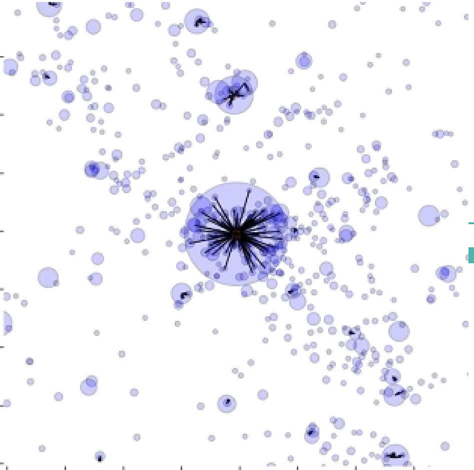
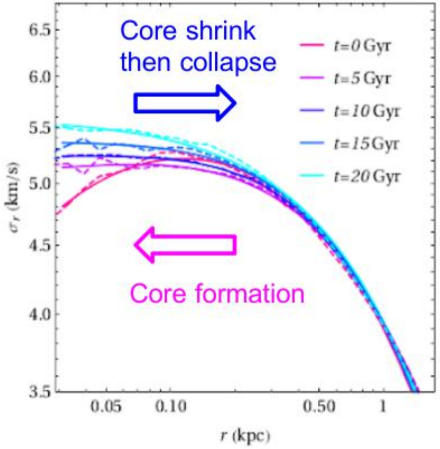
Based on: JCAP 02, 032 (2024)
arXiv:2405.03787
arXiv:2406.10753
JCAP, 09:077, 2022

Modeling Self-Interacting Dark Matter Halos with Galaxies and Growth Histories



Daneng Yang
September 9, 2024
Purple Mountain Observertory, CAS

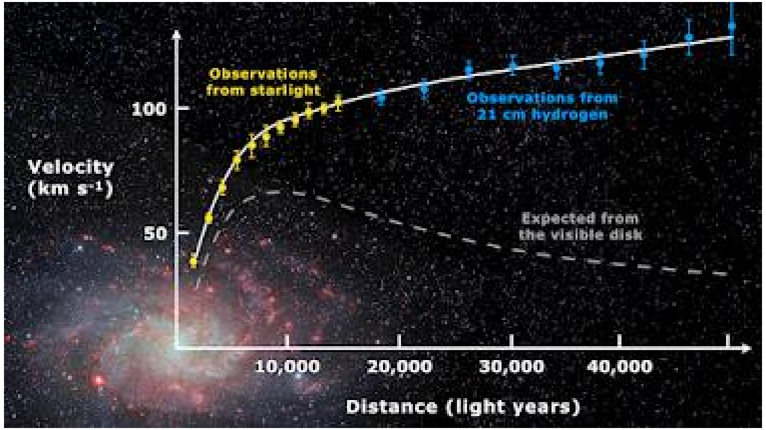
第十三届新物理研讨会, 威海

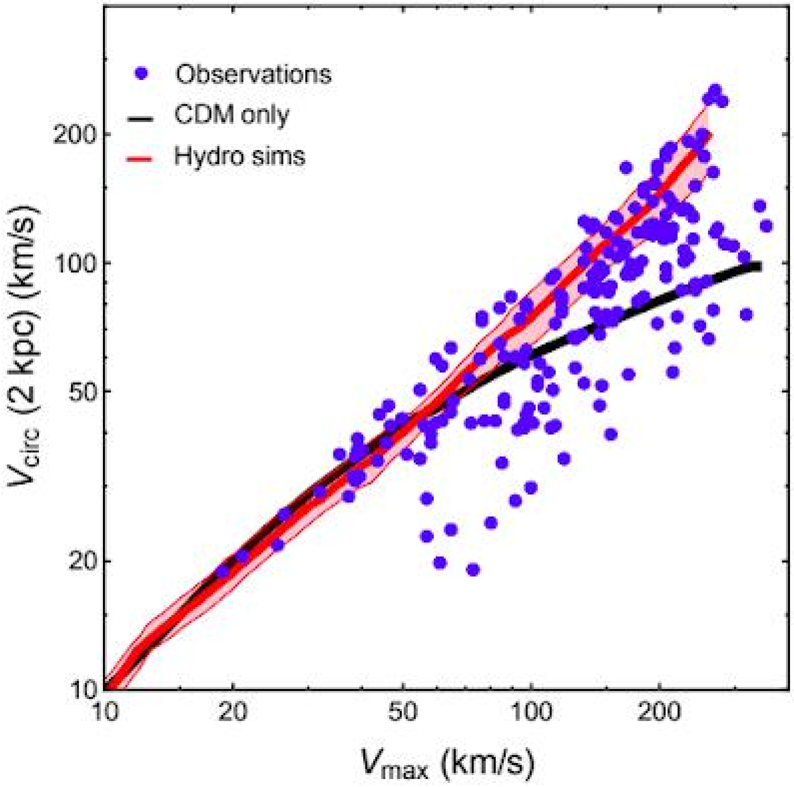


Puzzles in small scale observations

Tulin and Yu 2017 (Review)
data compiled in Oman+ 2015

- **The diversity problem**
- Core vs Cusp
- Too Big To Fail
- DM-deficient galaxies & Ultra-diffuse galaxies & Dense lensing perturber





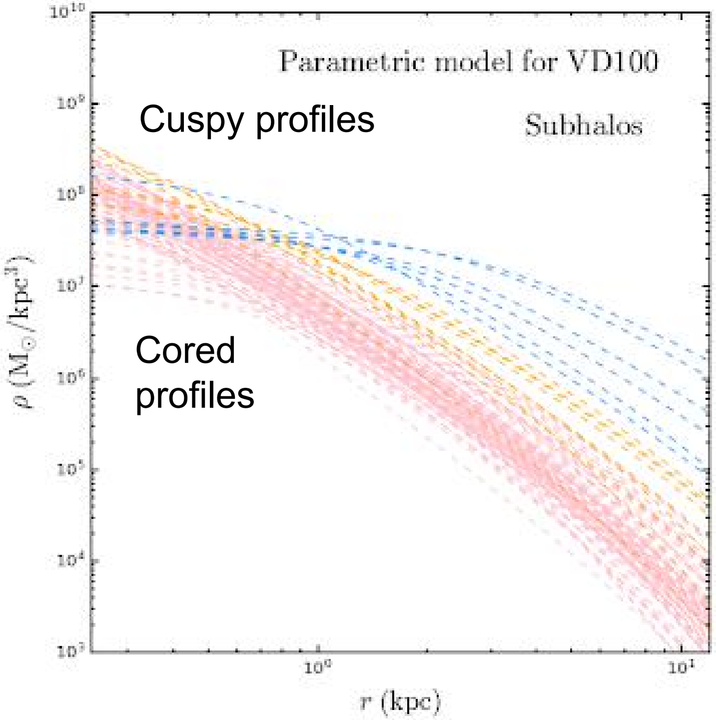
Outline

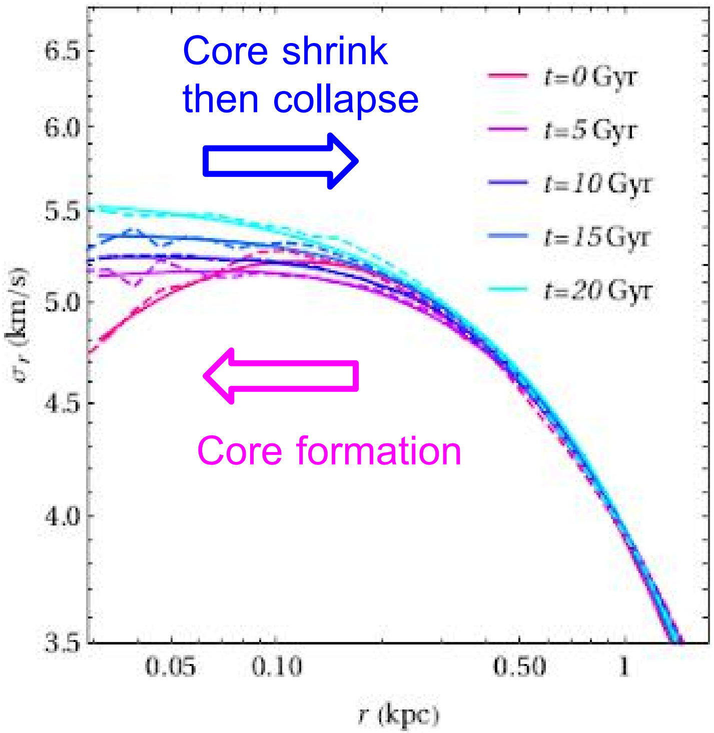
T

1. **Diverse rotation curves** from Self-Interacting Dark Matter (SIDM)
2. A **generic solution** for the evolutiono of SIDM halo build on **gravothermal phase** $\tilde{t} \equiv t/t_c$
3. Effect of baryons
4. Interface to **new physics** (SIDM) models

*Reformulate the problem for **machine learning**

A diversity in the density profile from SIDM





Spergel & Steinhardt 2000 and many other works

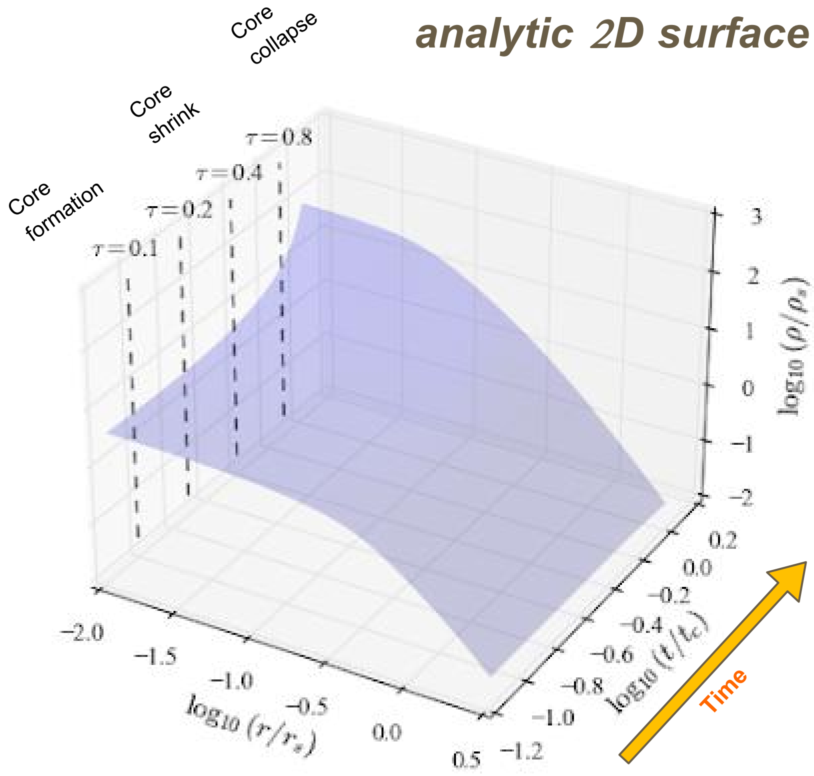
SIDM leads to a **self-gravitating** & **thermalizing** system

