Image: LIGO collaboration

Probing dark matter with radio surveys

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Ely Kovetz
Alvise Raccanelli
Adam Riess

Two different dark-matter candidates

A compact stellar-sized object

A new particle with interactions

Two different dark-matter candidates

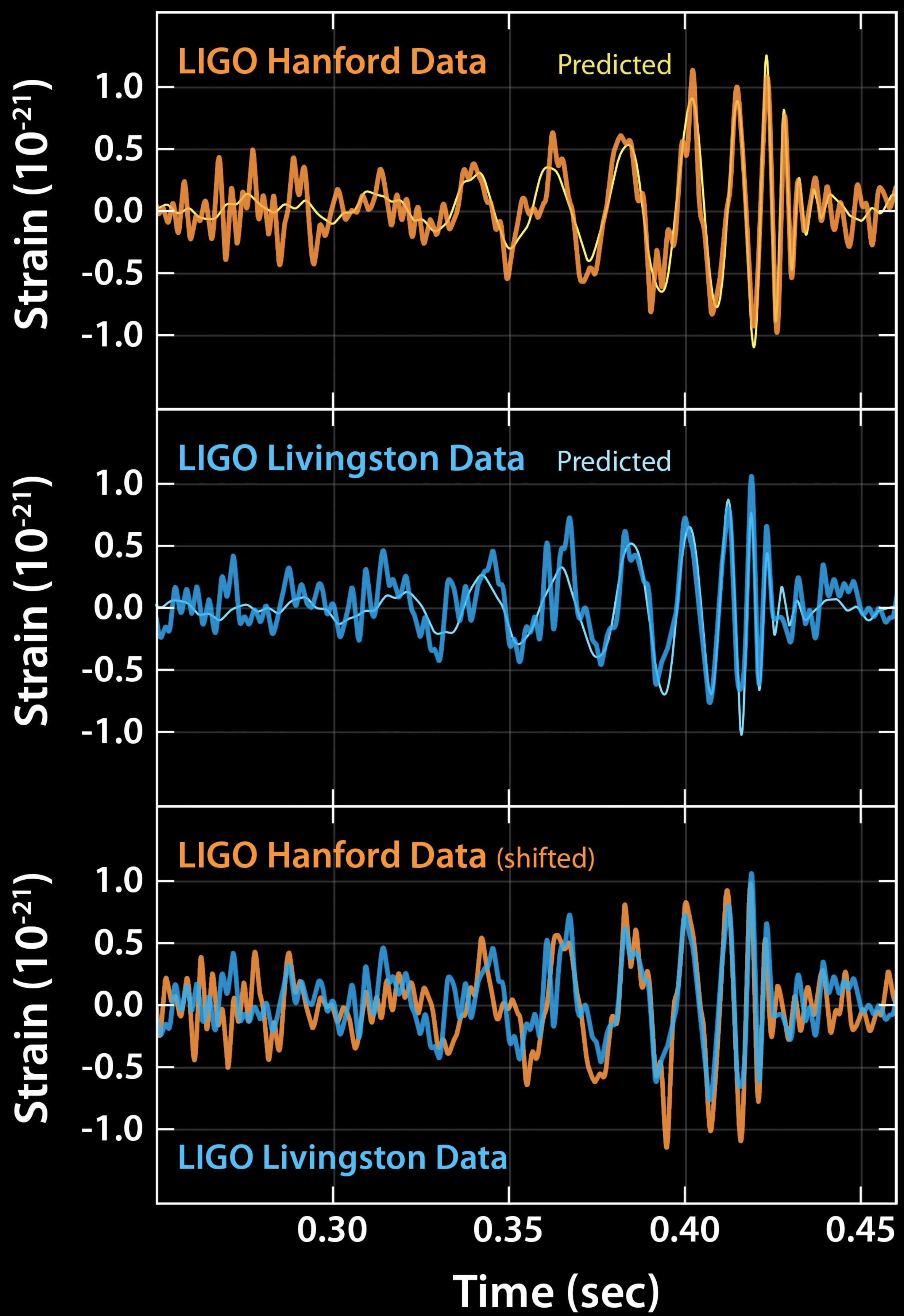
A compact stellar-sized object

→ FRBs

A new particle with interactions

→ 21-cm

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



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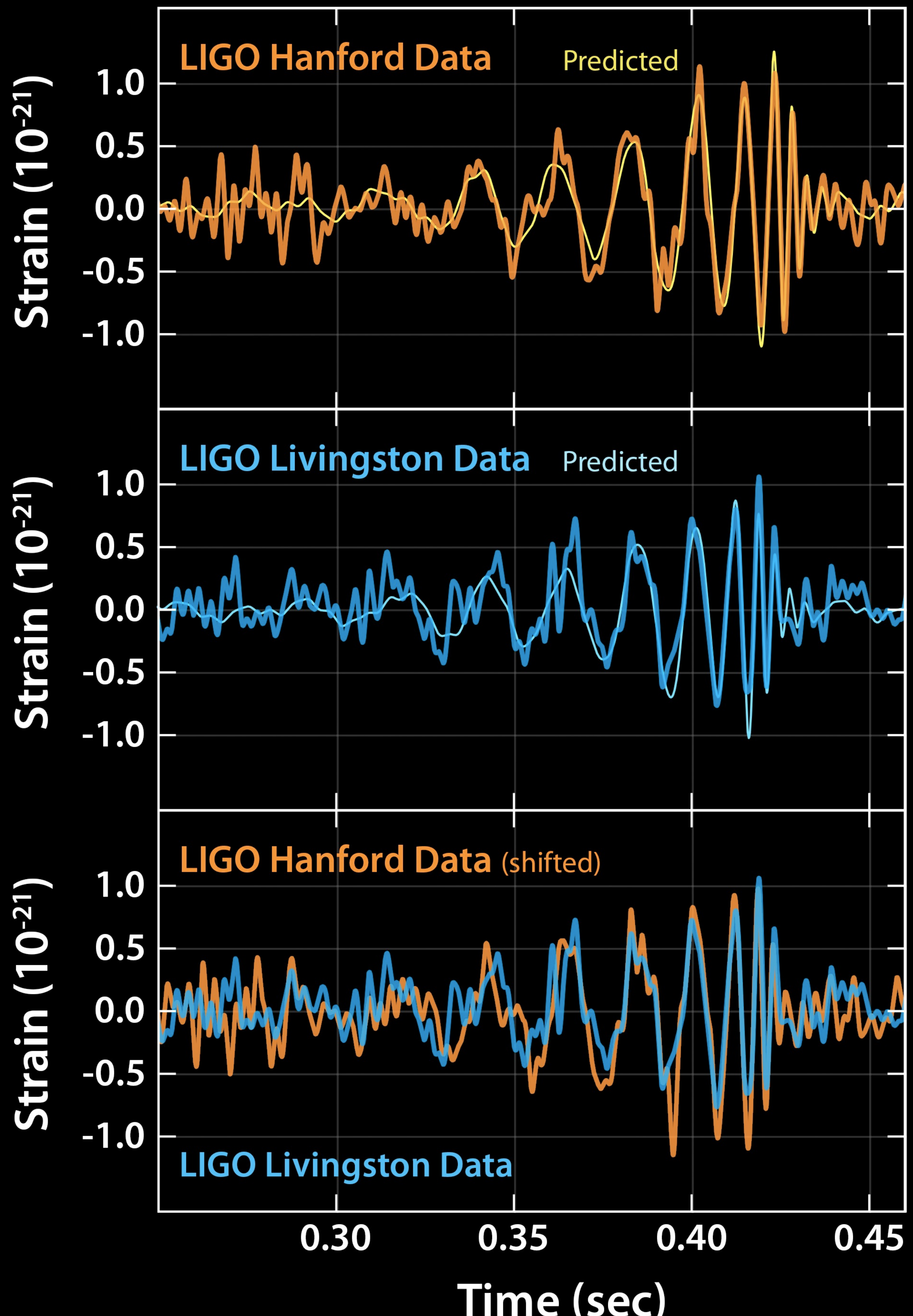

$$\mathcal{R} = 0.6 - 12\ \mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$$

$$M_{\mathrm{bh}} = 29 - 36 M_{\odot}$$

Primordial Black Holes

They form (?) from overdensities at time

$$M_{\rm pbh} \sim 100\, M_\odot \times \frac{t}{1\,{\rm ms}}$$

No new particles required!

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

Primordial Black Holes

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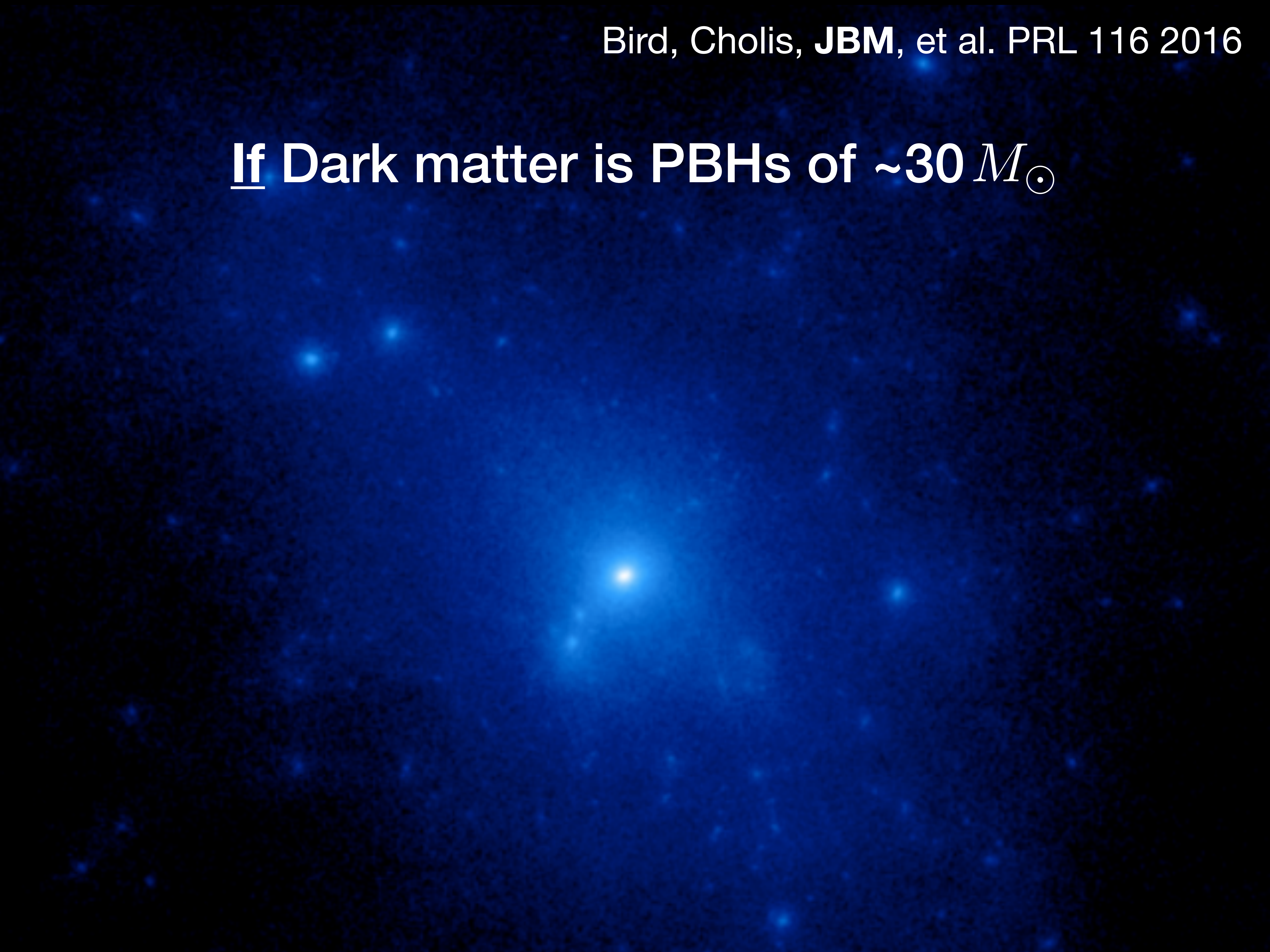
No new particles required!

What causes the overdensities?

Fine tuning problem $$\frac{\rho_{\rm pbh}}{\rho_{\rm rad}} \sim 10^{-8}$$

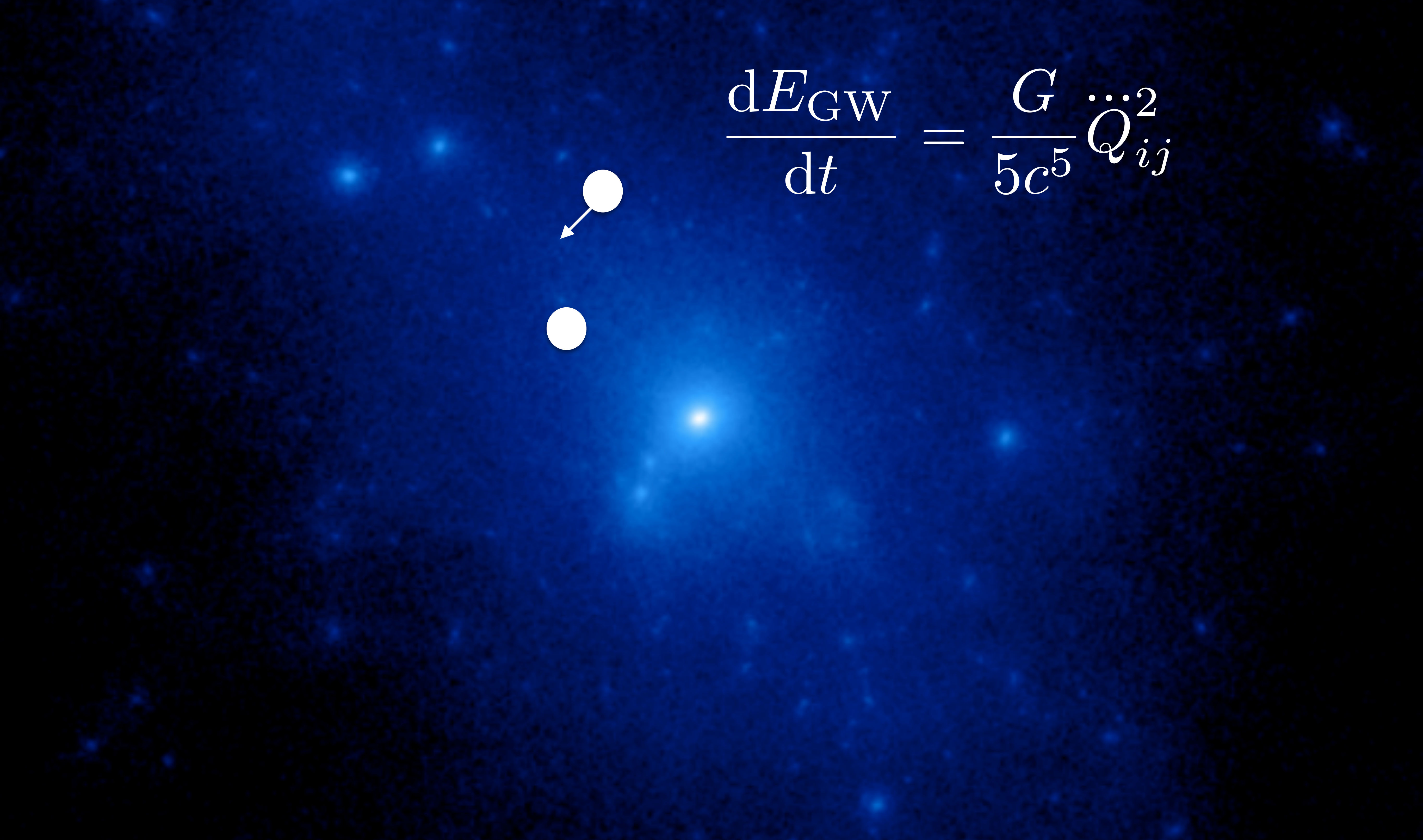
Zel'dovich & Novikov (1967), Hawking (1971), Carr & Hawking (1974)


Bird, Cholis, **JBM**, et al. PRL 116 2016
If Dark matter is PBHs of ~30 $M_\odot$

Bird, Cholis, **JBM**, et al. PRL 116 2016

If Dark matter is PBHs of ~30 $M_\odot$

$$\frac{\mathrm{d}E_{\mathrm{GW}}}{\mathrm{d}t} = \frac{G}{5c^5}\dddot{Q}_{ij}^{2}$$



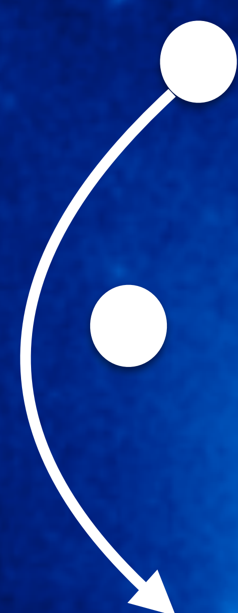
Bird, Cholis, **JBM**, et al. PRL 116 2016

If Dark matter is PBHs of ~30 $M_\odot$

$$\delta E_{\mathrm{GW}} = \frac{G^{7/2}}{c^5} \frac{M^{9/2}}{r_p^{7/2}}$$

Bird, Cholis, **JBM**, et al. PRL 116 2016

<u>If</u> Dark matter is PBHs of ~30 $M_\odot$



$$\delta E_{\rm GW} = \frac{G^{7/2}}{c^5} \frac{M^{9/2}}{r_p^{7/2}}$$

Binary formed if:

$$\delta E_{\rm GW} > \frac{1}{2} M v_\infty^2$$

Bird, Cholis, **JBM**, et al. PRL 116 2016

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Binary formed if:

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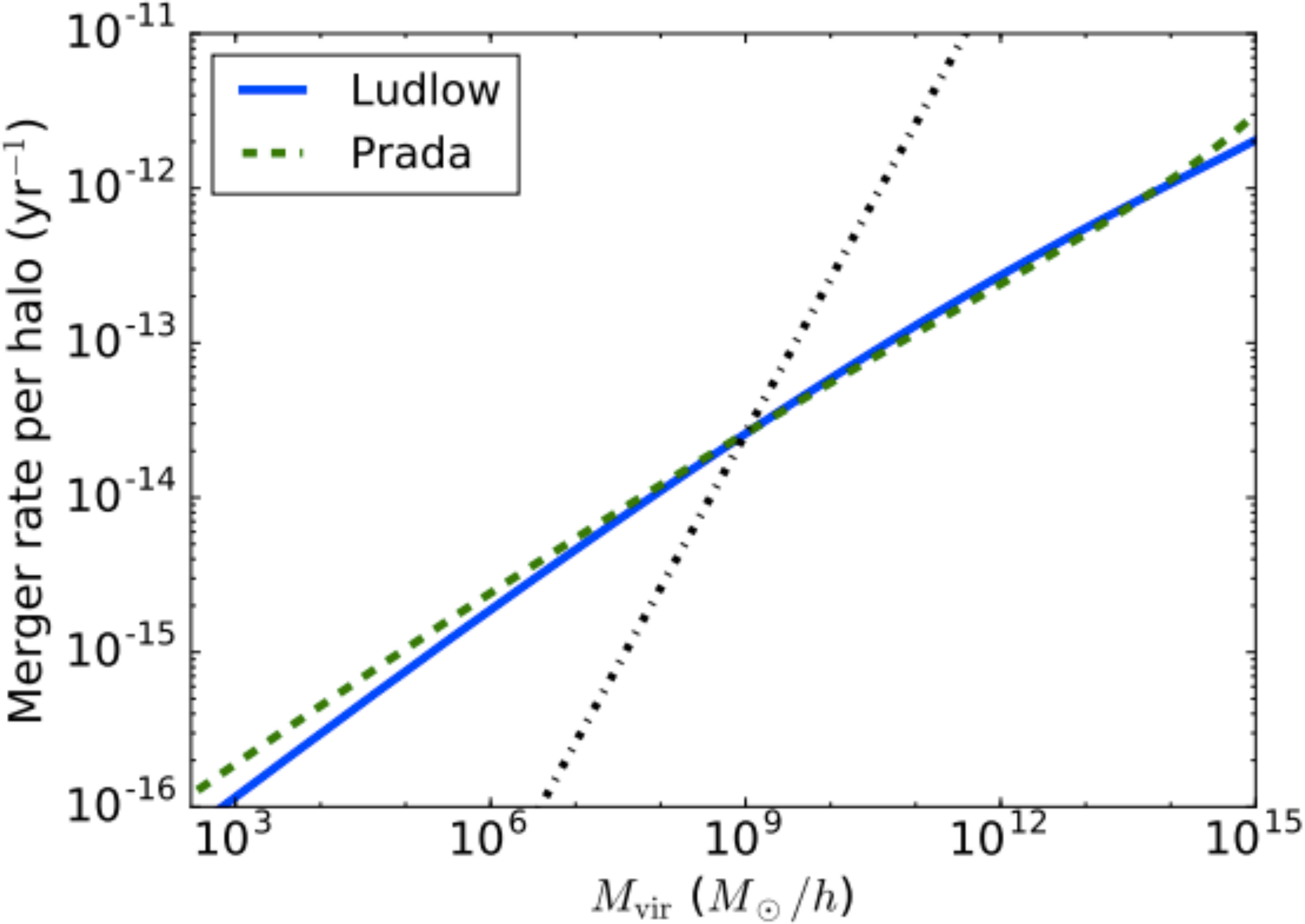
$$\sigma_{\rm GW} \approx R_s^2 \left(\frac{v_\infty}{c}\right)^{-18/7}$$

Quinlan and Shapiro 1987

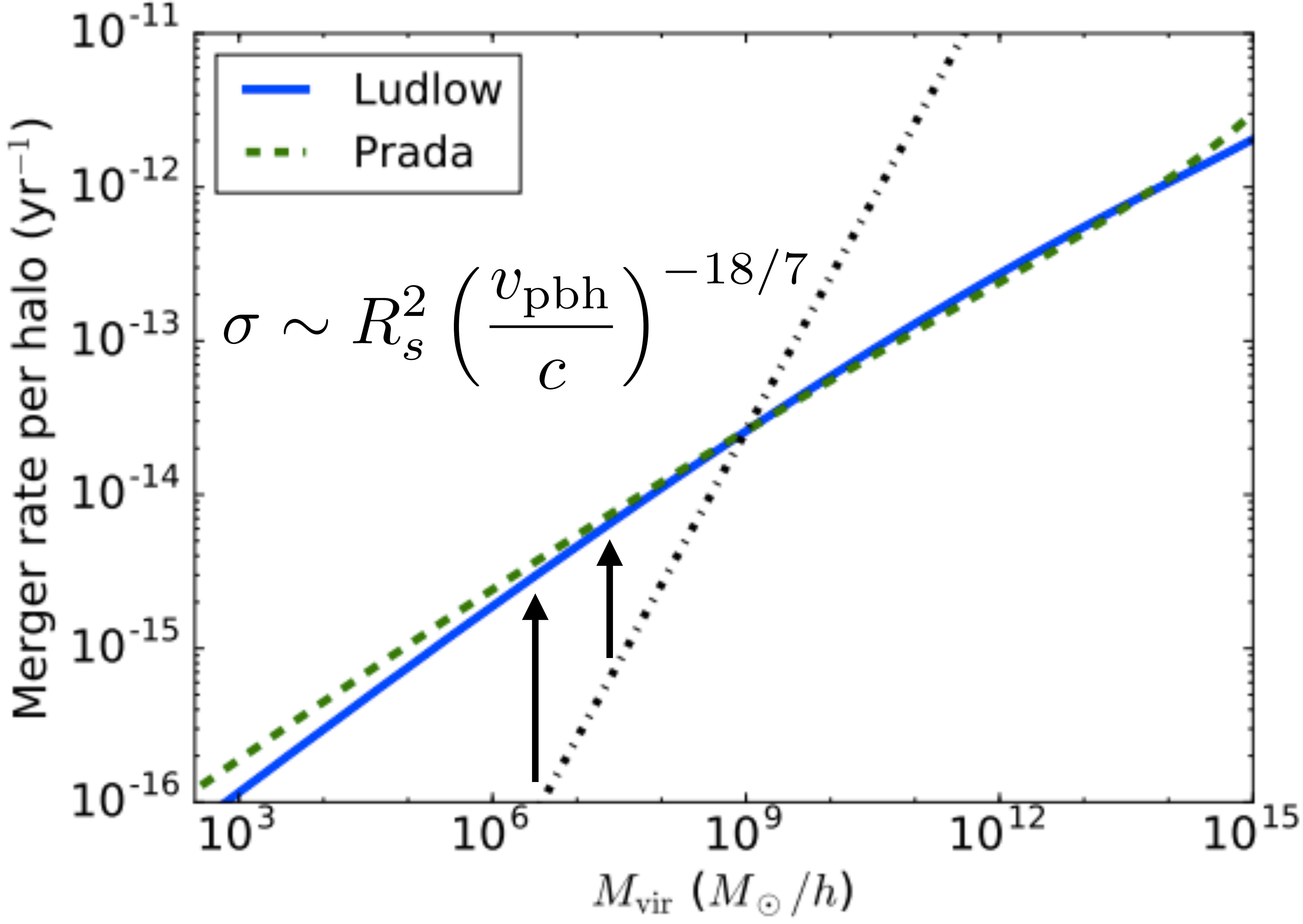
Capture rate per halo:

$$\sigma_{\rm GW} \approx R_s^2 \left(\frac{v_\infty}{c} \right)^{-18/7}$$

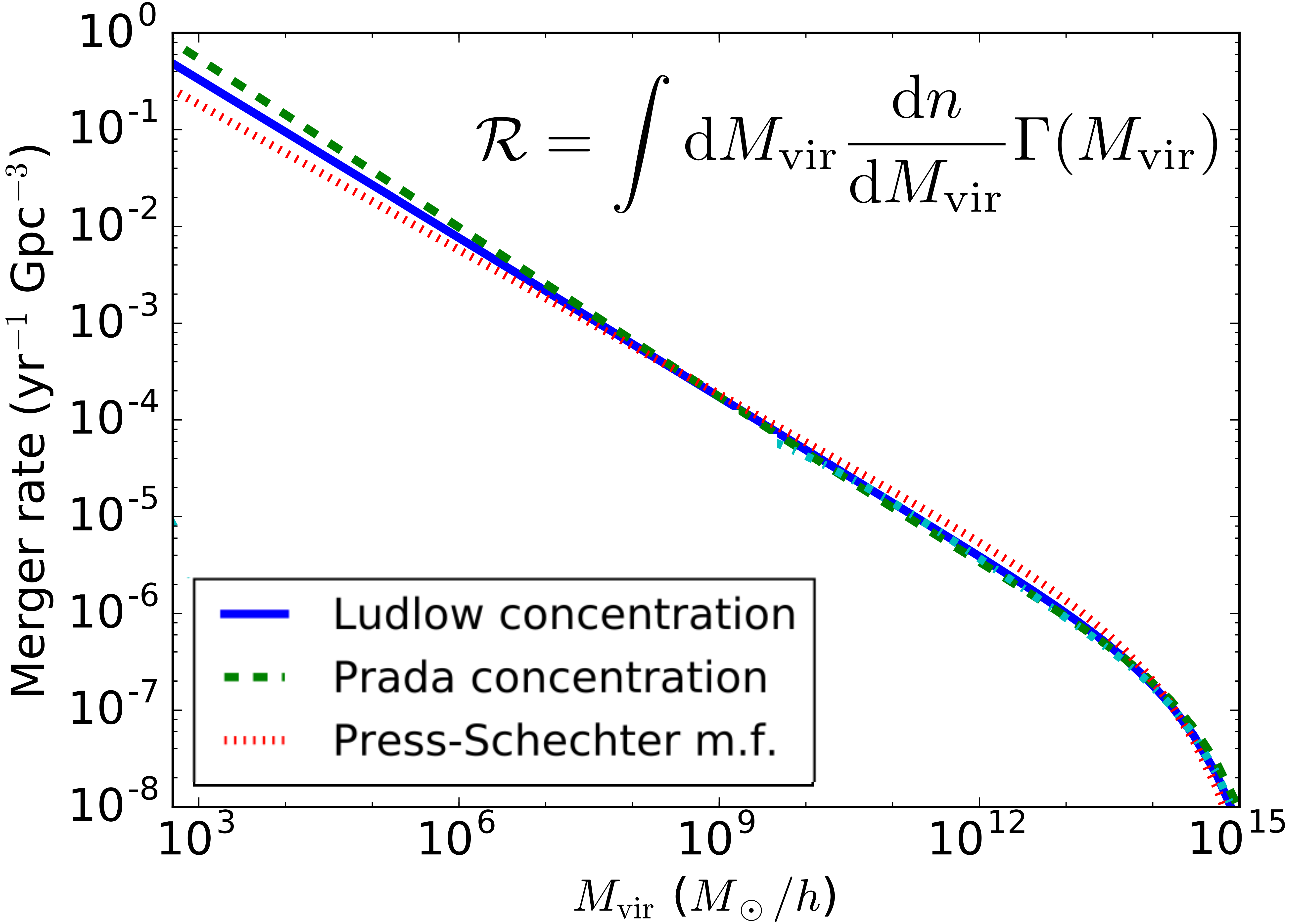
$$\Gamma_{\rm halo} \propto \int {\rm d}^3 r \, \frac{\rho_{\rm NFW}^2}{M_{\rm pbh}^2} \, \langle \sigma v \rangle$$



