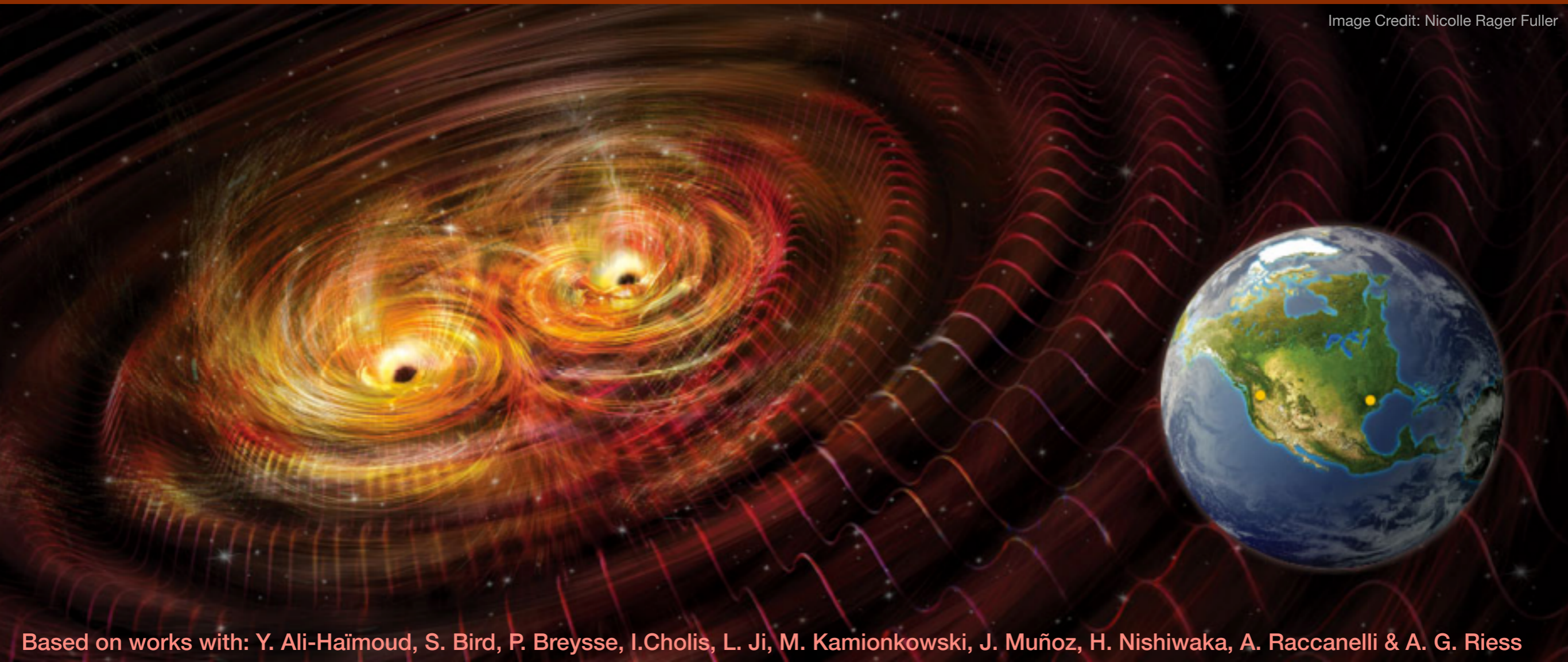


Probing Primordial Black Hole Dark Matter

Ely D. Kovetz

Johns Hopkins University

Image Credit: Nicolle Rager Fuller



Based on works with: Y. Ali-Haïmoud, S. Bird, P. Breysse, I. Cholis, L. Ji, M. Kamionkowski, J. Muñoz, H. Nishiwaka, A. Raccanelli & A. G. Riess

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Wager on Supersymmetry

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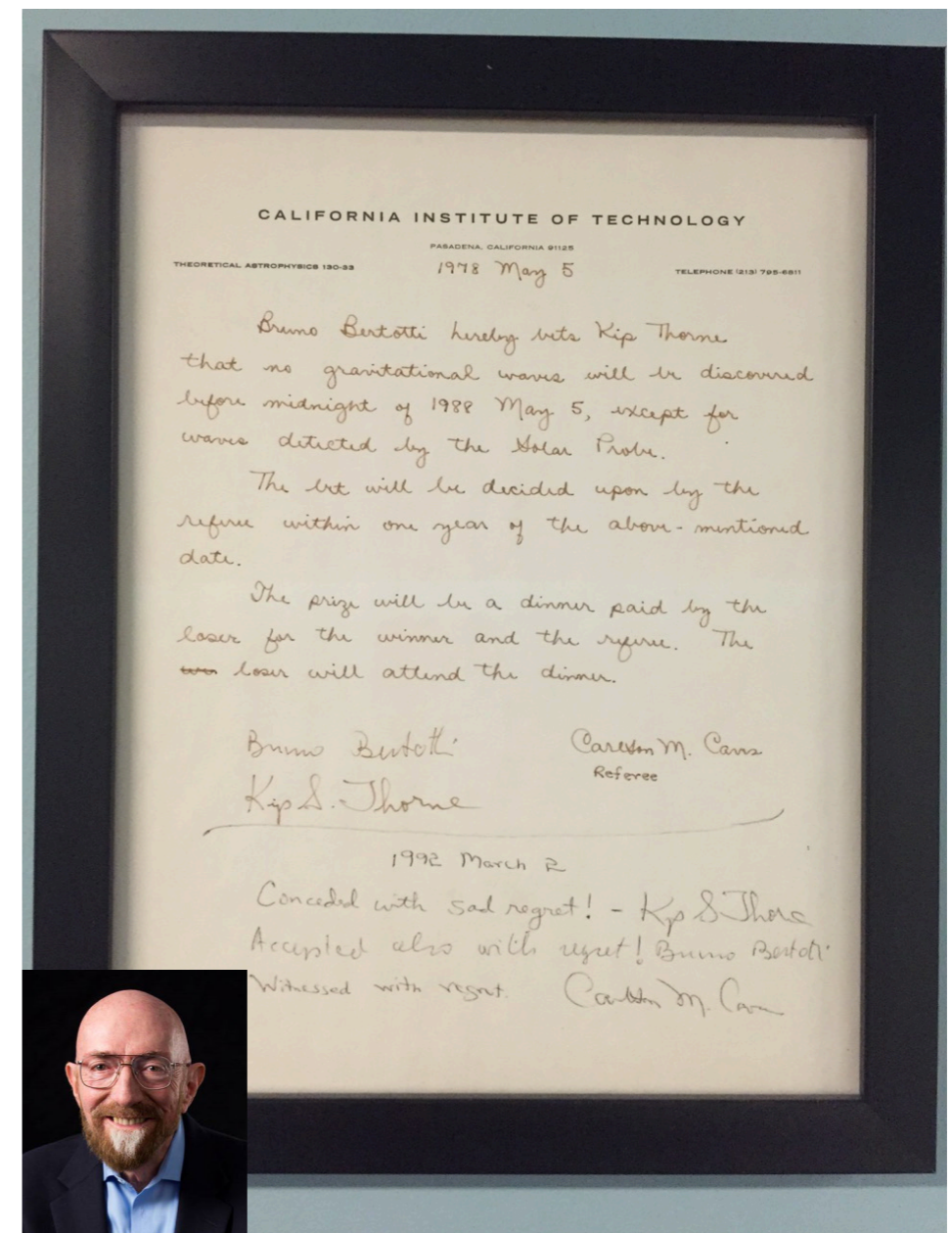
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Motivation: 1st Detection of Gravitational Waves

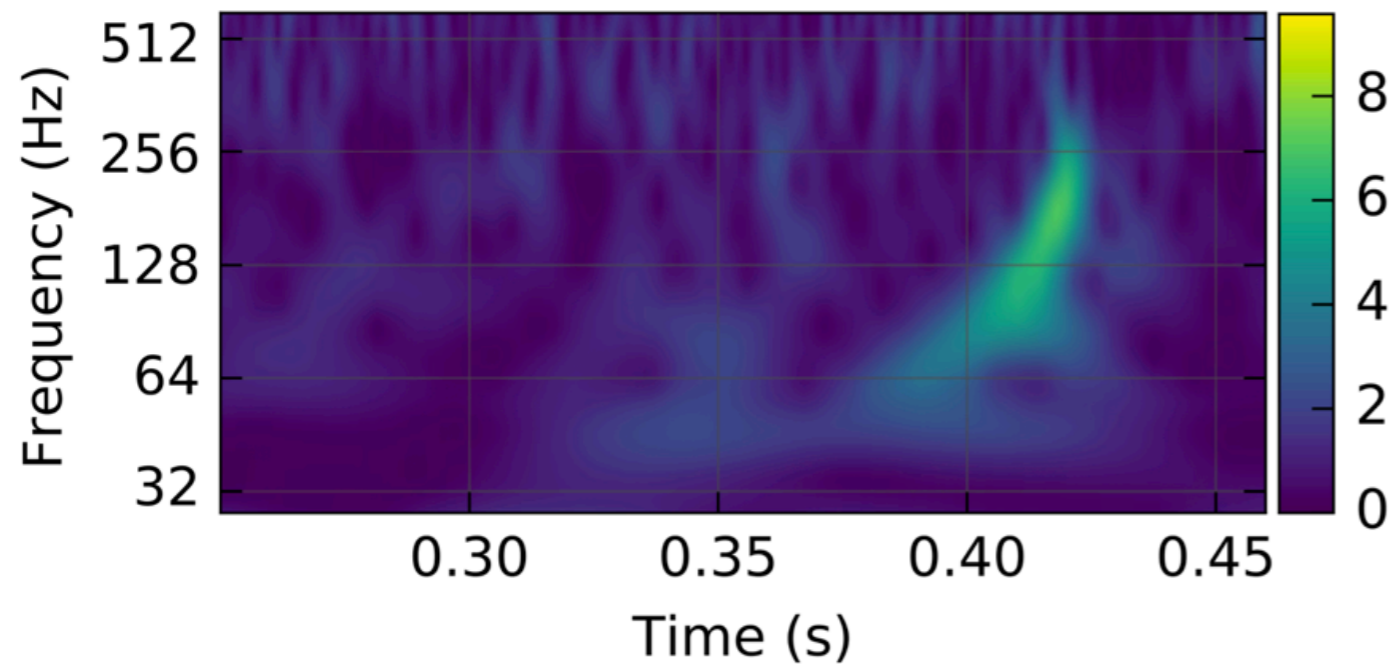
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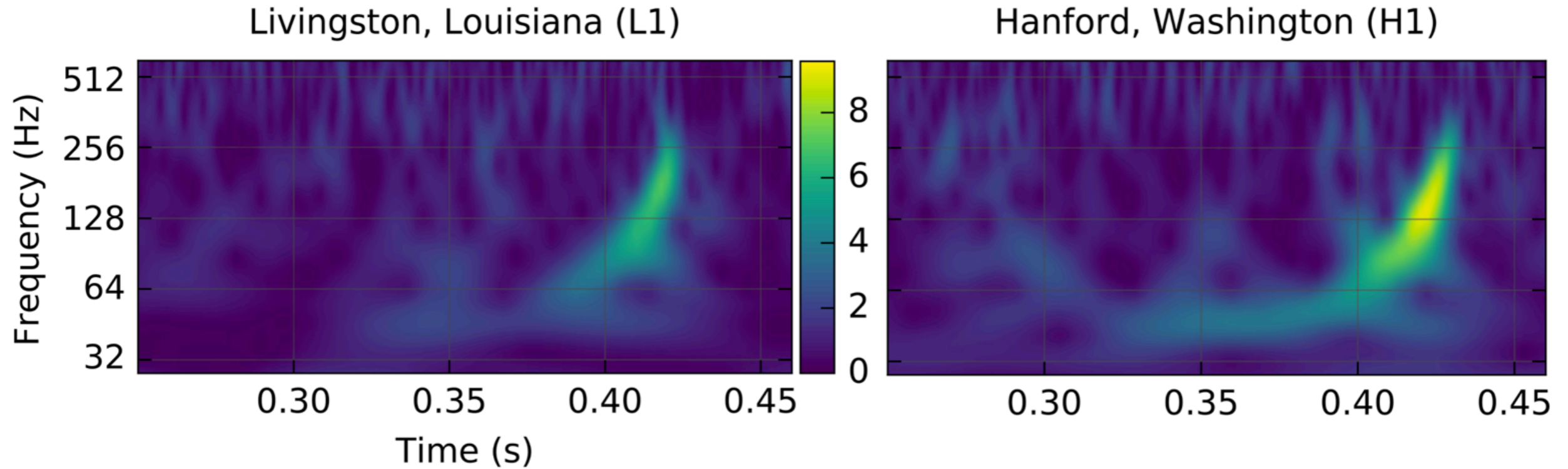
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Livingston, Louisiana (L1)



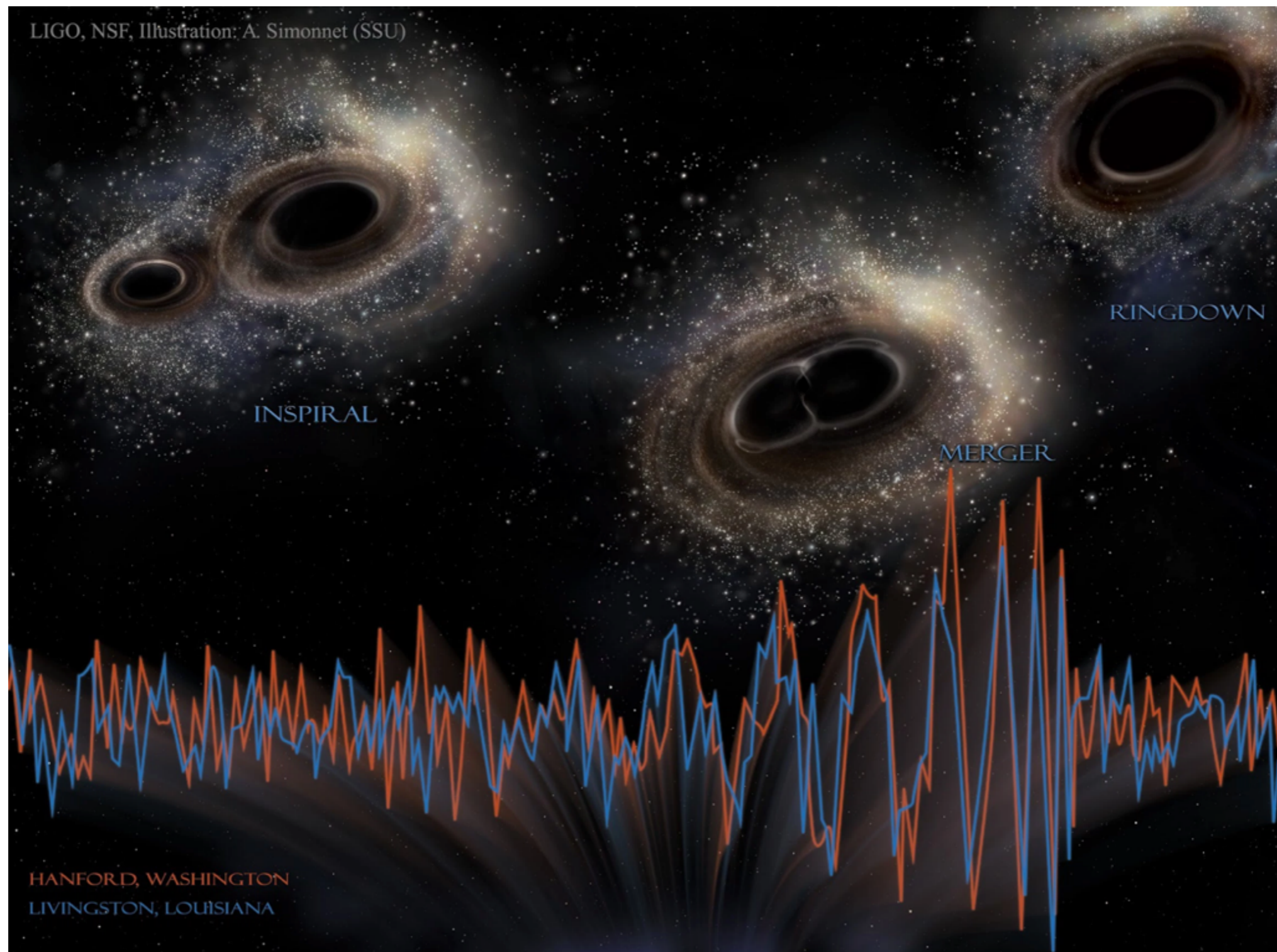
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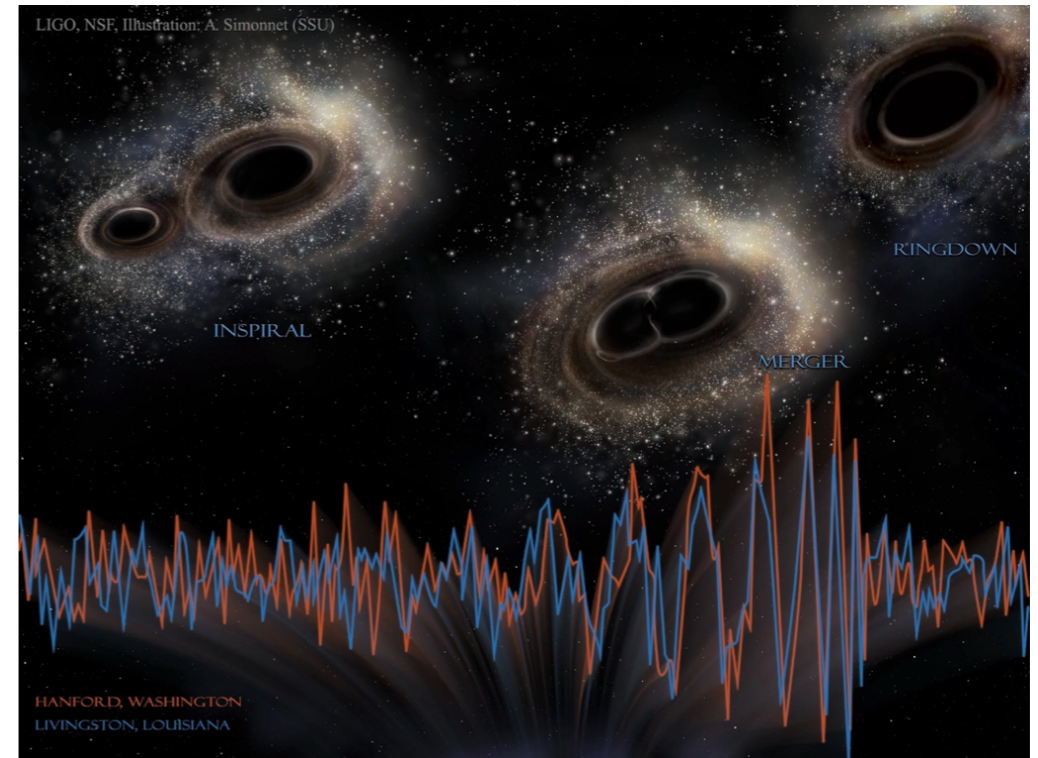
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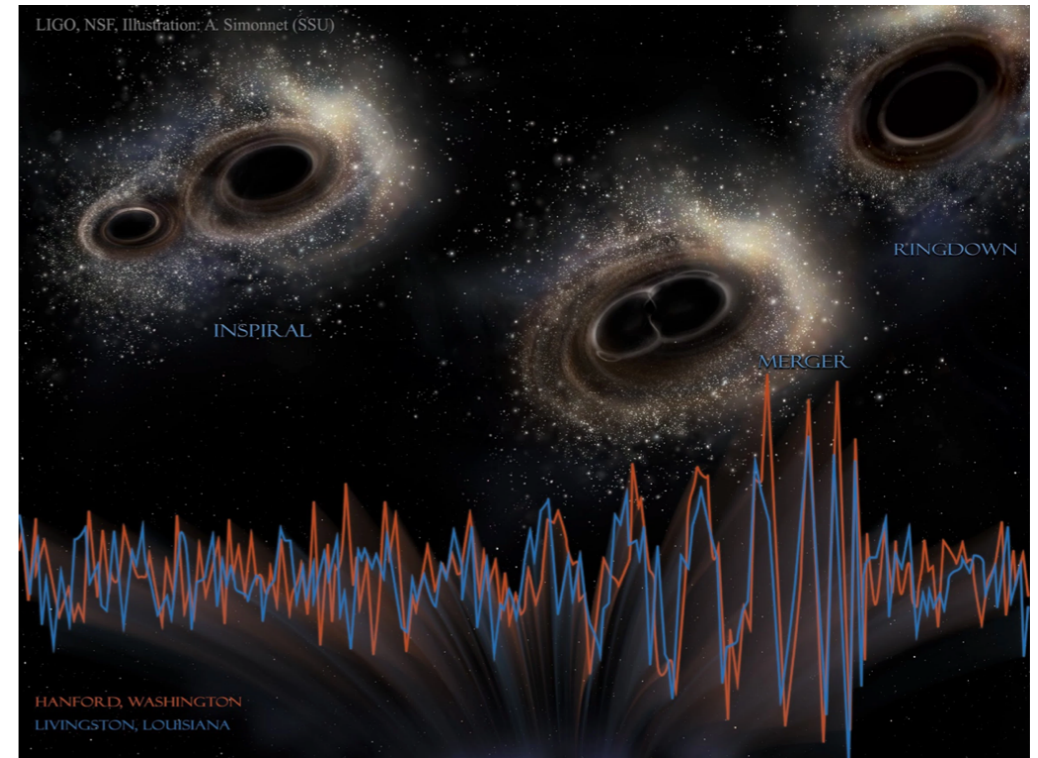
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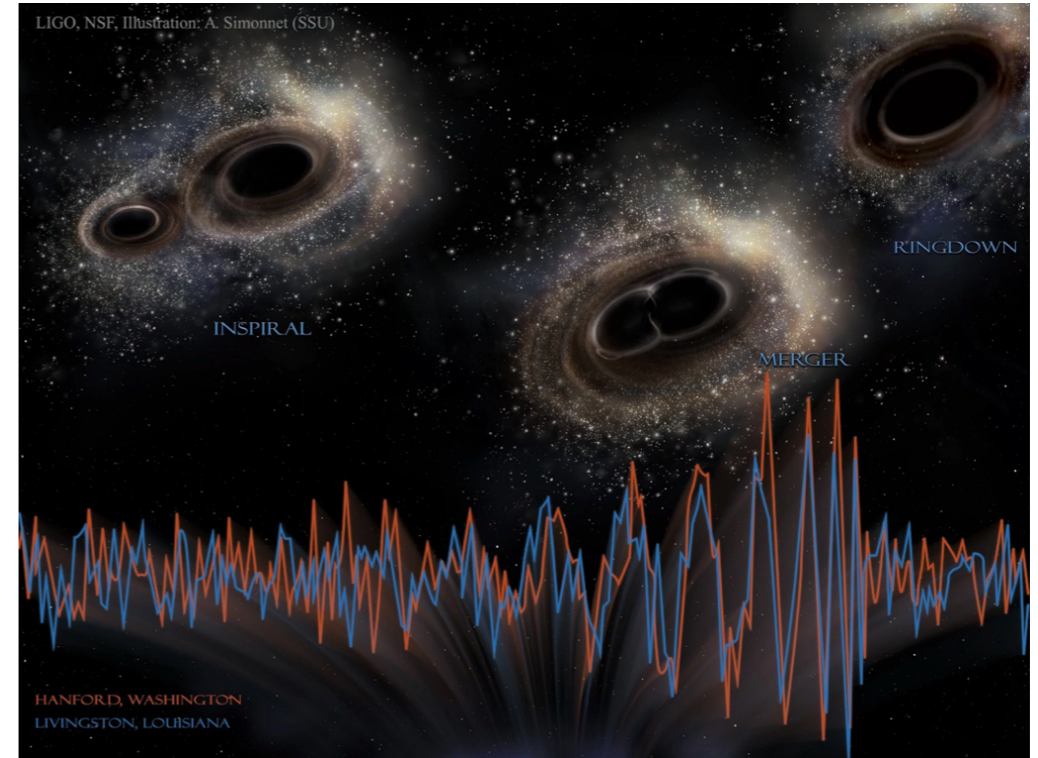


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Lots of information....

Black hole masses: $\sim 29, 36M_{\odot}$

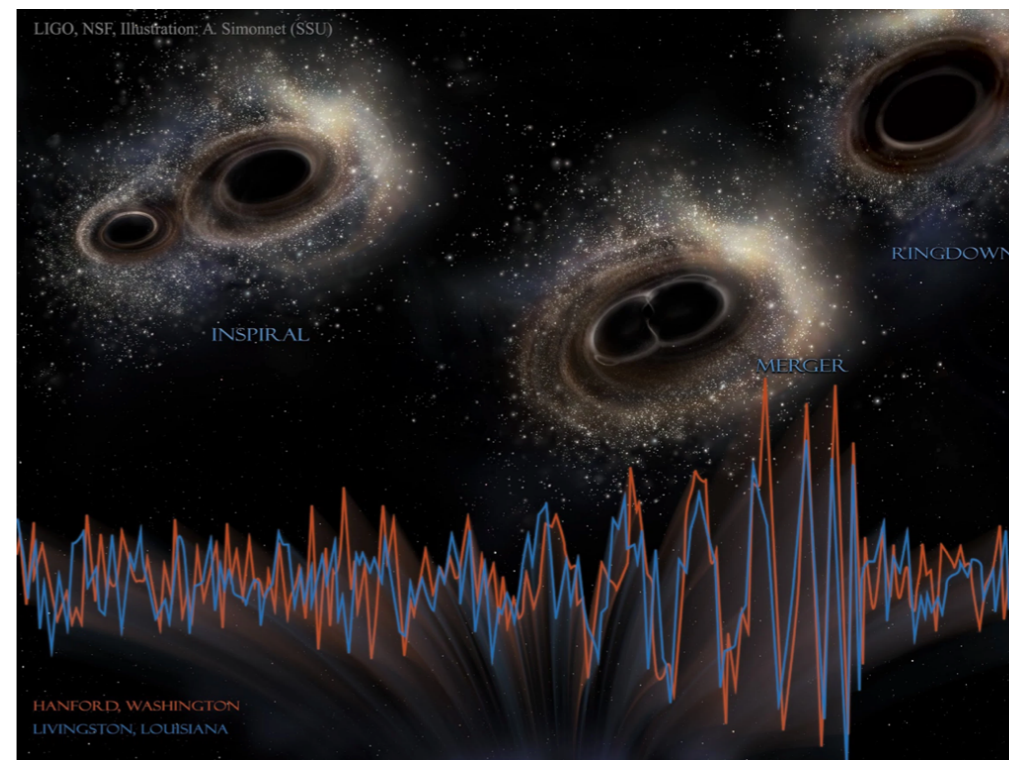


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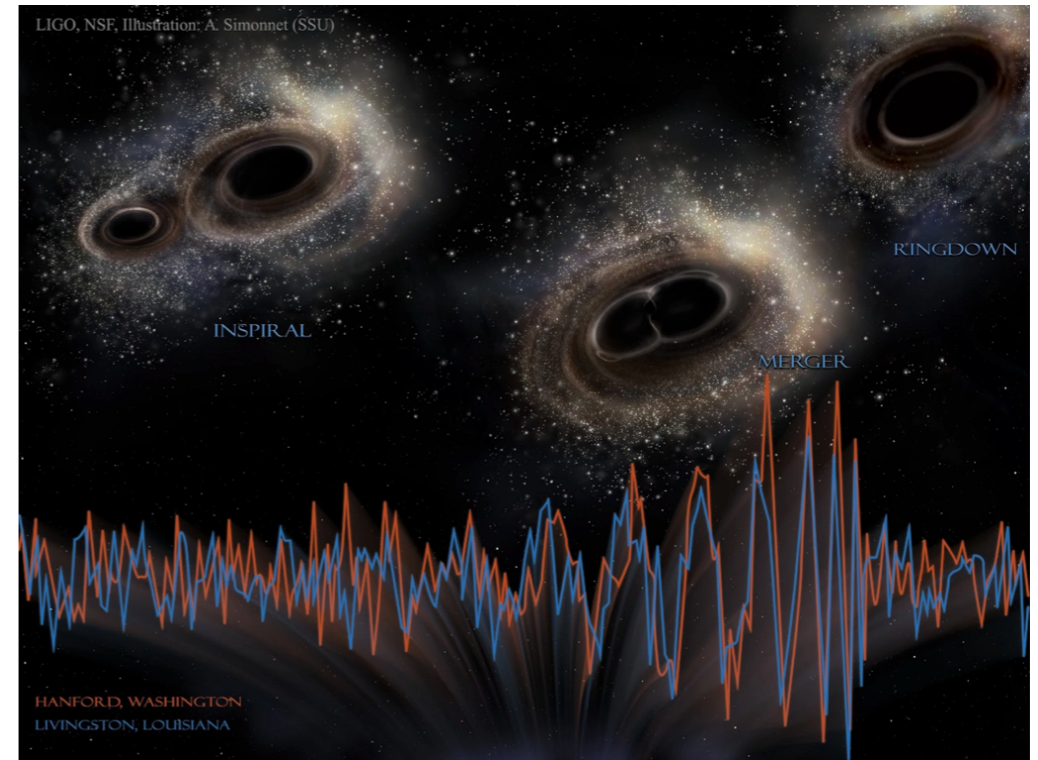
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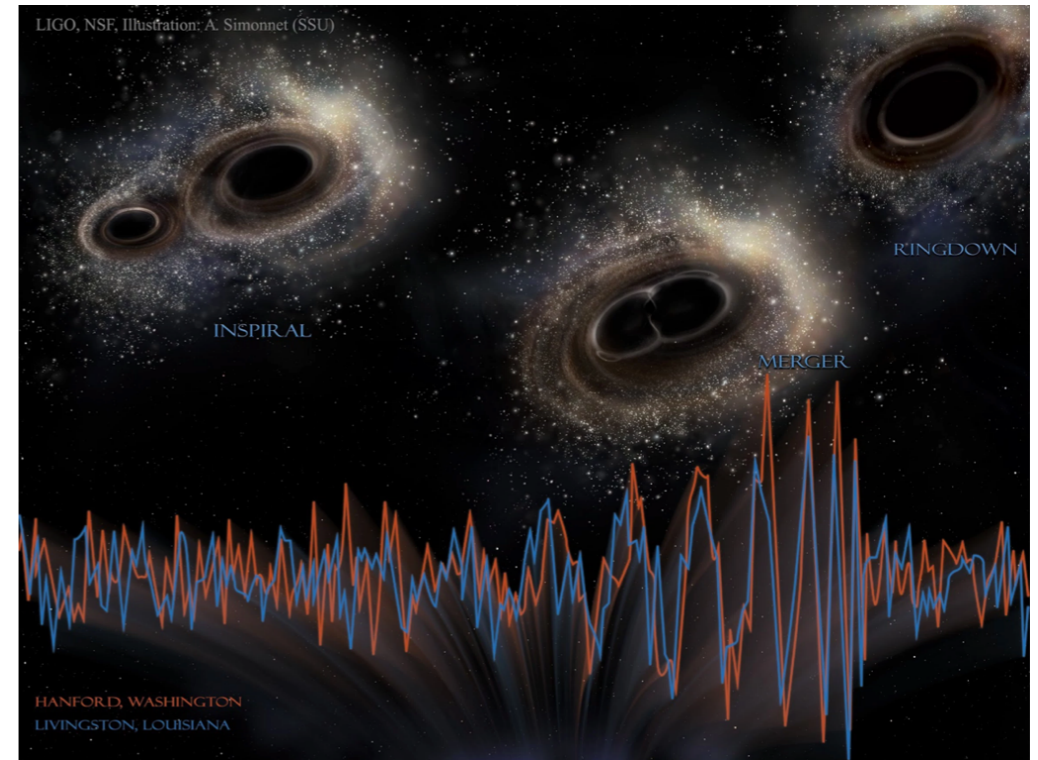
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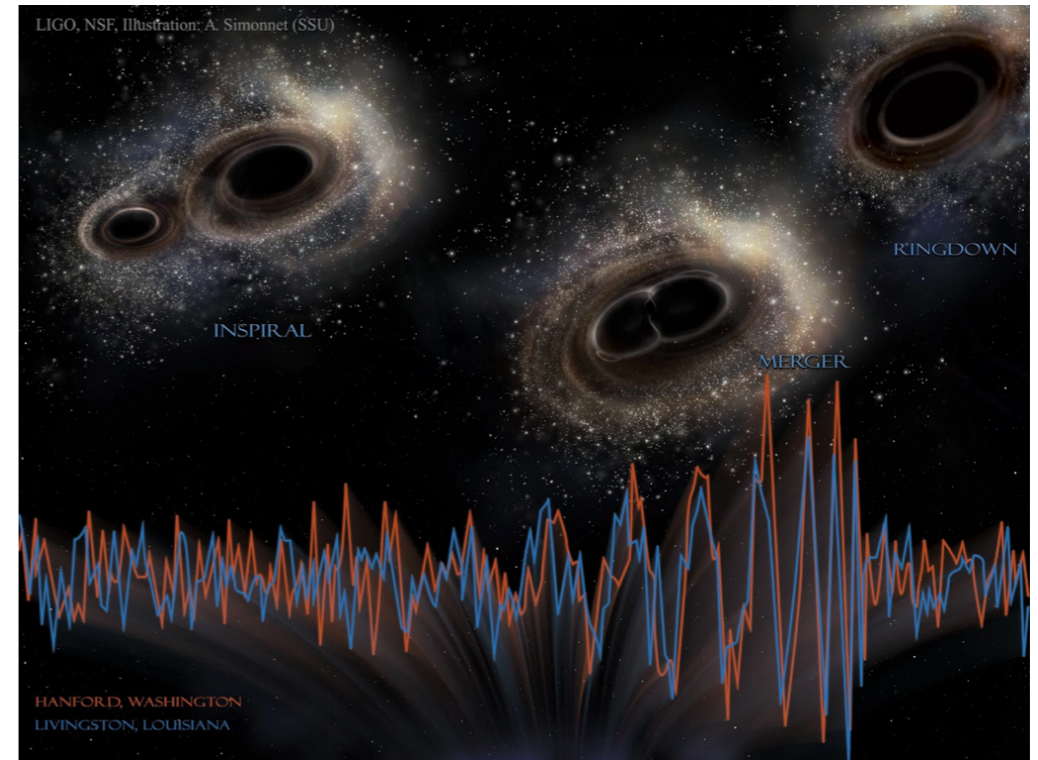
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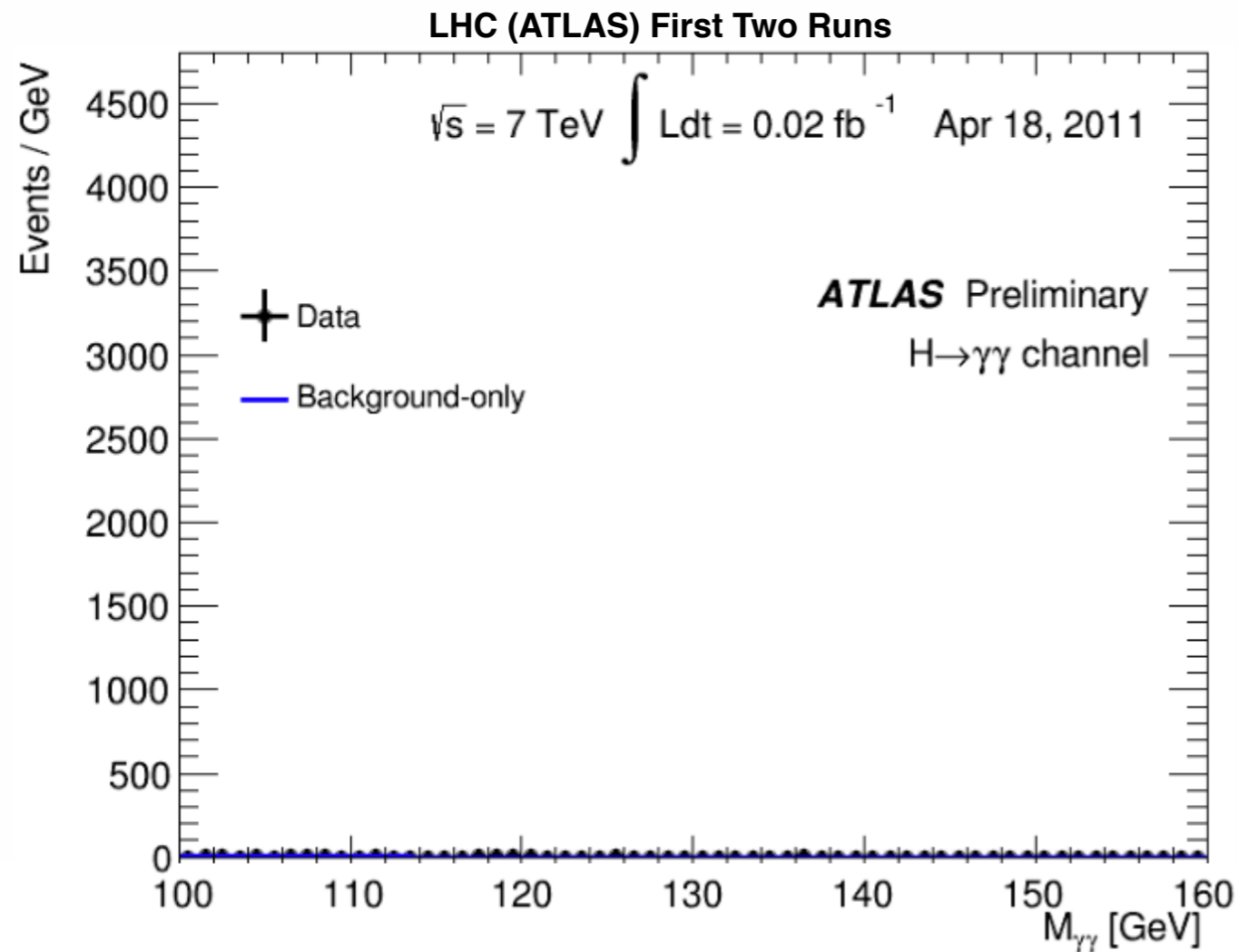
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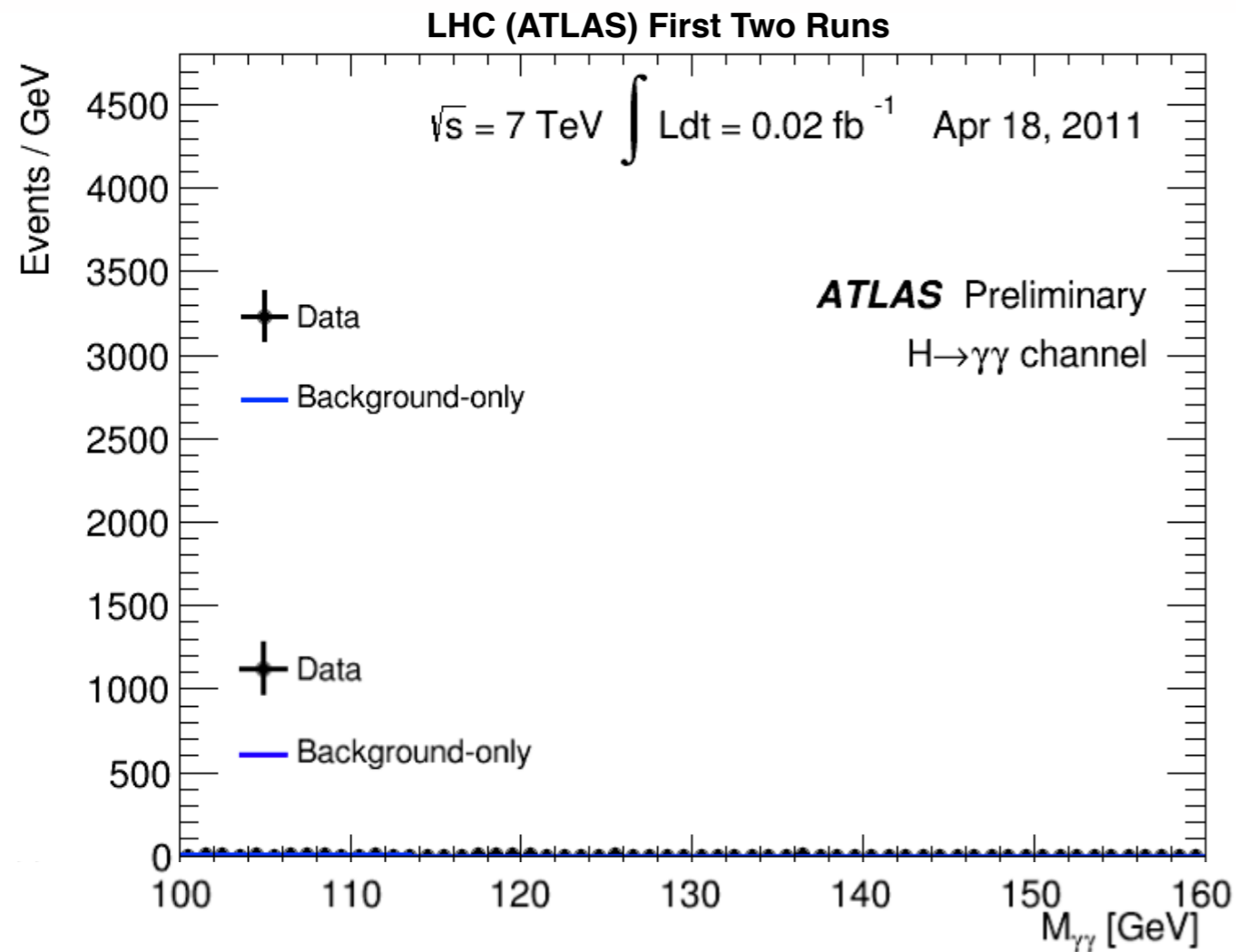
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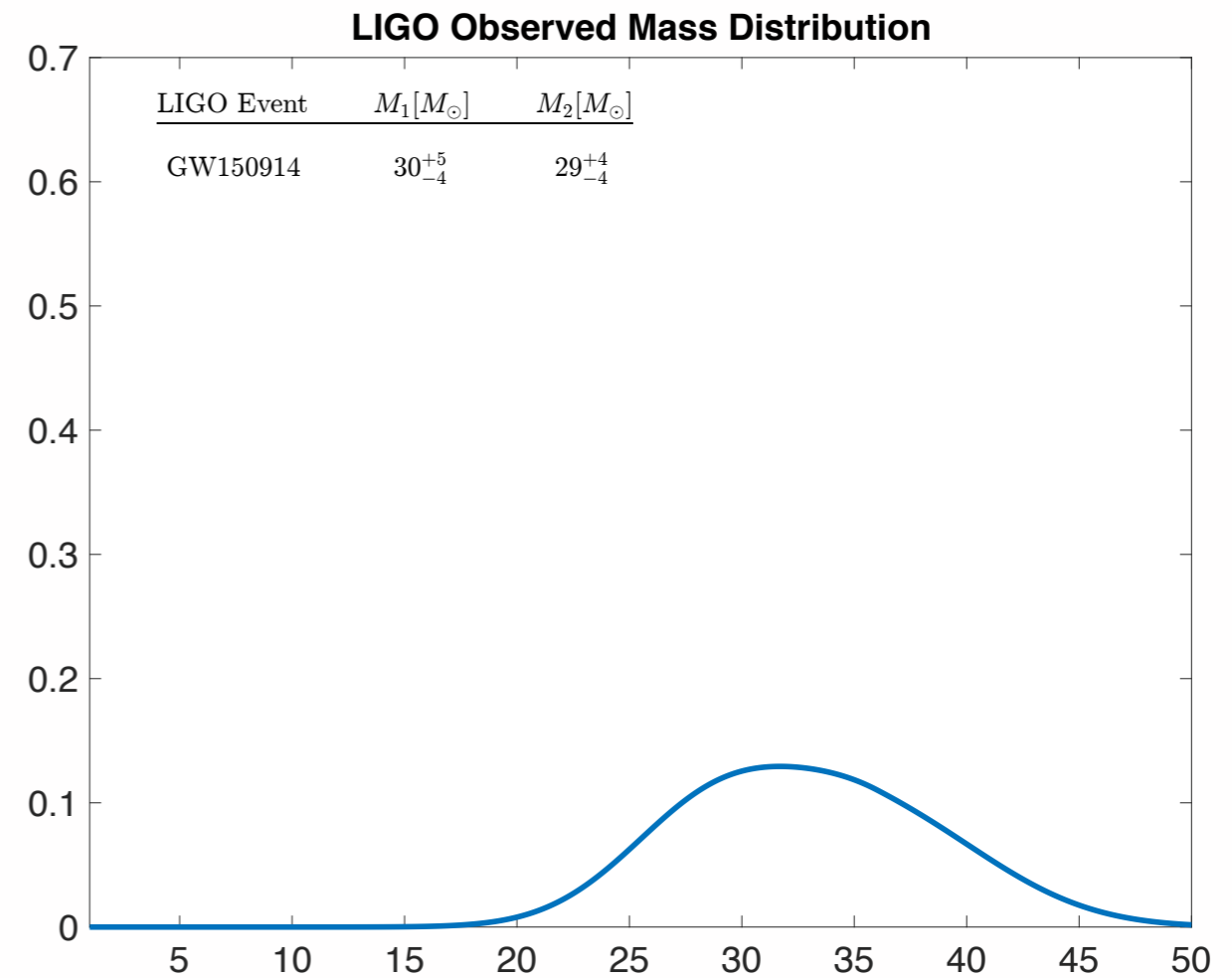
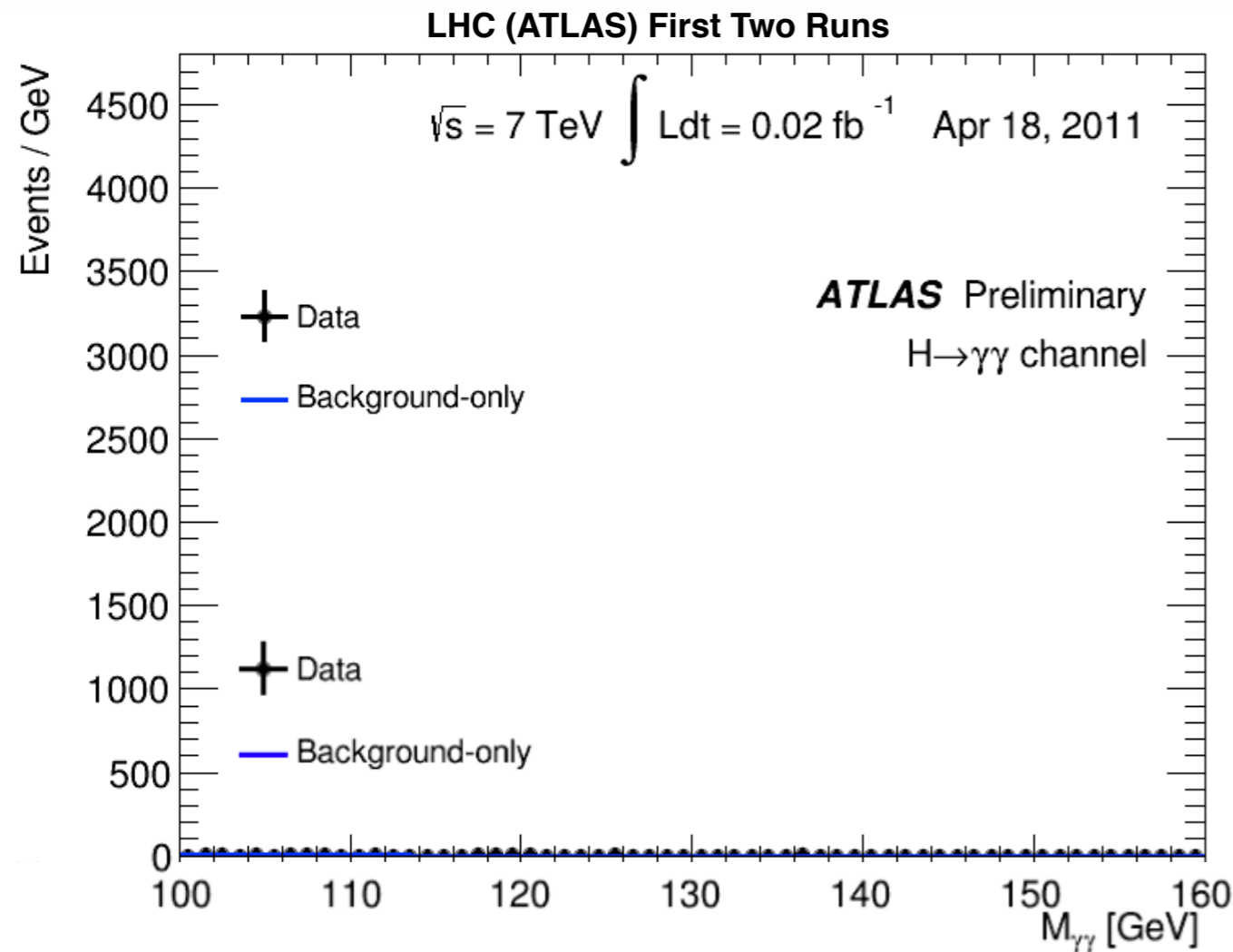
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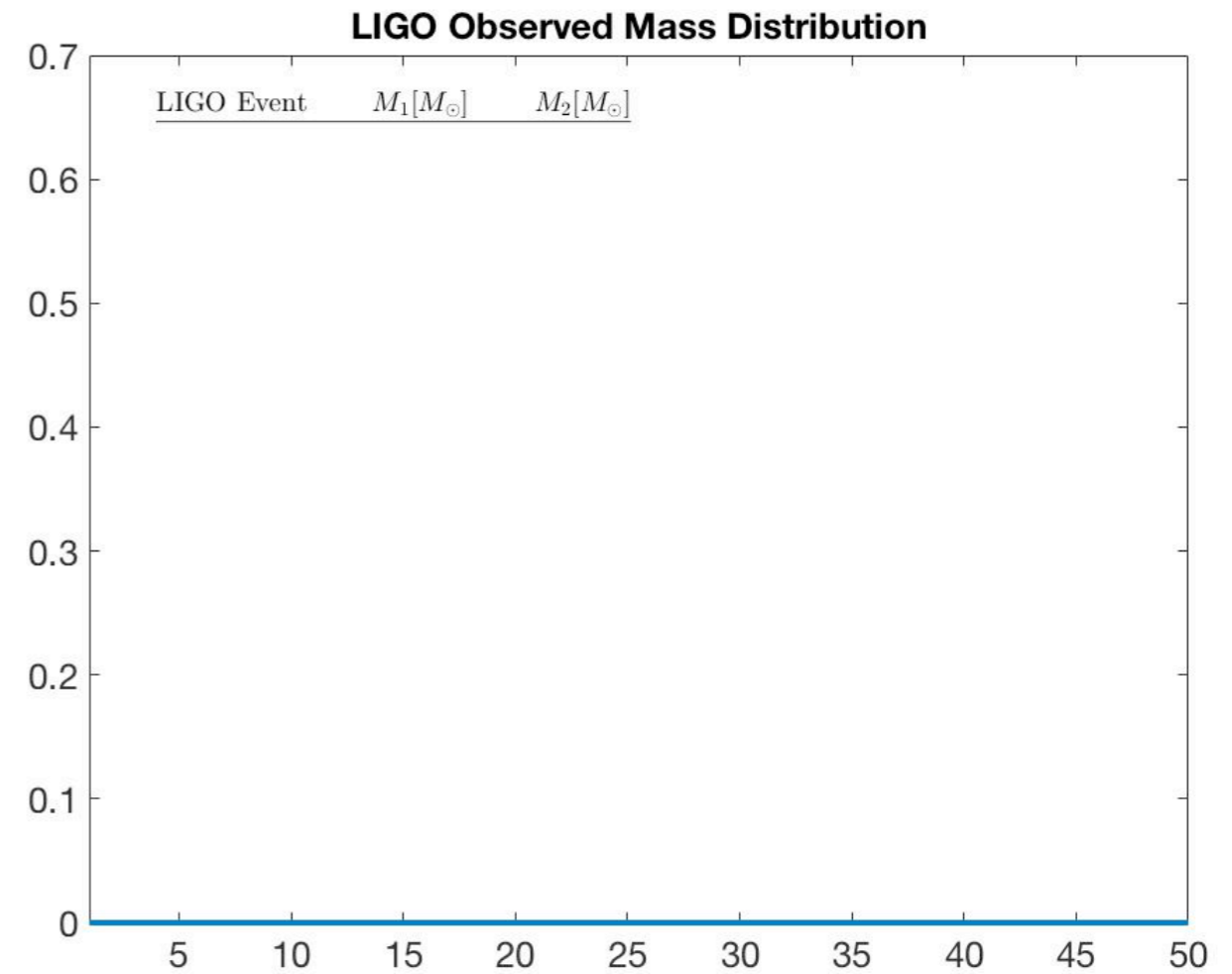
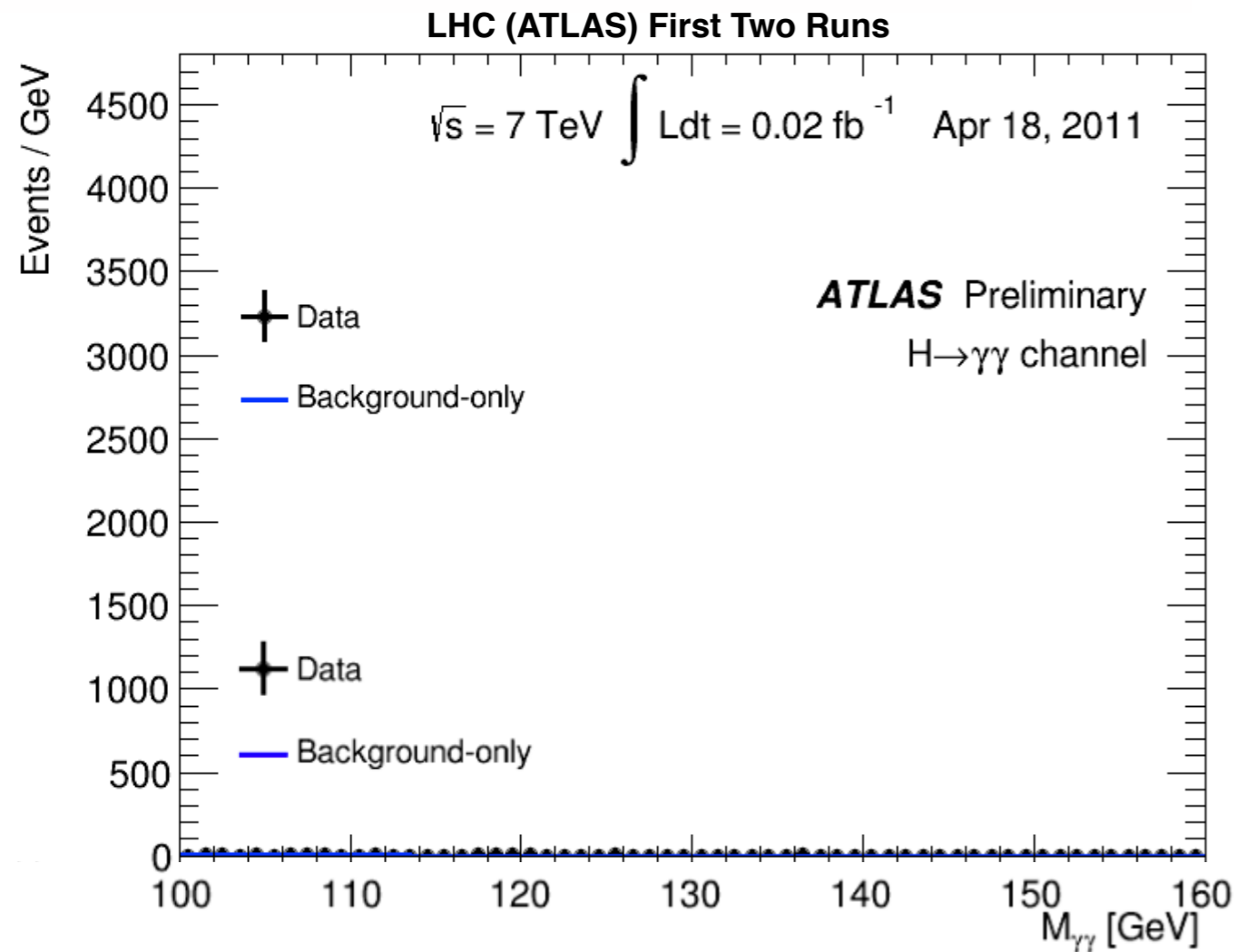
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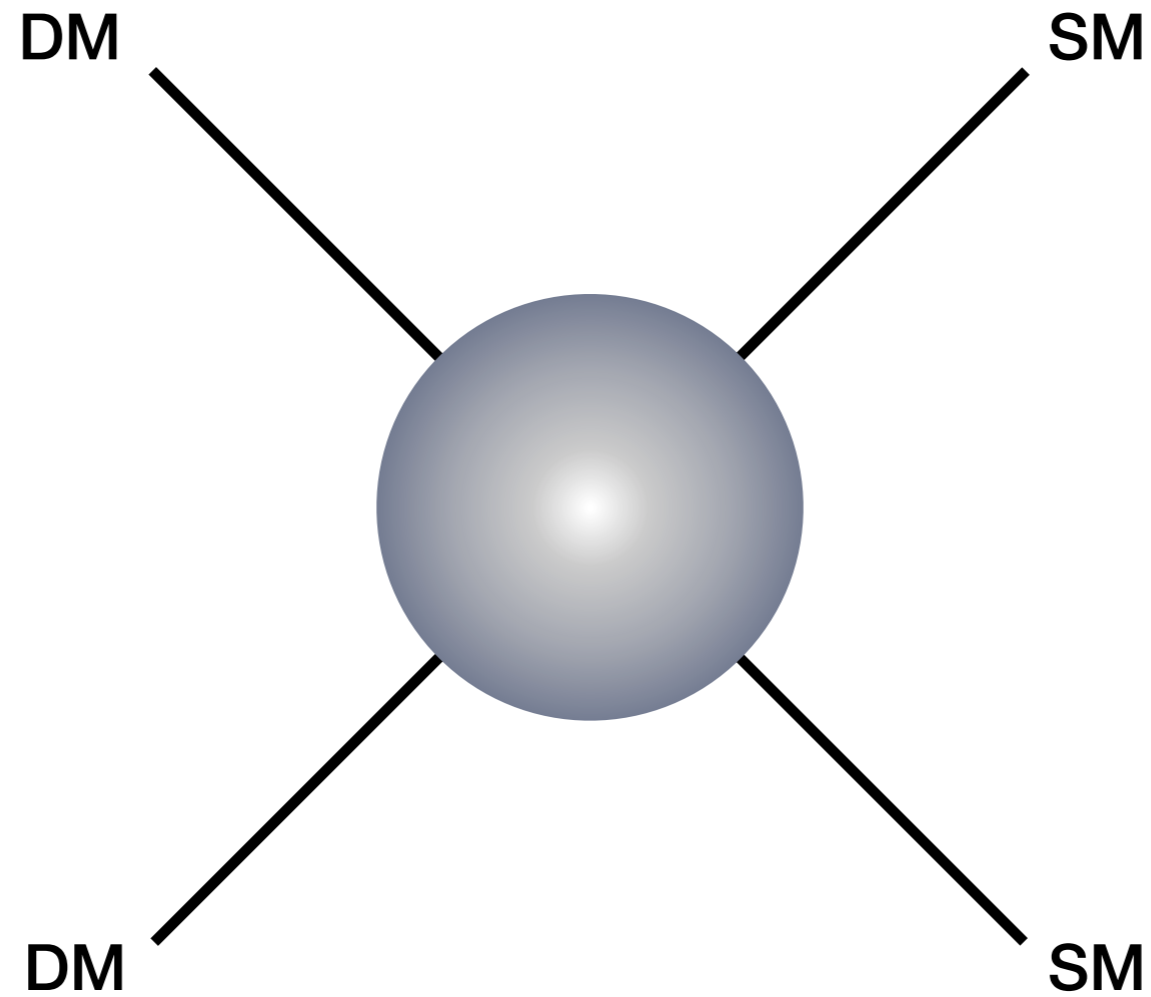
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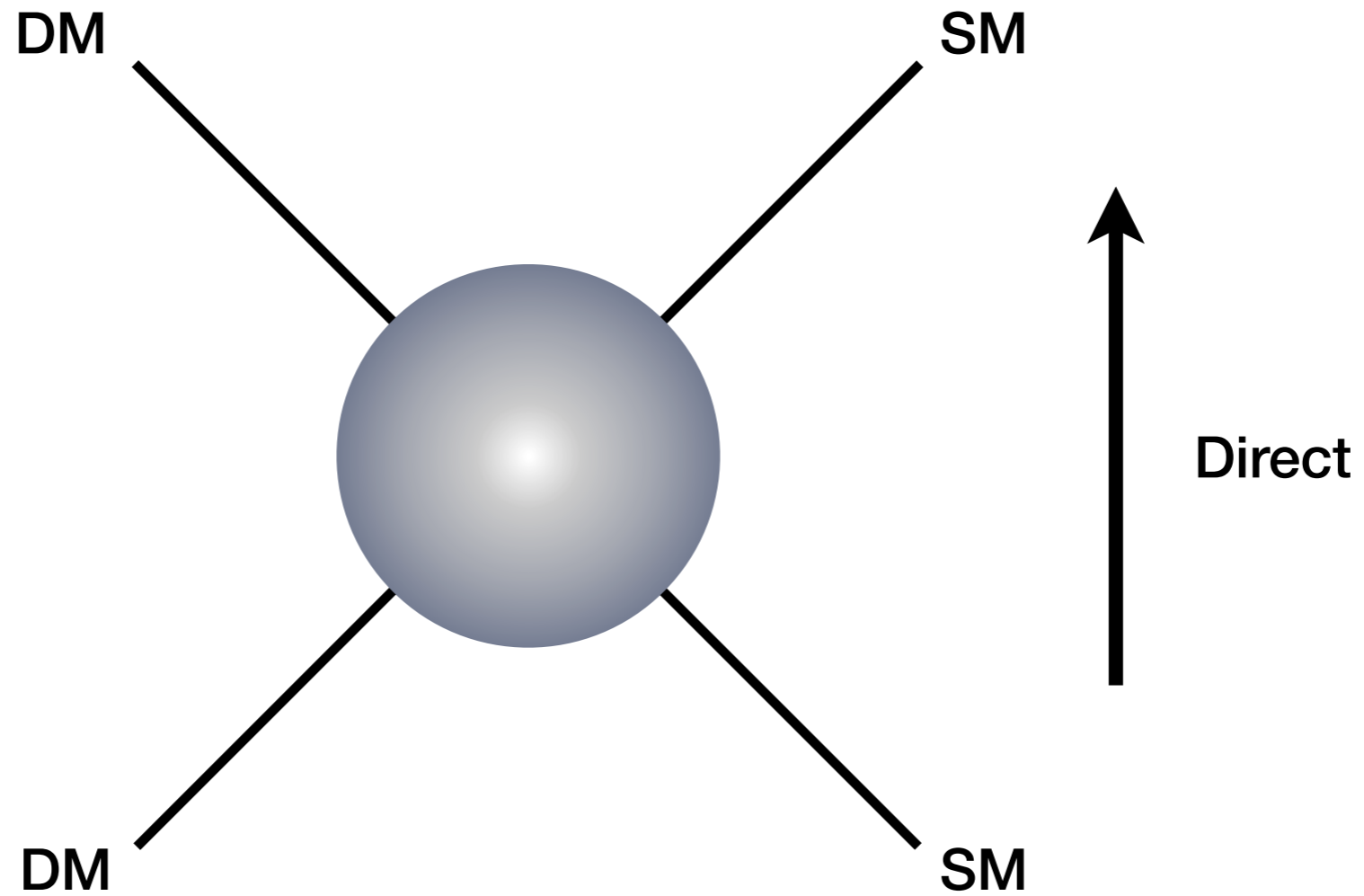
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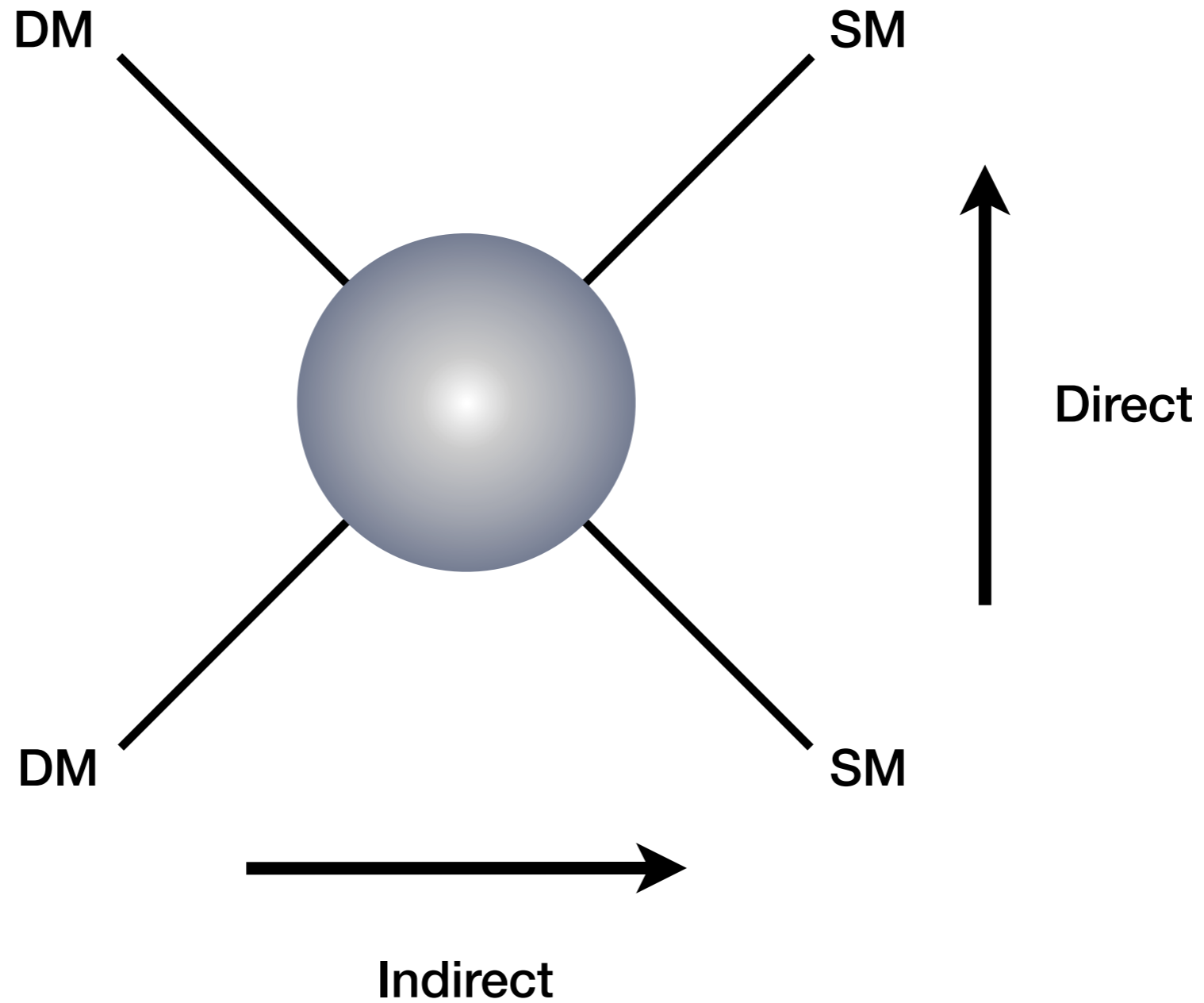
Analogy: How do we search for Dark Matter?



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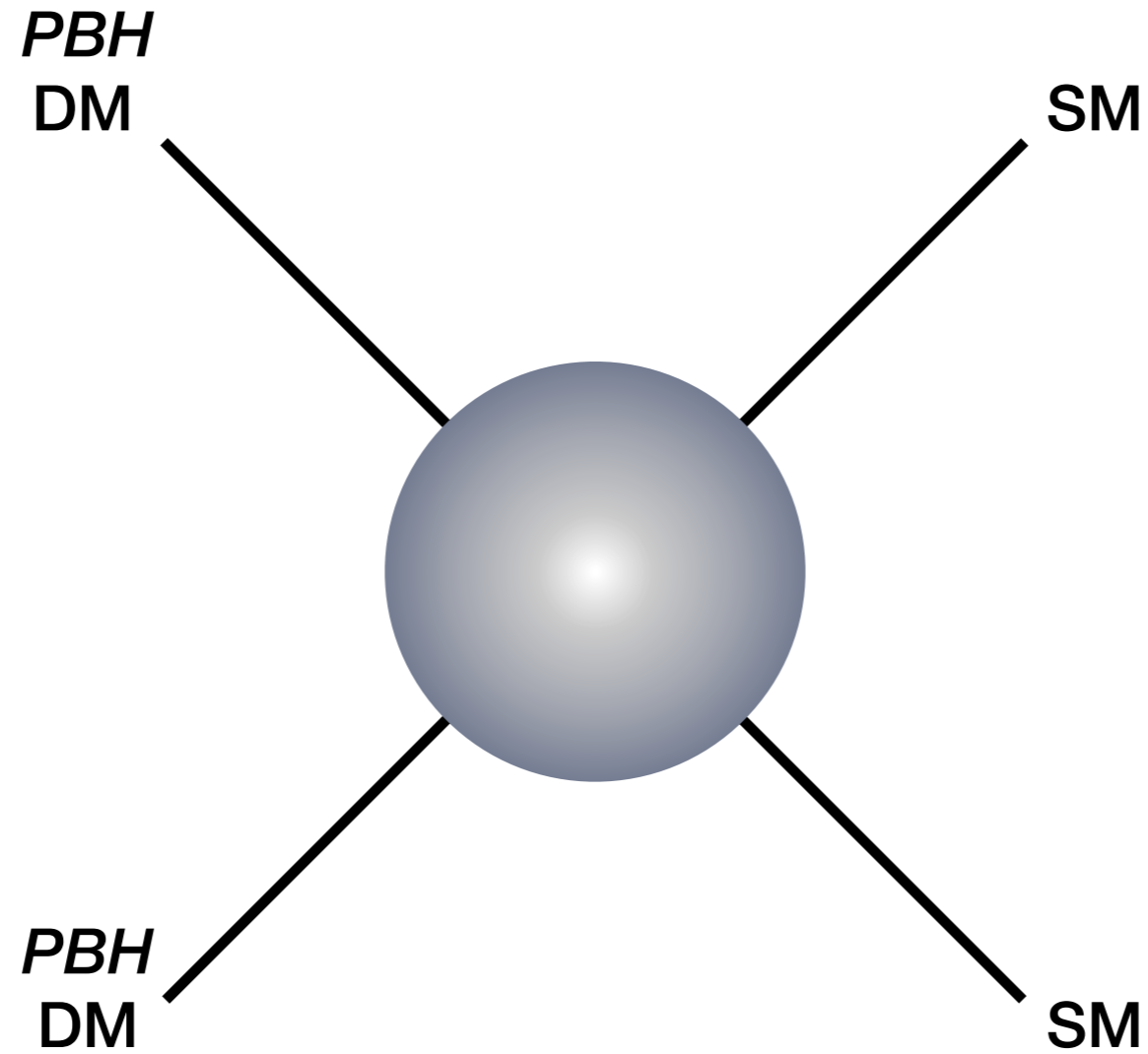


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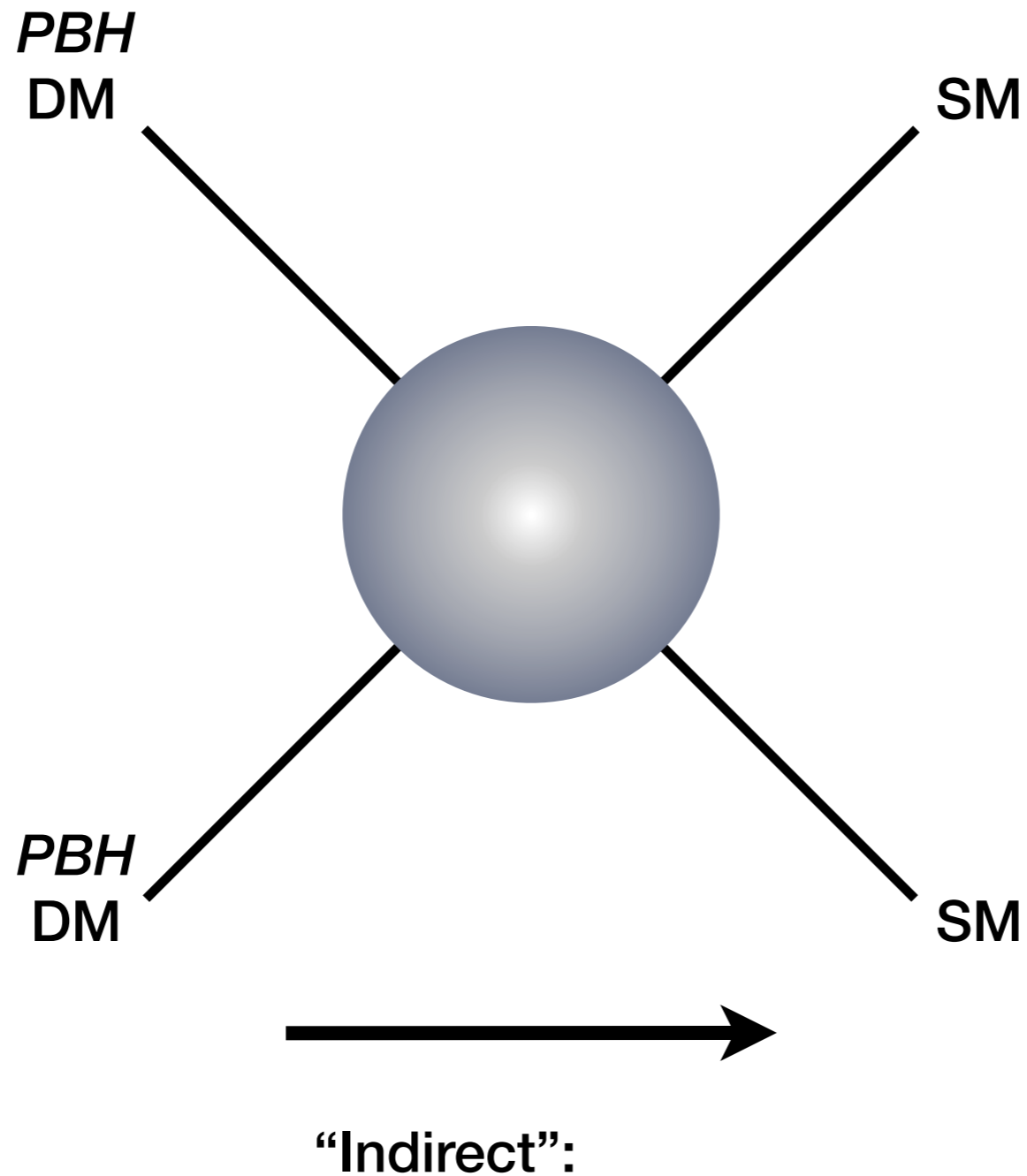
This talk: How can we detect PBH Dark Matter?

(Kovetz, PRL 2017)



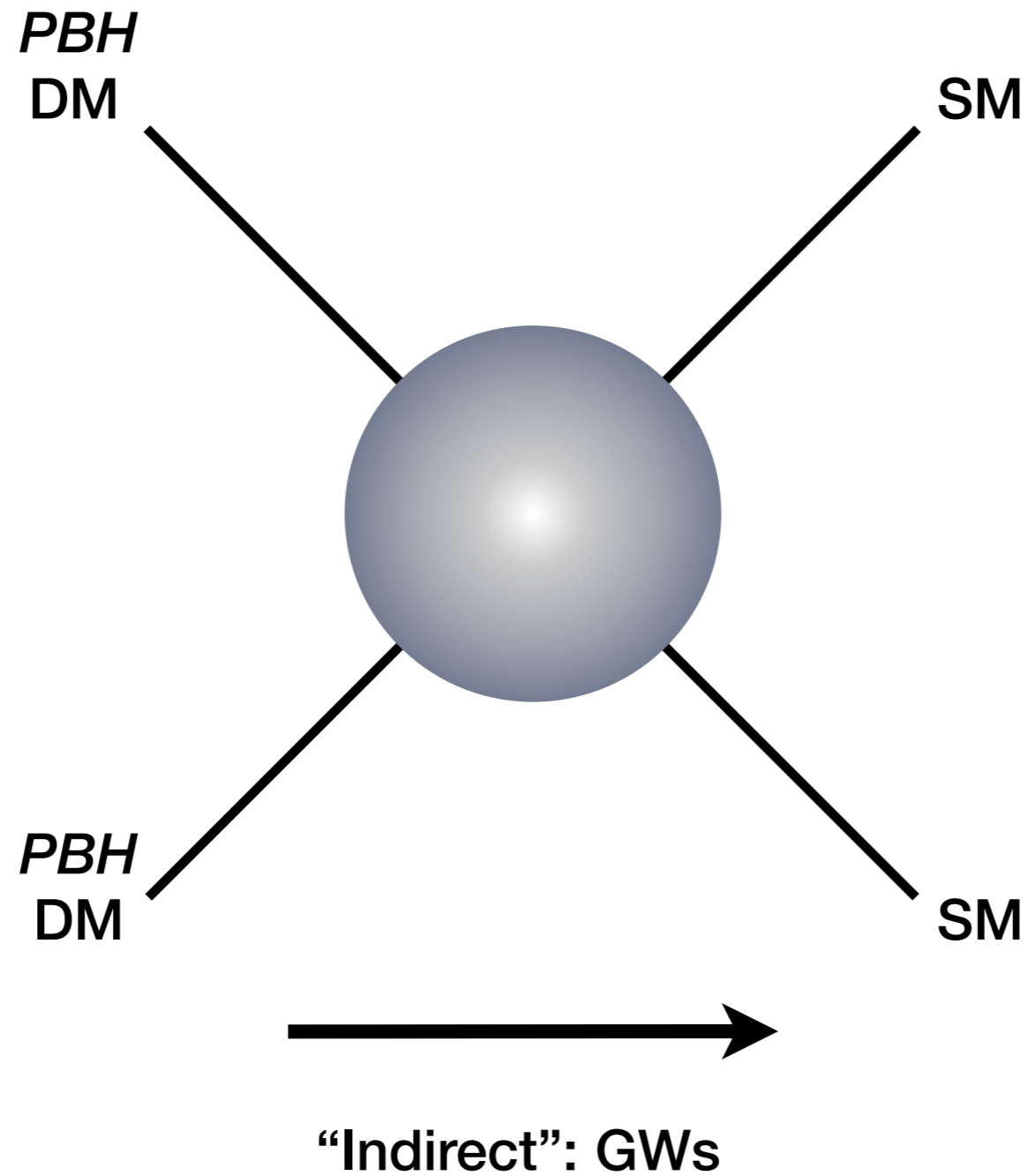
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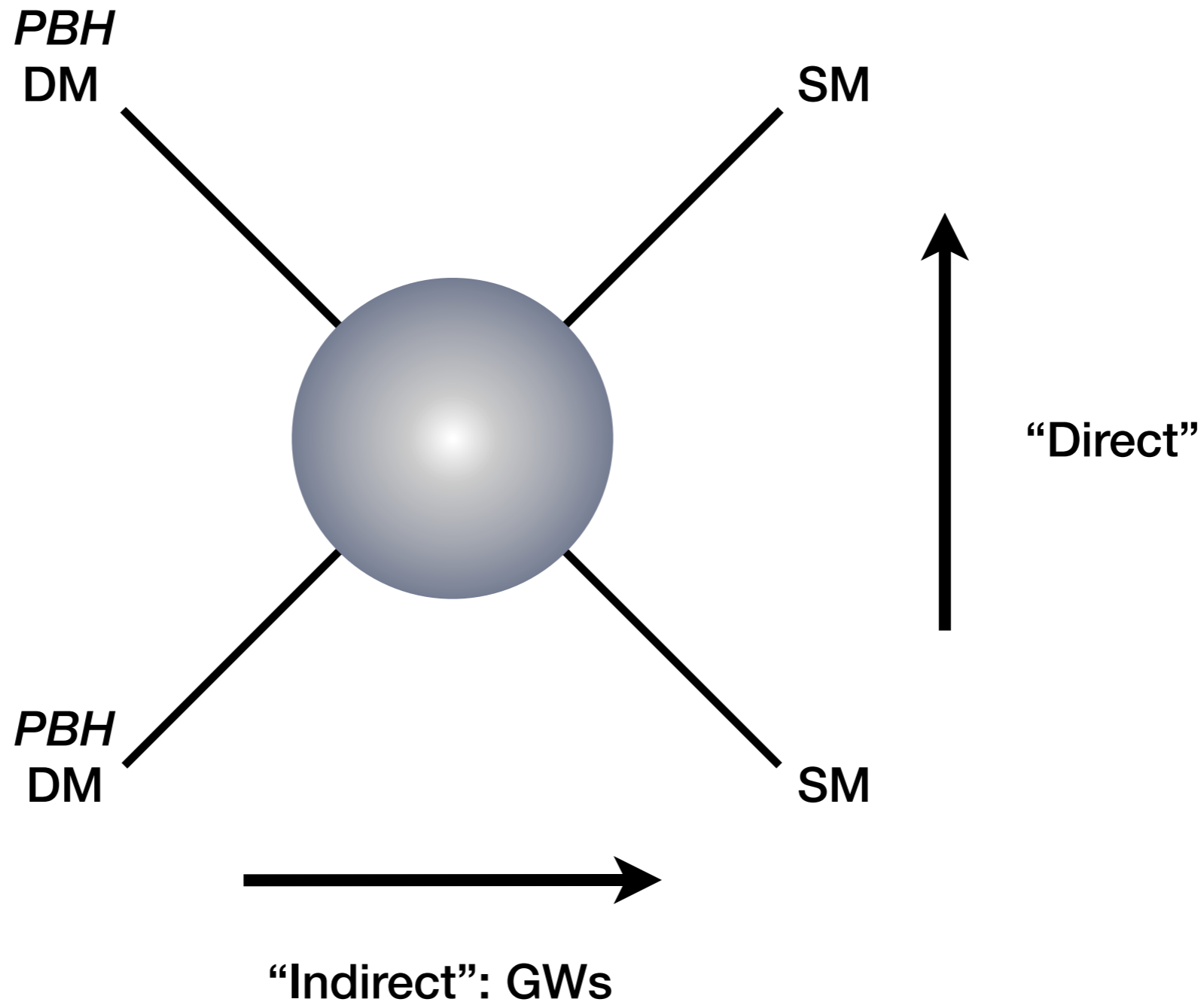
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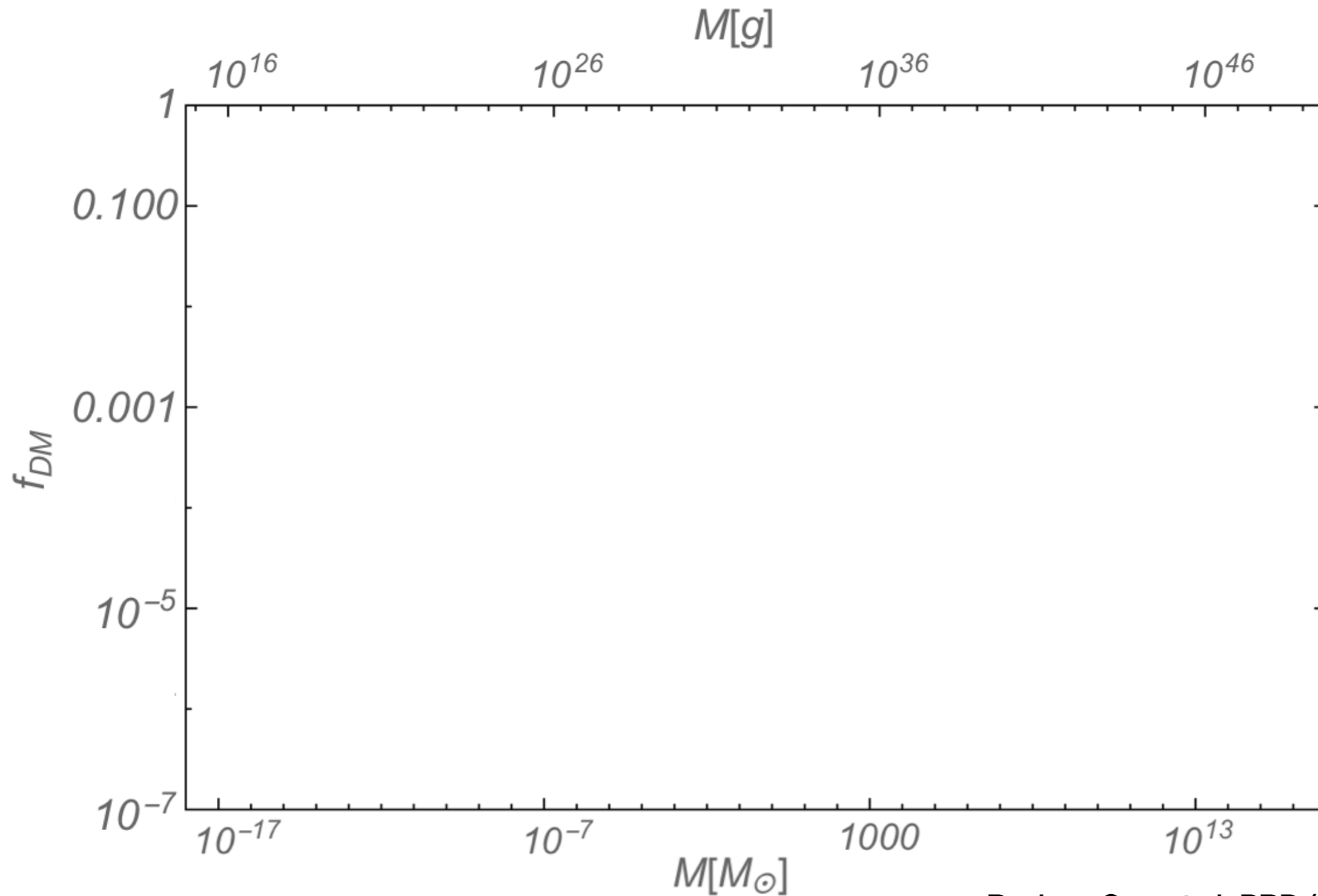


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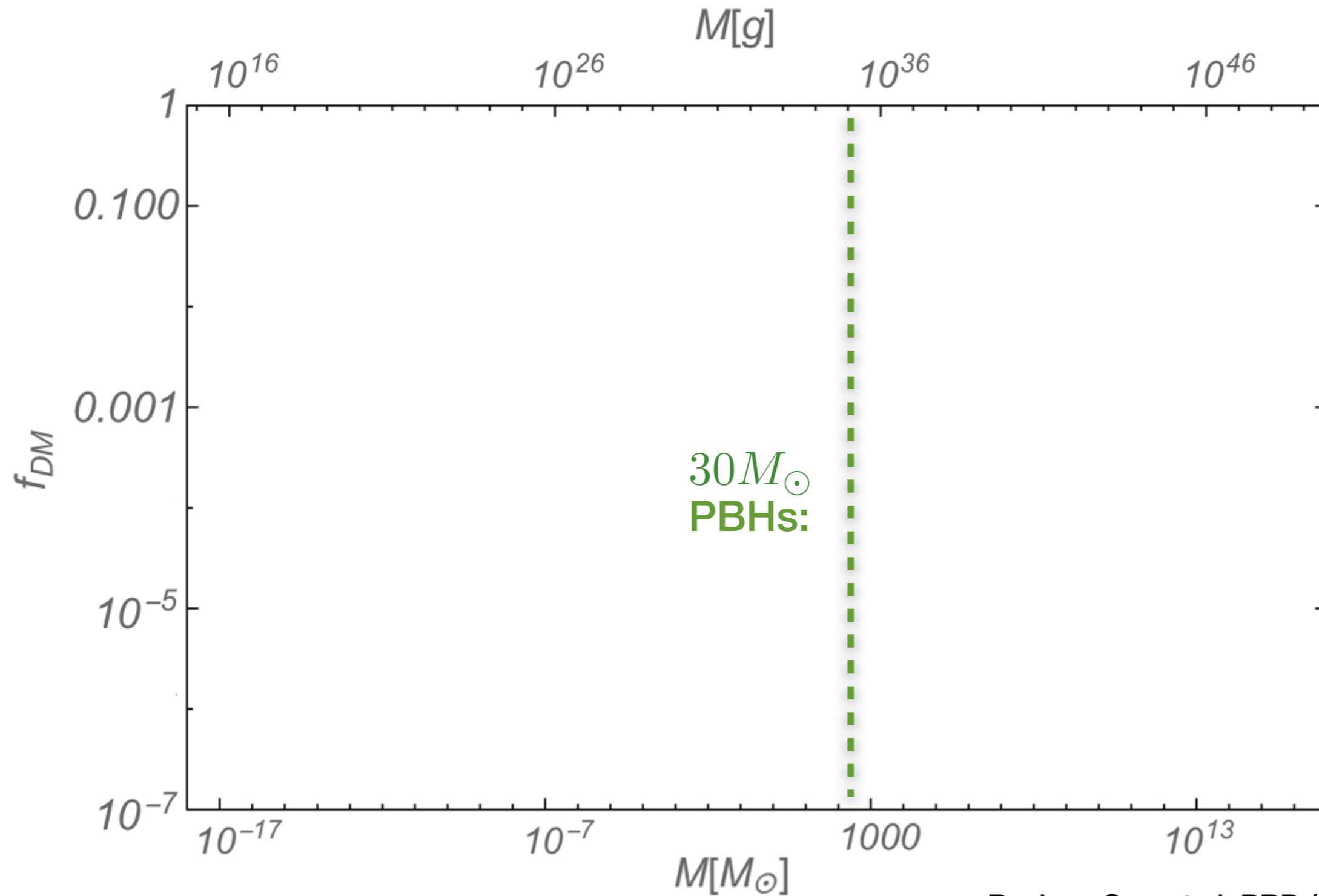
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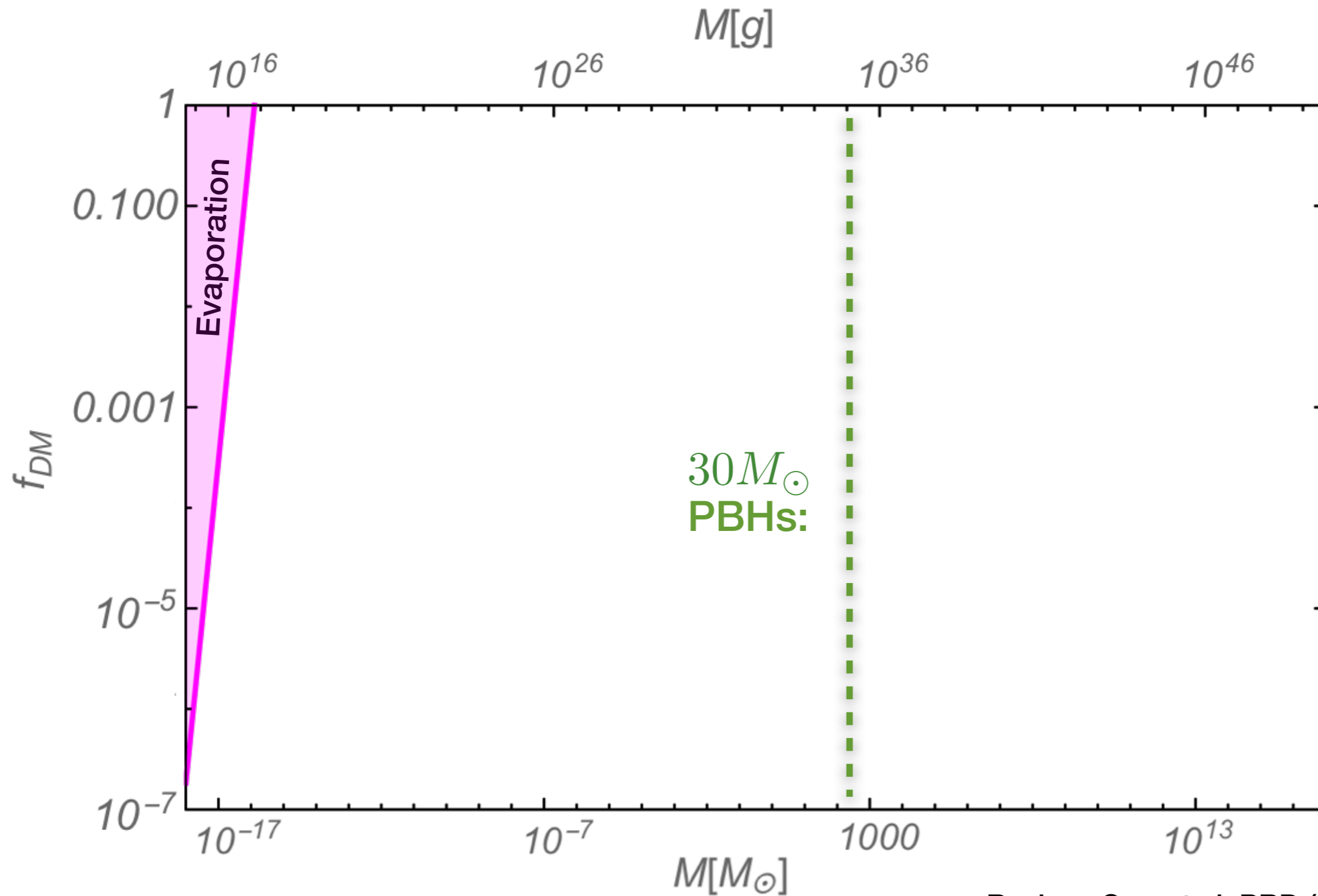
PBH Dark Matter: Existing Constraints



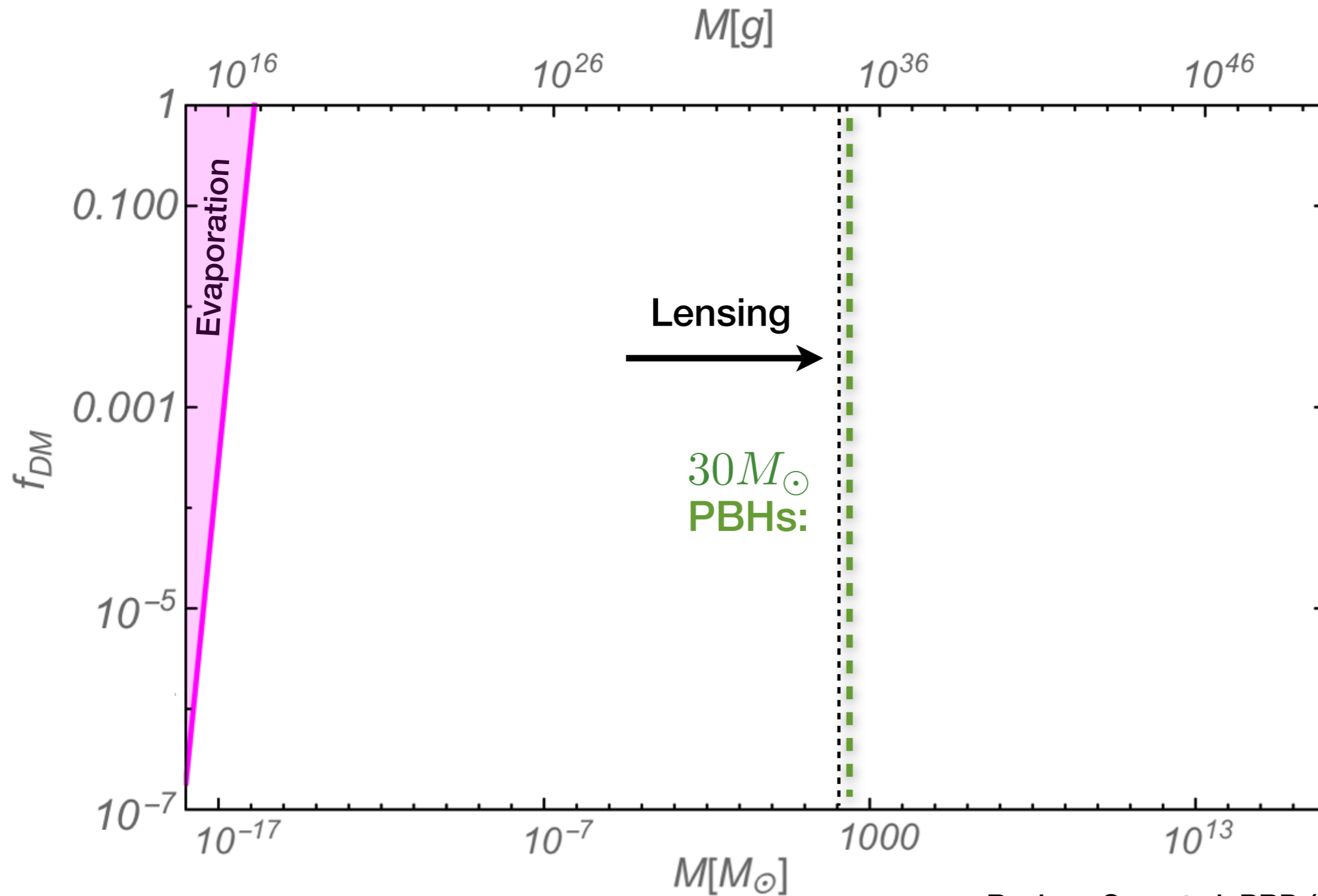
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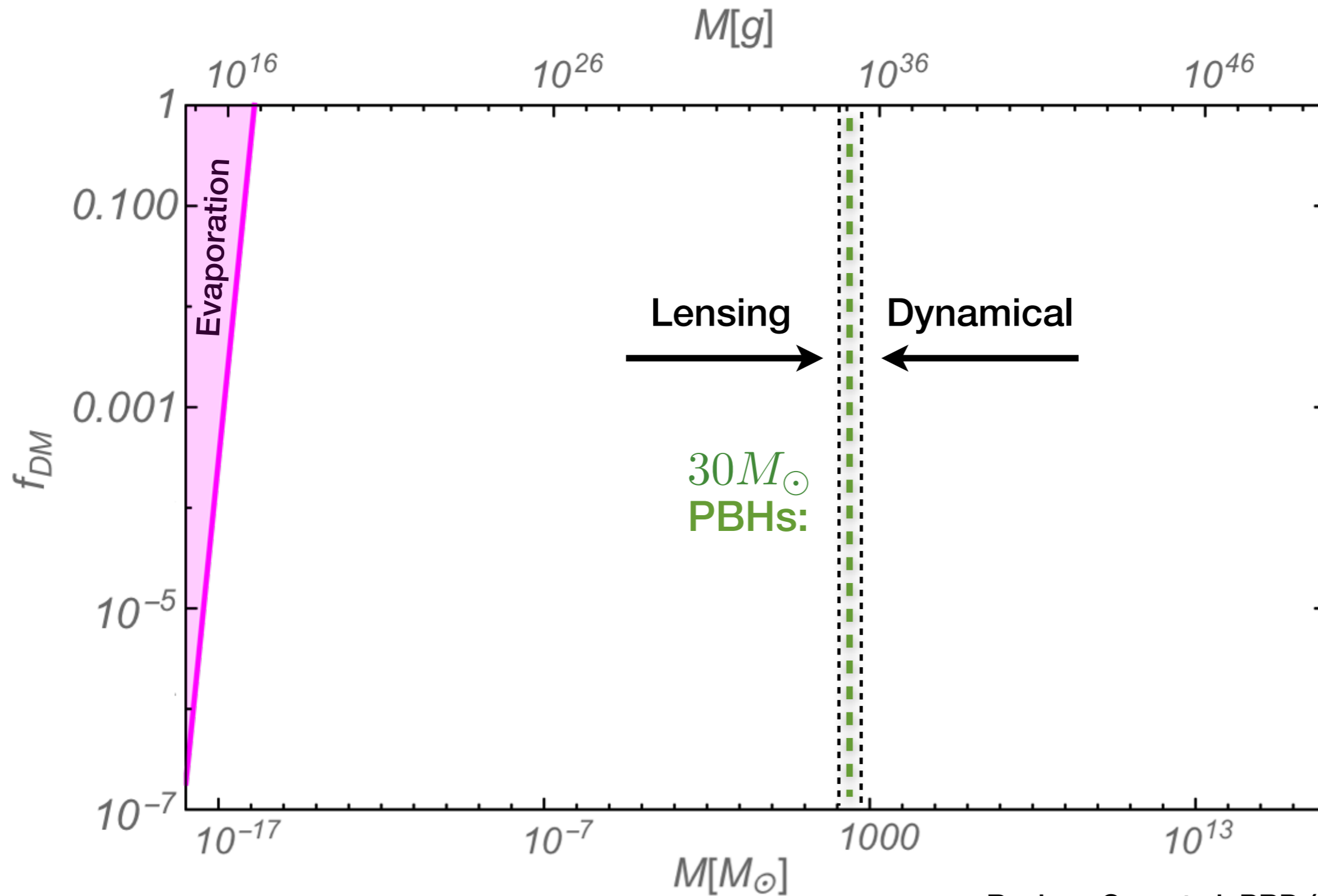
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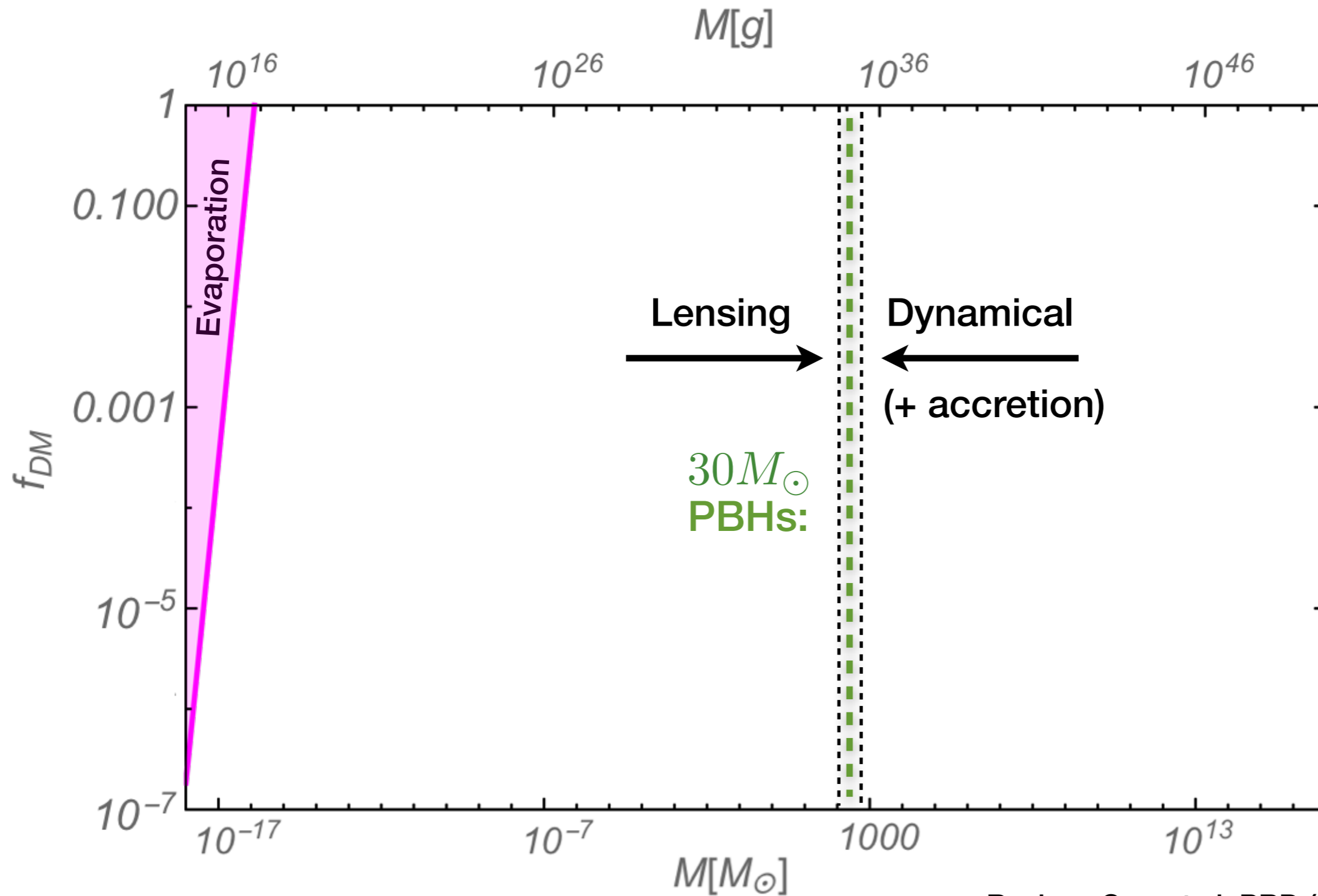
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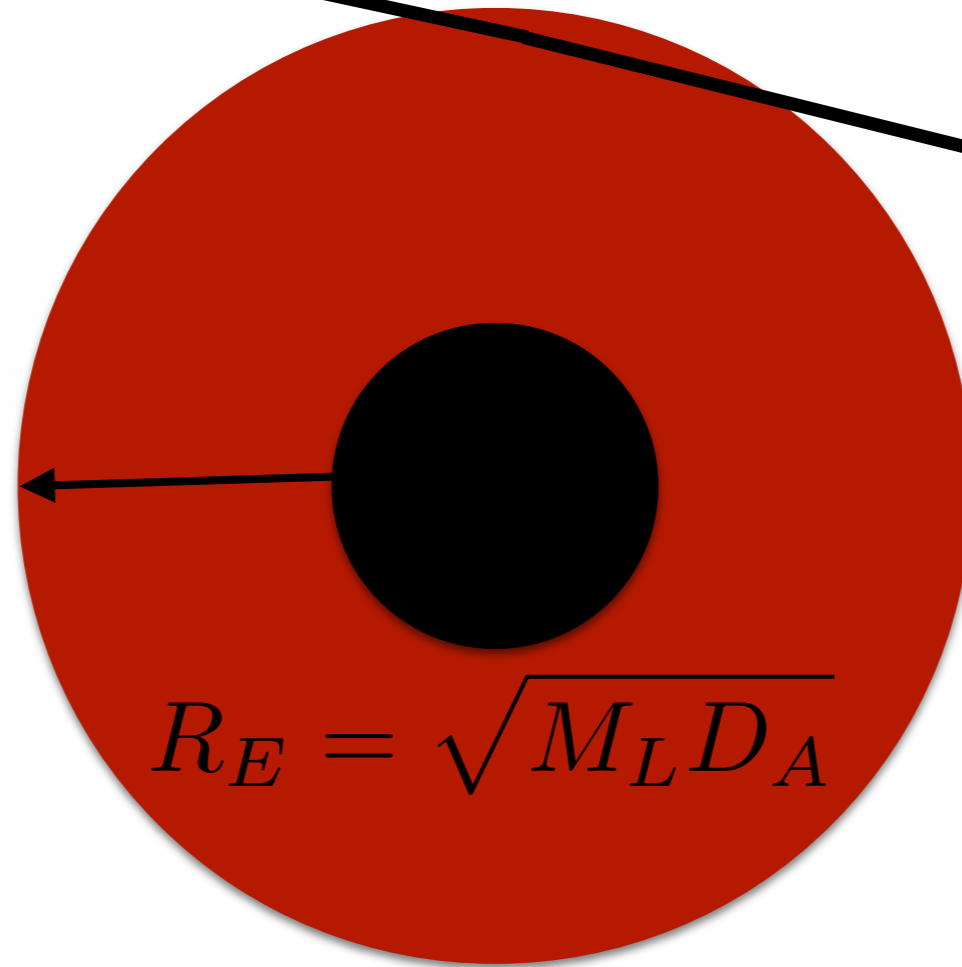


