

Picolensing as a probe of massive compact DM states



PBHs + extended lenses

Light Dark World 2026

Carleton University
Ottawa, ON, Canada

July 30, 2026

Phys. Rev. D 111 (2025) 063060 [2411.12947]

w/ Sergey Sibiryakov

+ [26XX.YYYYYY]

w/ Sergey Sibiryakov + Eleni-Anna Kolonia

Michael A. Fedderke

mfedderke@perimeterinstitute.ca

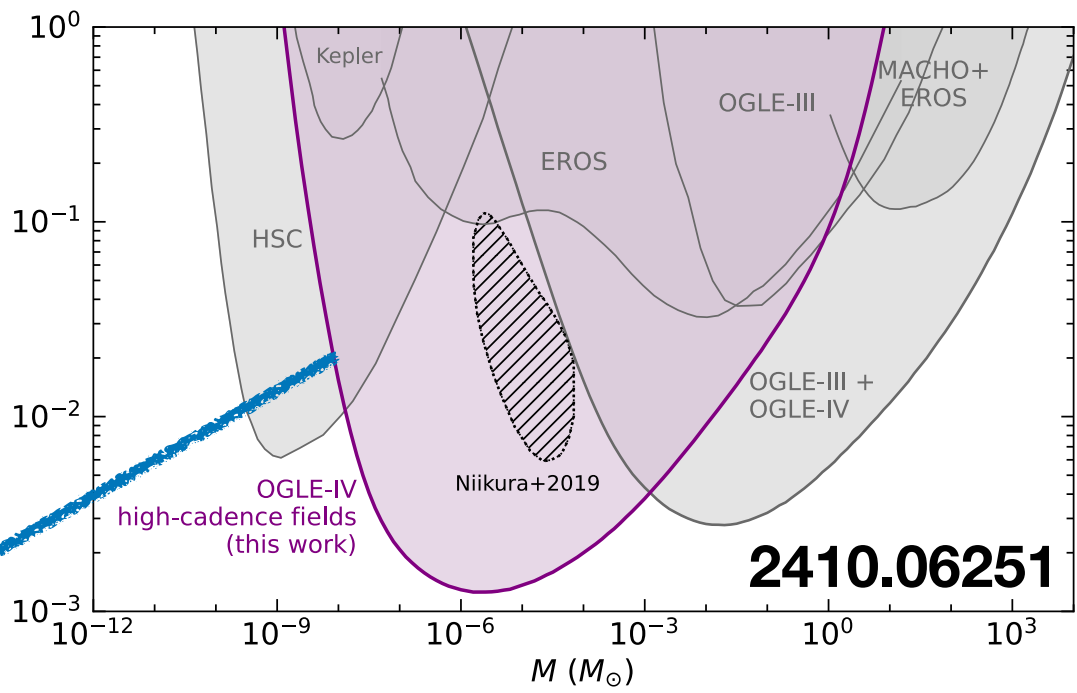
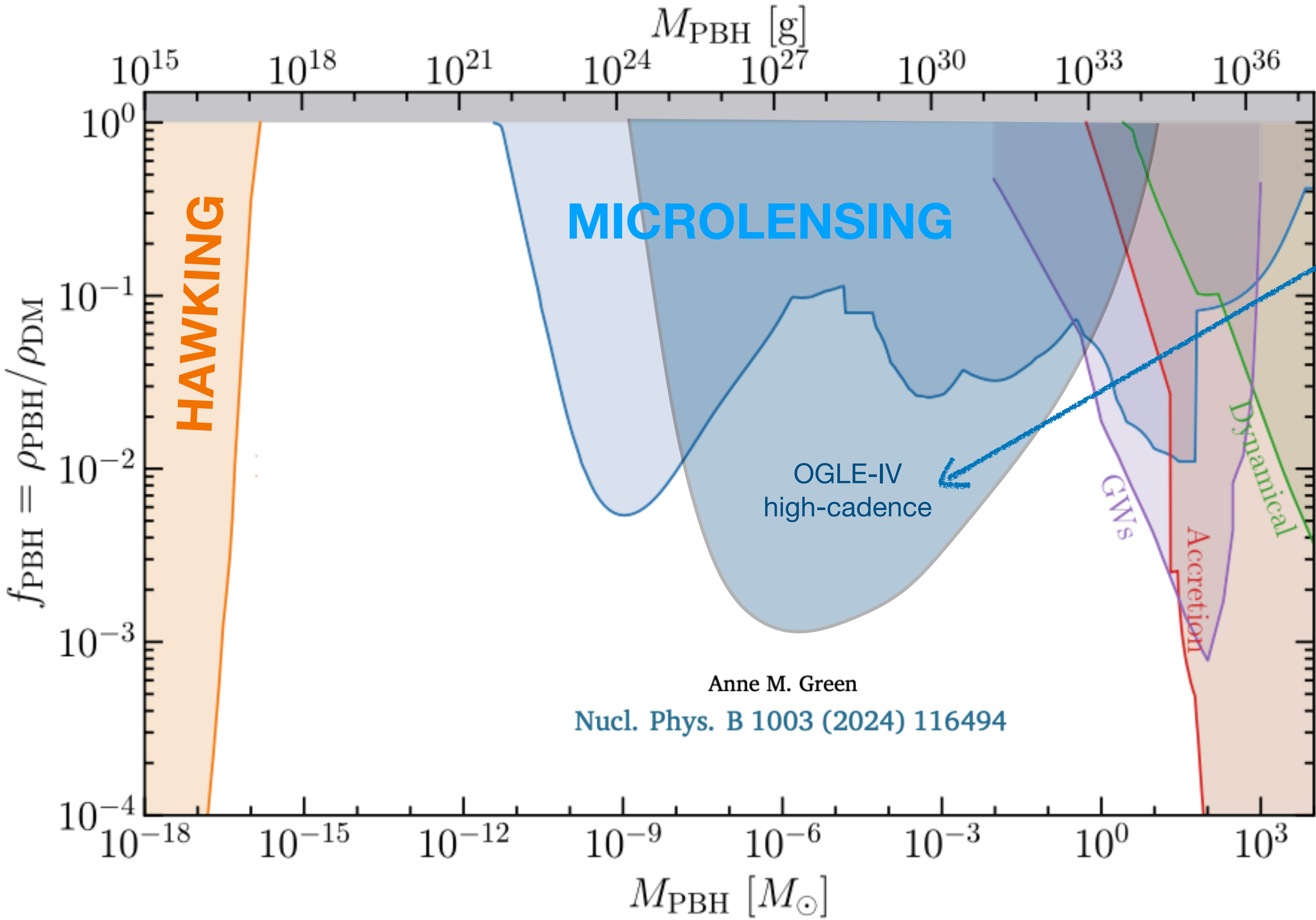


PBH dark matter

$M_{\text{PBH}} \ll M_{\odot}$. Formed in the early-universe.

GRAVITATIONALLY COLLAPSED OBJECTS OF VERY LOW MASS

Stephen Hawking



This talk
Agnostic to the
production
mechanism

Annu. Rev. Nucl. Part. Sci. 2020. 70:355–94
Bernard Carr¹ and Florian Kühnel²

A. M. Green and B. J. Kavanagh, *Primordial Black Holes as a dark matter candidate*, *J. Phys. G* **48** (2021) 043001 [[arXiv:2007.10722](#)].

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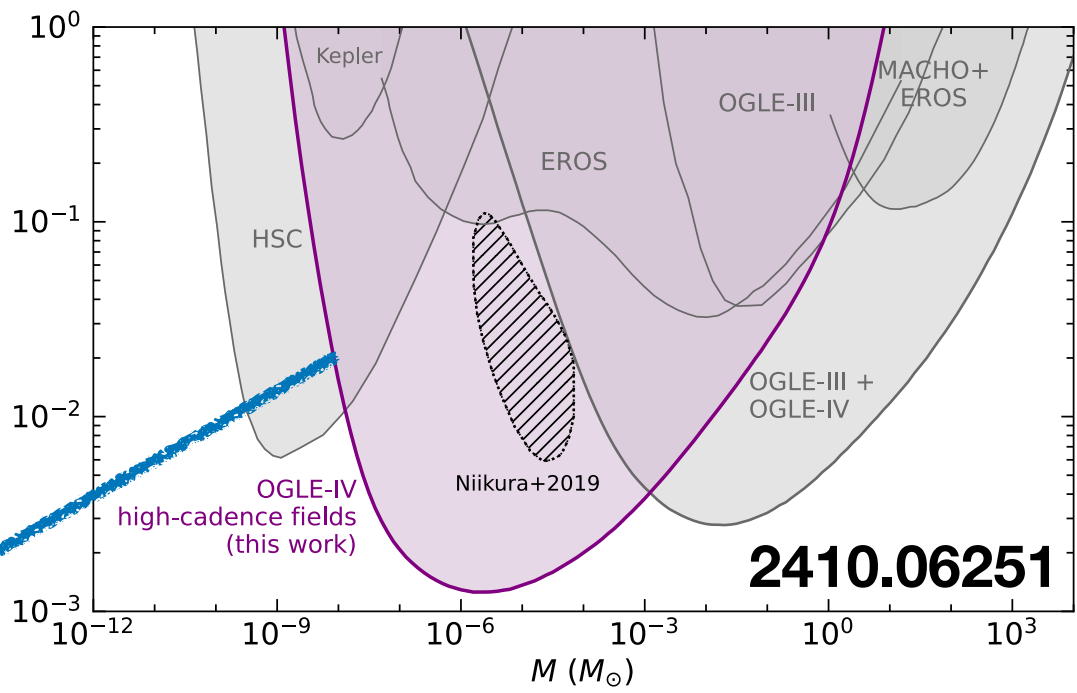
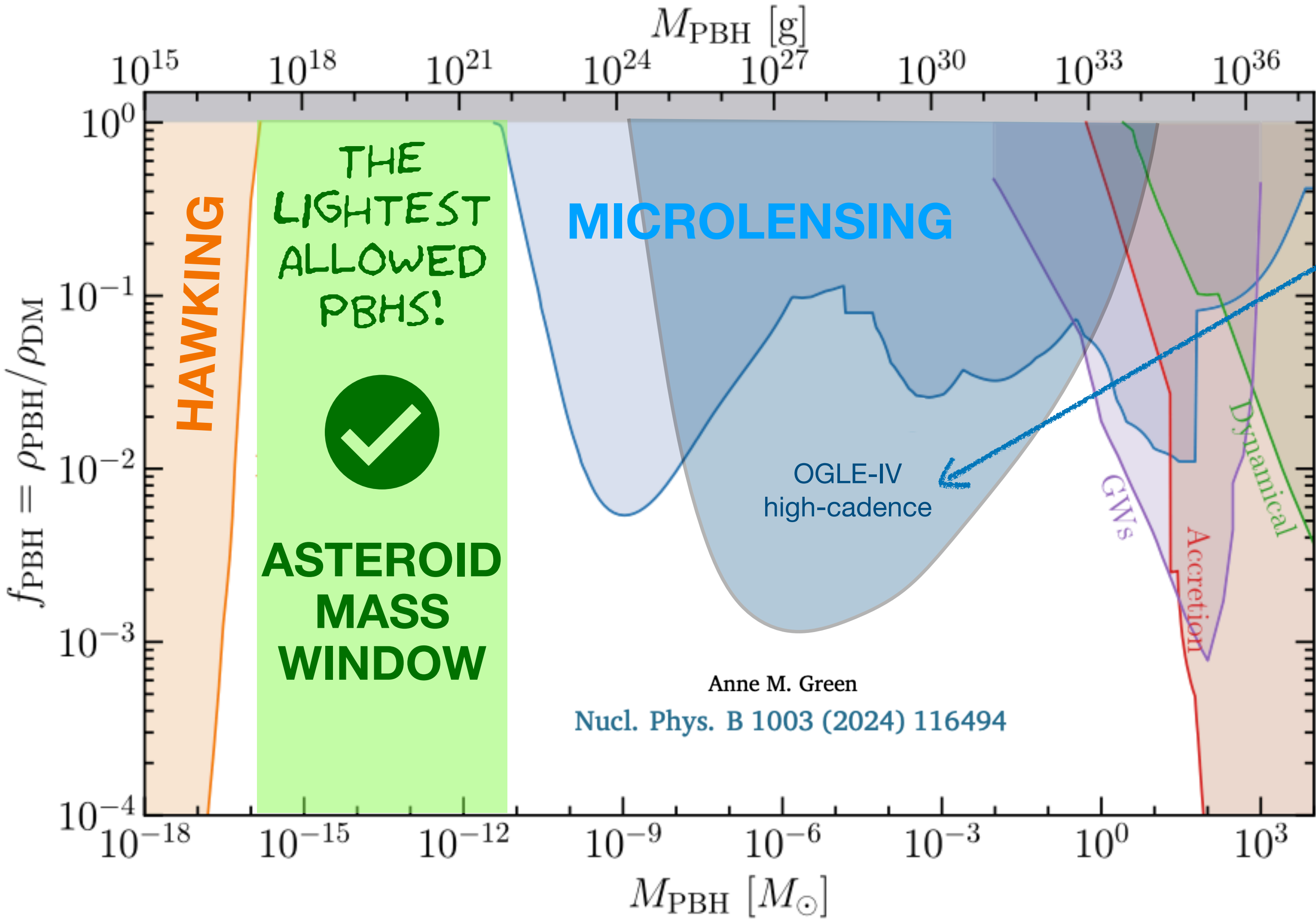
Anne M. Green
Nucl. Phys. B 1003 (2024) 116494

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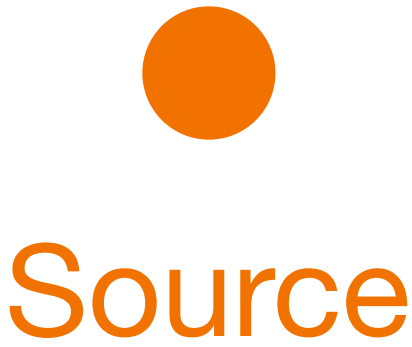
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Picolensing

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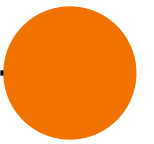


Picolensing

Observer 1



Observer 2

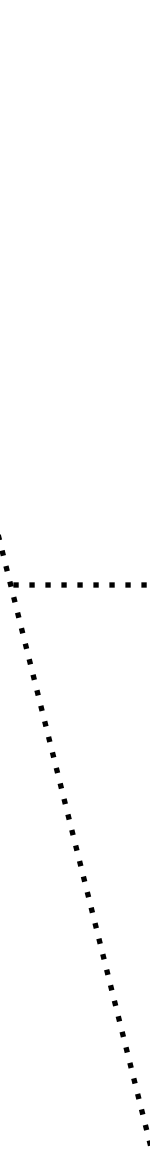


Source

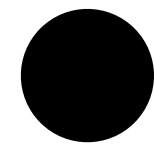
NOT TO SCALE (angles similar to a basketball at the outer edge of the Oort cloud) 3

Picolensing

Observer 1



Observer 2



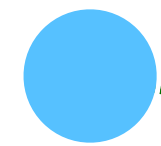
Gravitational Lens
(e.g., PBH)



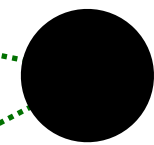
Source

Picolensing

Observer 1

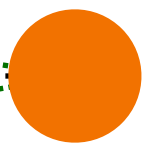


β_1



Gravitational Lens
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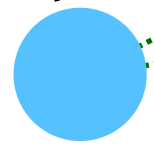
Parallax!



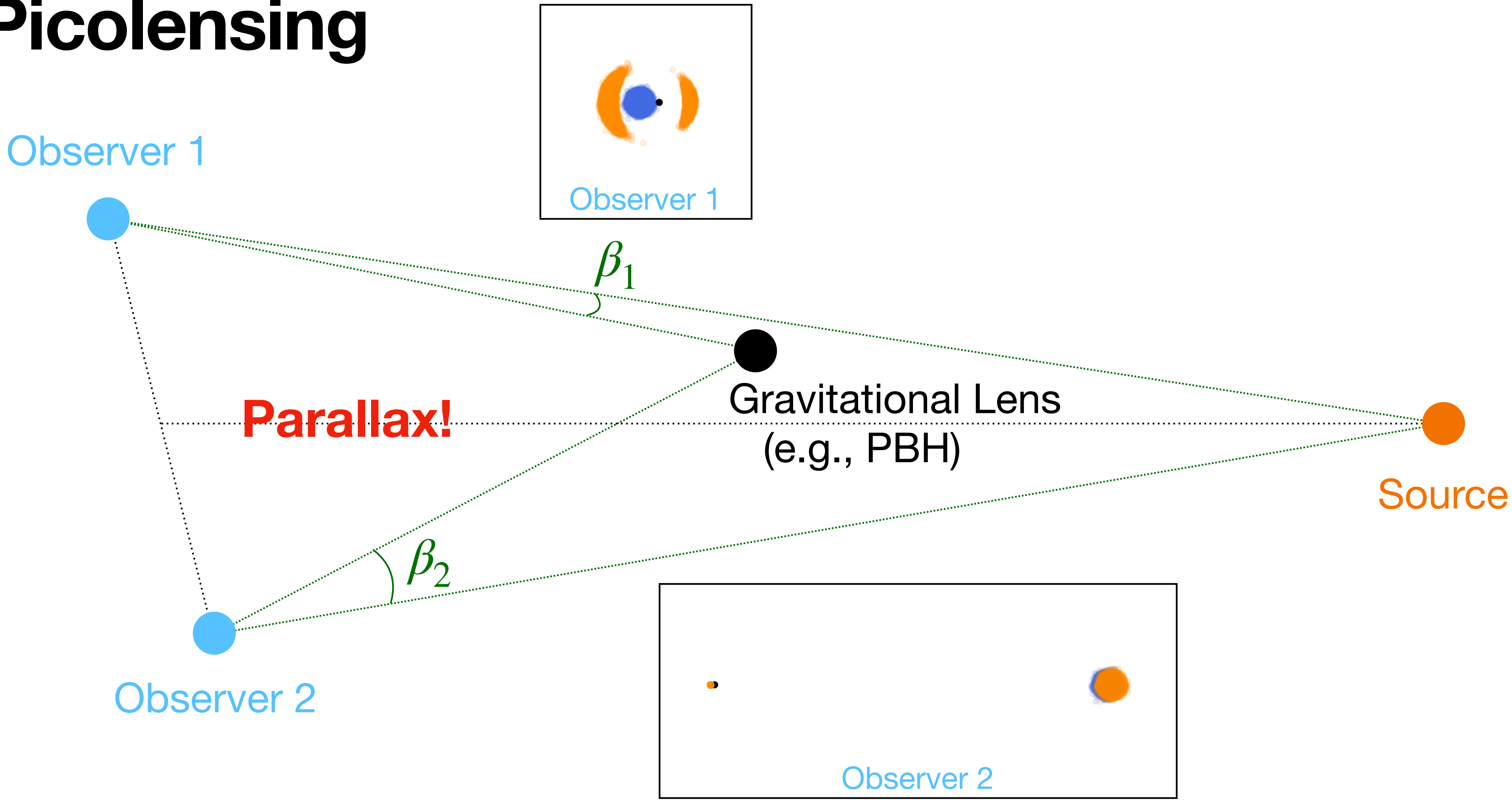
Source

β_2

Observer 2



Picolensing



NOT TO SCALE (angles similar to a basketball at the outer edge of the Oort cloud) 3

Picolensing

Observer 1



Signal: **differential observed brightness of a single source that is observed simultaneously by spatially separated detectors**

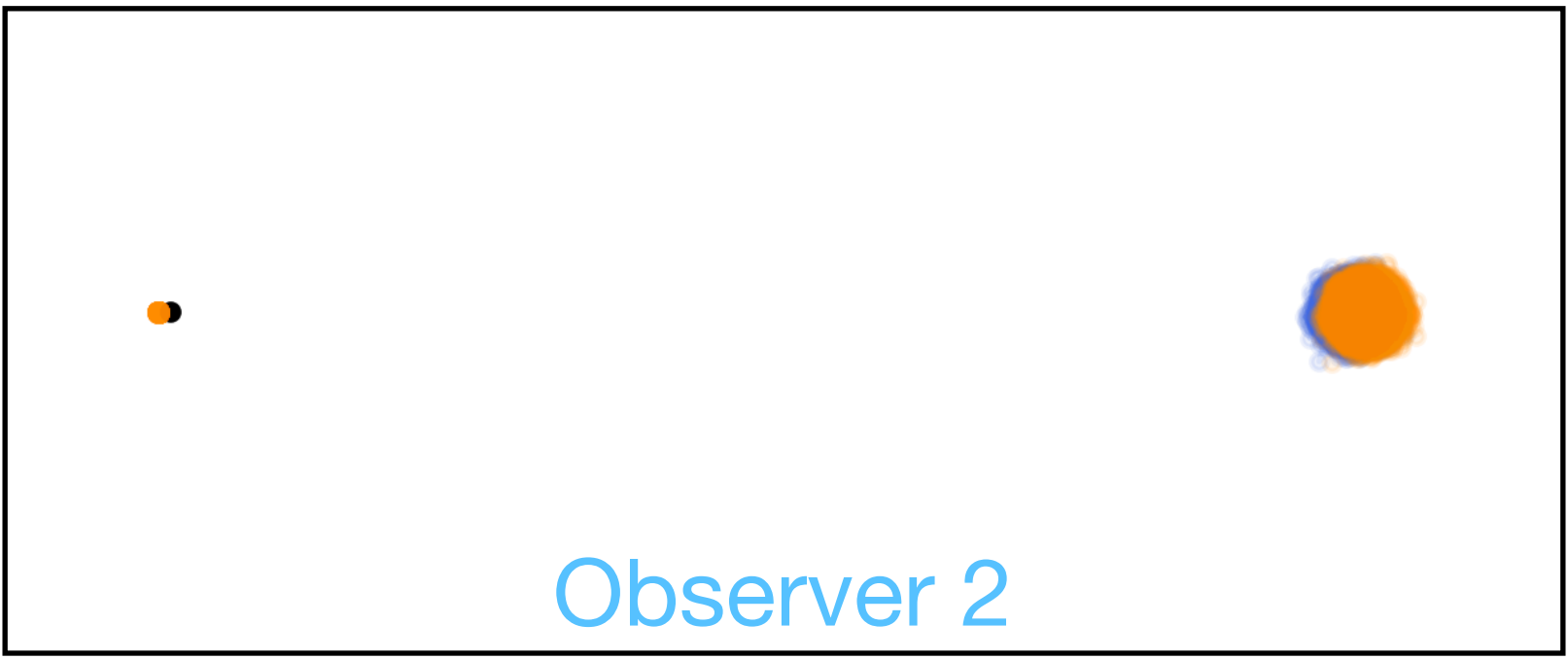
Nemiroff and Gould [astro-ph/9505019]
Kolb and Tkachev [astro-ph/9510043]
Marani et al. [astro-ph/9810391]
Nemiroff [astro-ph/9806012]

