Related works:
Phys. Rev. Lett. 125, 111105 (2020), Editor's suggestion
arXiv:2102.02375 [astro-ph]

TeVPA 2021

Searching for dark matter self-interactions in tidally formed ultra-diffuse galaxies and cluster substructures

Daneng Yang (UCR)

in collaboration with:

Hai-bo Yu (UCR), Haipeng An (THU)

Oct 27th, 2021
Chengdu, China

OUTLINE

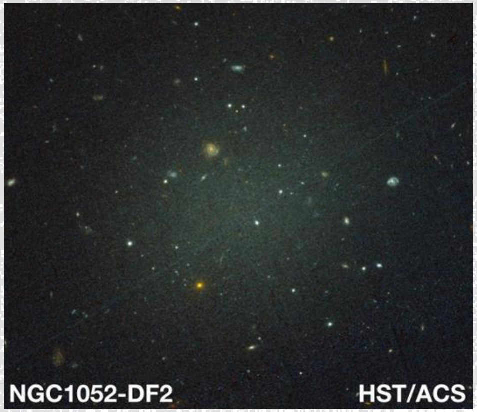
- Halo mass accretion in a tidal environment
- Impact of self-interacting dark matter (SIDM) on tidal evolution

◆SIDM and the origin of DM deficient galaxies

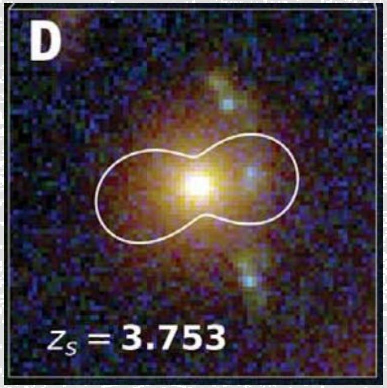
In light of the NGC1052-DF2/DF4 observations

◆SIDM and the formation of core-collapsed galaxies

In light of the statistics of small scale lenses in clusters



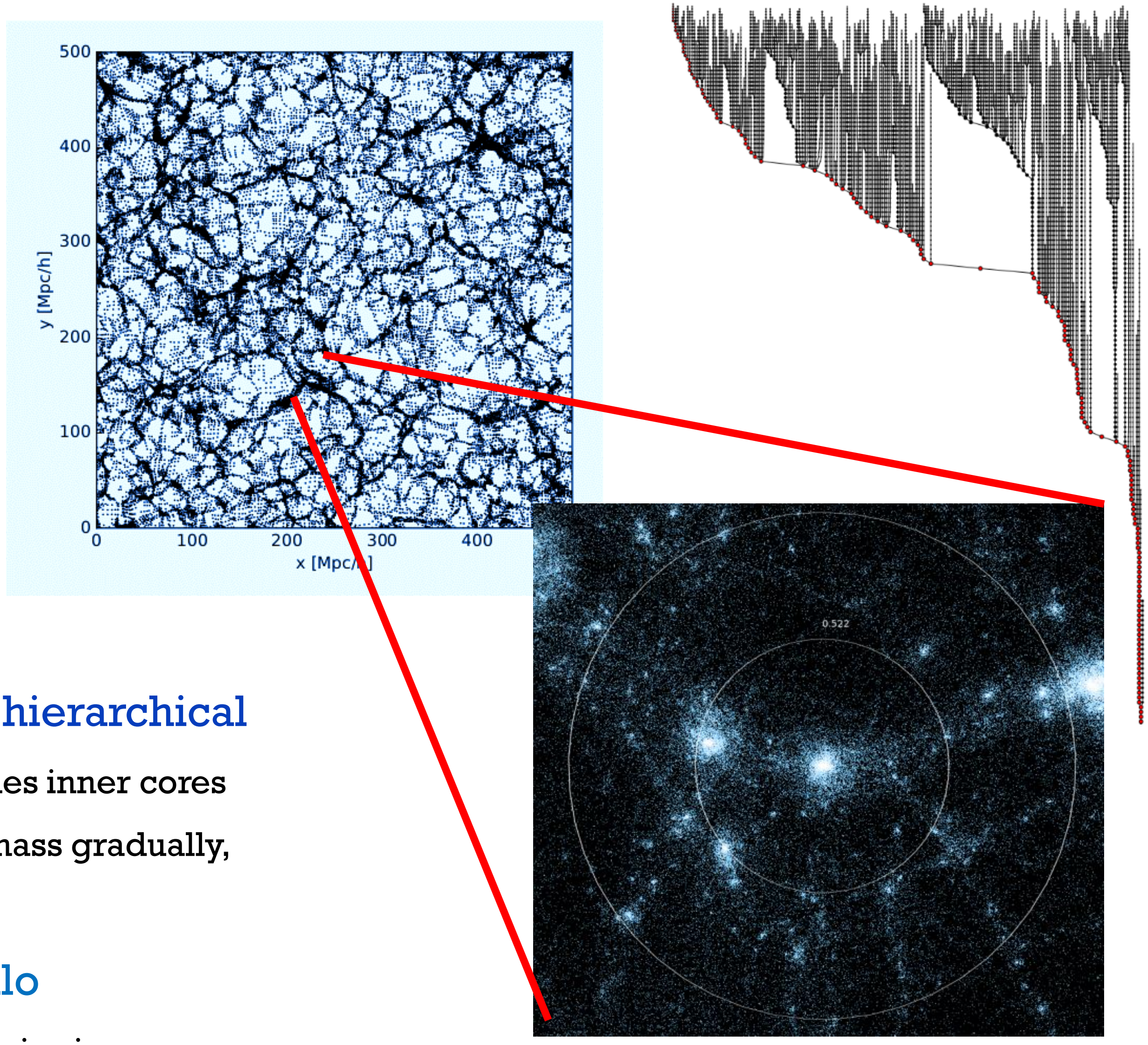
Nature vol. 555, 629-632 (29 March 2018)



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

CMB & Large scale structure

- Dark matter is cold and loses pressure support at an early time
- Collapsing dark matter acquires kinetic energy and re-establish pressure equilibrium in a halo



Mass accretion of a halo is hierarchical

- High z: major merger establishes inner cores
- Low z: minor mergers add on mass gradually, extending the halo

