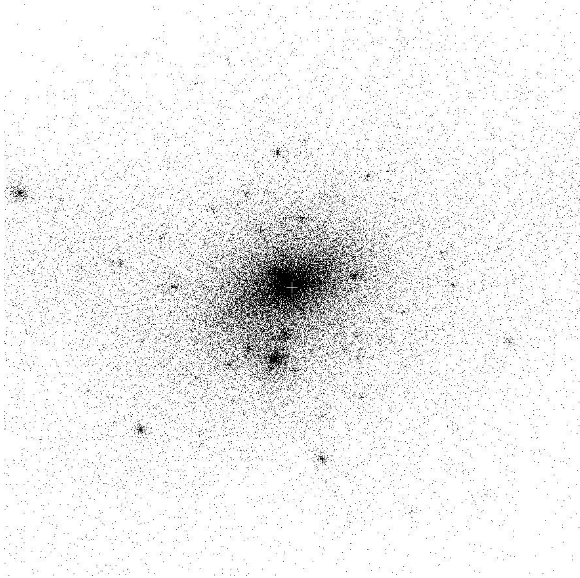
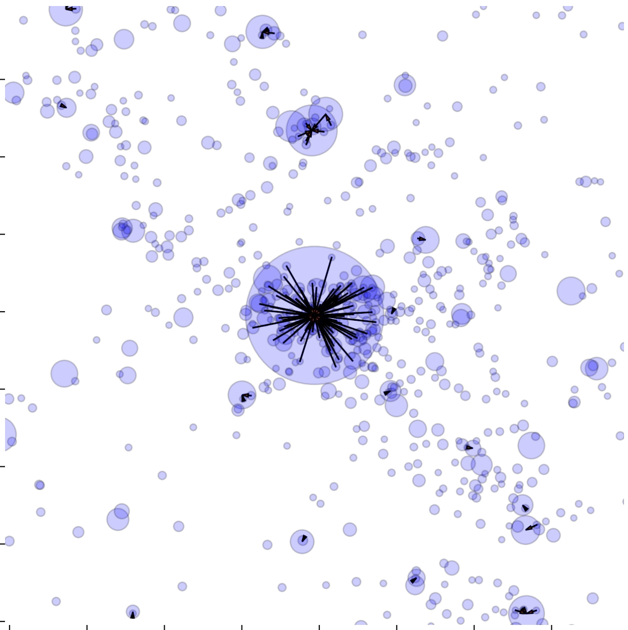
Based on recent works with
Hai-Bo Yu (UCR),
Ethan O. Nadler (Carnegie OBSY & USC),
Yi-Ming Zhong (UChicago & CityU HK)



A parametric model for dark matter halos with particle self-interaction

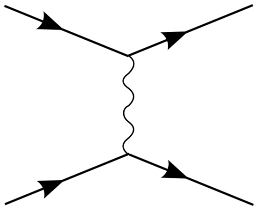
Daneng Yang (UCR)

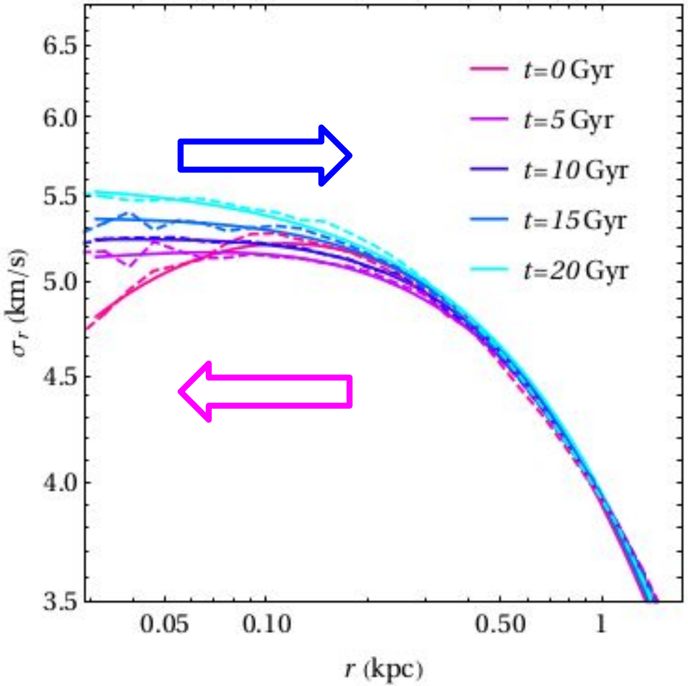
- 2305.16176 [astro-ph.CO]
- JCAP 09 (2022) 077 2205.03392
- 2306.08028 [astro-ph.CO]
- Astrophys.J. 949 (2023) 2, 67 2211.13768
- 2306.01830 [astro-ph.GA]



PASCOS June 2023

Self-interacting dark matter





First stage
-heat flux + capacity => core formation

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

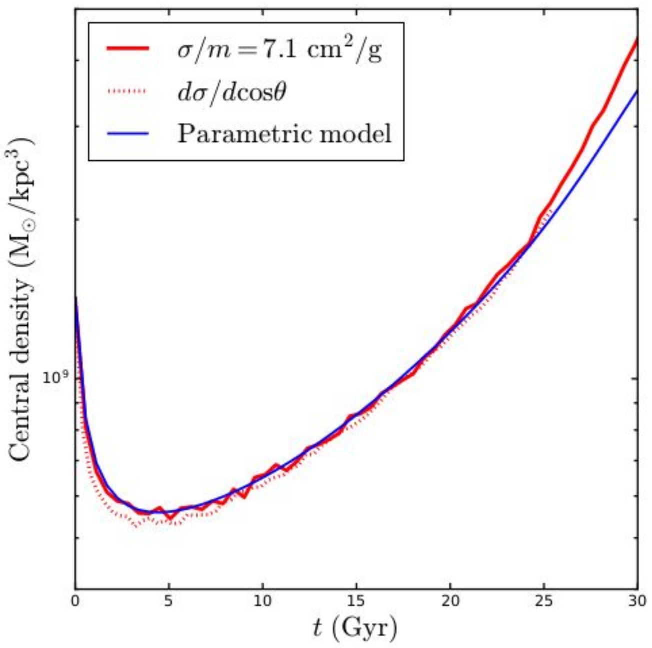
SIDM + Gravity: Gravothermal evolution

SIDM introduces a (short-range) collision term
Thermodynamic description

$$\nabla(\rho\sigma_{1D}^2) = -\rho\nabla\Phi$$ Pressure equilibrium

$$\frac{1}{4\pi}\frac{\partial L}{\partial r} = -\rho\sigma_{1D}^2\frac{Ds}{Dt}$$ Energy transport

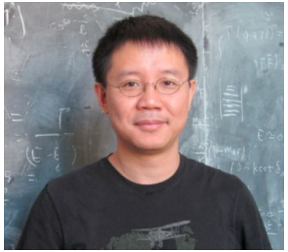
Checked using N-body simulations
(Yang & Yu 2205.03392)



An SIDM solution to small scale challenges of CDM?

