Phys. Rev. Lett., 125:111105
Astrophys.J. 949 (2023) 2, 67
JCAP, 02:032, 2024
JCAP 09 (2022) 077
MNRAS, 526(1):758–770, 2023
APJL,965(2):L19, 4 2024
APJL,968(1):L13, 2024
APJL,958(2):L39, 202 2023
PRD,104(10):103031
Phys. Lett. B, 139062, 2024
arXiv:2405.03787
arXiv:2406.10753

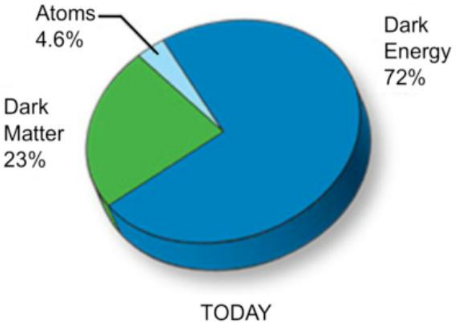
Searching for signatures of self-interacting dark matter

Daneng Yang (杨大能)
University of California, Riverside
Purple Mountain Observertory, CAS

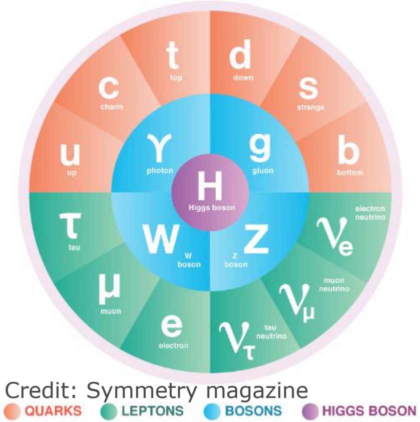
November 14, 2024
2024年紫金山暗物质研讨会

Based on works with
Hai-Bo Yu (UCR),
Ethan O. Nadler (Carnegie OBSY & USC & UCSD),
Yi-Ming Zhong (CityU HK),
Haipeng An,
Xingyu Zhang (THU),
Simeon Bird,
Yanou Cui,
Chia-Feng Chang,
Demao Kong (UCR)

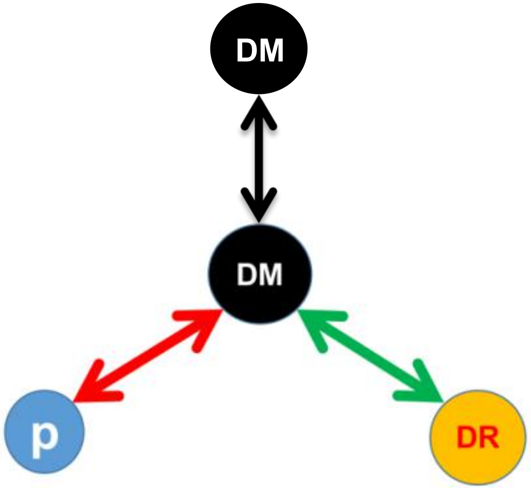
Dark matter is cold and collisionless, overall
However, it is not part of the
standard particle physics model ...



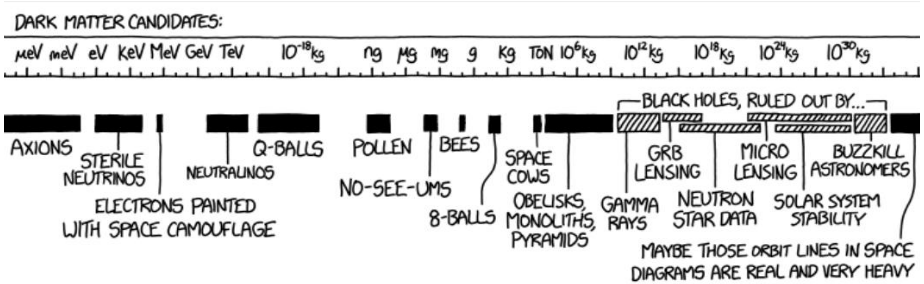
Credit: Swinburne



Credit: Symmetry magazine



Fuzzy dark matter
(with self-interactions)
1e-22 eV



https://explainxkcd.com/wiki/index.php/2035:_Dark_Matter_Candidates

MACHO
1-10000 Msun

Puzzles in small scale observations

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

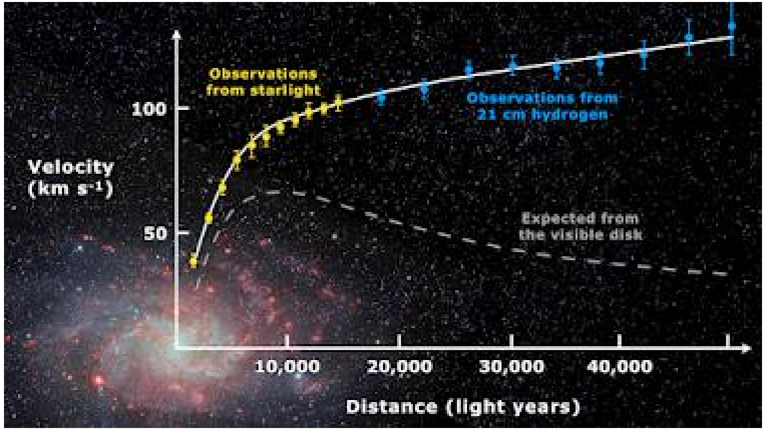
- **The diversity problem**

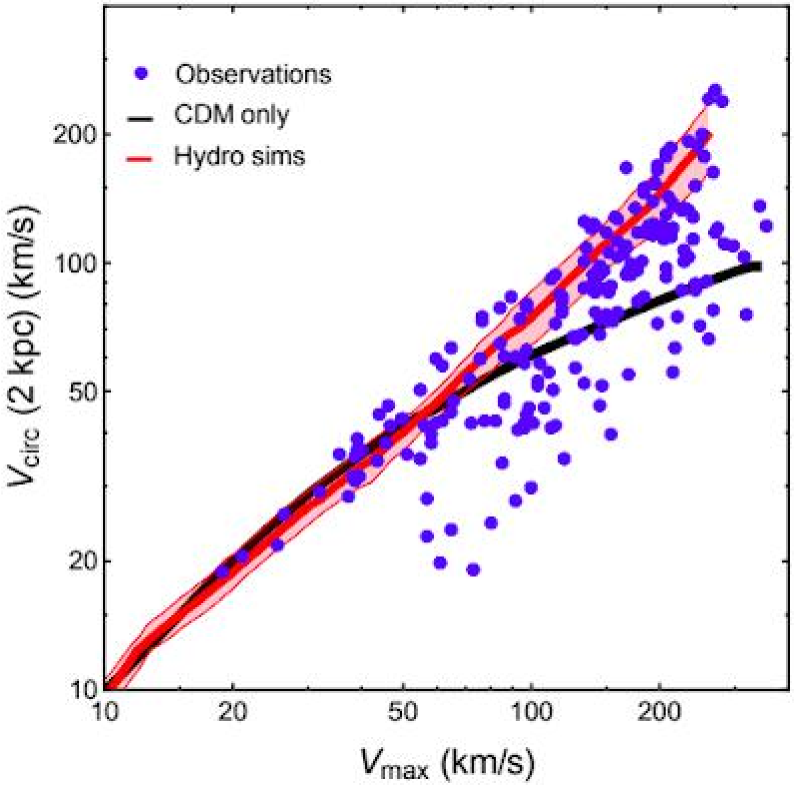
  Core vs Cusp & Too Big To Fail

- **Recent discussion**

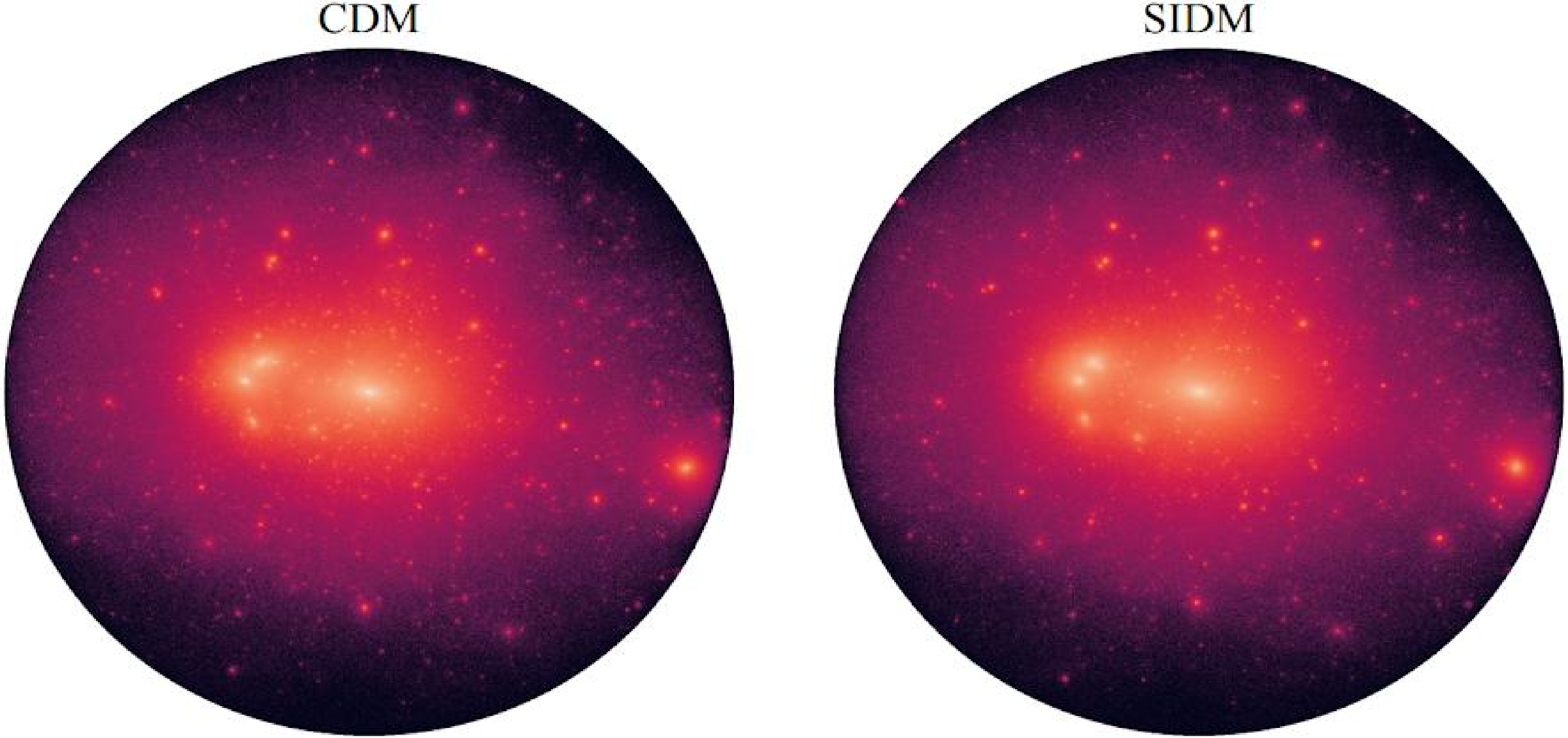
DM-deficient galaxies & Ultra-diffuse galaxies