Evolution of an infalling halo

- Mass loss mainly due to tidal stripping
- Inner core may become a satellite

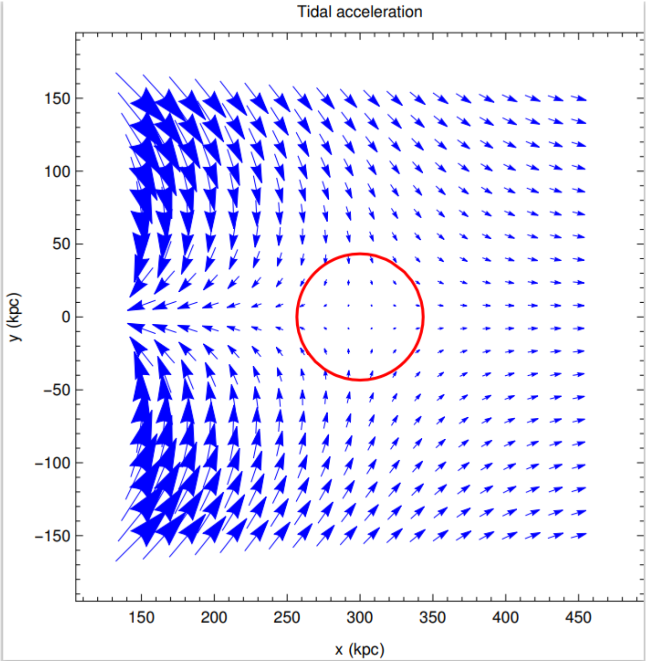
Minor merger: a small halo falling into the host

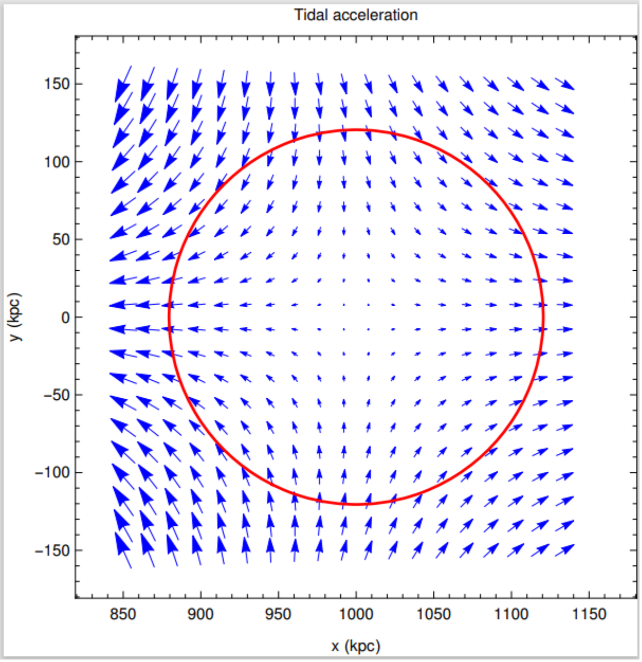
$M_{host} \sim 10^{15}\ M_{\odot}$

$M_{sub} \sim 10^{12}\ M_{\odot}$
(at infall)

- Tidal distortion traces the tidal field, as td of the satellite is shorter than the host, and the pressure balance is achieved faster than the dynamical & thermal equilibrium
- Tidal stripping gets stronger as it approaches the host center

(corresponds to the scenario of our second work)





Distance to the host center: 300 kpc (left), 1000 kpc (right)

Tidal radius: r_t $$M_s(r_t)/r_t^3 = M_h(r)/r^3$$

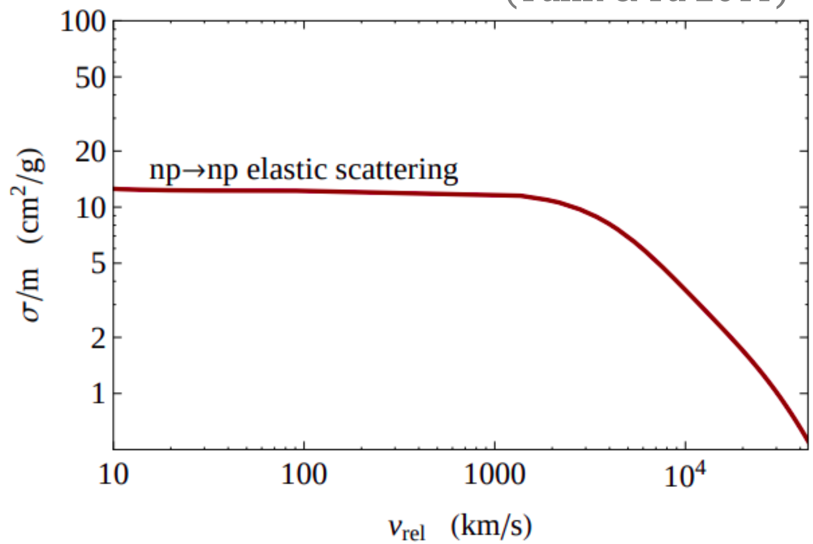
Tidal acceleration: $$a_i^{\text{tid}} = -r_j \partial_j \partial_i \Phi(R)$$

Self-interacting dark matter (SIDM)

At low velocities, DM could have a self-interaction of similar magnitude as baryons

- Scattering is mainly elastic: halos are more extend and diffuse than galaxies
- Effective mainly at small scales and can explain some anomalies

(Tulin & Yu 2017)



SIDM may explain the observed DM distributions in various systems

- Satellites of the Milky Way
- Spiral galaxies in the field
- Galaxy clusters
- Ultra diffuse DM deficient galaxies

Impact of SIDM in a tidal field

- **Core formation** boost tidal stripping, amplify tidal distortion
- Tidal stripping & deep baryon potential: boost **gravothermal evolution** and result in some core-collapsing subhalos

SIDM significantly reduce the relaxation time

Dynamical time: $t_d = \frac{\lambda_J}{v_0} \approx \frac{1}{\sqrt{4\pi G\rho}}$