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Source

Observer 2



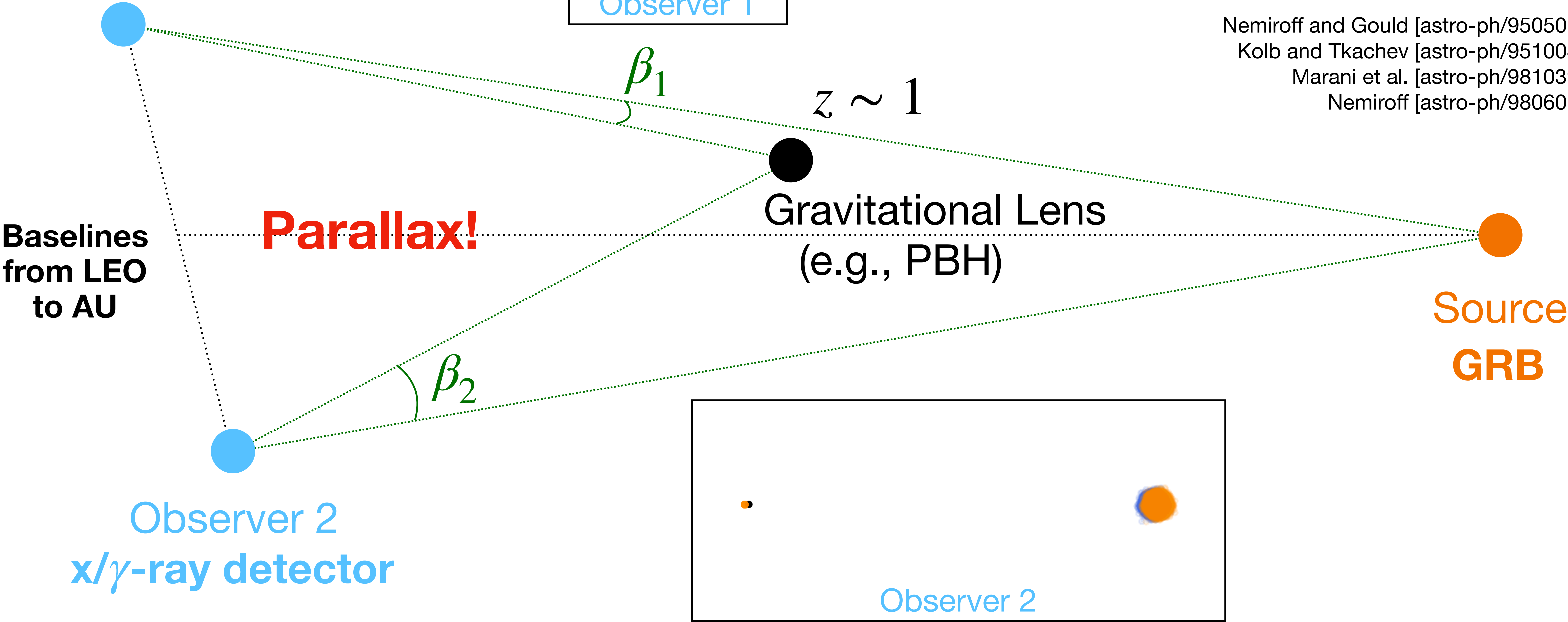
Picolensing

x/ γ -ray detector
Observer 1



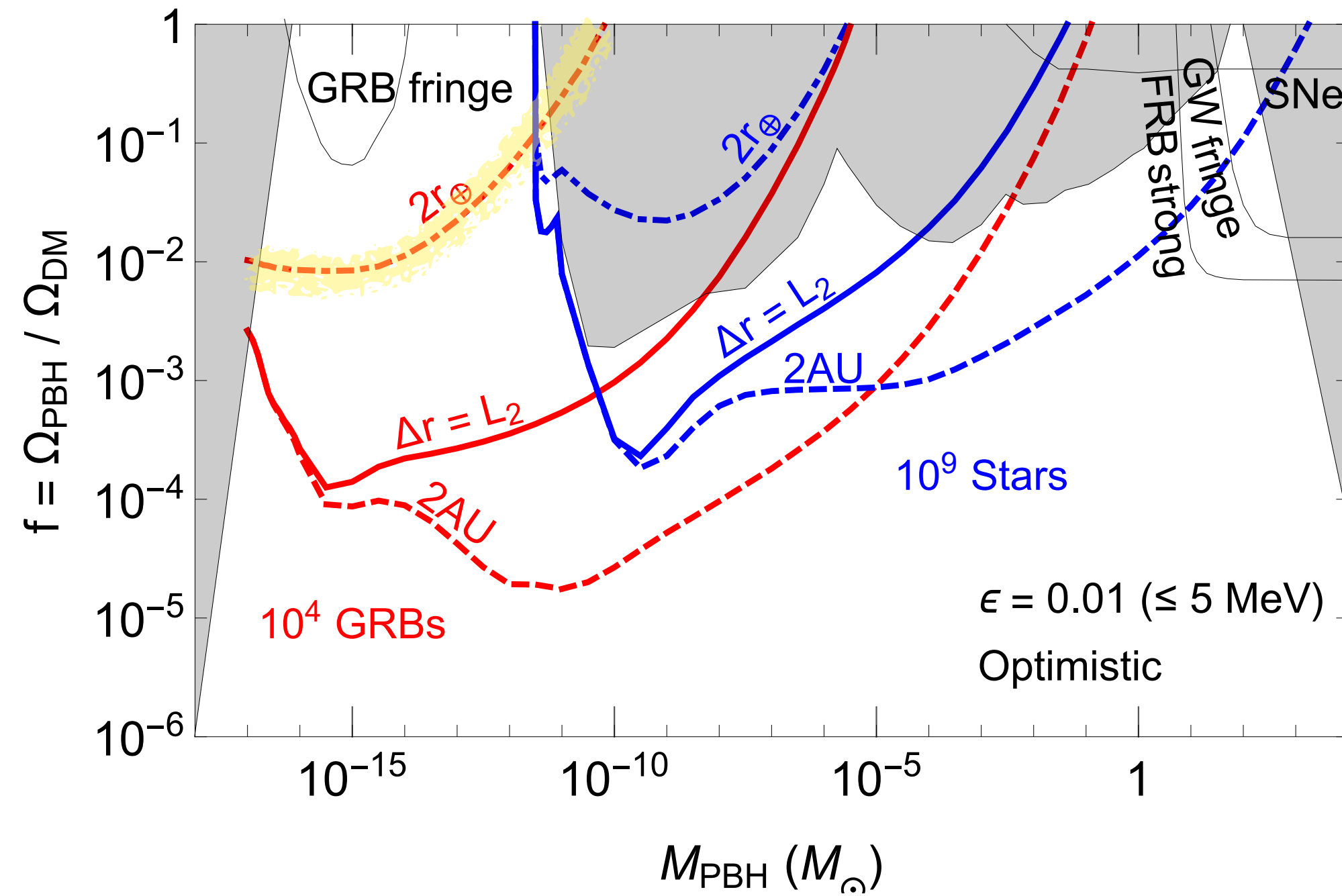
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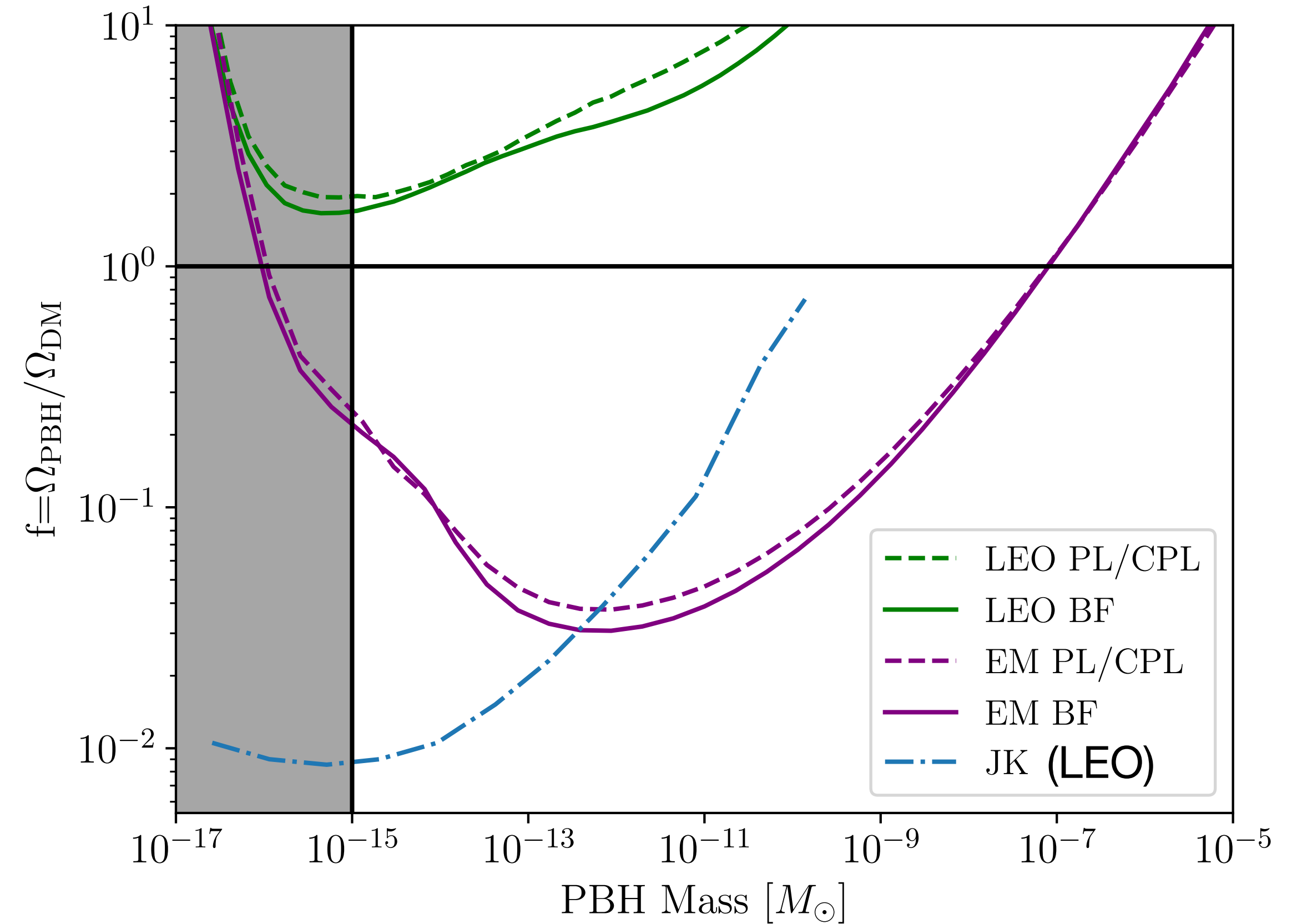


Prior state of the literature (PBH)

(b)



Jung and Kim [1908.00078]

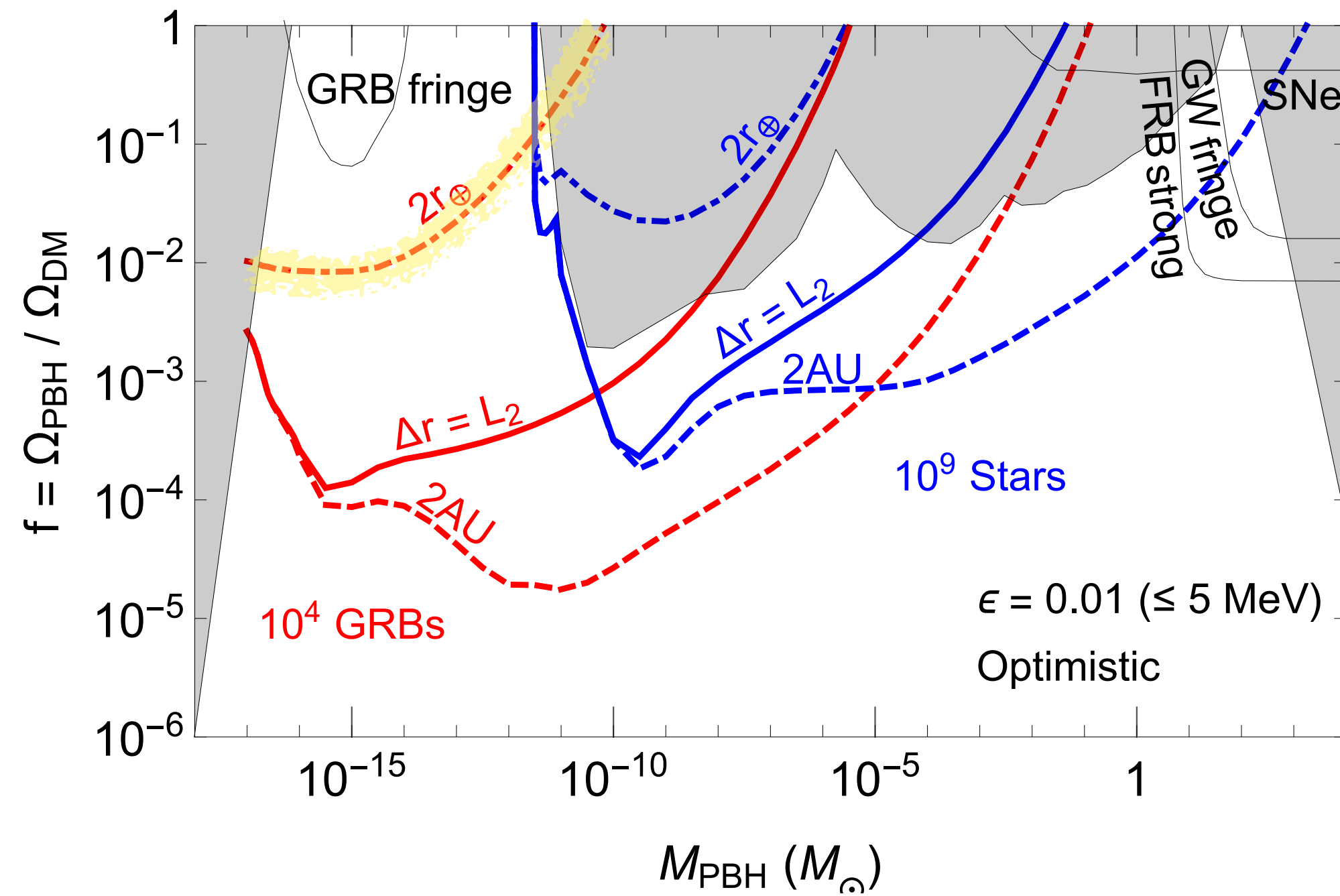


Gawade, More, Bhalerao [2308.01775]

- * proper statistical treatment
- * more conservative detector assumptions

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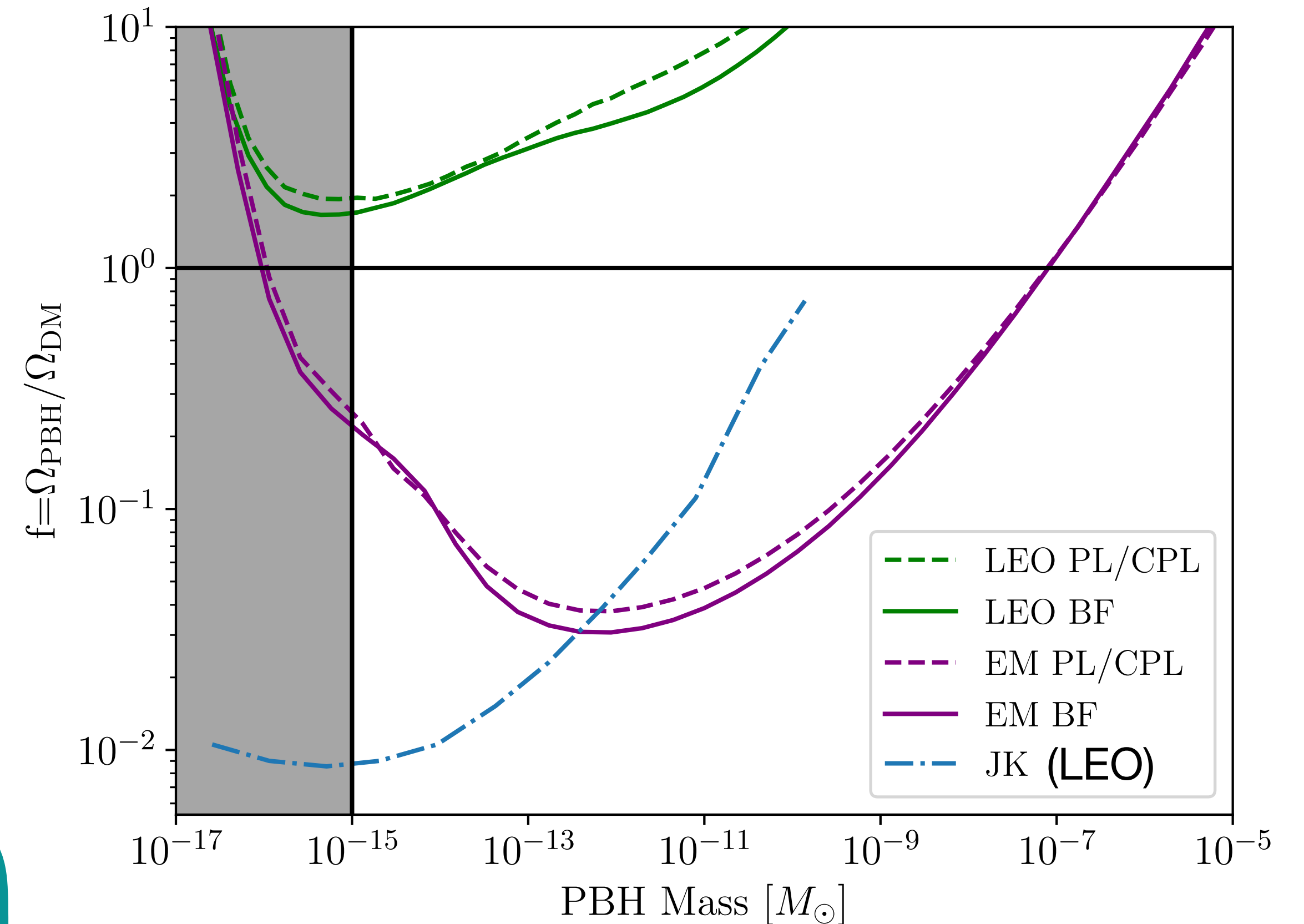


Jung and Kim [1908.00078]

ROBUSTNESS TO SOURCE SIZE UNCERTAINTIES?

LARGER DETECTOR SEPARATION?

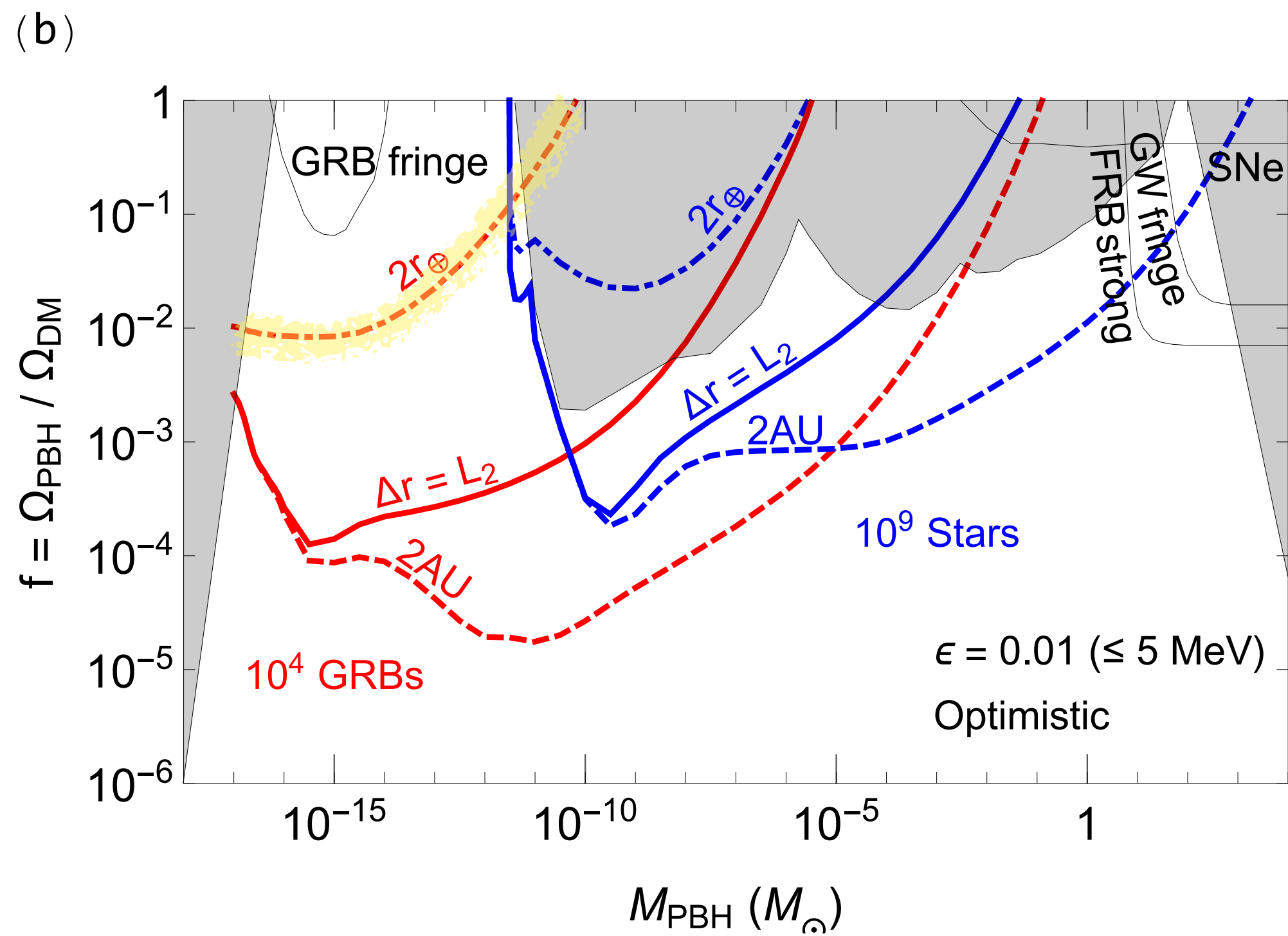
IN PROGRESS: EXTENDED LENSES?



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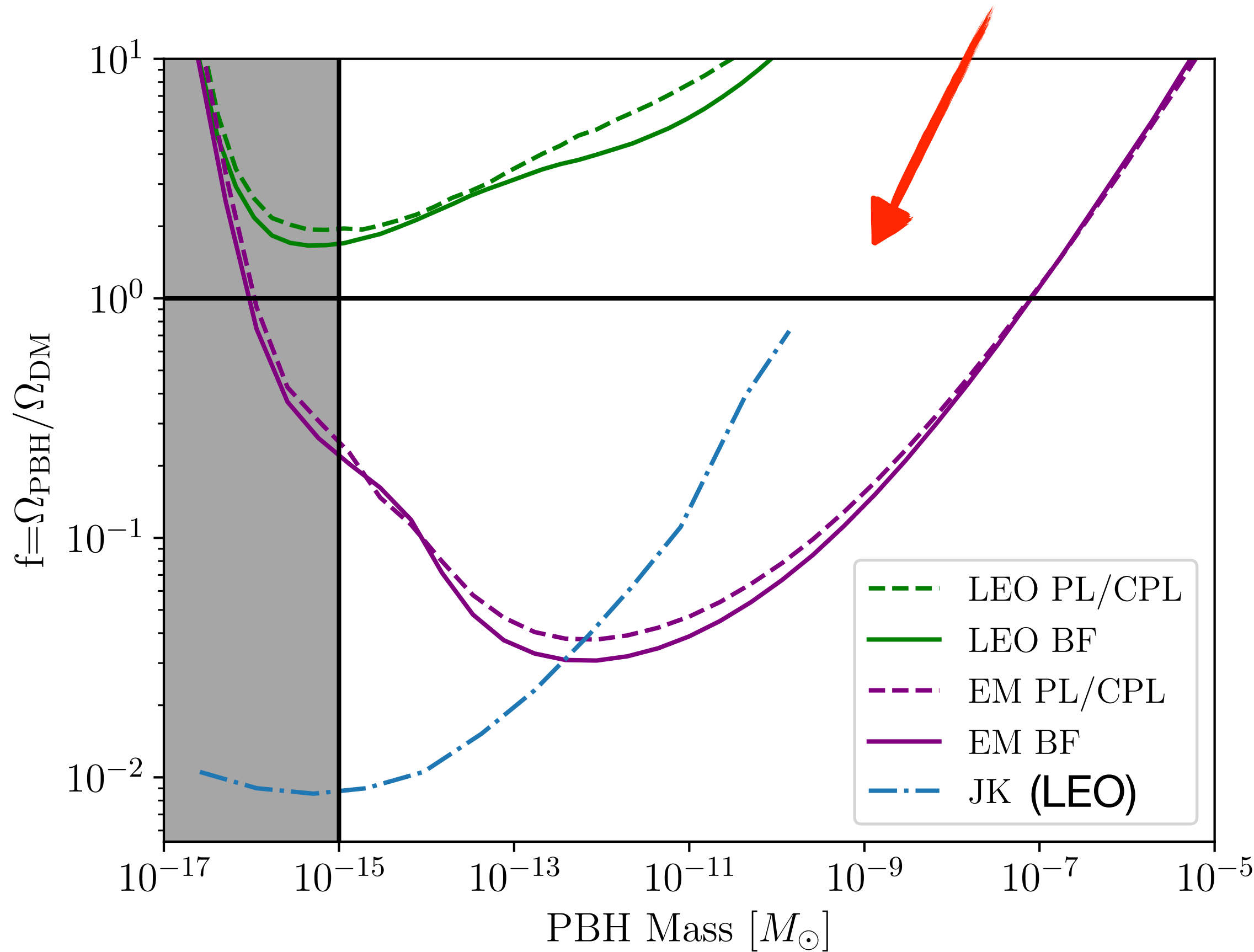
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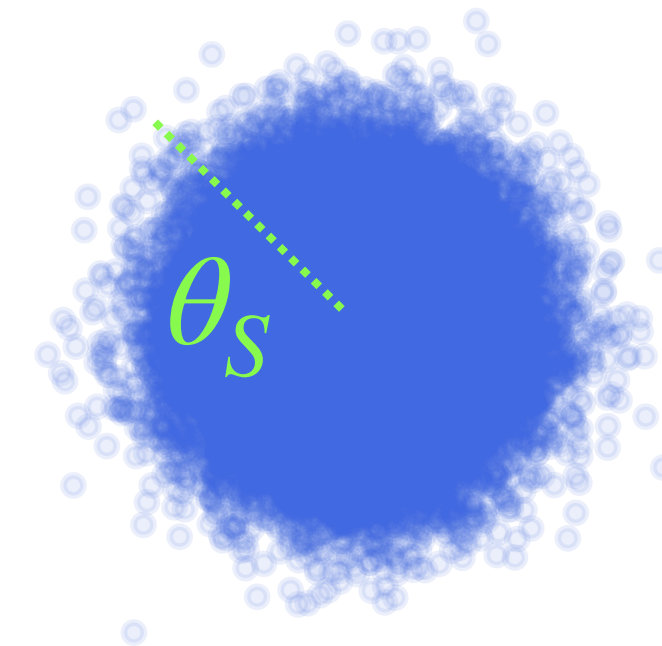
We follow the methodology of this paper



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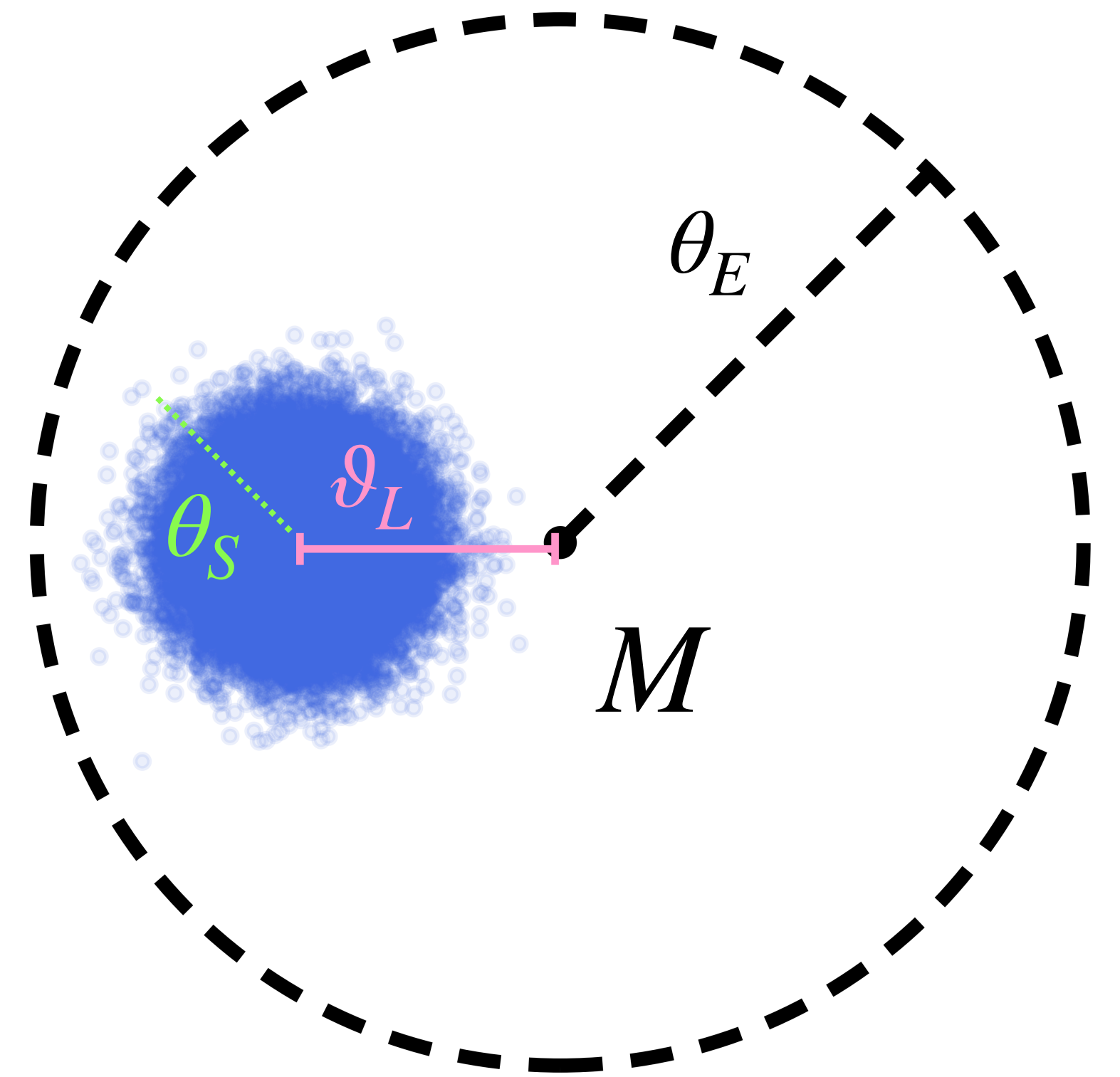
Gravitational Lensing 101