*Major features of this evolution can be encoded into an **analytic 2D surface***

Core formation
- energy flux + capacity => core formation

Core shrink
+ energy flux + capacity => quasi-stable core

Second stage
+ energy flux - **capacity** => **core collapse**



Kaplinghat, Tulin, and Yu 1508.03339
Yang & Yu 2205.03392
and many more…

A “clock” in the gravothermal evolution: Gravothermal phase

SIDM generates an arrow of time

Normalized to give a “clock” / “phase”

$$\frac{\partial}{\partial r}\left(r^2 \kappa m \frac{\partial \nu^2}{\partial r}\right) = r^2 \rho \nu^2 \frac{D}{\boxed{Dt}} \ln \frac{\nu^3}{\rho}$$

When **κ** ∝ # of scatterings ∝ **σ** (long-mean-free-path regime)

The **cross section (σ)** dependence can be absorbed into the **arrow of time as: t -> t σ**

$$T \equiv t/t_c$$

$$t_{c,0} = \frac{150}{C} \frac{1}{\frac{\sigma}{m}\rho_s} \left(\frac{1}{4\pi G \rho_s r_s^2}\right)^{\frac{1}{2}}$$

Essig+2019, Balberg+2002

SIDM independence ≠ unitless

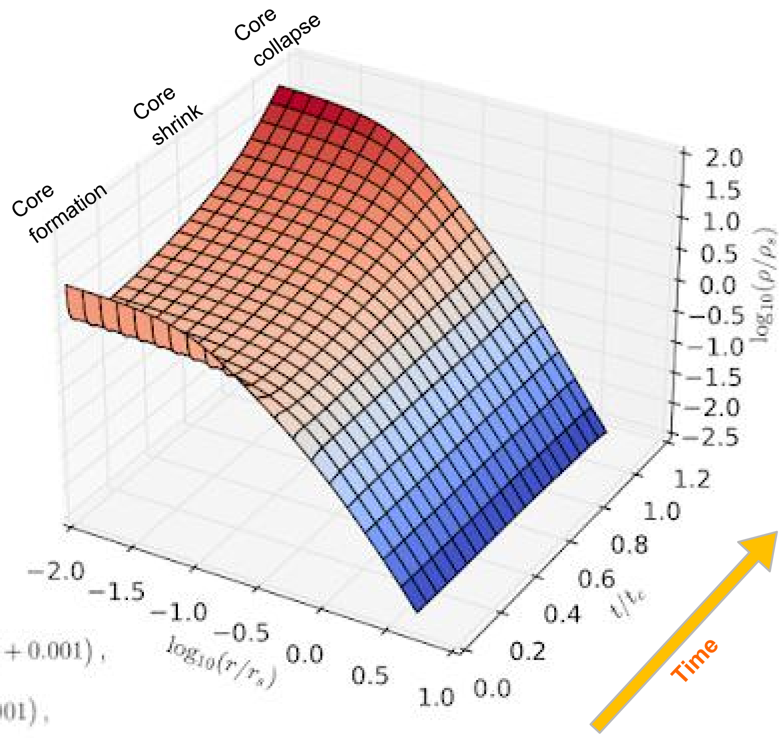
Related discussion in the context of “universality”:
Outmezguine+ 2204.06568; Yang+ 2305.16176;
Zhong+2306.08028; Yang2405.03787

The parametic model

$$\rho_s \qquad r_s \qquad \sigma_{\rm eff}/m$$

Halo initial condition dependence can be removed for the NFW profile by making the halo IC dimensionless.

Evolution trajectories extracted from a single high-resolution SIDM simulation



$$\rho_{\rm SIDM}(r) = \frac{\rho_s}{\frac{\left(r^\beta + r_c^\beta\right)^{1/\beta}}{r_s}\left(1+\frac{r}{r_s}\right)^2}$$

β=4

$$\frac{\rho_s}{\rho_{s,0}} = 2.033 + 0.7381\tilde{t} + 7.264\tilde{t}^5 - 12.73\tilde{t}^7 + 9.915\tilde{t}^9 - (1-2.033)(\ln 0.001)^{-1}\ln\left(\tilde{t}+0.001\right),$$
$$\frac{r_s}{r_{s,0}} = 0.7178 - 0.1026\tilde{t} + 0.2474\tilde{t}^2 - 0.4079\tilde{t}^3 - (1-0.7178)(\ln 0.001)^{-1}\ln\left(\tilde{t}+0.001\right),$$
$$\frac{r_c}{r_{s,0}} = 2.555\sqrt{\tilde{t}} - 3.632\tilde{t} + 2.131\tilde{t}^2 - 1.415\tilde{t}^3 + 0.4683\tilde{t}^4,$$

$$\tilde{t} \equiv t/t_c$$

Influence of accretion history on the gravothermal phase

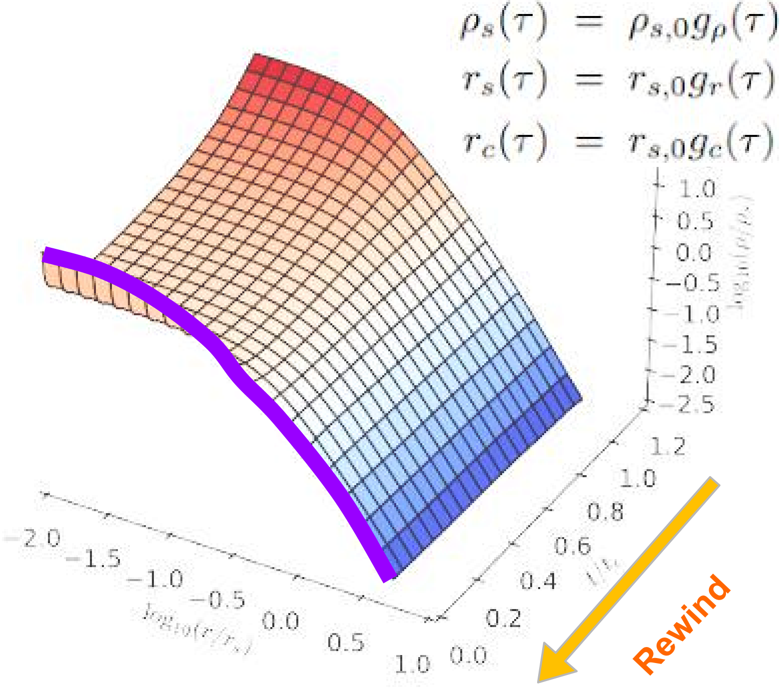
Step 1: a fictitious CDM halo

Rewinding the gravothermal phase would result in a **fictitious** CDM halo

Assuming that all the SIDM effect in an *isolated* halo is captured by the phase:

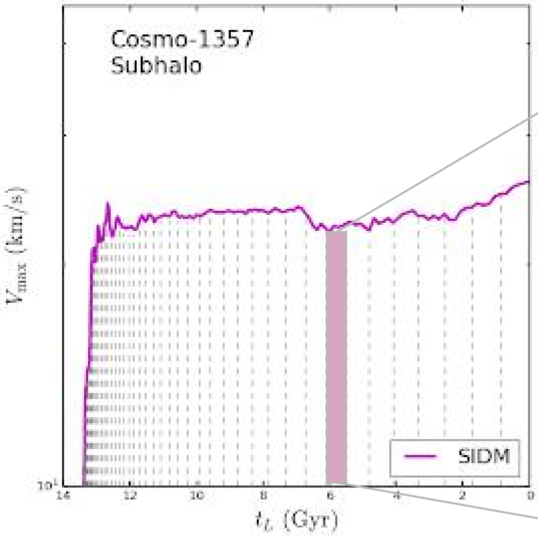
Fictitious CDM halo == Simulated CDM halo

In reality, a halo has an **accretion history**, which may change both the phase and the fictitious CDM halo



t/tc=0 corresponds to an **NFW profile**

Step 2: gravothermal phase from a population of fictitious CDM halos



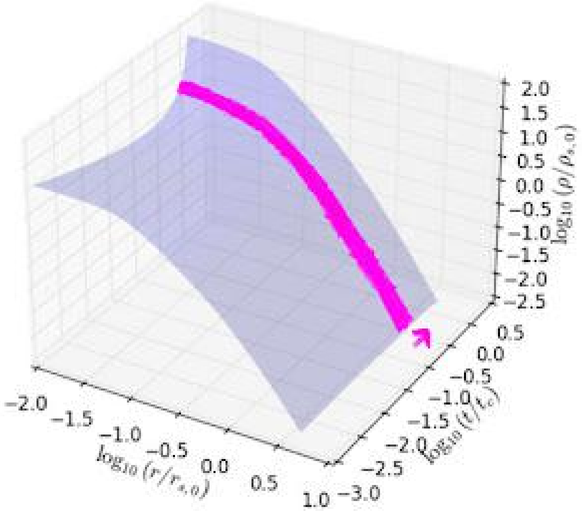
For **every** small time increment, the **Δτ** can be computed using the **fictitious CDM halo**

Example: τ=t/tc≈0.6

In Δt=0.5 Gyr, almost no mass change. Then the increment in gravothermal phase is:

Δτ=(Δt)/tc

where tc is computed using the fictitious CDM halo params



arXiv:2305.16176

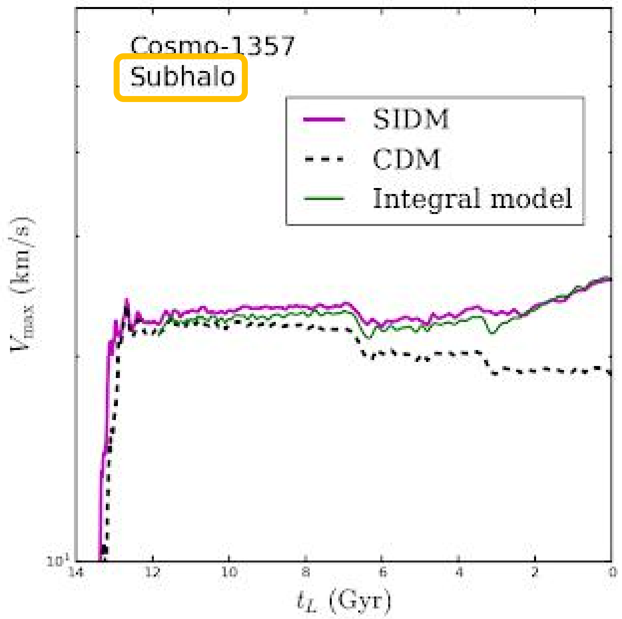
The integral approach

Model (Integral) prediction agree with the SIDM simulation well:

Gravothermal phase and its increments successfully capture the leading effects of SIDM halo evolution

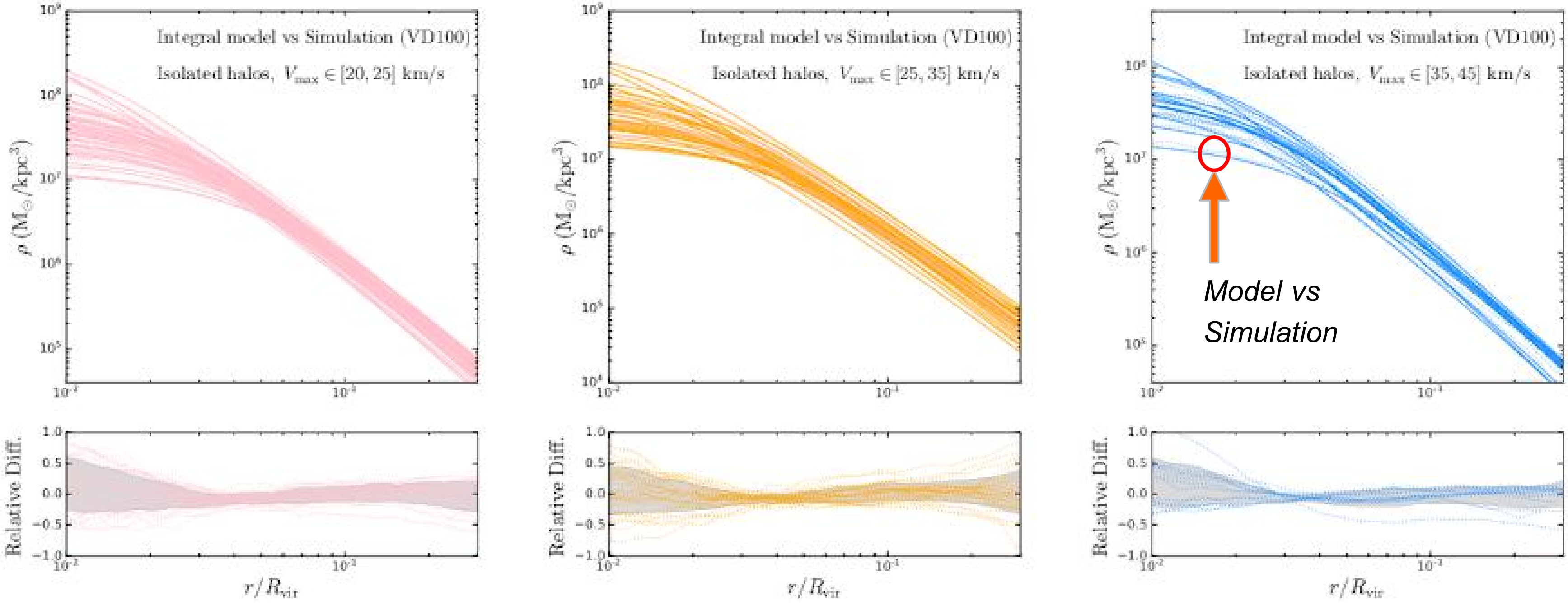
Applicability

- Small Δτ during the Δt of a merger
- CDM halo mass close to SIDM halo mass at all times



$$V_{\rm max}(t) = V_{\rm max,CDM}(t) + \int_0^{\tau(t)} d\tau' \frac{dV_{\rm max,Model}(\tau')}{d\tau'}$$

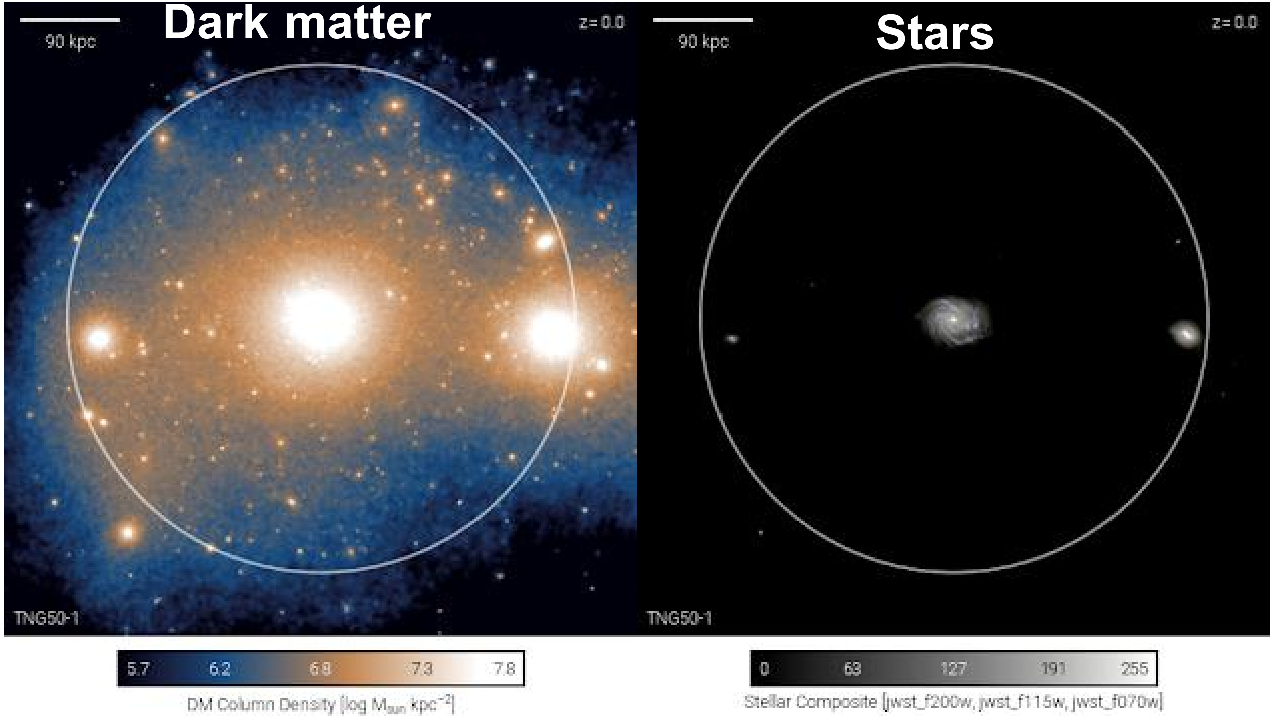
$$R_{\rm max}(t) = R_{\rm max,CDM}(t) + \int_0^{\tau(t)} d\tau' \frac{dR_{\rm max,Model}(\tau')}{d\tau'}$$



Quantify the level of agreement using matched pairs of halos in cosmological CDM and SIDM simulations

Yang & Nadler & Yu 2406.10753

SIDM effect is most prominent in the central region, where baryons populate



Figs. credit: TNG collaboration

Incorporating baryons

A new equation for the core collapse time

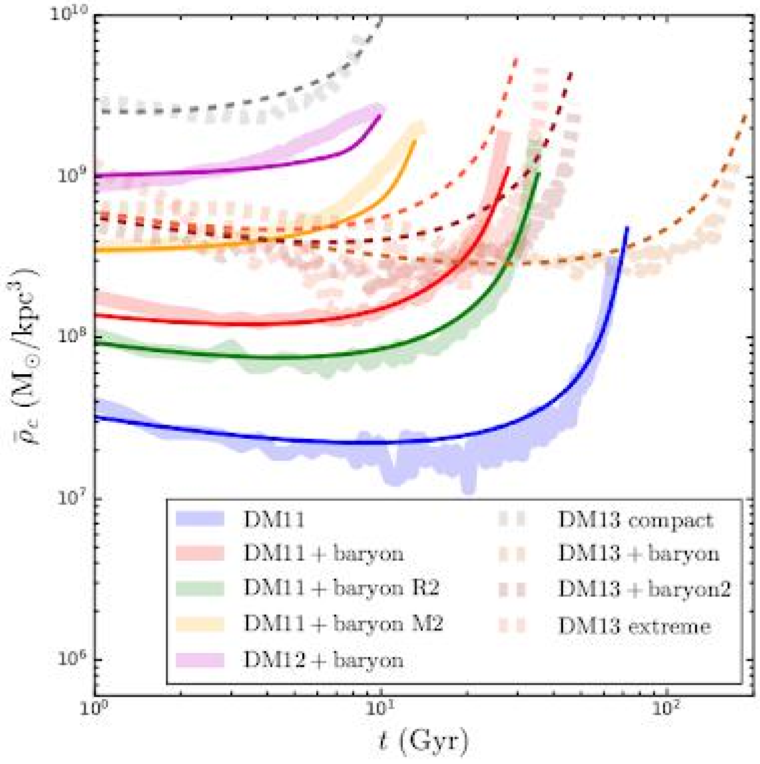
- Based on energy transfer
- Incorporate baryons
- *Collision rate => Energy transport*

$$t_R(r) \propto \frac{M(r)|\Phi(r)|/2}{4\pi r^2 \kappa |\nabla T|}$$

A density profile that allows incorporating adiabatic contraction effect

$$\rho_{\rm CoredDZ}(r) = \frac{f_{\rm in}(r)\rho_x f_{\rm out}(r)}{\frac{(r^k+r_c^k)^{1/k}}{r_x}\left(1+\left(\frac{r}{r_x}\right)^{1/2}\right)^{2(3.5-a)}}$$

