Extreme Testing of Self-Interacting Dark Matter

Hai-Bo Yu
University of California, Riverside

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WIMP Search Status

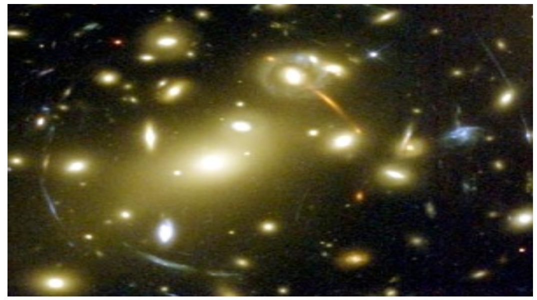
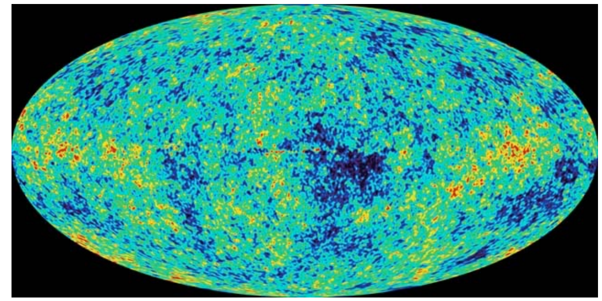
“上穷碧落下黄泉，两处茫茫皆不见。”白居易《长恨歌》

He exhausted all avenues in heaven and the nether world,
… he could not bring her existence to light.

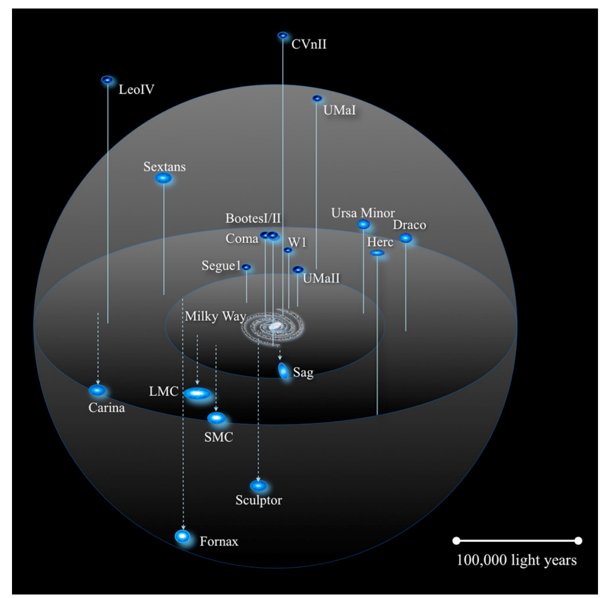
A Song of Immortal Regret, Bai Juyi (772-846)

A Critical Rethinking: Cold Dark Matter (CDM)

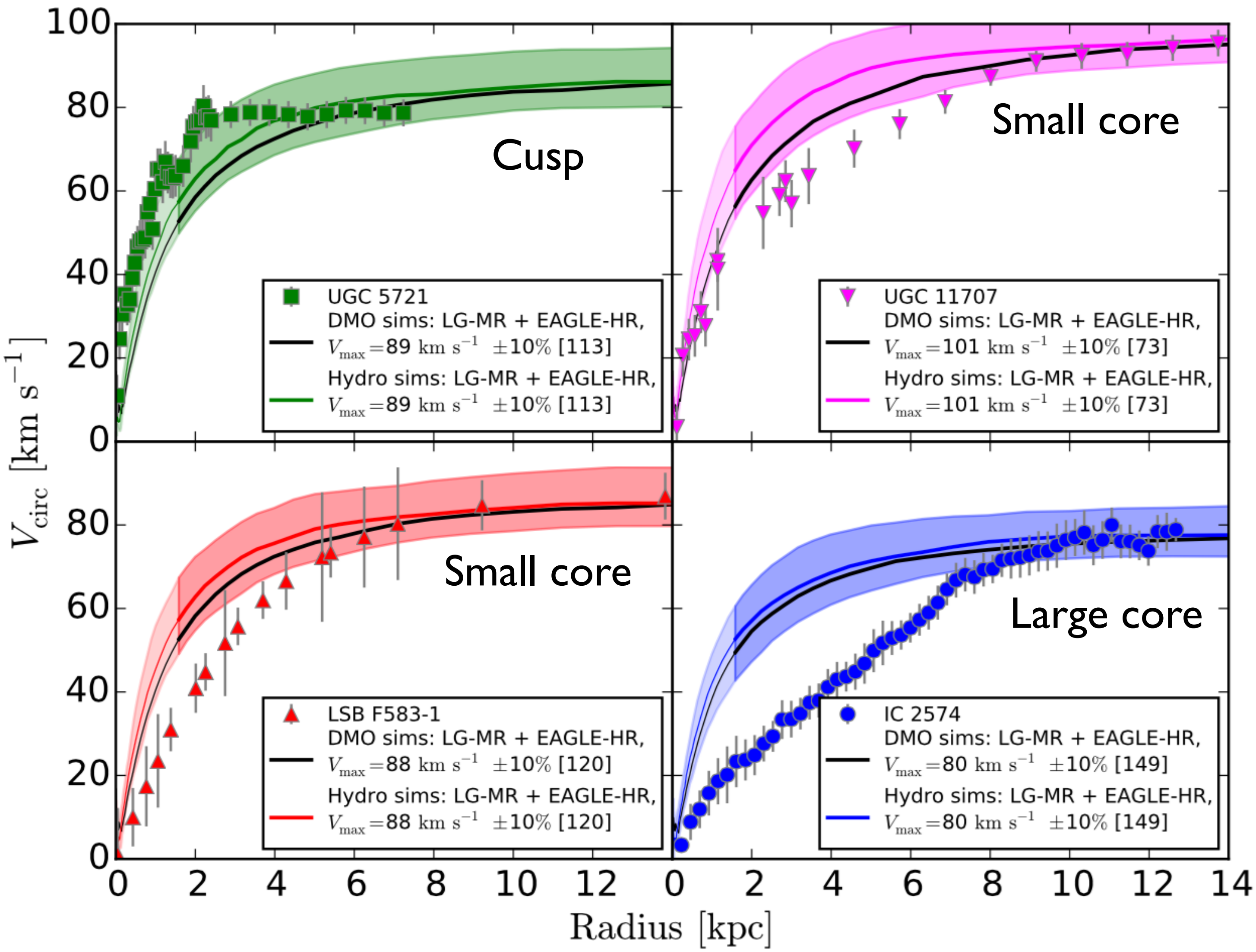
- Large scales: very well

- Small scales (dwarf galaxies, sub-halos, galaxy clusters)
  - Core vs Cusp
  - Diversity
  - Too Big To Fail
  - Cores in clusters
  - Ultra diffuse galaxies

The Diversity Problem



All galaxies have the same observed Vmax!

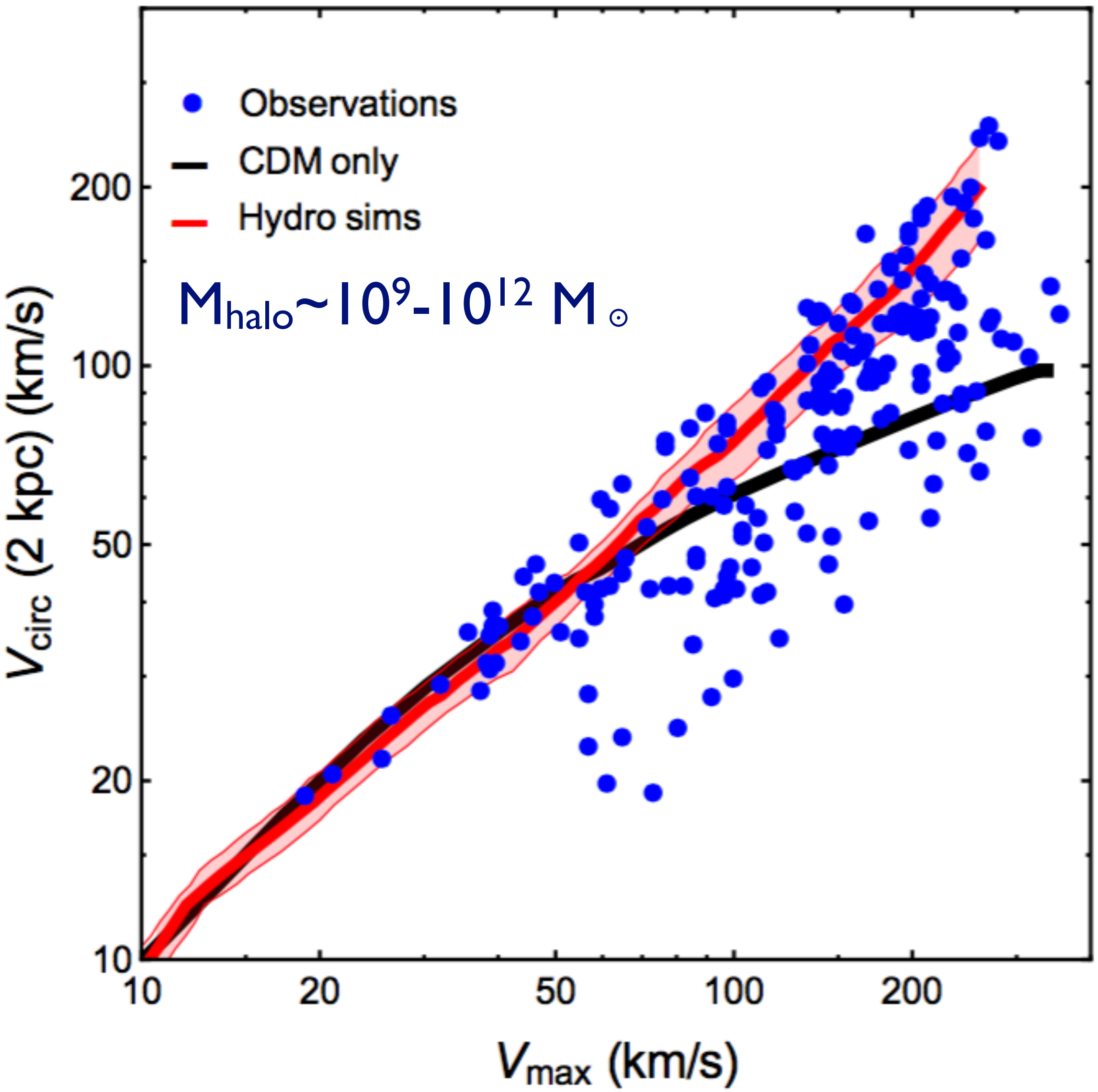
$$V \sim \sqrt{GM/r}$$

Colored bands: hydrodynamical simulations of CDM

Oman+(2015)

