Dark Matter and Its Interactions

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UCR PHYSICS & ASTRONOMY

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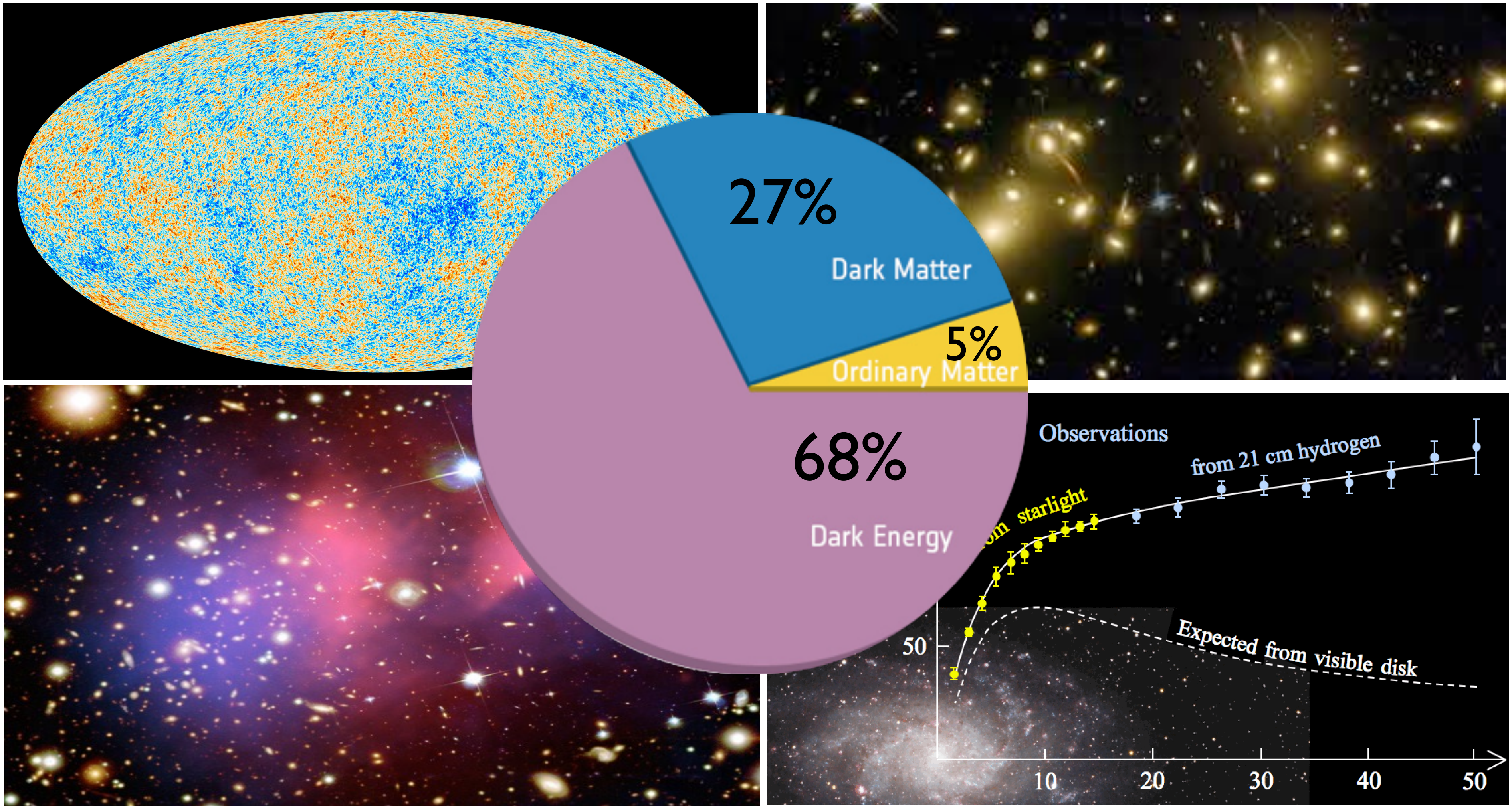
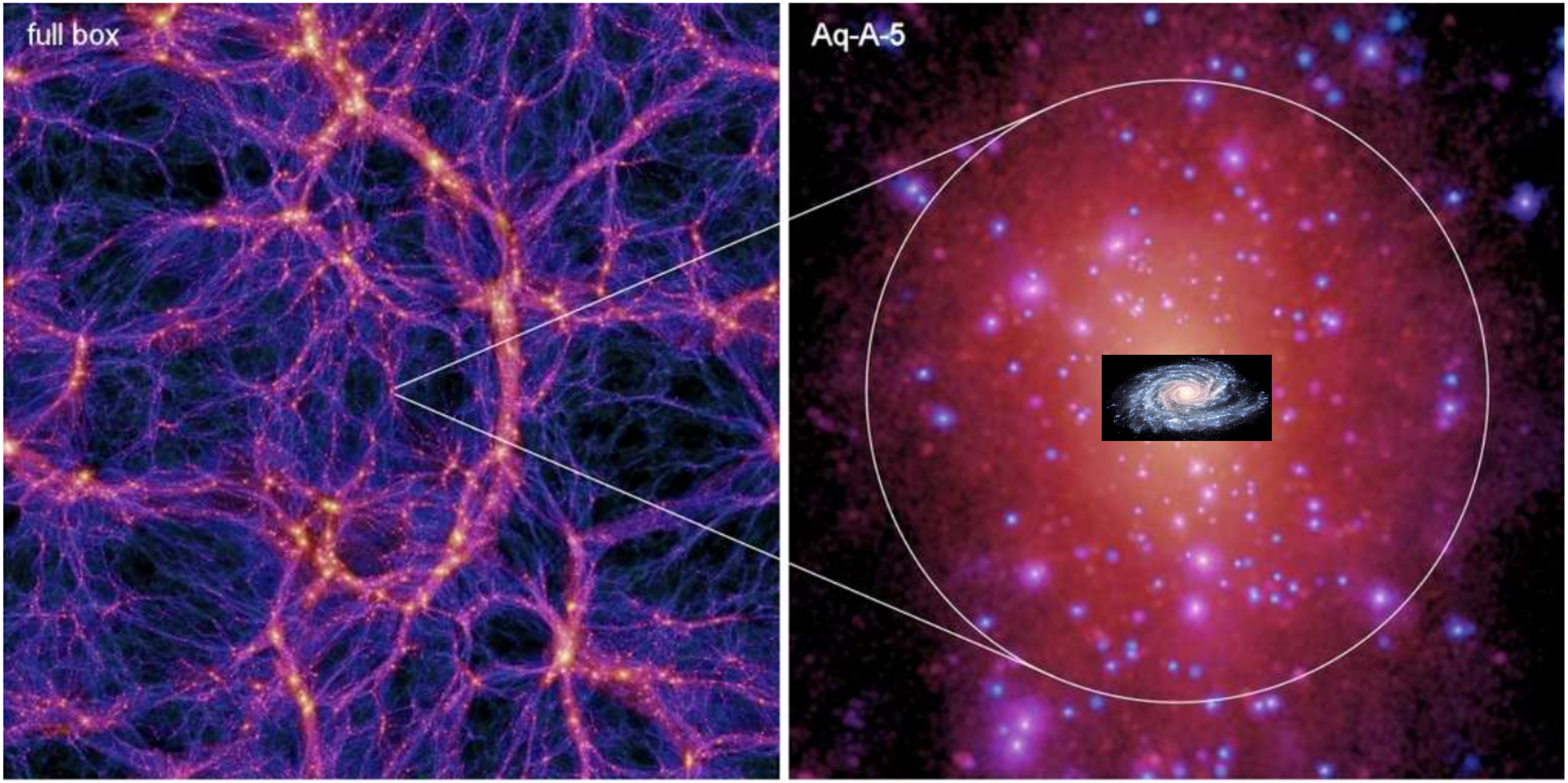
Dark Matter


27%
Dark Matter
5%
Ordinary Matter
68%
Dark Energy
Observations
from 21 cm hydrogen
starlight
Expected from visible disk
50
10
20
30
40
50

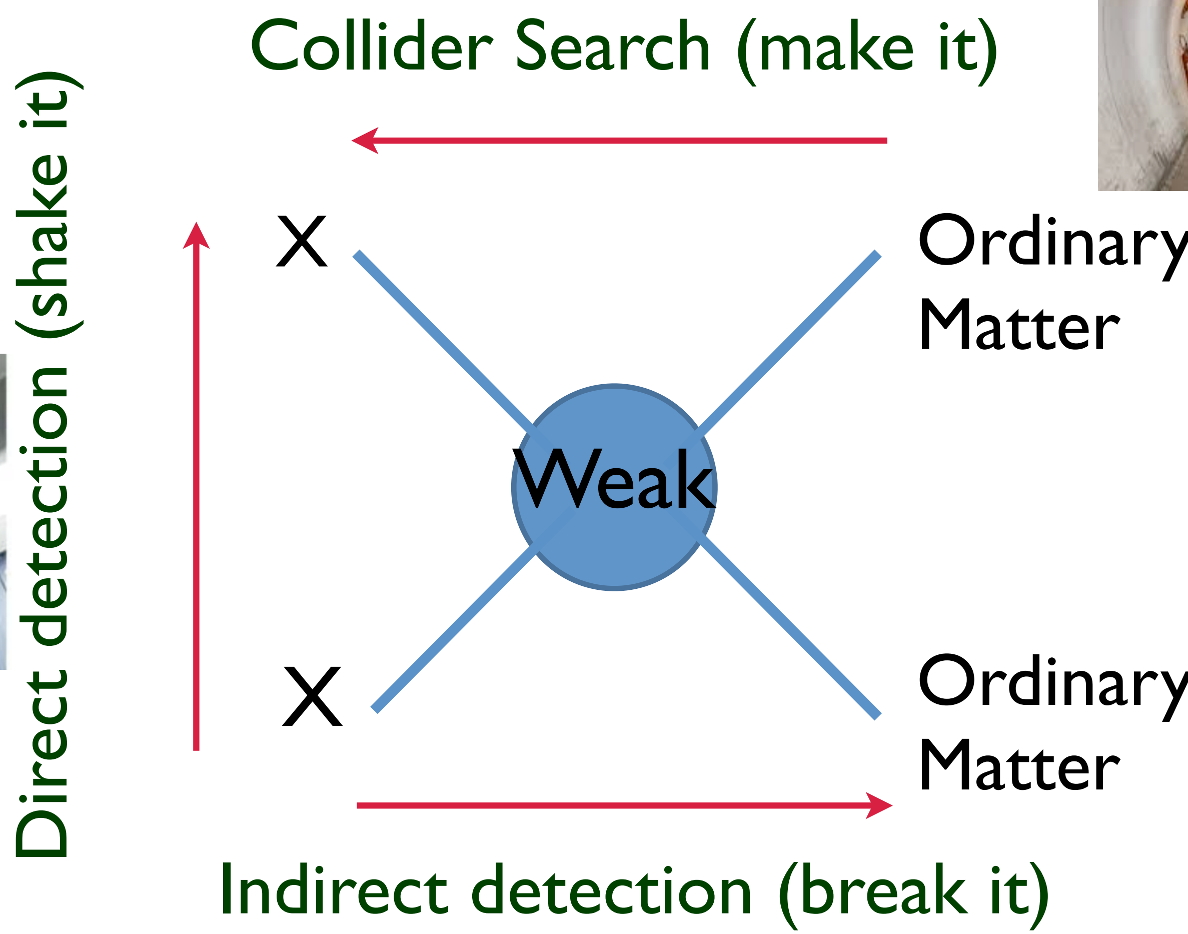
Dark Matter Halos: Hosting Galaxies

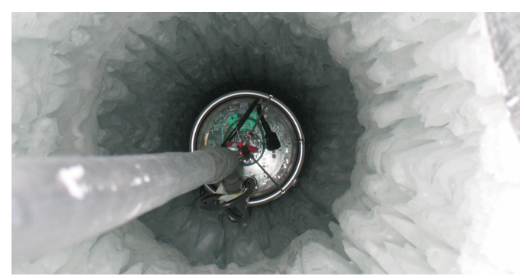


Aquarius Project, Springel+(2008)

Dark matter is critical for understanding structure formation of the universe

Hunting For WIMPs





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.

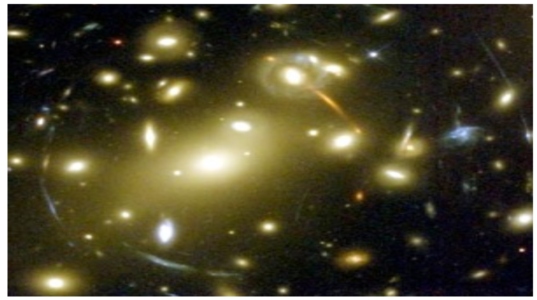
A Song of Immortal Regret, Bai Juyi (772-846)

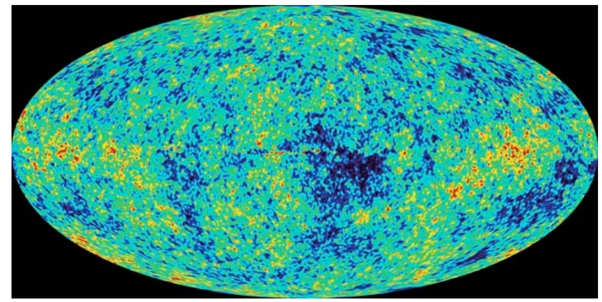
A Critical Rethinking

- Dark matter is light, below a few GeV, hidden from terrestrial searches
- How can we determine the particle nature of dark matter from astrophysical observations?
- The nightmare scenario: dark matter does not interact with the standard model particles, aside from gravity?

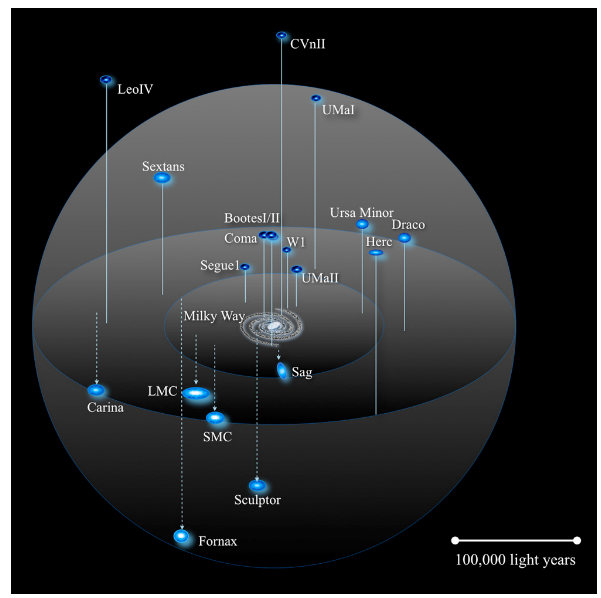
Cold Dark Matter (CDM)

