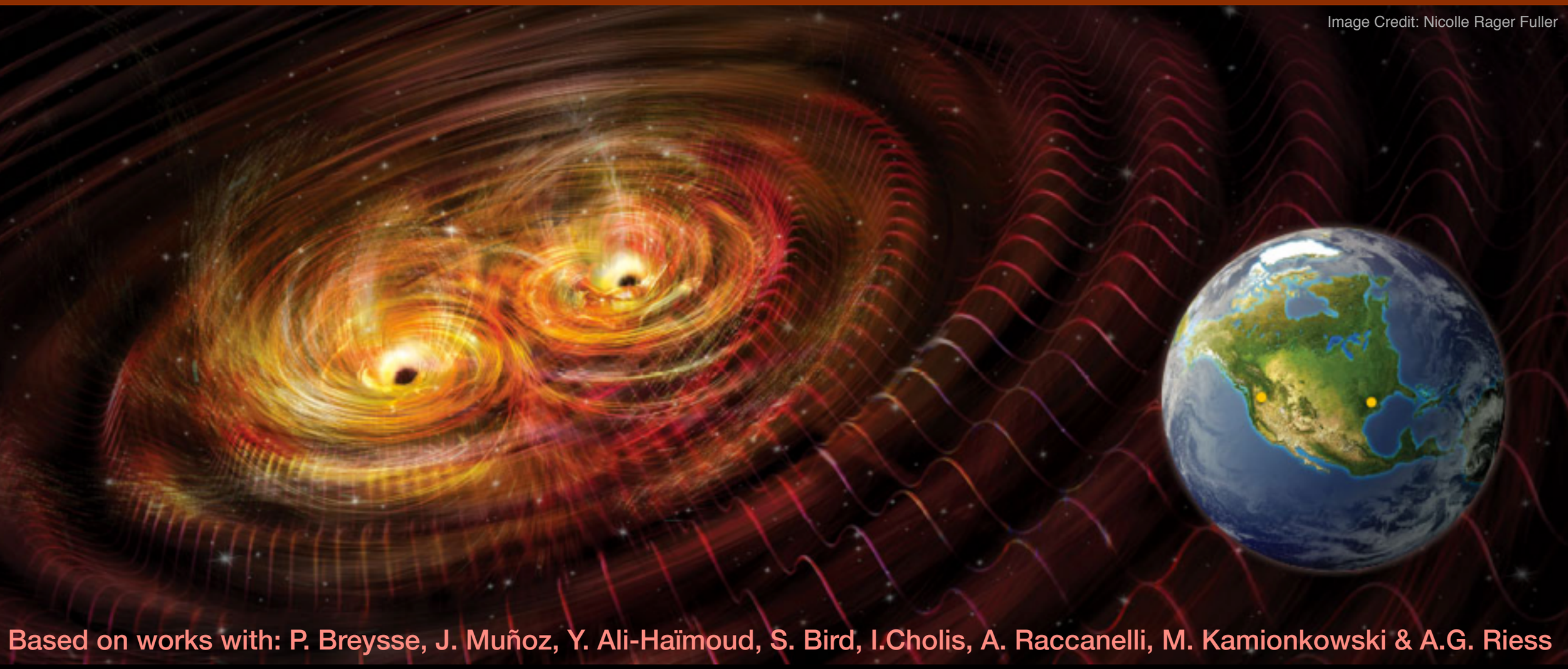
The Status of Primordial Black Holes as Dark Matter

Ely D. Kovetz
Johns Hopkins University

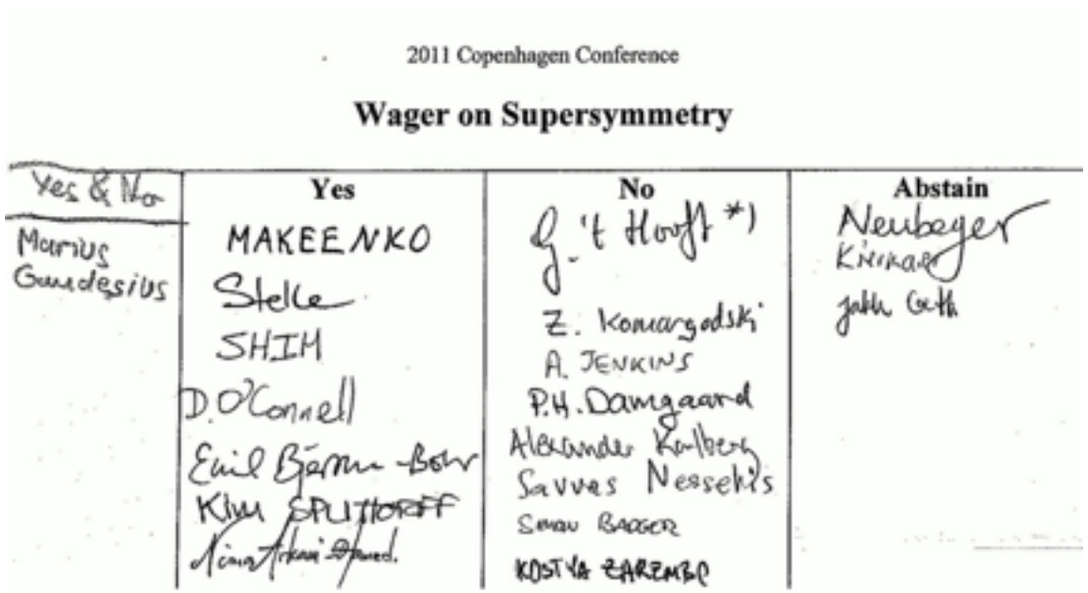


Based on works with: P. Breysse, J. Muñoz, Y. Ali-Haïmoud, S. Bird, I.Cholis, A. Raccanelli, M. Kamionkowski & A.G. Riess

What is Dark Matter? WIMPs? MACHOs?

Willing to bet?

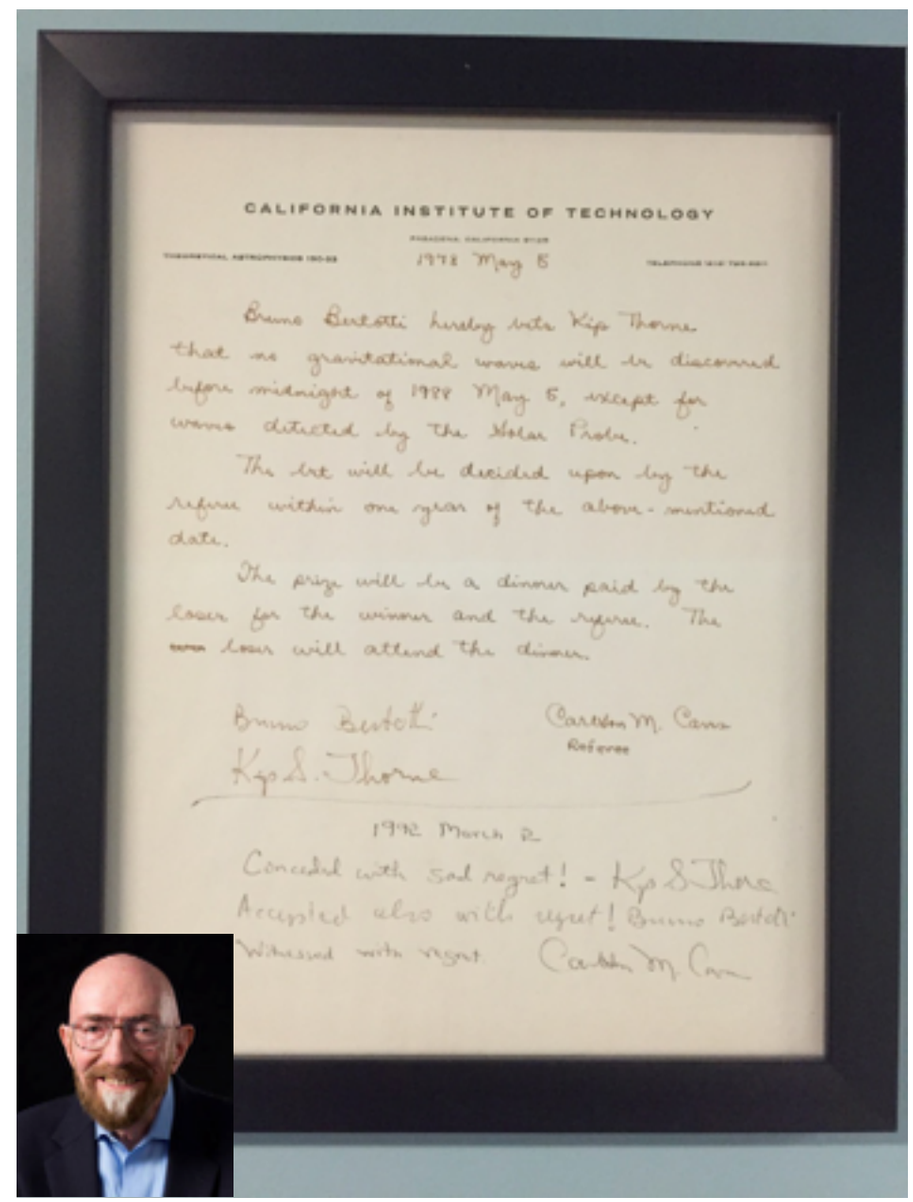
Careful, physicists have mixed betting records:



2011 Copenhagen Conference

Wager on Supersymmetry

Yes & No	Yes	No	Abstain
Marius Gundersen	MAKEENKO	G. 't Hooft *)	Neubeyer
	Stelle	Z. Komargodski	Kirkar
	SHIM	A. JENKINS	John Cath
	D. O'Connell	P.H. Damgaard	
	Emil Bjerrum-Bohr	Alexander Kurlberg	
	KIM SPILLHOFF	Savvas Nesseris	
	Nima Arkani-Hamed	Simon Badger	
		KOSTYA ZAREMBO	



CALIFORNIA INSTITUTE OF TECHNOLOGY

1972 May 5

Bruno Benetti hereby bets Kip Thorne that no gravitational waves will be discovered before midnight of 1988 May 5, except for waves detected by the Solar Probe.

The bet will be decided upon by the referee within one year of the above-mentioned date.

The prize will be a dinner paid by the loser for the winner and the referee. The loser will attend the dinner.

Bruno Benetti — Carlton M. Caves, Referee

Kip S. Thorne

1972 March 2

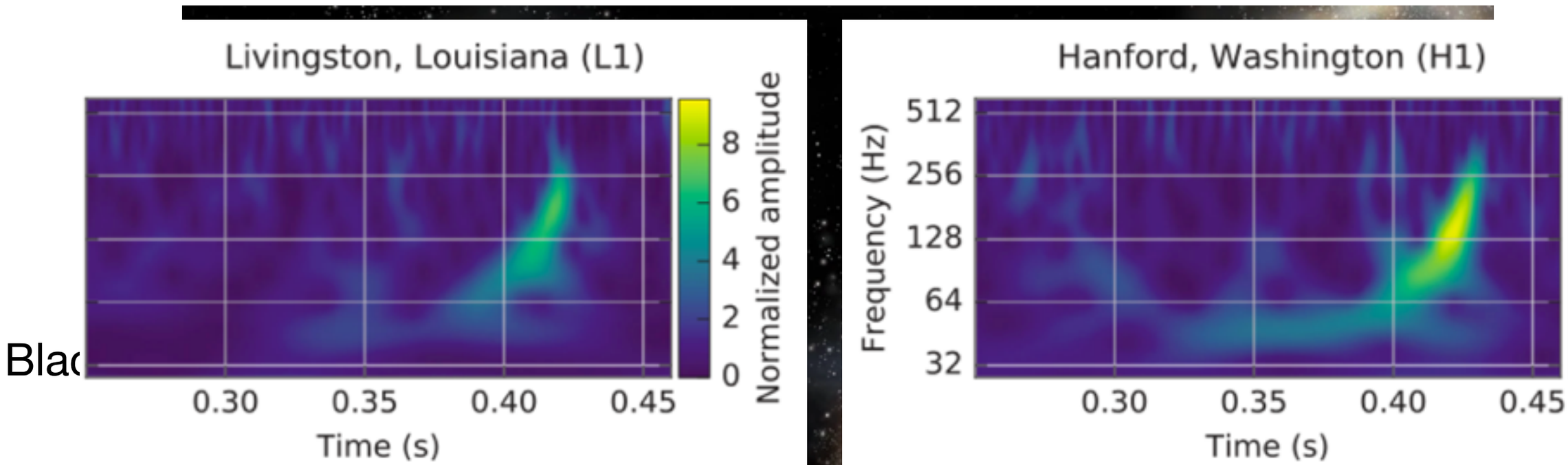
Concluded with sad regret! - Kip S. Thorne

Accepted also with regret! Bruno Benetti

Witnessed with regret Carlton M. Caves

Motivation: 1st Detection of Gravitational Waves

On September 14, 2015 at 09:50:45 GMT:

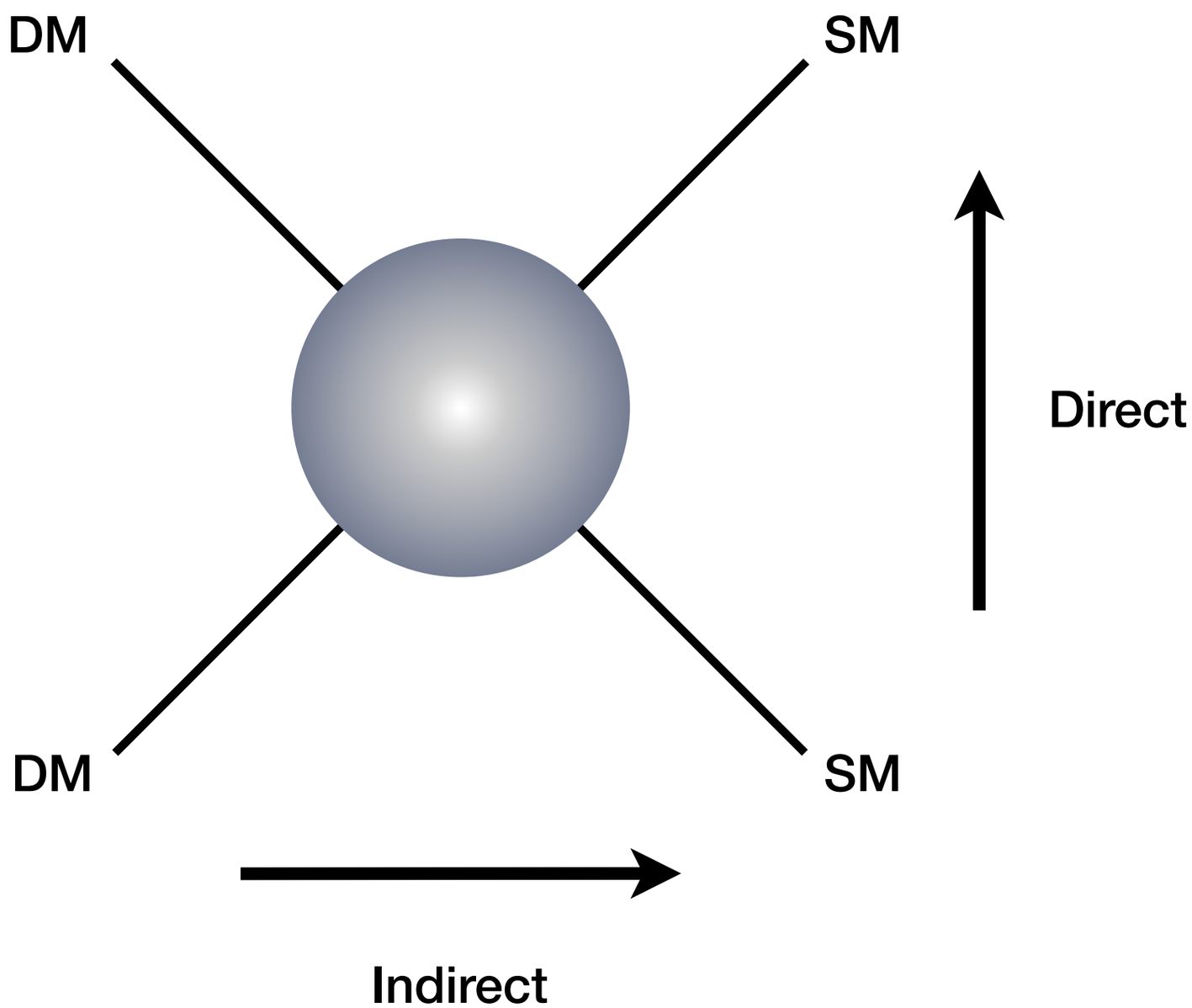


Blac

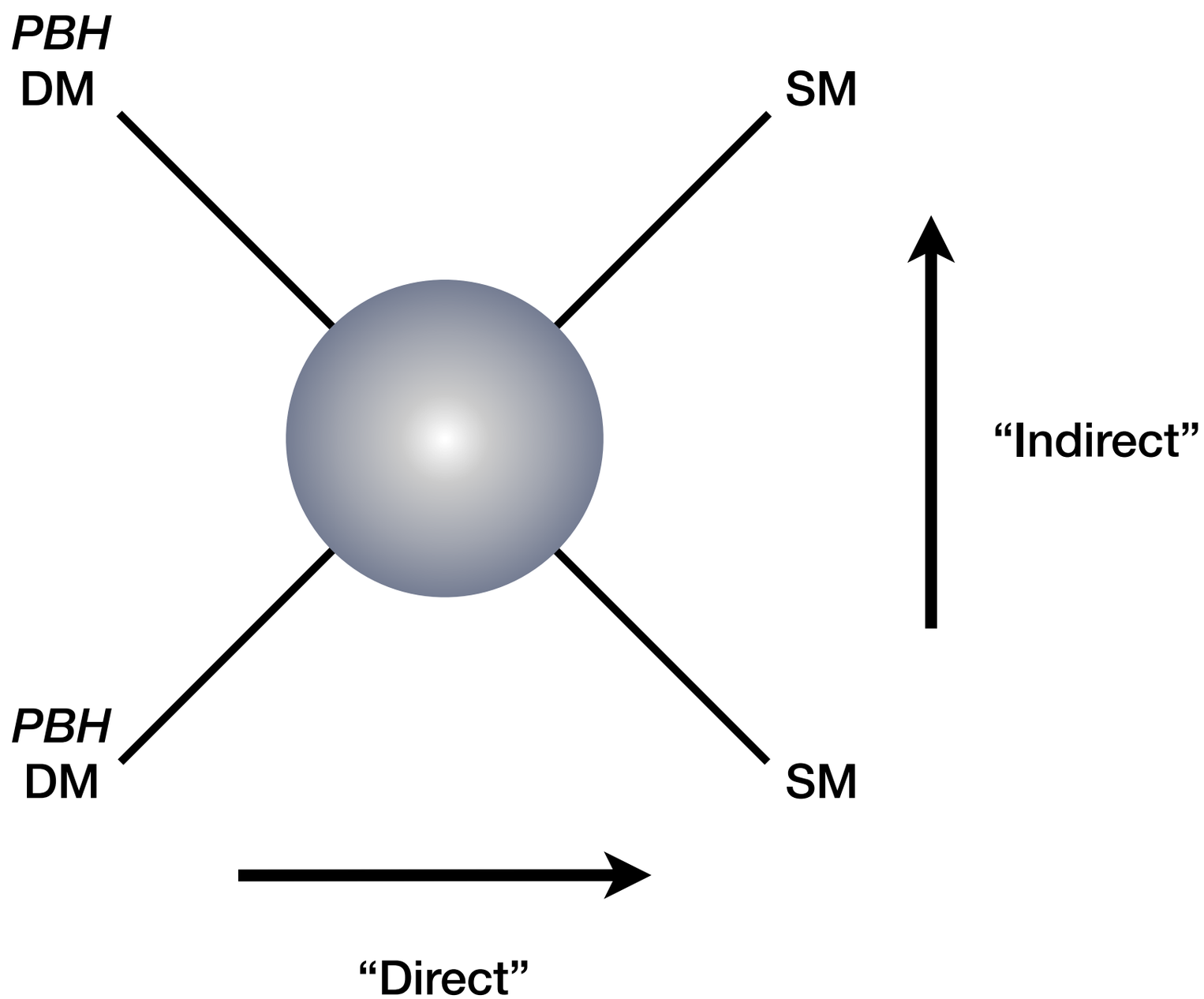
Could these be primordial black holes?