Dark matter distributions are diverse in spiral galaxies

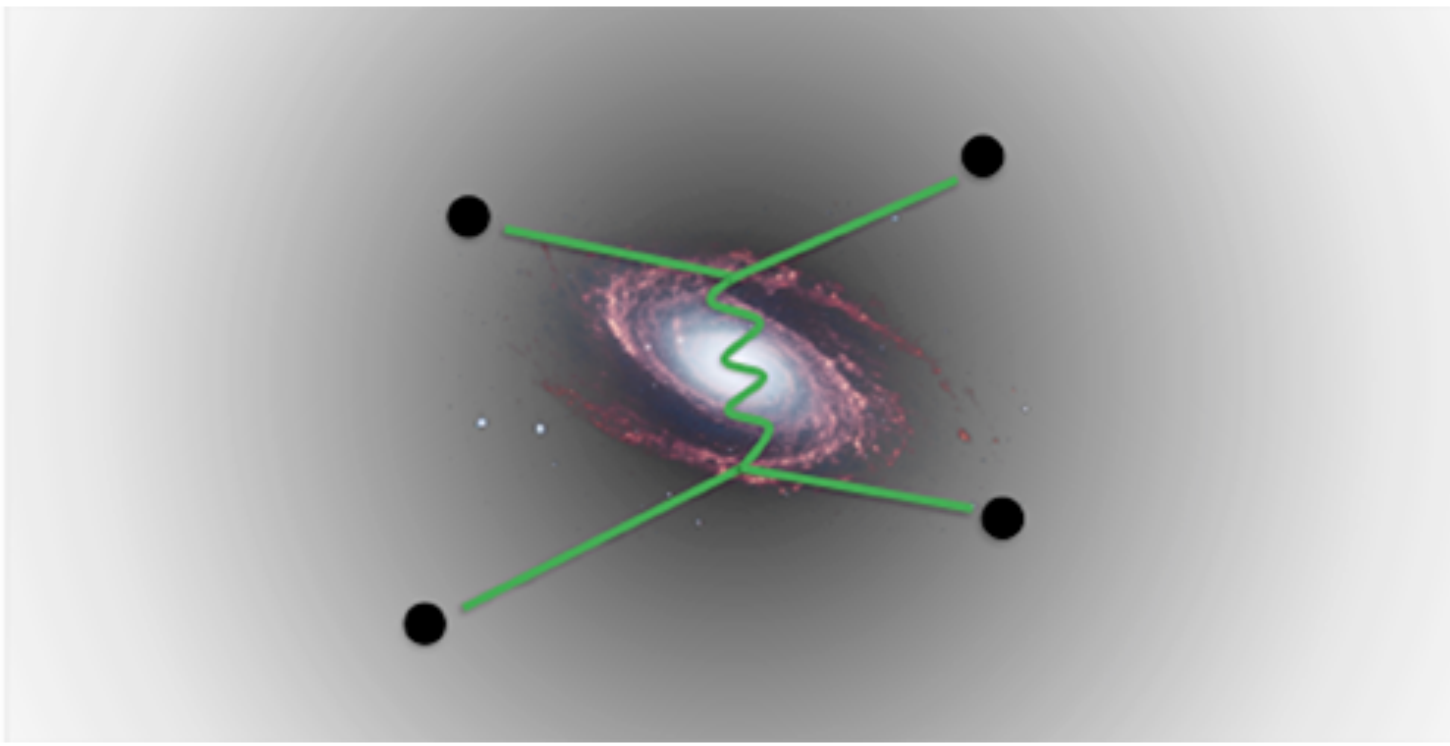
A Big Challenge



V_{circ}(2kpc) has a factor of ~4 scatter for fixed V_{max}

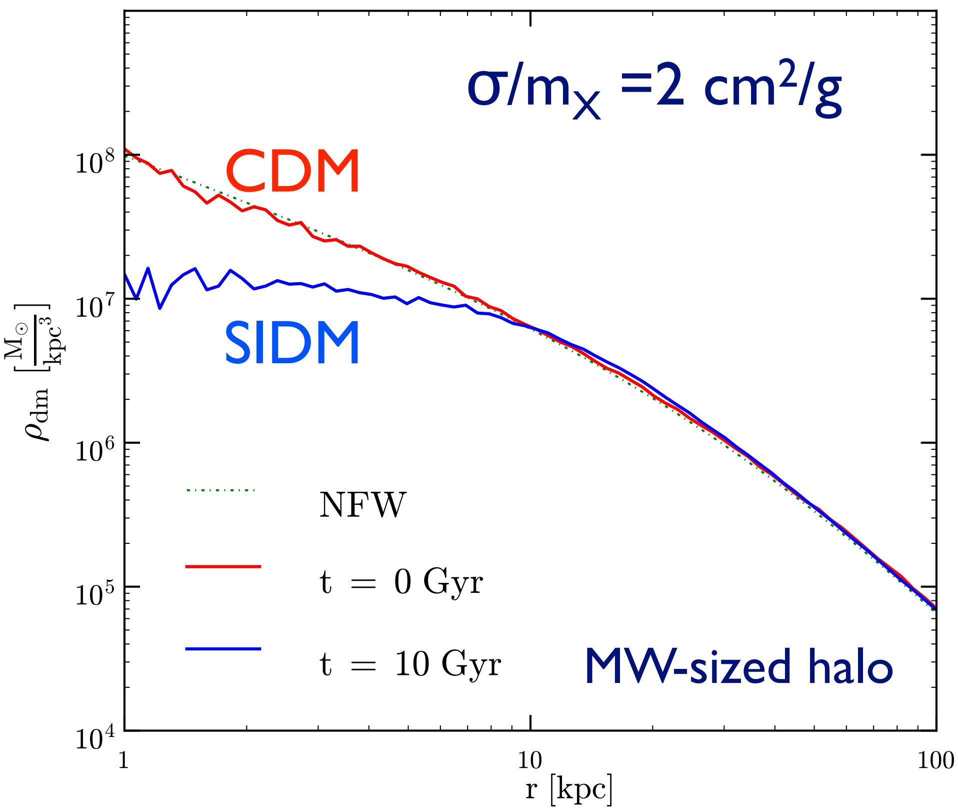
Reproduced from the data compiled in Oman+(2015)

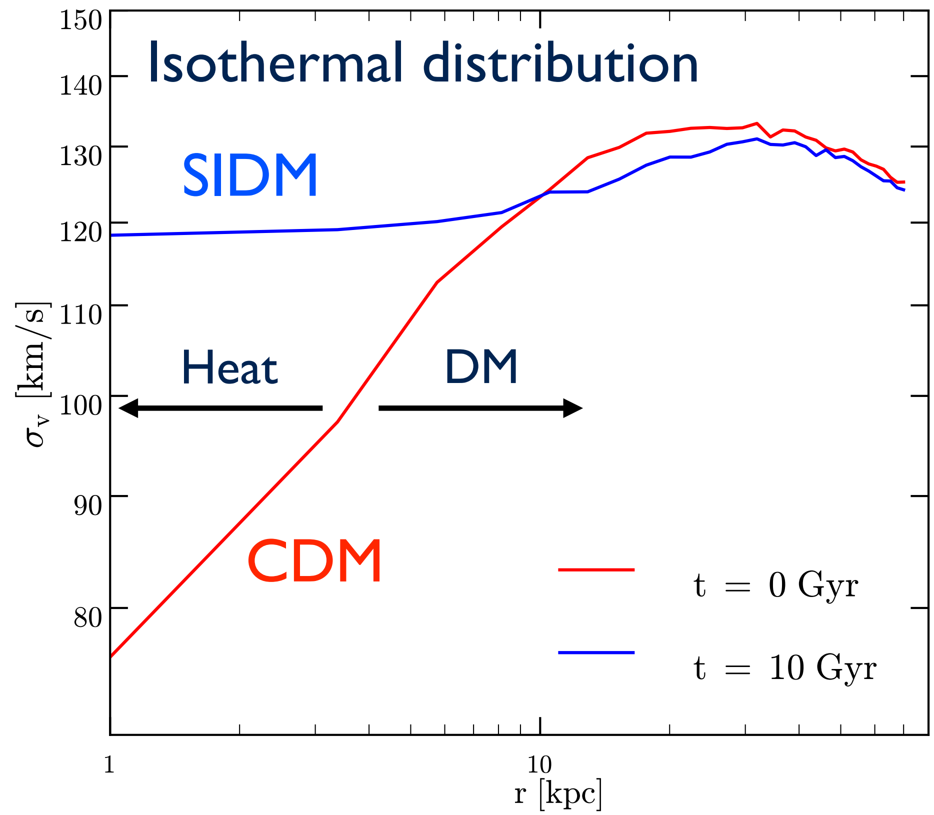
The diversity can be explained if dark matter has strong self-interactions



Self-Interacting Dark Matter

- Self-interactions thermalize the inner halo





$\sigma/m_X \sim 1$ cm^2/g (nuclear scale)

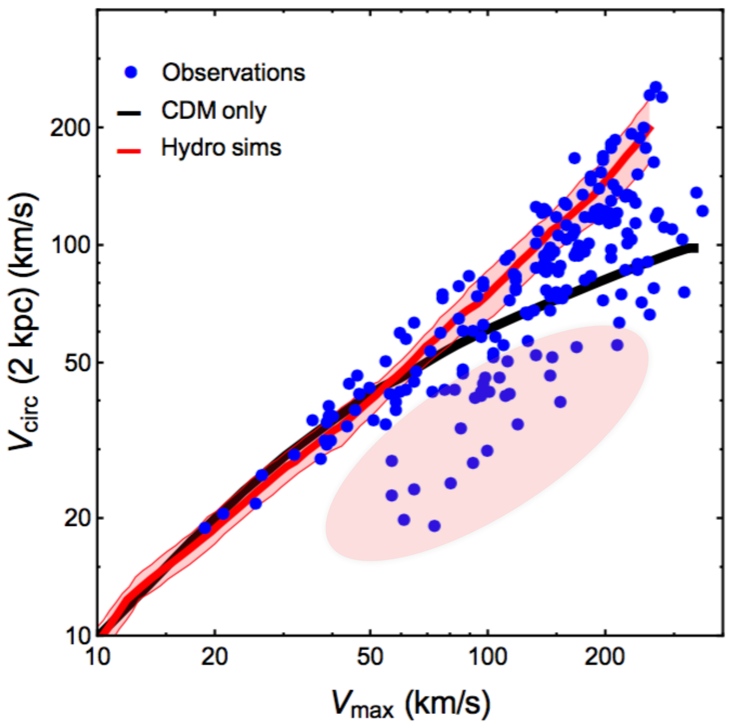
From Ran Huo

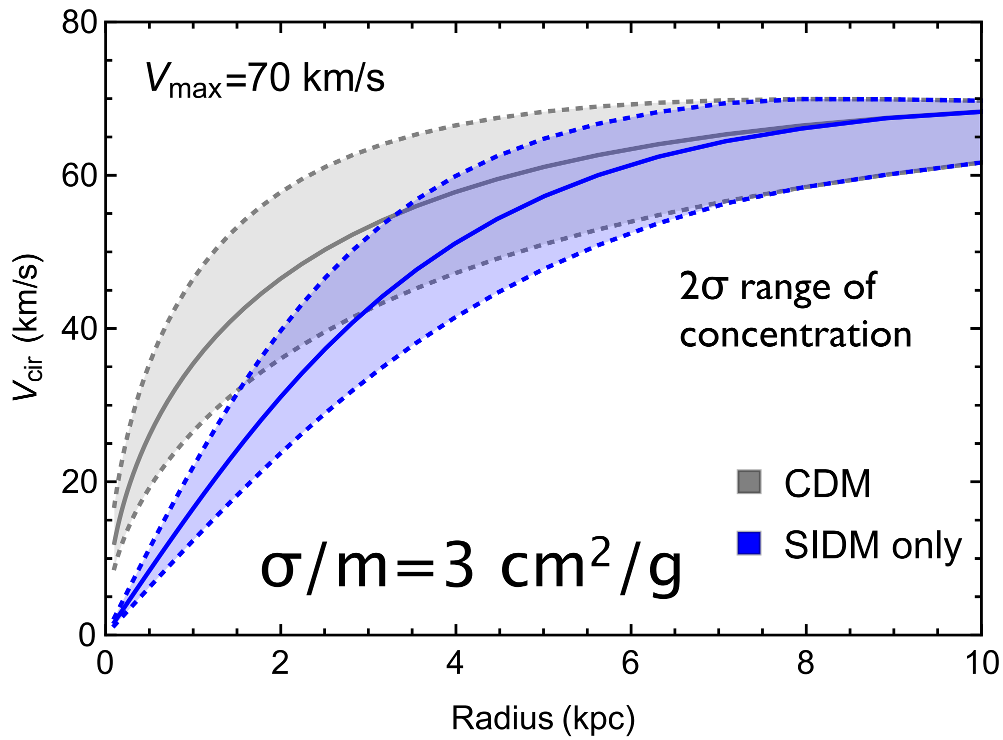
$$\Gamma \simeq n\sigma v = (\rho/m_X)\sigma v \sim H_0$$

Review: w/ Tulin (Physics Reports 2017)

Low Surface Brightness Galaxies

- DM self-interactions thermalize the inner halo





w/ Kamada, Kaplinghat, Pace (PRL 2017)

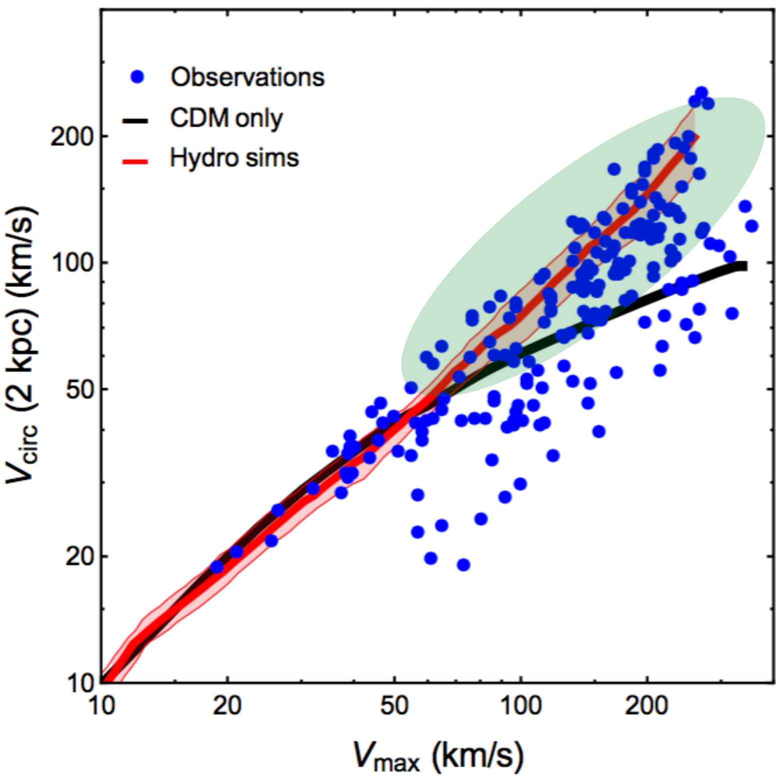
DM-dominated galaxies: Lower the central density and the circular velocity

