Talk prepared for DMLAND, MITP (12 Sept 2024)

Work with Djuna Croon

Current Constraints on Extended Dark matter Objects

Based on arXiv:2403.13072

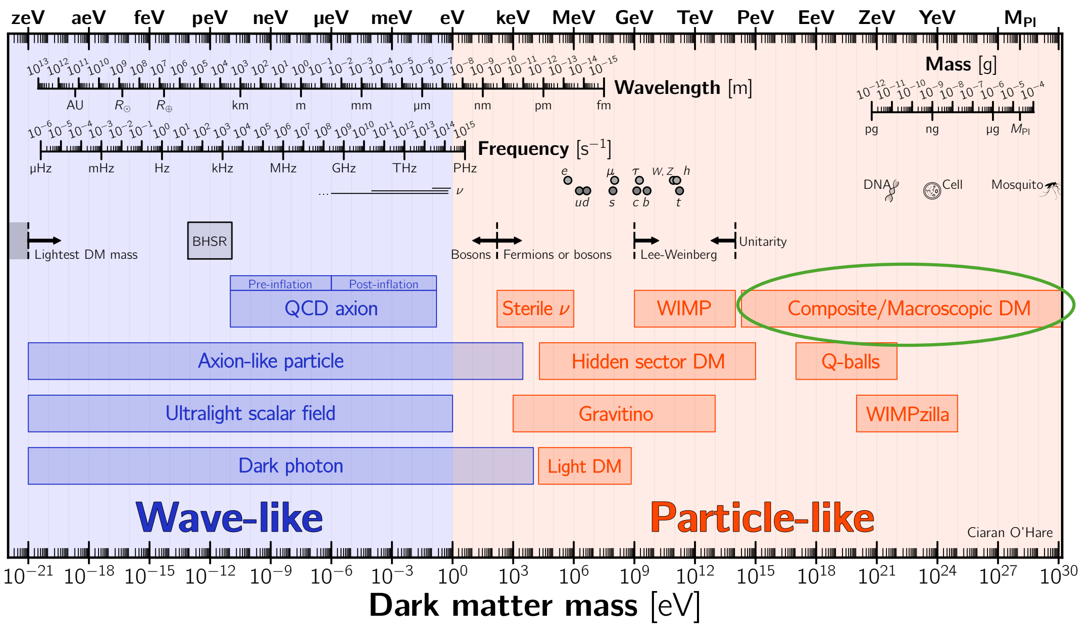
Sergio Sevillano Muñoz

Based on arXiv:2403.13072

Introduction to EDOs

Extended Dark matter Objects are a popular option for dark matter

-Macroscopical objects that only interact gravitationally with matter



Give similar signals to PBHs,
but they are not BHs

Introduction to EDOs

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-They have multiple formation mechanisms:

-Uniform sphere (Witten 1984)

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

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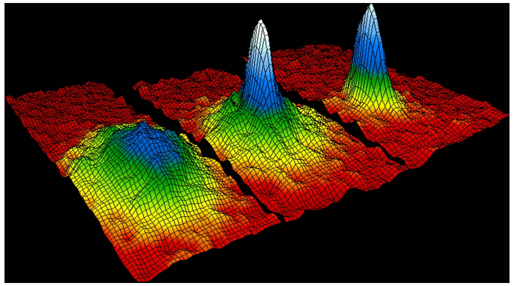

$$i\partial_t\psi = -\frac{1}{2m}\nabla^2\psi + m\Phi\psi,$$
$$\nabla^2\Phi = 4\pi G|\psi|^2.$$

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-NFW sub-halos

$$M(r) = \int_0^r \mathrm{d}\hat{r}\, 4\pi \hat{r}^2 \rho_{\mathrm{NFW}}(\hat{r}),$$

$$\rho_{\mathrm{NFW}}(\hat{r}) = \frac{\rho_0}{\frac{\hat{r}}{R_s}\left(1 + \frac{\hat{r}}{R_s}\right)^2},$$

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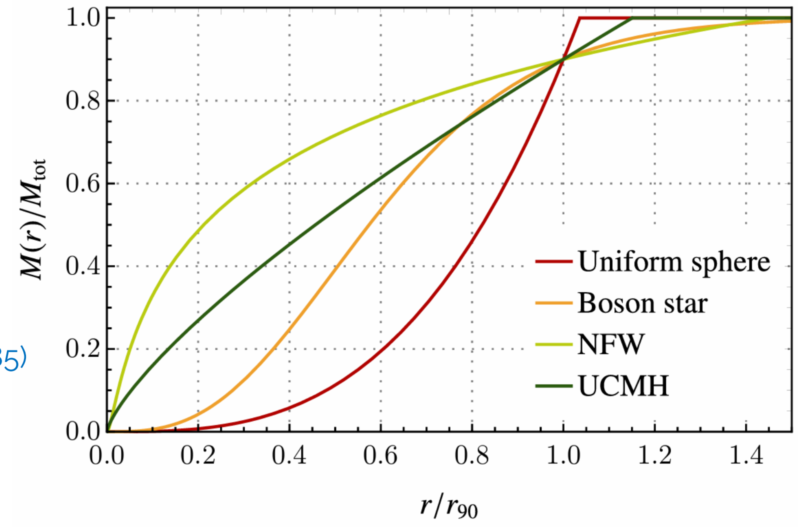

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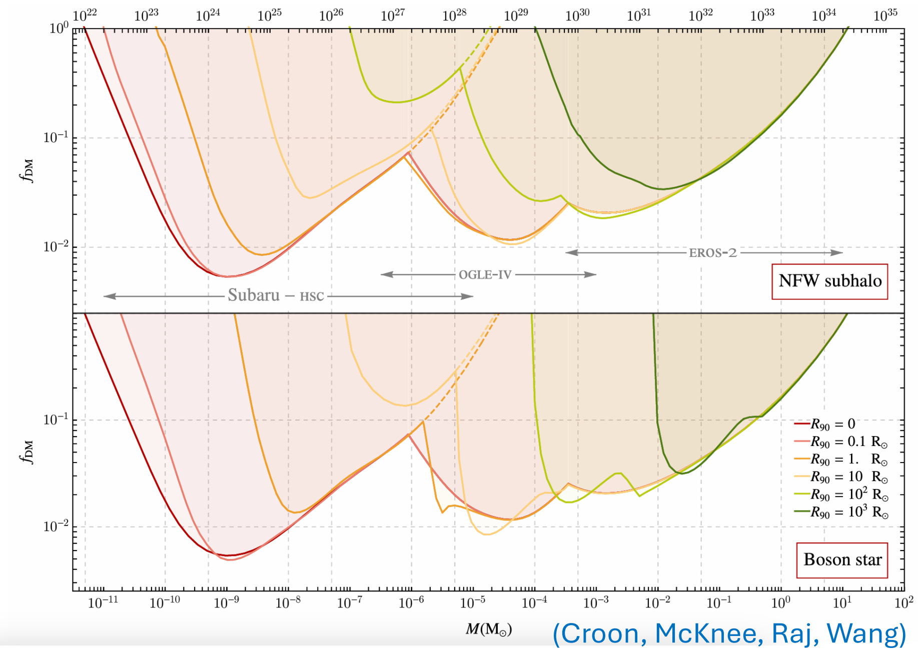
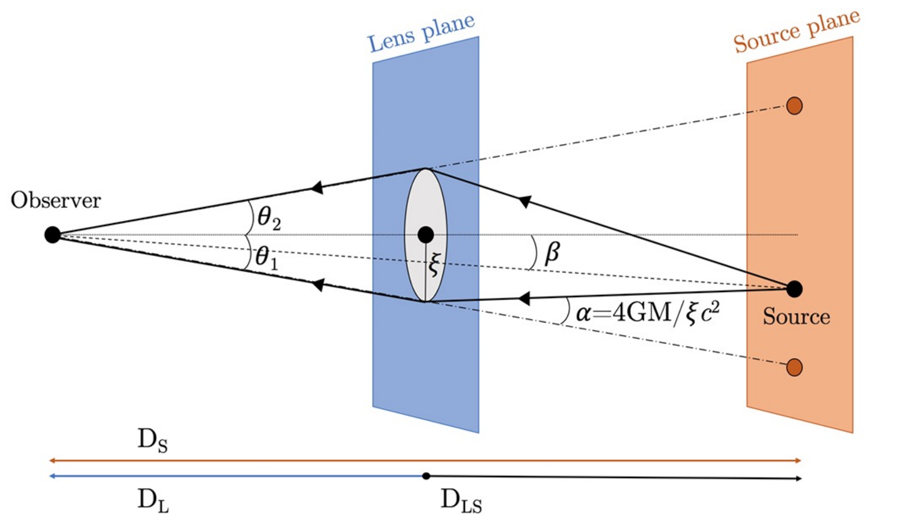
Introduction to EDOs

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)



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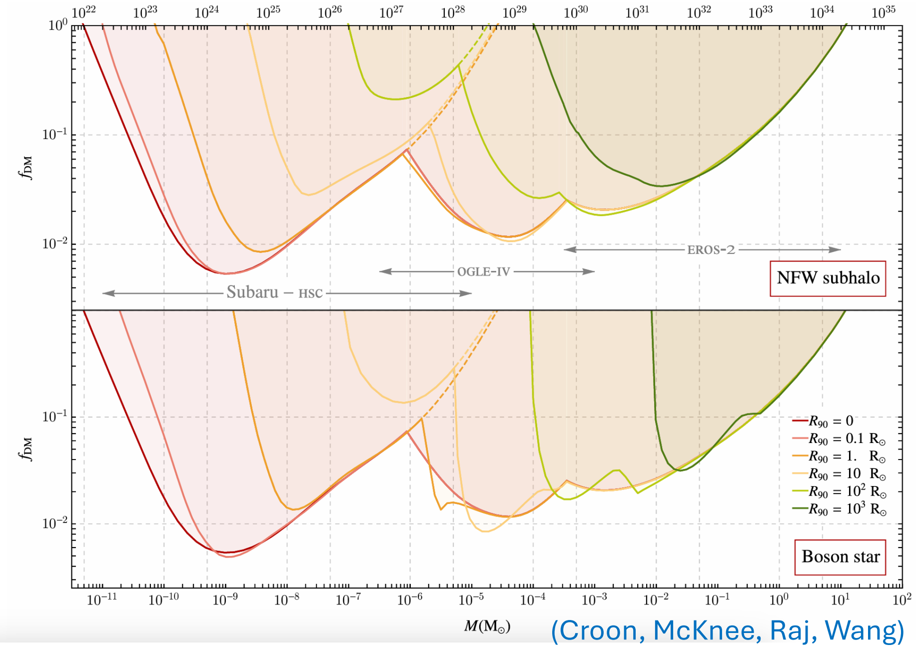

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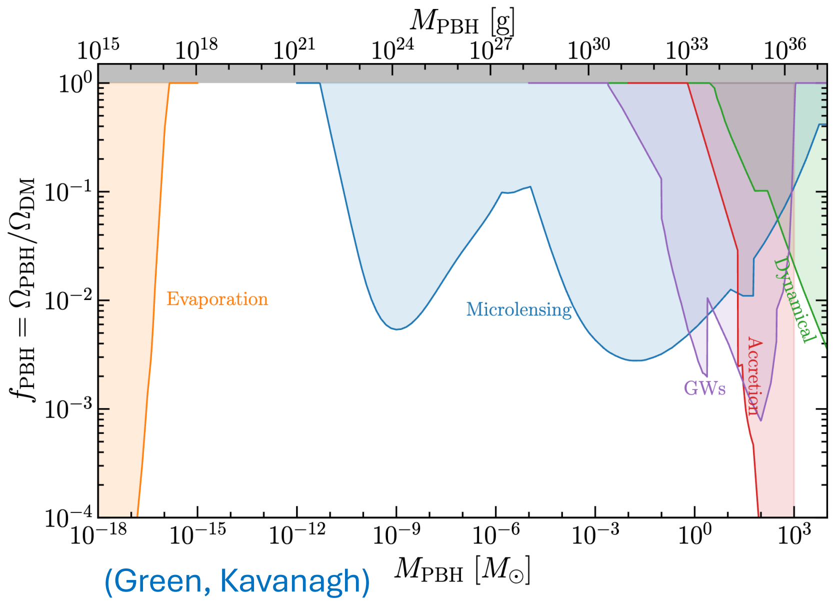

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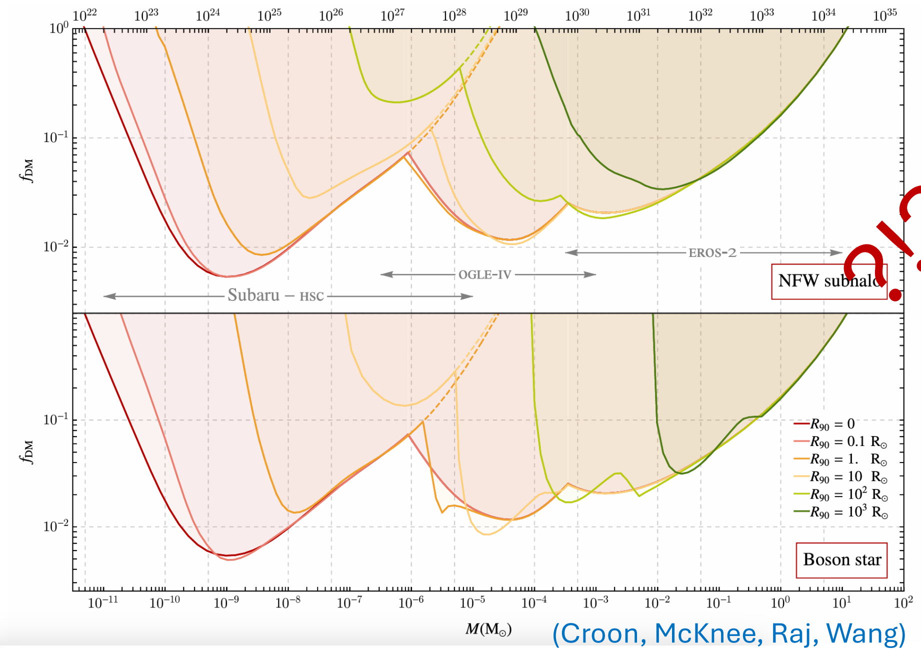

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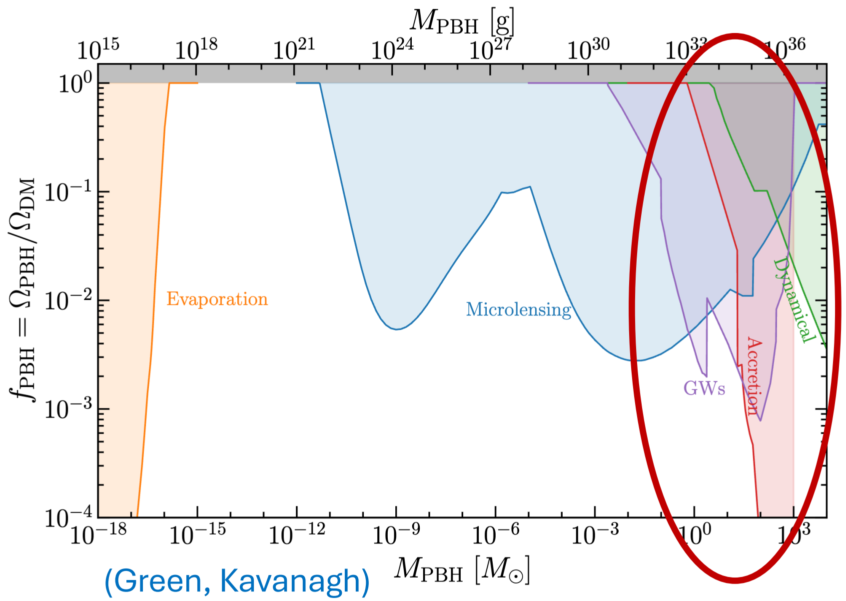

