Talk prepared for Dark Matter beyond the Weak scale, 25th of March

CMB bounds on accreting Extended Dark matter Objects

Based on arXiv:2403.13072

Sergio Sevillano Muñoz

Durham University

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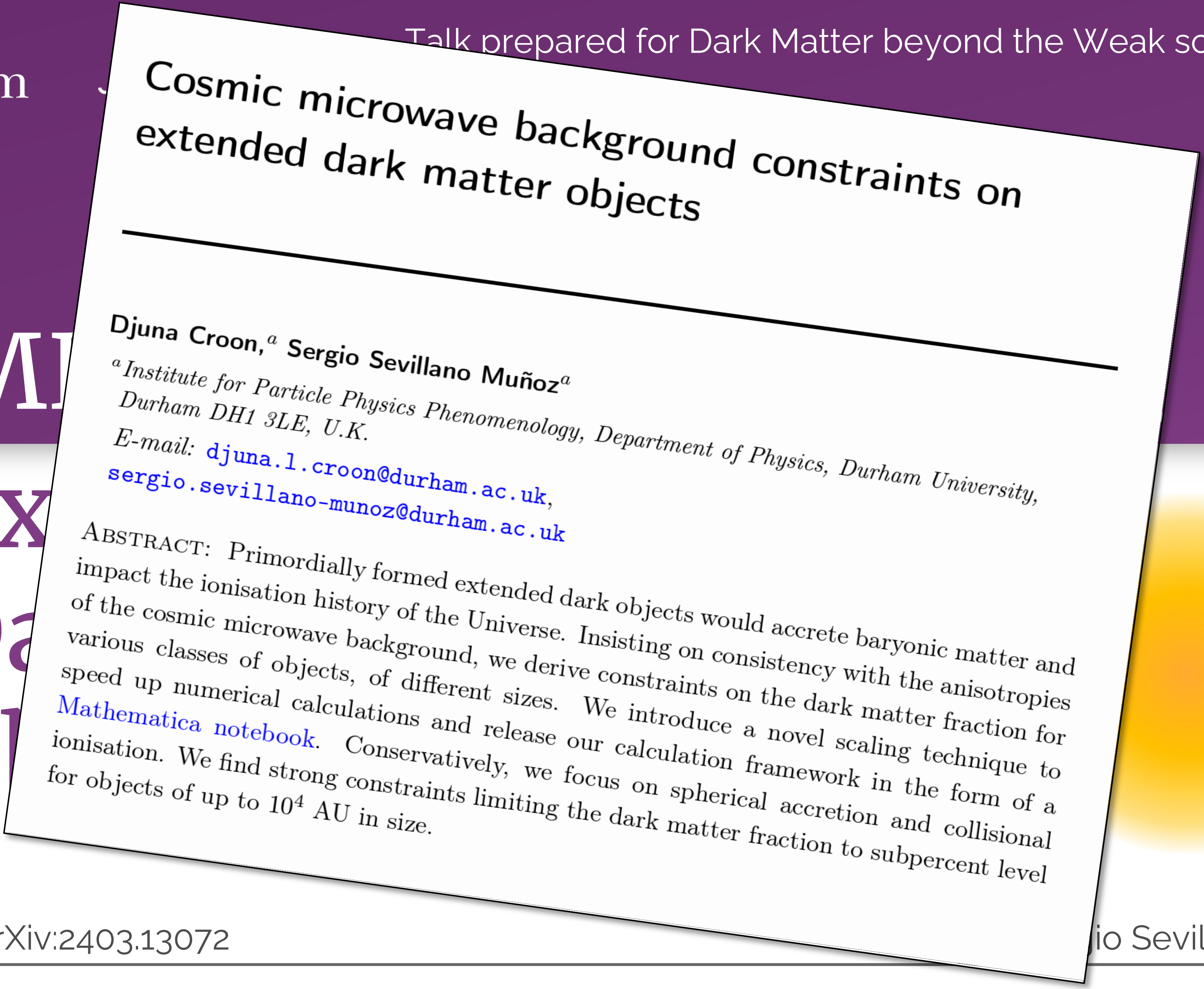

Cosmic microwave background constraints on extended dark matter objects

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Abstract: Primordially formed extended dark objects would accrete baryonic matter and impact the ionisation history of the Universe. Insisting on consistency with the anisotropies of the cosmic microwave background, we derive constraints on the dark matter fraction for various classes of objects, of different sizes. We introduce a novel scaling technique to speed up numerical calculations and release our calculation framework in the form of a Mathematica notebook. Conservatively, we focus on spherical accretion and collisional ionisation. We find strong constraints limiting the dark matter fraction to subpercent level for objects of up to 10^4 AU in size.

Based on arXiv:2403.13072

gio Sevillano Muñoz

Introduction to EDOs

Extended Dark matter Objects are a popular option for dark matter

-Macroscopical objects that only interact gravitationally with matter

-They have multiple formation mechanisms:

Introduction to EDOs

Extended Dark matter Objects are a popular option for dark matter

-Macroscopical objects that only interact gravitationally with matter

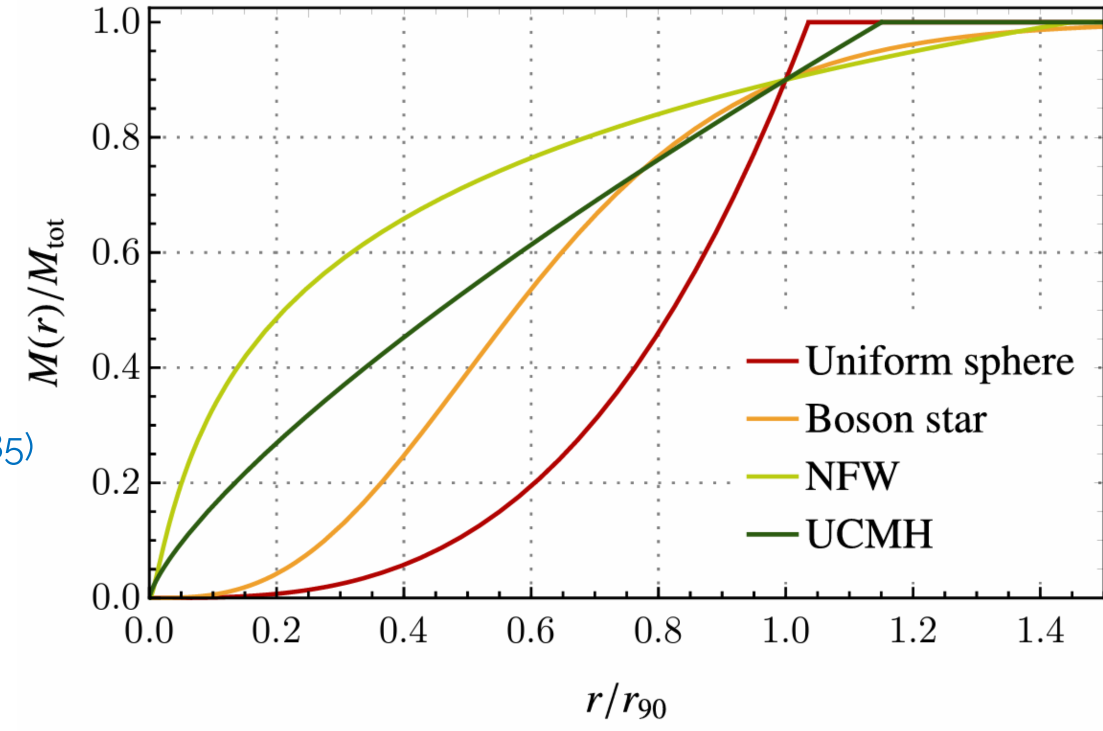
-They have multiple formation mechanisms:

-Uniform sphere (Witten 1984)

-Boson stars (Bar, Blas, et al. 2018)

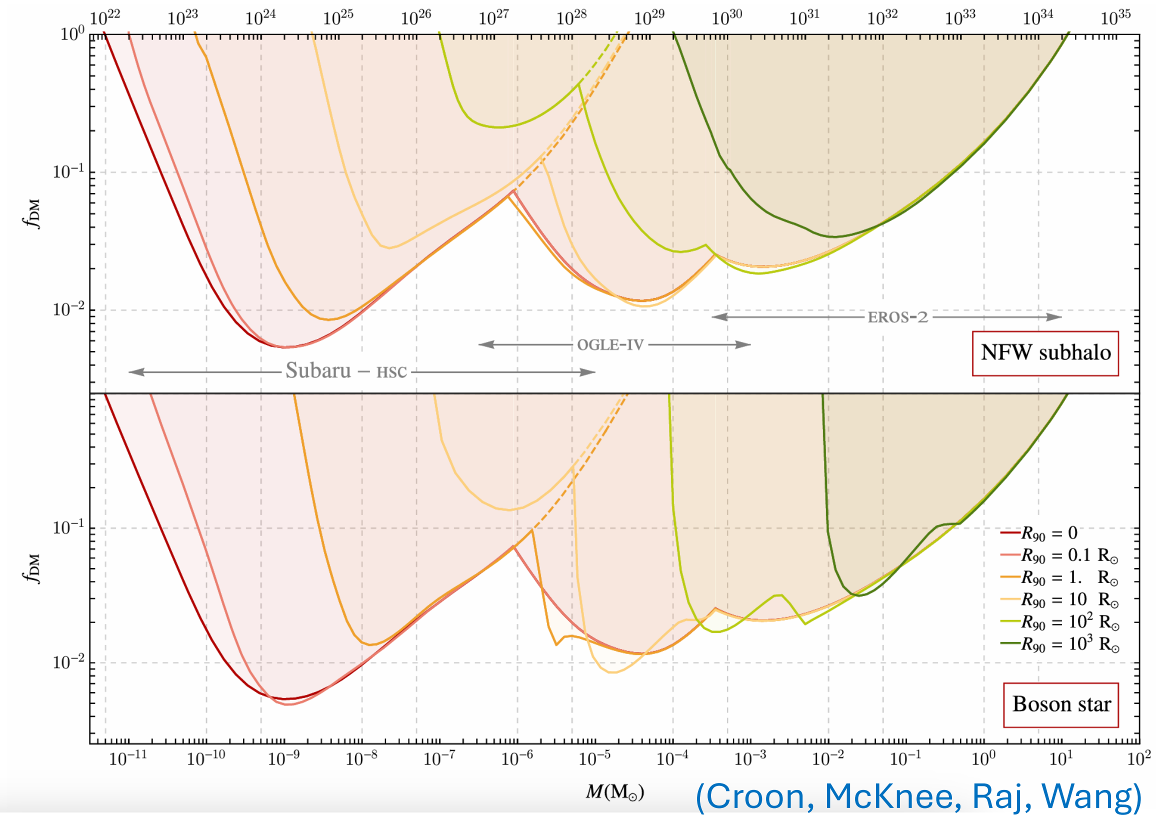
-NFW sub-halos

-Ultracompact minihalos (Bertschinger 1985)

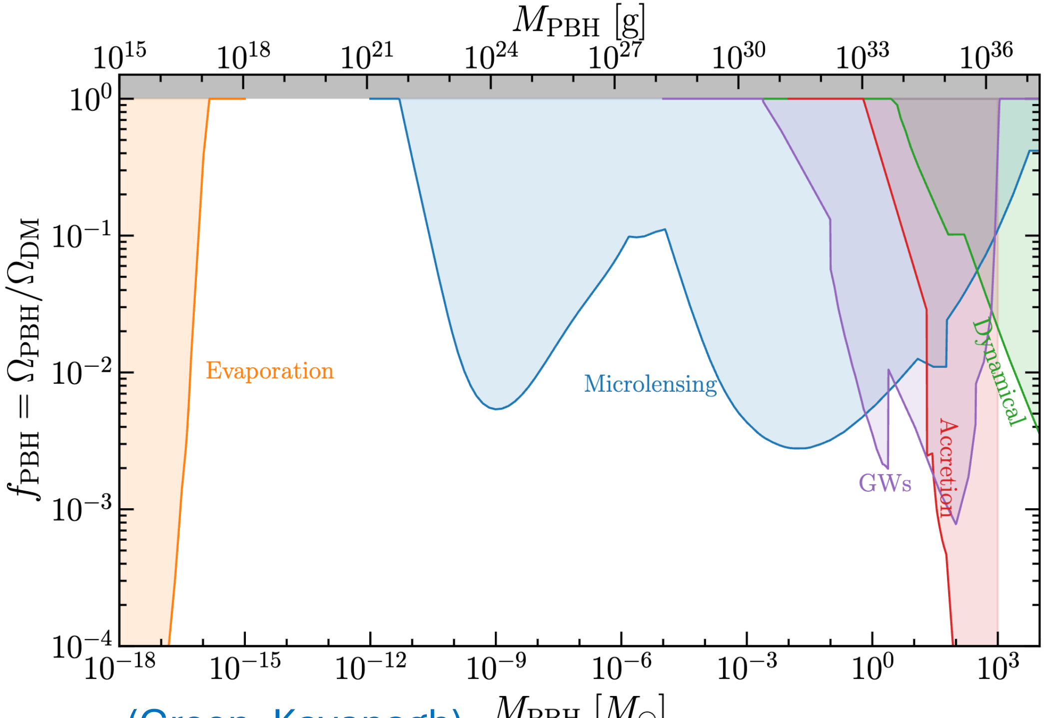


Introduction to EDOs

However, the different formation mechanisms also makes it necessary to test them case-by-case; for example, see Microlensing/Weak lensing:



(Croon, McKnee, Raj, Wang)



(Green, Kavanagh)

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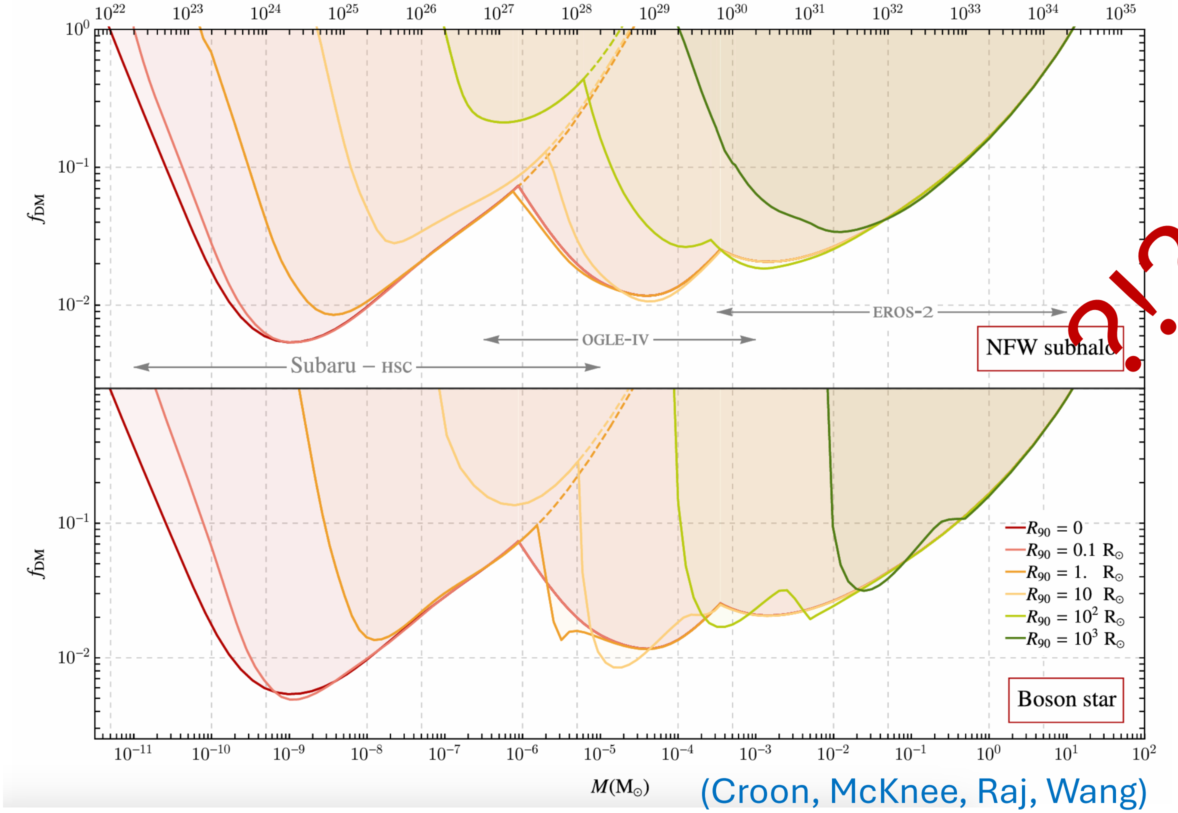

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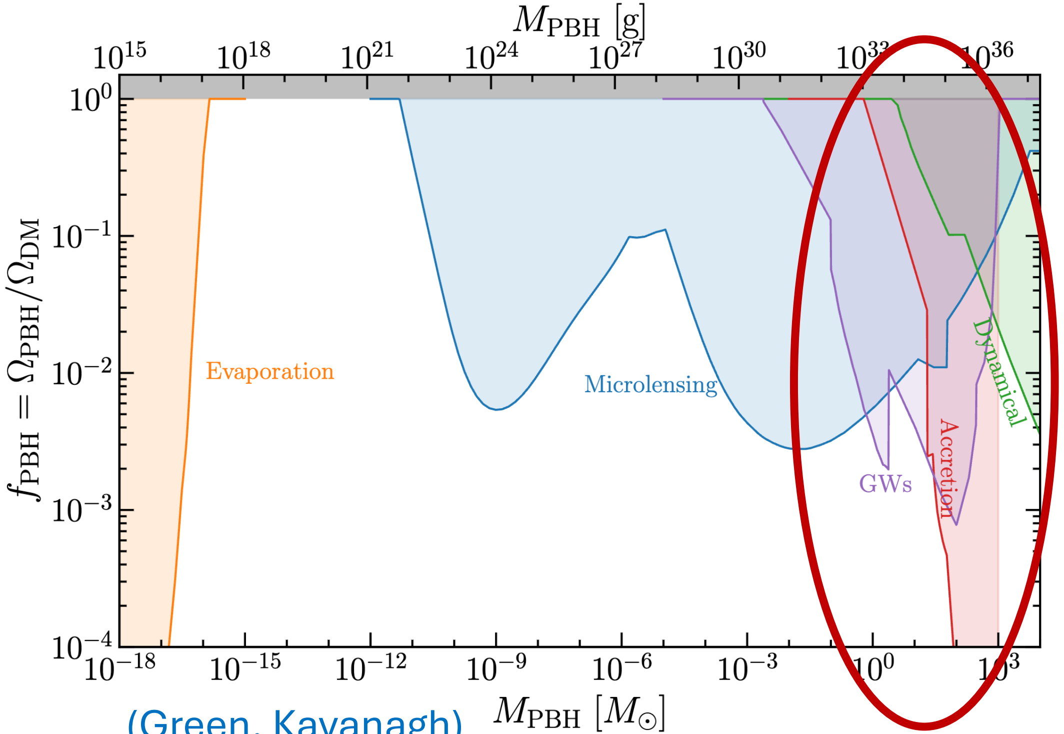
?!?!?



(Green, Kavanagh)

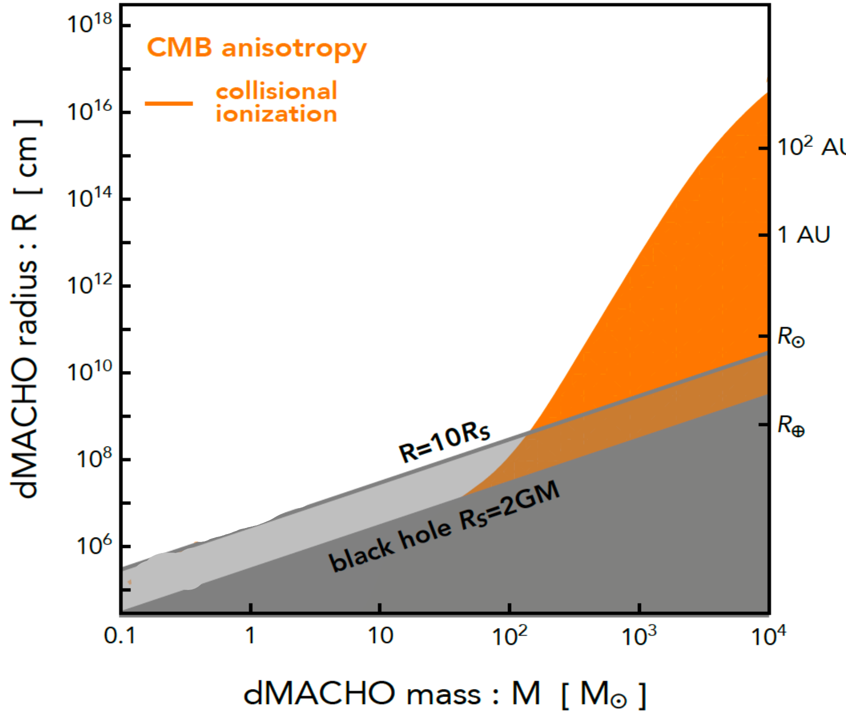
Introduction to EDOs

That's what we will be doing today!