Microensing: Illustration

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Illustration: J. Muñoz

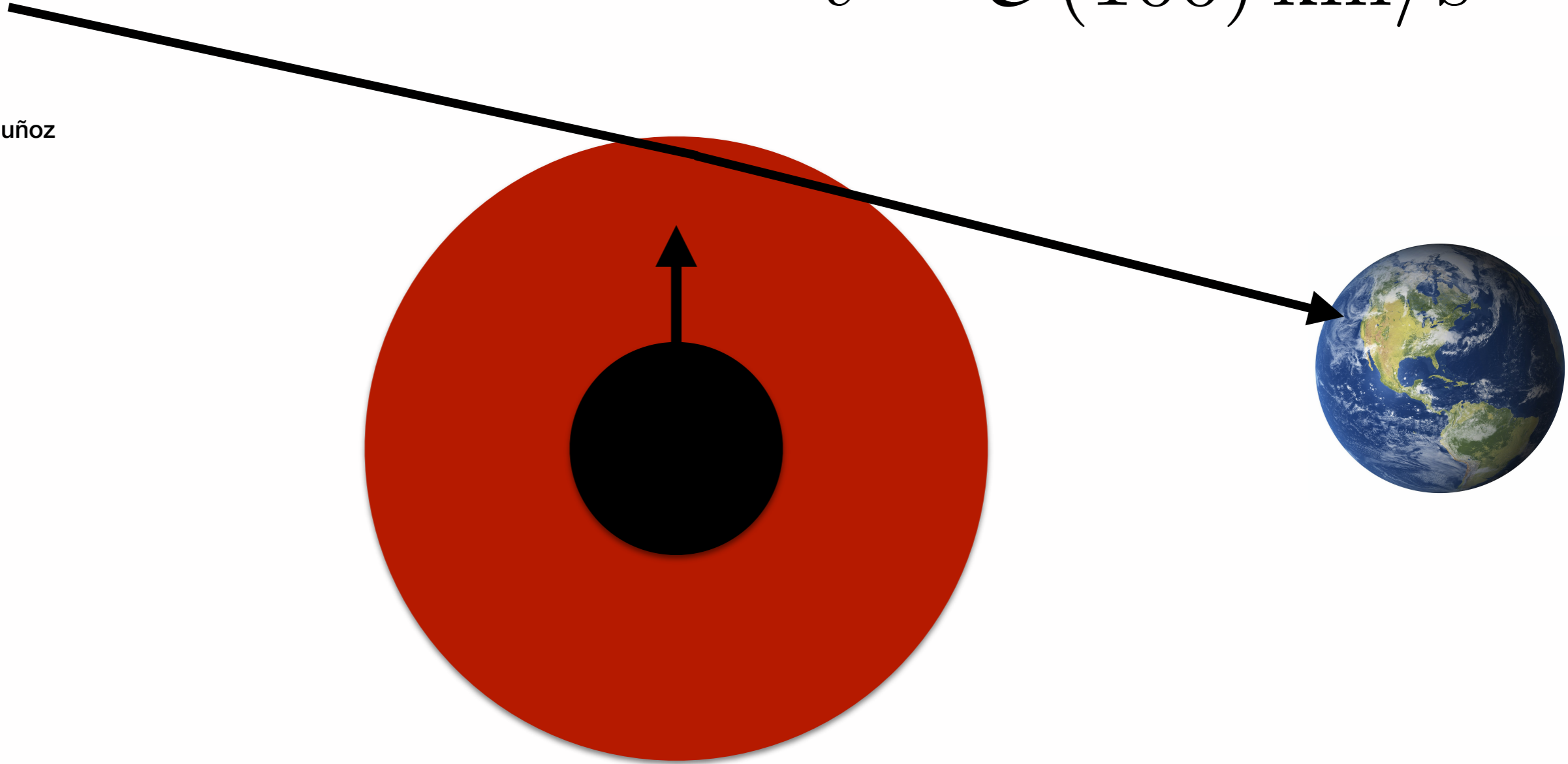


Microlensing: Illustration



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$$v \sim \mathcal{O}(100) \text{ km/s}$$

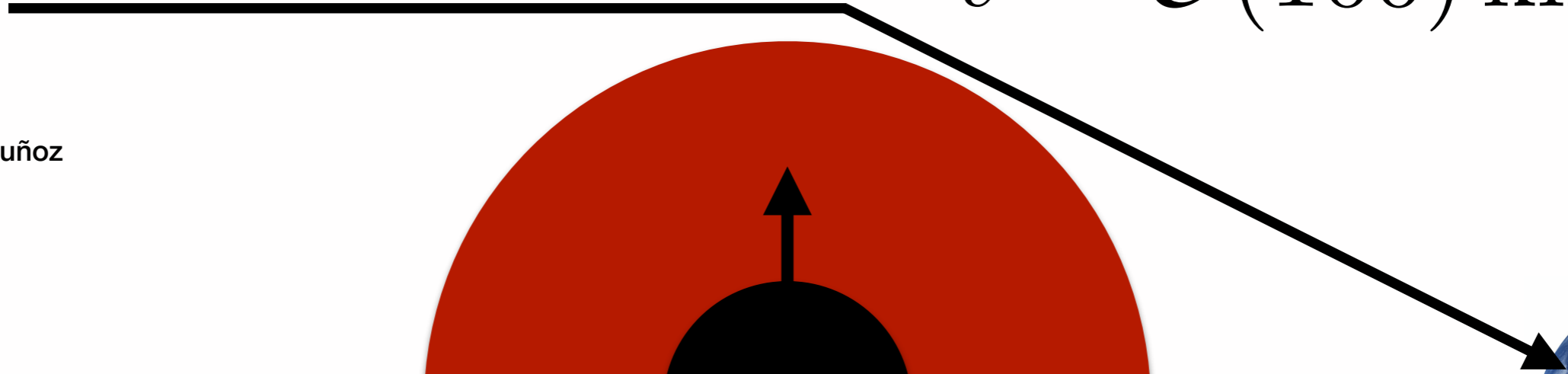
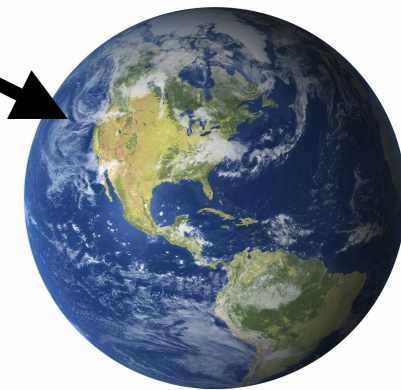
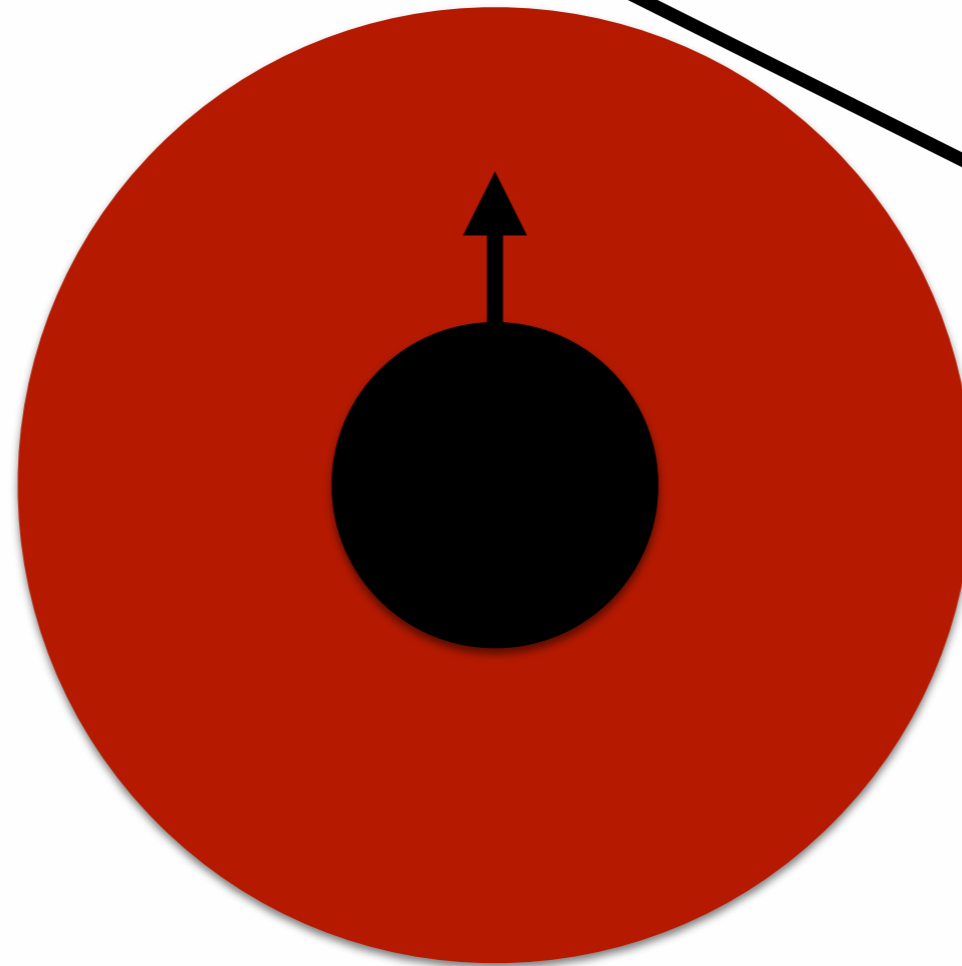


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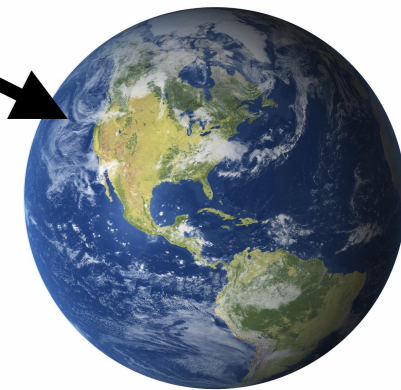
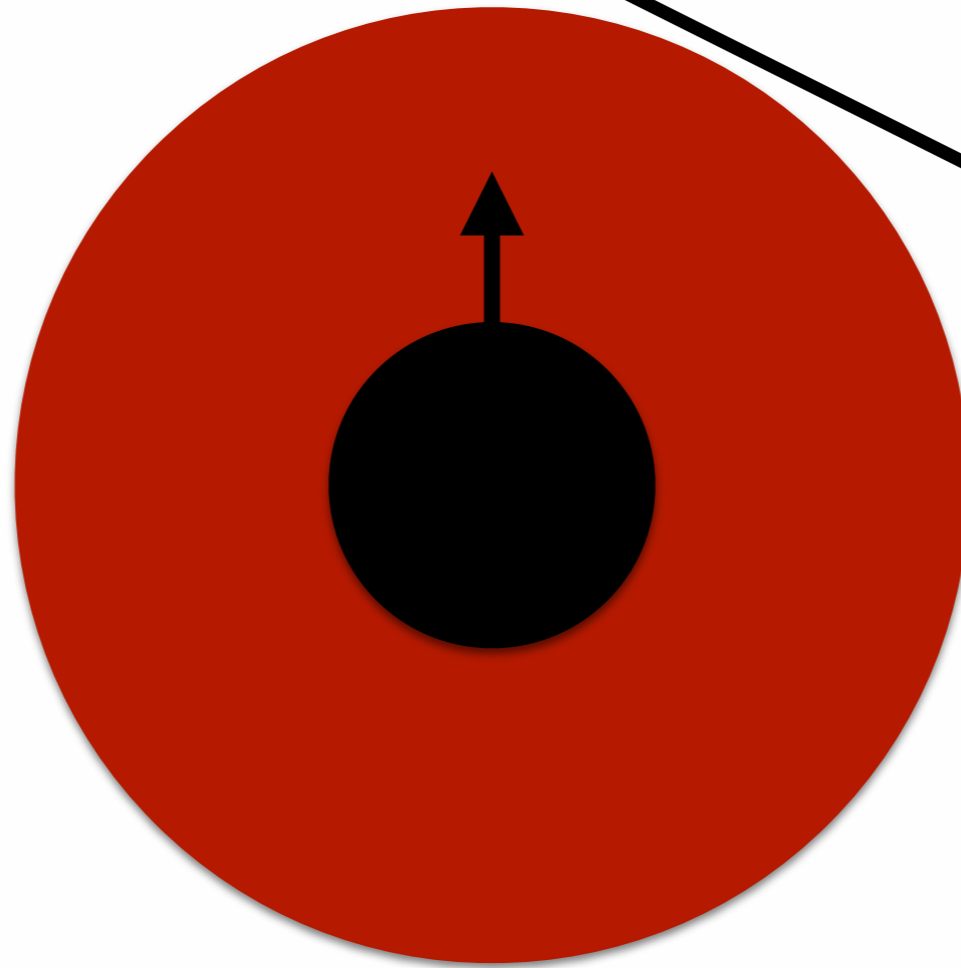


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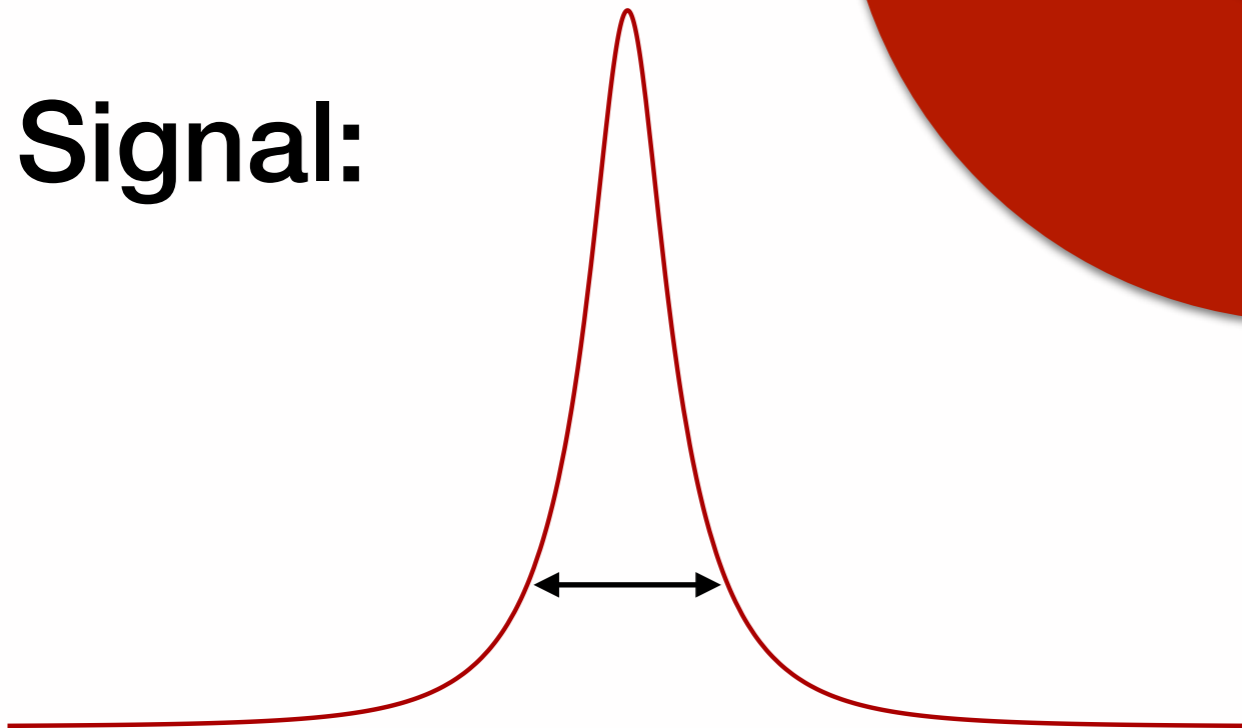


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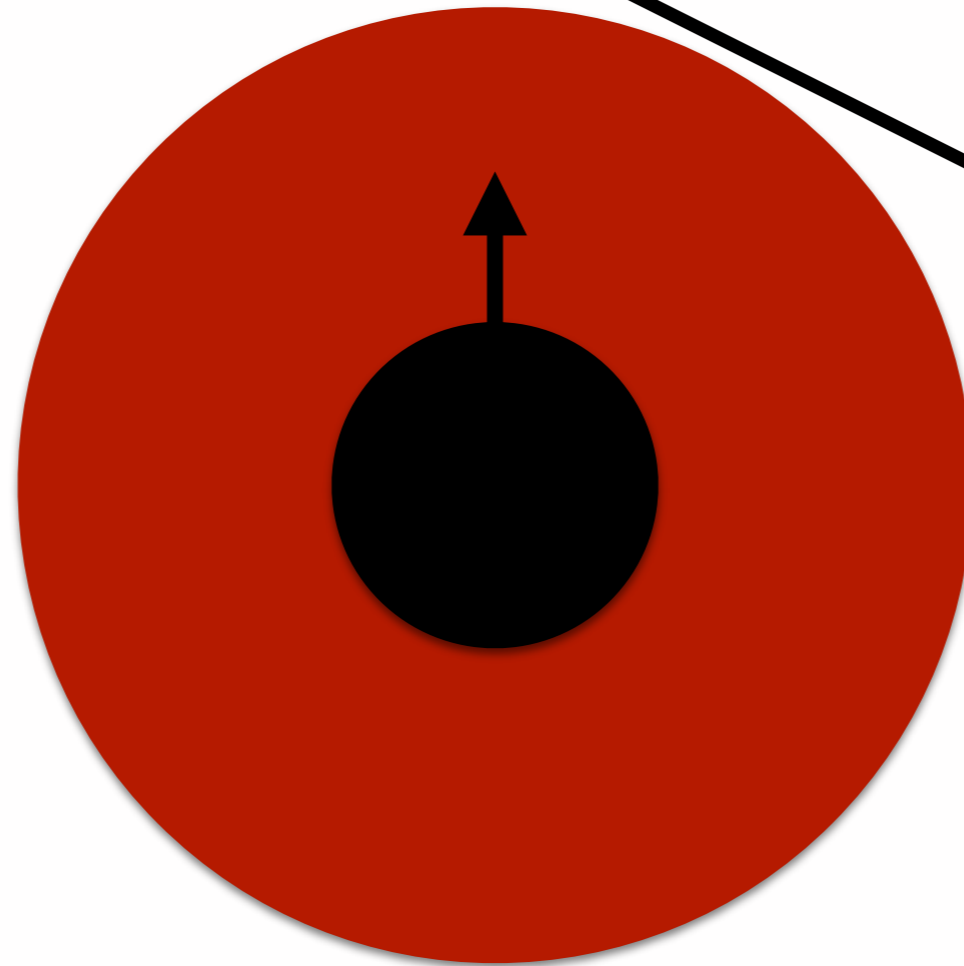


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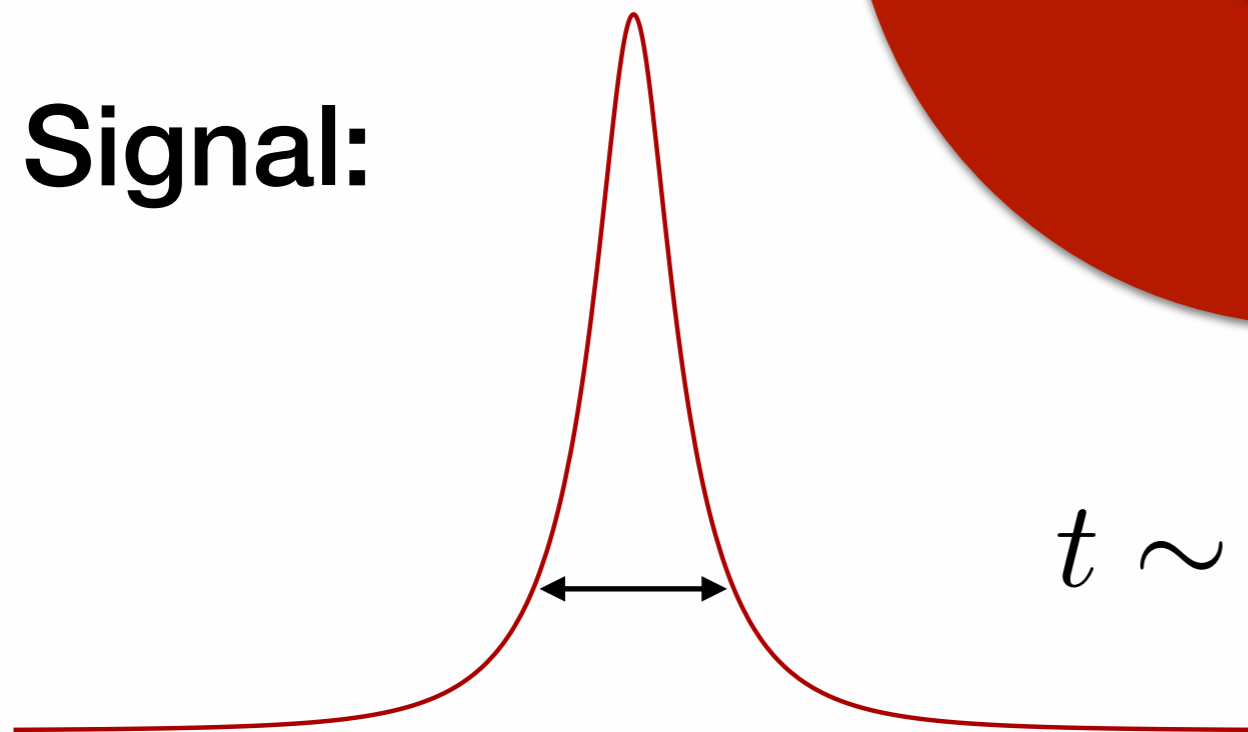


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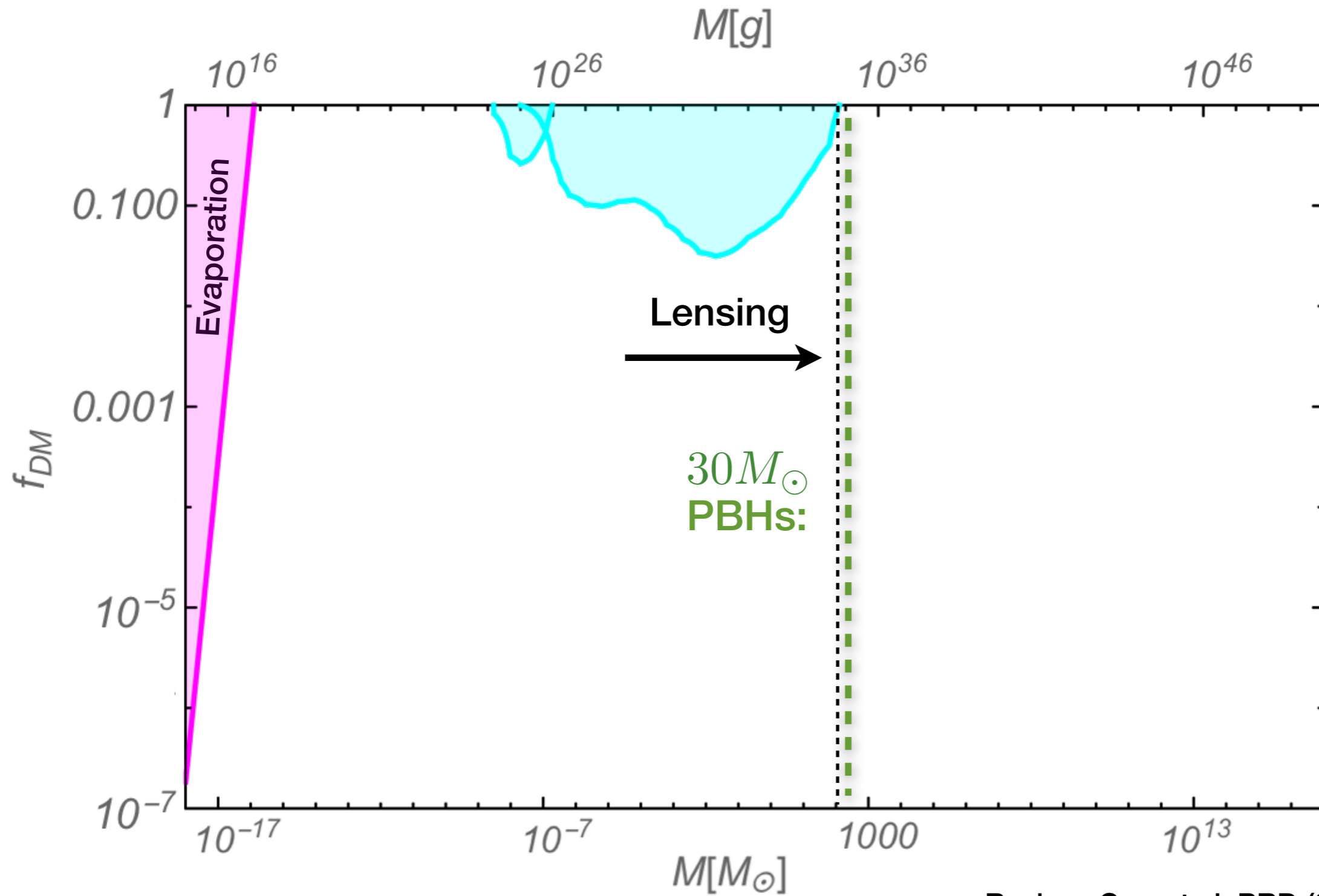


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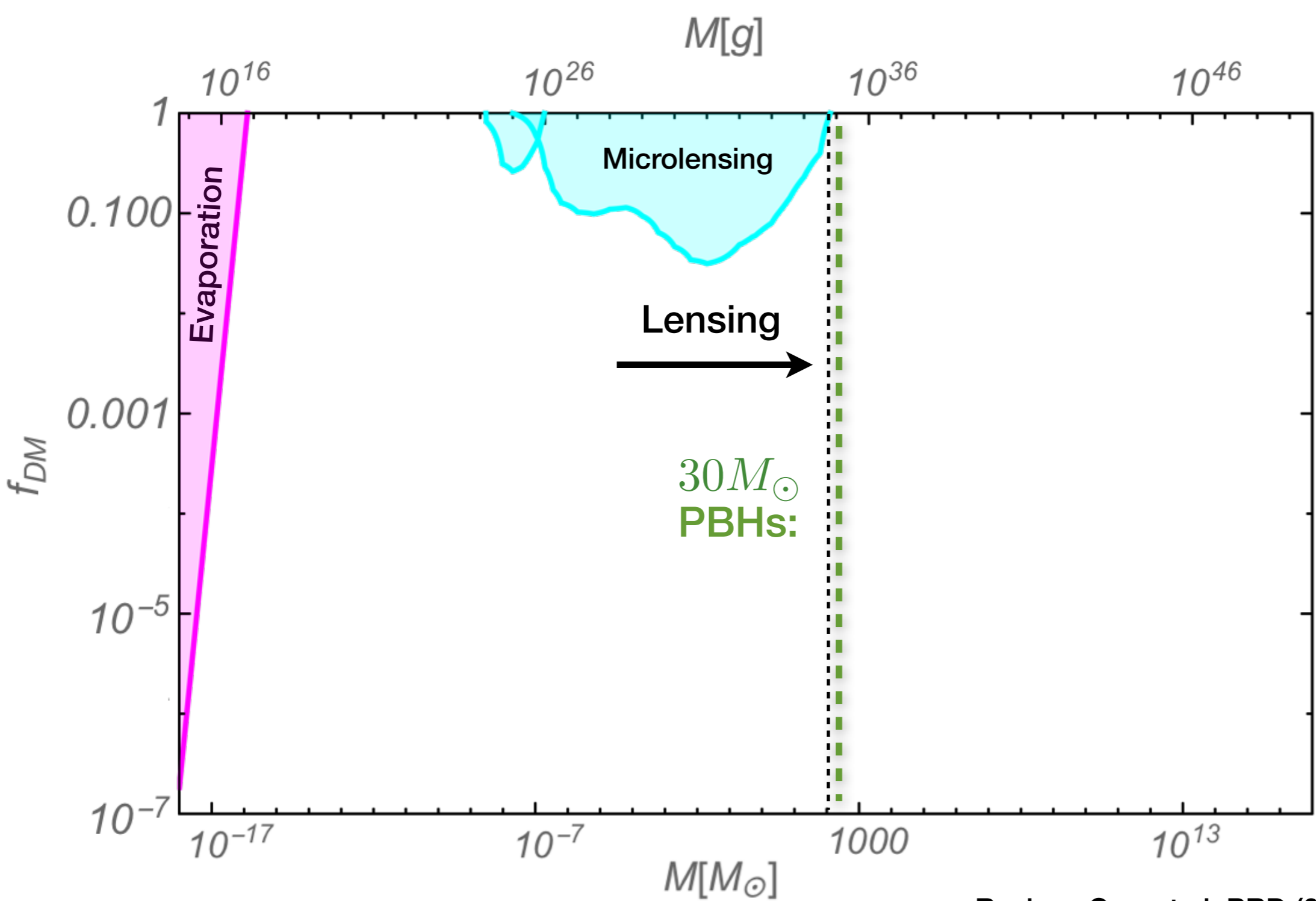


$$t \sim \frac{R_E}{v} \sim \text{yrs} \times \sqrt{\frac{M_L}{10 M_\odot}}$$

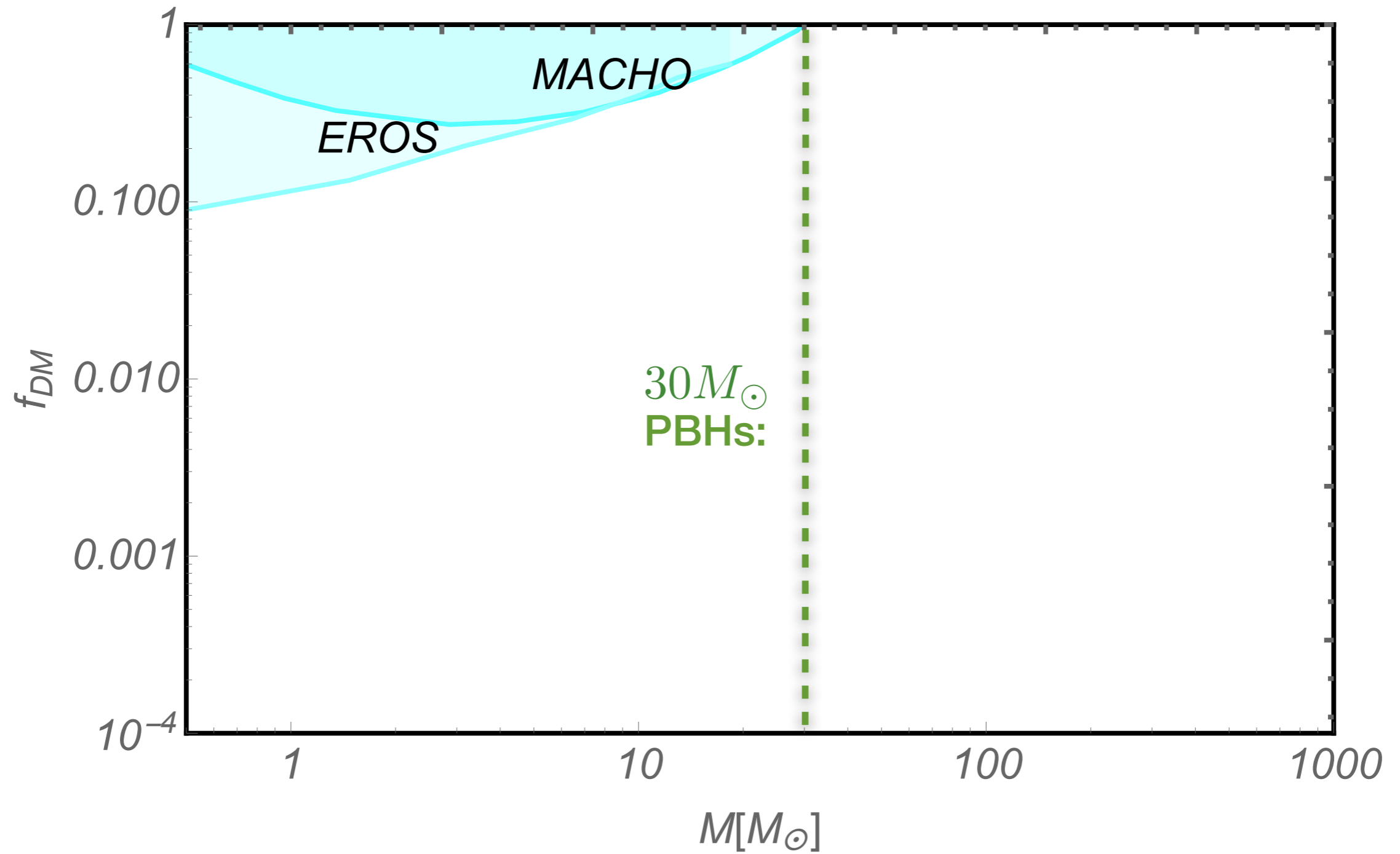
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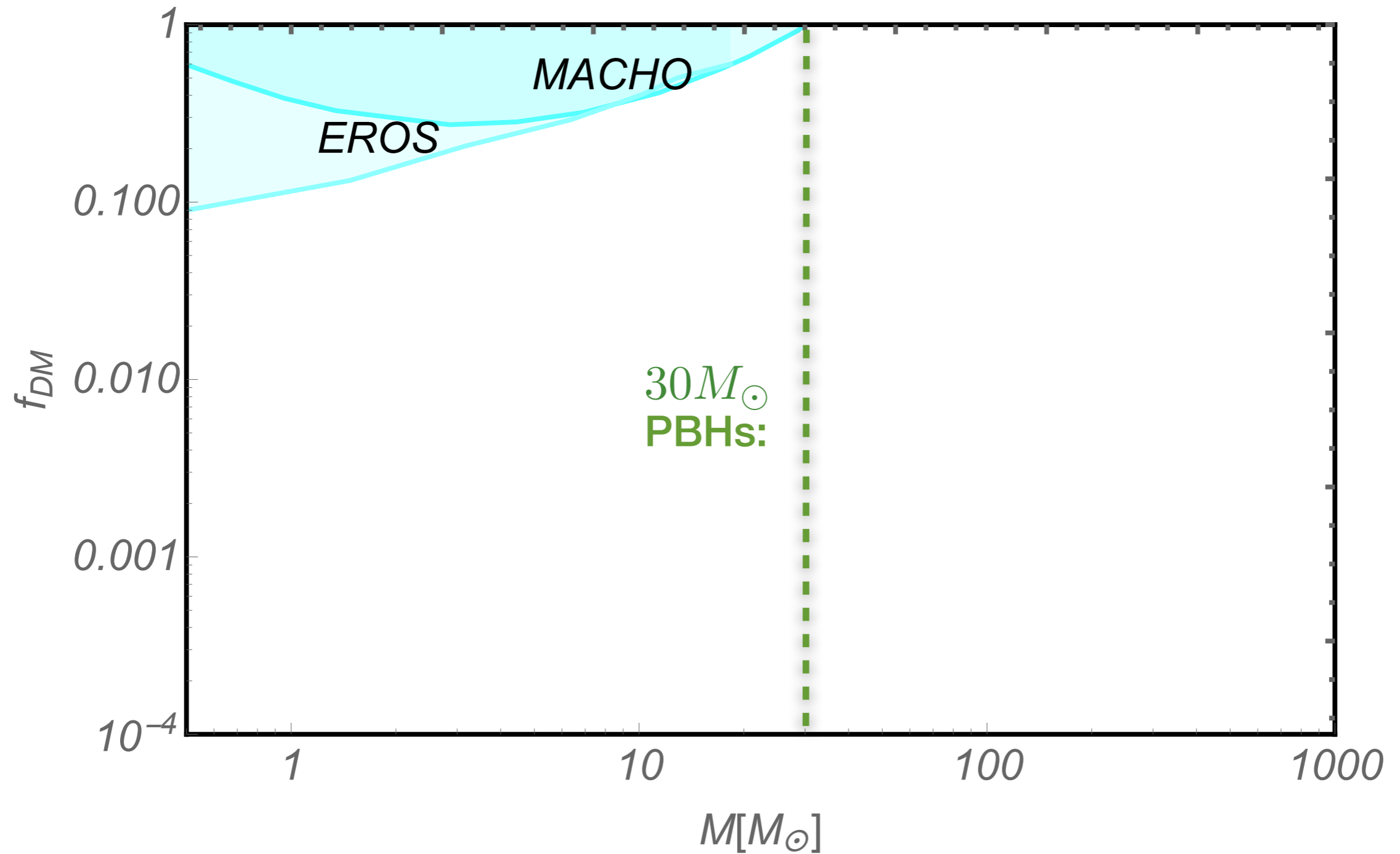


PBH Dark Matter: The “LIGO Window”



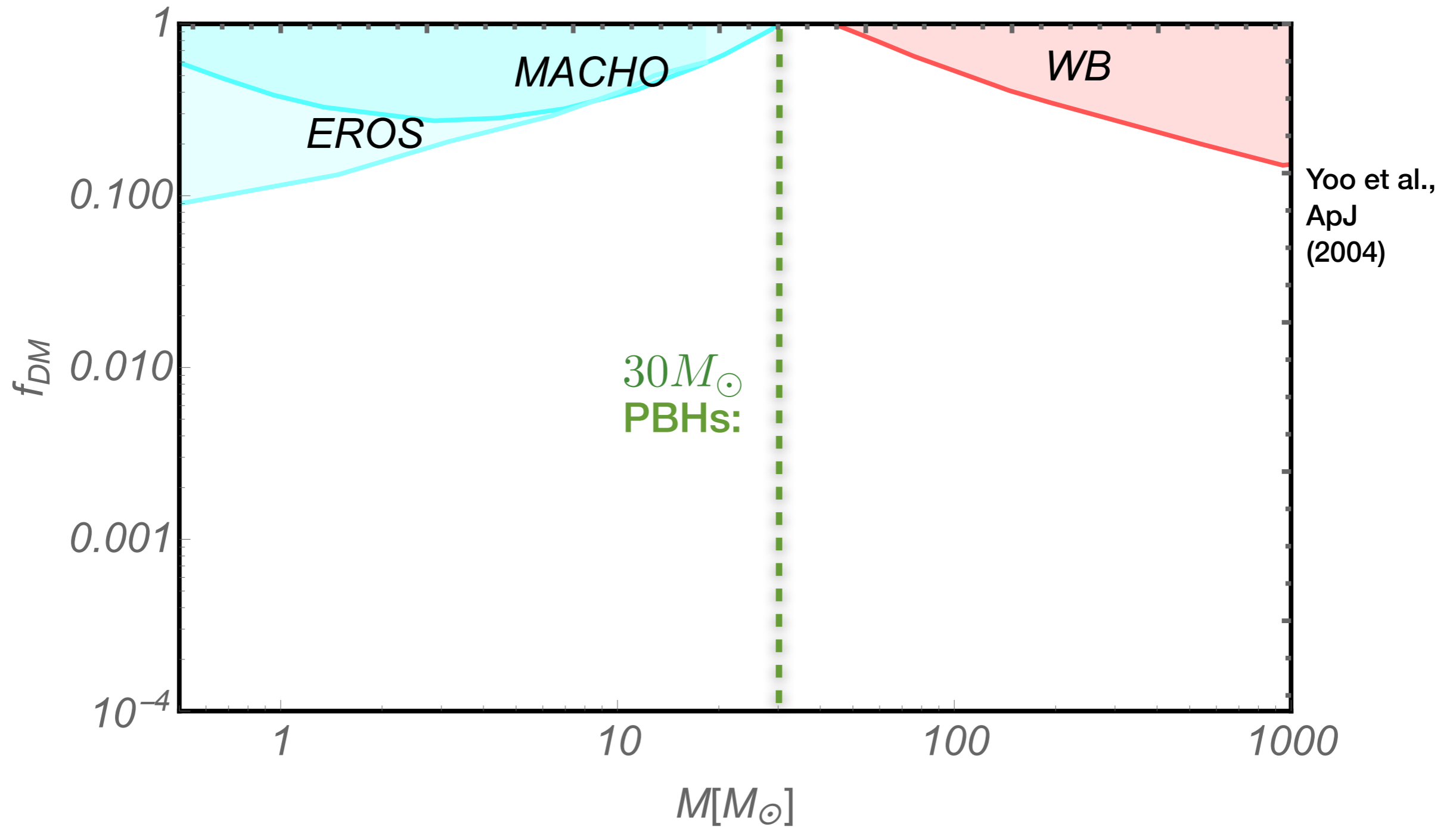
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Revisiting wide binary and CMB bounds has opened up a window for PBH DM:



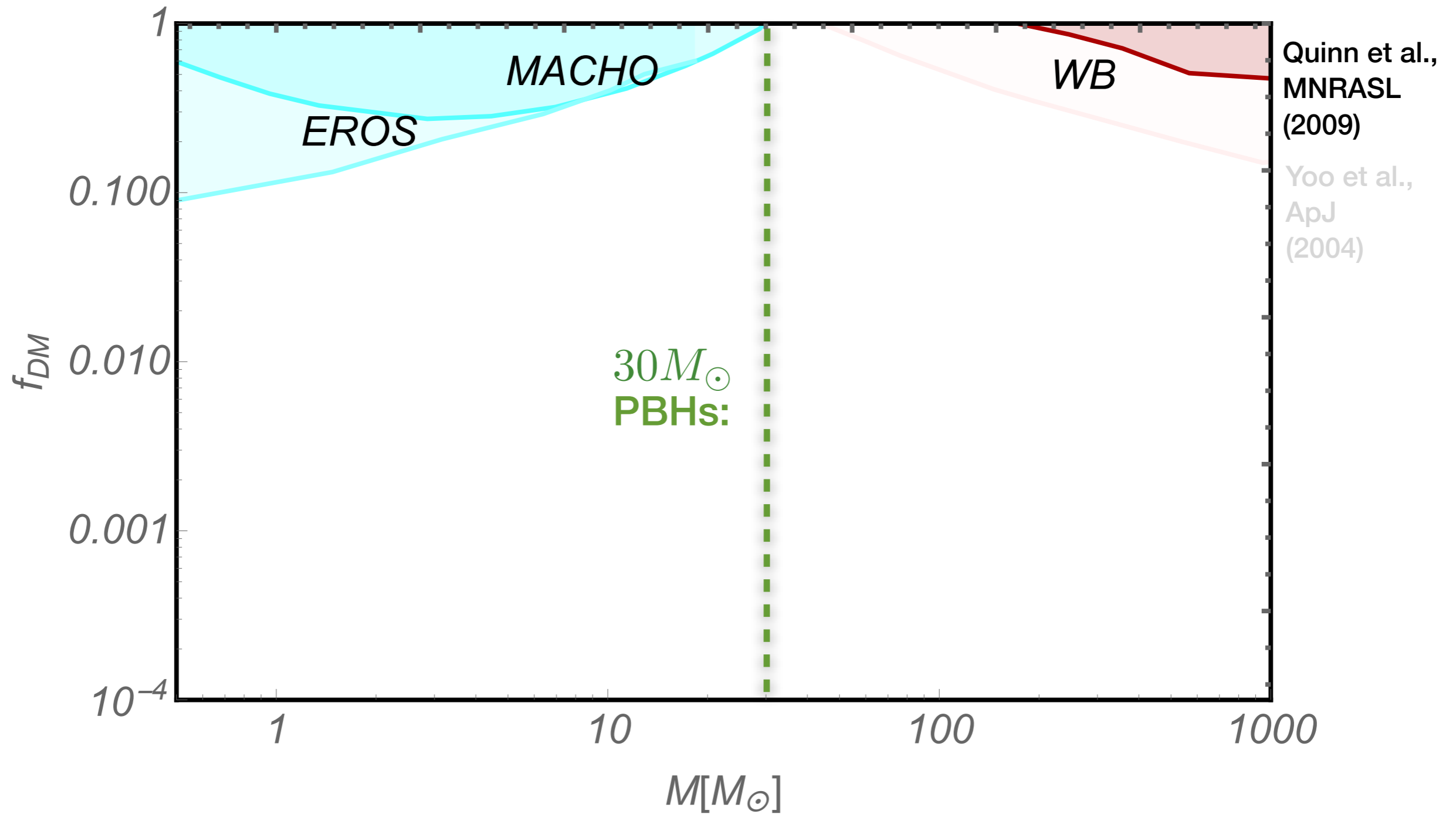
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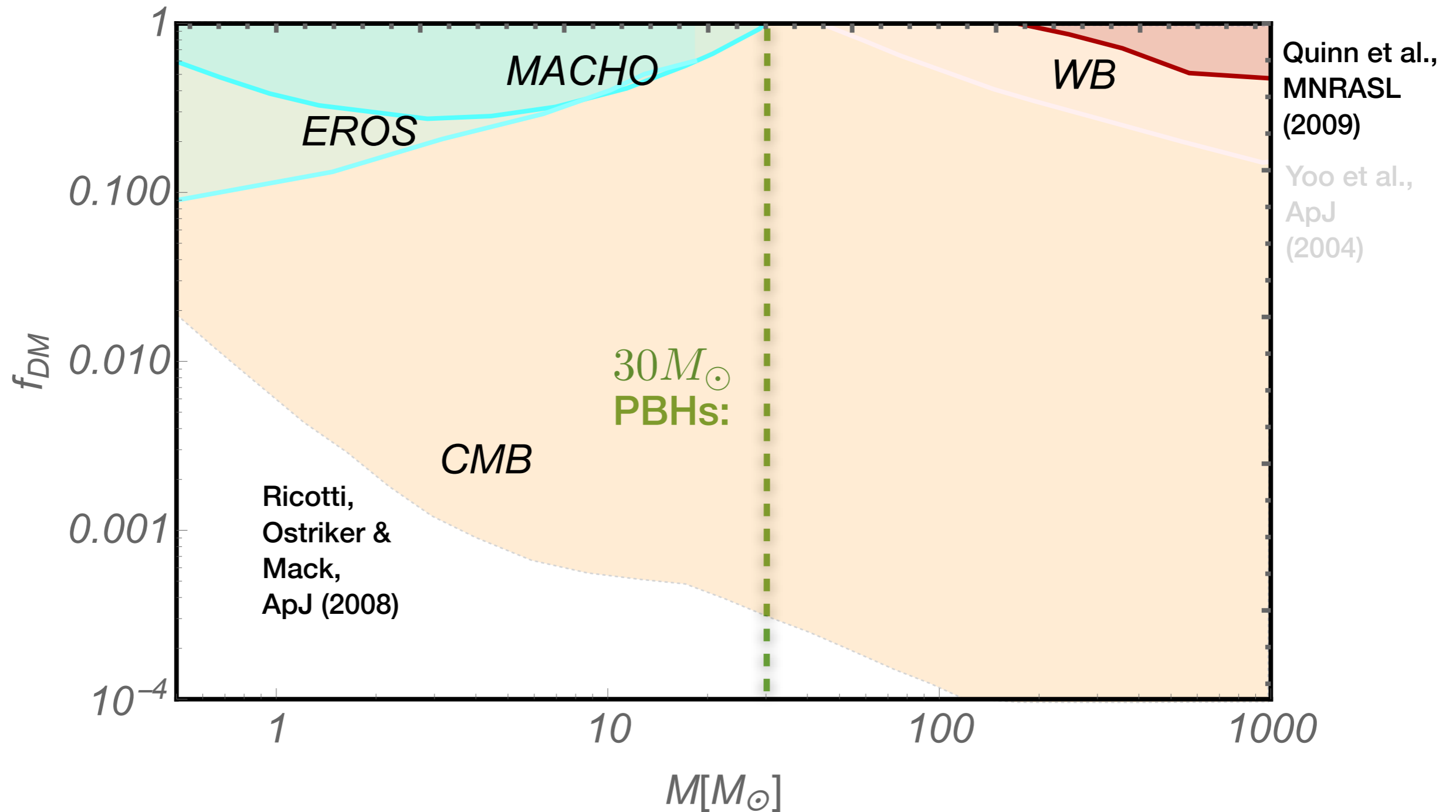
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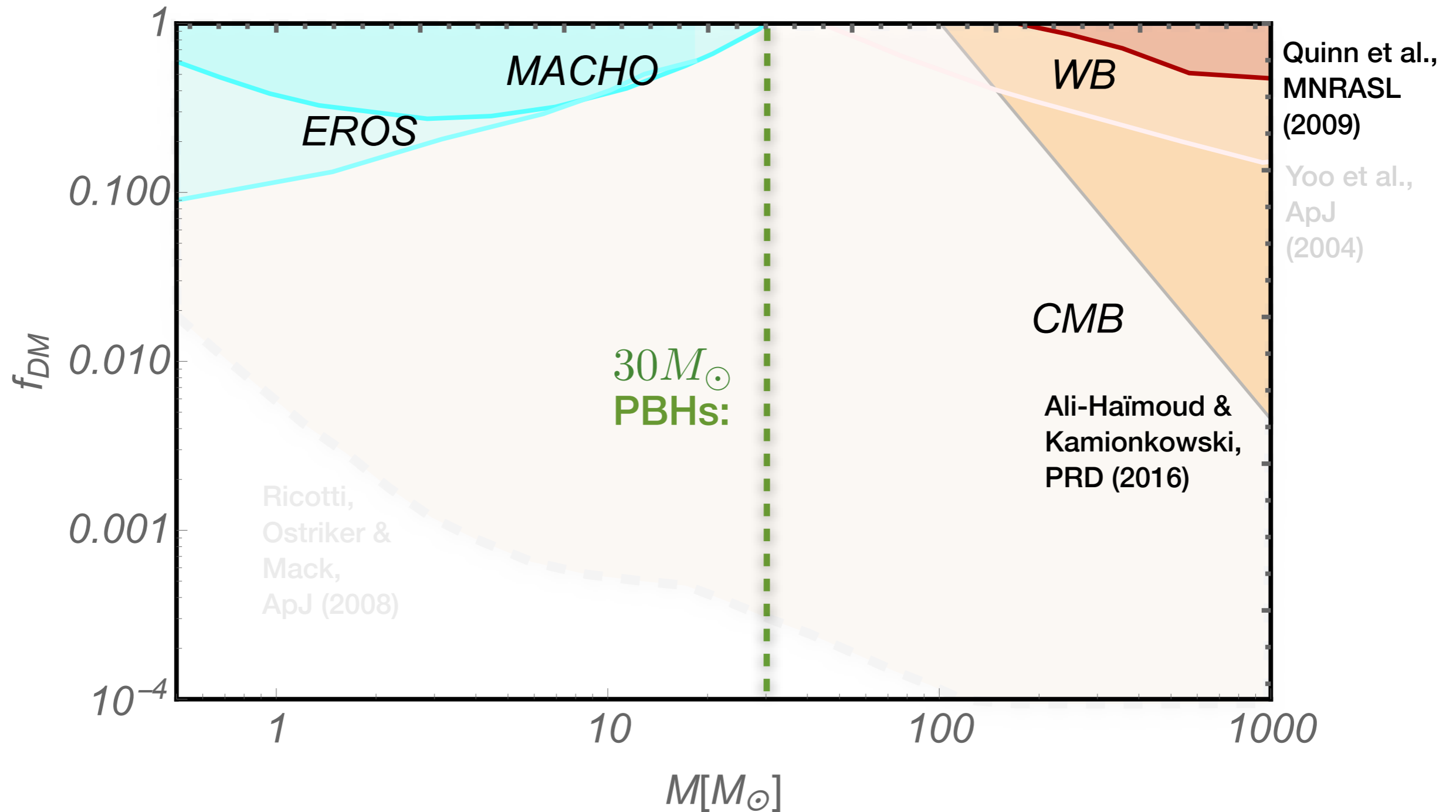
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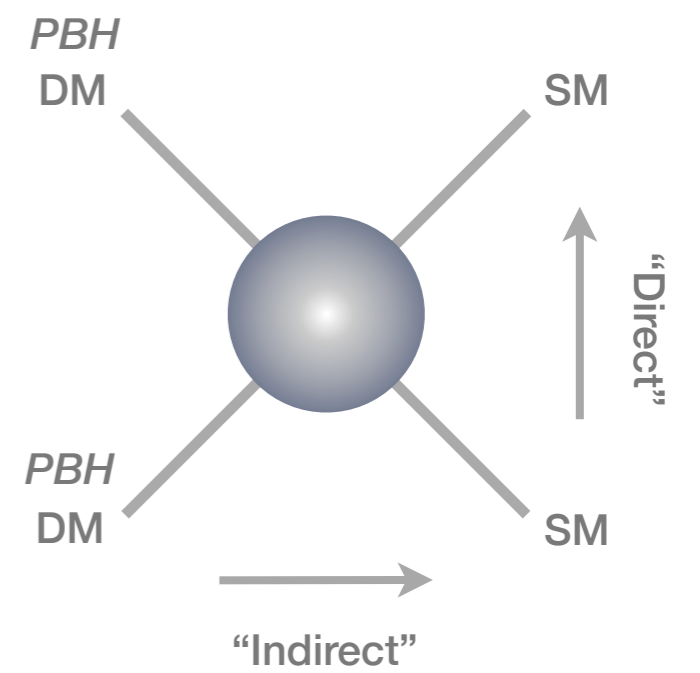


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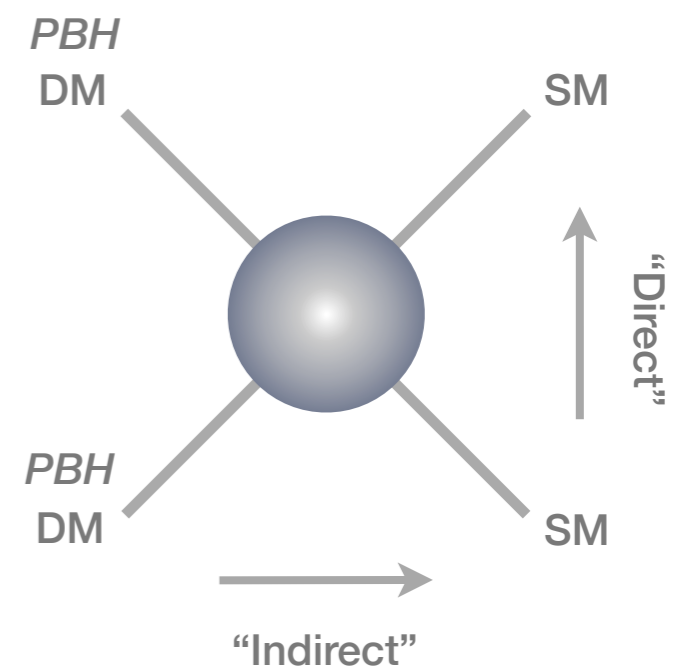


Outline



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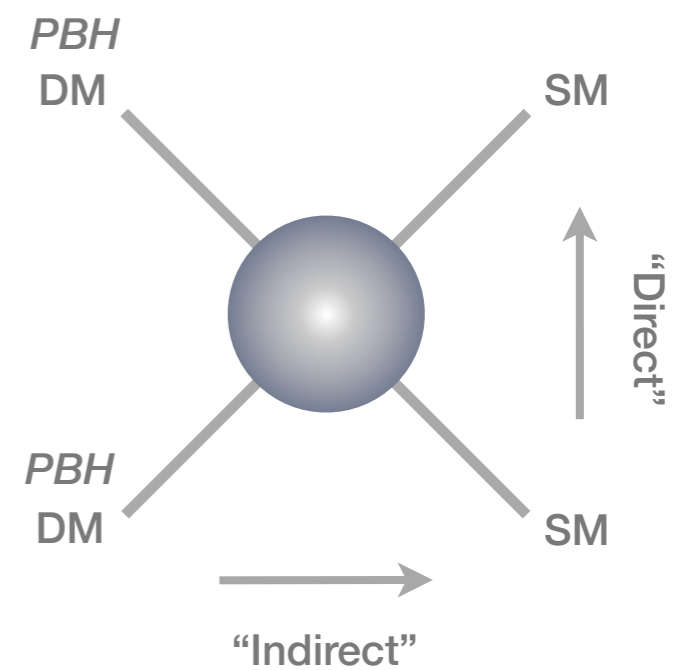
- Indirect Detection: GWs from PBH mergers



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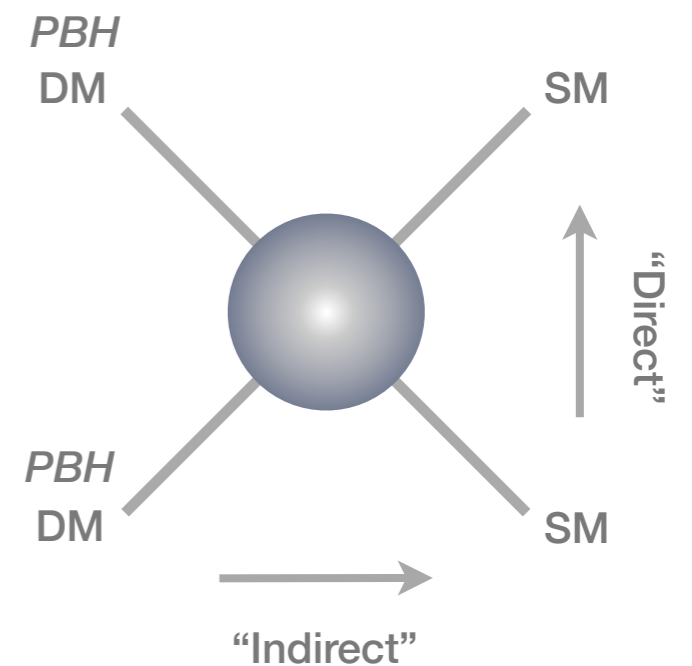
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Outline

- Indirect Detection: GWs from PBH mergers
- Direct Detection: PBH DM Constraints
- Summary and observational outlook



Outline

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Merger Rates:

Outline

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Merger Rates: “Did LIGO Detect Dark Matter?”

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“The Merger Rate of Primordial-Black-Hole Binaries ”

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*GW Mass
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GW Features:

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GW Features: “Orbital Eccentricities in Primordial Black Hole Binaries”
Cholis, EDK, Ali-Haïmoud, Bird, Kamionkowski, Muñoz & Raccanelli, Phys. Rev. D 94, 084013 (2016)

(“Determining the Progenitors of Merging Black Hole Binaries”)
(Raccanelli, EDK, Bird, Cholis & Muñoz, Phys. Rev. D 94 (2016))

PBH Binaries: Formation and Coalescence

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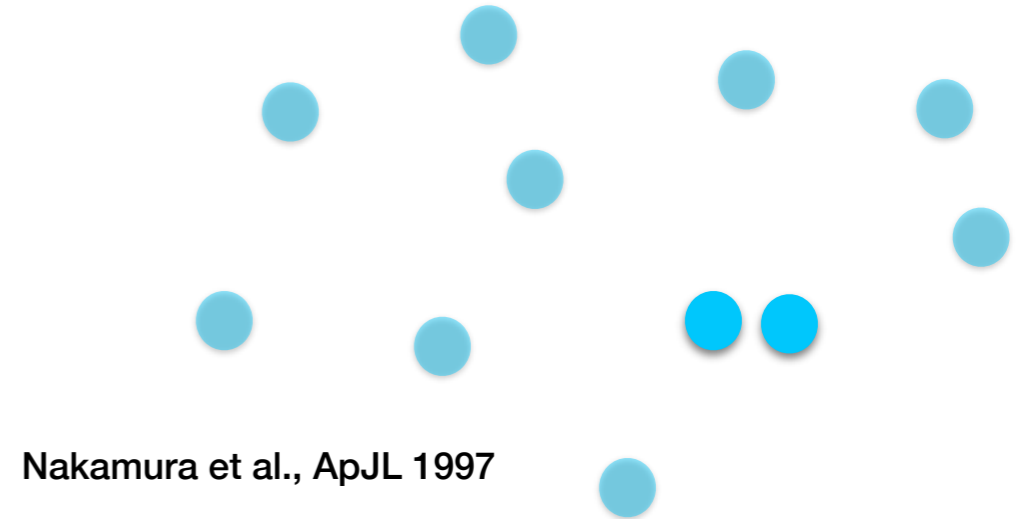
1) They can become bound early on:

PBH Binaries: Formation and Coalescence

(Bird et al., PRL 116 (2016))

How do the binaries form?

1) They can become bound early on:



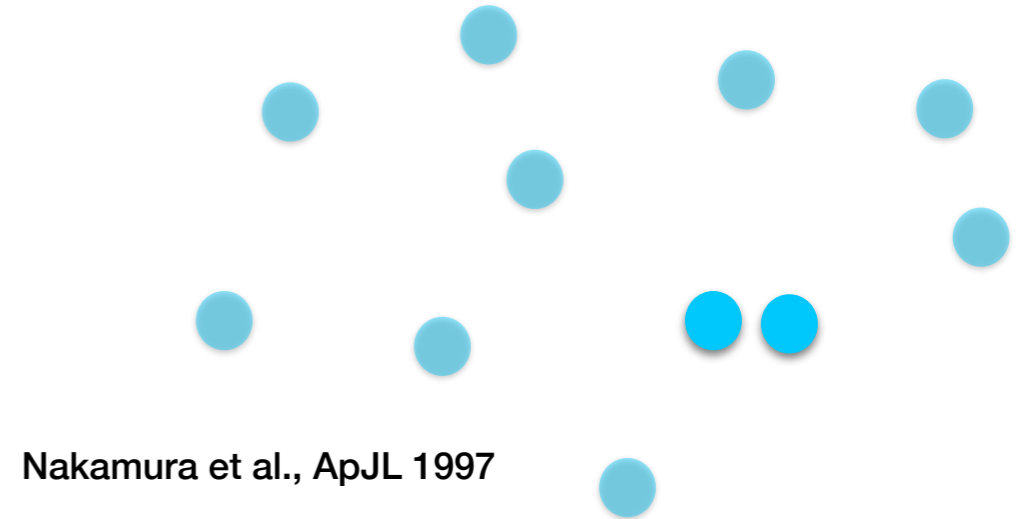
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How do the binaries form?

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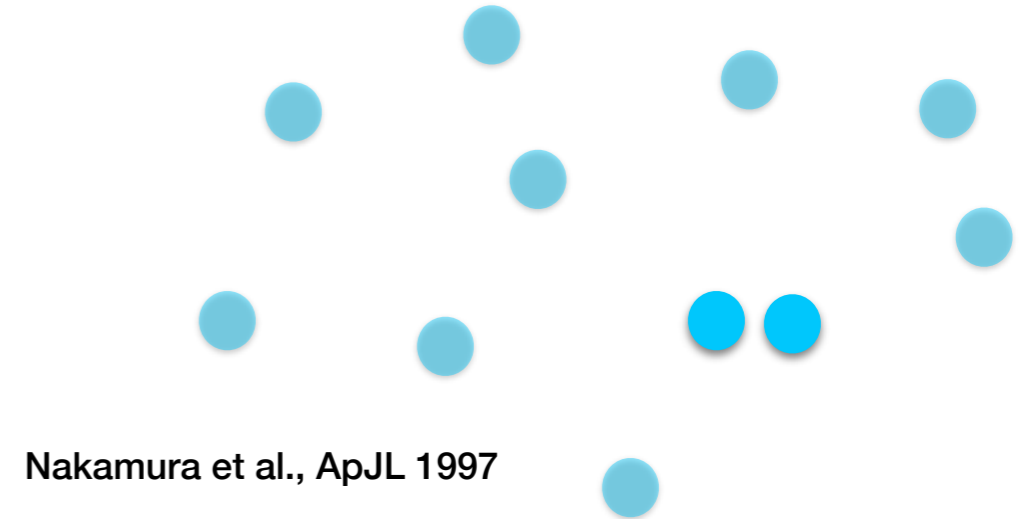
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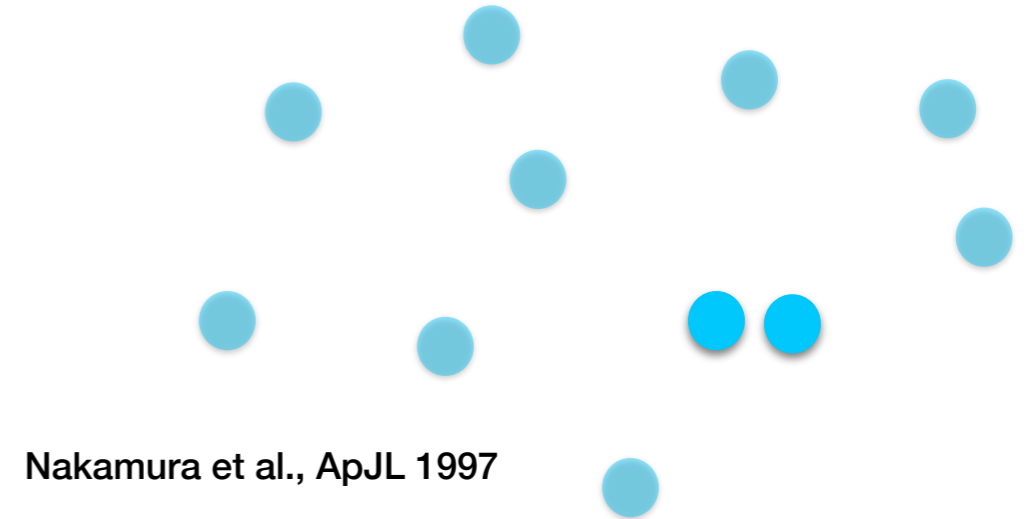
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Ali-Haïmoud, EDK and Kamionkowski, arXiv:1709.06576



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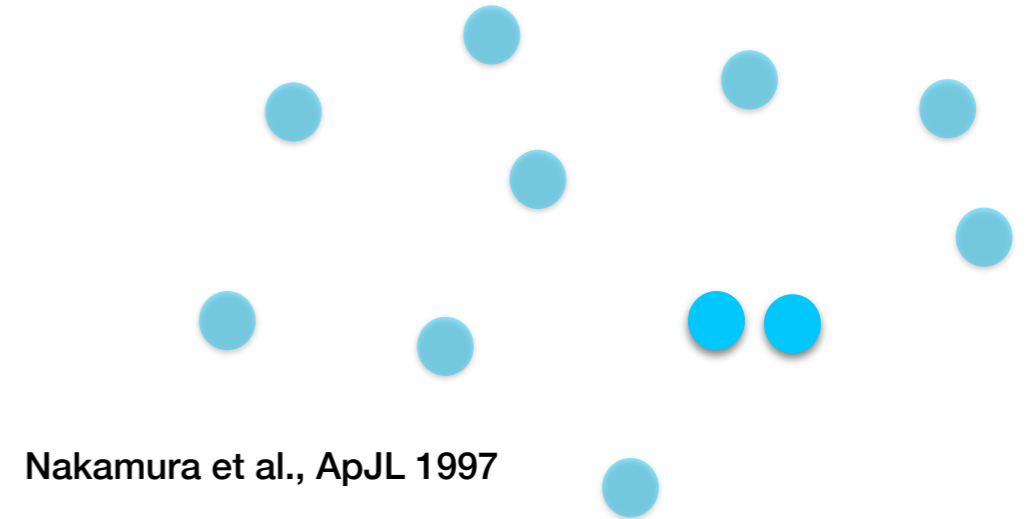
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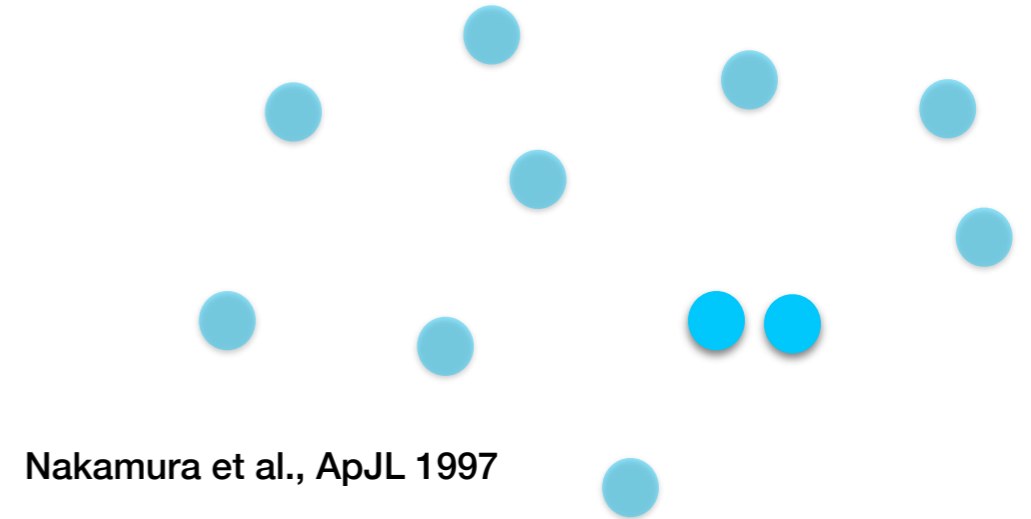
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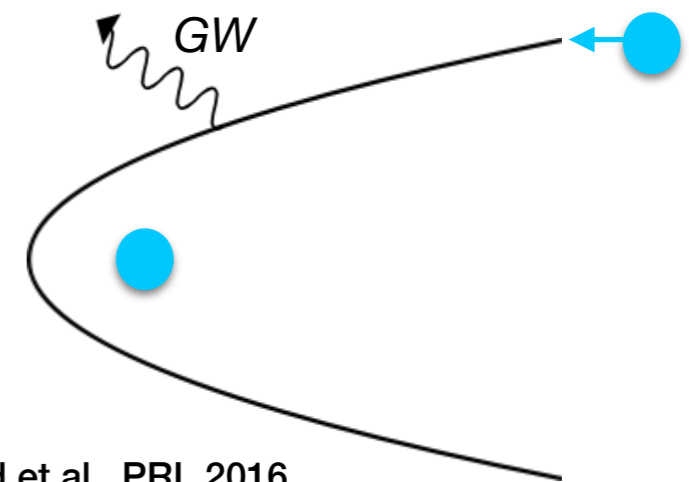
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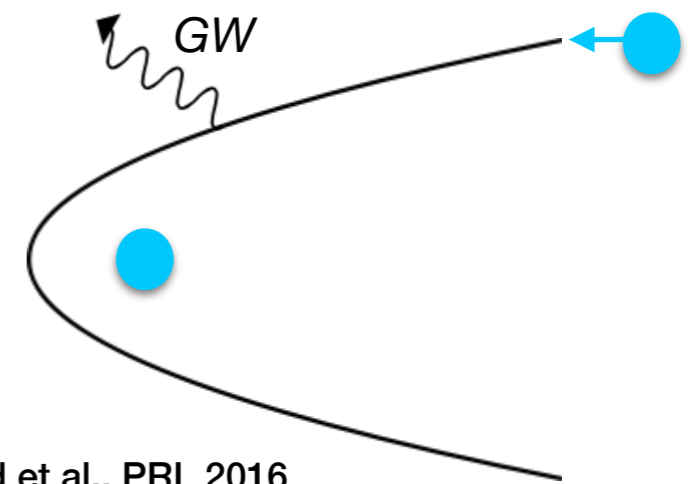
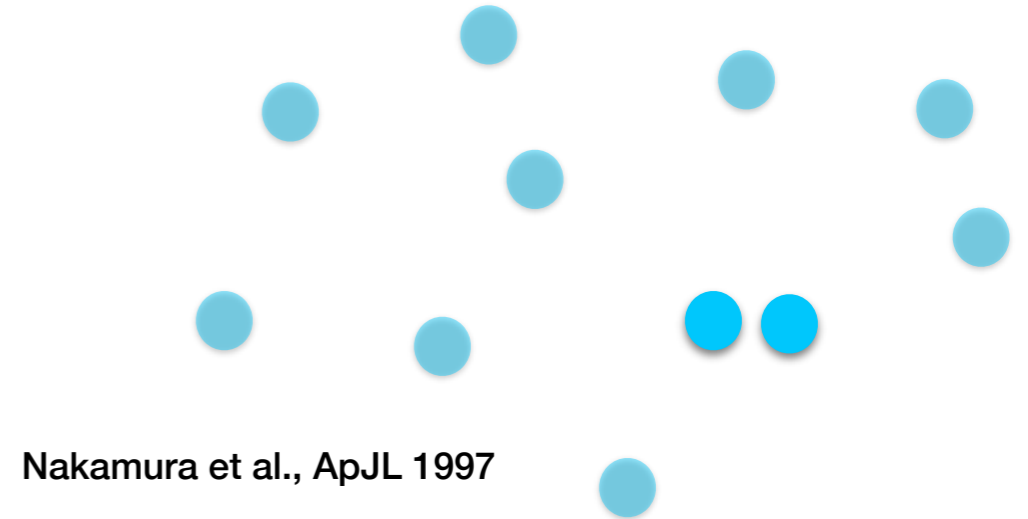
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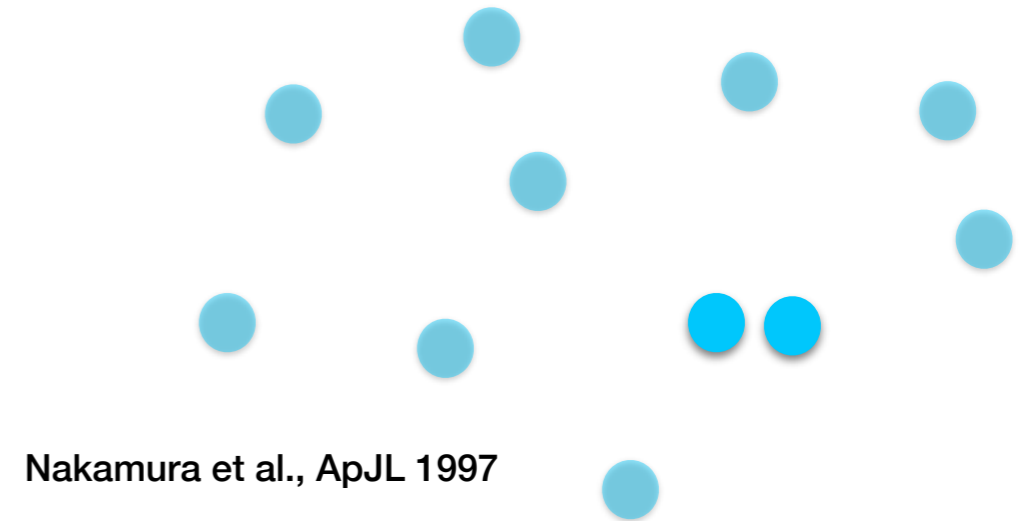
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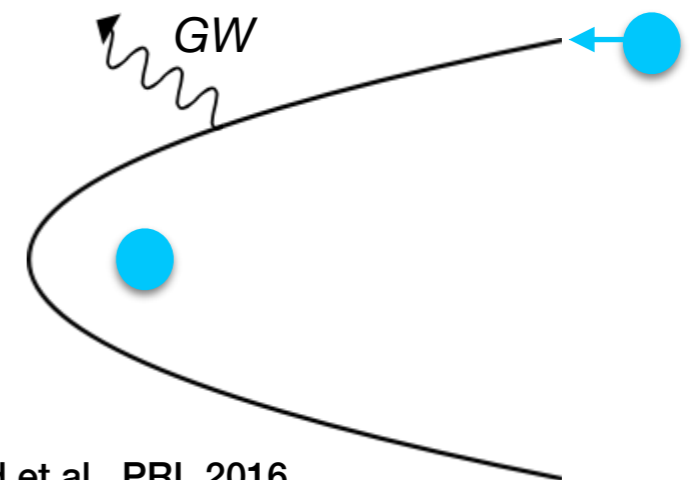
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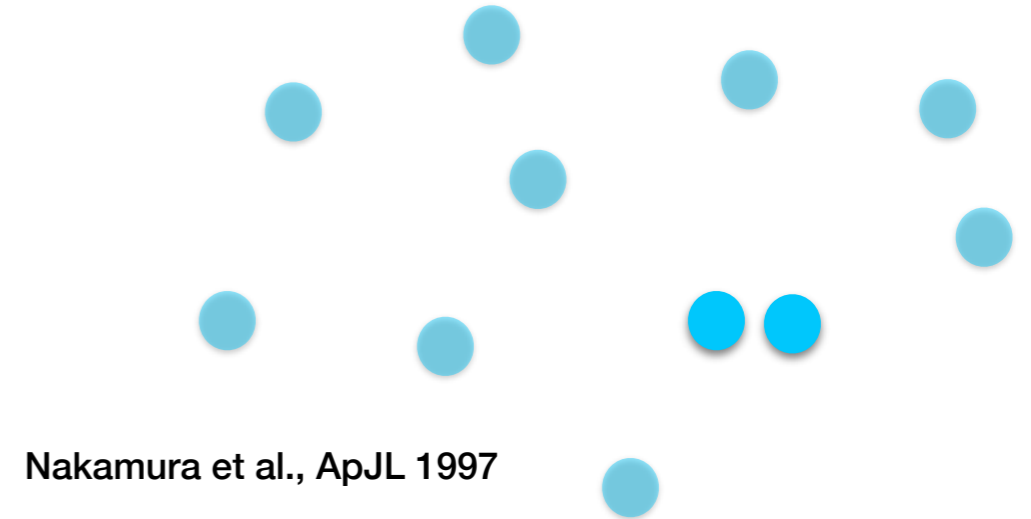
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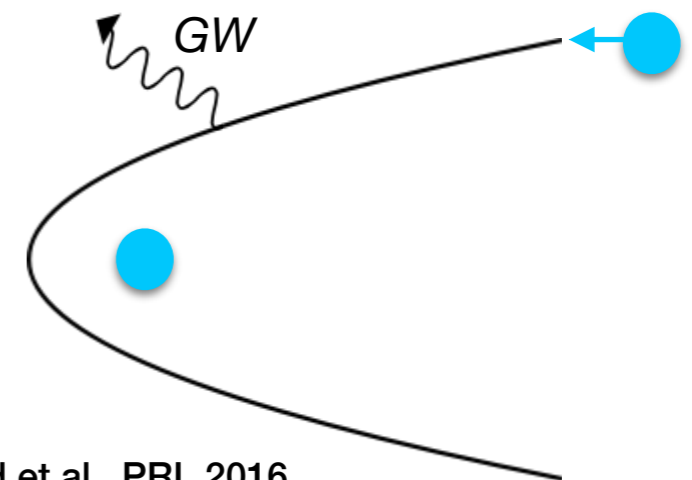
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Nakamura et al., ApJL 1997

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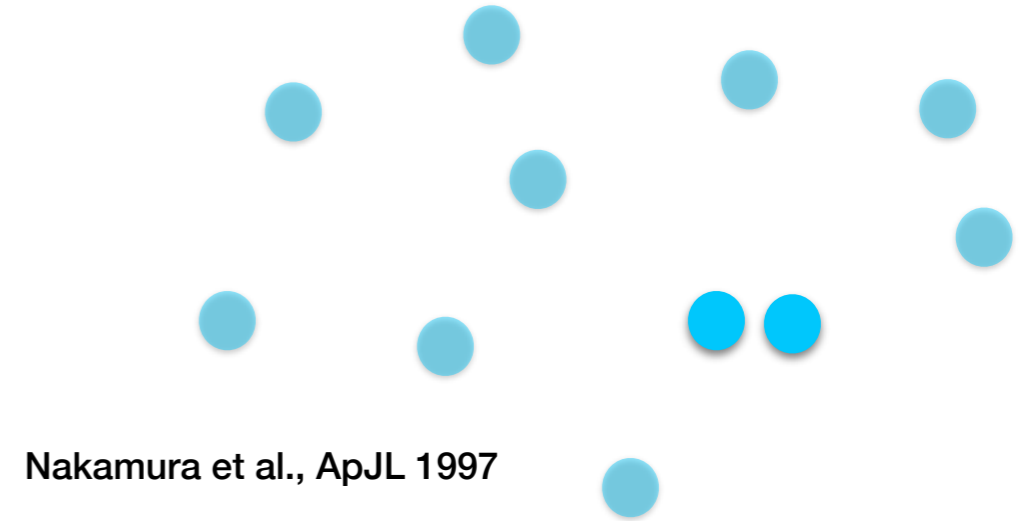
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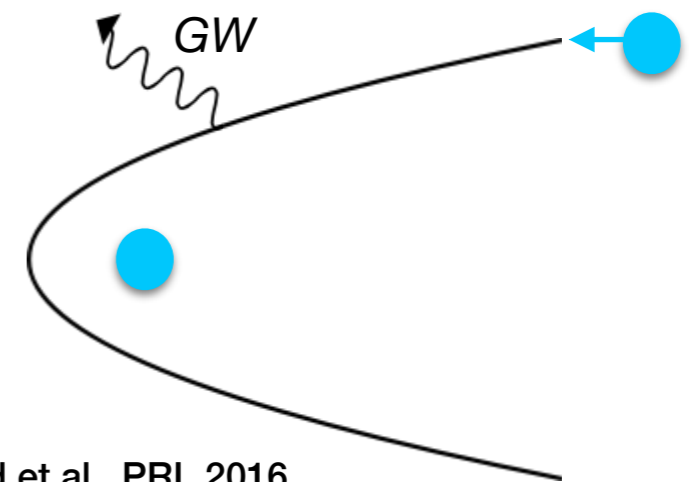
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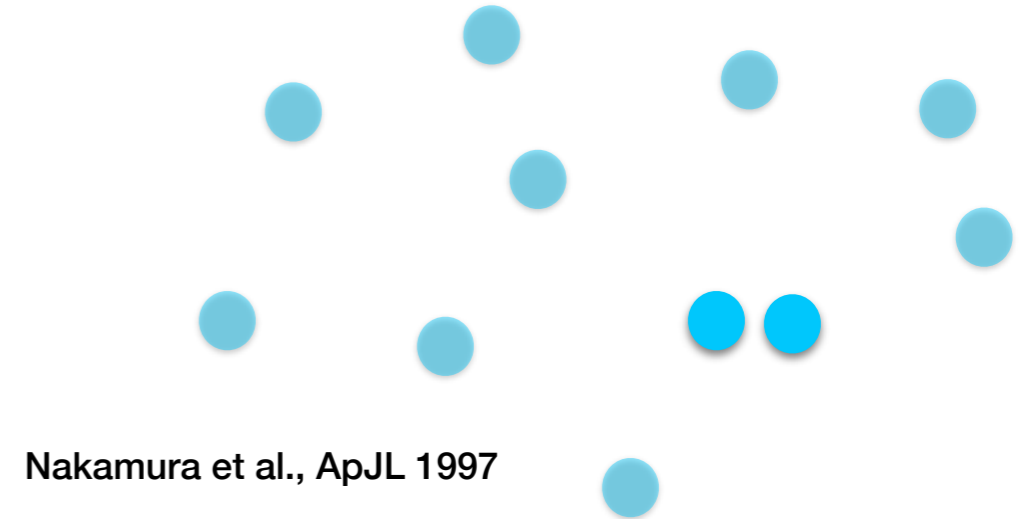
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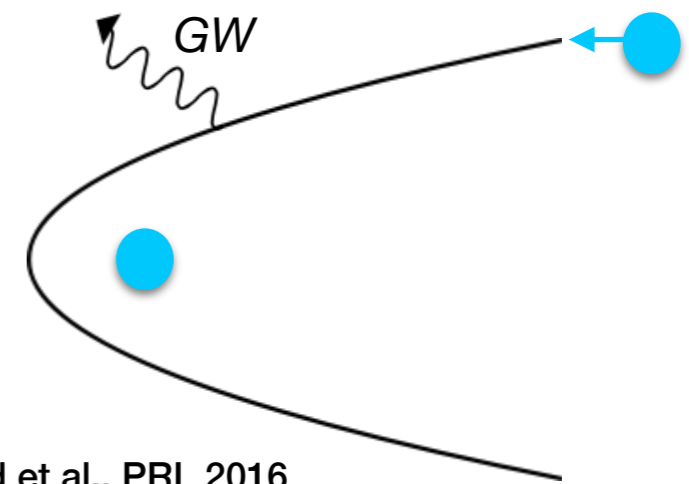
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Nishikawa, EDK, Kamionkowski and Silk, arXiv:1708.08449



GWs from PBH Mergers: Results

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Next!



Orbital Eccentricity

Signatures of GWs from PBH Mergers: Eccentricity

(Cholis, EDK et al., PRD 94 (2016))

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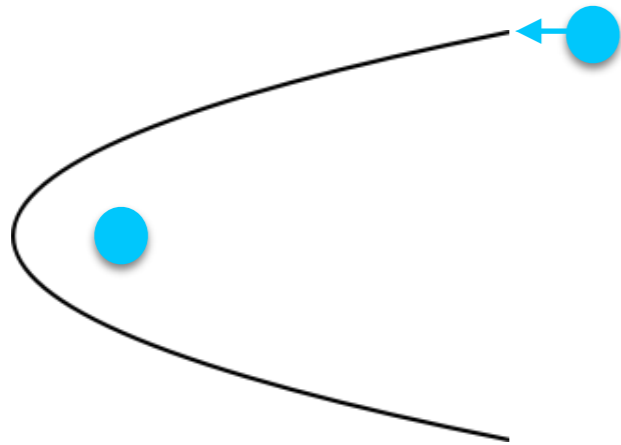
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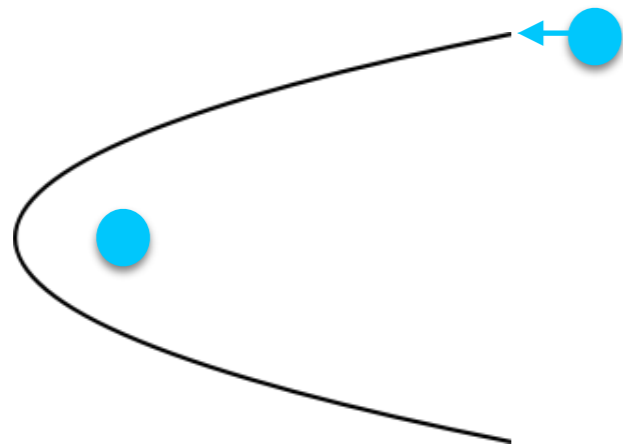
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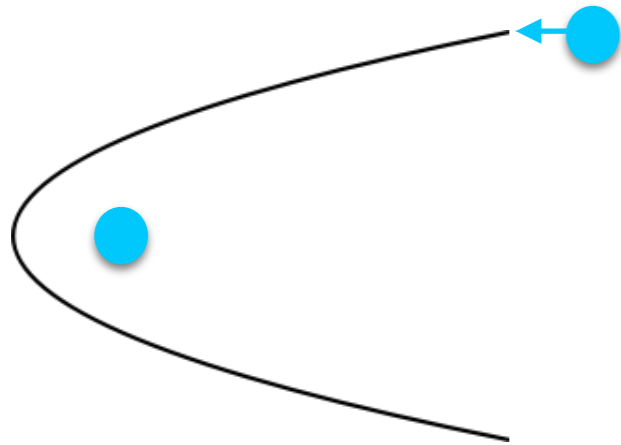


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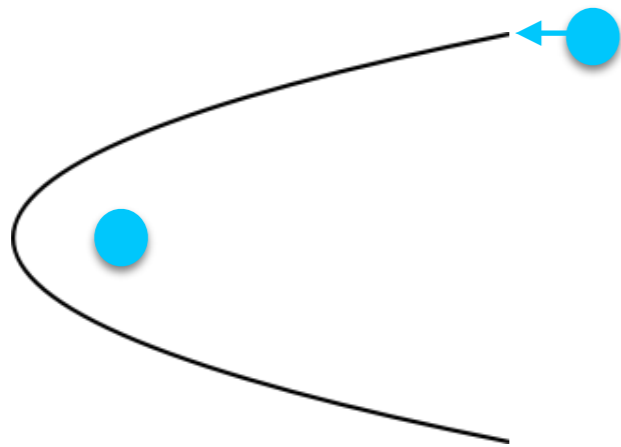
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*semi-major axis;
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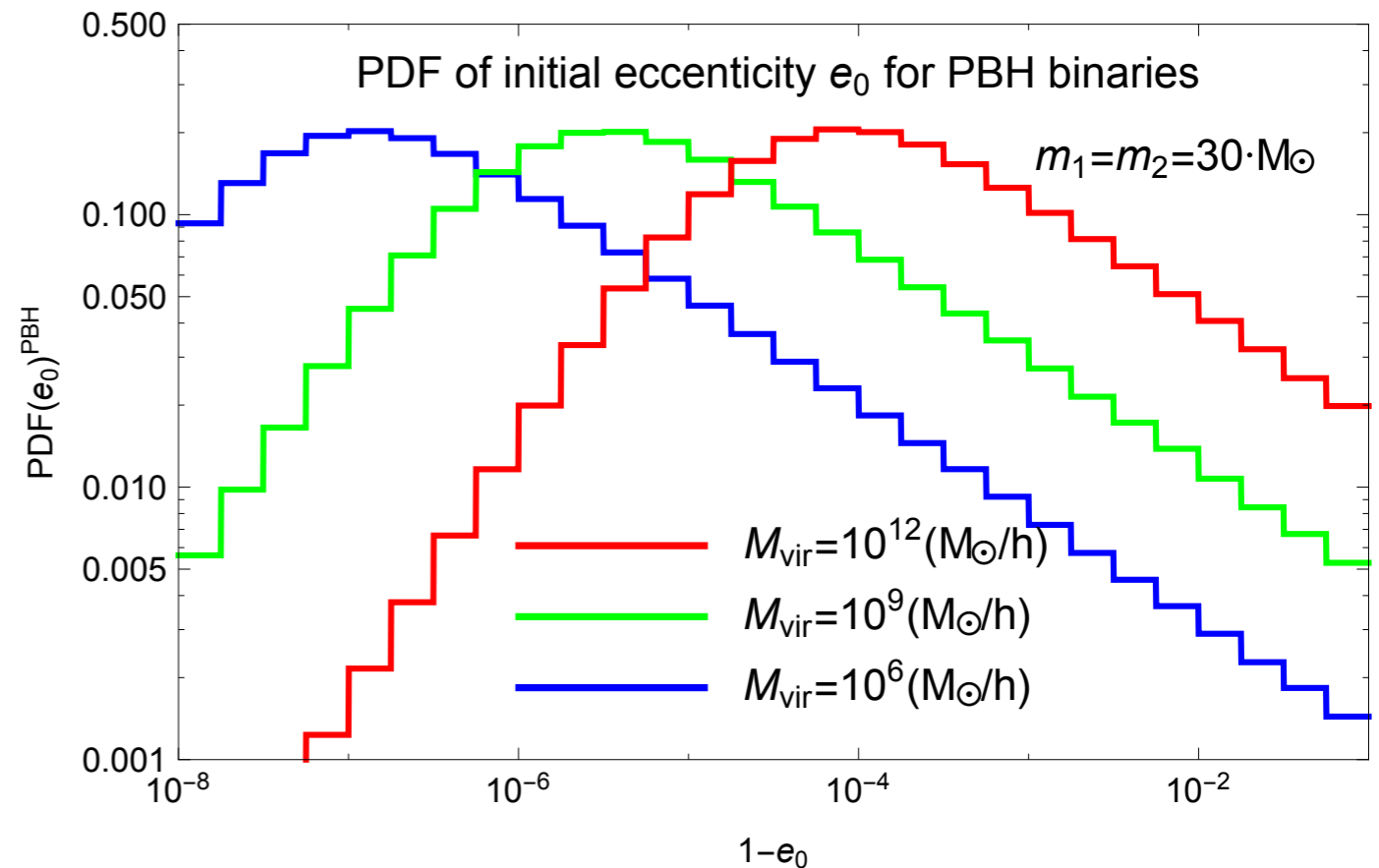
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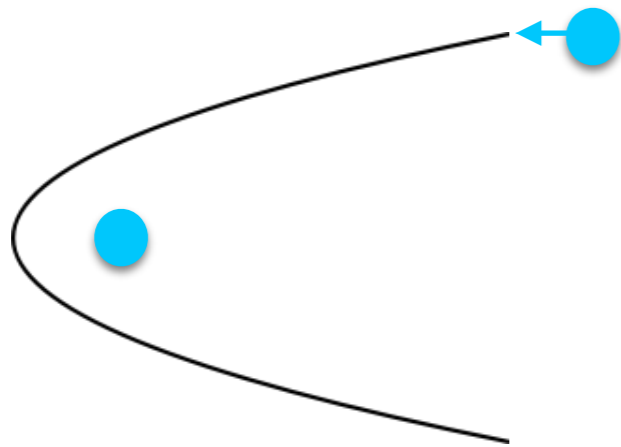
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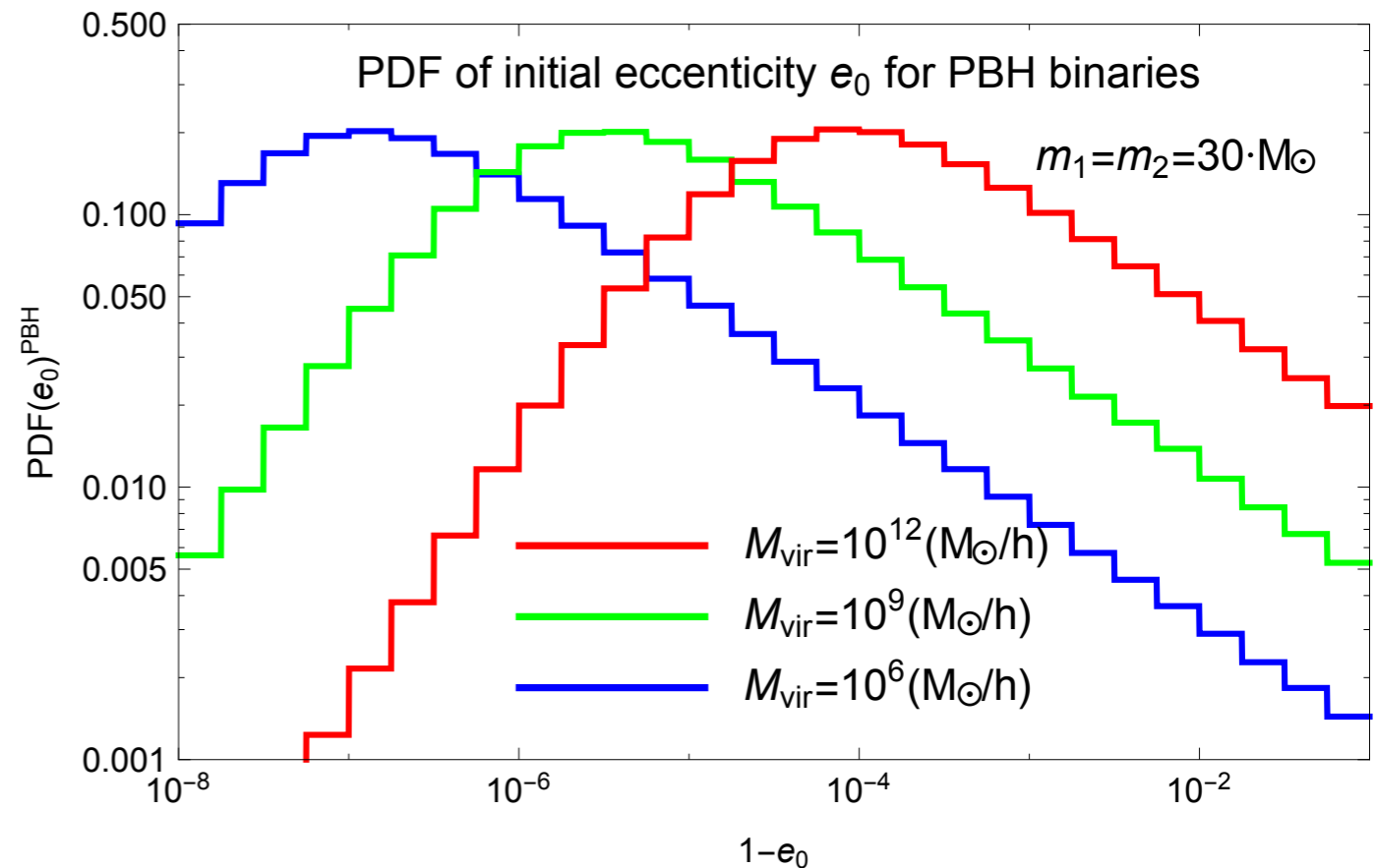
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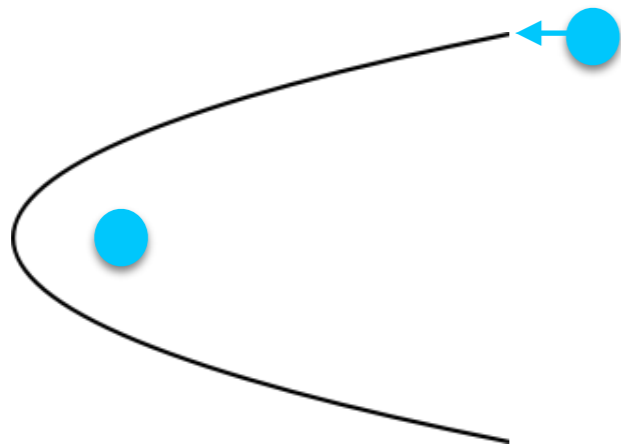
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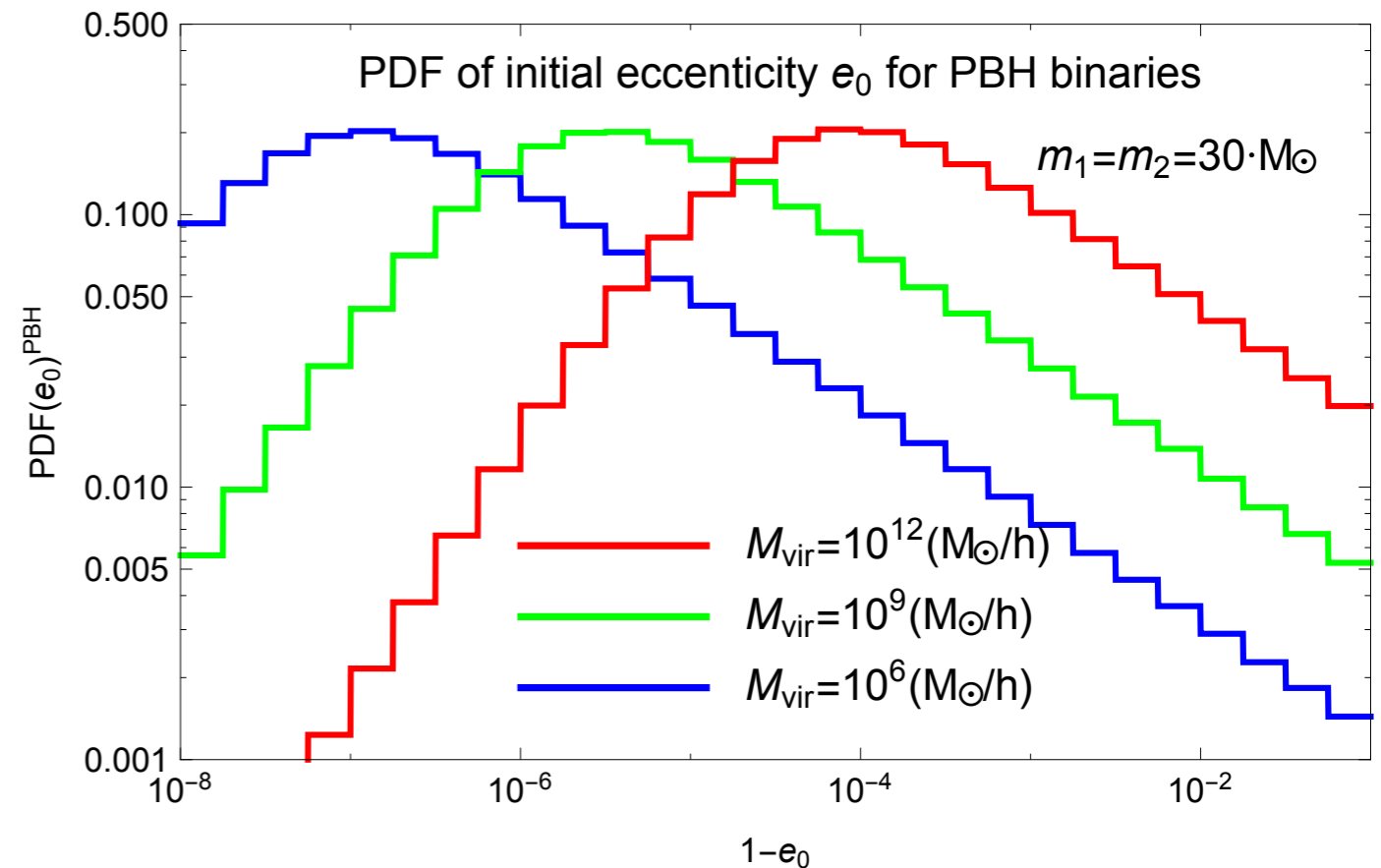


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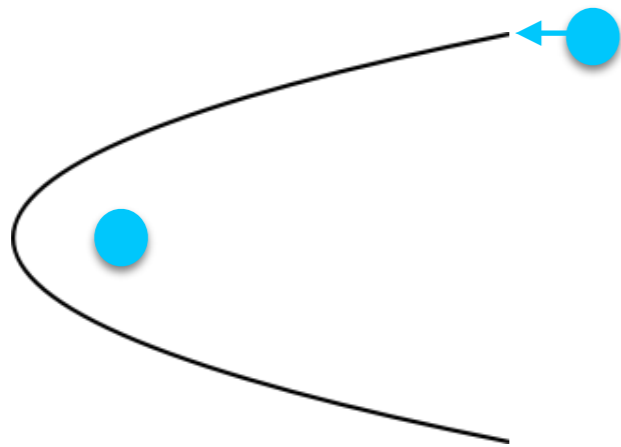
Merger time?