- Large scales: very well

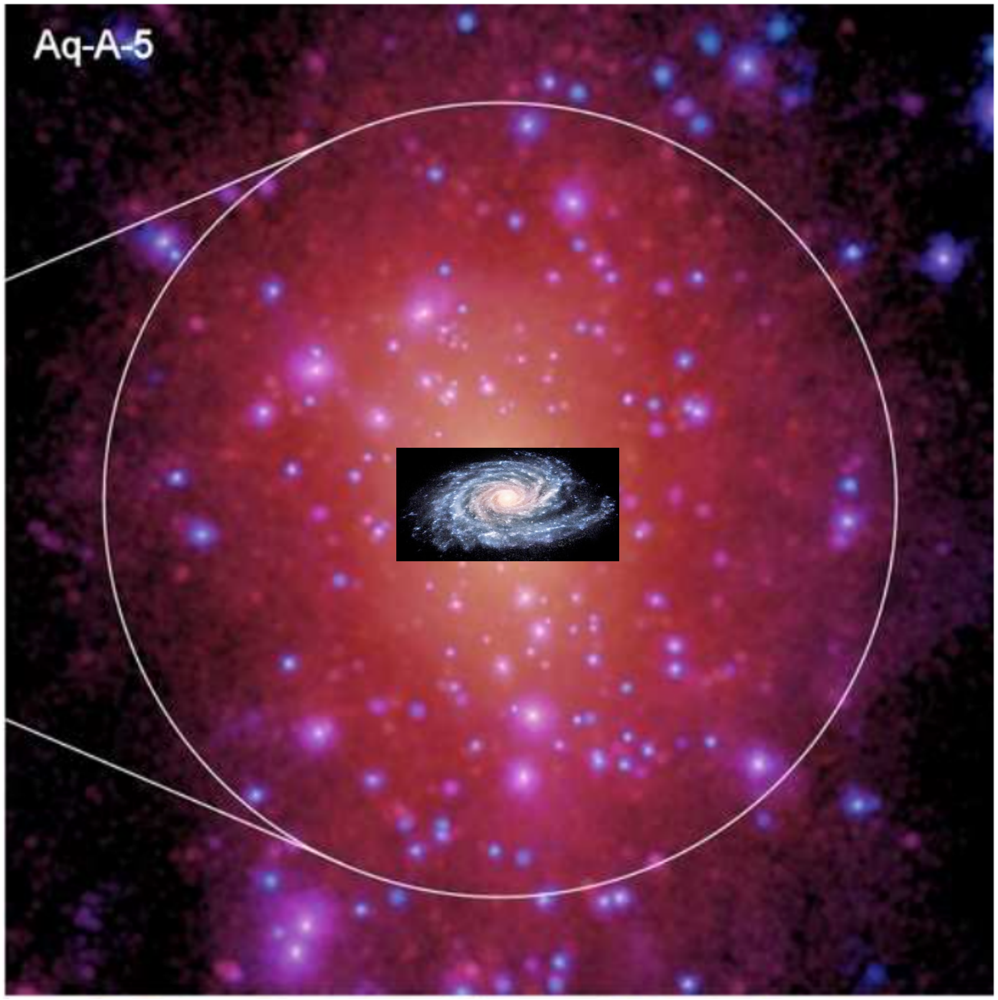




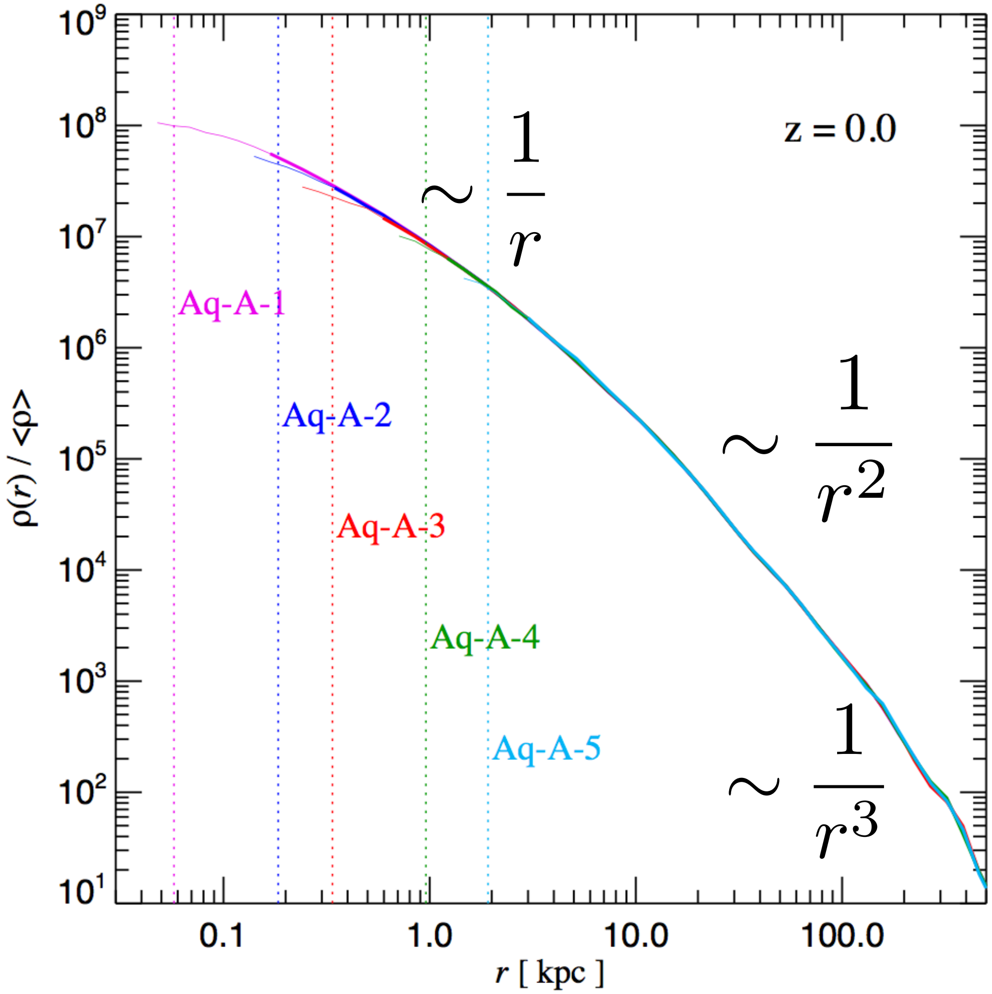
- Small scales (dwarf galaxies, sub-halos, galaxy clusters)
  - Core vs Cusp
  - Diversity
  - Too Big To Fail
  - “Cores” in clusters
  - Ultra diffuse galaxies



CDM: Universal Density Profile



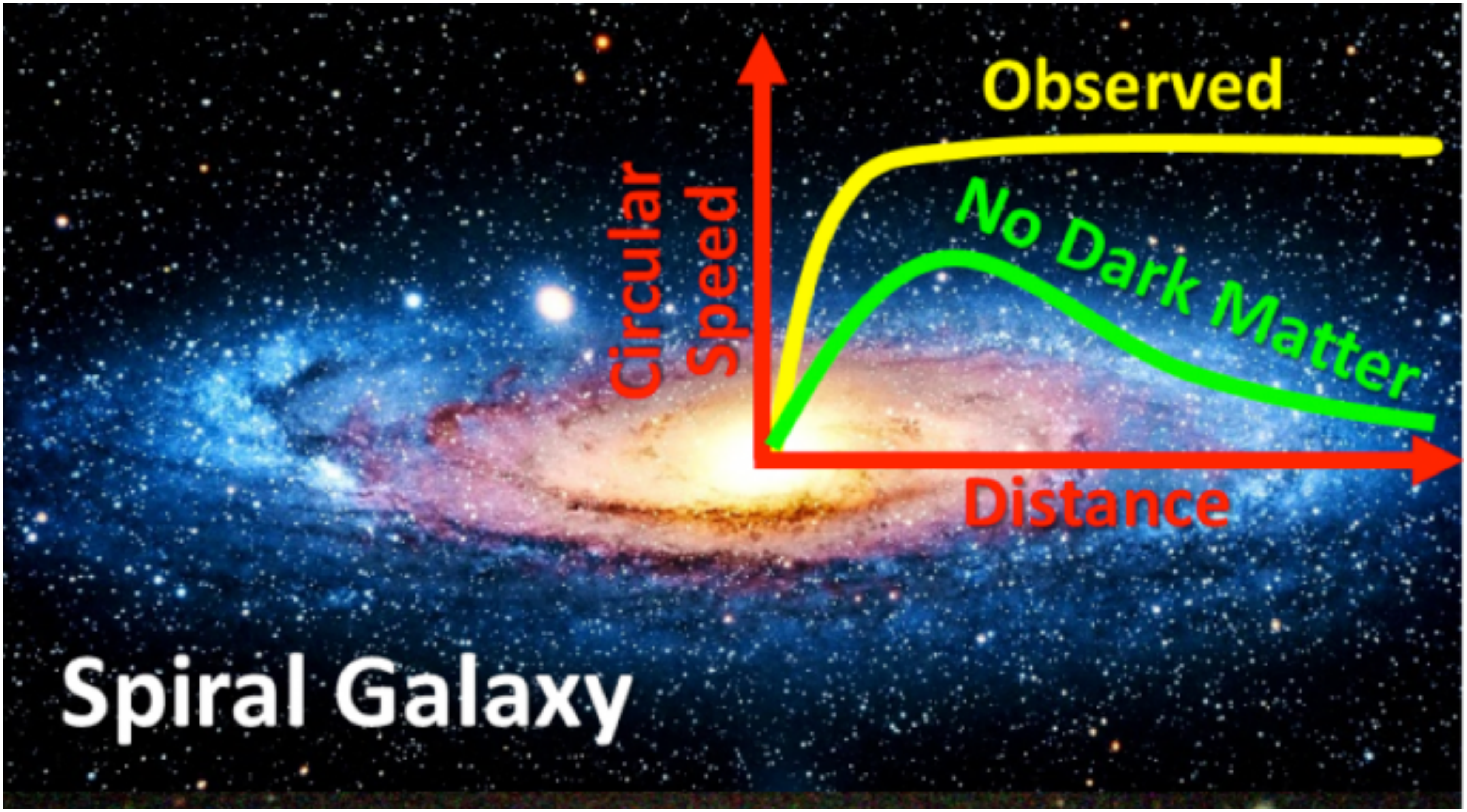
Aquarius Project, Springel+ (2008)



$$\frac{\rho_s}{r/r_s(1 + r/r_s)^2}$$

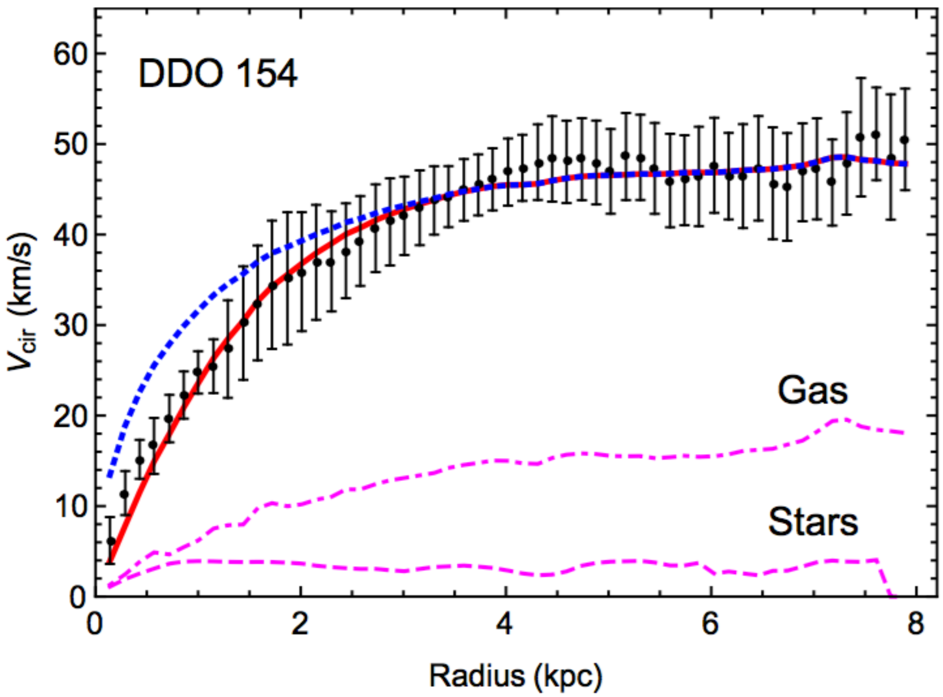
the Navarro-Frenk-White (NFW) profile (1996)

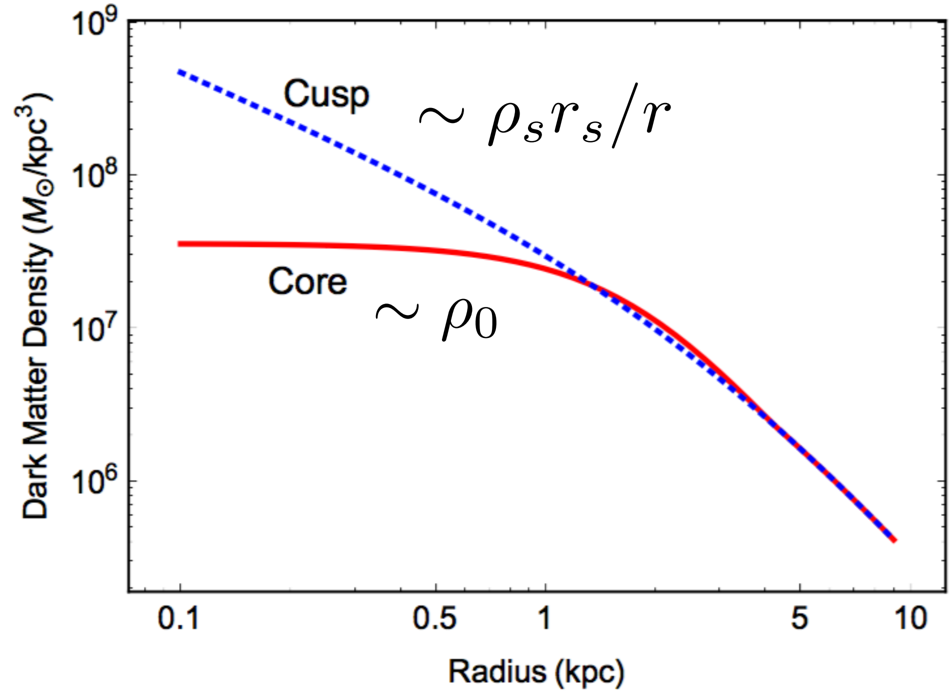
Testing Ground



Core vs Cusp Problem

- DM-dominated systems (dwarfs, LSBs)





$$V_{\rm circ}(r) = \sqrt{V_{\rm halo}(r)^2 + \Upsilon_* V_{\rm star}(r)^2 + V_{\rm gas}(r)^2}$$

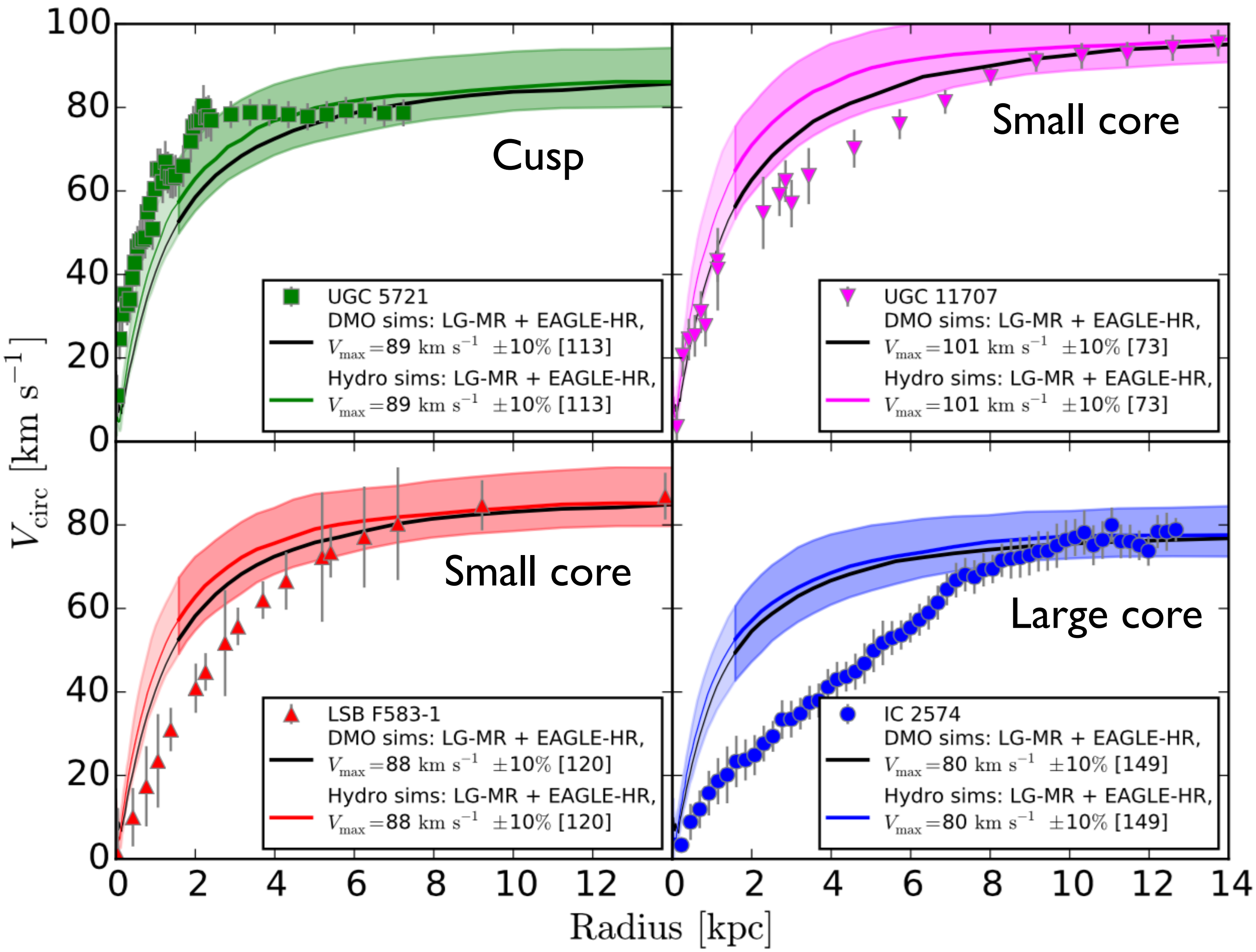
mass-to-light ratio

$$\frac{\rho_s}{r/r_s(1+r/r_s)^2}$$

NFW (1996)

Flores & Primack (1994); Moore (1994); de Blok & McGaugh (1997)…

The Diversity Problem



All galaxies have the same observed Vmax!