& Dense lensing perturber & Black hole merger

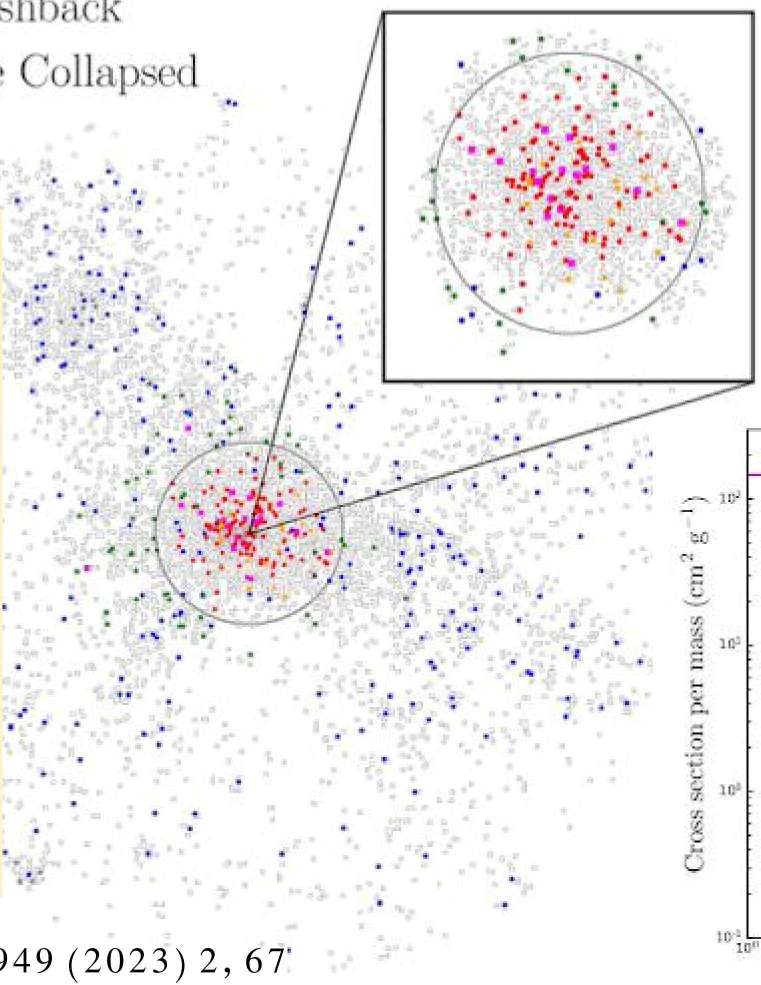




Features of Self-Interacting Dark Matter



Yang, Nadler, Yu, Astrophys.J. 949 (2023) 2, 67



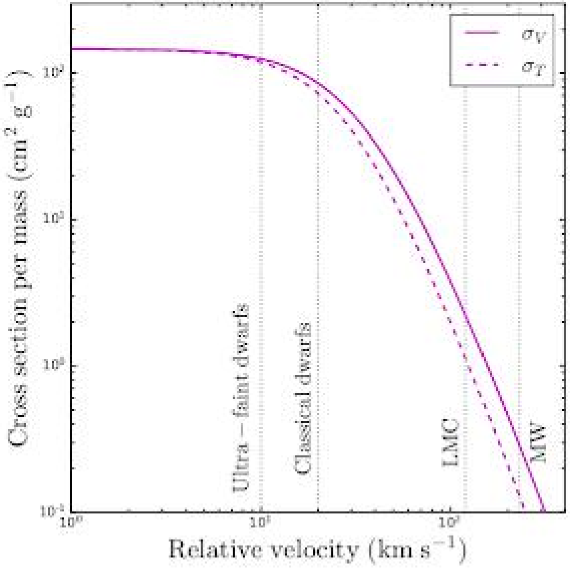
- **High resolution**
- **Realistic** MW accretion with ***LMC*** & ***Gaia-Enceladus*** analog, ***disk*** effect to be incorporated
- **Strong & velocity-dependent** cross section
- Various **core collapsed** halos

We perform cosmological zoom-in simulation of a Milky Way analog system.

Particle mass: $5.7 \times 10^4 M_\odot$

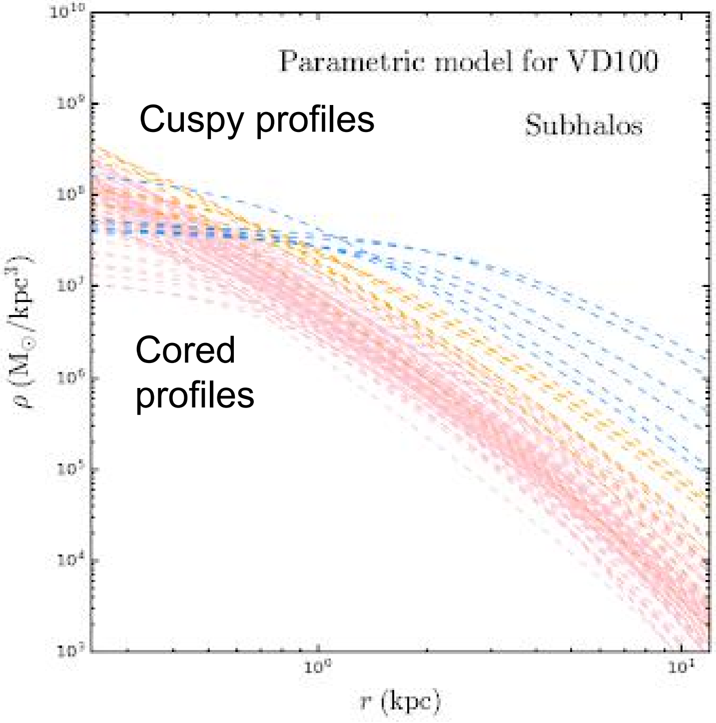
MW mass: $1.6 \times 10^{12} M_\odot$

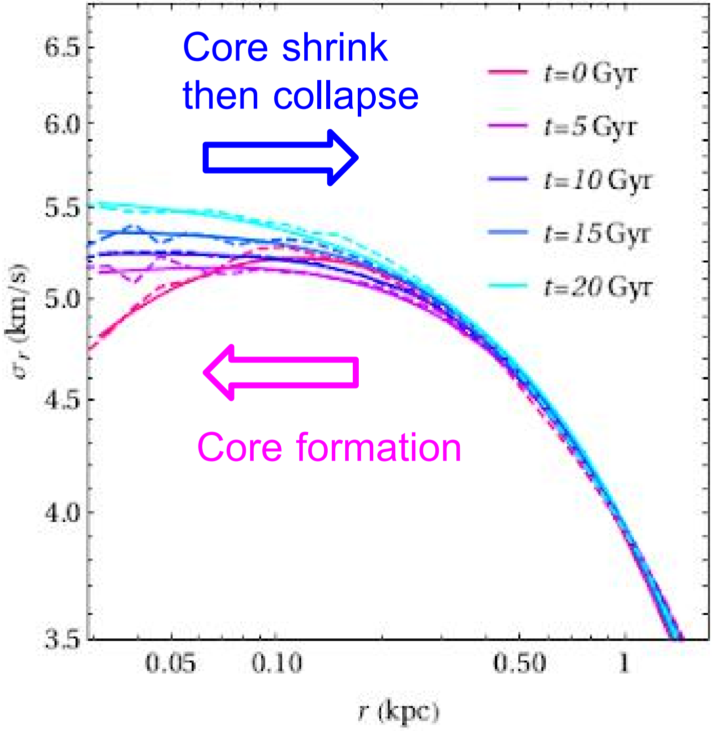
LMC mass: $1.8 \times 10^{11} M_\odot$



Yang, Nadler, Yu, Astrophys.J. 949 (2023) 2, 67

SIDM give rise to diverse density profiles

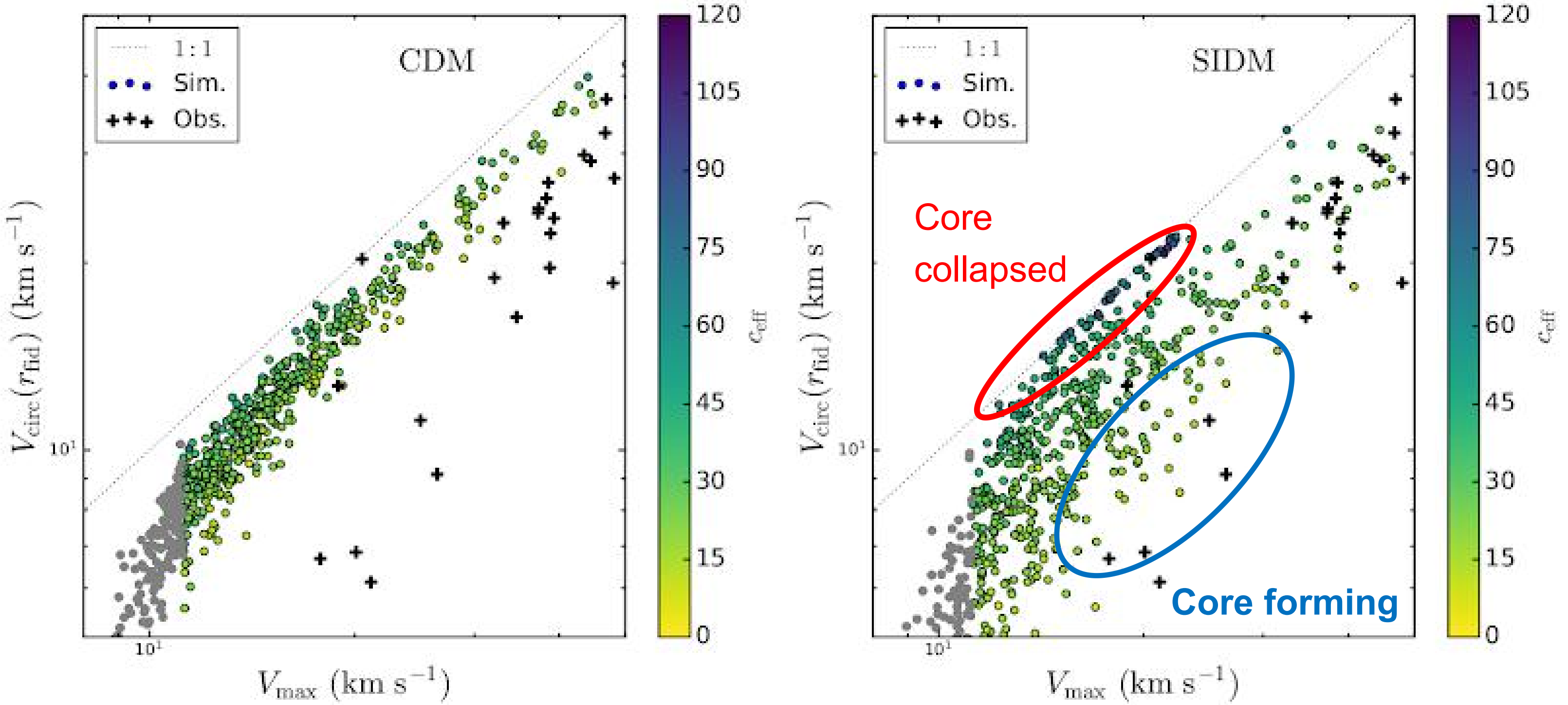




Spergel & Steinhardt 2000 and many other works

Probing the diversity through cosmological SIDM simulations

Vfid: rotation curves at $r_{\rm fid} = 2V_{\rm max}/(70\ {\rm km/s})\ {\rm kpc}$



Yang, Nadler, Yu, Astrophys.J. 949 (2023) 2, 67

"+" from Santos-Santos+(2022); See also TangoSIDM, Correa+(2022)

Dark matter deficient galaxies in SIDM

LCDM predicts that halos hosting **ultra-diffuse galaxies** DF2 & DF4 should be dominated by dark matter

$$M_{DM}/M_{star} \sim 200$$

However...

