Simulating Self-Interacting Dark Matter: From Particle Physics to Structure Formation

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Self-Interacting Dark Matter (SIDM)

Do dark matter particles scatter off each other?

Would this leave imprints on small-scale cosmic structures?
For example: cored central halo densities, diverse rotation curves, rounder halos, subhalo evaporation, merger offsets, …

Might this probe the particle physics of dark matter?

Particle-physics ingredients of SIDM

Field / particle content

Field	Symbol	Spin	Analogy in the SM
Scalar DM	s	0	Higgs boson, mesons (e.g. pions)
Fermionic DM	χ	1/2	Quarks, leptons (e.g. electron), baryons (e.g. proton, neutron)
Vector DM	χ_μ	1	Gauge bosons (e.g. photon, $W^\pm$, Z^0)
Scalar mediator	ϕ	0	Higgs boson (scalar interaction mediator)
Vector mediator	ϕ_μ	1	Photon, $W^\pm$, Z^0, gluons (force carriers)

+

Symmetries & constraints

- Lorentz invariance
- Gauge symmetry
- Global symmetries
- Renormalizability, …

→

Lagrangian interaction terms

$$\mathcal{L}_{\rm int} \supset \begin{cases} -\frac{\lambda}{4!}\, s^4, & \text{(real scalar)} \\ -\lambda\,(s^\dagger s)^2, & \text{(complex scalar)} \end{cases}$$

$$\mathcal{L}_{\rm int} \supset \begin{cases} \frac{\mu}{2}\, s^2\phi & \text{(real scalar DM)} \\ \mu\,(s^\dagger s)\phi & \text{(complex scalar DM)} \end{cases}$$

$$\mathcal{L}_{\rm int} \supset \begin{cases} \frac{\kappa}{4}\, s^2\phi^2 & \text{(real scalar DM)} \\ \kappa\,(s^\dagger s)\phi^2 & \text{(complex scalar DM)} \end{cases}$$

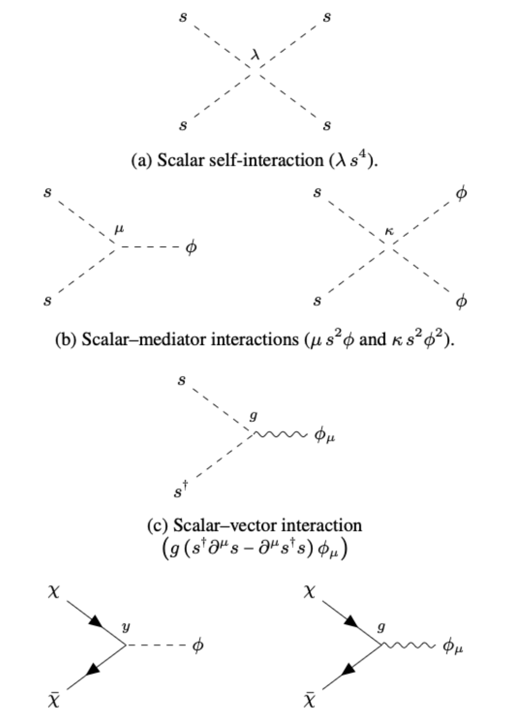
$$\mathcal{L}_{\rm int} \supset g\,(s^\dagger \partial^\mu s - \partial^\mu s^\dagger s)\,\phi_\mu$$

$$\mathcal{L}_{\rm int} \supset y\,\bar{\chi}\chi\,\phi,$$

$$\mathcal{L}_{\rm int} \supset g\,\bar{\chi}\gamma^\mu\chi\,\phi\mu,$$

→

Fundamental interactions



(a) Scalar self-interaction ($\lambda\, s^4$).

(b) Scalar–mediator interactions ($\mu\, s^2\phi$ and $\kappa\, s^2\phi^2$).

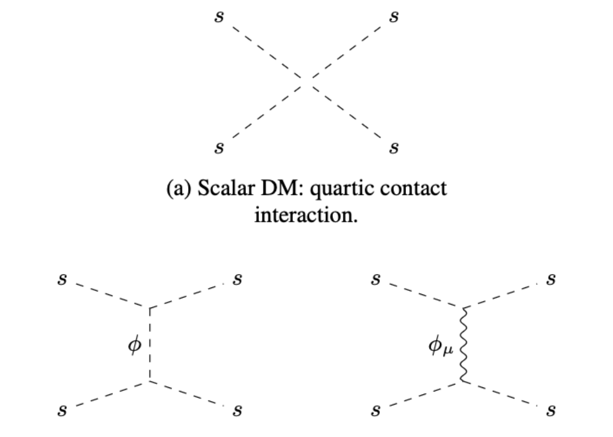
(c) Scalar–vector interaction ($g\,(s^\dagger\partial^\mu s - \partial^\mu s^\dagger s)\,\phi_\mu$)

(d) Fermion–scalar (Yukawa) interaction ($y\,\bar{\chi}\chi\,\phi$).

(e) Fermion–vector interaction ($g\,\bar{\chi}\gamma^\mu\chi\,\phi_\mu$).

→

Scattering Feynman diagrams



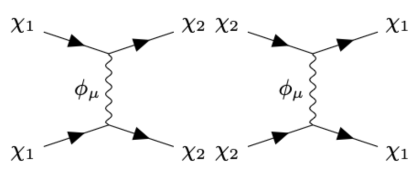
(a) Scalar DM: quartic contact interaction.

(b) Scalar DM: scalar mediator exchange (ϕ).

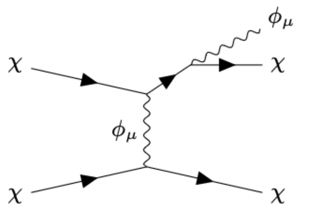
(c) Scalar DM: vector mediator exchange (ϕ_μ).

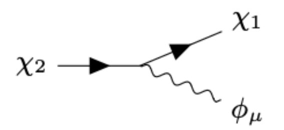
(d) Fermionic DM: scalar mediator exchange (ϕ).

(e) Fermionic DM: vector mediator exchange (ϕ_μ).



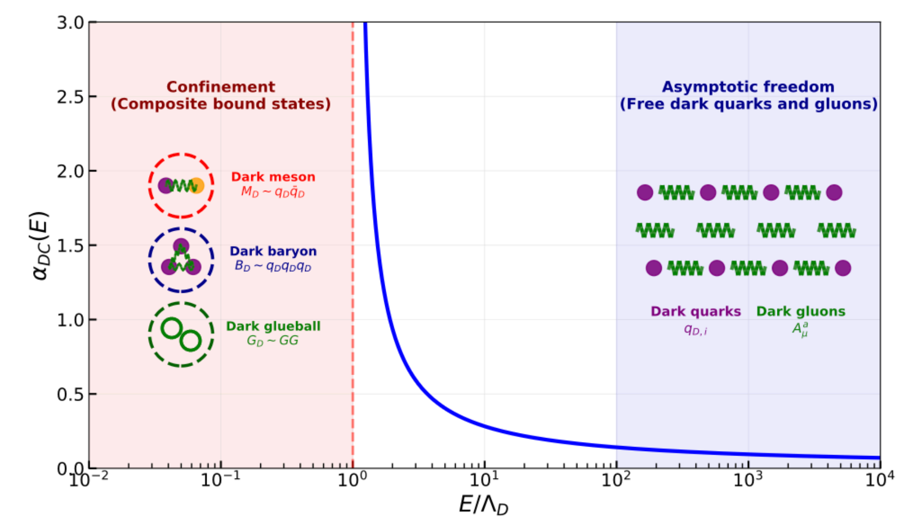
(a) $\chi_1\chi_1 \to \chi_2\chi_2$ (b) $\chi_2\chi_2 \to \chi_1\chi_1$





Particle-physics ingredients of composite SIDM

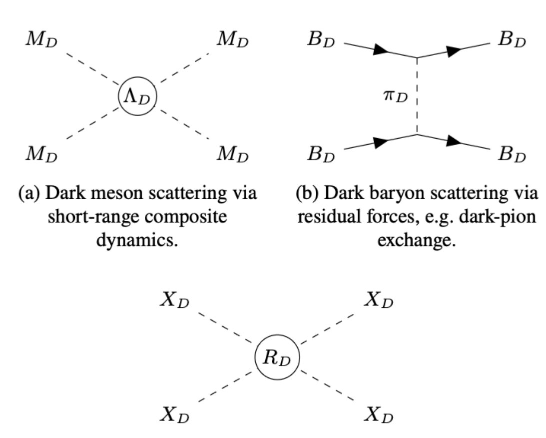
Strong coupling → confinement → composite bound states