Cosmological zoom-in simulations with SIDM

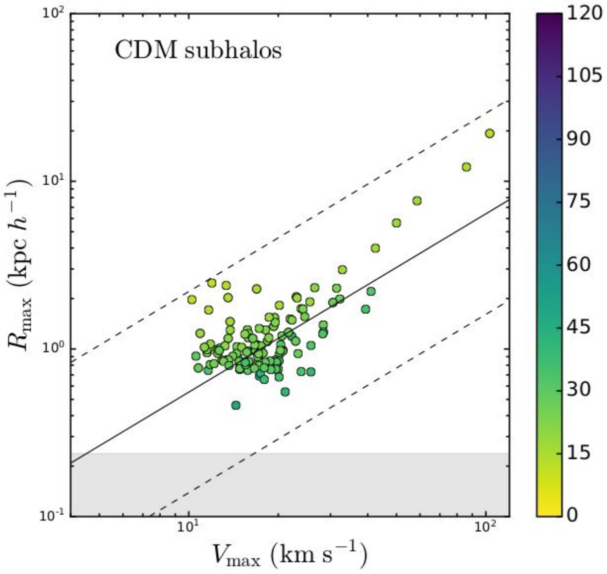
Ethan O. Nadler
(Carnegie OBSY & USC)

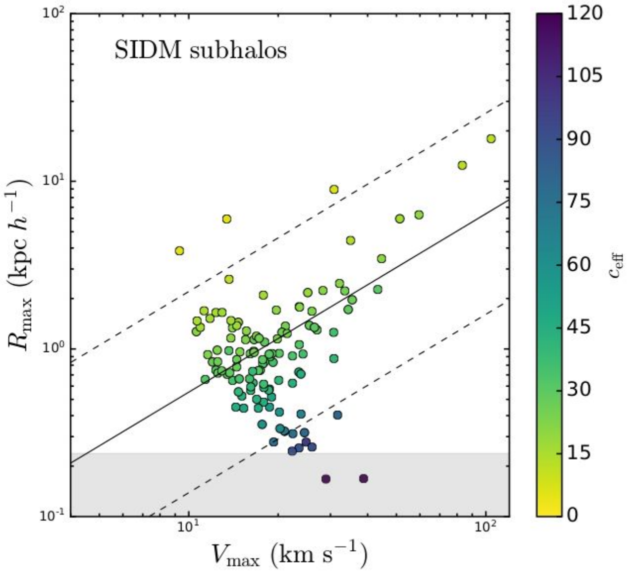


Hai-Bo Yu
(UCR)

Diverse rotation curves of MW dwarfs
(Yang, Nadler, Yu 2211.13768)

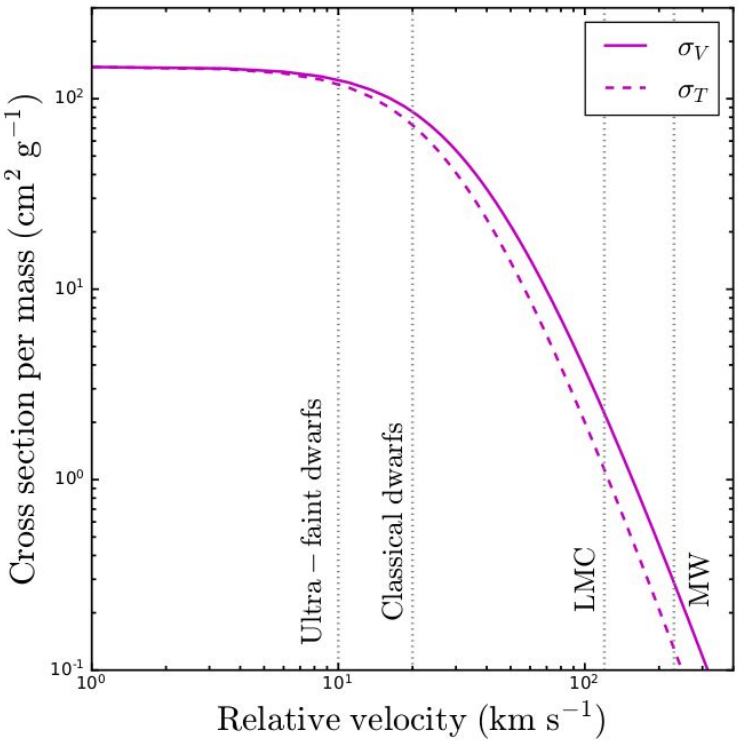
Strong lensing perturber & ultra diffuse galaxies
(Nadler, Yang, Yu 2306.01830)





SIDM cross sections can have nontrivial velocity dependencies

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



How to probe and distinguish SIDM models?

Heat conduction drives the evolution of an SIDM halo

- Particle scattering affects short range energy exchange
- Post scattering evolution controlled by gravity

Weight a *differential cross section* in the same way as heat conductivity

$$\sigma_\kappa(r) = \frac{2\int v^2 dv d\cos\theta \frac{d\sigma}{d\cos\theta}\sin^2\theta v^5 \exp\left[-\frac{v^2}{4\sigma_{\rm 1D}^2(r)}\right]}{\int v^2 dv d\cos\theta \sin^2\theta v^5 \exp\left[-\frac{v^2}{4\sigma_{\rm 1D}^2(r)}\right]}$$

Halo velocity dispersion $\sigma_{\rm 1D}$ couples to **velocity dependence of SIDM**

One halo probes **One** effective constant cross section

The σ_{1D} in inner halo region evolves slowly, allowing a constant
veff~0.64*Vmax
Effective constant cross section

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

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

Yang & Yu
2205.03392

See also
Outmezguine+
2204.06568 and
S.Yang+
2205.02957 for
analogous
definitions

Need to explore a **diverse sample** of halos to distinguish SIDM features, **efficiently**

A parametric model for dark matter halos with particle self-interaction

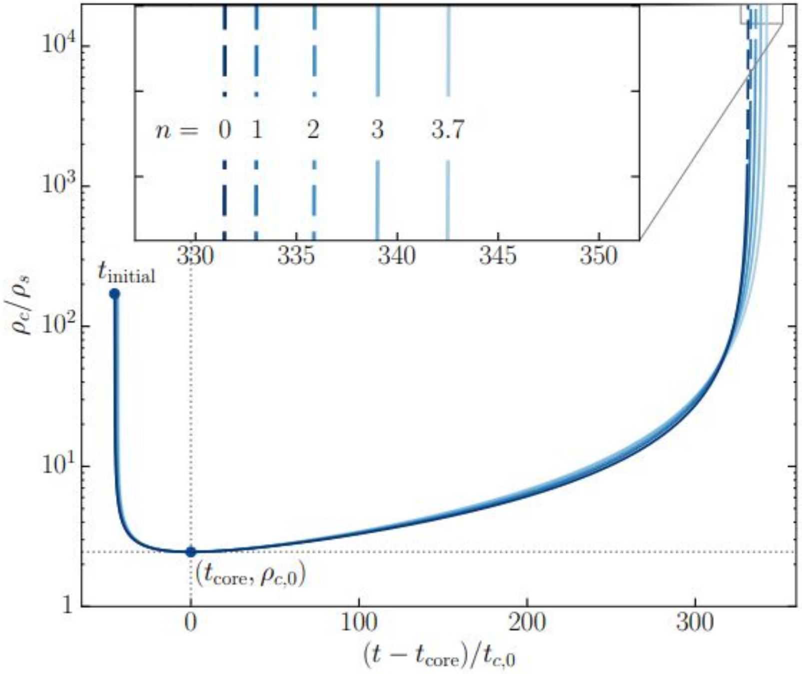
2305.16176 [astro-ph.CO] Yang, Nadler, Yu, and Zhong

A universal way to incorporate SIDM effects

Features of gravothermal evolution are largely universal

(Outmezguine+ 2204.06568)

A single solution could be used to describe the evolution of all halos!



