Direct Collapse Black Holes from Dark Matter Annihilation

Flip Tanedo

work with Anson D'Aloisio & Yash Aggarwal

18 June 2024

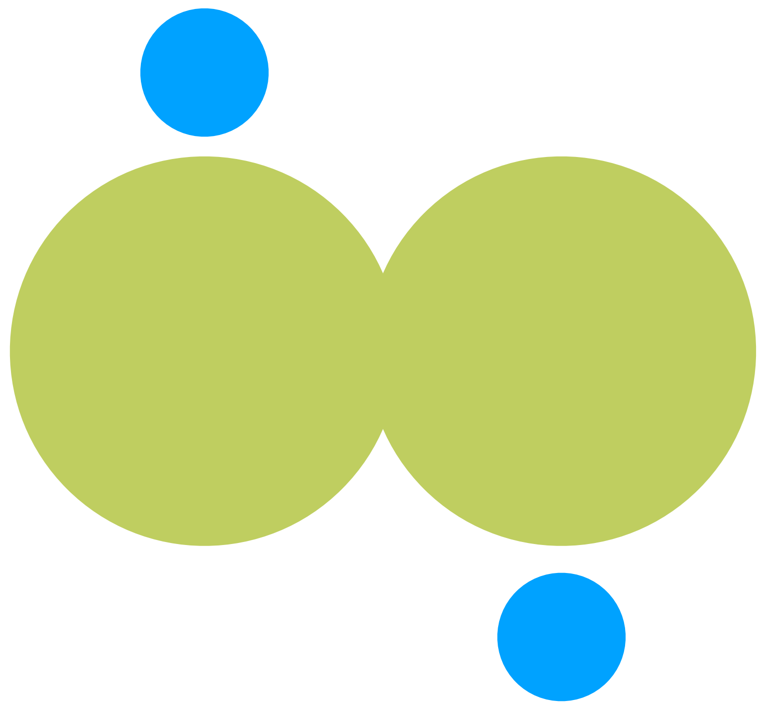
CETUP* 2024

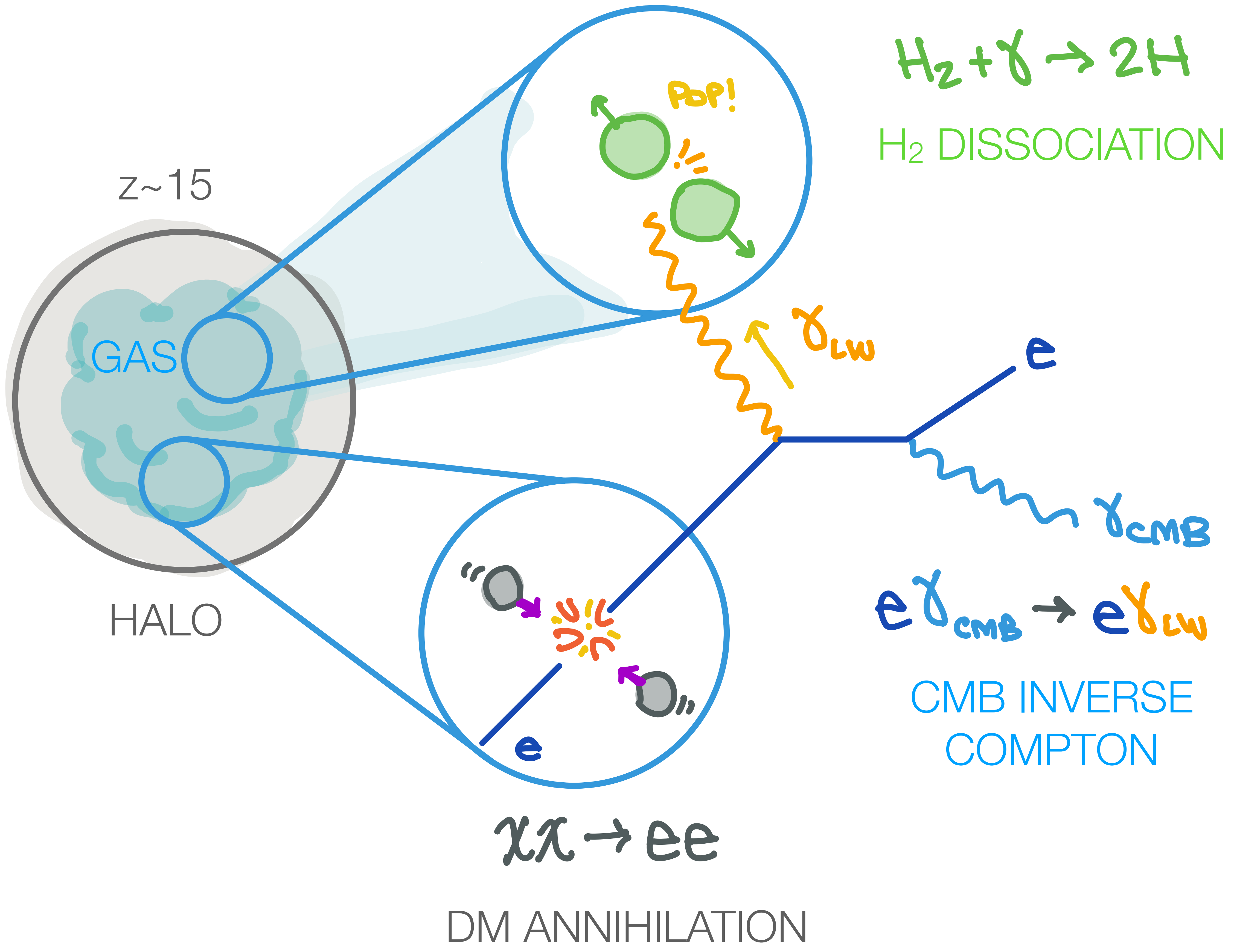
Can dark matter induce direct collapse black holes in pre-star forming halos?

I am not sure… **maybe**.

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

the adversary: H_2





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

Images: Montañez, "Puzzle of the First Black Holes," P. Natarajan, *Scientific American* 318, 2, 24-29 (2018); BBC Frozen Planet, "Criminal Penguins" (2011)

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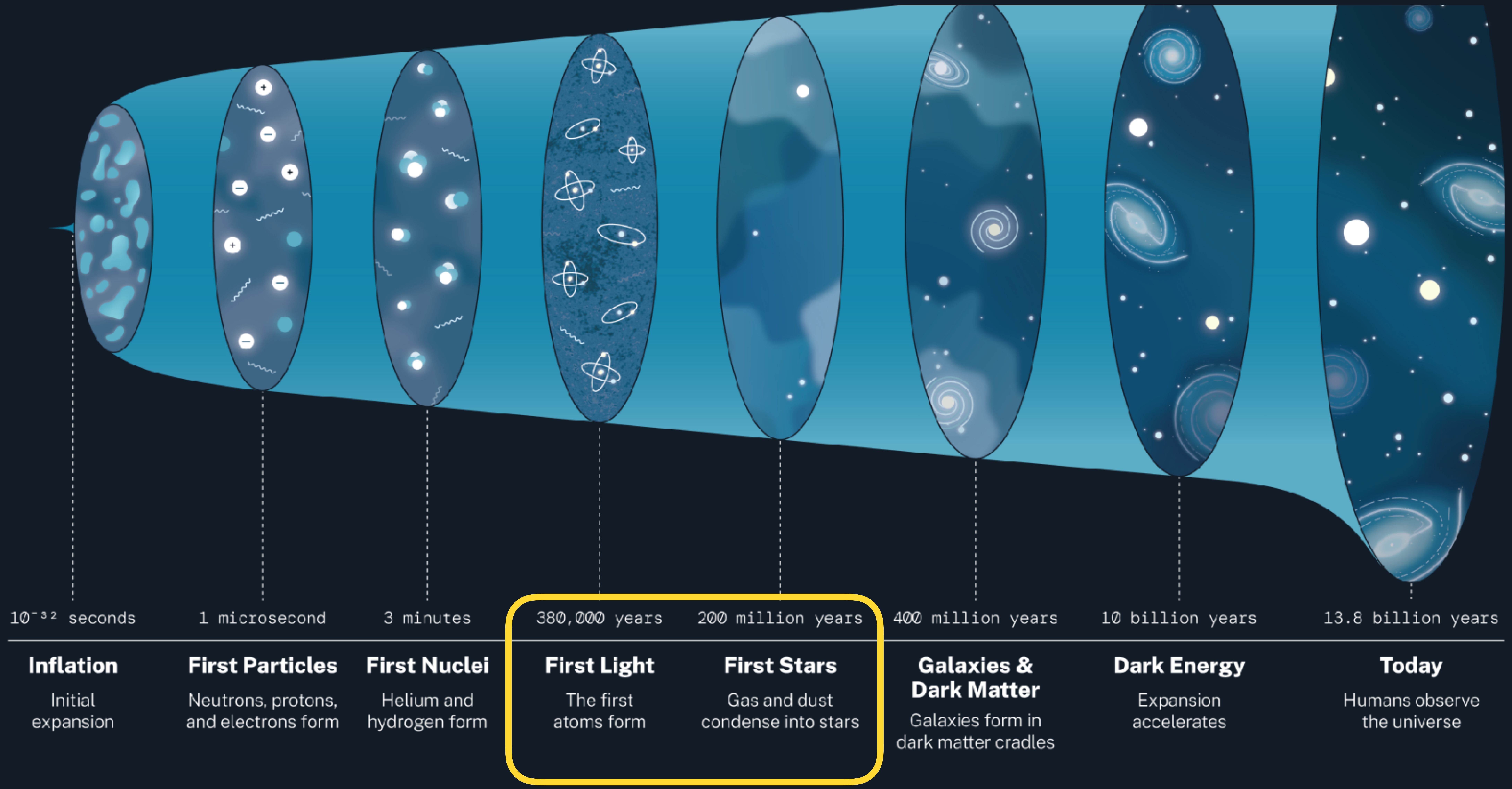


Ideal “indirect detection” laboratory

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

SUPERMASSIVE BLACK HOLES

HOW DID THEY GET SO LARGE?

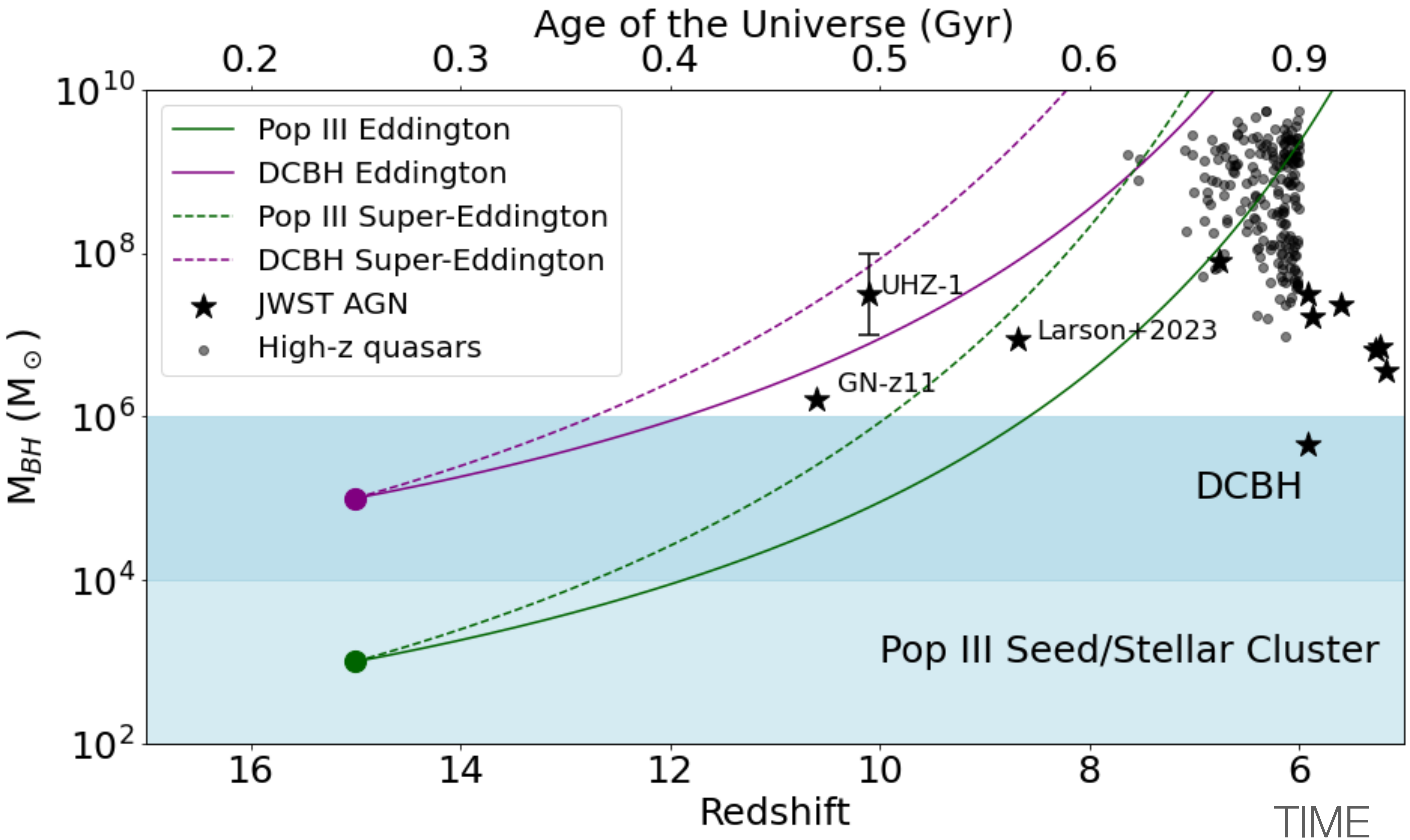
BIG BLACK HOLES USUALLY COME FROM MERGING LITTLE BLACK HOLES.

EDDINGTON LIMIT: THIS CANNOT EXPLAIN THE LARGEST BLACK HOLES.

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

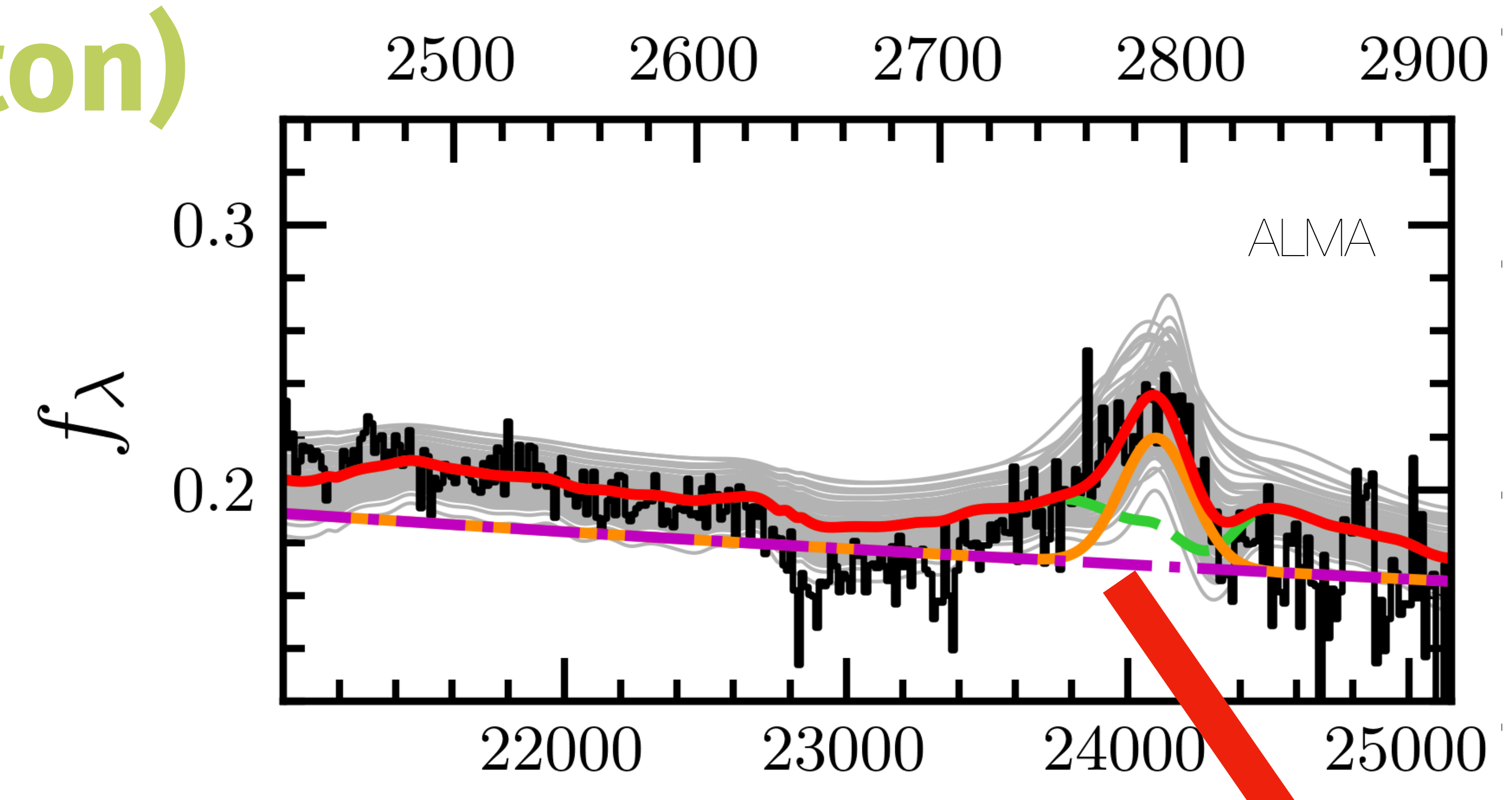
Mystery: supermassive black holes at high z

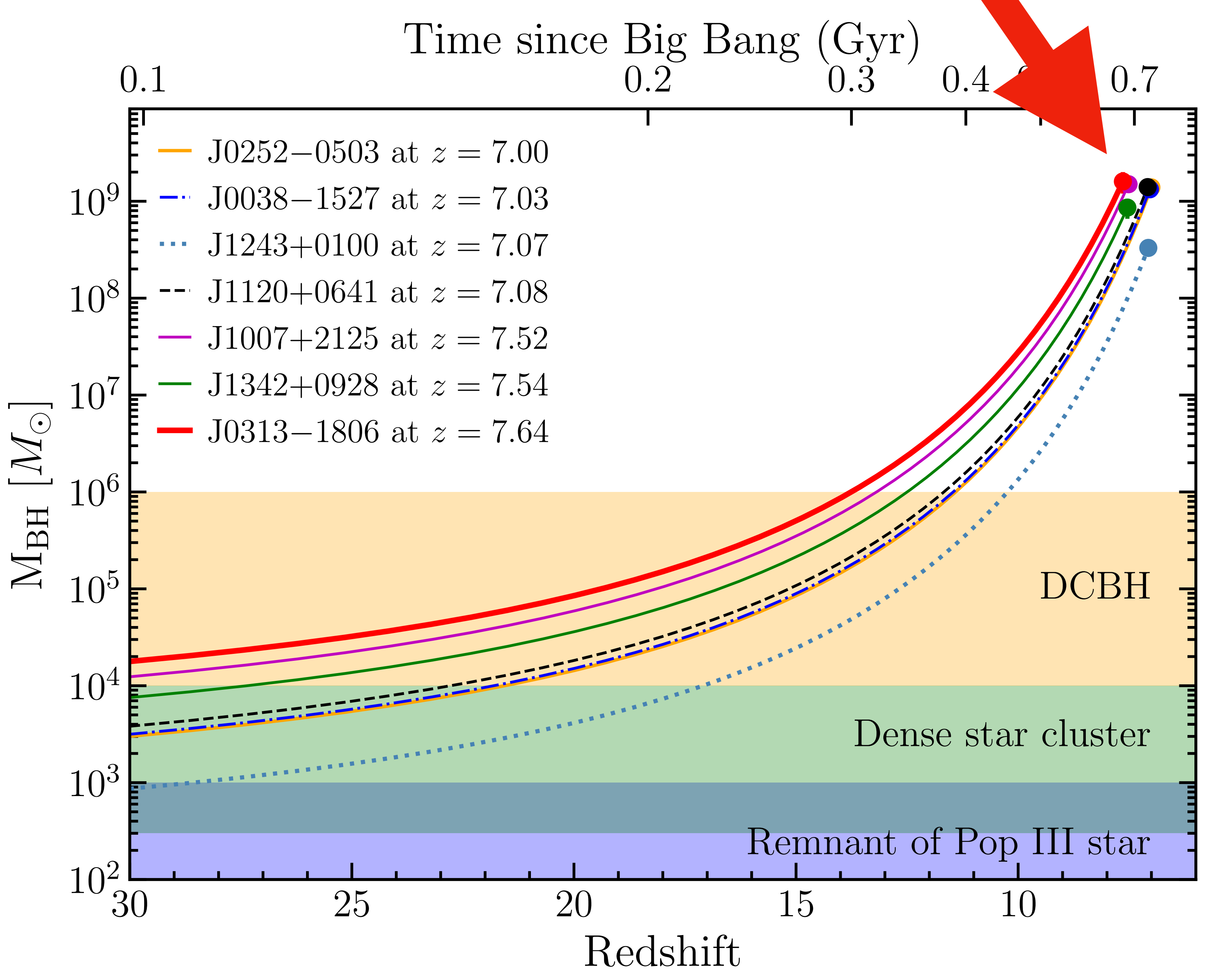
... not from ordinary black hole formation (Pop III Eddington)



TIME →

Jeon, Bromm, Liu, Finkelstein 2402.18773 (JWST)





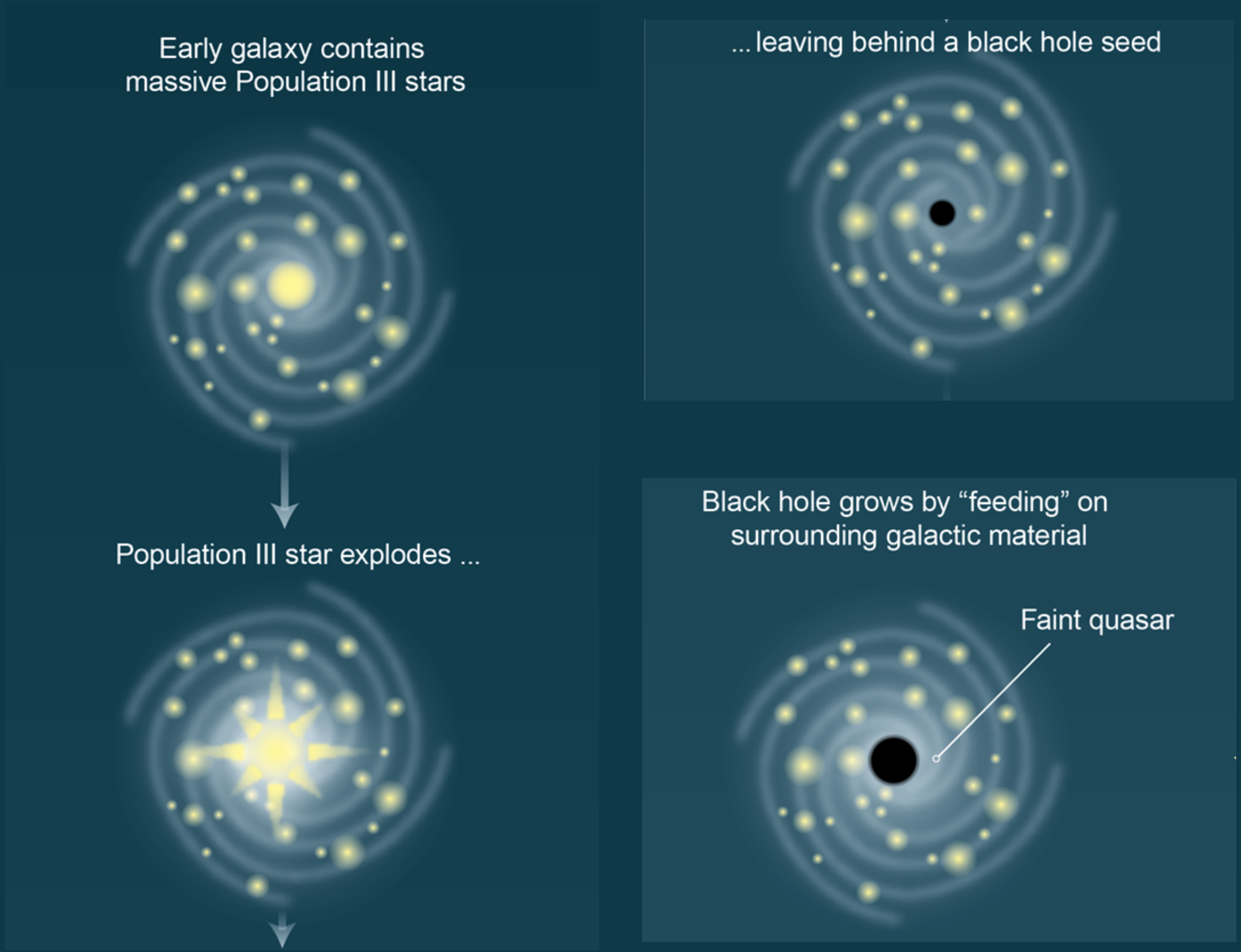
2101.03179 Wang et al. "A luminous quasar at z=7.2

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.