Elementary and composite dark particles

Microscopic ingredient	Symbol / structure	Dark-sector interpretation	Visible-sector analogue
Dark constituent fermion	$q_{D,i}$	Dark quark	Quark
Dark gauge boson	A^a_μ	Dark gluon	Gluon
Dark gauge group	$SU(N)_{\rm DC}$, $SO(N)_{\rm DC}$, $Sp(N)_{\rm DC}$	Dark gauge symmetry	QCD color group
Dark meson	$M_D \sim q_D\bar{q}_D$	Composite boson	Pion, kaon, ρ meson
Dark baryon	$B_D \sim q_D q_D \cdots q_D$	Composite fermion or boson	Proton, neutron
Dark glueball	$\mathcal{O}_{\rm GB} \sim {\rm Tr}(G_{\mu\nu}G^{\mu\nu})$	Pure gauge bound boson	Glueball
Dark pion (pNGB)	$\pi_D \sim q_D\bar{q}_D$ (pNGB)	Light composite boson	QCD pion
Weakly bound state	$(p_D e_D)_{\rm bound}$	Dark atom / molecule	Hydrogen atom / molecule

Scattering Feynman diagrams



(a) Dark meson scattering via short-range composite dynamics.

(b) Dark baryon scattering via residual forces, e.g. dark-pion exchange.

(c) Resonantly enhanced scattering via a near-threshold composite state R_D.

Fundamental Lagrangian

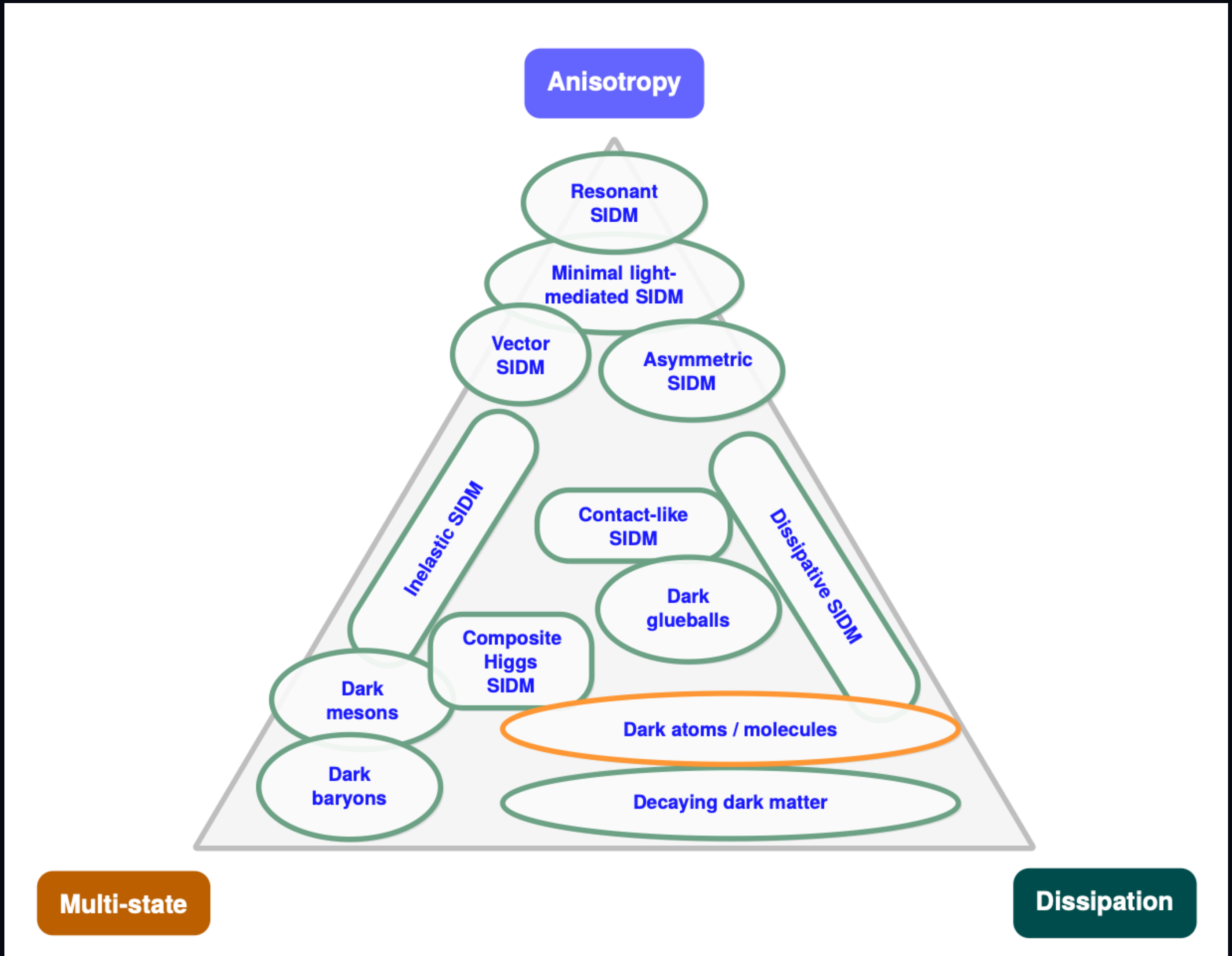
$$\mathcal{L}_{\rm DC} = -\frac{1}{4}G^a_{\mu\nu}G^{a\,\mu\nu} + \sum_i \bar{q}_{D,i}(i\gamma^\mu D_\mu - m_i)q_{D,i}$$

$$D_\mu = \partial_\mu + i g_{\rm DC} T^a A^a_\mu$$

Effective Lagrangian term With composite DM particles

$$\mathcal{L}_{\rm eff} \supset \frac{C_6}{\Lambda_D^2}(M_D^\dagger M_D)^2$$

SIDM particle-physics model classes



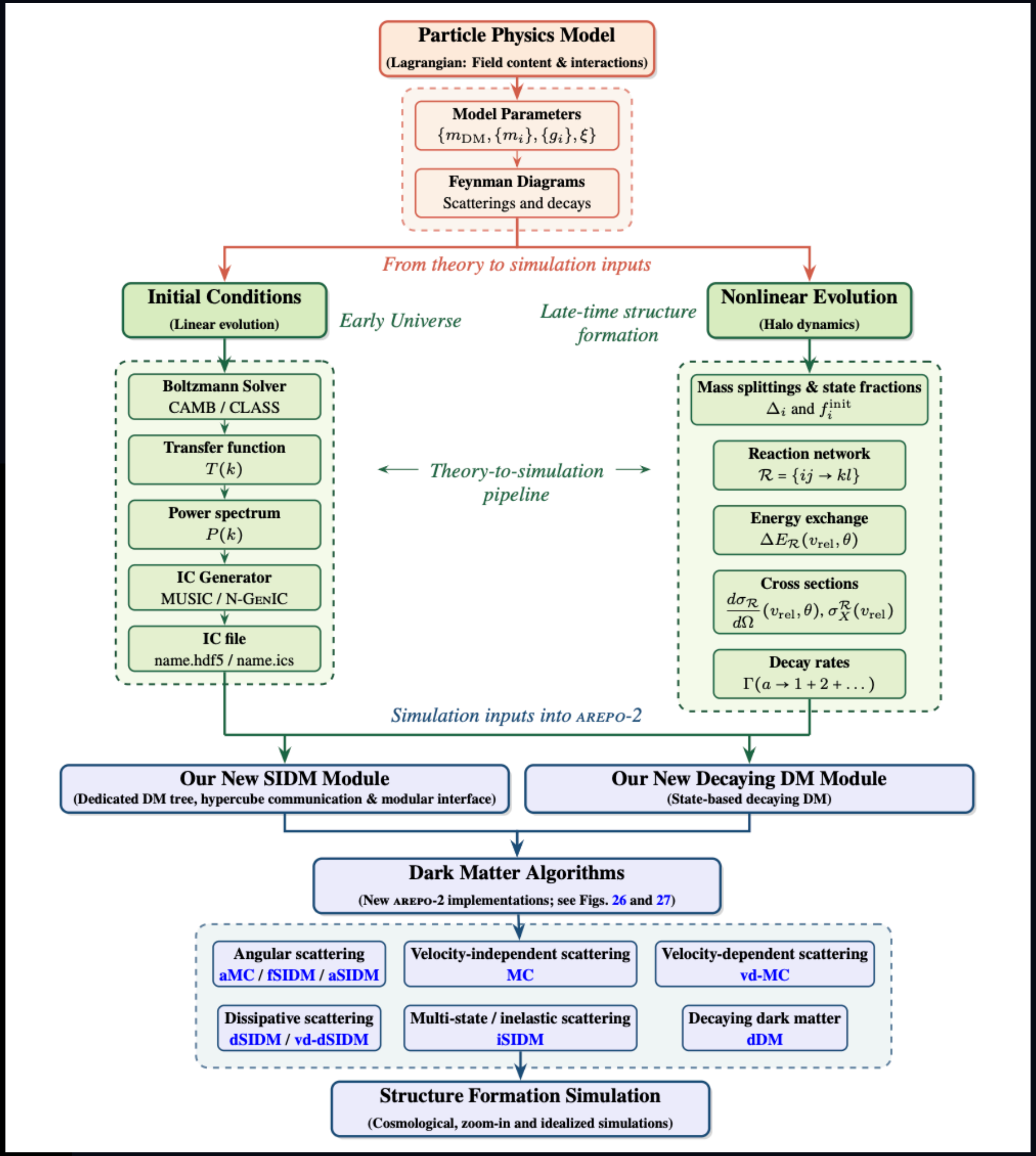
Qualitative three-axis map of SIDM particle-physics models according to (i) interaction range and anisotropy, (ii) internal-state structure and (iii) thermodynamic character. From arXiv:2608.xxxxx