N-body simulation: bands
Parametric model: lines



arXiv:2405.03787

Puting baryon effects into a form factor

$$t_{c,b} = t_{c,0}\mathcal{F}_t(\hat{\rho}_H, \hat{r}_H)$$

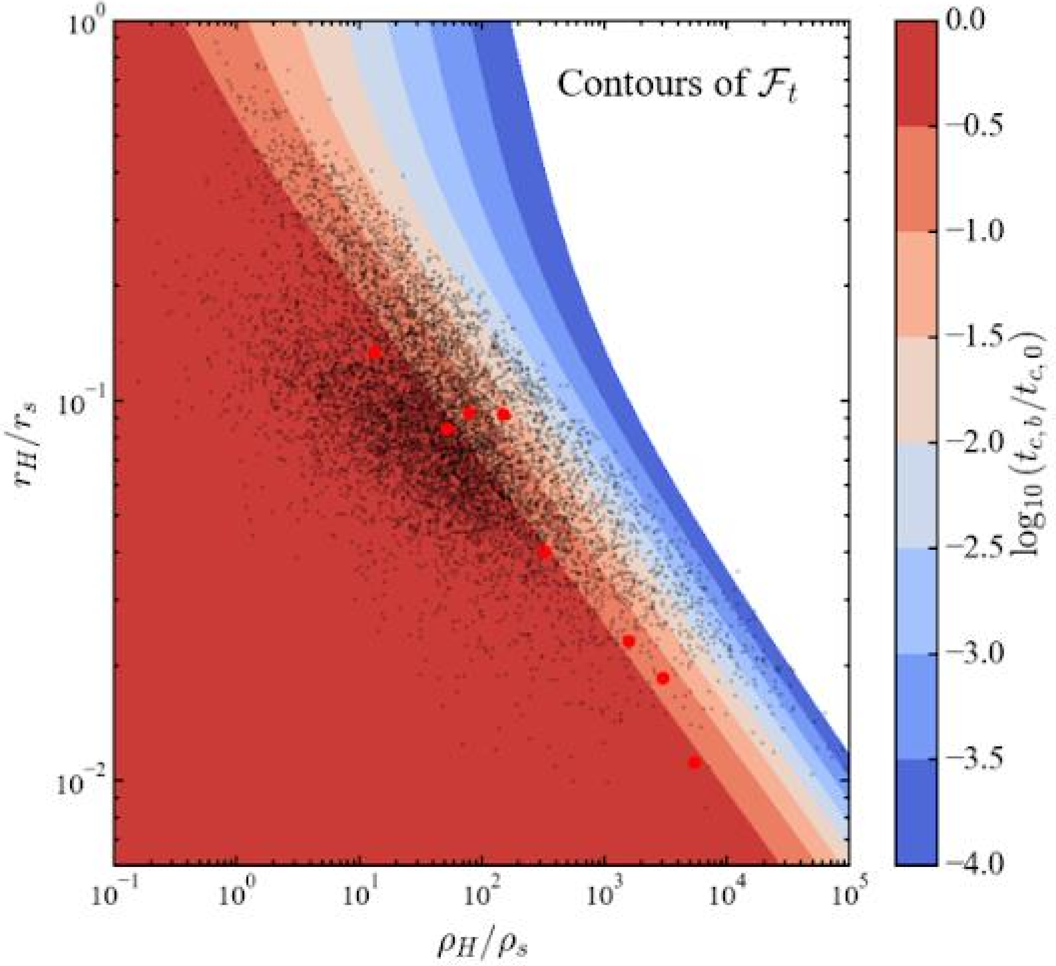
The ratio of core collapse times w&o baryons

$$\mathcal{F}_t = \left(\frac{1}{\hat{r}_{\rm eff}} + \frac{\gamma\hat{\rho}_H\hat{r}_H^3}{\hat{r}_{\rm eff}(\hat{r}_{\rm eff}+\hat{r}_H)^2}\right)^{-1}\left(1+\alpha\frac{\hat{\rho}_H\hat{r}_H^2}{2}\right)^{-\frac{1}{2}}$$

Lower-left: marginal effect

Upper-right: can be orders of magnitude large

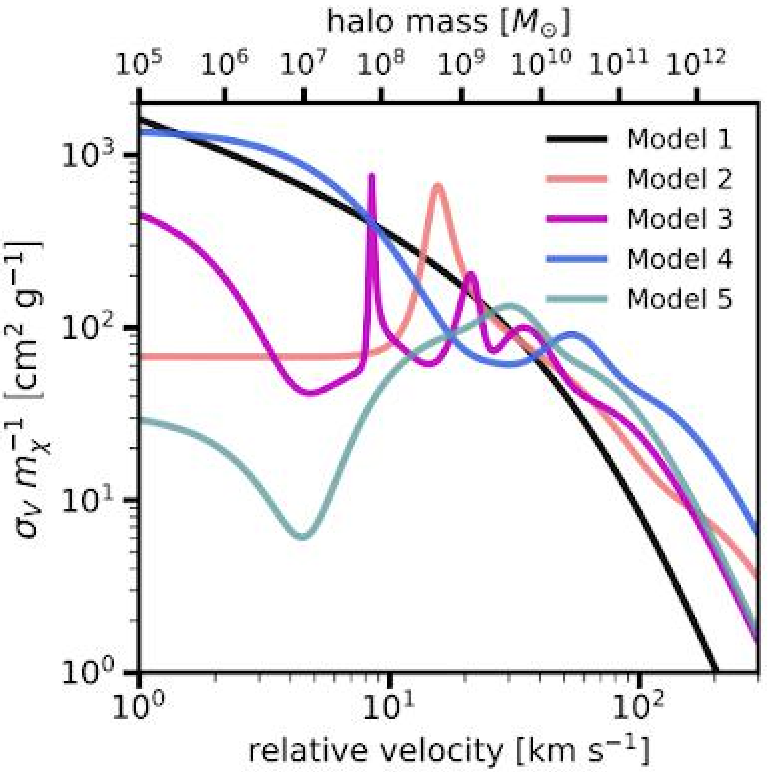
ρH, rH: Hernquist scale radius and density of the stellar component



SIDM cross sections can have nontrivial velocity dependencies

- Yukawa potential/Gravity: v^-4 at large v
- Massive mediator: flatten the inner dependence
- Quantum resonances

Interface to **new physics** (SIDM) models?

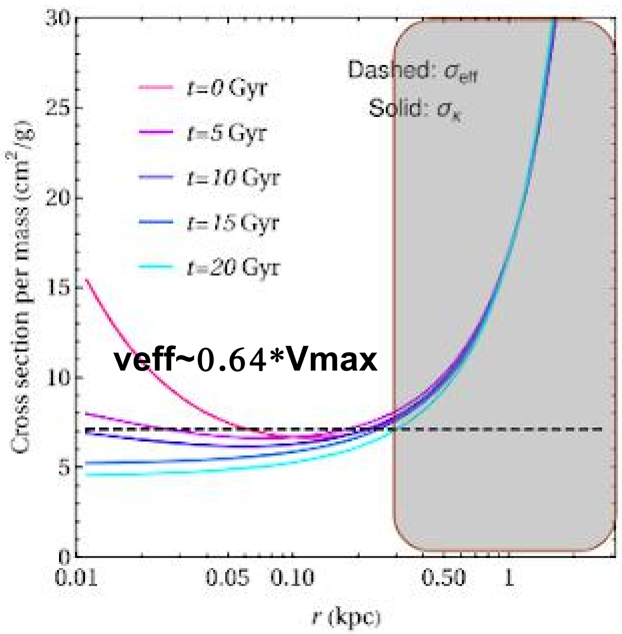


Gilman+2207.13111

One halo probes
One effective constant cross section

Effective constant cross section
(motivated by heat conduction)

$$\sigma_{\mathrm{eff}} = \frac{2\int v^2 dv d\cos\theta \boxed{\frac{d\sigma}{d\cos\theta}} \boxed{\sin^2\theta v^5} \boxed{\exp\left[-\frac{v^2}{4\nu_{\mathrm{eff}}^2}\right]}}{\int v^2 dv d\cos\theta \boxed{\sin^2\theta v^5} \boxed{\exp\left[-\frac{v^2}{4\nu_{\mathrm{eff}}^2}\right]}}$$



Yang & Yu 2205.03392

- Angular dependence is completely integrated out
- Only the ***velocity dependence of SIDM*** couples to the ***halo velocity dispersion***
- *Details of an SIDM model **hidden** in a single halo*

