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

Microlensing searches of primordial black holes (in clusters)

B. Carr, S. Clesse, J. Garcia-Bellido, M. Hawkins, F. Kühnel, in preparation

News from the Dark workshop
Montpellier, June 15-17, 2022

Background picture: artist view of GW190521 by Ingrid Bourgault

Source: NASA https://svs.gsfc.nasa.gov/20315

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    - **MACHO**: detections
    - **EROS**: limits
    - **OGLE**: limits + detection(s)

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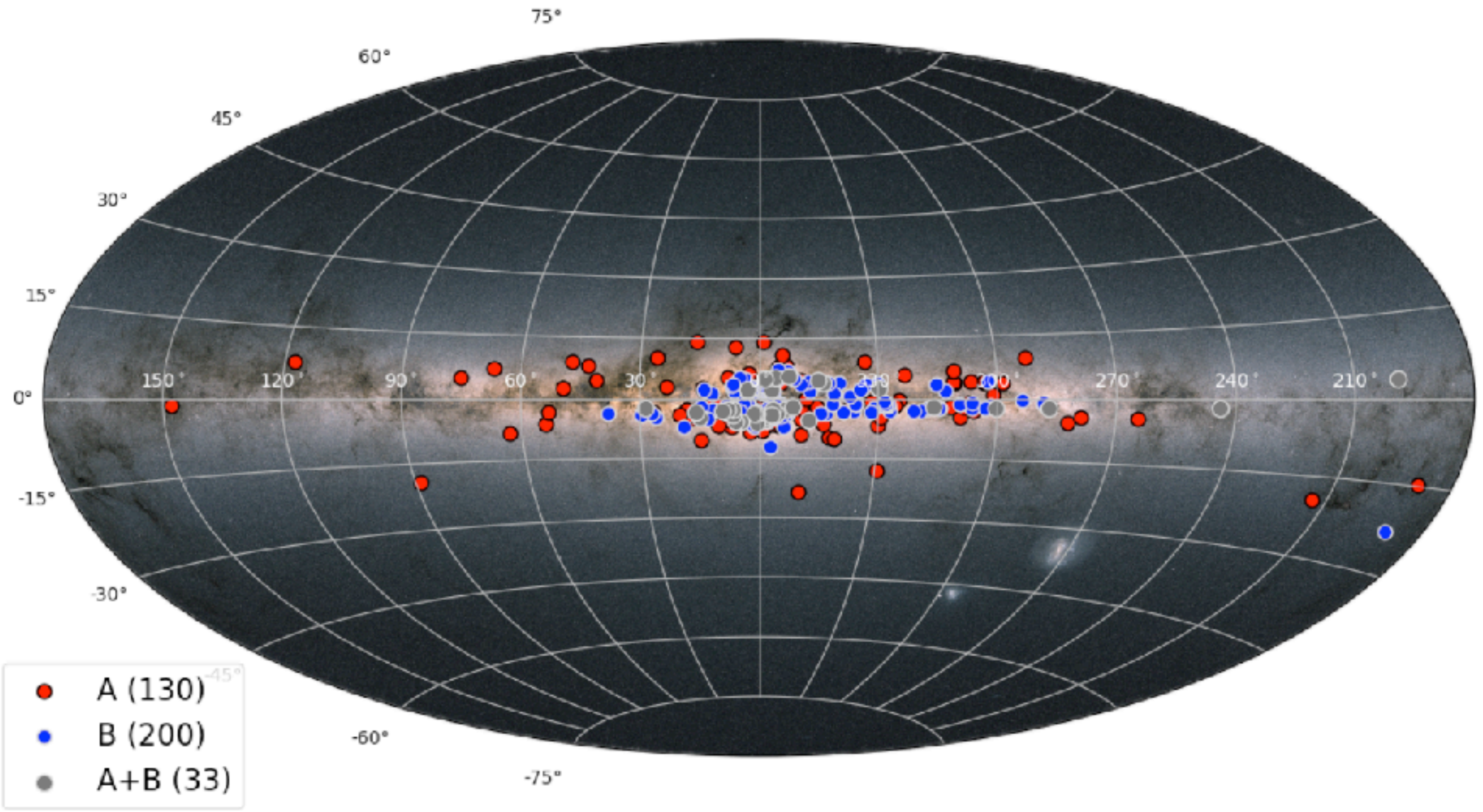
   - **GAIA:** 363 events (2206.06121)



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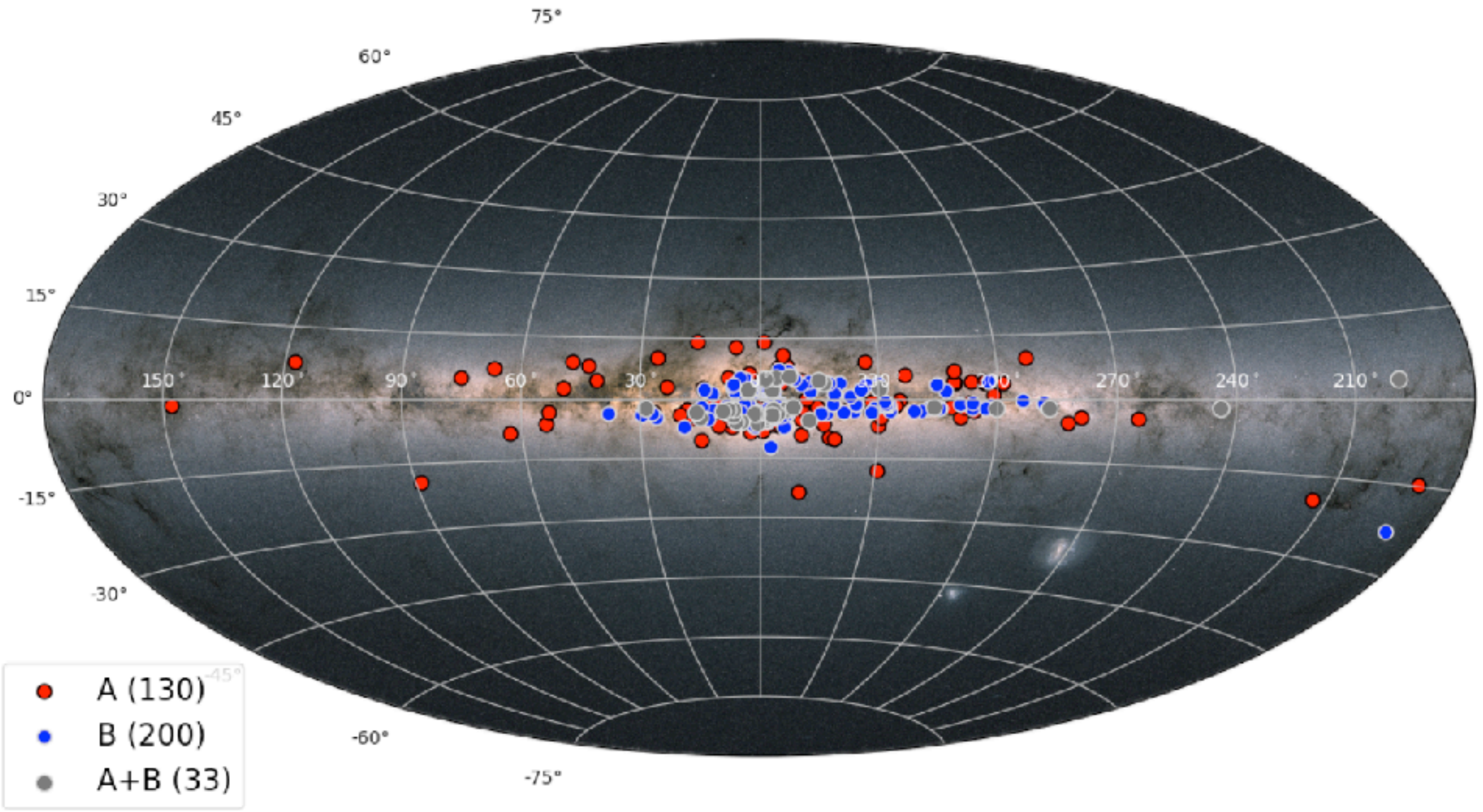

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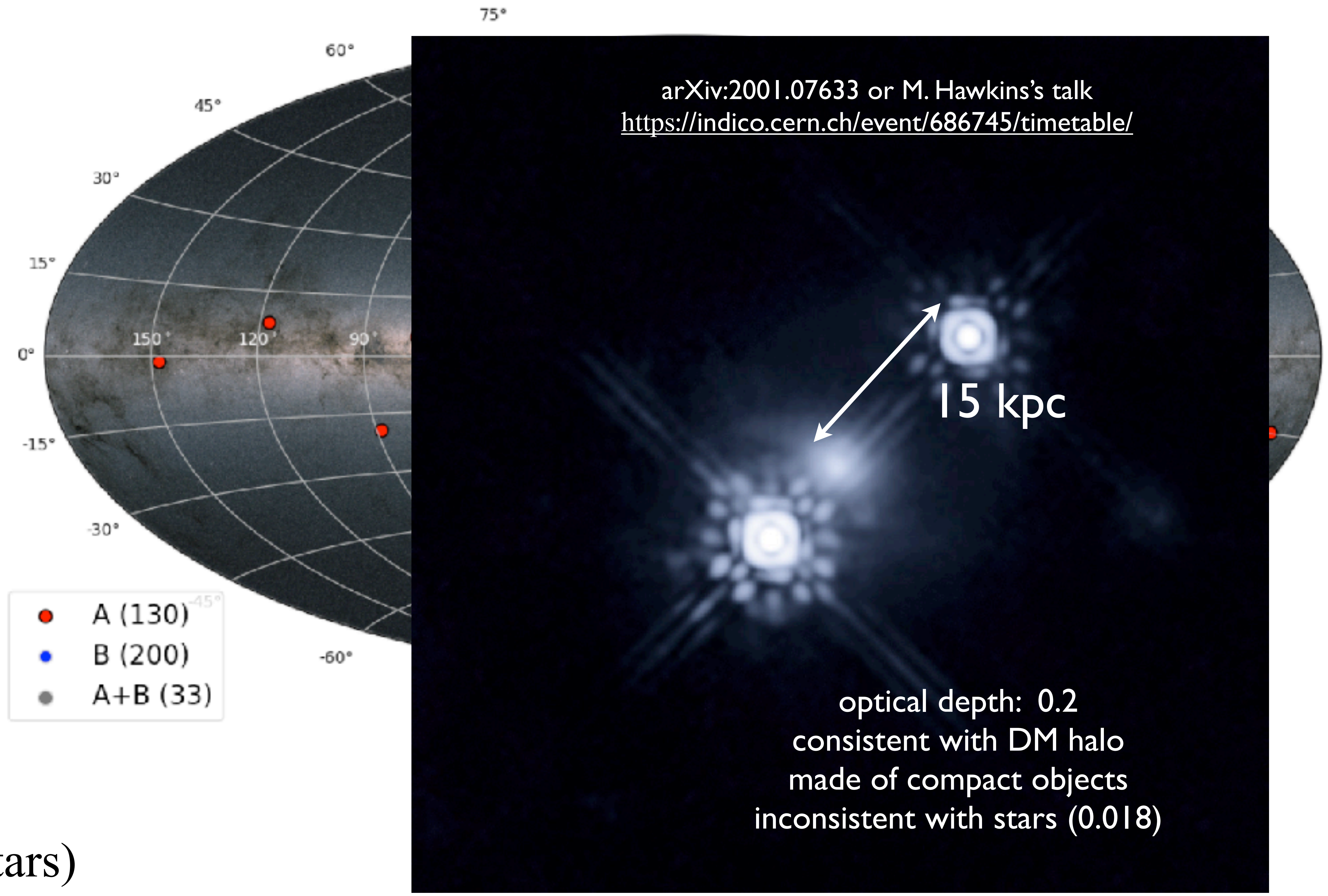

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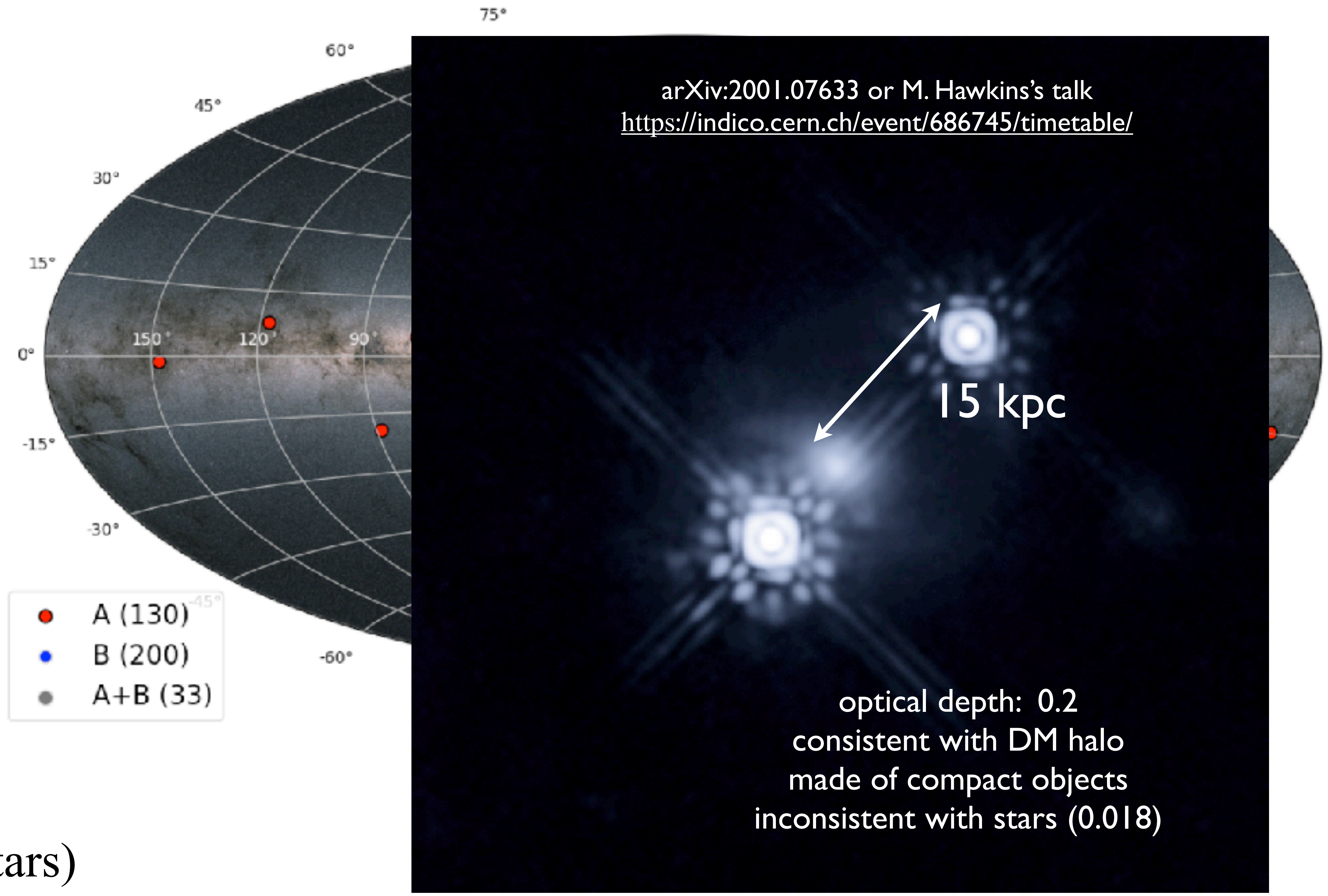
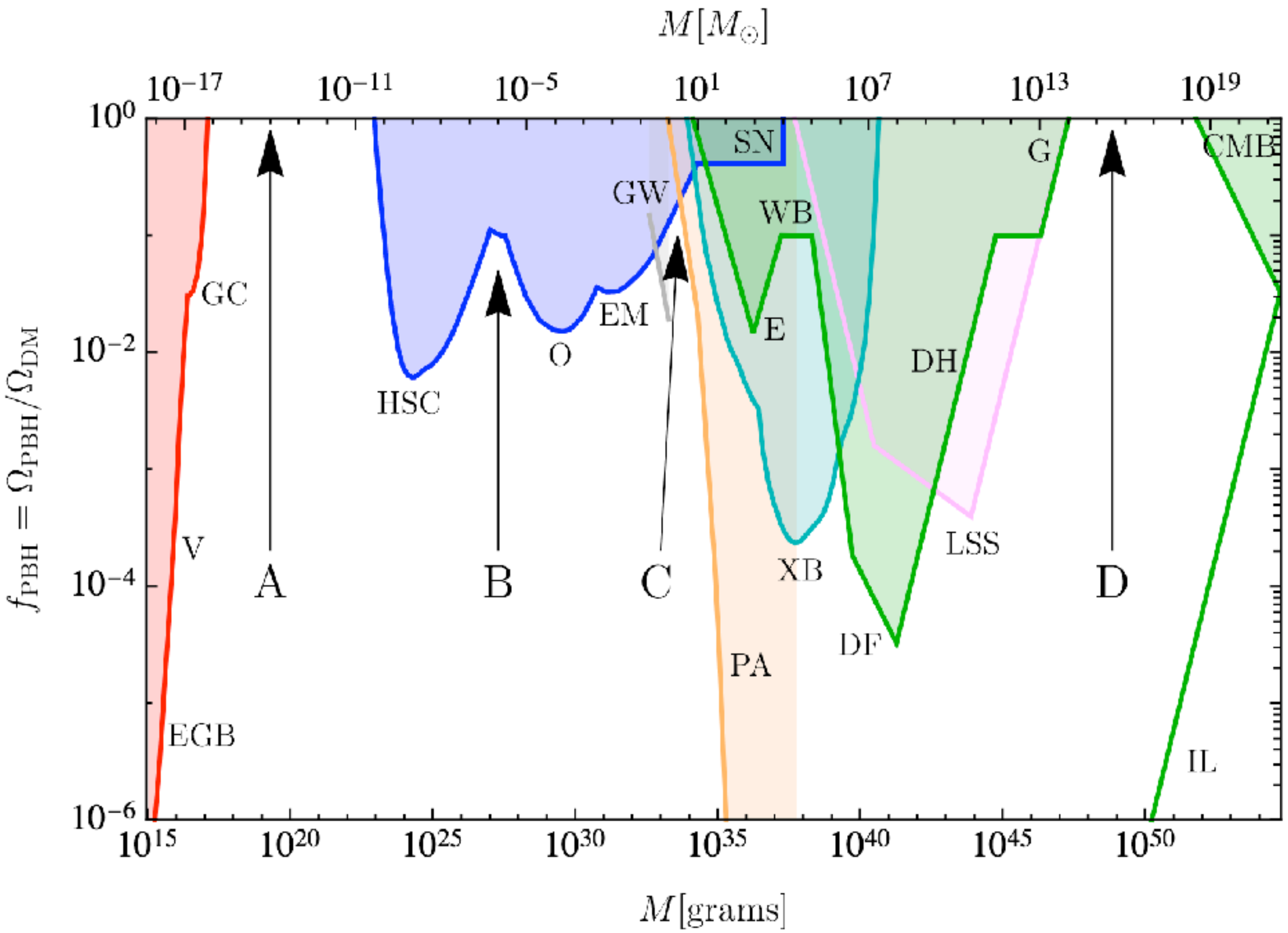
5. In **Supernovae** (Zumalacarregui&Seljak 18, Garcia-Bellido,S.C., Fleury 18)
   - **Weak limits or no limit** in stellar-mass range



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

CMB

Dynamical effects

Accretion

Large scale structures

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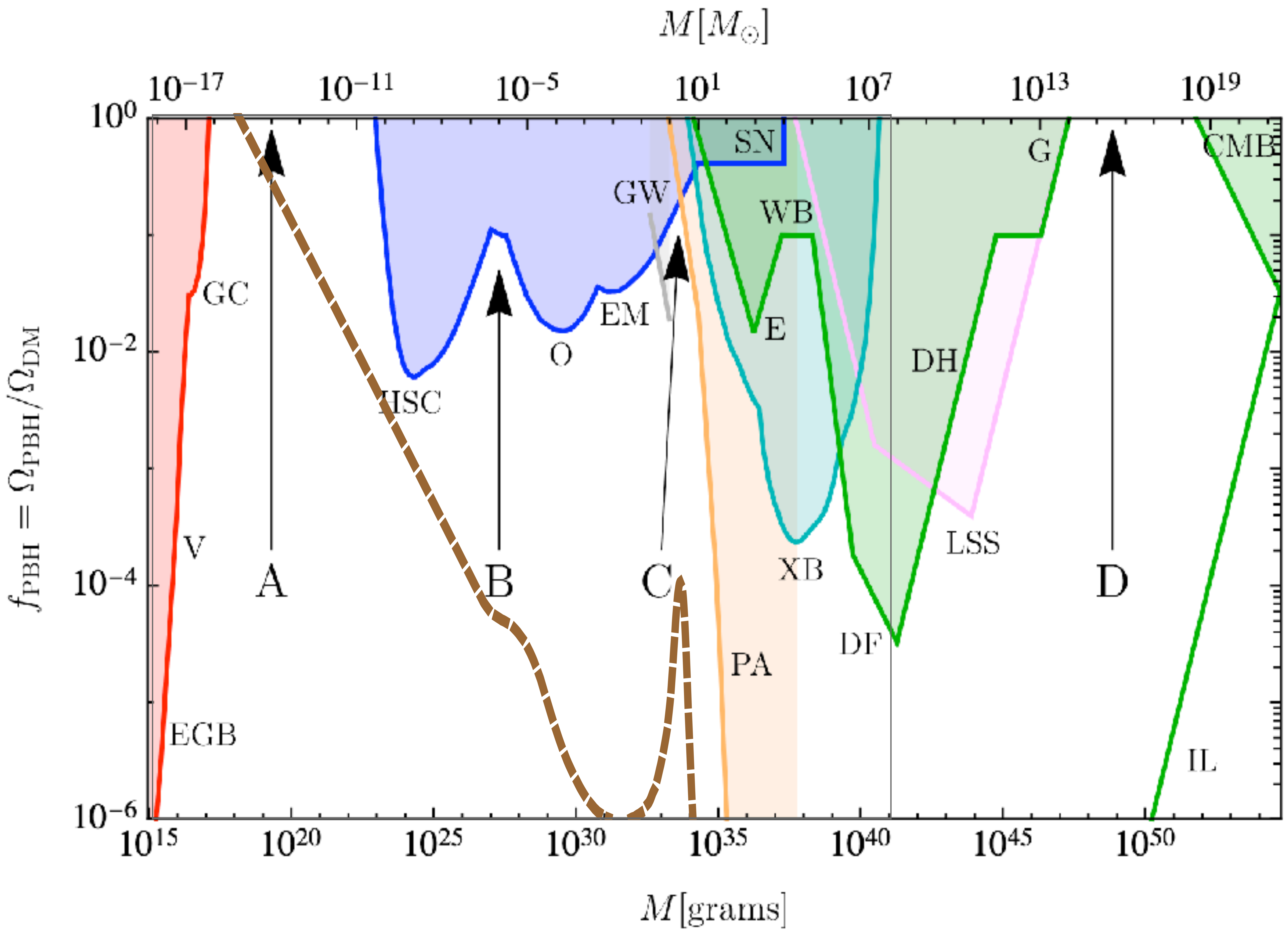

