Dissipative Dark Matter in a Slow Cooker:
Delayed Dark Clumps and Primordial Black Holes

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Dissipative Dark Sectors

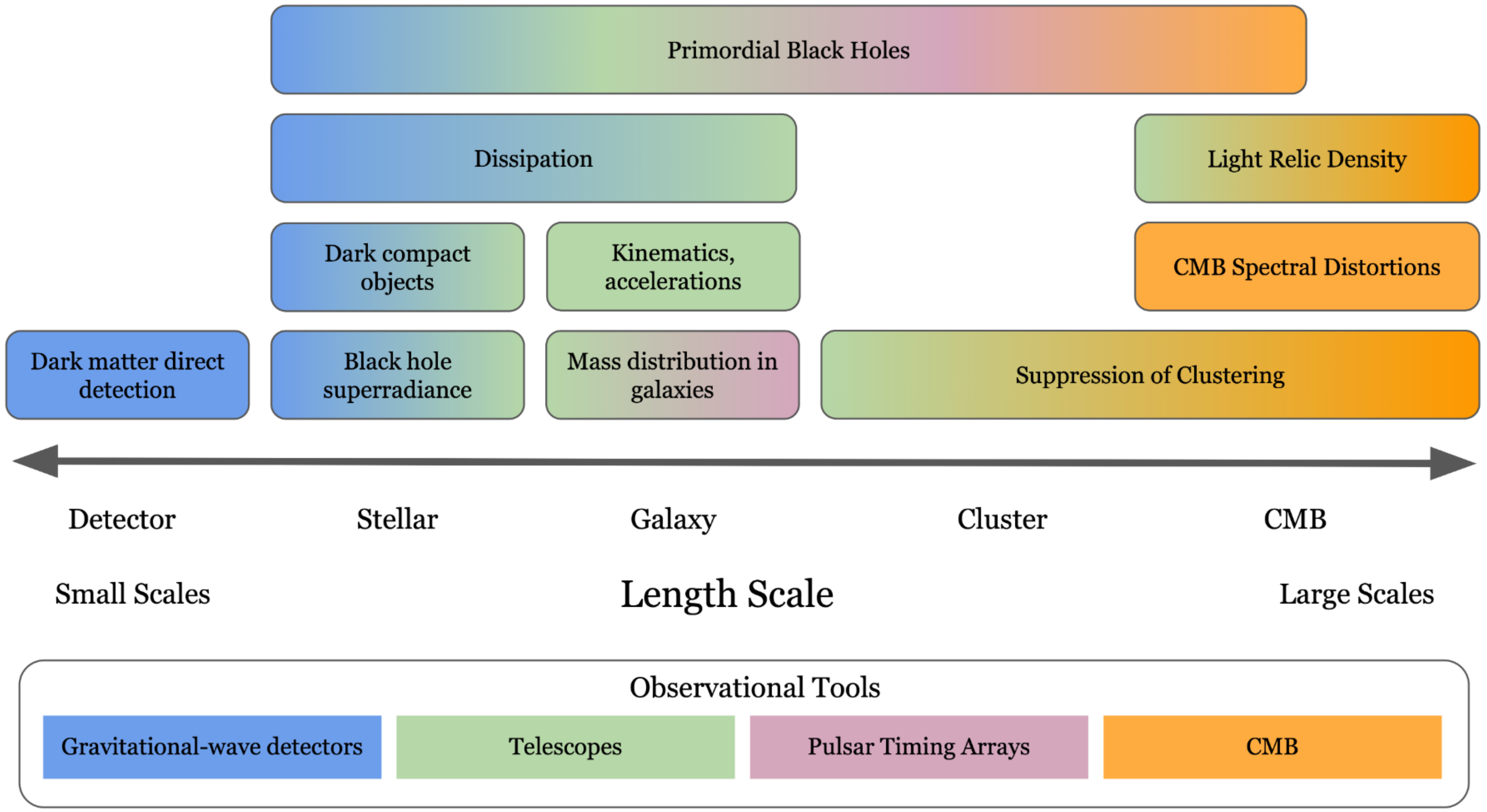


Figure from Snowmass 2021
White Paper (Brito et al., 2021)

Dissipative Dark Sectors

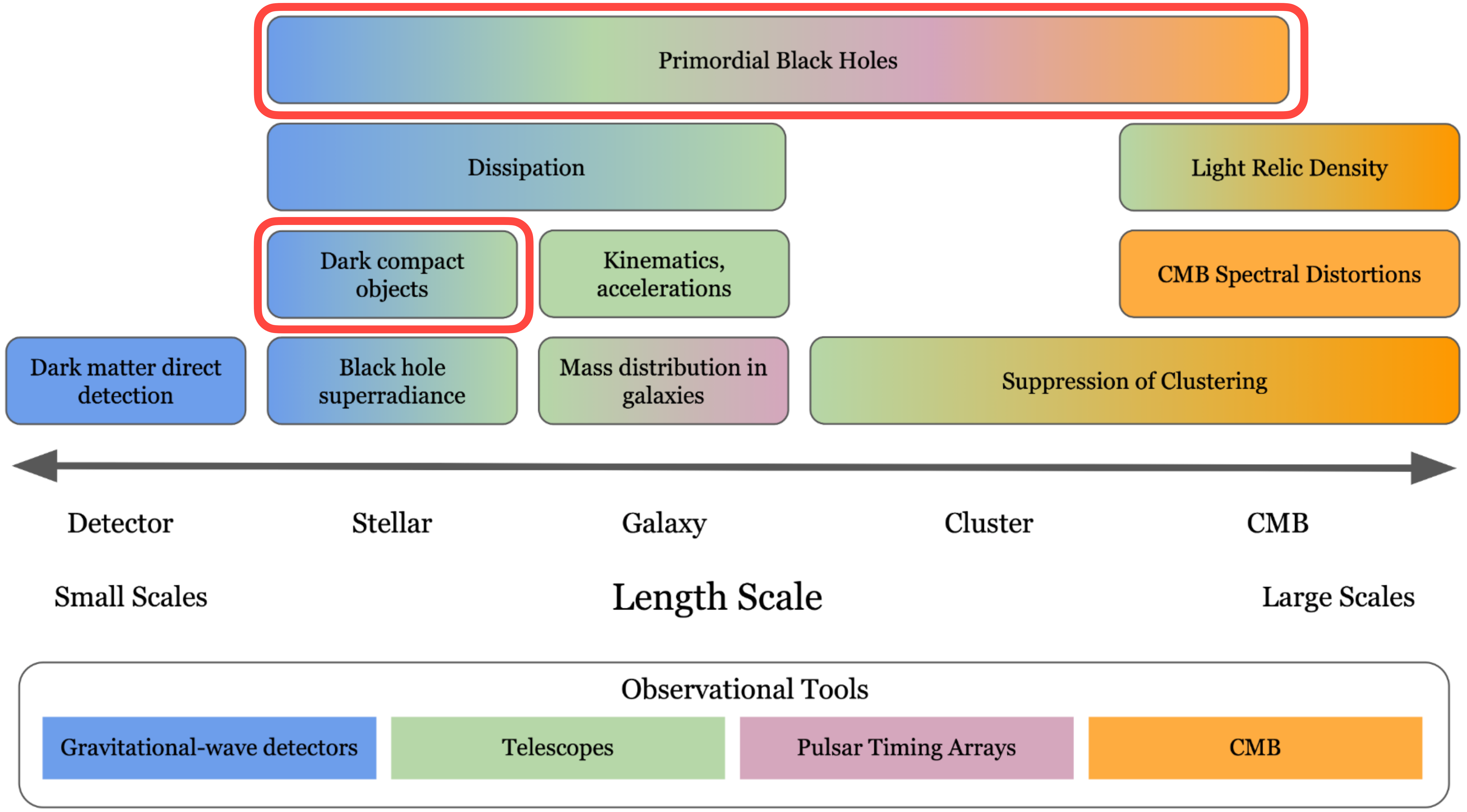


Figure from Snowmass 2021 White Paper (Brito et al., 2021)

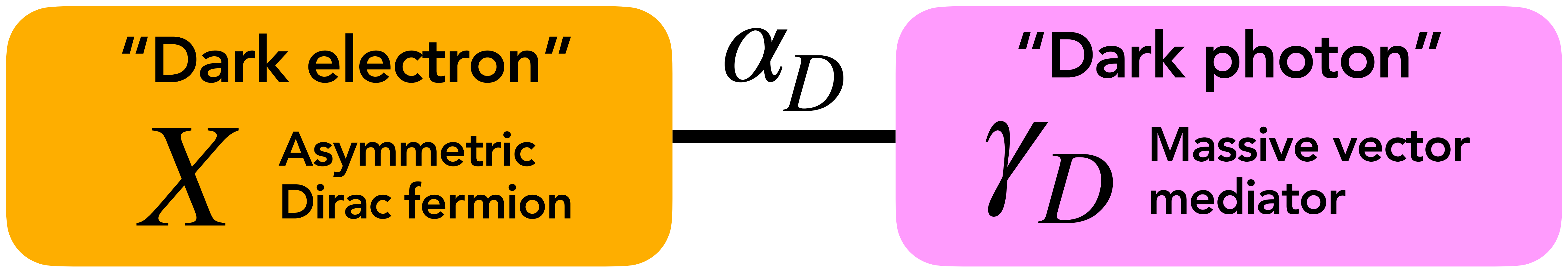
Punchline:

- Dark compact objects and primordial black holes — with new exciting observables
- All of dark matter can be dissipative, with some fraction in these objects

The Particle Model

- Dissipative dark sectors can result in dark compact structure formation (e.g. Buckley and DiFranzo 2018, Chang et al. 2019, Roy et al. 2023, Bramante et al. 2024, Gemmell et al. 2024)

- Simple asymmetric model:



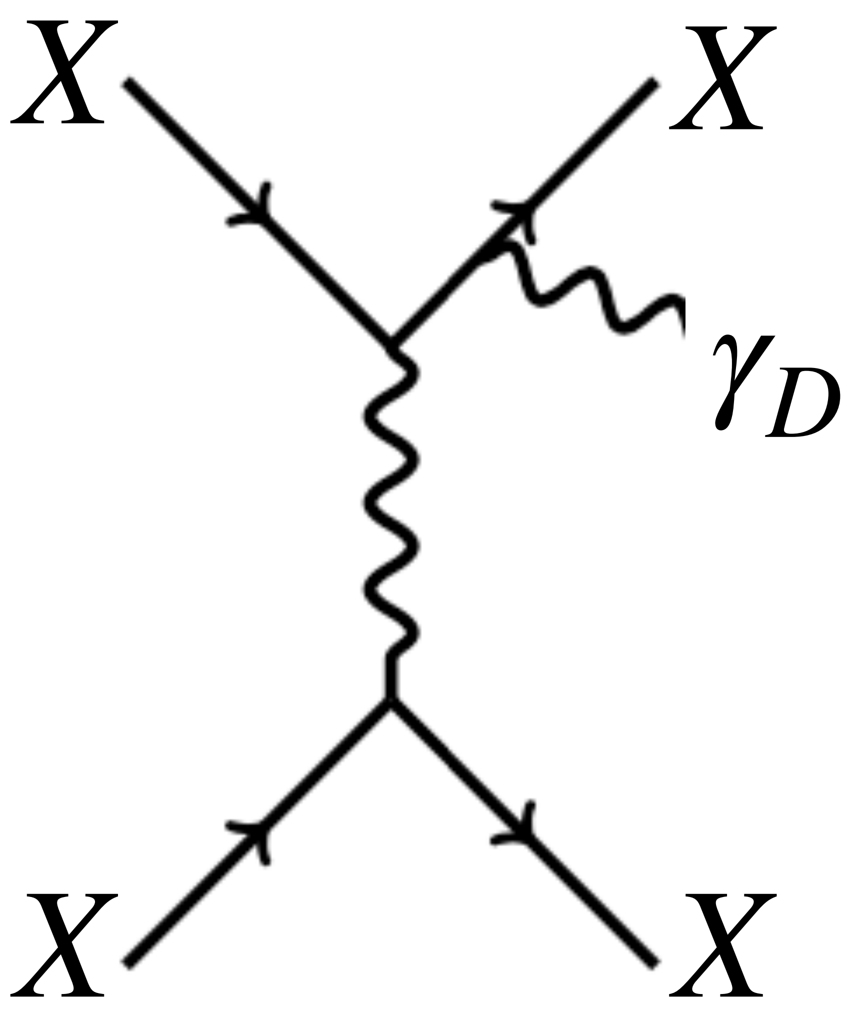


Figure from Chang et al. 2019

- Gas of dark electrons can cool via bremsstrahlung and form compact structures (Chang et al. 2019)

The Cosmological Model

- Begin with bath of dark sector and visible sector particles before Big Bang Nucleosynthesis (BBN)

- Expansion of the Universe cools the bath, heavy dark electrons come to dominate energy density — **early matter dominated era** (EMDE)!