A universal parametrization of the solution

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

Normalize the initial condition

ρs/ρs0, rs/rs0, rc/rc0

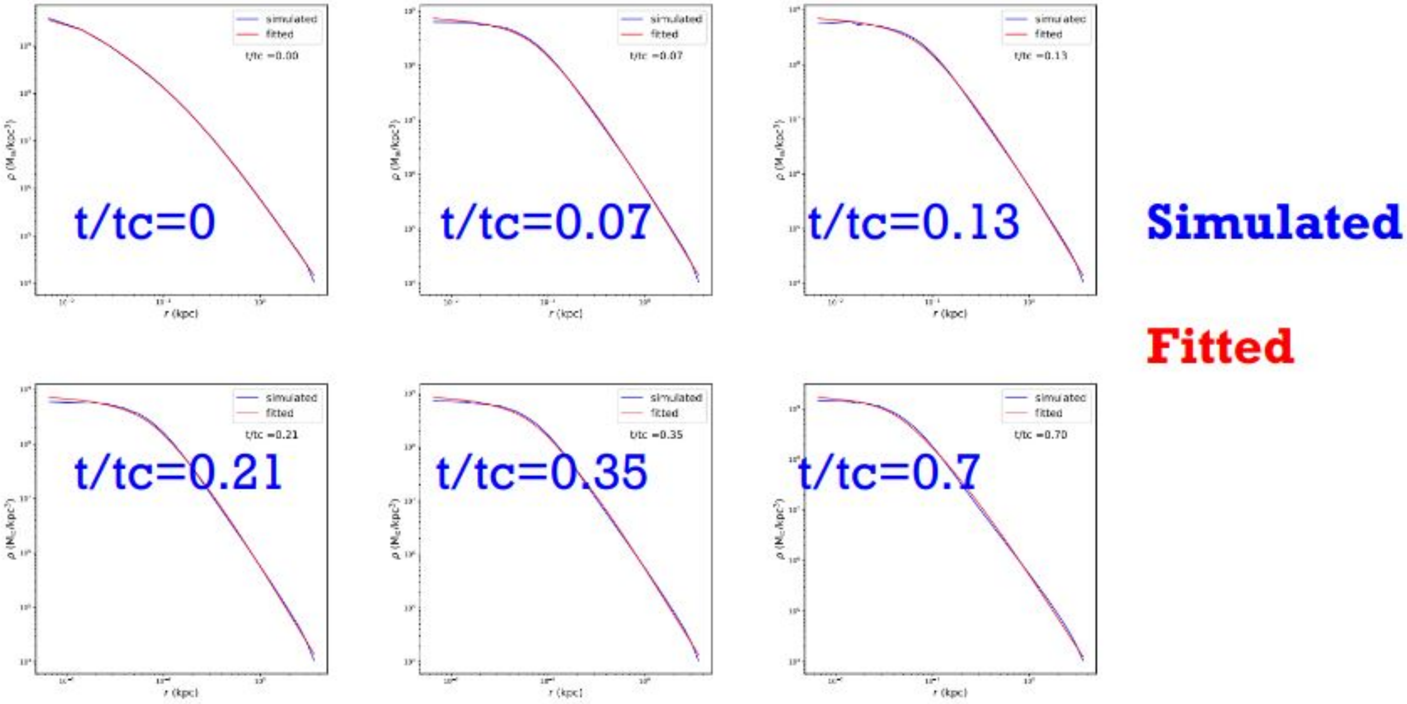
Parametrize their evolution in terms of $\tilde{t} \equiv t/t_c$

$$t_{\rm c} = \frac{150}{C}\frac{1}{(\sigma_{\rm eff}/m)\rho_{\rm eff} r_{\rm eff}}\frac{1}{\sqrt{4\pi G\rho_{\rm eff}}}$$

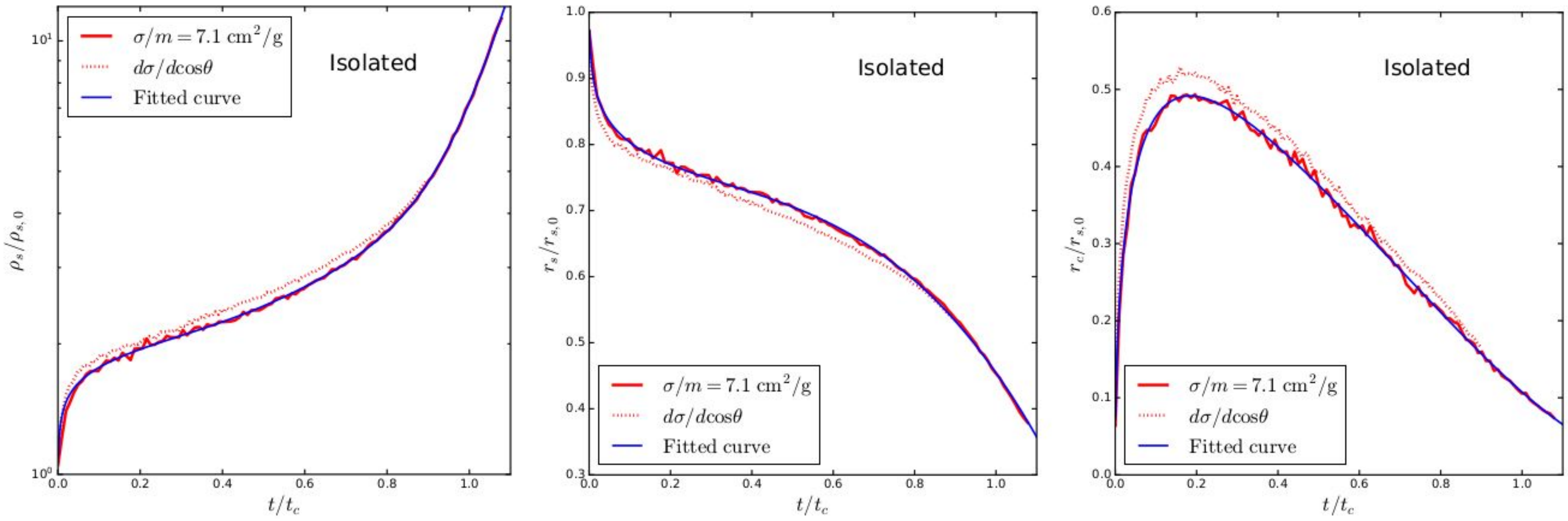
Normalize the gravothermal timescale:

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

Quality of the parameterization: SIDM density profiles



Quality of the parameterization: parameter trajectories



$$\frac{\rho_s}{\rho_{s,0}} = 2.033 + 0.7381\tilde{t} + 7.264\tilde{t}^5 - 12.73\tilde{t}^7 + 9.915\tilde{t}^9 - (1 - 2.033)(\ln 0.001)^{-1}\ln\left(\tilde{t} + 0.001\right),$$

$$\frac{r_s}{r_{s,0}} = 0.7178 - 0.1026\tilde{t} + 0.2474\tilde{t}^2 - 0.4079\tilde{t}^3 - (1 - 0.7178)(\ln 0.001)^{-1}\ln\left(\tilde{t} + 0.001\right),$$

$$\frac{r_c}{r_{s,0}} = 2.555\sqrt{\tilde{t}} - 3.632\tilde{t} + 2.131\tilde{t}^2 - 1.415\tilde{t}^3 + 0.4683\tilde{t}^4,$$

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

Apply the parameterized solution to CDM halos

Basic approach

- Solve for ρs0, rs0 from Vmax, Rmax @z=0
- Estimate halo formation time based on mass

★ *Fully analytic and requires only two quantities for each halo* (mass can be solved)

★ Ideal for isolated halos

Integral approach

- Make use of the evolution history in LCDM: Vmax, Rmax, distance to the host

★ Incorporate the effect of mass accretion/loss

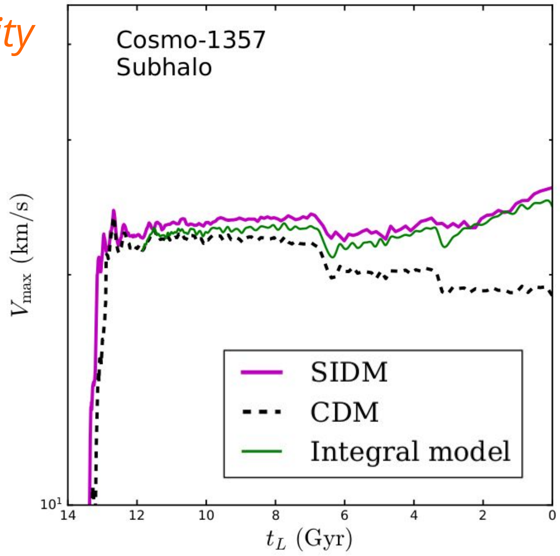
★ Incorporate effect of tidal evolution

★ Less sensitive to the choice of formation time

★ *Suitable for all halos*

Subhalos

Leave the majority of the complexity to the CDM accretion history



Truncate the profile at the tidal radius

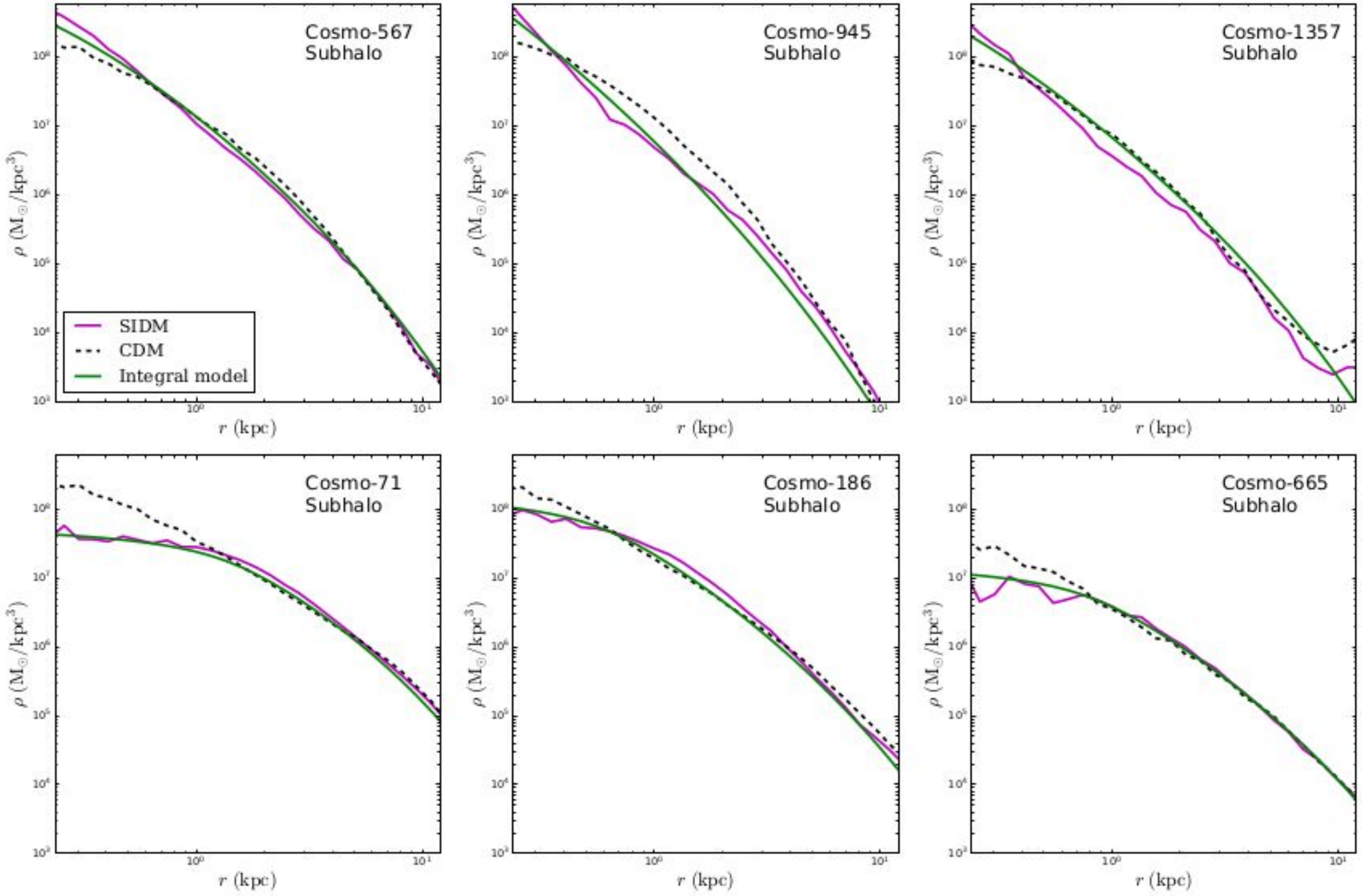
$$\rho_{\rm tSIDM}(r) = \frac{\rho_s}{\frac{(r^\beta + r_c^\beta)^{1/\beta}}{r_s}\left(1+\frac{r}{r_s}\right)^2\left(1+\left(\frac{r}{r_t}\right)^{2-u}\right)^{1+3u}}$$

$$V_{\rm max}(t) = V_{\rm max,CDM}(t_f) + \int_{t_f}^{t} dt' \frac{dV_{\rm max,CDM}(t')}{dt'} + \int_{t_f}^{t} \frac{dt'}{t_c(t')} \frac{dV_{\rm max,Model}(\tilde{t'})}{d\tilde{t'}}$$