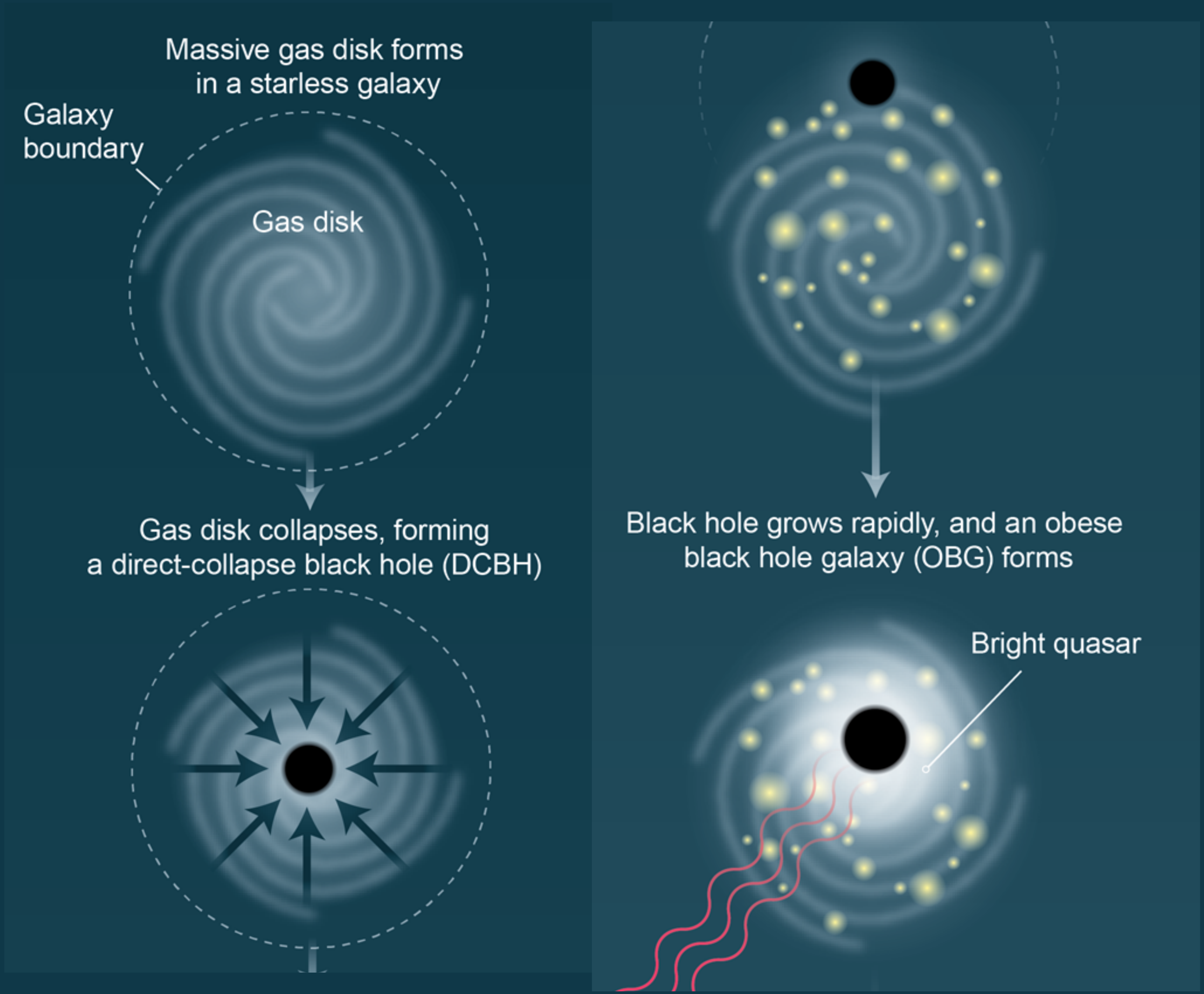
Amanda Montañez, "Puzzle of the First Black Holes," P. Natarajan, *Scientific American* 318, 2, 24-29 (2018)

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.

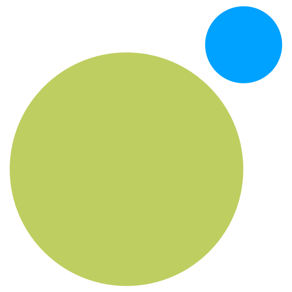
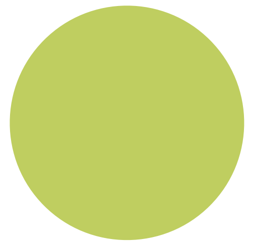
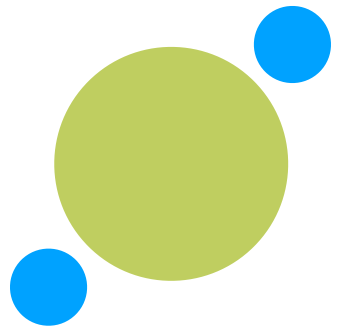
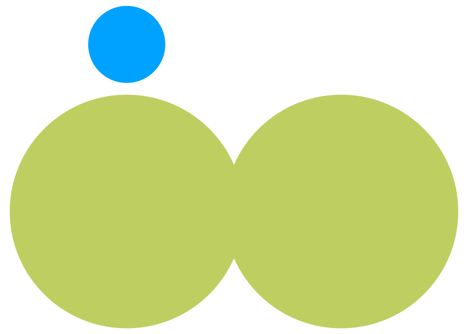
However, gas is unstable: it *wants* to collapse into stars. Direct collapse seems unlikely.



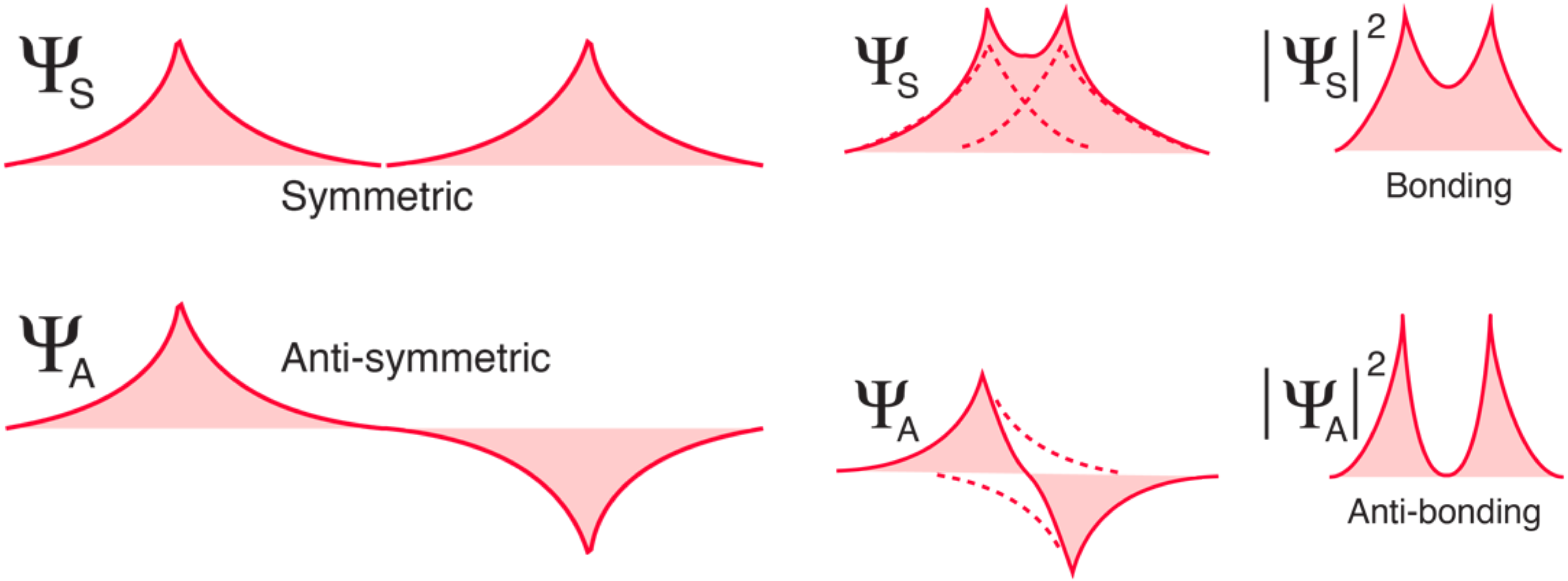
Amanda Montañez, "Puzzle of the First Black Holes," P. Natarajan, *Scientific American* 318, 2, 24-29 (2018)

Images: Montañez, "Puzzle of the First Black Holes," P. Natarajan, *Scientific American* 318, 2, 24-29 (2018); BBC Frozen Planet, "Criminal Penguins" (2011)

Types of hydrogen

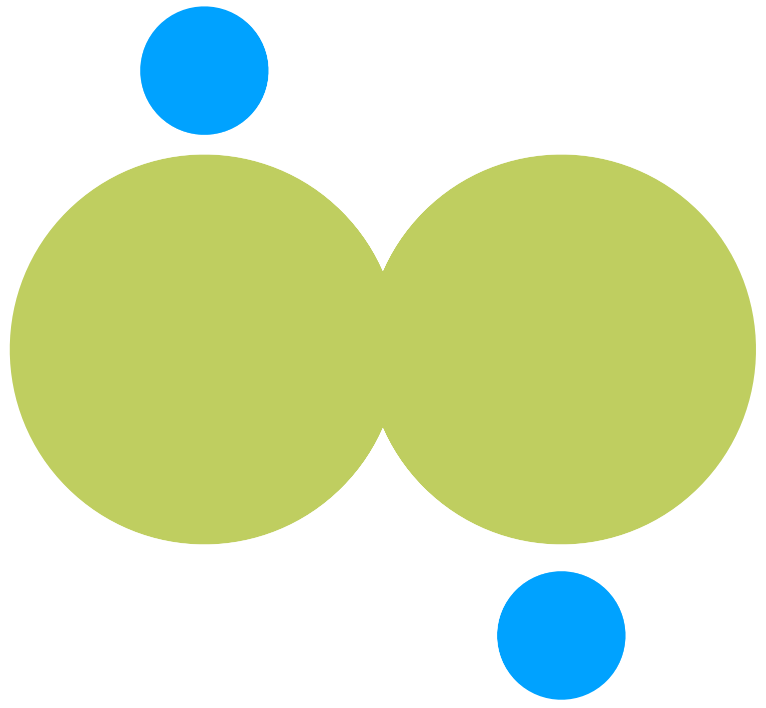
		Astro	Particle	
	atomic/neutral	HI	H	Abundance: ~1
	ionized	HII	H^+	
	hydride	H^-	H^-	
	molecular	H_2	H_2	Abundance: 10^{-5} molecular cooling is responsible for pop III stars
	deuterium	$_2H$	$_2H^-$	

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



ground

unbound



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

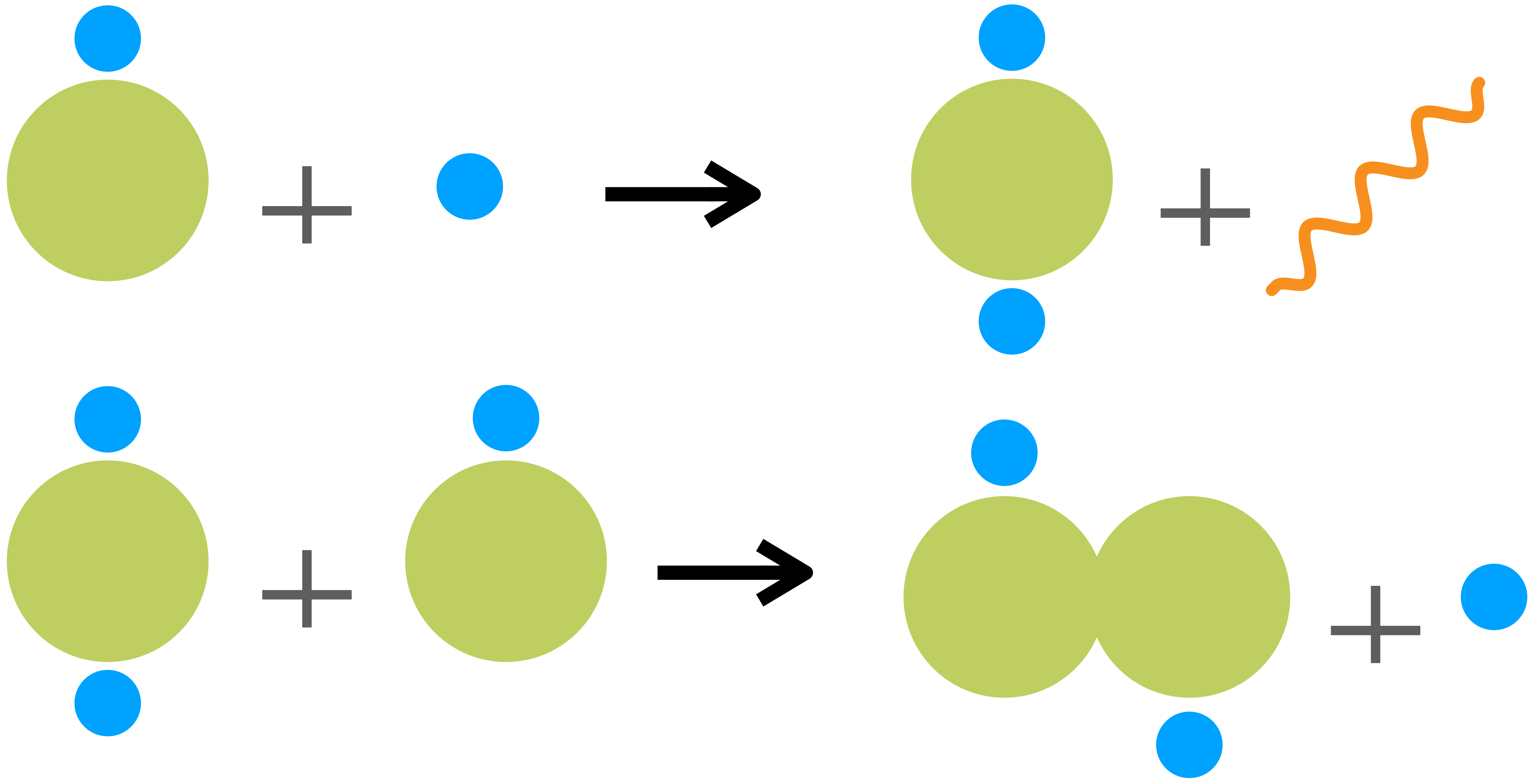
Dissociation: need O(10 eV) excitation to Lyman/Werner bands, then probability to de-exciting into unbound state (no direct E. dipole transition)

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

Molecular Hydrogen H_2

Formation of Molecular Hydrogen

Formation



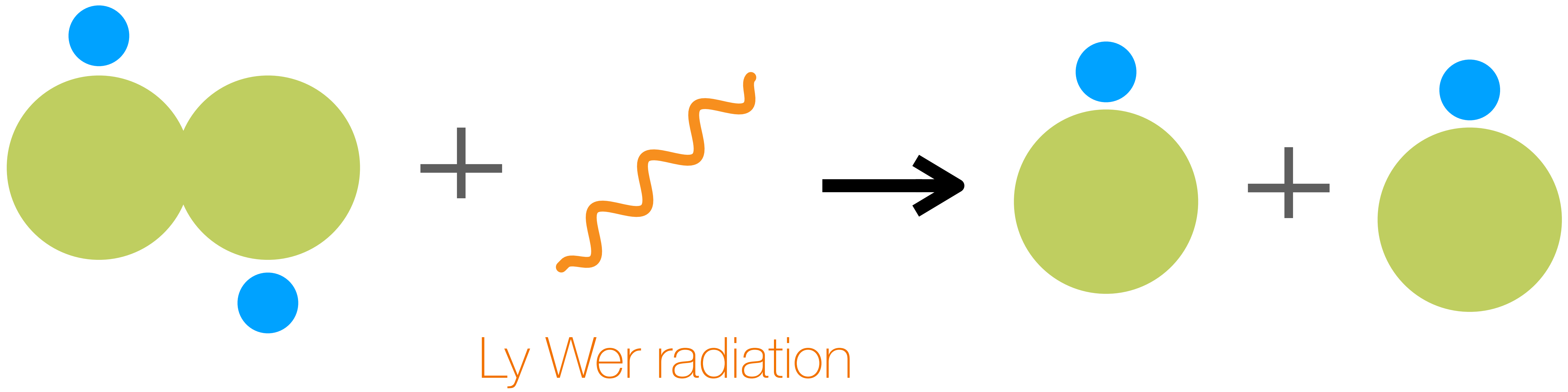
$$\mathrm{H} + \mathrm{e}^- \to \mathrm{H}^- + \gamma\,,$$

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

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)

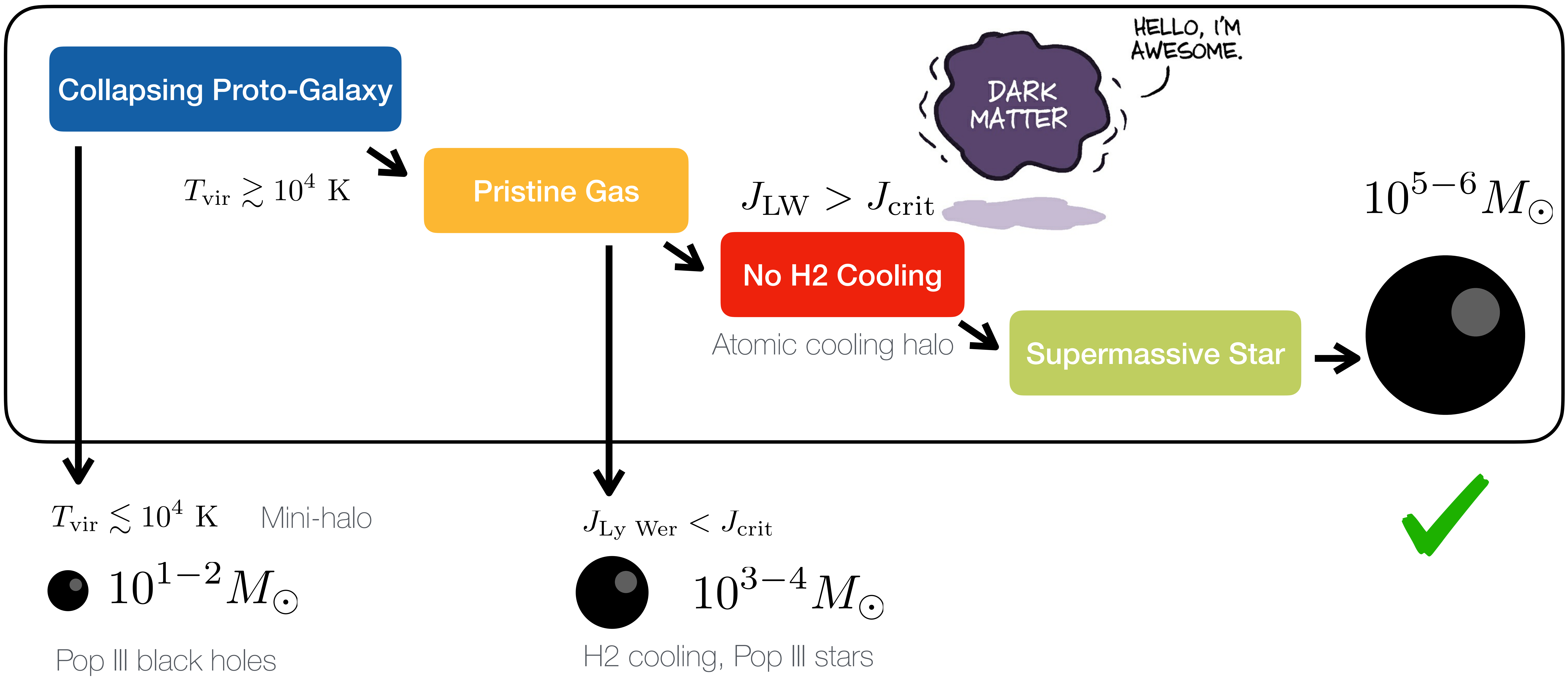
Dissociation



Photodissociation

$$H_2 + \gamma_{\mathrm{LW}} \to H + H$$

& photodetachment for lower energies.