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- Begin with bath of dark sector and visible sector particles before Big Bang Nucleosynthesis (BBN)

- Expansion of the Universe cools the bath, heavy dark electrons come to dominate energy density — **early matter dominated era** (EMDE)!

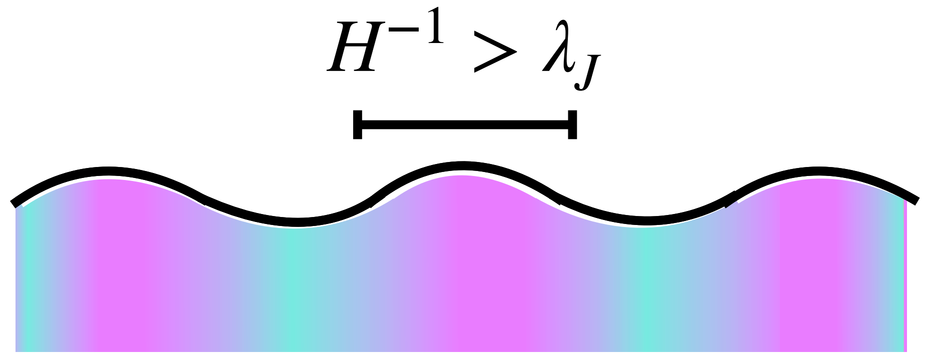
- To return to radiation domination & standard cosmology before BBN, invoke period of **thermal inflation**

  (see eg. Lyth and Stewart 1995, Lyth and Stewart 1996, Davoudiasl et al. 2016)

(Credit to Chris Cappiello for the meme)

Our Cosmology - Linear Growth

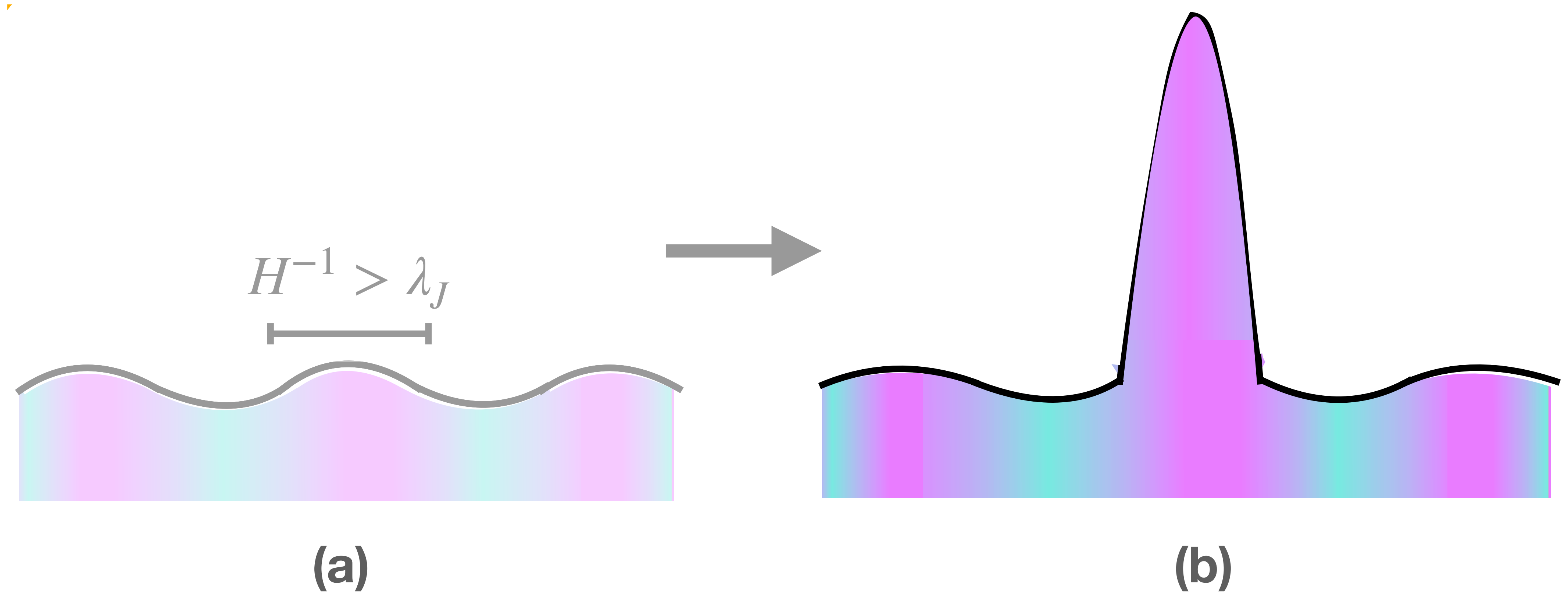
a) Density perturbations enter the horizon and begin to grow



(a)

Our Cosmology — Growth of Overdensities

b) Overdensities grow linearly with scale factor in a matter-dominated era

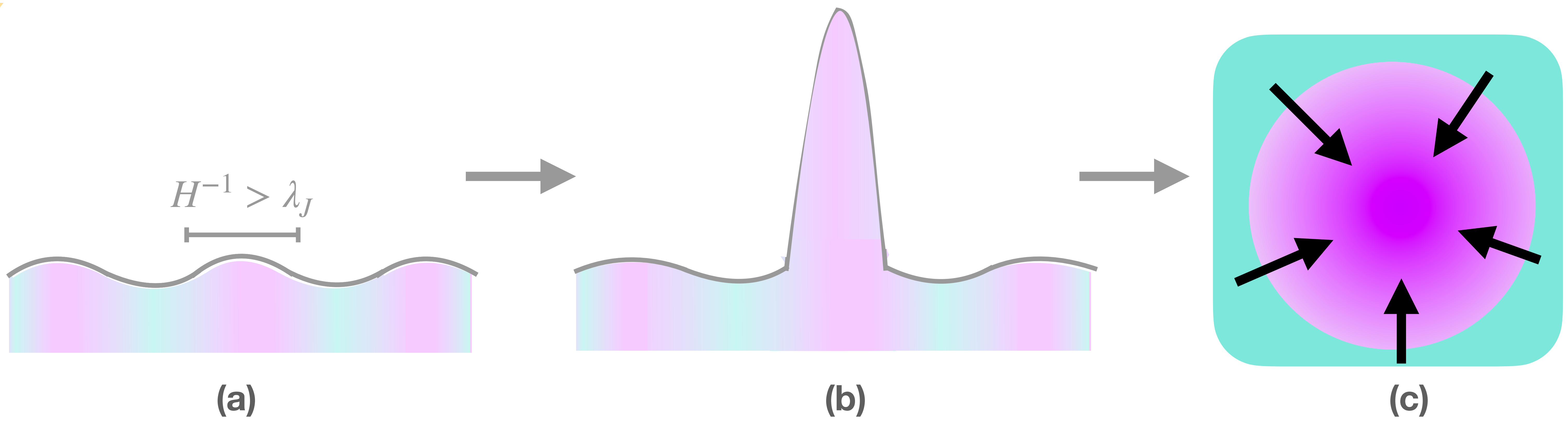


Our Cosmology — Primordial Halo Formation

c) Density perturbations become sufficiently large

Overdense regions decouple from Hubble flow

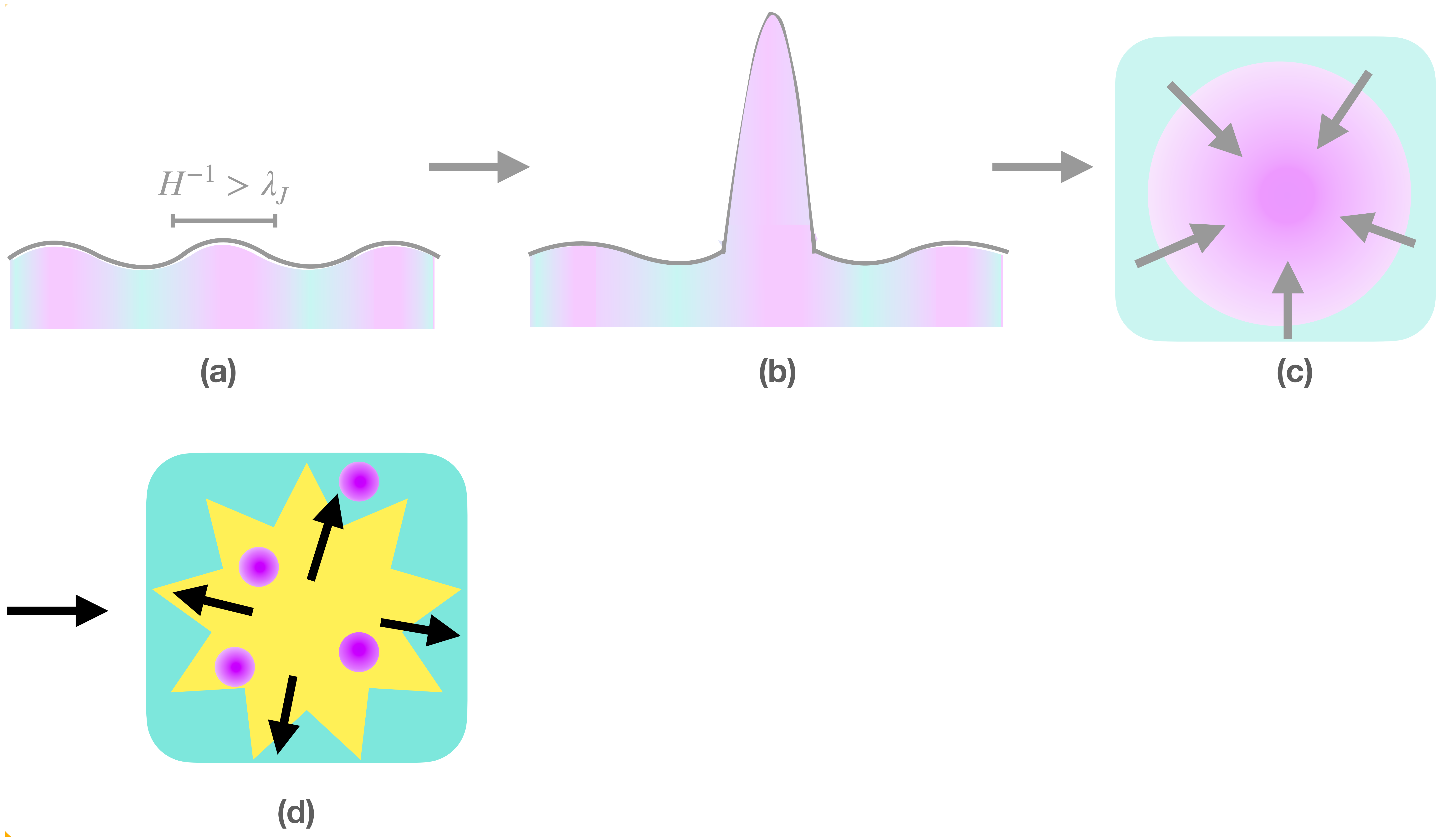
Self-gravitating gas of dark electrons virialize