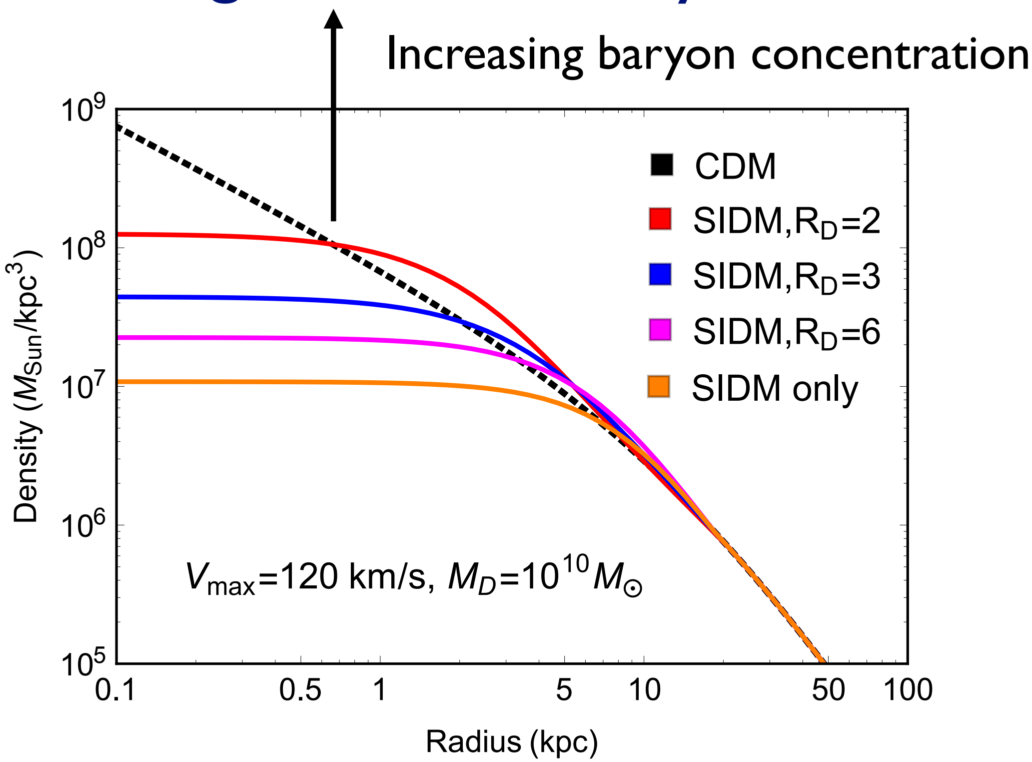
Isothermal distribution

$$\rho_X \sim e^{-\Phi_{tot}/\sigma_0^2} \sim e^{-\Phi_X/\sigma_0^2}$$

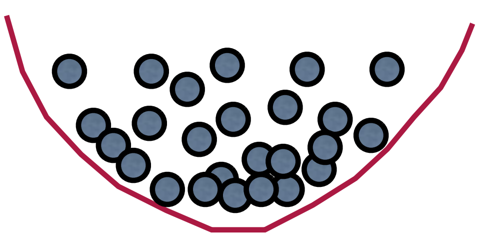
High Surface Brightness Galaxies

- DM self-interactions tie DM together with baryons





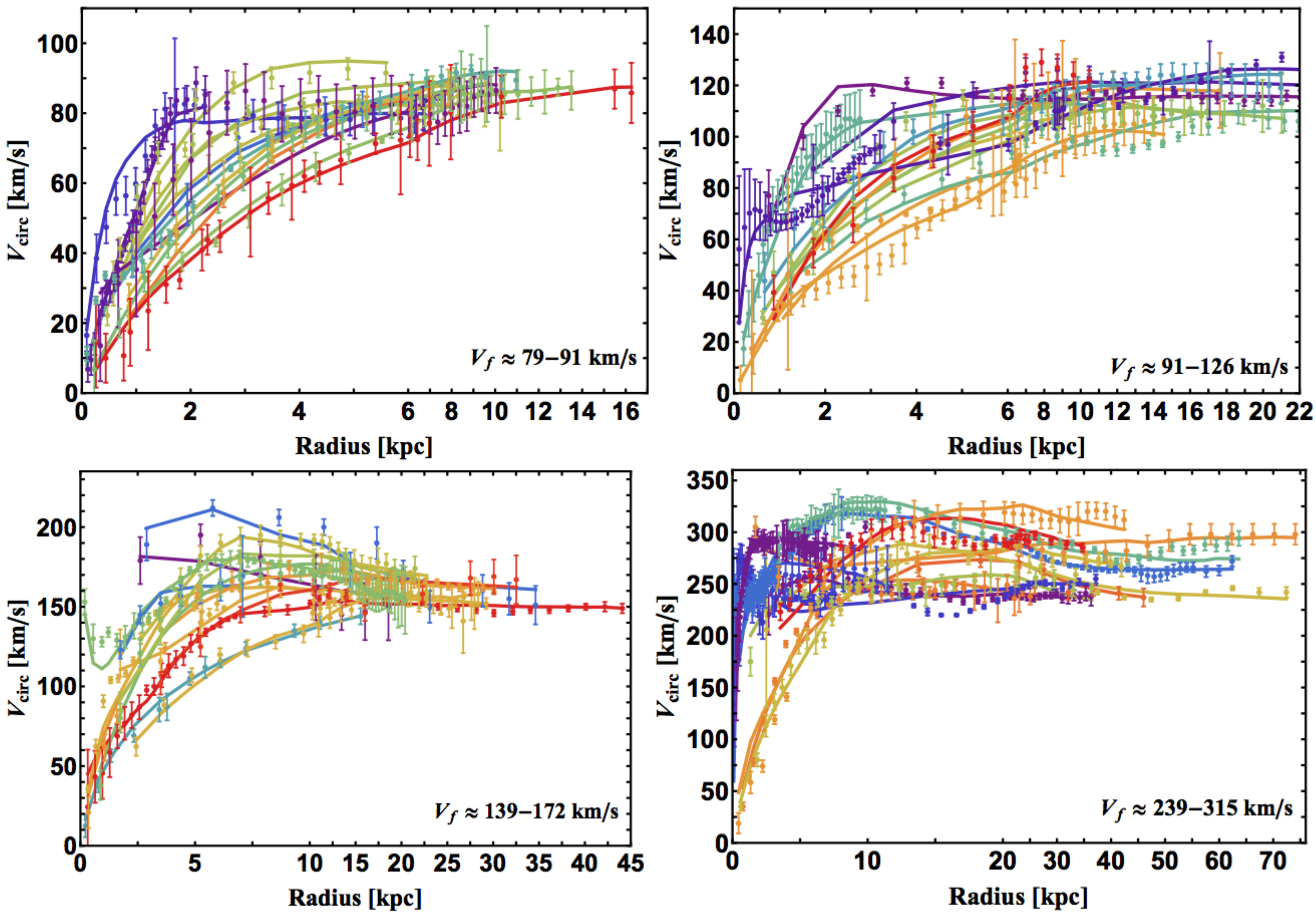
Thermalization leads to higher DM density due to the baryonic influence



$$\rho_X \sim e^{-\Phi_{\rm tot}/\sigma_0^2} \sim e^{-\Phi_{\rm B}/\sigma_0^2}$$

w/ Kaplinghat, Keeley, Linden (PRL 2014)
w/ Kamada, Kaplinghat, Pace (PRL 2017)

Addressing the Diversity Problem



$\sigma/\mathrm{m} = 3\ \mathrm{cm}^2/\mathrm{g}$

We fitted 135 galaxies (3.6 μm band)!

SPARC dataset, Lelli, McGaugh,Schombert (2016)

w/ Ren, Kwa, Kaplinghat (PRX 2018)
w/ Kamada, Kaplinghat, Pace (PRL 2017)
w/ Creasey, Sameie, Sales+(MNRAS 2017)

Add one more parameter σ/m

Explain the diverse rotation curves of spiral galaxies (puzzled us for ~25 years)

Beyond Field Galaxies

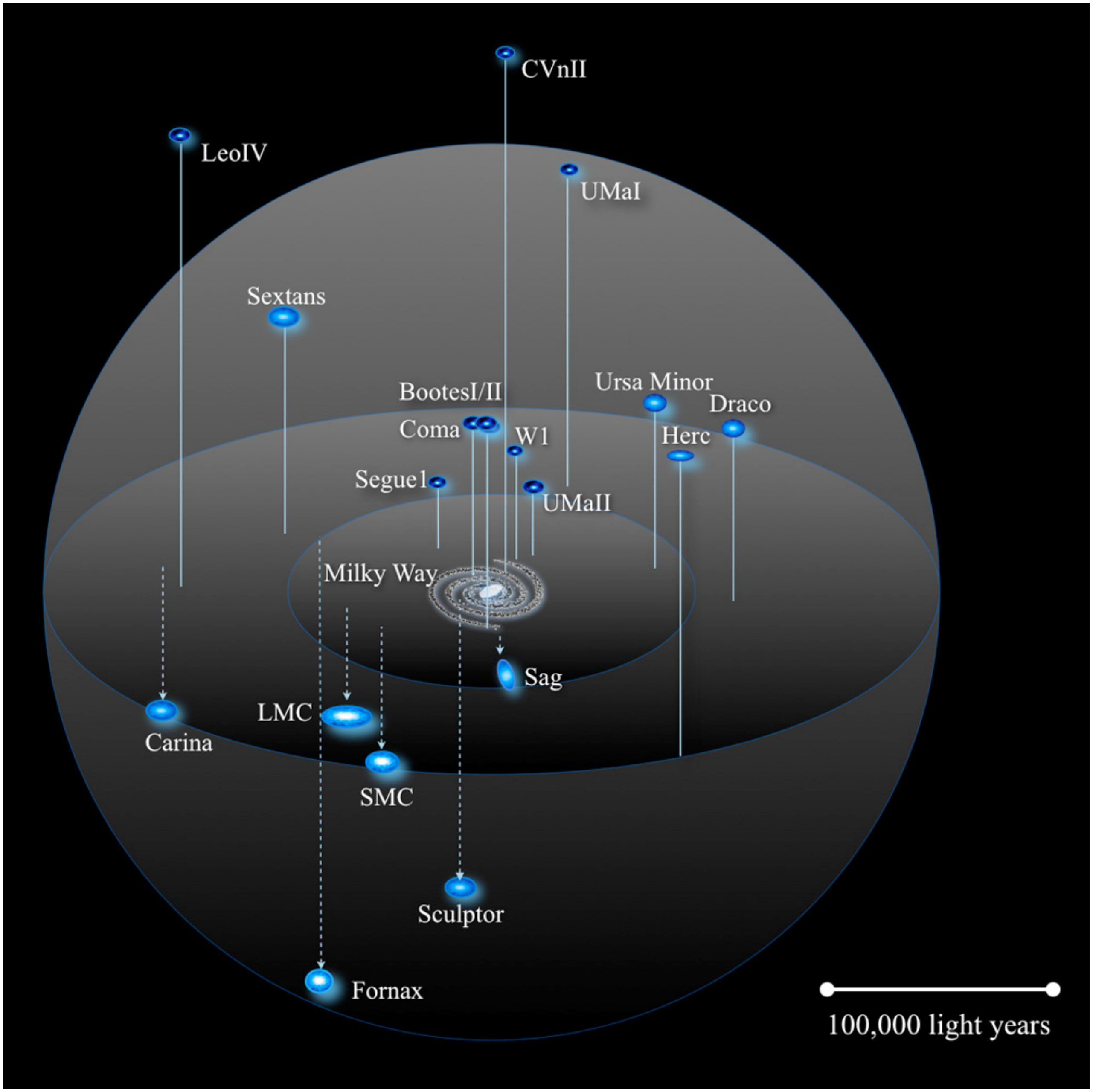
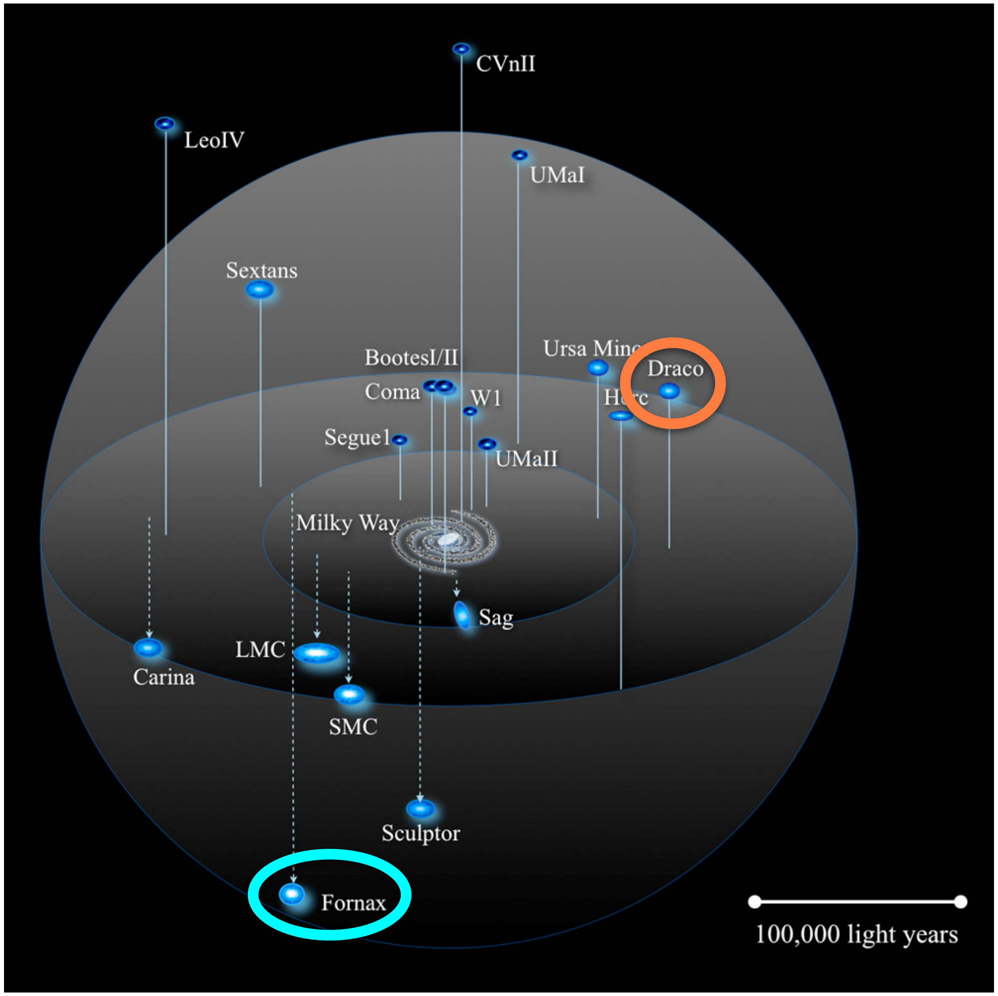
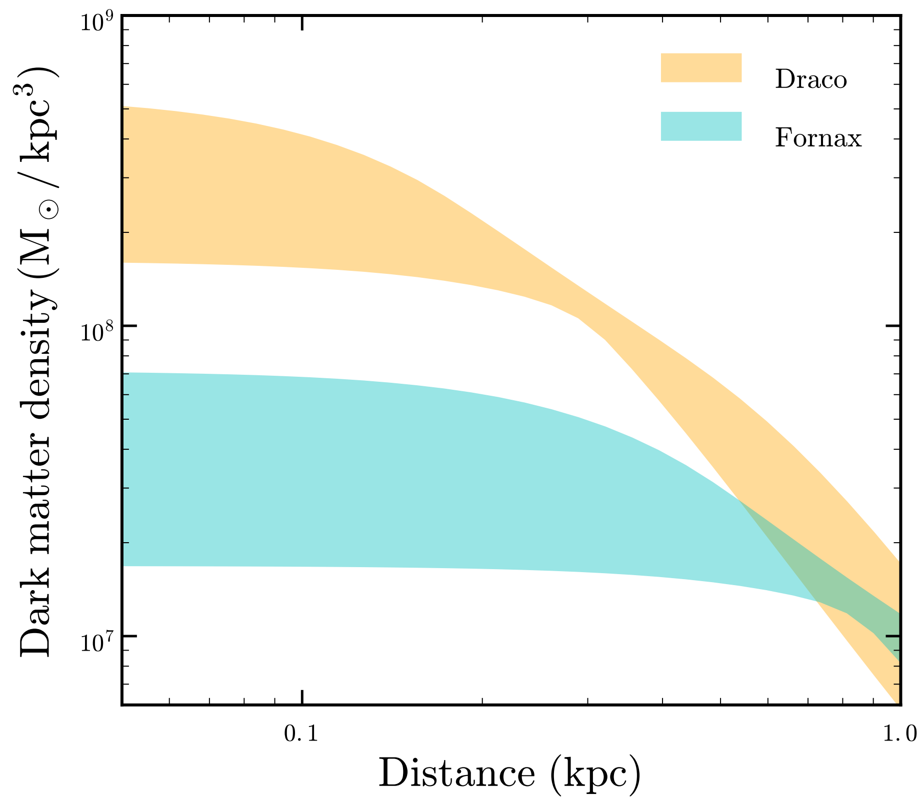


