PASCOS 2026, Sheffield

Gravothermal Evolution of Dissipative Self-interacting Dark Matter Halos

[arXiv:2606.19428]

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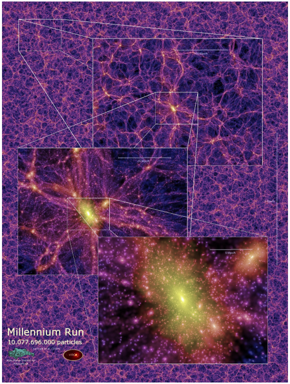
June 26, 2026

Motivation

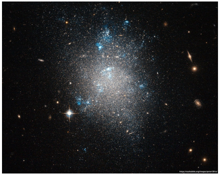
Simulations



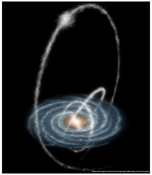
(Springel et al. 2005)

Observations

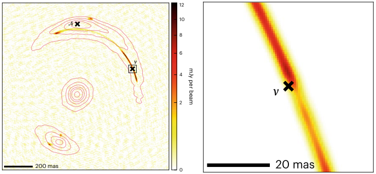
⇒ Small-scale DM distribution



Dwarf galaxies



Stellar streams



Strong lensing (Powell et al. 2025)

Particle physics of dark matter, e.g., self-interactions

Motivation
Particle physics

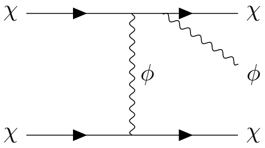
- **Mediator** models: “Bremsstrahlung”
  (Lankester-Broche and Pradler 2025)

$$\chi + \chi \to \chi + \chi + \phi$$

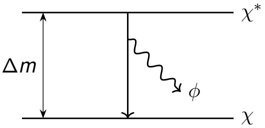
- More efficient dissipation: Decay of collisionally **excited (bound) states**

$$\chi + \chi \to \chi^* + \chi^*, \quad \chi^* \to \chi + \phi$$

  - Mirror DM (Foot 2004)
  - Atomic DM (Kaplan et al. 2010)
  - Asymmetric DM (Wise and Zhang 2014; Gresham et al. 2018)
  - Minimal two-state model (Schutz and Slatyer 2015)
  - Dark QCD (Kribs and Neil 2016)



Bremsstrahlung

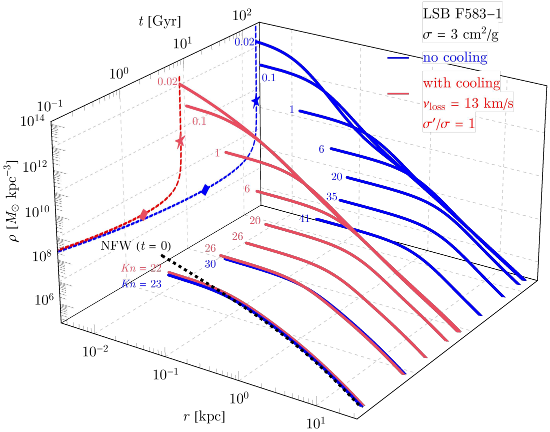


De-excitation

Motivation

Accelerated gravothermal evolution

Self-interacting DM: NFW ⇒ Core formation ⇒ Core collapse



(Essig et al. 2019)

- Exotic compact objects (Yu 2025)
- Early supermassive black holes (Choquette et al. 2019; Xiao et al. 2021)

Method

Method

N-body simulations

Goal: Solve **Poisson-Vlasov system** (6D)

$$\frac{\partial f}{\partial t} + \boldsymbol{v}\frac{\partial f}{\partial \boldsymbol{r}} - \frac{\partial \Phi}{\partial \boldsymbol{r}}\frac{\partial f}{\partial \boldsymbol{v}} = 0, \quad \nabla^2\Phi(\boldsymbol{r},t) = 4\pi G m \int \mathrm{d}^3\boldsymbol{v}\, f(\boldsymbol{r},\boldsymbol{v},t)$$