The theoretical framework was already developed by Bai, Long and Lu (2020) where they work with the uniform sphere case, and get these constrains:

-Only the uniform sphere -> Analytically

-Just for 100% dark matter fraction



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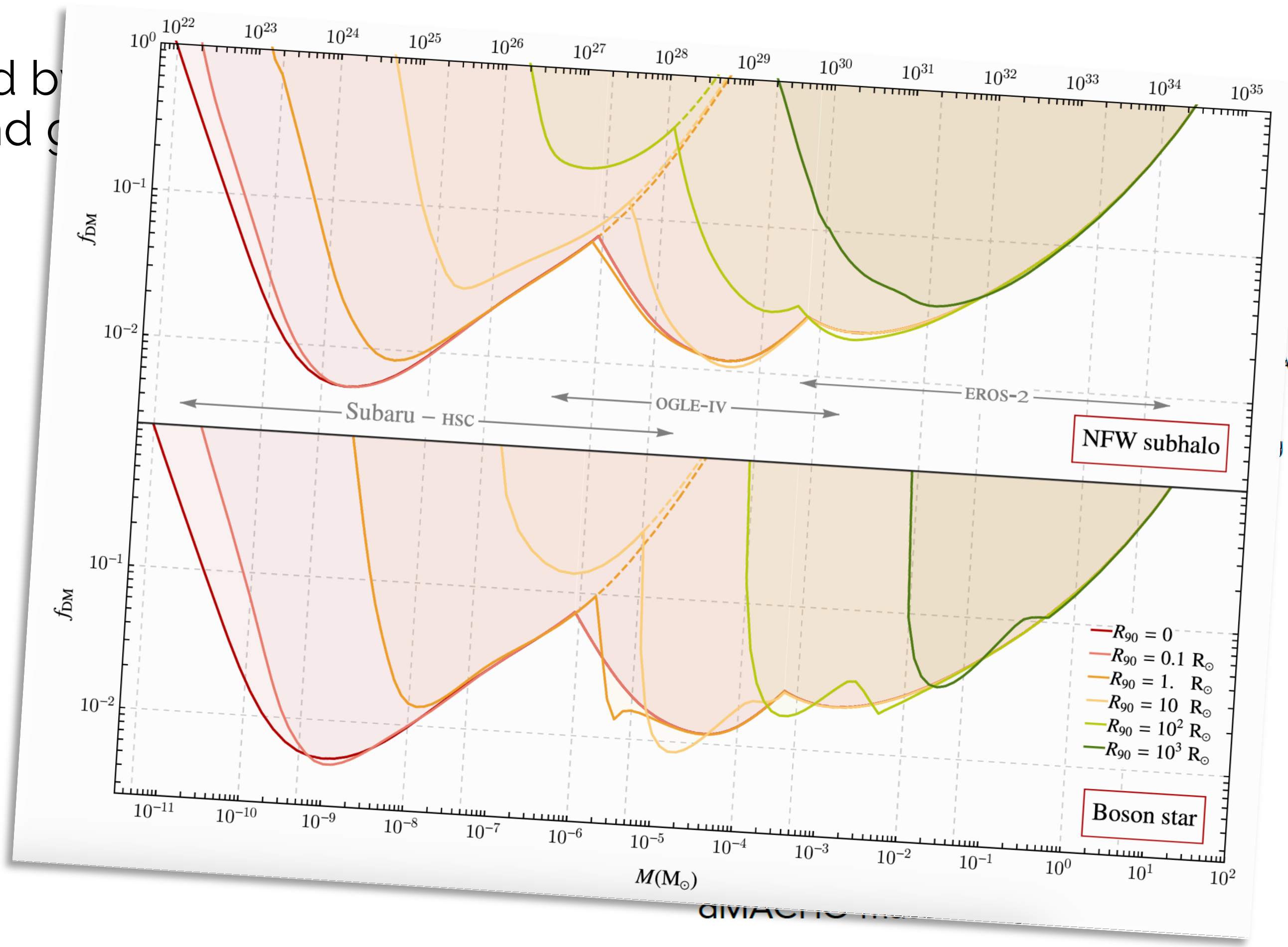
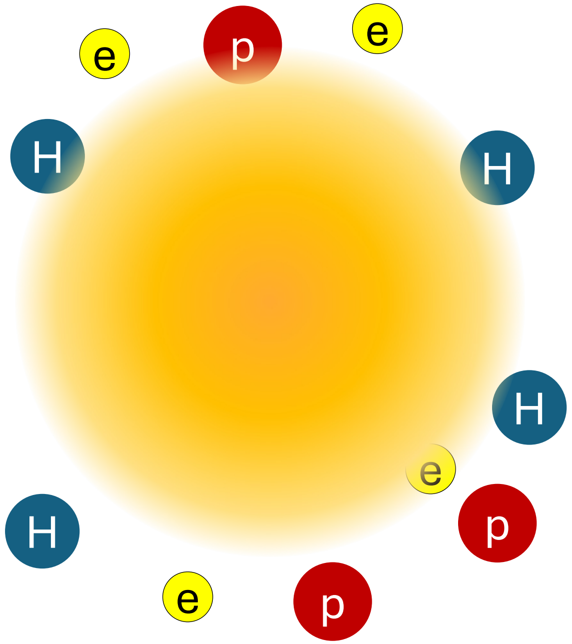


This is the context for our work, we allow for:

-Any mass function-> Numerically

-Any dark matter fraction

Matter accretion



Let's start with the accretion of matter into a single, isolated EDO,

like the one here:

We expect matter to interact gravitationally with it

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Matter accretion

Let's start with the accretion of matter into a single, isolated EDO,

like the one here:

We expect matter to interact gravitationally with it

The emitted luminosity depends on the following parameters:

- -Density
- -Temperature
- -Ionisation fraction
- -Number of electrons=protons

$$\rho = m_e n_e + m_p n_p + m_H n_H$$

$$x_e = \frac{n_e}{n_e + n_H}$$

Matter accretion

Given that baryons can be modeled as a fluid, they will be described by Navier-Stokes equations

$$\dot{\rho} + \frac{1}{r^2}(r^2 \rho v)' = 0,$$

$$\rho \dot{v} + \rho v v' + P' = \rho g,$$

$$\rho (\dot{\mathcal{E}/\rho}) + \rho v (\mathcal{E}/\rho)' + P \frac{1}{r^2}(r^2 v)' = \dot{q},$$

But we will need to take a series of approximations to simplify this system

Matter accretion

Approximations!

1. Static solutions
2. Hydrostatic approximation: $v(r) = 0$
3. $x_e(r)$ constant
4. Allow for adiabaticity

$$P(r) = K\rho(r)^\gamma$$

$$T(r) = K m_p \frac{\rho(r)^{\gamma-1}}{1 + x_e f_P}$$

$$\frac{GM(r)}{r^2} + \gamma K \rho(r)^{\gamma-2} \frac{d\rho(r)}{dr} = 0$$

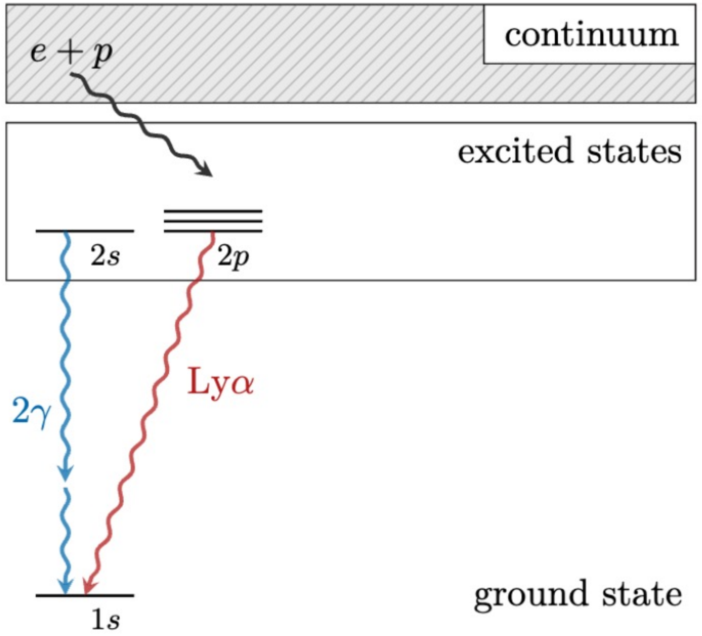
Matter accretion

We will solve this system imposing the boundary conditions at infinity to be given by the universe's background.

Use Peebles case B recombination, or three level atom

$$\frac{\mathrm{d}T_\mathrm{M}}{\mathrm{d}z} = \frac{1}{(1+z)}\left[2T_\mathrm{M} + \frac{8\pi^2\sigma_\mathrm{T}{T_\mathrm{cmb}}^4}{45H(z)m_e}\frac{x_e}{1+x_e}(T_\mathrm{M}-T_\mathrm{cmb})\right],$$

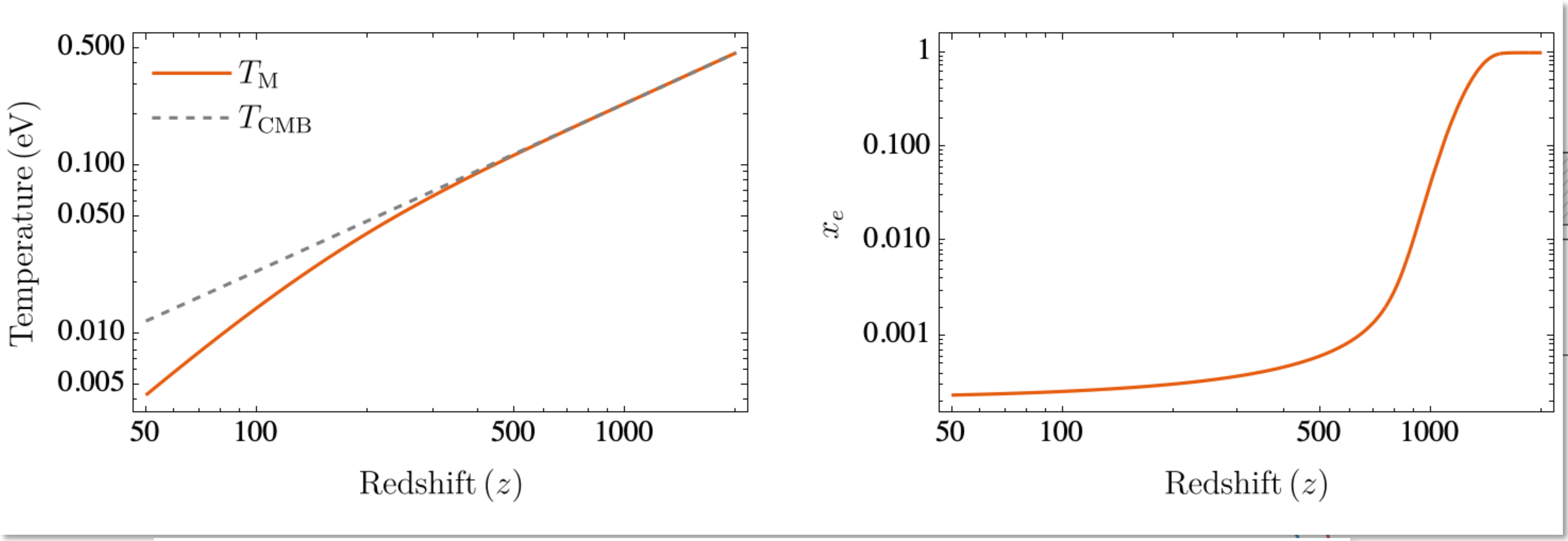
$$\frac{\mathrm{d}x_e}{\mathrm{d}z} = C_r(z)\frac{\alpha_\mathrm{B}(T_\mathrm{M})}{H(z)(1+z)}\left[nx_e^2 + \left(\frac{m_eT_\mathrm{M}}{2\pi}\right)^{3/2}e^{-\frac{E_\mathrm{I}}{T_\mathrm{M}}}(1-x_e)\right]$$

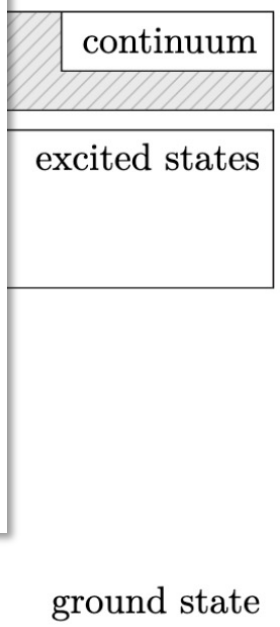


Baunmann, Cosmology

Matter accretion

We will solve this system imposing the boundary conditions at infinity to be given by





$$\rho_\infty \equiv m_p n(z), \qquad T_\infty \equiv T_{\rm M}(z), \qquad \bar{x}_e \equiv x_e(z)$$

Baunmann, Cosmology

Based on arXiv:2403.13072

We will solve this equation:

$$\frac{GM(r)}{r^2} + \gamma K \rho(r)^{\gamma-2} \frac{d\rho(r)}{dr} = 0$$

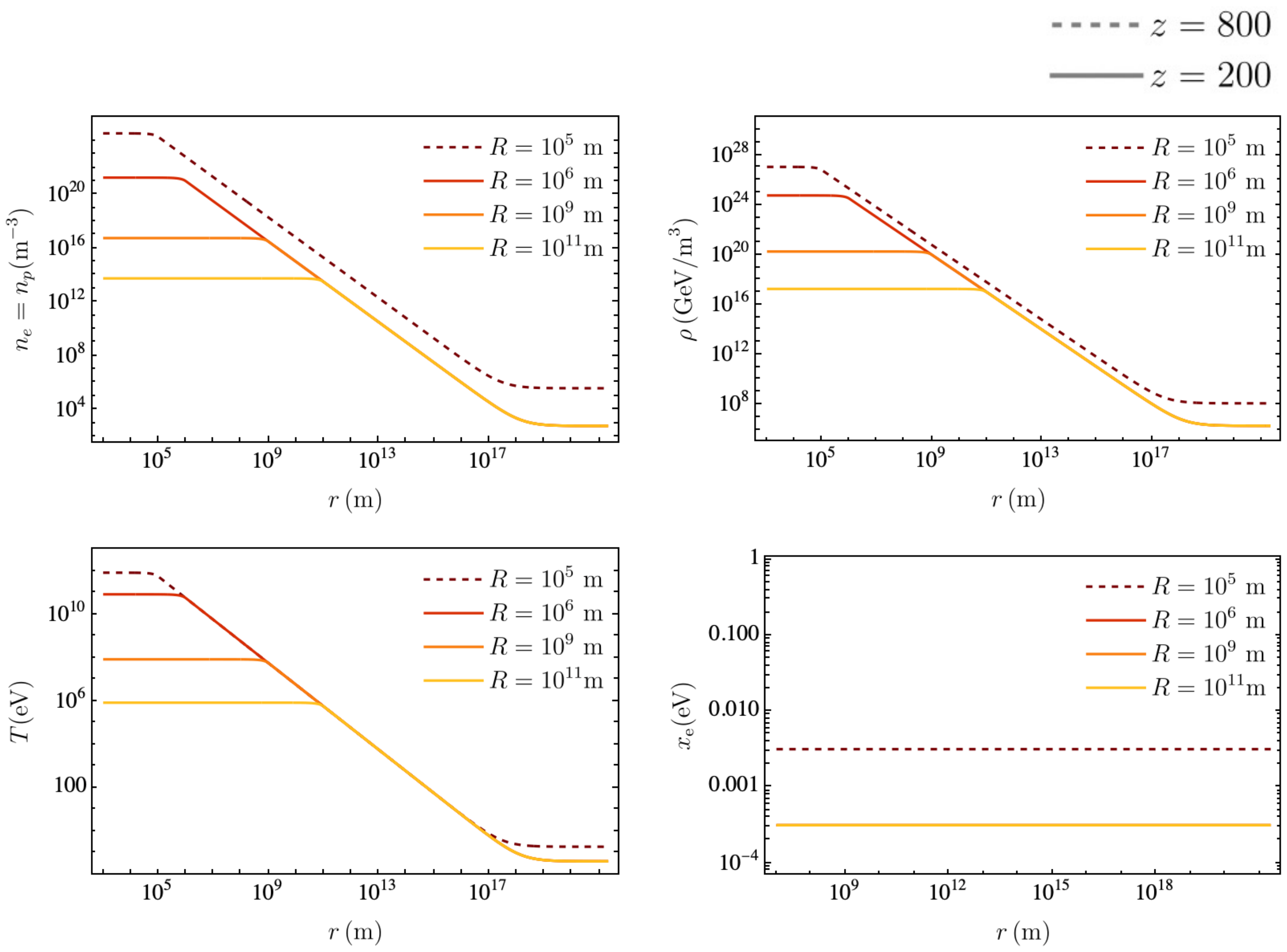
With this boundary conditions:

$$\rho_\infty \equiv m_p n(z), \qquad T_\infty \equiv T_{\rm M}(z),$$

$$\bar{x}_e \equiv x_e(z)$$

And the uniform sphere mass function:

$$M(r) = M \begin{cases} \left(\frac{r}{R}\right)^3 & r \leq R \\ 1 & R < r. \end{cases}$$



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$$\frac{GM(r)}{r^2} + \gamma K \rho(r)^{\gamma-2}\frac{d\rho(r)}{dr} = 0$$

But that is not enough! Add corrections:

-Interactions with CMB

$$\dot{\rho} + \frac{1}{r^2}(r^2\rho v)' = 0,$$
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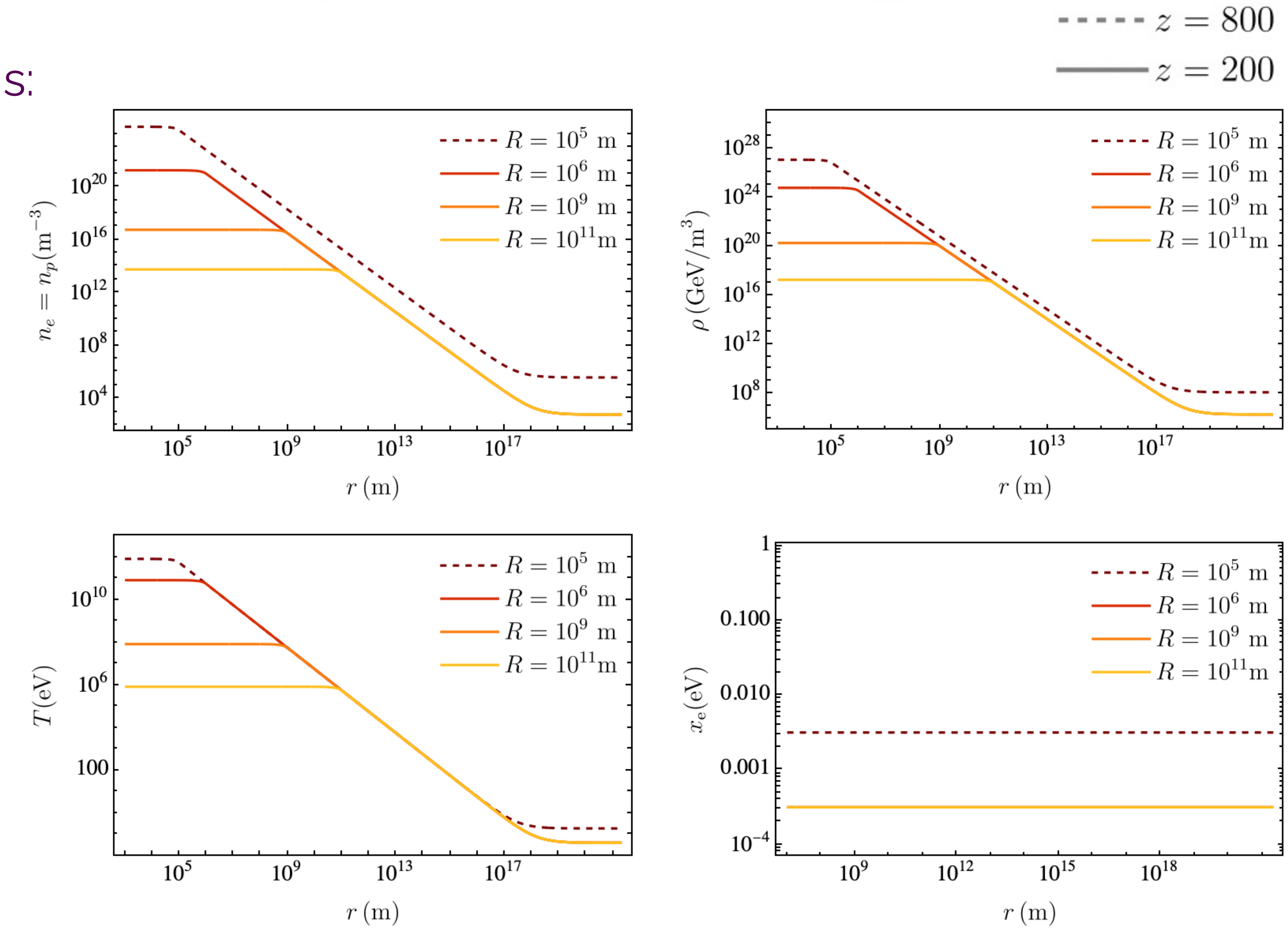

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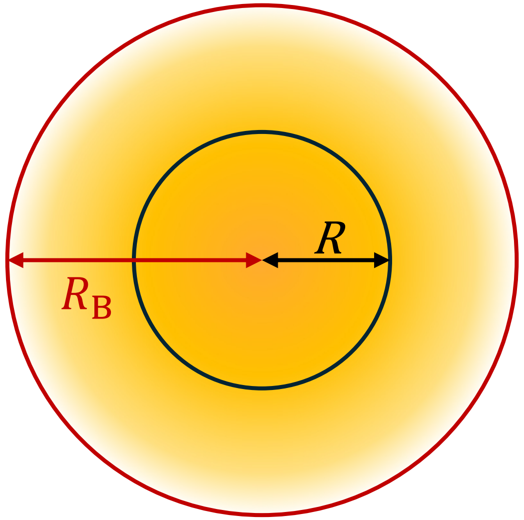
We need to define some new parameters:

Sounds speed at infinity: $c_\infty = \sqrt{\gamma_\infty P_\infty / \rho_\infty}$.

