New routes towards high redshift supermassive black holes

Yifan Lu (UCLA)

PACIFIC Conference, August 2024

- Based on

  [1] *Phys. Rev. D* 109 (2024), 123016 (arXiv: 2312.15062)

  [2] Phys. Rev. Lett. 133 (2024), 091001 (arXiv: 2404.03909)

- Collaborators:

Zachary Picker

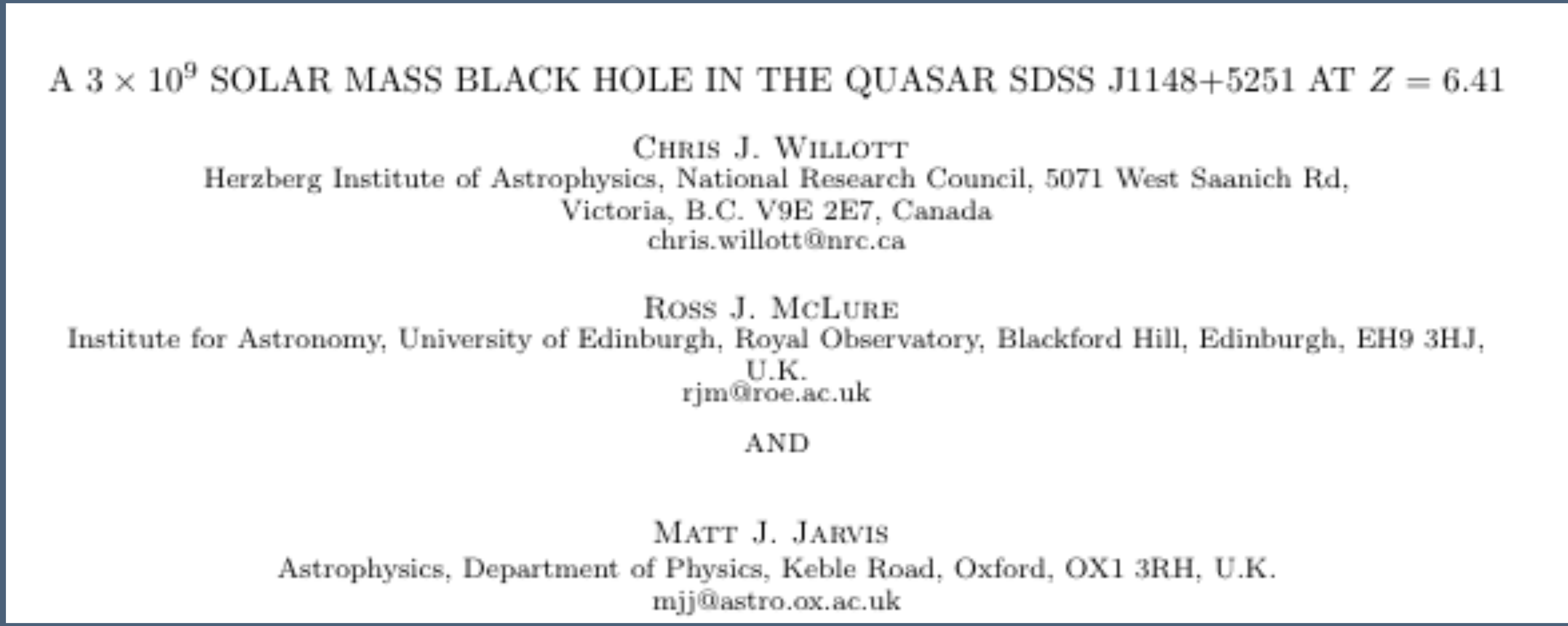
Alexander Kusenko

Outline

- The mystery of high redshift supermassive black holes
- Direct collapse mechanism
- Recipe I: heating via tiny primordial black holes
- Recipe II: dissociation via relic particle decay
- Observational signature and SMBH abundance

High redshift SMBH

- A SMBH population has been known to exist at z~6.



A 3×10^9 SOLAR MASS BLACK HOLE IN THE QUASAR SDSS J1148+5251 AT $Z = 6.41$

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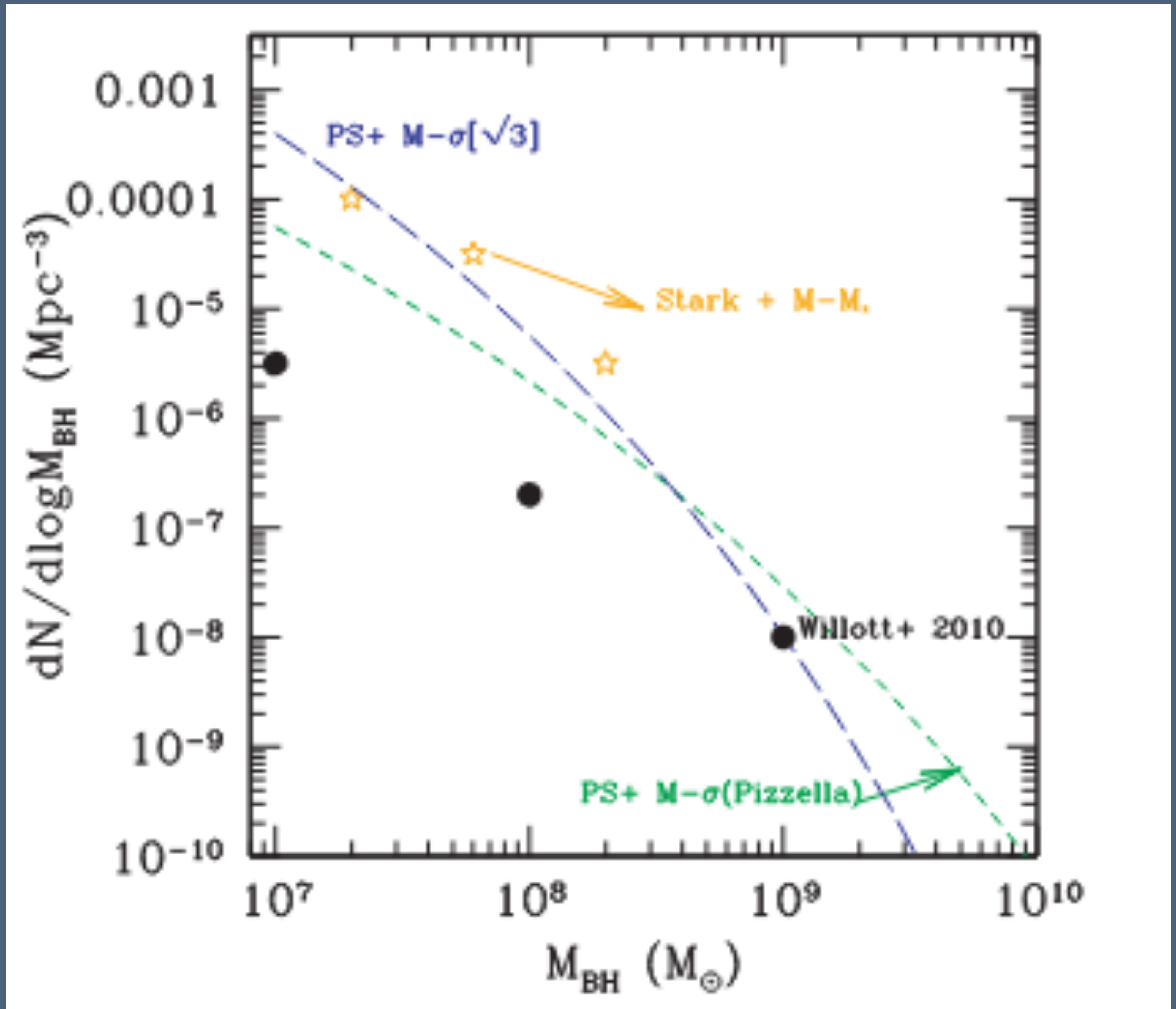
[Willott et al., 2003]



[Volonteri & Stark, 2011]

High redshift SMBH

- JWST discoveries show that quasars are just the tip of the iceberg...

A CEERS Discovery of an Accreting Supermassive Black Hole 570 Myr after the Big Bang: Identifying a Progenitor of Massive $z > 6$ Quasars

Rebecca L. Larson[1,40], Steven L. Finkelstein[1], Dale D. Kocevski[2], Taylor A. Hutchison[3,41], Jonathan R. Trump[4], Pablo Arrabal Haro[5], Volker Bromm[6], Nikko J. Cleri[7,8], Mark Dickinson[5], Seiji Fujimoto[1], Jeyhan S. Kartaltepe[9], Anton M. Koekemoer[10], Casey Papovich[7,8], Nor Pirzkal[11], Sandro Tacchella[12,13], Jorge A. Zavala[14], Micaela Bagley[1], Peter Behroozi[15,16], Jaclyn B. Champagne[17], Justin W. Cole[7,8], Intae Jung[10], Alexa M. Morales[18], Guang Yang[19,20], Haowen Zhang[15], Adi Zitrin[21], Ricardo O. Amorín[22,23], Denis Burgarella[24], Caitlin M. Casey[25,26], Óscar A. Chávez Ortiz[6], Isabella G. Cox[9], Katherine Chworowsky[6,40], Adriano Fontana[27], Eric Gawiser[28], Andrea Grazian[29], Norman A. Grogin[10], Santosh Harish[9], Nimish P. Hathi[30], Michaela Hirschmann[31], Benne W. Holwerda[32], Stéphanie Juneau[33], Gene C. K. Leung[34], Ray A. Lucas[10], Elizabeth J. McGrath[2], Pablo G. Pérez-González[35], Jane R. Rigby[3], Lise-Marie Seillé[24], Raymond C. Simons[4], Alexander de la Vega[36], Benjamin J. Weiner[37], Stephen M. Wilkins[38,39], and L. Y. Aaron Yung[3,41]

A JWST/NIRSpec First Census of Broad-Line AGNs at z = 4 – 7: Detection of 10 Faint AGNs with $M_{BH} \sim 10^6 - 10^8\ M_\odot$ and Their Host Galaxy Properties

Yuichi Harikane,[1] Yechi Zhang,[1,2] Kimihiko Nakajima,[3] Masami Ouchi,[3,1,4] Yuki Isobe,[1,5] Yoshiaki Ono,[1] Shun Hatano,[3,6] Yi Xu,[1,2] and Hiroya Umeda[1,5]

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[6]Department of Astronomical Science, The Graduate University for Advanced Studies, SOKENDAI, 2-21-
181-8588, Japan

EPOCHS VII: Discovery of high redshift ($6.5 < z < 12$) AGN candidates in JWST ERO and PEARLS data

Ignas Juodžbalis,[1]★ Christopher J. Conselice,[1] Maitrayee Singh,[1] Nathan Adams,[1] Katherine Ormerod,[1] Thomas Harvey,[1] Duncan Austin,[1] Marta Volonteri,[2] Seth H. Cohen, [3] Rolf A. Jansen, [3] Jake Summers, [3] Rogier A. Windhorst, [3] Jordan C. J. D'Silva, [4,5] Anton M. Koekemoer, [6] Dan Coe, [6,7,8] Simon P. Driver, [4] Brenda Frye, [9] Norman A. Grogin, [6] Madeline A. Marshall, [10,5]

CEERS Key Paper VI: JWST/MIRI Uncovers a Large Population of Obscured AGN at High Redshifts

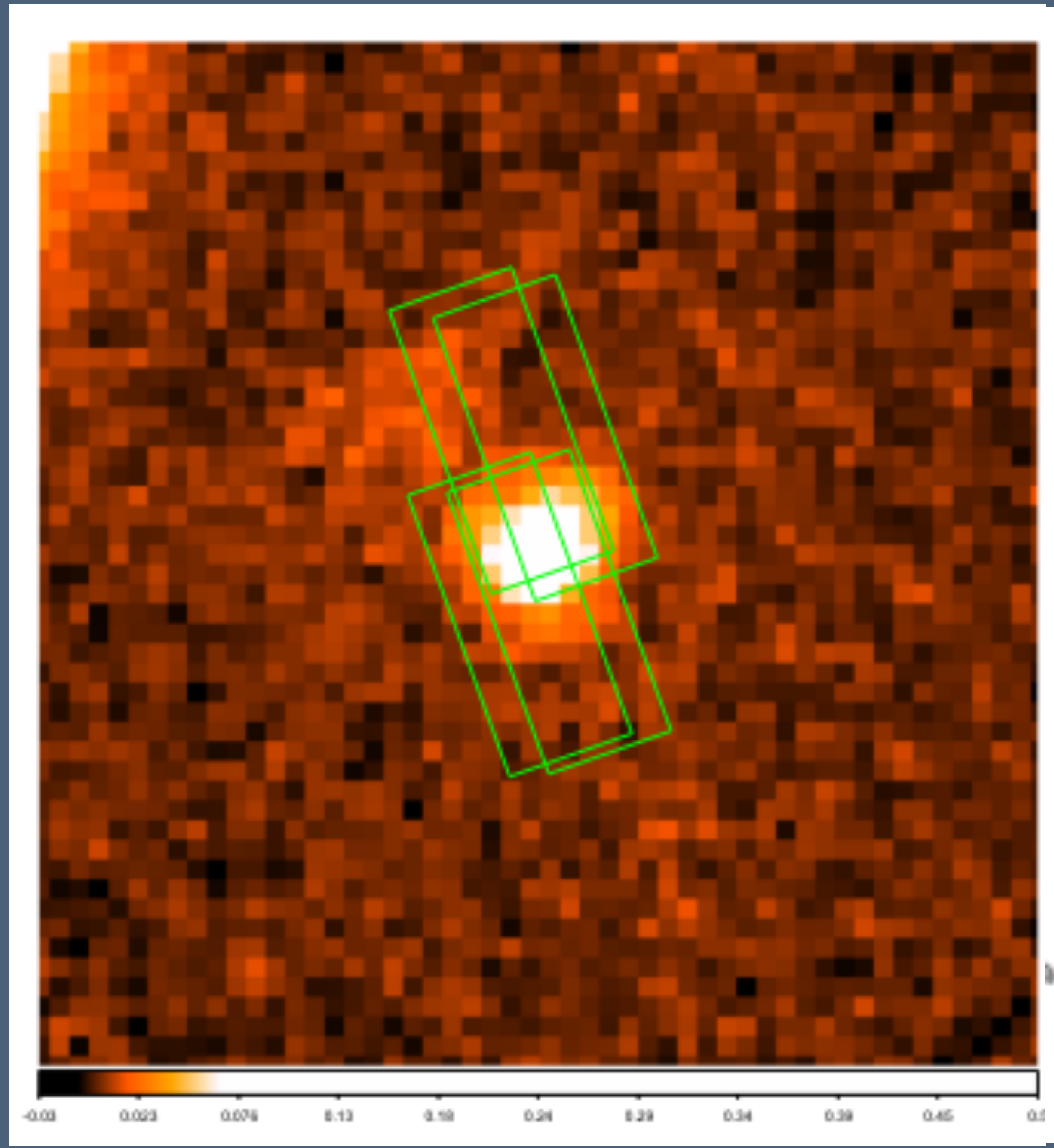
Yang, G. (杨光)[1,2] Caputi, K. I.,[1,3] Papovich, C.[4,5] Arrabal Haro, P.[6] Bagley, M. B.[7] Behroozi, P.[8,9] Bell, E. F.[10] Bisigello, L.[11,12] Buat, V.[13] Burgarella, D.[13] Cheng, Y.[14] Cleri, N. J.[4,5] Davé, R.[15,16] Dickinson, M.[6] Elbaz, D.[17] Ferguson, H. C.[18] Finkelstein, S. L.[7] Grogin, N. A.[19] Hathi, N. P.[18] Hirschmann, M.[20] Holwerda, B. W.[21] Huertas-Company, M.[22,23,24] Hutchison, T. A.[25,*] Iani, E.[1] Kartaltepe, J. S.[26] Kirkpatrick, A.[27] Kocevski, D. D.[28] Koekemoer, A. M.[19] Kokorev, V.[1] Larson, R. L.[29,30] Lucas, R. A.[31] Pérez-González, P. G.[32] Rinaldi, P.,[1] Shen, L.[4,5] Trump, J. R.[33] de la Vega, A.[34] Yung, L. Y. A.[25] and Zavala, J. A.[35]

GA-NIFS: A massive black hole in a low-metallicity AGN at $z \sim 5.55$ revealed by *JWST*/NIRSpec IFS

Hannah Übler[1,2]★, Roberto Maiolino[1,2,3], Emma Curtis-Lake[4], Pablo G. Pérez-González[5], Mirko Curti[6,1,2], Michele Perna[5], Santiago Arribas[5], Stéphane Charlot[7], Madeline A. Marshall[8,9], Francesco D'Eugenio[1,2], Jan Scholtz[1,2], Andrew Bunker[10], Stefano Carniani[11], Pierre Ferruit[12], Peter Jakobsen[13,14], Hans-Walter Rix[15], Bruno Rodríguez Del Pino[5], Chris J. Willott[8], Torsten Böker[16], Giovanni Cresci[17], Gareth C. Jones[10], Nimisha Kumari[18], and Tim Rawle[16]

High redshift SMBH

- JWST discoveries show that quasars are just the tip of the iceberg...
  - An AGN is found when the universe is only 0.43 Gyr old!



