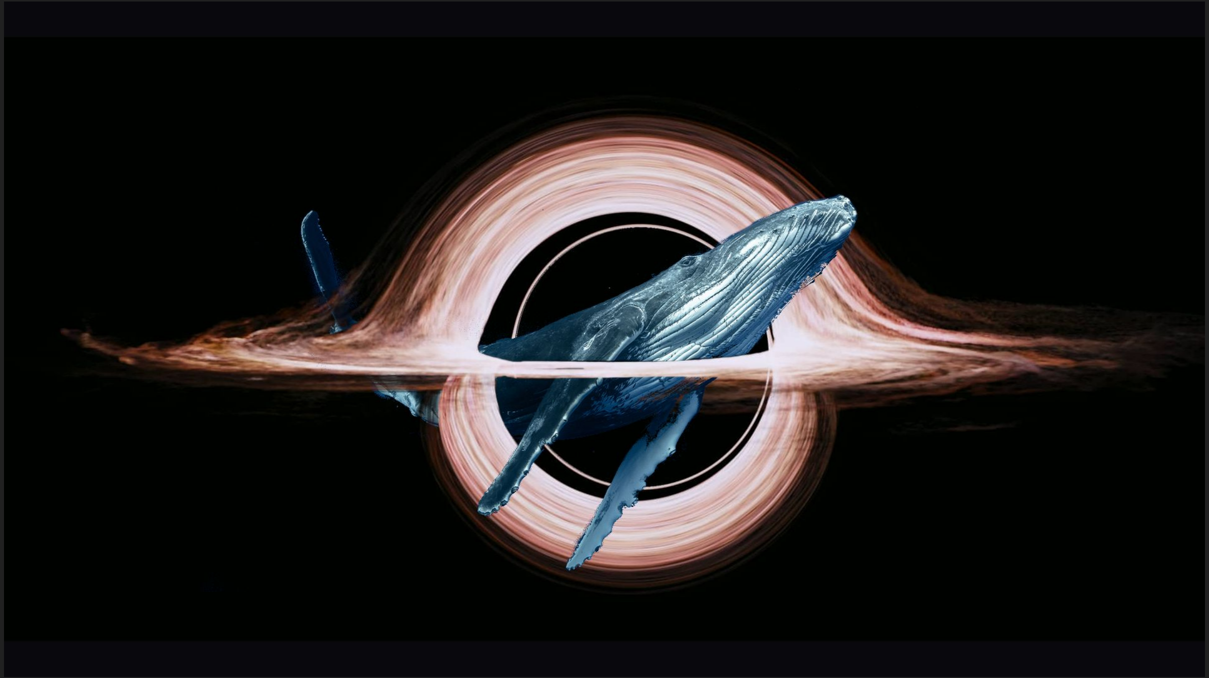
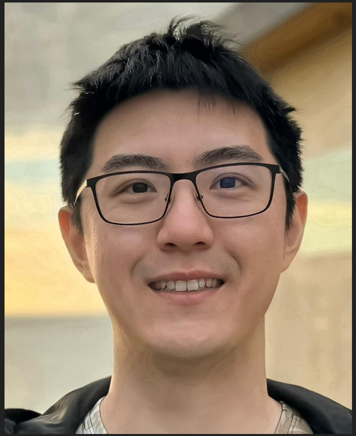
Early supermassive black hole Direct collapse with dark matter



Zachary S. C. Picker
UCLA

with Alexander Kusenko and Yifan Lu



Early supermassive black hole Direct collapse with dark matter

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UCLA

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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,‡]
[1]*Department of Physics and Astronomy, University of California Los Angeles, Los Angeles, California, 90095-1547, USA*
[2]*Kavli Institute for the Physics and Mathematics of the Universe (WPI), The University of Tokyo Institutes for Advanced Study, The University of Tokyo, Chiba 277-8583, Japan*

Direct-collapse supermassive black holes from relic particle decay

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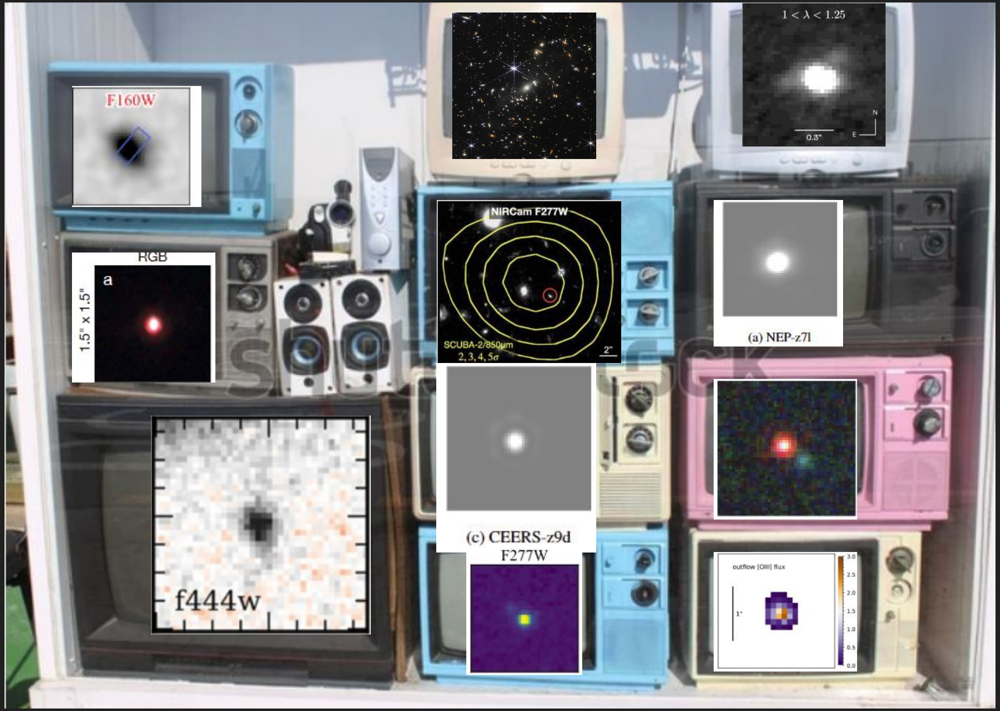
arXiv: 2312.15062, 2404.03909, … ?

High redshift supermassive black holes

Observations of high-z supermassive black holes (SMBHs):

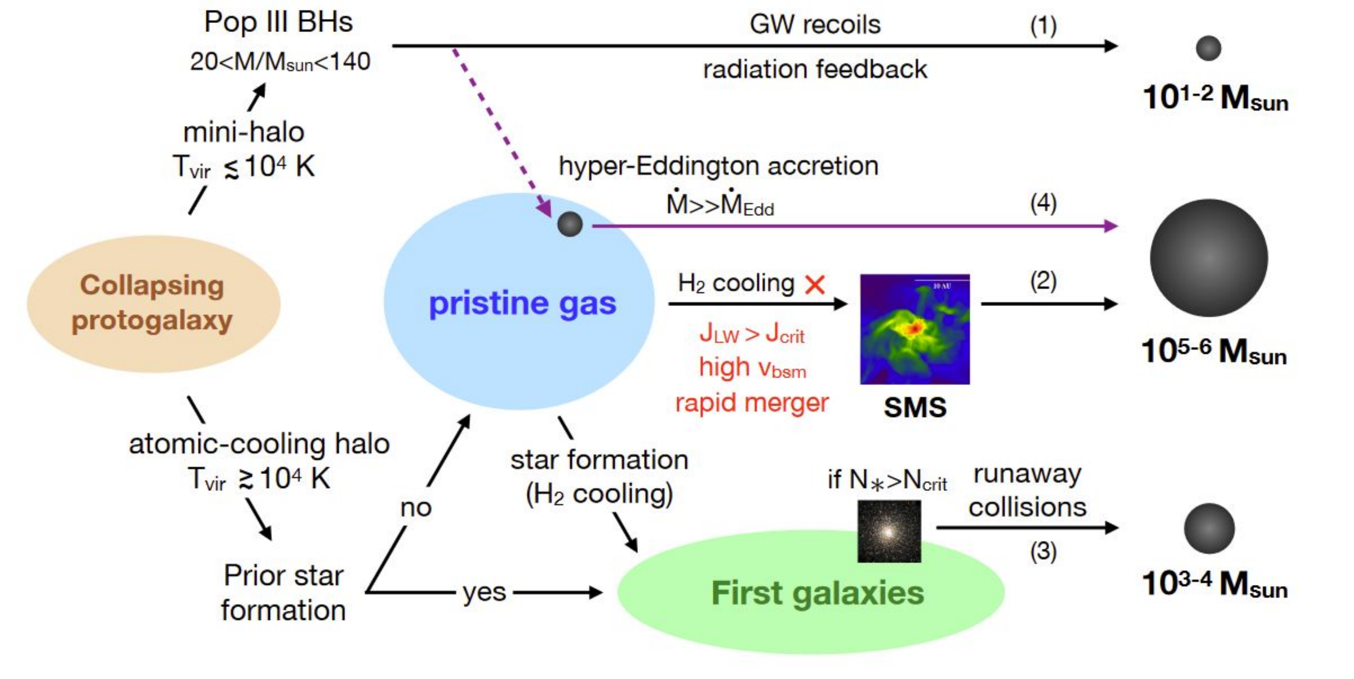
Observations of high-z supermassive black holes (SMBHs): Window shopping in the astronomy department



- Goulding et al 2023
- Juodžbalis et al 2023
- Übler et al 2023
- Larson et al 2023
- Harikane et al 2023
- Carnall et al 2023
- Onoue et al 2023
- Kocevski et al 2023