Ludlow
Prada
Merger rate per halo (yr^{-1})
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{3}
10^{6}
10^{9}
10^{12}
10^{15}
$M_{\rm vir}$ ($M_\odot/h$)



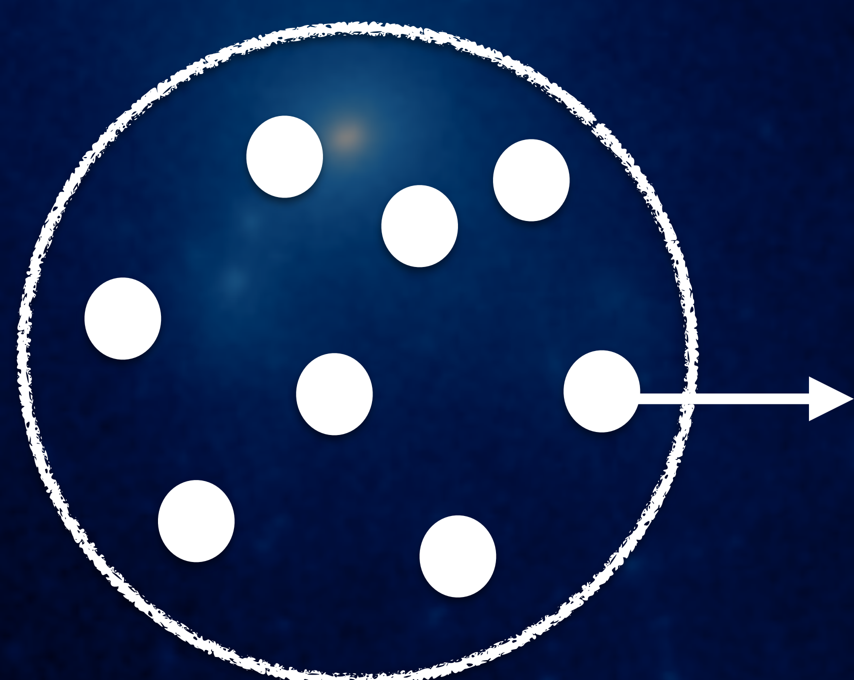
Ludlow
Prada
$\sigma \sim R_s^2 \left(\frac{v_{\rm pbh}}{c}\right)^{-18/7}$
Merger rate per halo (yr^{-1})
$M_{\rm vir}$ ($M_\odot/h$)
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{3}
10^{6}
10^{9}
10^{12}
10^{15}



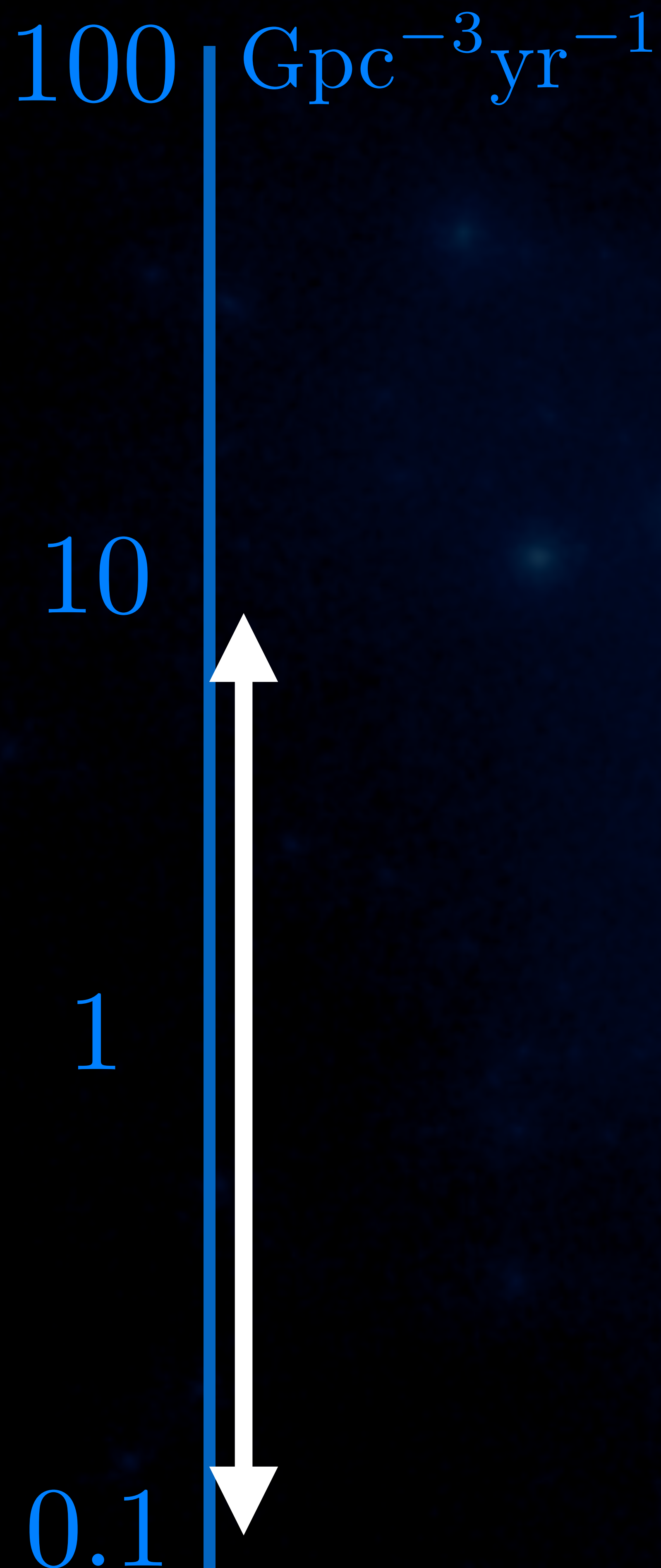
$\mathcal{R} = \int \mathrm{d}M_{\mathrm{vir}} \frac{\mathrm{d}n}{\mathrm{d}M_{\mathrm{vir}}} \Gamma(M_{\mathrm{vir}})$
Merger rate (yr^{-1} Gpc^{-3})
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{3}
10^{6}
10^{9}
10^{12}
10^{15}
M_{vir} ($M_{\odot}/h$)
Ludlow concentration
Prada concentration
Press-Schechter m.f.

We cut off at halos of $400\,M_\odot$
Lower-mass halos would evaporate

$$t_{\rm evap} \sim 3\,{\rm Gyrs} \times N_{\rm pbh}/15$$

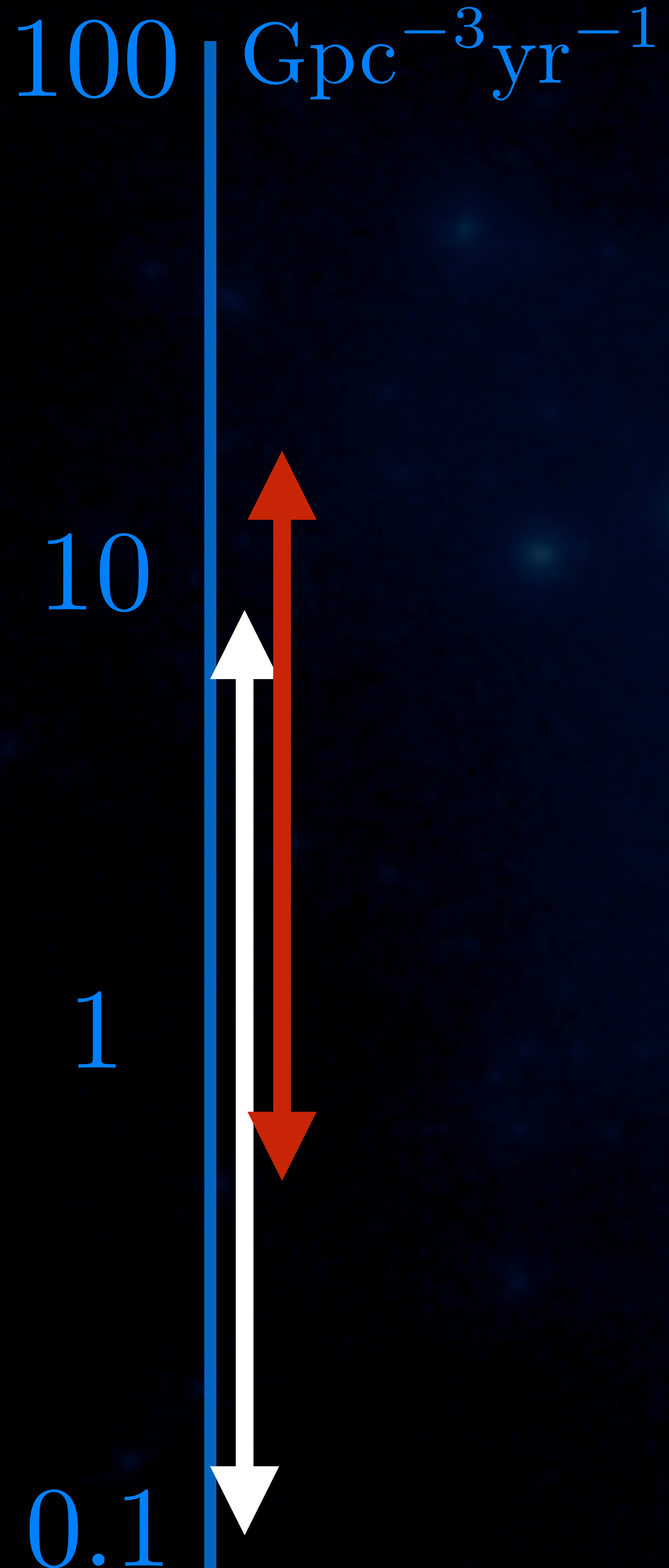


Binney and Tremaine 1987



Integrating the rate:

$$\mathcal{R} = O(1)\,\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$$



Integrating the rate:

$$\mathcal{R} = O(1)\,\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$$

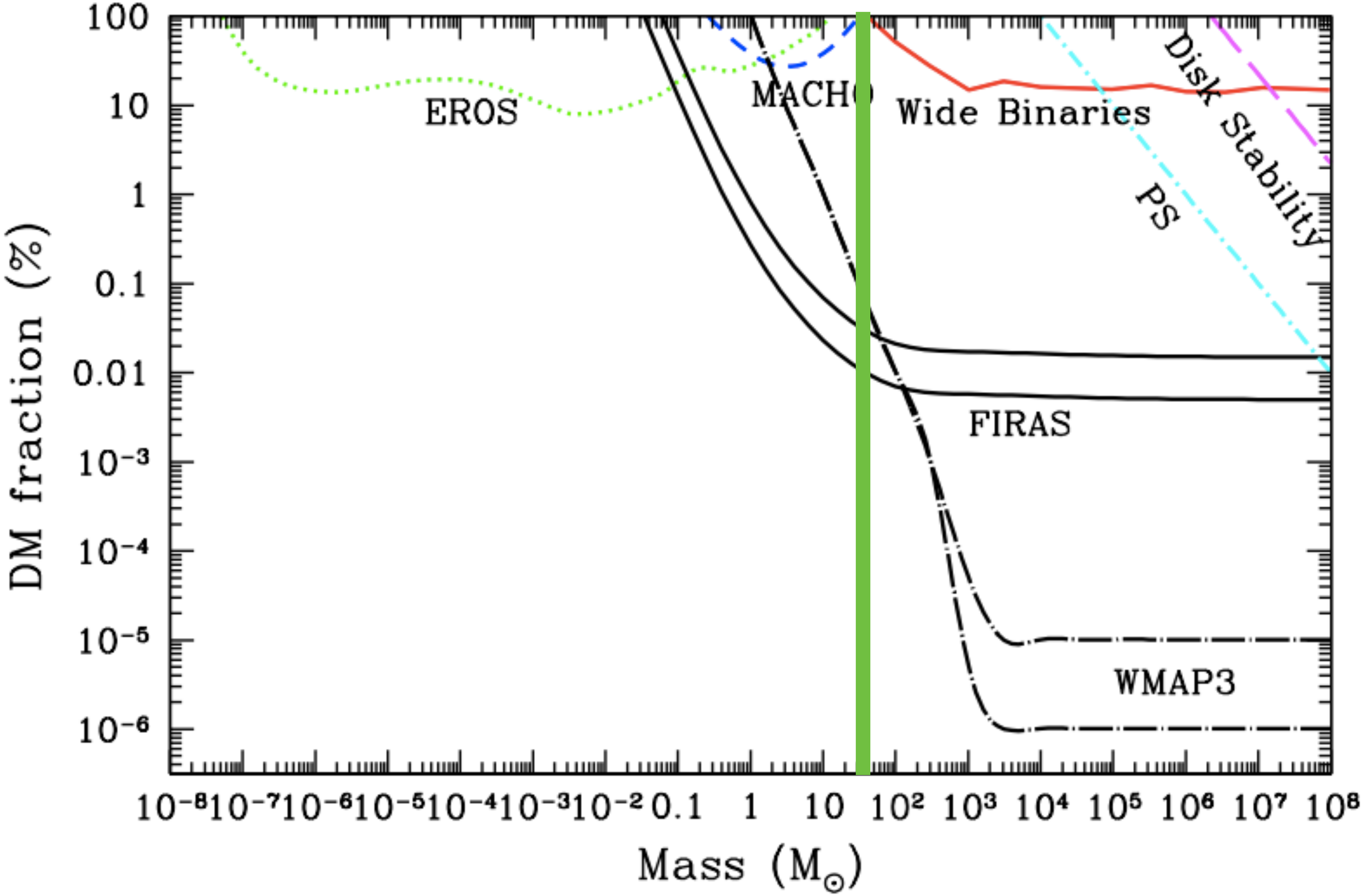
To be compared with GW150914:

(Abbot et al. arXiv: 1602.03842)

$$\mathcal{R} = 0.6 - 12\,\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$$

So they overlap!

But wait, are these masses allowed?



Ricotti, Ostriker, and Mack Ap.J. 680-829

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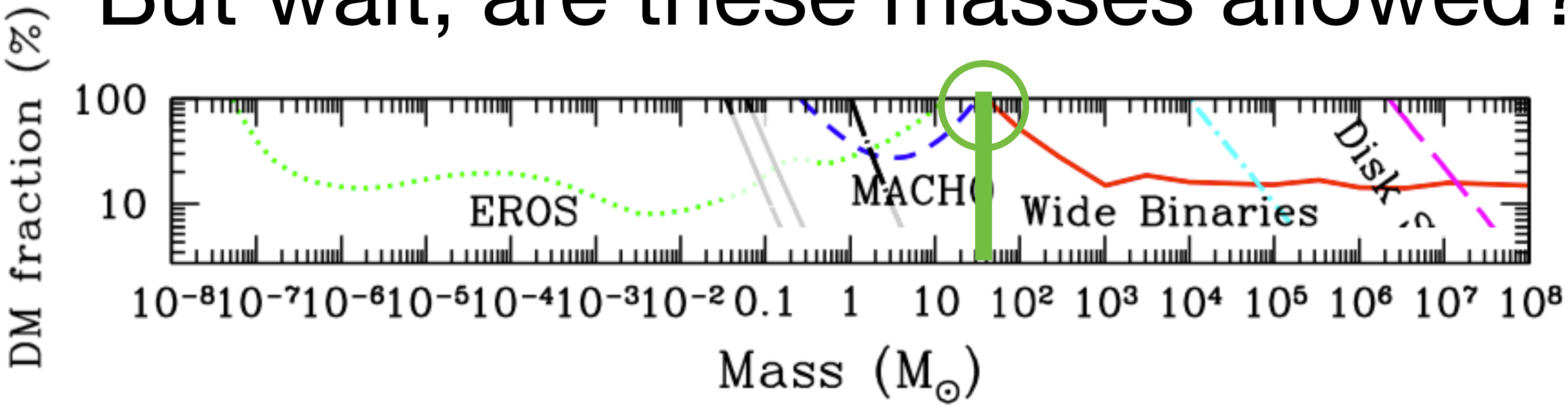


Ali-Haimoud and Kamionkowski (in prep.)

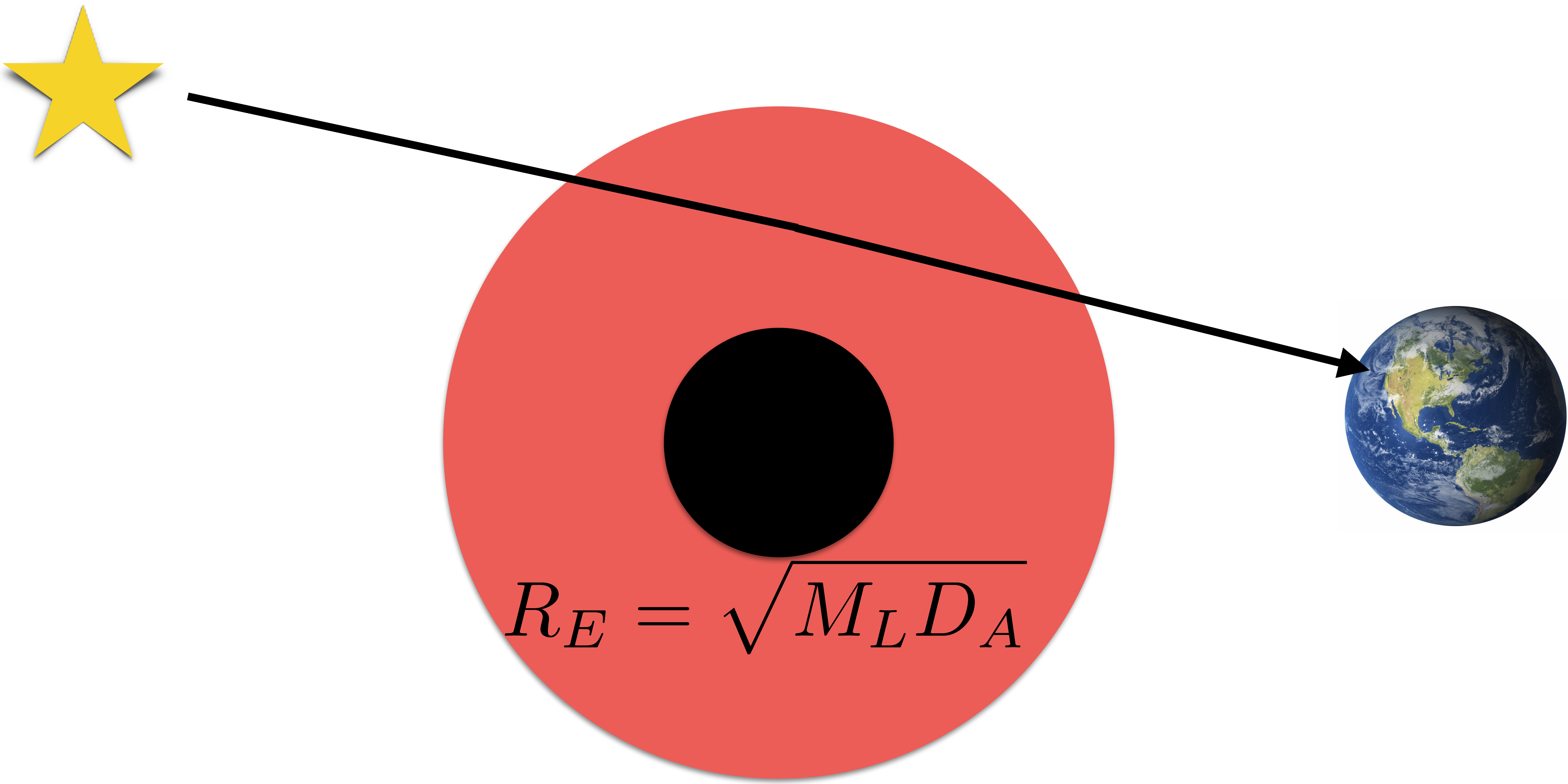
1- No spectral distortions

2- $M \gtrsim 100\, M_\odot$

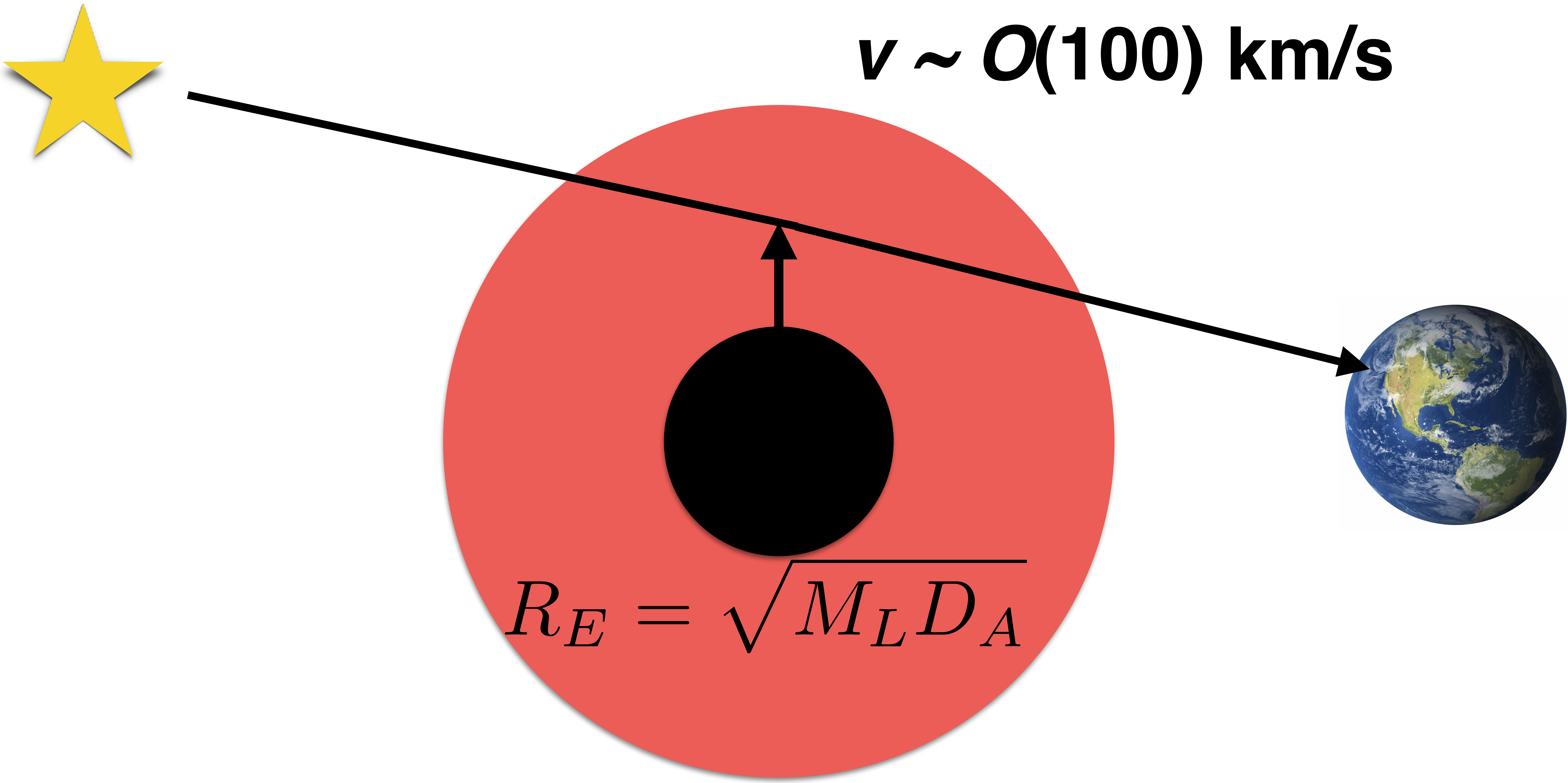
Also, what if it is not PBHs?

