Title: Direct Collapse Black Holes from Dark Matter Annihilation

Speakers:

Collection: Dark Matter, First Light

Date: February 27, 2024 - 9:45 AM

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Abstract: We present a simple dark matter model where resonant annihilation can dissociate molecular hydrogen and induce direct collapse black holes in proto-galaxies. In these models, O(10 MeV) dark matter annihilates into electron-positron pairs which, in turn, inverse Compton scatter CMB light to produce a flux of Lyman-Werner radiation. This mechanism could help explain observed supermassive black holes at high redshift.

Direct Collapse Black Holes from Dark Matter Annihilation

A challenge and an attempt...

Flip Tanedo

Work with Anson D'Aloisio & **Yash Aggarwal**
& thanks to Katie Mack, Sarah Schon, Lexi Costantino

UC RIVERSIDE PHYSICS & ASTRONOMY

See also talks today by
Aaron (2212.11100)
& Wenzer (2308.12992)

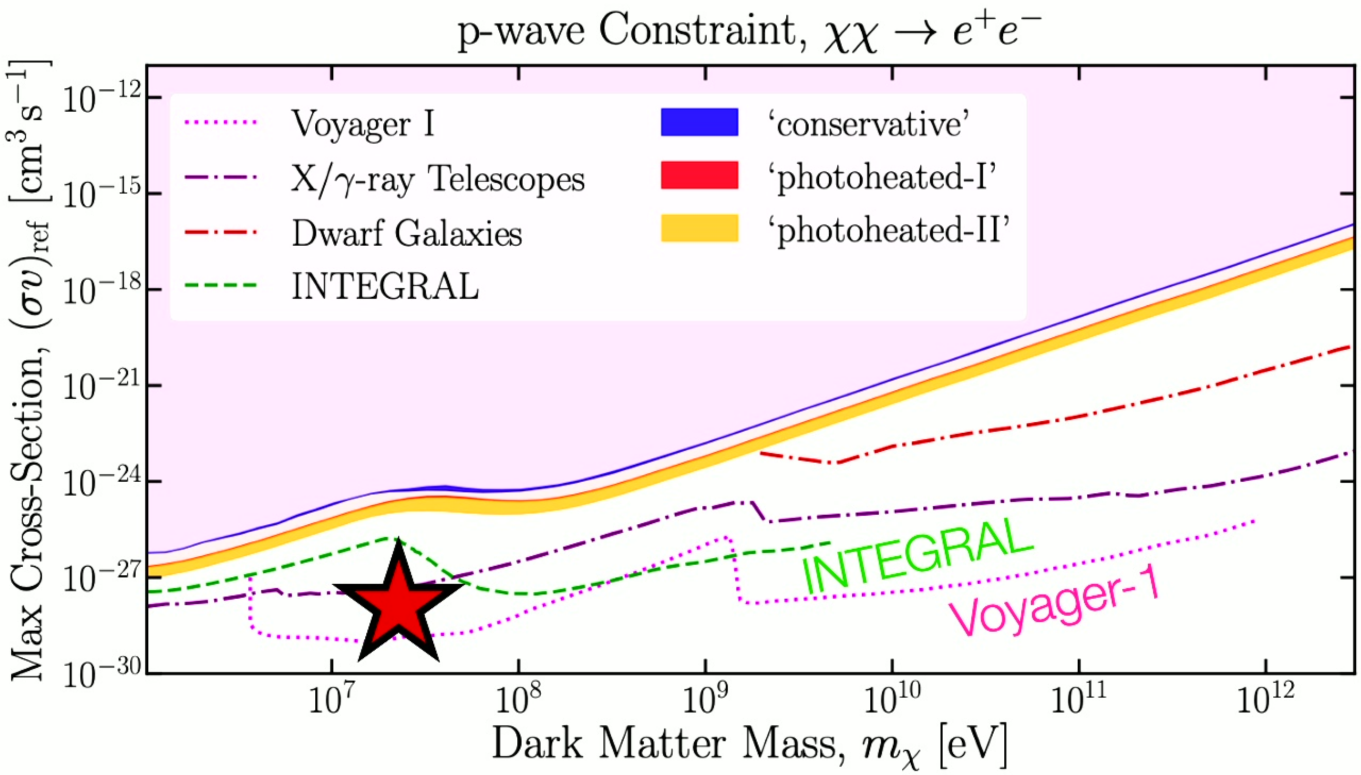
27 February, 2024
Dark Matter, First Light

PERIMETER INSTITUTE

Arthur B. McDonald Canadian Astroparticle Physics Research Institute

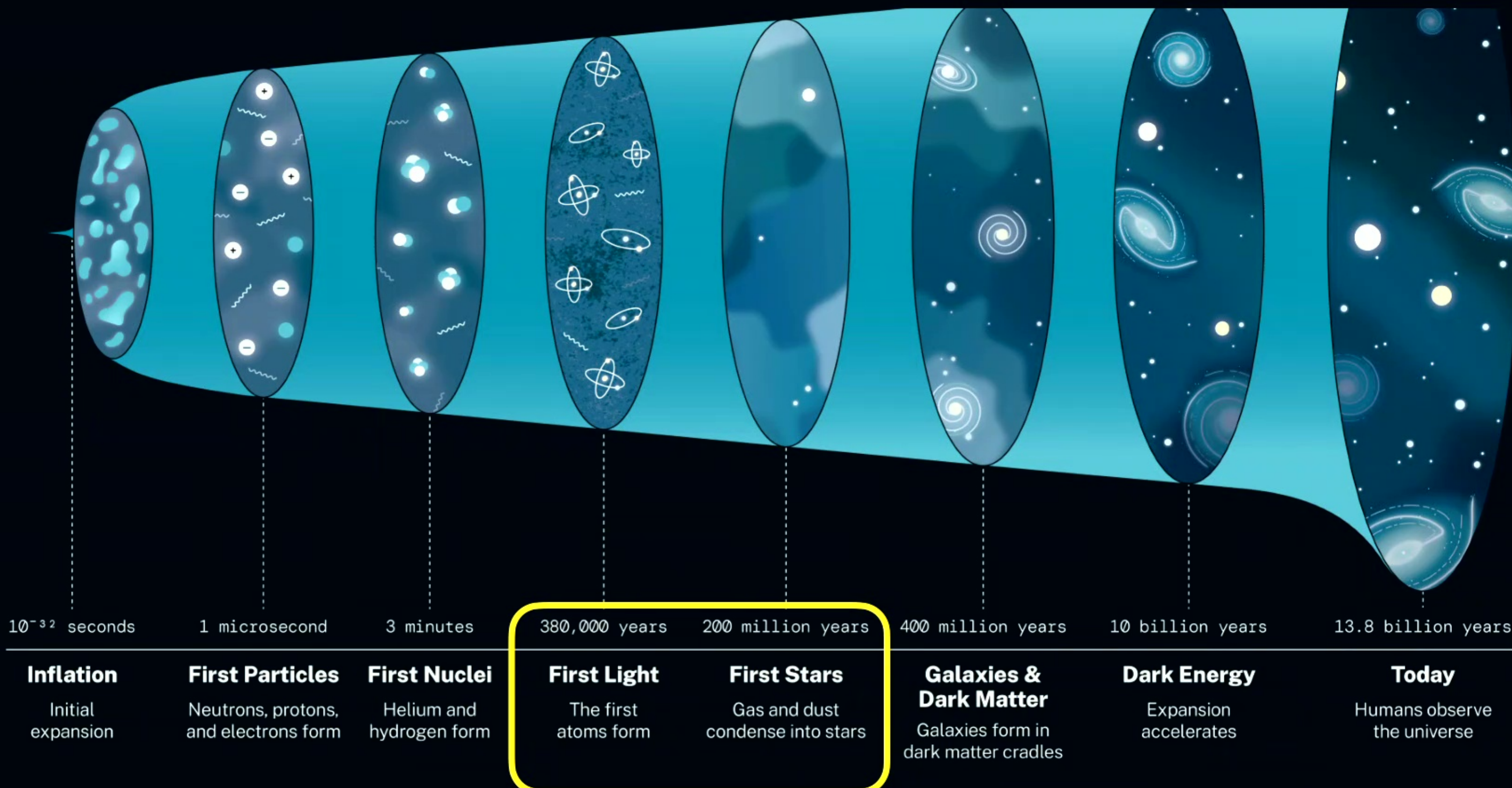
False advertising...

No "killer app" dark matter model here [yet?]



Voyager 1, NASA via Wikipedia

Image: Liu, Qin, Ridgway, Slatyer **2008.01084**; see also Cirelli et al. 2007.11493 and Boudaud et al 1810.01680



Ideal "indirect detection" laboratory

Image: NASA, 2022 science.nasa.gov/resource/history-of-the-universe/

Aaron Vincent

About 30 minutes ago

"At the end of this talk I'm going to ask you for better models…"

These are not the models that you're looking for…

Queen's U. Facullty page, Know Your Meme "These Are Not the Droids You Are Looking For"

SUPERMASSIVE BLACK HOLES

HOW DID THEY GET SO LARGE?

BIG BLACK HOLES USUALLY COME FROM MERGING LITTLE BLACK HOLES.

EDDINGTON LIMIT: THIS CANNOT EXPLAIN THE LARGEST BLACK HOLES.