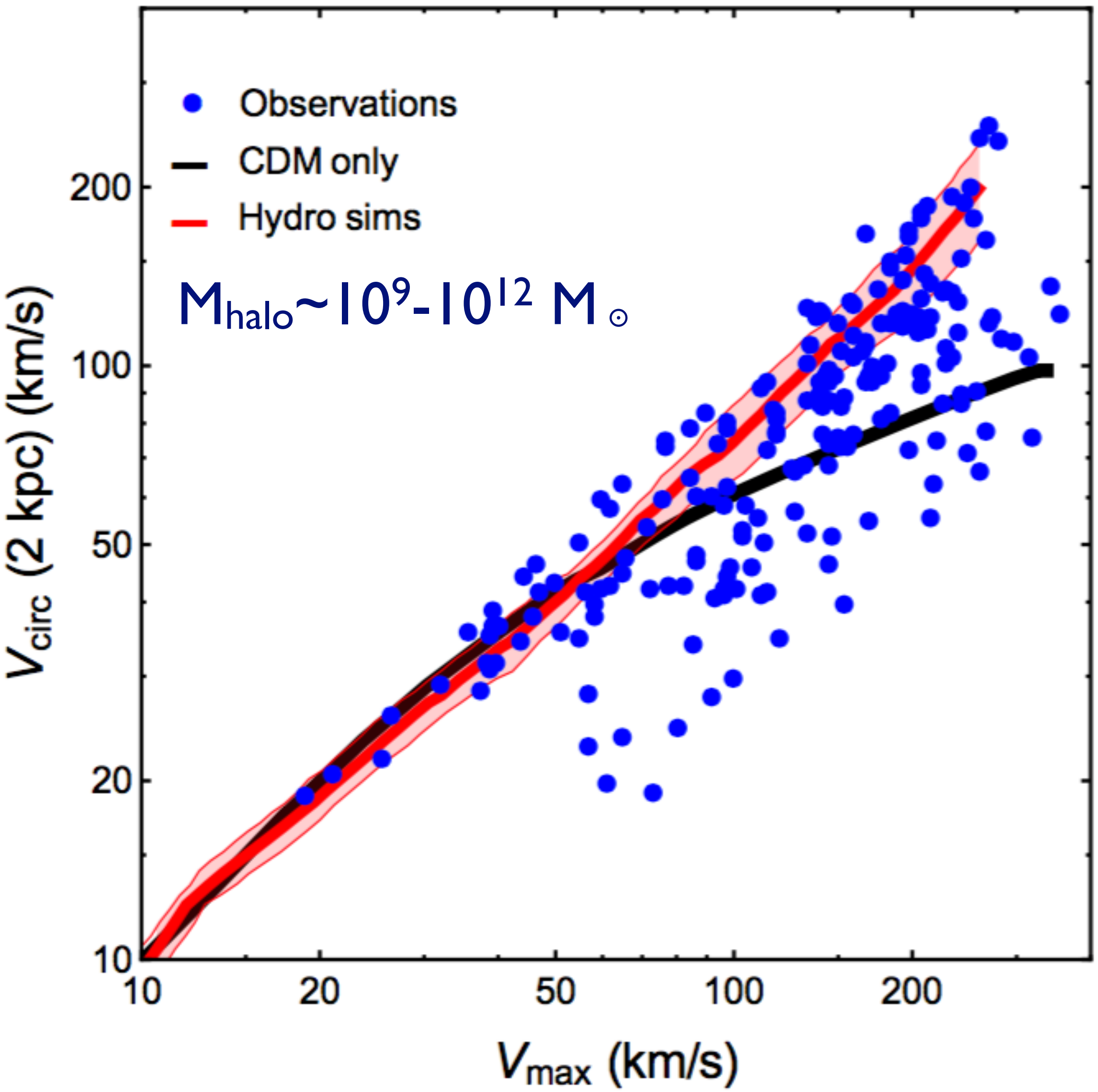
$$V \sim \sqrt{GM/r}$$

Colored bands: hydrodynamical simulations of CDM

Oman+(2015)

Dark matter distributions are diverse in spiral galaxies

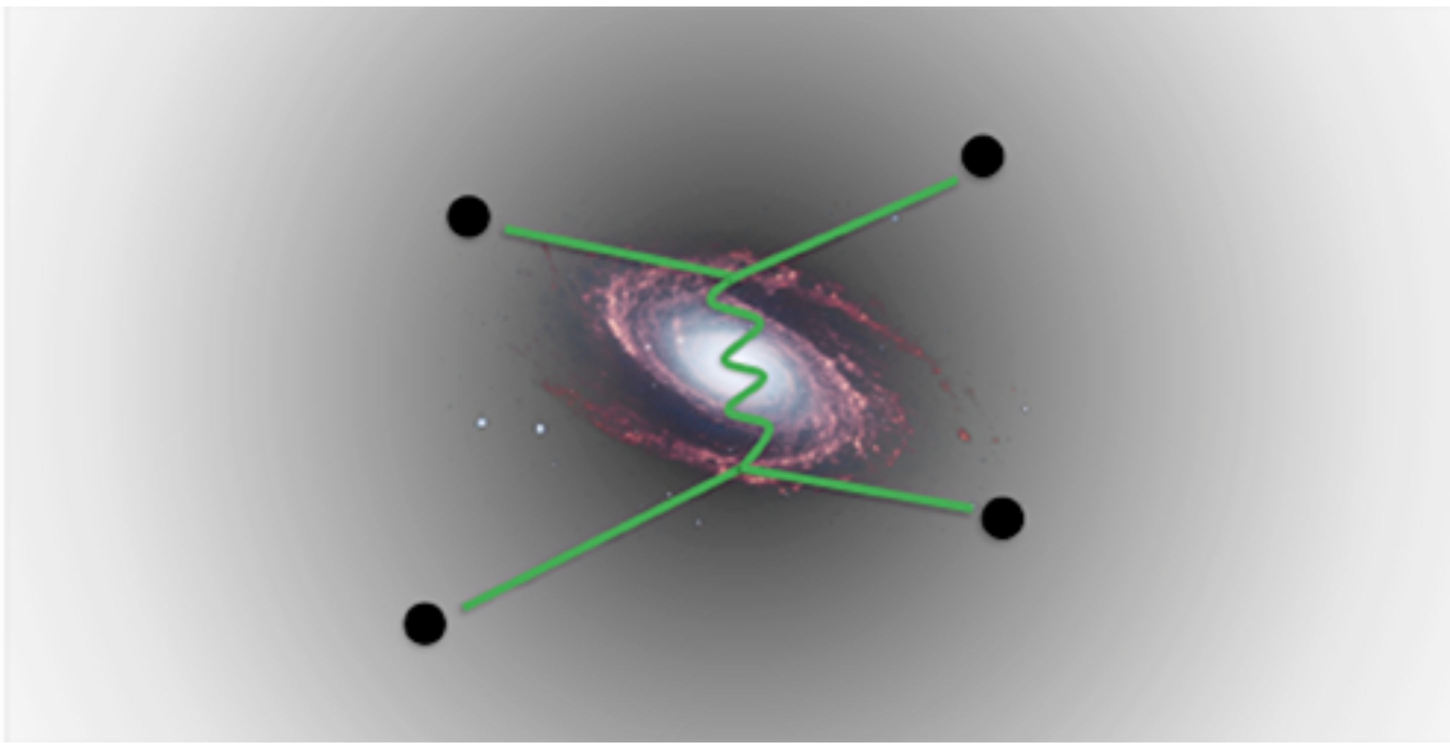
A Big Challenge



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

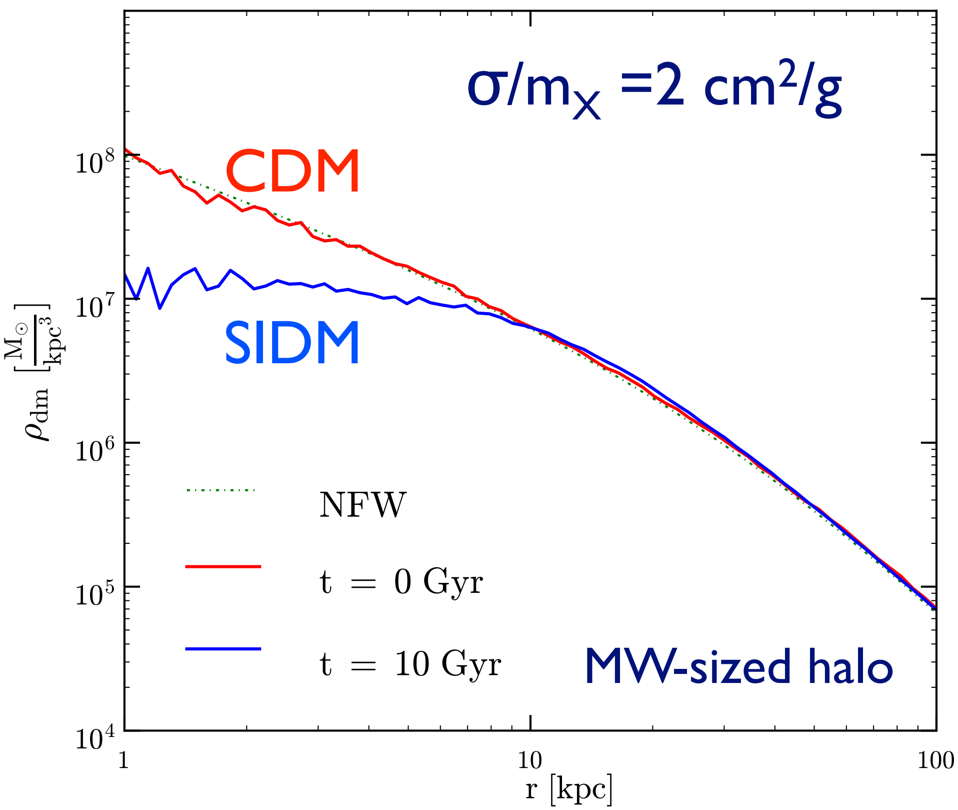
Reproduced from the data compiled in Oman+(2015)

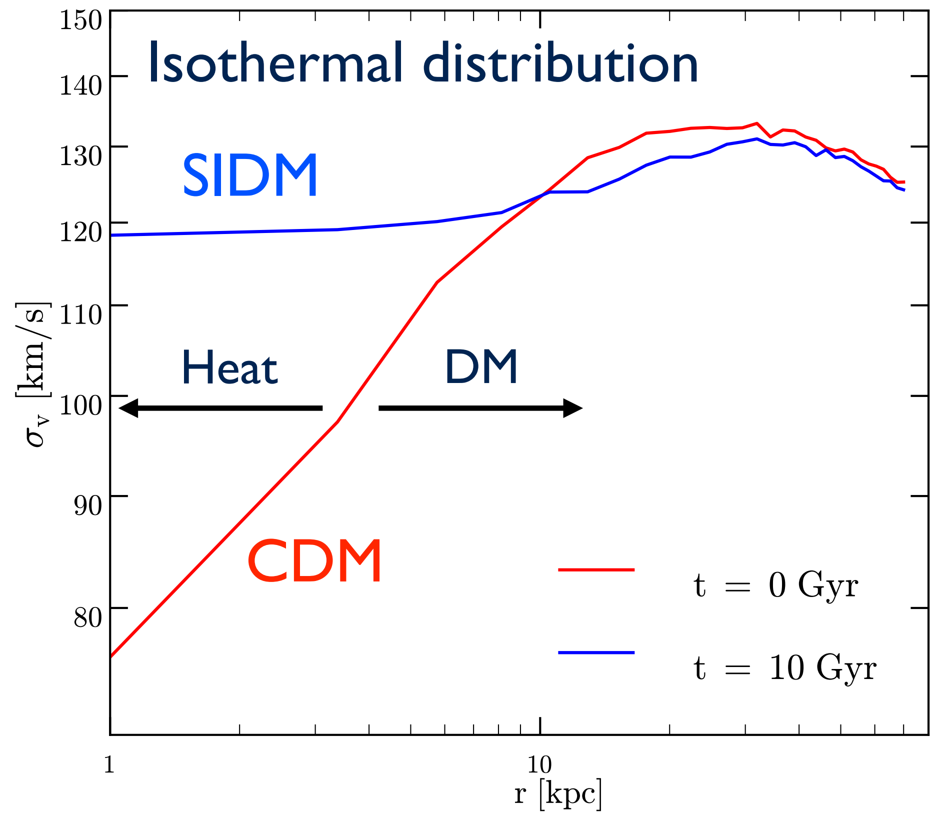
The diversity can be explained if dark matter has strong self-interactions



Self-Interacting Dark Matter

- Self-interactions thermalize the inner halo





σ/m_X ~1 cm^2/g (nuclear scale)

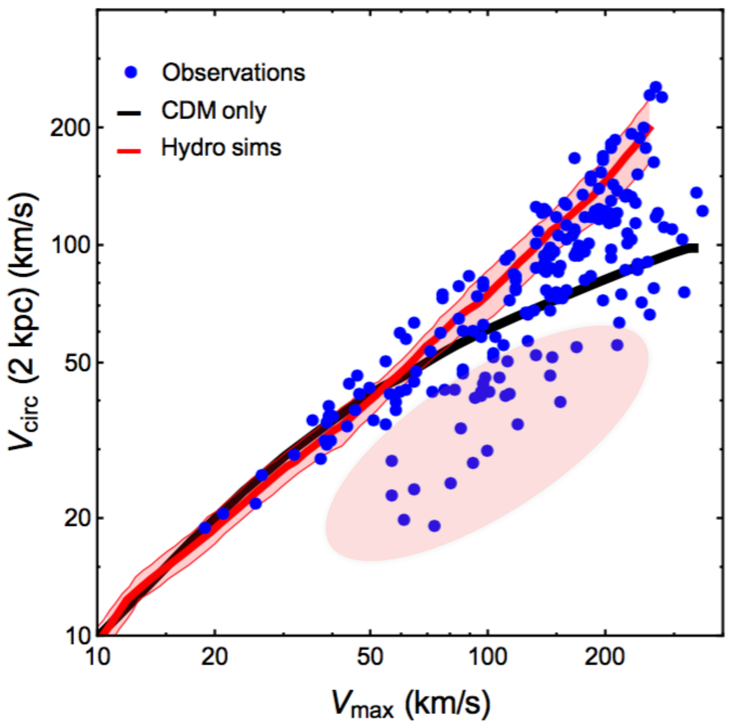
From Ran Huo

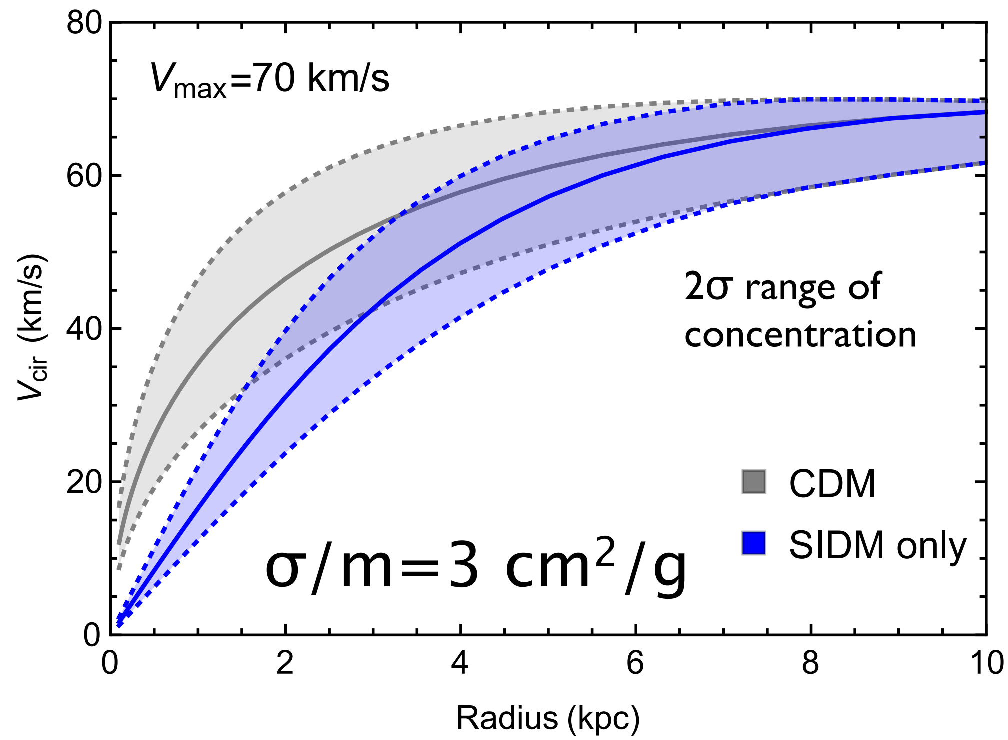
$$\Gamma \simeq n\sigma v = (\rho/m_X)\sigma v \sim H_0$$

Review: w/ Tulin (Physics Reports 2017)

Low Surface Brightness Galaxies

- DM self-interactions thermalize the inner halo





w/ Kamada, Kaplinghat, Pace (PRL 2017)