Bondi radius: $R_\mathrm{B} = GM/c_\infty^2$

Bondi time: $t_\mathrm{B} = GM/c_\infty^3$



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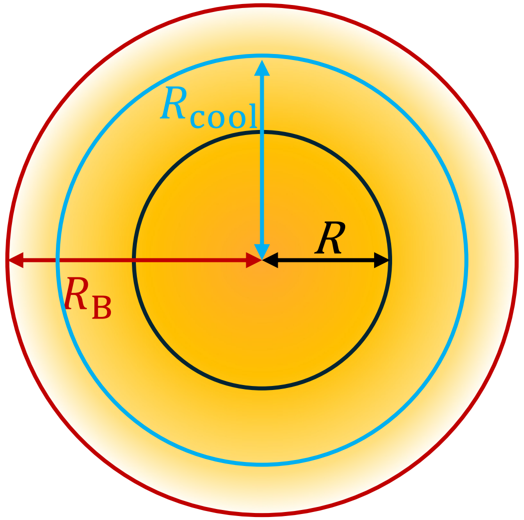
Bondi time: $t_\mathrm{B} = GM/c_\infty^3$

$$c_\mathrm{cool} = R_\mathrm{cool}/t_\mathrm{cool}$$

$$R_\mathrm{cool} = \Theta^{-2/3} R_\mathrm{B}$$

$$t_\mathrm{cool} = \frac{3m_e(1+\bar{x}_e)}{8\bar{x}_e\sigma_\mathrm{T}\rho_\mathrm{cmb}}$$



This allows to express the equations as follows

$$\frac{v}{c_\infty}\rho^{\gamma_\infty - 1} R_\mathrm{B}\frac{\mathrm{d}}{\mathrm{d}r}\left(\frac{T}{\rho^{\gamma_\infty-1}}\right) = \Theta(T_\mathrm{cmb} - T)$$

$$\Theta = \frac{8\bar{x}_e\sigma_\mathrm{T}\rho_\mathrm{cmb}}{3m_e(1+\bar{x}_e)} t_\mathrm{B} \qquad t_\mathrm{cool} = \frac{3m_e(1+\bar{x}_e)}{8\bar{x}_e\sigma_\mathrm{T}\rho_\mathrm{cmb}}$$

We will solve this equation:

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Only affects high redshifts

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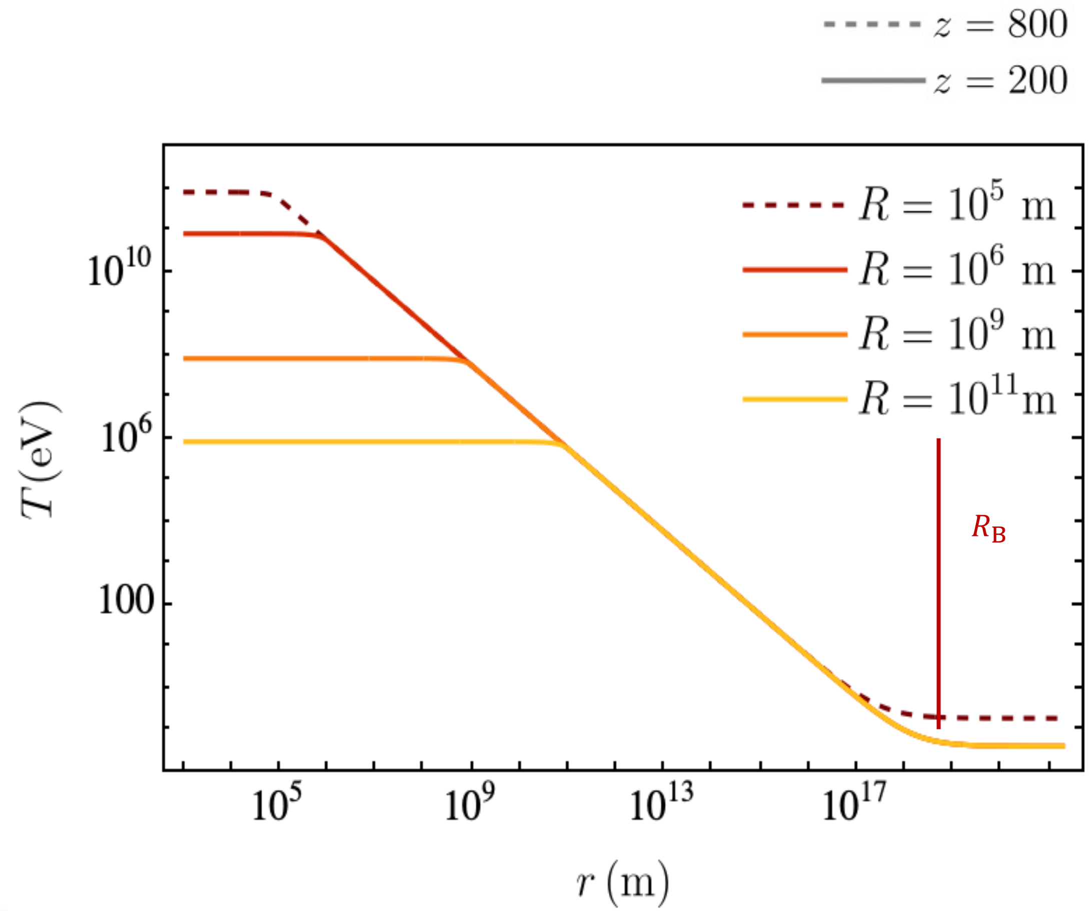

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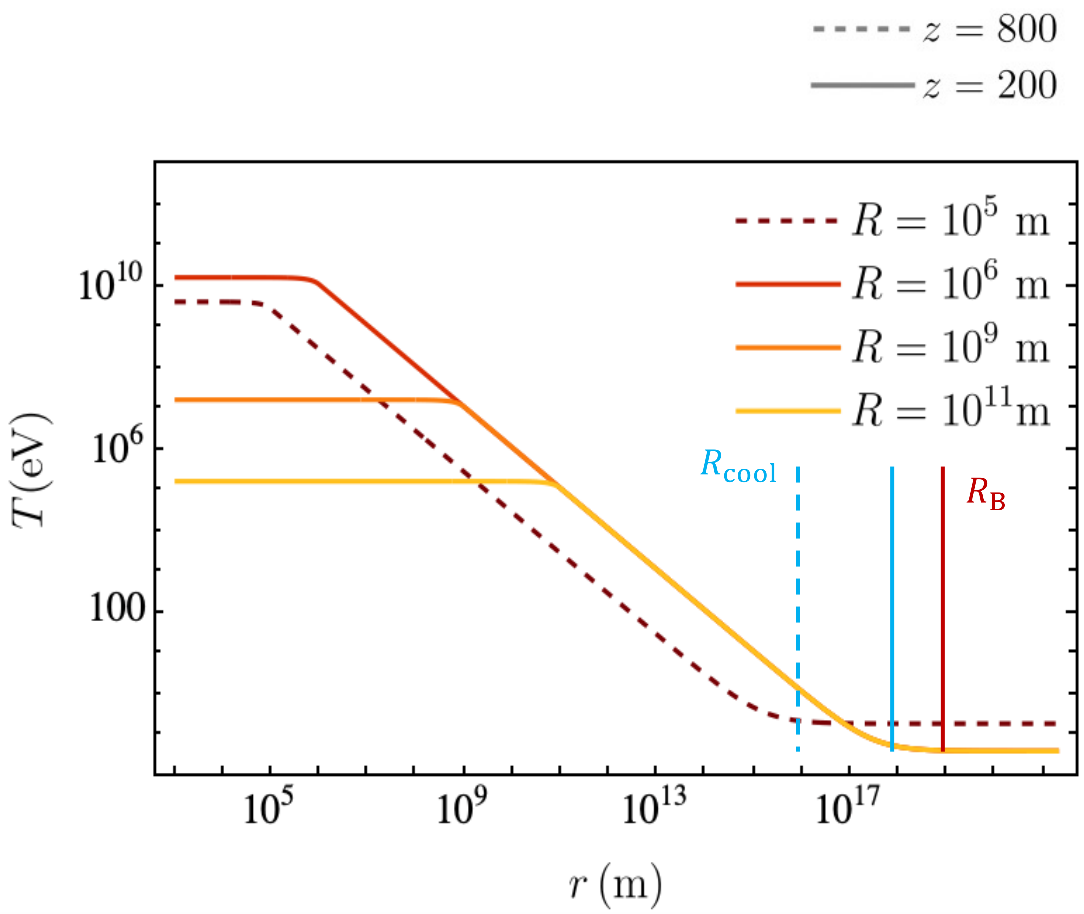

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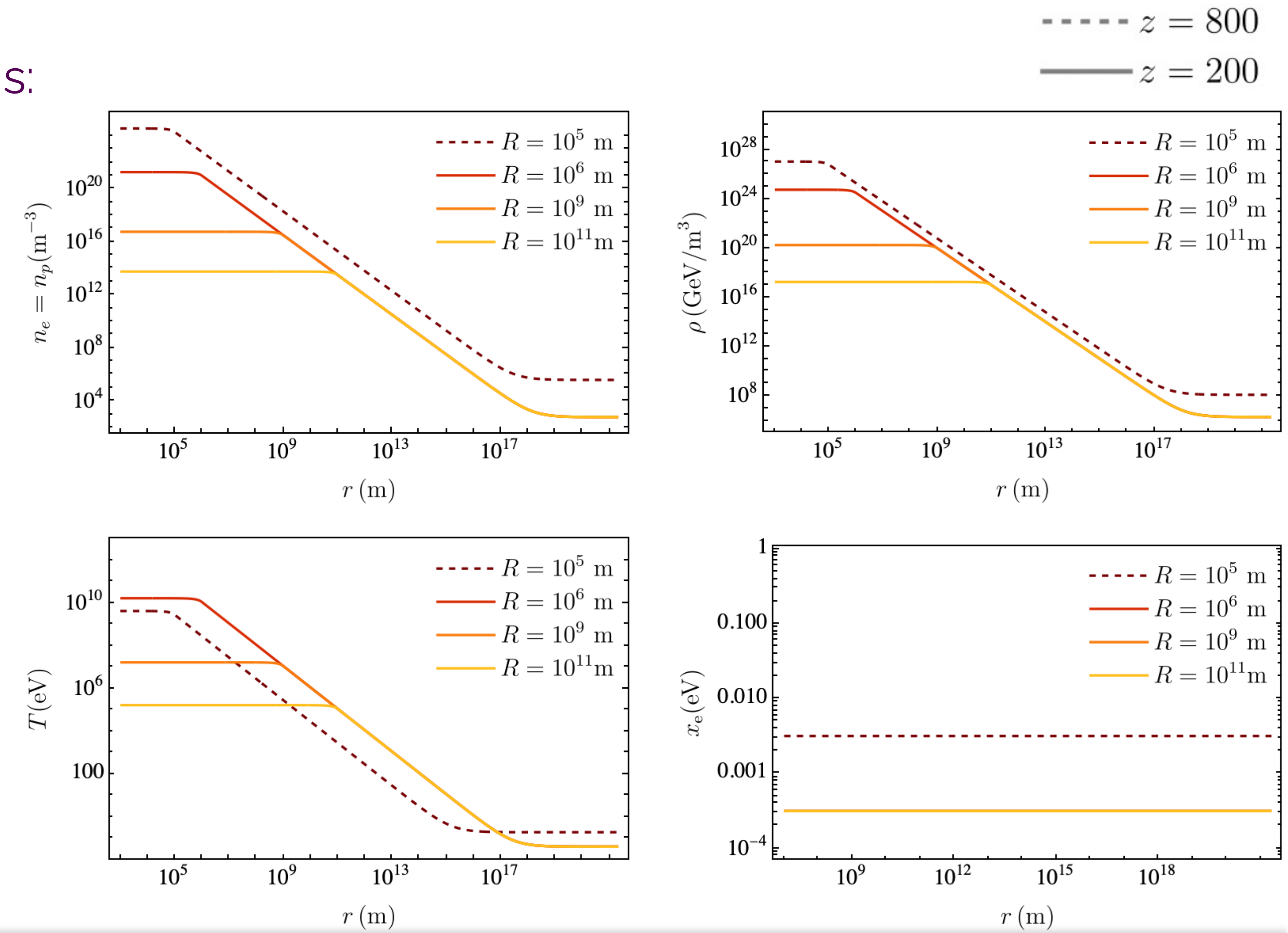
-Collisional ionisation:

$$H + H \rightarrow H + e + p + \gamma$$

$$T_{\text{ion}} \simeq 1.5 \times 10^4 \text{ K} \approx 1.3 \text{ eV}$$

Temperature distributes into new particles, ionization increases



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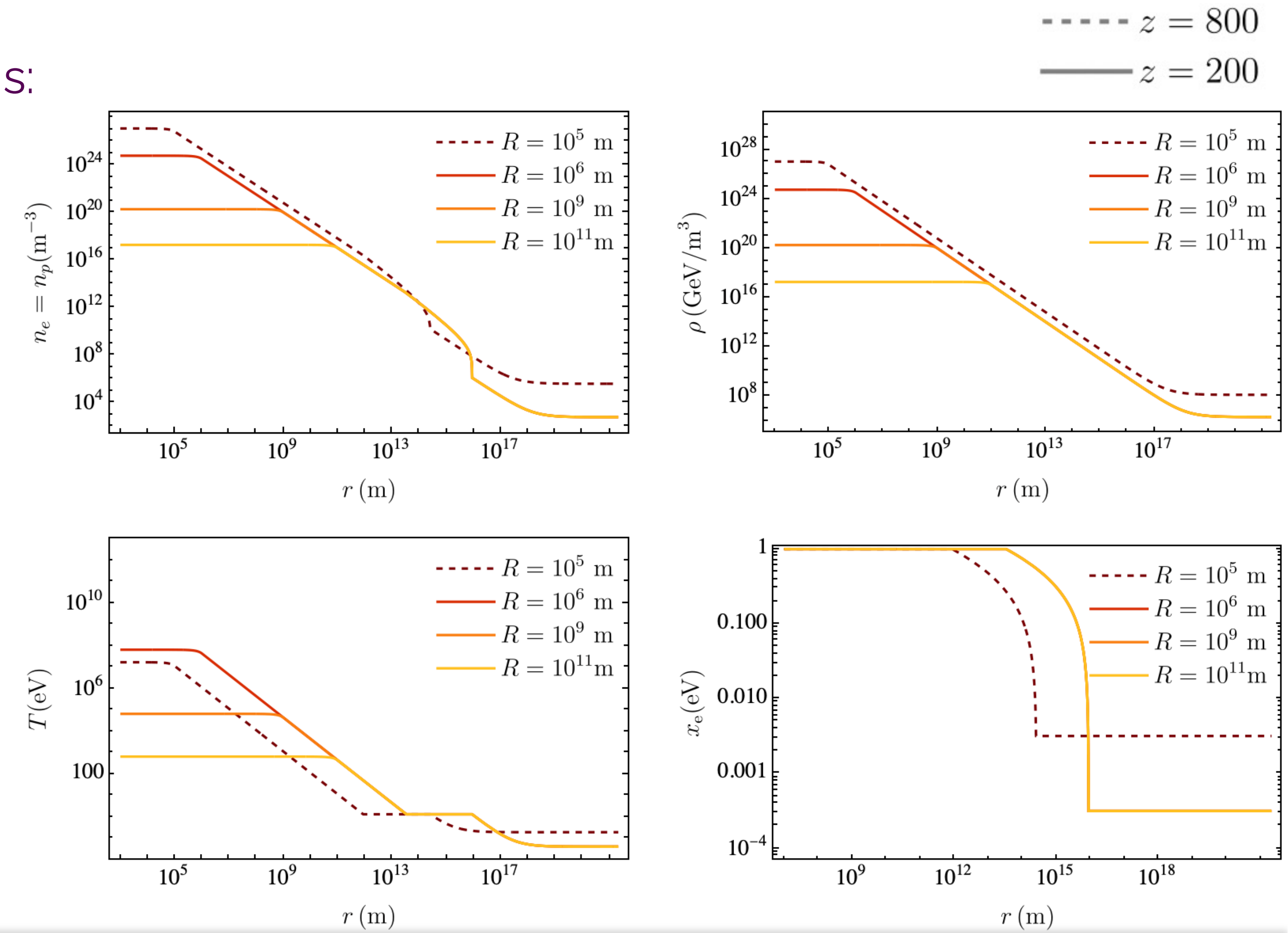
Photoionization also important,
but these are the tightest constraints



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But that is not enough! Add corrections:

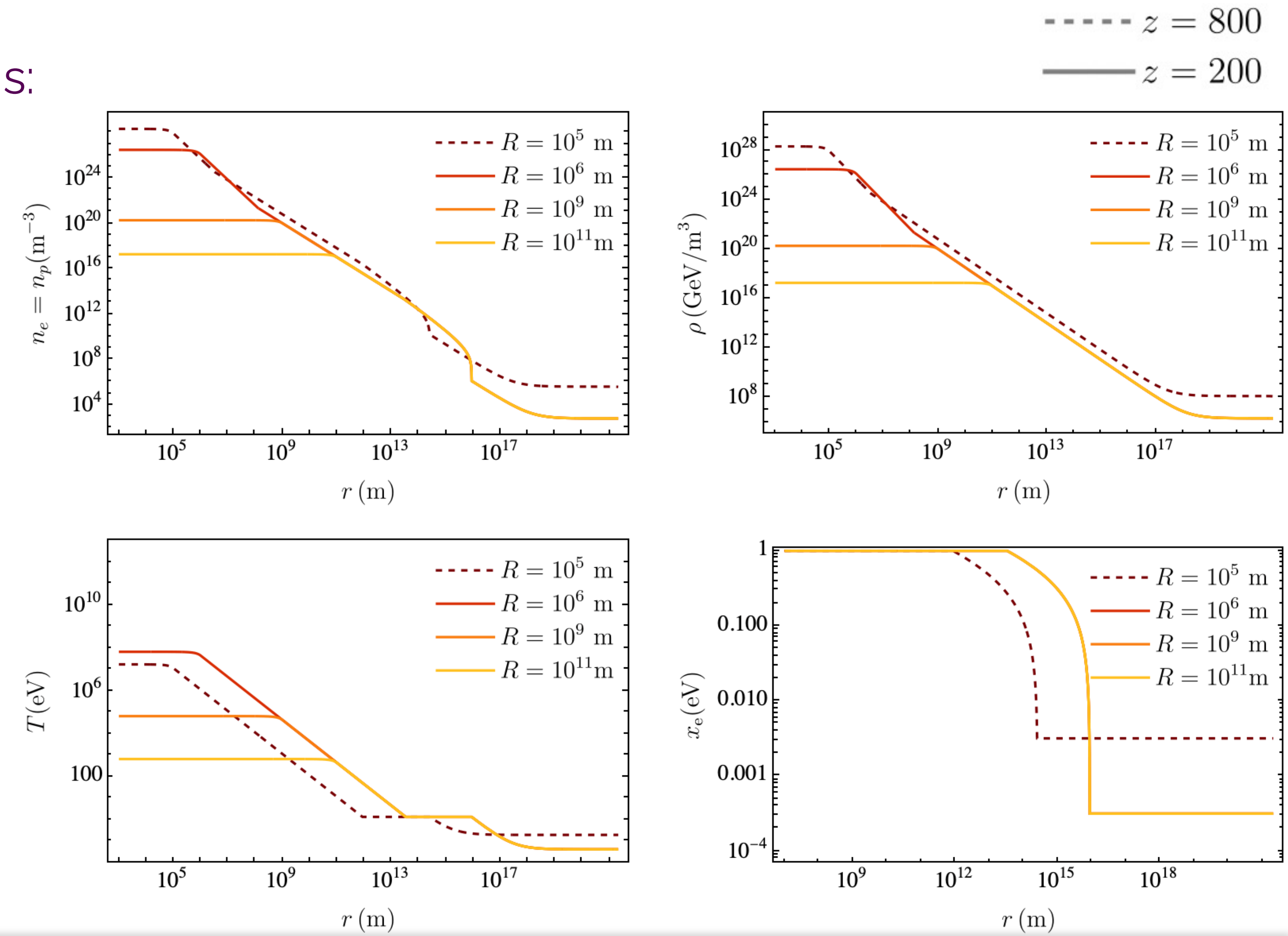
-Interactions with CMB

-Collisional ionisation:

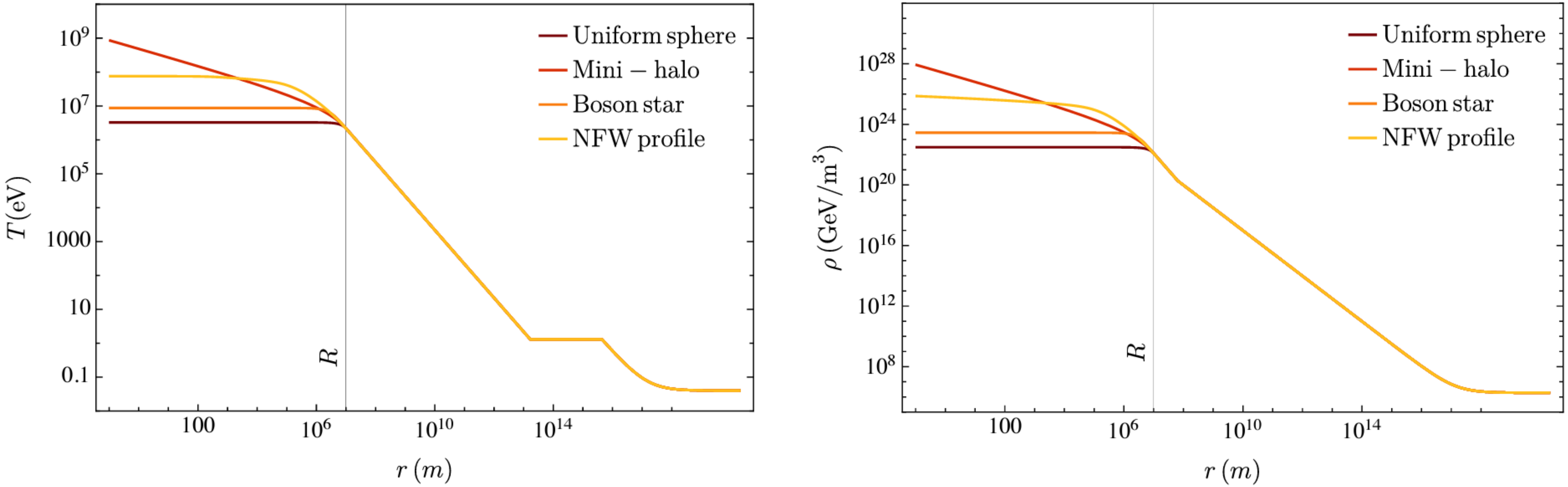
-Relativistic effects:

Relativistic electrons contribute differently to the internal energy

$$T(r) \geq 2m_e/3$$



Comparing different mass profiles, all the same until R:



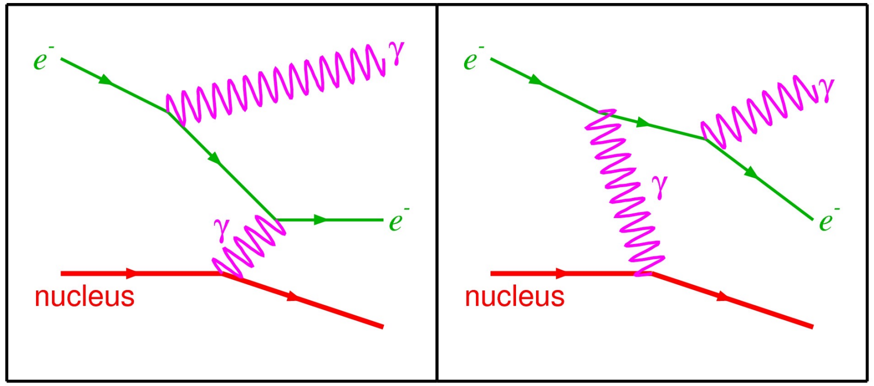
Now we can focus on the effect they will have on the background!

Placing EDOs in our Universe

The internal interactions of particles will emit light via bremsstrahlung

$$j_\nu(r) = \frac{8}{3}\left(\frac{2\pi m_e}{3T(r)}\right)^{1/2}\frac{\alpha^3}{m_e^2}g_{ff}(\nu, T(r))e^{-2\pi\nu/T(r)}n_e(r)n_p(r)$$

Bremsstrahlung



Integrate frequency:

$$\mathcal{L}(r) = n_e(r)n_p(r)\alpha\sigma_{\mathrm{T}}T(r)\mathcal{J}(T(r)/m_e)$$

Integrate over space:

$$L = \int_0^\infty \mathrm{d}r\, 4\pi r^2\left[\mathcal{L}(r) - \mathcal{L}(\infty)\right]$$

Placing EDOs in our Universe

However, we also need to account for relative velocities

$$\langle \mathcal{L} \rangle = \frac{4\pi}{(2\pi \langle v_s^2 \rangle /3)^{3/2}} \int_0^\infty \mathrm{d}v_{\mathrm{rel}}\, v_{\mathrm{rel}}^2 e^{-\frac{v_{\mathrm{rel}}^2}{2\langle v_s^2 \rangle /3}} \mathcal{L}\Big|_{c_\infty \to \sqrt{c_\infty^2 + v_{\mathrm{rel}}^2}}$$

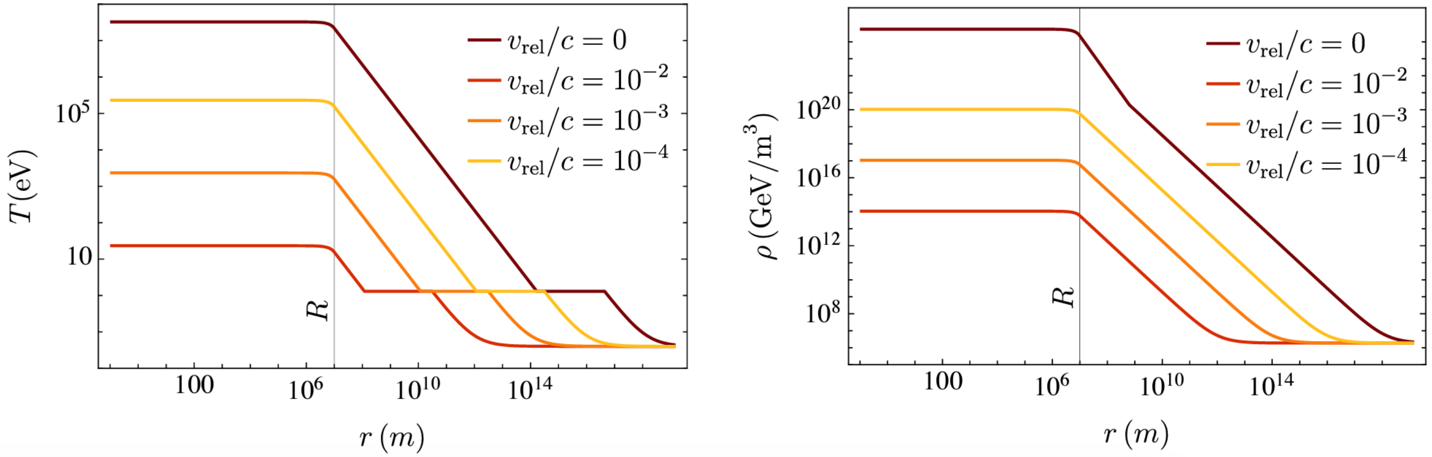
$$R_{\mathrm{B}} \to GM/(c_\infty^2 + v_{\mathrm{rel}}^2)$$

Gaussian distribution with

$$\langle v_s^2 \rangle^{1/2} = \min[1, z/10^3] \times 30\mathrm{km/s}$$

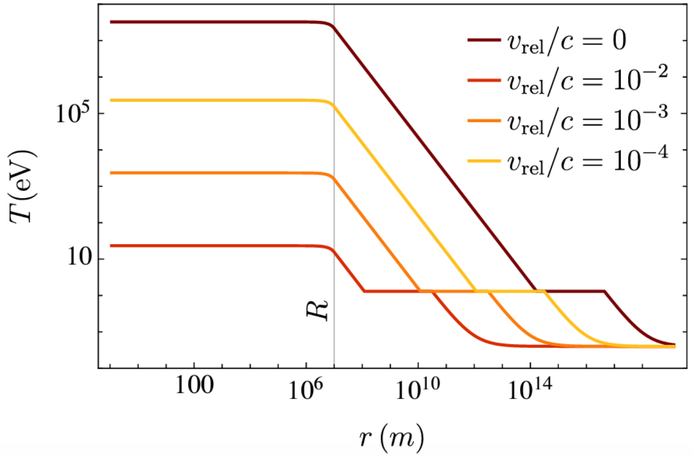
Placing EDOs in our Universe

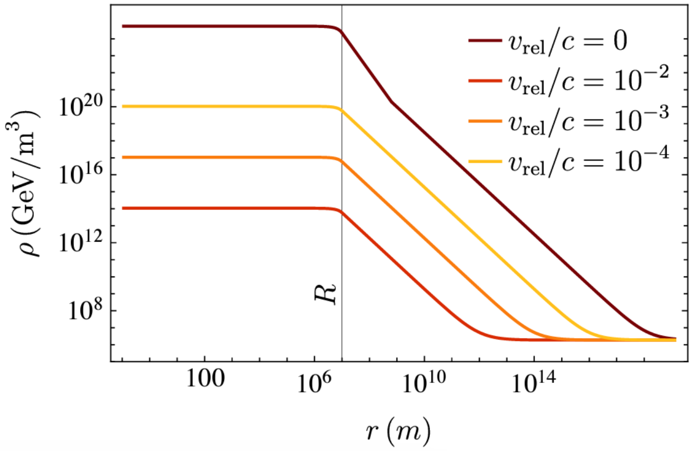
There's a nice trick for this

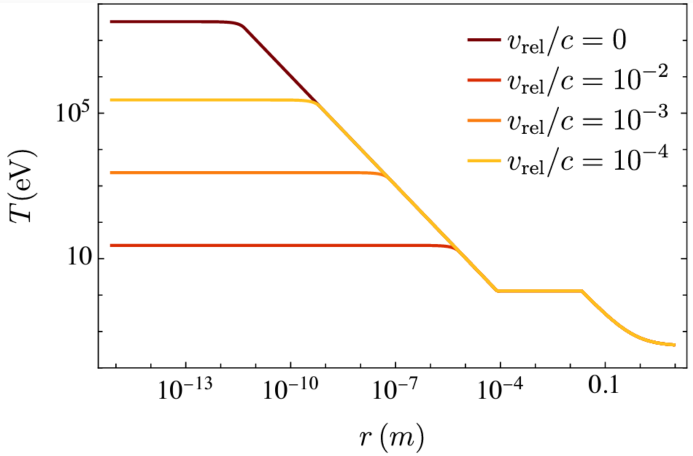


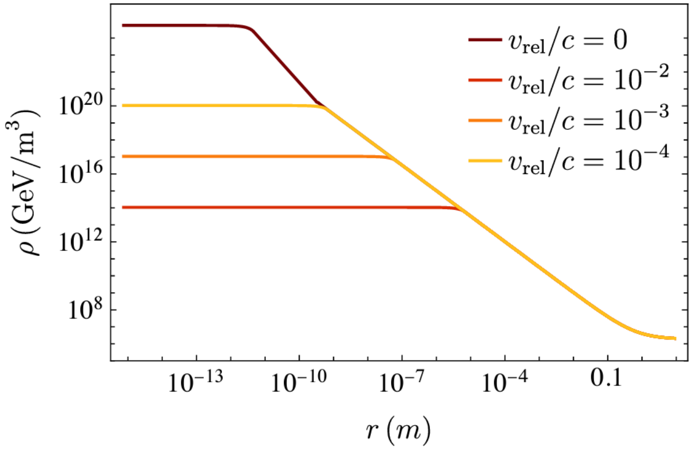
Placing EDOs in our Universe

There's a nice trick for this: rescale $r \to r\, R_B$



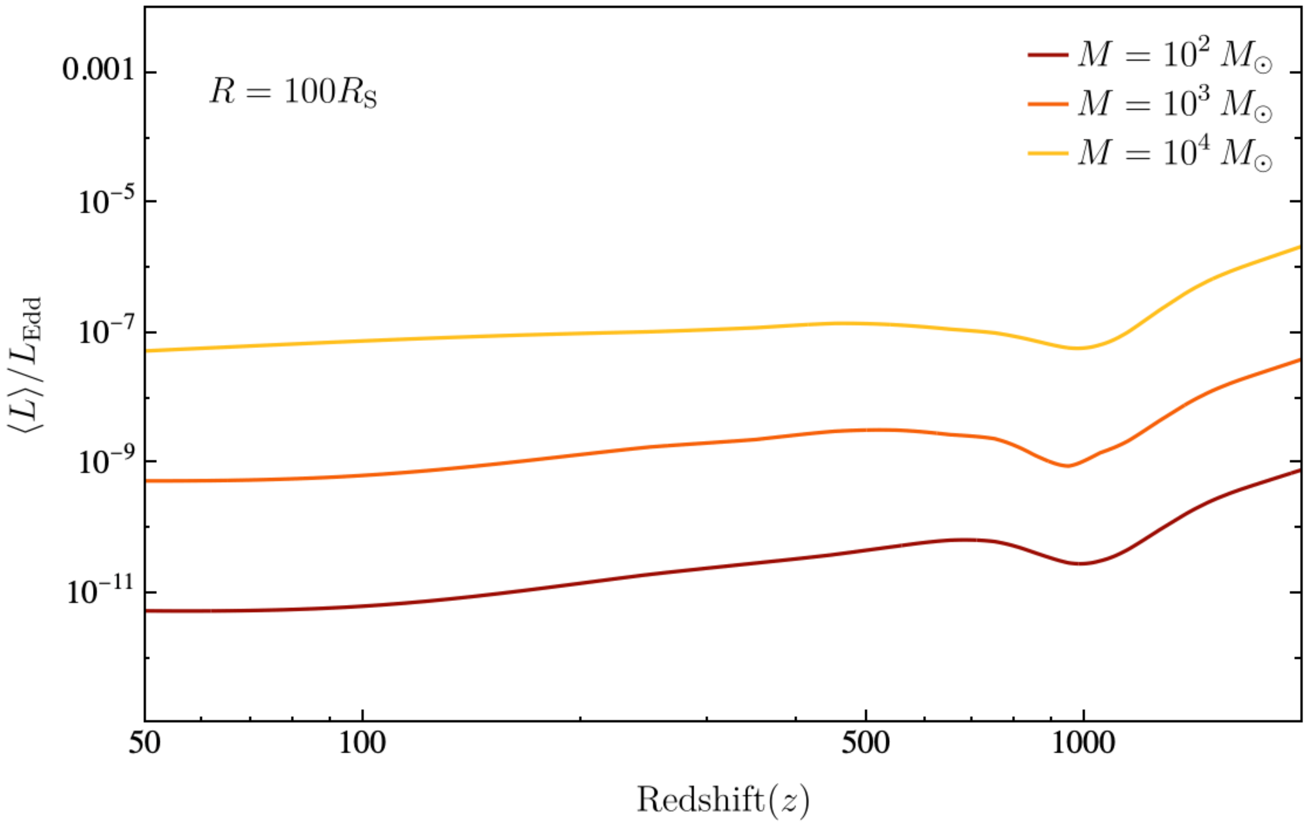




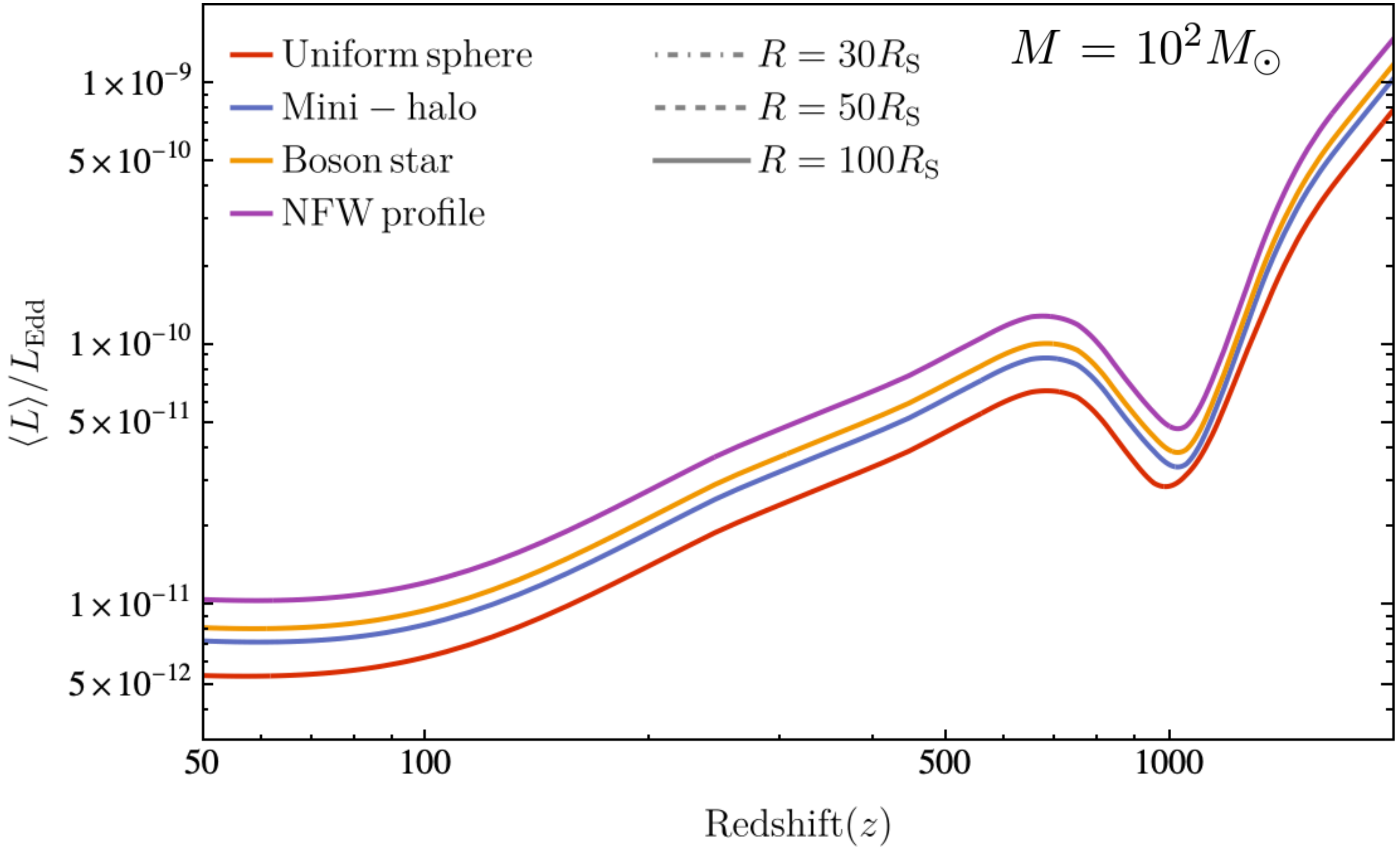


Placing EDOs in our Universe

Relative velocity averaged Luminosity for uniform sphere:

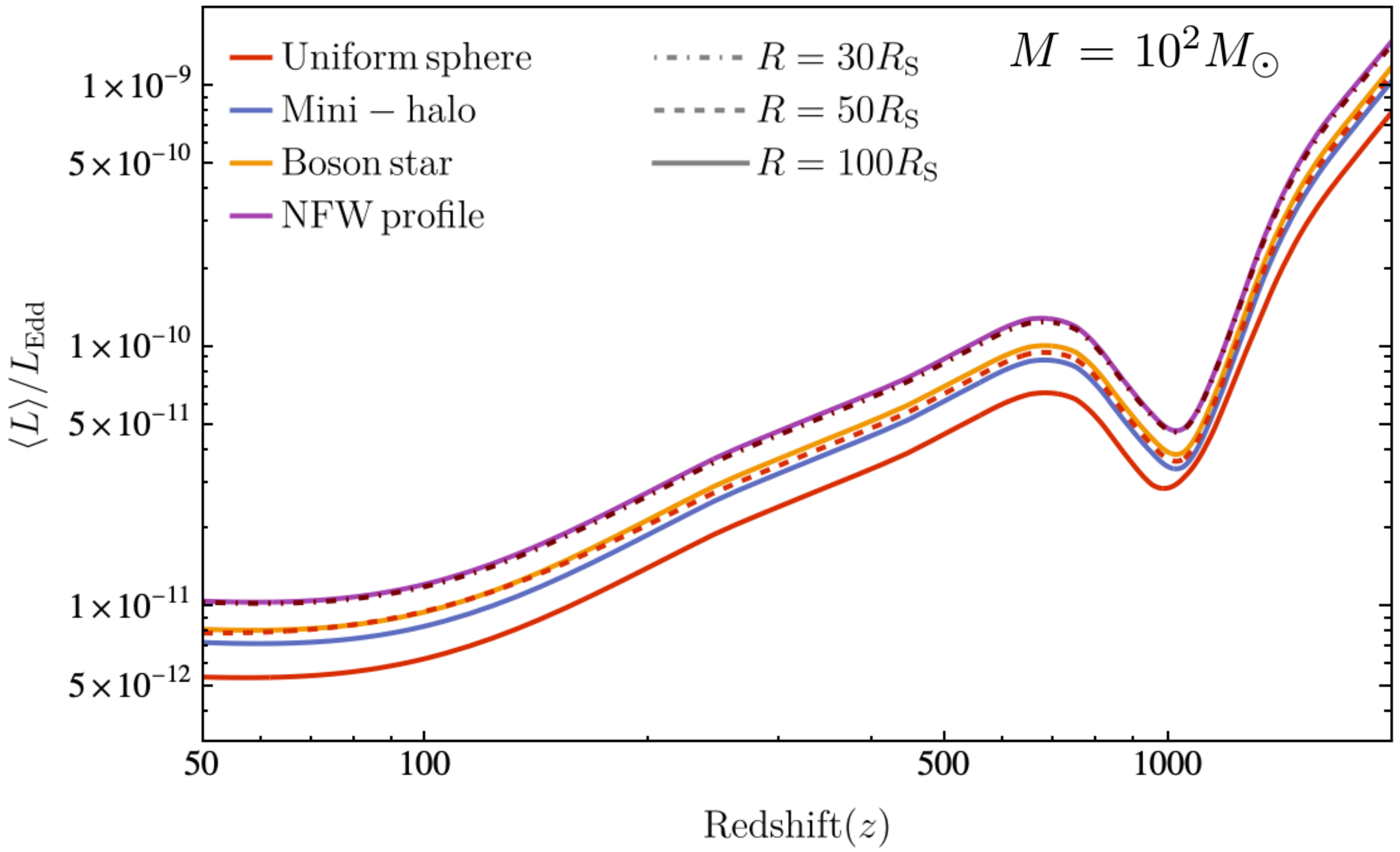


Placing EDOs in our Universe



Redshift(z)

Placing EDOs in our Universe



We can rescale uniform sphere to other solutions!!

Placing EDOs in our Universe

Once we have the luminosity, we need to calculate the power density

$$\langle P(z)\rangle = \langle L(z)\rangle n_{\rm EDO}(z)$$

$$n_{\rm EDO}(z) = f_{\rm DM}\,\rho_{\rm DM}(z)/M$$

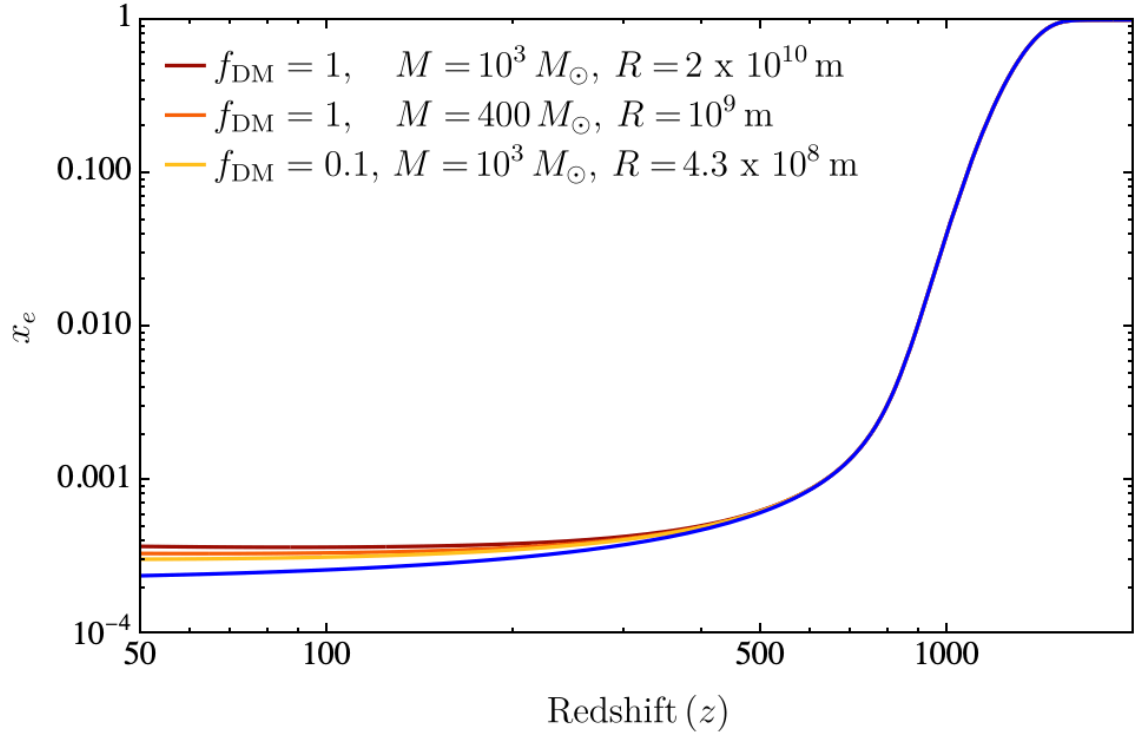
Only a fraction of this energy that will get deposited in the background

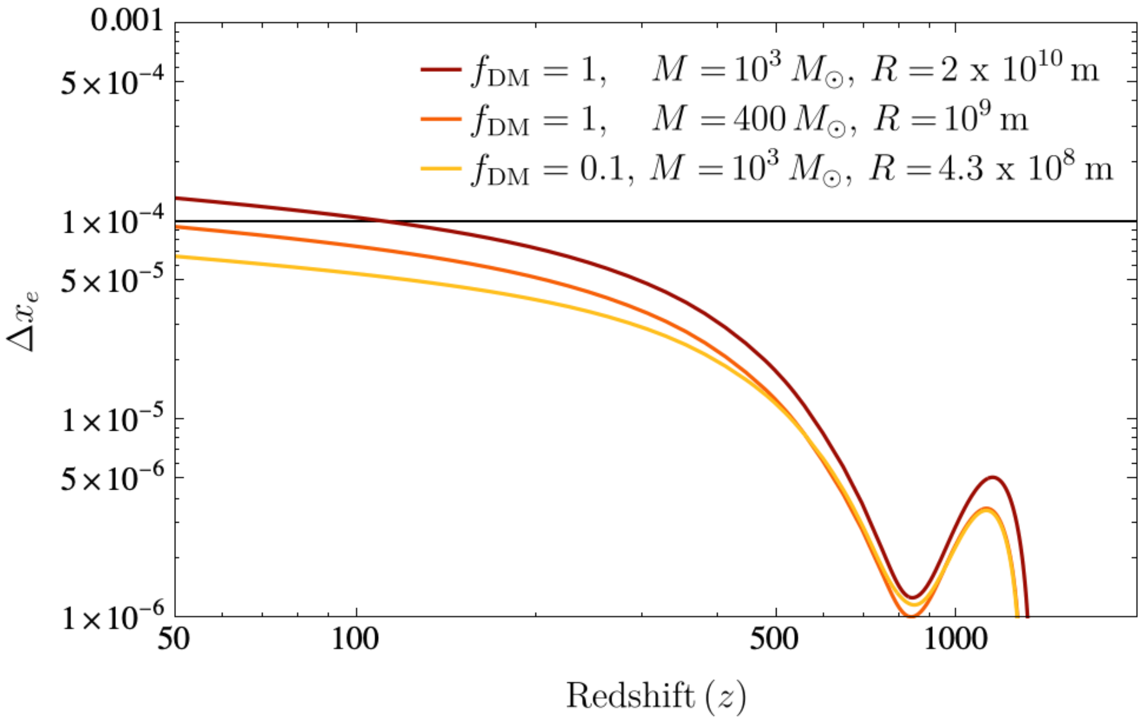
$$\frac{{\rm d}T_{\rm M}}{{\rm d}z} = \frac{1}{(1+z)}\left[2T_{\rm M} + \frac{8\pi^2\sigma_{\rm T}{T_{\rm cmb}}^4}{45H(z)m_e}\frac{x_e}{1+x_e}(T_{\rm M}-T_{\rm cmb})\right] - \frac{2}{3\,n}\frac{1+2x_e}{3H(z)(1+z)}\dot{\rho}_{\rm dep},$$

$$\frac{{\rm d}x_e}{{\rm d}z} = C_r(z)\frac{\alpha_{\rm B}(T_{\rm M})}{H(z)(1+z)}\left[nx_e^2 + \left(\frac{m_eT_{\rm M}}{2\pi}\right)^{3/2}e^{-\frac{E_{\rm I}}{T_{\rm M}}}(1-x_e)\right] - \frac{1-x_e}{3H(z)(1+z)}\frac{\dot{\rho}_{\rm dep}}{E_{\rm I}\,n}$$

Placing EDOs in our Universe

Solving the system of ODEs for the EDOs, we find the following modifications

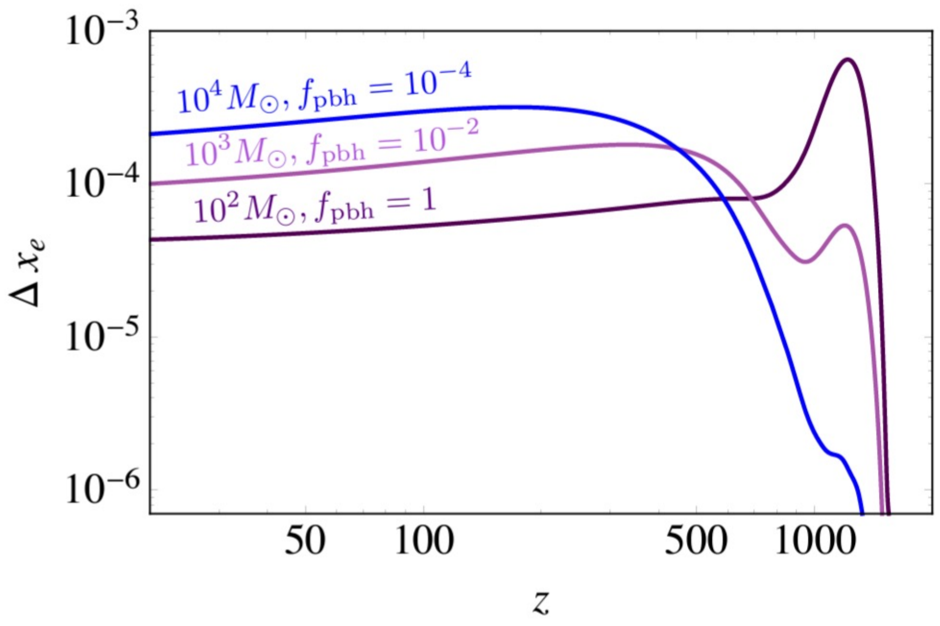


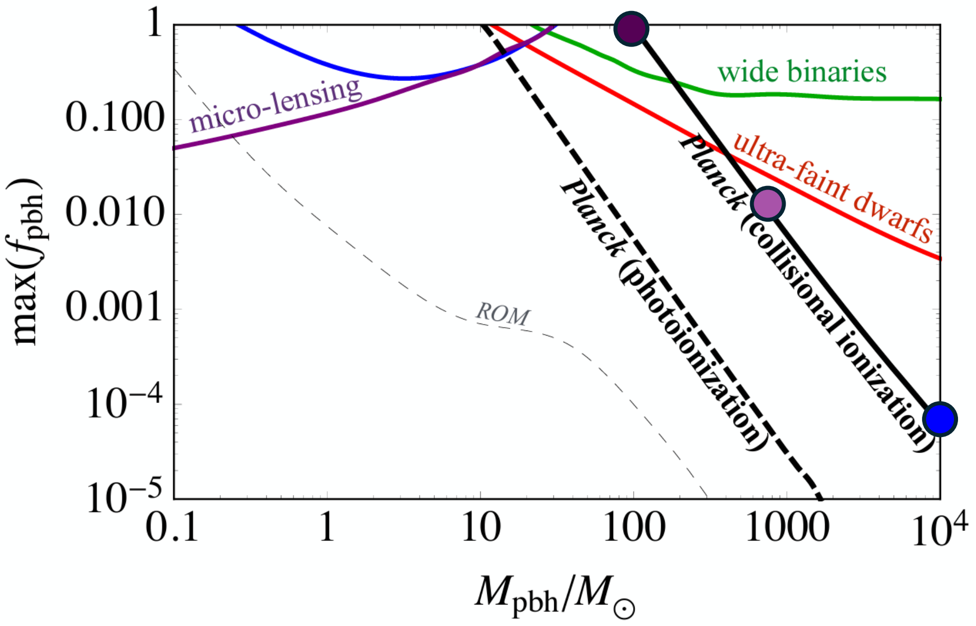


Placing EDOs in our Universe

At this point, we should use a Boltzmann code to constrain the ionisation history.

However, we can recast previous results from PBHs (Ali-Haïmoud, Kamionkowski)

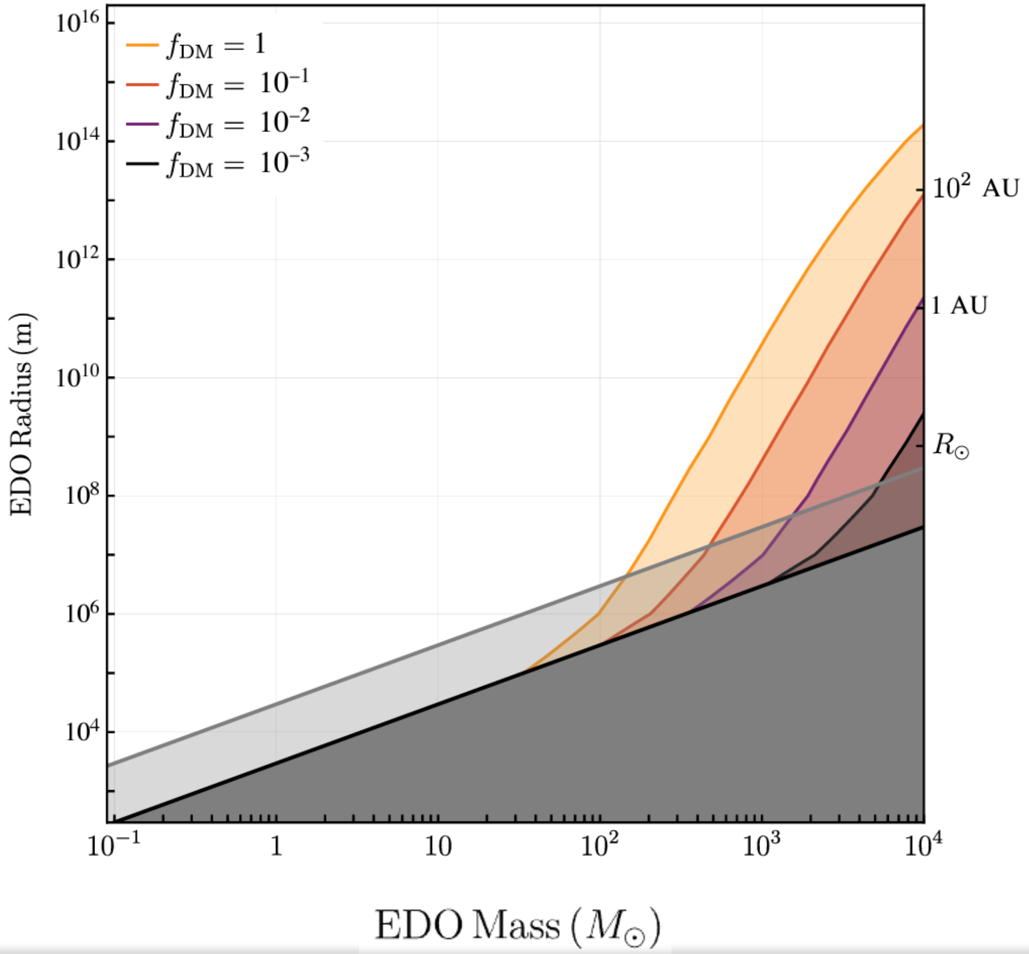


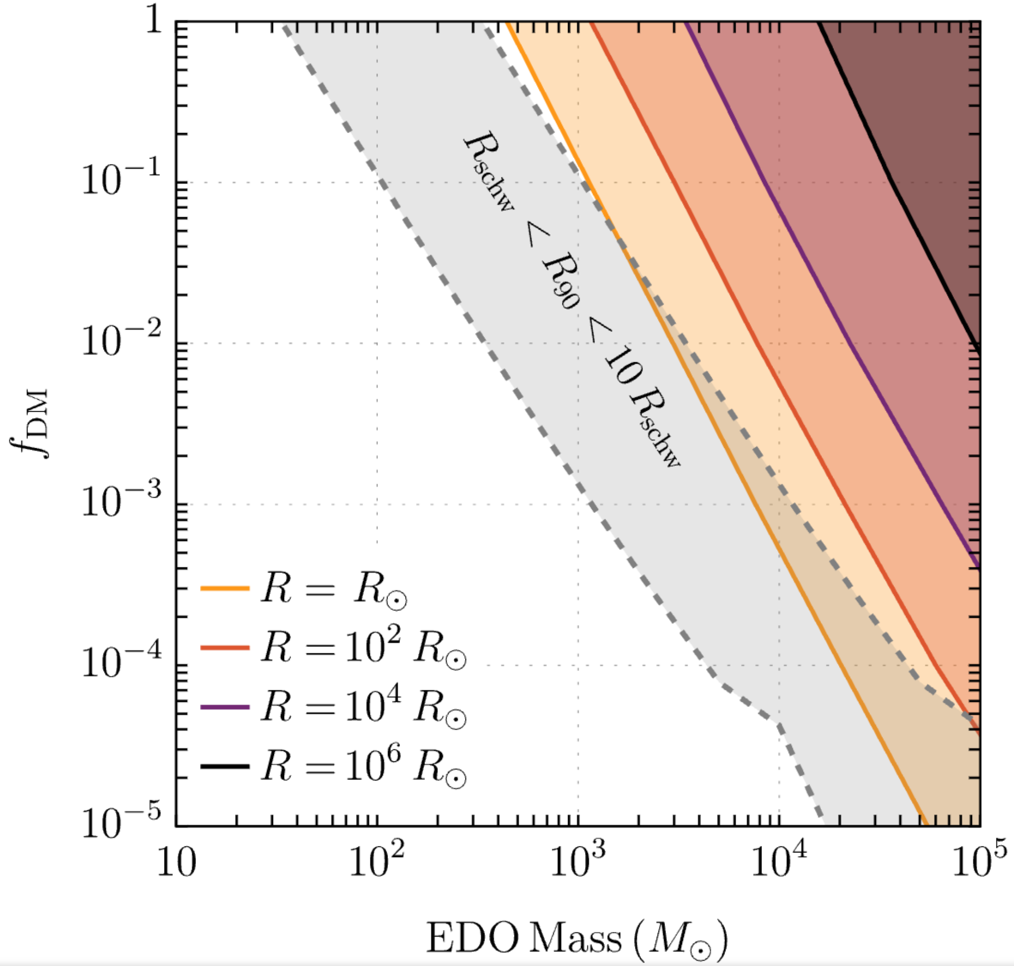


We will take $\Delta x_e(z = 50) < 10^{-4}$ as a constraining condition

Results

Uniform sphere:

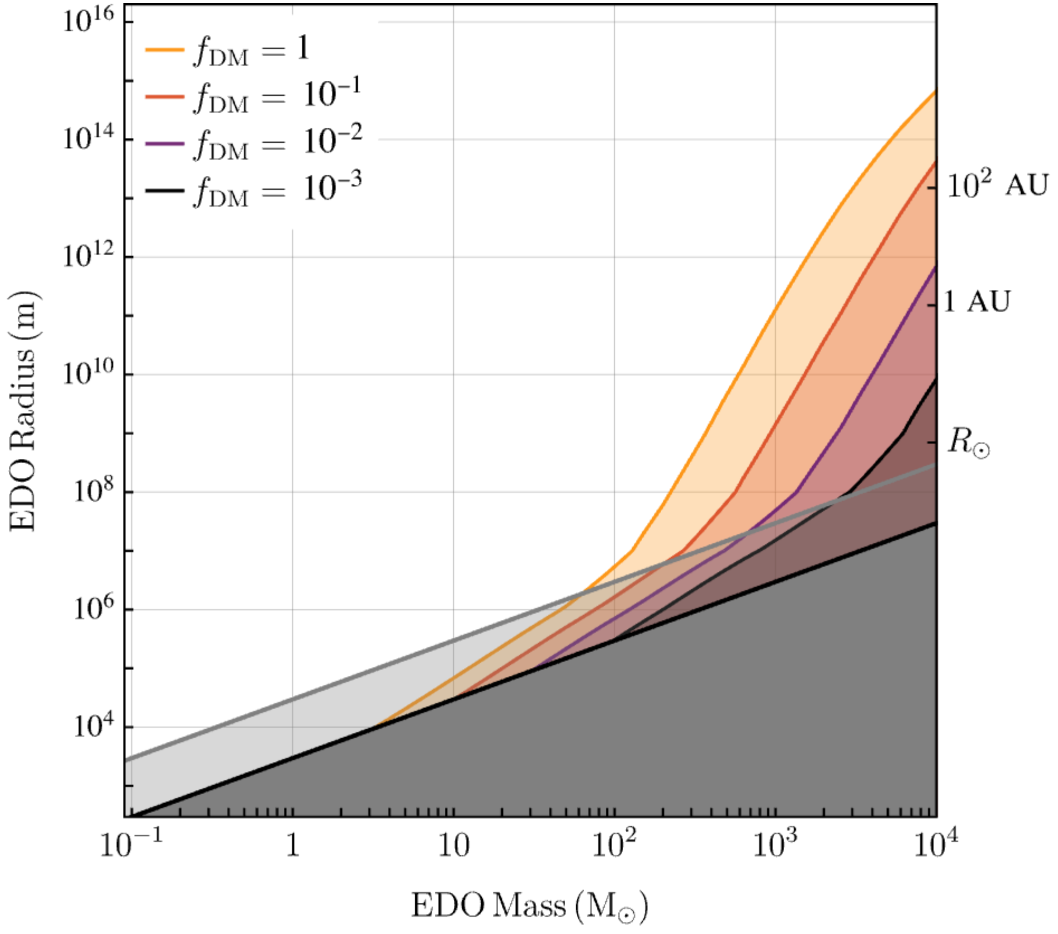




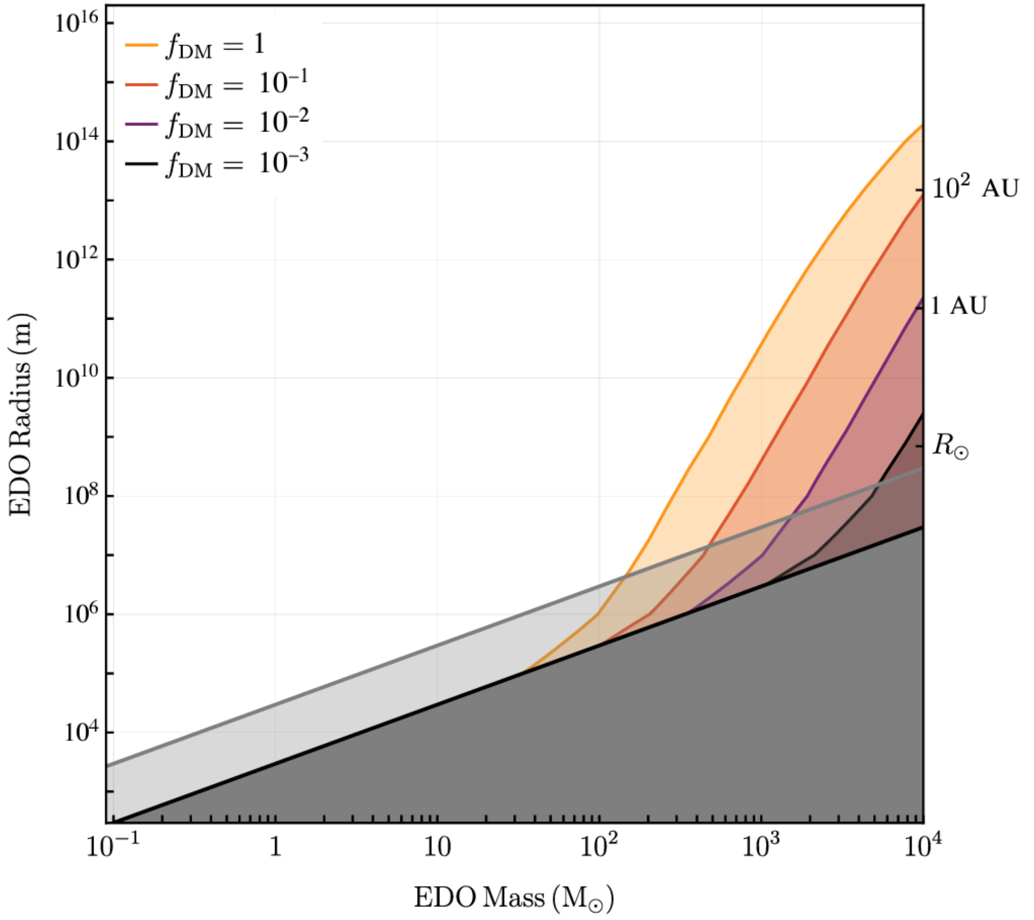
Results

Is the scaling reliable?

NFW sub-halo (R):



Uniform sphere:

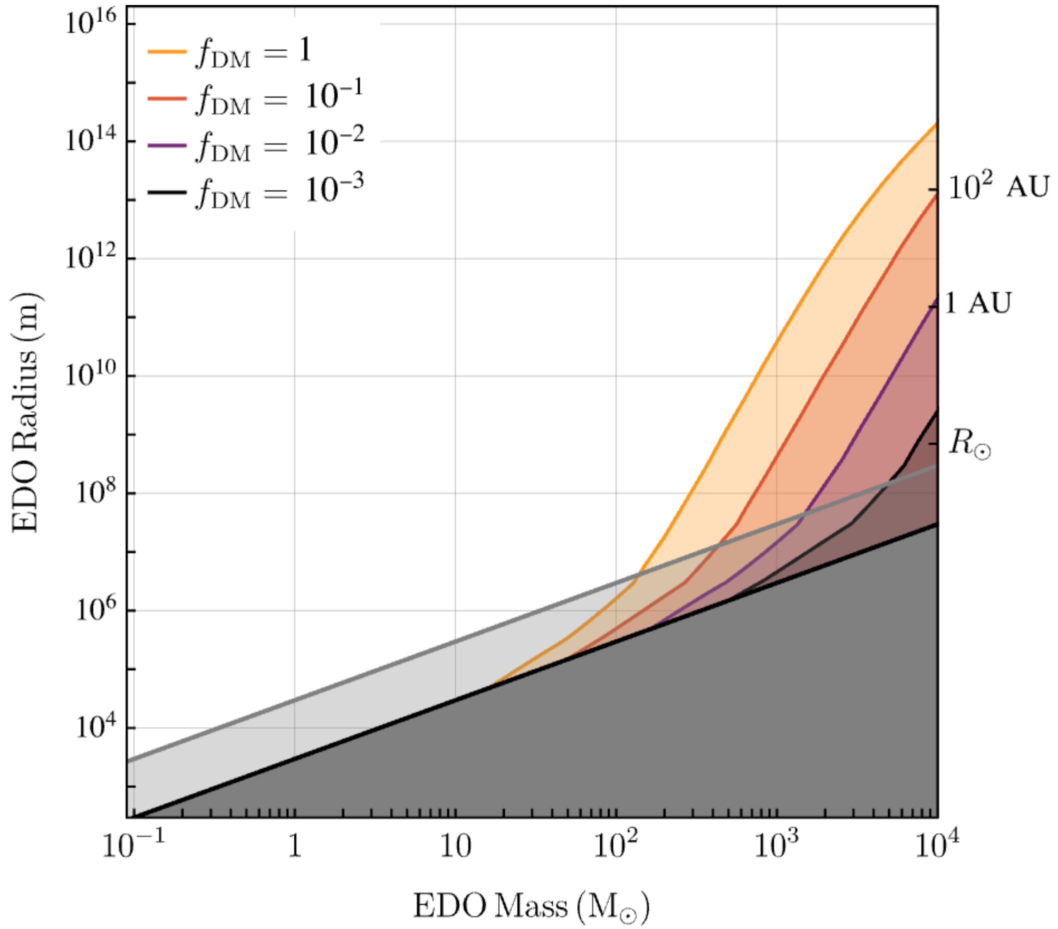


Based on arXiv:2403.13072

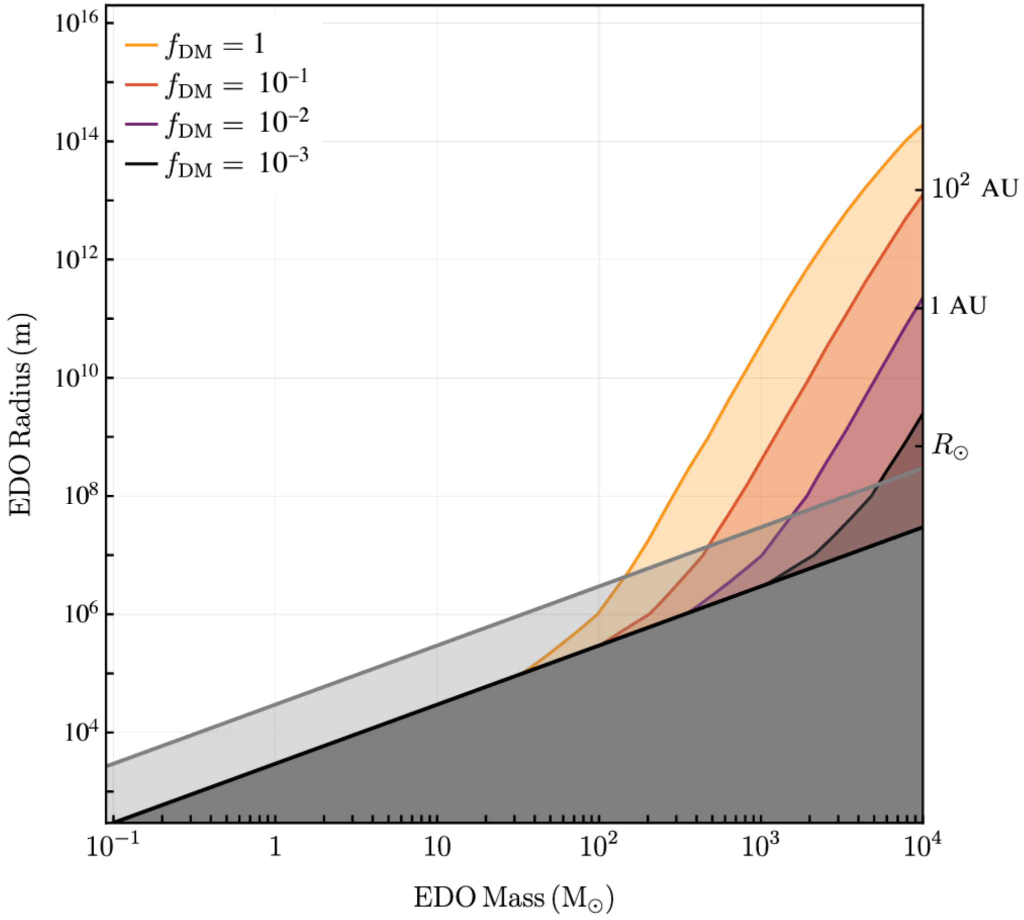
Results

Is the scaling reliable?

NFW sub-halo: rescaled(x0.3)



Uniform sphere:

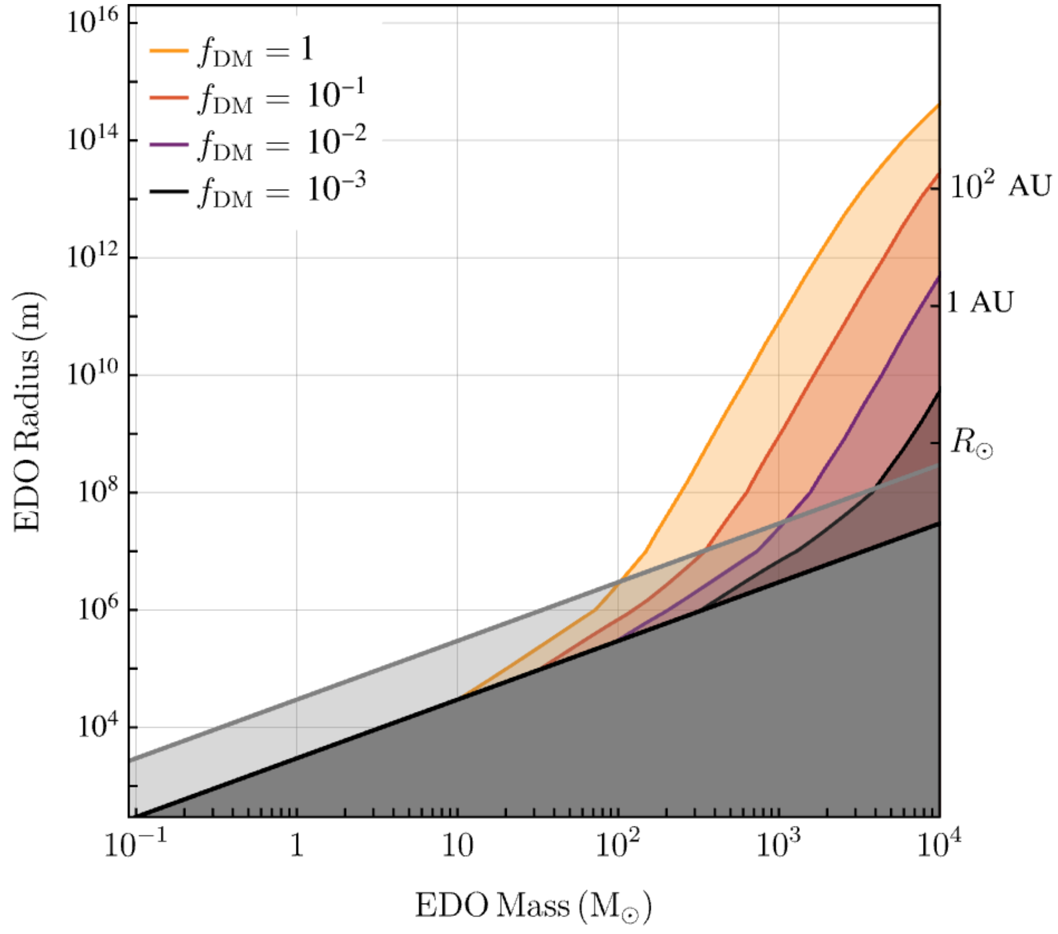


Based on arXiv:2403.13072

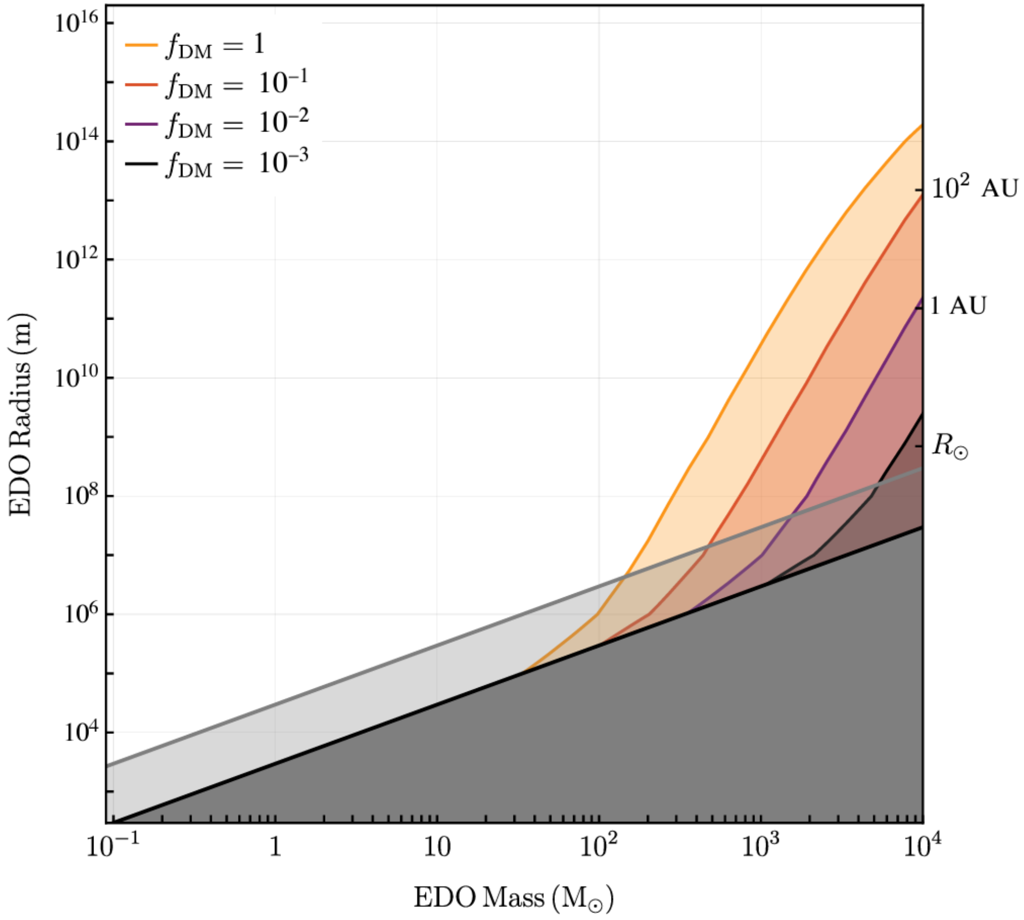
Results

Is the scaling reliable?