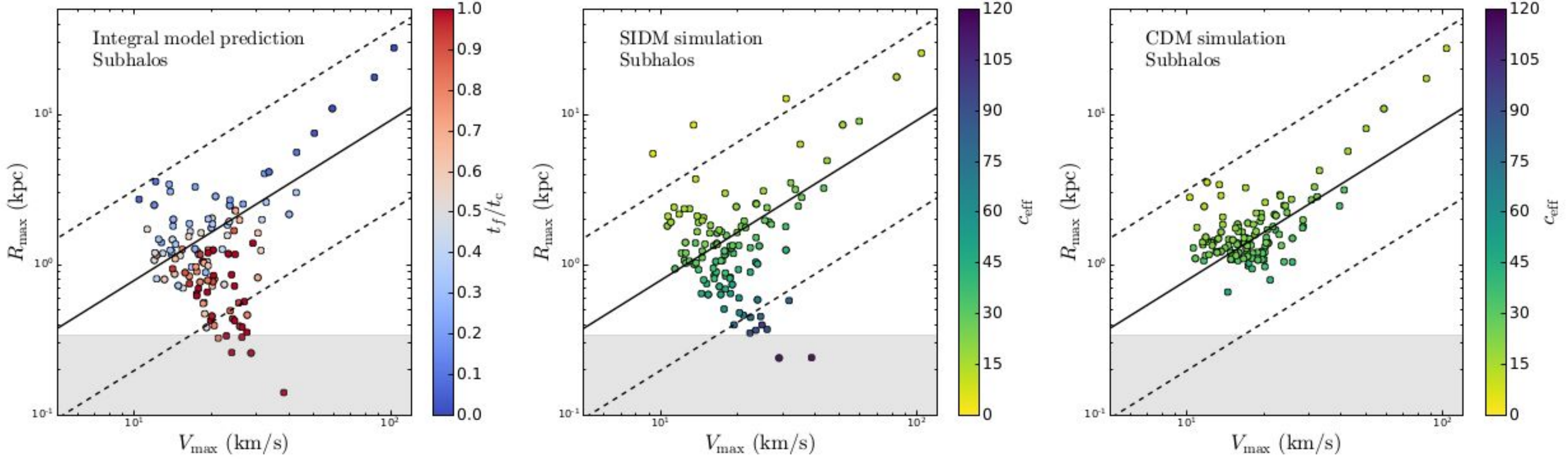
$$R_{\rm max}(t) = R_{\rm max,CDM}(t_f) + \int_{t_f}^{t} dt' \frac{dR_{\rm max,CDM}(t')}{dt'} + \int_{t_f}^{t} \frac{dt'}{t_c(t')} \frac{dR_{\rm max,Model}(\tilde{t'})}{d\tilde{t'}}$$

Accretion in CDM **Gravothermal evolution**

Density profiles of some example subhalos



Apply to a population of subhalos



Apply to a population of isolated halos

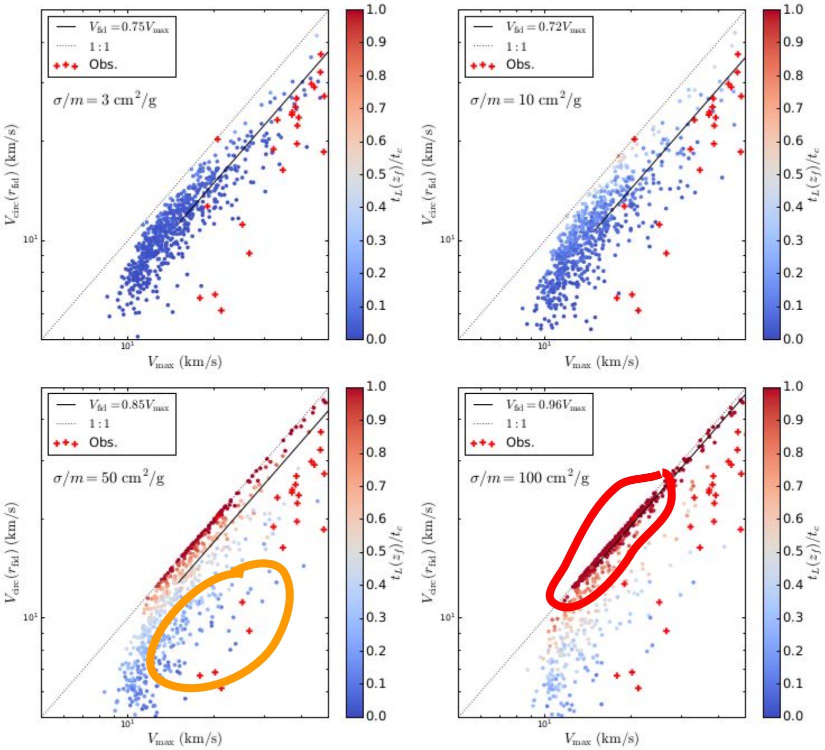
Vfid=Vcirc(rfid) with

$$r_{\rm fid} = 2V_{\rm max}/(70 \ {\rm km/s}) \ {\rm kpc}$$

Core forming

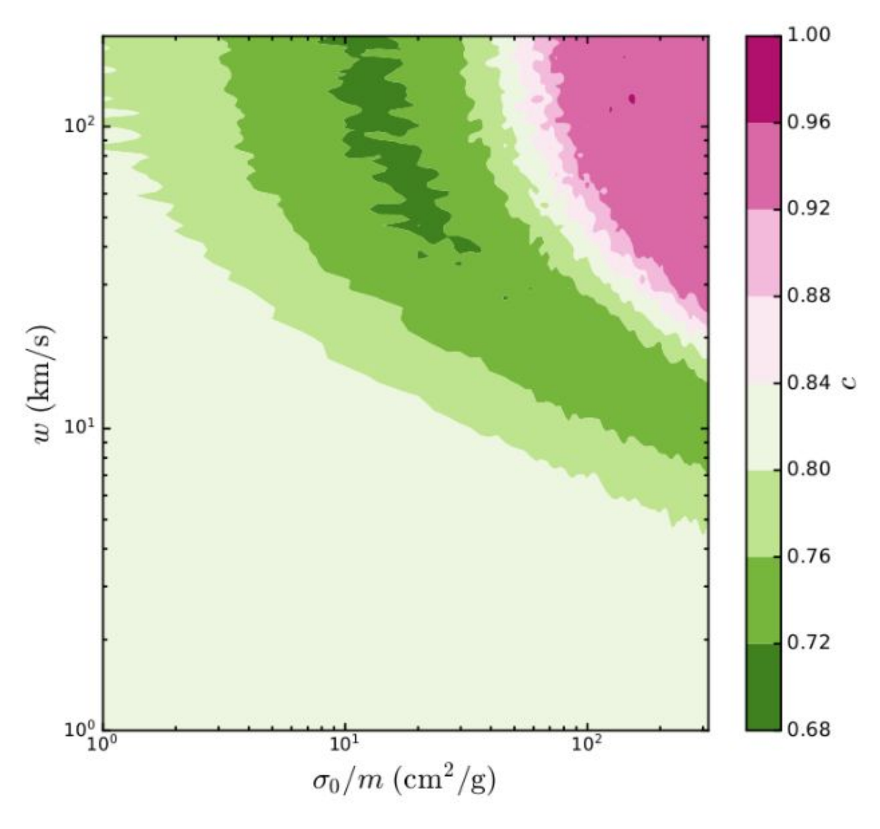
Core collapsing

Demonstrations here
Result is on the next page



Applications

SIDM parameter scan
Translate CDM simulations into SIDM
Semi-analytic model/MC program
……



Explore the parameter space on a laptop

Going beyond...