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

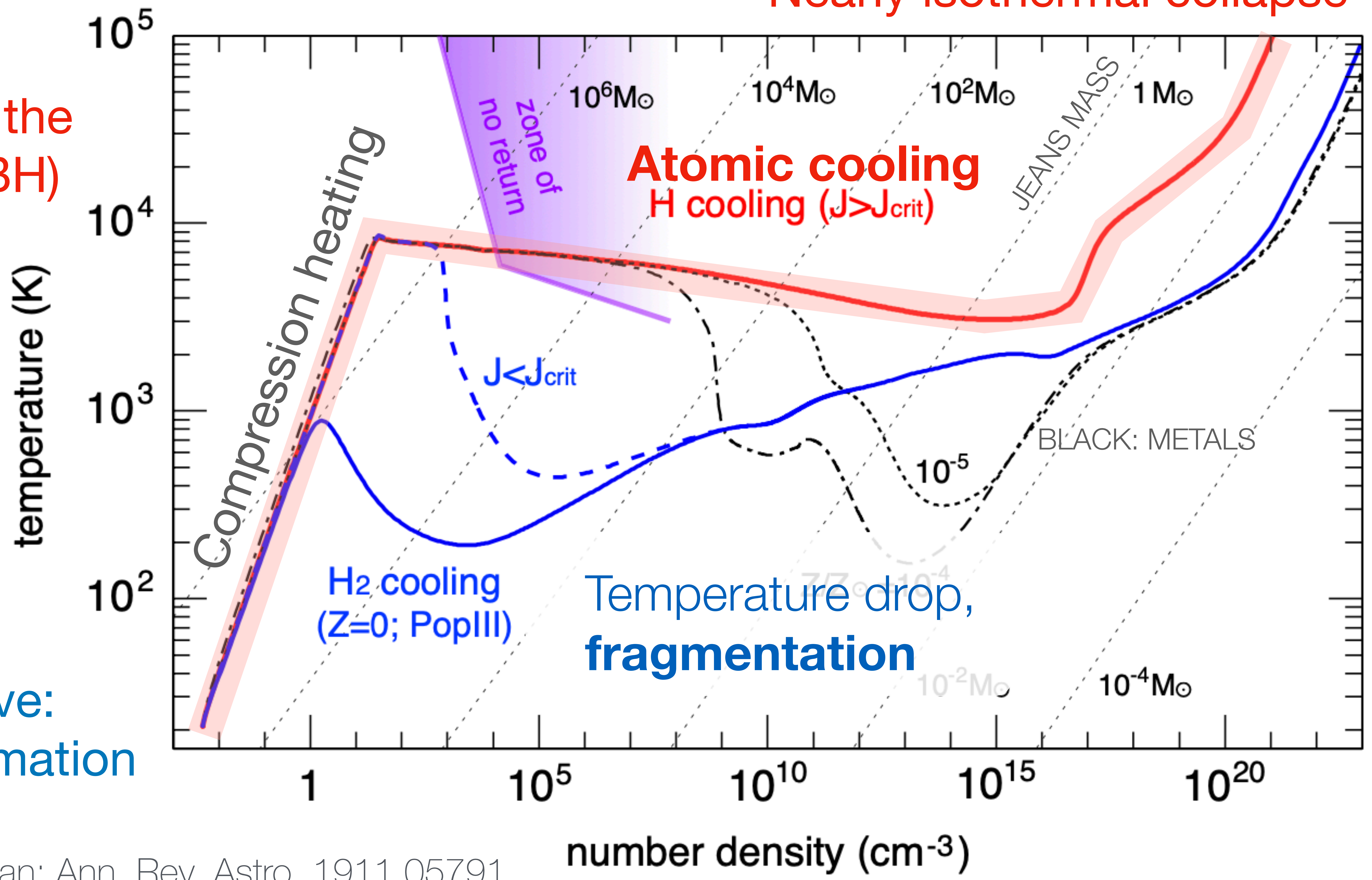
Cham & Whiteson , *We Have No Idea*

Conditions for direct collapse

Nearly isothermal collapse

Want to follow the red curve (DCBH)

Avoid blue curve: Pop III star formation



TIME →

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

Images: Montañez, "Puzzle of the First Black Holes," P. Natarajan, *Scientific American* 318, 2, 24-29 (2018); BBC Frozen Planet, "Criminal Penguins" (2011)

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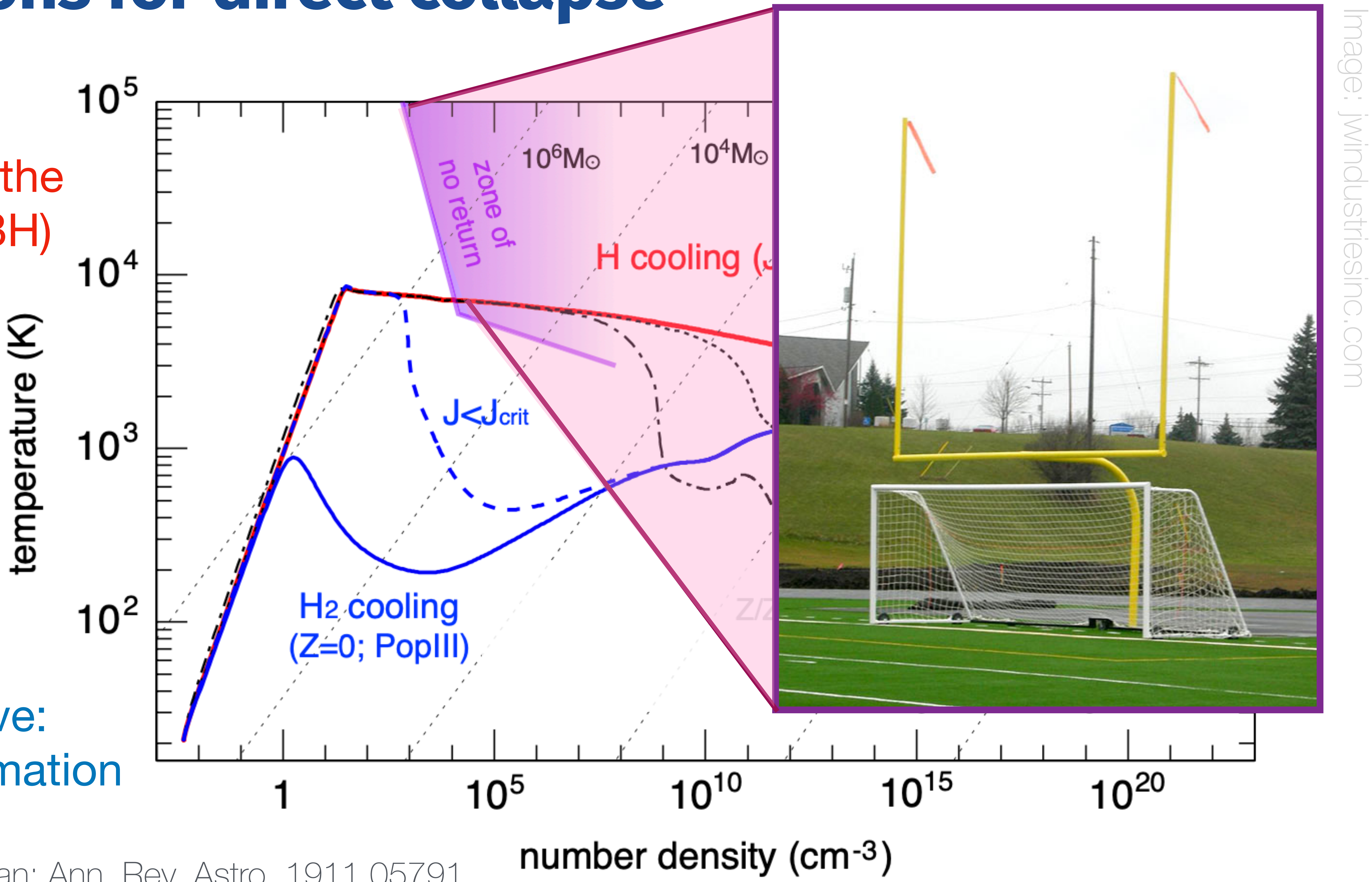

Inayoshi, Visbal, Haiman; Ann. Rev. Astro, 1911.05791

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).

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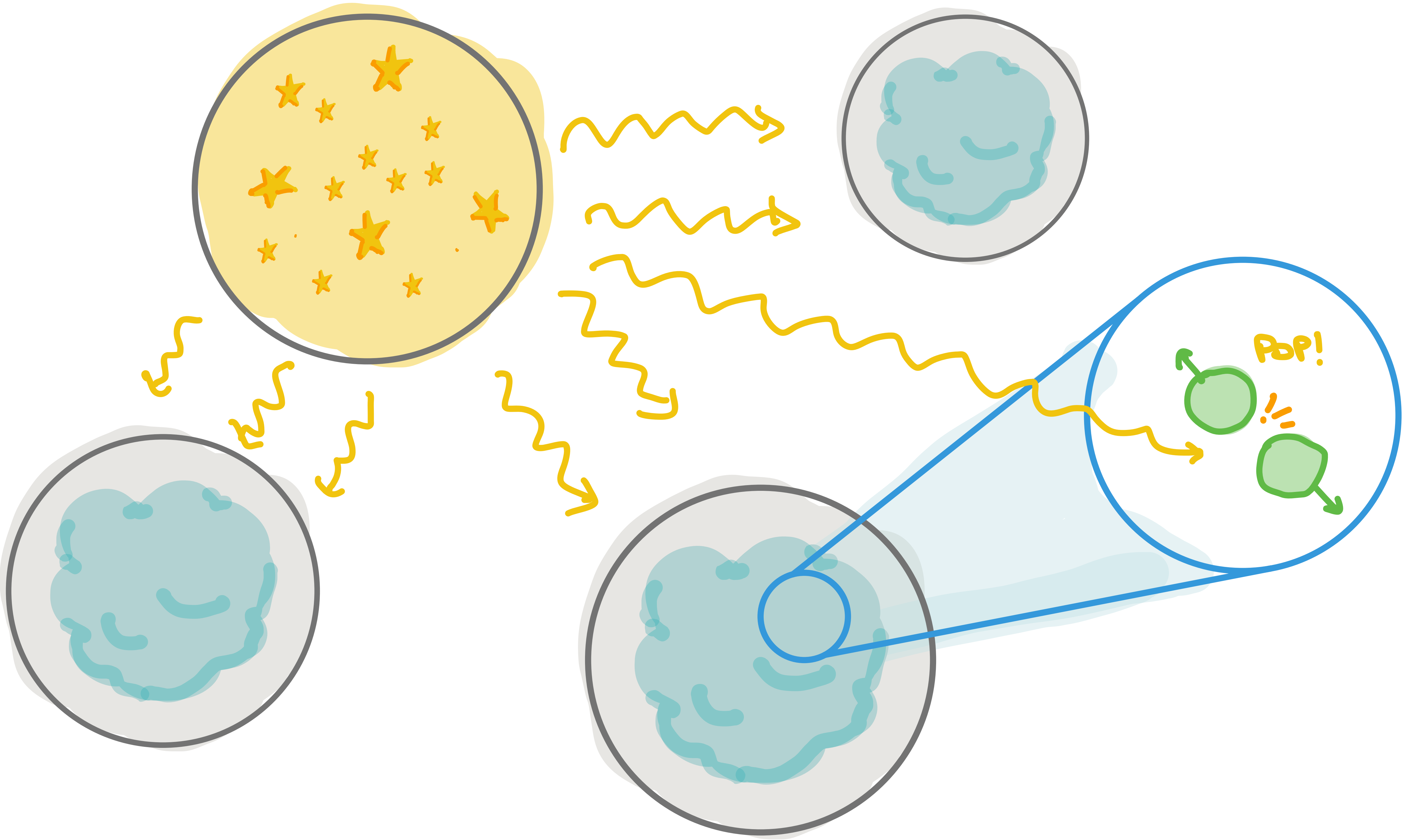
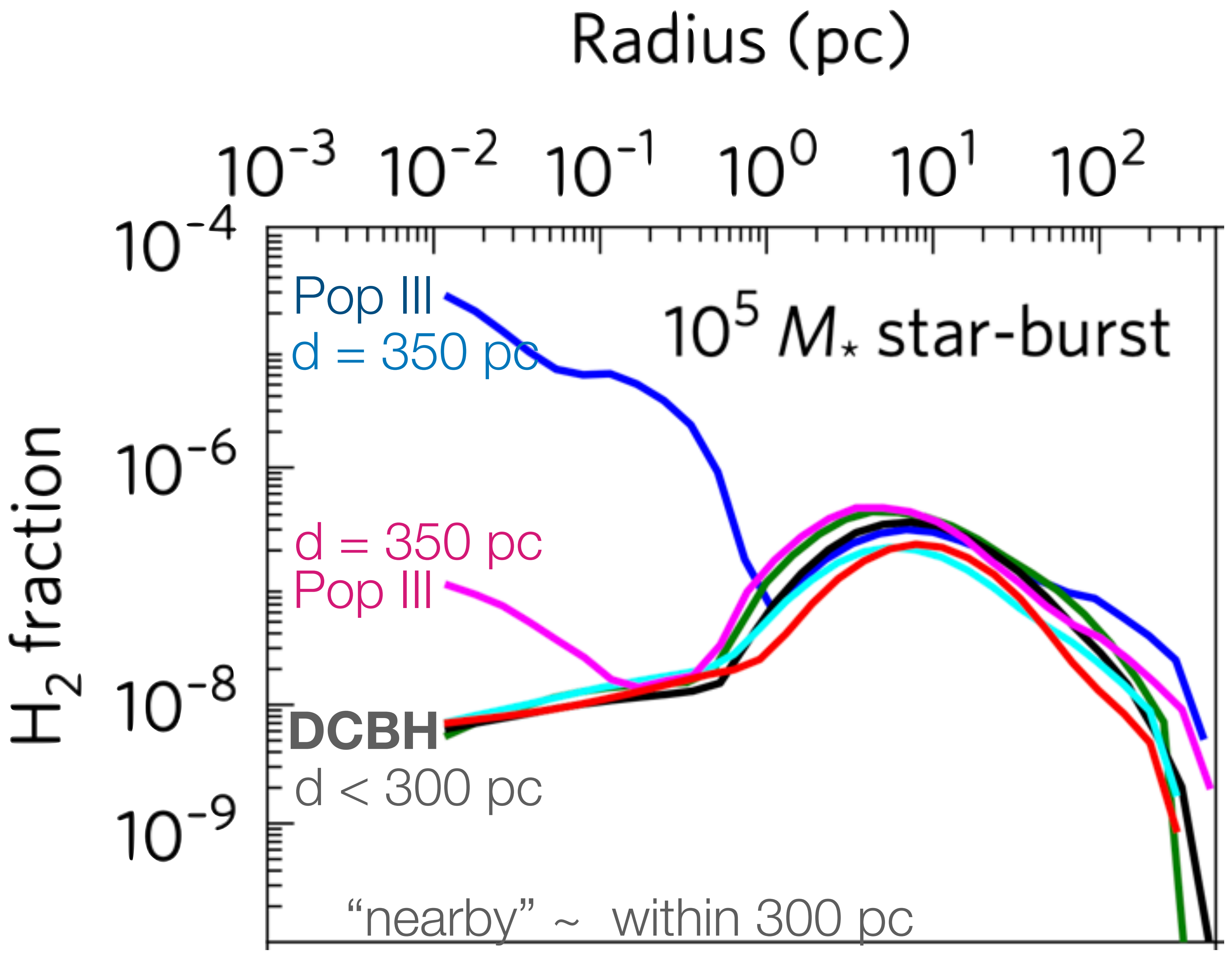
Image: jwindustriesinc.com

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

Nearby Starshine

With a little bit of luck...





Rapid formation of massive black holes in close proximity to embryonic protogalaxies

Regan, Visbal, Wise, Haiman, Johansson, & Bryan (1703.03805)
Nature Astronomy 1 0075 (2017)

Bromm and Loeb, astro-ph/0212400; Haiman, Rees, Loeb, astro-ph/9608130

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astrophysics

Halo DM?

Image: jwindustriesinc.com

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

Mapping to Dark Matter

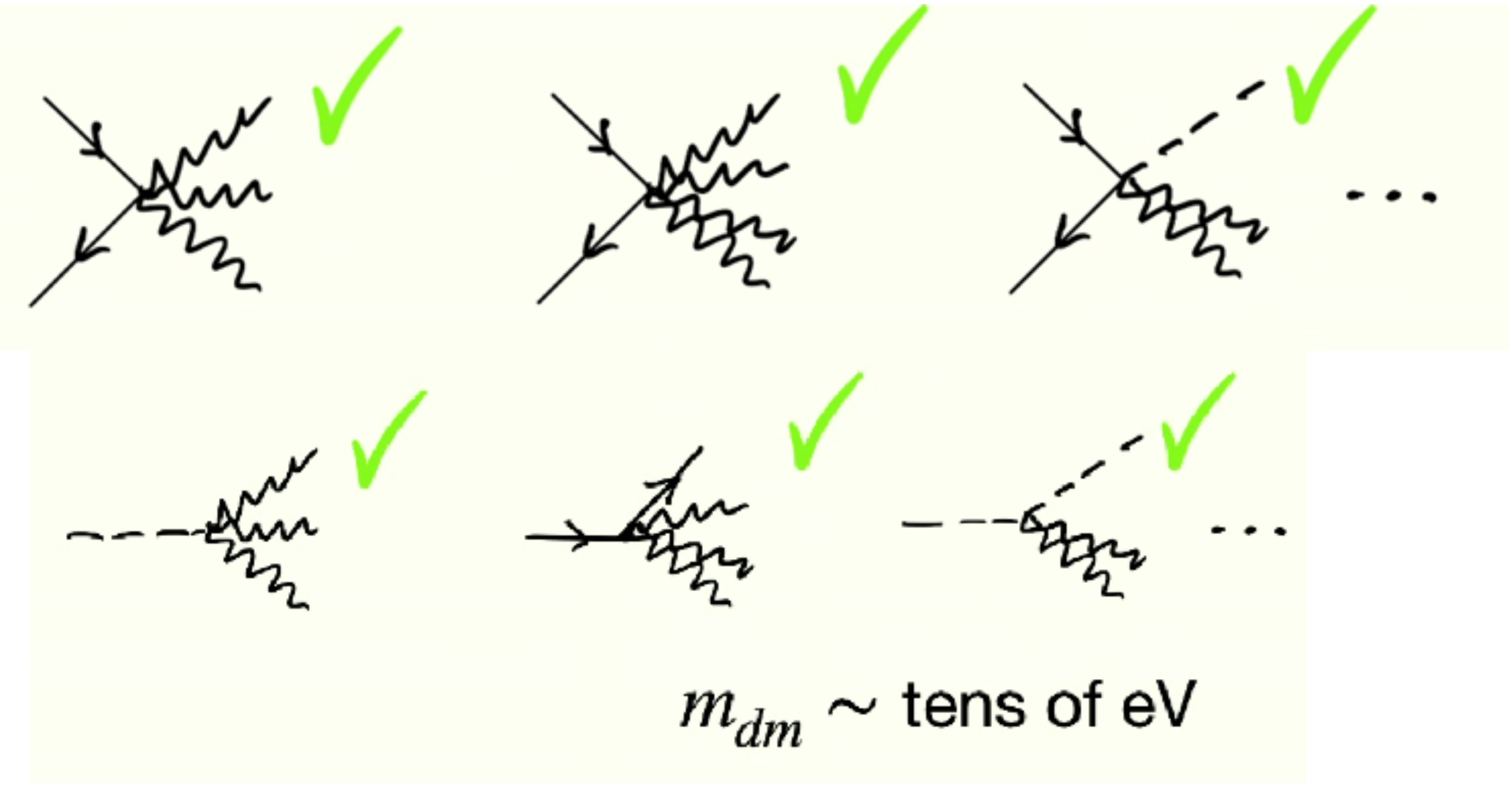
Friedlander, Schon, Vincent

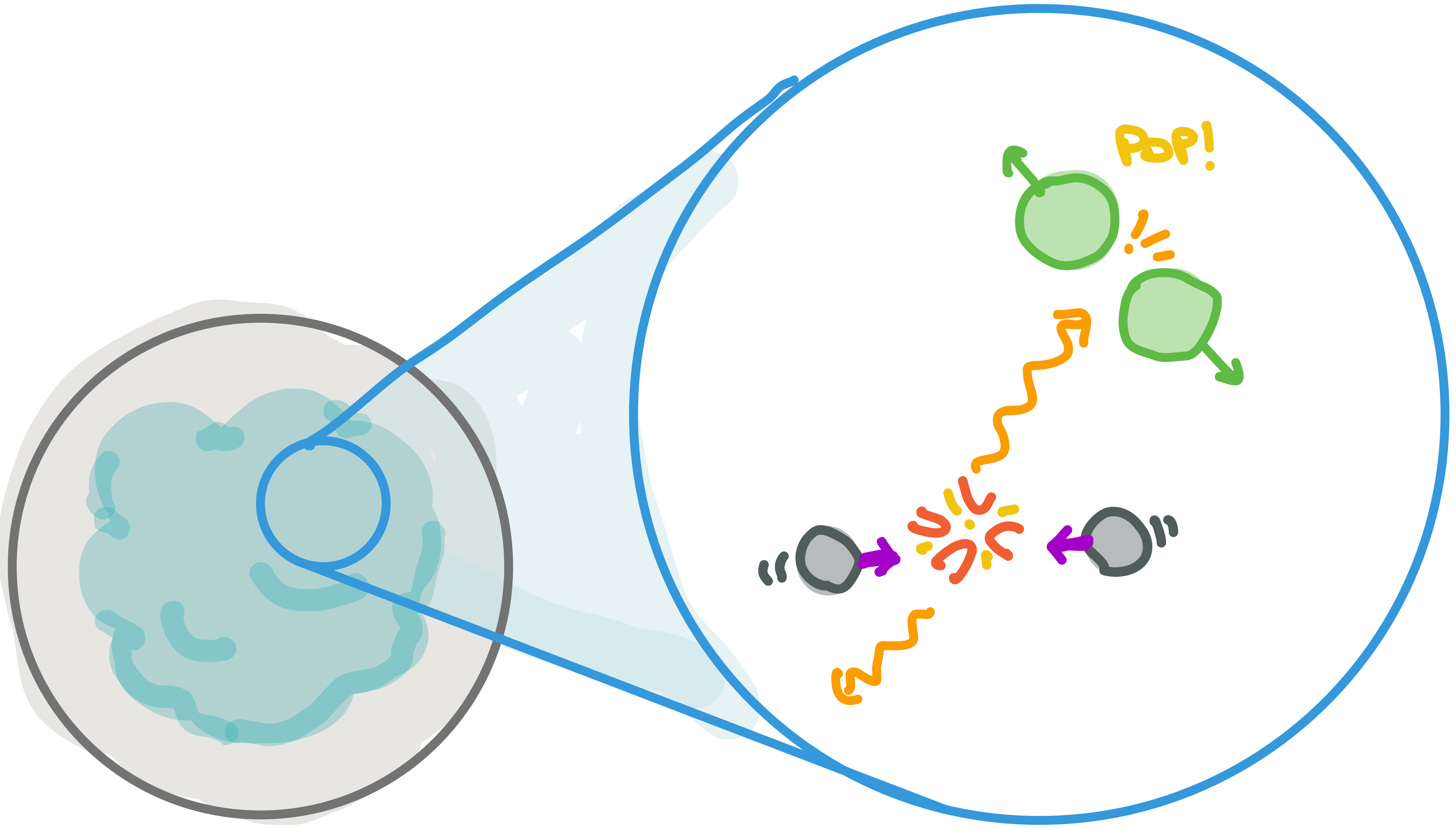
Supermassive black hole seeds from sub-keV dark matter

