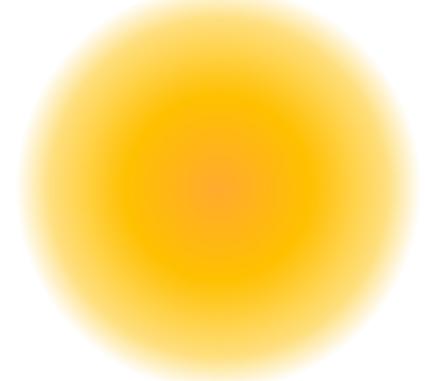


Current Constraints on Extended Dark matter Objects



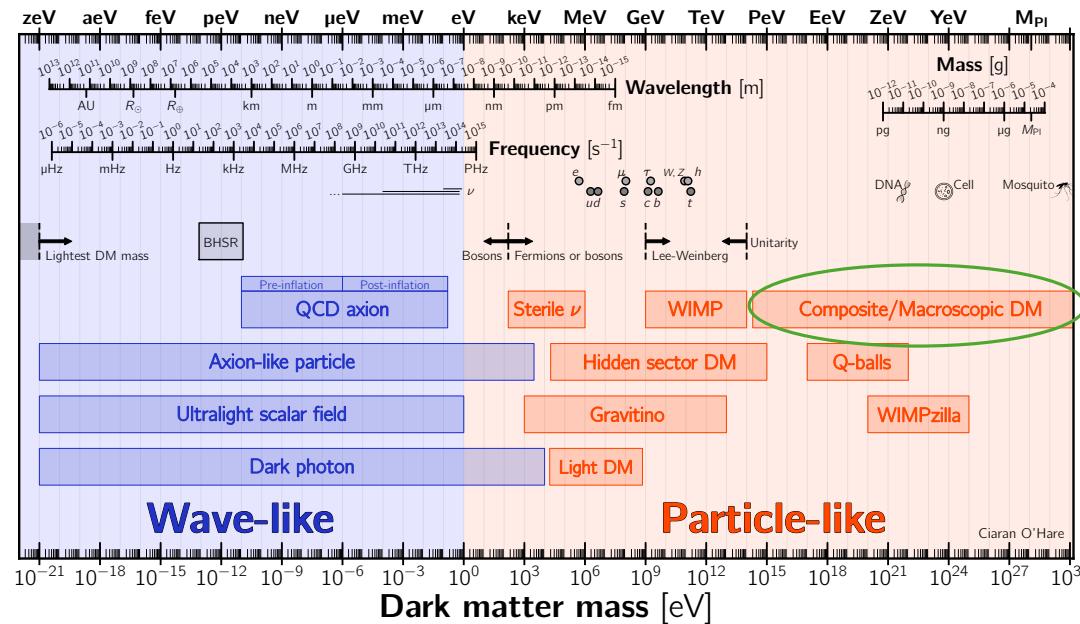
Based on arXiv:2403.13072

Sergio Sevillano Muñoz

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

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](#))

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

Introduction to EDOs

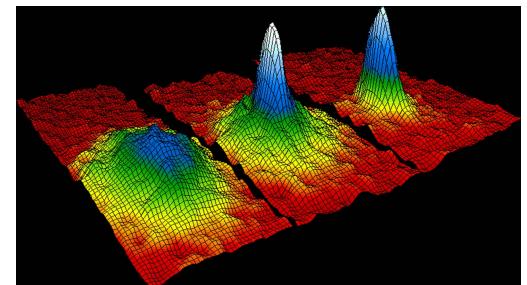
Extended Dark matter Objects are a popular option for dark matter

- Macroscopical objects that only interact gravitationally with matter

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 - Uniform sphere ([Witten 1984](#))

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



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

Introduction to EDOs

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 - Uniform sphere ([Witten 1984](#))

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 - NFW sub-halos

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

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

Introduction to EDOs

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$$M(r) = M \begin{cases} \left(\frac{r}{R}\right)^{3/4} & r \leq R \\ 1 & R < r. \end{cases}$$

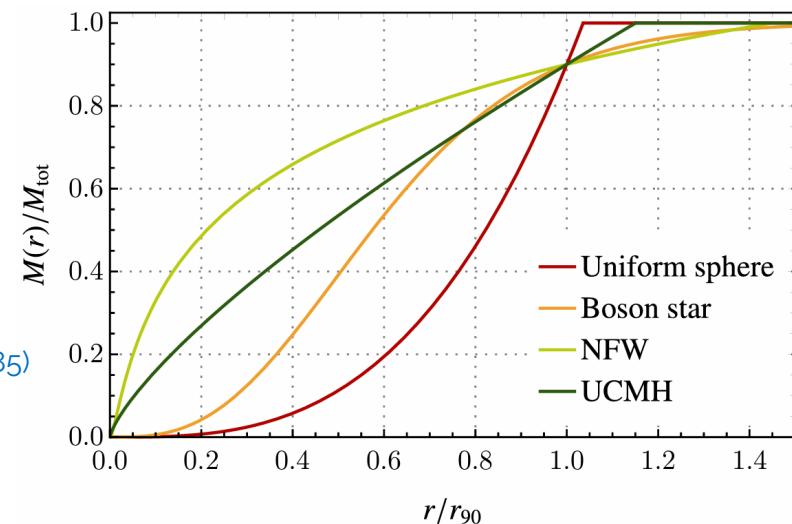
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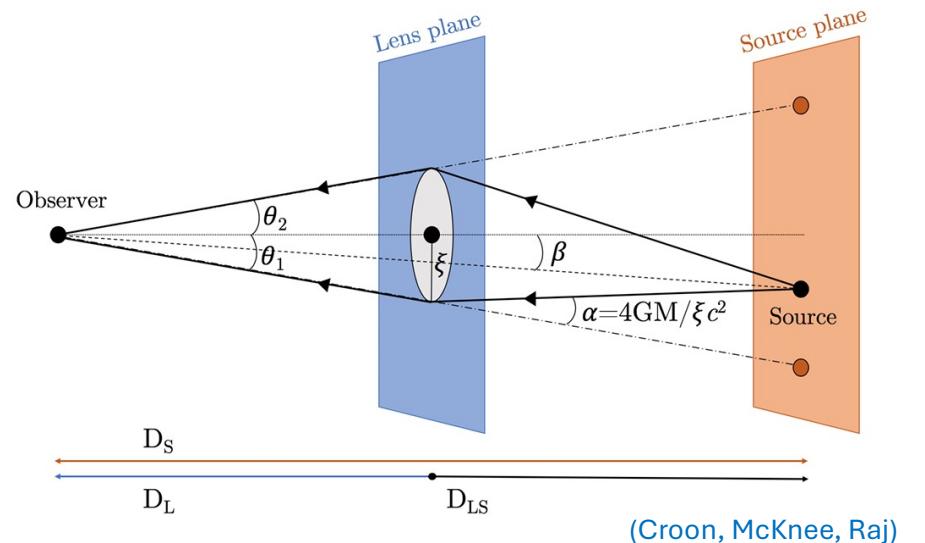
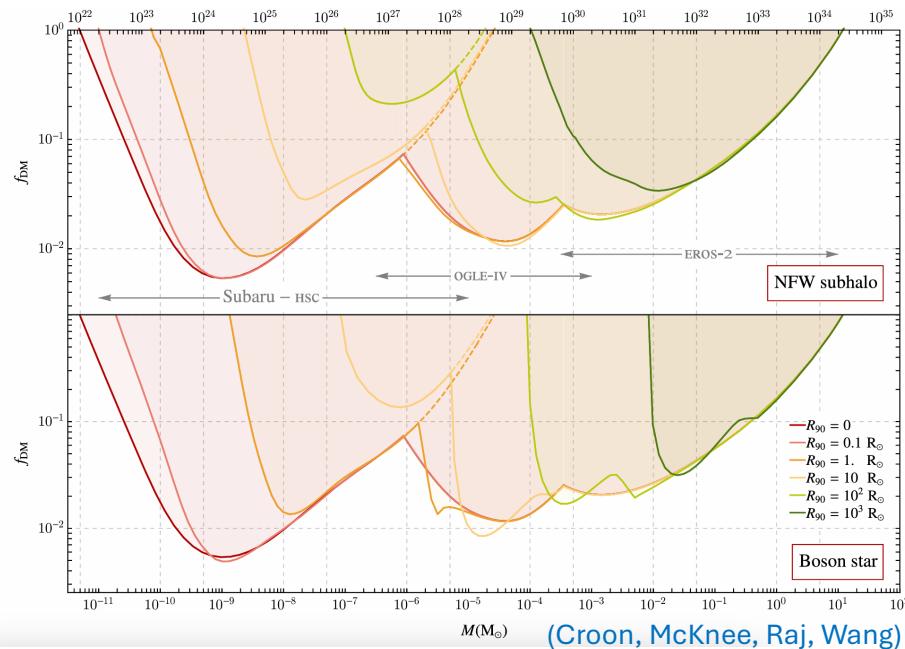
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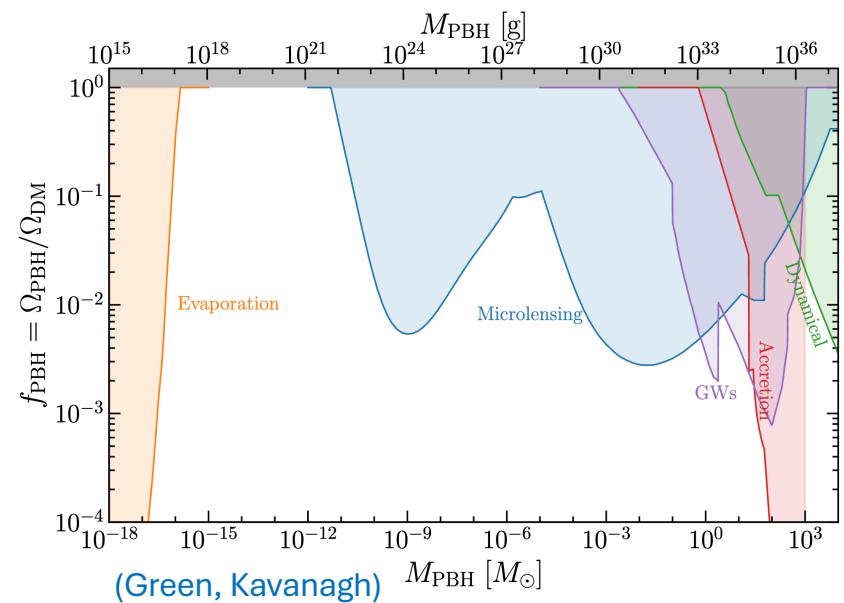
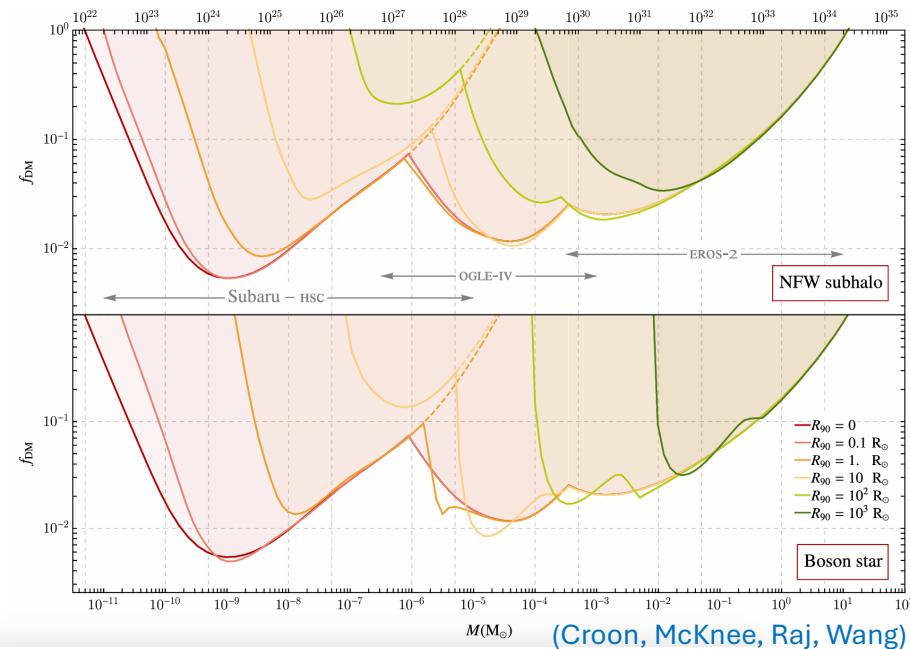
Introduction to EDOs

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



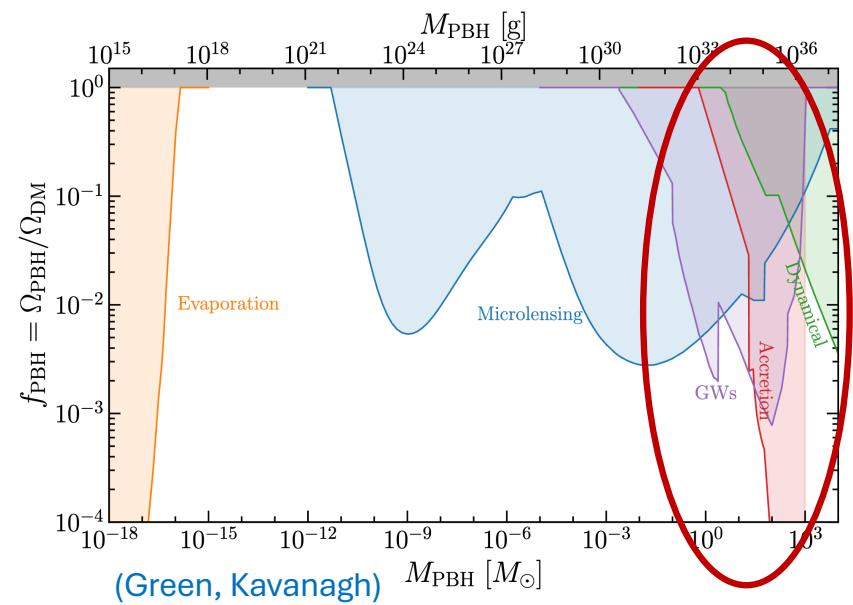
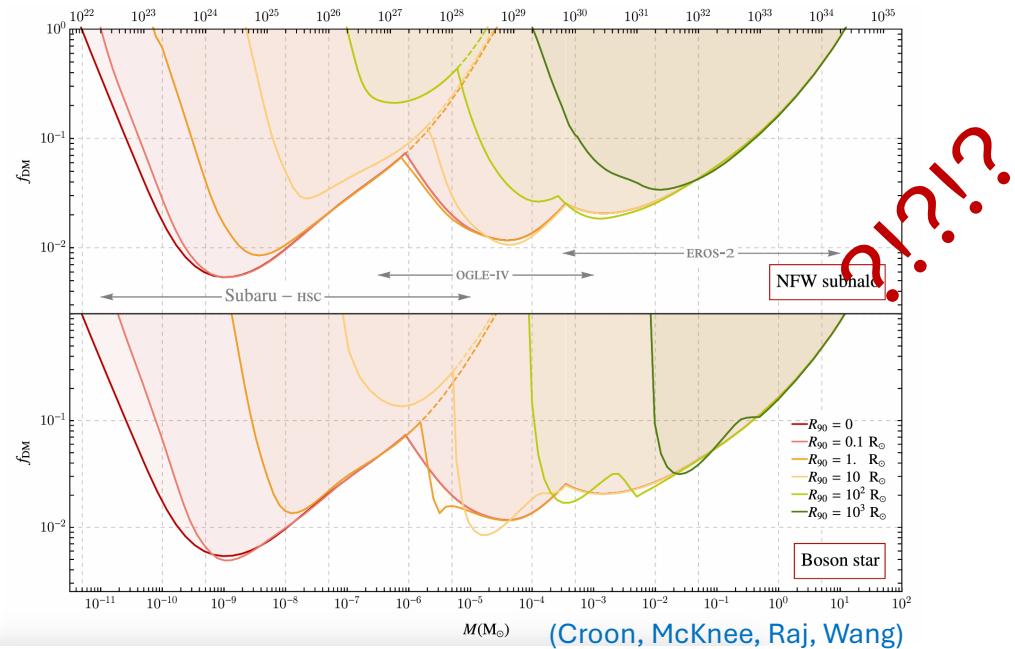
Introduction to EDOs