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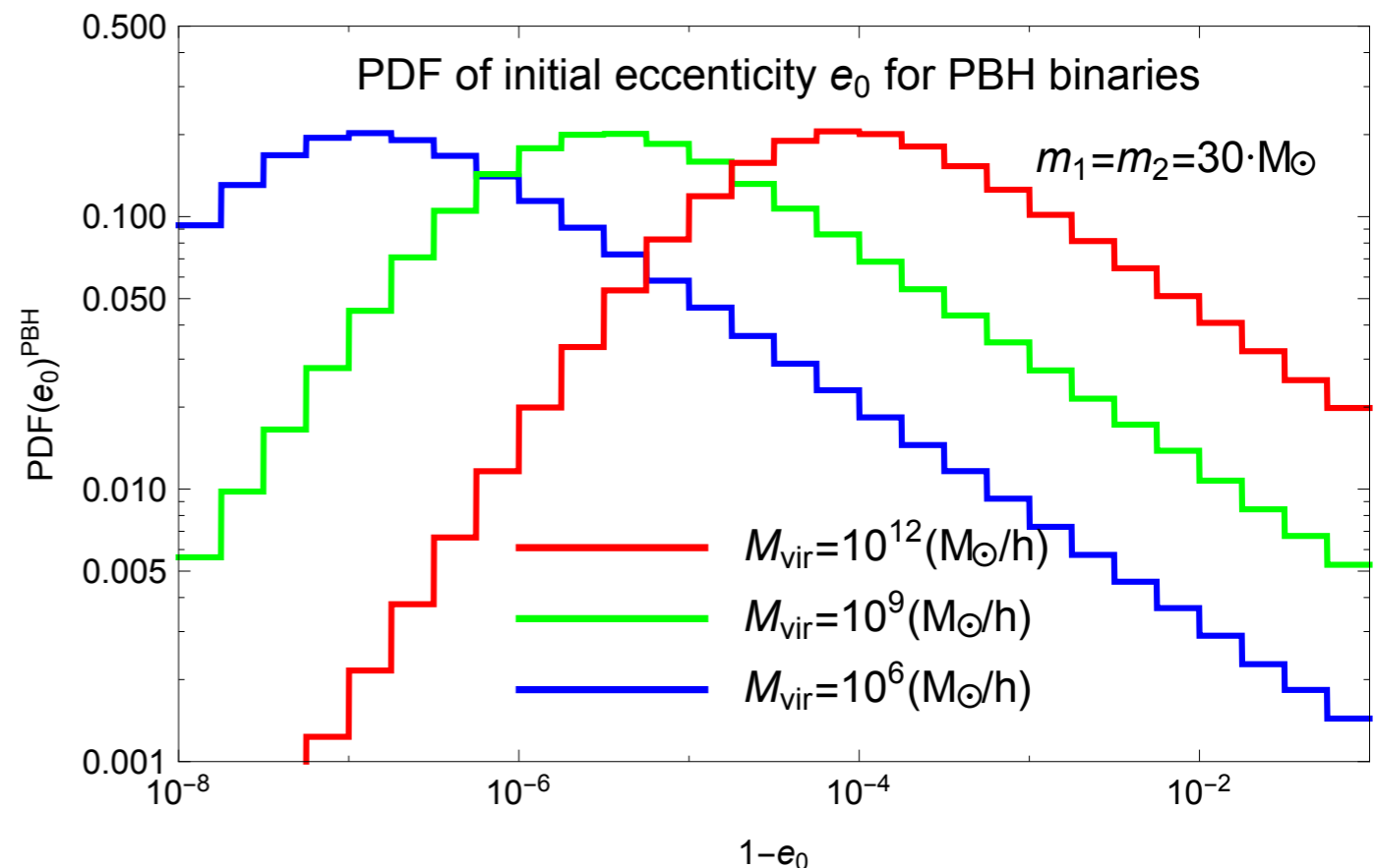


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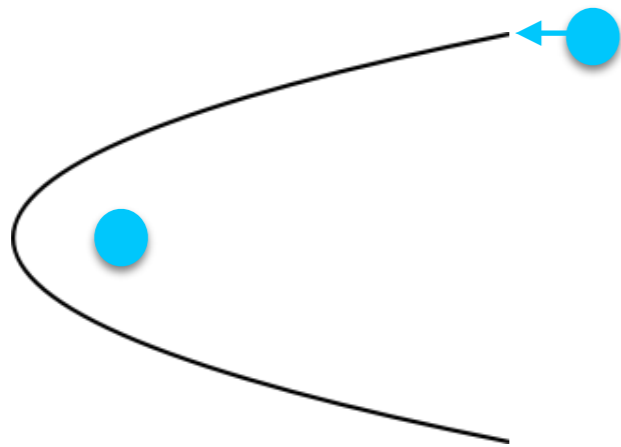
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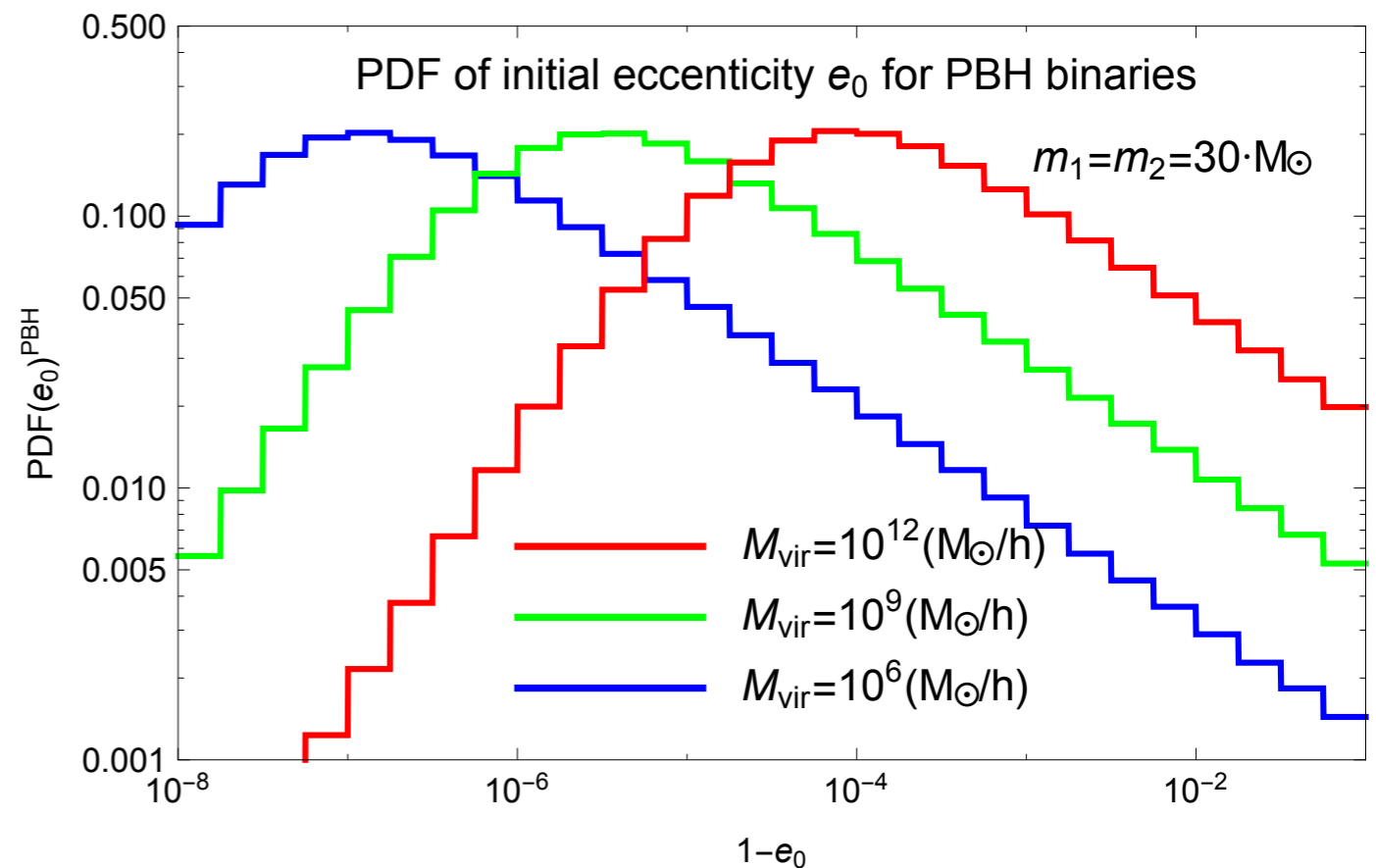
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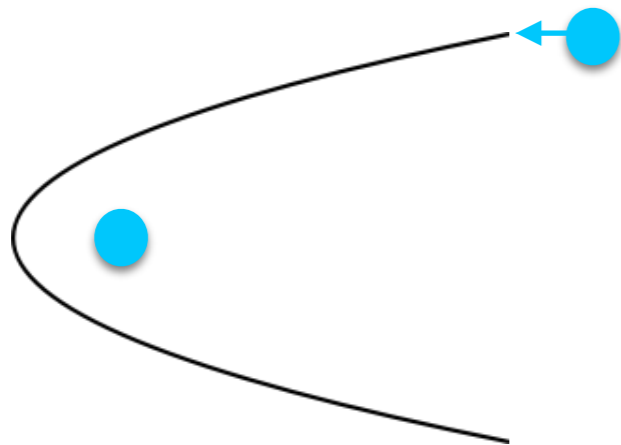
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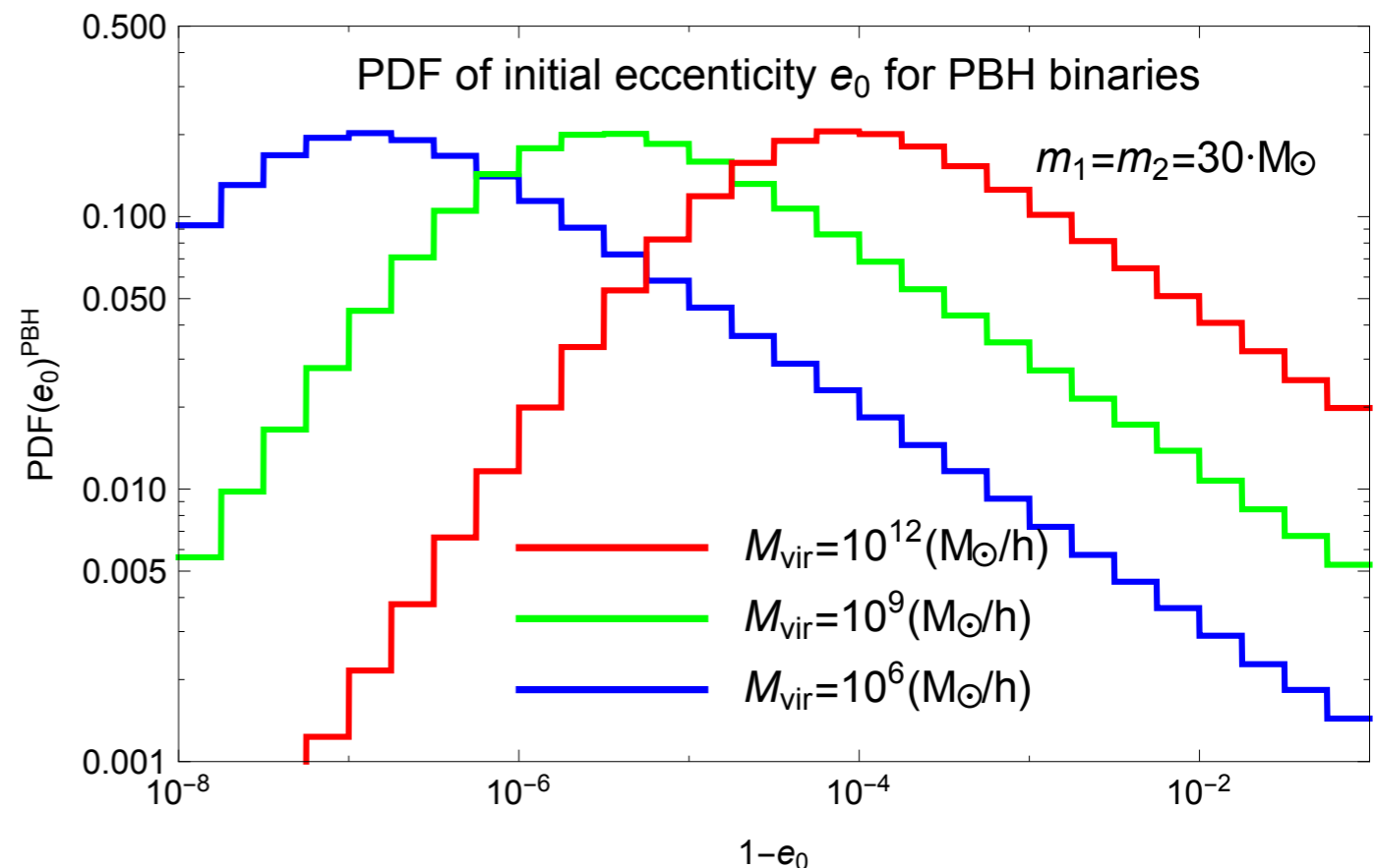
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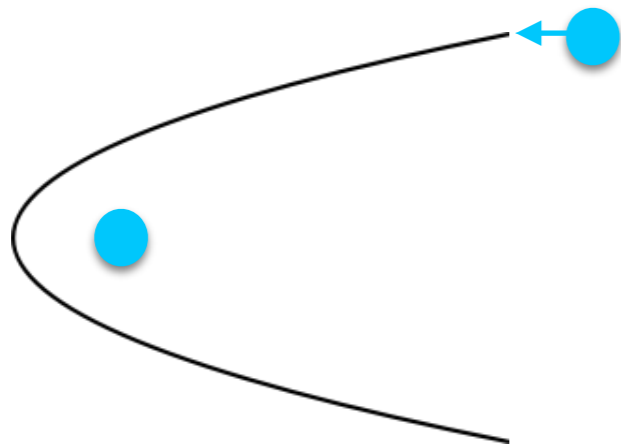
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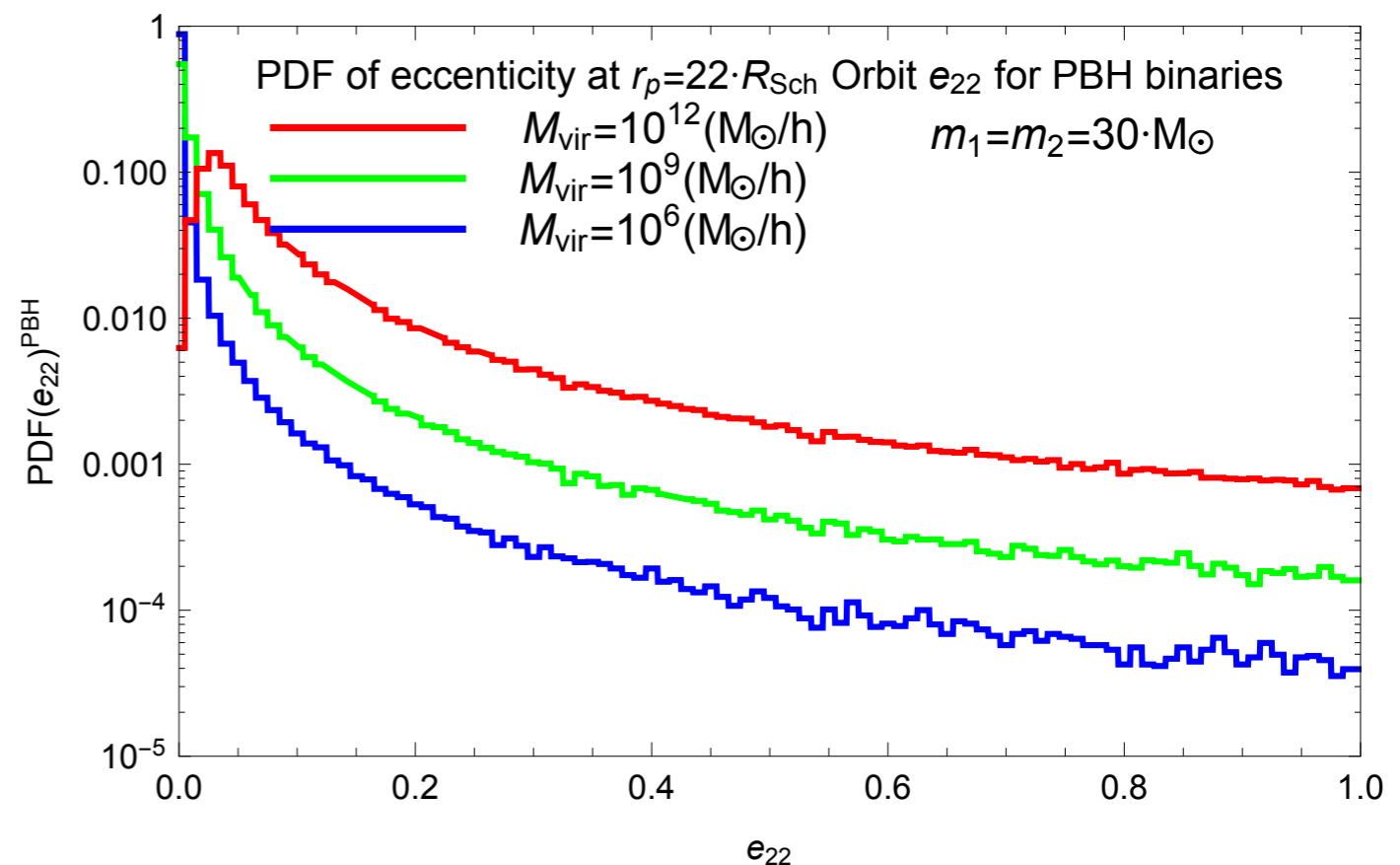
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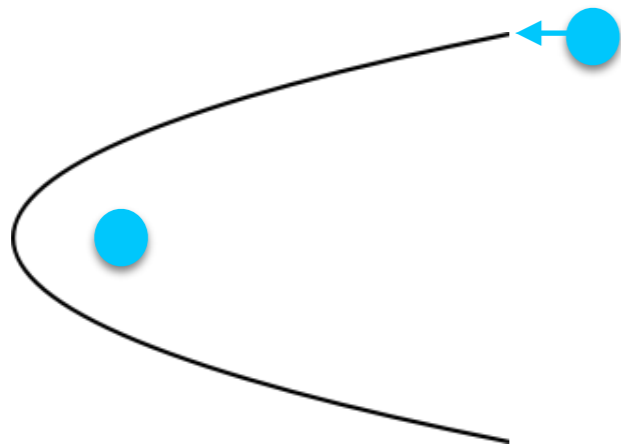
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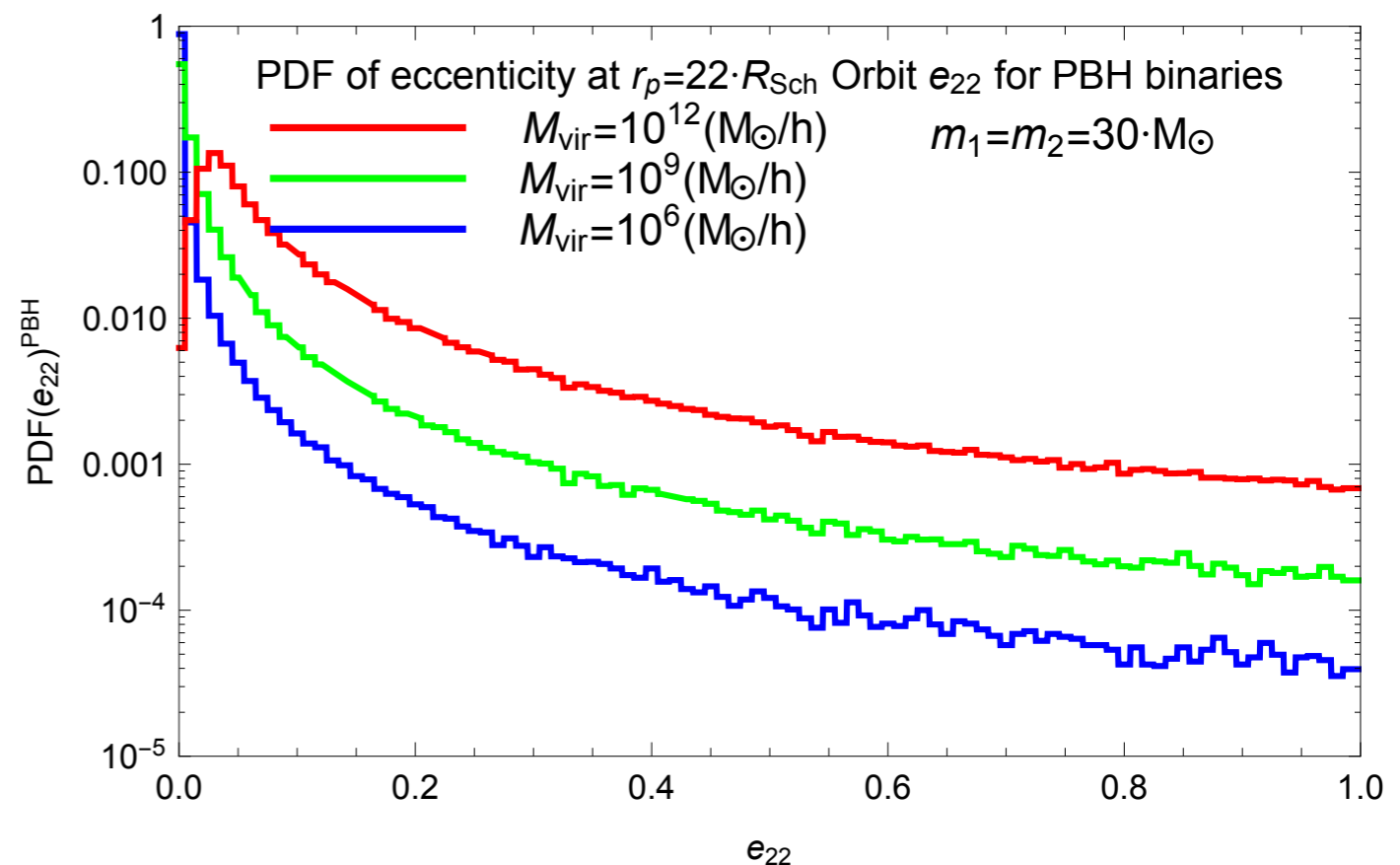
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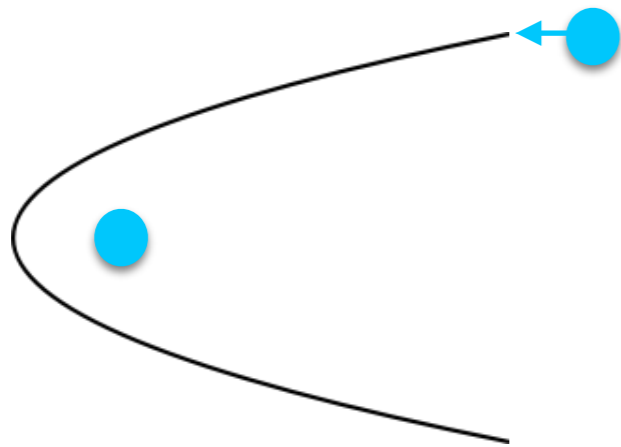
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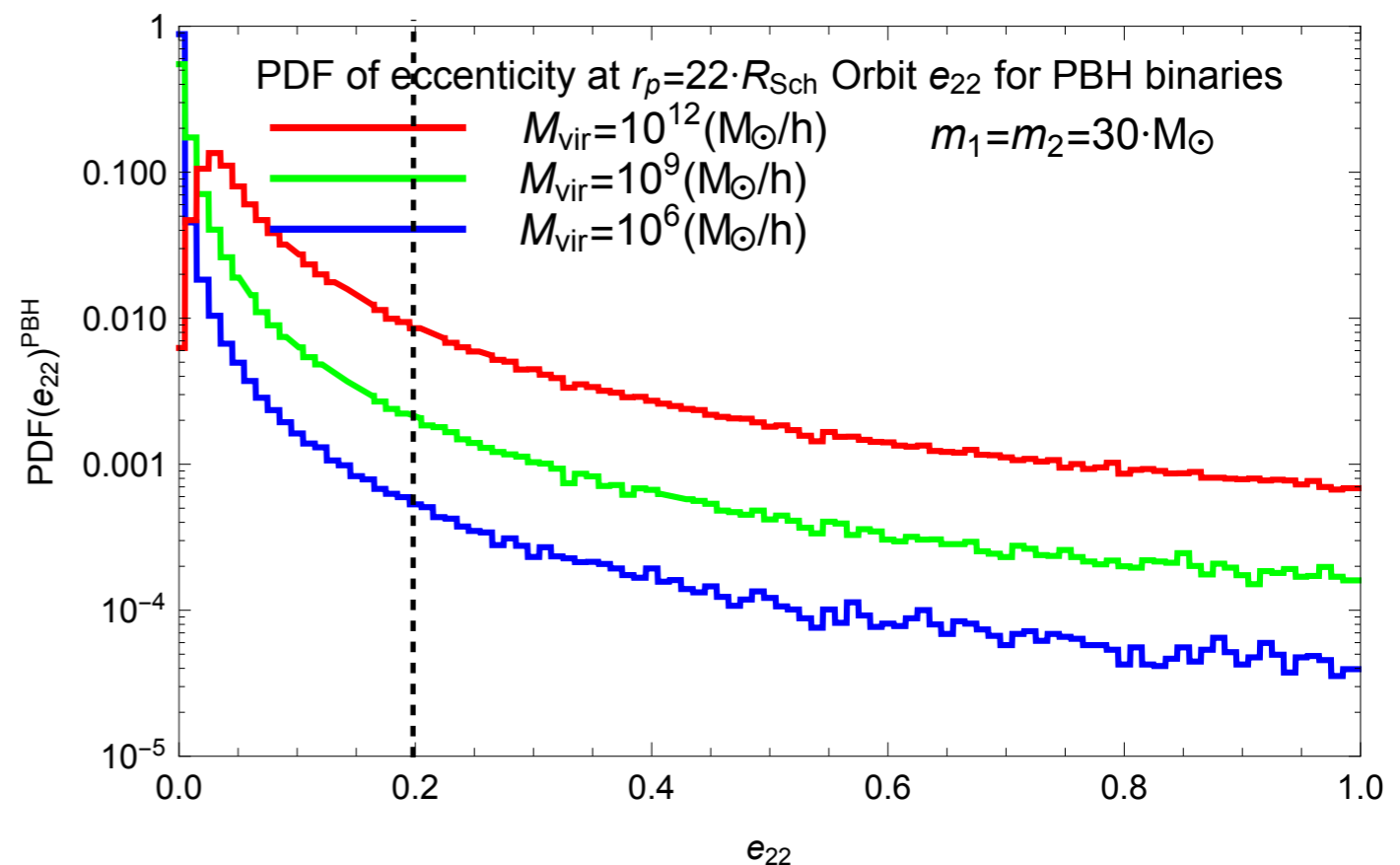
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$\sim 1\%$ of PBH GW events retain detectable final eccentricity:



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(Cholis, EDK et al., PRD 94 (2016))

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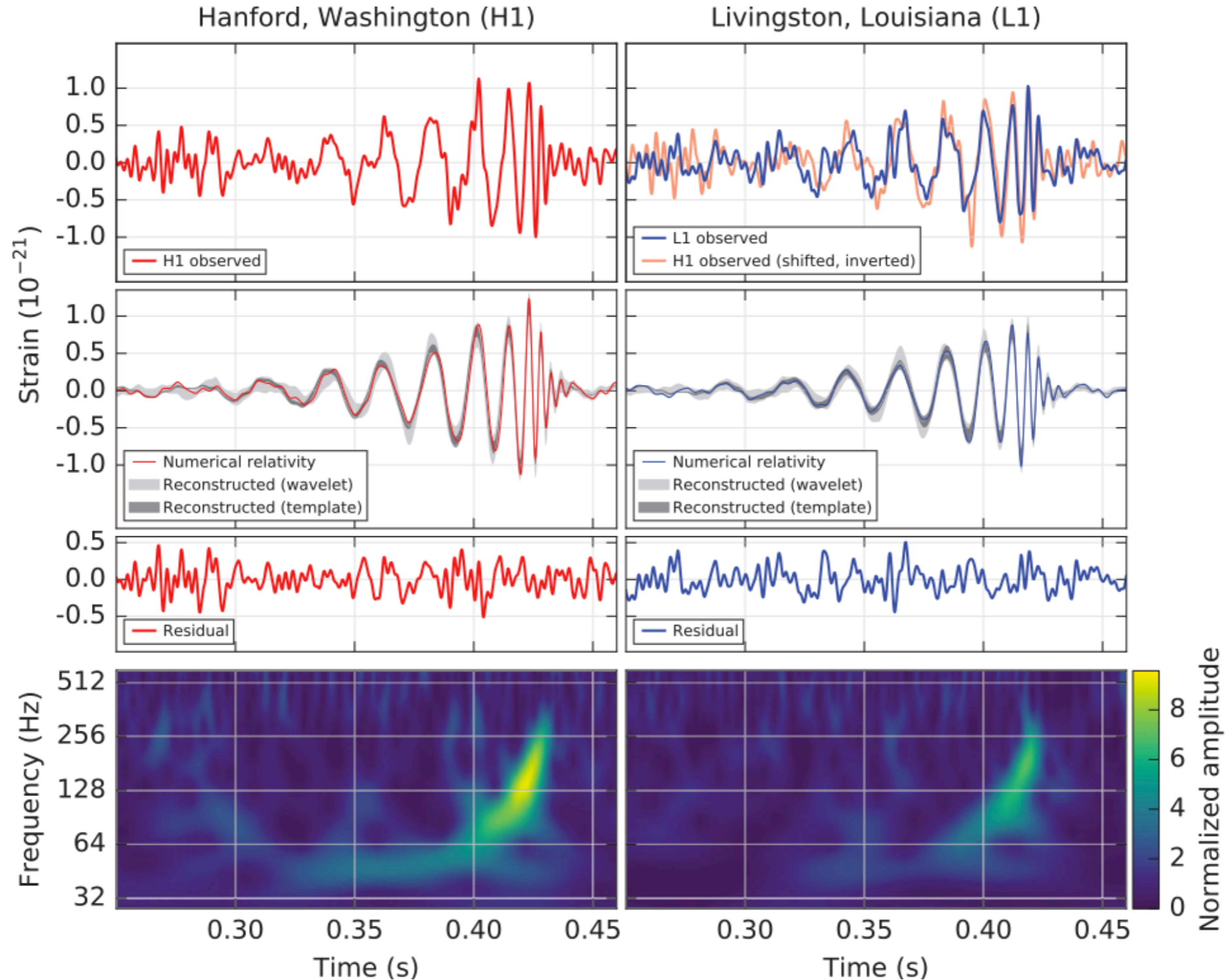
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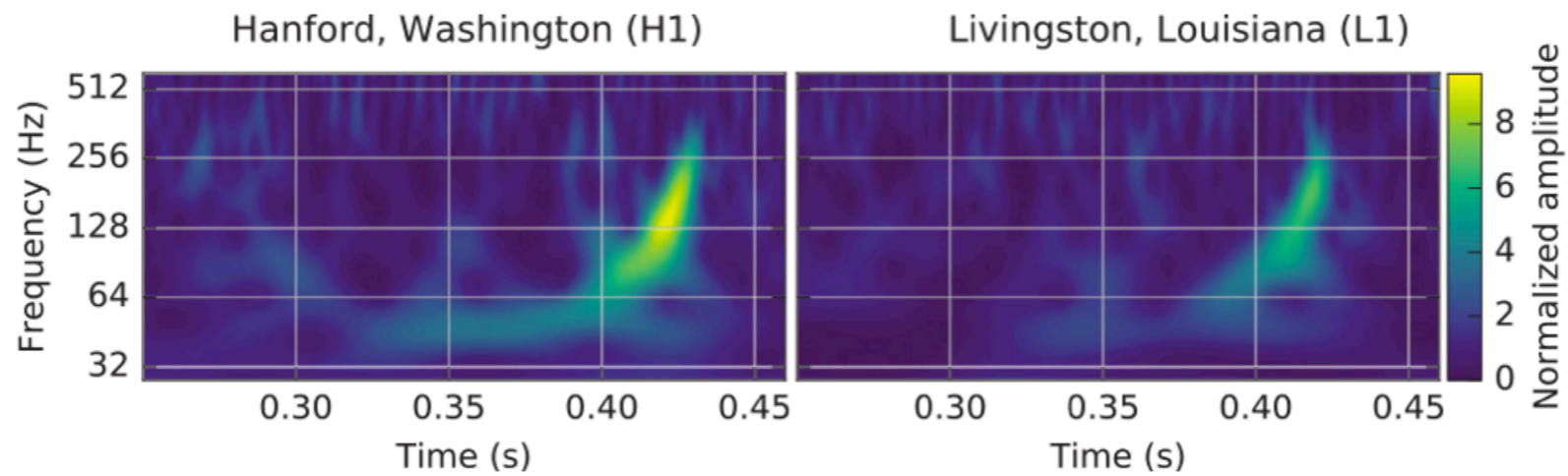
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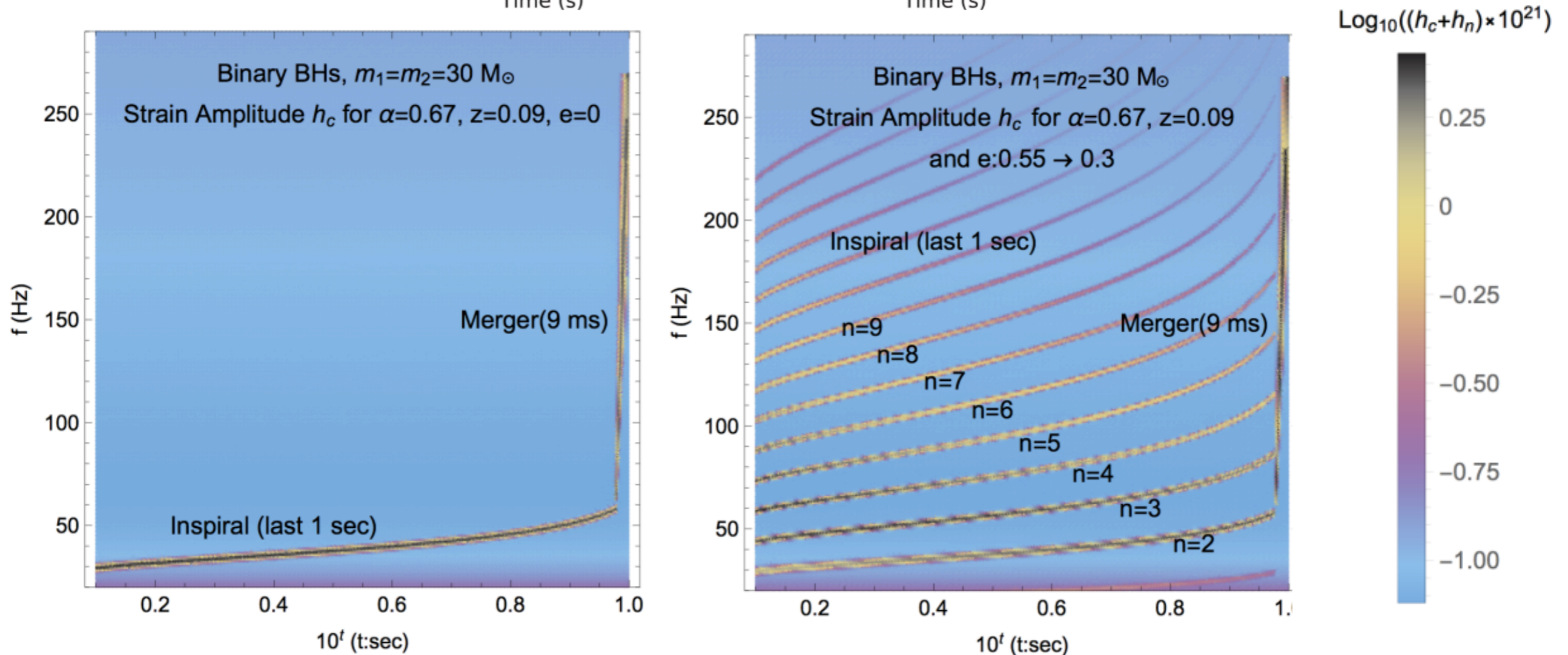
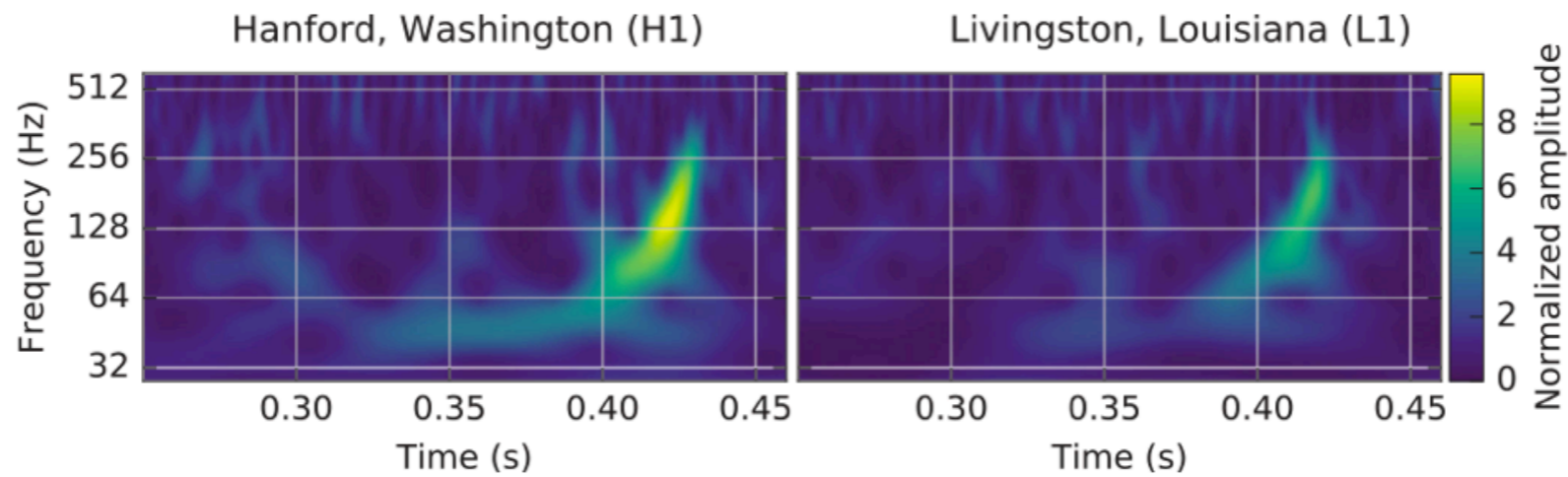
Detecting eccentricity:



Signatures of GWs from PBH Mergers: Eccentricity

(Cholis, EDK et al., PRD 94 (2016))

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Signatures of GWs from PBH Mergers: Eccentricity

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$$N_{e_f > 0.2} = 0.3 - 5$$

Advanced LIGO (6 yrs)

Signatures of GWs from PBH Mergers: Eccentricity

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(Cholis, EDK et al., PRD 94 (2016))

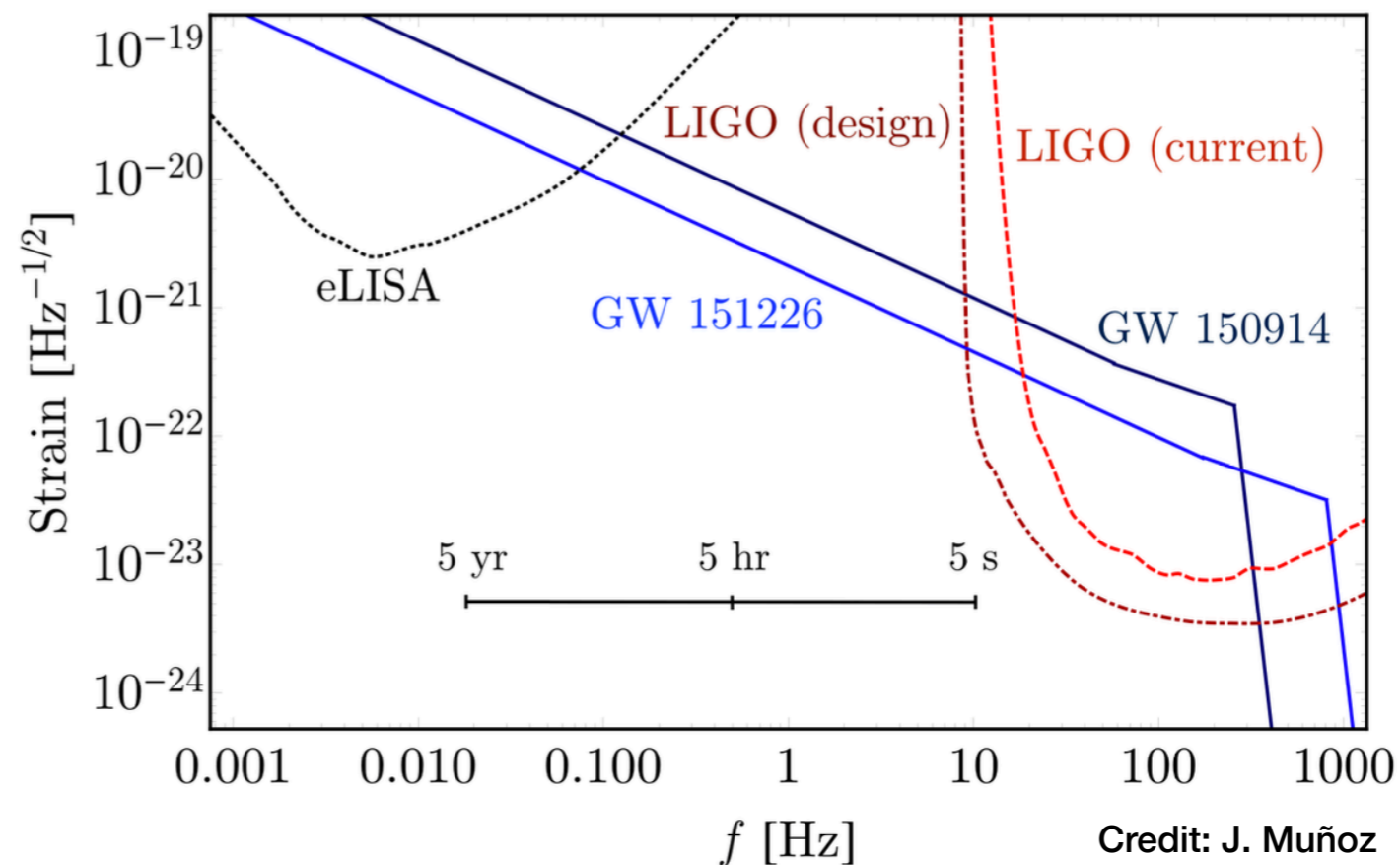
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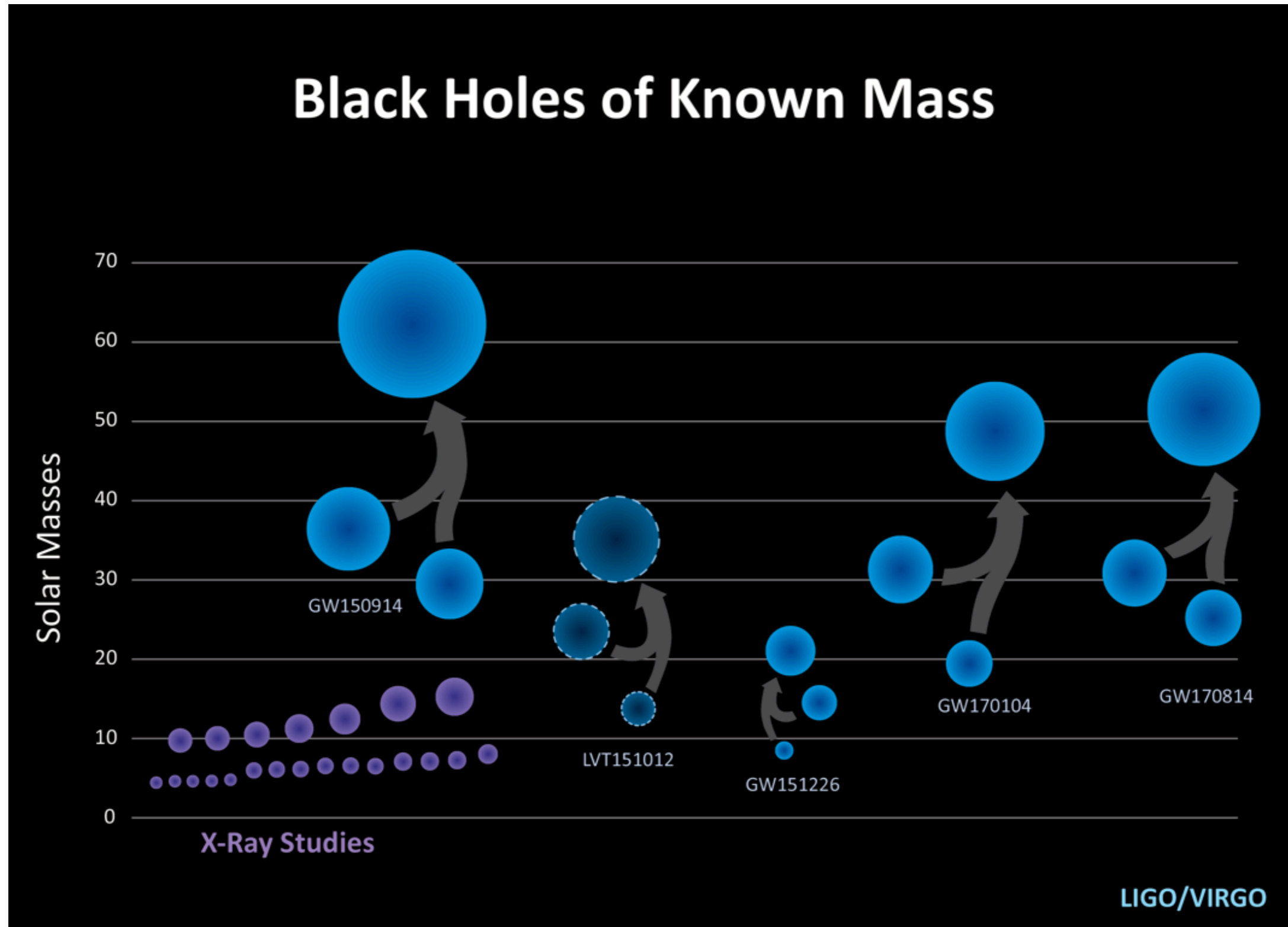
In the even more distant future:



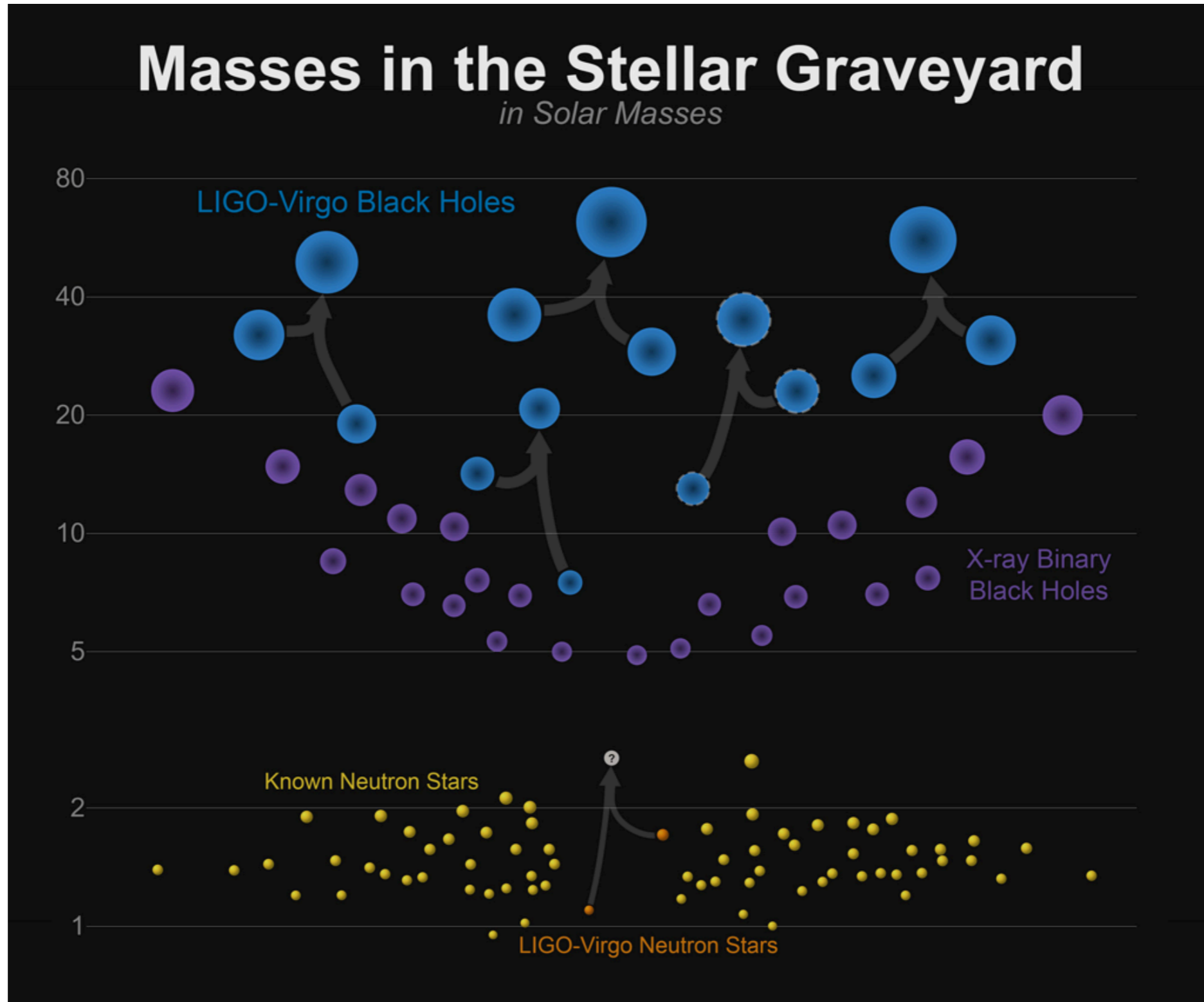
Mass Spectrum

The GW mass spectrum: Stellar Background

The GW mass spectrum: Stellar Background



The GW mass spectrum: Stellar Background



The GW mass spectrum: Stellar Background

(Kovetz et al., PRD 2017)

Stellar-BH mass function:

The GW mass spectrum: Stellar Background

(Kovetz et al., PRD 2017)

Stellar-BH mass function:

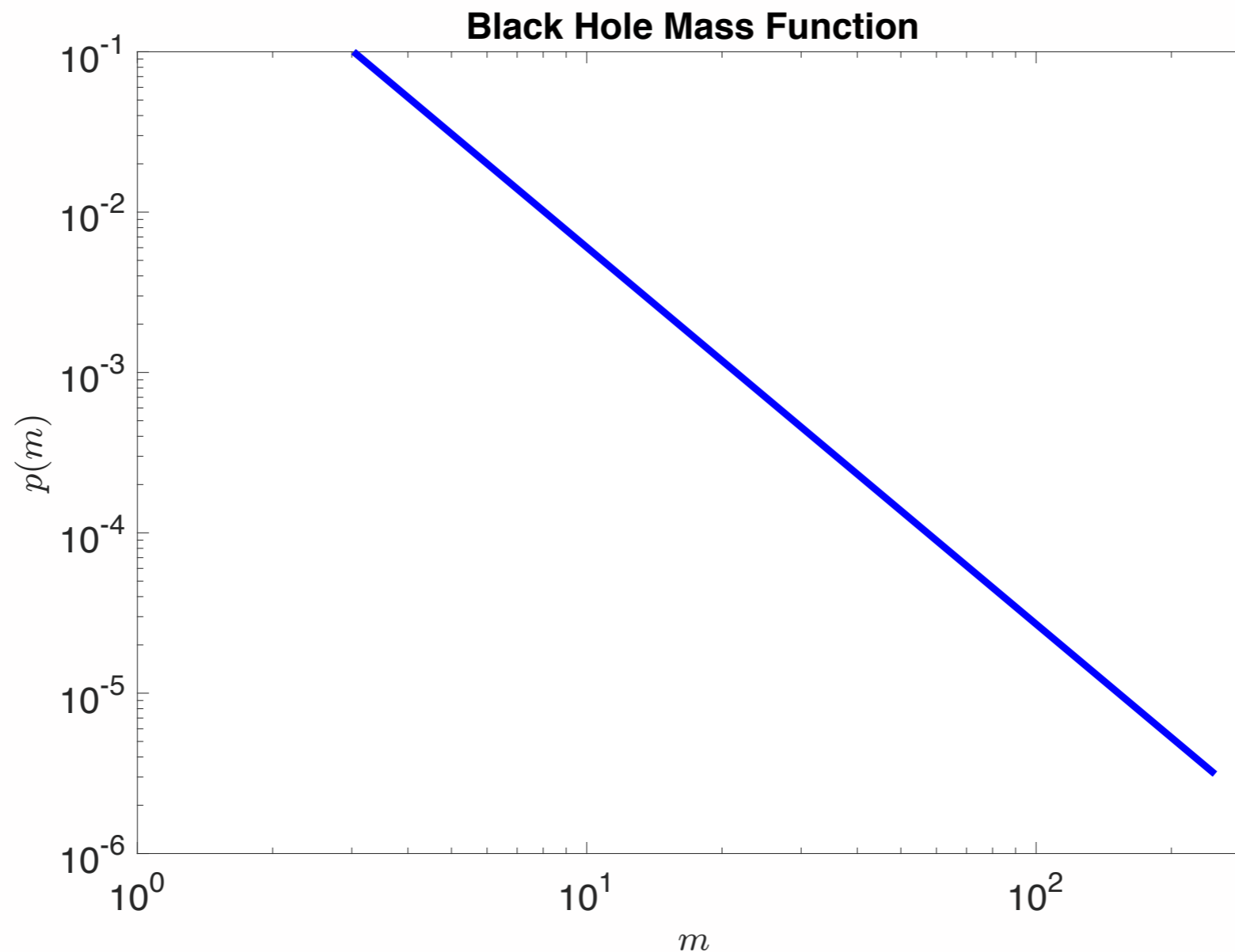
Ansatz:

The GW mass spectrum: Stellar Background

(Kovetz et al., PRD 2017)

Stellar-BH mass function:

Ansatz: $p(m) \propto m^{-\alpha}$



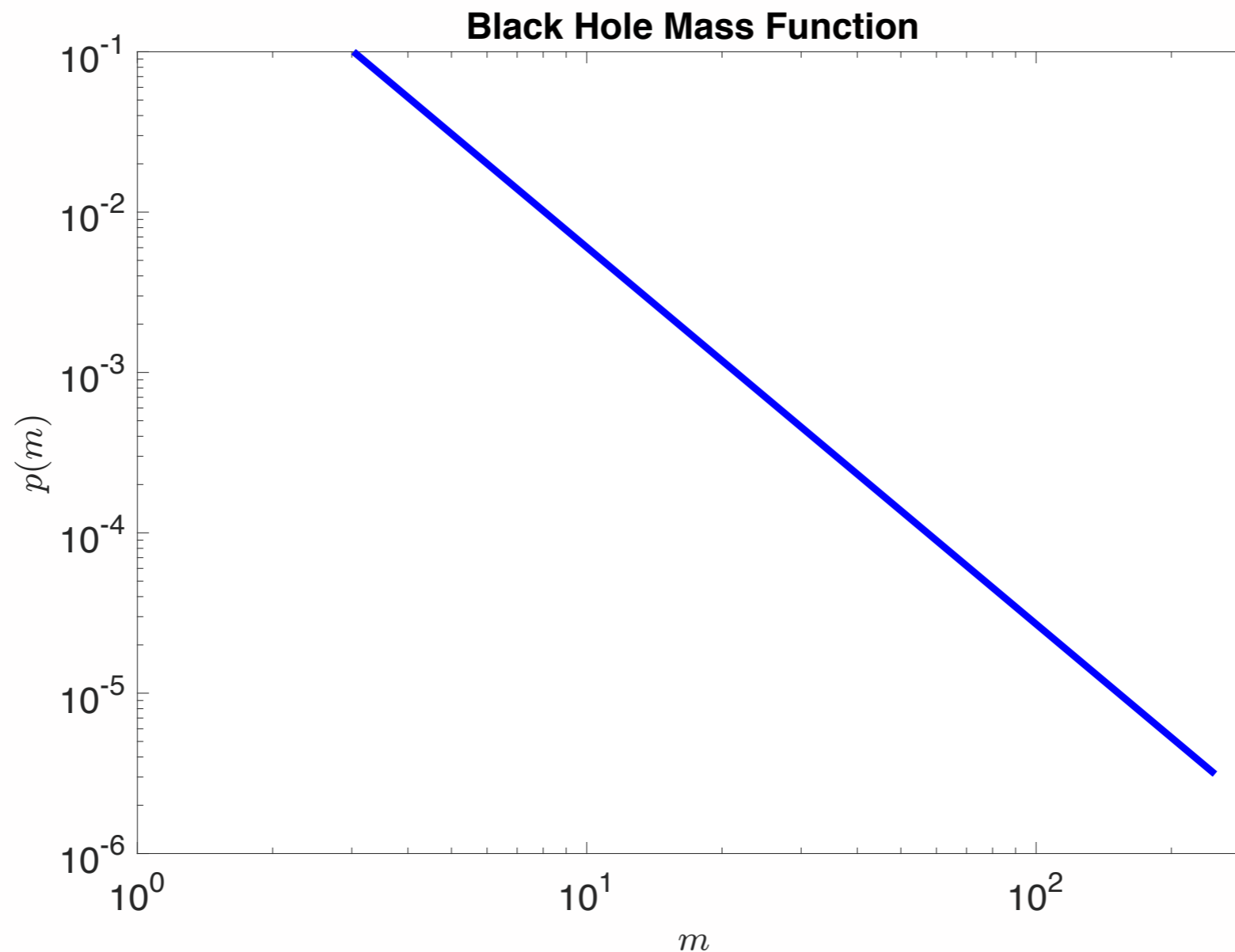
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Stellar IMF
 $\alpha = 2.35$



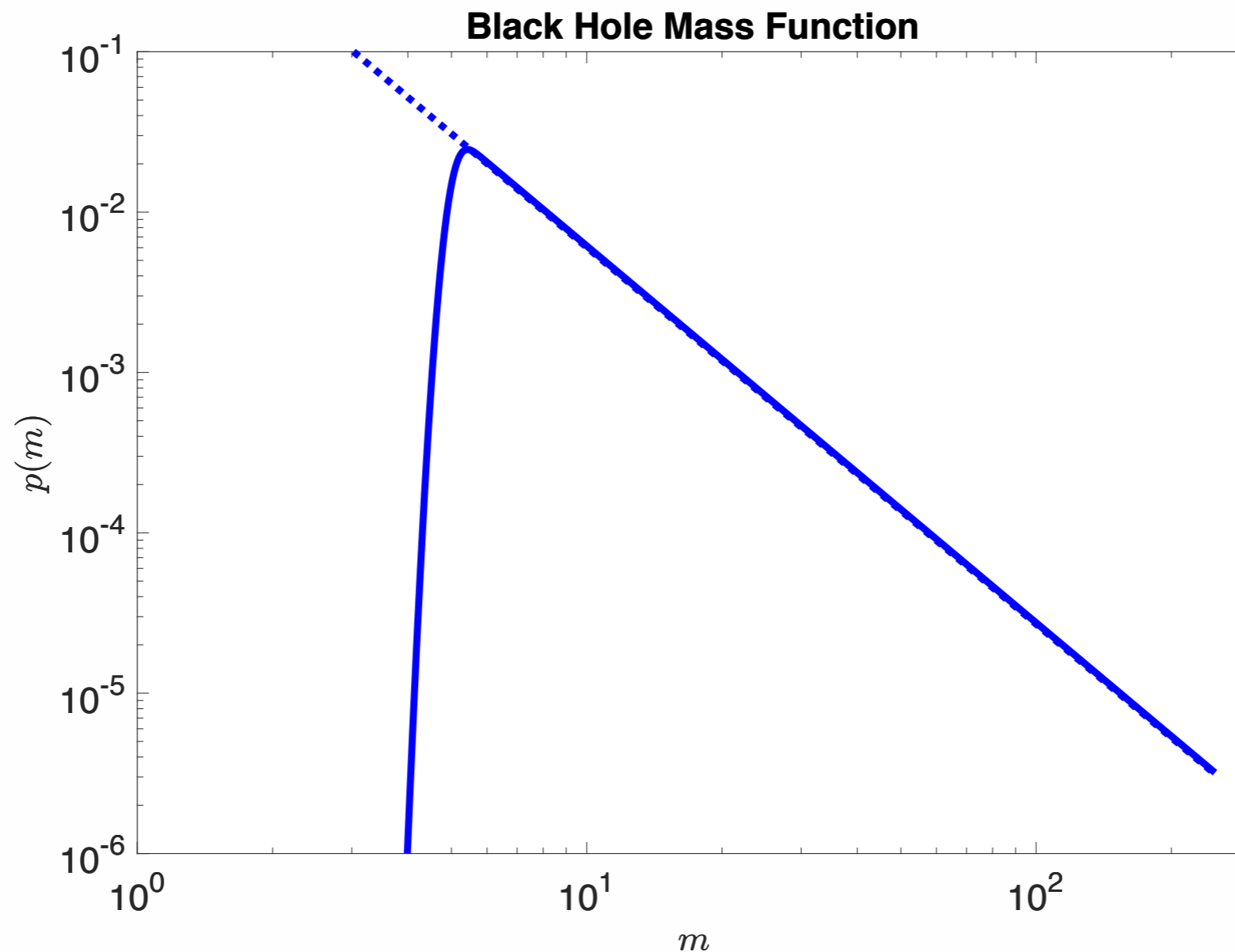
The GW mass spectrum: Stellar Background

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Stellar-BH mass function:

Ansatz: $p(m) \propto m^{-\alpha} \mathcal{H}(m - m_{\text{Gap}})$

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 $\alpha = 2.35$



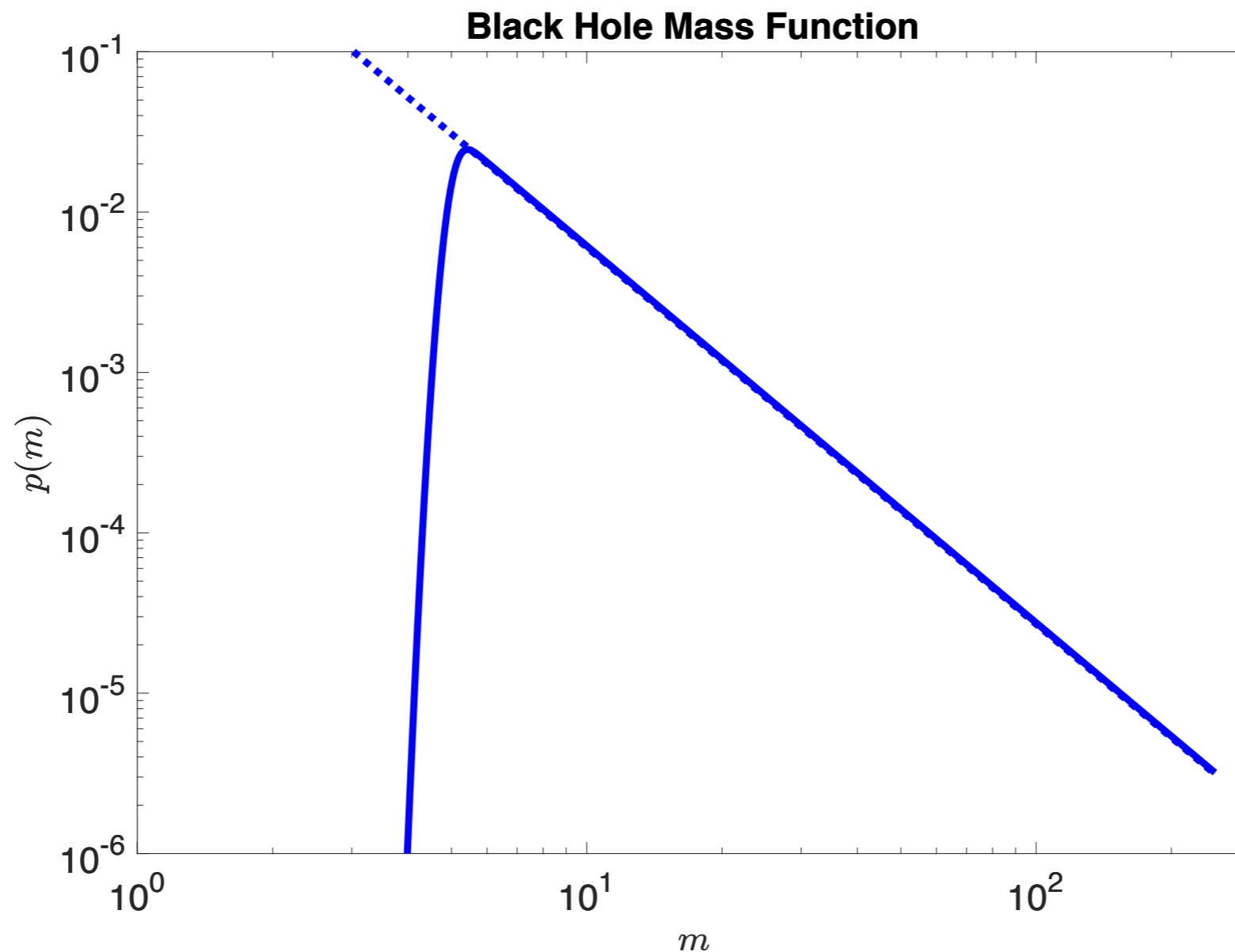
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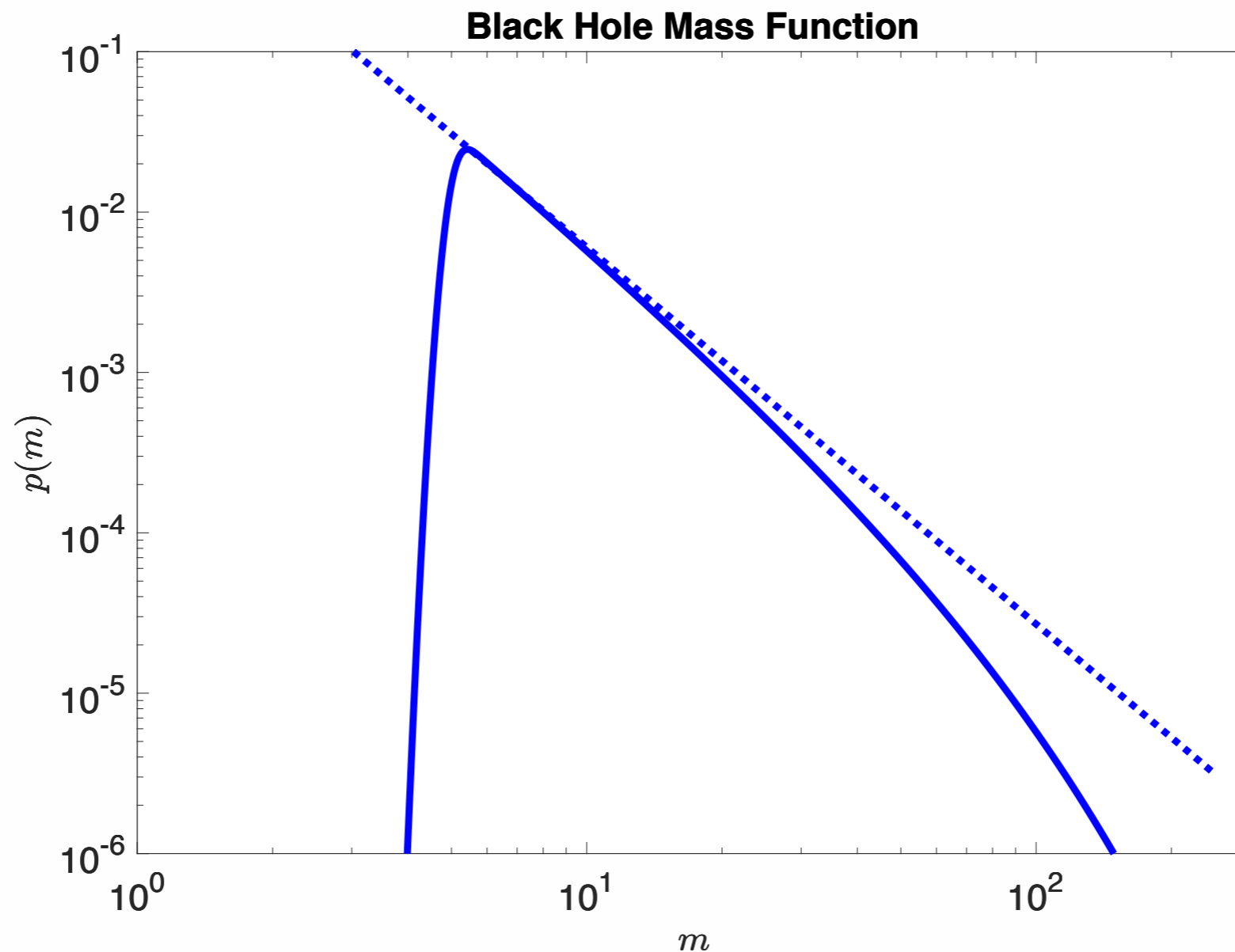
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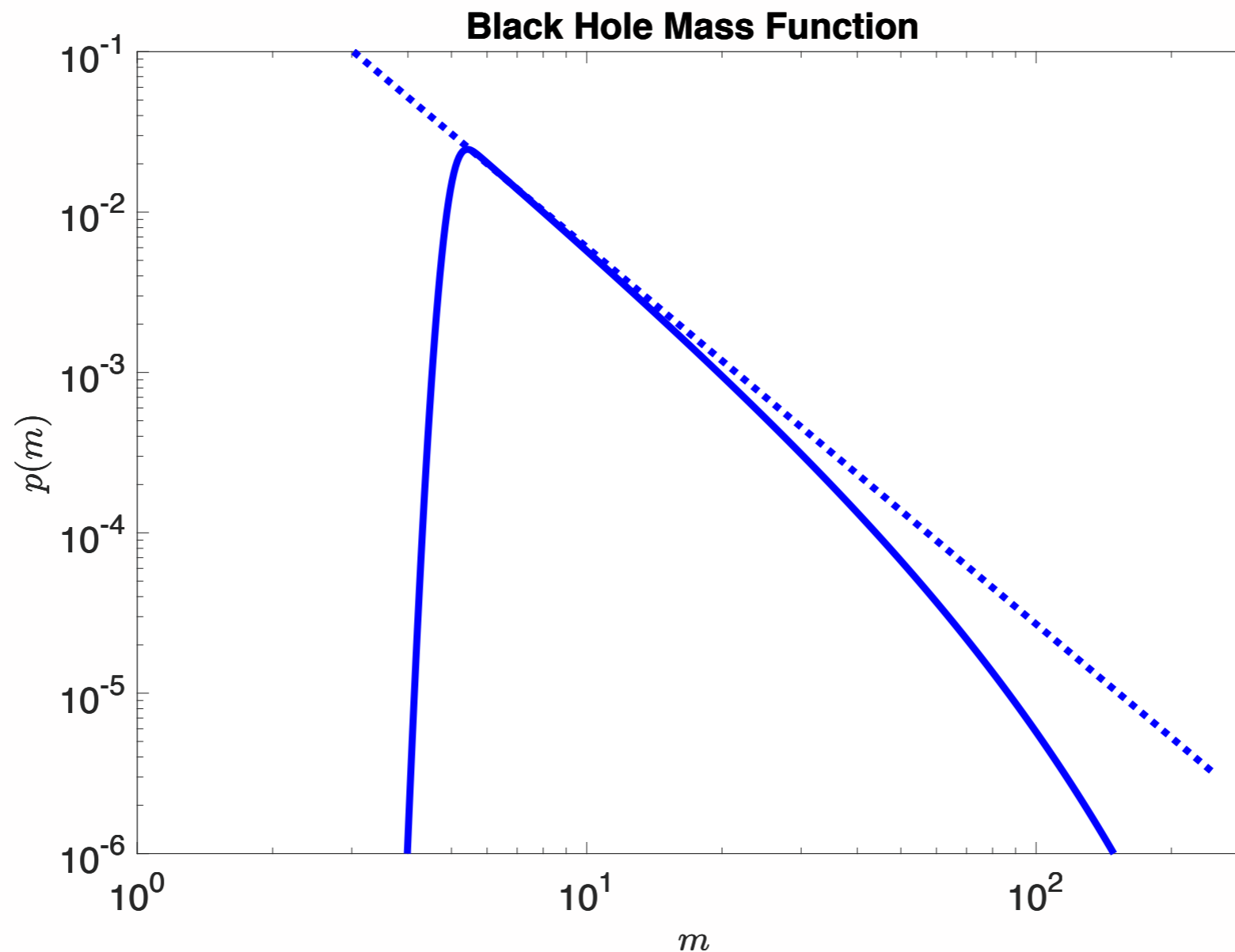
The GW mass spectrum: Stellar Background

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Stellar-BH mass function:

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Ansatz: $p(m) \propto m^{-\alpha} \mathcal{H}(m - m_{\text{Gap}}) e^{-m/m_{\text{Cap}}}$



The GW mass spectrum: Background

(Kovetz et al., PRD 2017)

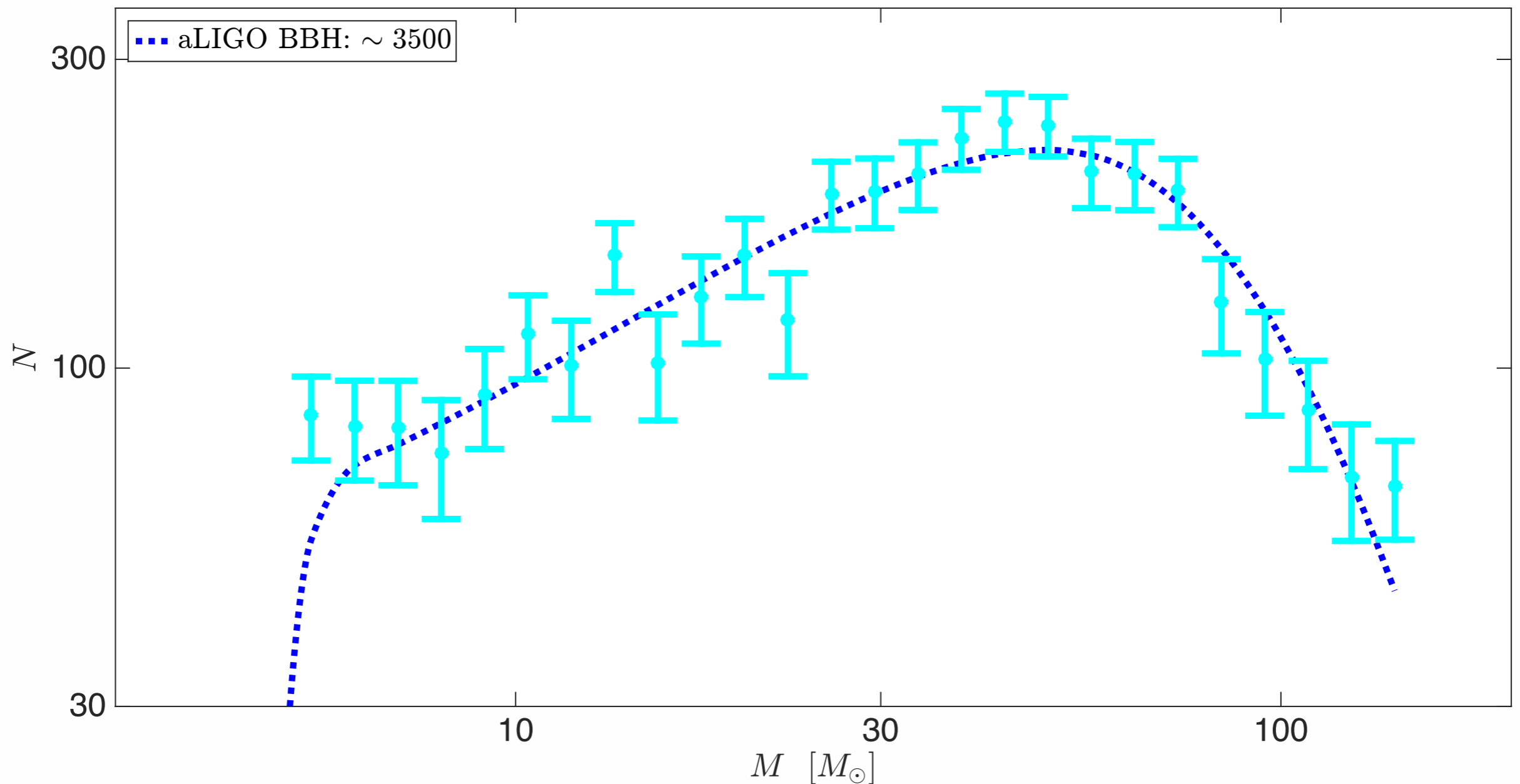
Observed mass spectrum with 5 years of advanced LIGO data:

The GW mass spectrum: Background

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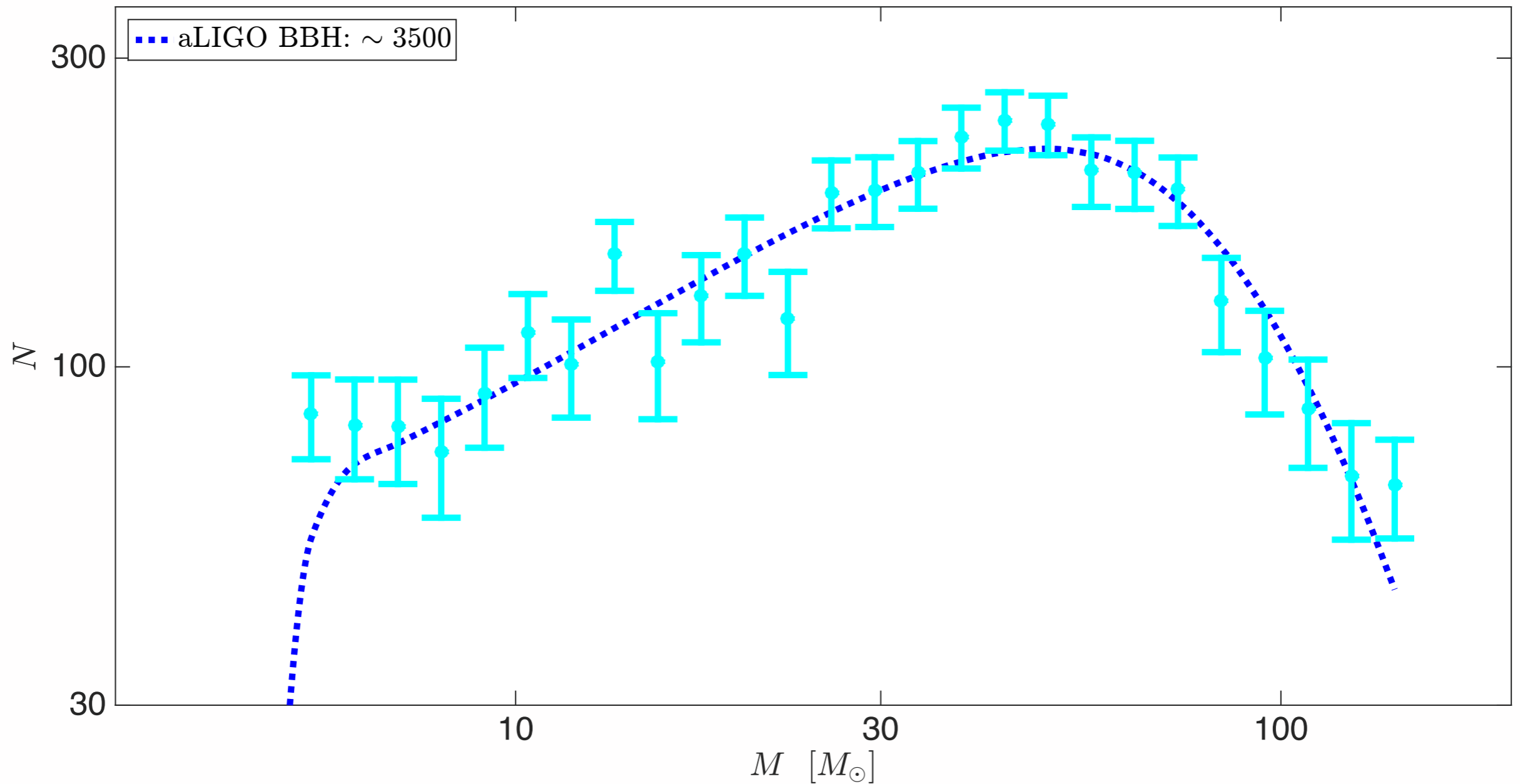
Observed mass spectrum with 5 years of advanced LIGO data:

(note logarithmic binning...)



The GW mass spectrum: Background + “Signal”

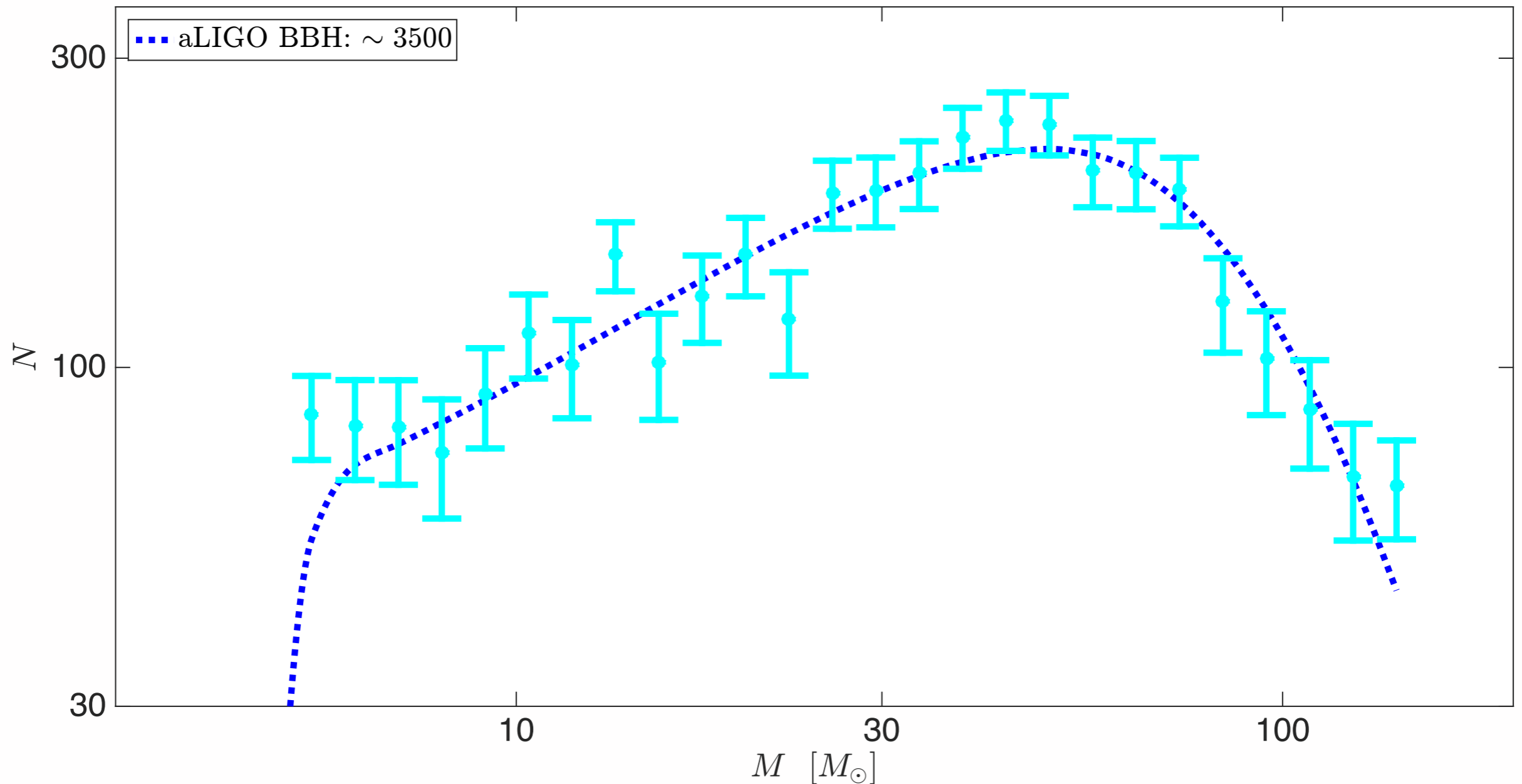
(Kovetz et al., PRD 2017)



The GW mass spectrum: Background + “Signal”

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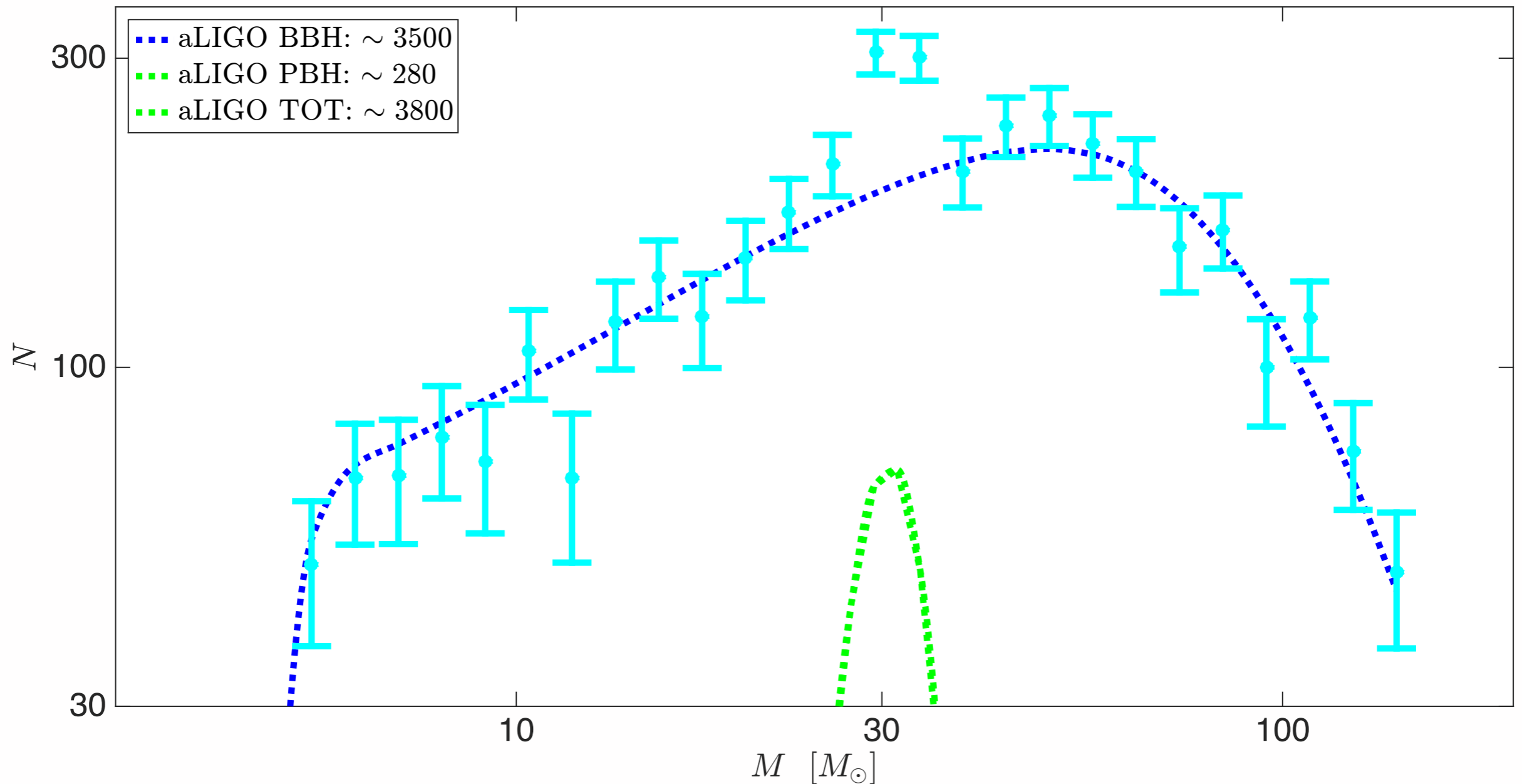
If we add Dark Matter PBHs: $M_{\text{PBH}} \sim \mathcal{N}(30M_{\odot}, \sigma_M^2)$



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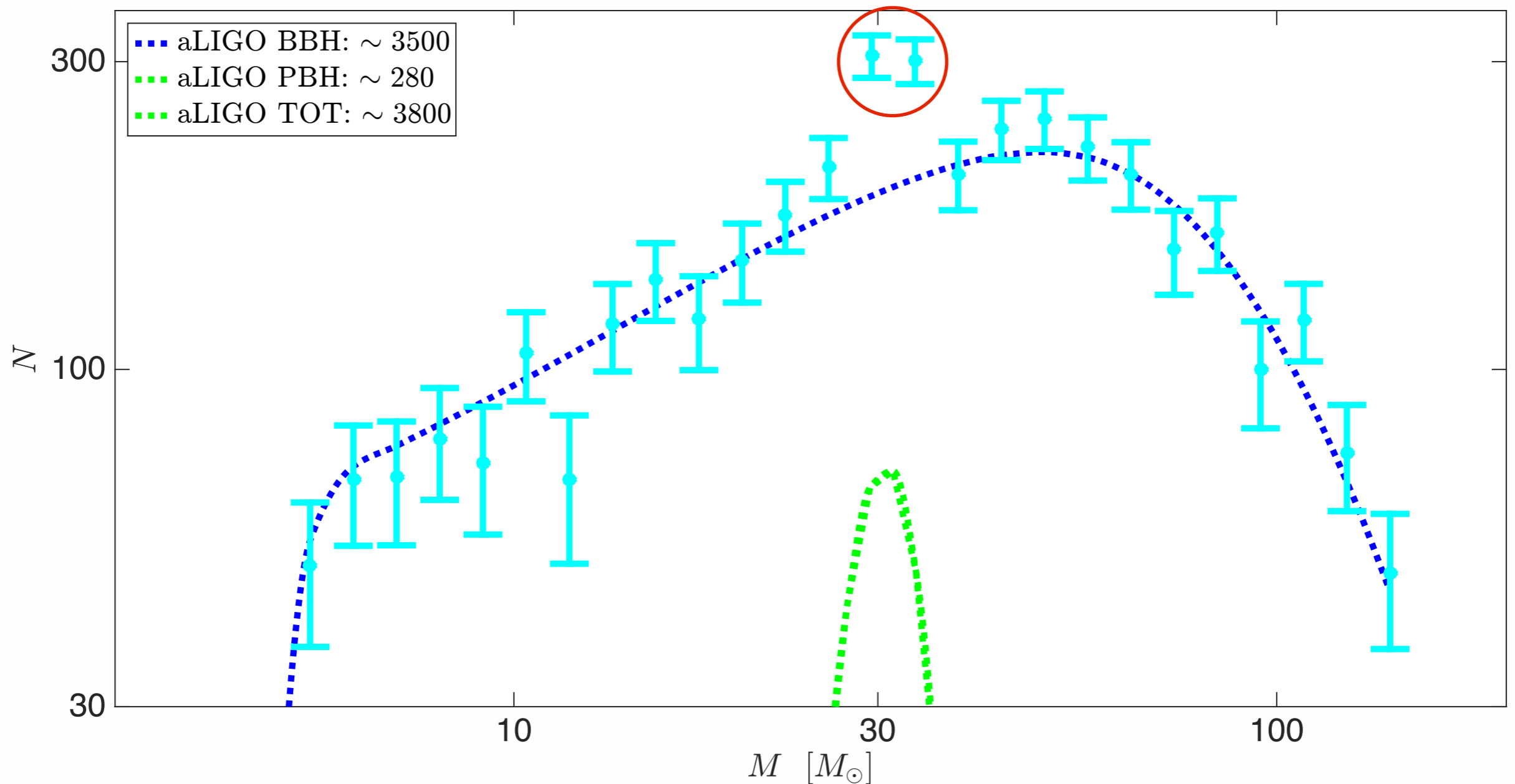
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The GW mass spectrum: 2D Distribution

(Kovetz et al., PRD 2017)

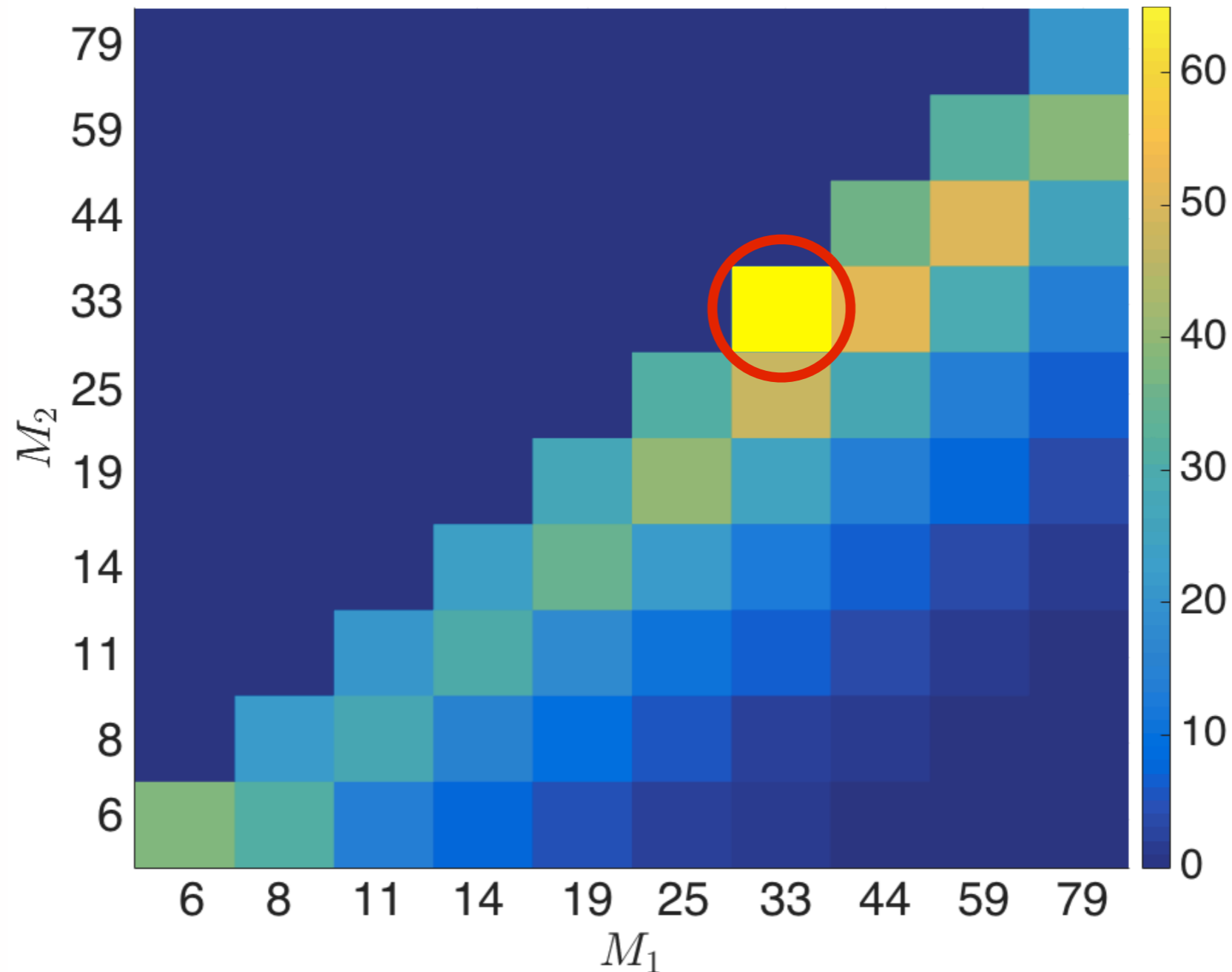
Using the 2D mass distribution (more model-dependent):

The GW mass spectrum: 2D Distribution

(Kovetz et al., PRD 2017)

Using the 2D mass distribution (more model-dependent):

2D Binned Mass Distribution of BBH Mergers:



The GW mass spectrum: PBH Constraints

(Kovetz, PRL 2017)

The GW mass spectrum: PBH Constraints

(Kovetz, PRL 2017)

No peak?

The GW mass spectrum: PBH Constraints

(Kovetz, PRL 2017)

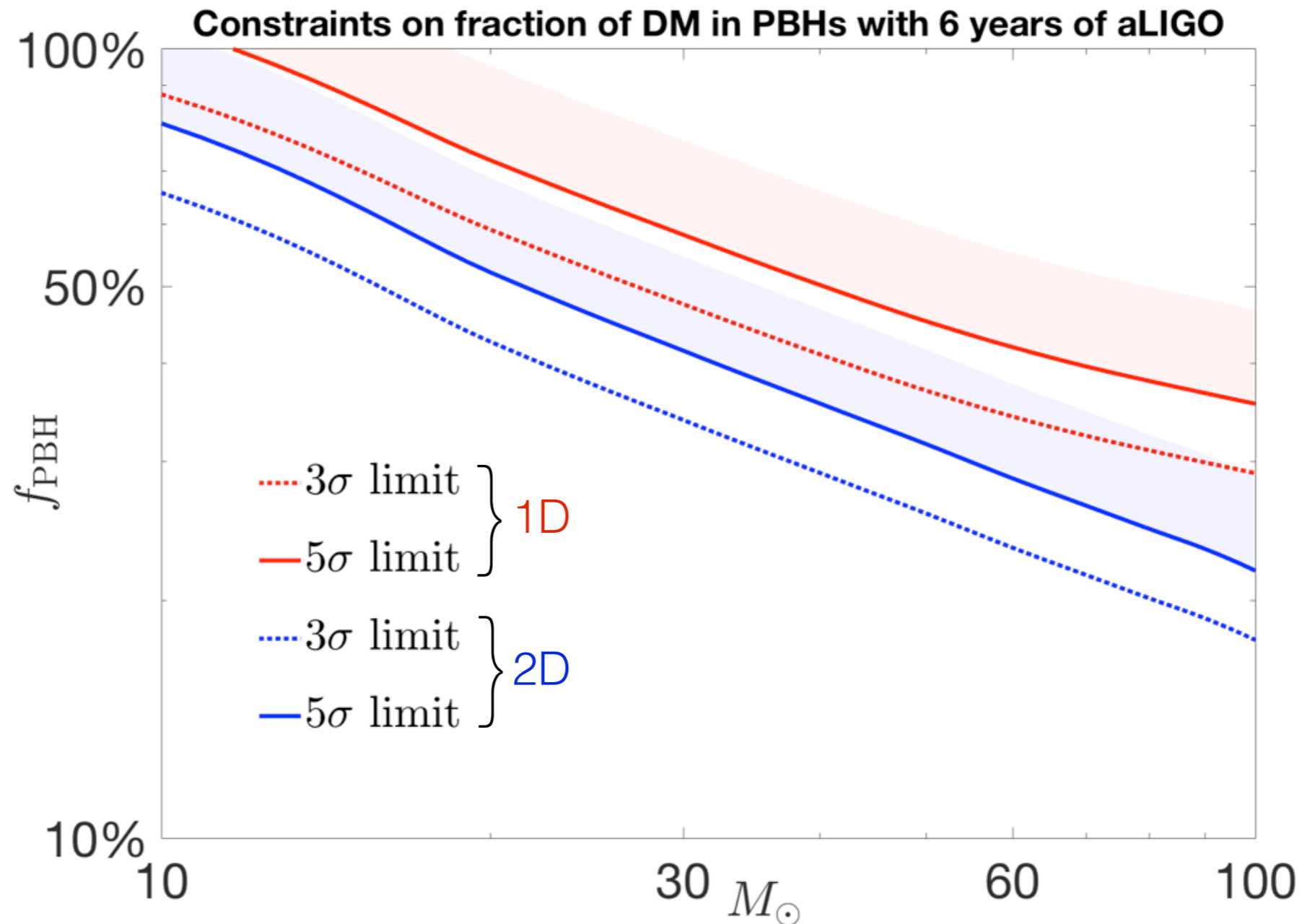
No peak? \longrightarrow Can constrain the fraction of DM in PBHs:

The GW mass spectrum: PBH Constraints

(Kovetz, PRL 2017)

No peak? \longrightarrow Can constrain the fraction of DM in PBHs:

(assumes a delta-function PBH mass distribution)



The GW mass spectrum: PBH Constraints

(Ali-Haïmoud, EDK & Kamionkowski, arXiv:1709.06576)

The GW mass spectrum: PBH Constraints

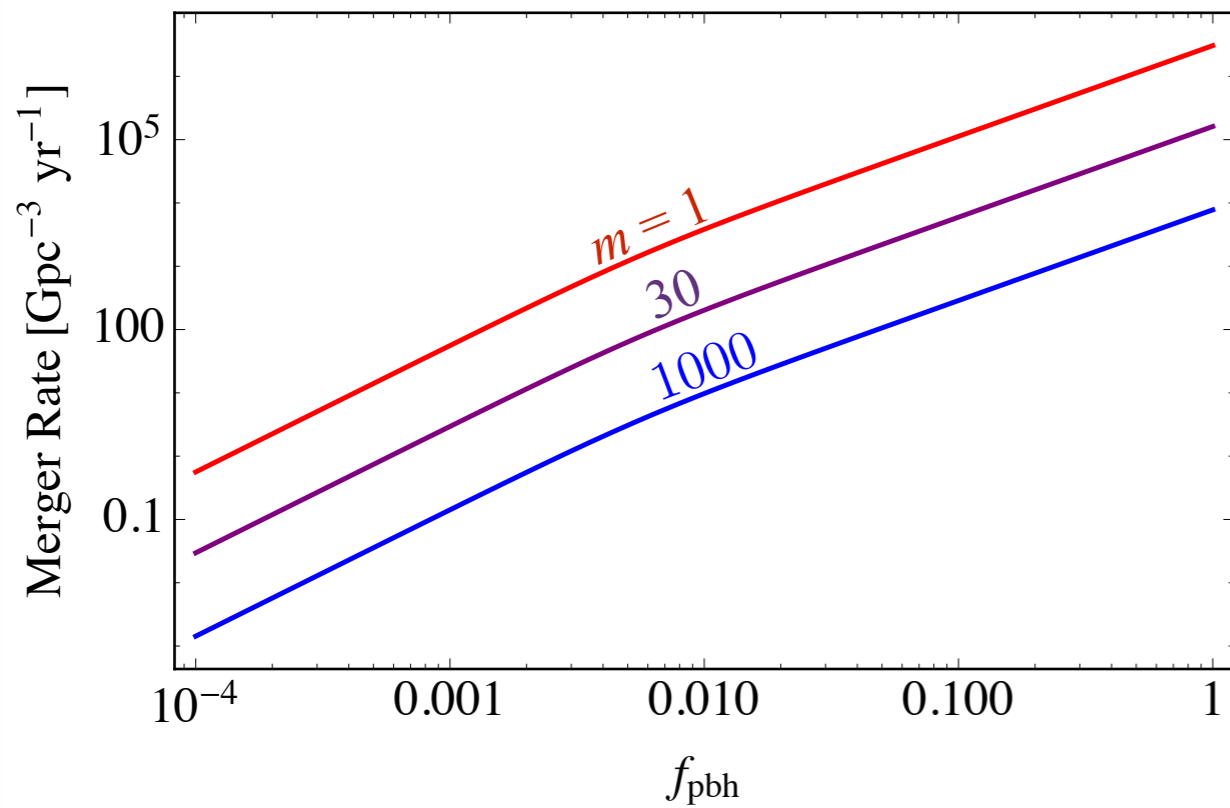
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Recall: larger rate predicted for early-Universe binaries!