Avi Friedlander,[1,2,*] Sarah Schon,[3,4,†] and Aaron C. Vincent[1,2,5,‡]

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)

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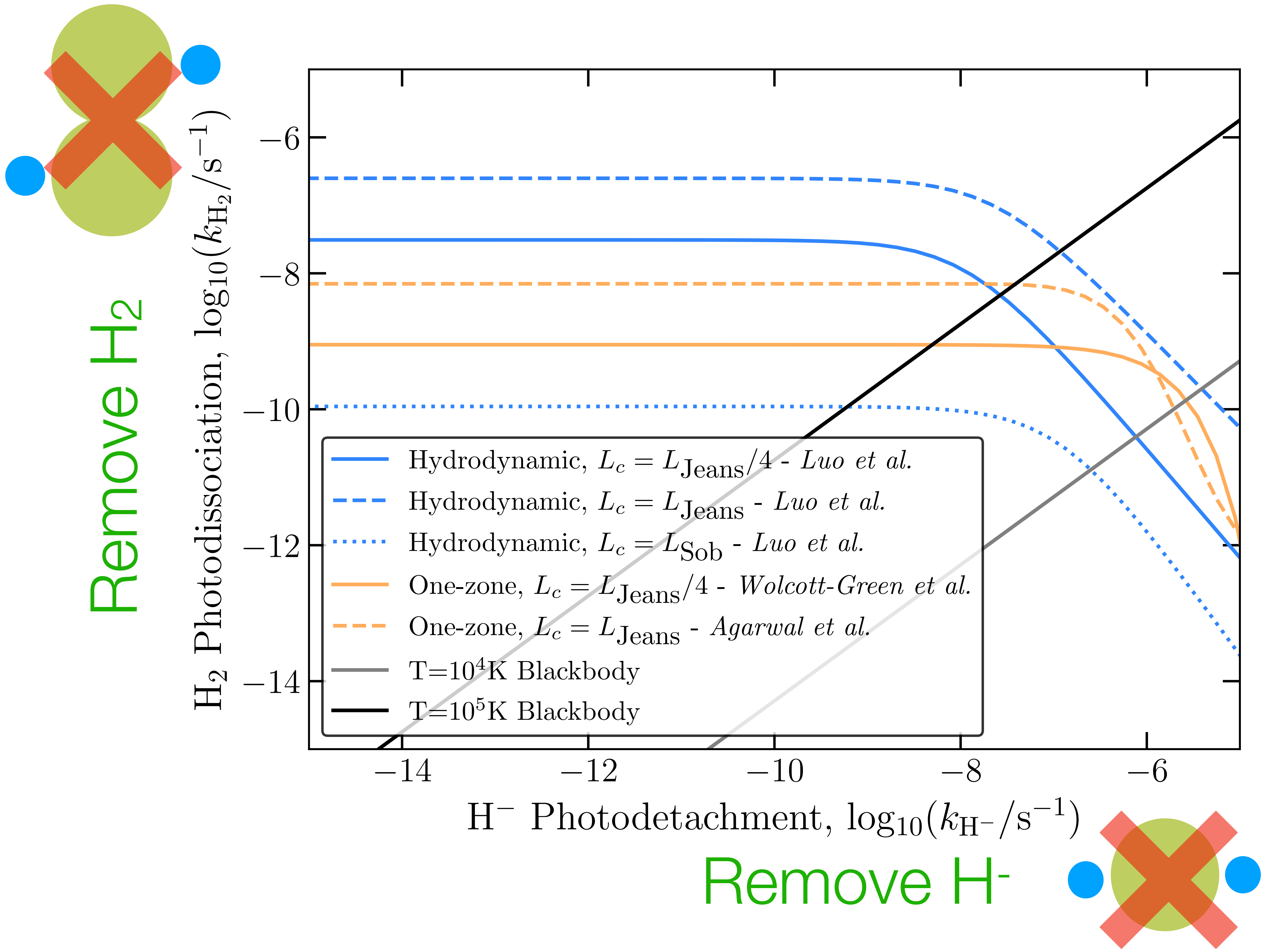
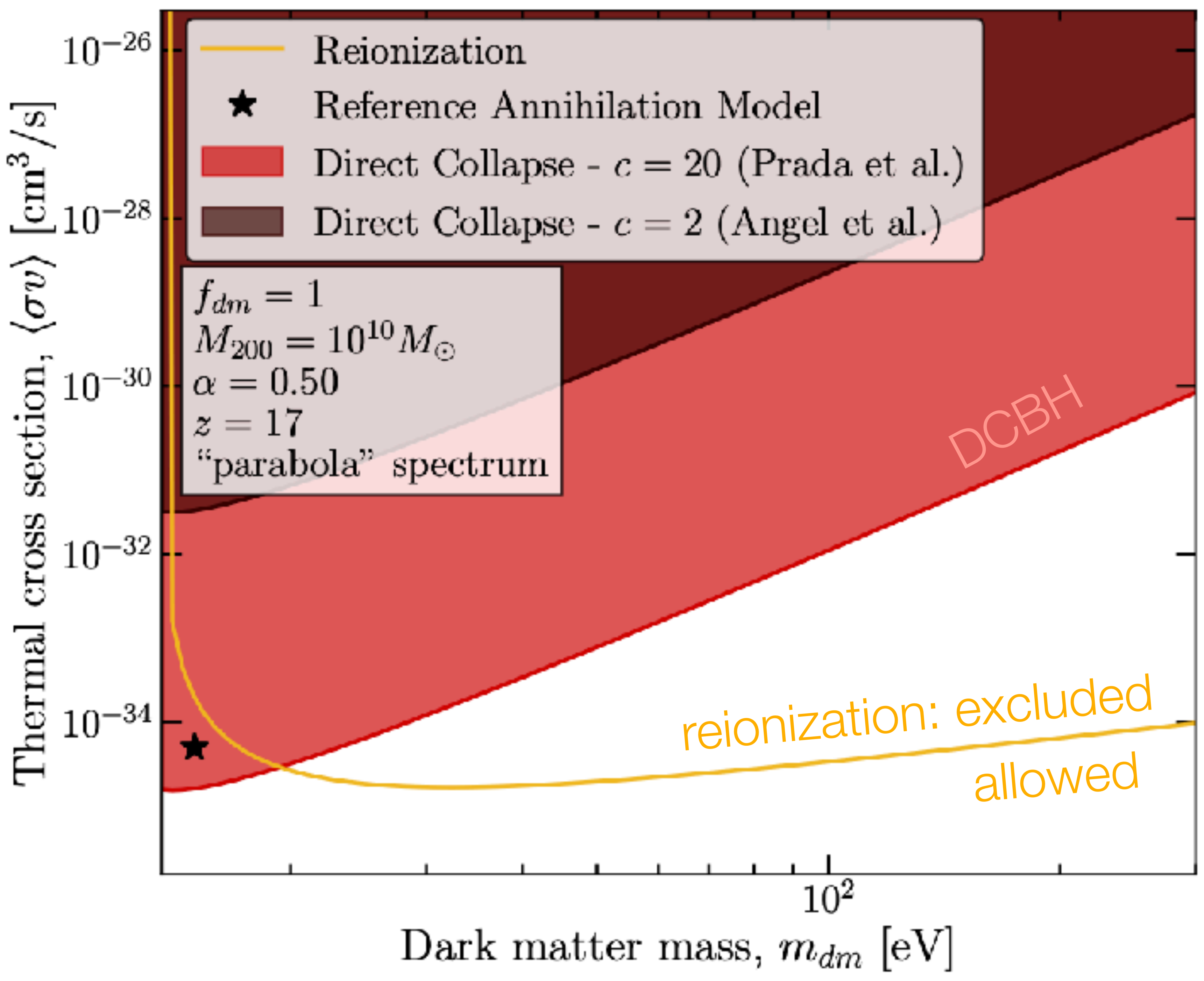
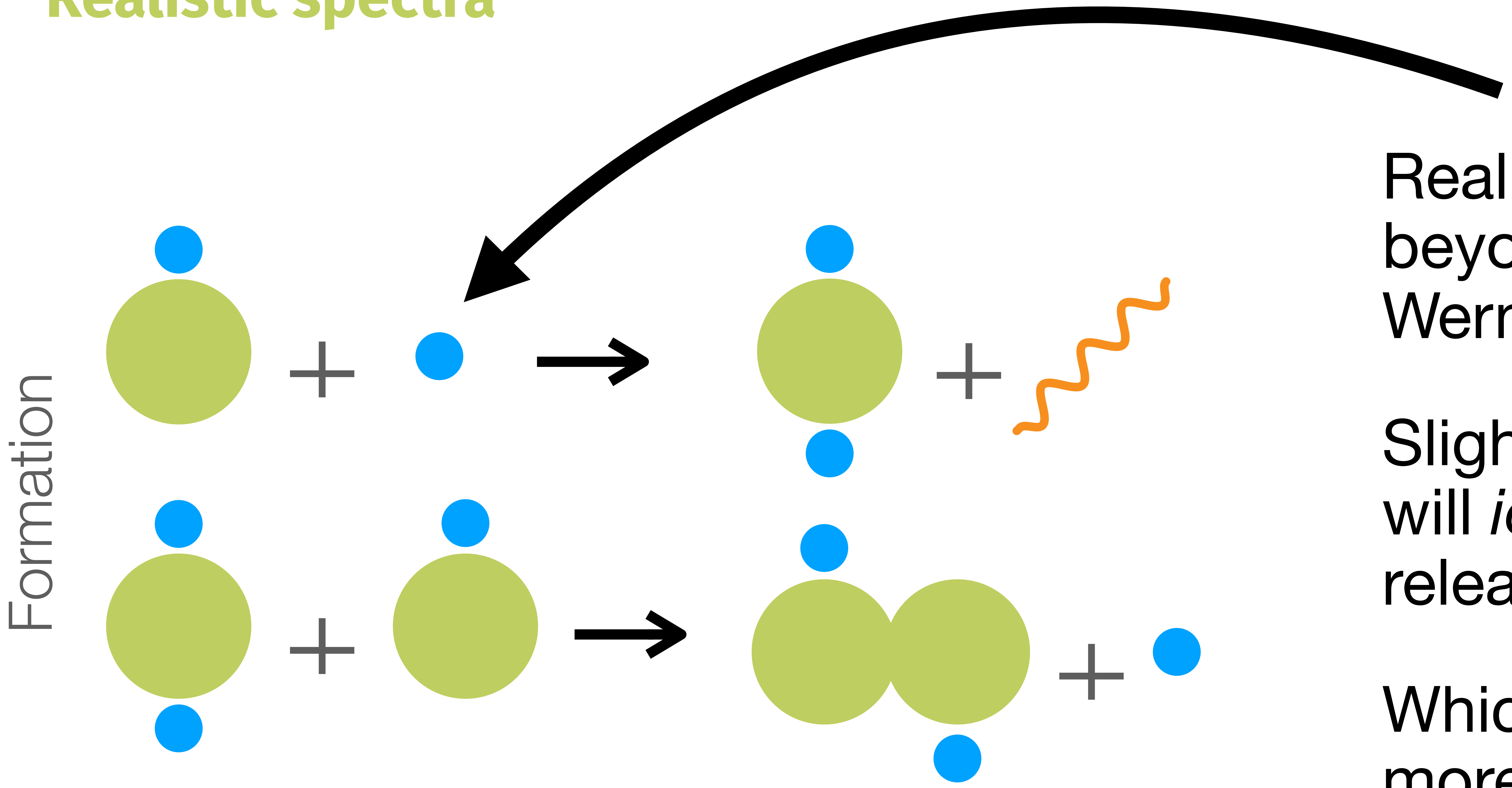




arXiv:2212.11100; A. Vincent's talk at Dark Matter First Light (Feb 2024, PI)

Why this is subtle

Realistic spectra



Realistic photon spectra extend beyond the narrow Lyman-Werner band **11.6 - 13.6 eV**.

Slightly higher-energy photons will *ionize atomic* hydrogen and release **electrons**…

Which catalyze the formation of more **molecular hydrogen**.

… molecular hydrogen self-shielding is challenging.
That's why there are so many critical curve lines on the previous plot.

Images: Montañez, “Puzzle of the First Black Holes,” P. Natarajan, *Scientific American* 318, 2, 24-29 (2018); BBC Frozen Planet, “Criminal Penguins” (2011)

Idea: Don't let self-shielding build up

BBC Frozen Planet, "Criminal Penguins" (2011)

Opposite of self-shielding

try to built it up, but it disappears

BBC Frozen Planet, “Criminal Penguins” (2011)

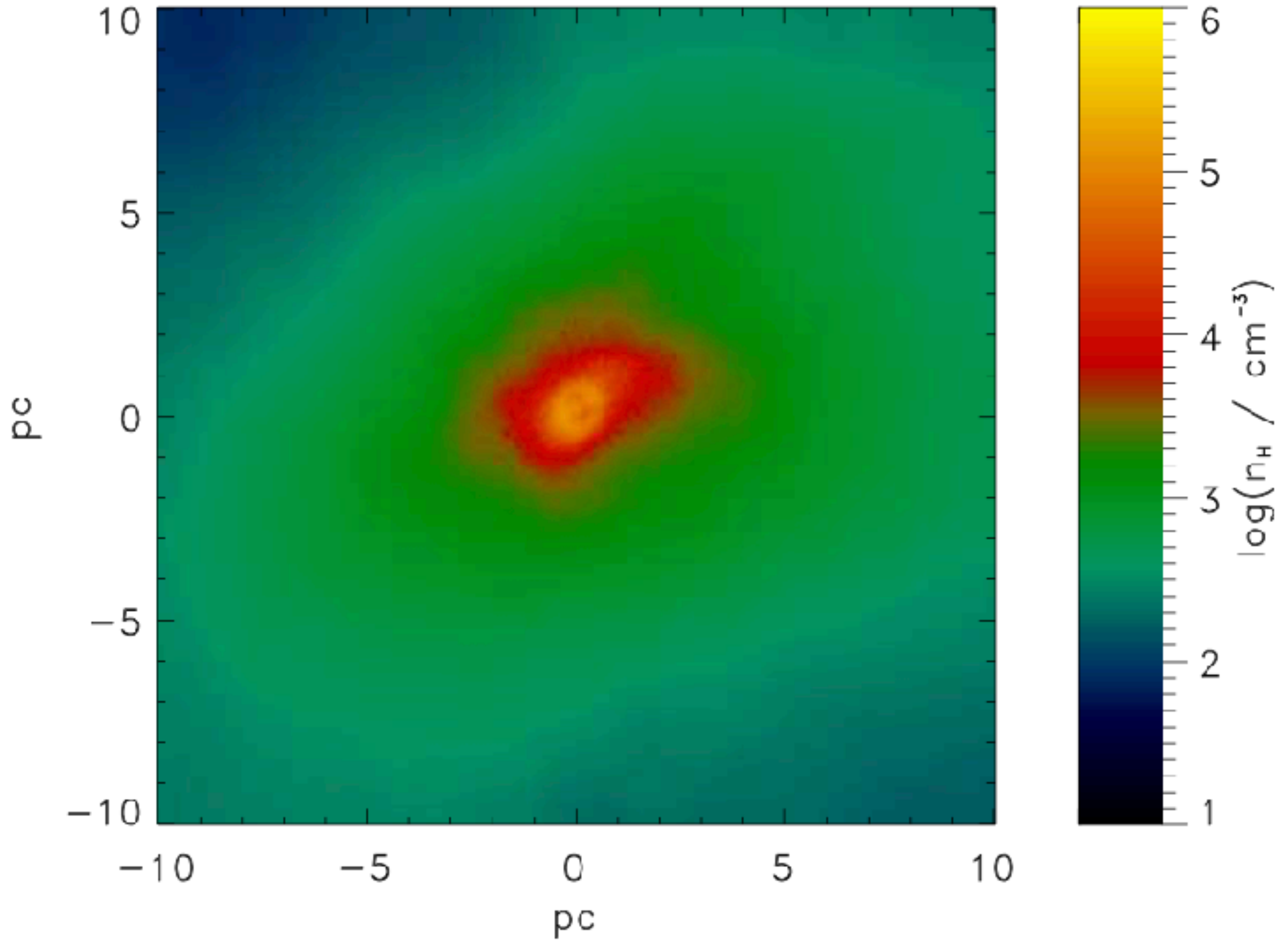
Start at 0:40

Self-shielding

Specific intensity units: $J_{21} = 10^{-21}\,\mathrm{erg\,s^{-1}\,cm^{-2}\,Hz^{-1}\,sr^{-1}}$

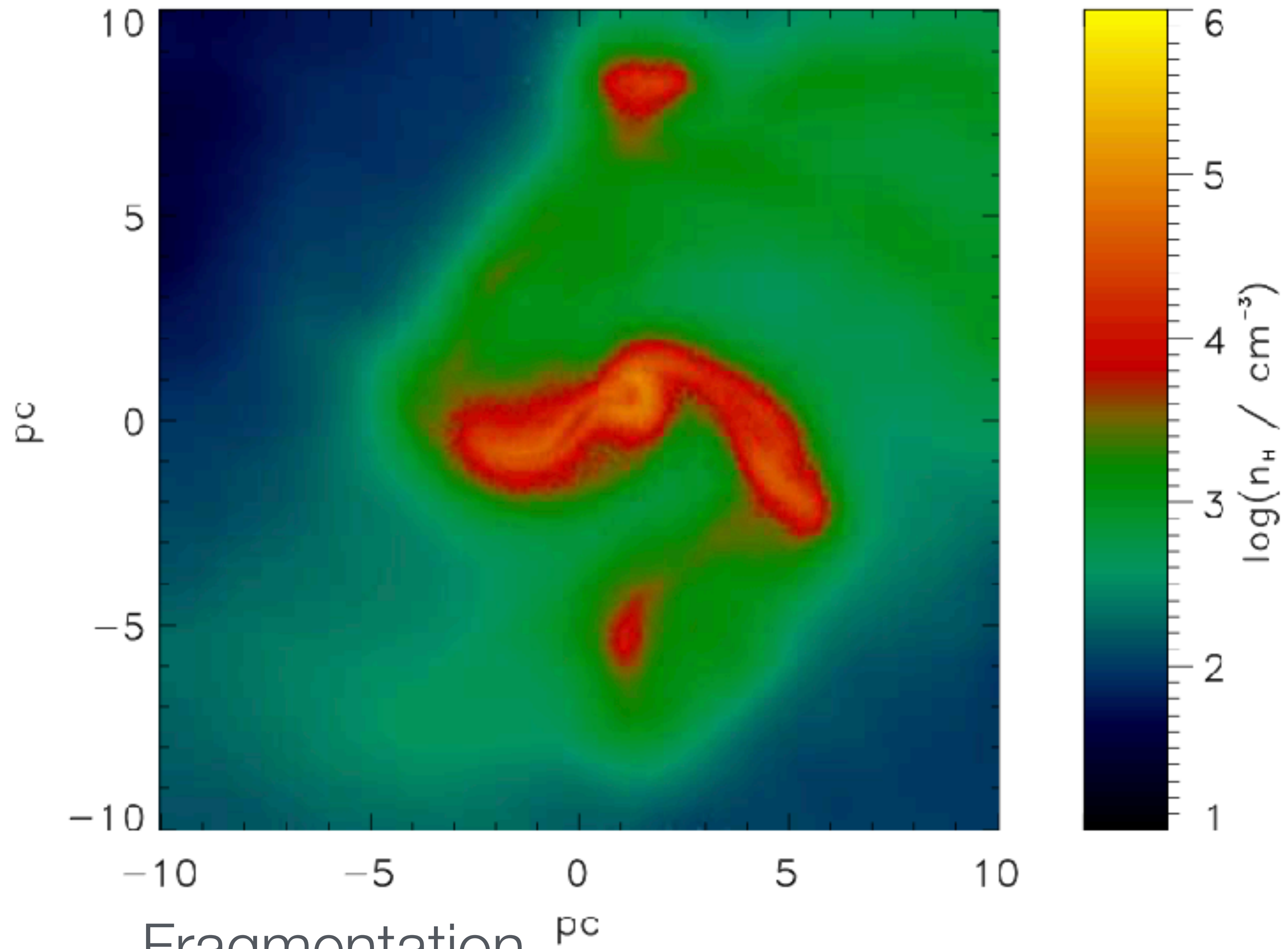
At large enough H2 density, Lyman-Werner radiation cannot penetrate halo.
Tricky to solve in general (numerical work)