Goal: Solve **Poisson-Boltzmann system** (6D)

$$\frac{\partial f}{\partial t} + \boldsymbol{v}\frac{\partial f}{\partial \boldsymbol{r}} - \frac{\partial \Phi}{\partial \boldsymbol{r}}\frac{\partial f}{\partial \boldsymbol{v}} = \boxed{\mathcal{C}[f]}, \quad \nabla^2\Phi(\boldsymbol{r},t) = 4\pi G m \int \mathrm{d}^3\boldsymbol{v}\, f(\boldsymbol{r},\boldsymbol{v},t)$$

$\Rightarrow$ Evolve **N-particle representation** of $f(\boldsymbol{r},\boldsymbol{v},t)$:

$$\ddot{\boldsymbol{r}} = -\nabla\Phi(\boldsymbol{r}_i); \qquad \Phi(r) = -G\sum_{j=1}^{N}\frac{m_j}{\left[(\boldsymbol{r}-\boldsymbol{r}_j)^2+\epsilon^2\right]^{1/2}}$$

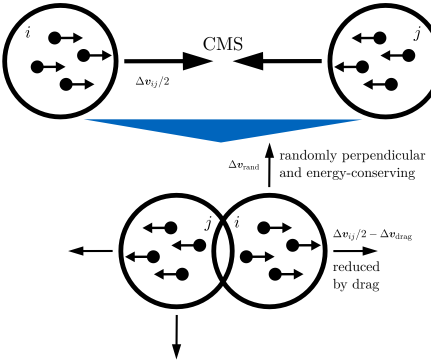
For SIDM: **Collision term** $\mathcal{C}[f]$

- Direct sampling from differential cross section (Burkert 2000)
- Frequent small-angle scattering: Drag + Diffusion (Fischer et al. 2021)

Method

Elastic fSIDM (Fischer et al. 2021)

→ `OpenGadget3` (Dolag et al., in prep.), based on `Gadget-2` (Springel 2005)



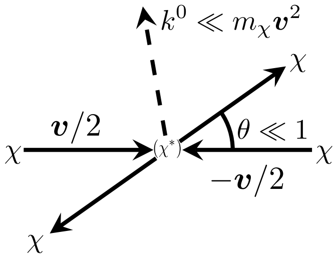
For all particles with kernel overlap:

1. Apply **drag**: $\Delta v_{\mathrm{drag}} = \Delta t \frac{\sigma_T}{2 m_\chi} \Delta v_{ij}^2 \int \mathrm{d}V \, \frac{\rho_i \rho_j}{m_{\mathrm{num}}}$
2. **Restore energy** perpendicularly ⇒ **Diffusion**

$$\Delta v_{\mathrm{rand}}^2 = \Delta v_{\mathrm{drag}} (\Delta v_{ij} - \Delta v_{\mathrm{drag}})$$

Method

Dissipative extension – Drag



$$\Leftrightarrow \qquad \frac{\mathrm{d}\sigma}{\mathrm{d}\Omega \mathrm{d}k^0}(v)$$

Over many frequent small-angle scatterings:

- Recoils $\boldsymbol{k}$ average out due to forward-backward symmetry
- Energy loss k^0 accumulates and **increases drag**:

$$\Delta \boldsymbol{v}_{\mathrm{drag}} \to \Delta \boldsymbol{v}_{\mathrm{drag}} \underbrace{\left[1 + \frac{8\pi}{\sigma_T} \int_0^{m_\chi \Delta v_{\mathrm{ij}}^2/4} \mathrm{d}k^0 \int_0^1 \mathrm{d}(\cos\theta) \boxed{\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega\, \mathrm{d}k^0}} \frac{k^0}{m_\chi \Delta v_{\mathrm{ij}}^2} \cos\theta\right]}_{\equiv\, r_{\mathrm{diss}} \,=\, \mathrm{const.\ for\ this\ work}}$$