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Typical angular scale associated with strong lensing: **Einstein angle**

$$\theta_E \equiv \sqrt{\frac{4G_N M (1 + z_L) \chi_{LS}}{\chi_S \chi_L}}$$



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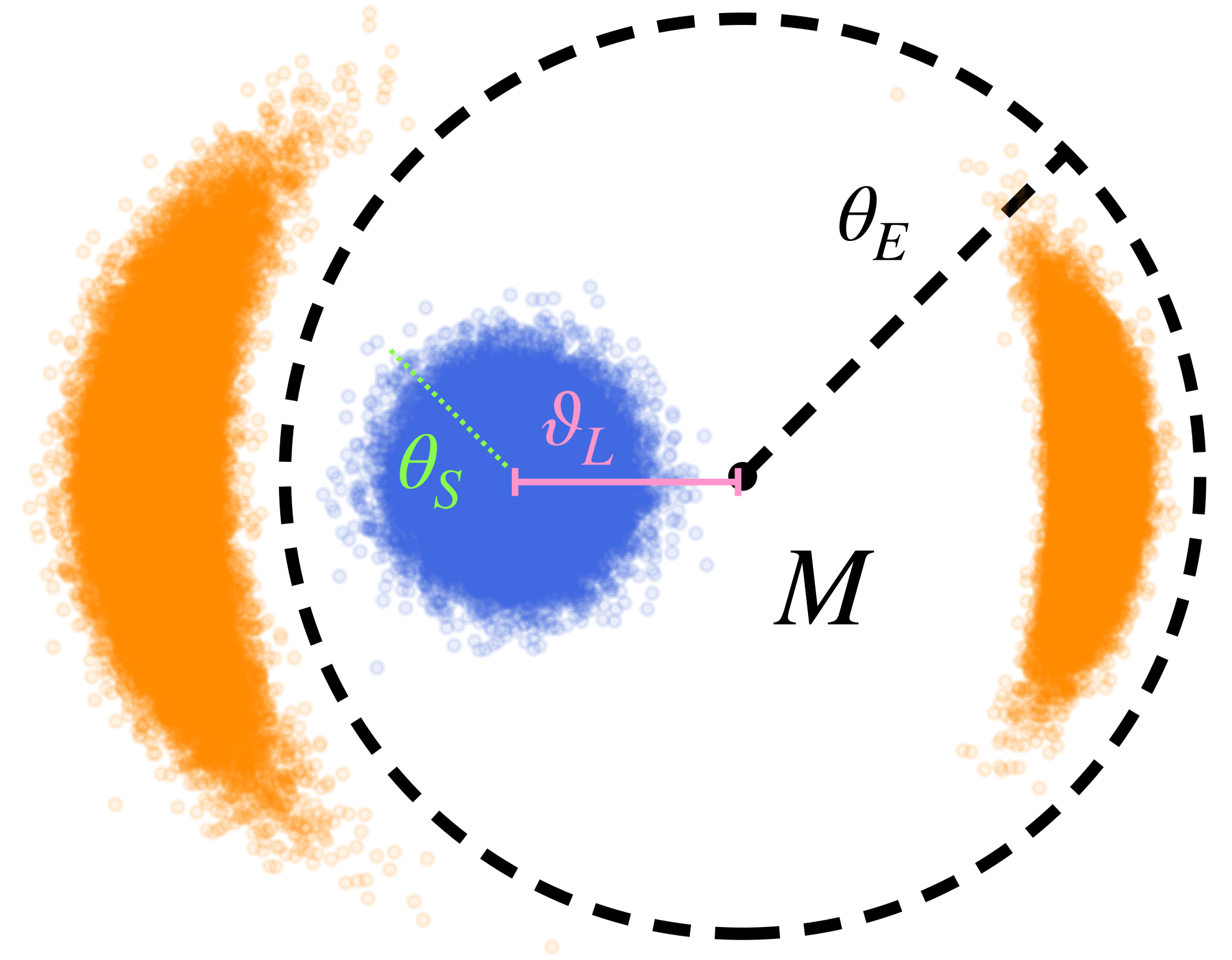


Image is magnified: $\mu \sim \frac{\theta_E}{\vartheta_L}$ ($\vartheta_L, \theta_S \ll \theta_E$)

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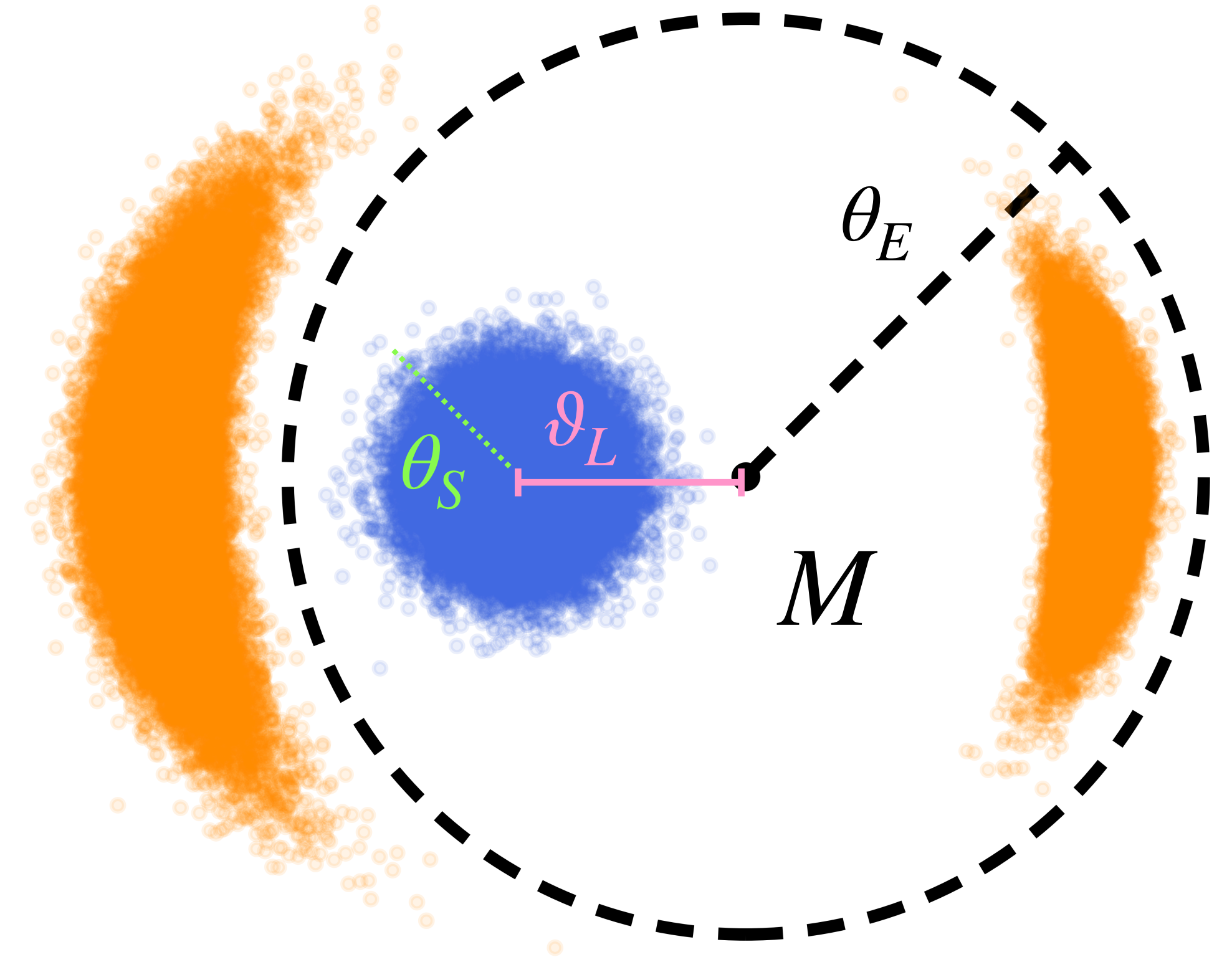


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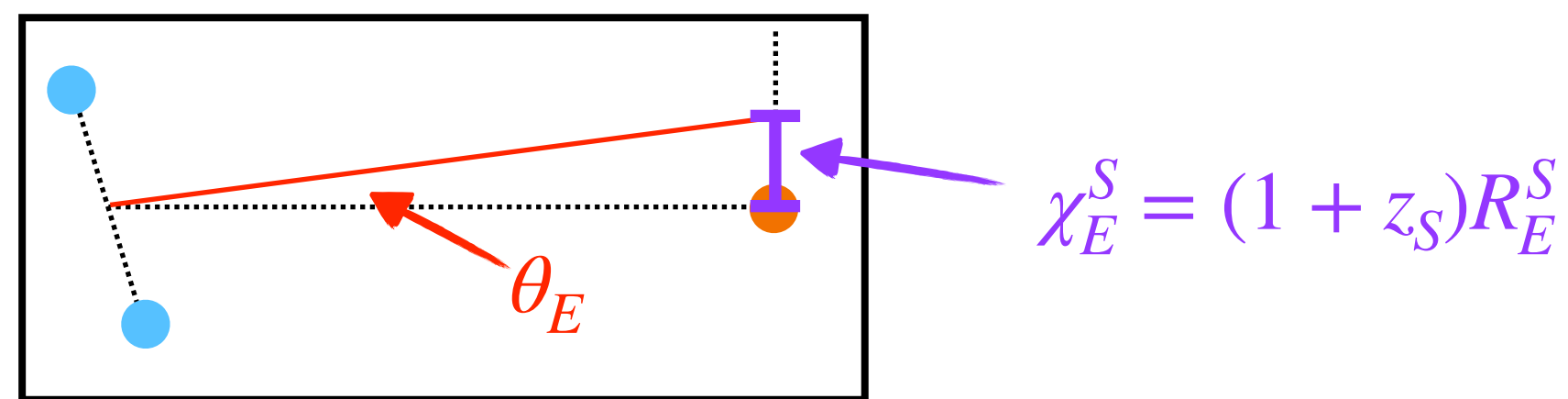
BUT: Finite sources ($\theta_S \gtrsim \theta_E$) have suppressed source-averaged magnification: $\bar{\mu} - 1 \sim \mathcal{O}(\theta_E^2/\theta_S^2)$

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$$\theta_E \sim \text{picoarcsec} \times \sqrt{\frac{M}{10^{-12} M_\odot}}$$



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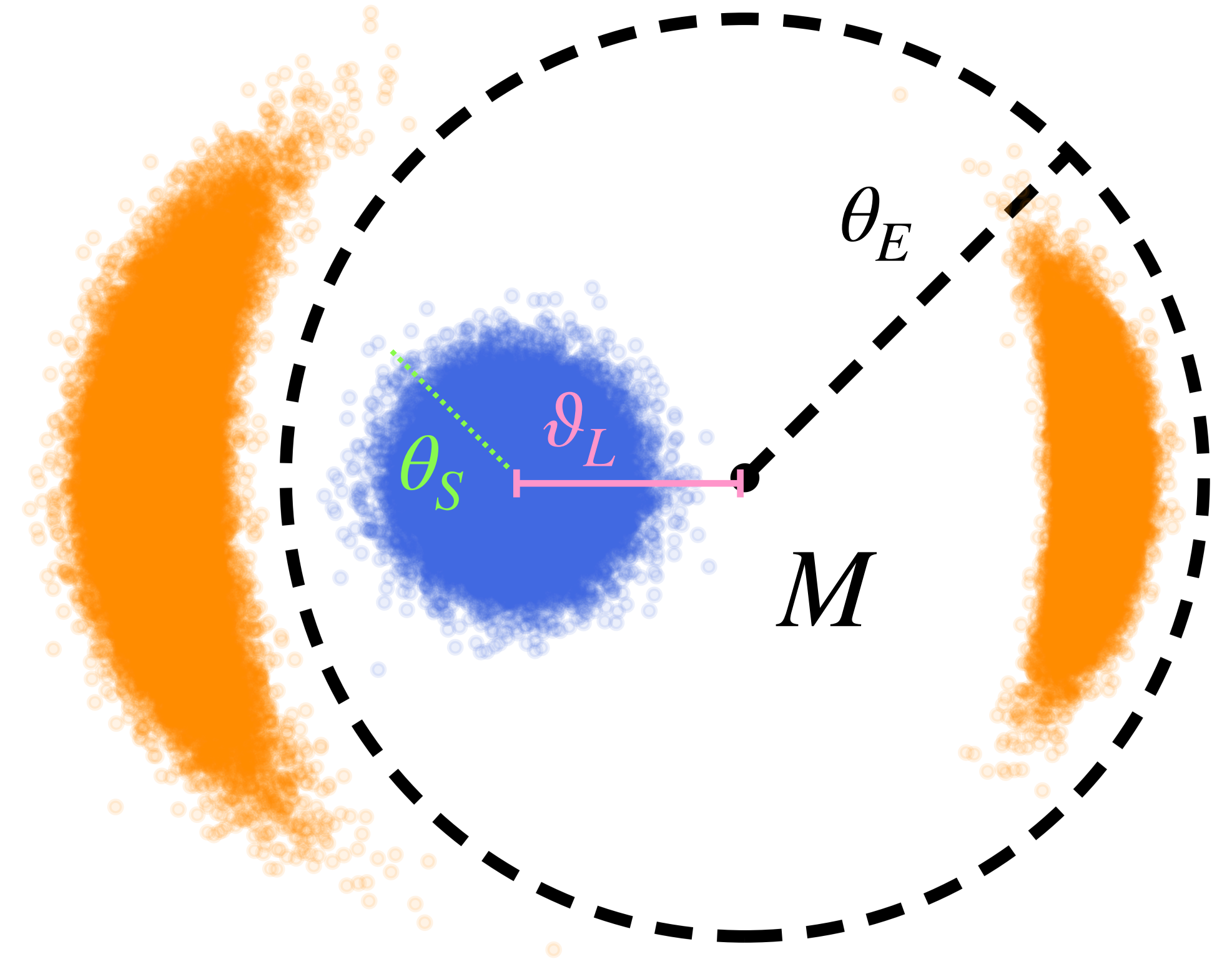


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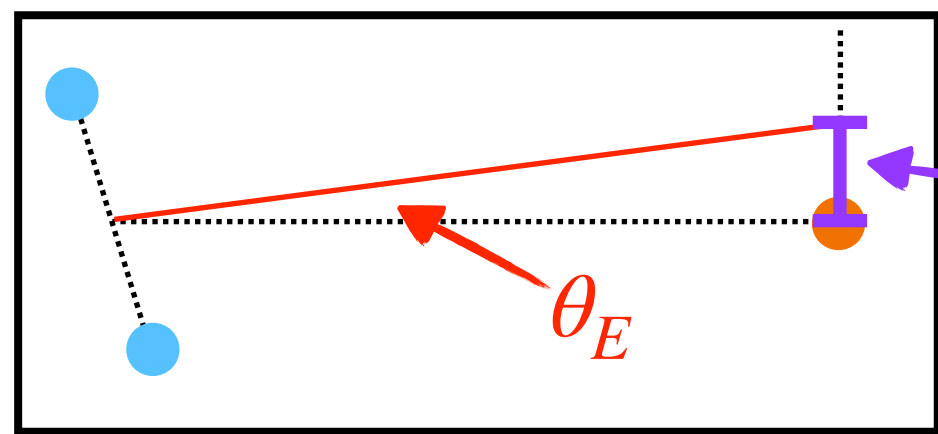
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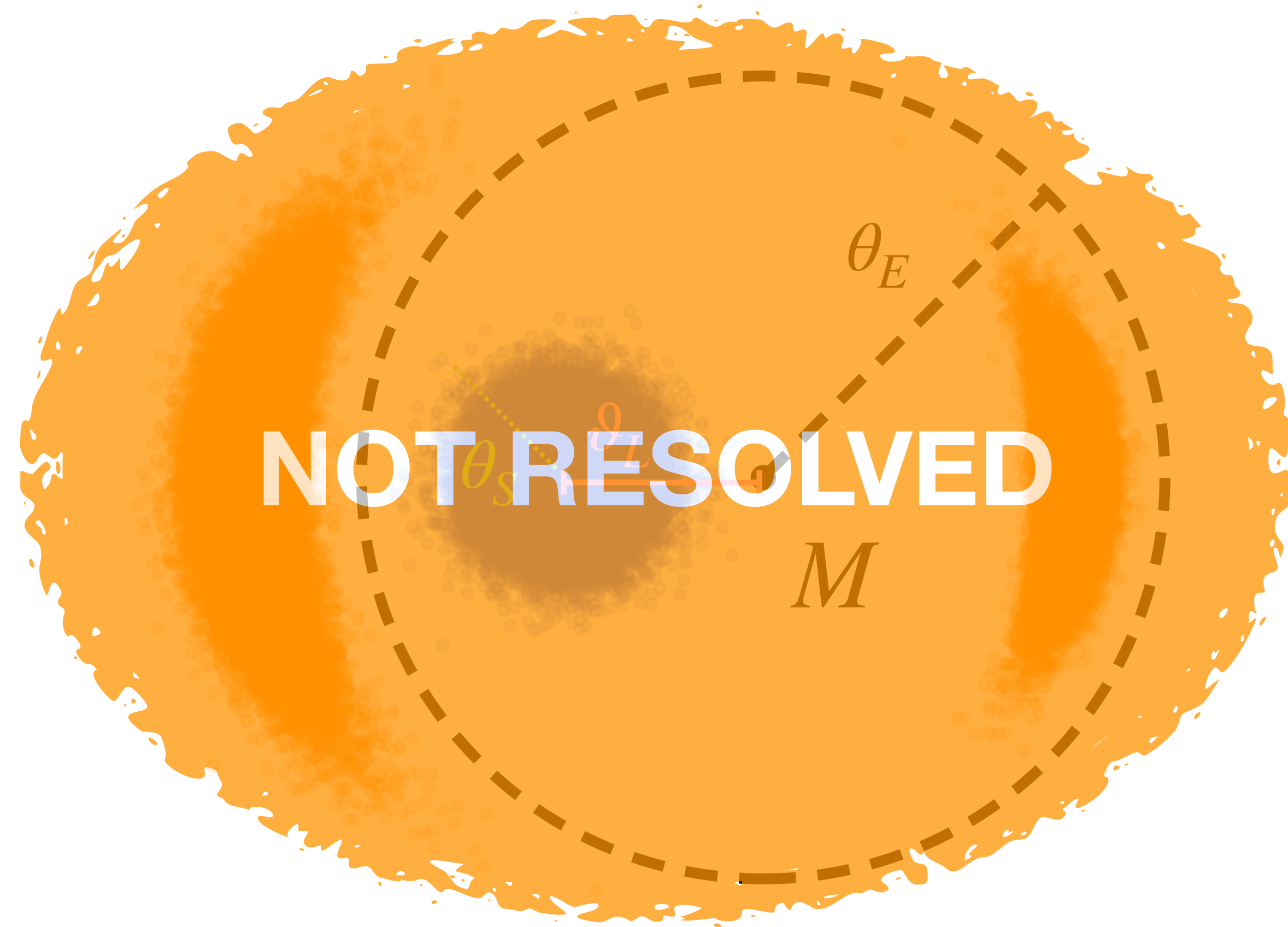
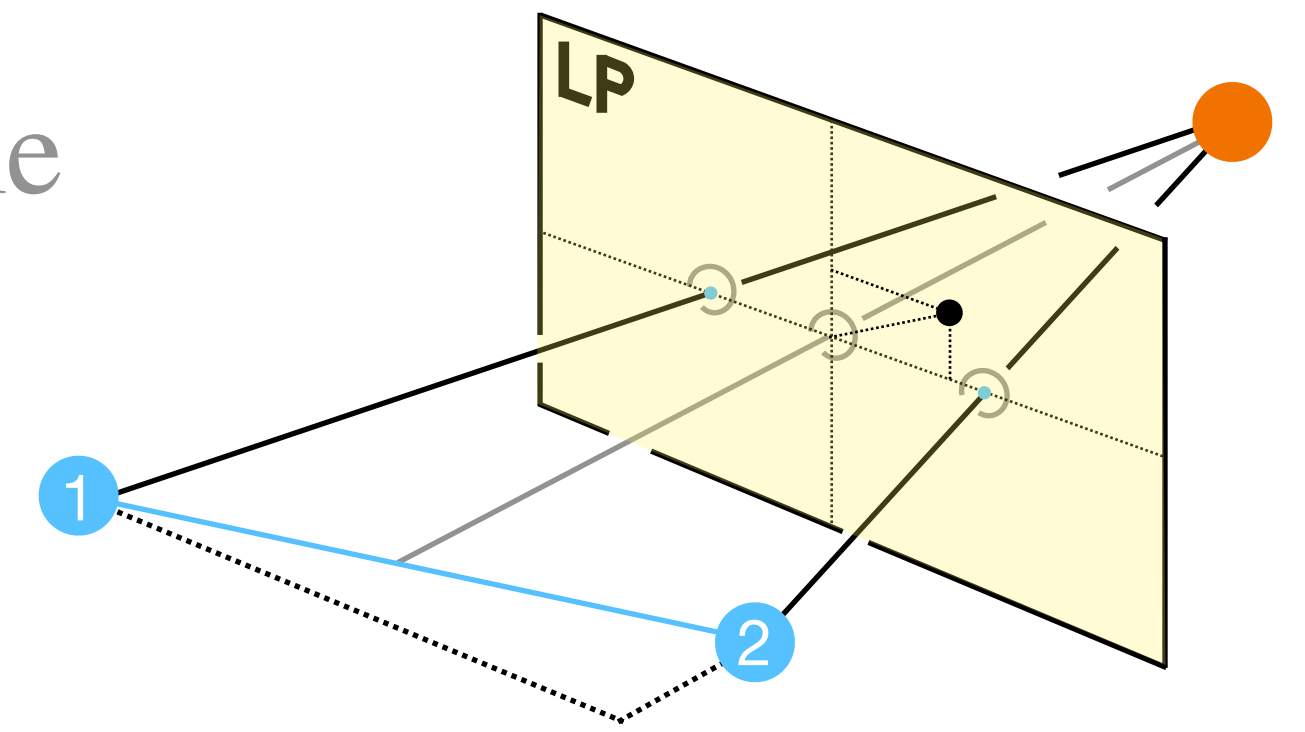


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Picolensing signal

$f = \text{flux} = \text{photons/area/time}$



Two detectors each measure photons: $N = S + B$.

Signal: $\langle S \rangle = \bar{\mu} \cdot f_S \cdot A_S \cdot T$

Background: $\langle B \rangle = f_B \cdot A_B \cdot T$

Uncertainty: $\sqrt{\langle N \rangle}$

Assumed identical
detectors, except for
magnification

Could generalise

Picolensing signal: $\Delta N = N_2 - N_1$.