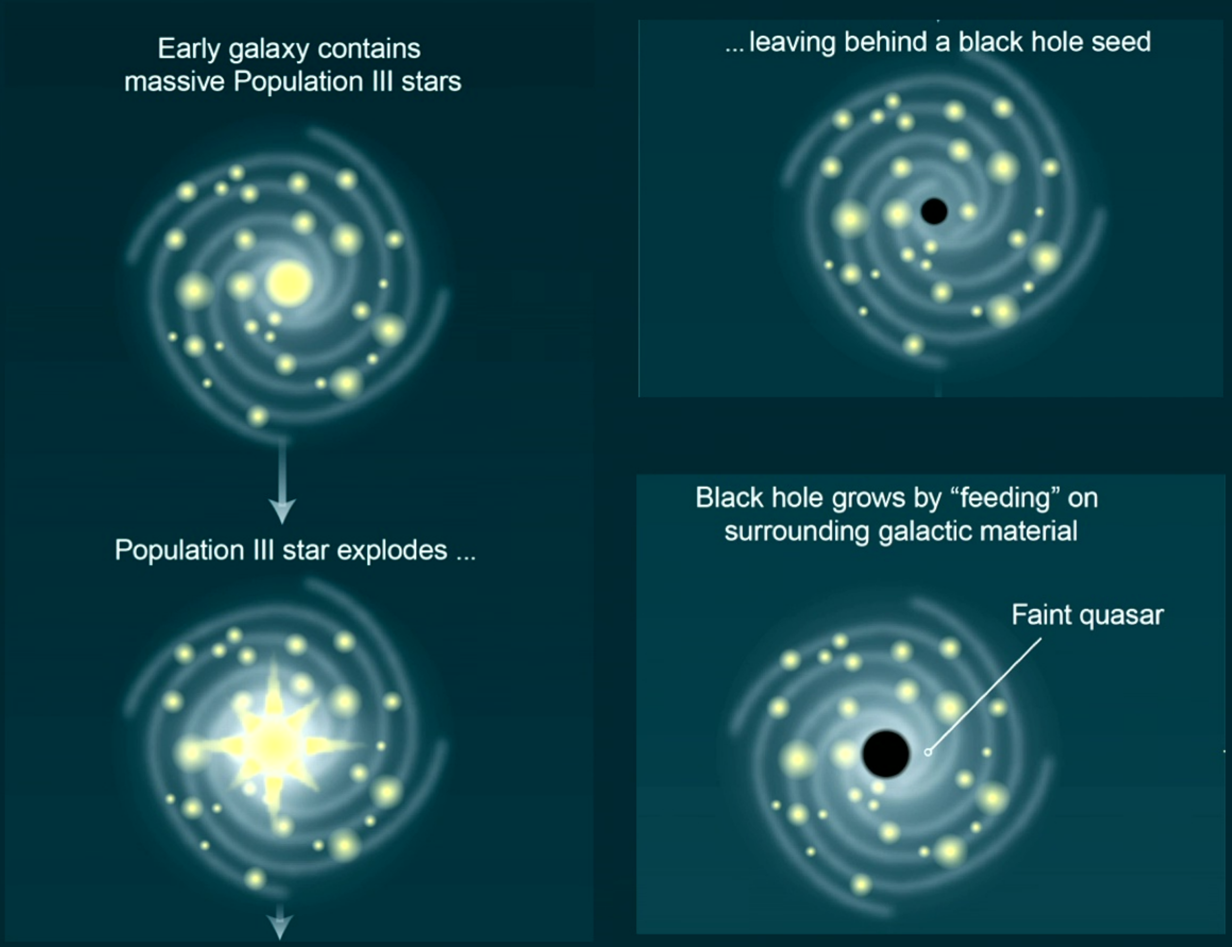
NASA, ESA and J. Olmsted (STScI) “Quasar Tsunamis Rip Across Galaxies,” NASA/Goddard (2020)

THE USUAL STORY

Galaxies form in a bubble of dark matter. As stars run through their lifecycle, some can produce black holes.

Black holes grow by eating its neighbors.

… this is **too slow** to produce the supermassive black holes seen in quasars.



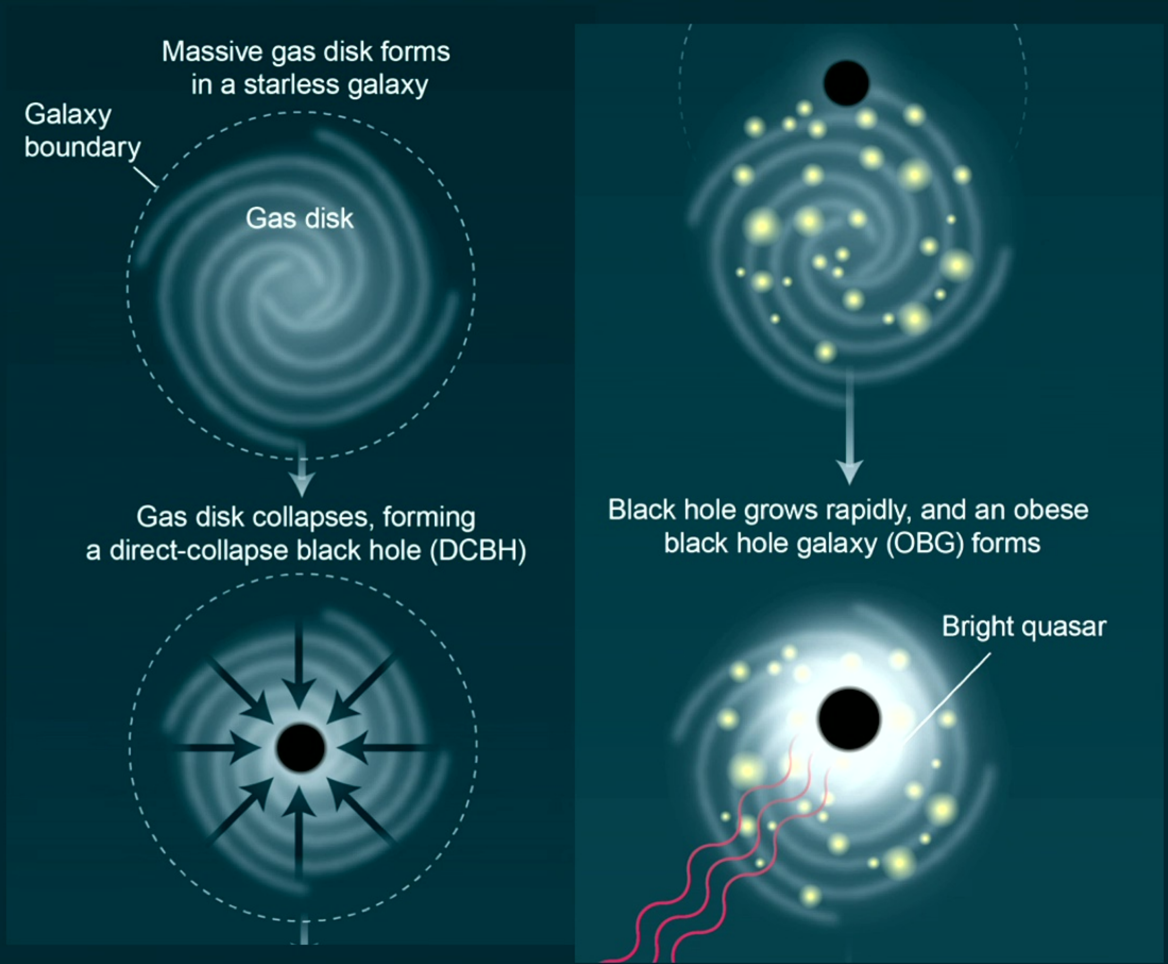
Amanda Montañez, "Puzzle of the First Black Holes," P. Natarajan, *Scientific American* 318, 2, 24-29 (2018)

DIRECT COLLAPSE

Recent hypothesis: maybe proto-galaxy's dust directly collapses into a black hole without first forming stars.

Quickly produces black holes that can grow very large.

However, gas is unstable: it *wants* to collapse into stars. Direct collapse seems unlikely.



