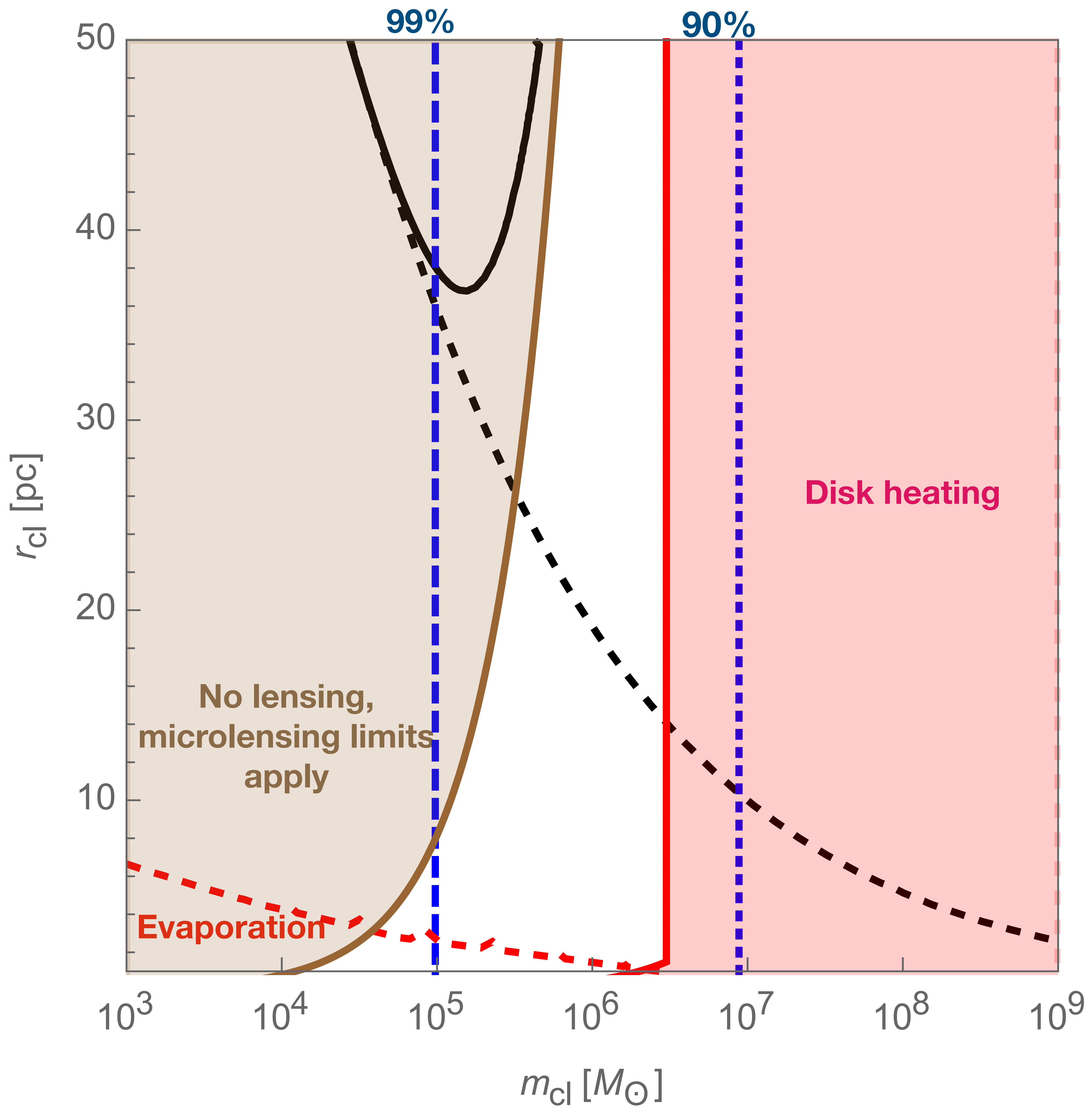
$$m_{\rm cl} < 3 \times 10^6 M_\odot$$

for all dark matter made of subhlos

Most of dynamically heated
Poisson PBH clusters would have
too much heated the galactic disk => excluded

4. Our playground

Initial cluster size



For dynamical heating, we assumed negligible initial size…

Size of the cluster at formation, in the theory of spherical collapse:
(when cluster density 178 times background density)