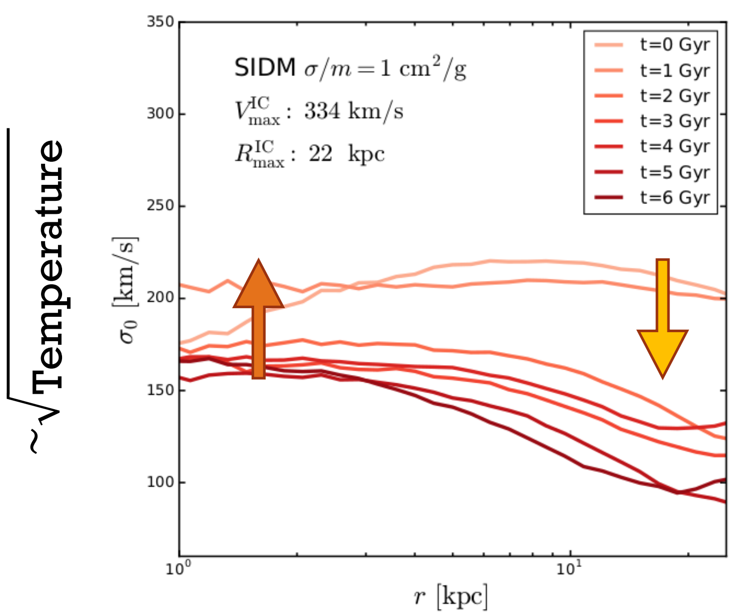
- CDM:

$$t_r \approx \frac{N}{10 \ln N} t_d > 10^{50} \text{ Gyr}$$
(MW, WIMP DM)

- SIDM:

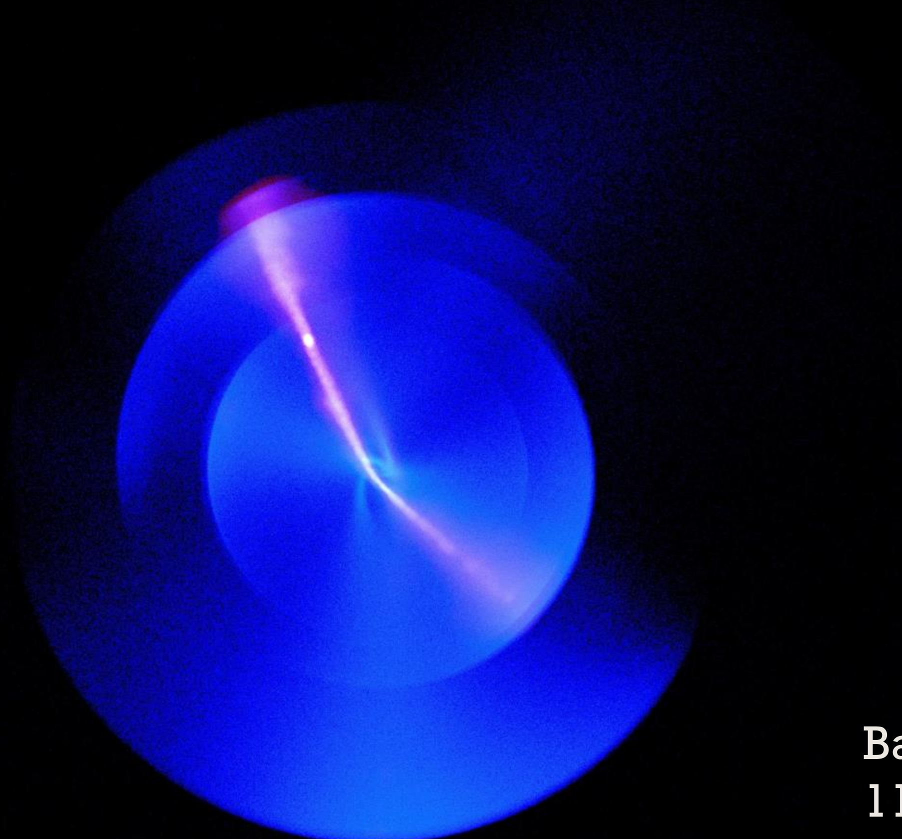
$$t_r \approx \frac{1}{n\sigma v} \sim O(0.01 \text{ Gyr})$$
$$(\text{dSph}, \frac{\sigma}{m} \sim \frac{\text{cm}^2}{\text{g}})$$

Core formation: $1\sim100\ t_r$
Core collapse in $\sim385\ t_r$
(Koda & Shapiro 2011)



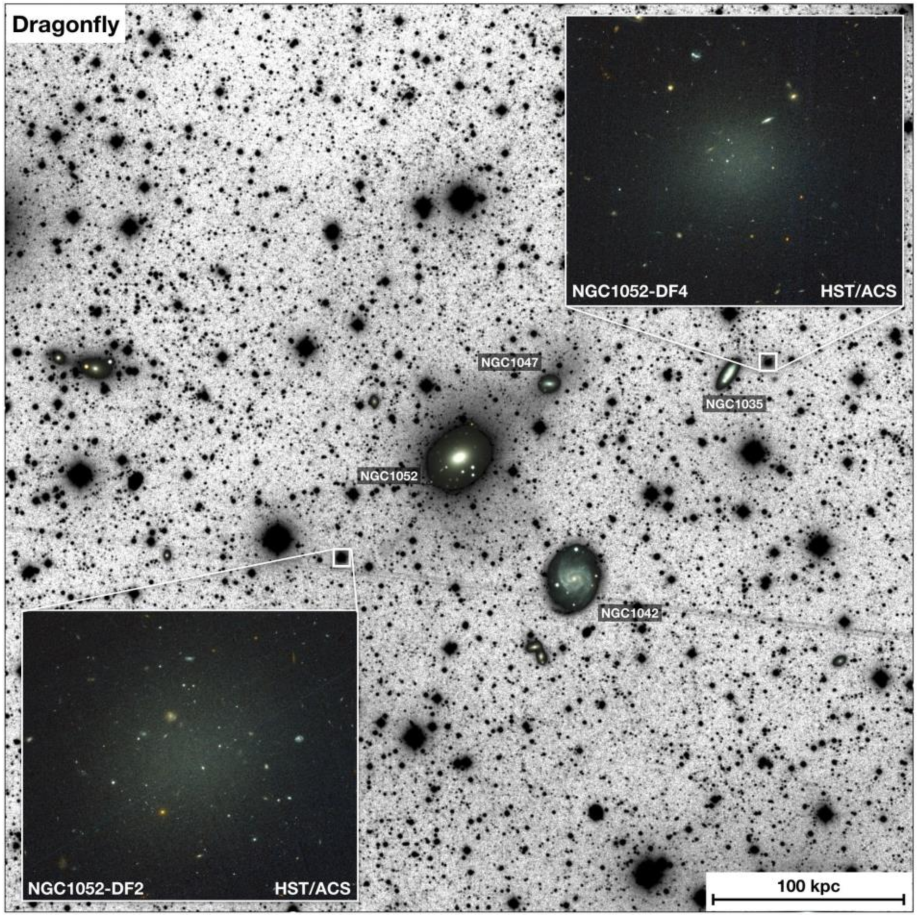
Example tidal evolution
(from the 2nd project)
$M_{host} \sim 10^{15}\ M_\odot$
$M_{sub} \sim 10^{12}\ M_\odot$ (at infall)