Z~5-10+

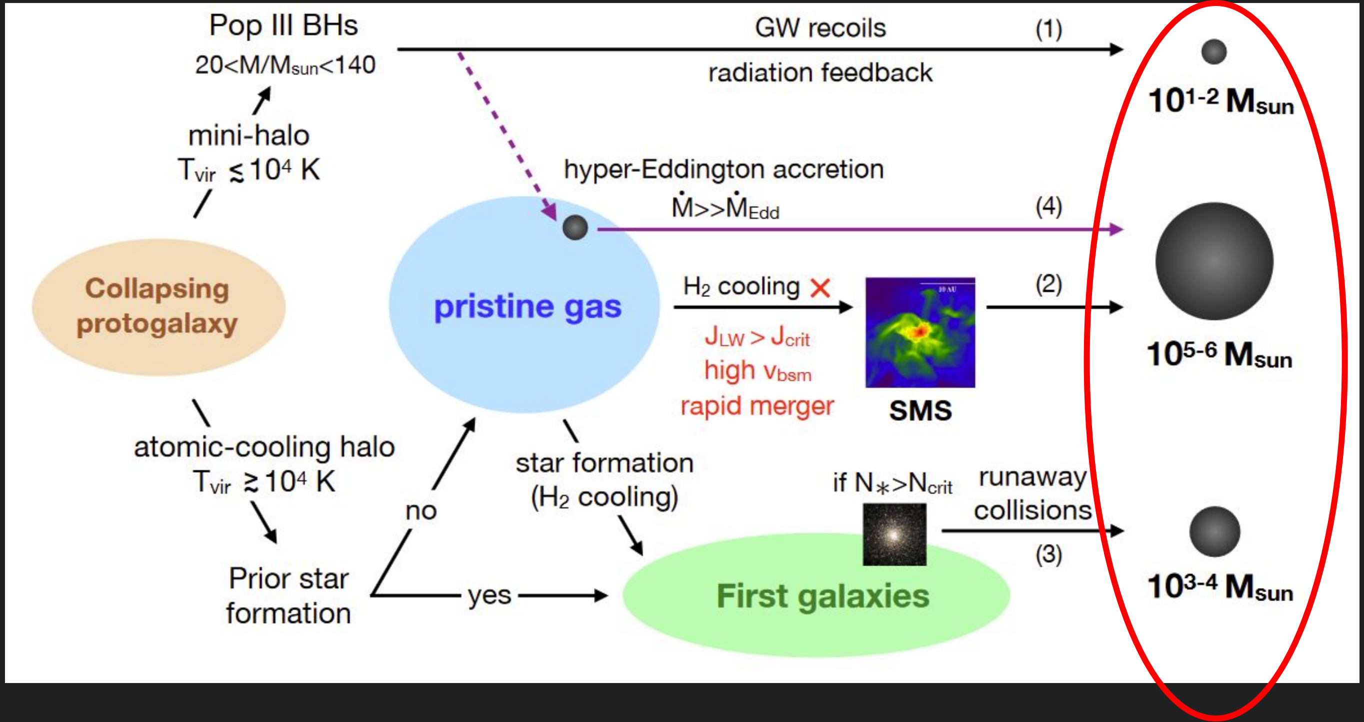
The puzzle of high-z SMBH formation



Inoyashi et al 2020

The puzzle of high-z SMBH formation

Seed mass



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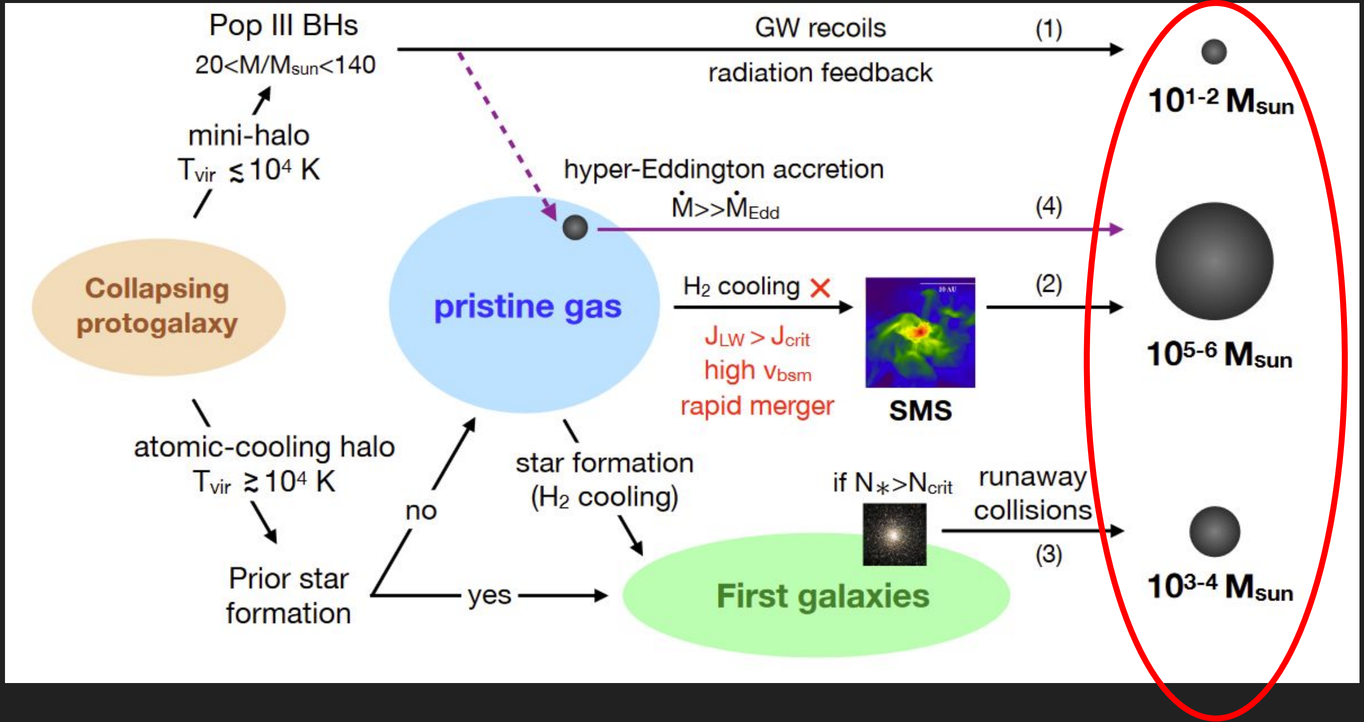
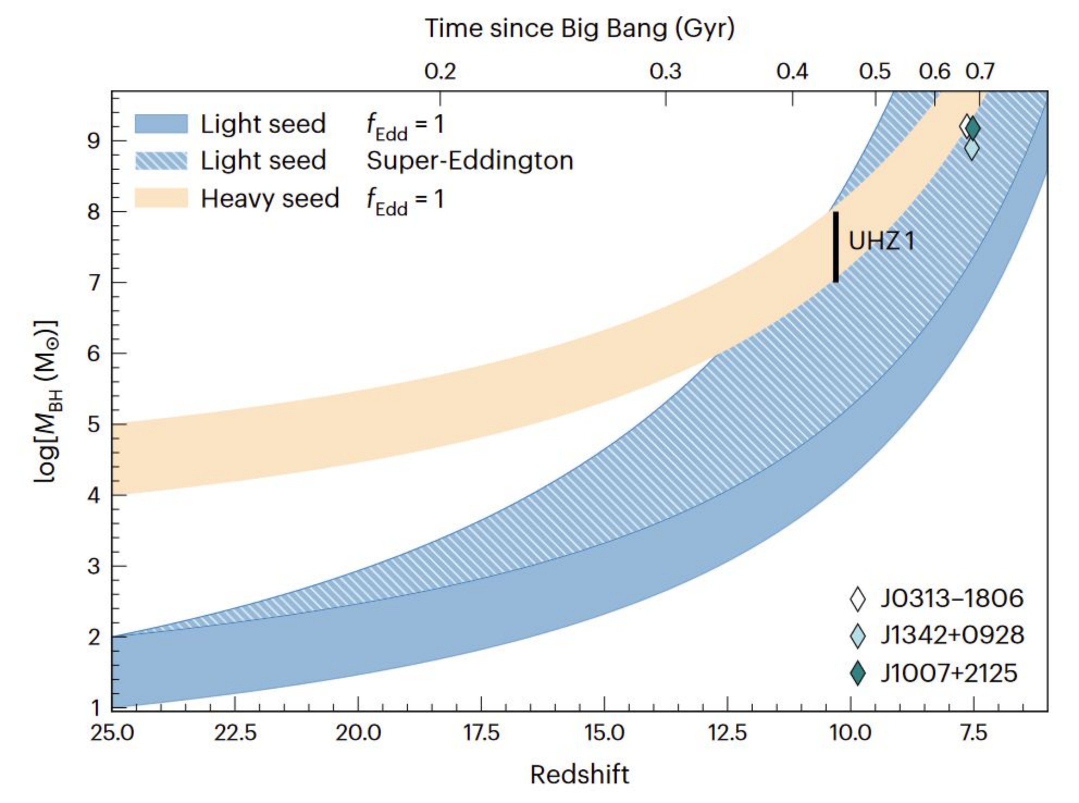