Method

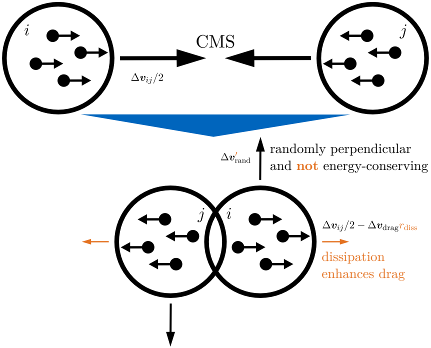
Dissipative extension – Kick

Energy loss per numerical interaction:

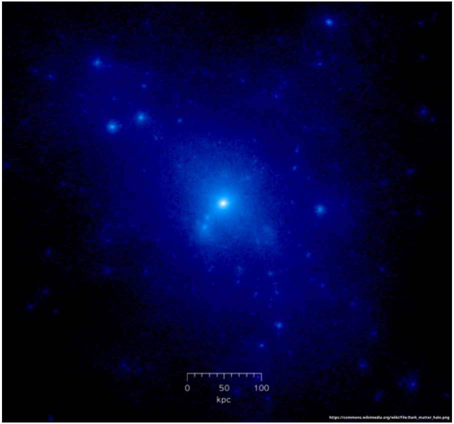
$$\Delta E = -\Delta t \frac{\sigma_T}{2m_\chi}(r_{\rm diss}-1)\Delta v_{ij}^3 \int \mathrm{d}V\, \rho_i \rho_j$$

$$\Downarrow$$

$$\Delta v_{\rm rand}'^2 = \Delta v_{\rm drag}\left(\frac{\Delta v_{ij}}{r_{\rm diss}} - \Delta v_{\rm drag}\right)$$



Isolated Halo

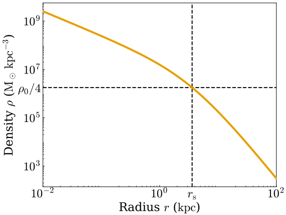


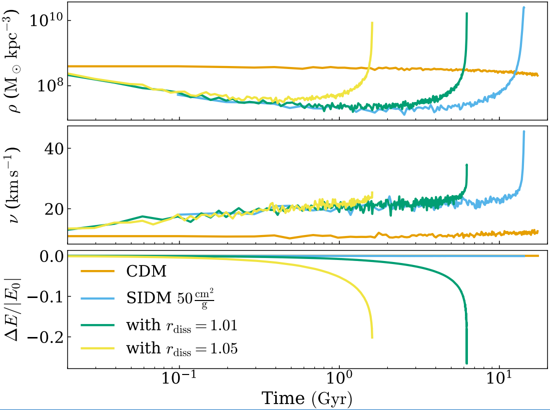
Isolated Halo

Central time evolution

NFW initial conditions:

- $r_s = 3.6\,\mathrm{kpc}$, $\rho_0 = 7.09 \times 10^6\,\mathrm{M_\odot\,kpc^{-3}}$
  $\Leftrightarrow M_{200} = 10^{10}\,\mathrm{M_\odot}$, $c_{200} \simeq 12$
- 5×10^6 particles

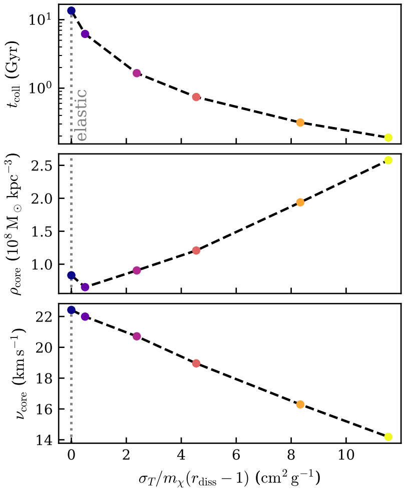




Isolated Halo

Varying simulation parameters

Vary cooling rate $\propto \frac{\sigma_\mathrm{T}}{m_\chi}(r_\mathrm{diss} - 1)$