Zel'dovich & Novikov (1967), Hawking (1971), Carr & Hawking (1974)

PBH Dark Matter Interactions



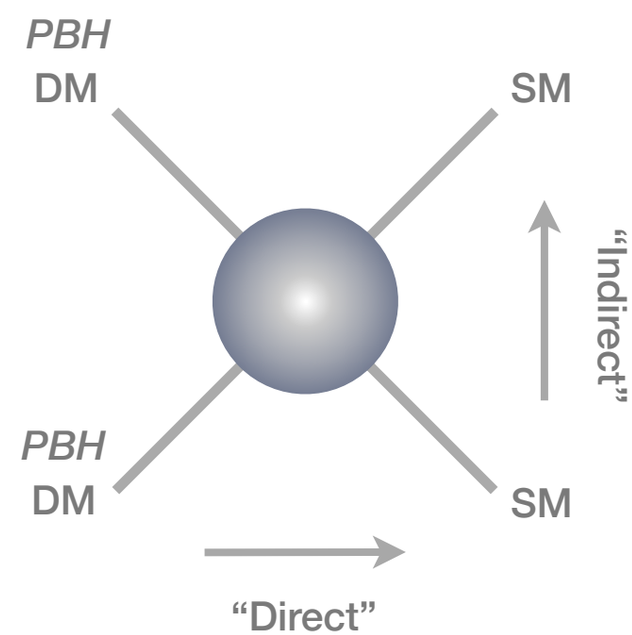
PBH Dark Matter Interactions



Outline

- Direct Detection: GWs from PBH mergers

- ndirect Detection: PBH DM Constraints



Outline

- Direct Detection: GWs from PBH mergers

“Did LIGO Detect Dark Matter?”
Bird, Cholis, Muñoz, Ali-Haïmoud, Kamionkowski, EDK, Raccanelli & Riess, Phys. Rev. Lett. 116 (2016)

“The Black Hole Mass Function from Gravitational Wave Measurements”
EDK, Cholis & Breysse, in preparation.

PBH Binaries: Formation and Coalescence

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

How do the binaries form?

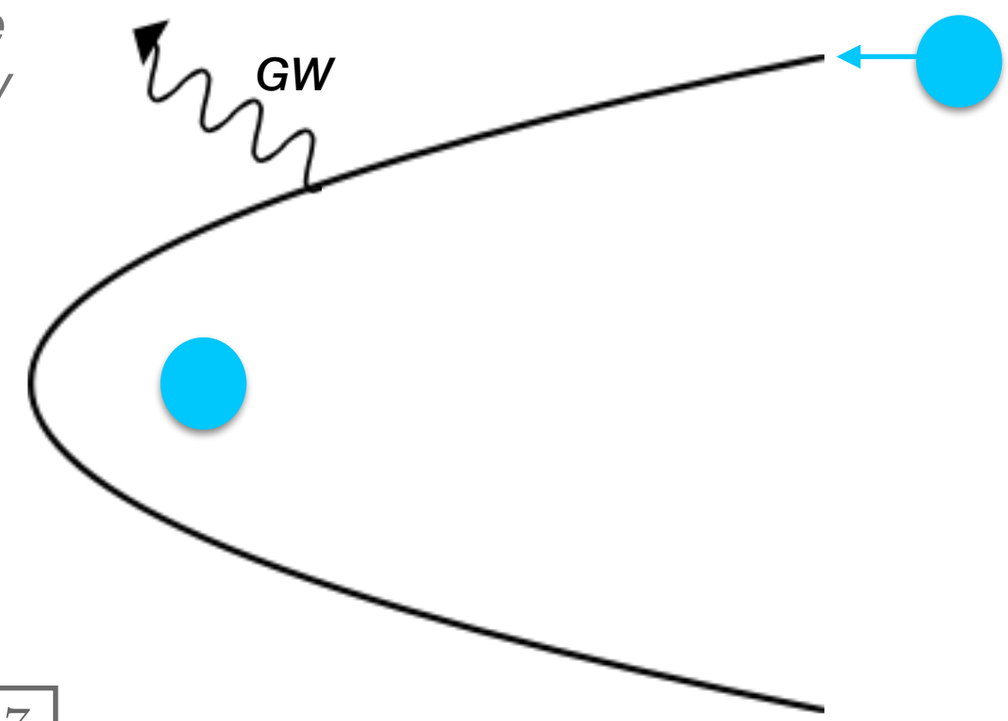
In close encounter, GW emitted: $$\frac{dE_{\rm GW}}{dt} = \frac{G}{5c^5}\langle \dddot{Q}_{ij}\dddot{Q}^{ij}\rangle$$

the *traceless mass quadrupole moment*

A. Einstein (1918)

Binary formed if: $$\boxed{\delta E_{\rm GW} > \frac{1}{2}\mu v_{\rm pbh}^2}$$

relative velocity



Energy loss:

$$\delta E_{\rm GW} \sim \frac{G^{7/2}}{c^5}\frac{\mu^2 M^{5/2}}{r_p^{7/2}}$$

pericenter

→ Cross-section: $$\boxed{\sigma \propto R_s^2\left(\frac{v_{\rm pbh}}{c}\right)^{-18/7}}$$

Schwarzschild radius

GWs from PBH Mergers: Event Rate Calculation

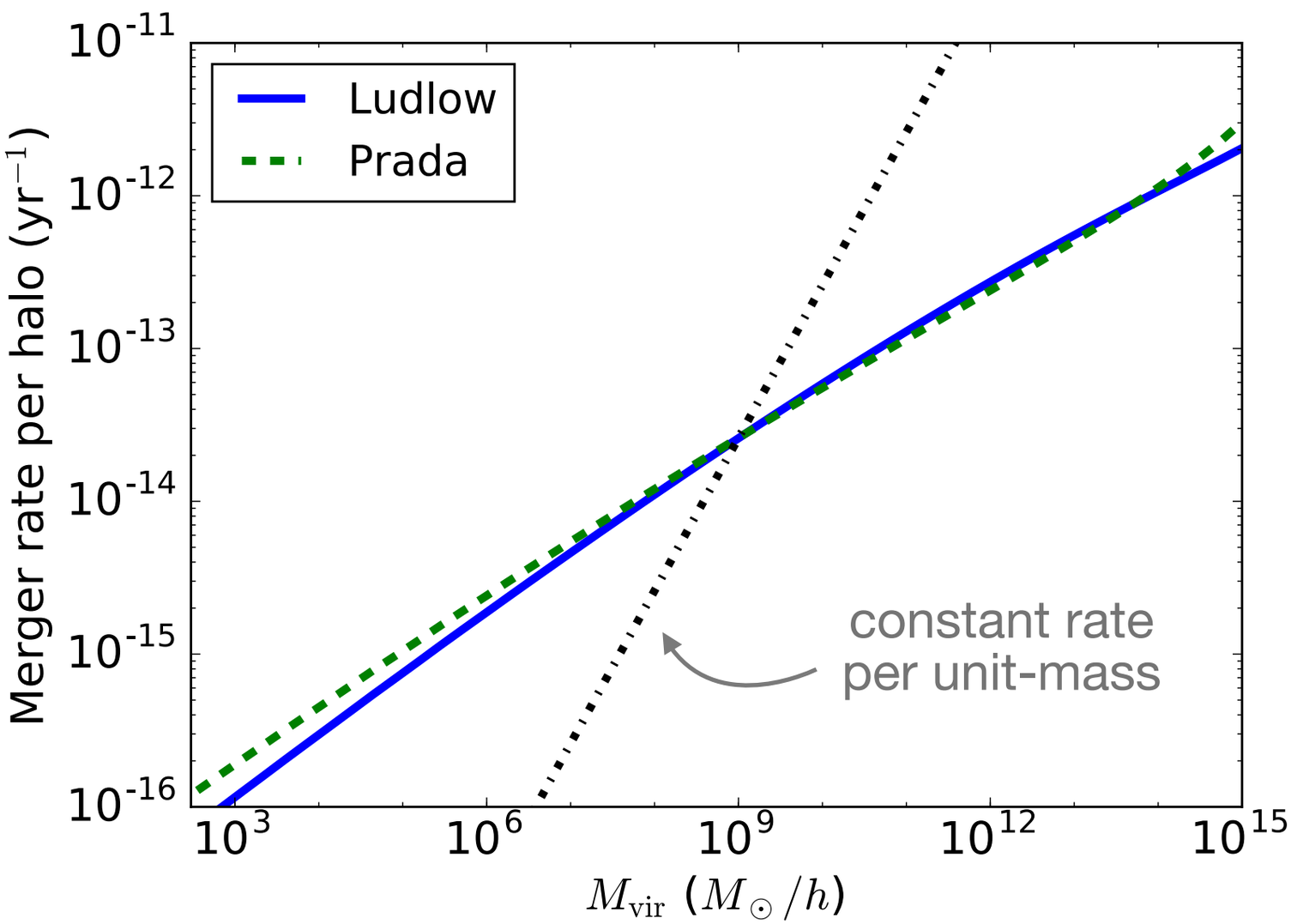
(Bird et al., PRL 116 (2016))

- The PBH merger rate within each halo:

halo density profile

Relative velocity MB distribution

$$\mathcal{R} = \frac{1}{2} n^2 \langle \sigma v_{\rm pbh} \rangle = 4\pi \int_0^{R_{\rm vir}} r^2 \frac{1}{2} \left(\frac{\rho_{\rm nfw}(r)}{M_{\rm pbh}} \right)^2 \langle \sigma v_{\rm pbh} \rangle \, dr$$



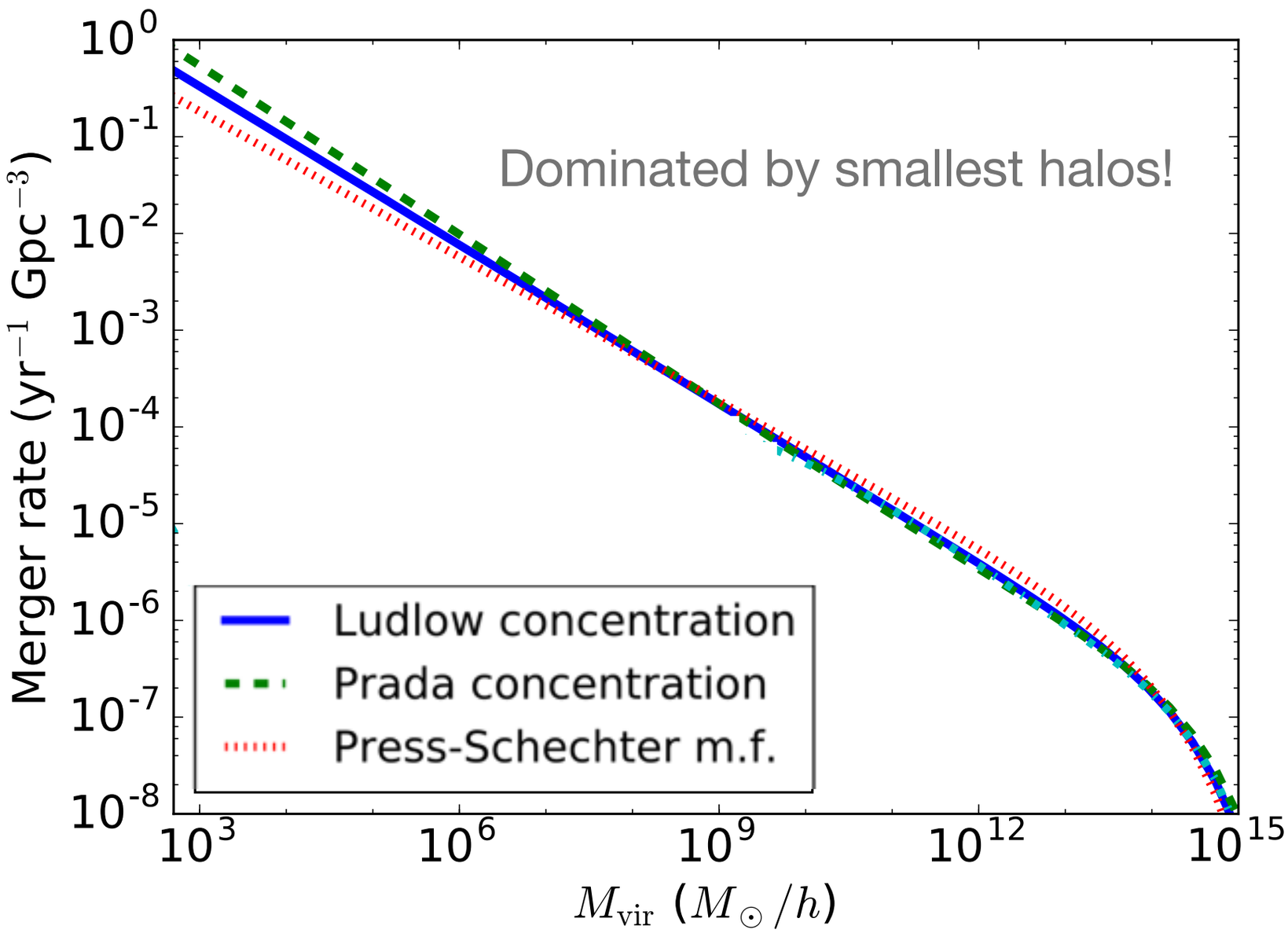
GWs from PBH Mergers: Event Rate Calculation

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

- Total merger rate:

Halo Mass Function

$$\mathcal{V}_{\rm pbh} = \int \frac{dn}{dM}(M)\,\mathcal{R}(M)\,dM$$



GWs from PBH Mergers: Results

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

We get a total LIGO event rate of: $\mathcal{V}_{\rm pbh} = 2\ {\rm Gpc}^{-3}\,{\rm yr}^{-1}$

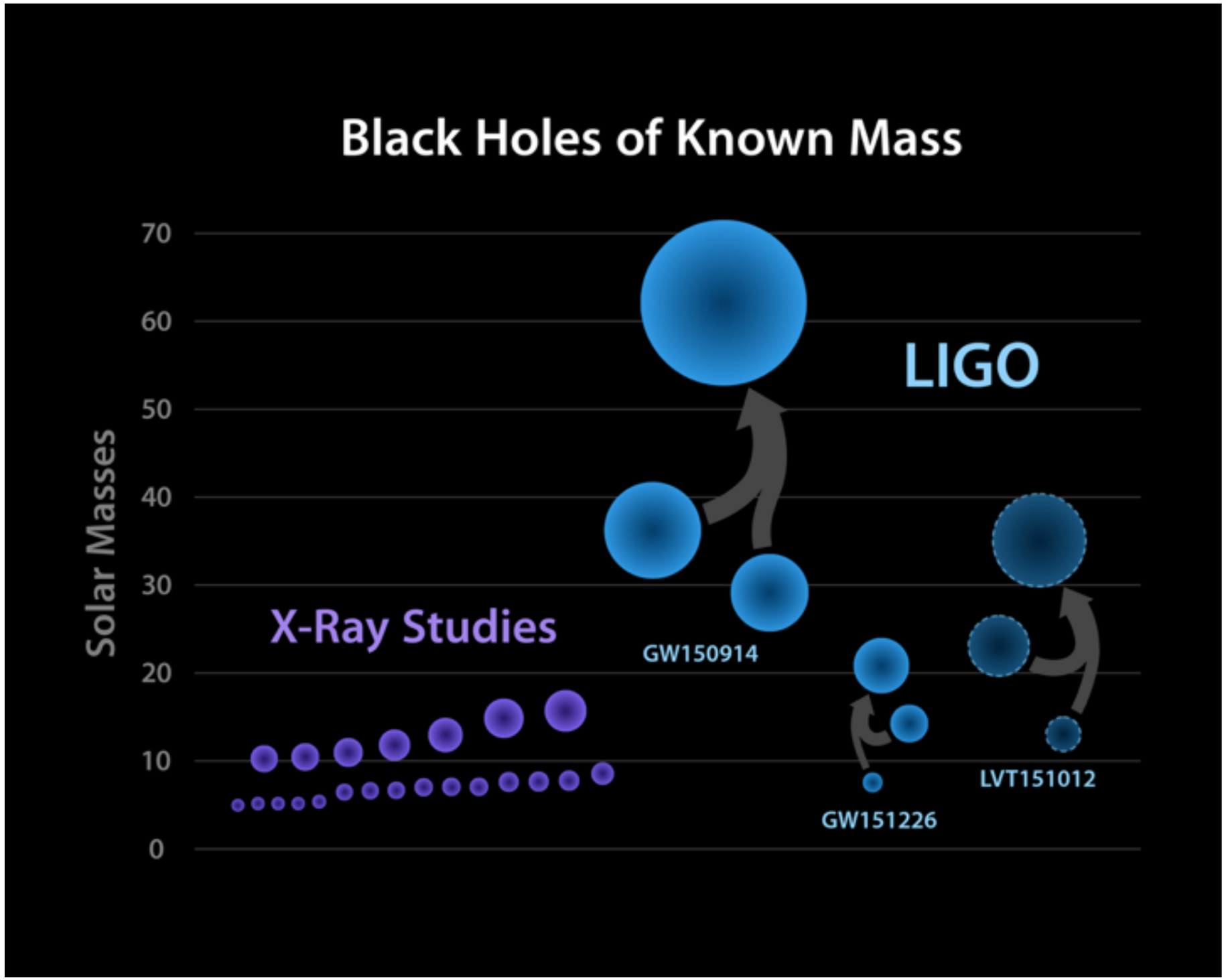
vs. the LIGO estimated event rate: $\mathcal{V}_{\rm LIGO} = 0.5 - 312\ {\rm Gpc}^{-3}\,{\rm yr}^{-1}$

Note: this could have been orders of magnitude in either direction!!!