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- ✓ 10-100 solar mass region excluded by several probes
- ✓ No limit on asteroid-masses
- ✓ If PBHs + WIMPs (or particle DM) => stronger limits (e.g. [Serpico+20] [Carr+20] [Byrnes+] [Boudaud+21])

De Luca, Franciolini, Riotto et al., 2009.08268

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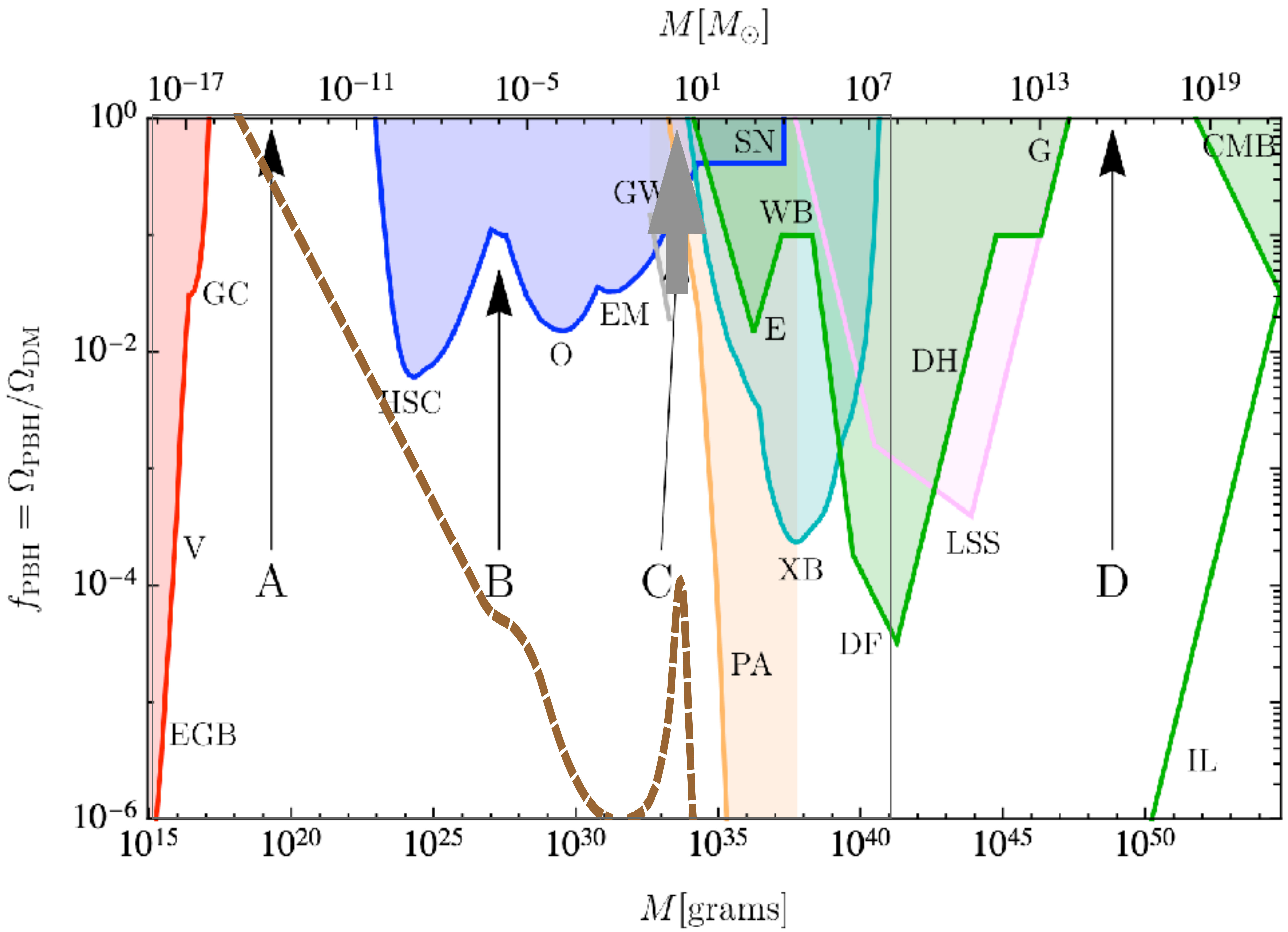

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- ✓ If PBHs + WIMPs (or particle DM) => stronger limits (e.g. [Serpico+20] [Carr+20] [Byrnes+] [Boudaud+21])

- ◉ Poisson clustering often not included in limits
- ◉ LIGO/Virgo subsolar limits less stringent
- ◉ Large levels of uncertainties in general

De Luca, Franciolini, Riotto et al., 2009.08268

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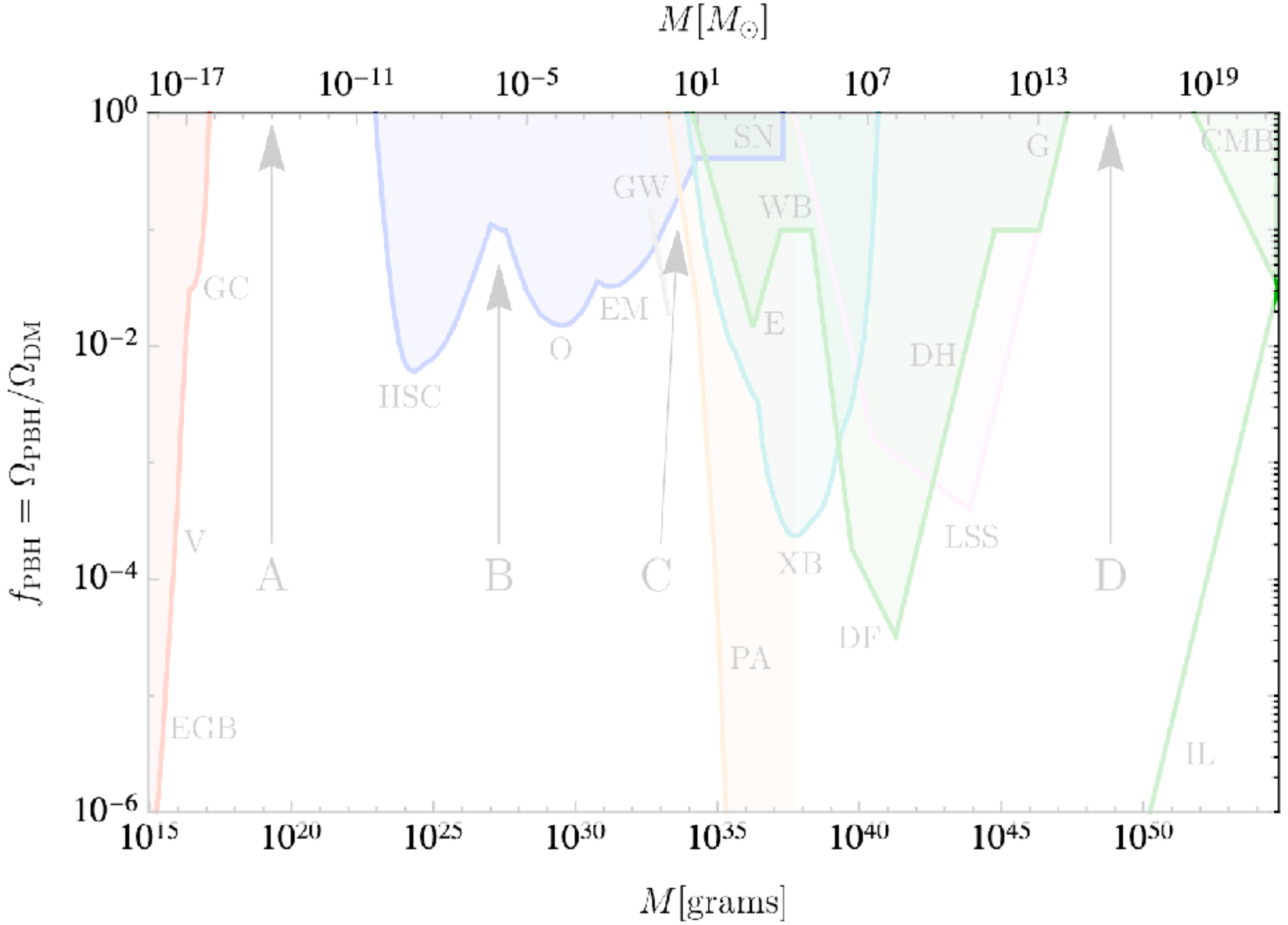
Carr+, 1906.08217



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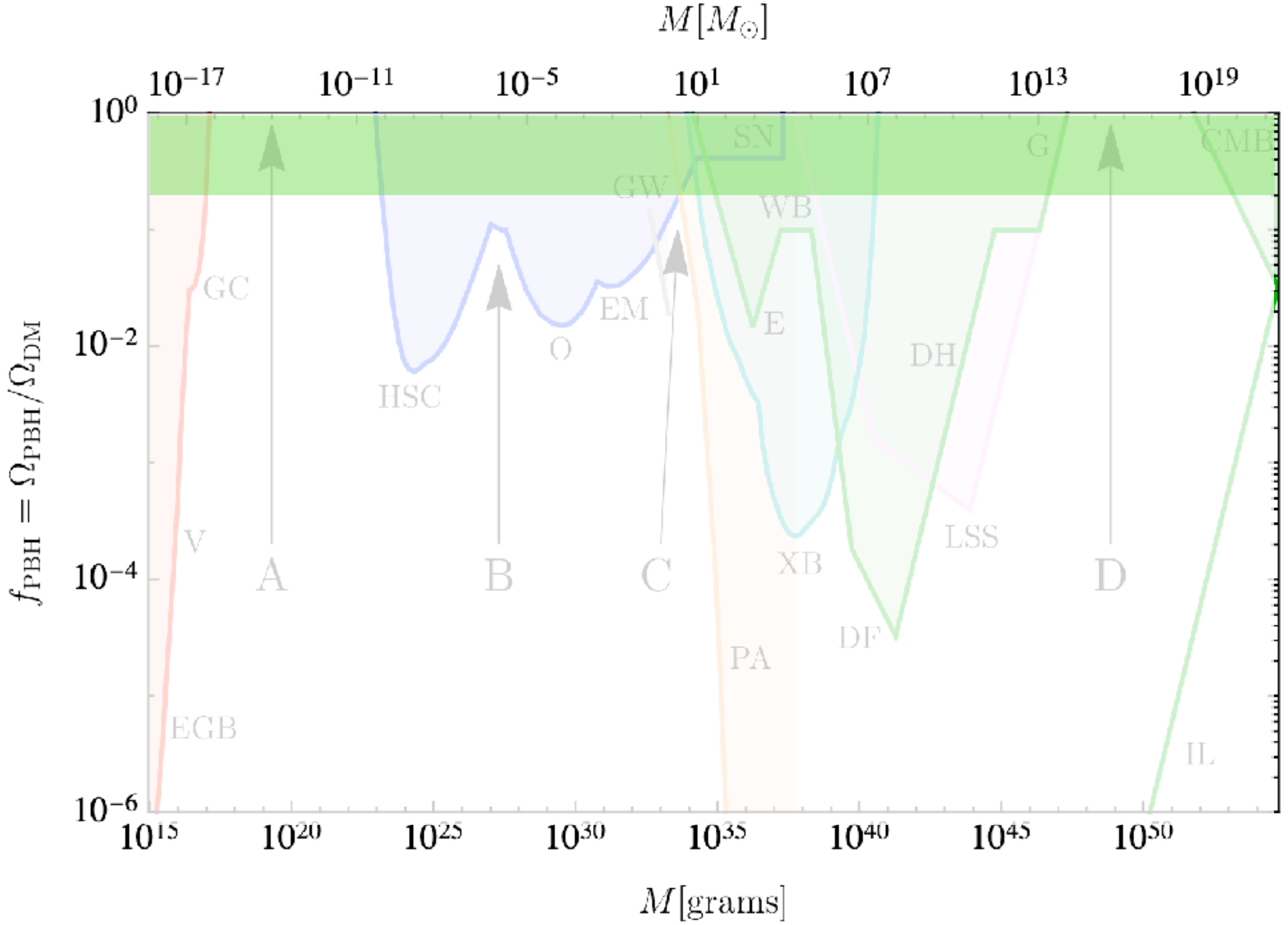

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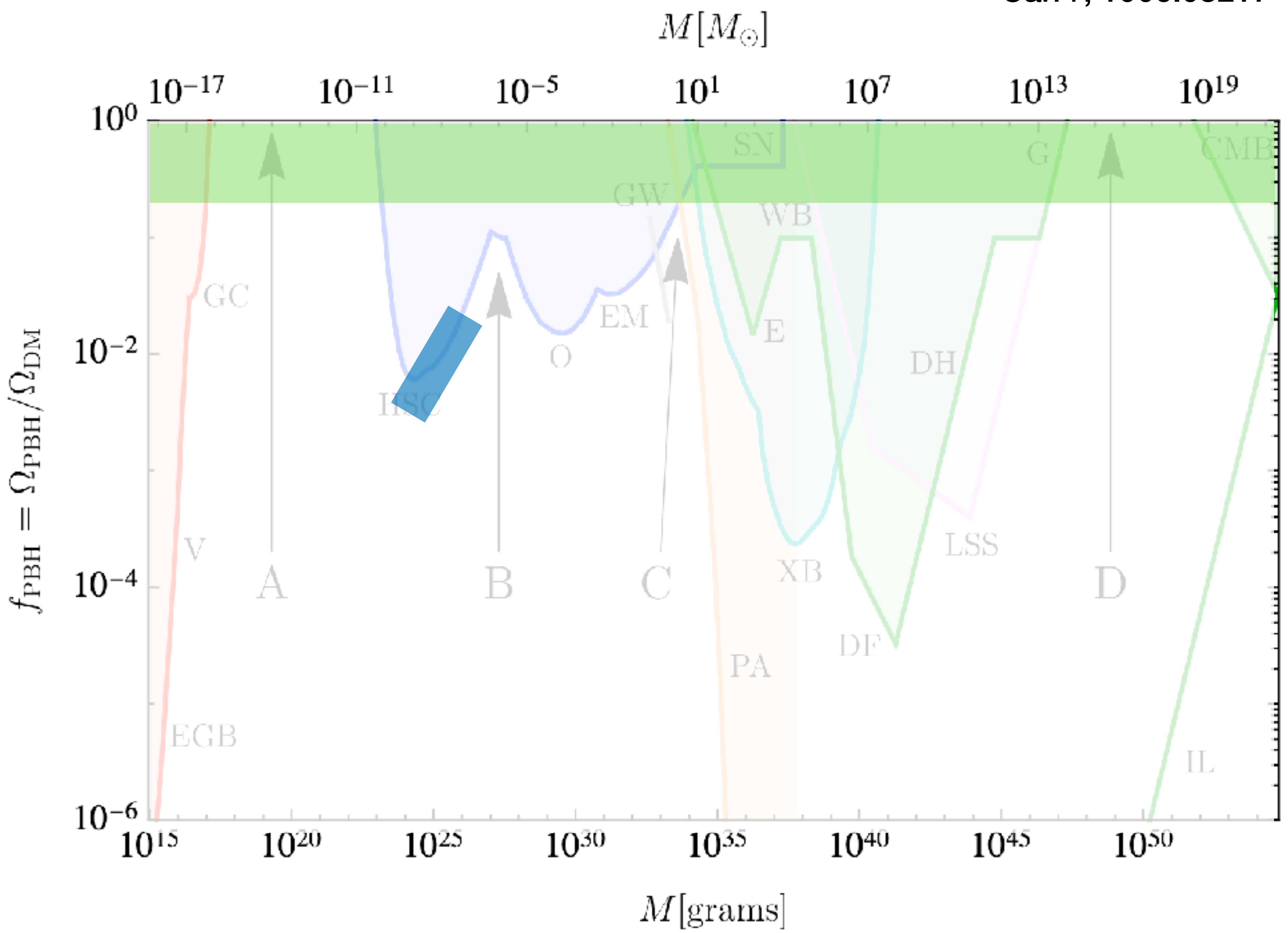

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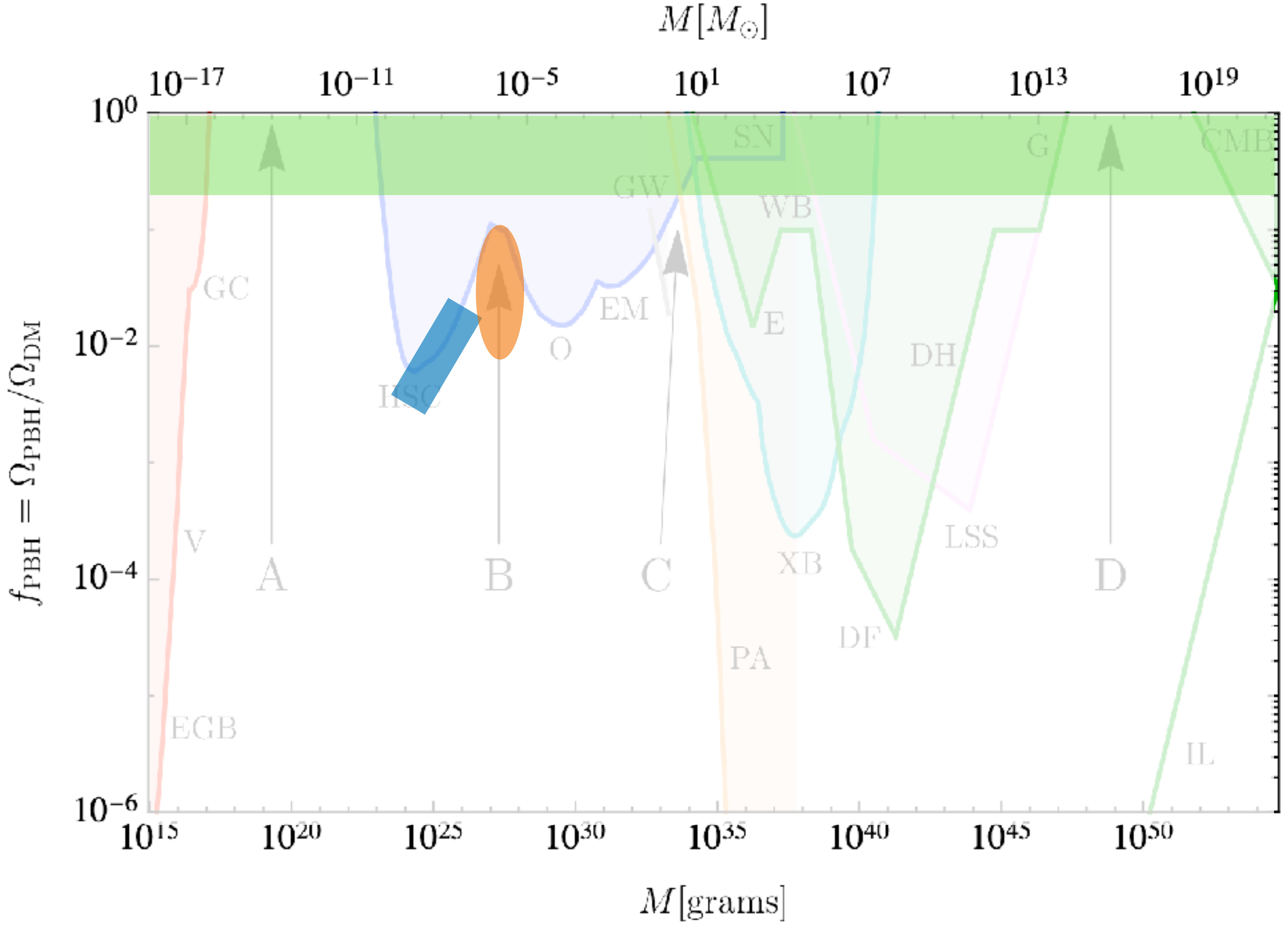

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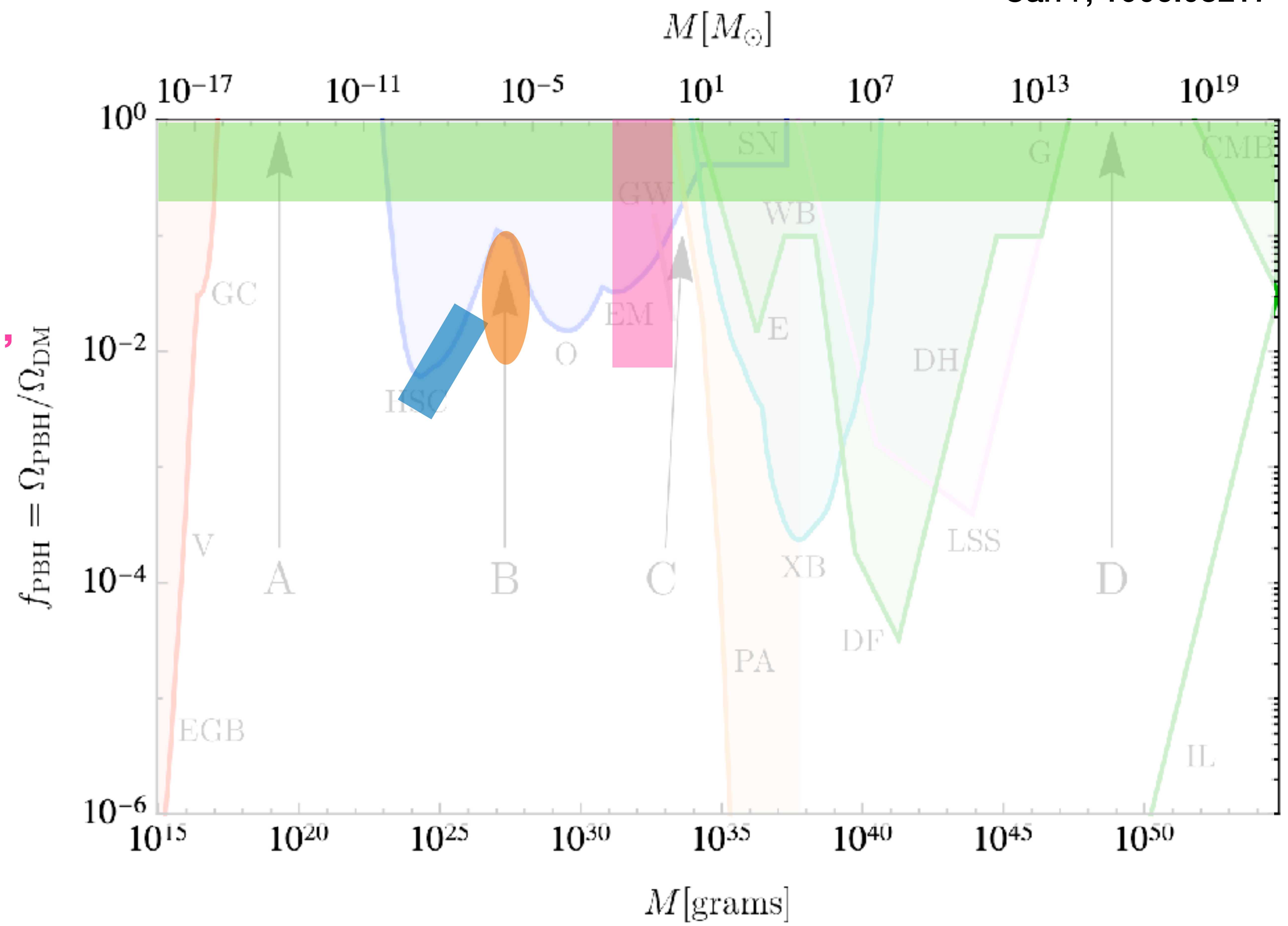