Inoyashi et al 2020

+ Primordial black hole seeds…

The puzzle of high-z SMBH formation



Bogdan et al 2023

Eddington limit: accretion rate balanced by radiation

The puzzle of high-z SMBH formation

Probing the Genesis of SMBH, Nov 2024 @Kavli IPMU

The puzzle of high-z SMBH formation

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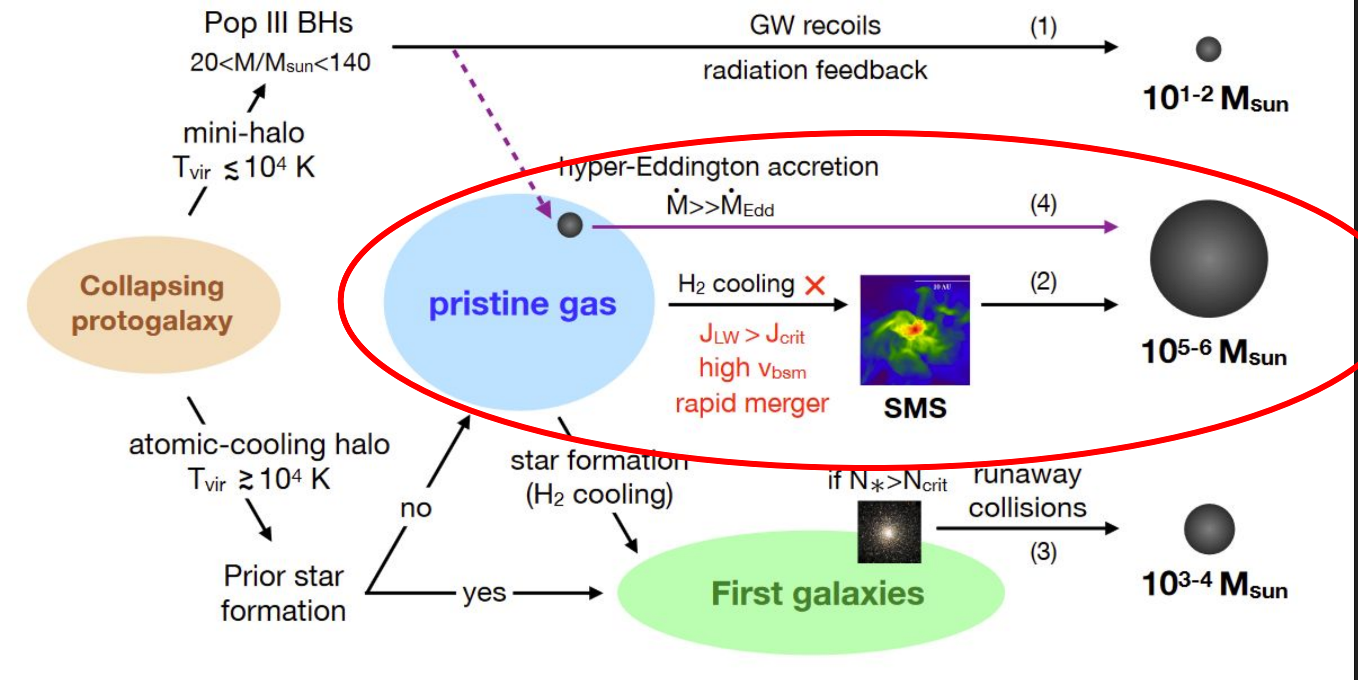
Direct collapse formation

Direct collapse black hole formation



Inoyashi et al 2020

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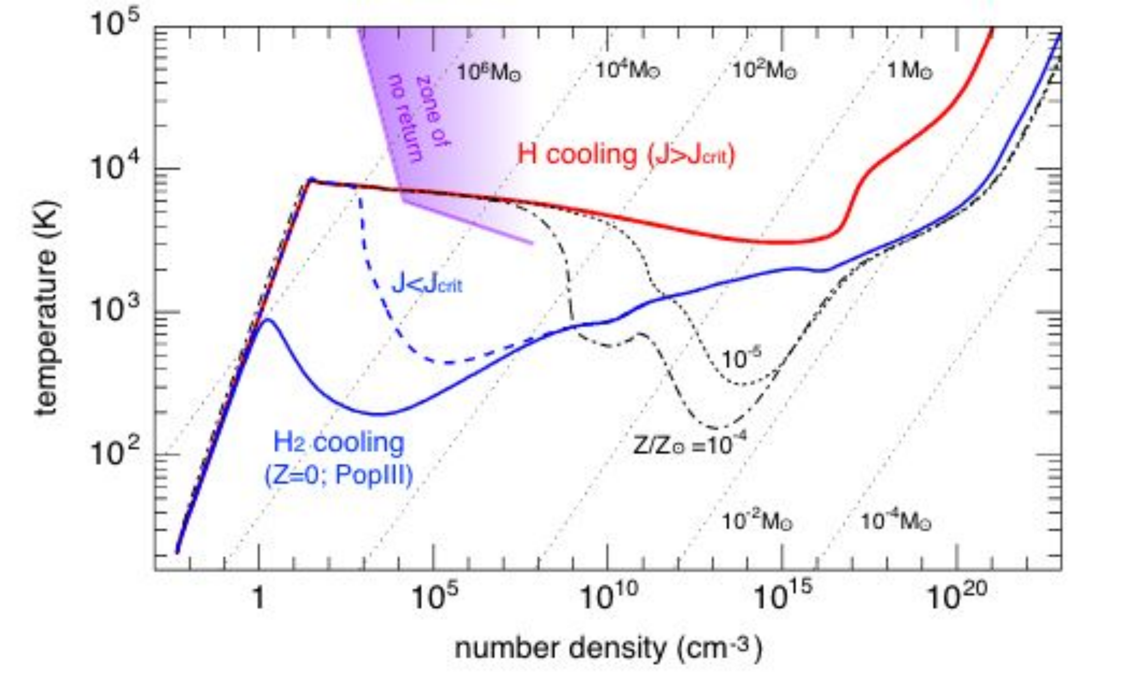
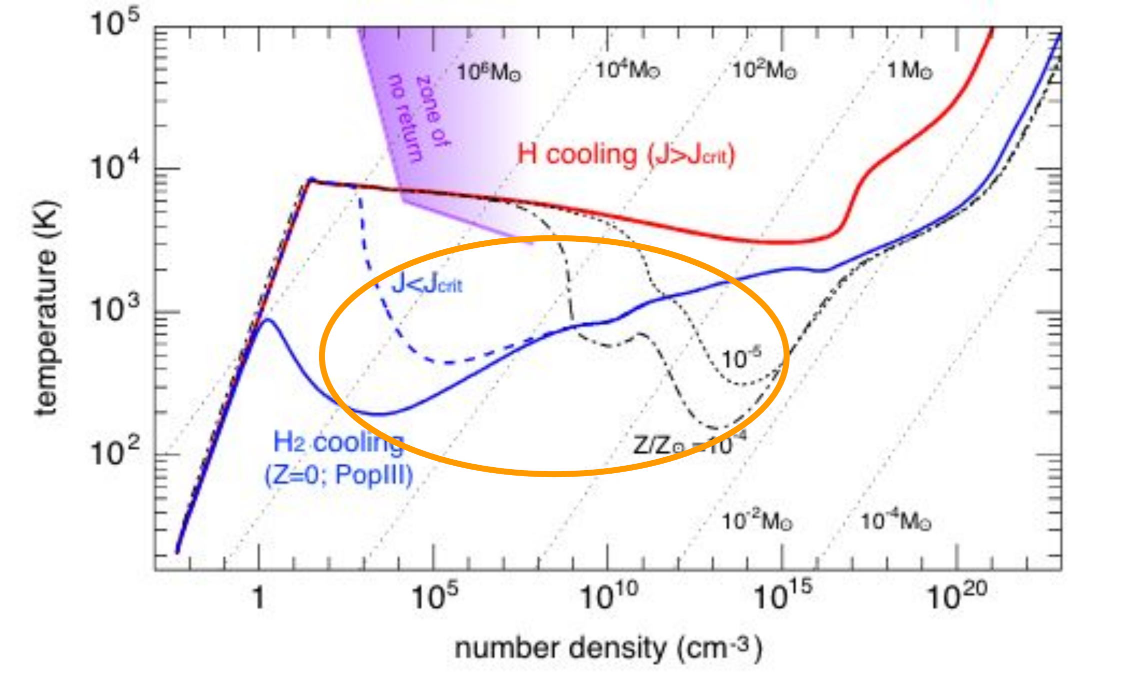


Inayoshi et al 2019

Direct collapse black hole formation

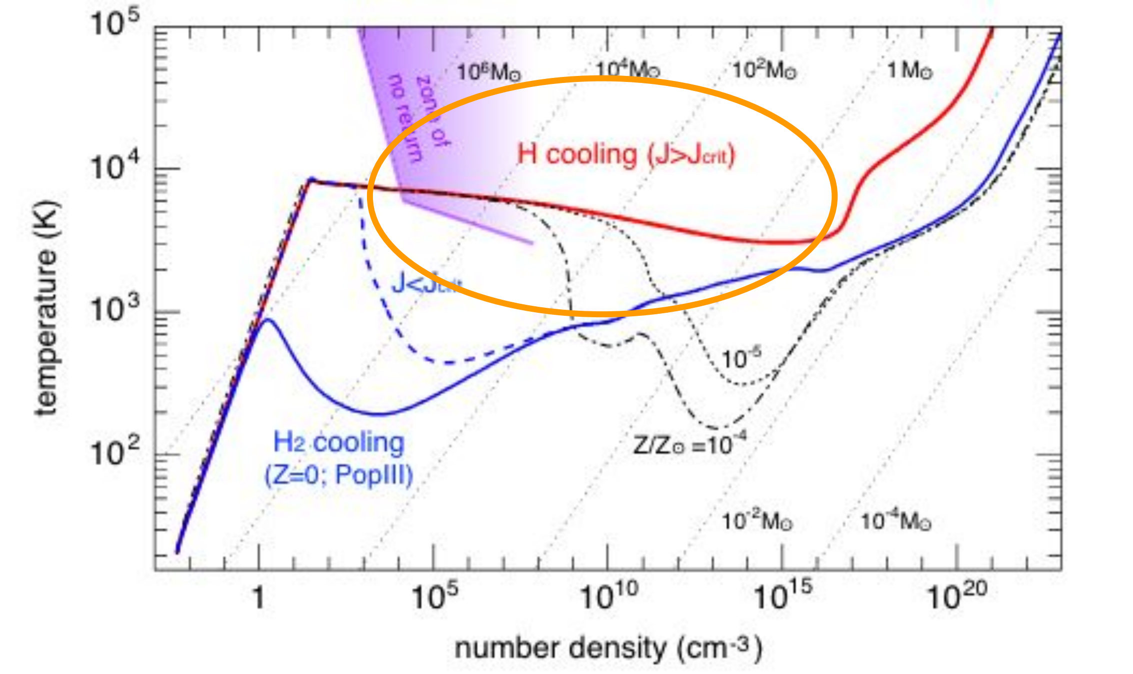


Inayoshi et al 2019

Jeans instability causes fragmentation of cloud

⇒No direct collapse!

