Gravothermal collapse beyond minimal models of self-interacting dark matter

Leo Kim

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Contributed Talk — Light Dark World 2026 @ Carleton University
July 30, 2026

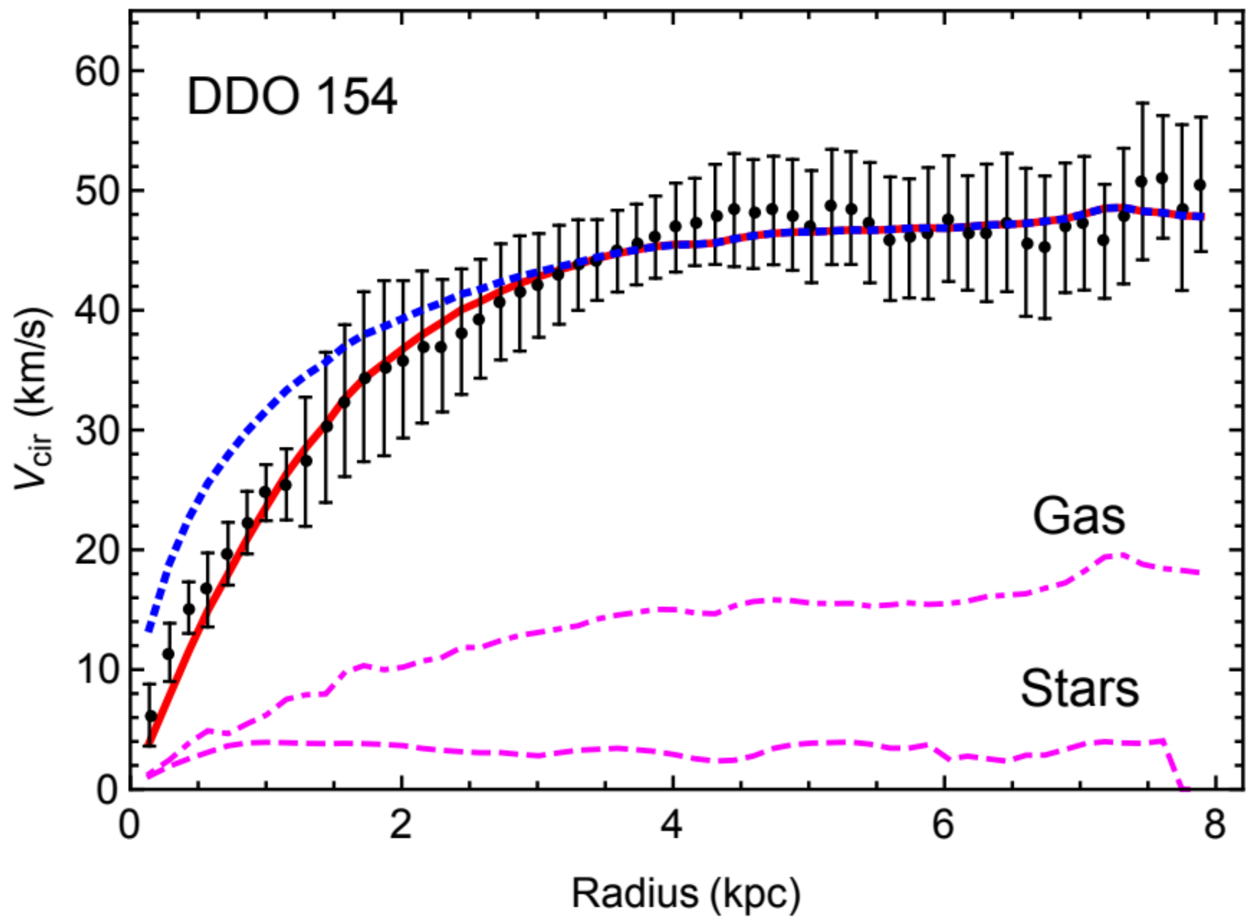
Why SIDM?

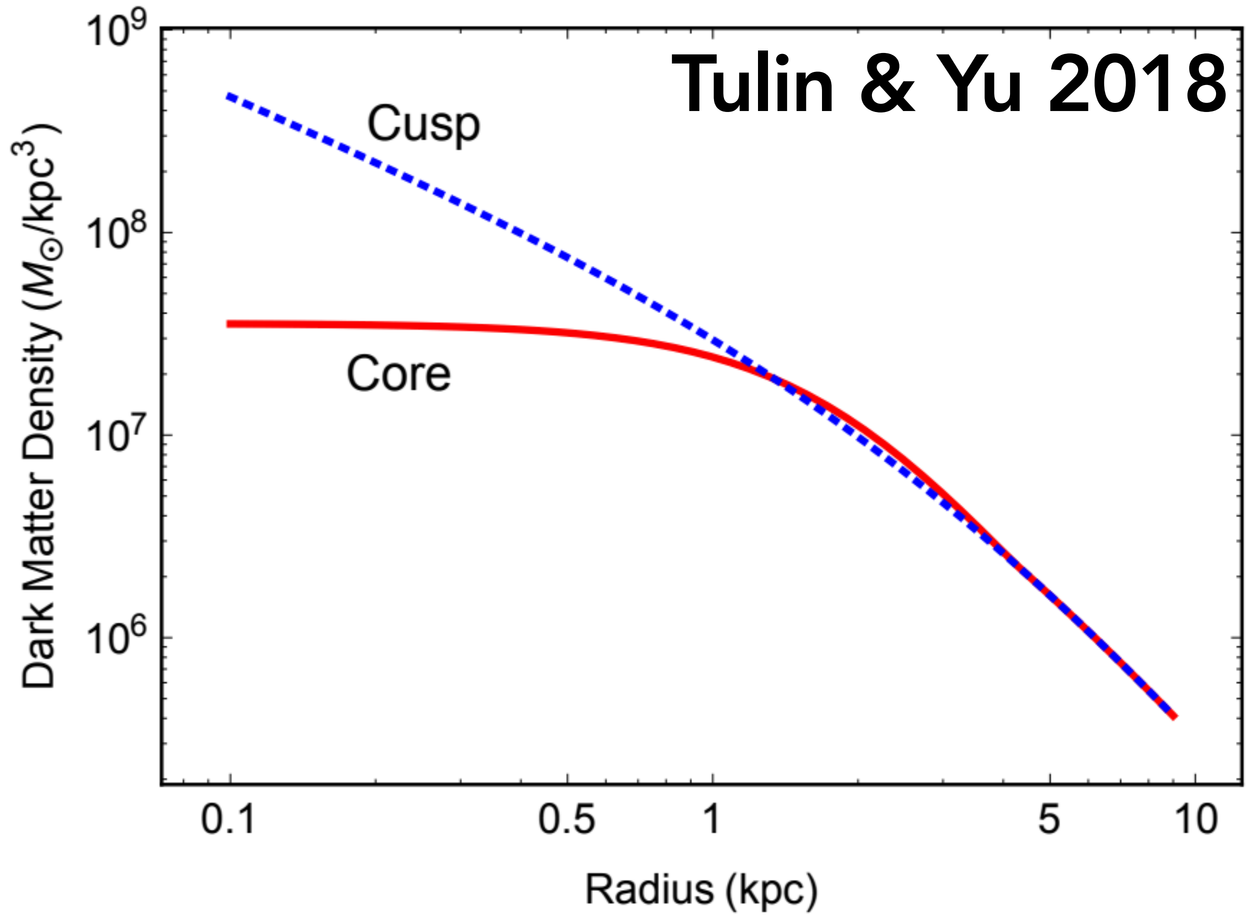
- Cold (collisionless) dark matter (CDM) does very well

- Why self-interacting dark matter (SIDM)?