Explore the particle nature of SIDM

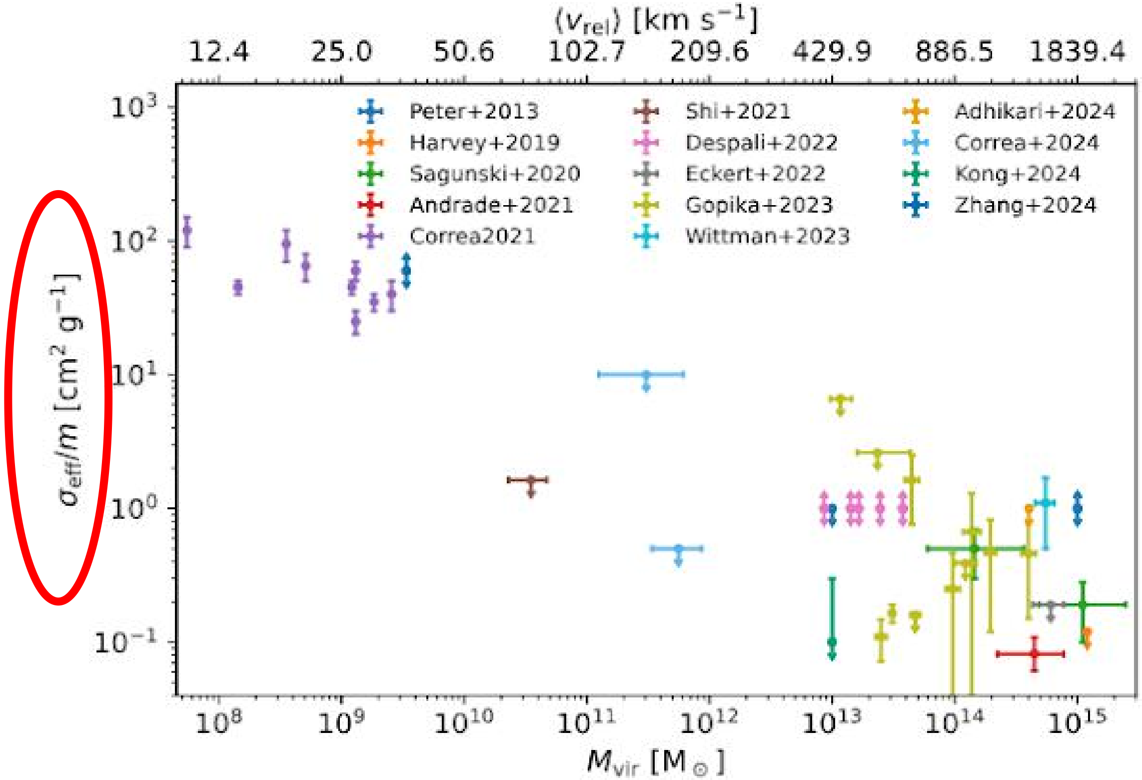
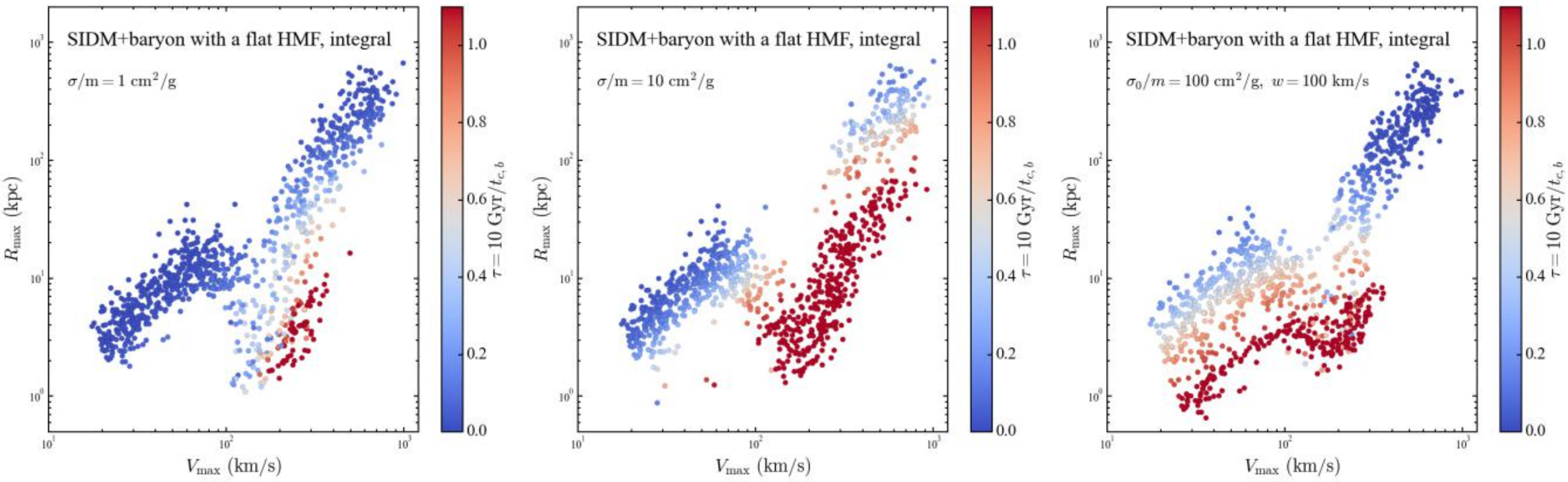


Figure by Fischer et al. 2024.
https://darkium.org/#about-card

Application 1: MC generator for SIDM halos



- Three SIDM models
- Baryon contents based on known cosmological relations

Application 2: fitting rotation curves

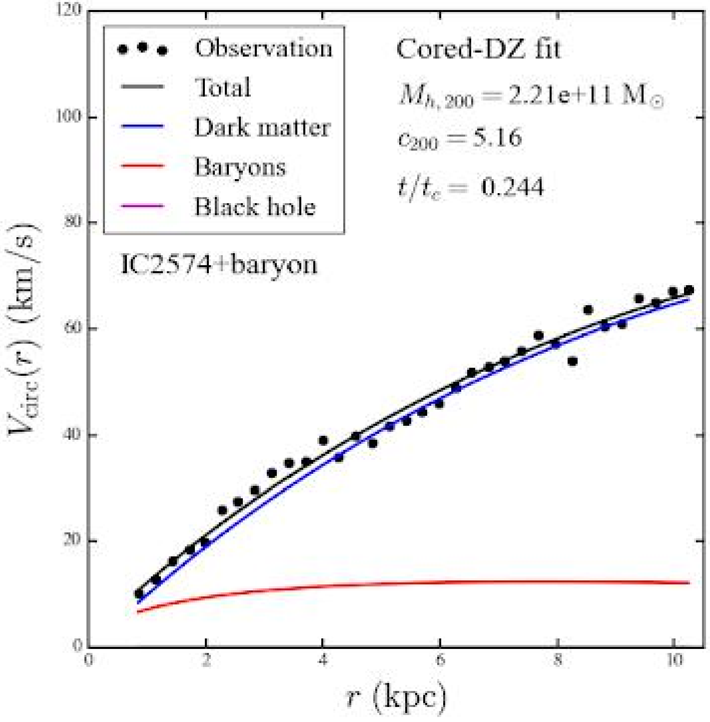
IC2574

Re=3.18 kpc

Mb=5.08e8 Msun

rH=1.317 kpc

rhoH= 3.5378e7 Msun/kpc^3



Parameter scan

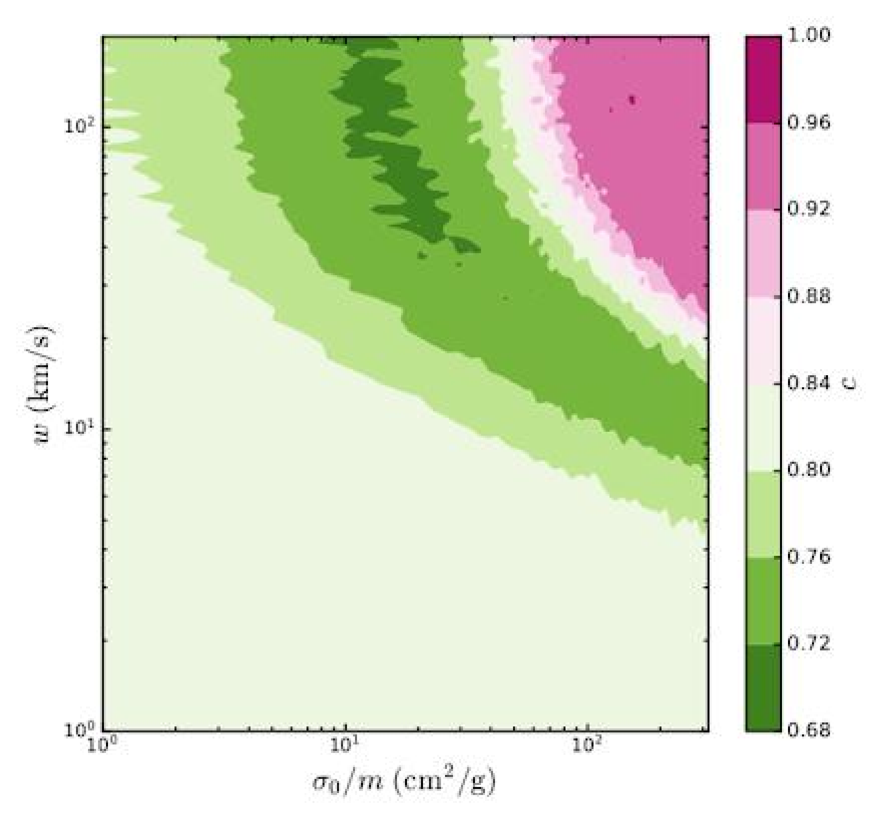
SIDM parameter scan (2305.16176)

Translate CDM simulations into SIDM

Rotation curve fit

Semi-analytic model/MC program, e.g.,
SASHIMI-SIDM S. Ando+2403.16633

……



Explore the parameter space on a laptop

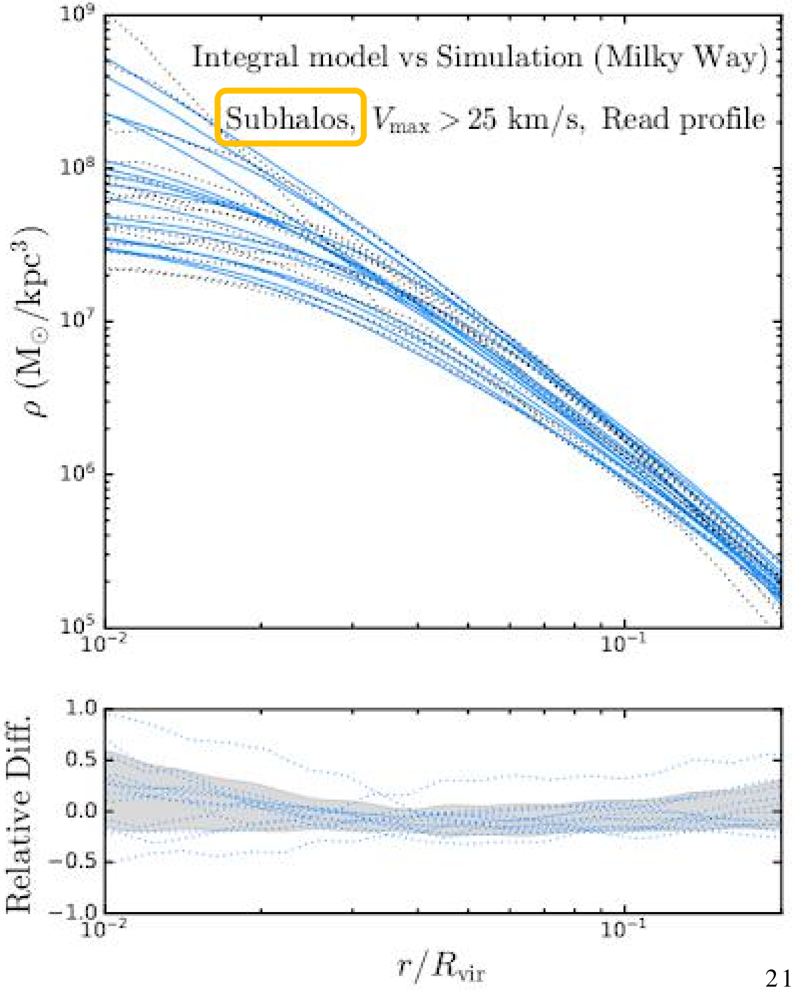
Parametric analysis tools for SIDM halos