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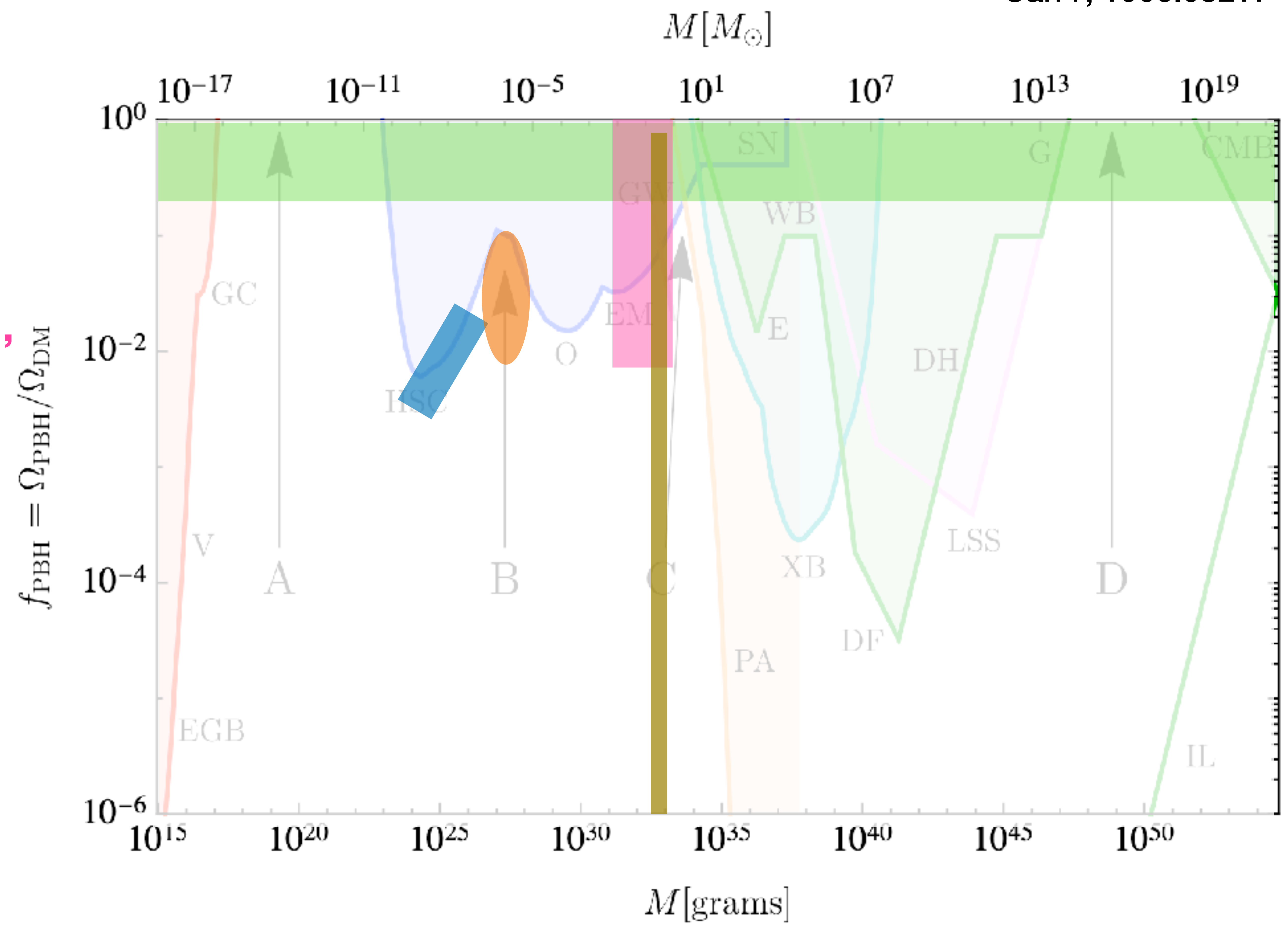

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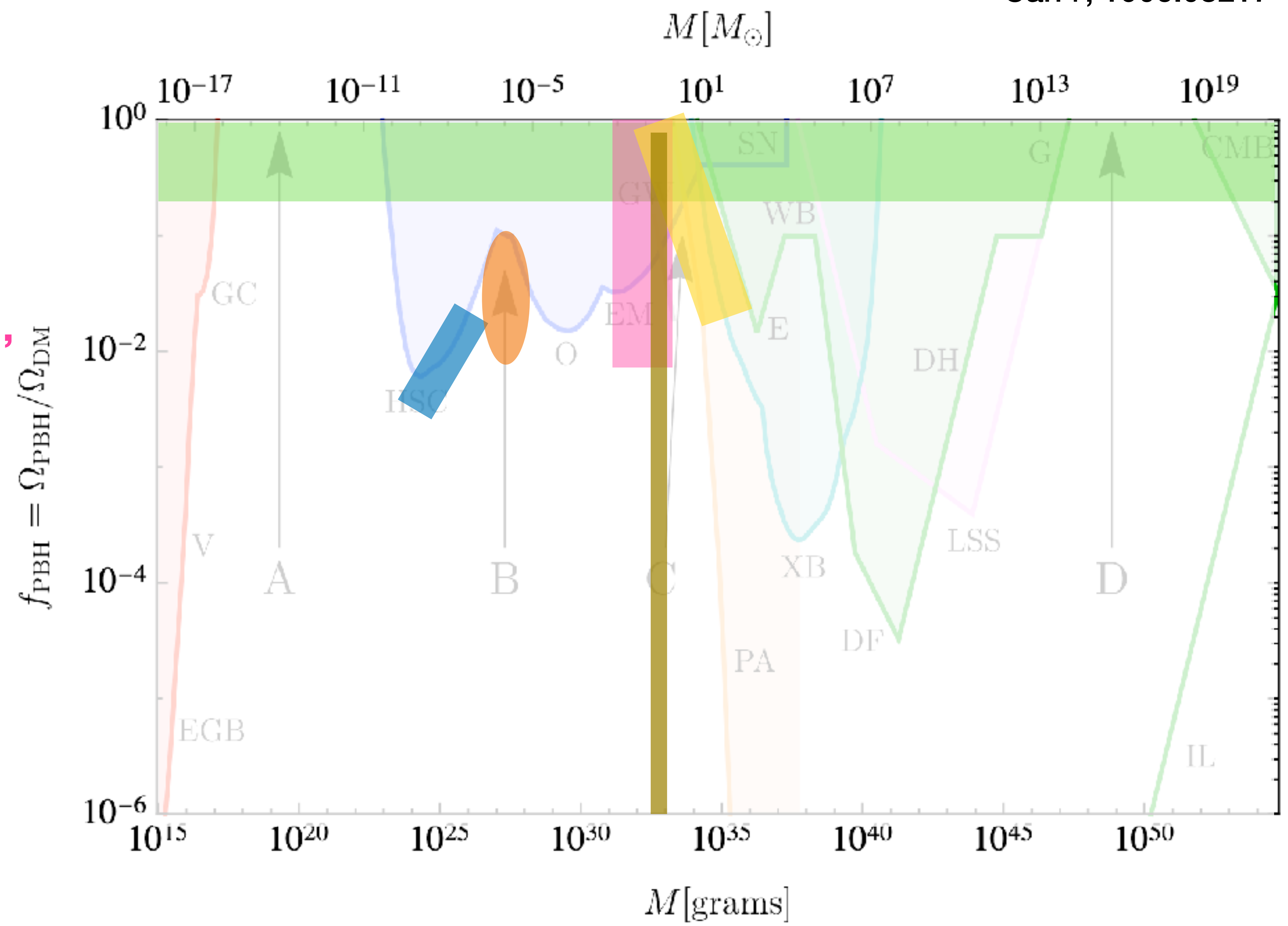

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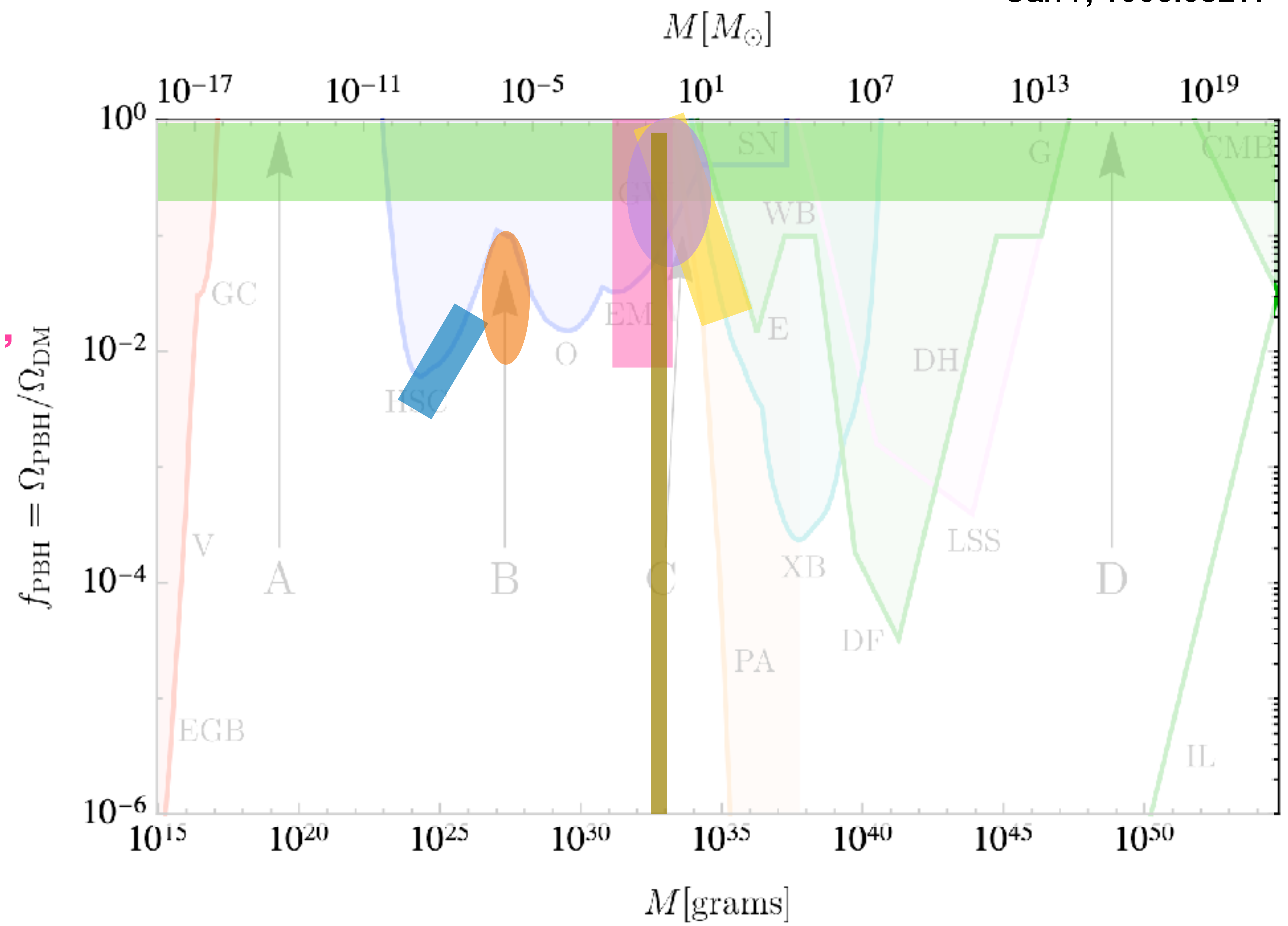

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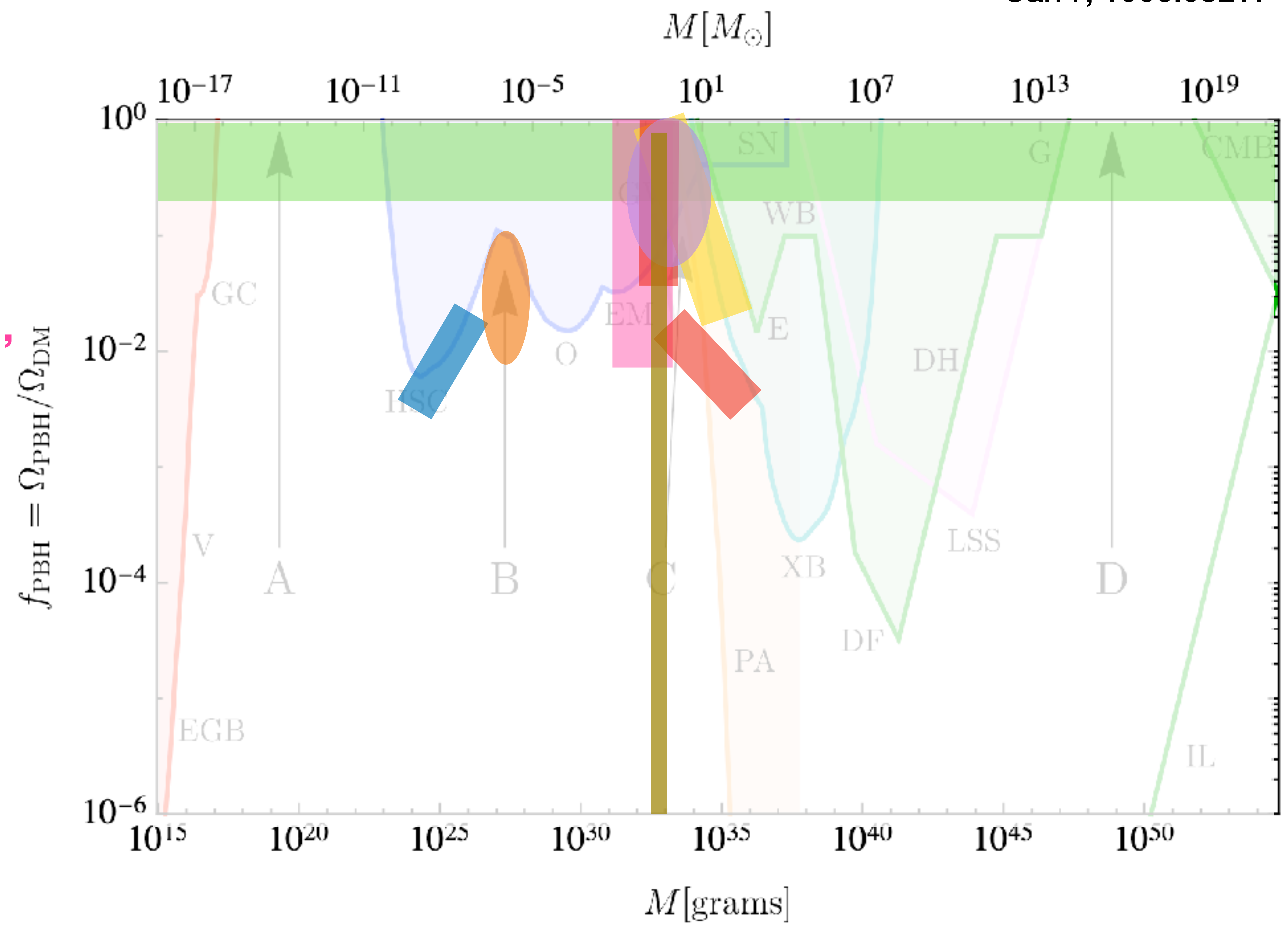

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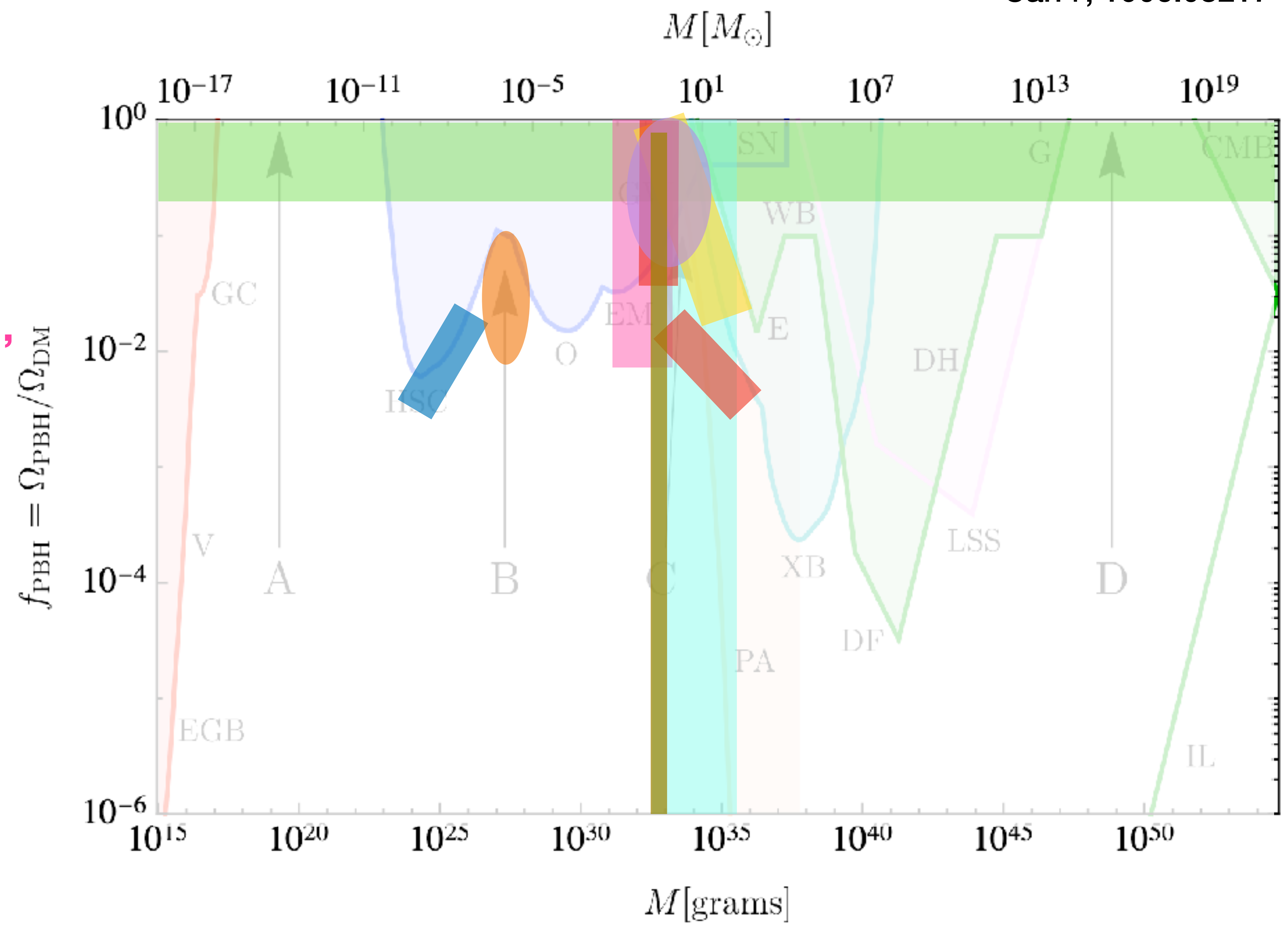

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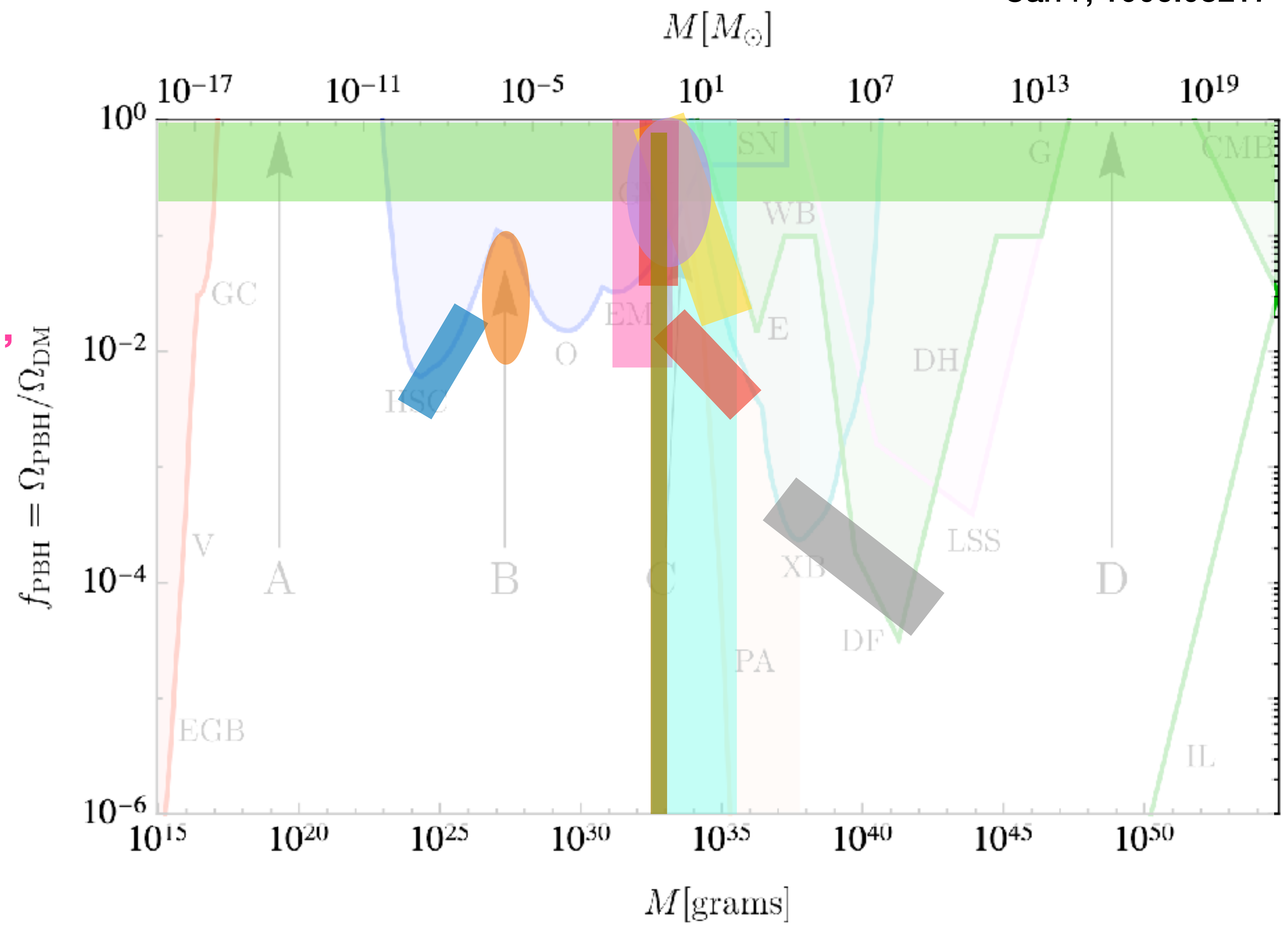

