Cosmology of Inelastic Self-Interacting Dark Matter: Linear Evolution and Observational Constraints

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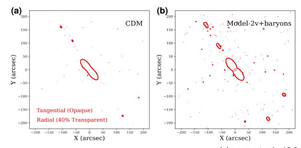
1 MOTIVATION

Secluded dark sector

- Multiple dark states
- Small mass splittings
- Inelastic conversion

Why Two-Component SIDM?

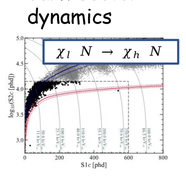
- Dwarf galaxies: large central cores
- Strong lensing: compact, dense subhalos
- GGSL: excess small-scale lenses



Yang et al. (2025)

Why Inelasticity ?

- Kinematically suppress direct detection(LZ-anomally)
- Preserve strong dark-sector dynamics



cite: LZ Collaboration (2026)

Inelastic SIDM:

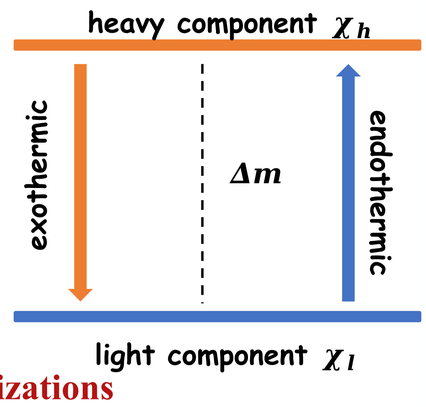
- Strong dark-sector dynamics, weak visible-sector signals
- A natural framework for diverse halo structures

Linear-cosmology imprint remains **unexplored**

2 MODEL SETUP

Inelastic conversion:

Exothermic: $\chi_h\chi_h \rightarrow \chi_l\chi_l$
Endothermic: $\chi_l\chi_l \rightarrow \chi_h\chi_h$



Cross-section parameterizations

(i) Power-law Scaling

$$\sigma_{\chi_h\chi_h \Leftrightarrow \chi_l\chi_l} \equiv \sigma_{\rm PL}\left(\frac{v_{\rm rel}}{c}\right)^{n-1}$$

(ii) Low-velocity saturation

$$\sigma_{\chi_h\chi_h \Leftrightarrow \chi_l\chi_l} \equiv \frac{\sigma_{\rm sat}(c/v_{\rm rel})}{1+(v_{\rm rel}/v_0)^4}$$

Free parameters :

$\{m, \Delta m\} + \{\sigma_{PL}, n,\}$ or $\{\sigma_{sat}, v_0\}$

3 THERMAL INITIAL CONDITIONS

- Start at DM-SM kinetic decoupling $T_\nu = T_{init}(z_{init})$
- $T_{init} = T_l = T_h$
- $r_h(z_{init})$ from the Boltzmann ratio

4 IMPLEMENTATION

Background Equations:

$$\frac{dr_h}{dz} = \frac{1}{H(z)}\{r_h\mathcal{R}_d - (1-r_h)\mathcal{R}_u\}$$

$$\frac{dT_l}{dz} = \underbrace{\frac{2T_l}{(1+z)}}_{\text{Adiabatic Cooling}} - \underbrace{\frac{2x\mathcal{R}_d}{3H(z)}\left[\Delta m + \frac{3}{2}(T_h - T_l)\right]}_{\text{Inelastic Heating \& Coupling}}$$

$$\frac{dT_h}{dz} = 2\frac{T_h}{(1+z)} - \frac{2}{3}\frac{\mathcal{R}_u}{xH(z)}\left[-\Delta m + \frac{3}{2}(T_l - T_h)\right]$$