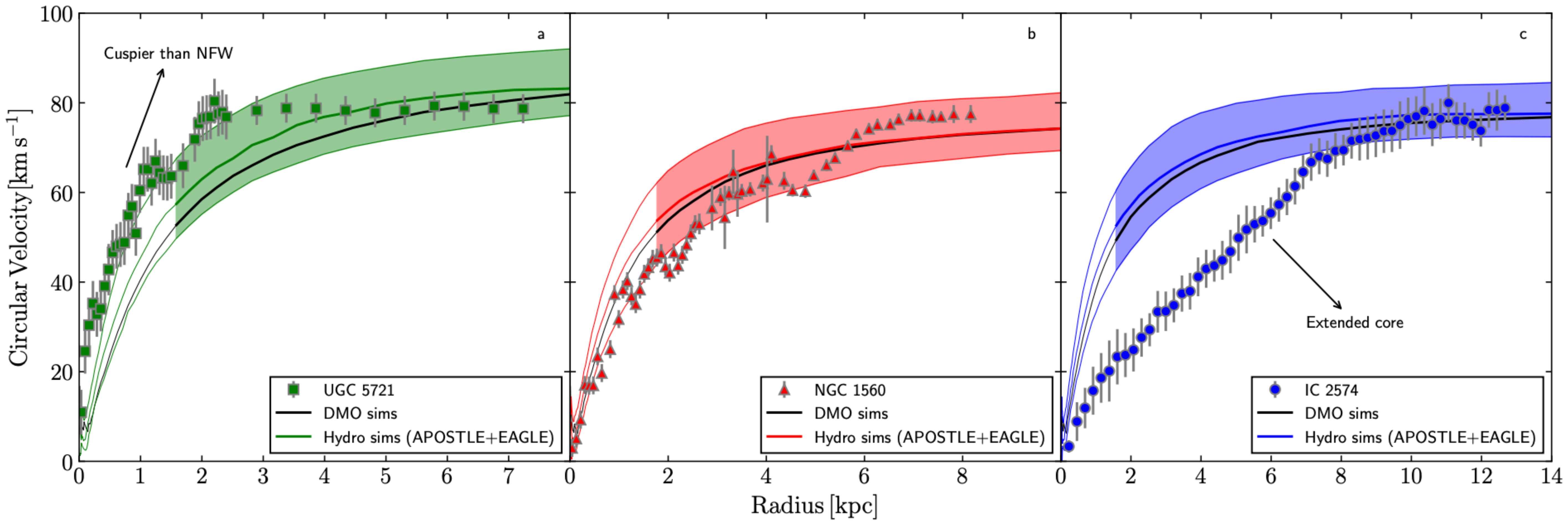
    - Can lead to new phenomena different from CDM

    - Historically, small-scale behaviours of CDM have been criticized: e.g. core-cusp, missing satellites, diversity, etc.. Including baryons in simulations can resolve these? (Kim et al. 2018, Sales, Wetzel, Fattahi 2022, Cruz et al. 2026)





Tulin & Yu 2018



Sales, Wetzel, Fattahi 2022

Why dSIDM?

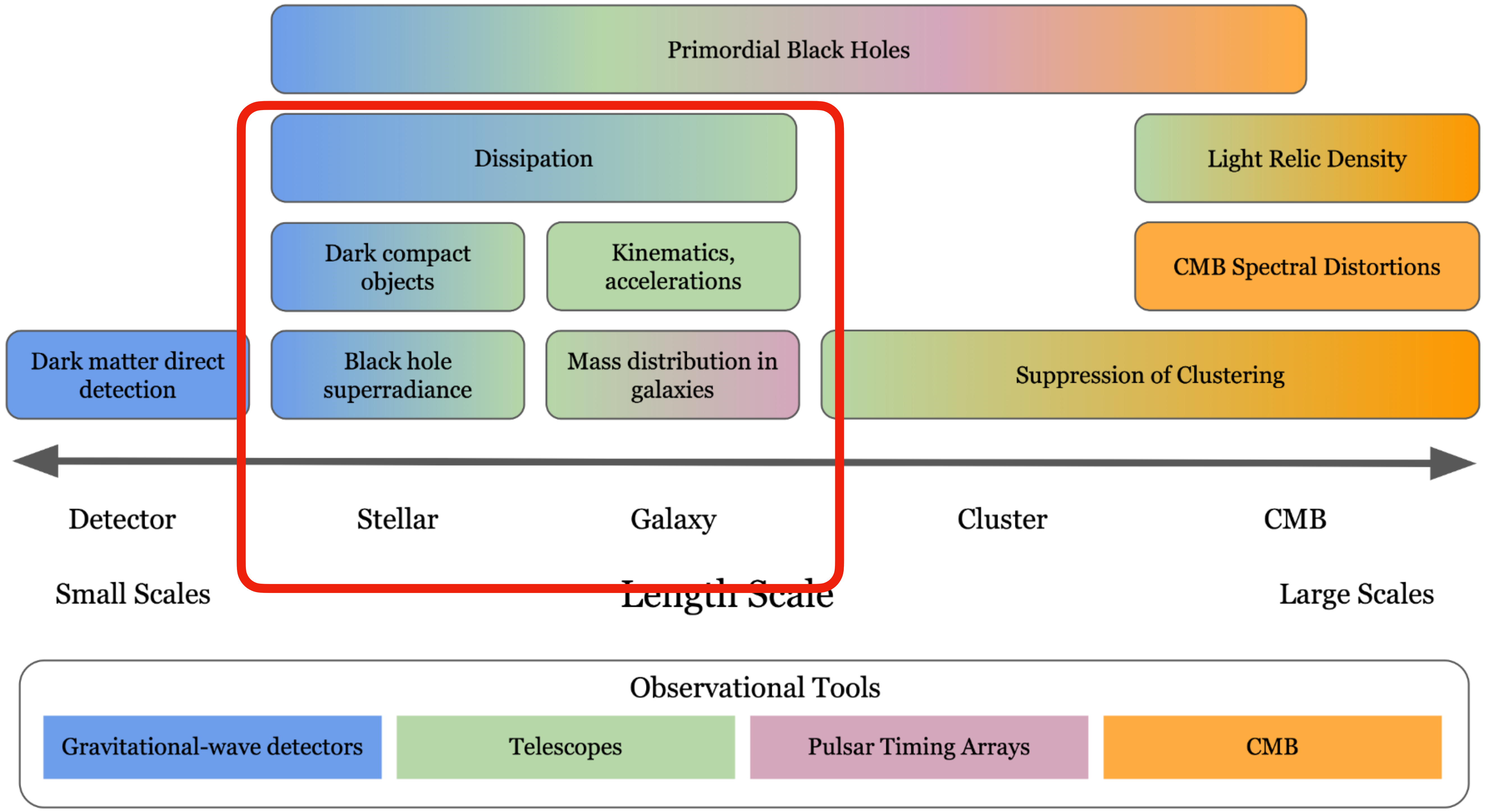


Figure from Snowmass 2021 White Paper (Brito et al., 2021)

- SIDM: umbrella term for DM which isn't collisionless, but usually refers to elastic scattering only
- **Dissipative** self-interacting dark matter (dSIDM) allows for inelastic scattering
- Why is it interesting?
  - Can lead to new phenomena different from CDM and SIDM
  - The Standard Model has inelastic processes, why not the dark sector?

Goals

- Q1: how would dissipation affect the gravothermal evolution of a dark matter halo?
- Q2: Can we use drastically modified collapse scenarios to rule out regions of DM parameter space?

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Cross sections

+

Simulations

Cross sections

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Inelastic dark matter

- Fermion ψ and light U(1) vector mediator ϕ
- Majorana mass term results mass splitting δ, leading to ground (χ_1) and excited (χ_2) states
- Only non-diagonal couplings $\mathscr{L} \supset i\frac{g_\chi}{2}\bar{\chi}_2\gamma^\mu\chi_1\phi + \text{h.c.}$