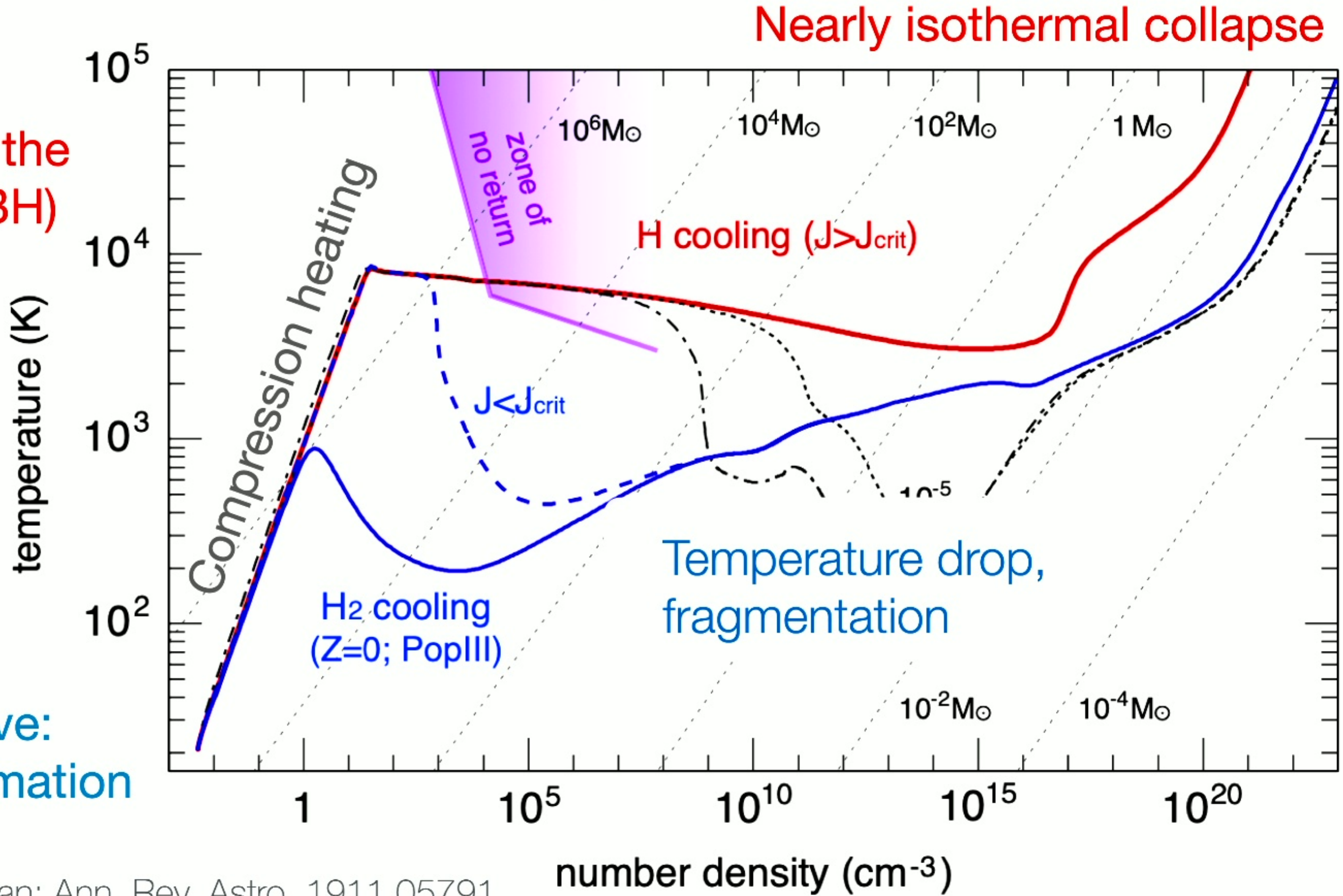
Amanda Montañez, "Puzzle of the First Black Holes," P. Natarajan, *Scientific American* 318, 2, 24-29 (2018)

Conditions for direct collapse

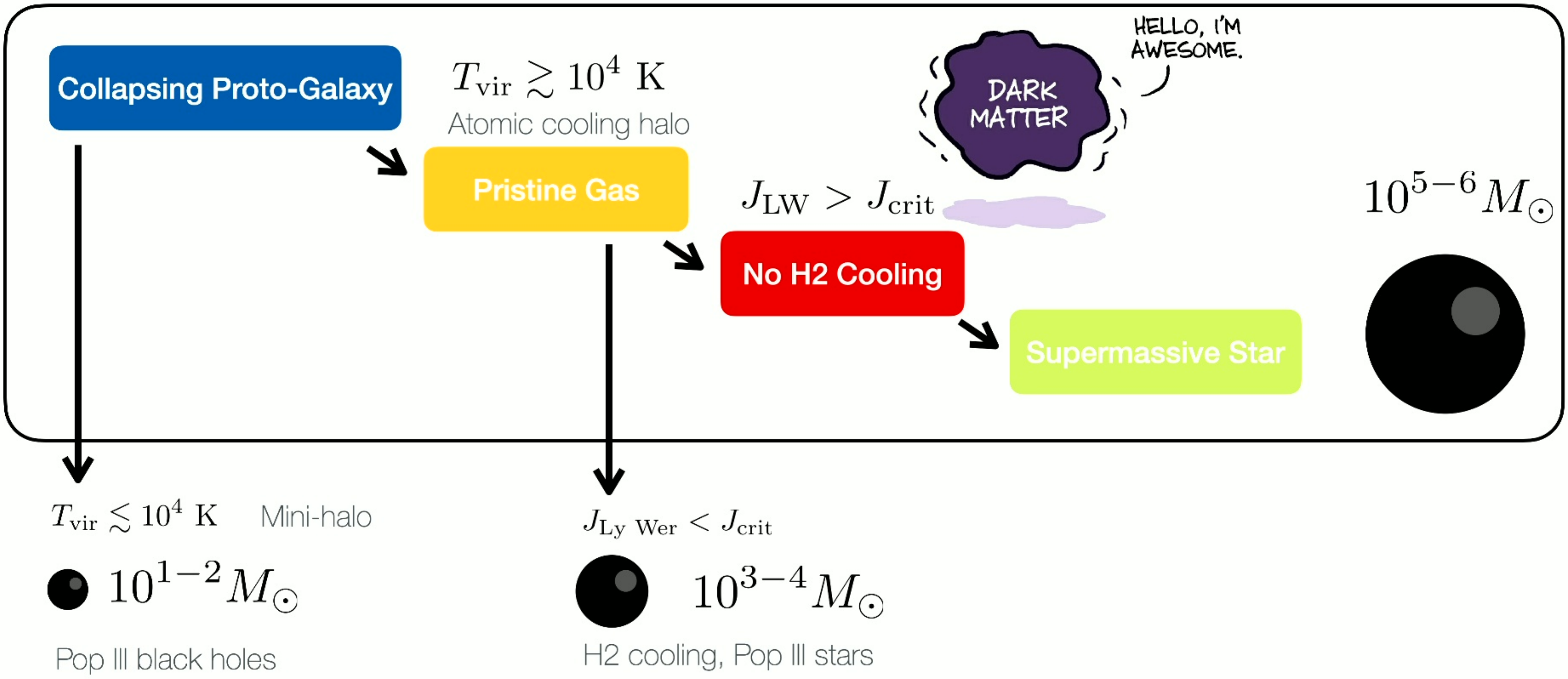
Want to follow the red curve (DCBH)

Cham & Whiteson, *We Have No Idea*

Avoid blue curve: Pop III star formation



Inayoshi, Visbal, Haiman; Ann. Rev. Astro, 1911.05791



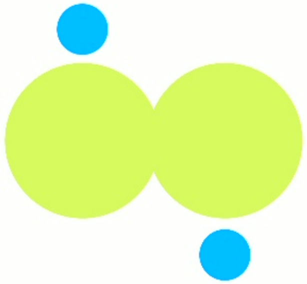
Adapted from Inayoshi, Visbal, Haiman; Ann. Rev. Astro, 1911.05791

Cham & Whiteson , *We Have No Idea*

Molecular Hydrogen H_2

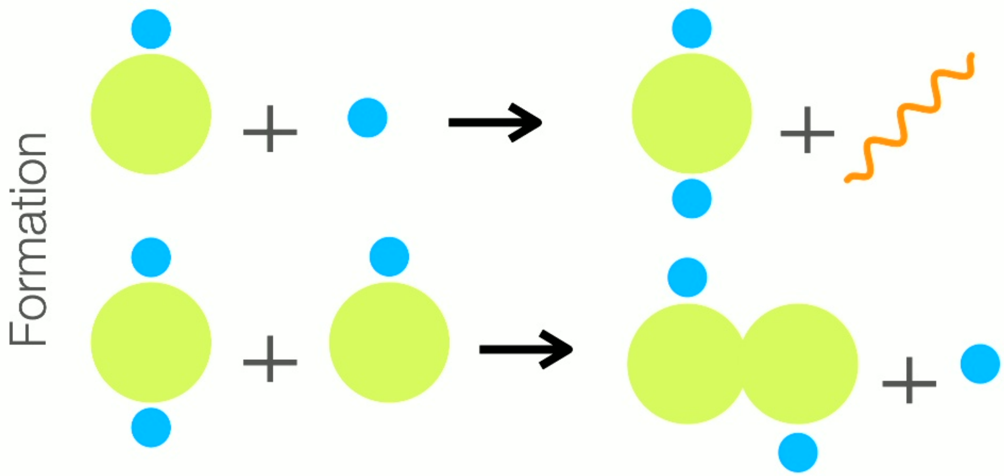
Proto-galaxy gas cannot cool atomically at below 10^4 K. It needs to cool down in order to fragment.

A small fraction of molecular hydrogen (**H_2**) provides pathways to cool at lower temperatures. This is a critical point in the formation of Pop III stars.