Uncertainty: $u[\Delta N] = \sqrt{2B + S_1 + S_2}$

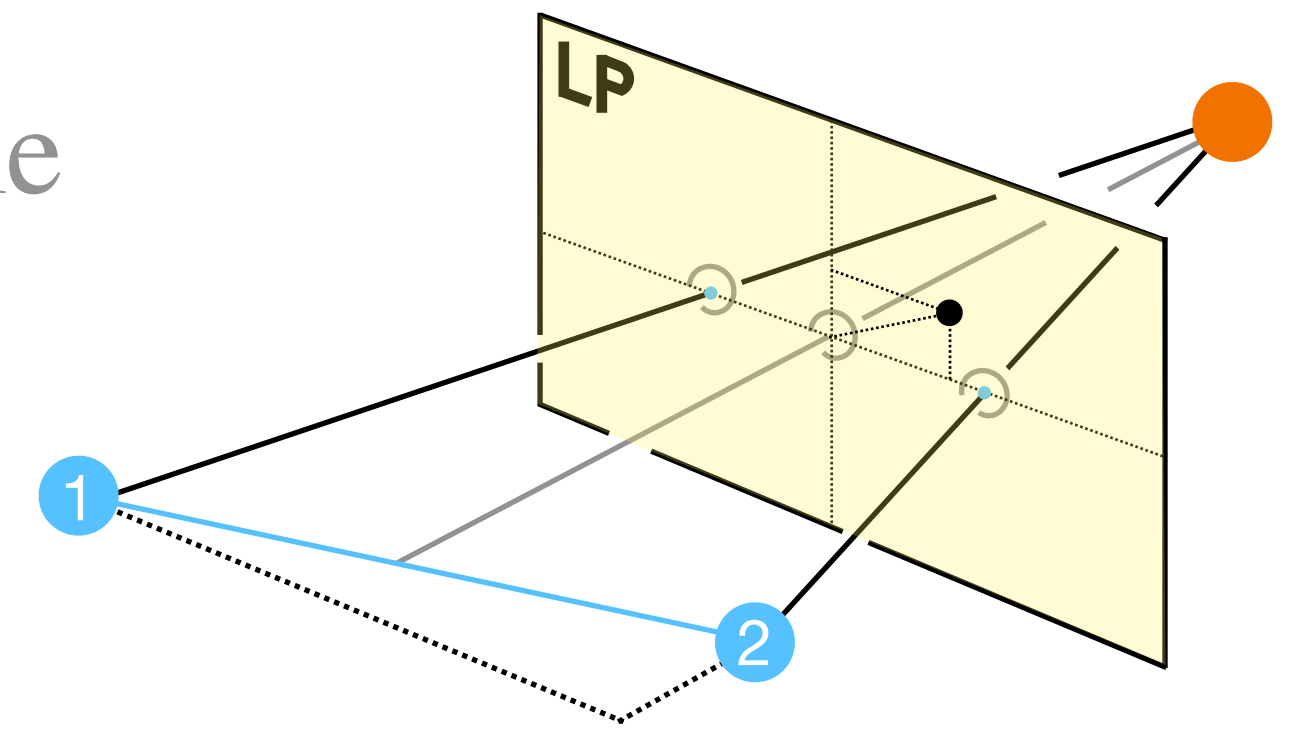
SNR: $\rho = |\langle \Delta N \rangle| / u[\Delta N]$

$$\langle \Delta N \rangle = \langle S_1 \rangle - \langle S_2 \rangle$$

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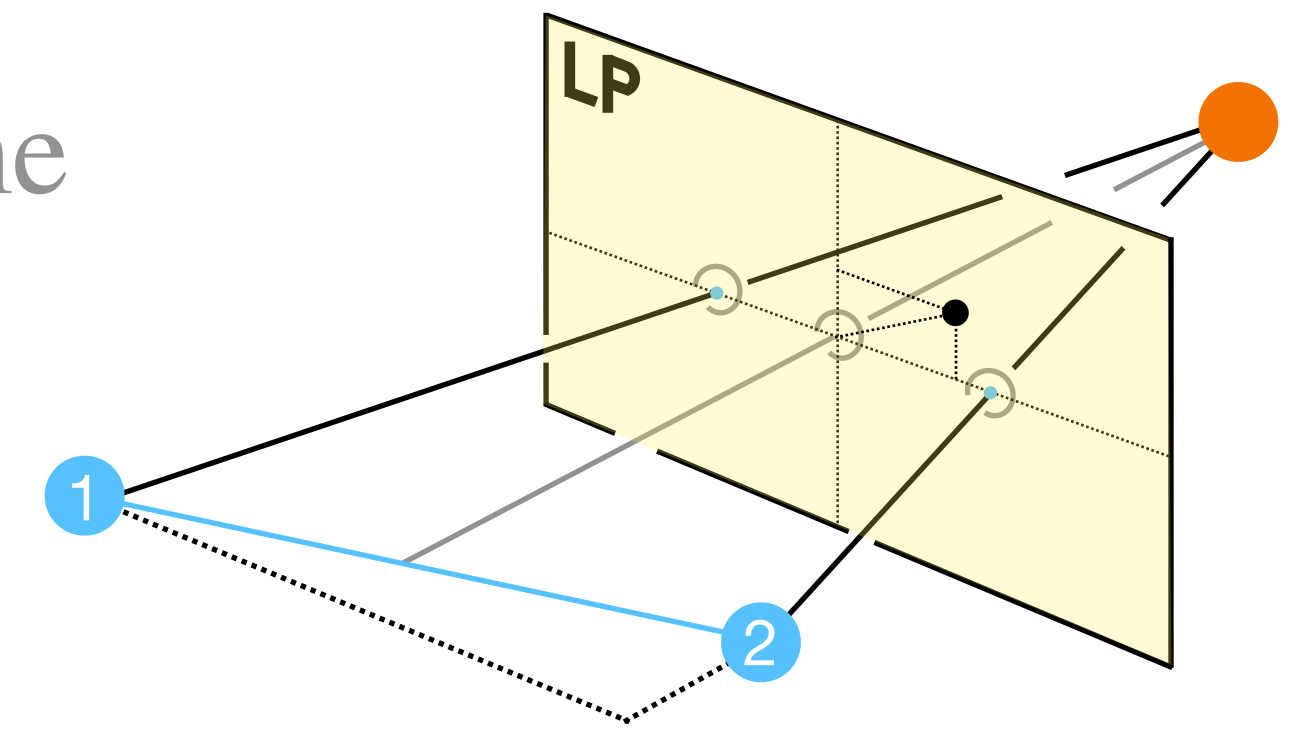
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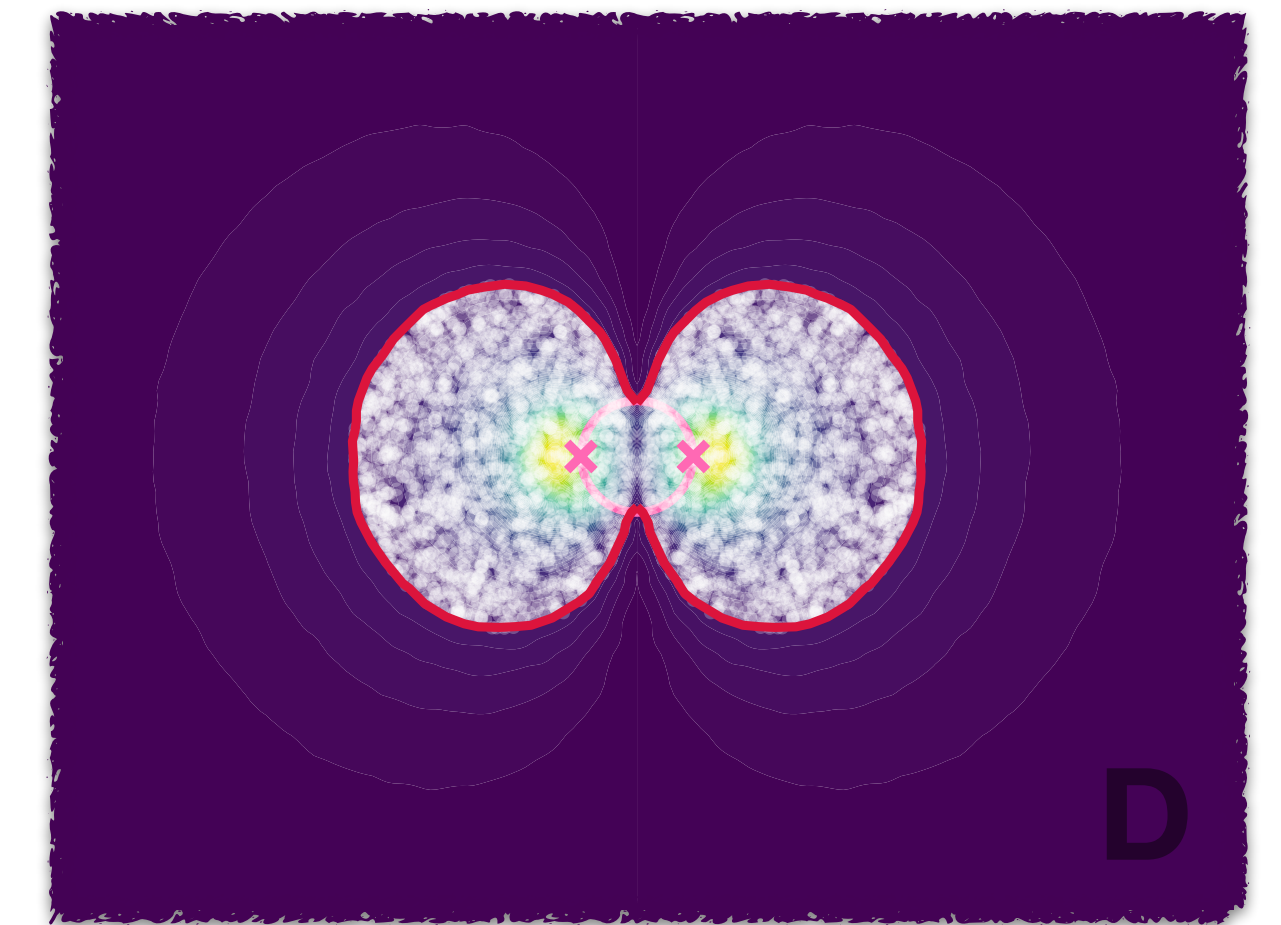
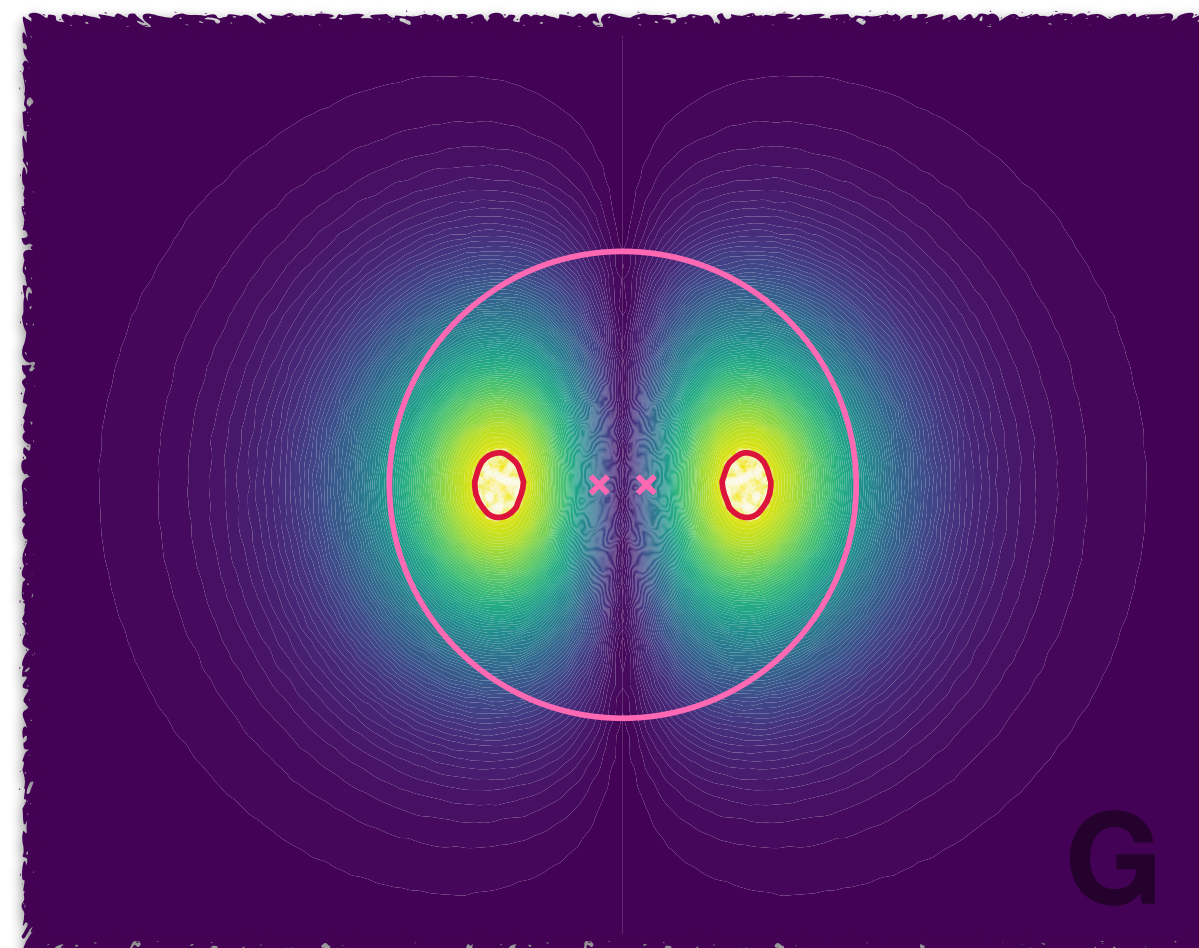
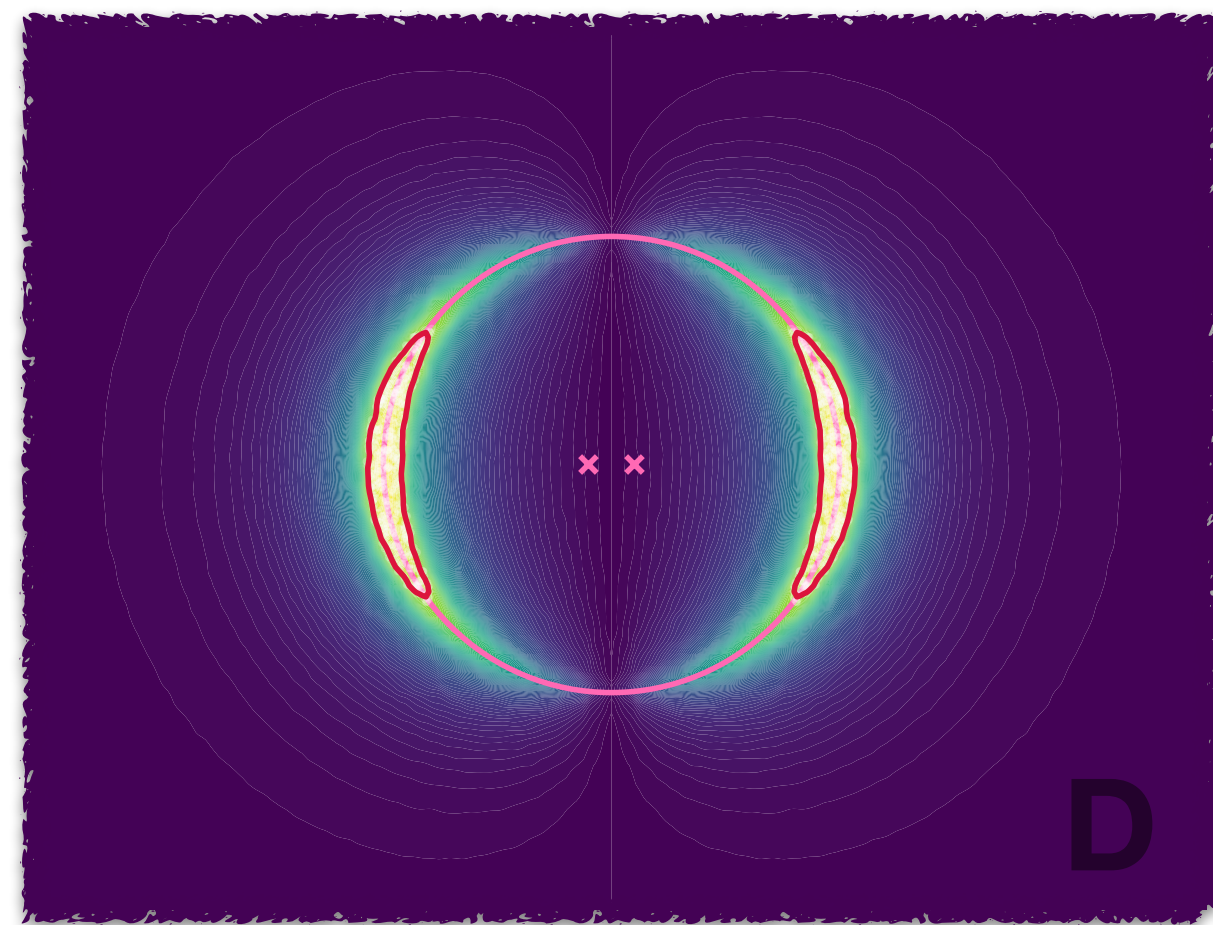
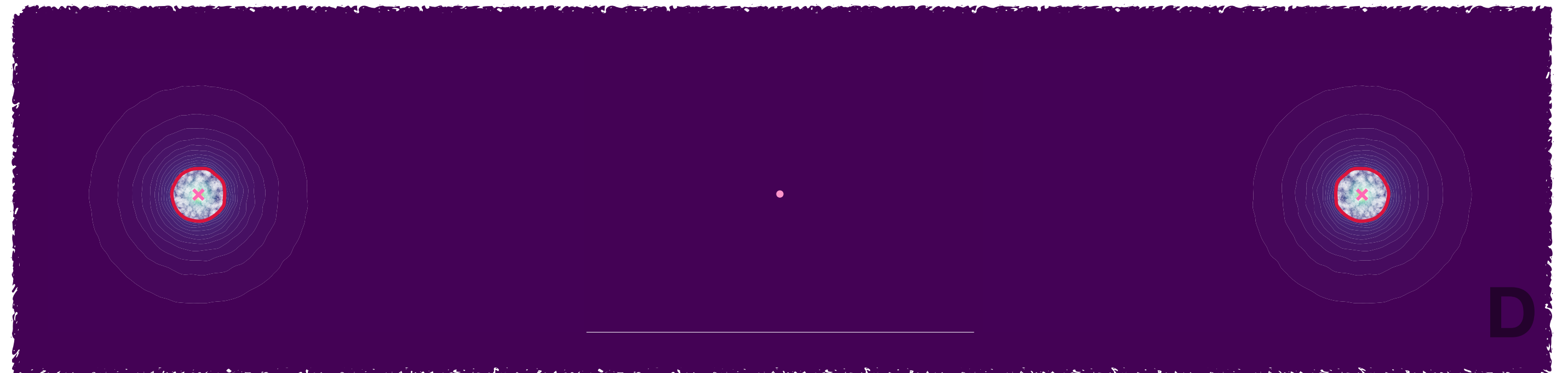
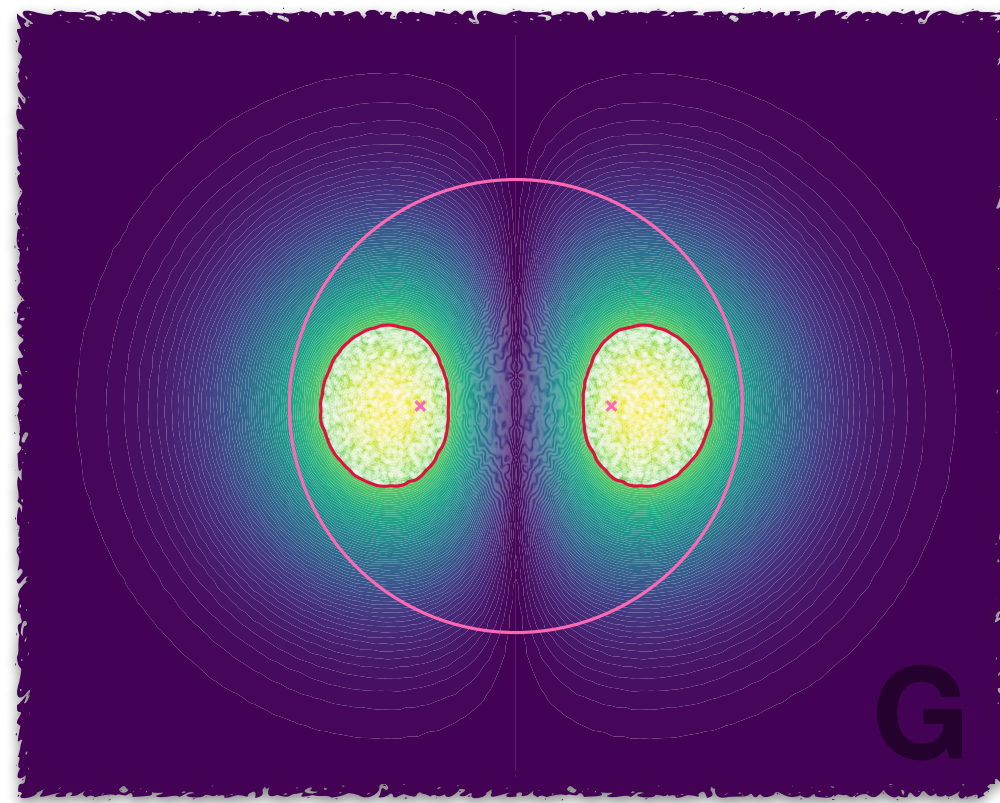
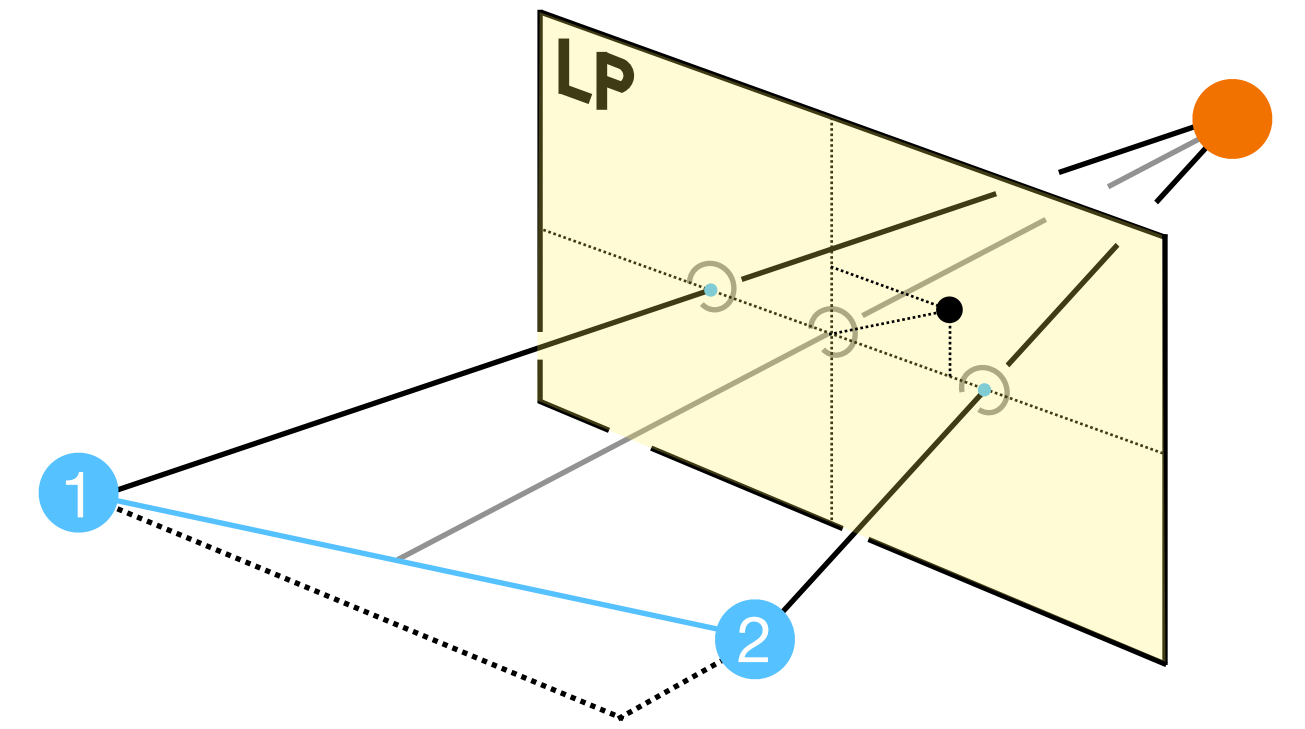
$$\propto \bar{\mu}_1 - \bar{\mu}_2$$

This is SNR for ONE lens and ONE source. Want a statement about number of expected events for populations...

Picolensing Cross-section σ

Region in lens plane where $\rho \geq \rho_*$, a threshold SNR.

Compute with Monte Carlo techniques.