<u>Testable predictions:</u>

- No EM or neutrino counterparts
- A Stochastic GW background
- Originate in low mass halos
- Traces of high eccentricities
- Potential peak in mass spectrum

The Black Hole Mass Distribution



Credit: LIGO

The Black-Hole Mass Function from GWs

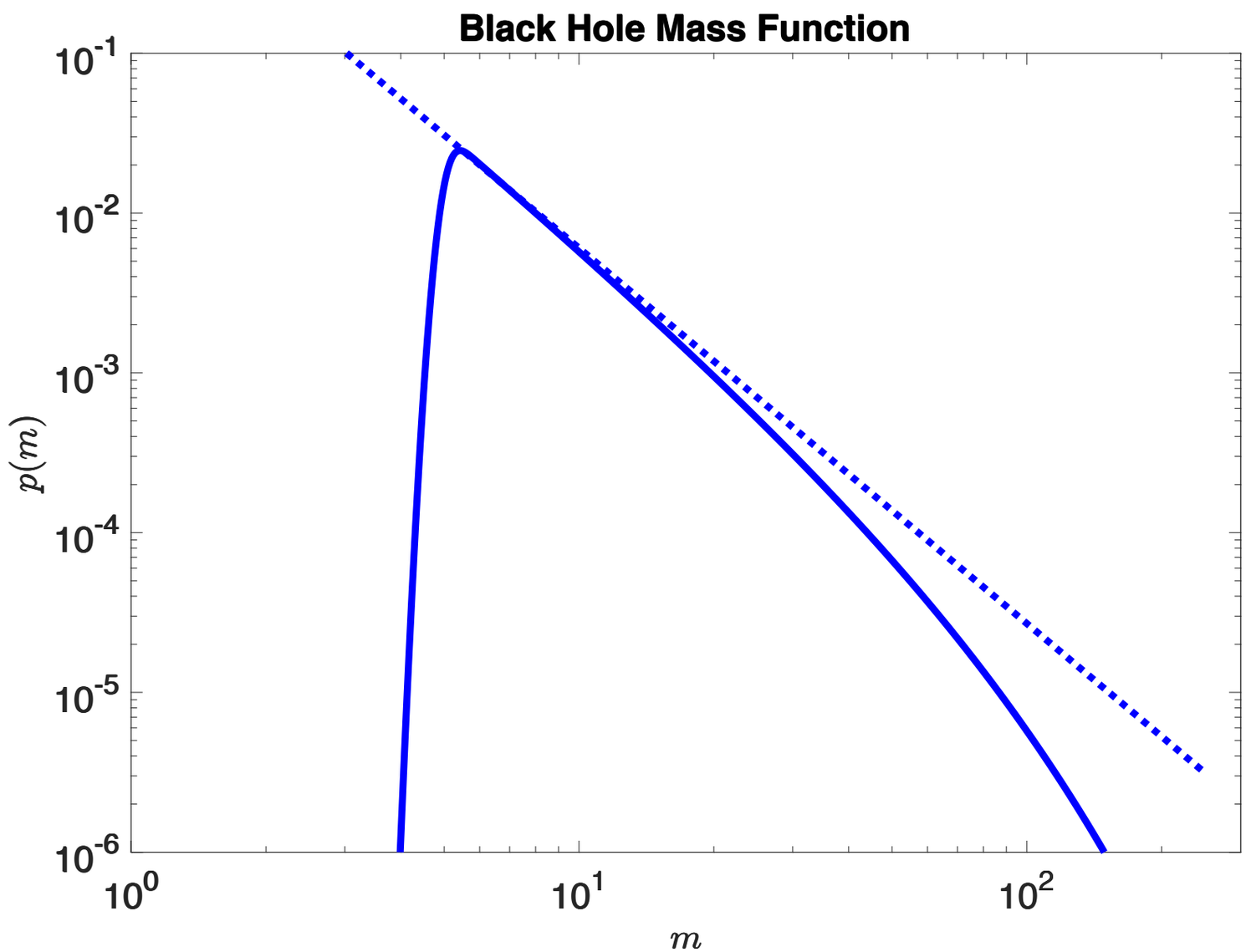
(EDK, Cholis & Breysse, in preparation)

Stellar IMF $\alpha = 2.35$

NS vs. BH $M_{\rm Gap} \sim 5?$

Mass Cutoff $M_{\rm Cap} \sim 100?$

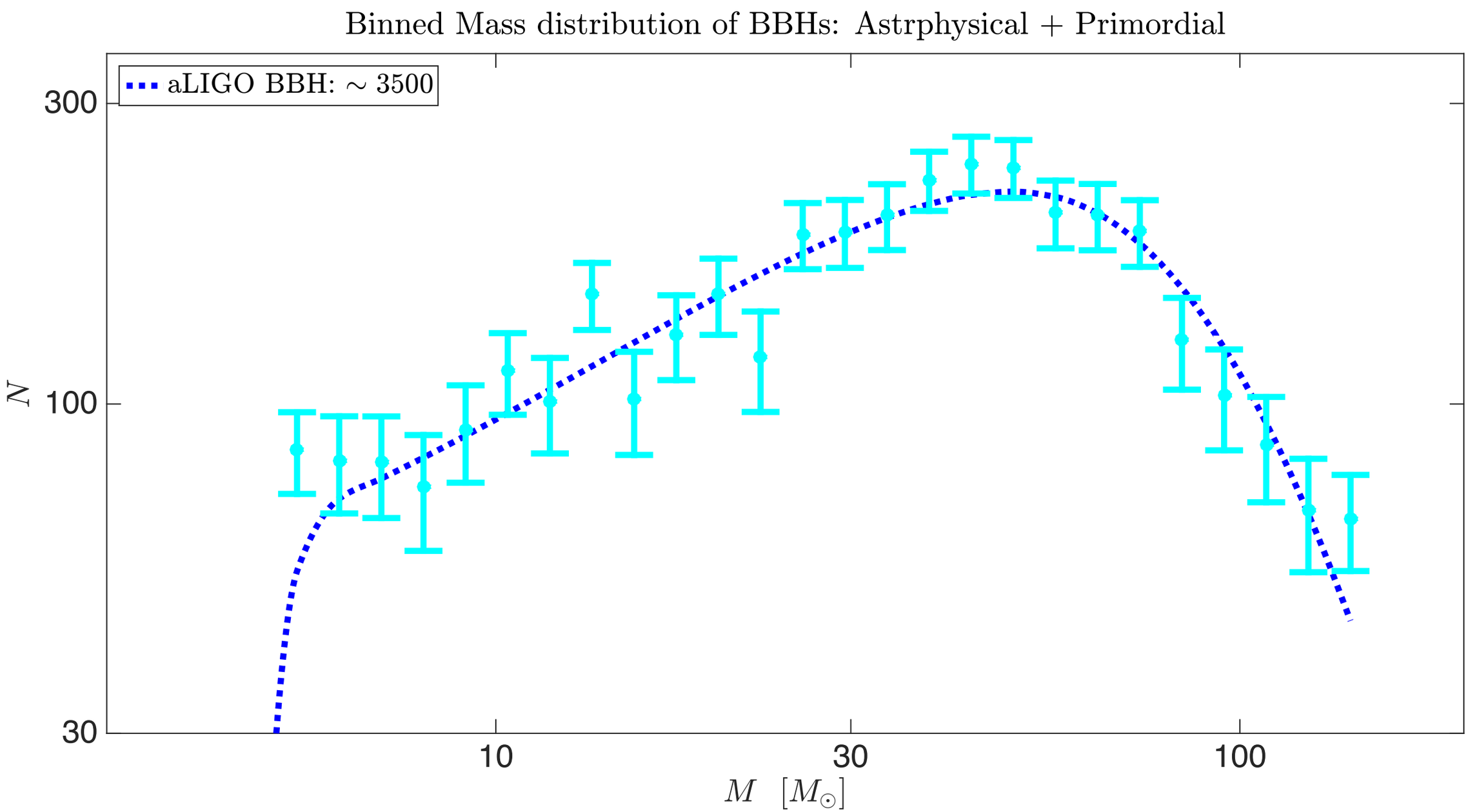
$$p(m) \propto m^{-\alpha}\mathcal{H}(m - m_{\rm Gap})e^{-m/m_{\rm Cap}}$$



The Black-Hole Mass Function from GWs

(EDK, Cholis & Breysse, in preparation)

Observed mass spectrum with (5 years of advanced LIGO data):

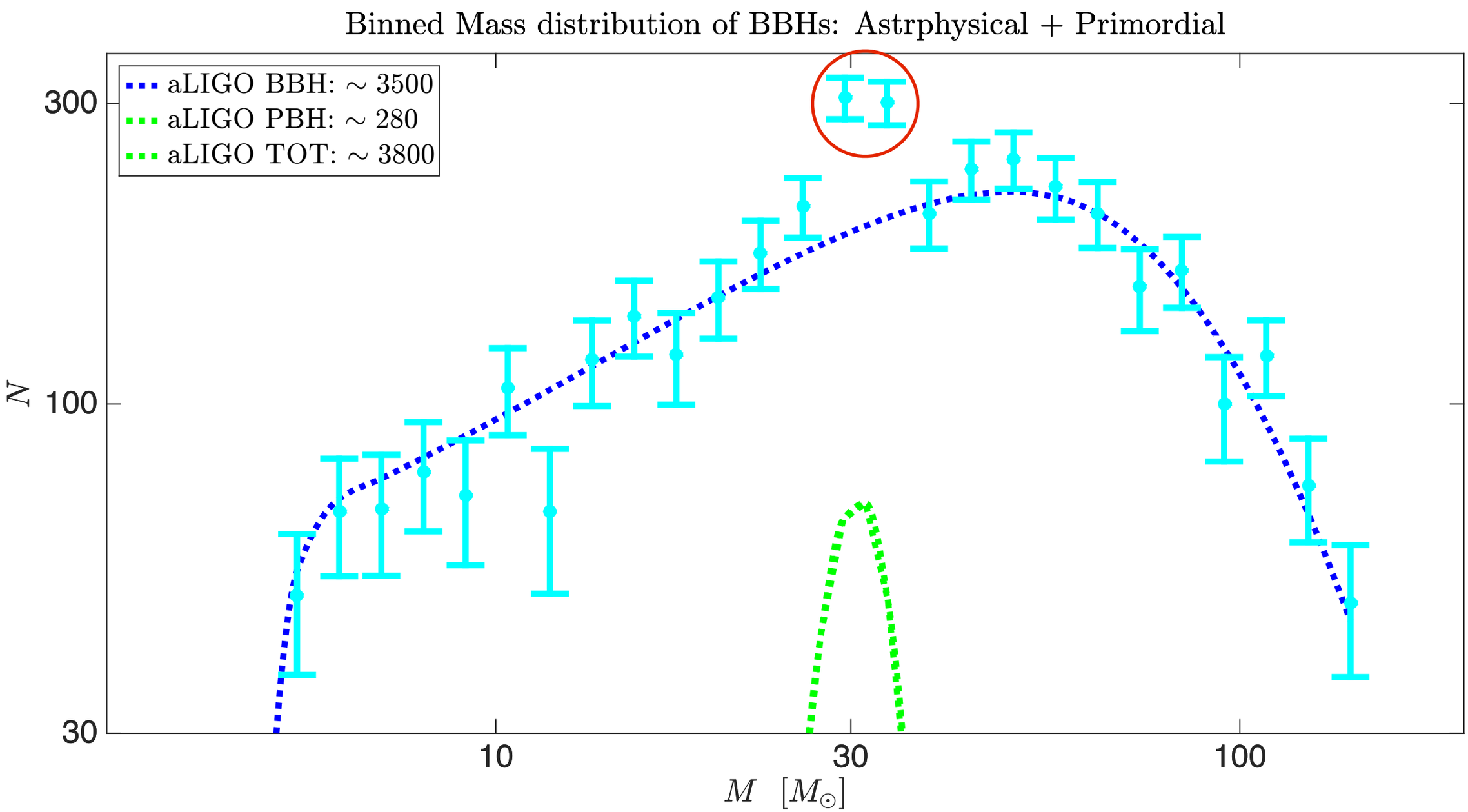


The Black-Hole Mass Function from GWs

(EDK, Cholis & Breysse, in preparation)

Observed mass spectrum with (5 years of advanced LIGO data):

Adding PBHs: $M_{\rm PBH} \sim \mathcal{N}(30 M_\odot, \sigma_M^2)$

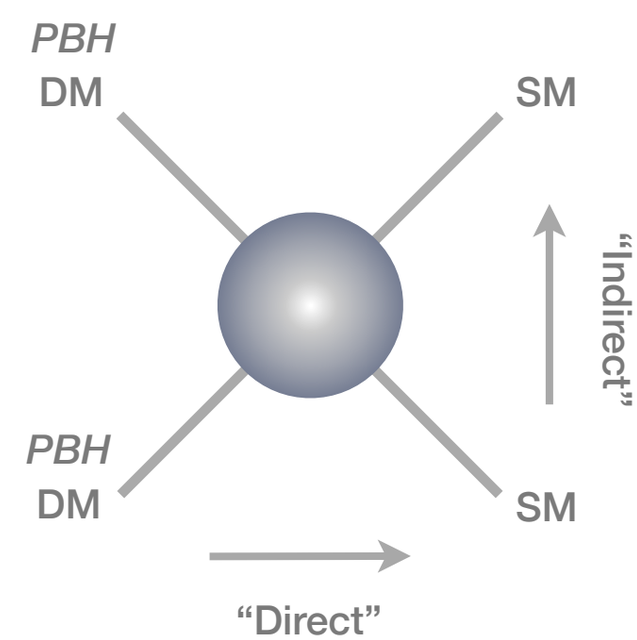


Outline

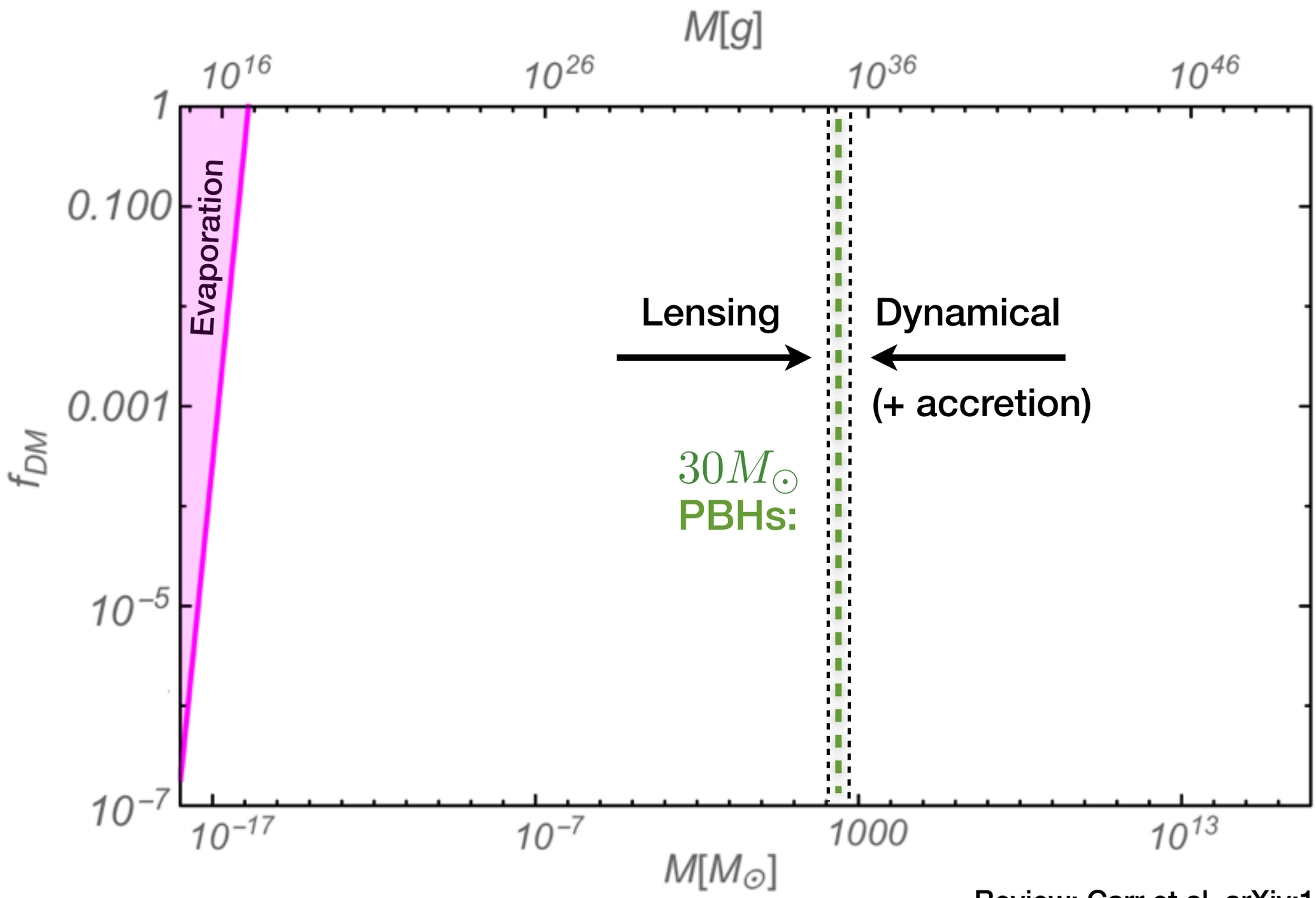
- Direct Detection: GWs from PBH mergers