Our Cosmology — Thermal Inflation

d) Thermal inflation ends the matter-dominated era

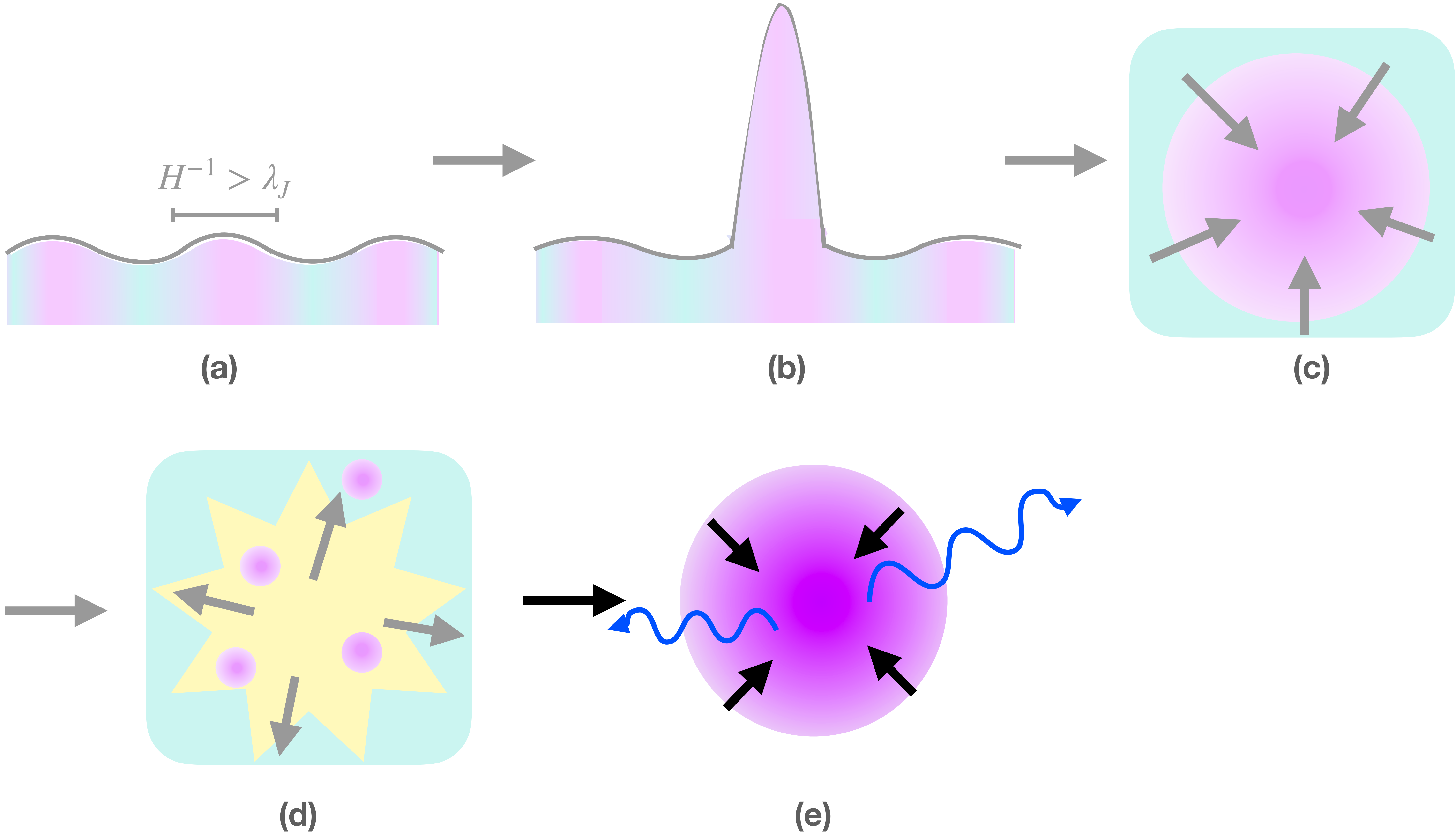
Dilutes background and transitions to radiation-dominated era



Our Cosmology — Primordial Halo Collapse

e) Primordial halos cool due to bremsstrahlung

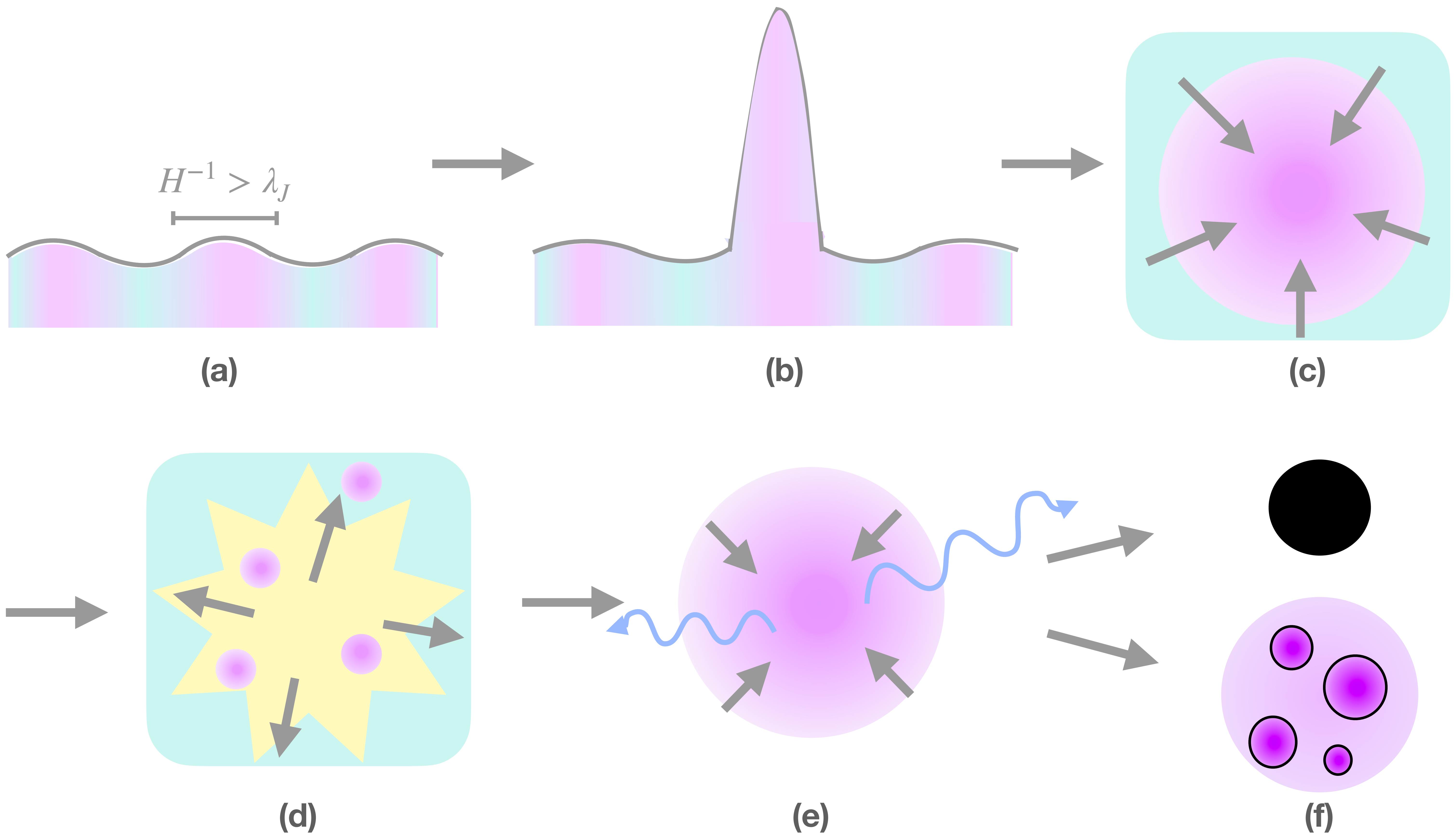
Collapse!



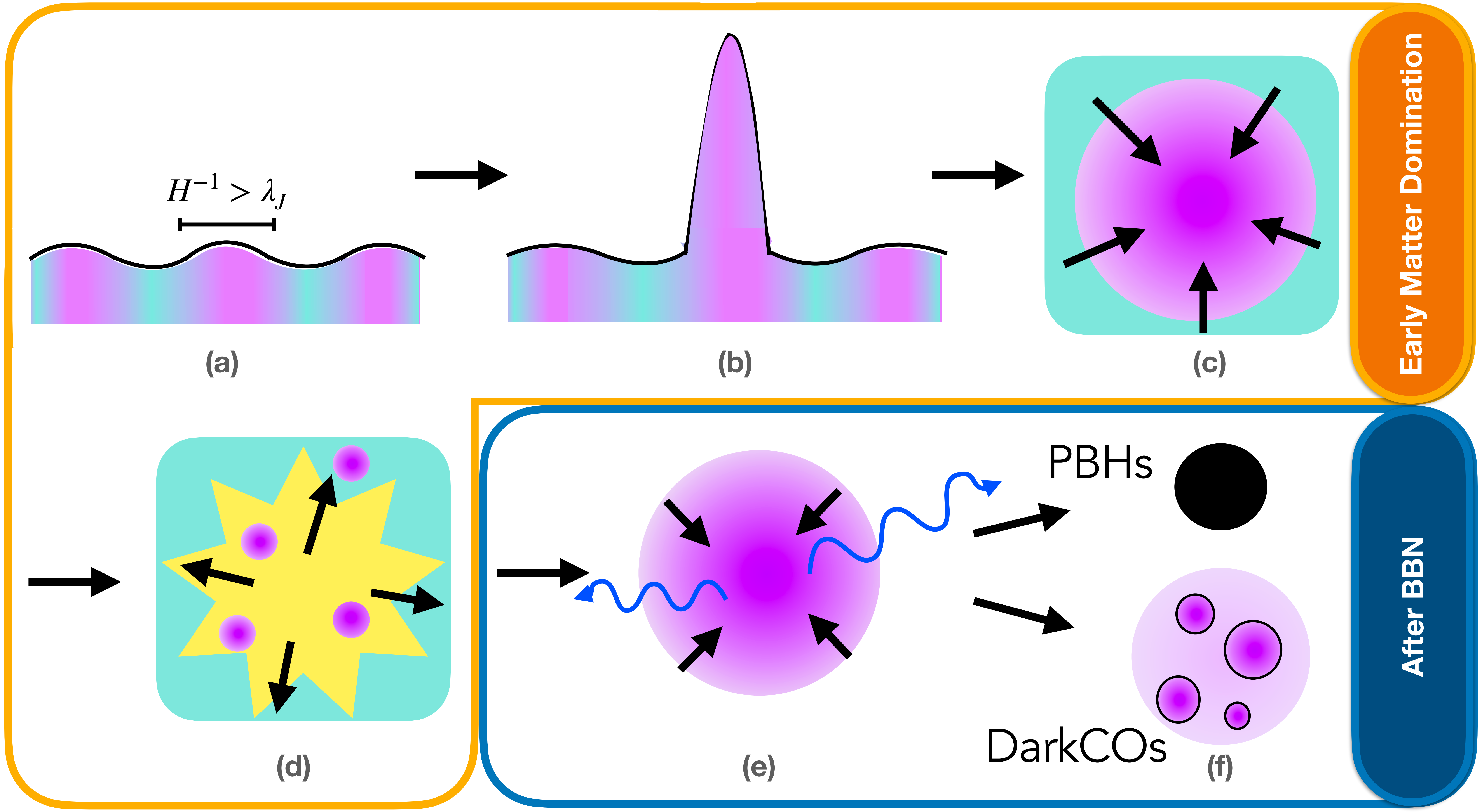
Our Cosmology — Compact Structures!

f) End up with collapsed objects

End states are either black holes, or dark compact objects (DarkCOs)