Molecular Hydrogen H_2

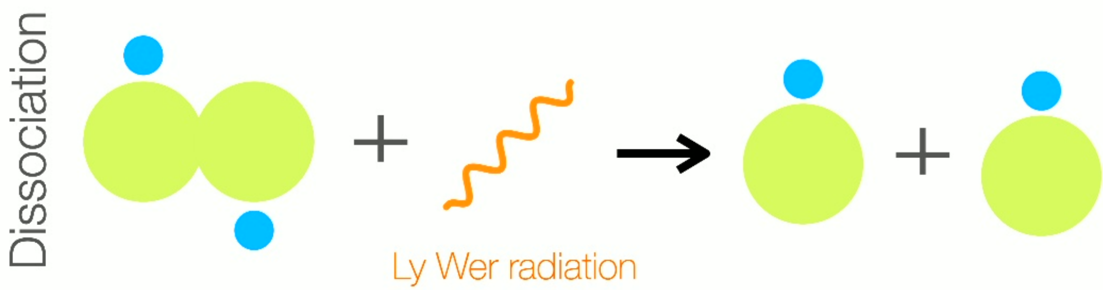
Formation of Molecular Hydrogen



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

e^- is a catalyst for H_2 formation; *ionizing* interactions tend to *create* H_2

(Difficult to form H_2 from simply colliding H+H; no dipole so does not radiate energy easily)

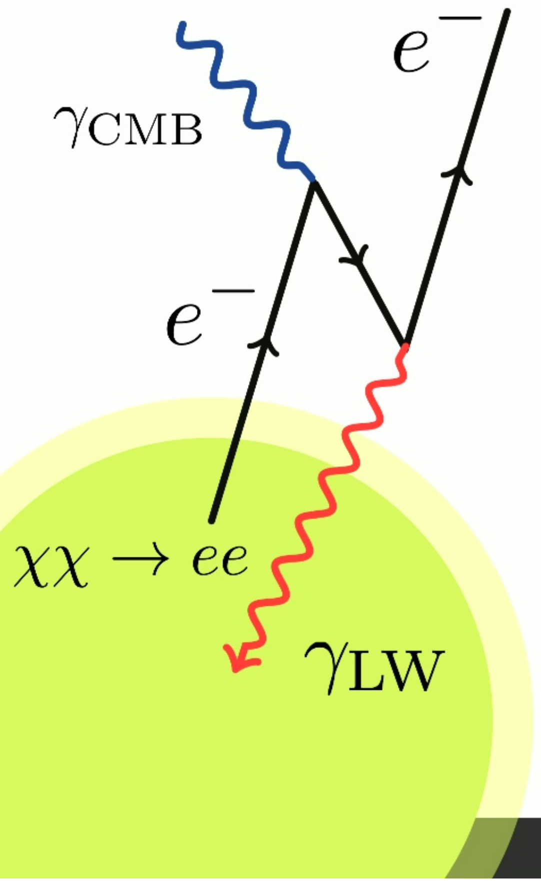


Photodissociation

$$\mathrm{H}_2 + \gamma_{\mathrm{LW}} \to H + H$$

& photodetachment for lower energies.

Goal



Turn off H_2 cooling in a $10^6\ M_\odot$ halo at $z \sim 25$: **20 MeV dark matter** annihilation to e^+e^-.

e^- inverse Compton scatters with CMB light to produce Lyman-Werner photons (~10 eV) that dissociate H_2.

Atomic cooling kicks in at $z \sim 12.5$ en route to a **direct collapse black hole**.

Challenge: self-shielding

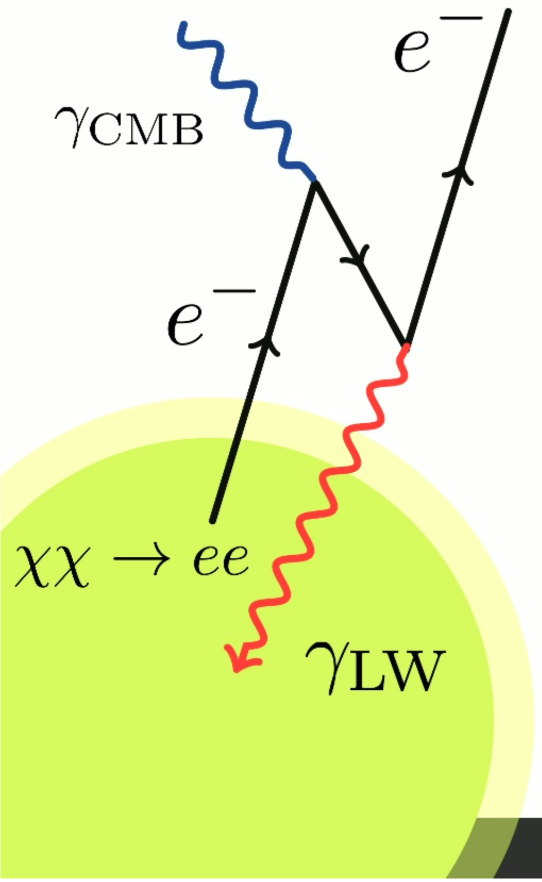
If H_2 does build up then our efforts fail because e's *increase* H_2 formation rate.

Cham & Whiteson , *We Have No Idea*

Idea: Don't let self-shielding build up

BBC Frozen Planet, “Criminal Penguins” (2011)

Some Assumptions



Pick a slow growing halo

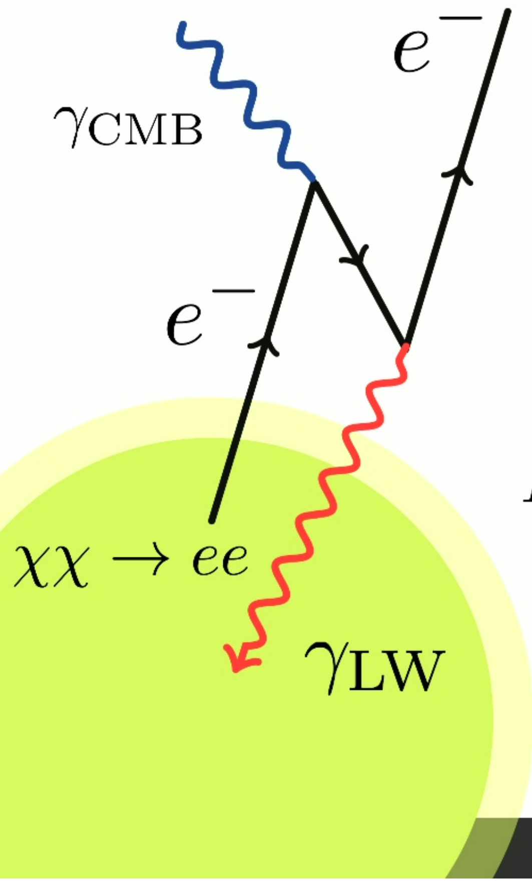
$$M_{\rm halo}(z) = 1.4 \times 10^8\, M_\odot\, e^{-0.2\, z}$$

$$M_{\rm halo}(z=25) = 10^6\, M_\odot$$
$$T_{\rm gas}(z=12) = 10^4\ \rm K$$

Avoid mixing in effect of dynamical heating

Model gas as isothermal halo. Valid in the absence of H_2 cooling. If you leave this regime, then there's no hope for DCBH.

ICS Outside the Halo



ICS spectrum is around the Ly-Wer range

the halo gas is optically thin in this frequency

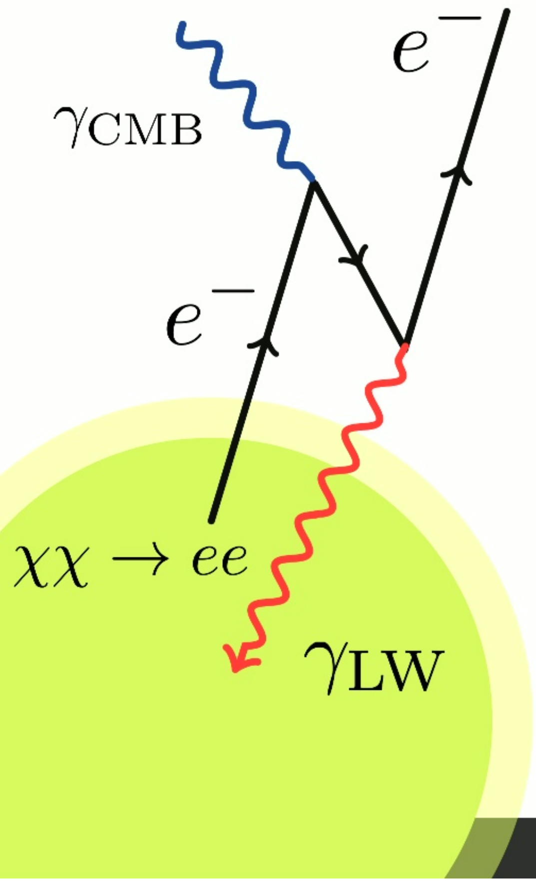
want these photons to enter halo & dissociate H_2

Higher-energy final states ionize and heat the gas

the IGM is optically thick and these do not return to the halo.

$$E'_\gamma \sim 4\left(\frac{E_e}{m_e}\right)^2 E_\gamma$$

Halo + Transport



Halo contribution dominates annihilation (vs IGM) by four orders of magnitude; not the case for decay