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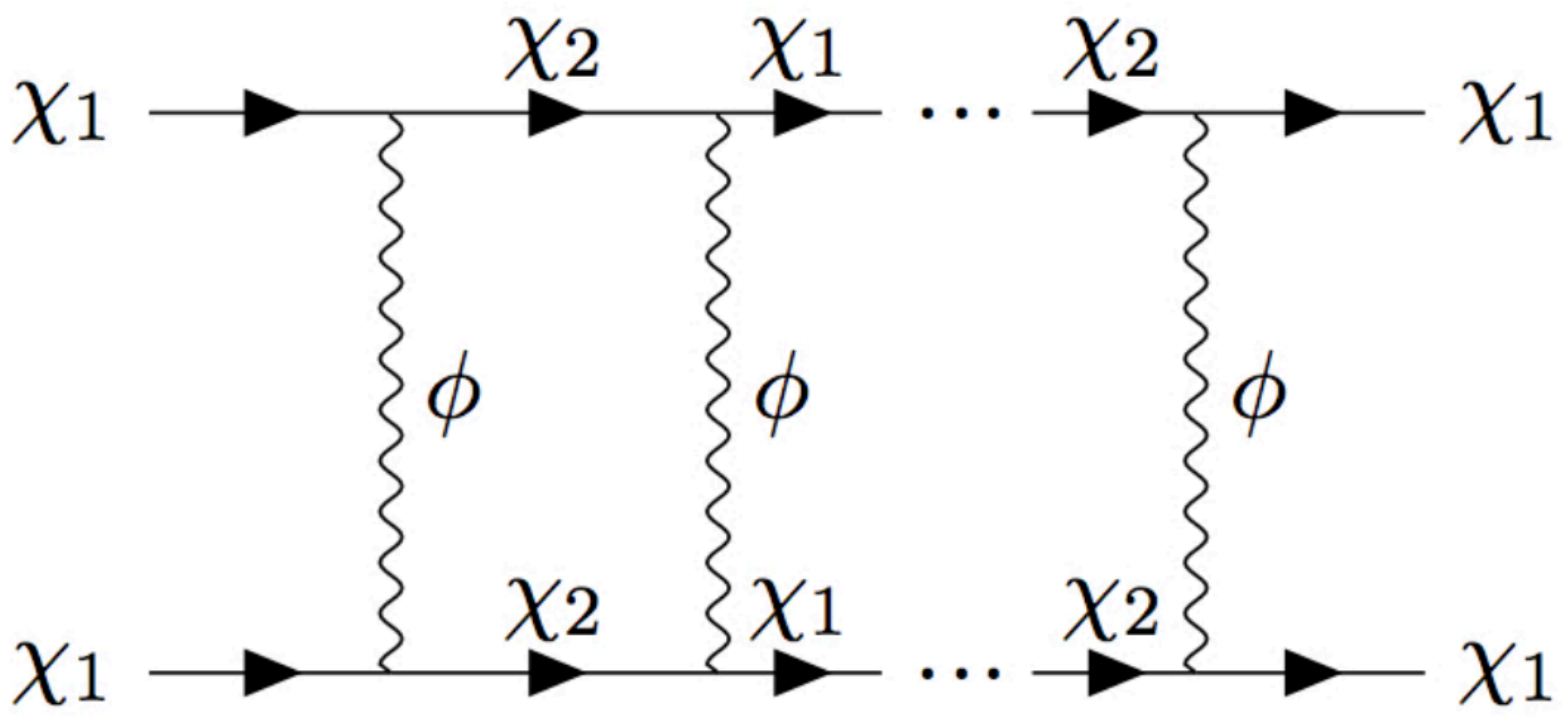
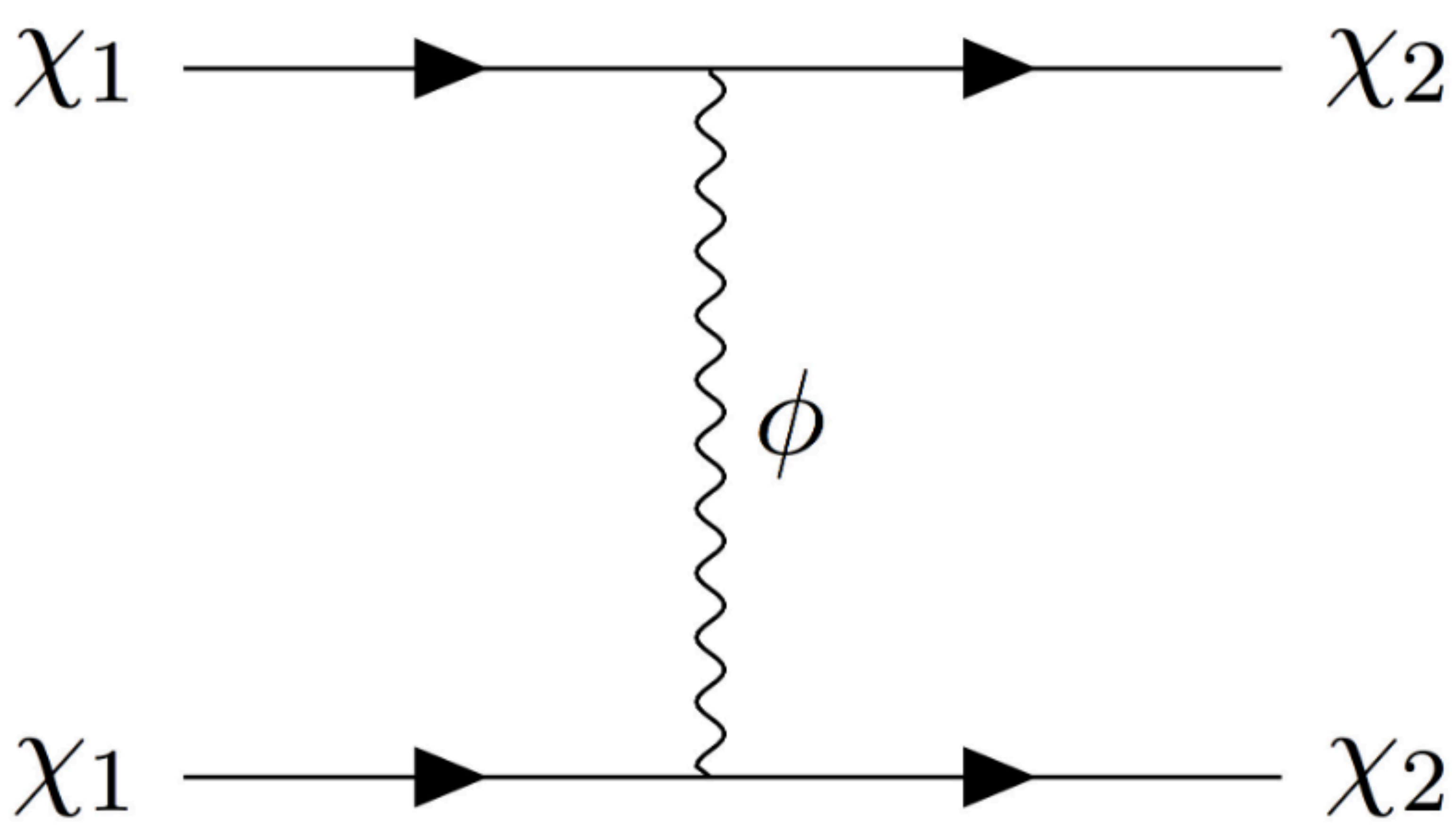
*We assume short lifetimes



Elastic scattering



Upscattering

Figs from Alvarez & Yu 2018

Cross section calculation

Cross section calculation

- In non-relativistic limit, we can solve the Schrödinger equation using partial wave scattering (e.g. Slatyer 2010, Schutz & Slatyer 2015, Blennow et al. 2017, Alvarez & Yu 2020)

$$i\frac{\partial}{\partial t}\tilde{\psi} = \left[-\frac{1}{2\mu}\nabla^2 + \mathbf{V}\right]\tilde{\psi}$$

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- Radial Schrödinger equation

$$\frac{1}{r^2}\frac{d}{dr}\left(r^2\frac{d\mathbf{R}_\ell}{dr}\right) + \left(\mathbf{k}^2 - \frac{\ell(\ell+1)}{r^2} - m_\chi \mathbf{V}(r)\right)\mathbf{R}_\ell = 0 \qquad \mathbf{V}(r) = \begin{pmatrix} 0 & -\frac{\alpha_\chi}{r}e^{-m_\phi r} \\ -\frac{\alpha_\chi}{r}e^{-m_\phi r} & 0 \end{pmatrix}$$

- Cross sections

$$\sigma_{\text{tot}}^{(\text{el})} = \int d\Omega \, \frac{d\sigma^{(\text{el})}}{d\Omega} = \frac{\pi}{k_1^2}\sum_\ell (2\ell+1)\,|A_\ell|^2 \qquad \sigma_{\text{vis}}^{(\text{el})} = \int d\Omega \, \frac{d\sigma^{(\text{el})}}{d\Omega}\, \sin^2\theta = \frac{\pi}{k_1^2}\sum_\ell \frac{(\ell+2)(\ell+1)}{2\ell+3}\left|A_{\ell+2} - A_\ell\right|^2$$