- ndirect Detection: PBH DM Constraints

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

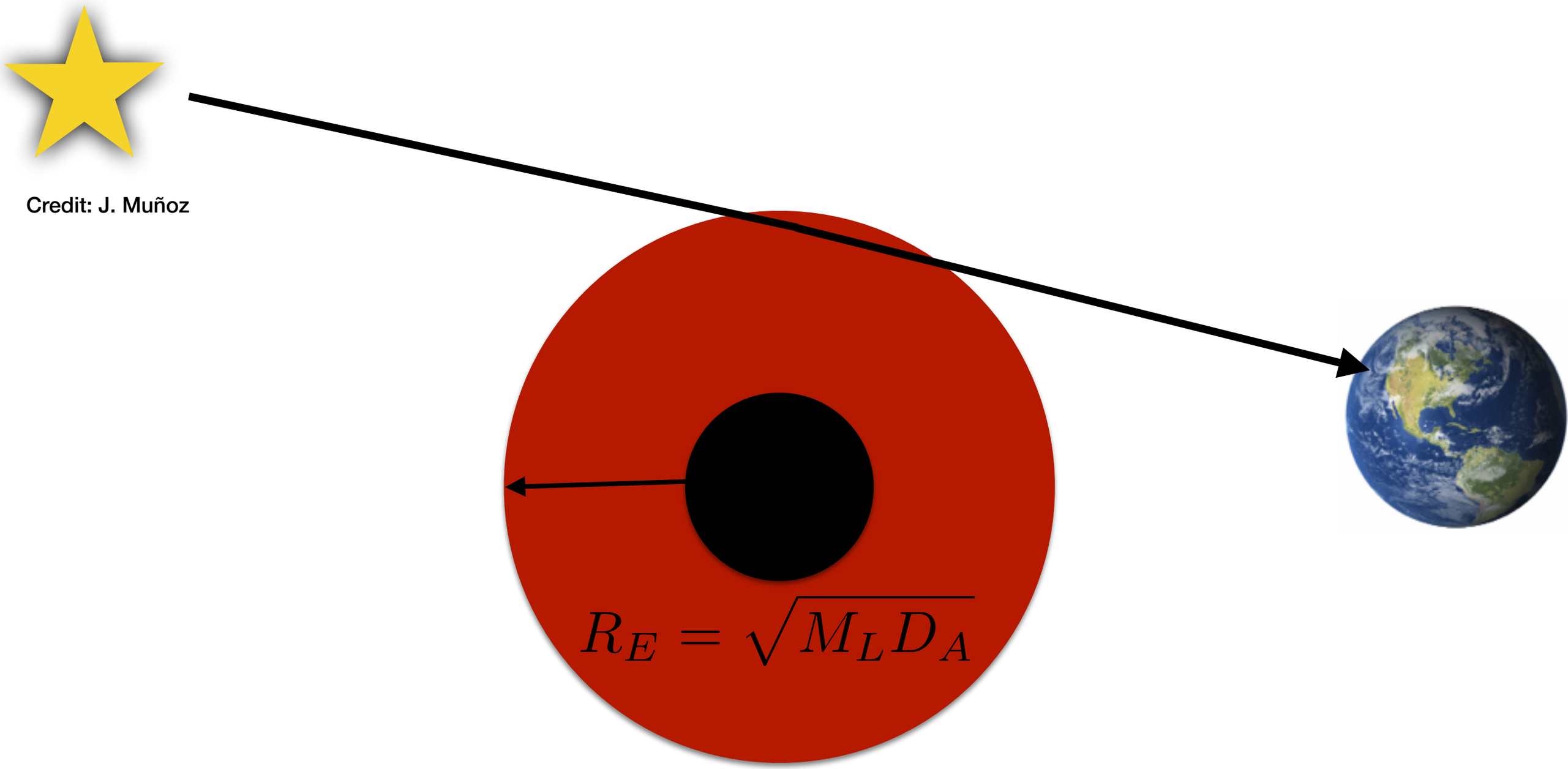


PBH DM: Indirect Detection Constraints



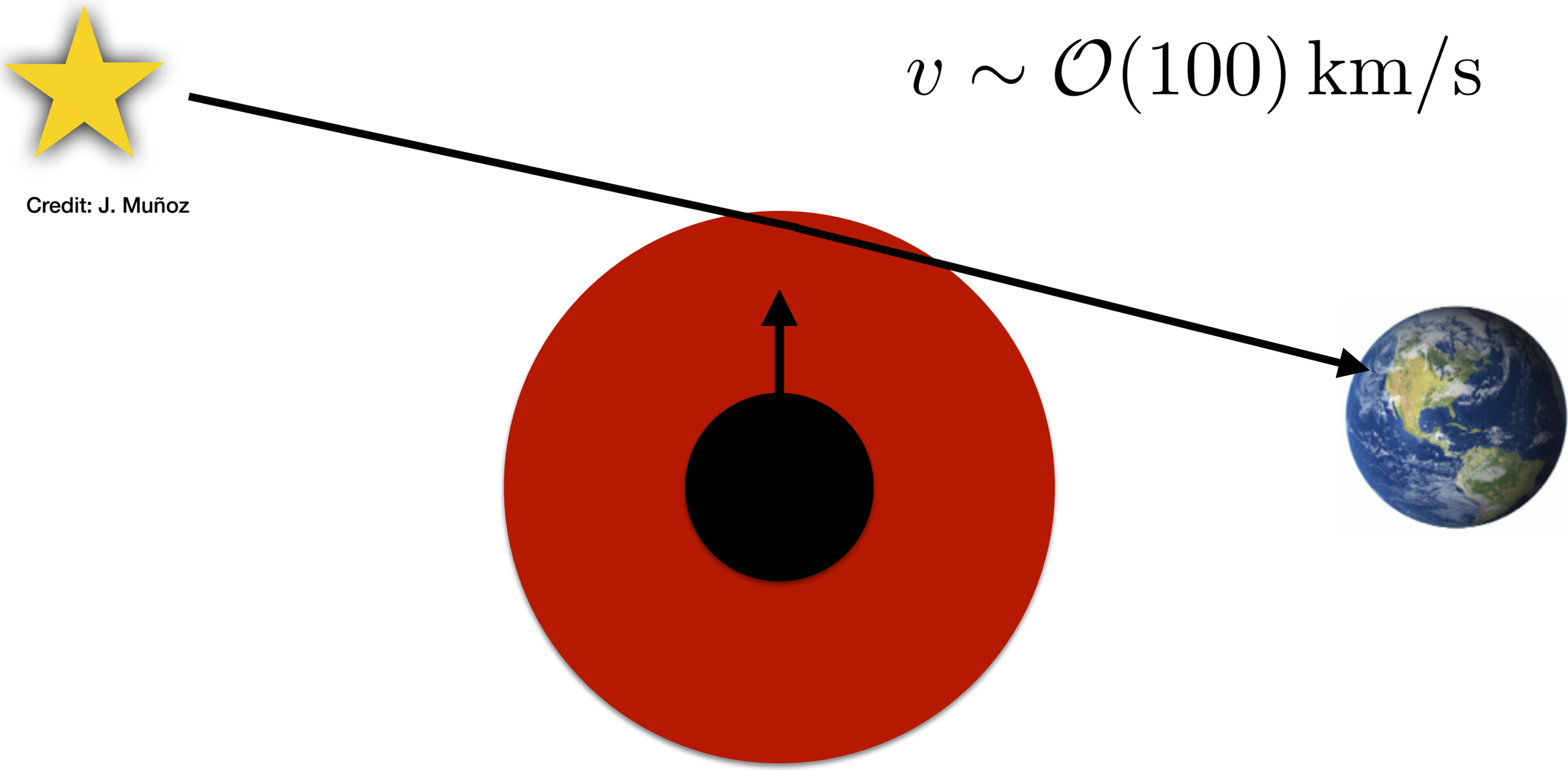
Review: Carr et al. arXiv:1607.06077

Microlensing: Illustration



Credit: J. Muñoz

Microlensing: Illustration

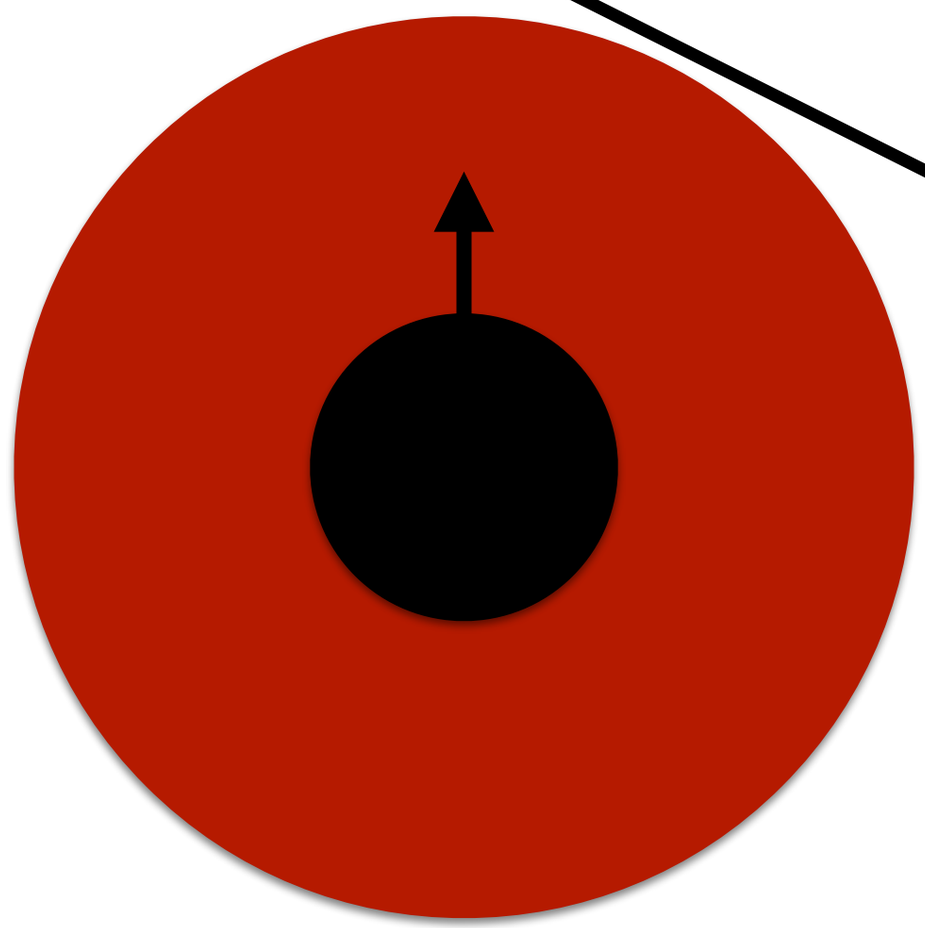


Credit: J. Muñoz

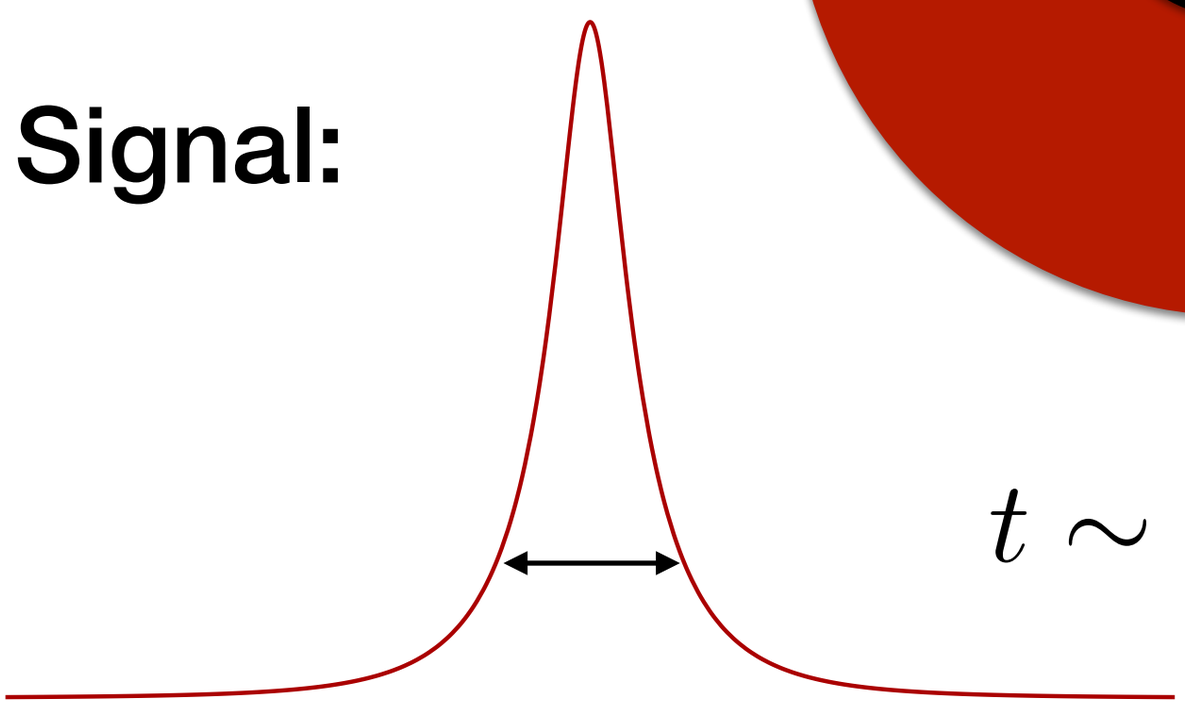
Microlensing: Illustration

Credit: J. Muñoz

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

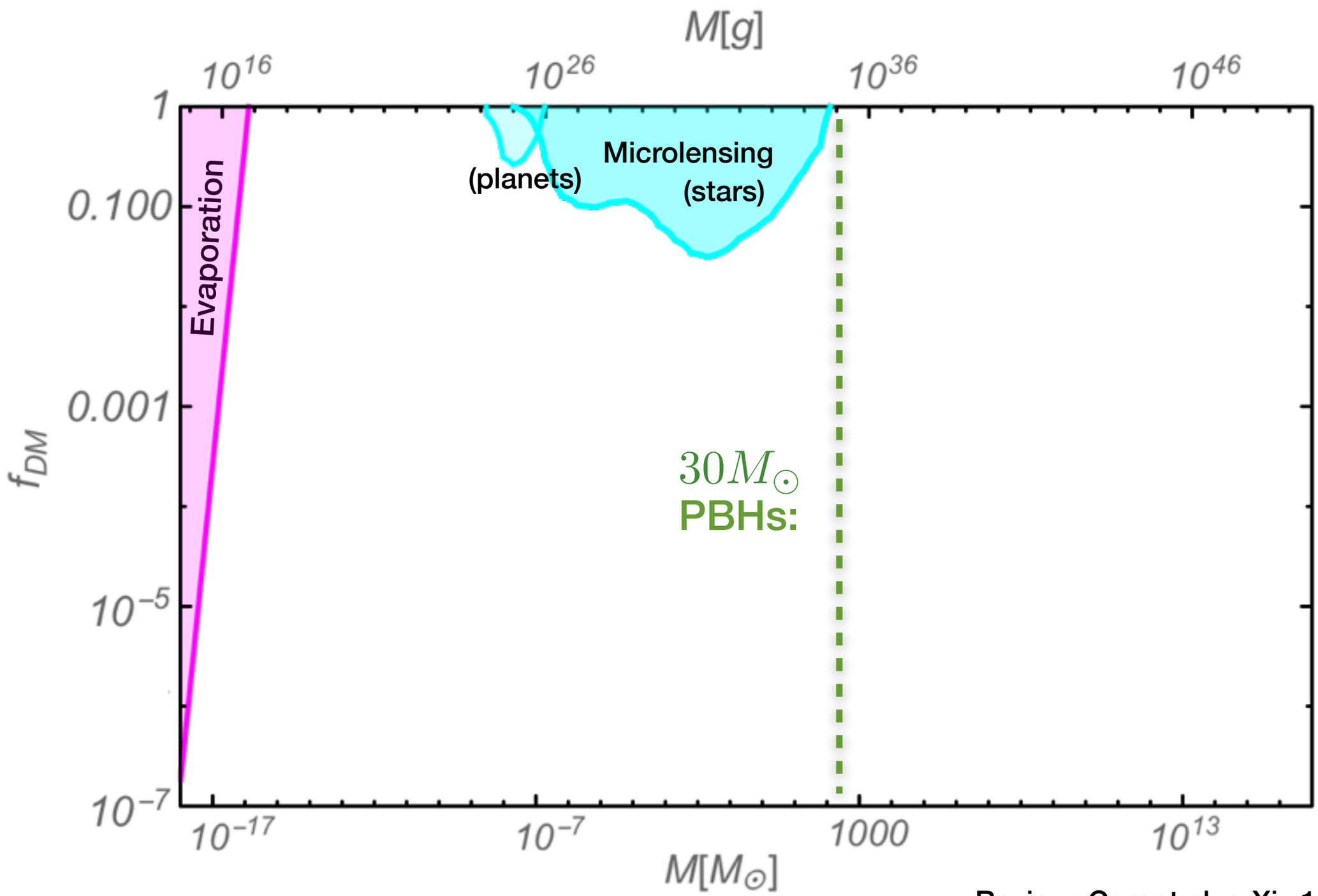


Signal:



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

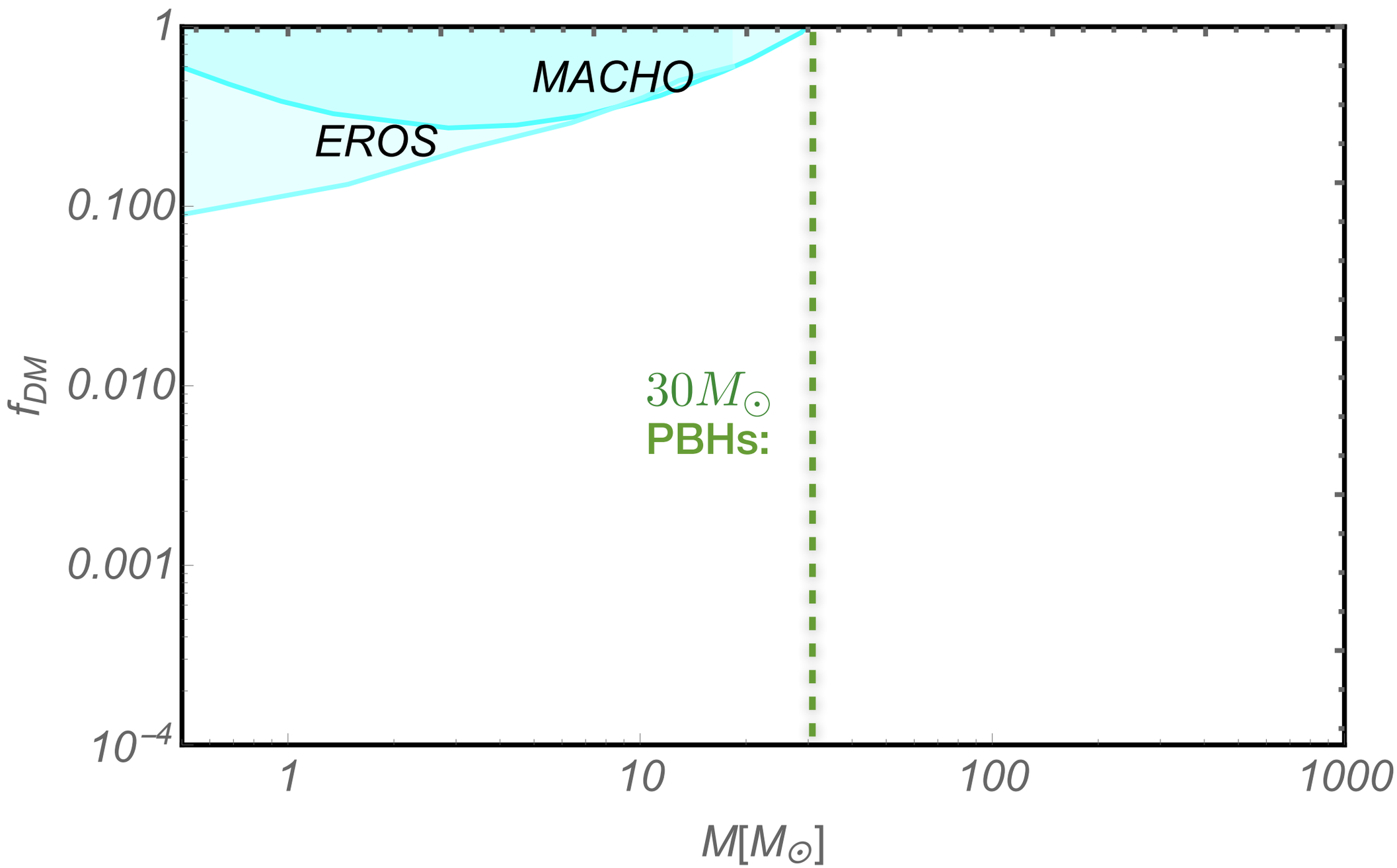
PBH DM: Indirect Detection Constraints



Review: Carr et al. arXiv:1607.06077

PBH DM: Constraining the LIGO Window

Zooming in:



Fast Radio Bursts

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

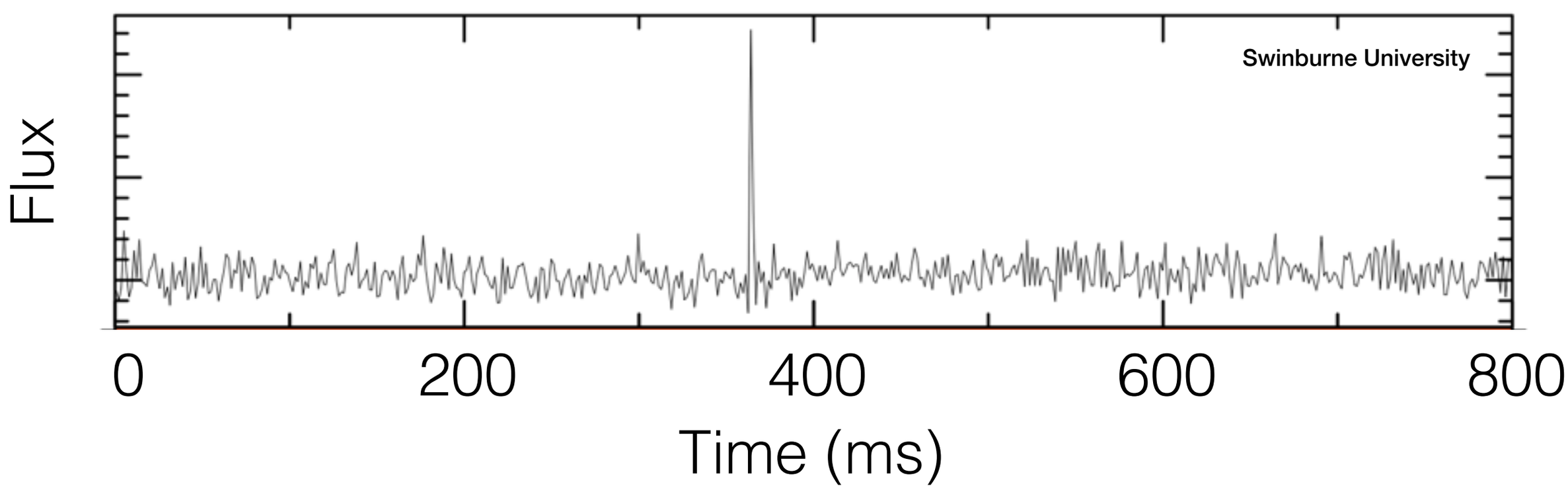
What are they?

- Literally:

Fast	Radio	Bursts
$\mathcal{O}(1)\,\mathrm{ms}$	$\sim 1\,\mathrm{GHz}$	$\mathcal{O}(1)\,\mathrm{Jy}$

$\mathcal{O}(1)\,\mathrm{Jy} \xrightarrow{@\,1\,\mathrm{Gpc}} \mathcal{O}(10^{39})\,\mathrm{ergs}$

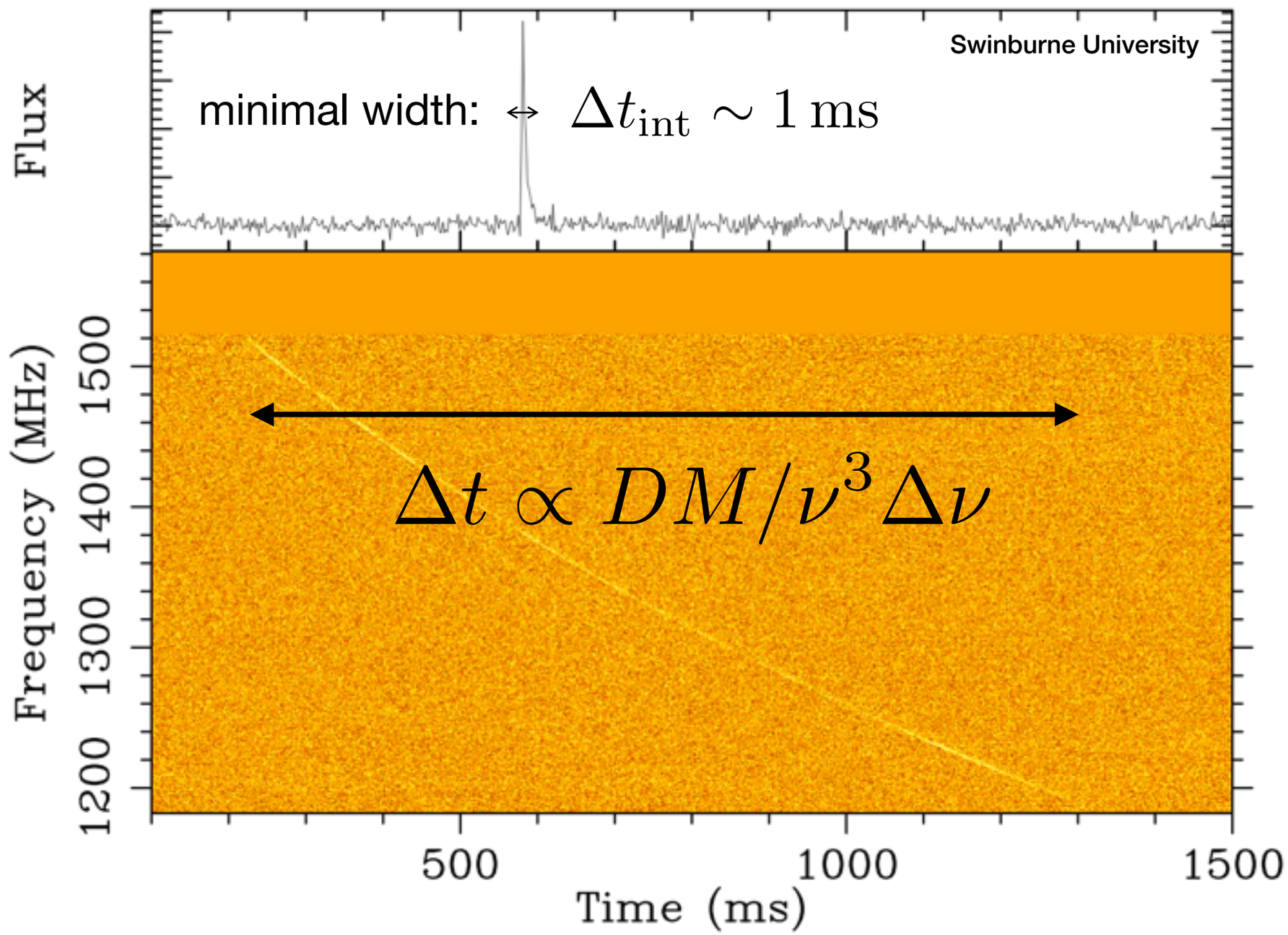
- Distance: cosmological?
- Estimated rate: $\mathcal{O}(10^4)\ \mathrm{sky}^{-1}\mathrm{day}^{-1}$ (based on handful observed)



Fast Radio Bursts: Cosmological?

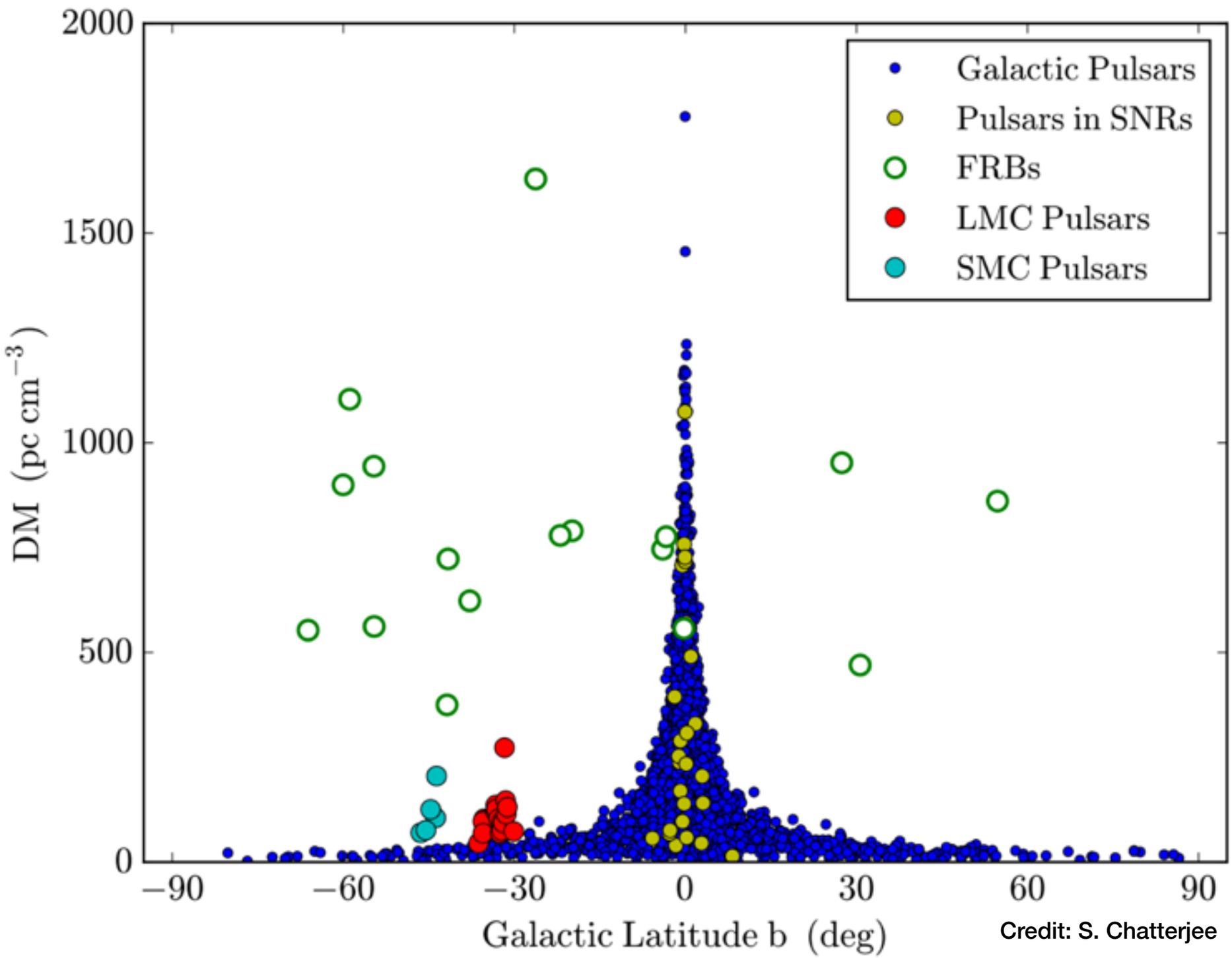
(Muñoz, EDK, Dai, Kamionkowski, PRL 117 (2016))

The Dispersion Measure: $$DM = \int_0^L dl\, n_e(l) \quad [\mathrm{cm}^{-3}\,\mathrm{pc}]$$



Fast Radio Bursts: Cosmological!

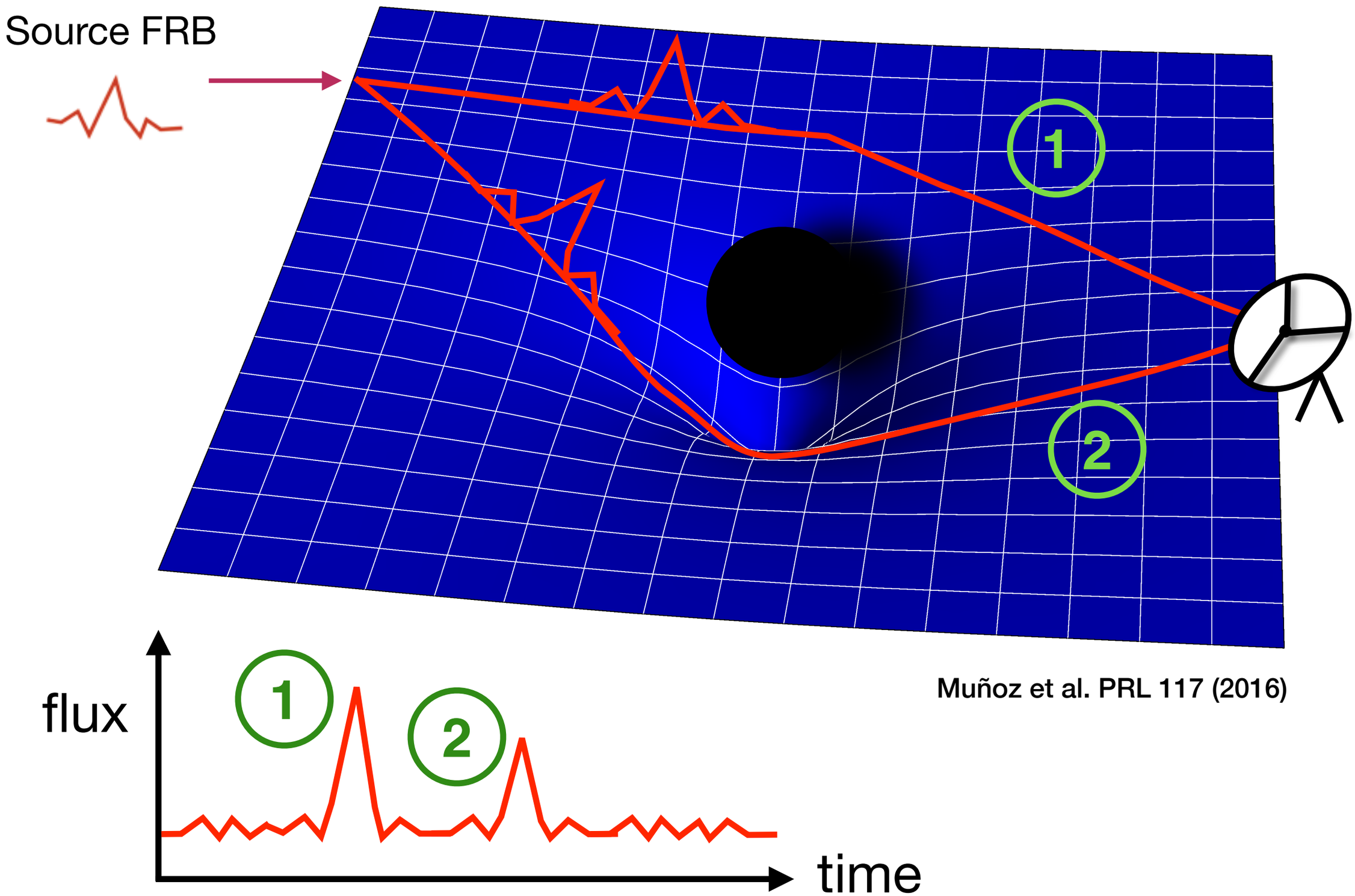
(Muñoz, EDK, Dai, Kamionkowski, PRL 117 (2016))



Credit: S. Chatterjee

Constraining MACHO Dark Matter: FRB Lensing

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

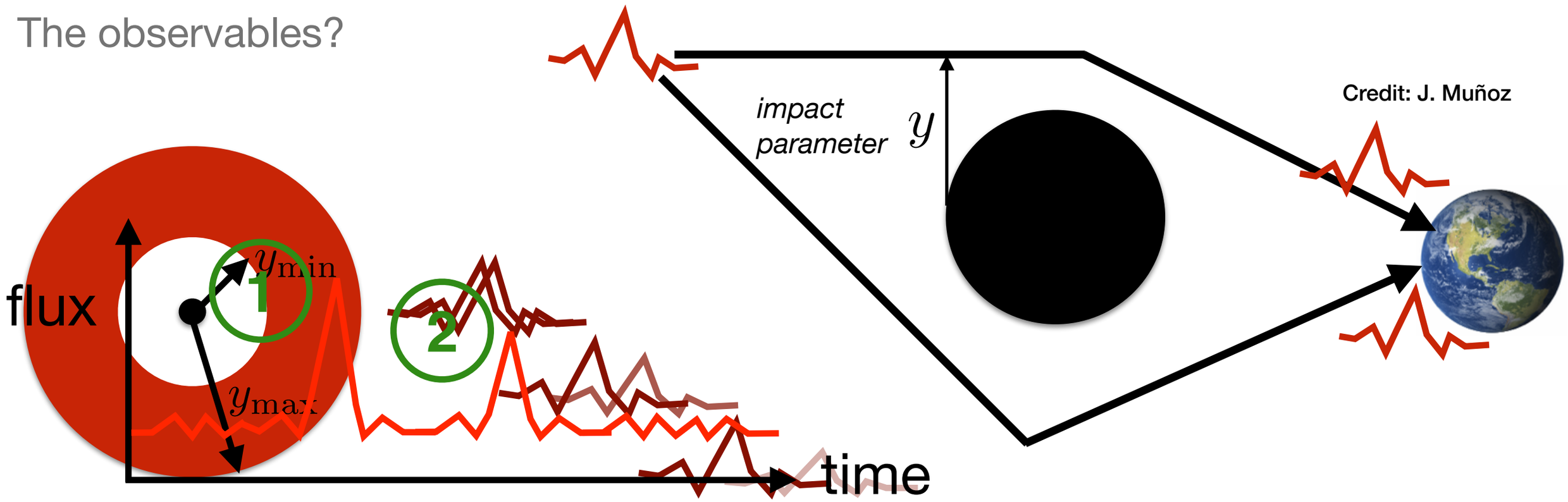


Muñoz et al. PRL 117 (2016)

Constraining MACHO Dark Matter: FRB Lensing

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

The observables?