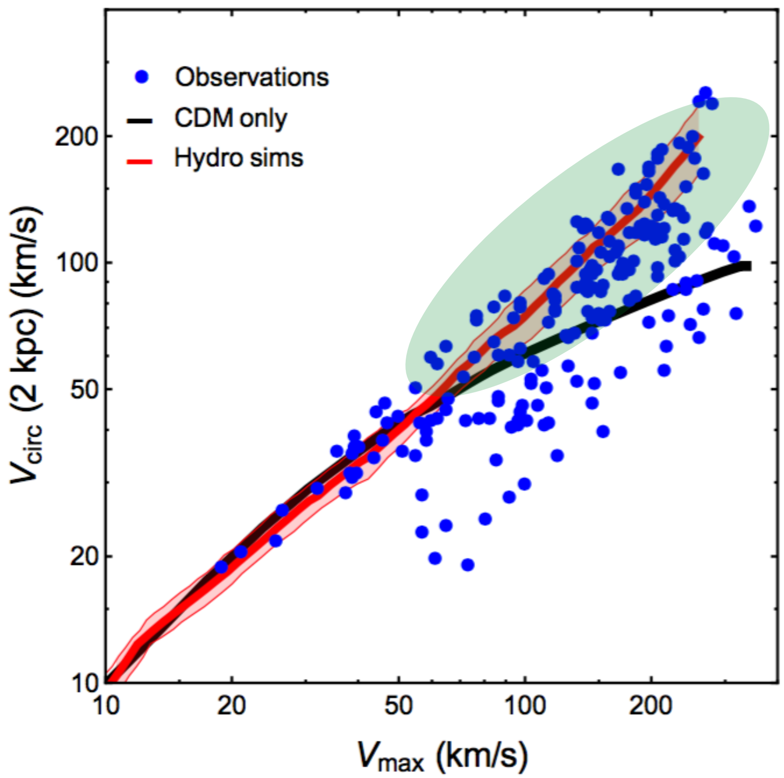
DM-dominated galaxies: Lower the central density and the circular velocity

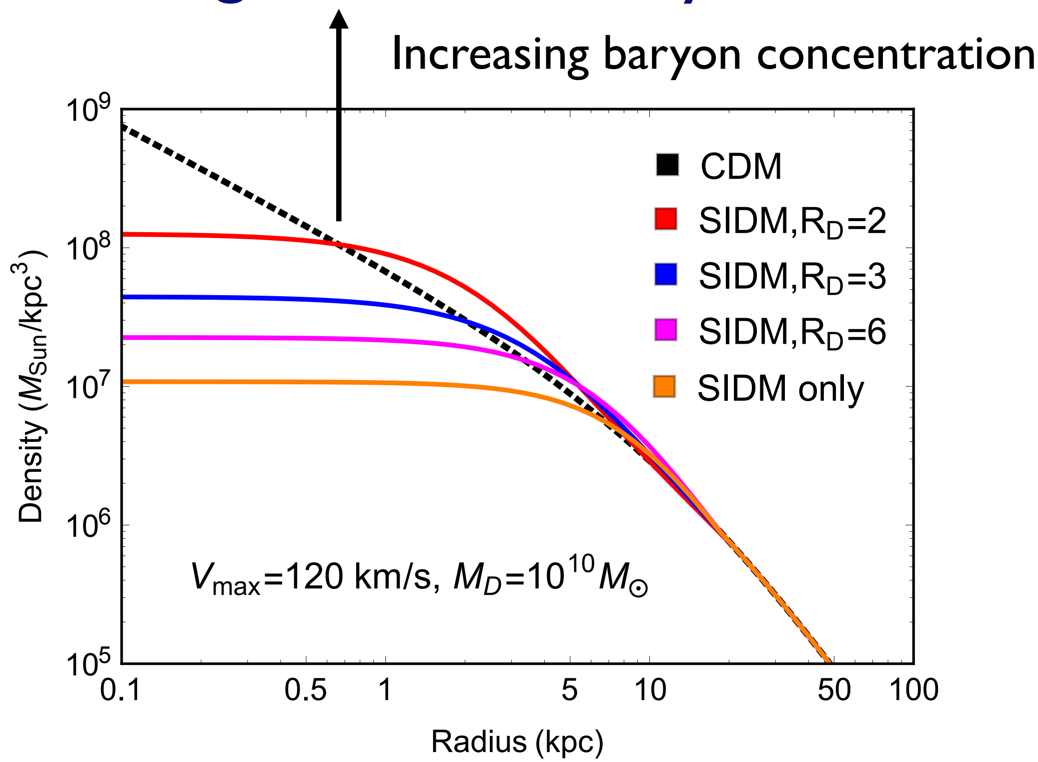
Isothermal distribution

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

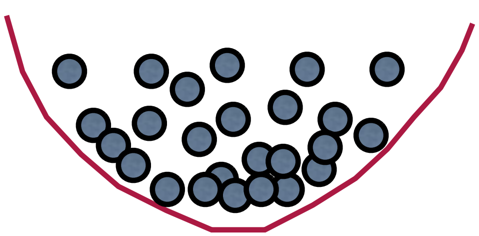
High Surface Brightness Galaxies

- DM self-interactions tie DM together with baryons





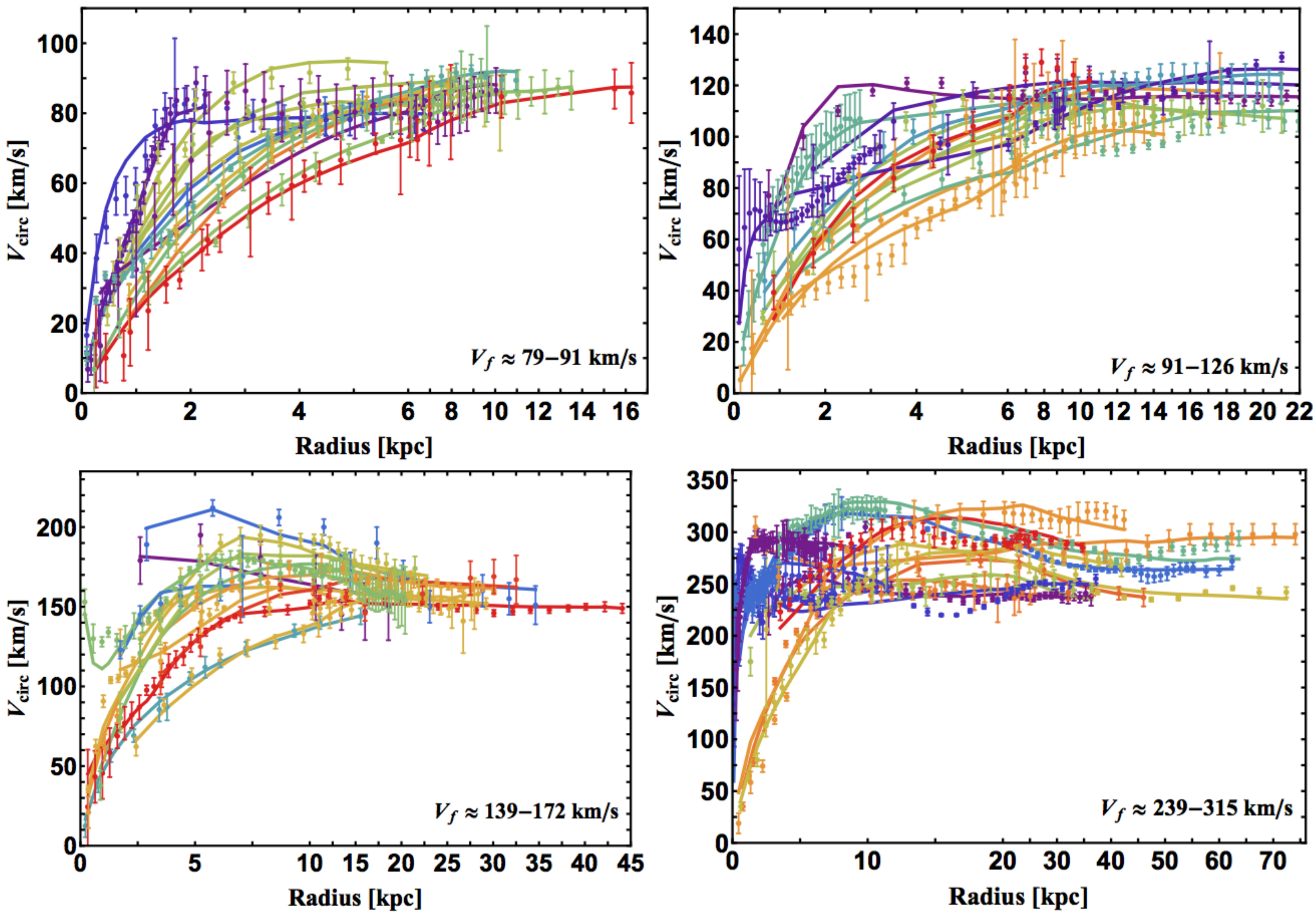
Thermalization leads to higher DM density due to the baryonic influence



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

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 analyzed 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

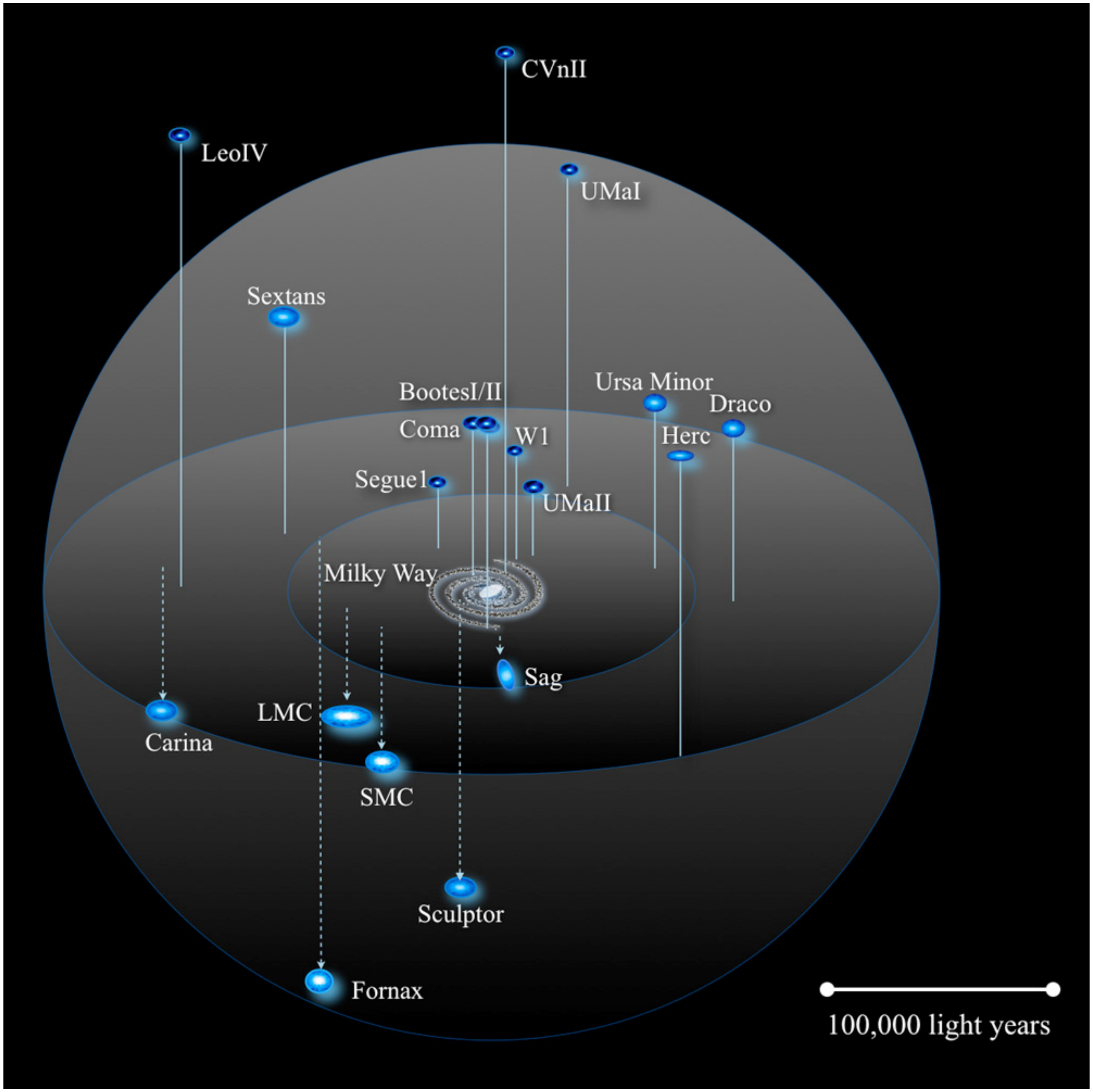
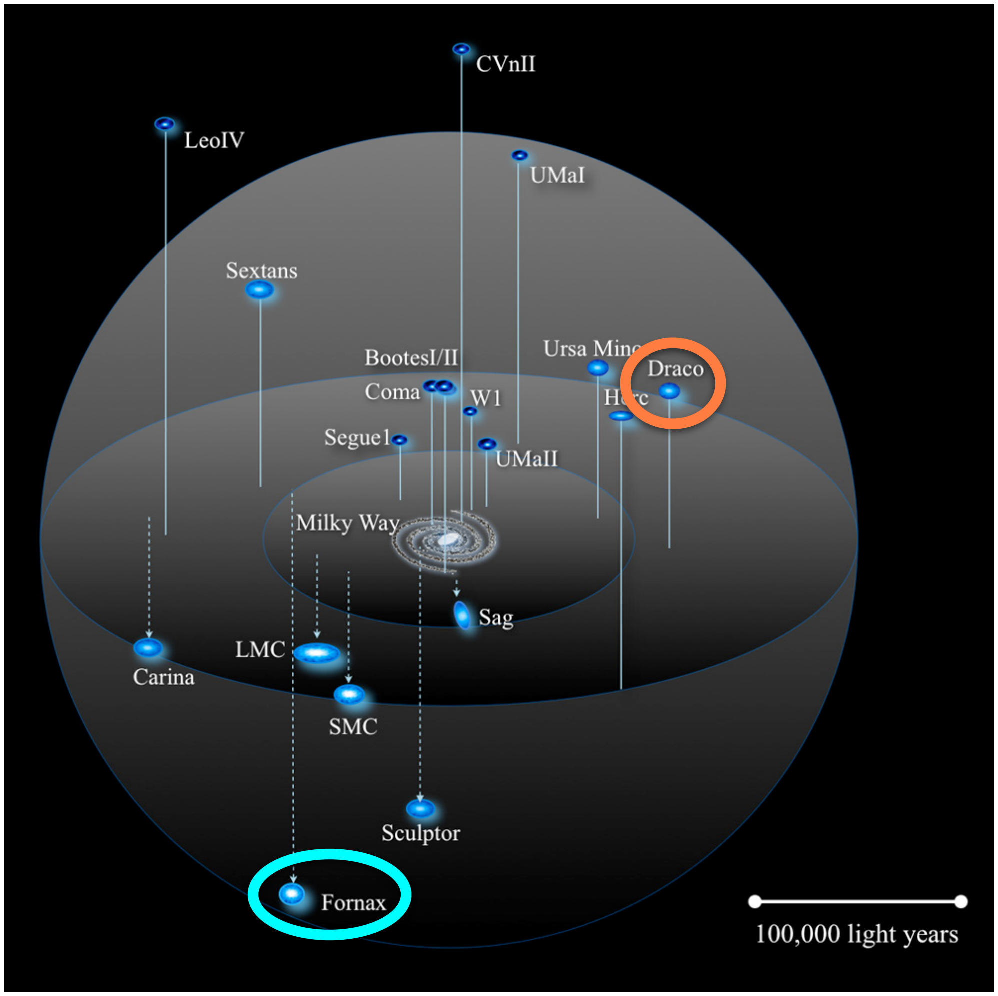
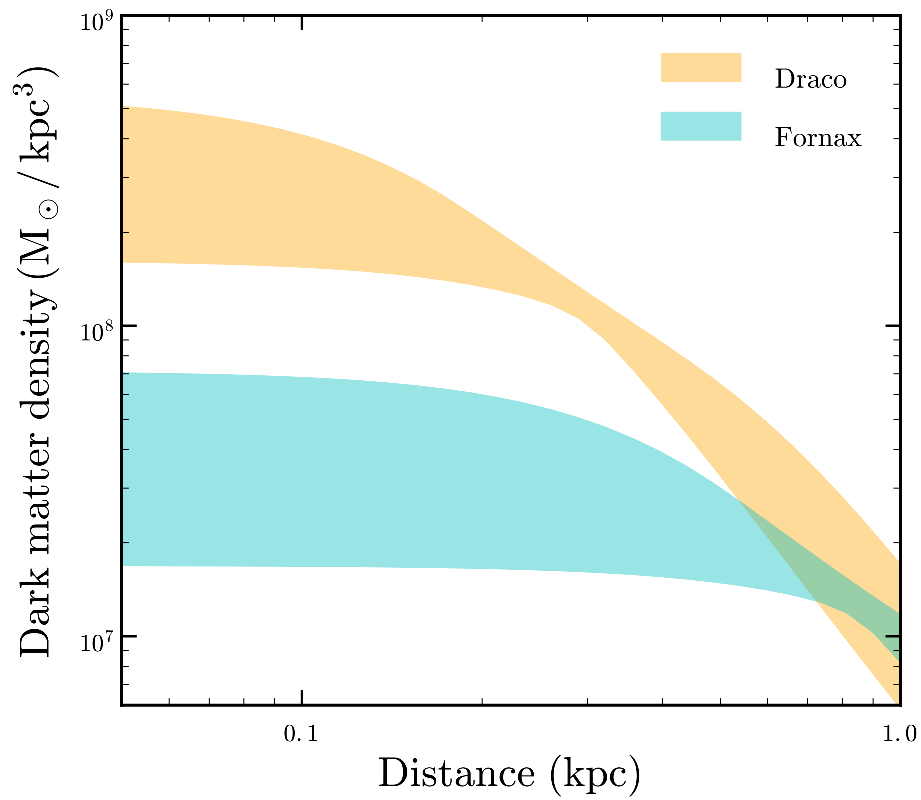


Image: Bullock+

But...