Ricotti, Ostriker, and Mack Ap.J. 680-829

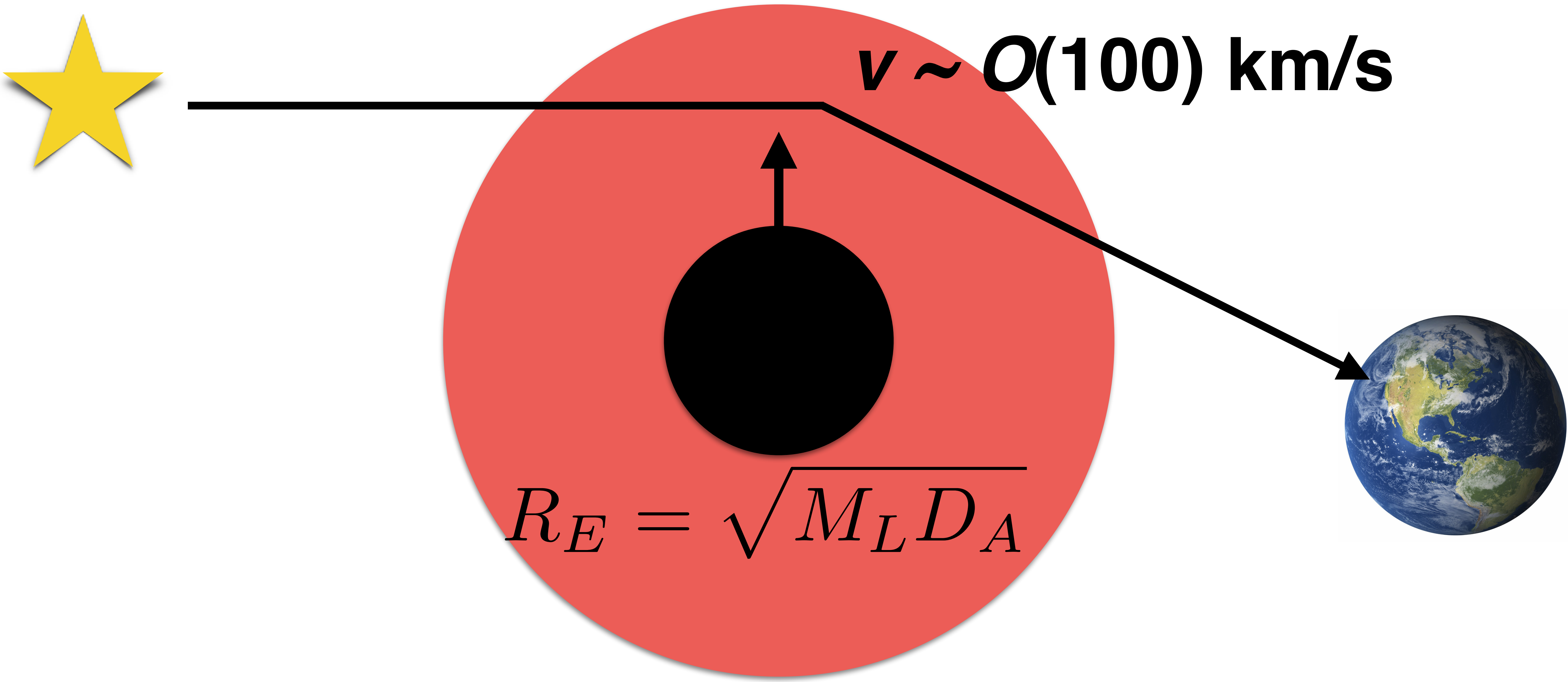
(Gravitational) Lensing



(Gravitational) Lensing

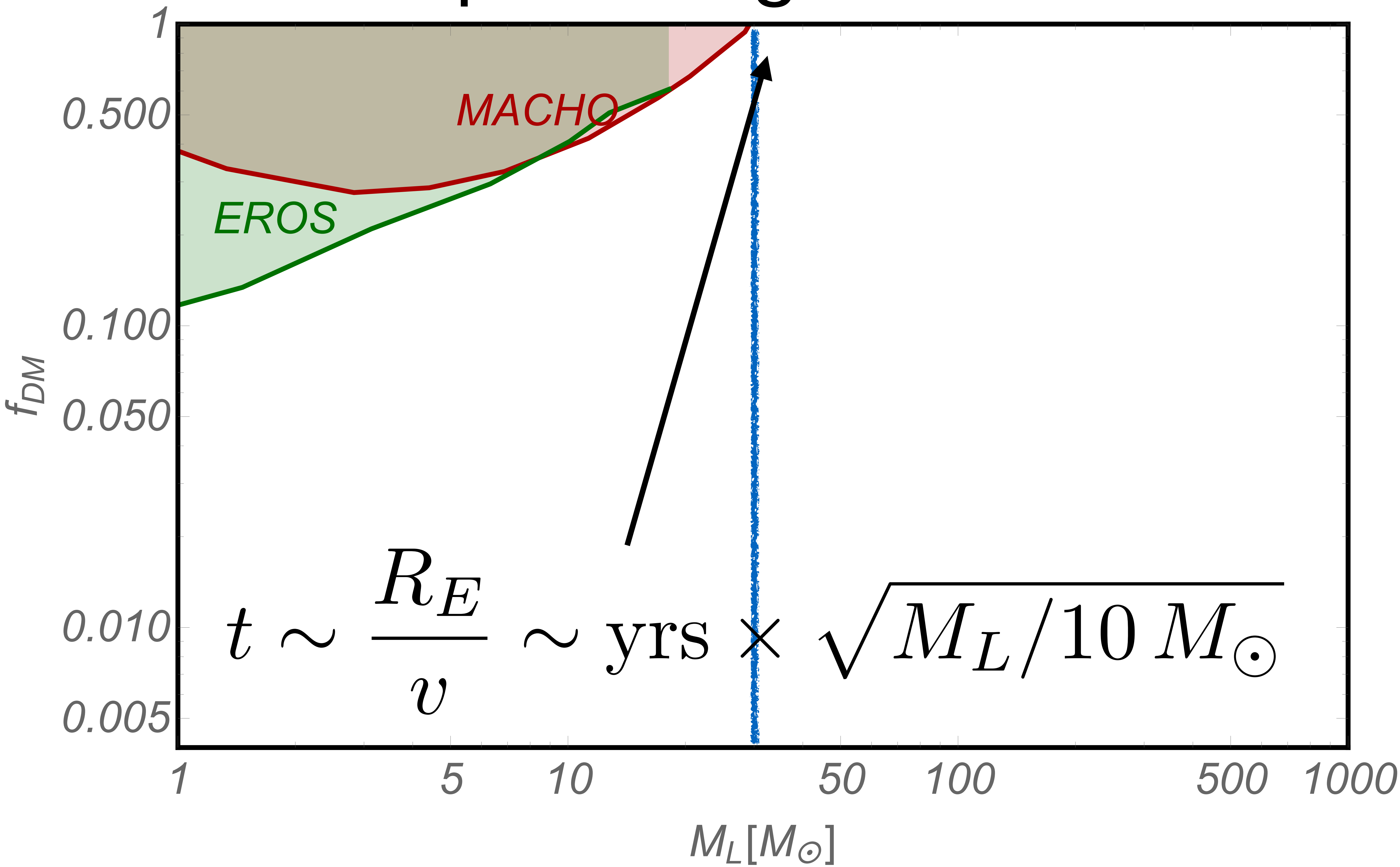


(Gravitational) Lensing



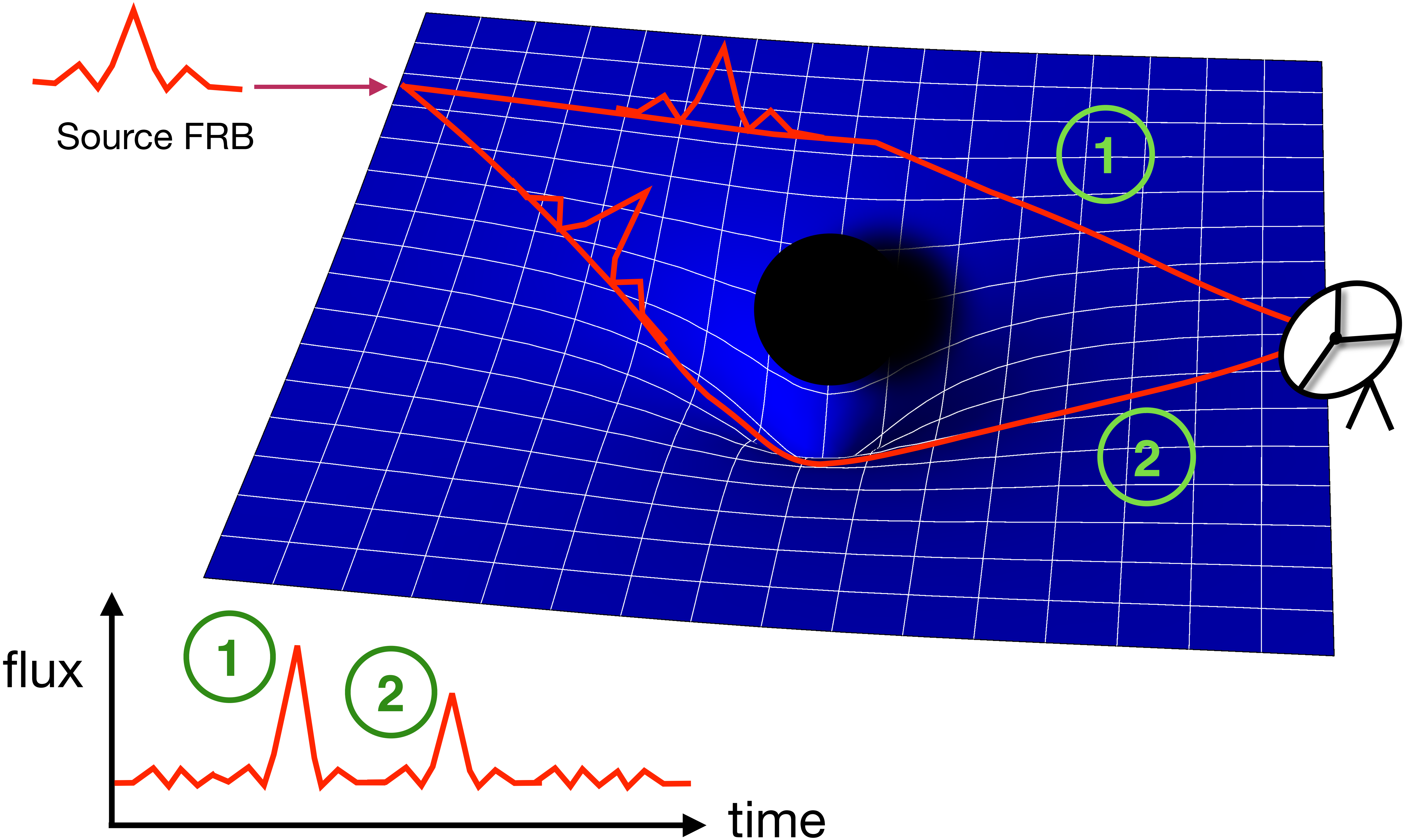
$$t \sim \frac{R_E}{v} \sim \mathrm{yrs} \times \sqrt{M_L / 10\, M_\odot}$$

How to probe higher masses?*



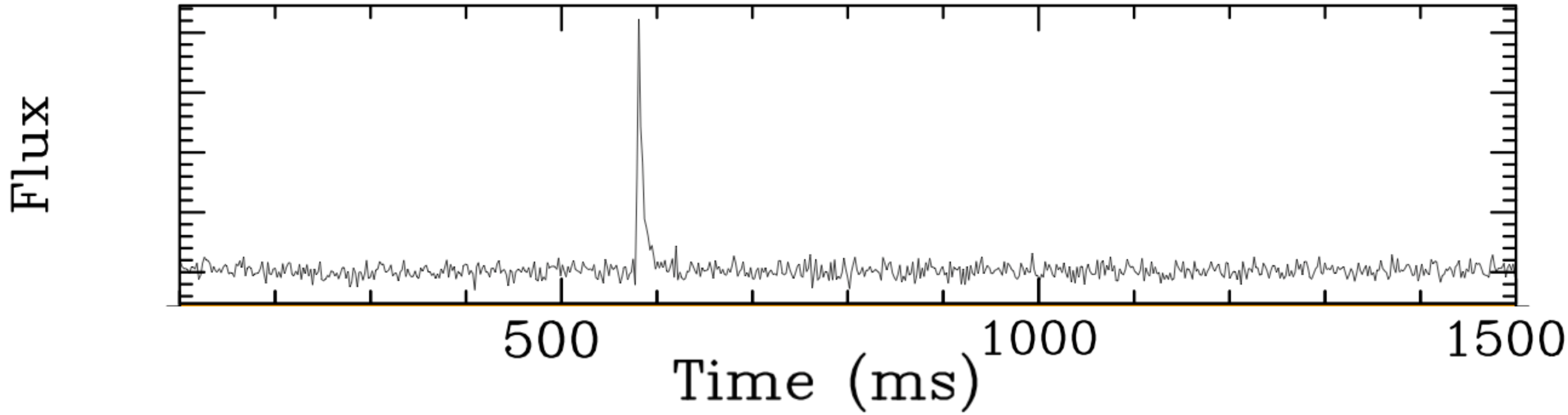
*Additional lines in this plot not shown

(Gravitational) Lensing of FRBs!



JBM, Kovetz, Dai, and Kamionkowski. PRL 2016

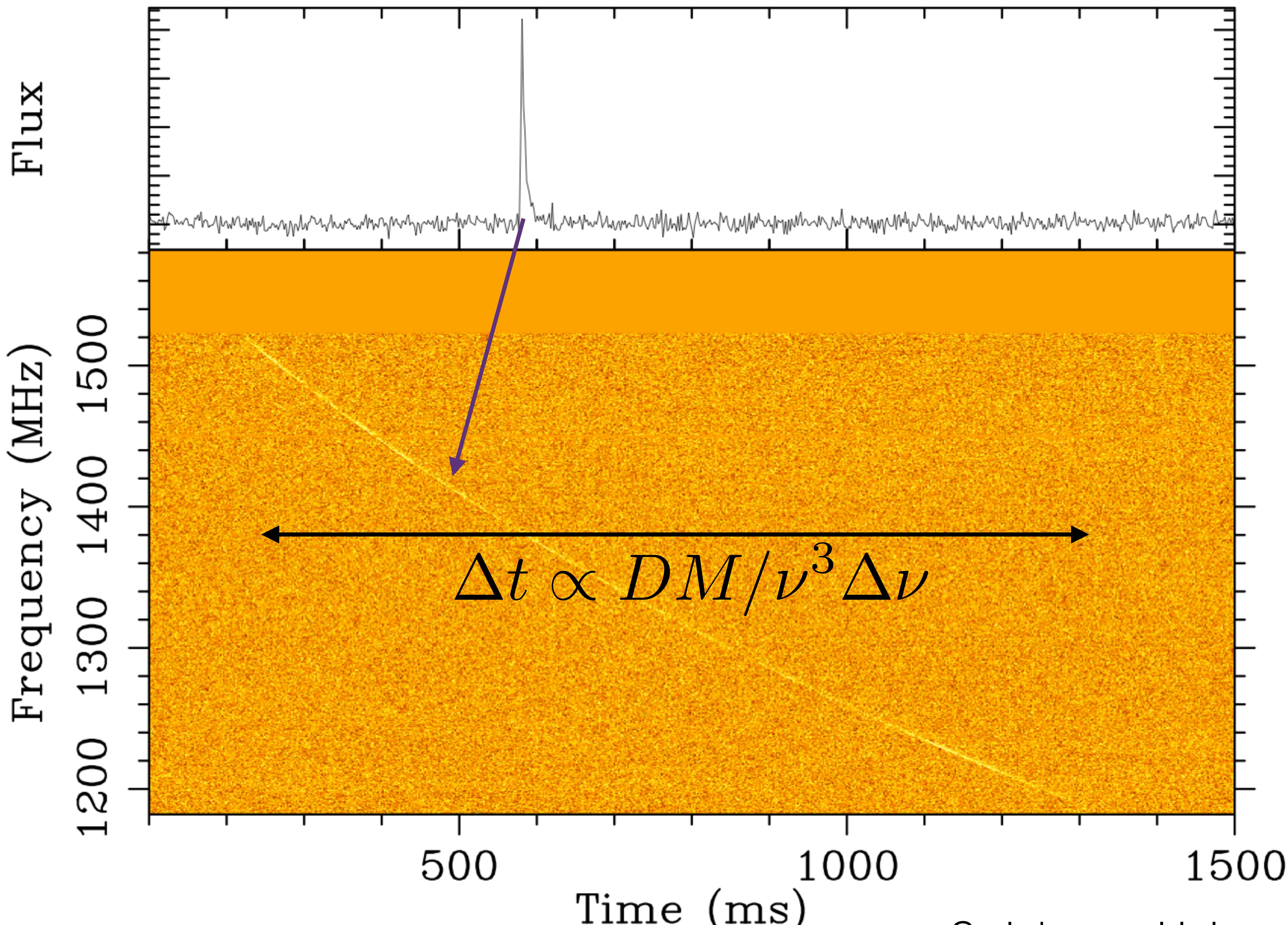
FRB 110220



Fast	$\Delta t \approx 1\,\mathrm{ms}$	
Radio	$f \sim 1\,\mathrm{GHz}$	???
Bursts	$F = \mathcal{O}(1)\,\mathrm{Jy}$	