Our Cosmology — The Full Picture



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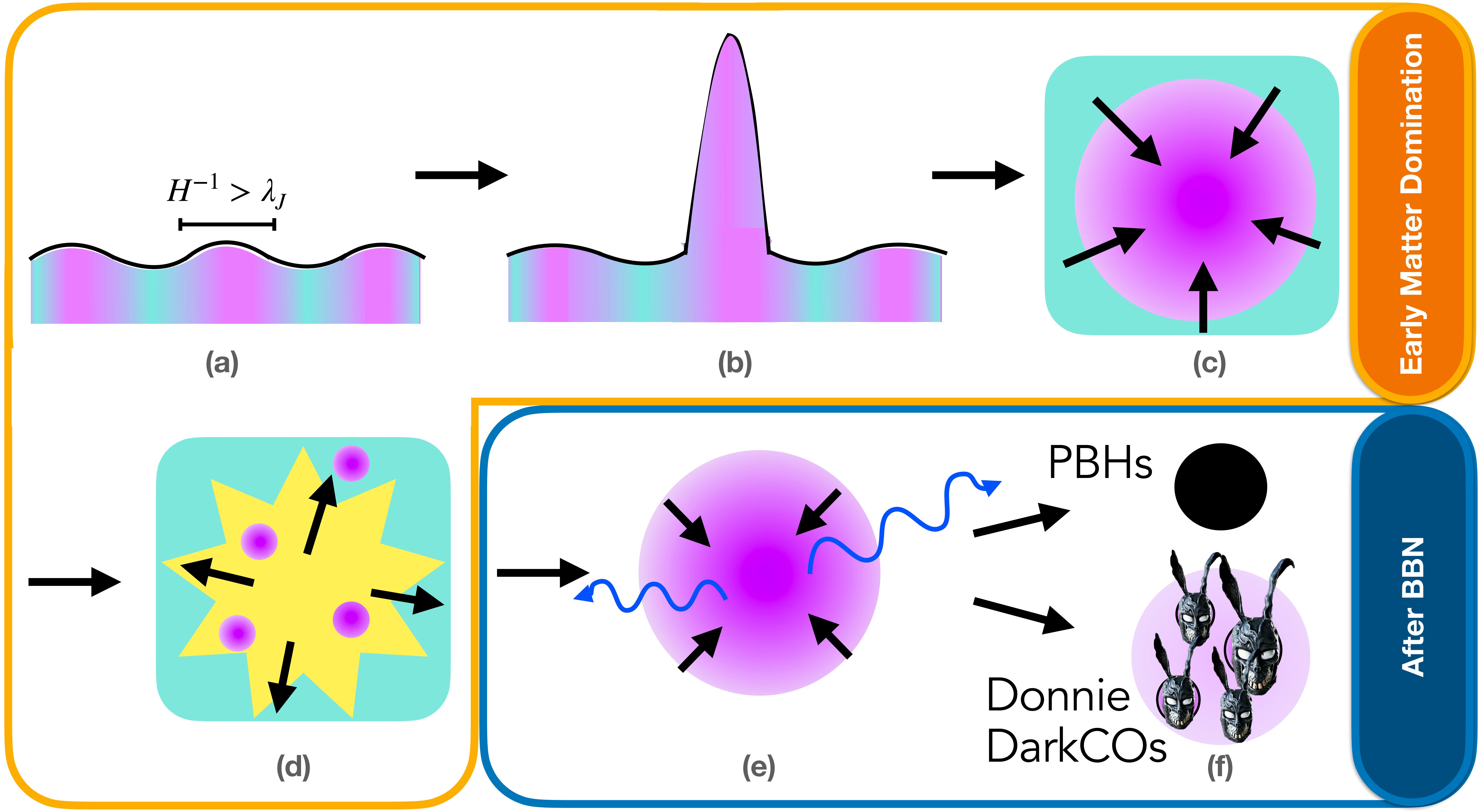
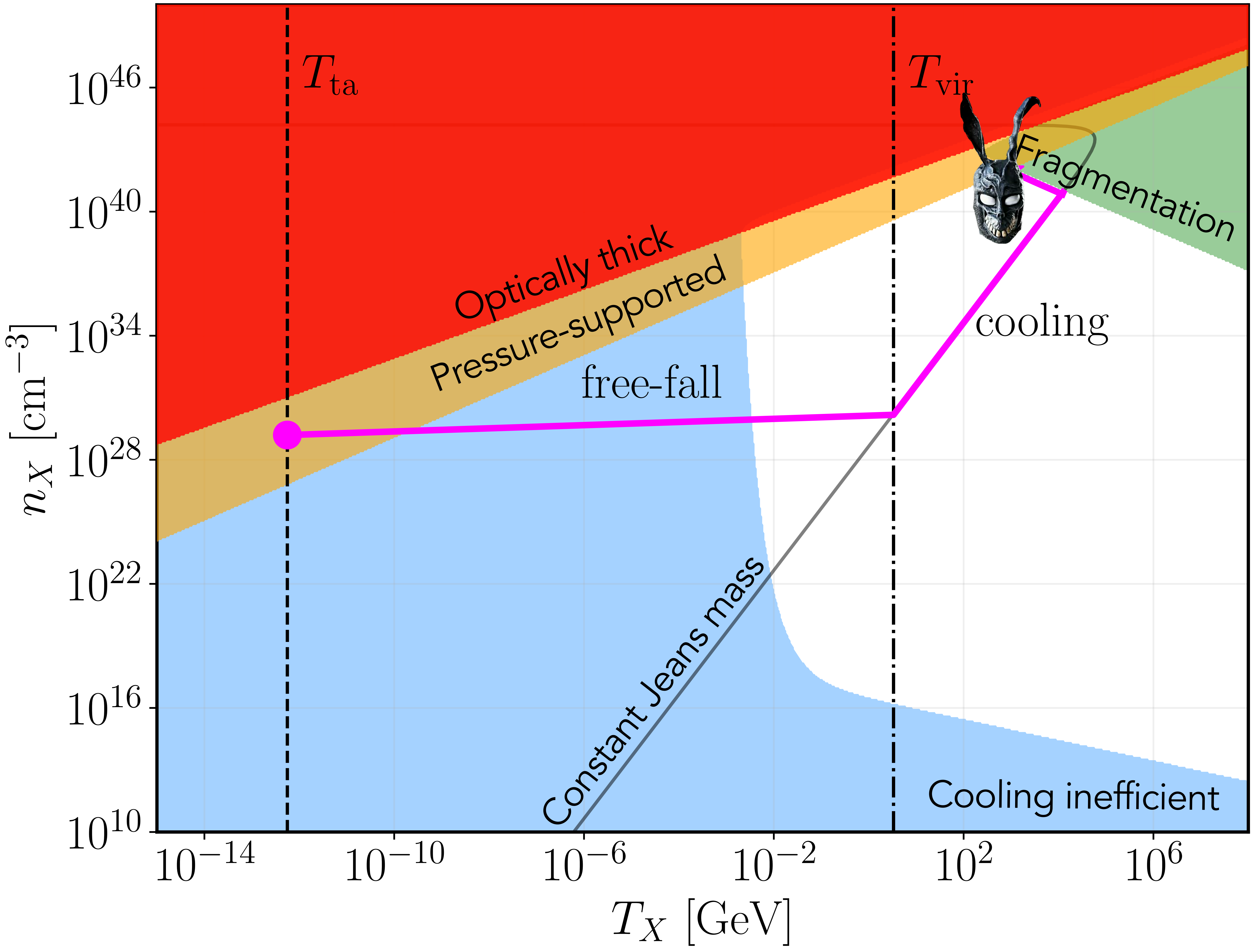


Example Collapse Trajectory

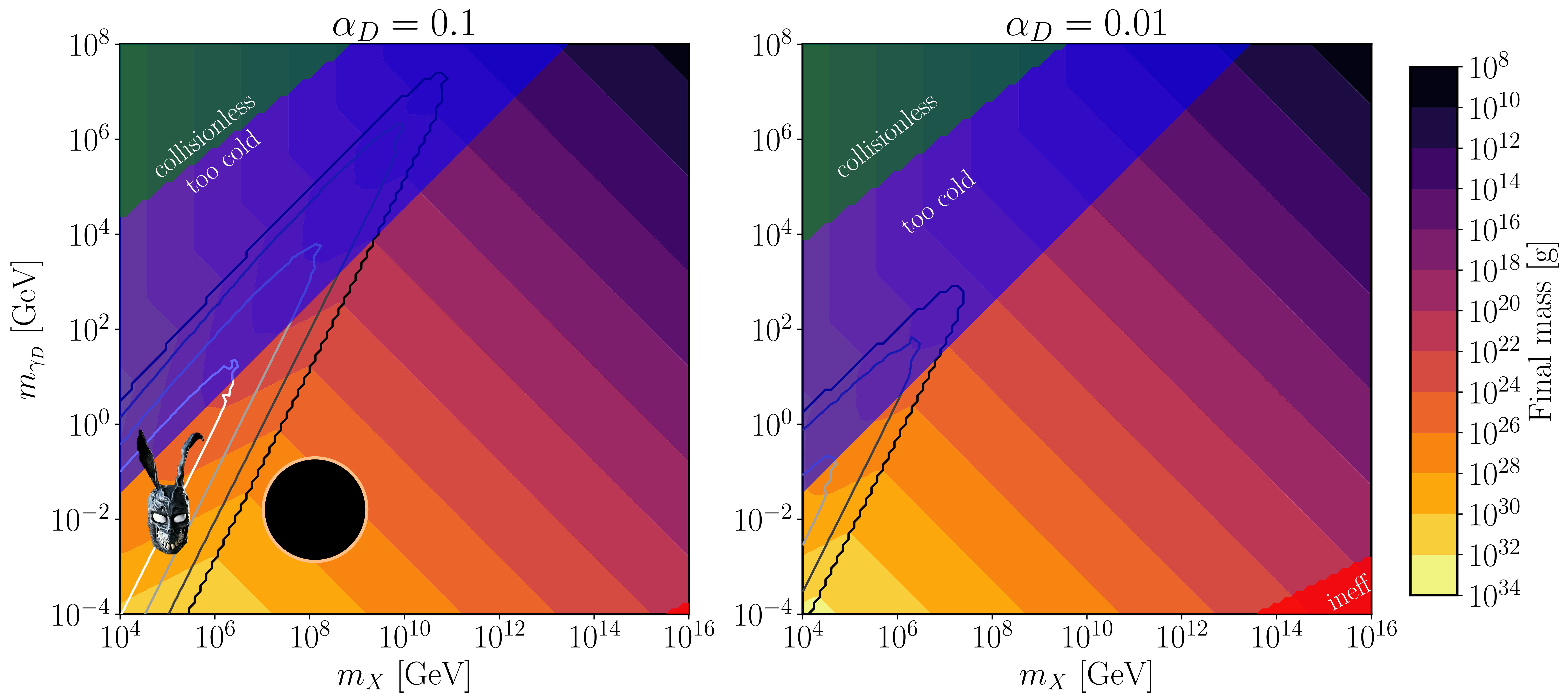
- Free-fall collapse (no cooling)
- Nearly-virialized contraction (cooling starts becoming efficient)
- Fragmentation (cooling very efficient)

