Direct Collapse Black Holes from Dark Matter Annihilation

A challenge and an attempt...

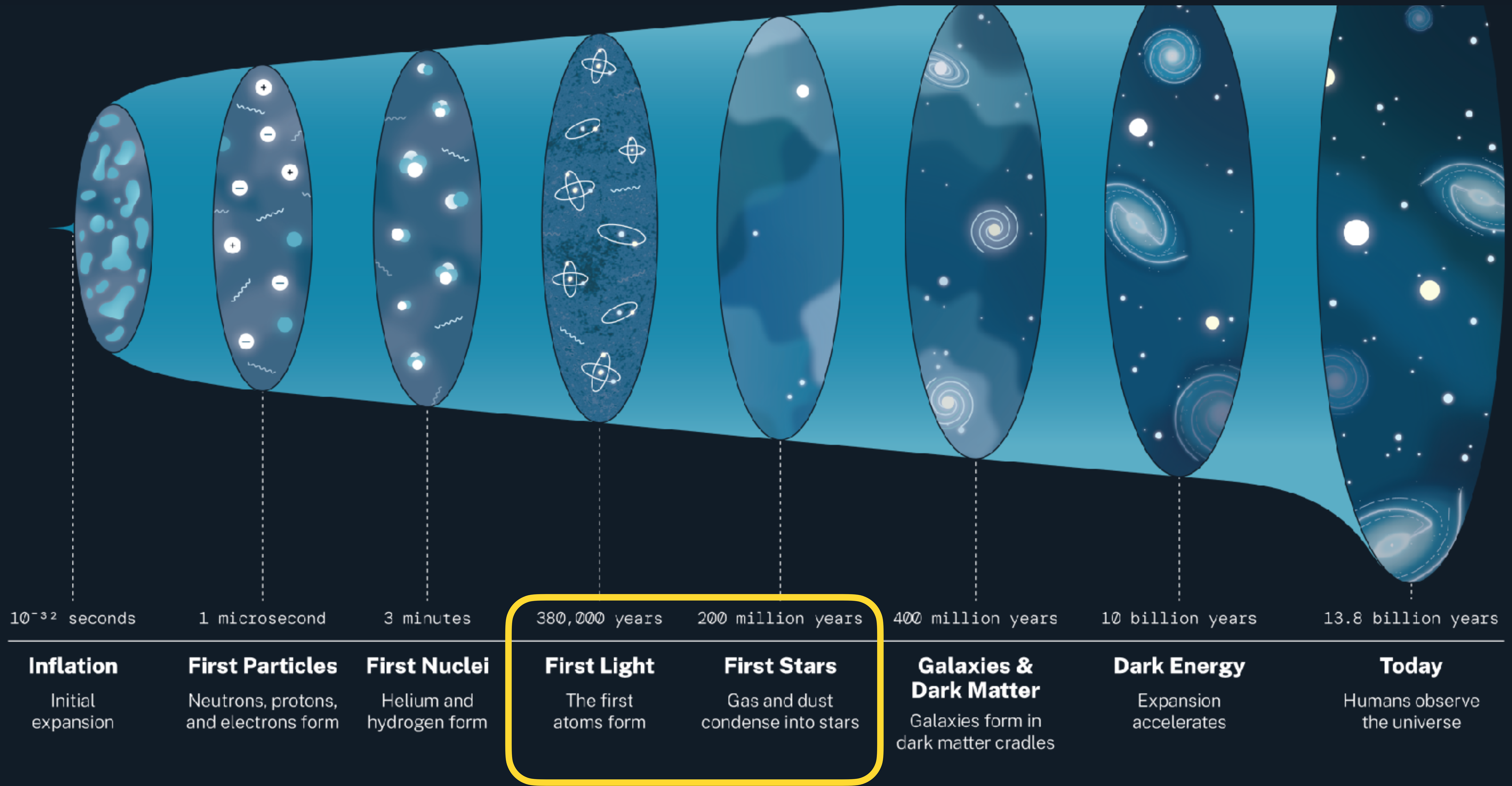
Flip Tanedo


Work with Anson D'Aloisio & Yash Aggarwal

UC RIVERSIDE
PHYSICS & ASTRONOMY

25 May 2024
Collider, Dark Matter, and Neutrino Physics 2024

TEXAS A&M UNIVERSITY
Mitchell Institute



Ideal “indirect detection” laboratory

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

SUPERMASSIVE BLACK HOLES

HOW DID THEY GET SO LARGE?

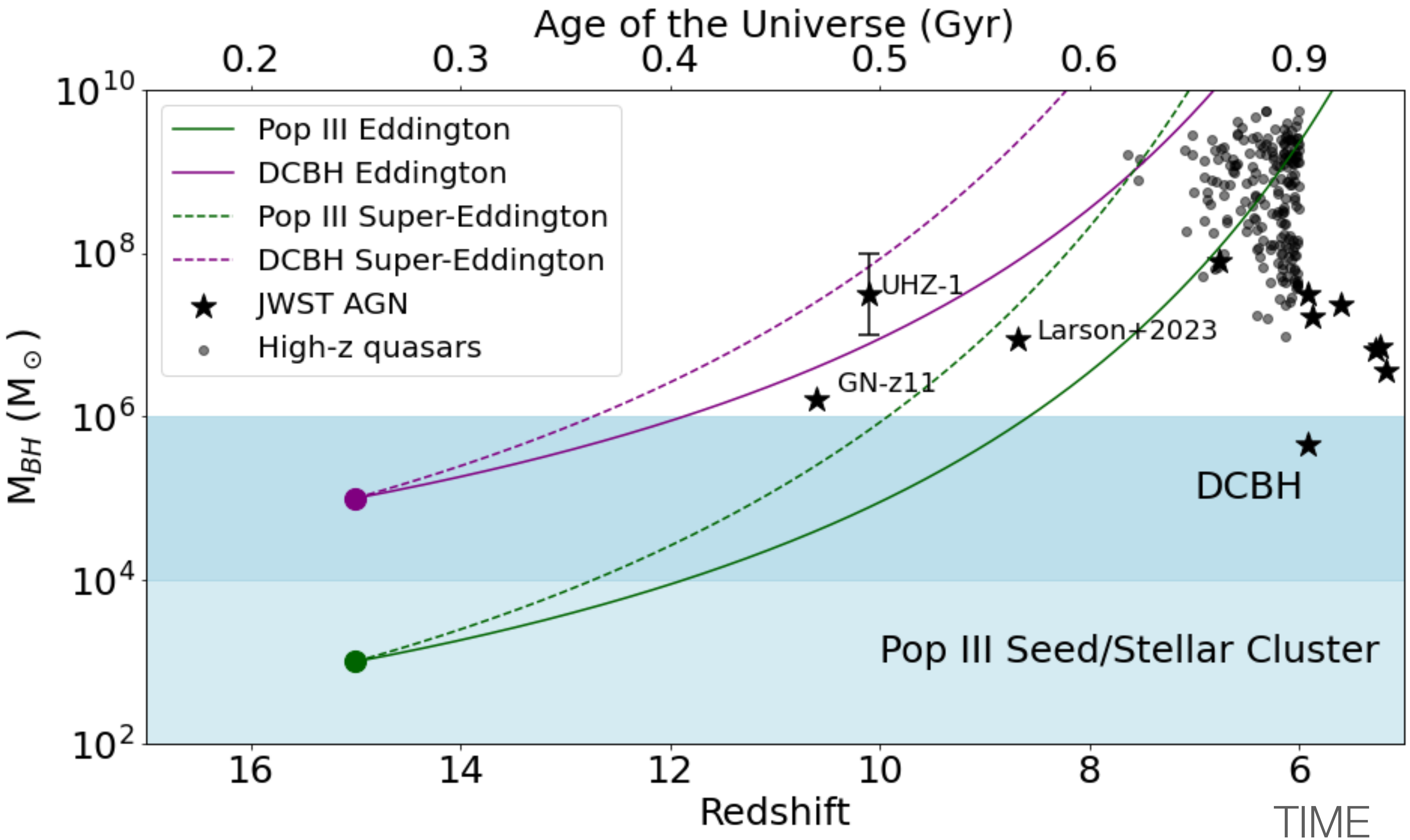
BIG BLACK HOLES USUALLY COME FROM MERGING LITTLE BLACK HOLES.

EDDINGTON LIMIT: THIS CANNOT EXPLAIN THE LARGEST BLACK HOLES.

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

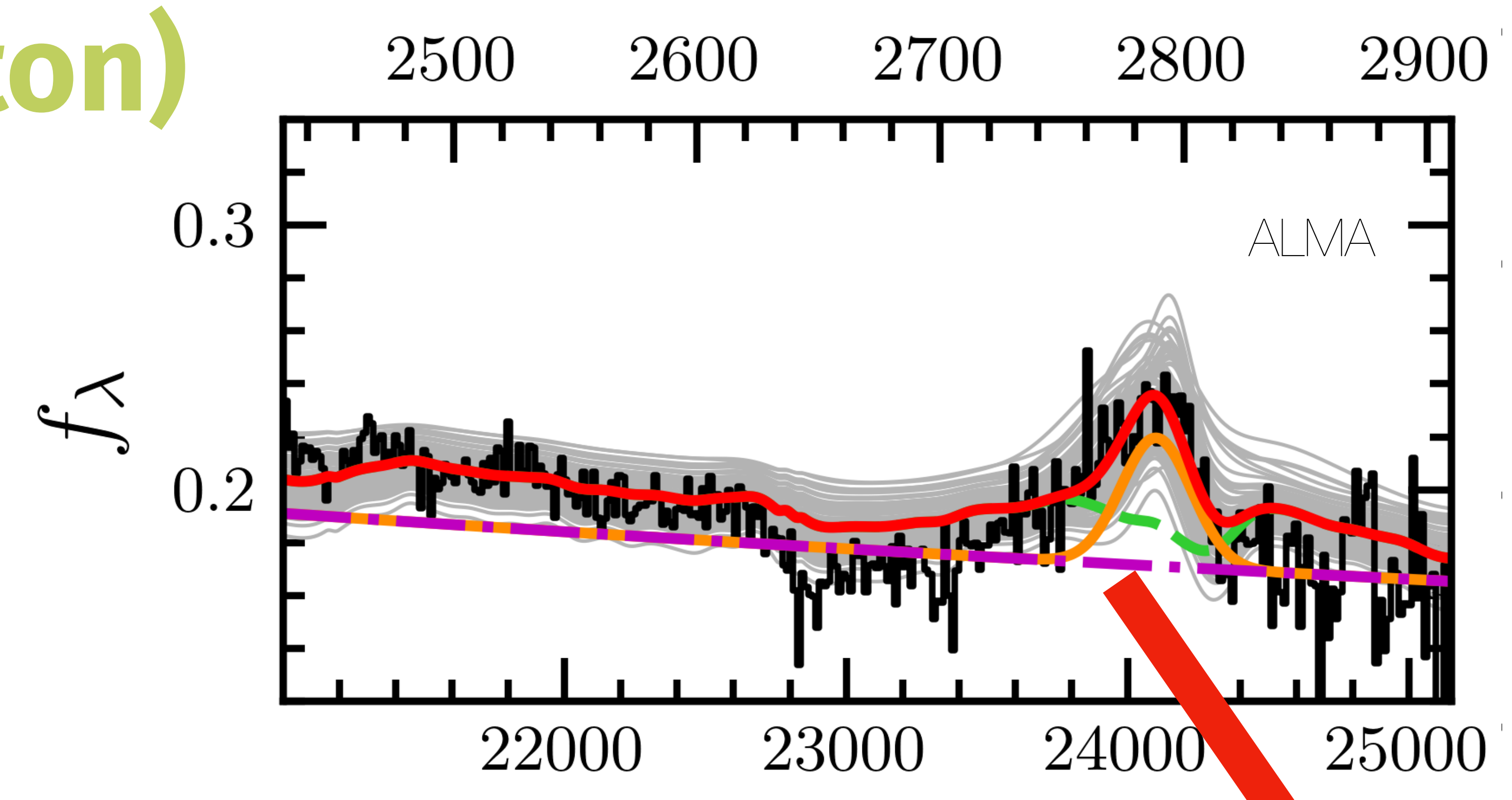
Mystery: supermassive black holes at high z

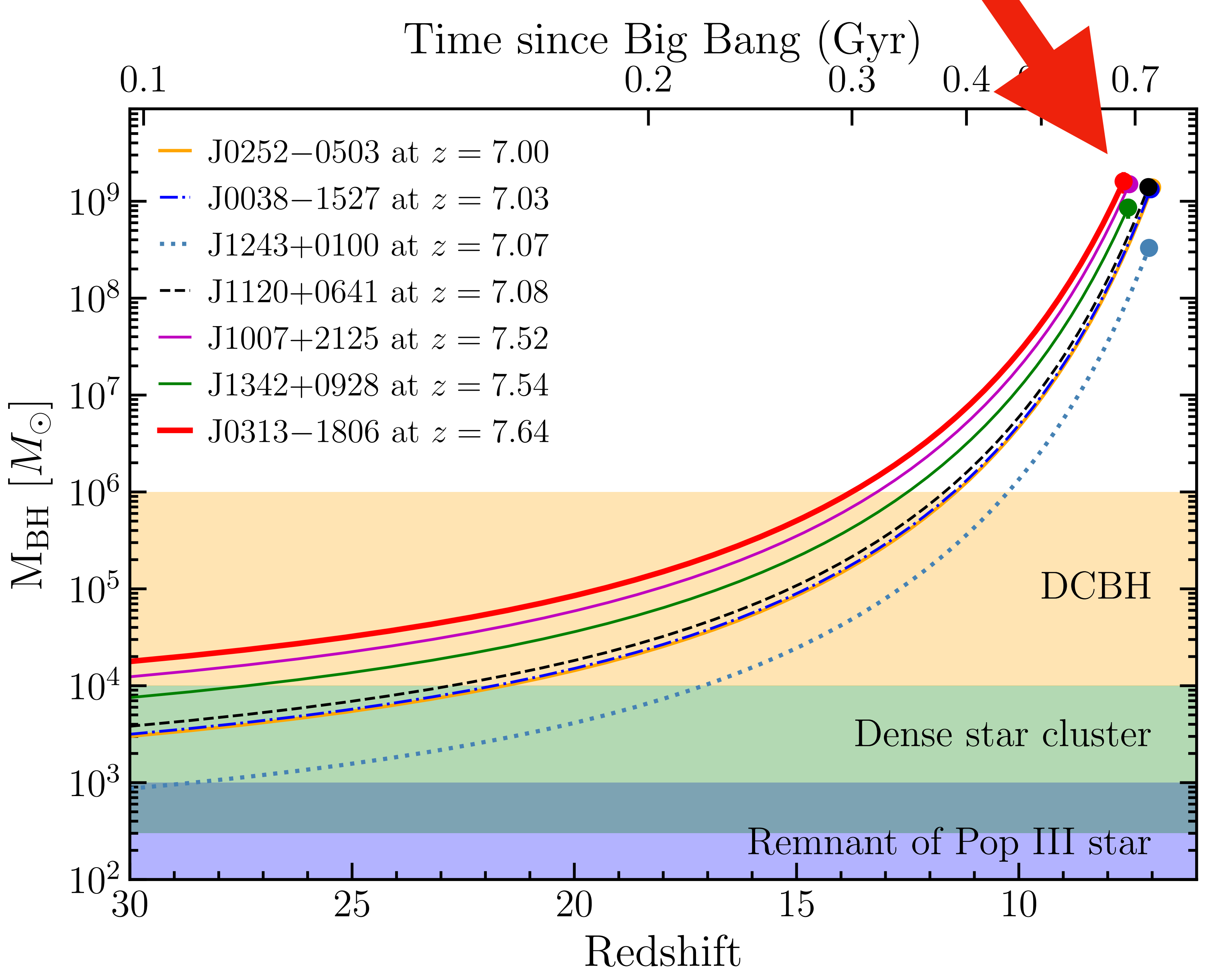
... not from ordinary black hole formation (Pop III Eddington)