Effect of baryons could be incorporated!

$$t'_c = \frac{150}{C}\frac{1}{\sigma_c \rho_{\rm eff}}\left(\frac{1}{4\pi G(\rho_s r_s^2 + \rho_H r_H^2/2)}\right)^{\frac{1}{2}}$$

$$\rho_{\rm eff} = \frac{\rho_{\chi,s} r_{\chi,s} + \gamma \rho_{b,s} r_{b,s}}{r_{\chi,s} + \gamma r_{b,s}}$$

Zhong, Yang, Yu
2306.08028

Modeling subleading effects on top of accurate CDM results could be easier

★ *An integral model for the disk effect on subhalos?!*

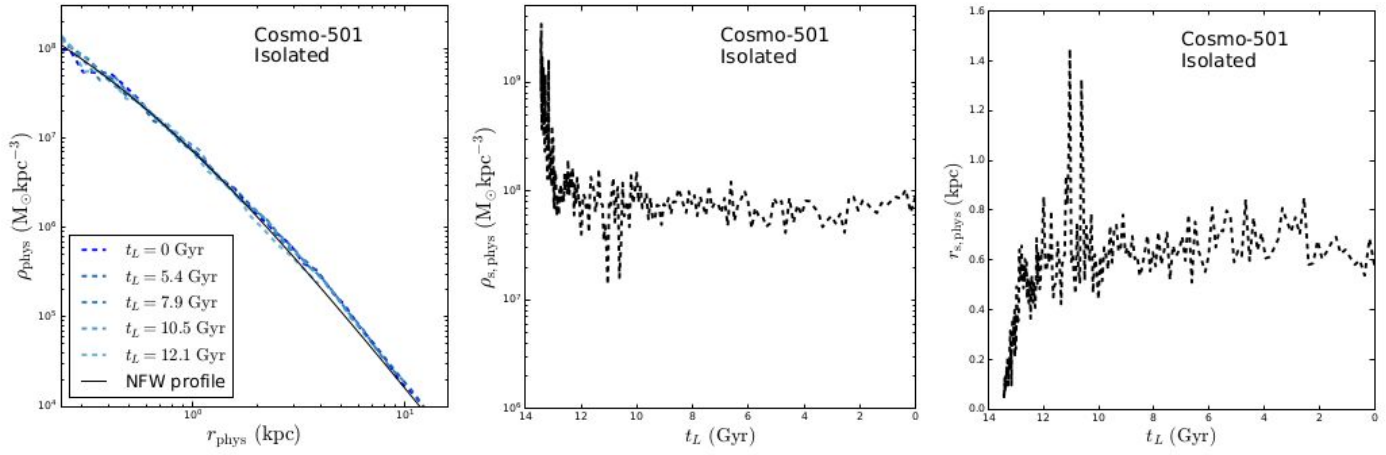
Stay tuned...

Thanks for your attention!

Backup

The Basic approach

- Take Vmax & Rmax from CDM halos
- A simple equation to estimate of halo formation time with a scatter (trade off uncertainty for simplicity)



Integral approach

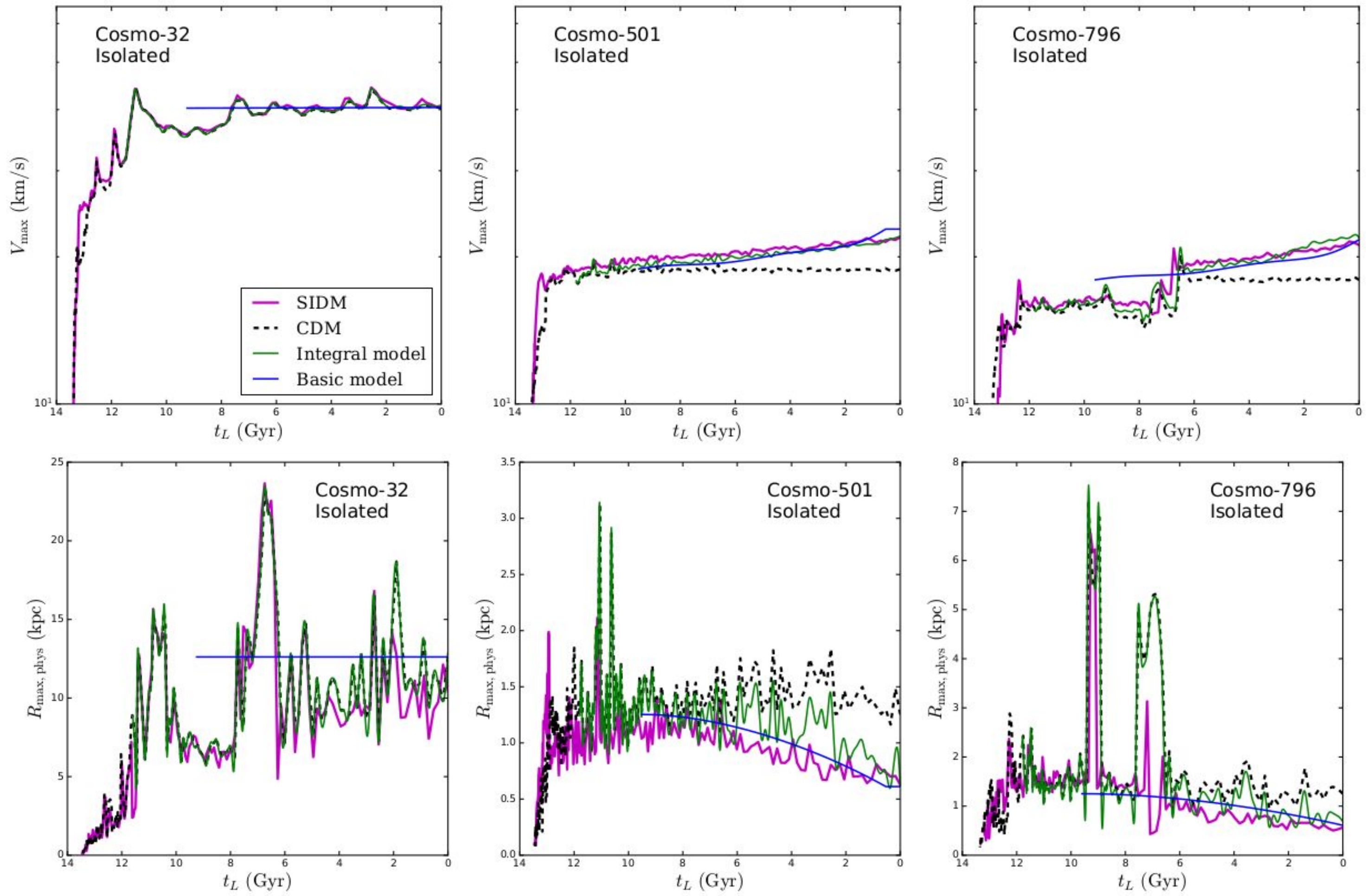
- Take Vmax & Rmax **accretion history** from CDM halos
- Insensitive to the choice of halo formation time, provided it is early enough and the accretion is accurately modeled

$$V_{\max}(t) = V_{\max,\mathrm{CDM}}(t_f) + \int_{t_f}^{t} dt' \frac{dV_{\max,\mathrm{CDM}}(t')}{dt'} + \int_{t_f}^{t} \frac{dt'}{t_c(t')} \frac{dV_{\max,\mathrm{Model}}(\tilde{t}')}{d\tilde{t}'}$$