$$m_X = 10^6 \text{ GeV}, m_{\gamma_D} = 10^{-1} \text{ GeV}, \alpha_D = 0.1$$



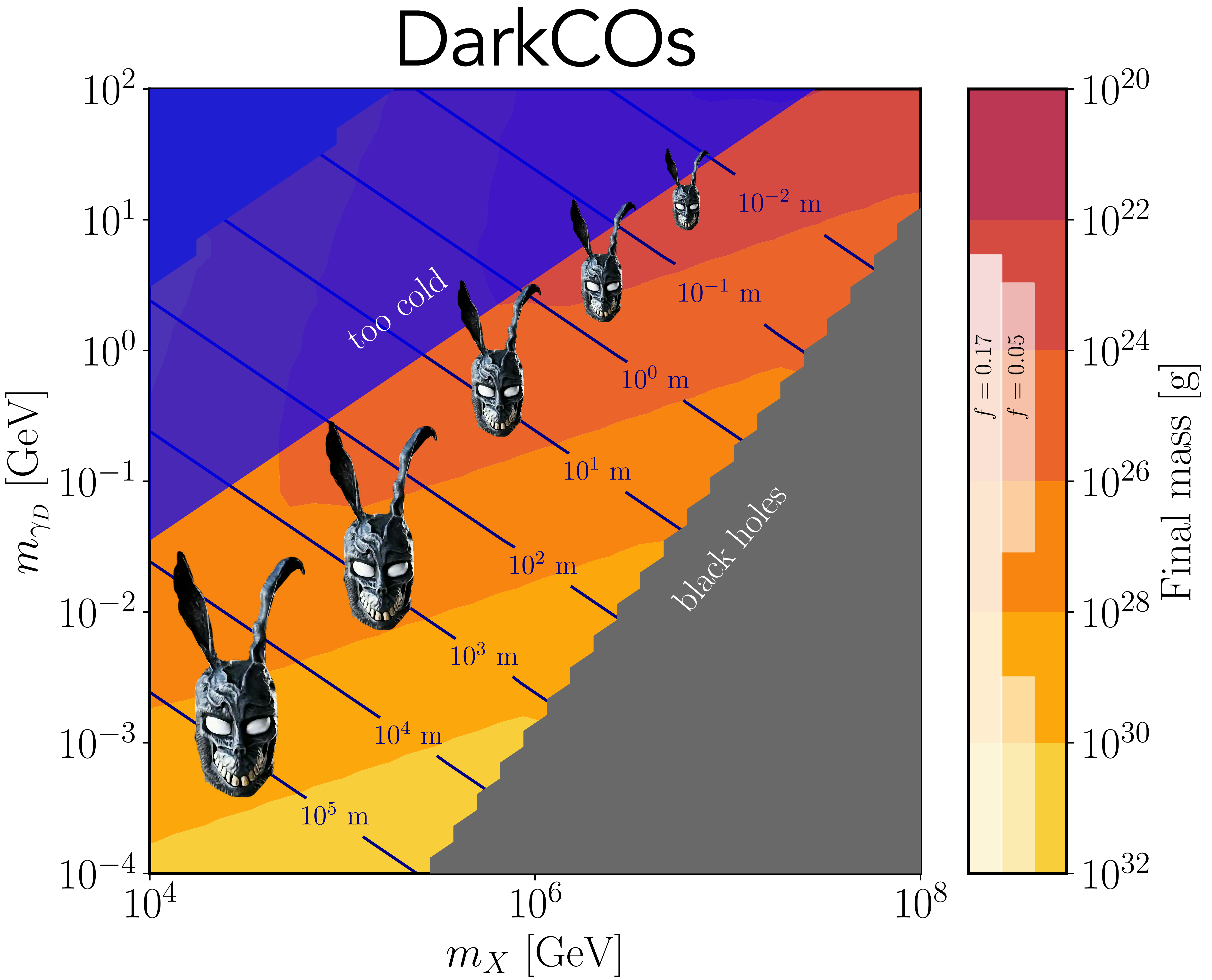
Landscape of Collapsed Structures

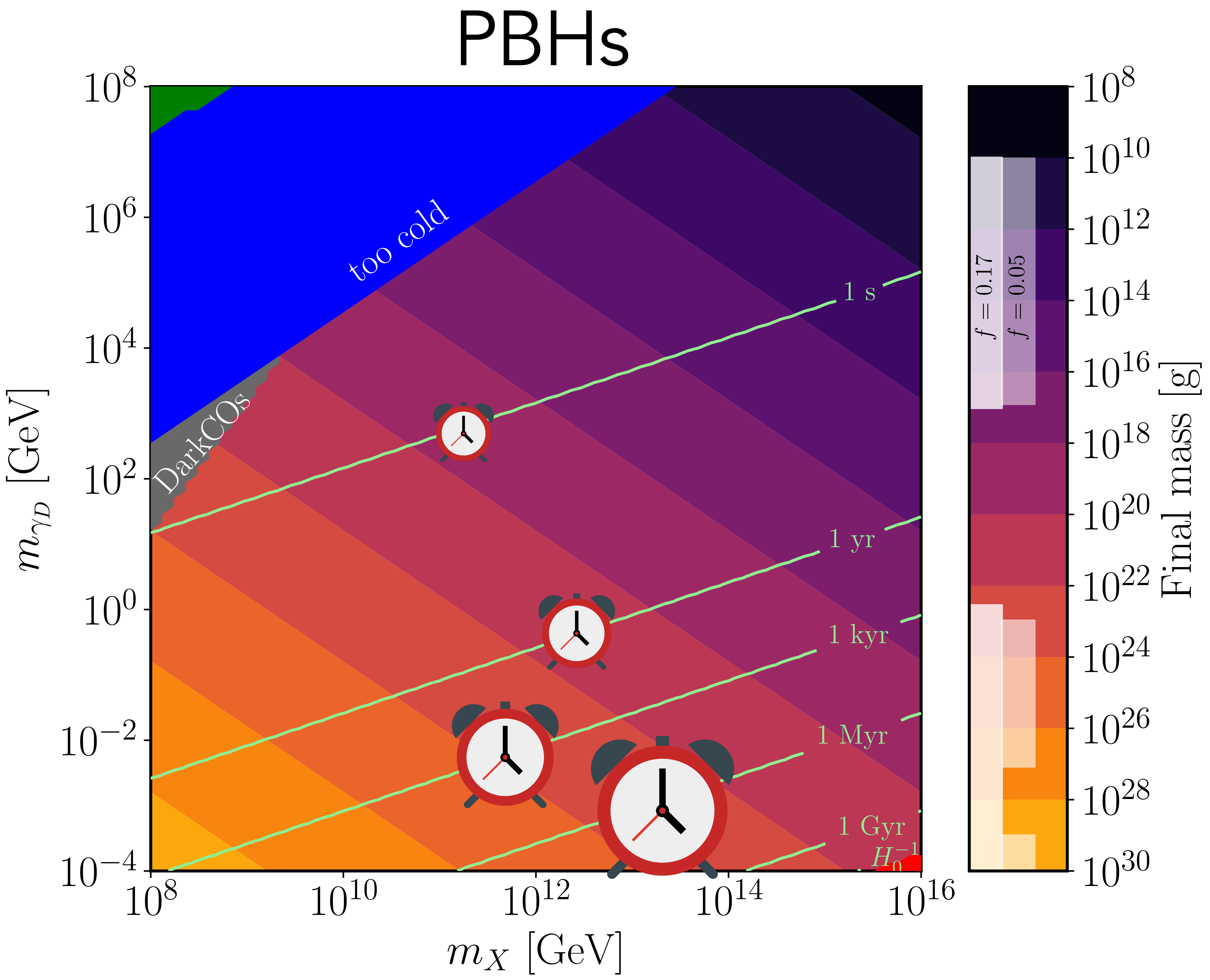
“You can't lump things into two categories. Things aren't that simple.” - Donnie Darko



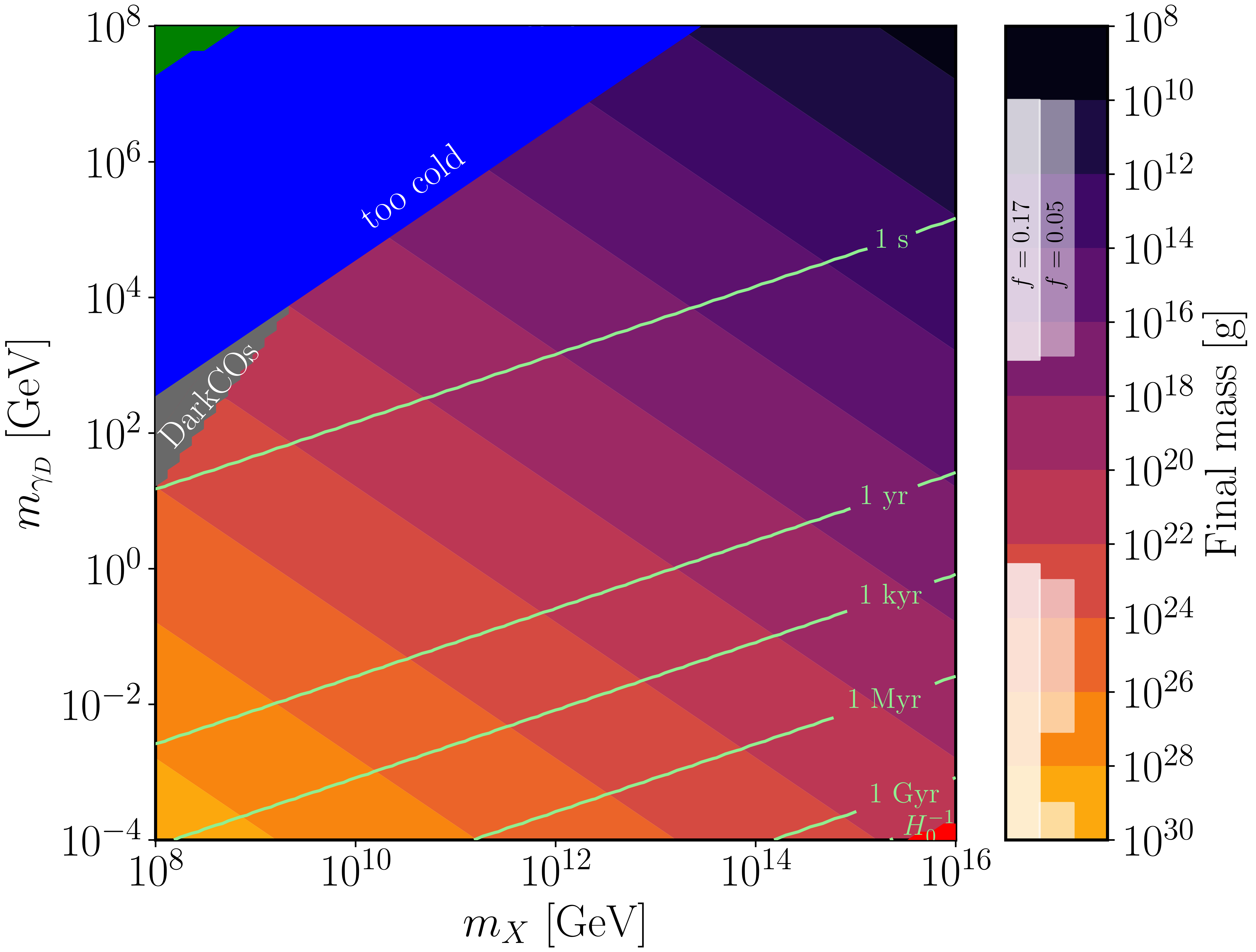
Zooming in on Collapsed Structures

"You *can* lump things into two categories. Things *are* that simple." - Donnie DarkCO



