Title: Supermassive black hole seeds from sub-keV dark matter

Speakers: Aaron Vincent

Collection: Dark Matter, First Light

Date: February 27, 2024 - 9:00 AM

URL: https://pirsa.org/24020074

Abstract: Quasars observed at redshifts z~6-7.5 are powered by supermassive black holes which are too large to have grown from early stellar remnants without efficient super-Eddington accretion. A proposal for alleviating this tension is for dust and metal-free gas clouds to have undergone a process of direct collapse, producing black hole seeds of mass Mseed~105M? around redshift z~17. For direct collapse to occur, a large flux of UV photons must exist to photodissociate molecular hydrogen, allowing the gas to cool slowly and avoid fragmentation. We investigate the possibility of sub-keV mass dark matter decaying or annihilating to produce the UV flux needed to cause direct collapse. We find that annihilating dark matter with a mass in the range of 13.6 eV<=mdm<=20 eV can produce the required flux while avoiding existing constraints. A non-thermally produced dark matter particle which comprises the entire dark matter abundance requires a thermally averaged cross section of ??v?~10-35 cm3/s. Alternatively, the flux could originate from a thermal relic which comprises only a fraction ~10-9 of the total dark matter density. Decaying dark matter models which are unconstrained by independent astrophysical observations are unable to sufficiently suppress molecular hydrogen, except in gas clouds embedded in dark matter halos which are larger, cuspier, or more concentrated than current simulations predict. Lastly, we explore how our results could change with the inclusion of full three-dimensional effects. Notably, we demonstrate that if the H2 self-shielding is less than the conservative estimate used in this work, the range of both annihilating and decaying dark matter models which can cause direct collapse is significantly increased.

Dark matter-catalyzed supermassive black holes

Aaron Vincent

Perimeter Institute | Dark matter, first light | 27 Feb 2024

Queen's University

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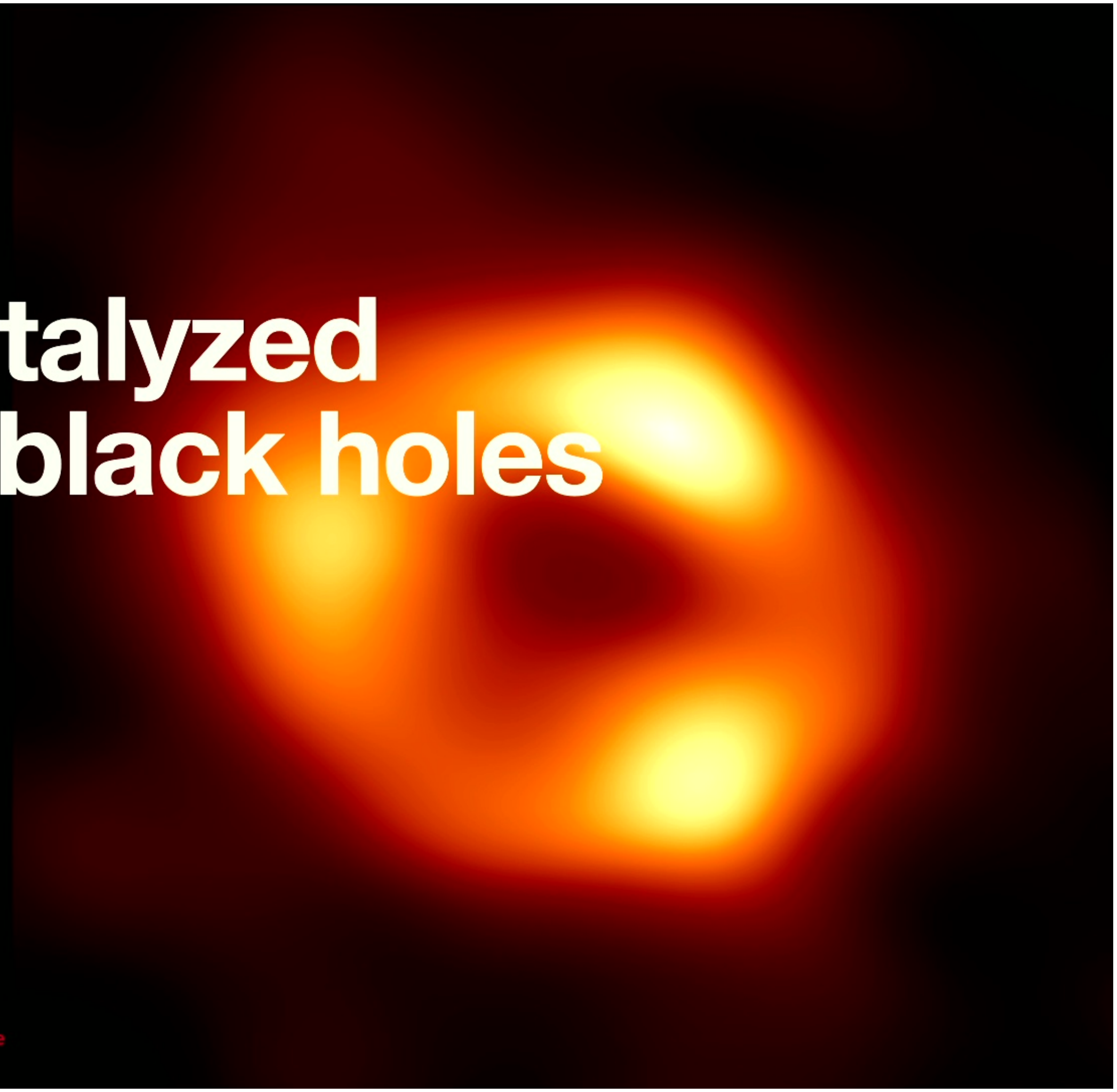