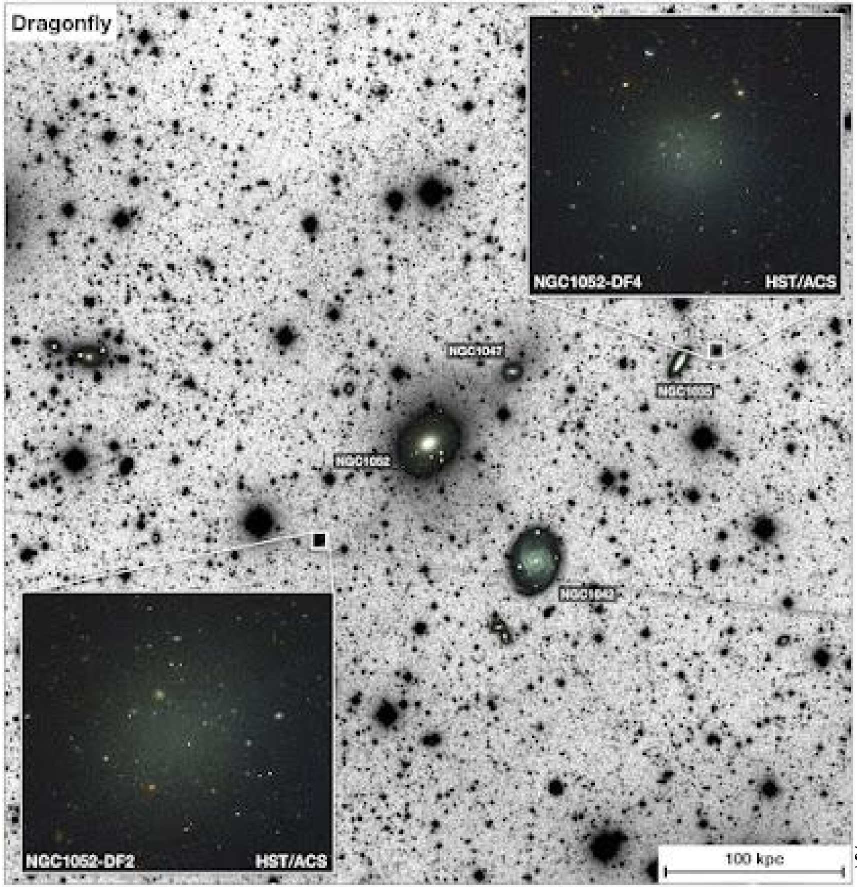
$$M_{DM}/M_{star} \lesssim 1$$

Explaining these observations in LCDM requires at least **-5 sigma from median** （Haslbauer et. al.）

SIDM can alleviate this tension

Yang, Yu, An, Phys. Rev. Lett., 125:111105

Nature vol. 555, 629-632 (29 March 2018)

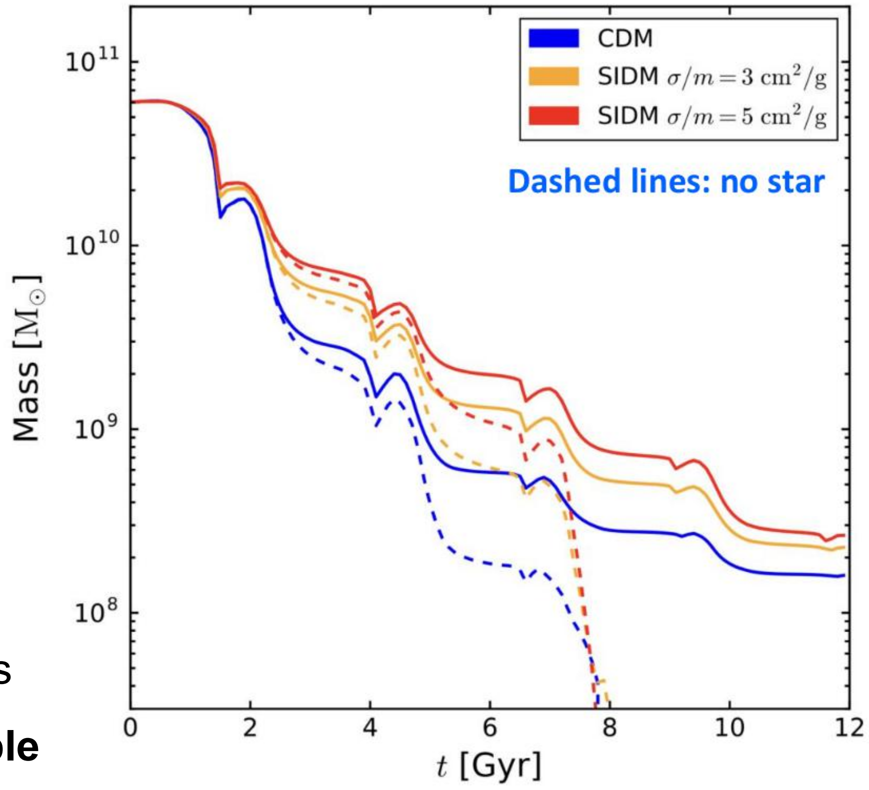


Dark matter deficient galaxies in SIDM

SIDM **core formation** can boost **tidal stripping** making it easier to explain DF2, DF4 observations

Dedicated high resolution simulations

- Under SIDM, a **-1.8 sigma** concentration halo (& 3cm^2/g) can explain observations
- Implications: there should be an **observable population** of DM deficient galaxies

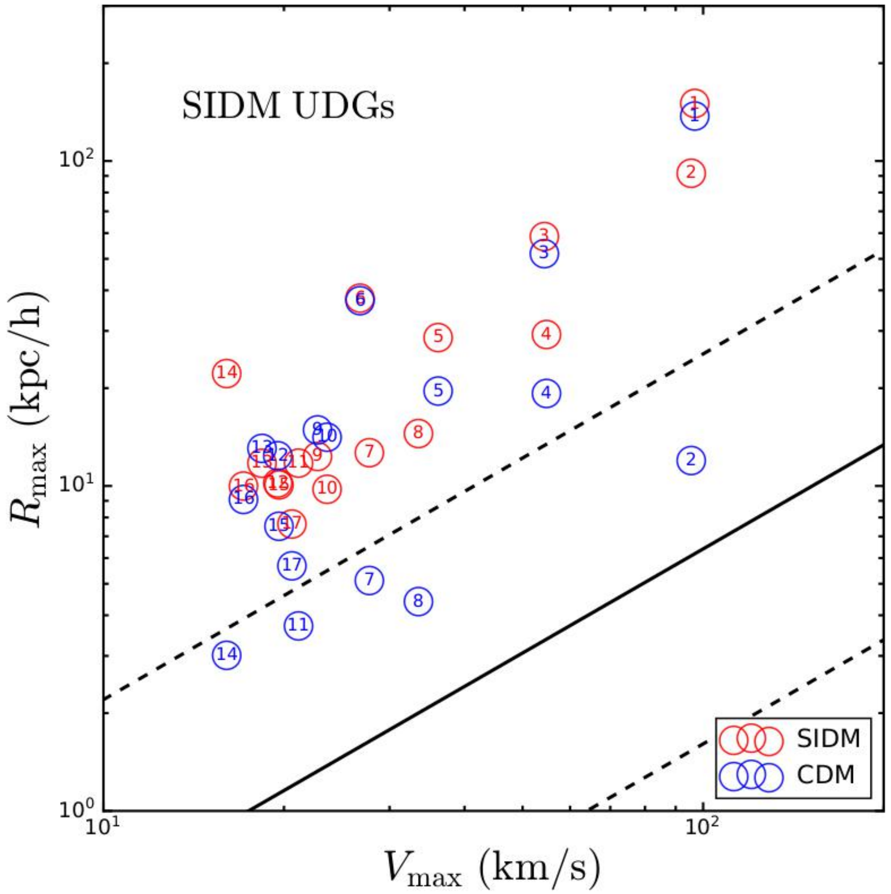


Yang, Yu, An, Phys. Rev. Lett., 125:111105

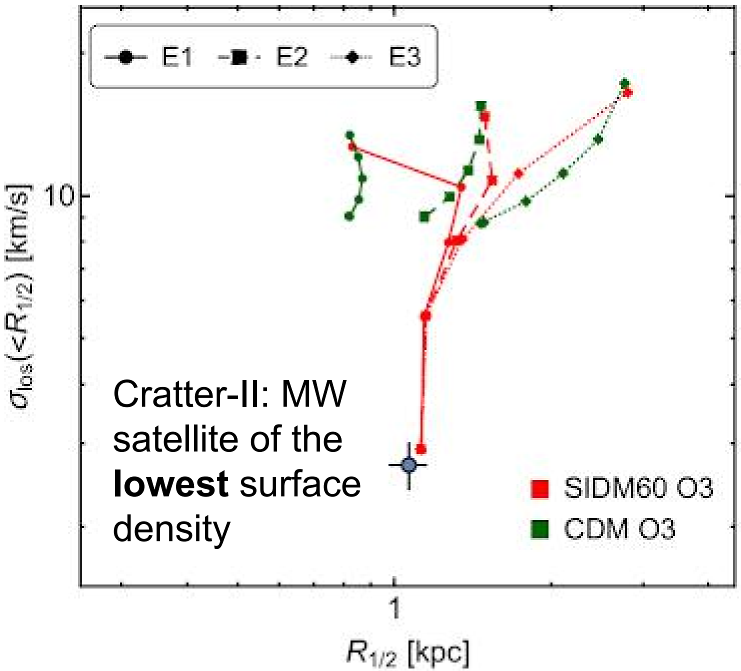
Dark matter deficient galaxies in the field?

Preliminary

- SIDM halos (in the field) with increased Rmax have mostly undergone slingshot/backsplash
- SIDM can boost the tidal stripping of dark matter



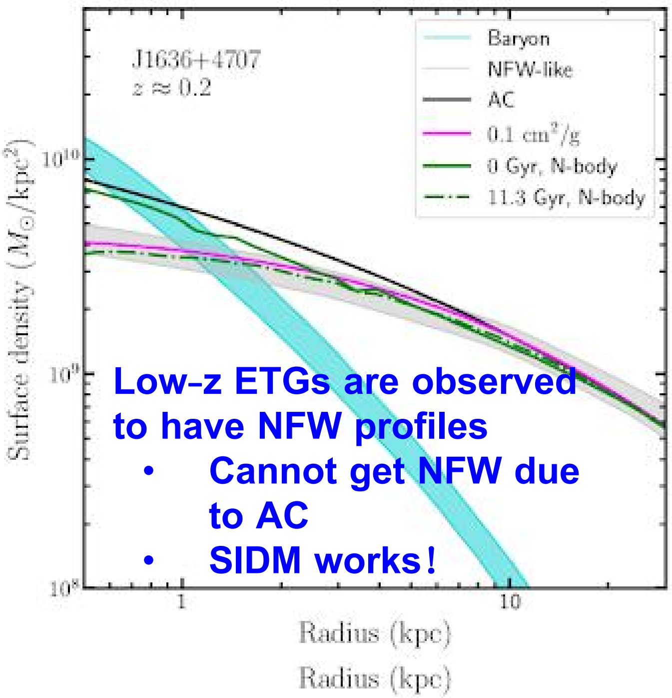
Explain diffuse outliers



With: Xingyu Zhang, Hai-Bo Yu, Haipeng An

APJL, 968 (1), L13, 2024

NFW profile in SIDM halos?!