An efficient tool for obtaining SIDM predictions

- Based on a few analytic functions/trajectories of the *gravothermal phase*
- Grounded in theory principles: not just an empirical model
- Tested against a large number of halos in cosmological simulations
- Has been extended to incorporate *mass changes* and *baryon potentials* arXiv:2405.03787

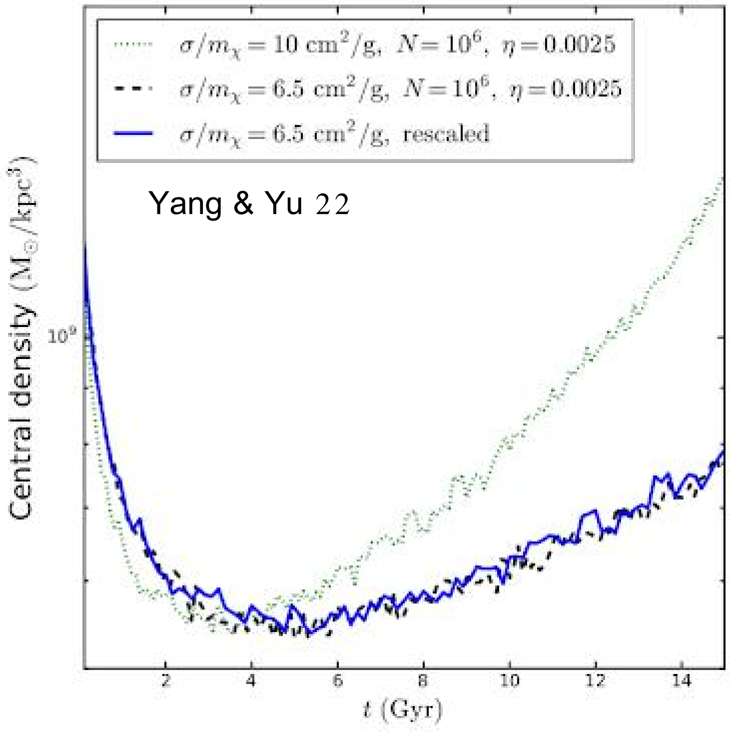
https://github.com/DanengYang/parametricSIDM

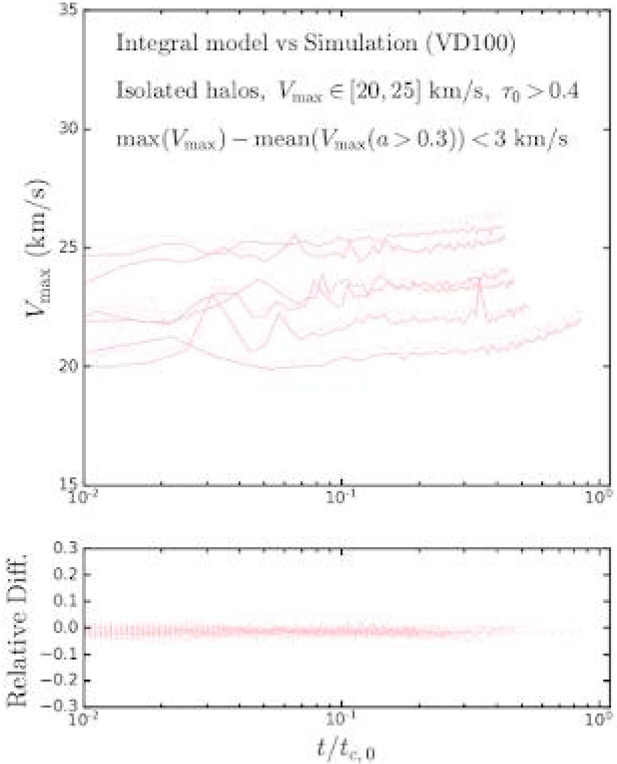
With Ethan O. Nadler, Hai-Bo Yu, Yi-Ming Zhong, S. Ando, S. Horigome



Backup

How well is tc being proportional to sigma/m？





"Isolated" halos in cosmological simulation (Yang, Nadler, Yu 23) with

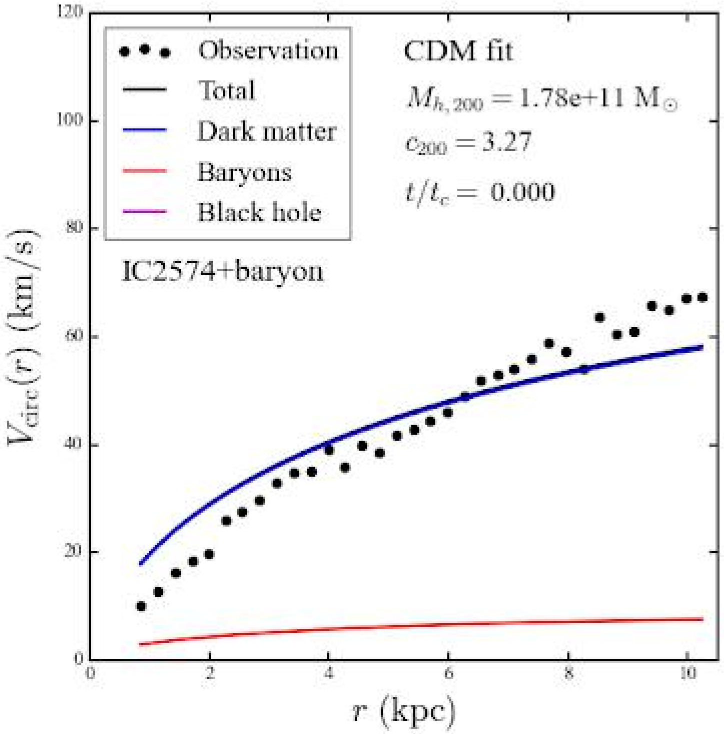
- t/tc＞0.4
- Exclude cases with major mergers

Model vs simulation

More in YNY24 to appear

<table><tr><td>

CDM



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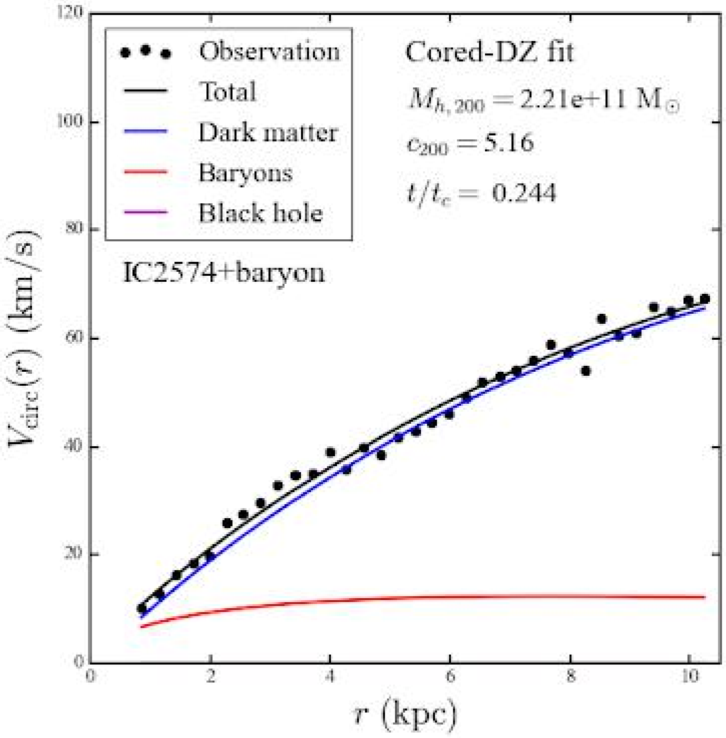
SIDM



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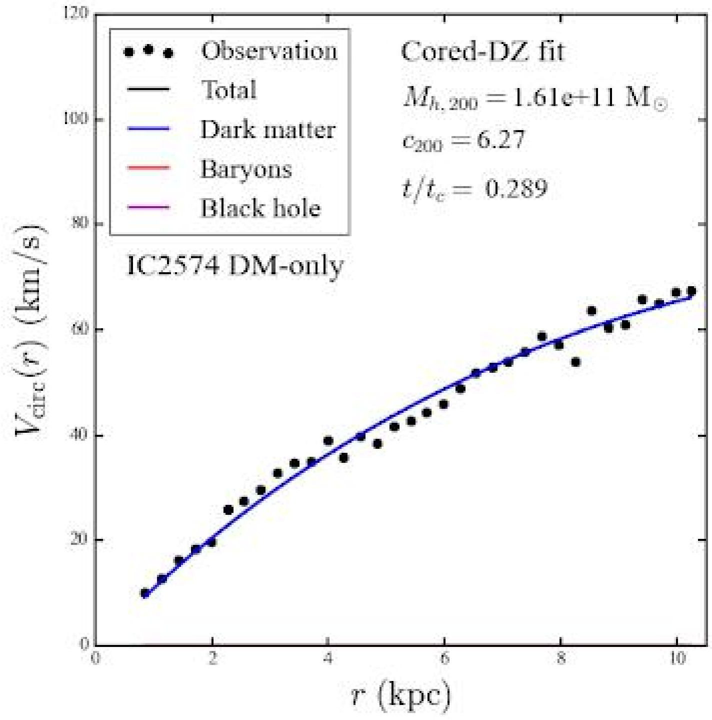
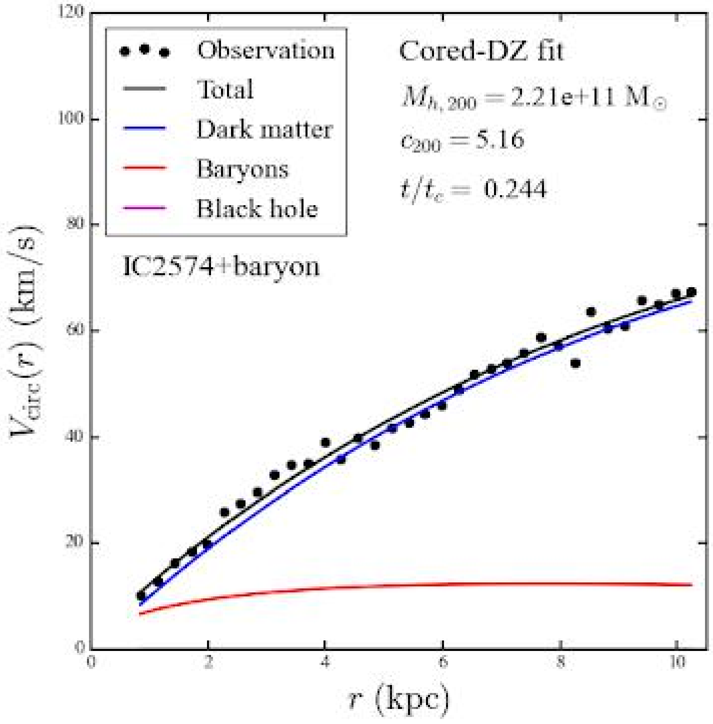
DM-only