Theory-to-simulation pipeline

Developed a theory-to-simulation pipeline that translates SIDM particle-physics models into simulation inputs and feeds them into the algorithms.

Theory-to-simulation pipeline:
Particle Physics → Simulation Inputs → Structure Formation Simulation

1. **Initial conditions**:
   Generated from the linear matter power spectrum $P(k)$, which specifies the amplitude of density fluctuations as a function of scale in the early Universe.
2. **Internal state structure**:
   Macroparticle mass splittings ΔM_i and initial state fractions $f_i^{\rm init}$ with $\sum f_i^{\rm init} = 1$, which encode the spectrum and relative abundance of internal states i.
3. **Reaction network**:
   $R = \{ij \to kl\}$, including all allowed elastic and inelastic scattering channels between dark-sector states.
4. **Energy exchange**:
   $\Delta E_{\rm R}(v_{\rm rel}, \theta)$ per reaction, including kinetic energy redistribution, inelastic transitions and dissipative energy loss through radiation or other channels.
5. **Differential and angle – weighted cross sections**:
   $\frac{d\sigma}{d\Omega}(\theta, v_{\rm rel})$ and $\sigma_X(v_{\rm rel})$, which determine both the scattering rate and the angular structure of momentum transfer.
6. **Decay rates**:
   $\Gamma(a \to 1 + 2 + \ldots)$ for unstable species a decaying into lighter states, $1 + 2 + \ldots$, which can dynamically modify the state populations and inject kinetic energy into daughter particles.



Mapping particle-physics models onto simulation inputs for structure-formation simulations. From arXiv:2608.xxxxx

A Novel Implementation of SIDM in AREPO-2

The new SIDM module features several key improvements:

Parallelization scheme that can handle multiple scatterings per timestep

Decoupled DM neighbour search from the gravity tree

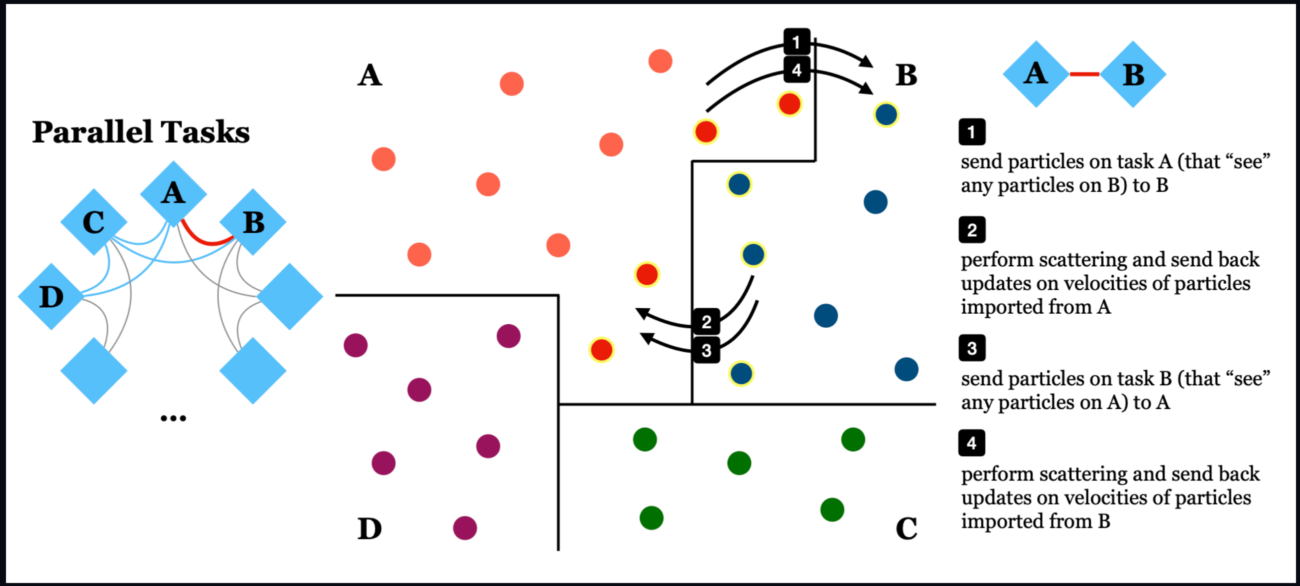
Batched tree walks

Flexible scattering rate estimators: one-sided kernel or kernel overlap.

State-dependent smoothing length in multi-state neighbor search

Extensible SIDM interface. We have implemented and extensively tested the algorithms:

- Isotropic Monte-Carlo scattering (MC)
- Velocity-dependent MC scattering (vd-MC)
- Anisotropic MC scattering (aMC)
- Frequent small-angle scattering (fSIDM)
- Anisotropic hybrid scattering (aSIDM)
- Multi-state Inelastic scattering (iSIDM)
- Constant dissipative SIDM (dSIDM)
- Velocity-dependent dissipative SIDM (vd-dSIDM)



Parallel communication scheme. From arXiv:2607.05504

A New decaying DM (DDM) module (independent of the SIDM module), with the algorithms:

- Standalone DDM algorithm
- State-based DDM algorithm

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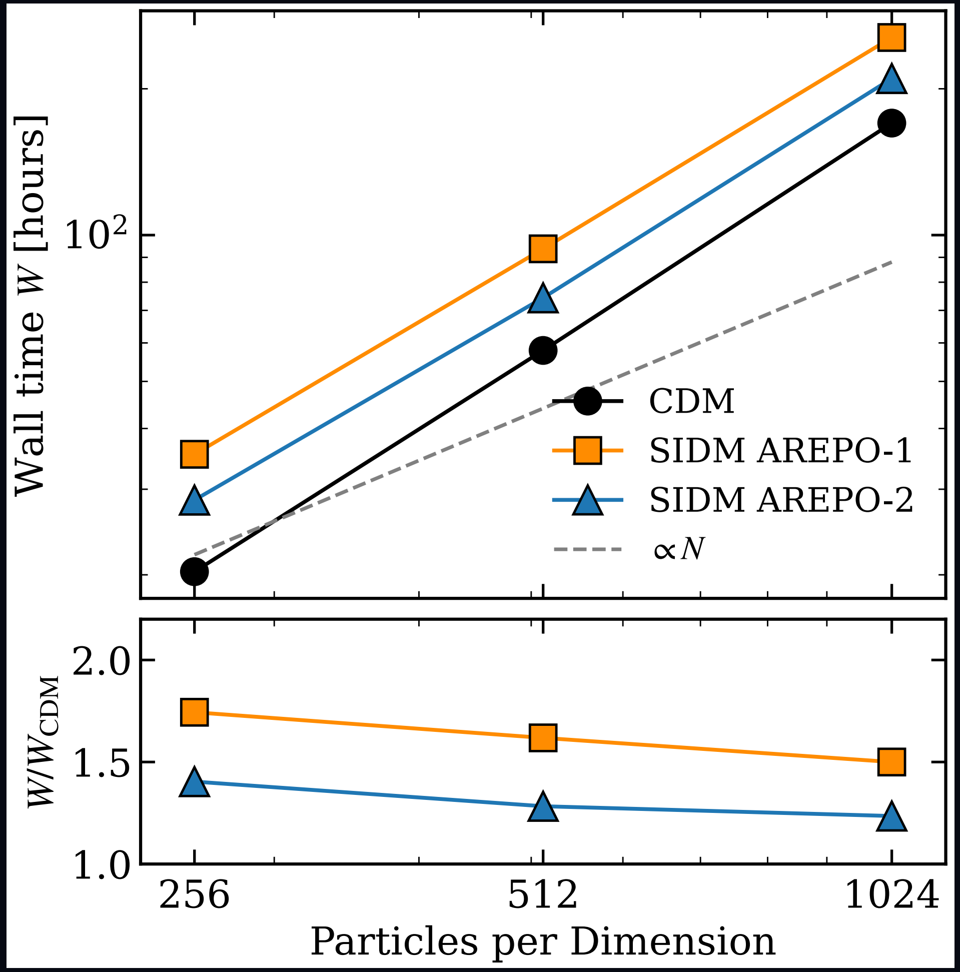
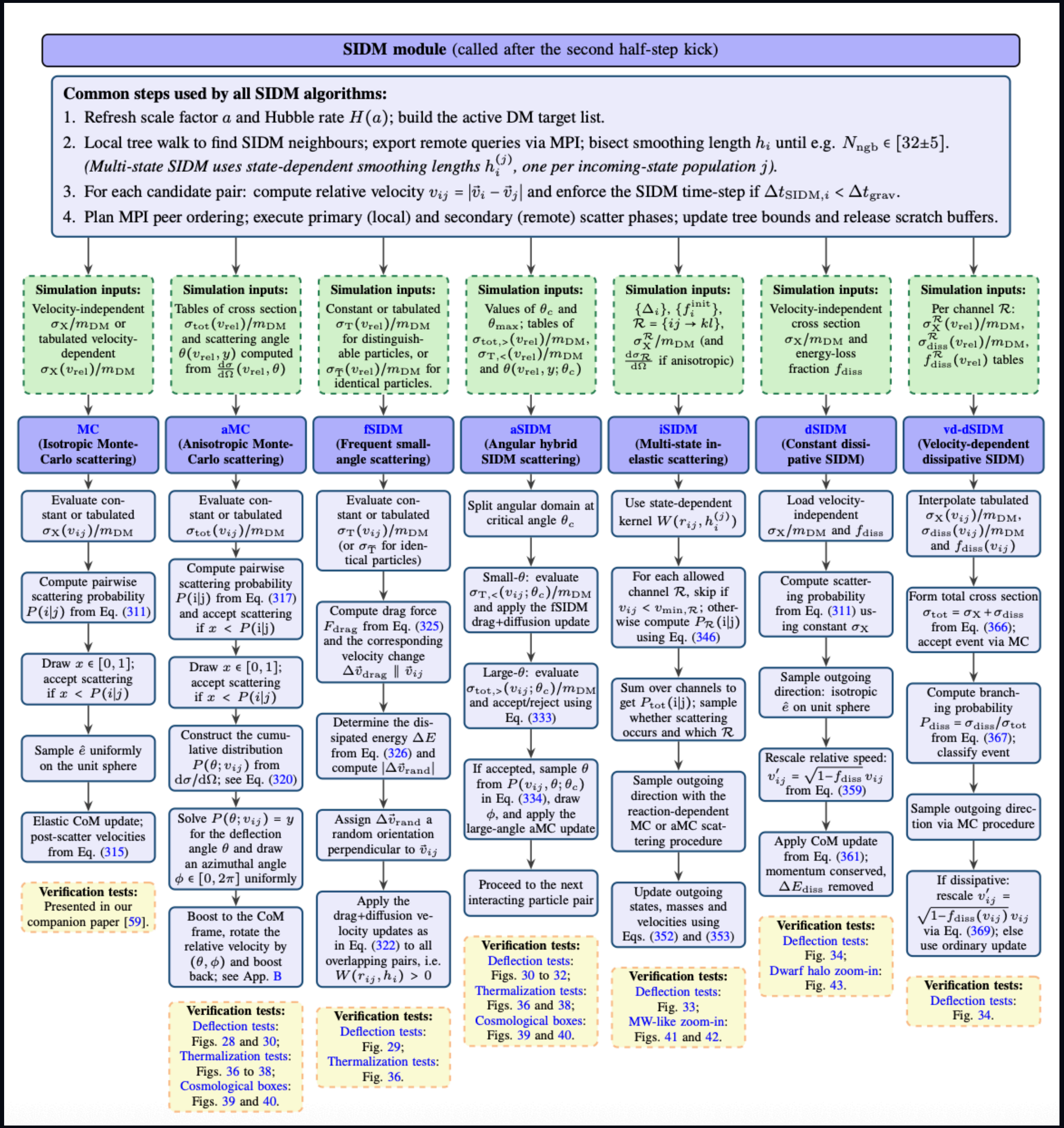
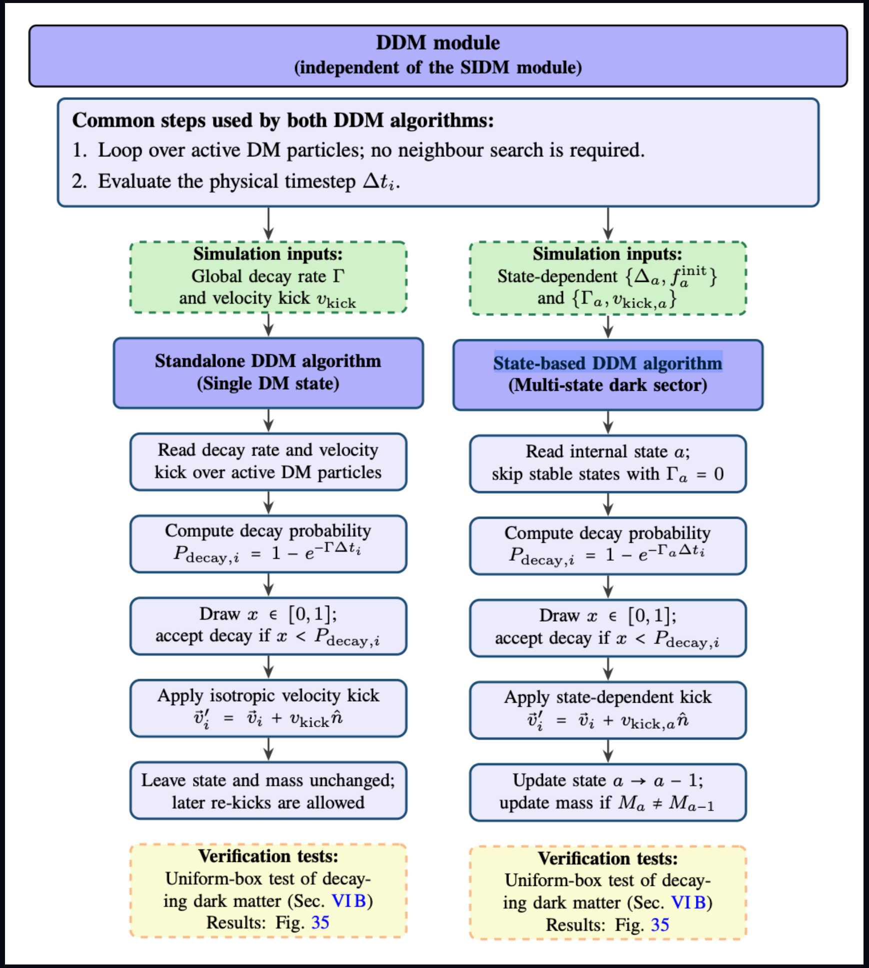


Wall-clock time for 25 Mpc cosmic-box runs at three resolutions.
From our new paper, arXiv:2607.05504.