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Introduction to EDOs

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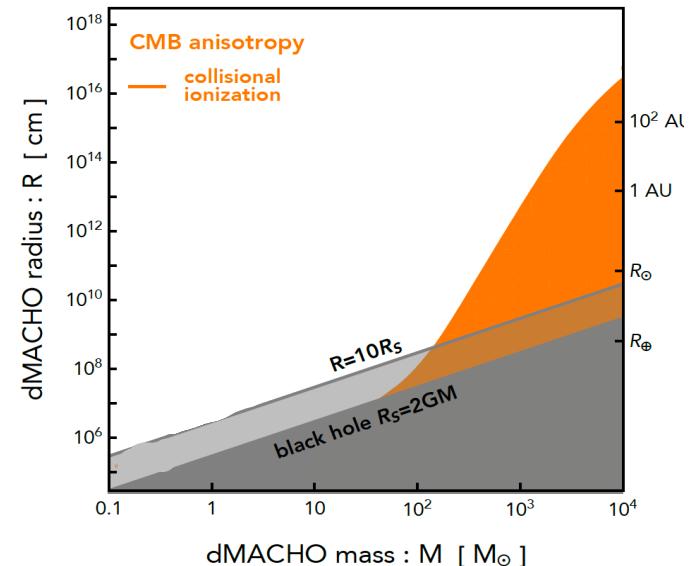


Introduction to EDOs

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 constraints:

- Only the uniform sphere -> [Analytically](#)
- Just for [100%](#) dark matter fraction



Introduction to EDOs

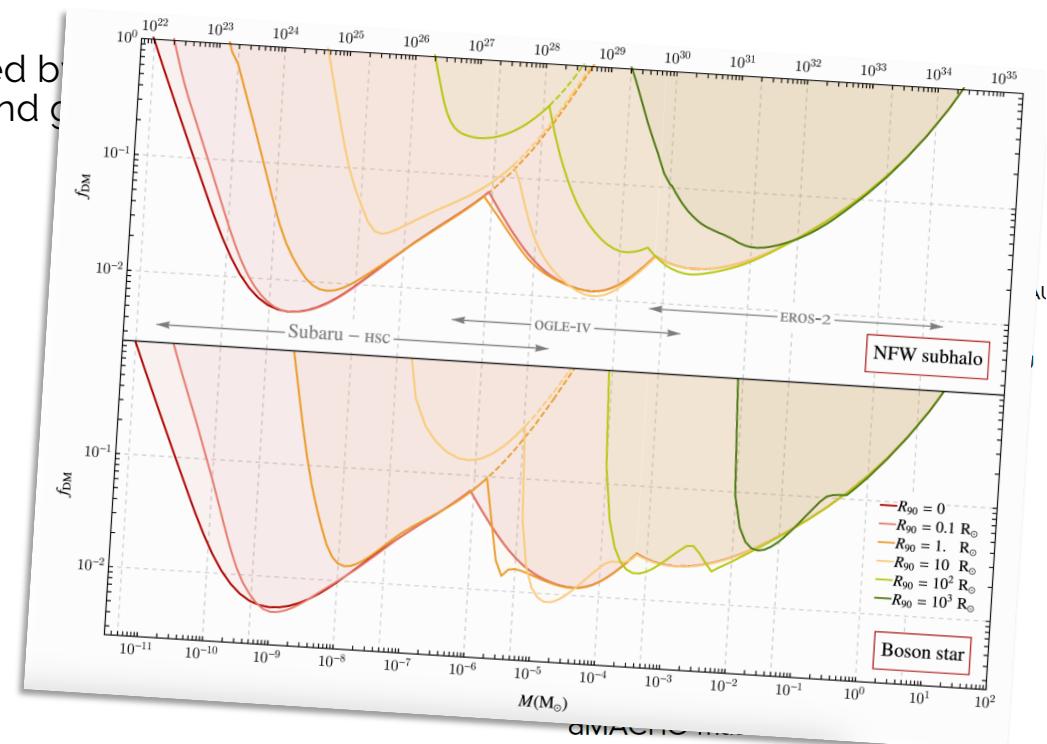
That's what we will be doing today!

The theoretical framework was already developed by [1], where they work with the uniform sphere case, and consider:

- Only the uniform sphere -> **Analytically**
- Just for **100%** dark matter fraction

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

- Any mass function-> **Numerically**
- Any** dark matter fraction

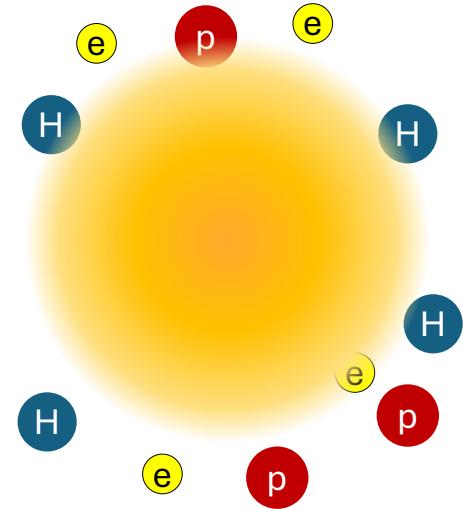


Based on arXiv:2403.13072

Matter accretion

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

like the one here:

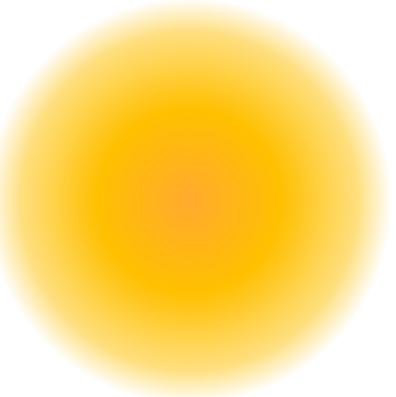


We expect matter to interact gravitationally with it

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

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

-Temperature

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

-Ionisation fraction

-Number of electrons=protons

Matter accretion

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

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

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

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

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

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

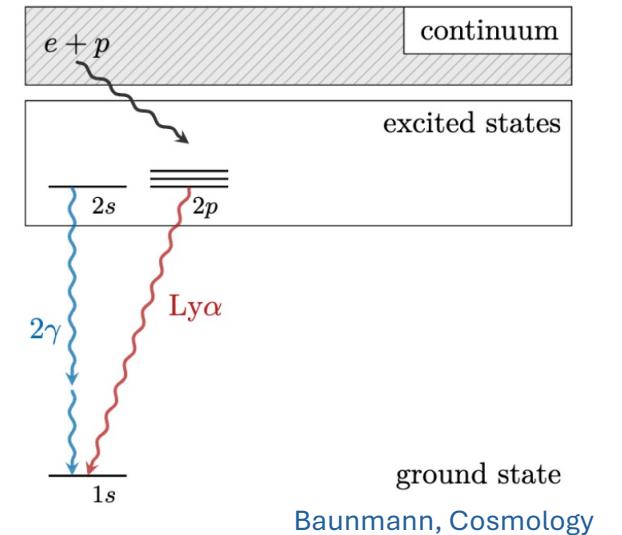
Matter accretion

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

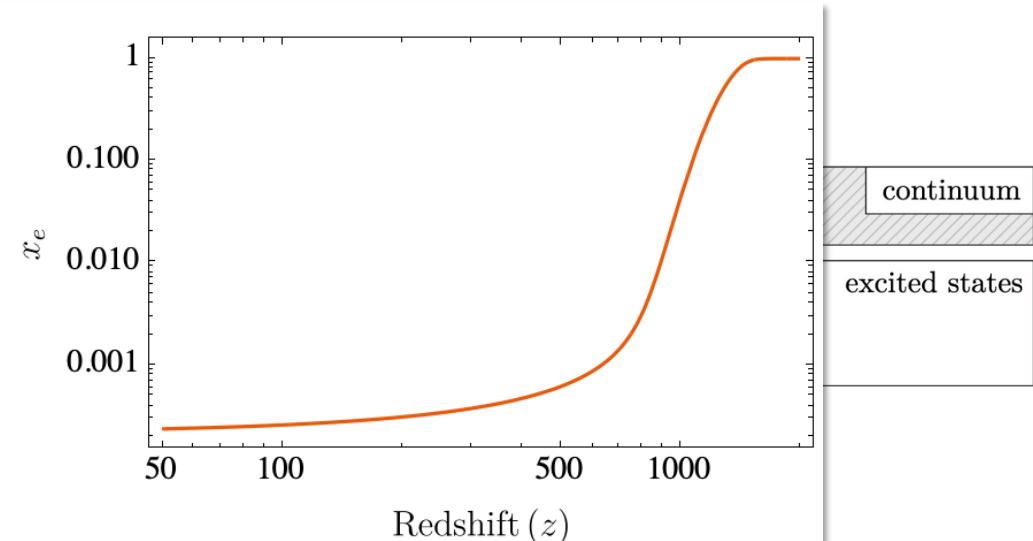
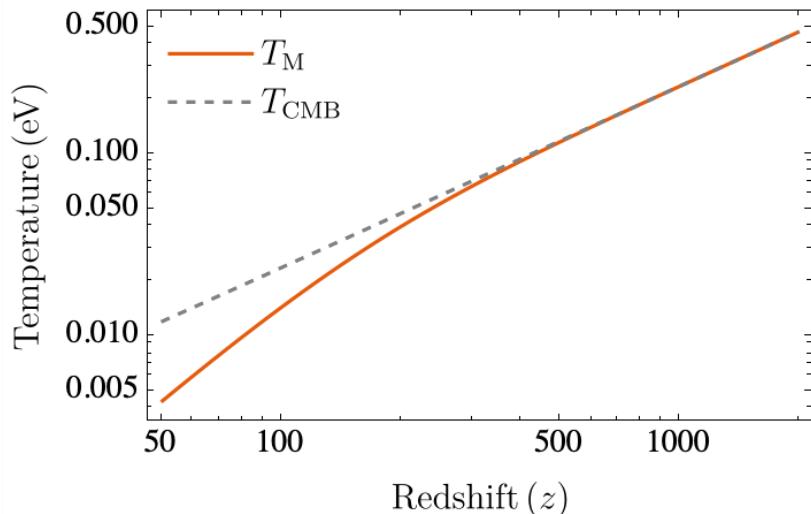
$$\frac{dT_M}{dz} = \frac{1}{(1+z)} \left[2T_M + \frac{8\pi^2 \sigma_T T_{\text{cmb}}^4}{45H(z)m_e} \frac{x_e}{1+x_e} (T_M - T_{\text{cmb}}) \right],$$

$$\frac{dx_e}{dz} = C_r(z) \frac{\alpha_B(T_M)}{H(z)(1+z)} \left[nx_e^2 + \left(\frac{m_e T_M}{2\pi} \right)^{3/2} e^{-\frac{E_I}{T_M}} (1-x_e) \right]$$



Matter accretion

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



$$\rho_\infty \equiv m_p n(z),$$

$$T_\infty \equiv T_M(z),$$

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

ground state

Baumann, 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:

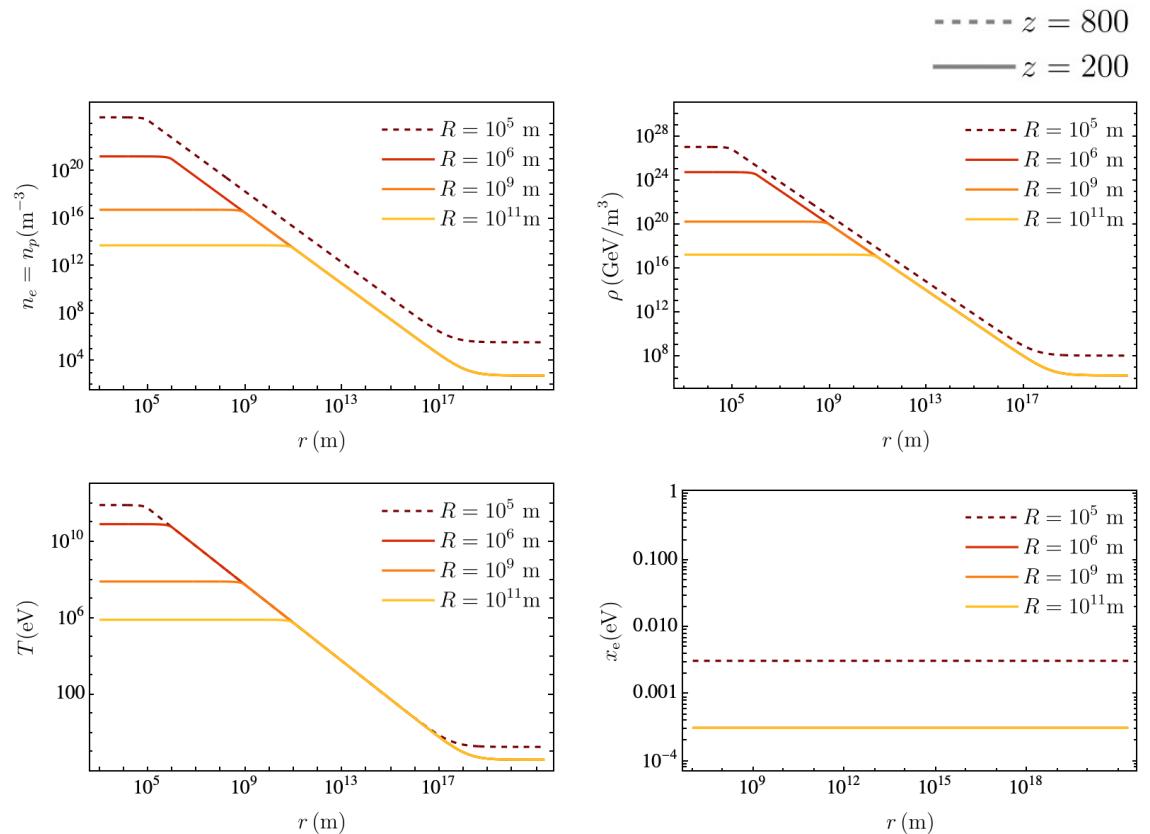
$$\rho_\infty \equiv m_p n(z), \quad T_\infty \equiv T_M(z),$$

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

And the uniform sphere

mass function:

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



We will solve this equation:

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

$\cdots \cdots z = 800$
 $\text{--- } z = 200$

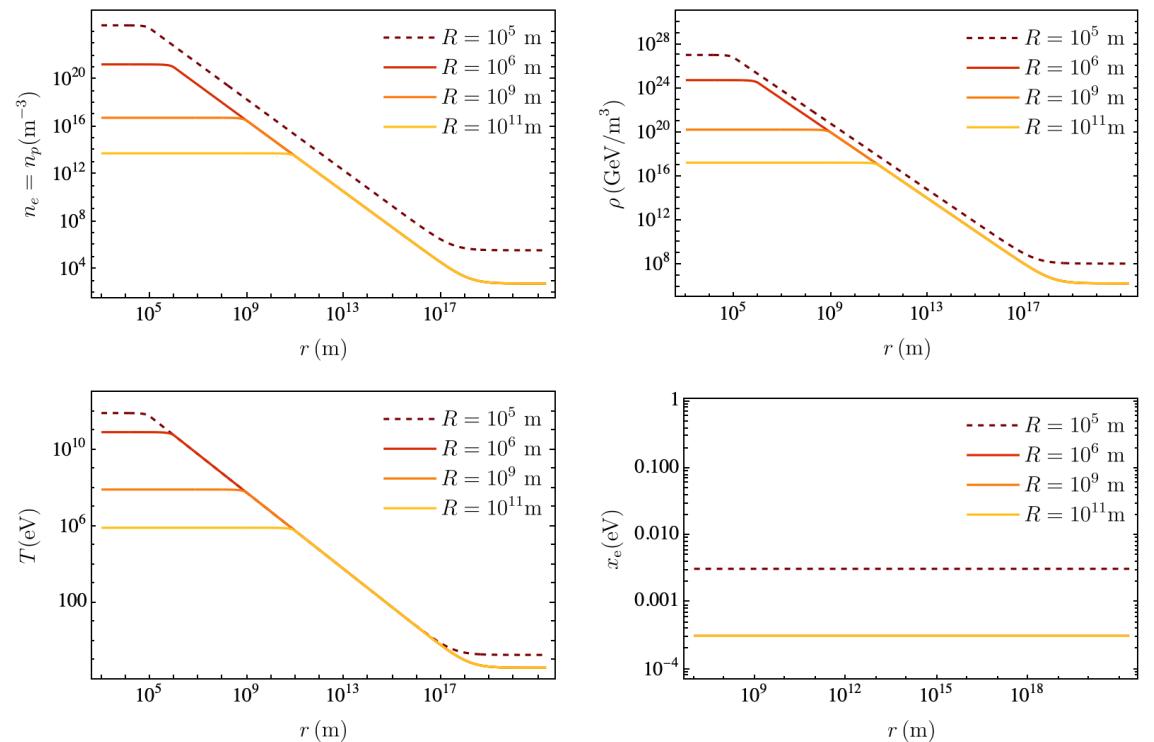
But that is not enough! Add corrections:

-Interactions with CMB

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

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

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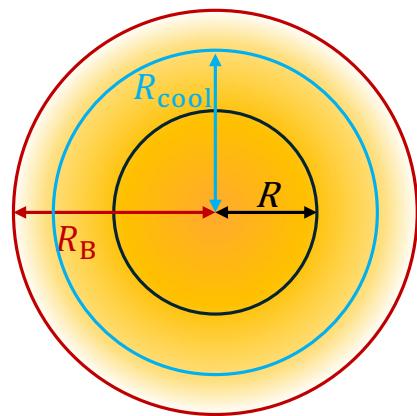
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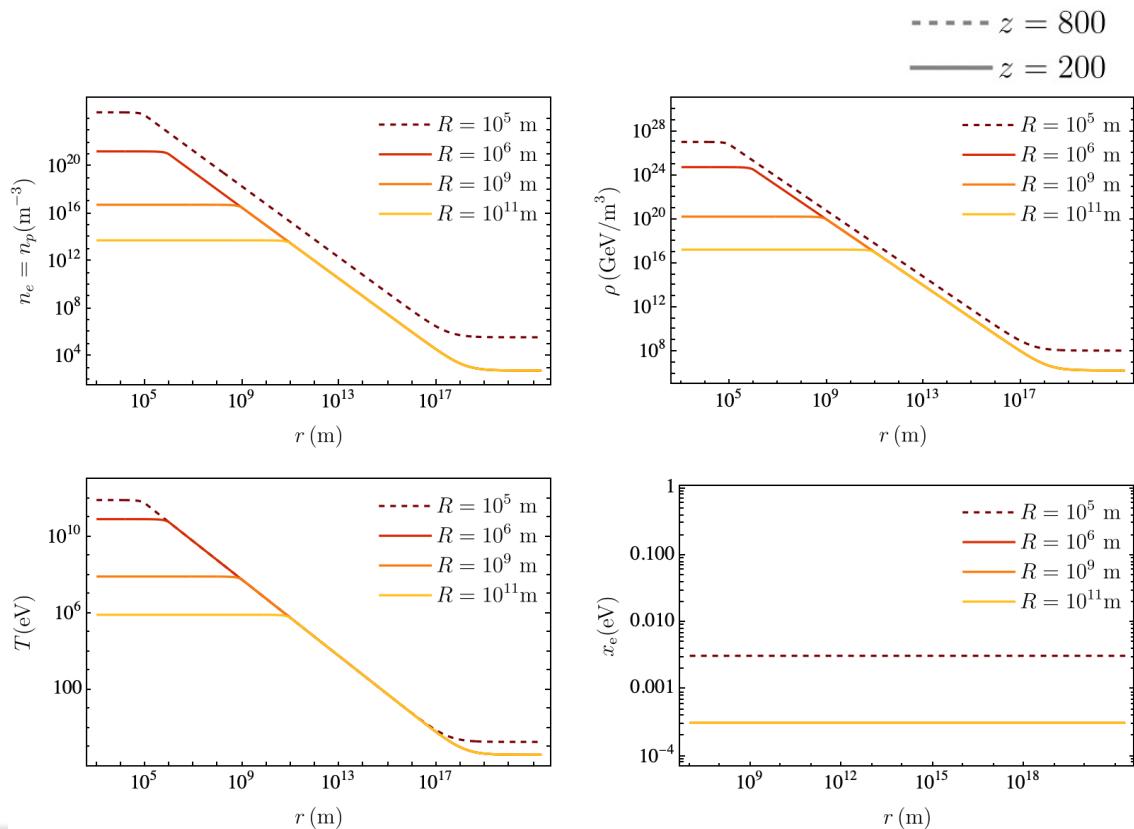
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Mainly affects high redshifts



$$R_B = GM/c_\infty^2$$



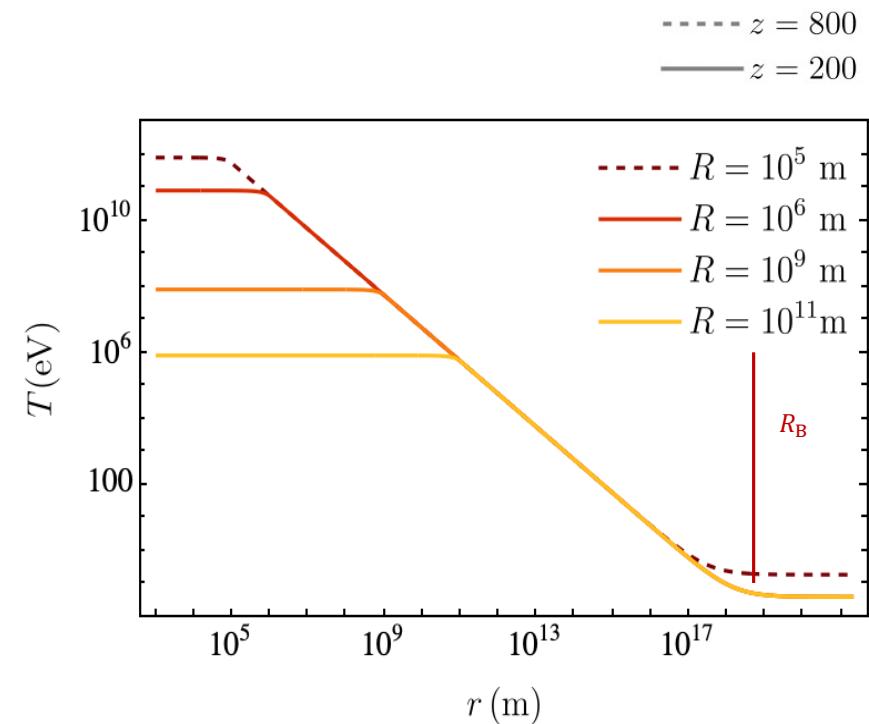
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But that is not enough! Add corrections:

-Interactions with CMB

Only affects high redshifts, as density is higher



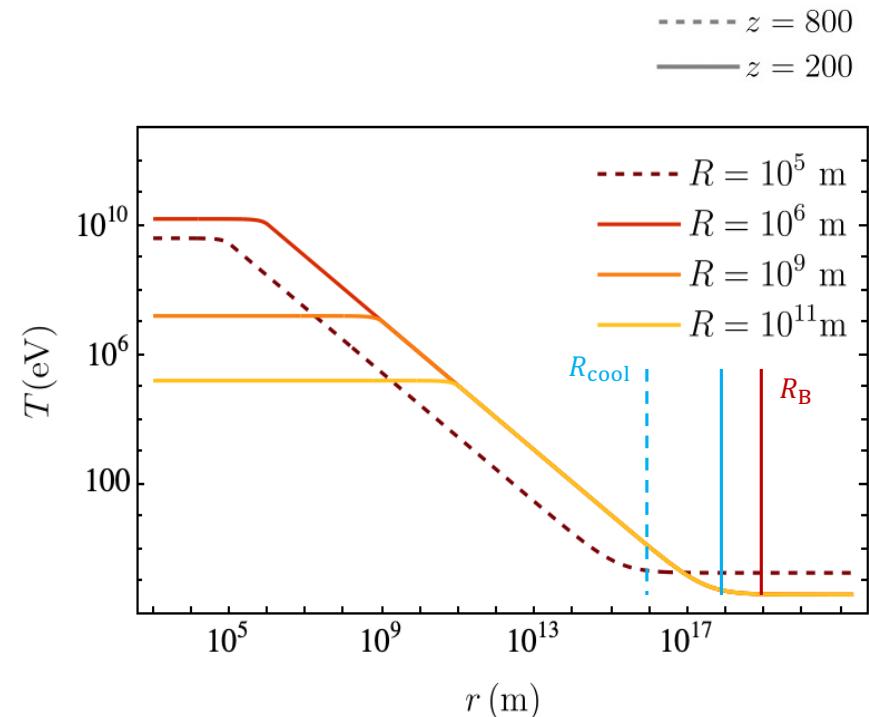
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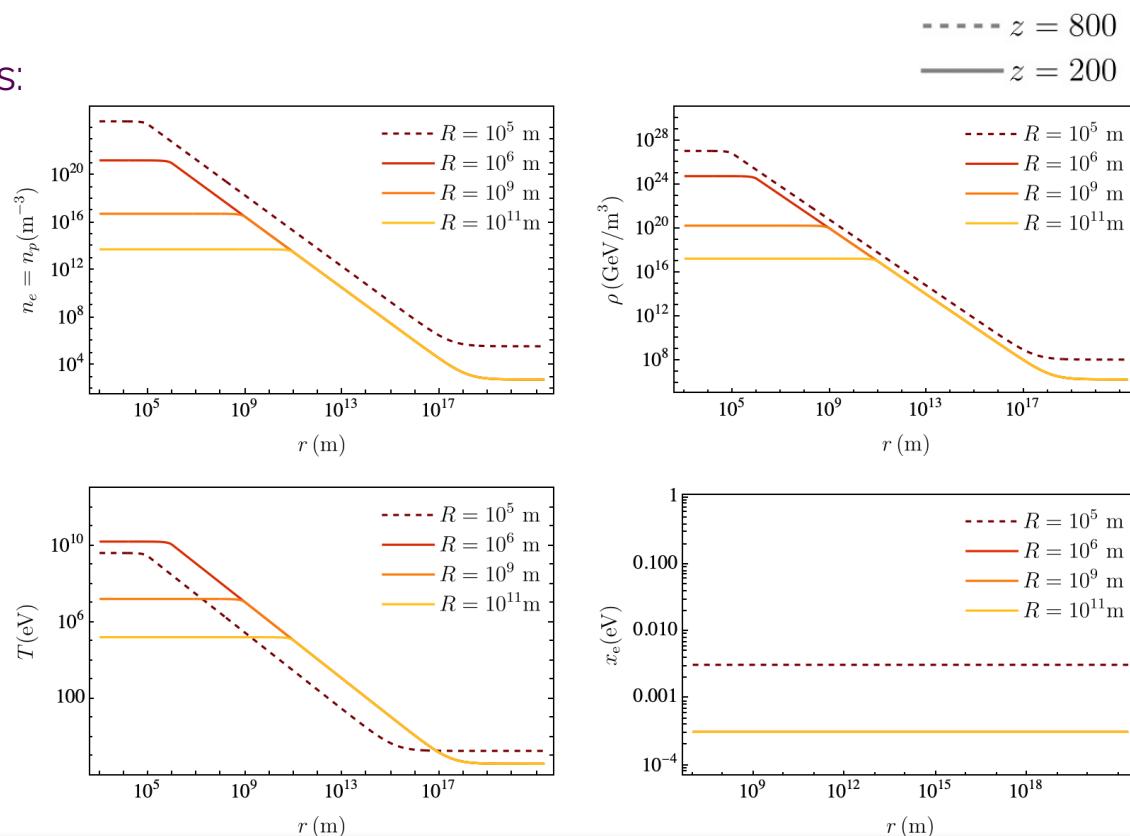
-Interactions with CMB

-Collisional ionisation:



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

Temperature distributes into new particles, ionization increases



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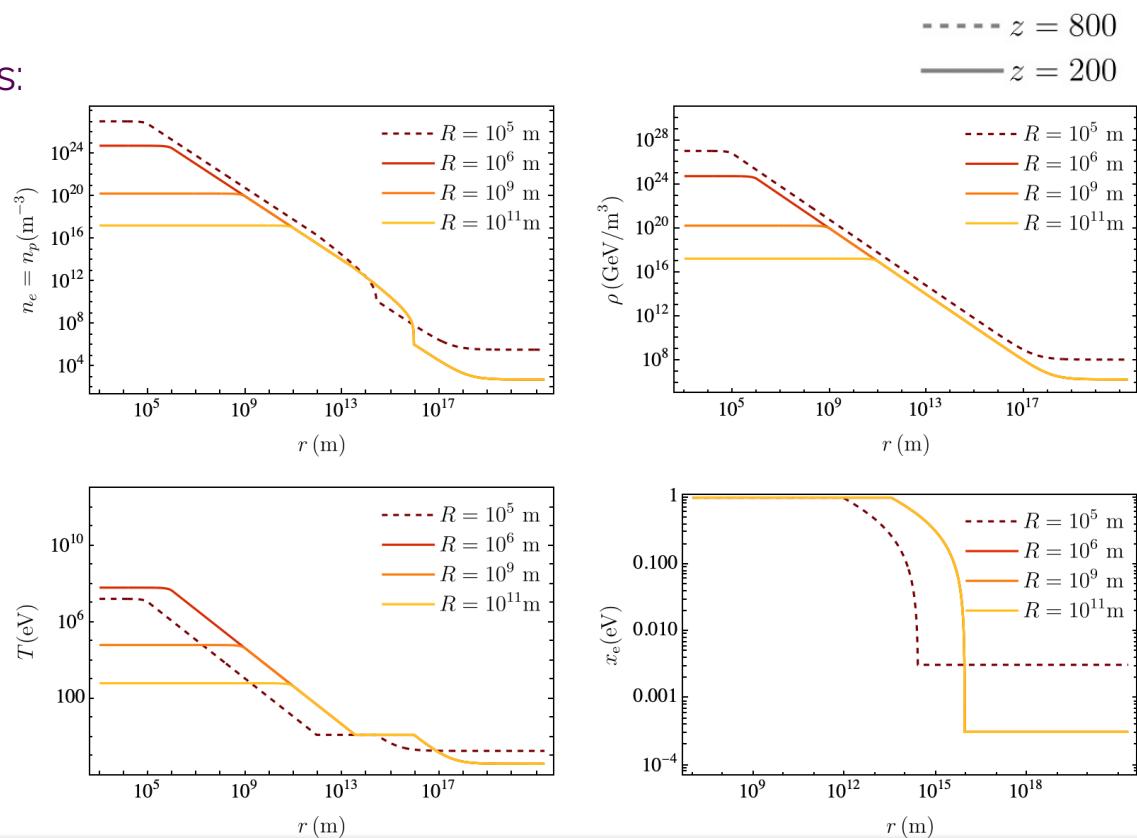
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Temperature distributes into
new particles, ionization increases