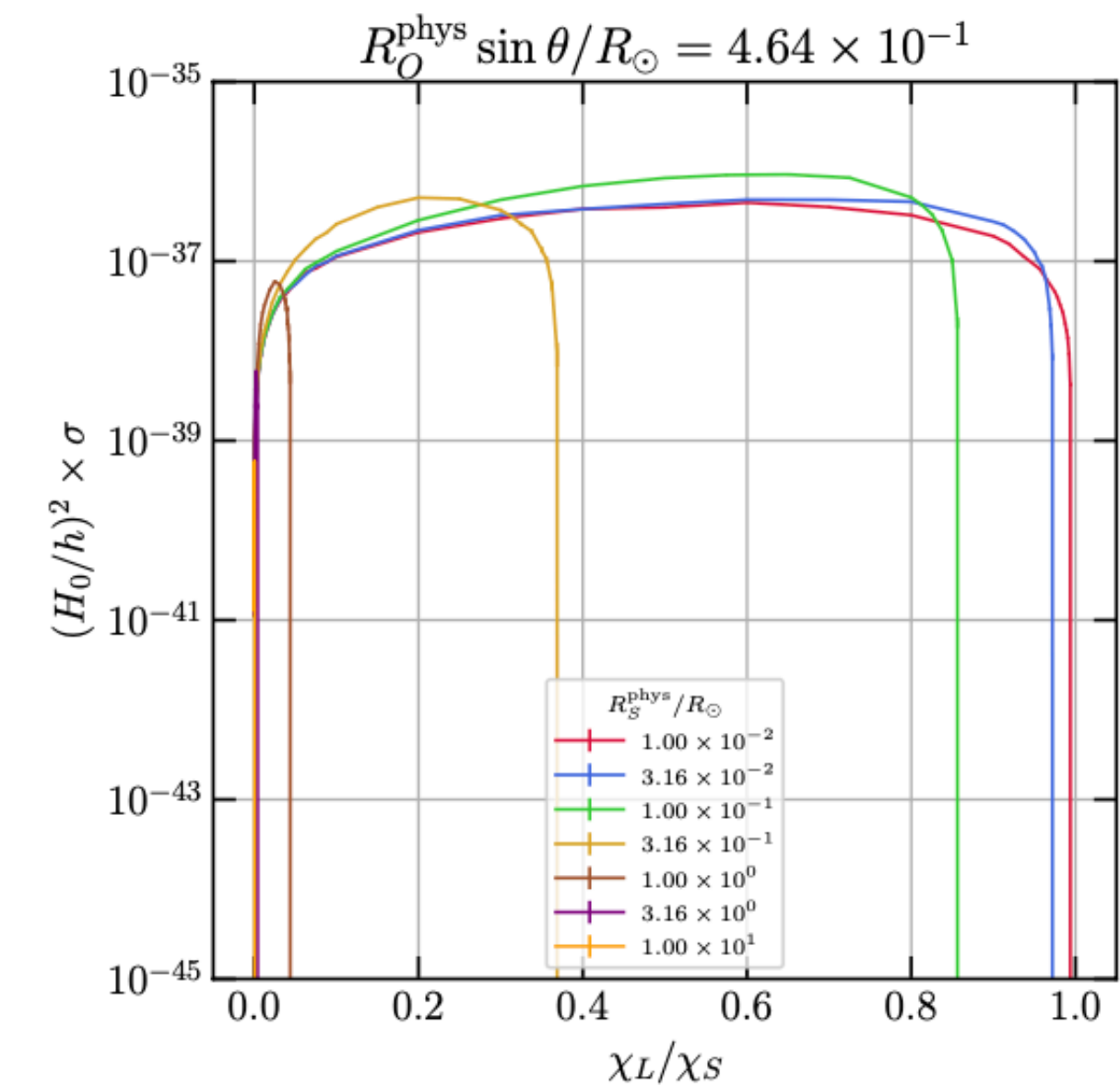


Picolensing volume & optical depth

$\sigma = \sigma(\chi_L, \dots)$ is a function of the distance to the lens plane χ_L

Co-moving picolensing volume:

$$\mathcal{V} = \int_0^{\chi_s} \sigma(\chi_L) d\chi_L$$



PBHs: can treat as uniform* co-moving lens number density n_0

Optical depth (= expected number of lenses) to source j is $\tau_j = n_0 \mathcal{V}_j$ (need $\tau_j \ll 1$ for validity)

N sources. Average lensing volume: $\overline{\mathcal{V}} \equiv \frac{1}{N} \sum_{j=1}^N \mathcal{V}_j \Rightarrow \bar{\tau} = n_0 \overline{\mathcal{V}}$ average optical depth

Straightforward Poisson statistics* to then get lensing probabilities and set limits / explore discovery space

*Jung and Kim [1908.00078] looked at clustering;
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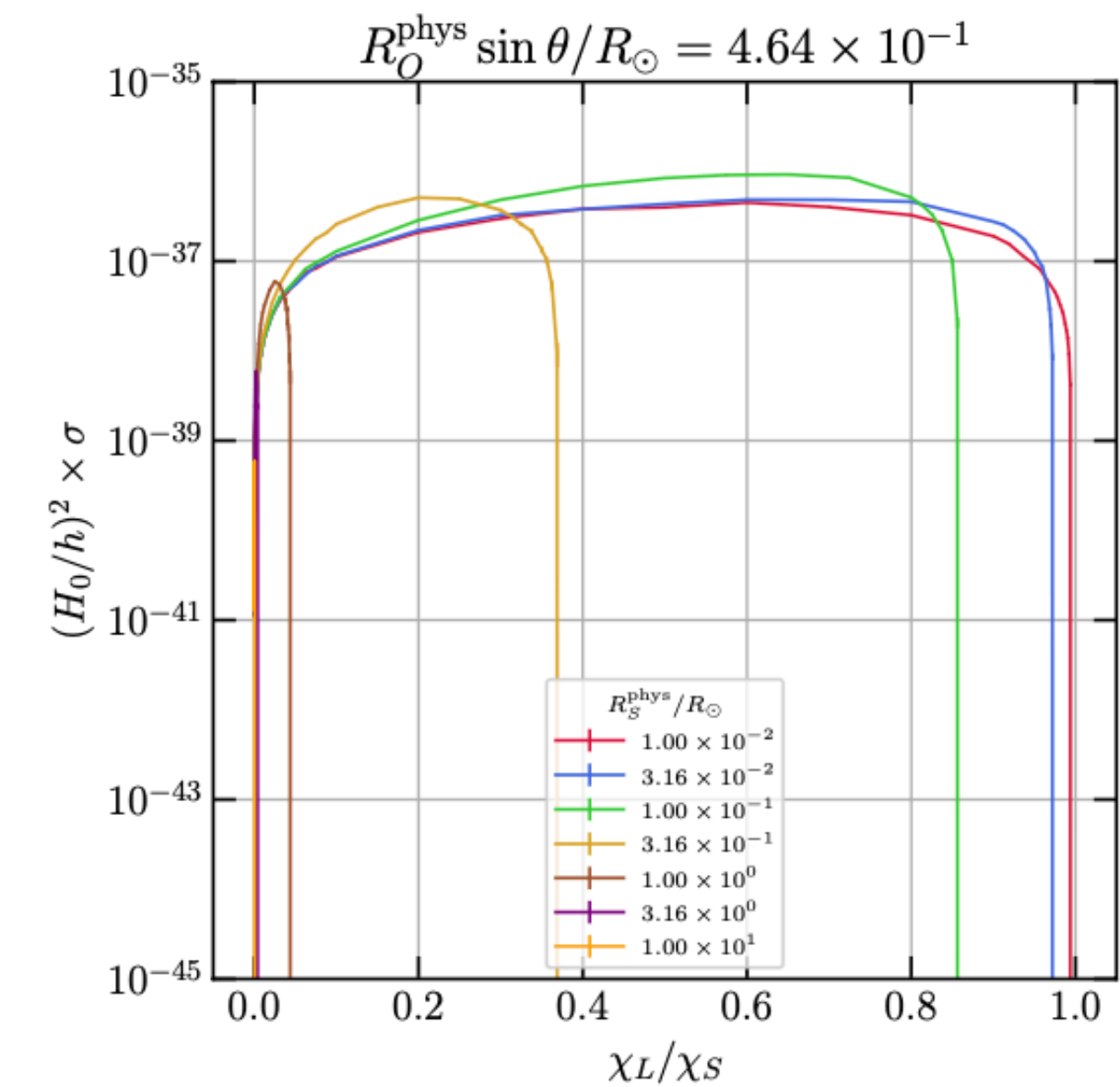
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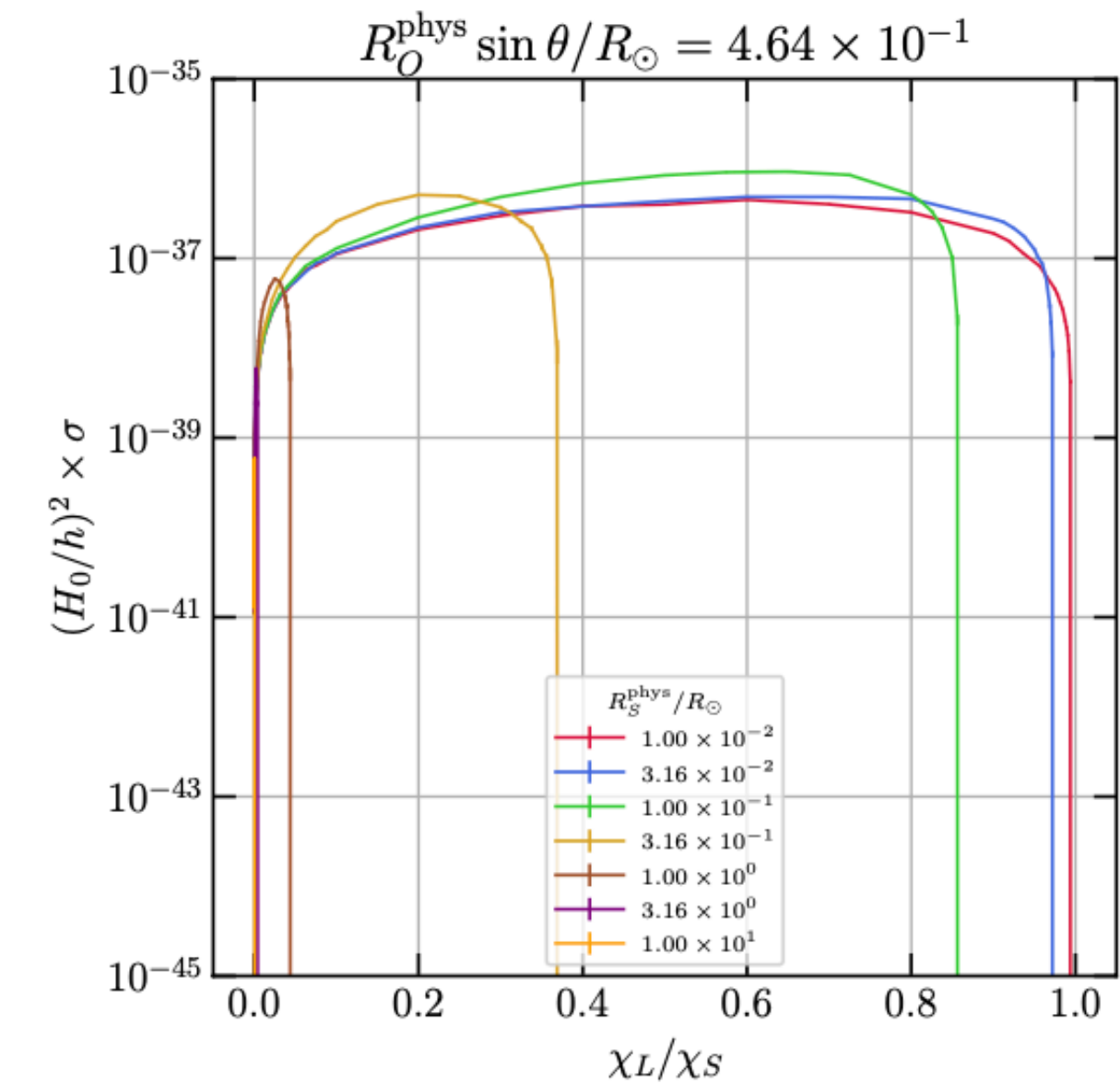


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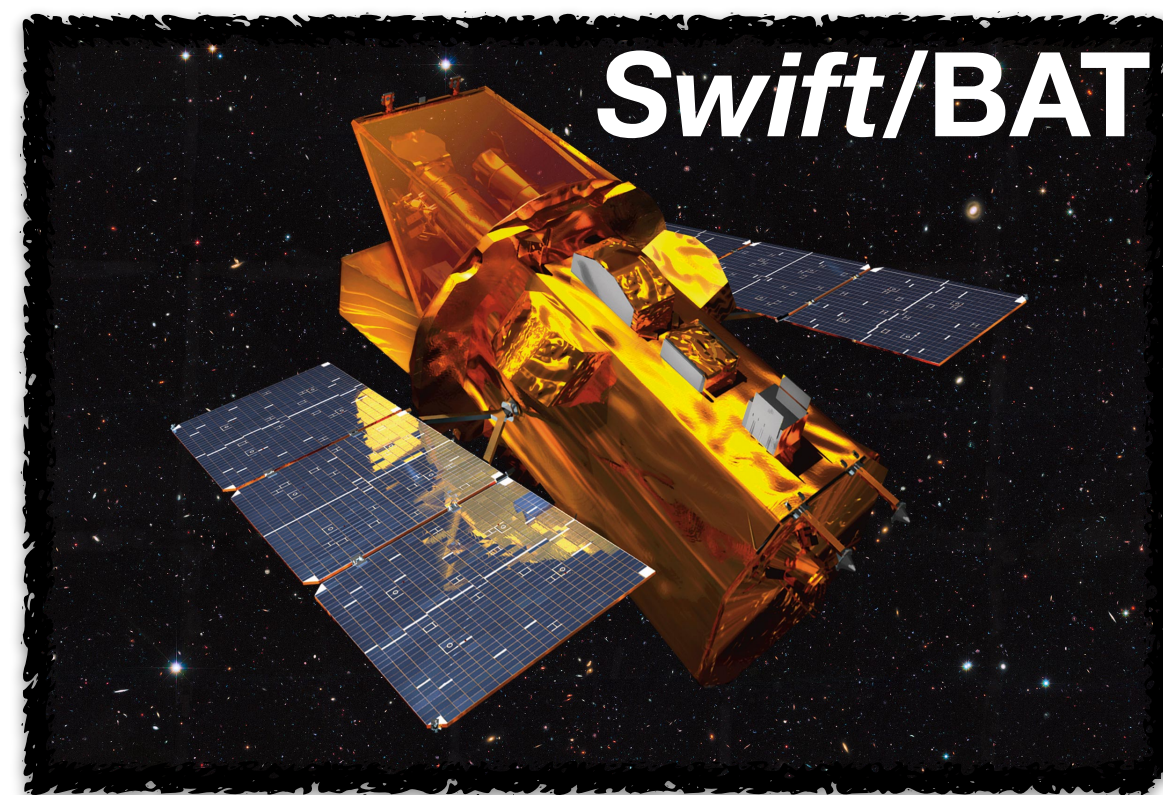
Sources: Gamma-Ray Bursts (GRBs)

LENSING:
GEOMETRICAL
OPTICS!

Transient. Two classes: long (> 2 s) and short (< 2 s)

Long: cosmologically distant ($\bar{z}_S \sim 2$) and **very** bright in x/ γ -rays.

Highly beamed emission: $\Gamma \sim 10^2$ $E_{\text{beam}} \sim 3 \times 10^{51} \text{ erg} \sim (2 - 3) \cdot E_{\text{SNIa}}$



$\sim 3 \times 10^3$ detections



Gawade et al [2308.01775] looked at a possible future ISRO project Daksha
($2 \times \sim$ Swift/BAT-class detectors in space, but each with *Fermi*/GBM sky coverage)

For results today: **assume similar parameters to $2 \times$ Swift/BAT** ($\sim$ Daksha)

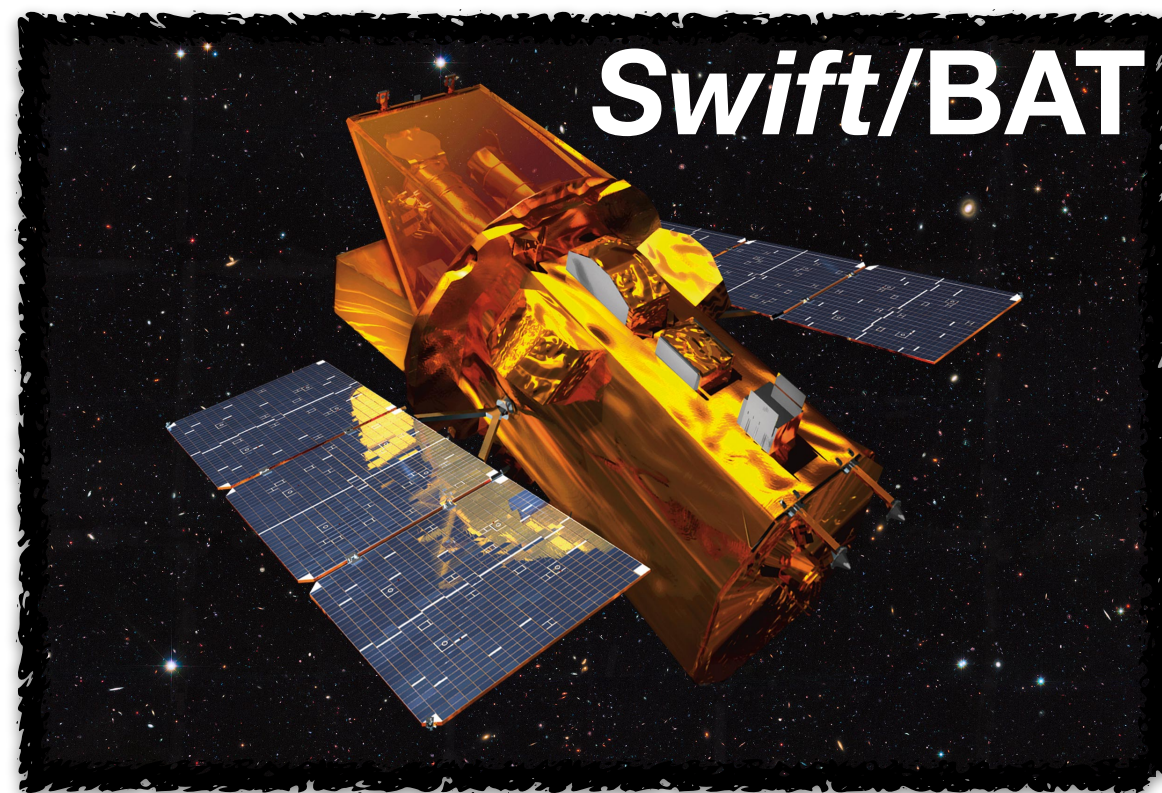
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Source characteristics: *Swift*/BAT catalogue

Use real GRBs to make population-informed projections.

For each GRB, need:

Duration: T_{90} — time for 90% of measured intensity after trigger

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... AND: SIZE θ_S

GRB size data are **very uncertain**

$$D_{\text{obs}}^{\text{fid}} \sim \frac{D'}{\Gamma} \sim \frac{\Gamma \times \Delta t_{\text{var}}}{1+z_S} \sim \frac{T_{90}}{1+z_S}$$

$$D' \sim \Gamma \times D_{\text{obs}}^{\text{fid}}$$

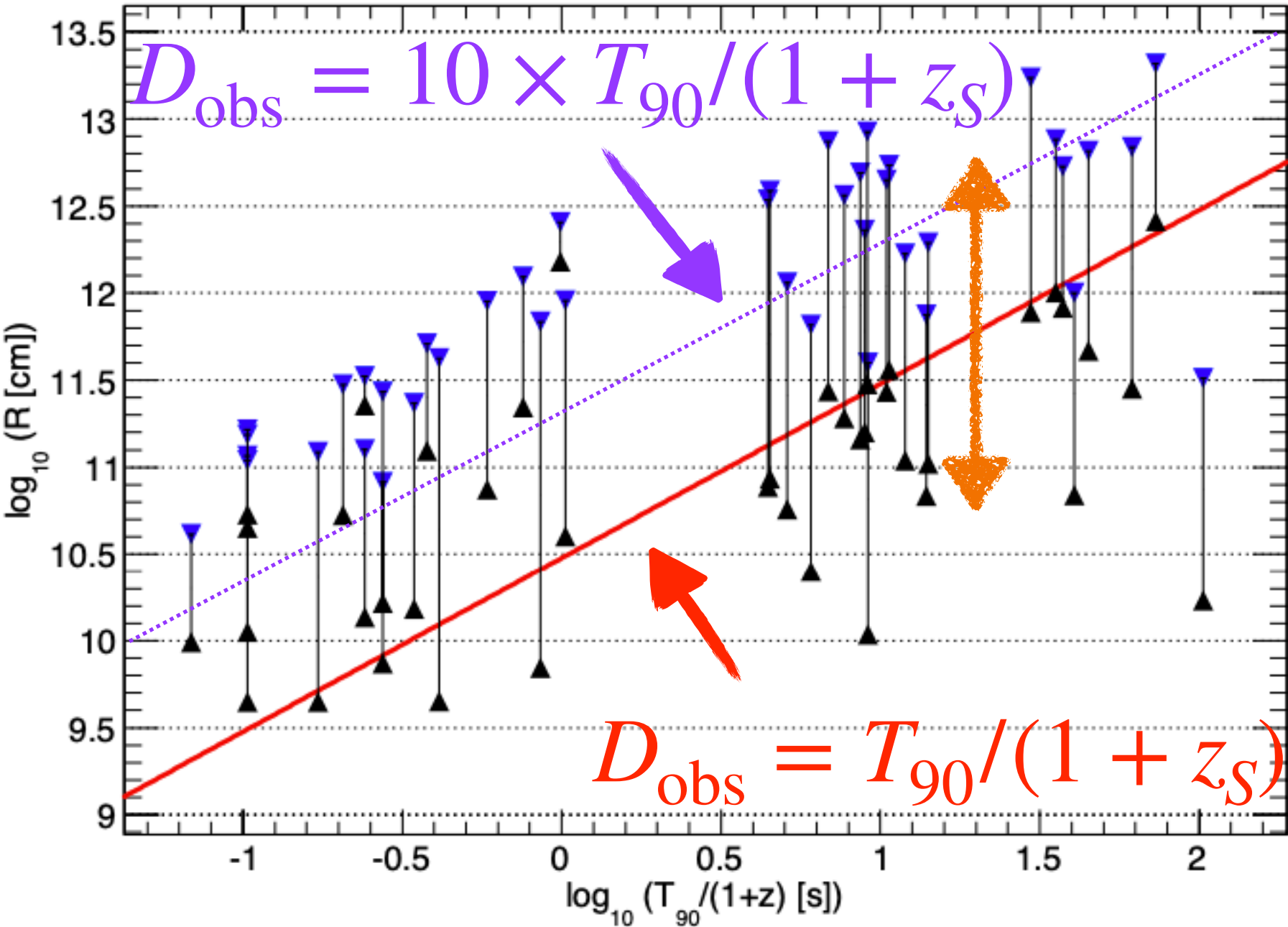
-Scatter?

-Offset?

-Trend?

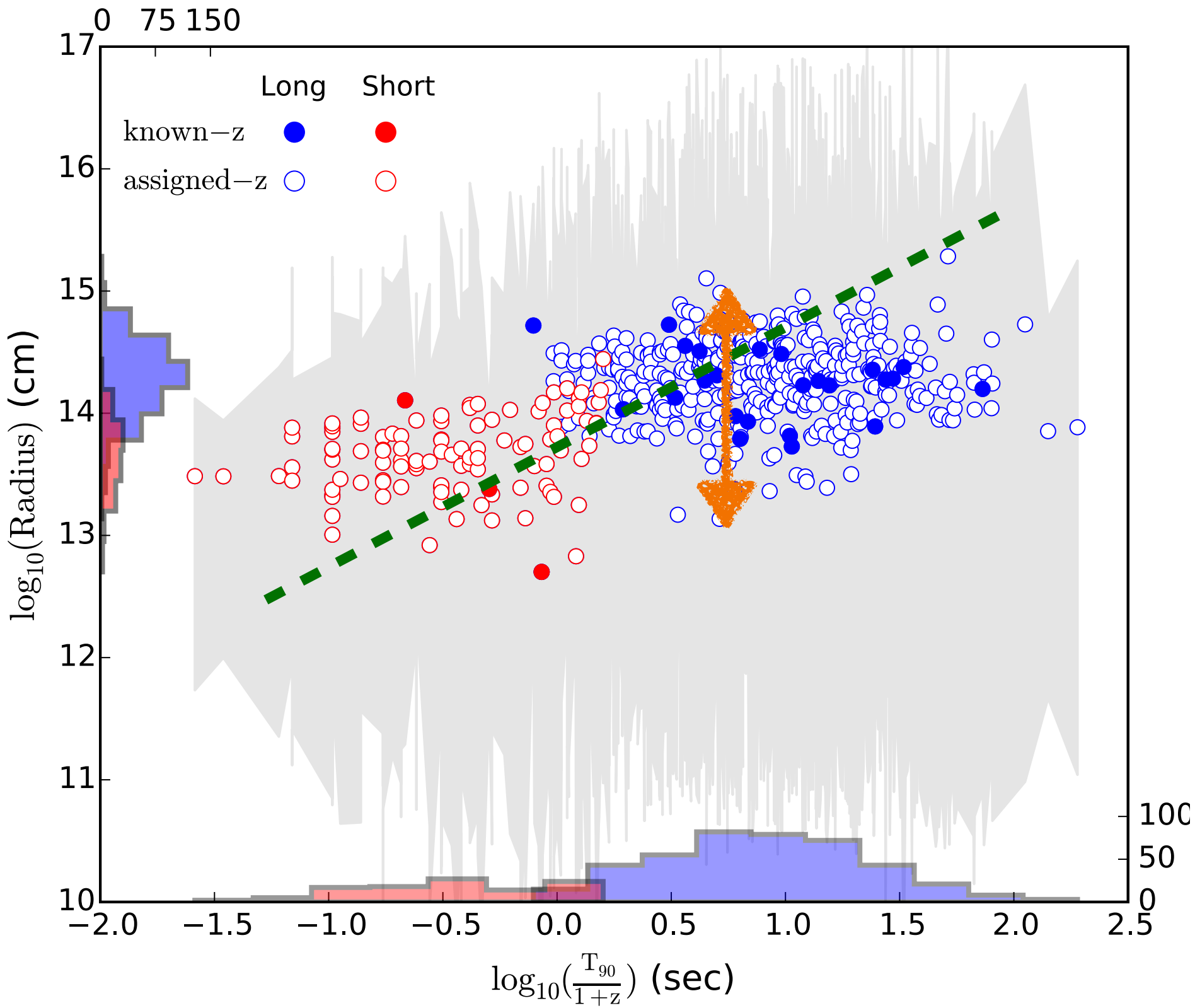


y-axes
differ by
 $\Gamma \sim 10^2$



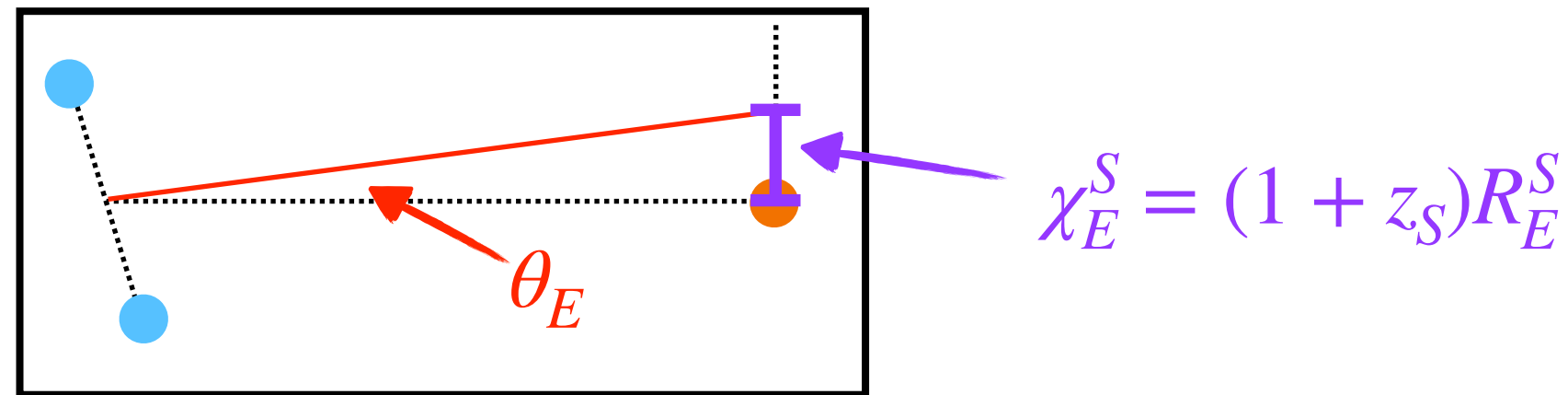
Note that this line is not attempting to fit the constraints from the data