The new DM algorithms



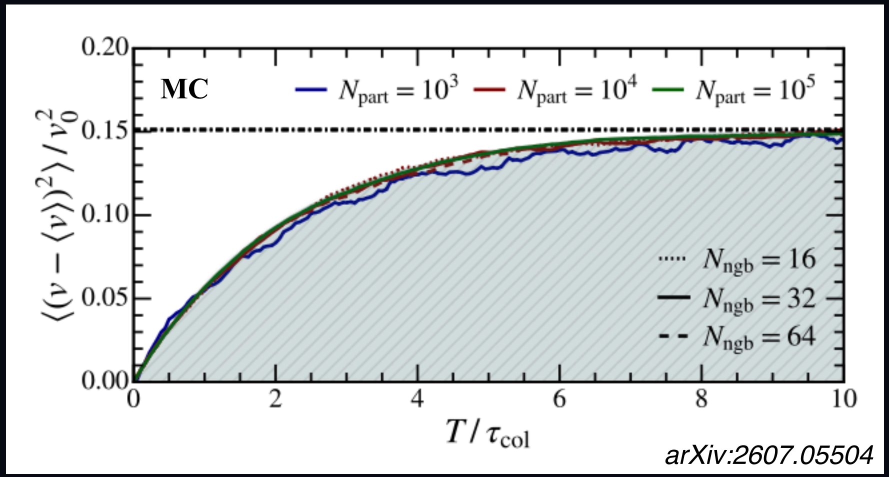
Flowchart of the new SIDM module in AREPO-2. From arXiv:2608.xxxxx

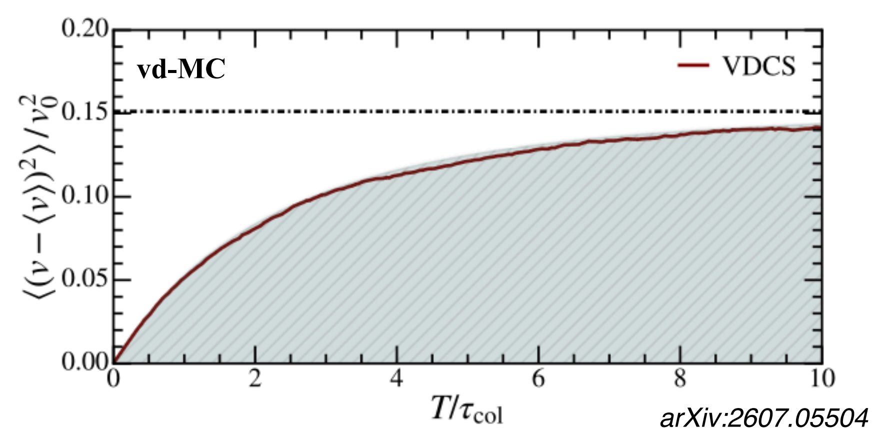


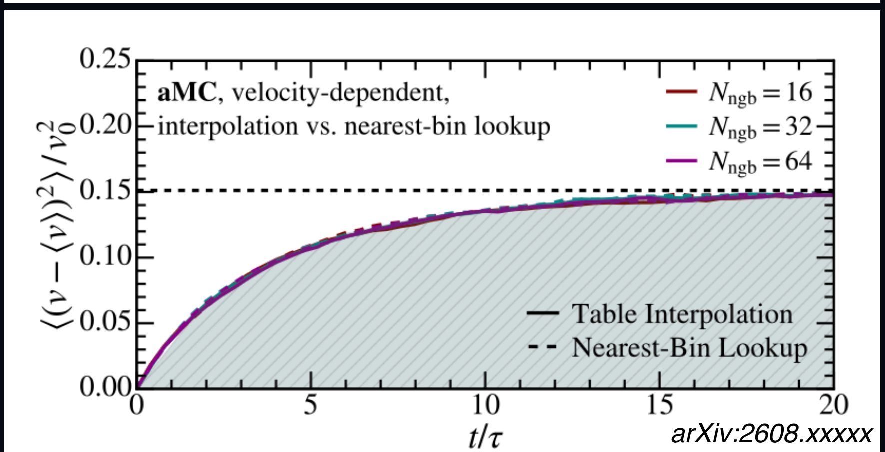
Flowchart of the new DDM module in AREPO-2.
From arXiv:2608.xxxxx