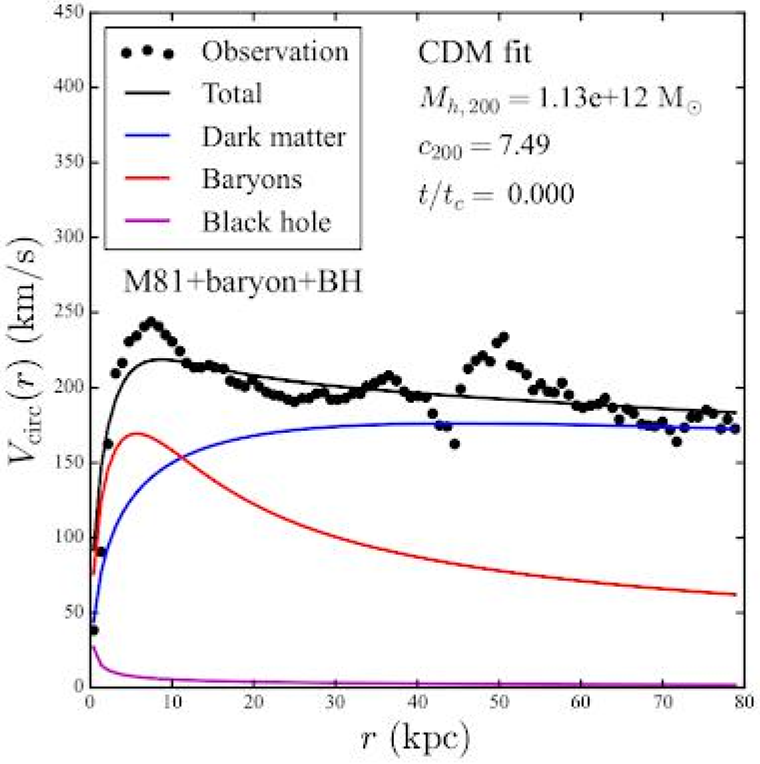
DM+baryons



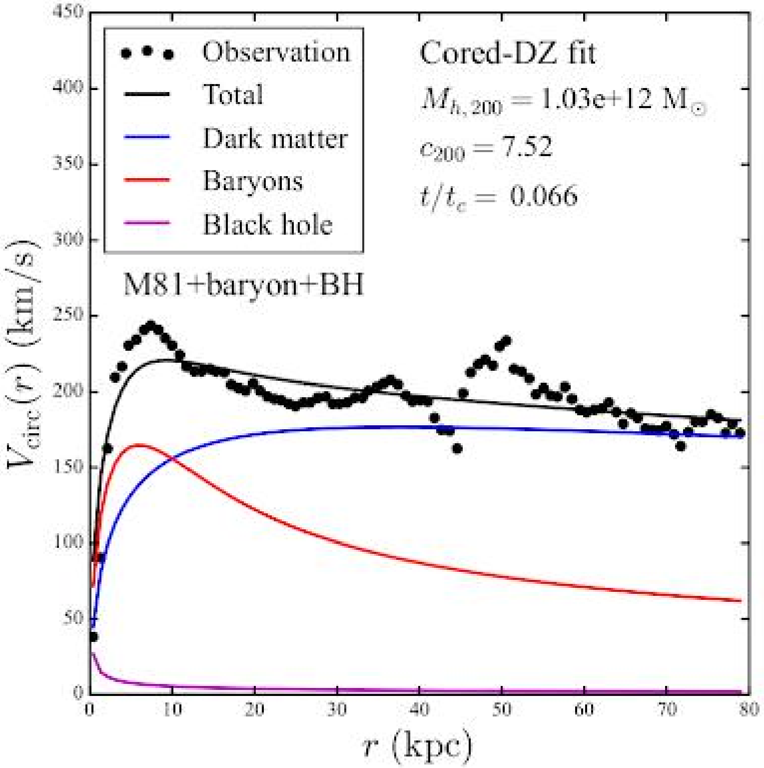


CDM

SIDM



Observation
Total
Dark matter
Baryons
Black hole
CDM fit
$M_{h,200} = 1.13\mathrm{e}{+}12\ M_\odot$
$c_{200} = 7.49$
$t/t_c = 0.000$
M81+baryon+BH
$V_{\rm circ}(r)$ (km/s)
r (kpc)



Observation
Total
Dark matter
Baryons
Black hole
Cored-DZ fit
$M_{h,200} = 1.03\mathrm{e}{+}12\ M_\odot$
$c_{200} = 7.52$
$t/t_c = 0.066$
M81+baryon+BH
$V_{\rm circ}(r)$ (km/s)
r (kpc)

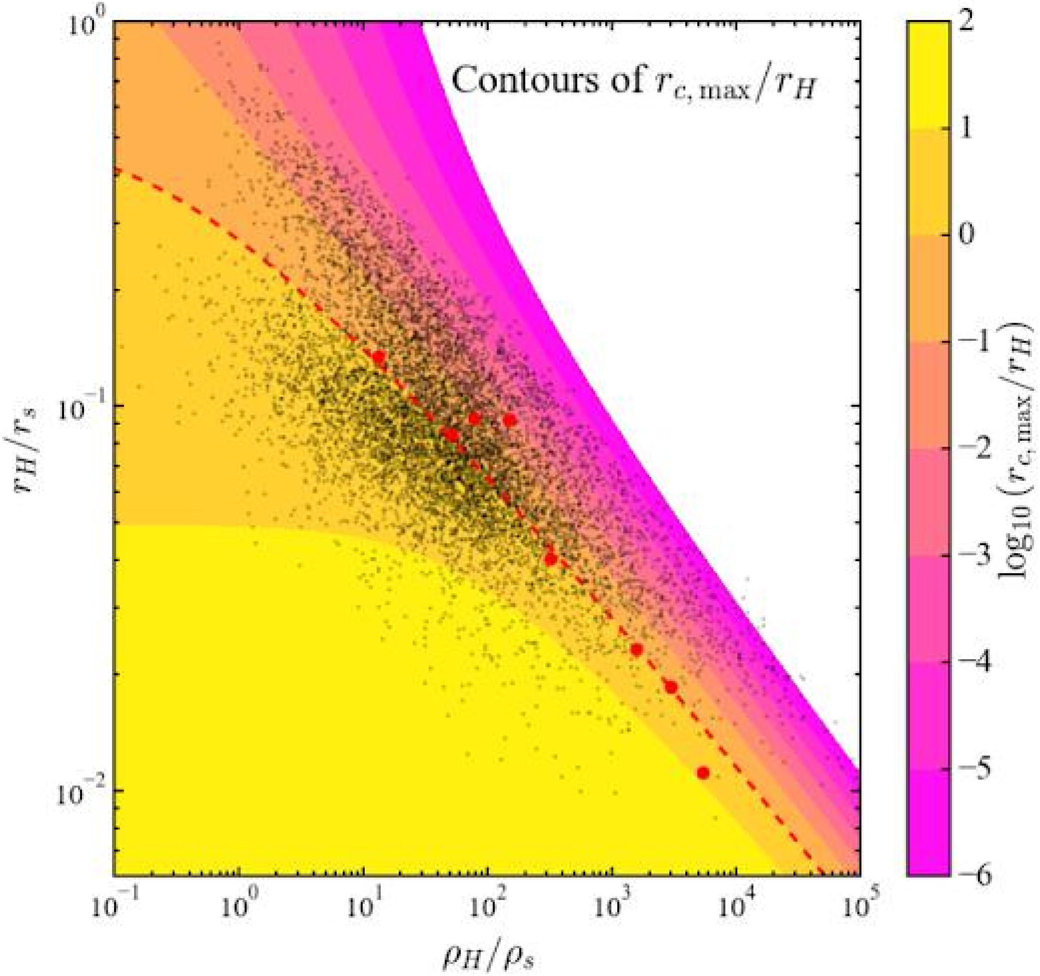
Interplay between the halo and baryon profiles

SIDM core shrinked:

rcmax=0.5 rs (tcb/tc)^2

Lower-left: Baryon may become more diffuse

Upper-right: Small effect during core formation, more compact during core collapse; for both the halo and baryon profiles



Model predicted vs simulated density profiles with baryons

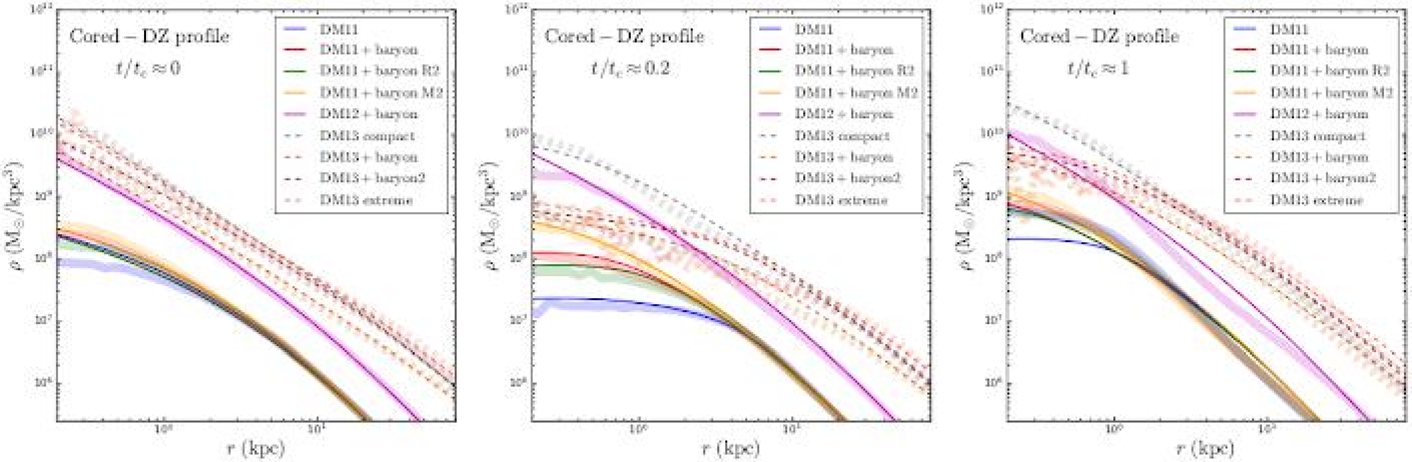


FIG. 5. The simulated (colored bands) and Core-DZ model predicted (colored curves) halo density profiles at three representative gravothermal phases: $t/t_c \approx 0, 0.2$, and 1. The *DM12* and *DM13* scenarios use a contracted CDM profile as the initial condition, whereas the *DM11* scenarios commence with an instant insertion method. In the left panel ($t/t_c \approx 0$), the *DM11* cases are depicted at $t = 0.25$ Gyr to allow some initial evolution away from the original NFW profile. At $t/t_c \approx 1$, the core collapse time, as calculated using Eq. (9), is found to be 10% (30%) shorter than the simulated *DM13+baryon2* (*DM13 extreme*). To align the profiles for equivalent gravothermal phases, we adjust the timing of the simulated curves accordingly in these specific cases.