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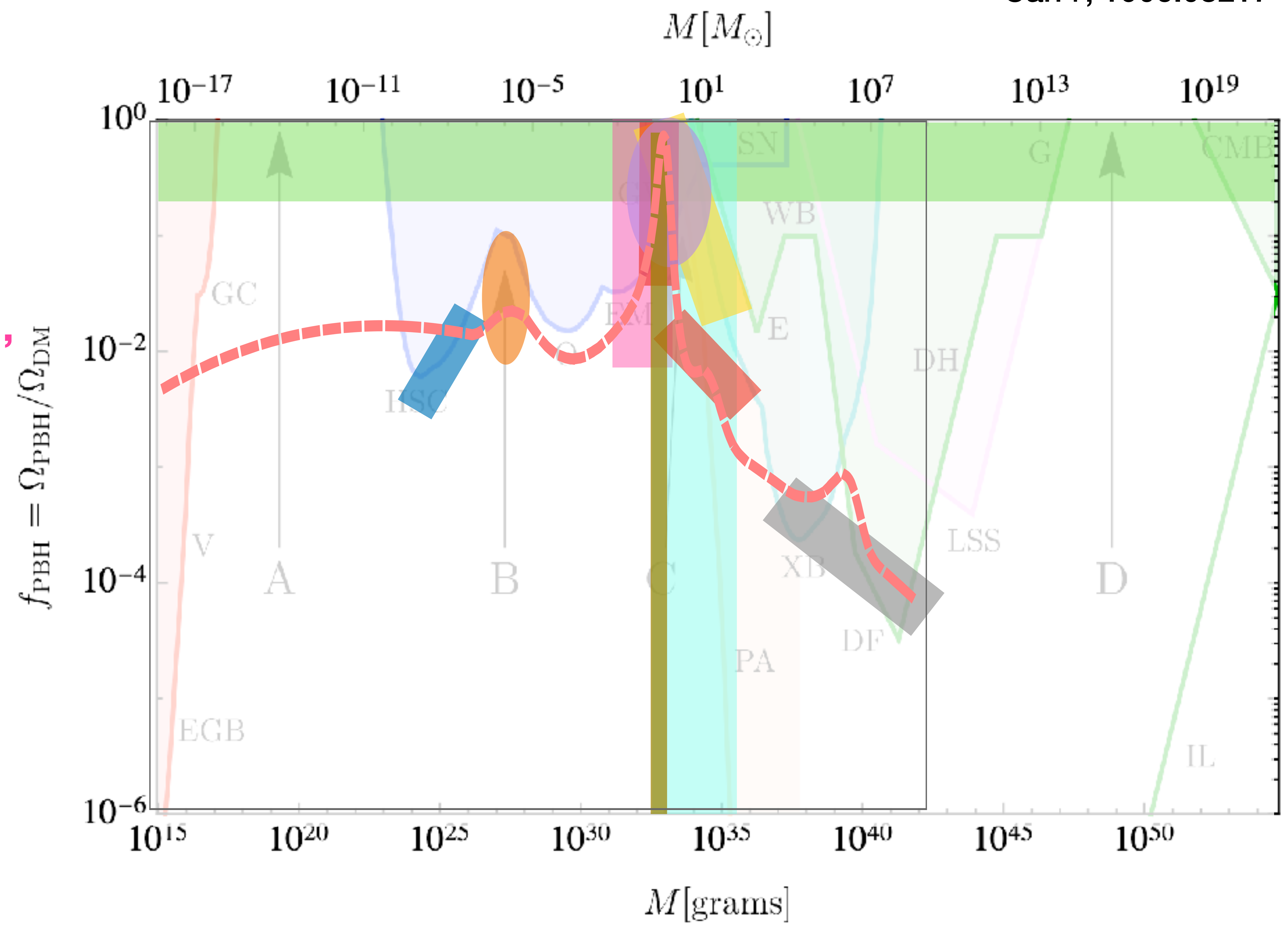

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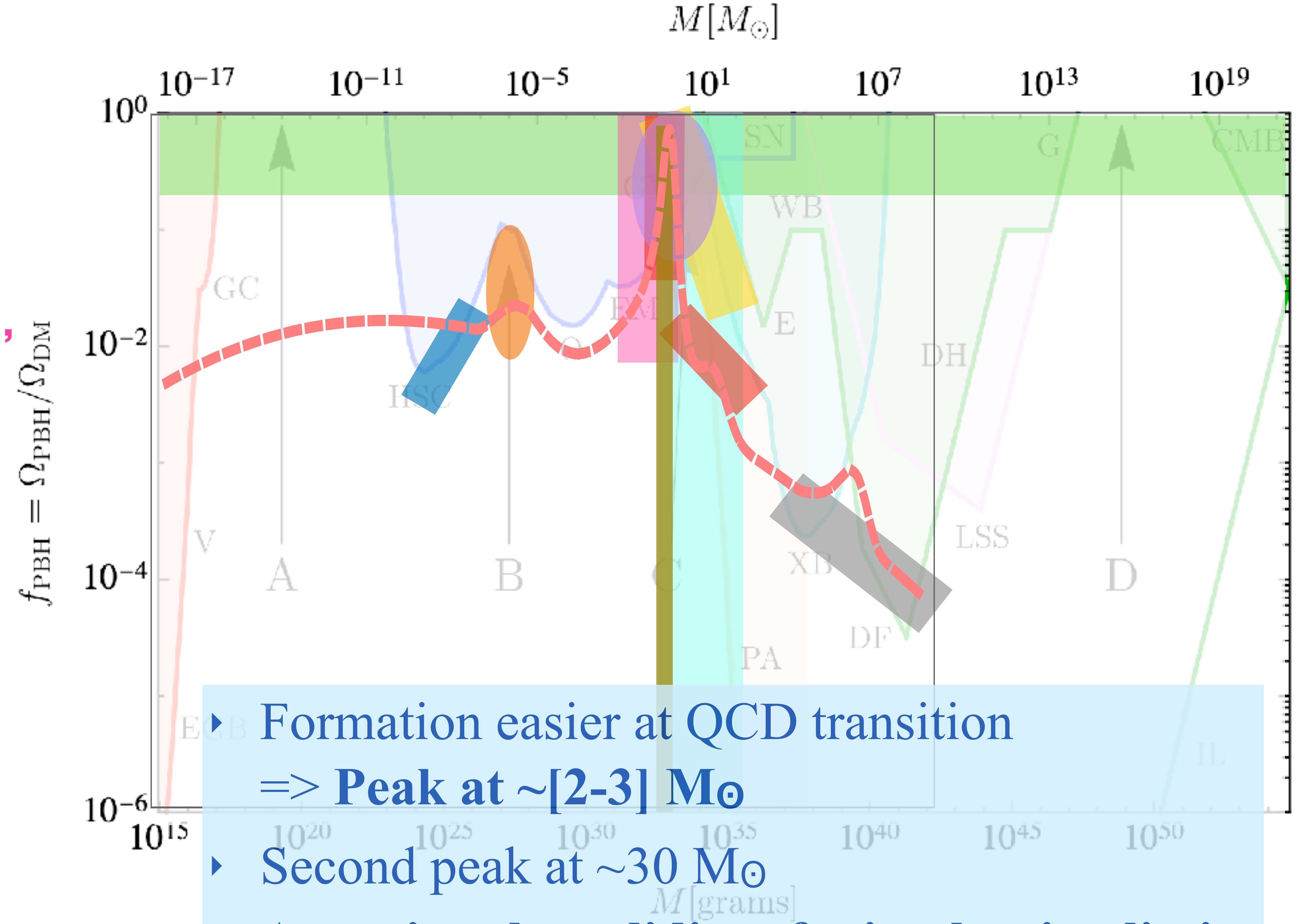


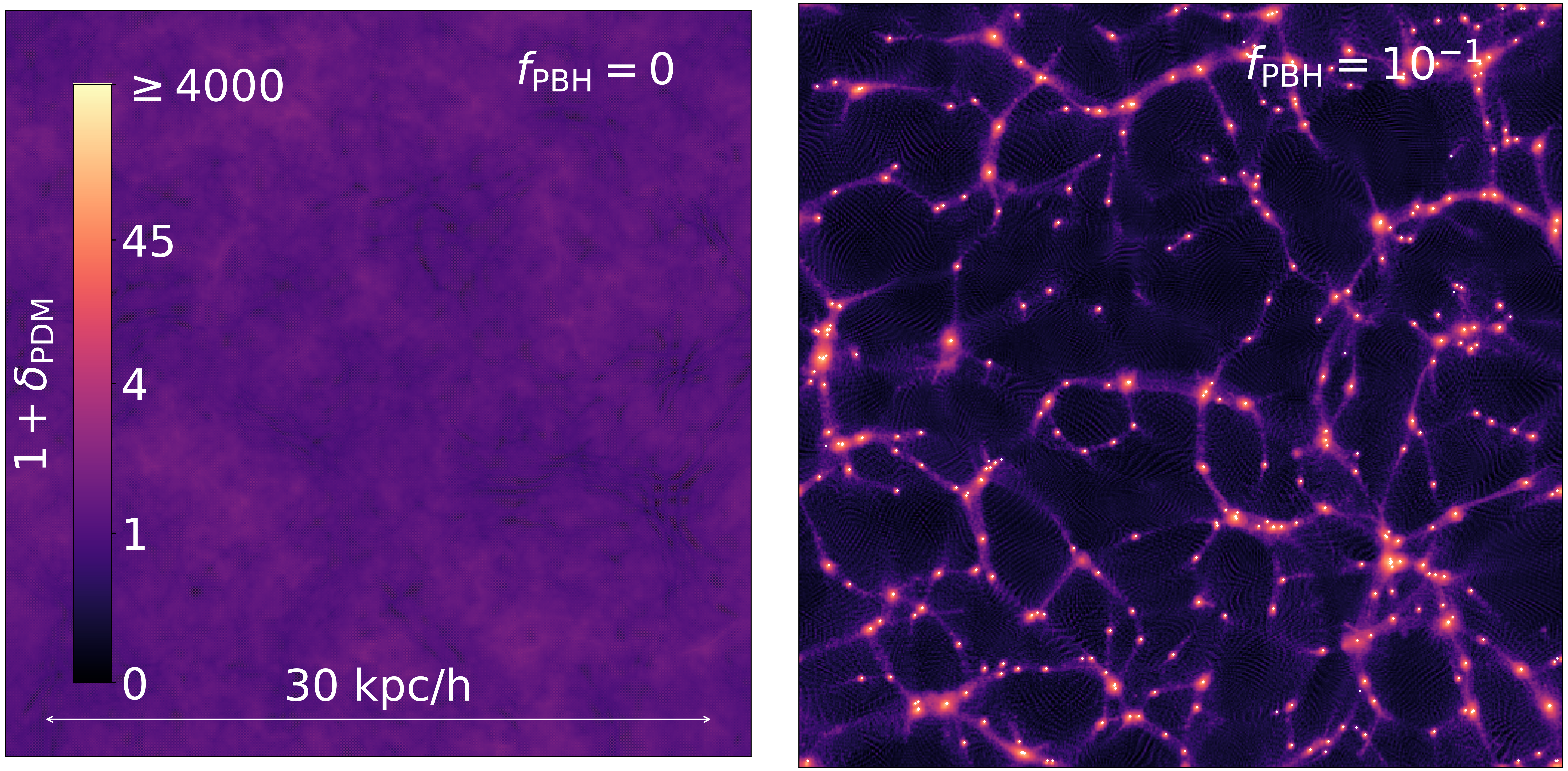
- Formation easier at QCD transition => **Peak at ~[2-3] M⊙**
- Second peak at ~30 M⊙
- **Assessing the validity of microlensing limits for Poisson clusters of PBHs is crucial**

3. The Poisson effect in a PBH sea

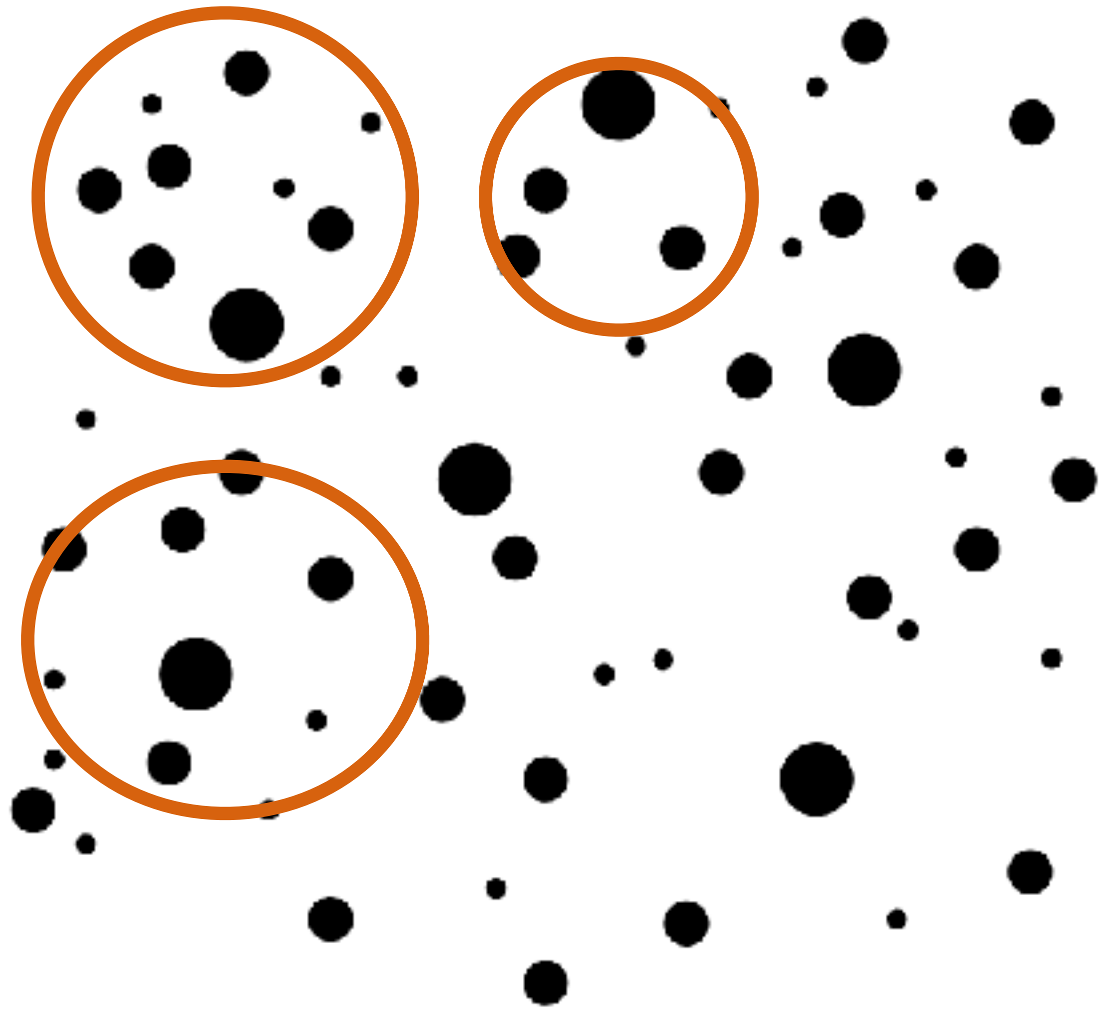
Inevitable clustering of primordial black holes

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

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



Ali-Haimoud 1805.05912

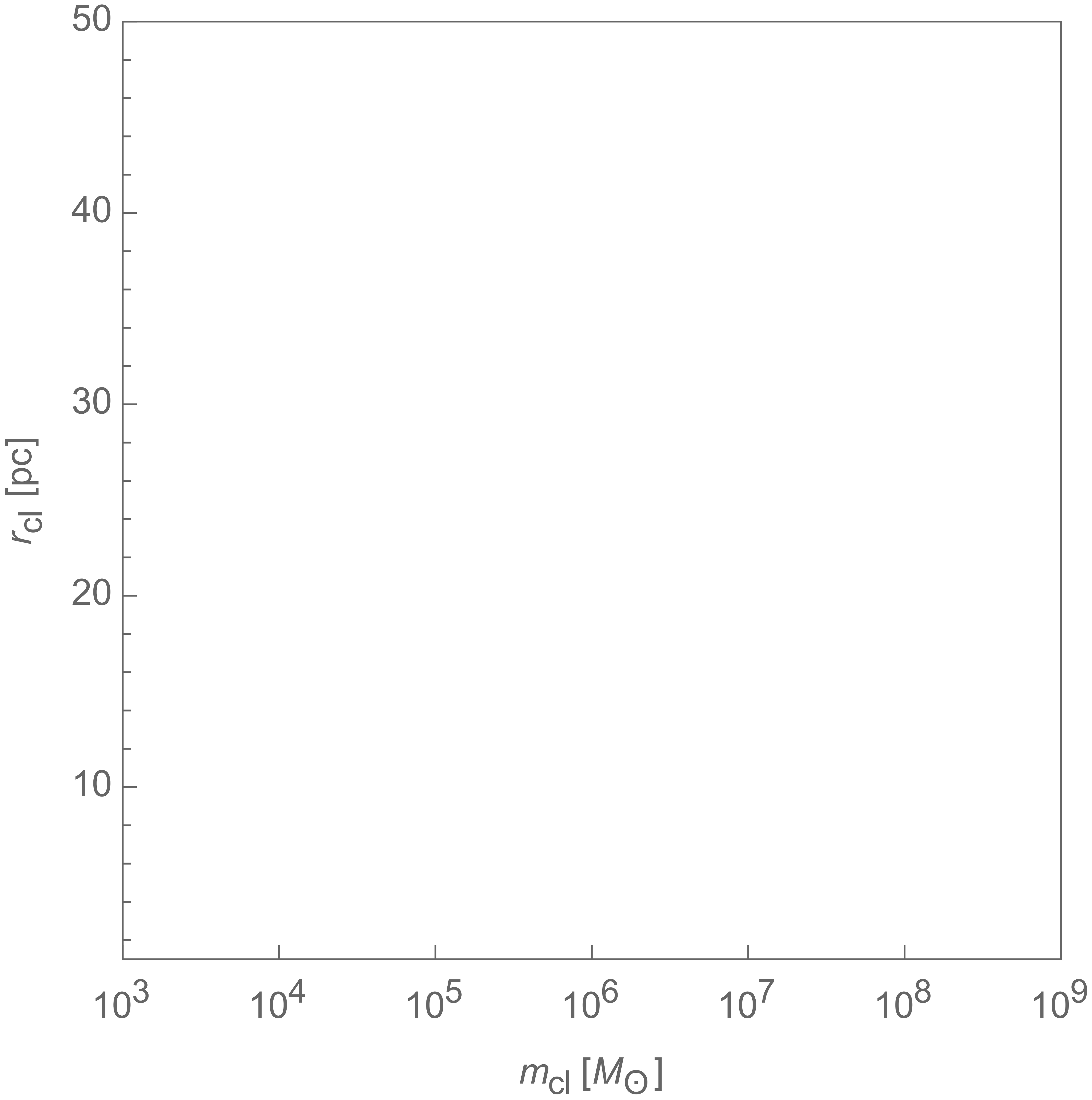


Sub-halos of 10^6 - 10^7 $M_{\odot}$

On small scales, completely different than particle-CDM !

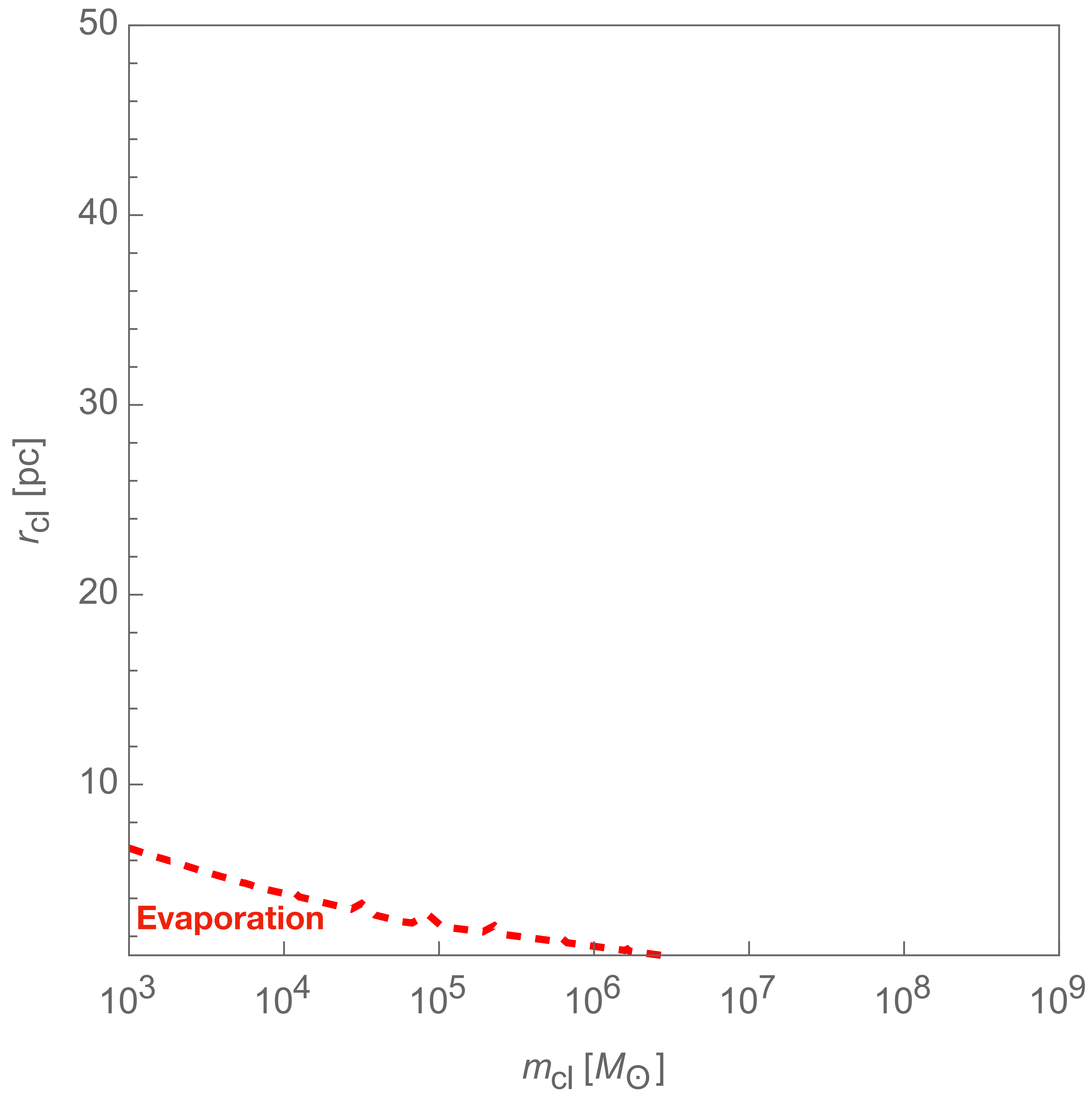
4. Our playground

PBH cluster size-mass relation



4. Our playground

PBH cluster evaporation

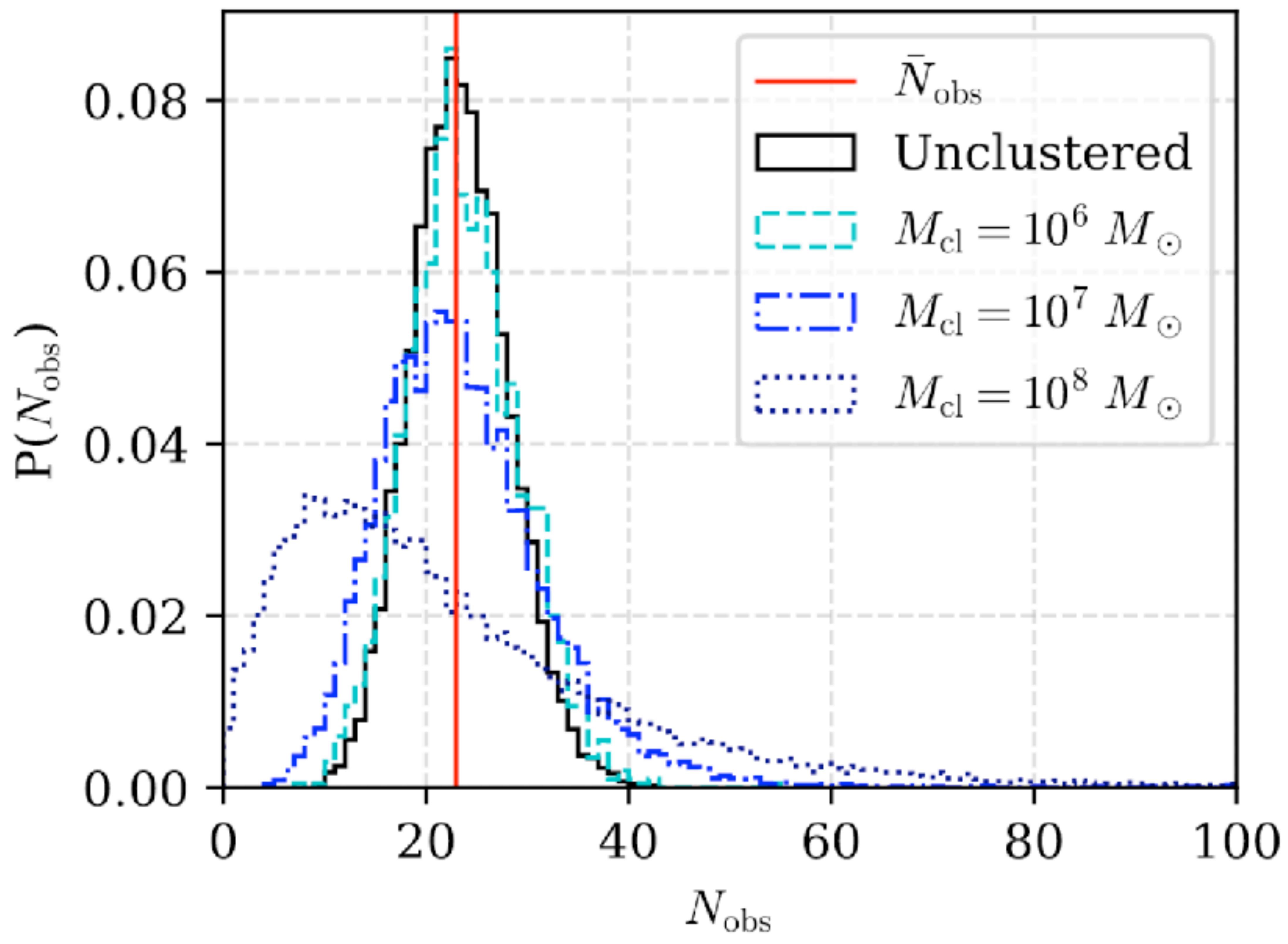


Compact clusters evaporate and are not single lenses: Petac, Lavalle, Jedamzik, 2201.02521