Direct collapse black hole formation



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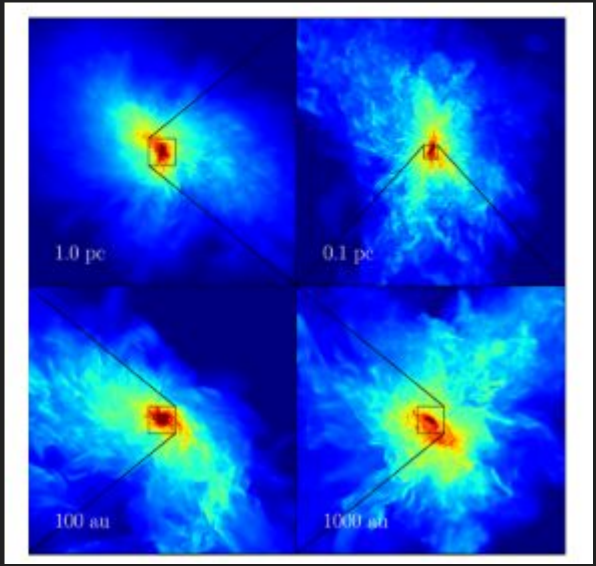

Becerra et al 2015

Direct collapse black hole formation

Essential requirement:

Suppression of H_2

Direct collapse black hole formation

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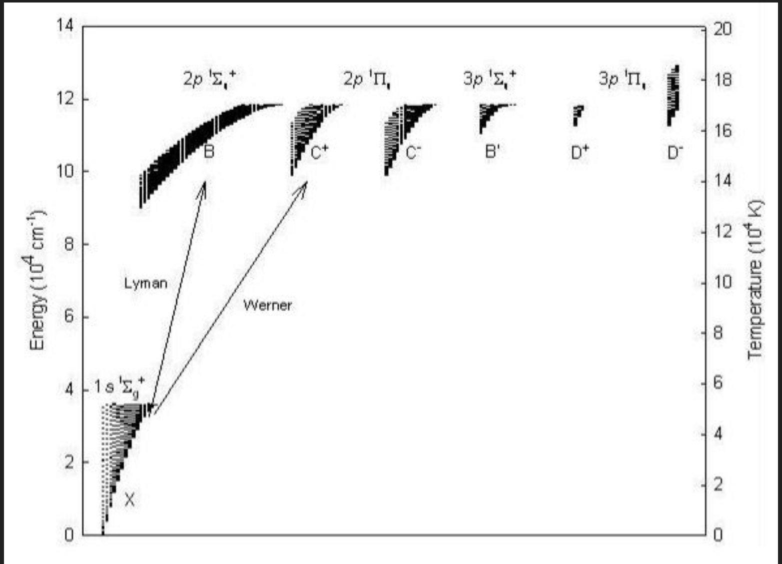

Shaw et al 2005

How to suppress molecular hydrogen?

Solutions: additional heating or ionizing radiation

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- For astronomers: Lymen-werner photons from nearby star formation
    - Haiman et al 1996, Shang et al 2009

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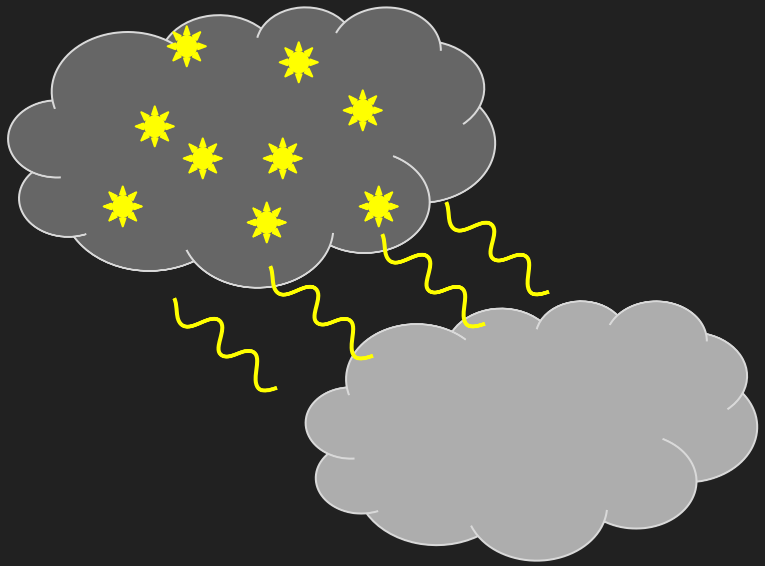
- For cosmologists: magnetic fields
  - Sethi et al 2010
- For astroparticle peeps: dark matter
  - Freese 2015
  - Friedlander et al 2022



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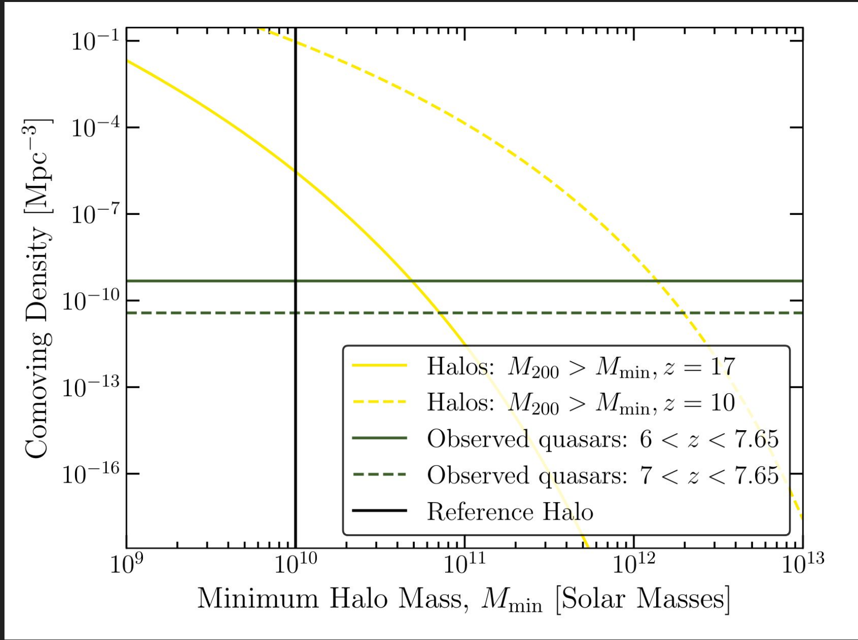

Our proposals for suppressing molecular Hydrogen:

Heating:

- Evaporation of small PBHs

Lyman-Werner radiation:

- Slow decay of dark matter
- Complete decay of new particle X
- More to come…

Simulating the direct collapse

Evolution of baryonic clouds

- Clouds (~10^8 solar masses) of baryons and dark matter enter non-linear regime
    - Model with spherical top-hat collapse

      Gunn and Gott 1972, Peebles 1980

- Eventually they decouple and virialize
    - Must turn on chemistry
    - Treat dark matter and baryons individually
        - Dissipative cooling (baryons) vs. gravity (DM)
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Evolution of halos after recombination: baryons

Temperature evolution

$$\frac{dT}{dt} = (\gamma - 1)\left(\frac{\dot{n}_b}{n_b}T + \frac{L_{\rm cool} + L_{\rm heat}}{k n_b}\right)$$

- Important heating/cooling channels:

  0. Adiabatic cooling
  1. Inverse Compton cooling (electrons scatter off CMB)
  2. Hydrogen line cooling (atomic hydrogen collides with free electrons)

  3. Molecular hydrogen cooling (collisional excitations)

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0. Adiabatic cooling
1. Inverse Compton cooling (electrons scatter off CMB)
2. Hydrogen line cooling (atomic hydrogen collides with free electrons)
   Dominant above 10,000 K, sets max T
3. Molecular hydrogen cooling (collisional excitations)
   Dominant below 10,000 K. Must be suppressed with extra heat or removal of molecular hydrogen

Evolution of halos after recombination: baryons

Chemical evolution

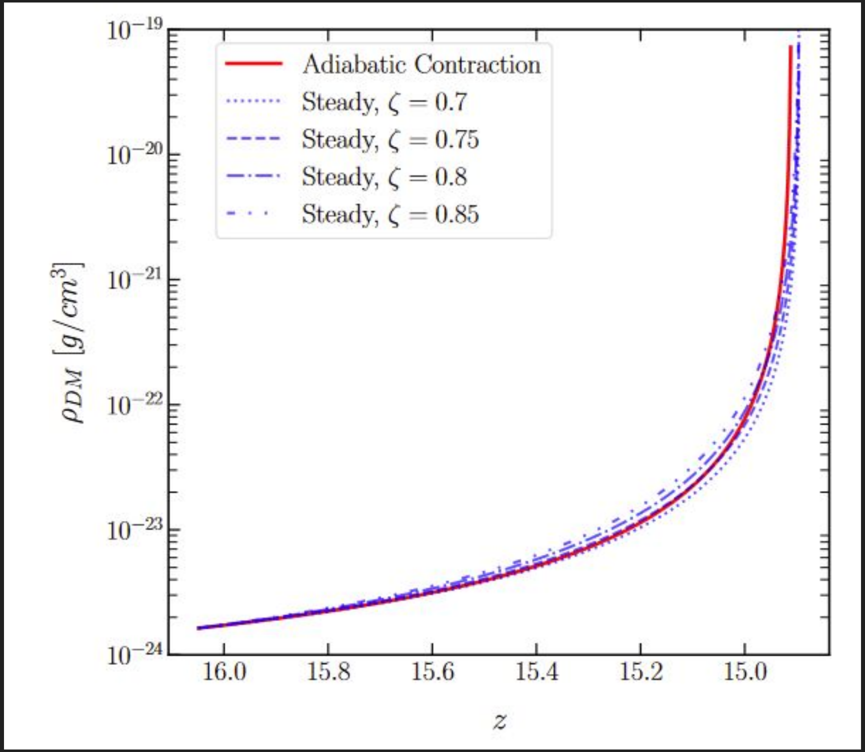
- Track atomic and molecular Hydrogen, ionized hydrogen (protons), free electrons, and helium (12 reactions tracked)
- Heavily coupled:
  - Free electrons density affected by photo- and collisional- ionization of Hydrogen atoms
  - Formation of molecular hydrogen via dominant channel:

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

Photodetachment
Photodissociation

Evolution of halos after recombination: dark matter

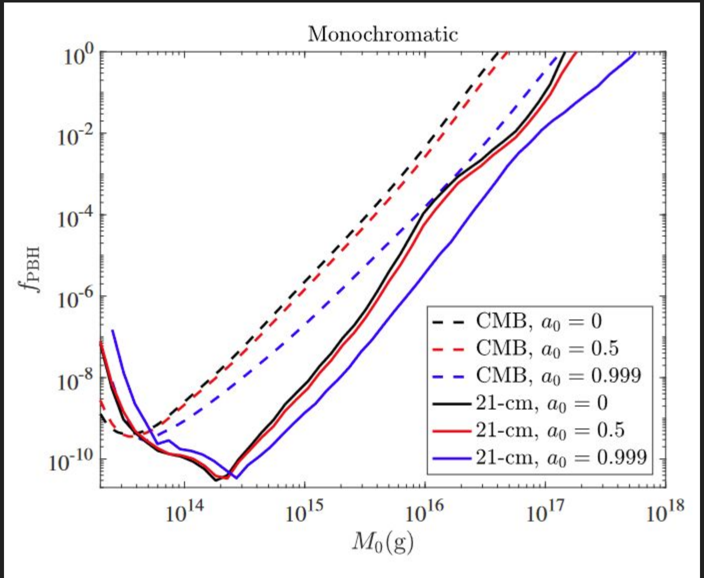
- Adiabatic contraction
  - Dark matter responds to collapsing baryons in center
  - Eggen, Lynden-Bell, & Sandage 1962
- We included this dynamically in our collapse simulation



Specific scenarios

Primordial black holes

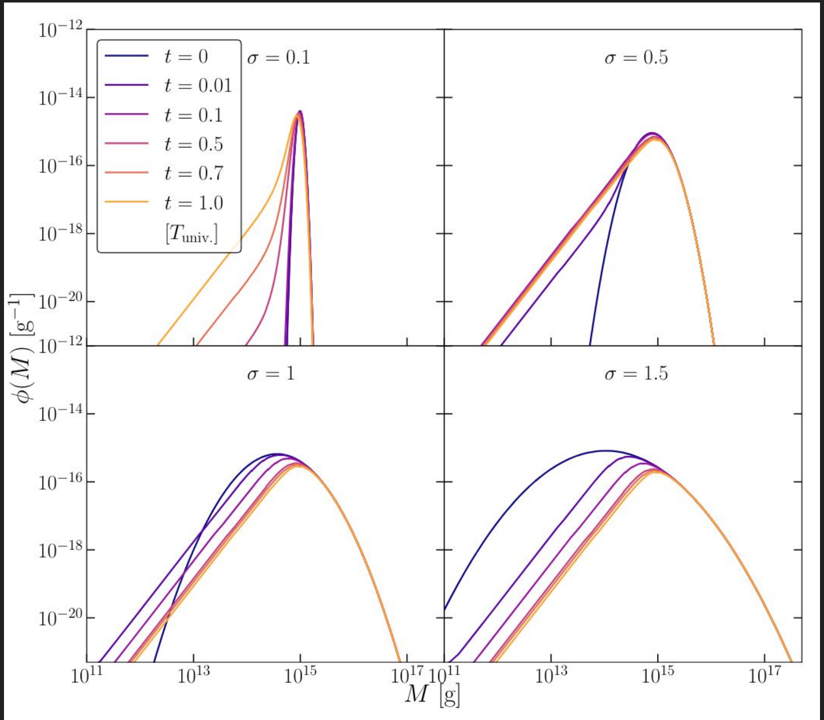
- Small PBHs are well constrained by (non) observation of Hawking evaporation effects
  - CMB, BBN, 21-cm line
  - Cang et al 2022, Carr et al 2010, Acharya & Khatri 2022, Chluba et al 2020
- In order to get enough heating, we consider halos with large PBH clustering
  - Ie large ‘local’ fraction



Cang, Gao, & Ma 2022

Heating the halos with PBH Hawking evaporation

- Black holes of mass $2 \times 10^{14}\ g$ evaporate at z~20
  - Narrow lognormal spectrum ⇒ broad collapse times
- Secondary spectra computed with BlackHawk
  - Arbey & Auffinger 2019
  - Electrons, photons, protons
- Compute attenuation in halo and assume that attenuated particles transfer their energy as heat
  - Freese et al 2016



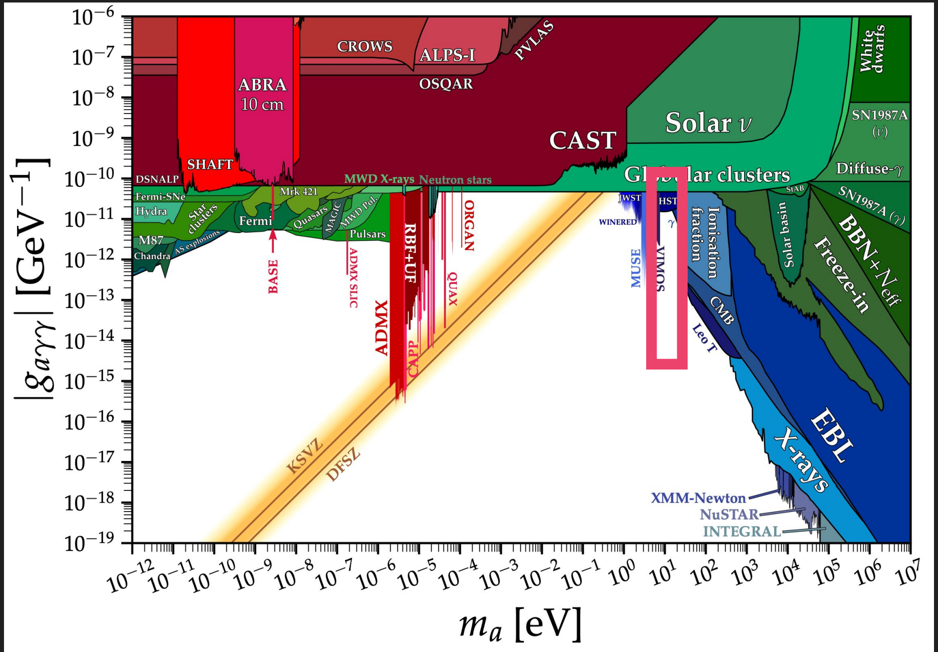
Mosbech and ZSCP 2022

Particle decay

Axion-like particles (ALP)

- If all of the dark matter:
  - Low decay rate
- If a subcomponent of a dark sector ('X')
  - Higher rate allowed

Considered two-body and three-body decay to photons



(Crayon O'hair)