Image: Bullock+

But…



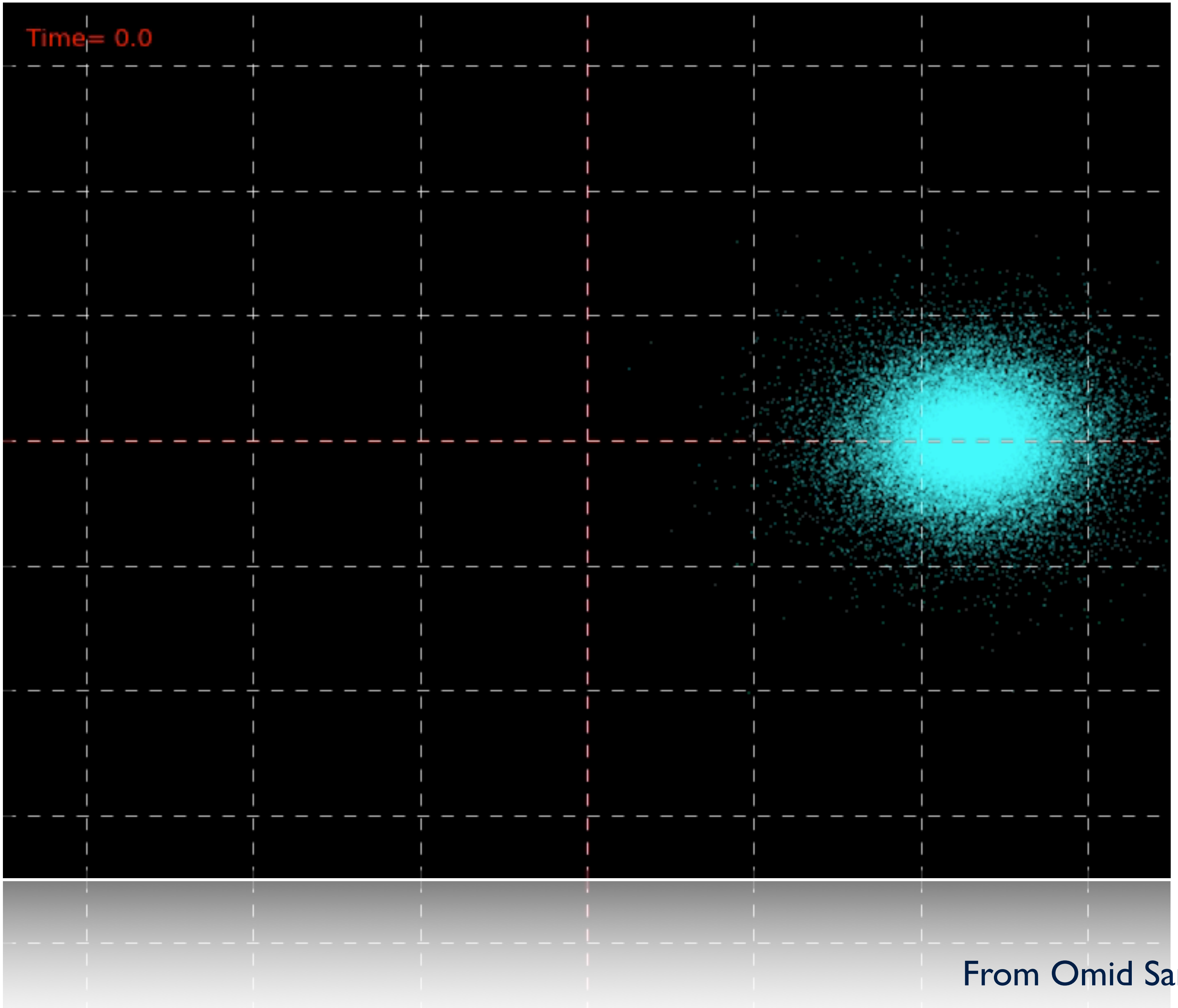
Observations



- Dark matter distributions are also diverse in satellite galaxies
- Naively, we would get σ/m_X ~10 cm^2/g for Fornax, but σ/m_X ~0.3 cm^2/g for Draco

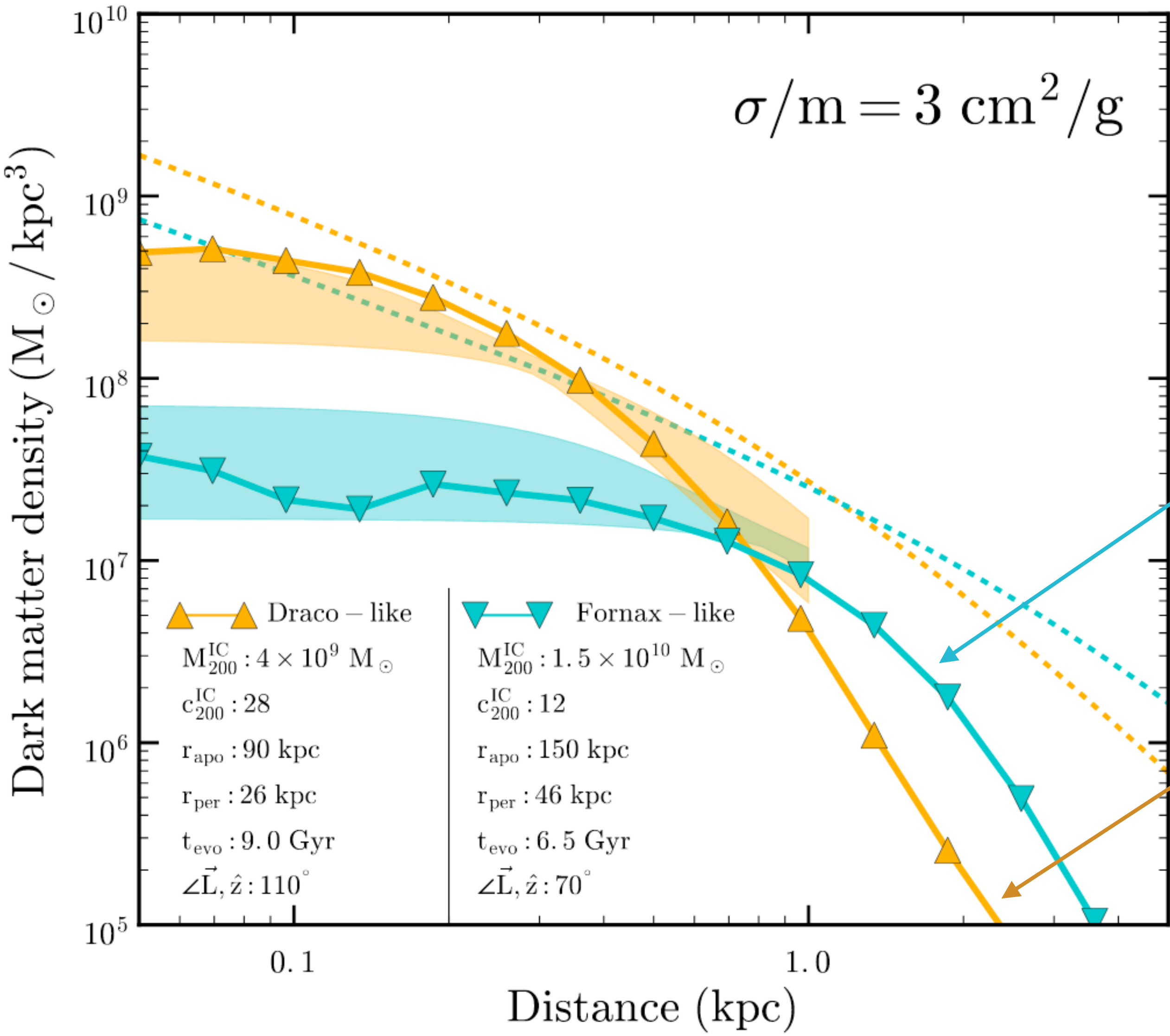
w/ Valli (Nature Astronomy 2018) w/ Kaplinghat, Valli (MNRAS, 2019)