Photoionization also important,
but these are the tightest constraints



We will solve this equation:

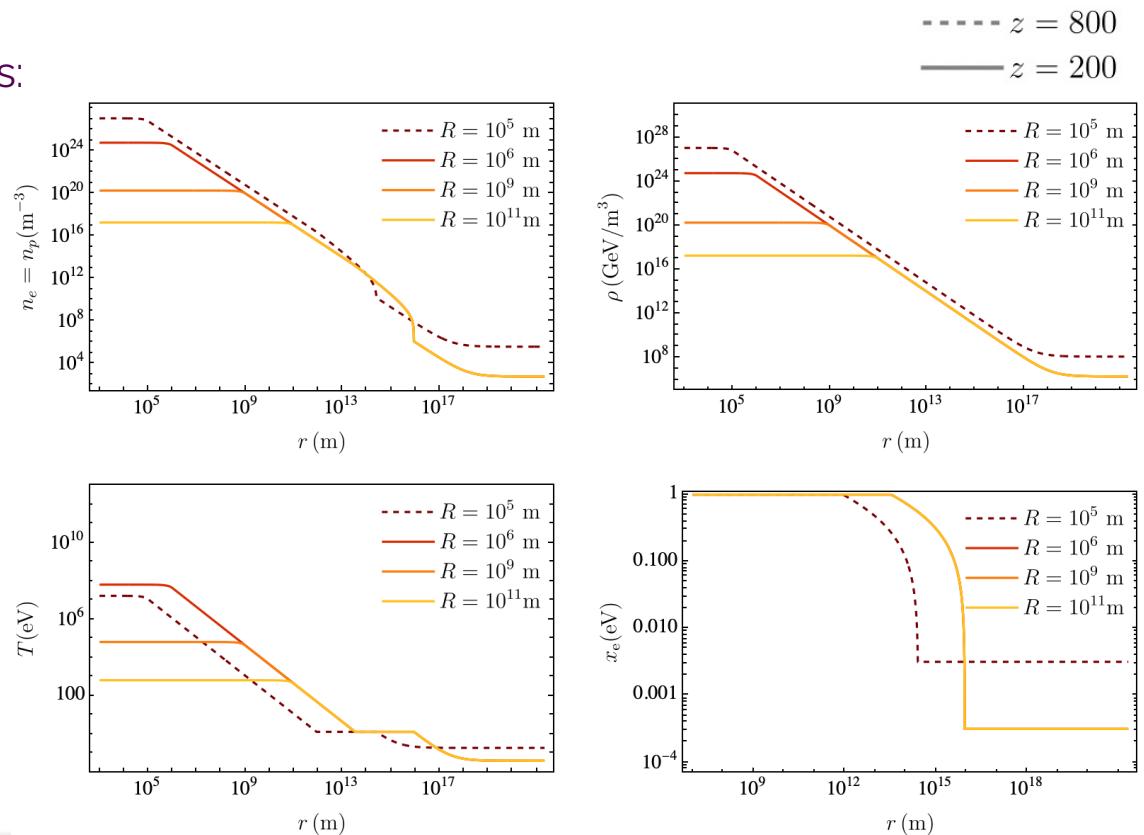
$$\frac{GM(r)}{r^2} + \gamma K \rho(r)^{\gamma-2} \frac{d\rho(r)}{dr} = 0$$

But that is not enough! Add corrections:

- Interactions with CMB
- Collisional ionisation:
- Relativistic effects:

Relativistic electrons contribute differently to the internal energy

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



We will solve this equation:

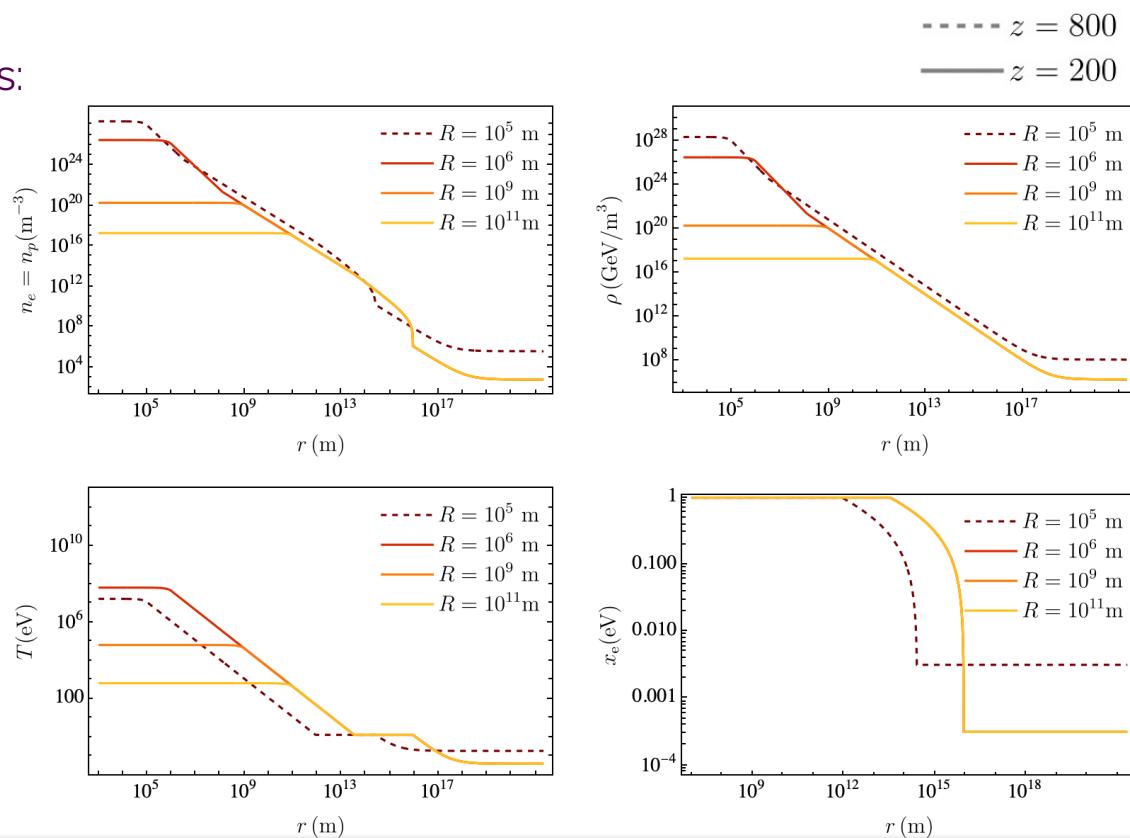
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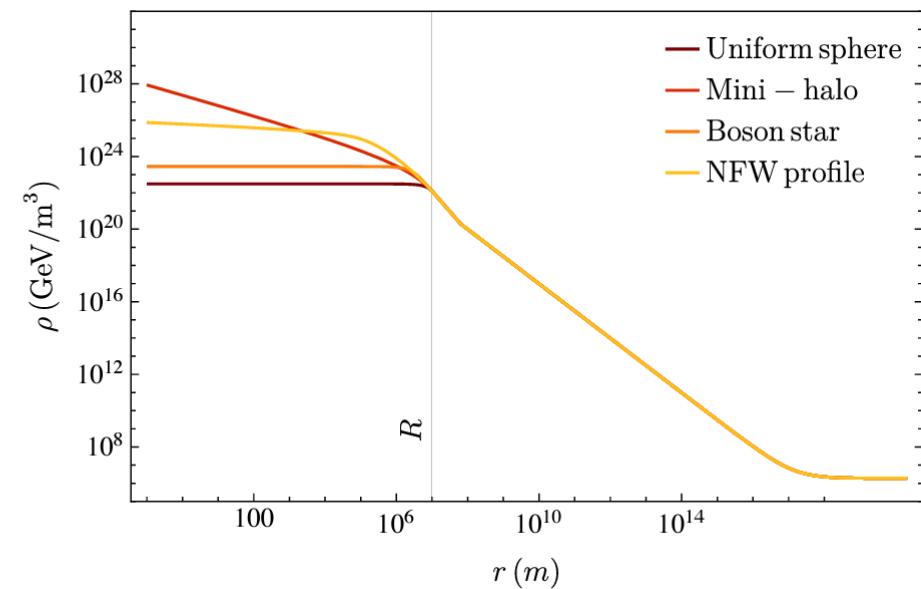
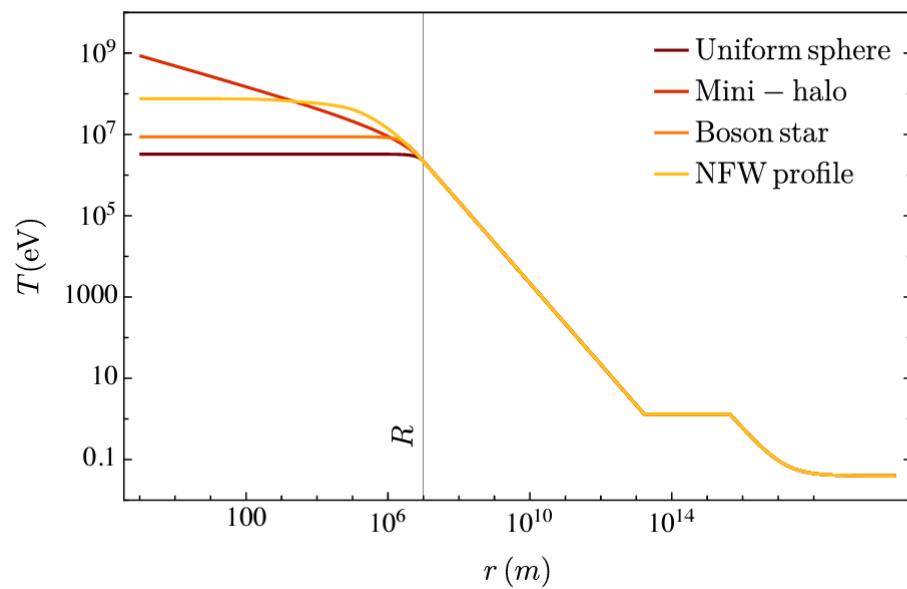
- Interactions with CMB
- Collisional ionisation:
- Relativistic effects:

Relativistic electrons contribute differently to the internal energy

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Comparing different mass profiles, all the same until R :



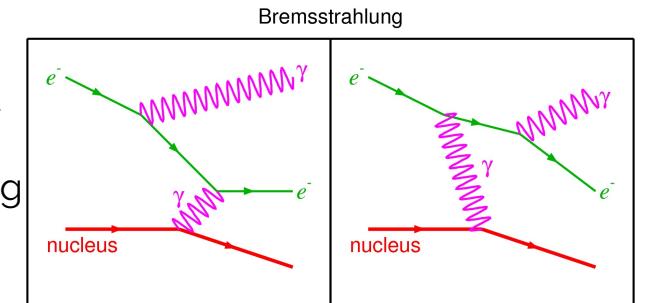
Now we can focus on the effect they will have on the background!

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

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



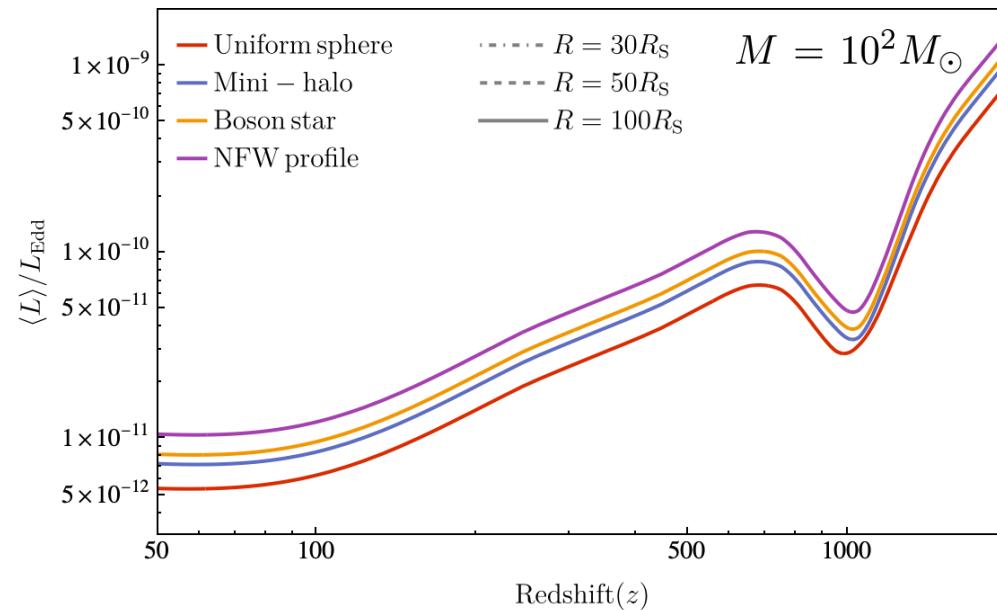
Integrate frequency:

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

Integrate over space:

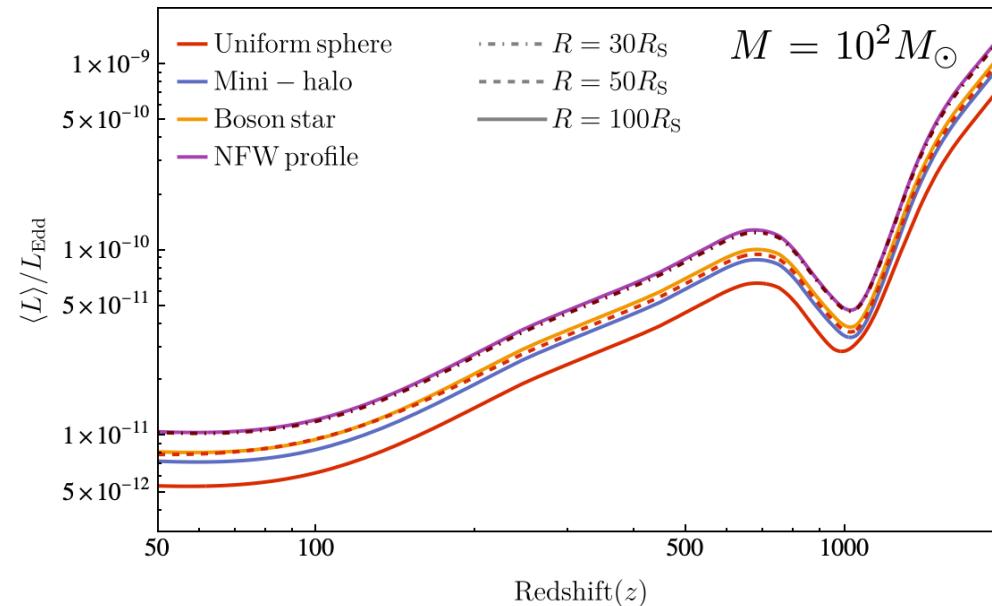
$$L = \int_0^\infty dr 4\pi r^2 [\mathcal{L}(r) - \mathcal{L}(\infty)]$$

Placing EDOs in our Universe



$$\langle \mathcal{L} \rangle = \frac{4\pi}{(2\pi\langle v_s^2 \rangle/3)^{3/2}} \int_0^\infty dv_{\text{rel}} v_{\text{rel}}^2 e^{-\frac{v_{\text{rel}}^2}{2\langle v_s^2 \rangle/3}} \mathcal{L} \Big|_{c_\infty \rightarrow \sqrt{c_\infty^2 + v_{\text{rel}}^2}} \quad \langle v_s^2 \rangle^{1/2} = \min[1, z/10^3] \times 30 \text{ km/s}$$