(Green, Kavanagh)

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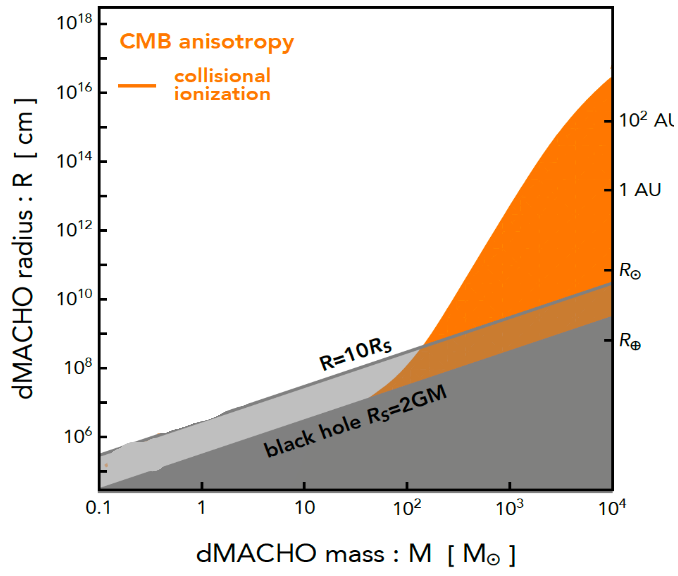
Introduction to EDOs

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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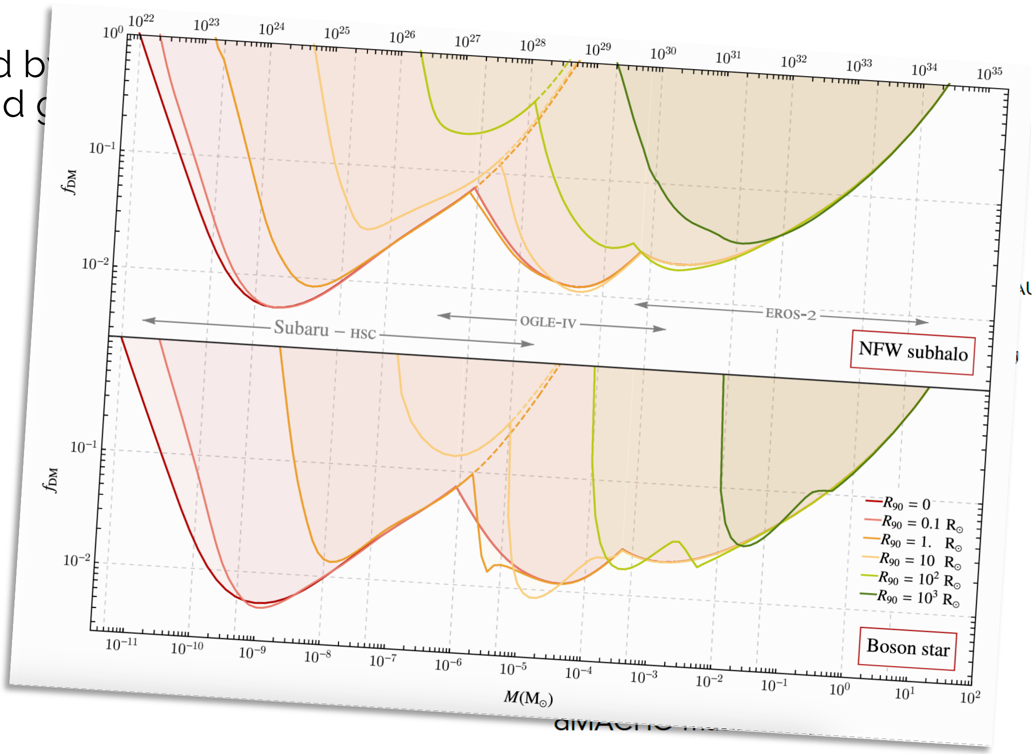


This is the context for our work, we allow for:

-Any mass function-> Numerically

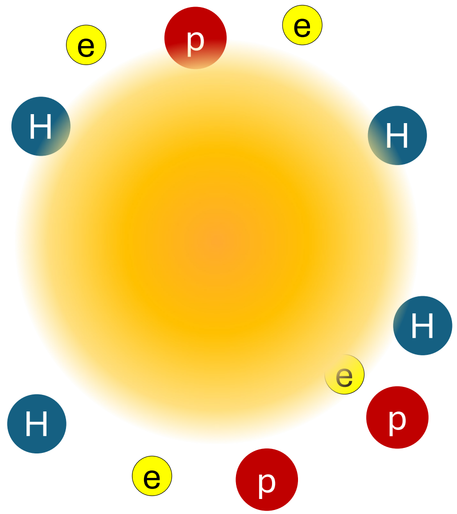
-Any dark matter fraction

Based on arXiv:2403.13072

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

Based on arXiv:2403.13072

Matter accretion

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We expect matter to interact gravitationally with it

The emitted luminosity depends on the following parameters:

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

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

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

Based on arXiv:2403.13072

Matter accretion

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

$$
\begin{aligned}
&\dot{\rho} + \frac{1}{r^2}(r^2 \rho v)' = 0, \\
&\rho \dot{v} + \rho v v' + P' = \rho g, \\
&\rho (\dot{\mathcal{E}/\rho}) + \rho v (\mathcal{E}/\rho)' + P \frac{1}{r^2}(r^2 v)' = \dot{q},
\end{aligned}
$$

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

Based on arXiv:2403.13072

Matter accretion

Approximations!

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

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

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

Based on arXiv:2403.13072

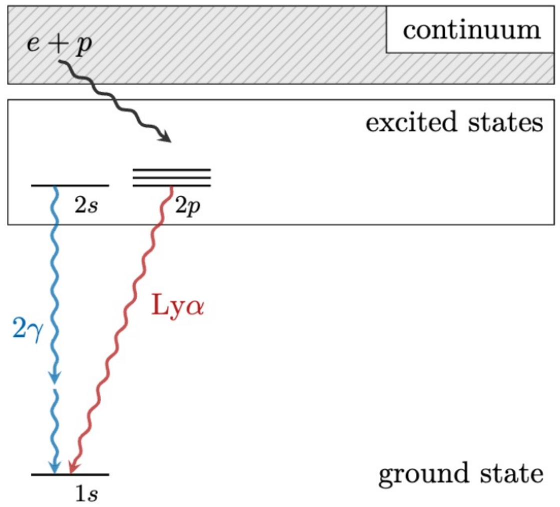
Matter accretion

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

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

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



Baunmann, Cosmology

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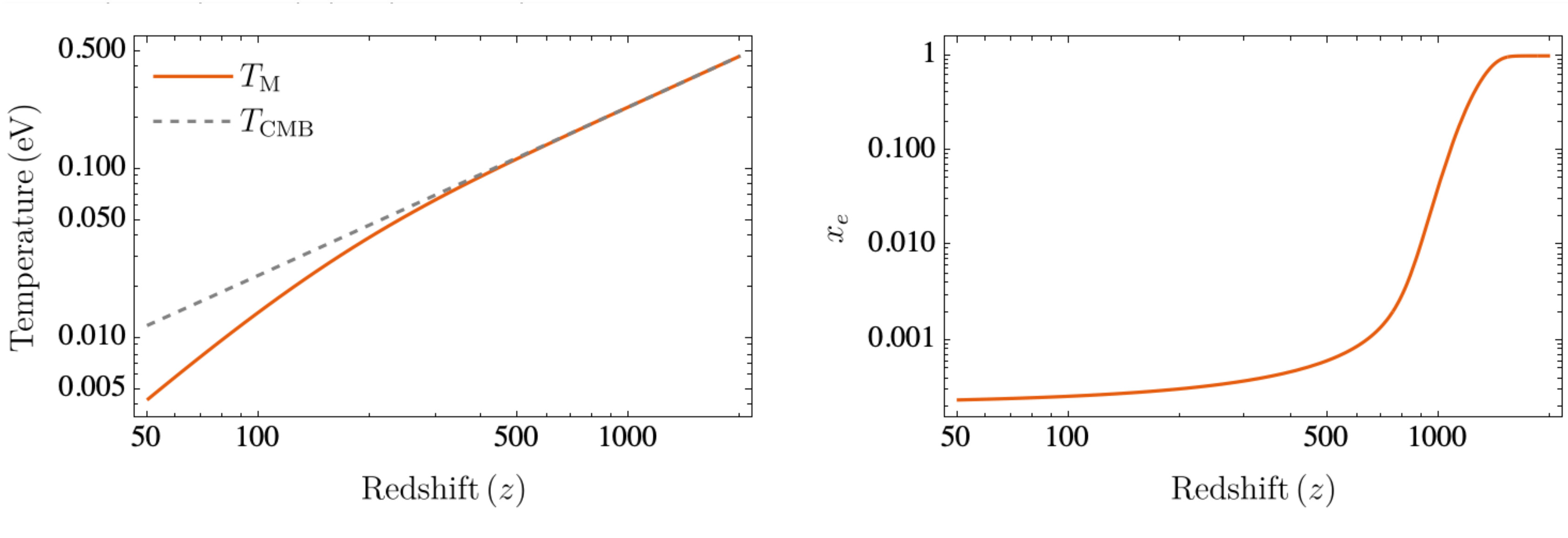

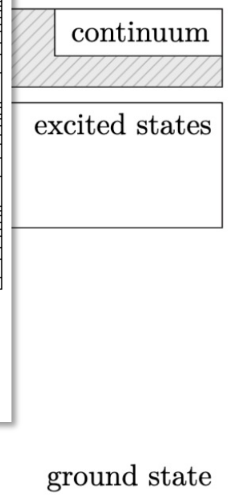

Baunmann, Cosmology

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

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:

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

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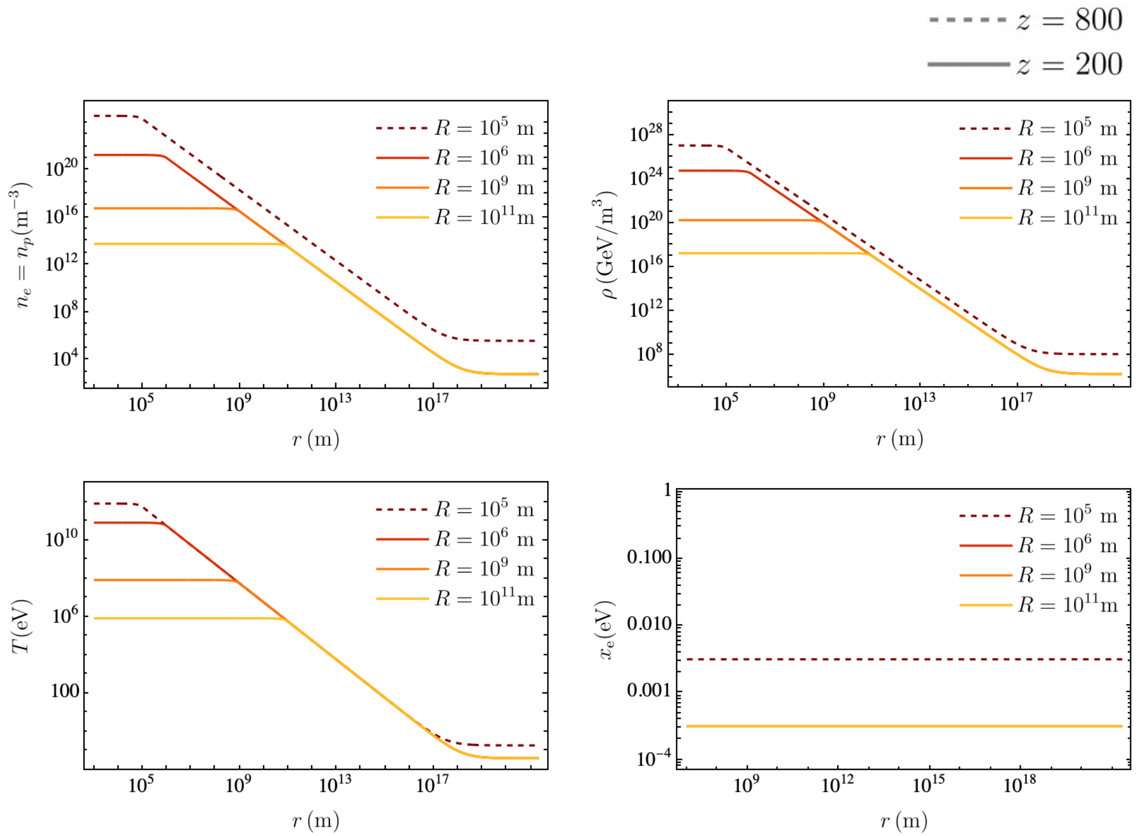
And the uniform sphere mass function:

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



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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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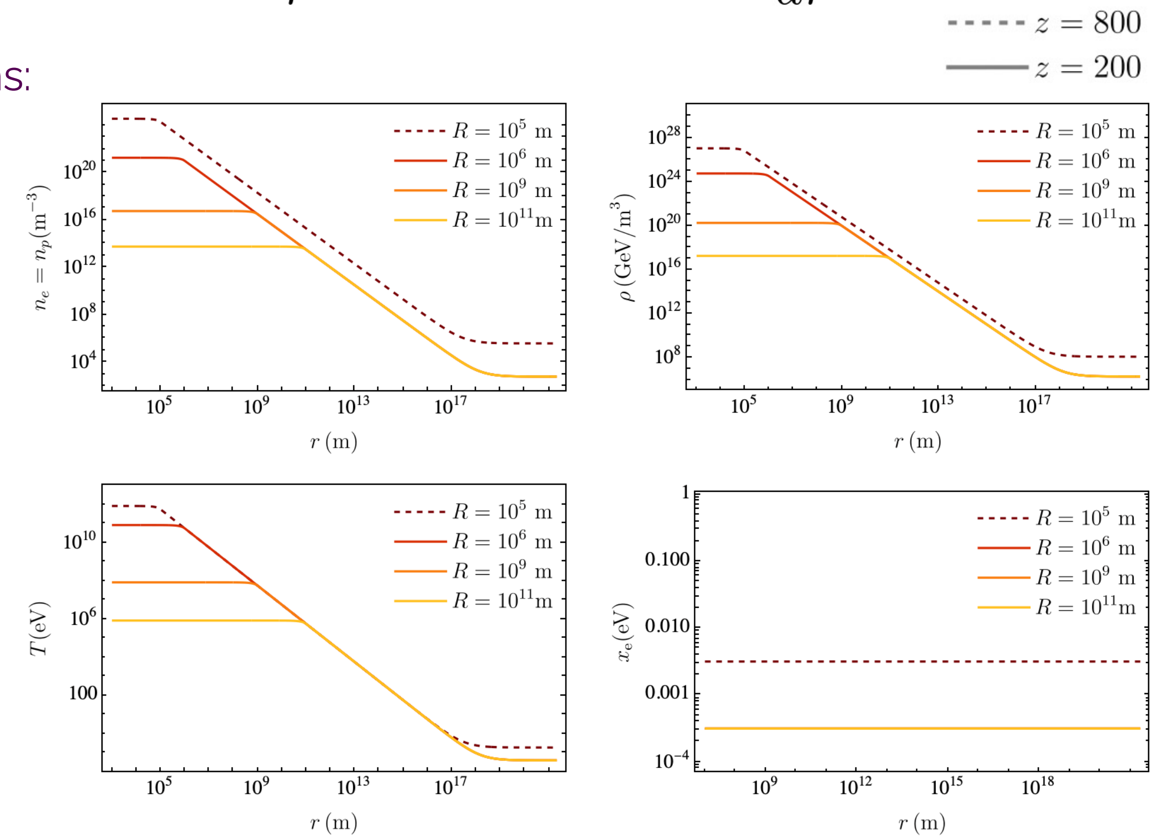