JADES NIRSpec Spectroscopy of GN-z11: Lyman-α emission and possible enhanced nitrogen abundance in a $z = 10.60$ luminous galaxy

Andrew J. Bunker[1,⋆], Aayush Saxena[1,2], Alex J. Cameron[1], Chris J. Willott[3], Emma Curtis-Lake[4], Peter Jakobsen[5,6], Stefano Carniani[7], Renske Smit[8], Roberto Maiolino[9,10,2], Joris Witstok[9,10], Mirko Curti[9,10,11], Francesco D'Eugenio[9,10], Gareth C. Jones[1], Pierre Ferruit[12], Santiago Arribas[13], Stephane Charlot[14], Jacopo Chevallard[1], Giovanna Giardino[15], Anna de Graaff[16], Tobias J. Looser[9,10], Nora Lützgendorf[17], Michael V. Maseda[18], Tim Rawle[17], Hans-Walter Rix[16], Bruno Rodríguez Del Pino[13], Stacey Alberts[19], Eiichi Egami[19], Daniel J. Eisenstein[20], Ryan Endsley[21], Kevin Hainline[19], Ryan Hausen[22], Benjamin D. Johnson[20], George Rieke[19], Marcia Rieke[19], Brant E. Robertson[23], Irene Shivaei[19], Daniel P. Stark[19], Fengwu Sun[19], Sandro Tacchella[9,10], Mengtao Tang[19], Christina C. Williams[24,19], Christopher N. A. Willmer[19], William M. Baker[9,10], Stefi Baum[25], Rachana Bhatawdekar[12,26], Rebecca Bowler[27], Kristan Boyett[28,29], Zuyi Chen[19], Chiara Circosta[12], Jakob M. Helton[19], Zhiyuan Ji[19], Jianwei Lyu[19], Erica Nelson[30], Eleonora Parlanti[7], Michele Perna[13], Lester Sandles[9,10], Jan Scholtz[9,10], Katherine A. Suess[23,31], Michael W. Topping[19], Hannah Übler[9,10], Imaan E. B. Wallace[1], and Lily Whitler[19]

High redshift SMBH

- The existence of these SMBHs poses a severe challenge in our understanding of galaxy formation at high redshift:
  - If they come from the remnant of the first generation (Pop III) stars, the seed mass is about $10^2\ M_\odot$
  - They need to grow to $10^9\ M_\odot$ by z~6
  - Accretion is Eddington limited: it takes about 0.8 Gyr to grow up 7 orders of magnitude
  - The age of the universe at z=6 is ~0.9 Gyr!

High redshift SMBH

- Why are they there?
  - **Light seeds**: from Pop III star remnant. Requires sustained super-Eddington accretion → Very difficult
  - **Primordial seeds**: PBHs are already formed before galaxies, with arbitrary mass.
  - **Heavy seeds**: if the gas cloud can collapse without fragmentation, a heavy, **direct collapse** black hole is produced →This talk

Outline

- The mystery of high redshift supermassive black holes
- Direct collapse mechanism
- Recipe I: heating via tiny primordial black holes
- Recipe II: dissociation via relic particle decay
- Observational signature and SMBH abundance

Direct collapse: overview

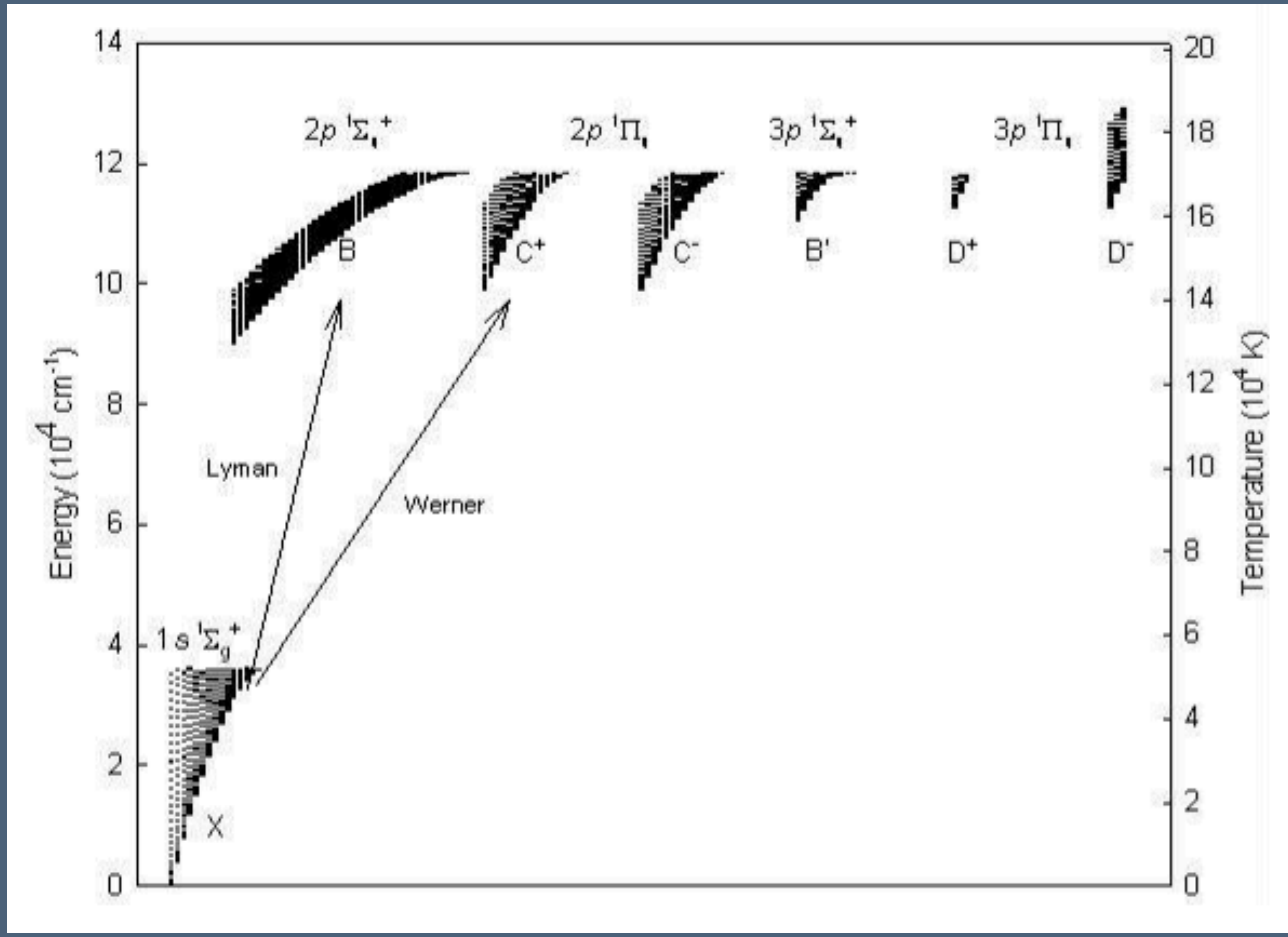
- General conditions for direct collapse black holes:
  - Halos with mass > $10^8\ M_\odot$ (virial temperature > $10^4\ K$)
  - Collapse at high redshift (z ~ 20)
  - Primordial metal-free gas: hydrogen (in various forms), ionized electron, helium (and lithium)
  - Suppression of gas fragmentation

Direct collapse: overview

- Only two channels dominate the cooling process: molecular hydrogen ($\mathbf{H_2}$), atomic hydrogen

- Atomic hydrogen cooling is inefficient when $T < 10^4\ K$

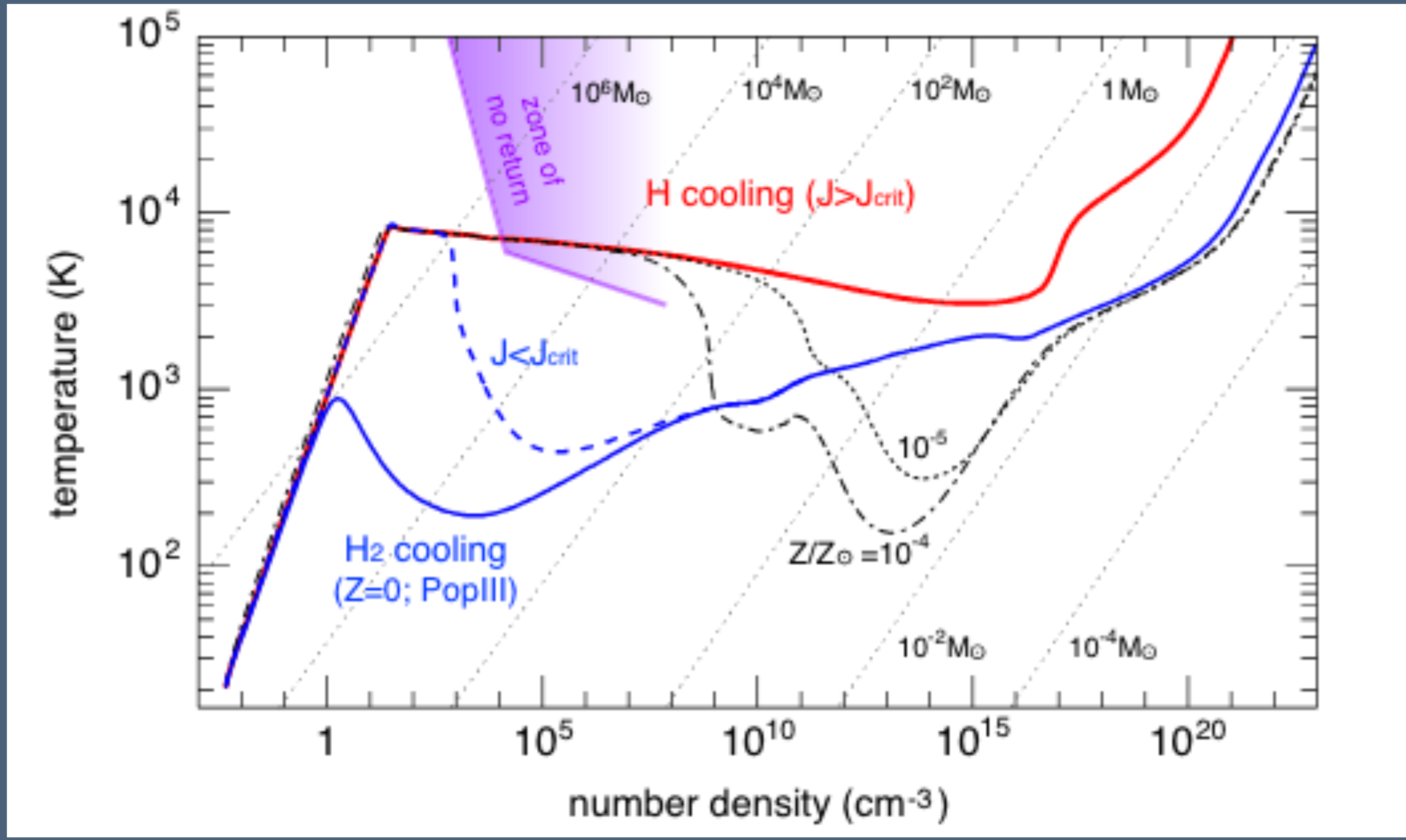
- $\mathbf{H_2}$ cooling takes over this regime due to fine spaced rotational-vibrational energy levels



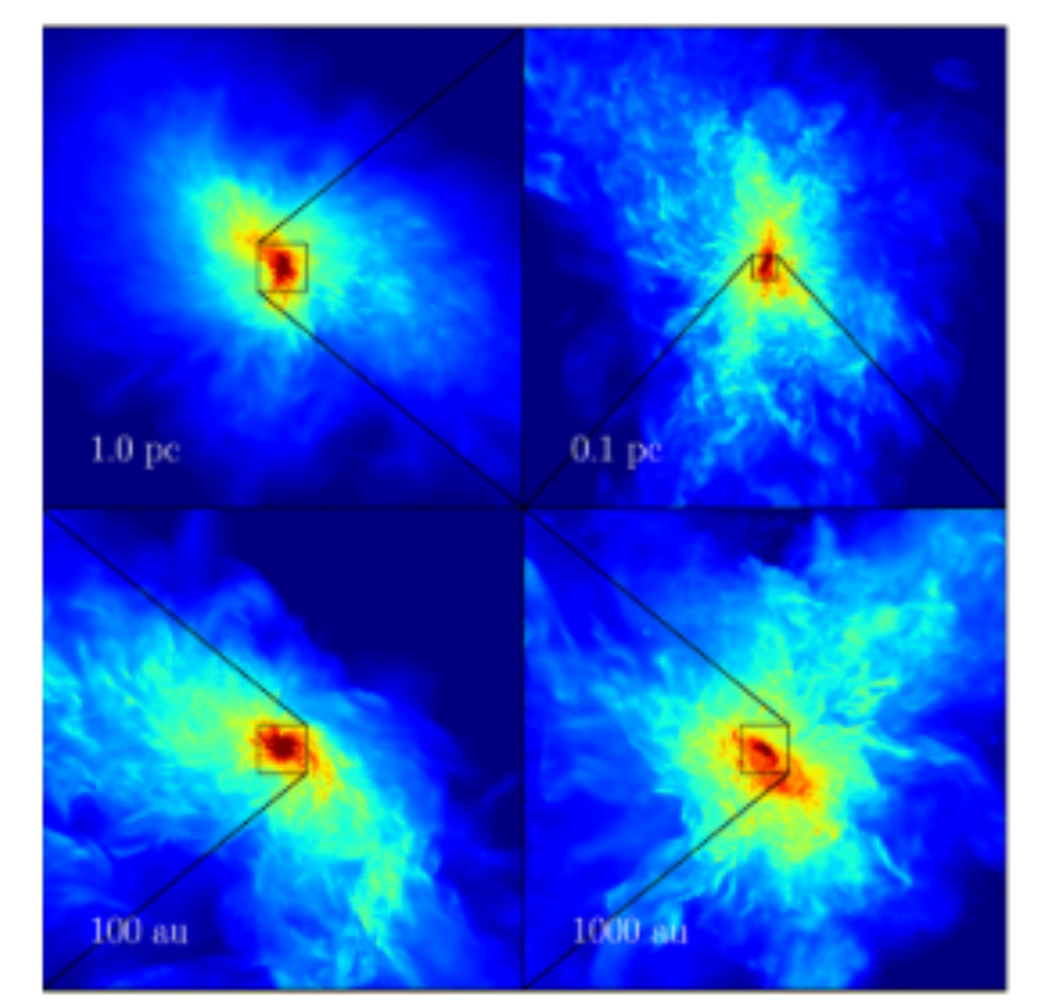
[Shaw et al., 2005]

Direct collapse: overview

- Cooling is undesirable for direct collapse: Rapid cooling → gas fragmentation → star formation
- The suppression of H_2 formation is the key to ensure direct collapse
  - The cloud collapses almost isothermally at $T \sim 10^4\ K$ without fragmentation