Verification Tests

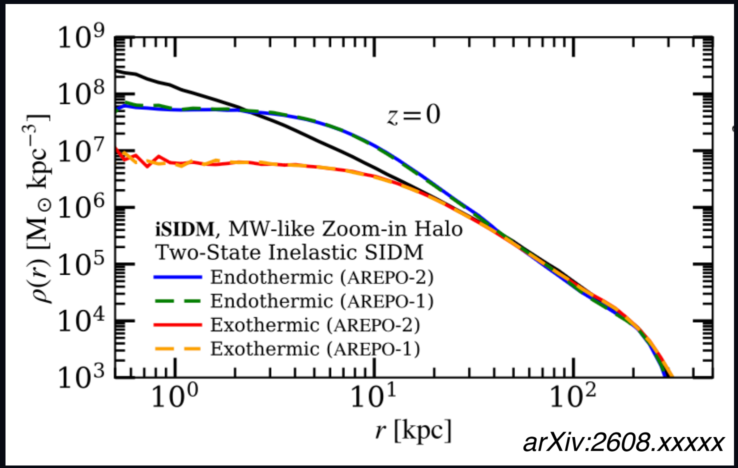
Thermalization Tests

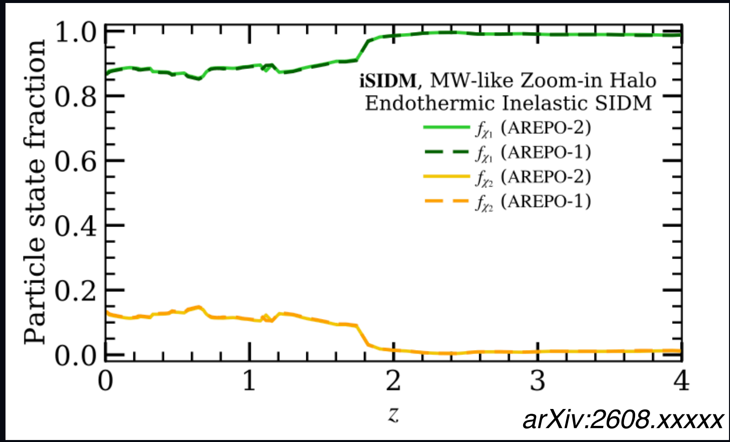


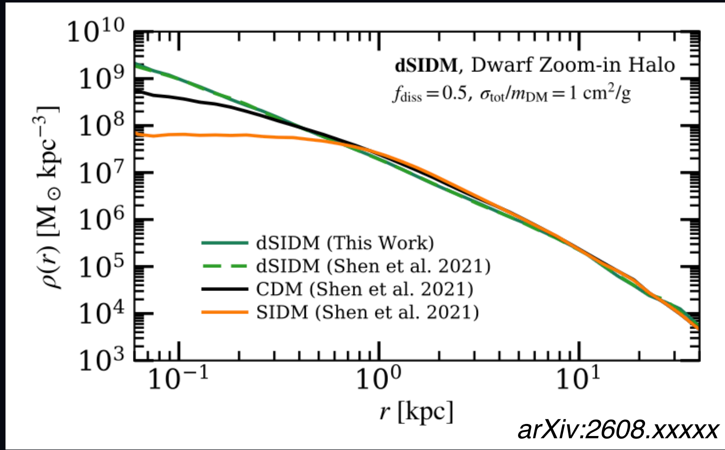




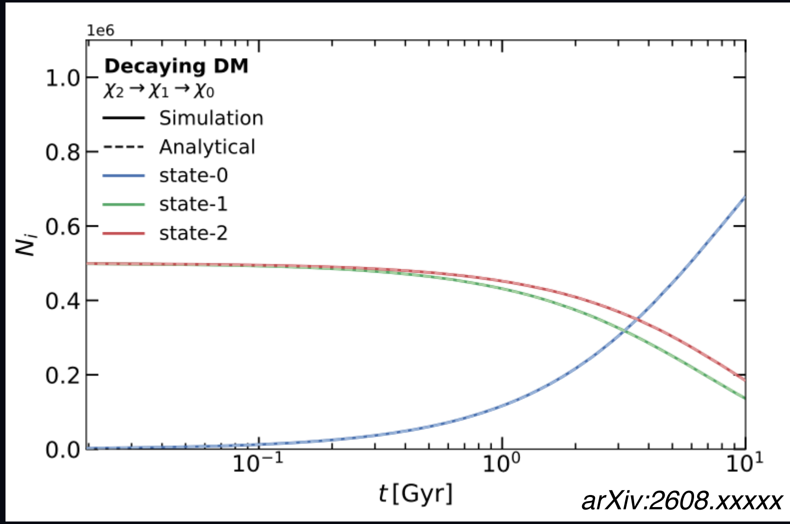
Zoom-in Halo Tests

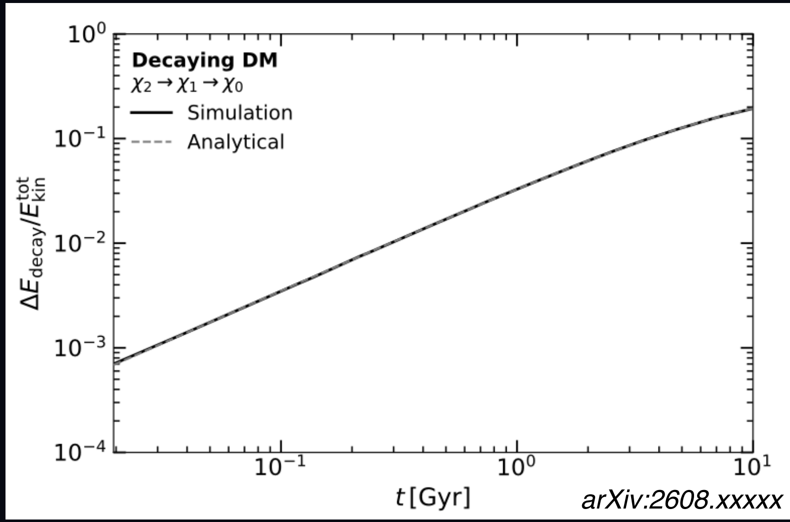




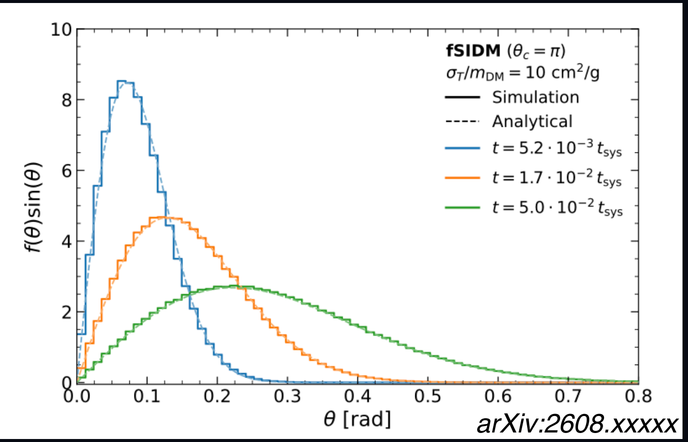


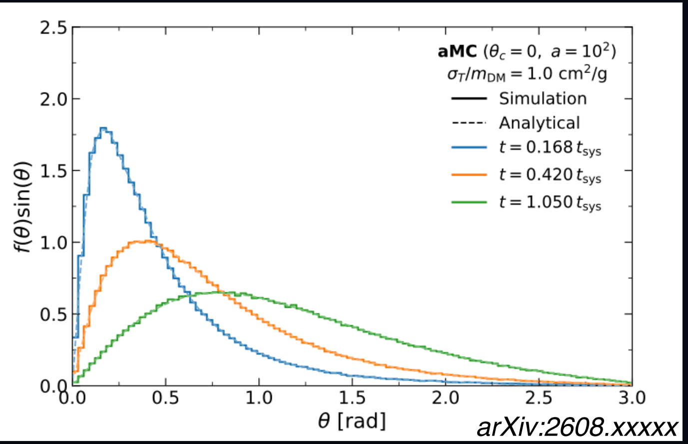
Decaying DM Tests

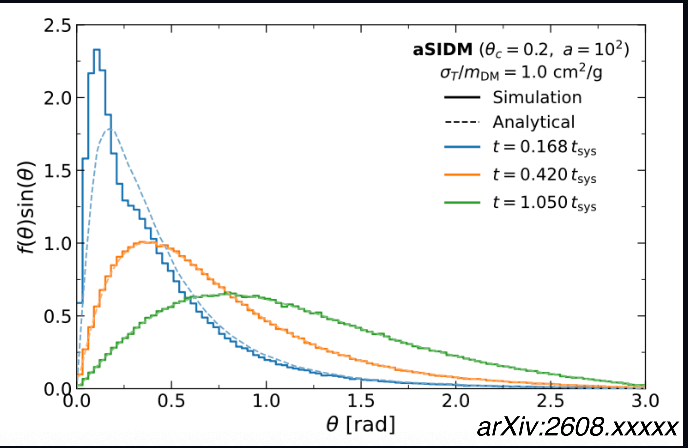




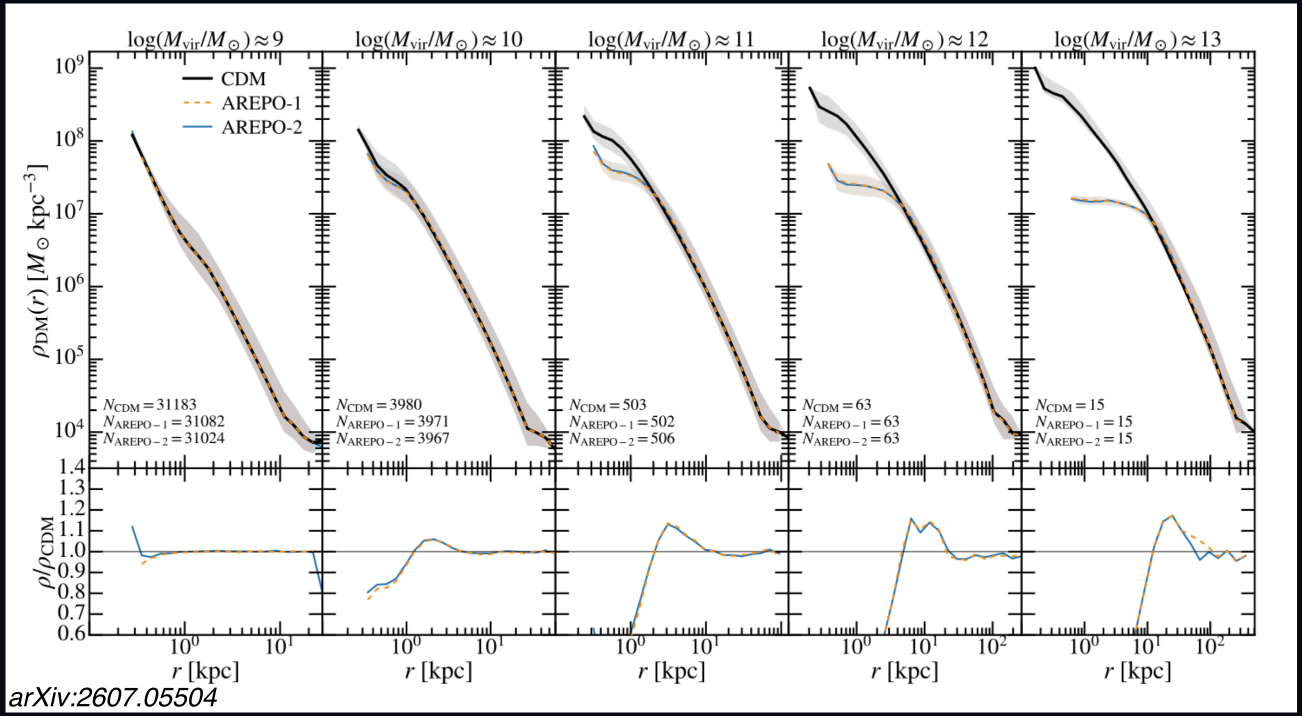
Deflection tests

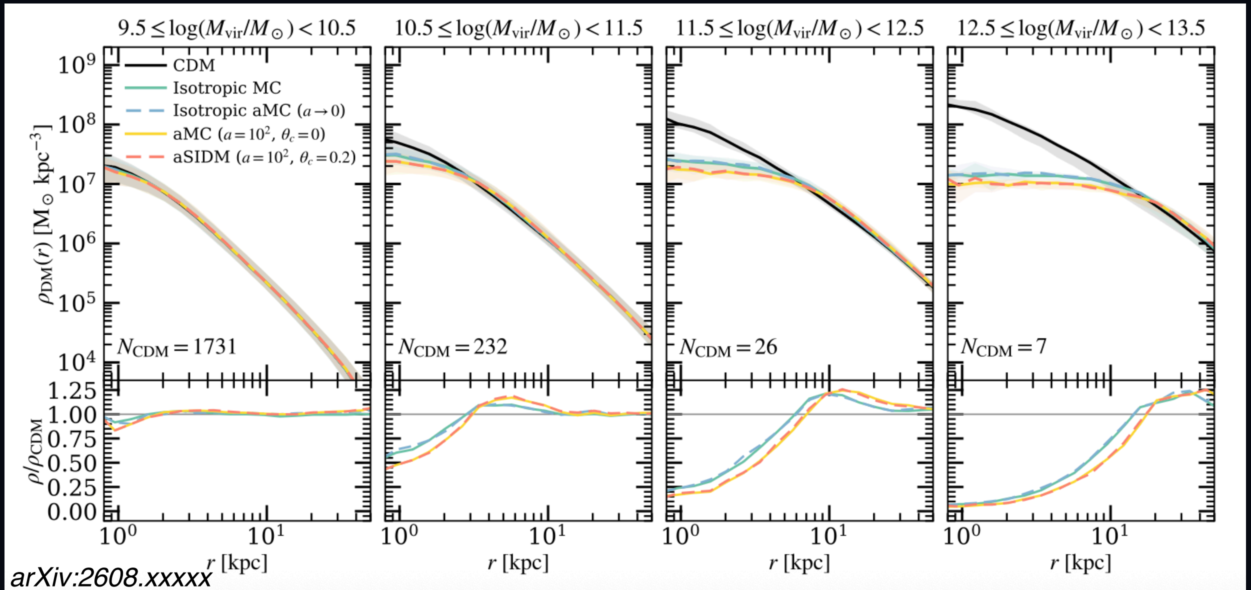






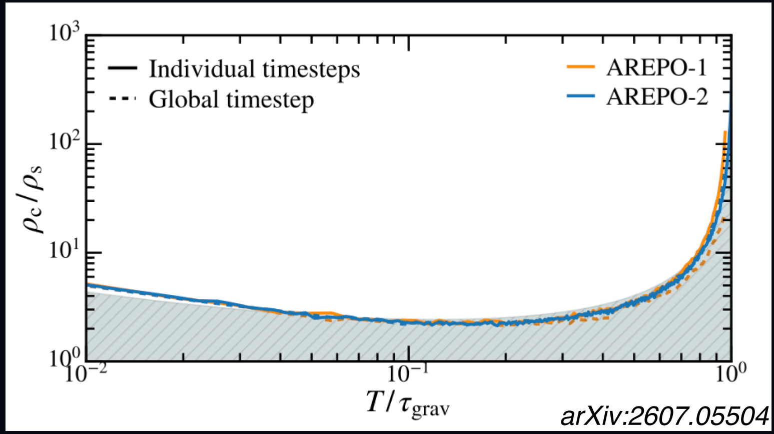
Cosmological box simulations

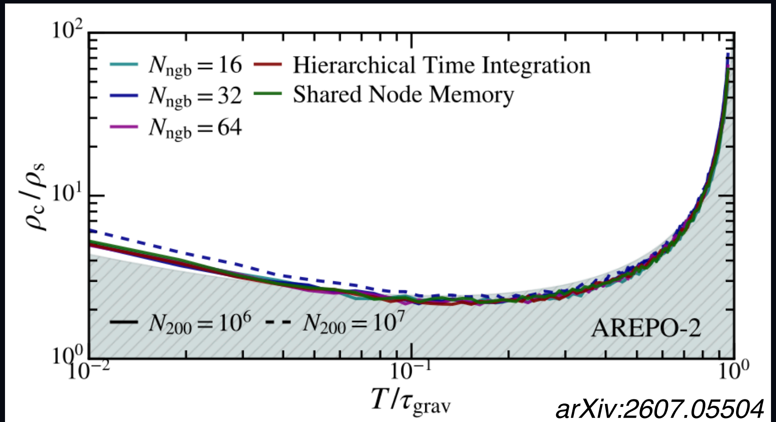


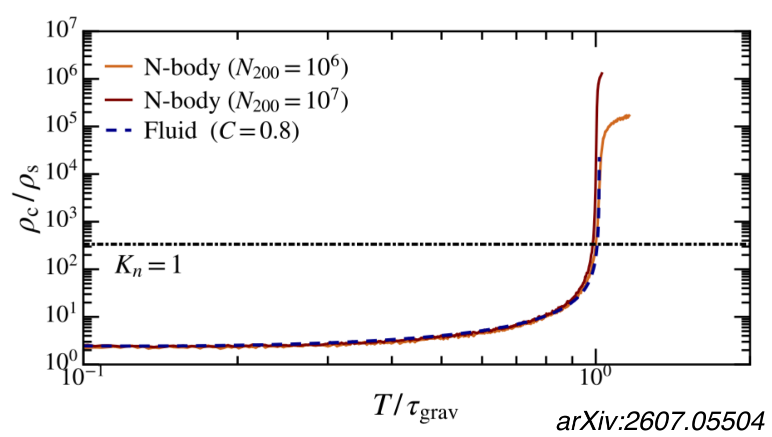


arXiv:2608.xxxxx

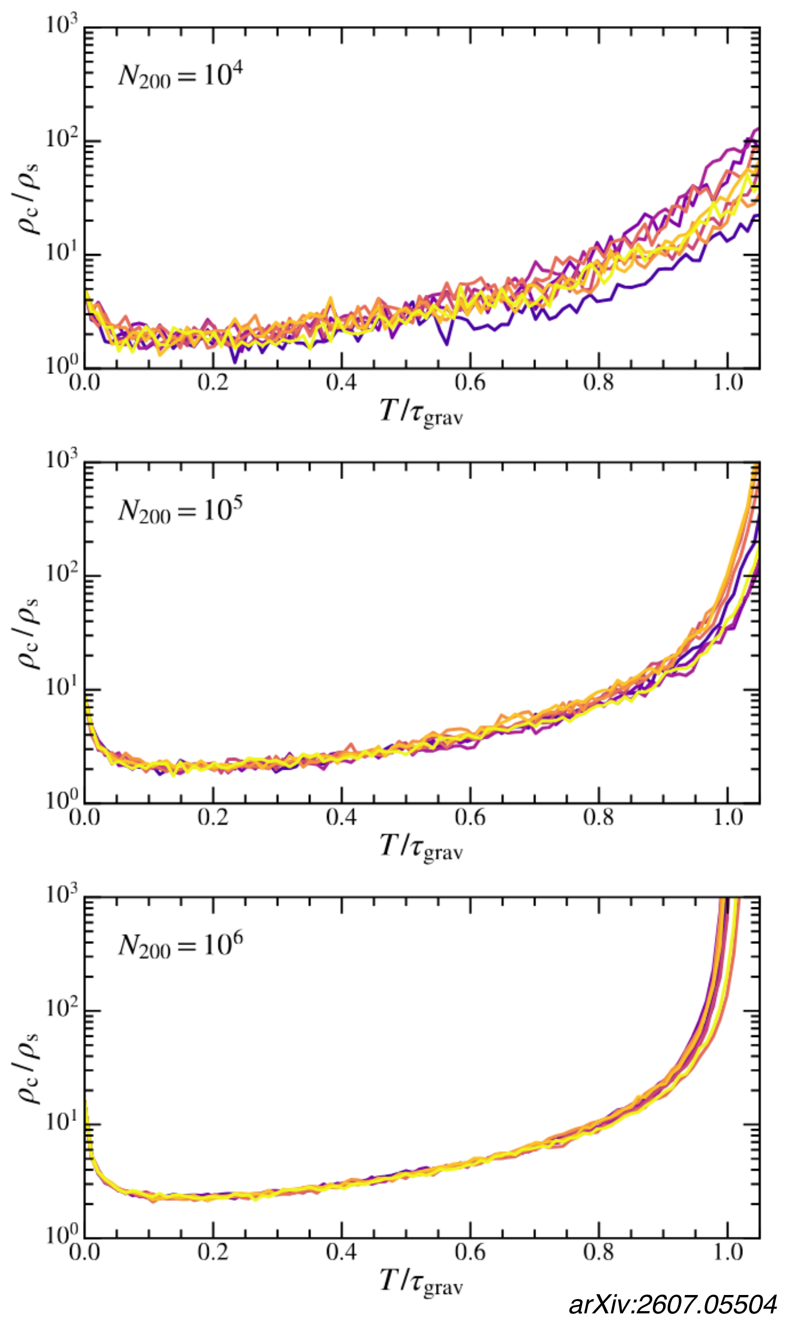
Core-collapse tests

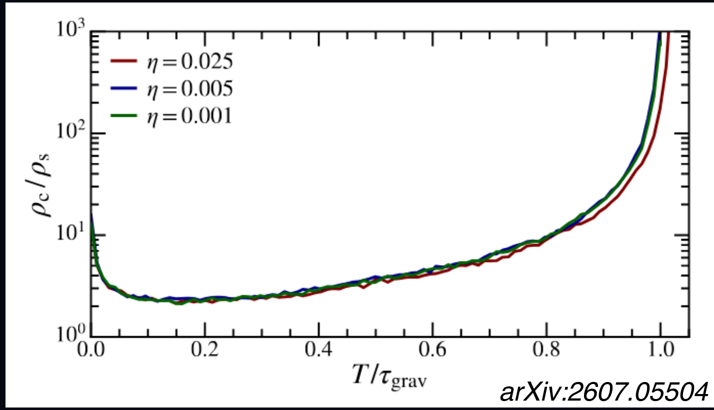




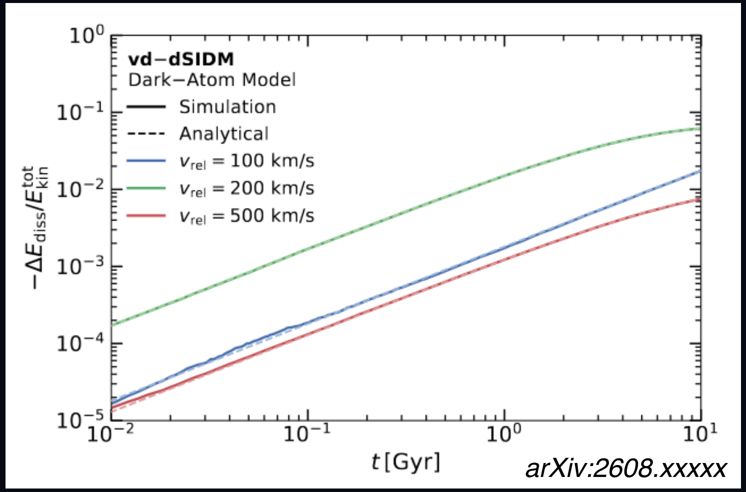


Convergence of the core-density evolution