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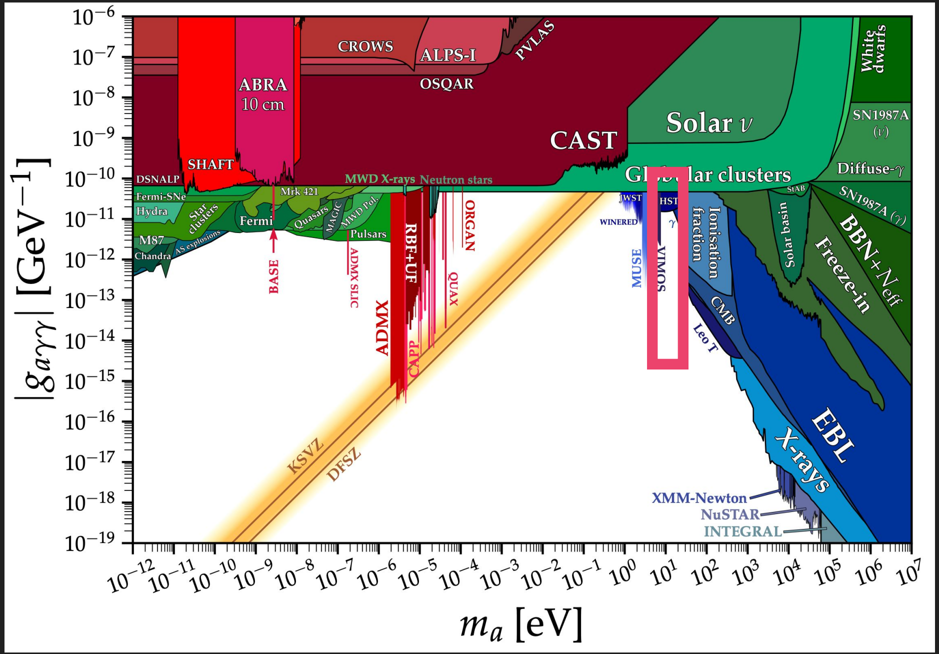
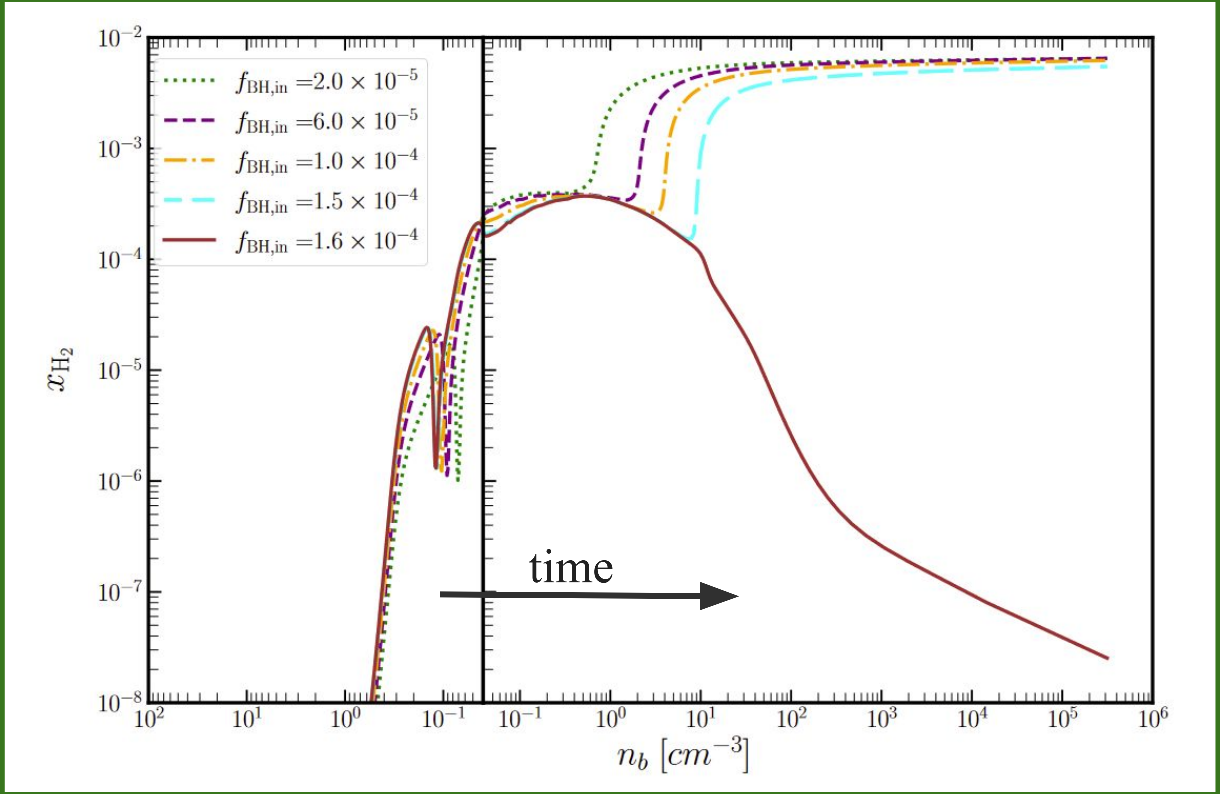
Axiverse?



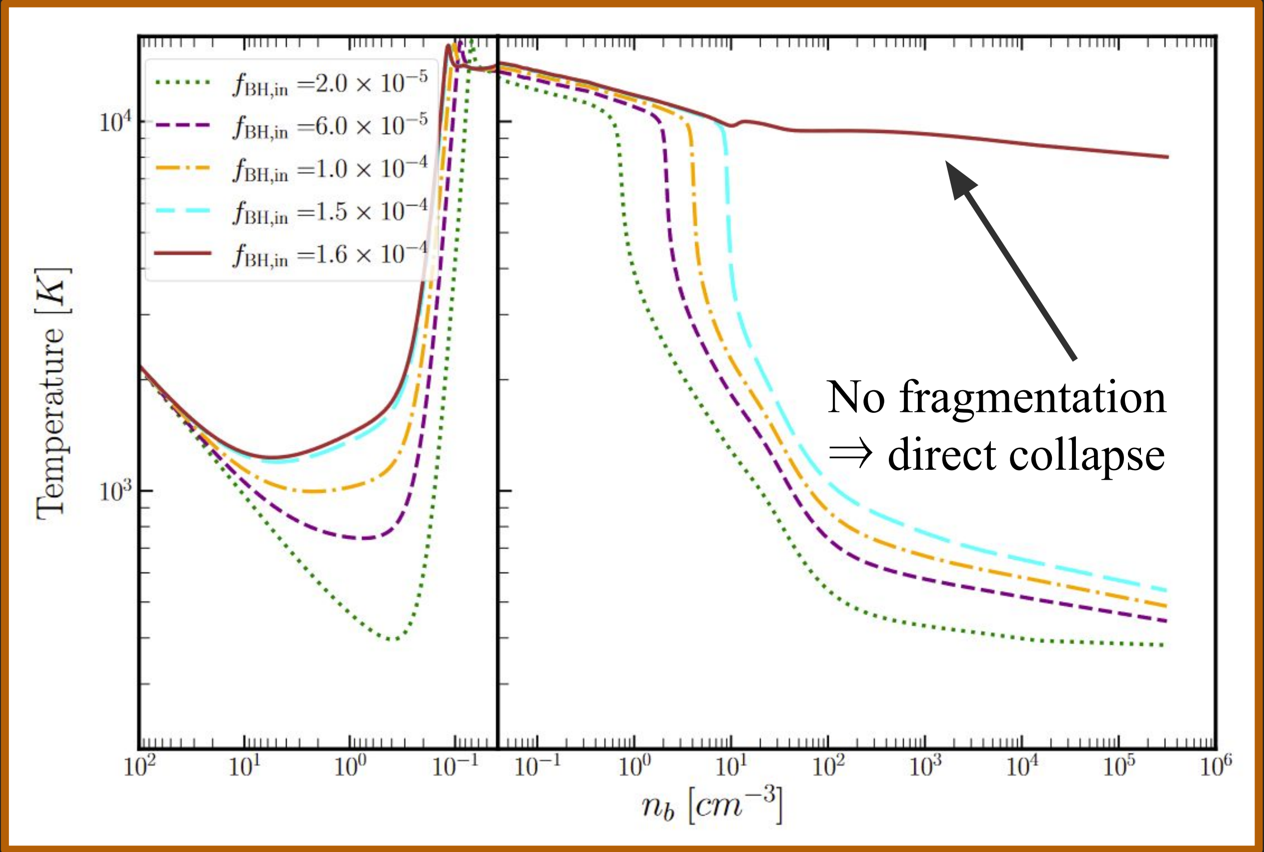
(Crayon O’hair)

Results

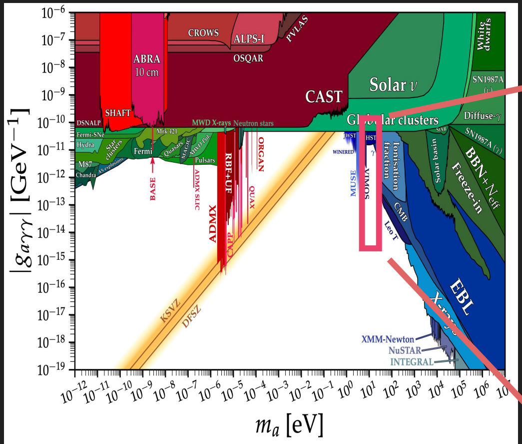
PBH results: molecular hydrogen fraction