Tidal Interactions



From Omid Sameie

Reconciling Draco & Fornax in SIDM



DM self-interactions and tidal interactions

core-expansion phase

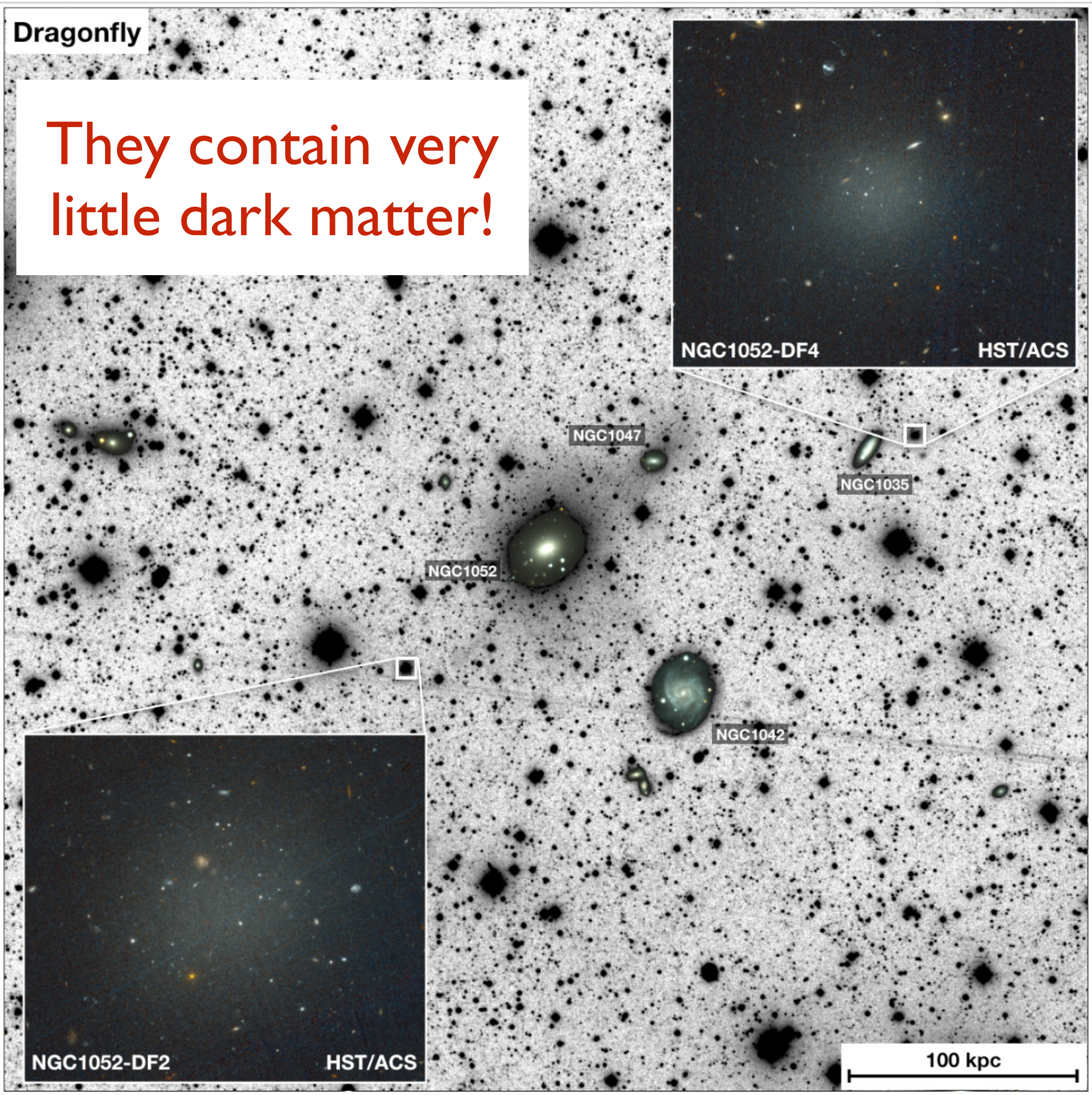
core-collapse phase

w/ Sameie, Sales+(PRL 2019)

SIDM can explain diverse DM distributions in both satellite and field galaxies

Ultra-Diffuse Galaxies

They contain very little dark matter!



Dragonfly team, van Dokkum+ (Nature 2018, AJPL 2019)

Milky Way

$$M_{\rm DM}/M_{\rm star} \approx 30$$

DF2 and DF4

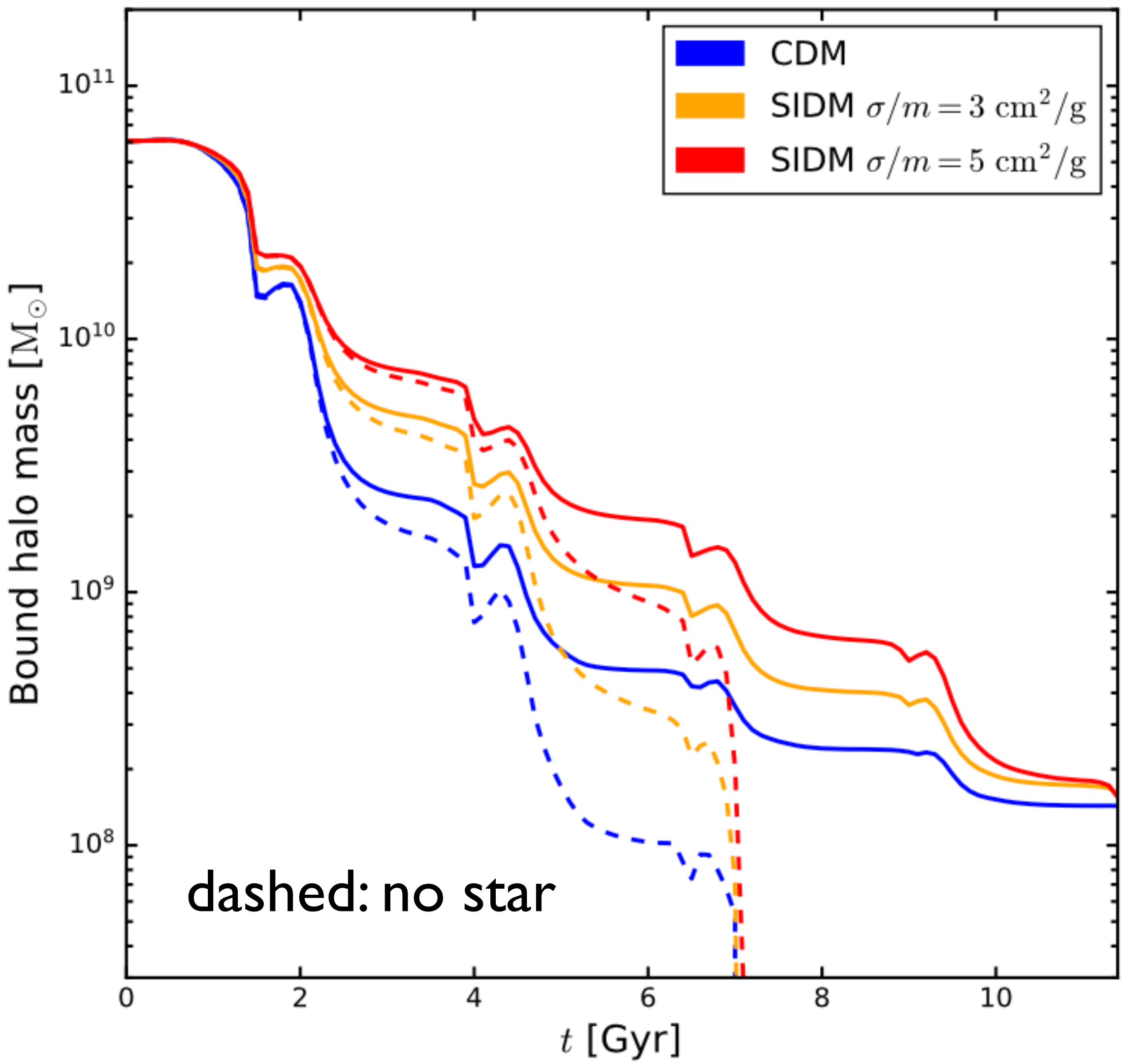
$$M_{\rm star} \approx 10^8\ \mathrm{M}_\odot$$

Expected

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

Observed

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



Halo concentration c_{200}

CDM: 4 (-4σ)

SIDM3: 7 (-1.8σ)

SIDM5: 10 (-0.4σ)

Initial, t=0 Gyr

$$M_{200} = 6 \times 10^{10}\ \mathrm{M_\odot}$$

$$M_* = 3.2 \times 10^{8}\ \mathrm{M_\odot}$$

$$M_{200}/M_* \approx 188$$

Final, t=11 Gyr

$$M_{\mathrm{DM}} = 1.5 \times 10^{8}\ \mathrm{M_\odot}$$

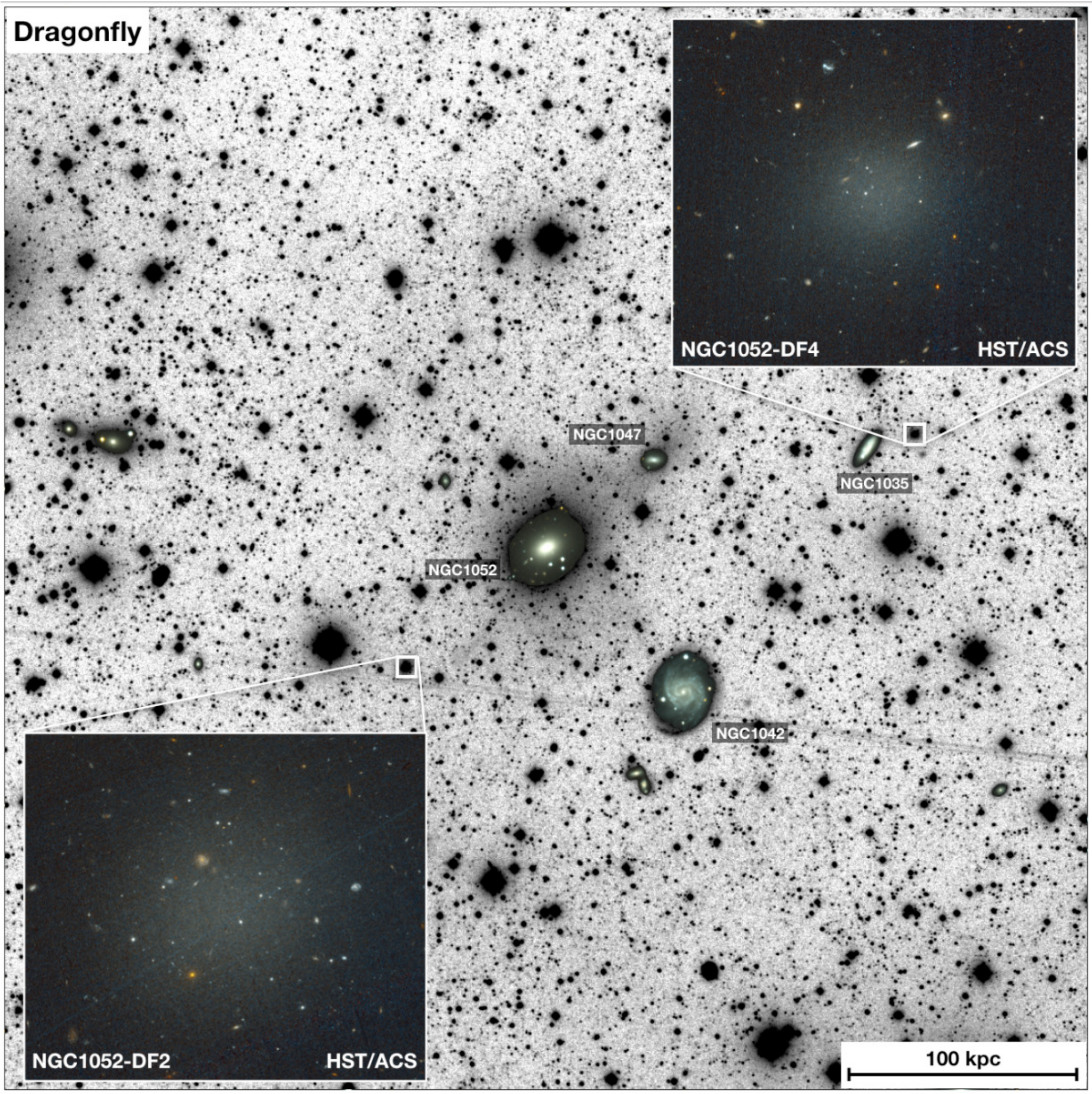
$$M_{\mathrm{star}} = 1.3 \times 10^{8}\ \mathrm{M_\odot}$$

$$M_{\mathrm{DM}}/M_{\mathrm{star}} \approx 1$$

SIDM leads to core formation, boosting tidal mass loss

w/ Yang, An (PRL 2020)

Galaxies with Little Dark Matter



DF2 and DF4 are most likely to be satellite galaxies (recently confirmed by observations)