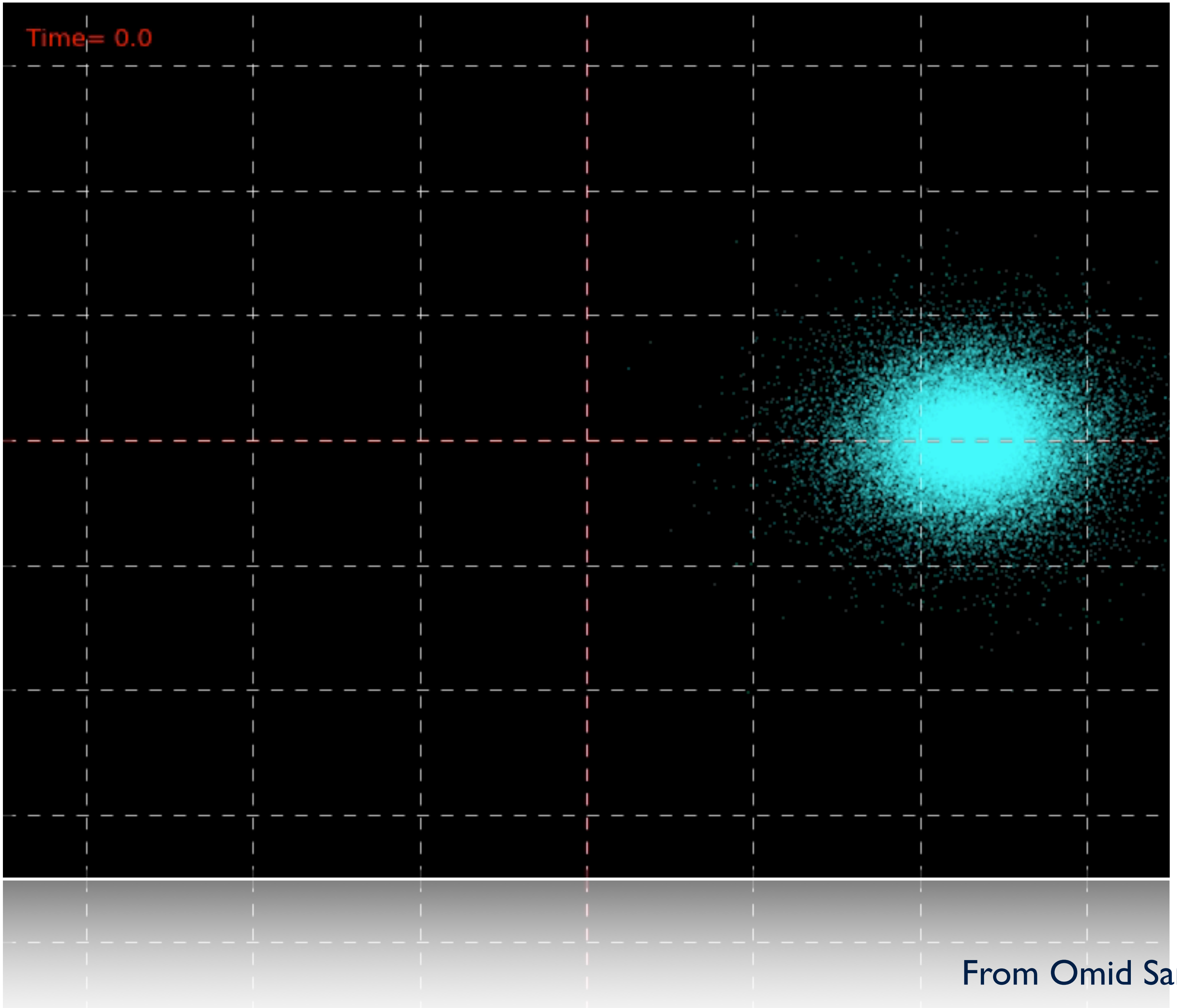
Observations



- 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

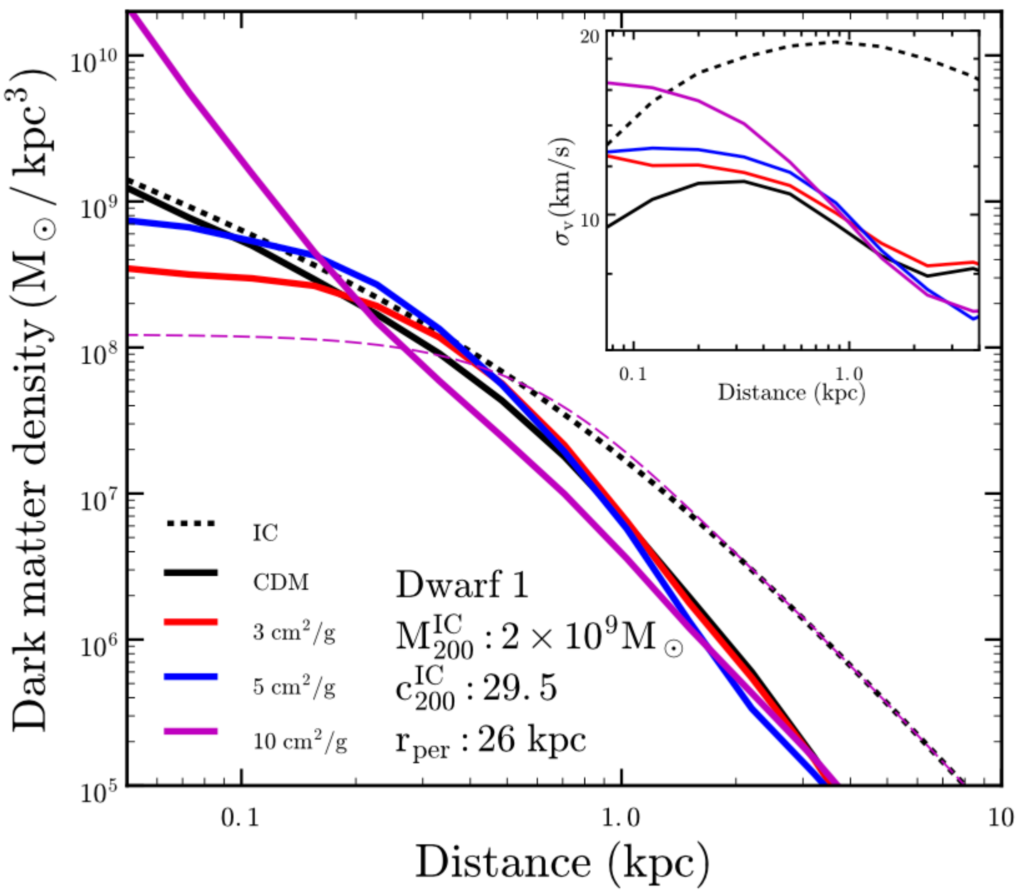
w/ Valli (Nature Astronomy 2018)   w/ Kaplinghat, Valli (MNRAS, 2019)

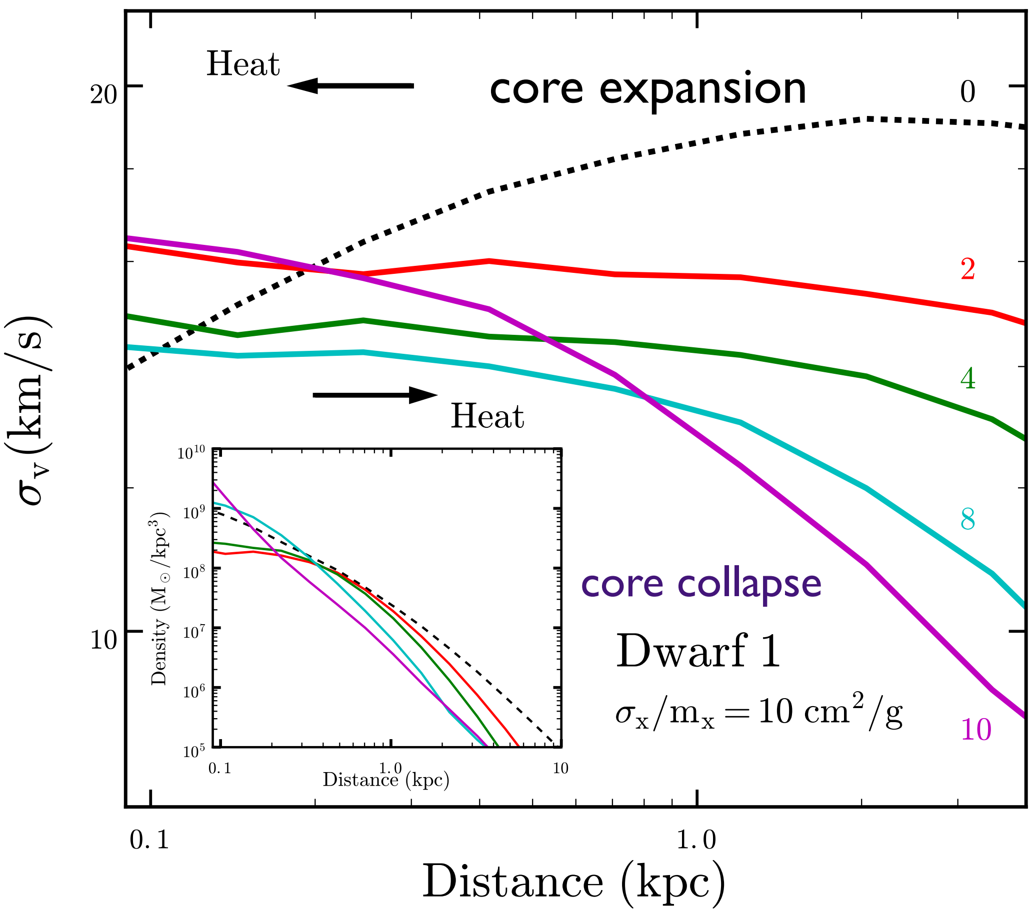
Tidal Interactions



From Omid Sameie

SIDM in the MW's Tides

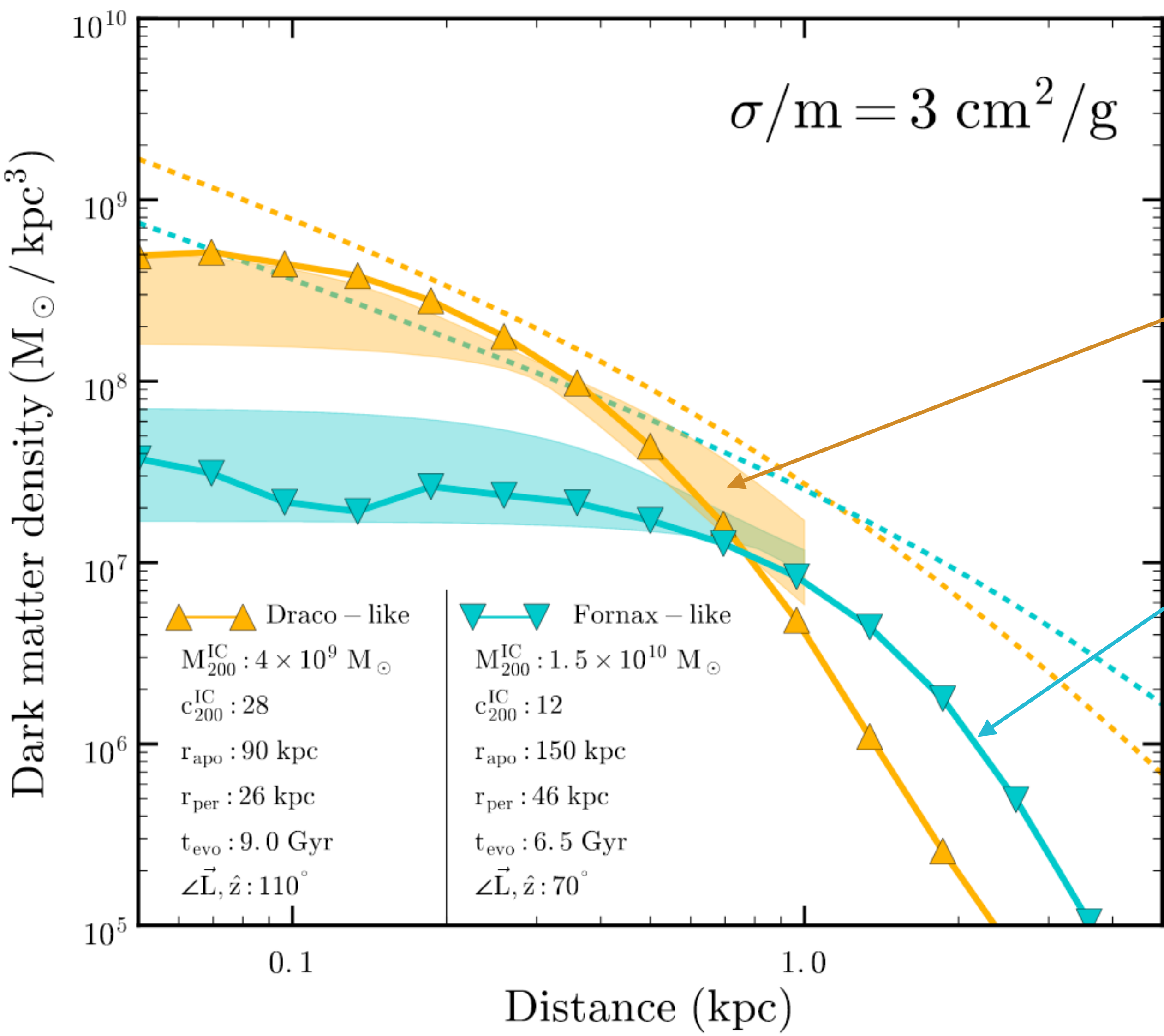




w/ Sameie, Sales+ (PRL 2019)

- SIDM thermalization occurs in the presence of the Milky Way's tides
- Tidal stripping can speed up the onset of core collapse

Reconciling Draco & Fornax in SIDM



DM self-interactions and tidal interactions

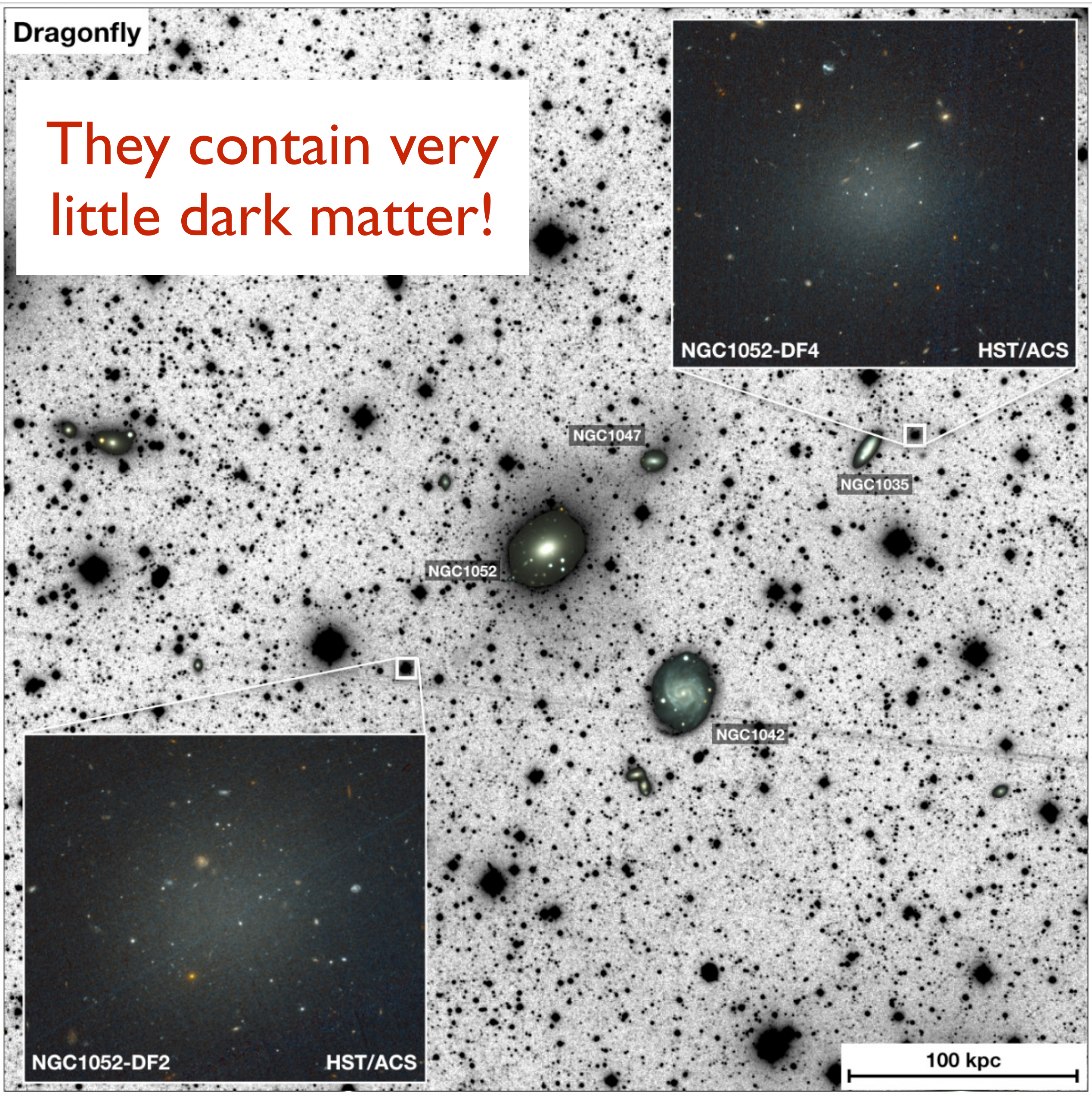
core-collapse phase

core-expansion phase

w/ Sameie, Sales+(PRL 2019)