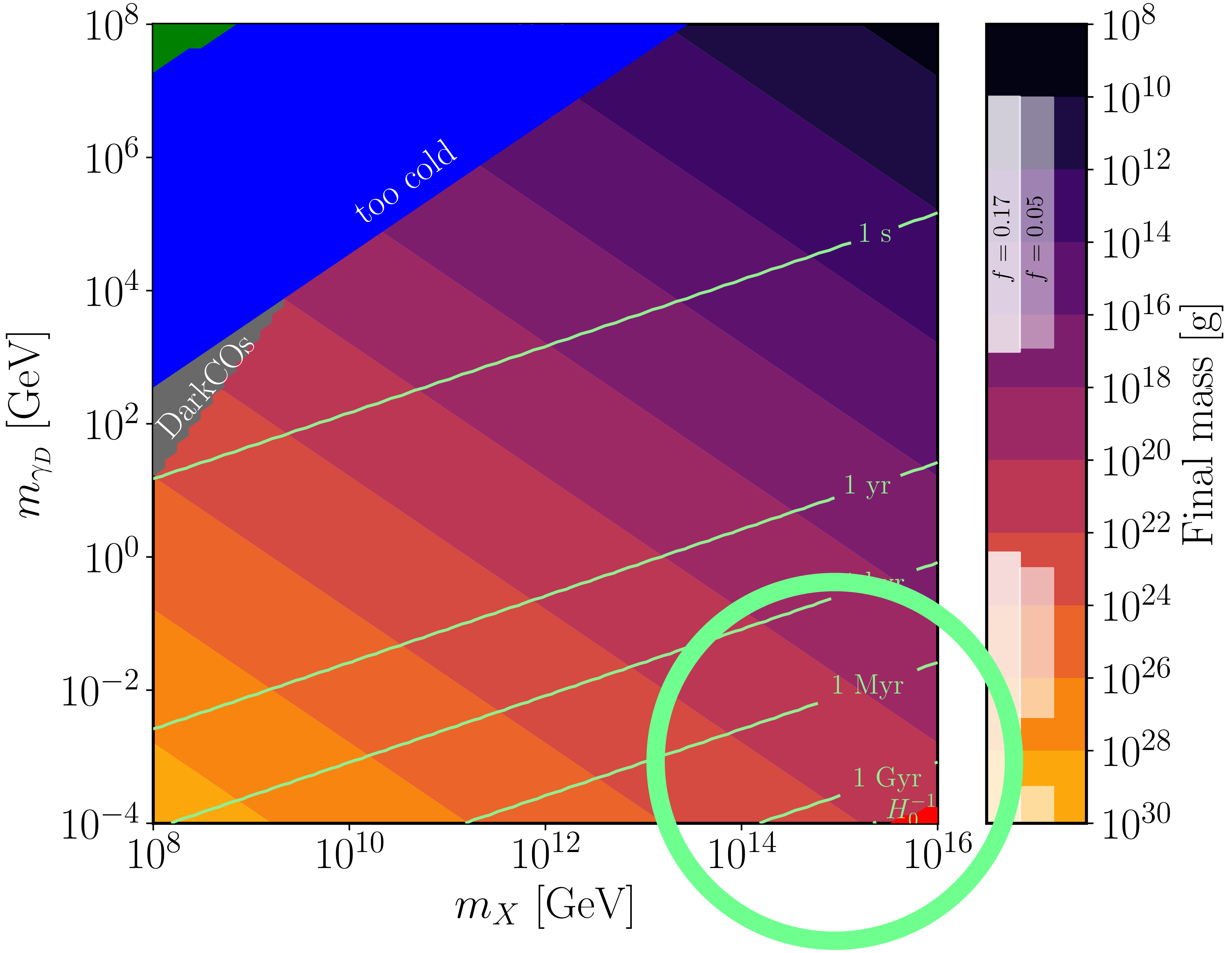


Oh?



too cold
DarkCOs
1 s
1 yr
1 kyr
1 Myr
1 Gyr
H_0^{-1}
$f = 0.17$
$f = 0.05$
m_{γ_D} [GeV]
m_X [GeV]
Final mass [g]
10^{8}
10^{6}
10^{4}
10^{2}
10^{0}
10^{-2}
10^{-4}
10^{10}
10^{12}
10^{14}
10^{16}
10^{18}
10^{20}
10^{22}
10^{24}
10^{26}
10^{28}
10^{30}

Oh?



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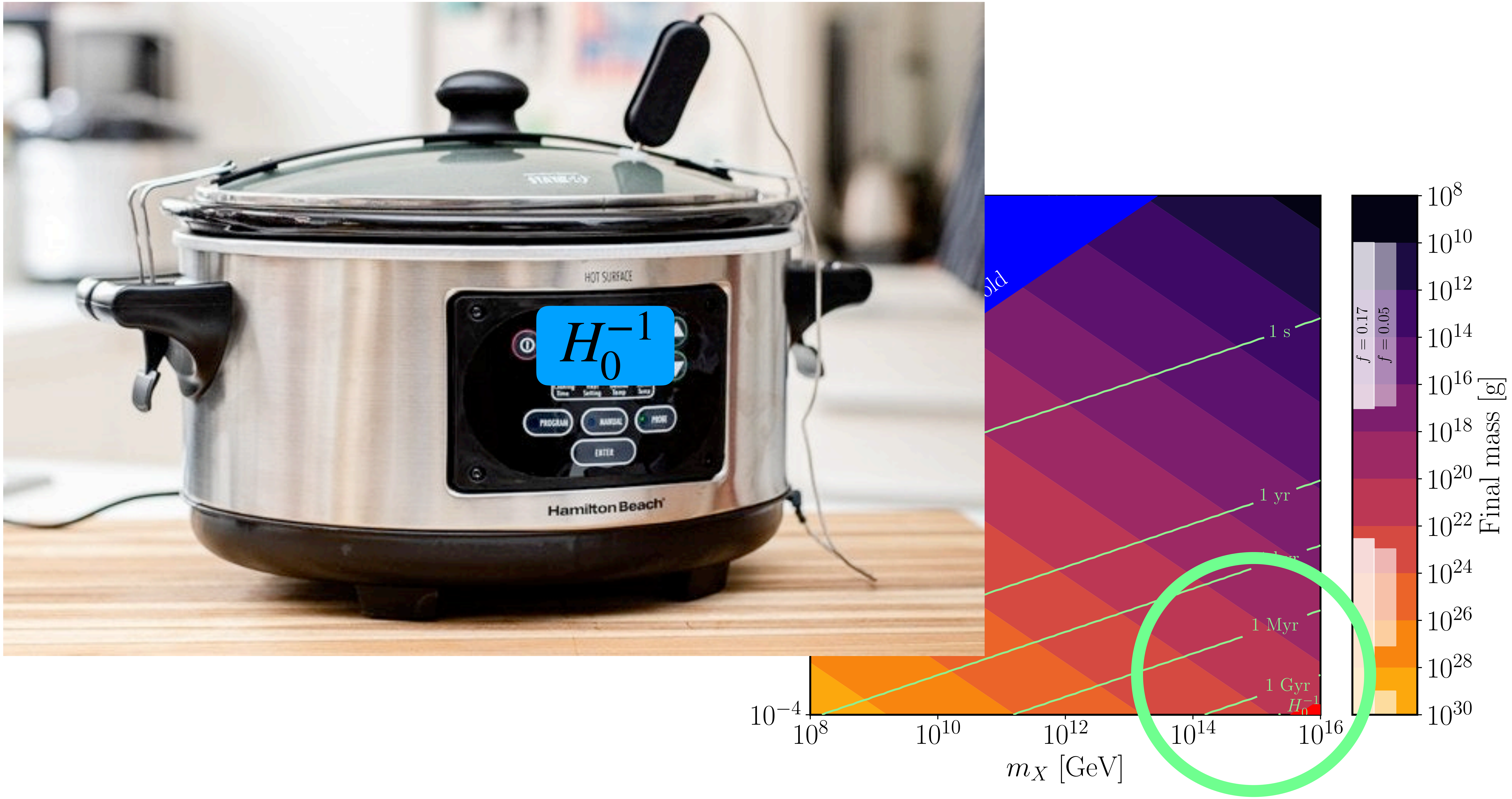
H_0^{-1}
HOT SURFACE
Hamilton Beach
PROGRAM
MANUAL
PROBE
ENTER
1 s
1 yr
1 Myr
1 Gyr
H_0^{-1}
10^{-4}
10^{8}
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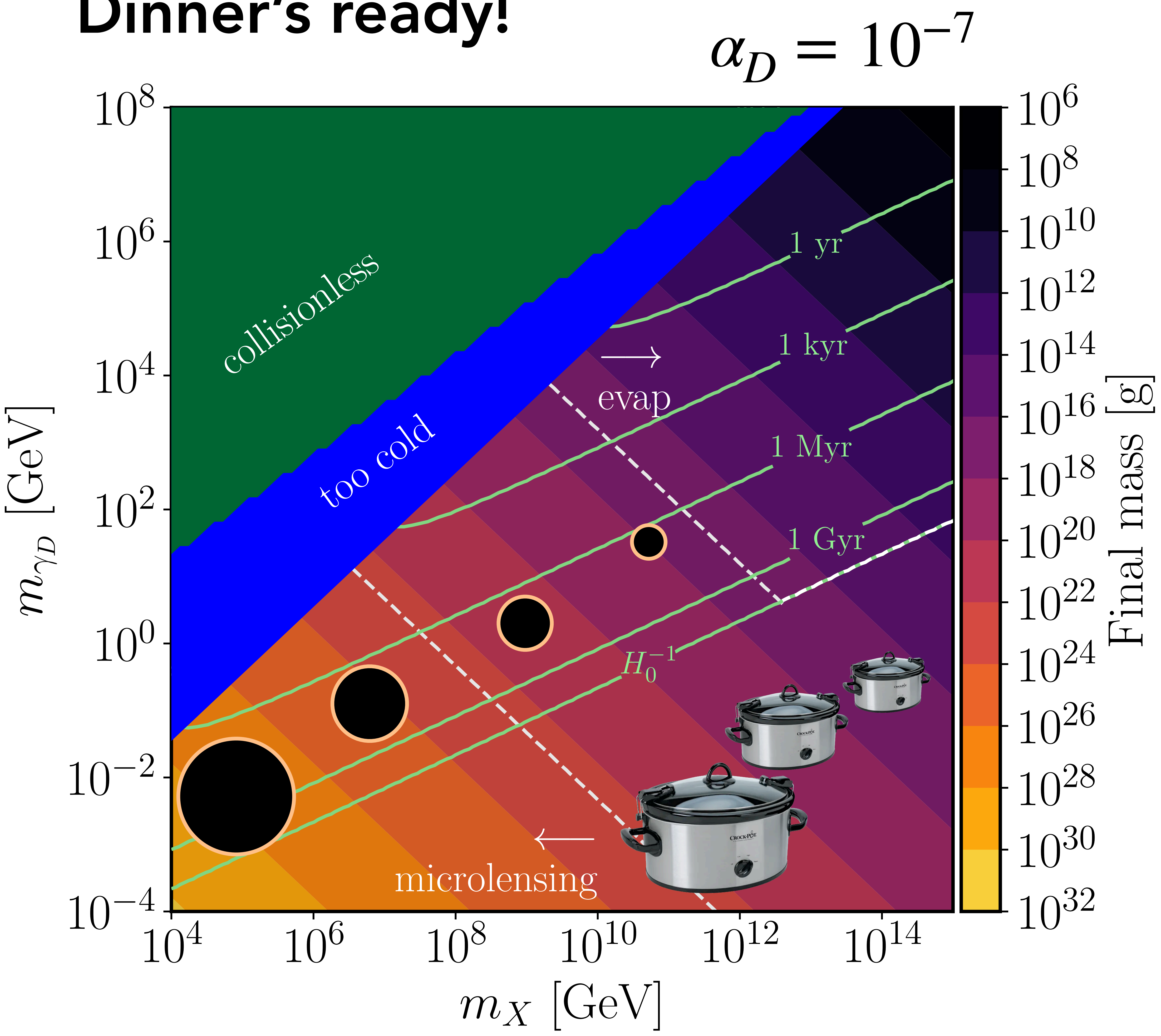
10^{20}
10^{22}
10^{24}
10^{26}
10^{28}
10^{30}
Final mass [g]

Slow Cooked PBHs

Dinner's ready!