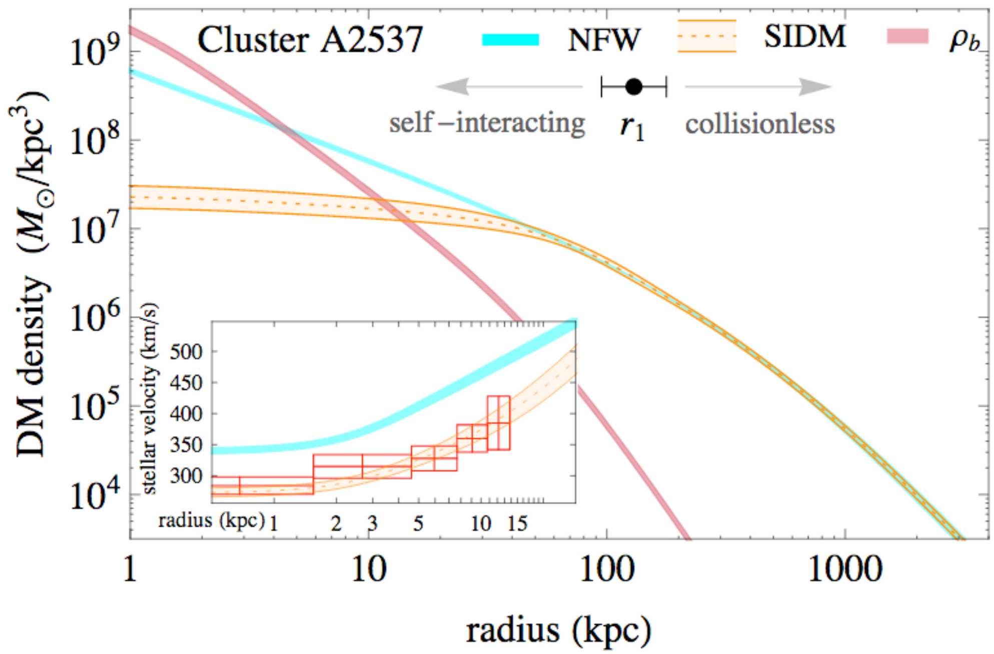
They are much more naturally realized in SIDM than in CDM through tidal stripping

w/ Yang, An (PRL 2020)

Dragonfly team, van Dokkum+ (Nature 2018, AJPL 2019)

Galaxy Clusters

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



w/ Kaplinghat, Tulin (PRL 2015)

Six well-relaxed galaxy clusters data from Newman+(2013)

Shallow inner DM density profiles
Core sizes ~10 kpc and smaller

Clusters: $\sigma/m \sim 0.1\ cm^2/g$

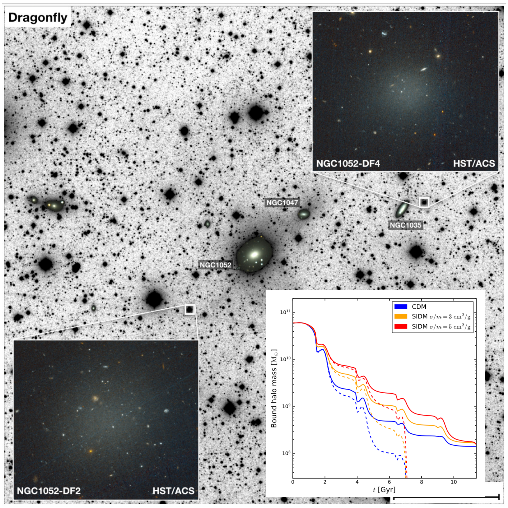
SIDM from Dwarfs to Clusters

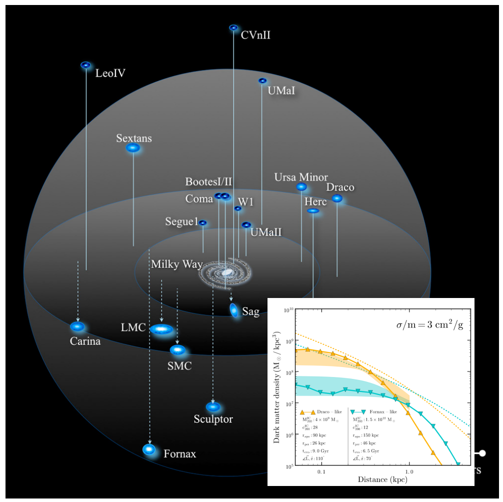
Ultra-diffuse galaxies (dark-matter-deficient)

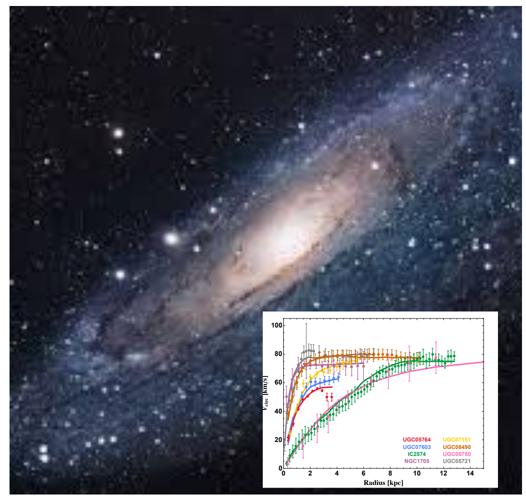
Milky Way satellites

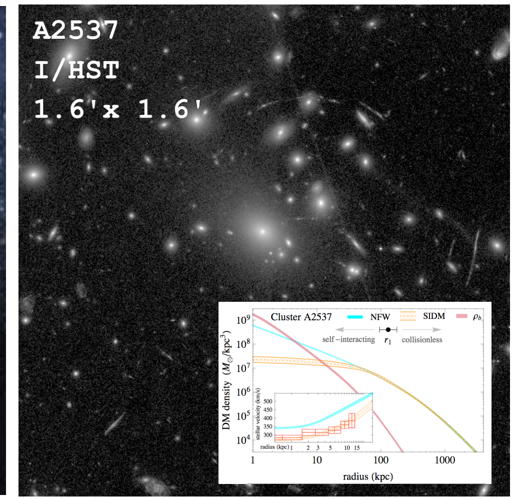
Spiral galaxies

Galaxy clusters









M_{halo}<~10^8 $M_\odot$

M_{halo}~10^8 $M_\odot$

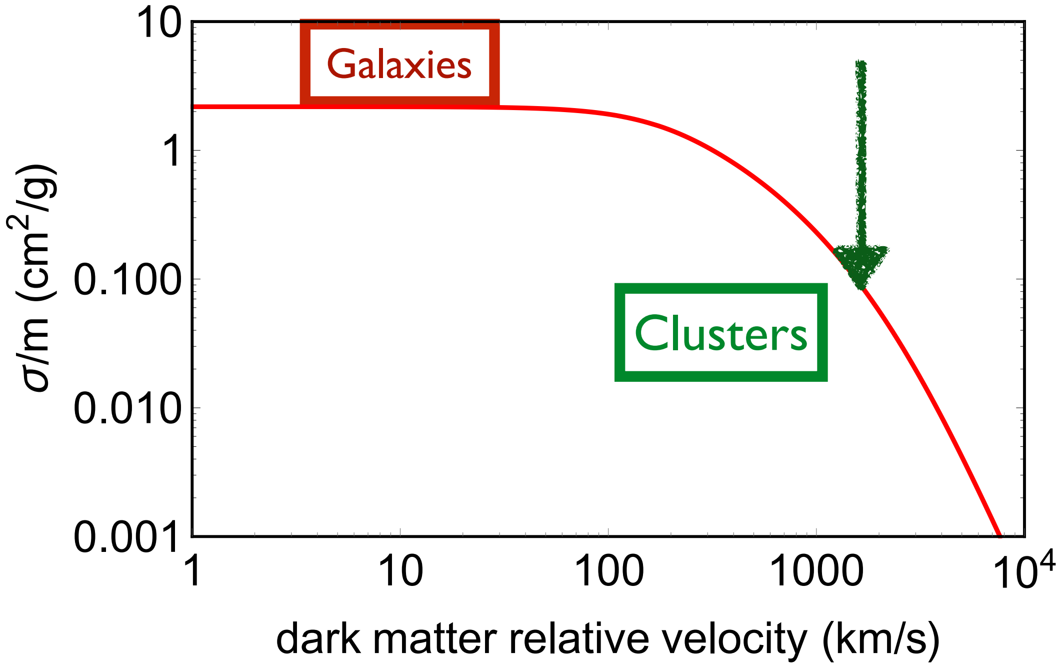
M_{halo}~10^9-10^{13} $M_\odot$

M_{halo}~10^{15} $M_\odot$

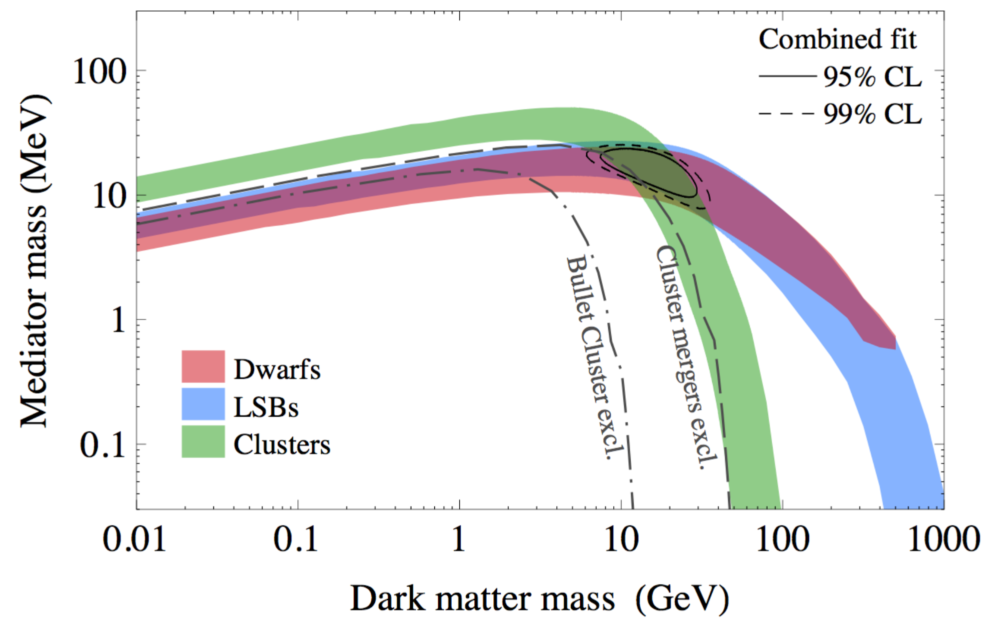
SIDM can explain diverse dark matter distributions over a wide range of galactic systems (halo masses ~10^8-10^{15} $M_\odot$)

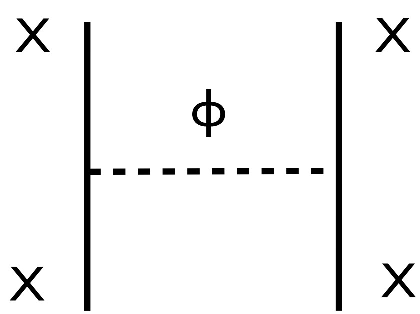
Particle Physics Models

Galaxies: $M_{halo} \sim 10^8$-10^{13} $M_\odot$



Galaxy clusters: $M_{halo} \sim 10^{14}$-10^{15} $M_\odot$





Dark halos as particle colliders

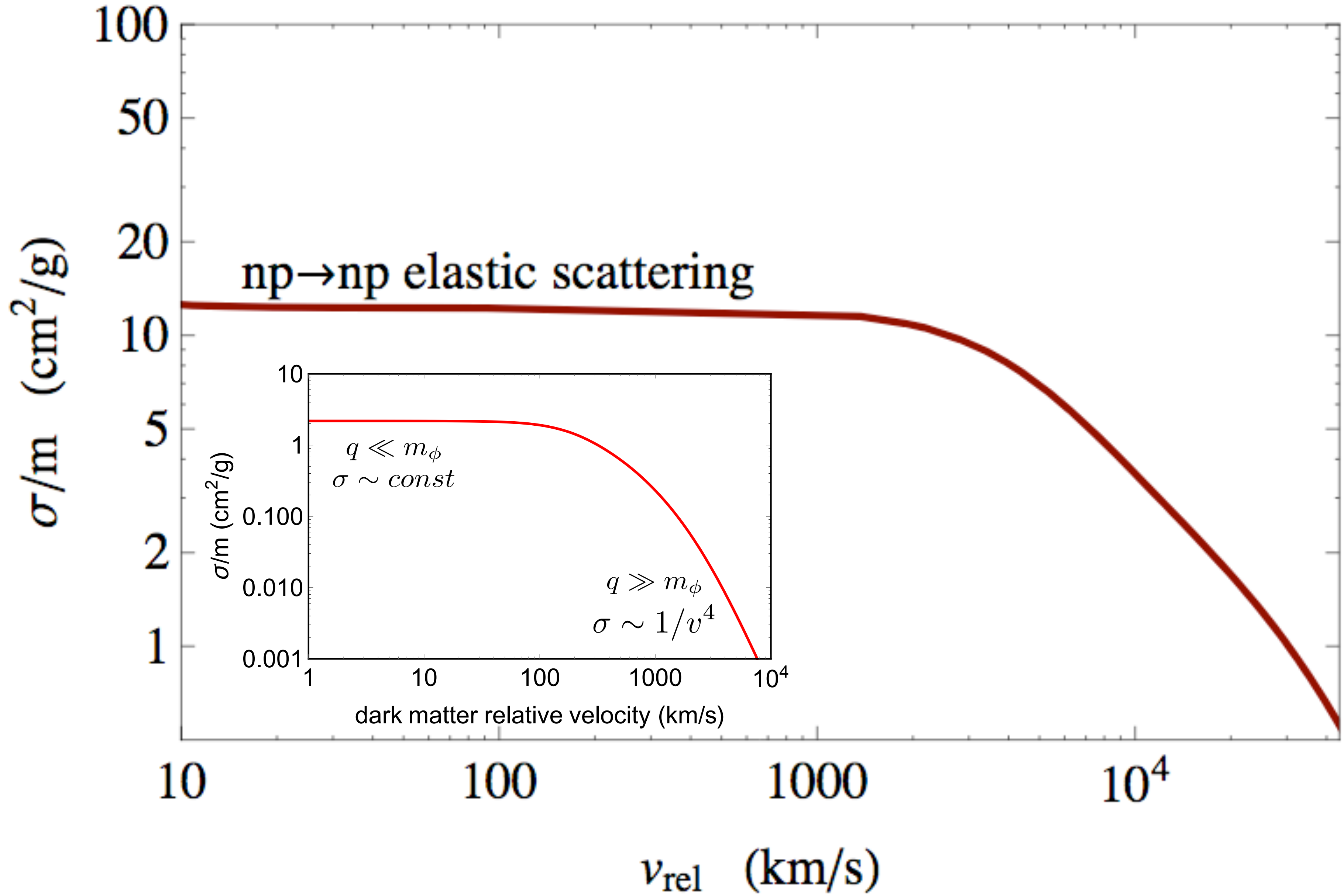
w/ Kaplinghat, Tulin (PRL 2015)