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

Ultra-Diffuse Galaxies



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

Milky Way

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

DF2 and DF4

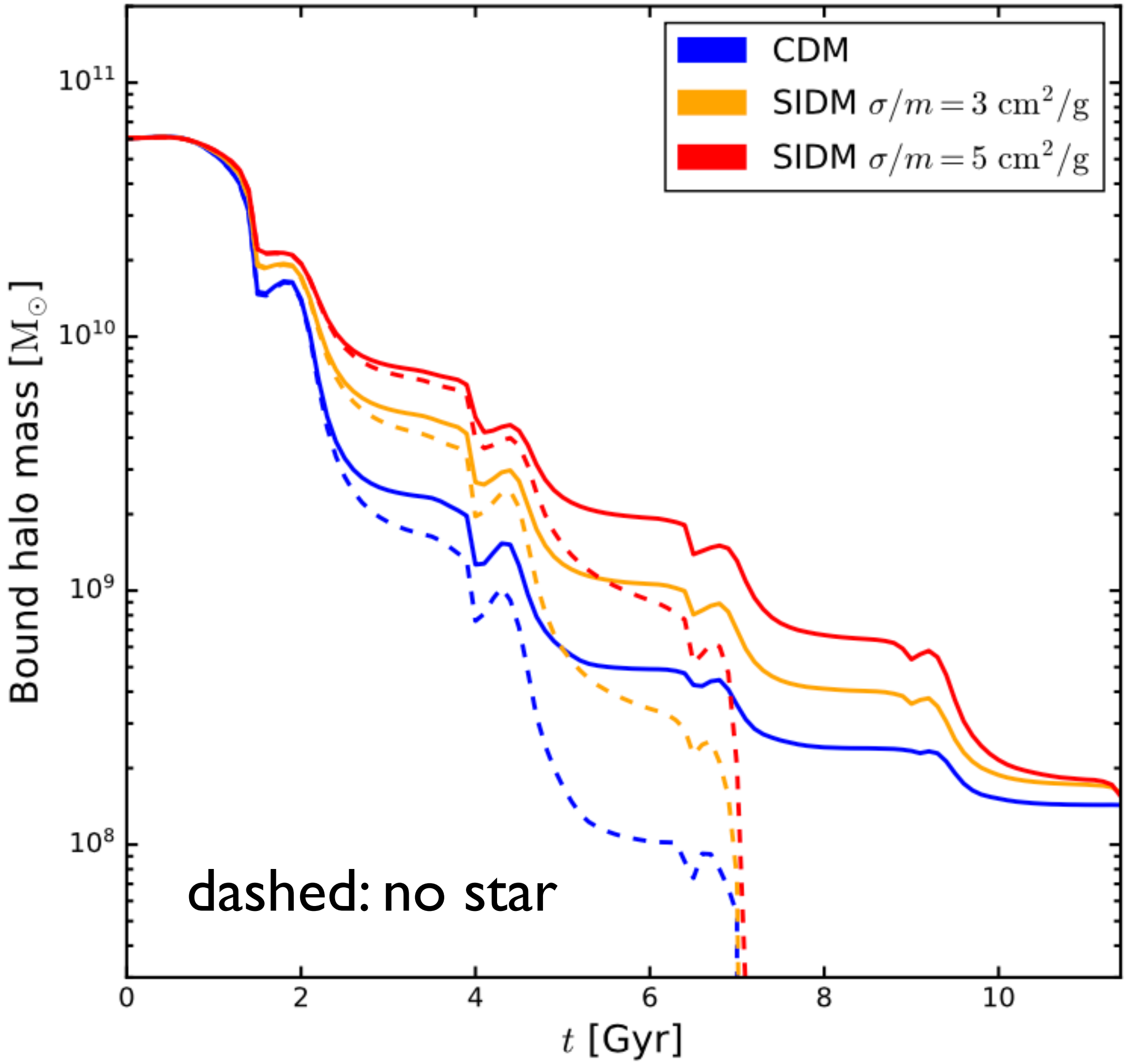
$$M_{\rm star} \approx 10^8 \ {\rm M}_\odot$$

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

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

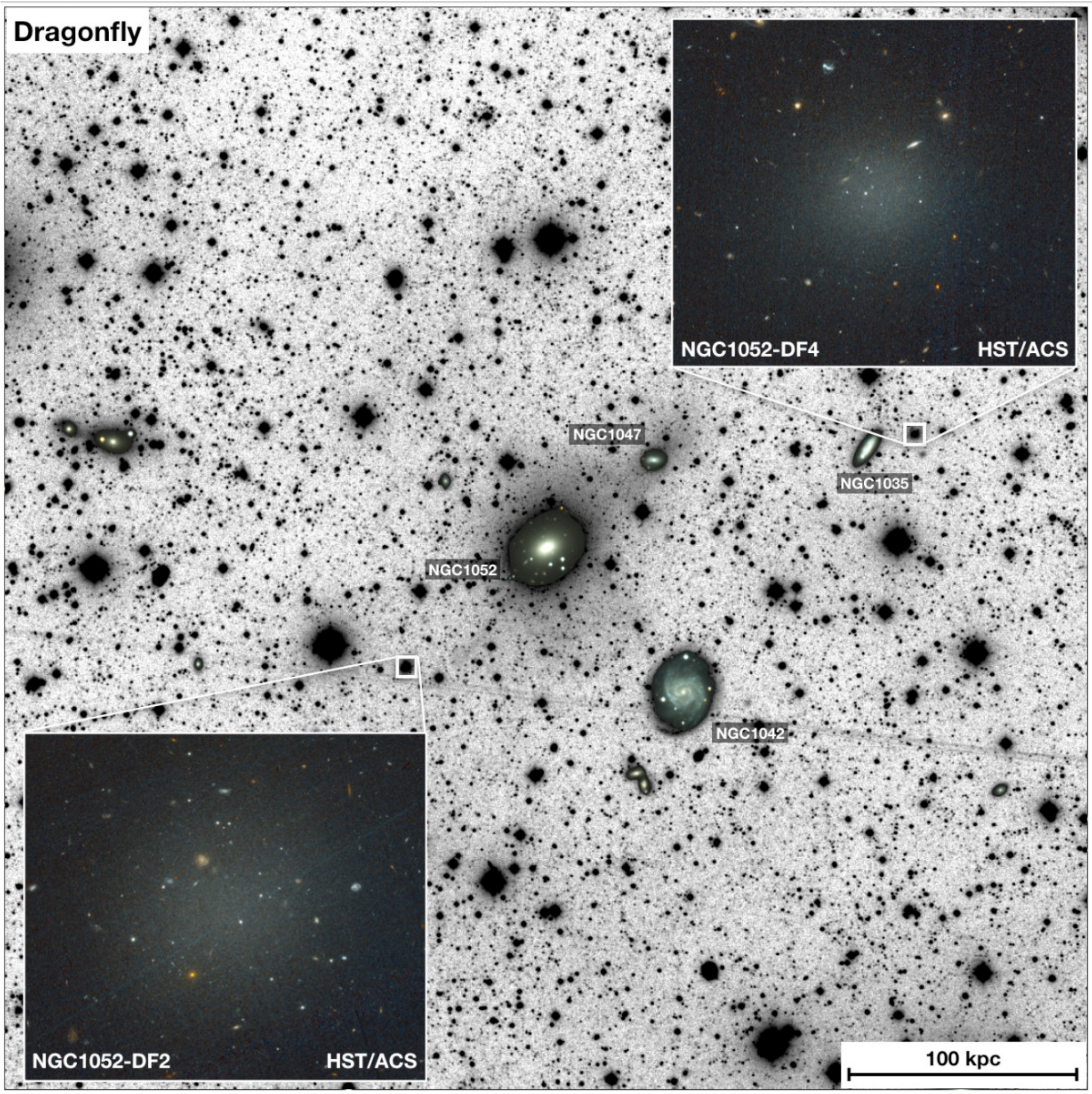
$$M_{\rm star} = 1.3 \times 10^8\ \mathrm{M_\odot}$$

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

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

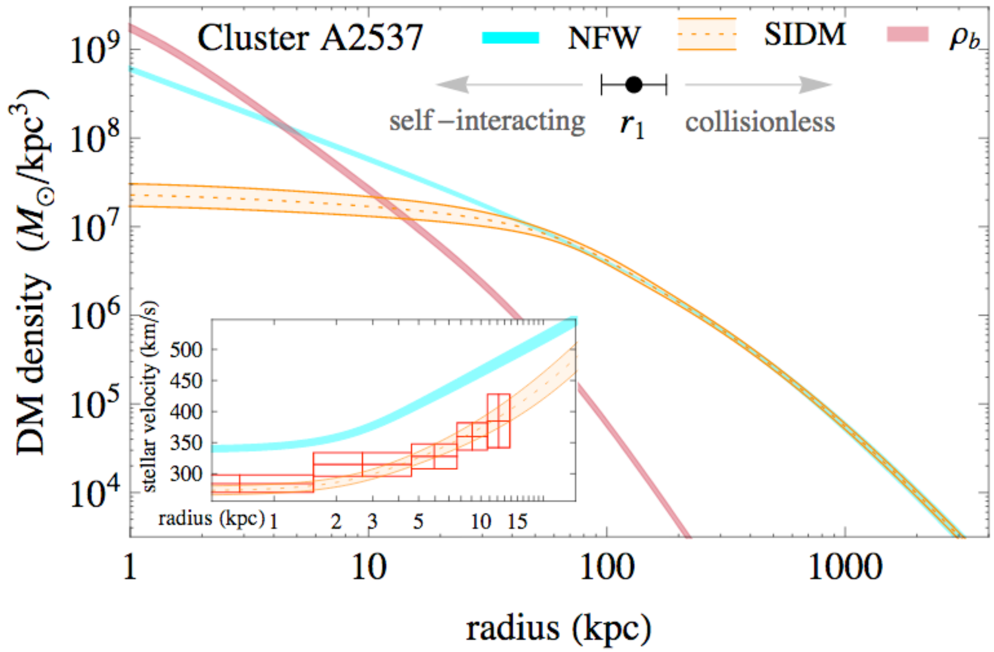
w/ Yang, An (PRL 2020)

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

Galaxy Clusters

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

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



w/ Kaplinghat, Tulin (PRL 2015)

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

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

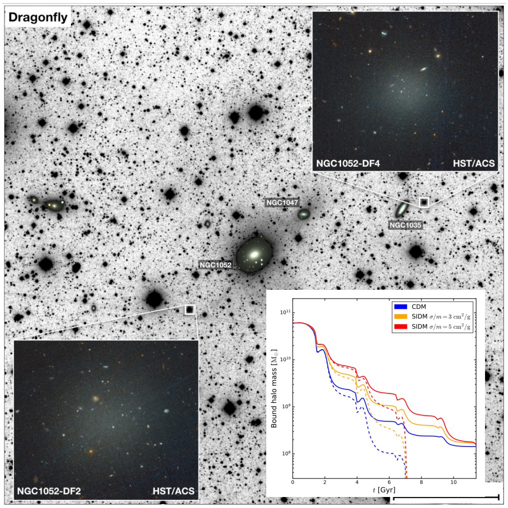
SIDM from Dwarfs to Clusters

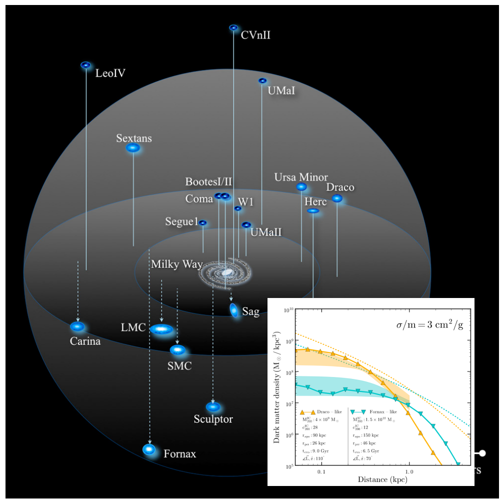
Ultra-diffuse galaxies (dark-matter-deficient)