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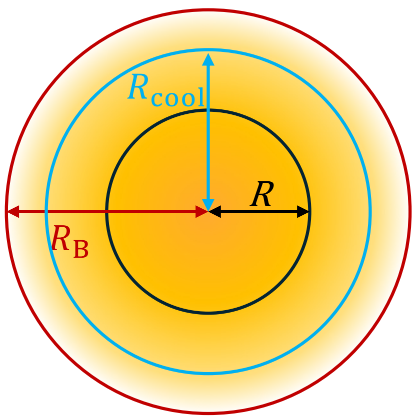
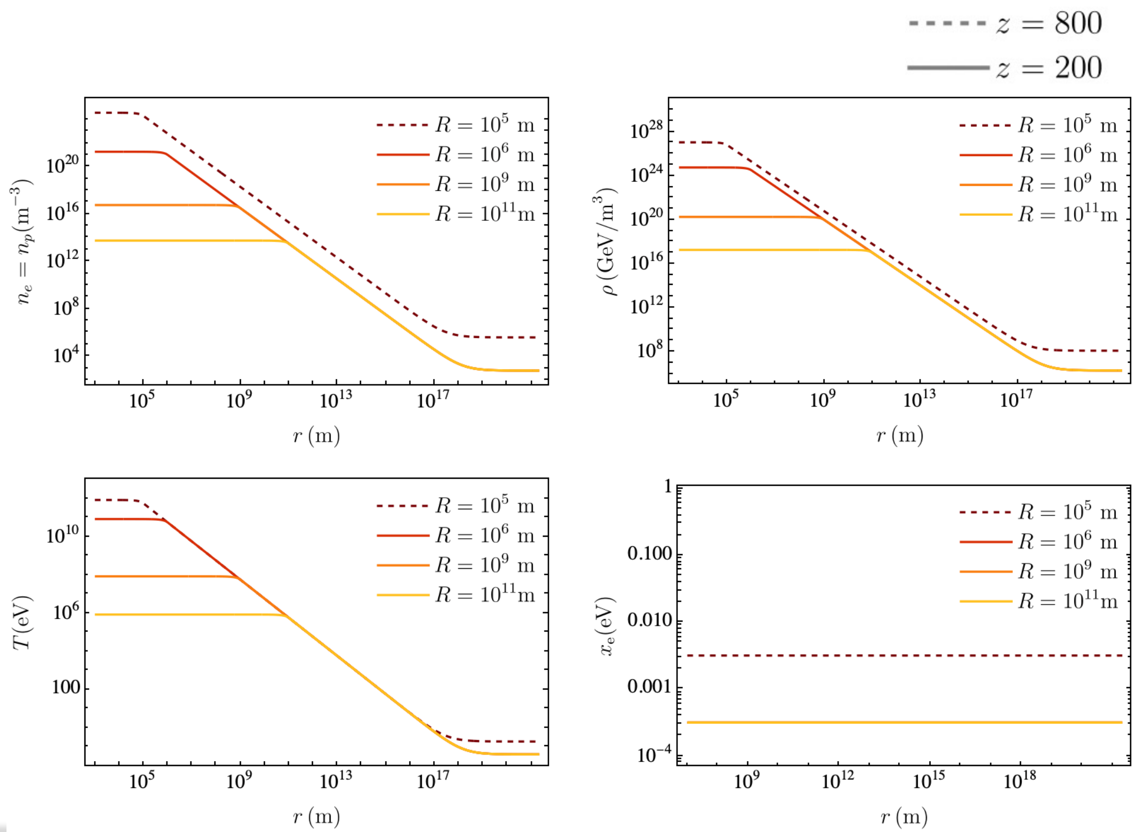
Mainly affects high redshifts



$$R_{\rm B} = GM/c_\infty^2$$



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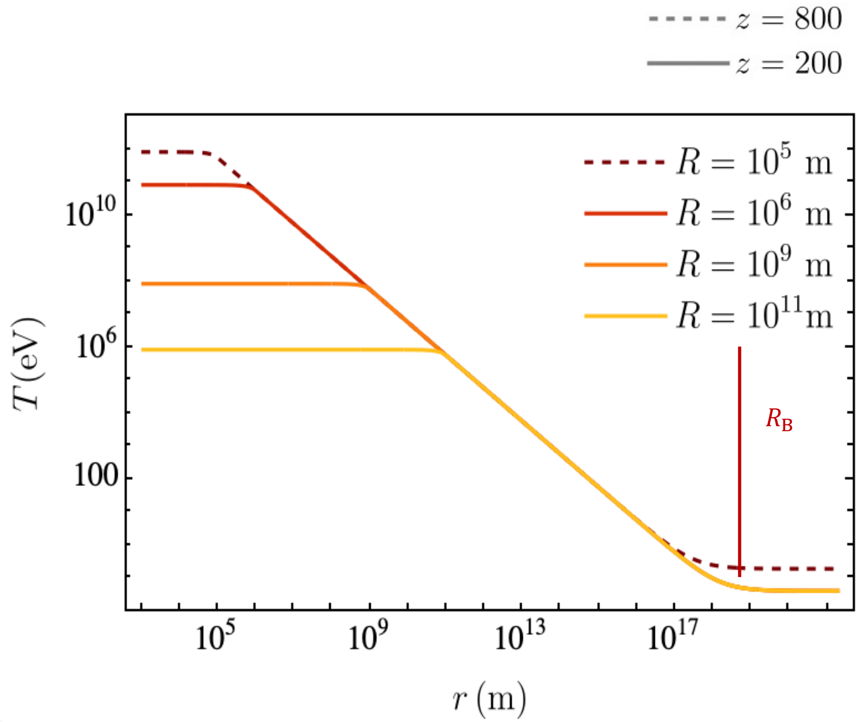
Only affects high redshifts, as density is higher



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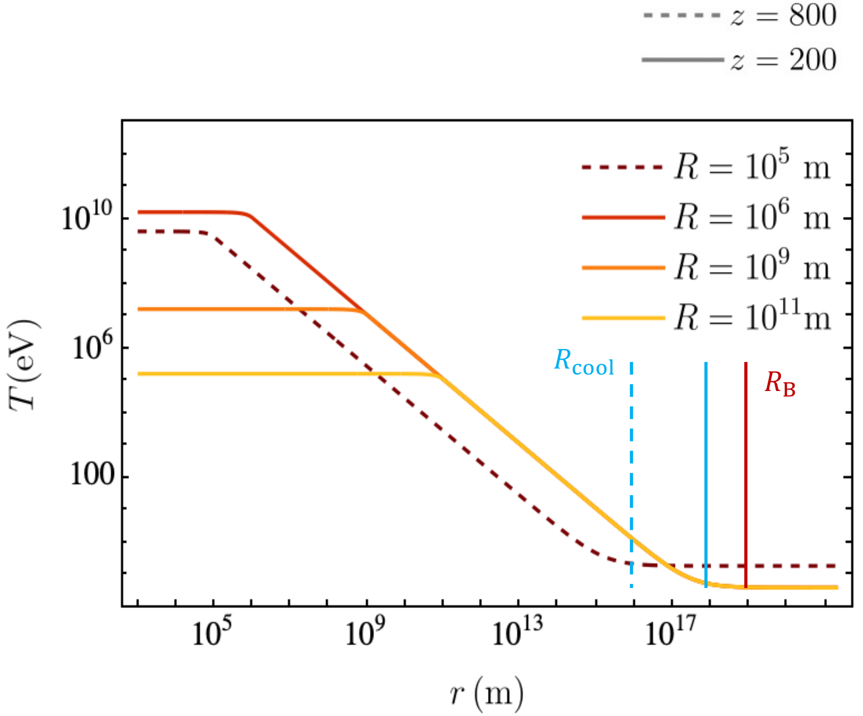

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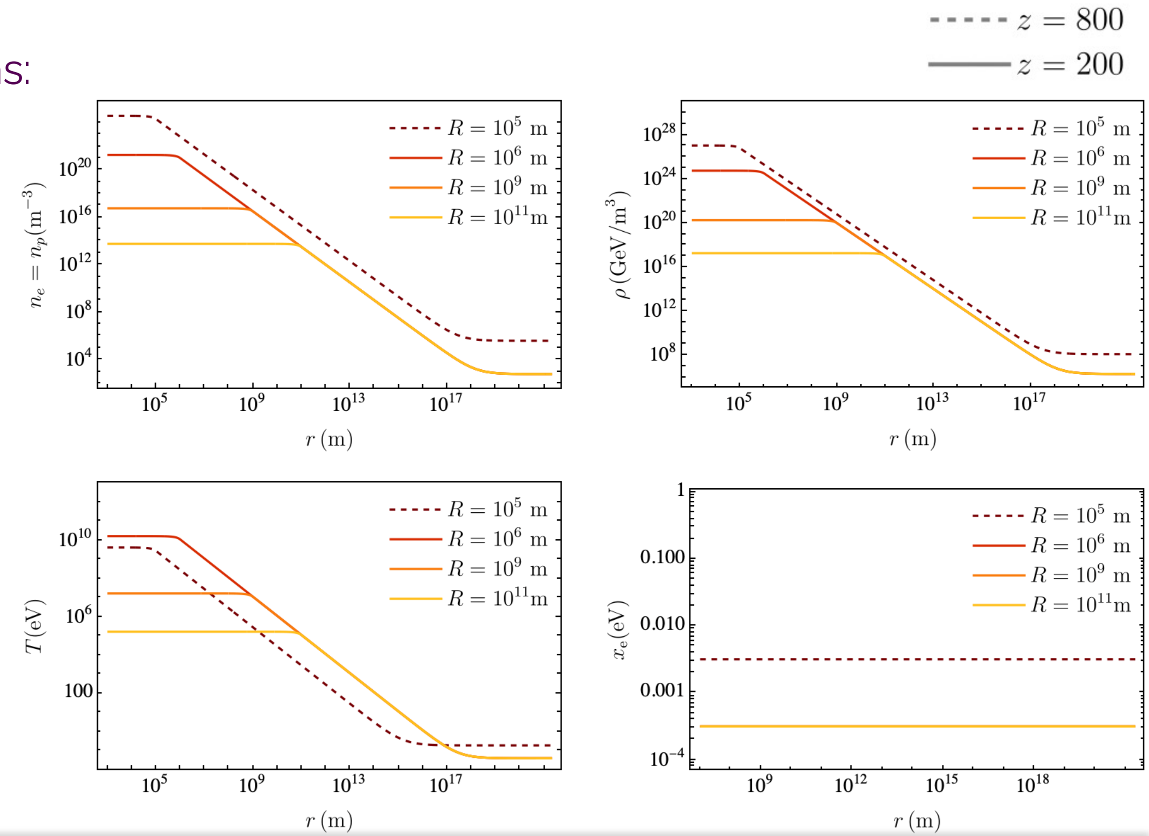
- -Collisional ionisation:

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

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

Temperature distributes into new particles, ionization increases



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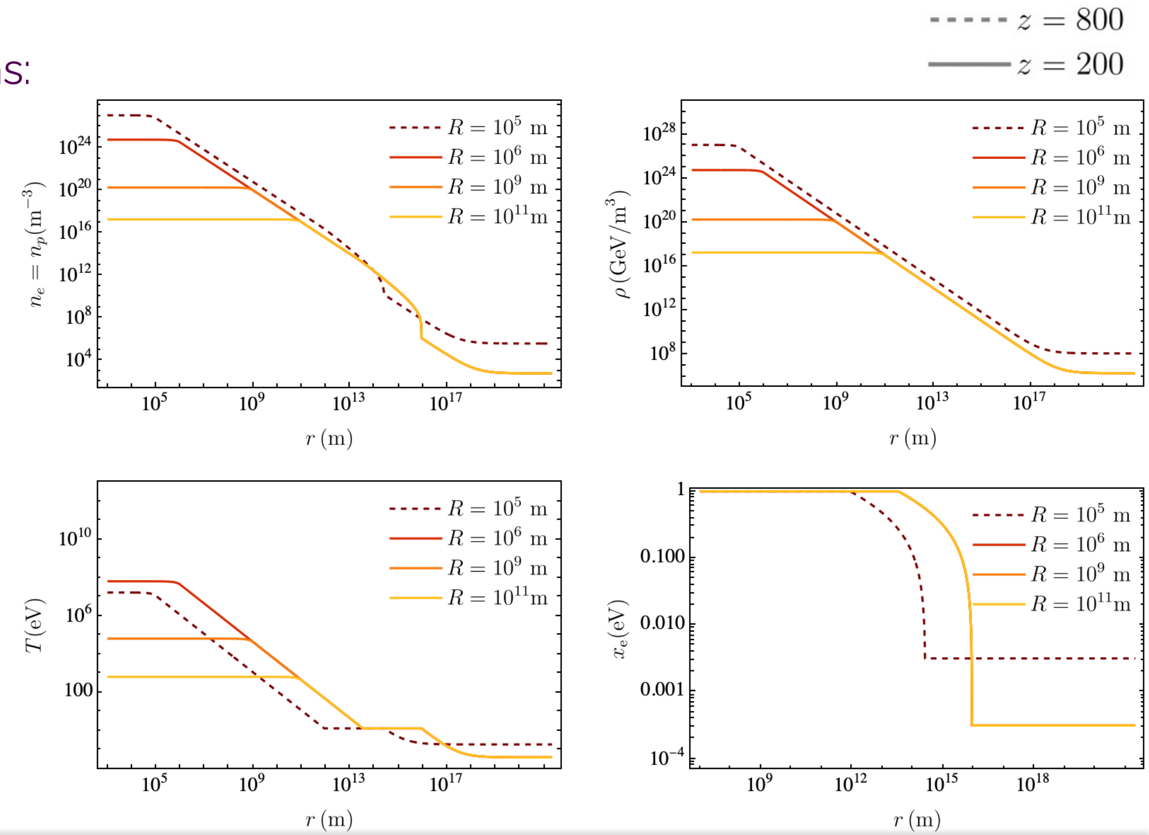
Photoionization also important,
but these are the tightest constraints