Supermassive black hole seeds from sub-keV dark matter

hep-ph>arXiv:2212.11100

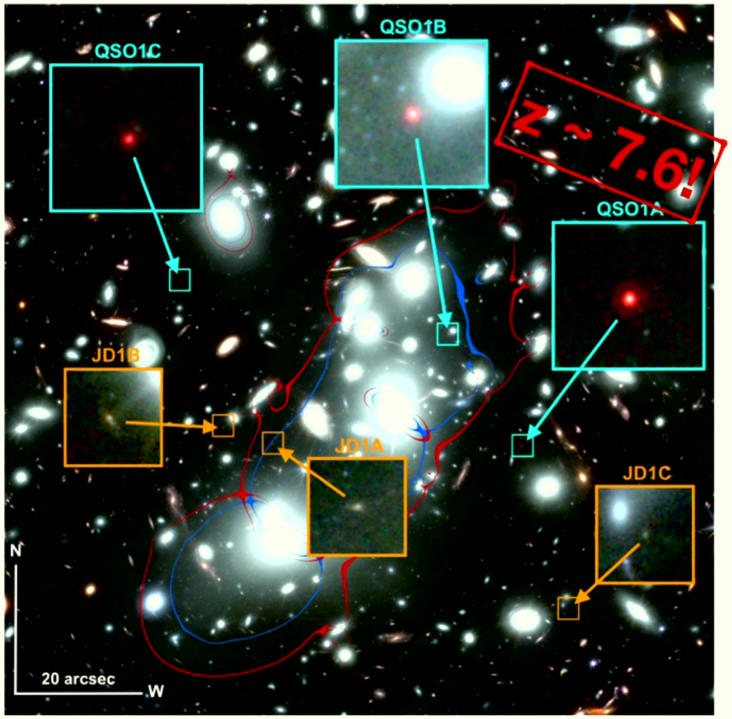
Work by…

Avi Friedlander

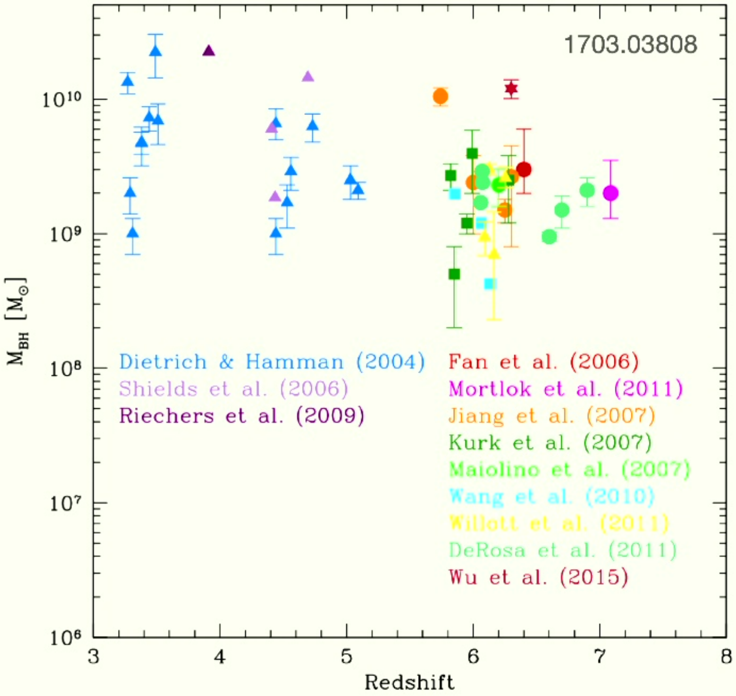
Sarah Schon

…and work in progress with Han Wu

High z quasars

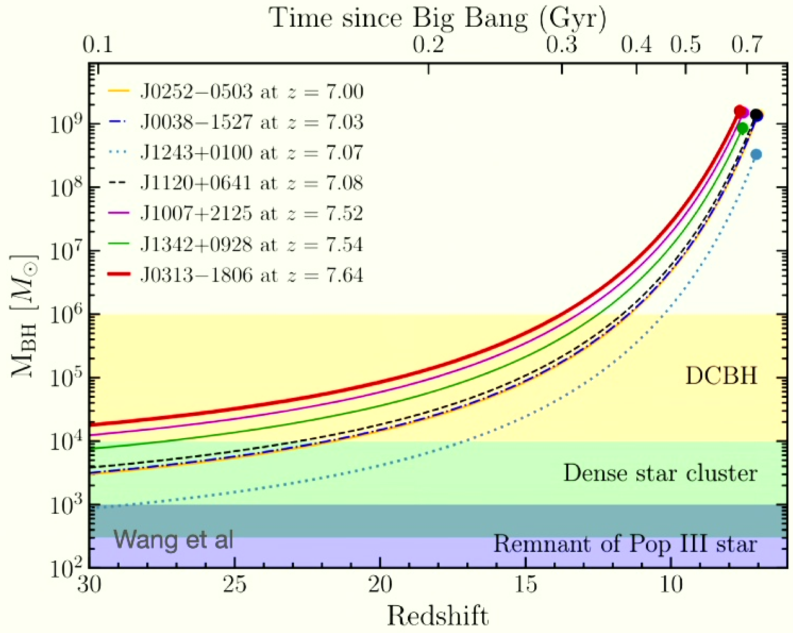


Furtak et al. 2023/JWST



Three “traditional” solutions

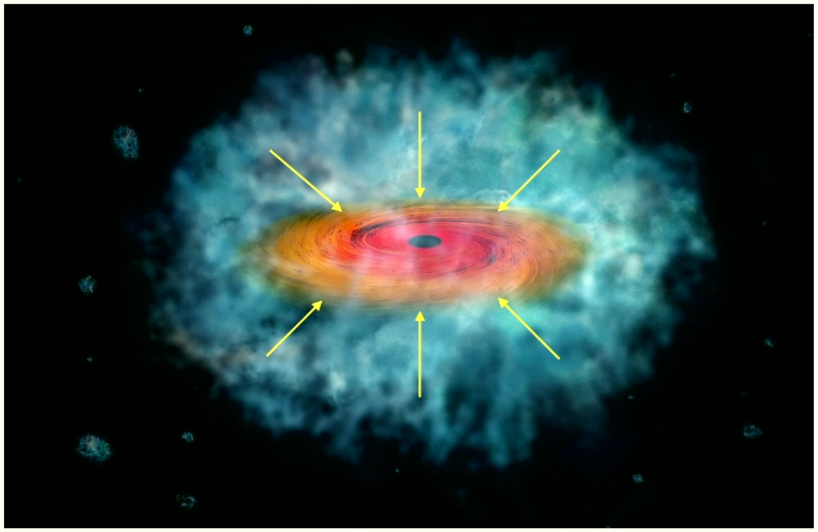
- *Very early* **Pop III** stellar mass black holes (~ 100 $M_\odot$)
- Intermediate mass black holes arising from collisions in **dense clusters**
- Direct Collapse Black Holes (**DCBH**): Heavy seeds forming in large halos, exposed to intense UV radiation



Other new physics ideas

- Self-interacting/dissipative dark matter (1501.00017,2010.15132,2103.13407)
- Inflation did it (astro-ph/0401532, many more)
- Cosmic strings 2202.01799
- Primordial supersonic gas streams (1709.09863)

Direct Collapse Black Holes



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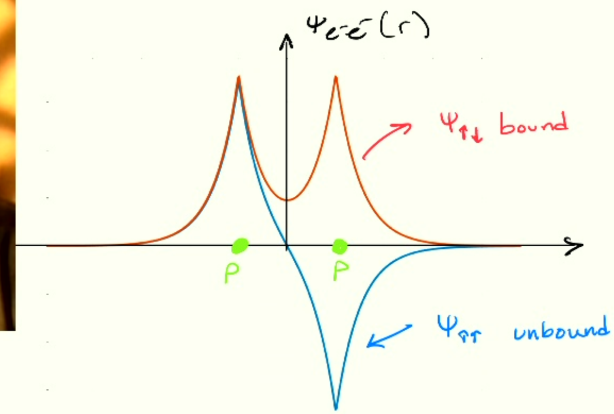
- No metals: cooling is inefficient. Great.
- Most efficient channel is H_2. Rotational & vibrational modes mean many cooling channels.
- These are enough to cause rapid cooling and **fragmentation.** Need to **dissociate** the H_2 that does form.