[Inayoshi et al., 2019]



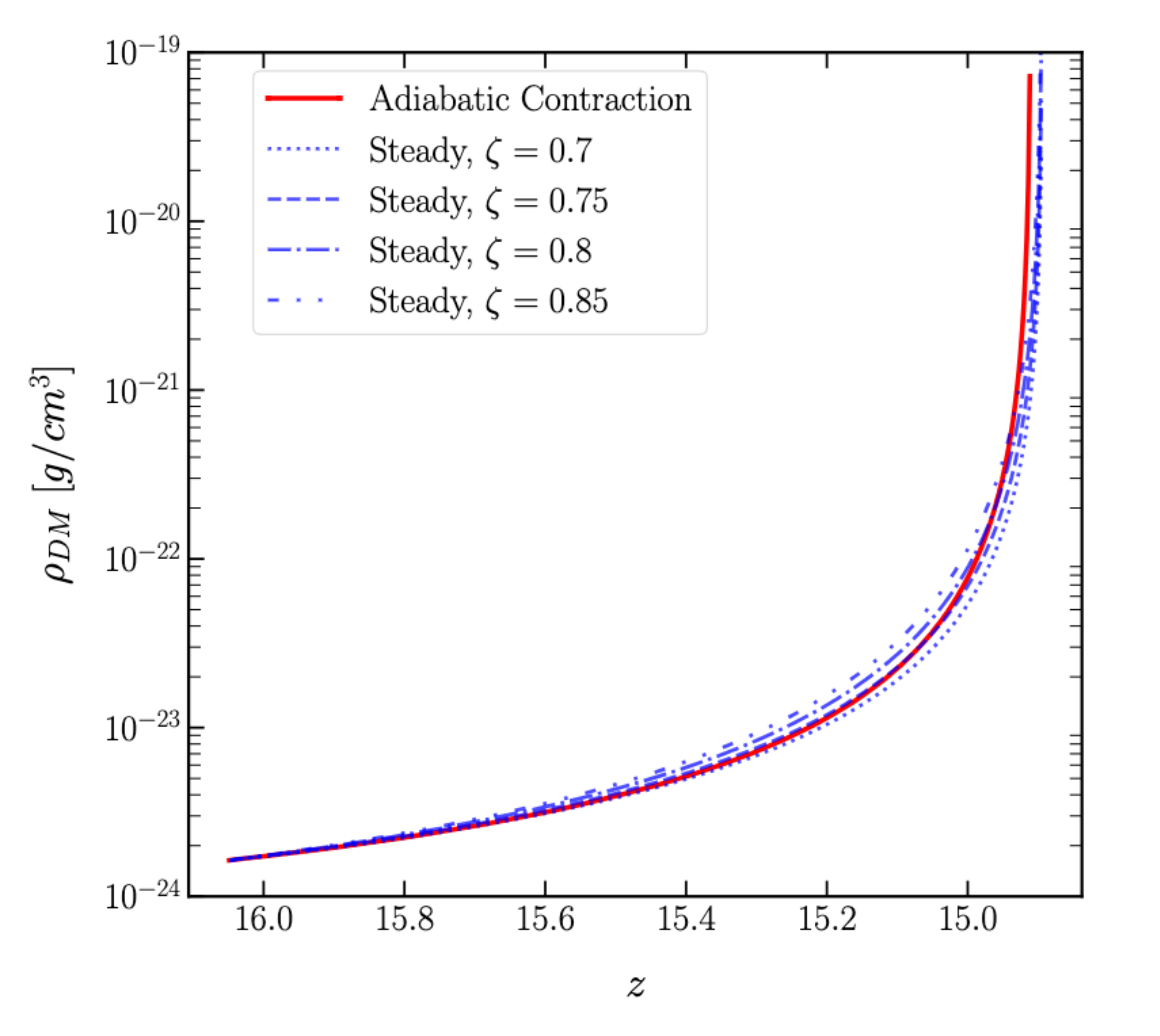
[Becerra et al., 2015]

Direct collapse: overview

- Other important astrophysical processes in direct collapse:
  - Angular momentum transport from the central compact object during collapse
  - The formation of supermassive star in the central region and its GR instability
  - See Inayoshi et al., 2019 for an excellent review
- We will only focus on the 'early stage' of the evolution.

Direct collapse: the key ingredients

- DM & baryon dynamics:
  - Spherical top-hat (z ~ 1000 — virialization)
  - Baryon free fall after virialization due to cooling
  - DM adiabatic contraction
- Chemical evolution of the baryonic sector

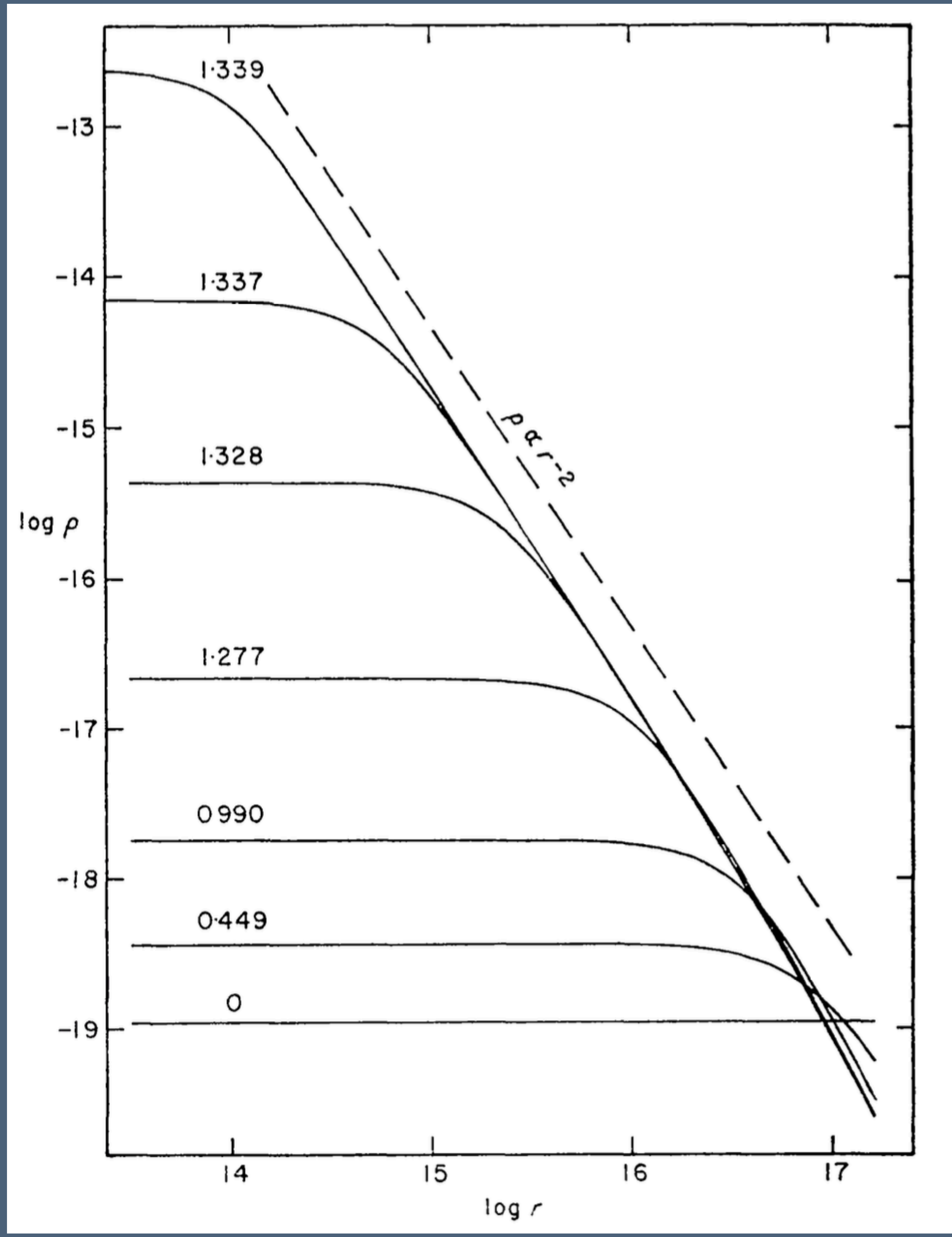


→ Collapse model and chemical evolution are combined to track the temperature

Direct collapse: the one zone model

- In lack of hydrodynamical simulation, Omukai suggested taking the DM and baryon density to be **uniform** [Omukai, 2001]

- This is motivated by the uniform density core in Penston-Larson solutions



[Larson, 1969]

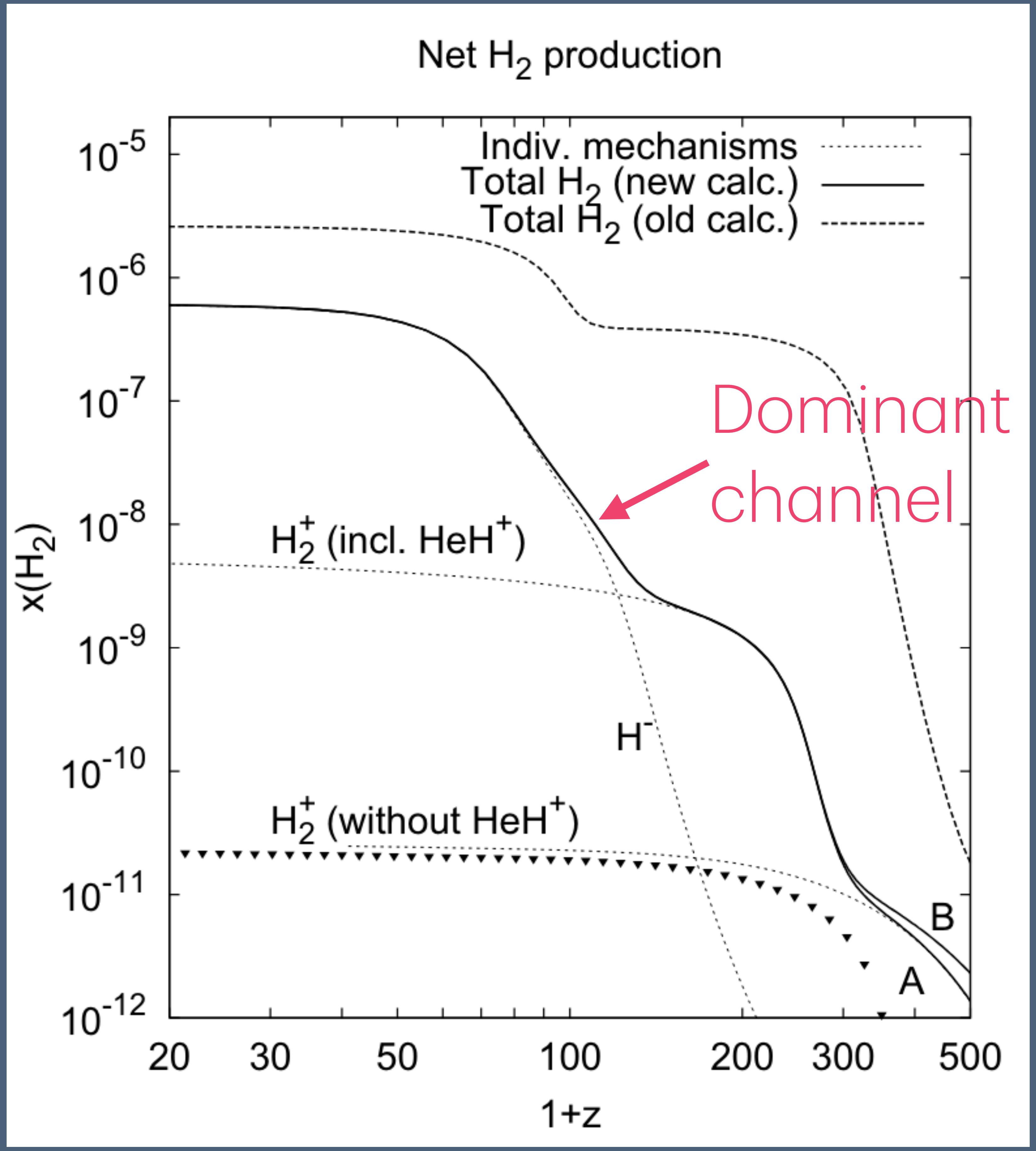
Direct collapse: chemistry

- 12 reactions tracked in the Boltzmann equation:
  - Free electron
  - $\mathbf{H_2}$: Two step process

$$H + e^- \rightarrow H^- + \gamma$$

$$H^- + H \rightarrow H_2 + e^-$$

  - Atomic hydrogen is determined from the total baryon density
  - Helium does not contribute significantly (but can be incorporated into the network)



[Hirata & Padmanabhan, 2006]

Direct collapse: chemistry

Need eV photons (in the Lyman-Werner band)

- How to destroy $\mathbf{H_2}$?

  - Directly dissociate it with photons (photodissociation)

  - Destroy intermediate product $\mathbf{H^-}$ with photons (photodetachment)

  - Heat the gas to increase collision rates (collisional dissociation)

Need additional heating mechanism

Direct collapse: recipes

- The standard recipe: a nearby star forming galaxy
  - LW radiation (11.2 - 13.6 eV) can be produced by star formation process
  - Two galaxies has to to get close (for high LW intensity)
  - Radiation has to penetrate the cloud into the core region
  - Could be polluted by metals due to star formation (and giving much higher cooling rates)!

Direct collapse: recipes

- Our recipes:
    - **Heating by PBH evaporation**
    - **LW radiation from ALP decay** (originated from [Friedlander et al, 2022])
- Allow for direct collapse at essentially arbitrary high redshift
- Avoid issues such as penetration depth and metal pollution
- Offer a new window to test/constrain astroparticle physics models!