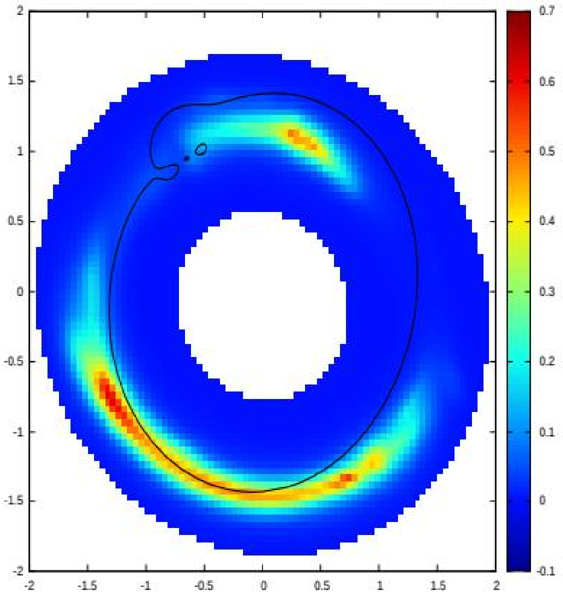


With Demao Kong & Hai-Bo Yu (UCR)

APJL,965(2):L19, 4 2024

Two approaches of probing SIDM subhalos

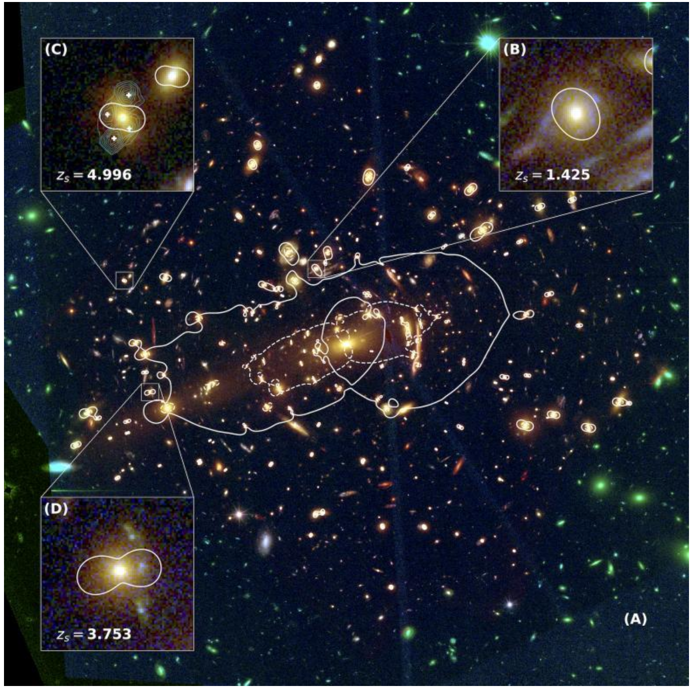
- Strong lensing perturber



(b) best-fit model, tNFW

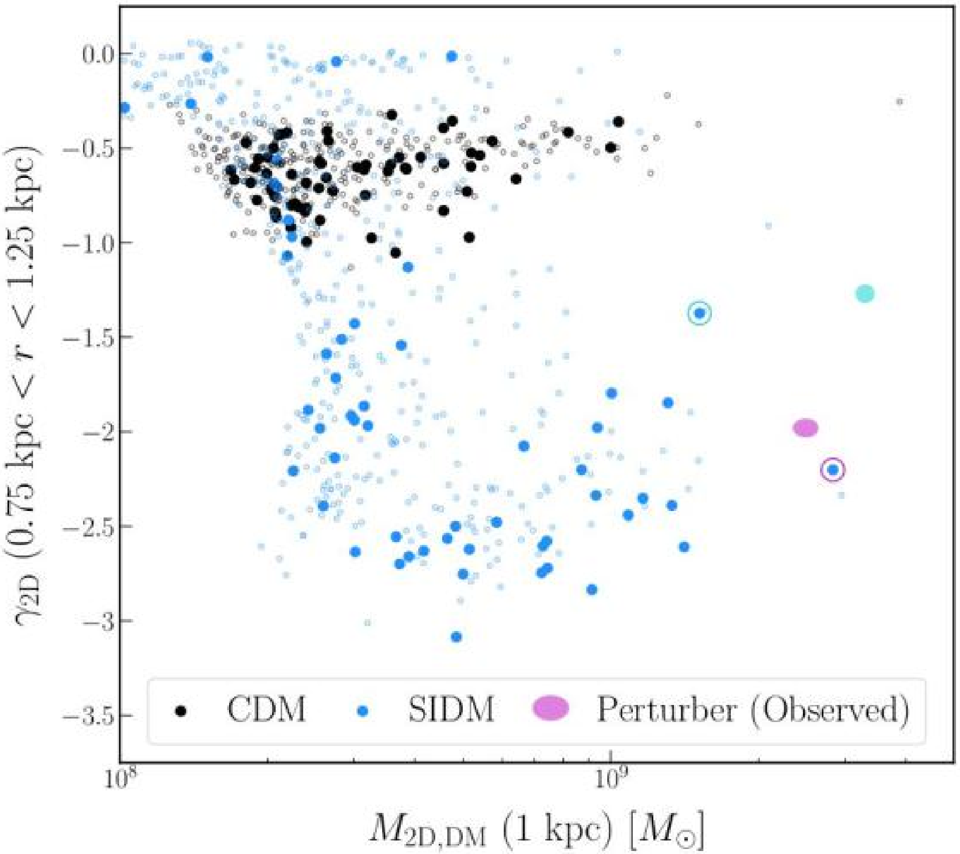
Minor+2011.10627

- Galaxy-galaxy strong lensing



Meneghetti+2009.04471

Dense Dark substructure/perturber



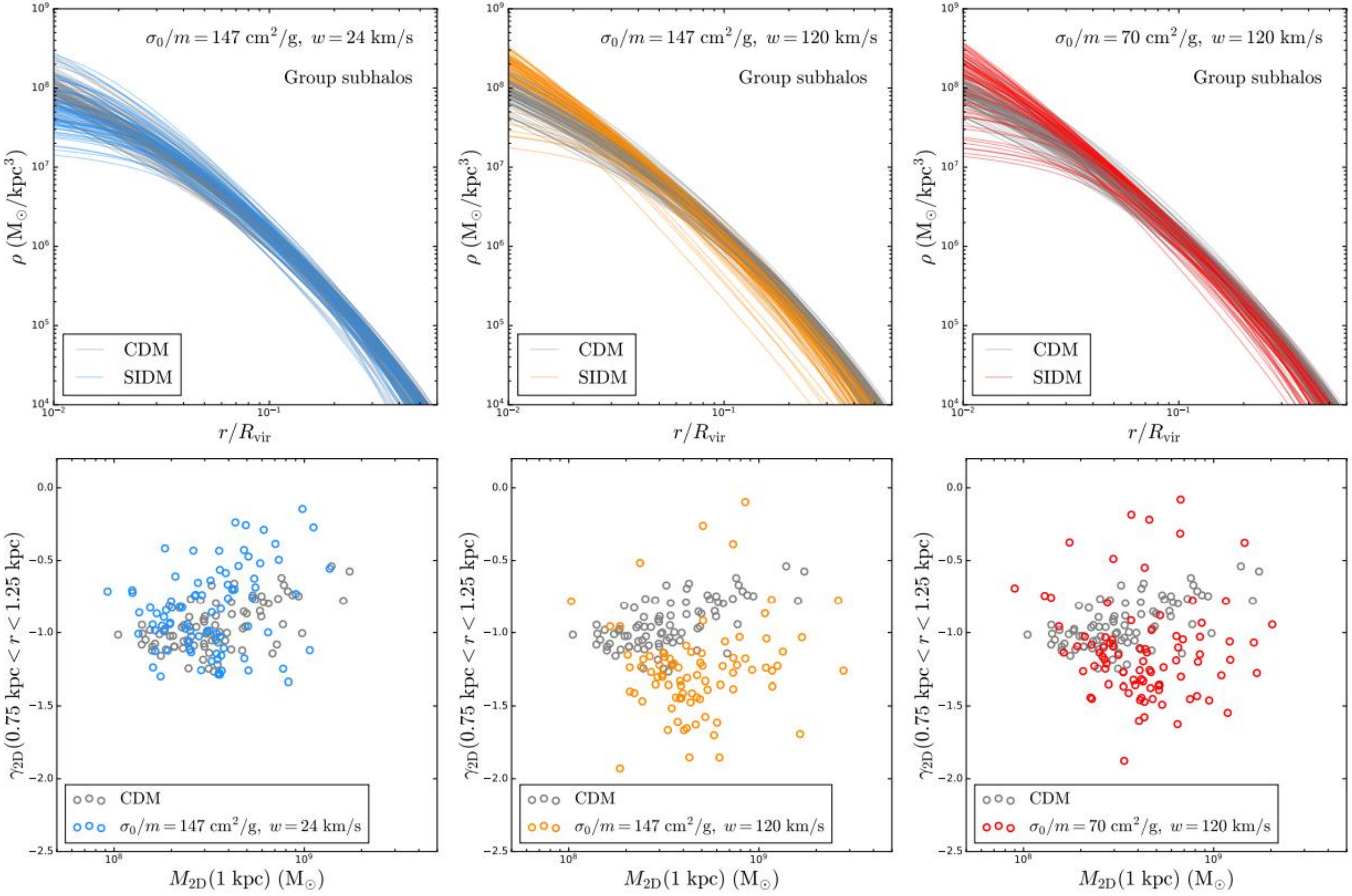
SDSSJ0946+1006 perturber
Minor+(2020)