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

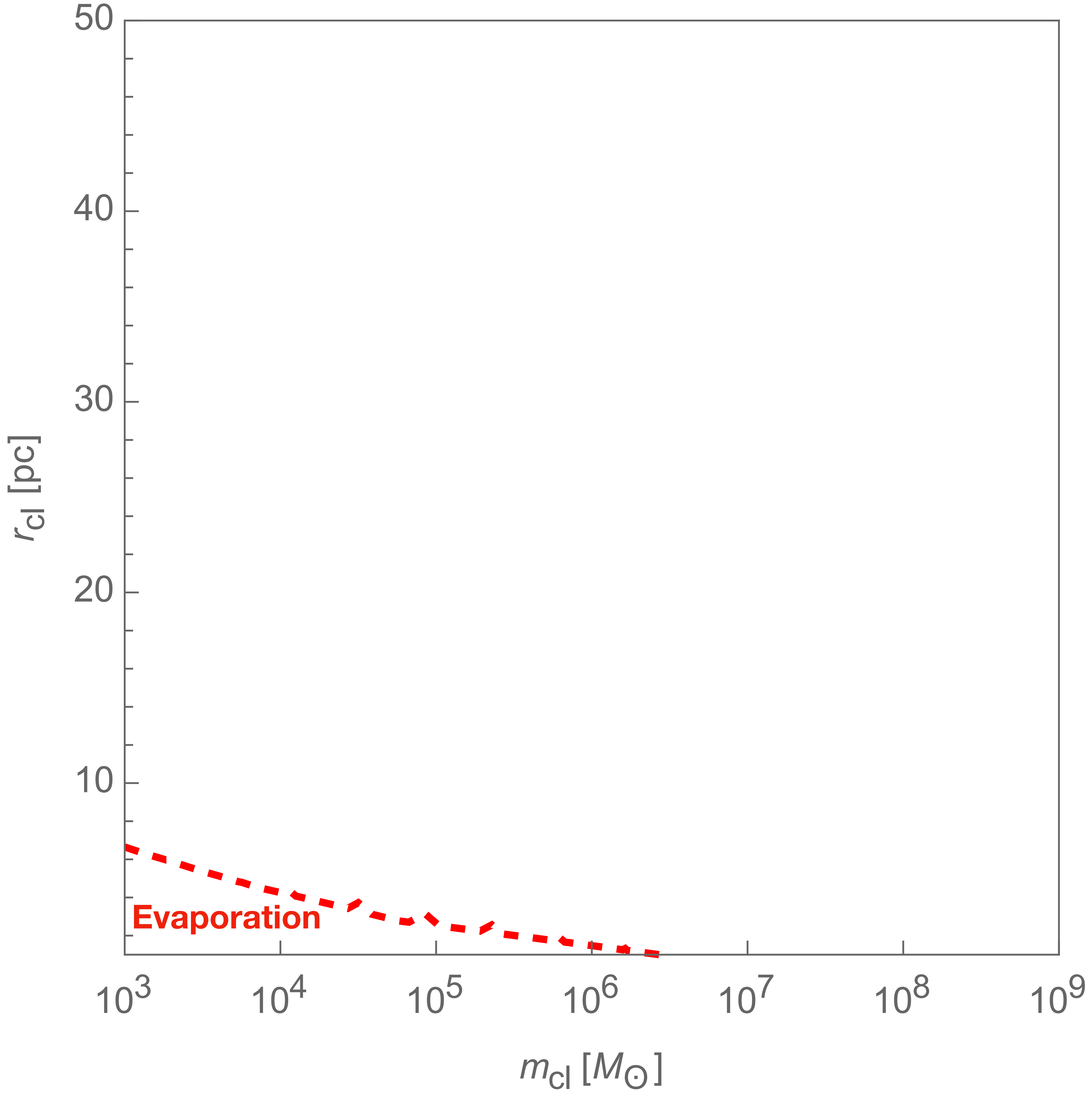
Crossing time: $t_{\rm cross} \sim r_{\rm cl}/v_{\rm cl}$

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



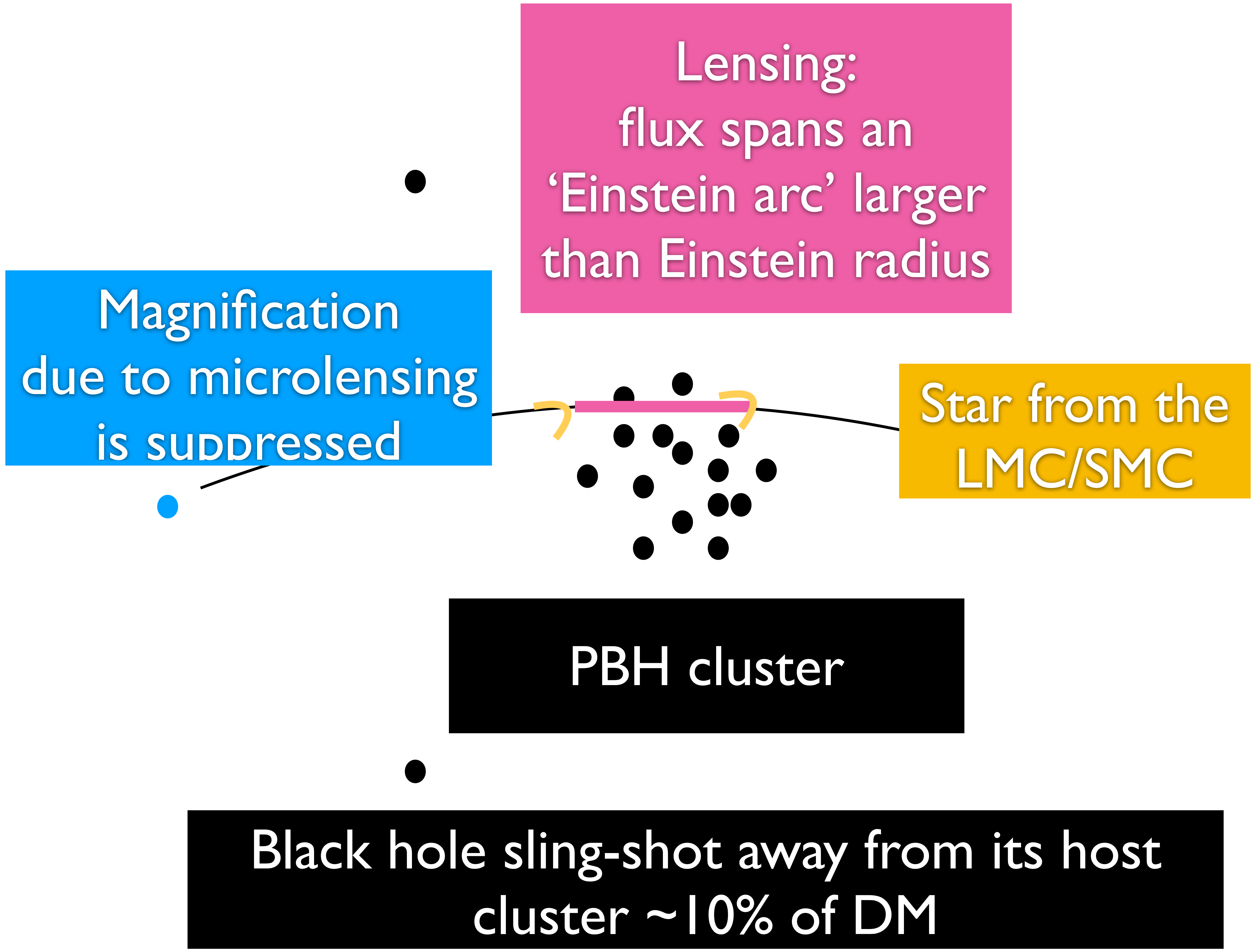
4. Our playground

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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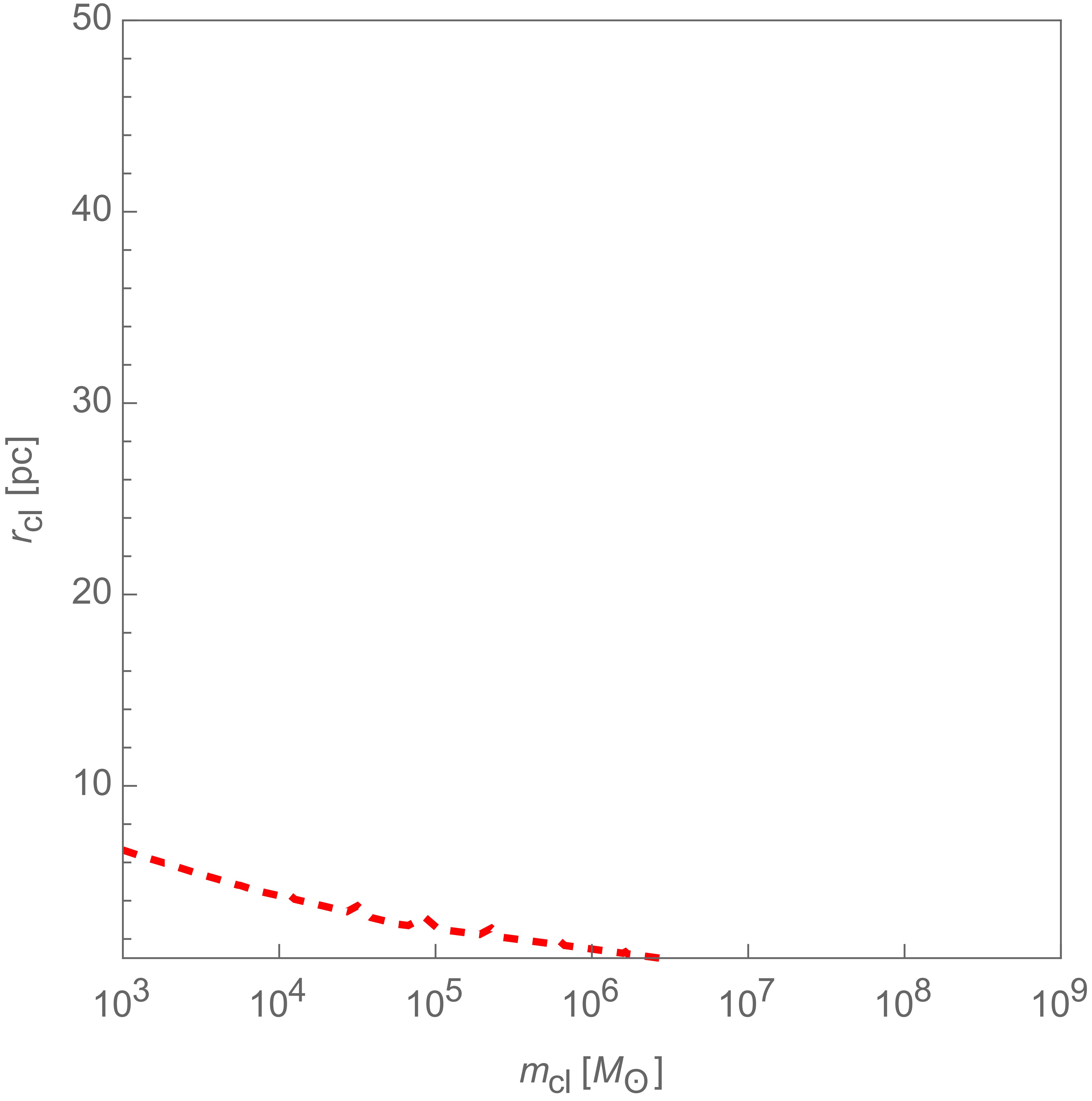

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Deflection angle:

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

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

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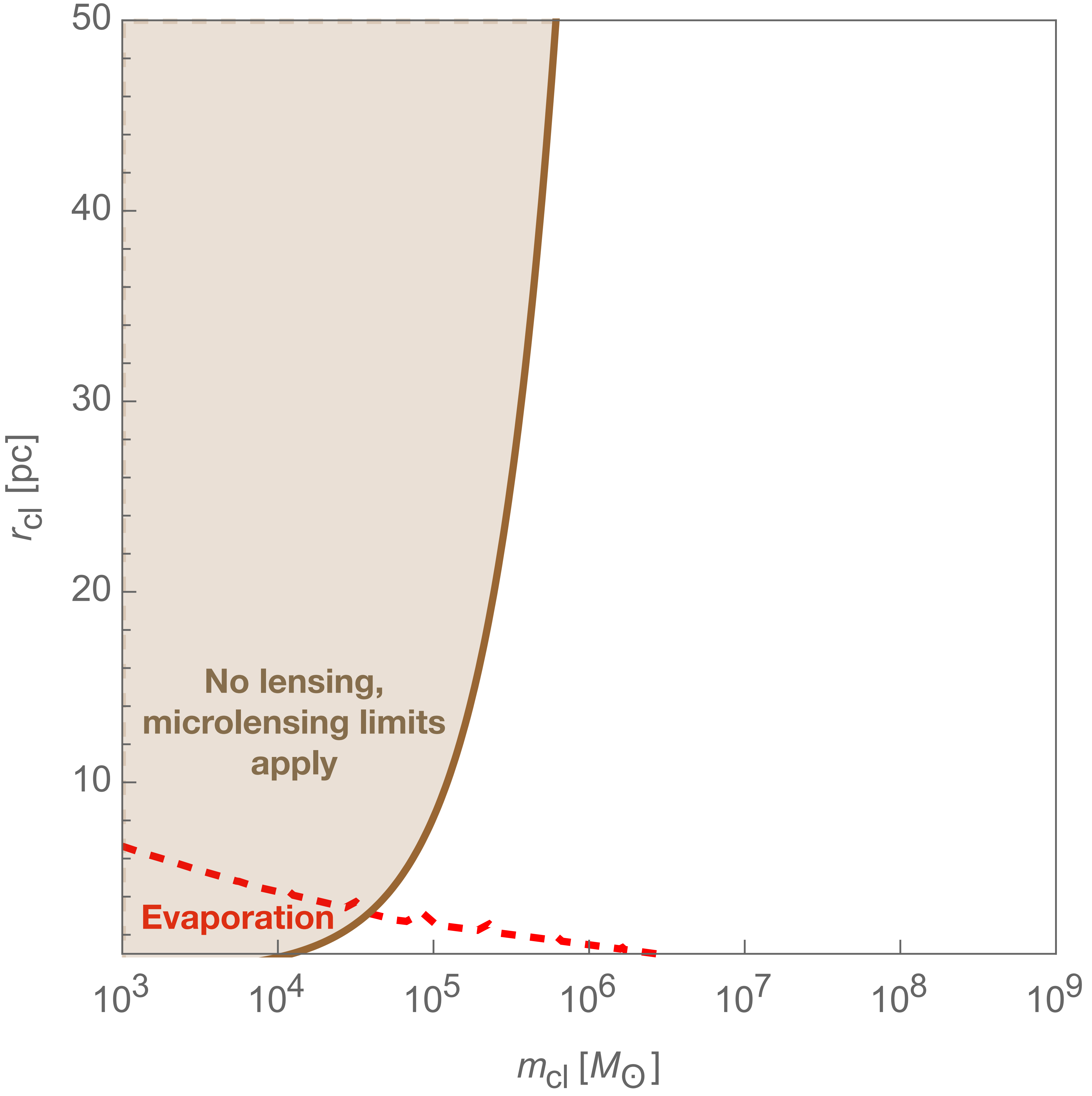

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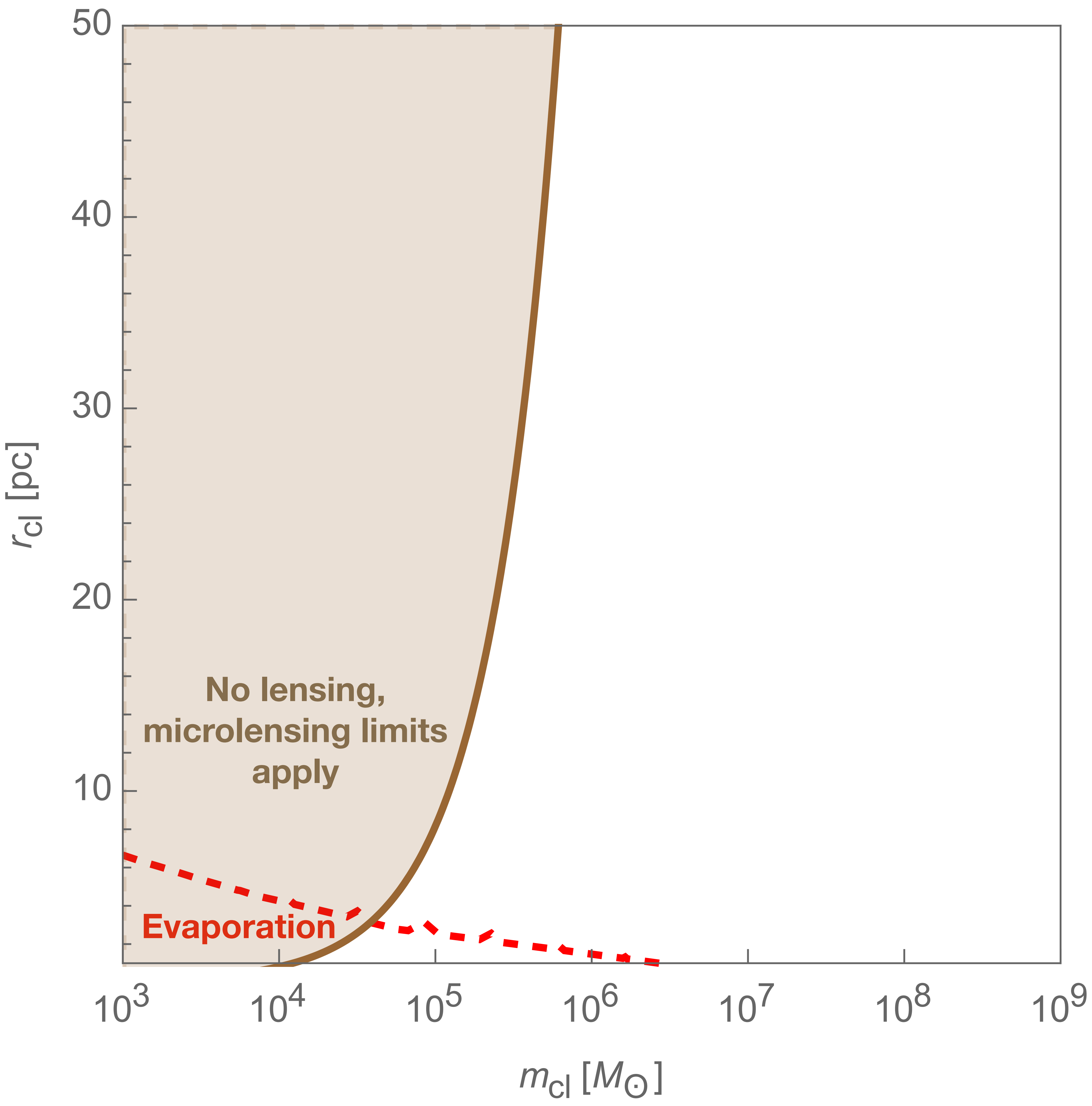
Dynamical heating



Compact clusters are dynamically heated

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

Increase of the cluster radius with time:

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

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)