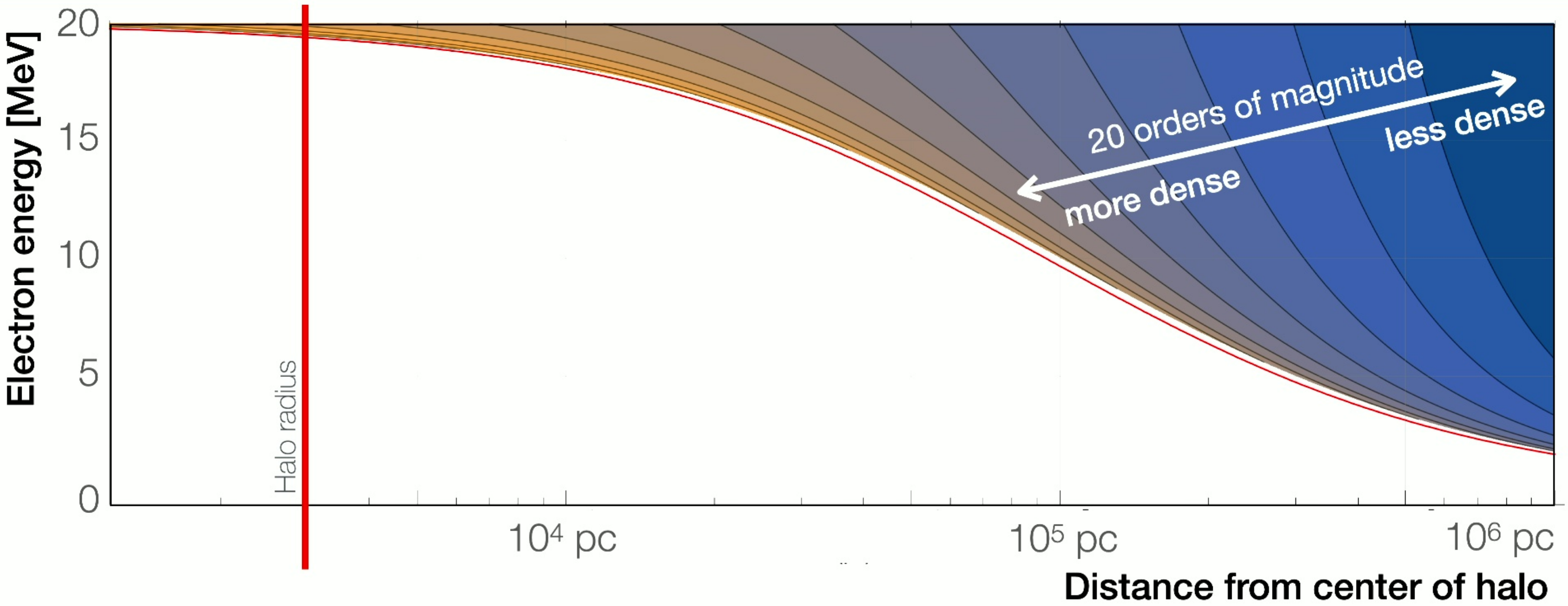
"Birth of the first stars amidst decaying and annihilating dark matter"
Wenzer Qin, Julian B. Munoz, Hongwan Liu, Tracy R. Slatyer (2308.12992)

Solve electron transport: linear regime; solvable analytically

$$\partial_t \mathcal{N}_e - \cancel{\nabla \cdot [\mathcal{K}(E,\mathbf{x})\nabla \mathcal{N}_e]} + \partial_E \left[\dot{\mathcal{E}}(E,\mathbf{x})\,\mathcal{N}_e\right] = Q_e(E,\mathbf{x})$$

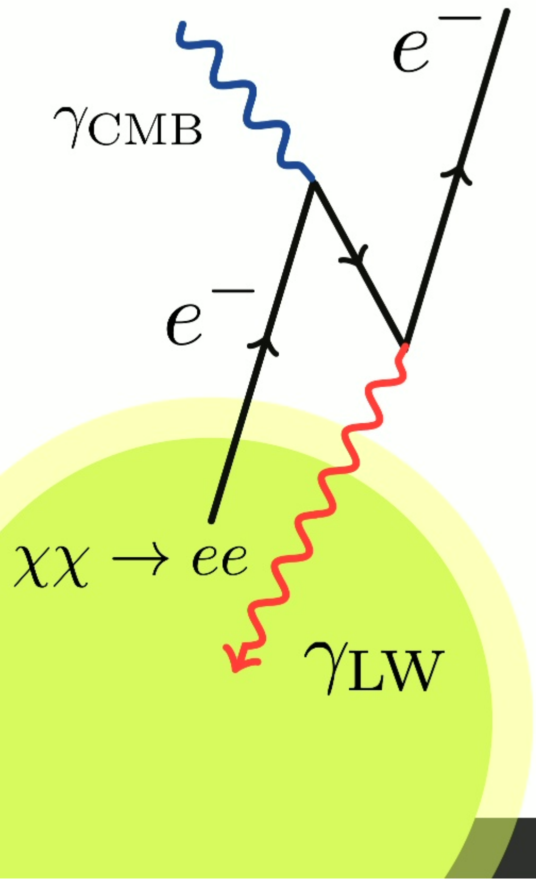
diffusion; no B fields — radiative energy loss — source (DM)

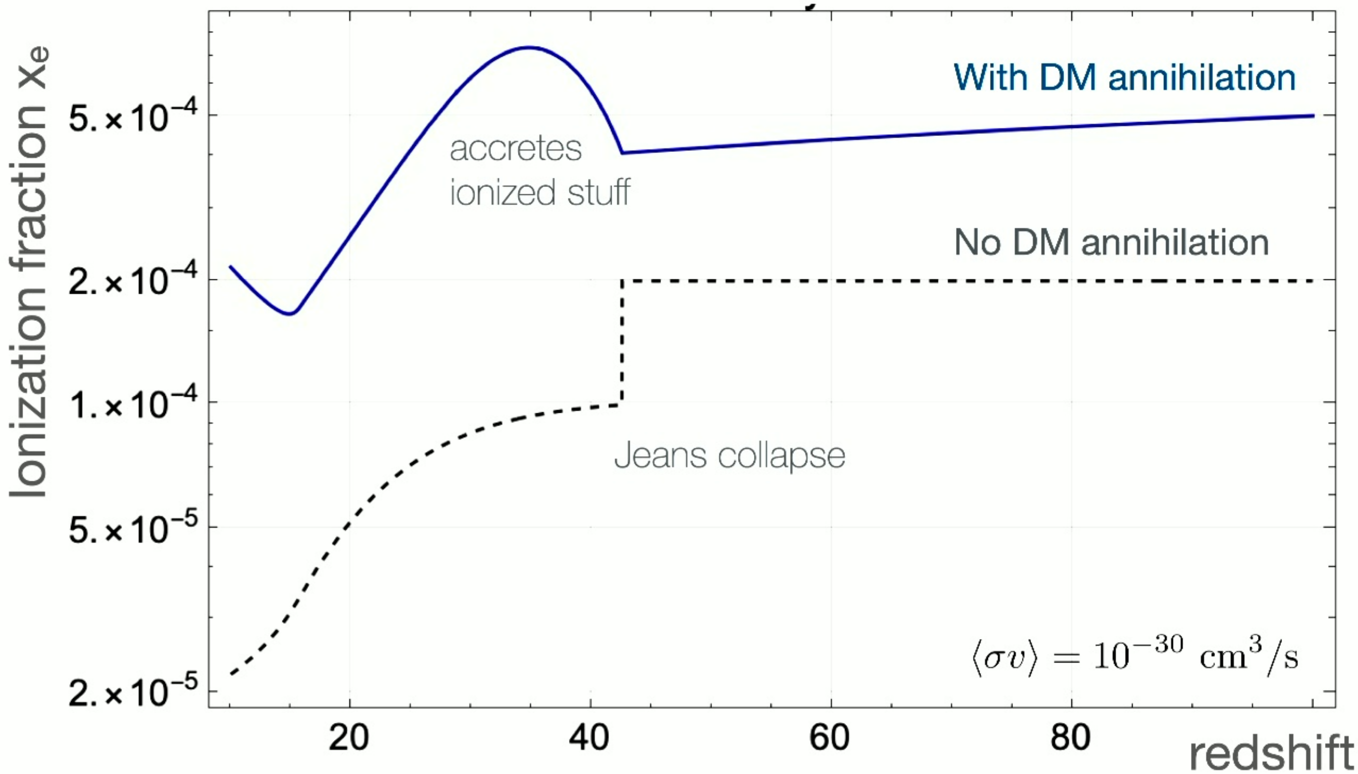
$$\dot{\mathcal{E}}(E,\mathbf{x}) = -\frac{4}{3}\sigma_{\rm Thompson}\gamma^2\beta^2\, u(T) \qquad \gamma = \frac{E}{m_e} \qquad Q_e = \frac{1}{2}\frac{\rho^2_{\rm DM}(\mathbf{x})}{m^2_{\rm DM}}\langle\sigma v\rangle \mathcal{N}_e$$



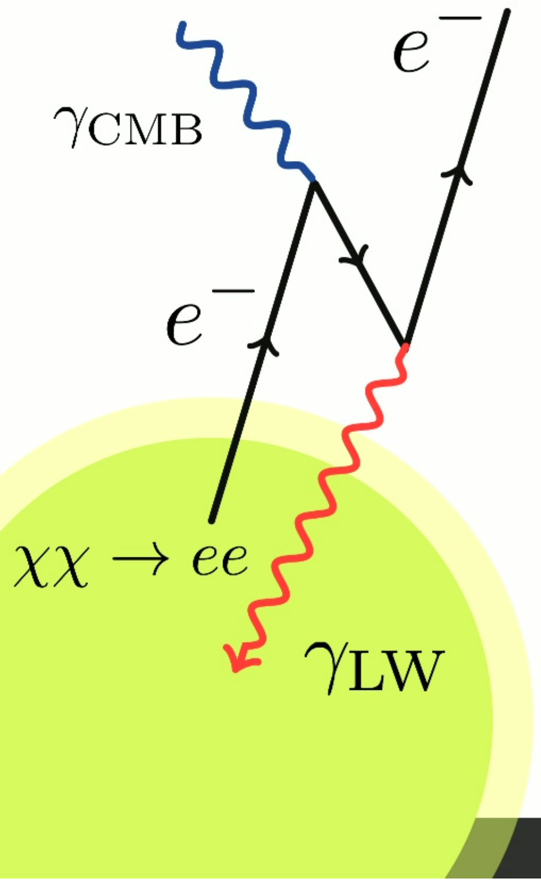
20 MeV electrons escape our pristine protogalaxy,
halo is essentially a point source of electrons