Swinburne University

FRB 110220

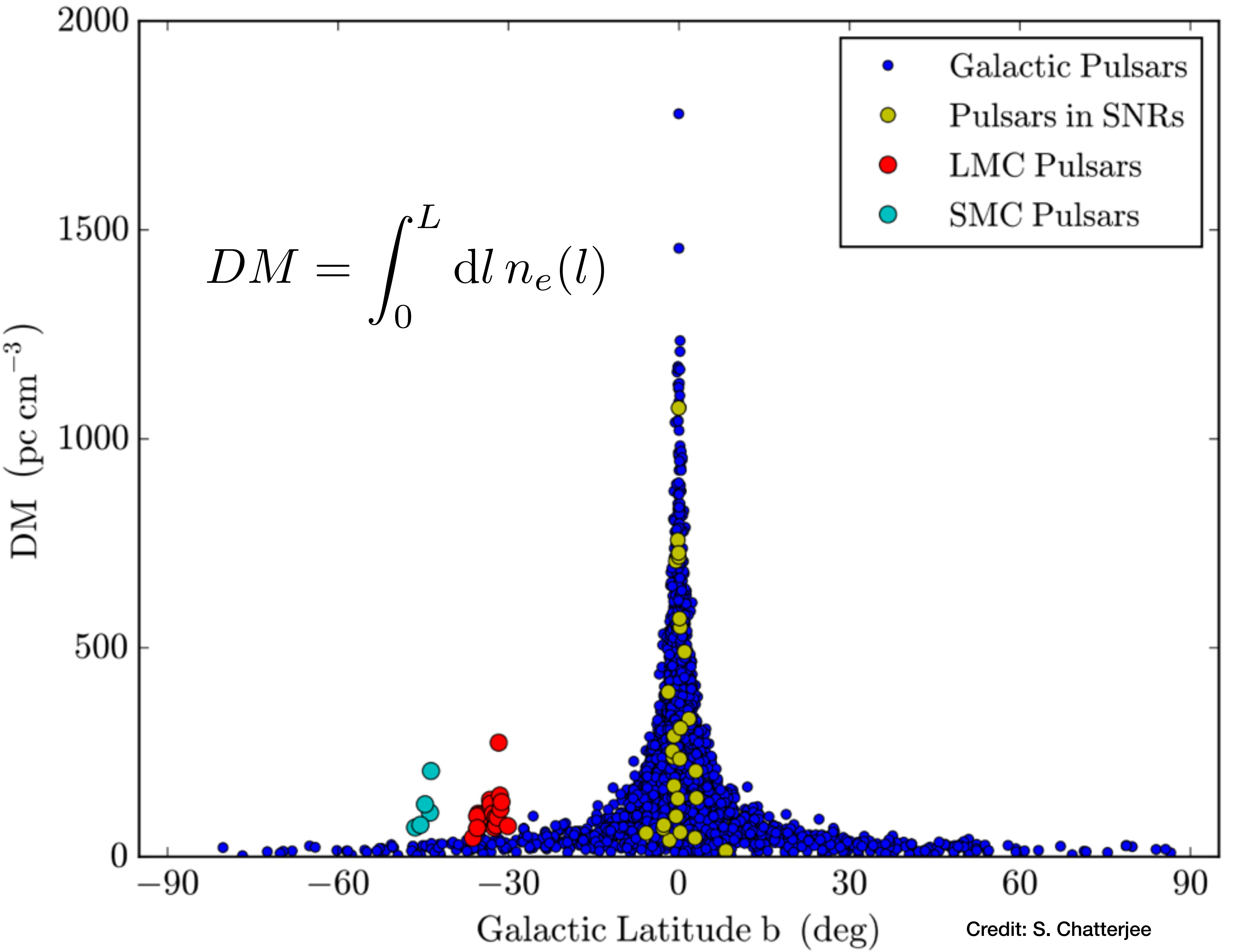


Swinburne University

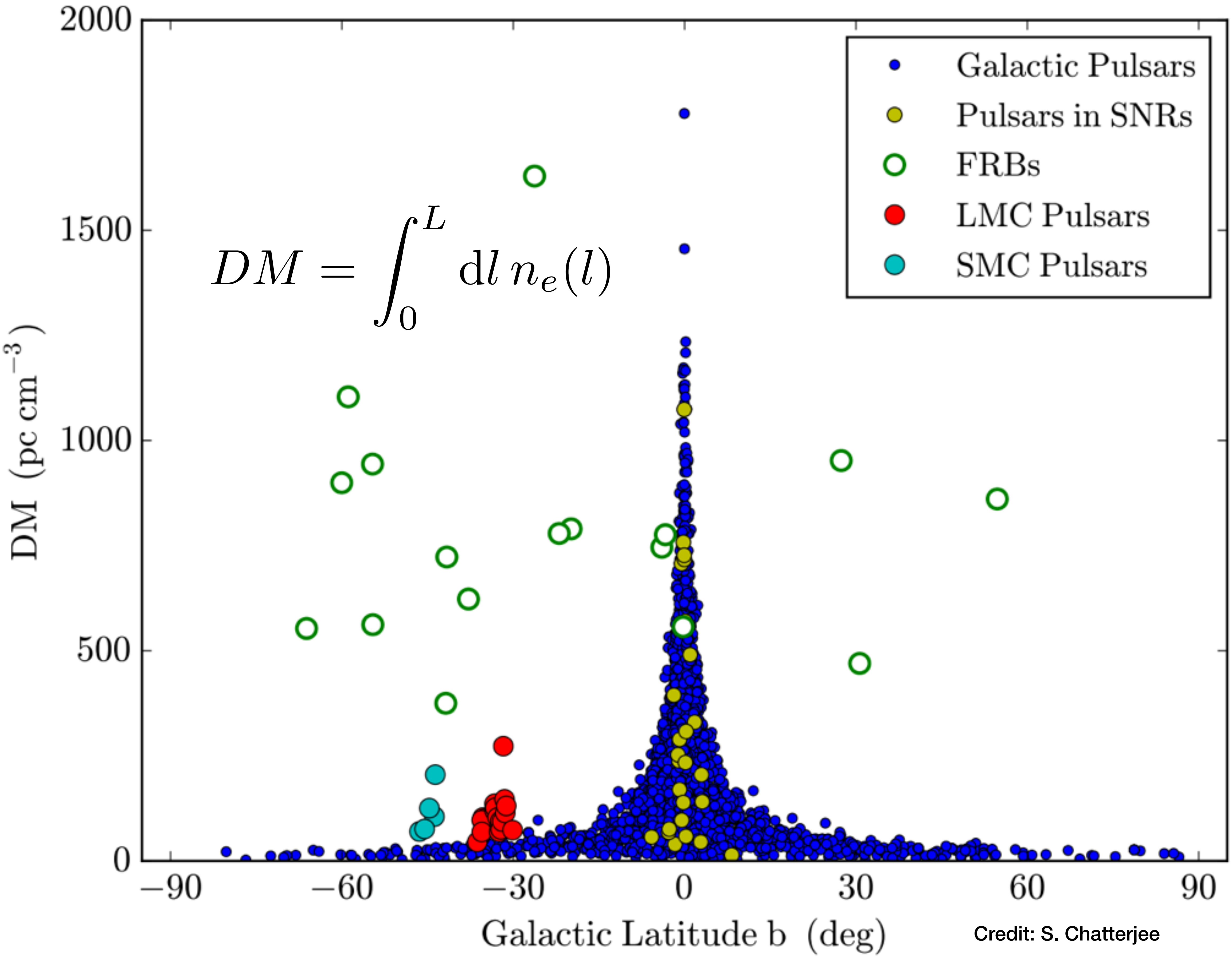
Thornton 2013

$$\Delta t \propto DM/\nu^3 \Delta\nu$$

$$DM = \int_0^L \mathrm{d}l \, n_e(l)$$



Credit: S. Chatterjee



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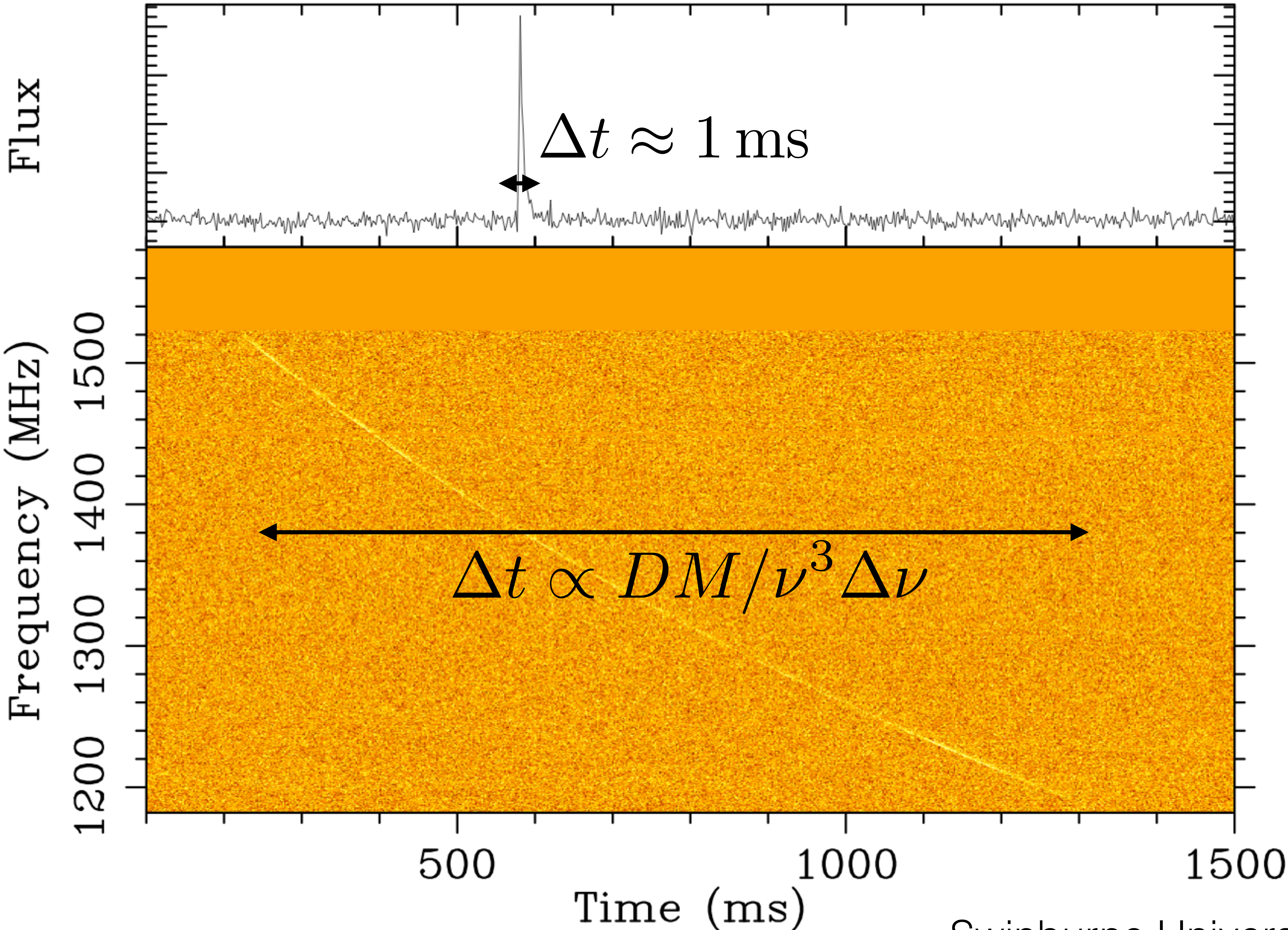
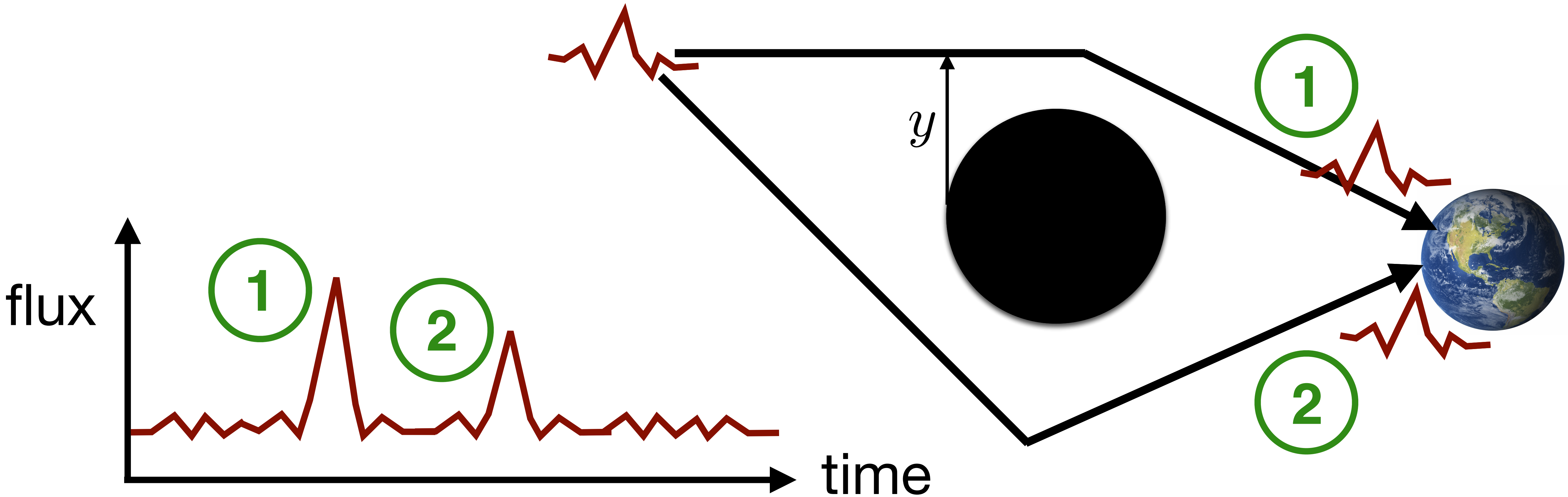


Swinburne University

How to see lensing:



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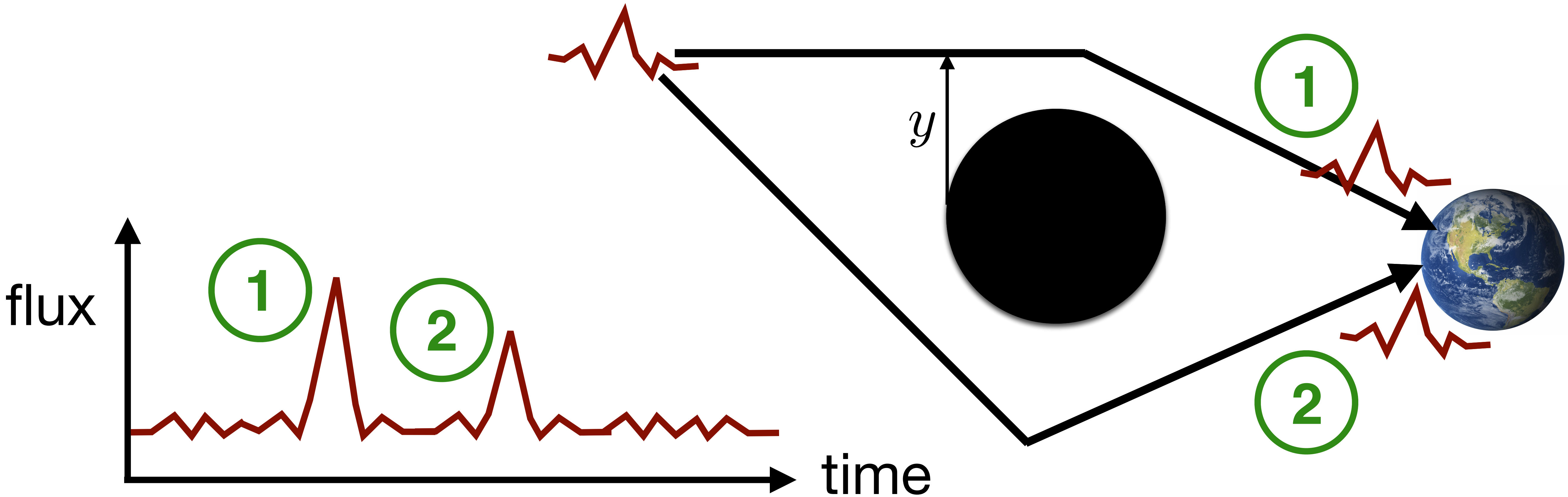

Flux ratio $\frac{F_1}{F_2} = g(y)$ $\longrightarrow$ $y < y_{\max}$ (both images need be detectable)

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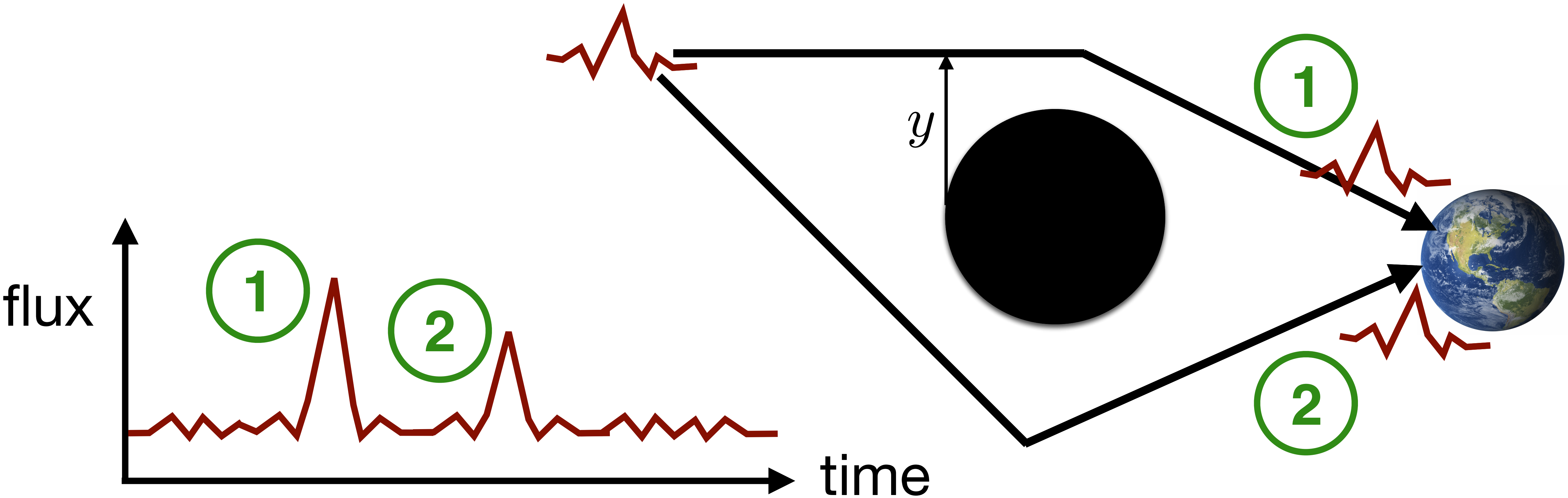

Flux ratio $\frac{F_1}{F_2} = g(y)$

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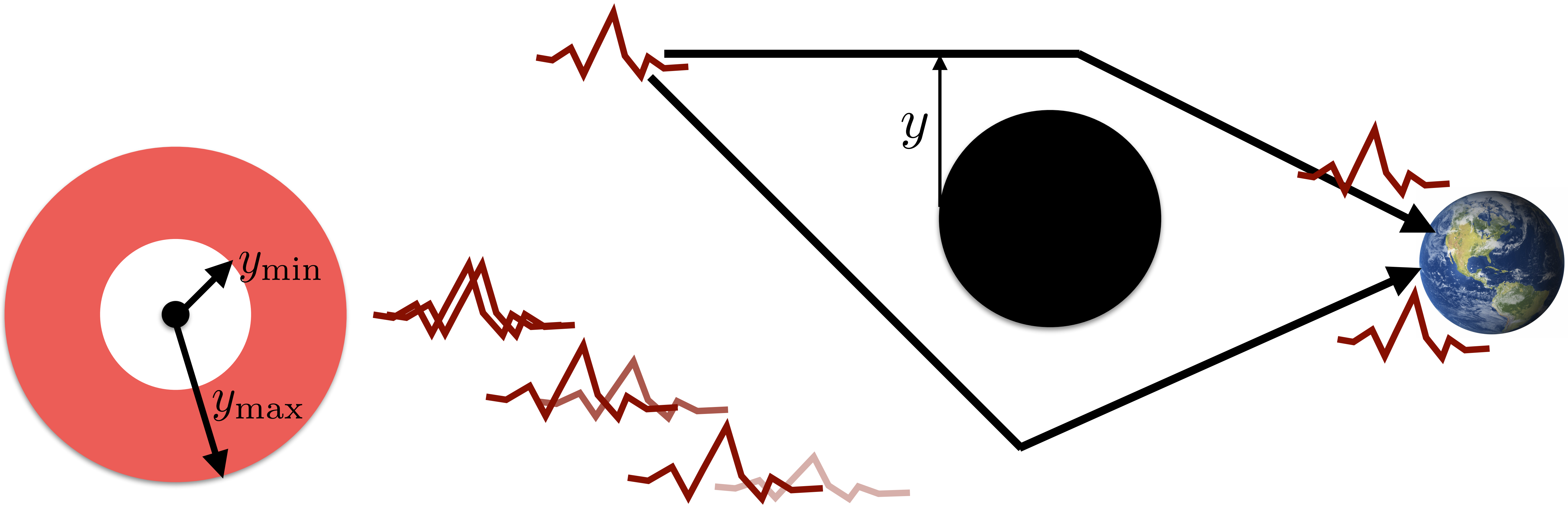
Time delay $\Delta t = 4M_L f(y) \sim 1\,\mathrm{ms} \times \frac{\mathrm{M_L}}{30\,\mathrm{M_\odot}}$

$\xrightarrow{>\Delta t_{\mathrm{int}}}$ $y > y_{\min}(M_L, z_s)$

How to see lensing:



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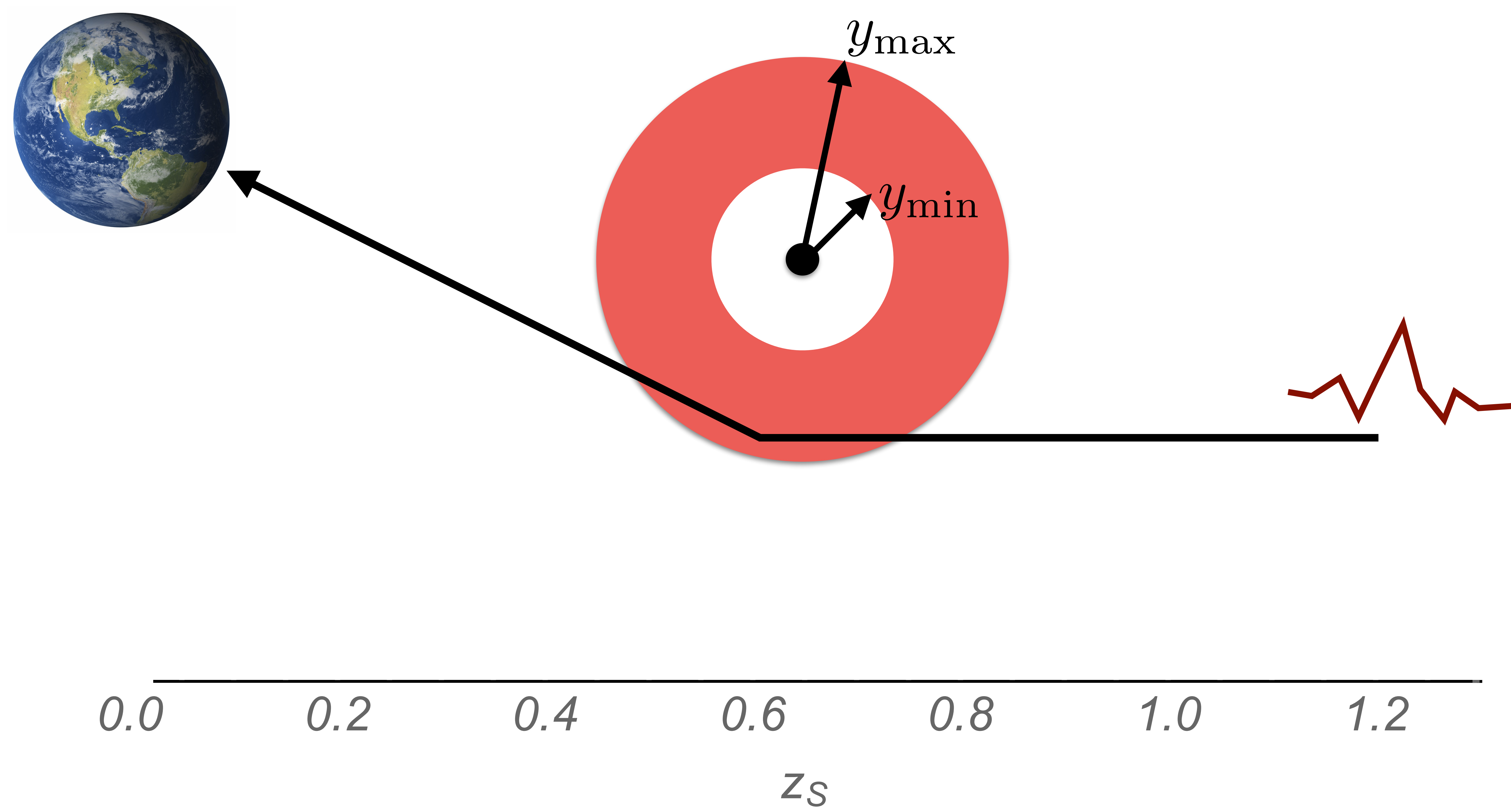
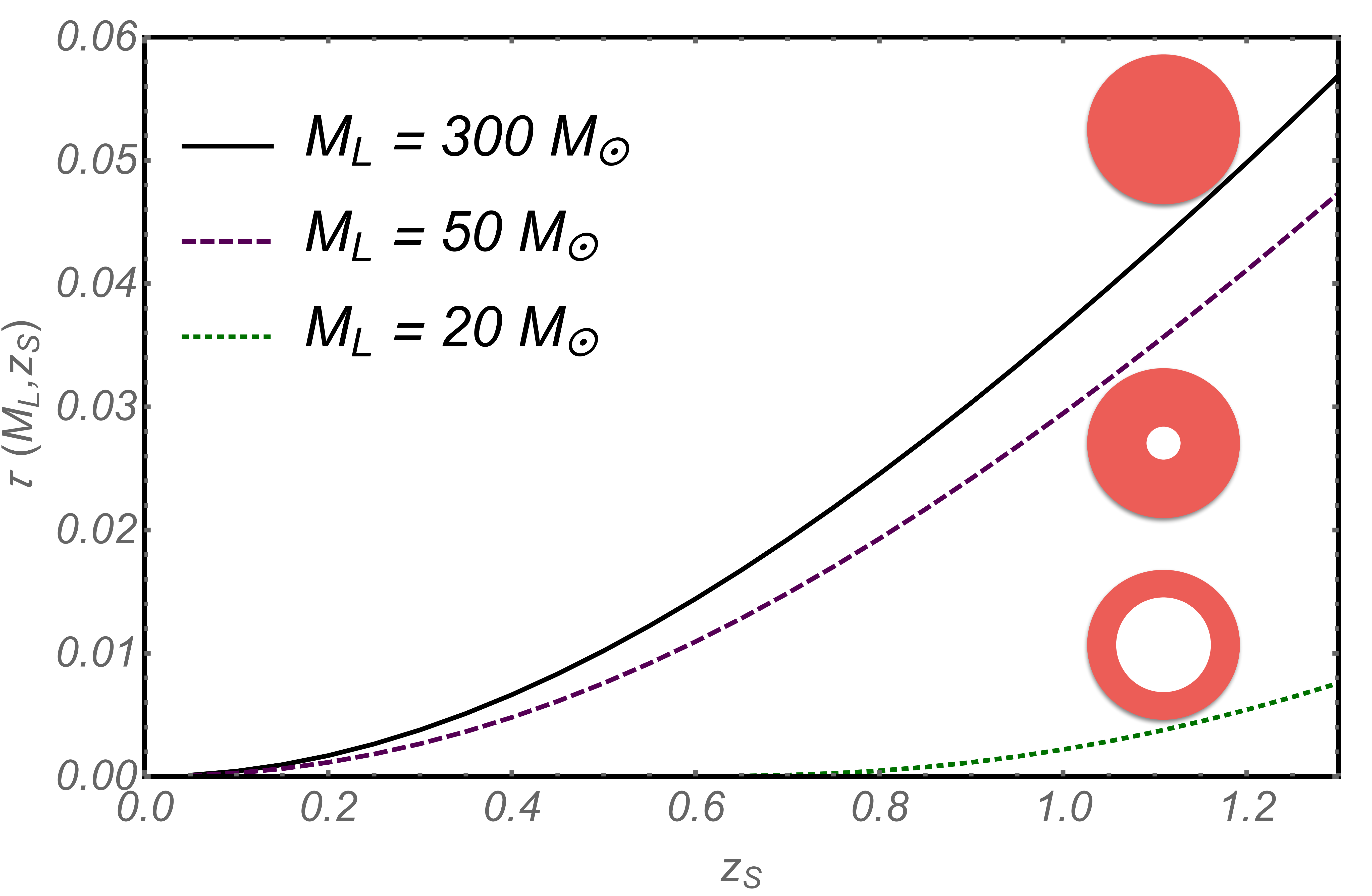
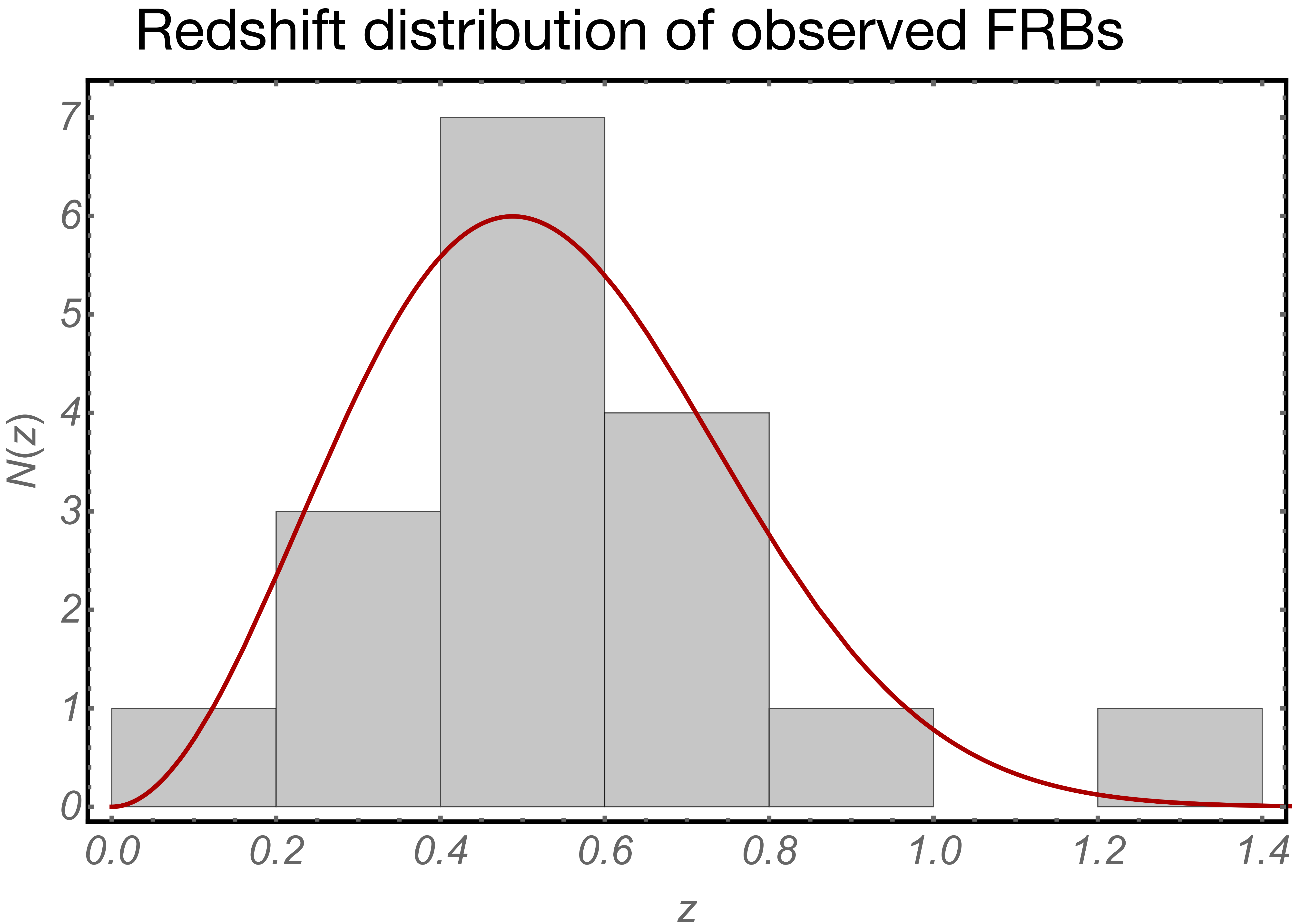
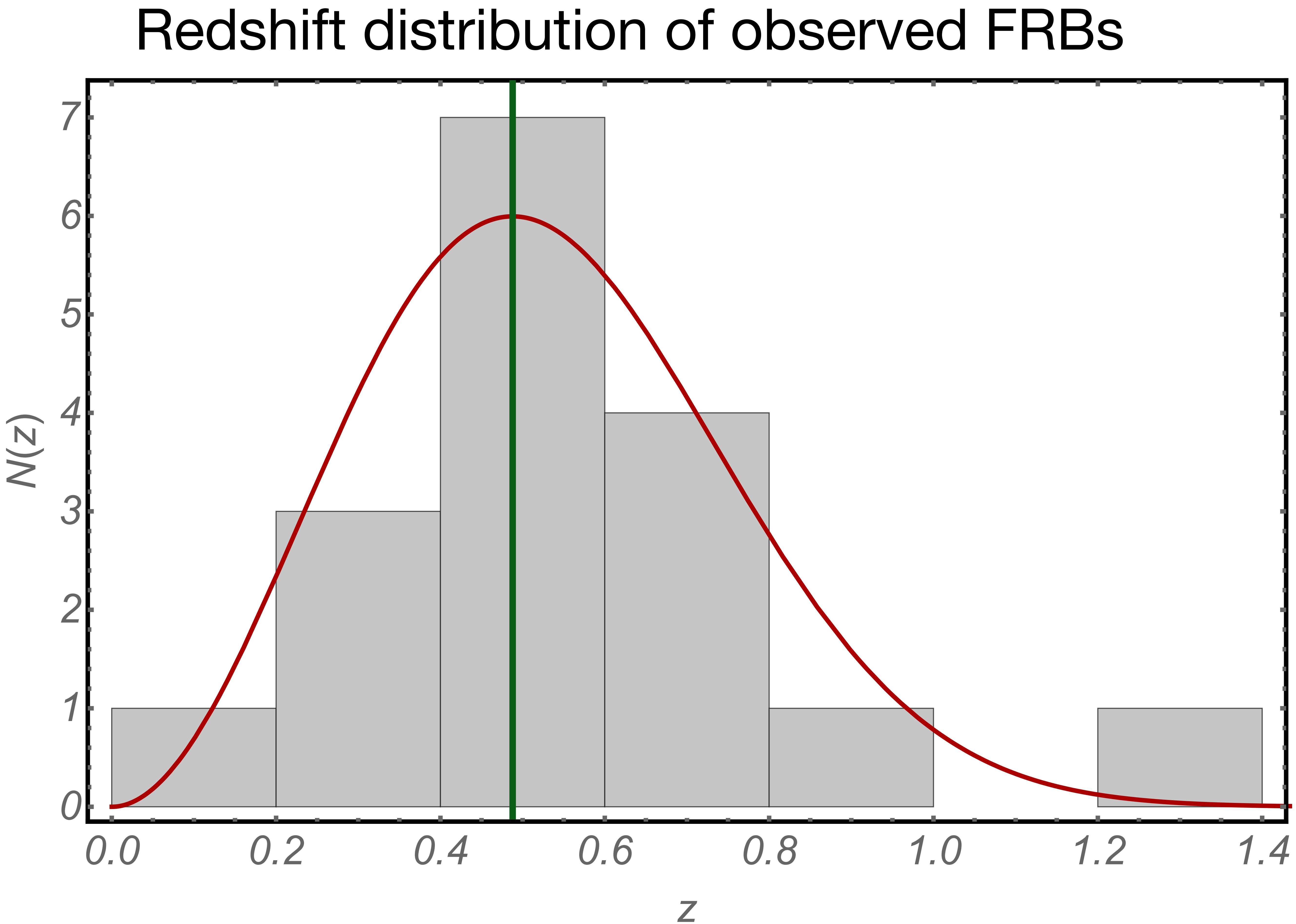
$$\tau(M_L, z_S) = \frac{3}{2} f_{\rm DM}\Omega_c \int_0^{z_S} dz_L \frac{H_0^2}{c\,H(z_L)} \frac{D_L D_{LS}}{D_S} \times (1+z_L)^2 \left[y_{\rm max}^2 - y_{\rm min}^2(M_L, z_L)\right]$$