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

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

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

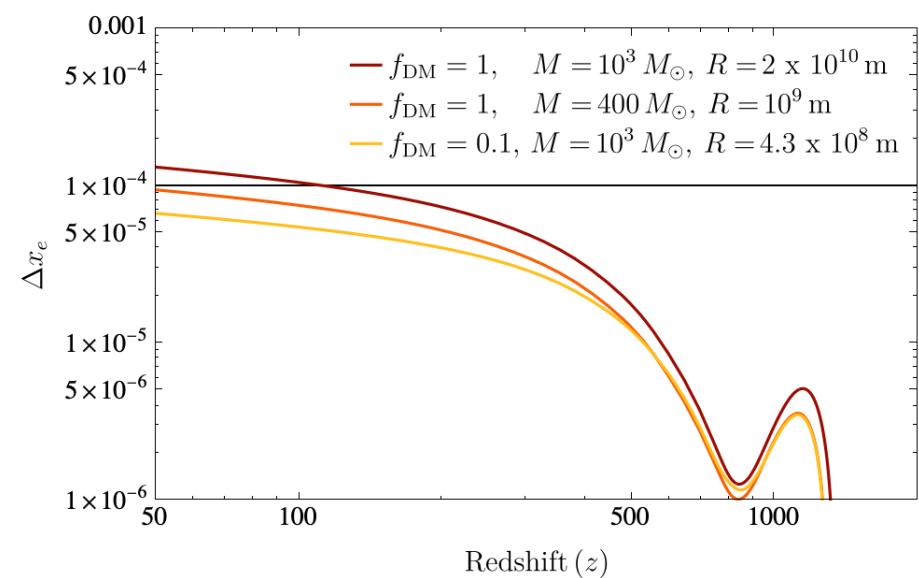
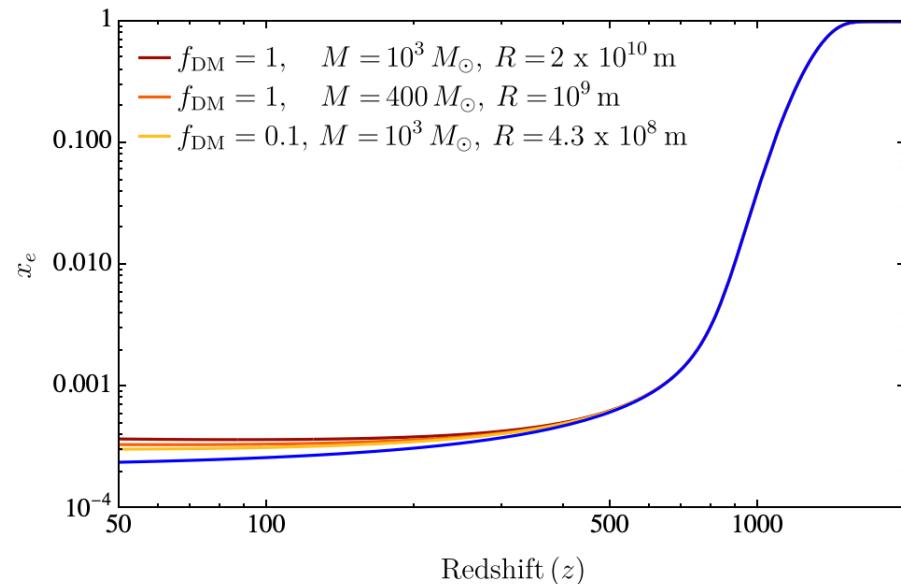
Only a fraction of this energy that will get deposited in the background

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

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

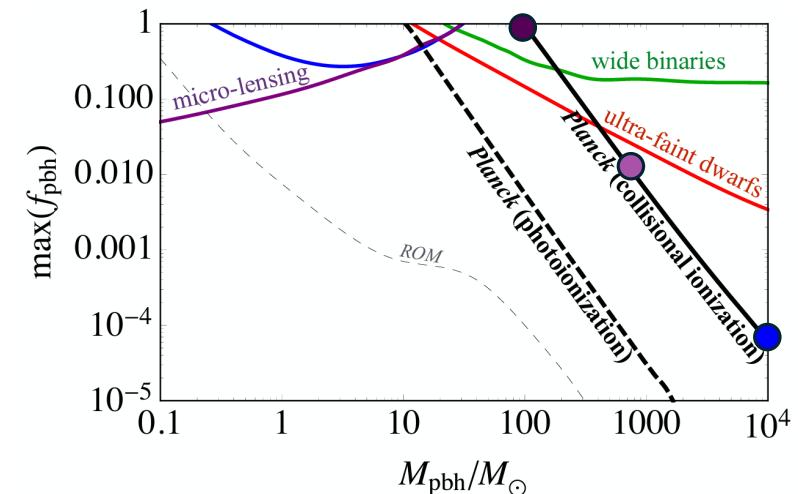
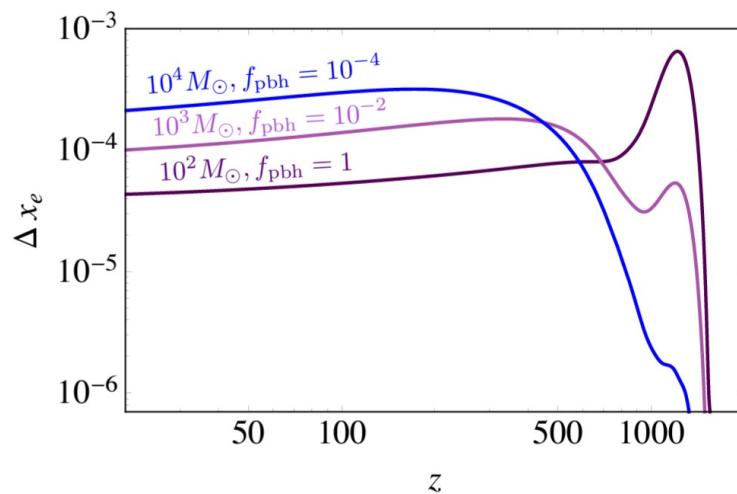
Placing EDOs in our Universe

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



Placing EDOs in our Universe

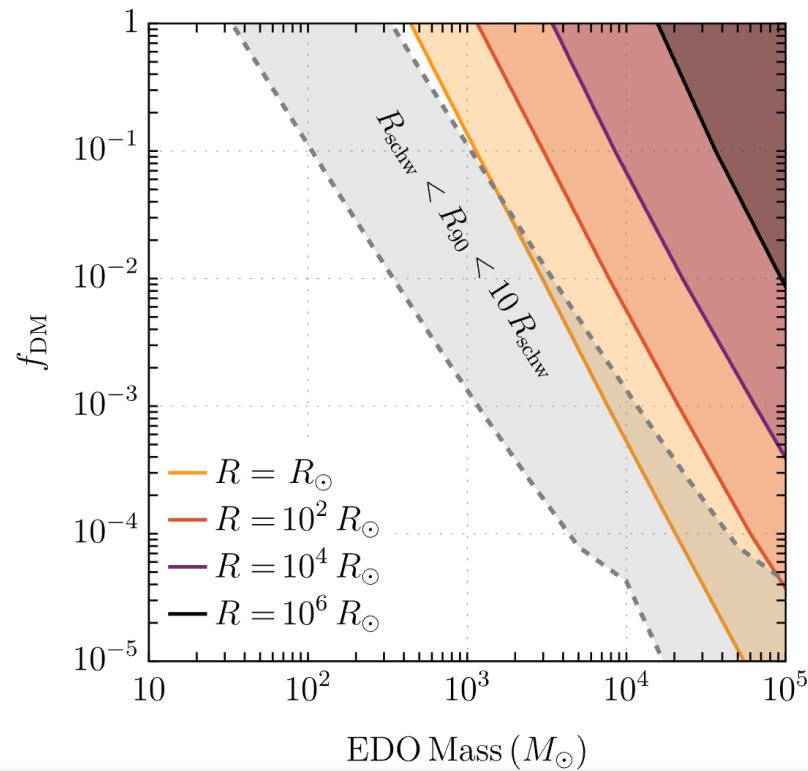
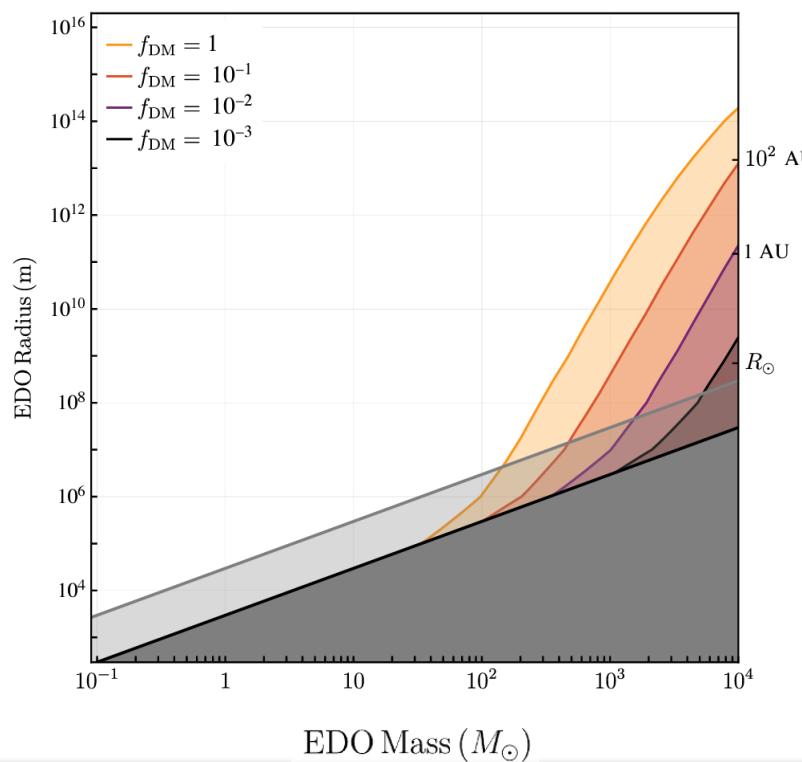
At this point, we should use a Boltzmann code to constrain the ionisation history.
 However, we can recast previous results from PBHs ([Ali-Haïmoud, Kamionkowski](#))



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

Results

Uniform sphere:



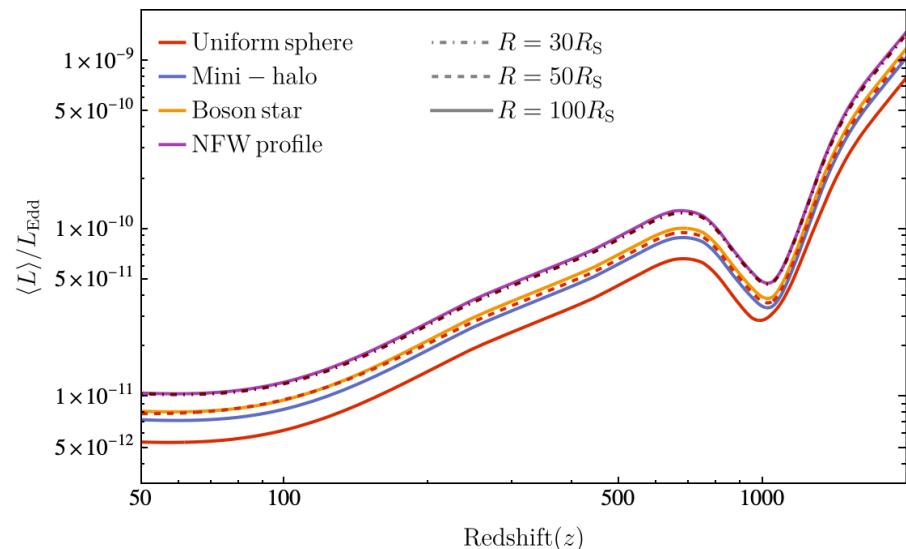
Results

Is the scaling reliable?

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

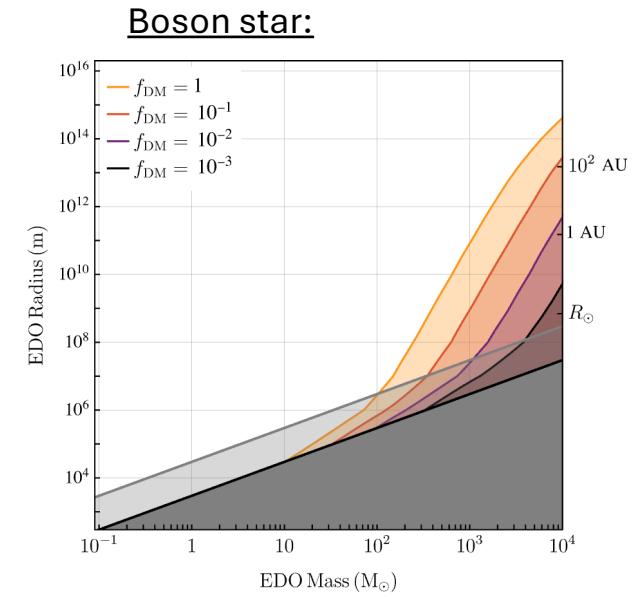
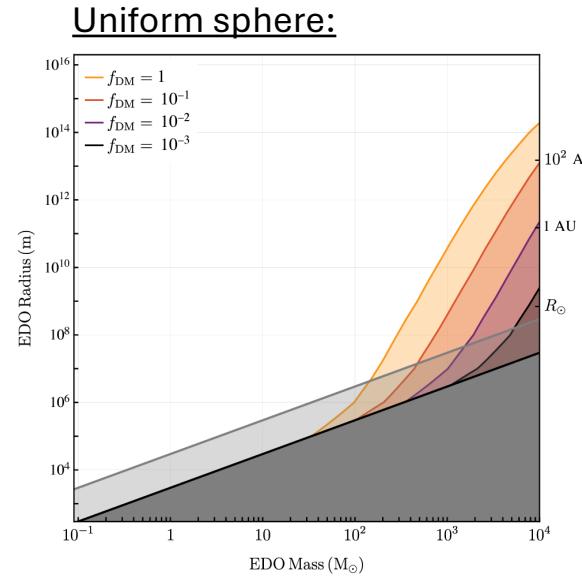
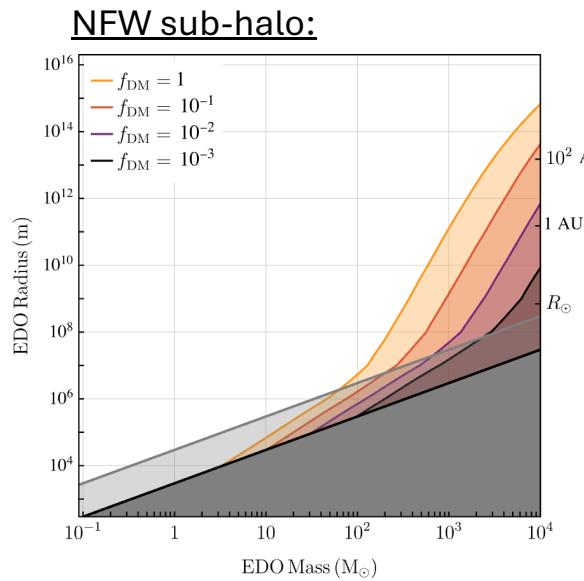
However, getting to the luminosity
was quite complicated already...



Results

Is the scaling reliable?