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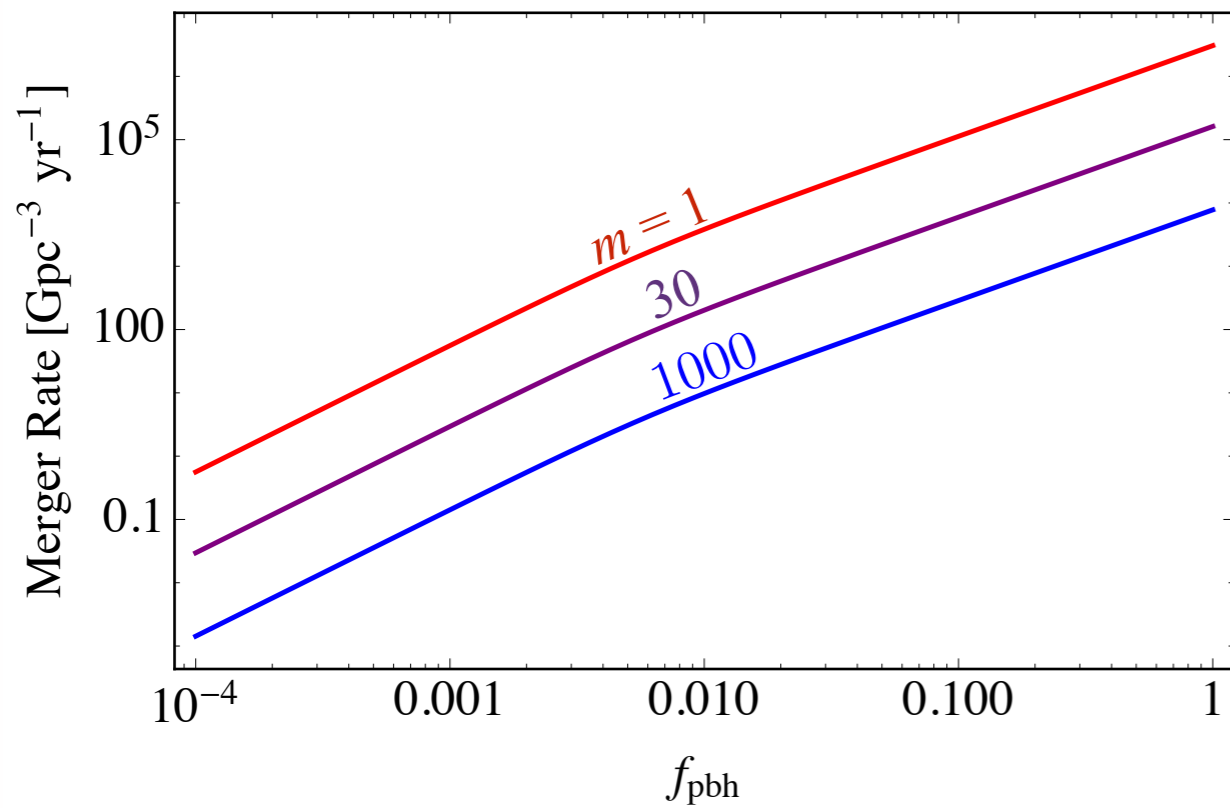


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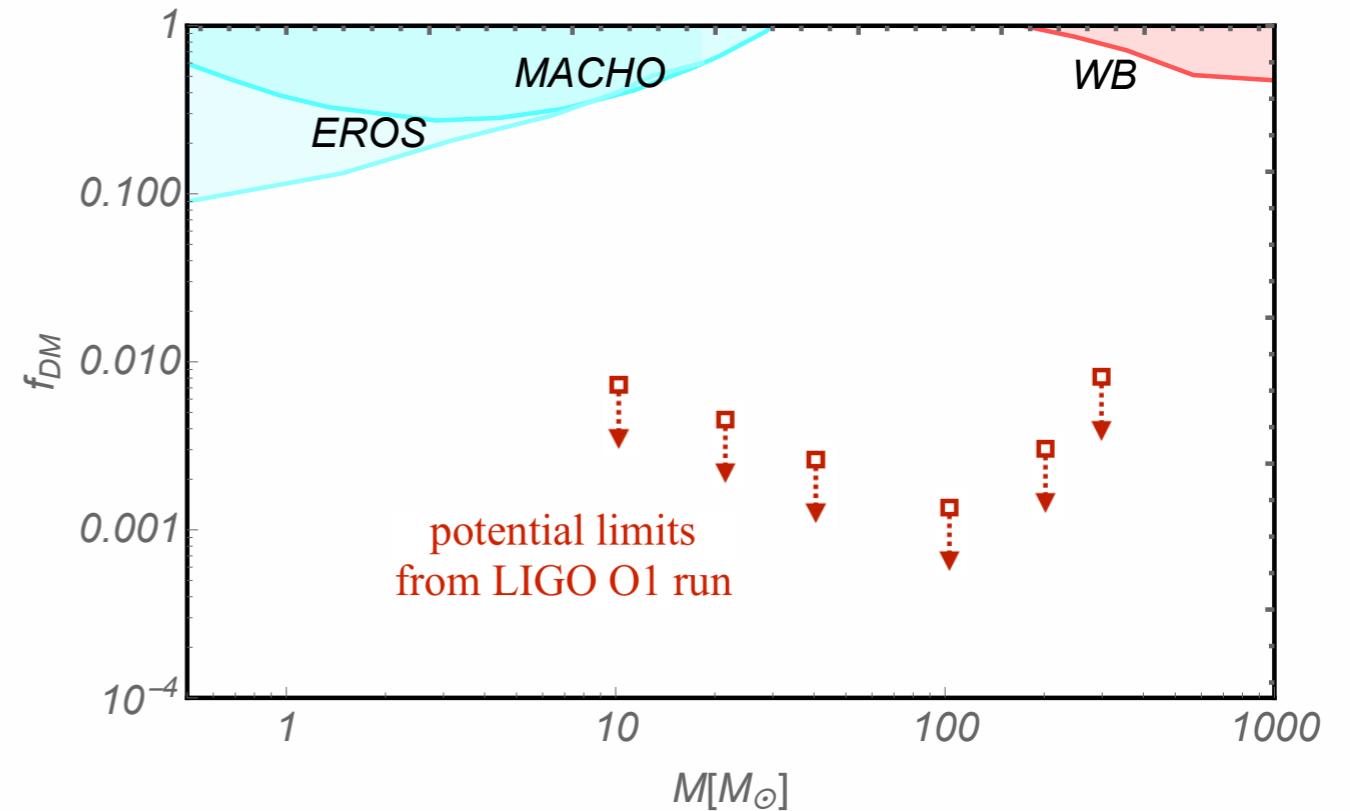
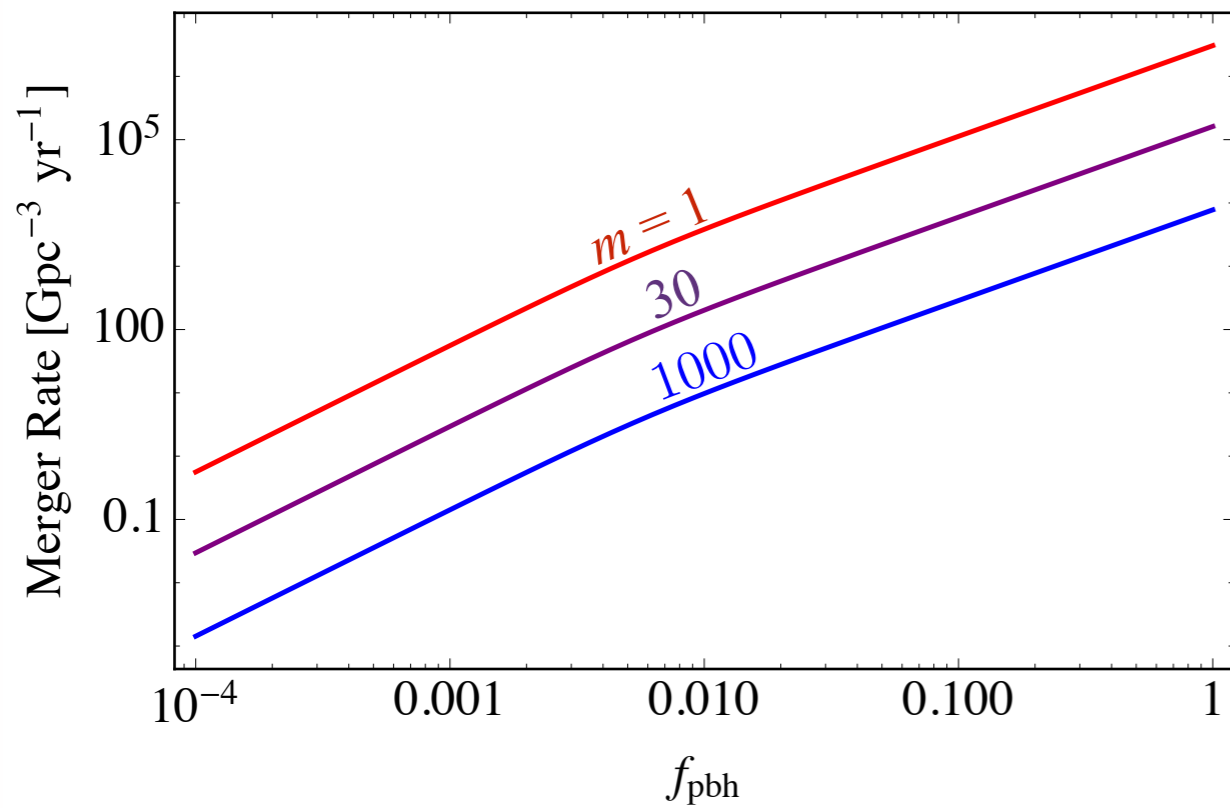


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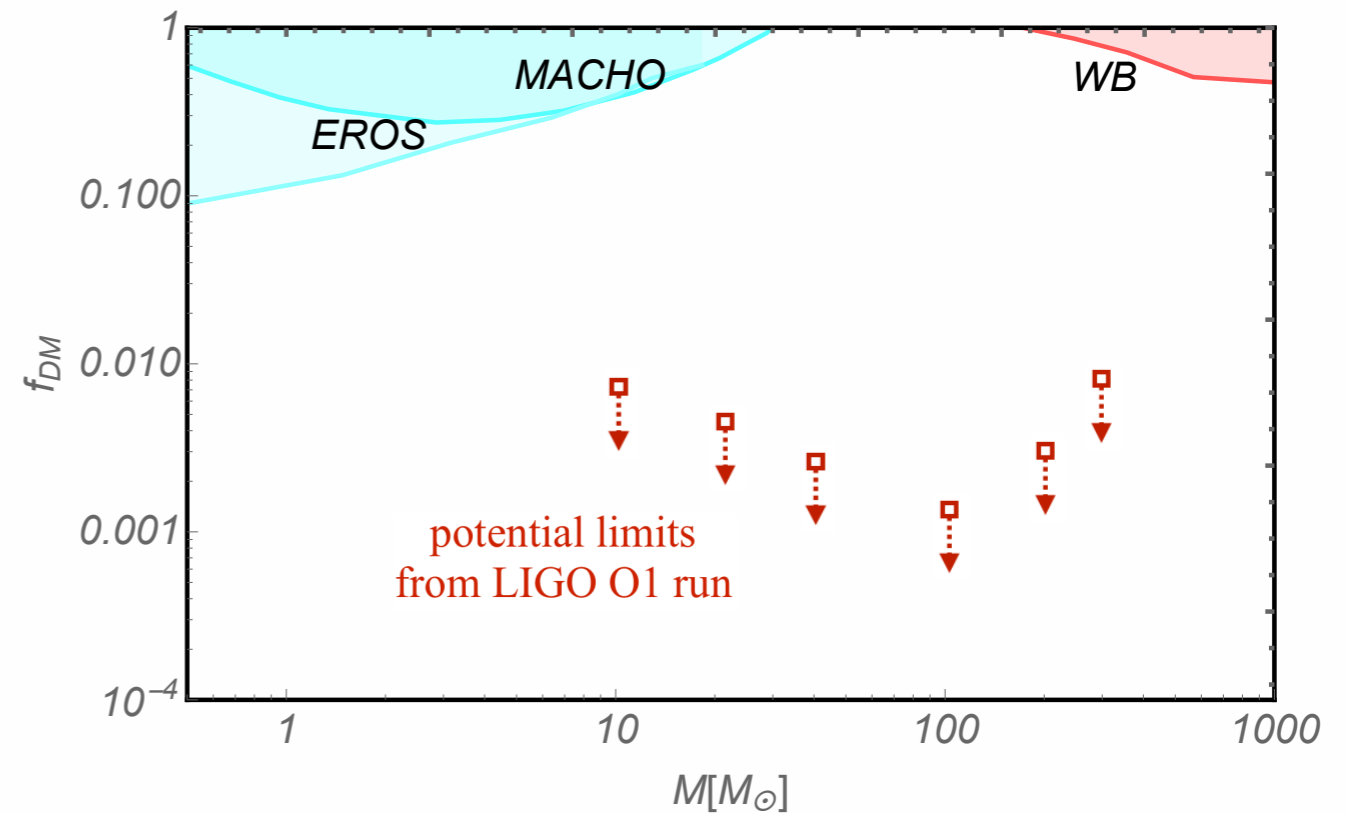
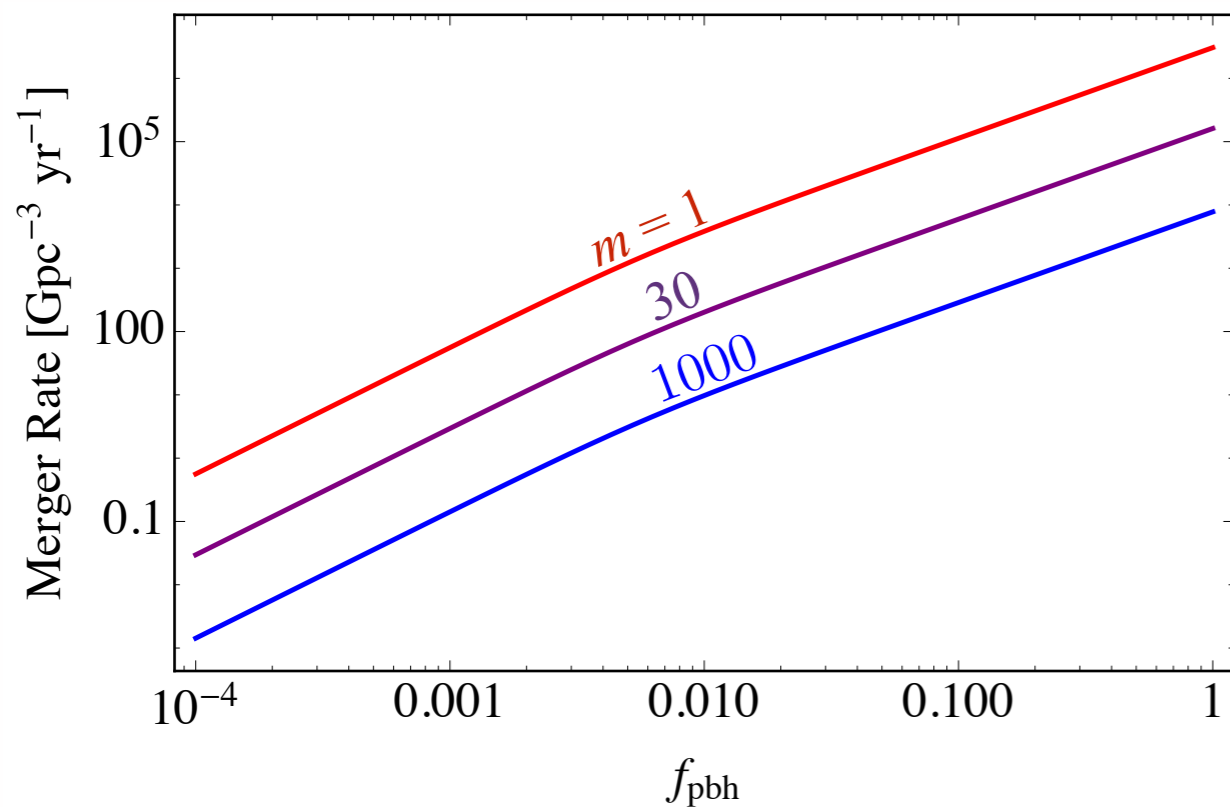


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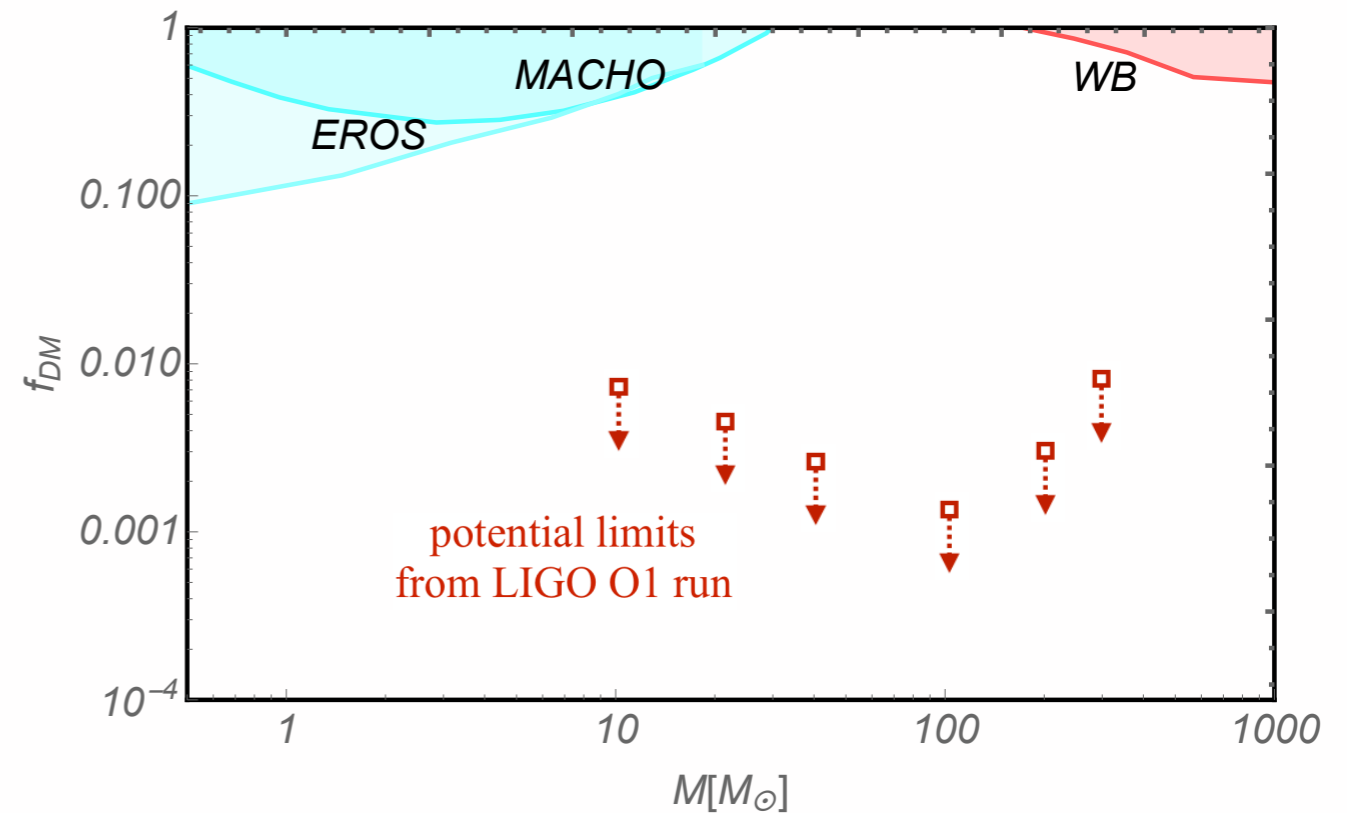
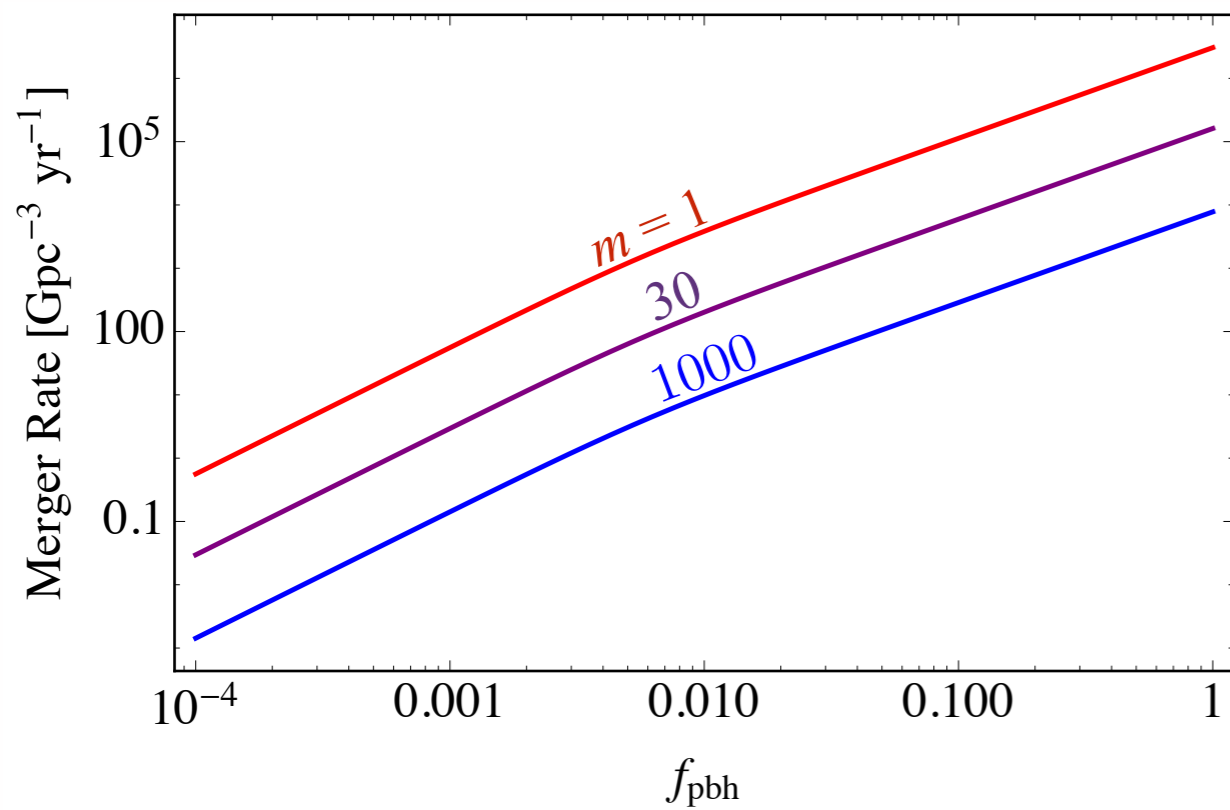
More (numerical) work needed to understand:

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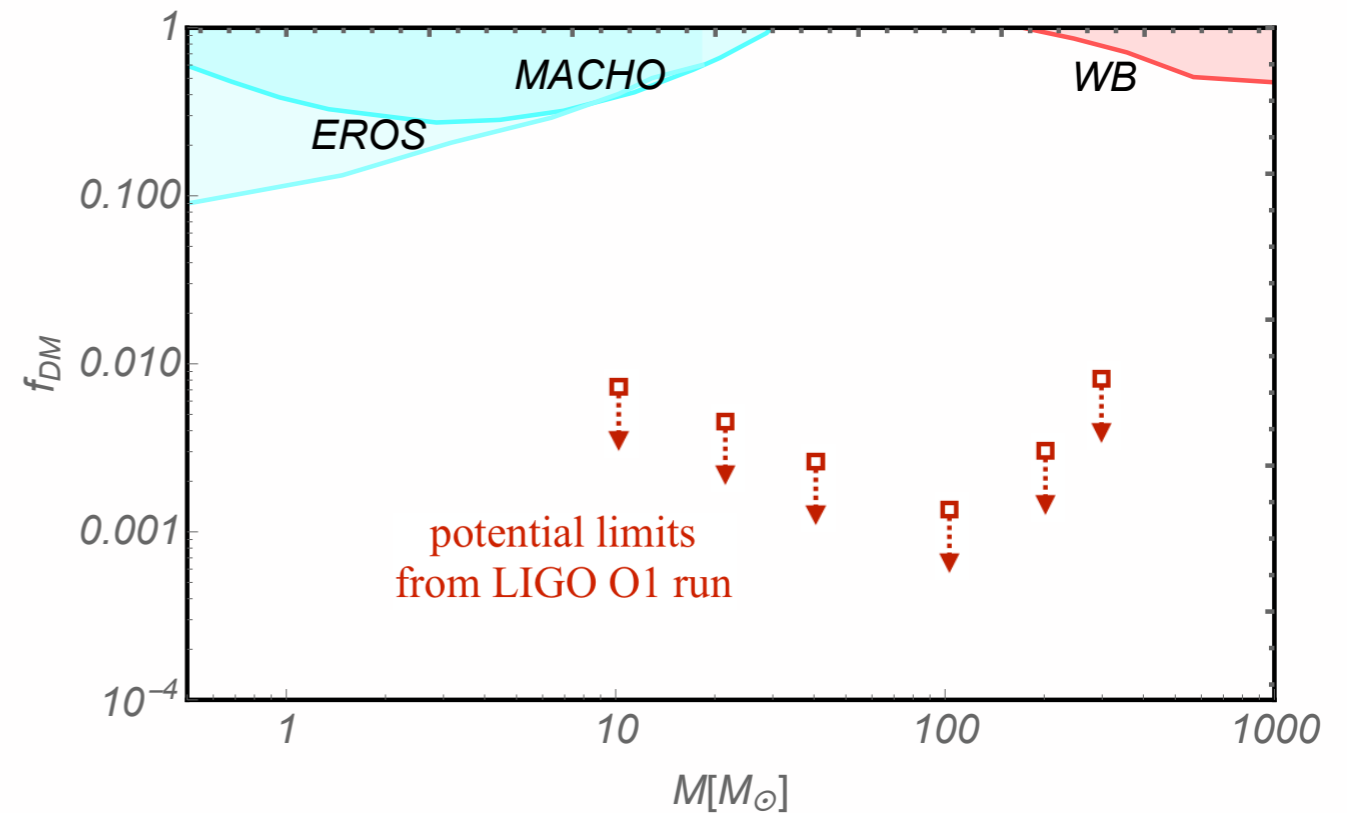
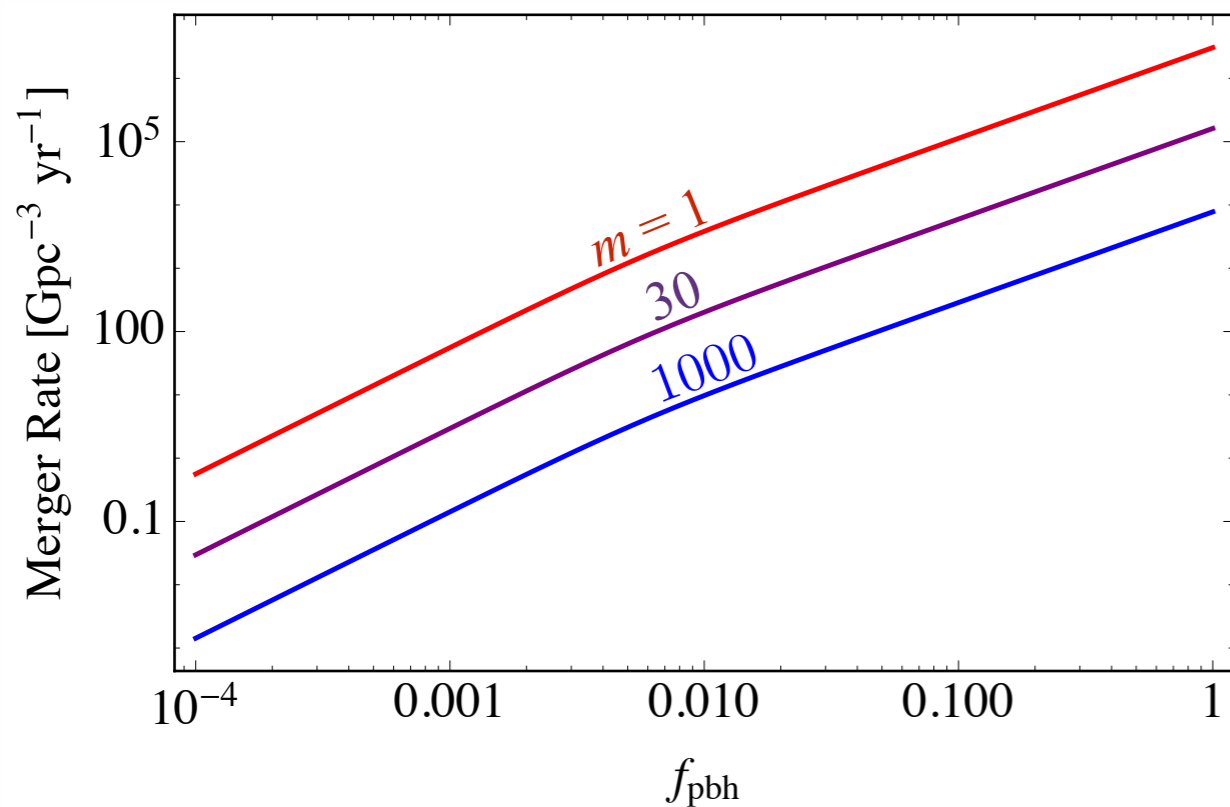
- effect of formation of first halos

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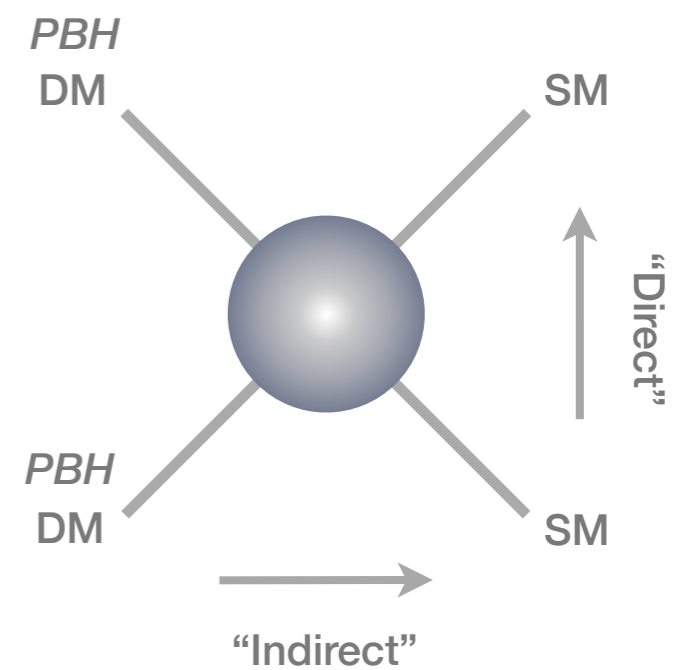


More (numerical) work needed to understand:

- effect of formation of first halos
- accretion onto extremely eccentric binaries

Outline

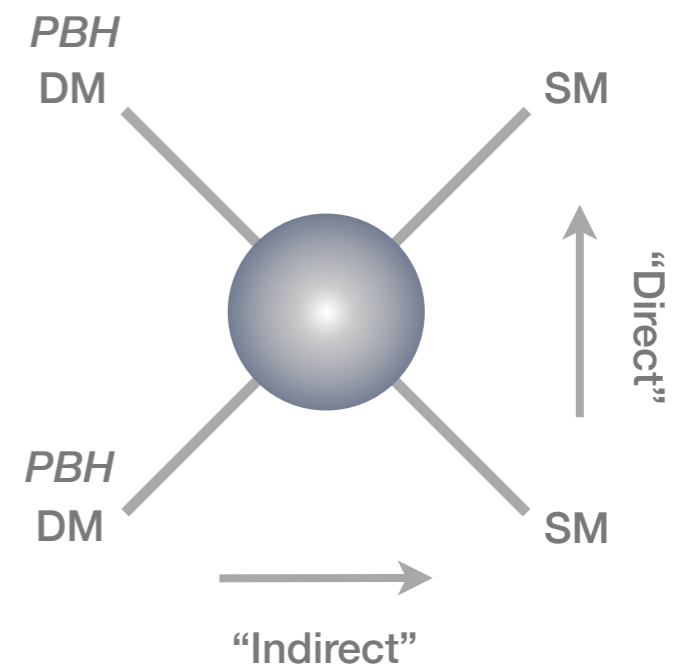
- Indirect Detection: GWs from PBH mergers



Outline

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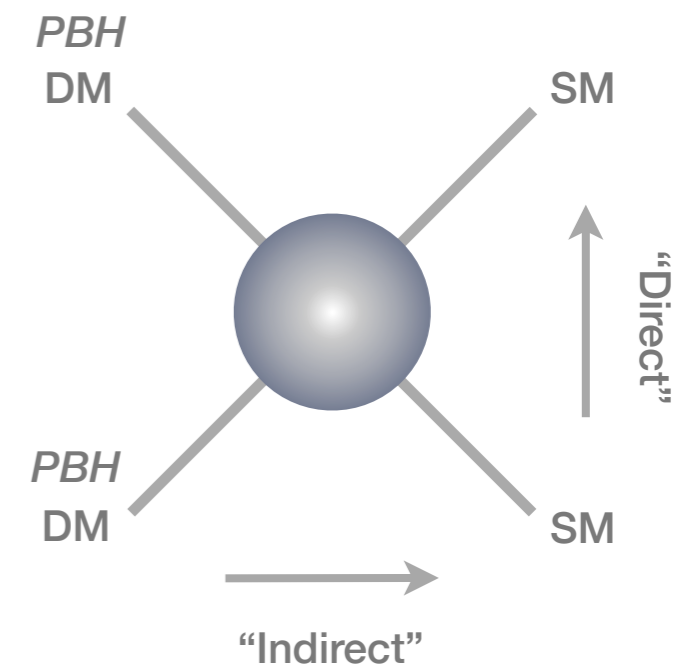


Outline

- Indirect Detection: GWs from PBH mergers

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“Lensing of Fast Radio Bursts as a Probe of Compact Dark Matter”
Muñoz, EDK, Dai & Kamionkowski, Phys. Rev. Lett. 117 (2016)



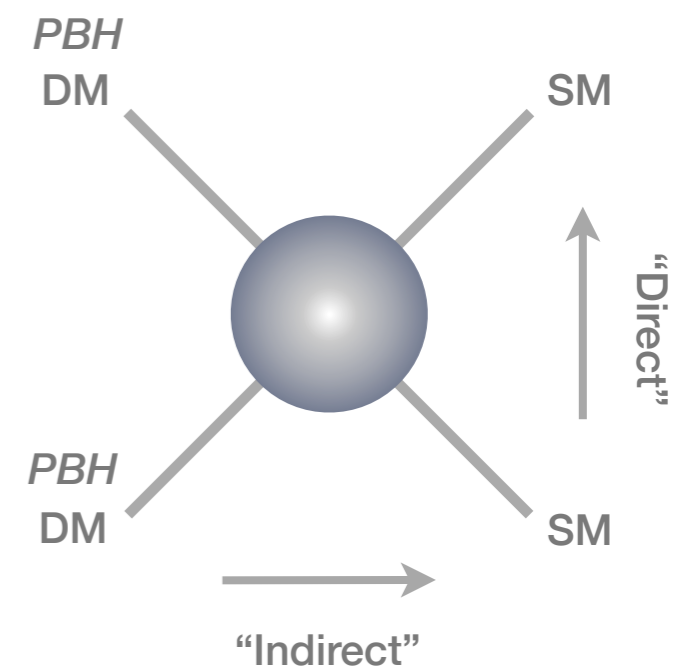
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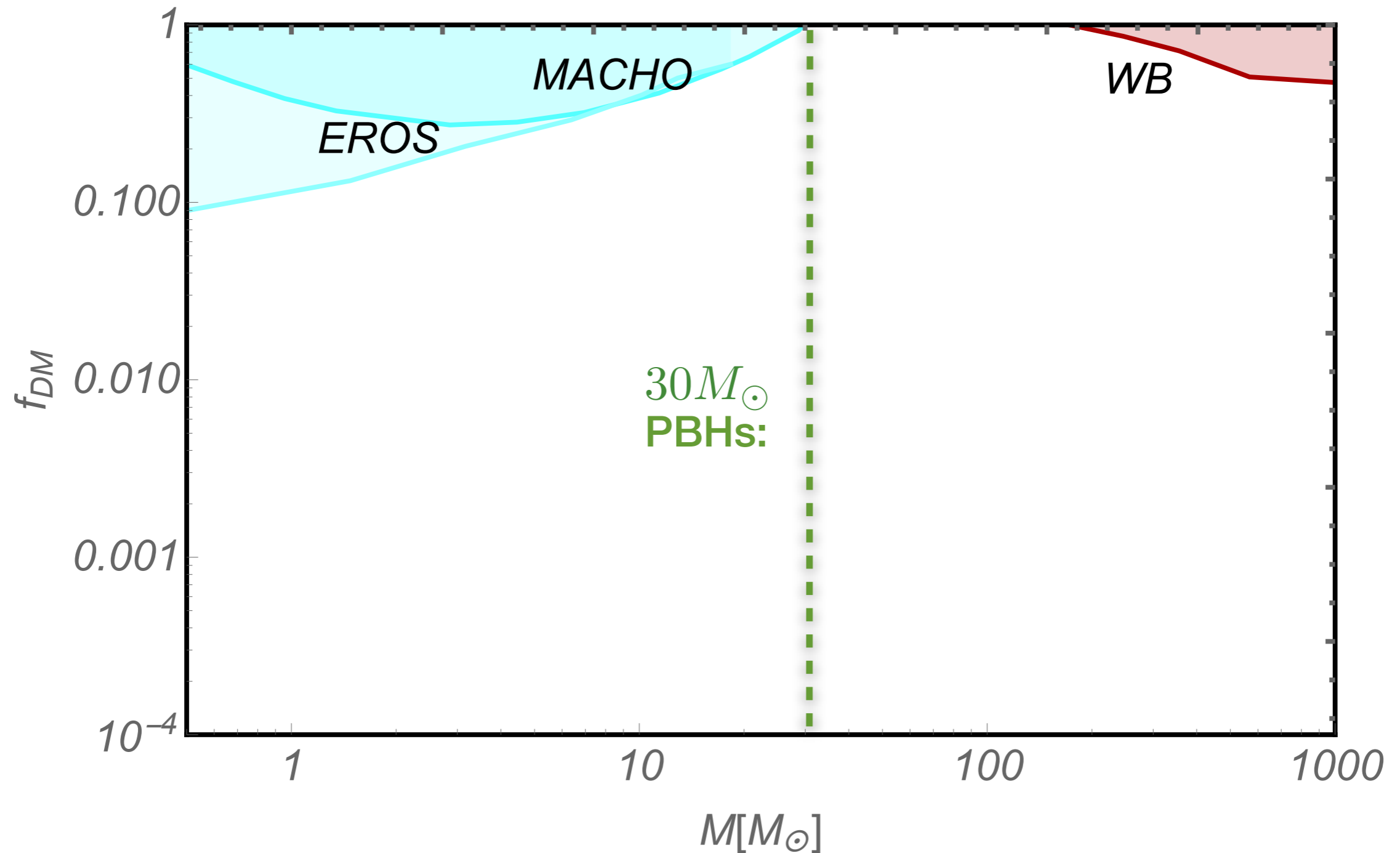
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“GRB Autocorrelations from Lensing by MACHOs”
Ji, EDK, Kamionkowski & Ménard, in preparation.



PBH DM: New Direct Constraints

Can we do better than with microlensing of stars?

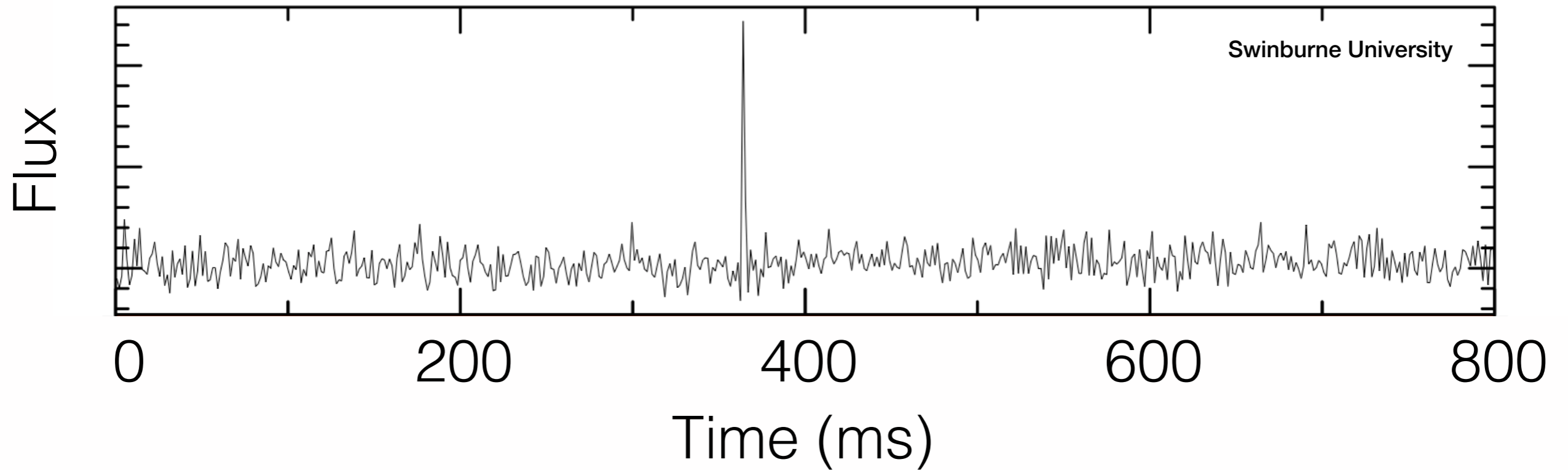


Fast Radio Bursts

(Muñoz, EDK, Dai, Kamionkowski, PRL 117 (2016))

Fast Radio Bursts

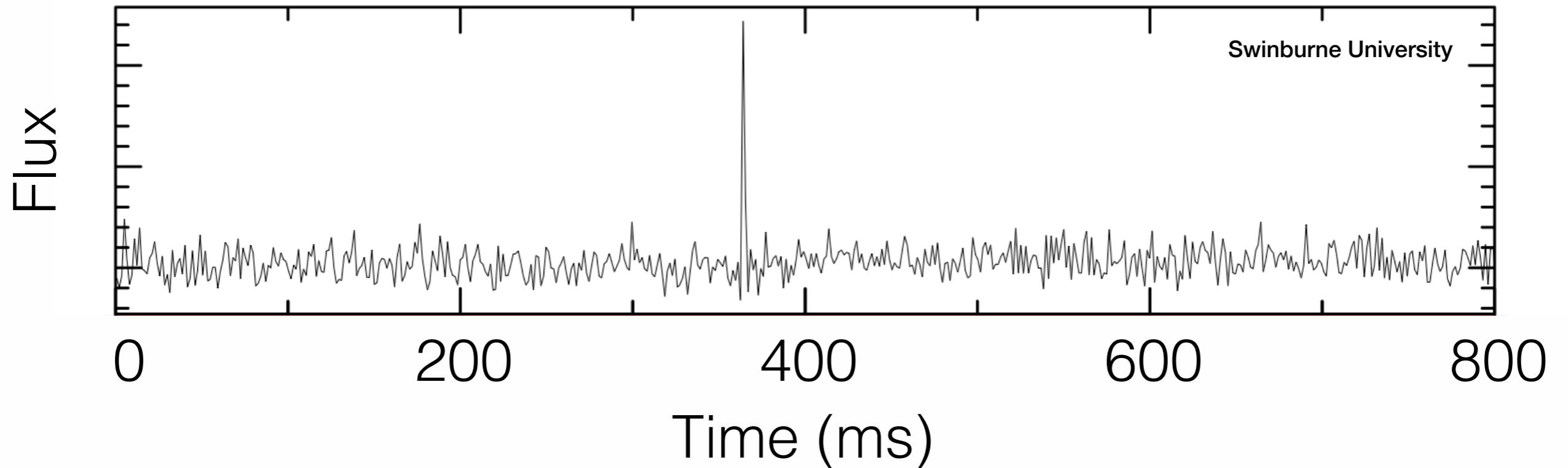
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Fast Radio Bursts

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What are they?

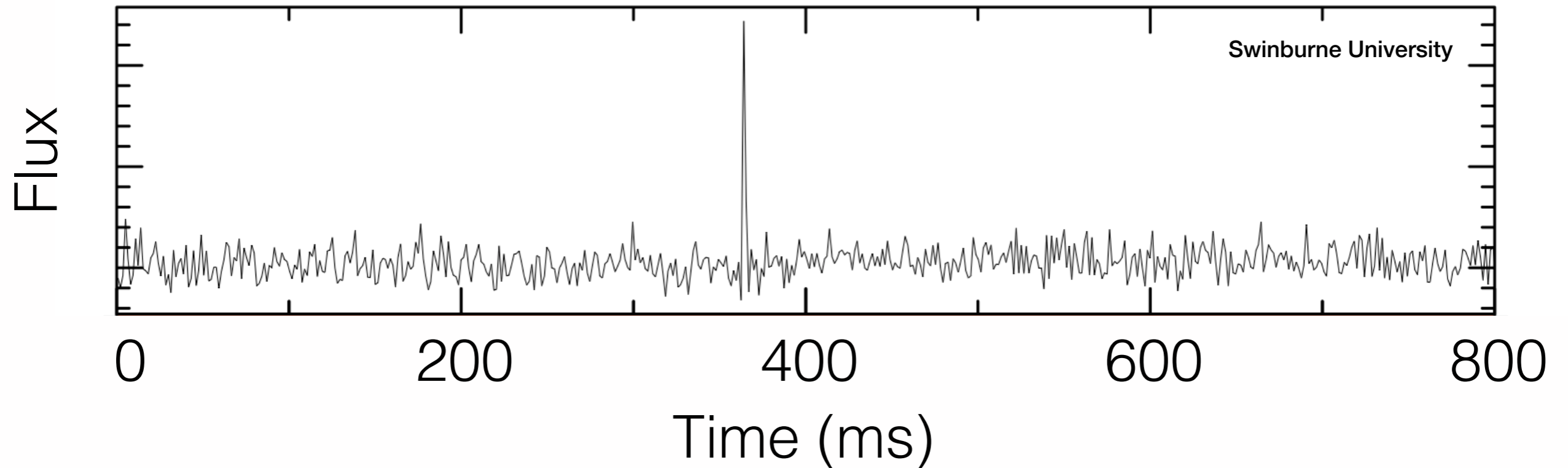


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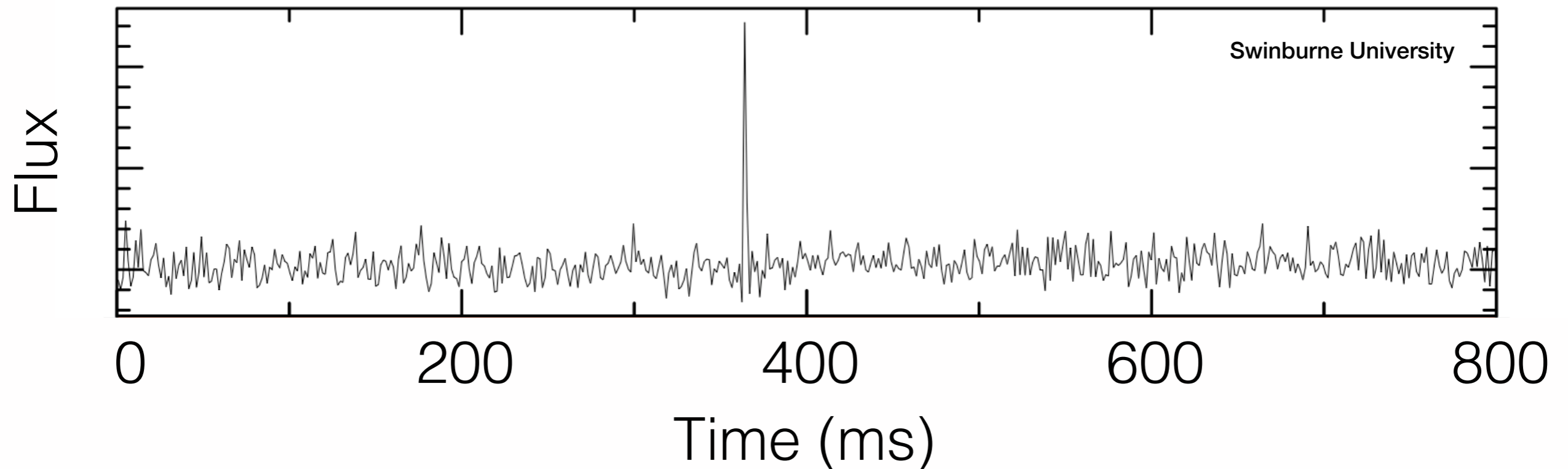


Fast Radio Bursts

(Muñoz, EDK, Dai, Kamionkowski, PRL 117 (2016))

What are they?

- Literally: Fast
 $\mathcal{O}(1)$ ms



Fast Radio Bursts

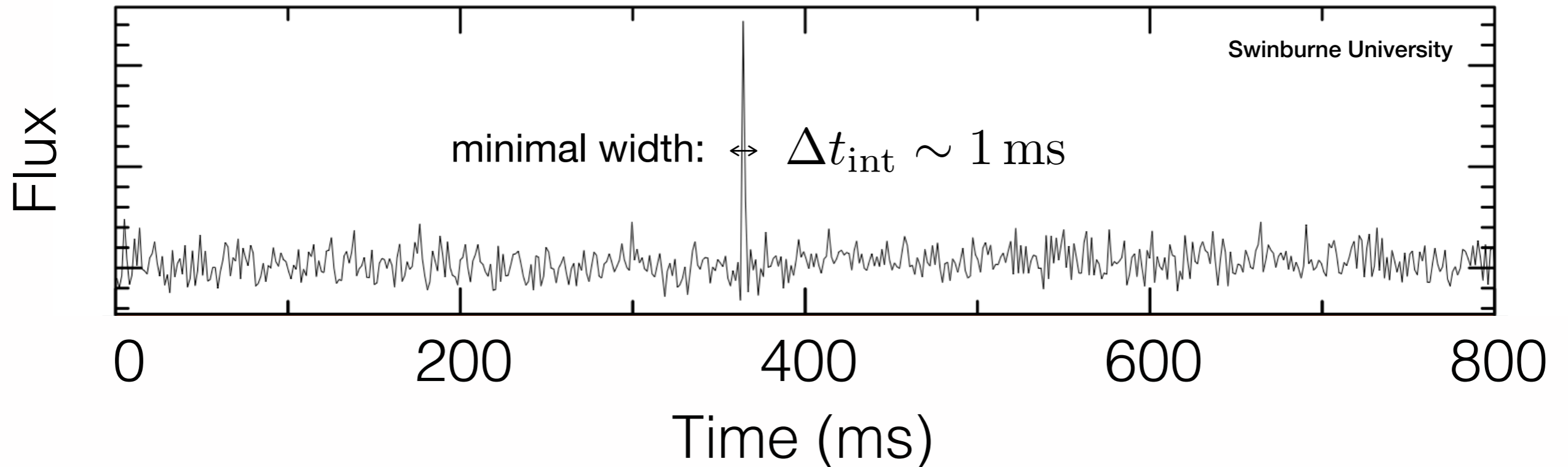
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Fast Radio Bursts

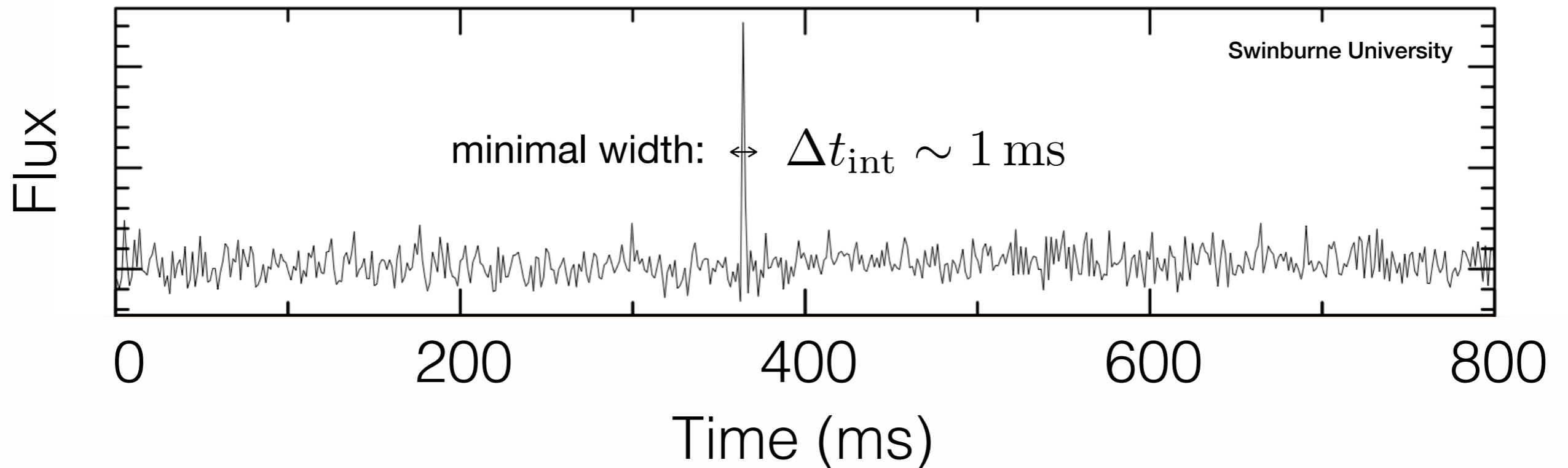
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Radio
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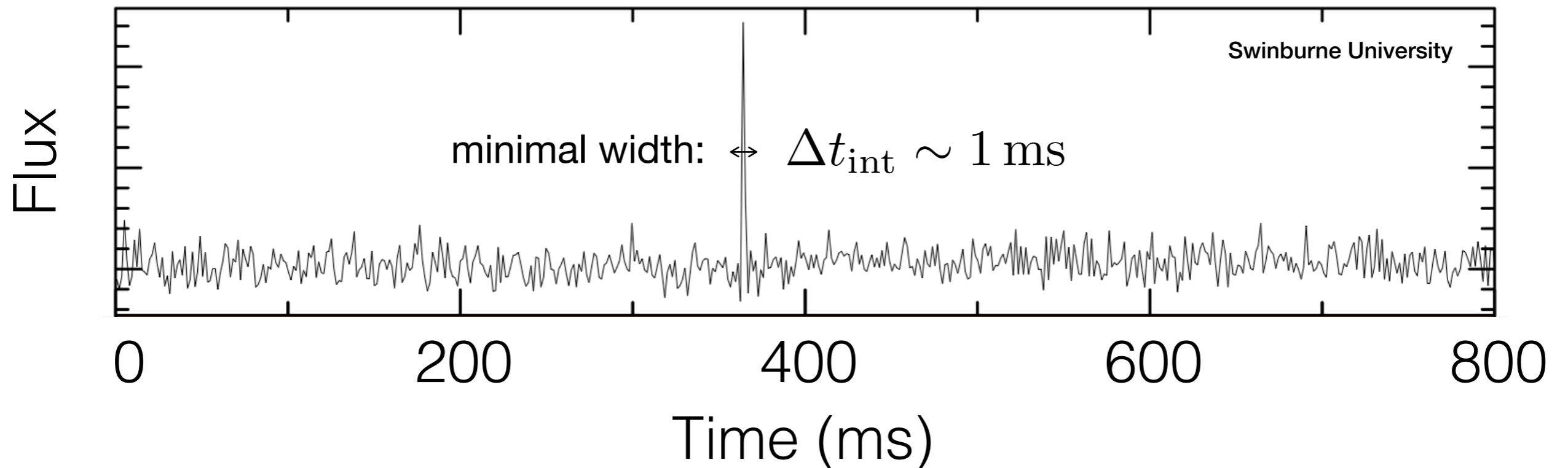
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Radio
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Bursts
 $\mathcal{O}(1)$ Jy



Fast Radio Bursts

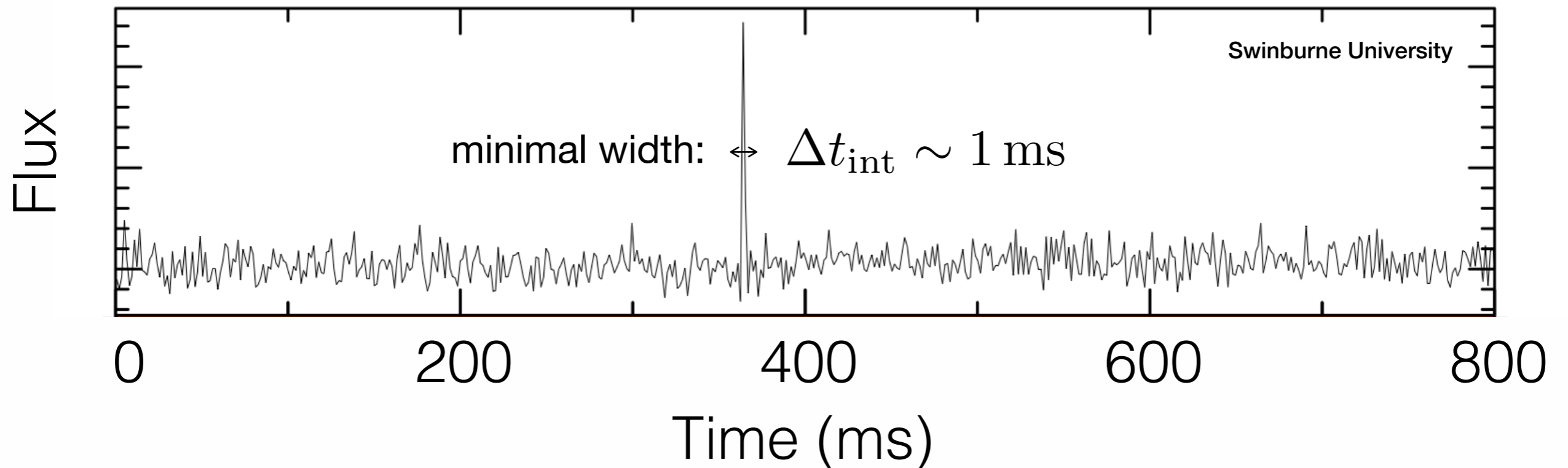
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- Literally:

Fast	Radio	Bursts
$\mathcal{O}(1)$ ms	~ 1 GHz	$\mathcal{O}(1)$ Jy

- Extragalactic (cosmological distances)



Fast Radio Bursts

(Muñoz, EDK, Dai, Kamionkowski, PRL 117 (2016))

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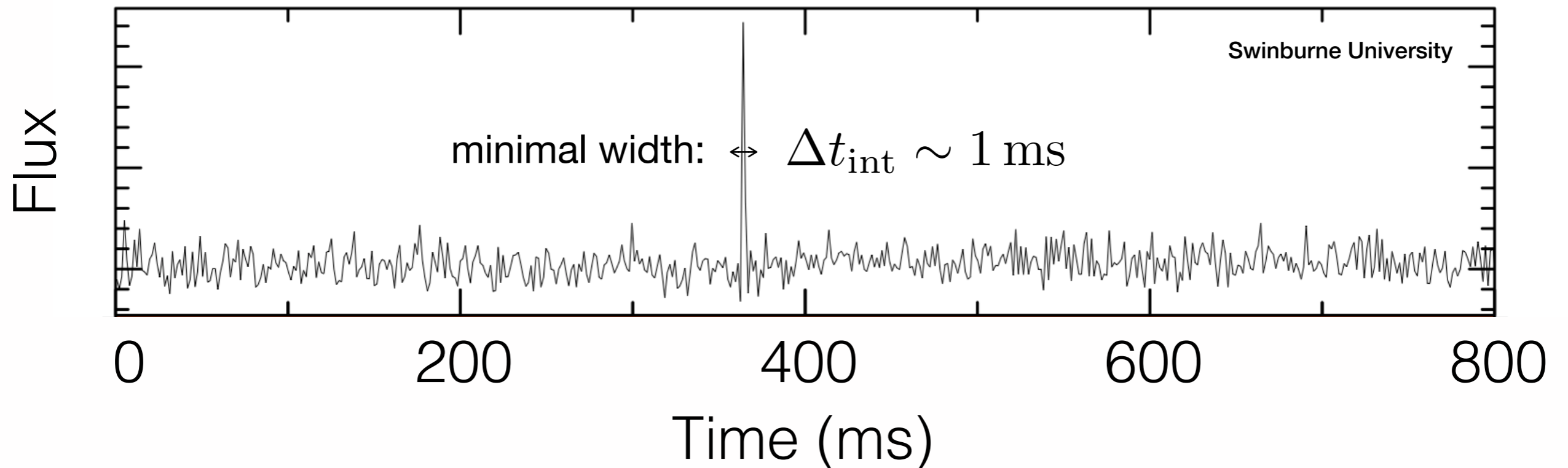
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Fast
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Radio
 ~ 1 GHz

Bursts
 $\mathcal{O}(1)$ Jy
↙ @ 1 Gpc

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Fast Radio Bursts

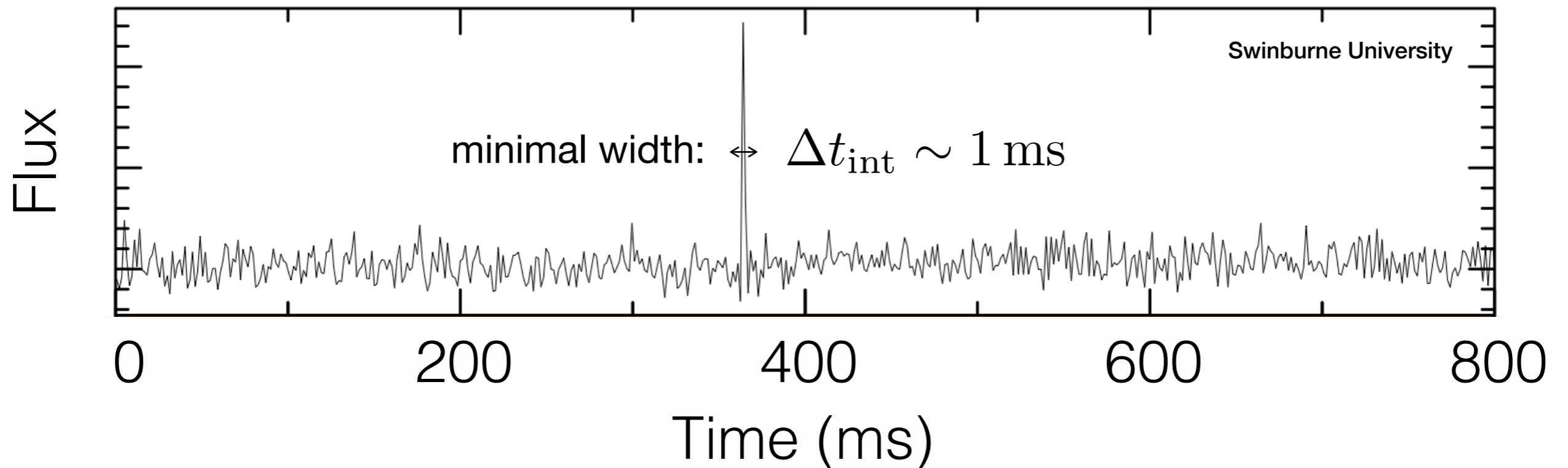
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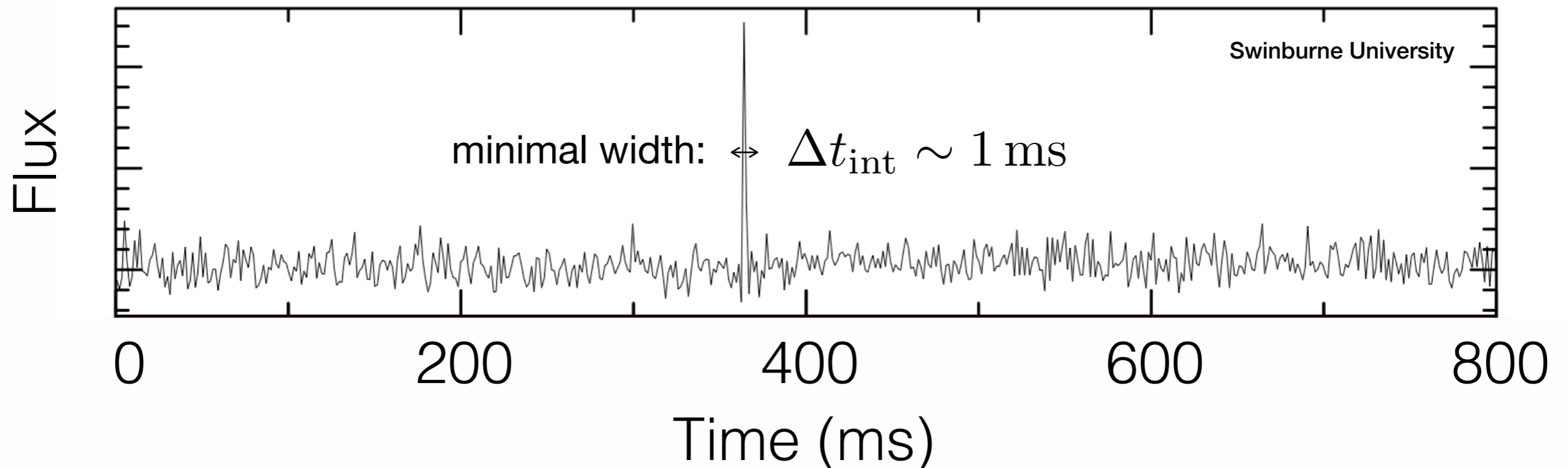
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- Extragalactic (cosmological distances)
 $\mathcal{O}(10^{39})$ ergs
- Estimated rate: $\mathcal{O}(10^4)$ sky $^{-1}$ day $^{-1}$ (based on handful observed)

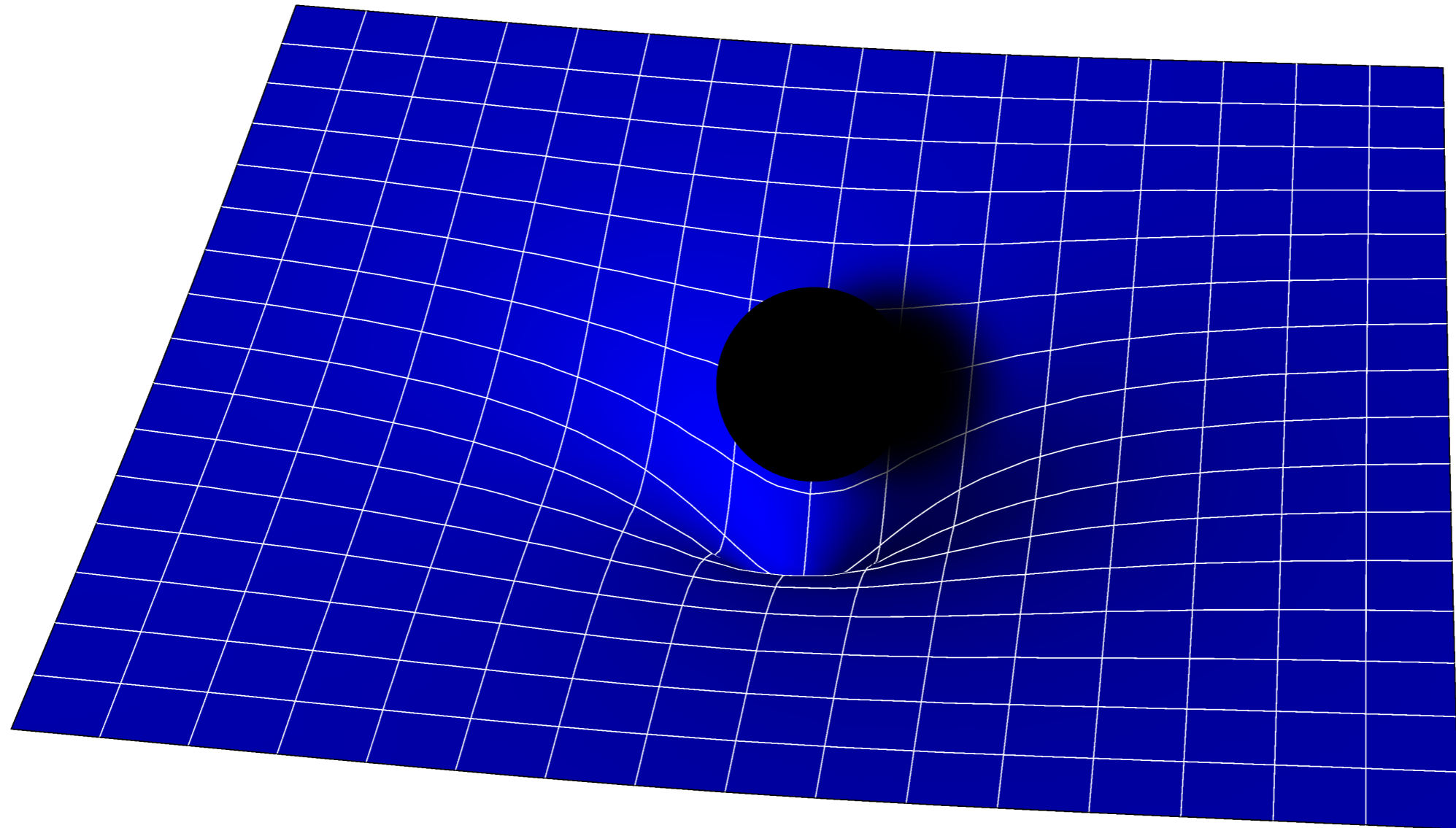


Constraining MACHO Dark Matter: FRB Lensing

(Muñoz, EDK, Dai, Kamionkowski, PRL 117 (2016))

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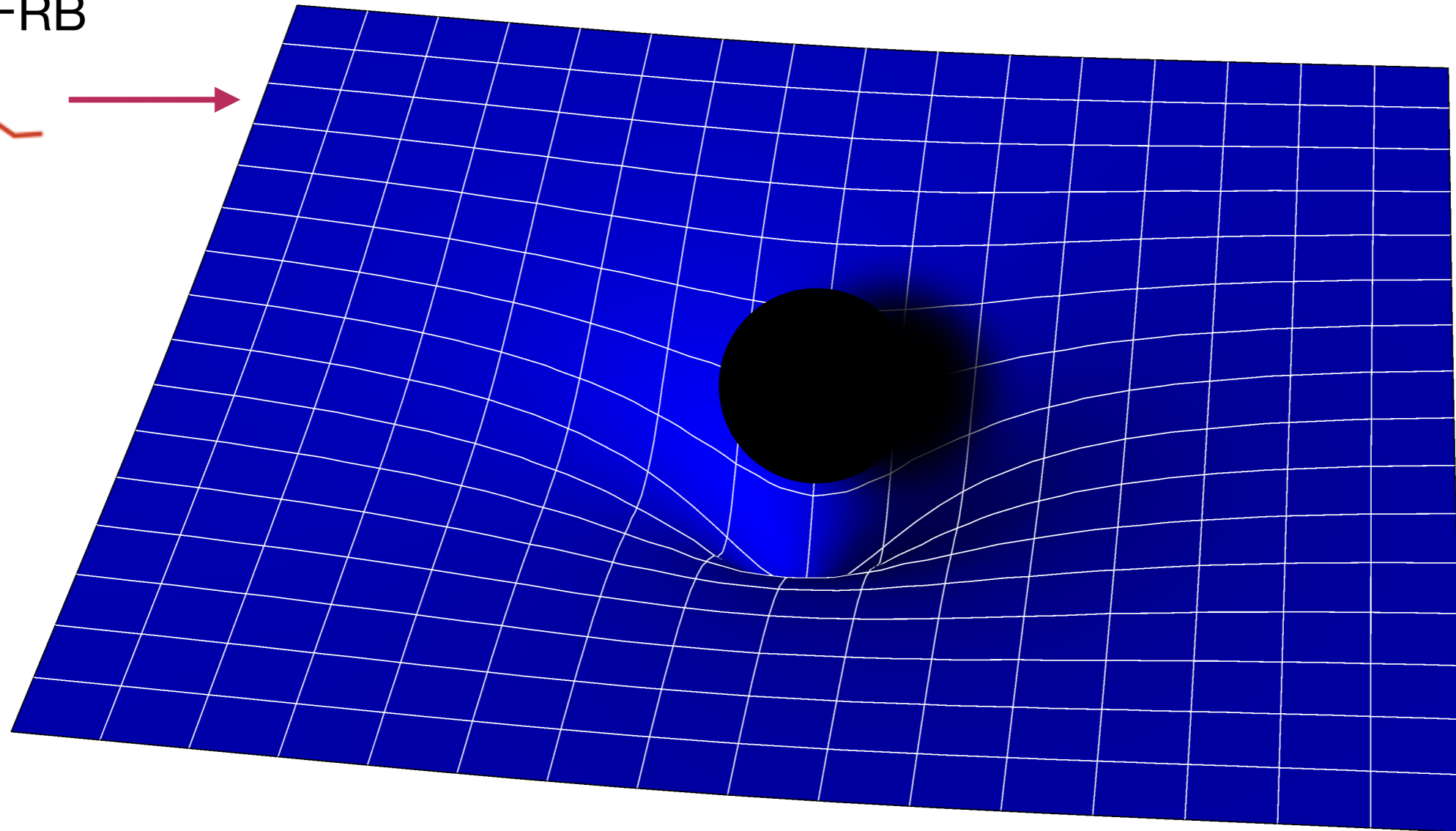
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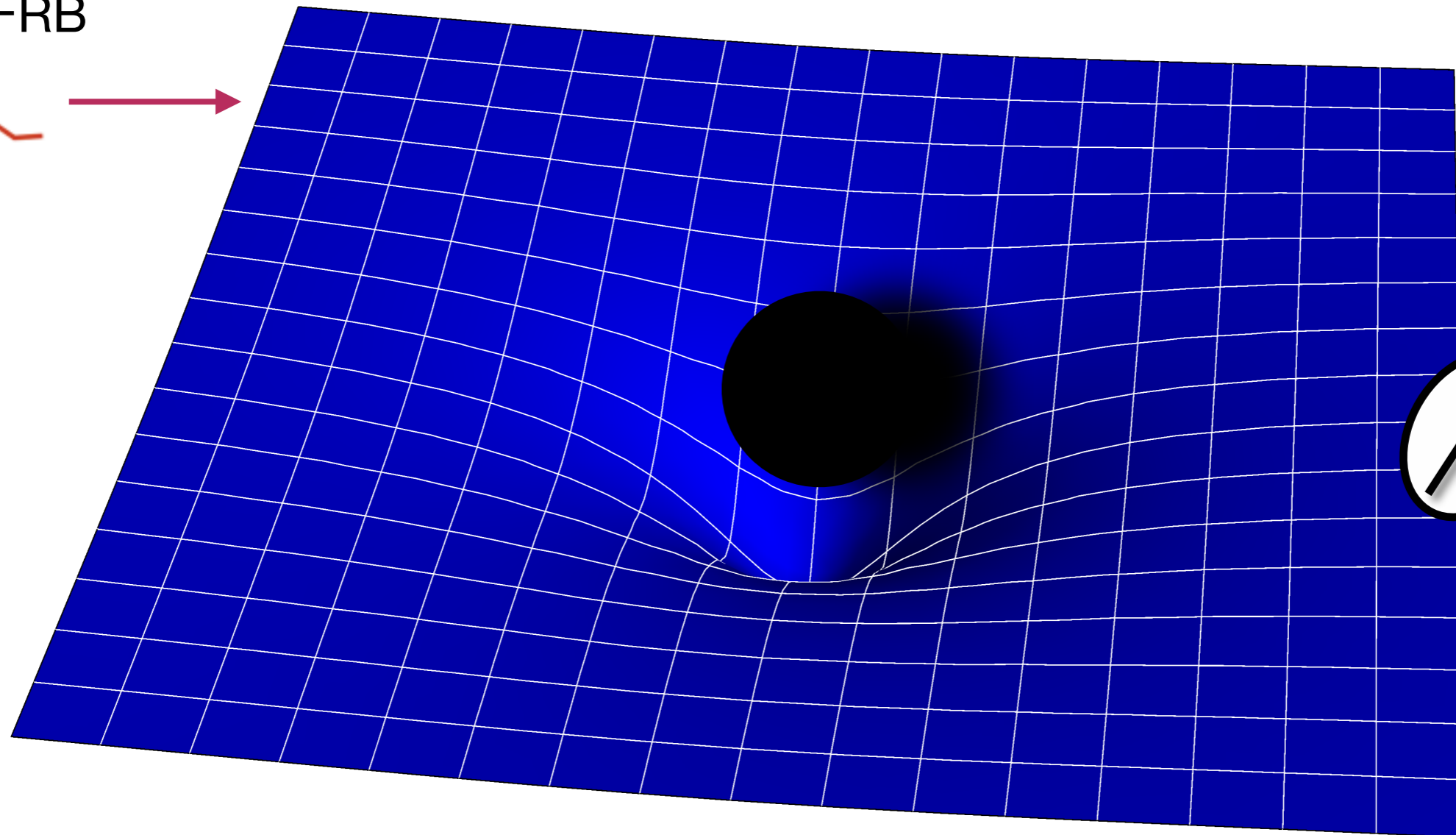
Source FRB



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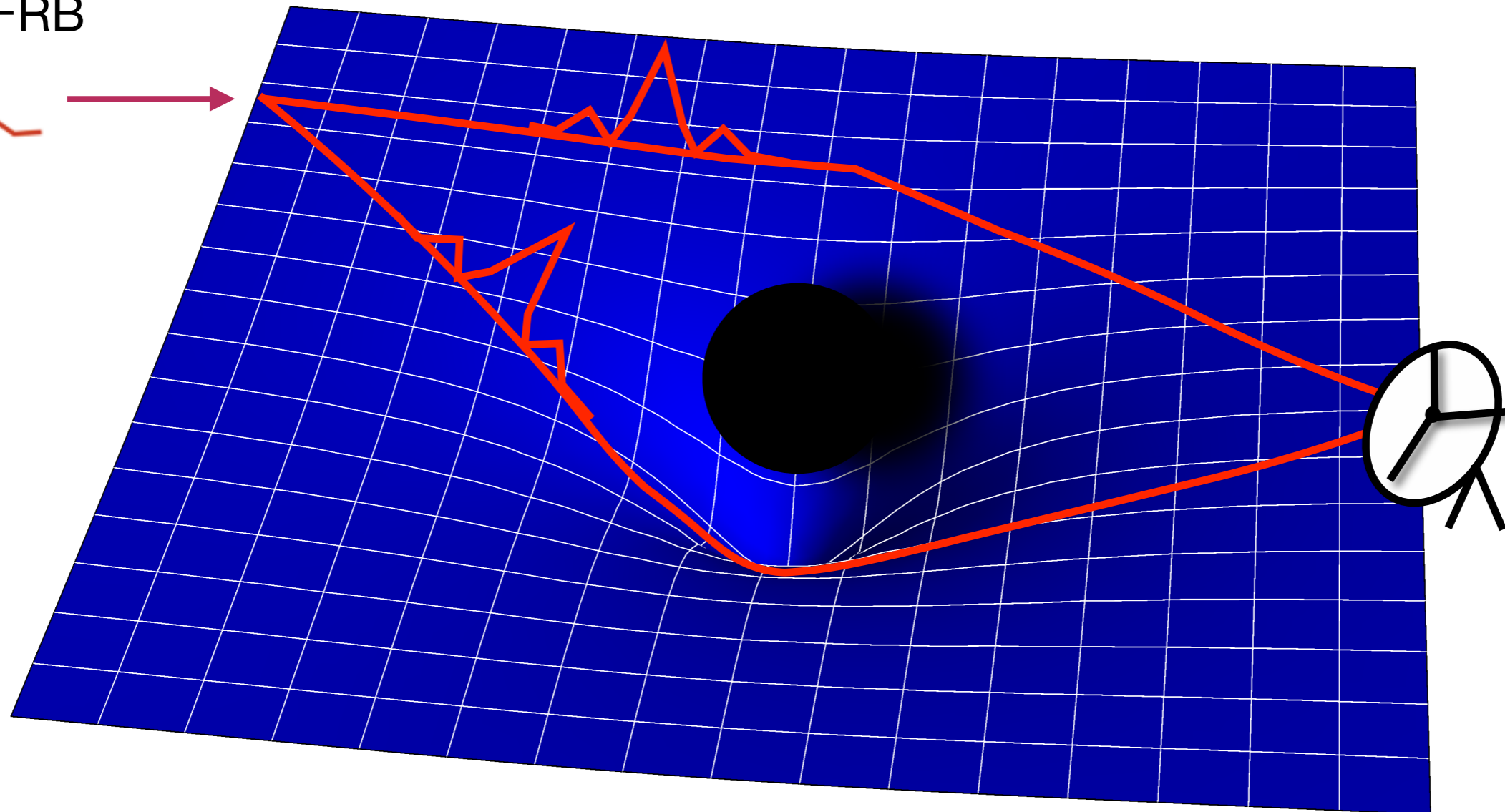
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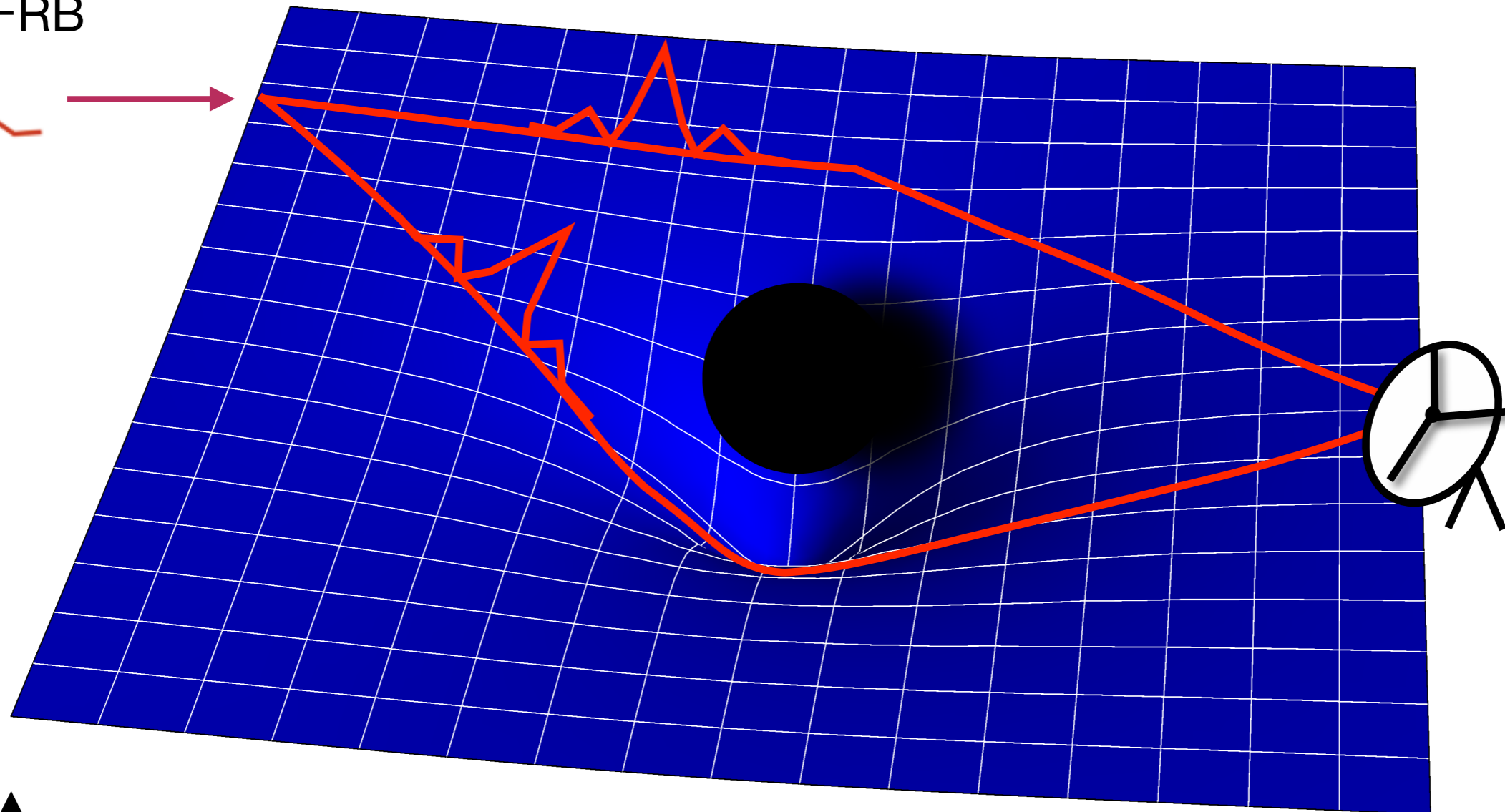
Source FRB



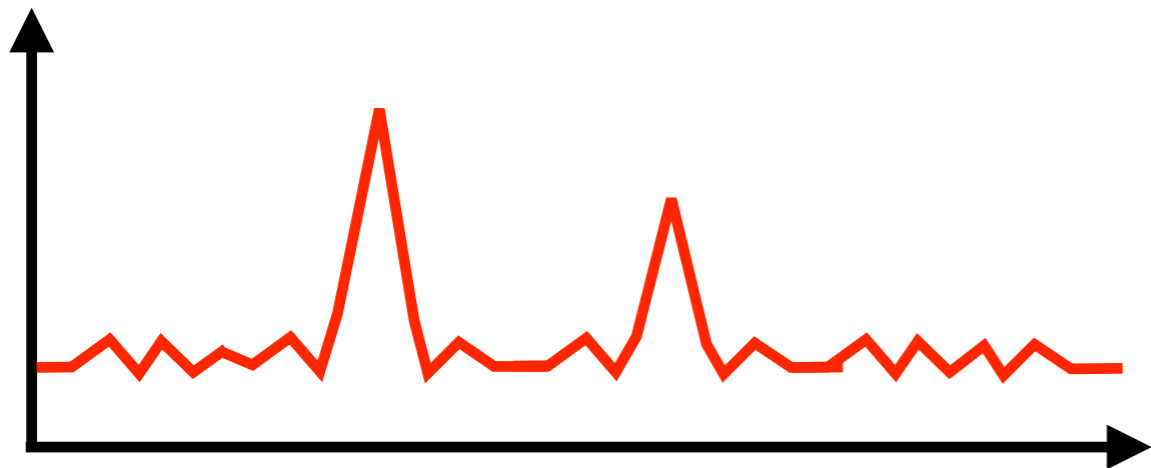
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Source FRB



flux

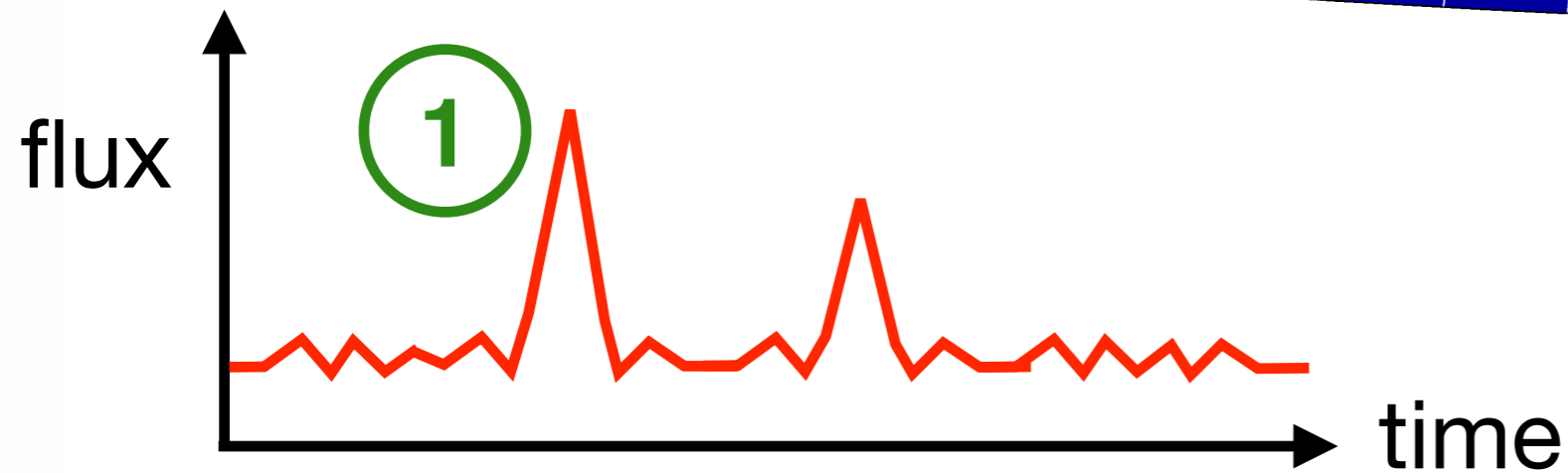
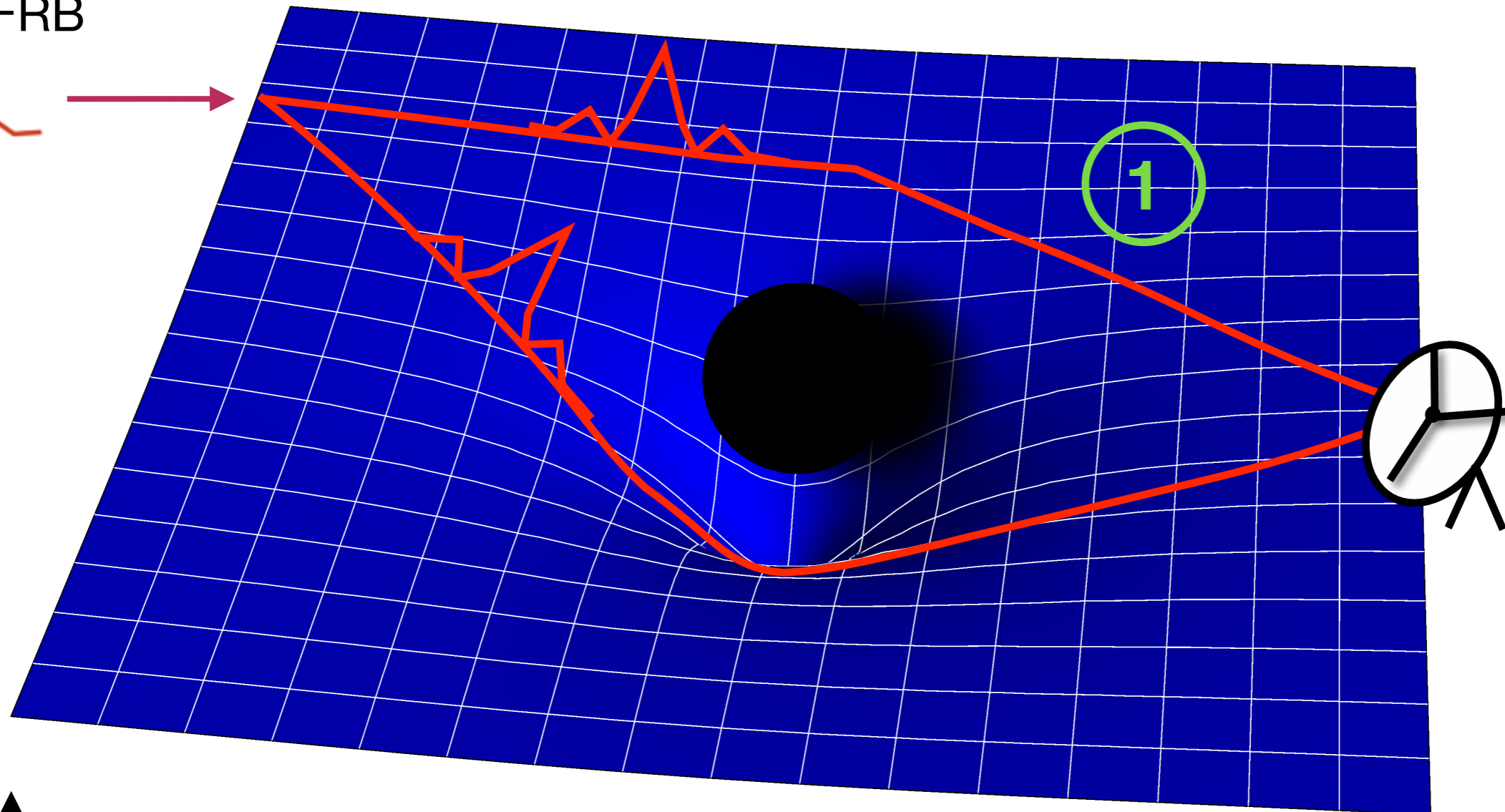


time

Constraining MACHO Dark Matter: FRB Lensing

(Muñoz, EDK, Dai, Kamionkowski, PRL 117 (2016))

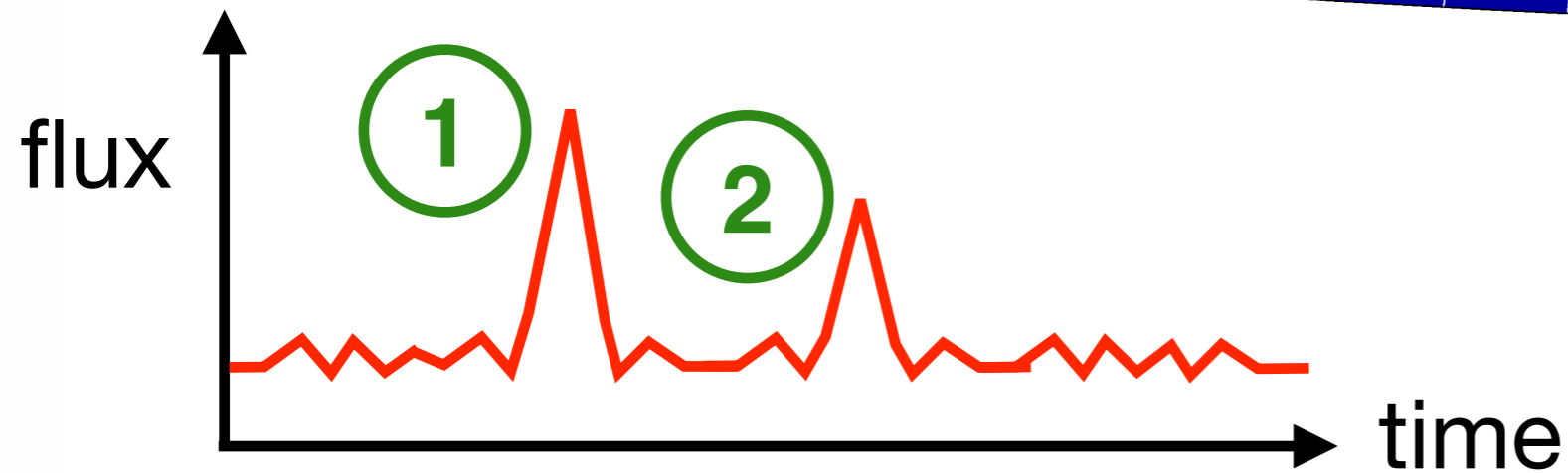
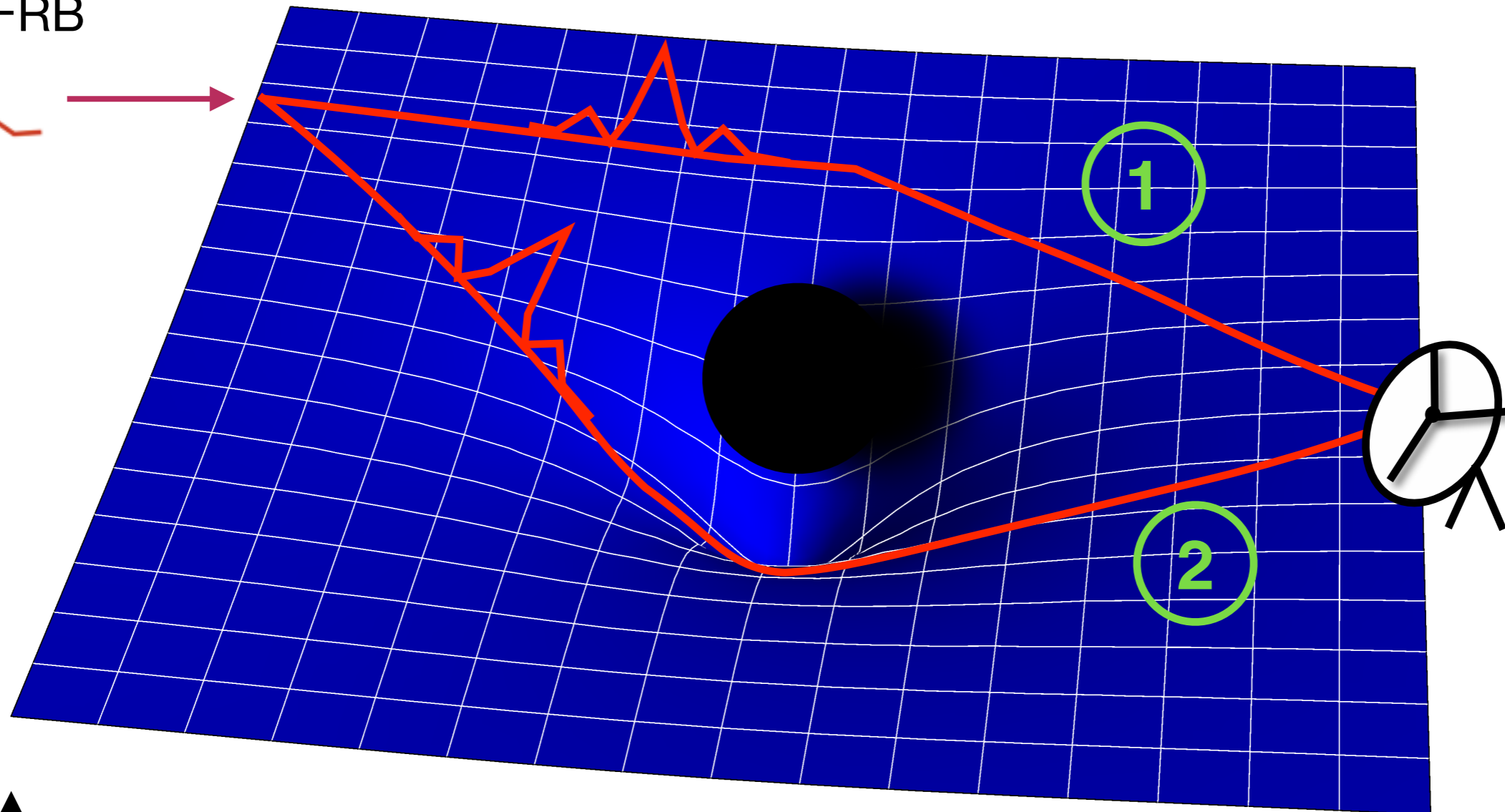
Source FRB



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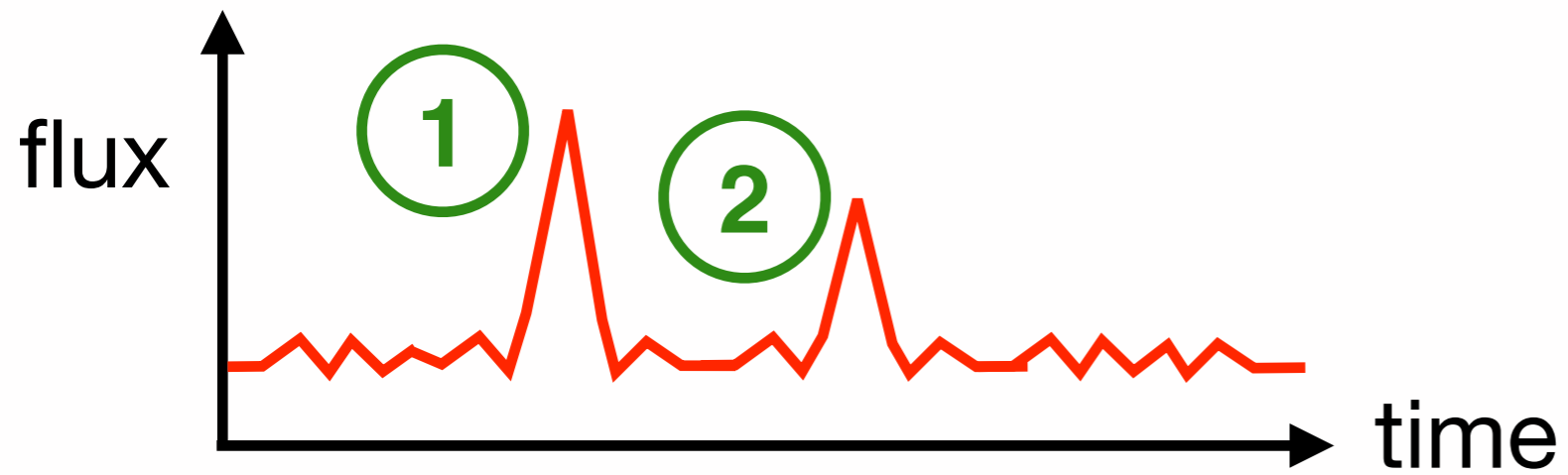
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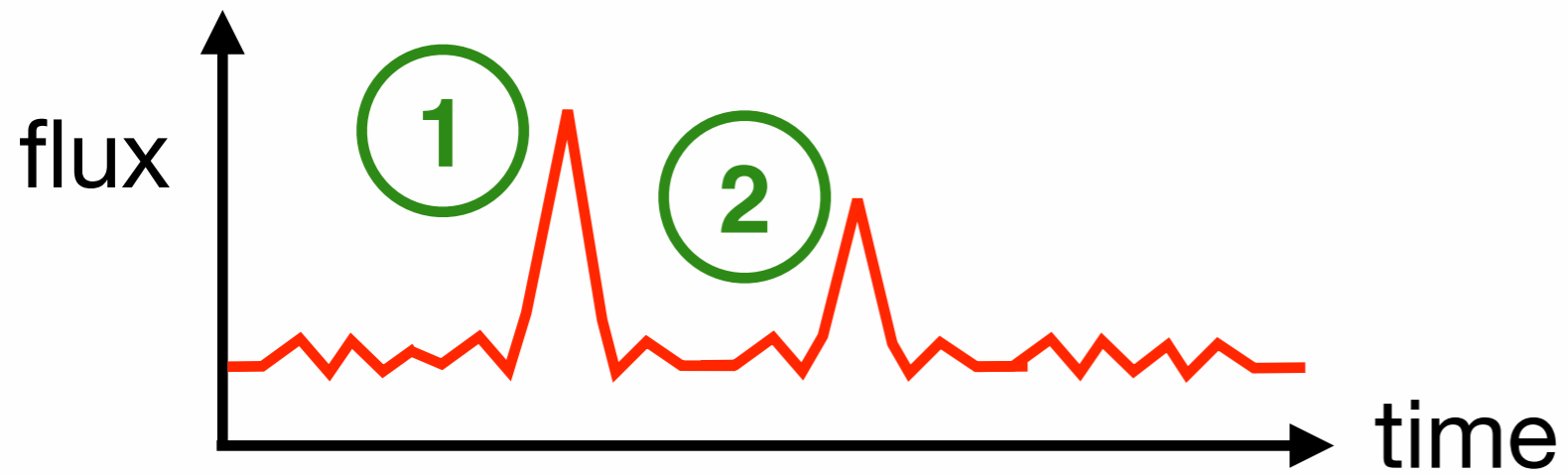
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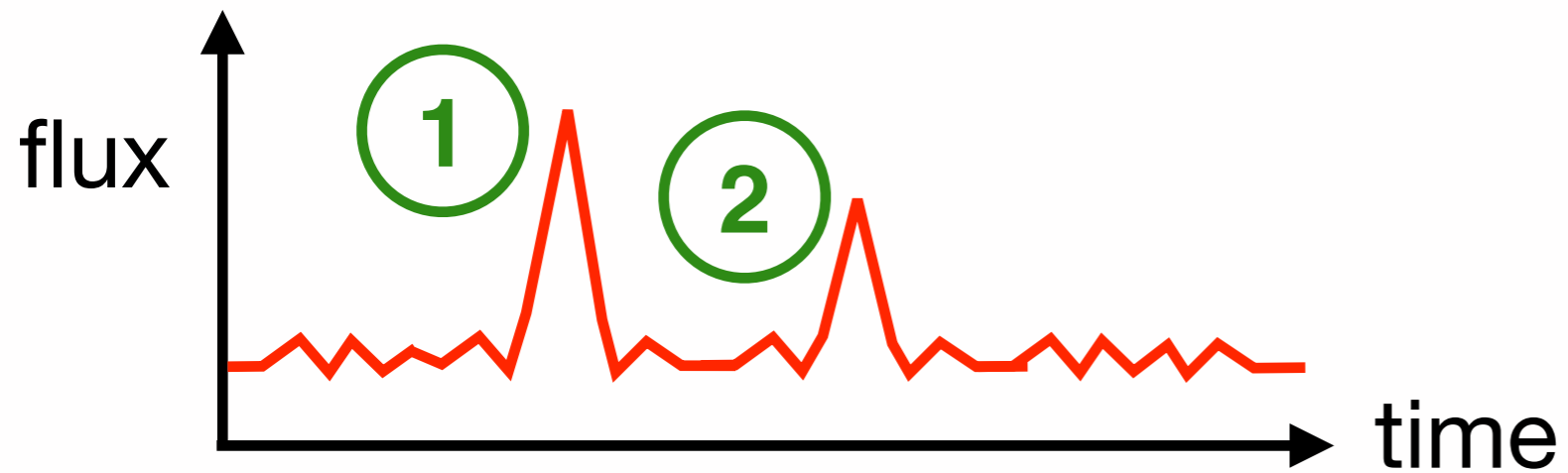