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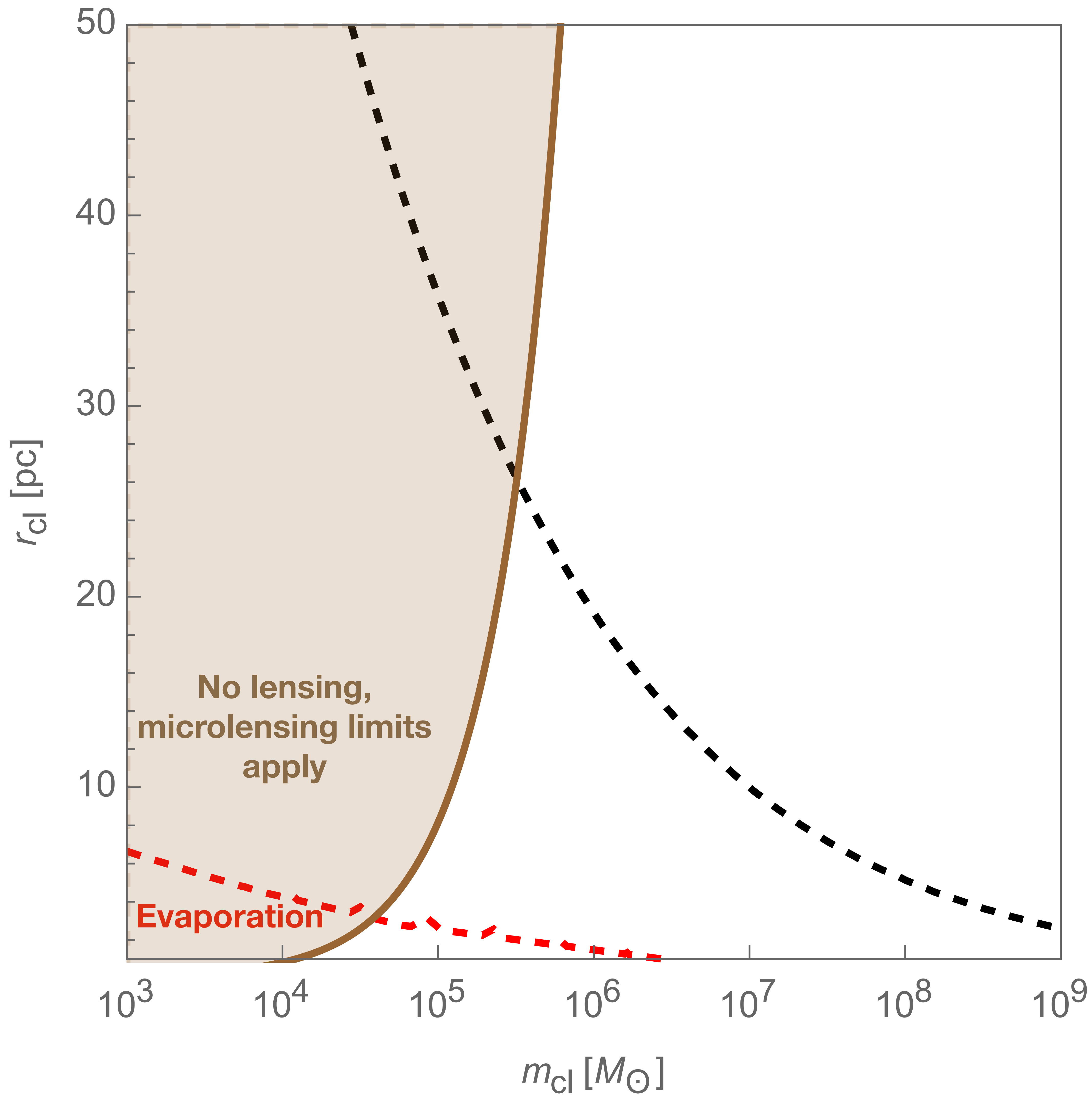

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S.C, Garcia-Bellido, 1711.10458

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

Poisson fluctuation = isocurvature fluctuation

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

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

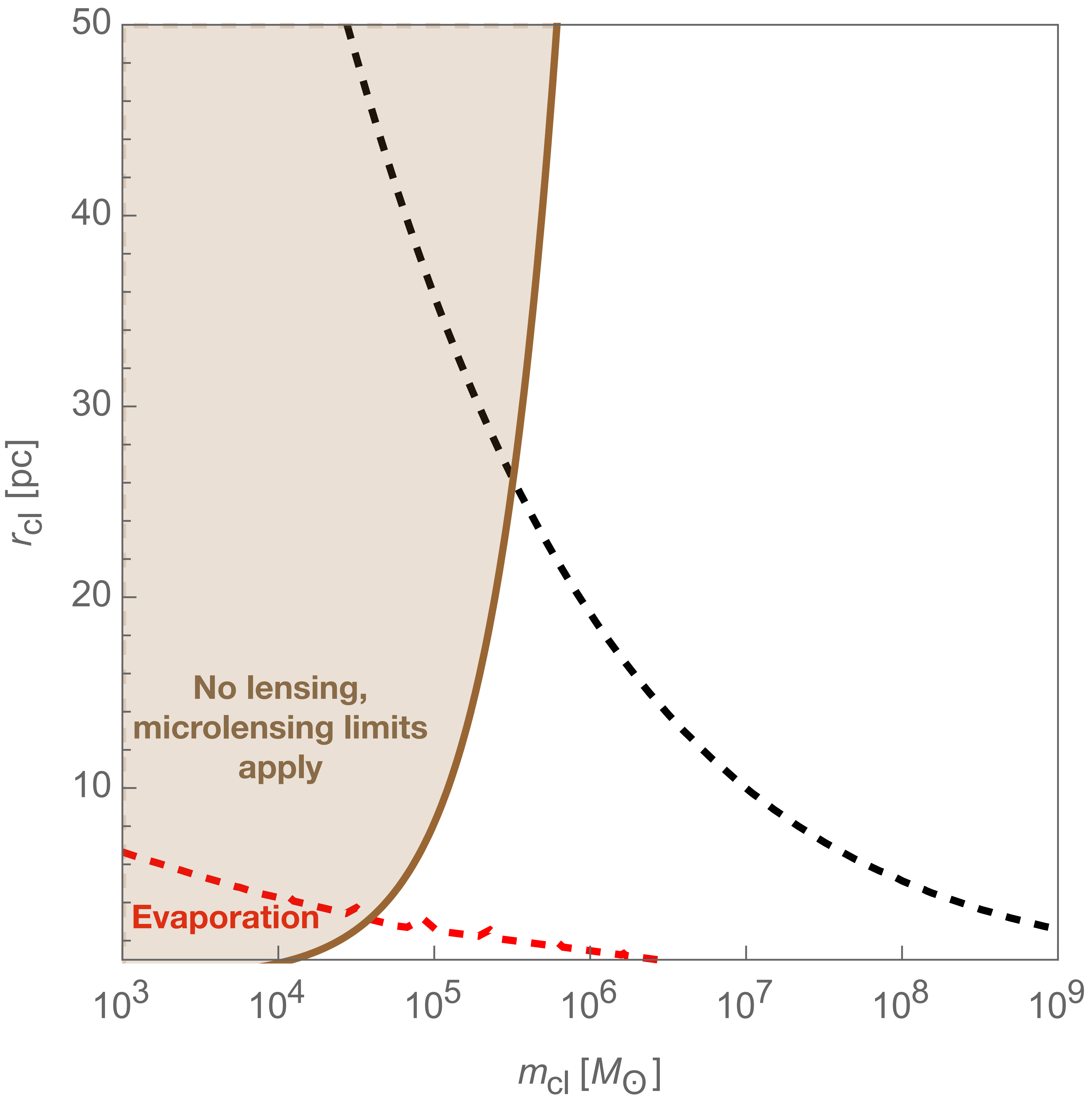
$$z_{\rm form} + 1 \simeq 3.7 \times 10^{-3} k^{-3/2} \left(\frac{m_{\rm PBH}}{M_\odot}\right)^{-1/2}$$

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

Very early (cf. N-body simulation)

4. Our playground

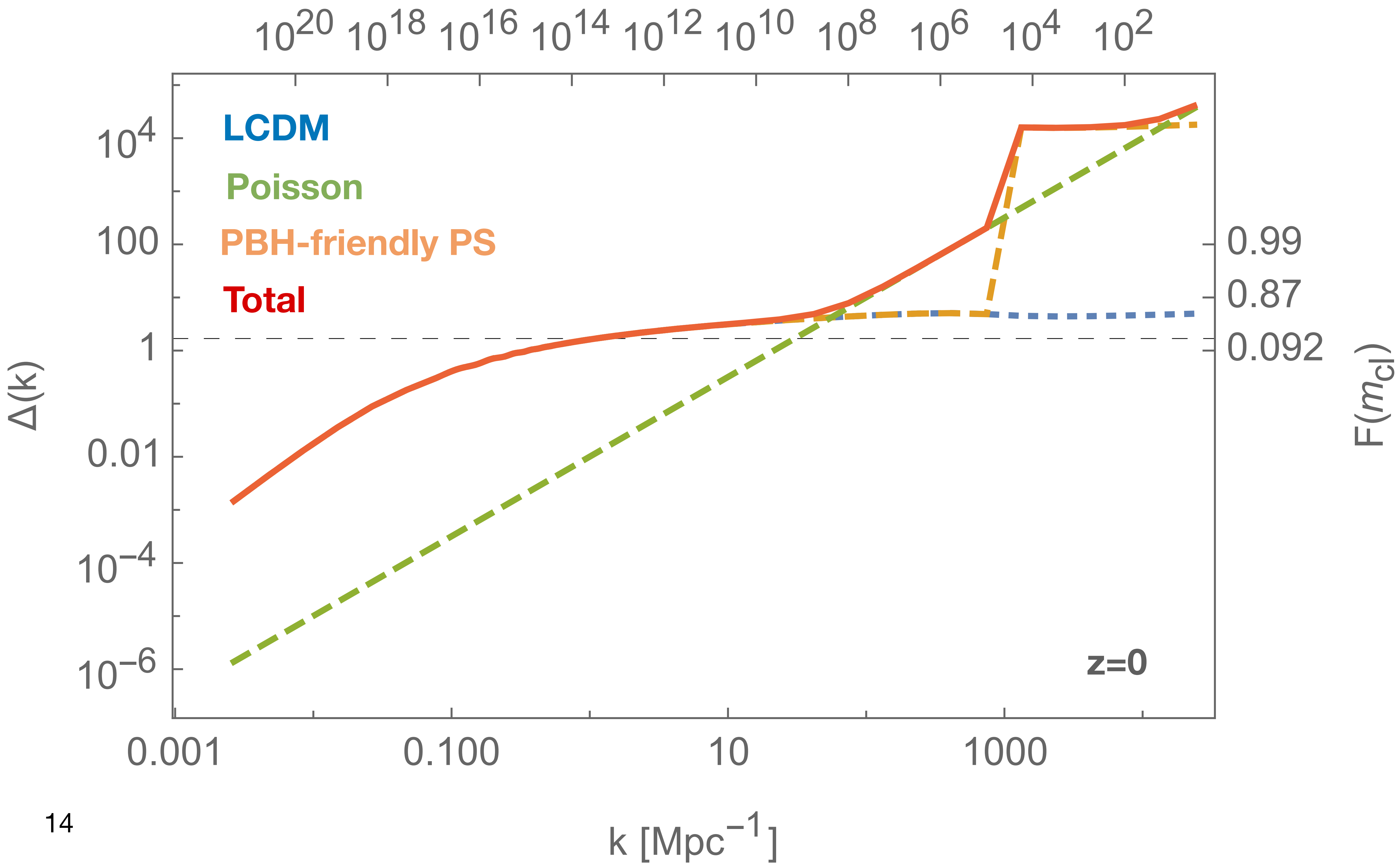
Probability of collapse



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

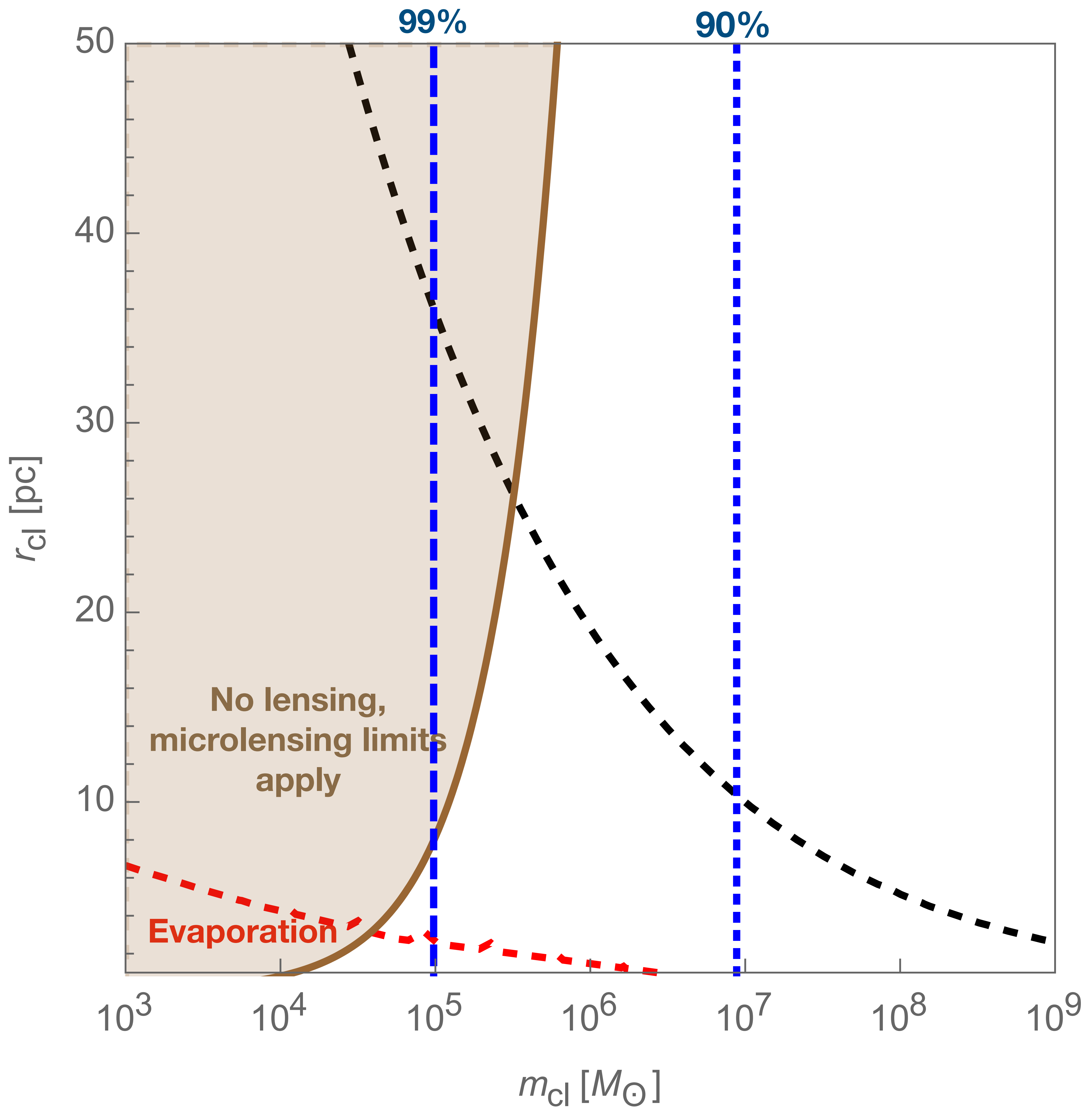
Fraction of (Poisson) fluctuations that collapse, in the Press-Schechter formalism:

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



4. Our playground

Probability of collapse



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

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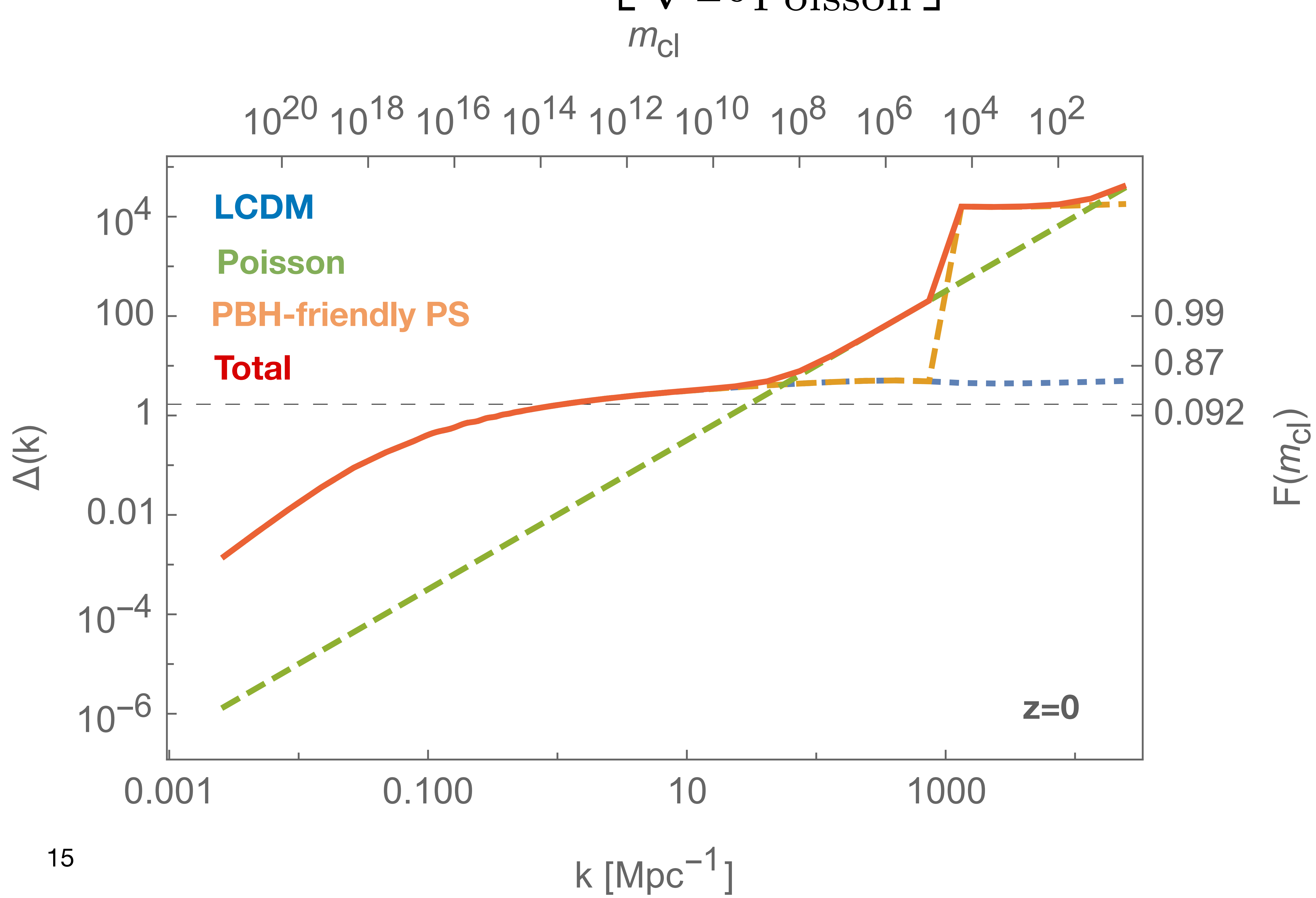
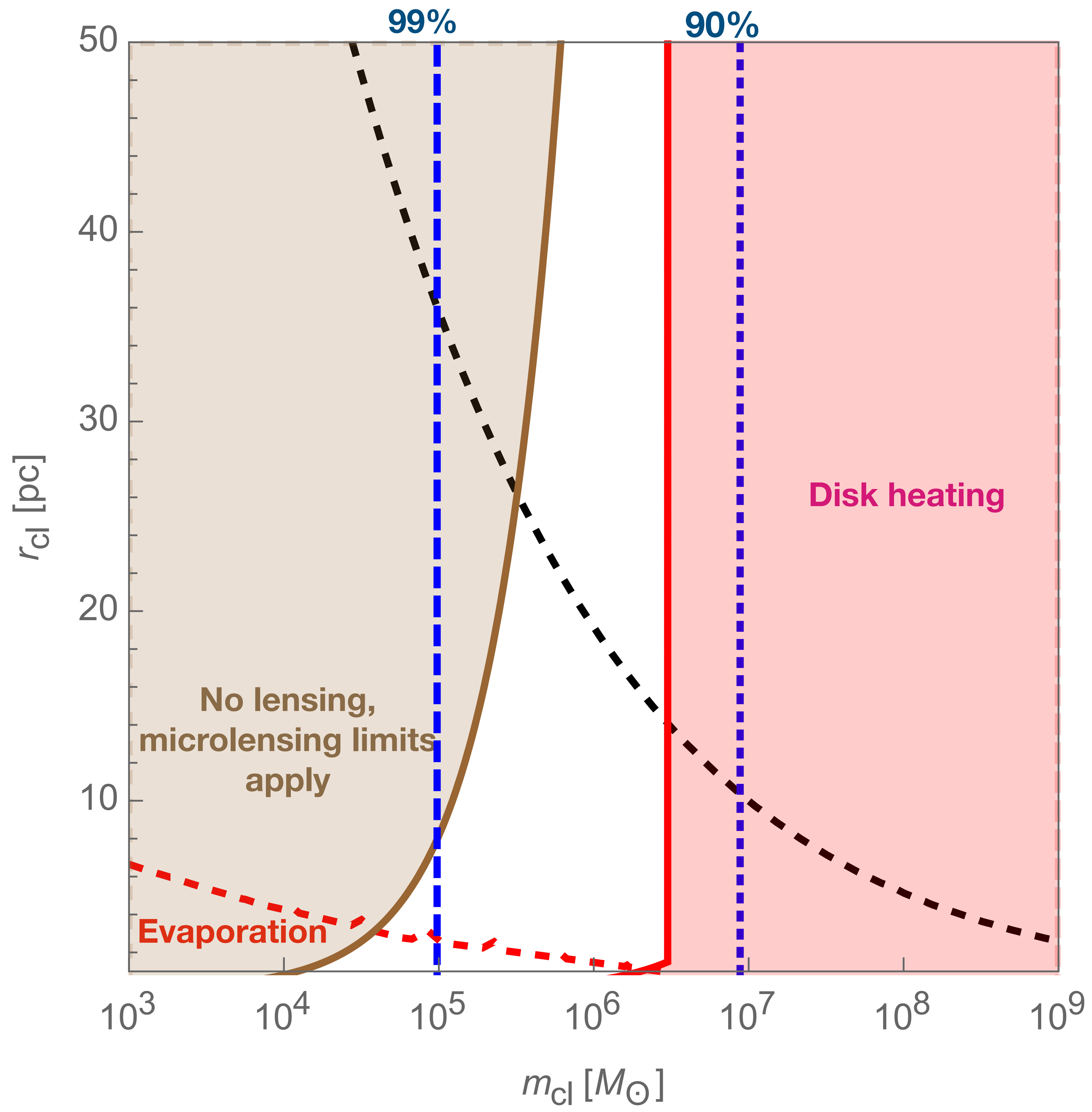


4. Our playground

Heating of the galactic disk



Clusters dynamically heat the galactic disk
Clue or limit ?