$J = 3 \times 10^3 > J_{crit}$



No fragmentation

$J = 10^3 < J_{crit}$

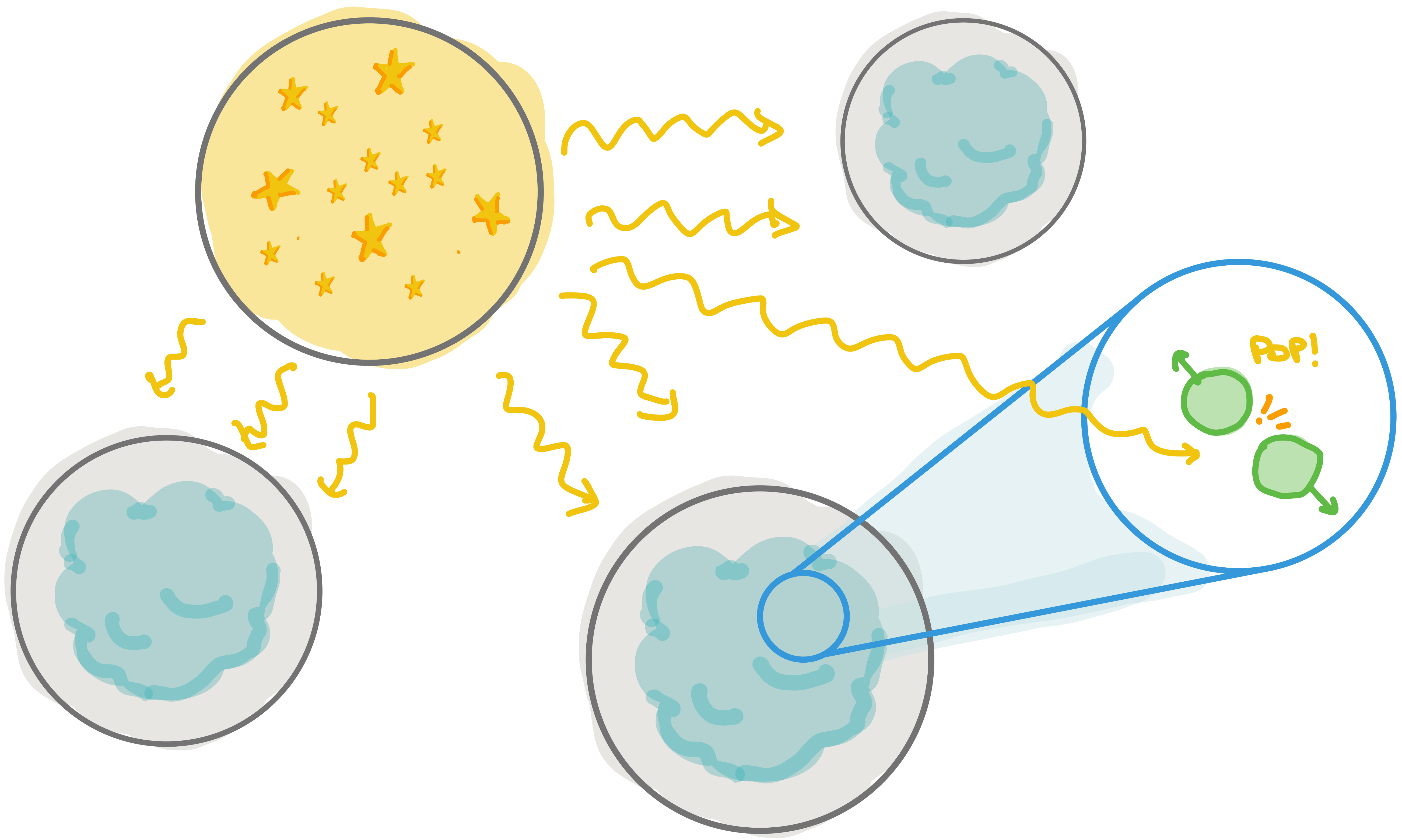


Fragmentation

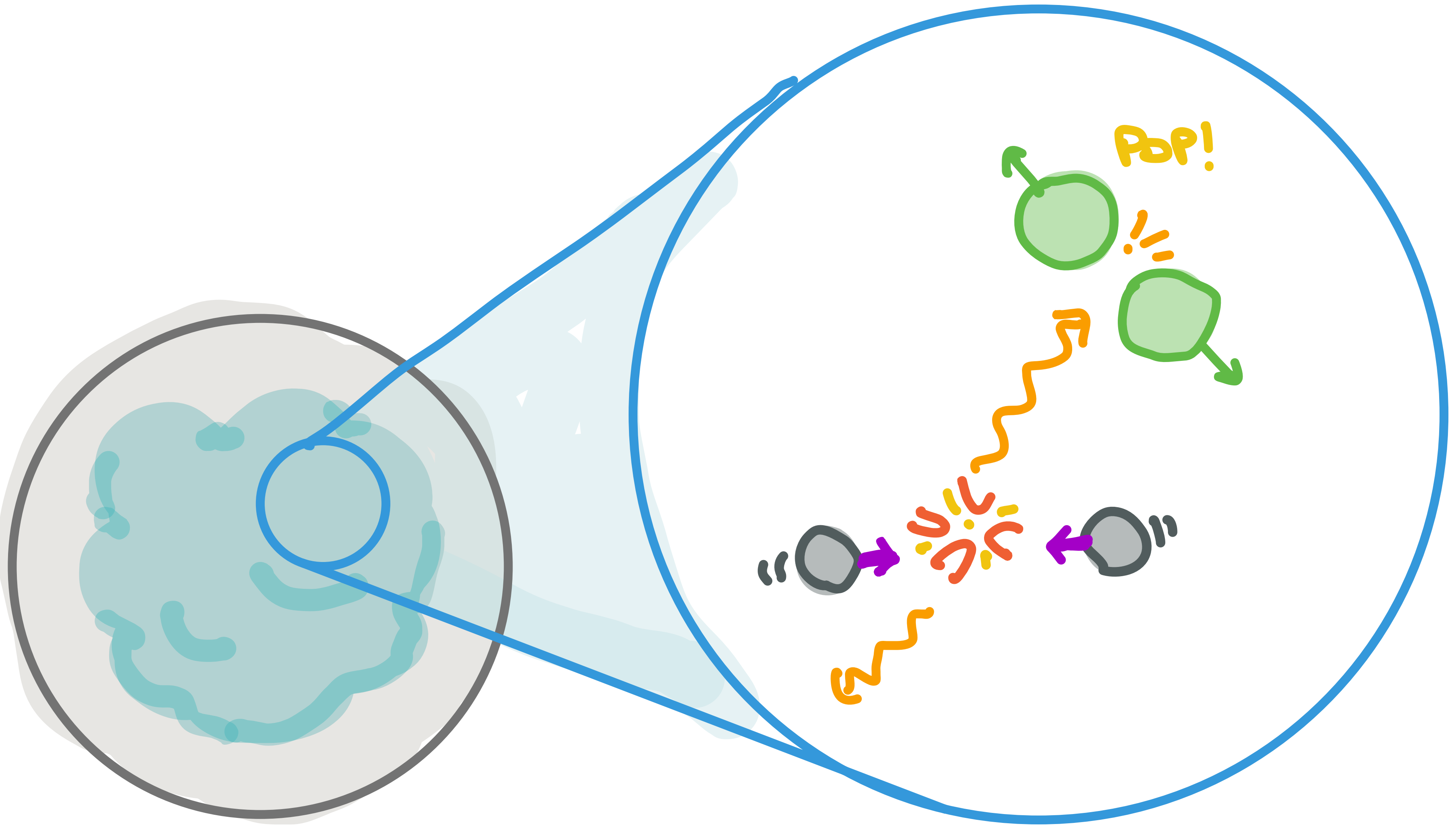
Hartwig et al. 1505.00263 “improved implementation of H2 self-shielding“; see also 2001.04480, 2205.08268

Self Shielding Challenges

Both "outside" and "inside" the house



Only dissociating H2 in outer region



Ionizing radiation from "tail" of spectrum injects electrons, which catalyze H2 *formation*.

Images: Montañez, "Puzzle of the First Black Holes," P. Natarajan, *Scientific American* 318, 2, 24-29 (2018); BBC Frozen Planet, "Criminal Penguins" (2011)

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Halo DM?

Halo DM
Inverse Compton

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

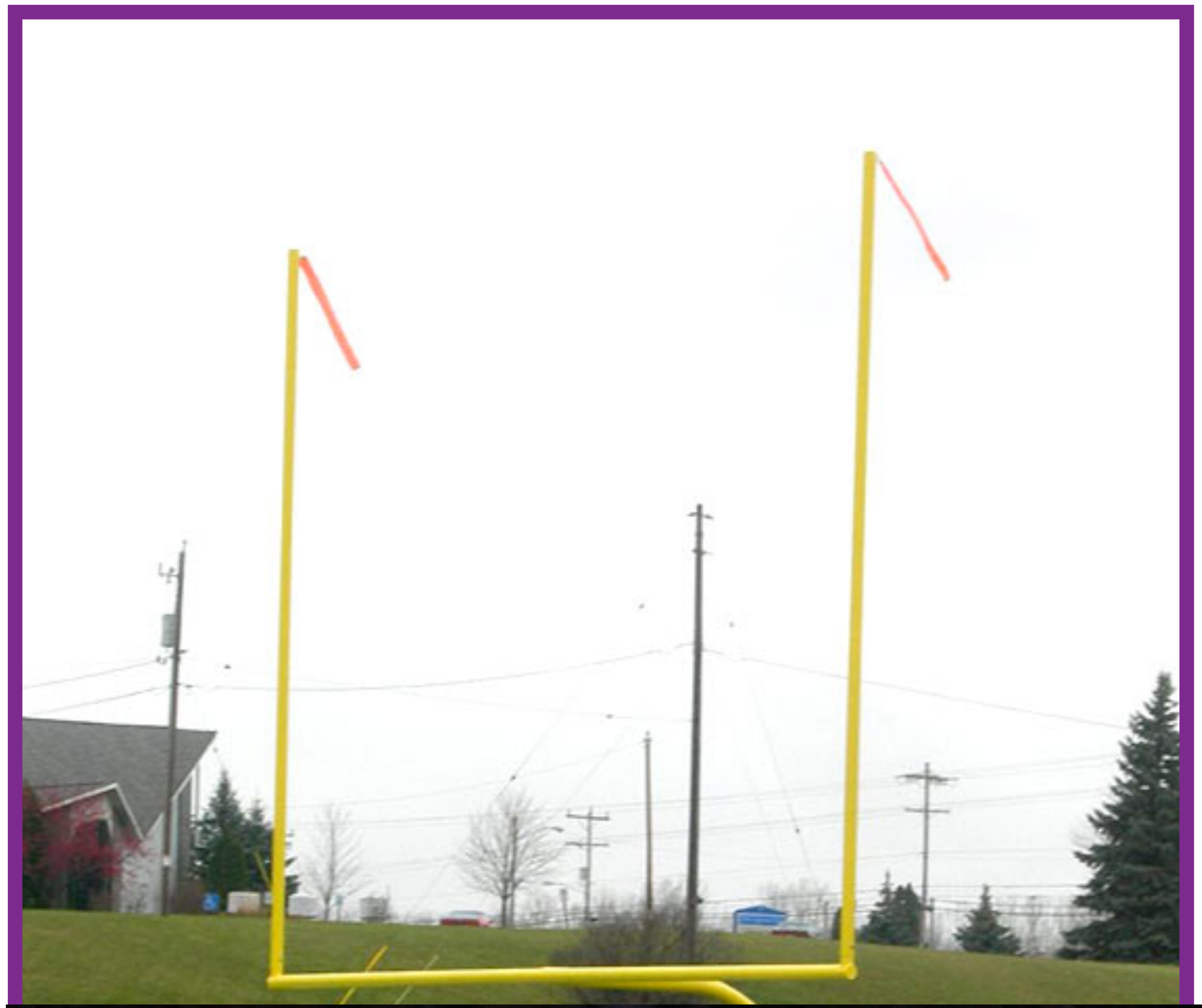
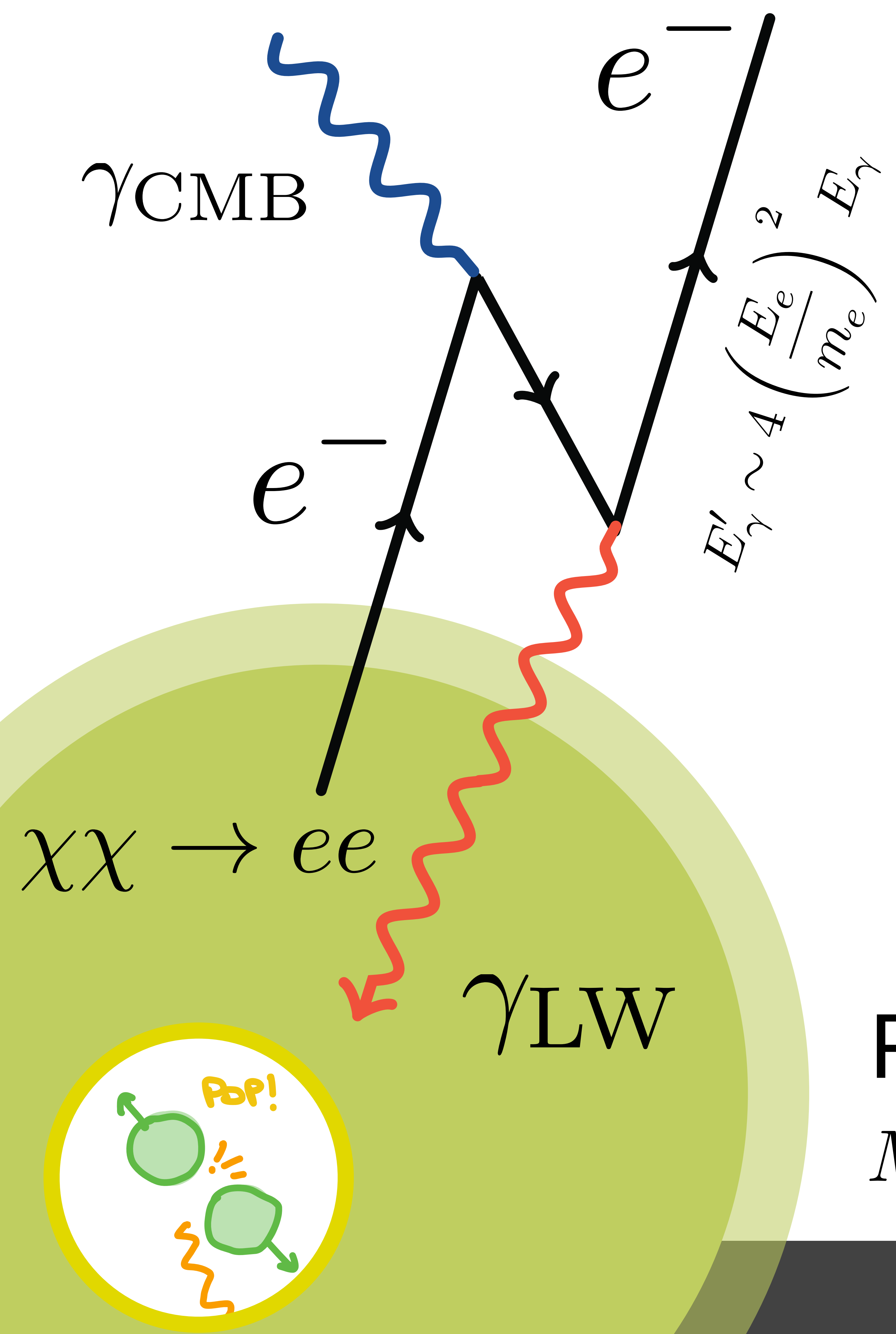


Image: jwindustriesinc.com

Robert Gauthier Los Angeles Times

Strategy



Start with: $10^6\ M_\odot$ halo at z ~ 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. (conservative estimate)

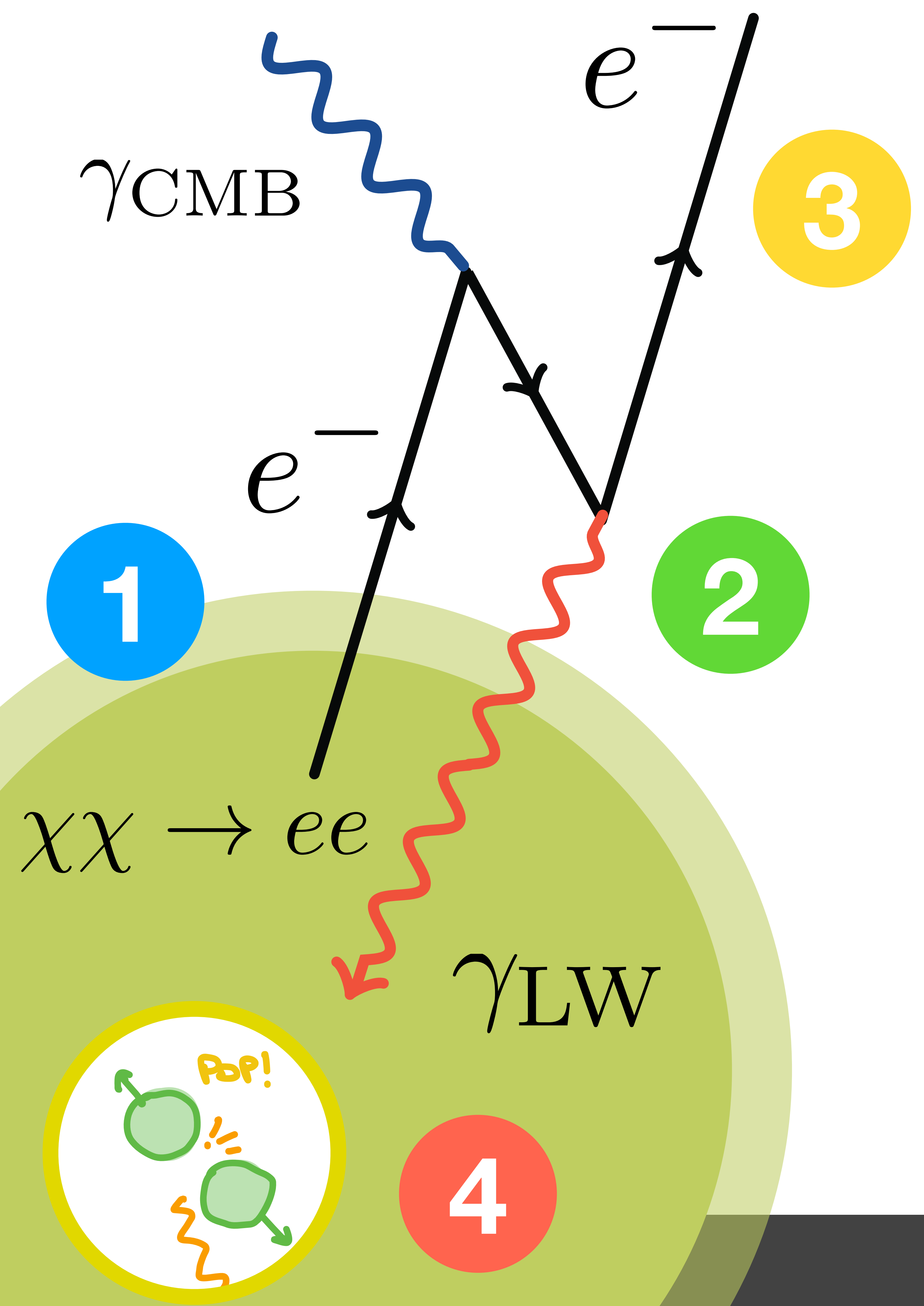
Pick a slow growing halo

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

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

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

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

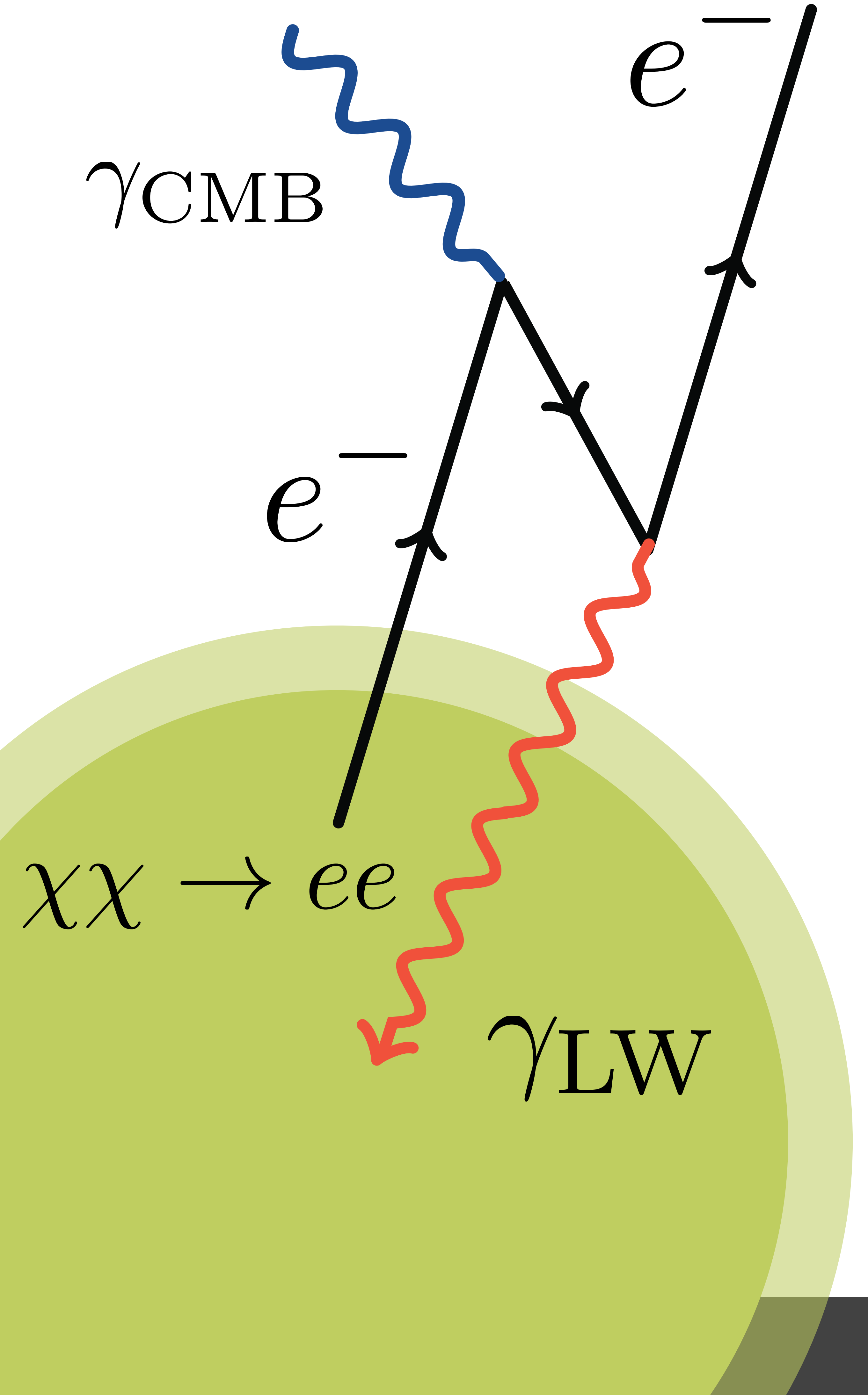
   Good: this stuff would change the gas chemistry and could cause *more* H2 formation.