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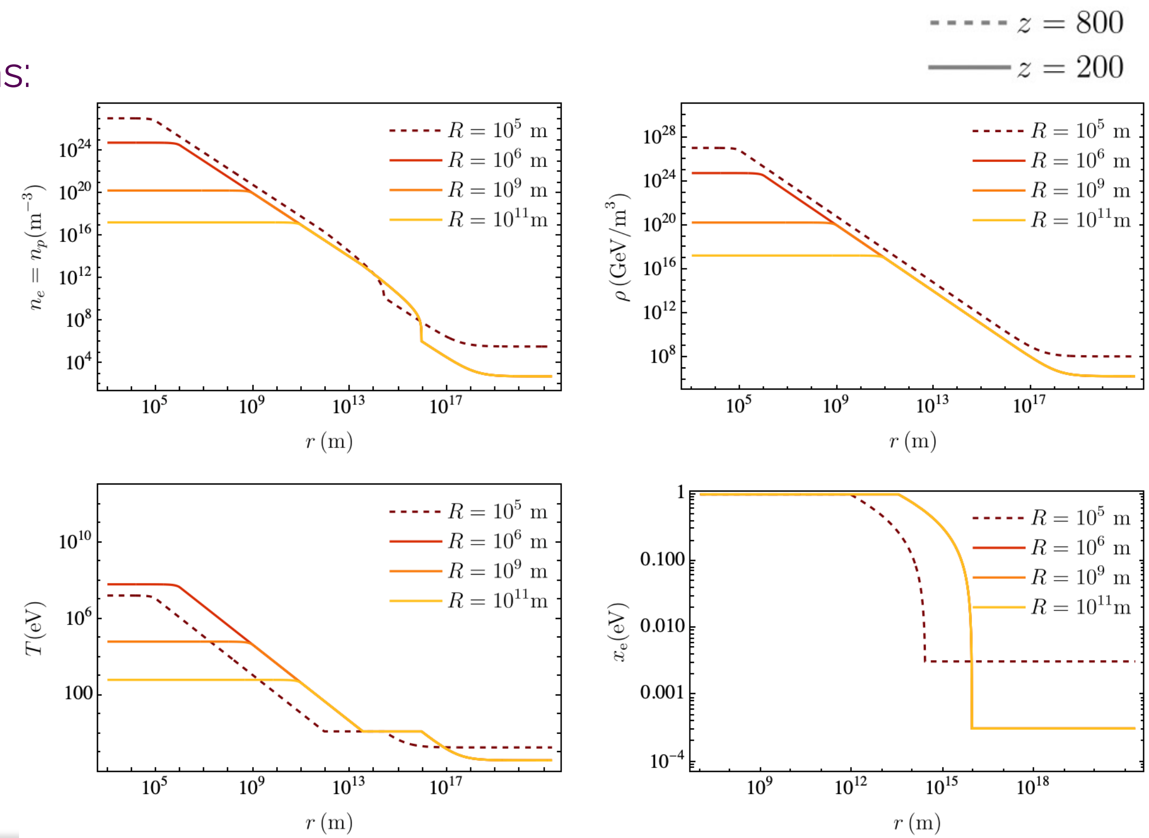
-Relativistic effects:

Relativistic electrons contribute differently to the internal energy

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



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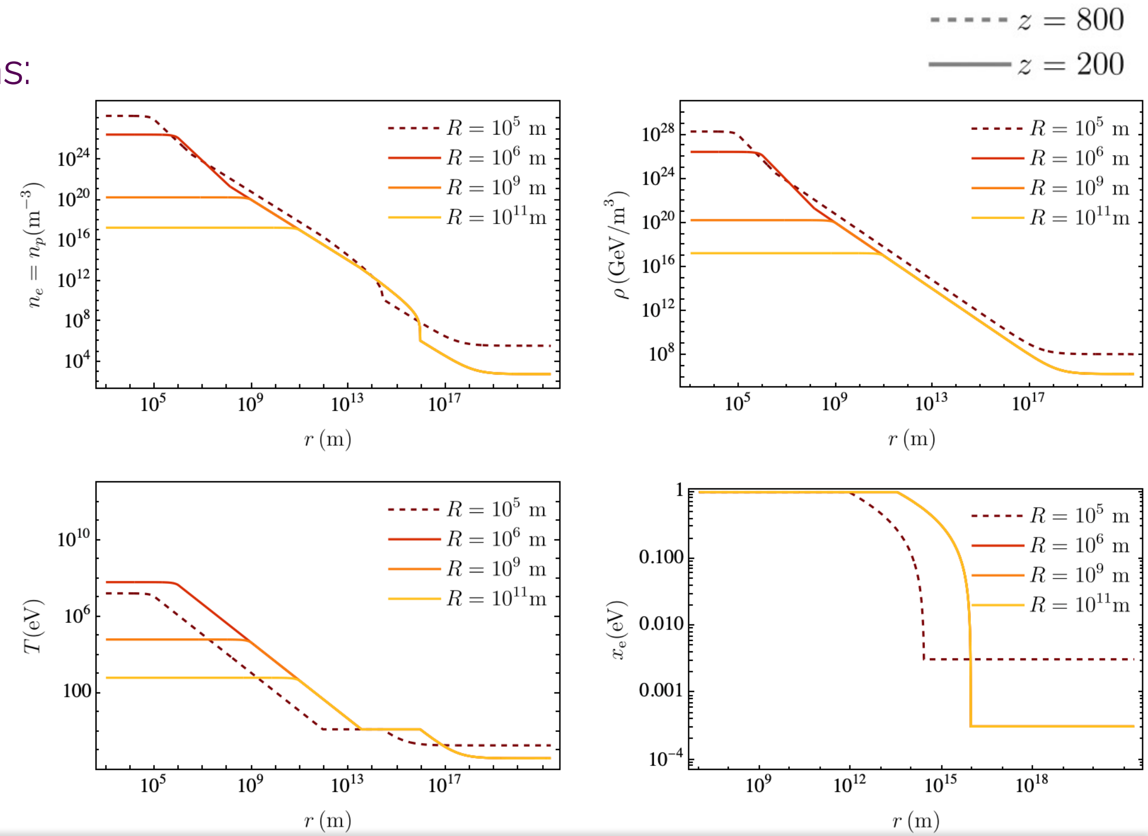

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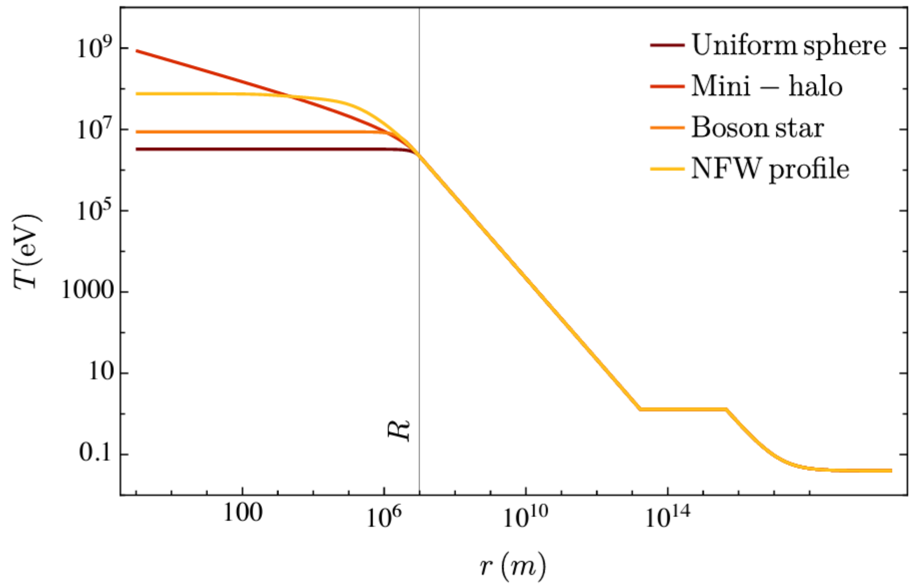
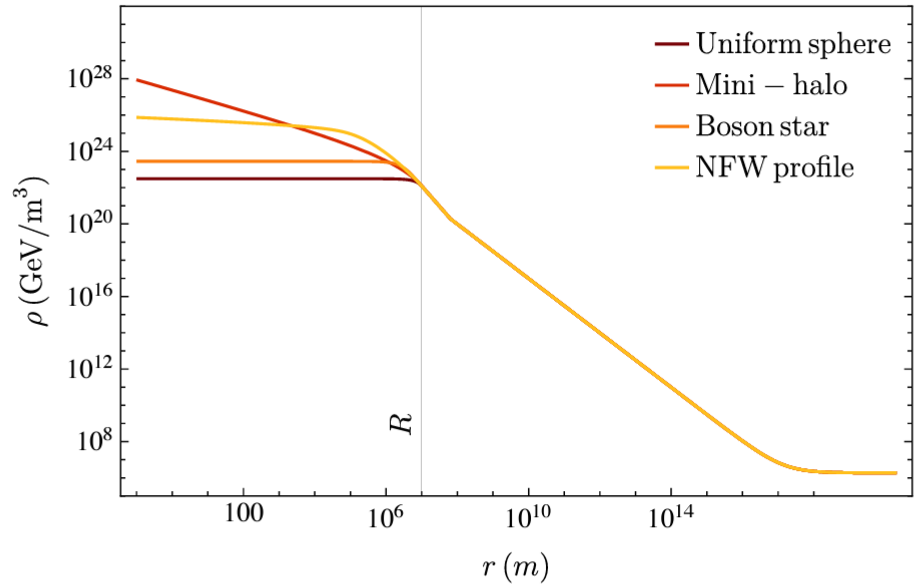
Comparing different mass profiles, all the same until R:

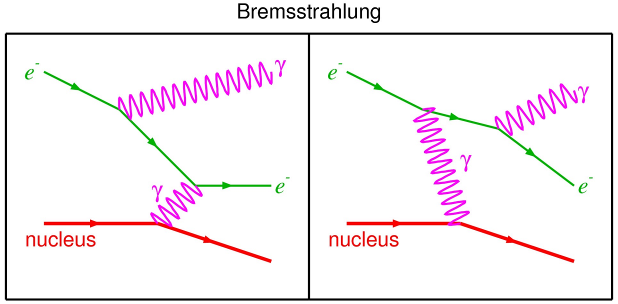




Now we can focus on the effect they will have on the background!

Based on arXiv:2403.13072

Placing EDOs in our Universe



Now we need to calculate the energy deposited into the background

The internal interactions of particles will emit light via bremsstrahlung

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

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:

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

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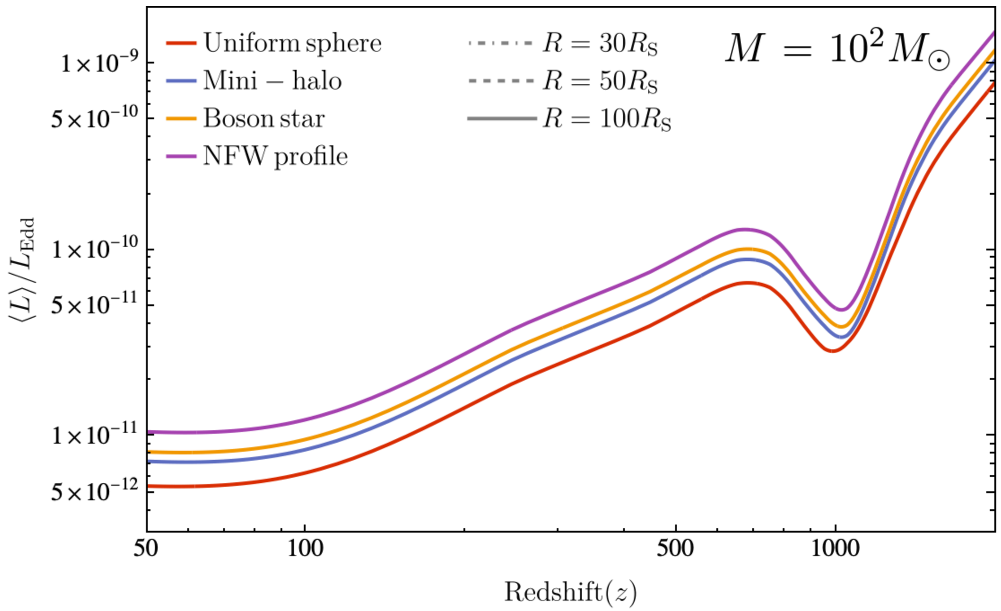
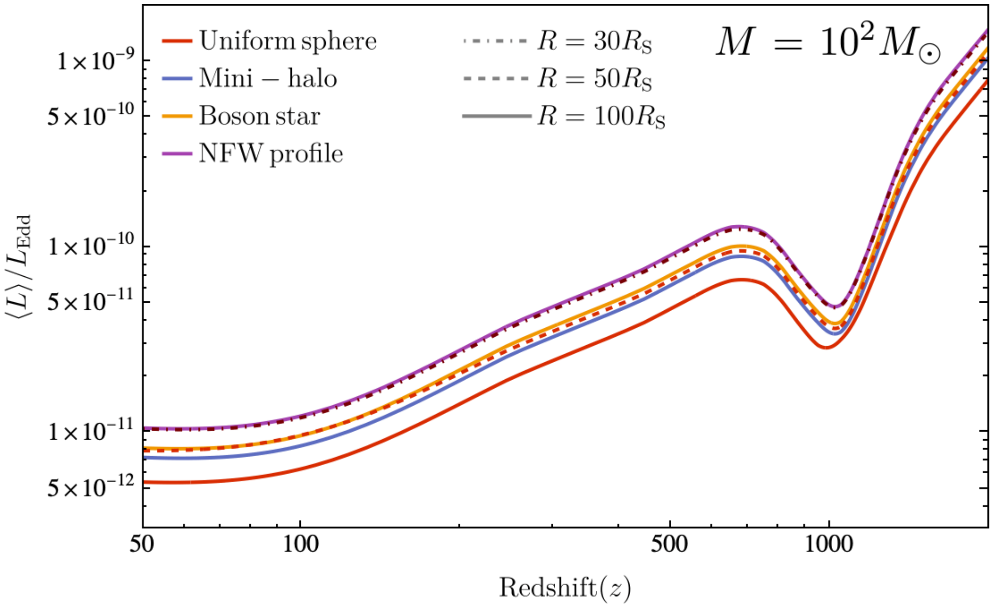


$$\langle \mathcal{L} \rangle = \frac{4\pi}{(2\pi \langle v_s^2 \rangle /3)^{3/2}} \int_0^\infty \mathrm{d}v_{\rm rel}\, v_{\rm rel}^2 e^{-\frac{v_{\rm rel}^2}{2\langle v_s^2 \rangle/3}} \mathcal{L}|_{c_\infty \to \sqrt{c_\infty^2 + v_{\rm rel}^2}}$$

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

Based on arXiv:2403.13072

Placing EDOs in our Universe



We can rescale uniform sphere to other solutions!!