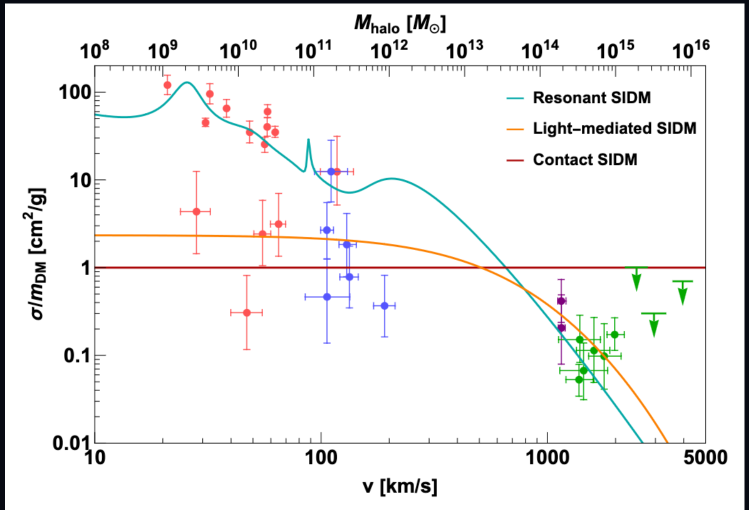




Deflection tests of velocity-dependent dSIDM



Extending to SIDM inference



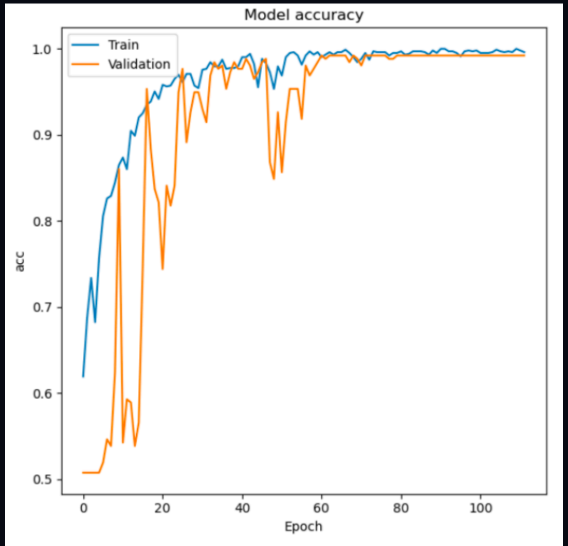
Goal:

Translate SIDM particle physics into observables — and map observables back to particle-physics constraints.

Theory-to-simulation-to-inference pipeline:
Particle Physics → Simulation Inputs → AREPO-2 Simulations → Observables → Constraints

Pilot study with ML inference already started:

- 3 benchmark models: isotropic, elastic SIDM (resonant / light-mediated / contact)
- CNNs already distinguish CDM and SIDM models at high accuracy (~700 DM-only halos)



CNN classification accuracy, CDM vs. SIDM

Next steps:

- Calibrate numerical parameters by scanning the full SIDM parameter space
- Add baryons — feedback can mimic or erase SIDM signatures, but ML may still distinguish between CDM and different SIDM models for robust constraints.