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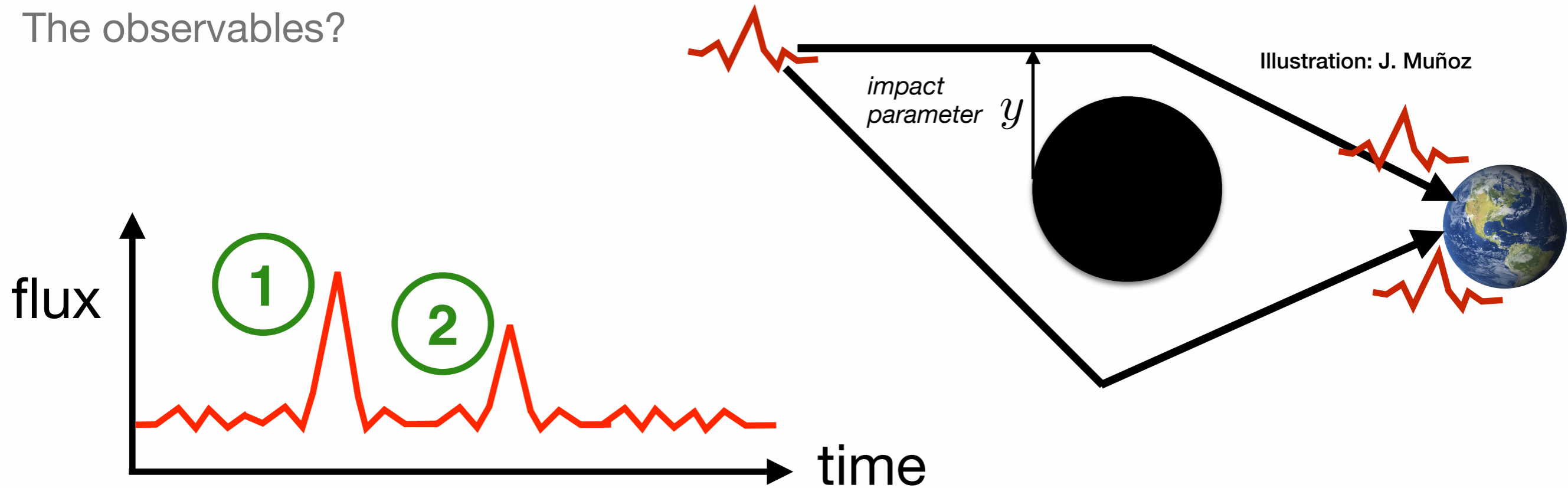
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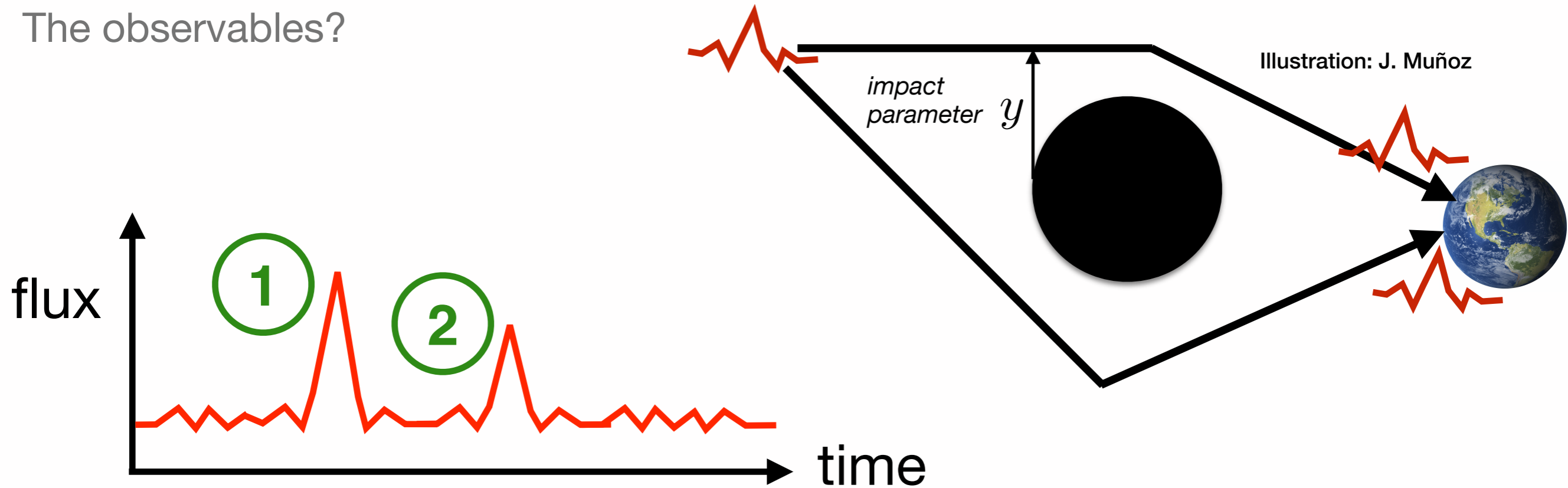
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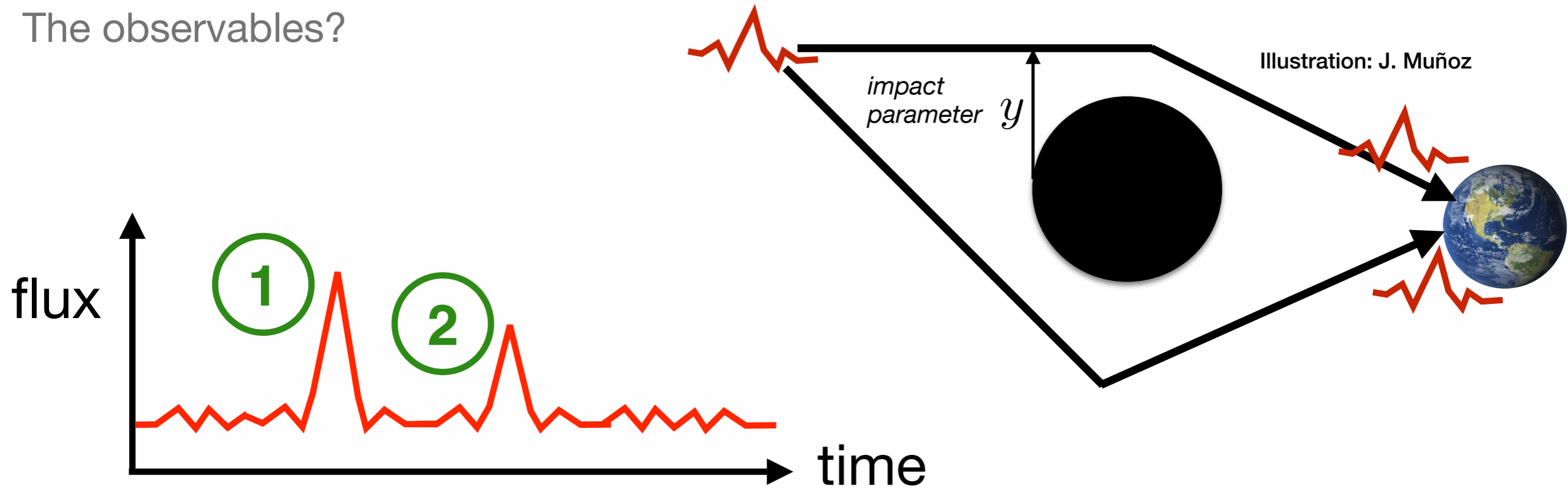
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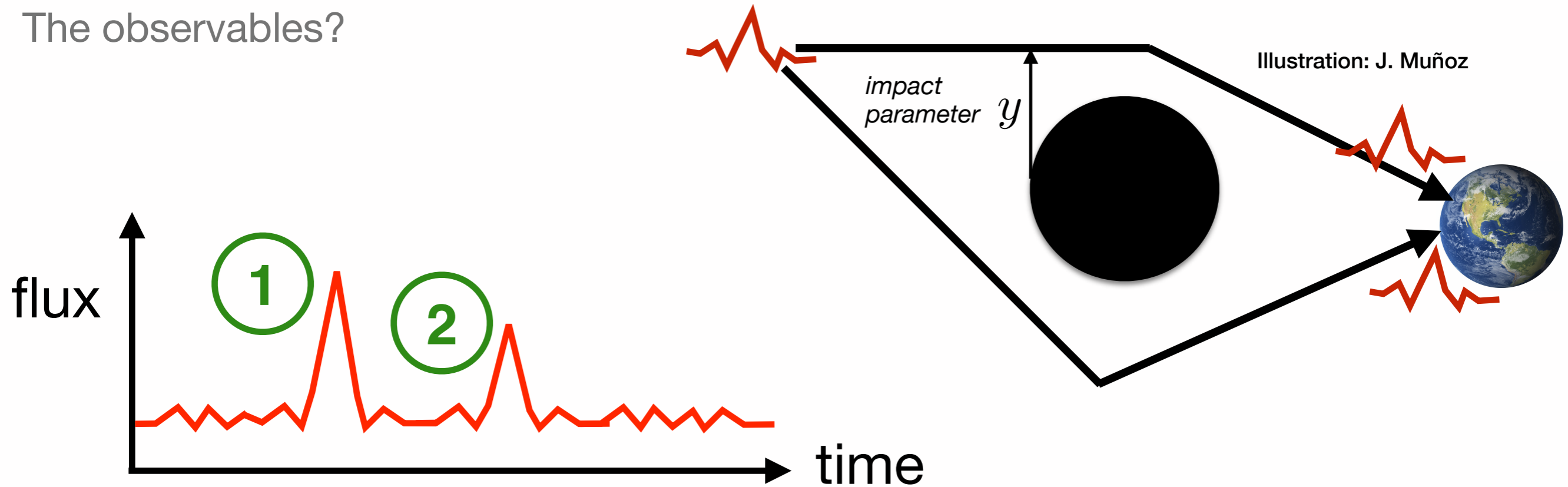
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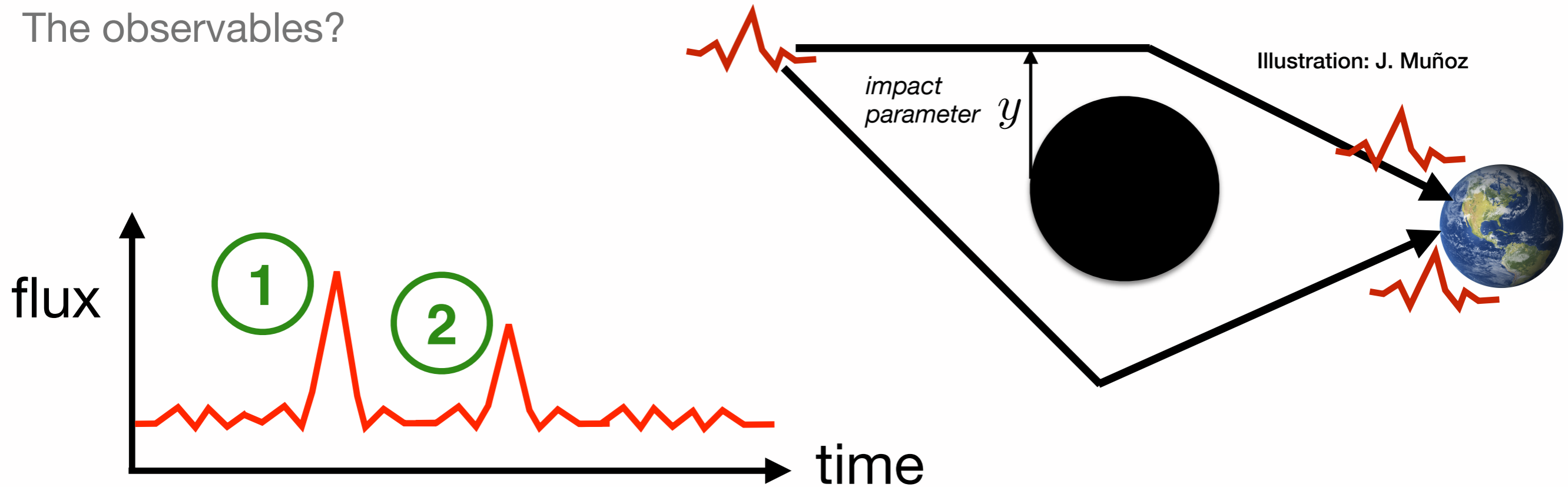
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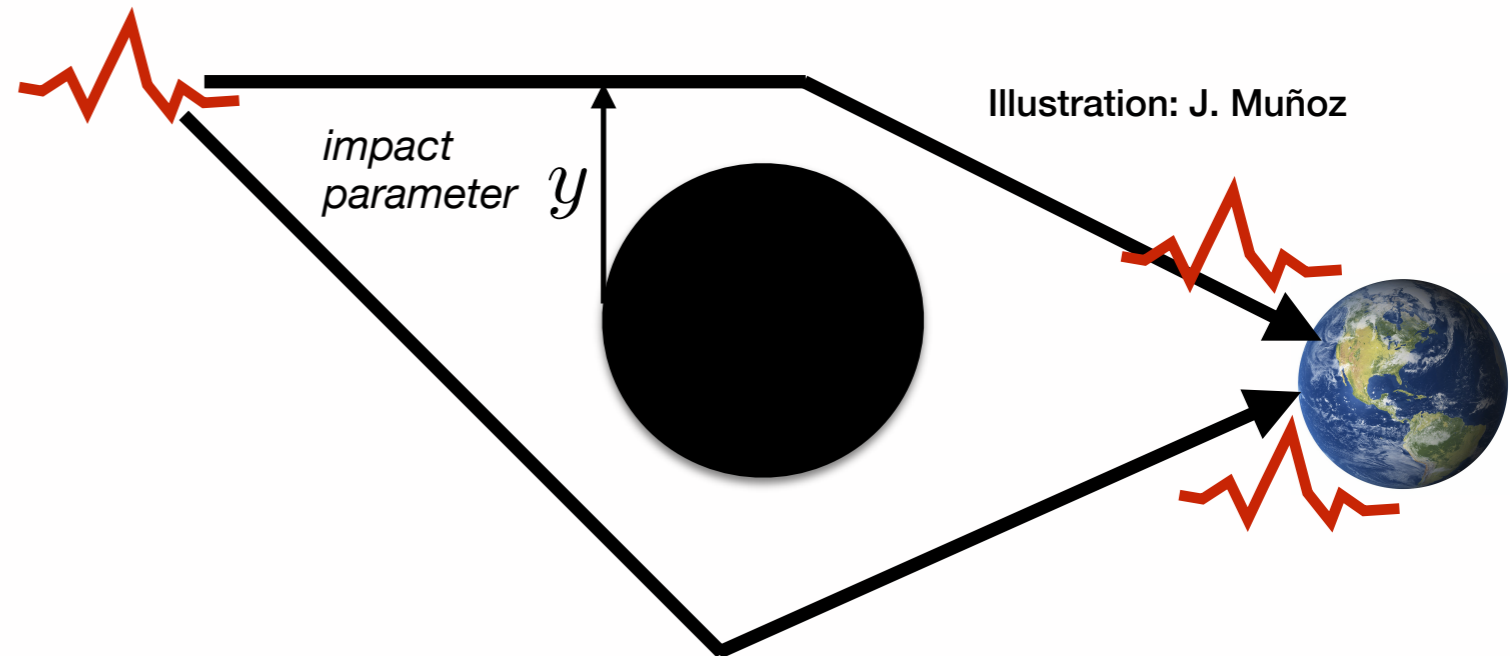
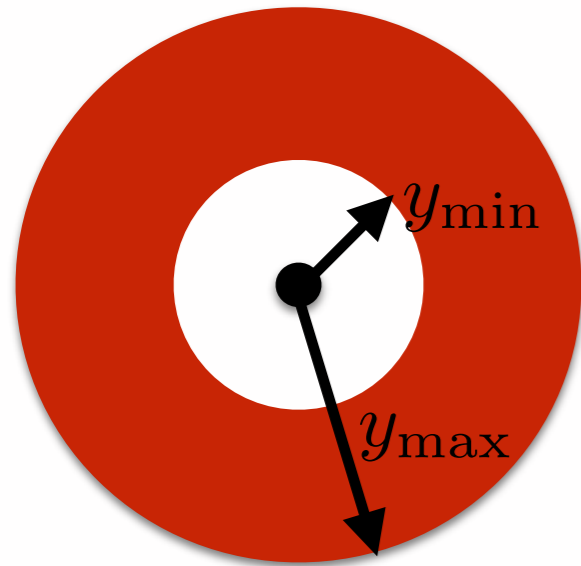
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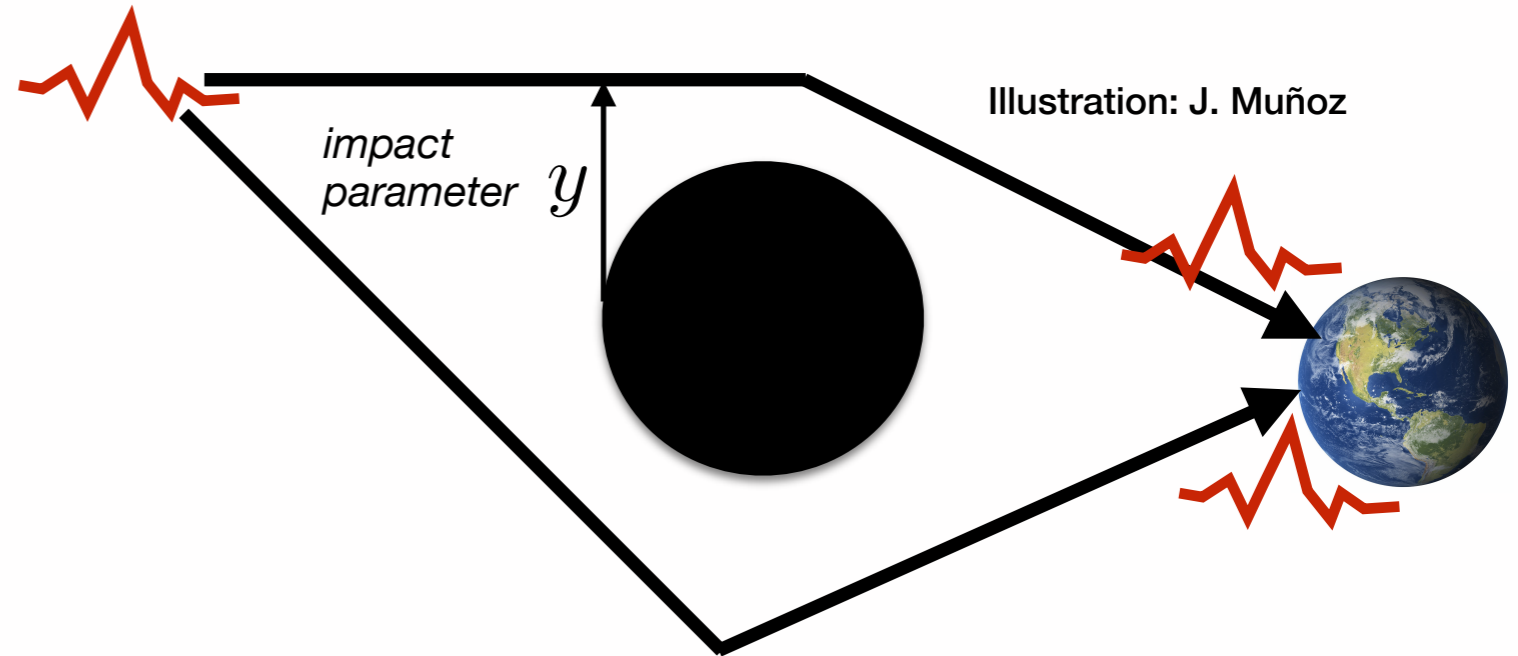
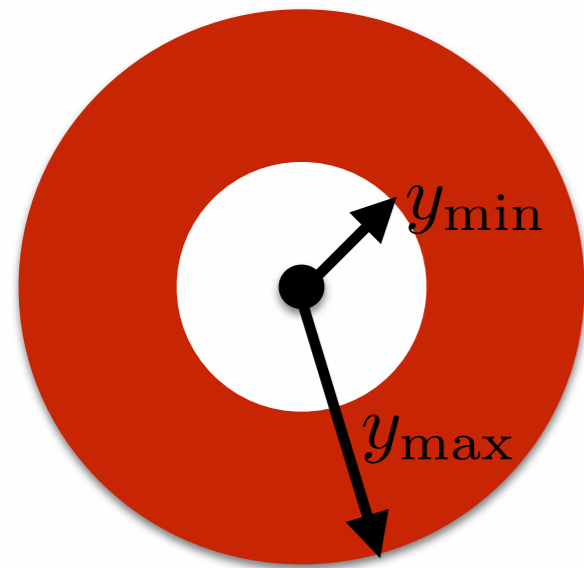
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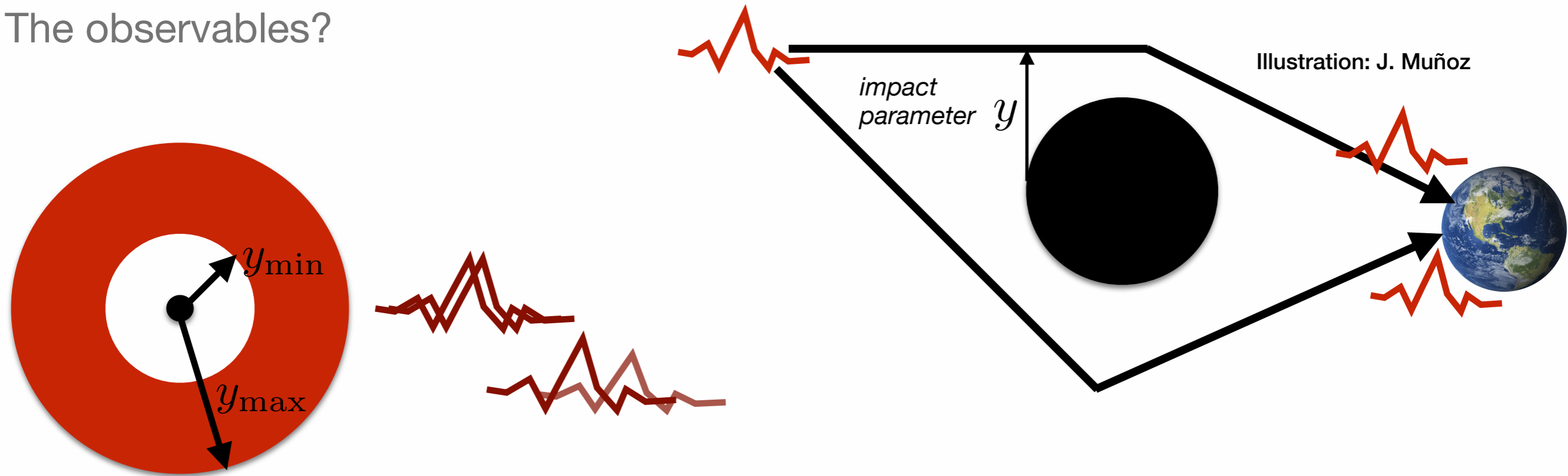
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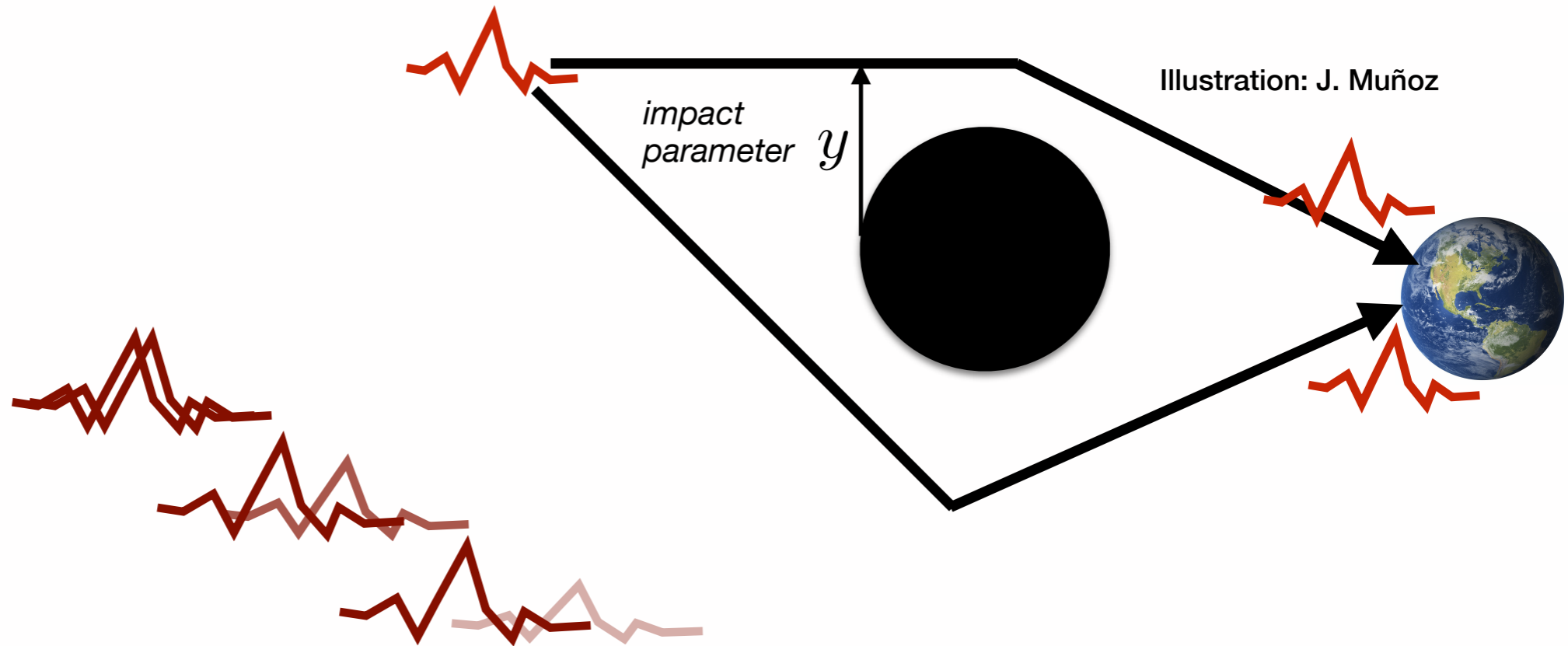
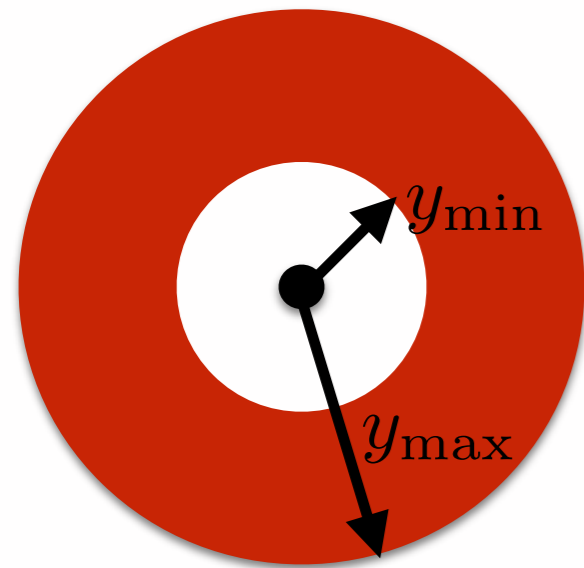
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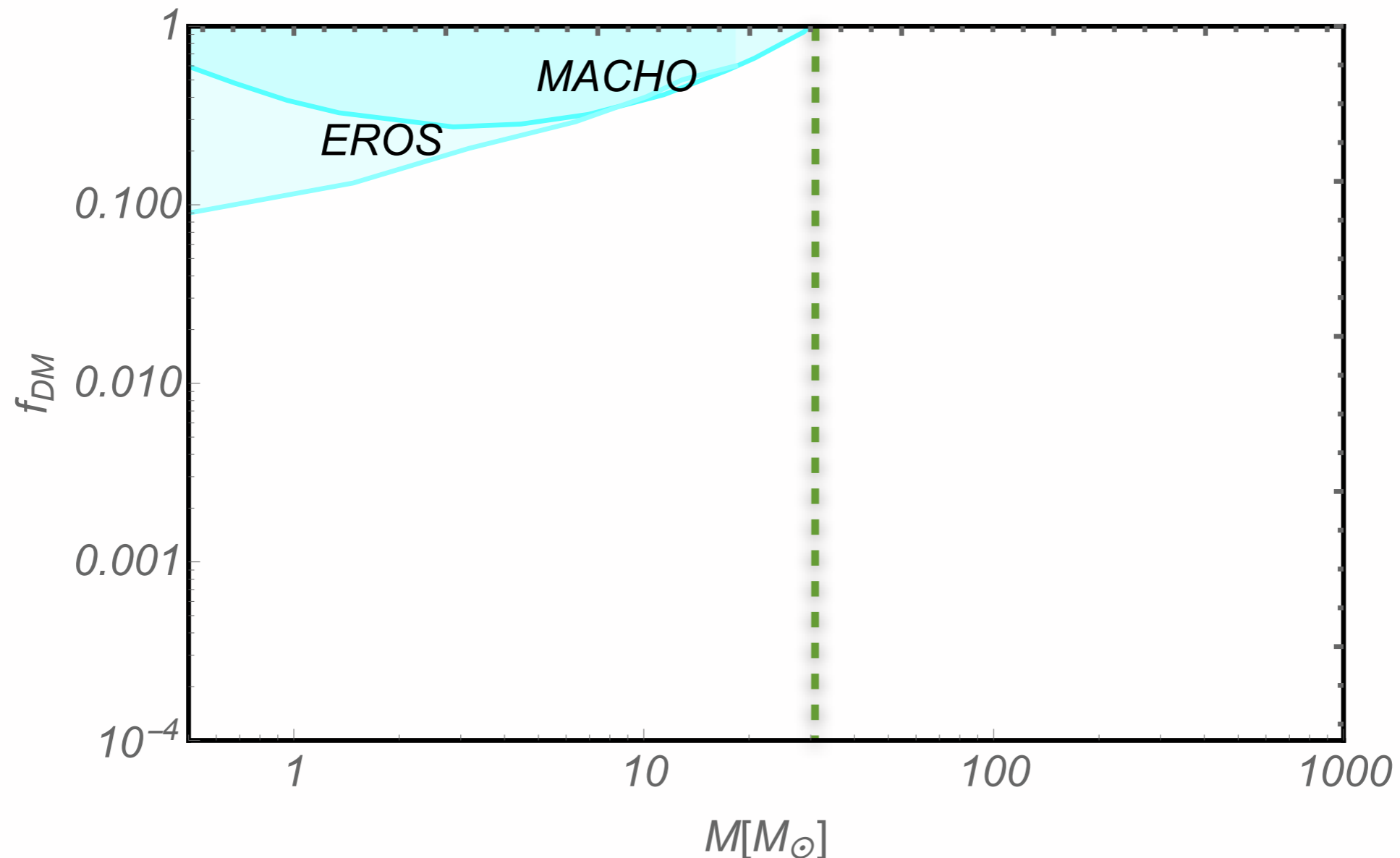
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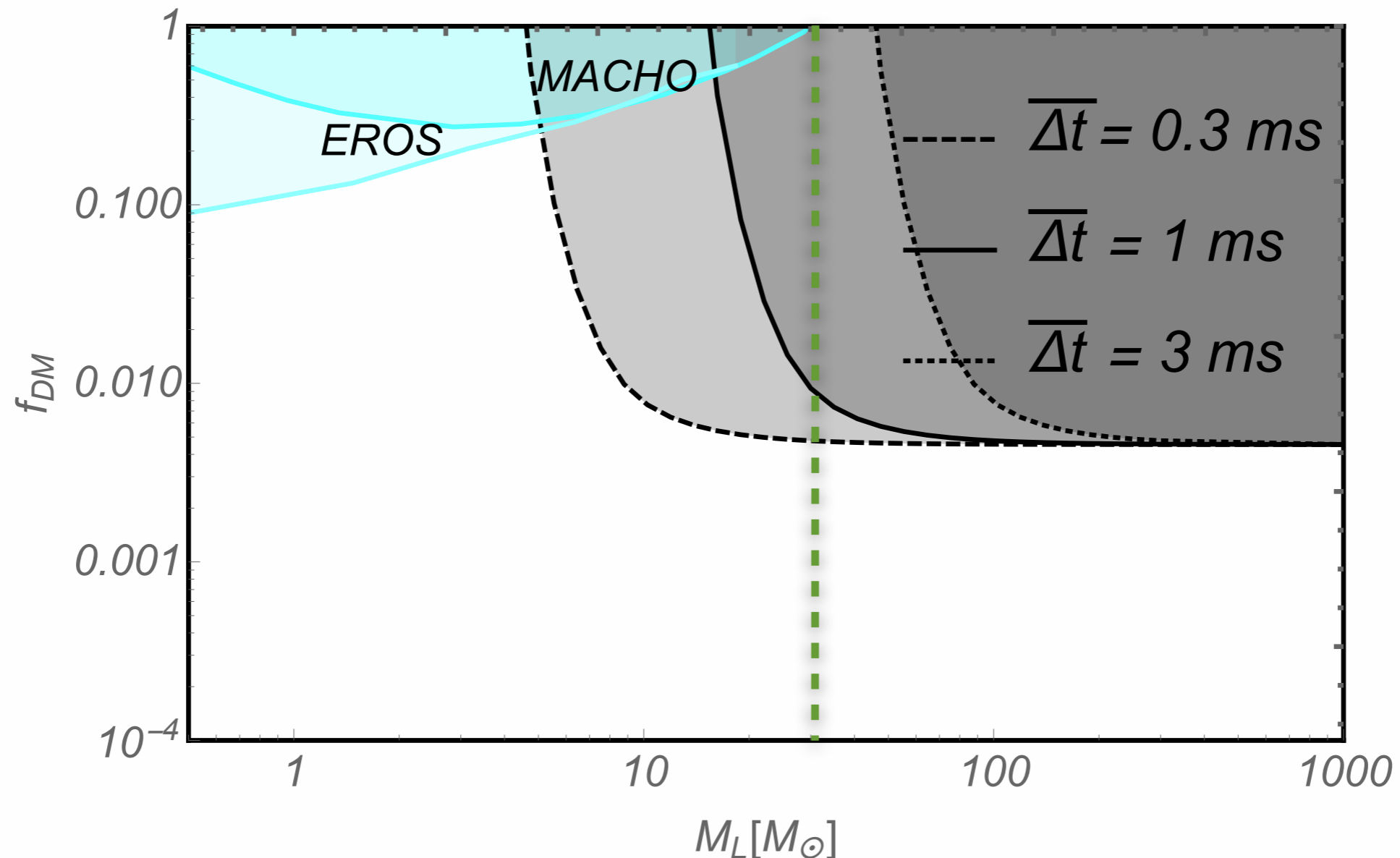
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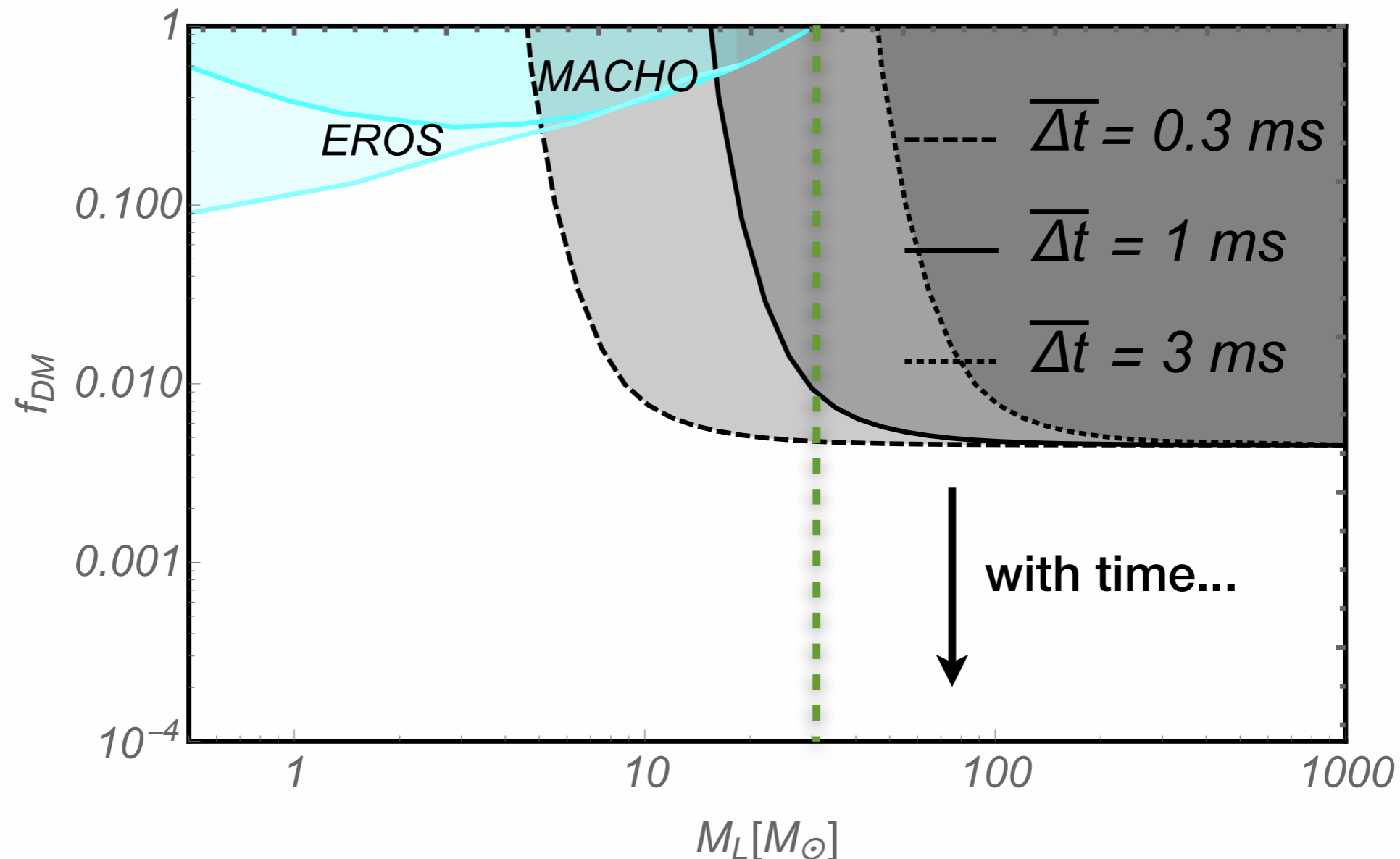
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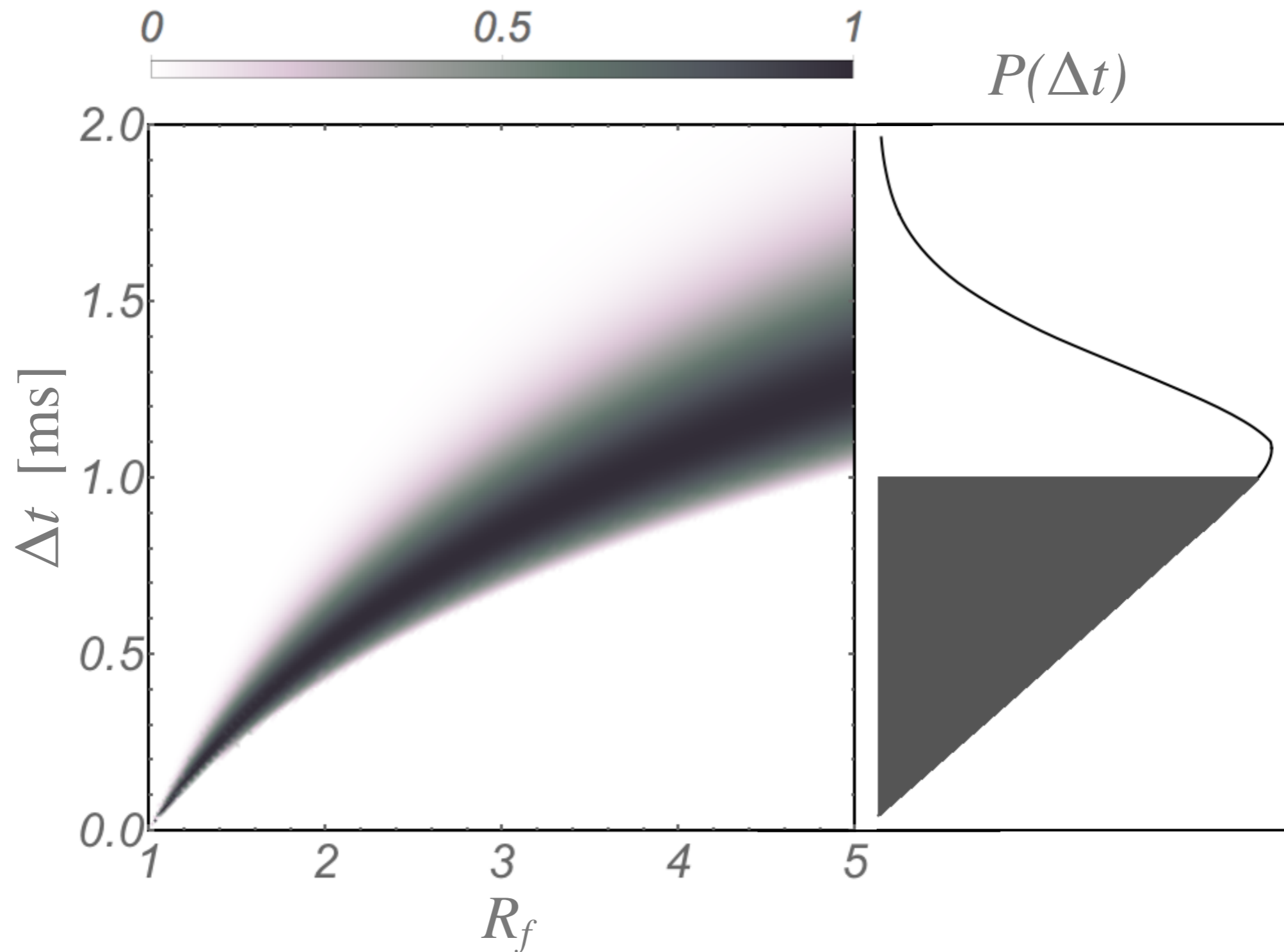
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Joint PDF of time delay and flux ratio indicates correlation:



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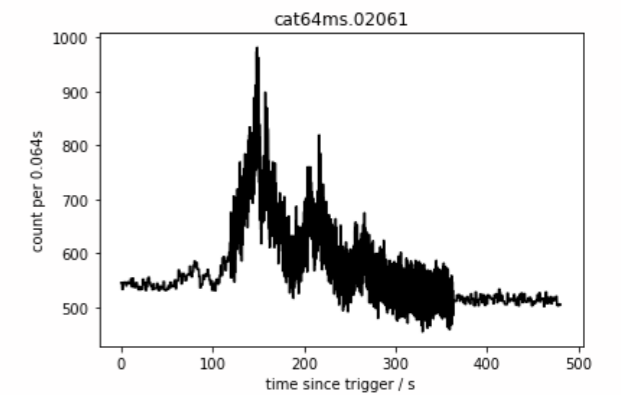
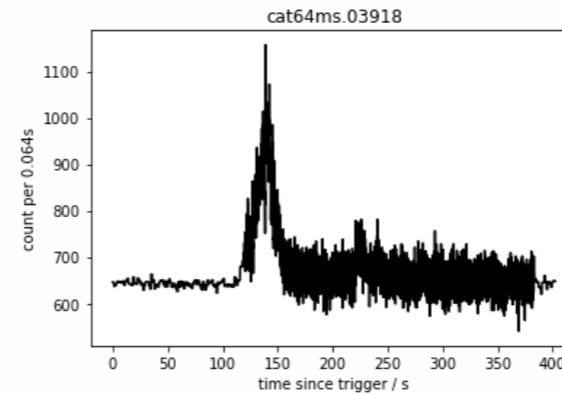
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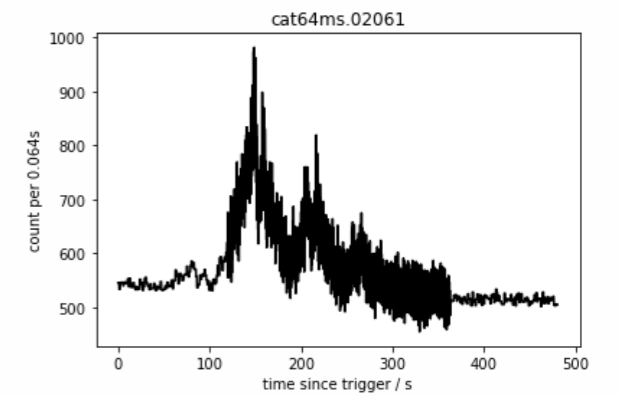
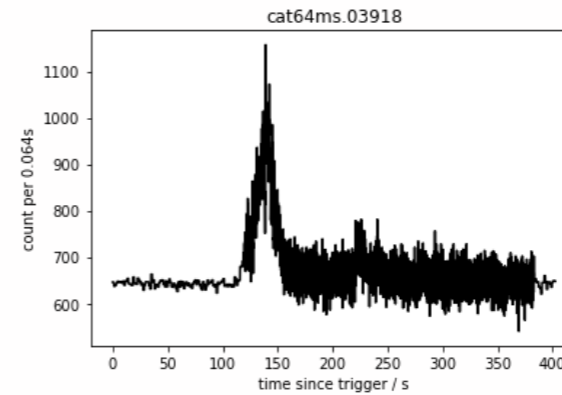
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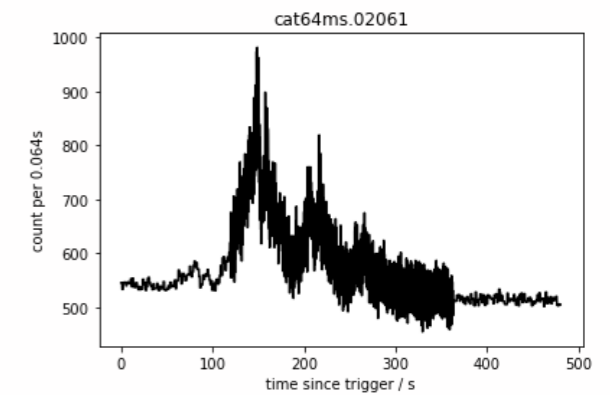
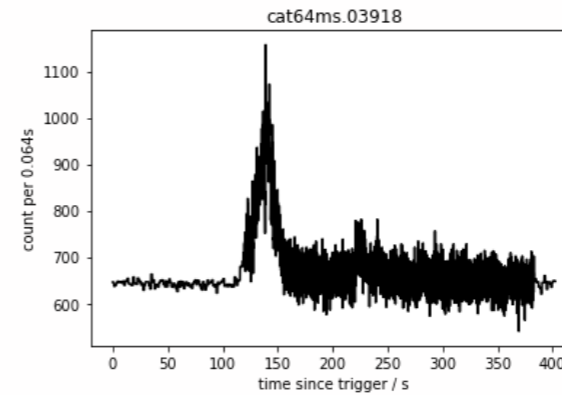
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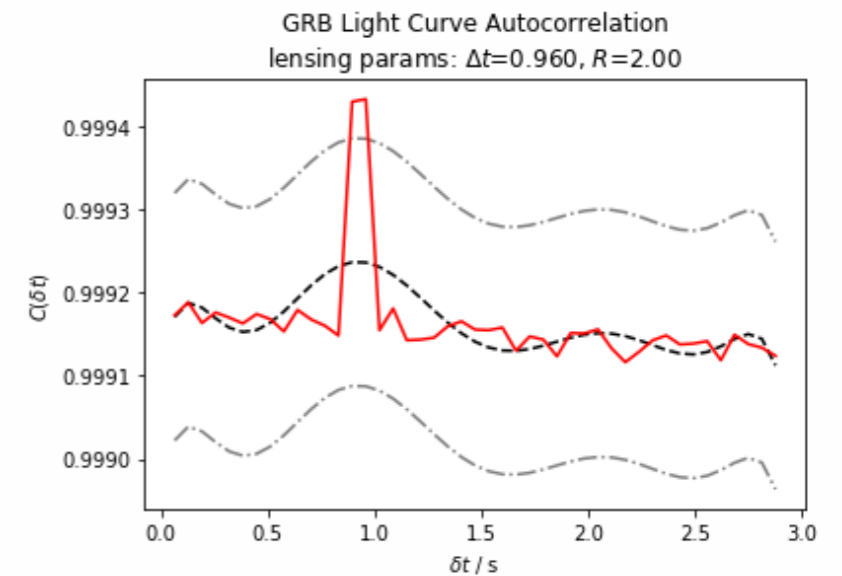
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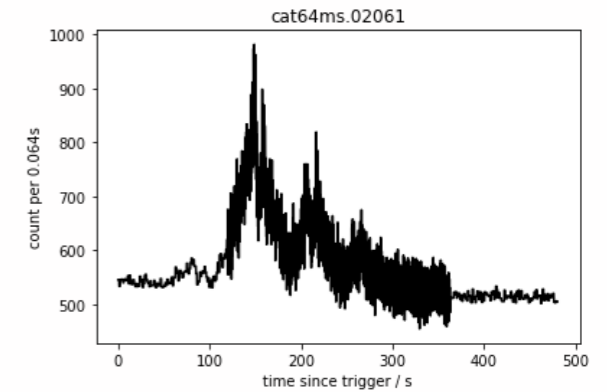
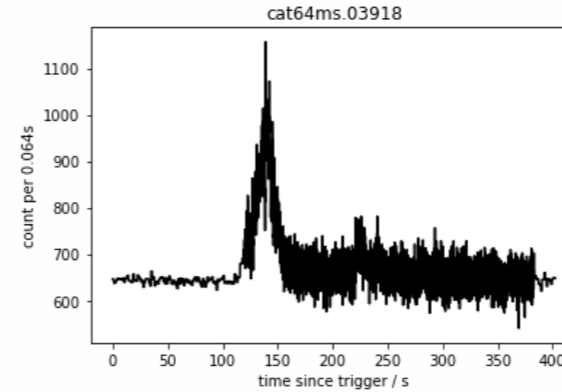
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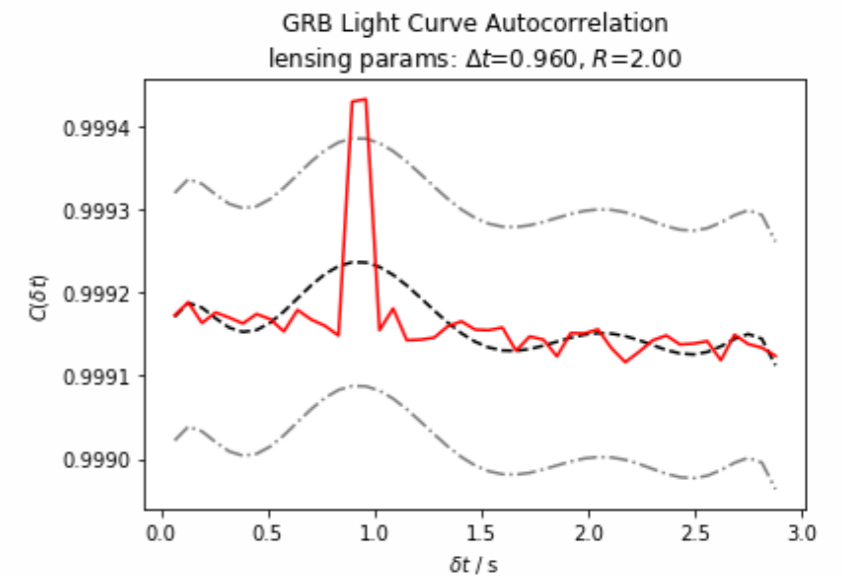
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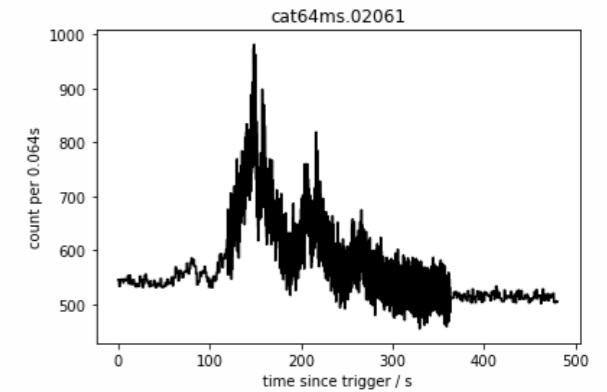
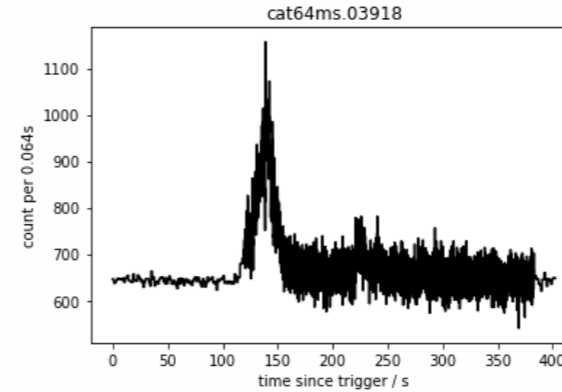
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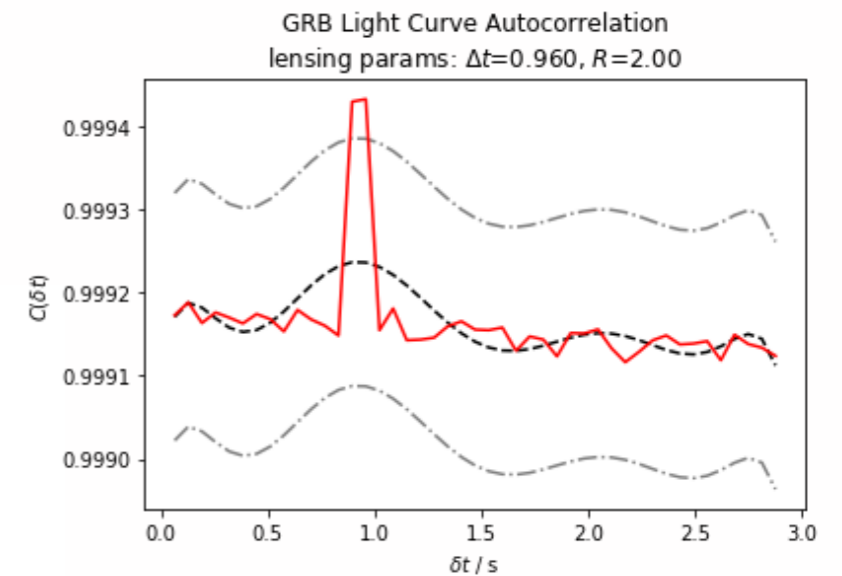
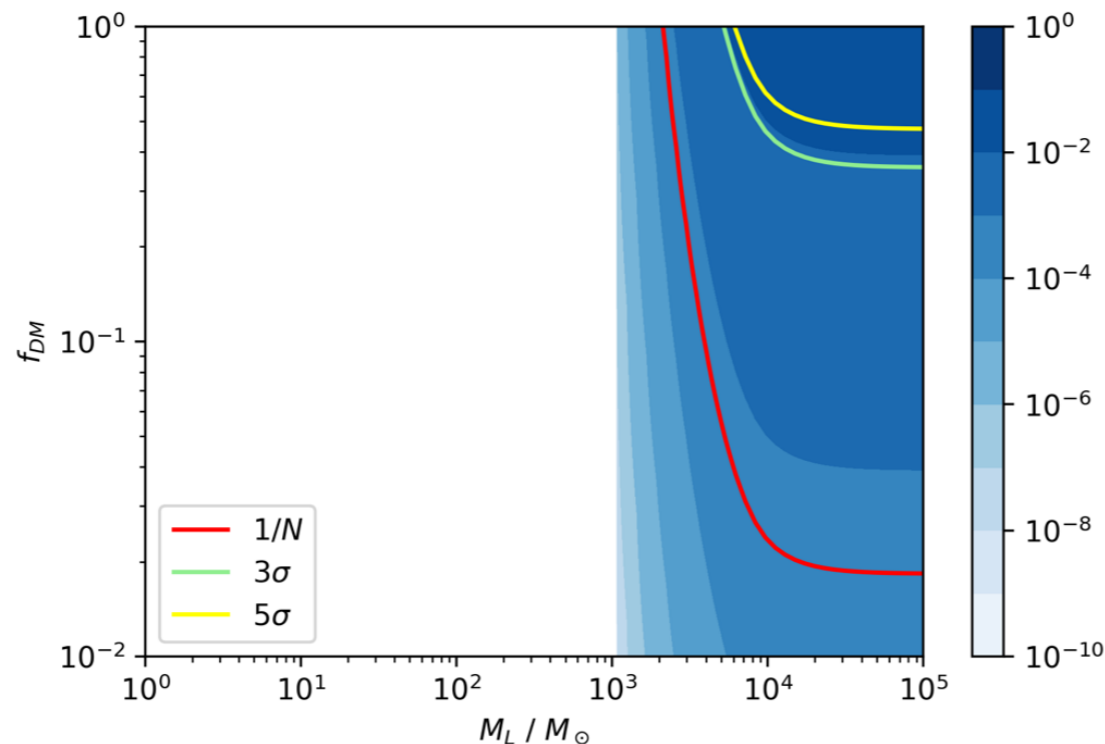
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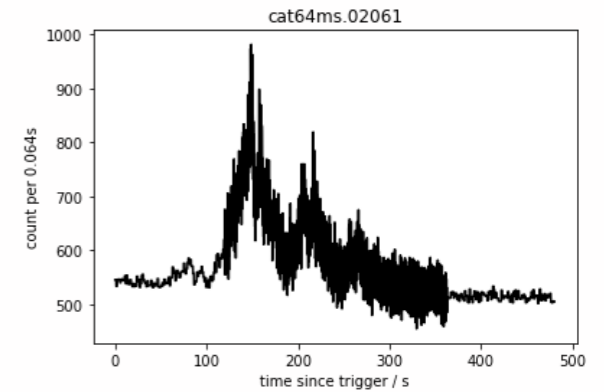
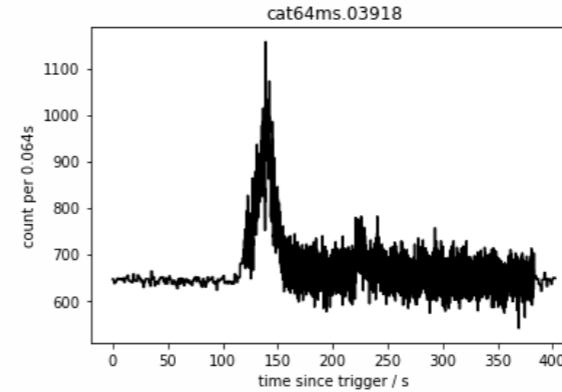
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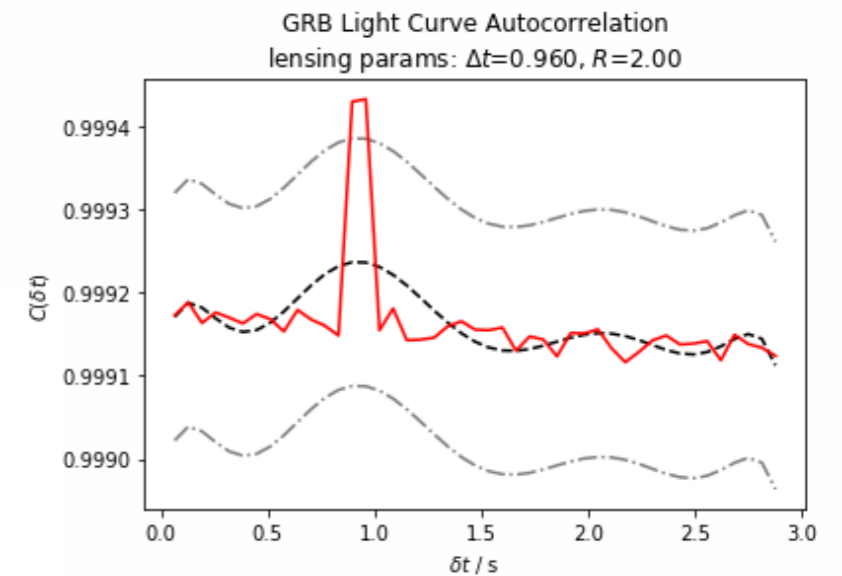
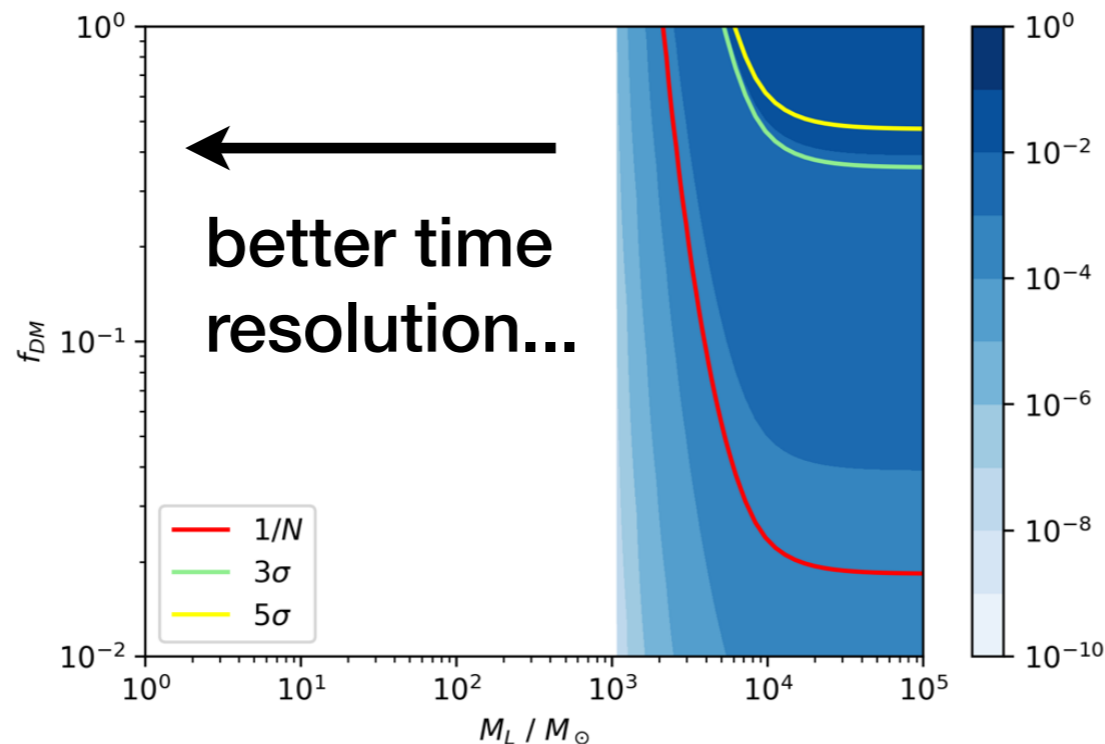
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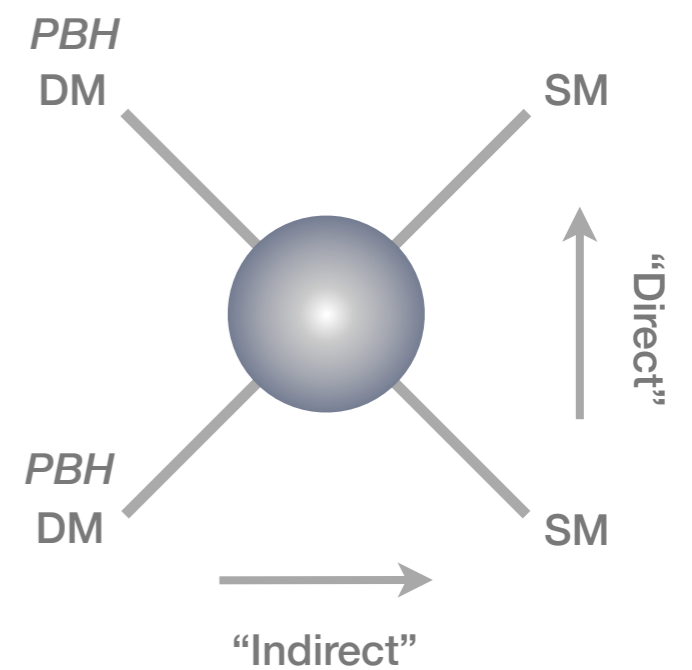
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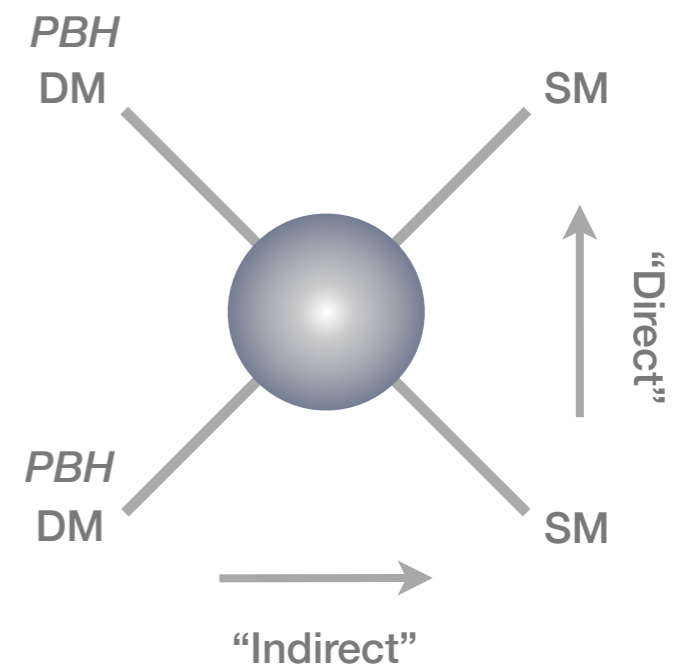
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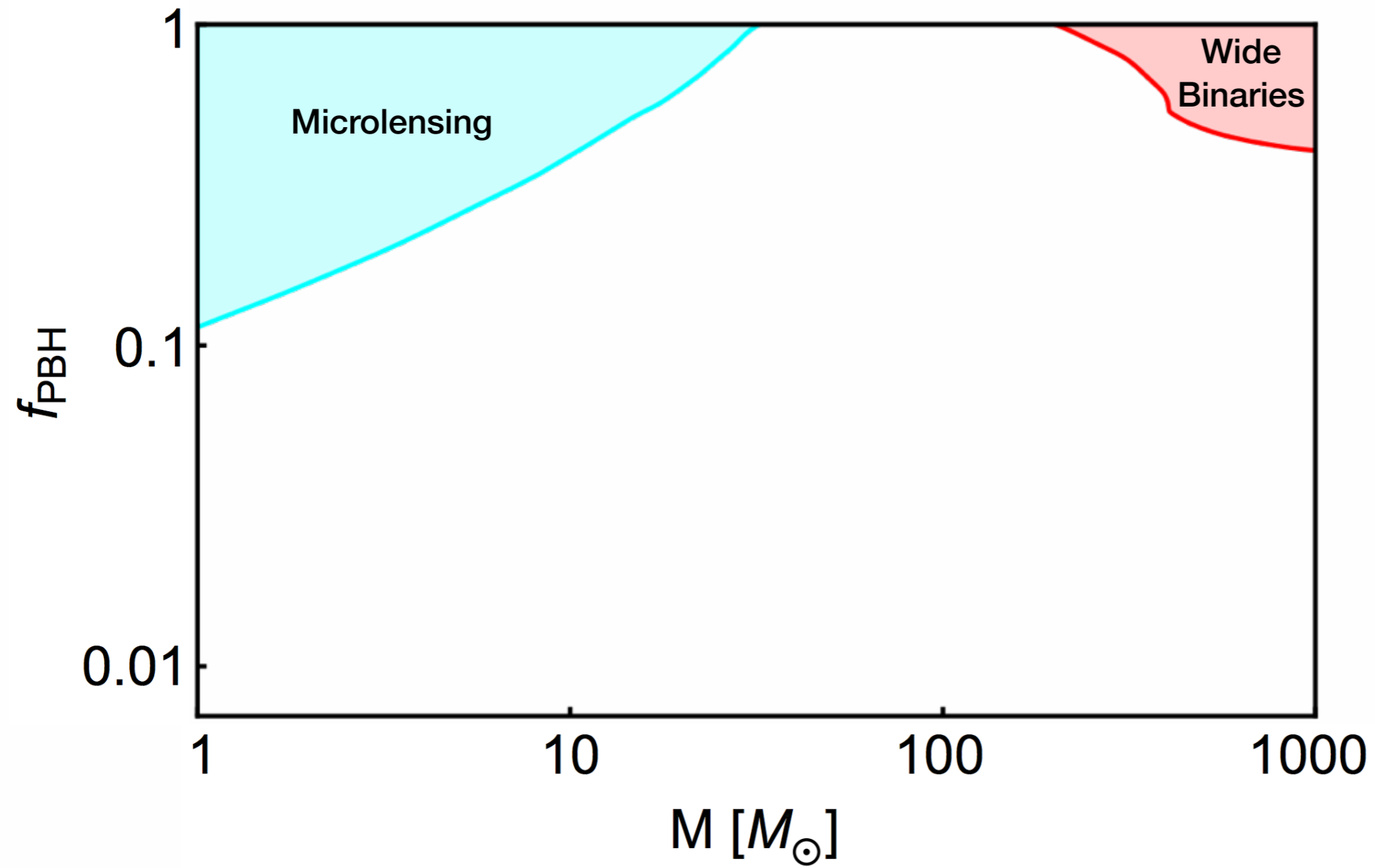
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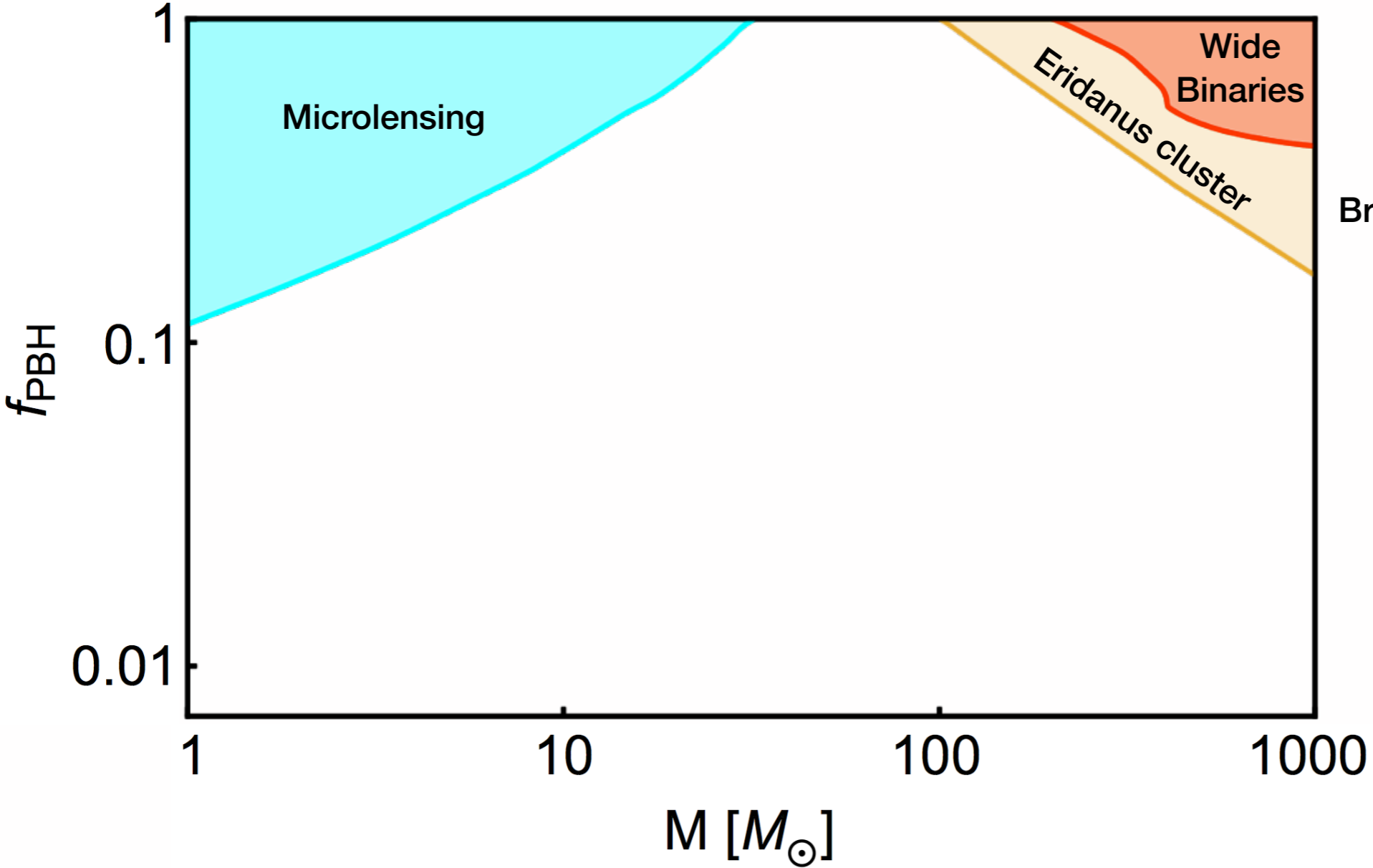


PBH DM LIGO Window: The Race is On

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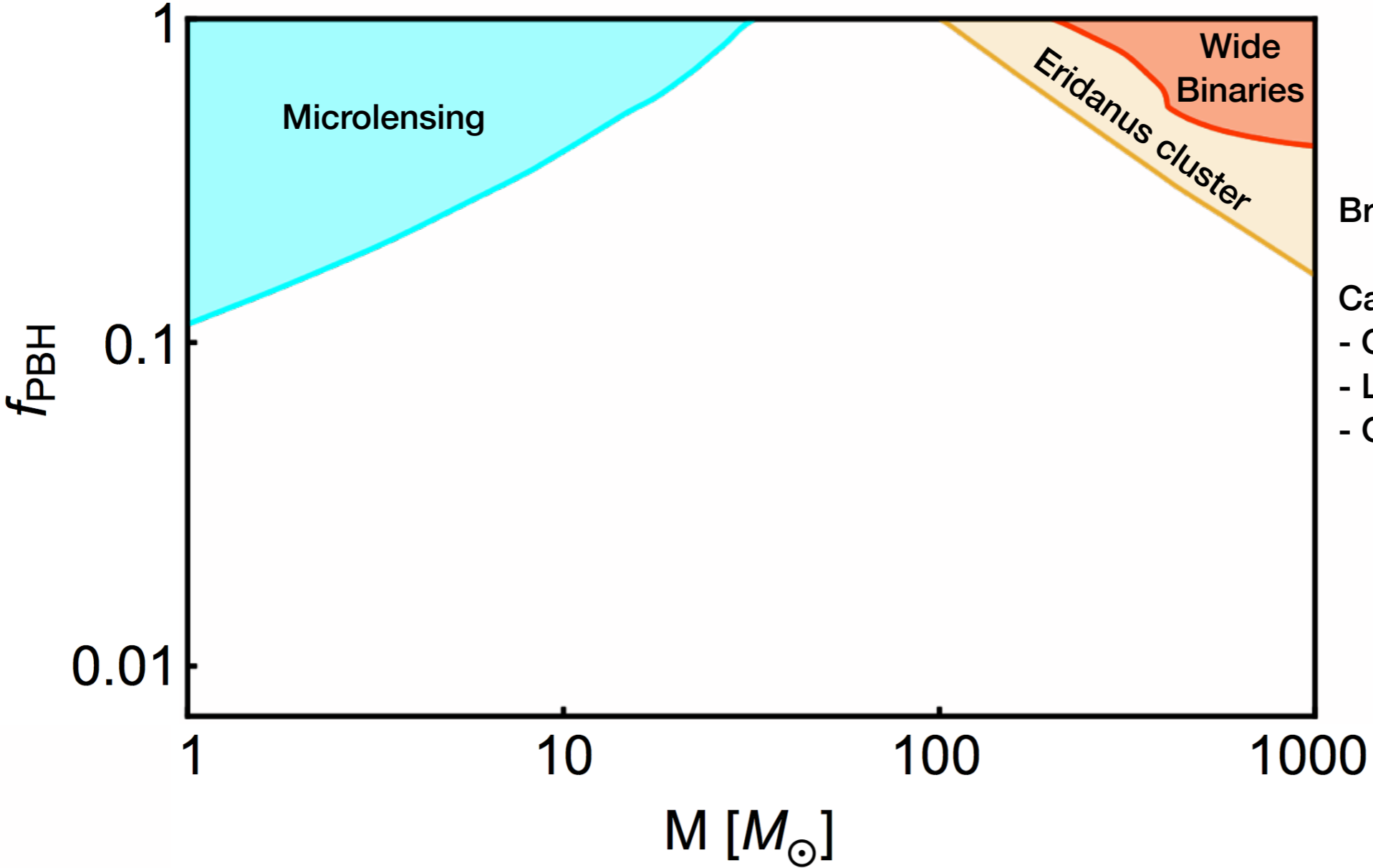


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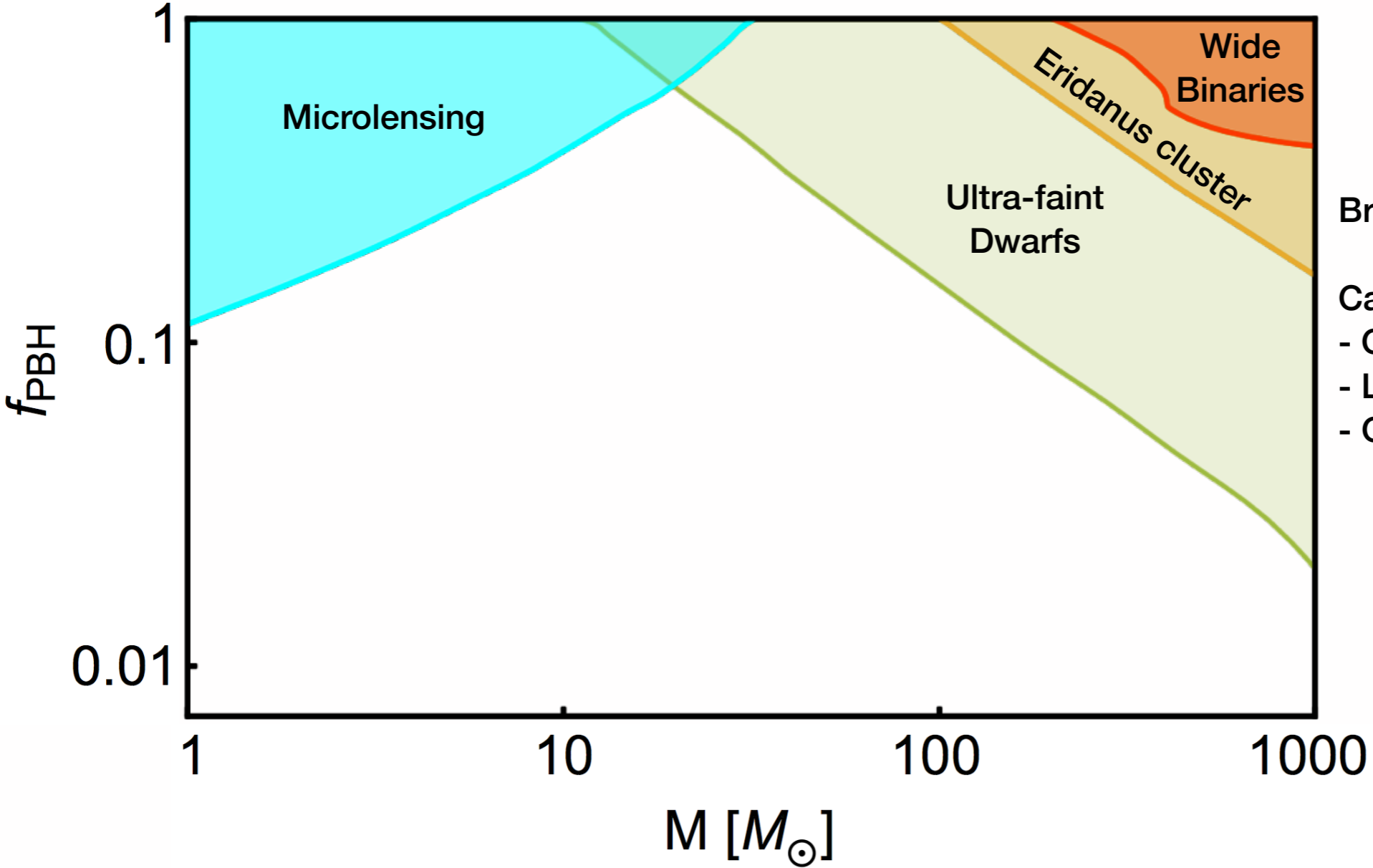


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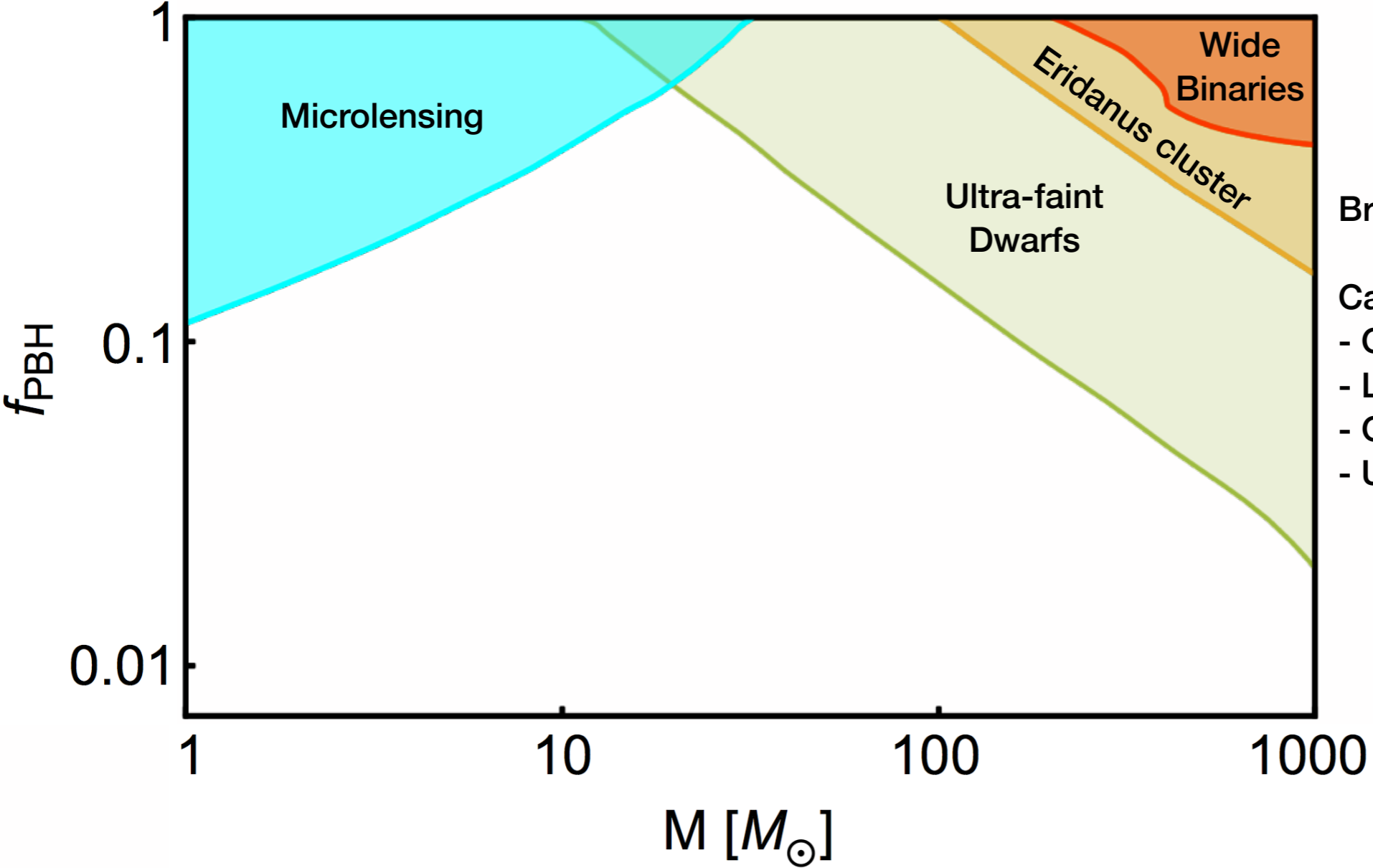


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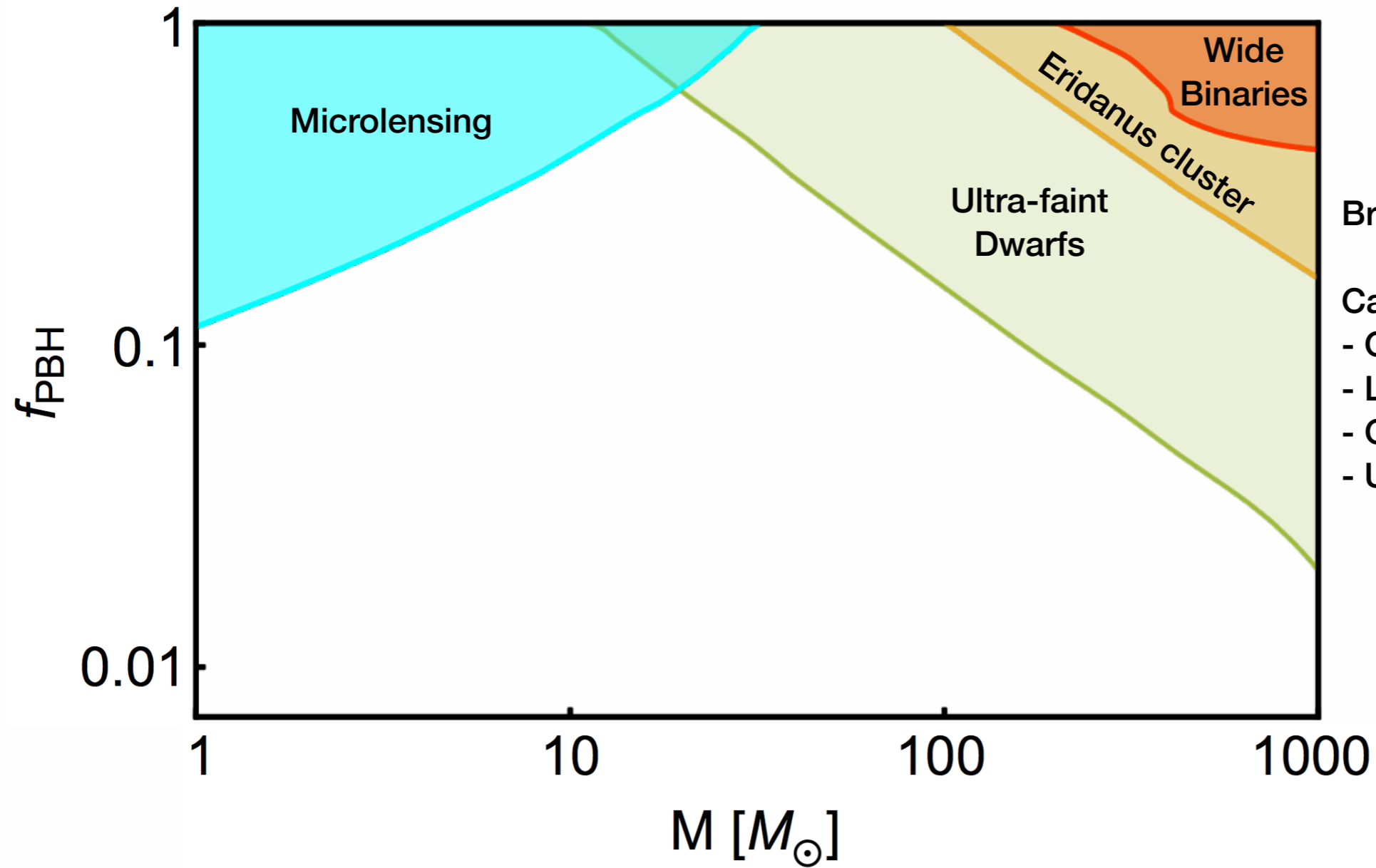
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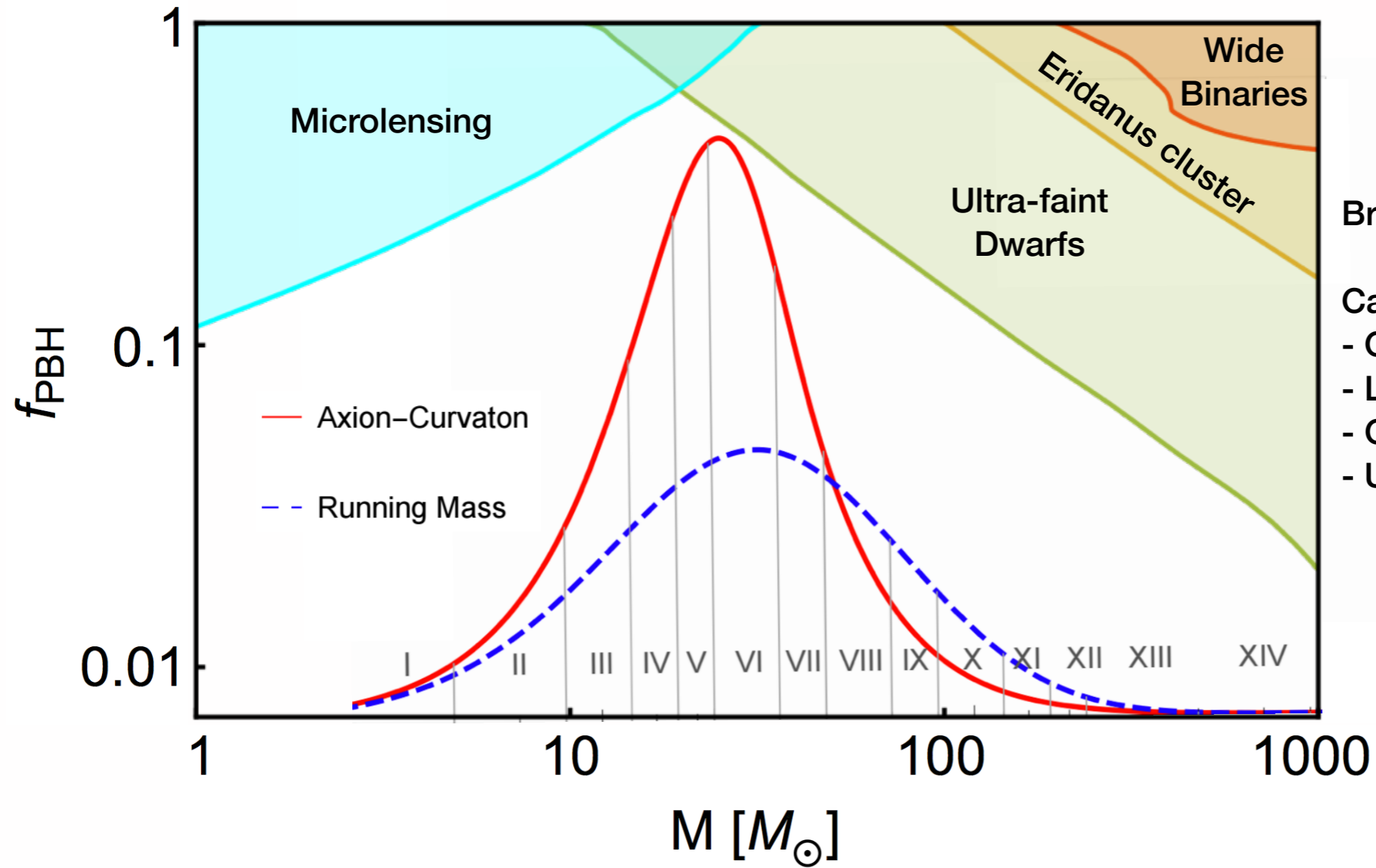
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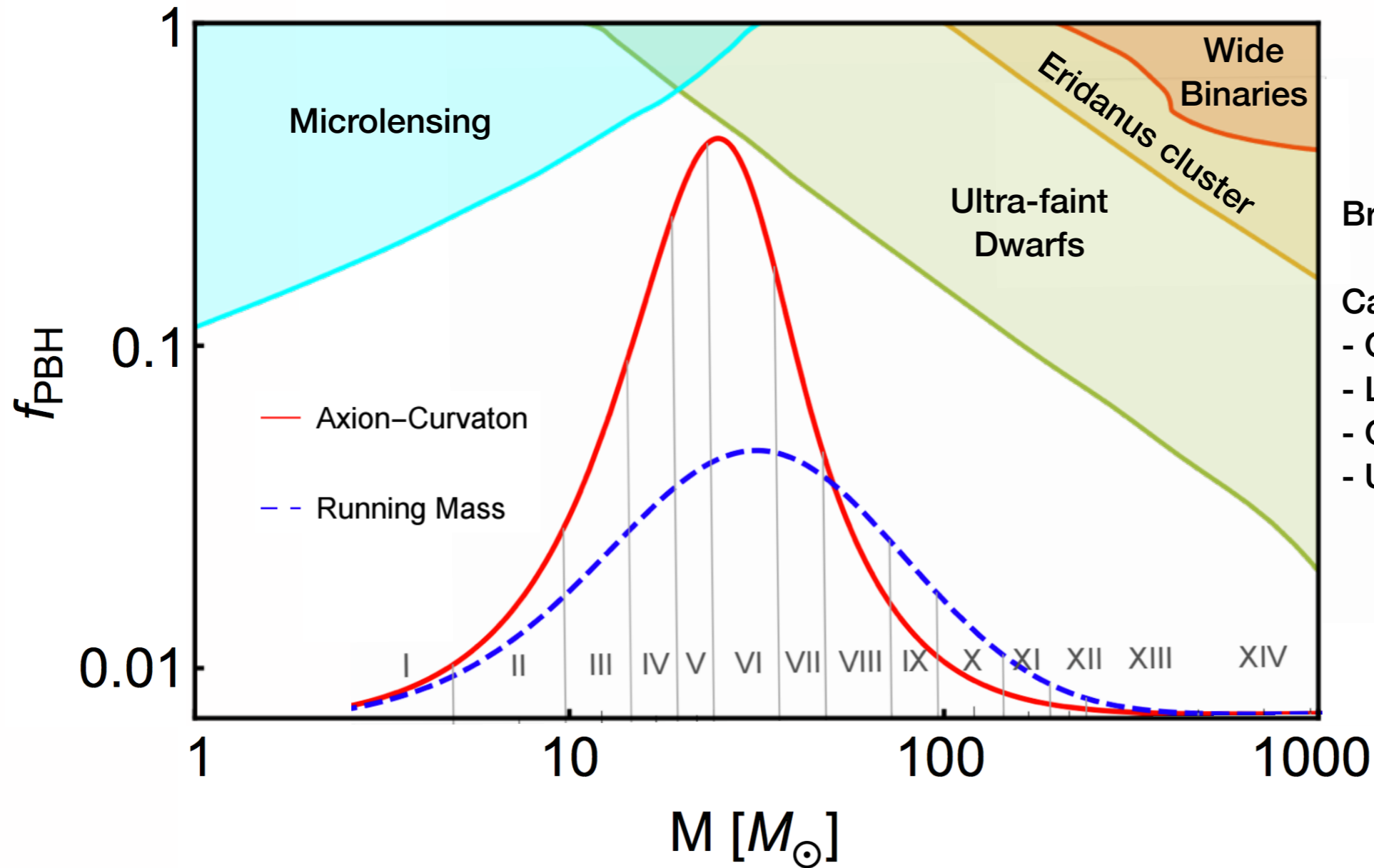
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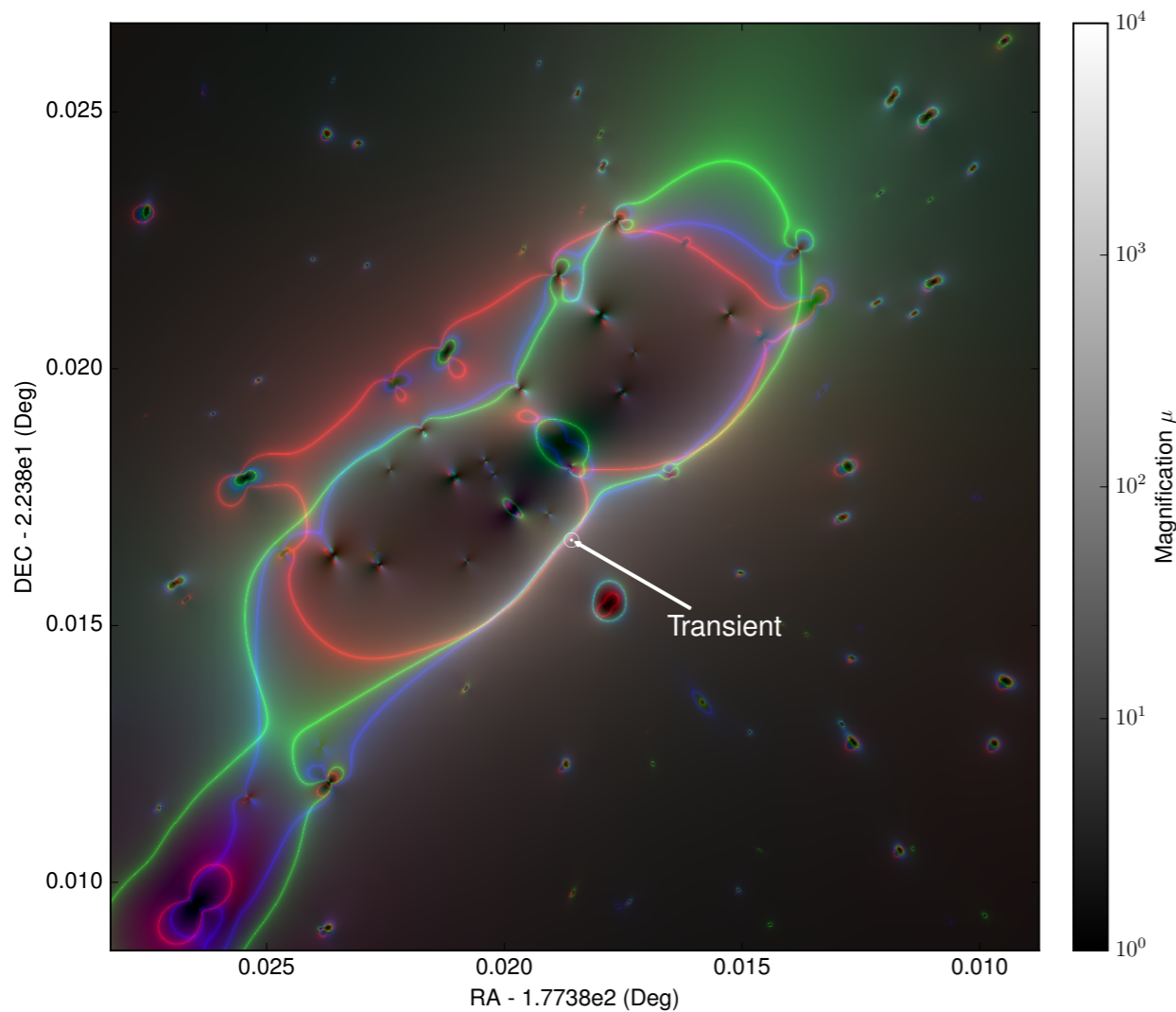
Needs to be done carefully: constraints assume delta-function mass function.