For a time delay longer than 1 ms




Redshift distribution of observed FRBs
N(z)
z
0
1
2
3
4
5
6
7
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4



Redshift distribution of observed FRBs
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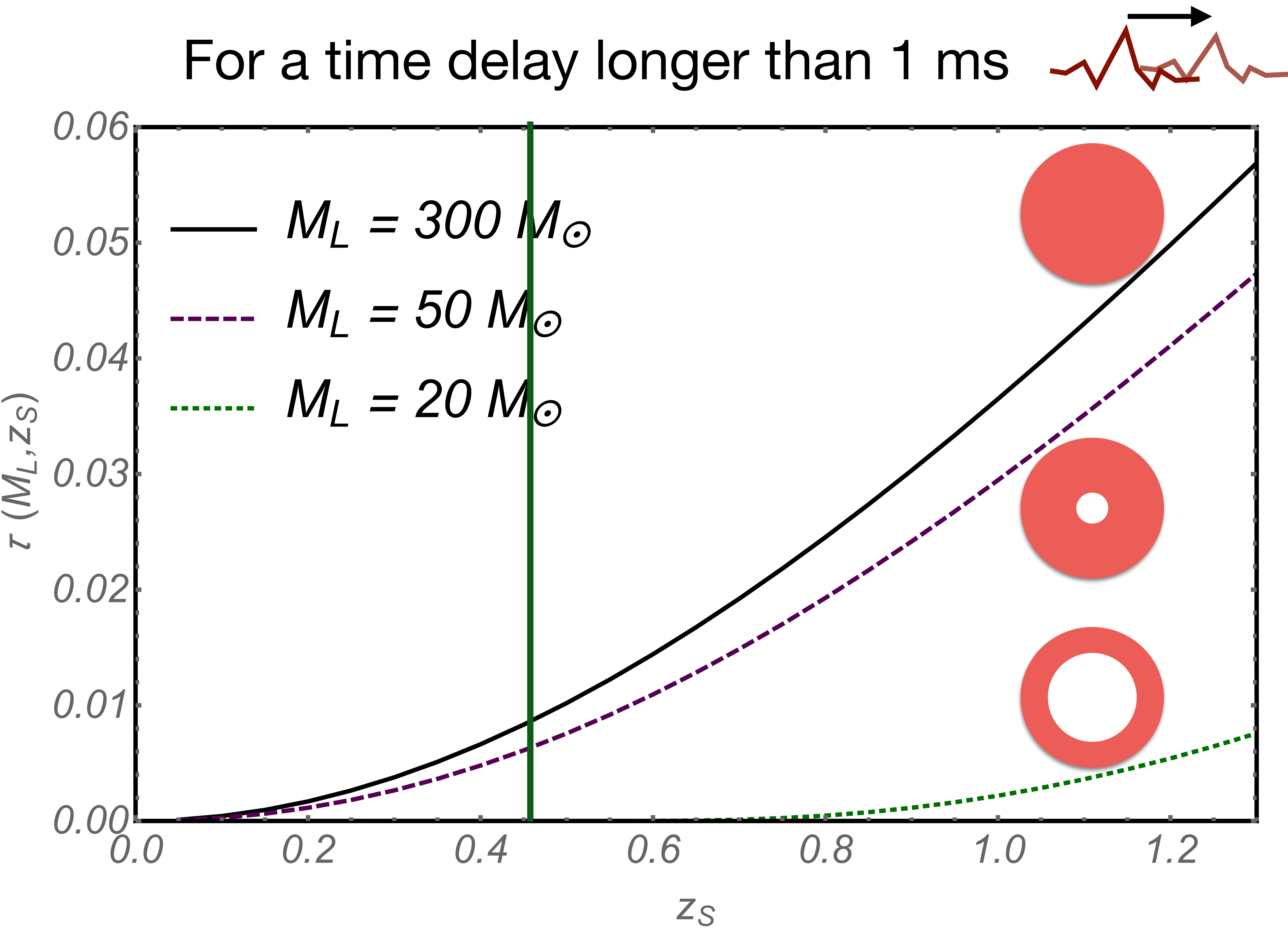
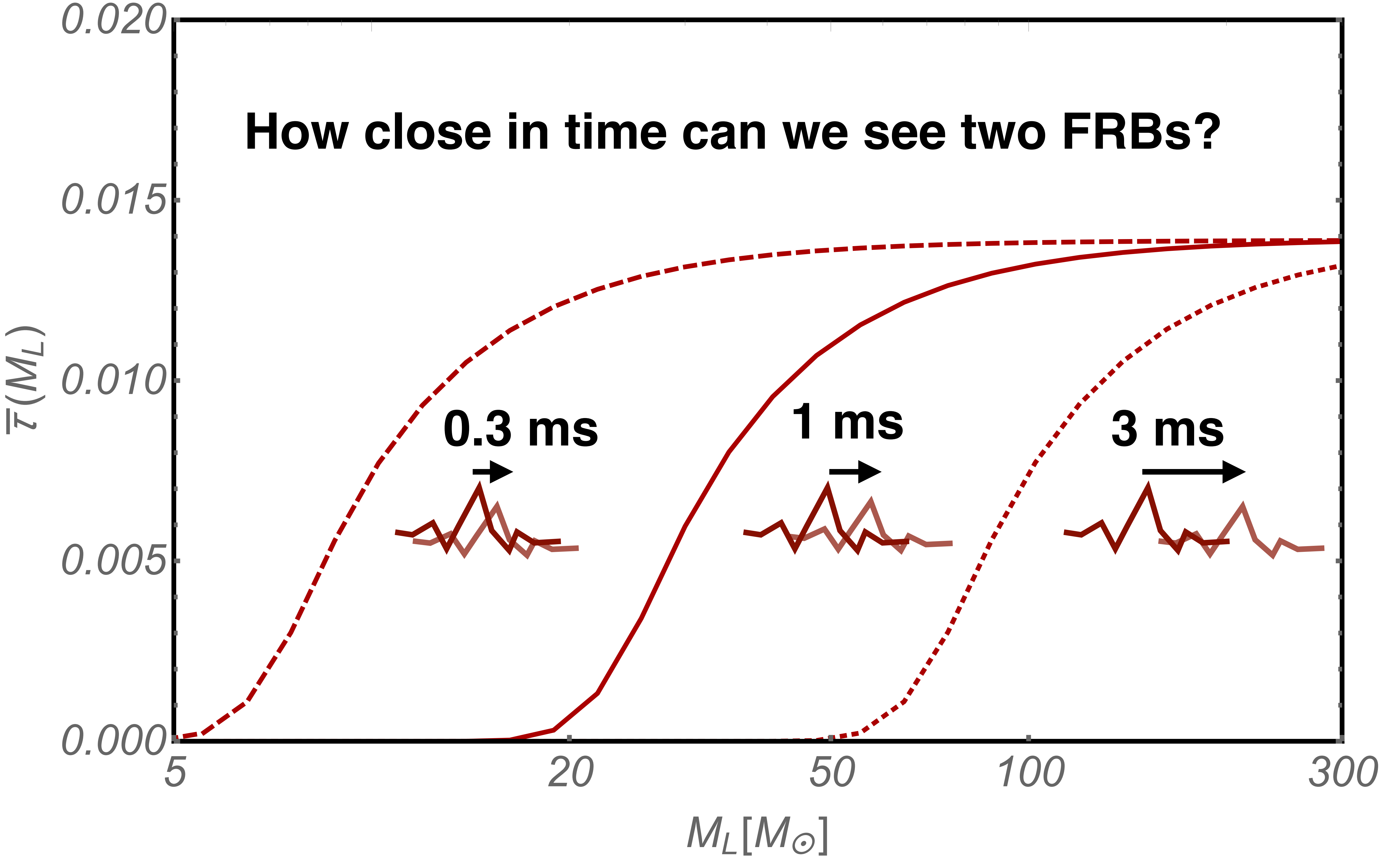
z

For a time delay longer than 1 ms



Optical depth of the FRB population

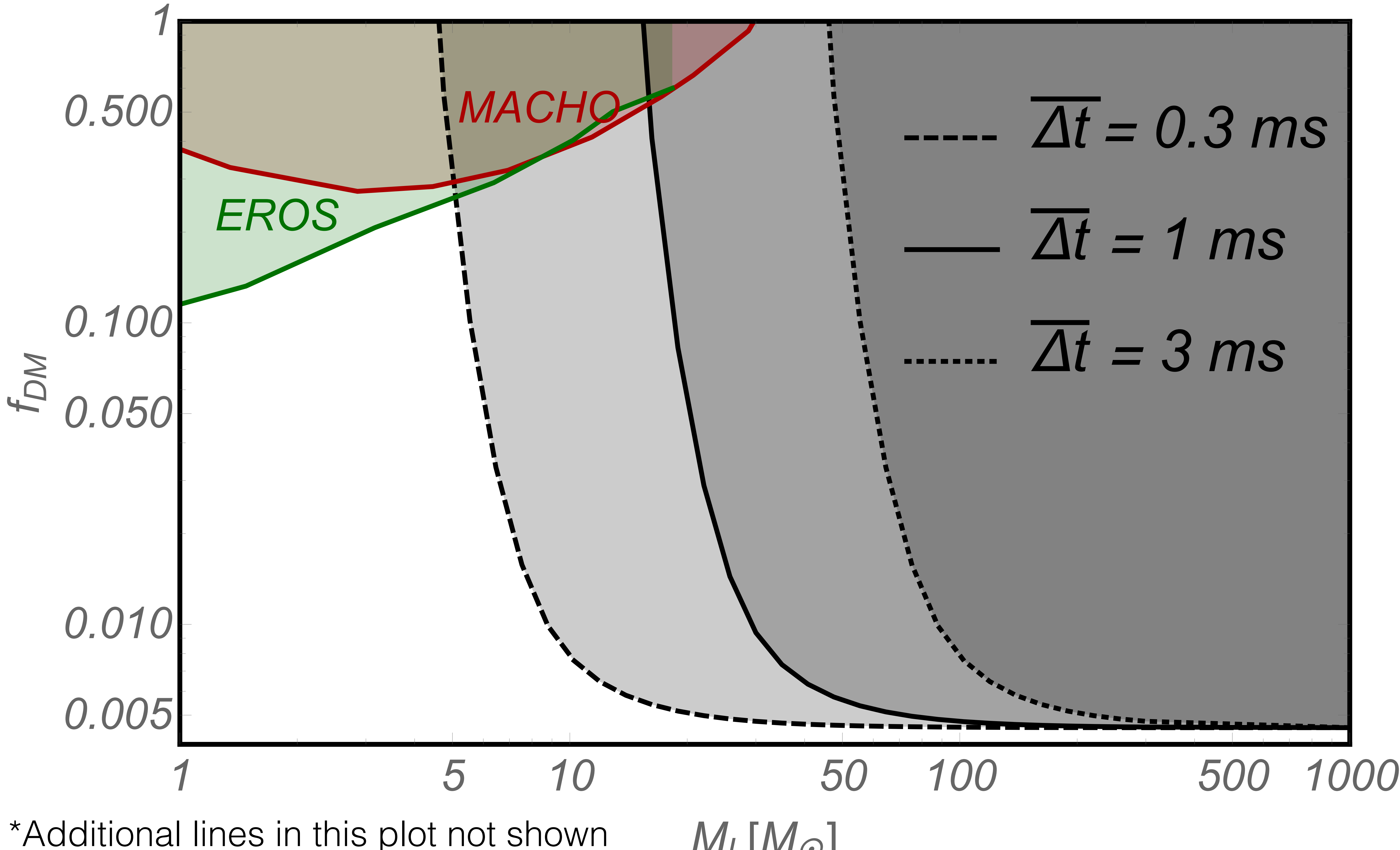


CHIME/HIRAX/HERA will see 10^4 FRBs per year!

$$N_{\mathrm{lensed}} = \tau N_{\mathrm{FRB}}$$

$$N_{\mathrm{lensed}} \sim 10 - 100$$

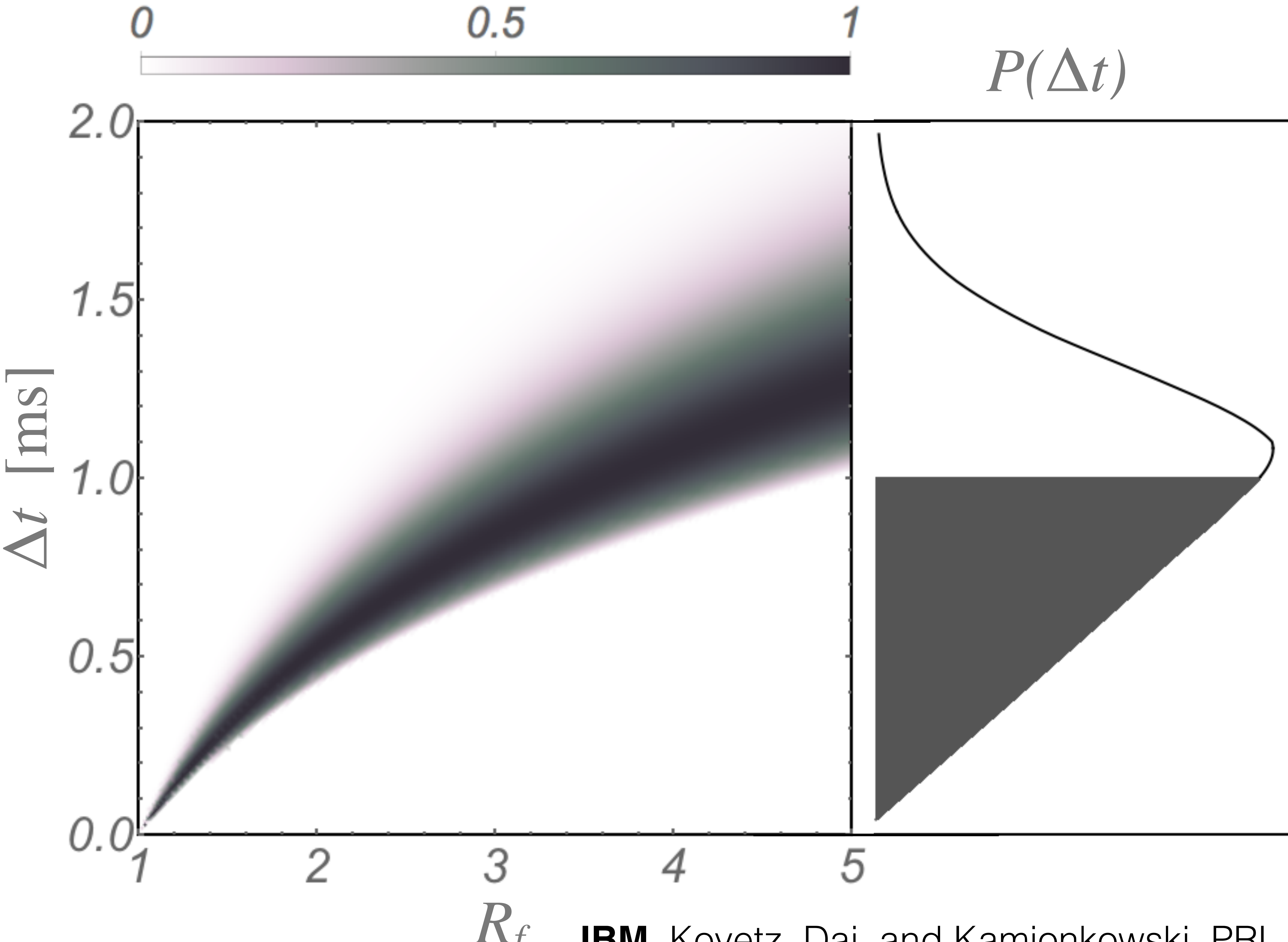
If you do not see any lensed FRBs:*



*Additional lines in this plot not shown

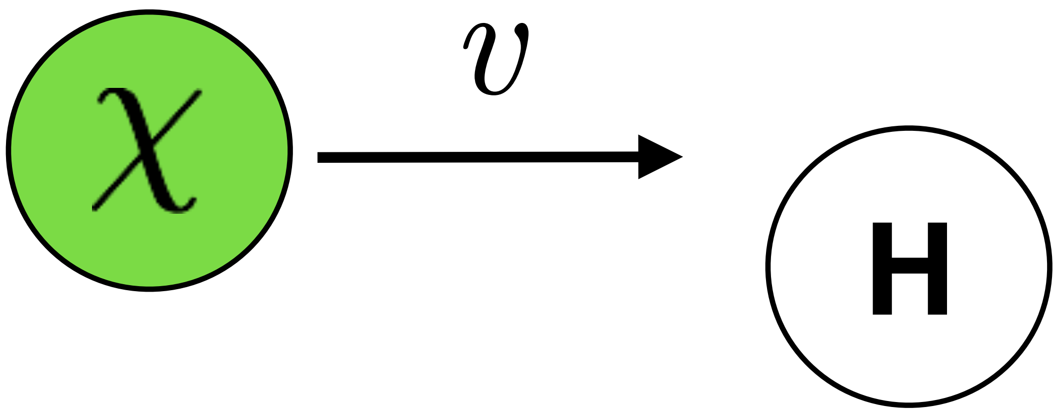
JBM, Kovetz, Dai, and Kamionkowski. PRL 2016