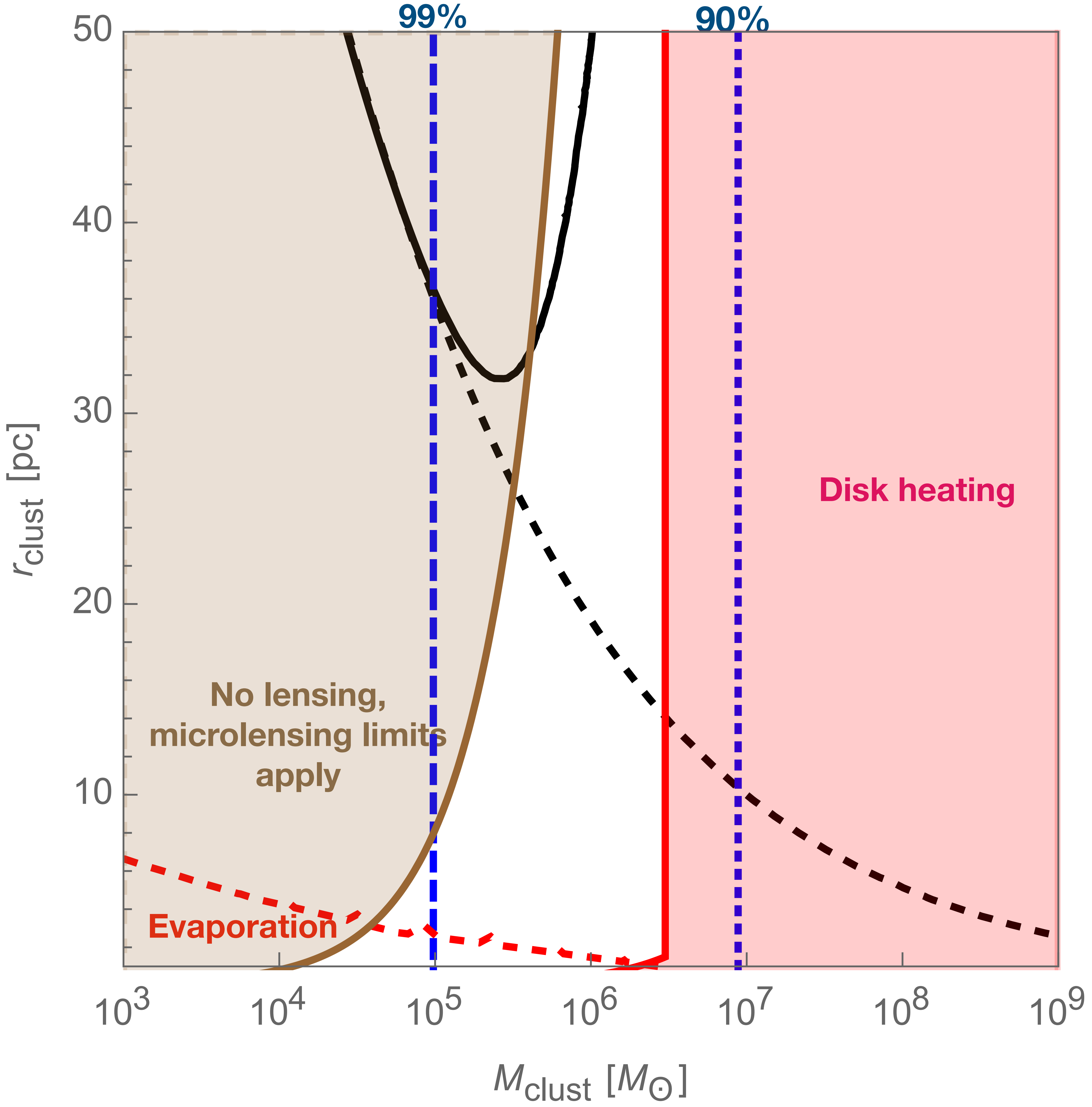
$$r_{\rm cl} \simeq 135\,{\rm pc}\, \left(\frac{m_{\rm PBH}}{M_\odot}\right)^{1/2} \left(\frac{m_{\rm cl}}{10^6\,M_\odot}\right)^{-1/6}$$

But then, microlensing limits apply !!!