Boson star:



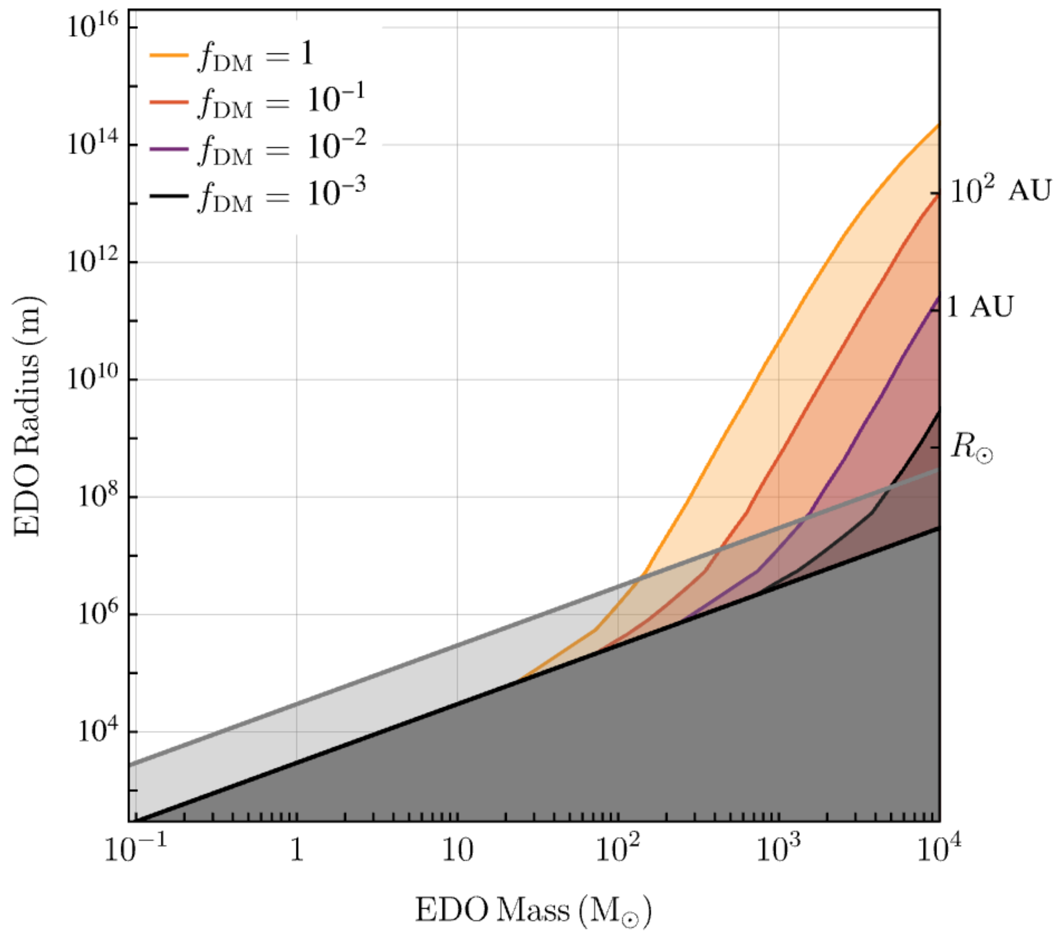
Uniform sphere:



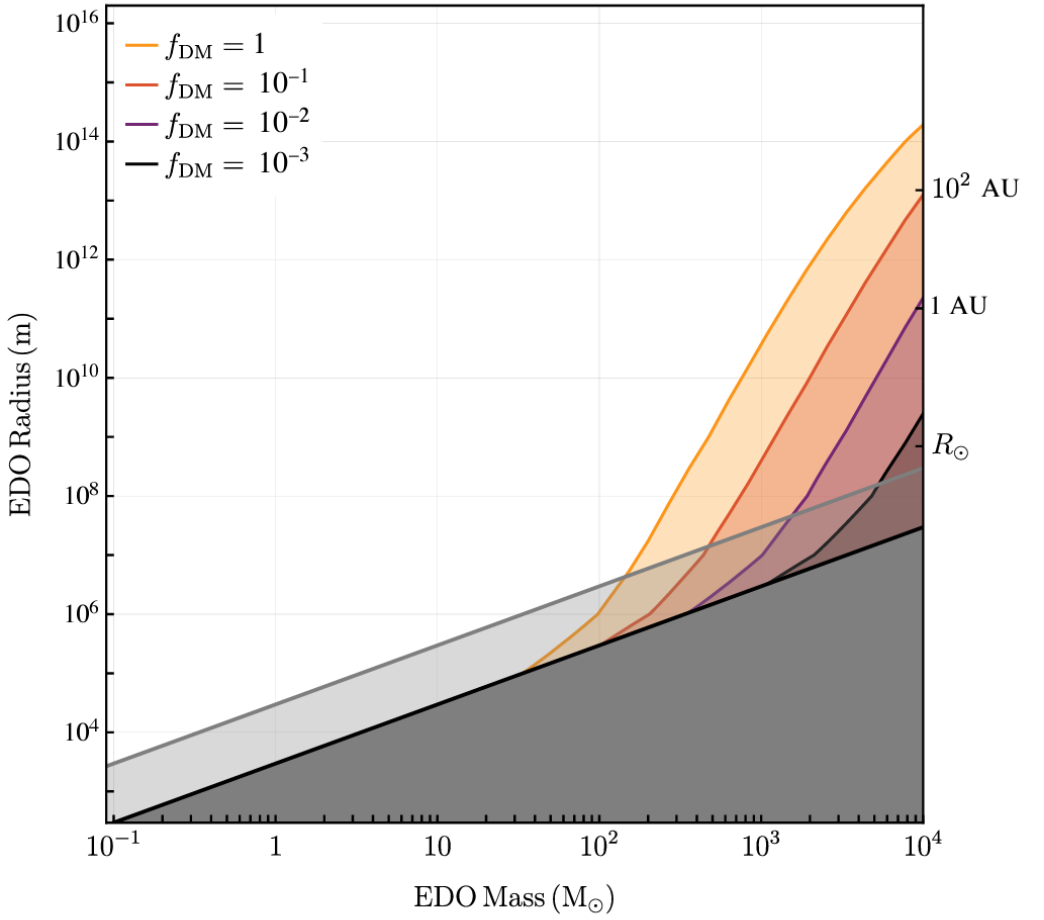
Results

Is the scaling reliable?

Boson star: rescaled(x0.45)



Uniform sphere:



Results

Is the scaling reliable?

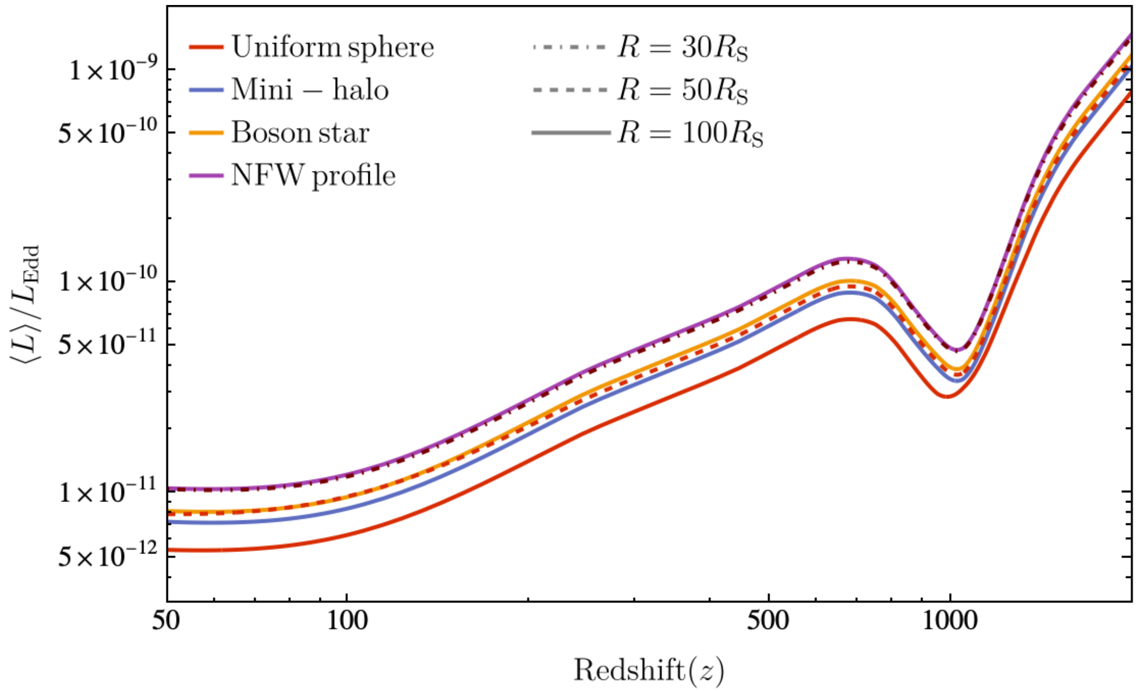
YES!

The important question: how can we extend this?

1)Plot the luminosity of a new Mass function, and find the necessary rescaling

2) Rescale the bounds from

However, getting to the luminosity was quite complicated already…



Results

Is the scaling reliable?

YES!

The important question: how can we extend this?

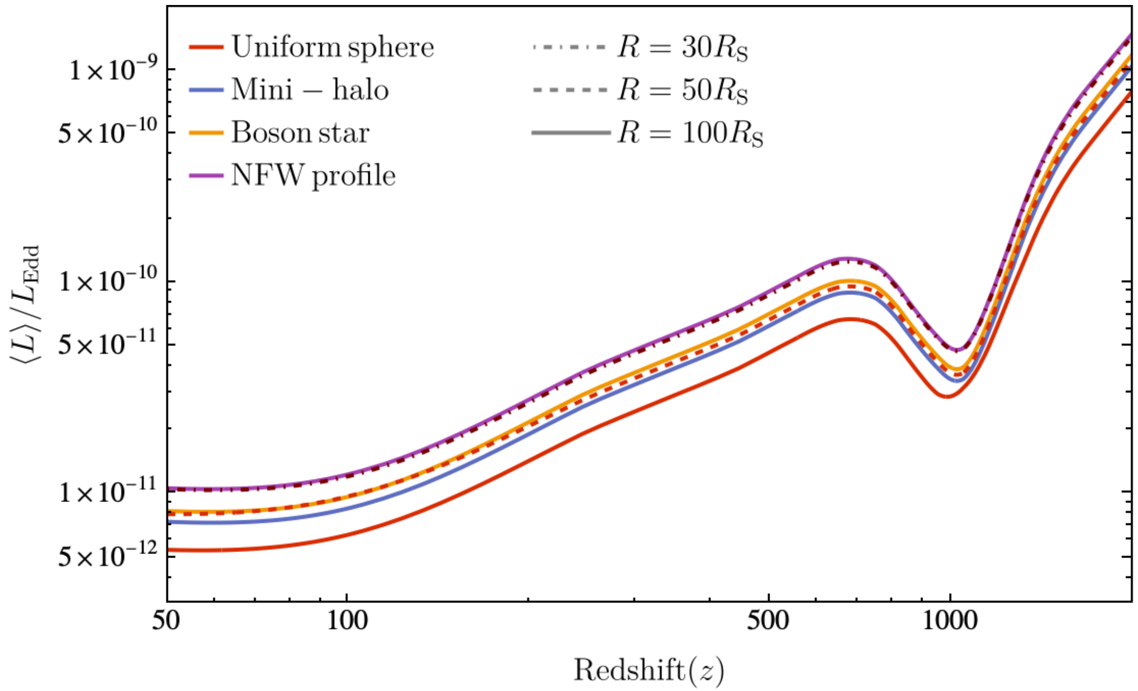
1)Plot the luminosity of a new Mass function, and find the necessary rescaling

2) Rescale the bounds from

However, getting to the luminosity was quite complicated already…

Use our code! Available here: gitlab.com/SergioSevillano/edo-accretion

Just need to provide a M(r/R) function!



Results

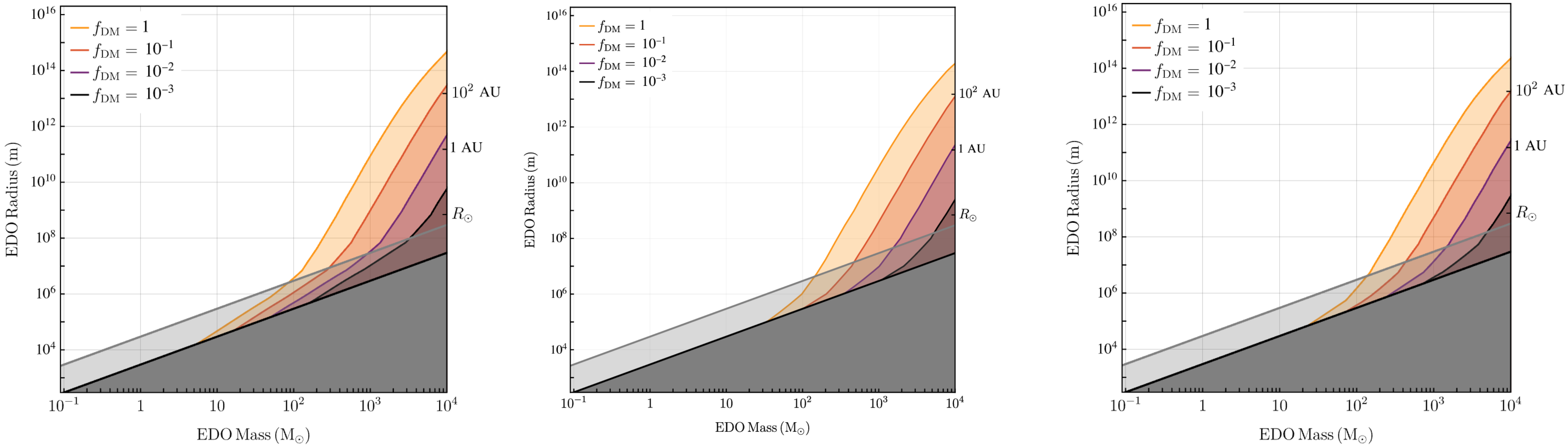
Is the scaling reliable?

YES!

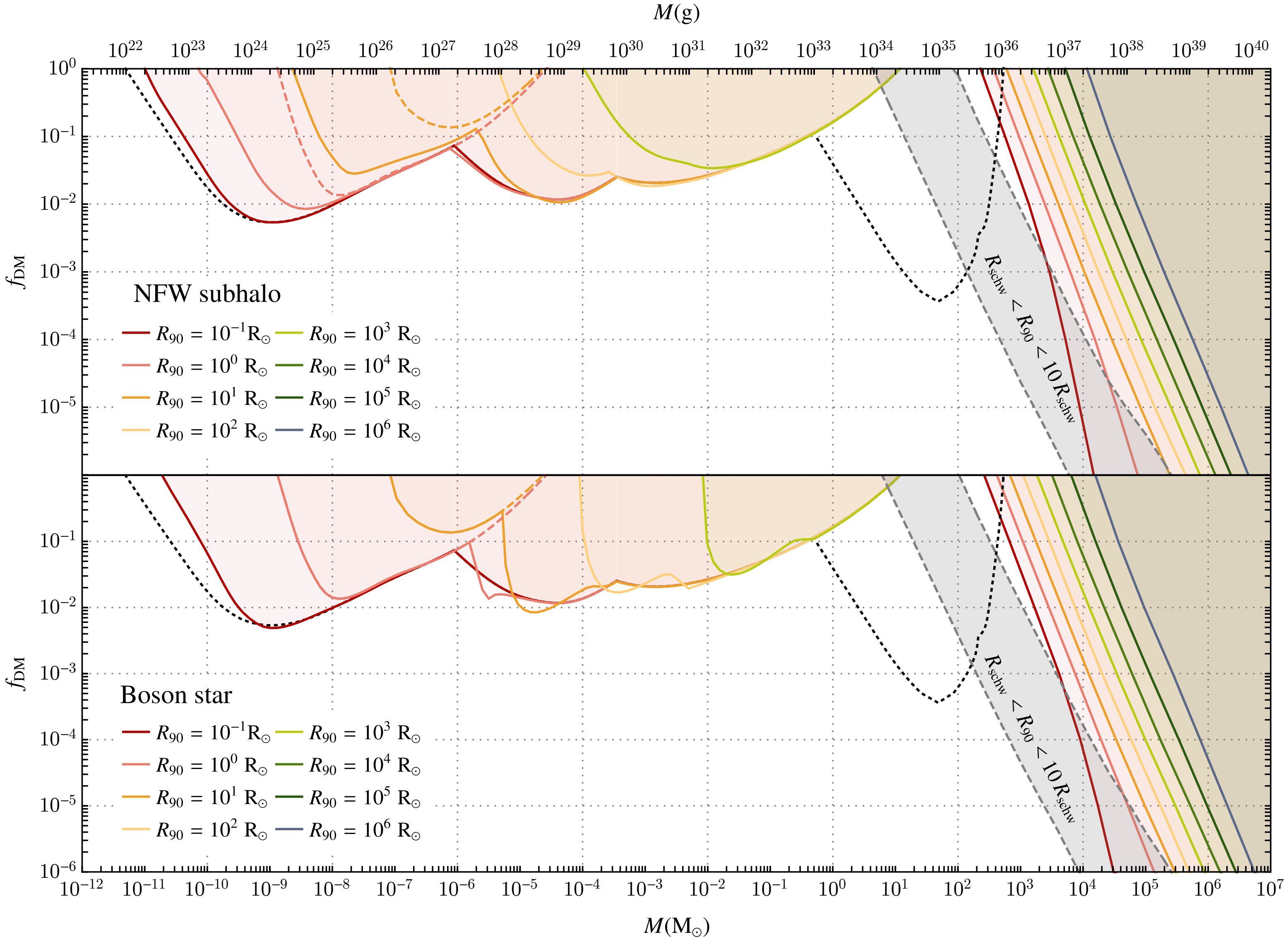
The important question: how can we extend this?

Or just rescale to R90 for your mass profile

NFW sub-halo: Uniform sphere: Boson star:



Finally combining with existing constraints, we obtain



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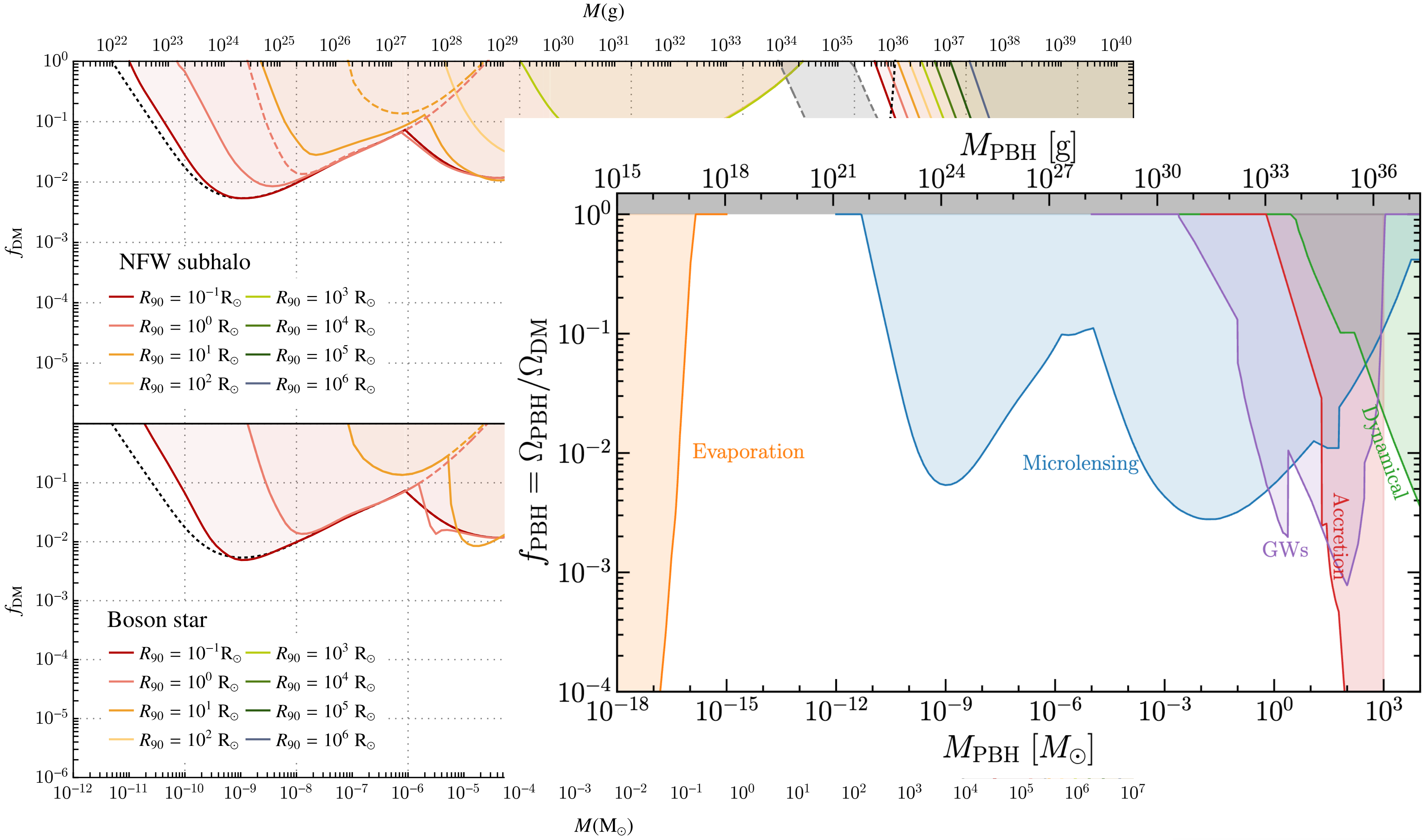