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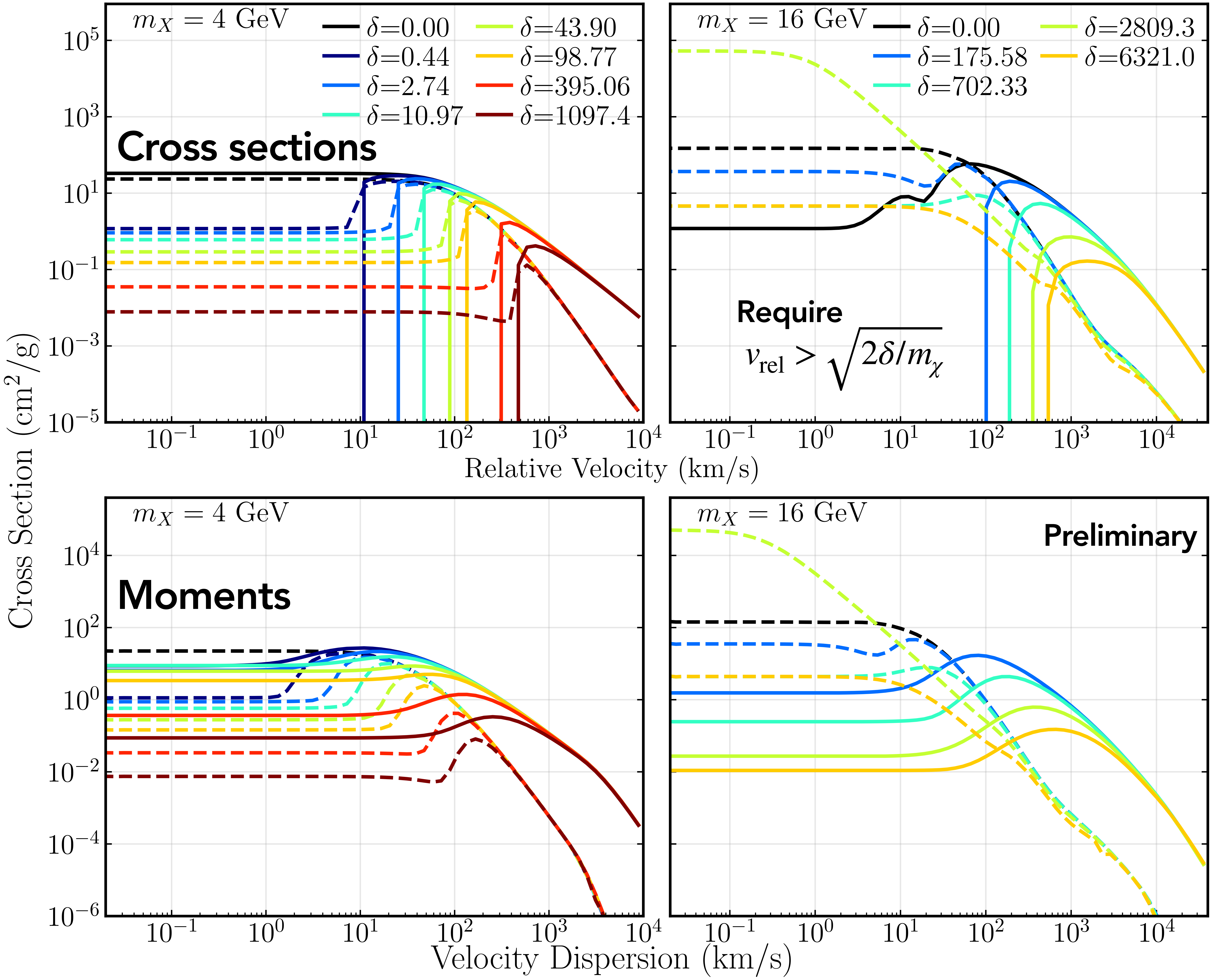

Simulations

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Simulating dSIDM

- To simulate our dSIDM halo, we consider two simulation suites:
  - **GravothermalSIDM**: uses the gravothermal fluid equations.
  - Elastic-only (Nishikawa, Boddy, Kaplinghat 2020, Outmezguine et al. 2022, Gad-Nasr et al. 2024)

$$\frac{\partial M}{\partial r} = 4\pi r^2 \rho, \qquad \frac{\partial(\rho \nu^2)}{\partial r} = -\frac{GM\rho}{r^2},$$

$$\frac{L}{4\pi r^2} = -\kappa \frac{\partial T}{\partial r}, \qquad \frac{1}{4\pi r^2}\frac{\partial L}{\partial r} = -\rho \nu^2 \left(\frac{\partial}{\partial t}\right)_M \ln\left(\frac{\nu^3}{\rho}\right) - \Gamma_{\rm cool}\,.$$

  - Dissipative modification in Essig, McDermott, Yu, Zhong 2019

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- **SPHerical**: a smoothed particle hydrodynamics framework, using results from Navier-Stokes equations to model spherically symmetric shells (Blaff 2021, MSc Thesis)

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Without dissipation

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$$D_t\mathbf{v} = -\frac{\nabla P}{\rho} + \mathbf{g}$$

$$D_t e = -\frac{P}{\rho}\nabla\cdot\mathbf{v} + \frac{1}{\rho}\nabla\cdot(\tilde{\kappa}\nabla e)$$

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With dissipation

$$D_t\rho_i = -\rho_i\nabla\cdot\mathbf{v}_i + \mathcal{S}_{\mathrm{decay},i} + \mathcal{S}_{\mathrm{up},i}$$

$$D_t\mathbf{v}_i = -\frac{\nabla P_i}{\rho_i} + \mathbf{g} + \boldsymbol{\mathcal{S}}_{\mathrm{decay},i} + \boldsymbol{\mathcal{S}}_{\mathrm{up},i}$$

$$D_t e_i = -\frac{P_i}{\rho_i}\nabla\cdot\mathbf{v}_i + \frac{1}{\rho_i}\nabla\cdot(\kappa_i\nabla e_i) + \tilde{\mathcal{S}}_{\mathrm{decay},i} + \tilde{\mathcal{S}}_{\mathrm{up},i}$$

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$$\tilde{\mathcal{S}}_{\text{decay},i} = \pm\int d\Pi_p d\Pi_q d\Pi_k (2\pi)^4\delta^4(q-p-k)\left(\sum|\mathcal{M}|^2\right)\mathbf{g}(\mathbf{u}_i)f_2(\mathbf{q})$$

$$\tilde{\mathcal{S}}_{\text{up},i} = \pm\int d\Pi_p d\Pi_{p'} d\Pi_q d\Pi_{q'} (2\pi)^4\delta^4(p+p'-q-q')\left(\sum|\mathcal{M}|^2\right)\mathbf{g}(\mathbf{u}_i)f_1(\mathbf{p})f_1(\mathbf{p}')$$

Fluid equations

Decays

Ground state

$$D_t\rho_1 = -\rho_1\nabla\cdot\mathbf{v}_1 + \Gamma_2\rho_2 - \frac{\rho_1^2}{2\sqrt{\pi}\nu_1^3}\int_0^\infty dv_{\rm rel}v_{\rm rel}^3\frac{\sigma_{\rm in}(v_{\rm rel})}{m_1}\exp\left(-\frac{v_{\rm rel}^2}{4\nu_1^2}\right),$$

$$D_t\mathbf{v}_1 = -\frac{\nabla P_1}{\rho_1} + \mathbf{g} - \Gamma_2\frac{\rho_2}{\rho_1}\mathbf{v}_{12},$$

$$D_t e_1 = -\frac{P_1}{\rho_1}\nabla\cdot\mathbf{v}_1 + \frac{1}{\rho_1}\nabla\cdot(\kappa_1\nabla e_1) + \Gamma_2\frac{\rho_2}{\rho_1}\left(\frac{1}{2m_1^2}(\delta^2 - m_\phi^2) + \frac{1}{2}|\mathbf{v}_{12}|^2 + (e_2 - e_1)\right)$$

$$-\frac{\rho_1}{16\sqrt{\pi}\nu_1^3}\int_0^\infty dv_{\rm rel}v_{\rm rel}^3\left(v_{\rm rel}^2 - 6\nu_1^2\right)\frac{\sigma_{\rm in}(v_{\rm rel})}{m_1}\exp\left(-\frac{v_{\rm rel}^2}{4\nu_1^2}\right),$$