Green, PRD (2016); Kuhnel & Freese, PRD (2017)

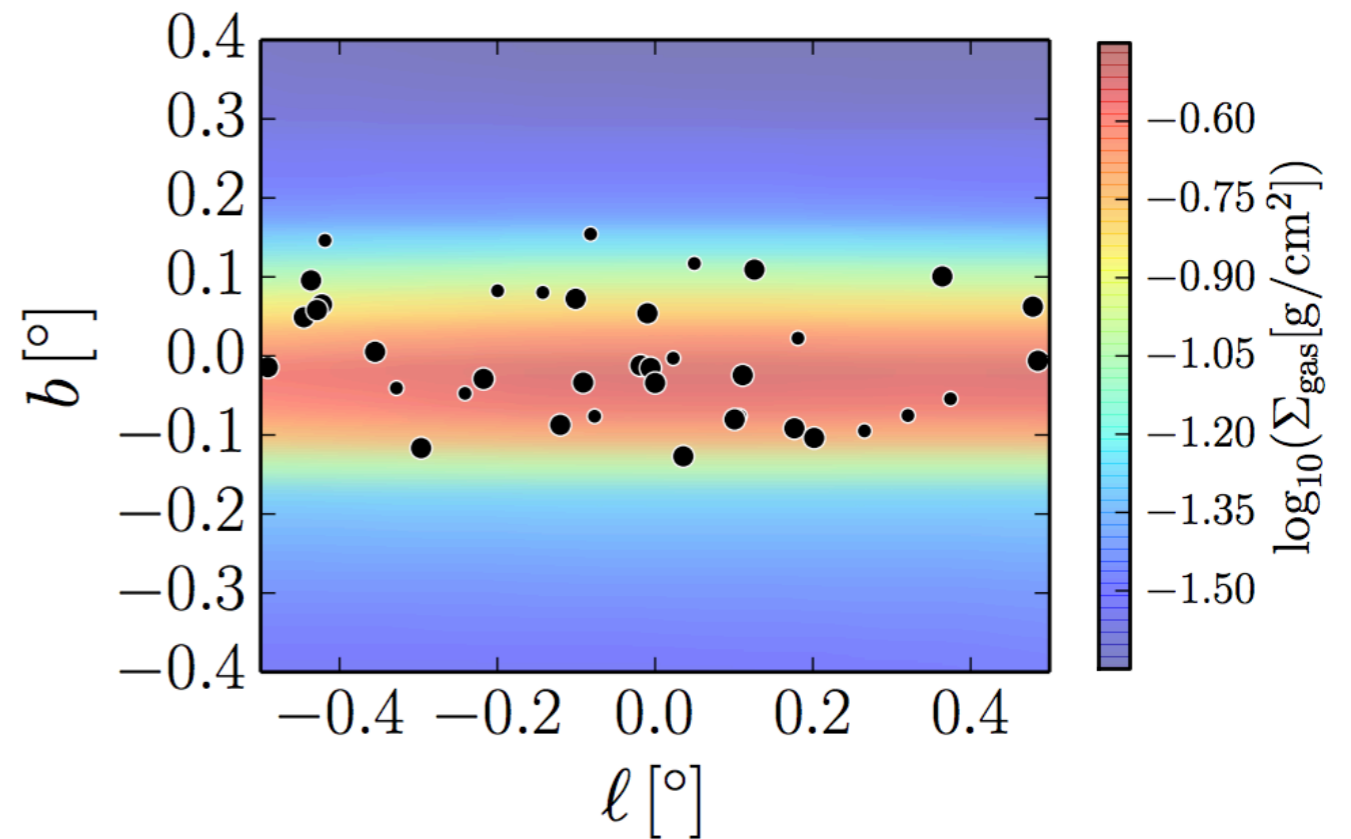
PBH DM LIGO Window: The Race is On

Additional exciting ideas abound with $\sim 10\%$ constraints in the LIGO mass range:

Microlensing near caustic crossings



Radio and X-Ray emission from gas accreting PBHs near the Galactic center



Venumadhav, Dai & Miralda-Escude, arXiv:1707.00003

Diego et al., arXiv:1706.10281

Oguri et al., arXiv:1710.00148

Gaggero et al., PRL 2017

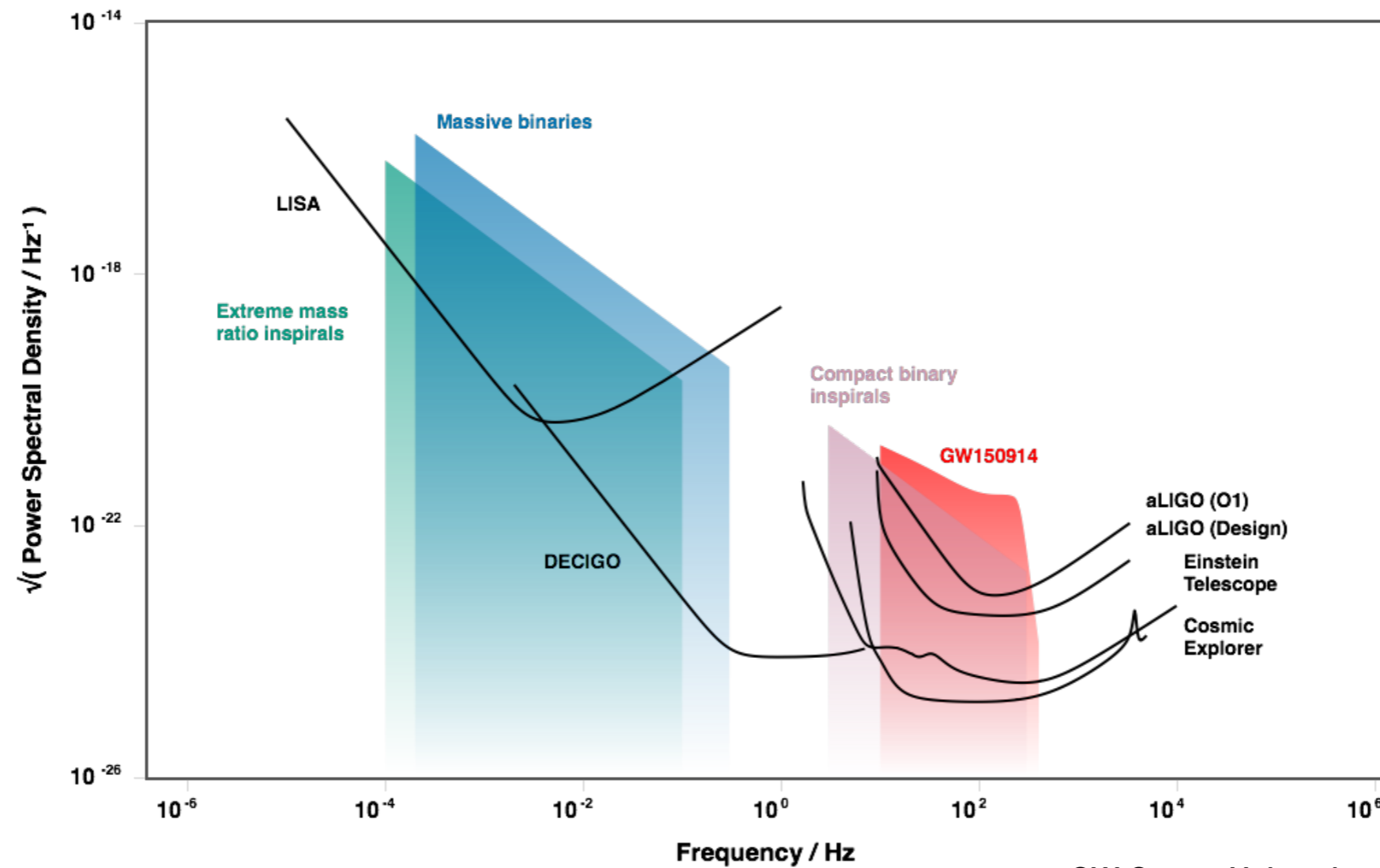
Observational Outlook: Upcoming Experiments

Observational Outlook: Upcoming Experiments

Gravitational waves:

Observational Outlook: Upcoming Experiments

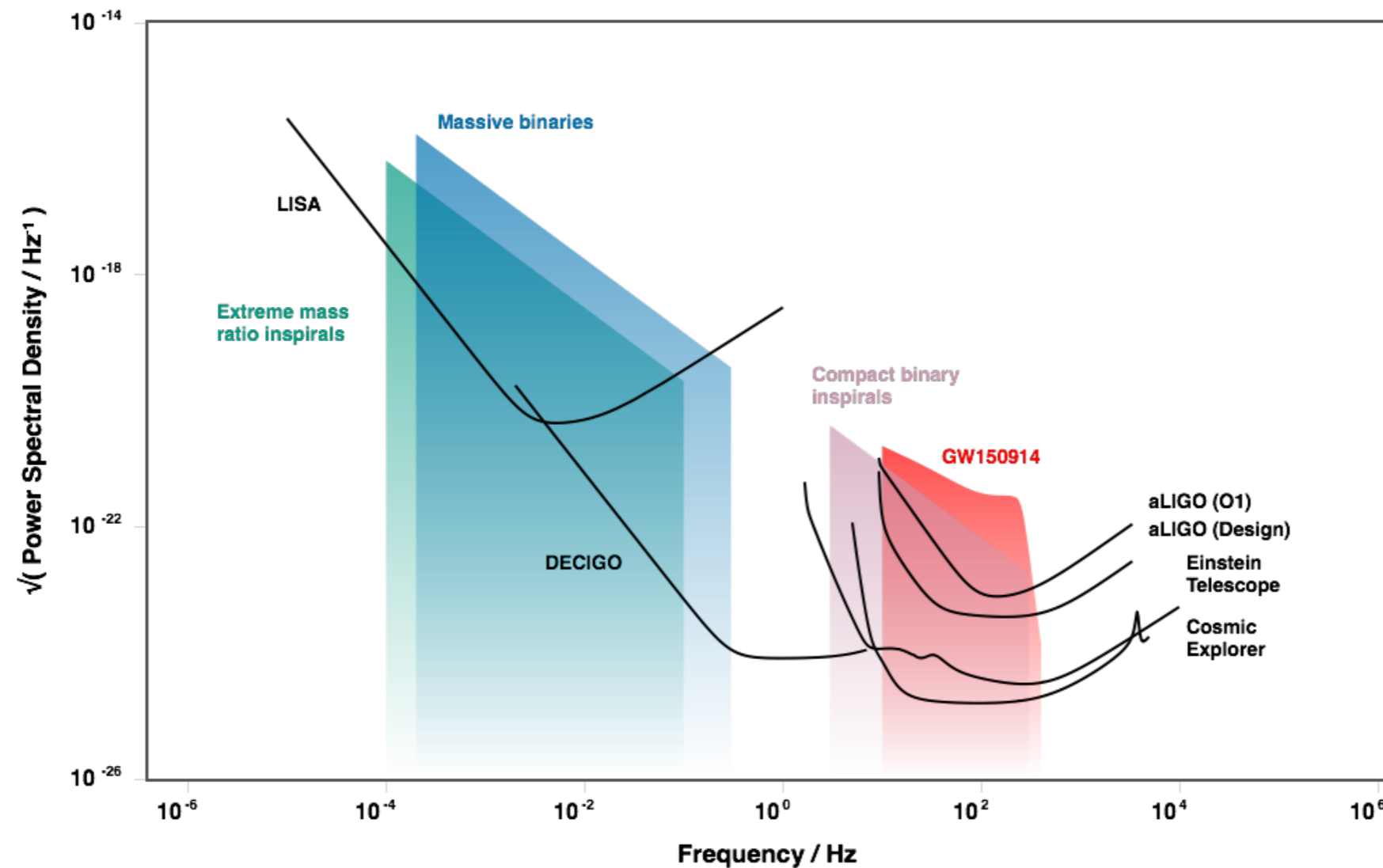
Gravitational waves:



GW Group, University of Cambridge

Observational Outlook: Upcoming Experiments

Gravitational waves:

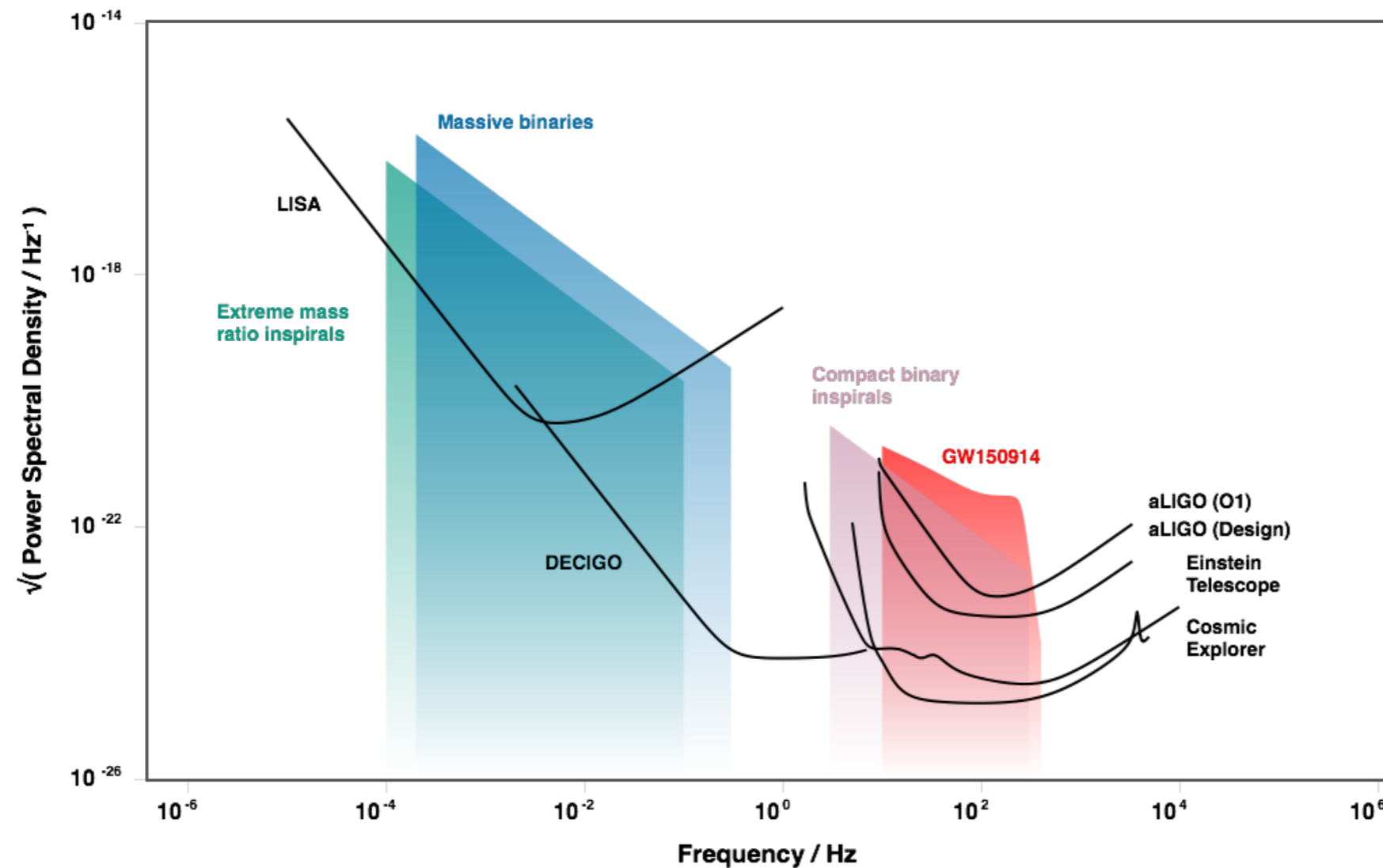


GW Group, University of Cambridge

Fast radio bursts:

Observational Outlook: Upcoming Experiments

Gravitational waves:



GW Group, University of Cambridge

Fast radio bursts: many instruments, including CHIME, HIRAX...

Observational Outlook: Timeline

Observational Outlook: Timeline

Experiment

2015

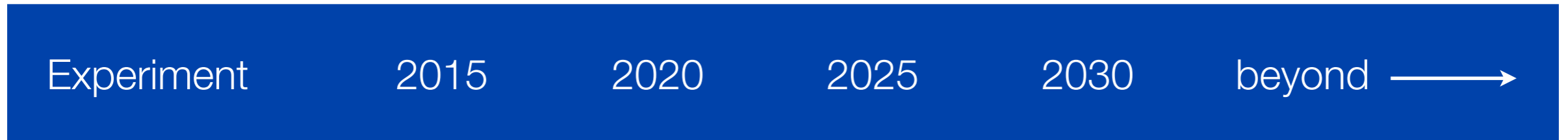
2020

2025

2030

beyond 

Observational Outlook: Timeline



aLIGO (O1+)



Observational Outlook: Timeline



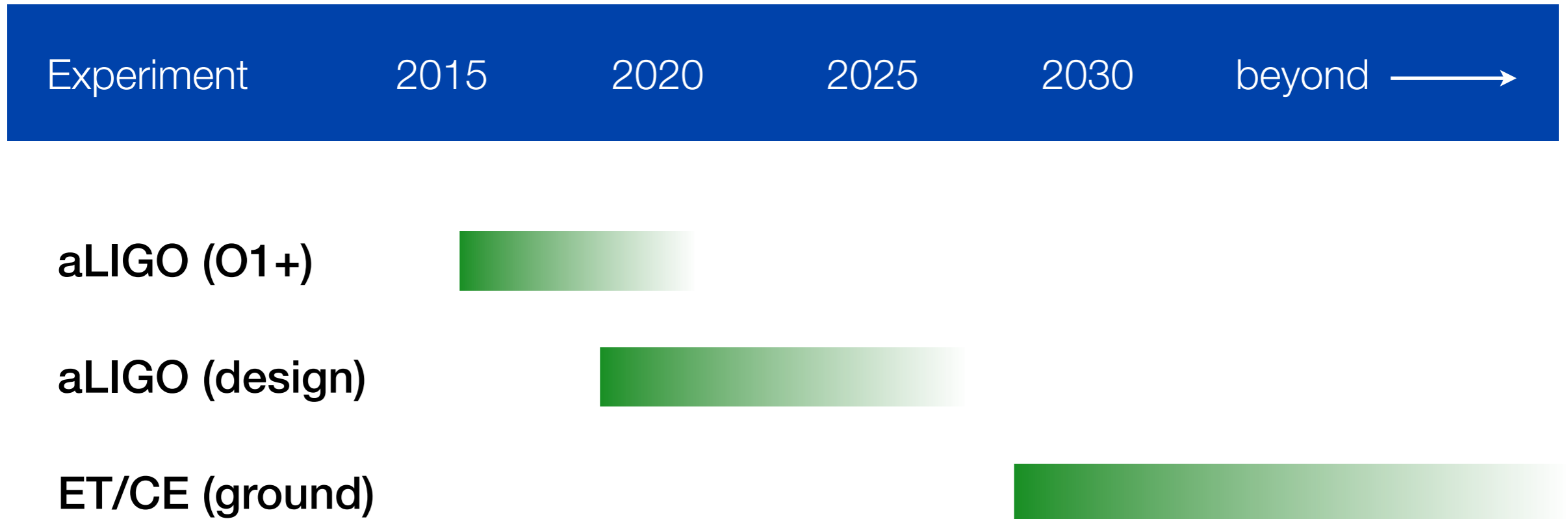
aLIGO (O1+)



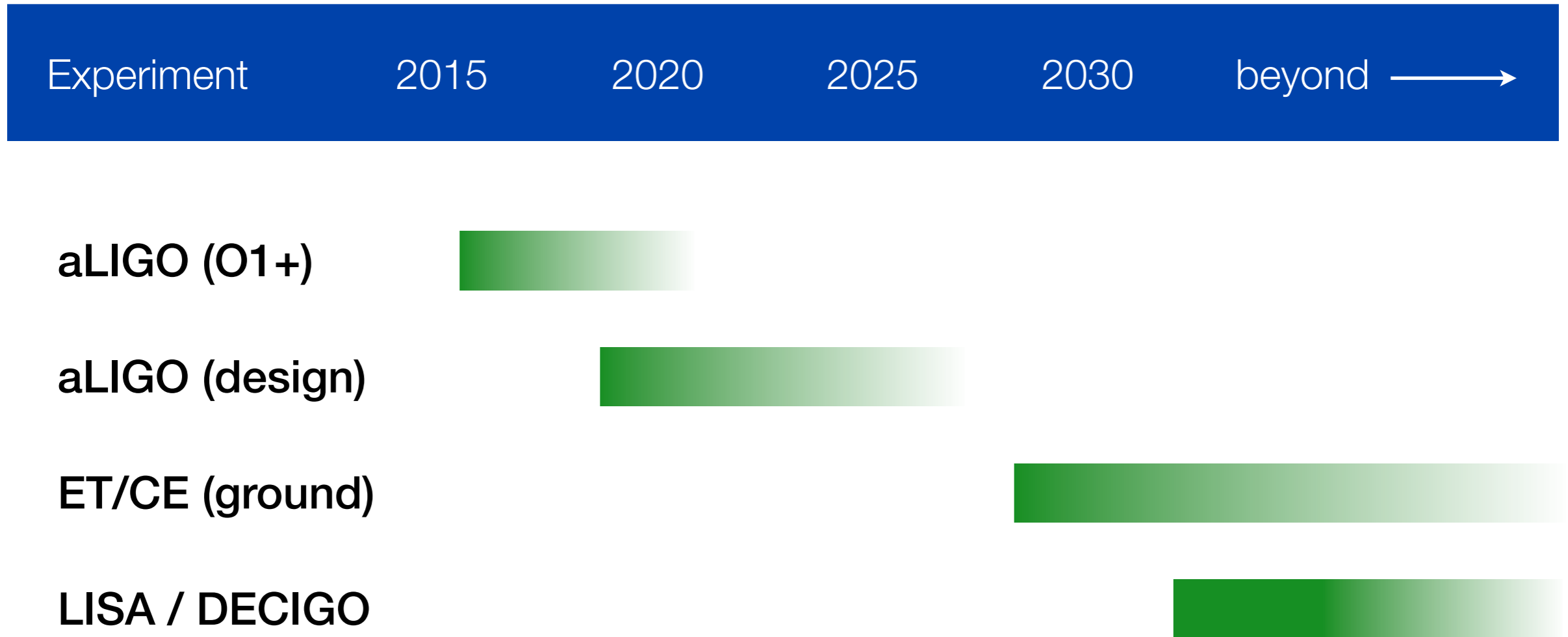
aLIGO (design)



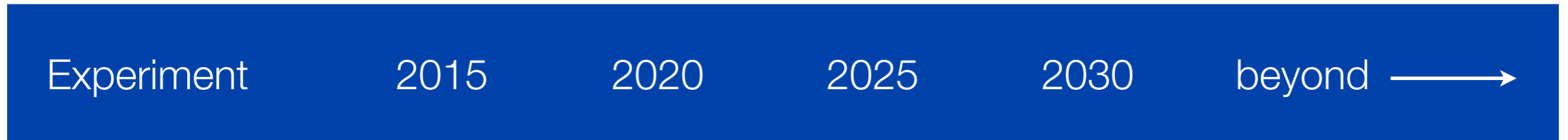
Observational Outlook: Timeline



Observational Outlook: Timeline



Observational Outlook: Timeline



aLIGO (O1+)



aLIGO (design)



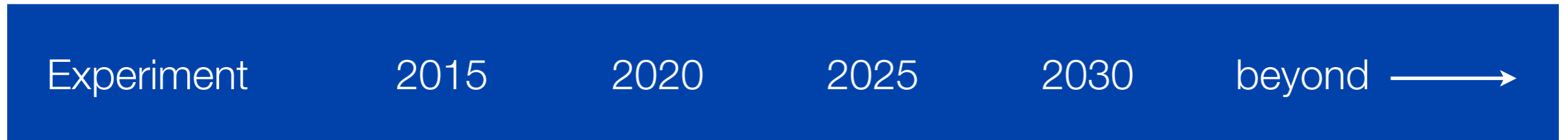
ET/CE (ground)



LISA / DECIGO



Observational Outlook: Timeline



aLIGO (O1+)



aLIGO (design)



ET/CE (ground)



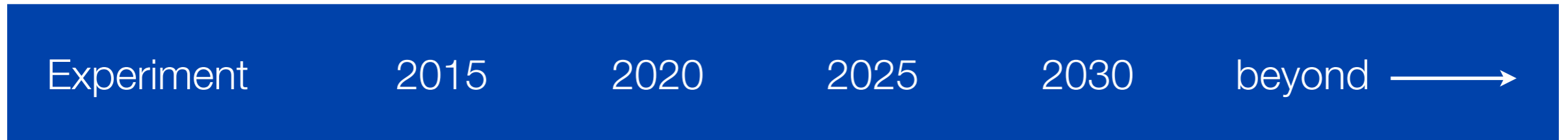
LISA / DECIGO



CHIME-FRB



Observational Outlook: Timeline



aLIGO (O1+)



aLIGO (design)



ET/CE (ground)



LISA / DECIGO



CHIME-FRB



HIRAX



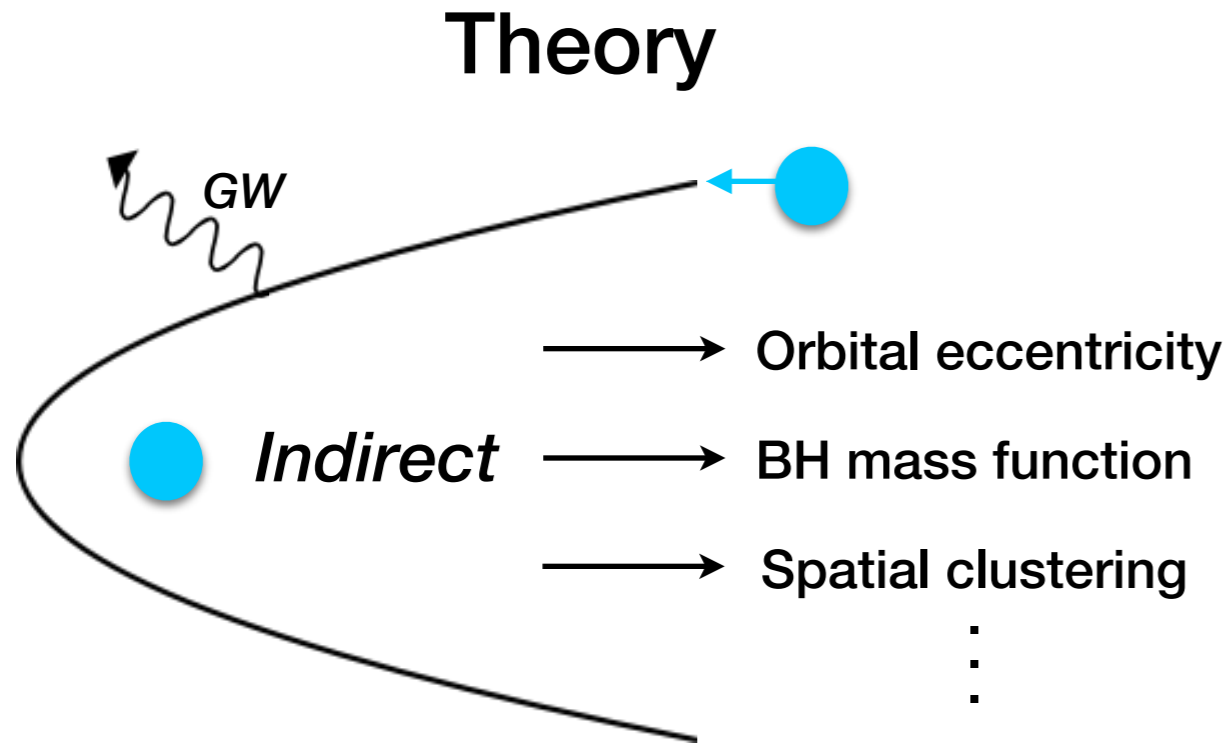
Takeaway:

Takeaway: We Can Test if PBHs are Dark Matter!

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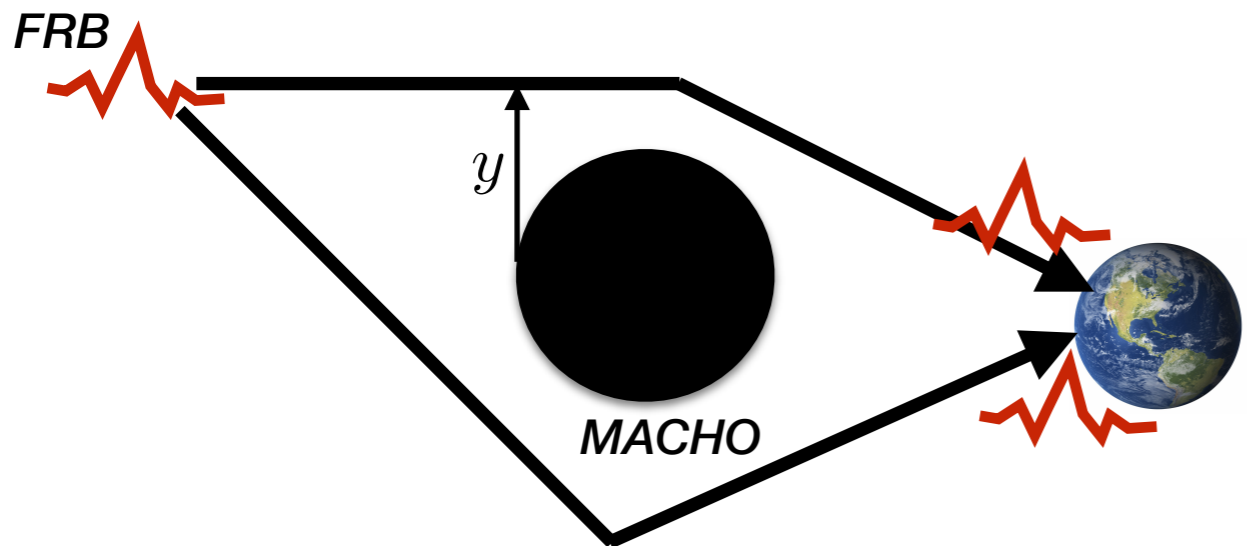
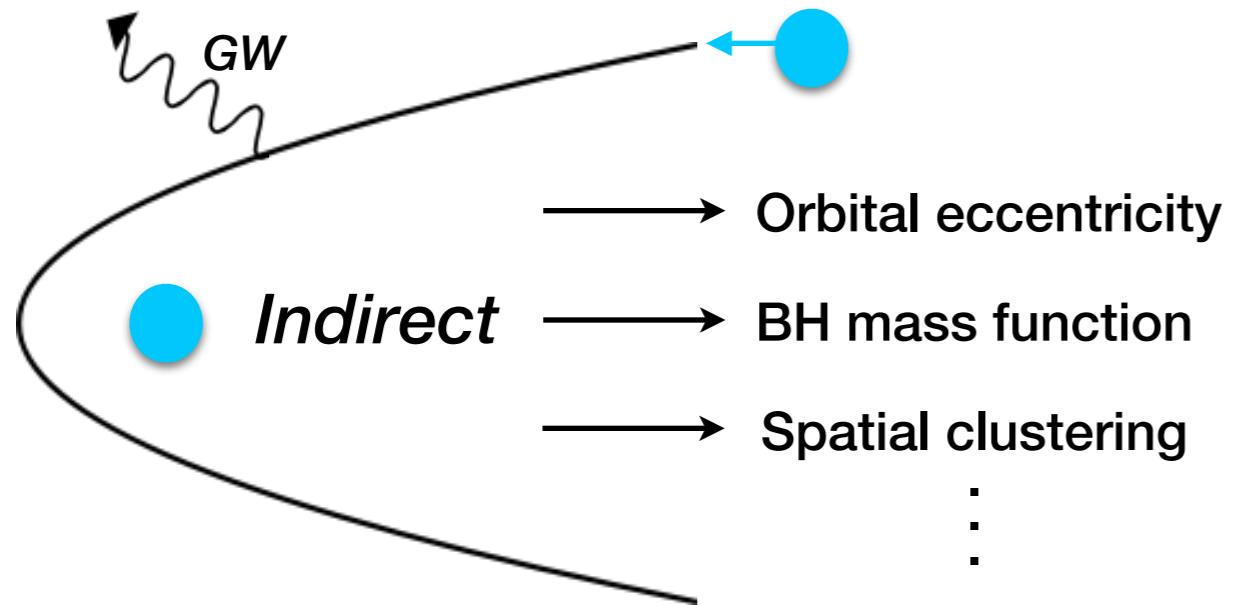
Theory

Takeaway: We Can Test if PBHs are Dark Matter!



Takeaway: We Can Test if PBHs are Dark Matter!

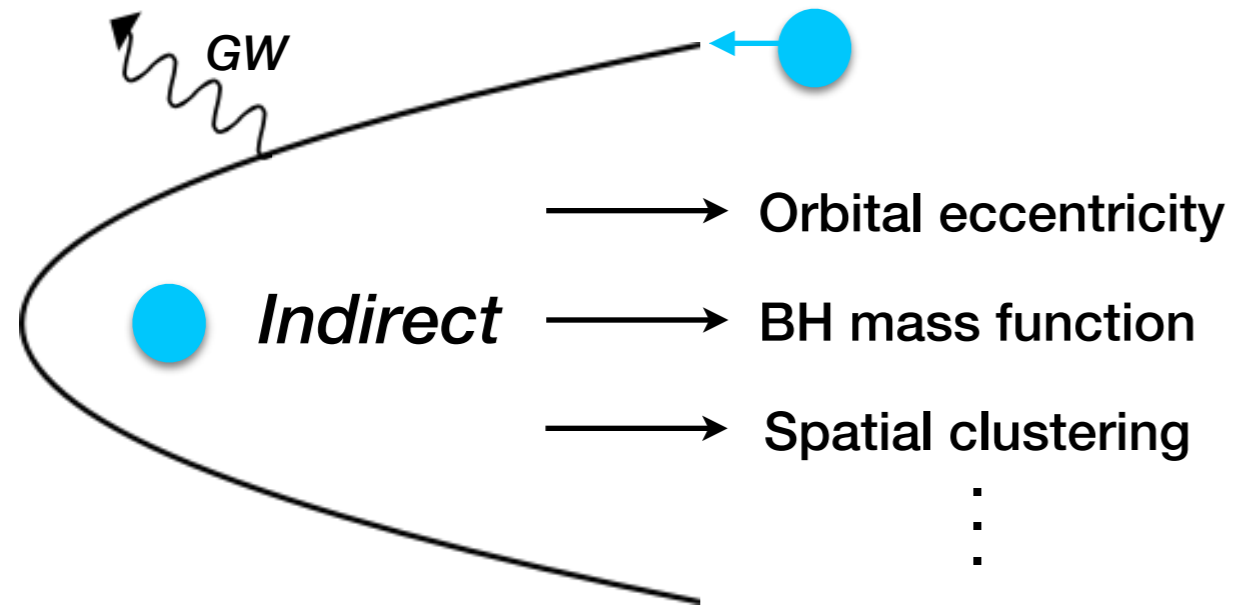
Theory



Direct → Repeating FRBs
→ GRB autocorrelations
⋮

Takeaway: We Can Test if PBHs are Dark Matter!

Theory



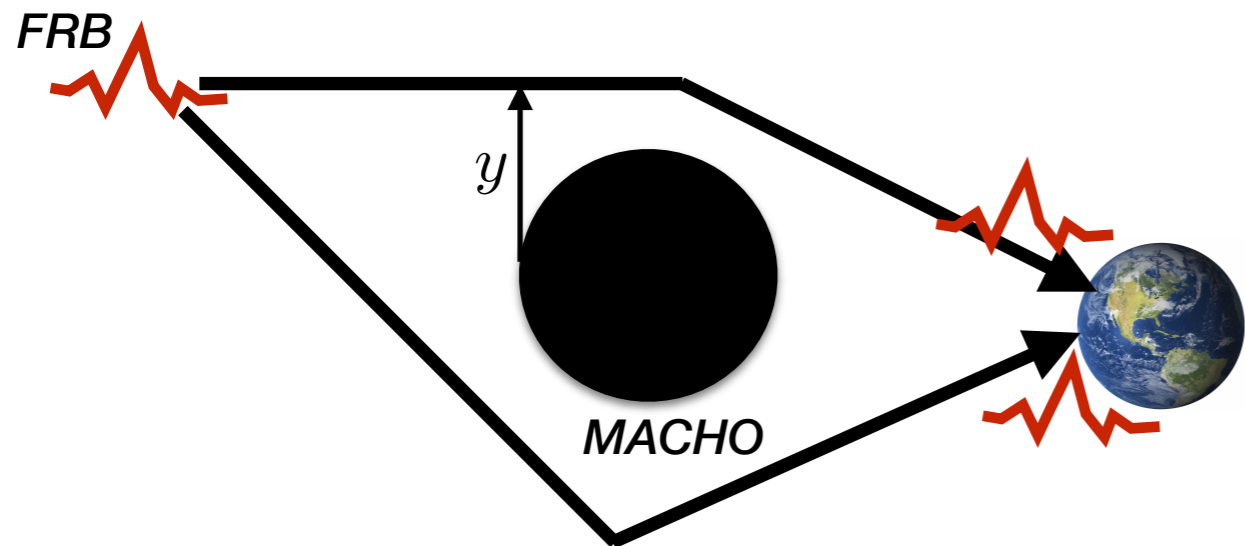
Indirect

Orbital eccentricity

BH mass function

Spatial clustering

⋮



Direct

Repeating FRBs

GRB autocorrelations

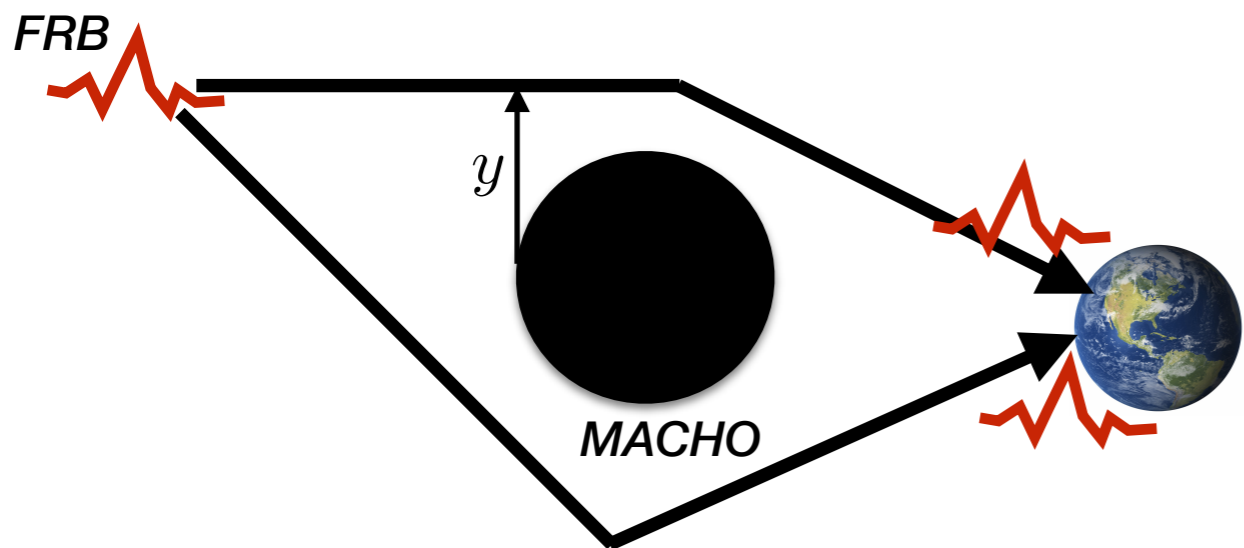
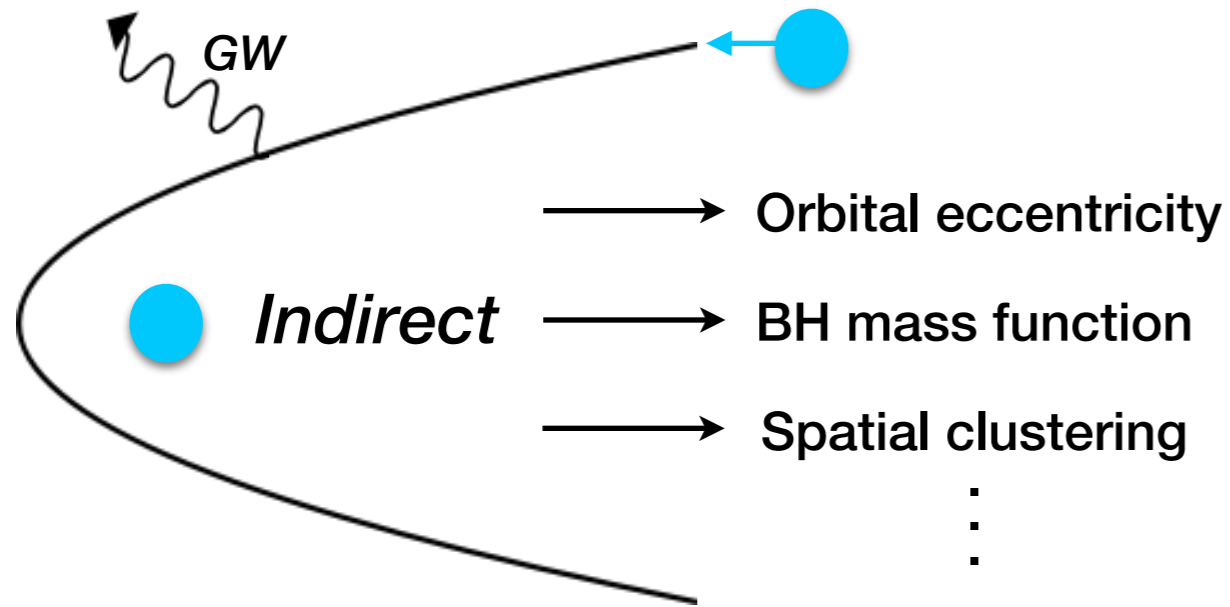
⋮

Experiment



Takeaway: We Can Test if PBHs are Dark Matter!

Theory



Experiment



Next Decade is promising!

Forming Primordial Black Holes

Requires high density:

$$R_s = \frac{2GM}{c^2} = 3 \left(\frac{M}{M_\odot} \right) \text{ km}$$

$$\rho_s = 10^{18} \left(\frac{M}{M_\odot} \right)^{-2} \text{ g cm}^{-3}$$

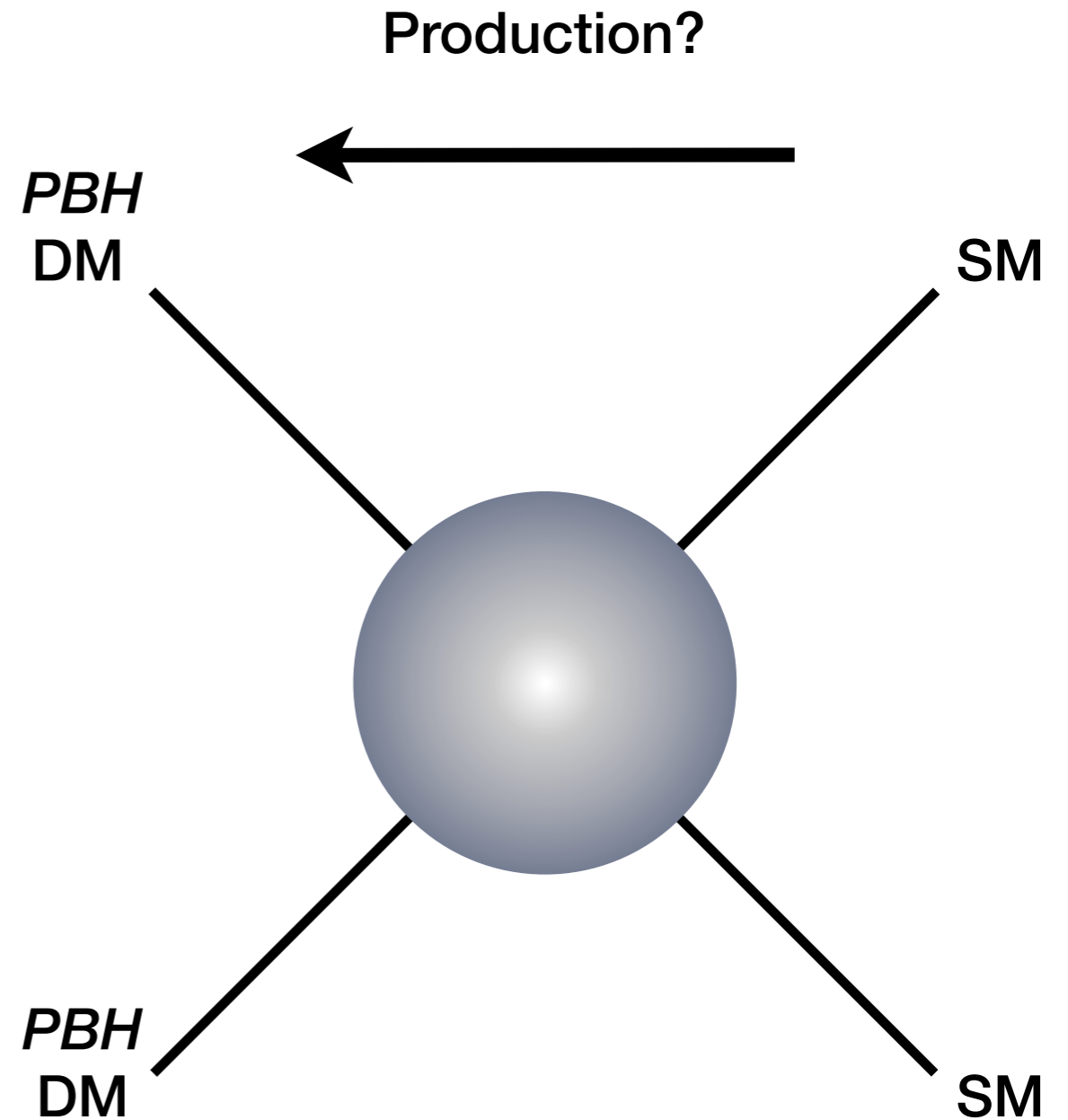
Possibly in the early Universe?

$$M_H \approx \frac{c^3 t}{G} = 10^{15} \text{ g} \left(\frac{t}{10^{-23} \text{ s}} \right)$$

(Planck mass) $10^{-5} \text{ g} : t \sim 10^{-43} \text{ s}$

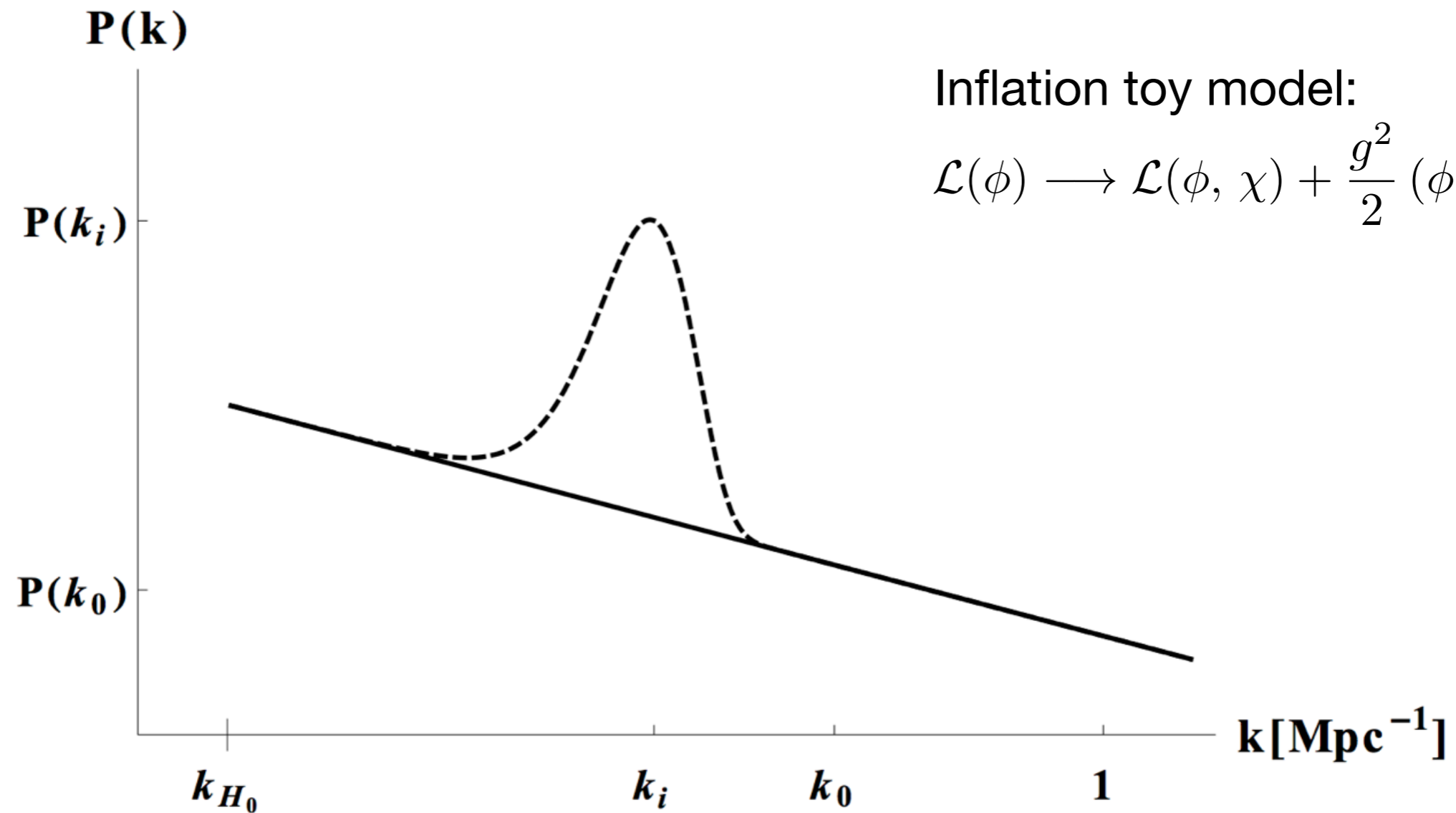
(QCD transition) $30 M_\odot : t \sim 1 \text{ ms}$

(Nucleosynthesis) $10^5 M_\odot : t \sim 1 \text{ s}$



Forming Primordial Black Holes: Toy Model

A peak in the primordial power spectrum can generate PBHs at a given scale:



To get $M \sim 30M_\odot$, we need a feature at: $k_i \sim 10^6 \text{ Mpc}^{-1}$

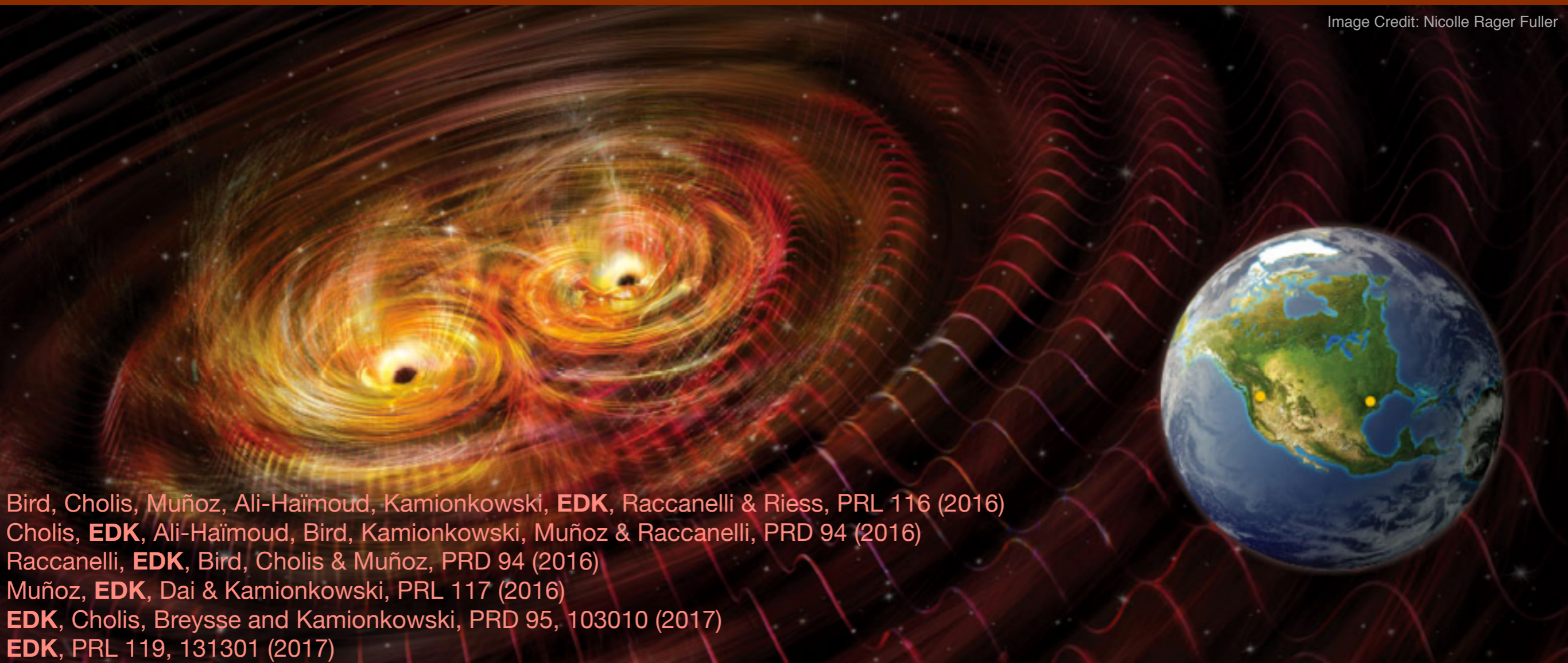
This is well outside the constrained region by CMB and LSS: $k < 0.1 - 1 \text{ Mpc}^{-1}$

Thank you!

Ely D. Kovetz

Johns Hopkins University

Image Credit: Nicolle Rager Fuller



Bird, Cholis, Muñoz, Ali-Haïmoud, Kamionkowski, **EDK**, Raccanelli & Riess, PRL 116 (2016)

Cholis, **EDK**, Ali-Haïmoud, Bird, Kamionkowski, Muñoz & Raccanelli, PRD 94 (2016)

Raccanelli, **EDK**, Bird, Cholis & Muñoz, PRD 94 (2016)

Muñoz, **EDK**, Dai & Kamionkowski, PRL 117 (2016)

EDK, Cholis, Breysse and Kamionkowski, PRD 95, 103010 (2017)

EDK, PRL 119, 131301 (2017)

Nishikawa, **EDK**, Kamionkowski and Silk, arXiv:1708.08449

Ali-Haïmoud, **EDK** and Kamionkowski, arXiv:1709.06576

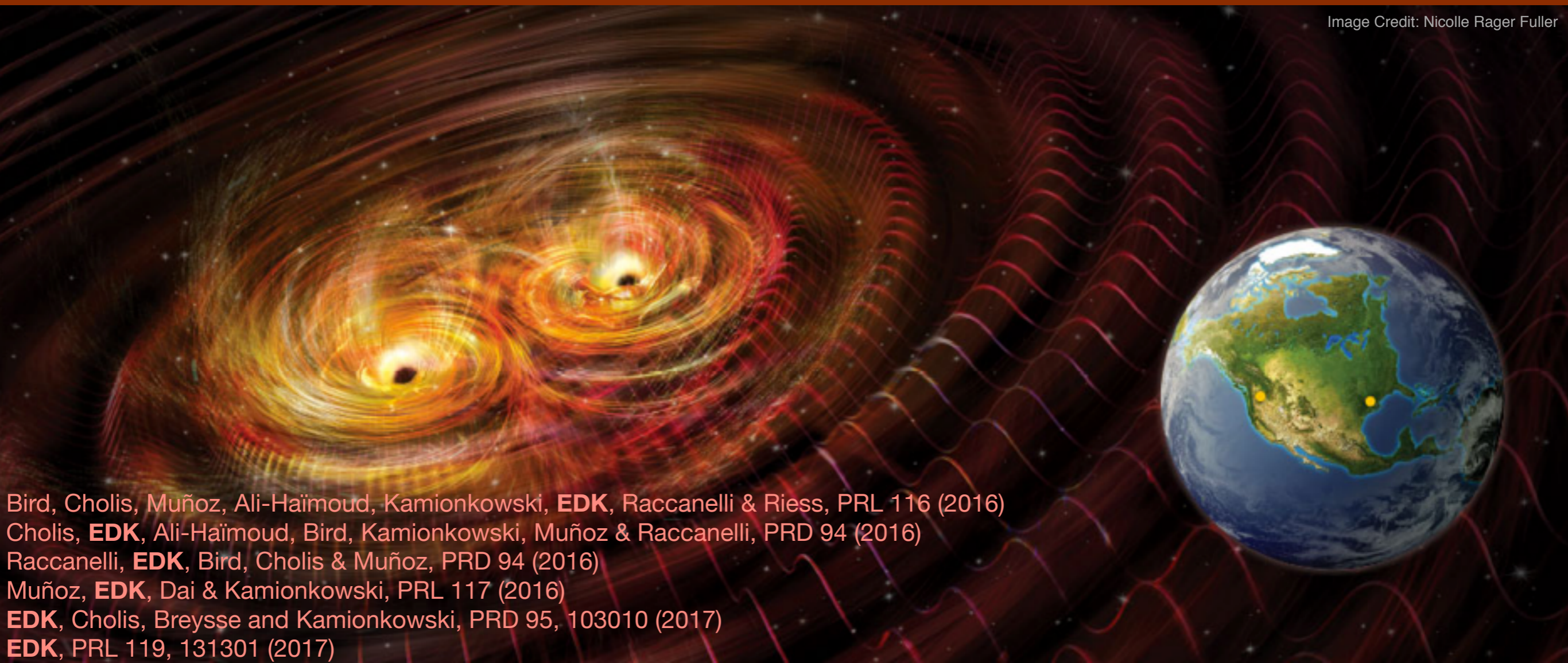
Ji, **EDK**, Kamionkowski and Ménard, in preparation.

Thank you!

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Image Credit: Nicolle Rager Fuller



Bird, Cholis, Muñoz, Ali-Haïmoud, Kamionkowski, **EDK**, Raccanelli & Riess, PRL 116 (2016)

Cholis, **EDK**, Ali-Haïmoud, Bird, Kamionkowski, Muñoz & Raccanelli, PRD 94 (2016)

Raccanelli, **EDK**, Bird, Cholis & Muñoz, PRD 94 (2016)

Muñoz, **EDK**, Dai & Kamionkowski, PRL 117 (2016)

EDK, Cholis, Breysse and Kamionkowski, PRD 95, 103010 (2017)

EDK, PRL 119, 131301 (2017)

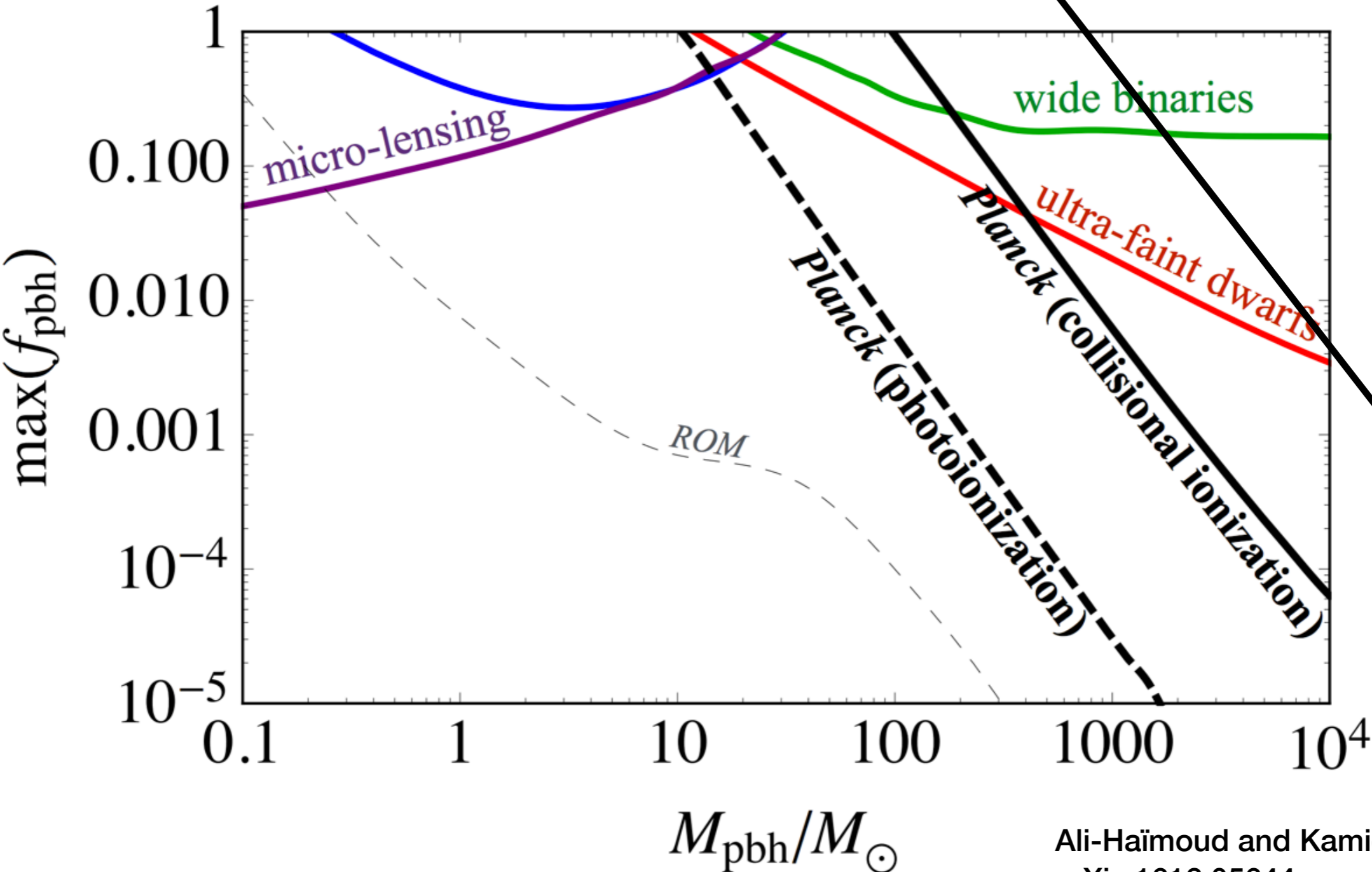
Nishikawa, **EDK**, Kamionkowski and Silk, arXiv:1708.08449

Ali-Haïmoud, **EDK** and Kamionkowski, arXiv:1709.06576

Ji, **EDK**, Kamionkowski and Ménard, in preparation.

PBH DM: Constraints from the CMB

CMB Constraints:



The mass spectrum of merging PBHs: 2D Signal

(Kovetz et al., PRD 2017)

Using the 2D mass distribution (more model-dependent):

GW150914

GW170814

GW170104

LVT1151012

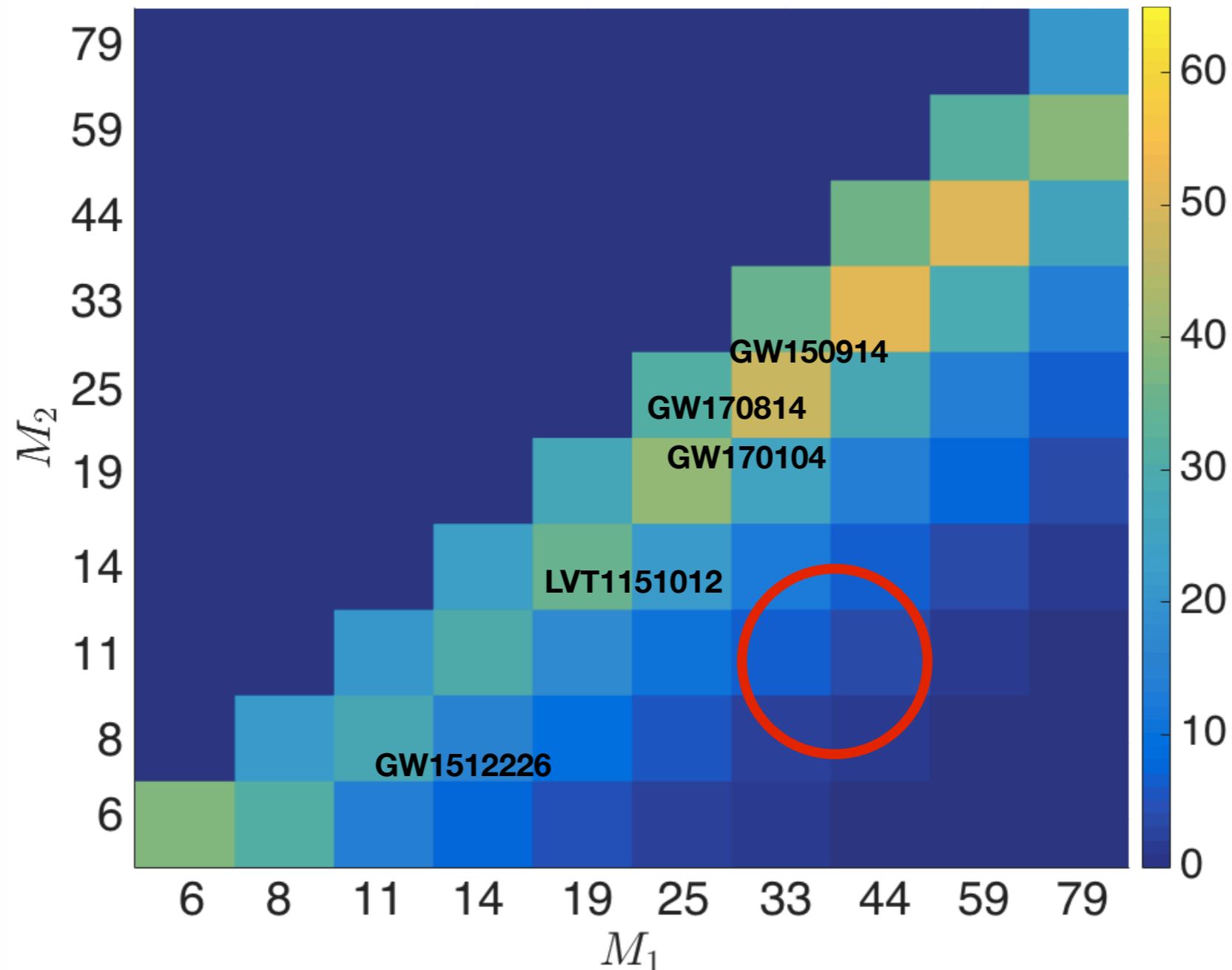
GW1512226

The mass spectrum of merging PBHs: 2D Signal

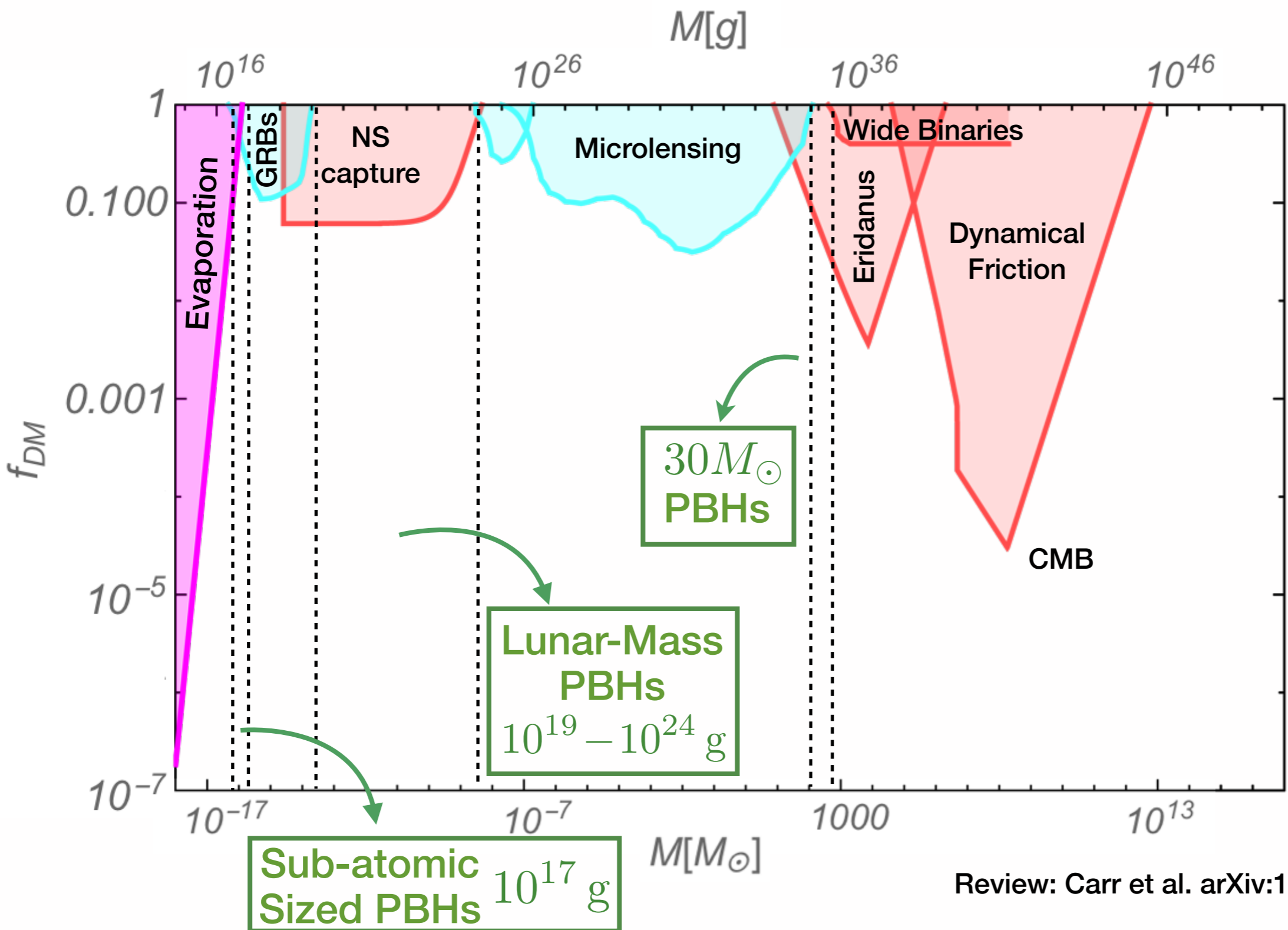
(Kovetz et al., PRD 2017)

Using the 2D mass distribution (more model-dependent):

2D Binned Mass Distribution of BBH Mergers:



PBH DM: Other Allowed Windows?



The Stellar BH Mass Function from GWs: 2D

(EDK et al., arXiv:1611.01157)

Consider the 2D mass function:

The Stellar BH Mass Function from GWs: 2D

(EDK et al., arXiv:1611.01157)

Consider the 2D mass function:

Heavier mass:

The Stellar BH Mass Function from GWs: 2D

(EDK et al., arXiv:1611.01157)

Consider the 2D mass function:

Heavier mass: $p(m) \propto m^{-\alpha} \mathcal{H}(m - m_{\text{Gap}}) e^{-m/m_{\text{Cap}}}$

The Stellar BH Mass Function from GWs: 2D

(EDK et al., arXiv:1611.01157)

Consider the 2D mass function:

Heavier mass: $p(m) \propto m^{-\alpha} \mathcal{H}(m - m_{\text{Gap}}) e^{-m/m_{\text{Cap}}}$

Lighter mass:

The Stellar BH Mass Function from GWs: 2D

(EDK et al., arXiv:1611.01157)

Consider the 2D mass function:

Heavier mass: $p(m) \propto m^{-\alpha} \mathcal{H}(m - m_{\text{Gap}}) e^{-m/m_{\text{Cap}}}$

Lighter mass: $p(m') \propto (m'/m)^{\beta}$

The Stellar BH Mass Function from GWs: 2D

(EDK et al., arXiv:1611.01157)

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Lighter mass: $p(m') \propto (m'/m)^\beta$ Mass Ratio
 $\beta = 0?$

The Stellar BH Mass Function from GWs: 2D

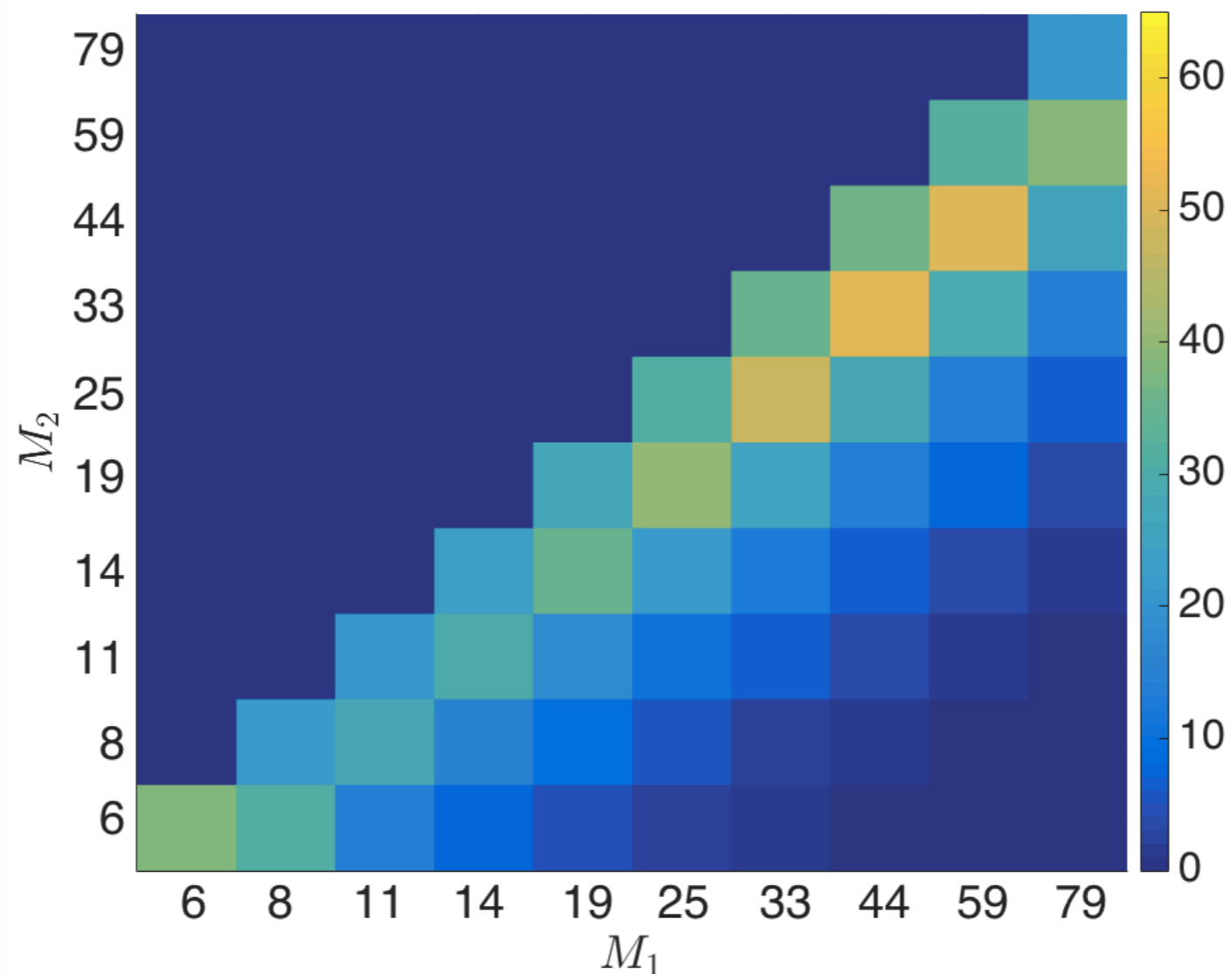
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2D Binned Mass Distribution of BBH Mergers: $\beta = 0$



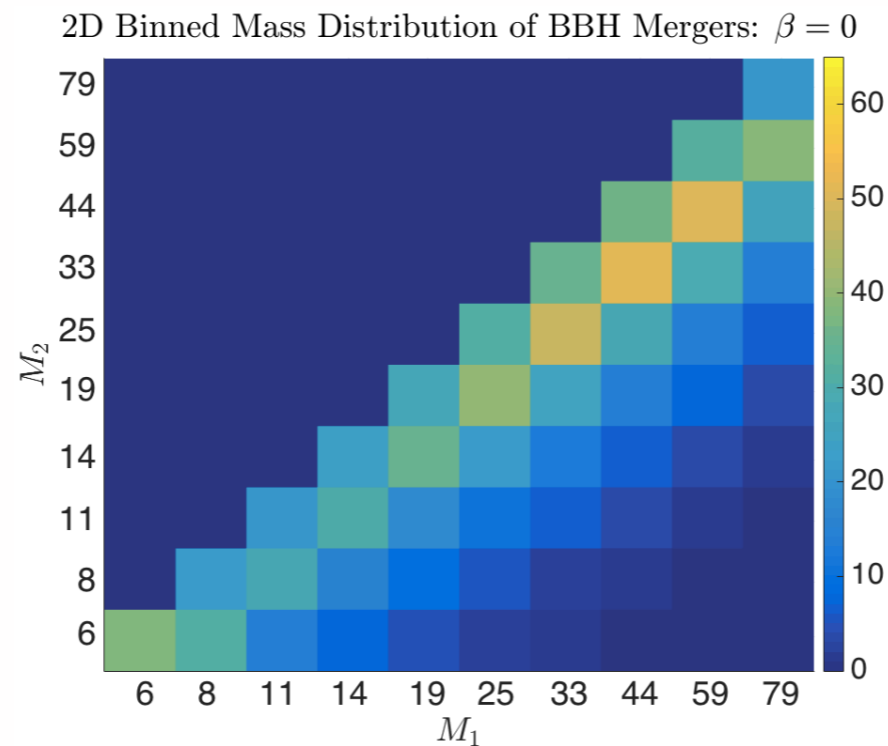
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The Stellar BH Mass Function from GWs: 2D

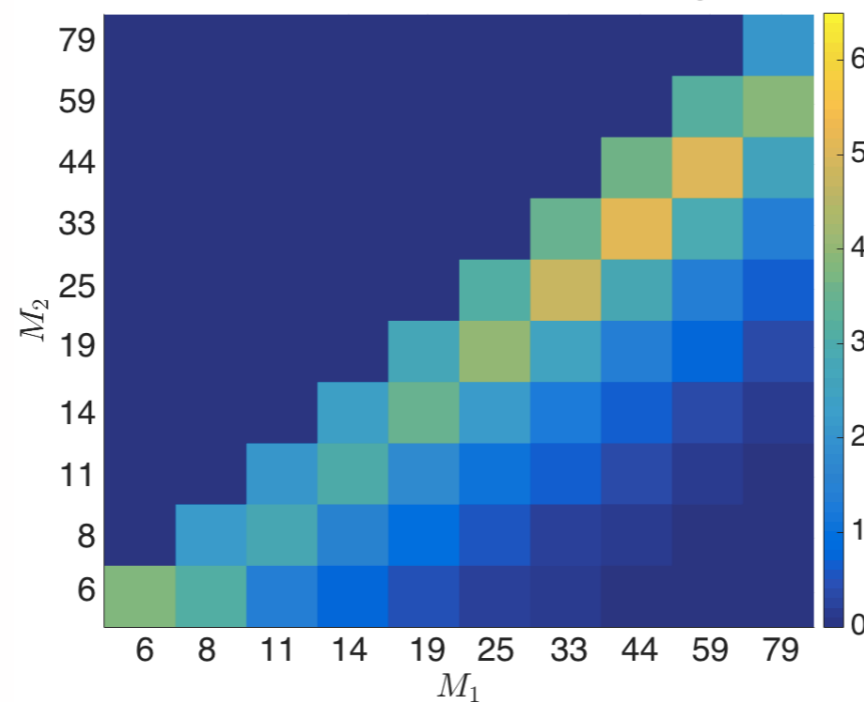
(EDK et al., arXiv:1611.01157)

Consider the 2D mass function:

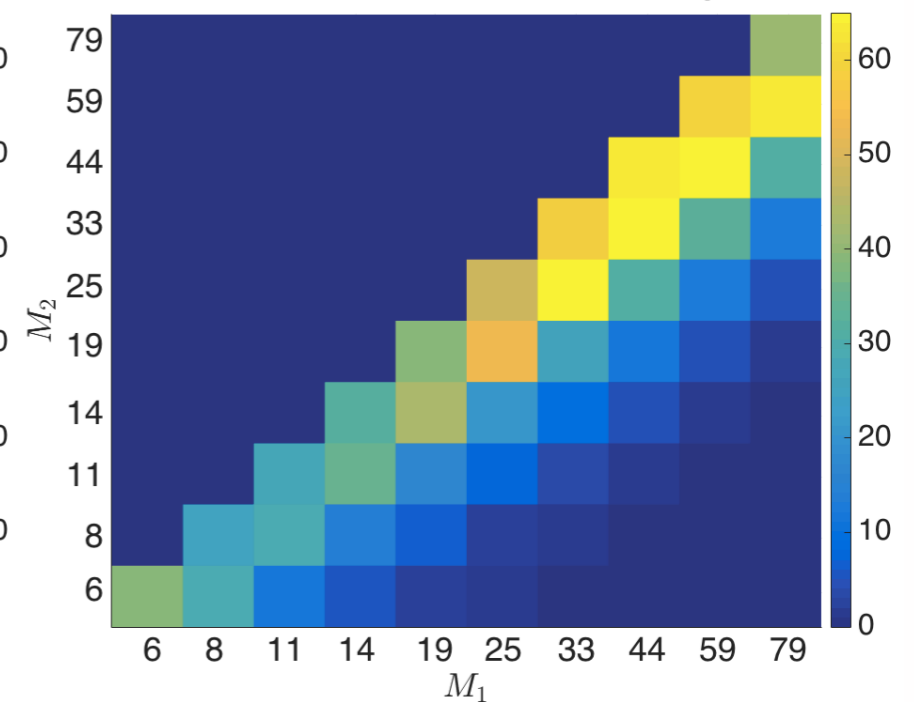
Heavier mass: $p(m) \propto m^{-\alpha} \mathcal{H}(m - m_{\text{Gap}}) e^{-m/m_{\text{Cap}}}$

Lighter mass: $p(m') \propto (m'/m)^{\beta}$ Mass Ratio
 $\beta = 0?$

2D Binned Mass Distribution of BBH Mergers: $\beta = 0$



2D Binned Mass Distribution of BBH Mergers: $\beta = 1$



The Stellar BH Mass Function from GWs: 2D

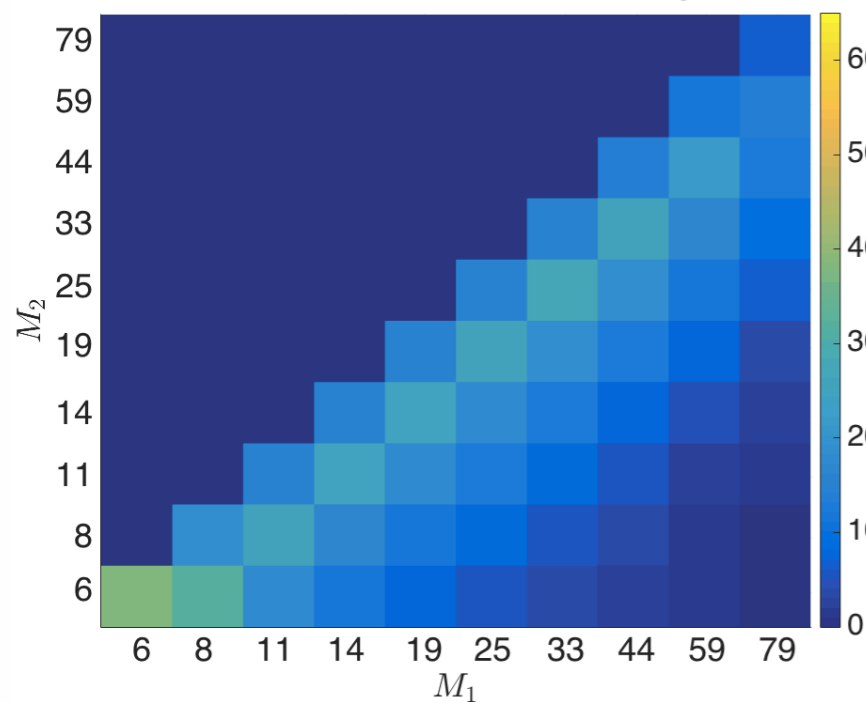
(EDK et al., arXiv:1611.01157)

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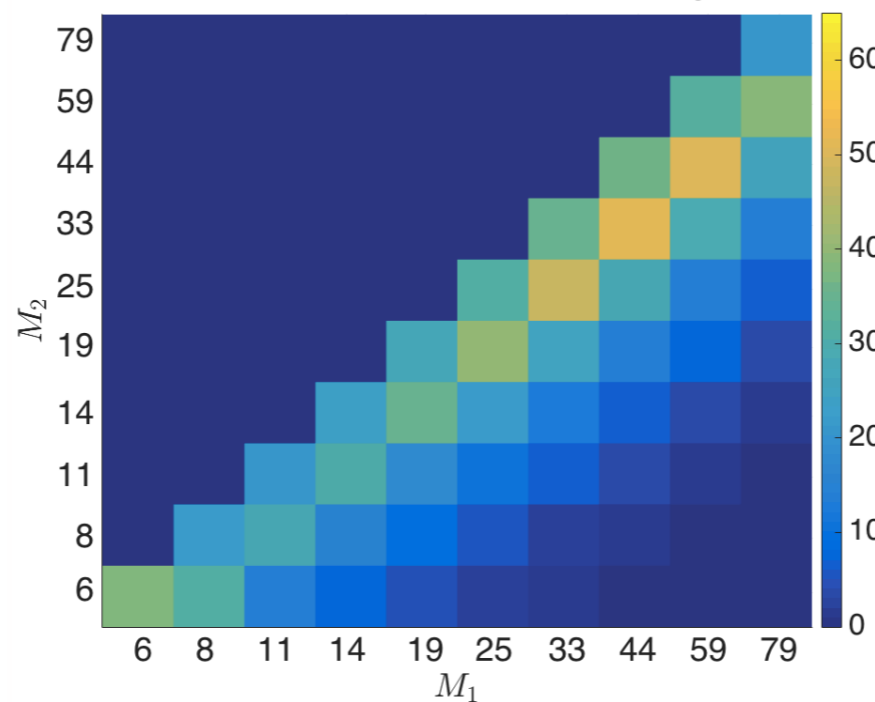
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Lighter mass: $p(m') \propto (m'/m)^{\beta}$ Mass Ratio
 $\beta = 0?$

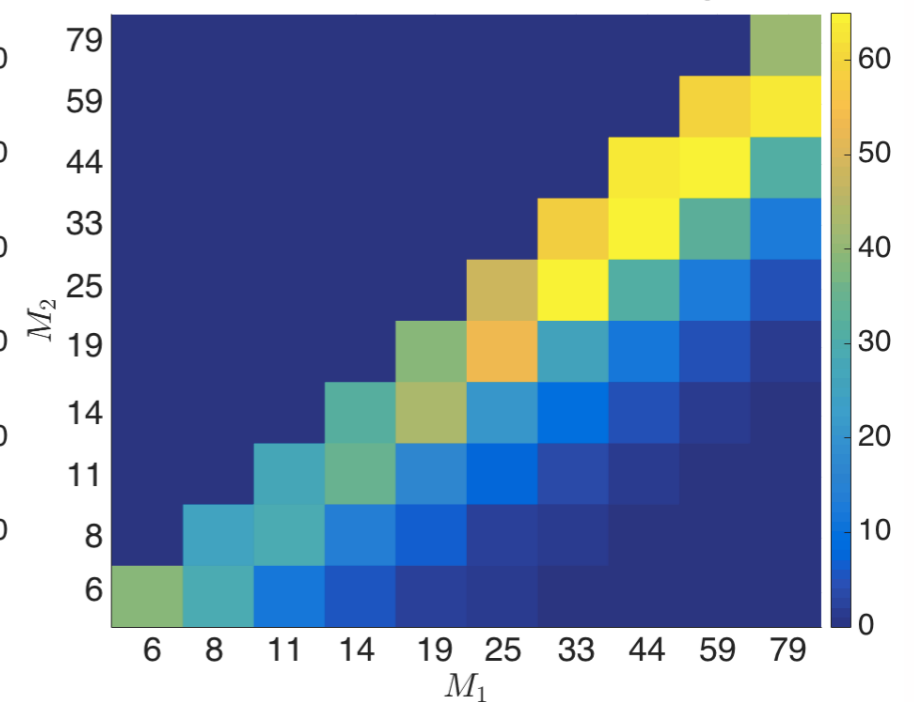
2D Binned Mass Distribution of BBH Mergers: $\beta = -1$



2D Binned Mass Distribution of BBH Mergers: $\beta = 0$



2D Binned Mass Distribution of BBH Mergers: $\beta = 1$



The Stellar BH Mass Function from GWs: 2D

(EDK et al., arXiv:1611.01157)

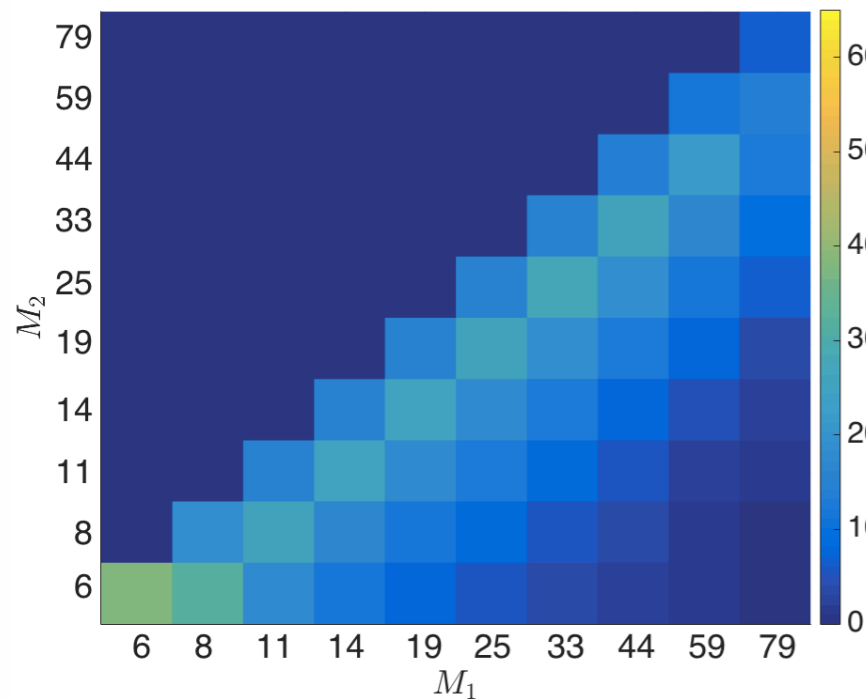
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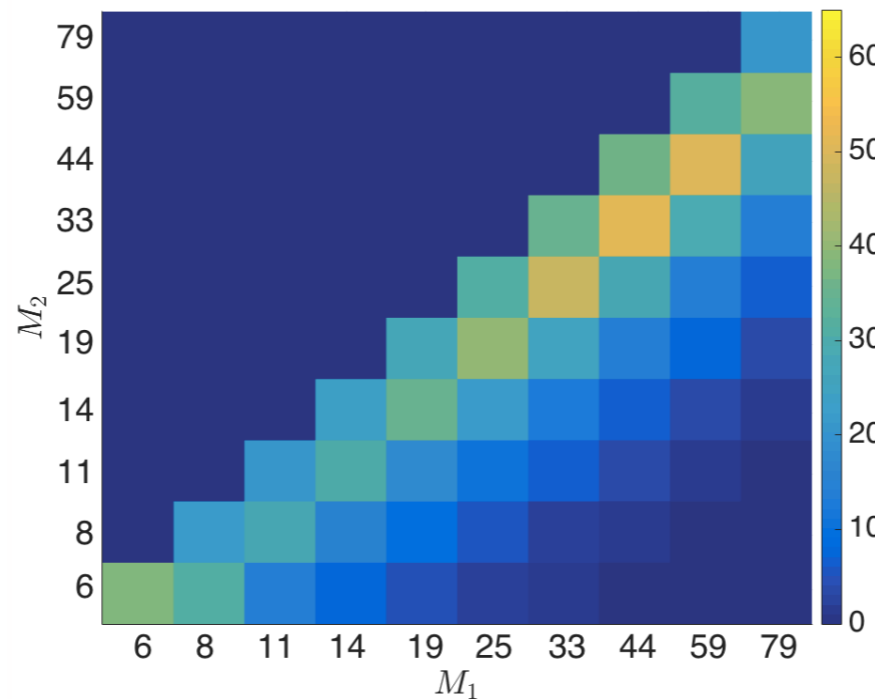
Lighter mass: $p(m') \propto (m'/m)^{\beta}$ Mass Ratio
 $\beta = 0?$

The 2D distribution is a sensitive probe of the progenitor model!