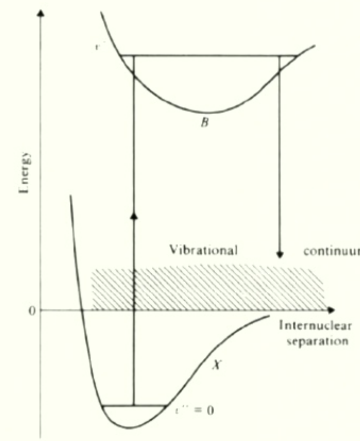
•Bound state is parity-even



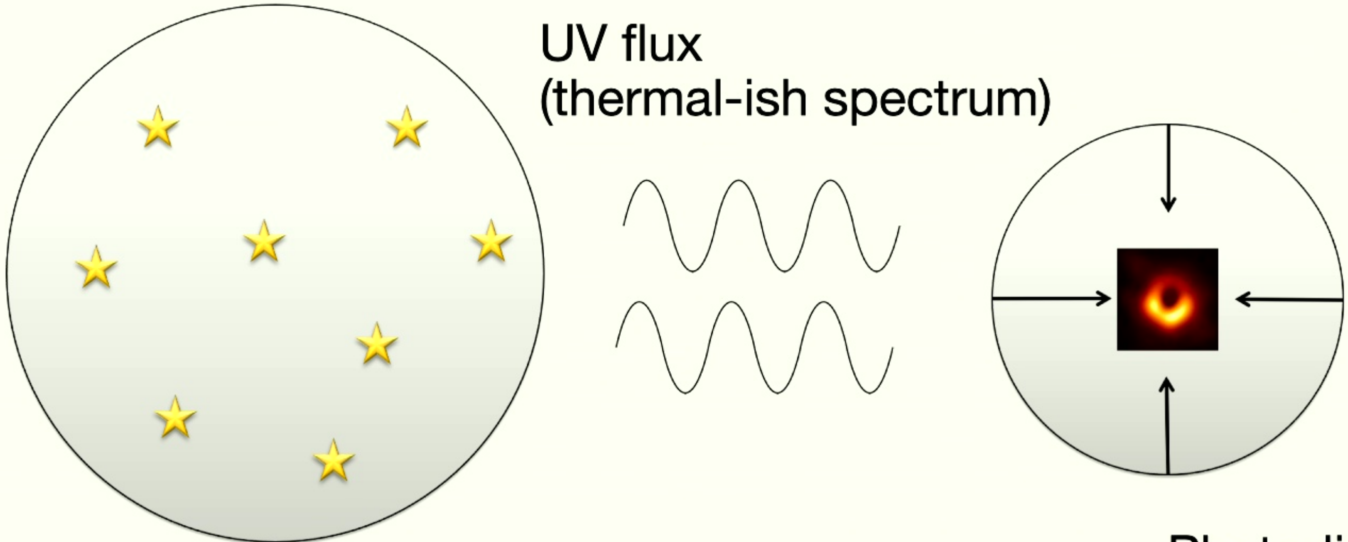
•transition to unbound state requires a spin-flip, but the dipole operator does not couple $|\psi_{\uparrow\uparrow}\rangle$ to $|\psi_{\uparrow\downarrow}\rangle$

•Two-step process: first excite to a higher electronic level, then deexcite to the unbound state.

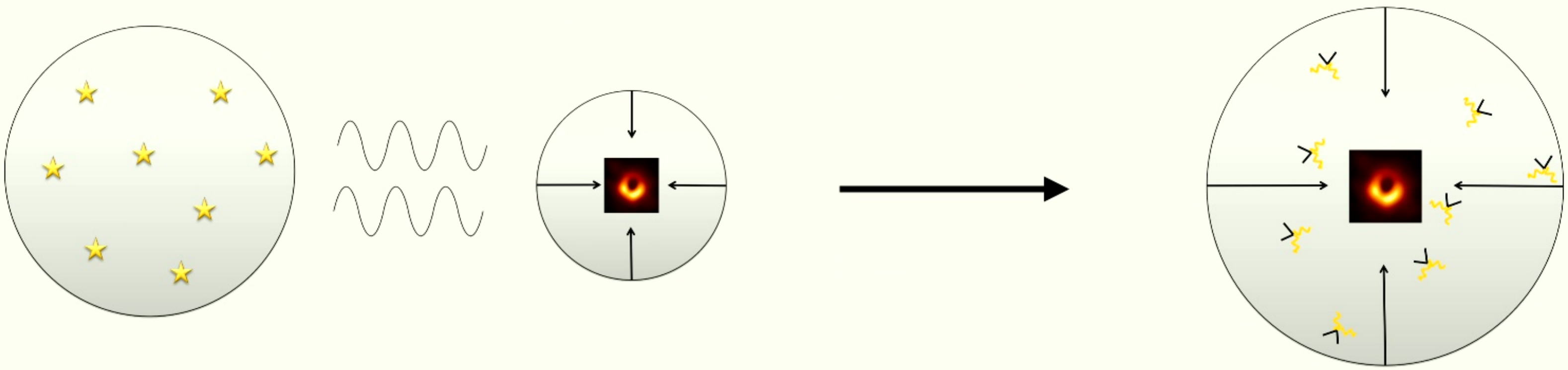
•This requires a **UV photon flux** in the Lyman-Werner band 11.2 eV $\leq E_\gamma \leq 13.6$ eV



The standard astrophysical scenario



Dark matter catalysis



Instead of a nearby galaxy forming the UV background

Annihilating or decaying dark matter provides the required Lyman-Werner flux

Critical curves

- For the same reason dissociation is difficult, H2 formation is a two-step process:

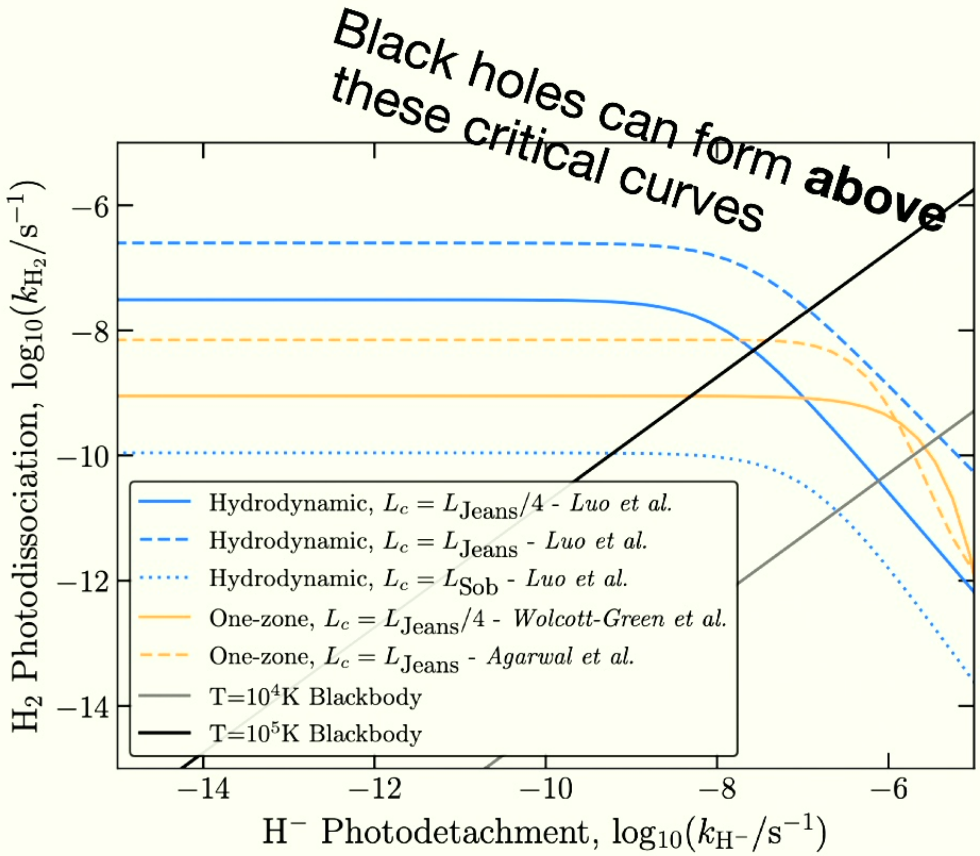
$$\mathrm{H} + e^- \rightarrow \mathrm{H}^- + \gamma,$$
$$\mathrm{H} + \mathrm{H}^- \rightarrow \mathrm{H}_2 + e^-$$