Self-interacting Dark Matter and the Origin of NGC1052-DF2 and -DF4



Based on: Phys. Rev. Let. 125, 111105 (2020), Editor's suggestion

Galaxies lacking dark matter



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

- $\rho_{DM}/\rho_{baryon} \sim 5$
- **Milky Way:** $M_{DM}/M_{star} \approx 30$
- **DF2 and DF4:** $M_{star} \approx 10^8 M_\odot$
- **Expect:** $M_{DM}/M_{star} \sim 200$
- **Turns out:** $M_{DM}/M_{star} \lesssim 1$

Taking into account various observed properties, Haslbauer et. al. show that DF2/DF4 in ~**5 sigma** tension with LCDM

Tidal evolution could be the key

Ogiya MNRAS, 480, L106, **201**

CDM could work, provided there is large core in the inner halo profile, BUT,

@Without SIDM, CDM halos maybe cored due to baryon feedback, however

@Baryon feedback will lead to a too diffuse stellar distribution

Jing et. al. MNRAS 488, 3298 (**2019**)

~2% satellites are DM deficient, BUT,

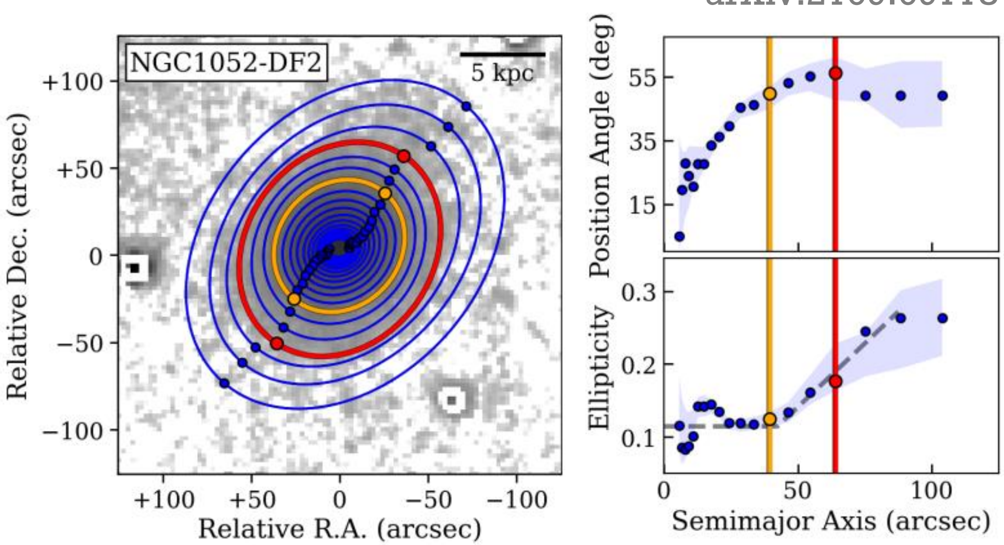
@ Need VERY compact stellar distribution

@ DF2/DF4 are very diffuse

All the @'s will be addressed in our work

arXiv:2109.09778

Keim et al. 2021: tidal distortions observed in DF2 & DF4



Tidal evolution

Host galaxy (static potential)

- DM: Mhalo $\approx 10^{13}\ M_{\odot}$
- Stars: Mstar $\approx 10^{11}\ M_{\odot}$

Satellite galaxy

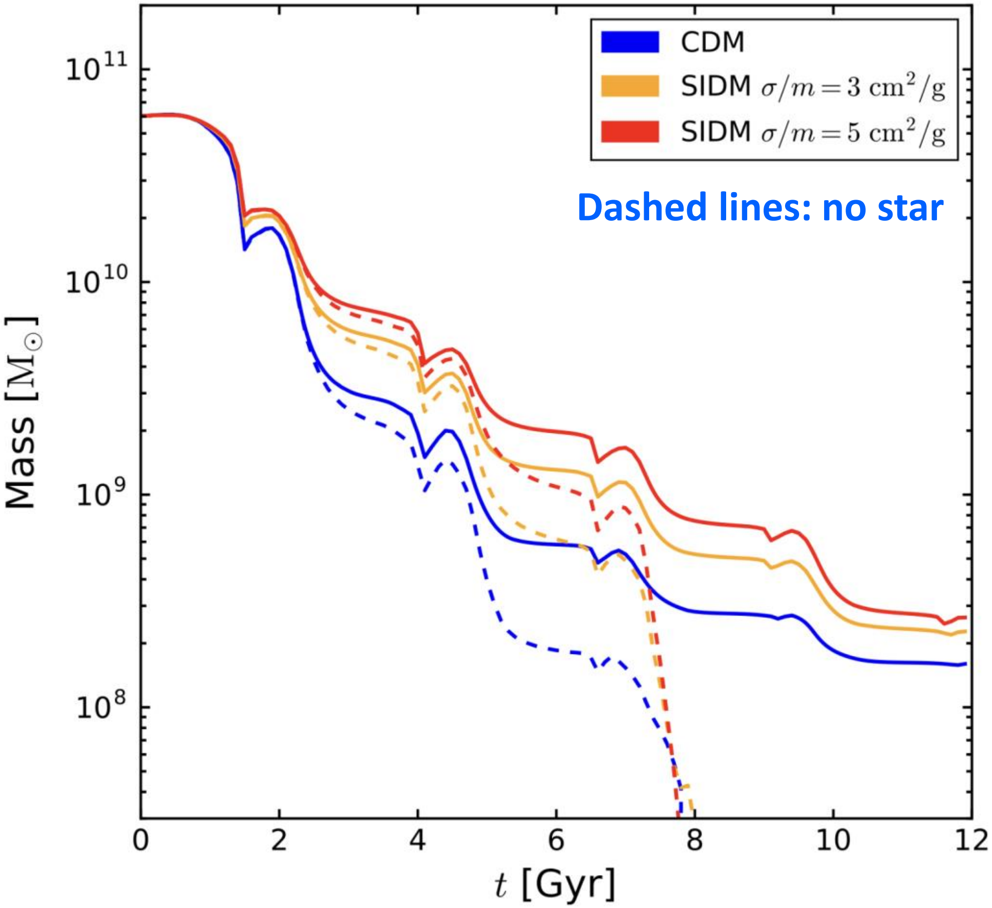
- **Live particles of mass $10^{4} M_{\odot}$**
- Mhalo=$6 \times 10^{10}\mathrm{M}_{\odot}$
- Mstar=$3.2 \times 10^{8}\mathrm{M}_{\odot}$