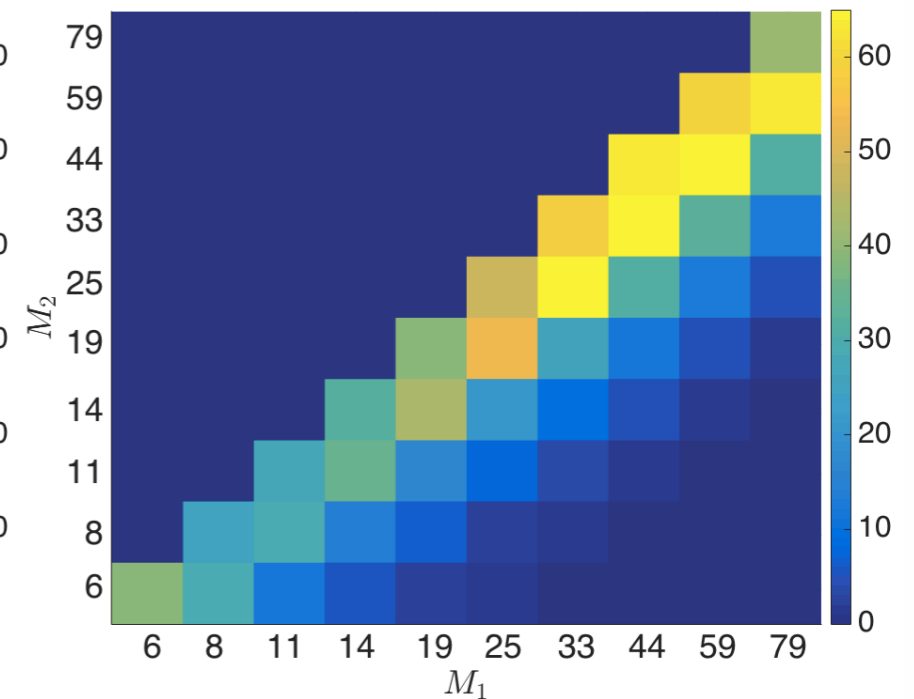
2D Binned Mass Distribution of BBH Mergers: $\beta = -1$



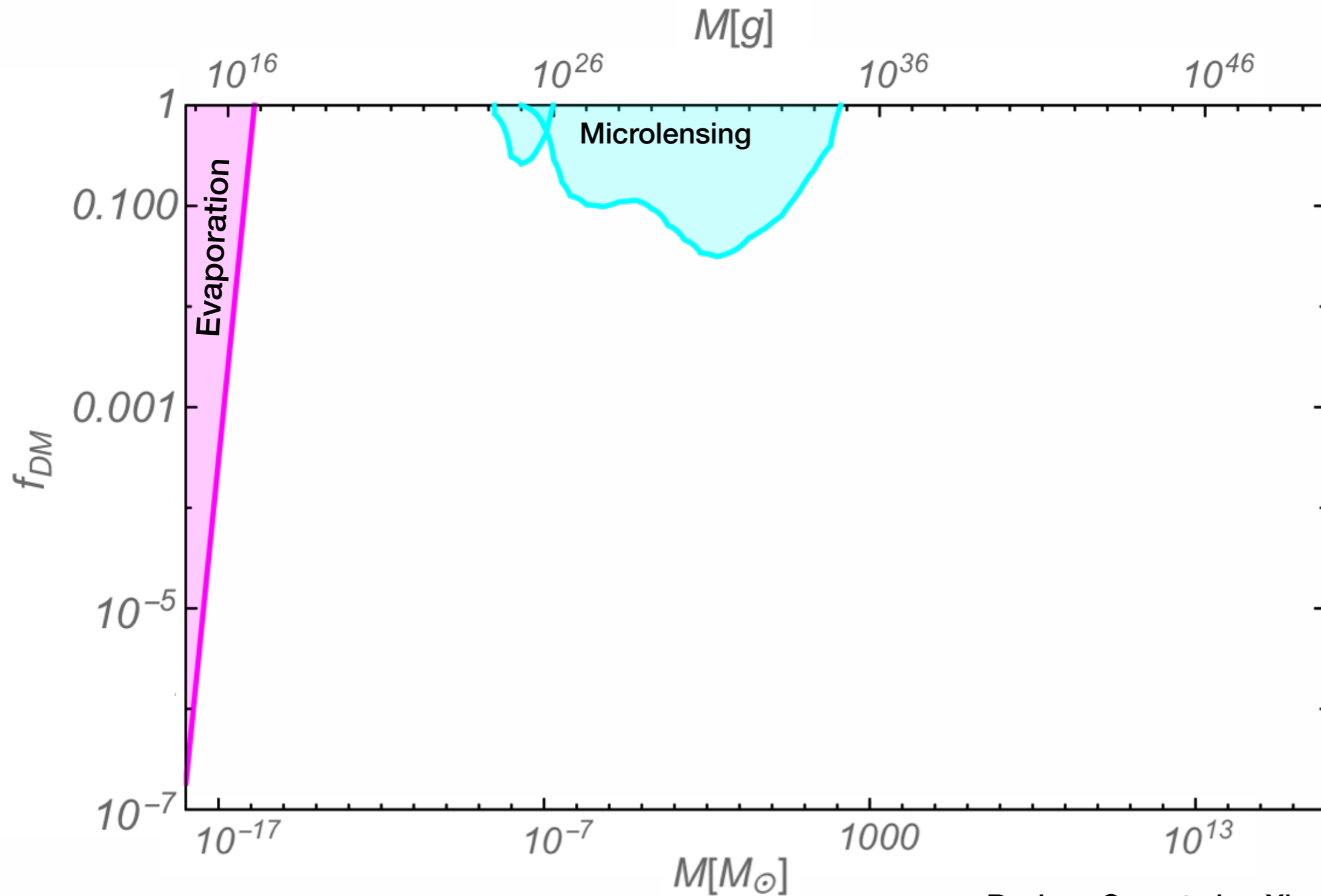
2D Binned Mass Distribution of BBH Mergers: $\beta = 0$



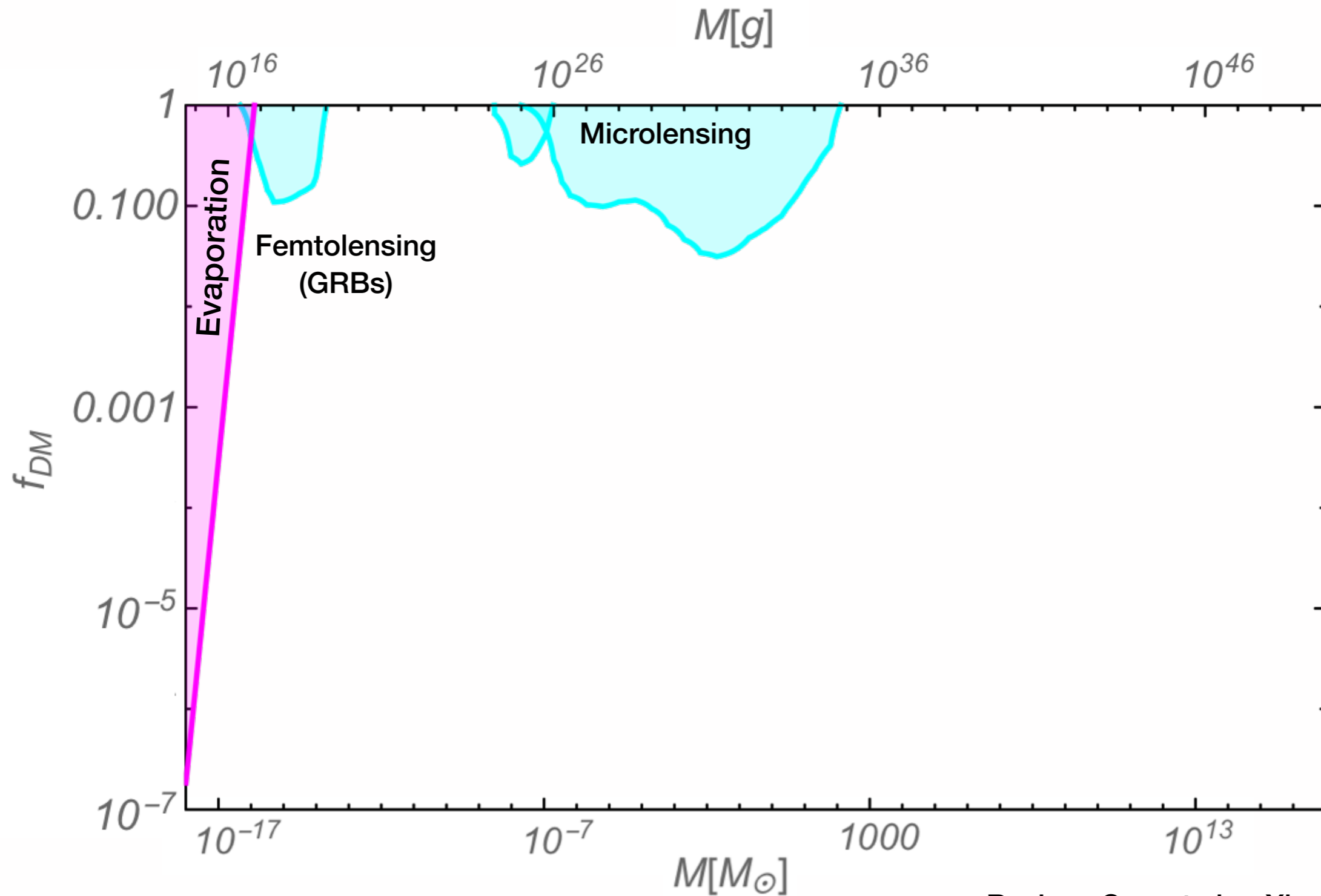
2D Binned Mass Distribution of BBH Mergers: $\beta = 1$



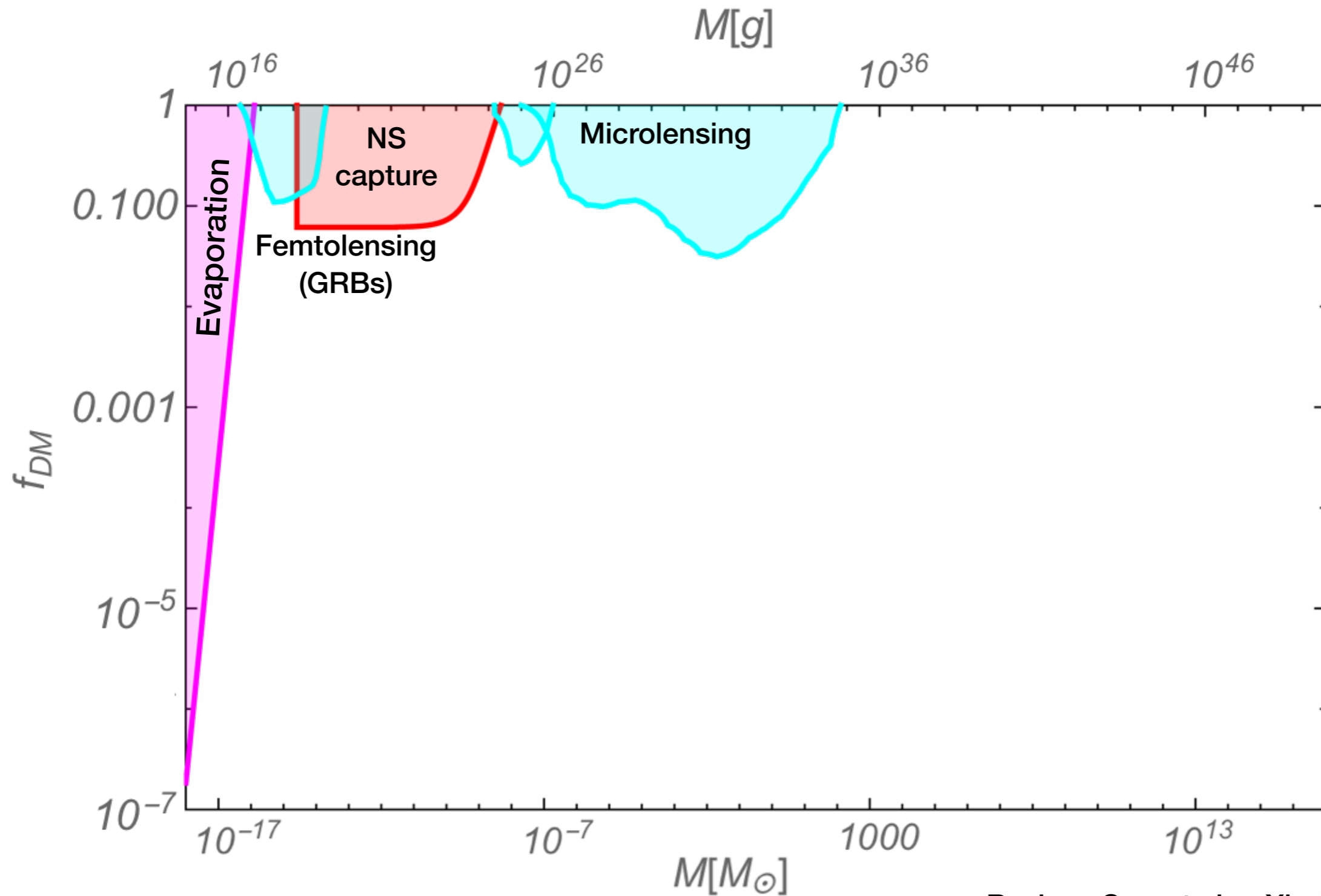
PBH DM: More Indirect Detection Constraints



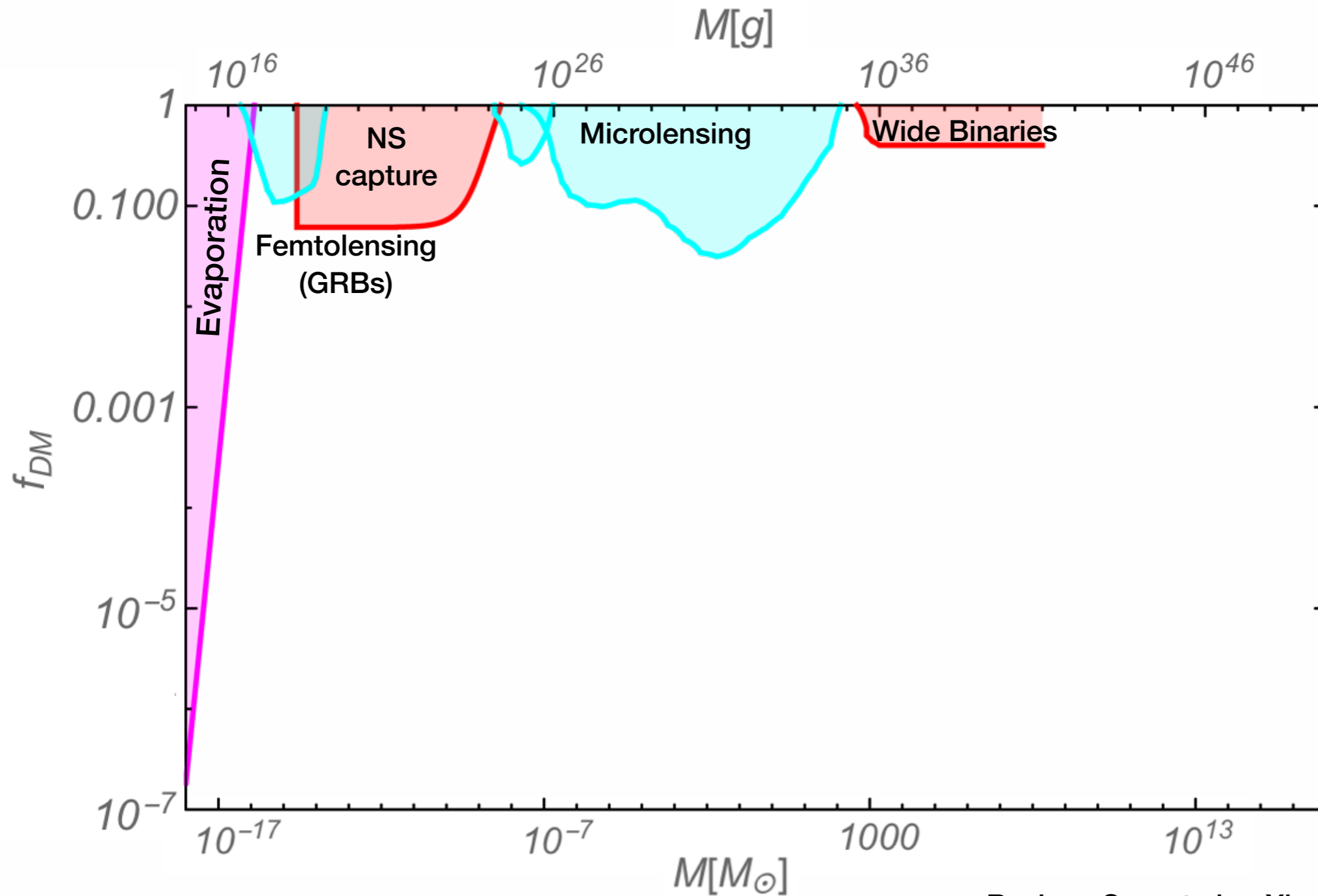
PBH DM: More Indirect Detection Constraints



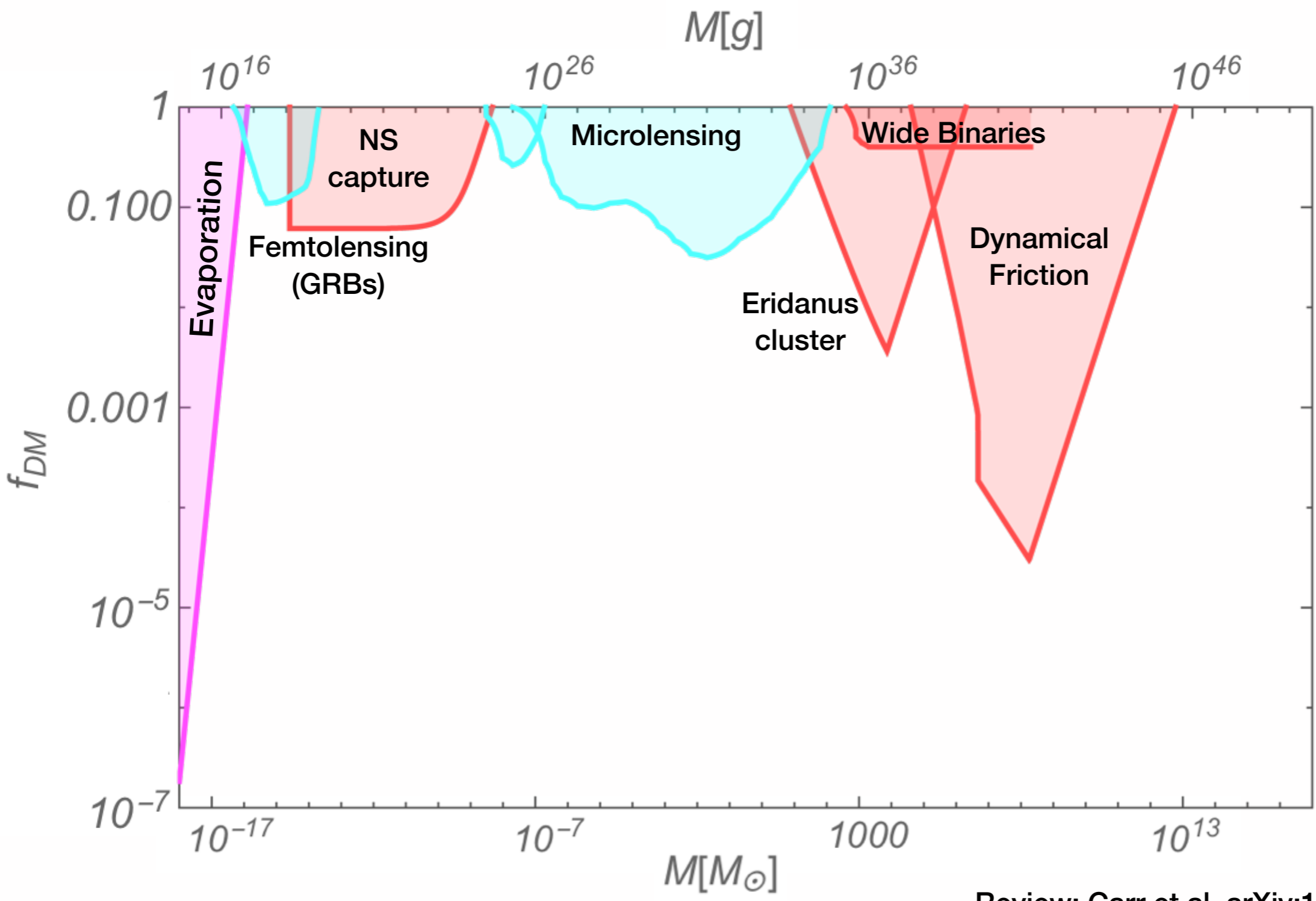
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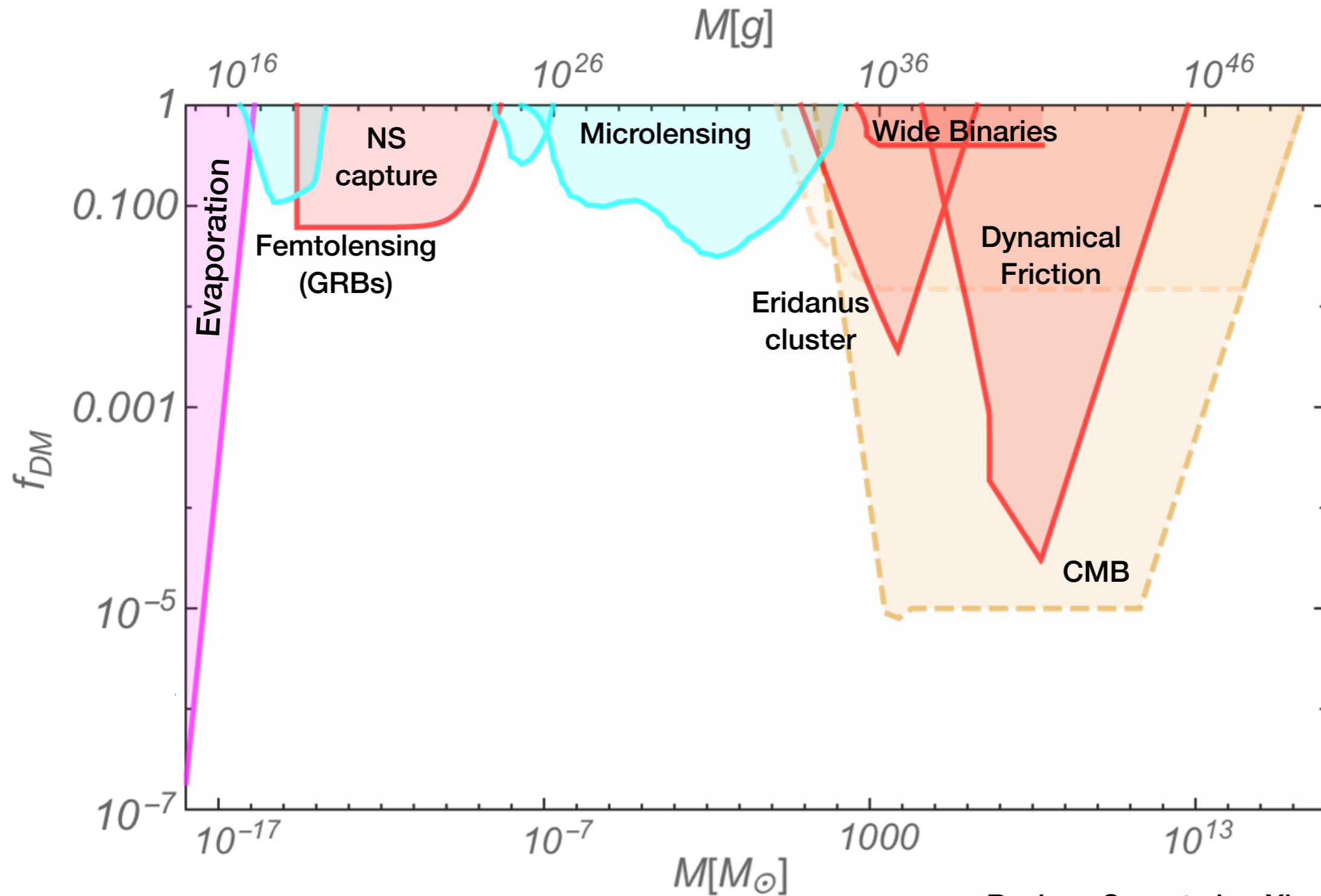
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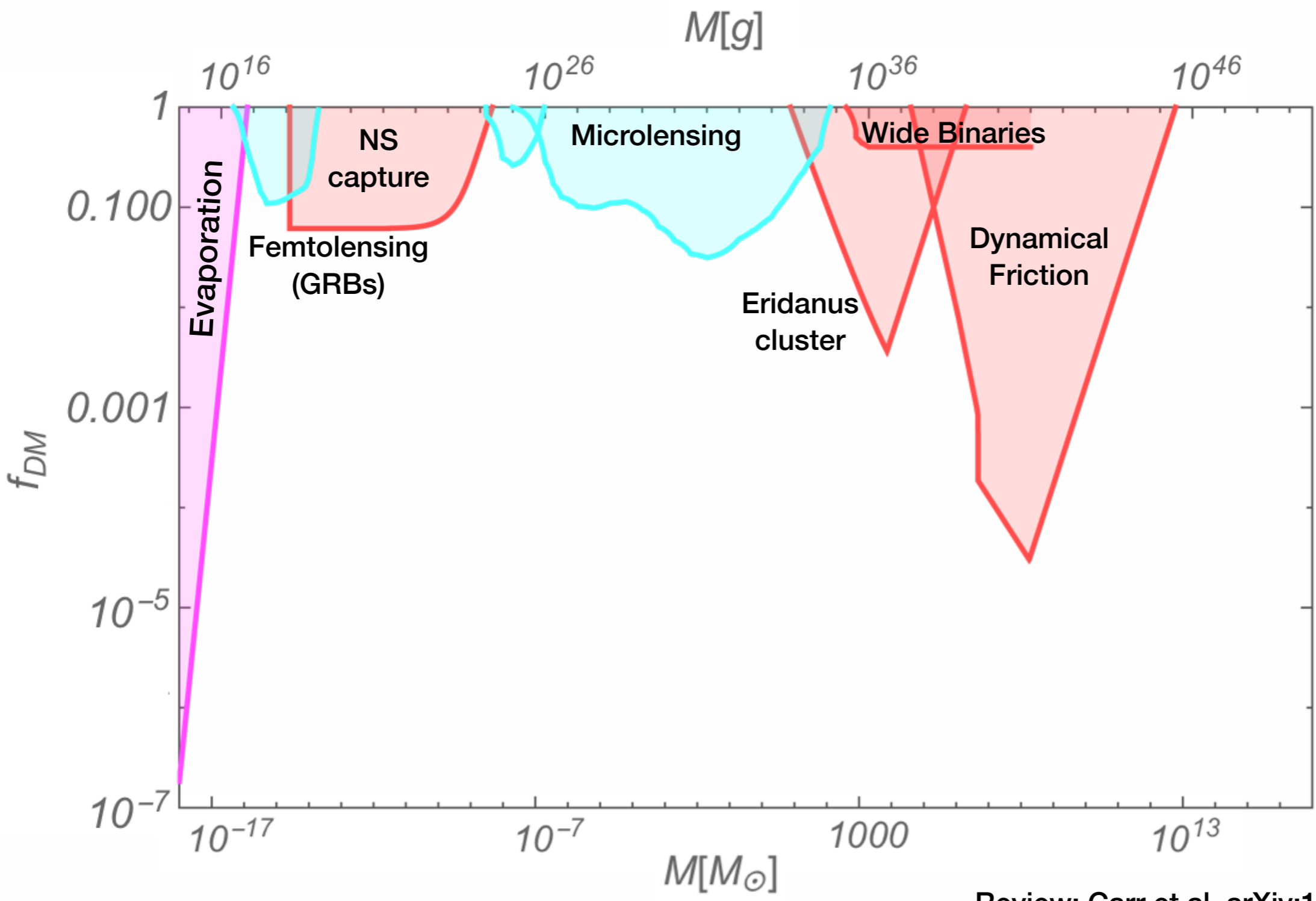
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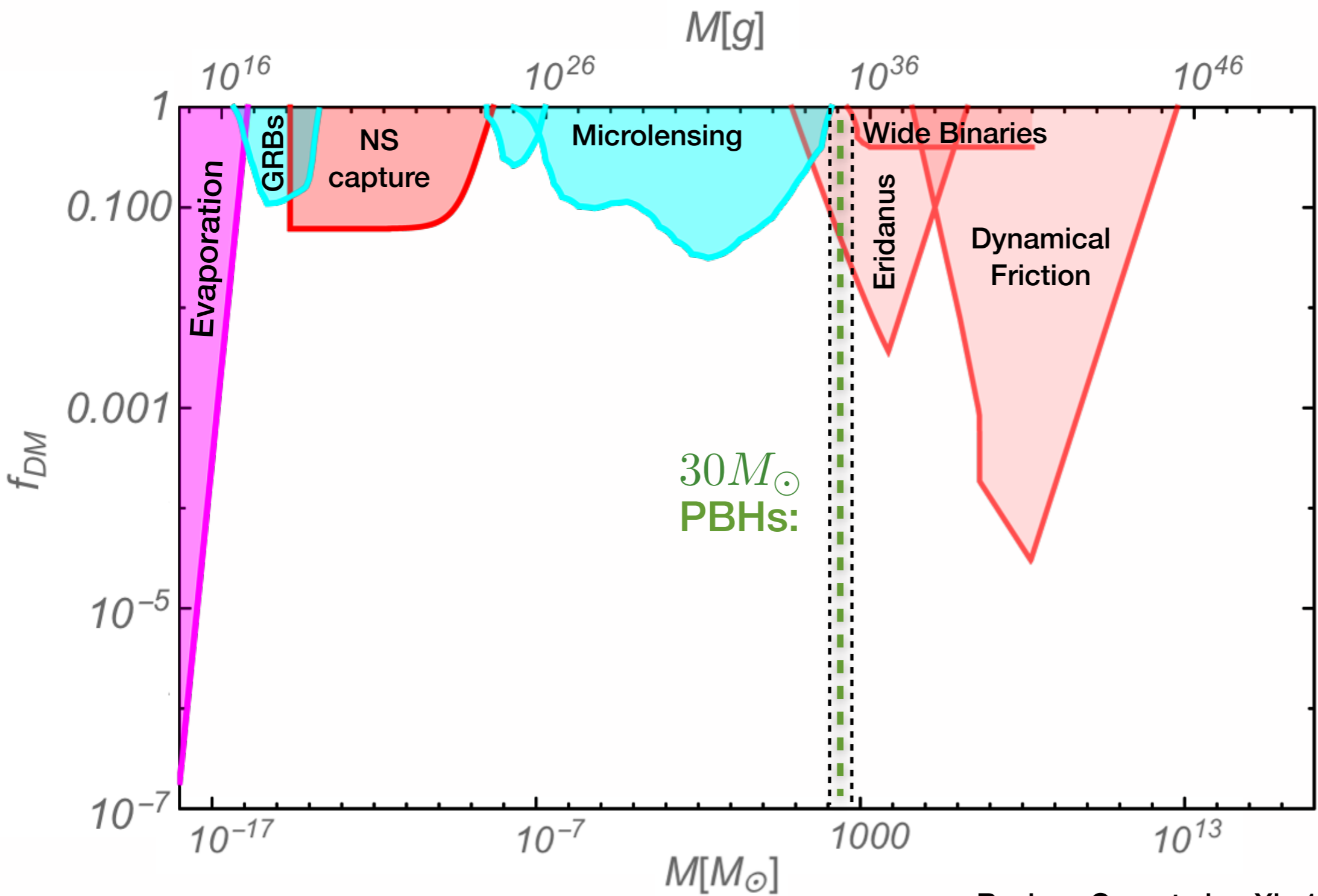
PBH DM: More Indirect Detection Constraints



PBH DM: More Indirect Detection Constraints



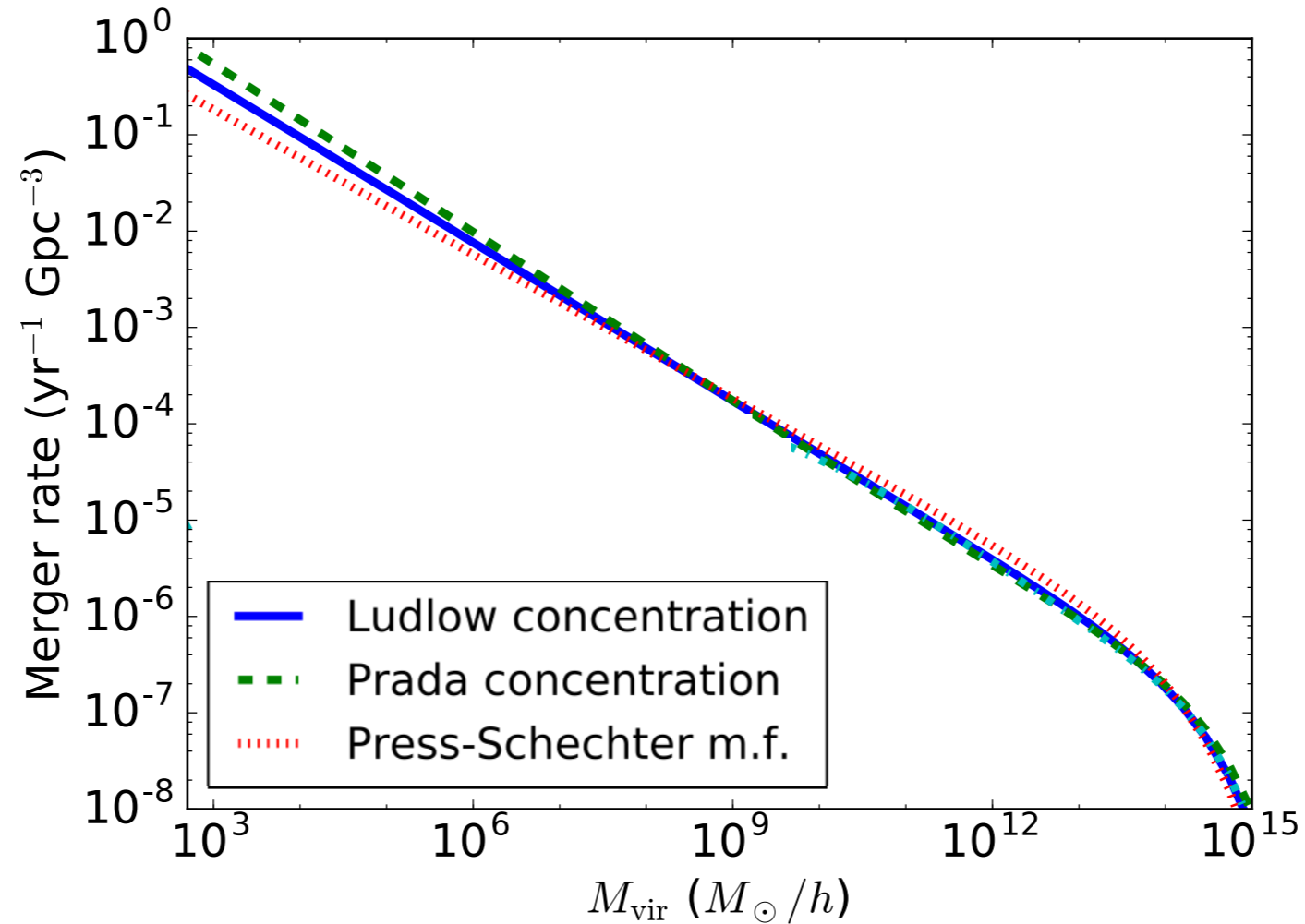
PBH Dark Matter: Is the LIGO Mass Window Alive?



Determining the Progenitors: Host Properties

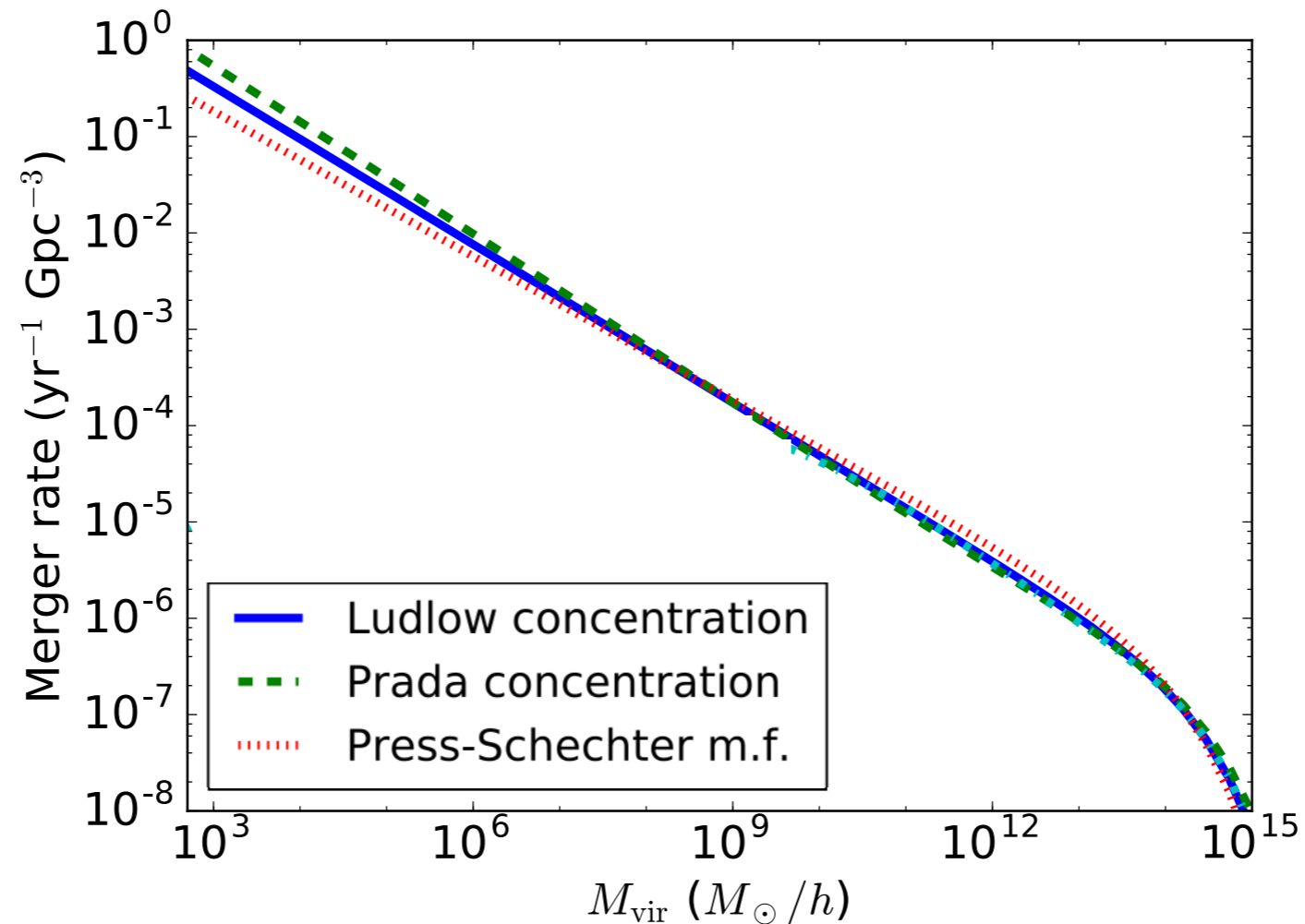
Determining the Progenitors: Host Properties

Recall:



Determining the Progenitors: Host Properties

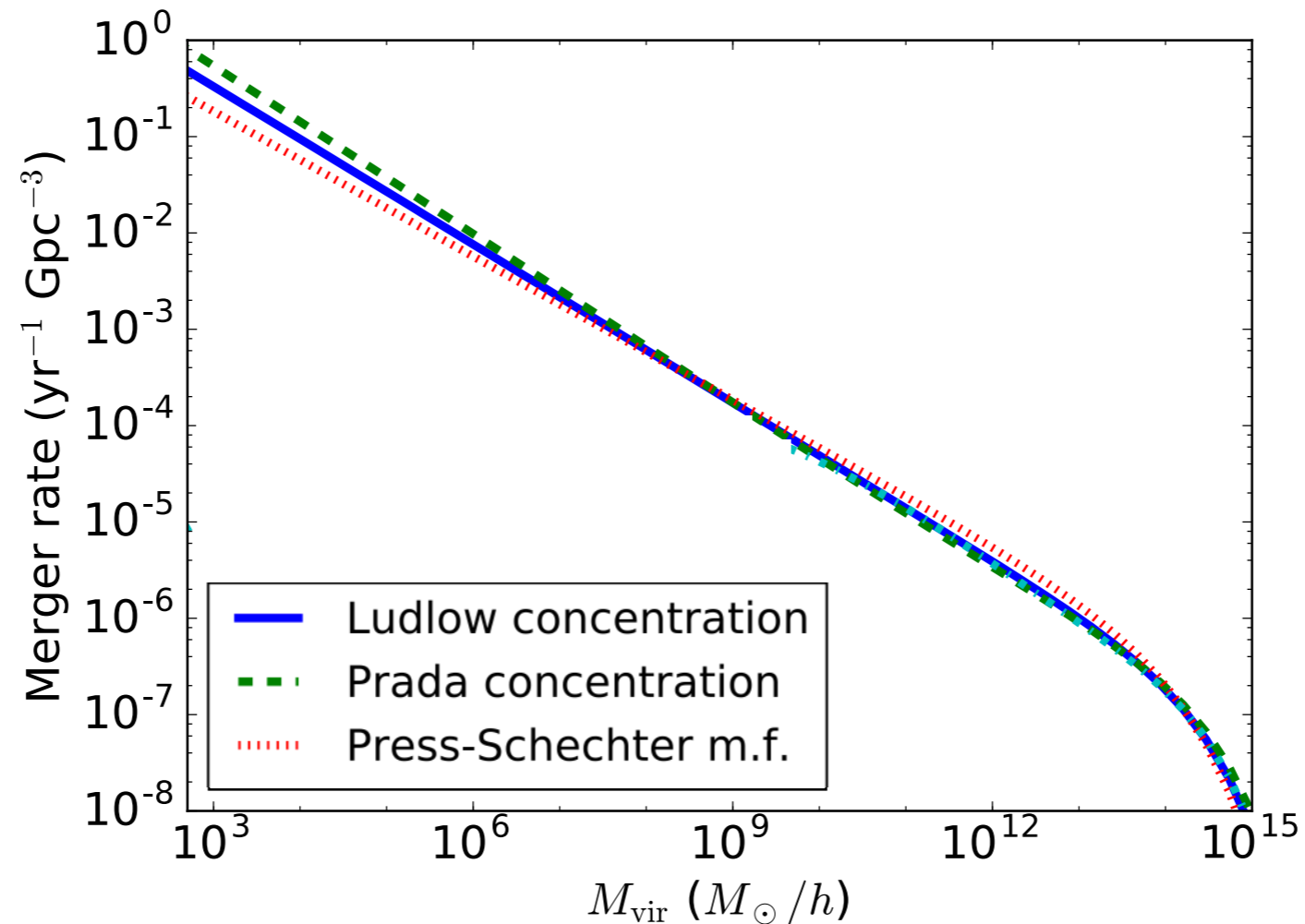
Recall:



PBH mergers reside primarily in low mass halos.

Determining the Progenitors: Host Properties

Recall:

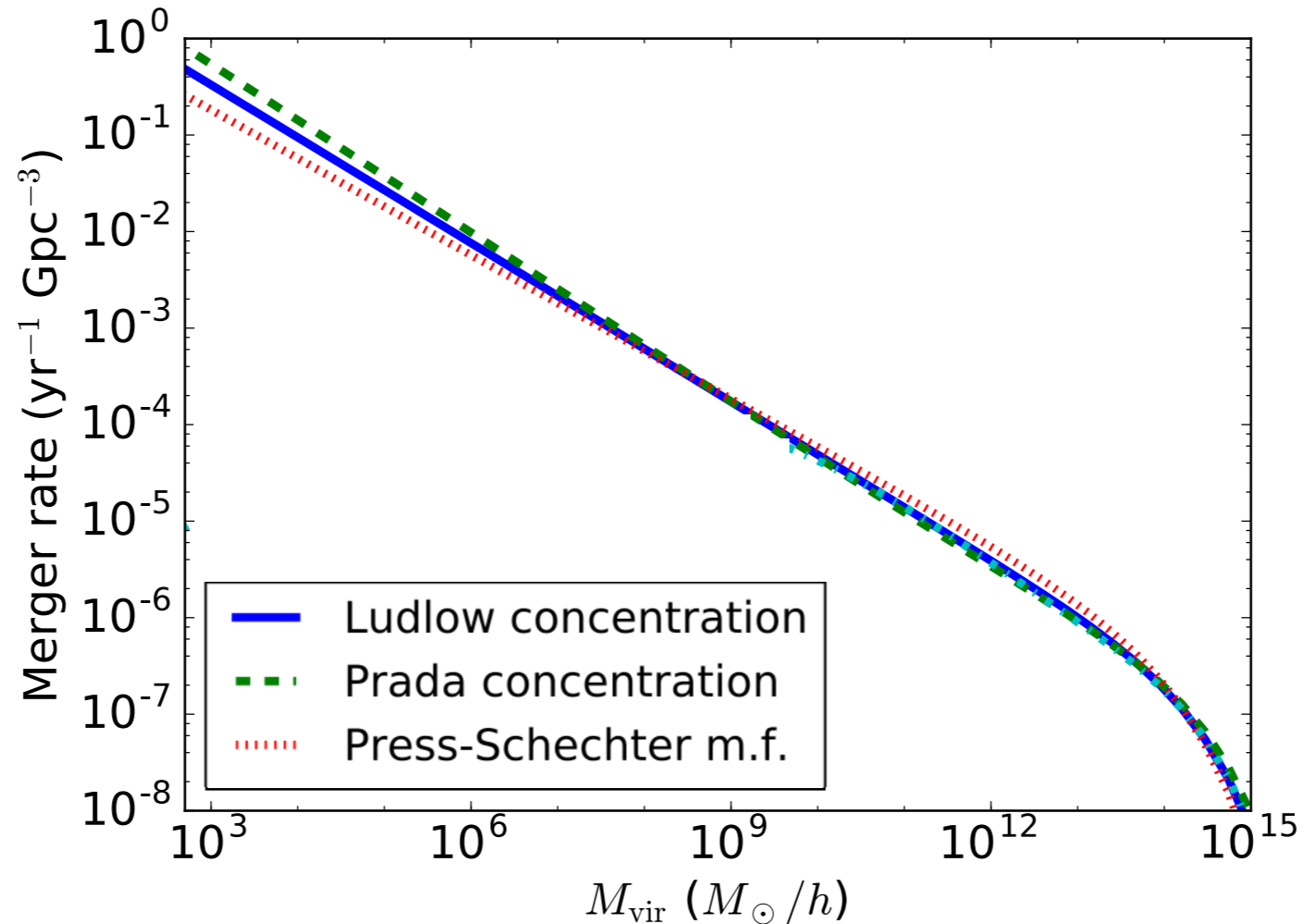


PBH mergers reside primarily in low mass halos.

These are low-biased tracers of the underlying dark-matter mass distribution.

Determining the Progenitors: Host Properties

Recall:



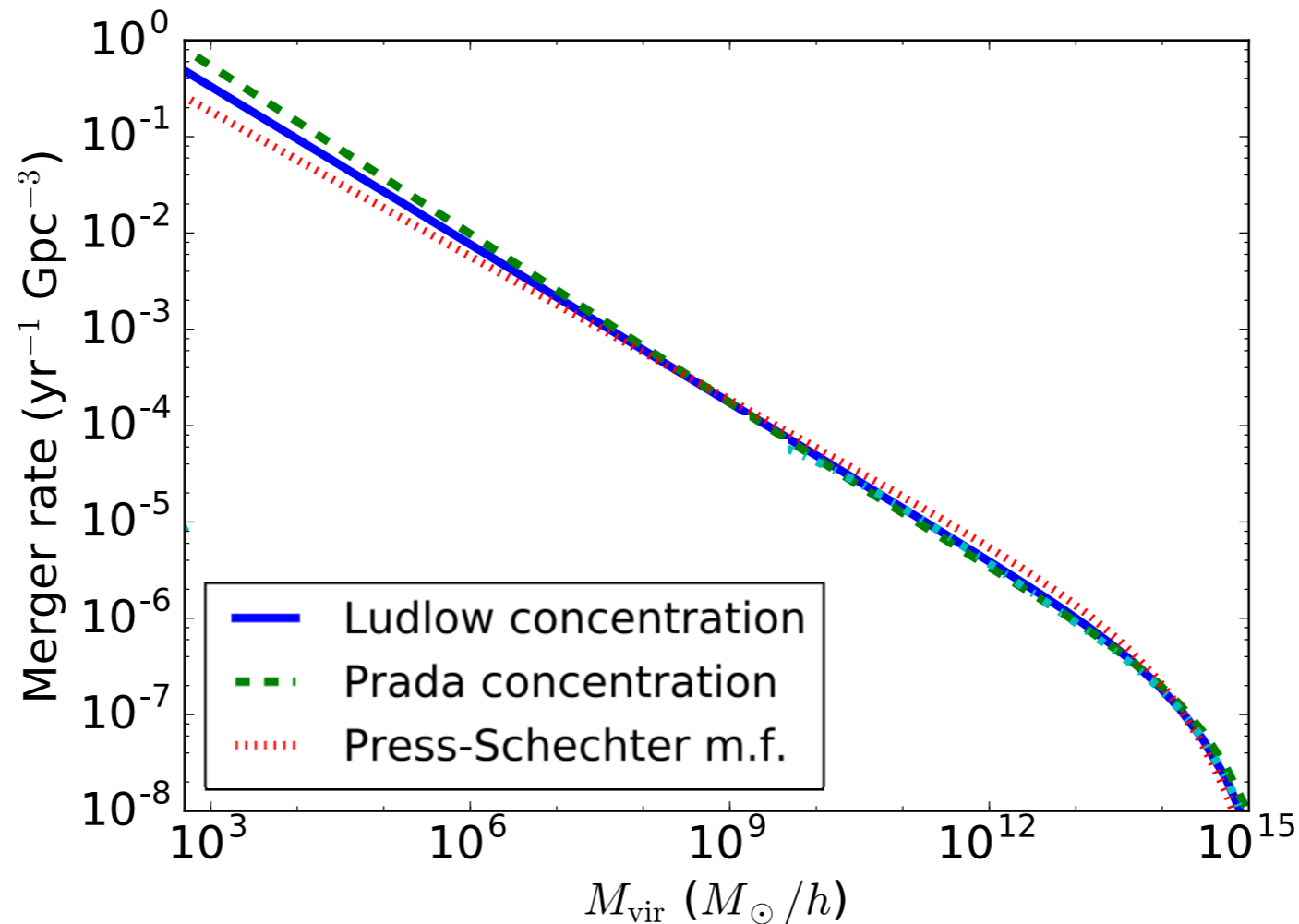
PBH mergers reside primarily in low mass halos.

These are low-biased tracers of the underlying dark-matter mass distribution.

→ Cross-correlate with galaxy catalogues!

Determining the Progenitors: Host Properties

Recall:



PBH mergers reside primarily in low mass halos.

These are low-biased tracers of the underlying dark-matter mass distribution.

→ Cross-correlate with galaxy catalogues!

Distinguish between $b_{\text{Stellar}} \sim 1.4$ and $b_{\text{PBH}} \sim 0.5$

Localization of Gravitational Wave Sources

Localization of Gravitational Wave Sources

Where do the GWs originate from?

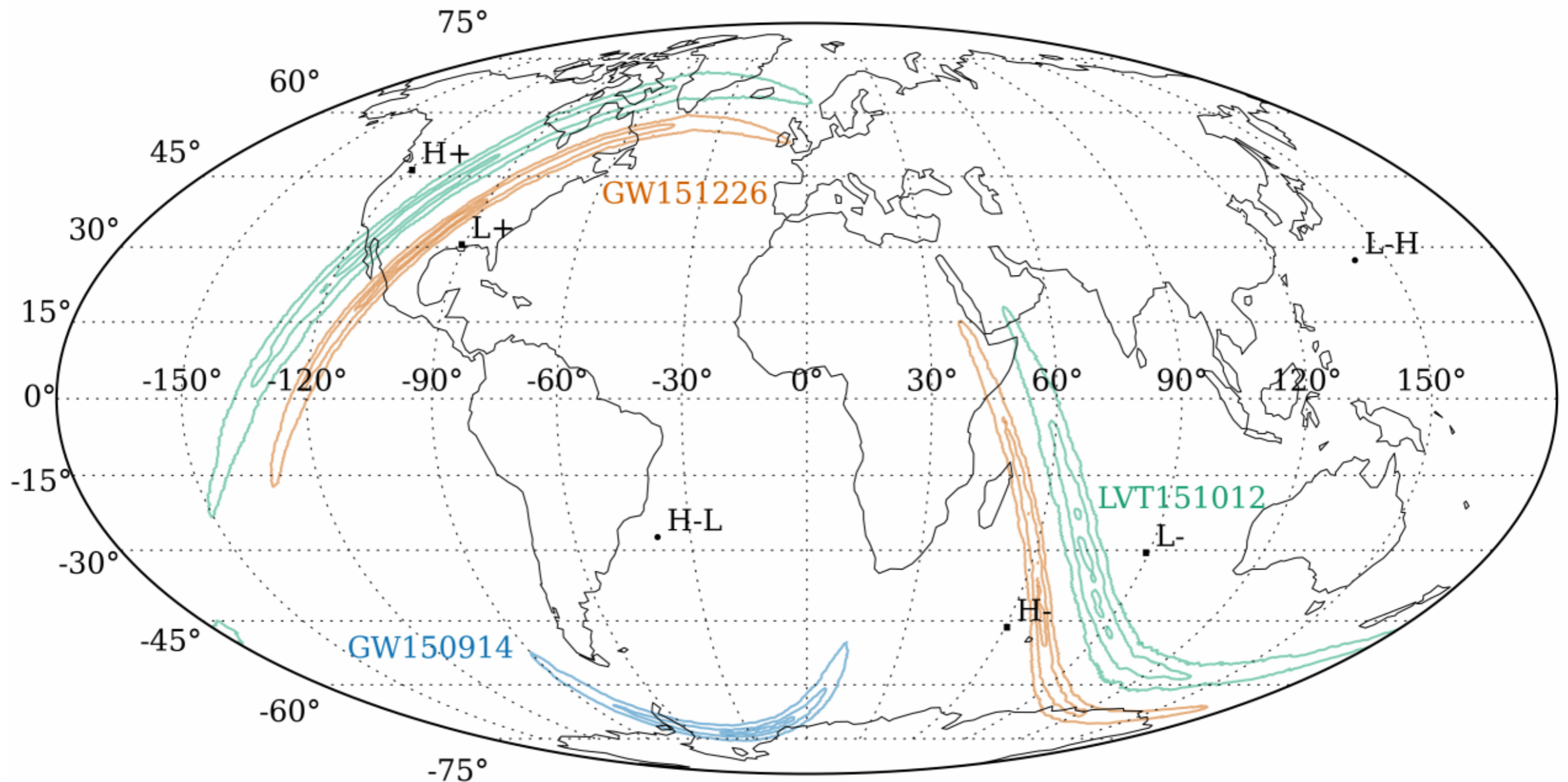
Localization of Gravitational Wave Sources

Where do the GWs originate from?

GW150914: 230 deg²

LVT151012: 1600 deg²

GW151226: 850 deg²



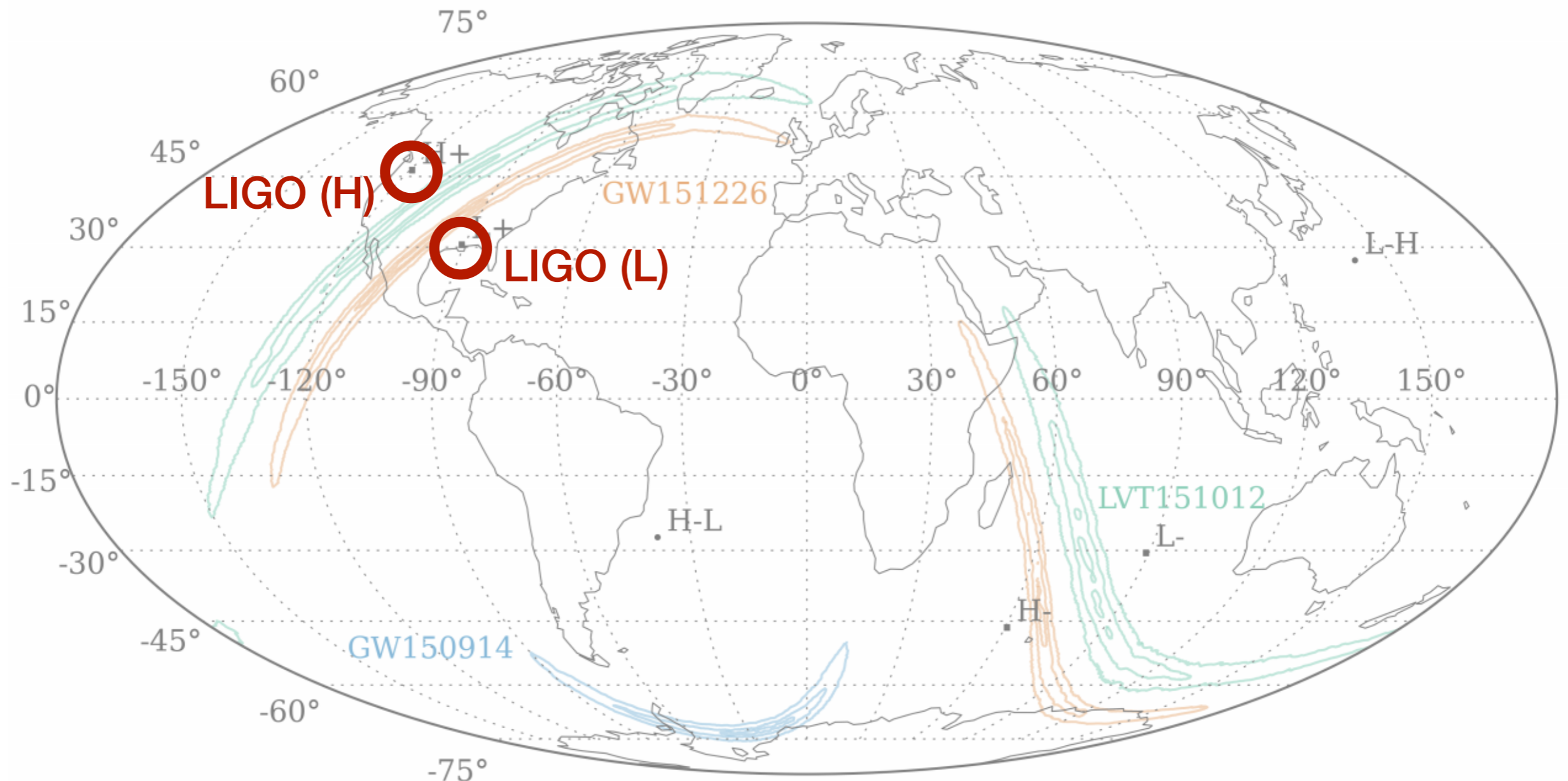
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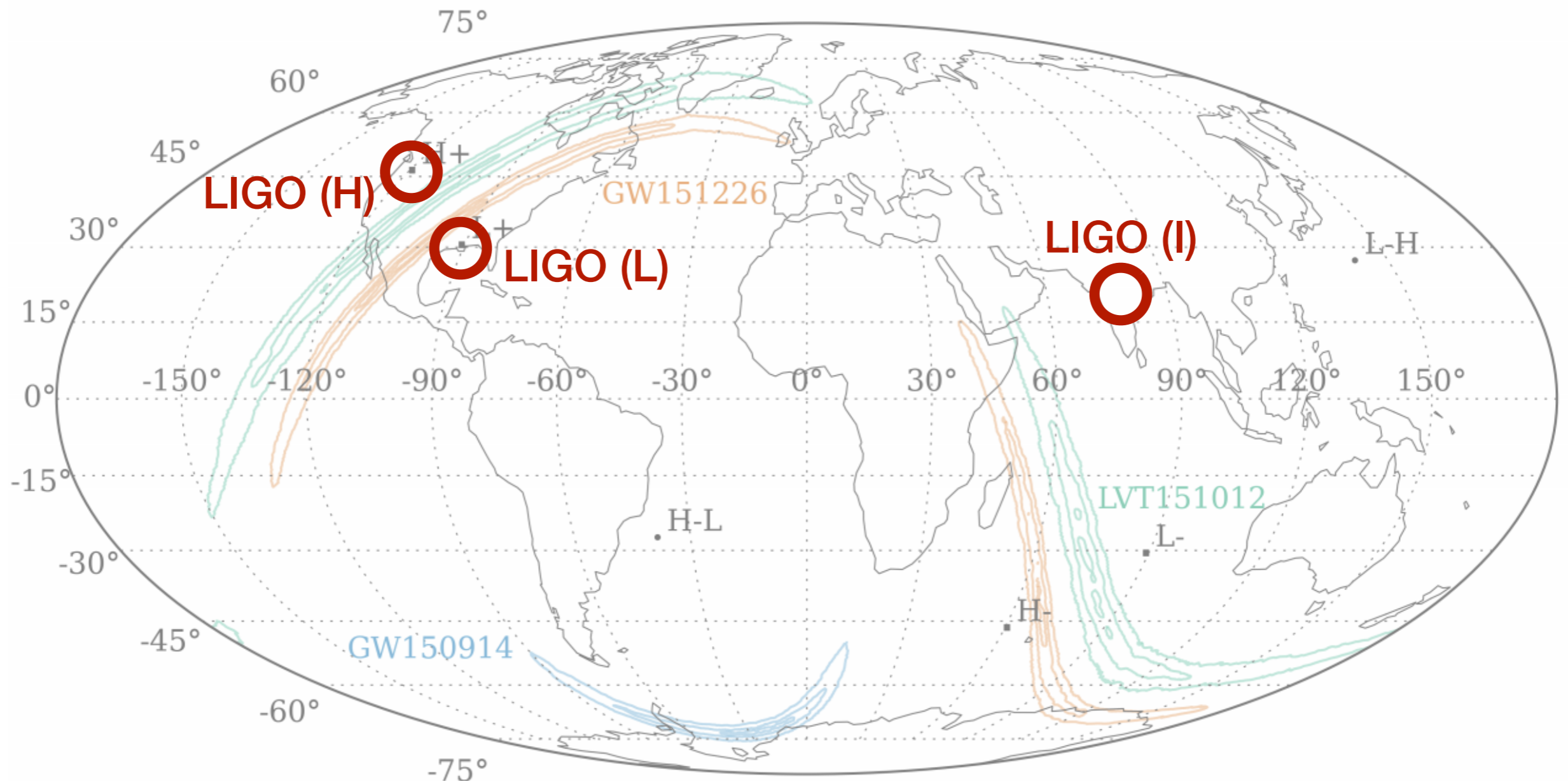
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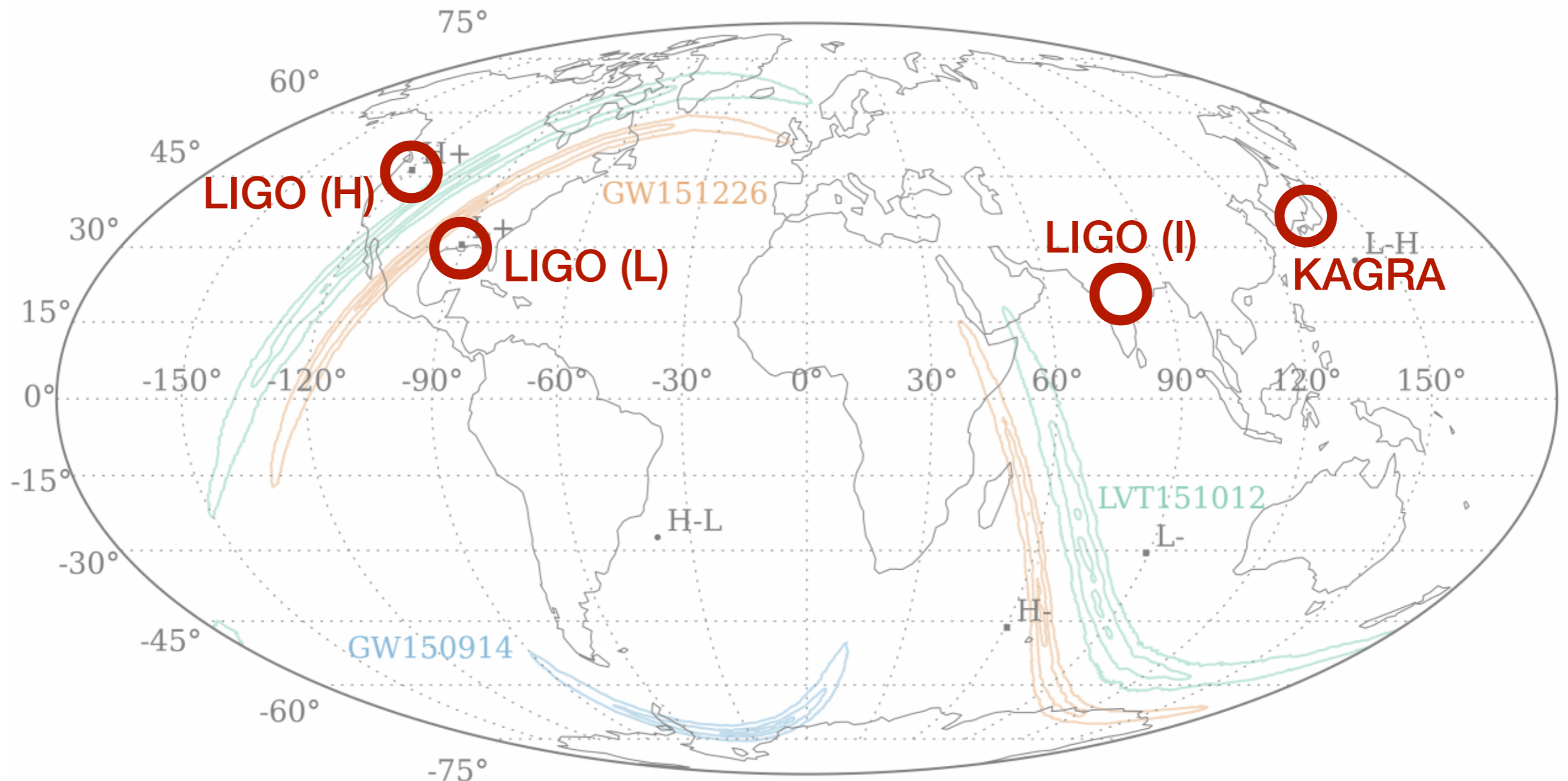
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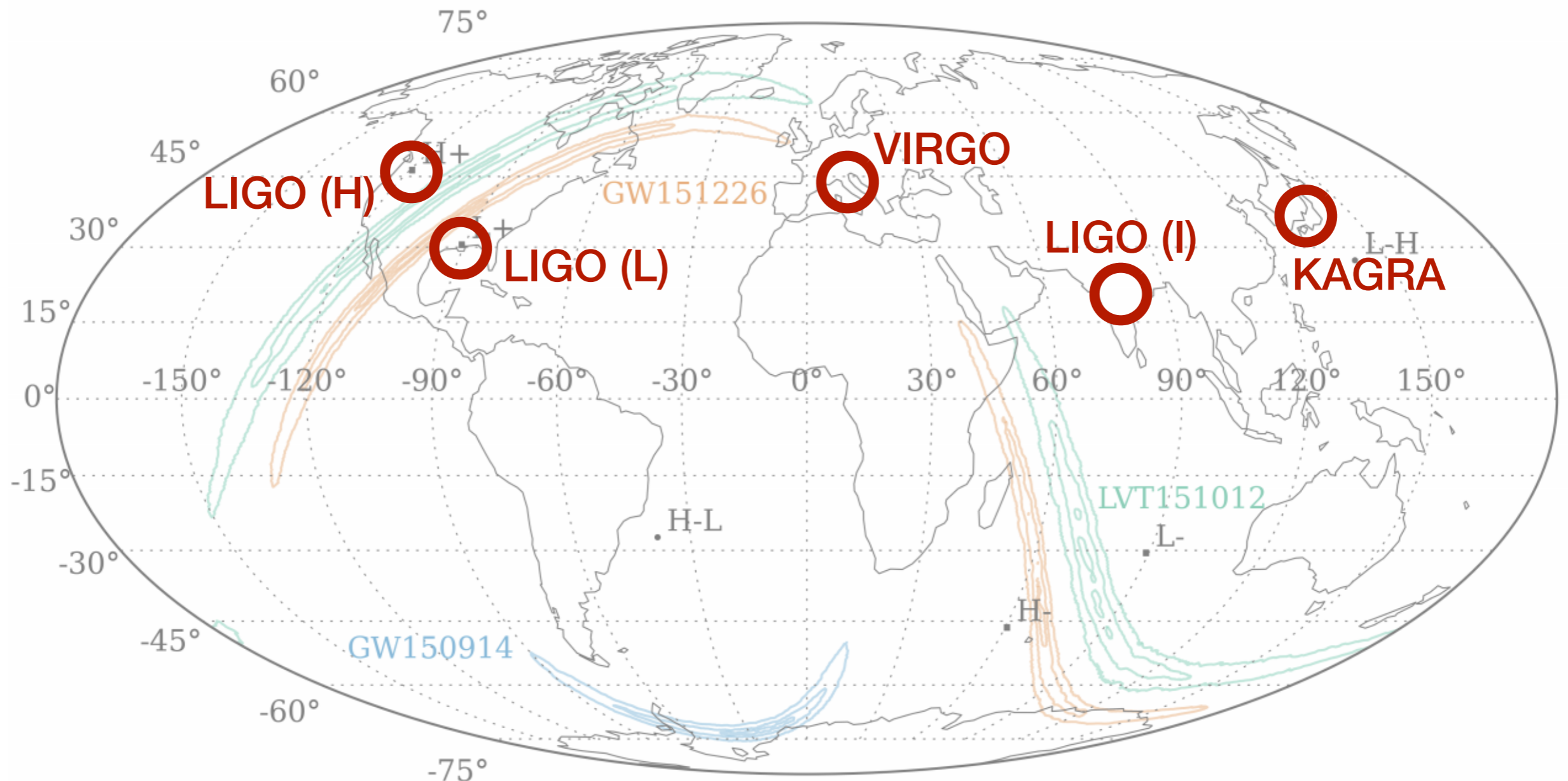
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Localization of Gravitational Wave Sources

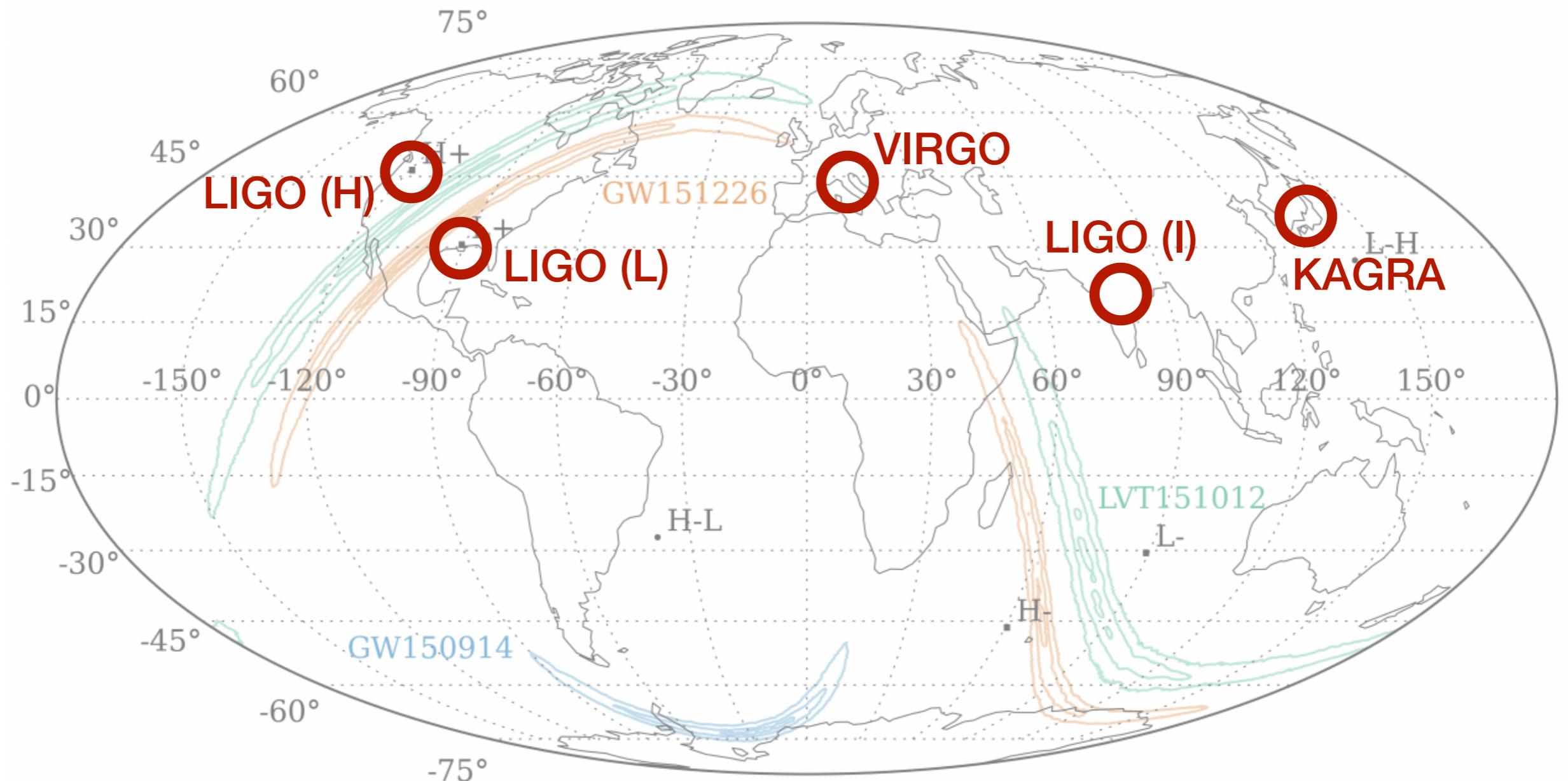
Where do the GWs originate from?

Expect: **LIGO net: ~2-5 deg²**

GW150914: 230 deg²

LVT151012: 1600 deg²

GW151226: 850 deg²



Localization of Gravitational Wave Sources

Where do the GWs originate from?

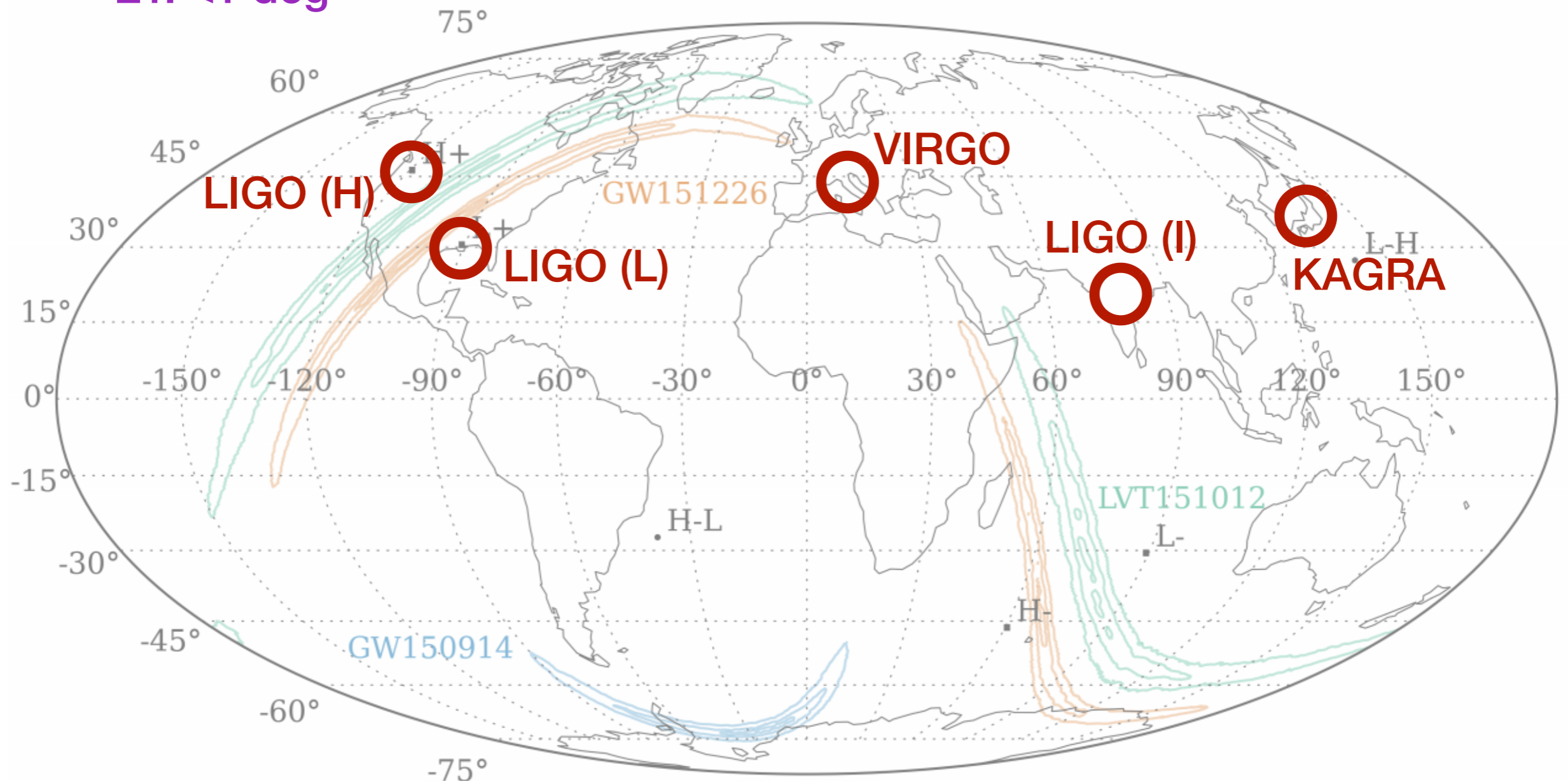
Expect: **LIGO net: ~2-5 deg²**

ET: <1 deg²

GW150914: 230 deg²

LVT151012: 1600 deg²

GW151226: 850 deg²



Cross-Correlating GWs and Galaxies

(Raccanelli et al., PRD94 (2016))

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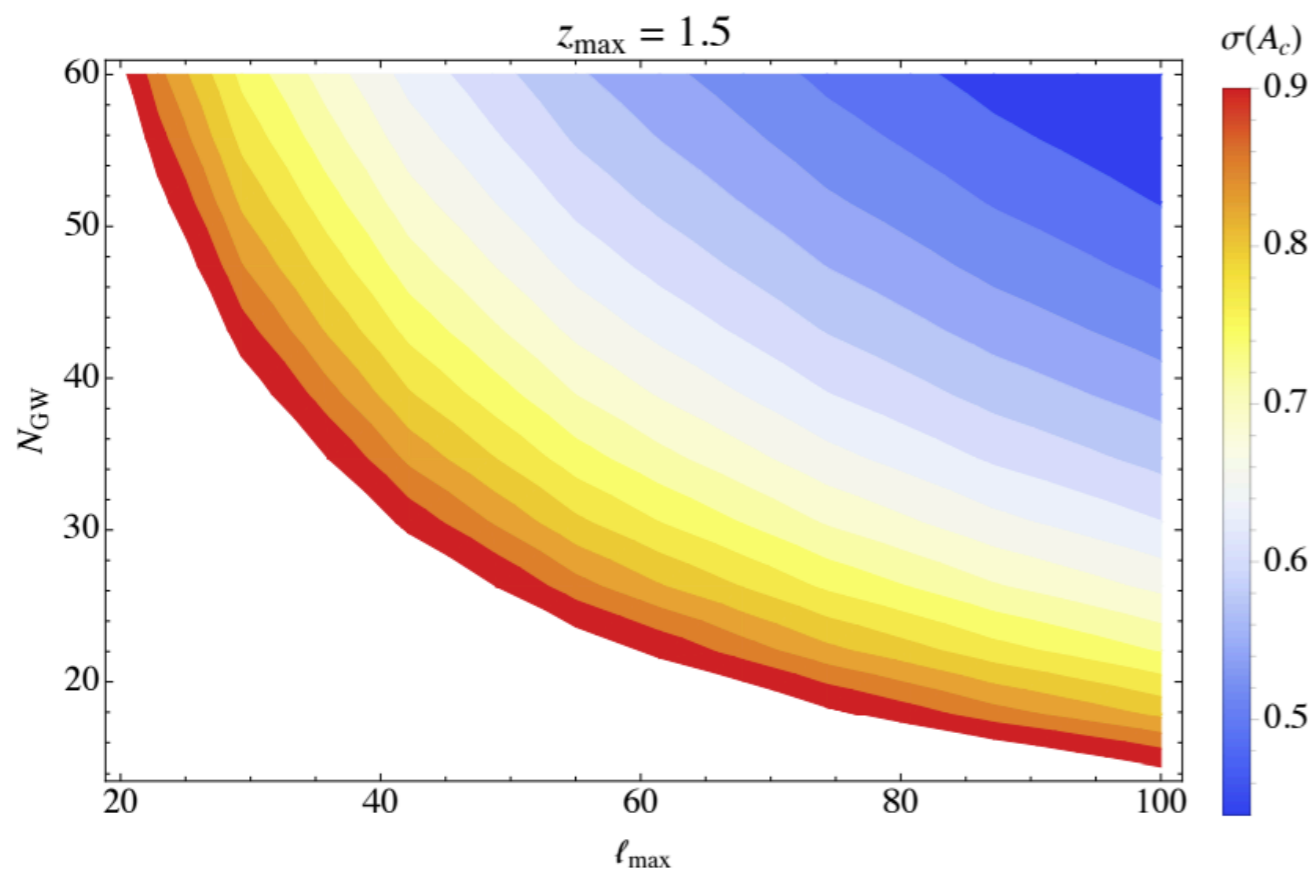
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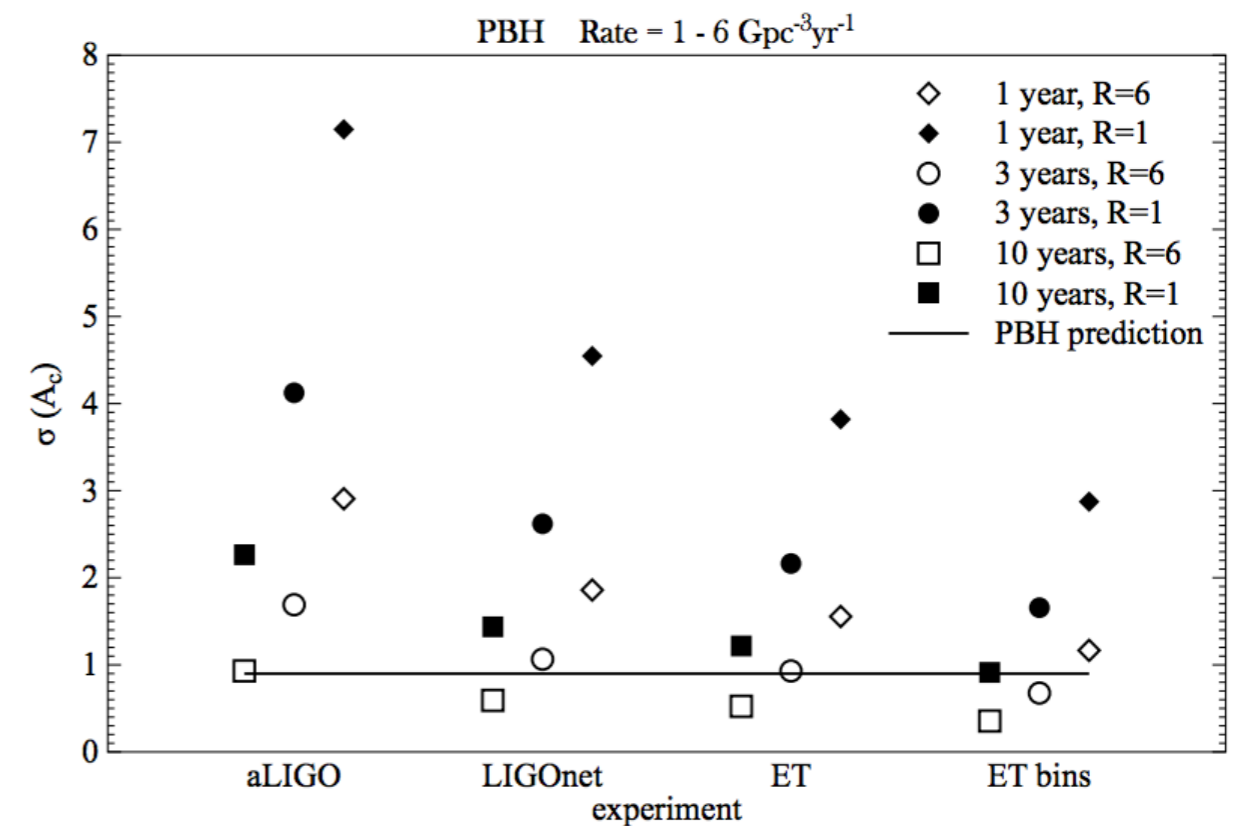
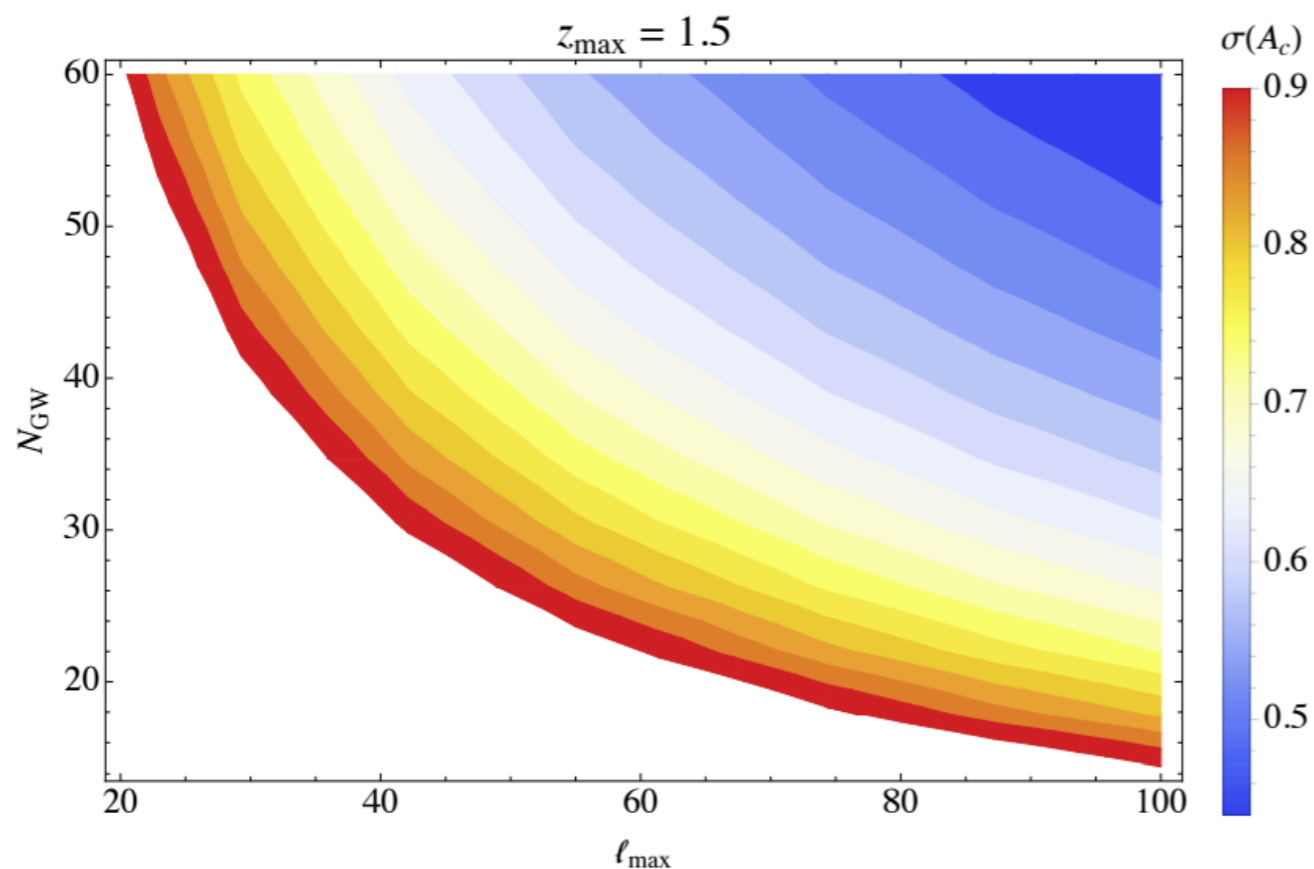
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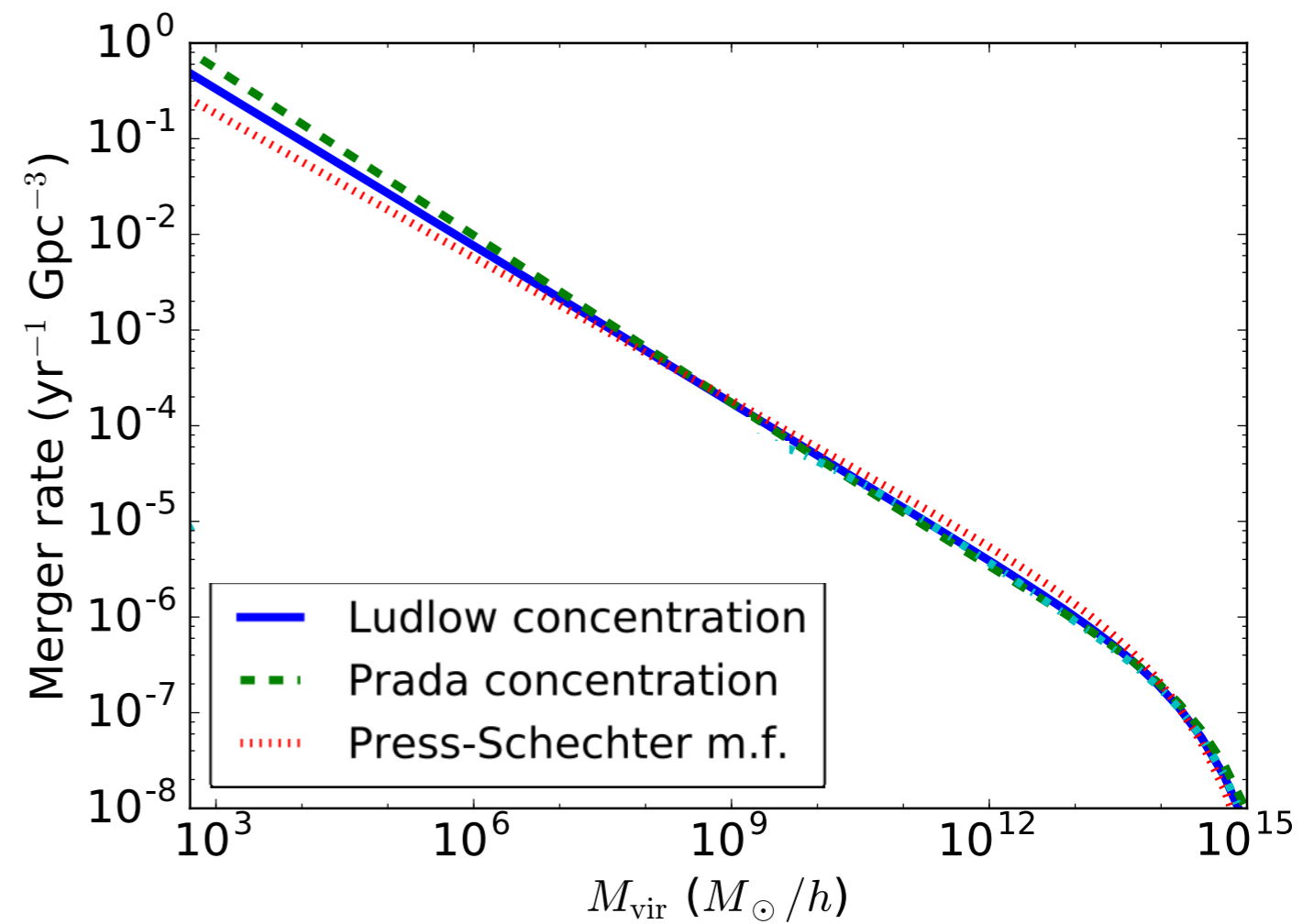


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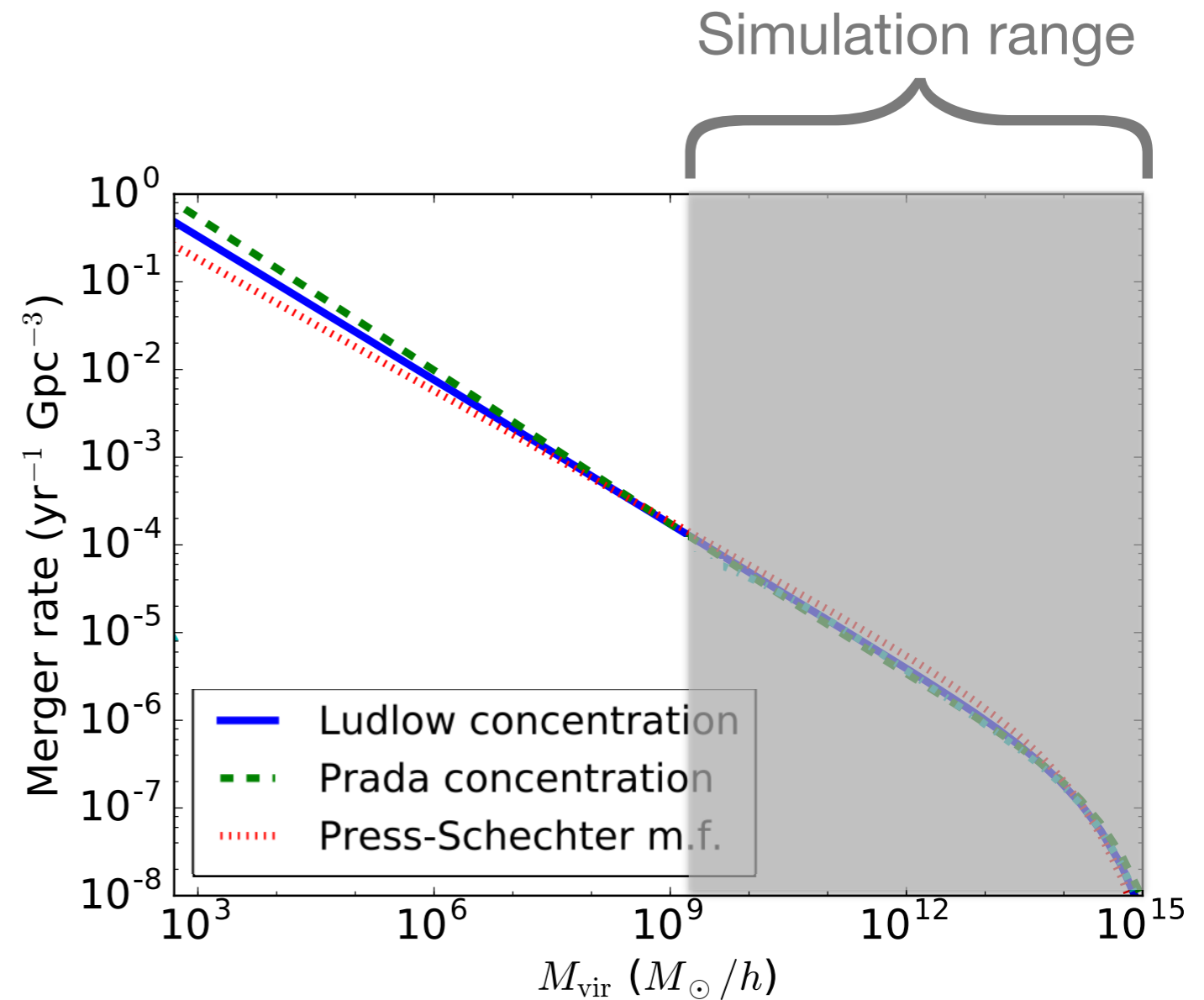
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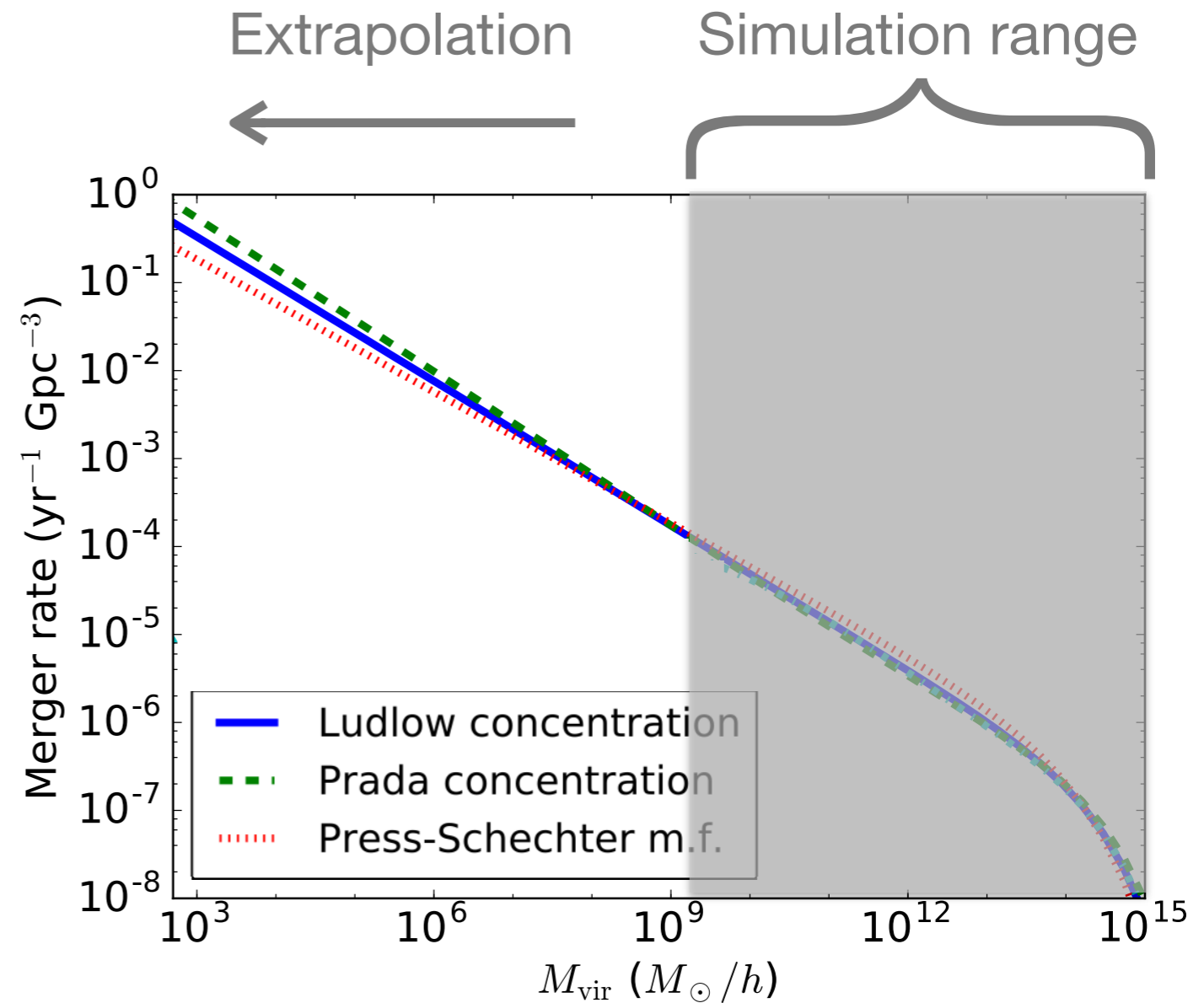
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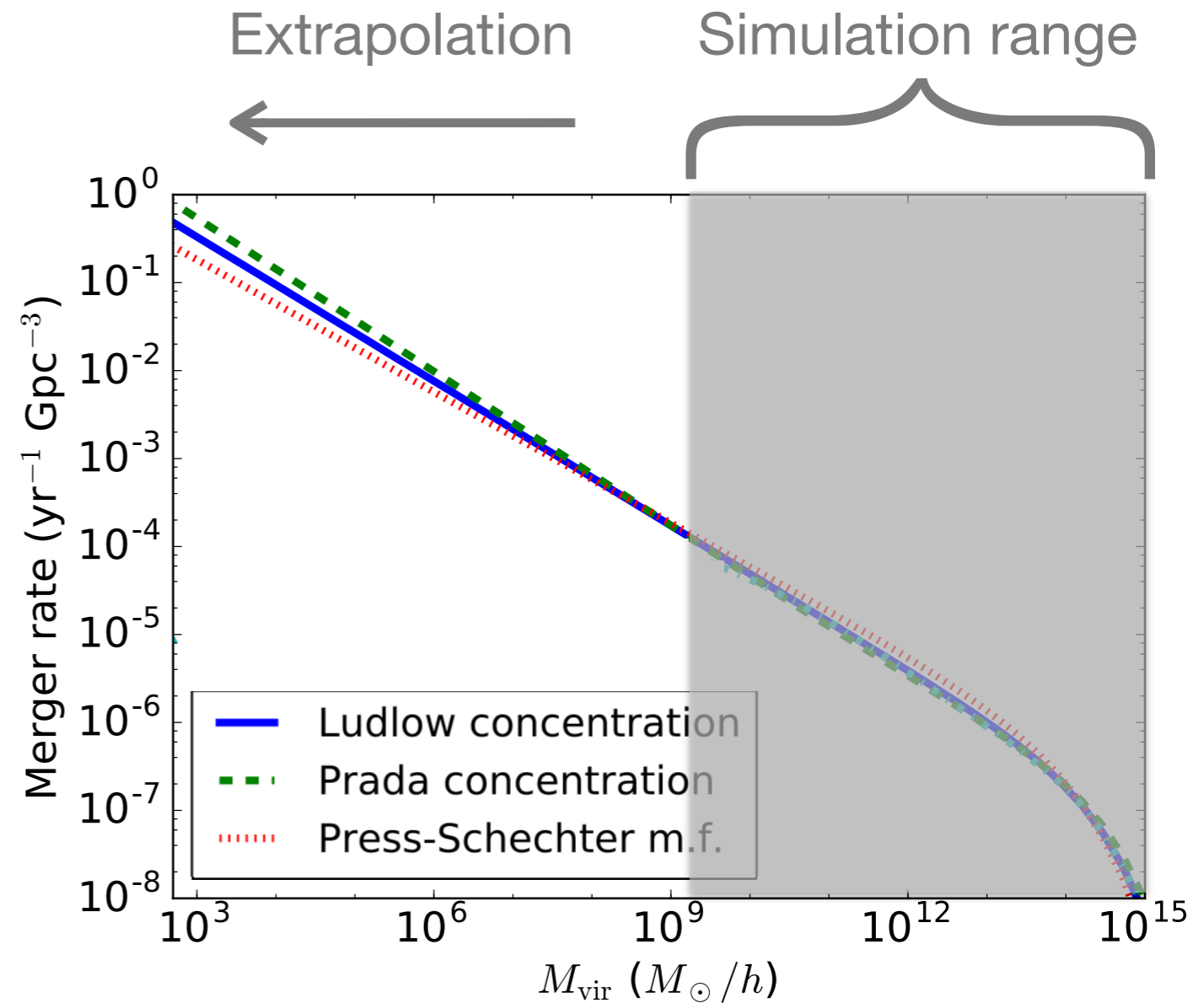
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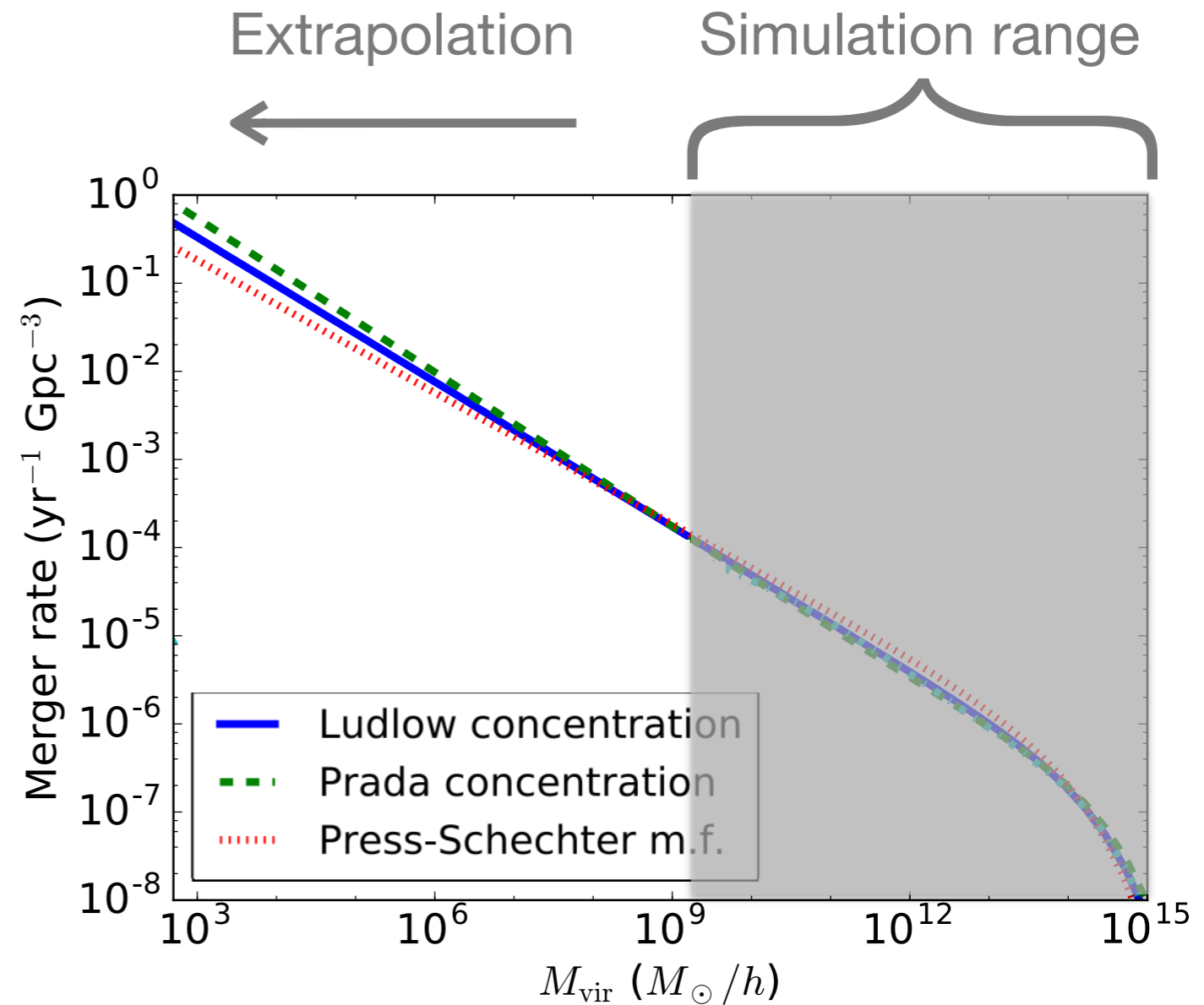


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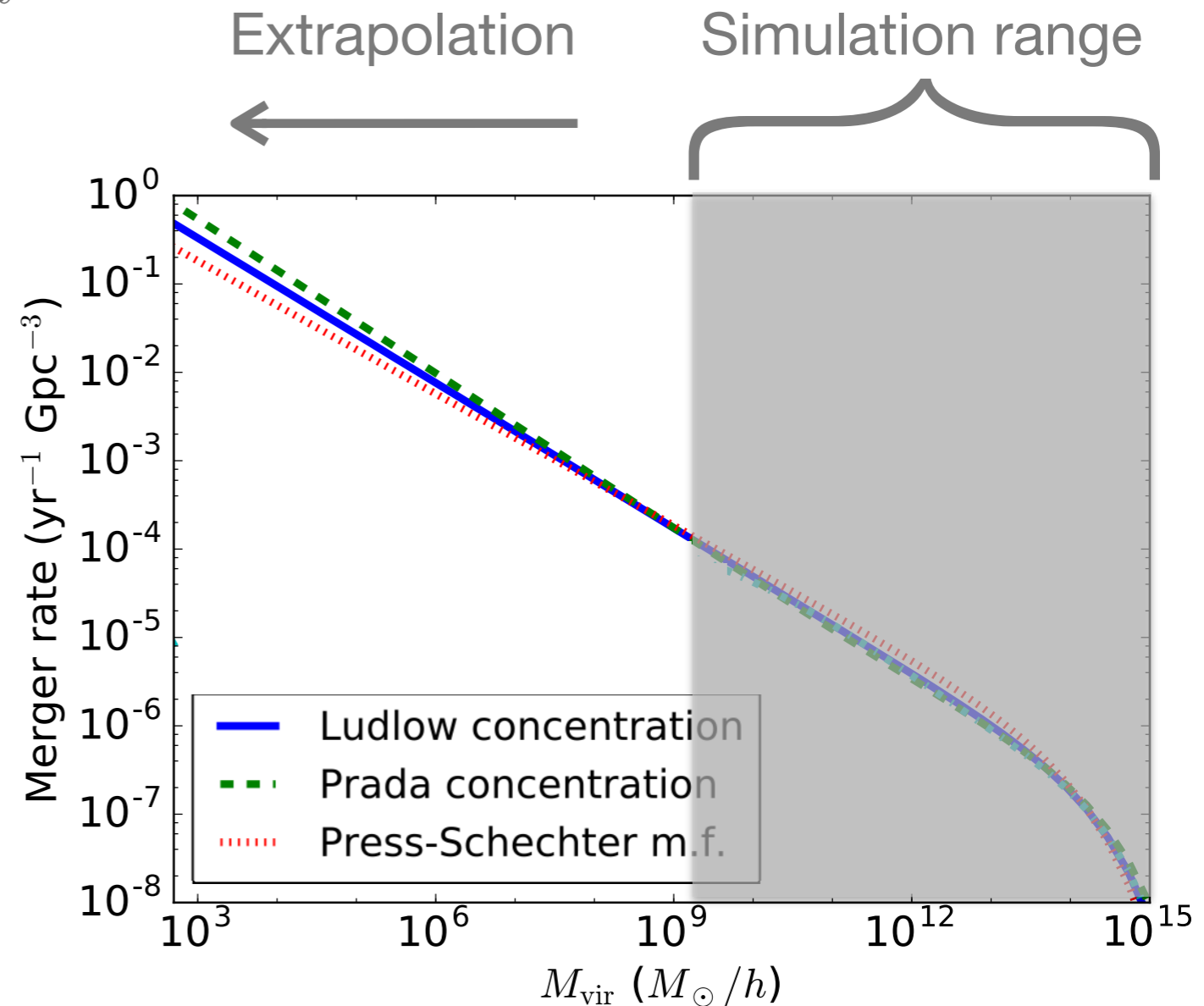
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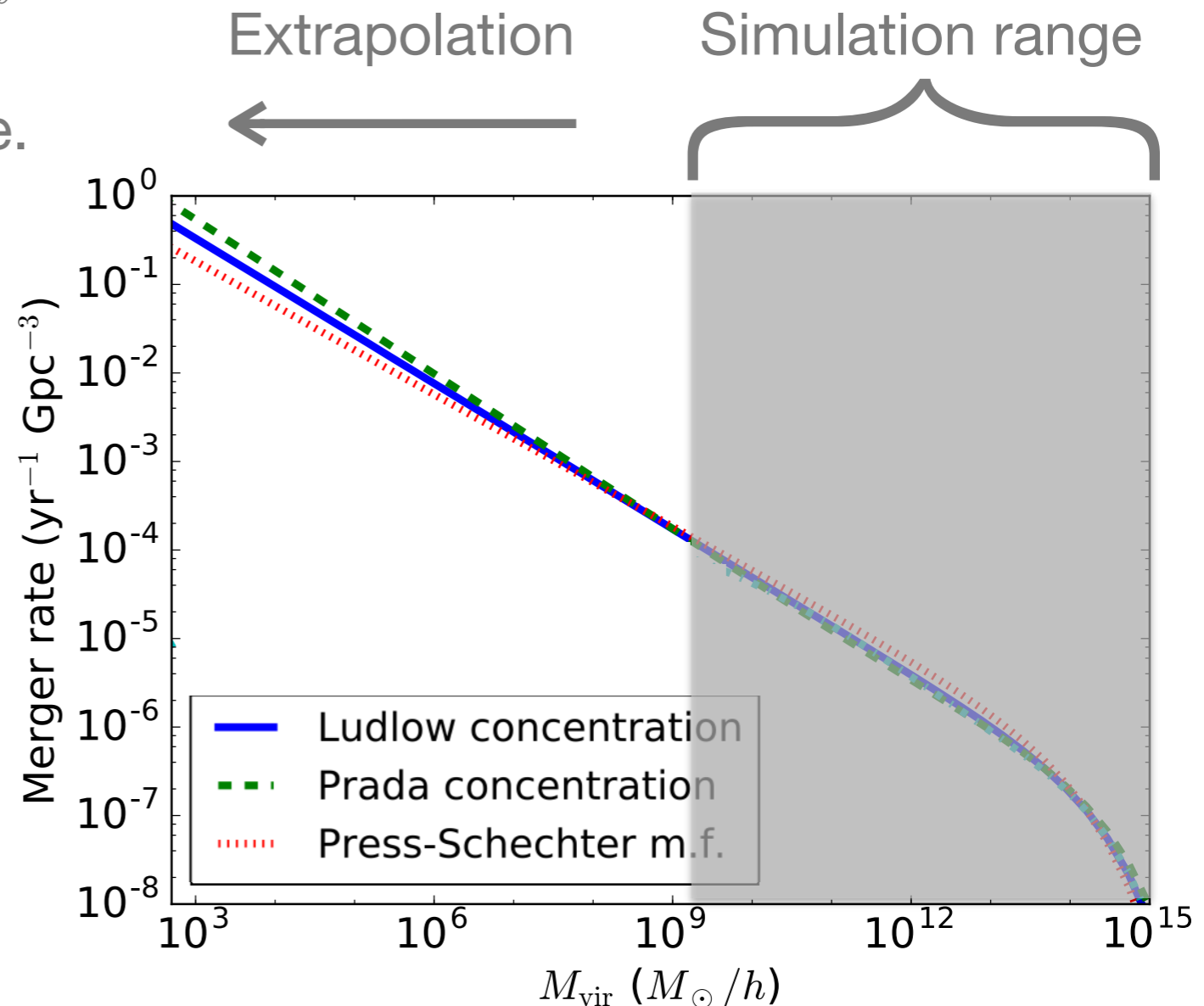
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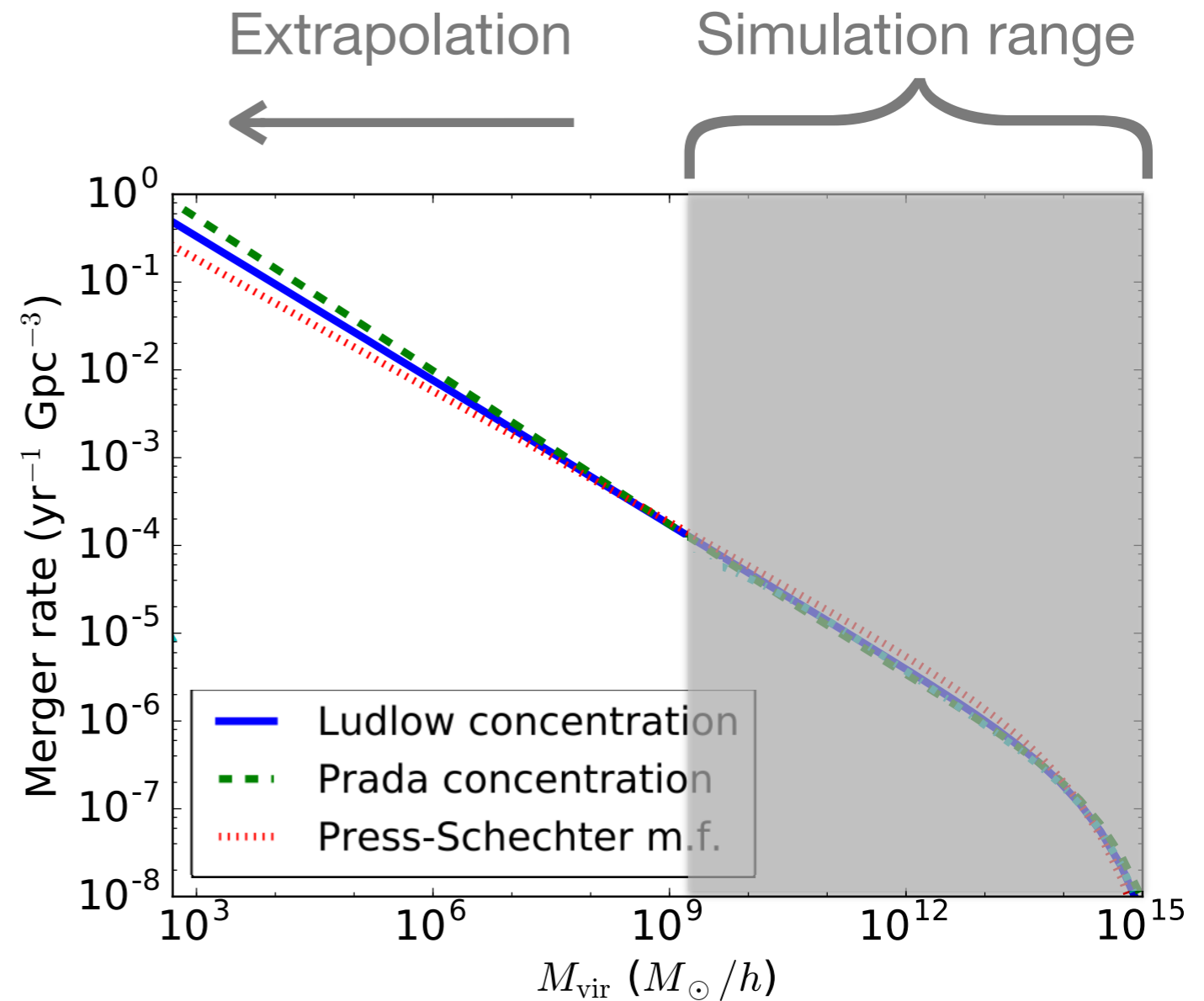
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→ $M_{\text{halo}} > 400 M_{\odot}$ do not evaporate.