There is a slight offset in mass, as our main halo mass is on the lower end of the favored range

$$10^{13}\ \mathrm{M_\odot} - 6 \times 10^{13}\ \mathrm{M_\odot}$$

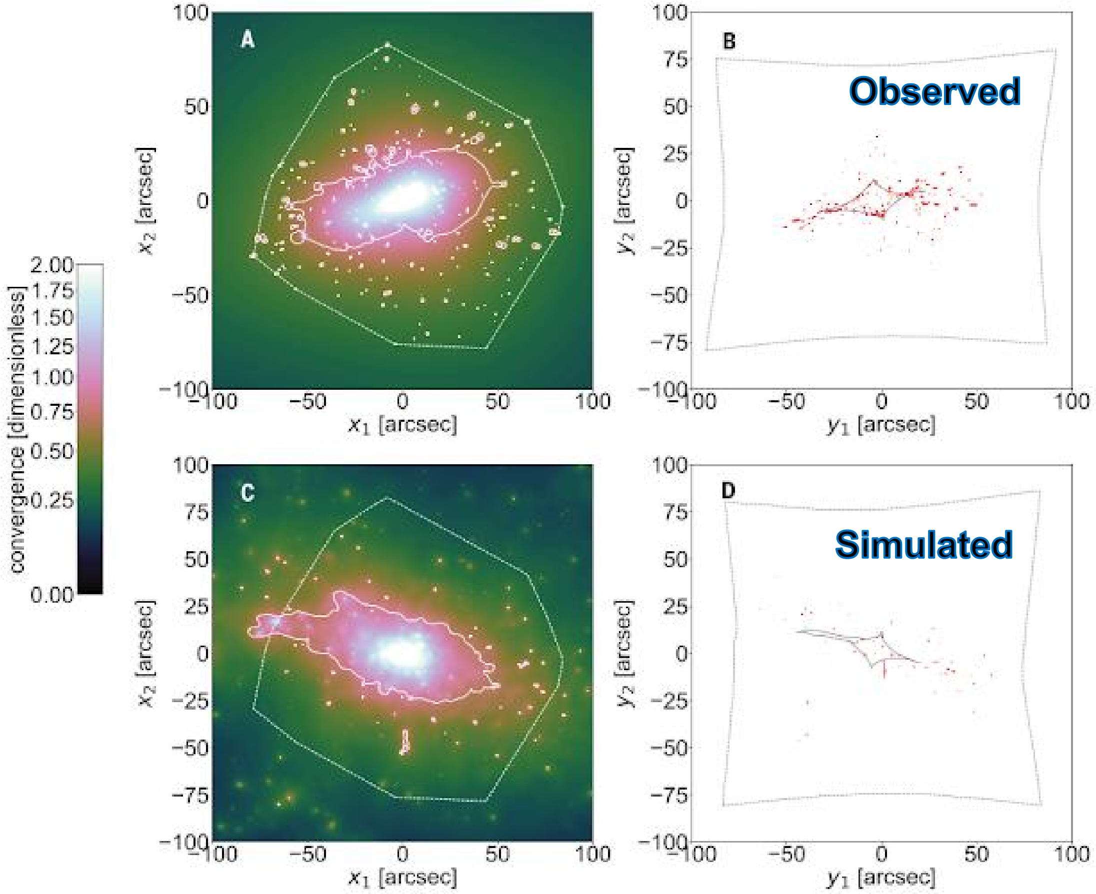
Nadler, Yang, Yu, APJL 958(2):L39, 2023

Effect of SIDM models on halo profiles and strong lensing perturbers



Yang, Yu, Nadler
arXiv 2406.10753,
based on the parametric model for SIDM halos
Yang+2305.16176
JCAP, 02:032, 2024

Meneghetti et al., Science 369, 1347–1351 (2020)



Critical lines

Caustics

Galaxy-galaxy strong lensing

Significantly more
secondary caustics
Expect more dense subhalos

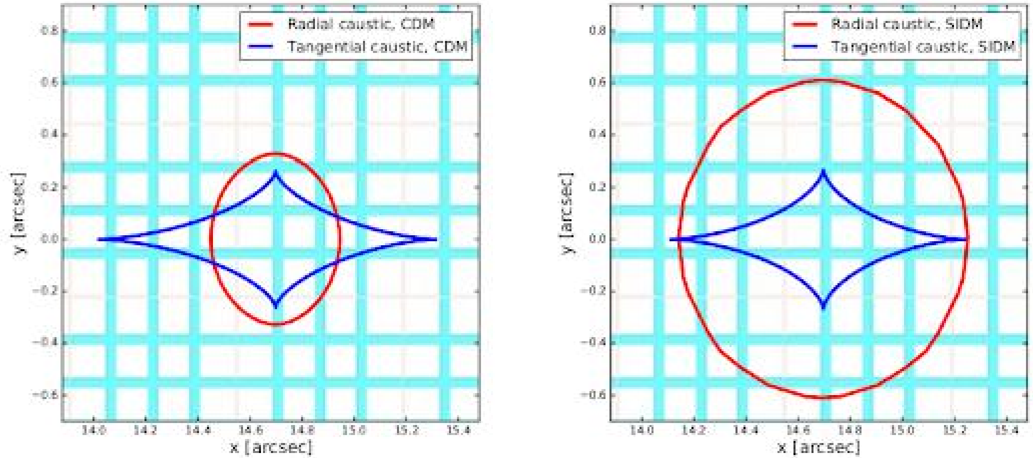
Numerical issue ? Baryonic solutions ?

Yannick M. Bahé, Jan 2021 & Andrew Robertson, Jan 2021

Dark matter interaction solutions ?

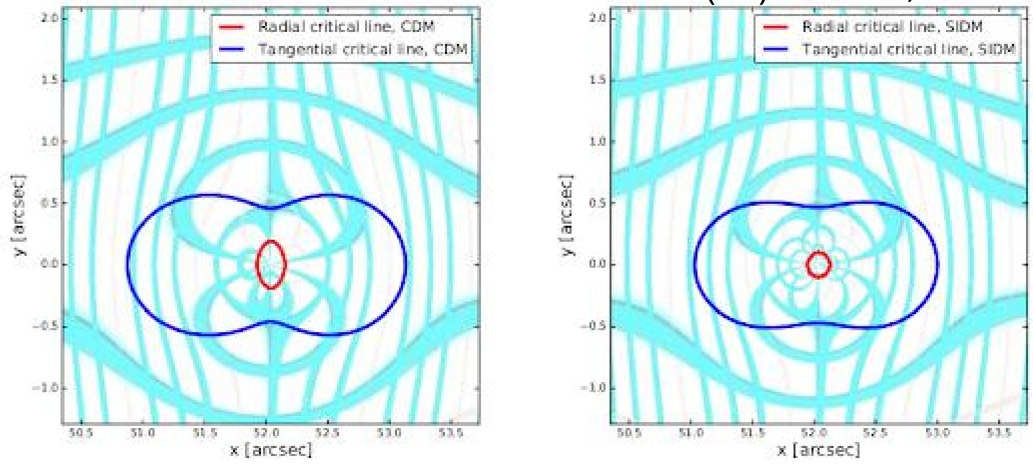
- *Enhanced structure formation*
- *Dissipative dark matter*
- *Self-interacting dark matter*
- *... ...*

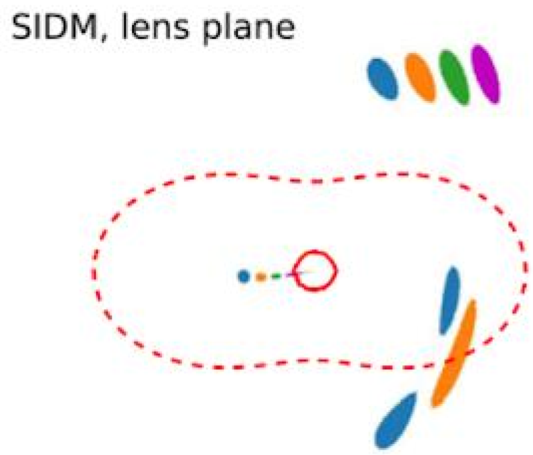
SIDM core collapse tends to introduce more lensing structures in the inner region



For collapsed subhalos

Yang & Yu PRD, 104(10):103031, 2021

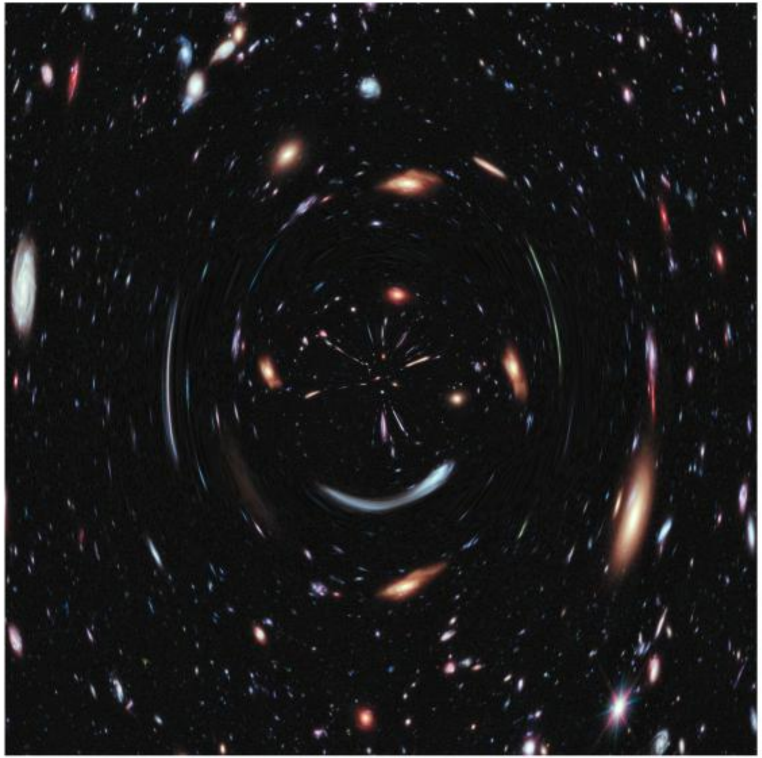




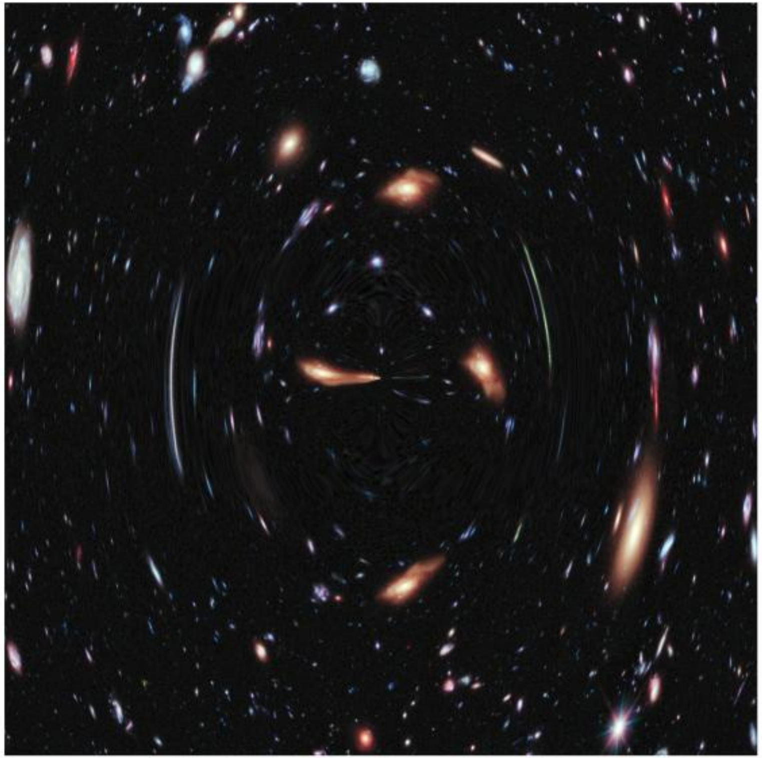
The ratio of 2 image vs 4 image events probes the density slope of the substructure

A comparison of mock images

Yang & Yu PRD, 104(10):103031, 2021



SIDM



CDM

SIDM from gravitational scattering ?