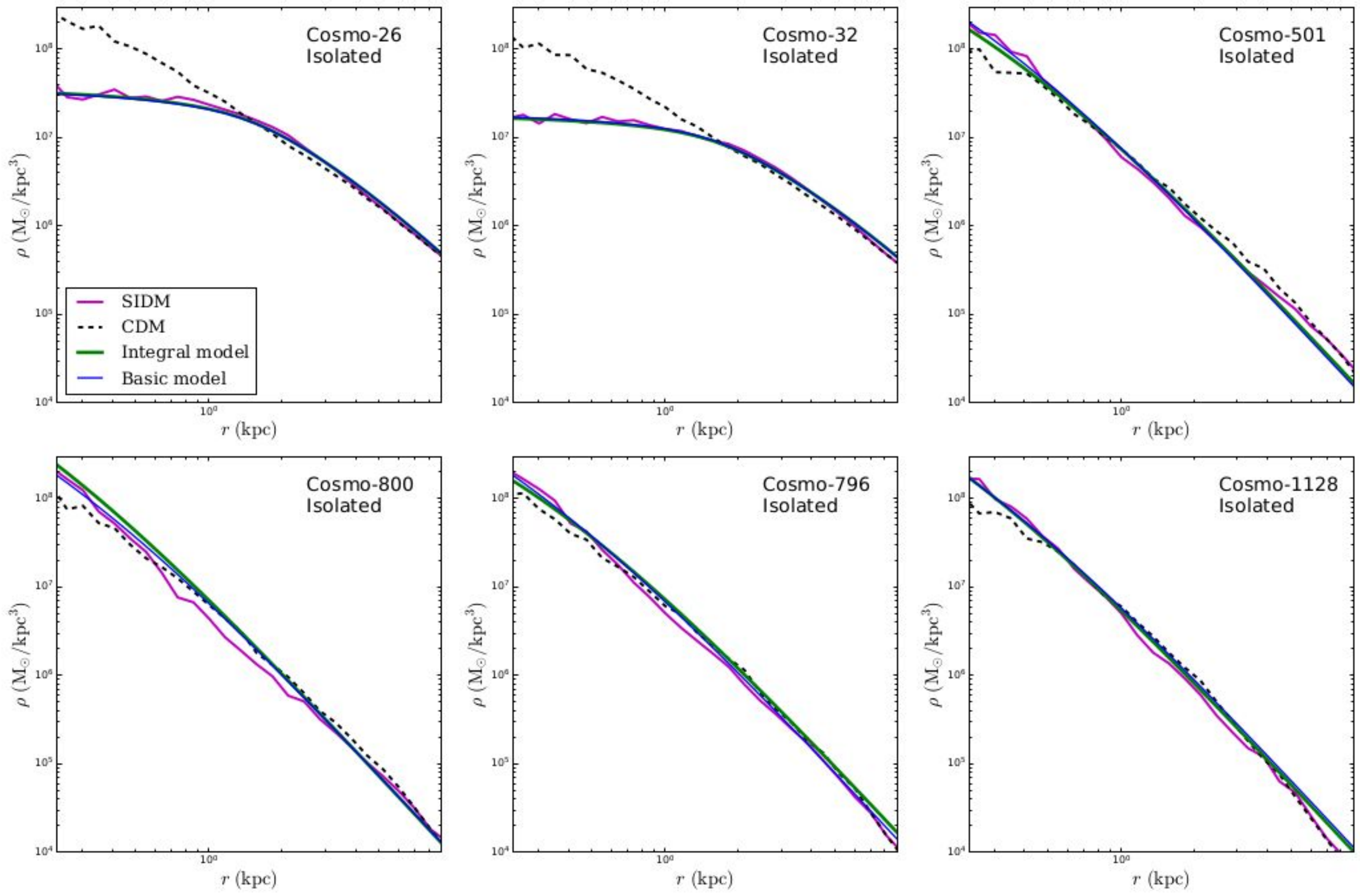
$$R_{\max}(t) = R_{\max,\mathrm{CDM}}(t_f) + \int_{t_f}^{t} dt' \frac{dR_{\max,\mathrm{CDM}}(t')}{dt'} + \int_{t_f}^{t} \frac{dt'}{t_c(t')} \frac{dR_{\max,\mathrm{Model}}(\tilde{t}')}{d\tilde{t}'}$$