GWs from PBH Mergers: Subtleties

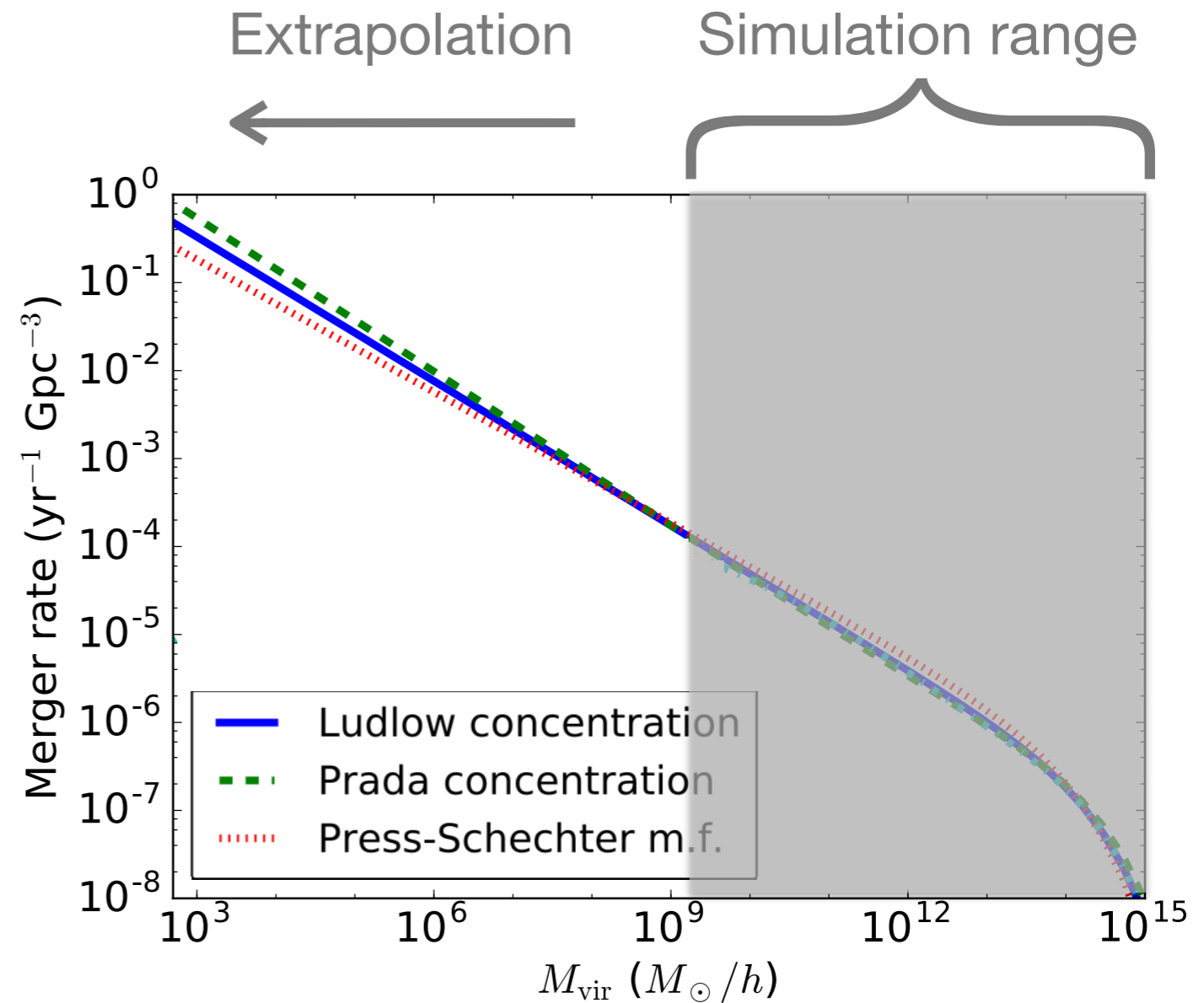
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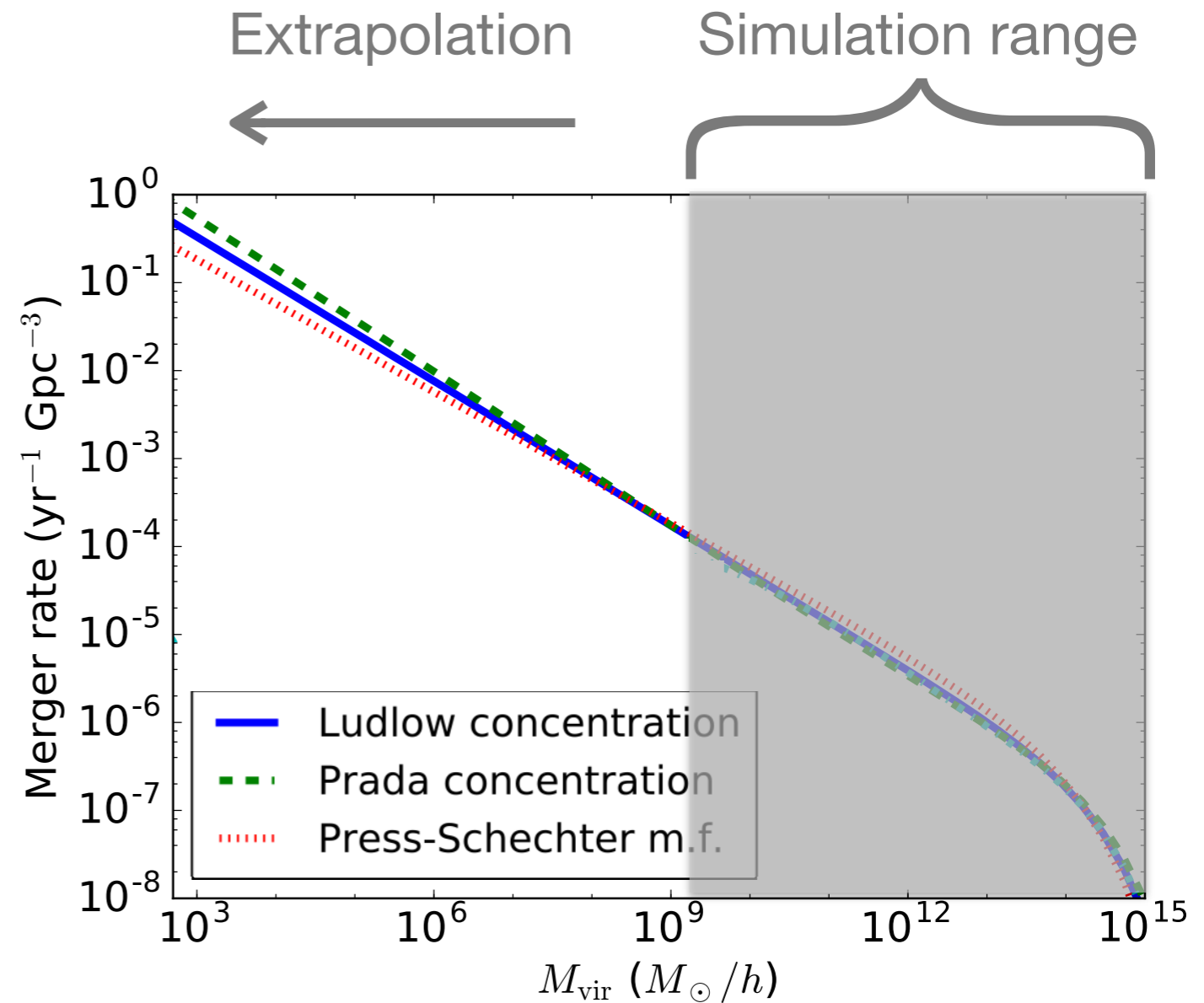
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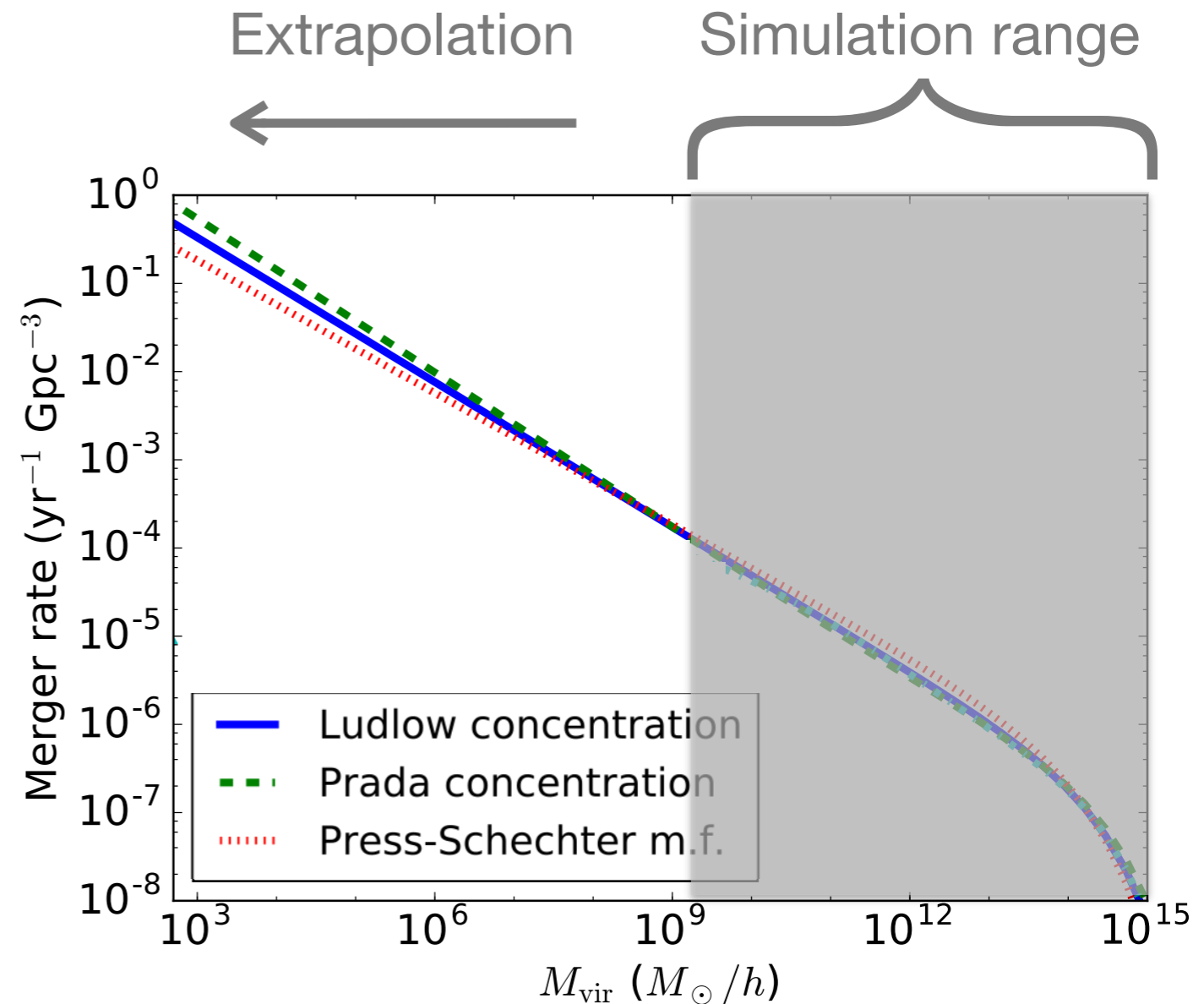
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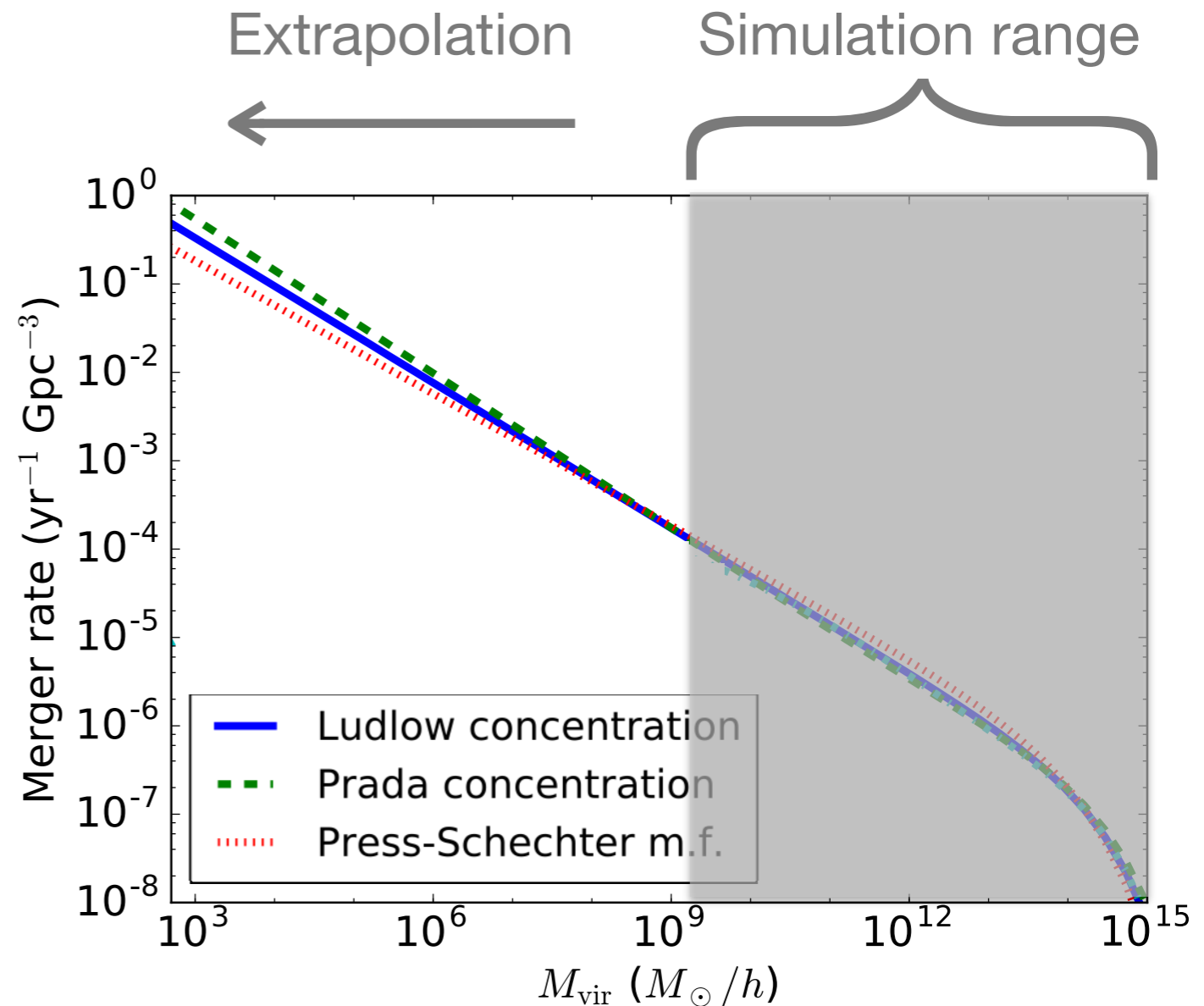
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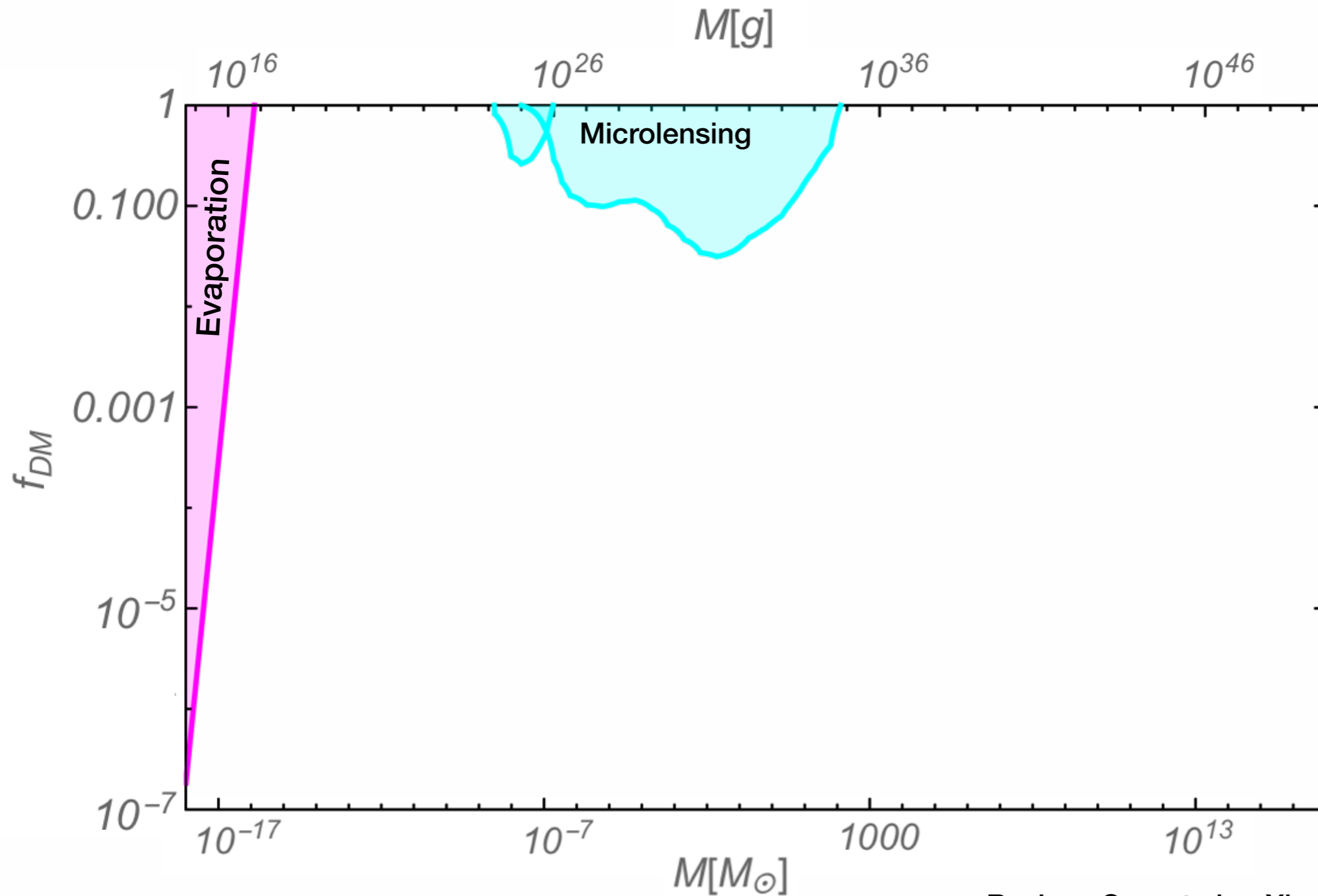
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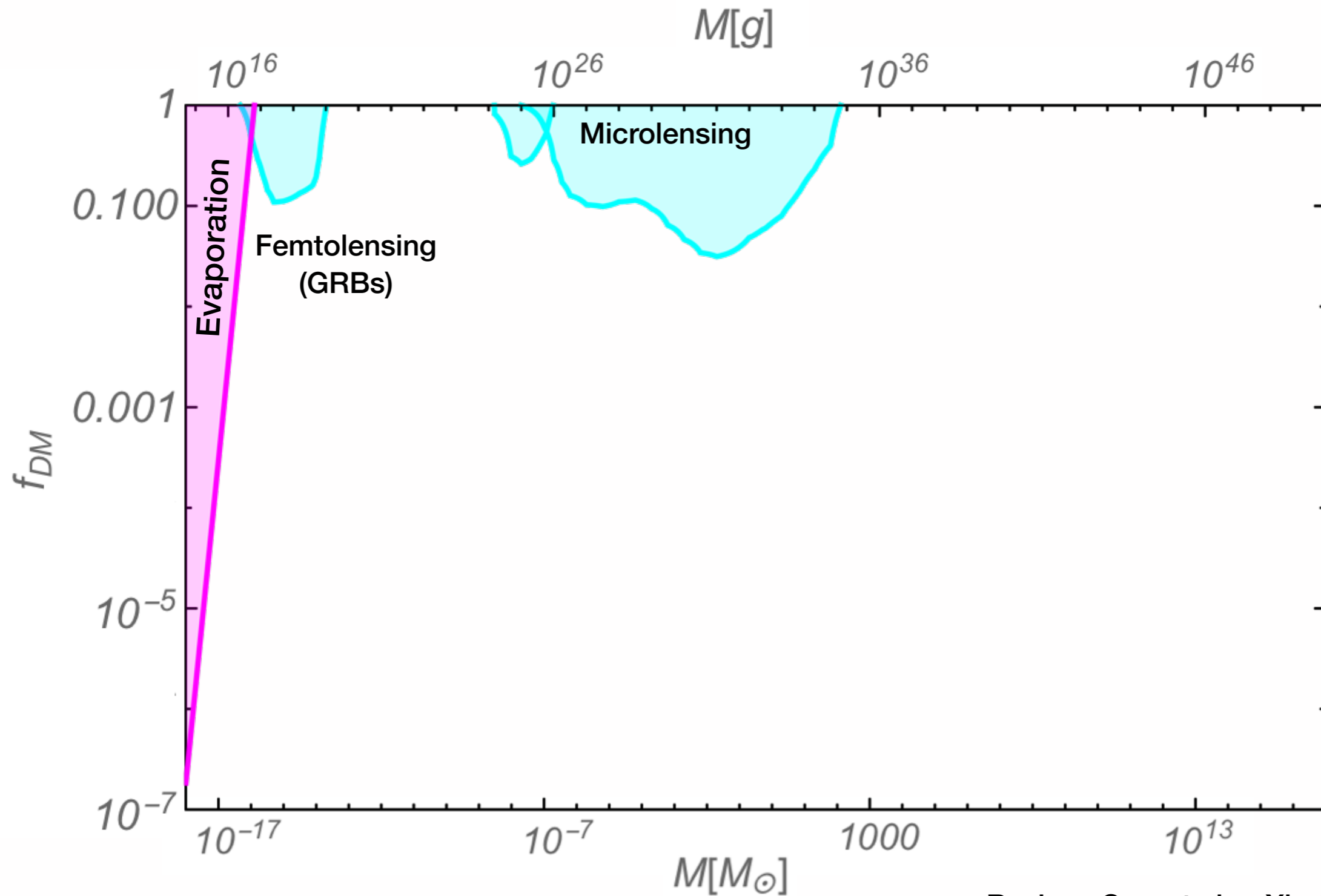
→ roughly factor of 2



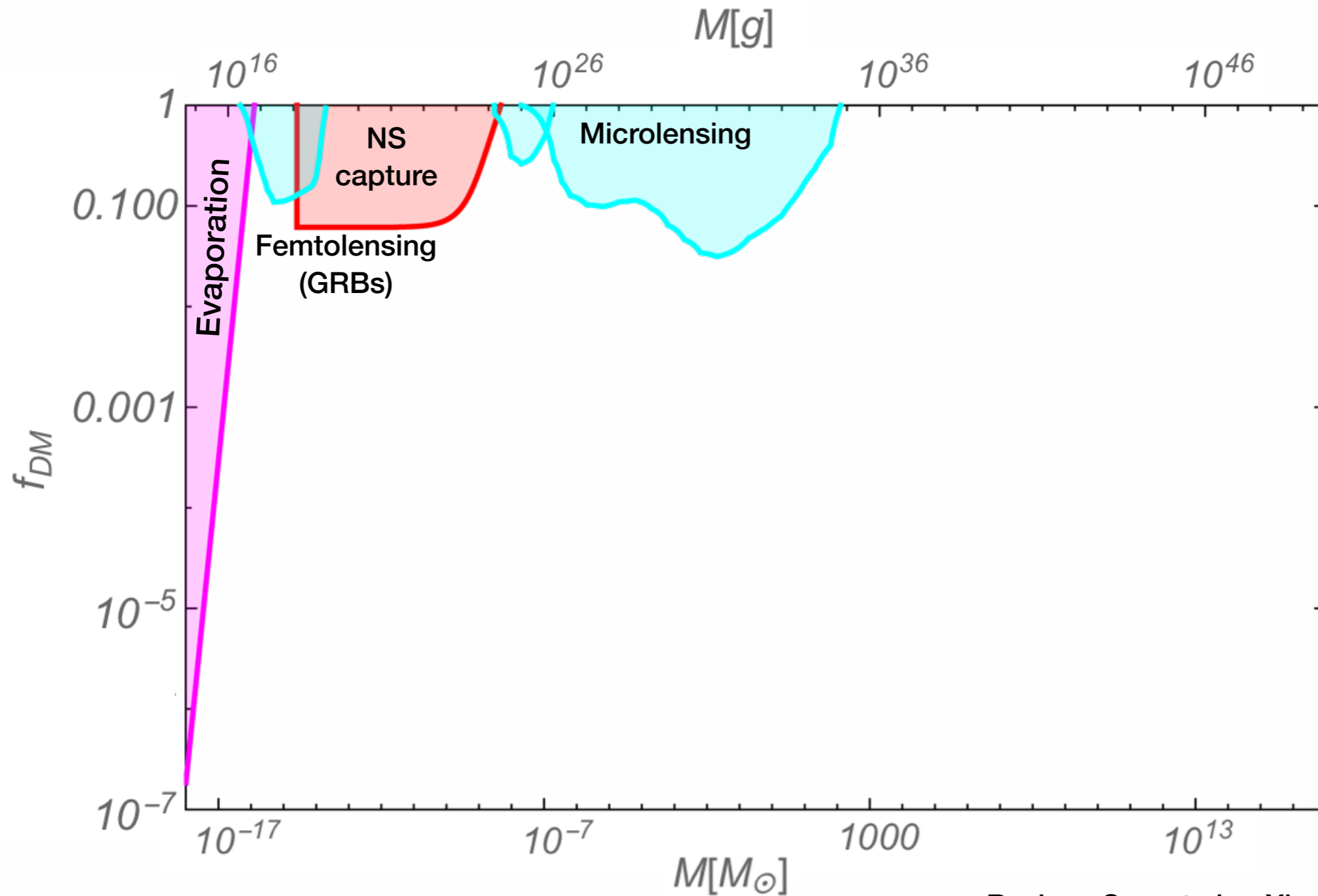
PBH DM: More Indirect Detection Constraints



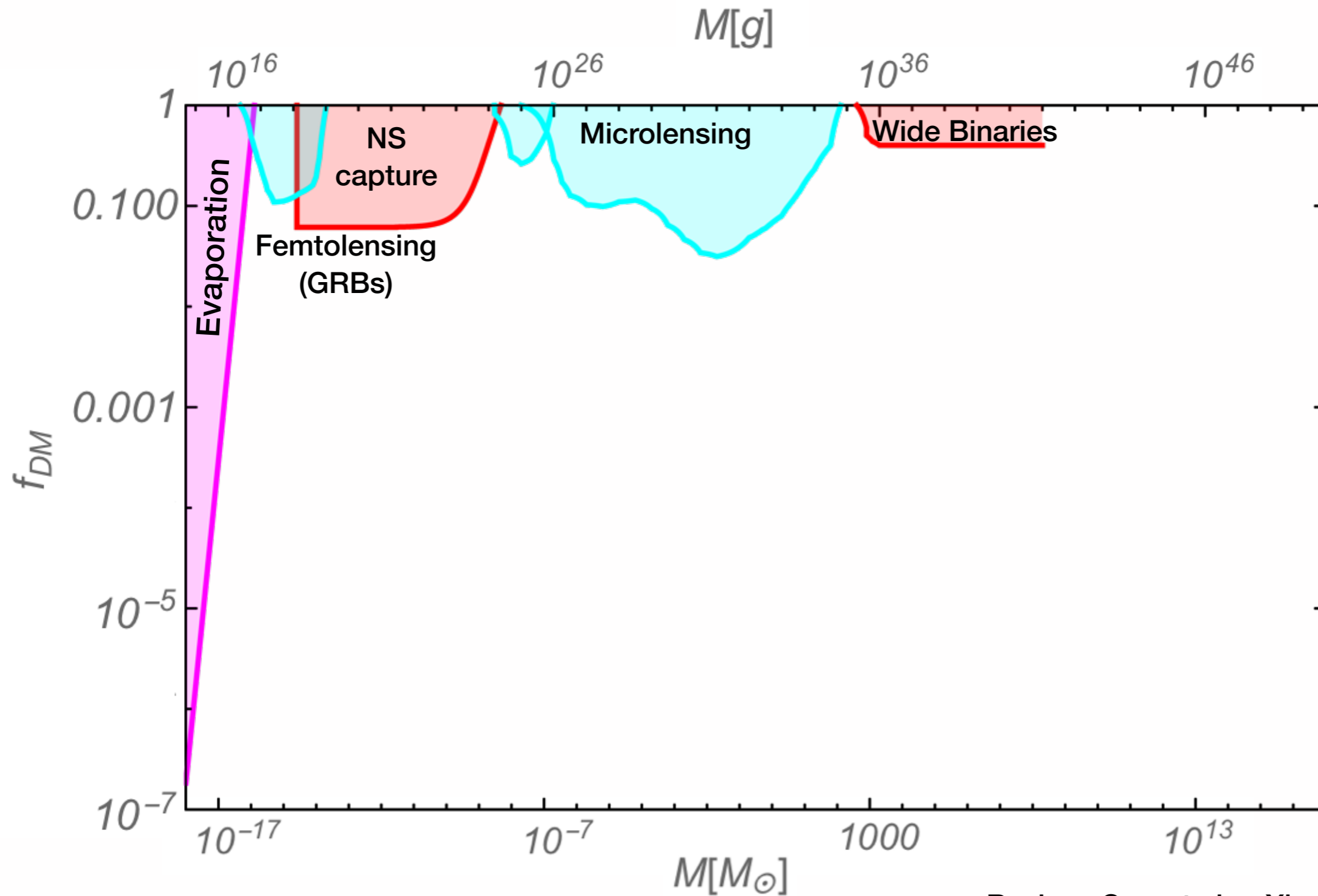
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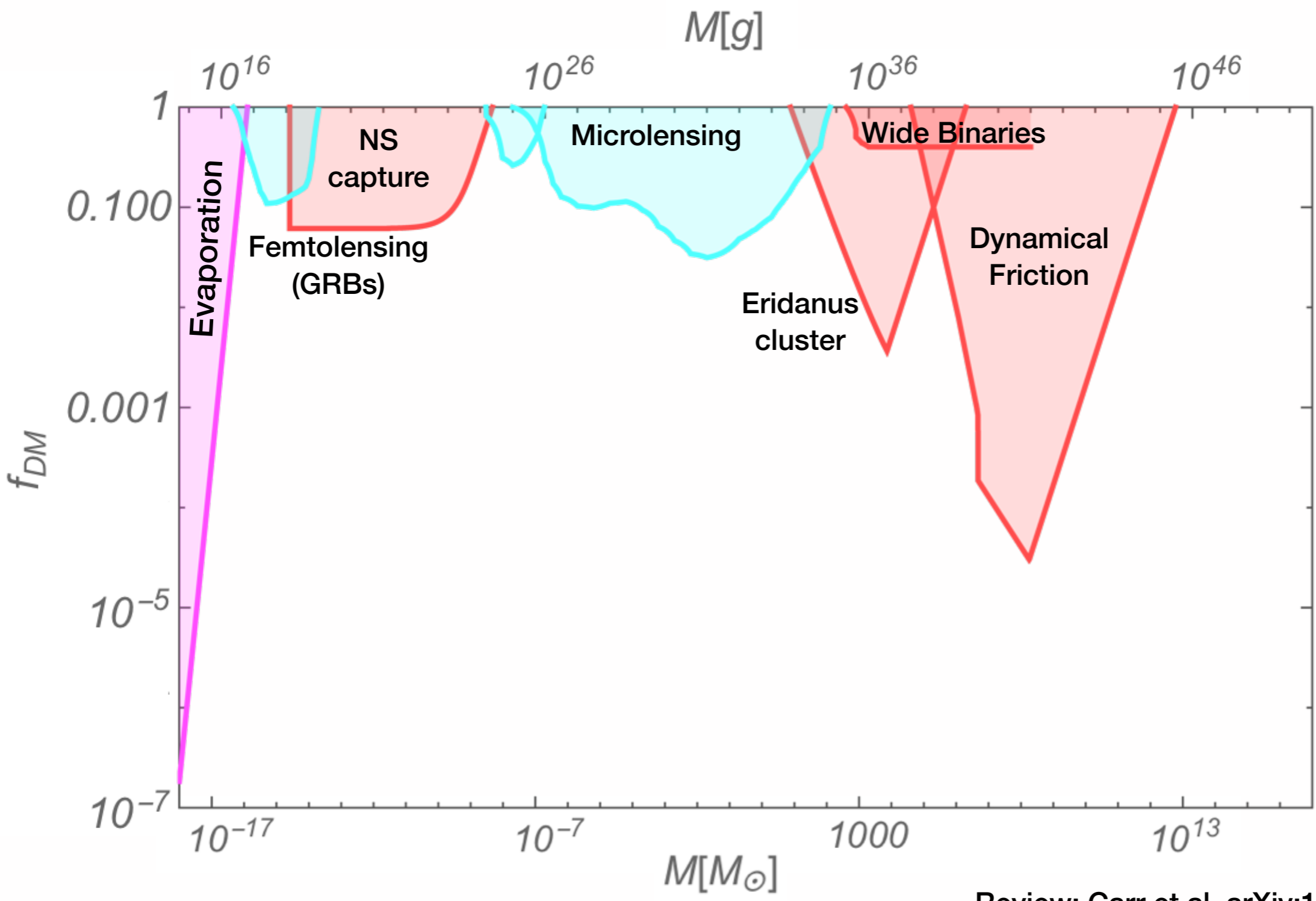
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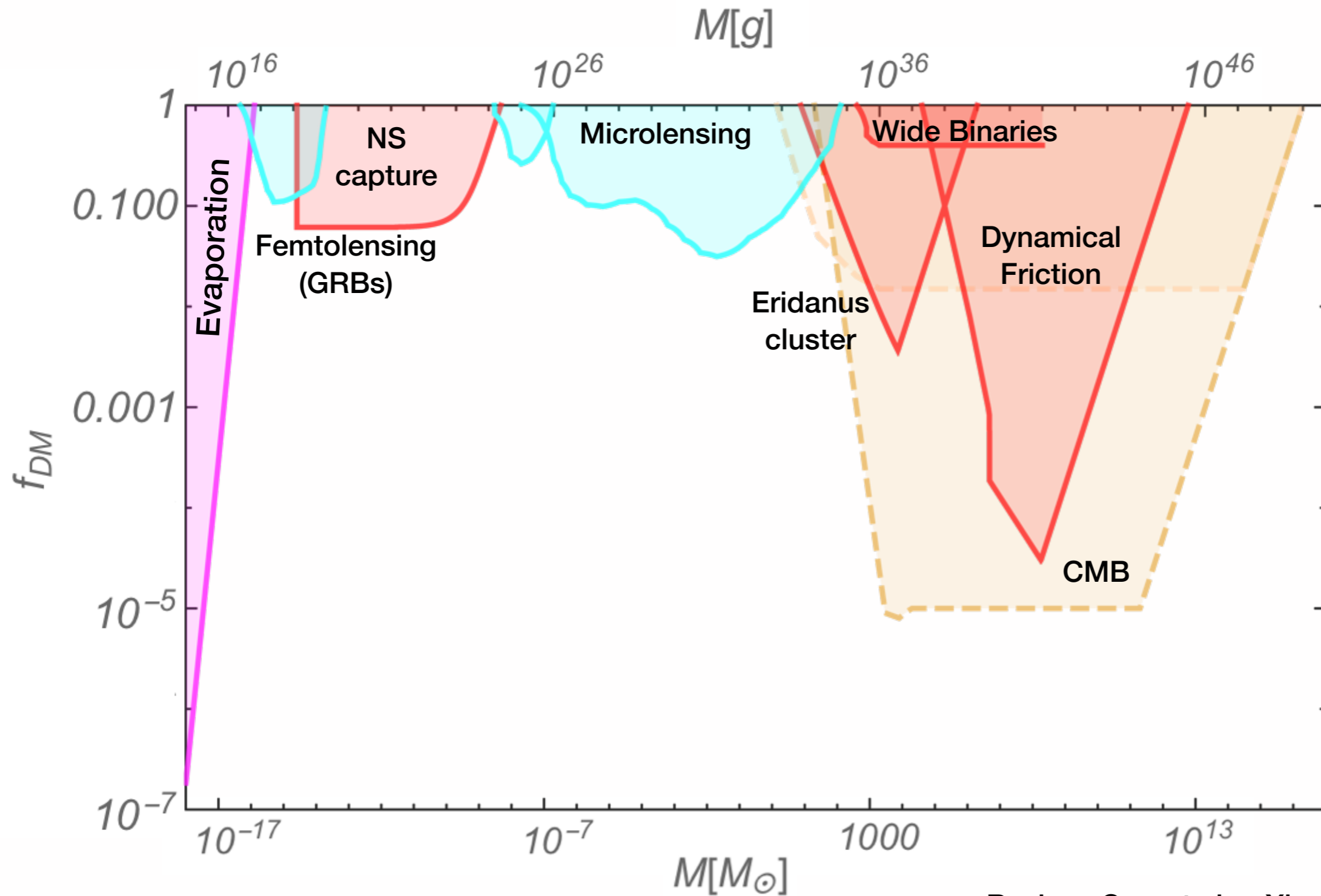
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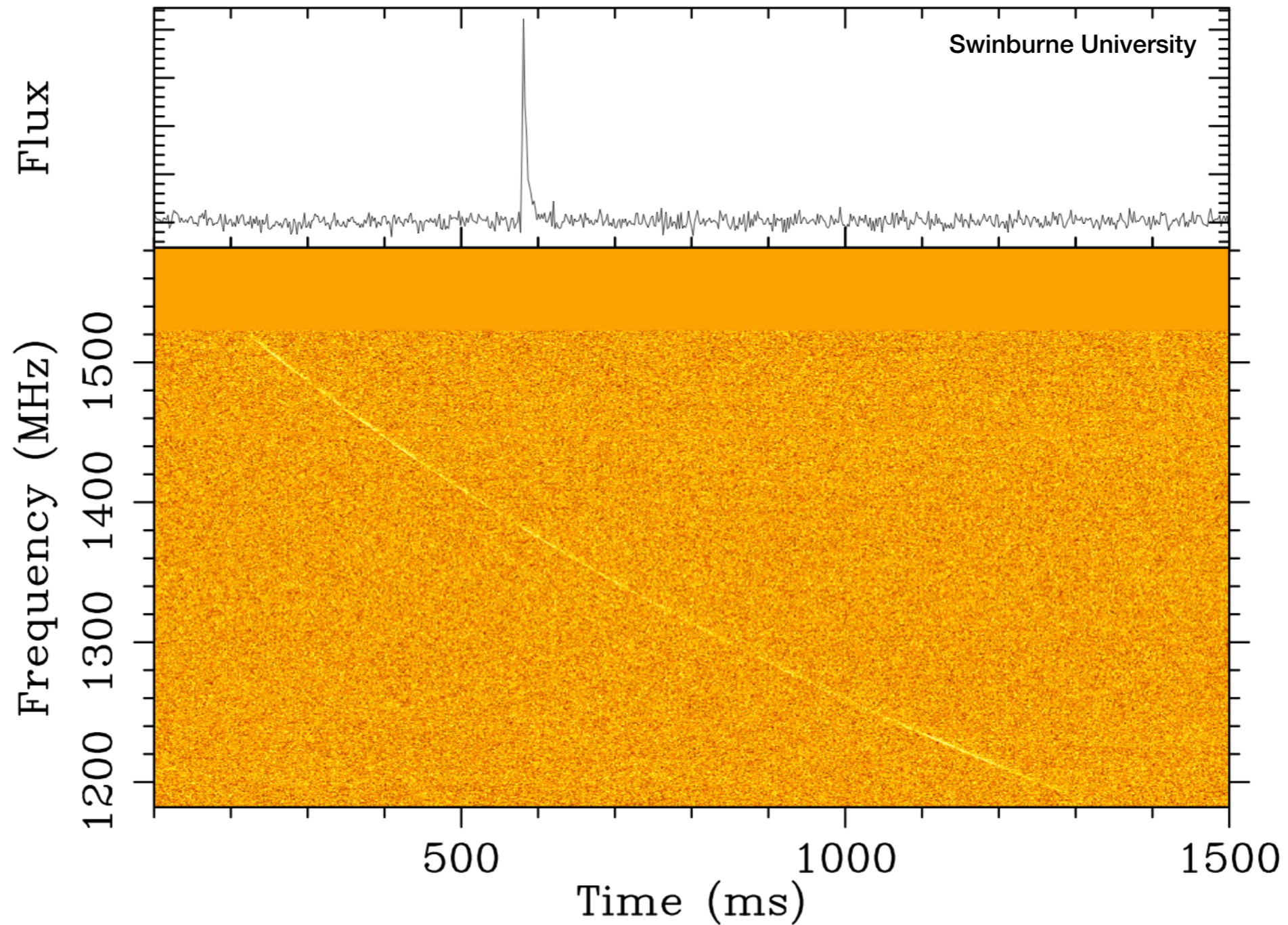


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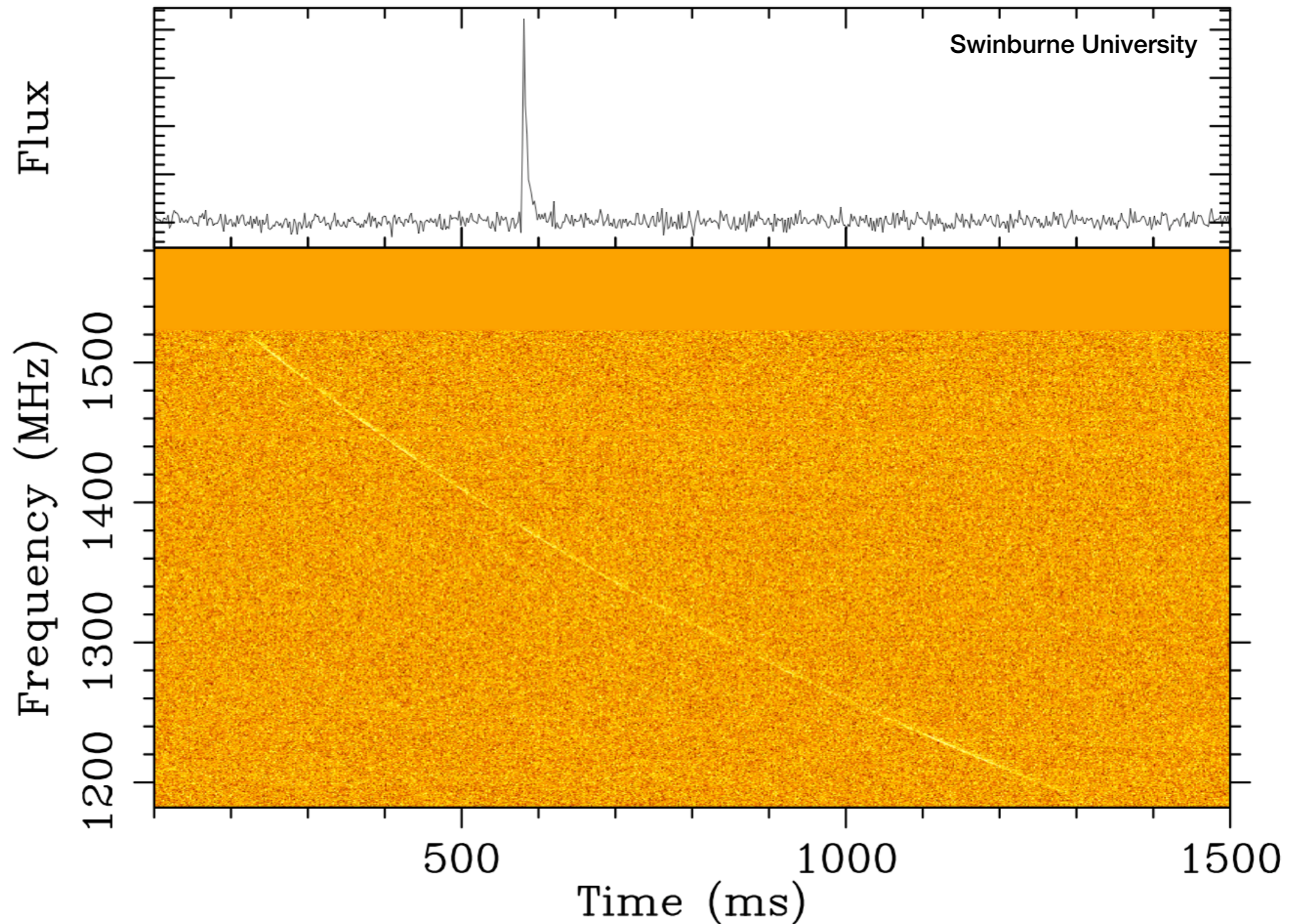
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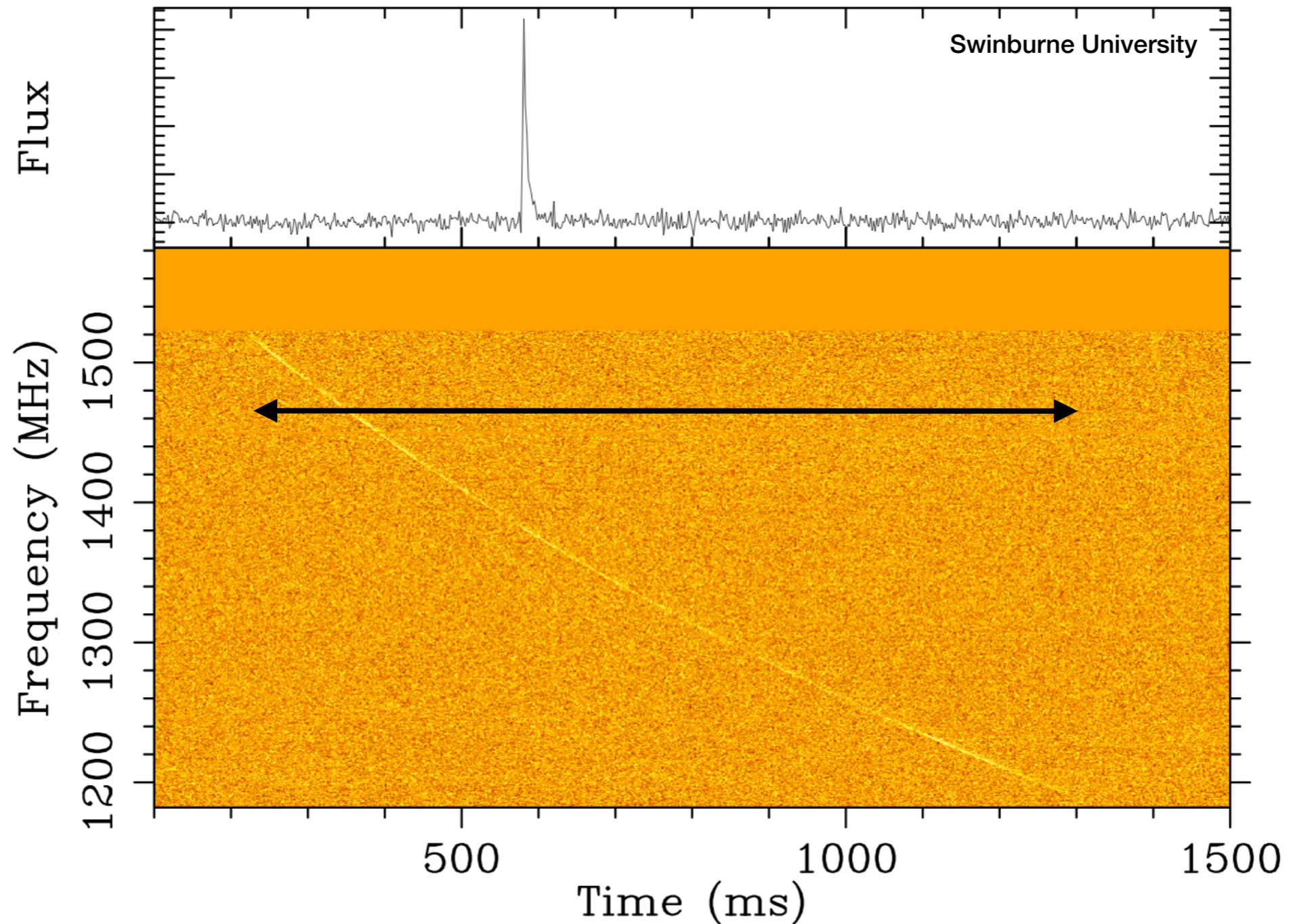
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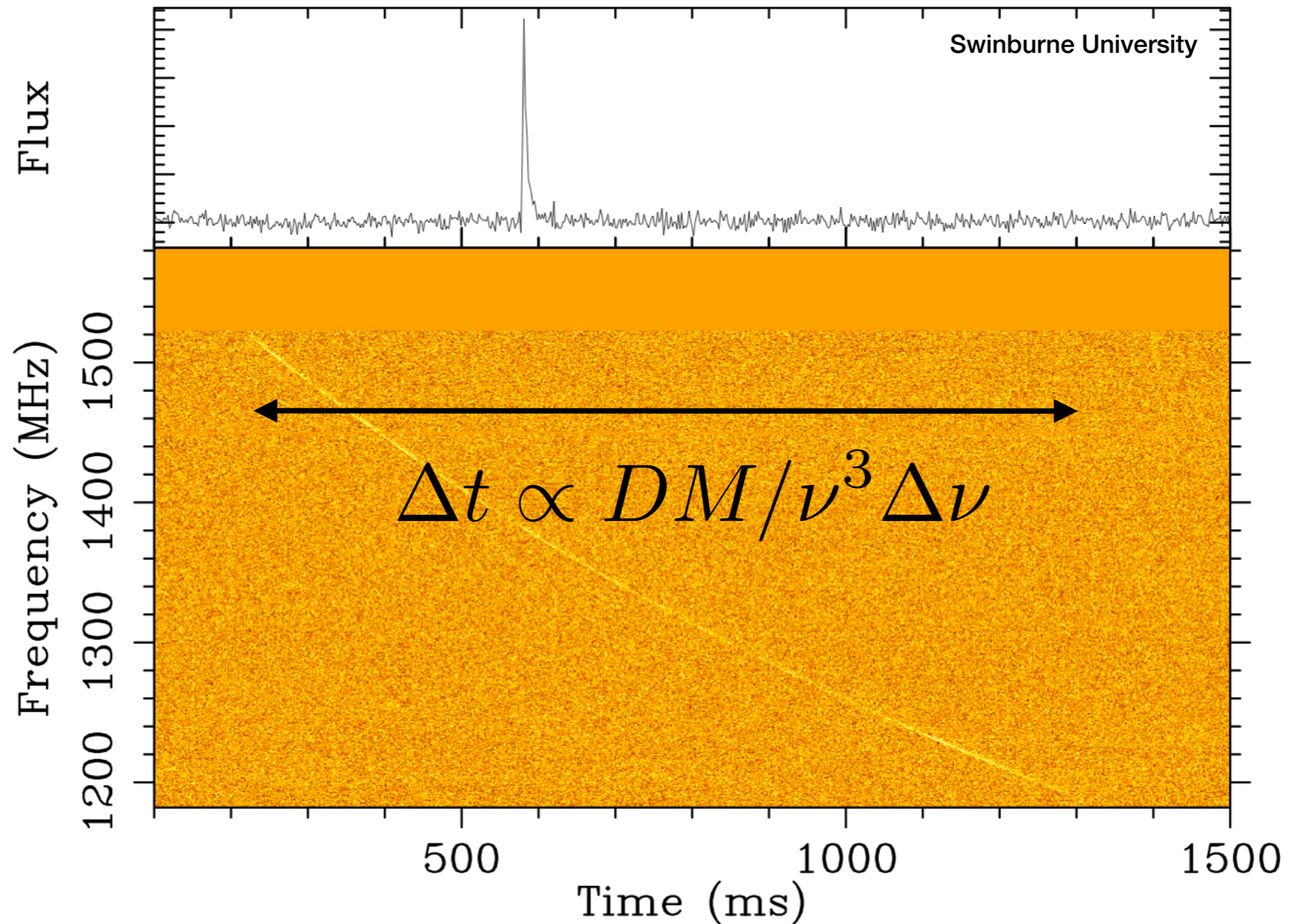
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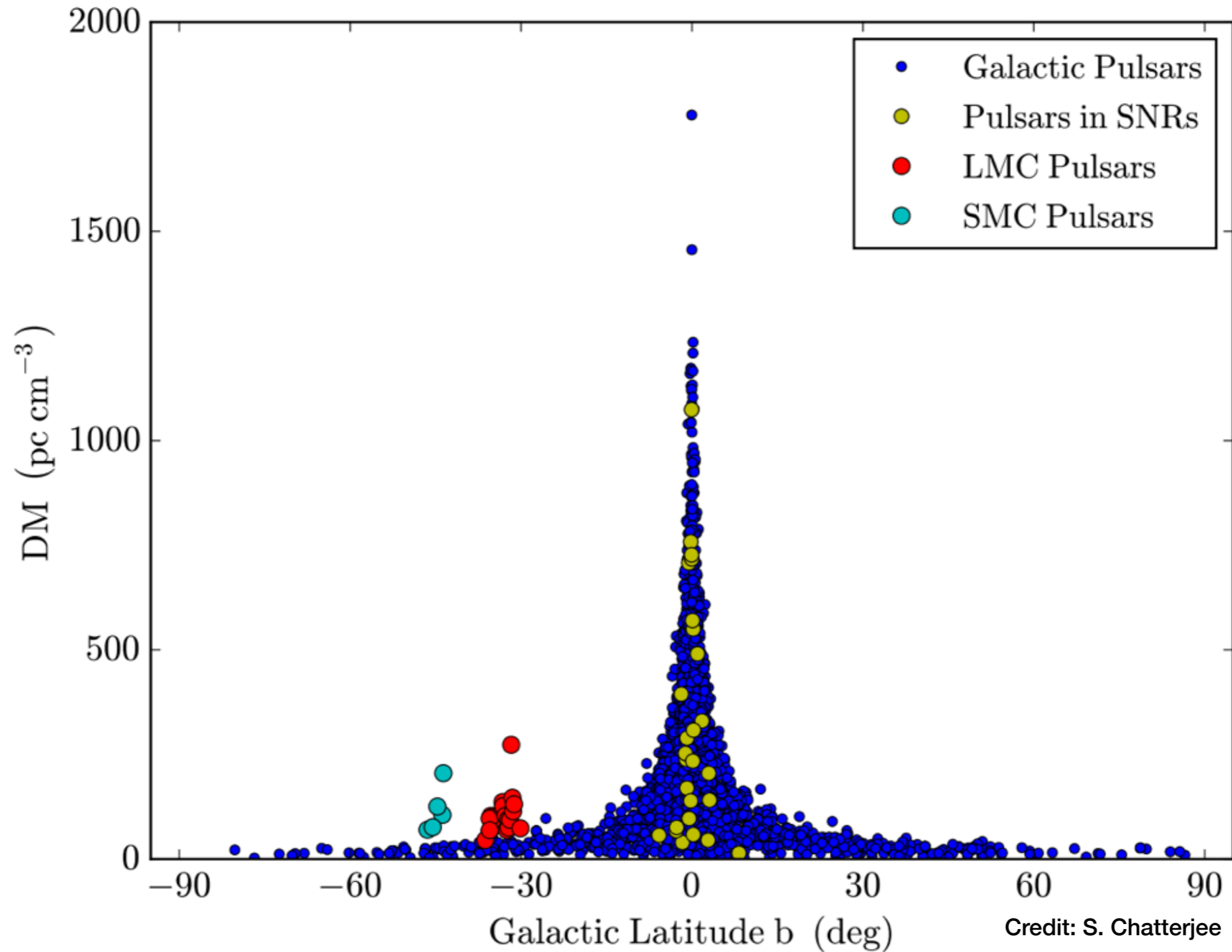
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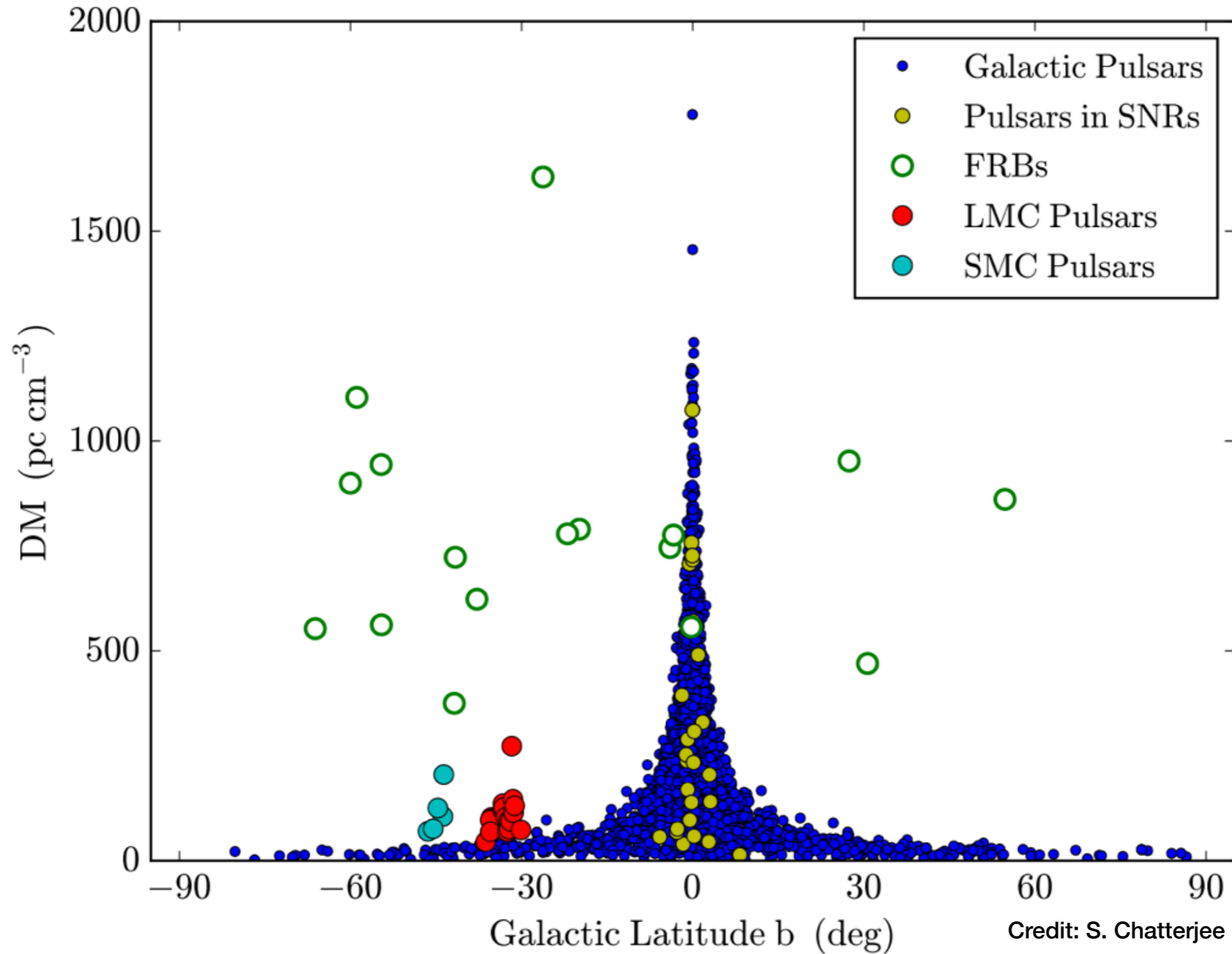
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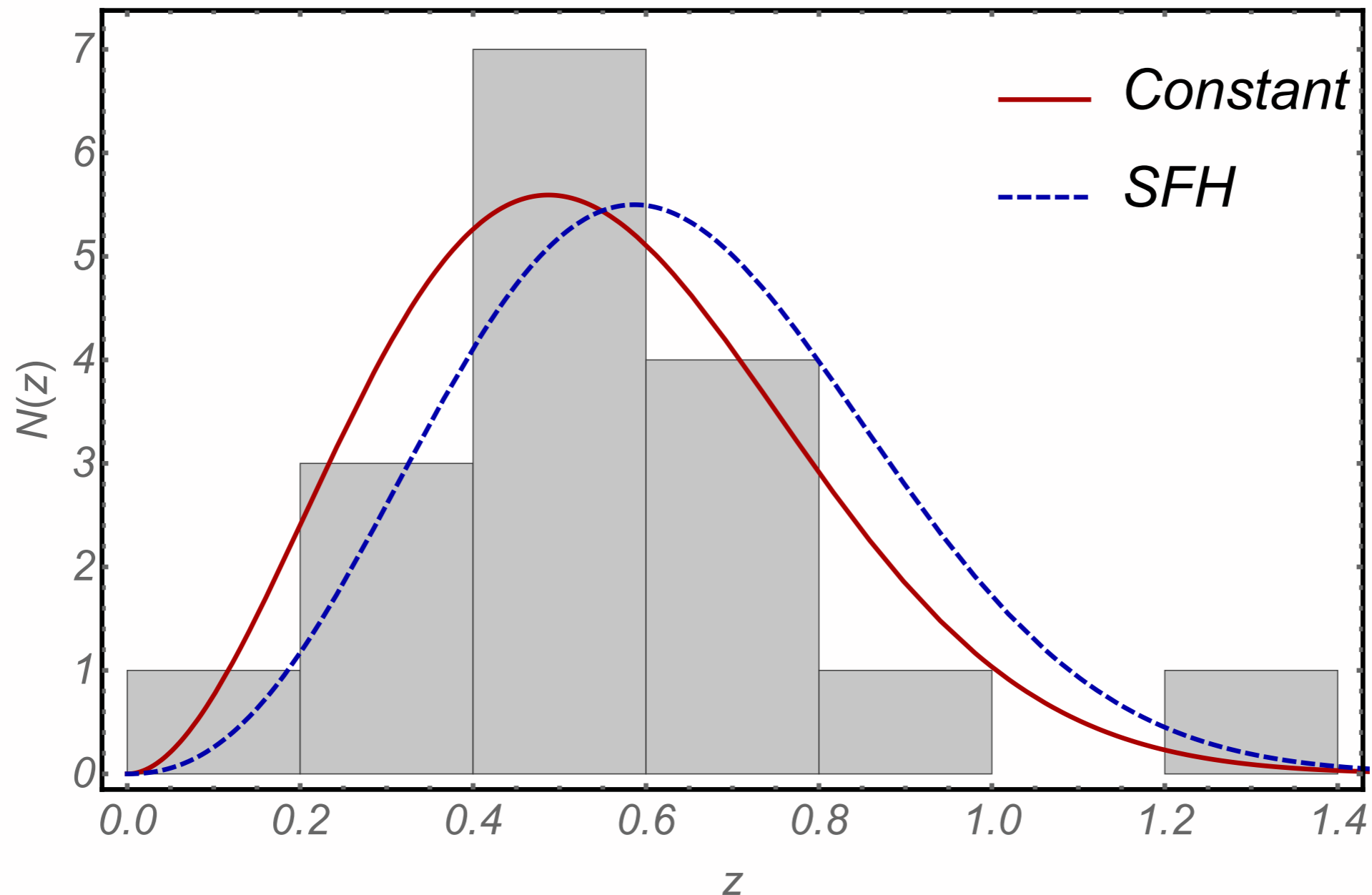
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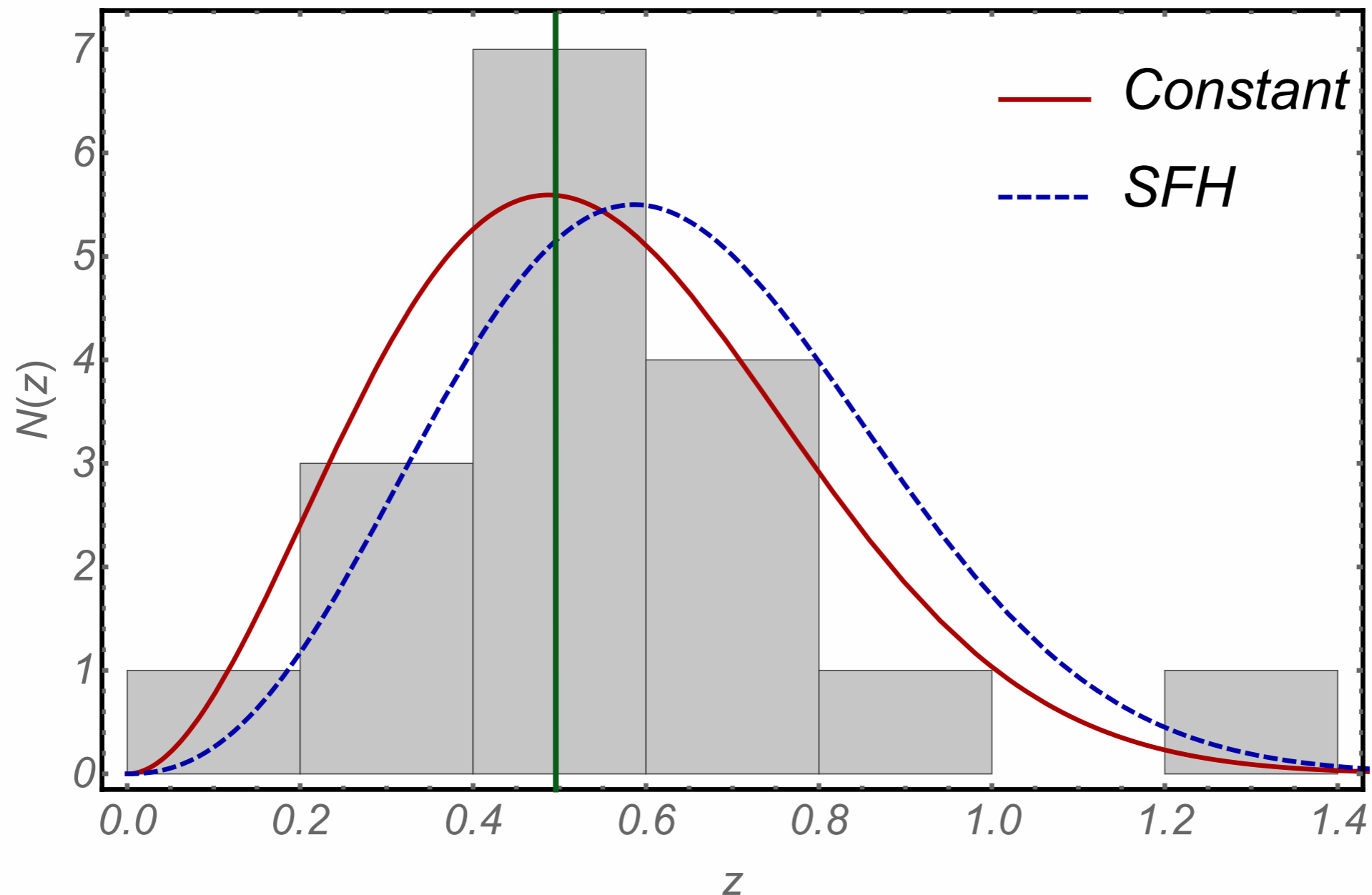


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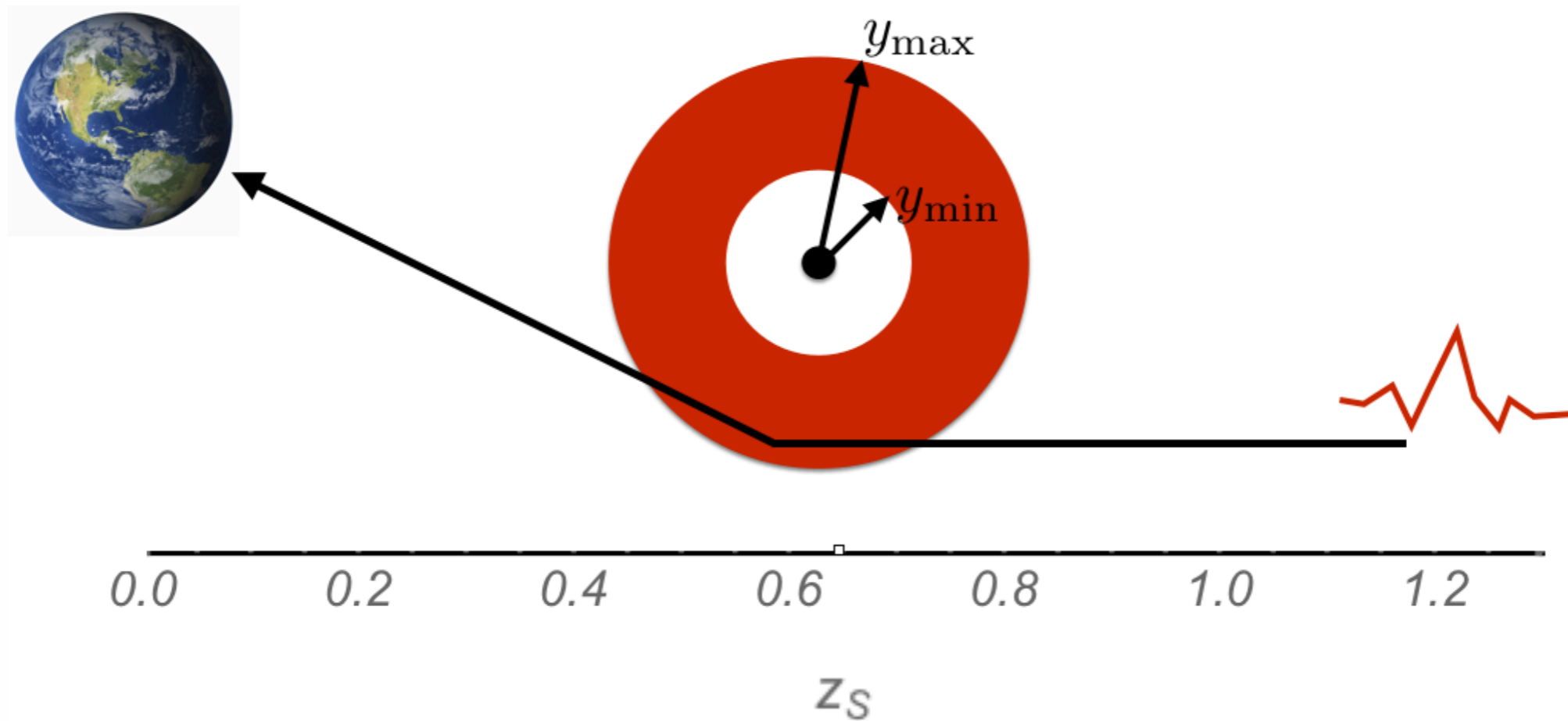
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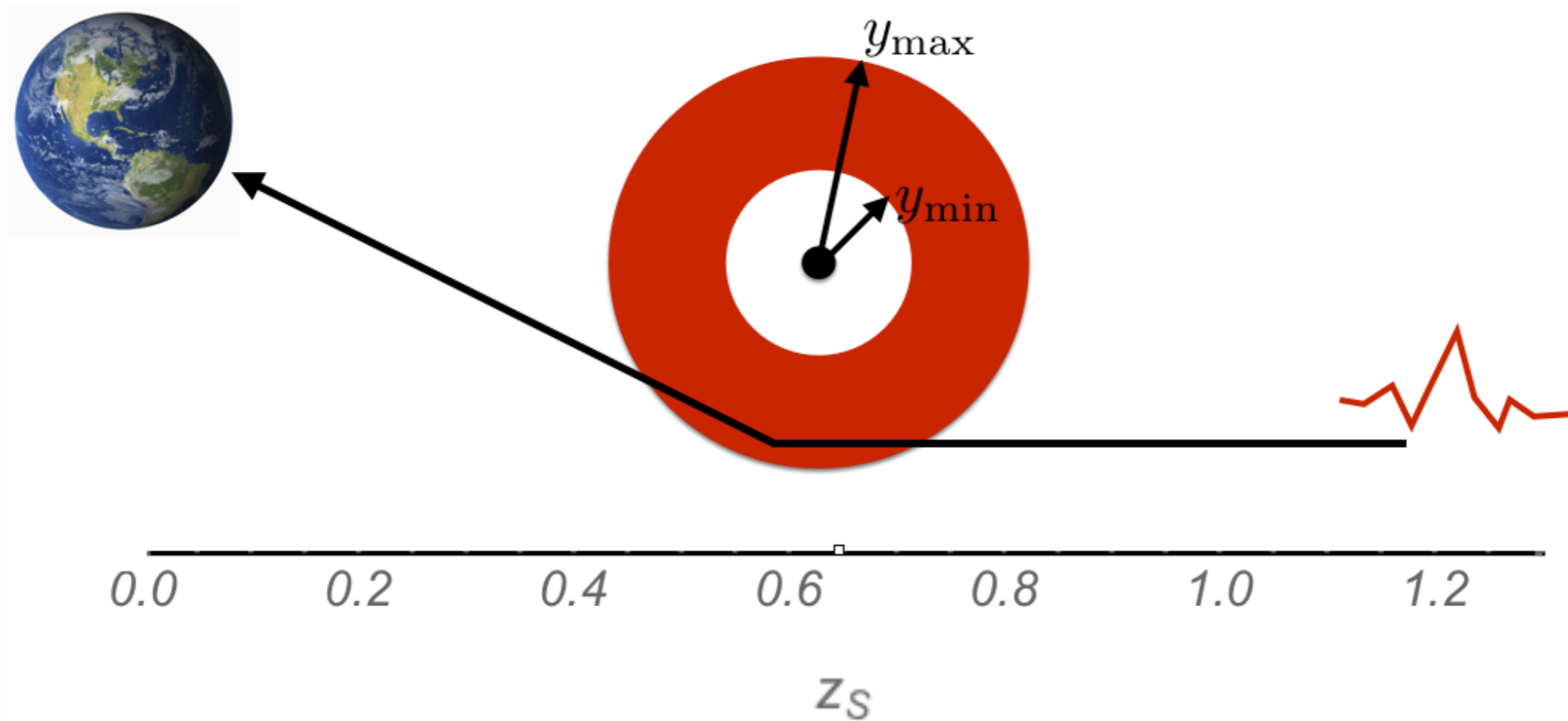
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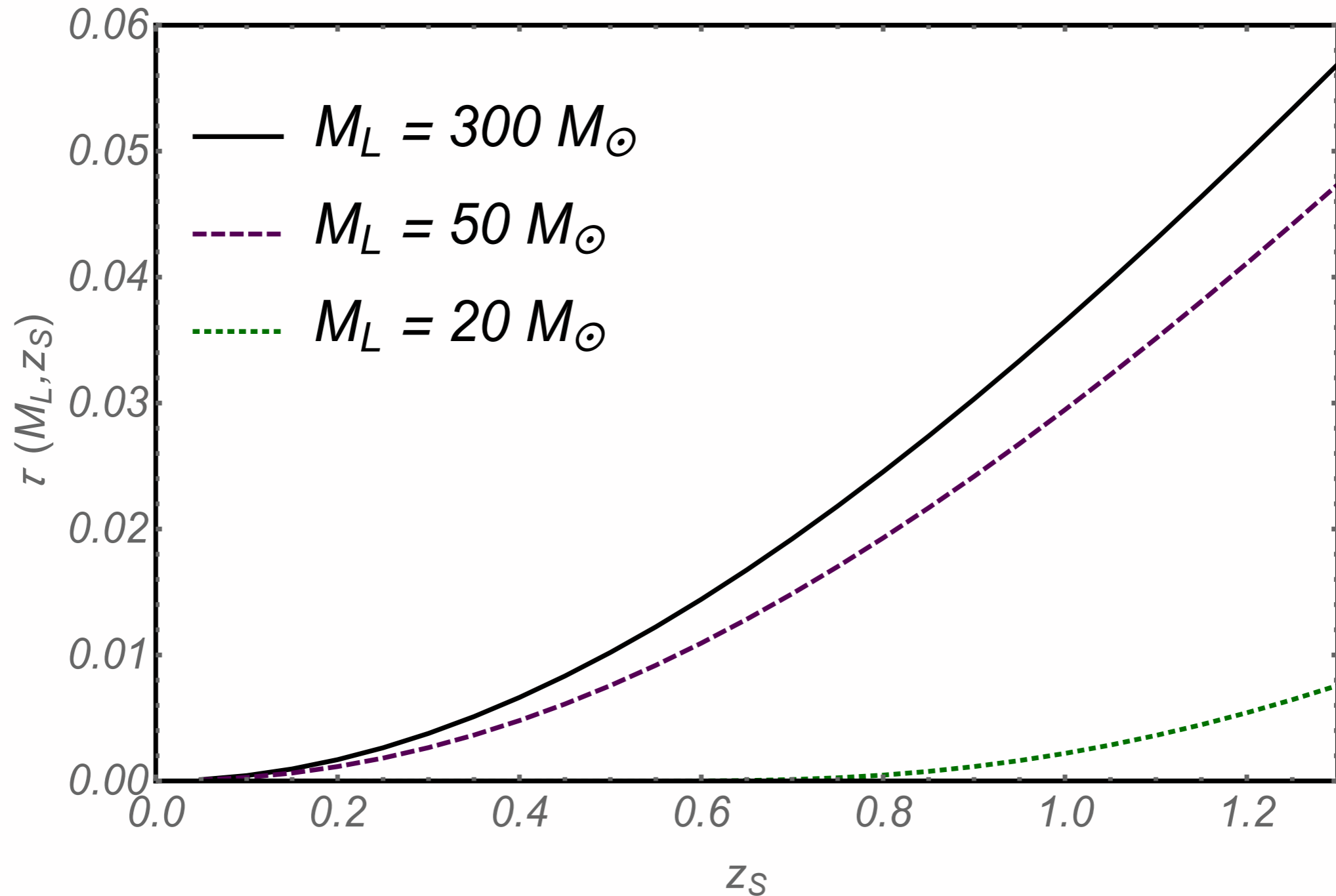
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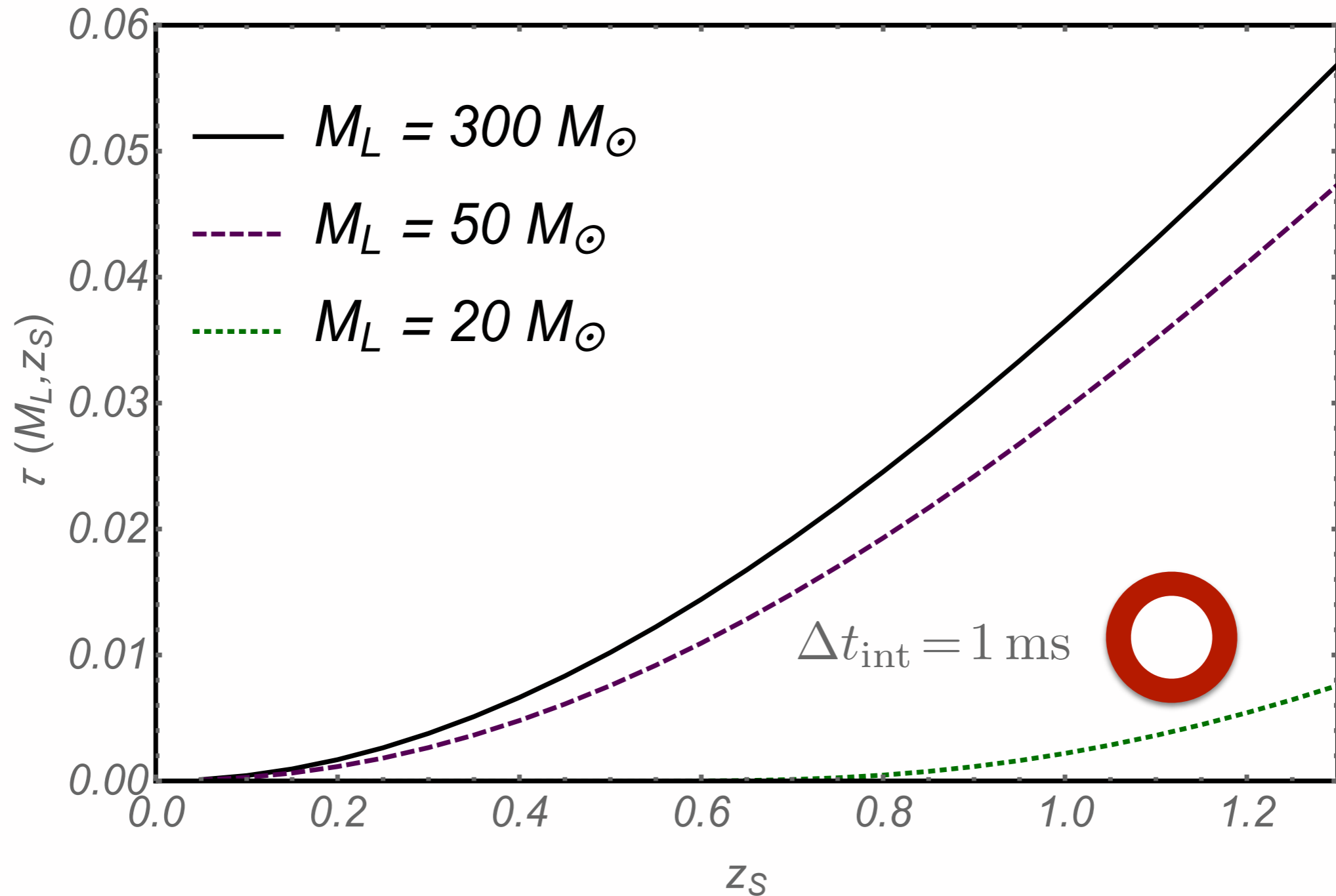
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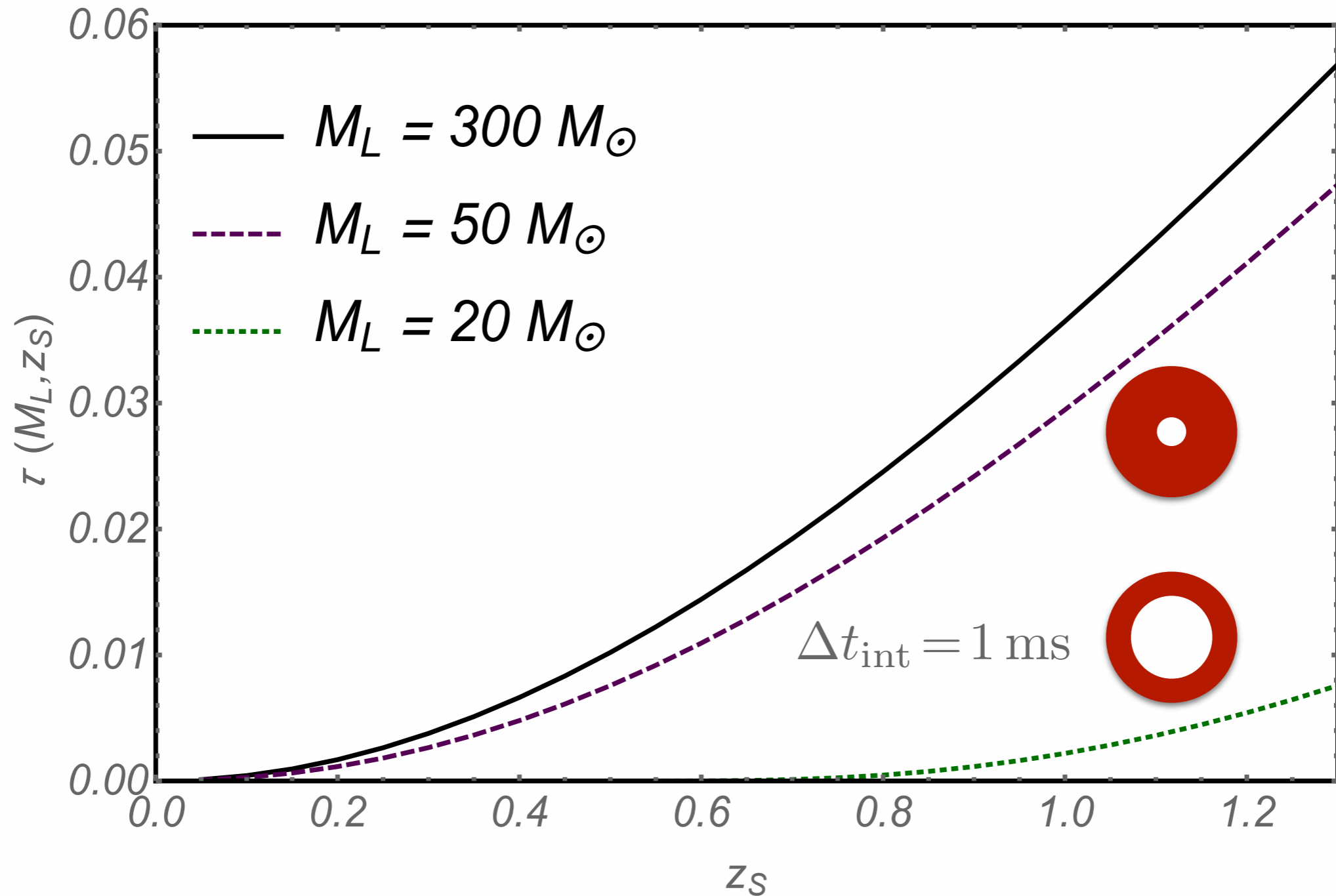
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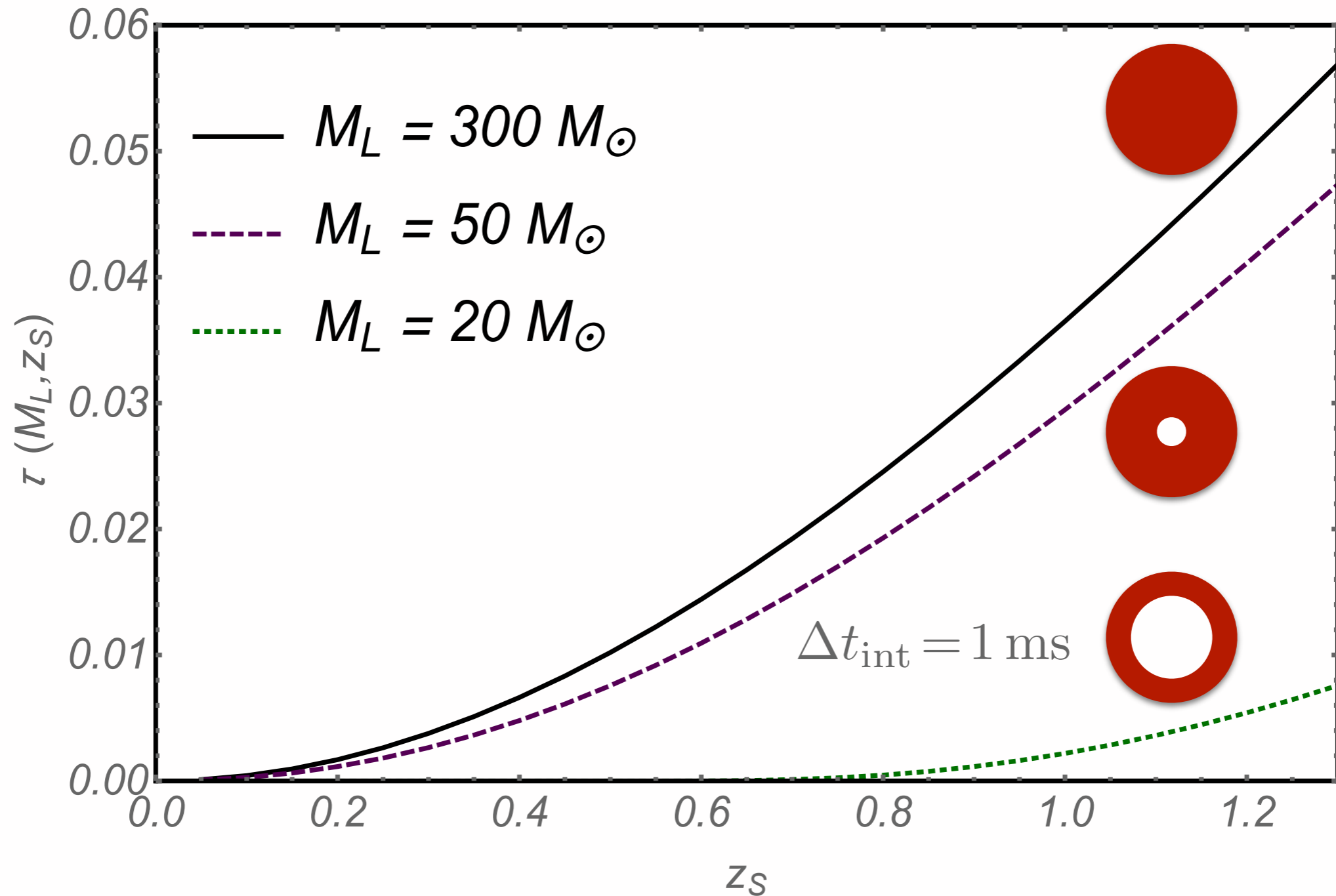
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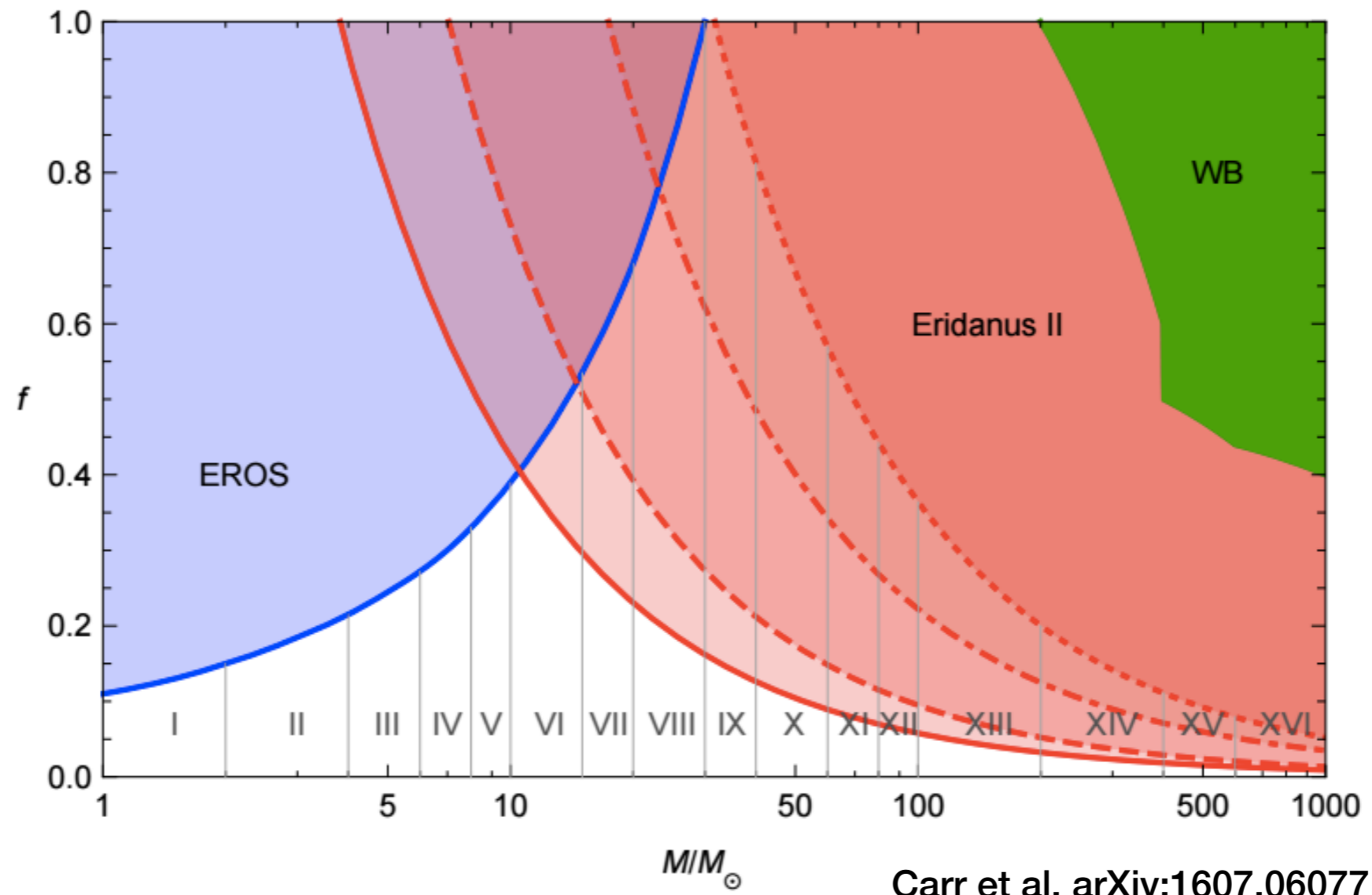
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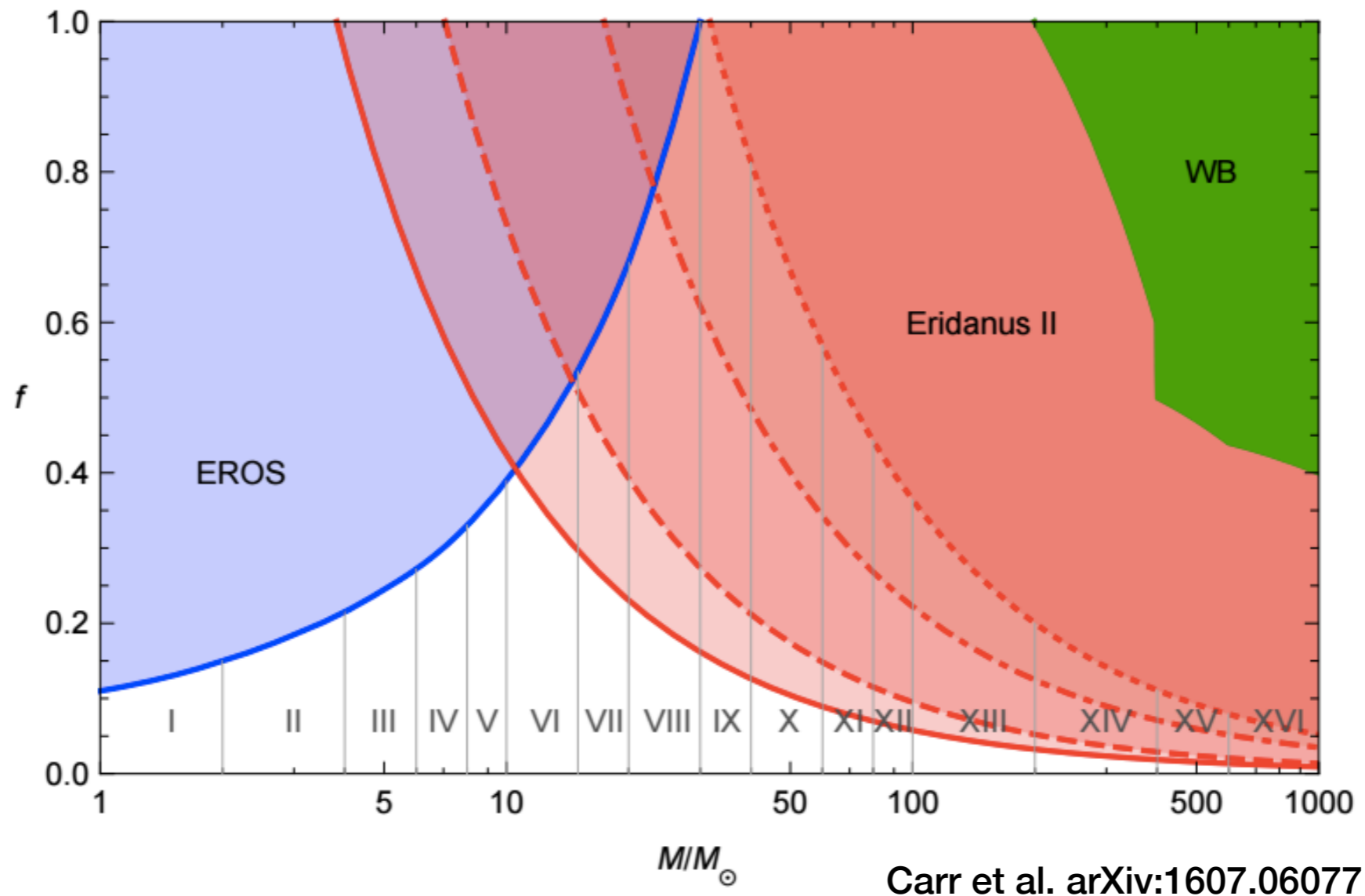


PBH DM LIGO Window: Tension Increasing?



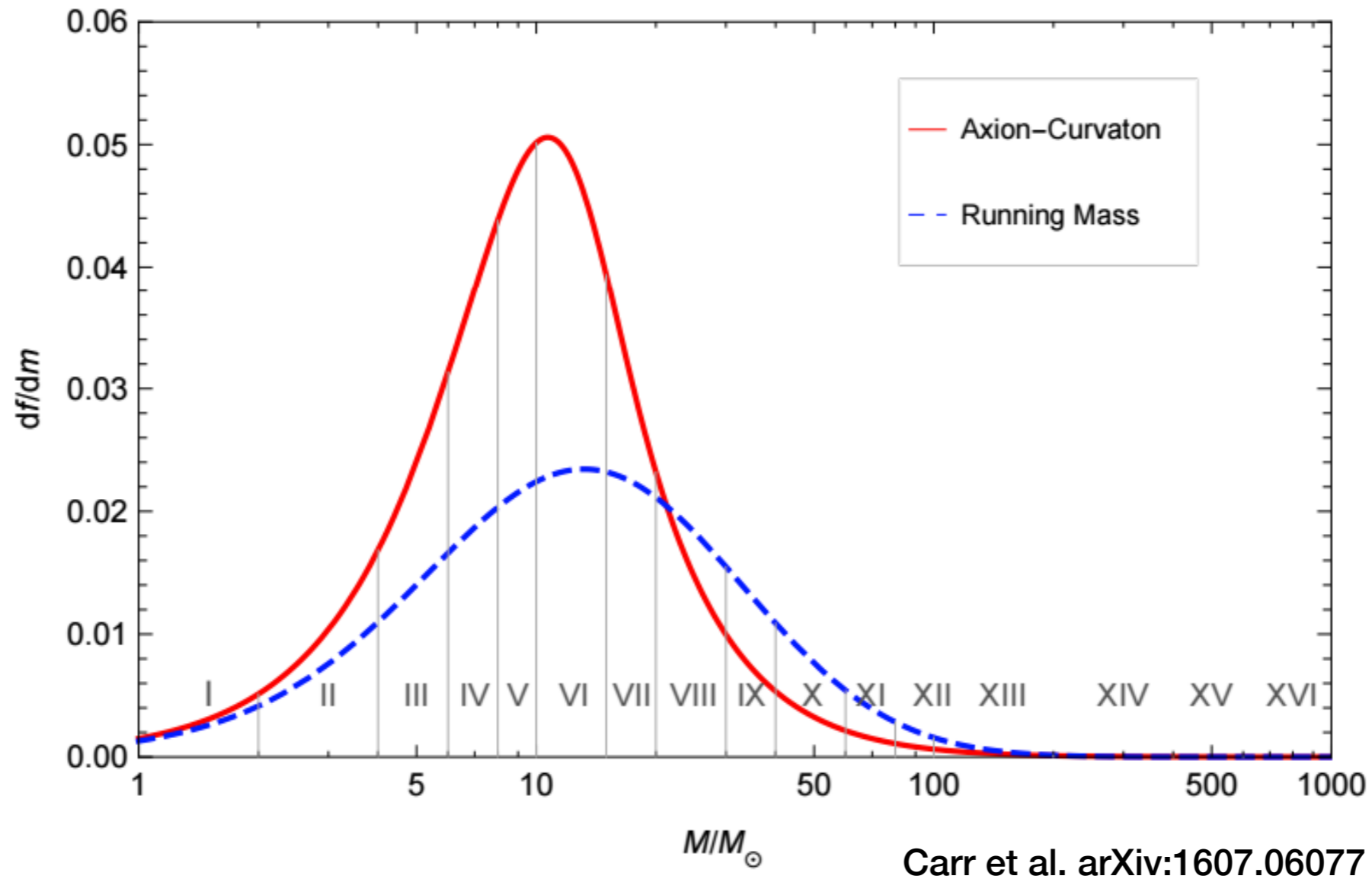
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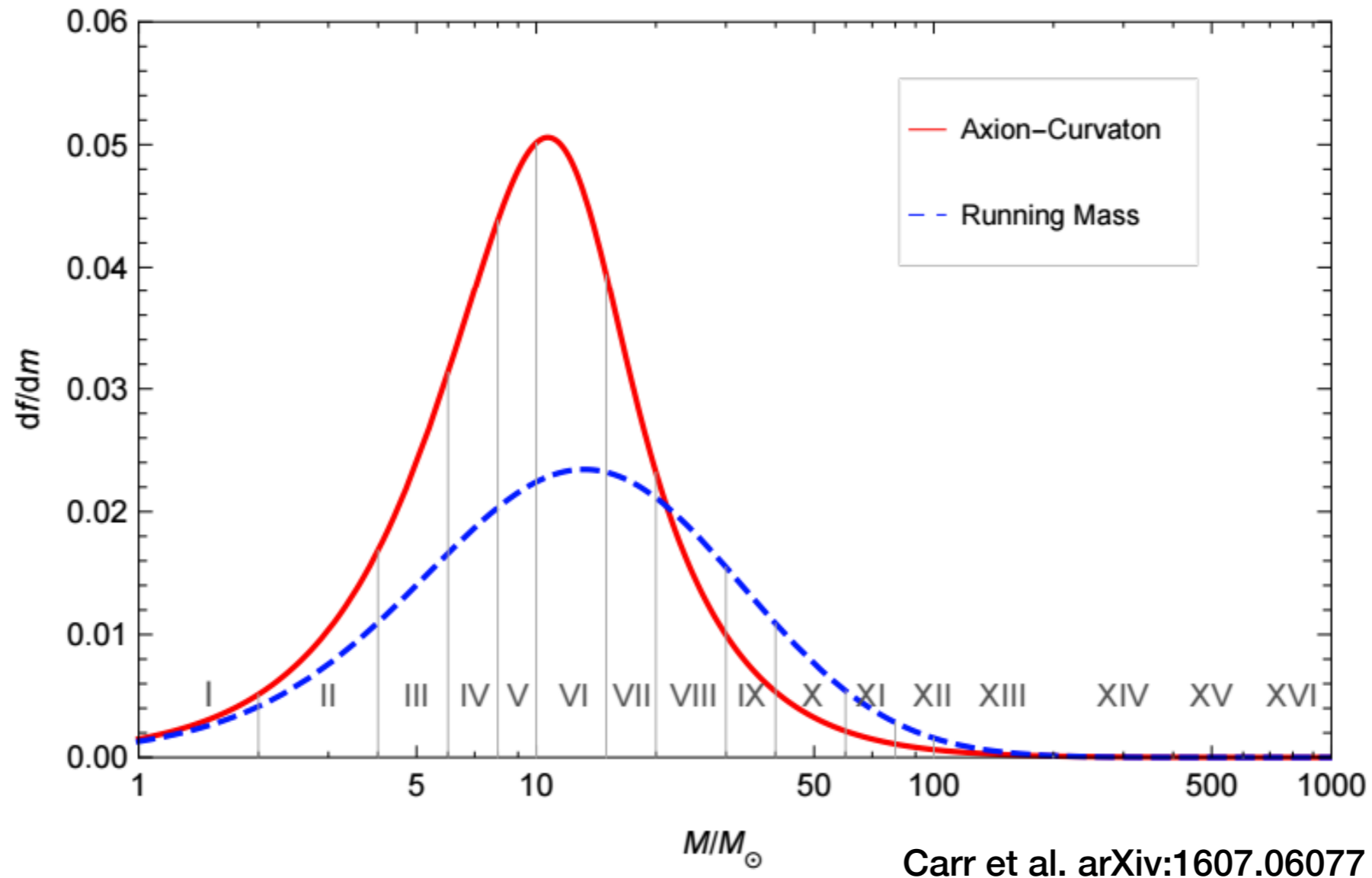
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Needs to be done carefully: constraints assume delta-function mass function.

Green, arXiv:1609.01143; Kuhnel & Freese, arXiv:1701.07223