More Ways to (Be) Cool: Compact Objects from Inelastic Dark Matter

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Ongoing work to appear soon: arXiv:23xx.xxxx

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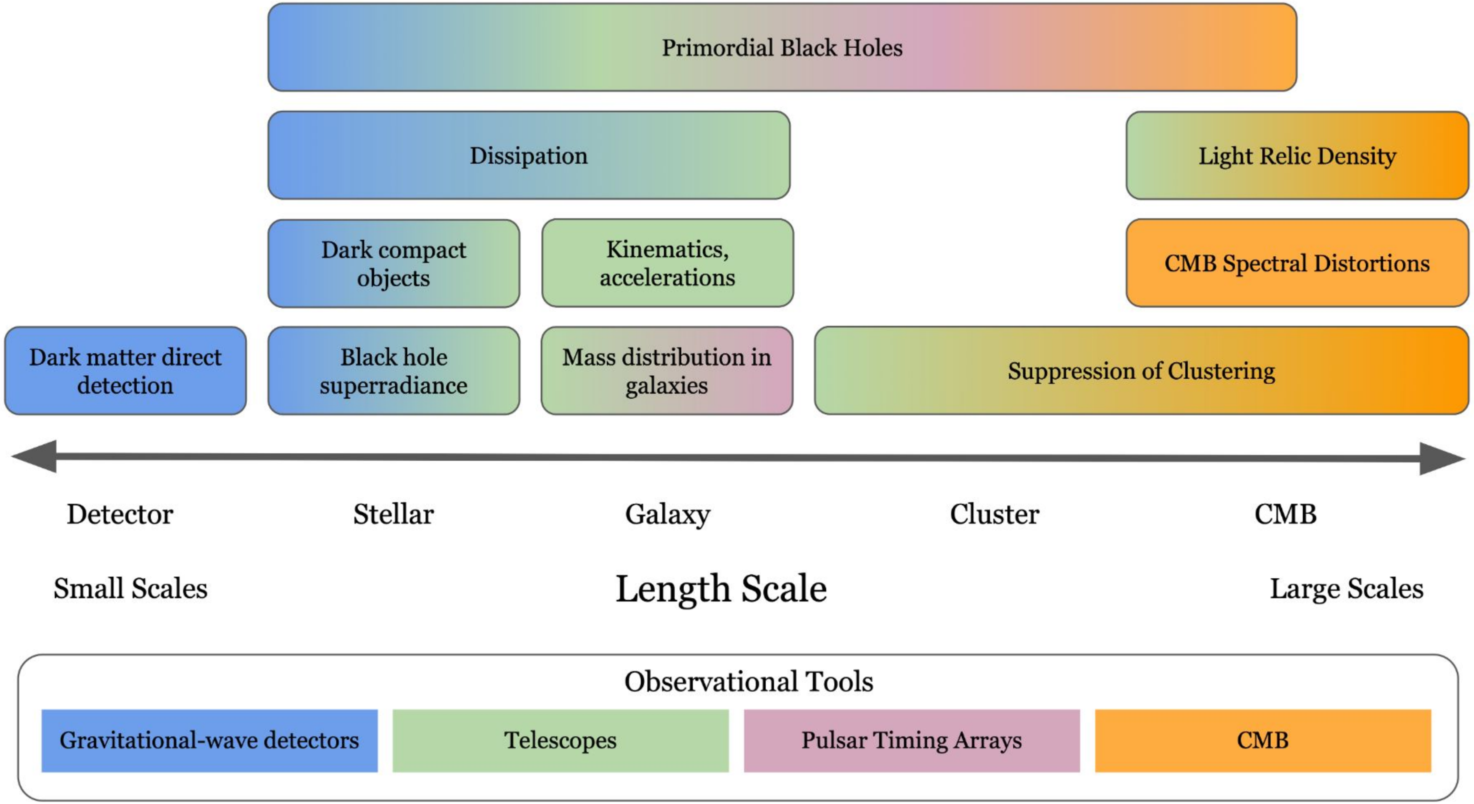

Figure from Snowmass 2021 White Paper (Brito et al., 2021)

How to Make Compact Objects

- Perturbations grow under linear theory, then moves to non-linear collapse
- SM forms stars due to dissipative processes
- Loss of kinetic energy -> particles fall into gravitational potential

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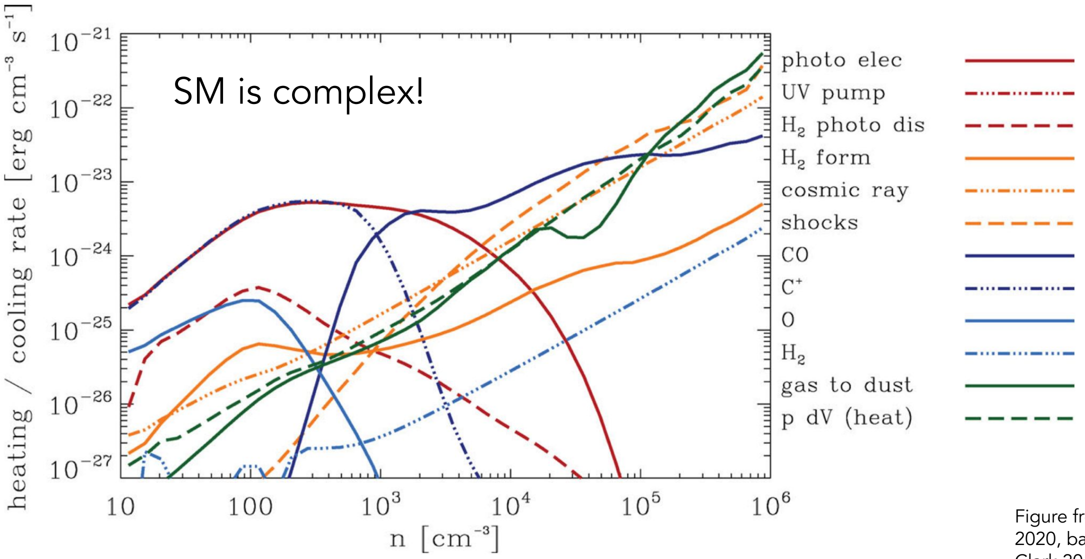

Figure from Girichidis et al. 2020, based on Glover & Clark 2012

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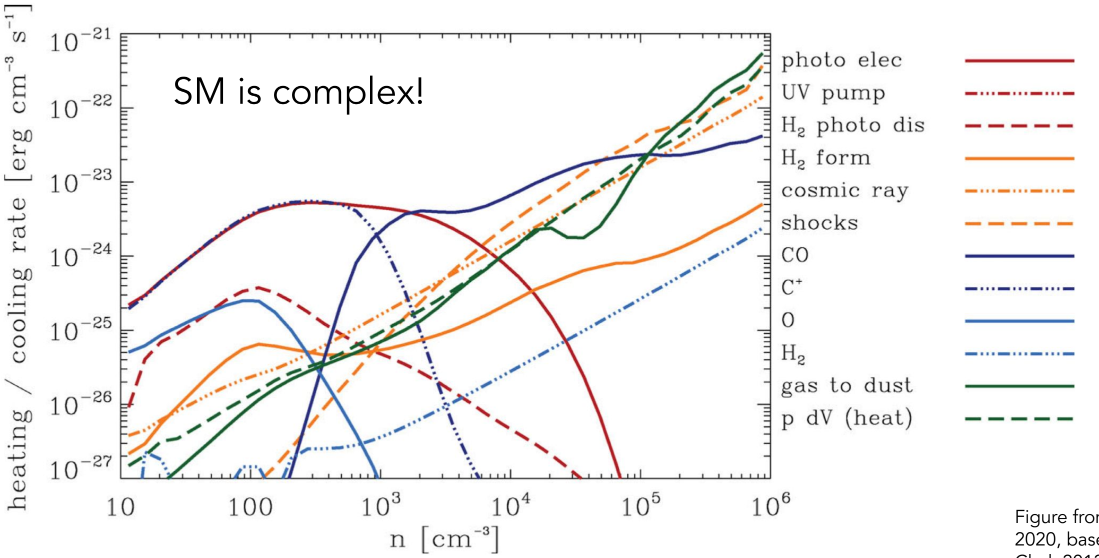

Let's make DM cool in a simple dark sector!