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

Yifan Lu,[1,*] Zachary S. C. Picker,[1,†] and Alexander Kusenko[1,2,‡]

PBH heating

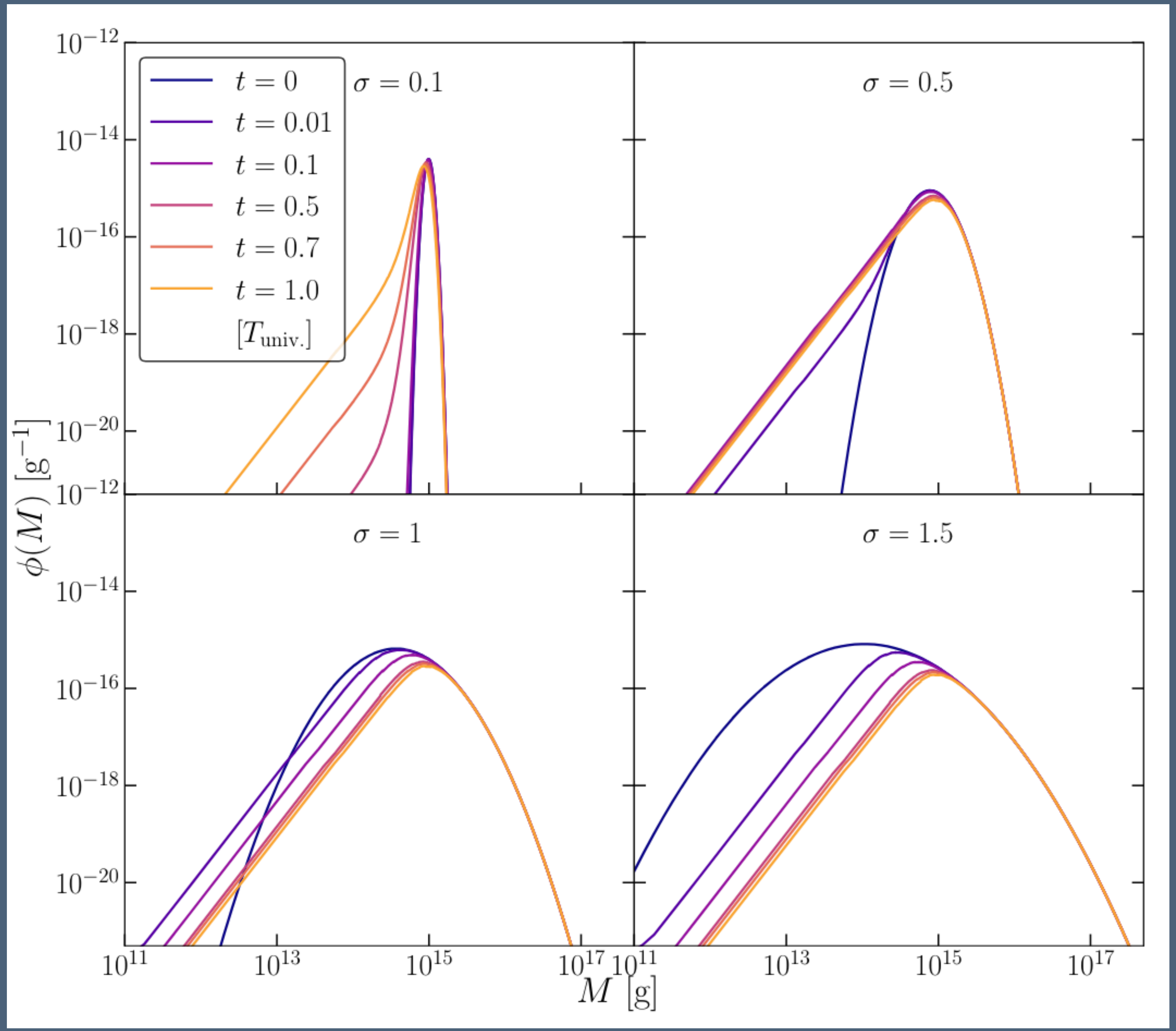
- PBHs are capable of injecting energy into the baryon sector by evaporation:

$$\frac{d^2N_i}{dtdE} = \frac{1}{2\pi}\sum_{\text{dof}}\frac{\Gamma_i(E, M, a^*)}{e^{E'/T} \pm 1}$$

- Higher injection rate near the end of lifetime: ideal lifetime ends near collapse redshift

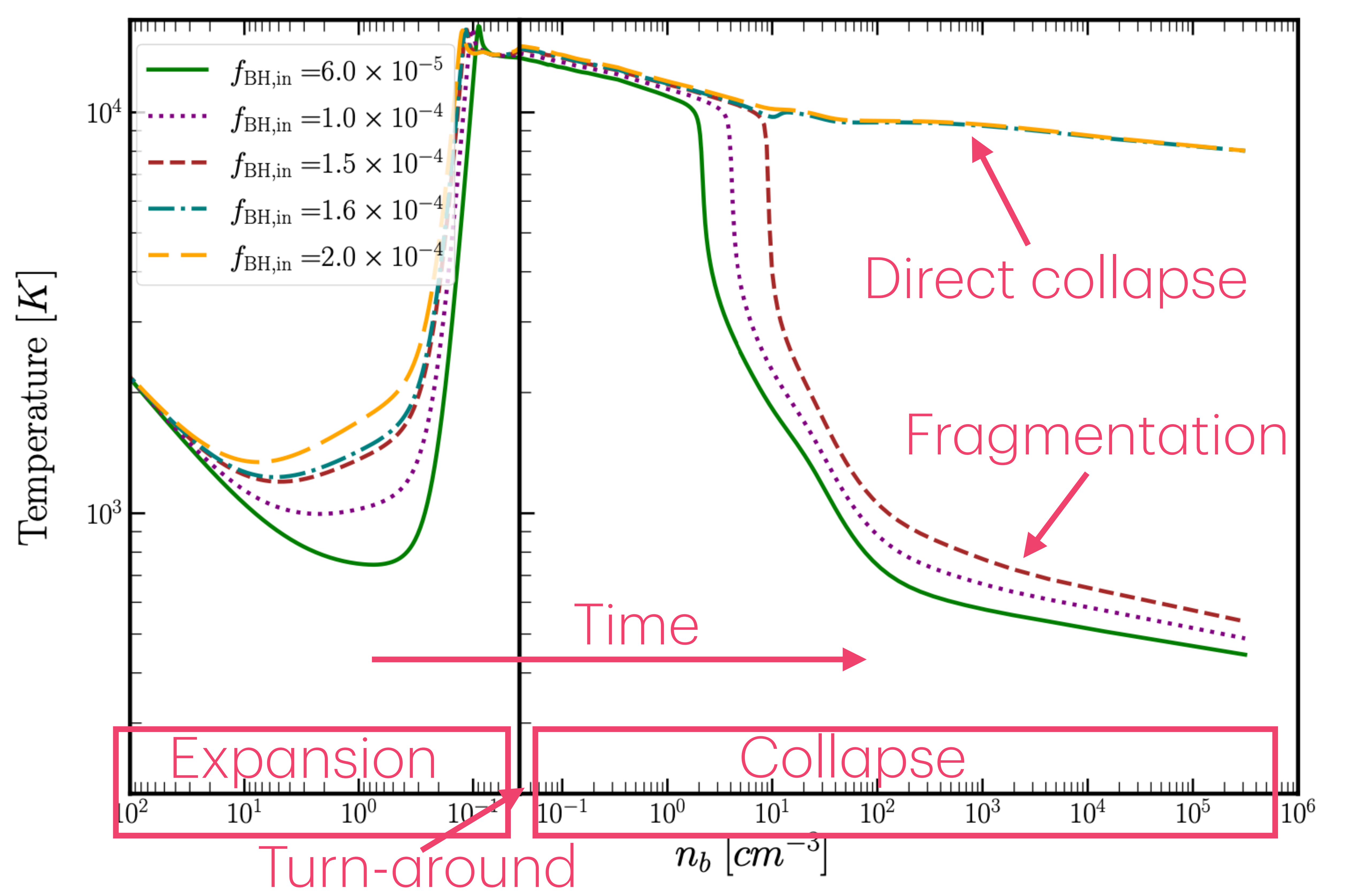
  $\rightarrow M_{PBH} \sim 10^{14} g$

- Heating from attenuated secondary spectra (electrons, photons, protons)

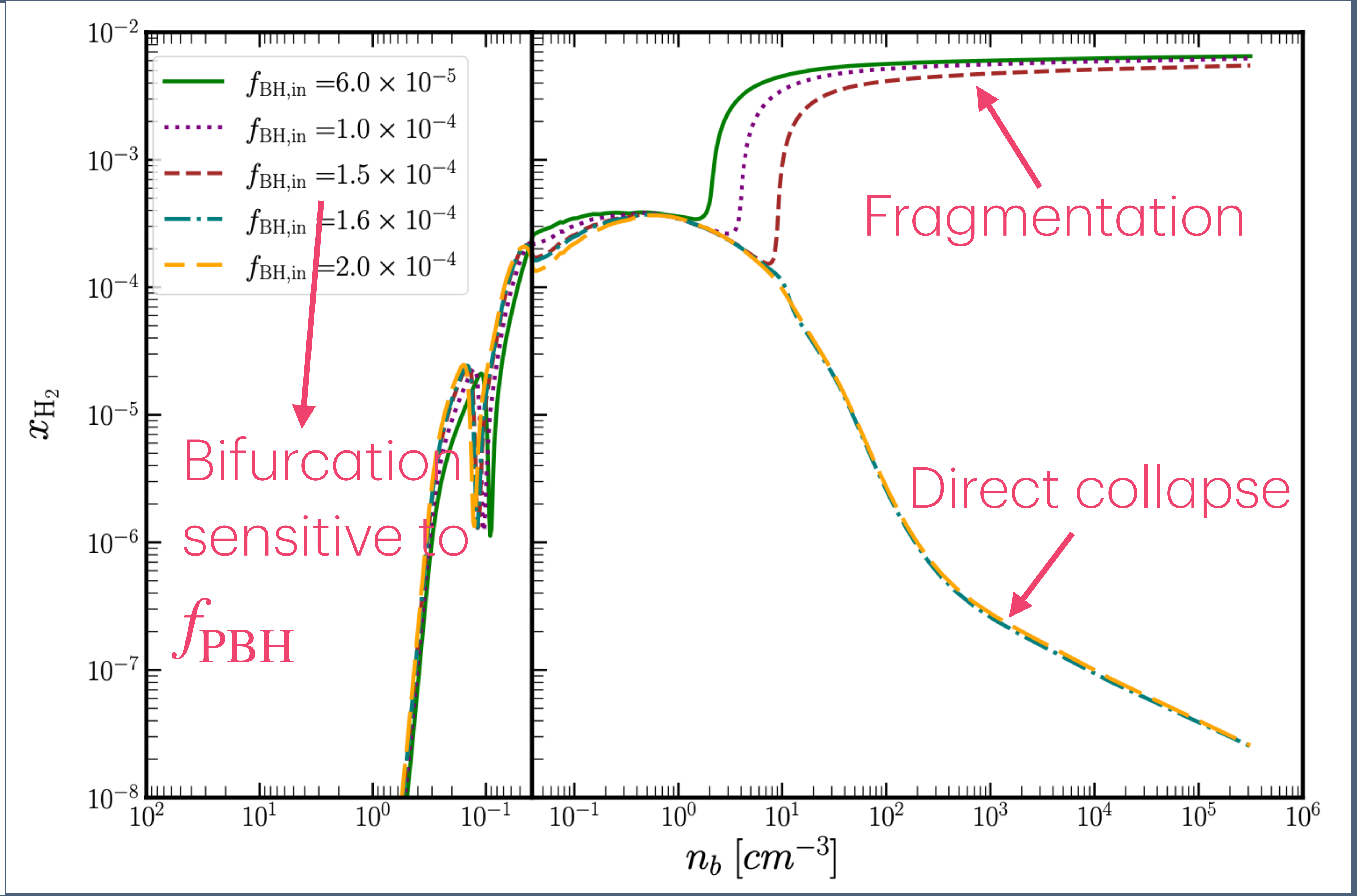


[Mosbech & Picker, 2022]

PBH heating



Temperature [K]
$f_{\rm BH,in} = 6.0 \times 10^{-5}$
$f_{\rm BH,in} = 1.0 \times 10^{-4}$
$f_{\rm BH,in} = 1.5 \times 10^{-4}$
$f_{\rm BH,in} = 1.6 \times 10^{-4}$
$f_{\rm BH,in} = 2.0 \times 10^{-4}$
Direct collapse
Fragmentation
Time
Expansion
Collapse
Turn-around
$n_b\ [cm^{-3}]$



$x_{\rm H_2}$
$f_{\rm BH,in} = 6.0 \times 10^{-5}$
$f_{\rm BH,in} = 1.0 \times 10^{-4}$
$f_{\rm BH,in} = 1.5 \times 10^{-4}$
$f_{\rm BH,in} = 1.6 \times 10^{-4}$
$f_{\rm BH,in} = 2.0 \times 10^{-4}$
Fragmentation
Bifurcation sensitive to $f_{\rm PBH}$
Direct collapse
$n_b\ [cm^{-3}]$

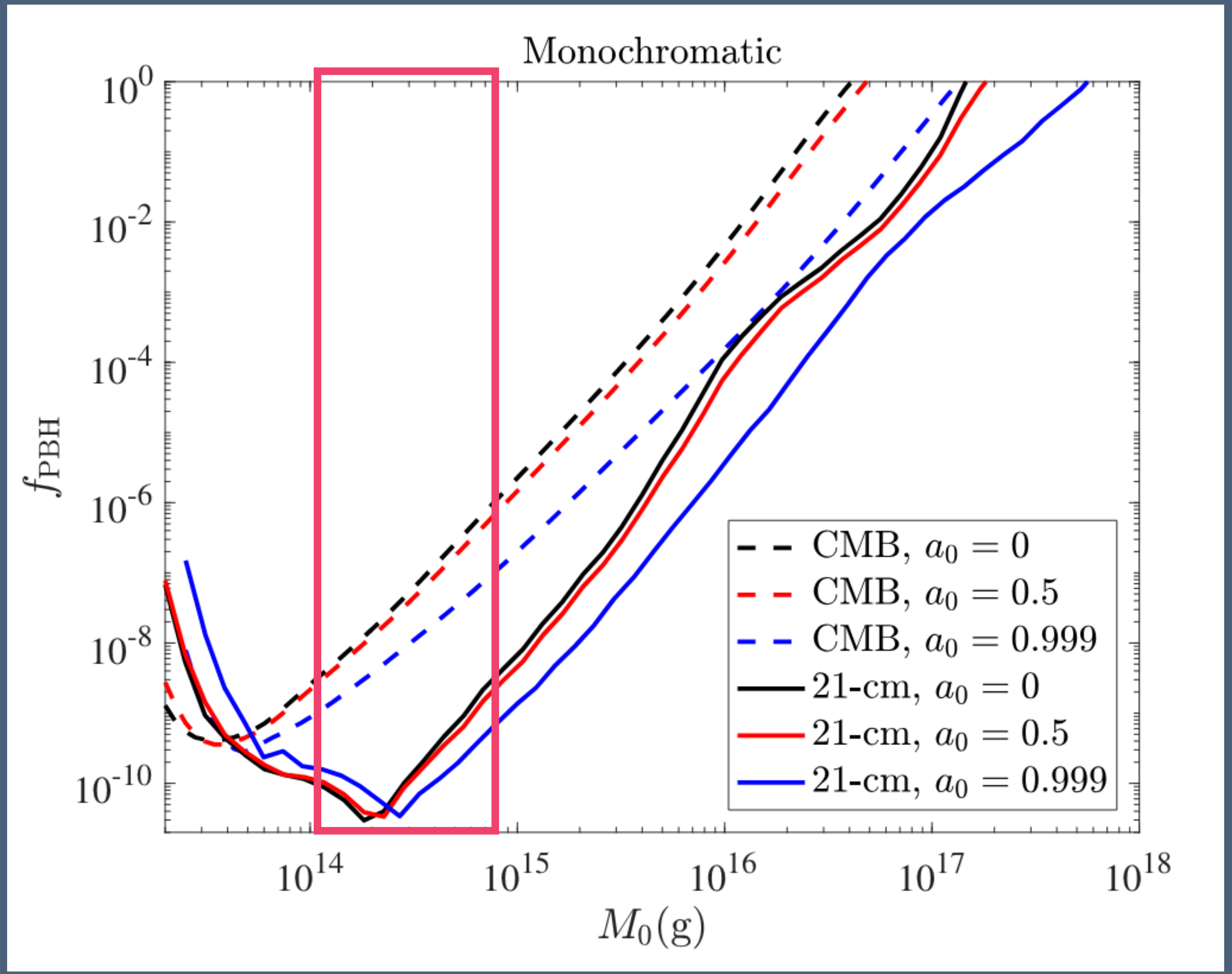
PBH clustering

- PBH abundance is strongly constrained in this mass range from 21 cm and CMB observations.