Subhalo concentrations c_{200}

CDM: **4 (-4σ)**

SIDM3: **7(-1.8σ)**

SIDM5: **9(-0.4σ)**

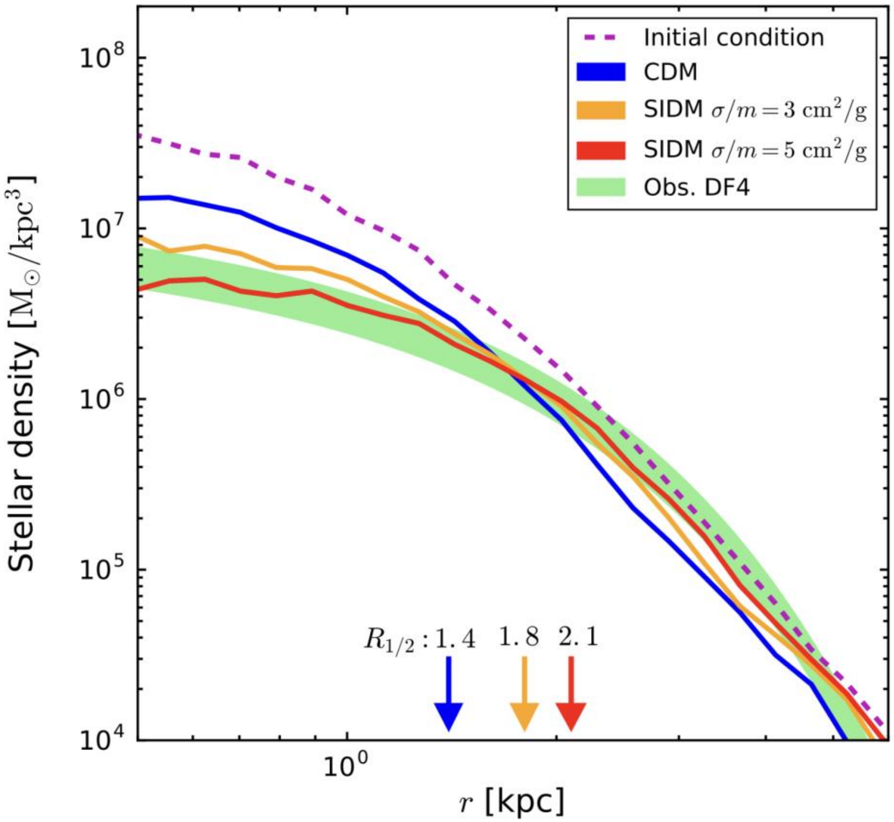


SIDM boosts tidal stripping, resulting in $M_{DM}/M_{star} \approx 1$

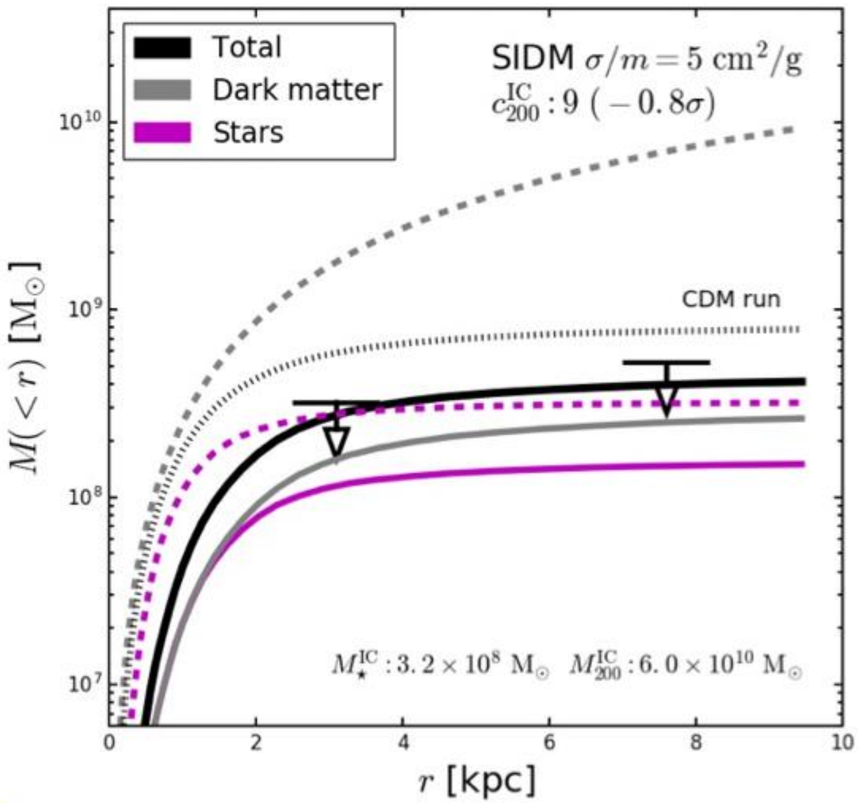
Stellar profiles

Mass profiles

Stars expand more significantly in SIDM halos



Dashed: $t = 0$ Gyr Solid: $t = 11.2$ Gyr



Observed half-mass radii:

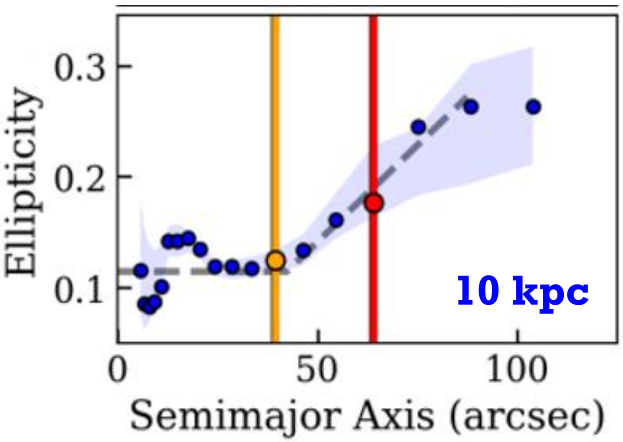
DF2: 2.7 kpc, DF4: 2.0 kpc

Ellipticity of the stellar content

arXiv:2109.09778

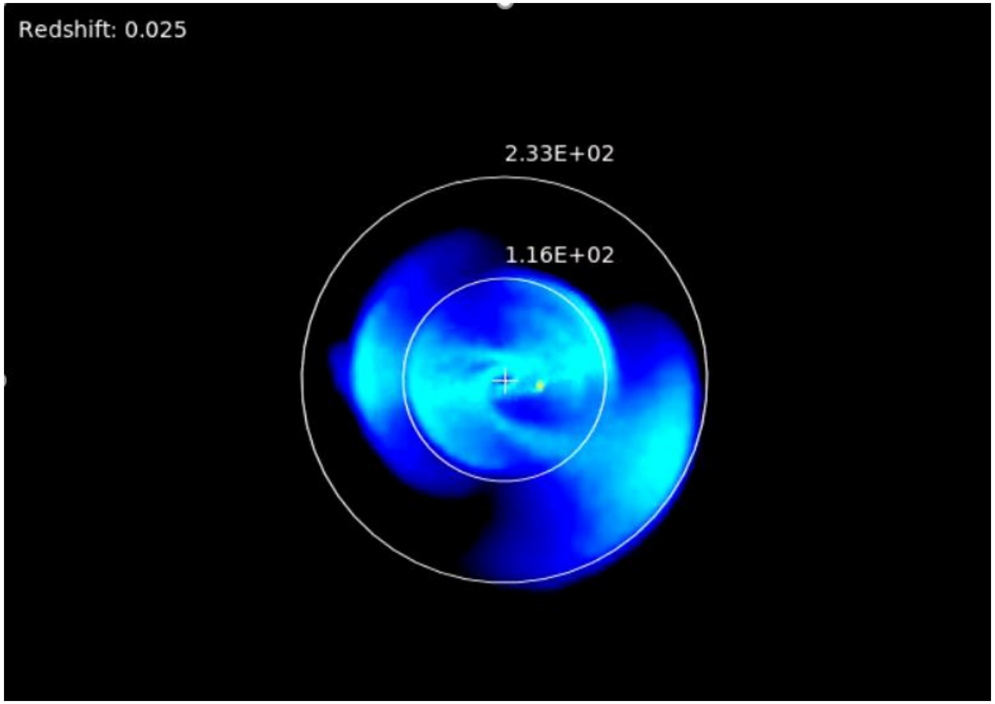
Benchmark	Radius (kpc)	Ellipticity
CDM	11.6	0.15
SIDM3	11.3	0.21
SIDM5	11.3	0.32

SIDM halos more elliptical due to stronger tidal stripping



***Preliminary*: cosmological simulation with growing potential**

- Orbital parameters become much closer to median
- Similar amount of tidal stripping



Self-Interacting Dark Matter and the Excess of Small-Scale Gravitational Lenses

- Dense object that play as lens and leads to observable multiple images
- Background image created based on our SIDM simulation

Based on: arXiv:2102.02375 [astro-ph]

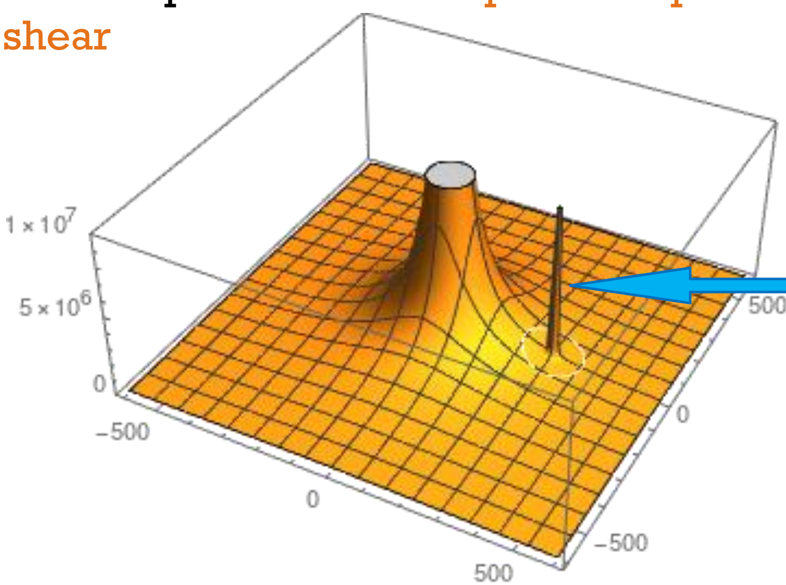
Strong gravitational lensing

Strong lensing probes the total mass distribution: sensitive to dark matter

Tidal field plays a significant role for the small scale lenses

A subscale lens can both perturb existing lensed images, and adding more (we focus on the latter)

Tangential strong lensing cross section vanishes for a symmetric Singular Iso-thermal profile: need elliptical shape and/or shear