Fix $\alpha_X = 1/137$

Predict: $m_X \sim 15$ GeV, $m_\phi \sim 17$ MeV

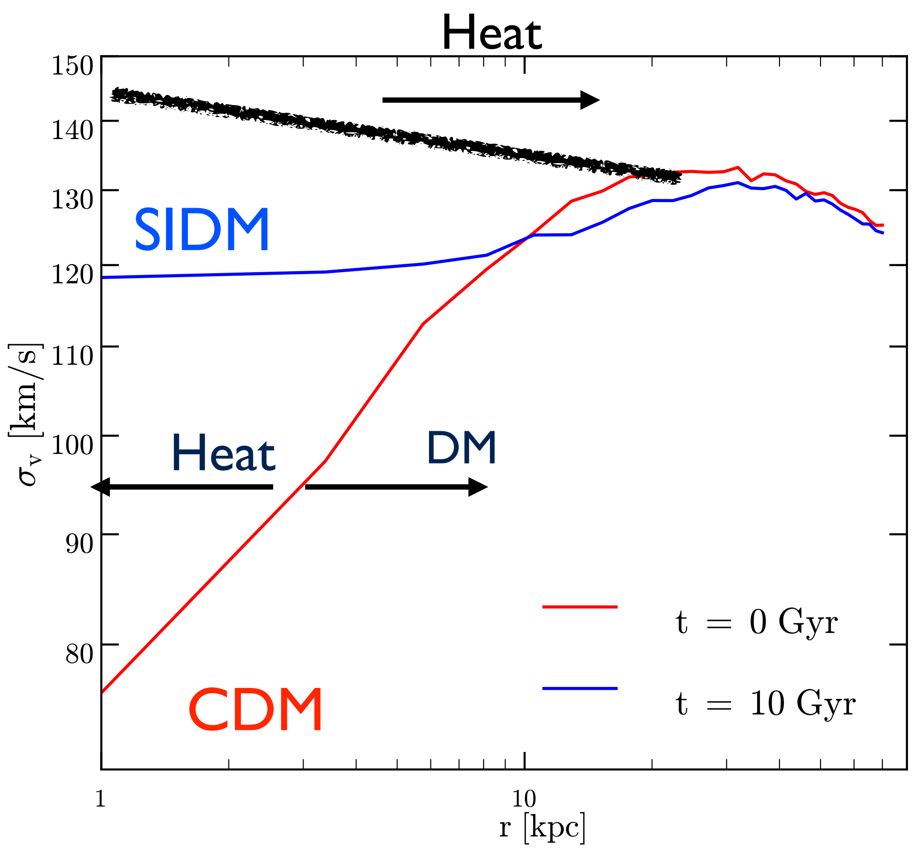
The nightmare scenario is not hopeless!

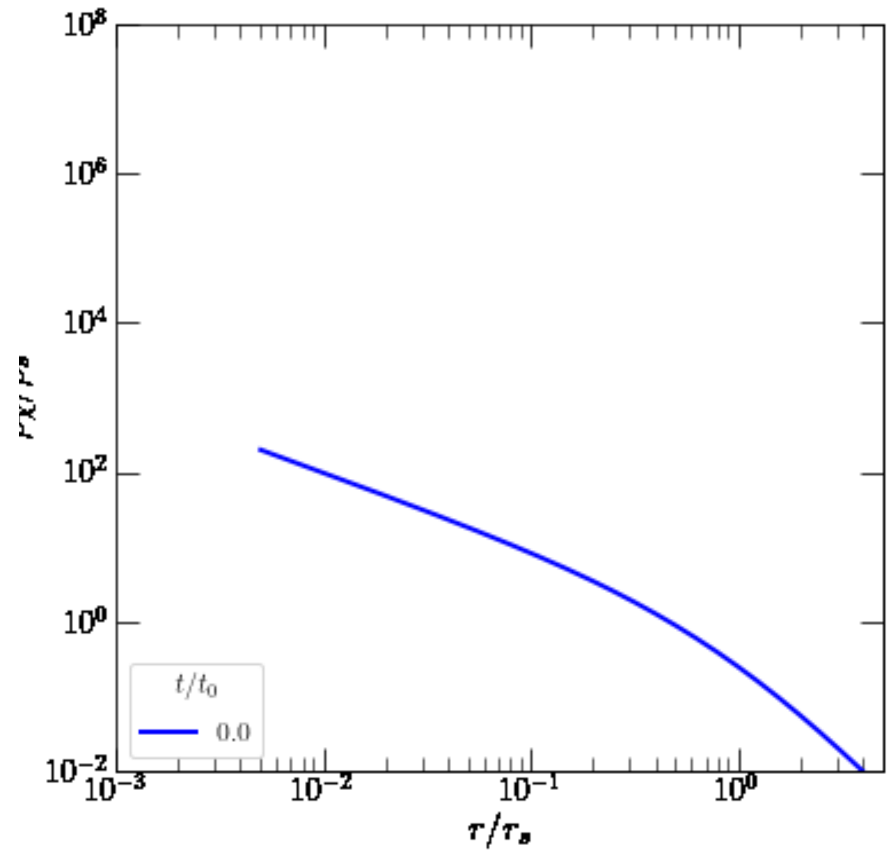
N-P vs. DM-DM Scatterings



Tulin, HBY (2017); data from Obloinsk+(2011)

Gravothermal Catastrophe





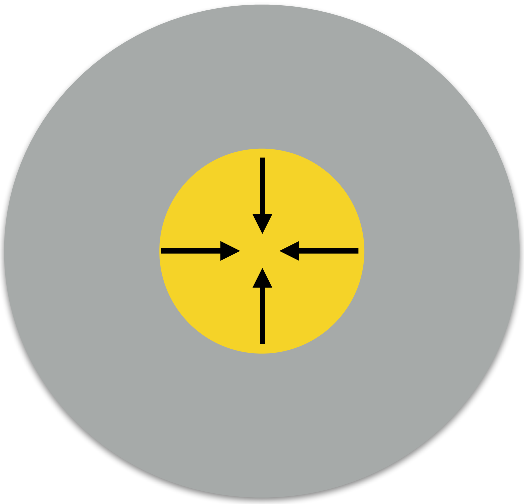
From Yi-Ming Zhong

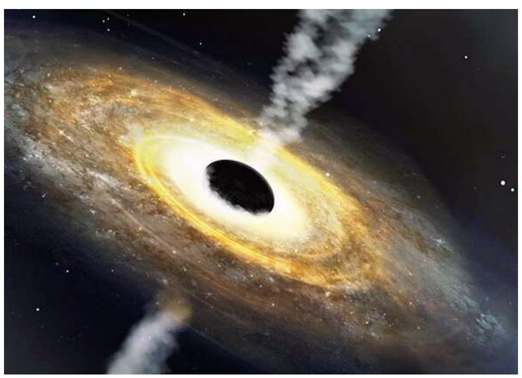
The first stage: heat comes in, DM goes out, core expansion

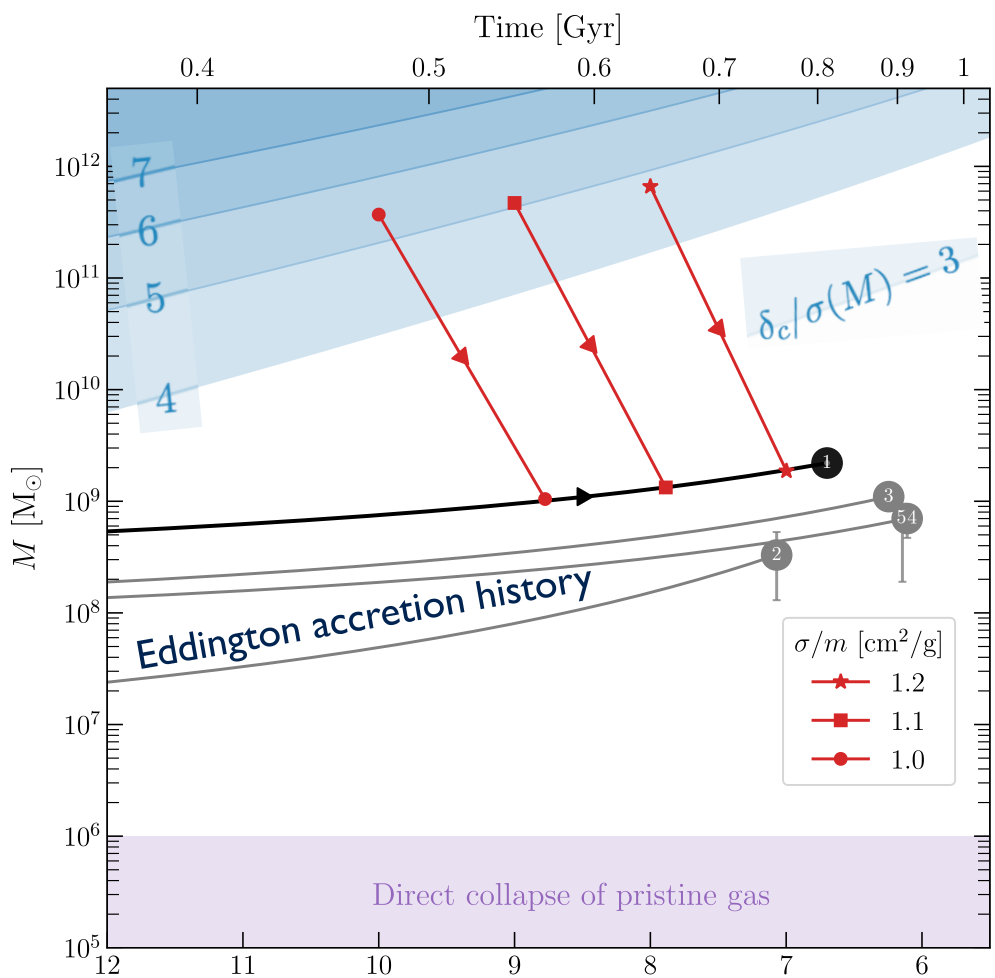
The second stage: heat goes out, DM comes in, core collapse

Balberg , Shapiro, Inagaki (APJ 2002), Balberg, Shaprio (PRL 2002), w/ Essig, McDermott, Zhong (PRL 2019)

Seeding Supermassive Black Holes







The most challenging one, J1205-0000

Mass 2.2×10^9 $M_\odot$

z=6.7

f_{Edd}=0.16

Onoue et al. (2019)

~800 Myr after the Big Bang

w/ Feng, Zhong (2020)