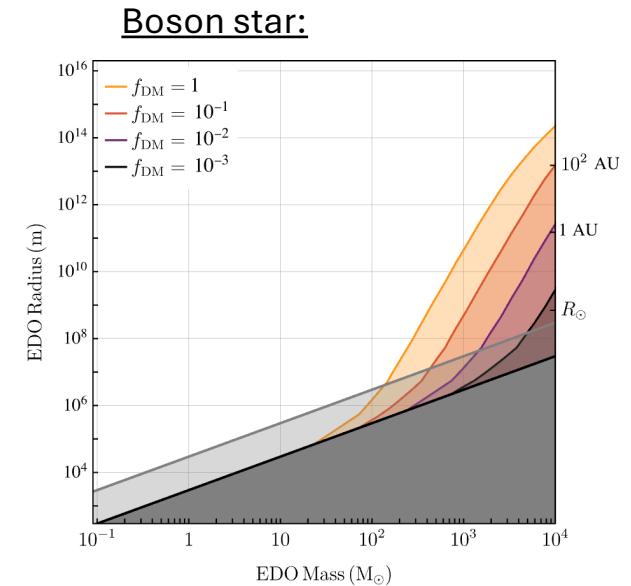
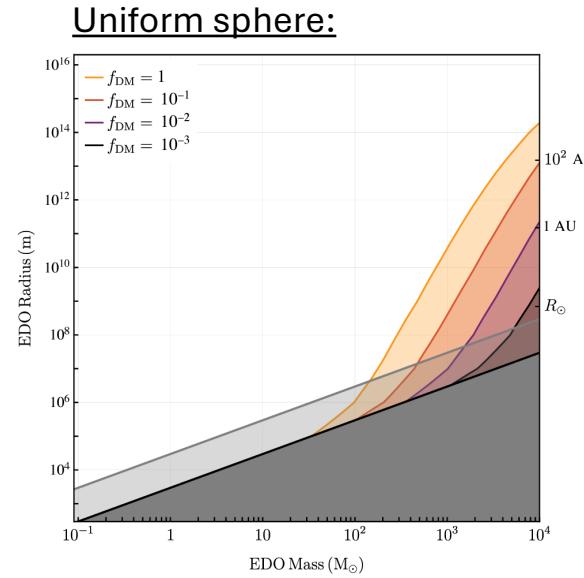
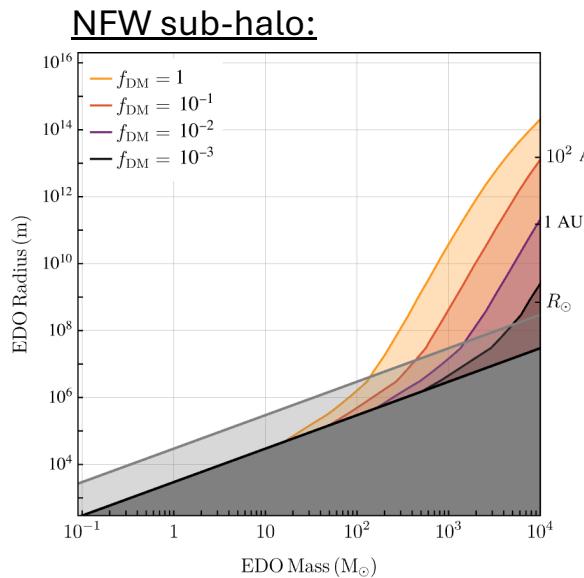
Different shapes on CMB accretion



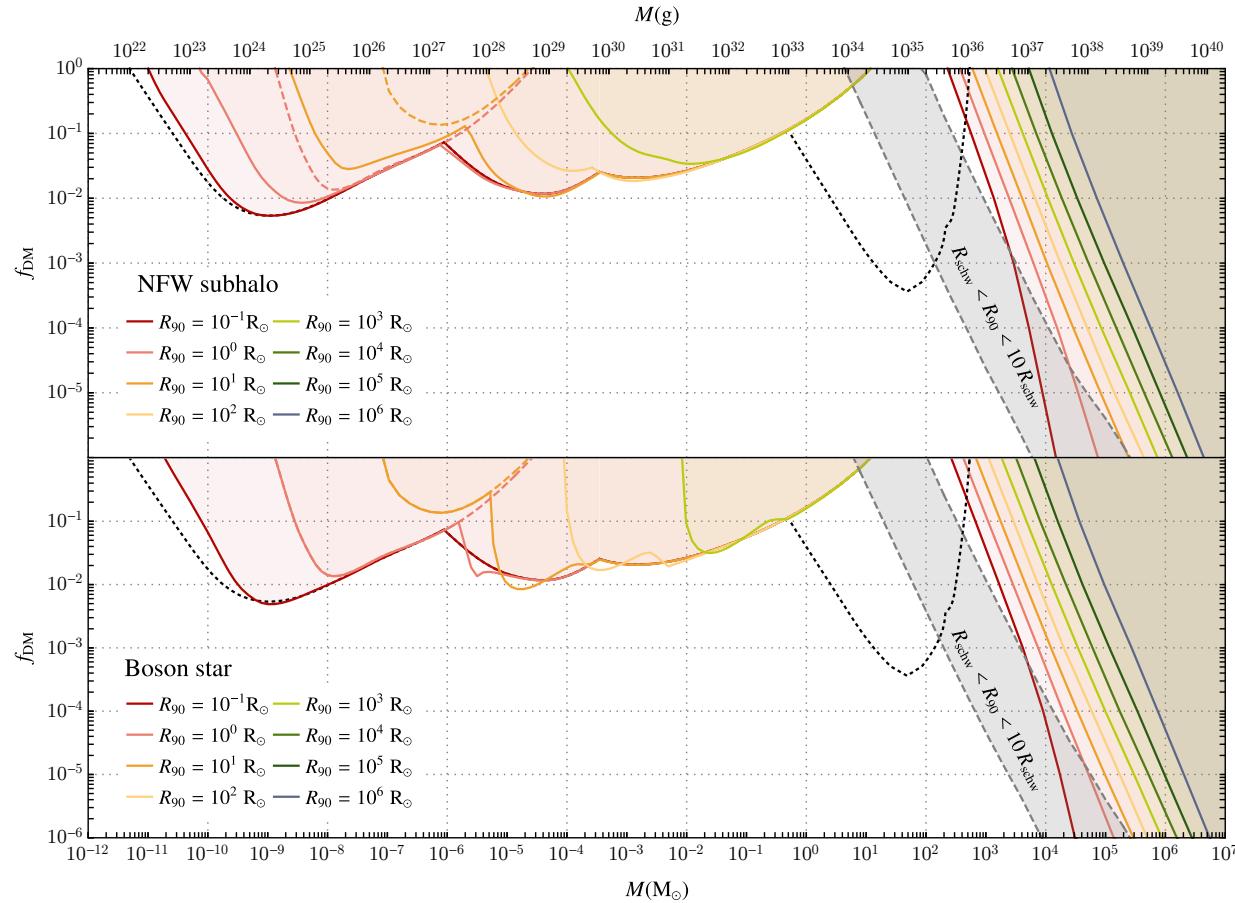
Results

Is the scaling reliable? **YES!**

Different shapes on CMB accretion



Finally combining with existing constraints, we obtain



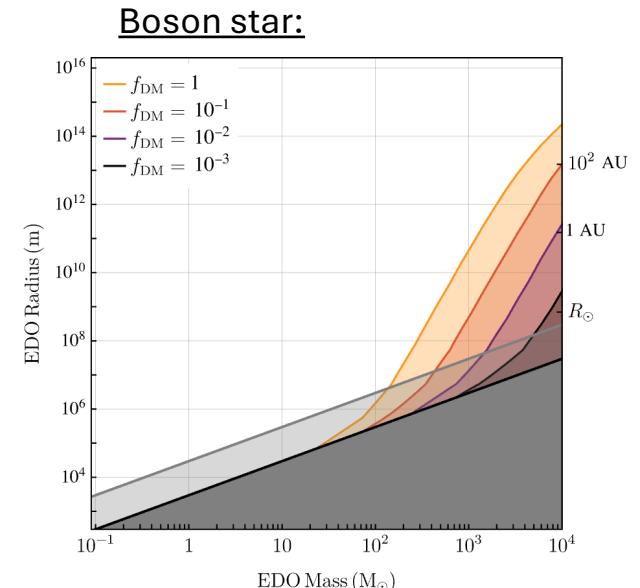
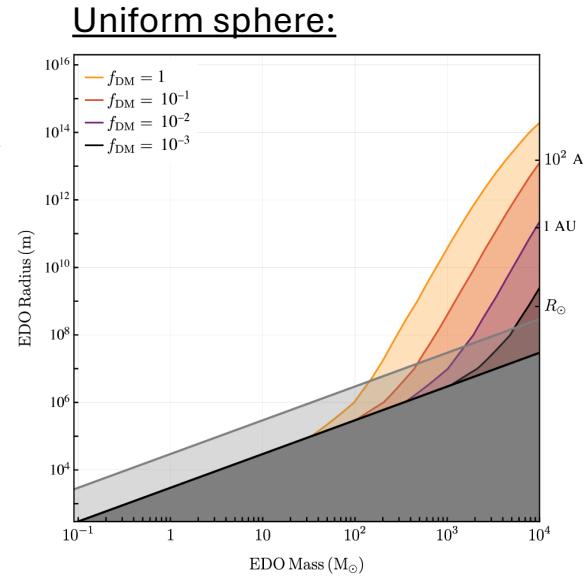
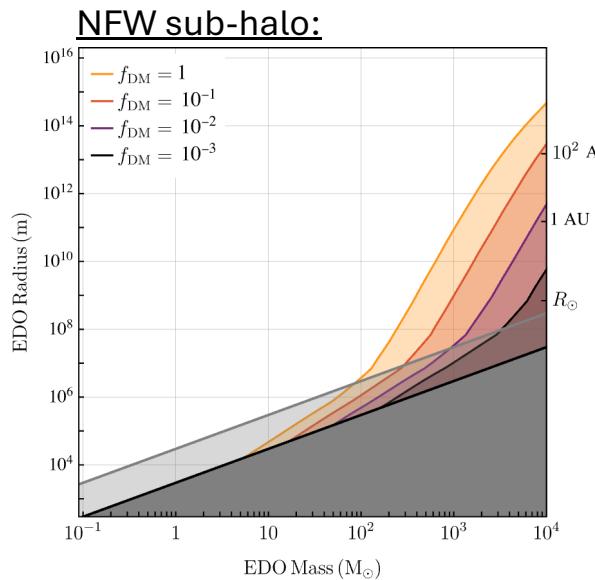
Results

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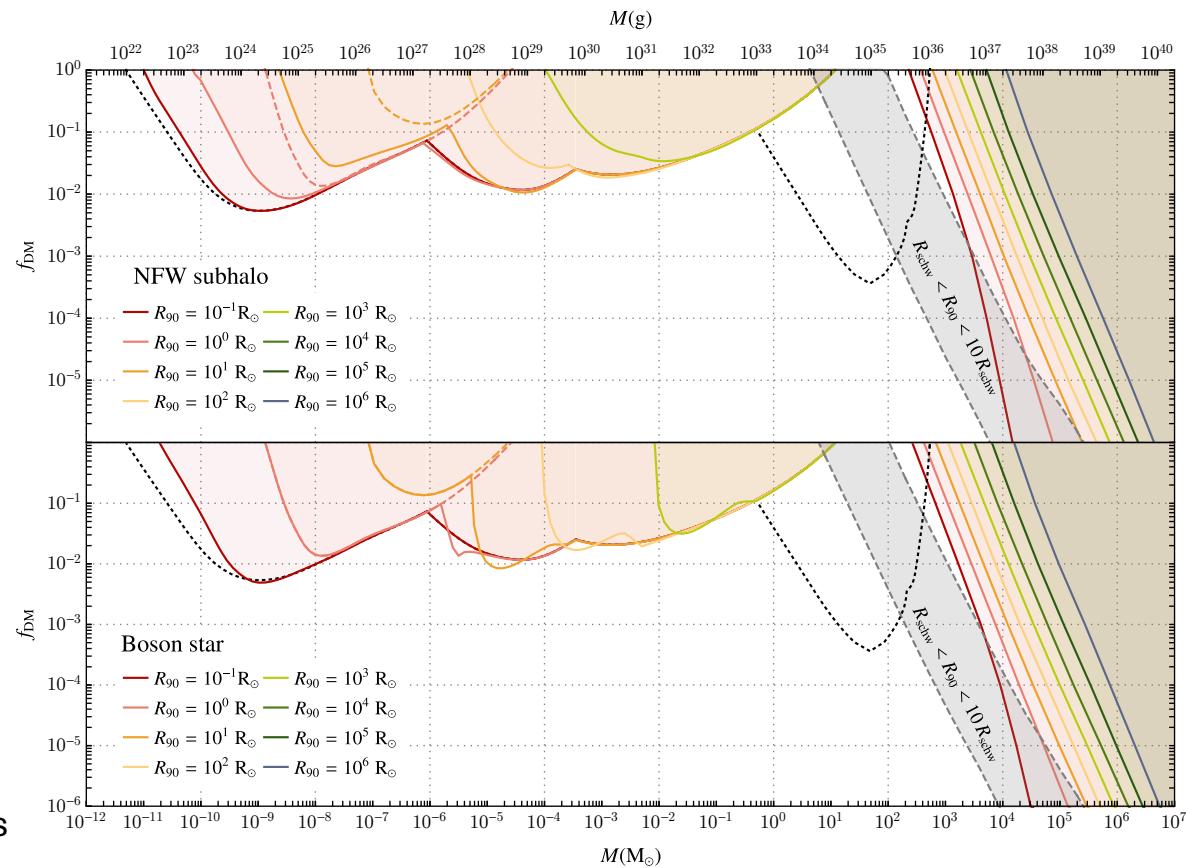
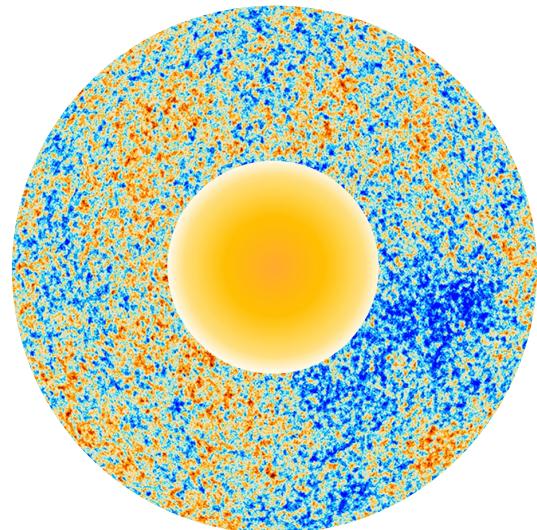
YES!