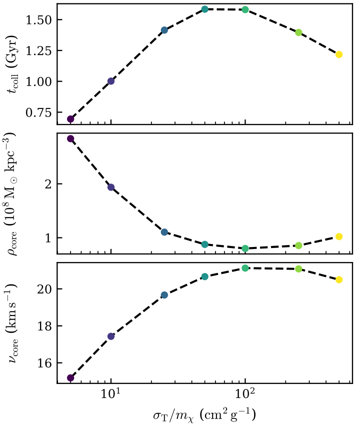
Take-home message

Dissipation suppresses core formation and accelerates collapse

Isolated Halo

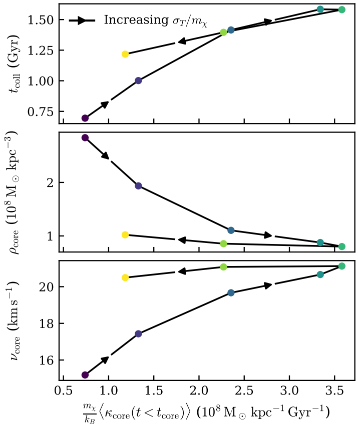
Varying simulation parameters

Vary cross section $\frac{\sigma_T}{m_\chi}$



$\Longrightarrow$

Heat conduction $\kappa \propto \begin{cases} \sigma_T, & \text{LMFP} \\ \sigma_T^{-1}, & \text{SMFP} \end{cases}$

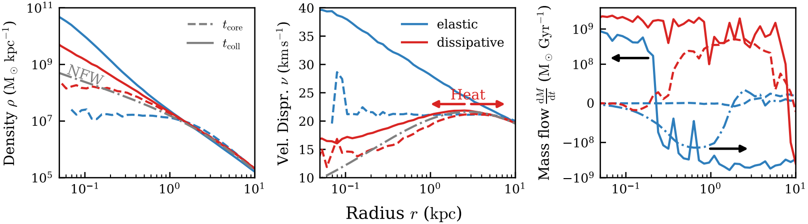


Take-home message

Heat conduction enhances core formation and delays collapse

Isolated Halo

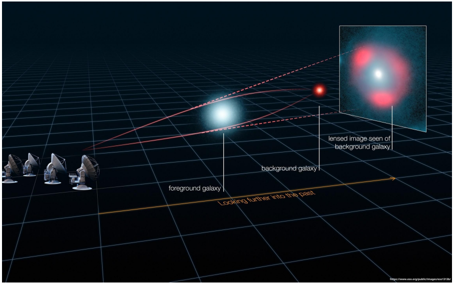
Radial profiles



Take-home messages

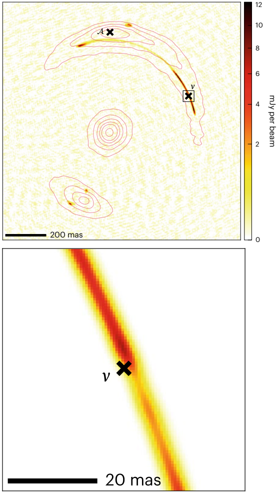
- Heat conduction remains directed inward and inhibits dissipation-induced collapse
- Radially more extended mass infall

JVAS B1938+666



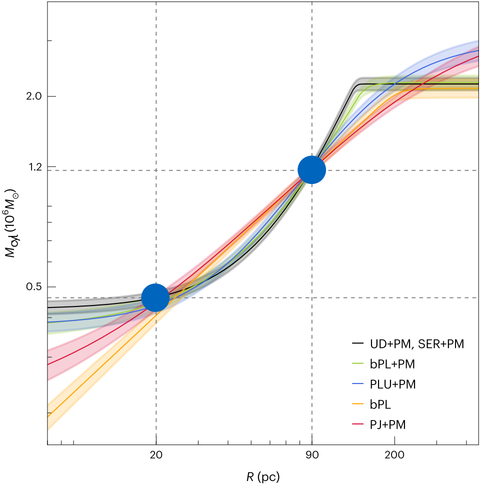
Exotic compact object in JVAS B1938+666 ($z = 0.881$)