Slow Cooked PBHs

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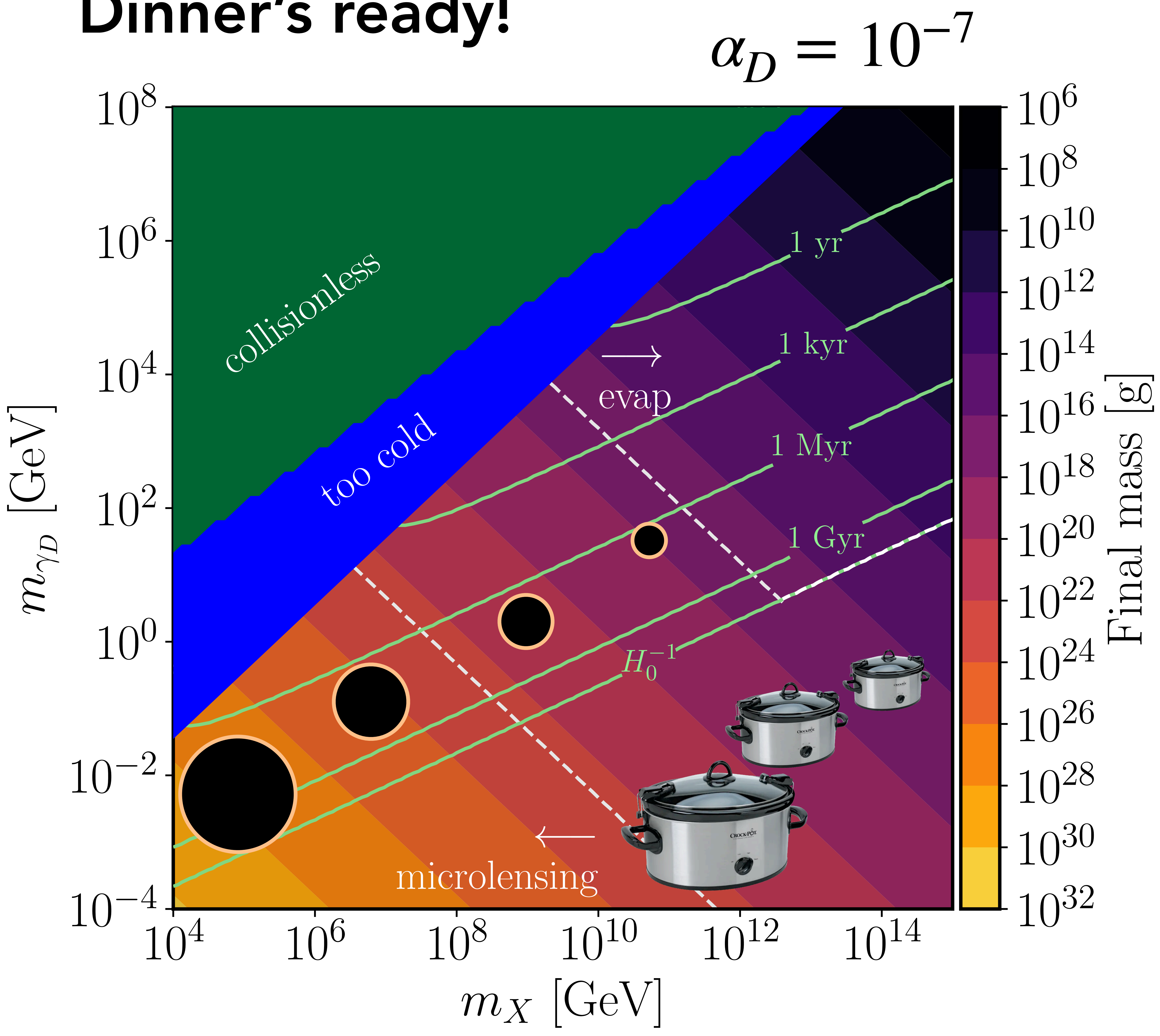

Cool observables!

- **Black hole explosions*** (eg. Hawking 1974, Boluna et al. 2023, Korwar and Profumo 2024)
- **Gravitational waves from mergers** (eg. Raidal et al. 2017, Shandera et al. 2018, Diamond et al. 2021)
- **Gravitational waves from cosmology and BH evaporation** (eg. Dalianis and Kouvaris 2012, Fernandez et al. 2023, Ireland et al. 2023)
- And more!

Conclusions

- We have shown a novel mechanism to produce DarkCOs and PBHs
- Can get PBHs to form today, avoiding PBH constraints while providing cool new observables!

Future Studies

- Can we get a distribution of compact structures?
- What if we introduce interactions between the dark and visible sectors?
- Explore the rich observable phenomena
- Investigate other cosmological scenarios with early dissipative dark sectors

Thank you!

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Supplemental Slides

Lagrangian

$$\mathscr{L} \supset \bar{X}(i\gamma^\mu D_\mu - m_X)X - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m_{\gamma_D}^2 A_\mu A^\mu$$

$$D_\mu = \partial_\mu - ig_D A_\mu$$

$$\alpha_D = \frac{g_D^2}{4\pi}$$

Gas of dark electrons

- Gas pressure: $P_X = n_X T_X + \frac{2\pi\alpha_D n_X^2}{m_{\gamma_D}^2}$

- Sound speed: $c_s^2 = \frac{T_X}{m_X} + \frac{4\pi\alpha_D n_X}{m_X m_{\gamma_D}^2}$

- Jeans length/mass: $\lambda_J = c_s \left(\frac{\pi}{\rho_X G}\right)^{1/2}$ $\quad m_J = \frac{4\pi}{3}\left(\frac{\lambda_J}{2}\right)^3 \rho_X$

Linear growth of perturbations

- Once Jeans length falls below Hubble length, perturbations can grow. We only track the first perturbations which can collapse

$$M_H = \frac{4\pi\rho_{\text{grow}}}{3H_{\text{grow}}^3} \qquad \rho_{\text{grow}} = \frac{3\zeta(3) m_X T_{\text{grow}}^3}{4\pi^2} \qquad H_{\text{grow}} = \left(\frac{8\pi G \rho_{\text{grow}}}{3} \right)^{1/2}$$

$$T_{\text{grow}} = \min \left[\sqrt{\frac{3}{80\pi^2}} m_X, \left(\frac{m_X m_{\gamma_D}^2}{2\pi\zeta(3)\alpha_D} \right)^{1/3} \right]$$

Cooling dynamics

See Chang et al. 2019

- Cooling rate: $$\Lambda = \frac{32\alpha_D^3 \rho_X T_X}{\sqrt{\pi} m_X^3} \sqrt{\frac{T_X}{m_X}} e^{-m_{\gamma_D}/T_X} e^{-V^{1/3}\sqrt{N_{\rm sc}}/\ell_{\gamma_D}^{\rm abs}}$$

- Dynamical equation: $$\frac{d \log T_X}{d \log \rho_X} = \frac{2}{3}\frac{m_X P_X}{\rho_X T_X} - 2\frac{t_{\rm collapse}}{t_{\rm cool}}$$

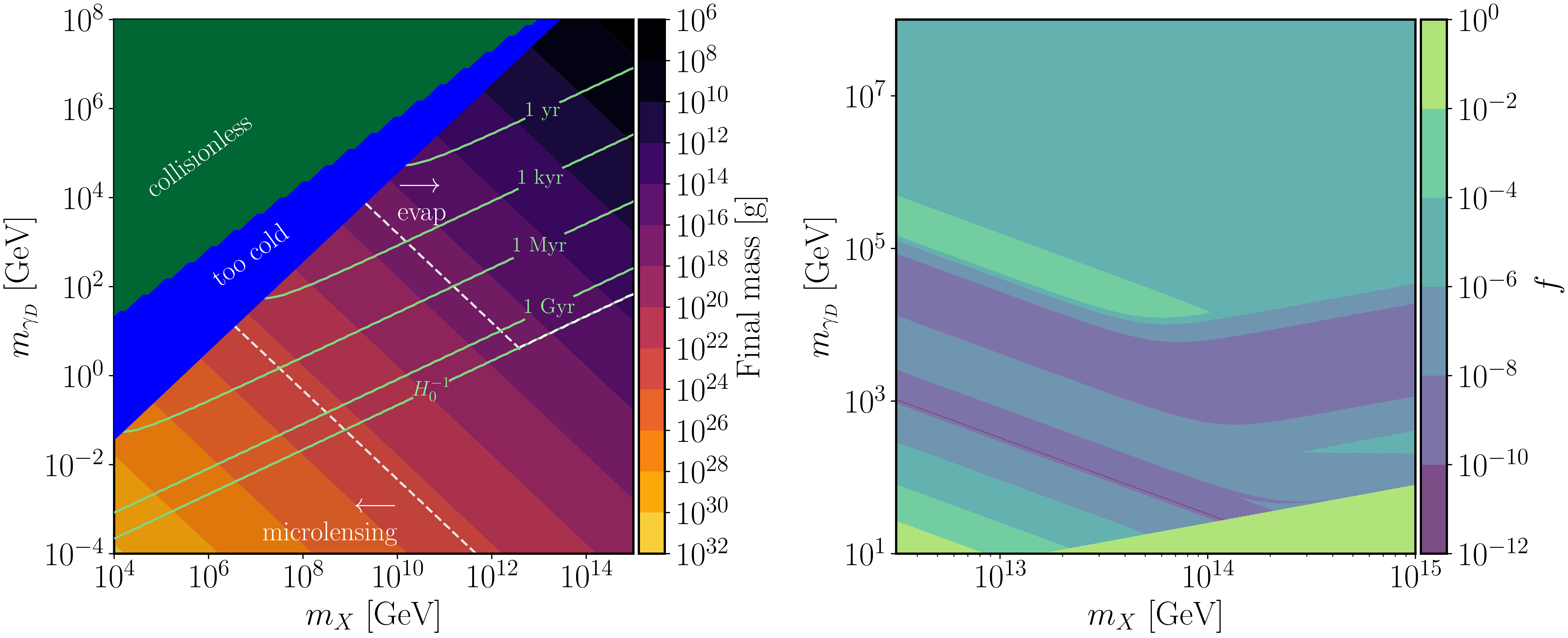
$$t_{\rm collapse} = \left(\frac{d \log \rho_X}{dt}\right)^{-1}$$

$$t_{\rm cool} = \frac{3T_X}{\Lambda}$$

Collisional or not?

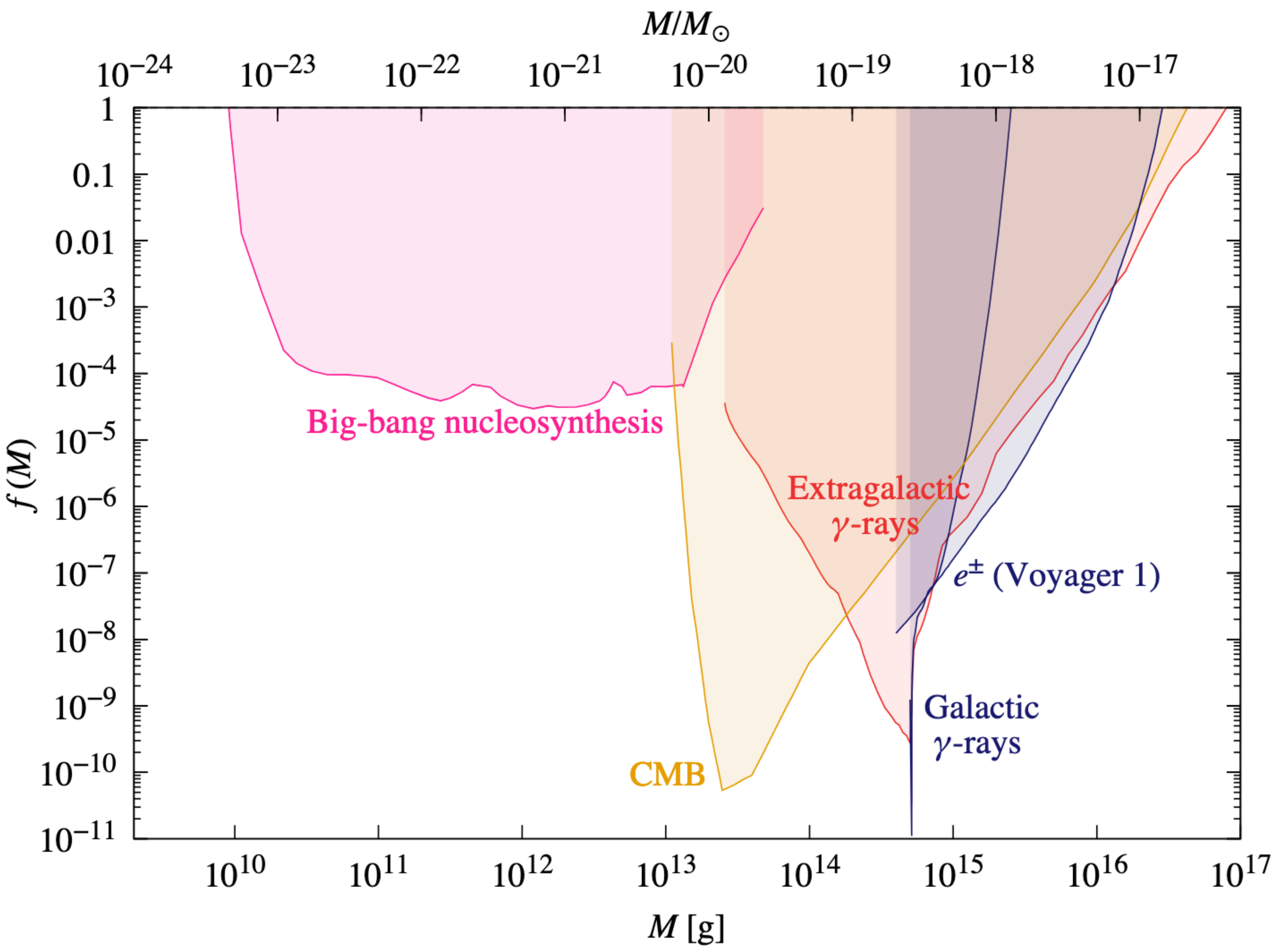
- For gas to be collisional, we require $N_{X,\mathrm{sc}}\ell_X < r_{\mathrm{ta}}$ at the turnaround radius $r_{\mathrm{ta}} = (8\pi G\rho_{\mathrm{grow}}/3)^{-1/2}\delta_0^{-1}$