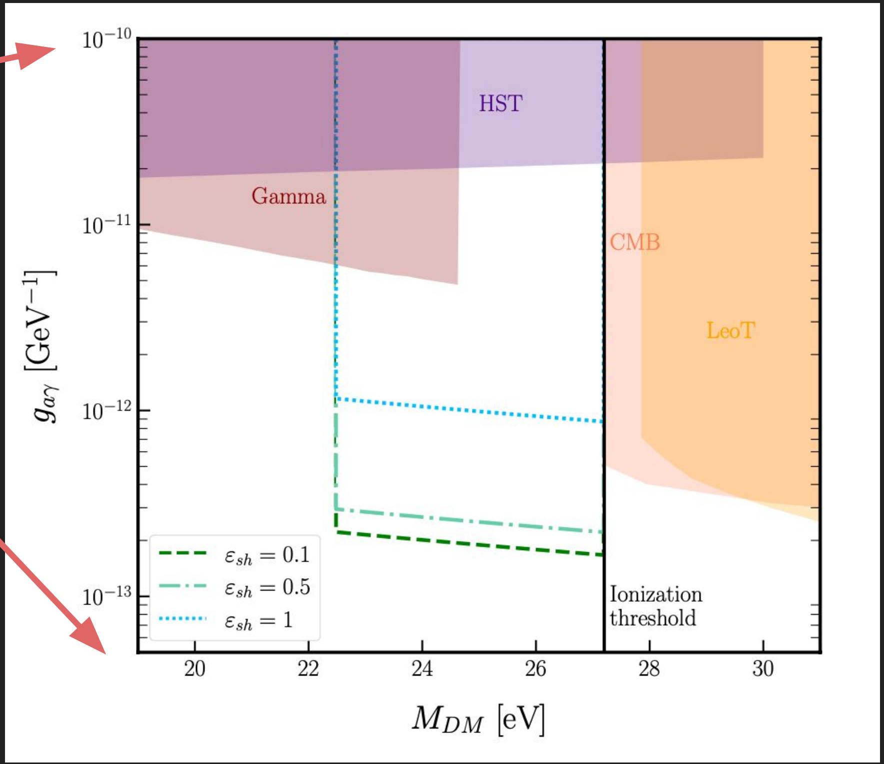


PBH results: halo temperature

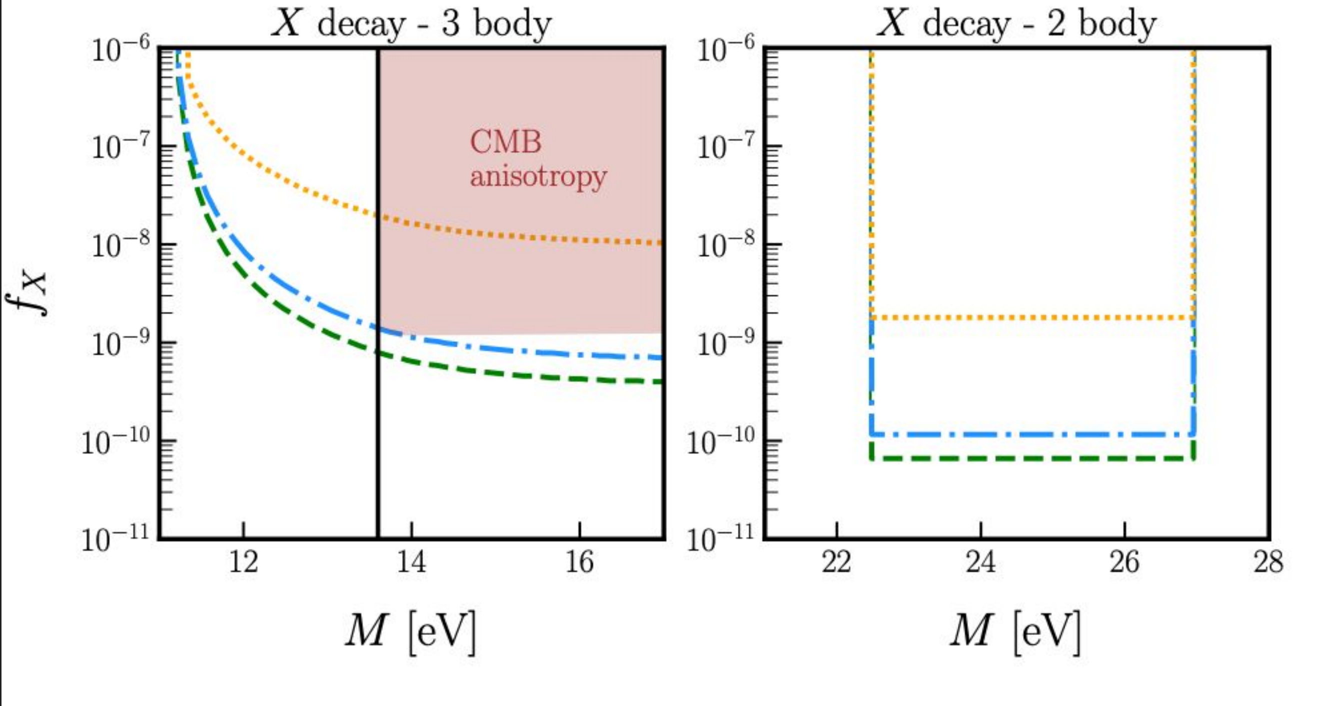


Results: ALP dark matter decay



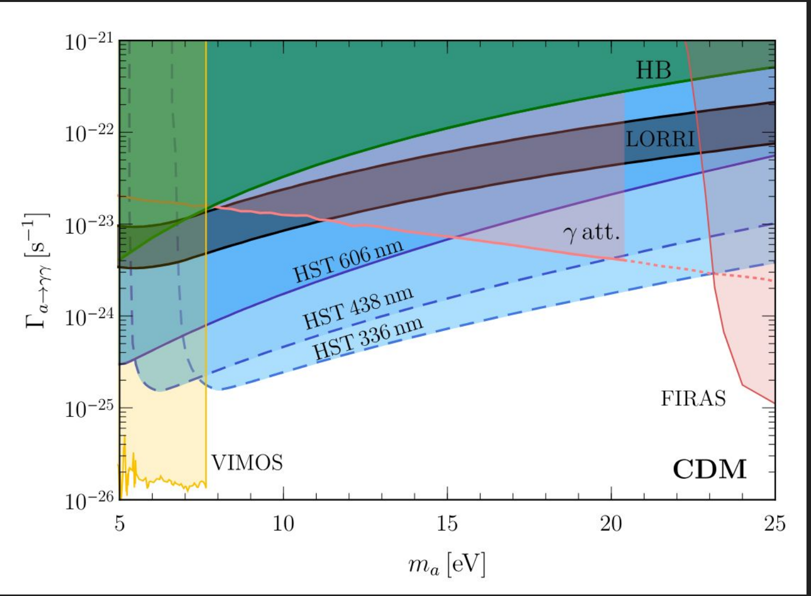


Results: X particle decay



Observational consequences

- ‘Hot spots’ at formation sites?
  - Point-like x-ray or gamma sources
  - Possibly dwarfed by other radiation from direct collapse
  - Failed direct collapse sites??
- Particle decay - contributes to cosmic optical background
  - Future HST observation?



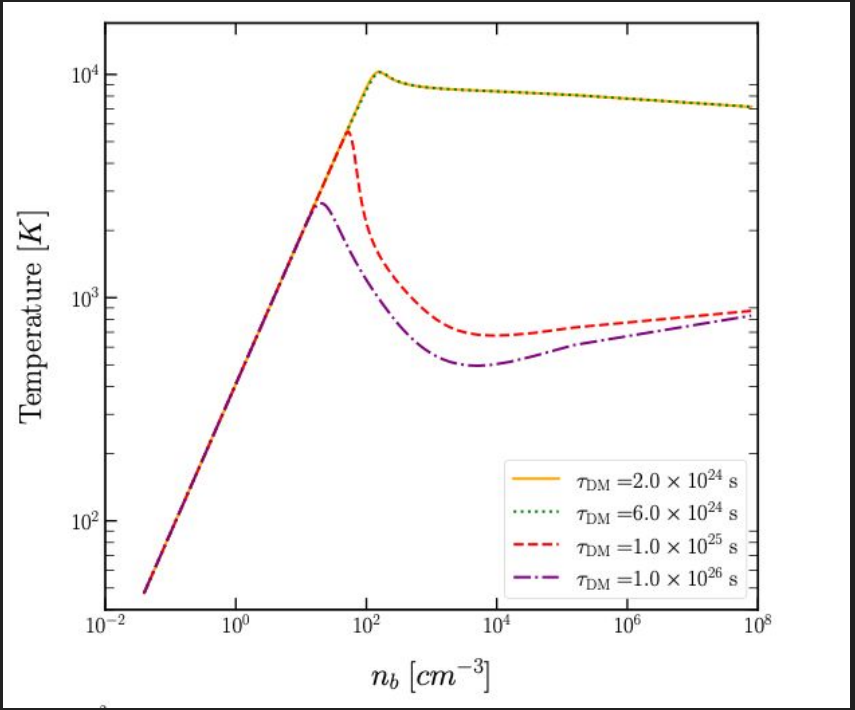
Carenza et al 2023

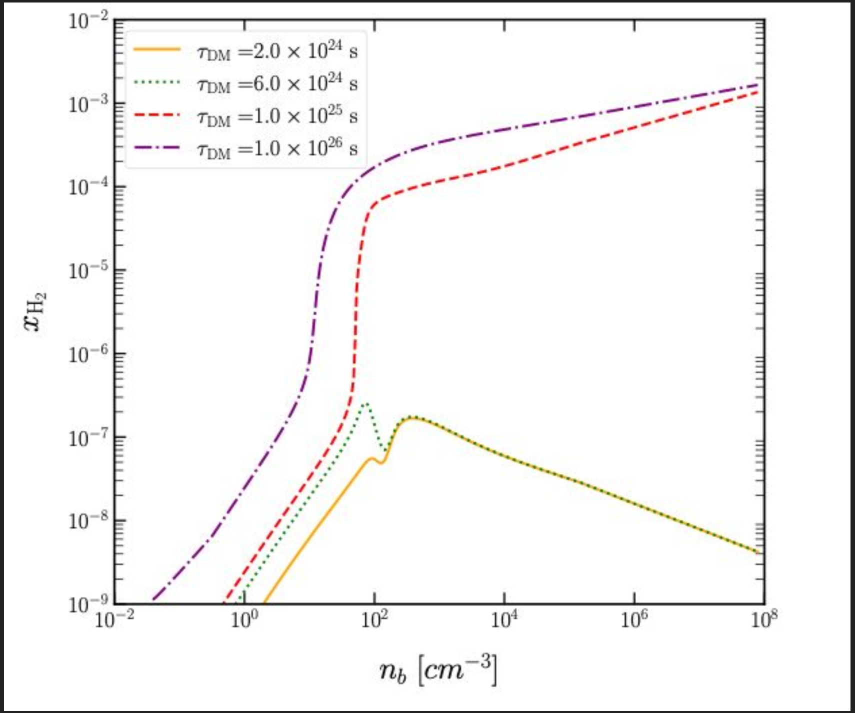
Conclusions

- How are the earliest SMBH formed??
  - Not enough time to accrete from small seeds…
- Direct collapse of gas clouds can help
  - Requires extra injection of radiation
    - Evaporating PBHs?
    - Decaying dark matter?
    - Decaying new particles?
    - …even more exotic things…?