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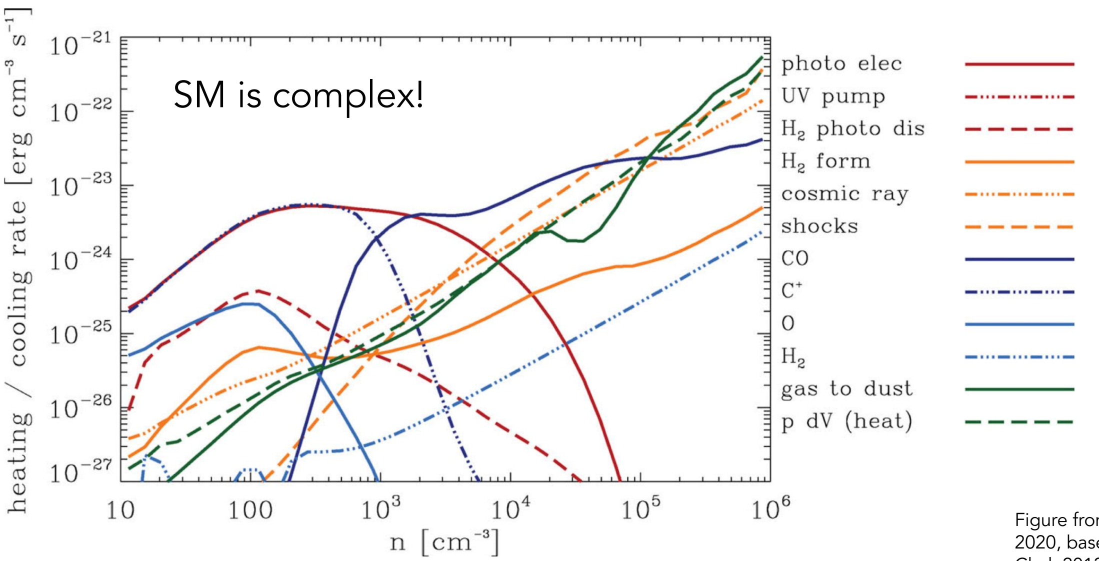

Let's make DM cool in a simple dark sector!

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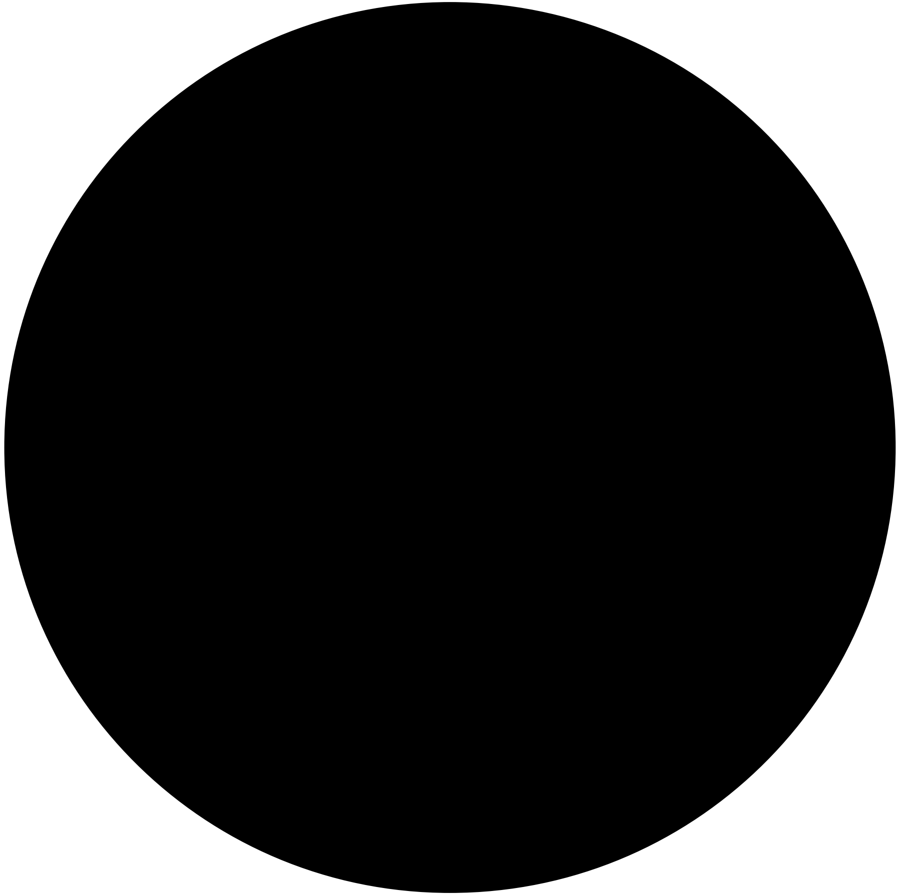
Dark Compact Objects

- What if we can have compact objects made up of purely dark matter?
- Dense clumps of dark matter can collapse if necessary conditions are met
- Results in a *landscape* of objects: dark stars and dark black holes (!)
- Dark BHs from dissipative dark sectors can have subsolar masses! Interesting GW prospects… (see Shandera et al. 2018, Chang et al. 2019, Gurian et al. 2023)

Chang et al. 2019: A Simplified History:



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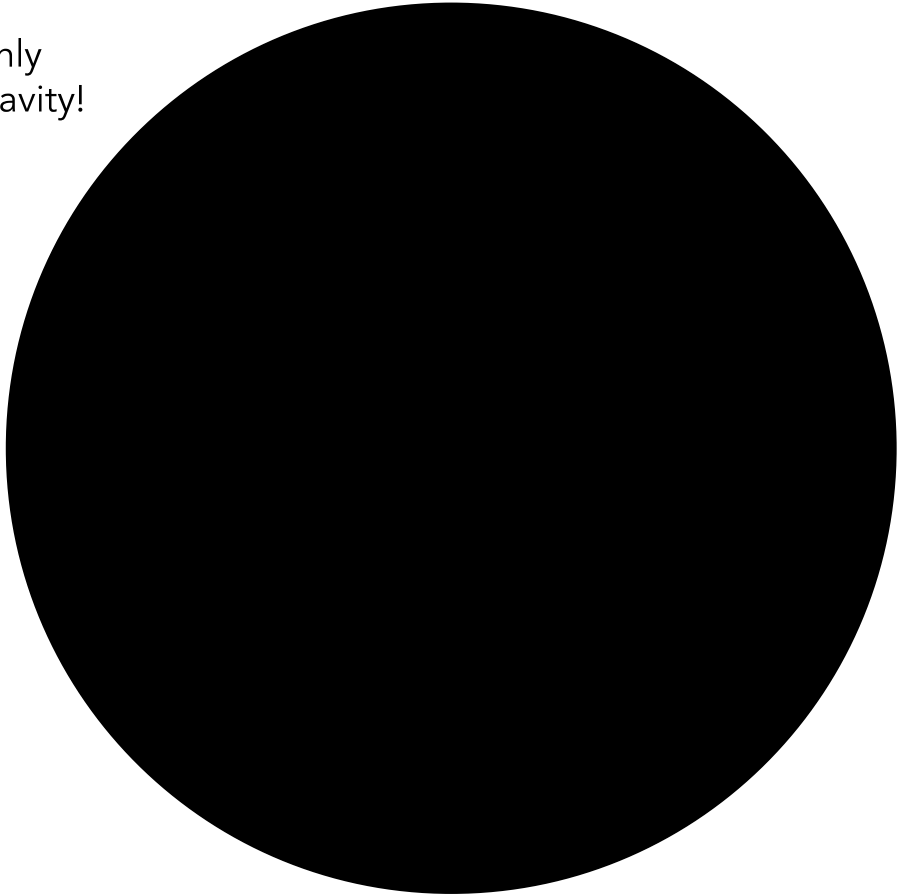
1. Adiabatic free-fall: dark halo free-falls



Only gravity!