Strong lensing observation



(Powell et al. 2025)

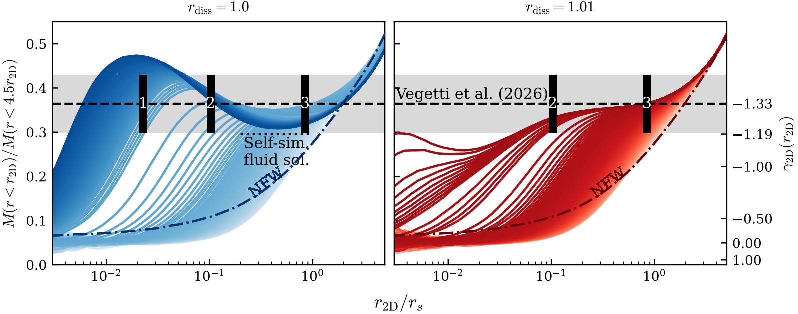
$\Longrightarrow$



(Vegetti et al. 2026)

Exotic compact object in JVAS B1938+666 ($z = 0.881$)

Explained by elastic and dissipative SIDM



(1) No collapse before $z = 0.881$

(3) 5σ above median mass-concentration relation

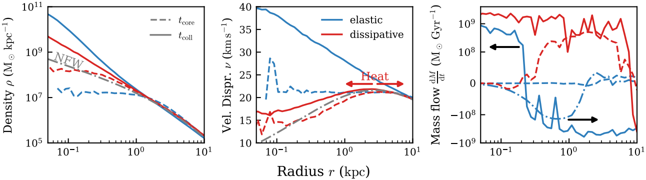
(2) Plausible in both cases with $\sigma_T/m_\chi \sim 10^2\,\mathrm{cm}^2/g$

Take-home message

Dissipative SIDM explains exotic compact object in JVAS B1938+666 with shorter evolution time or, equivalently, smaller cross section

Take-home messages

- Dissipation qualitatively alters gravothermal evolution beyond acceleration:
  - Suppressed core formation
  - Conduction remains directed inward and inhibits dissipation-induced collapse
  - Radially more extended mass infall
- Dissipative SIDM explains exotic compact object in JVAS B1938+666 with shorter evolution time or, equivalently, smaller cross section



For more details: [arXiv:2606.19428]

Thanks for Listening!

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Backup

Dissipative fSIDM with multiple reactions

Multiple reactions labeled by r:

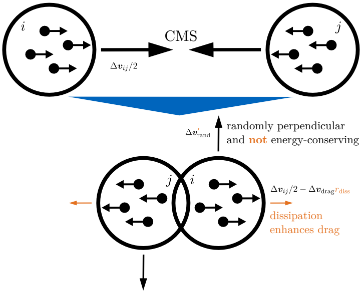
- Both drag velocity $|\Delta \boldsymbol{v}^r_{\text{drag}}|$ and ΔE^r directly sum up:

$$|\Delta \boldsymbol{v}_{\text{drag}}| \propto \sum_r \sigma_T^r r^r_{\text{diss}}$$
$$\Delta E \propto \sum_r \sigma_T^r (r^r_{\text{diss}} - 1)$$

- Identifying these with the expressions for $r = 1$ defines effective quantities:

$$\sigma_T^{\text{eff}} = \sum_r \sigma_T^r, \quad r^{\text{eff}}_{\text{diss}} = \frac{\sum_r \sigma_T^r r^r_{\text{diss}}}{\sum_r \sigma_T^r}$$