- So we can suppress H2 formation through **photodissociation:**

$$\mathrm{H}_2 + \gamma \rightarrow \mathrm{H} + \mathrm{H},$$
$$11.2 \text{ eV} \leq E_\gamma \leq 13.6 \text{ eV}$$

- or **photodetachment**

$$\mathrm{H}^- + \gamma \rightarrow \mathrm{H} + e^- \qquad E_\gamma \geq 0.76 \text{ eV}$$



Self-shielding & using previous results

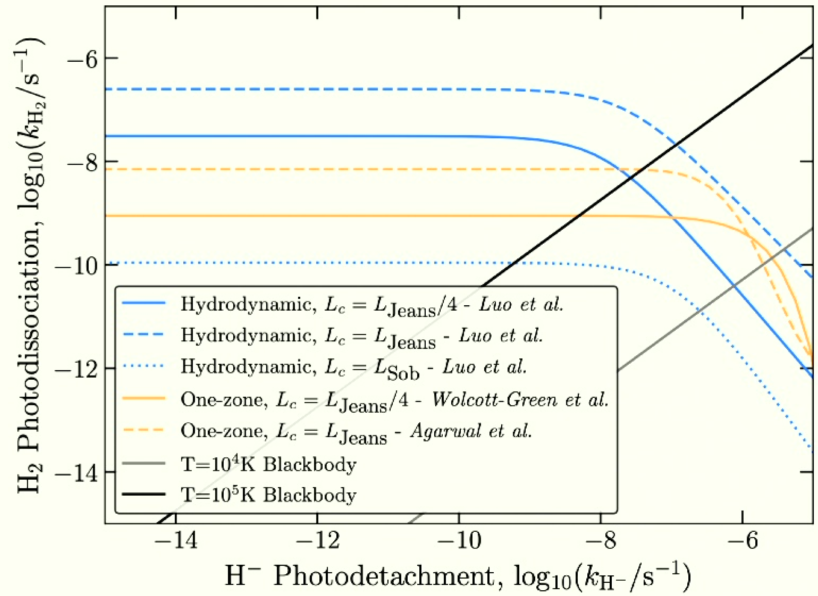
- Previous studies using a uniform UV flux have produced these effective critical curves (see blackbody lines).

- Important aspect: self-shielding. At finite optical depth, the Ly-Werner flux only goes so far.

- Previous work (one zone, and 3d hydro) have used shielding length $L_c \propto L_{Jeans}$ and also

$$L_c = L_{\text{Sobolev}} = \frac{\rho}{|\nabla \rho|}$$

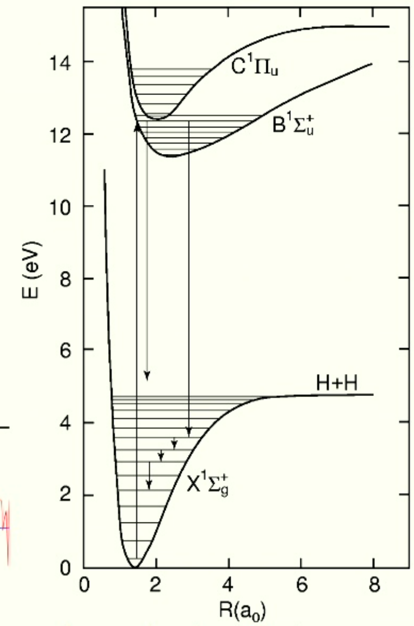
- We'll explore how these affect our results.

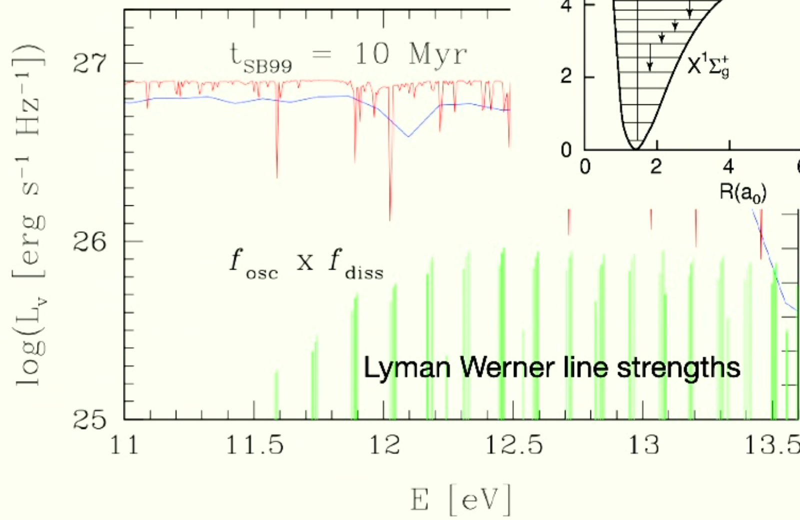


Dark matter models

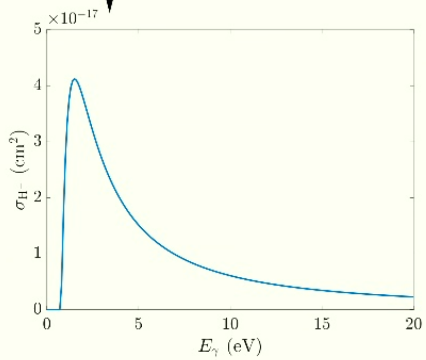
- The photodissociation cross section consists of many very sharp lines: need a **broadband flux** across the ~10-14 eV range.