TIME →

Jeon, Bromm, Liu, Finkelstein 2402.18773 (JWST)





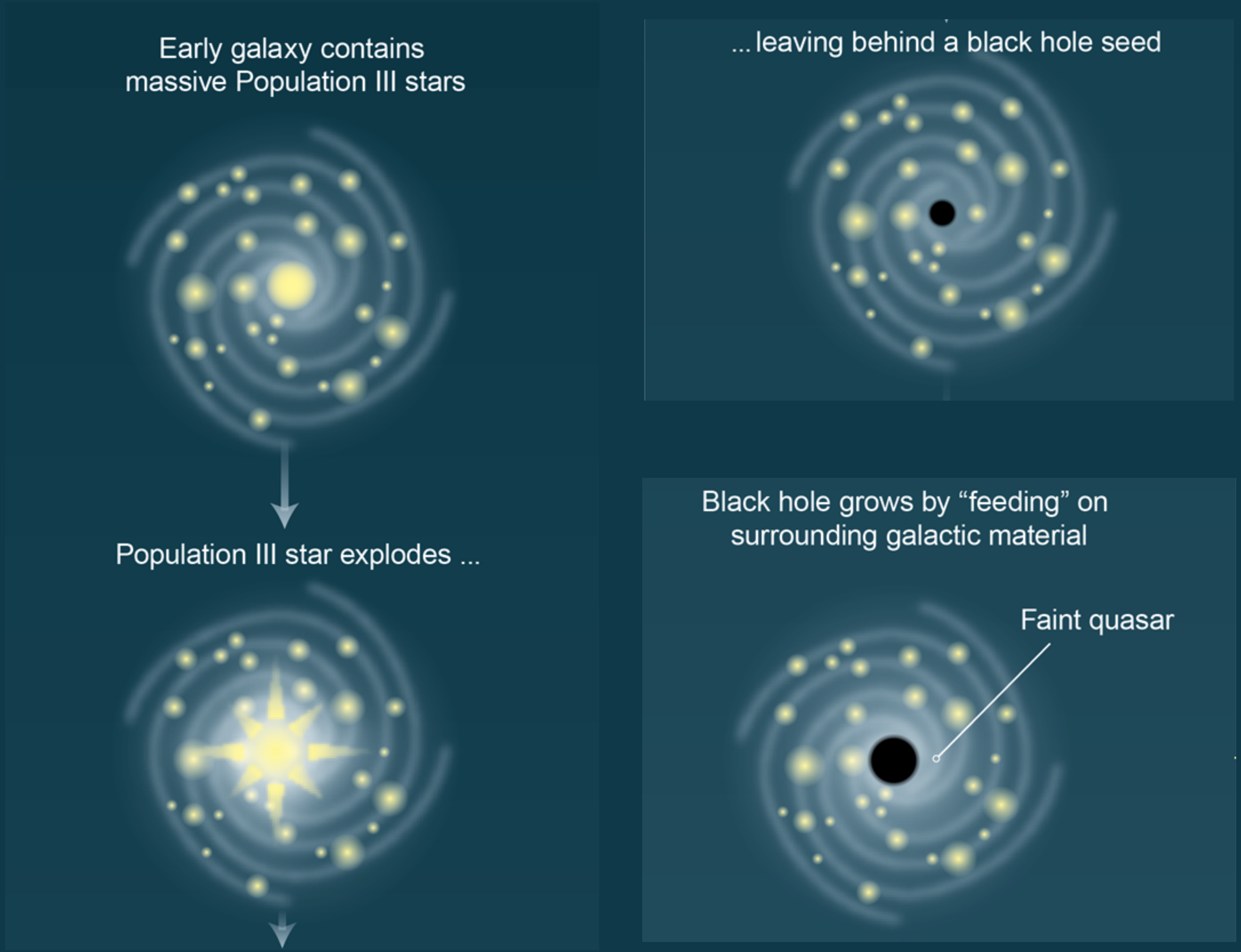
2101.03179 Wang et al. "A luminous quasar at z=7.2

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.



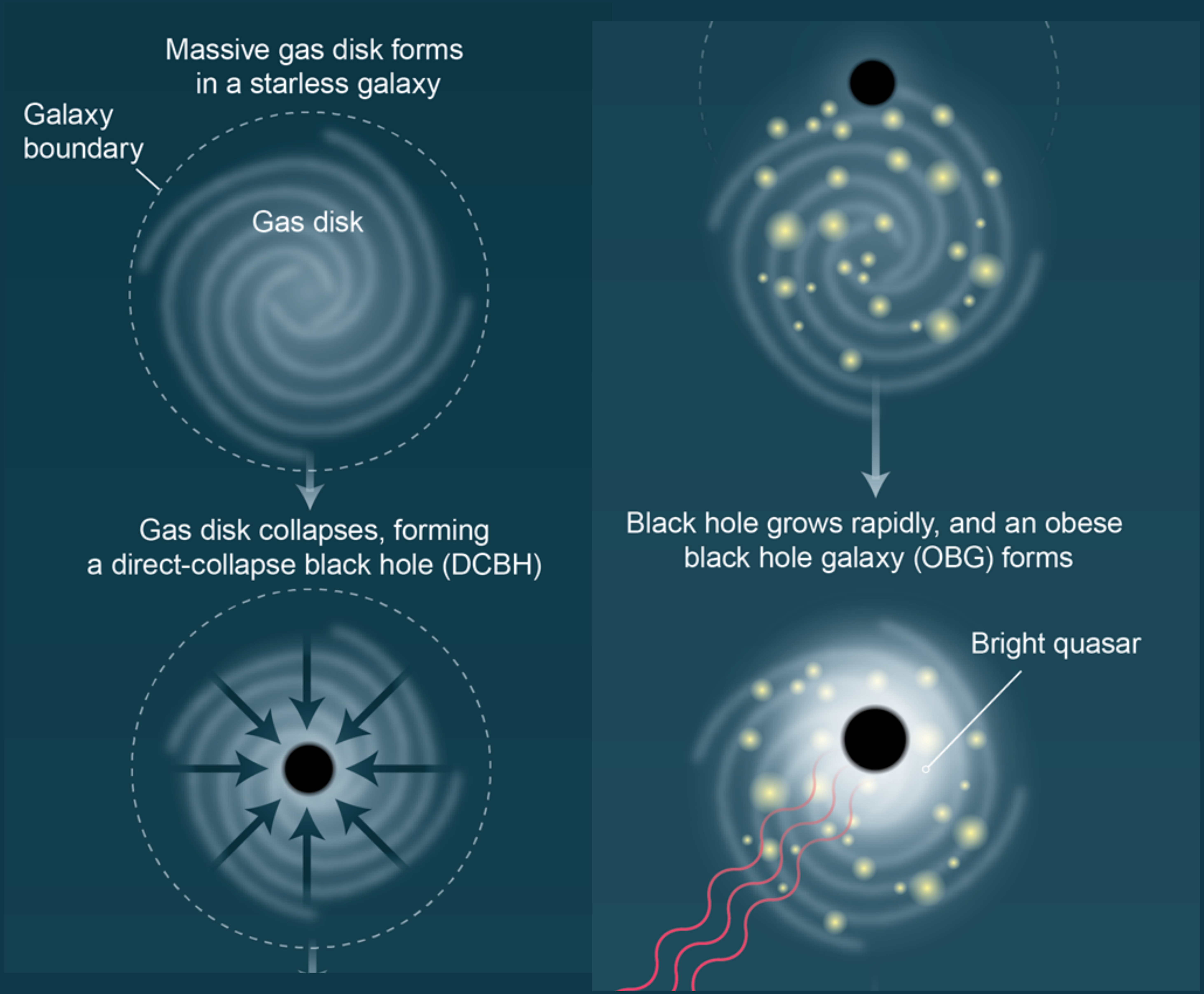
Amanda Montañez, "Puzzle of the First Black Holes," P. Natarajan, *Scientific American* 318, 2, 24-29 (2018)

DIRECT COLLAPSE

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

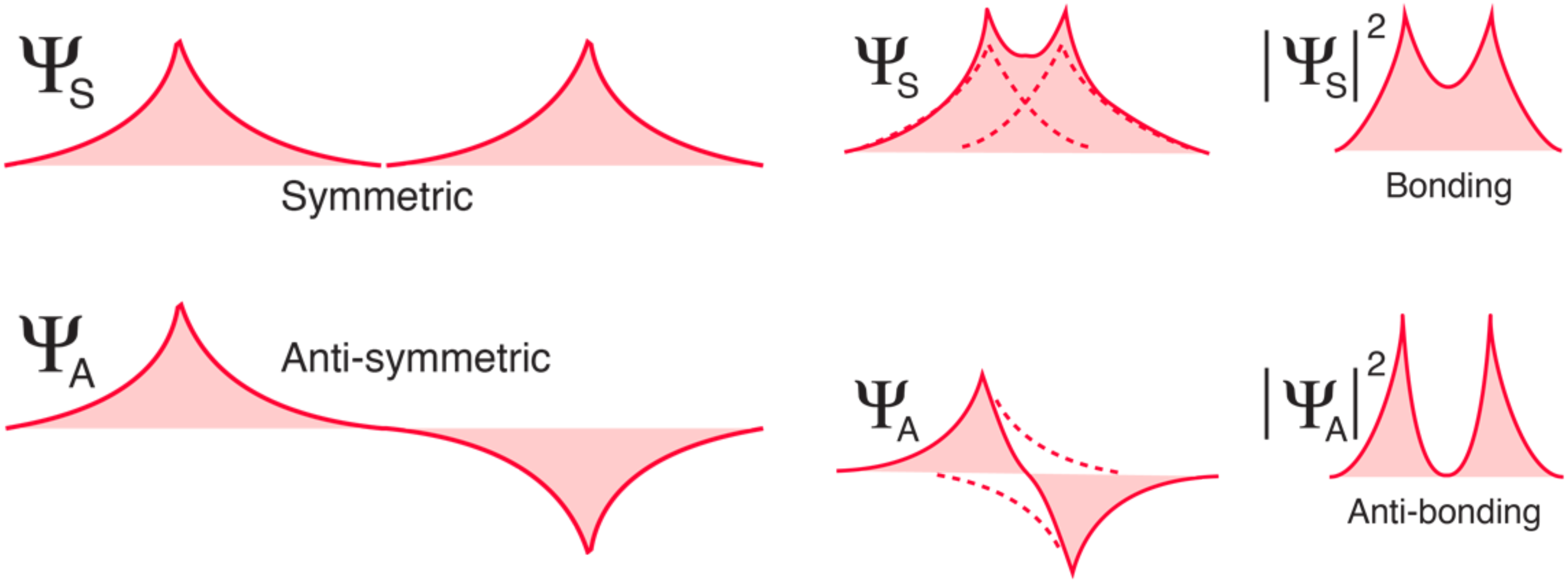
Quickly produces black holes that can grow very large.

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



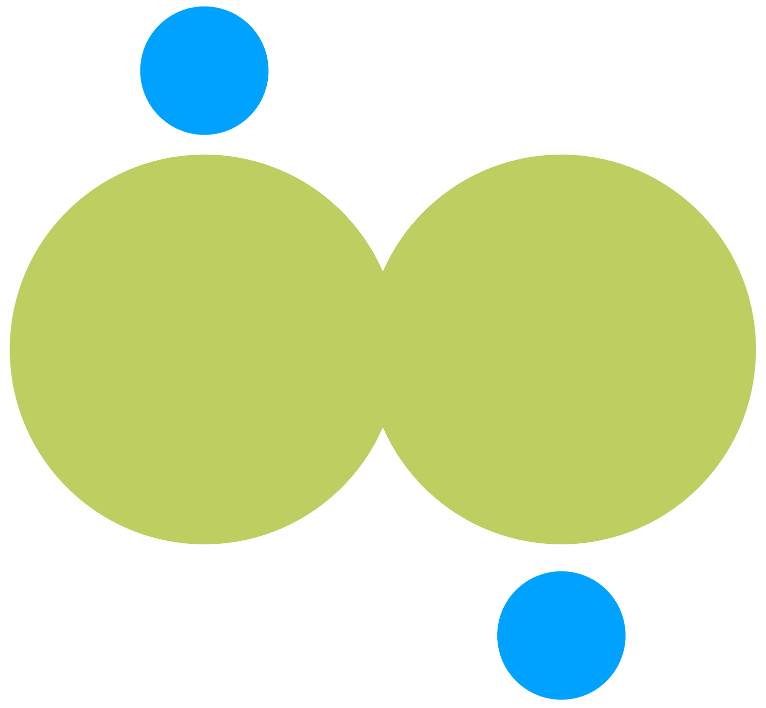
Amanda Montañez, "Puzzle of the First Black Holes," P. Natarajan, *Scientific American* 318, 2, 24-29 (2018)

The game: do not let molecular hydrogen H_2 cool the gas



ground

unbound



Vibrational modes: efficient cooling (*only* channel in low temp protogalaxy)