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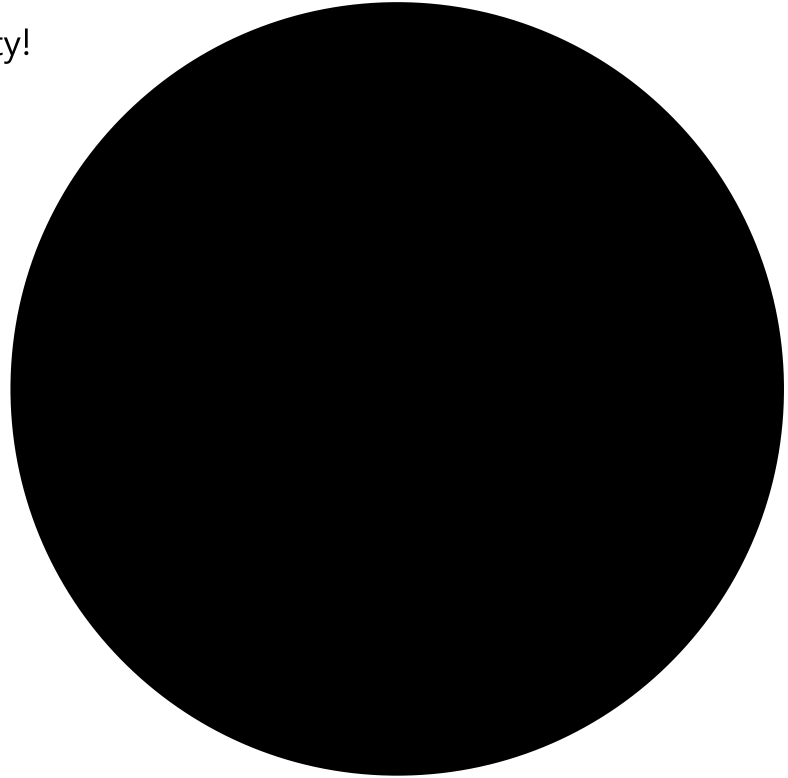

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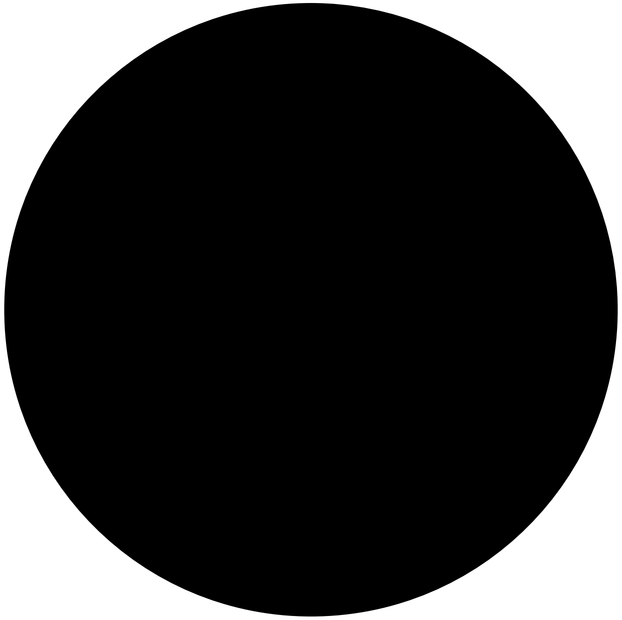

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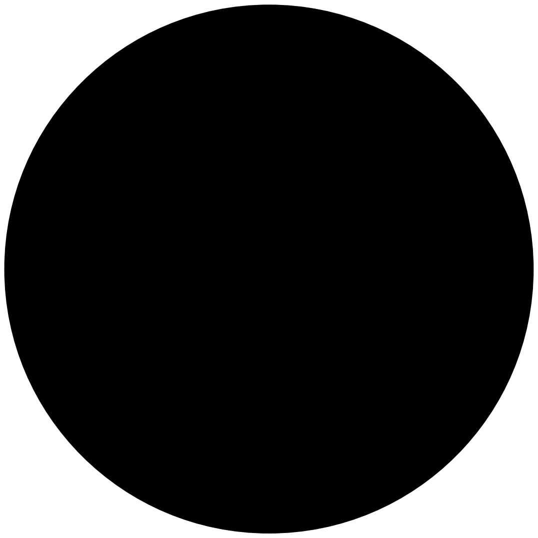

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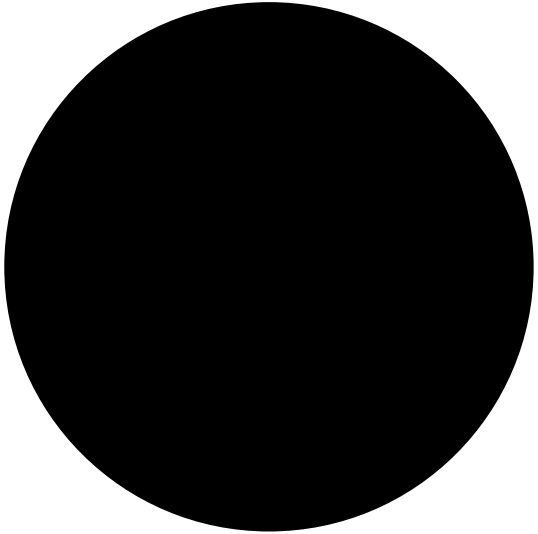
Gravity +
Pressure



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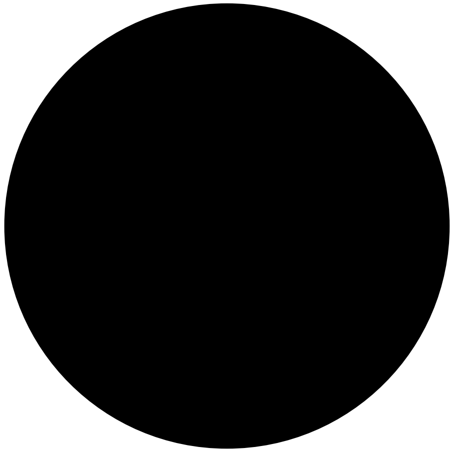

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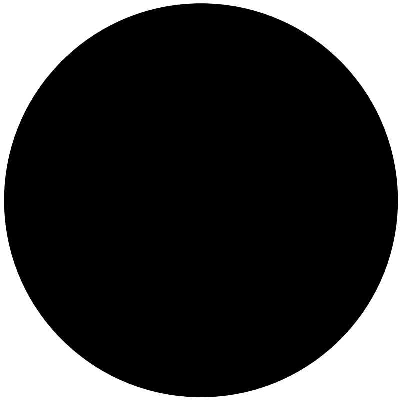

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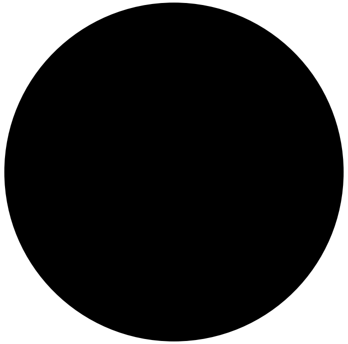

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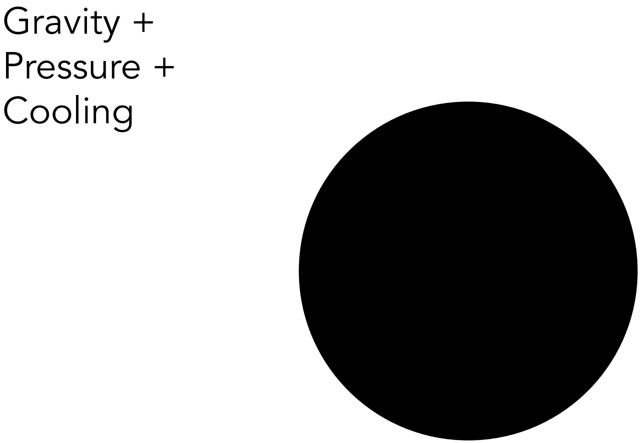