Dissociation →



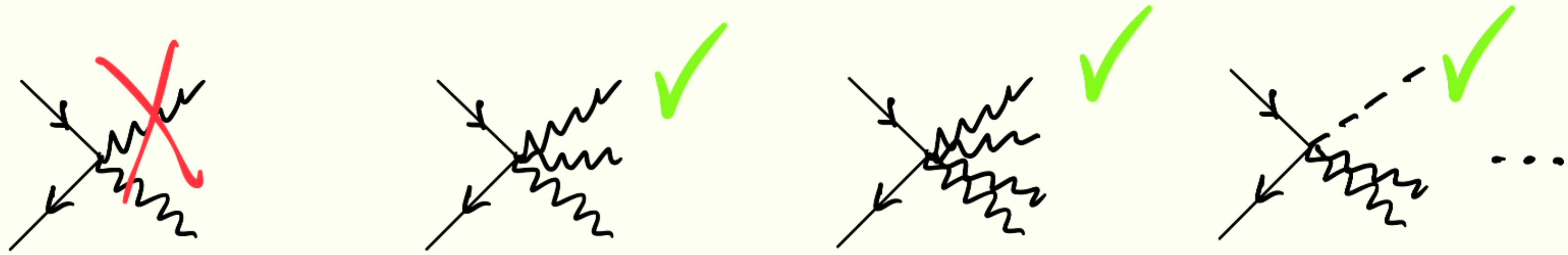


Detachment ↓



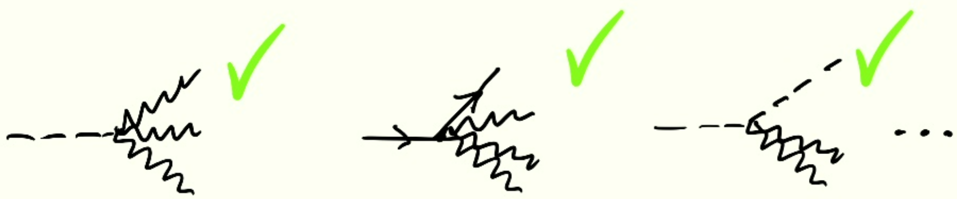
Dark matter models

Need a **broadband flux** across the ~10-14 eV range



Annihilation

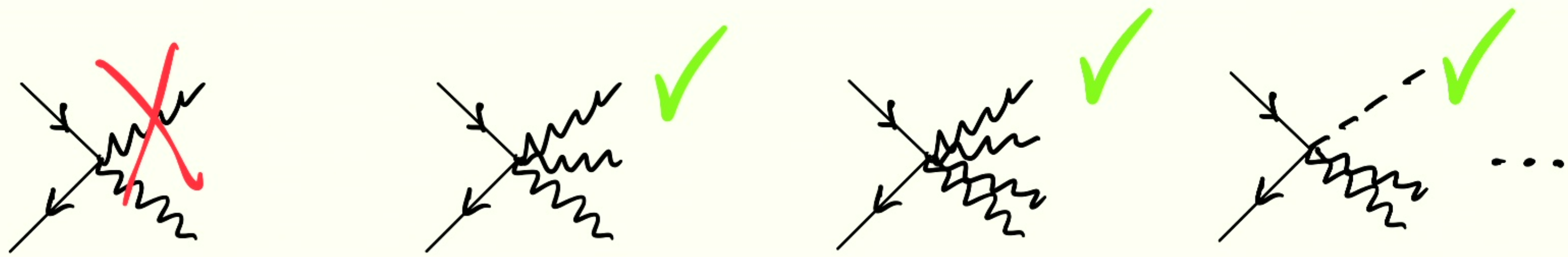
or decay



$m_{dm} \sim$ tens of eV

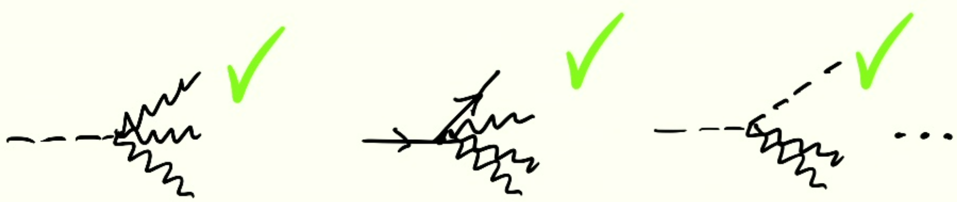
Dark matter models

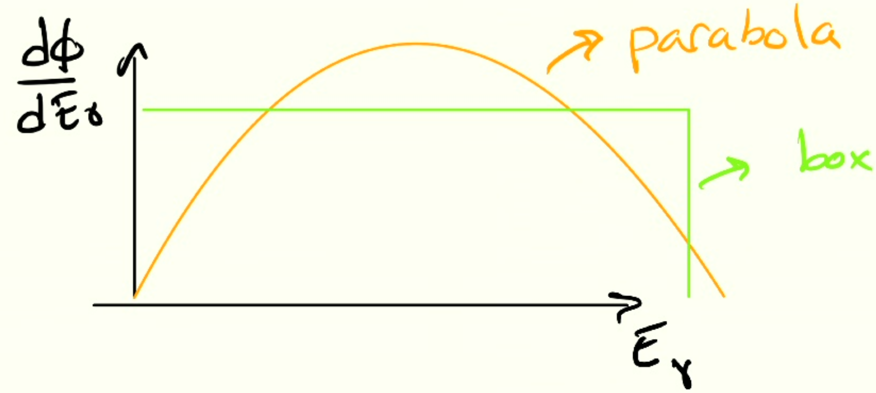
Need a **broadband flux** across the ~10-14 eV range



Annihilation

or decay

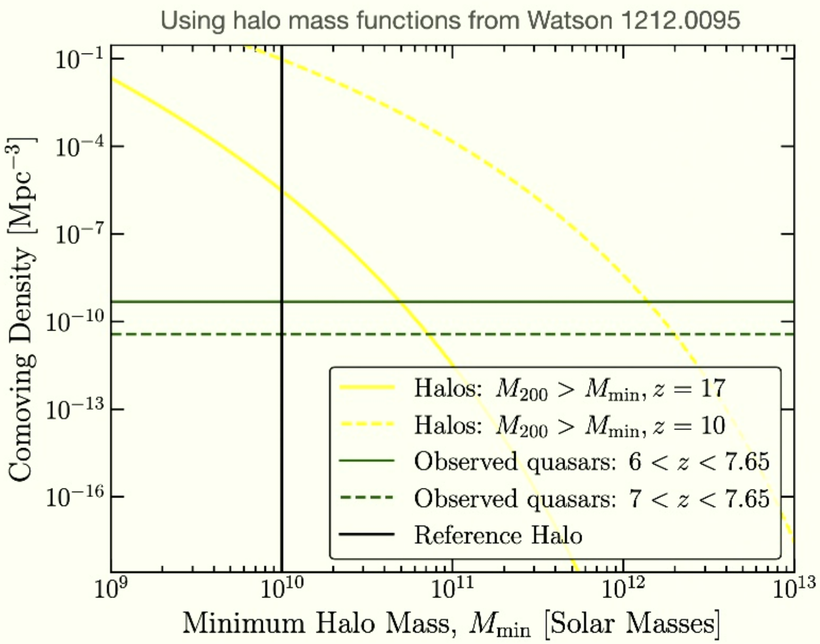




$m_{dm} \sim$ tens of eV

Halo parametrization

- We need enough large halos to produce enough black hole seeds early enough.



Halo mass-concentration relation

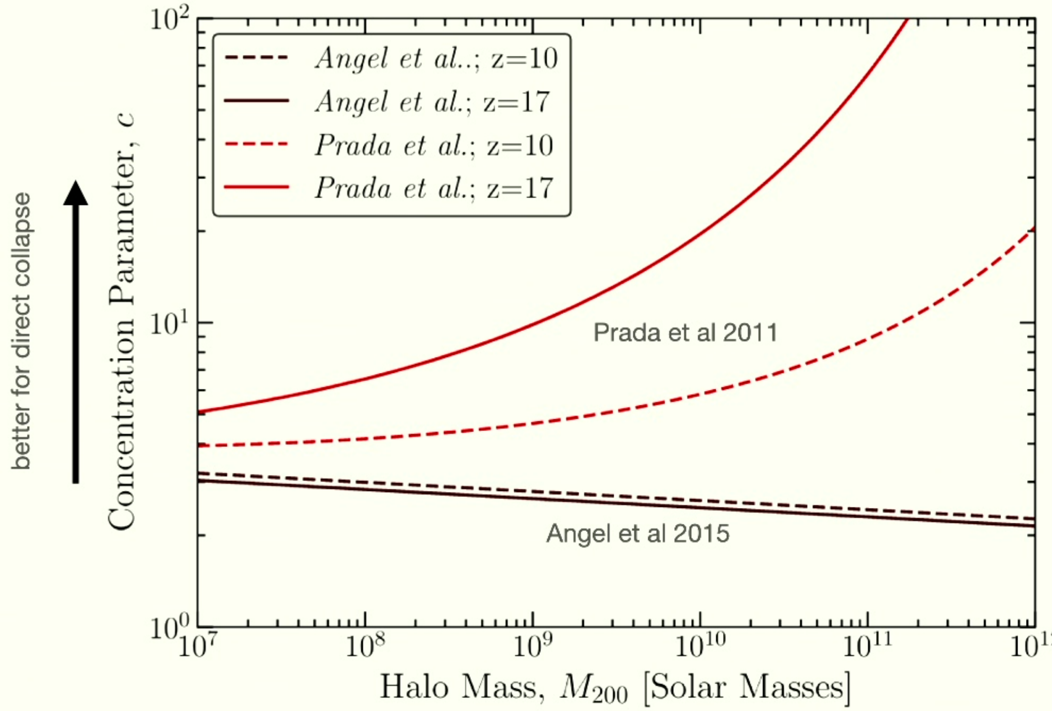
- Varies as a function of redshift and author
- Concentration parameter