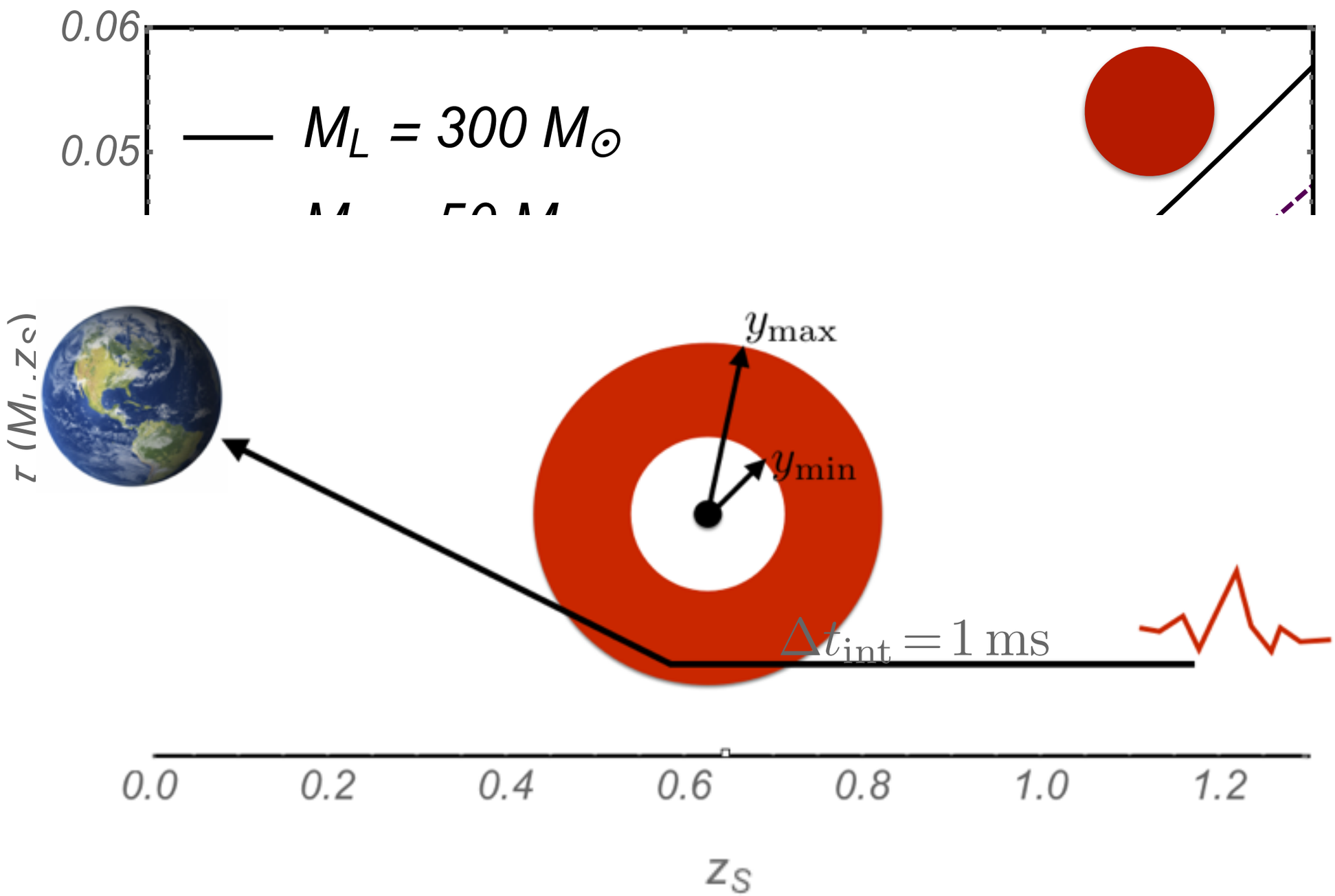
Flux ratio $\dfrac{F_1}{F_2} = g(y)$ $\longrightarrow$ $y < y_{\rm max}$ (both images need be detectable)

Time delay $\boldsymbol{\Delta t} = 4 M_L f(y) \sim 1\,\mathrm{ms} \times \dfrac{\mathrm{M_L}}{30\,\mathrm{M}_\odot}$ $\xrightarrow{> \Delta t_{\rm int}}$ $y > y_{\rm min}(M_L, z_s)$

Strong Lensing of FRBs: Optical depth

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

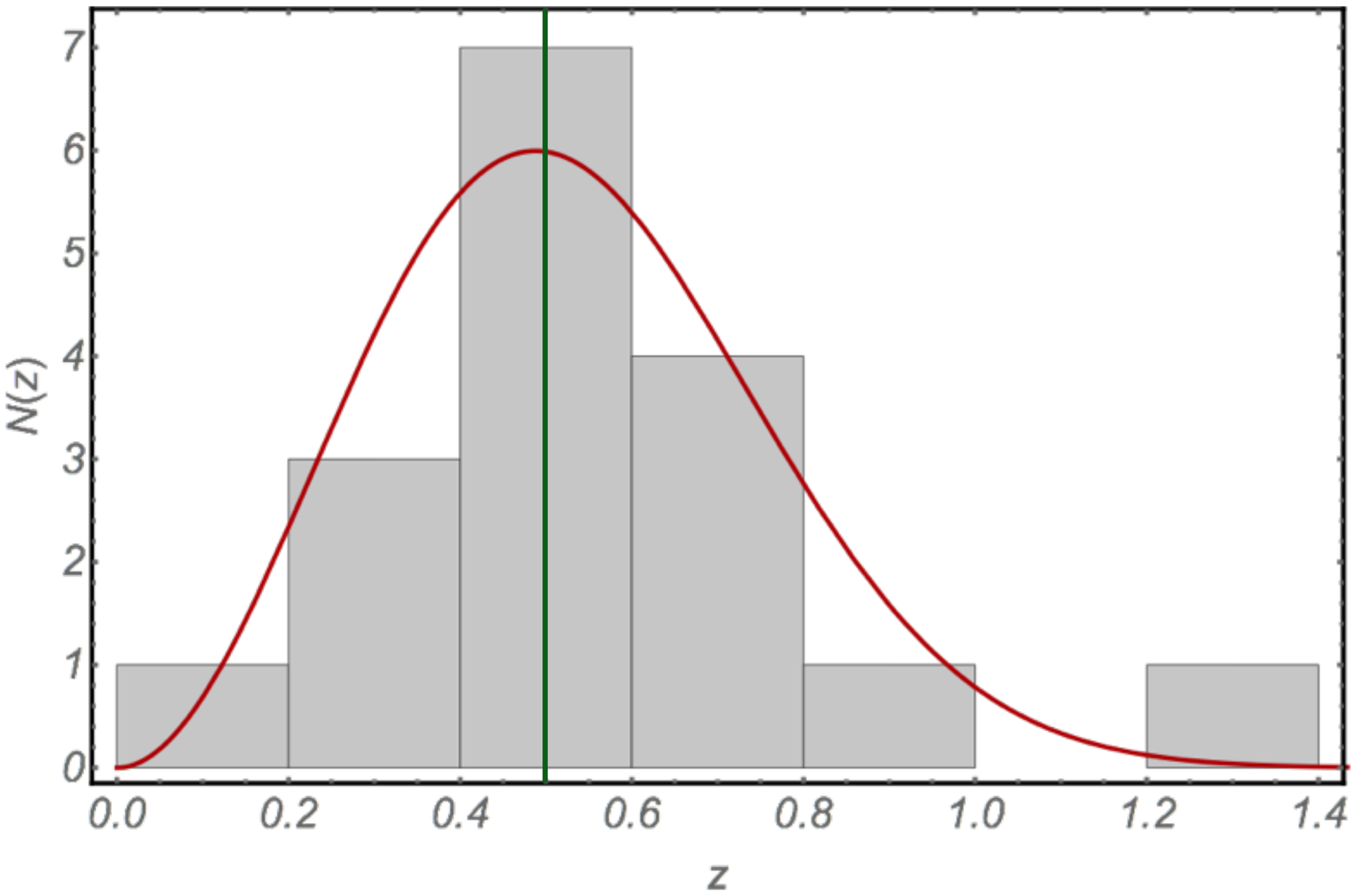
Optical depth: $\tau(M_L, z_S) = \frac{3}{2} f_{\rm DM} \Omega_c \int_0^{z_S} dz_L \frac{H_0^2}{c\,H(z_L)} \frac{D_L D_{LS}}{D_S} \times (1+z_L)^2 \left[y_{\rm max}^2 - y_{\rm min}^2(M_L, z_L)\right]$



Strong Lensing of FRBs: Redshift Distribution

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

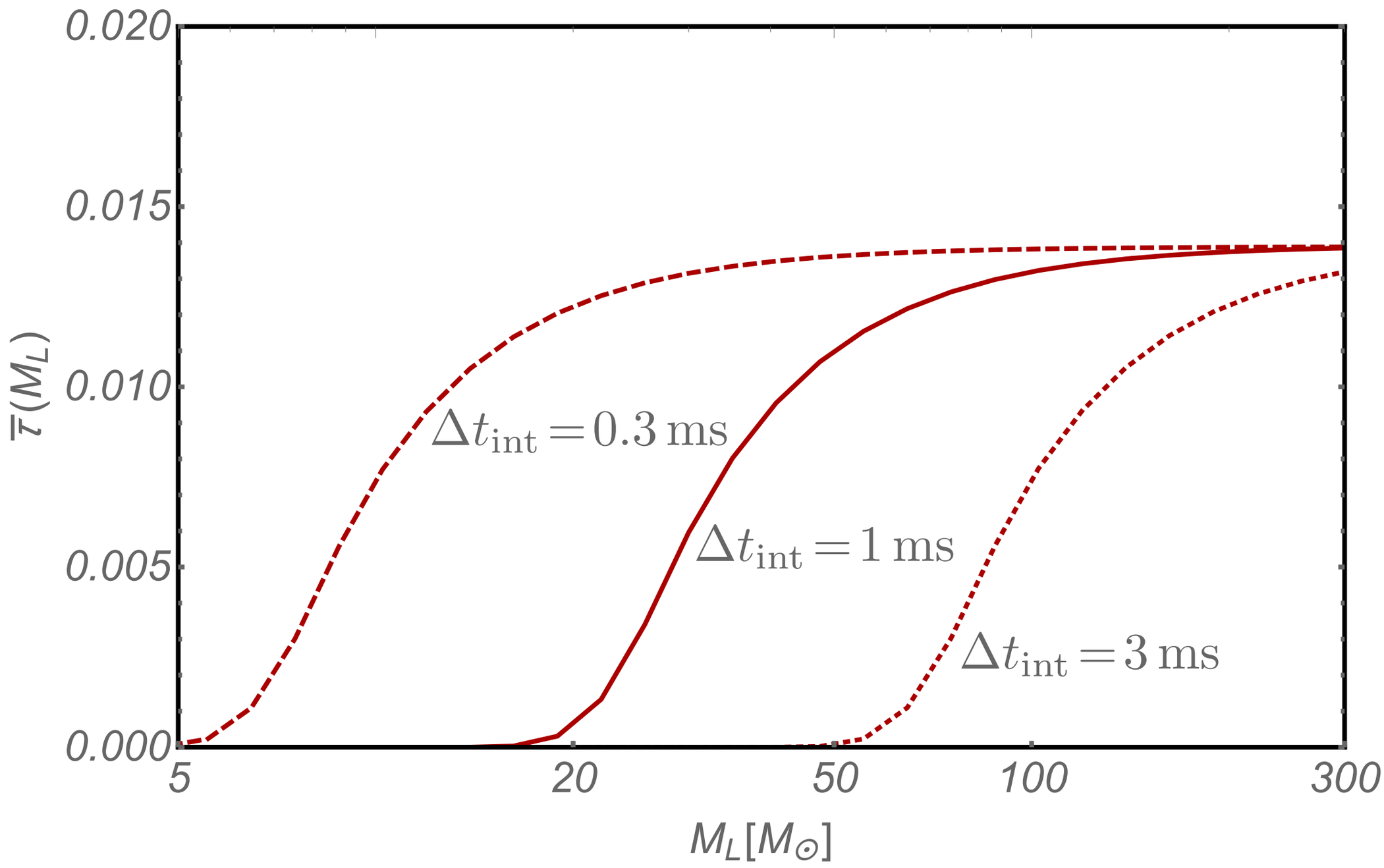
Convolve the optical depth with an FRB redshift distribution:



Strong Lensing of FRBs

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

Integrated optical depth: $\bar{\tau}(M_L)$



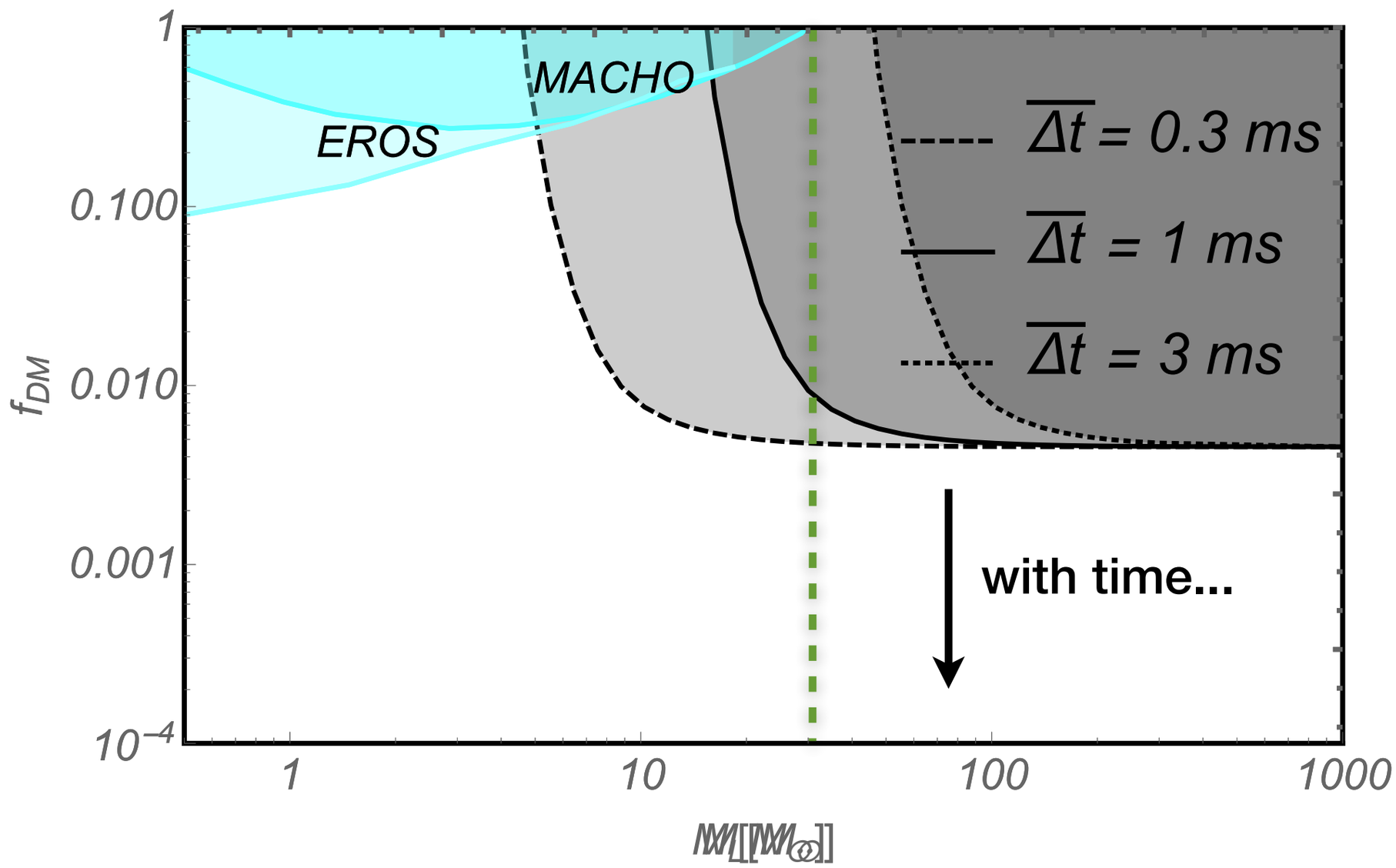
Strong Lensing of FRBs

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

CHIME experiment: expected rate of $\mathcal{O}(10^4)$ FRBs per year

$$N_{\rm lensed} = \bar{\tau} N_{\rm FRB} \longrightarrow N_{\rm lensed} = 10 - 100 \ {\rm yr}^{-1}$$