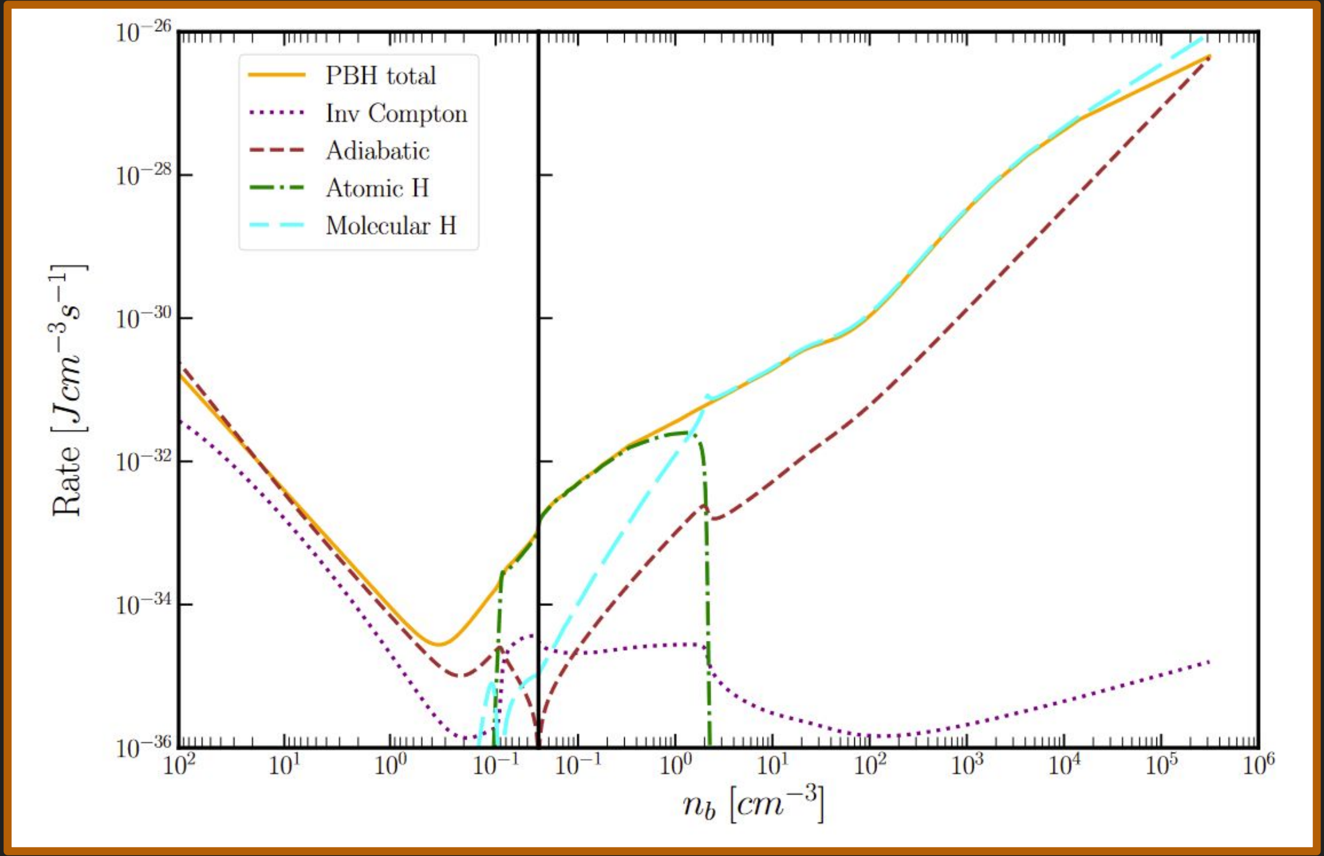
Thanks!

Results for particle decay





Results: heating/cooling rates for *insufficient* PBH heating



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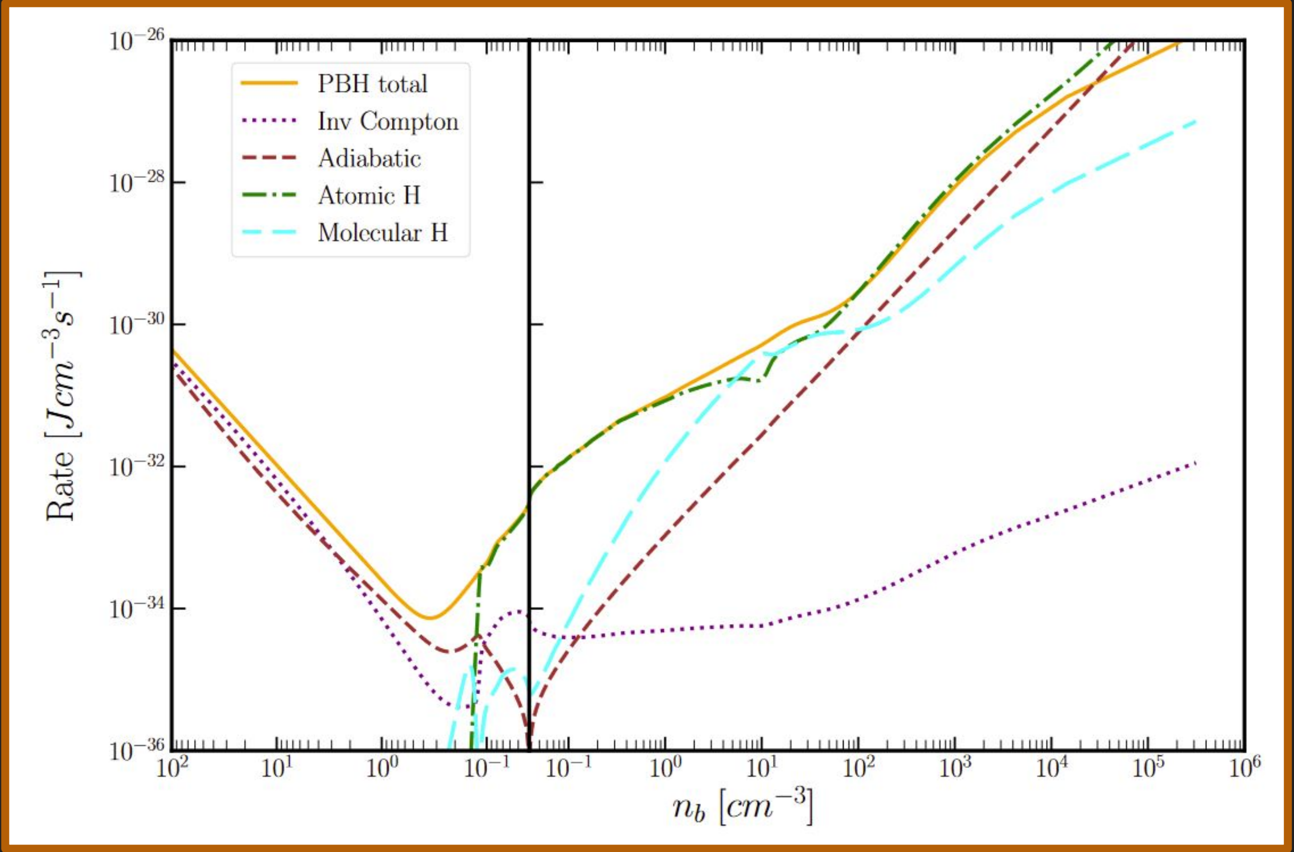
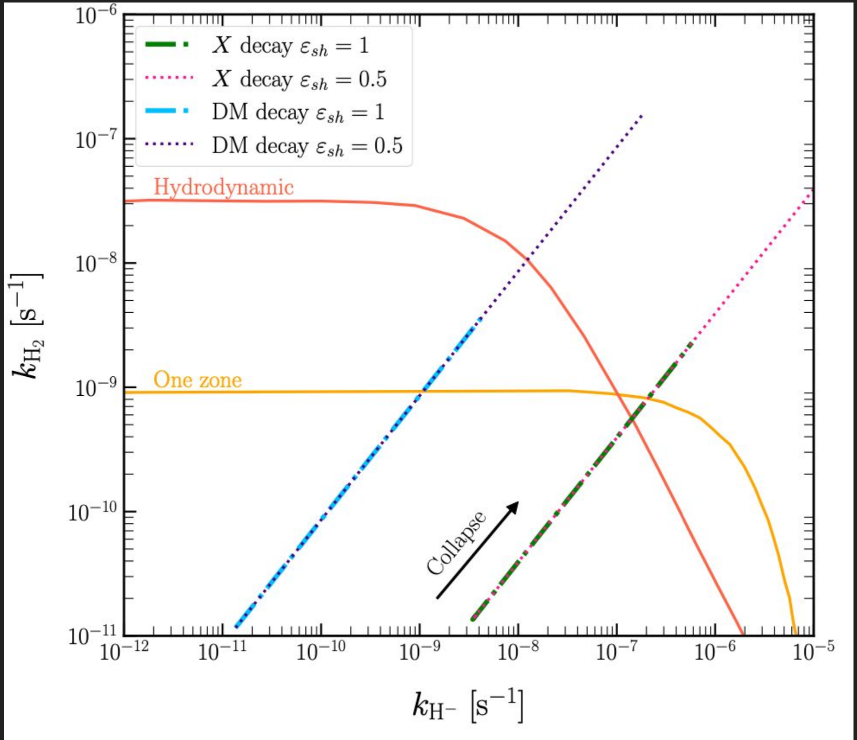


‘Critical curve’ comparison

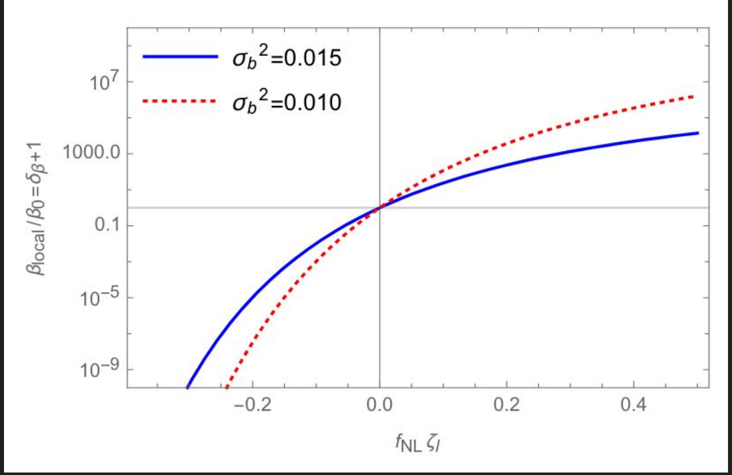
Dissociation rate



Detachment rate

Primordial black hole clustering: justifications

- Non-Gaussianities from inflation
  - curvature perturbation ζ,
    non-Gaussianity parameter f
  - $\zeta f \sim 0.5 \Rightarrow 10^7$ increase in local number density
  - Young & Byrnes 2020, Ferrante et al 2023, Franciolini et al 2023
- Other PBH formation mechanisms which depend on DM density
  - Yukawa force collapse in dark sector
  - Q-Ball or oscillon DM
  - PBH dominated clustering (Holst et al 2024)



Young and Byrnes 2019