Gravitational Rutherford scattering is similar as SIDM (A. Loeb 22)

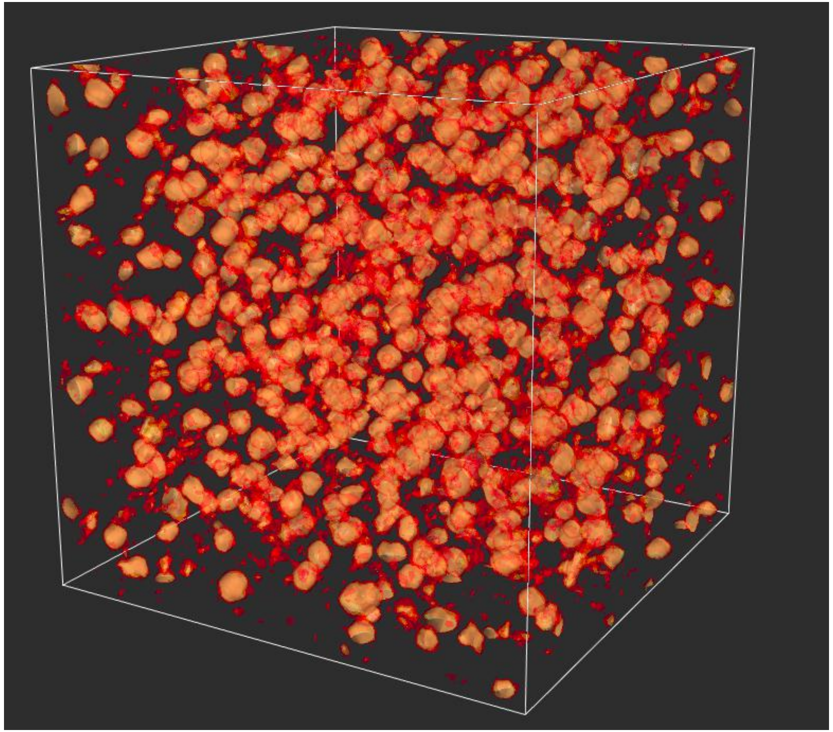
$$\frac{\sigma}{M_0} \approx 10\ \mathrm{cm}^2/\mathrm{g} \left(\frac{M_0}{10^4 \mathrm{M}_\odot}\right) \left(\frac{10\ \mathrm{km/s}}{v}\right)^4$$

Self-interacting Fuzzy-DM models can lead to MACHO objects in the early universe

Enhanced structure formation

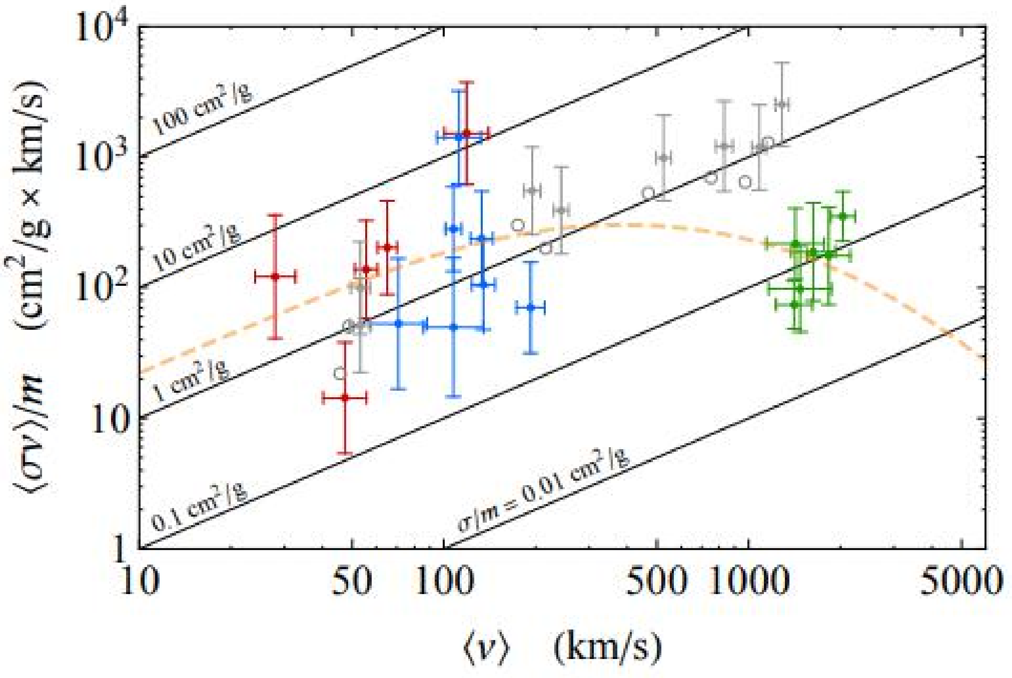
New window for Fuzzy Dark Matter

Cored and cuspy density profiles



Bird,Chang,Cui,Yang PLB, 139062, 2024
Cui & Yang 24 to appear

Exploring SIDM particle properties



Kaplingha, Tulin & Yu, 1508.03339 PRL

SIDM particle properties can be extracted from rotation curves, in principle

Need to **significantly** reduce ***uncertainties*** from both observations and theories

New method to reduce theoretical uncertainty & obtain predictions efficiently

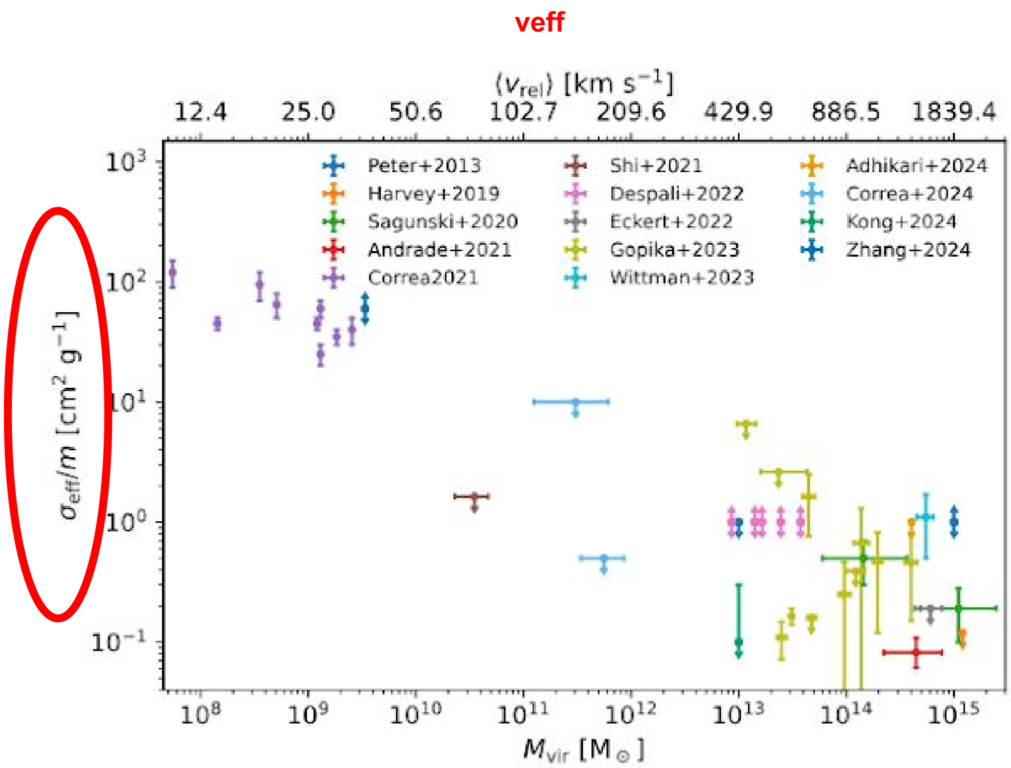
Yang & Yu 2205.03392 JCAP

Yang+2305.16176 JCAP

Yang+2406.10753

Yang 2405.03787 ...

Exploring SIDM particle properties

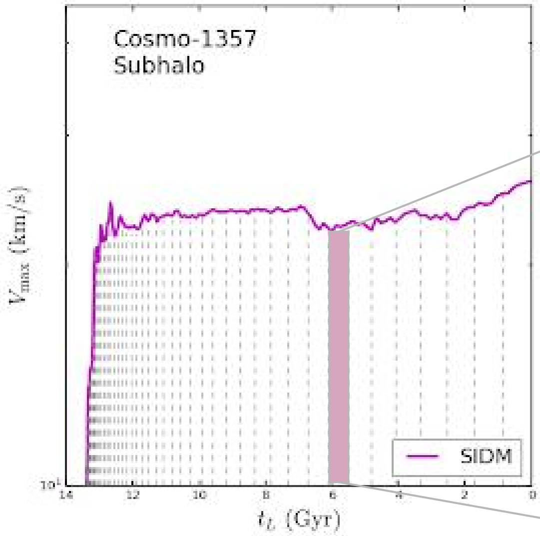


- Reduce SIDM effects on halos onto **effective quantities**
- Systematically uncover particle features from data, based on a universal parametric model

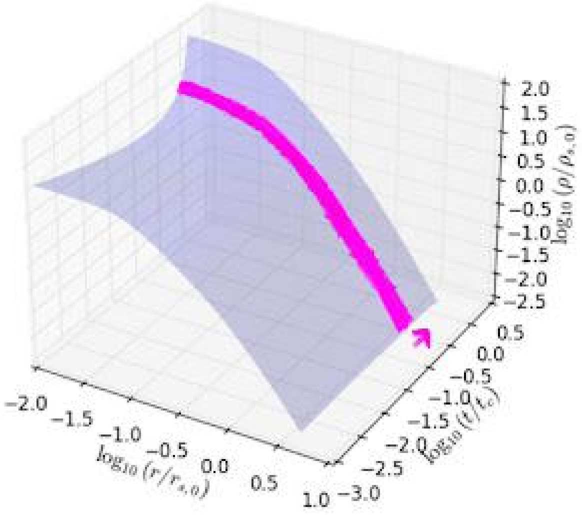
（Yang & Yu 22 JCAP）

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

A parametric model for SIDM halos with accretion histories



One analytic evolution profile can be applied for all isolated halos



Effects of **accretion** is incorporated by **summing over** contributions from **many isolated halos**, each with a small increment in the **gravothermal phase**:

Δτ=(Δt)/tc

where tc (collapse time) is computed using the ***instantaneous*** CDM halo params