Excited state

$$D_t\rho_2 = -\rho_2\nabla\cdot\mathbf{v}_2 - \Gamma_2\rho_2 + \frac{\rho_1^2}{2\sqrt{\pi}\nu_1^3}\int_0^\infty dv_{\rm rel}v_{\rm rel}^3\frac{\sigma_{\rm in}(v_{\rm rel})}{m_1}\exp\left(-\frac{v_{\rm rel}^2}{4\nu_1^2}\right),$$

$$D_t\mathbf{v}_2 = -\frac{\nabla P_2}{\rho_2} + \mathbf{g},$$

$$D_t e_2 = -\frac{P_2}{\rho_2}\nabla\cdot\mathbf{v}_2 + \frac{1}{\rho_2}\nabla\cdot(\kappa_2\nabla e_2)$$

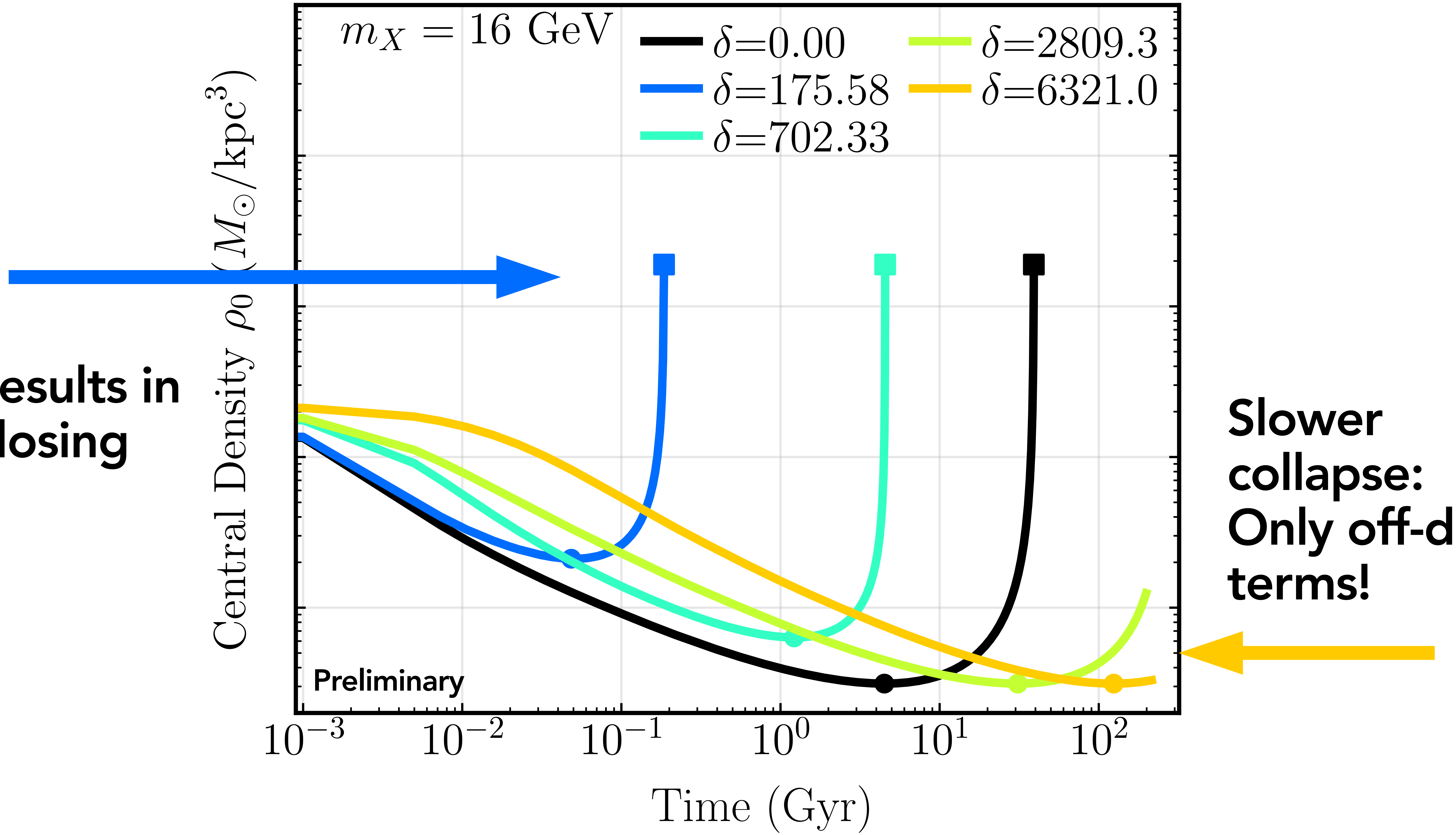
$$+\frac{\rho_1^2}{16\sqrt{\pi}\rho_2\nu_1^3}\int_0^\infty dv_{\rm rel}v_{\rm rel}^3\left(v_{\rm rel}^2 + 6\nu_1^2 + 4|\mathbf{v}_{12}|^2 - 8\frac{\delta}{m} - 8e_2\right)\frac{\sigma_{\rm in}(v_{\rm rel})}{m_1}\exp\left(-\frac{v_{\rm rel}^2}{4\nu_1^2}\right),$$

Upscattering

$$\Gamma_{\rm cool} = \frac{\rho\nu_{\rm loss}^2}{4\sqrt{\pi}\nu^3}\int_{2\nu_{\rm loss}}^\infty dv_{\rm rel}v_{\rm rel}^3\frac{\sigma_{\rm in}(v_{\rm rel})}{m}\exp\left(-\frac{v_{\rm rel}^2}{4\nu^2}\right)$$