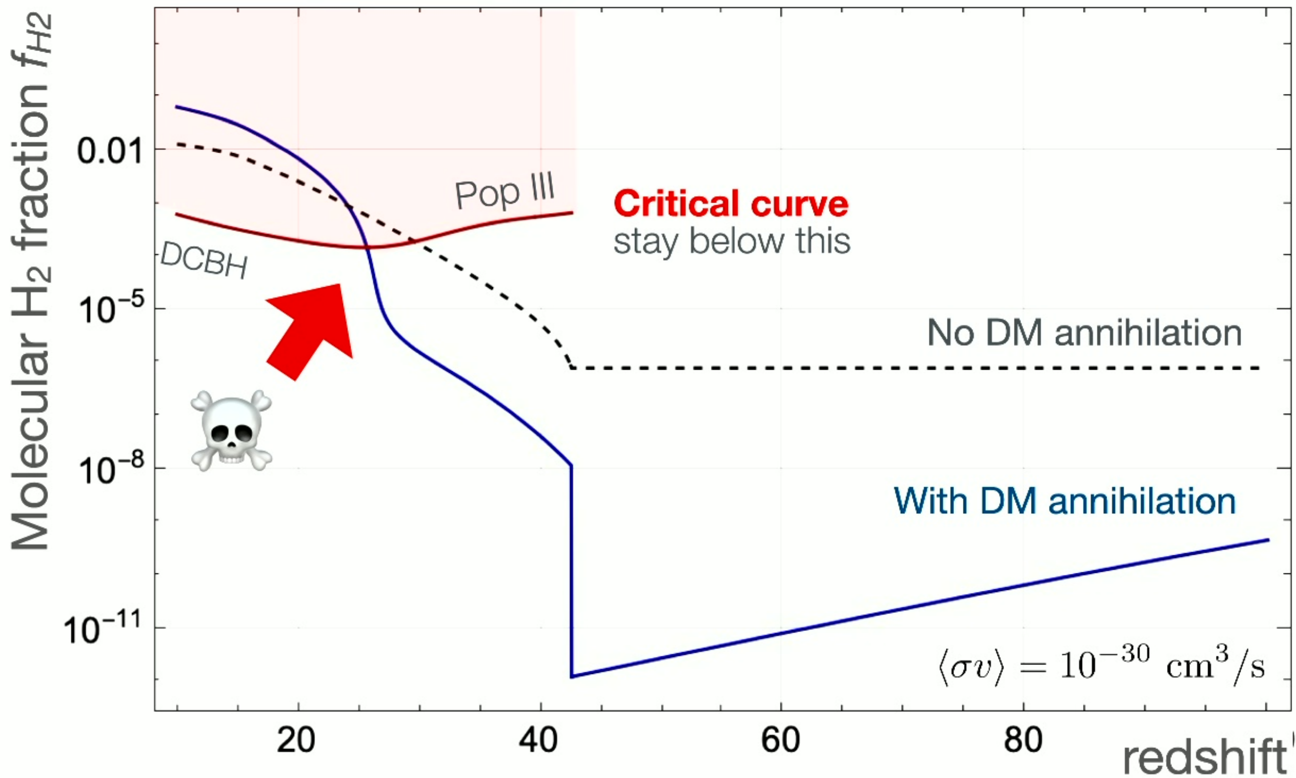
Ionization History





H_2 fraction





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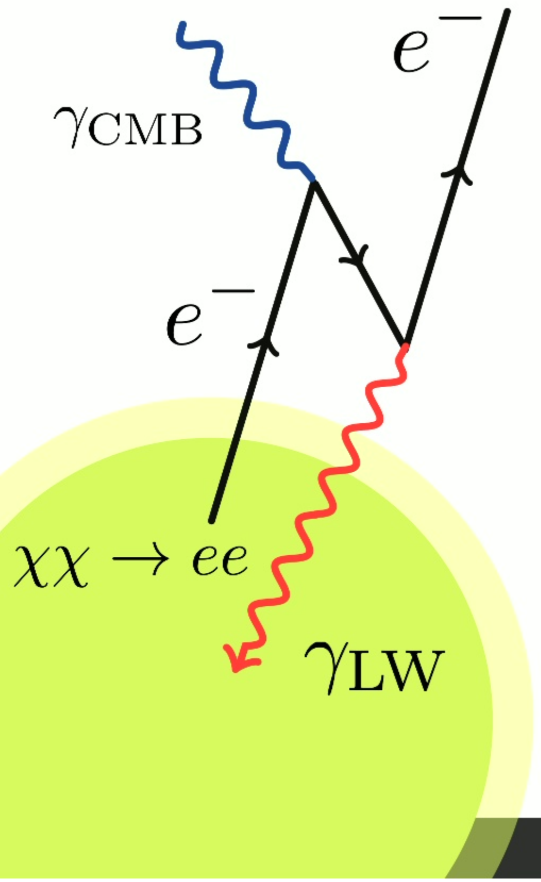
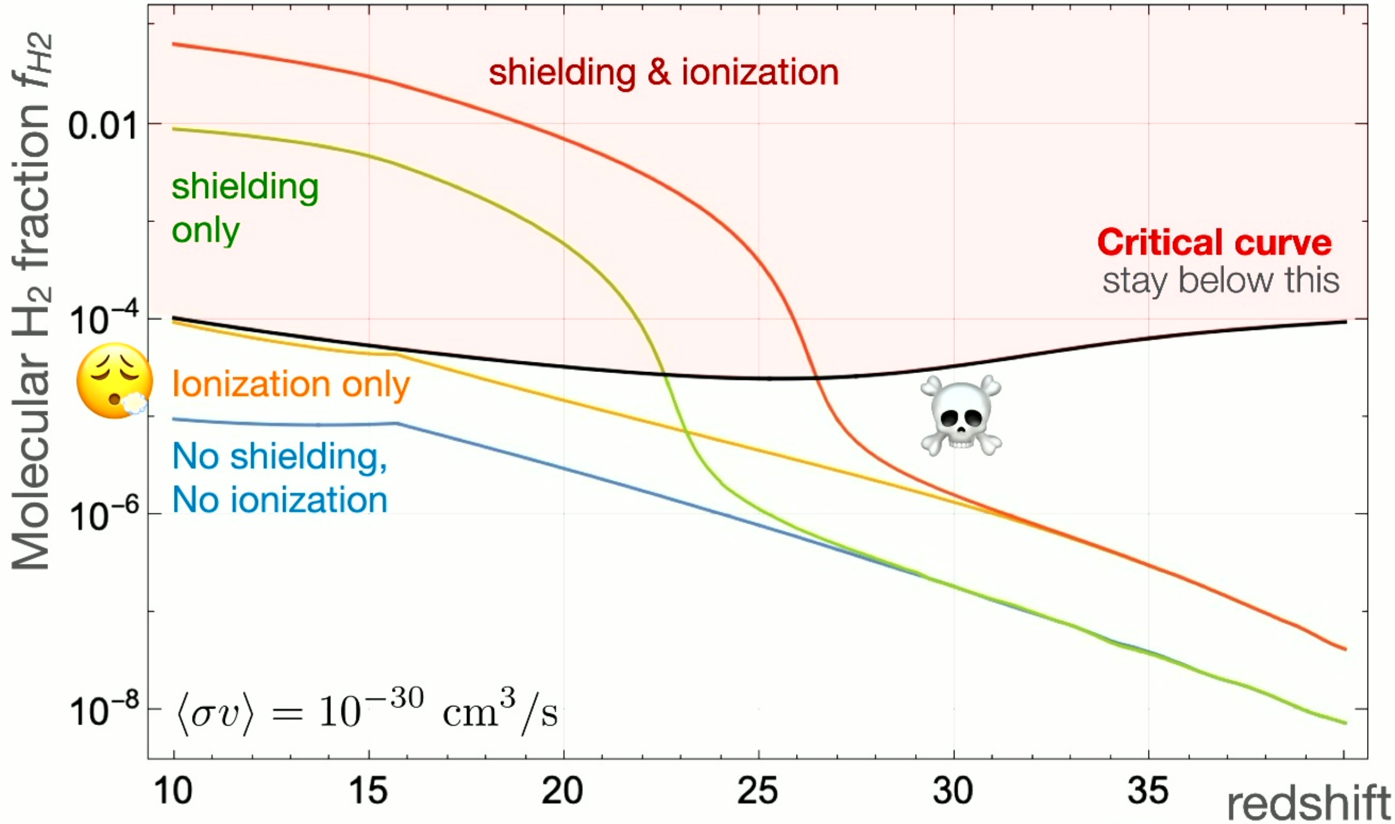
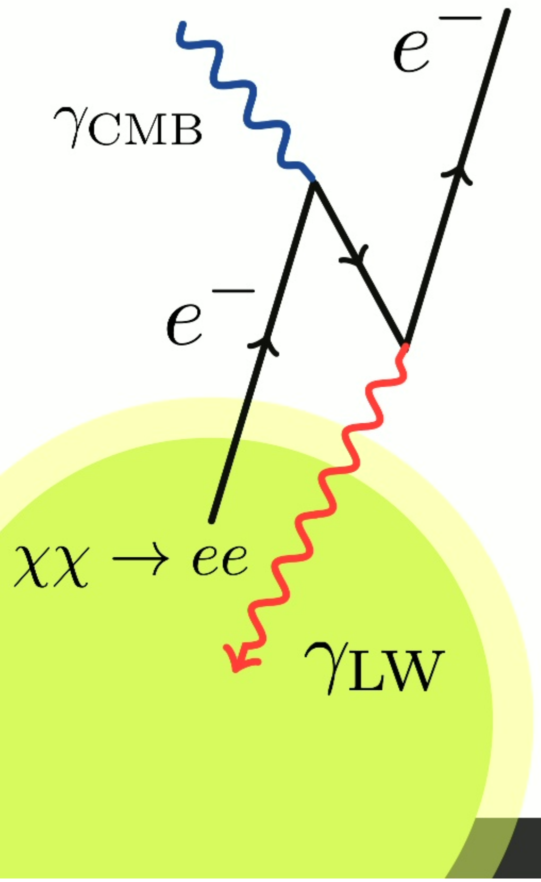
H_2 fraction