How to identify lensing? E.g. $30\ M_\odot$



JBM, Kovetz, Dai, and Kamionkowski. PRL 2016

A new particle with interactions



$$\sigma = \sigma_0 v^{-4}$$

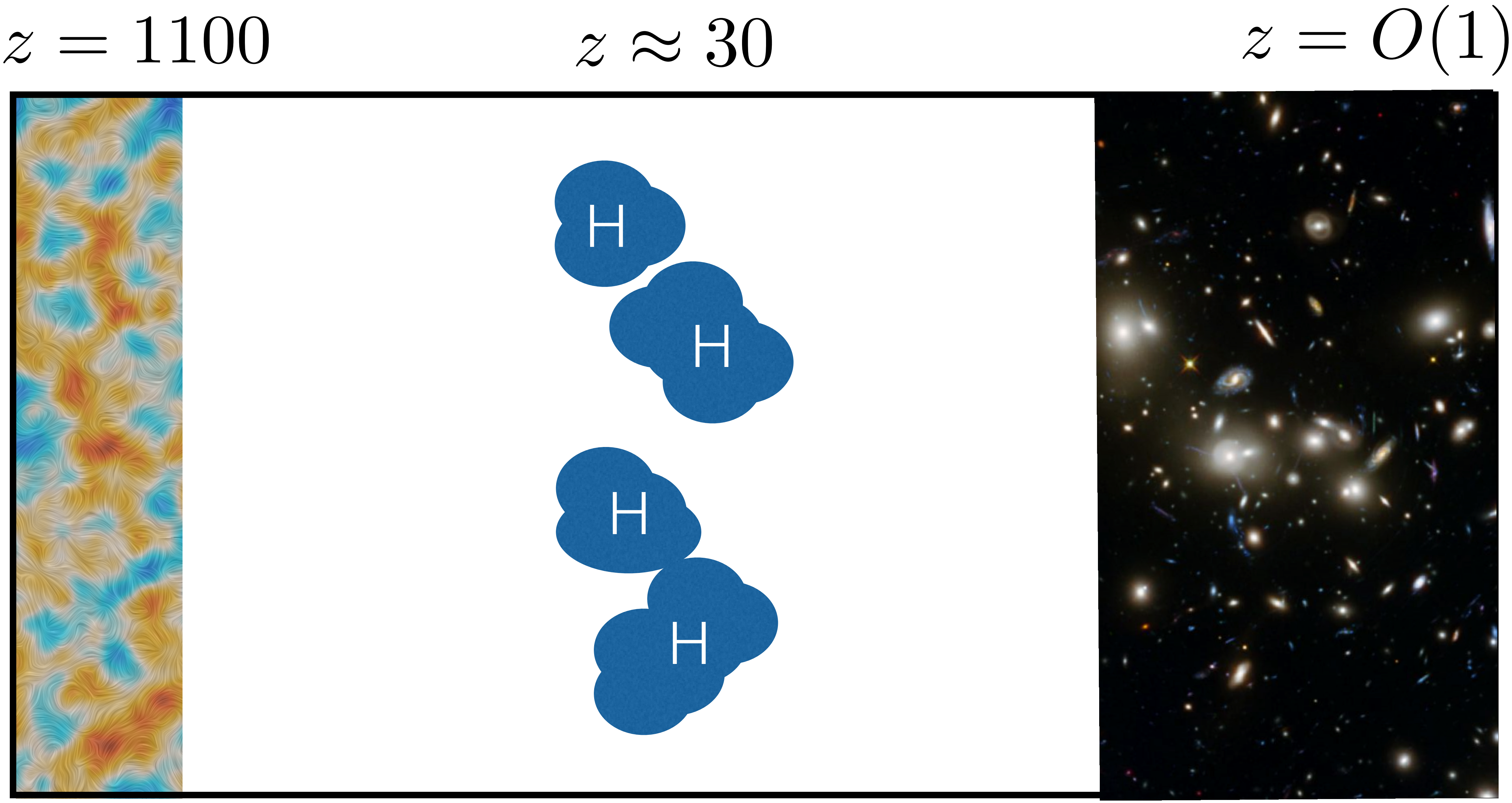
A new particle with interactions

$z = 1100$ $z = O(1)$

$$\sigma = \sigma_0 v^{-4}$$

Dvorkin et al. PRD 2013

A new particle with interactions



$$\sigma = \sigma_0 v^{-4}$$

Triplet

$$\frac{n_1}{n_0} = \frac{g_1}{g_0} e^{-T_*/T_s}$$

Singlet

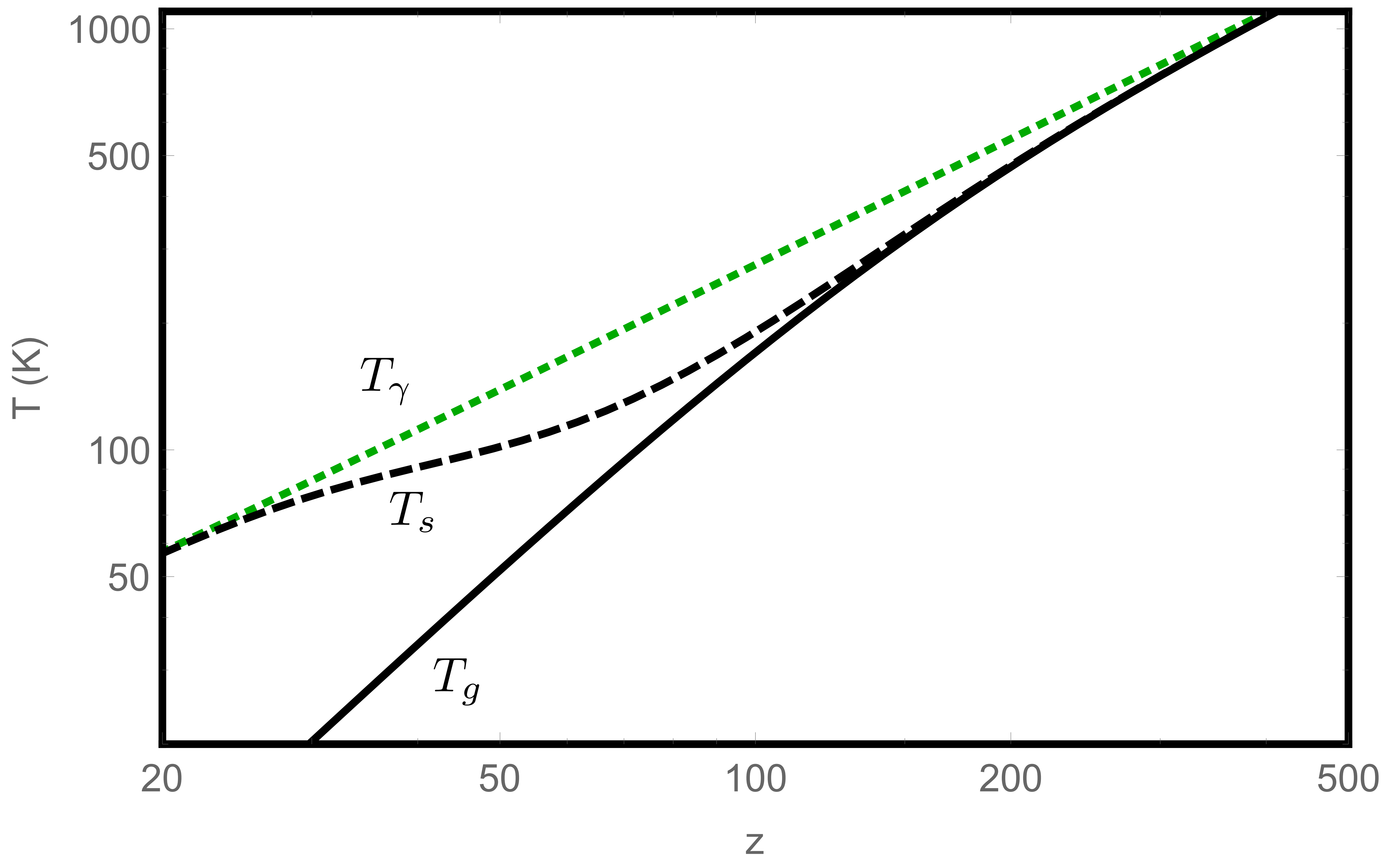
Triplet

$$\frac{n_1}{n_0} = \frac{g_1}{g_0} e^{-T_*/T_s}$$

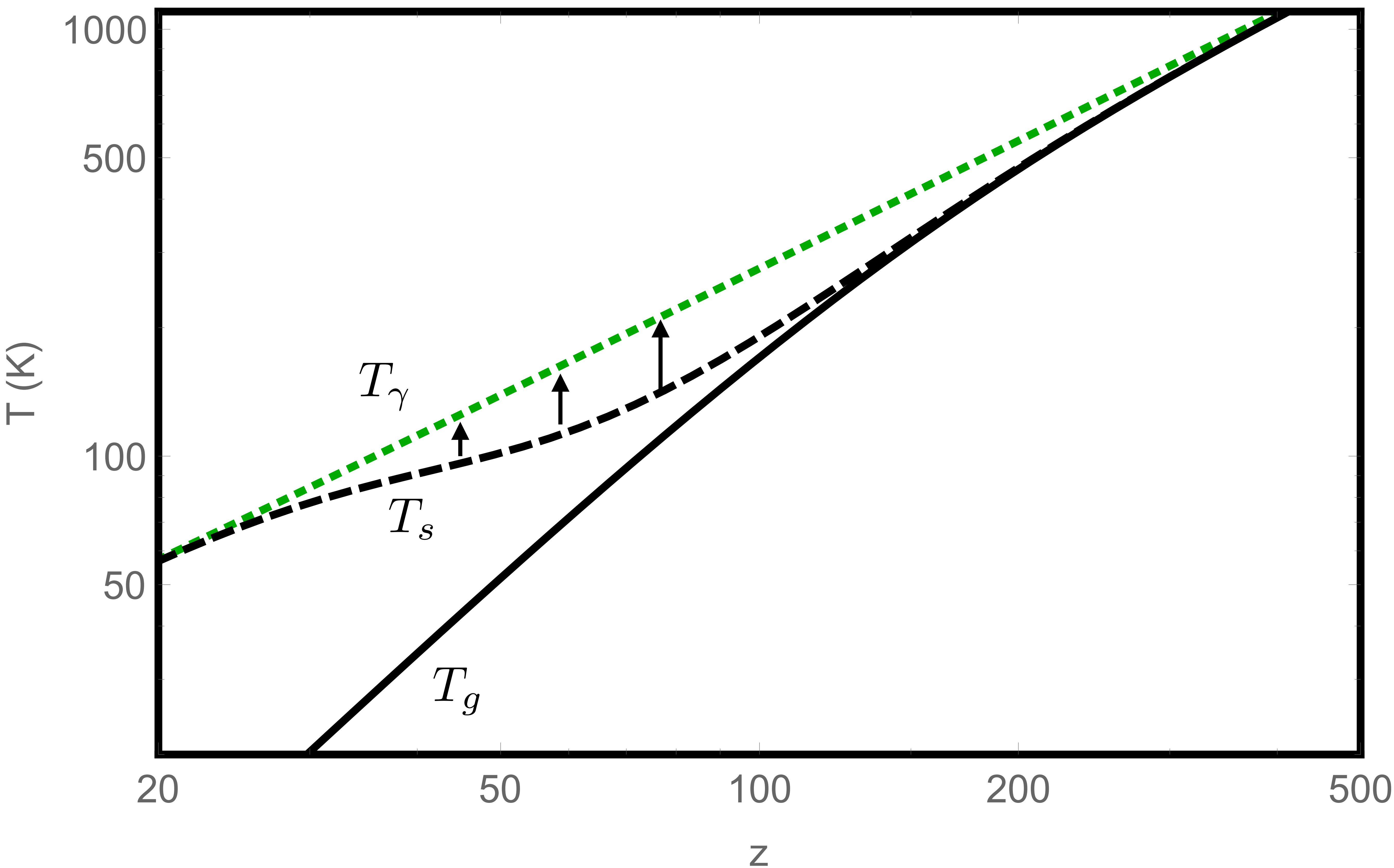
Singlet

3

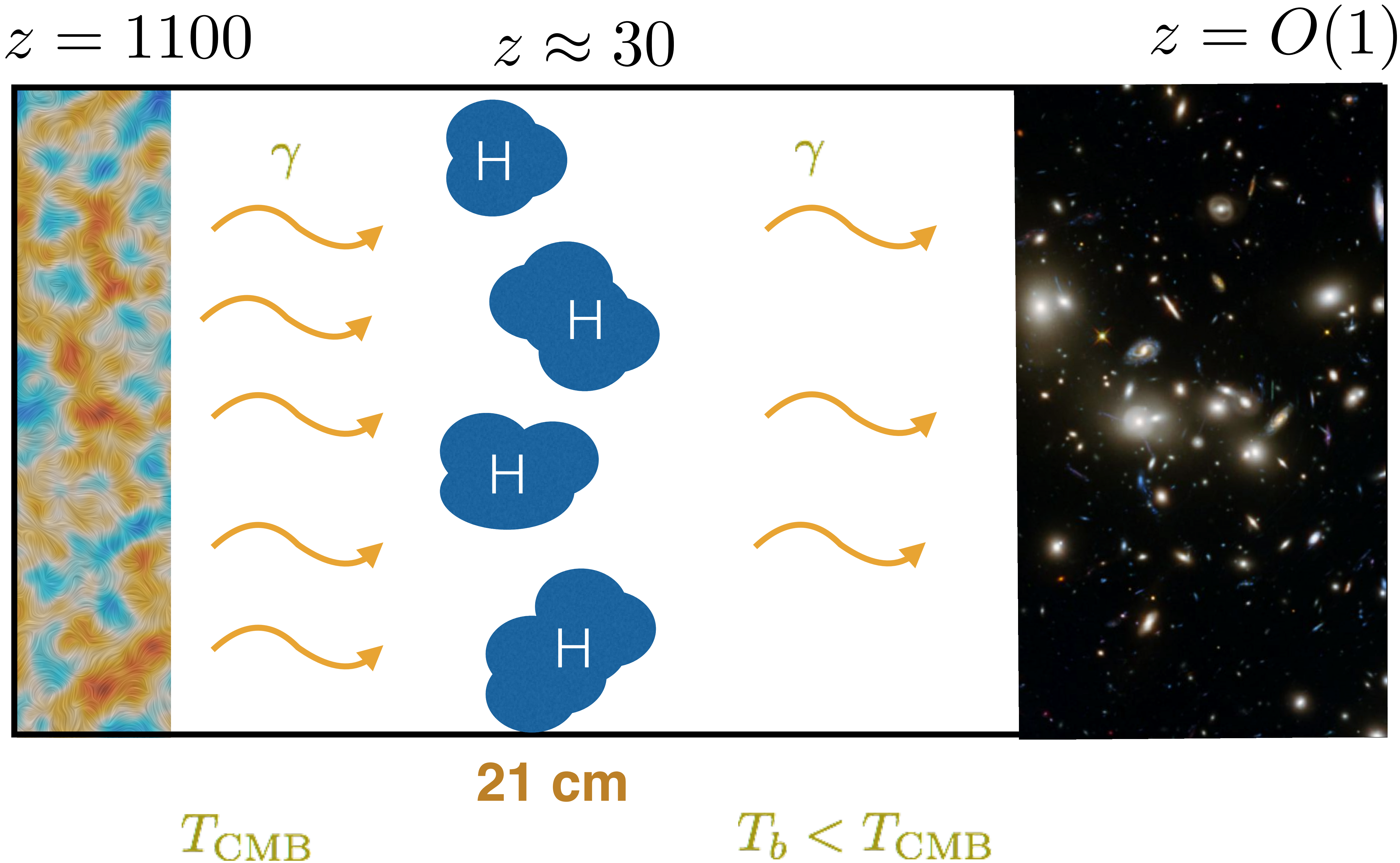
$6\ \mathrm{mK}$



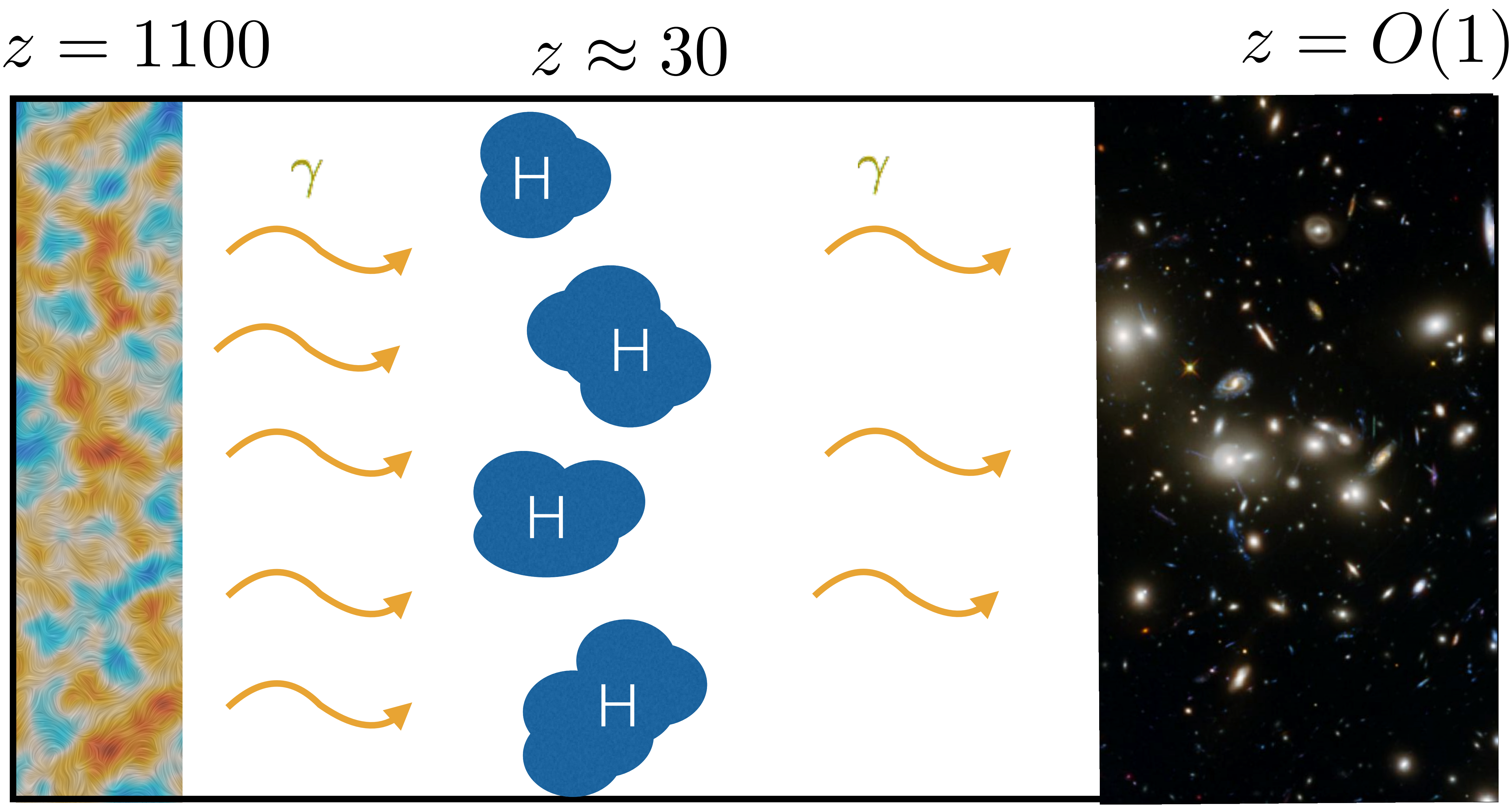
Loeb & Zaldarriaga PRL 92 211301



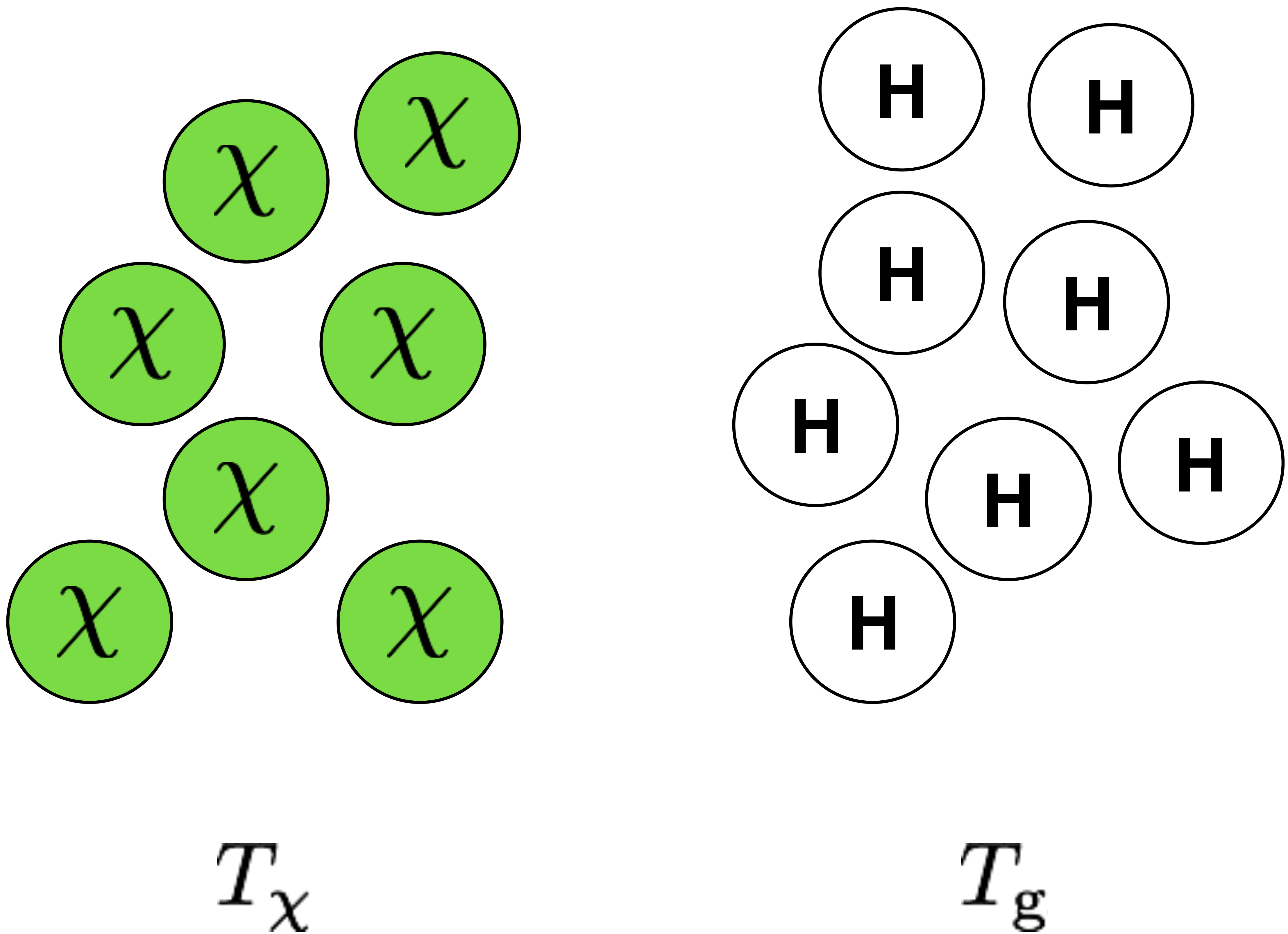
Loeb & Zaldarriaga PRL 92 211301

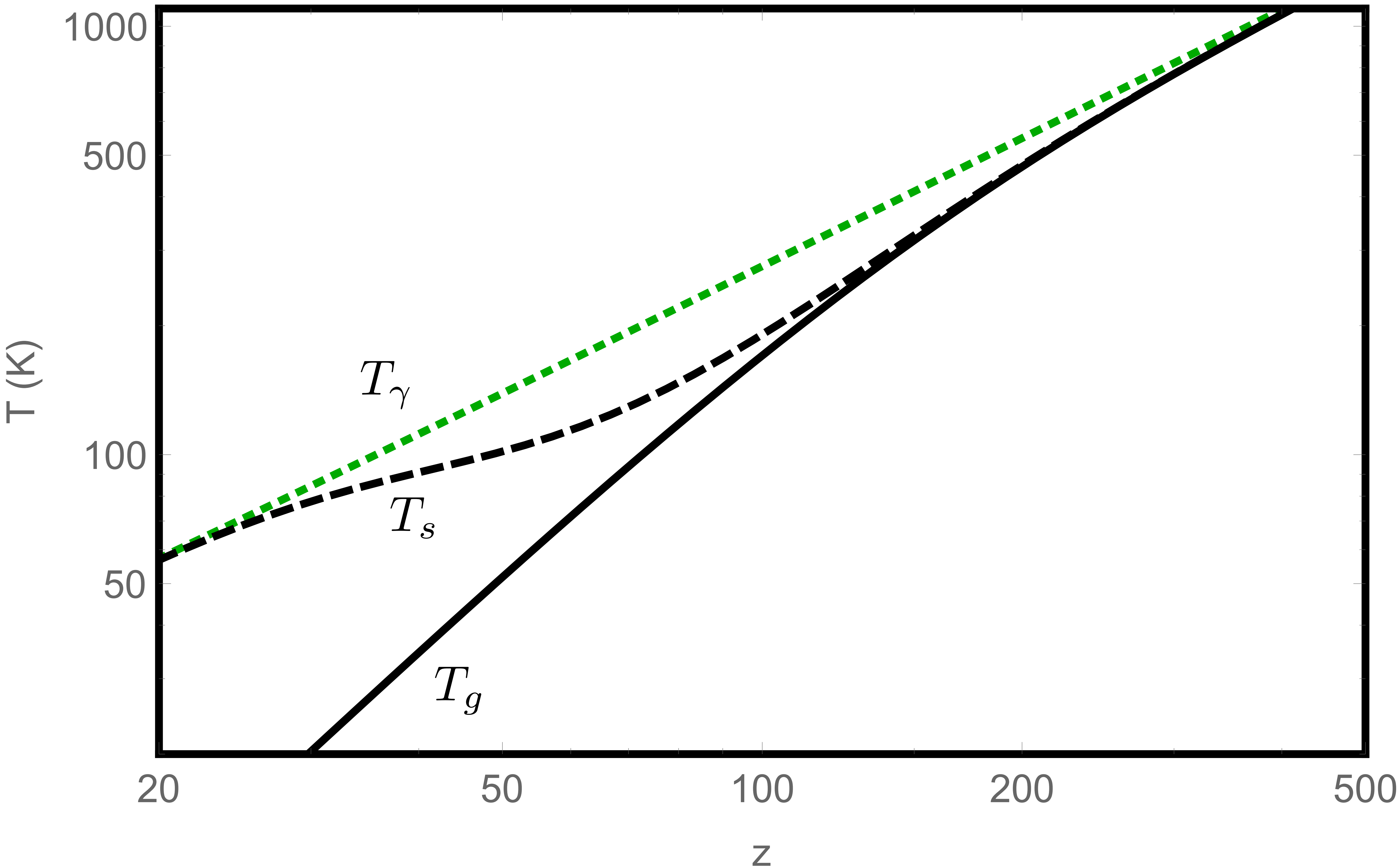


$z = 1100$
$z \approx 30$
$z = O(1)$
γ
H
H
γ
H
H
21 cm
$T_{\rm CMB}$
$T_b < T_{\rm CMB}$