Shear matrix

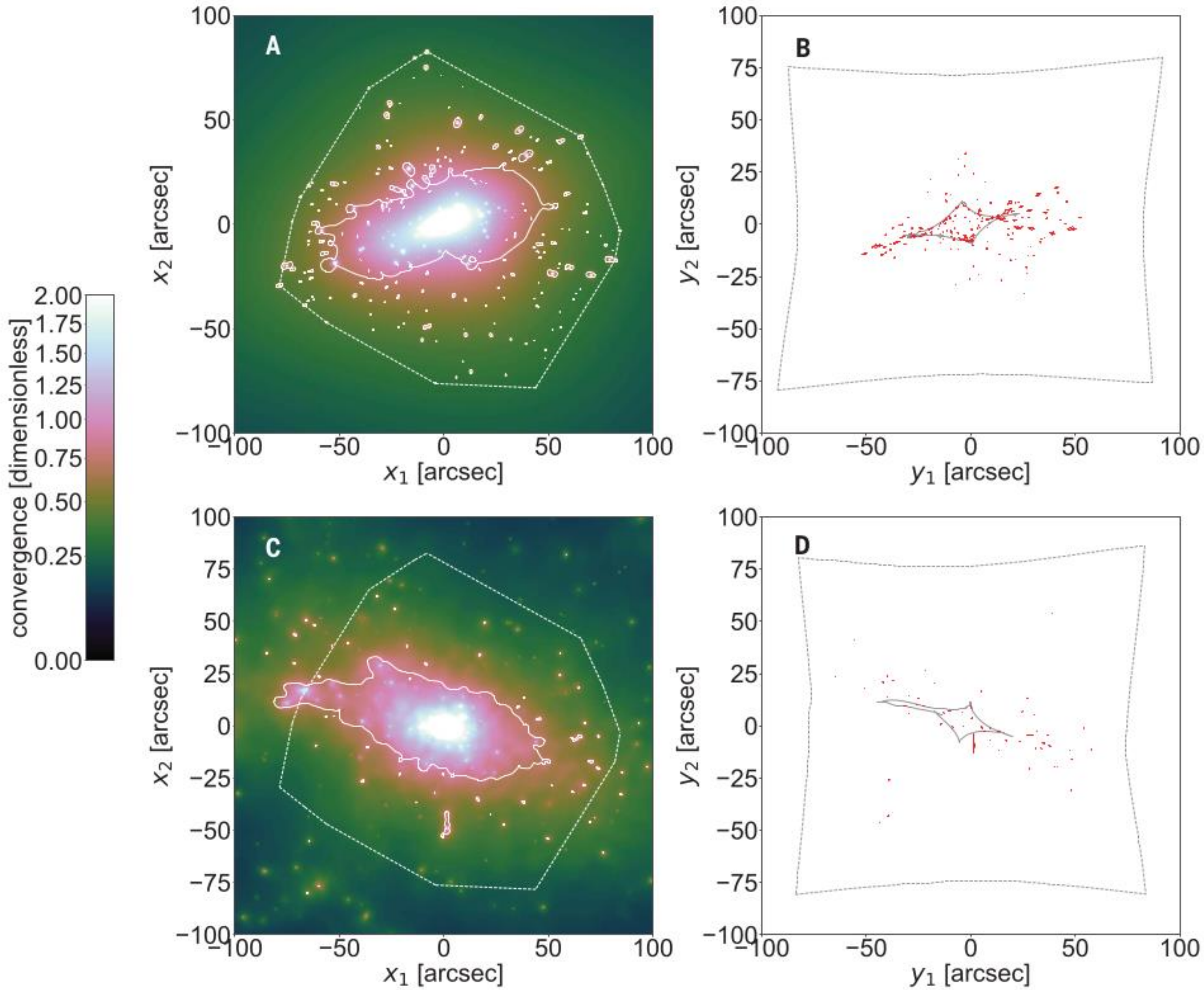
$$\mathcal{A} \equiv \partial\beta_i/\partial\theta_j = (\delta_{ij} - \Psi_{ij})$$

$$\Psi_{ij} \equiv \partial^2\Psi/\partial\theta_i\partial\theta_j$$

- Tidal field of the host halo contributes a significant shear
- Radial GGSL cross section sensitive to the inner density slope

There will be number of substructure; we simulate only one each time

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



Critical lines

Caustics

Observed

Significantly more secondary caustics & larger GGSL cross section (area enclosed by red curves)

Simulated

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

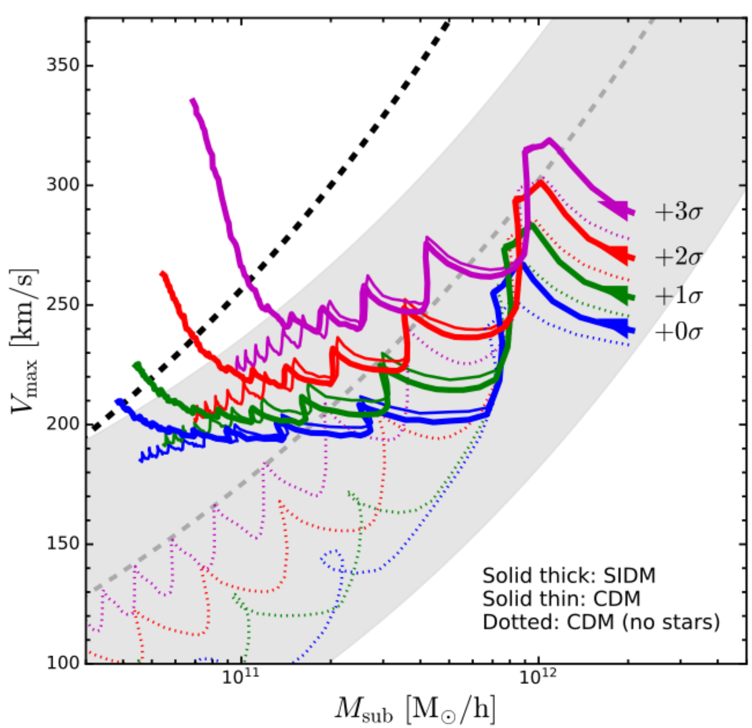
- Not a problem in the most massive cluster of Hydrangea simulation 100 times higher resolution
- More concentrated and massive baryon distributions