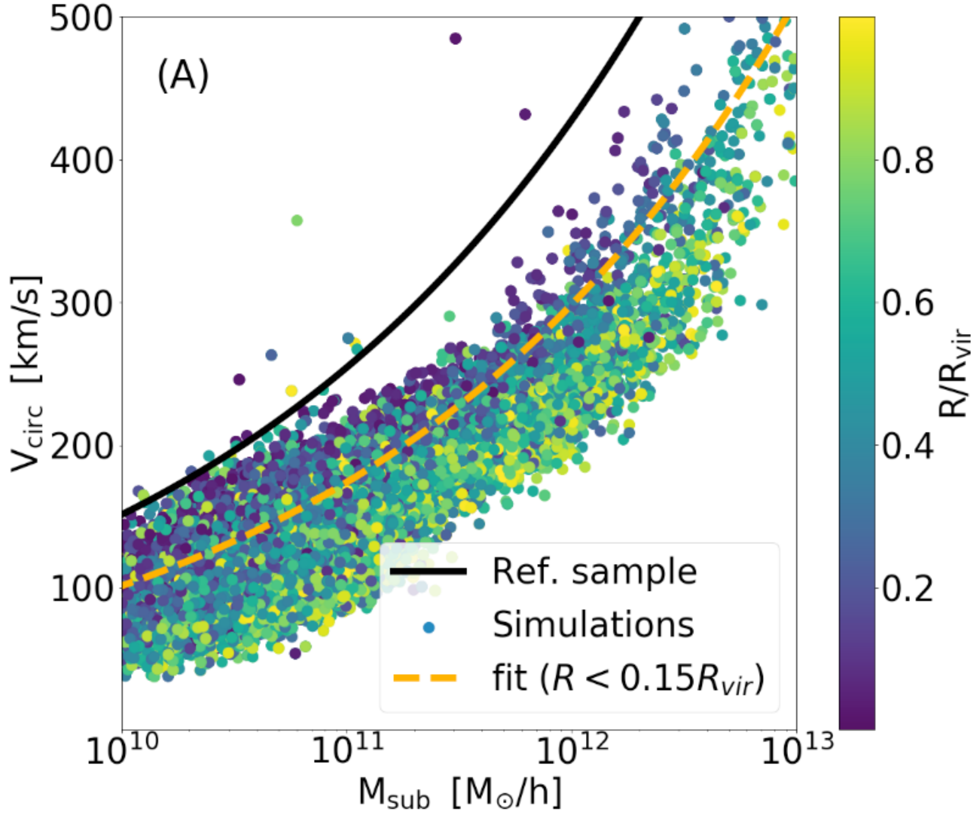
The predicted self-scattering cross section is broadly consistent with the one used to explain diverse dark matter distributions in galaxies

REPORT

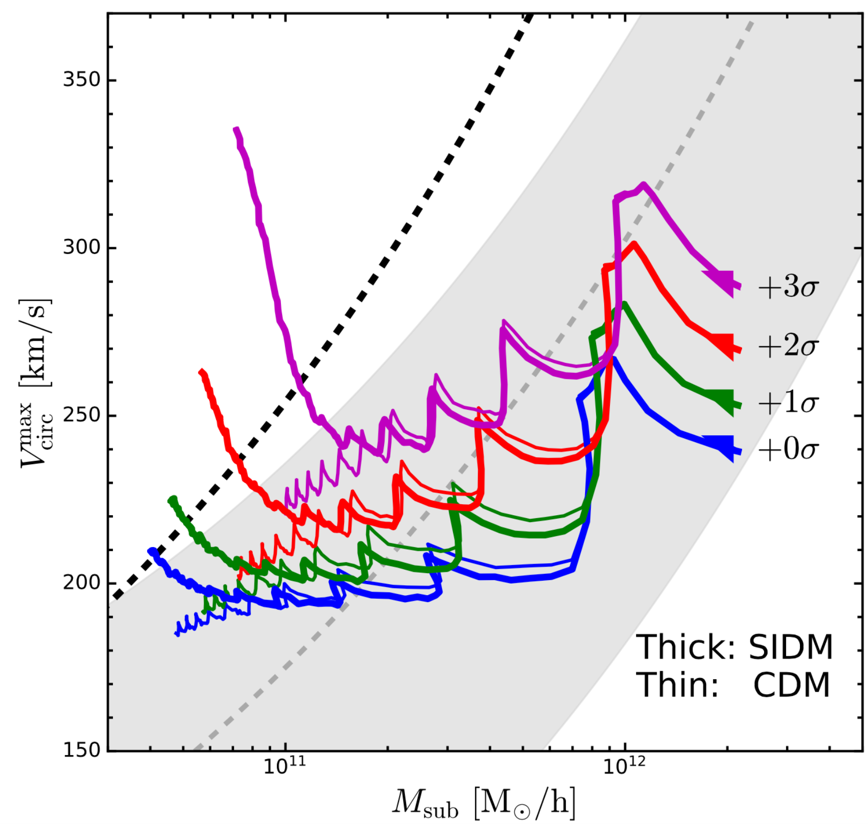
An excess of small-scale gravitational lenses observed in galaxy clusters

Science 11 Sep 2020:
Vol. 369, Issue 6509, pp. 1347-1351
DOI: 10.1126/science.aax5164

Massimo Meneghetti[1,2,3,*], Guido Davoli[1,4], Pietro Bergamini[1], Piero Rosati[5,1], Priyamvada Natarajan[6], Ca...



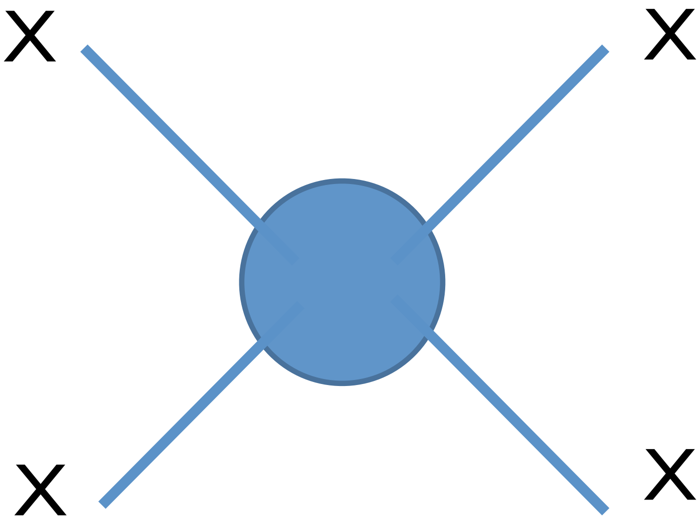
Meneghetti+(2020)



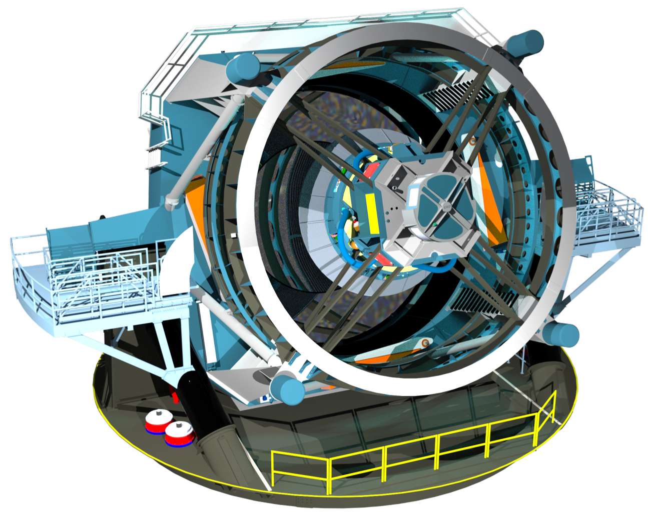
w/ Yang (to appear)

We may have already seen "gravothermal collapse" of SIDM halos!

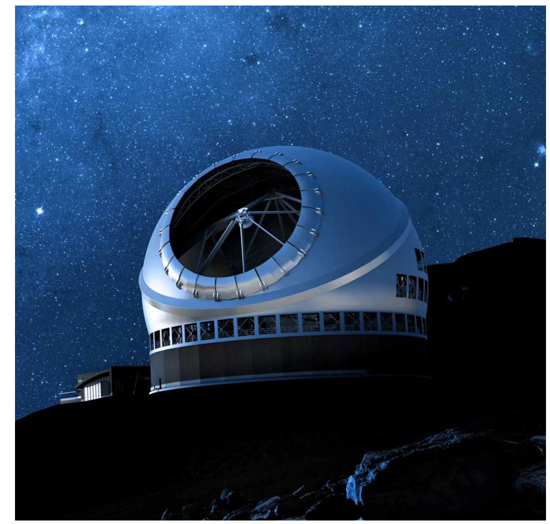
Conclusions & Outlook



Strong hints/evidence

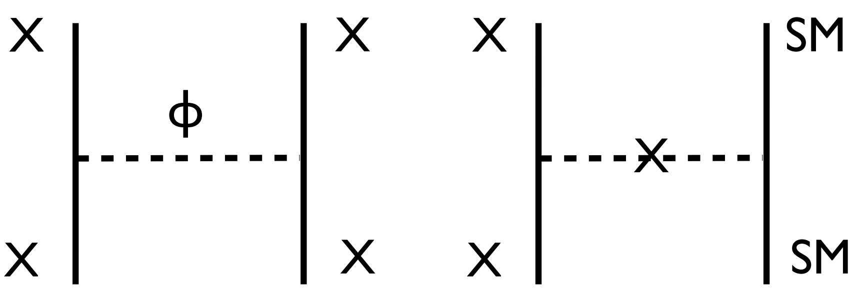


Vera C. Rubin Observatory



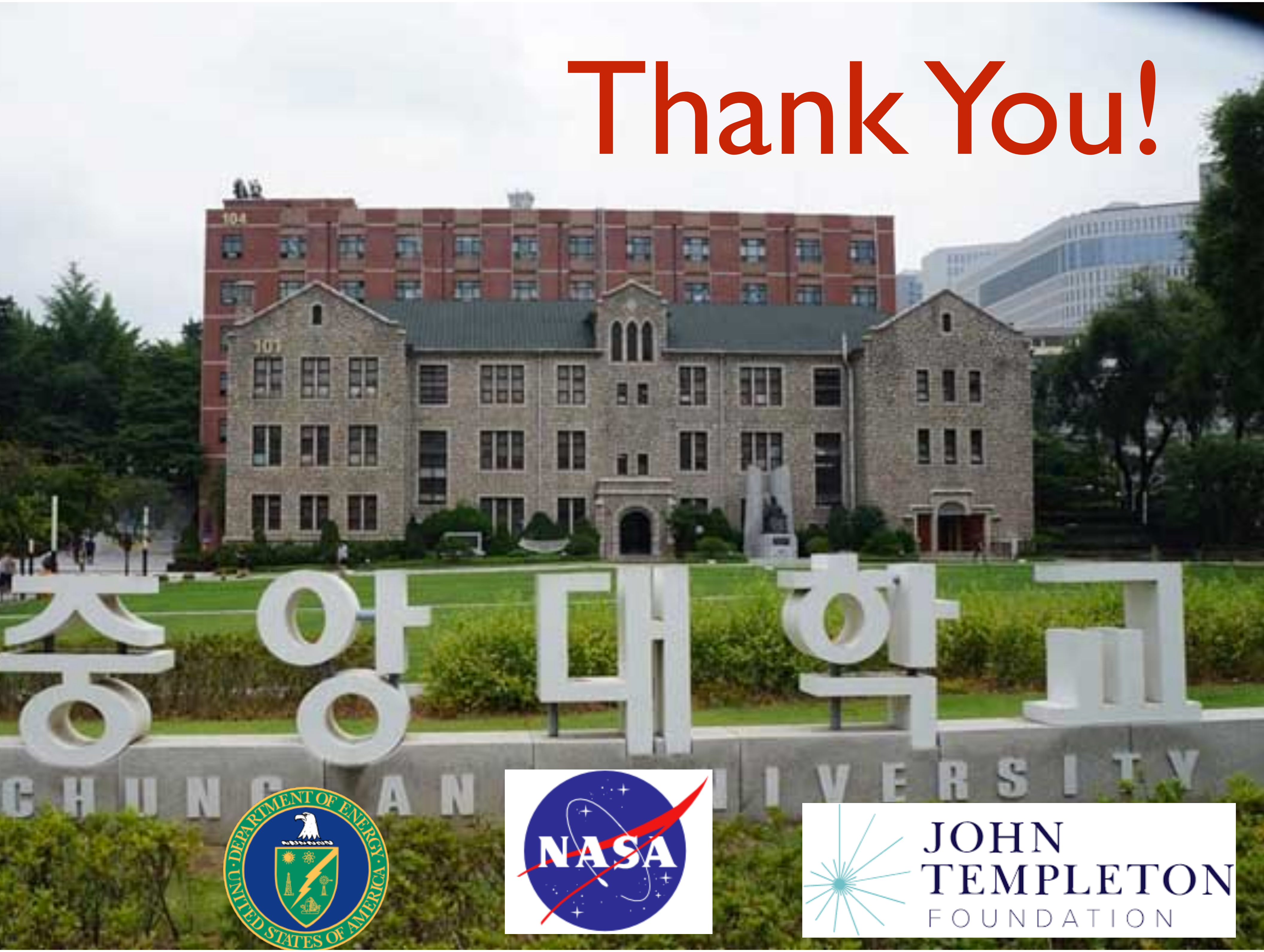
Thirty Meter Telescope

- SIDM predicts rich phenomenology



light dark sectors (MeV-GeV)
resonant regimes

Thank You!



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