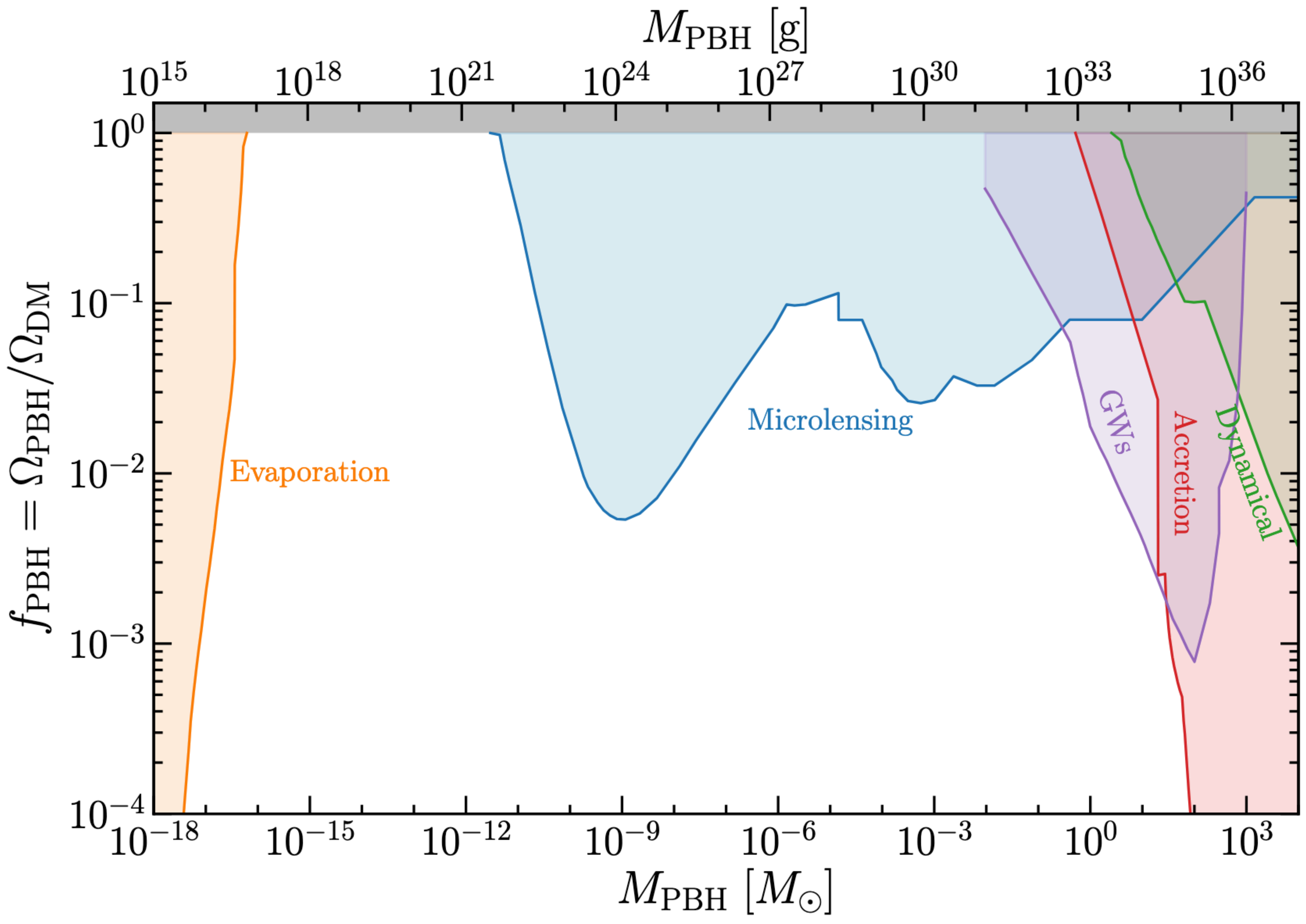
$$N_{X,\mathrm{sc}} = \frac{0.5\int d\cos\theta \frac{d\sigma}{d\Omega}}{\int d\cos\theta \frac{d\sigma}{d\Omega}(1-\cos(\theta))} \qquad \ell_X = \left(n_X \int \frac{d\sigma}{d\Omega} d\Omega\right)^{-1}$$



collisionless
too cold
evap
microlensing
1 yr
1 kyr
1 Myr
1 Gyr
H_0^{-1}
m_{γ_D} [GeV]
m_X [GeV]
Final mass [g]
f

PBH & MACHO Constraints





Figures from
Carr et al. 2021,
Green and Kavanagh 2020

Hubble horizon

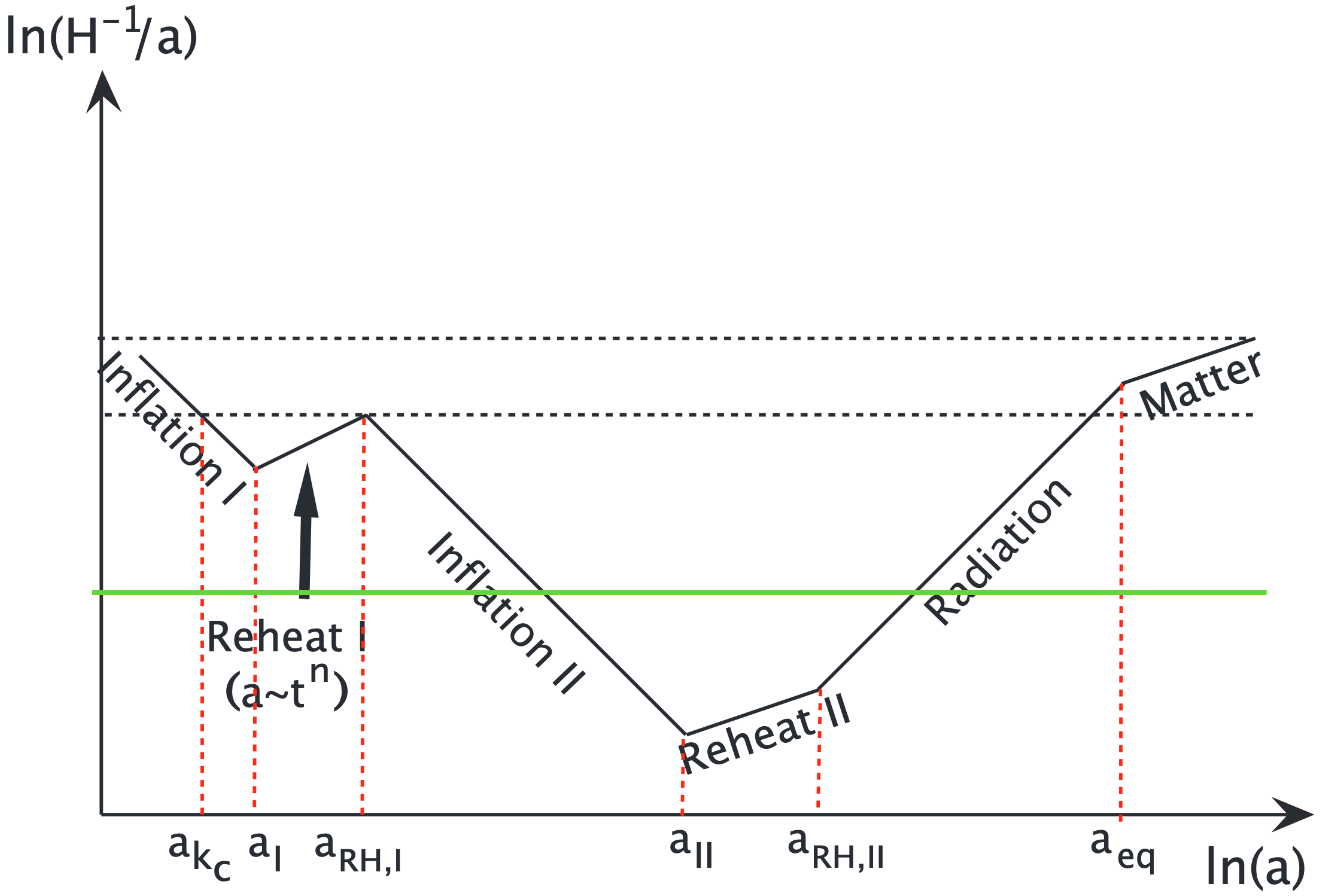


Figure from Burgess et al. 2005

Thermal Inflation

$$V(\phi) = V_0 - \frac{1}{2}m_\phi^2 |\phi|^2 + \lambda_s T^2 |\phi|^2 + \cdots$$

- Note we assume ϕ couples to another field with $\lambda_s = 1$ which decays only to SM particles with a weaker coupling
- For additional information, see Lyth and Stewart 1995, Lyth and Stewart 1996, and Davoudiasl et al. 2016.

$$T_i \sim \left(\frac{3V_0}{g^*_{\rm MD} T_{\rm MD}}\right)^{1/3} \qquad T_{\rm PT} \approx \frac{m}{\sqrt{2\lambda_s}}$$

$$\mathcal{N} \simeq 10.3 + \frac{1}{3}\ln\left(\frac{V_0}{10^{24}\ \text{GeV}^4} \cdot \frac{\text{GeV}^3}{T_{\rm PT}^3} \cdot \frac{10^9\ \text{GeV}}{T_{\rm MD}} \cdot \frac{100}{g^*_{\rm MD}}\right)$$

Thermal Inflation

- Do we get correct relic abundance?

$$m_X \lesssim 6 \times 10^{15}\ \mathrm{GeV} \left(\frac{10}{g^*_{\mathrm{PT}}} \right) \left(\frac{g^*_{\mathrm{RH}}}{100} \right)^{1/4} \left(\frac{10^{-2}\ \mathrm{GeV}}{T_{\mathrm{PT}}} \right)^{3} \left(\frac{V_0}{10^{24}\ \mathrm{GeV}^4} \right)^{3/4}$$

- Do our primordial halos virialize before inflation?

$$m_X \gtrsim 2 \times 10^{12}\ \mathrm{GeV} \left(\frac{g^*_{\mathrm{MD}}}{100} \right)^{3/4} \left(\frac{10^{-5}}{\delta_0} \right)^{3/4} \left(\frac{V_0}{10^{24}\ \mathrm{GeV}^4} \right)^{1/4}$$

SIDM Restrictions

Phew

- Bullet Cluster observations set limit of $\sigma/m_X \lesssim 1\ \mathrm{cm^2/g}$ in contact interaction regime (Markevitch et al. 2004).
- In this regime (and not in this regime), we are always $\sigma/m_X \ll 10^{-10}\ \mathrm{cm^2/g}$
- Warping of galactic disks require $\tilde{\sigma}/m_X \lesssim 3 \times 10^{-13}\ \mathrm{cm^2/g}$, where $\tilde{\sigma} = 16\pi\alpha_D^2/m_X^2$ (Pardo et al. 2019)
- Our maximum value is $\tilde{\sigma}/m_X \simeq 10^{-16}\ \mathrm{cm^2/g}$