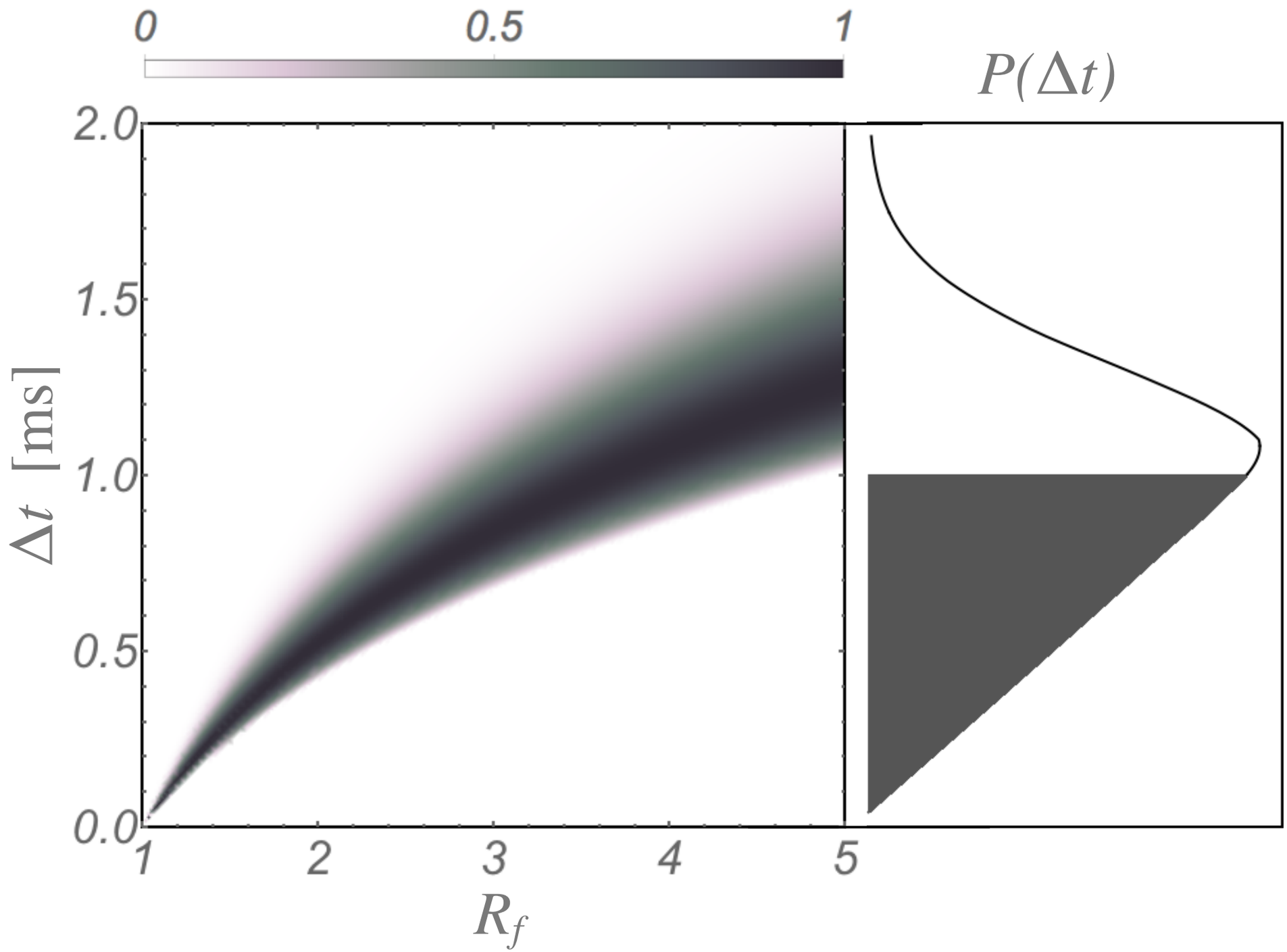
A null detection will close the "window":



Strong Lensing of FRBs: Unique Feature

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

Joint PDF of time delay and flux ratio indicates correlation:



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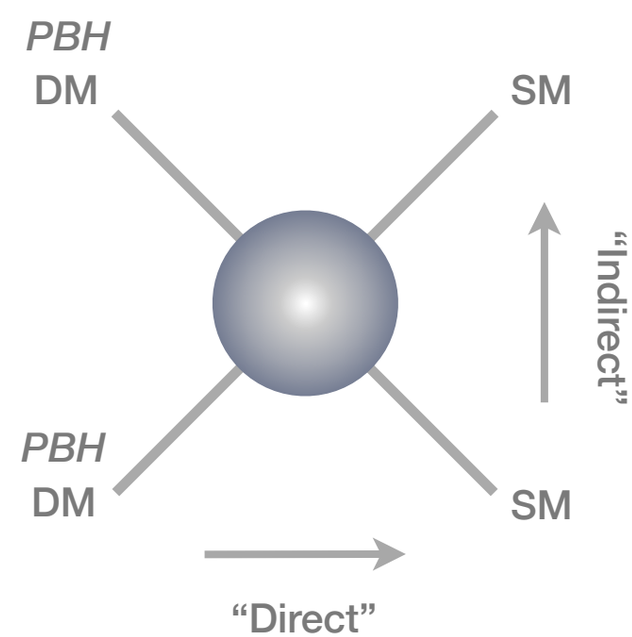
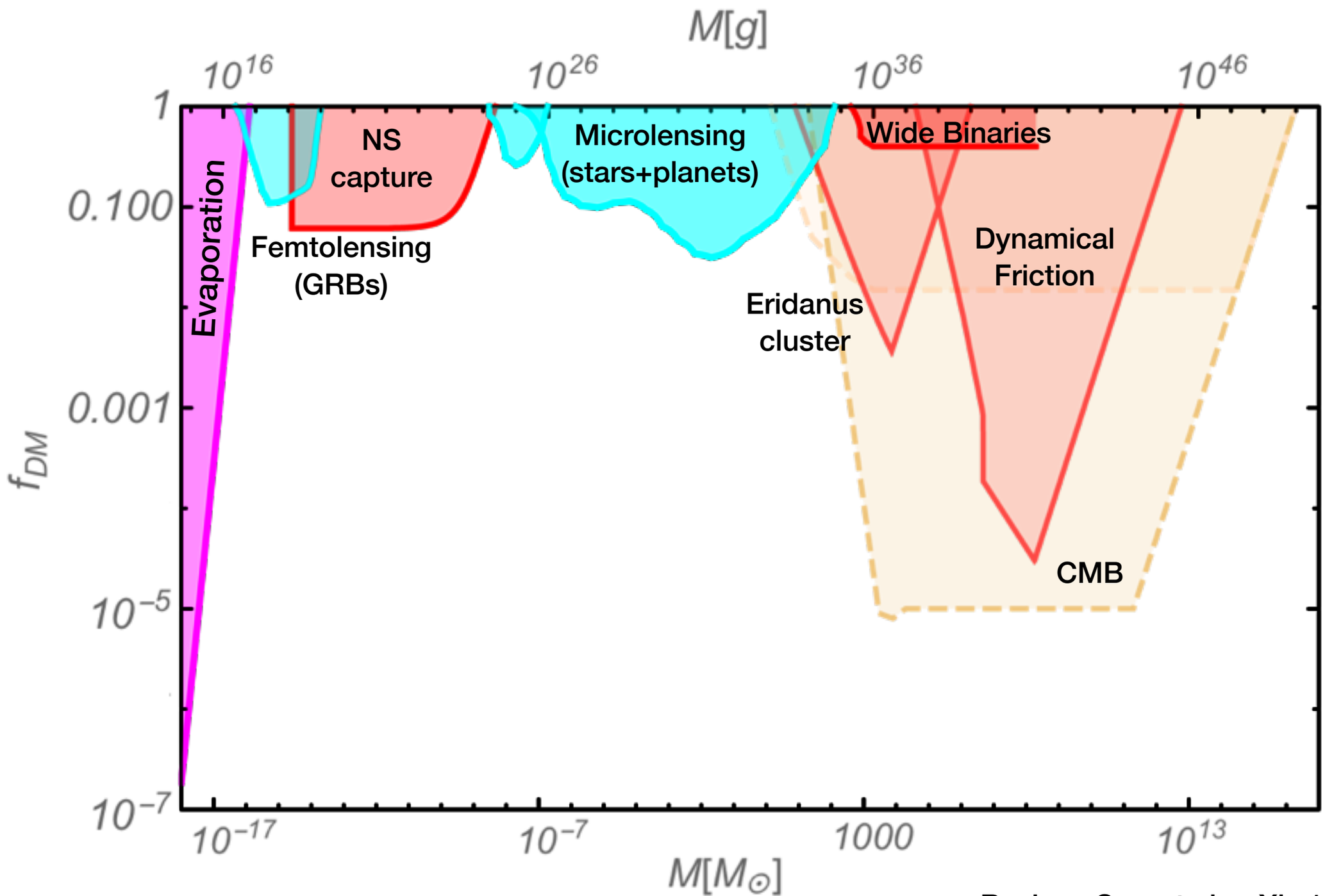
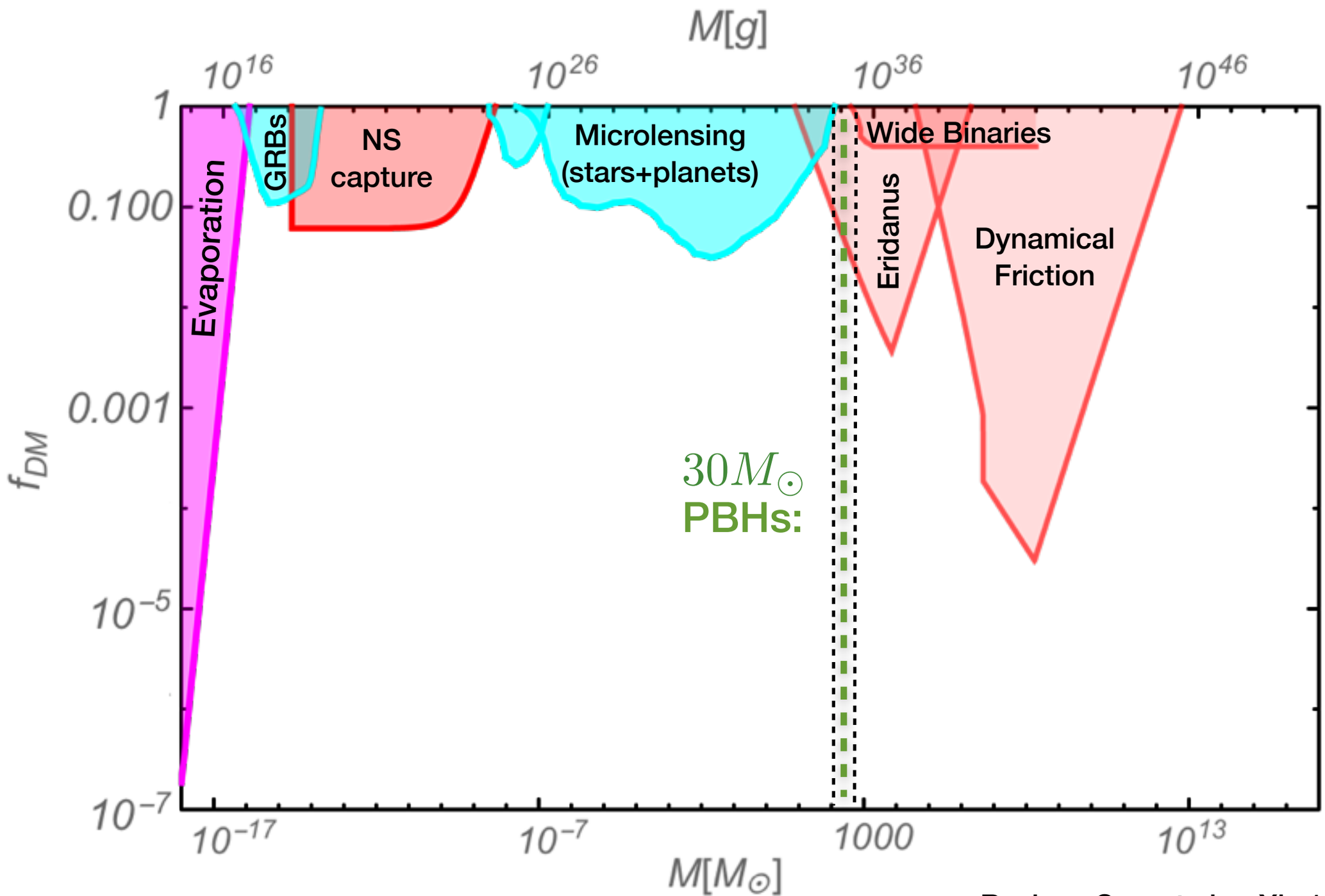


PBH DM: More Indirect Detection Constraints



Review: Carr et al. arXiv:1607.06077

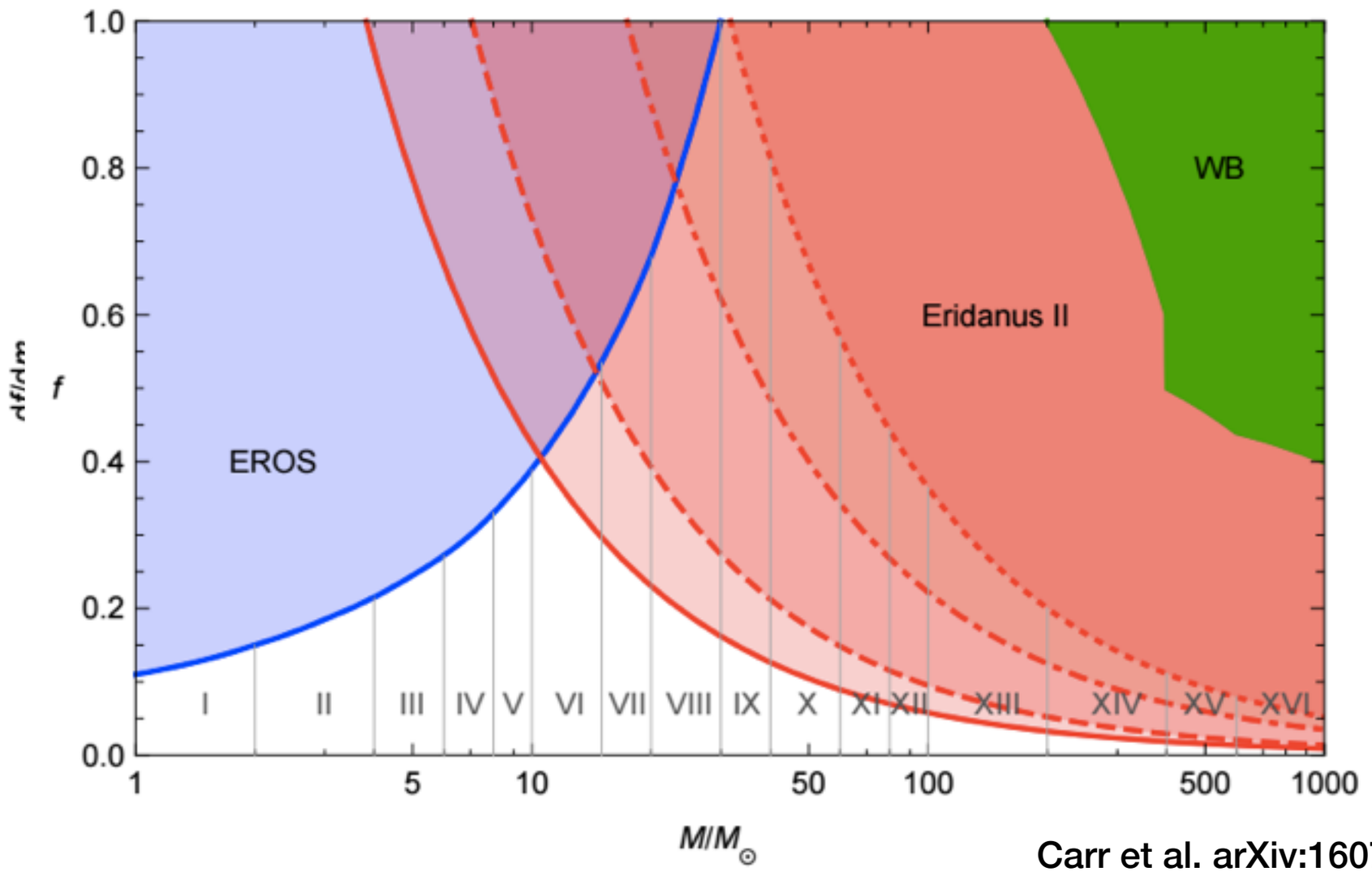
PBH DM: Is the LIGO Window Alive?



Review: Carr et al. arXiv:1607.06077

PBH DM LIGO Window: All Hope Not Lost

Constraints may be evaded if the PBHs have an extended mass function:



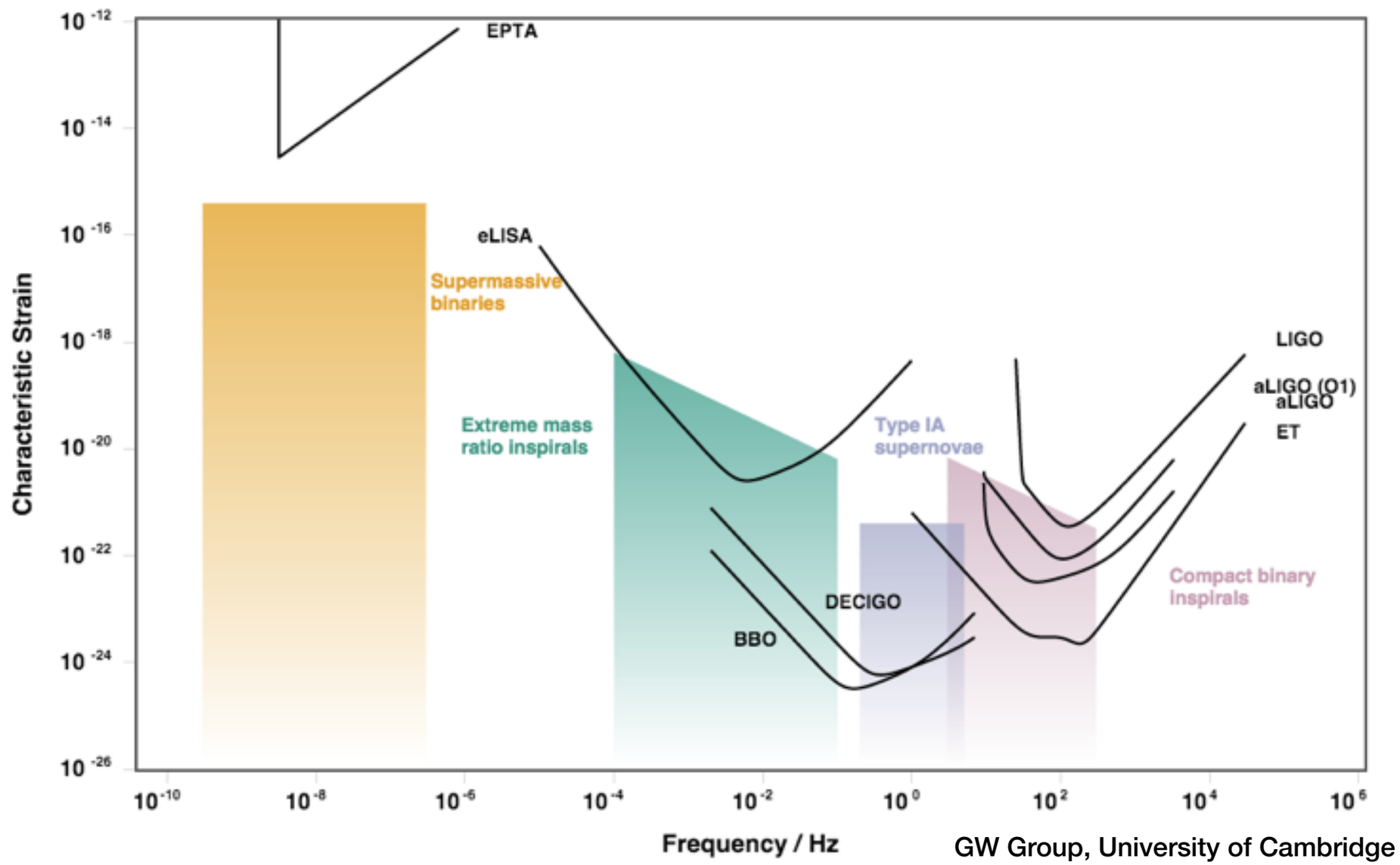
Carr et al. arXiv:1607.06077

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

Green arXiv:1609.01143

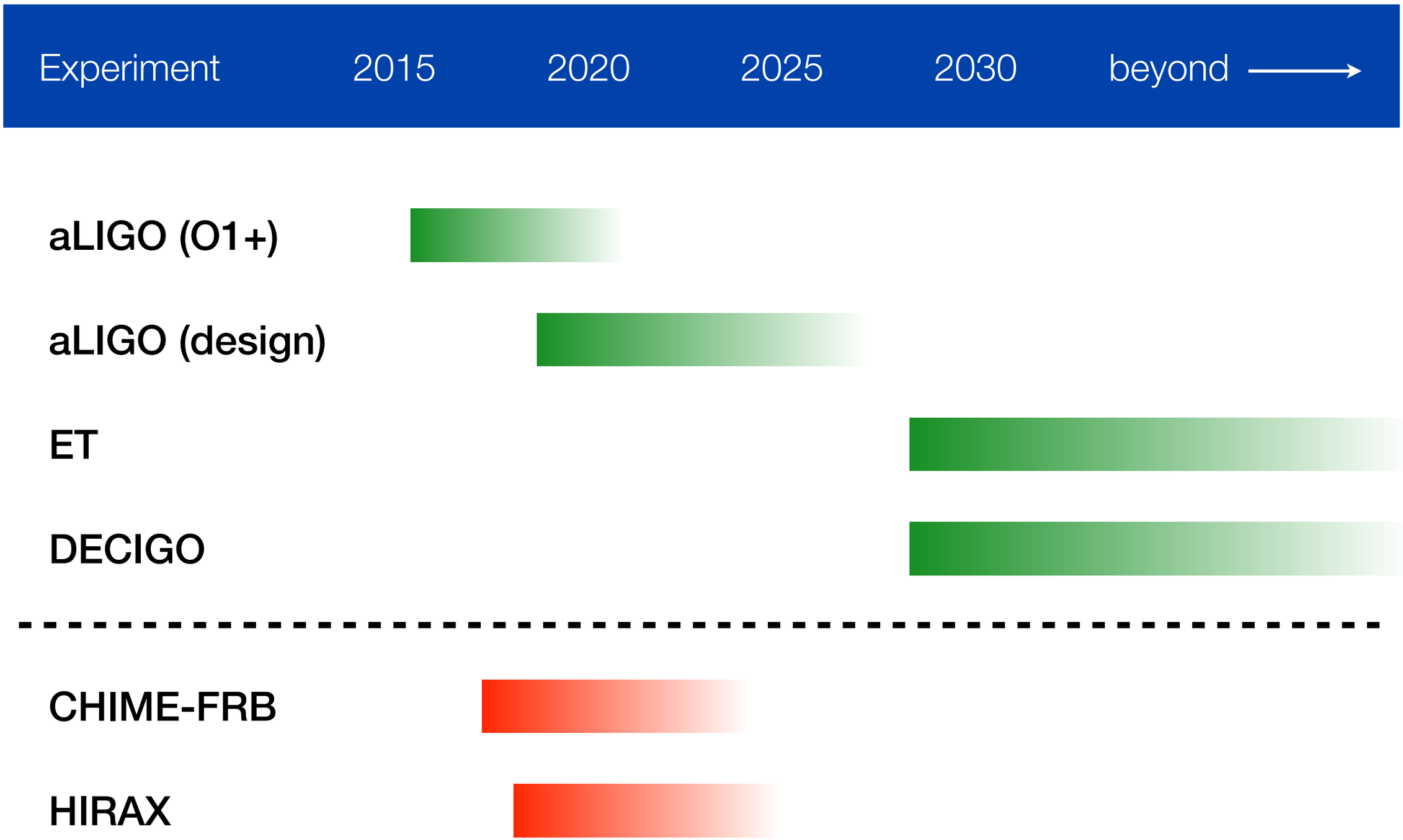
PBH DM LIGO Window: Observational Outlook

Gravitational waves:

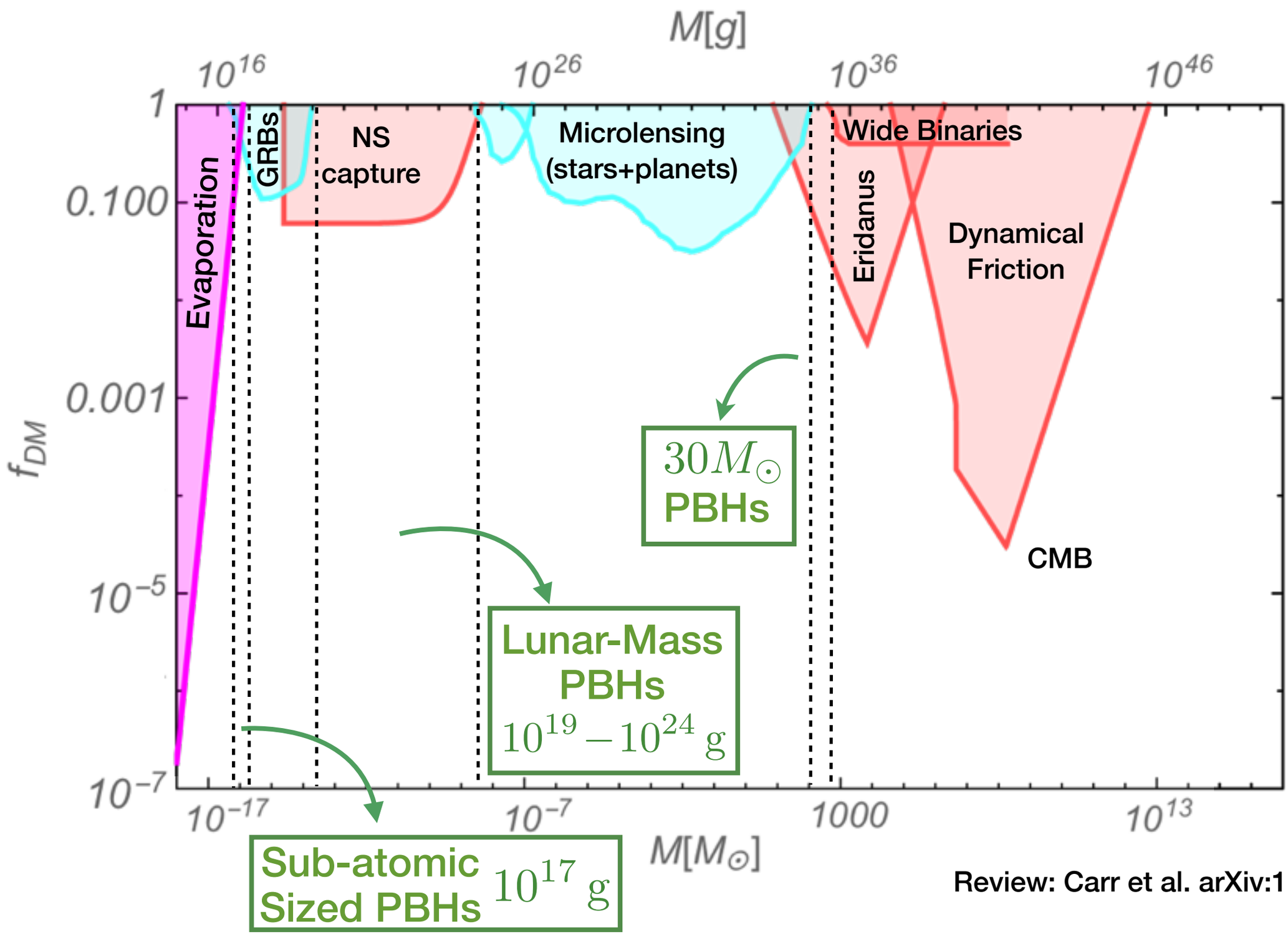


Fast Radio Bursts: Lots of instruments, including CHIME, HIRAX...

PBH DM LIGO Window: Experiment Timeline



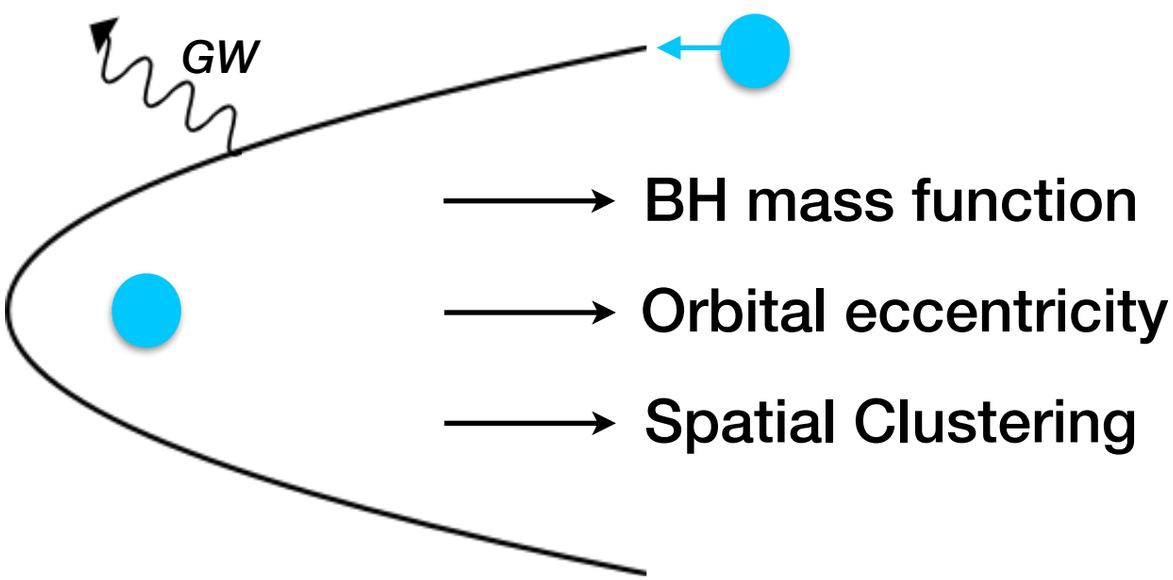
PBH DM: Other Allowed Windows?

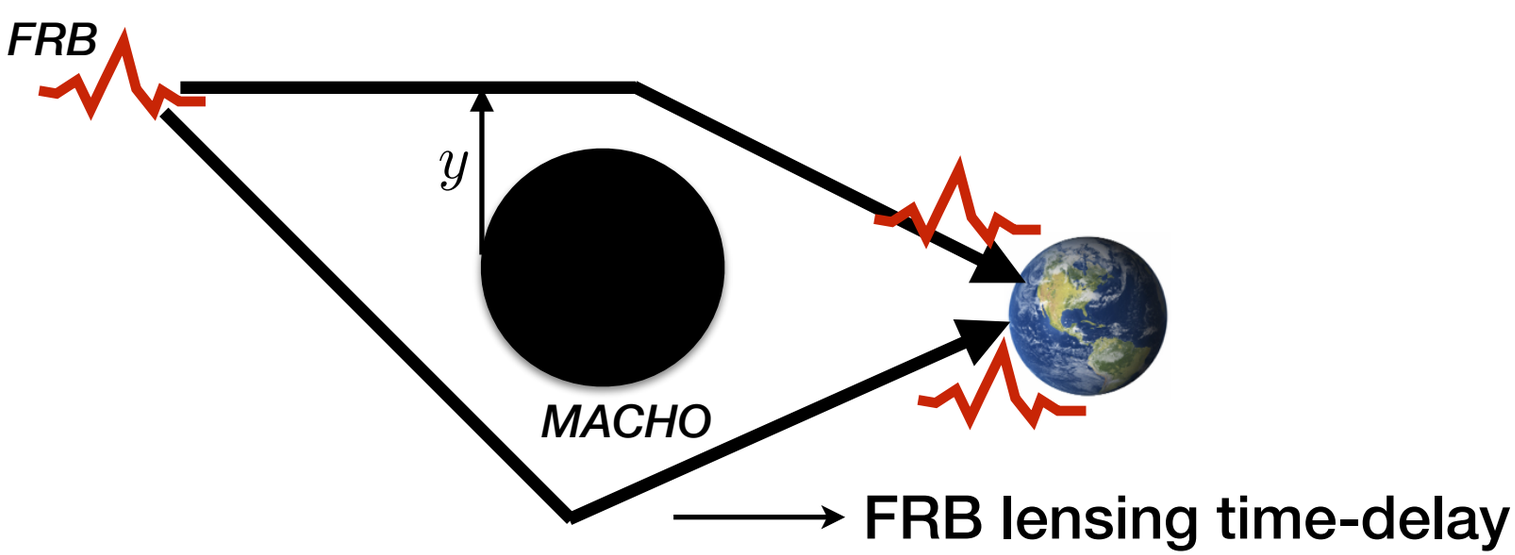


Review: Carr et al. arXiv:1607.06077

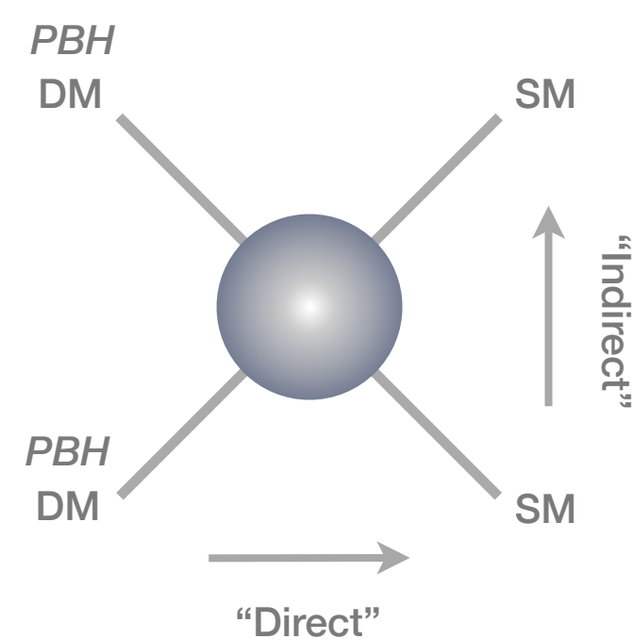
Conclusion: PBH DM is a Testable Scenario!

Theory rich with ideas





Experiments underway....



Thank you!

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Johns Hopkins University

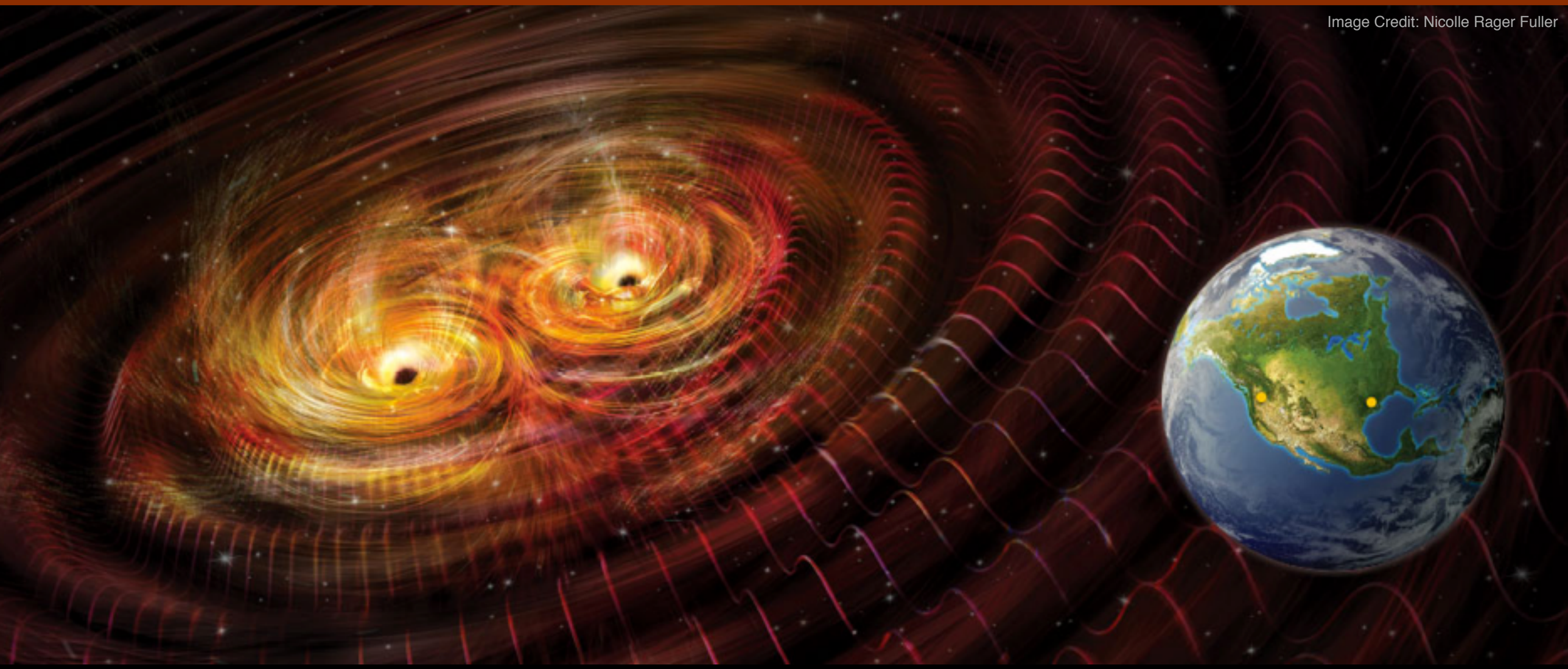

Image Credit: Nicolle Rager Fuller