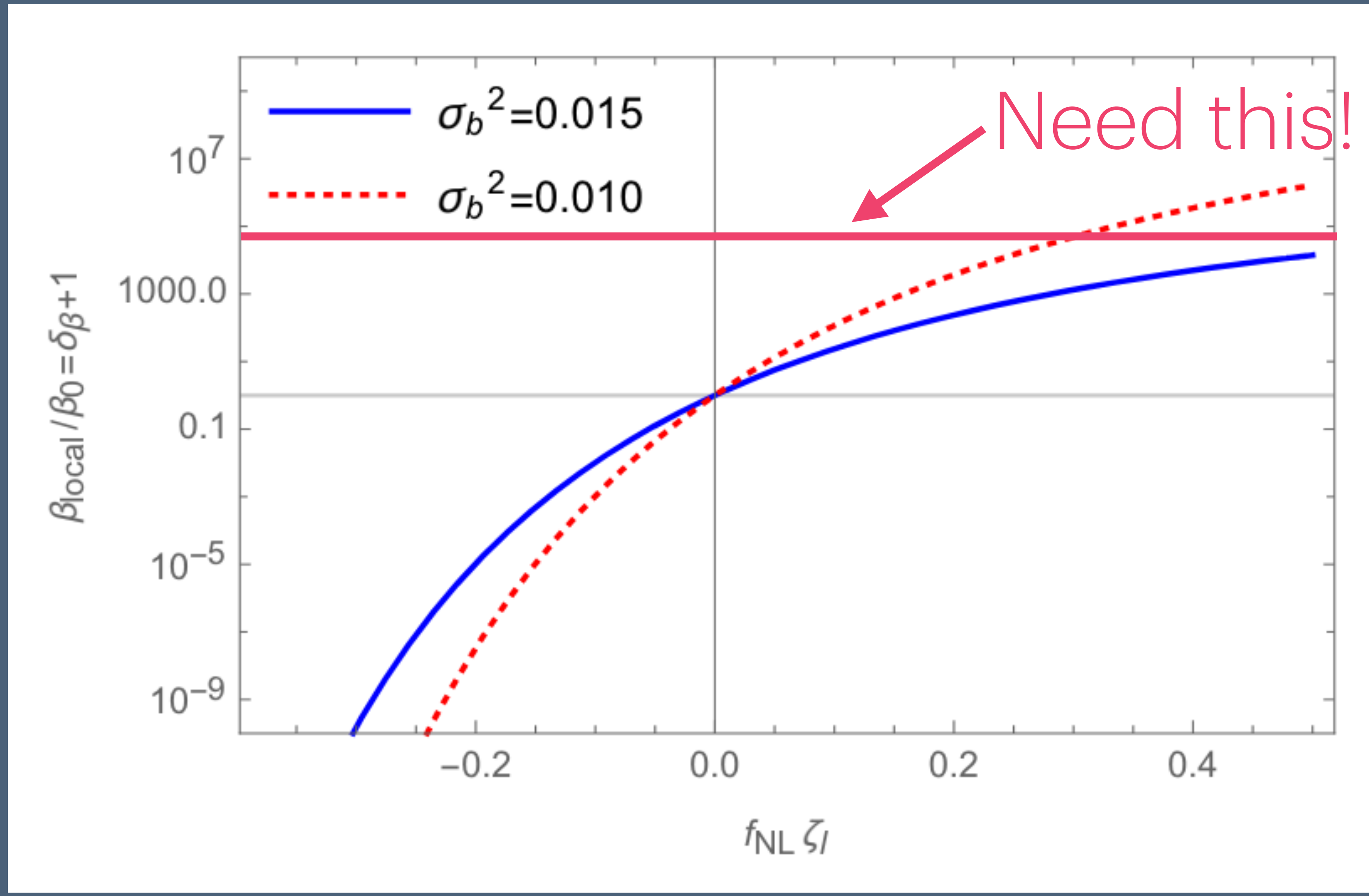
- But PBH clustering is a feature in many formation scenarios:

  - Primordial non-Gaussianity in critical collapse

  - Yukawa structure formation in the dark sector (no explicit calculation as far as I know)



[Cang et al., 2021]



[Young & Byrnes, 2019]

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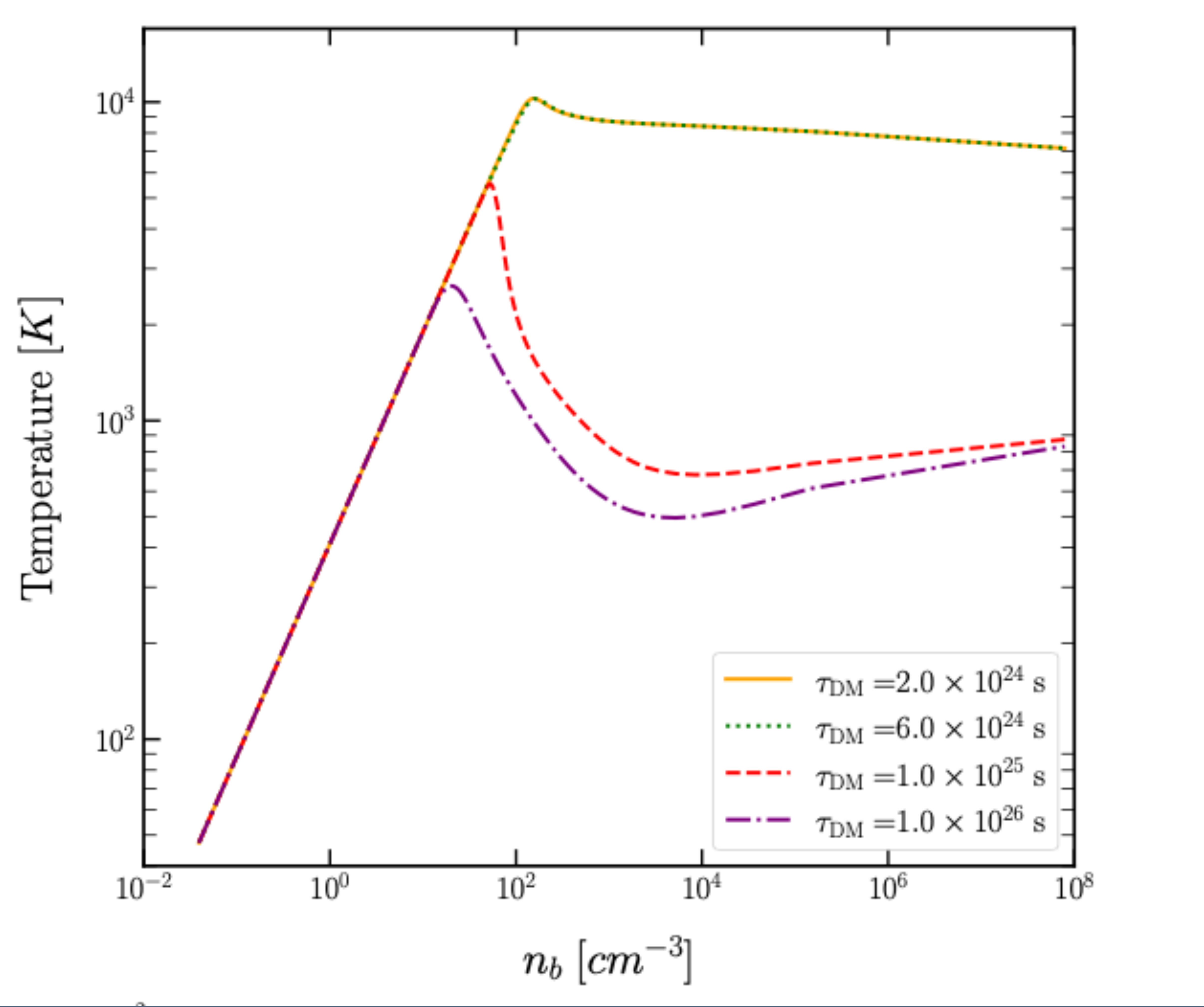
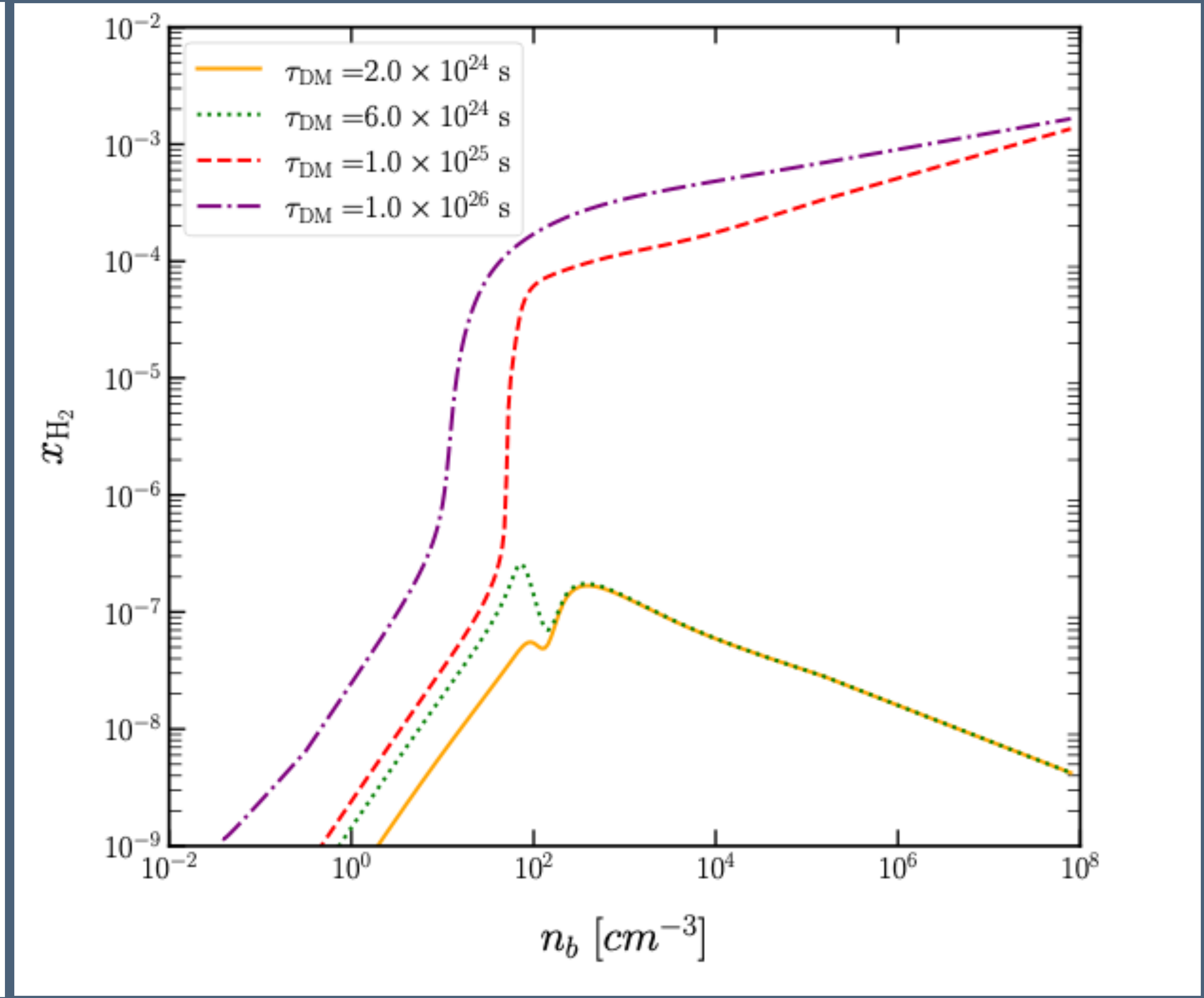
Dissociation of H_2

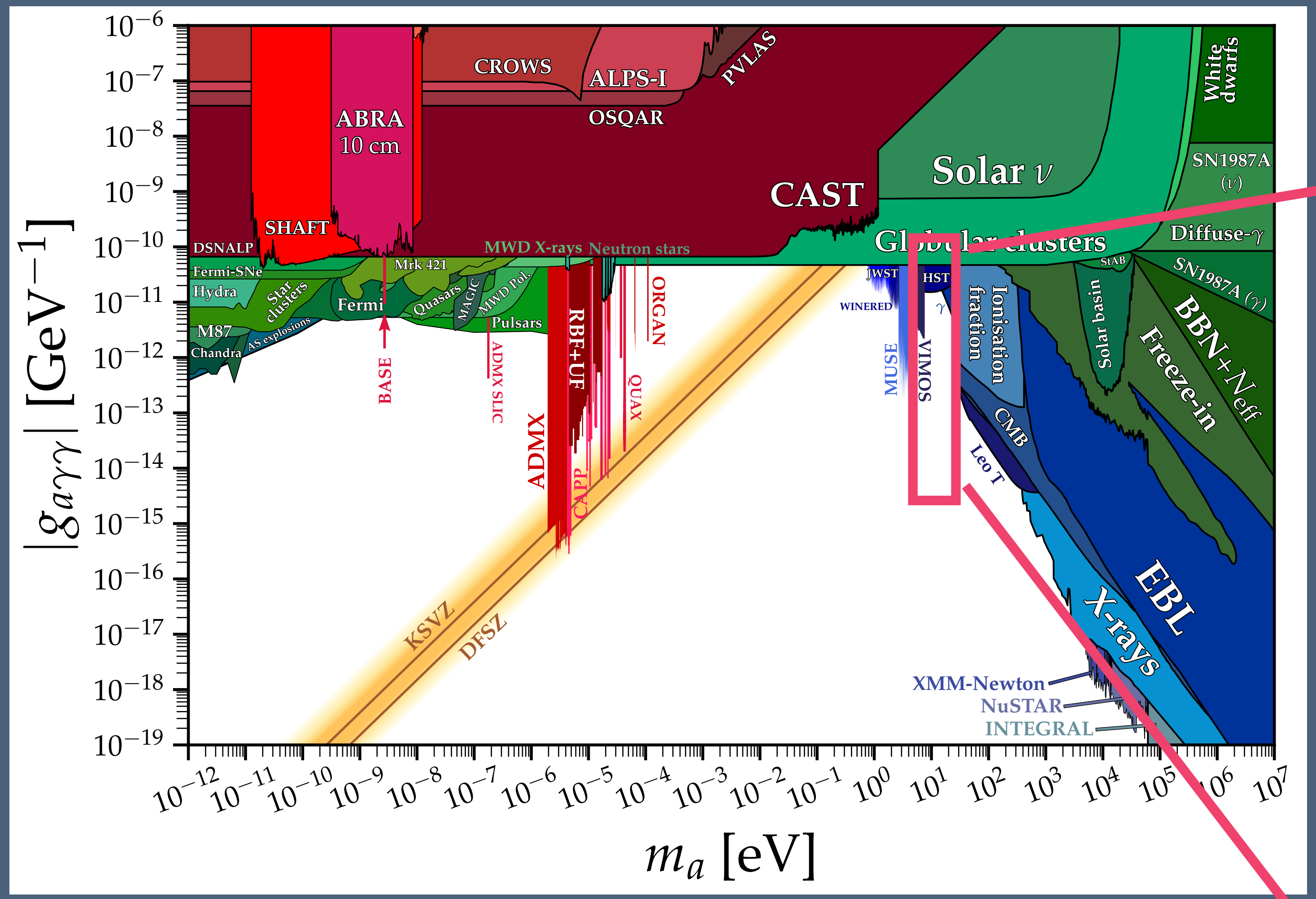
- Photodissociation & photodetachment require a LW radiation background.
- ALP decay can produce such a background! (Ruled out for QCD axions)
- They can be ALL of the DM (with a low decay rate), or a fraction of DM (particle X, with higher decay rate)
    - Two body decay: monochromatic (relevant for ALP)
    - Three body decay: parabola (generic for energy independent amplitudes)