Based on arXiv:2403.13072

Placing EDOs in our Universe

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

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

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

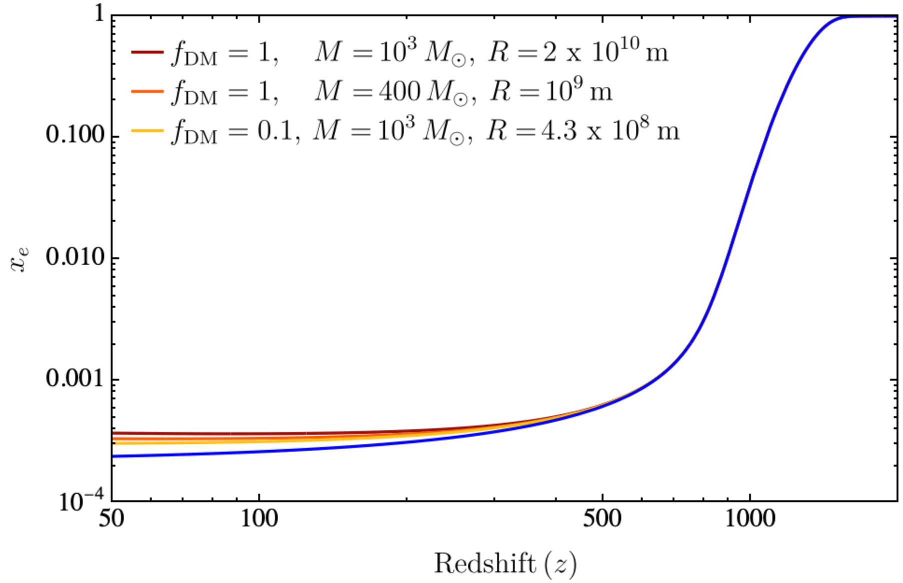
Only a fraction of this energy that will get deposited in the background

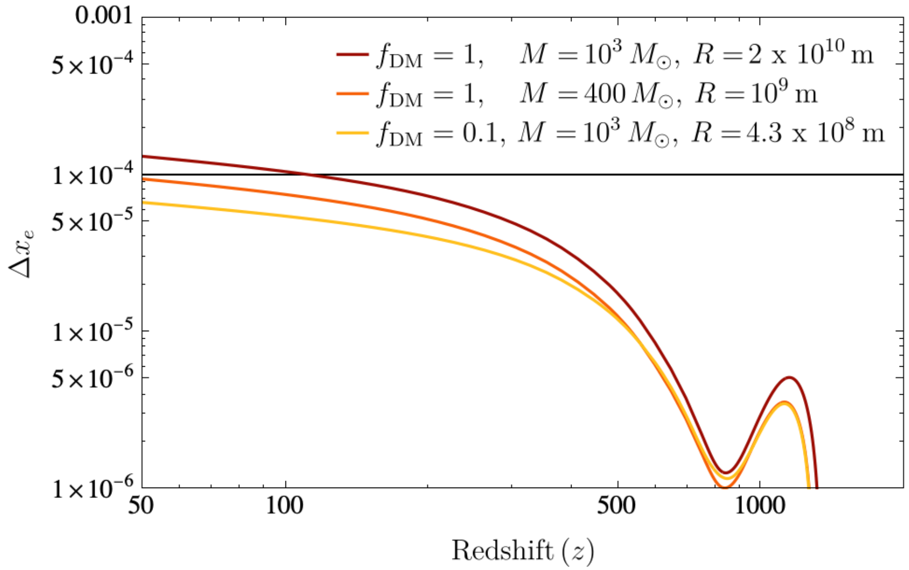
$$\frac{{\rm d}T_{\rm M}}{{\rm d}z} = \frac{1}{(1+z)}\left[2T_{\rm M} + \frac{8\pi^2\sigma_{\rm T}{T_{\rm cmb}}^4}{45H(z)m_e}\frac{x_e}{1+x_e}(T_{\rm M}-T_{\rm cmb})\right] - \frac{2}{3\,n}\frac{1+2x_e}{3H(z)(1+z)}\dot{\rho}_{\rm dep},$$

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

Placing EDOs in our Universe

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





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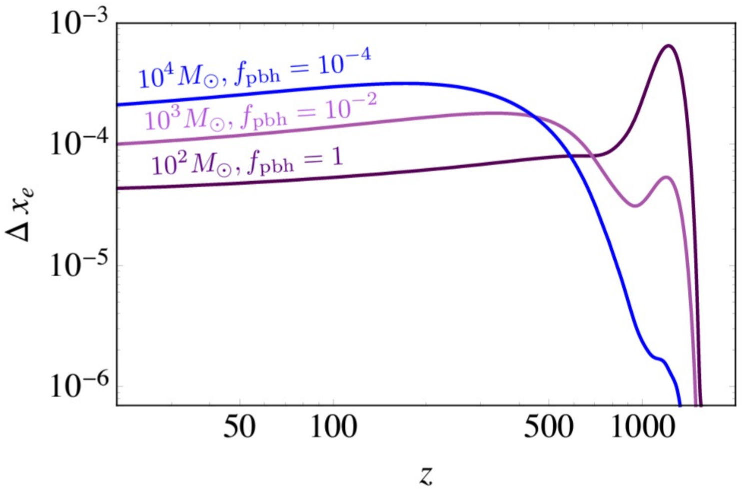
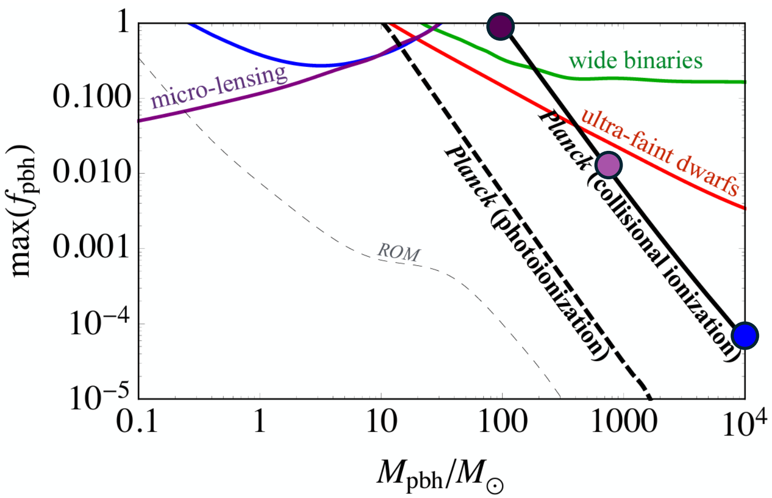
Placing EDOs in our Universe

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

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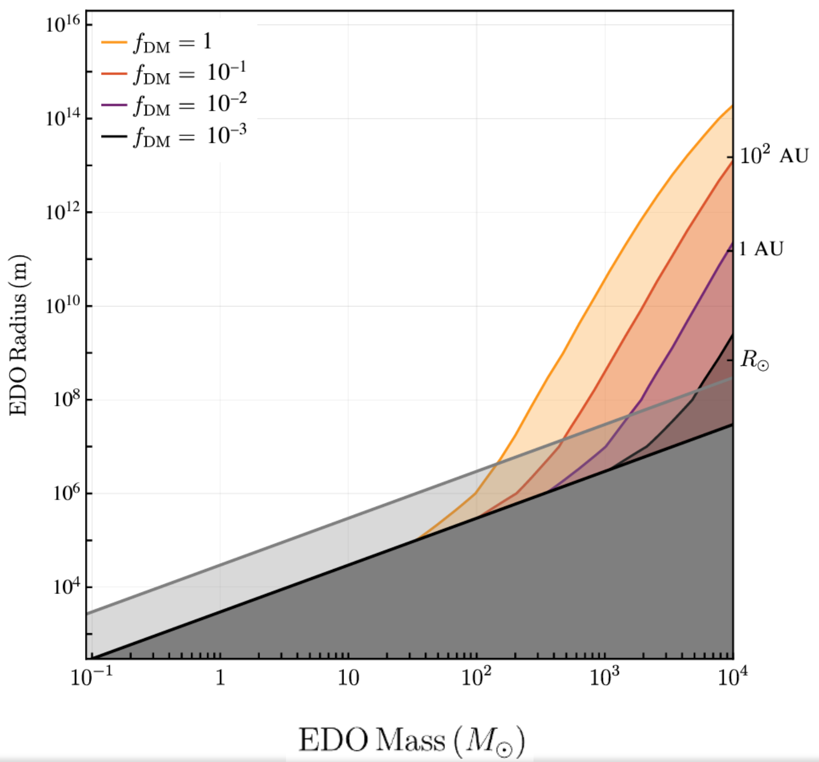
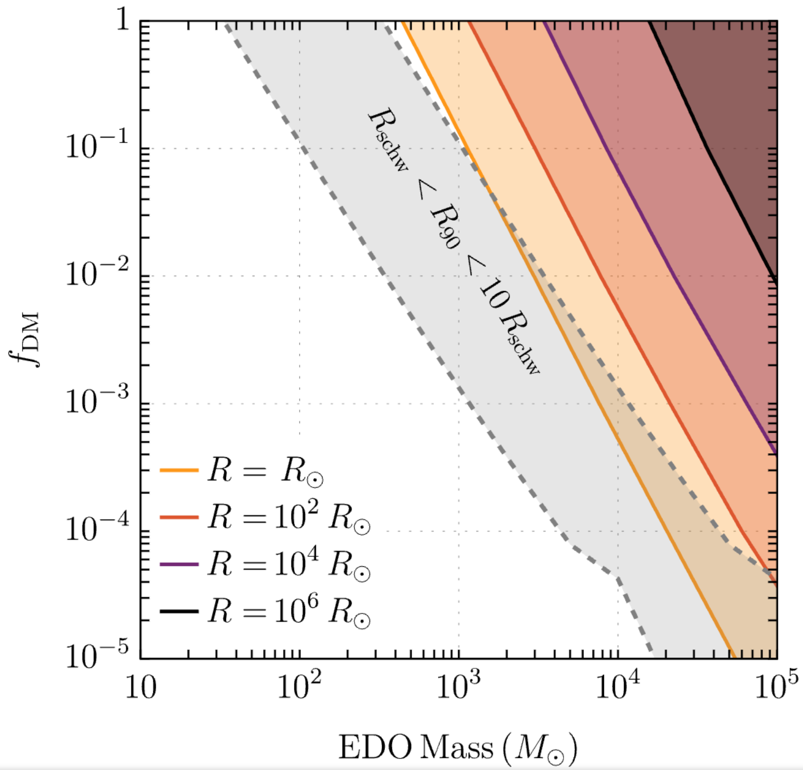
Results

Uniform sphere:





Based on arXiv:2403.13072

Results

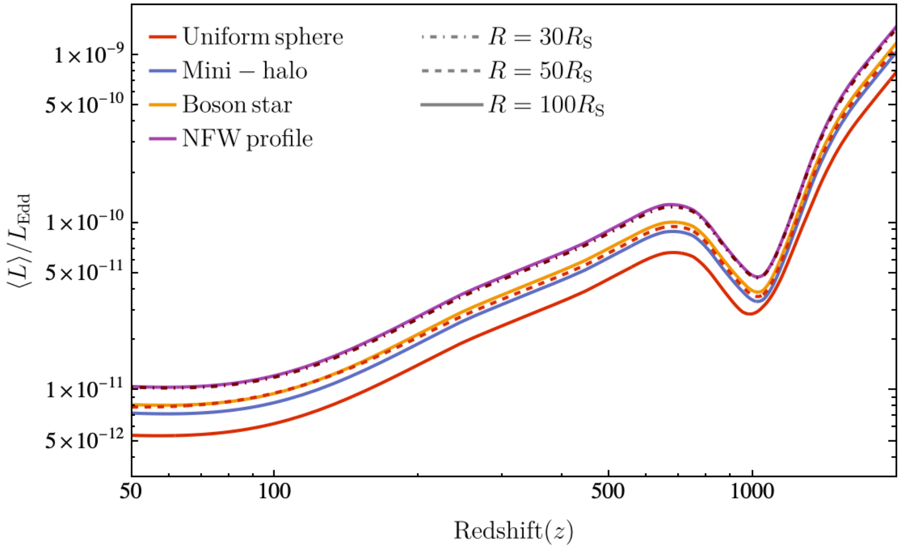
Is the scaling reliable?

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…



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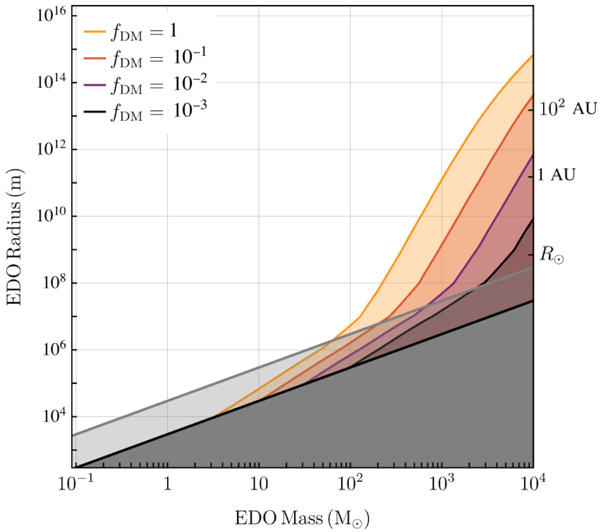
Results

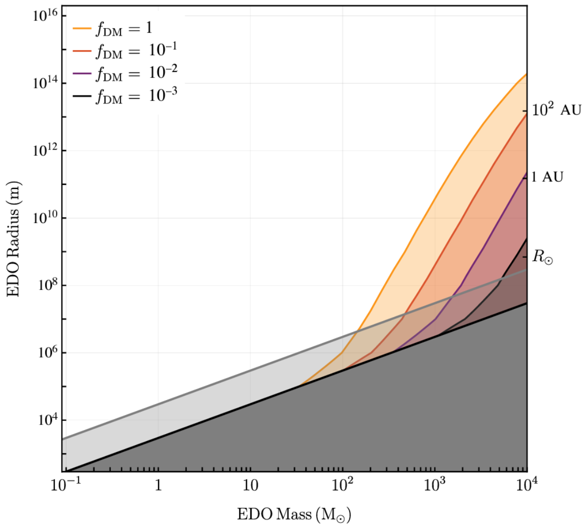
Is the scaling reliable?

Different shapes on CMB accretion

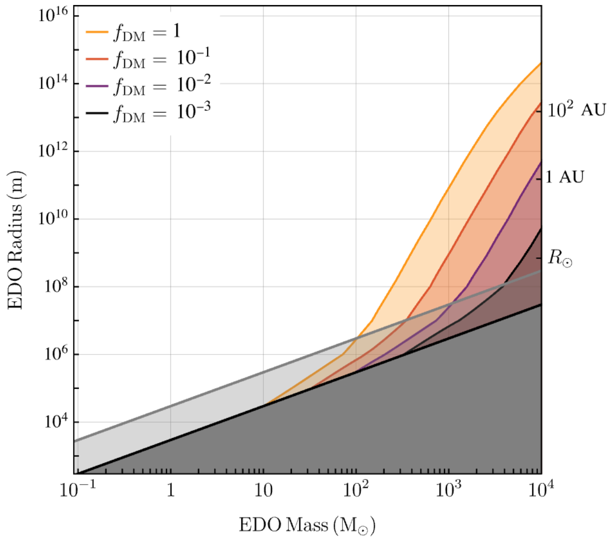
NFW sub-halo:



Uniform sphere:



Boson star:



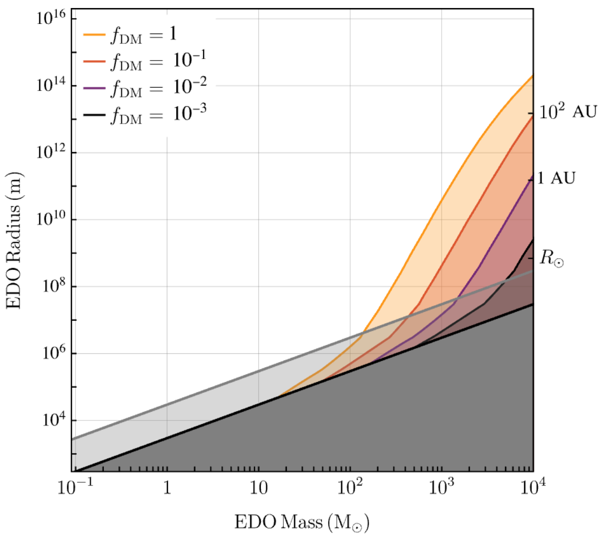
Based on arXiv:2403.13072

Results

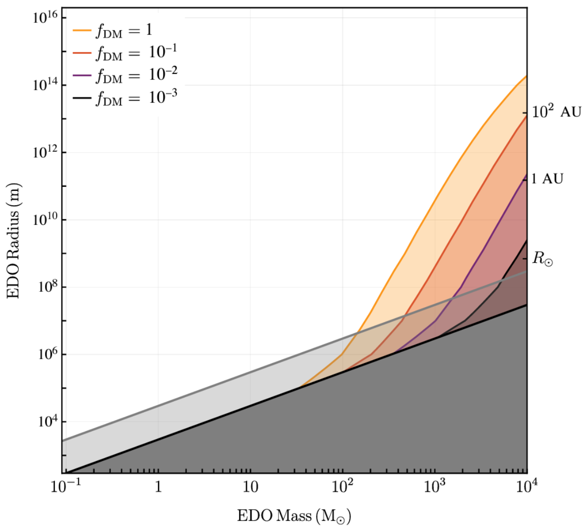
Is the scaling reliable? YES!