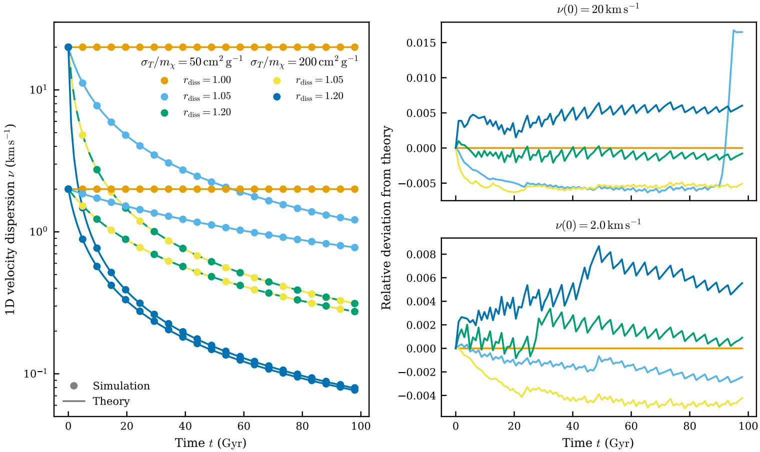
$\Rightarrow$ Use standard algorithm with these



Method

Validation

- Periodic box, constant density, no gravity, Maxwell-Boltzmann velocities around velocity dispersion ν
- Expected cooling: $\frac{\mathrm{d}E}{\mathrm{d}V\,\mathrm{d}t} = -\frac{8}{\sqrt{\pi}}\frac{\sigma_T}{m_\chi}(r_{\mathrm{diss}} - 1)\rho^2\nu^3 = \frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{3}{2}\rho\nu^2\right)$



Gravothermal evolution of an isolated halo

Comparison with simple isotropic model

$$\boldsymbol{v} \to \boldsymbol{v}'$$

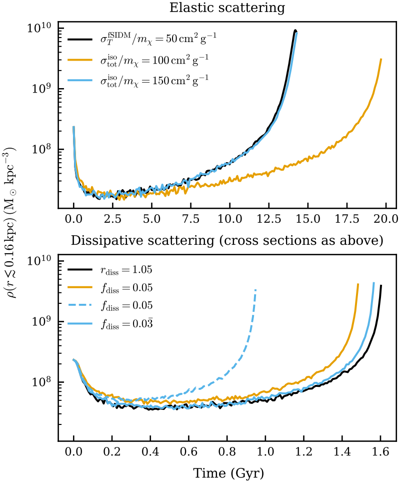
with

- uniform $\hat{v}'$
- reduced kinetic energy
  $v' = \sqrt{1 - f_{\mathrm{diss}}}\, v$ (cf. Shen et al. 2021)

$$\Downarrow$$

Similar evolution as fSIDM if

$$\boxed{\sigma_{\mathrm{tot}}^{\mathrm{iso}} \leftrightarrow 3\sigma_{\mathrm{T}}^{\mathrm{fSIDM}}, \quad f_{\mathrm{diss}} = \frac{2}{3}(r_{\mathrm{diss}} - 1)}$$



Take-home message

Subdominant impact of angular dependence

Gravothermal fluid model (Balberg et al. 2002; Essig et al. 2019)

$$\frac{\partial M}{\partial r} = 4\pi r^2 \rho$$ continuity equation

$$\frac{\partial(\rho\nu^2)}{\partial r} = -\frac{GM\rho}{r^2}$$ hydrostatic equilibrium

$$\frac{L}{4\pi r^2} = -\frac{m_\chi}{k_B}\kappa\frac{\partial\nu^2}{\partial r}$$ luminosity (Fourier's law)

$$\rho\nu^2\left(\frac{\mathrm{d}}{\mathrm{d}t}\right)_M \log\frac{\nu^3}{\rho} = -\frac{1}{4\pi r^2}\frac{\partial L}{\partial r} - \boxed{\underbrace{C(\rho,\nu)}_{\text{cooling}}}$$ energy flow

with pressure $P = \rho\nu^2 = \frac{\rho}{m_\chi}k_B T$ and heat conductivity

$$\kappa = \left(\kappa_{\mathrm{SMFP}}^{-1} + \kappa_{\mathrm{LMFP}}^{-1}\right)^{-1} \propto \begin{cases} \nu/\sigma_{\mathrm{tot}}, & \text{SMFP } \lambda \ll H \\ \beta\sigma_{\mathrm{tot}}\rho\nu^3, & \text{LMFP } \lambda \gg H \end{cases}$$