$$r_s = r_{200}/c$$

$$\rho_{NFW} = \frac{4\rho_s}{\frac{r}{r_s}\left(1+\frac{r}{r_s}\right)^2}$$

$$\rho_s = \frac{c^3(1+c)M_{200}}{16\pi r_{200}^3[-c+(1+c)\ln(1+c)]}.$$

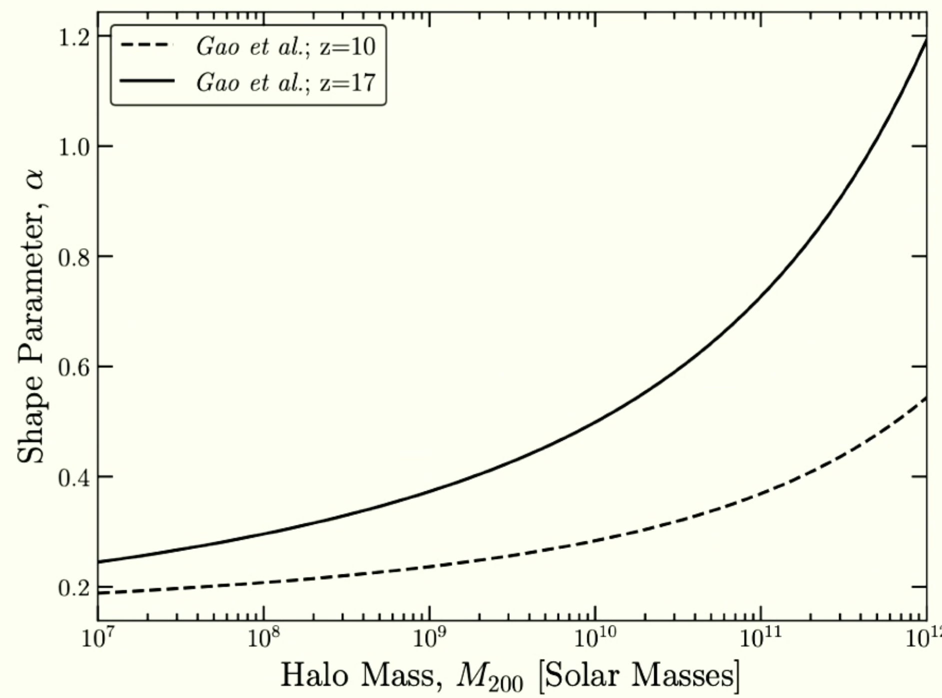
(actually use an Einasto profile to make integrals easier, don't worry about it)



(actually using an Einasto profile)

Don't worry

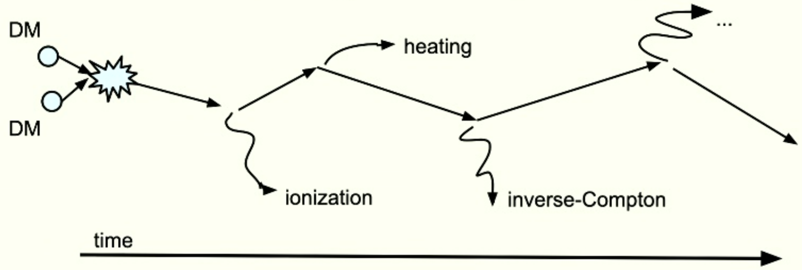
$$\rho_{dm}(r) = \rho_0 \exp\left(\frac{-2}{\alpha}\left[\left(\frac{r}{r_0}\right)^{\alpha} - 1\right]\right).$$

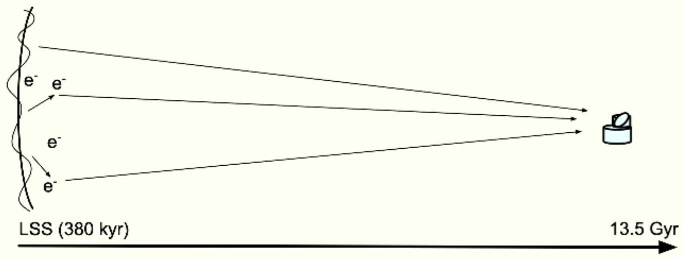


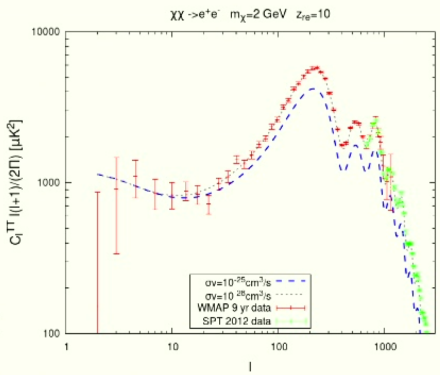
Constraints on decaying eV dark matter

Cosmic microwave background (CMB)

Above 13.6 eV:







Nakayama & yin 2205.01079

Constraints on decaying eV dark matter

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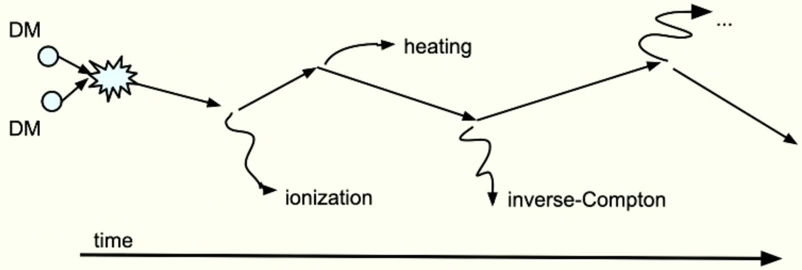
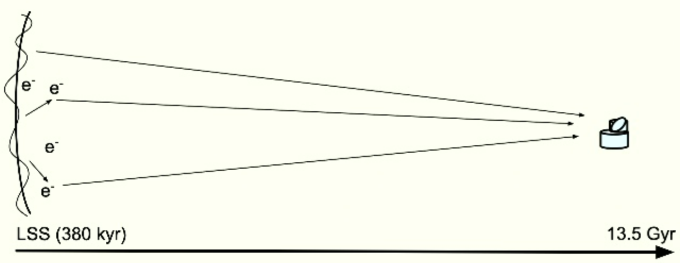
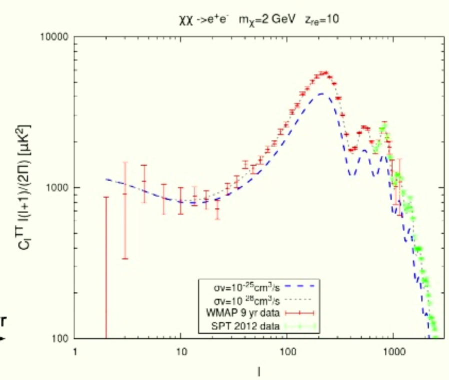
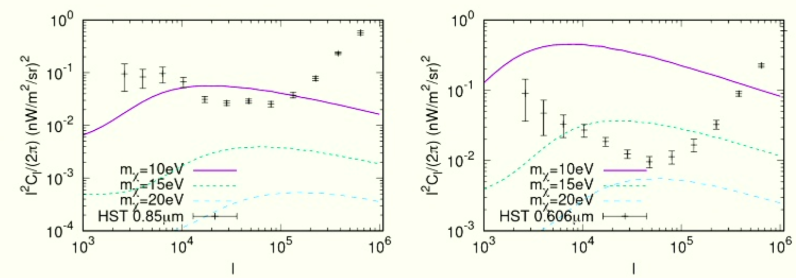
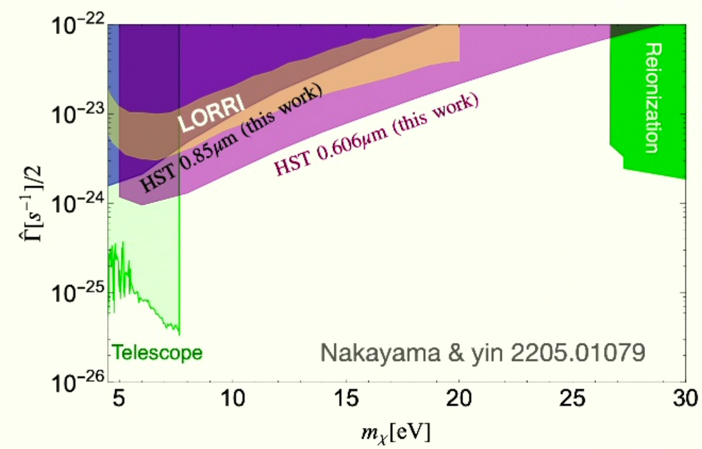






Cosmic Optical Background (COB)





All together

$$J(\vec{r}, E) = \frac{E}{4\pi} \int dV' \frac{dn_\gamma}{dEdt}(\vec{r'}, E) \frac{1}{(\vec{r'} - \vec{r})^2}.$$

the factors you get from doing the integral

- Decay:

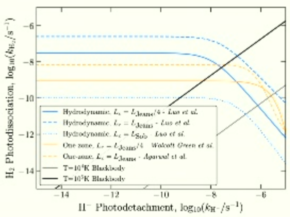
$$J(E) = \frac{f_\gamma f_{dm}}{\tau m_{dm}} E \frac{dN}{dE} \rho_0 r_0 g_{dec}(\alpha)$$

- Annihilation

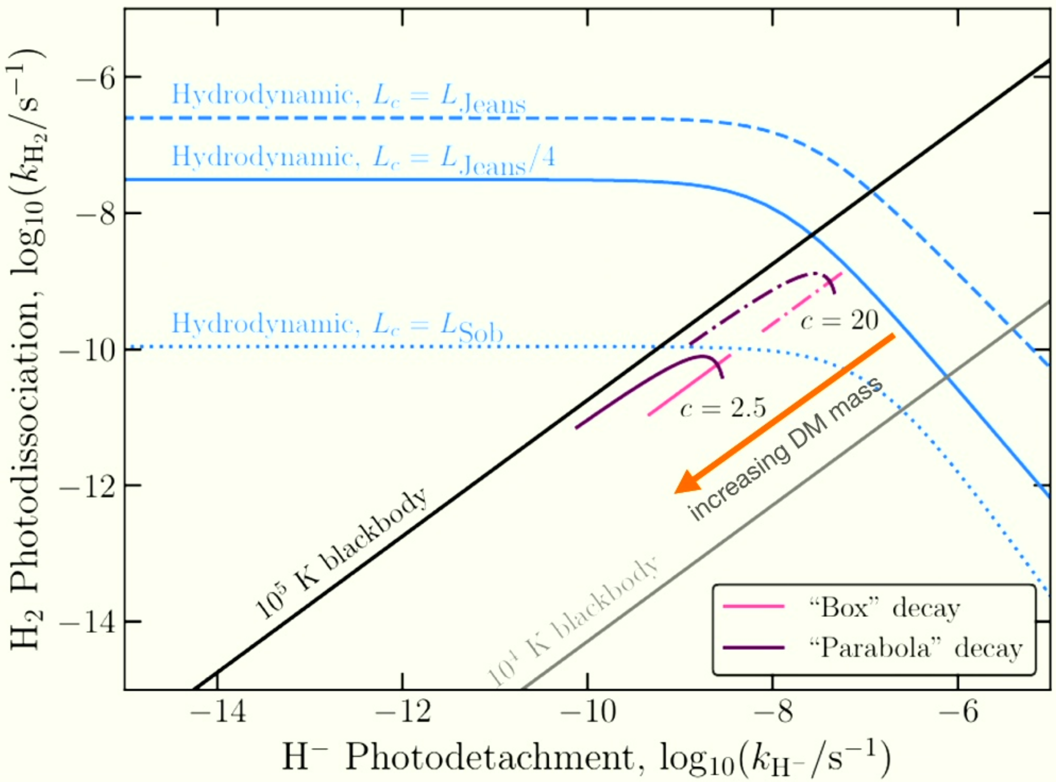
$$J(E) = \frac{f_\gamma f_{dm}^2 \langle \sigma v \rangle}{m_{dm}^2 2^p} E \frac{dN}{dE}(E) \rho_0^2 r_0 g_{ann}(\alpha),$$

Photodetachment and photodissociation rates

Are we above or below the critical curve(s)?
Are we compatible with previous constraints?



Dark matter decay & the critical curves

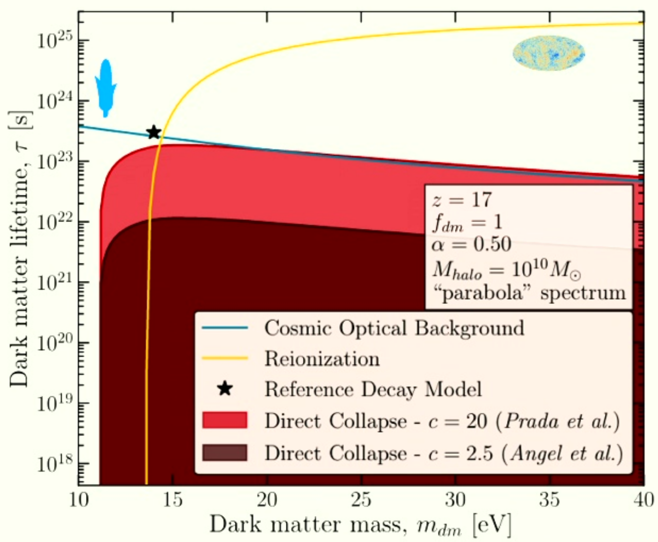


Rates for dark matter masses from 13.6 eV (most efficient, because there's more energy dumped into Ly-Werner) to 100 eV (least efficient)