Bifurcation

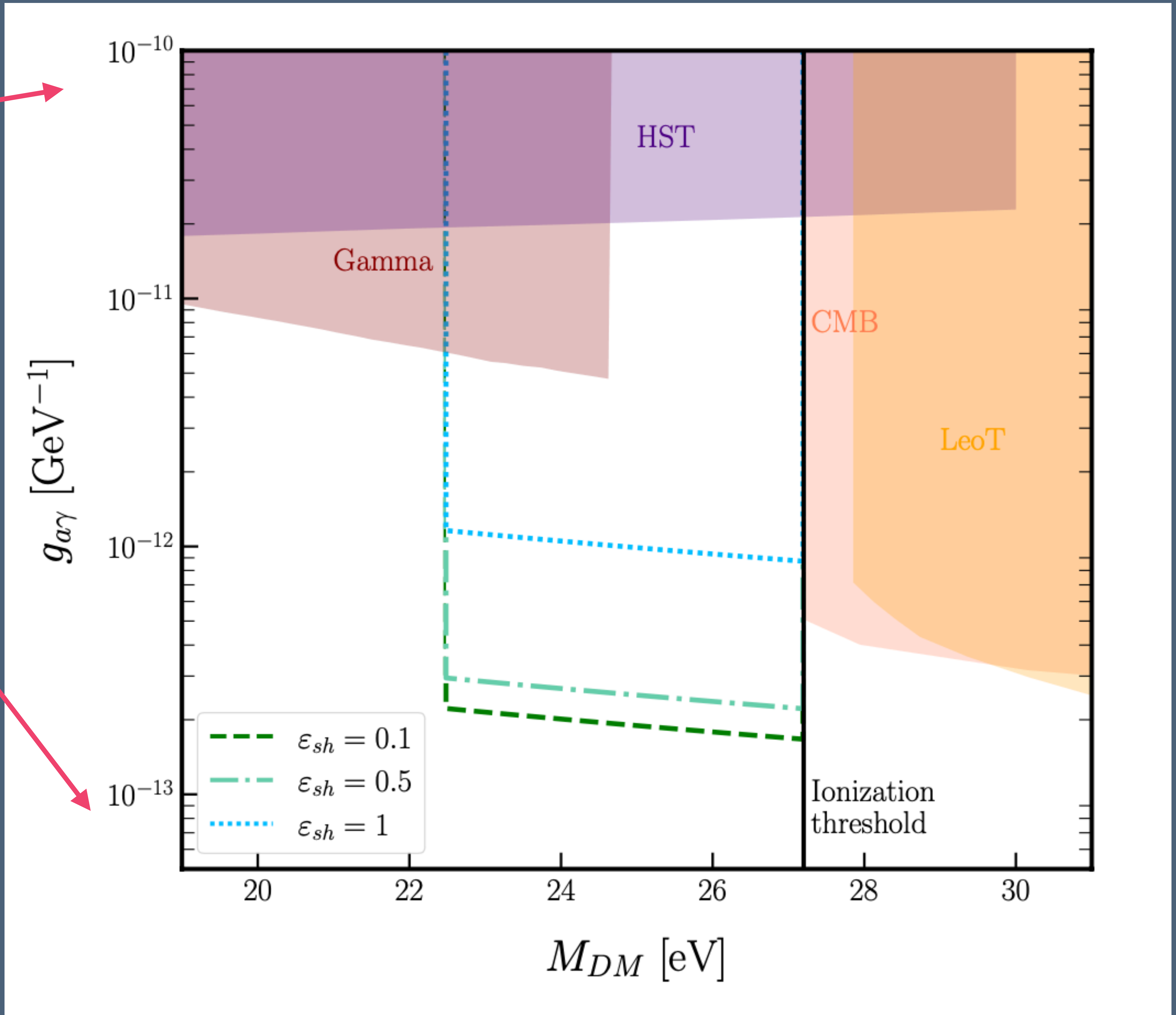




ALP decay

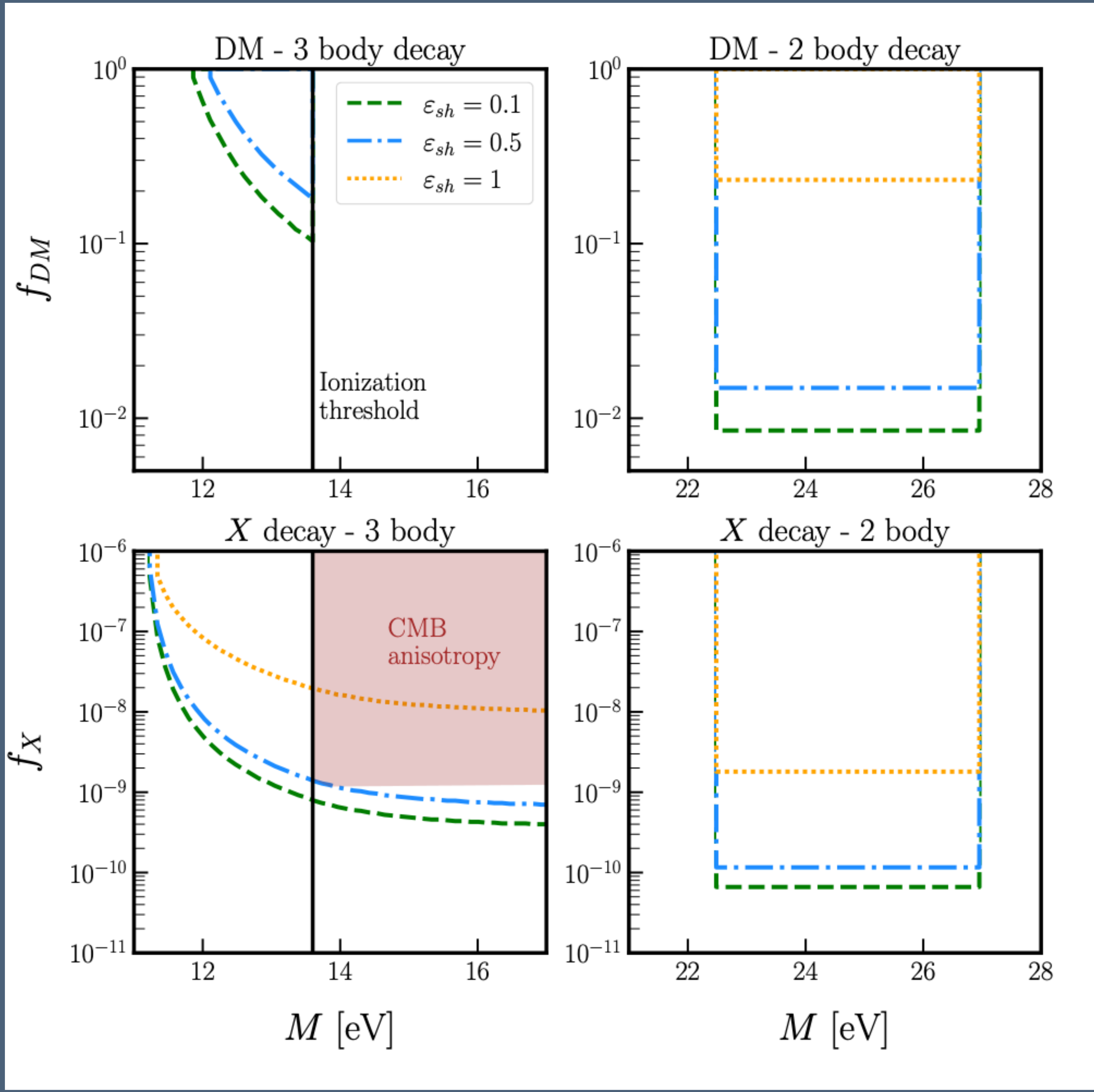


[Credit: Ciaran O'Hare]



X decay

- The required decay fraction is much lower compared to heating.
- Only very weak constraints (CMB spectral distortion) exist below the ionization threshold
- The decay redshift does not need to be fine tuned! (Span from z=50 ~ 5 if the halo collapses at z=20)



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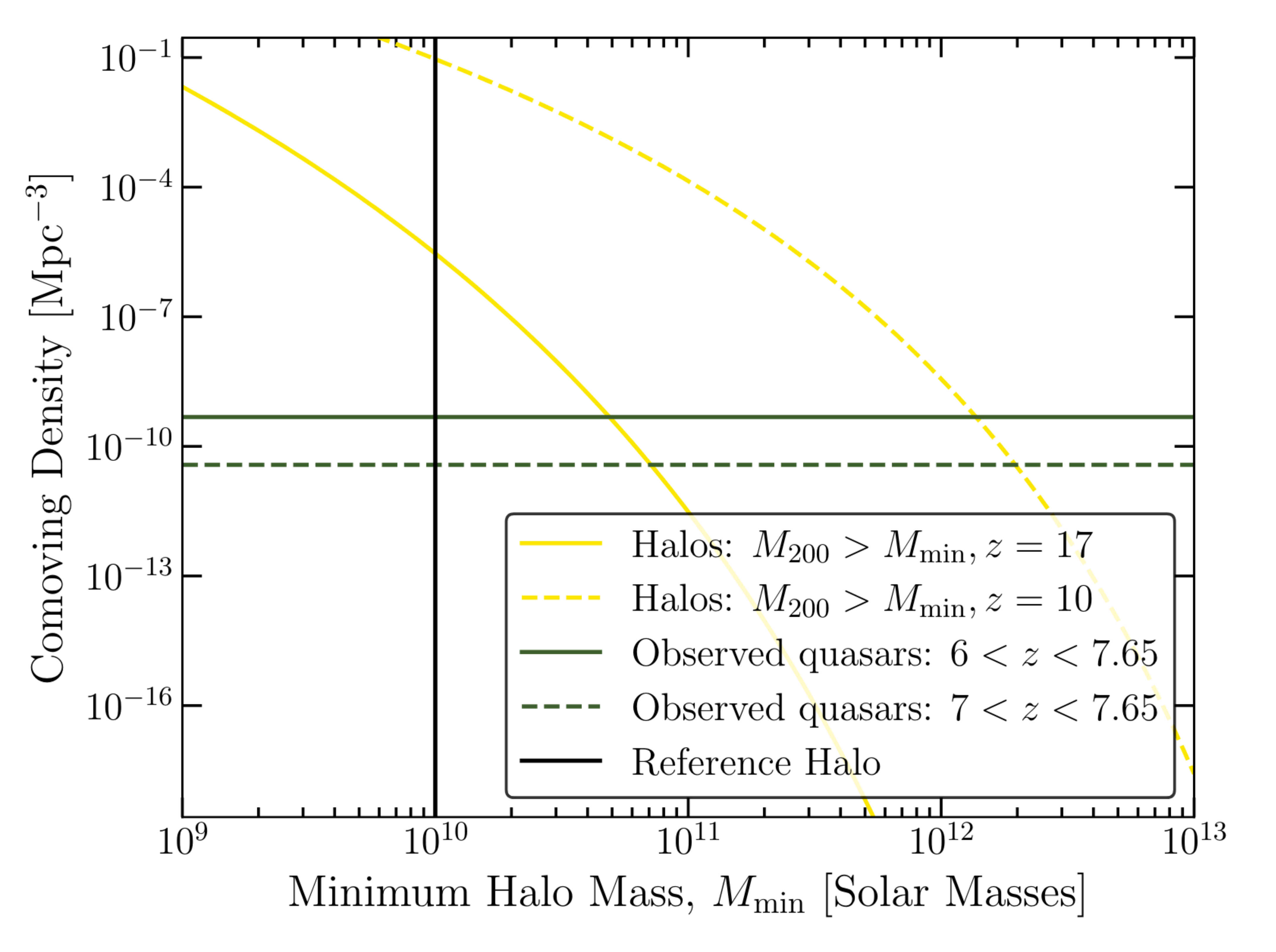
SMBH abundance

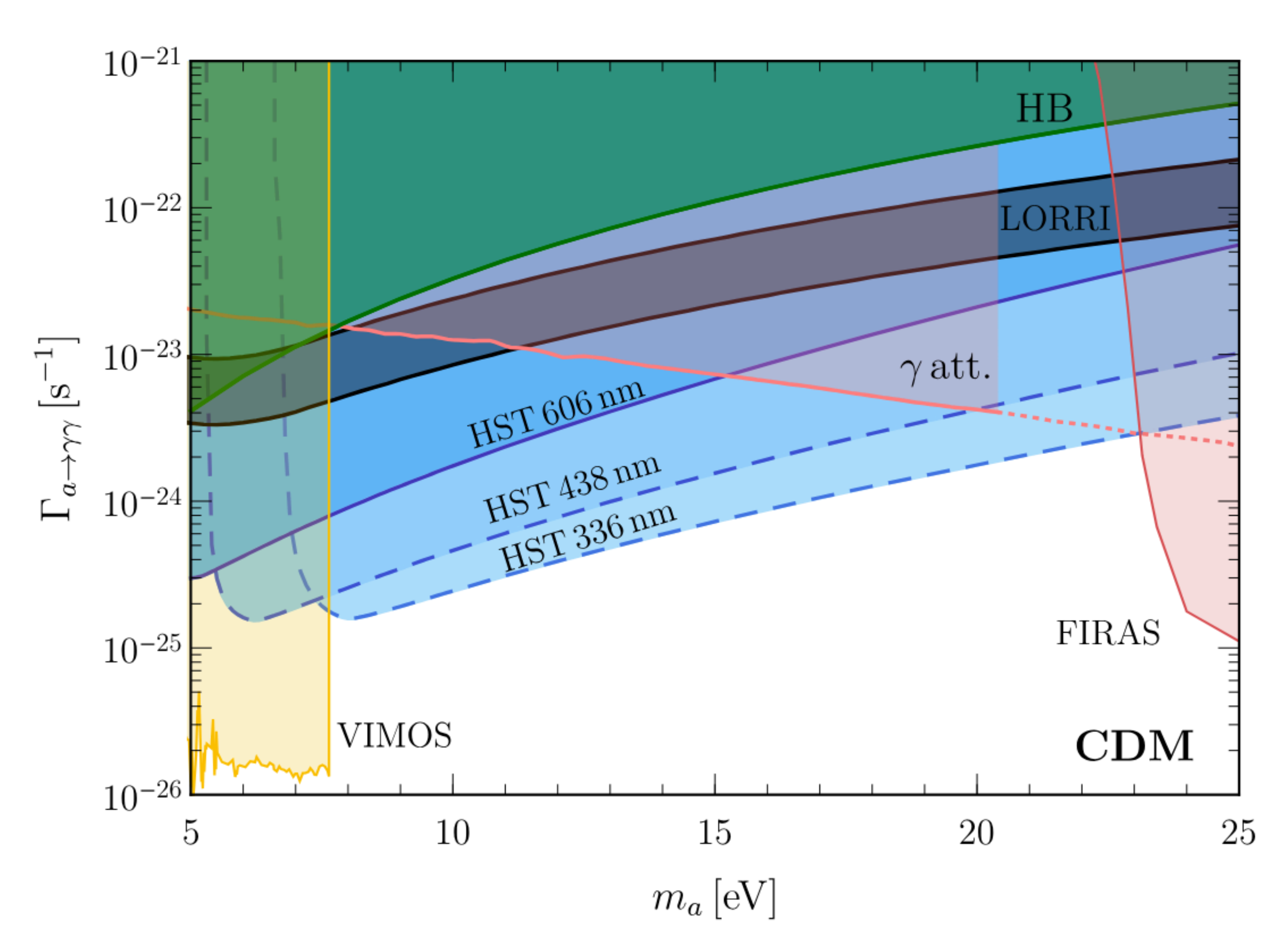
- ALP decay can trigger direct collapse in all eligible halos
- In the case of PBH heating, direct collapse happens in rare, highly clustered halos
    - Clustering is model dependent
    - Uncertainty in AGN/quasar density



[Friedlander et al., 2022]

Observational signature

- PBH evaporation with local clustering can create 'hot spots':
  - Point-like X-ray/gamma-ray sources?
  - Small scale infrared background excess by PBH heating? (Could be overwhelmed by collapsing BH itself)
  - Constraints have not been studied in this scenario
- ALP decay in our mass range produces UV—optical light
  - Future HST measurements can probe/constrain the parameter space [Carenza et al., 2023]



Summary

- Our current understanding of the origin of high redshift SMBH is not complete, and this is a topic with increasing importance given JWST observations.
- Traditional direct collapse mechanisms may face challenges.
- Well motivated astroparticle physics models can be incorporated into the direct collapse process, alleviating tensions with observations.
- Hydrodynamic simulation can test our model beyond the one-zone regime.
- Direct collapse black holes have many signatures (gravitational waves, X ray, IR emission...) that can be tested with current and near future instruments such as JWST and LISA.