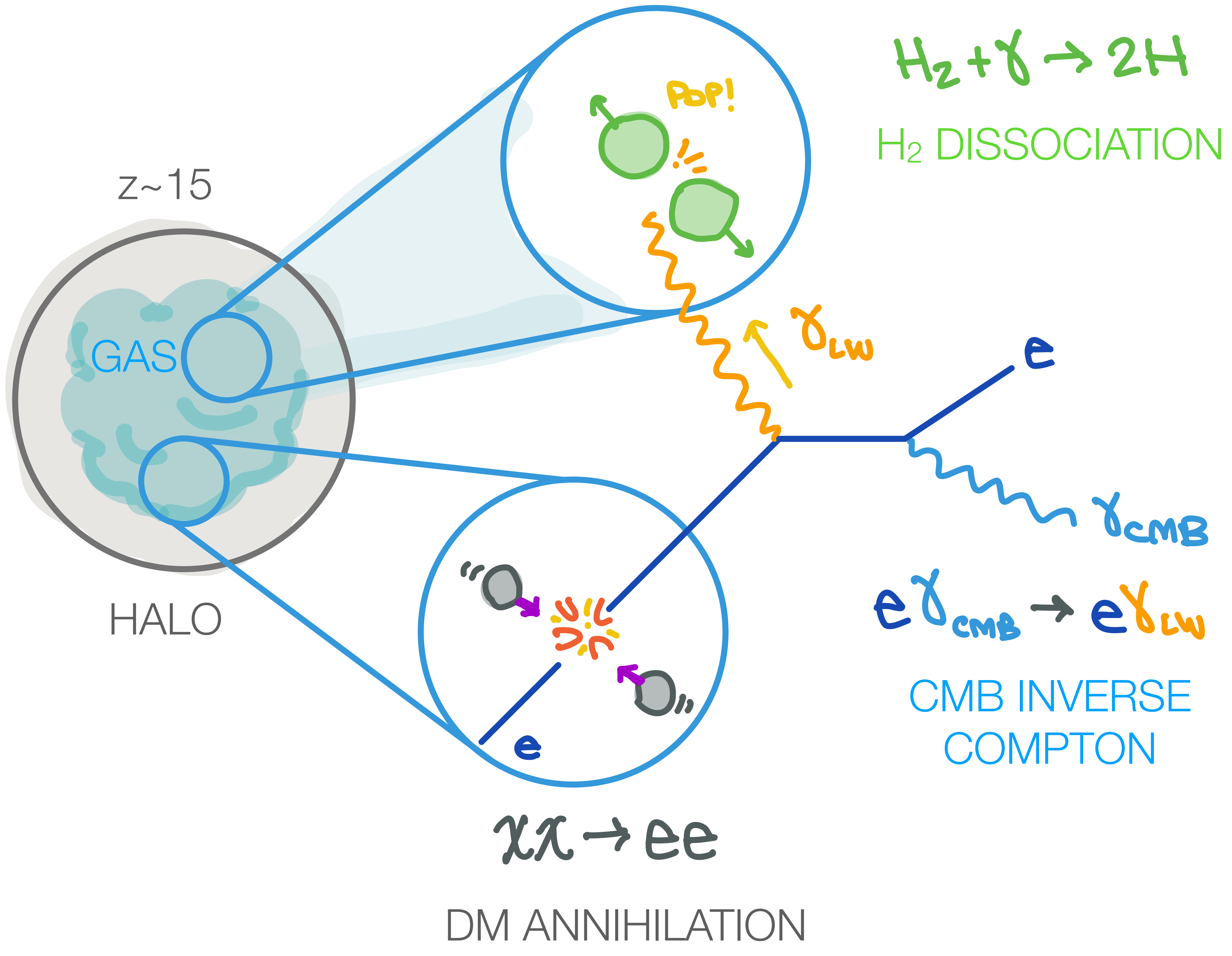
Dissociation: need O(10 eV) excitation to Lyman/Werner bands, then probability to de-exciting into unbound state (no direct E. dipole transition)

hyperphysics.phy-astr.gsu.edu/hbase/molecule/hmol.html

Can dark matter induce direct collapse black holes in pre-star forming halos?

I am not sure… **maybe**.

Current focus is clarifying the challenge relative to a simple benchmark model



Recent Work: SMBH and dark matter

SMBH seeds from sub-keV dark matter
Avi Friedlander, Sarah Schon, Aaron C. Vincent
arXiv:**2212.11100**

Feeding plankton to whales: high-z SMBH from tiny black hole explosions
Yifan Lu, Zachary S. C. Picker, Alexander Kusenko
arXiv:2312.15062

Direct collapse SMBH from relic decay
Yifan Lu, Zachary Picker, Alexander Kusenko
arXiv:2404.03909

SMBH Seeds from Dissipative Dark Matter
H. Xiao, X. Shen, P. Hopkins, K. Zurek
arXiv:2103.13407

Primordial seeds of supermassive black holes
M. Kawasaki, A. Kusenko, T. Yanagida
arXiv:1202.3848

Seeding SMBH with SIDM
Wei-Xiang Feng, Hai-Bo Yu, Yi-Ming Zhong
arXiv:2010.15132

SMBH from Ultra-Strongly SIDM
Jason Pollack, David Spergel, Paul Steinhardt
arXiv:1501.00017

DM and the 1st stars: a new phase of stellar evolution
Douglas Spolyar, Katherine Freese, Paolo Gondolo
arXiv:0705.0521

DM Annihilation and Primordial Star Formation
Aravind Natarajan, Jonathan Tan, Brian O'Shea
arXiv:0807.3769

Please let me know if there are missing references!

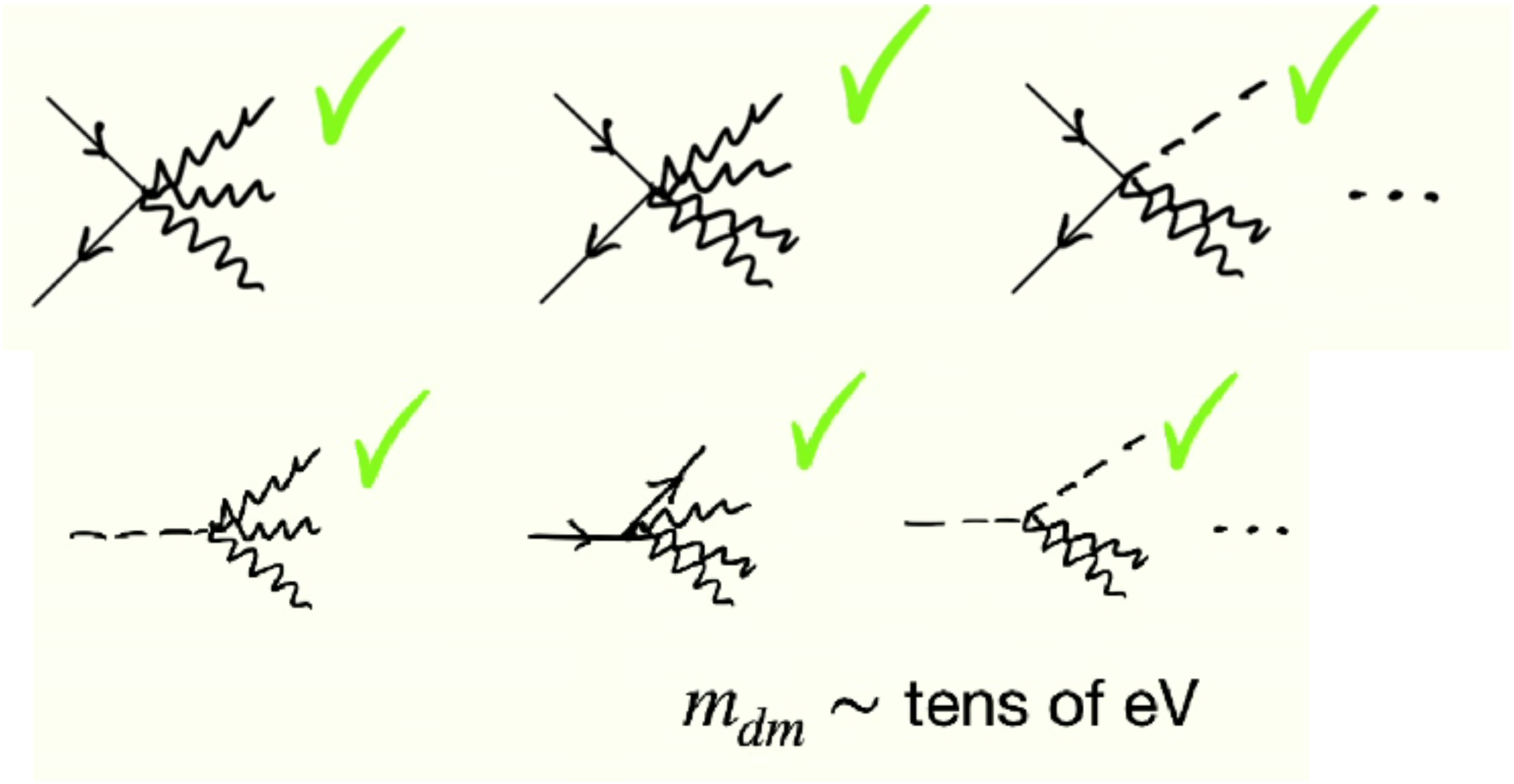
SMBH: Super Massive Black Hole; SIDM: Self-Interacting Dark Matter

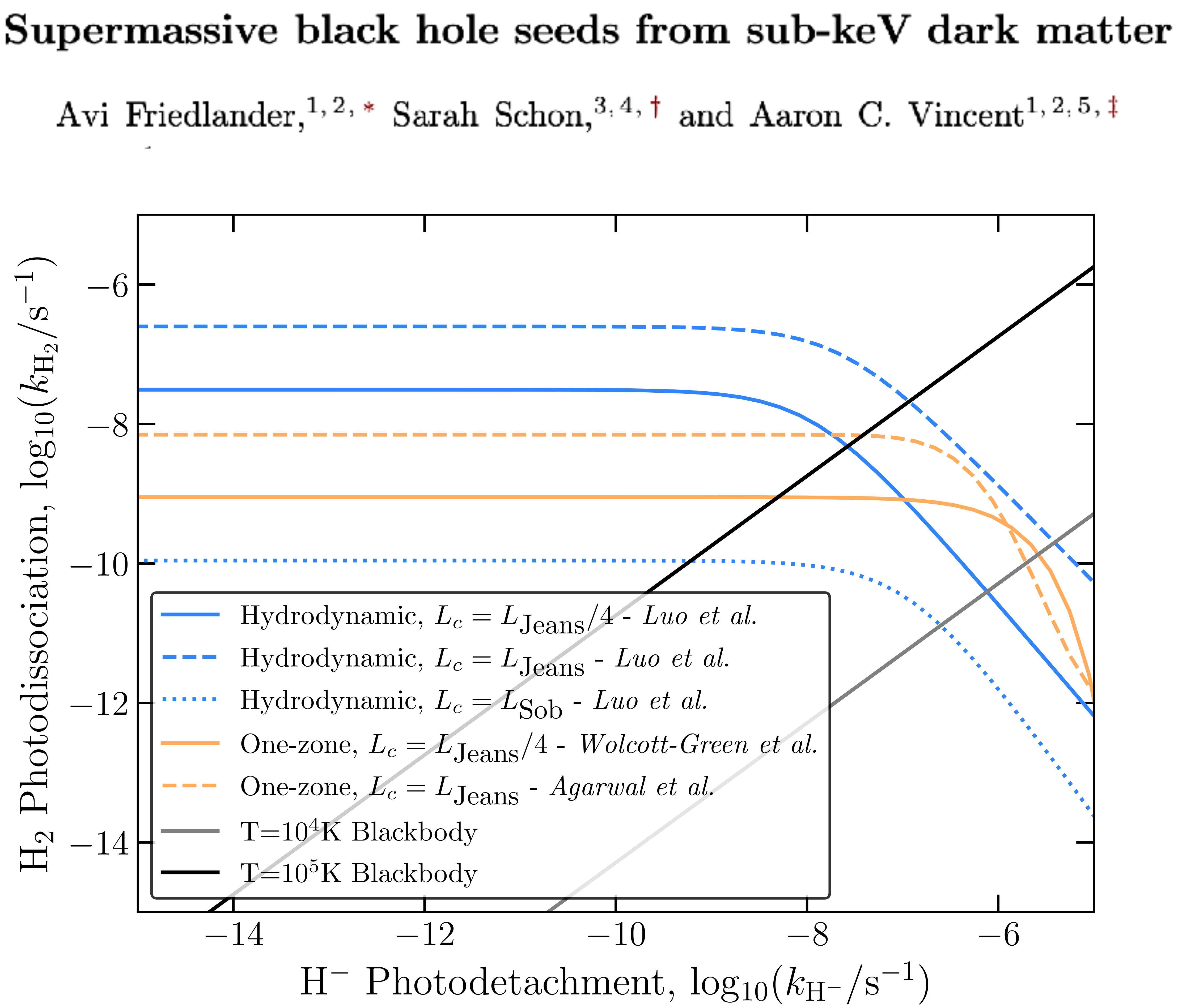
Mapping to Dark Matter

Friedlander, Schon, Vincent

First 'diagnosis' of new particle physics, identifies **self shielding** as a challenge.

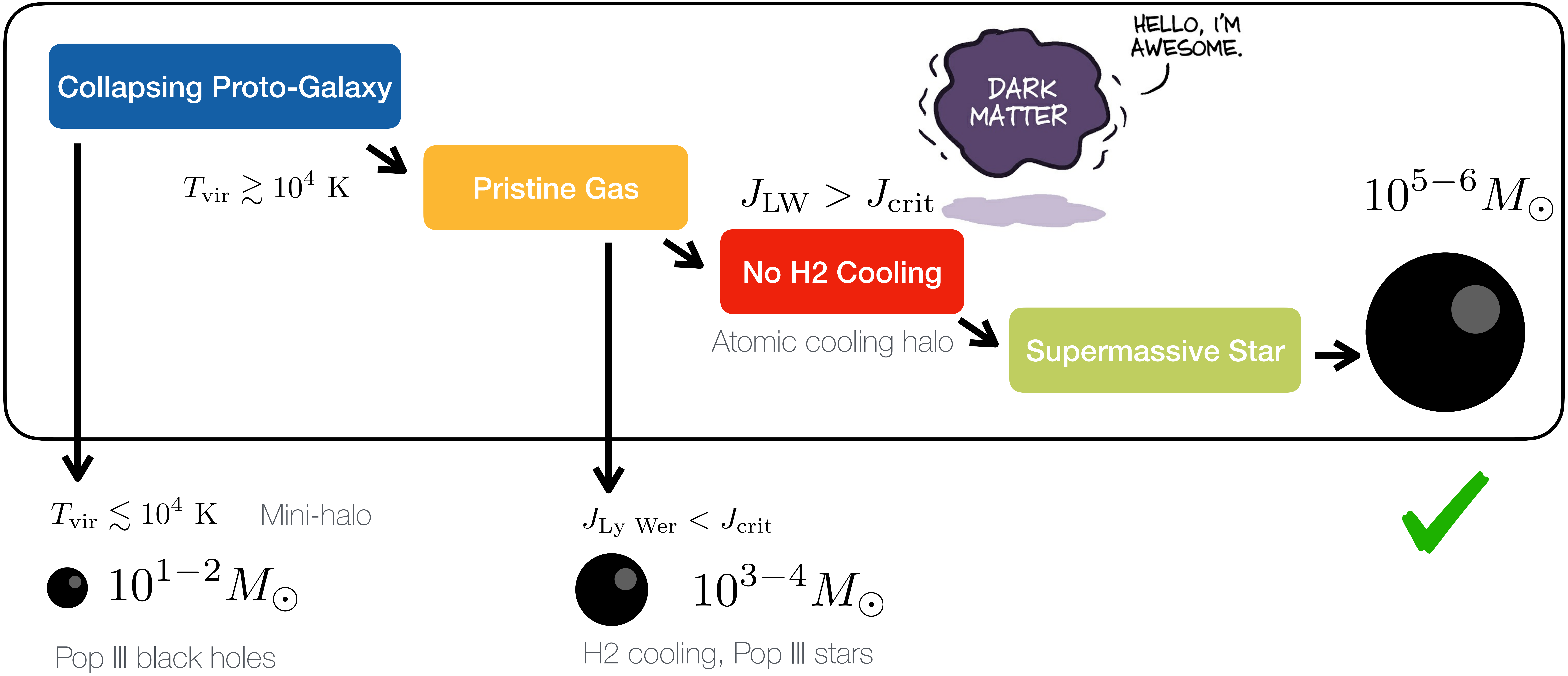
Direct production of multiple photons. (Broad Ly-Wer band)