Barnacka, Loeb [1409.1232]



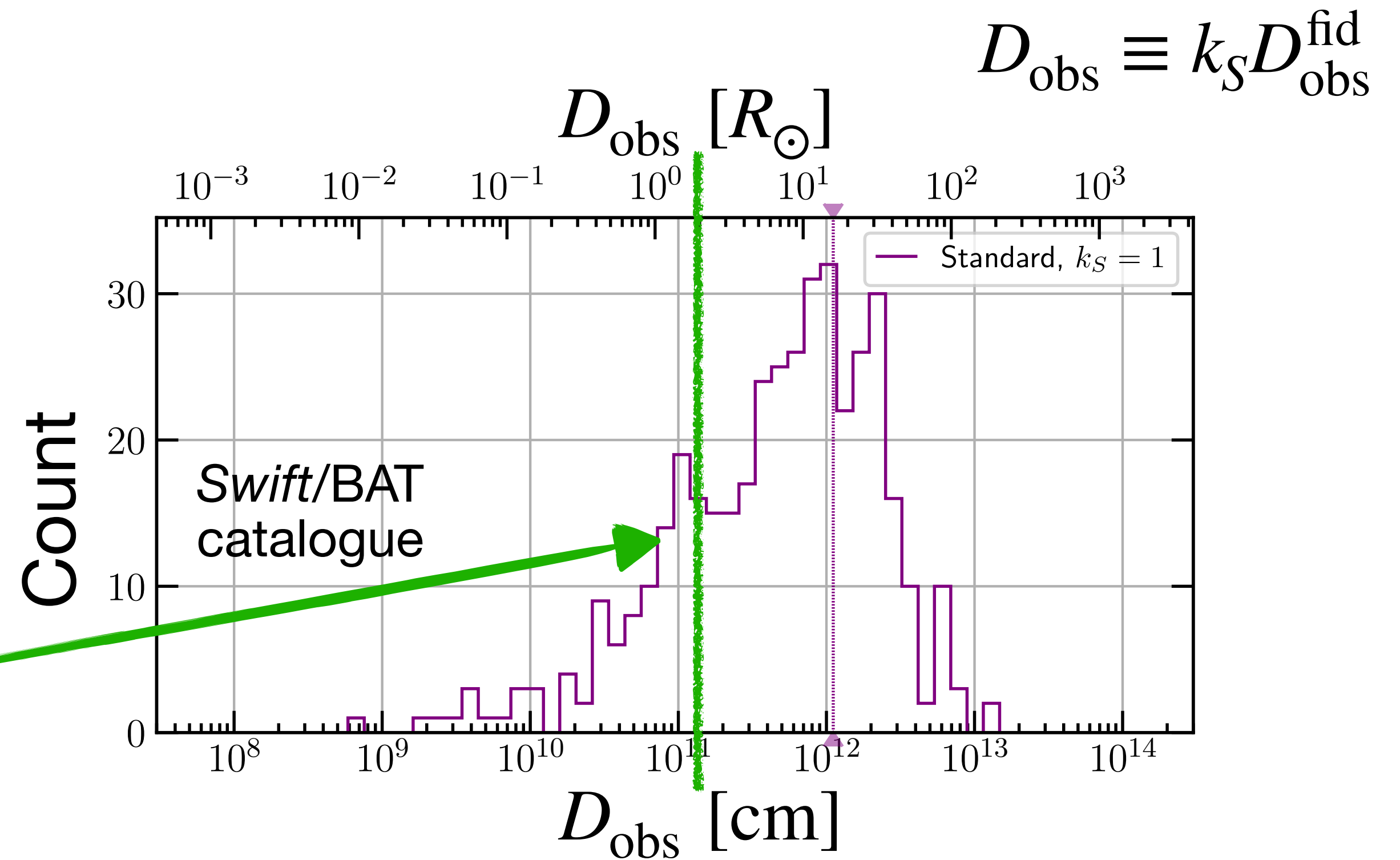
Golkhou et al [1501.05948]

This can be important!



$$\chi_E^S = (1 + z_S) R_E^S$$

$$R_E^S = \mathcal{D}_S \theta_E \sim R_\odot \times \sqrt{\frac{M}{10^{-12} M_\odot}}$$

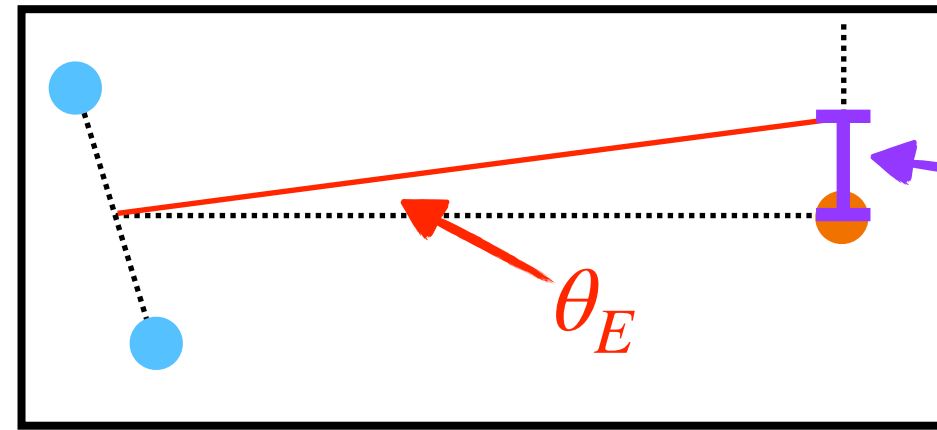


Source sizes can be large vs the Einstein radius in the source plane!

Magnifications are sensitive to source size uncertainties!

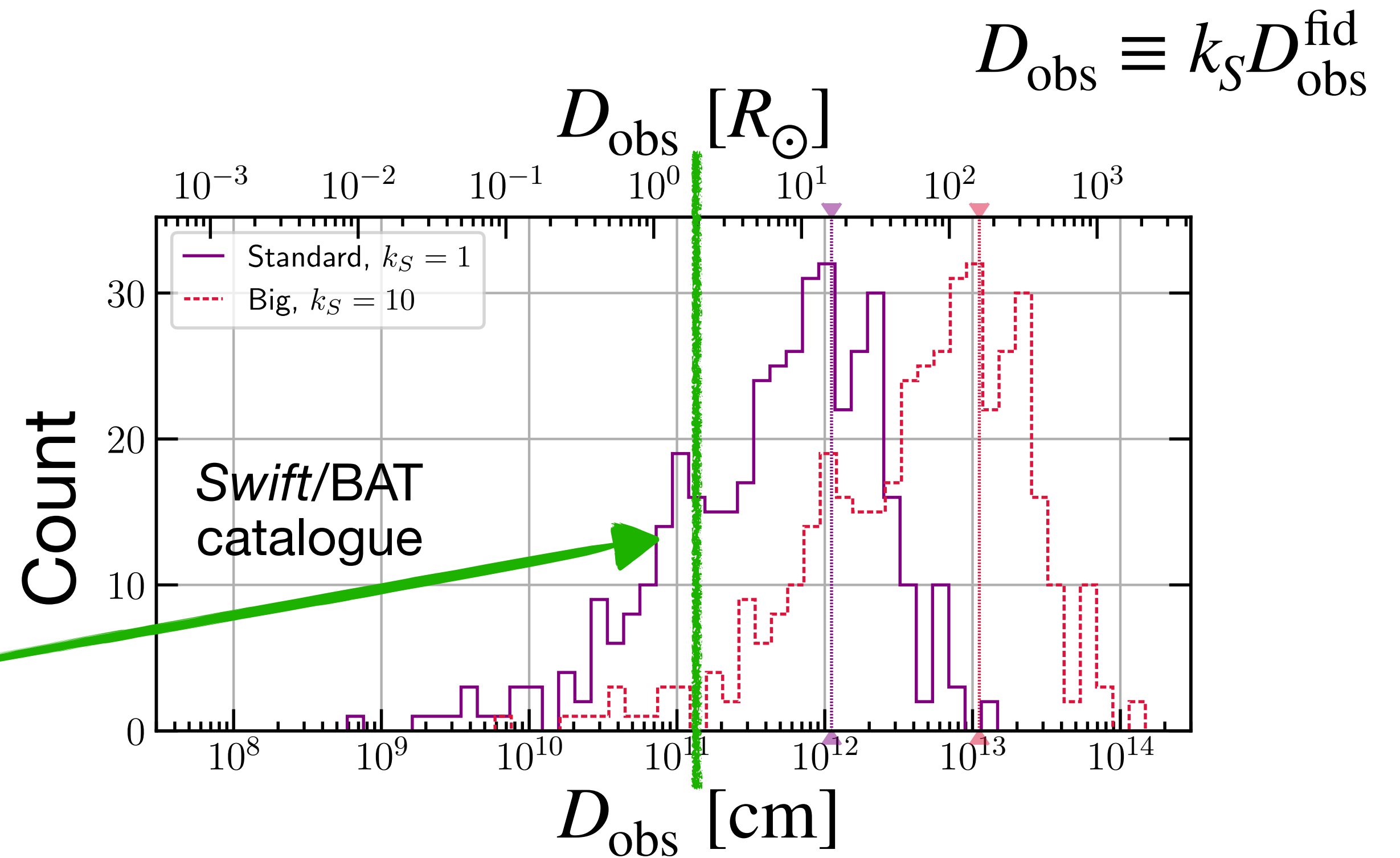
Enormous uncertainties, so we just bracket: $k_S = 0.1, 1, 10, 10^{\mathcal{U}[-1,1]}$

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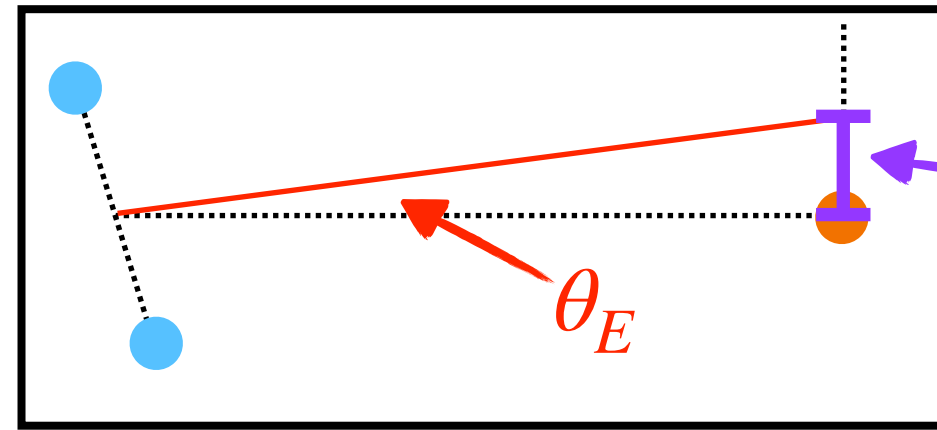


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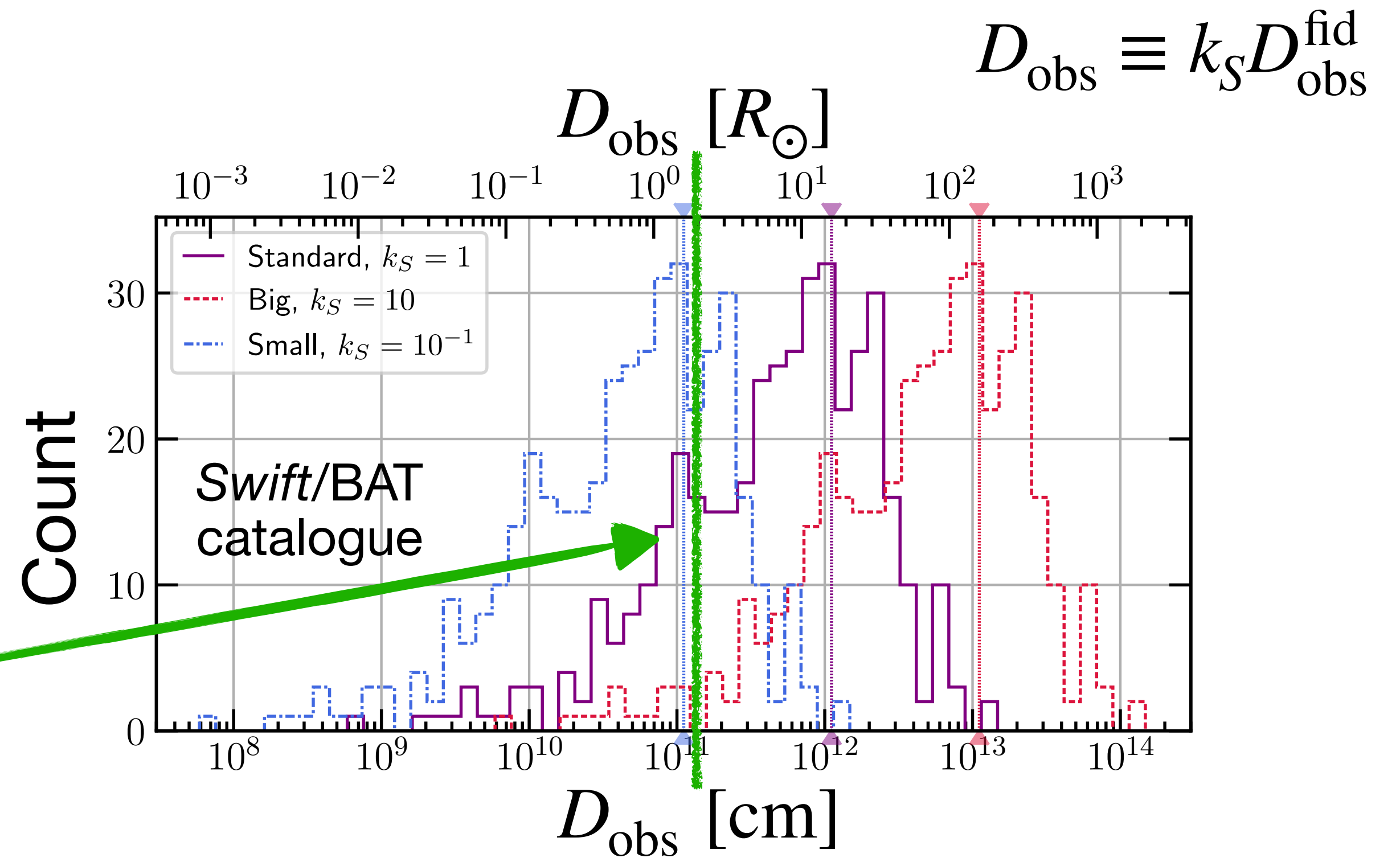
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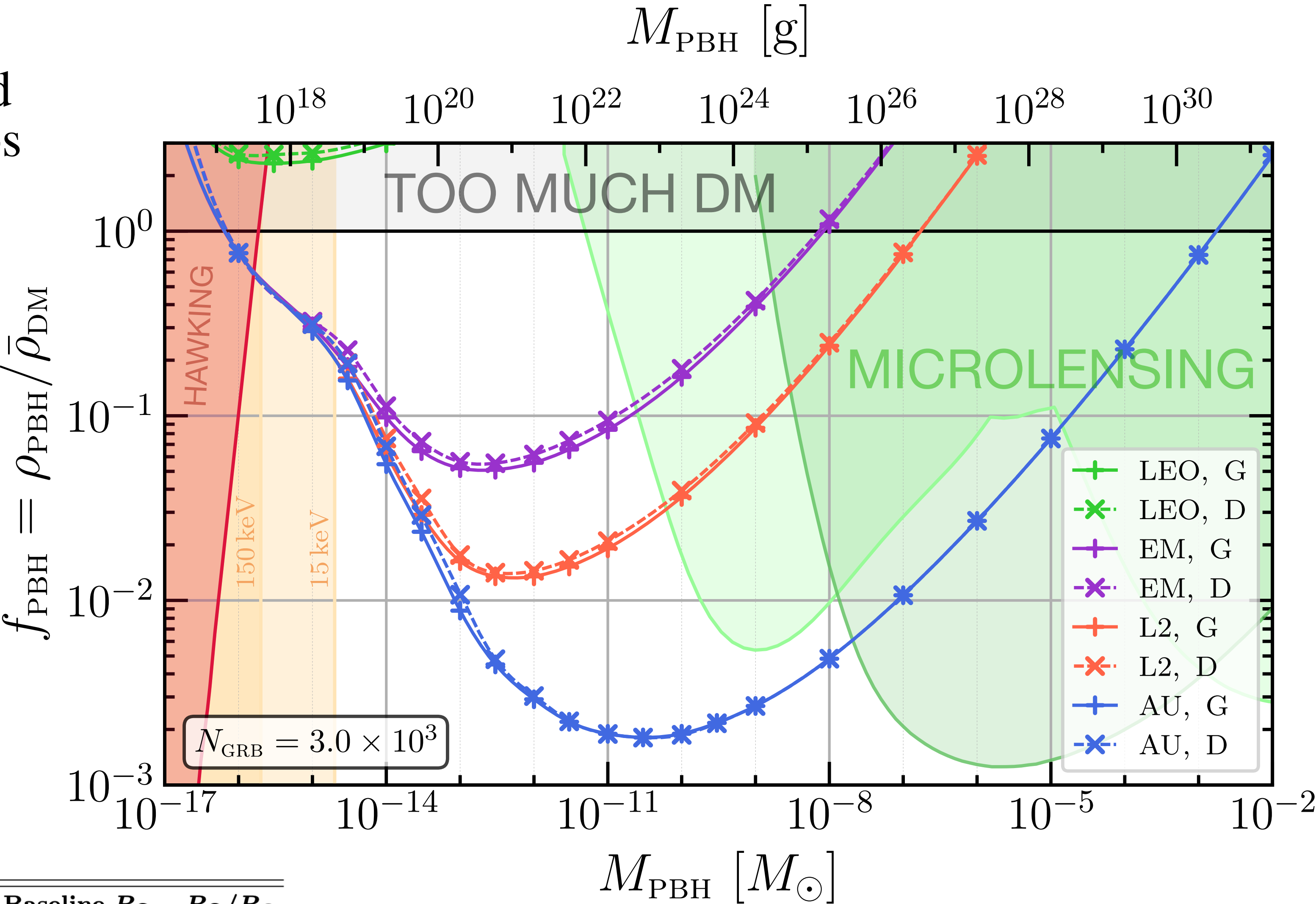
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RESULTS

Different baselines, different source profiles

$$D_{\text{obs}} \equiv D_{\text{obs}}^{\text{fid}}$$

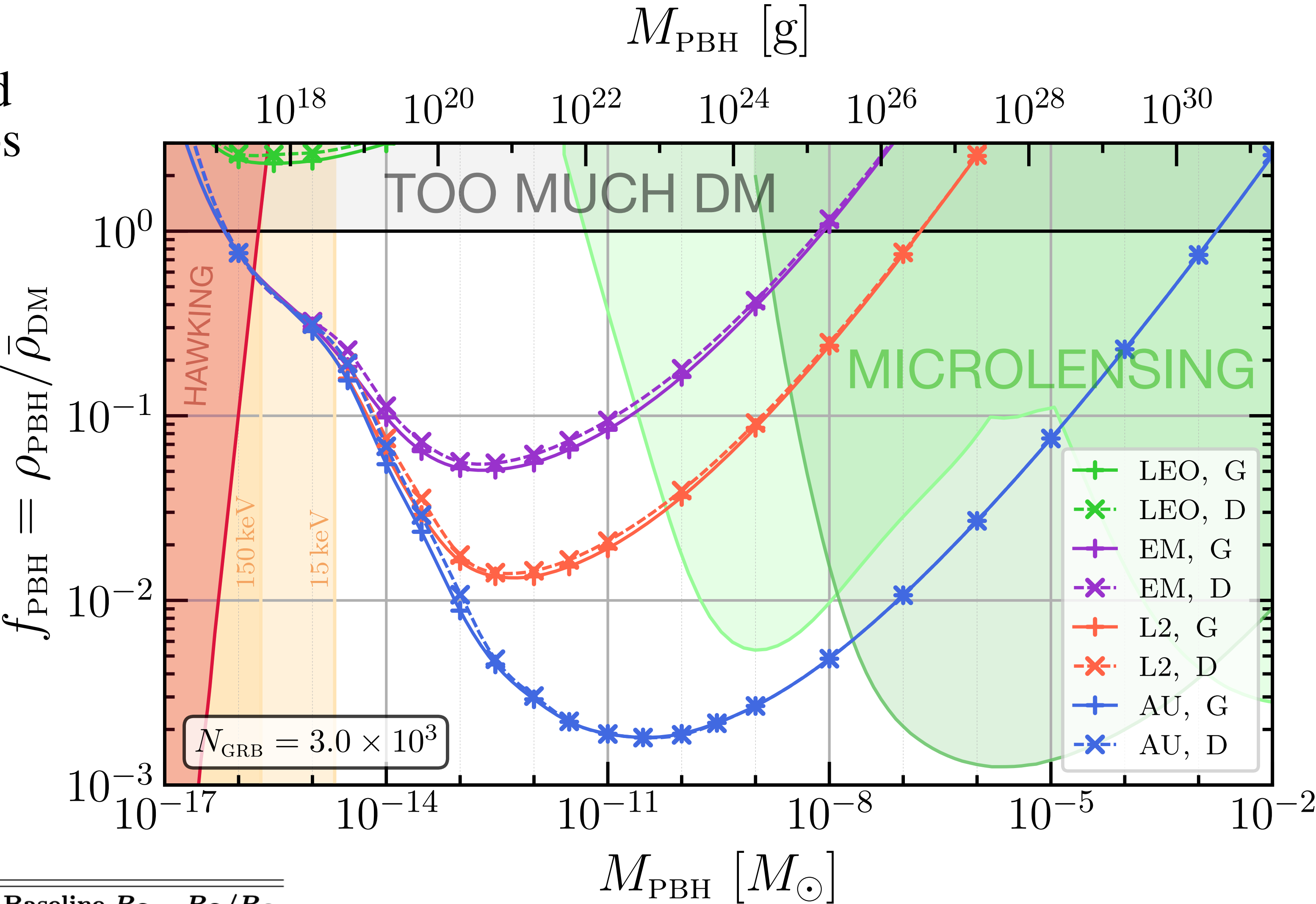


Scenario	Abbrev.	Baseline R_{O}	$R_{\text{O}}/R_{\odot}$
Low Earth Orbit	LEO	$1.40 \times 10^4 \text{ km}$	0.020
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95% CL exclusion projections assuming no 5σ detections

Different baselines, different source profiles

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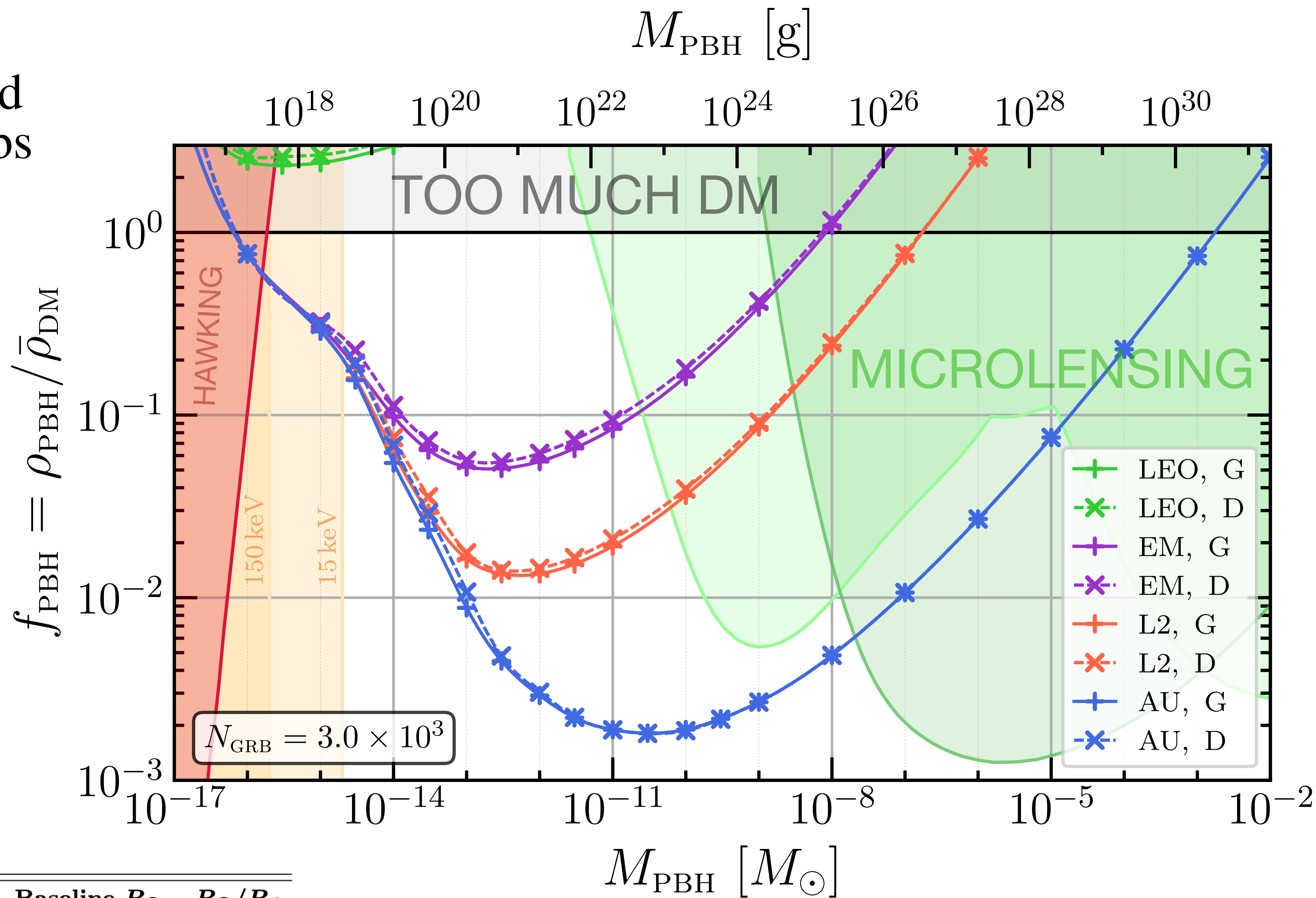
Essentially no difference in Gaussian (G) vs. Disk (D) source profiles