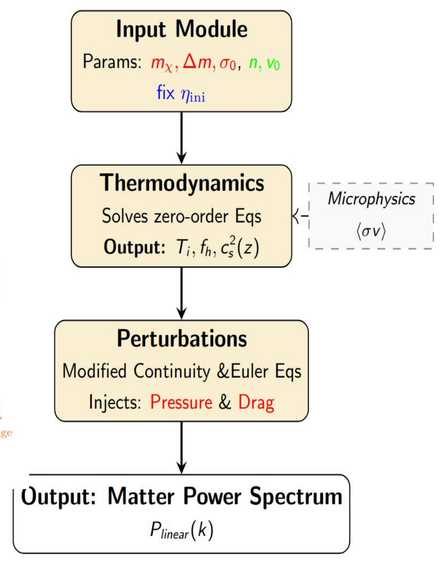
Linear Perturbation Equations:

$$\frac{d\delta_l}{d\tau} = -\theta_l + 3\phi' + x\mathcal{R}_d\left(2\delta_h - \delta_l + \Psi\right) - \mathcal{R}_u\left(\delta_l + \Psi\right),$$

$$\frac{d\delta_h}{d\tau} = -\theta_h + 3\phi' + \frac{1}{x}\mathcal{R}_u\left(2\delta_l - \delta_h + \Psi\right) - \mathcal{R}_d\left(\delta_h + \Psi\right)$$

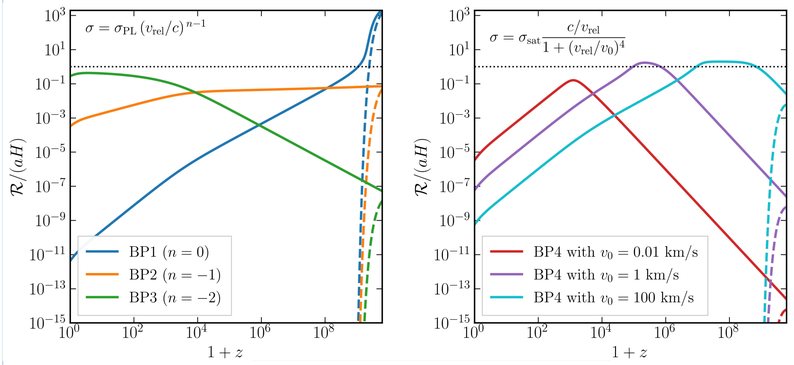
$$\frac{d\theta_l}{d\tau} = -\mathcal{H}\theta_l + k^2\Psi + \underbrace{k^2c_s^2\delta_l}_{\text{Dark Pressure}} + \underbrace{x\mathcal{R}_d(\theta_h - \theta_l)}_{\text{Momentum Exchange}}$$

$$\frac{d\theta_h}{d\tau} = -\mathcal{H}\theta_h + k^2\Psi + \frac{1}{x}\mathcal{R}_u(\theta_l - \theta_h)$$