4. Intergalactic medium is transparent to LW radiation, so this returns to the halo

   Good: this stuff breaks down H2!

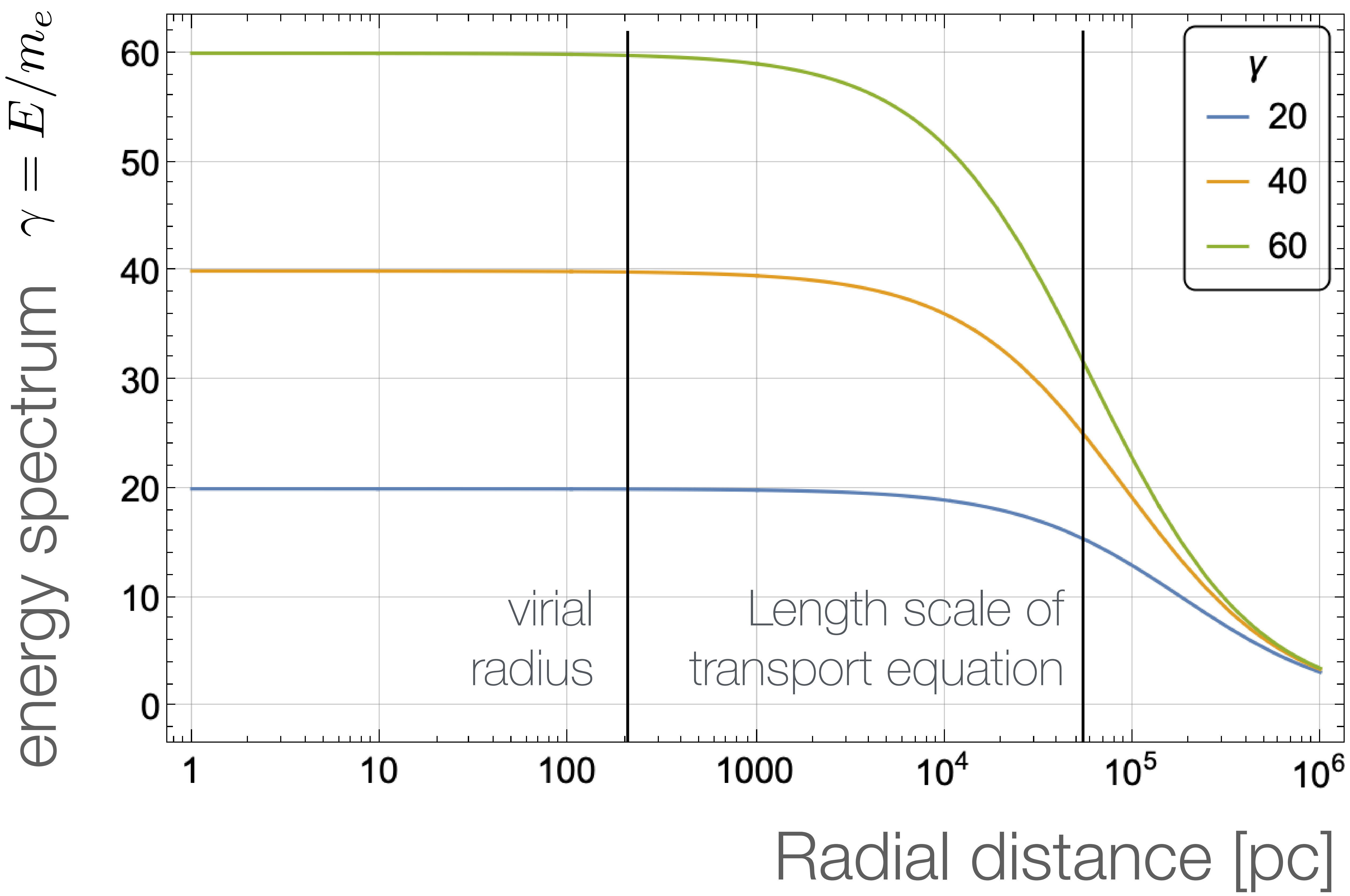
Electron transport

linear regime; solvable analytically



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

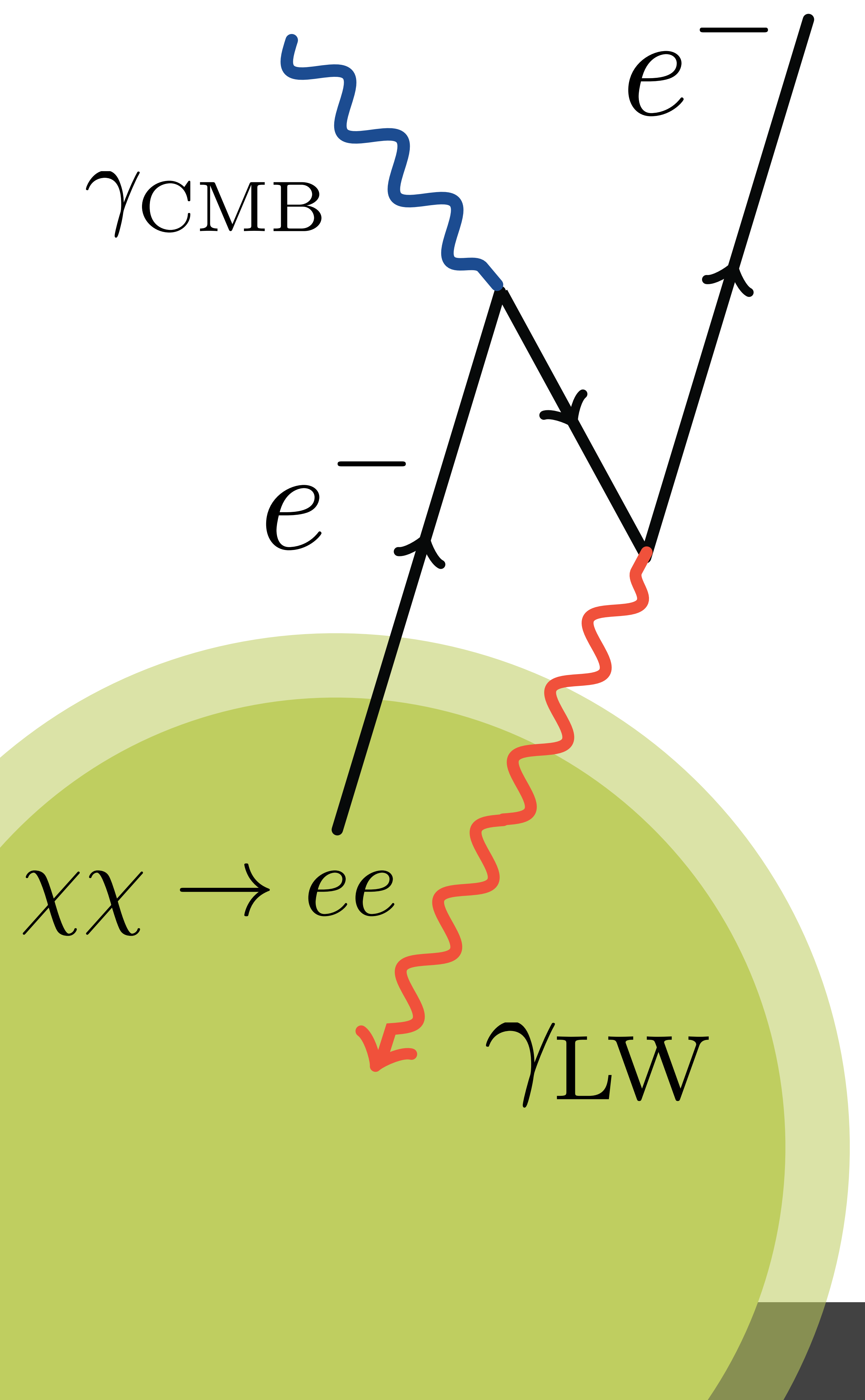
diffusion; no B fields — radiative energy loss — source (DM)



Electrons lose energy *outside* the halo.

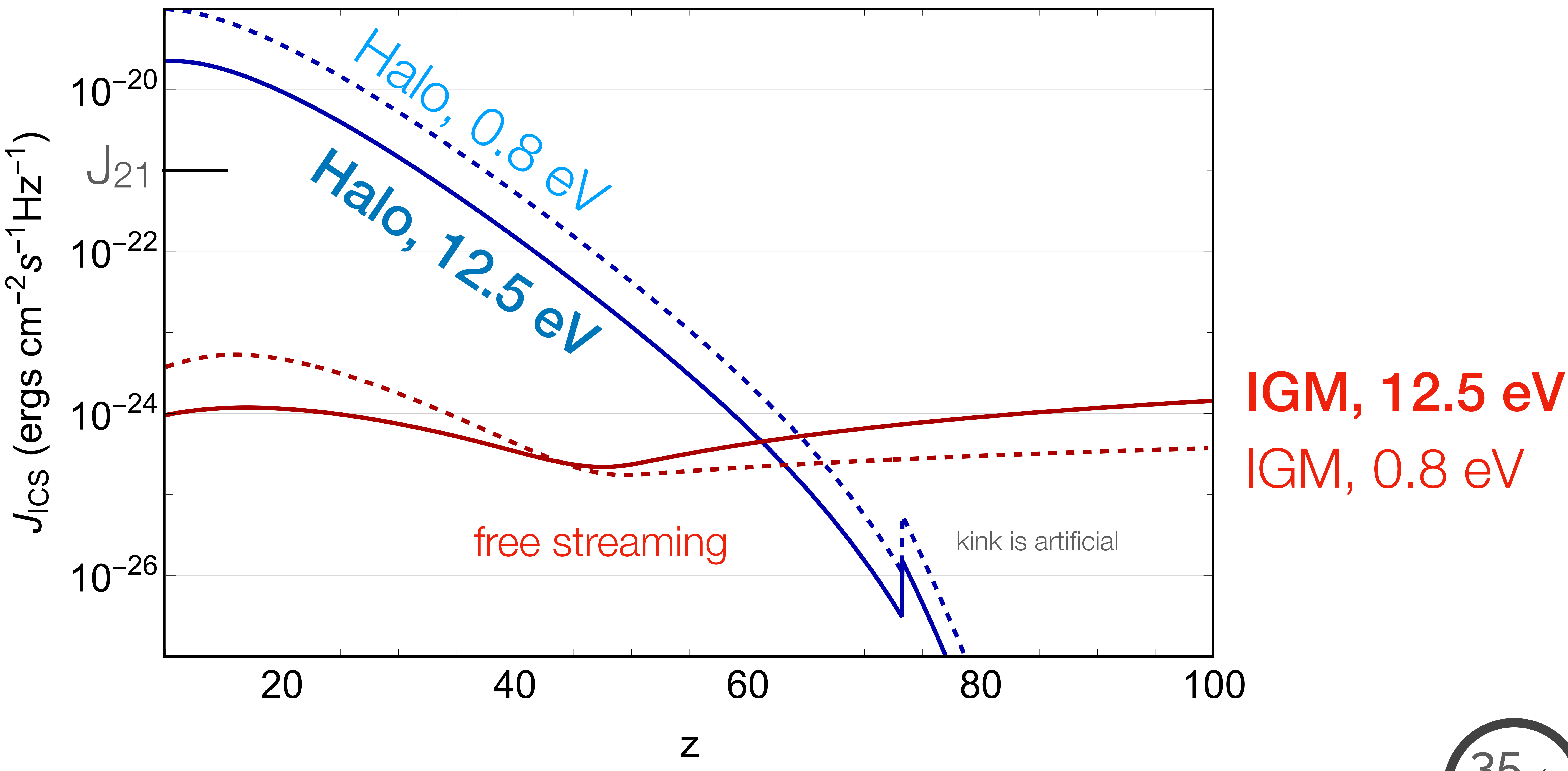
IGM is optically thick to ionizing photons, but transparent to Ly-Wer photons.

Halo v. IGM

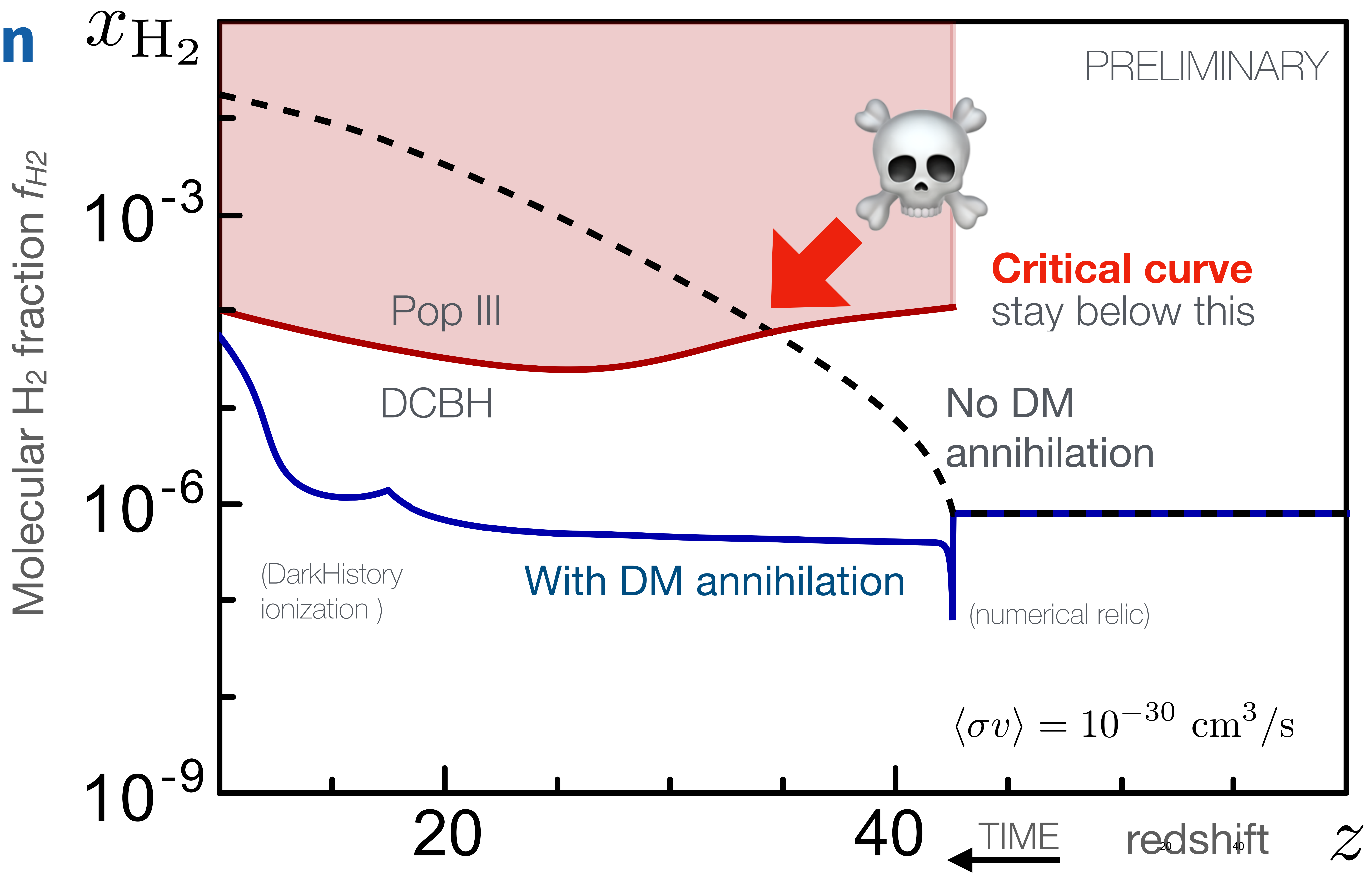


Halo contribution dominates annihilation (vs IGM) by four orders of magnitude; not the case for decay

Compare to: “Birth of the first stars amidst decaying and annihilating dark matter” Wenzer Qin, Julian B. Munoz, Hongwan Liu, Tracy R. Slatyer (2308.12992)
(Appears contradictory, but sits in a regime where their approximation breaks down.)

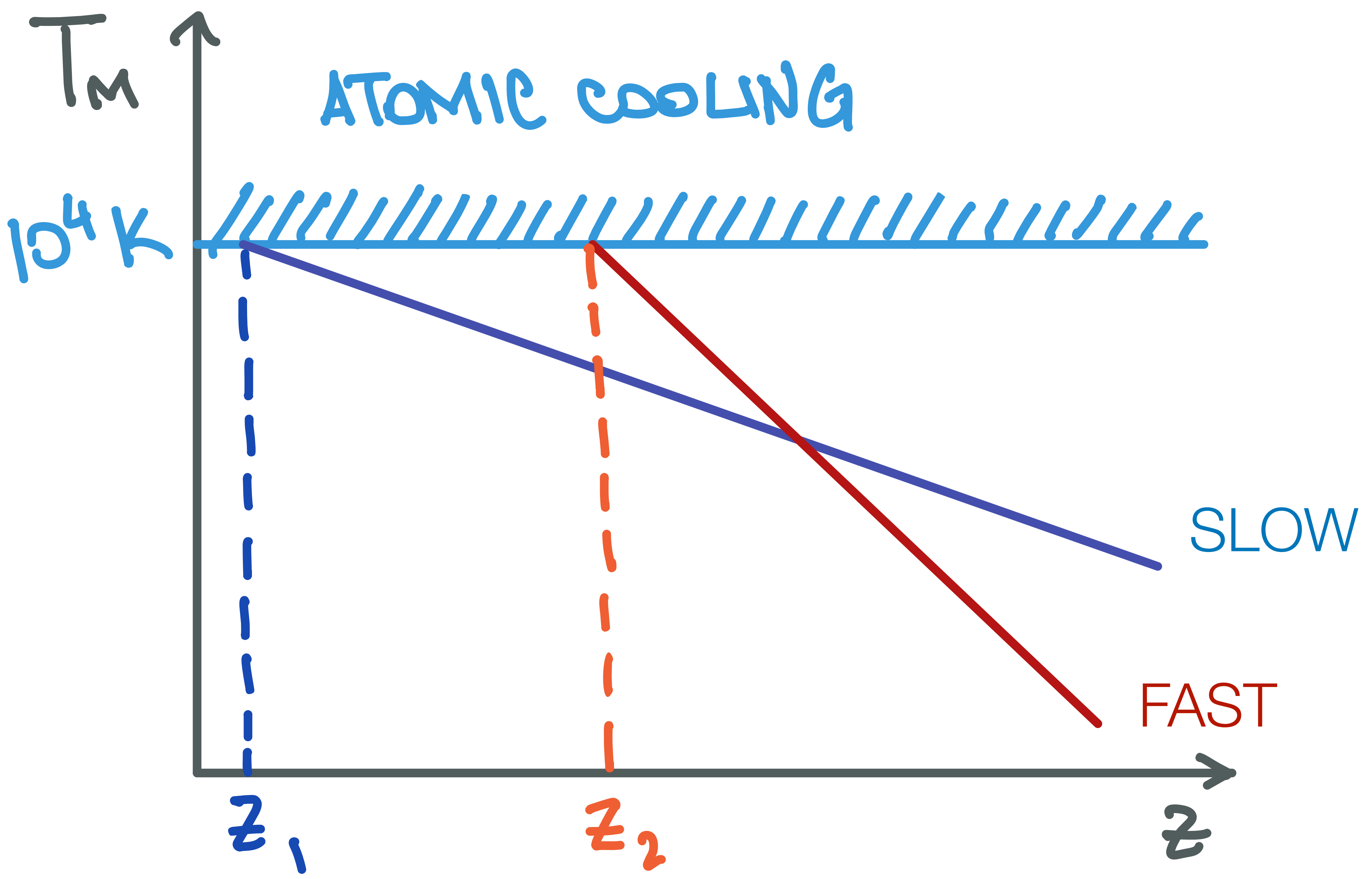


H_2 fraction

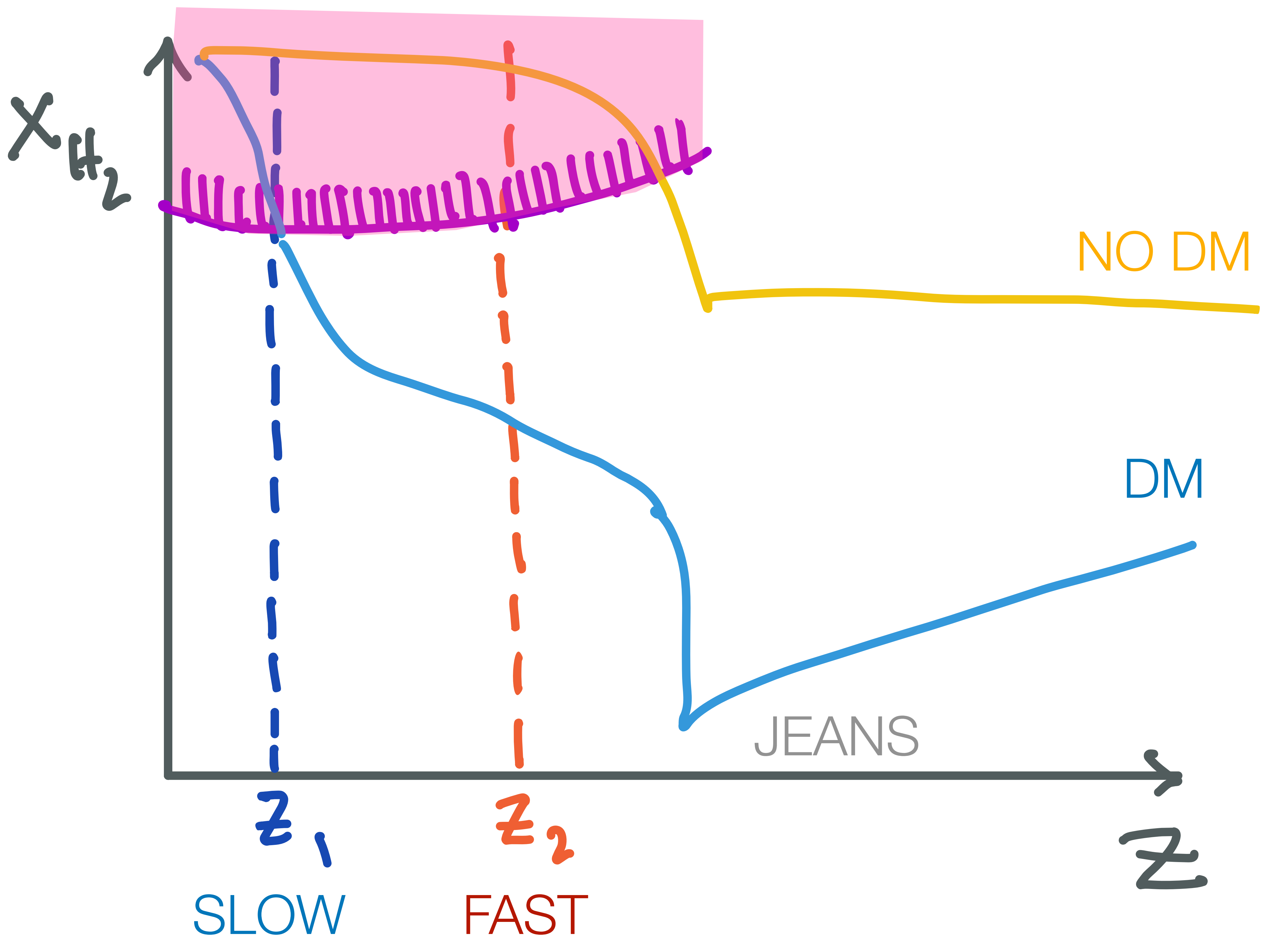

x_{H_2}
Molecular H_2 fraction f_{H2}
10-3
10-6
10-9
PRELIMINARY
Critical curve
stay below this
Pop III
DCBH
No DM
annihilation
(DarkHistory
ionization)
With DM annihilation
(numerical relic)
$\langle \sigma v \rangle = 10^{-30}\ \mathrm{cm}^3/\mathrm{s}$
20
40
TIME
redshift
z