Yang+2305.16176 JCAP

https://github.com/DanengYang/parametricSIDM

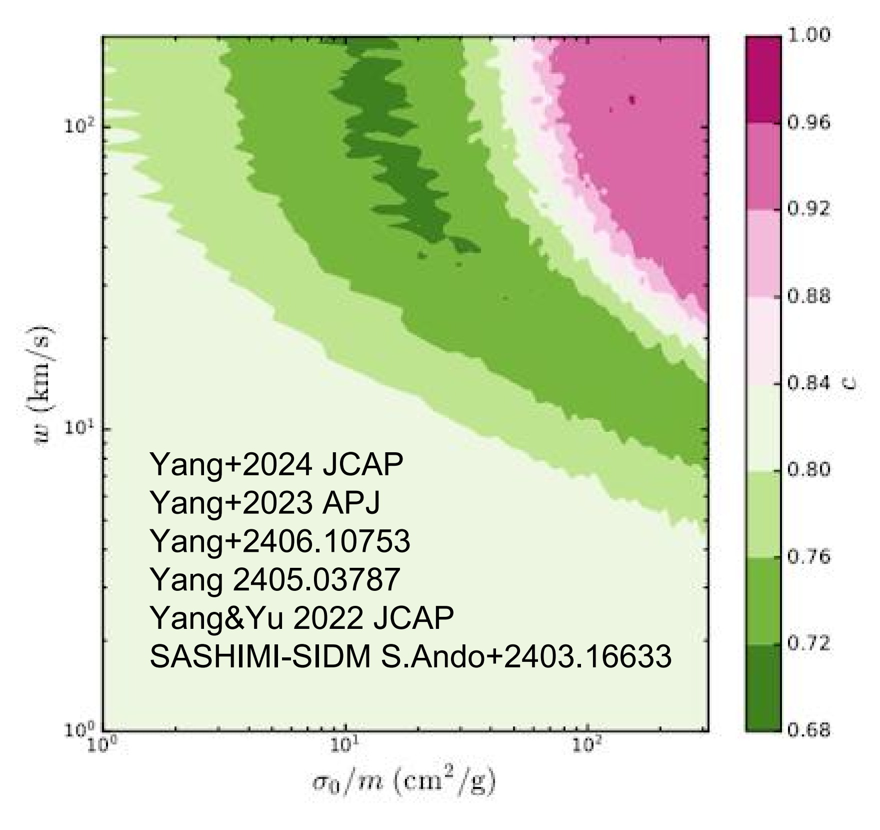
Exploring SIDM particle parameter space

Traditional method

- **One** N-body simulation for **one** SIDM model, using a computing cluster, **numerically expensive**

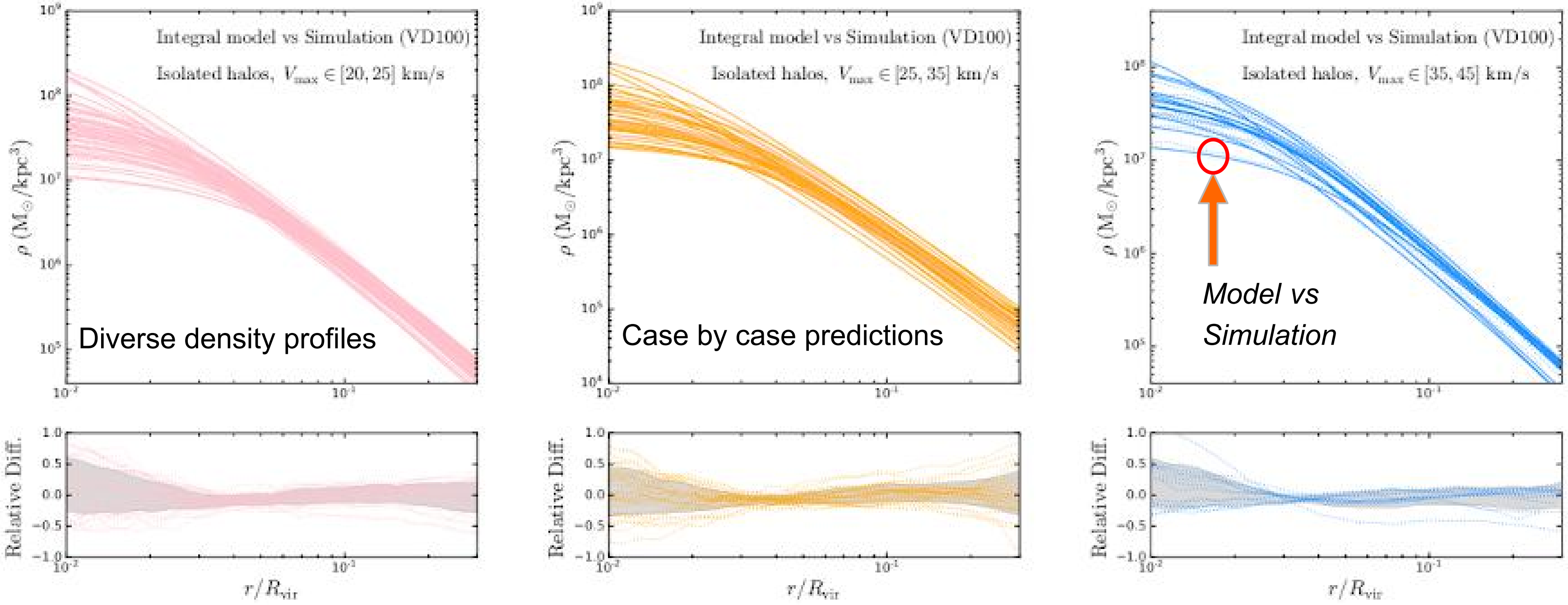
Parametric model

- Use existing CDM simulations (or semi-analytic model), which incorporates the most of the nonlinear effects (**Reuse expensive CDM simulations**)
- A **high accuracy** model is constructed based on **theoretical universality**
- Obtain SIDM predictions of **thousands halos in minutes**



Exploring SIDM parameter space on a laptop (DM-only)

https://github.com/DanengYang/parametricSIDM



N-body simulation results commonly include uncertainties that are difficult to discuss or quantify

Our **N-body simulation** results and **parametric model predictions** can validate each other

Yang, Nadler, Yu 2406.10753

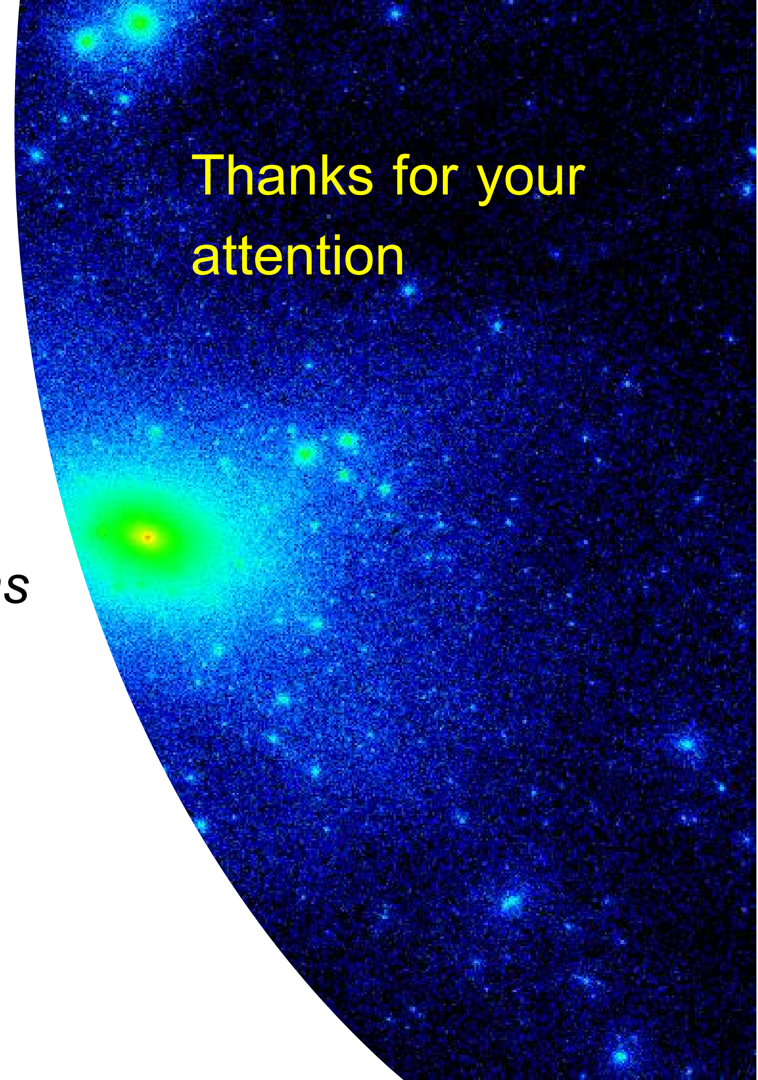
Summary

While dark and cold...
SIDM can modify DM distribution, resulting in observable signatures

Can explain intriguing anomalous observations & offer discovery opportunities

DM-deficient galaxies & Ultra-diffuse galaxies & Dense lensing perturber & Black hole merger

We can do efficient predictions, with uncertainties under control



Backup

Gravothermal evolution

Core formation

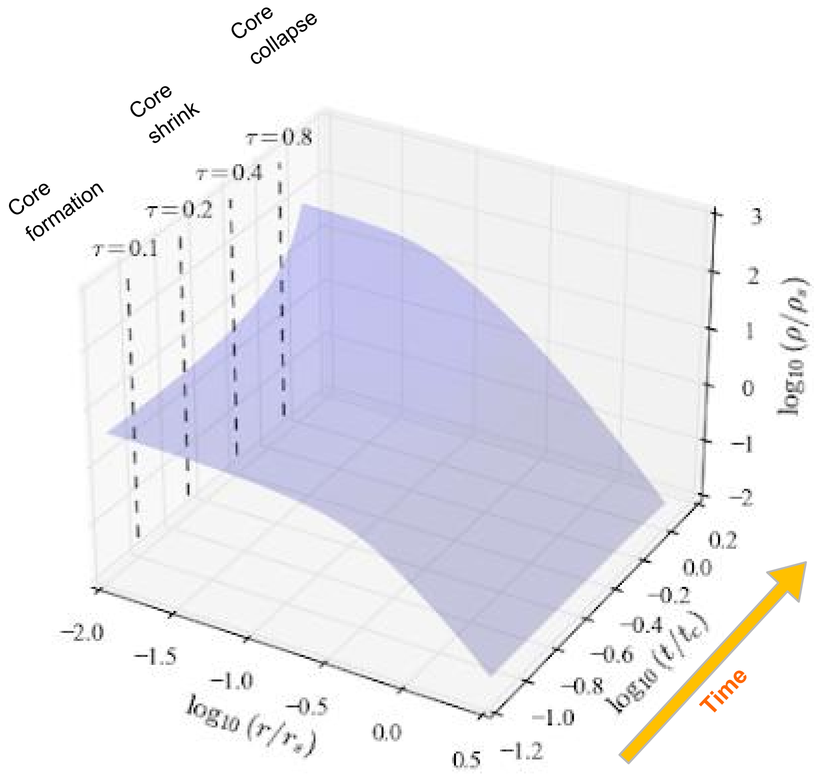
- heat flux + capacity $\Rightarrow$ core formation

Core shrink

+ heat flux + capacity $\Rightarrow$ quasi-stable core

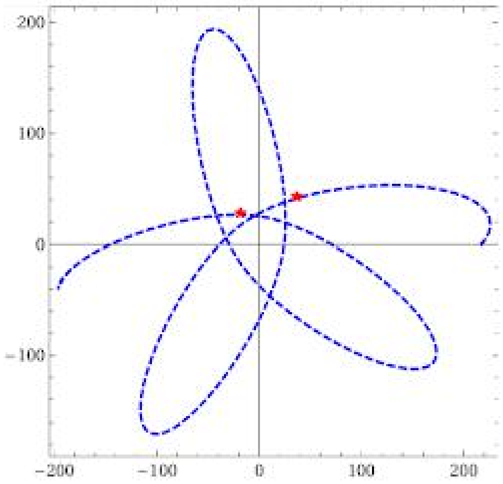
Second stage

+ heat flux - **capacity** $\Rightarrow$ **core collapse**



Thermodynamic quantities reconstructed from N-body simulations (JCAP 09 (2022) 077)

Conductivity cross section (r-dependent)



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

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

A “clock” in the gravothermal evolution

Heat conduction breaks time reversal invariance

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

Arrow of time dependent on SIDM (the collision term)