The important question: **how can we extend this?**

Just rescale to R_{go} for your mass profile

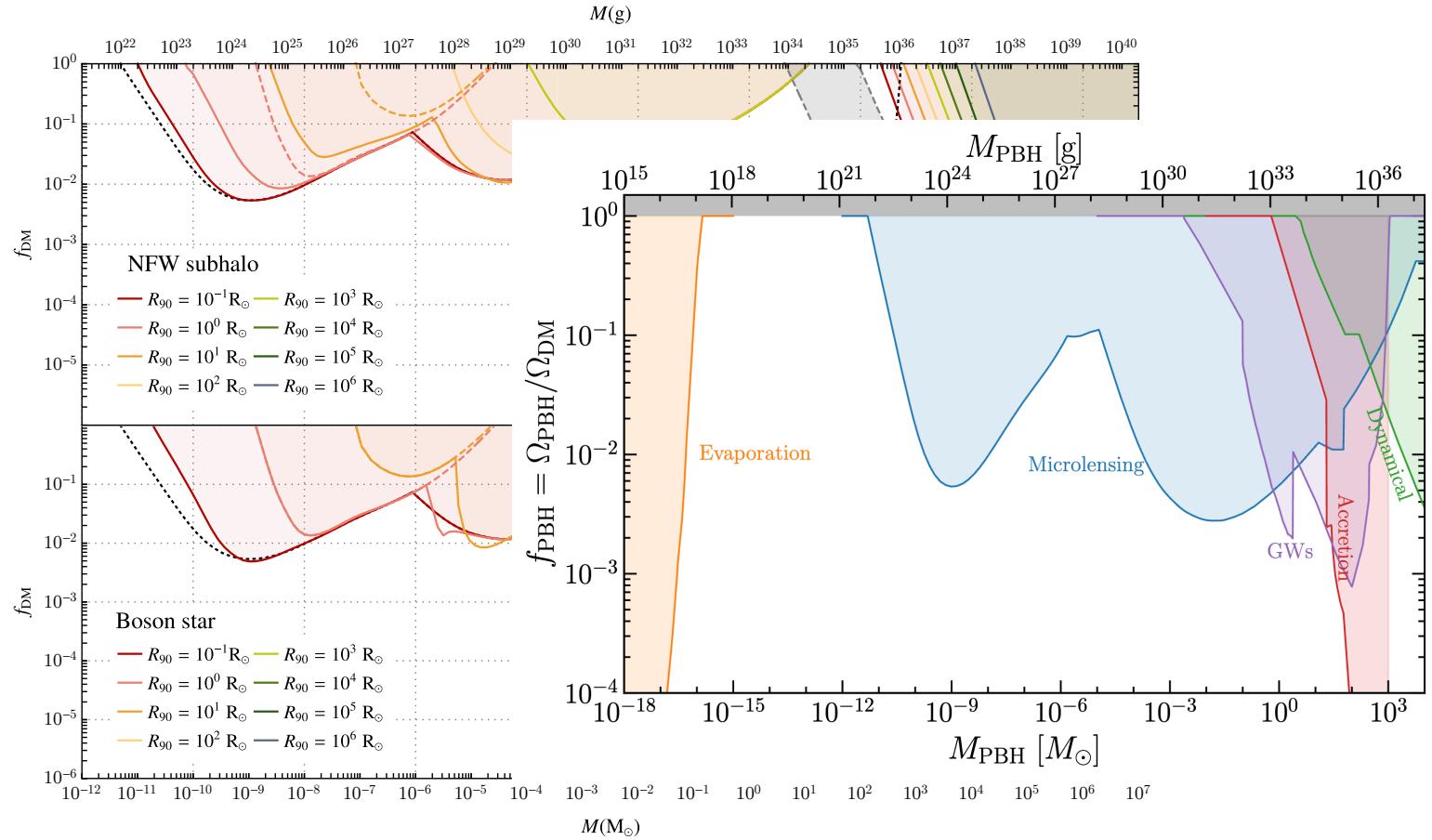


CMB constraints on Extended dark matter objects

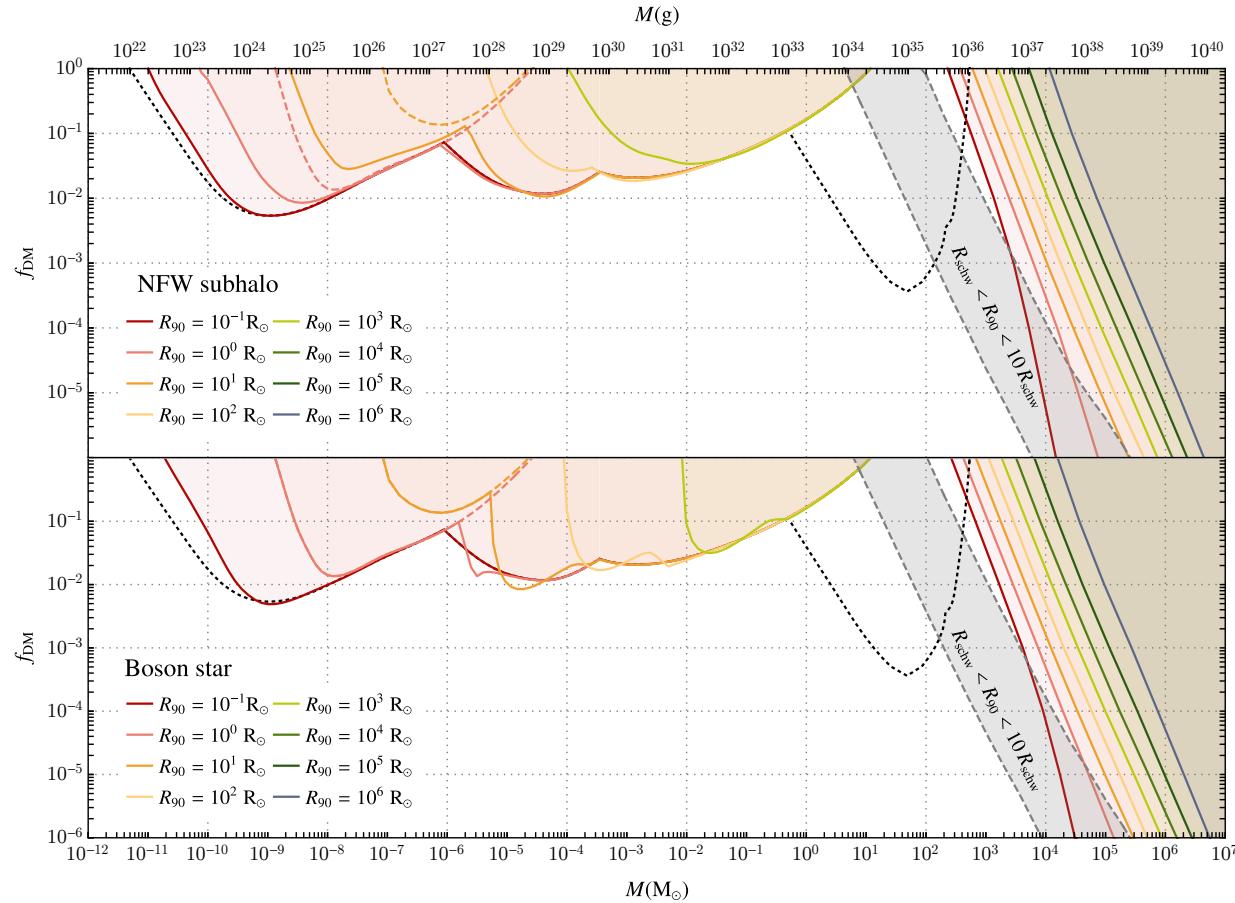


<https://github.com/SergioSevi/EDObounds>

Finally combining with existing constraints, we obtain

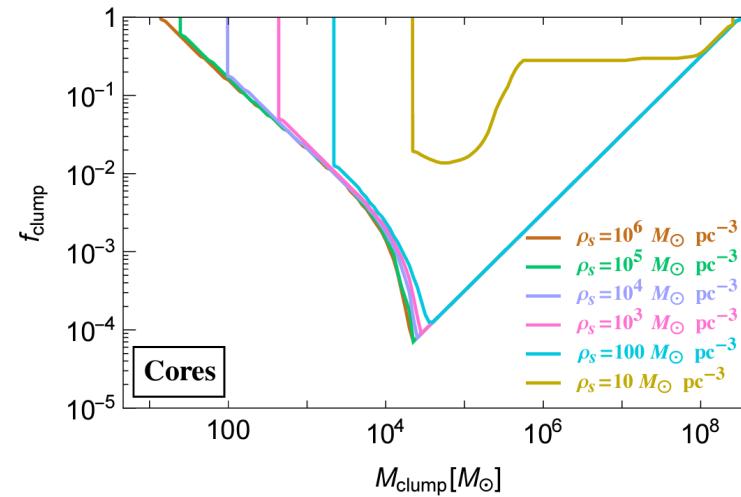
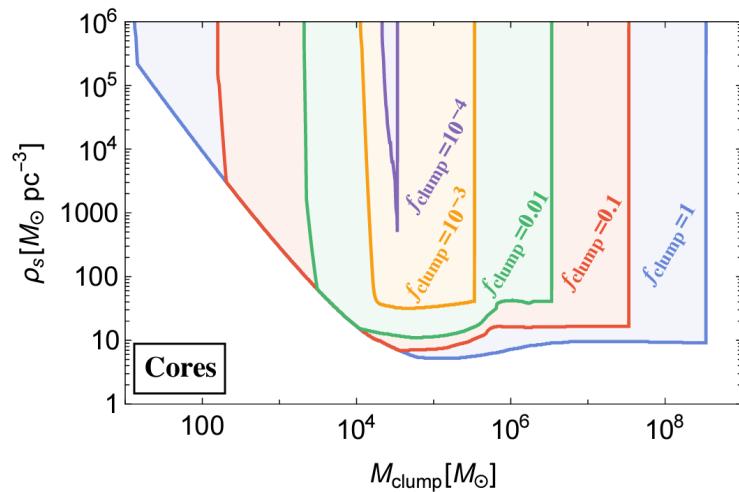


Finally combining with existing constraints, we obtain



Extra!

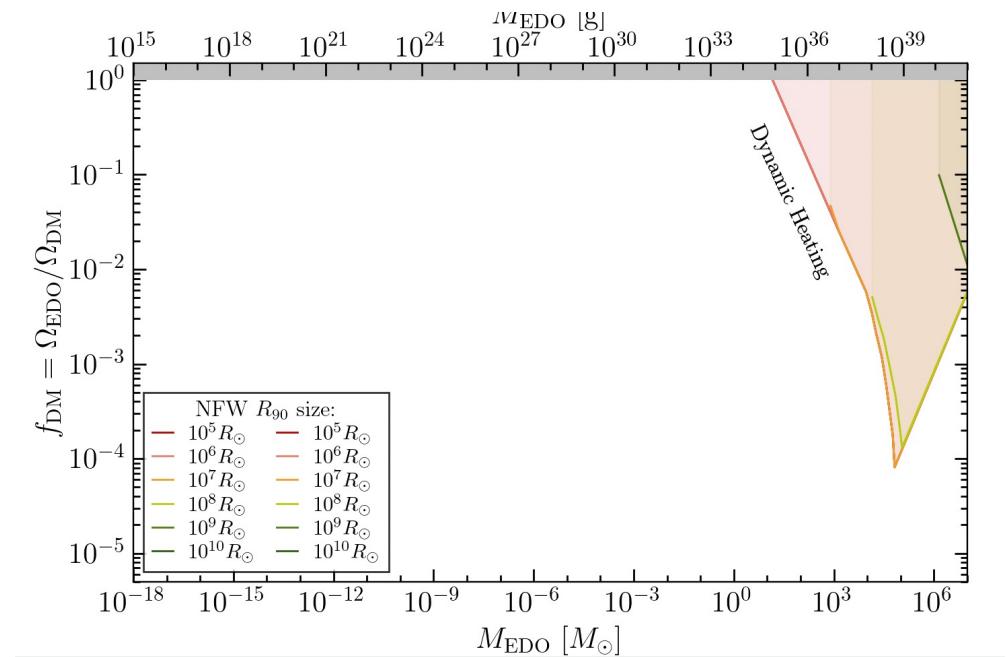
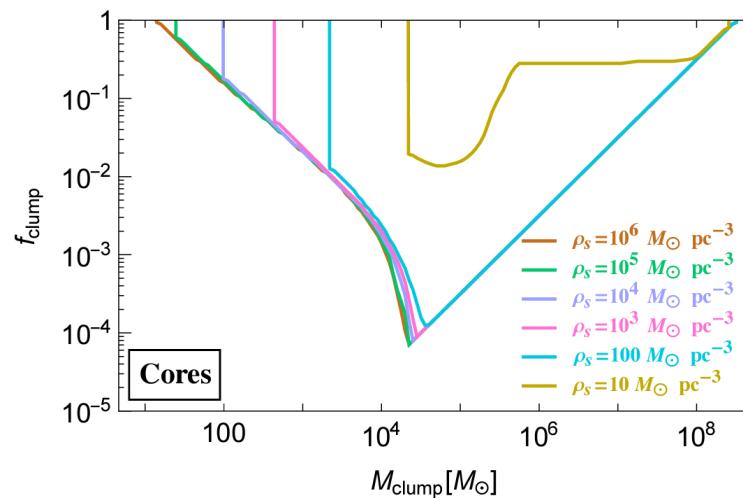
Recently new bounds from dynamical heating of stars due to energetic EDOs
 (Graham and Ramani)



NFW mini-halo

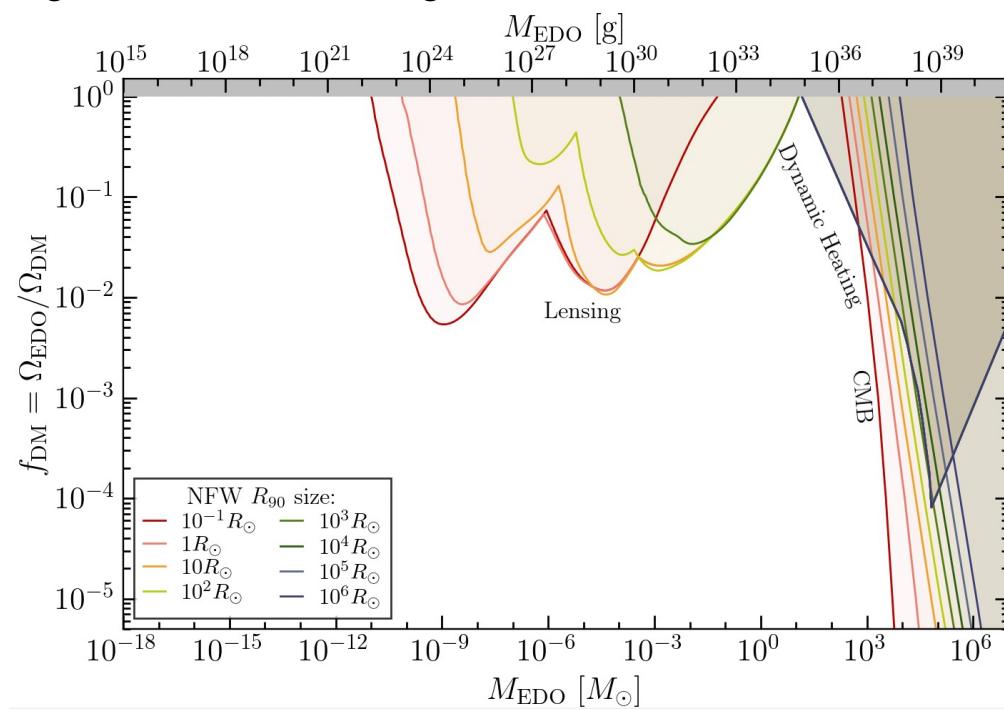
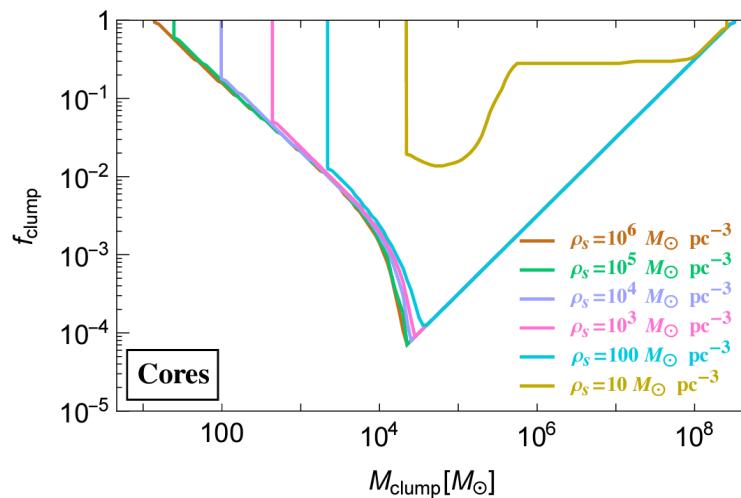
Extra!

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



Extra!