Fast halo growth (dynamical heating)

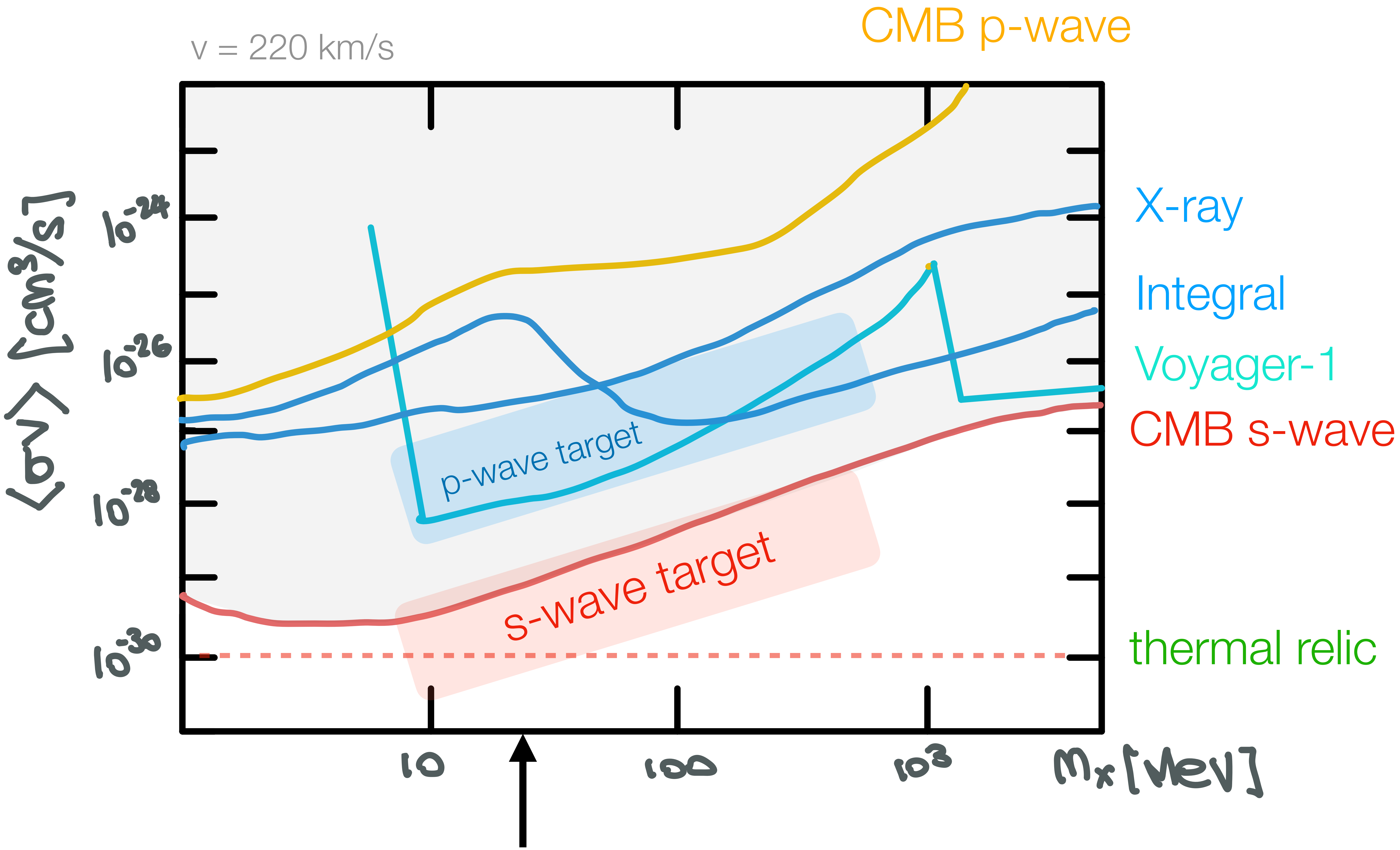
Move the finish line



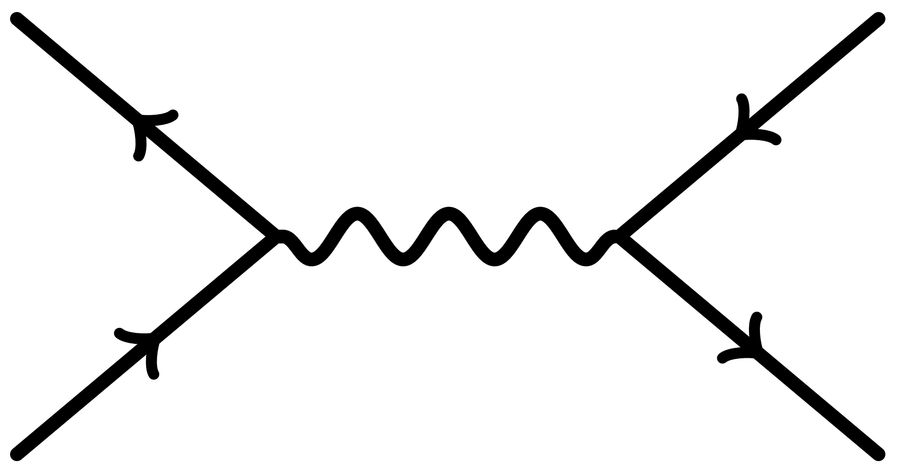
GOAL: STAY BELOW PURPLE LINE
WHEN YOU CROSS DASHED LINE



Hypothetical plot (mostly correct)



Bag of tricks:
Dynamical heating
Halo Substructure
Cascade decay



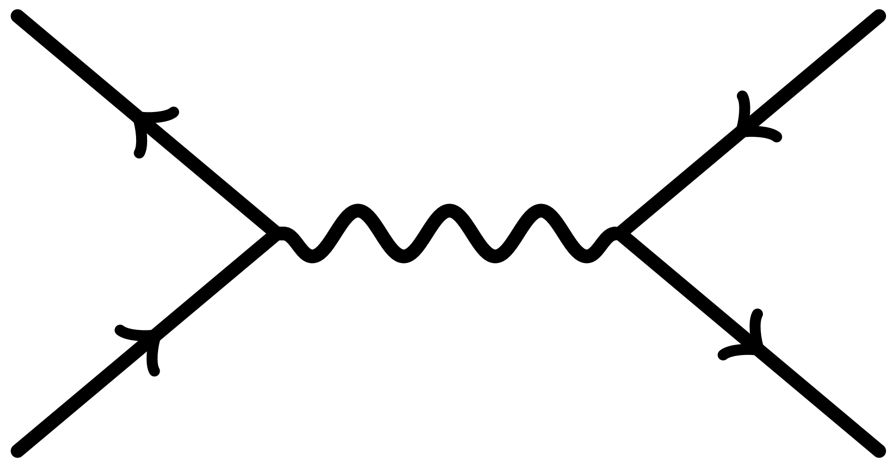
"Resonant Sub-GeV Dirac Dark Matter" Bernreuther, et al. (2010.14522); see also Feng (1707.03835)

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

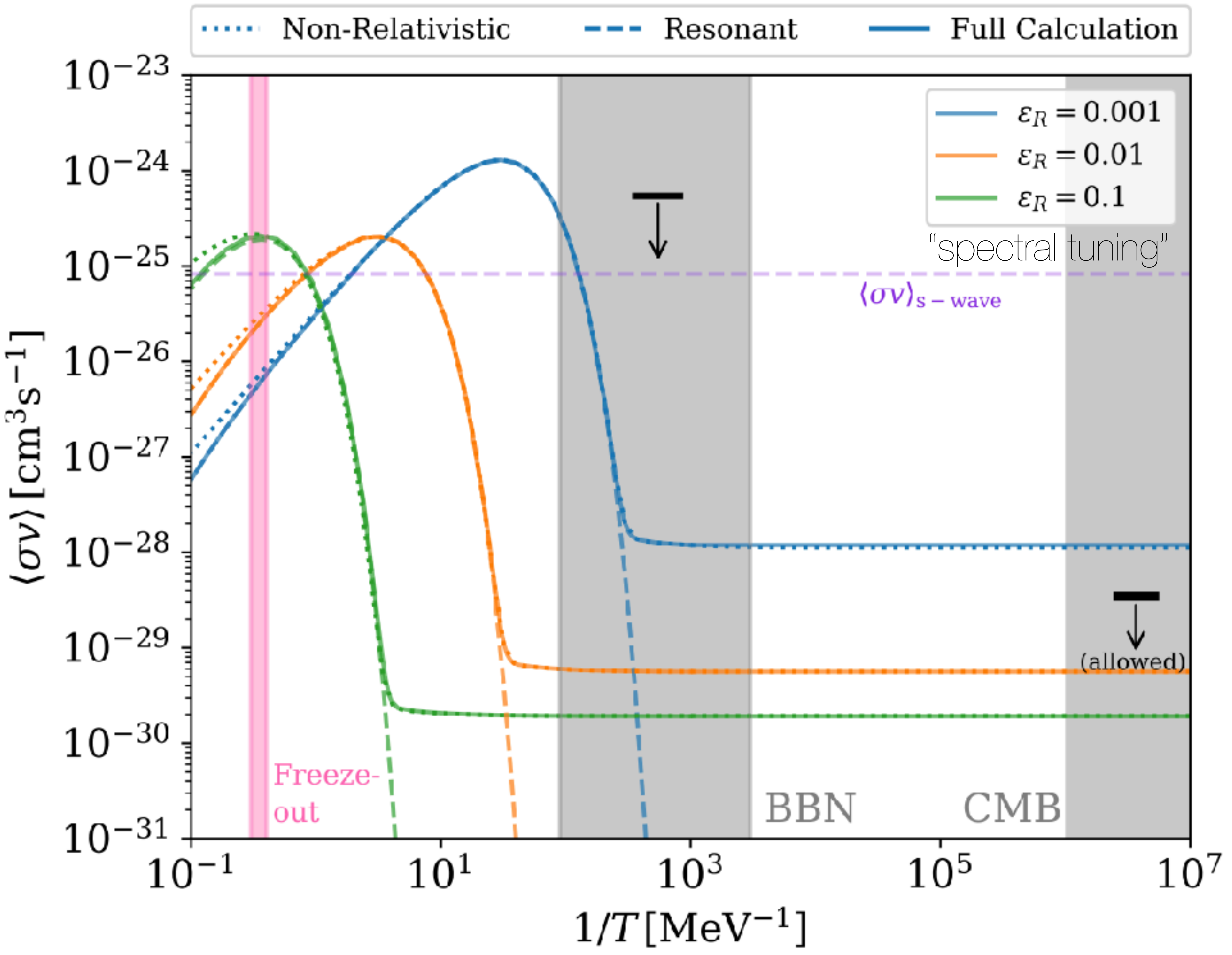
Model building

"Thermal relic with one modest trick..."

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

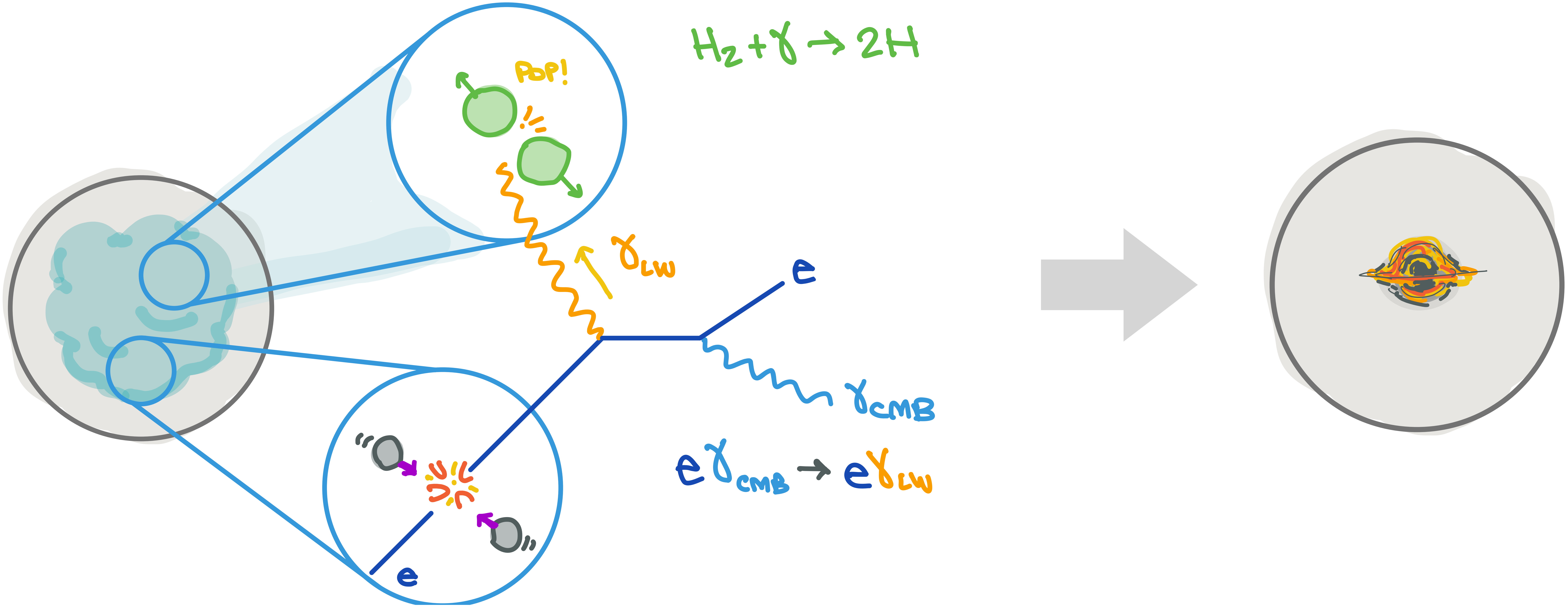


Playing limbo on BBN, CMB bounds.



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

Thanks!



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

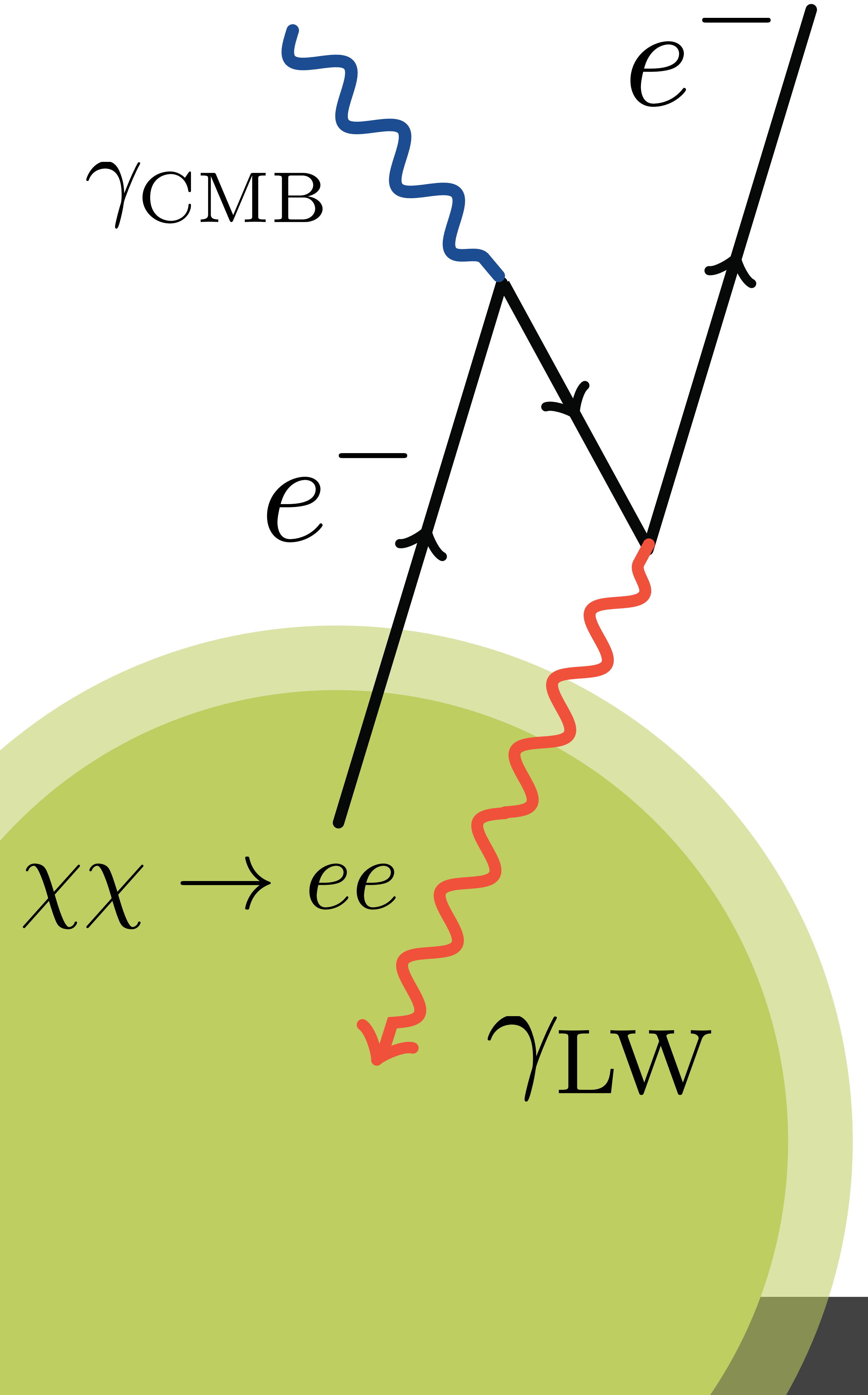
Extra Slides

... mainly for those looking at the slides afterward

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

- A shorter version of this talk at the 2024 Mitchell Conference
  https://mitchell.tamu.edu/collider-dark-matter-and-neutrino-physics-2024/

The fine print



Pick a slow growing halo

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

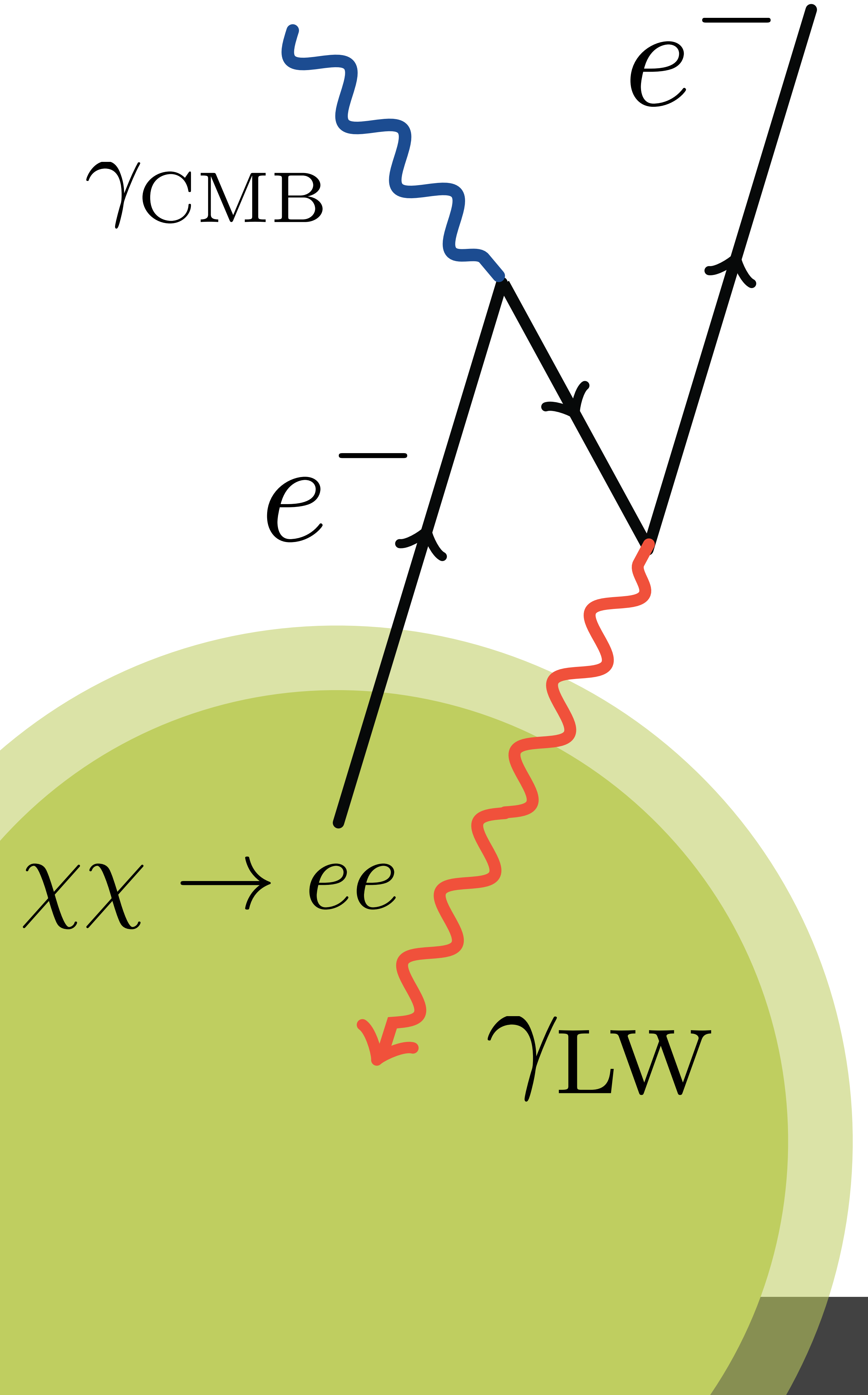
$$M_{\rm halo}(z=25) = 10^6\, M_\odot$$
$$T_{\rm gas}(z=12) = 10^4\ {\rm K}$$

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.