"The [Ly-Wer] call is coming from inside the house"

arXiv:2212.11100; A. Vincent's talk at Dark Matter First Light (Feb 2024, PI)



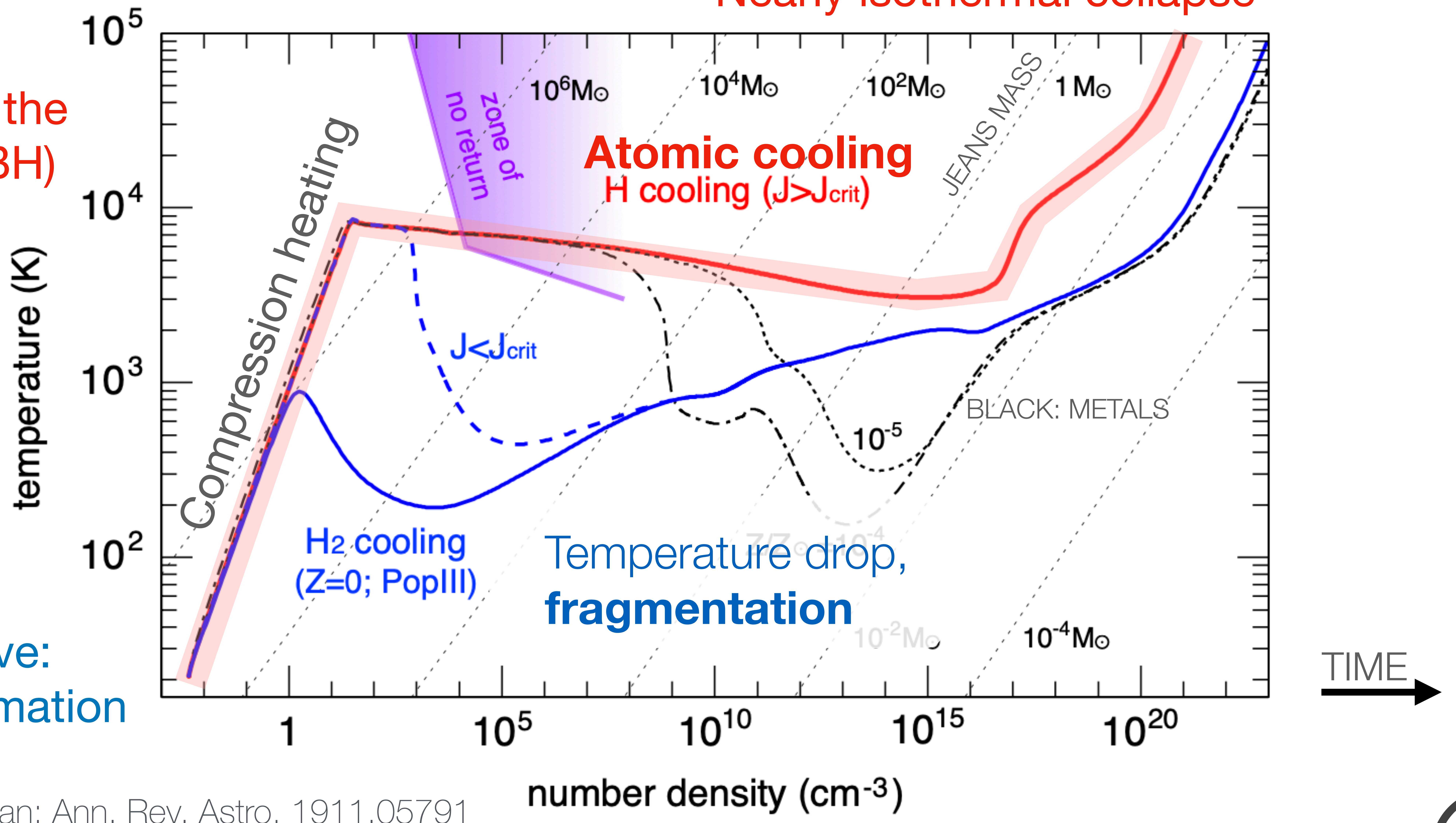
Adapted from Inayoshi, Visbal, Haiman; Ann. Rev. Astro, 1911.05791

Cham & Whiteson , *We Have No Idea*

Conditions for direct collapse

Want to follow the red curve (DCBH)

Avoid blue curve: Pop III star formation



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

Conditions for direct collapse

Want to follow the red curve (DCBH)

Avoid blue curve: Pop III star formation

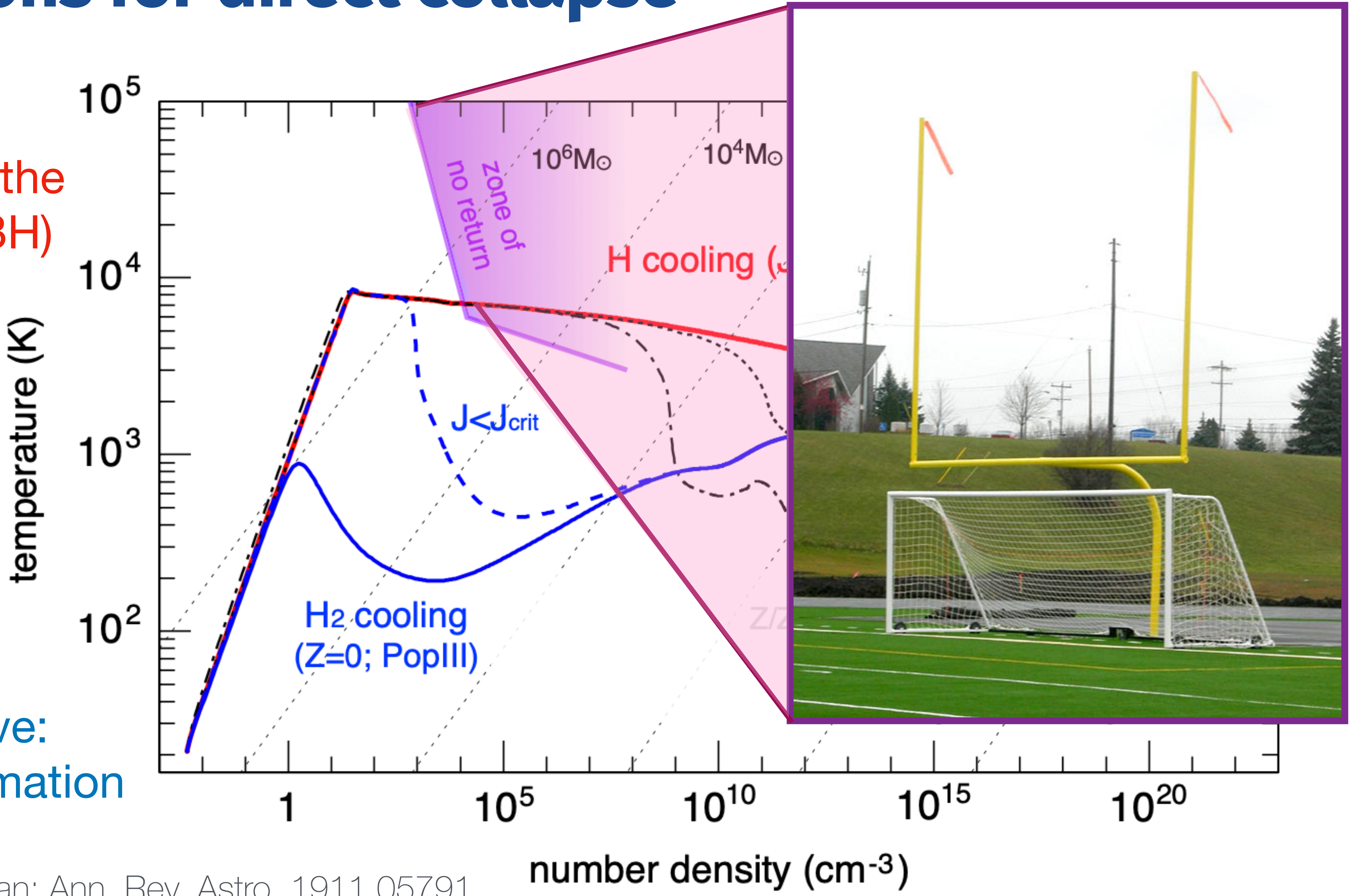


Image: jwindustriesinc.com

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

Conditions for direct collapse

- No metals (pre-stellar halo)
  Metals are the usual gas coolants in modern halos.

- Atomic cooling at 10^4 K
  Gas near virial temperature, allows collapse but not fragmentation.

- Suppress H_2 formation
  Molecular cooling leads to a rapid temperature drop and gas fragmentation (leads to Pop III stars).

astrophysics

Image: jwindustriesinc.com

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

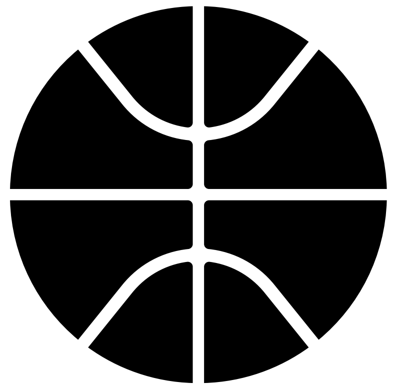
Conditions for direct collapse

- No metals (pre-stellar halo)
  Metals are the usual gas coolants in modern halos.

- Atomic cooling at 10^4 K
  Gas near virial temperature, allows collapse but not fragmentation.

- Suppress H_2 formation
  Molecular cooling leads to a rapid temperature drop and gas fragmentation (leads to Pop III stars).

astrophysics



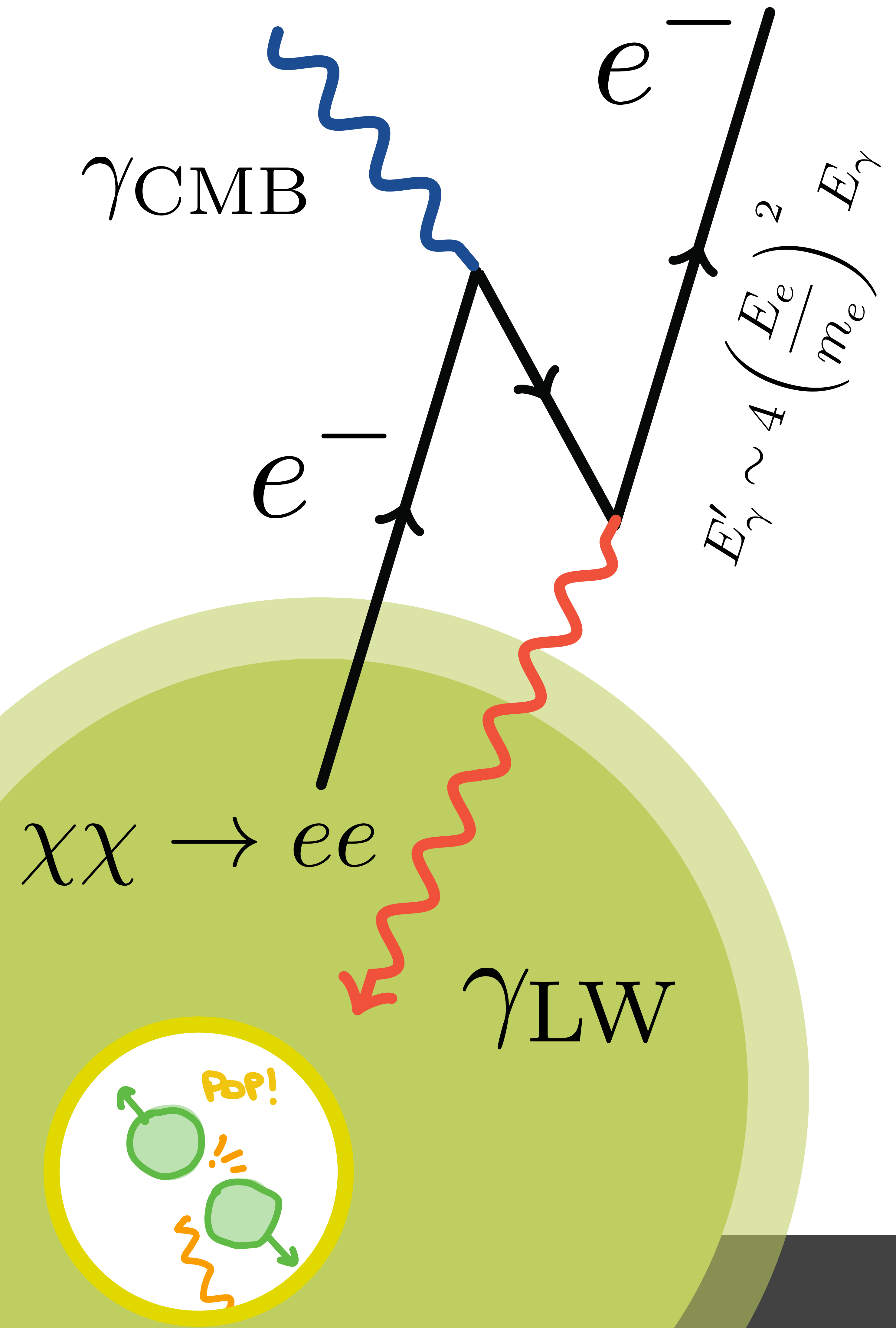
Dark matter?