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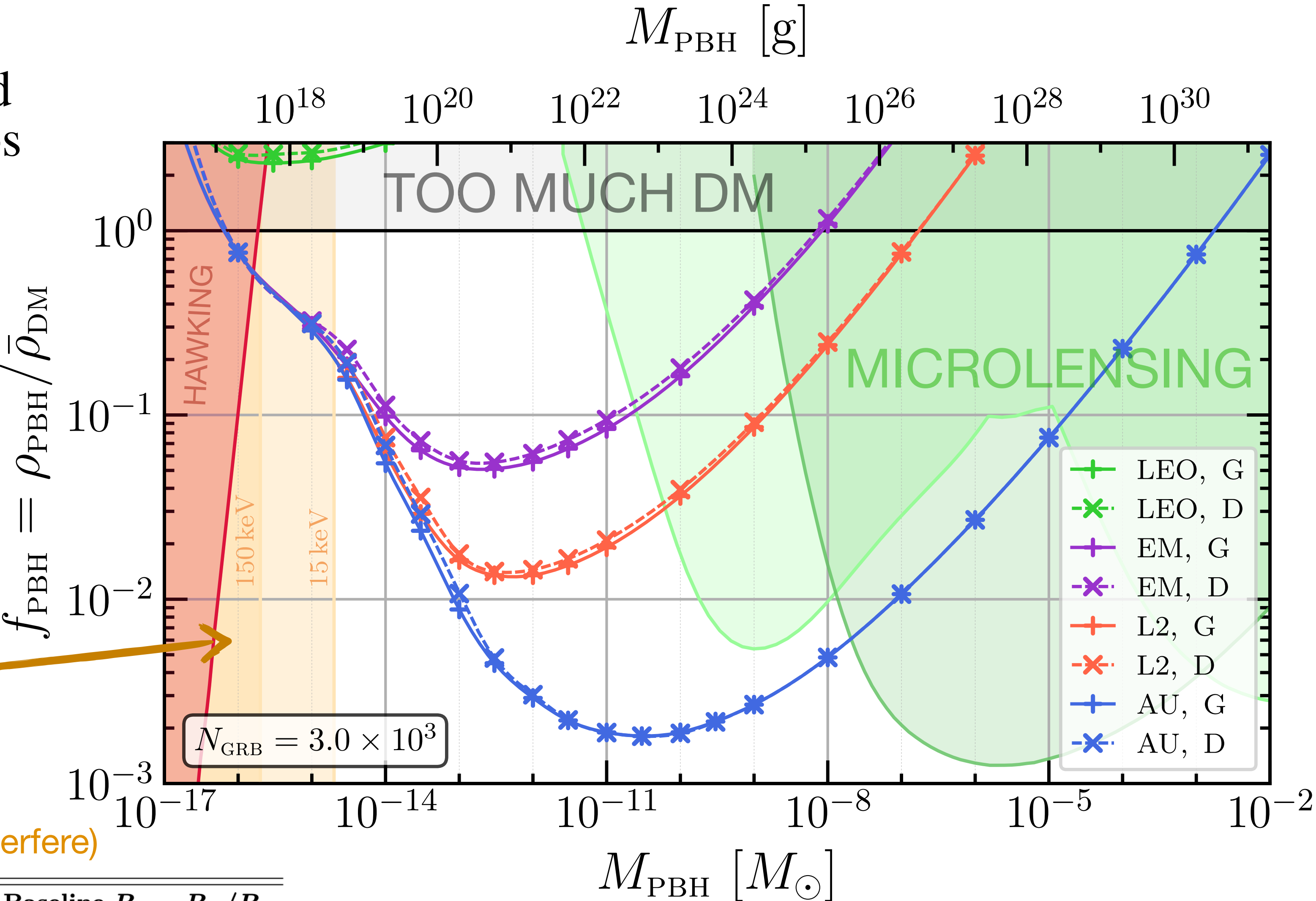
**AU baselines
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cf. Jung and Kim
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(but for different
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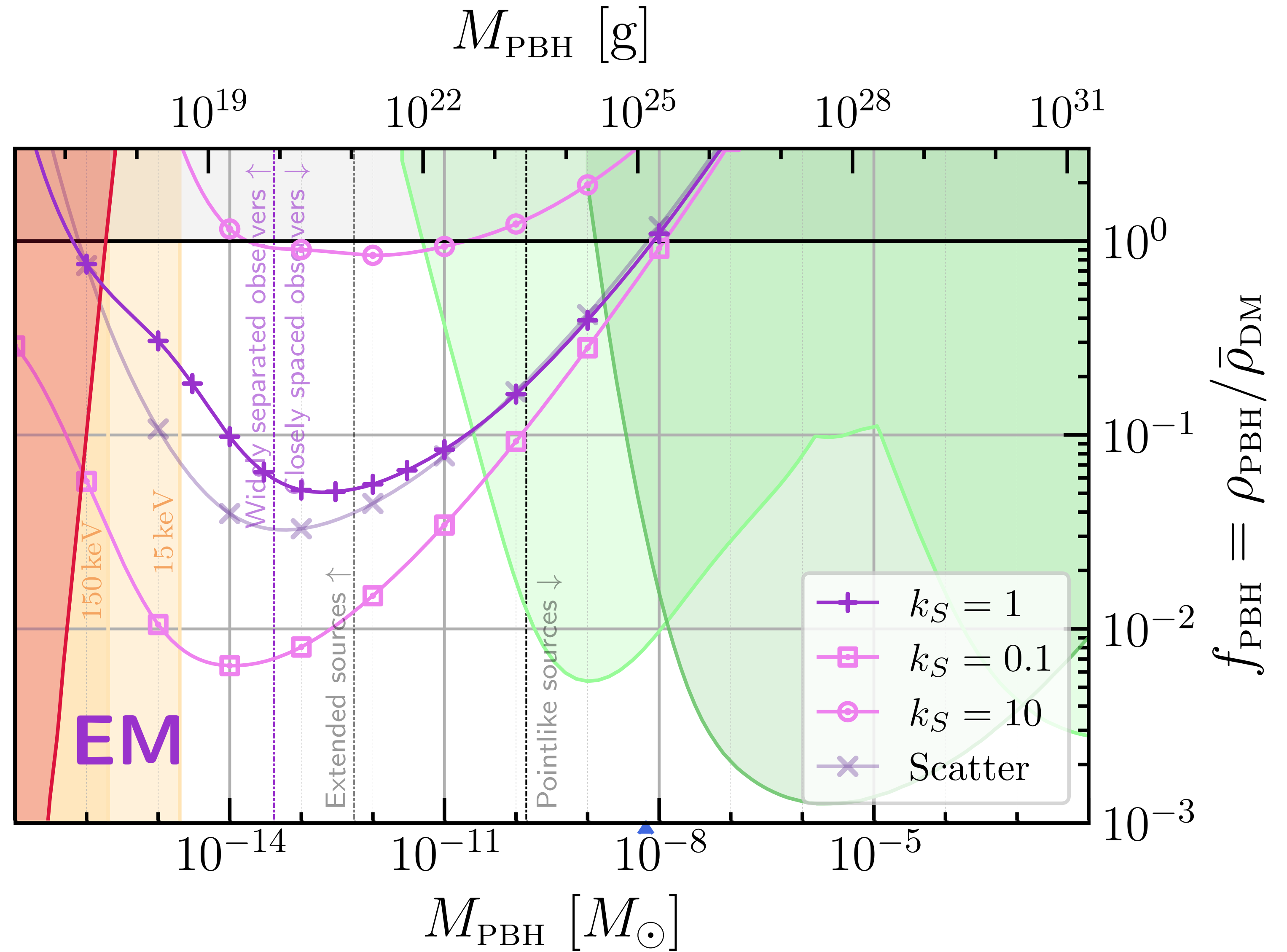
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Vary the source sizes

$$N_{\text{GRB}} = 3 \times 10^3$$

$$D_{\text{obs}} \equiv k_S D_{\text{obs}}^{\text{fid}}$$

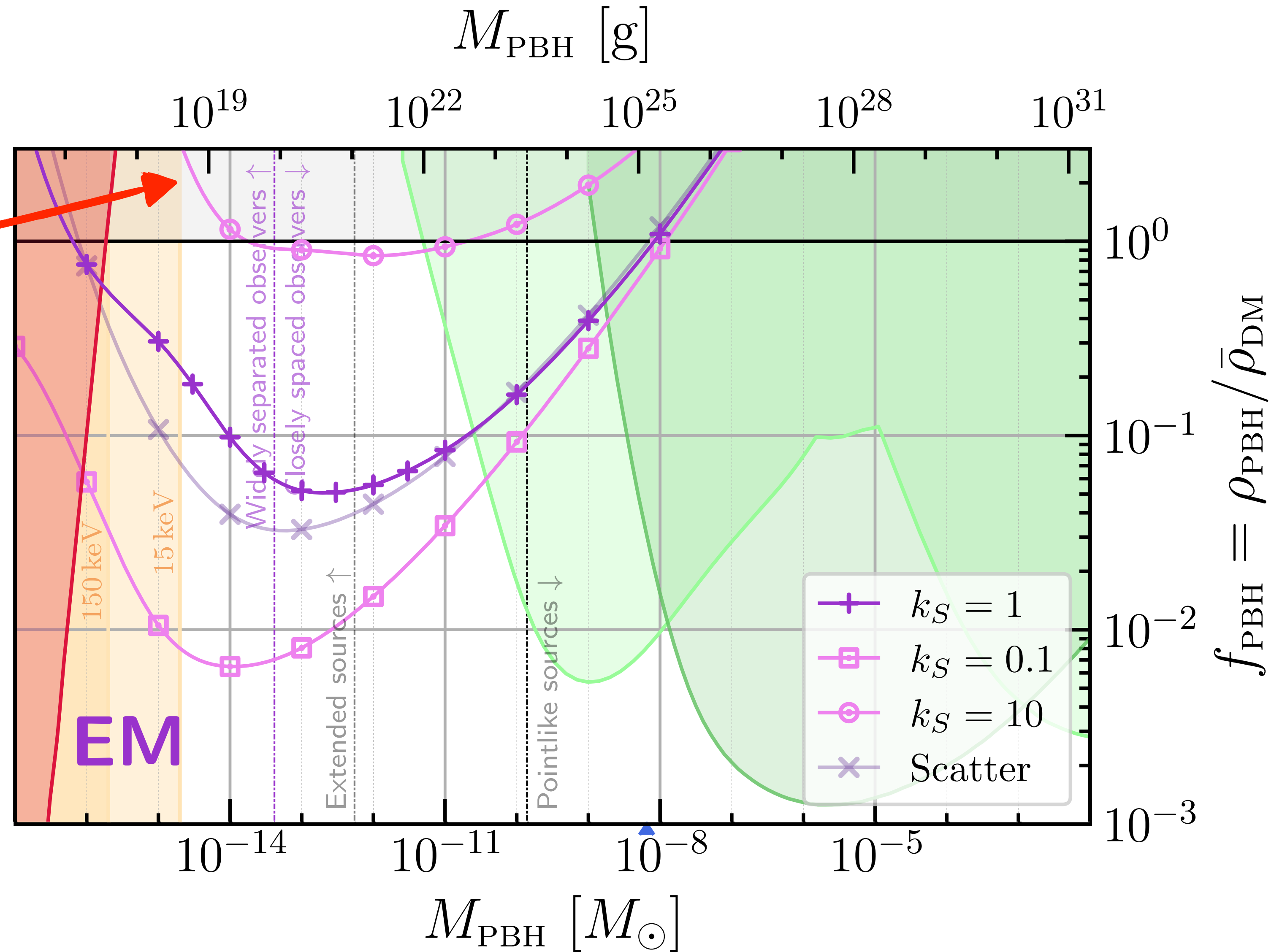


Vary the source sizes

$$N_{\text{GRB}} = 3 \times 10^3$$

Questionable
whether you can
robustly rule out
 $f_{\text{DM}} = 1$ with this
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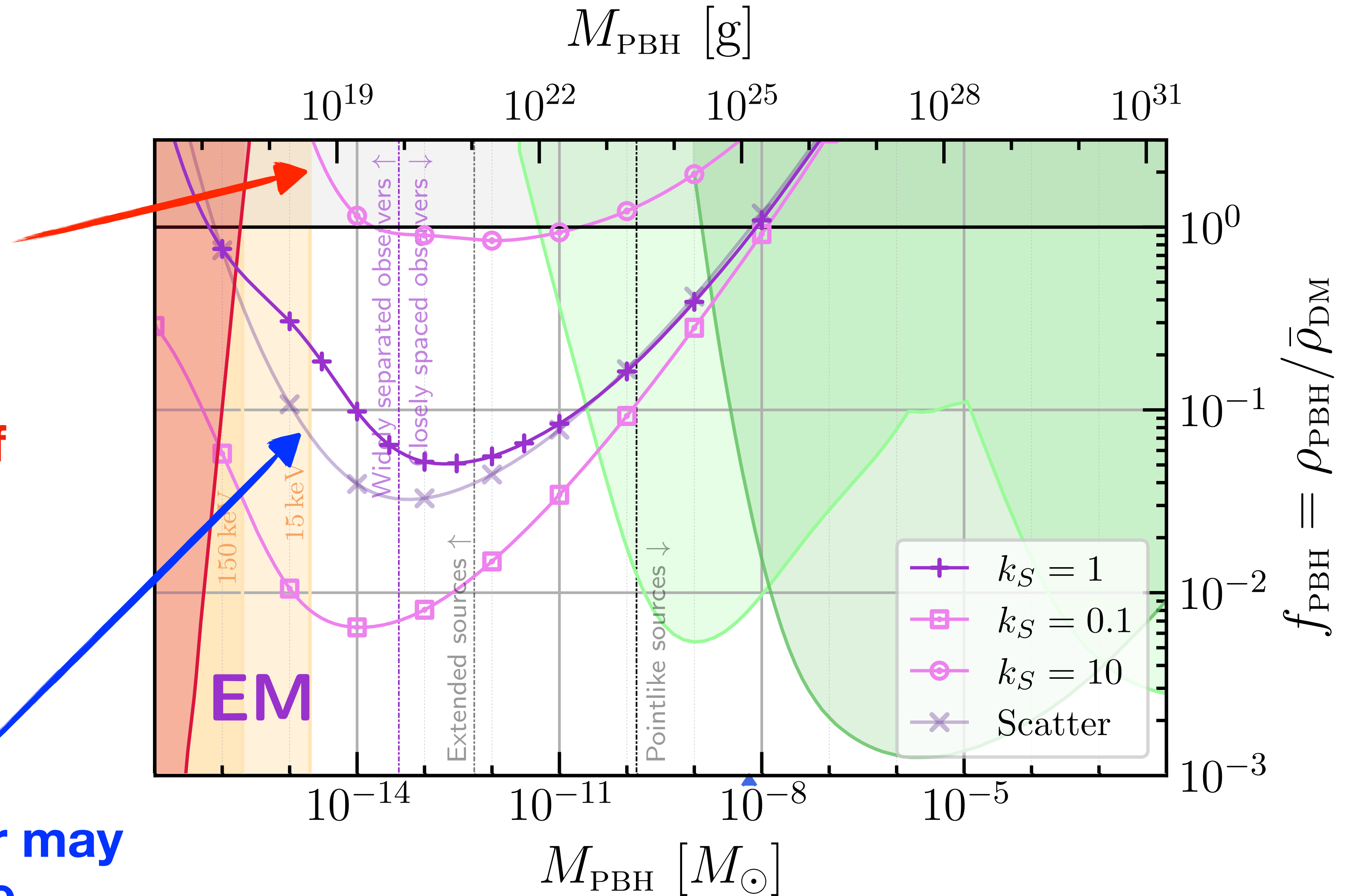
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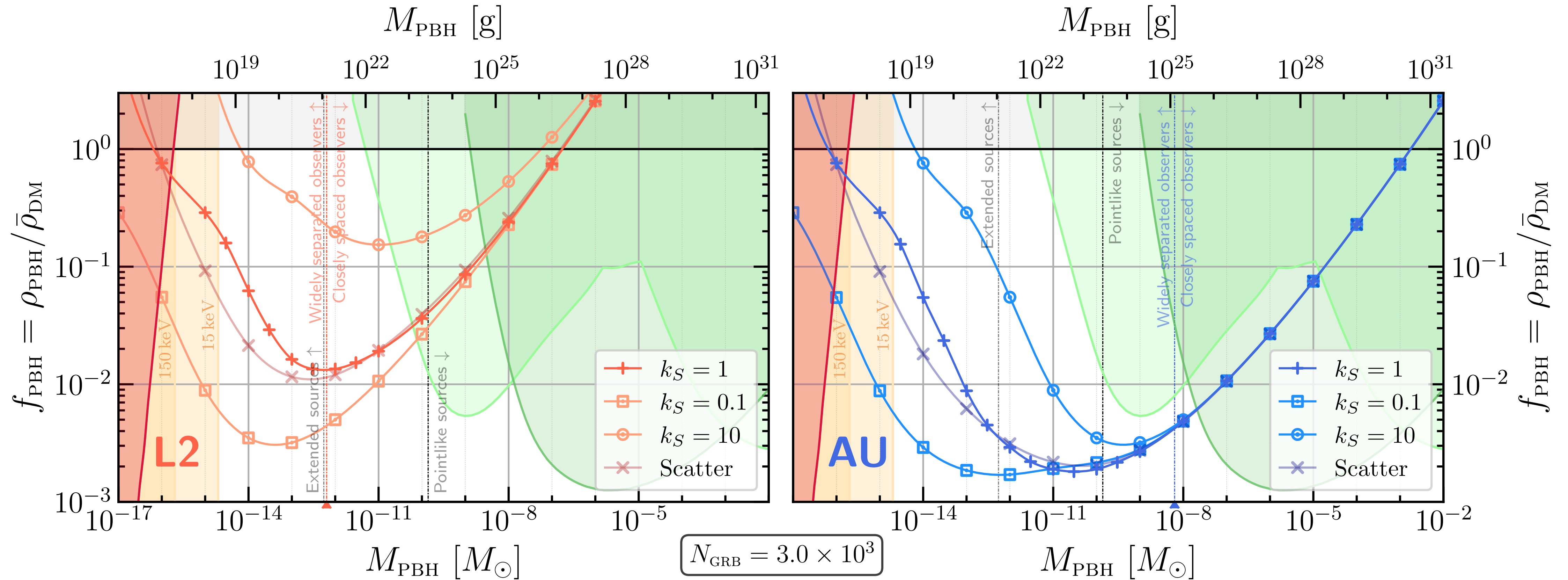
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**But the scatter may
not be an issue**



Vary source sizes for each baseline

$$D_{\text{obs}} \equiv k_S D_{\text{obs}}^{\text{fid}}$$

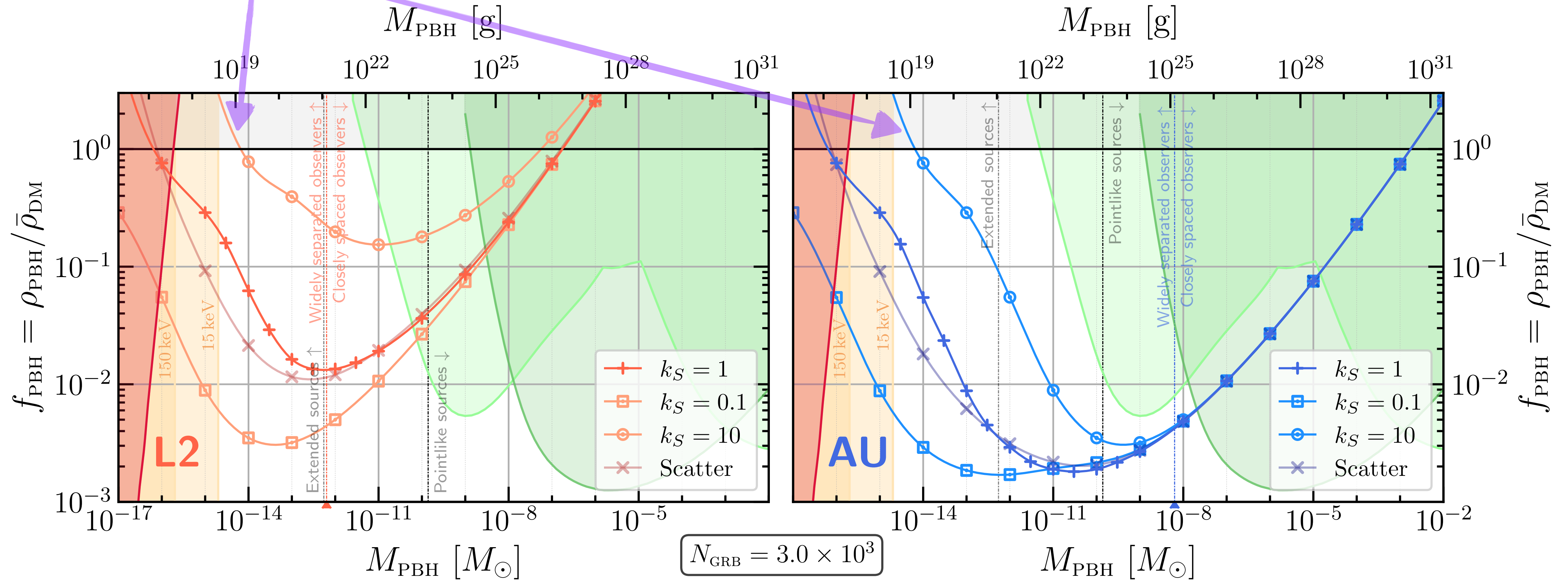


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ROBUST $f_{\text{DM}} = 1$ EXCLUSIONS FOR L2, AU

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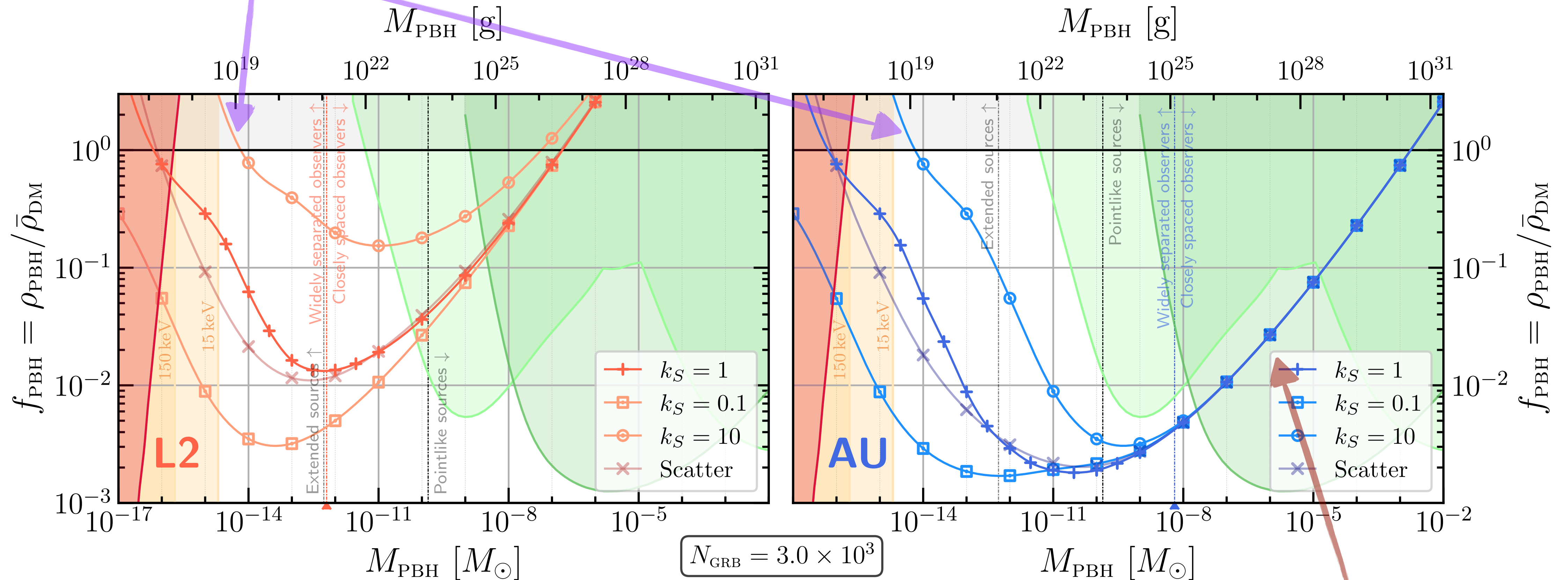


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ROBUST $f_{\text{DM}} = 1$ EXCLUSIONS FOR L2, AU

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$N_{\text{GRB}} = 3.0 \times 10^3$

**LARGE-MASS REACH AT AU
INDEPENDENT OF SOURCE
UNCERTAINTIES!**

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Constraints on diffuse lenses look interesting (axion miniclusters, etc.)