Carr & Lacey, 1987

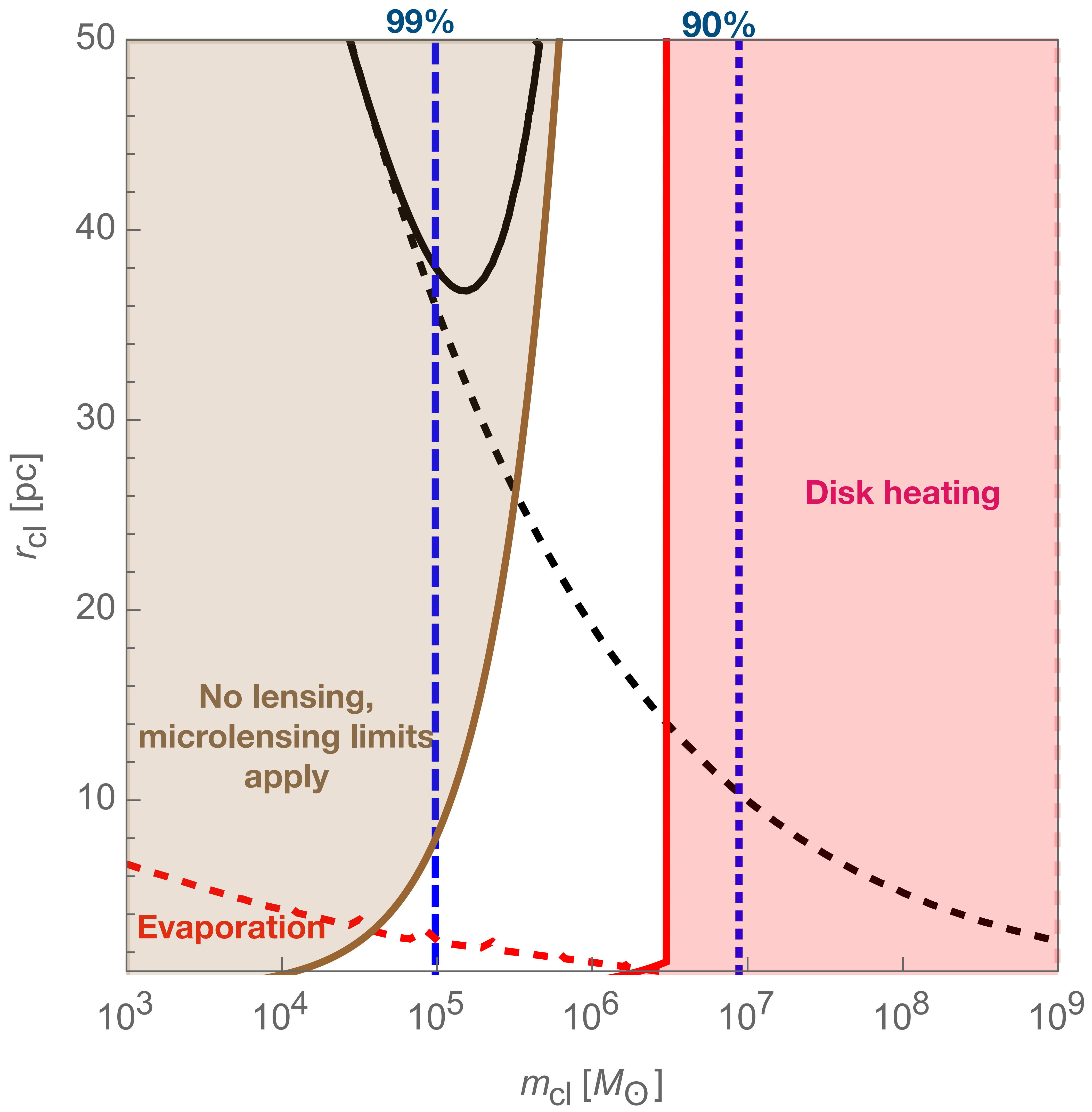
$$m_{\rm cl} < 3 \times 10^6 M_\odot$$

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)

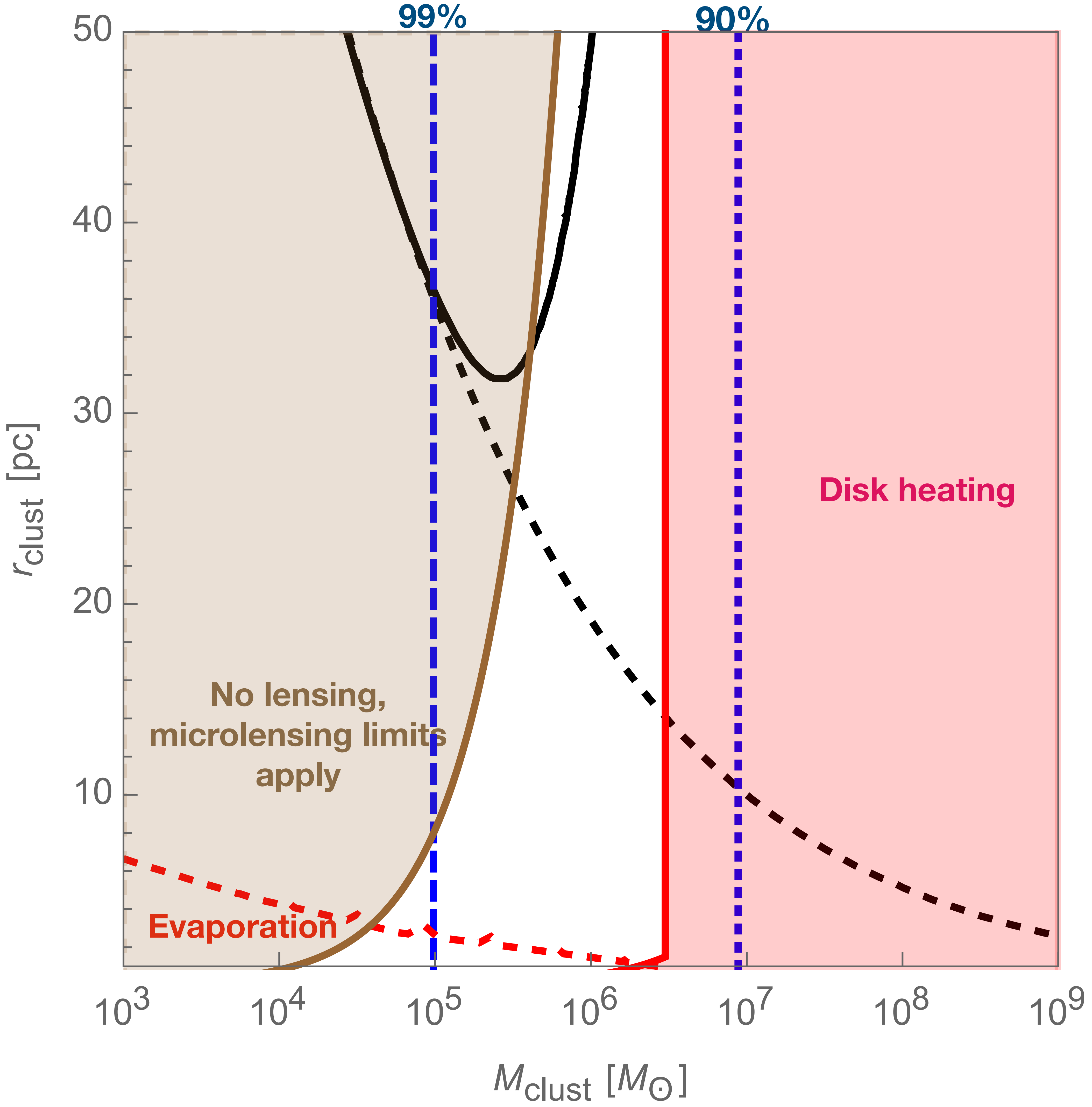
$$r_{cl} \simeq 135\,\mathrm{pc}\left(\frac{m_{PBH}}{M_\odot}\right)^{1/2}\left(\frac{m_{cl}}{10^6\,M_\odot}\right)^{-1/6}$$

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:

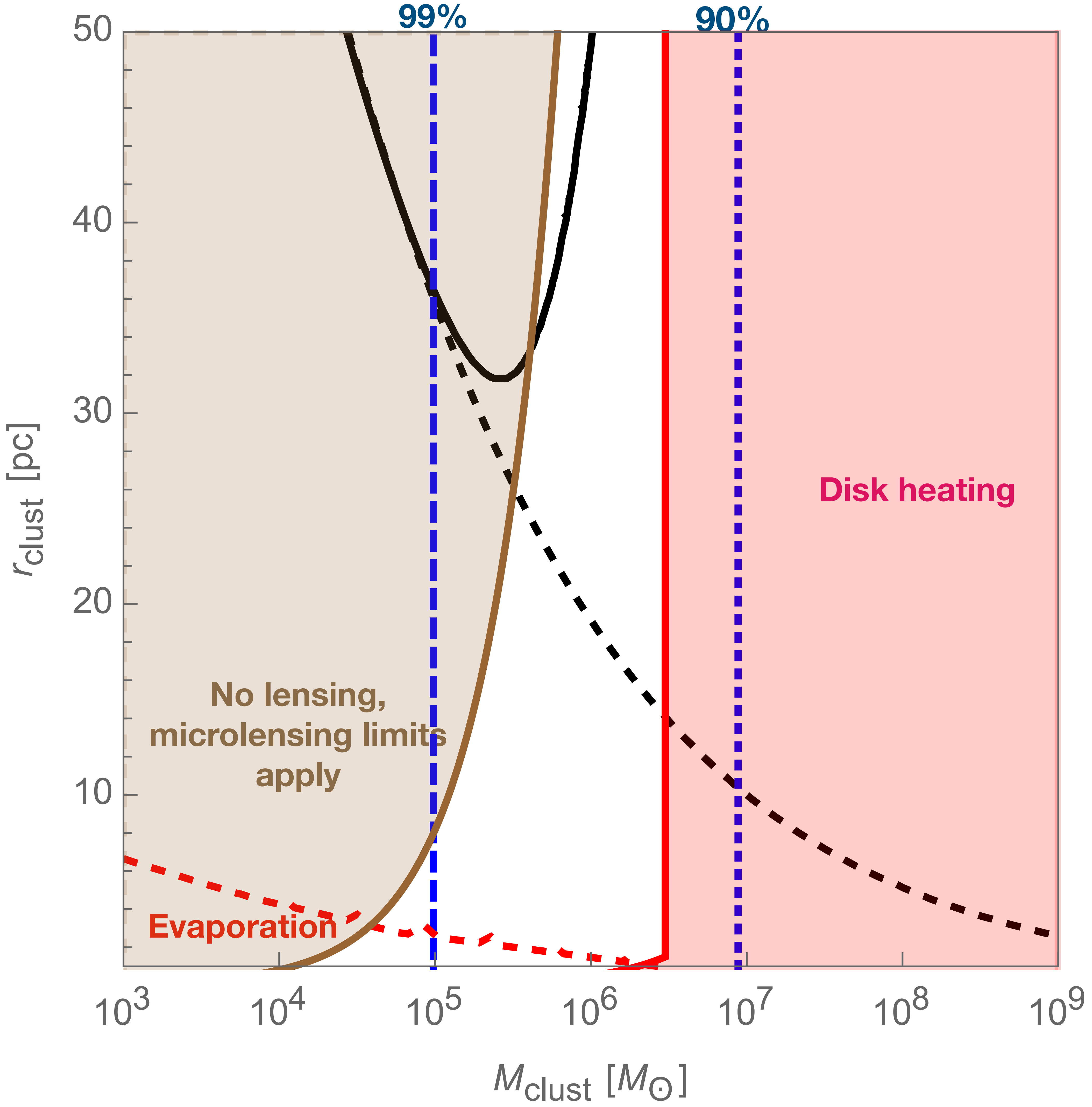
$$\delta \propto \int m_{\rm PBH} f_{\rm PBH} f(m_{\rm PBH}) {\rm d} \ln {\rm m_{PBH}} \sim 10 - 100$$

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:

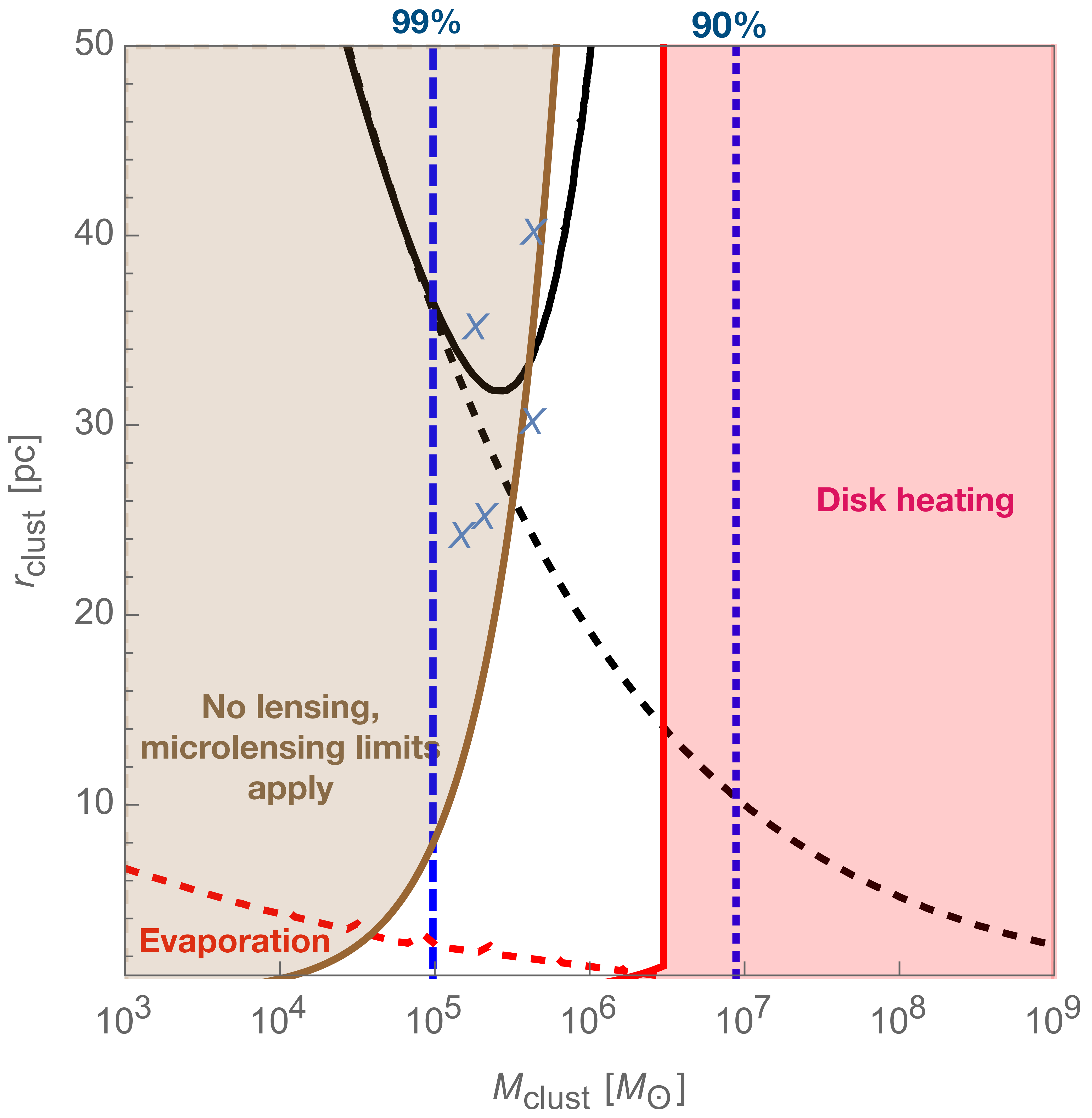
$$r_{cl} \lesssim 30\mathrm{pc}$$

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

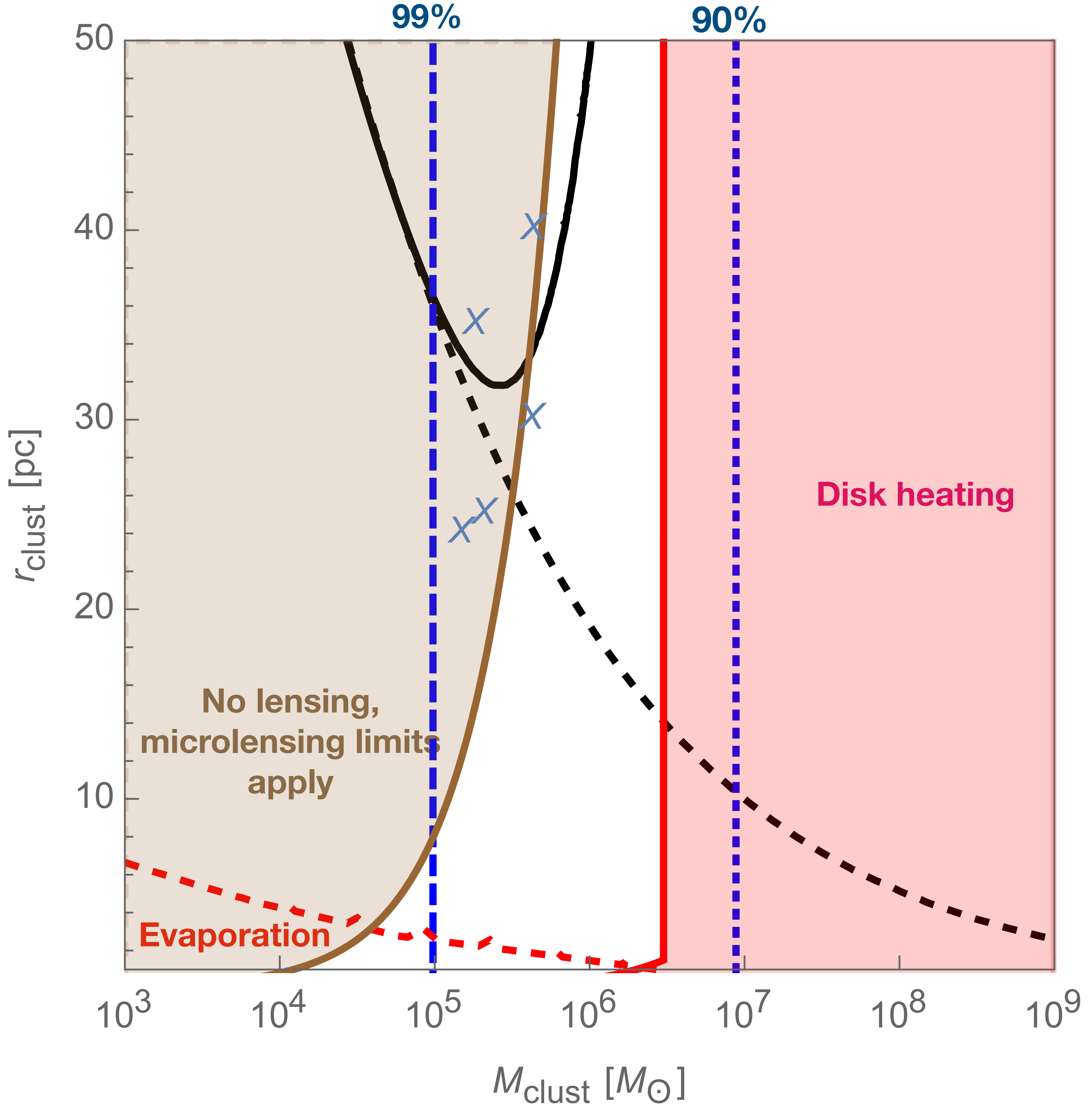
Brandt 2017, Simon 2019…

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**

4. Our playground

PBH merger rates



- **LIGO/Virgo (GW190425) :** 250-2800 yr^{-1} Gpc^{-3}
- **Early binaries** (Hutsi et al, 2020)**:** 2400 yr^{-1} Gpc^{-3}
  see Hardi's talk - debate about the fraction of binaries not in clusters

$$\frac{d\tau}{d\ln m_1 \, d\ln m_2} \approx 1.6\times 10^6\,\mathrm{Gpc}^{-3}\mathrm{yr}^{-1} f(m_1) f(m_2) f_{\rm sup} \times \left(\frac{m_1+m_2}{M_\odot}\right)^{-\frac{32}{37}} \left[\frac{m_1 m_2}{(m_1+m_2)^2}\right]^{-\frac{34}{37}} \quad (2)$$

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

- **Late binaries :** ~1000 yr^{-1} Gpc^{-3}

$$\frac{d\tau_{\rm clust}}{d\ln m_1 d\ln m_2} = R_{\rm clust} \times f(m_1) f(m_2) \times (m_1+m_2)^{10/7} (m_1 m_2)^{2/7} \times \mathrm{yr}^{-1}\mathrm{Gpc}^{-3},$$

- **Three-body interactions:** (Francioloini 22) rates at odds with late binaries

Conclusion:

Lot of effects and uncertainties still to include

My two-cents:

- Natural clustering scale around 10^5-10^7 $M_\odot$
- Microlensing limits evaded due to the lensing+microlensing effect
- Need of broad PBH mass distribution
- Effects: evaporation, dynamical heating, initial cluster size and redshift, fraction of collapsed halos, lensing by clusters, disk heating, collisions, tidal disruptions…

To be improved:

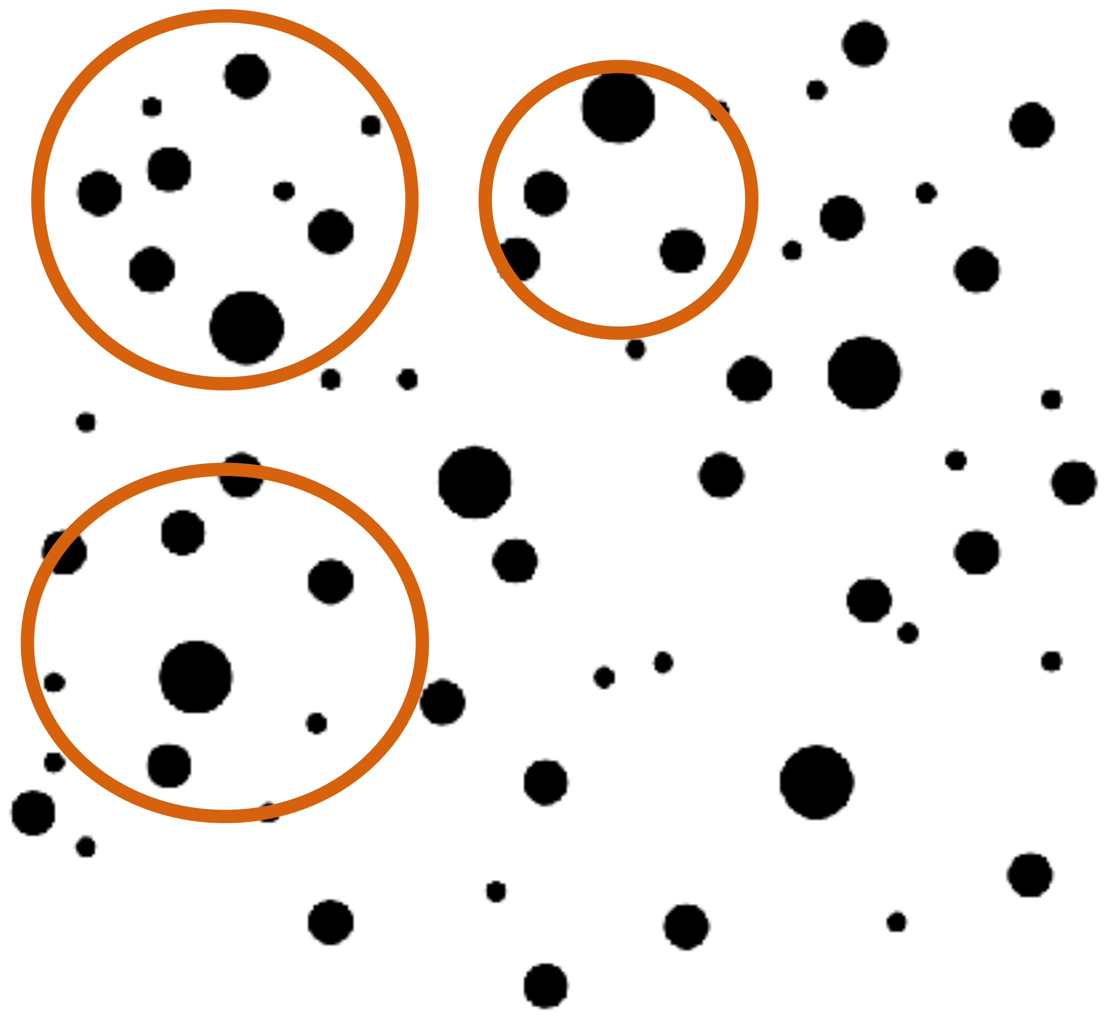
- Radiation-Matter transition
- Mass/size of UFDGs from luminosity
- PBH cluster profile and mass segregation
- CMB limits for PBH clusters
- Disruption of sub-sub halos in sub-halos
- Simulations of microlensing events including the lensing effect
- N-body simulations of cluster formation/evolution
- etc…