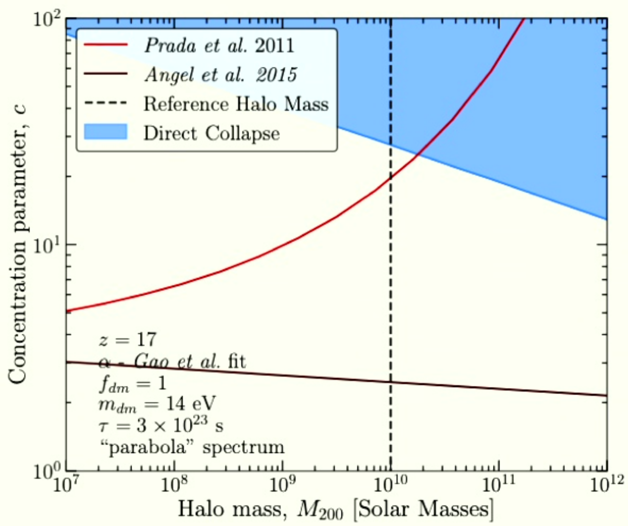
$10^{10} M_\odot$ halo, $\alpha = 0.5$ Enasto profile

Dark matter decay

- Self-shielding $L_c = L_{Jeans}/4$



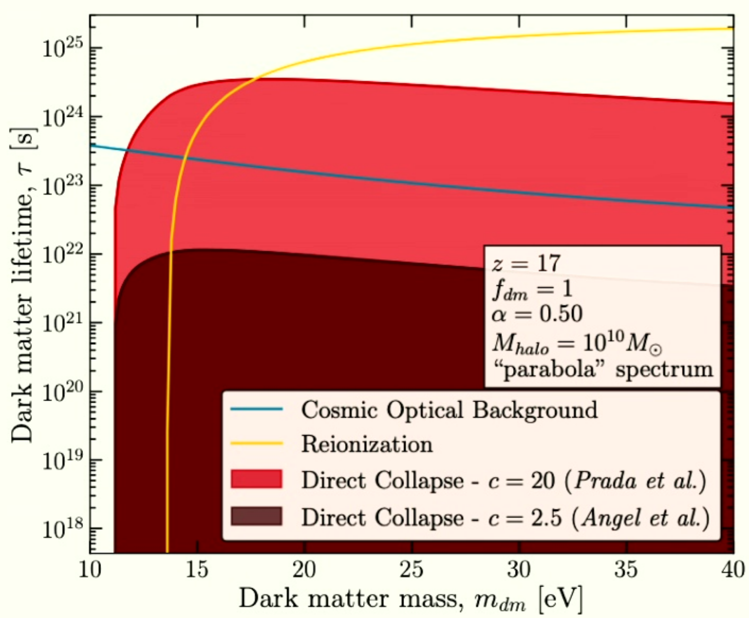
Fixed halo mass

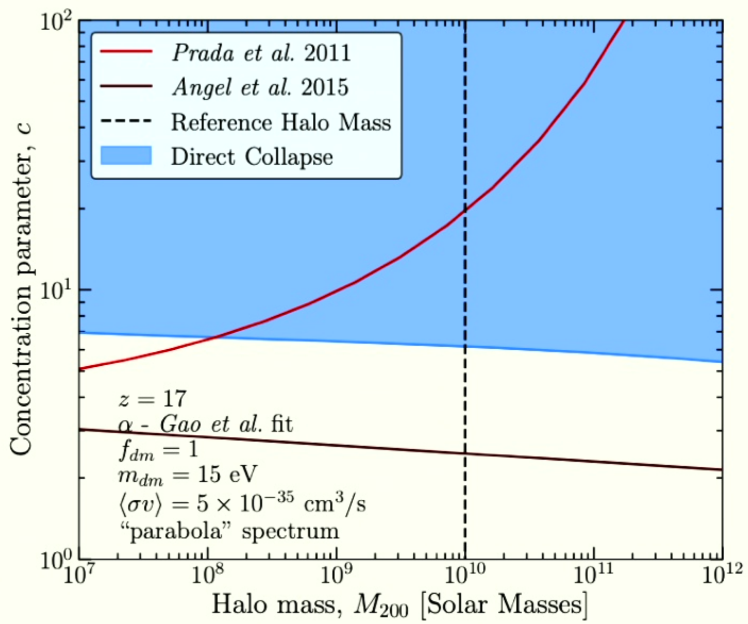


Fixed dark matter mass

Dark matter decay
Sobolev-like self-shielding

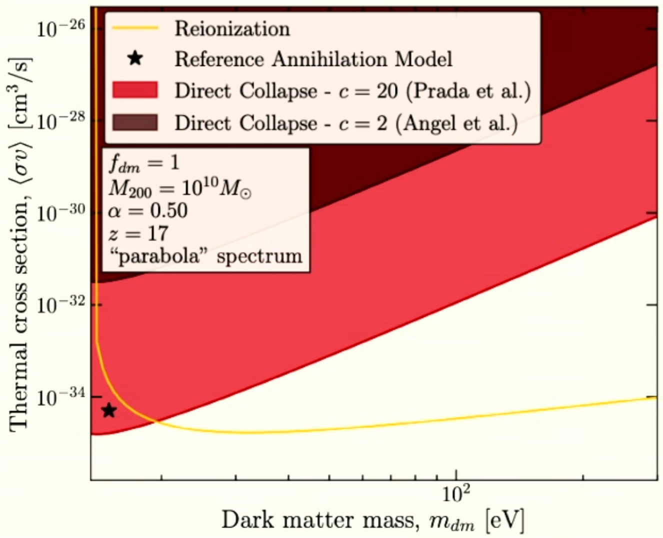
- Smaller column density in the halo centre



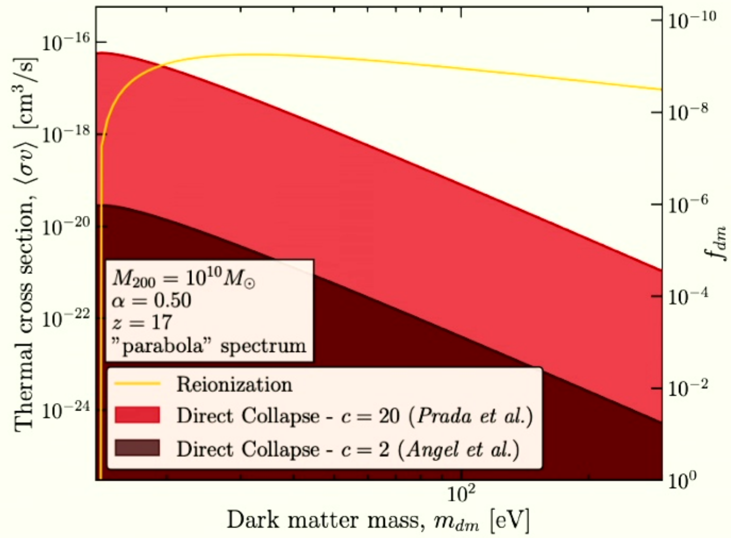


Annihilating dark matter

Very weak interactions



Thermal subcomponent



Summary, future steps

- There are very high redshift quasars. We don't know why.
- Dissociating H2 with some UV radiation helps: new physics to the rescue?
- We have a proof of concept, but the minimal model is on the edge of believable. We still need to work out what a realistic dark matter model would do.
- XDM?
- Higher mass of dark matter -> higher energies injected. What happens?
- Looking at a one-zone model: consistently modelling collapse + chemistry.
- 3D models?

Bye