Image: jwindustriesinc.com

From TAMU visitor guide

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

Strategy



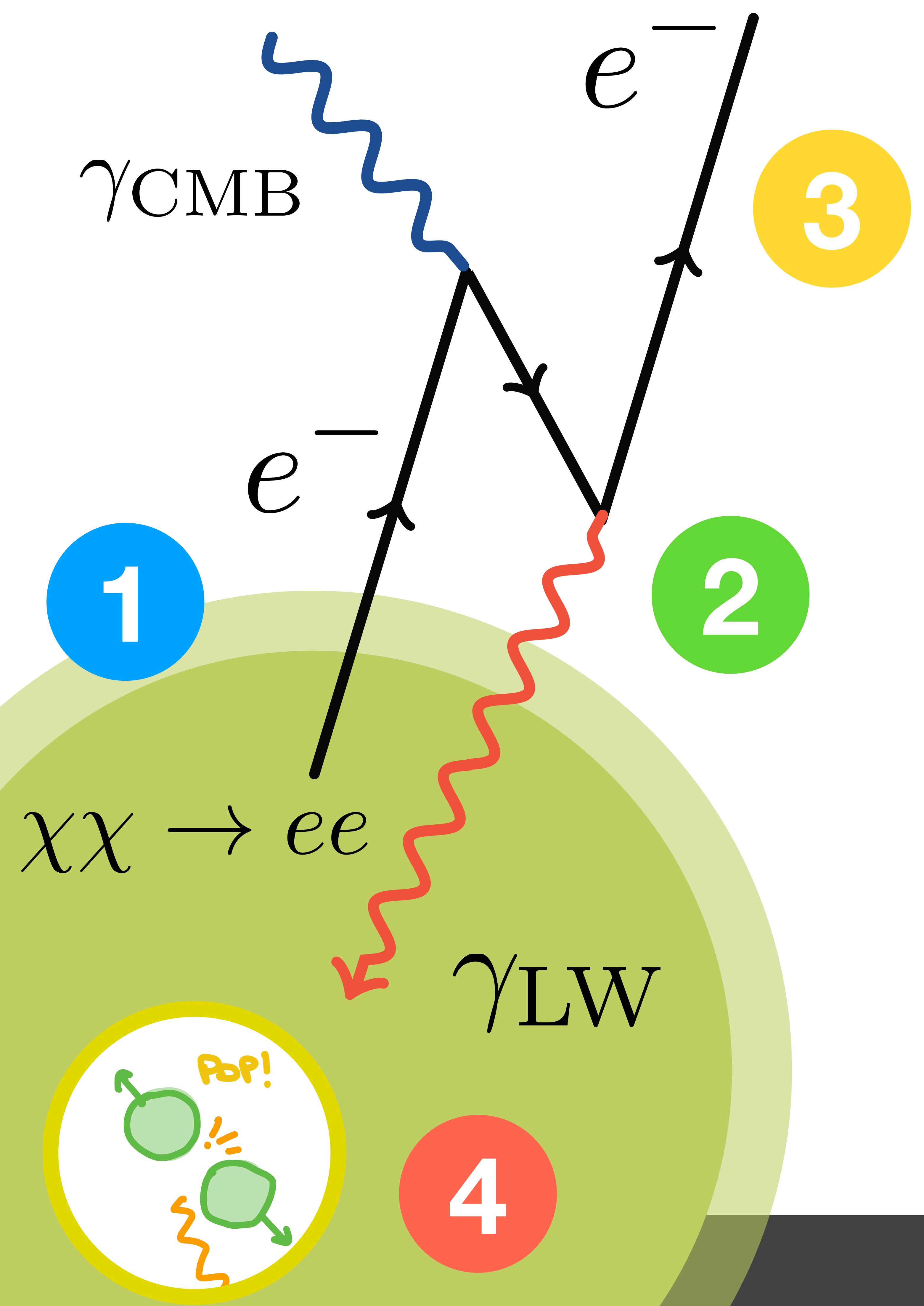
Start with: 10^6 $M_\odot$ halo at $z \sim 25$

20 MeV dark matter annihilates to e^+e^-.

e^- **Inverse Compton** scatters off CMB; produces ~10 eV photons (Ly-Wer) that dissociate H_2.

Atomic cooling kicks in at z ~ 12.5, expect DCBH.

Strategy



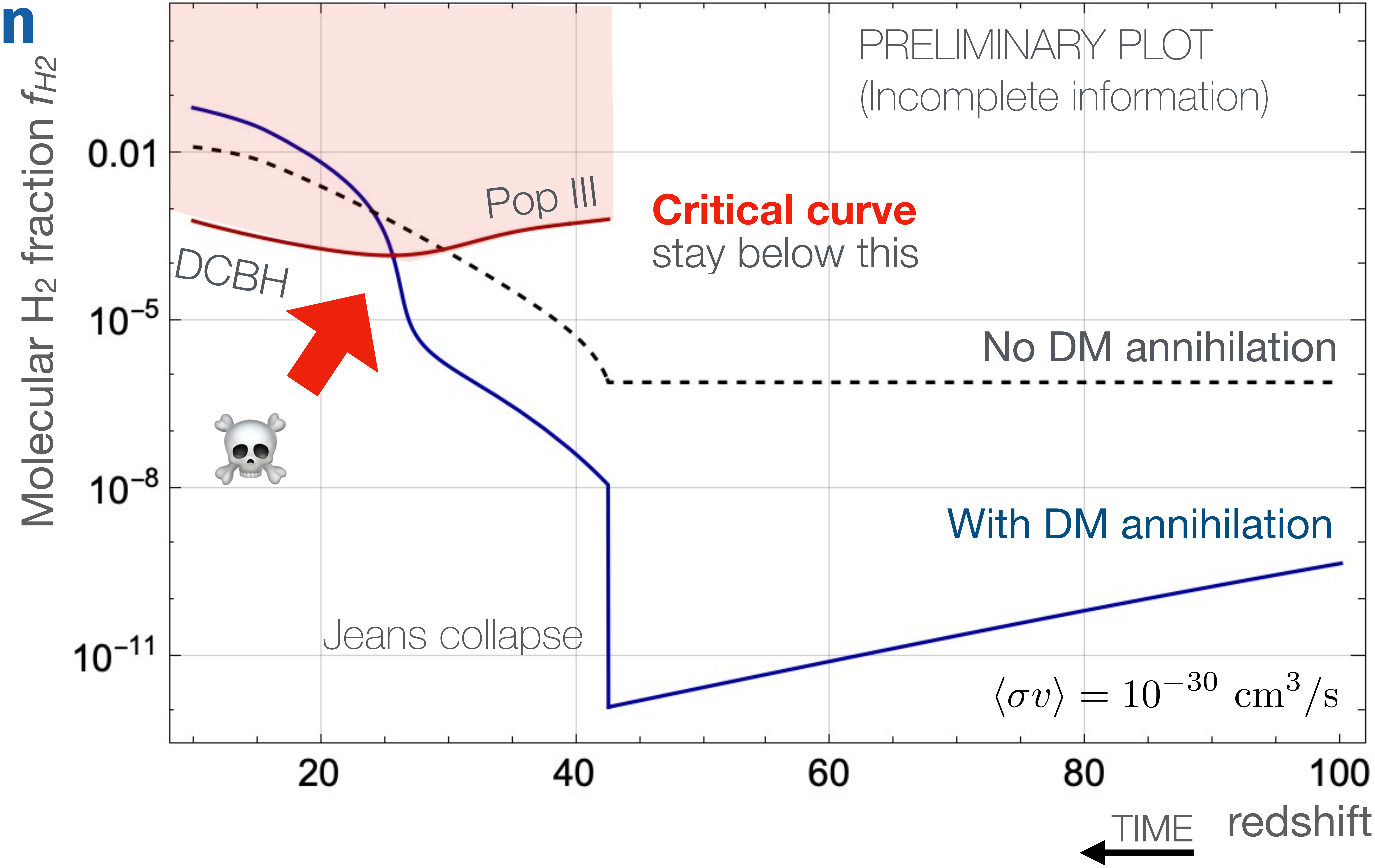
1. Tie annihilation rate to χ abundance
e at this energy leave halo
… so halo is a point source; radial trajectory
solve transport equation for E spectrum

2. $$E'_\gamma \sim 4\left(\frac{E_e}{m_e}\right)^2 E_\gamma$$
Select χ mass to produce LW photons

3. Intergalactic medium is optically thick to heating and ionization
Good: this stuff would change the gas chemistry and could cause *more* H2 formation.

4. Intergalactic medium is transparent to LW radiation, so this returns to the halo
Good: this stuff breaks down H2!

H_2 fraction



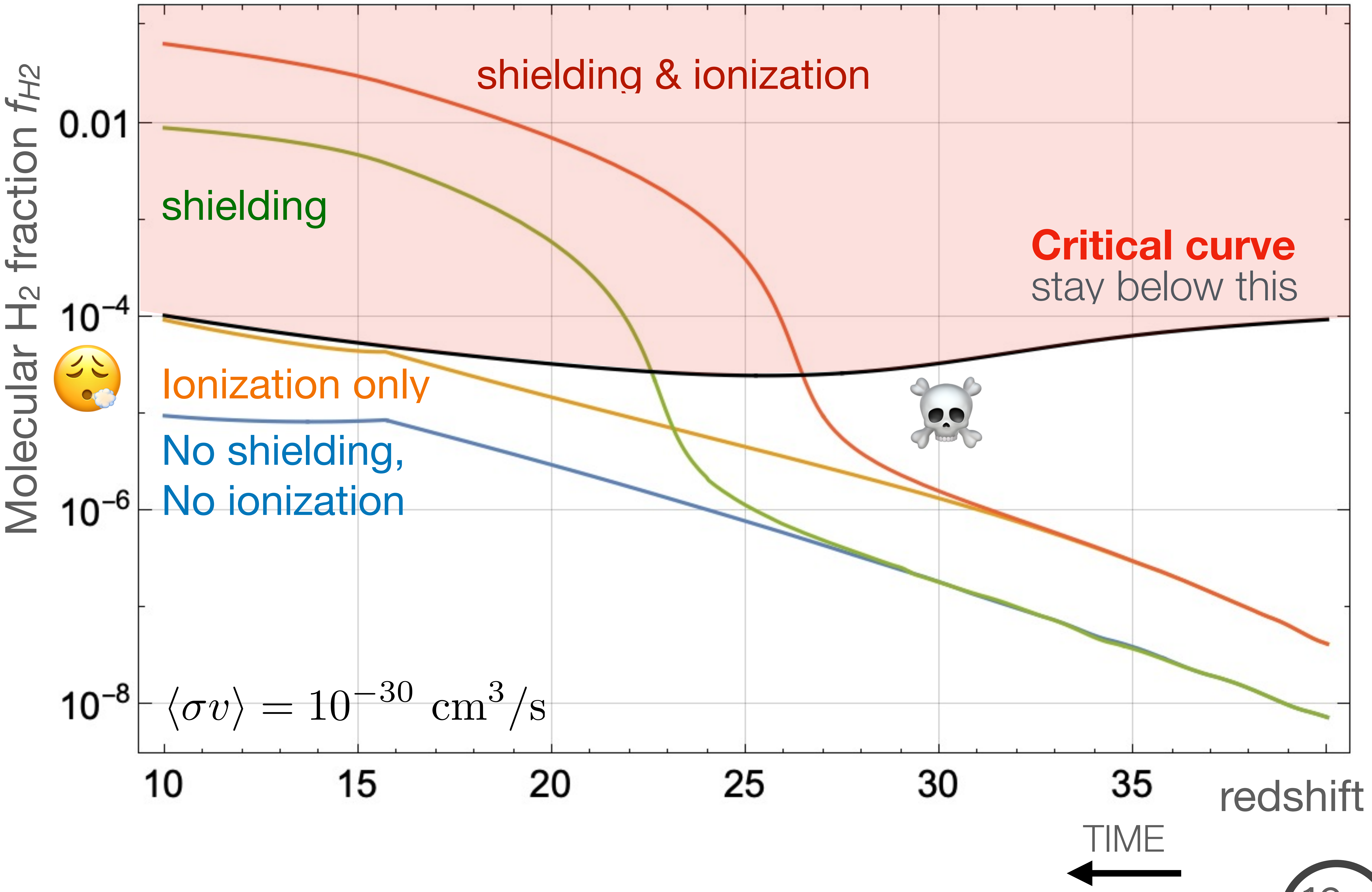
Molecular H_2 fraction f_{H2}
0.01
10^{-5}
10^{-8}
10^{-11}
20
40
60
80
100
redshift
TIME
PRELIMINARY PLOT
(Incomplete information)
Pop III
DCBH
Critical curve
stay below this
No DM annihilation
With DM annihilation
Jeans collapse
$\langle \sigma v \rangle = 10^{-30}\ \mathrm{cm}^3/\mathrm{s}$

H_2 fraction

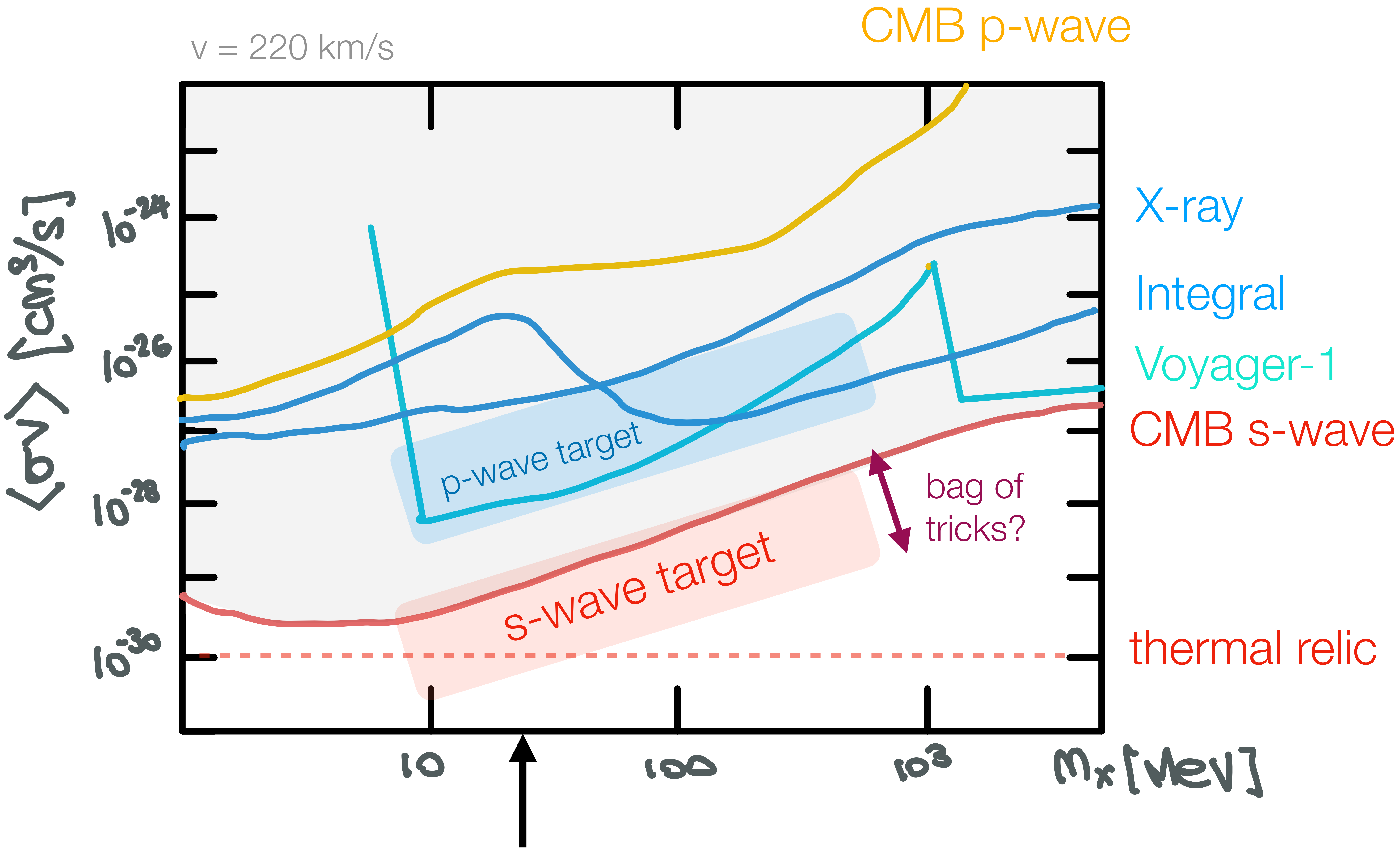
Challenge:
self-shielding

If H_2 does build up, then our efforts fail because electrons catalyze H_2 formation