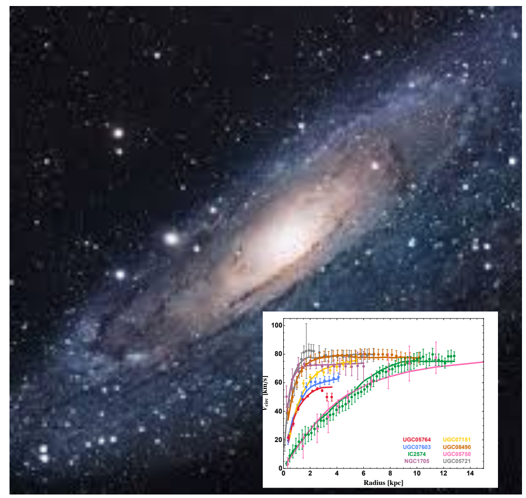
Milky Way satellites

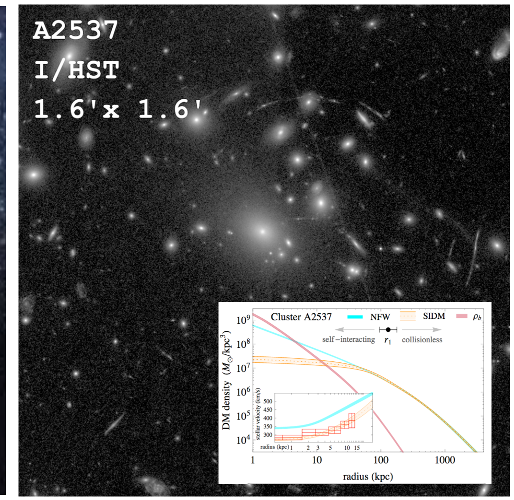
Spiral galaxies

Galaxy clusters









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

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

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

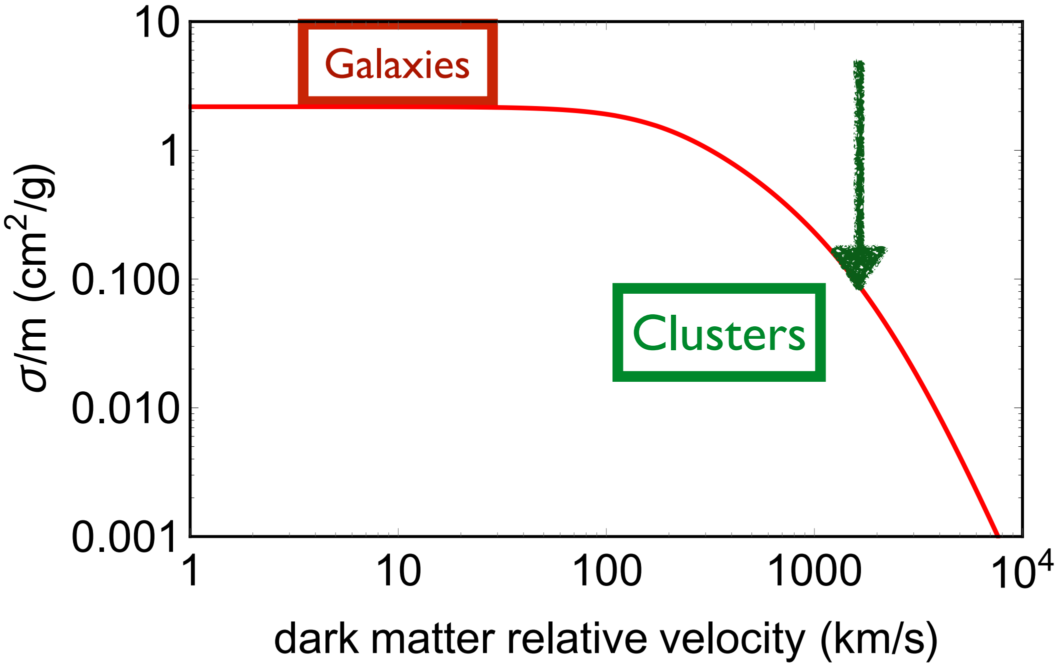
M_{halo}~10^{15} $M_\odot$

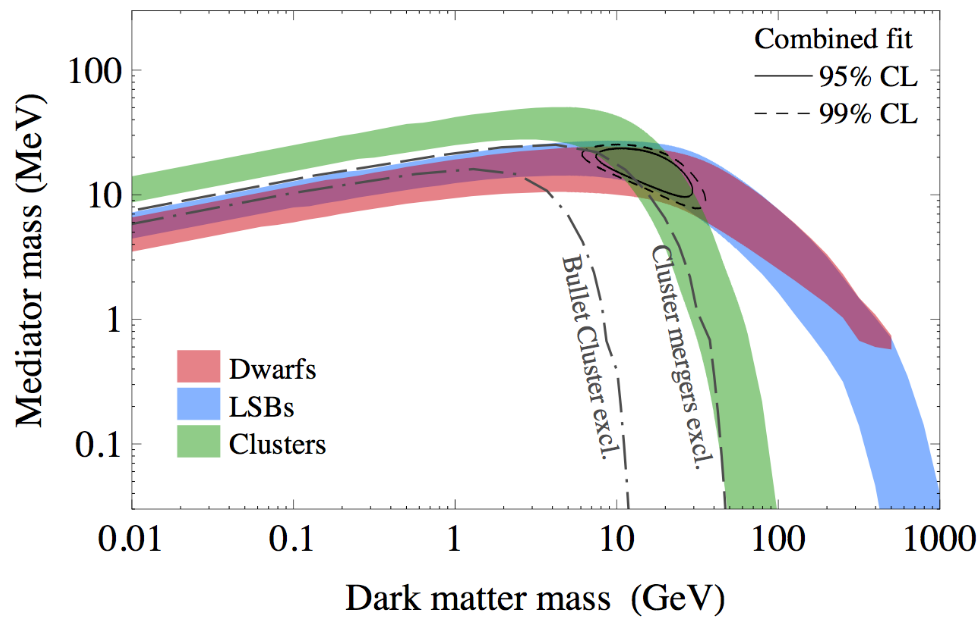
SIDM can explain diverse dark matter distributions over a wide range of galactic systems (halo masses ~10^8-10^{15} $M_\odot$)

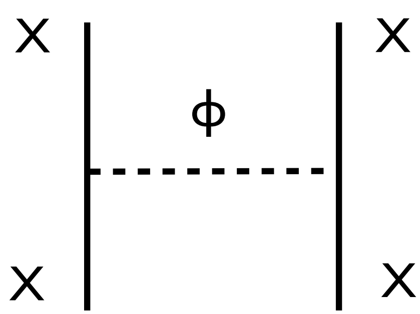
Particle Physics Models

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

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







w/ Kaplinghat, Tulin (PRL 2015)

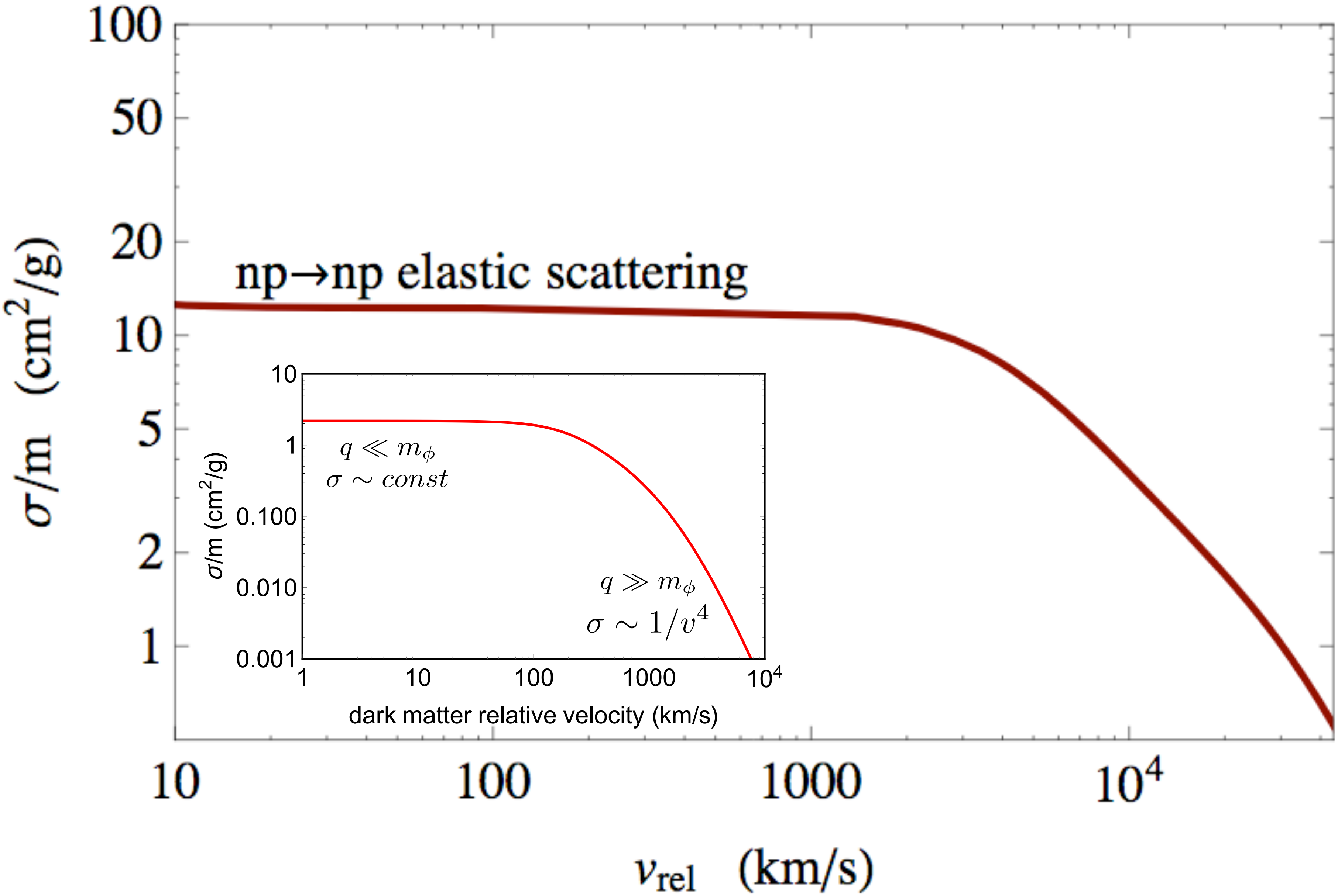
Fix α_X=1/137

Predict: m_X~15 GeV, m_ϕ ~17 MeV

The nightmare scenario is not hopeless!

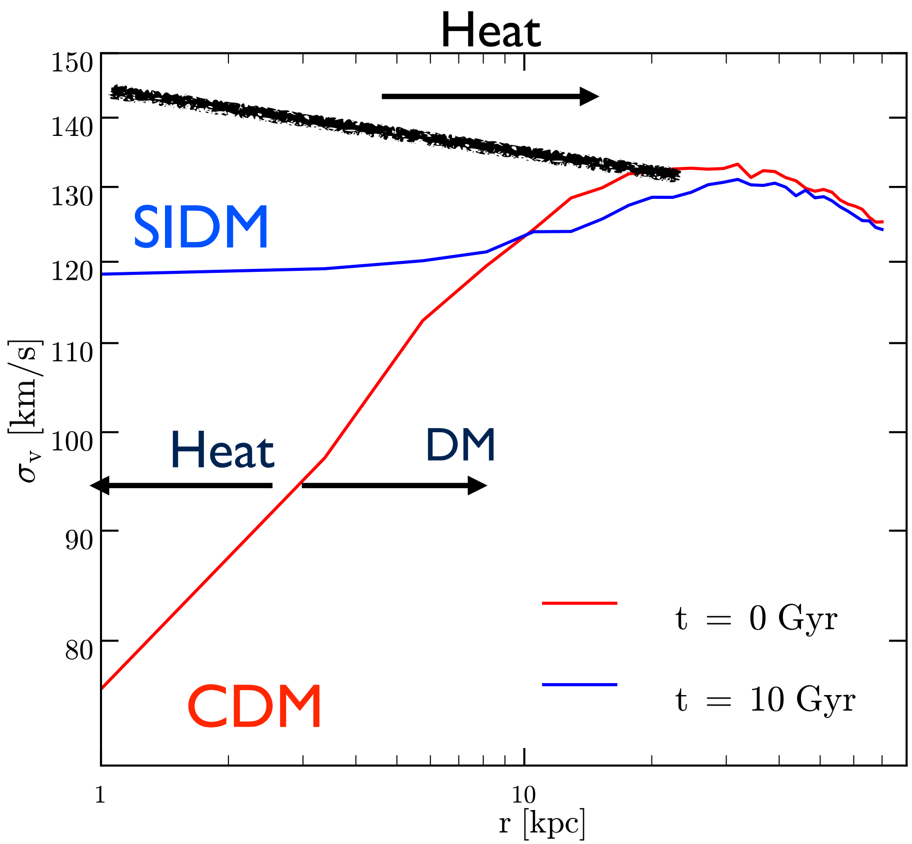
SIDM with a Yukawa interaction
w/ Feng, Kaplinghat (PRL 2010)