Different shapes on CMB accretion

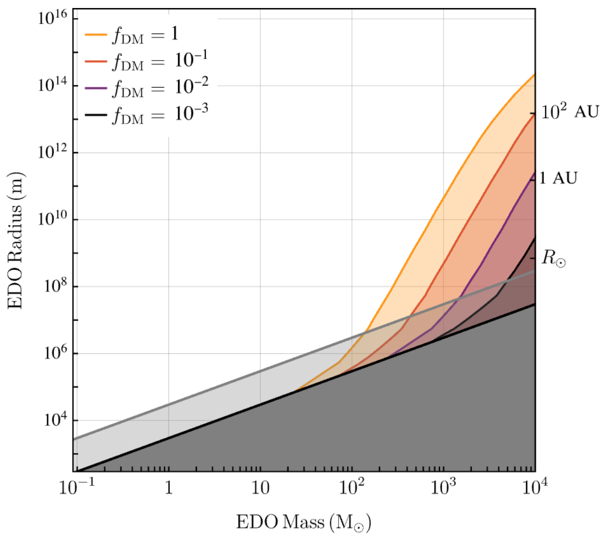
NFW sub-halo:



Uniform sphere:

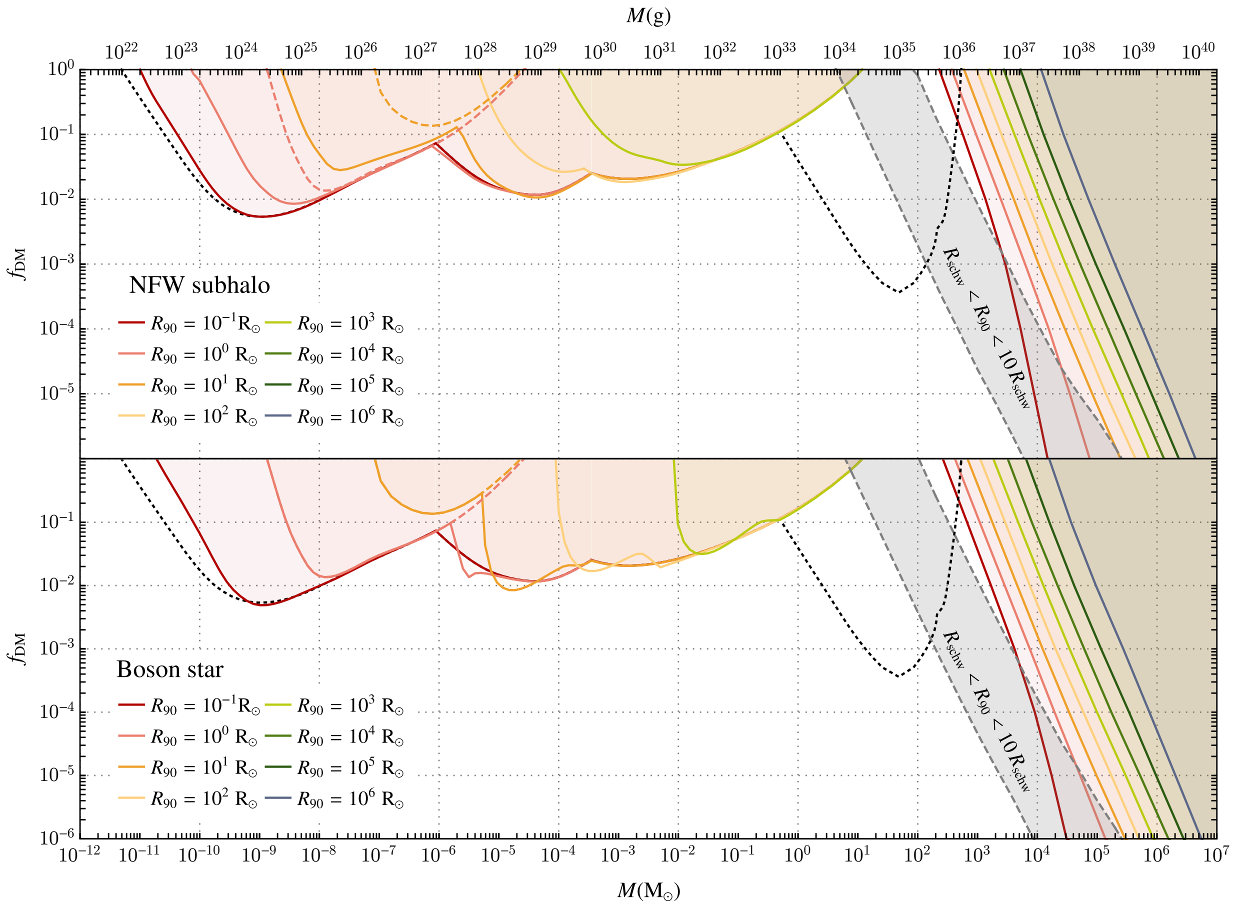


Boson star:



Based on arXiv:2403.13072

Finally combining with existing constraints, we obtain



Based on arXiv:2403.13072

Results

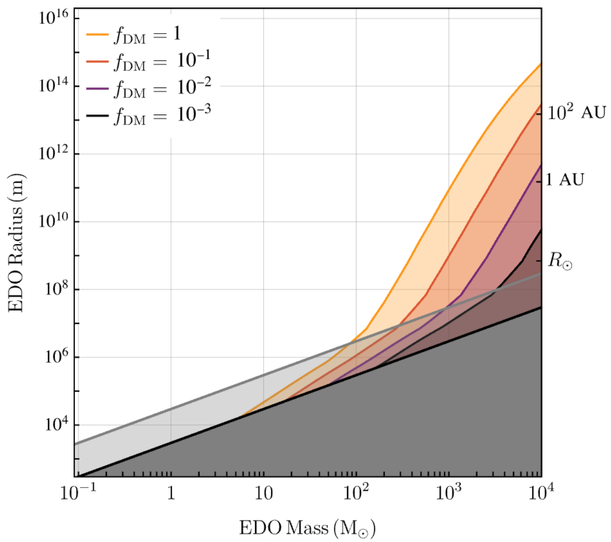
Is the scaling reliable?

YES!

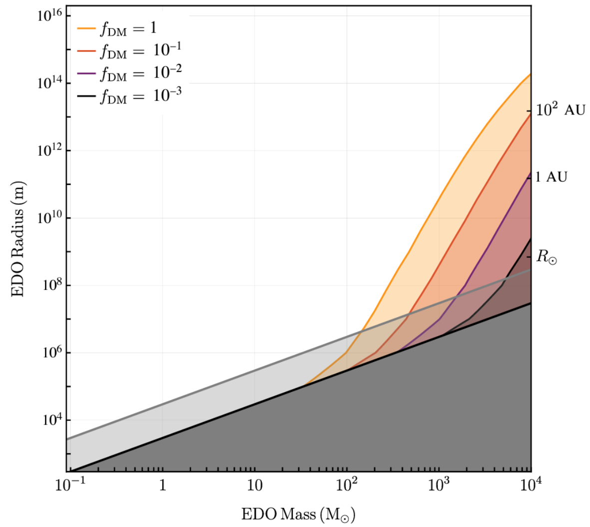
The important question: how can we extend this?

Just rescale to R90 for your mass profile

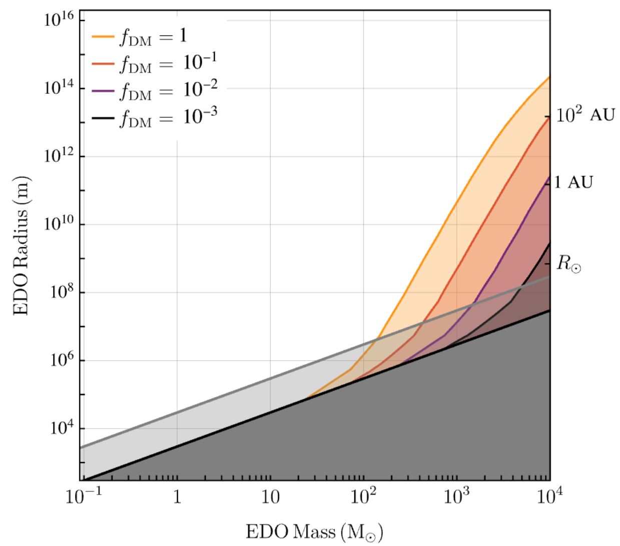
NFW sub-halo:



Uniform sphere:

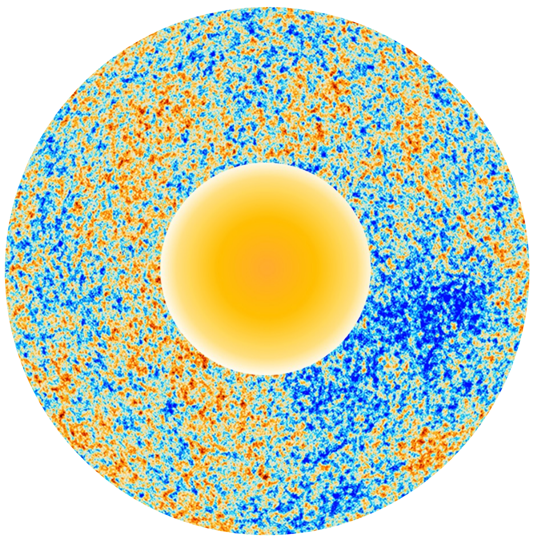


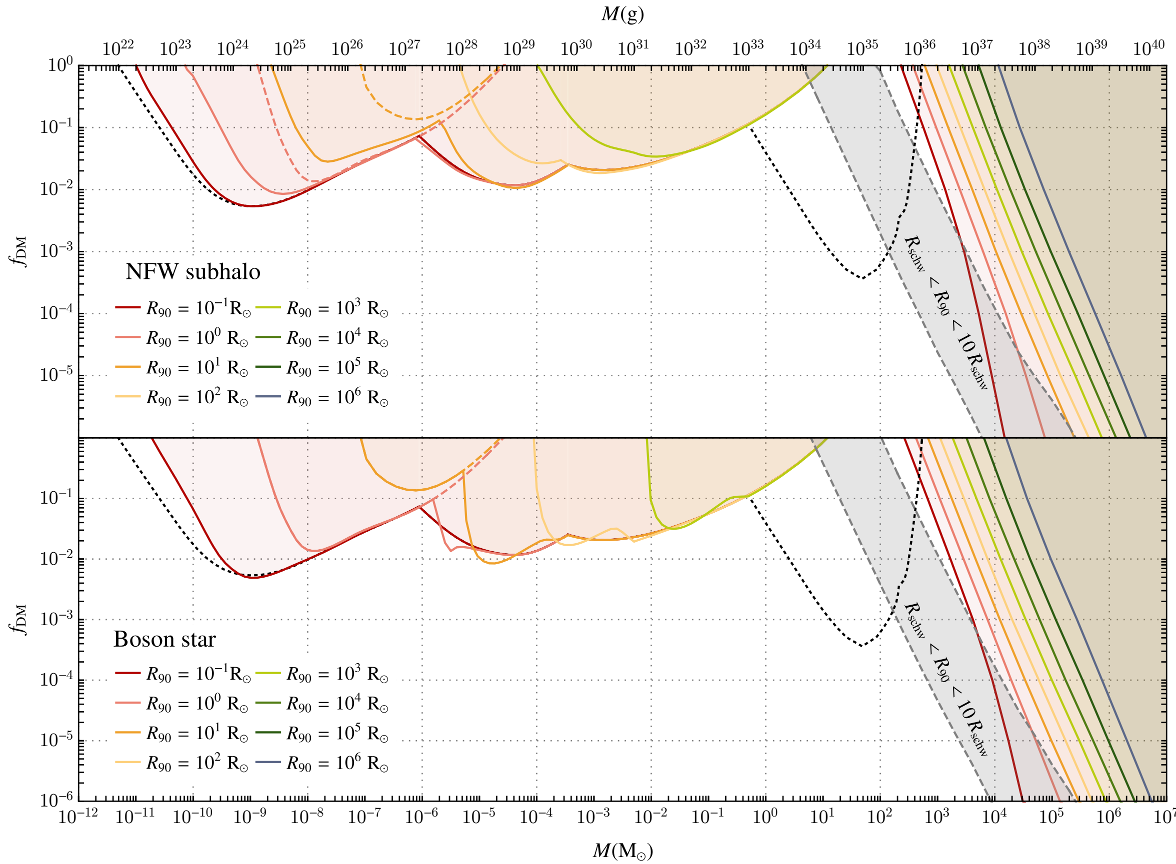
Boson star:



Based on arXiv:2403.13072

CMB constraints on Extended dark matter objects

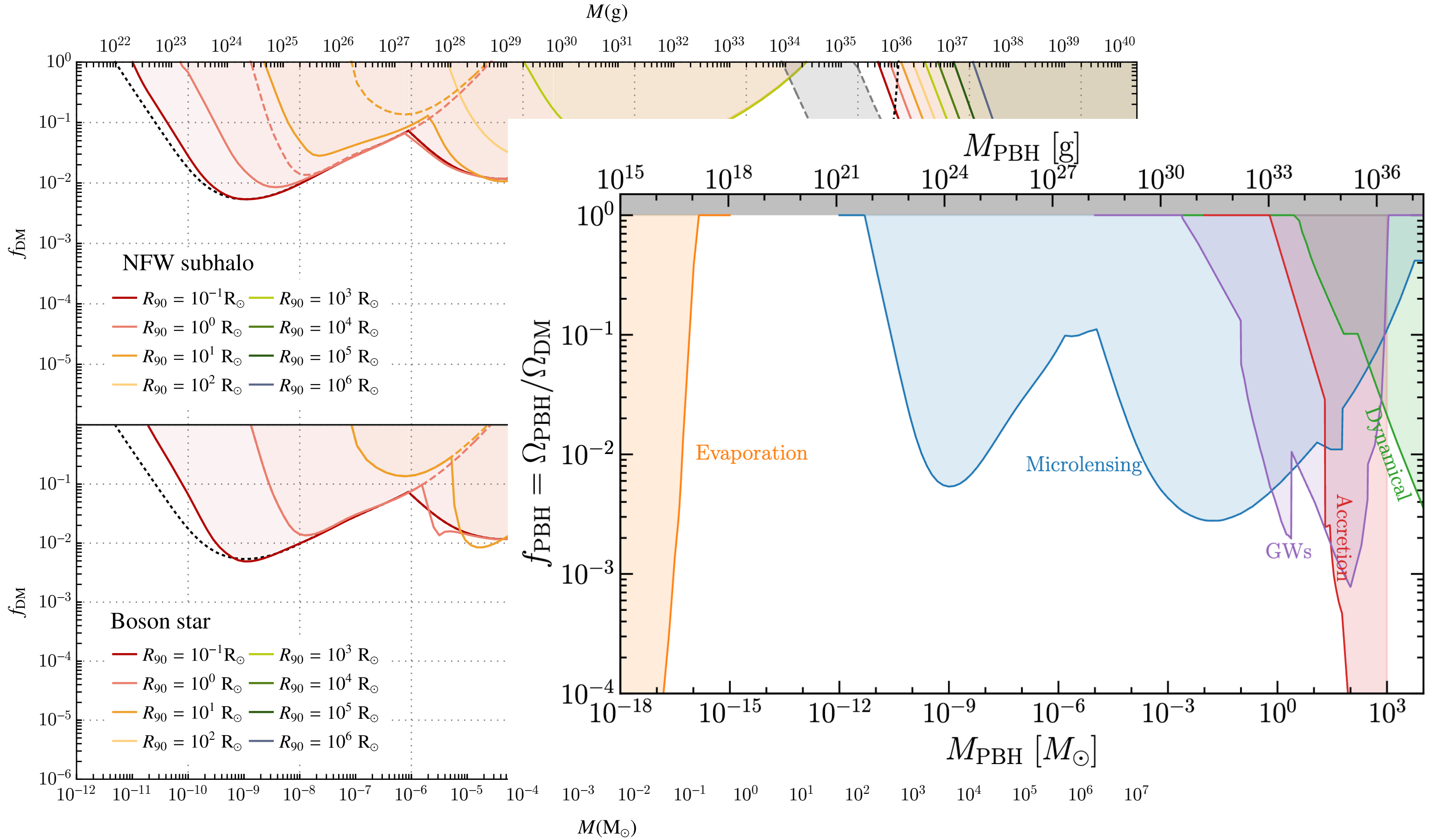




https://github.com/SergioSevi/EDObounds

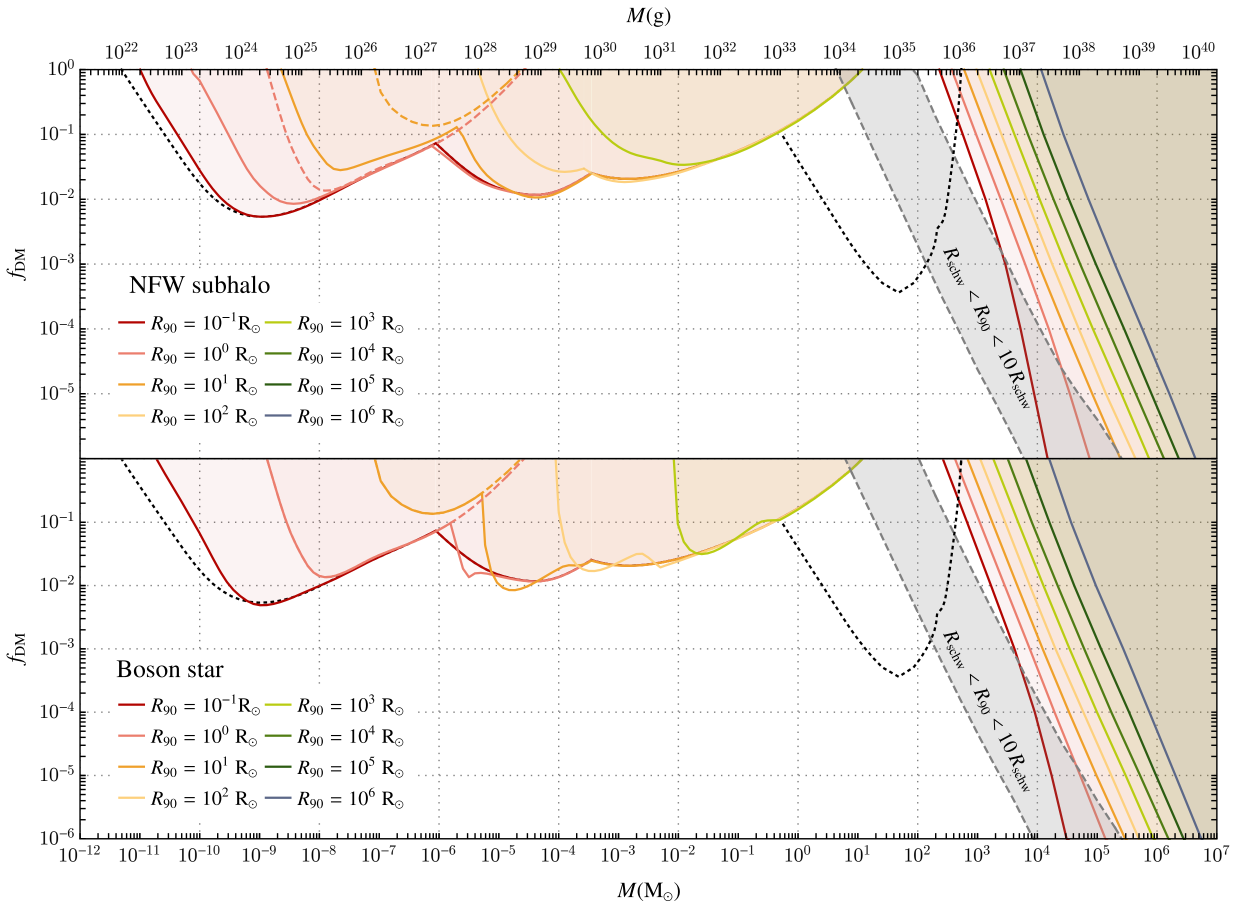
Based on arXiv:2403.13072

Finally combining with existing constraints, we obtain



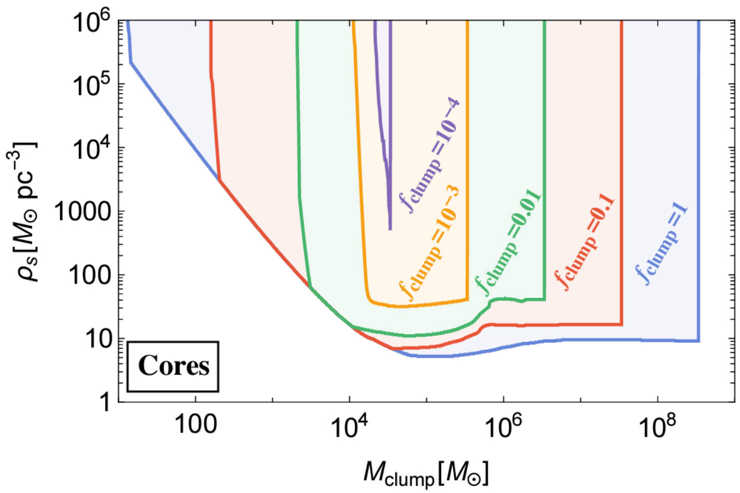
Based on arXiv:2403.13072

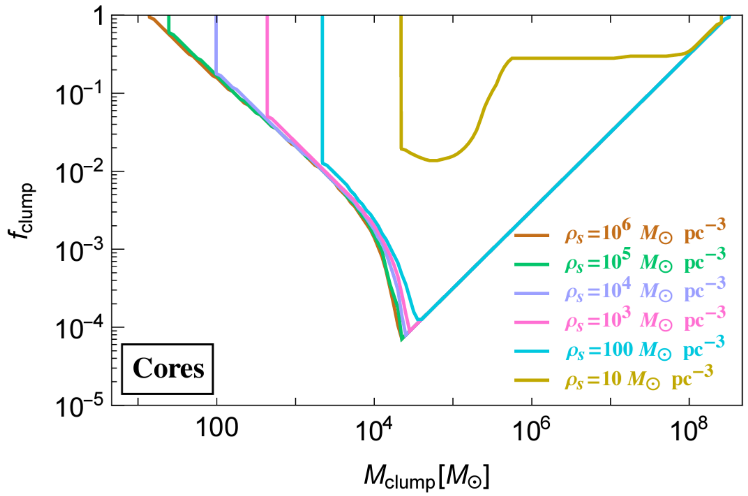
Finally combining with existing constraints, we obtain



Extra!

Recently new bounds from dynamical heating of stars due to energetic EDOs
(Graham and Ramani)

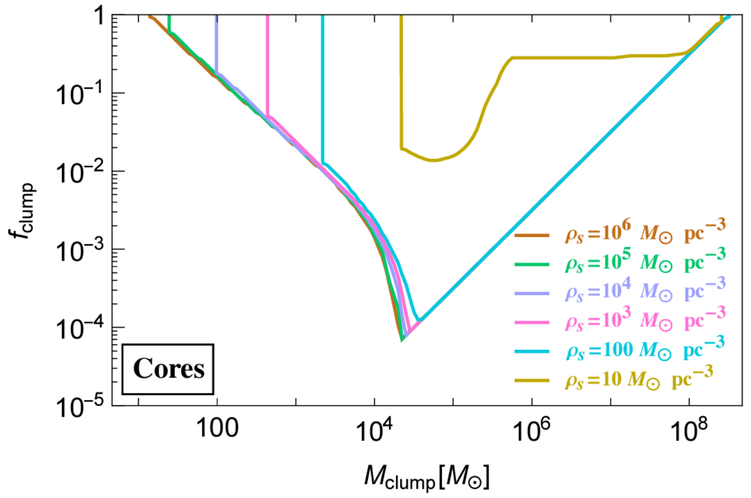


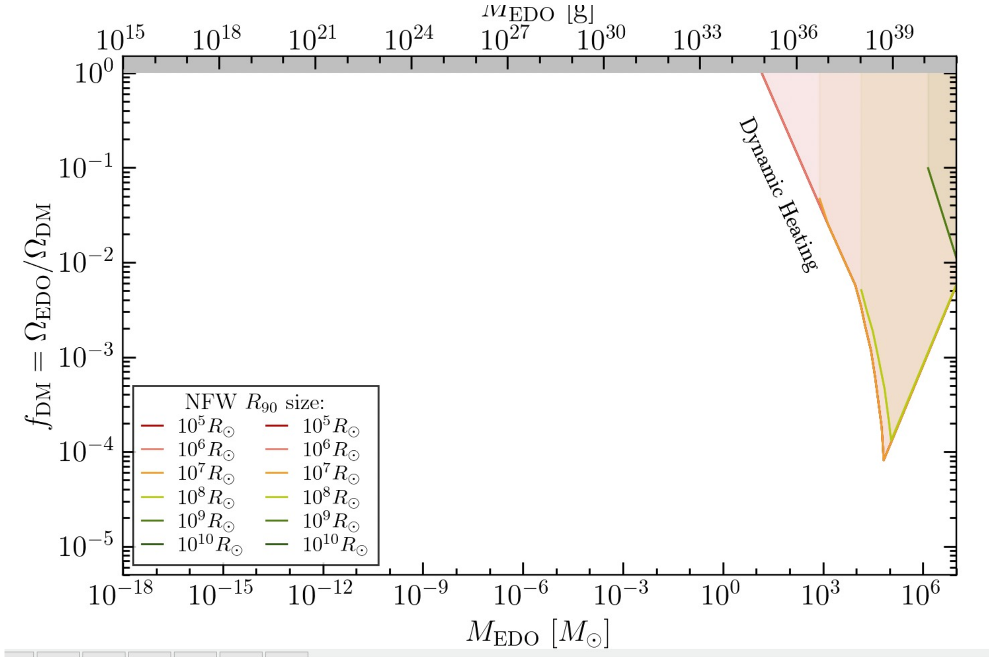


NFW mini-halo

Extra!

Recently new bounds from dynamical heating of stars due to energetic EDOs
(Graham and Ramani)





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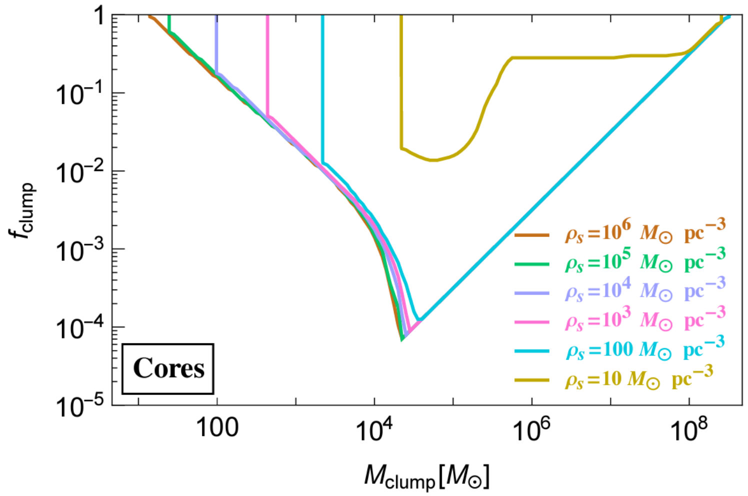
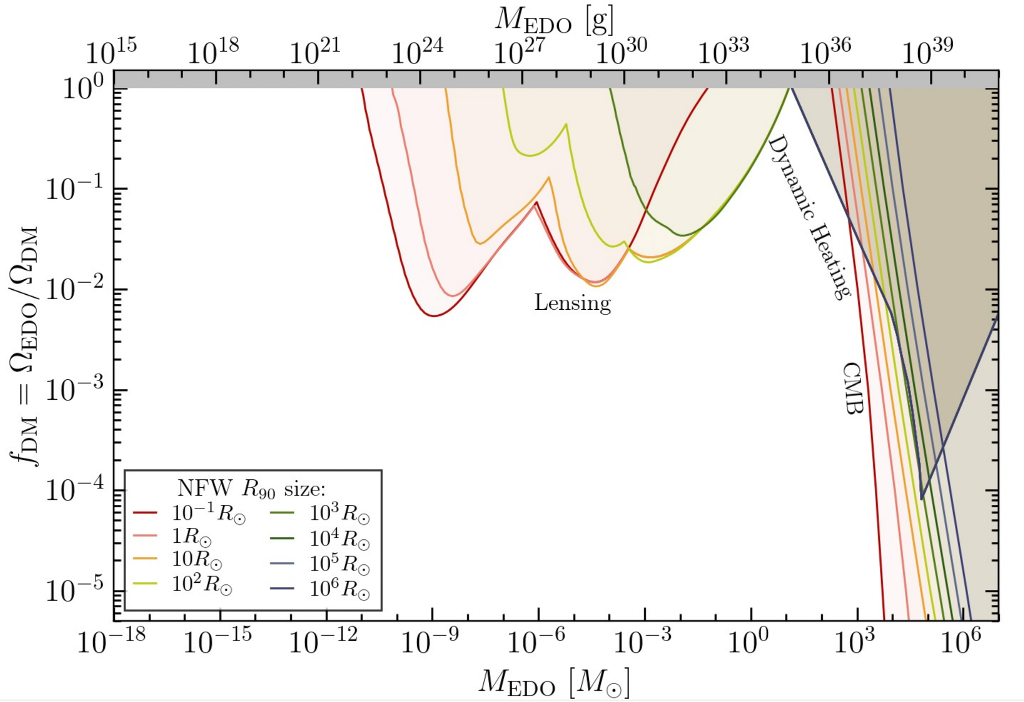