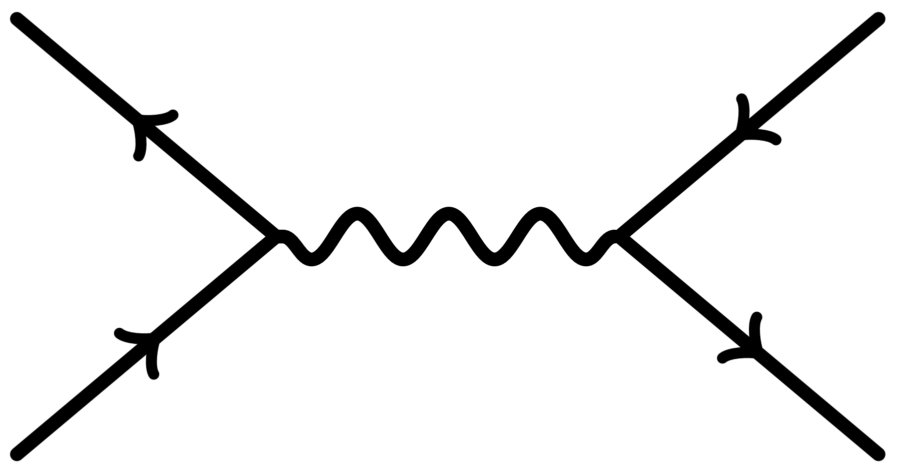
Solve rate eqns.



Hypothetical plot

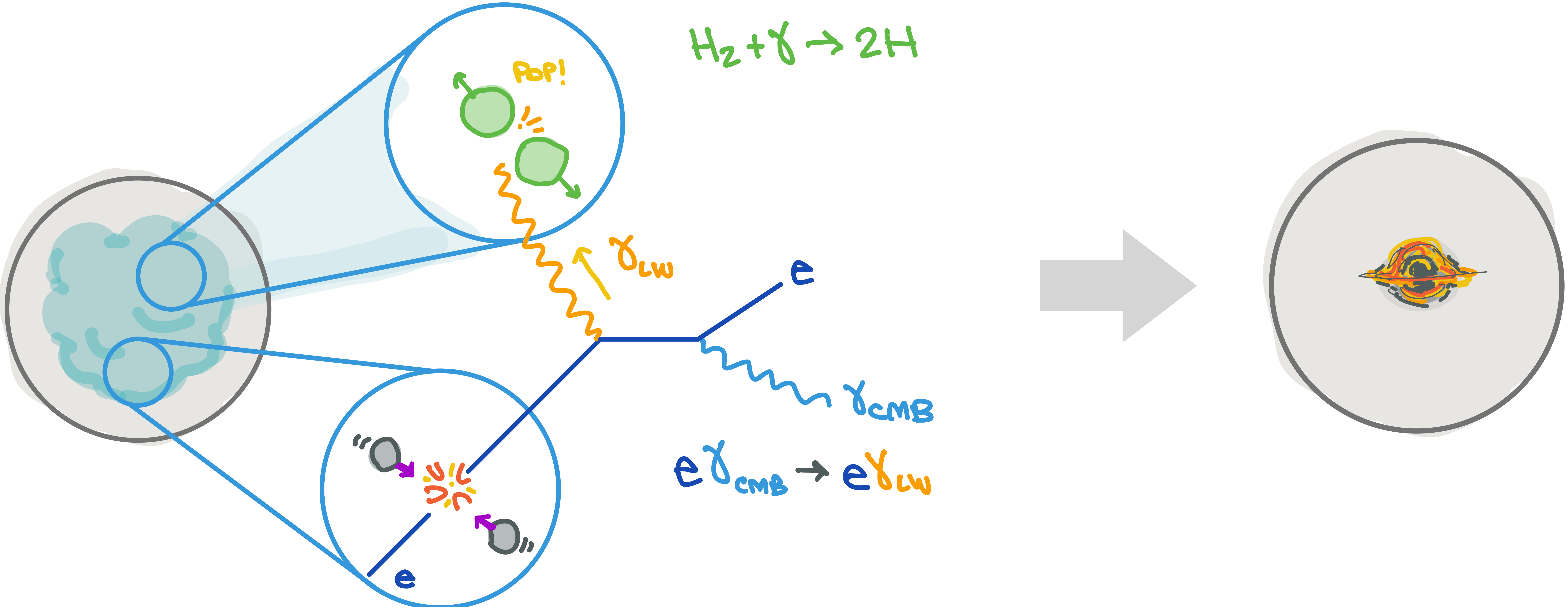


Based on Cirelli, Fornengo, Kavanah, Pinetti; Fig. 52007.11493



"Resonant Sub-GeV Dirac Dark Matter" Bernreuther, et al. (2010.14522); see also Feng (1707.03835)

Thanks!



POP!
$H_2 + \gamma \to 2H$
γ_{LW}
e
γ_{CMB}
$e\gamma_{CMB} \to e\gamma_{LW}$
e

Extra Slides

… mainly for those looking at the slides afterward

- See also talks & discussion at *Dark Matter, First Light* (Feb 2024)
  https://pirsa.org/c24015

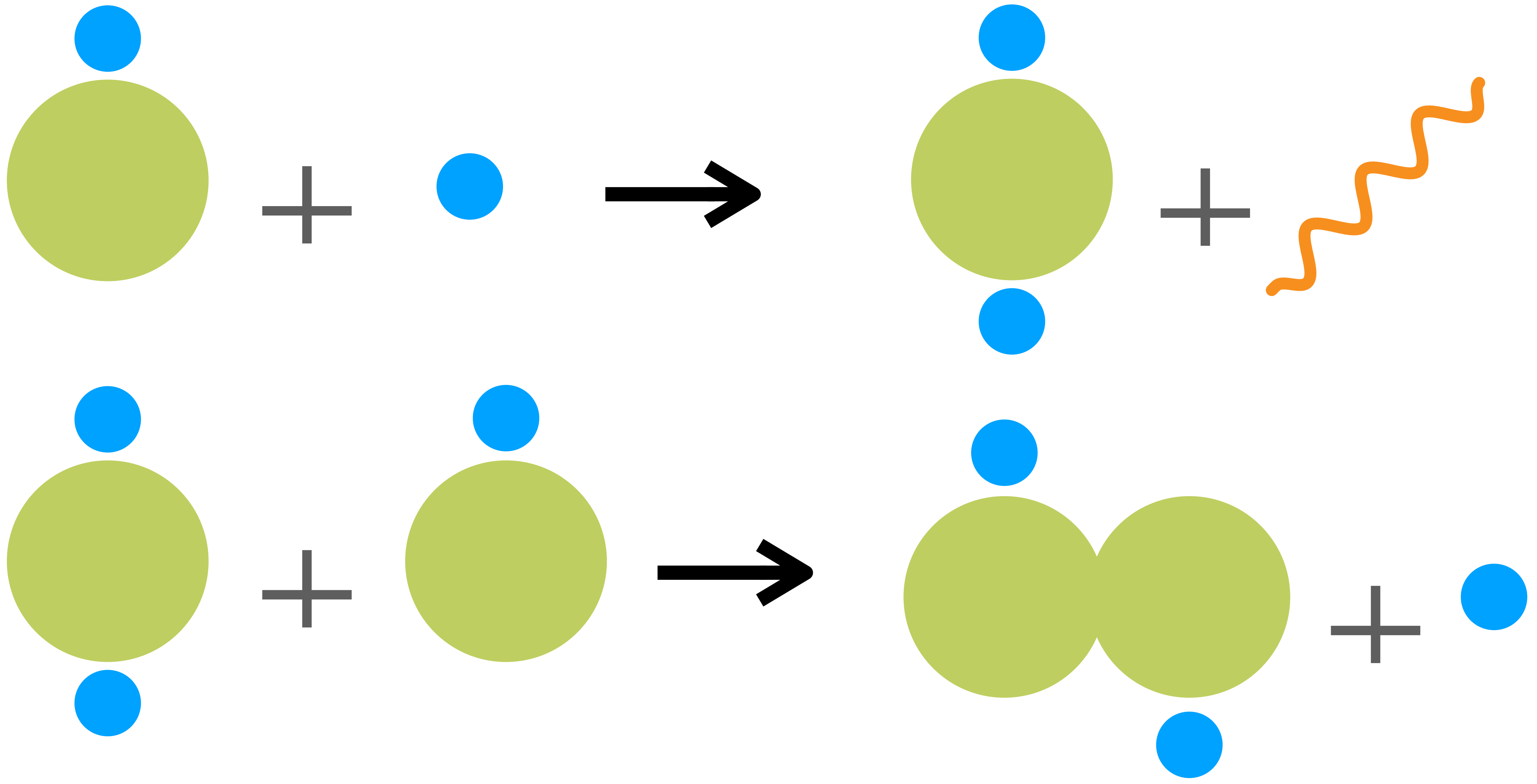
Molecular Hydrogen H_2

Formation of Molecular Hydrogen

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

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

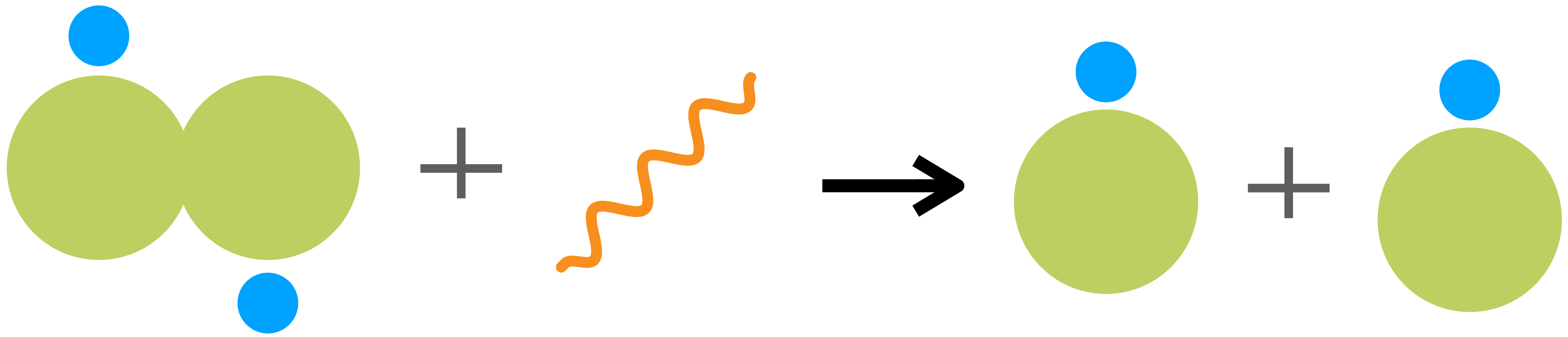
Formation



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)

Dissociation



Ly Wer radiation

Photodissociation

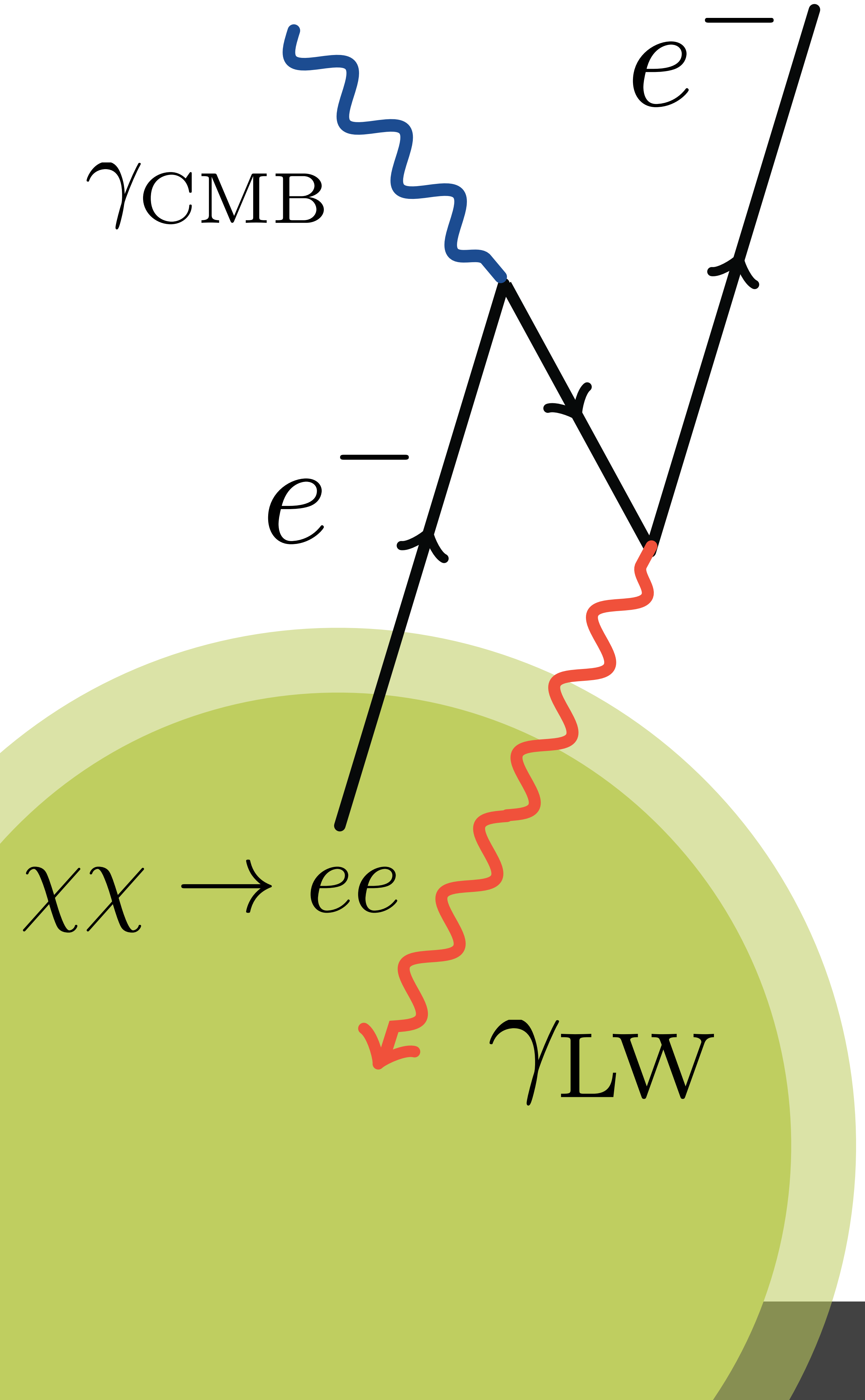
$$\mathrm{H}_2 + \gamma_{\mathrm{LW}} \rightarrow H + H$$

& photodetachment for lower energies.