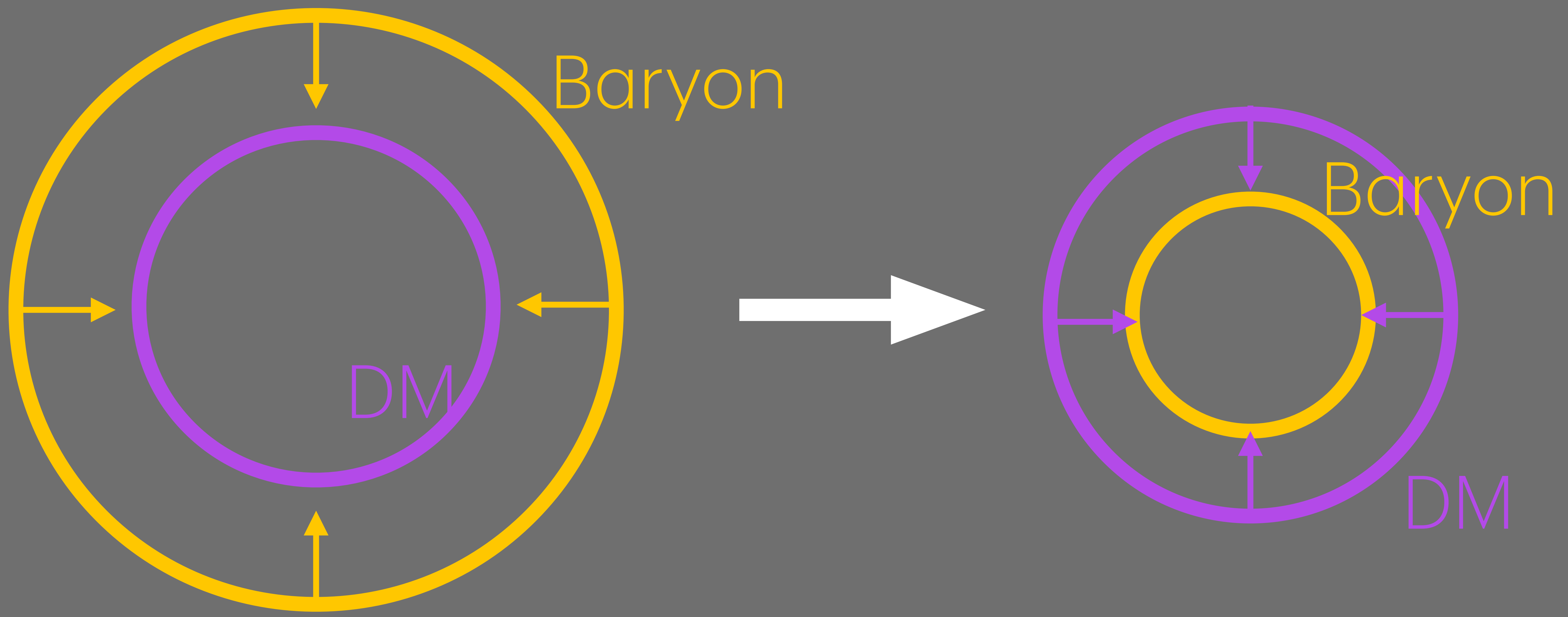
Thank you!

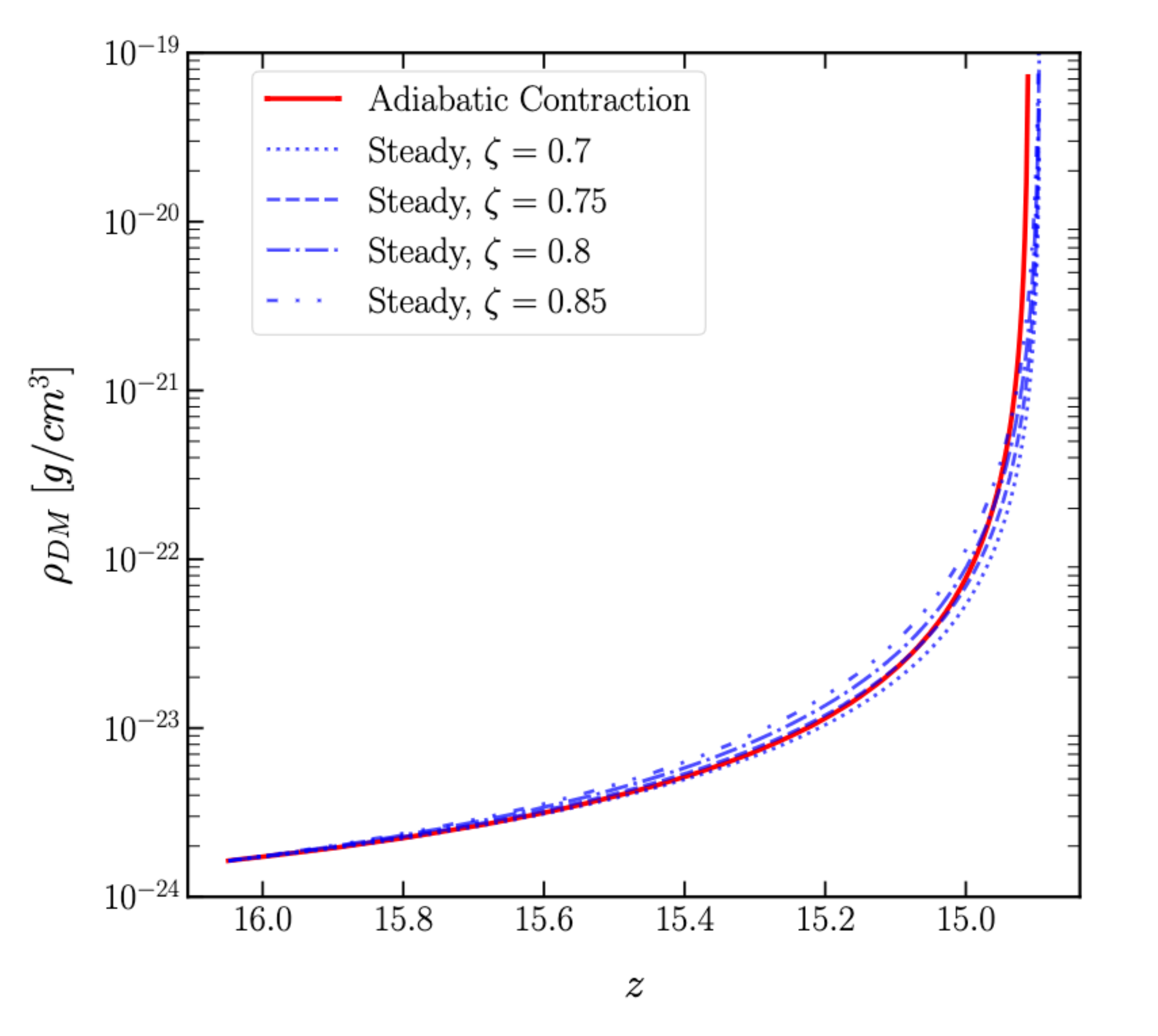
Supplemental slides

Densities in the one zone model

- Before virialization: $1 + \delta = \frac{9}{2}\frac{(\alpha - \sin\alpha)^2}{(1 - \cos\alpha)^3}$
- DM undergoes adiabatic contraction due to the changing gravitational potential:

$$r(M_b(r) + M_{DM}(r)) = r_i M_i(r_i)$$





Cooling channels

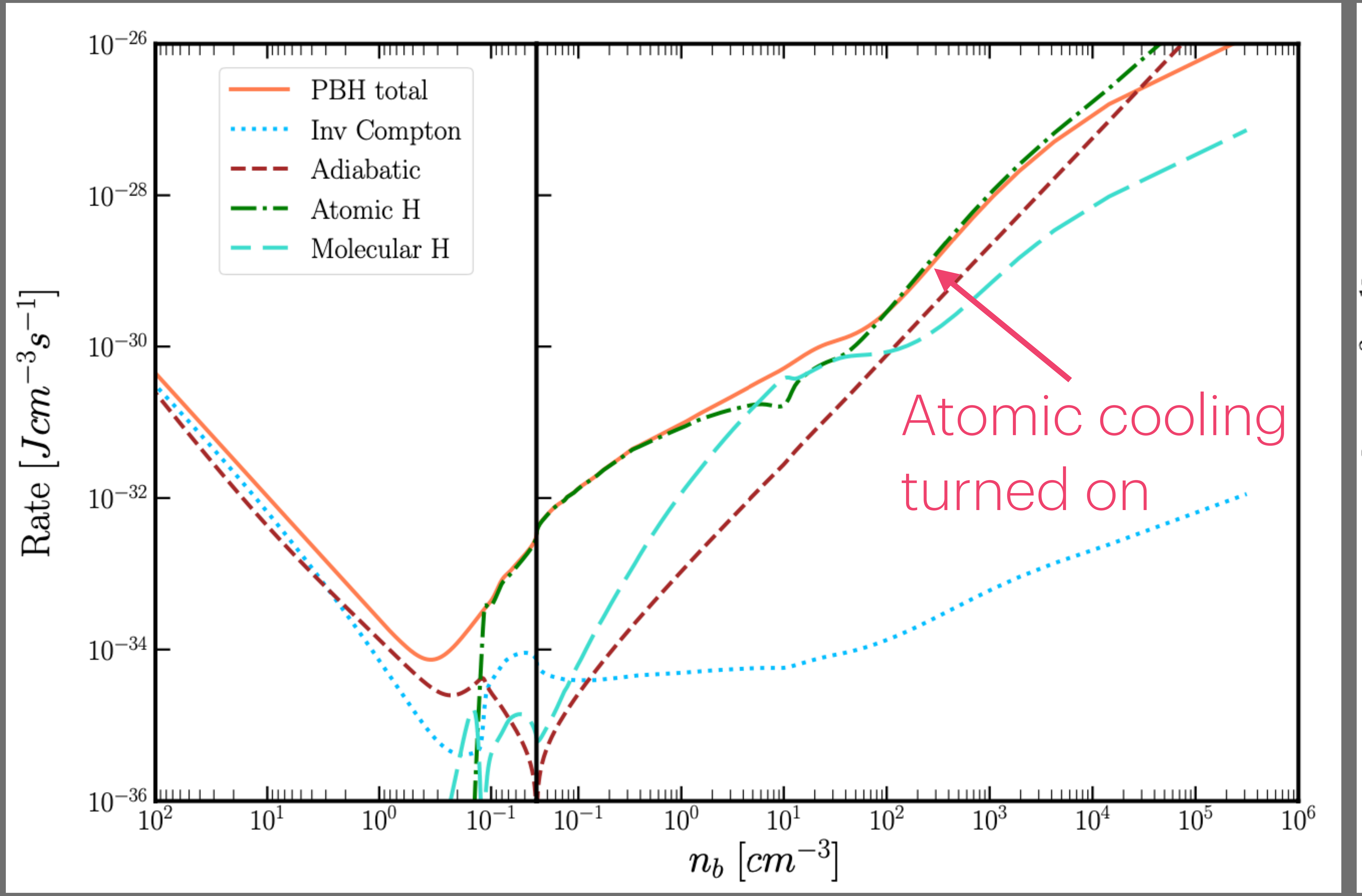
- Adiabatic cooling (heating)
- Inverse Compton: $L_{ic}(T) = 1.017 \times 10^{-44} T_{CMB}^4 (T - T_{CMB}) x_e n$
- Hydrogen line:

$$L_{HI}(T) = 7.9 \times 10^{-26} \left(1 + \left(\frac{T}{10^5\ \mathrm{K}}\right)^{0.5}\right)^{-1} \times \exp(-118348\ \mathrm{K/T}) n_e n_H$$

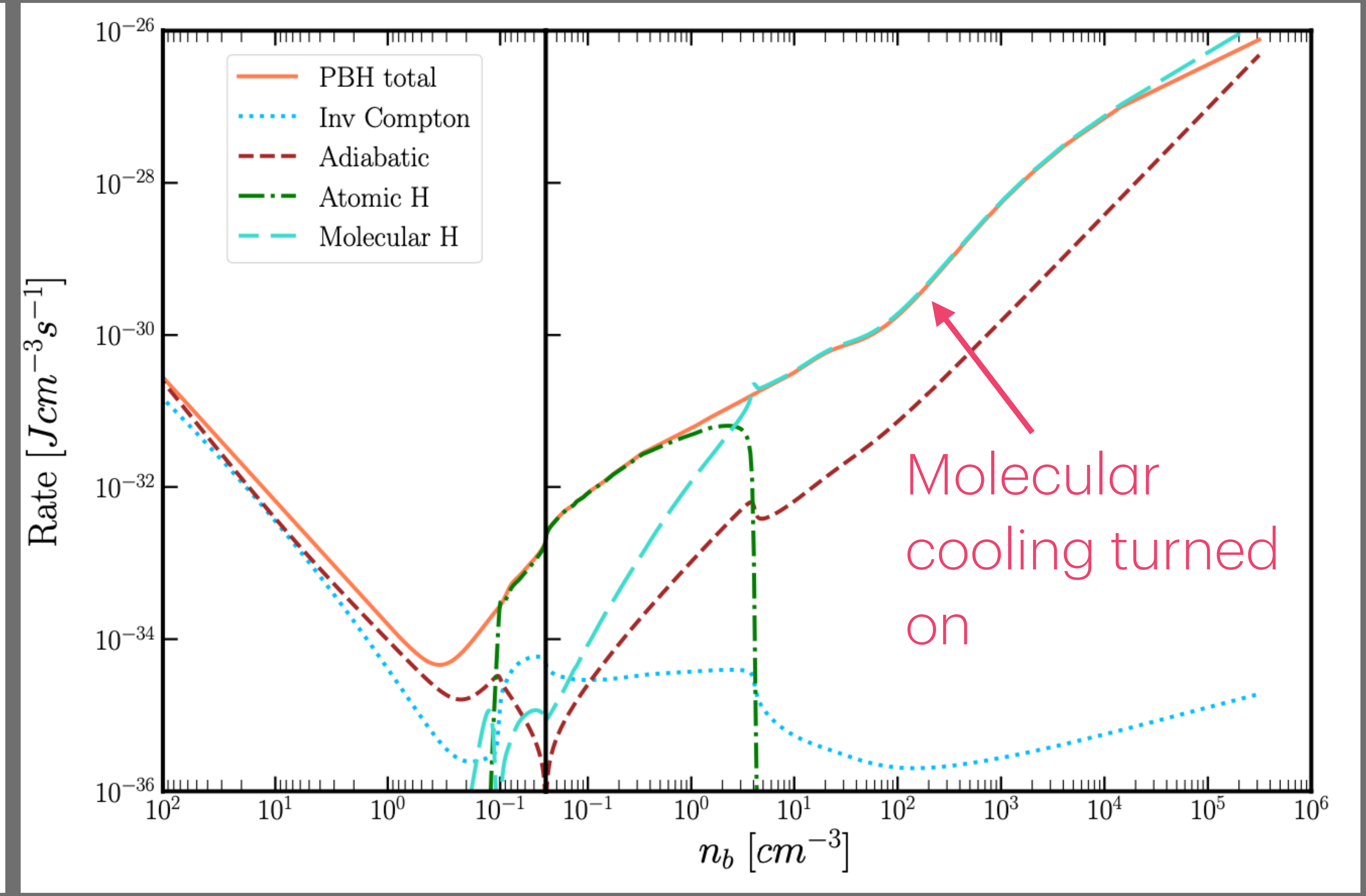
- Molecular hydrogen: taken from Hollenbach & McKee, 1979