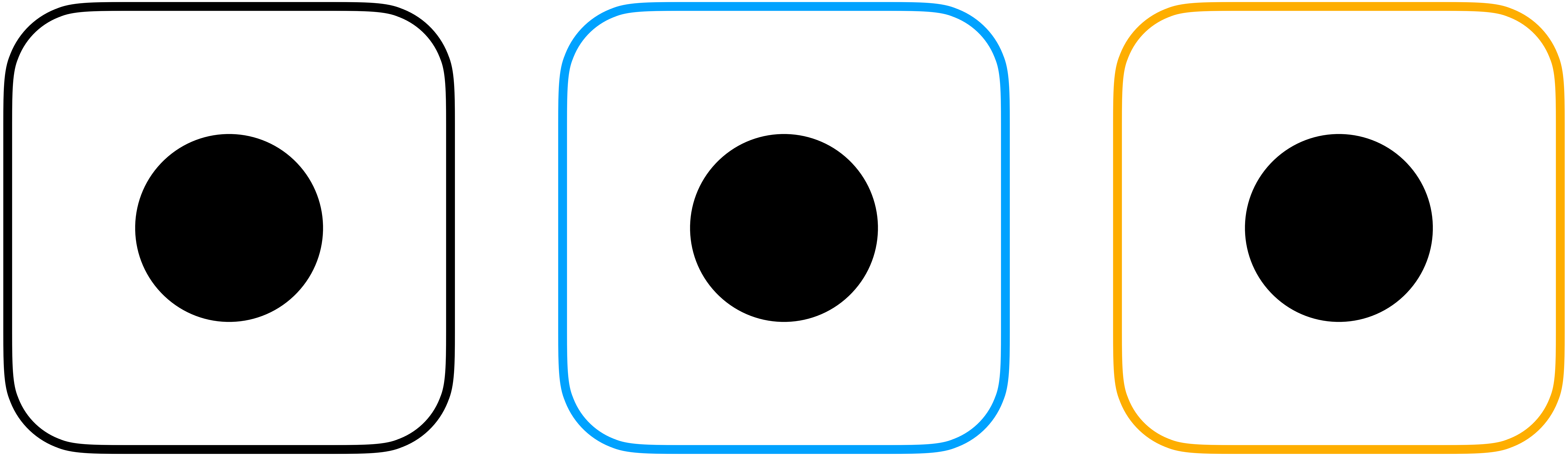
Core collapse

Faster collapse: Cooling results in particles losing energy



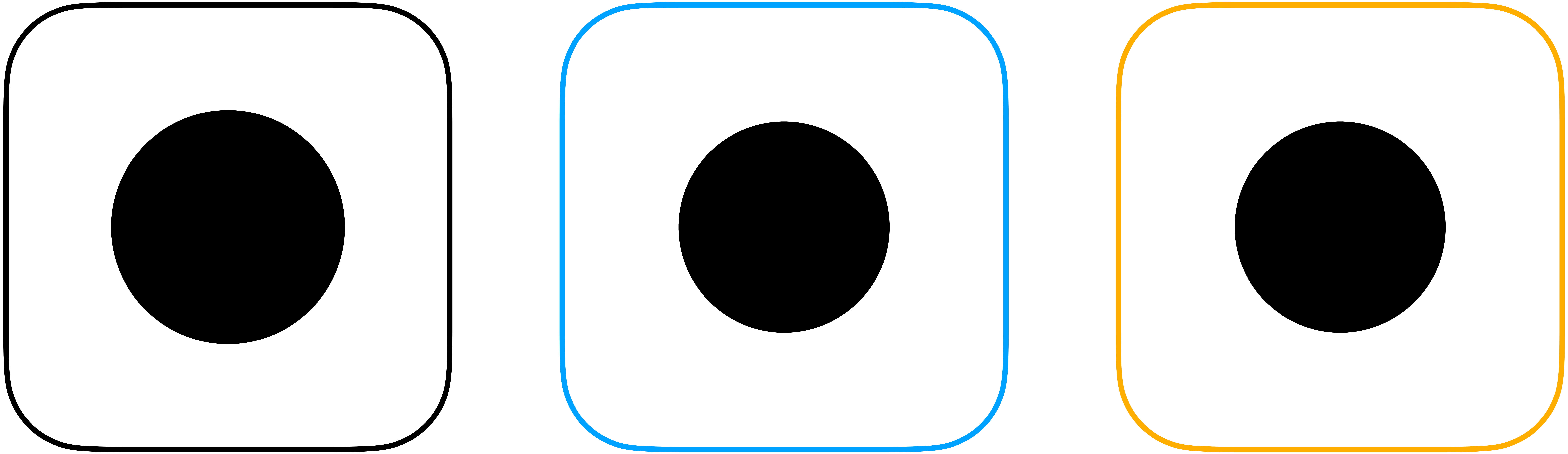
Slower collapse: Only off-diagonal terms!

Collapse animation (the worst, possibly)



$\delta = 0$ | δ small | δ large

Collapse animation (the worst, possibly)



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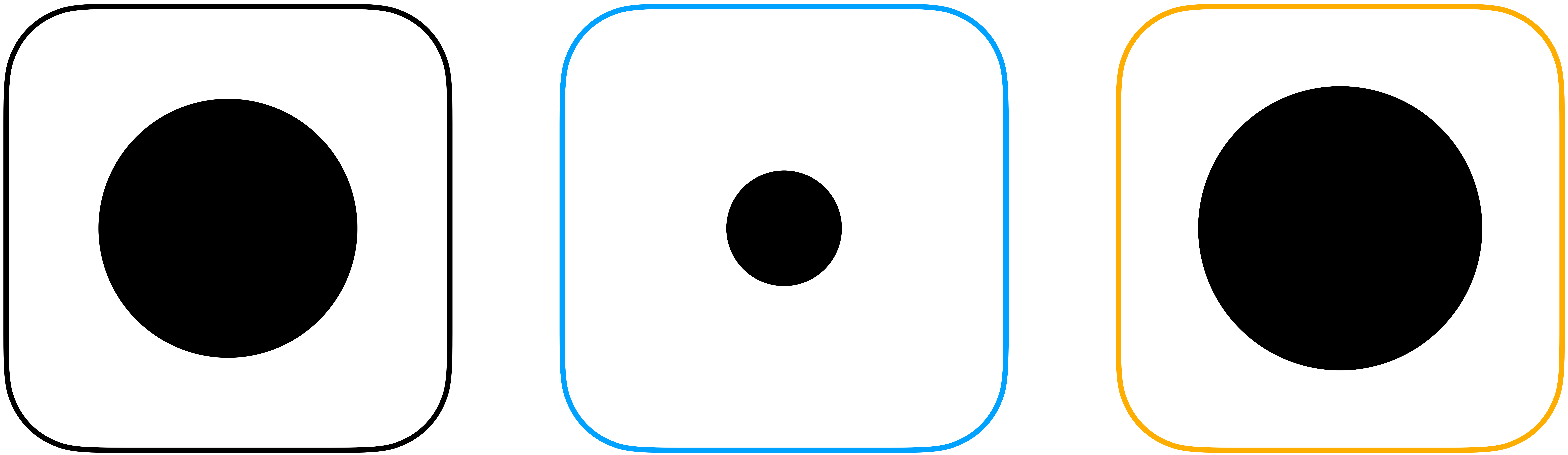

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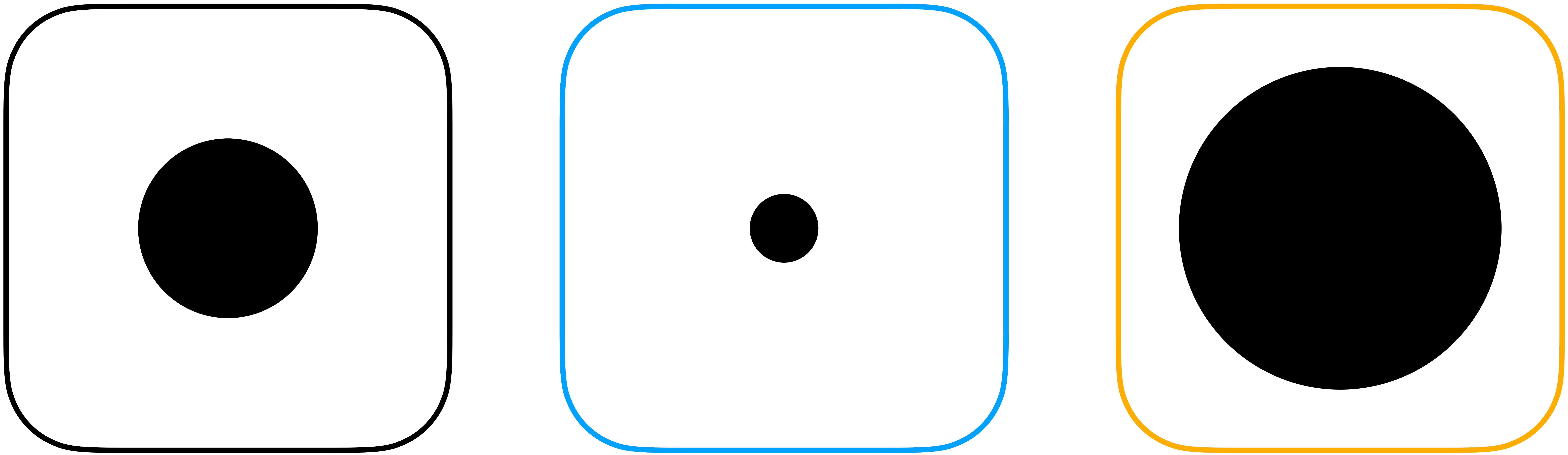