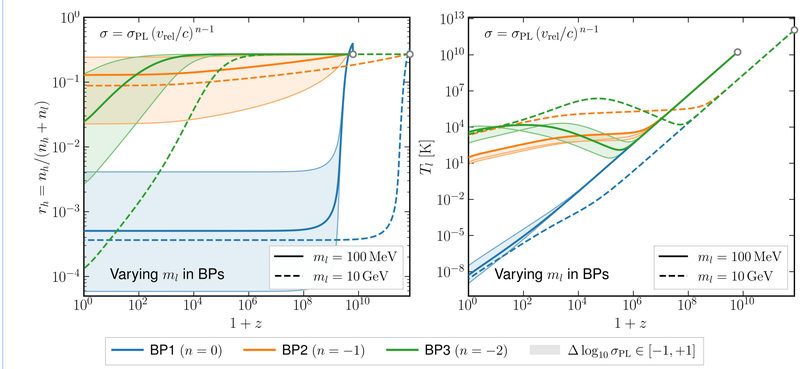


5 BACKGROUND EVOLUTION

Reaction rate and thermochemical history



Heavy fraction and temperature



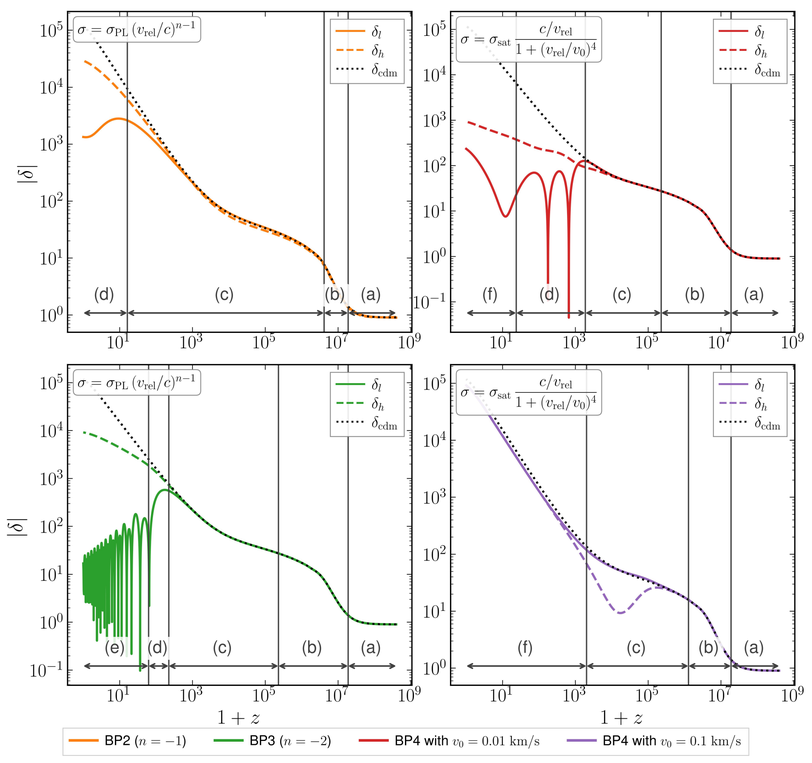
- Exothermic conversion depletes the heavy component
- The light component is heated by the released Δm
- The timing of heating and depletion is crucial

6 PERTURBATION EVOLUTION

Evolution of density perturbations (k = 60 h Mpc−1)

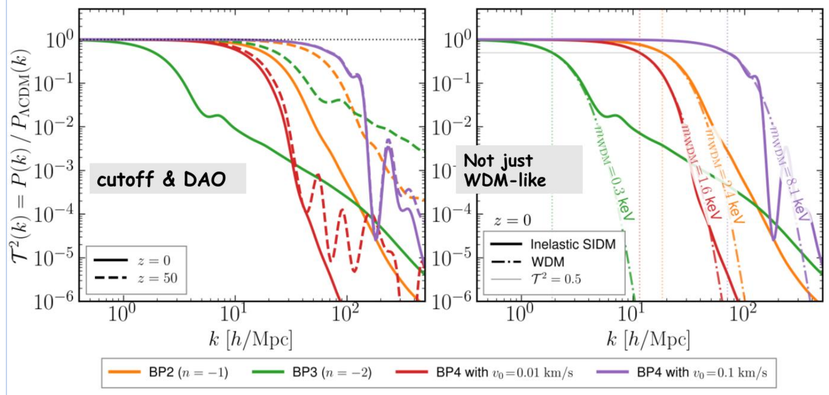
Regime guide

- (a) superhorizon
- (b) early CDM-like growth
- (c) conversion-driven transition
- (d) acoustic oscillation
- (e) damping
- (f) late-time gravitational growth



Conversion heating → **Larger sound speed** → **Pressure support** → **Dark acoustic oscillations** → **Small-scale suppression**