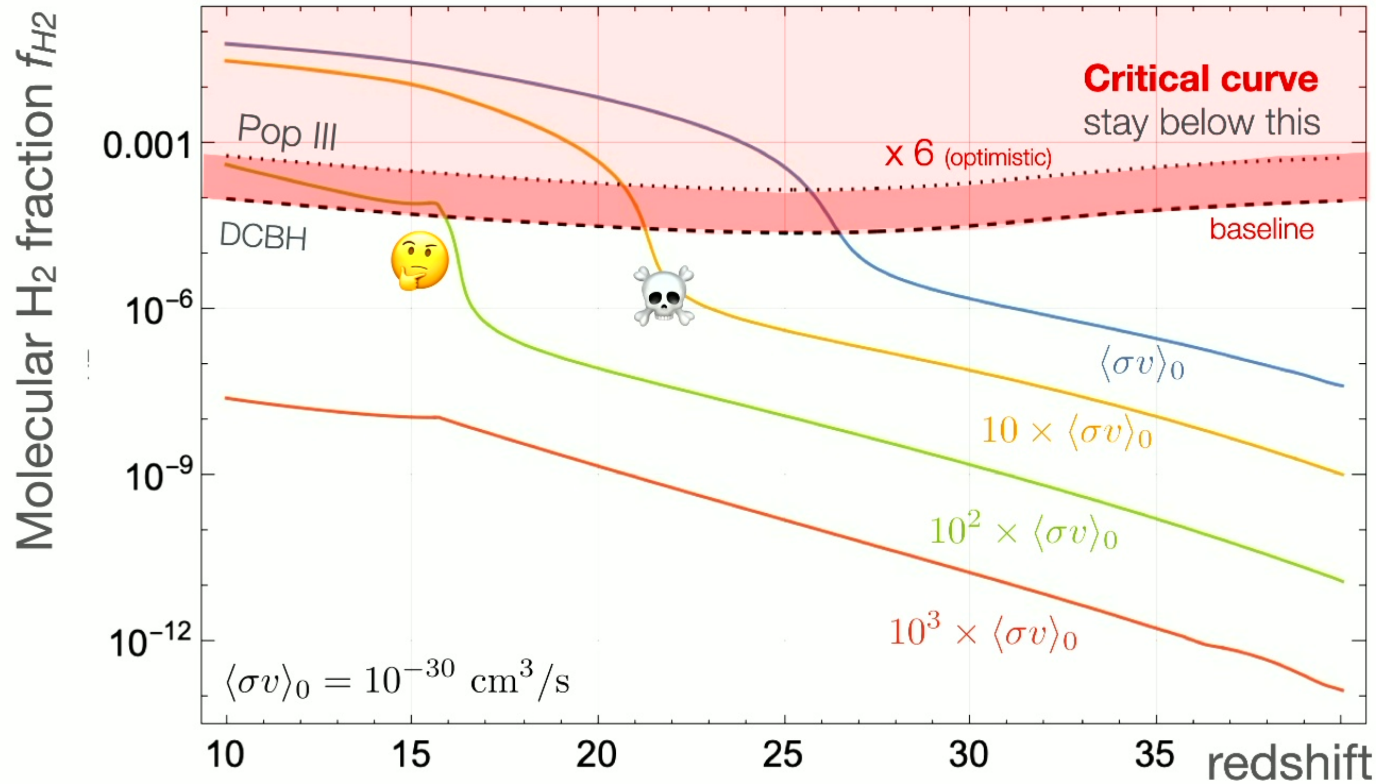




H_2 self-shielding is the main impediment for DCBH in this scenario

H_2 fraction





Optimistically, DCBH for annihilation x-section:

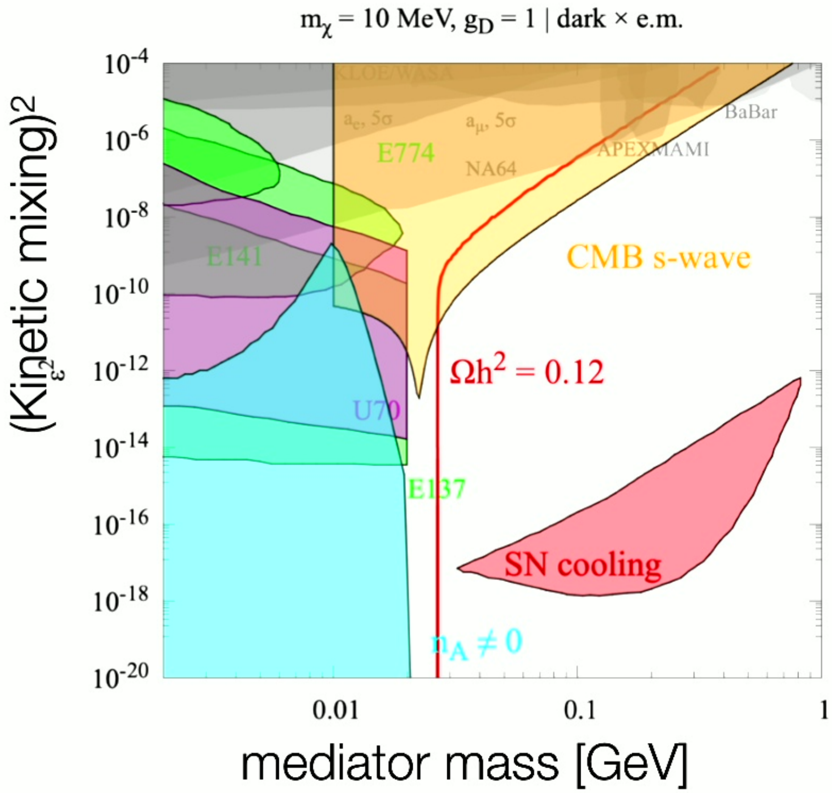
$$\langle\sigma v\rangle \sim 10^{-28}\ \mathrm{cm}^3/\mathrm{s}$$

Model building attempts

… from the guy who kept bringing up Lagrangians yesterday

"Sub-GeV regime is observationally timely… let's see if we're consistent with a thermal relic…"

Dark matter + mediator (dark photon)

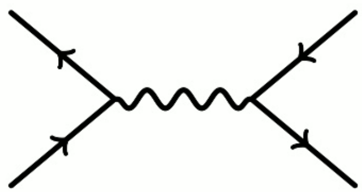


"MeV Dark Matter with MeV Dark Photons" Compagnin, Profumo, Fornengo (2211.13825)

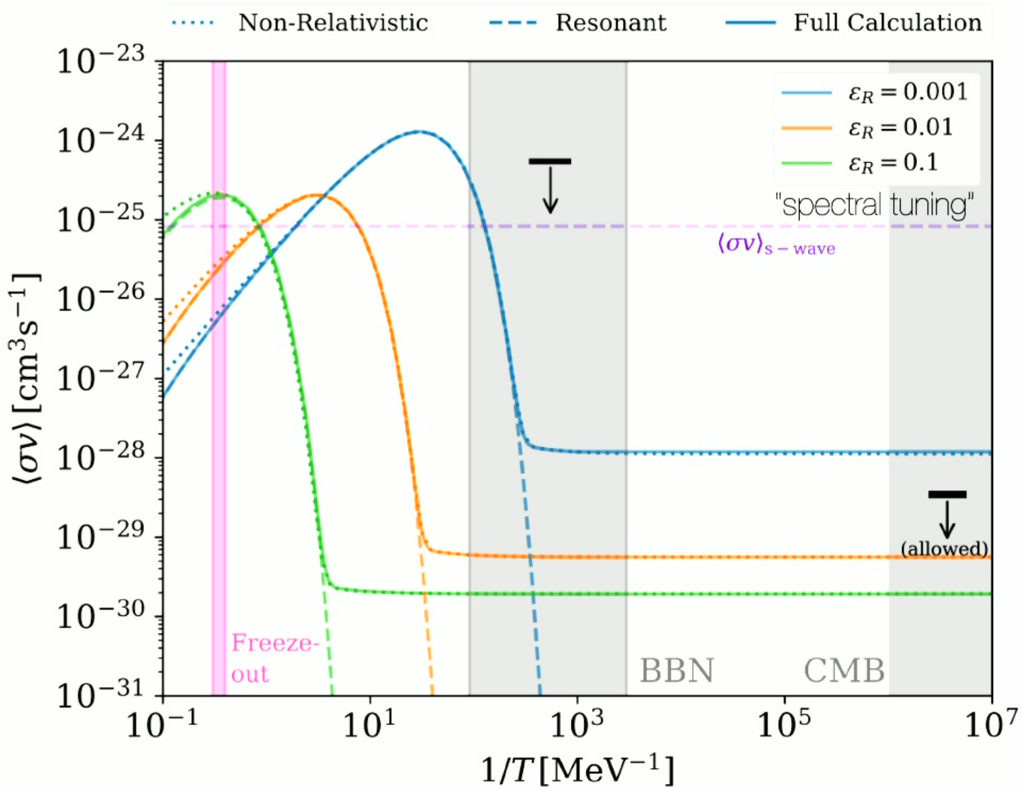
Model building attempts

... from the guy who kept bringing up Lagrangians yesterday

We want a large annihilation rate at later times; can we use an s-channel resonance to boost it?