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

The **cross section (σ)** dependence can be absorbed into the **arrow of time: $t \to t\,\sigma$**

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

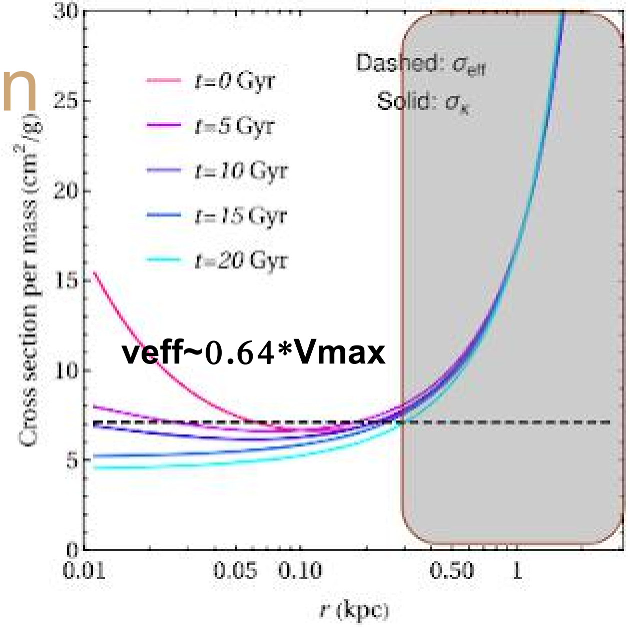
$$t_c = \frac{150}{C} \frac{1}{(\sigma_{\rm eff}/m)\rho_s r_s} \frac{1}{\sqrt{4\pi G \rho_s}}$$

Related discussion in: Outmezguine+ 2204.06568; Yang+ 2305.16176; Zhong+2306.08028 & Yang+24 to appear

One halo probes
One effective constant cross section

Effective constant cross section
(motivated by heat conduction)

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



Yang & Yu 2205.03392

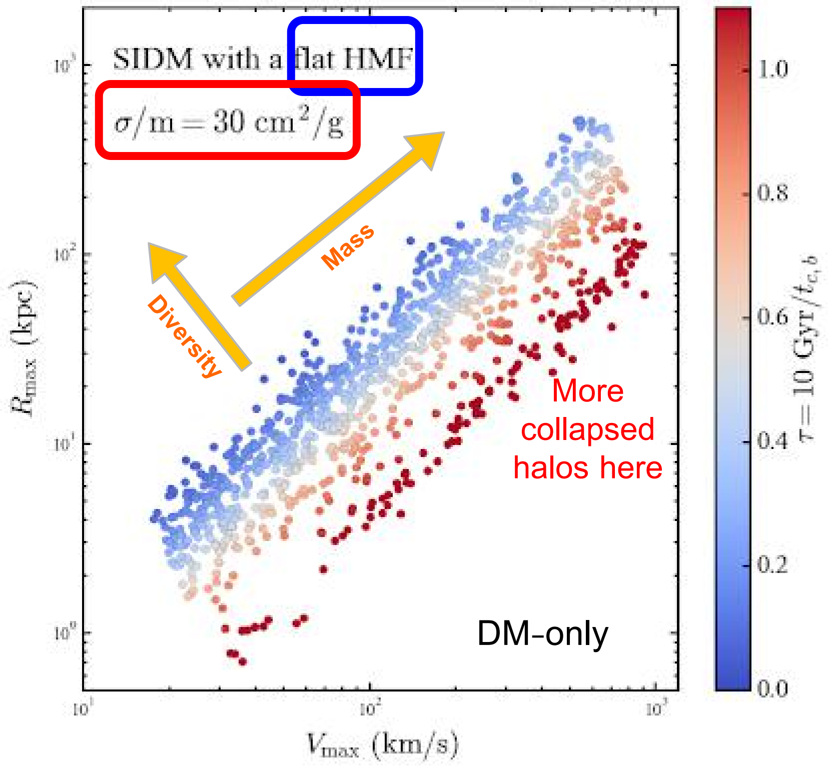
- Angular dependence is completely integrated out
- Only the ***velocity dependence of SIDM*** couples to the ***halo velocity dispersion***
- *Details of an SIDM model* ***hidden*** *in a single halo*

A constant SIDM cross section does not affect halos in the same way

Collisional relaxation

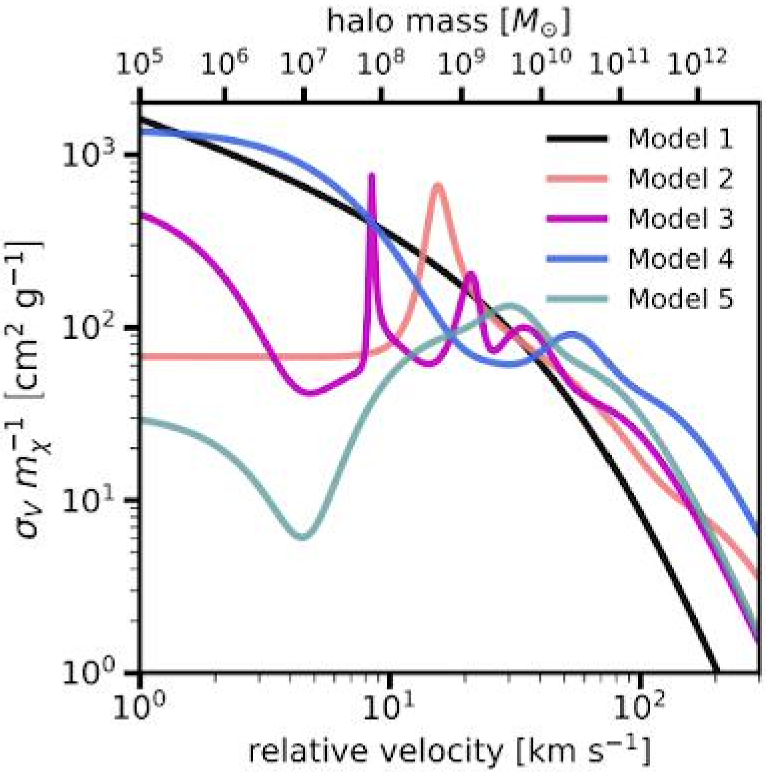
$$t_{c,0} = \frac{150}{C} \frac{1}{\frac{\sigma}{m}\rho_s} \left(\frac{1}{4\pi G \rho_s r_s^2} \right)^{\frac{1}{2}}$$

Phys. Rev. Lett. 123, 121102 (2019)
Astrophys. J. 568, 475–487 (2002)



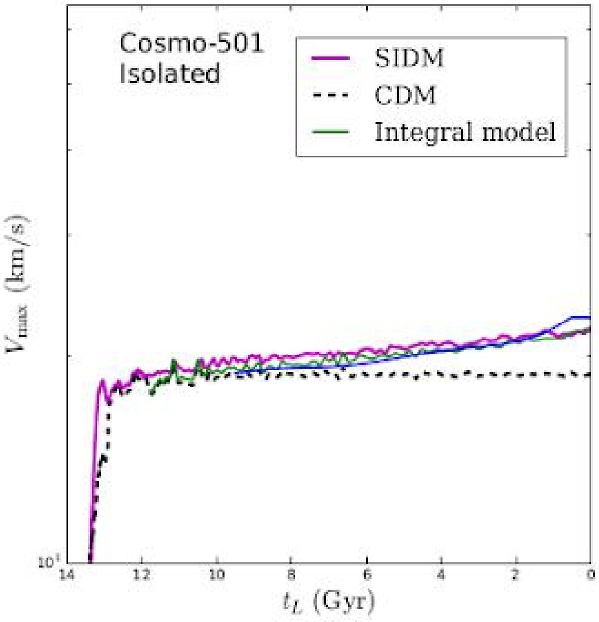
SIDM cross sections can have nontrivial velocity dependencies

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



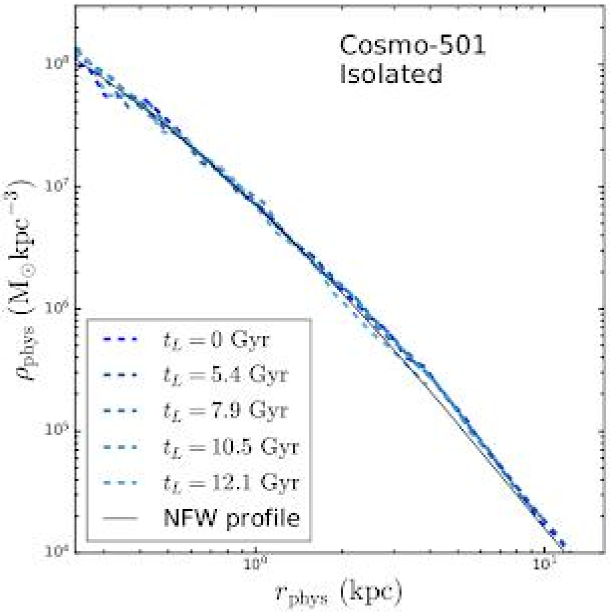
Gilman+2207.13111

Realistic field halos



Mass growth through mergers

Inner NFW profile established quickly and remains almost untouched



Basic approach

- Solve for $\rho s0$, $rs0$ from Vmax, Rmax @z=0
- Estimate halo formation time based on mass

A simple Mathematica notebook:
https://github.com/DanengYang/parametricSIDM/blob/main/basicHalos.nb

Subhalos

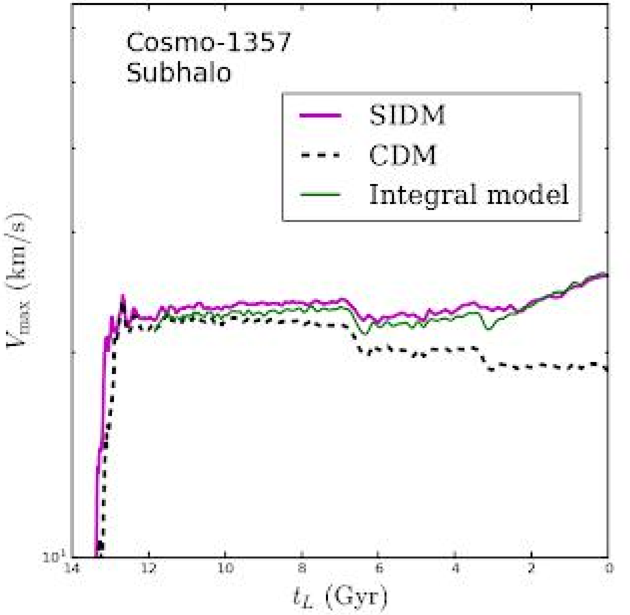
The integral approach

Each gravothermal state () can arise from a "***fictitious***" progenitor of the same CDM halo & configurations.

$$\rho_{\rm SIDM}(r, \text{“CDM” halo \& baryon params at } t, \tau)$$
$$\Downarrow \quad t \to t + \delta t$$
$$\rho_{\rm SIDM}(r, \text{“CDM” halo \& baryon params at } t+\delta t, \tau + \delta\tau)$$

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

$$\tau(t) = \int_0^t \frac{dt}{t_{c,b}[\sigma_{\rm eff}(t)/m, \rho_s(t), r_s(t), \rho_H(t), r_H(t)]}$$



Consistently compute δτ incorporating the accretion in CDM & effective SIDM cross section

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