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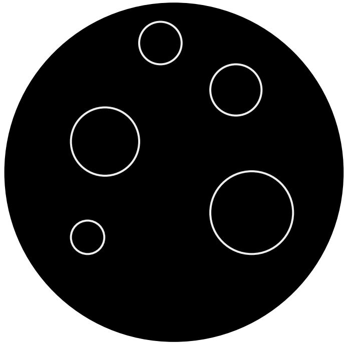
3. Fragmentation: decrease in Jeans mass results in the halo dividing into smaller clumps

Chang et al. 2019: A Simplified History:

Gravity +
Pressure +
Cooling



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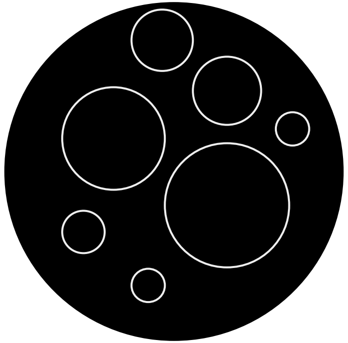

1. **Adiabatic free-fall**: dark halo free-falls

2. **Nearly virialized contraction**: dark halo virializes due to increase in kinetic pressure; halo collapses at const. Jeans mass

3. **Fragmentation**: decrease in Jeans mass results in the halo dividing into smaller clumps

Stops for 2 reasons:

- Cooling becomes inefficient
- Pressure of halo becomes dominated by dark repulsive force -> Jeans mass is independent of temperature, doesn't decrease!

Structure Formation from Dissipative Dark Sectors

- In Chang et al. 2019, a simple, asymmetric, subdominant dark sector composed of the dark electron + dark photon was studied
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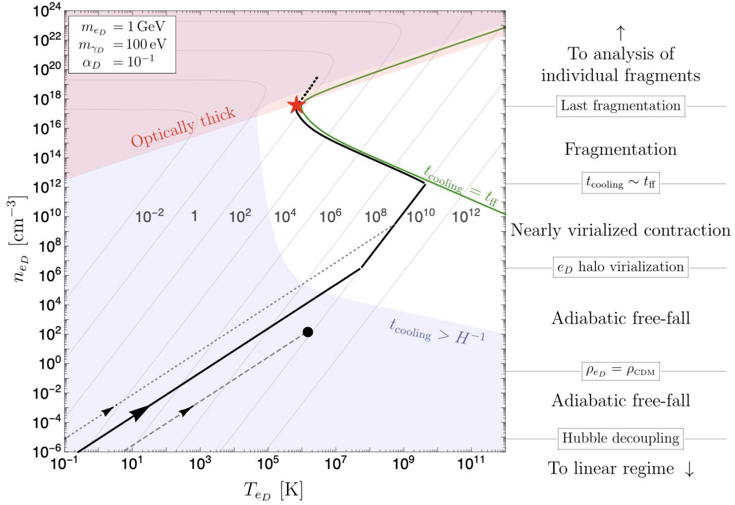

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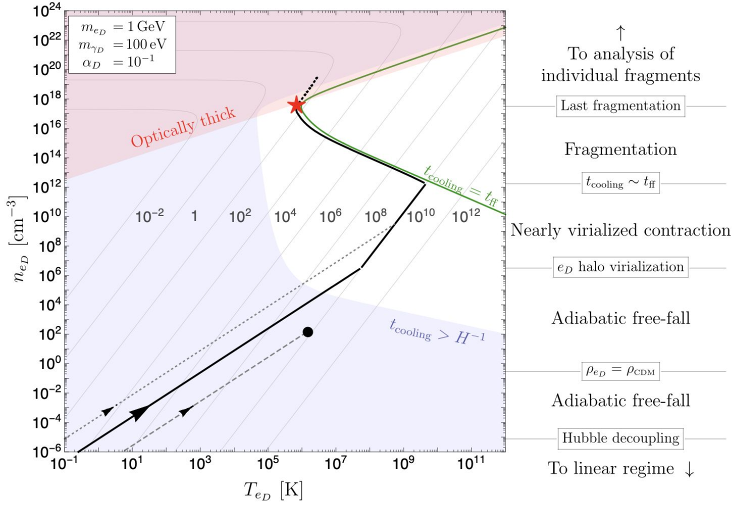

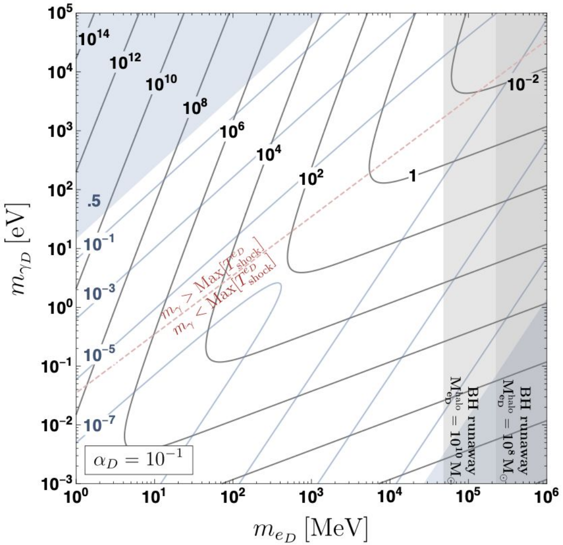

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Inelastic Dark Matter

- *Simple*, asymmetric, subdominant model: dark proton & dark photon
- Mass splitting for dark proton results in an excited state and ground state
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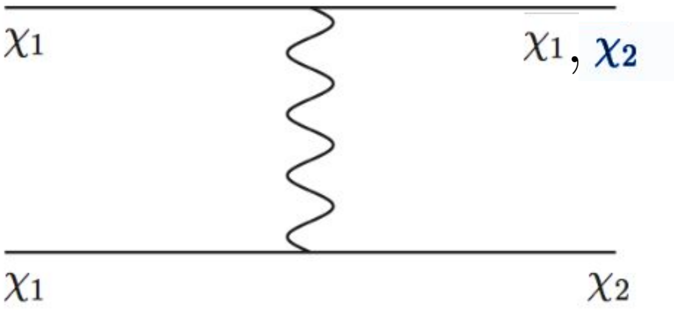
- *Simple*, asymmetric, subdominant model: dark proton & dark photon
- Mass splitting for dark proton results in an excited state and ground state
- New inelastic processes allow for new ways to (be) cool!
- Our goal is to see how the *landscape* of these compact objects look like (see excellent Atomic Dark Matter (ADM) talks yesterday for detailed study of compact objects & dissipative DM)
- Only 4 particle physics parameters in our simplified model:

$$m_\chi, m_{\gamma_D}, \alpha_D, \delta$$

Cooling Rates



Figures & cross section. from Schutz & Slayter 2015

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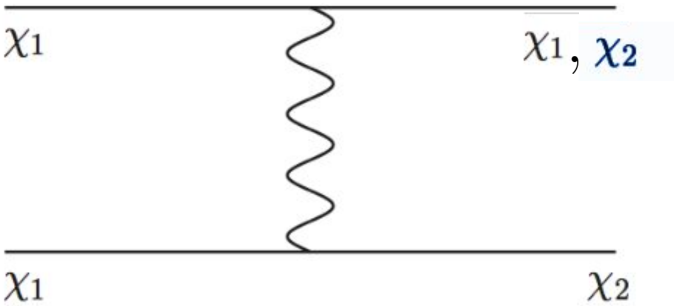