Heating/Cooling channels

Direct collapse

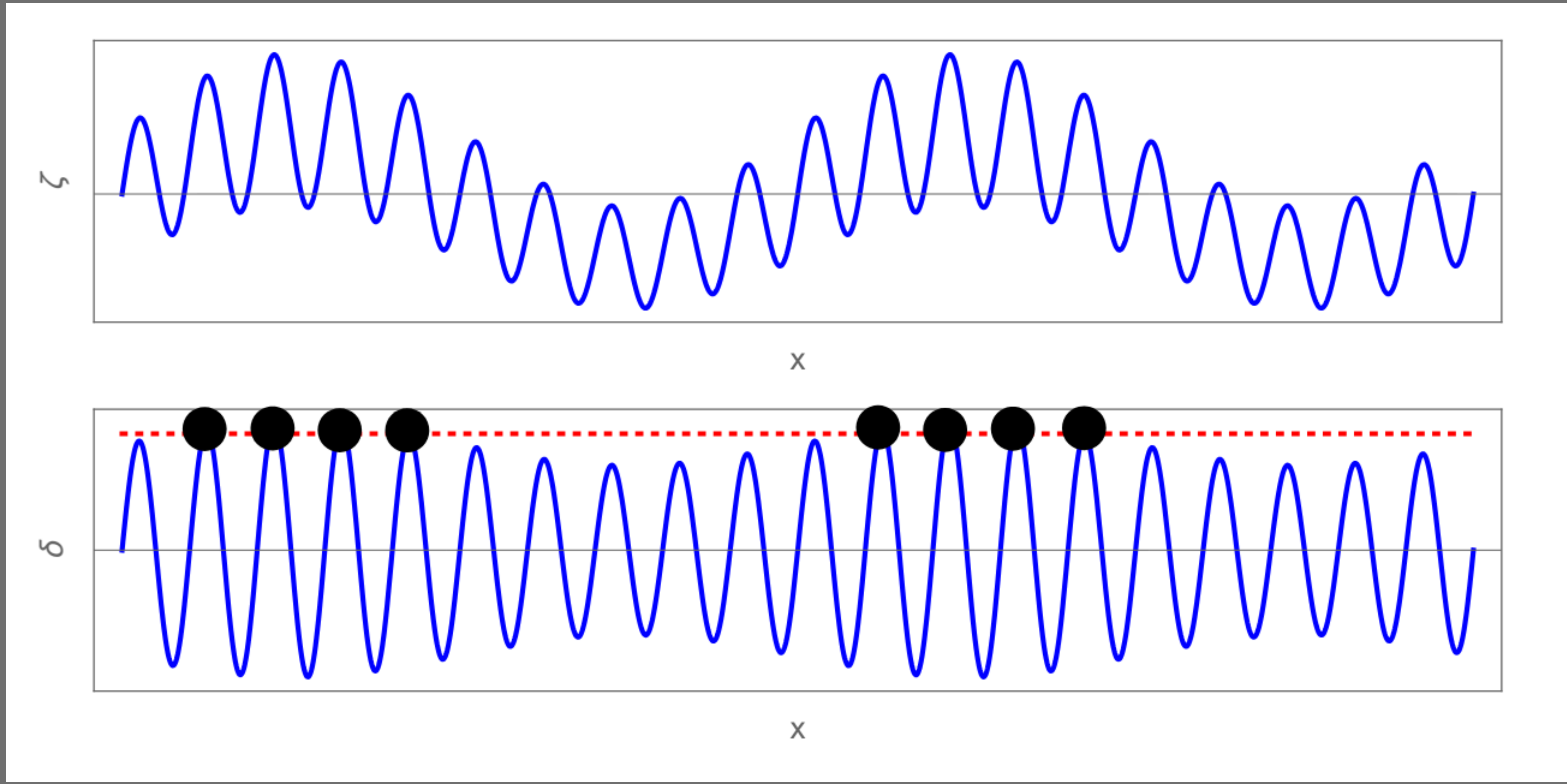


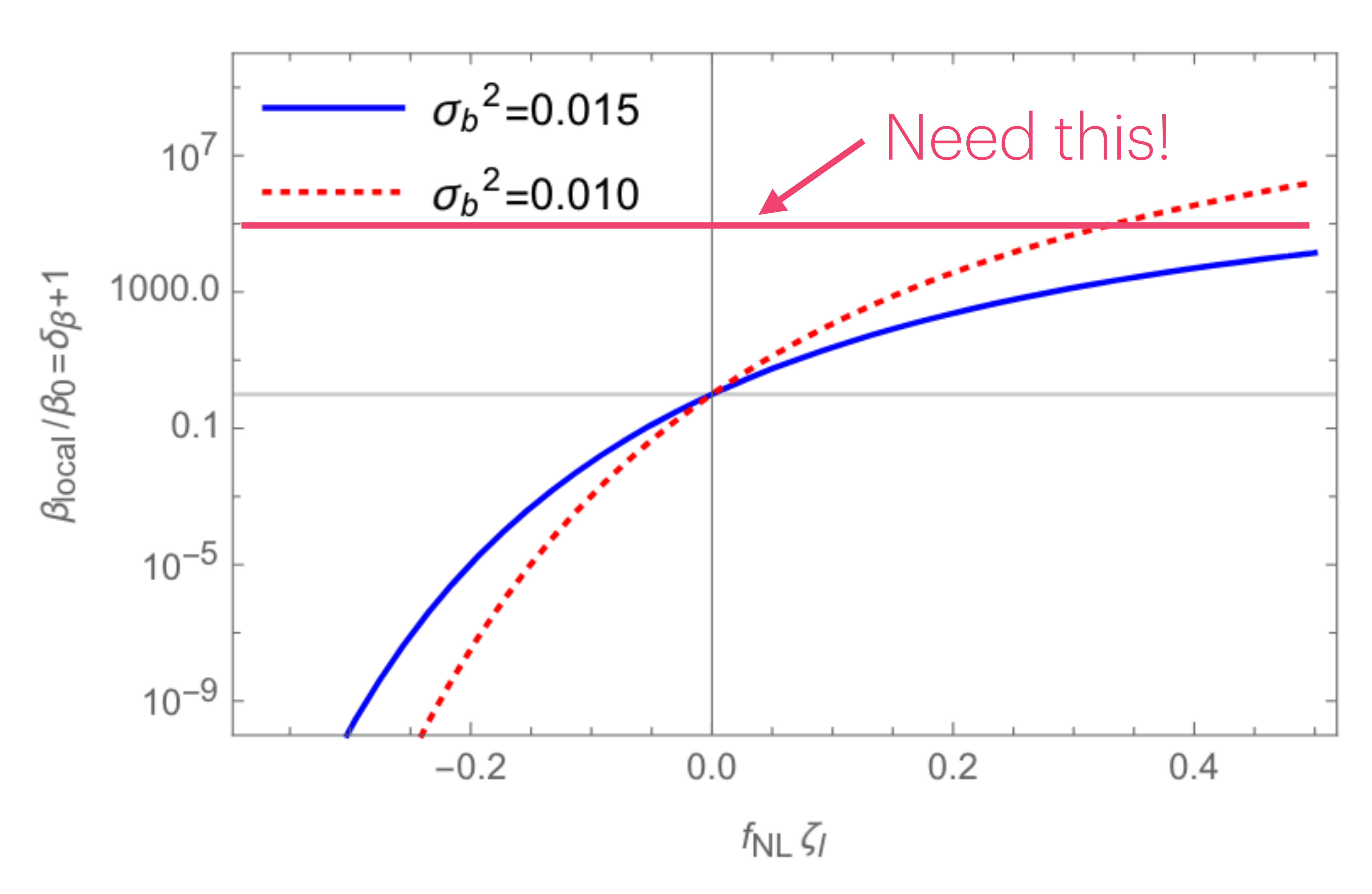
Fragmentation



PBH clustering

- Primordial non-Gaussianity: $\zeta = \zeta_G + \frac{3}{5} f_{\mathrm{NL}} \left(\zeta_G^2 - \langle \delta_G^2 \rangle \right)$





[Young & Byrnes, 2019]

LW intensity

- The one-zone intensity:

$$J(E,z) = E \int dr' \frac{dn_\gamma}{dEdt}(r', E, z)$$

- $\frac{dn_\gamma}{dEdt}$ is given by the particle physics model, some spectra we considered:
  - Two body decay: monochromatic (relevant for ALP)
  - Three body decay: parabola (generic for energy independent amplitudes)
- k_{H_2} and k_{H^-} can be calculated from J

LW rates

$$k_{H^-}(z) = \int_{0.76\mathrm{eV}}^{13.6\mathrm{eV}} 4\pi\sigma_{H^-}(E)\frac{J(E,z)}{E}\frac{dE}{h}$$

$$k_{H_2}(z) \approx 1.39 \times 10^{-12}\ \mathrm{s}^{-1}\frac{J_{LW}(z)}{J_{21}}$$

$$J_{21} = 10^{-21}\mathrm{erg\ s^{-1}\ Hz^{-1}\ cm^{-2}\ sr^{-1}}$$

Injection rate

$$\frac{dn_\gamma}{dEdt}(E,z) = \frac{f_X(z)\Gamma\bar{\rho}_{DM}}{m}\frac{dN}{dE}(E)$$

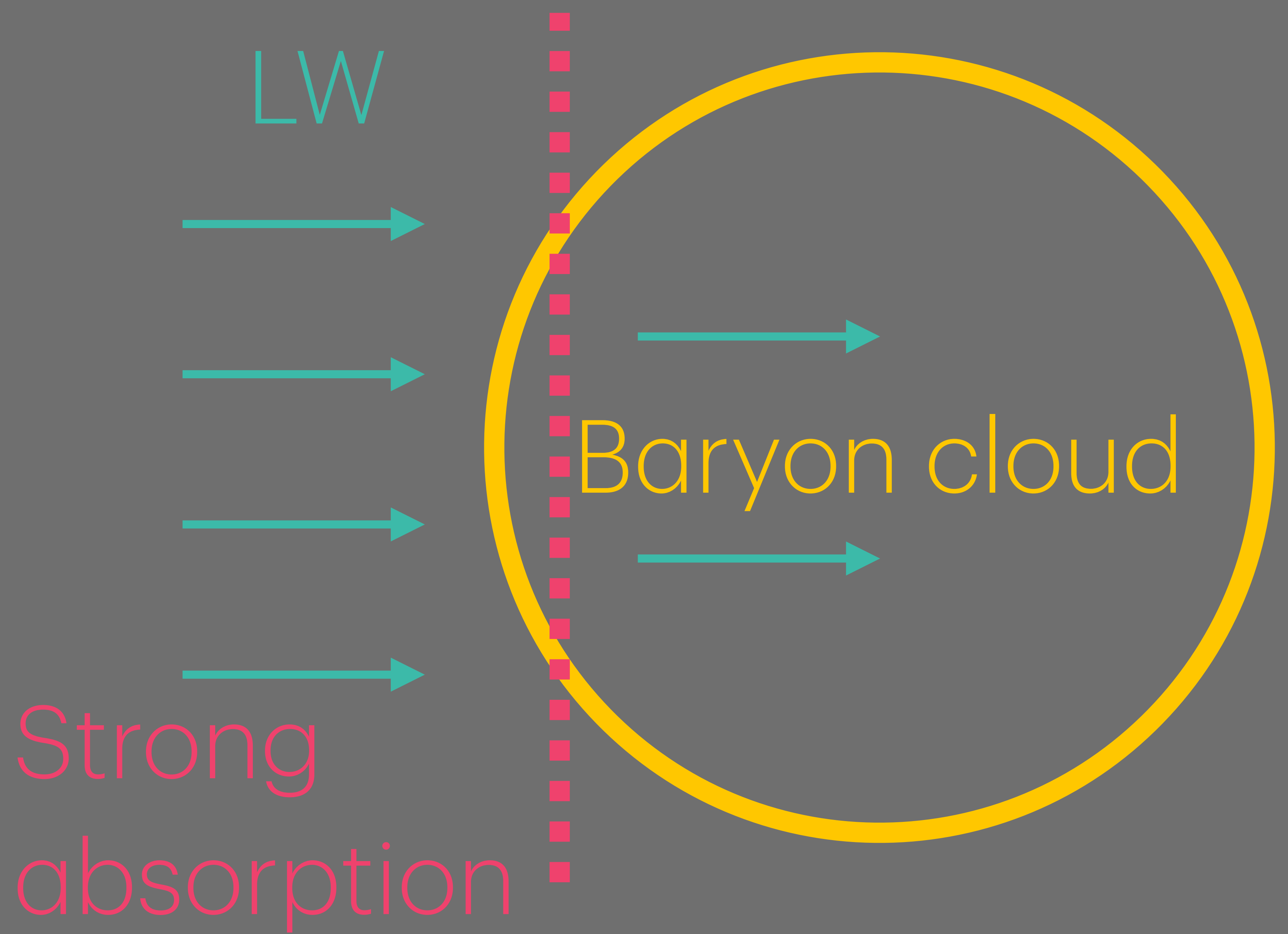
Two body: $E\dfrac{dN}{dE} = 2\delta\left(1 - \dfrac{2E}{m_X}\right)$

Three body: $E\dfrac{dN}{dE} = 6\left[\dfrac{E}{m_X} - \left(\dfrac{E}{m_X}\right)^2\right]\Theta\left(1 - \dfrac{E}{m_X}\right)$

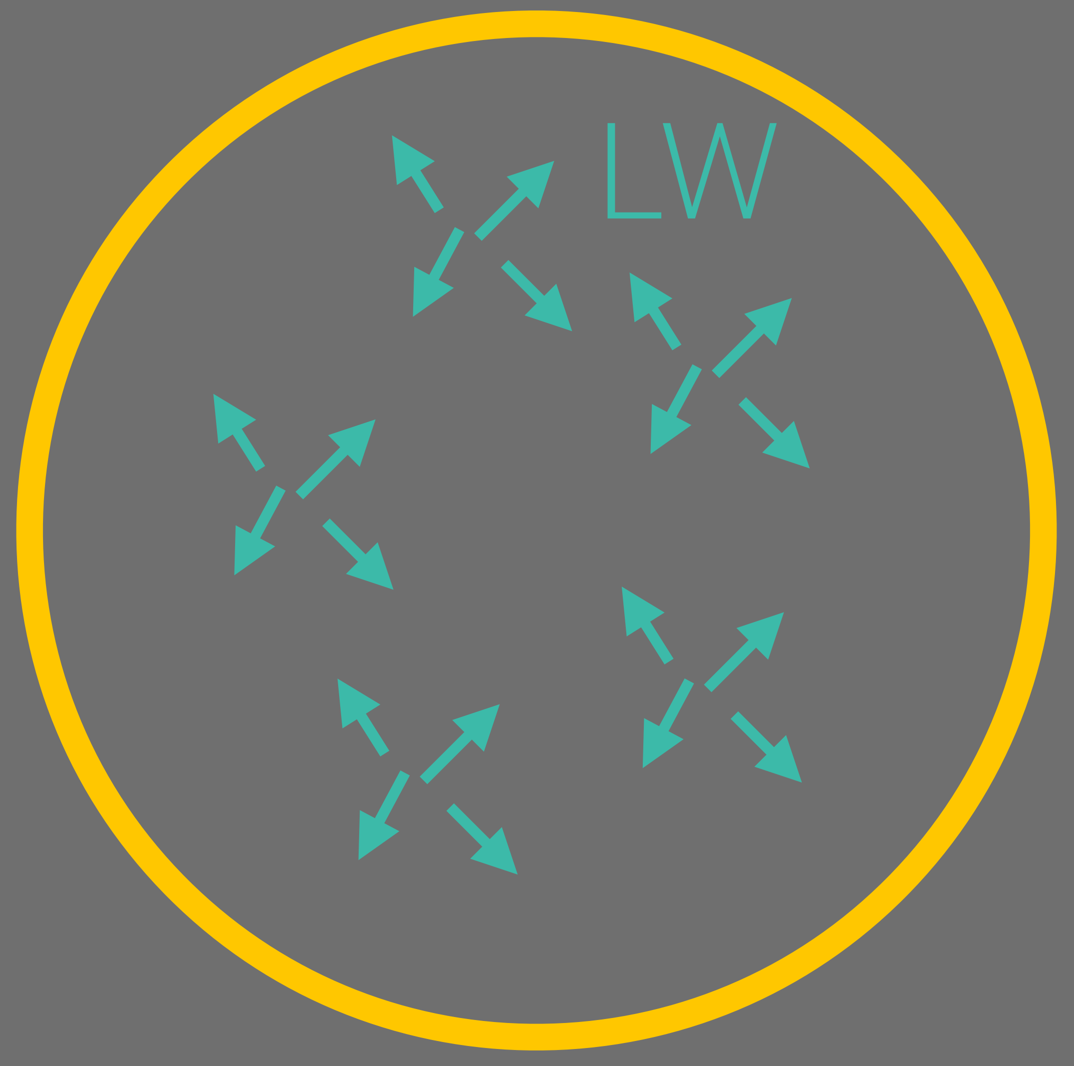
Shielding

- Not all LW radiation can penetrate the cloud (at least in the traditional scenario)
- Modeling column density is intractable even in hydrodynamic simulations!

$$k_{H_2}(N_{H_2}, T) = k_{H_2} f_{\text{shield}}(N_{H_2}, T)$$



$$f_{in-situ} = 1 - \varepsilon_{sh}(1 - f_{\text{shield}})$$



Comparison to critical curve

- The critical curve for LW background:
  - Only works for a constant background
  - Only exterior source
  - No dynamics
- No simulation available with a consistent shield fraction
- Even a moderate reduction increases the rates by orders of magnitude!