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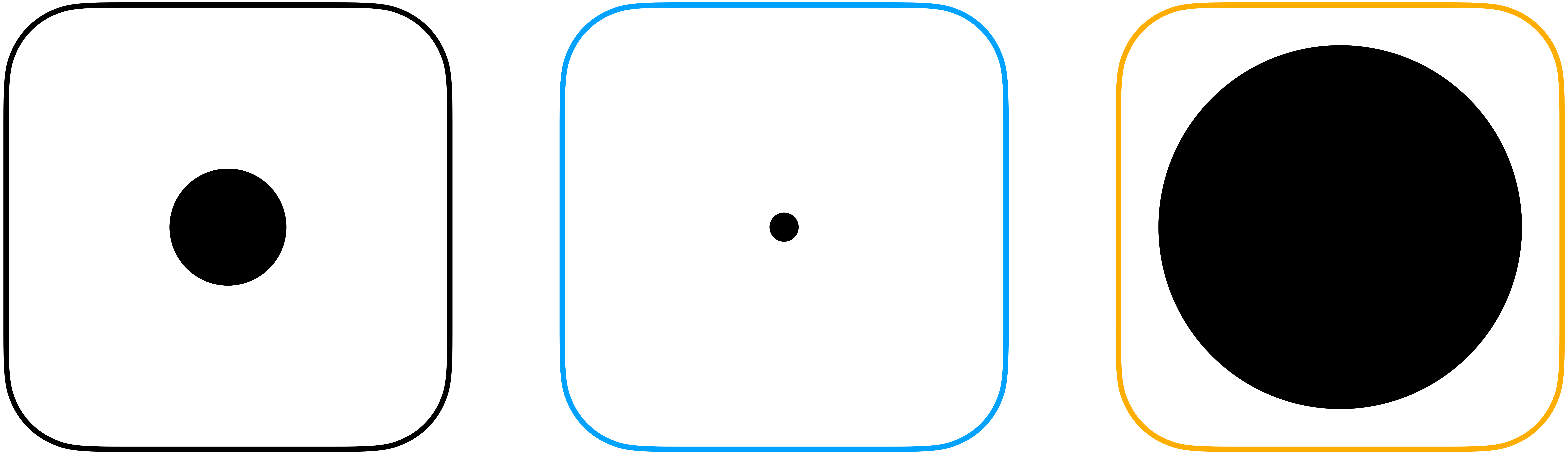

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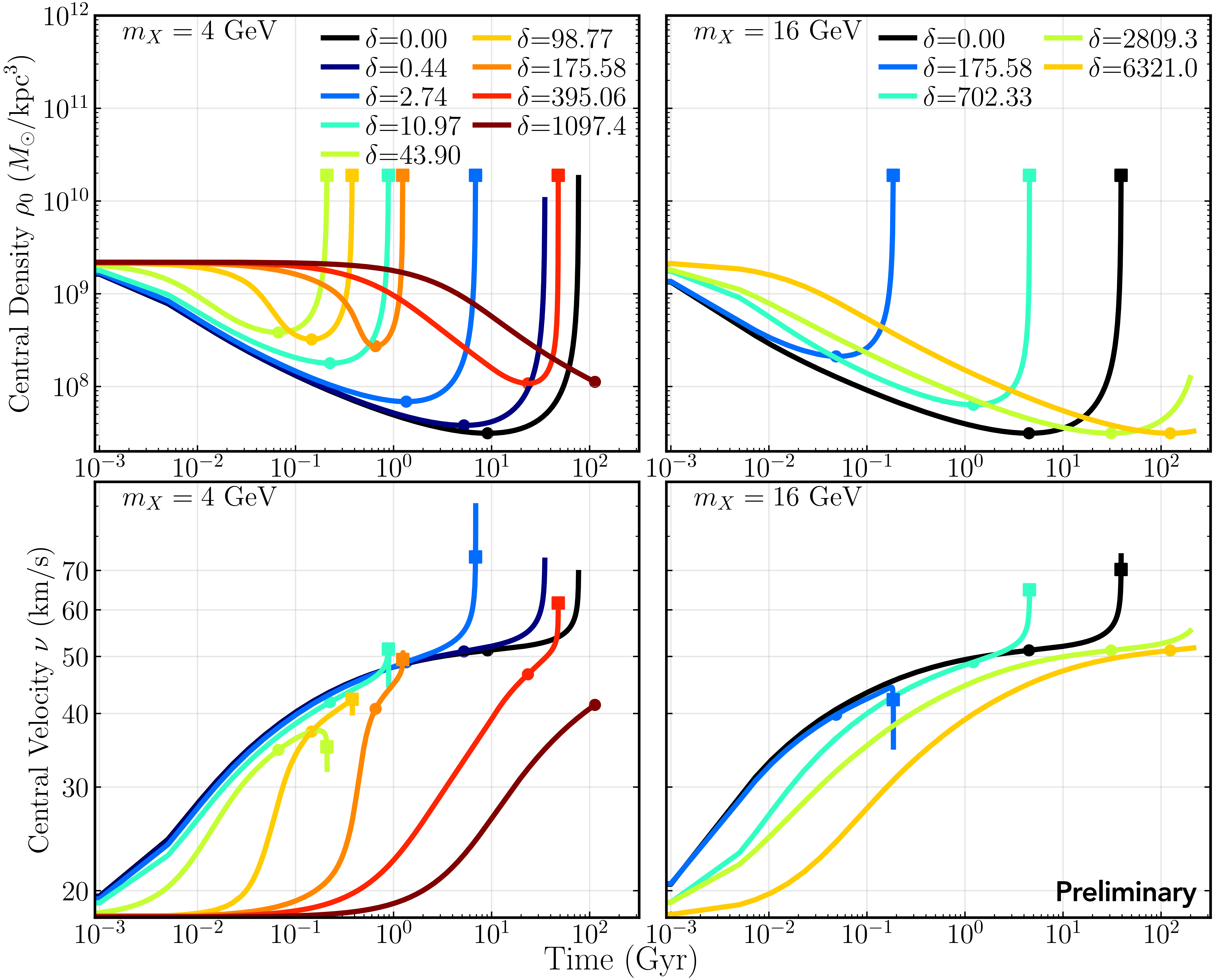
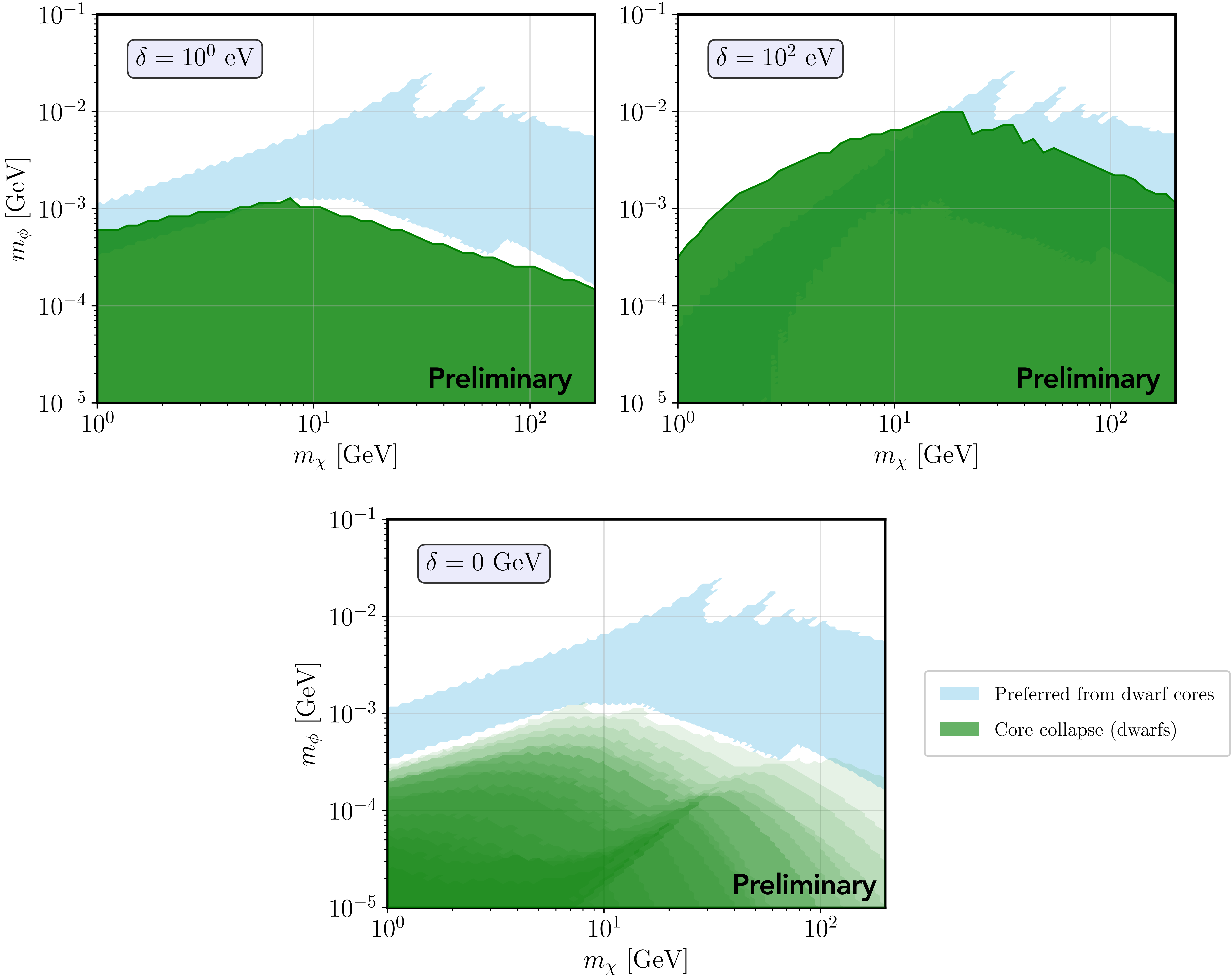