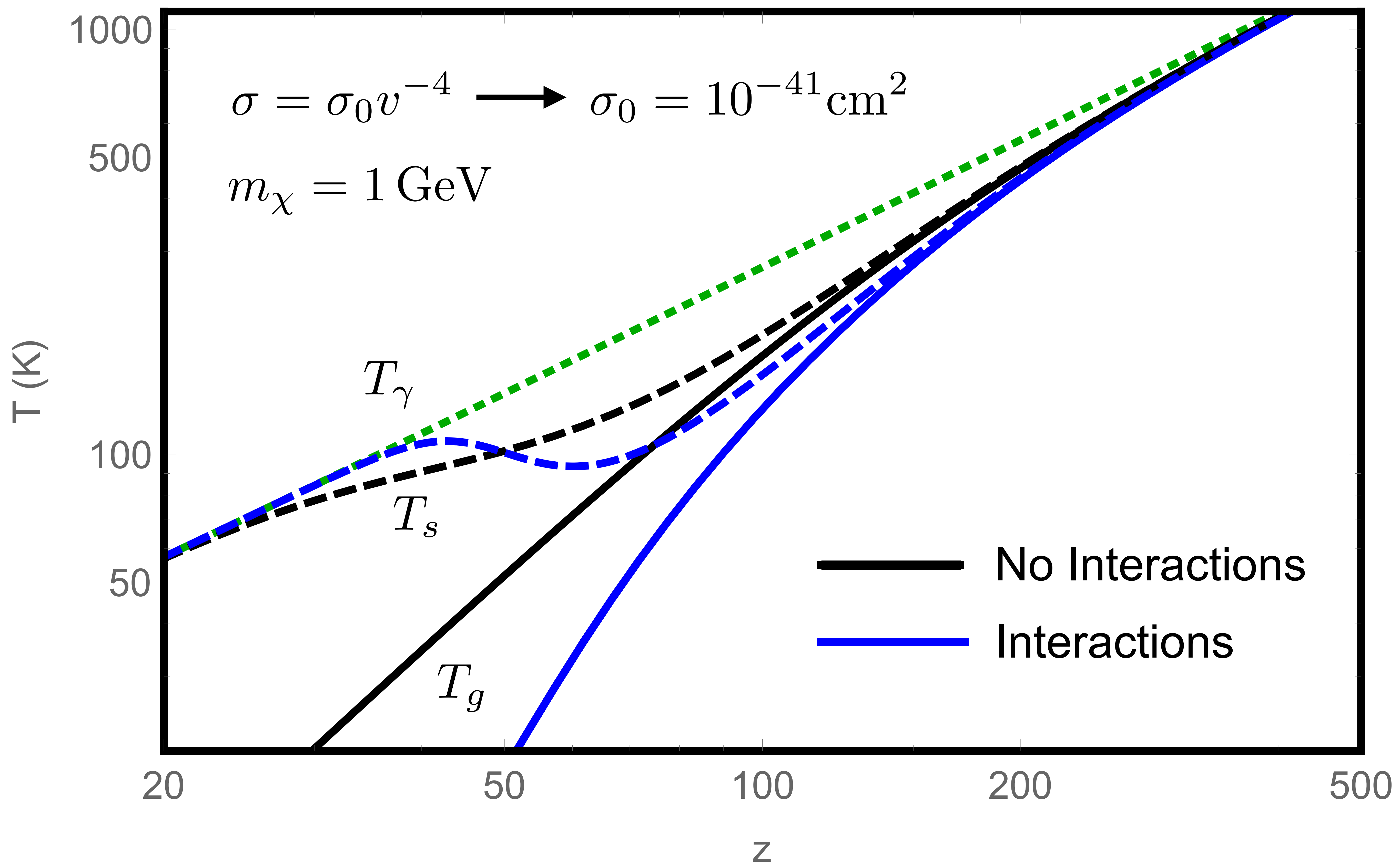


$$T^{(21)} = \tau \frac{T_s - T_{\rm cmb}}{1+z}$$


χ
H
T_χ
T_g



JBM, Kovetz, Ali-Haimoud PRD 2015



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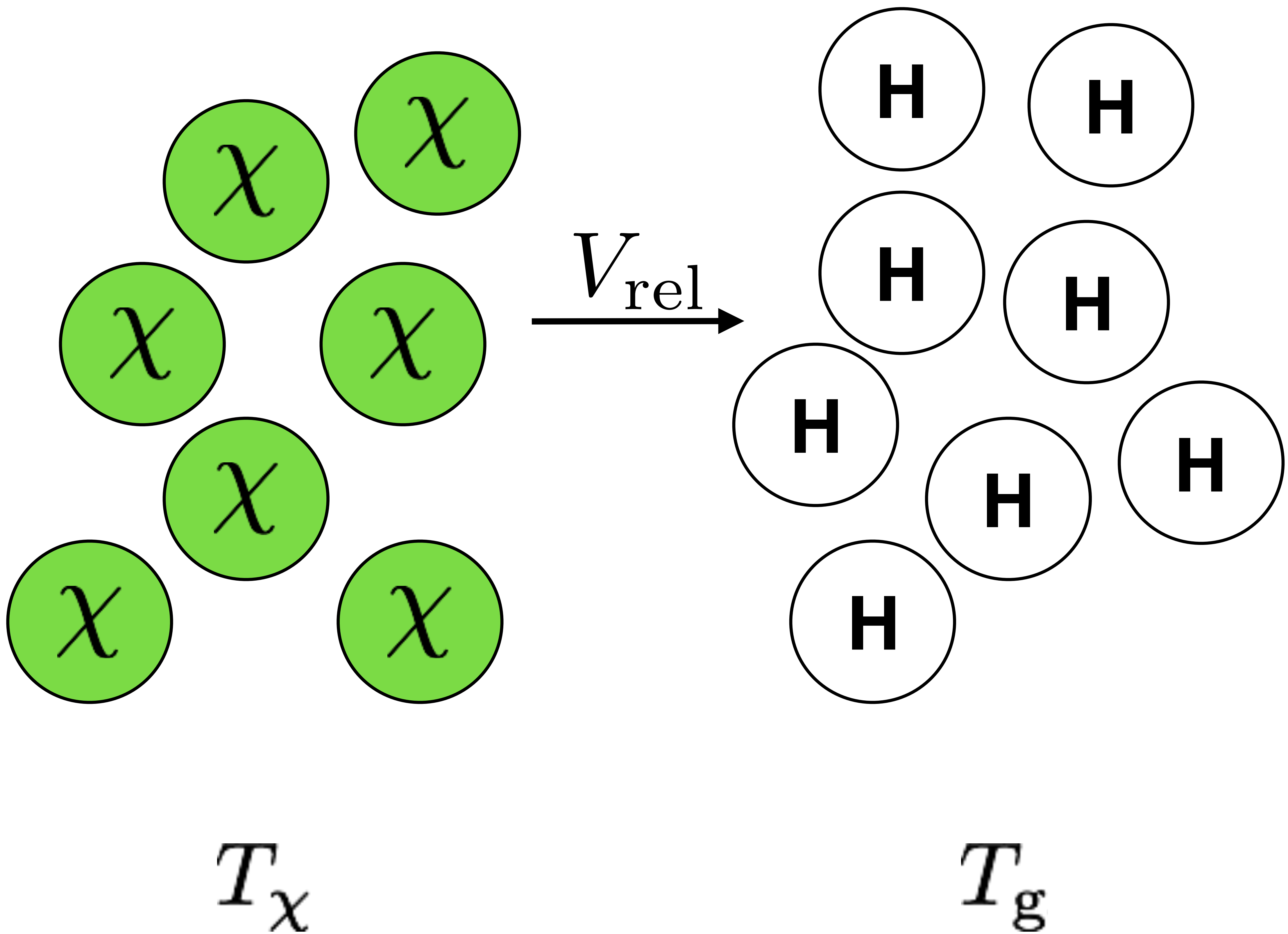
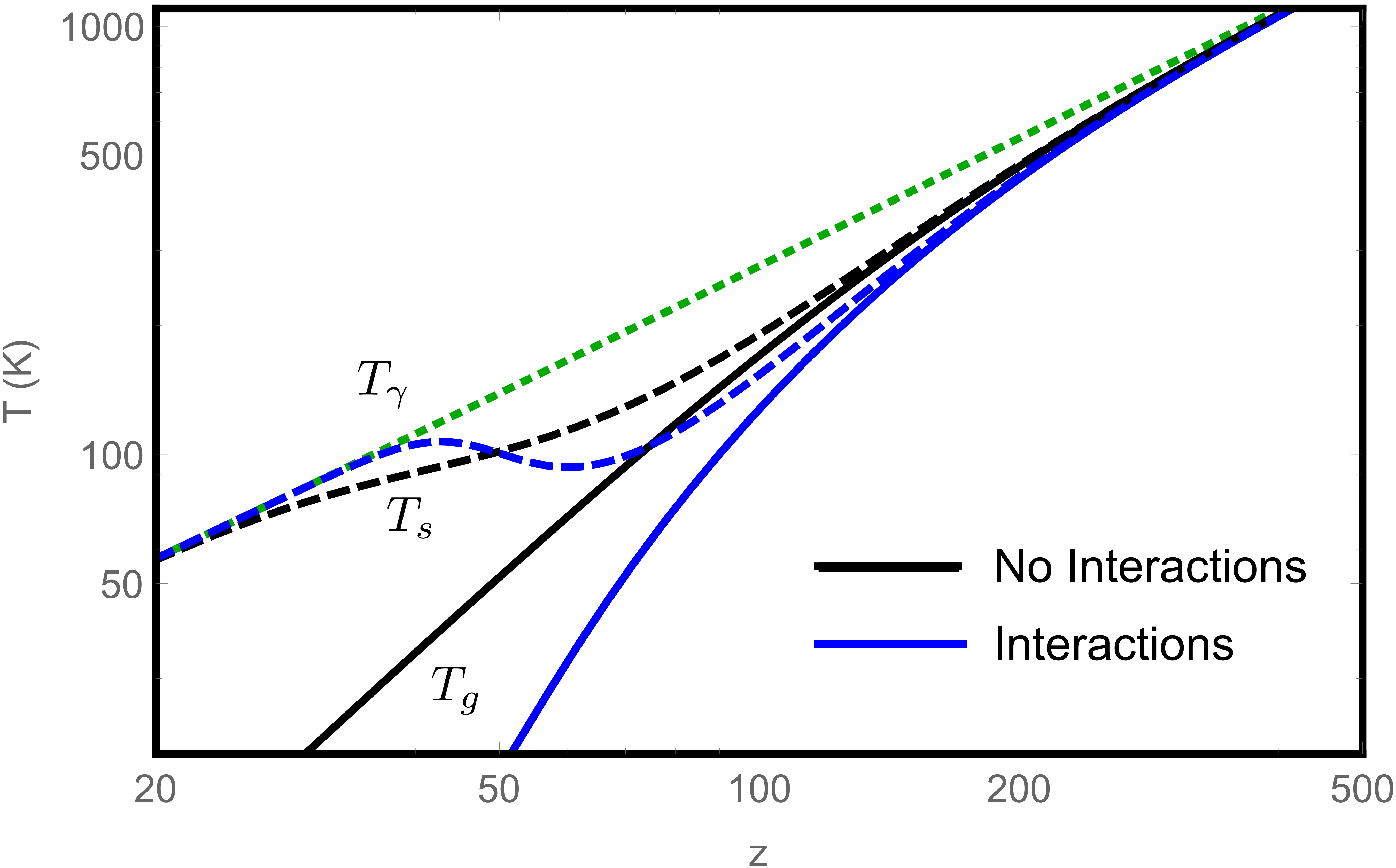
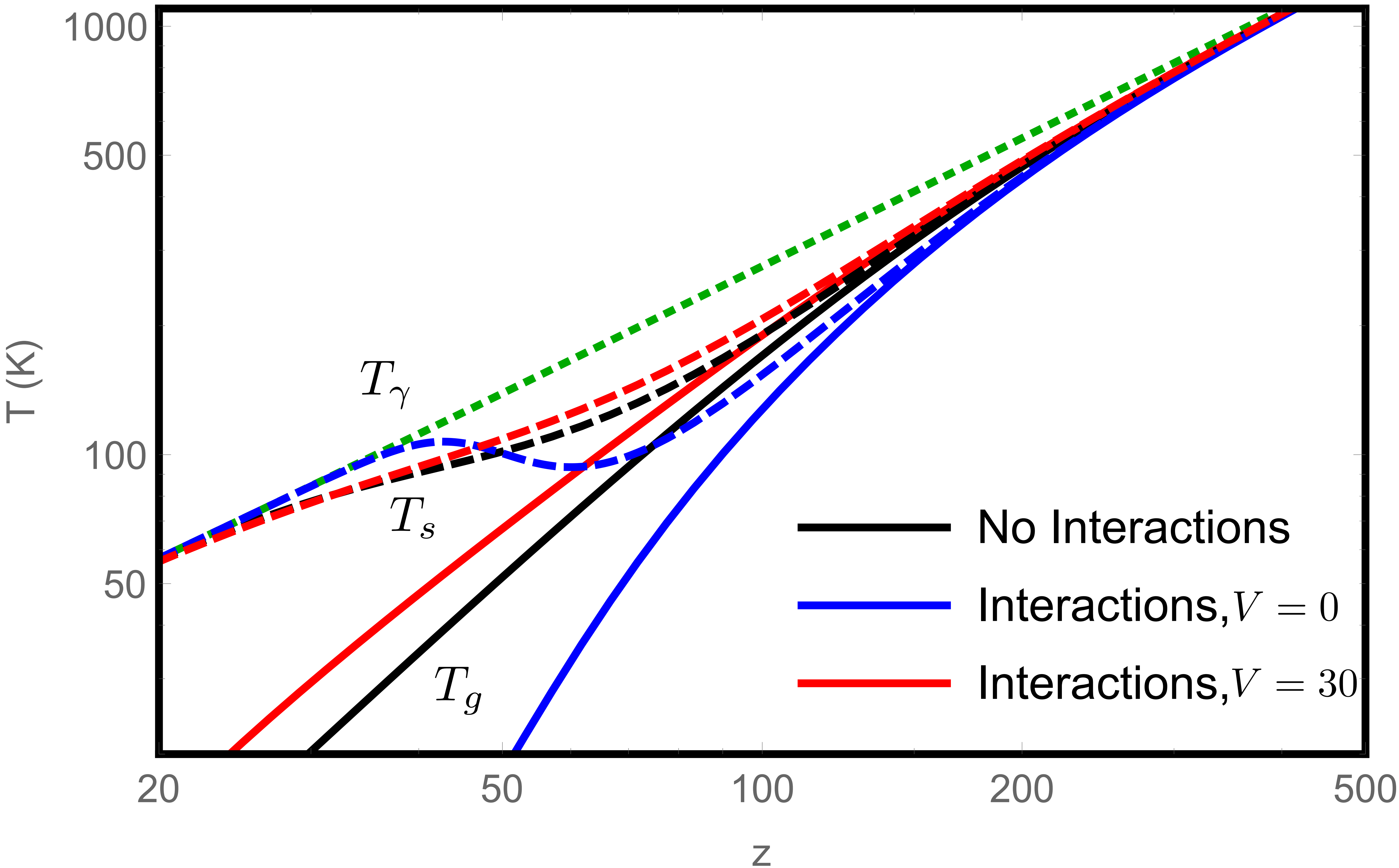


Tseliakhovich and Hirata PRD 2010



JBM, Kovetz, Ali-Haimoud PRD 2015



JBM, Kovetz, Ali-Haimoud PRD 2015

$$T^{(21)} = \tau \frac{T_s - T_{\rm cmb}}{1+z}(V_{\rm rel})$$

Relative velocity at decoupling

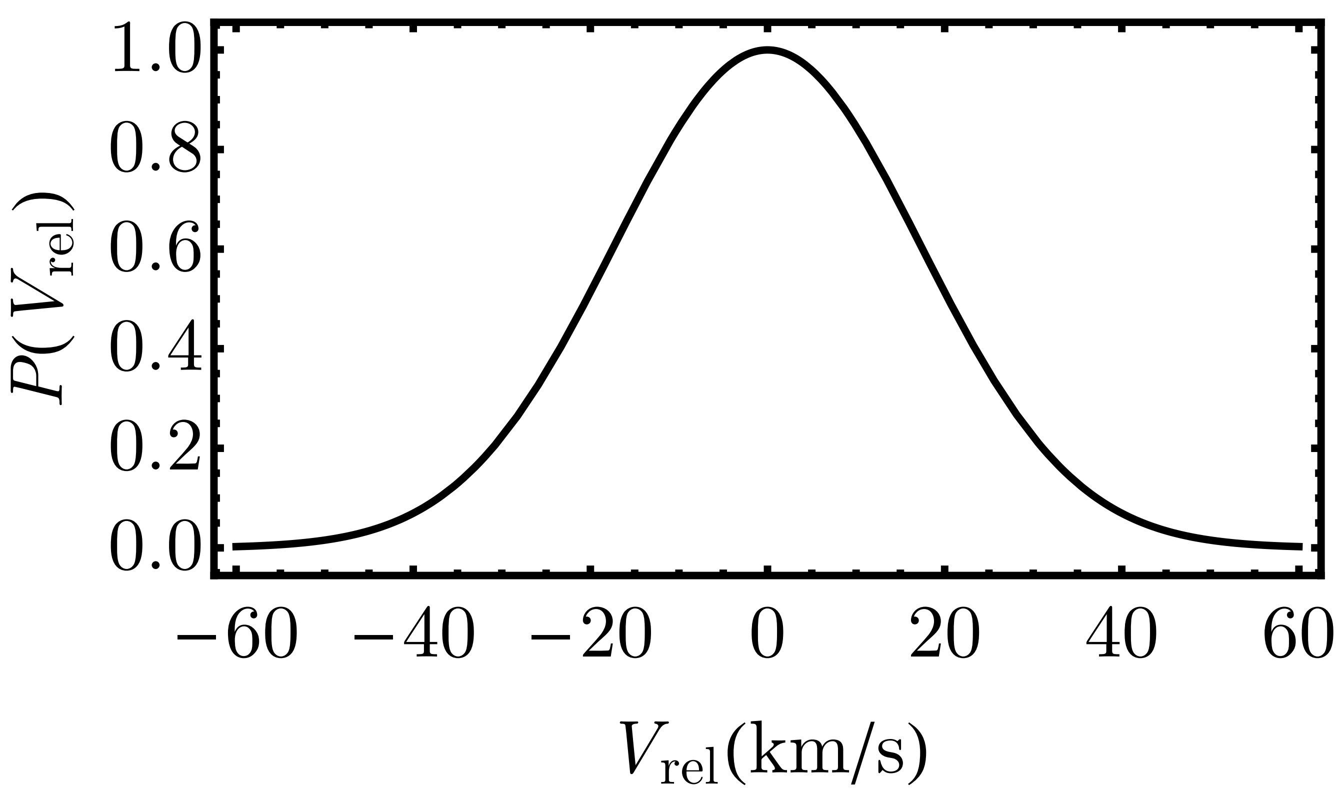
JBM, Kovetz, Ali-Haimoud PRD 2015

$$T^{(21)} = \tau \frac{T_s - T_{\rm cmb}}{1+z}(V_{\rm rel})$$

Relative velocity at decoupling

$$\left\langle T^{(21)} \right\rangle = \int {\rm d}^3 V_{\rm rel} \mathcal{P}(V_{\rm rel}) T^{(21)}(V_{\rm rel})$$

$V_{\rm rms} \approx 30\,{\rm km/s}$



JBM, Kovetz, Ali-Haimoud PRD 2015

$$T^{(21)} = \tau \frac{T_s - T_{\rm cmb}}{1+z}(V_{\rm rel})$$

Relative velocity at decoupling

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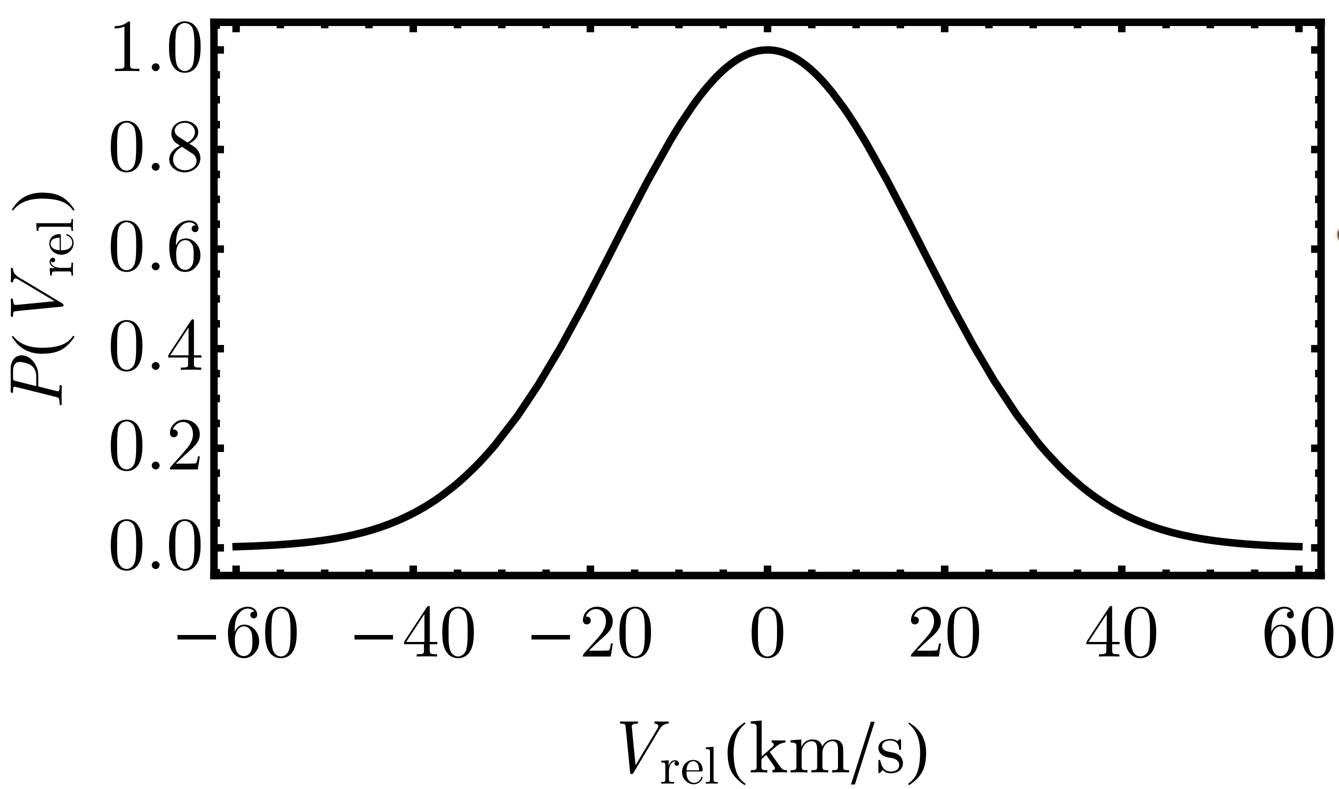
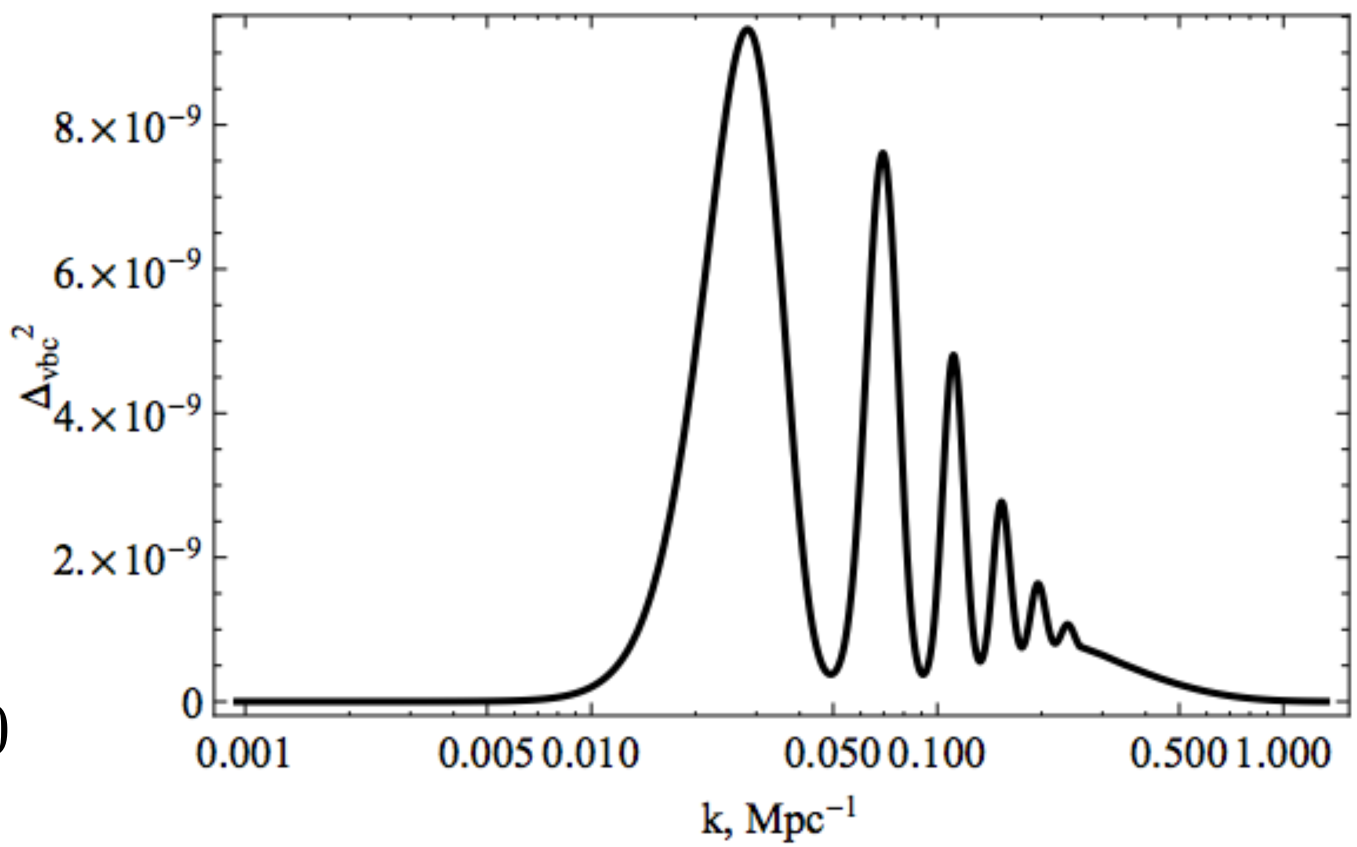