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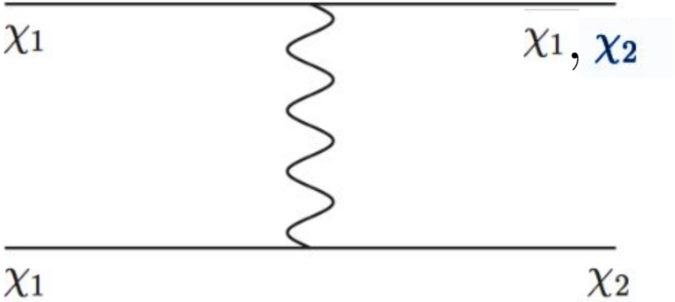
$$\sigma_{\mathrm{IE},1(2)} = \frac{4\pi\alpha^2 m_\chi^2 \sqrt{1 - \frac{(2)\delta}{m_\chi v^2}}}{m_{\gamma_D}^4 \left[\left(1 - (2)\delta m_\chi / m_{\gamma_D}^2\right)^2 + 4 m_\chi^2 v^2 / m_{\gamma_D}^2\right]}$$

Cooling Rates



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$$\Lambda_{\mathrm{IE},1(2)} = n_\chi \sigma_{\mathrm{IE},1(2)} v \frac{(2)\delta}{m_\chi}$$

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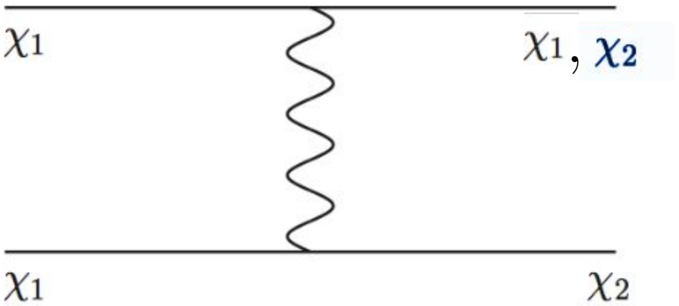

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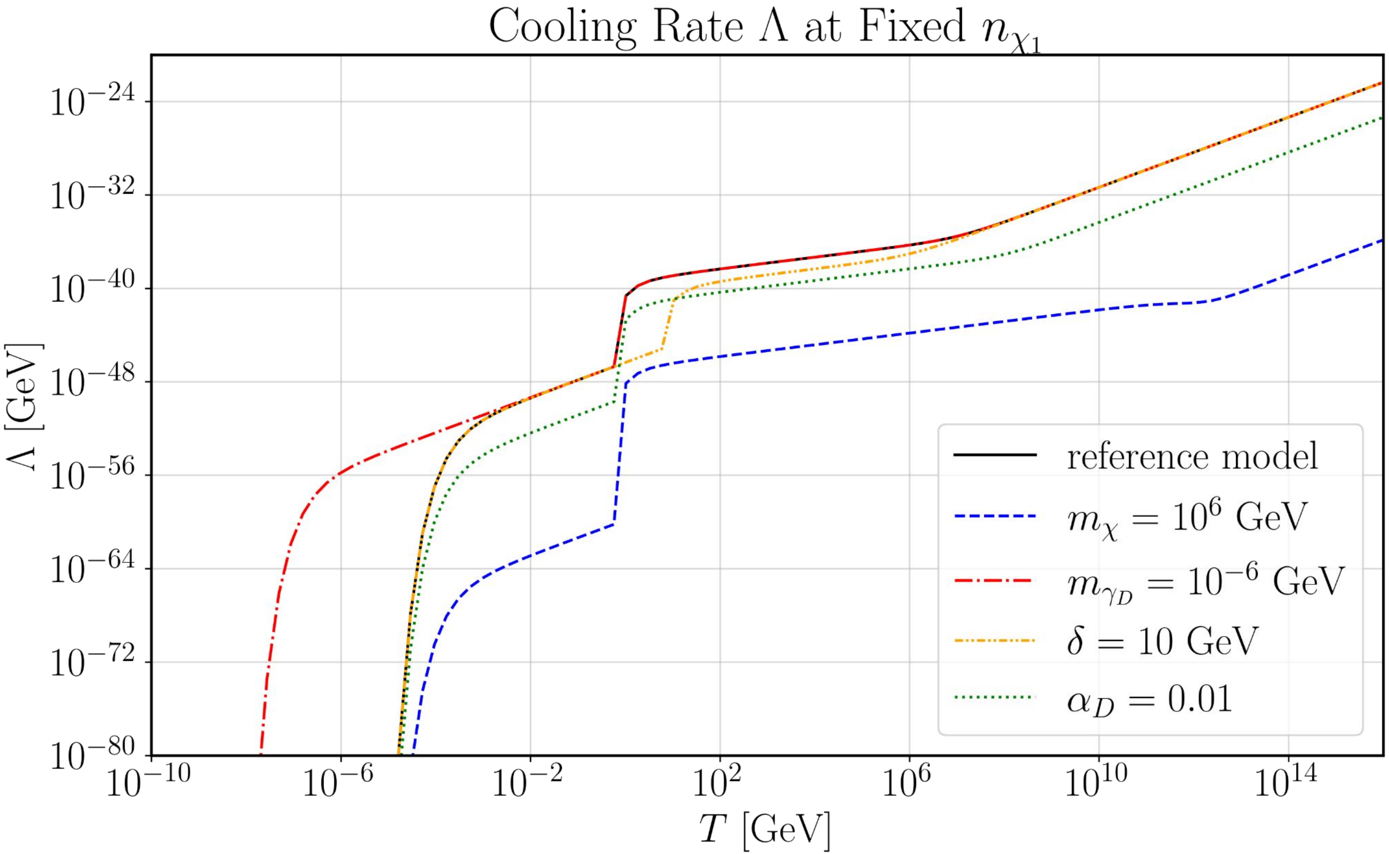
$$\Lambda = (\Lambda_{\mathrm{Compton}} + \Lambda_{\mathrm{BS}}) e^{-V^{1/3}\sqrt{N_{\mathrm{sc}}}/\ell_{\gamma_D}^{\mathrm{abs,BS}}} + (\Lambda_{\mathrm{IE},1} + \Lambda_{\mathrm{IE},2}) e^{-V^{1/3}\sqrt{N_{\mathrm{sc}}}/\ell_{\gamma_D}^{\mathrm{abs,IE}}}$$

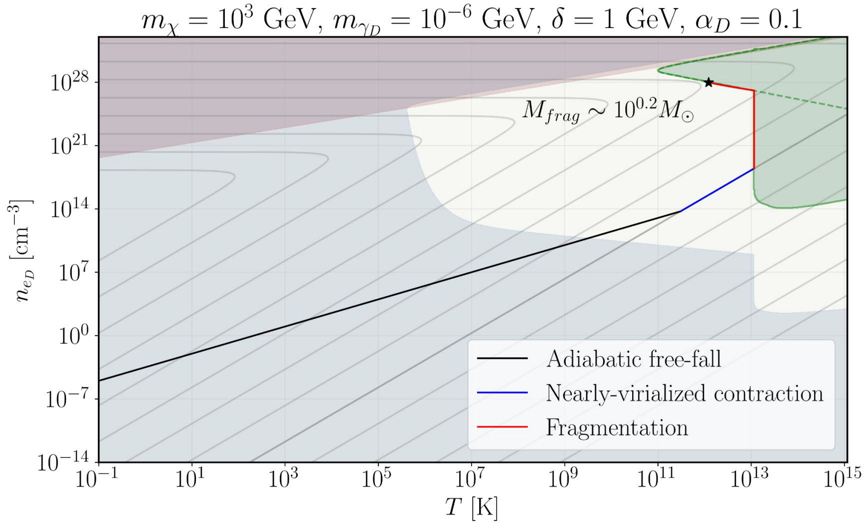
Cooling Rates

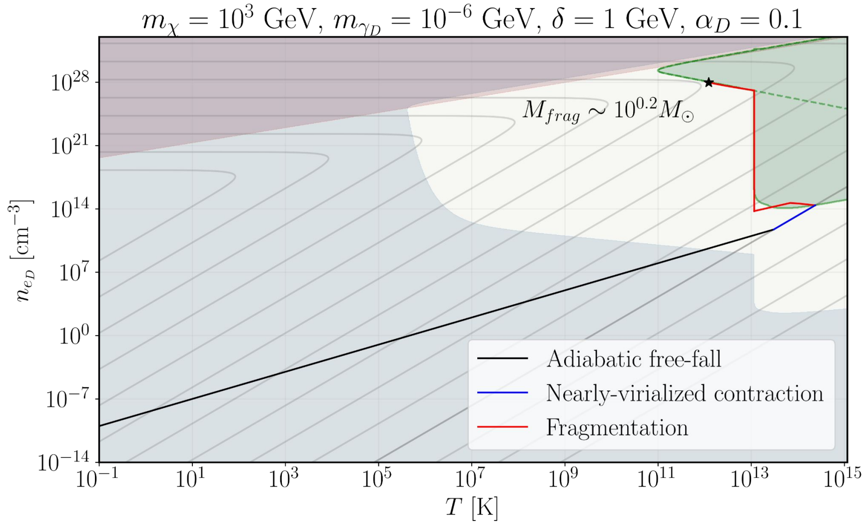


Reference model:

$$m_\chi = 10^3 \text{ GeV}$$
$$m_{\gamma_D} = 10^{-3} \text{ GeV}$$
$$\delta = 1 \text{ GeV}$$
$$\alpha_D = 0.1$$