In all plots, $m_\phi = 10^{-3}$ GeV and units of δ are in eV

Parameter space

- DM-dominated dwarf galaxies prefer elastic cross sections between 0.5-50 cm²/g
- Can place constraints considering a catalog of dwarf galaxies that don't exhibit core collapse

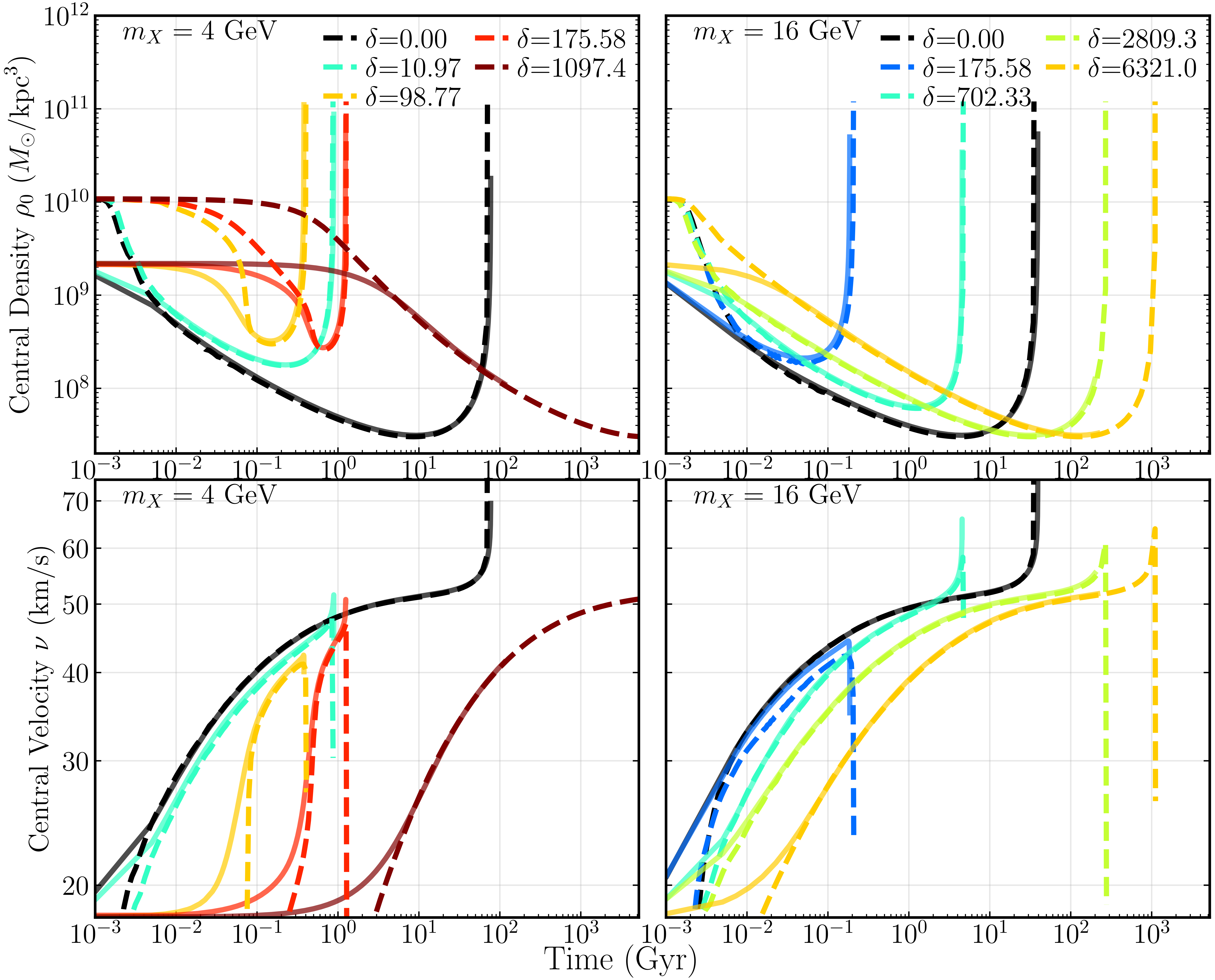


Summary

- Dissipation introduces new phenomenology beyond minimal SIDM models which only consider elastic scattering
- Cooling results in faster collapse
- Or, cooling may not be accessible while also suppressing elastic collisions, resulting in delayed collapse
- Can allow for more or less constraints for a given DM particle mass
- Fragmentation? -> Inelastic dark matter stars/compact objects/blobs?

Thank you!

Supplemental Slides



m_X = 4 GeV
δ=0.00
δ=10.97
δ=98.77
δ=175.58
δ=1097.4
m_X = 16 GeV
δ=0.00
δ=175.58
δ=702.33
δ=2809.3
δ=6321.0
Central Density ρ_0 ($M_\odot$/kpc^3)
Central Velocity ν (km/s)
Time (Gyr)
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{8}
10^{9}
10^{10}
10^{11}
10^{12}
20
30
40
50
60
70


Computation time [s] ($d = 10^{-1}$)
a
b
10^{2}
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
$\ell_{\max}$
b
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
100
30
16
11
7
0

More detail for cross sections

- This follows Blennow et al. 2017 and also Alvarez & Yu 2020
- Change of variables gives $$\left(\frac{d^2}{dx^2} + \mathbf{p}^2 - \frac{\ell(\ell+1)}{x^2} - \boldsymbol{\mathcal{V}}(x)\right)\boldsymbol{\chi}_\ell(x) = 0$$

where $$\boldsymbol{\chi}_{\boldsymbol{\ell}} = r\mathbf{R}_\ell\,, \quad x = \alpha_\chi m_\chi r\,, \quad \mathbf{p} = \begin{pmatrix} a & 0 \\ 0 & c \end{pmatrix}, \quad \boldsymbol{\mathcal{V}} = \begin{pmatrix} 0 & -\frac{1}{x}e^{-x/b} \\ -\frac{1}{x}e^{-x/b} & 0 \end{pmatrix}$$

$$a = \frac{v_{\rm rel}}{2\alpha_\chi}\,, \quad b = \frac{\alpha_\chi m_\chi}{m_\phi}\,, \quad c = \sqrt{a^2 - d^2}\,, \quad d = \sqrt{\frac{2\delta}{\alpha_\chi^2 m_\chi}}\,,$$

$$\frac{d\mathbf{U}_\ell}{dx} = \mathbf{p} + \left\{\mathbf{p}\frac{g_\ell'(\mathbf{p}x)}{g_\ell(\mathbf{p}x)}, \mathbf{U}_\ell\right\} - \mathbf{U}_\ell\,\mathbf{p}^{-1}\,\boldsymbol{\mathcal{V}}\,\mathbf{U}_\ell$$

$$f_\ell(z) = z\,j_\ell(z), \qquad g_\ell(z) = iz\,h_\ell^{(1)}(z)$$

$$\boldsymbol{\chi}_\ell(x) = f_\ell(\mathbf{p}x)\,\boldsymbol{\alpha}_\ell(x) - g_\ell(\mathbf{p}x)\,\boldsymbol{\beta}_\ell(x)\,.$$

$$A_\ell = \lim_{x\to\infty} \frac{f_\ell(ax)g_\ell(ax) - U_\ell(x)_{11}}{a g_\ell(ax)^2}$$

$$B_\ell = \lim_{x\to\infty} -\frac{U_\ell(x)_{21}}{c g_\ell(ax) g_\ell(cx)}$$