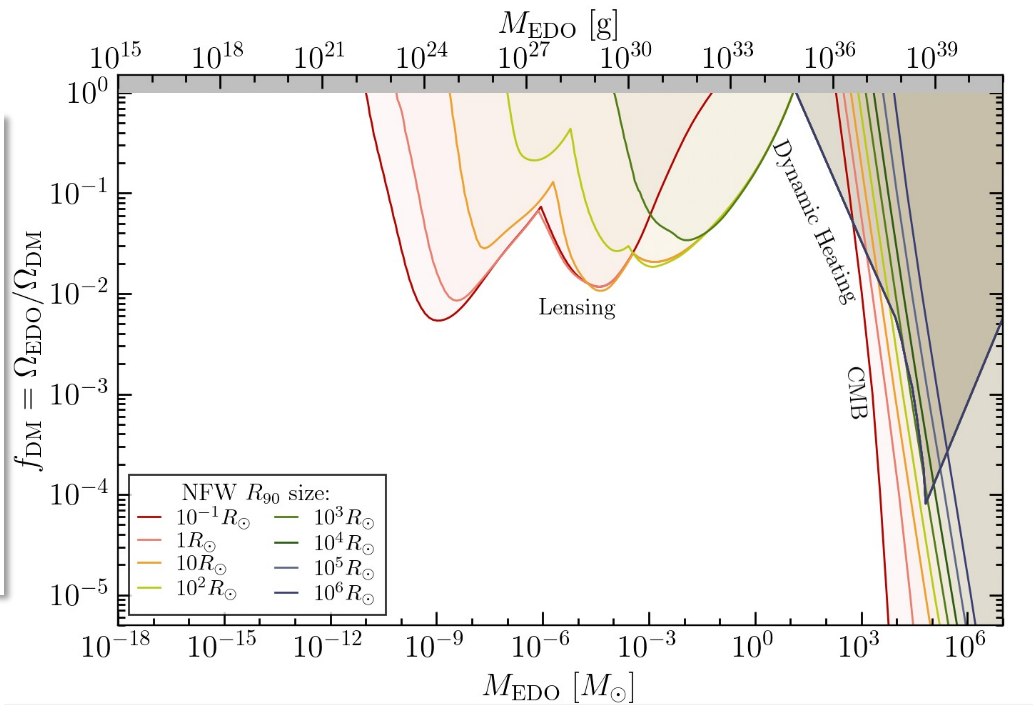
Based on arXiv:2403.13072

Repository for EDO bounds:

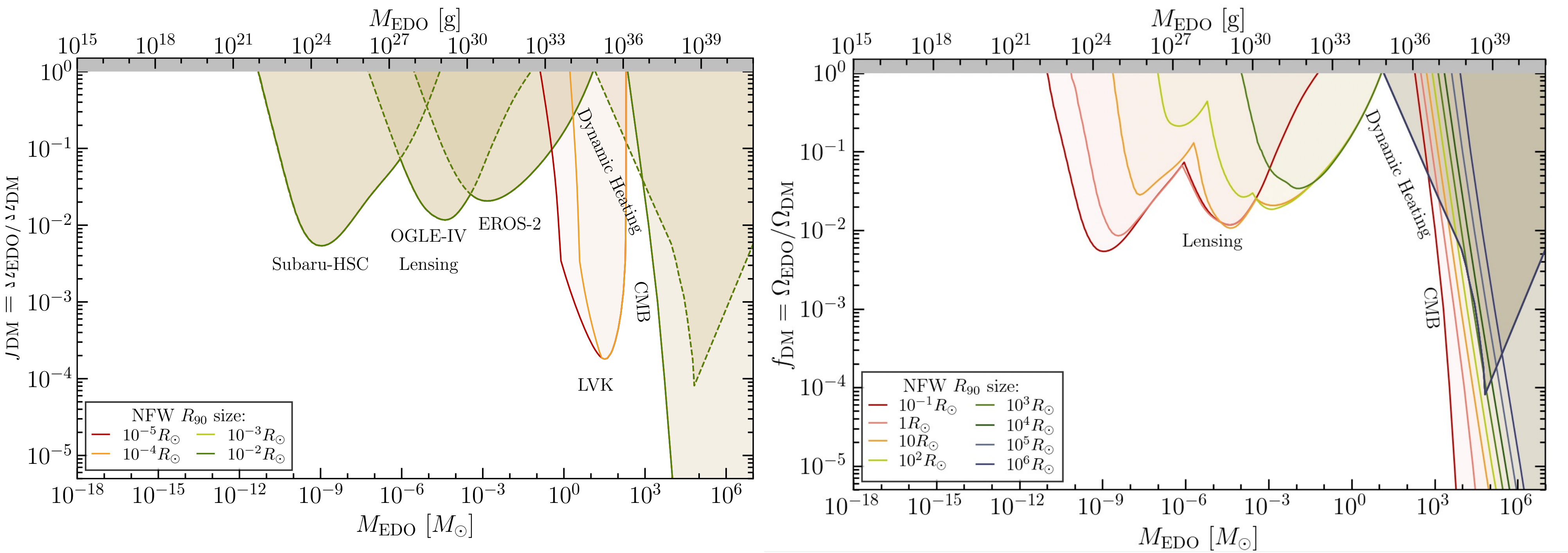
```
#Shape: Choose from NFW, Uniform, Boson or UCMH
NFW

#Radius r: rmin, rmax, rjumps, where R_90=10^r RSun
           -1      6         1

# Bound,      linestyle,  x,          y,         rotation, display name
CMBAccretion.    -        700         1e-3         -85       CMB
EROS-2          --        1e-2        1e-2         0         EROS-2
OGLE-IV         --        1e-5        7e-3         0         OGLE-IV
Subaru-HSC.     --        1e-9        3e-3         0         Subaru-HSC
Lensing          -        1e-5        7e-3         0         Lensing
Dynamic-heating --         50         5e-2         -65       Dynamic_Heating
LVK              -        1e-5        7e-3         0         LVK
```

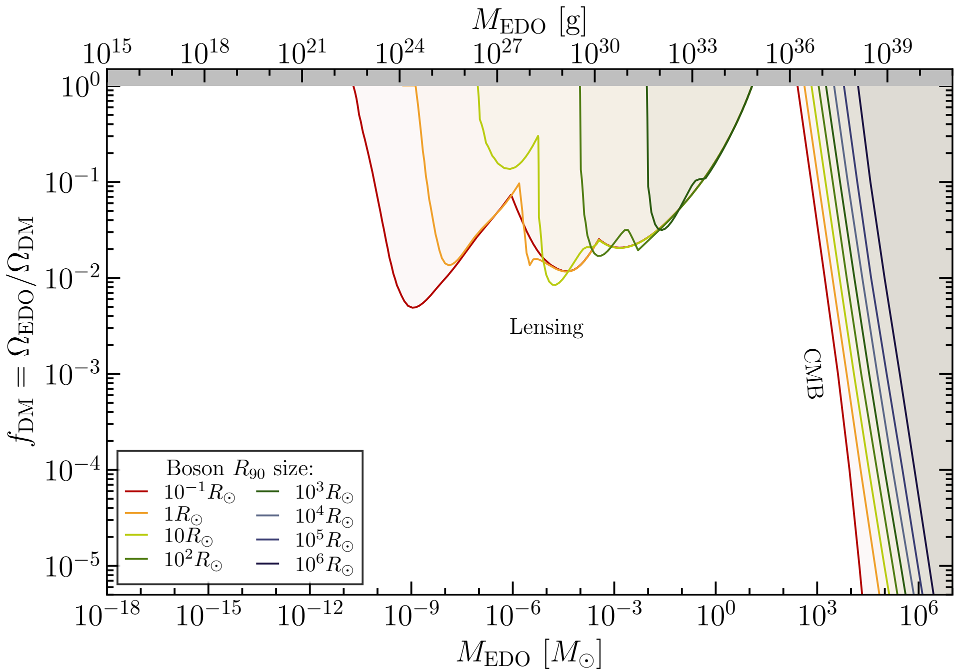


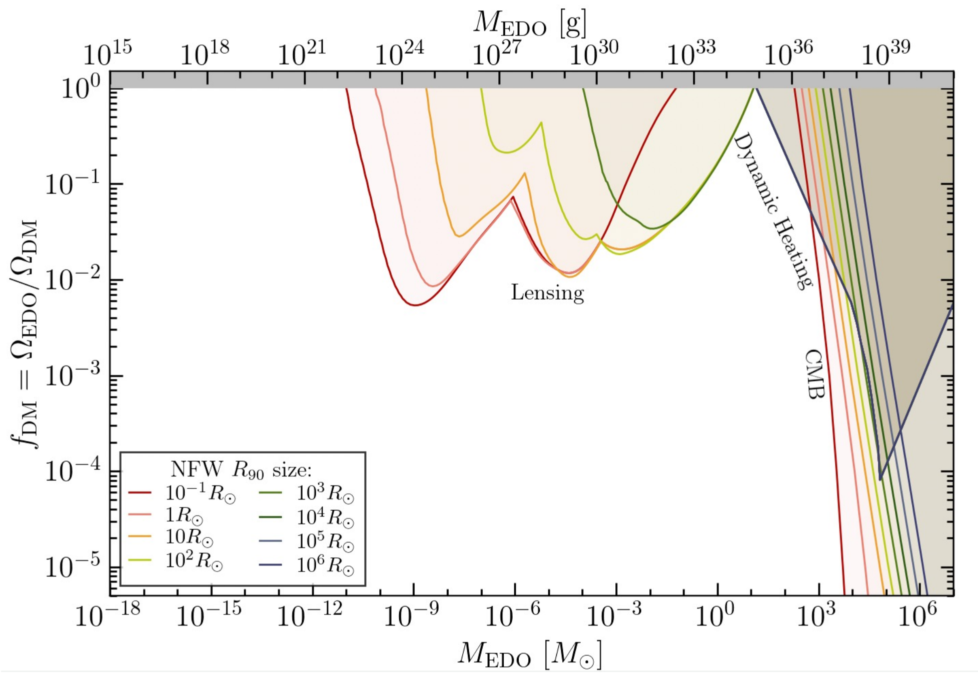
Repository for EDO bounds:



Based on arXiv:2403.13072

Repository for EDO bounds:

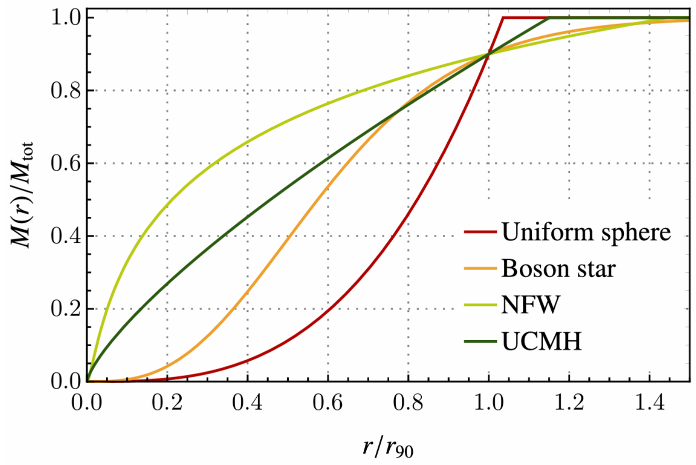


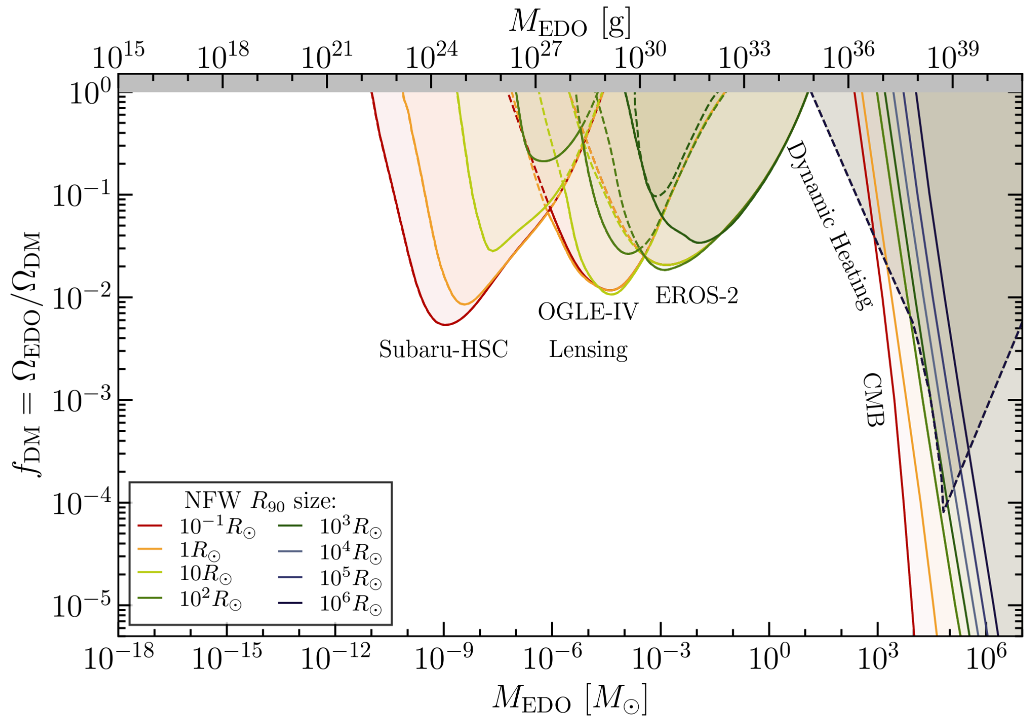


Based on arXiv:2403.13072

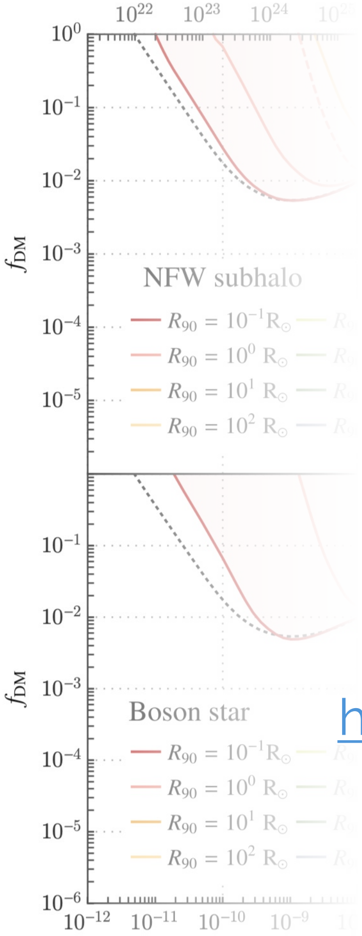
Repository for EDO bounds:

arXiv:2407.02573





Based on arXiv:2403.13072



Thank you for your attention!

Any questions?

https:// gitlab.com/SergioSevillano/edo-accretion

https://github.com/SergioSevi/EDObounds