Electron transport

linear regime; solvable analytically



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

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

$$\dot{\mathcal{E}} = -\frac{4}{3}\sigma_{\rm Thom}\gamma^2\beta^2 u(T_{\rm CMB})$$

$$Q_e = \frac{1}{2}\frac{\rho_{\rm DM}^2(\mathbf{x})}{m_{\rm DM}^2}\langle\sigma v\rangle \mathcal{N}_e$$

$$\beta\frac{\partial \mathcal{N}_e}{\partial x} - b_0\frac{\partial}{\partial \gamma}(\beta^2\gamma^2\mathcal{N}_e) = \frac{Q_e(E, x)}{4\pi}$$

$$b_0 \sim 10^5 \text{ pc} \gg r_{\rm vir} = 100 \text{ pc}$$

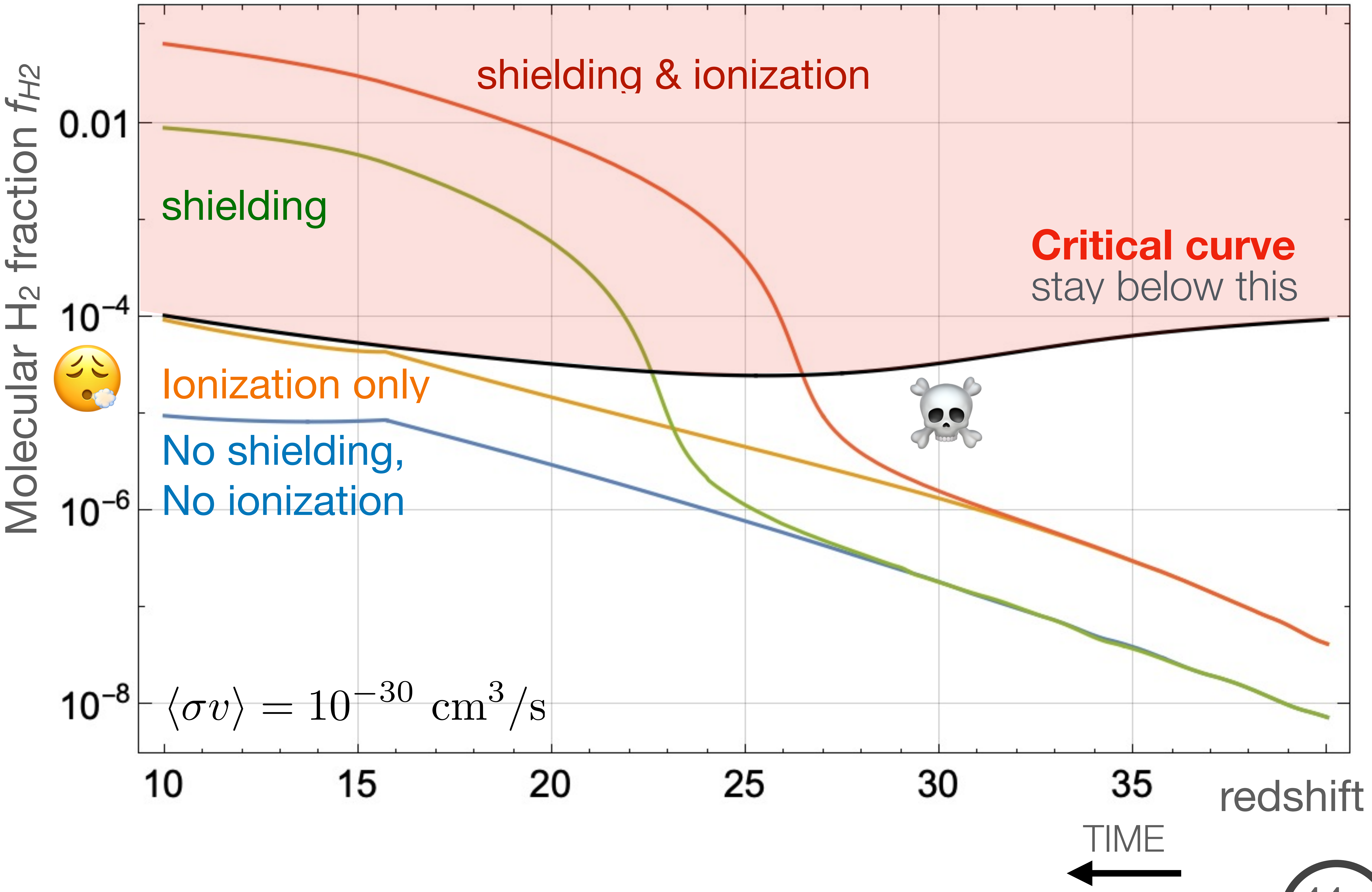
$$\gamma = \frac{E}{m_e}$$

H_2 fraction

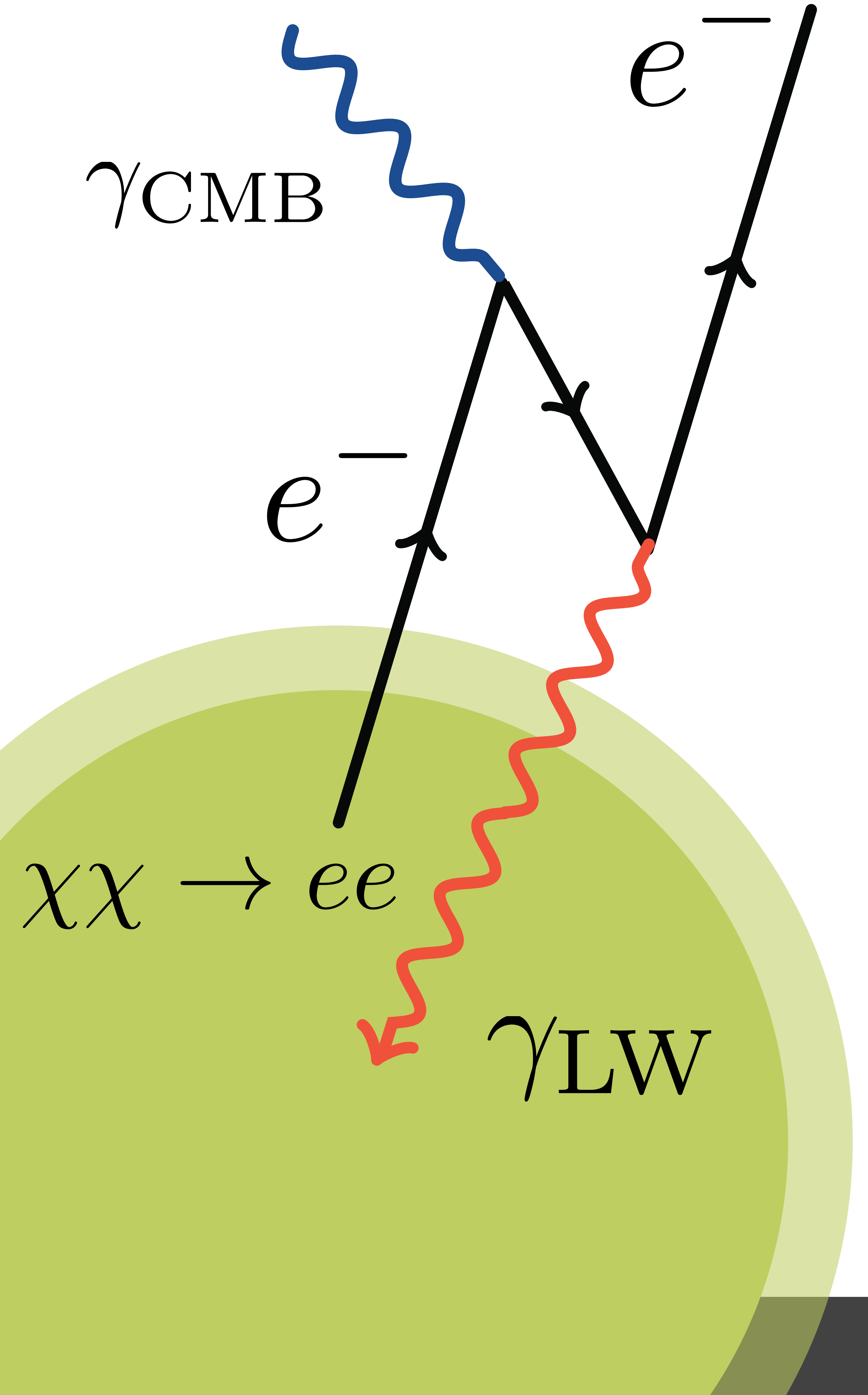
Challenge:
self-shielding

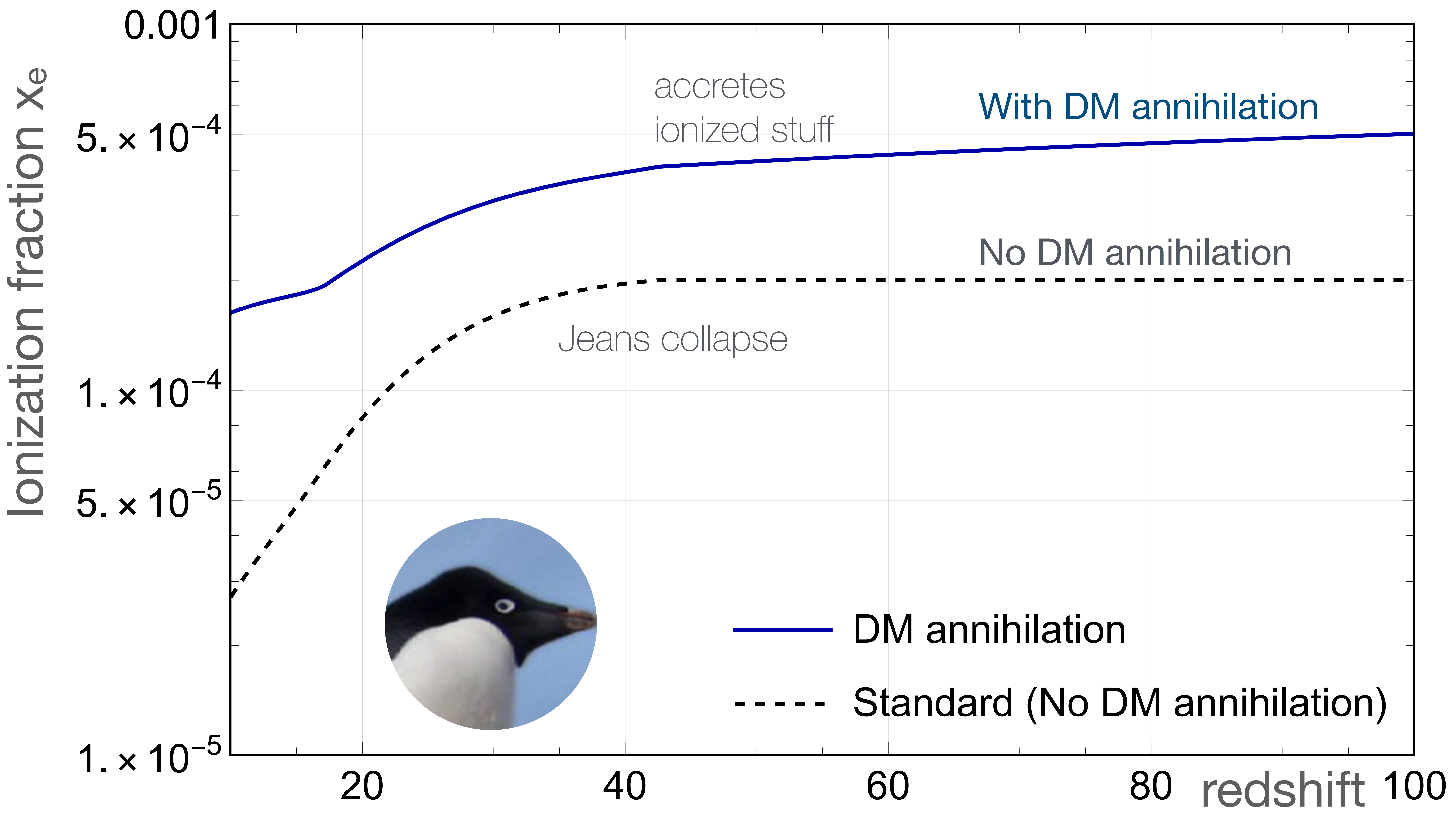
If H_2 does build up, then our efforts fail because electrons catalyze H_2 formation

Solve rate eqns.



Ionization History





$\langle \sigma v \rangle = 10^{-30}\ \mathrm{cm^3/s}$

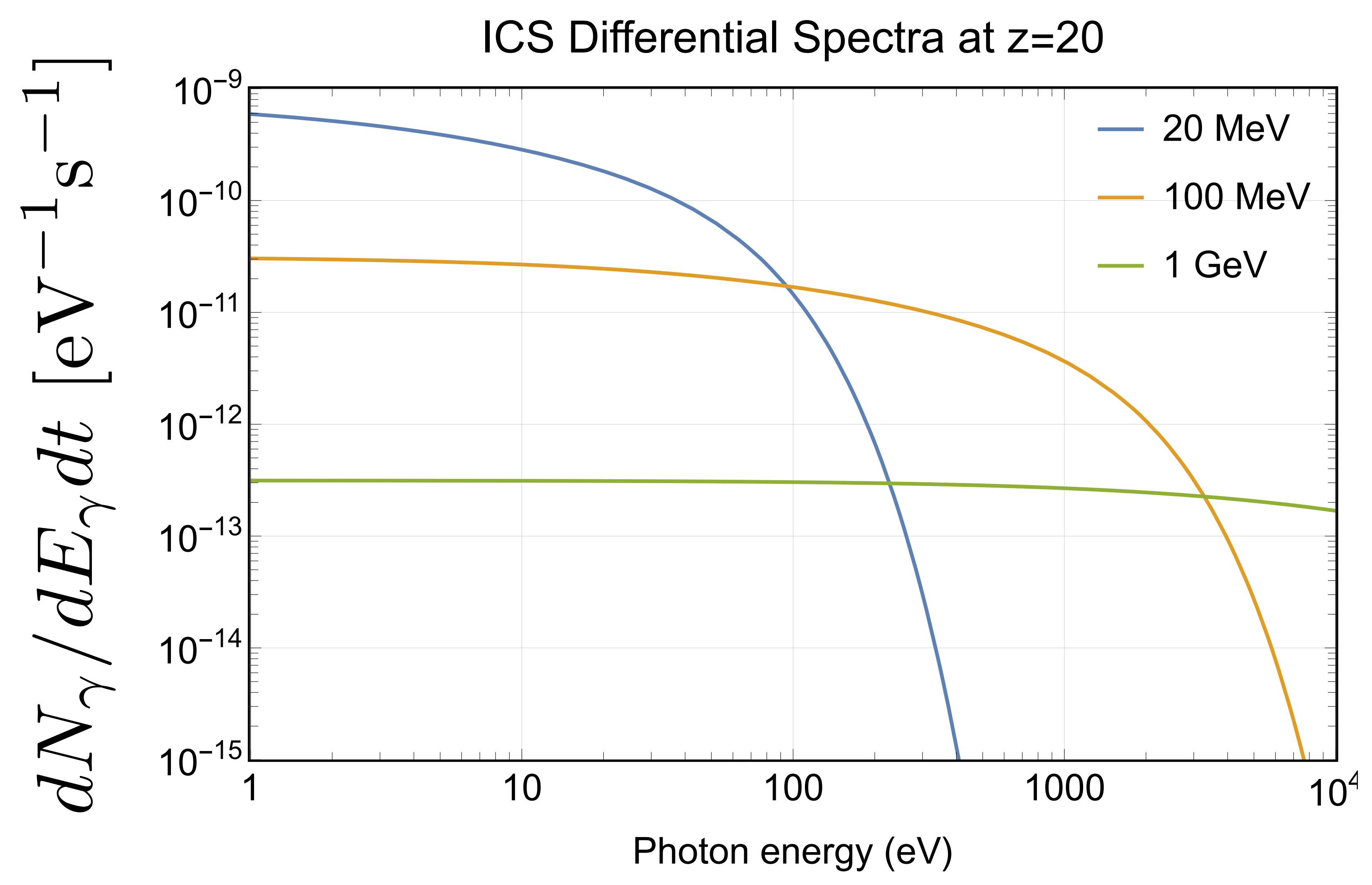
Lesson: Standard ionization history *not* significantly altered.

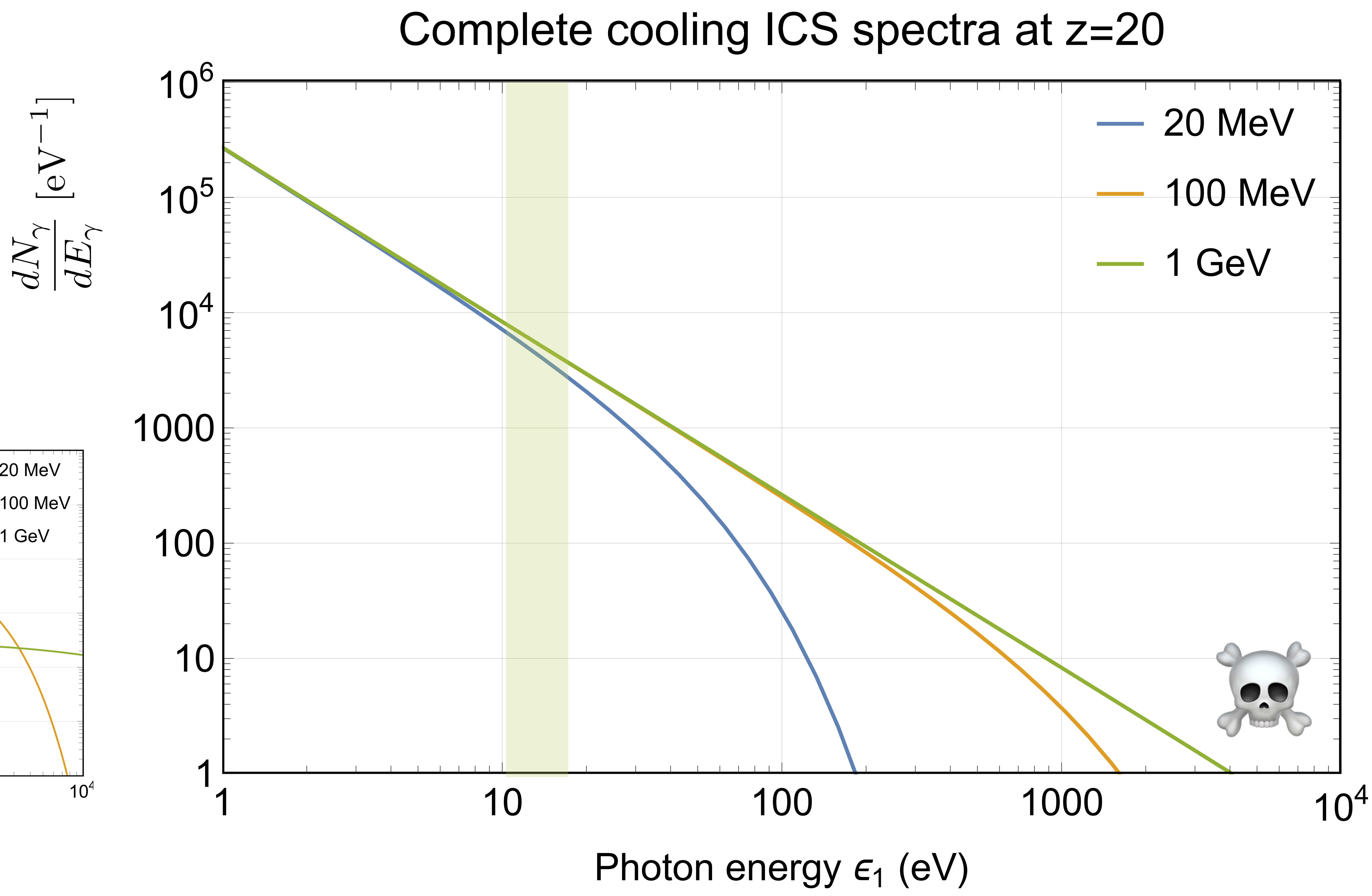
Heavier Dark Matter

Why can you extend the plot to GeV dark matter?

Same Ly-Wer flux

Beyond 1 GeV, flux of hi-E photons is large enough that "EFT breaks down"





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.