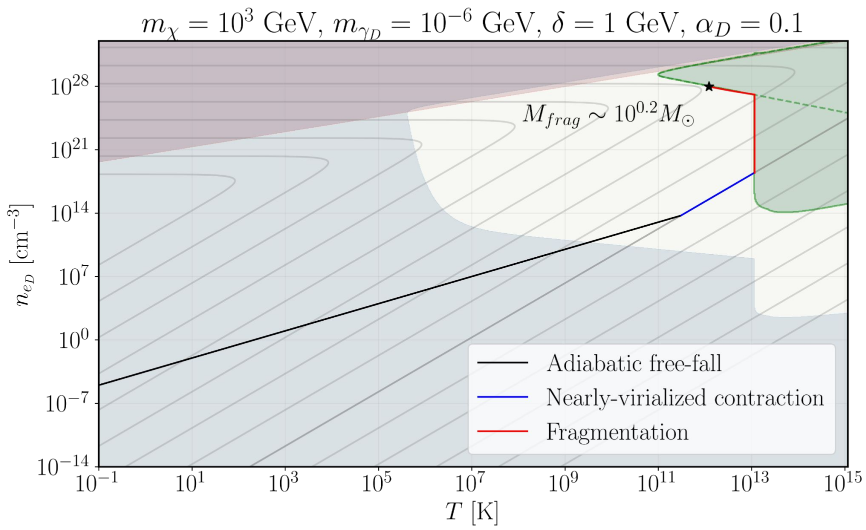
The Lives of Dark Compact Objects

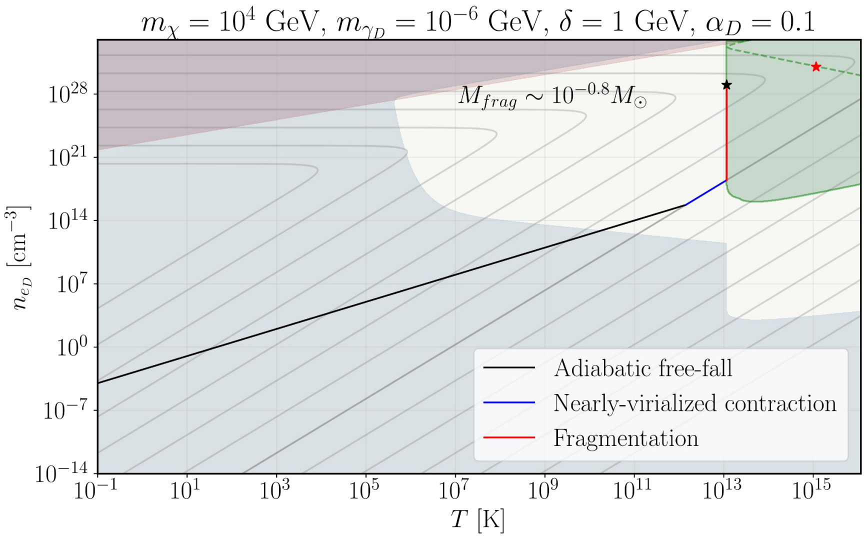




Fragments with same masses can have an entirely different history of formation!

The Lives of Dark Compact Objects





Different formation histories can lead to different fragmentation masses!

The Landscape of Compact Objects

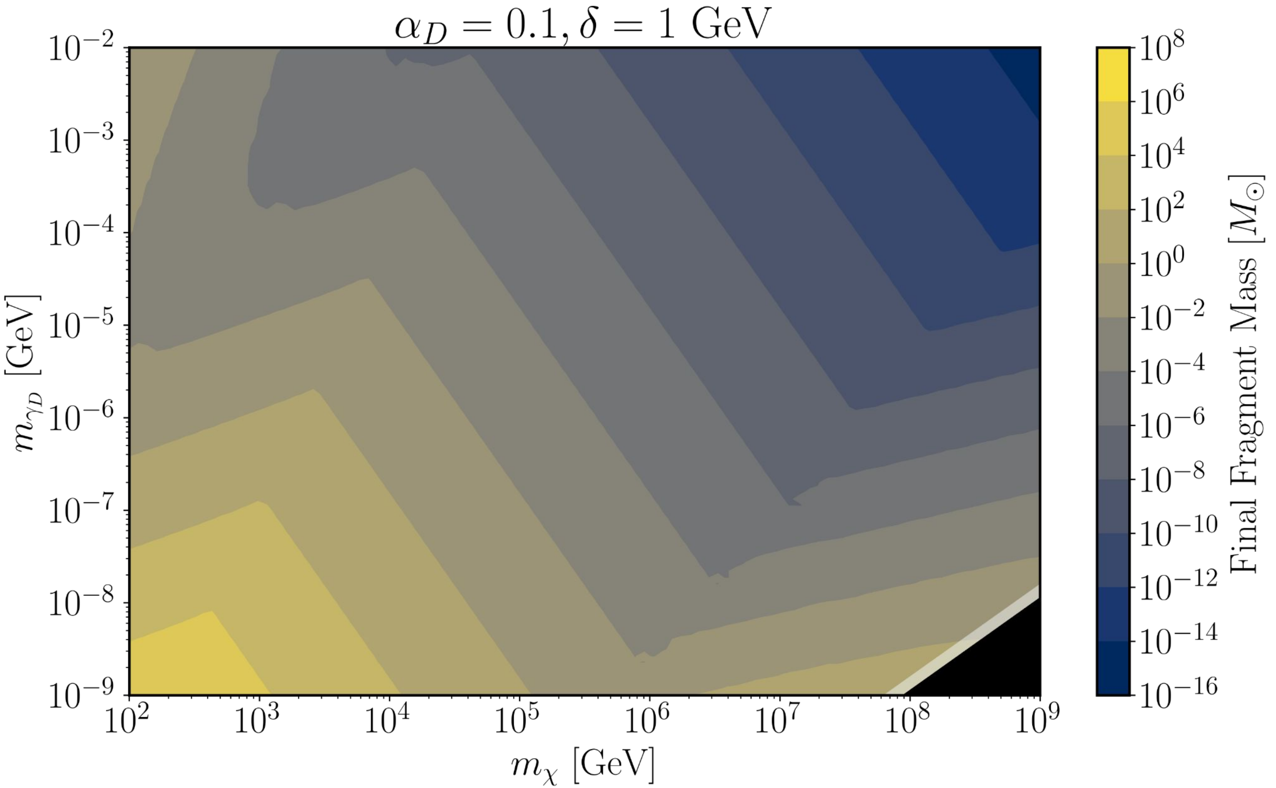
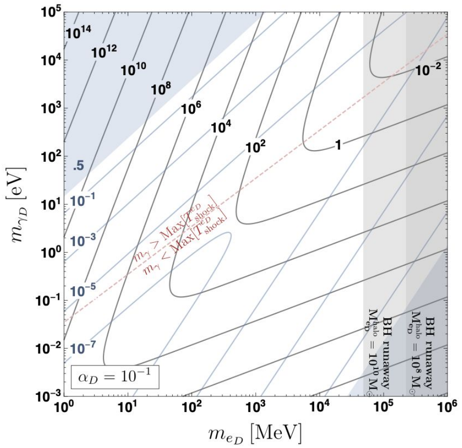