Gravothermal core collapse with AREPO-2

Faster in the most demanding SIDM regime

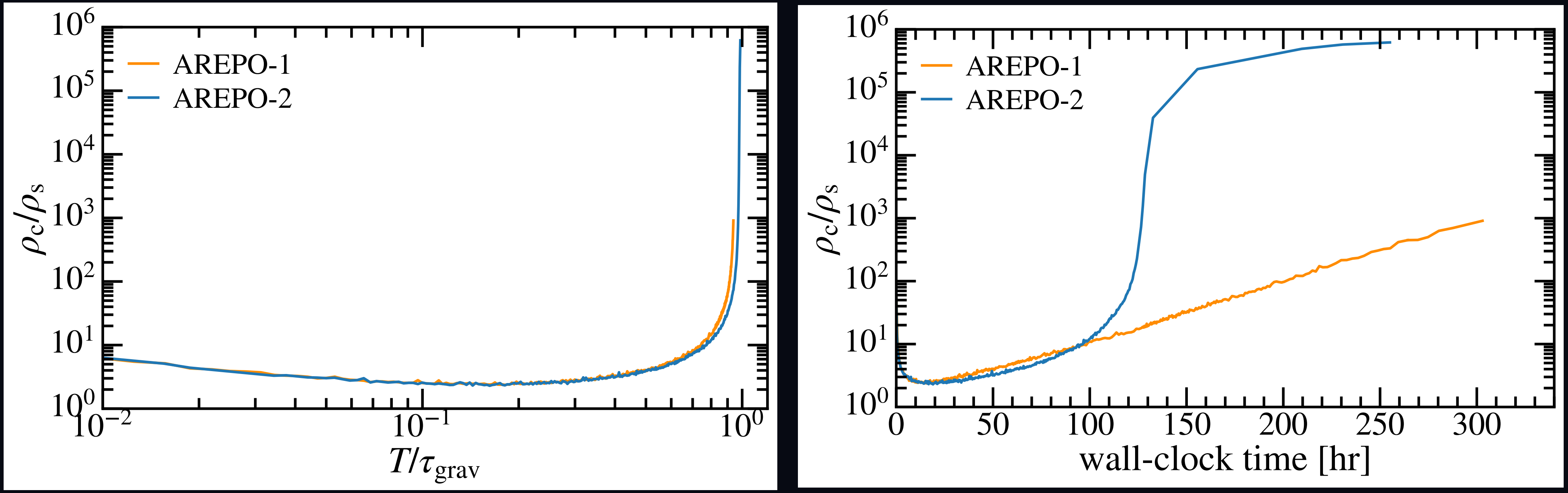
AREPO-2 reaches the deep core-collapse phase substantially faster than AREPO-1.

A calibration benchmark

Core collapse is the stiffest test of the SIDM solver, we use it to validate and calibrate the new AREPO-2 module.

New science enabled

This opens up dense, core-collapsed subhaloes probed by stellar streams and strong lensing,
as well as SIDM-driven massive black hole seeds in the early Universe (Little Red Dots).



Gravothermal core collapse of an isolated halo ($N_{200} = 10^7$), on one node. AREPO-2 reaches collapse far faster in wall-clock time. From arXiv:2607.05504.

Toward a bright horizon!

Faster simulations. Richer data. Powerful AI/ML.

Let's uncover the fundamental nature of dark matter

— together