Idea: Don't let self-shielding build up

BBC Frozen Planet, "Criminal Penguins" (2011)

Some Assumptions



Pick a slow growing halo

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

$$M_{\rm halo}(z=25) = 10^6\, M_\odot$$

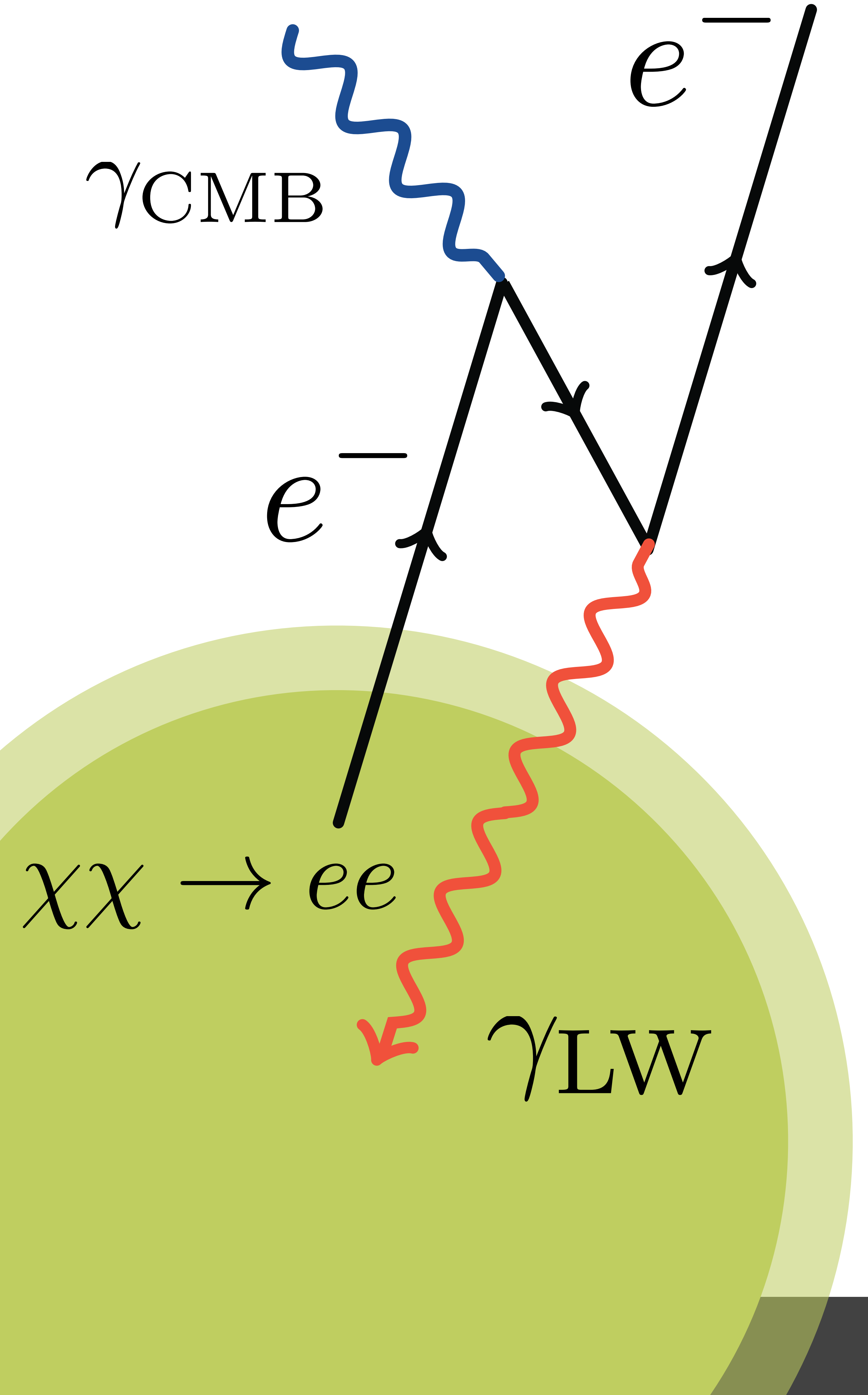
$$T_{\rm gas}(z=12) = 10^4\ {\rm K}$$

Conservative (slow) halo growth rate; faster growth can cause dynamical heating (which helps)

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.

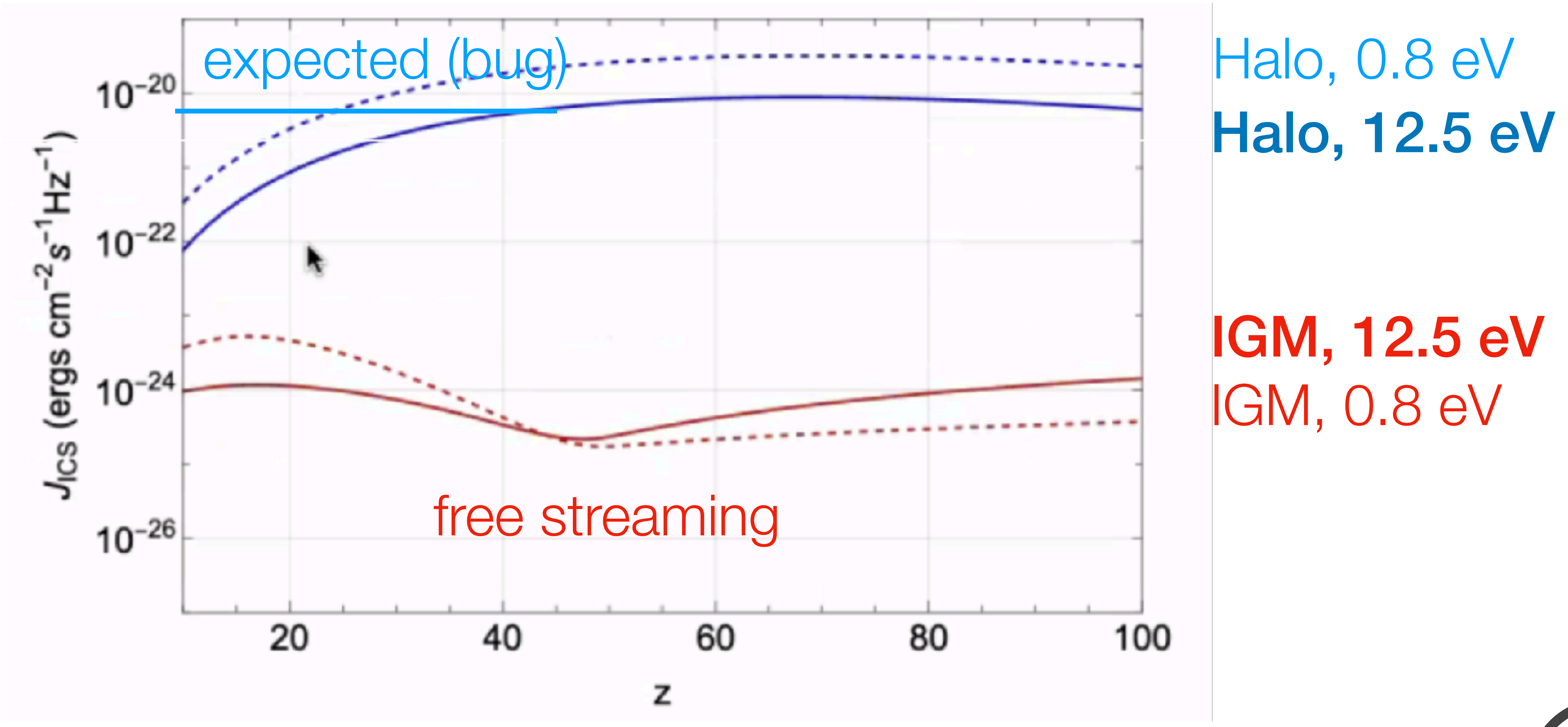
Halo + Transport

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

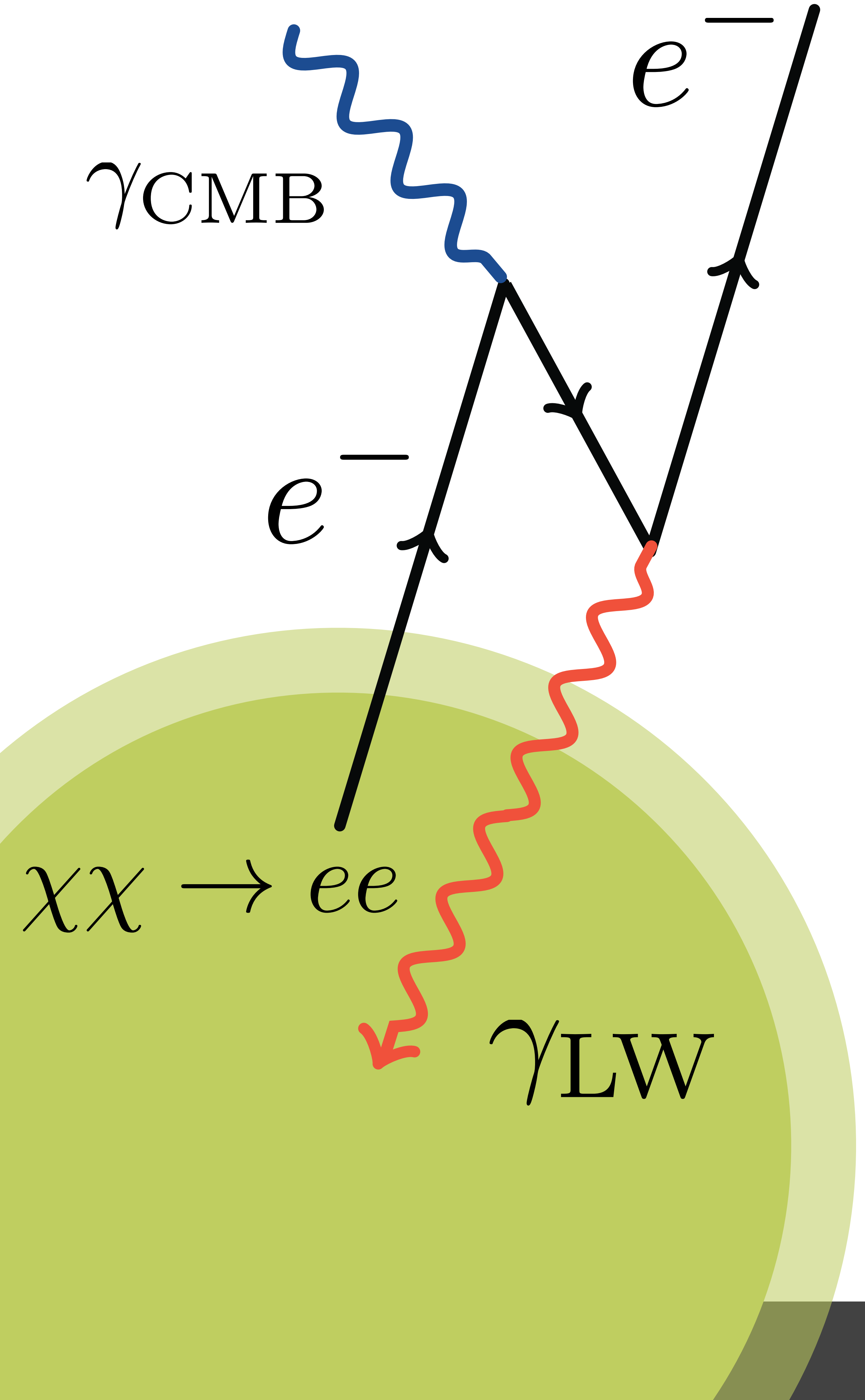


"Birth of the first stars amidst decaying and annihilating dark matter"
Wenzer Qin, Julian B. Munoz, Hongwan Liu, Tracy R. Slatyer (2308.12992)