Figure from Chang et al. 2019



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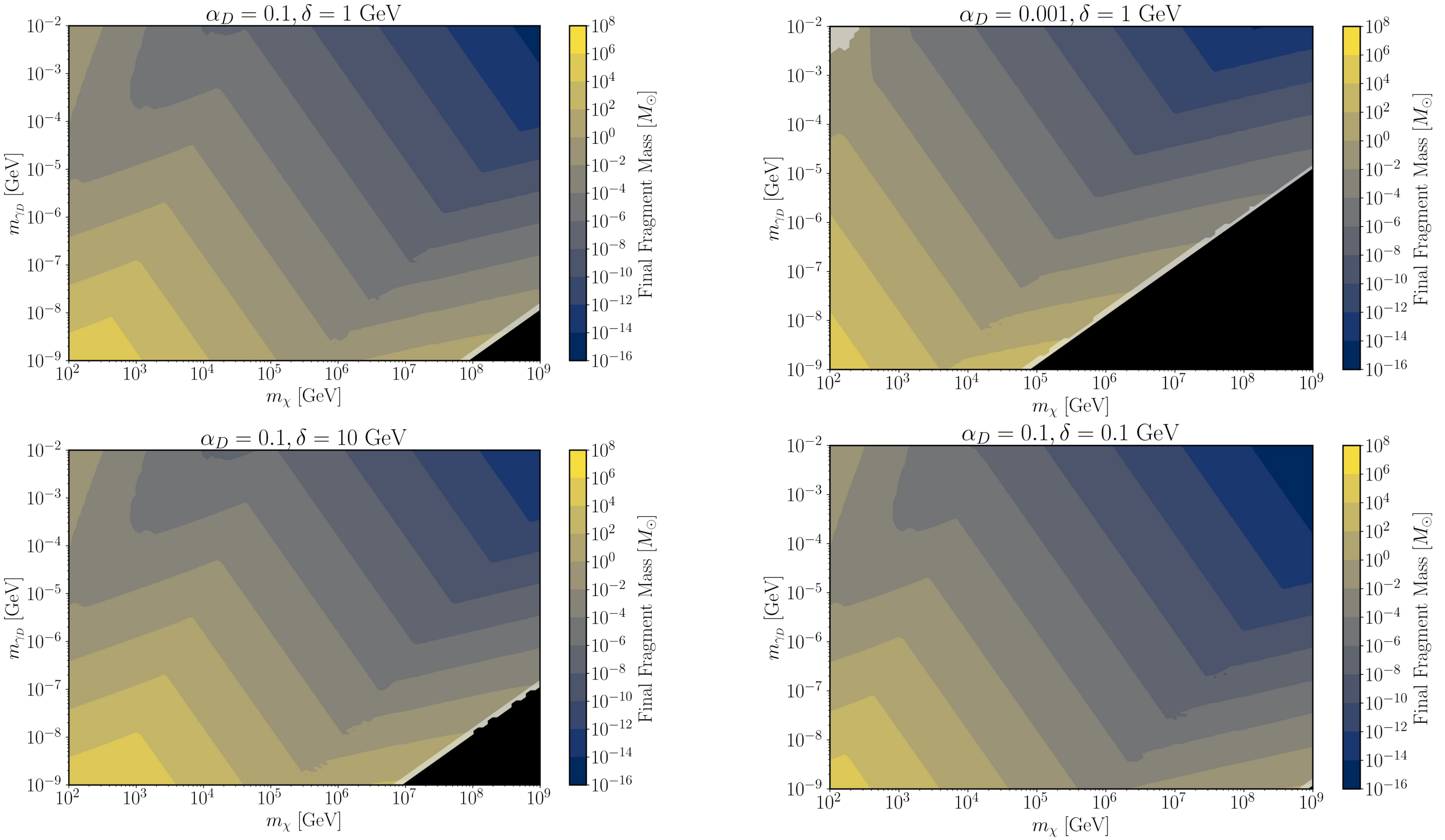


To Summarize…

- Dissipative dark sectors can influence the formation and evolution of astrophysical compact objects
- We considered a dark sector with multiple cooling channels
- Lives of compact objects are significantly different, leading to different landscape!

Next Steps…

- Explore new parameter space unlocked by model & possible observables
- We only considered masses of the minimal fragments, can also consider simulations to get better picture (see Roy et al. 2023 for Atomic DM simulation)

Thank you!

Back-up slides

Let's Make Dark Stars!

$$\frac{d\log T_\chi}{d\log \rho_\chi} = \frac{2}{3}\frac{m_\chi P_\chi}{\rho_\chi T_\chi} - 2\frac{t_{\rm collapse}}{t_{\rm cooling}}$$