Accretion in CDM | **Gravothermal evolution**

Isolated halos



Isolated halos



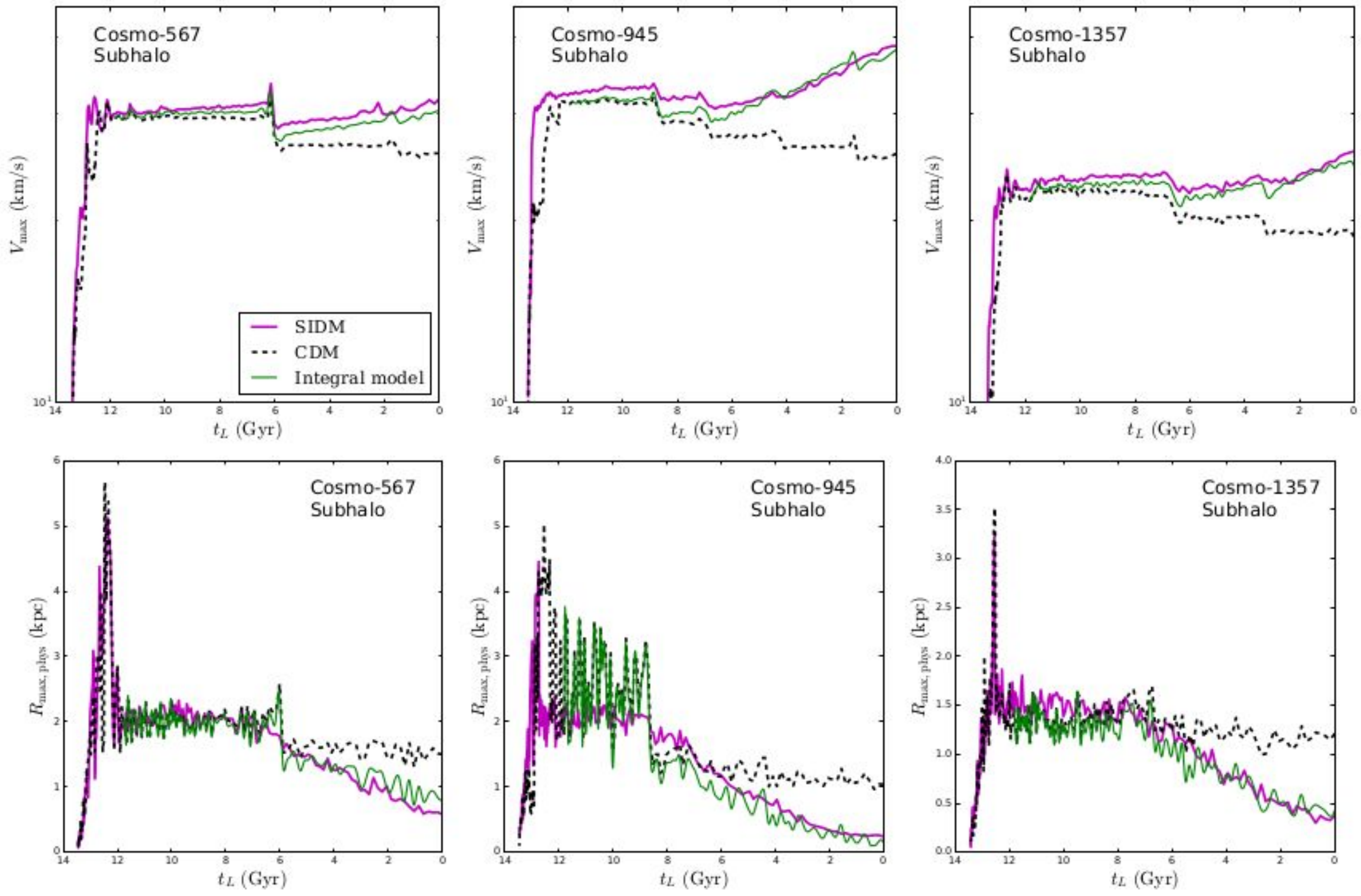
Modeling subhalos

Assuming the inner region to be modeled by the **same** profile and introduce a concentration dependent **truncation** at around the tidal radius

$$\rho_{\rm tSIDM}(r) = \frac{\rho_s}{\frac{(r^\beta + r_c^\beta)^{1/\beta}}{r_s}\left(1+\frac{r}{r_s}\right)^2\left(1+\left(\frac{r}{r_t}\right)^{2-u}\right)^{1+3u}}$$

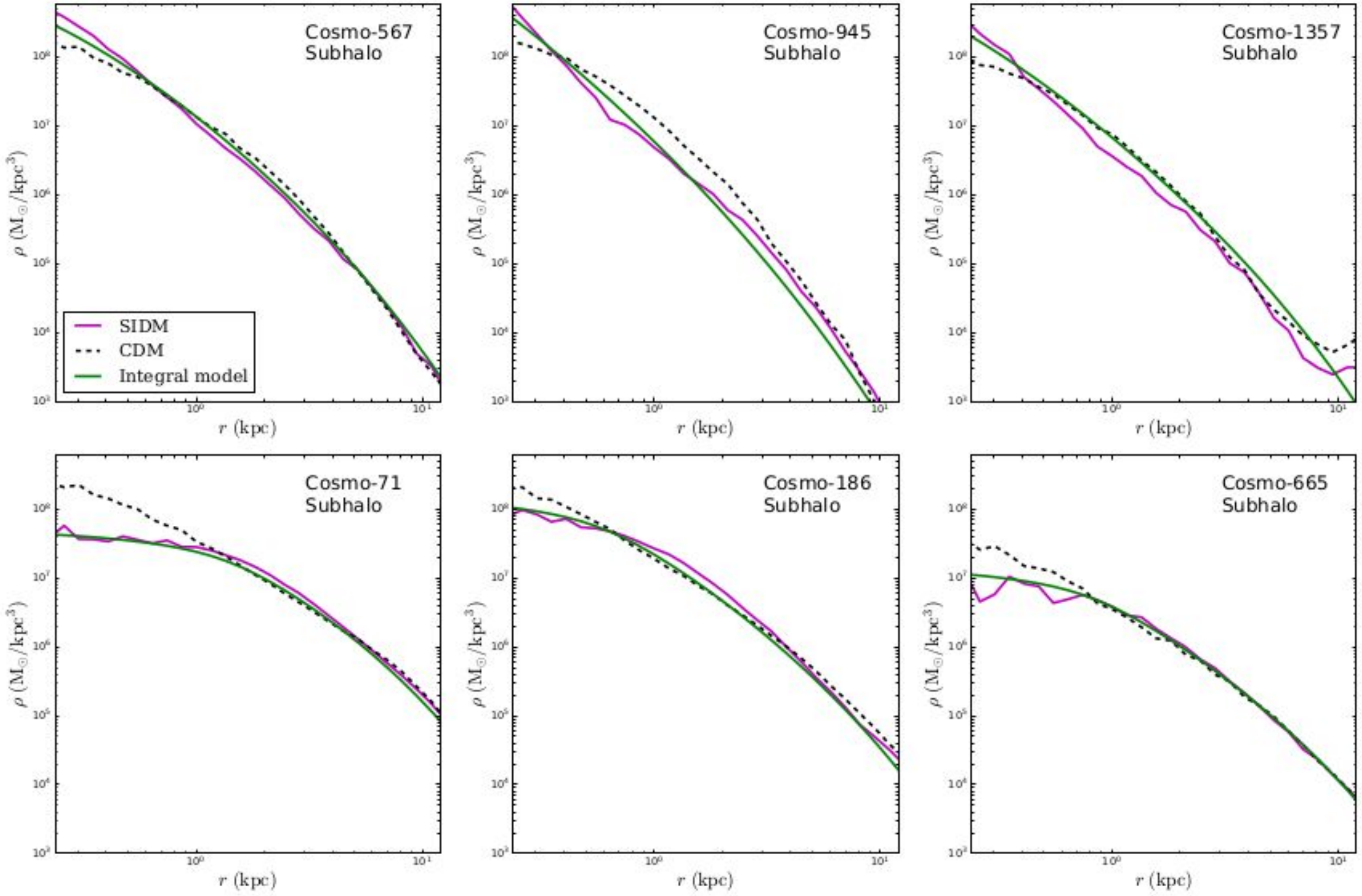
$$u(c_{\rm eff}) \;=\; {\rm Min}(1, 0.0004 c_{\rm eff}^{2.2}) \qquad r_t = d\left(\frac{M_{\rm sub}}{M_{\rm host}(r<d)}\right)^{1/3}$$

subhalos



Cosmo-567
Subhalo
Cosmo-945
Subhalo
Cosmo-1357
Subhalo
V_{max} (km/s)
t_L (Gyr)
SIDM
CDM
Integral model
$R_{max, phys}$ (kpc)

Density profiles of example subhalos



Contours of the coefficient c

Vfid=c Vmax

c=0.82 in CDM

c=0.6 for the UDG sample

The valley in green seems to be favored, need further studies