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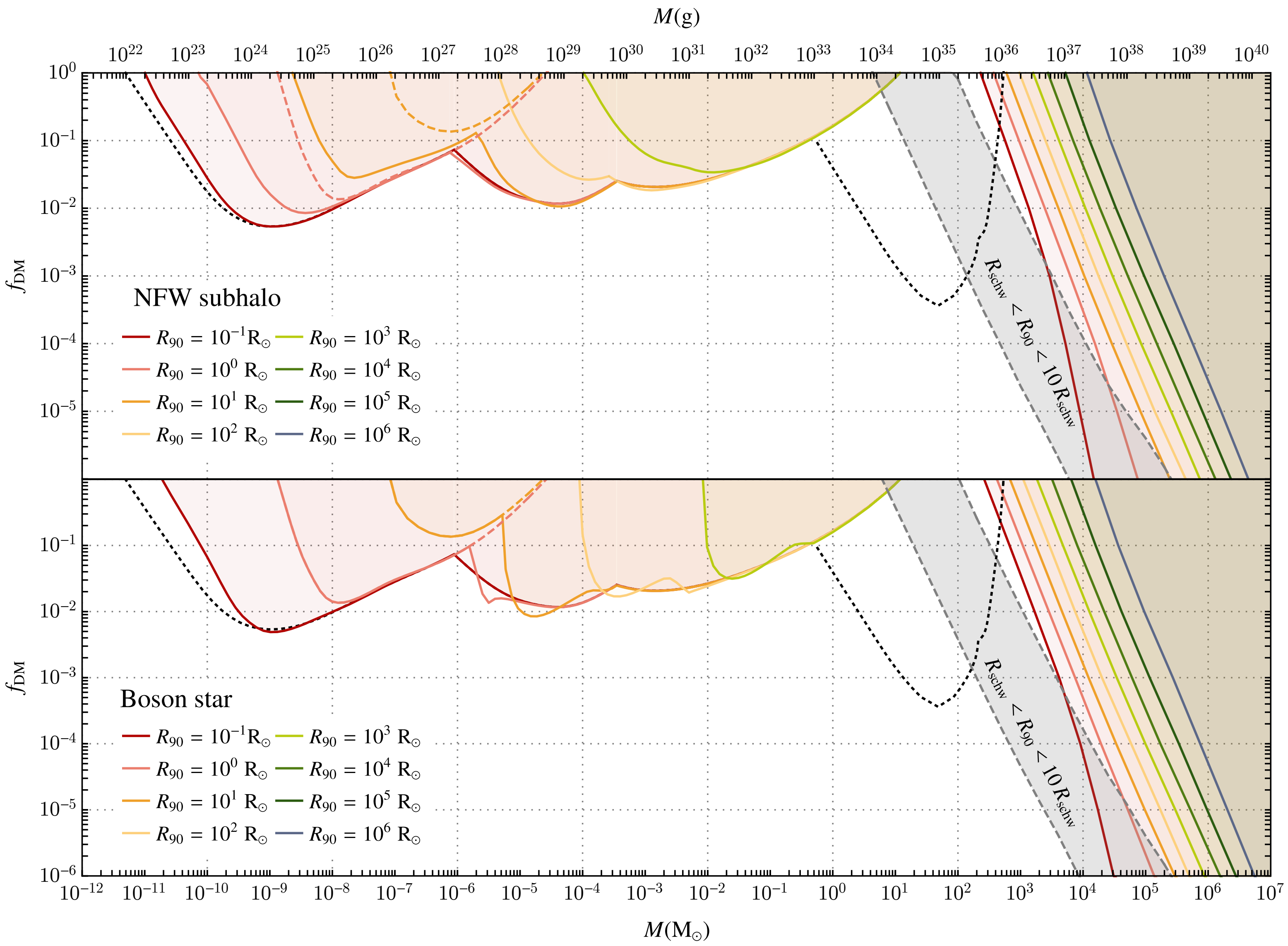


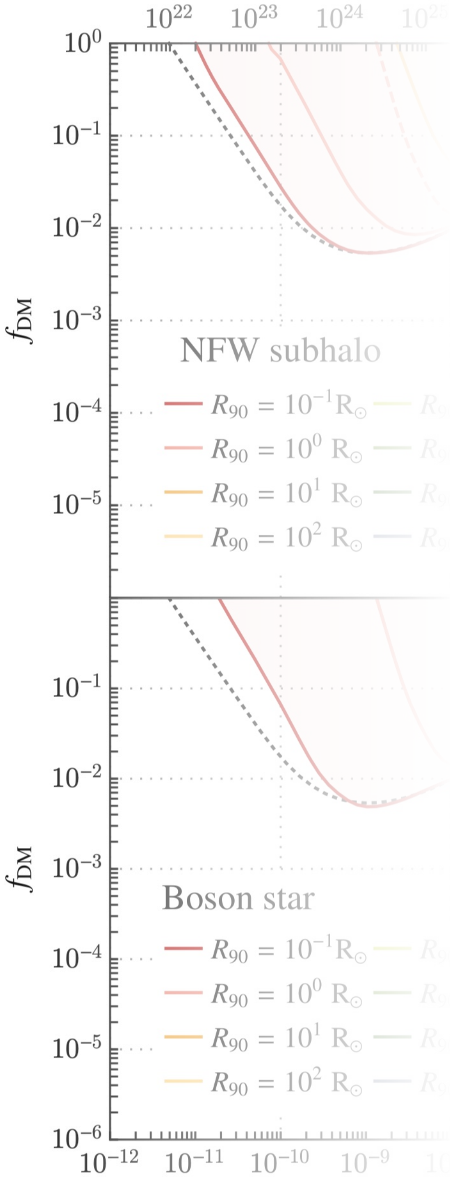
Conclusion

Extended dark matter objects are a popular DM candidate, we study uniform sphere, baoson stars and NFW subhalos.

Similar to PBHs, they can accrete matter, impacting the visibility of the CMB

We calculated the total impact on ionisation, especially at z=50, allowing for fraction of dark matter

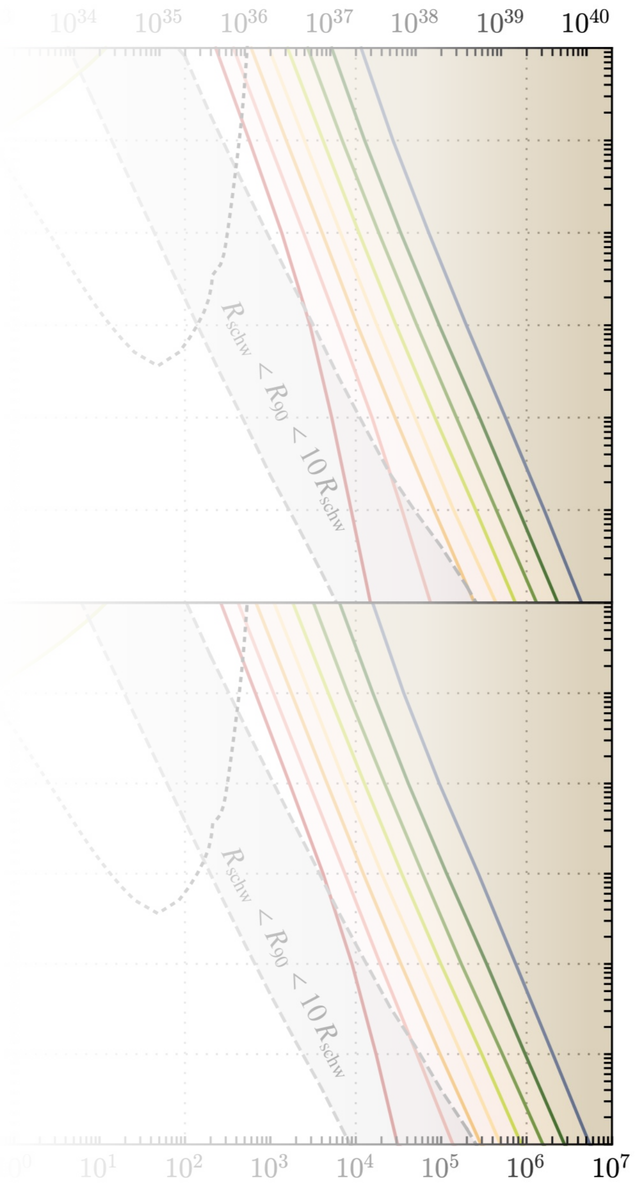
We find strong constraints at high EDO masses, which get weaker the higher is the radius.



Thank you for your attention!

Any questions?

gitlab.com/SergioSevillano/edo-accretion

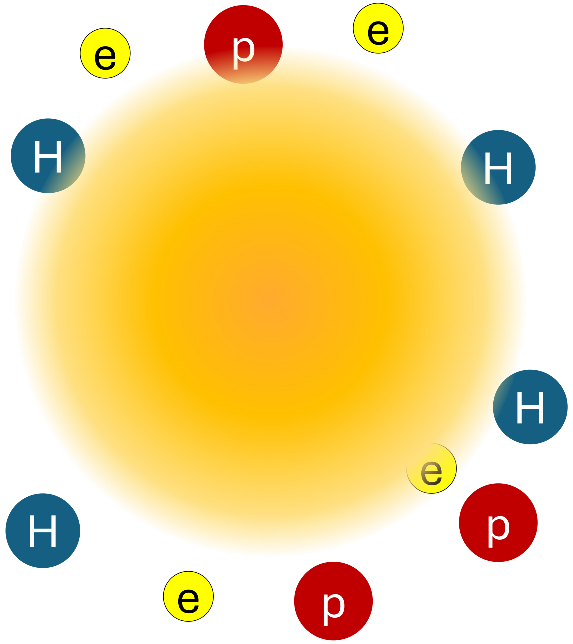


Results

We made it this far! Let's do a short recap of the greatest hits of the talk before wrapping up

We saw that EDOs, although invisible,

accrete matter around them and radiate away photons



Results

We made it this far! Let's do a short recap of the greatest hits of the talk before wrapping up

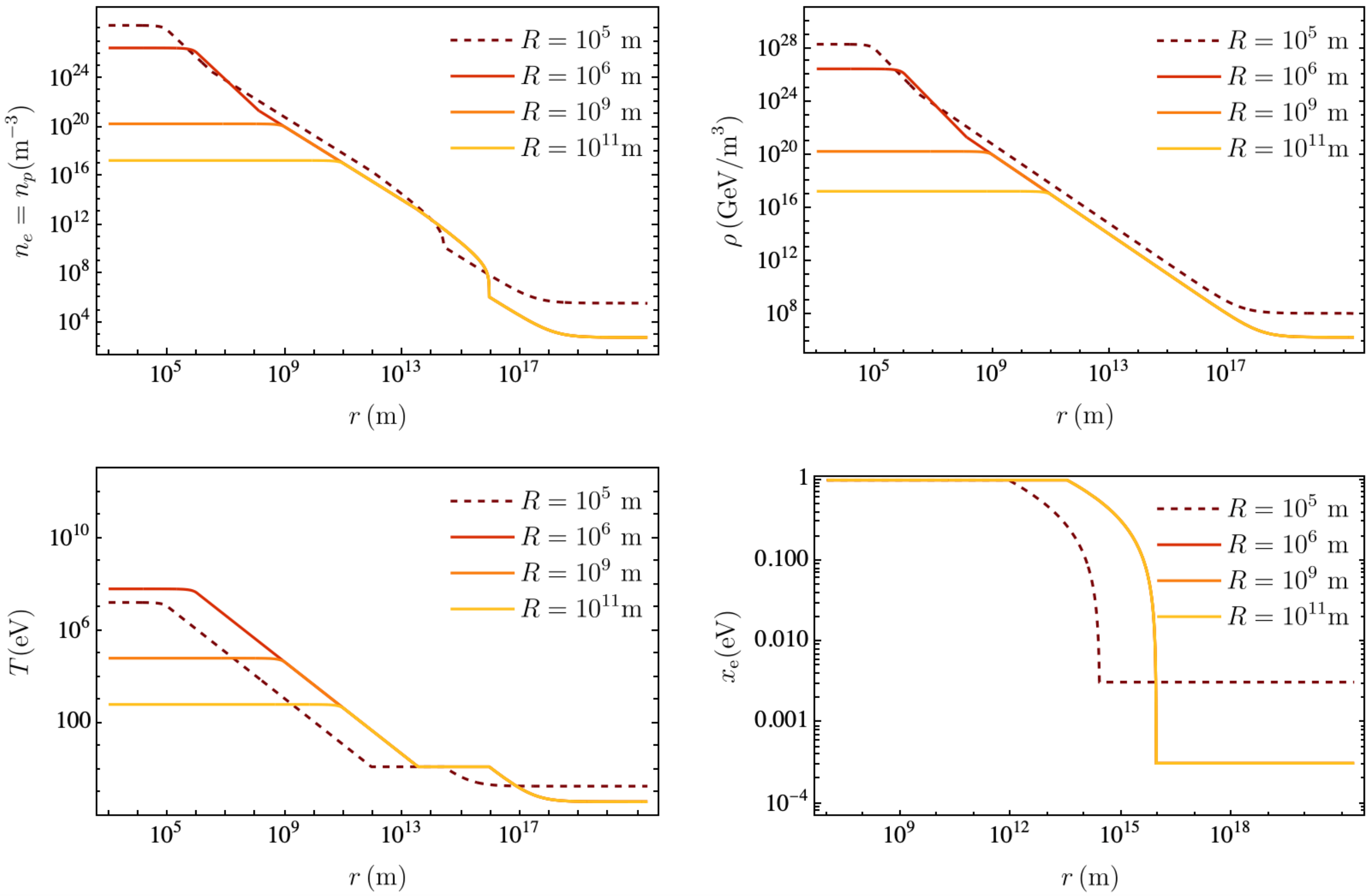
The accreted matter had these properties once accounted for:

-CMB cooling

-Ionisation (collisional)

-Relativistic effects

Uniform Sphere:



Results

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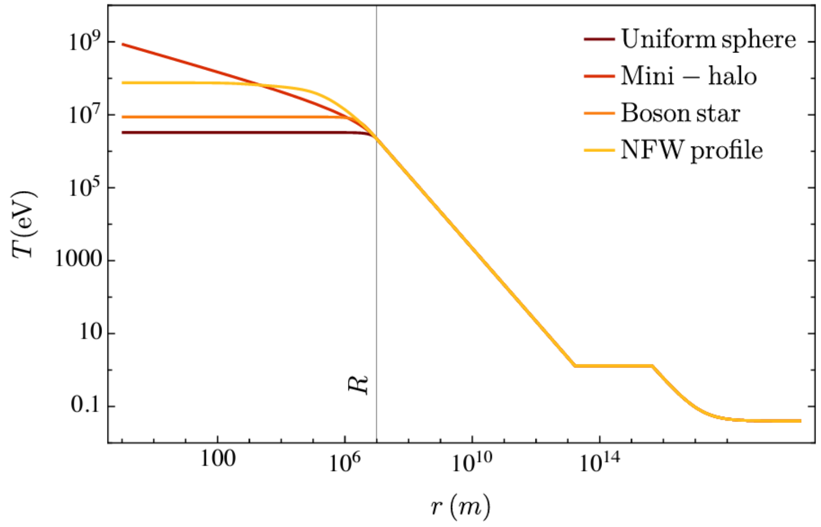
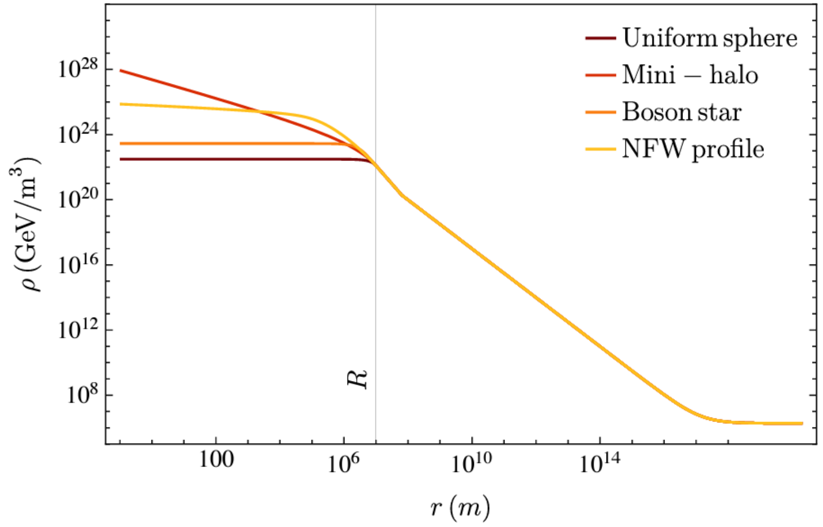
Different mass profiles:



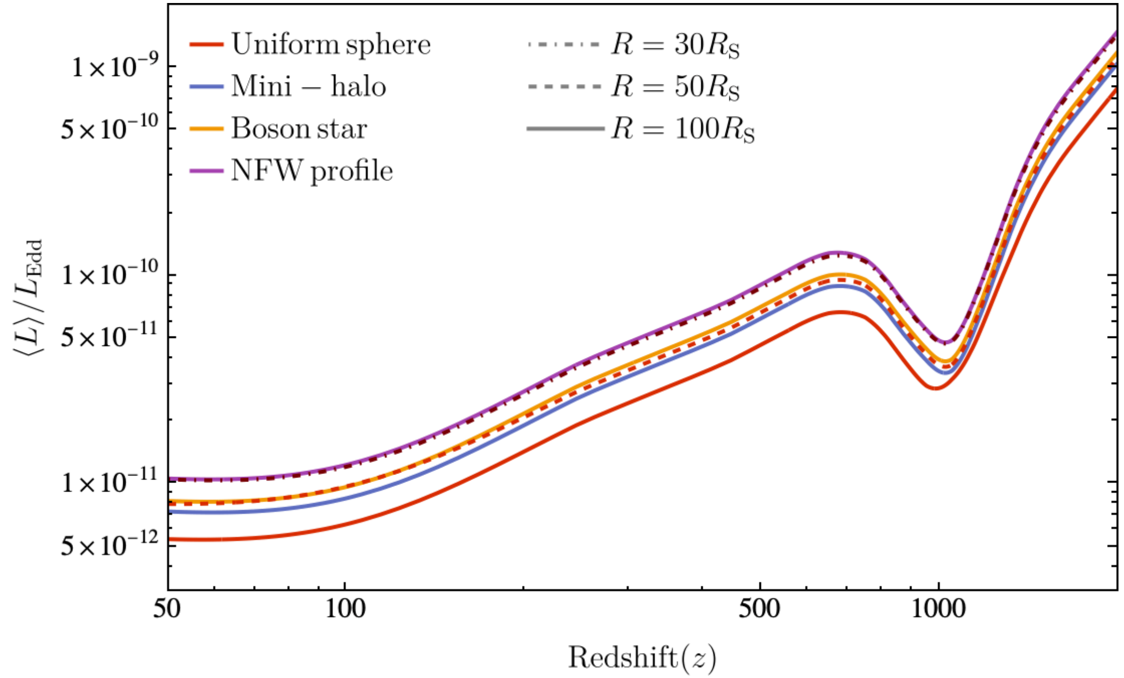


Results

We made it this far! Let's do a short recap of the greatest hits of the talk before wrapping up

The interactions of electrons and protons emit radiation via bremsstrahlung, which is forms a total luminosity

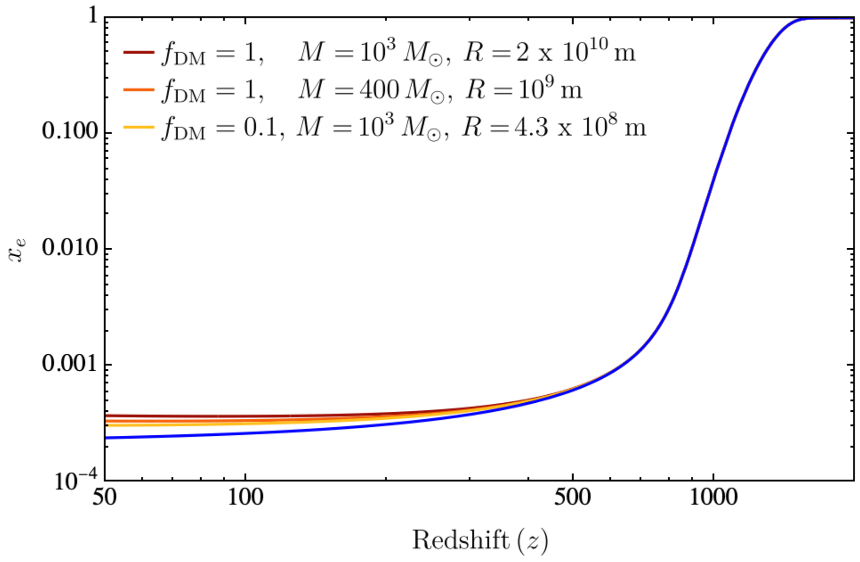
Moreover, we can rescale the uniform sphere into any other mass function!

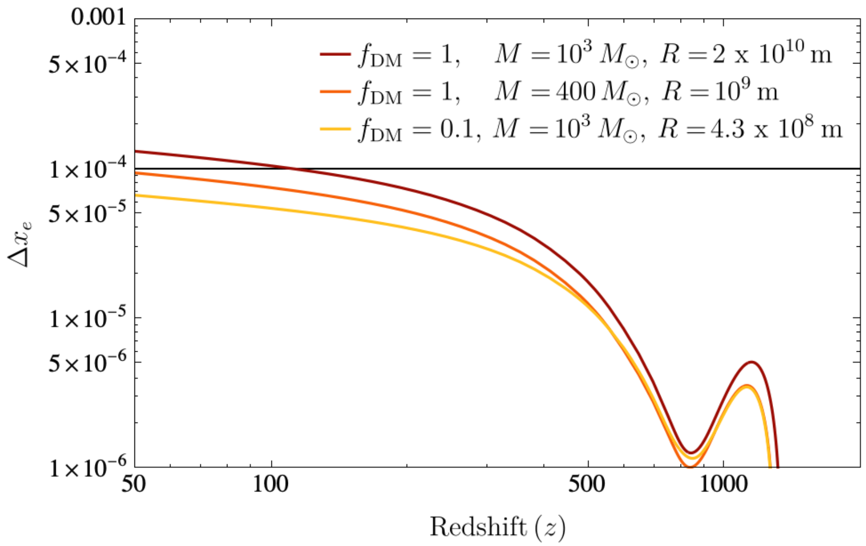


Results

We made it this far! Let's do a short recap of the greatest hits of the talk before wrapping up

From this luminosity, depending on the dark matter fraction, we obtain a different effect on recombination history





We will consider as constrained any set of EDOs with same mass that $\Delta x_e(z=50)<10^{-4}$