Equations

The CoredDZ profile is parameterized as

$$\rho_{\mathrm{CoredDZ}}(r) = \frac{f_{\mathrm{in}}(r)\rho_x f_{\mathrm{out}}(r)}{\frac{(r^k+r_c^k)^{1/k}}{r_x}\left(1+\left(\frac{r}{r_x}\right)^{1/2}\right)^{2(3.5-a)}} \quad (19)$$

where we have introduced two functions to reshape the inner and outer profiles

$$f_{\mathrm{in}}(r) = \left(\frac{r}{r_x} + \frac{r_c}{0.4r_s}\left(\frac{\rho_{x,0}r_{x,0}}{\rho_s r_s + 0.4\rho_H r_H}\right)^{1/(a-1)}\right)^{1-a} \quad (20)$$

$$f_{\mathrm{out}}(r) = \left(1+\frac{r}{R_{\mathrm{cut}}}\left(\frac{r_x}{r_{x,0}}-1\right)\right)^{-1/2}.$$

$$\begin{aligned} r_{\mathrm{eff}} &= \frac{r_s\Phi_{0,\mathrm{NFW}} + \alpha r_H\Phi_{\mathrm{Hern}}(0)}{\Phi_{0,\mathrm{NFW}} + \alpha\Phi_{\mathrm{Hern}}(0)} \\ &= \frac{\rho_s r_s^3 + \alpha\rho_H r_H^3/2}{\rho_s r_s^2 + \alpha\rho_H r_H^2/2} \\ &= r_s\frac{1+\alpha\hat{\rho}_H\hat{r}_H^3/2}{1+\alpha\hat{\rho}_H\hat{r}_H^2/2} \equiv r_s\hat{r}_{\mathrm{eff}}, \end{aligned}$$

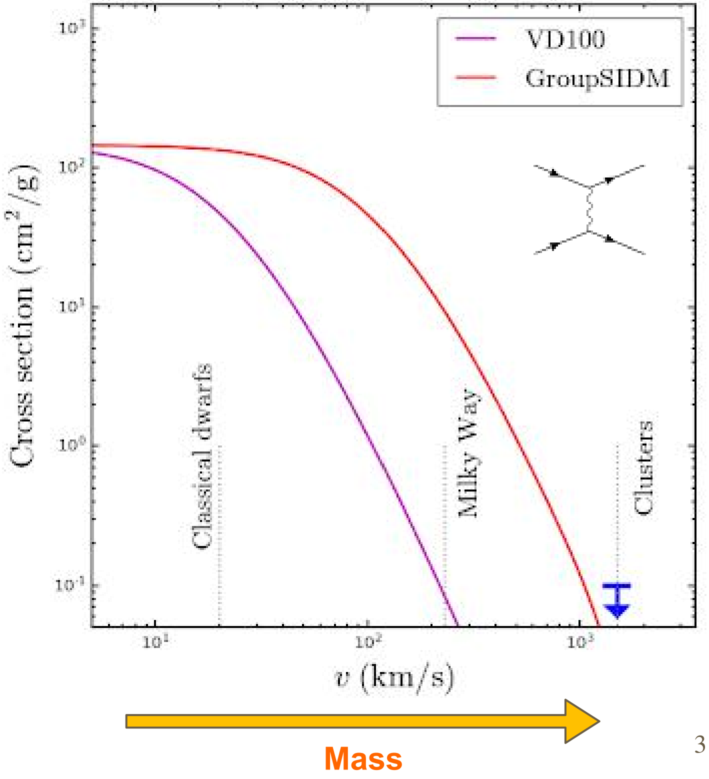
Velocity-dependence accommodate constraints and explain anomalies

$$\frac{d\sigma}{d\cos\theta} = \frac{\sigma_0 w^4}{2\left[w^2 + v^2\sin^2(\theta/2)\right]^2}$$

Rutherford

For identical particles, consider Moller scatterings;
(JCAP 09 (2022) 077)

Velocity and angular dependence determined by particle physics models

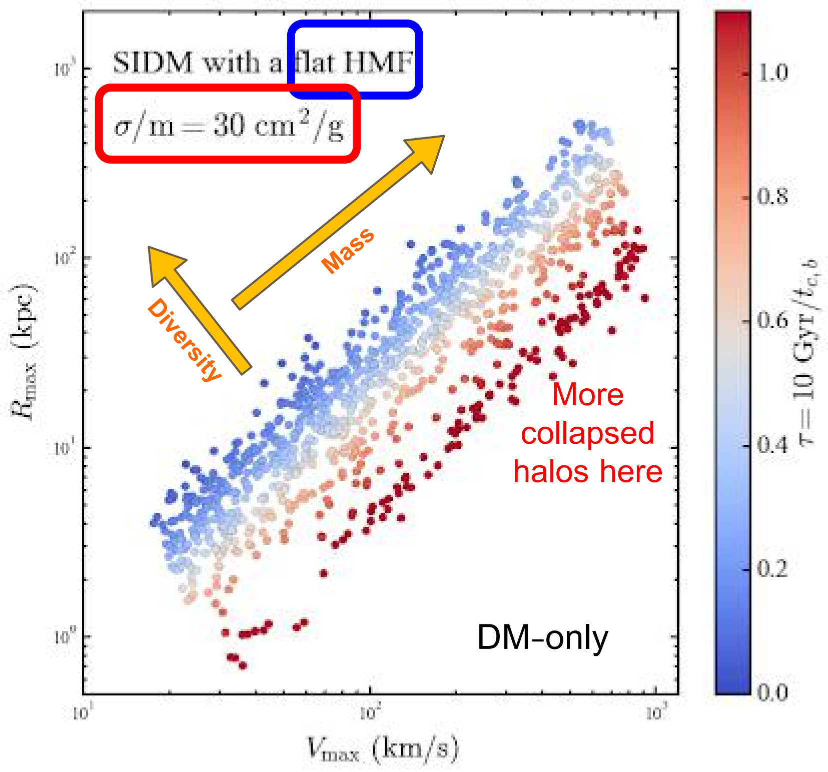


A constant SIDM cross section does not affect halos in the s

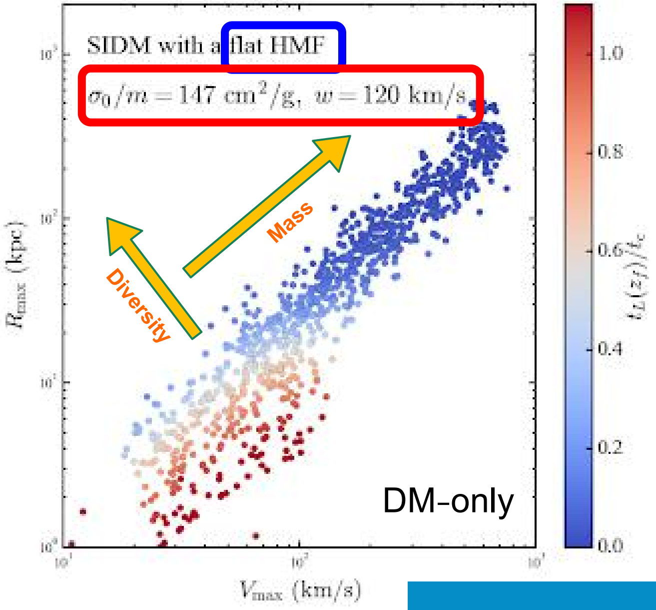
Collisional relaxation

$$t_{c,0} = \frac{150}{C}\frac{1}{\frac{\sigma}{m}\rho_s}\left(\frac{1}{4\pi G\rho_s r_s^2}\right)^{\frac{1}{2}}$$

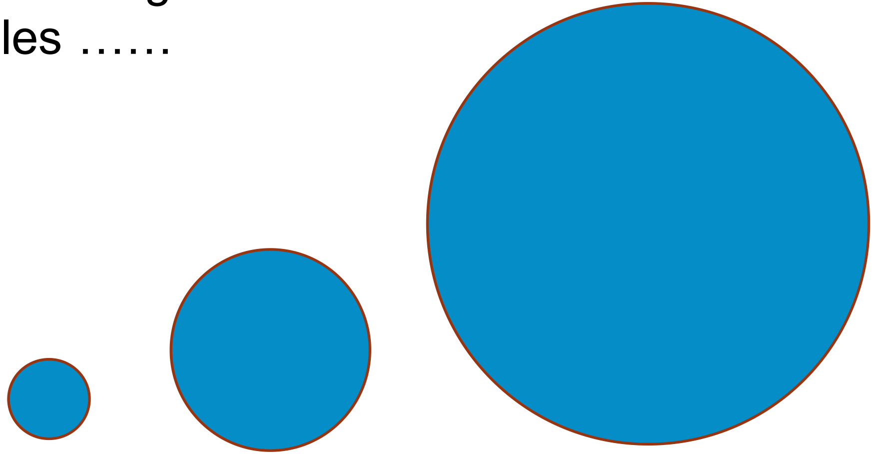
Essig+2019
Balberg+2002



Opportunities



- Rich existing & upcoming observations
- Particle physics scattering information can be recovered by considering halos of different scales ……



	Halo 1	Halo 2	Halo 3
Model 0	SIDM 1	SIDM 1	SIDM 1
Model 1	SIDM 10	SIDM 1	SIDM 0.1
Model 2	SIDM 100	SIDM 10	SIDM 0.01