Axion miniclusters

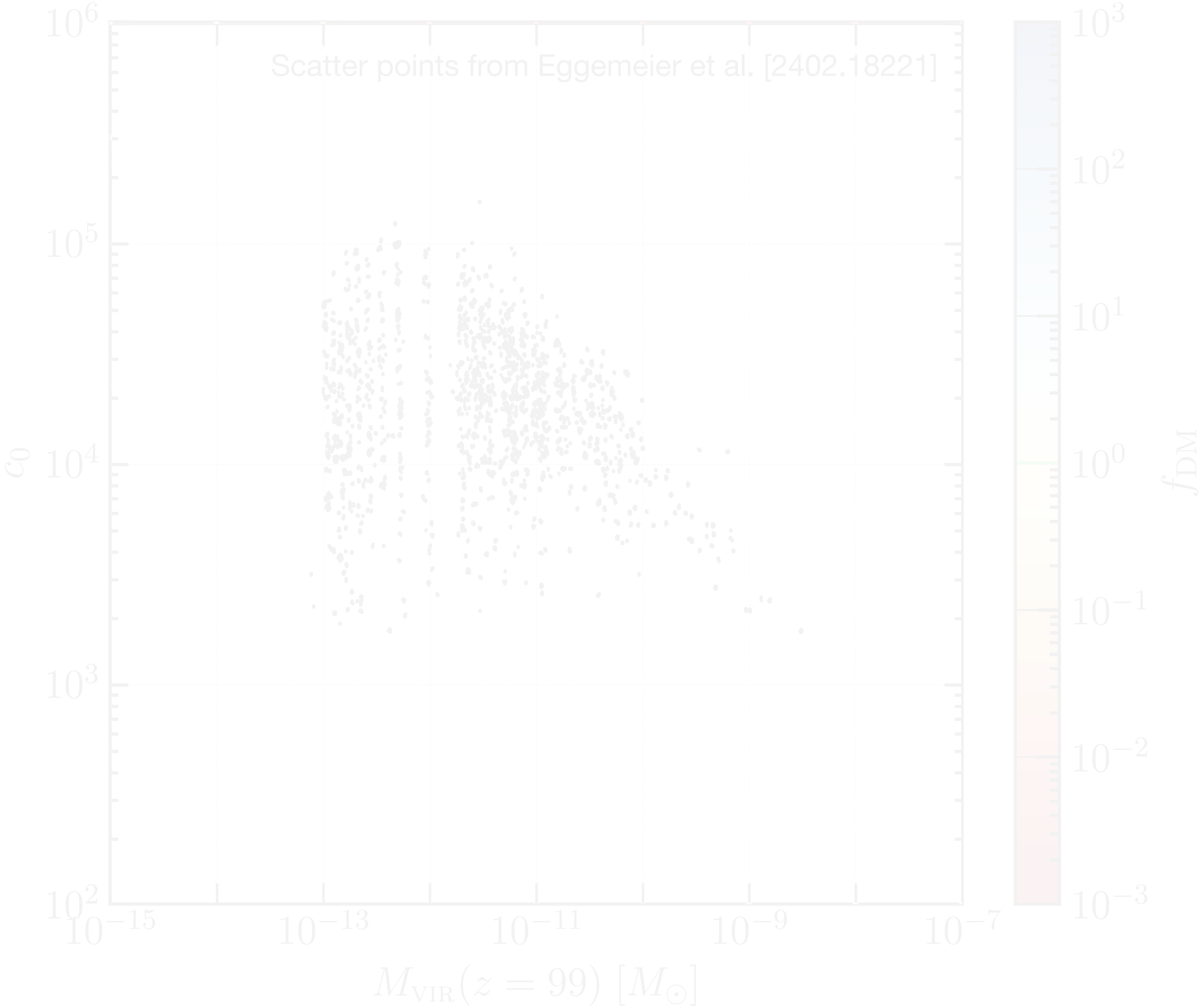
Dense clusters of QCD DM axions formed from large isocurvature fluctuations + self-interactions

Motivated by recent high-resolution QCD axion minicluster simulations

$$\rho_{\text{mNFW}}(r) = \frac{\rho_0}{(r/r_s)^2(1 + r/r_s)}$$
$$\rho_{\text{NFW}}(r) = \frac{\rho_0}{(r/r_s)(1 + r/r_s)^2}$$

Relax point-lens assumption

WORK NEARING COMPLETION



$$M_{\text{vir}} \equiv \frac{4\pi}{3} \Delta_{\text{vir}} \rho_c r_{\text{vir}}^3$$
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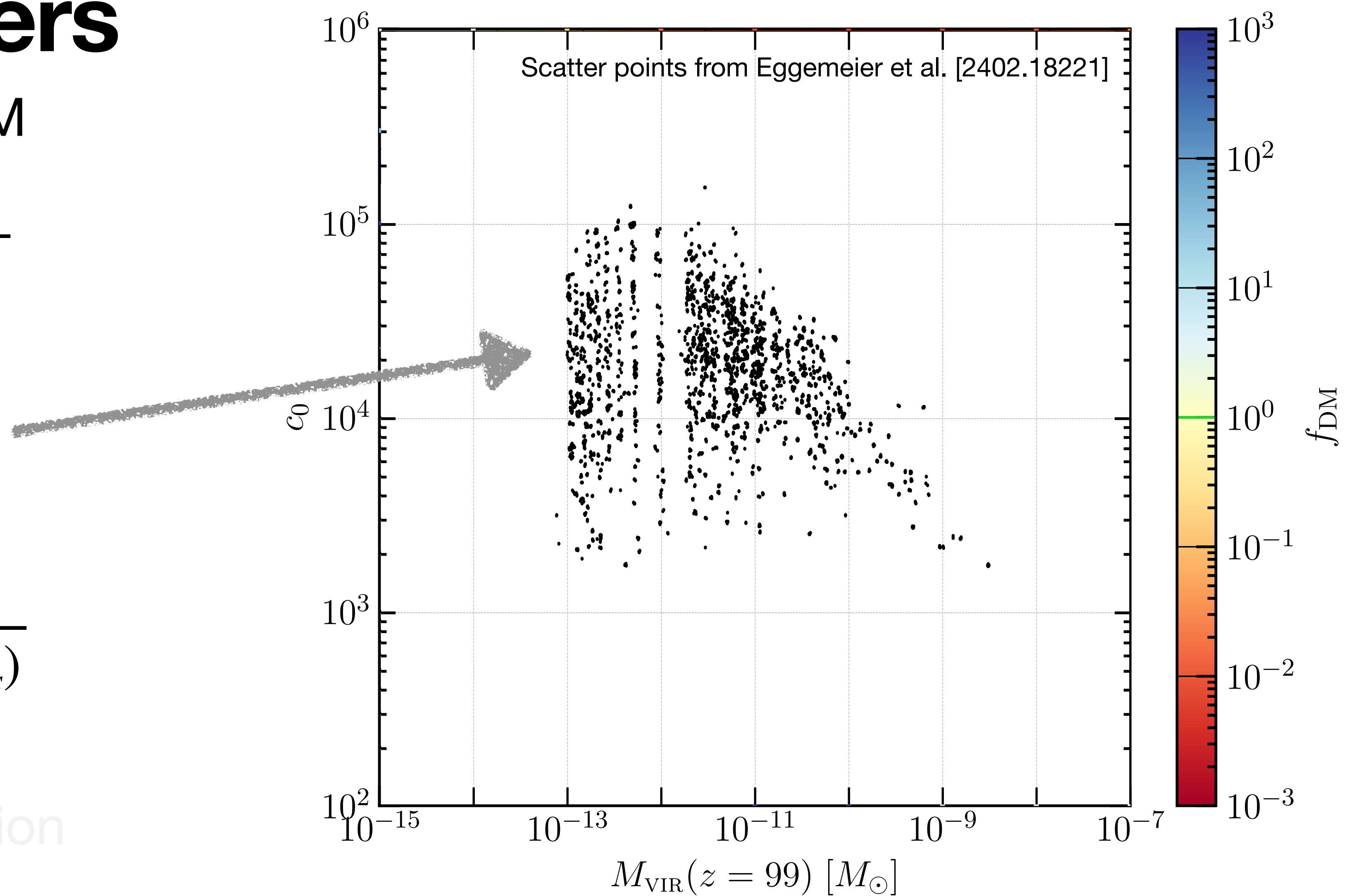
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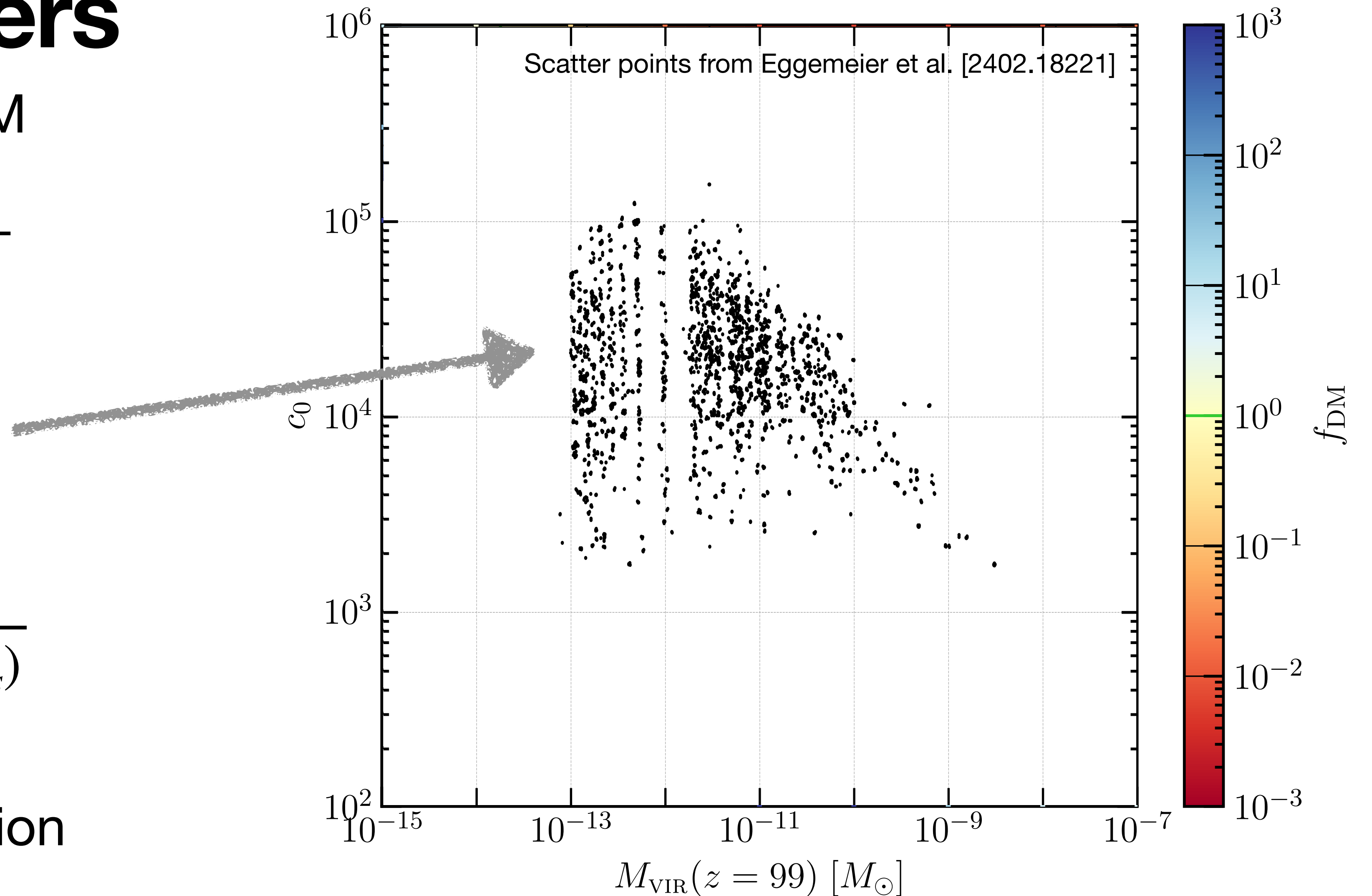
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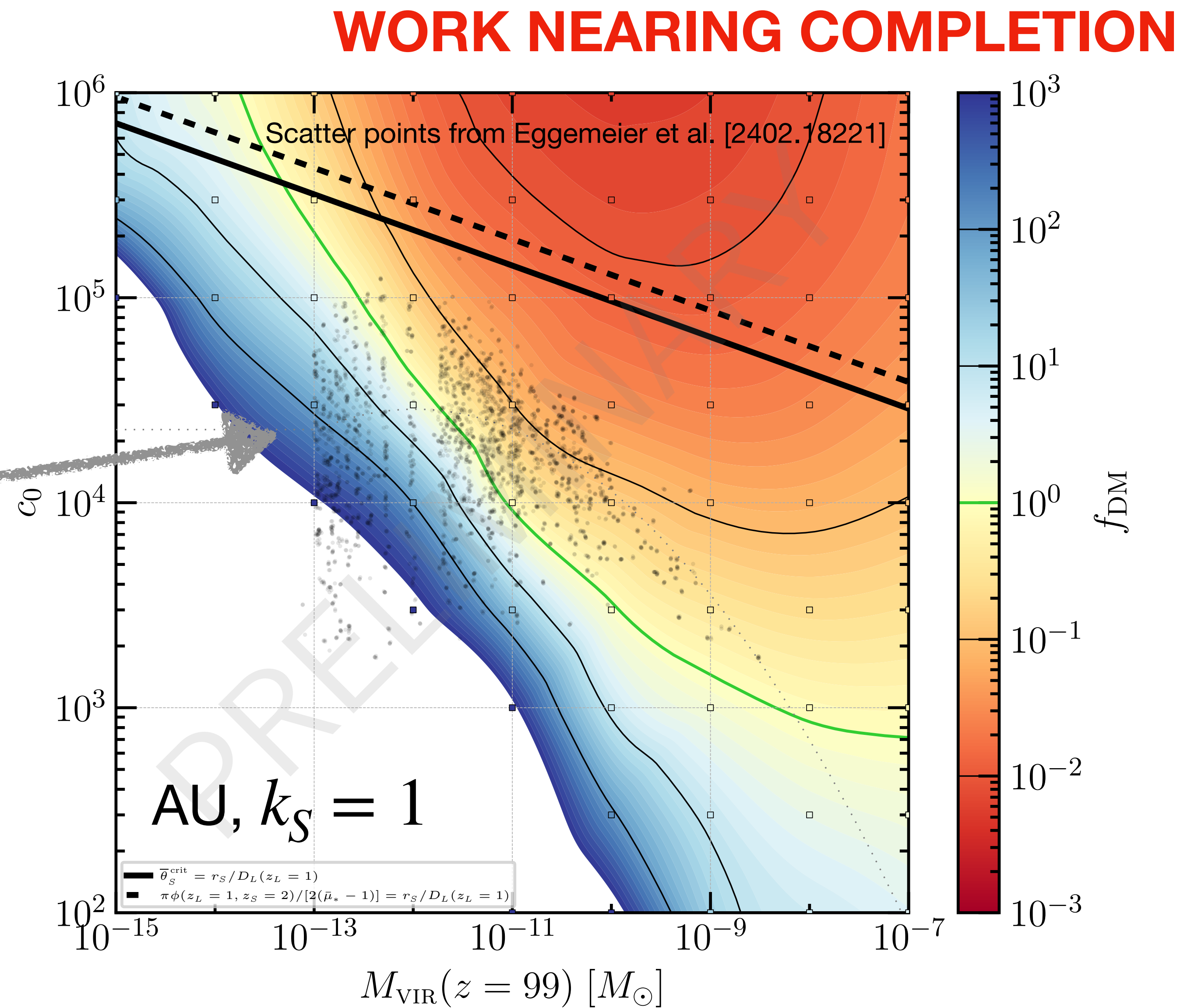
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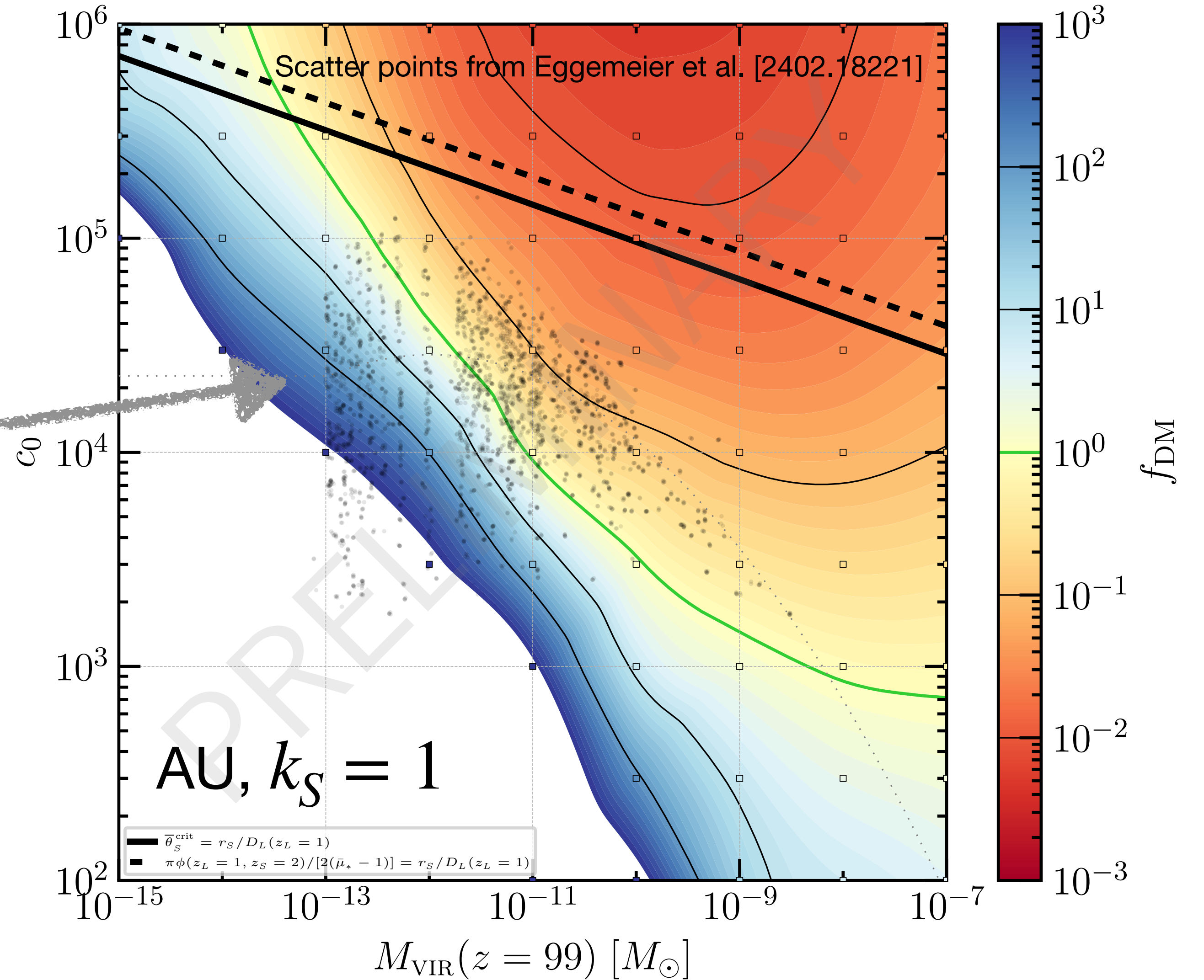
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Picolensing may have sensitivity to see these...

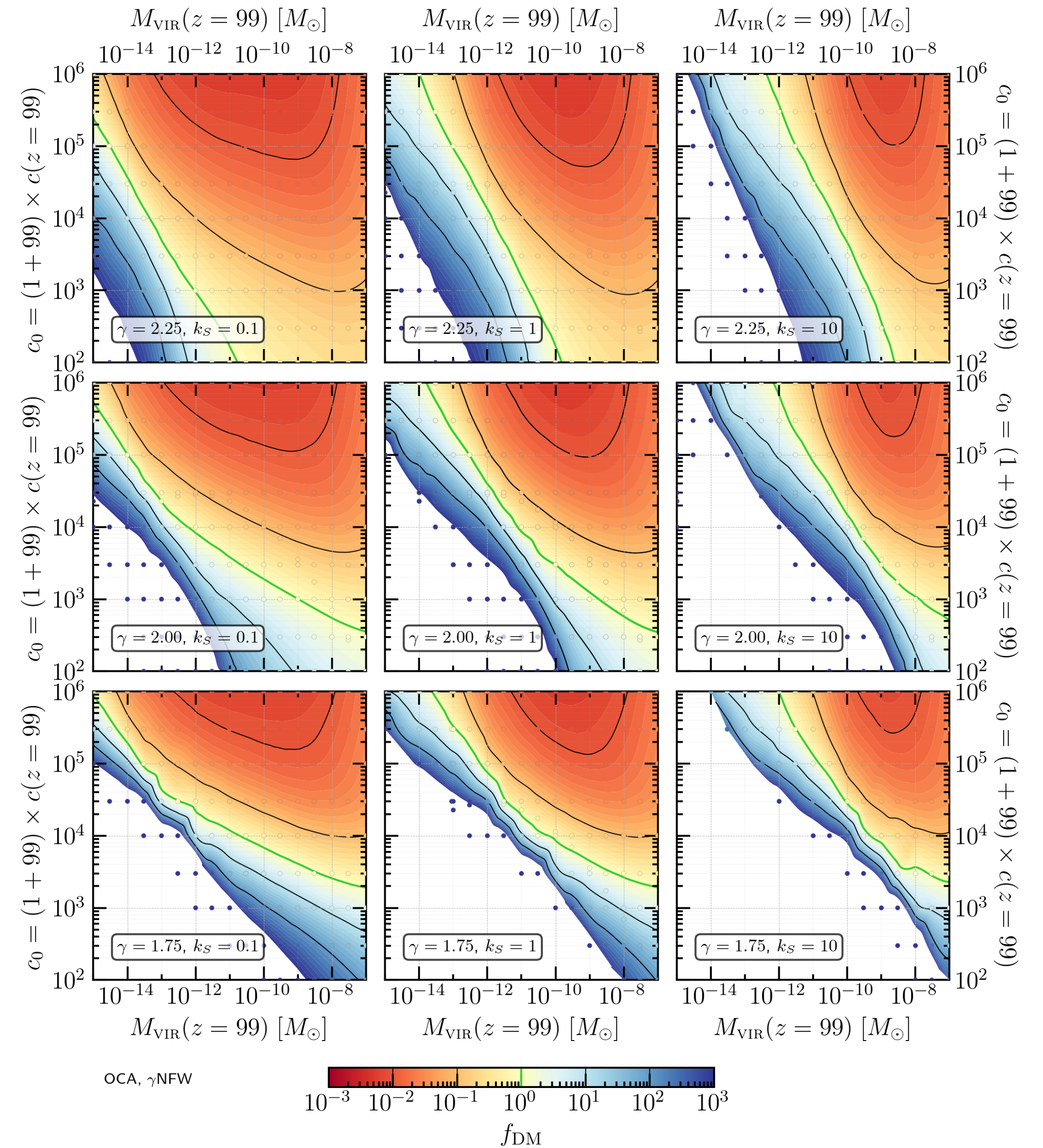
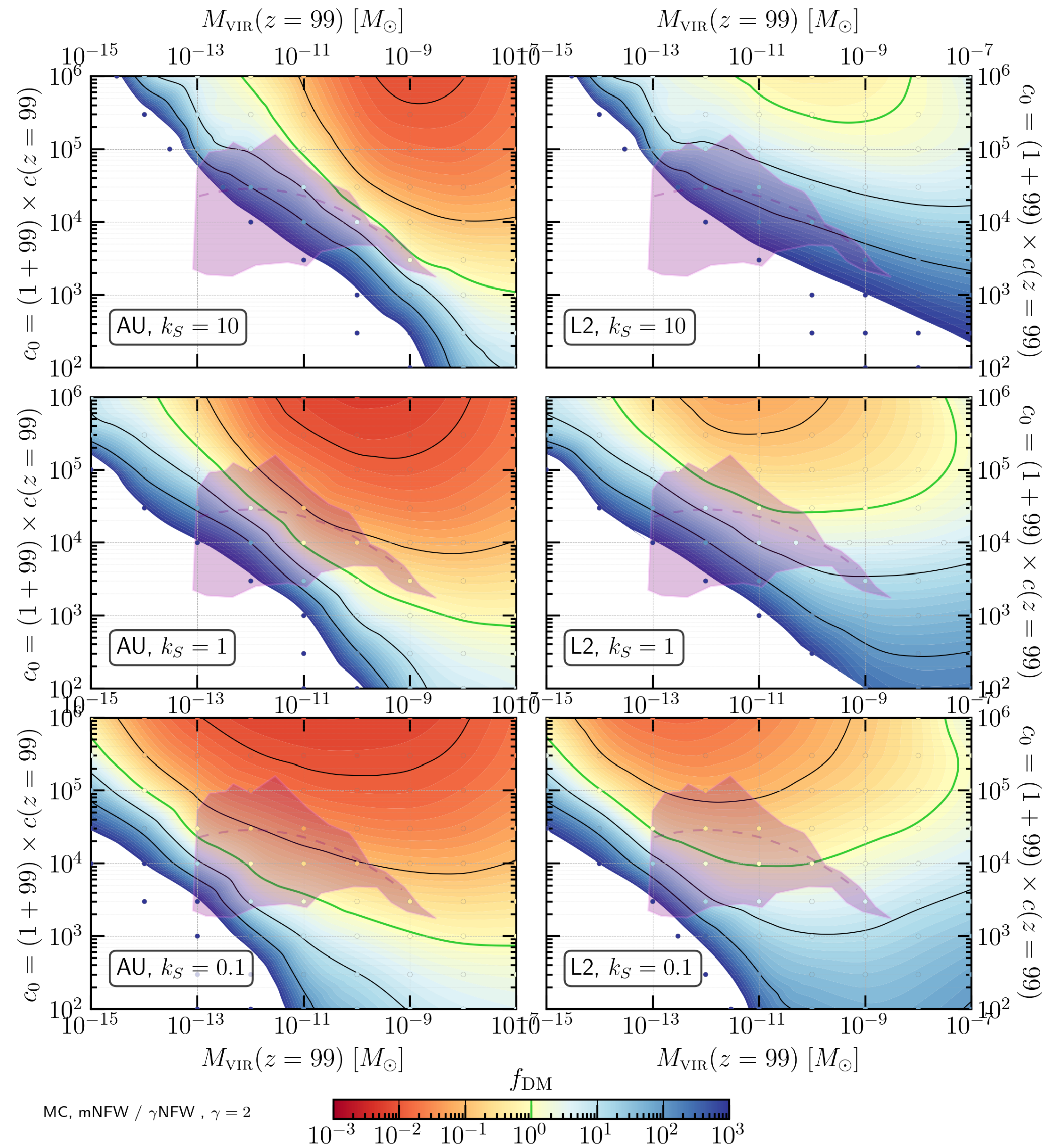
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Extended Lenses



Shaded regions from Eggemeier et al. [arXiv:2402.18221]

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Fin