7 MATTER POWER SPECTRUM

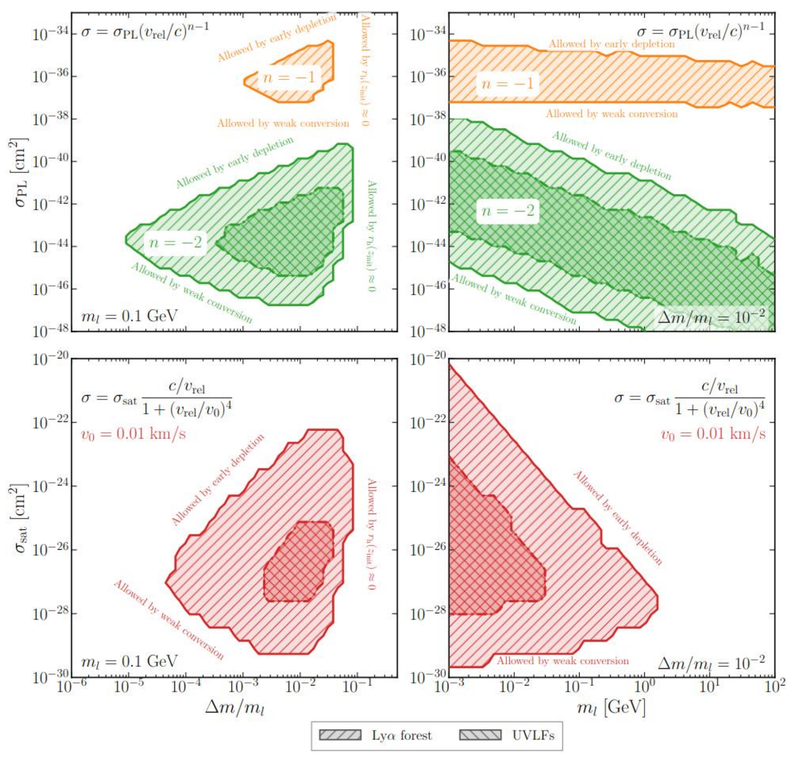


Main signatures

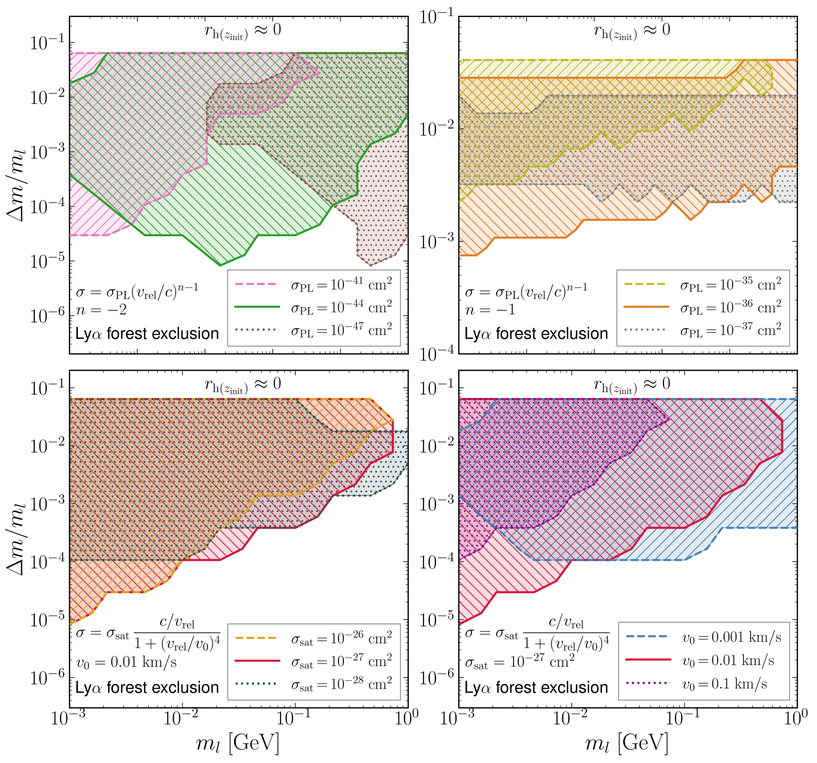
- Suppression appears at k ~ 1–10 h Mpc−1.
- DAO features.
- Differs from WDM free-streaming.

8 OBSERVATIONAL CONSTRAINTS

Exclusion regions from Lyman-α and High-z UVLF



Closed exclusion regions



These bounds are obtained independently of visible-sector signals

9 SUMMARY

- We study a two-component inelastic SIDM model with small mass splitting.
- Exothermic conversion heats the light component and generates pressure support.
- The matter power spectrum exhibits a small-scale cutoff and, in some cases, DAO features.
- Recast Lyman-α and high-z UVLF constraints exclude closed regions in parameter space.
- Internal thermodynamics of a secluded multi-component dark sector can be probed by cosmological data.

Contact: xcduan@pmo.ac.cn | Code: TcCLASS is available on https://github.com/xcduan-1/2cSIDM-CLASS.