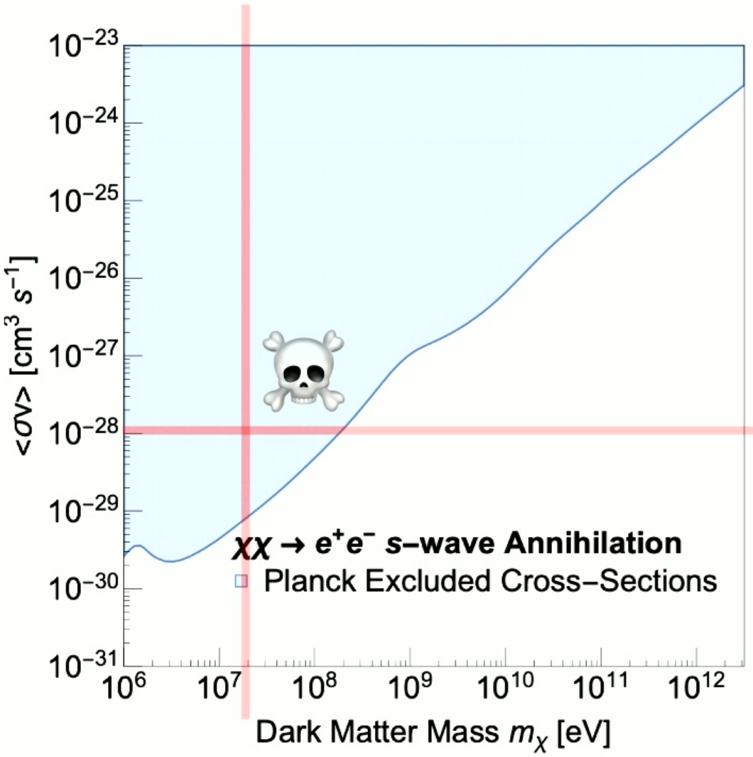


Playing limbo on BBN, CMB bounds.



"Resonant Sub-GeV Dirac Dark Matter" Bernreuther, Heeba, Kahlhoefer (2010.14522); see also Feng (1707.03835)

What observations tell us

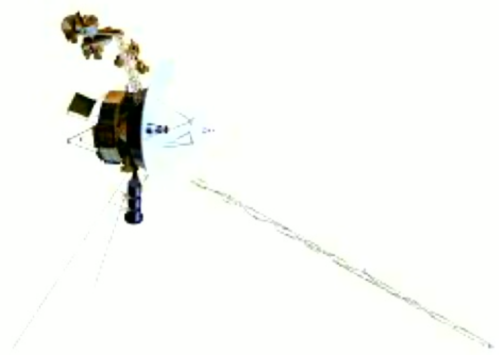


Liu, Slatyer, Zavala 1604.02457

"Oh… well, that's okay. The dark matter velocity is larger in a halo than in the CMB, so we can try **p-wave annihilation** which should ease the CMB constraints…"

Damn you, Voyager

Voyager 1, NASA via Wikipedia



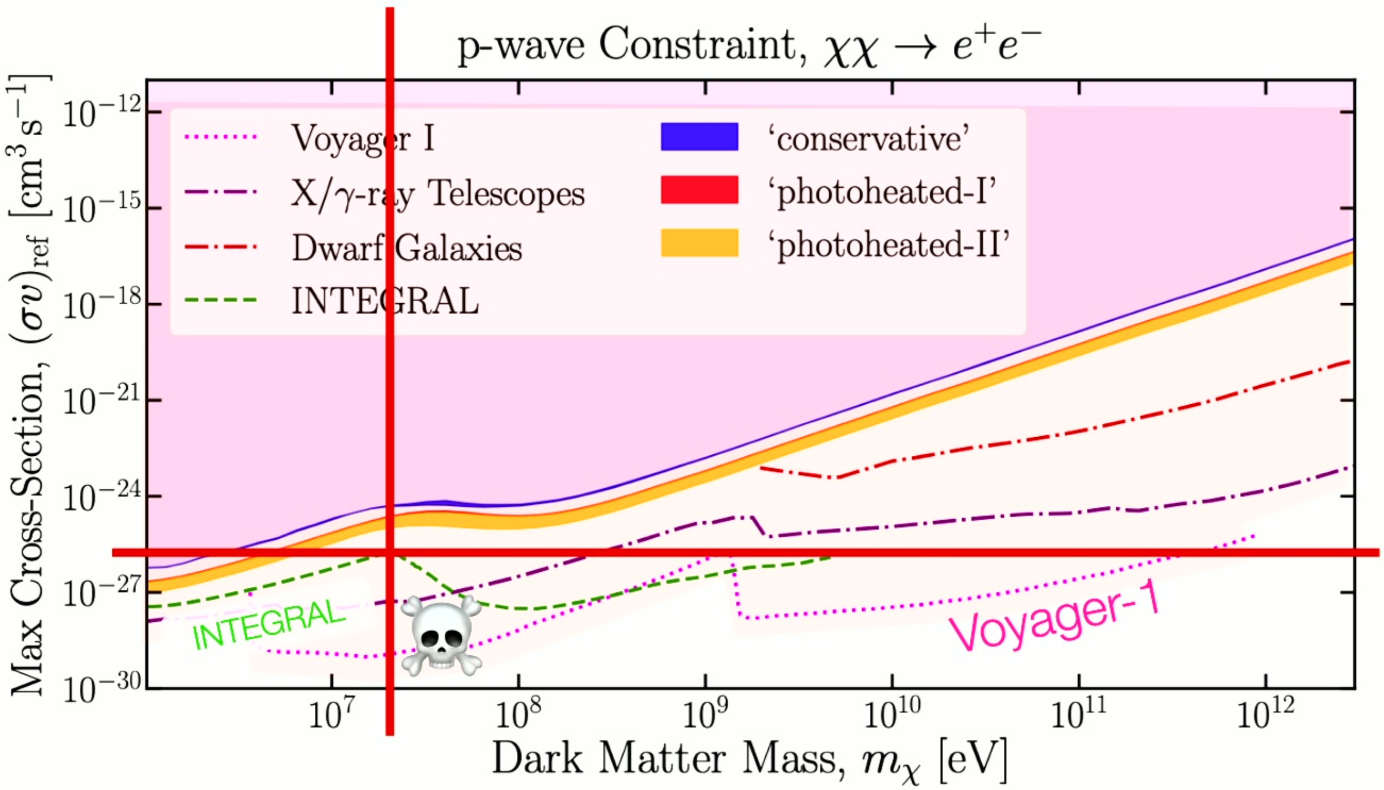


Image: Liu, Qin, Ridgway, Slatyer **2008.01084**; see also Cirelli et al. 2007.11493 and Boudaud et al 1810.01680

Alternative

Feeding plankton to whales: high-redshift supermassive black holes from tiny black hole explosions

Yifan Lu, Zachary S. C. Picker, Alexander Kusenko

Recent observations of the high-redshift universe have uncovered a significant number of active galactic nuclei, implying that supermassive black holes (SMBHs) would have to have been formed at much earlier times than expected. Direct collapse of metal-free gas clouds to SMBHs after recombination could help explain the early formation of SMBHs, but this scenario is stymied by the fragmentation of the clouds due to efficient molecular hydrogen cooling. We show that a subdominant population of tiny, evaporating primordial black holes, with significant clustering in some gas clouds, can heat the gas sufficiently so that molecular hydrogen is not formed, and direct collapse to to black holes is possible even at high redshifts.

arxiv:2312.15062

~~Conclusion~~ Inconclusive thoughts

- The first proto-galaxies are an excellent laboratory for dark matter “indirect detection at high redshift”
- **Direct collapse black holes** may be a dramatic signature of DM energy density deposition. The game: dissociate molecular hydrogen. Our strategy: ICS from 20 MeV electron final states.
- Challenge: if you let H_2 form, self-shielding is unforgiving.
- Challenge: bounds on late time O(10 MeV) electron injection rate are too stringent by O(100).
- Other options? Inject only Ly-Wer photons, “time bomb” injection of energy at recent times (but not today), or use more sophisticated tool to understand broader set of energy deposition channels (see Wenzer’s talk!)