You are back to your starting point…

4. Our playground

Broad PBH mass function



If PBHs explain LIGO/Virgo black holes they also seed Poisson clusters

Poisson fluctuations:

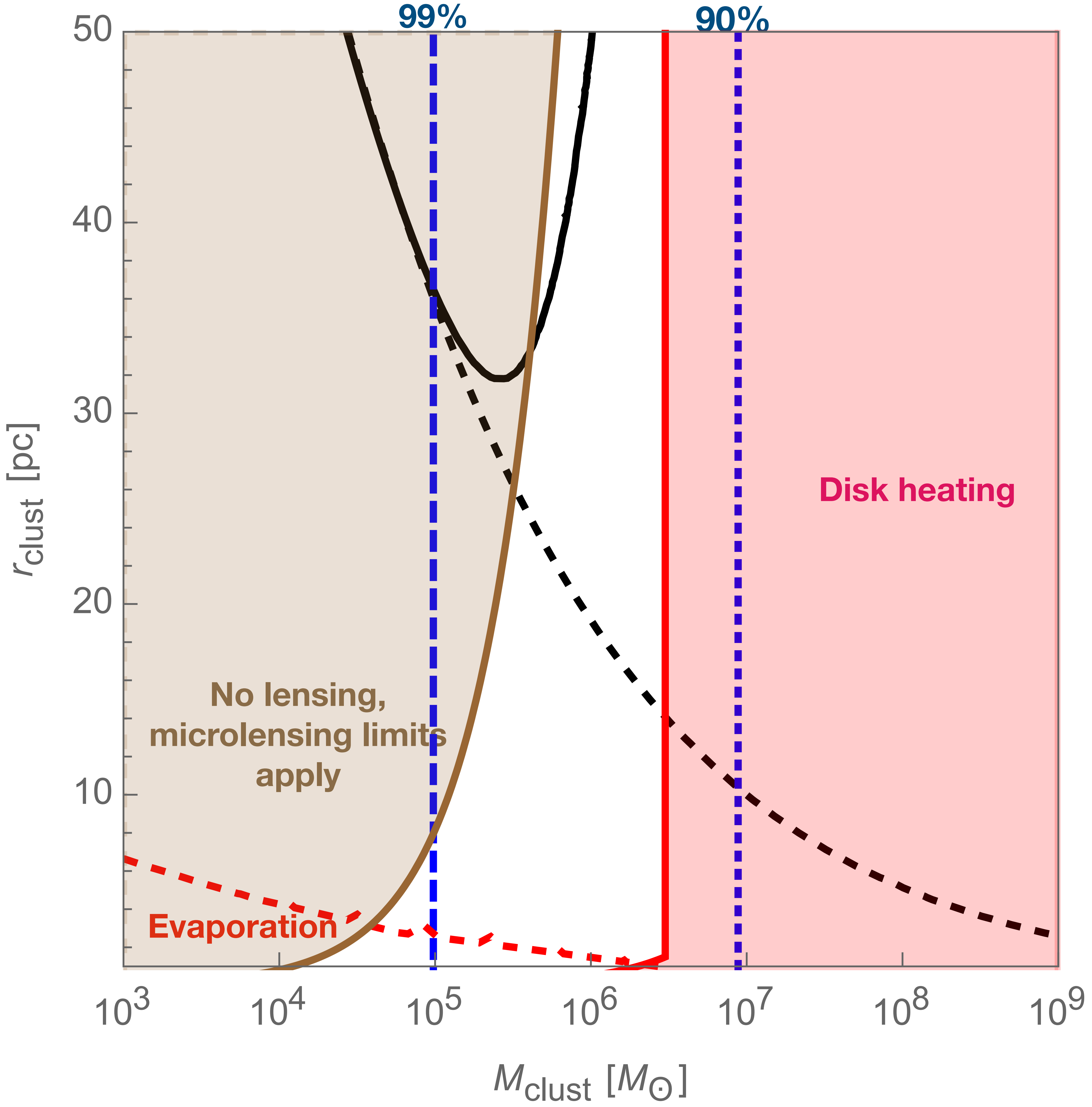
$$\delta \propto \int m_{\rm PBH} f_{\rm PBH} f(m_{\rm PBH}) \mathrm{d}\ln \mathrm{m}_{\rm PBH} \sim 10 - 100$$

but still, PBH peak around 3 M☉

We get a minimal clustering scale around 10^5-10^6 M☉

4. Our playground

Collisional/tidal disruption



If clusters are too large:

Carr & Lacey, 1987

- Disruption by the galactic tidal field:

$$r_{cl} \lesssim 100\mathrm{pc} \left(\frac{m_{cl}}{10^6 M_\odot} \right)^{1/3}$$

- Tidal shocking when they traverse the galactic disk:

$$r_{cl} \lesssim 30\mathrm{pc} \left(\frac{m_{cl}}{10^6 M_\odot} \right)^{1/3}$$

- Disruption by collisions between clusters:

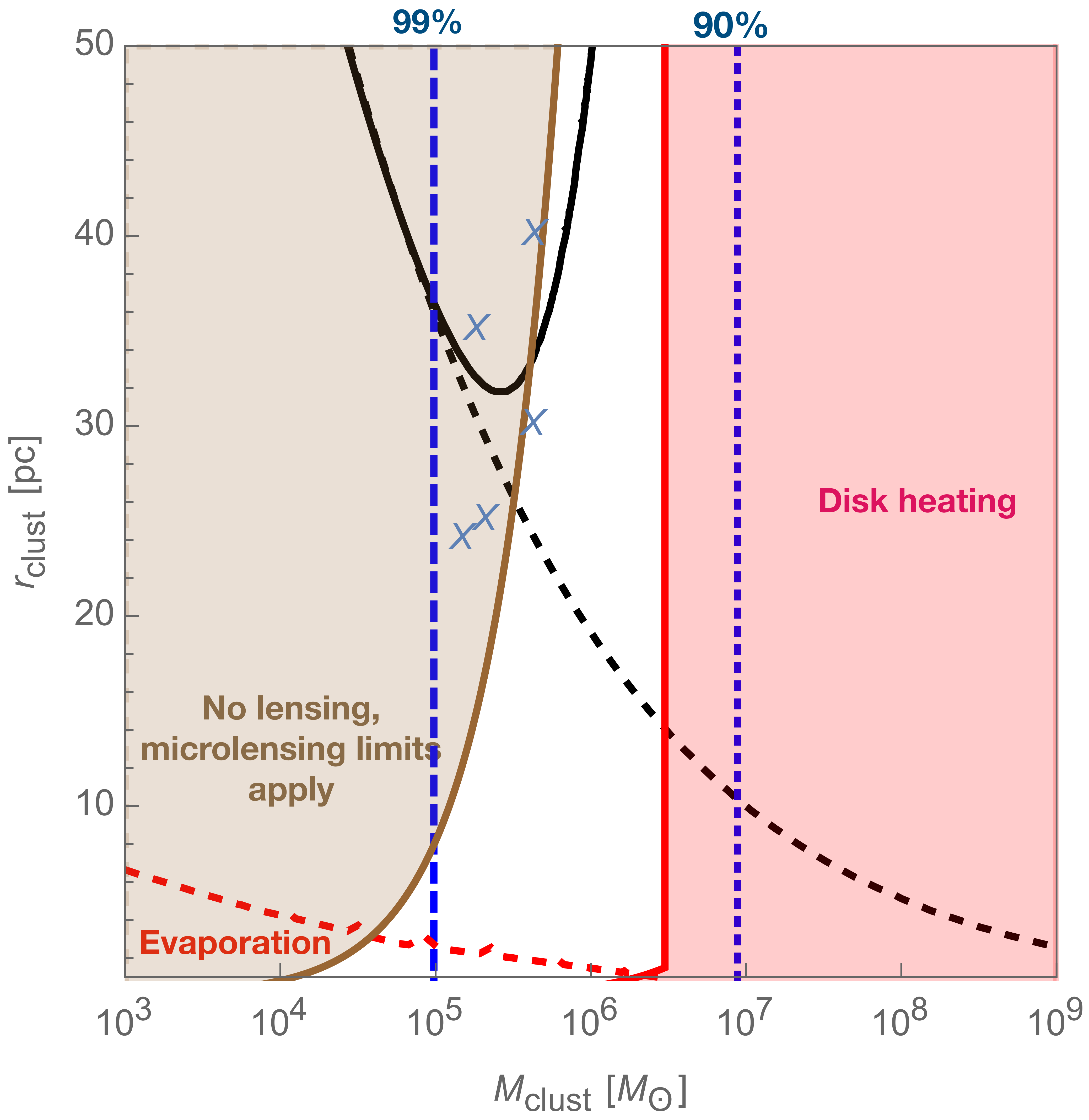
$$r_{cl} \lesssim 30\mathrm{pc}$$

all this, if they are the dark matter and at our **galactocentric radius**

Minimal -> Natural clustering scale around 10^5-10^6 $M_\odot$

4. Our playground

Observations of UFDGs



Ultra-faint dwarf galaxies

Brandt 2017, Simon 2019…

Naïve estimation :
Half light radius vs dynamical mass from the Virial theorem

- **Minimum size and mass of UFDGs could be explained by dynamical heating** (Clesse, Garcia-Bellido 2017)
- **Large mass-to-light ratios could be explained by PBH accretion** (Clesse, Garcia-Bellido 2017)
- **High-redshift formation could explain spatial correlations between X-ray and infrared backgrounds** (Kashlinsky 2016)
- **Many UFDGs expected below the detection limit**
- **No clusters in the galactic center**