Strong claims are premature

Conclusion:

Do not neglect the Poisson effect 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]

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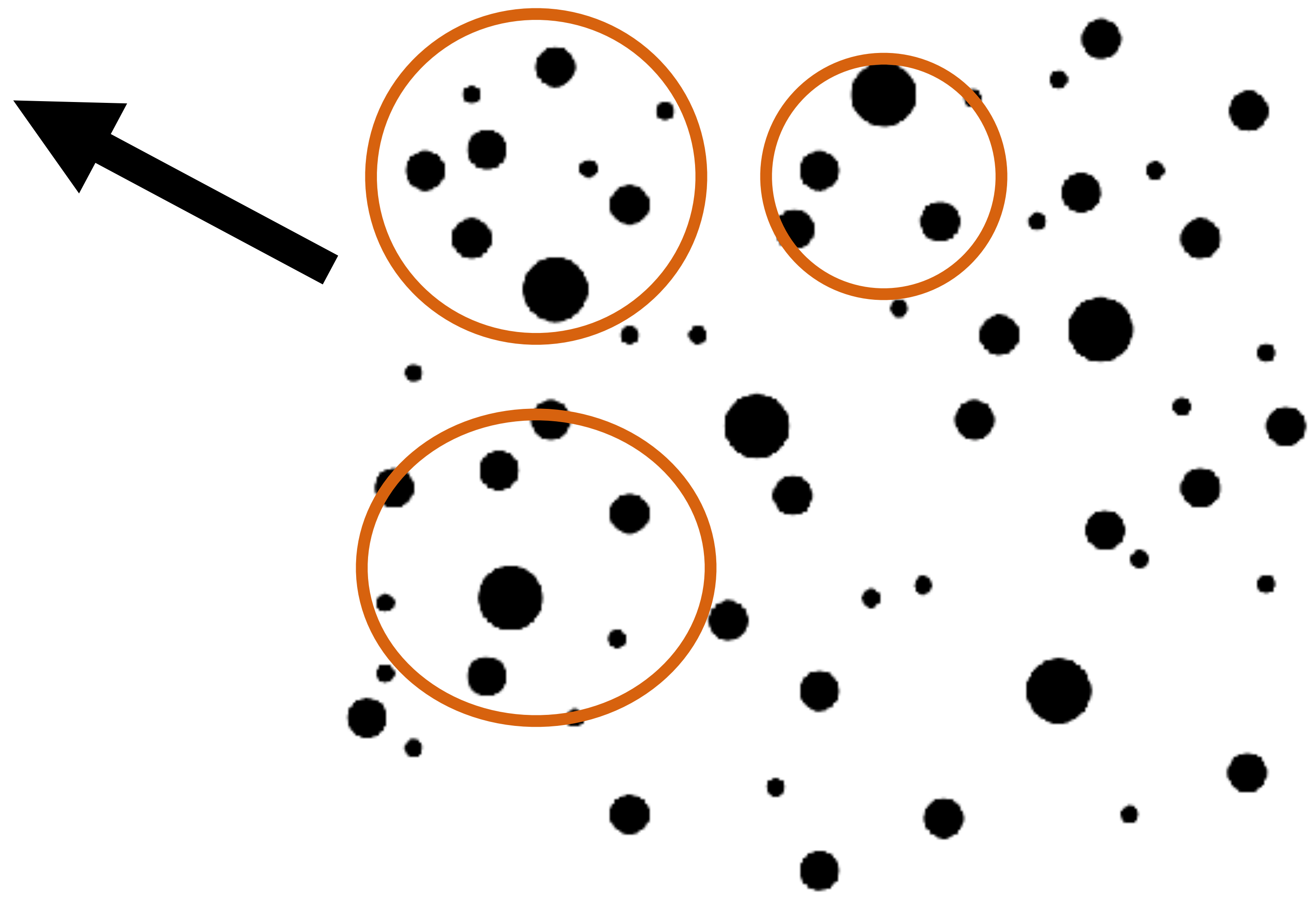

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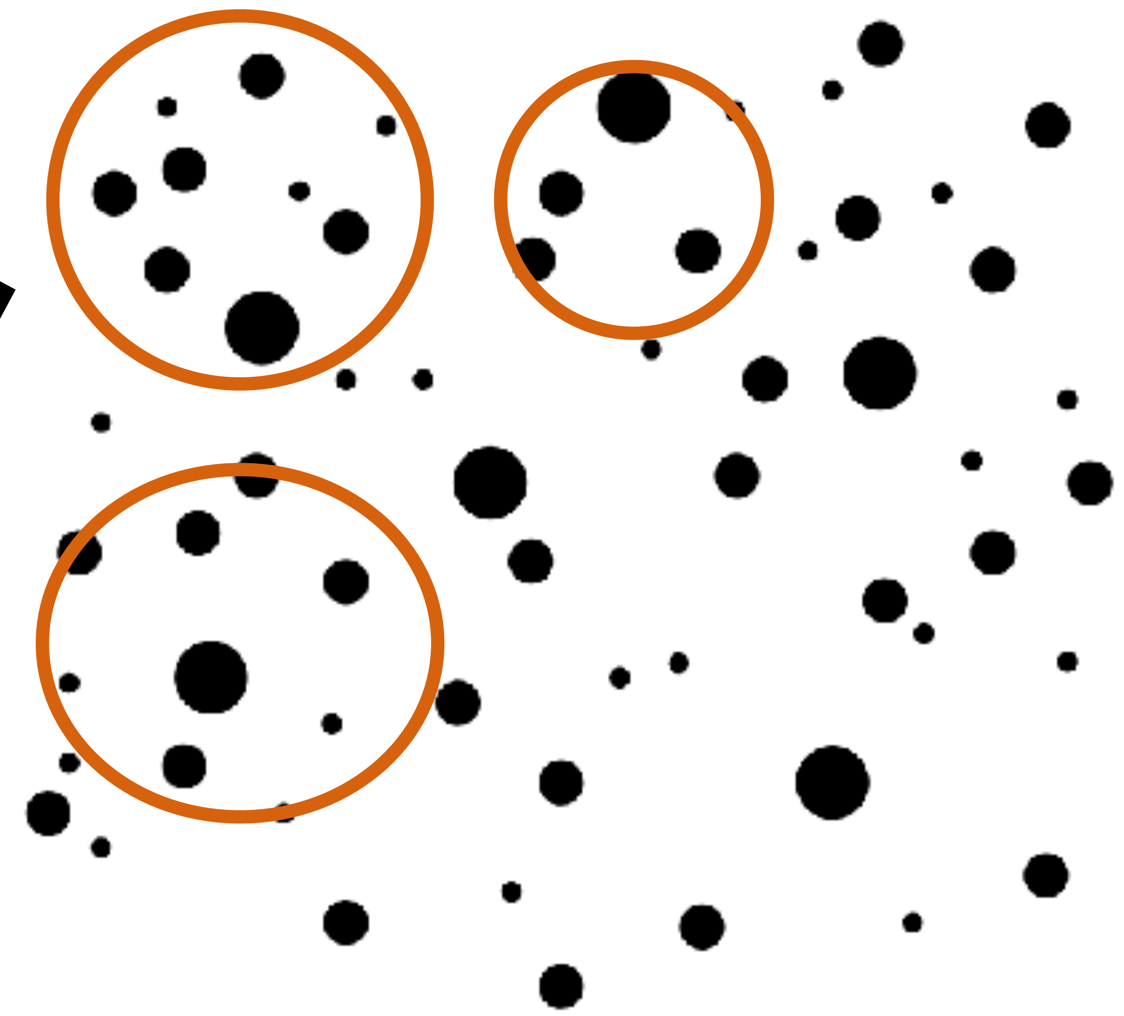

High-z clusters: spatial correlations in IR and X-ray backgrounds
[Kashlinsky 16]

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

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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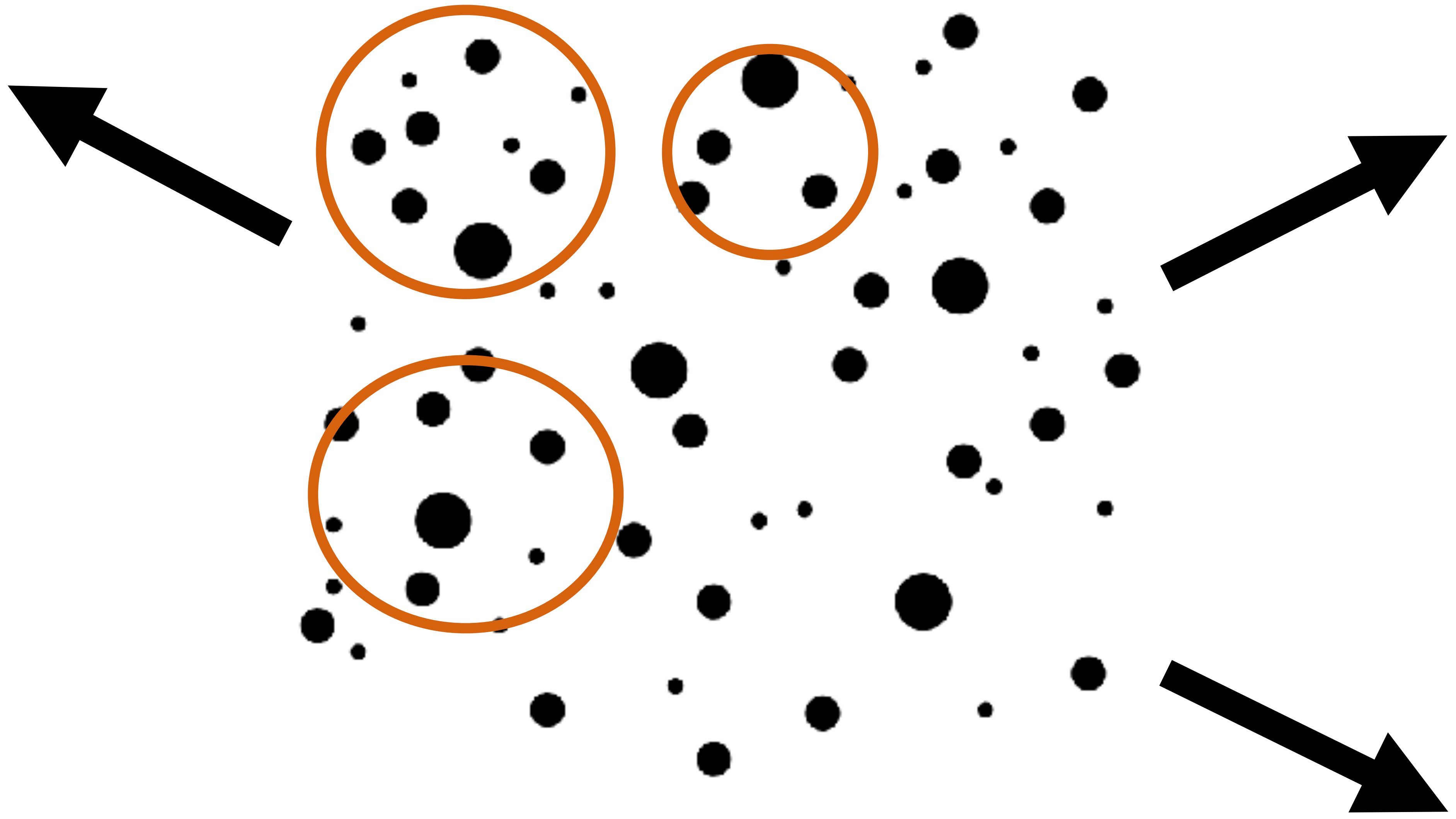

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Ultra-faint dwarf galaxies
min radius ~20 pc and
large mass-to-light ratios
(dynamical heating + accretion)
[S.C.+17, S.C.+20]

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

subhalos diluted in larger halos

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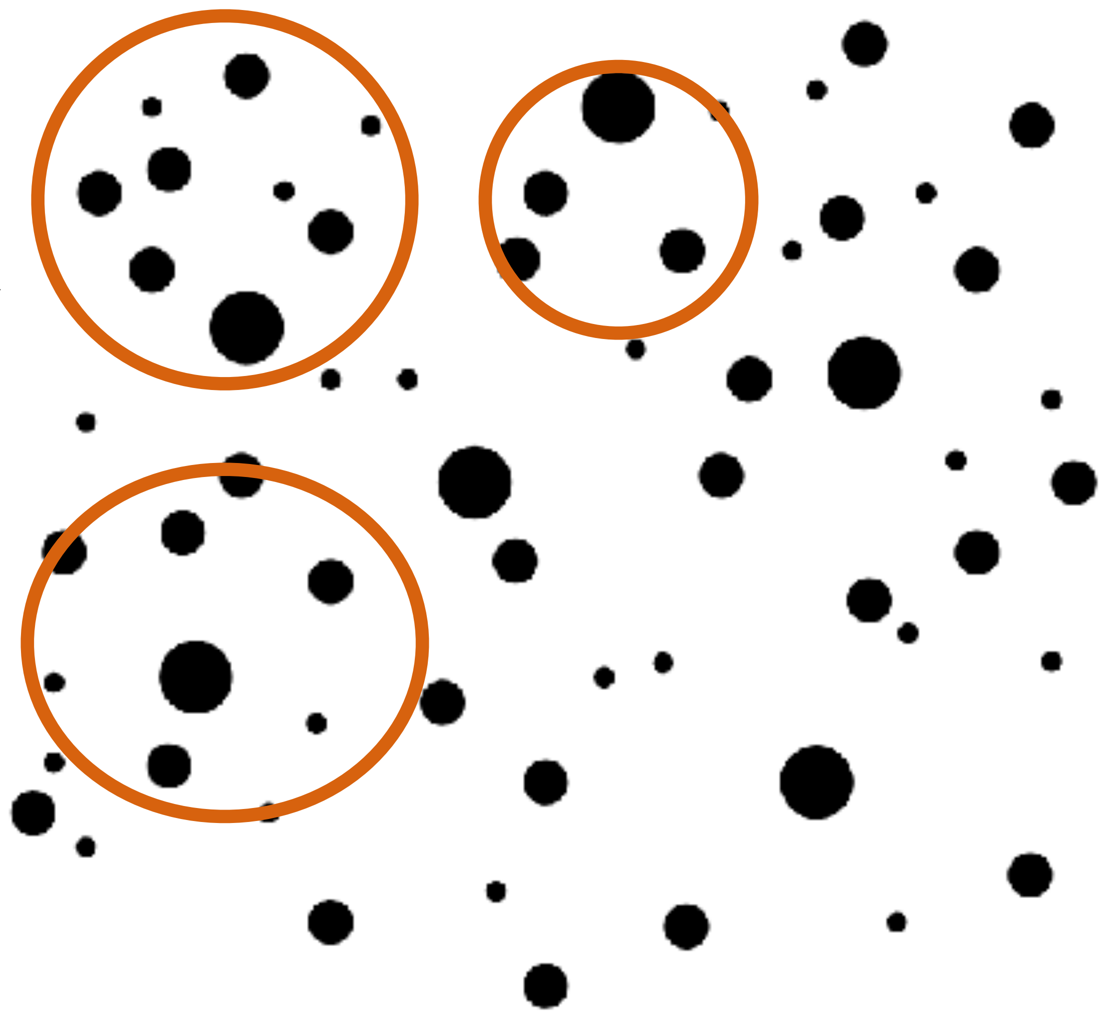

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subhalos diluted in larger halos

Boost the merging rate of late binaries
up to LIGO/Virgo rates
[S.C.+20]

Conclusion:

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Merging rate suppression for early binaries
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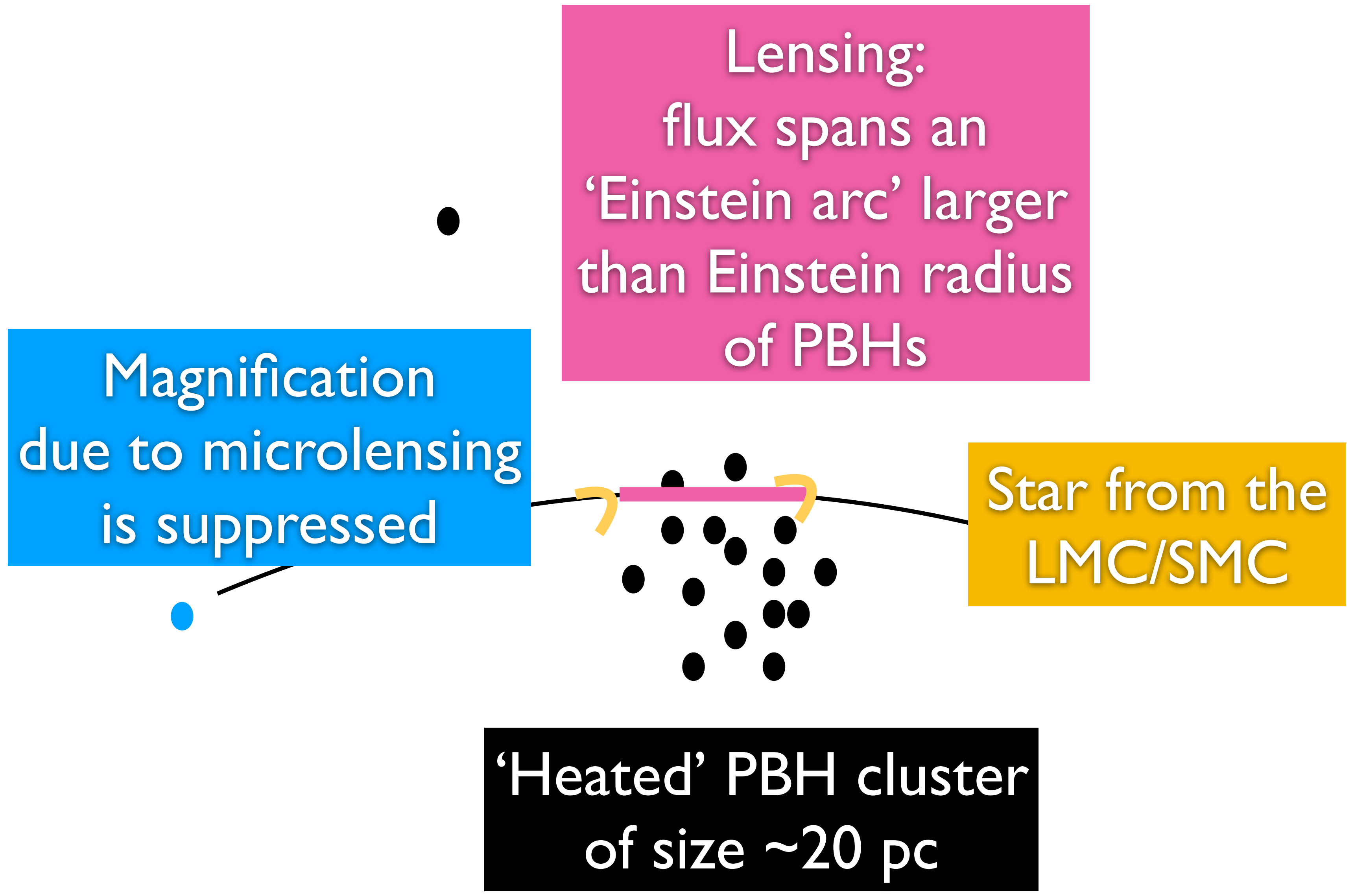
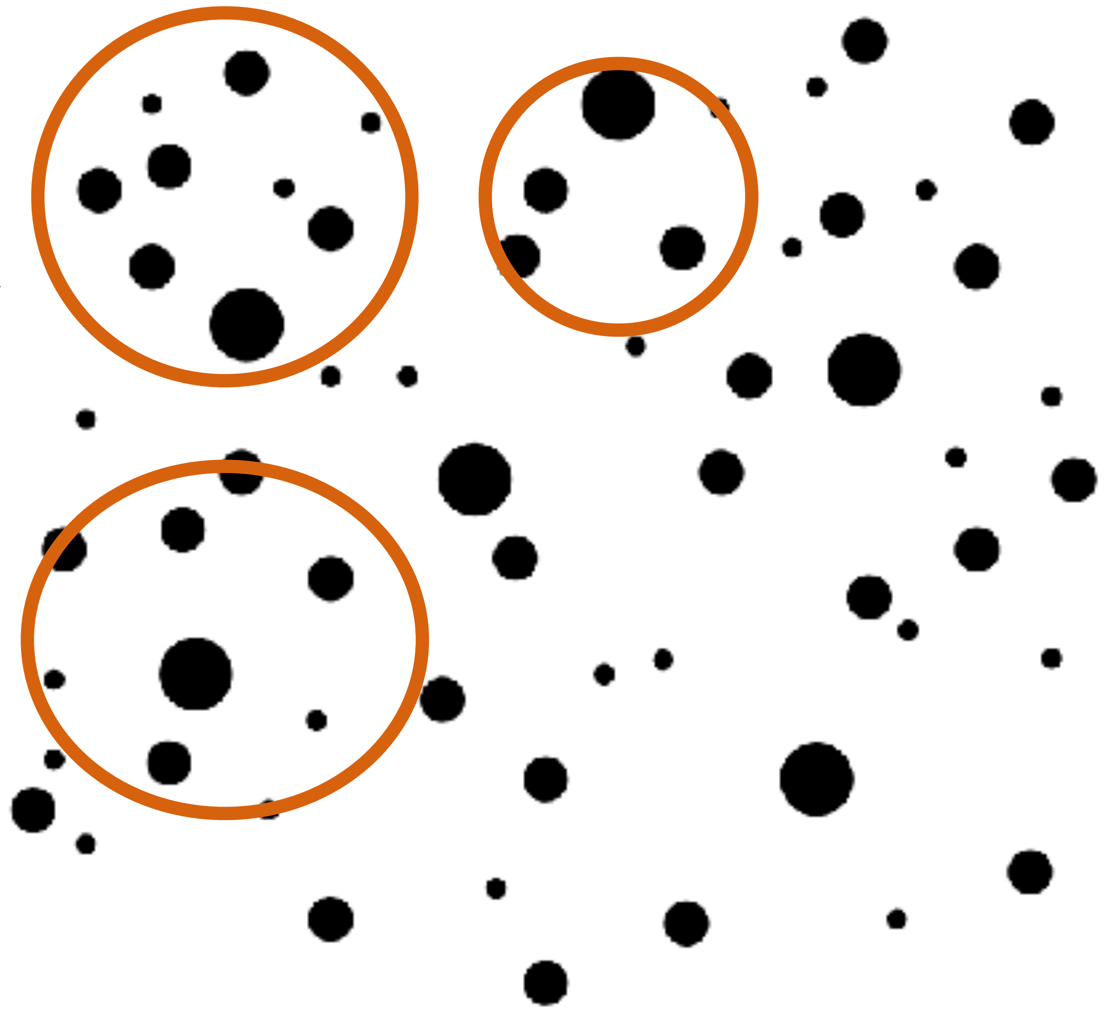
Evade micro-lensing limits [Carr+19]



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

Ali-Haimoud 1805.05912



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