PRELIMINARY



Halo + Transport



Solve electron transport: linear regime; solvable analytically

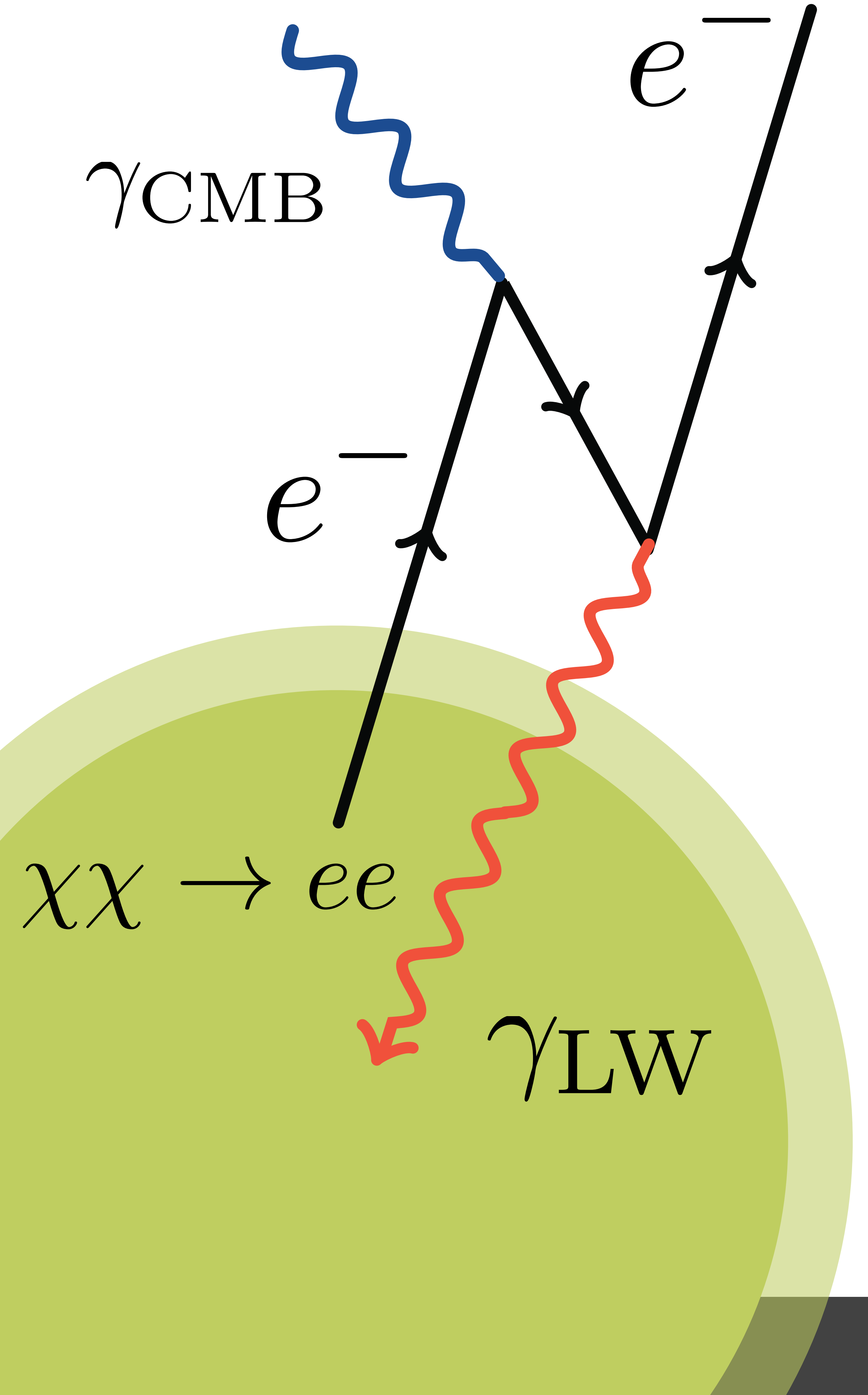
$$\partial_t \mathcal{N}_e - \nabla \cdot \left[\mathcal{K}(E,\mathbf{x})\,\nabla \mathcal{N}_e\right] + \partial_E \left[\dot{\mathcal{E}}(E,\mathbf{x})\,\mathcal{N}_e\right] = Q_e(E,\mathbf{x})$$

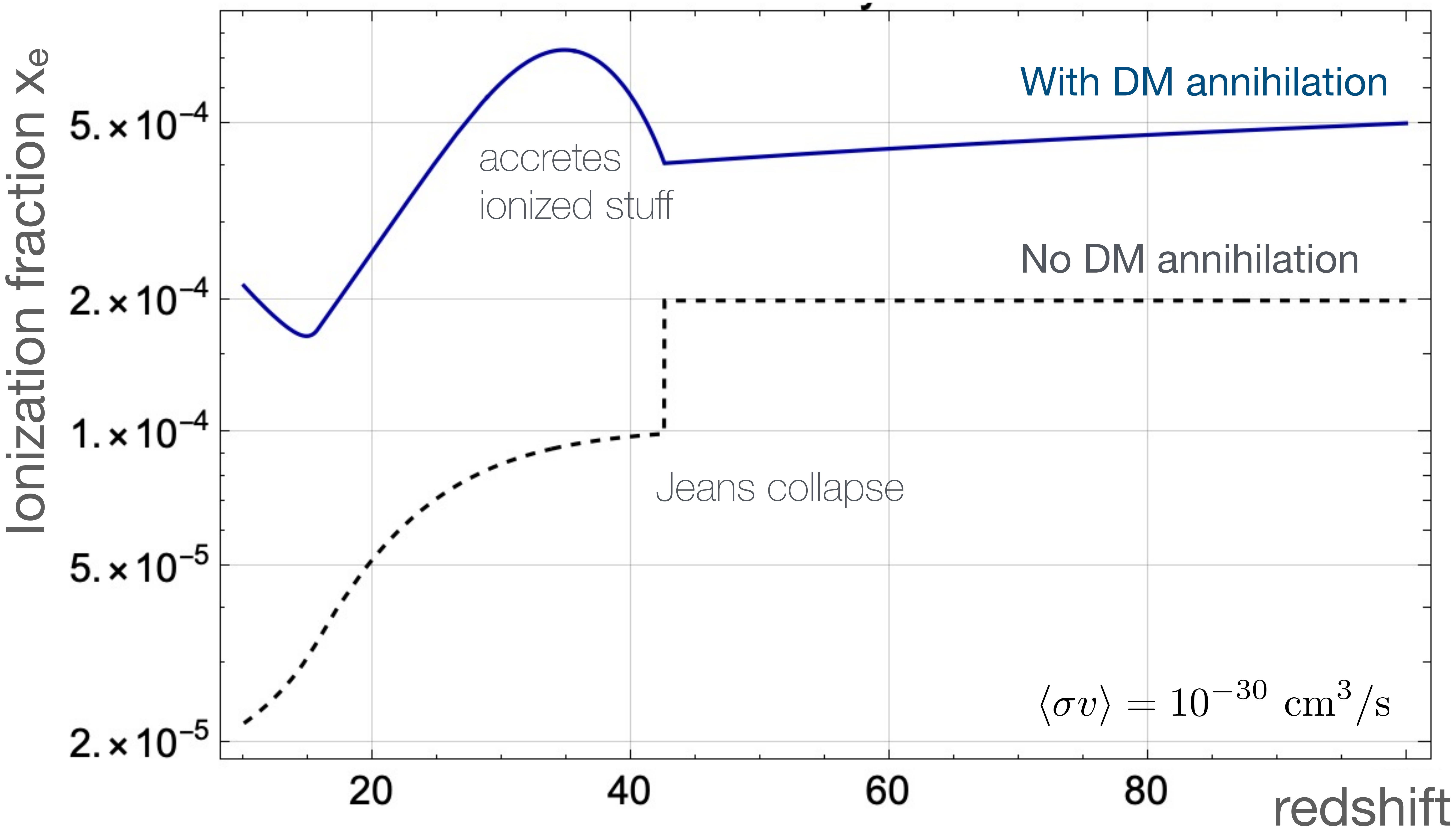
diffusion; no B fields — radiative energy loss — source (DM)

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

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

Ionization History

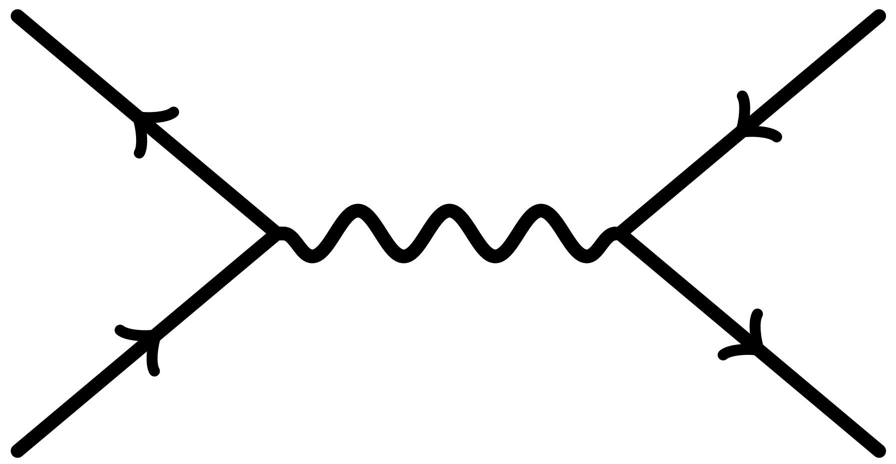




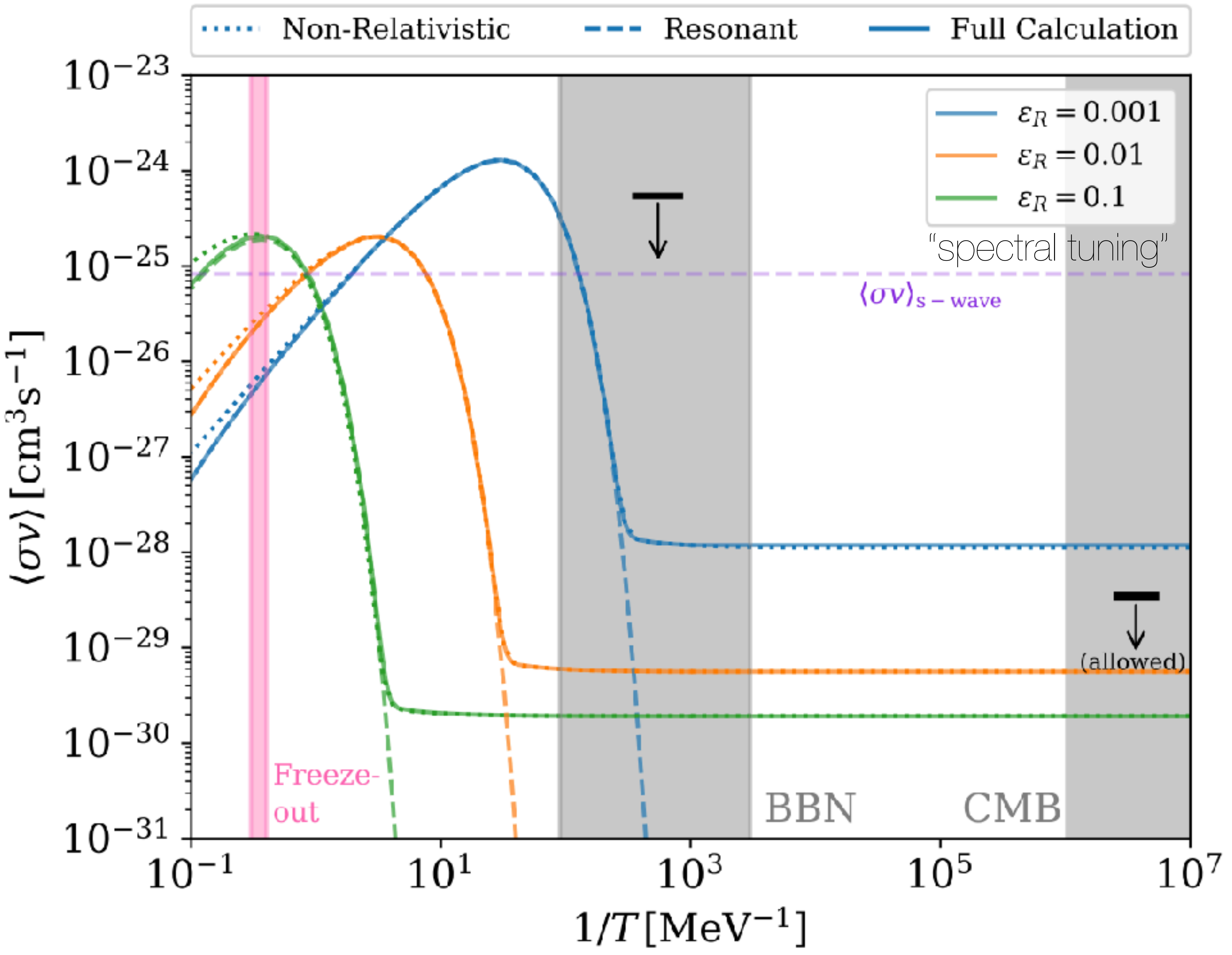
Model building attempts

… 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.

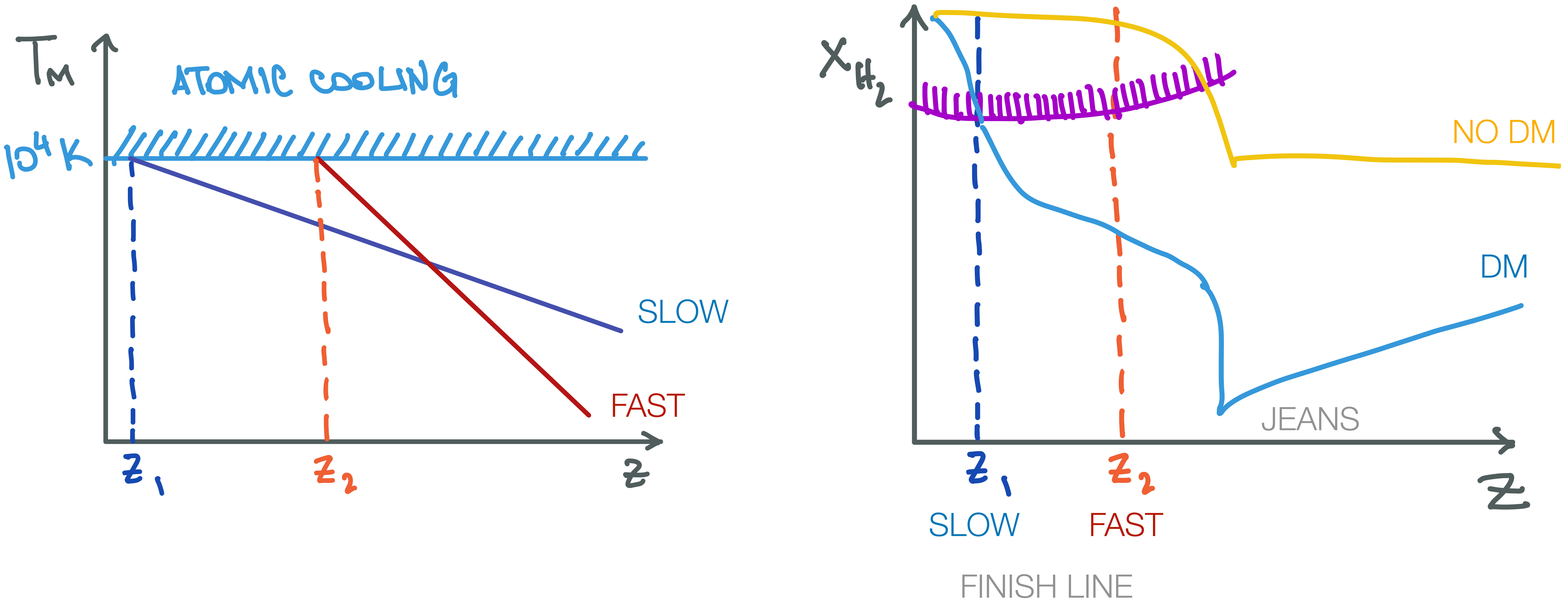


"Resonant Sub-GeV Dirac Dark Matter" Bernreuther, Heeba, Kahlhoefer (2010.14522); see also Feng (1707.03835)

Fast halo growth (dynamical heating)

Move the finish line

GOAL: STAY BELOW PURPLE LINE
WHEN YOU CROSS DASHED LINE



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.