Tseliakhovich and Hirata PRD 2010



JBM, Kovetz, Ali-Haimoud PRD 2015

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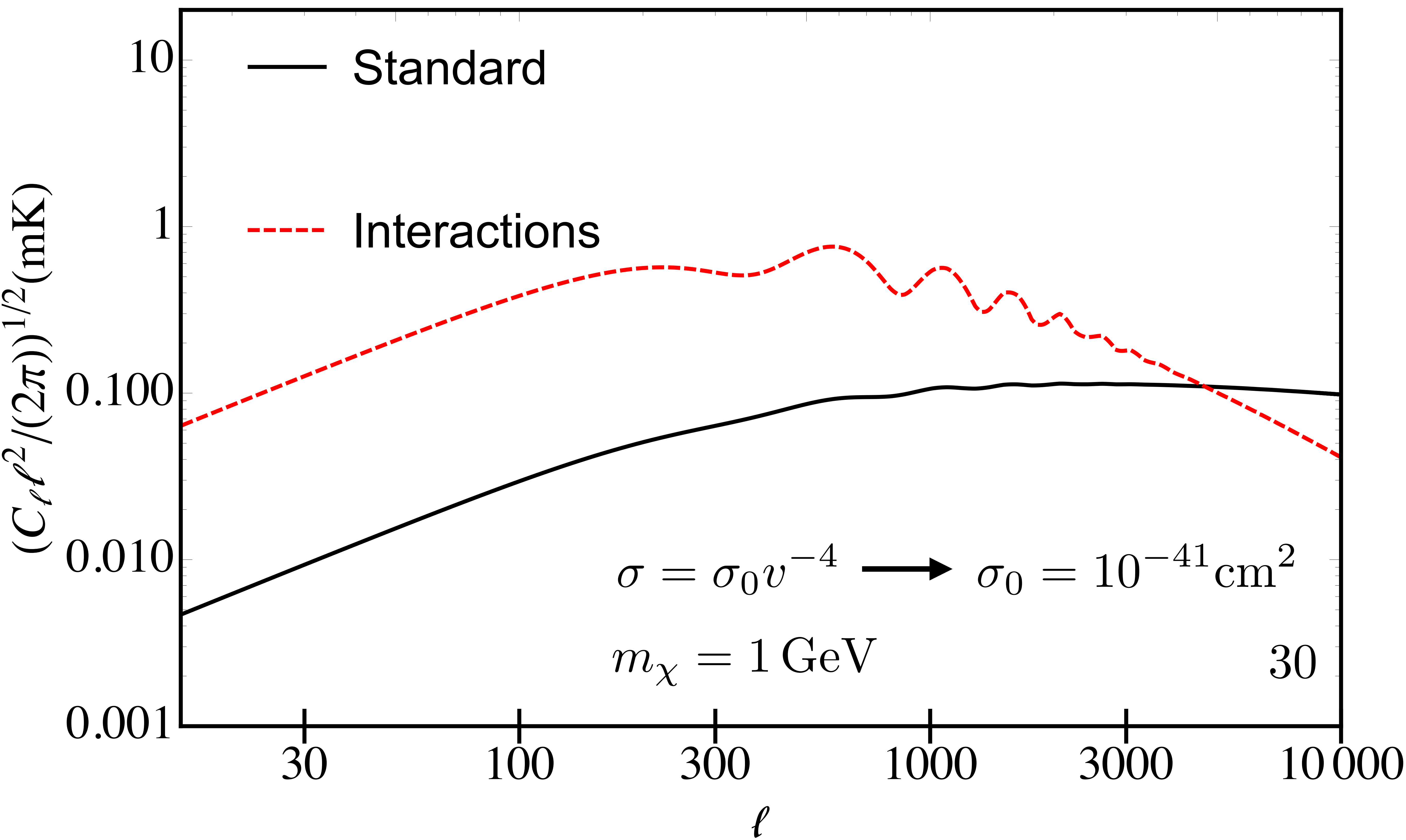
← Relative velocity at decoupling

$$\left\langle T^{(21)} \right\rangle = \int \mathrm{d}^3 V_{\rm rel} \mathcal{P}(V_{\rm rel}) T^{(21)}(V_{\rm rel})$$

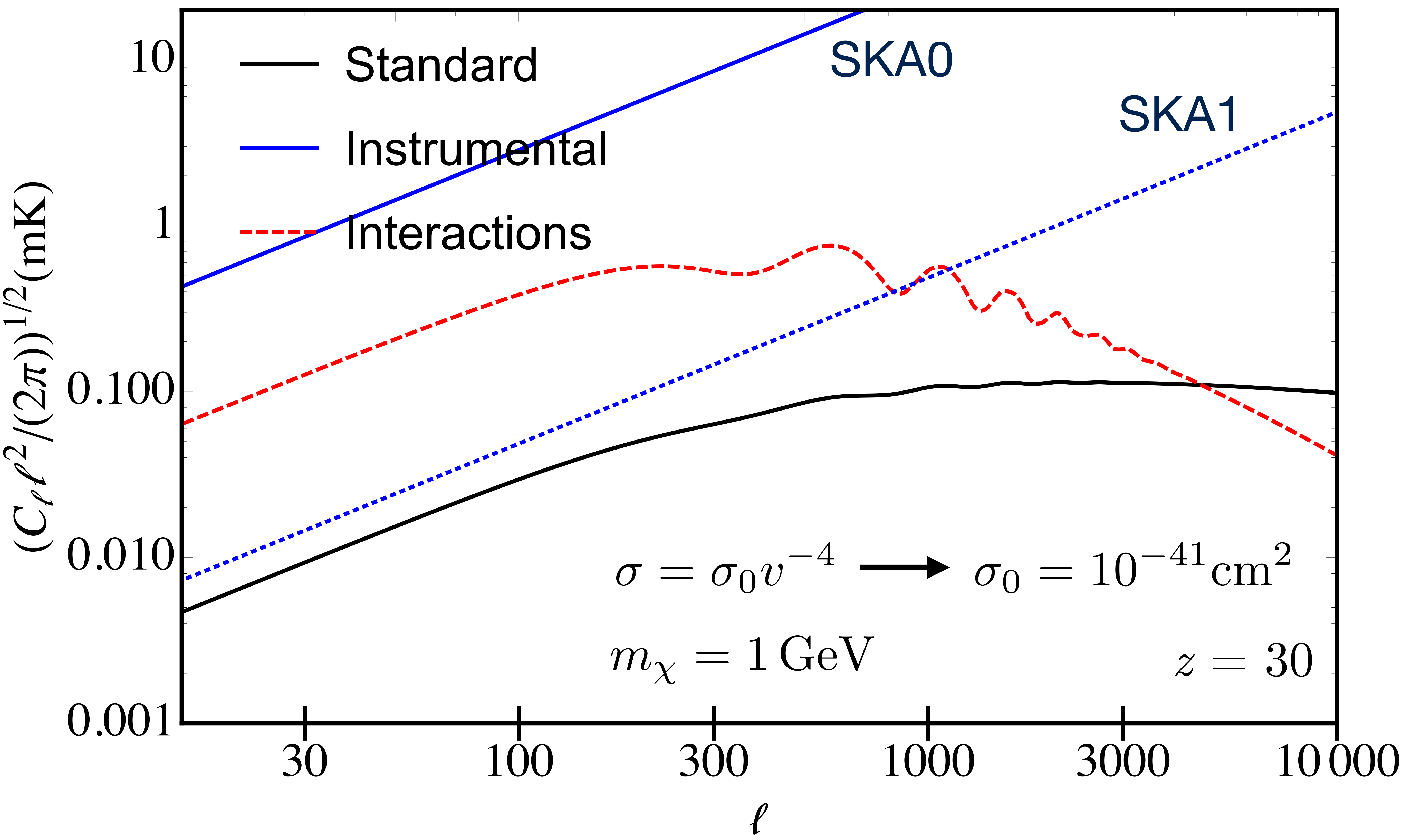
$$T^{(21)}_{\rm rms} = \sqrt{\left\langle \left(T^{(21)}\right)^2 \right\rangle - \left\langle T^{(21)} \right\rangle^2}$$

$$P_{21}^{\rm new}(k) = \left(T^{(21)}_{\rm rms}\right)^2 P_{V_{\rm rel}^2}(k)$$

JBM, Kovetz, Ali-Haimoud PRD 2015

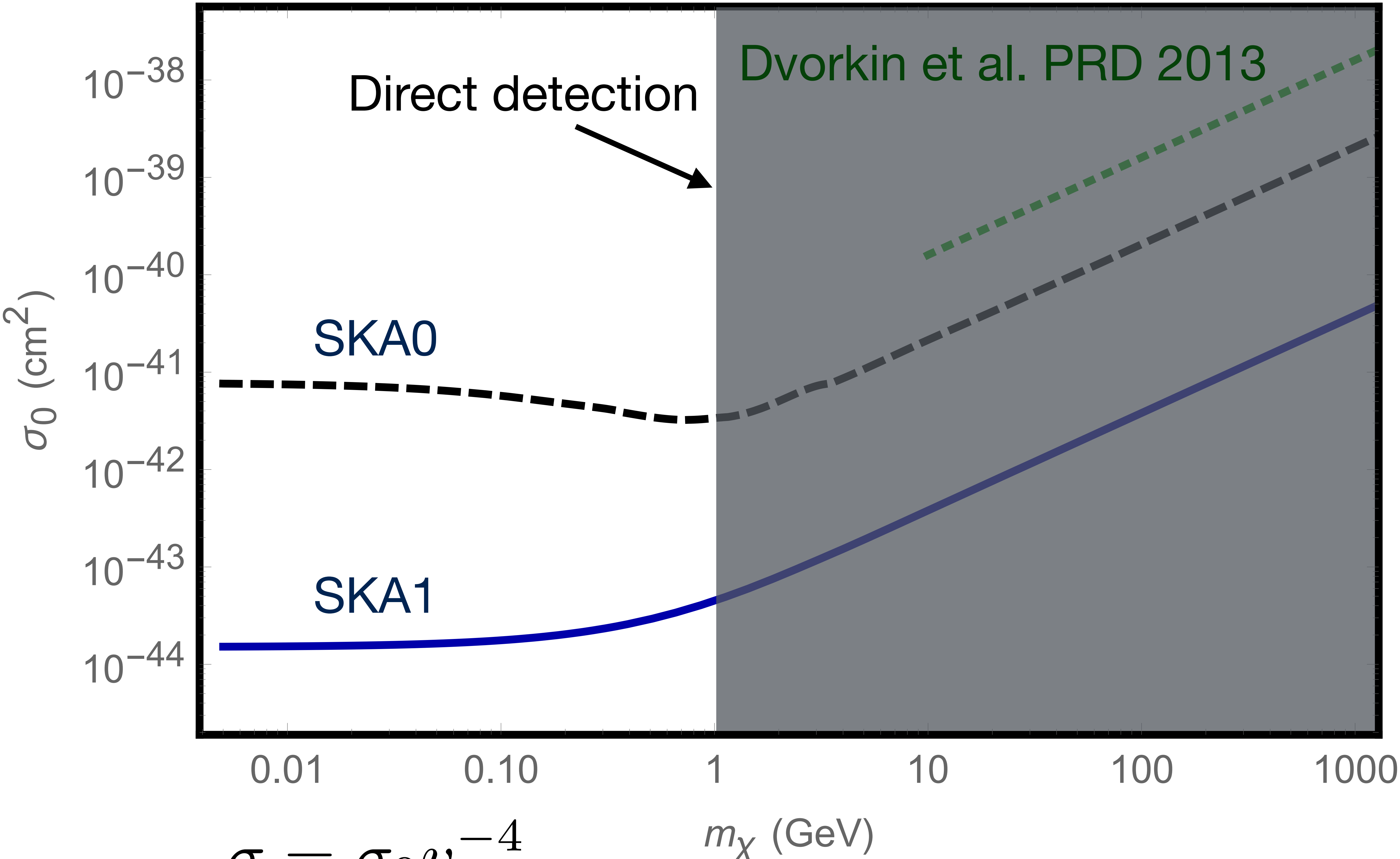


JBM, Kovetz, Ali-Haimoud PRD 2015



JBM, Kovetz, Ali-Haimoud PRD 2015

Forecast $z=20\text{-}30$

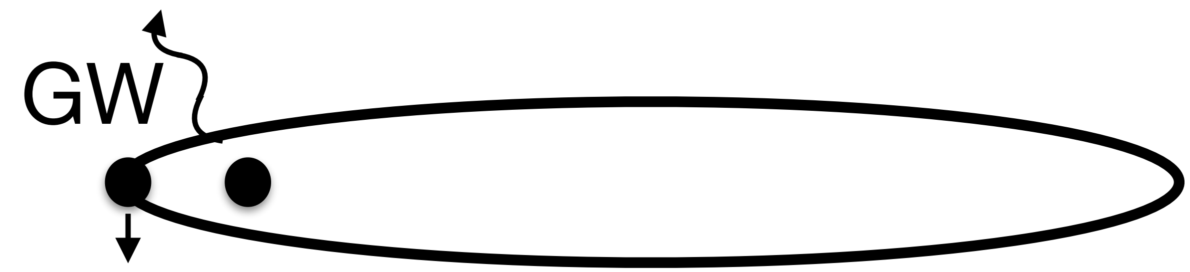


$$\sigma = \sigma_0 v^{-4}$$

JBM, Kovetz, Ali-Haimoud PRD 2015

Is the dark matter compact?

(Bird, Cholis, **JBM** et al., arXiv: 1603.00464)



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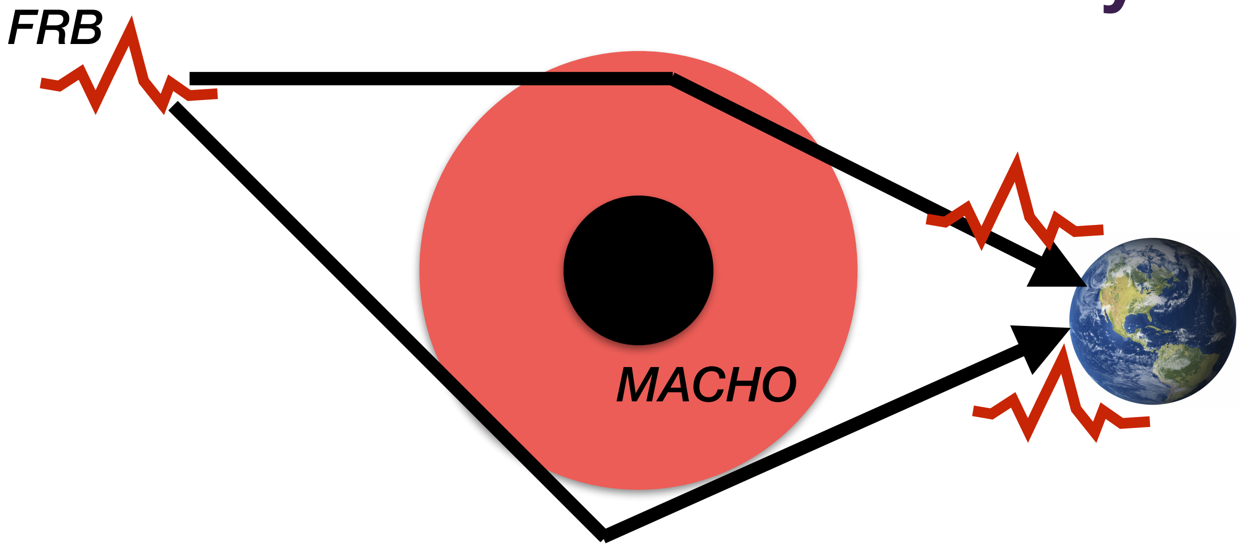
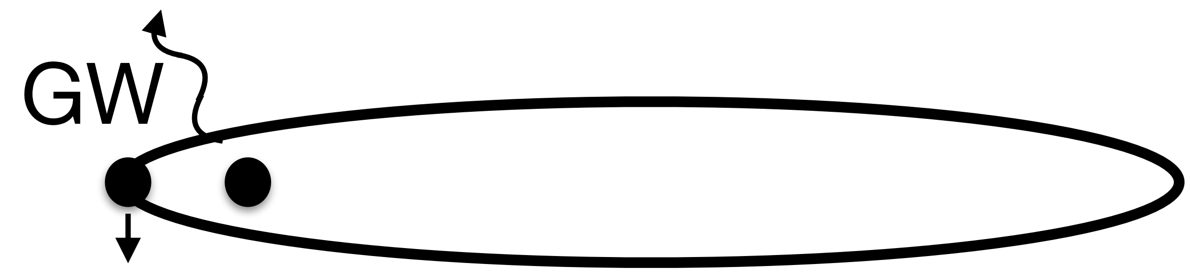


→ FRB lensing

(**JBM** et al., arXiv: 1605.00008)



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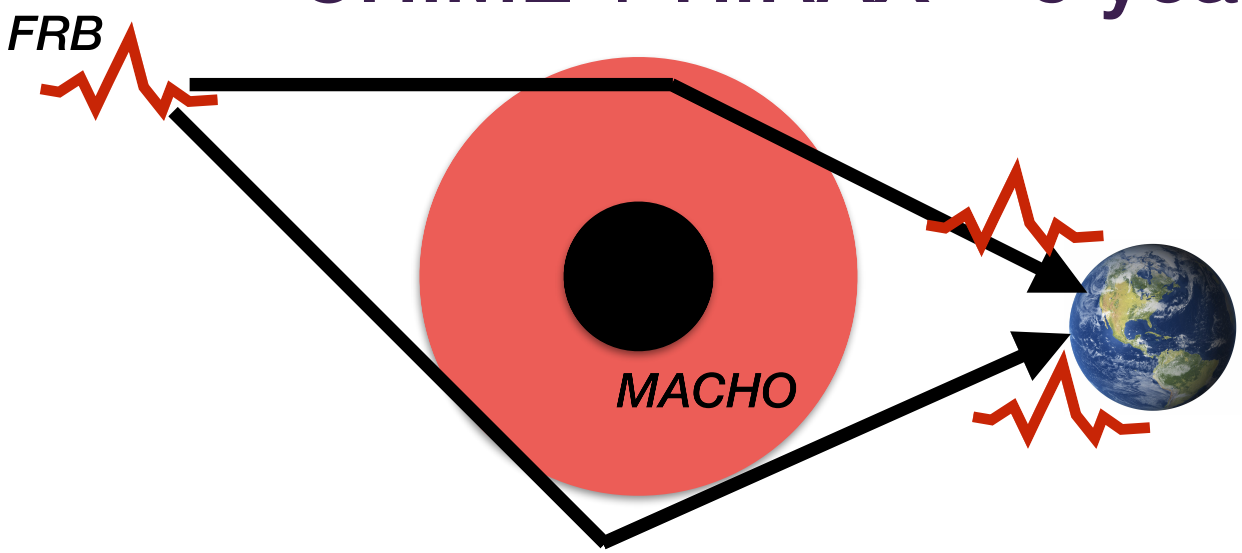
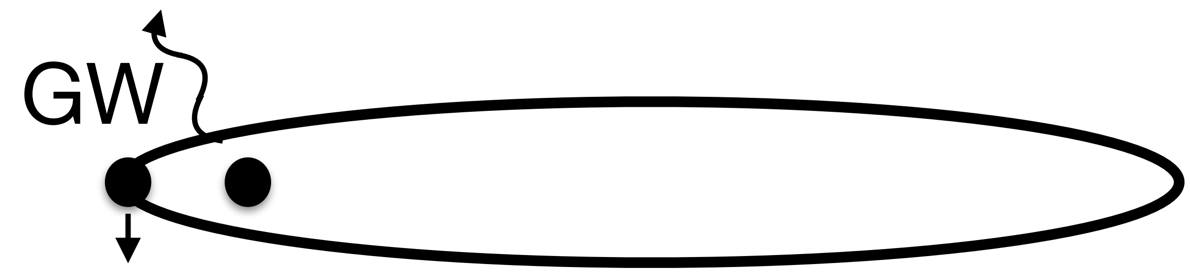
CHIME + HIRAX ~ 5 years





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CMB anisotropies; spectral distortions

Ricotti et al. arXiv:0709.0524

Microlensing of distant QSOs

Mediavilla et al. arXiv:0910.3645

Hawkins arXiv:1106.3875

Disruption of stellar clusters

Brandt arXiv:1605.03665

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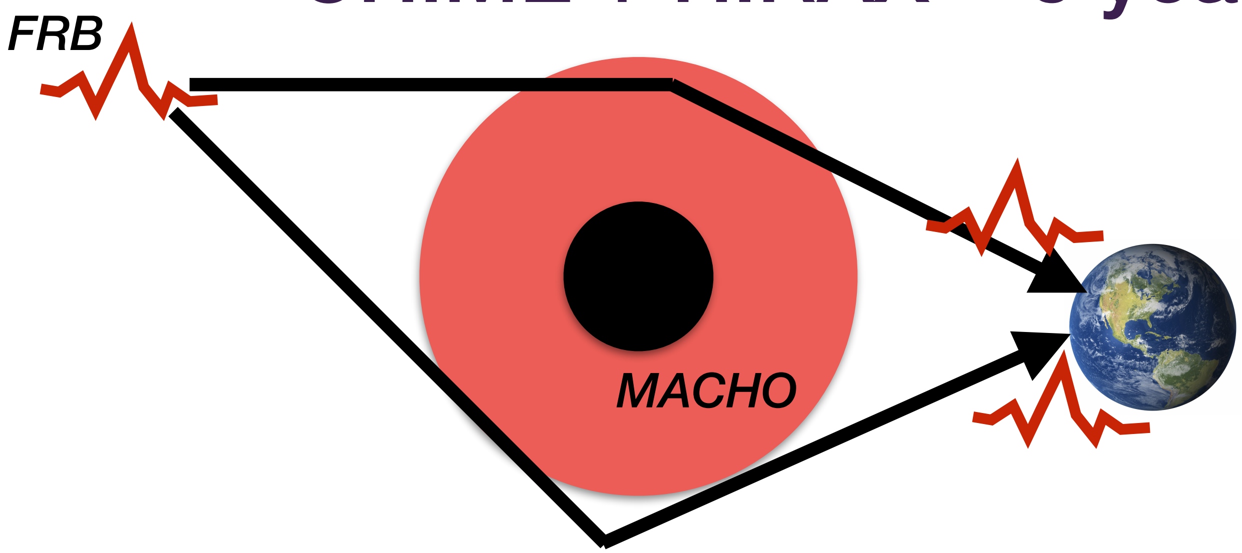

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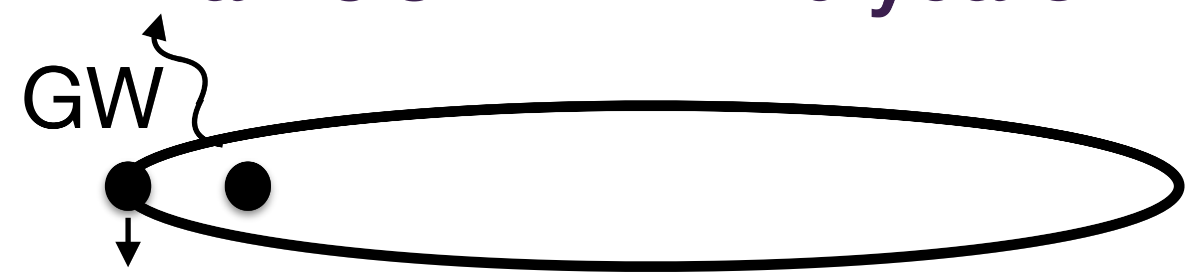
aLIGO + ET ~ 10 years



Spatial Clustering

(Raccanelli et al. (including **JBM**), arXiv: 1605.01405)

Orbital eccentricity

(Cholis et al. (including **JBM**), arXiv: 1606.07437)

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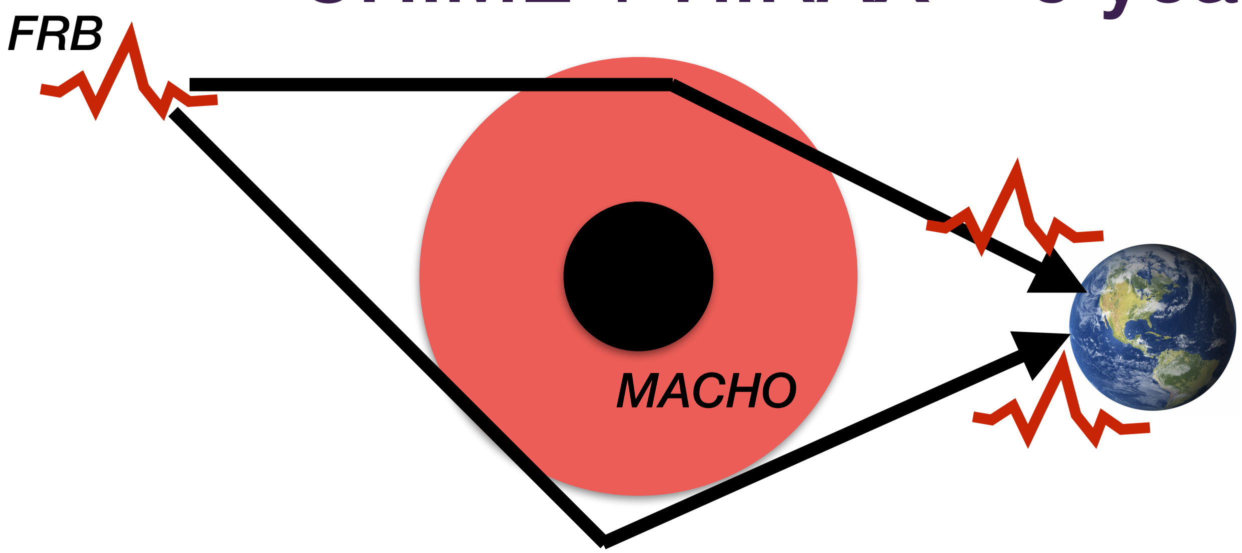

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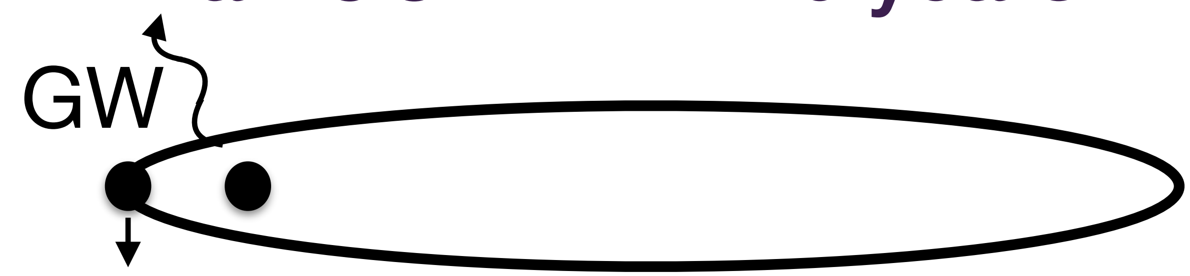

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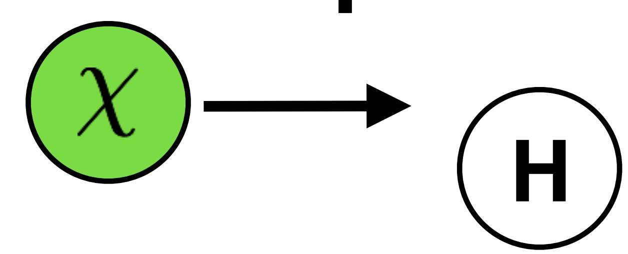
Or is it a particle?



HERA + SKA ~ 10 years

(**JBM,** Kovetz, and Ali-Haimoud, arXiv: 1509.00029)