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

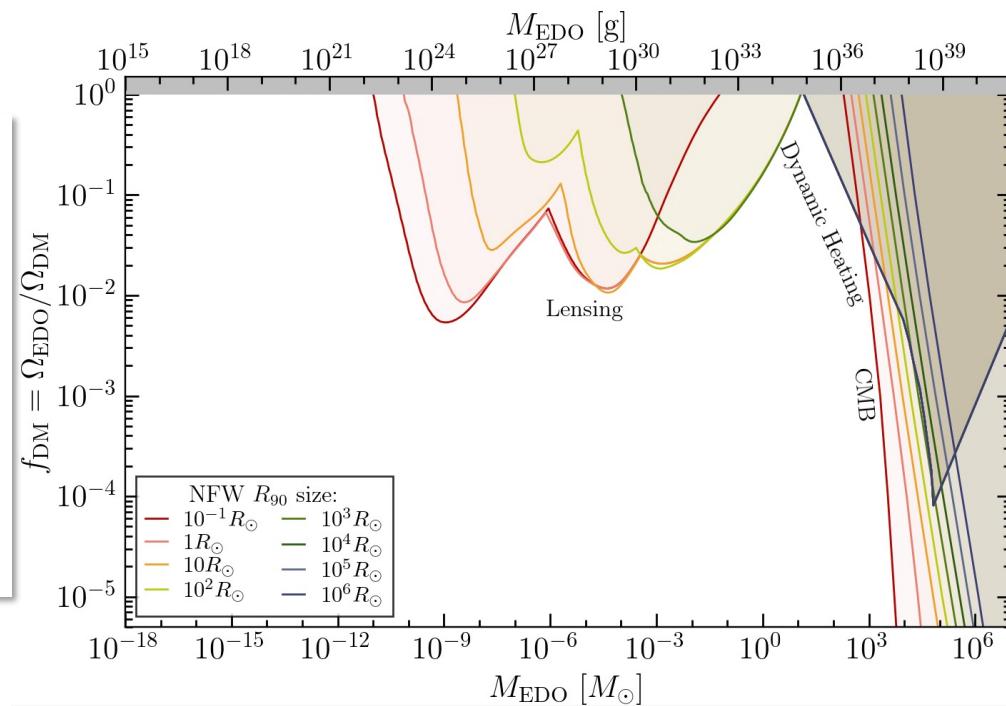


Repository for EDO bounds:

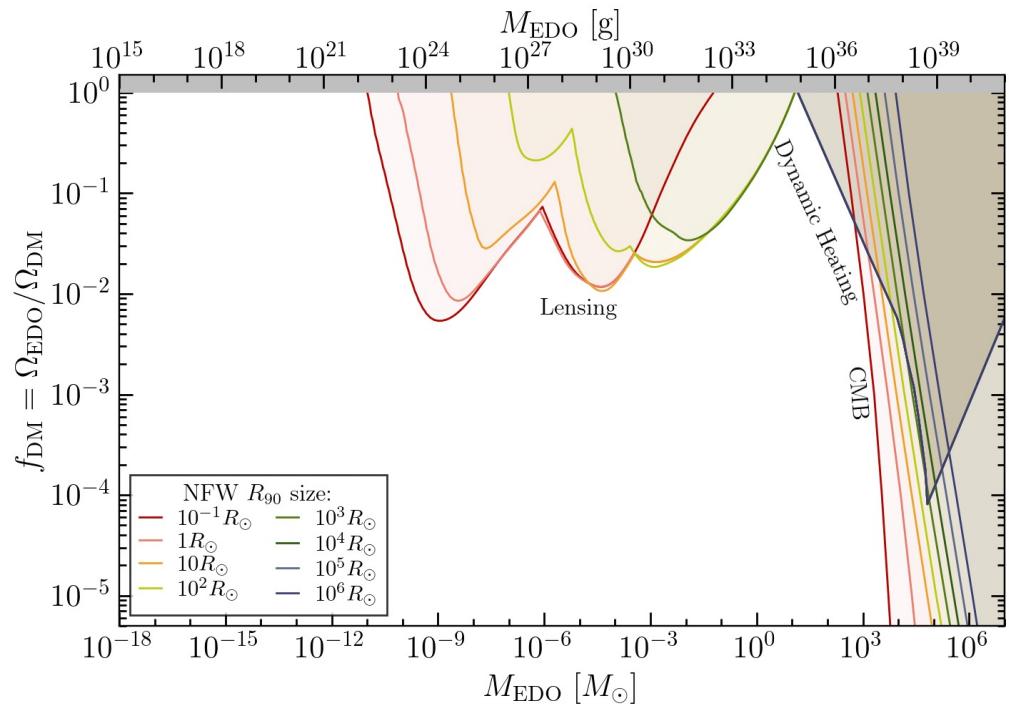
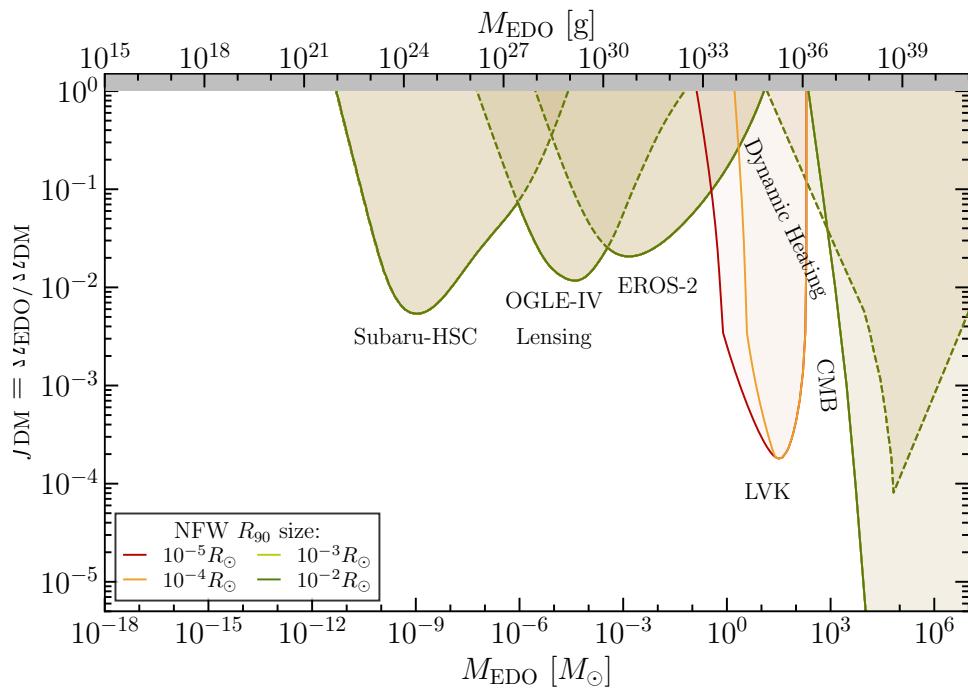
```
#Shape: Choose from NFW, Uniform, Boson or UCMH
NFW

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

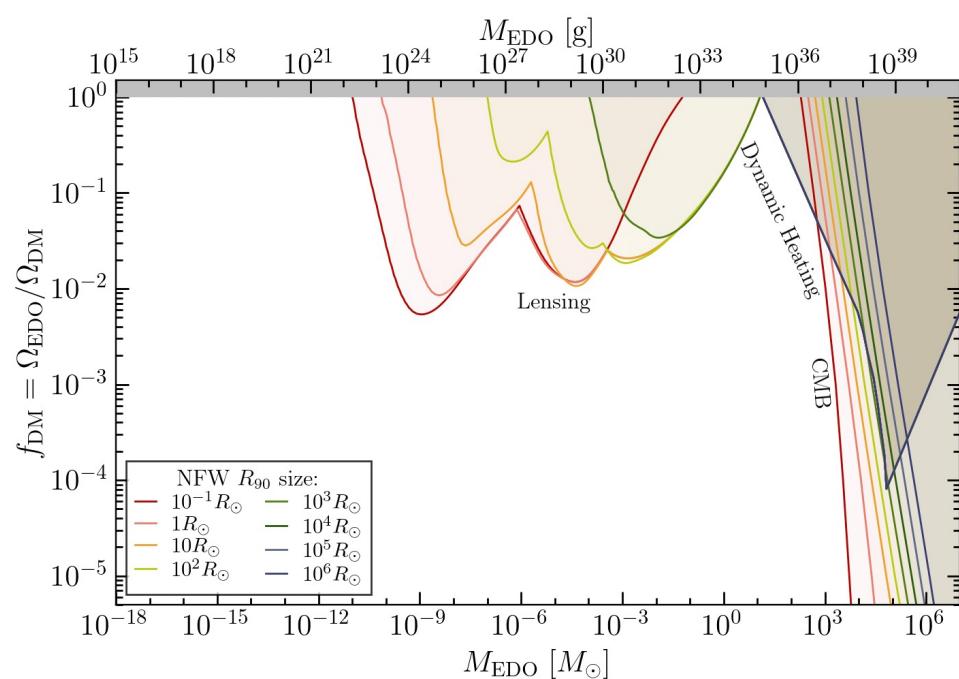
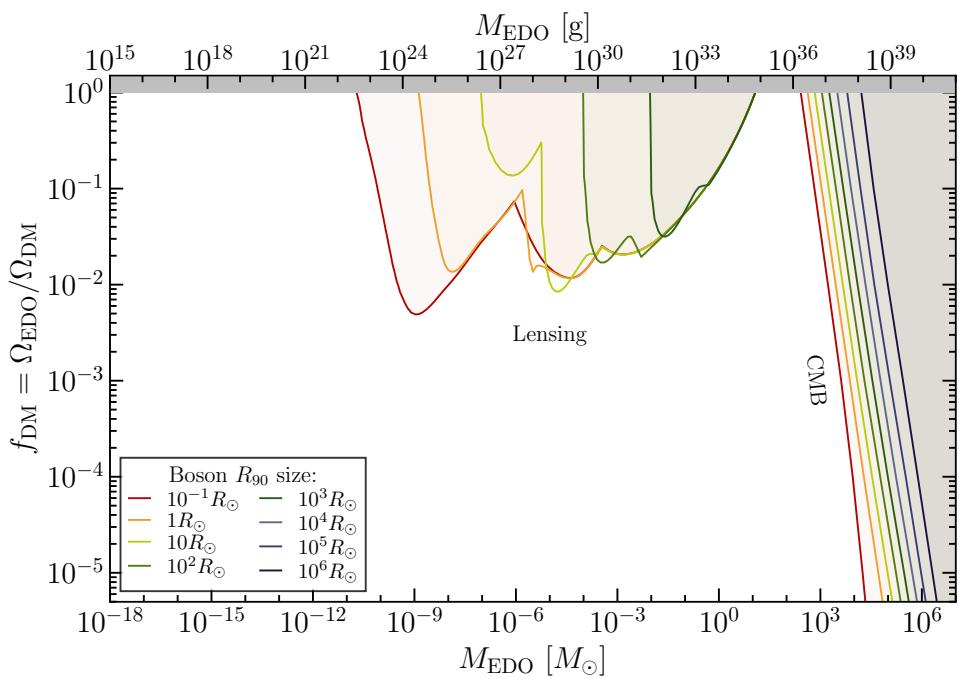
# Bound,   linestyle,   x,           y,           rotation, display name
CMBAccretion. - 700 1e-3 -85 CMB
EROS-2        -- 1e-2 1e-2 0 EROS-2
OGLE-IV       -- 1e-5 7e-3 0 OGLE-IV
Subaru-HSC.   -- 1e-9 3e-3 0 Subaru-HSC
Lensing        - 1e-5 7e-3 0 Lensing
Dynamic-heating -- 50  5e-2 -65 Dynamic_Heating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



Repository for EDO bounds:



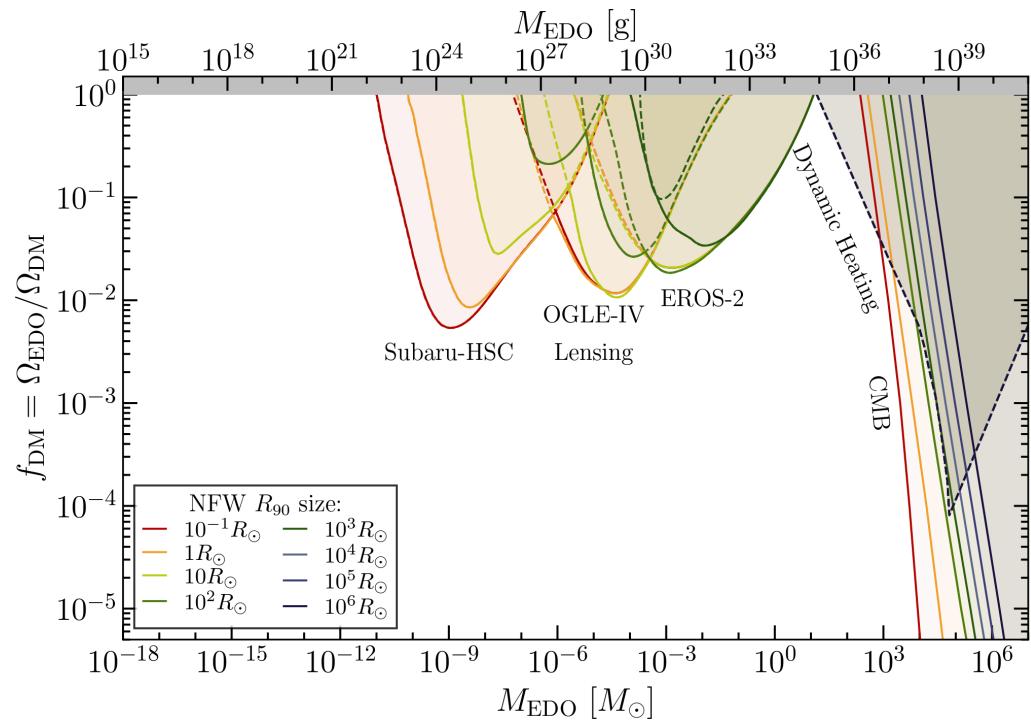
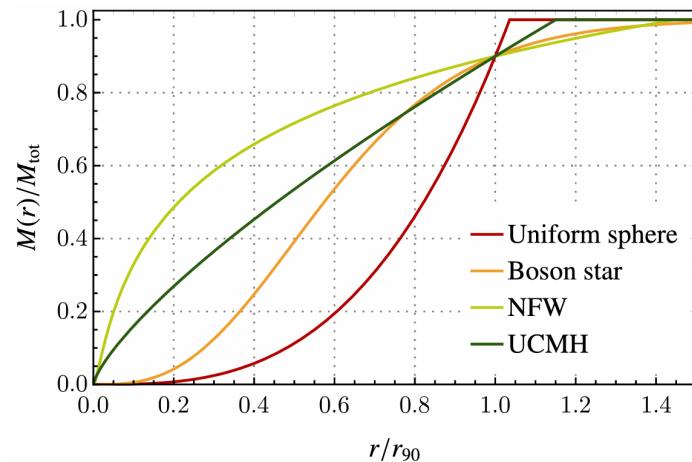
Repository for EDO bounds:



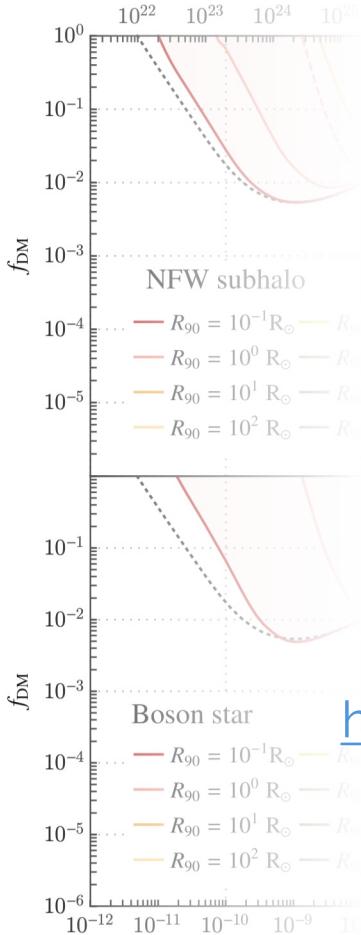
Repository for EDO bounds:



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>