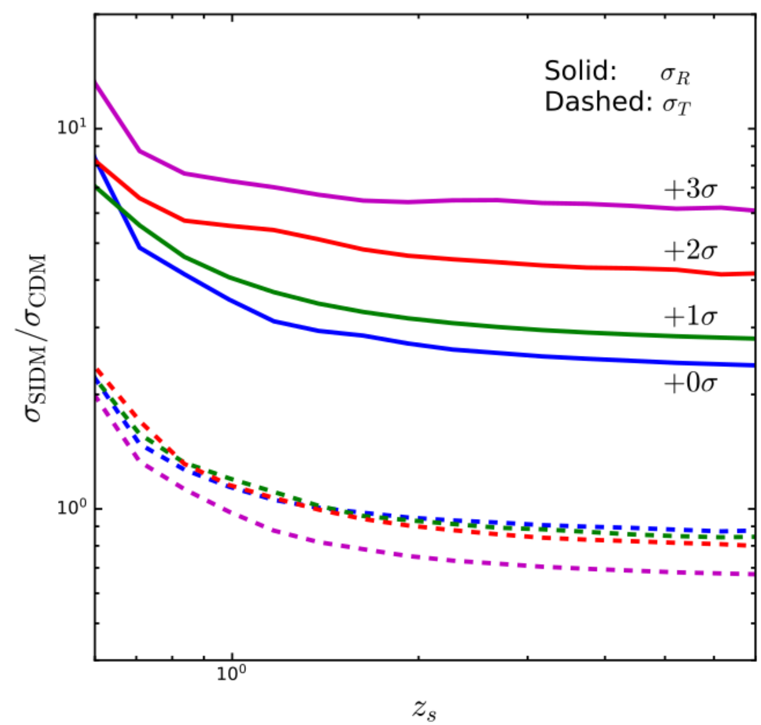
We perform controlled N body simulation to address this observation

- Gravothermal evolution significantly boosted by tidal stripping & baryon potential
- Simulate and compare strong lensing effects of SIDM and CDM simulations

A compact baryon is important

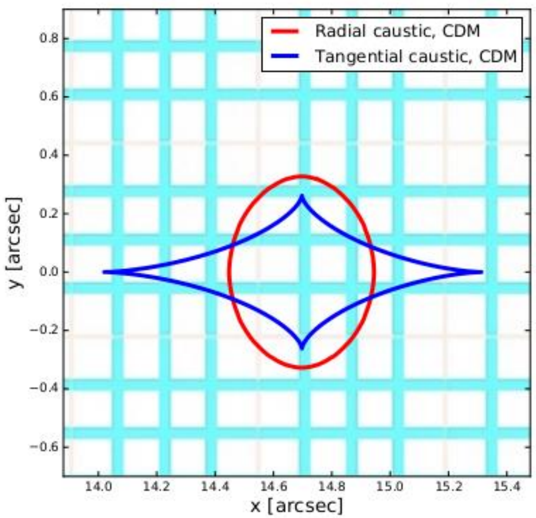
- Pre-in-fall, early type galaxy profiles are well measured to be SIS
- Core collapse happens for $+0\sigma$ halo concentration
- Supported by *Yamick & Andrew*'s paper appear at around the same time

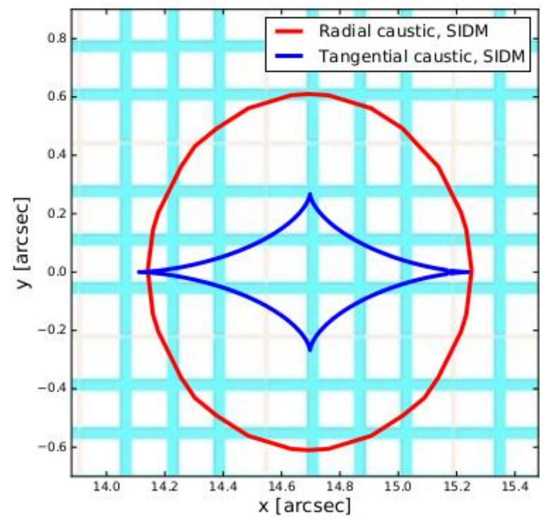


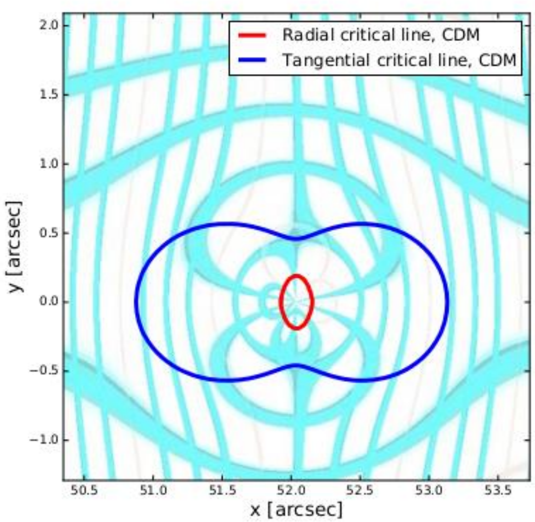


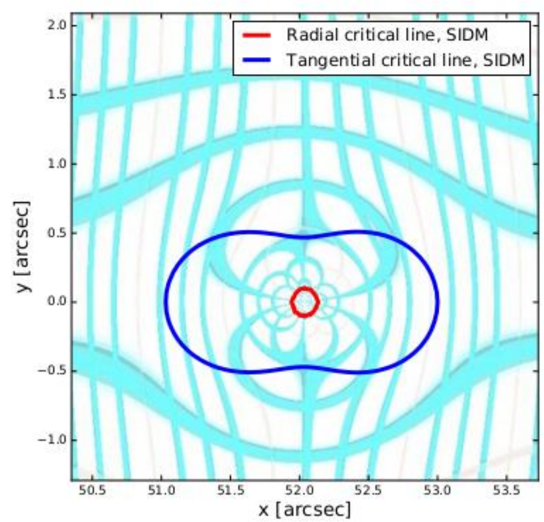
CDM, no core collapse

SIDM, core collapsing









Features of SIDM simulation

- Rich inner structure
- Larger radial GGSL cross section
- Significantly more two image events

Two image events are more difficult to measure

- Inner images de-magnified
- Inner halo region can be bright, but foreground can be subtracted.
- Need dedicated studies

SUMMARY

- Both tidal evolution and a compact baryon potential can boost the gravothermal evolution of a halo, making some halos core-collapsing today.
- Lensing features of a substructure is sensitive to its tidal environment. Statistics of different categories of lensed images (GGSL cross section) is sensitive to structure of the subhalos.
- Radially stretched images in the inner subhalo region are more difficult to observe, but can be used to probe the inner density profiles.

SIDM has novel interplays with the baryon content and the tidal evolution history of a subhalo. Related observable-imprints could be found in both ultra-diffuse and compact galaxies. Future observations could provide crucial tests of dark sector dynamics.