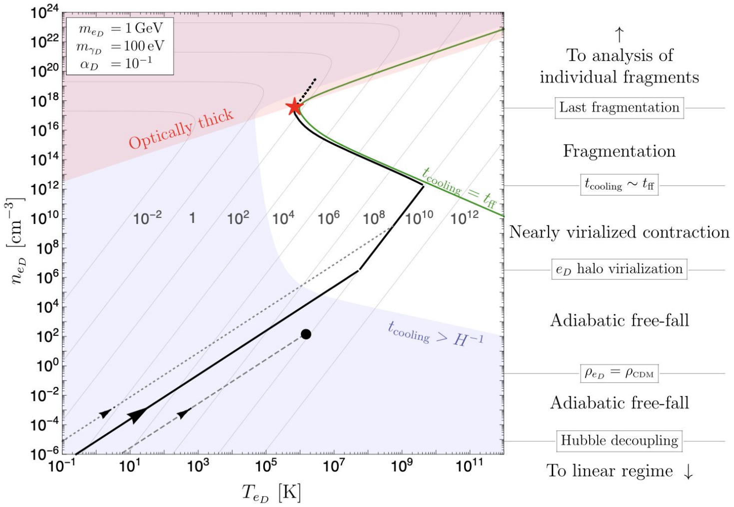


Figure from Chang et al. 2019

$$t_{\rm cooling} = \frac{3T_\chi}{m_\chi \Lambda}$$

Extra Cooling Equations

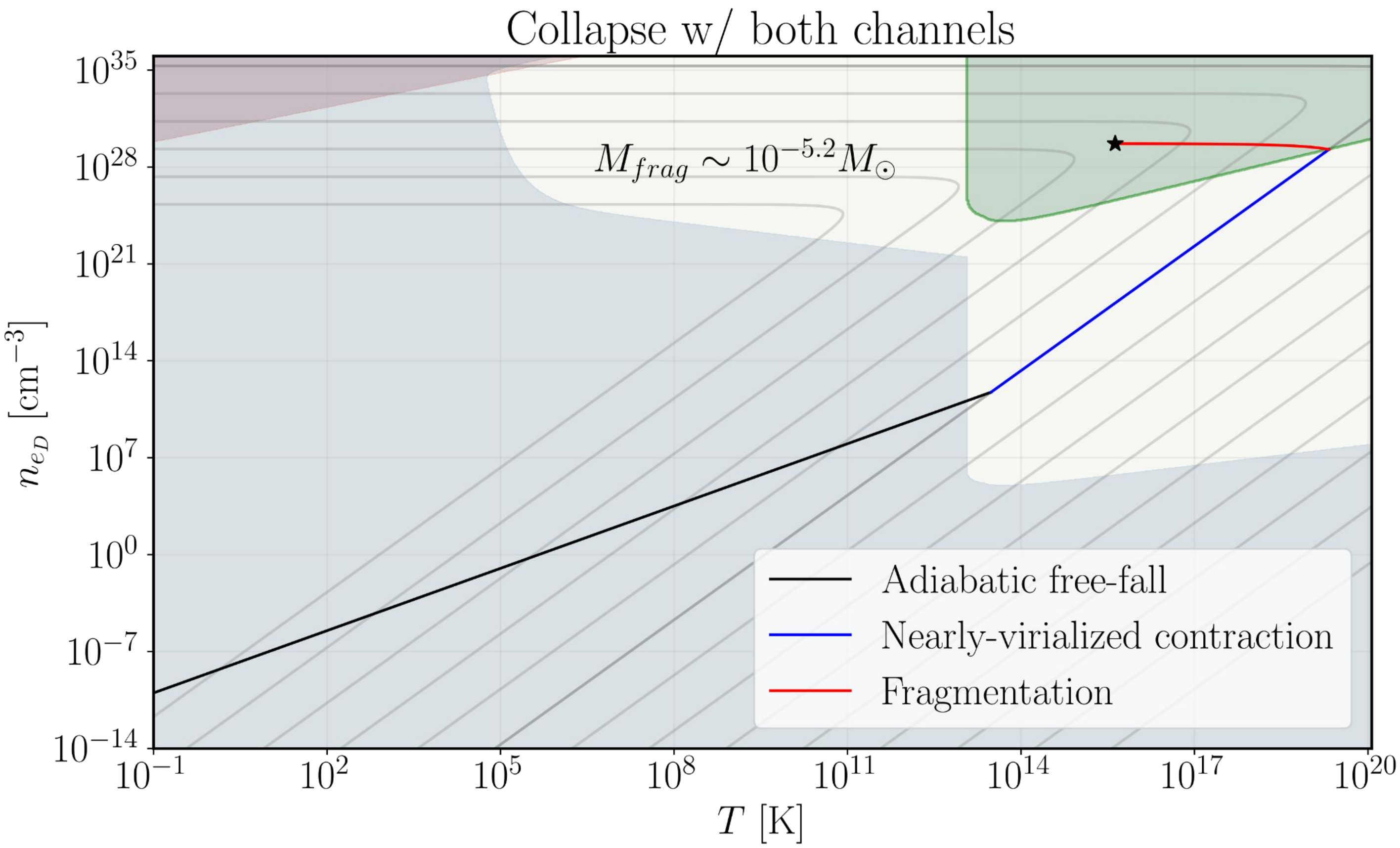
$$\Lambda_{\mathrm{BS}} = \frac{32\alpha_D^3 \rho_\chi T_\chi}{\sqrt{\pi} m_\chi^4} \sqrt{\frac{T_\chi}{m_\chi}} e^{-m_{\gamma_D}/T_\chi}$$

$$t_{\mathrm{collapse}} = \begin{cases} t_{ff} = (16\pi G \rho_\chi)^{-1/2} & M > m_J, \\ \frac{1}{6} t_{\mathrm{cooling}} & M = m_J \text{ and } t_{\mathrm{cooling}} > t_{ff}, \\ t_{ff} & t_{\mathrm{cooling}} \simeq t_{ff}. \end{cases}$$

Adiabatic free-fall

Nearly virialized contraction

Fragmentation



Collapse w/ both channels
$M_{frag} \sim 10^{-5.2} M_\odot$
10^{35}
10^{28}
10^{21}
10^{14}
10^{7}
10^{0}
10^{-7}
10^{-14}
n_{e_D} [cm^{-3}]
10^{-1}
10^{2}
10^{5}
10^{8}
10^{11}
10^{14}
10^{17}
10^{20}
T [K]
Adiabatic free-fall
Nearly-virialized contraction
Fragmentation

Linear Collapse

- Overdensities collapse!
- Perturbations grow if their wavelengths are > Jeans length
- Eventually reach "turnaround" point, transition into non-linear region

$$\delta(z_{\rm ta}) = \frac{9\pi^2}{16} \qquad \rho_{e_D} \simeq \frac{9\pi^2}{16}\rho_0^{e_D} = \frac{9\pi^2}{16} f \rho_0^{\rm DM}$$

$$\frac{k^3}{2\pi^2} P(k, z_{\rm ta}) = 1 \qquad \langle \delta_{\mathbf{k}} \delta^*_{\mathbf{k}} \rangle \equiv (2\pi)^3 P(k)\, \delta^3(0)$$

	Radiation domination		Matter domination	
CDM	$\log(a)$		a	
Interacting Matter	$\lambda_P < \lambda_J^{\rm m}$	–	$\lambda_P < \lambda_J^{\rm m}$	–
	$\lambda_P > \lambda_J^{\rm m}$	$\log(a)$	$\lambda_P > \lambda_J^{\rm m}$	a
Radiation	–		–	

$$\partial_t^2\, \delta_{\mathbf{k}}(t) + 2H\partial_t\, \delta_{\mathbf{k}}(t) + \left[c_s^2 k^2/a^2 - 4\pi G \rho_0\right]\delta_{\mathbf{k}} = 0$$

$$c_s^{e_D} = \sqrt{\frac{T_{e_D}}{m_{e_D}} + \frac{4\pi\alpha_D n_{e_D}}{m_{e_D} m_{\gamma_D}^2}}$$

Equations from Chang et al. 2019

Nonlinear collapse (Jeans analysis)

$$\lambda_J = c_s \left(\frac{\pi}{\rho G}\right)^{1/2}$$

$$M \geq m_J \quad , \quad m_J \equiv \frac{4\pi}{3}\left(\frac{\lambda_J}{2}\right)^3 \rho_{e_D} = \frac{\pi}{6} c_s^3 \left(\frac{\pi}{\rho G}\right)^{3/2} \rho_{e_D},$$

- DE initially collapses due to CDM and further collapses into centre of halo. Then CDM can be neglected since the DE halo collapses under its own gravity
- Baryons and DE are most likely correlated, *assume* that ignoring baryons do not make significant differences in solution

$$m_J = \frac{\pi}{6} c_s^3 \left(\frac{\pi}{G}\right)^{3/2} \left(\frac{1}{\rho_{e_D}}\right)^{1/2} \quad ,$$

Equations from Chang et al. 2019

Nonlinear collapse - temperature and density

$$\frac{de_{\rm kin}}{dt} = \frac{3}{2m_{e_D}}\frac{dT_{e_D}}{dt} = -\frac{P_{e_D}}{M}\frac{dV}{dt} - \Lambda \quad \Longrightarrow \quad \frac{d\log T_{e_D}}{d\log \rho_{e_D}} = \frac{2}{3}\frac{m_{e_D}P_{e_D}}{\rho_{e_D}T_{e_D}} - 2\,\frac{t_{\rm collapse}}{t_{\rm cooling}}$$

$$t_{\rm collapse} \equiv \left(\frac{d\log\rho_{e_D}}{dt}\right)^{-1} \quad , \quad t_{\rm cooling} \equiv \frac{3T_{e_D}}{m}\frac{1}{\Lambda}$$

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

$$\begin{cases} t_{\rm ff} \equiv \left(\dfrac{1}{16\pi G\rho_{e_D}}\right)^{1/2} & M > m_J & \text{Adiabatic free-fall} \\ \frac{1}{6}t_{\rm cooling} & M = m_J \text{ and } \quad t_{\rm cooling} > t_{\rm ff} & \text{Nearly virialized contraction} \end{cases}$$

Equations from Chang et al. 2019

Nonlinear collapse - nearly virialized contraction

- As Jeans mass gets equal to mass of halo, we enter nearly virialized collapse
- In order for this, the collapse time must accommodate for m_J = M
- Pressure can be released via cooling if the main source of pressure is kinetic

$$\lambda_J = c_s \left(\frac{\pi}{\rho G} \right)^{1/2} \qquad M \geq m_J \quad , \quad m_J \equiv \frac{4\pi}{3} \left(\frac{\lambda_J}{2} \right)^3 \rho_{e_D} = \frac{\pi}{6} c_s^3 \left(\frac{\pi}{\rho G} \right)^{3/2} \rho_{e_D} \, ,$$

Equations from Chang et al. 2019