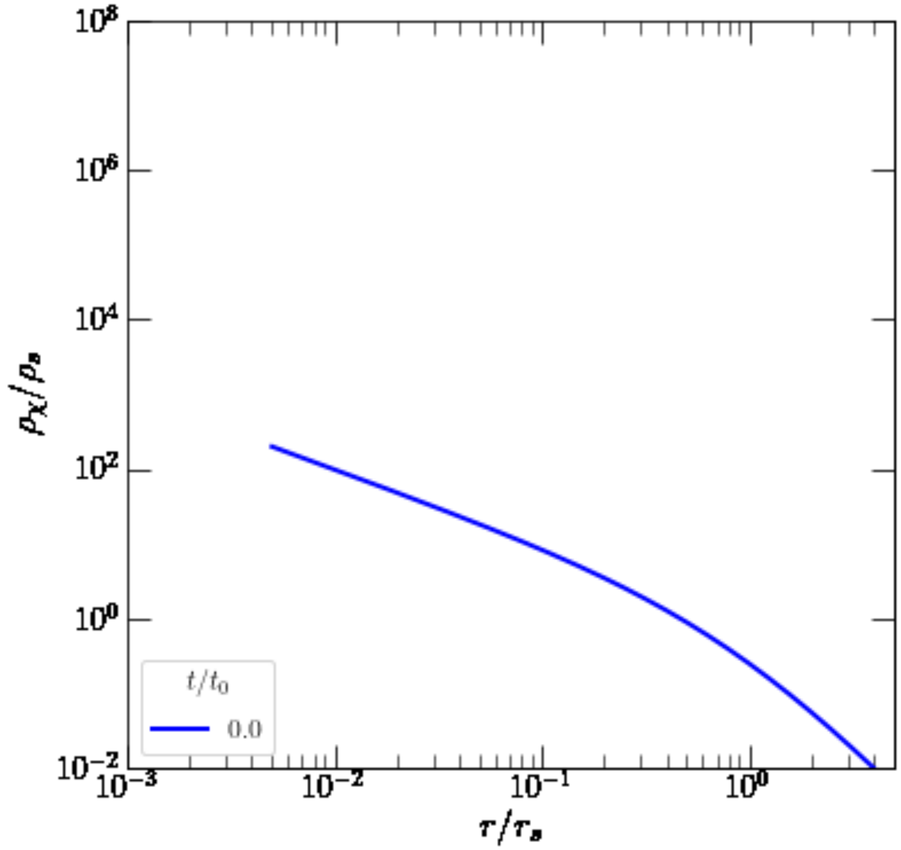
N-P vs. DM-DM Scatterings



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

Gravothermal Catastrophe





$$2K.E. + P.E. = 0$$
$$E_{\rm tot} = -K.E.$$

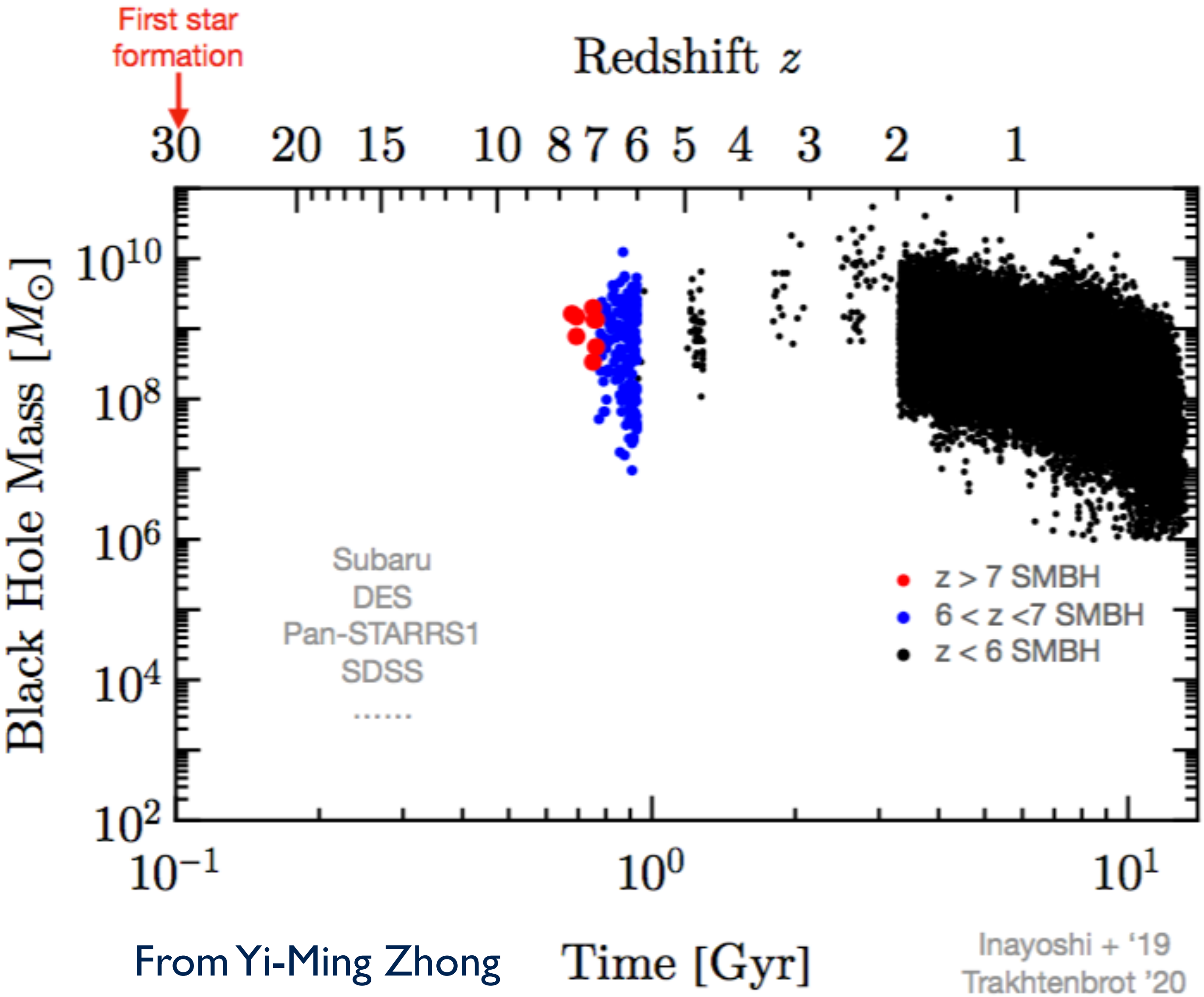
$$\frac{E_{\rm tot}}{T} < 0$$

Negative heat capacity!
⇒ gravothermal collapse

From Yi-Ming Zhong

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

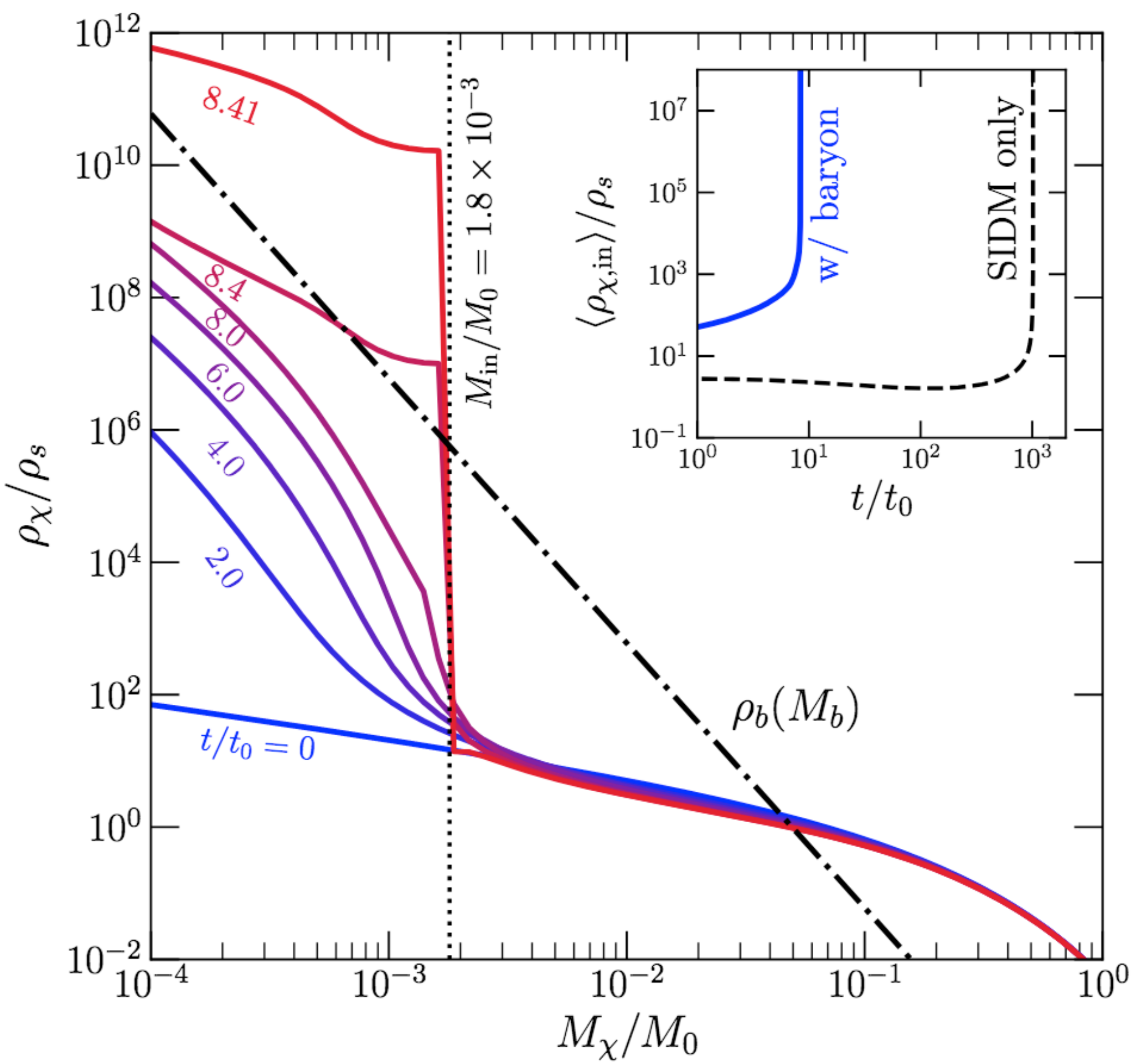
Supermassive Black Holes



From Yi-Ming Zhong

- ~200 BHs with mass $>10^6\ M_\odot$ at z>6
- 7 BHs with mass $>10^8\ M_\odot$ at z>7

Gravothermal Collapse



Modelling dynamical evolution

$$\frac{\partial M_\chi}{\partial r} = 4\pi r^2 \rho_\chi, \quad \frac{\partial(\rho_\chi \nu_\chi^2)}{\partial r} = -\frac{G(M_\chi + M_b)\rho_\chi}{r^2}$$

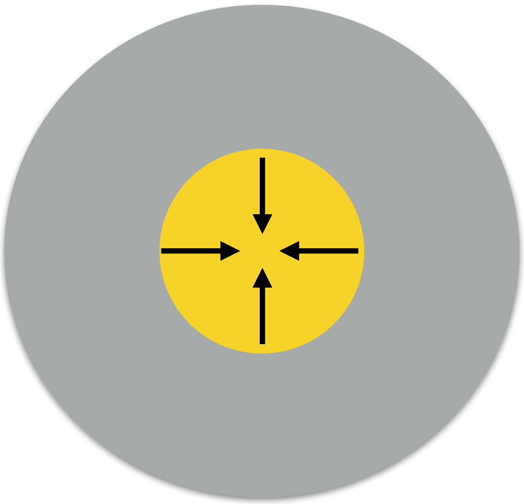
$$\frac{\partial L_\chi}{\partial r} = -4\pi \rho_\chi r^2 \nu_\chi^2 D_t \ln \frac{\nu_\chi^3}{\rho_\chi}, \quad \frac{L_\chi}{4\pi r^2} = -\kappa \frac{\partial T_\chi}{\partial r}$$

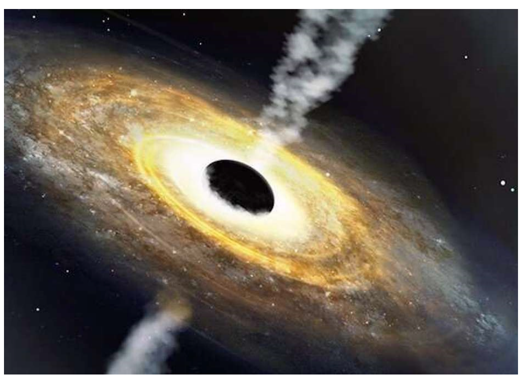
"heat conduction equation"

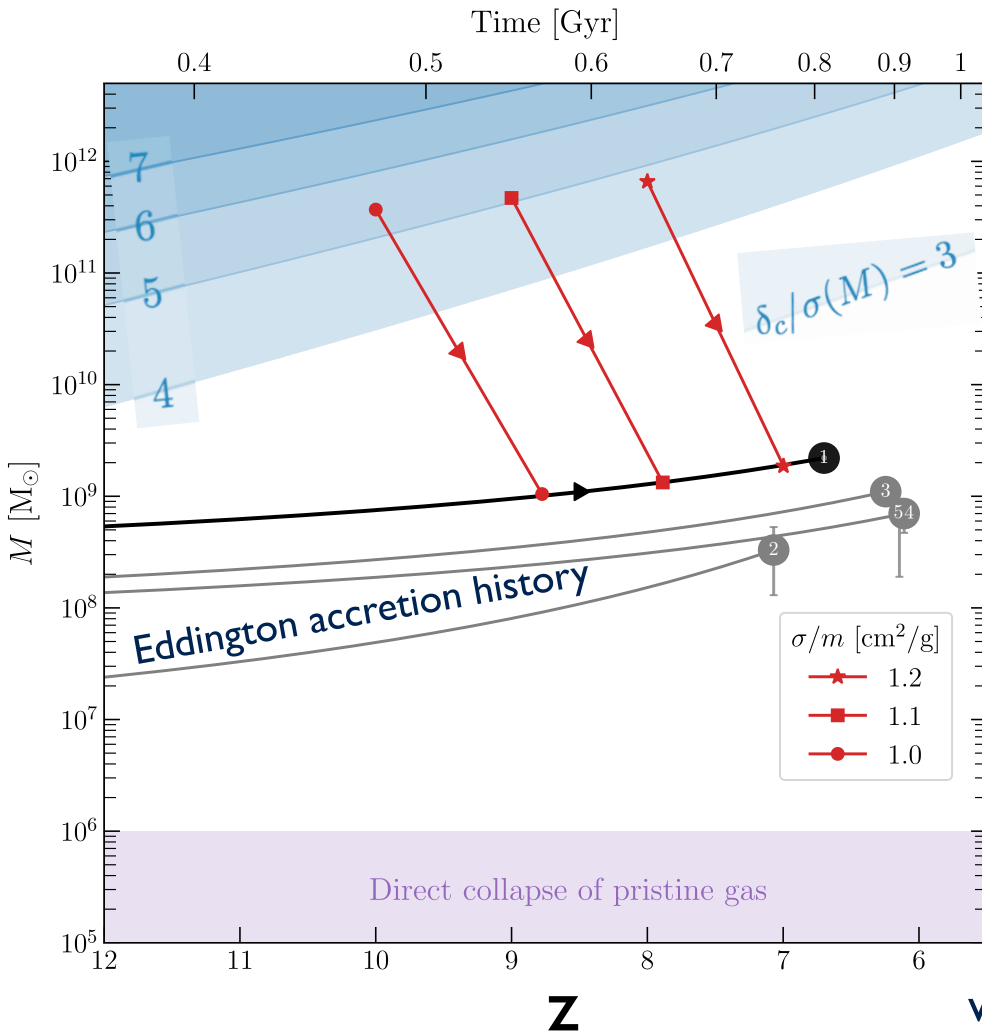
The presence of baryons could significantly speed up the onset of the collapse

w/ Feng, Zhong (2020)

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)

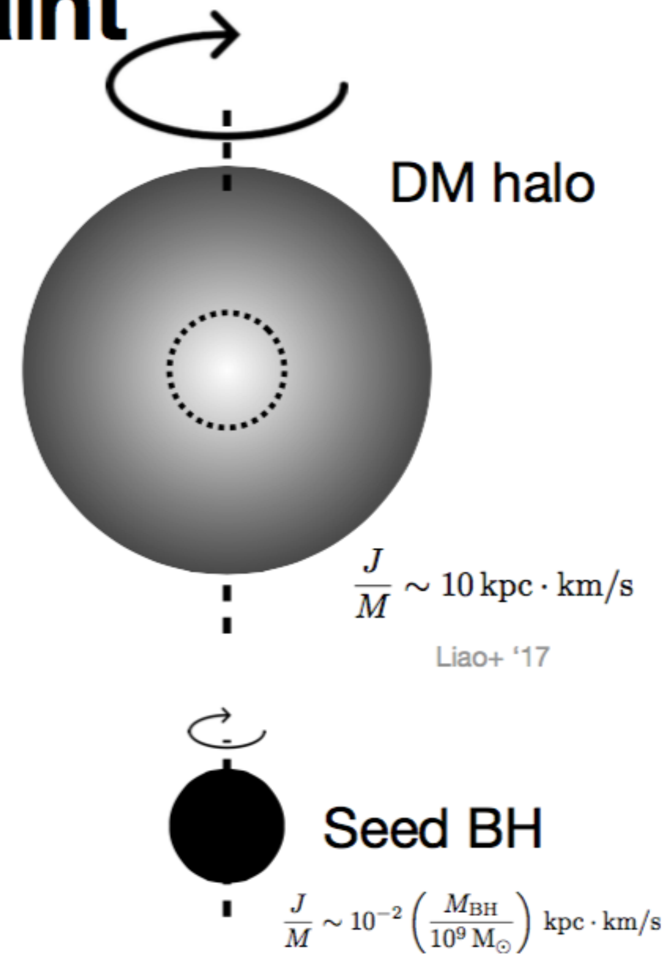
~800 Myr after the Big Bang

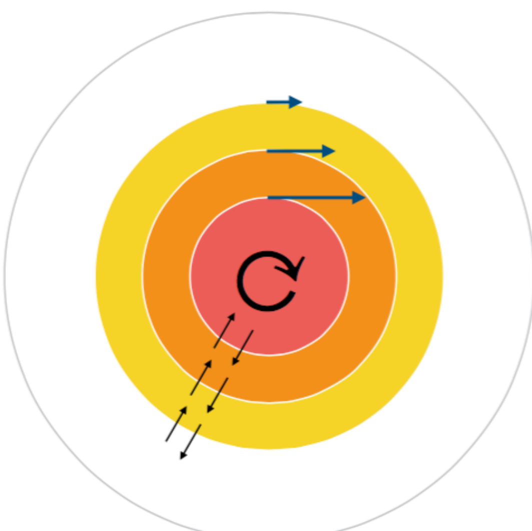
w/ Feng, Zhong (2020)

The predicted σ/m is consistent with the one used to explain diverse dark matter distributions in galaxies

Angular momentum constraint

- BH has a max specific angular momentum of $(G/c)M_{\rm BH}$
- Halos gain angular momentum through tidal torques, asymmetric collapse, or major mergers Mo+ '10
- For a typical halo, the specific angular momentum of the halo central region is $10^2 - 10^5$ times larger than the max value of the corresponding BH
- Need a way to dissipate angular momentum



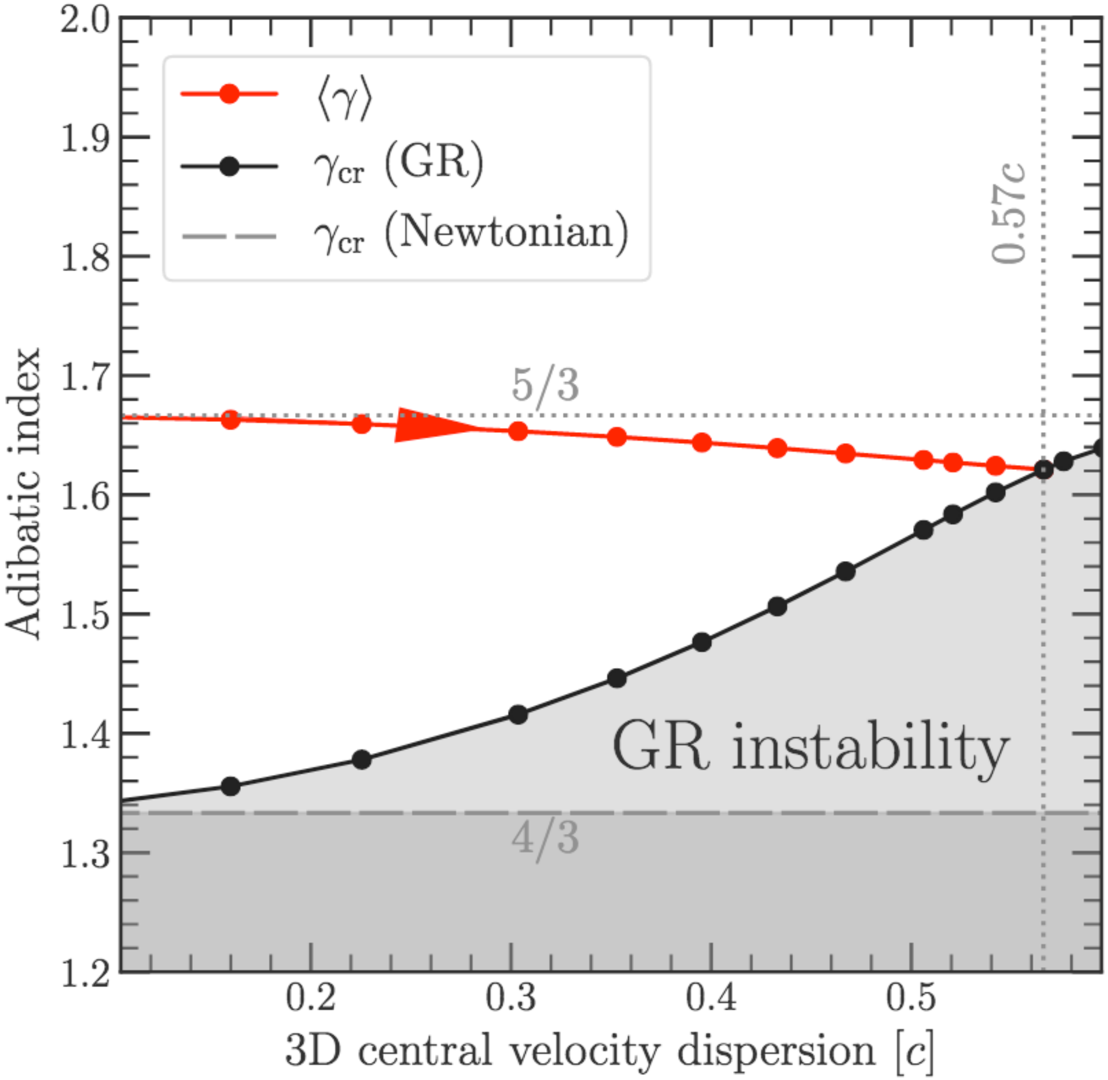


DM self-interactions also introduce viscosity between the halo shells.

$$\dot{J}_{\rm in} \sim -\eta_{\rm in}\frac{r_{\rm in}}{M_{\rm in}} J_{\rm in} \qquad t_{\rm dis} \sim \mathcal{O}(1\%)t_c$$

w/ Feng, Zhong (2020)

General Relativistic Instability



w/ Feng, Zhong (2020)

Truncated Maxwell-Boltzmann distribution

$$\begin{cases} (e^{-\epsilon/kT} - e^{-\epsilon_c/kT}) d^3 p(\epsilon) & (\epsilon \leq \epsilon_c) \\ 0 \quad (\epsilon > \epsilon_c), \end{cases}$$

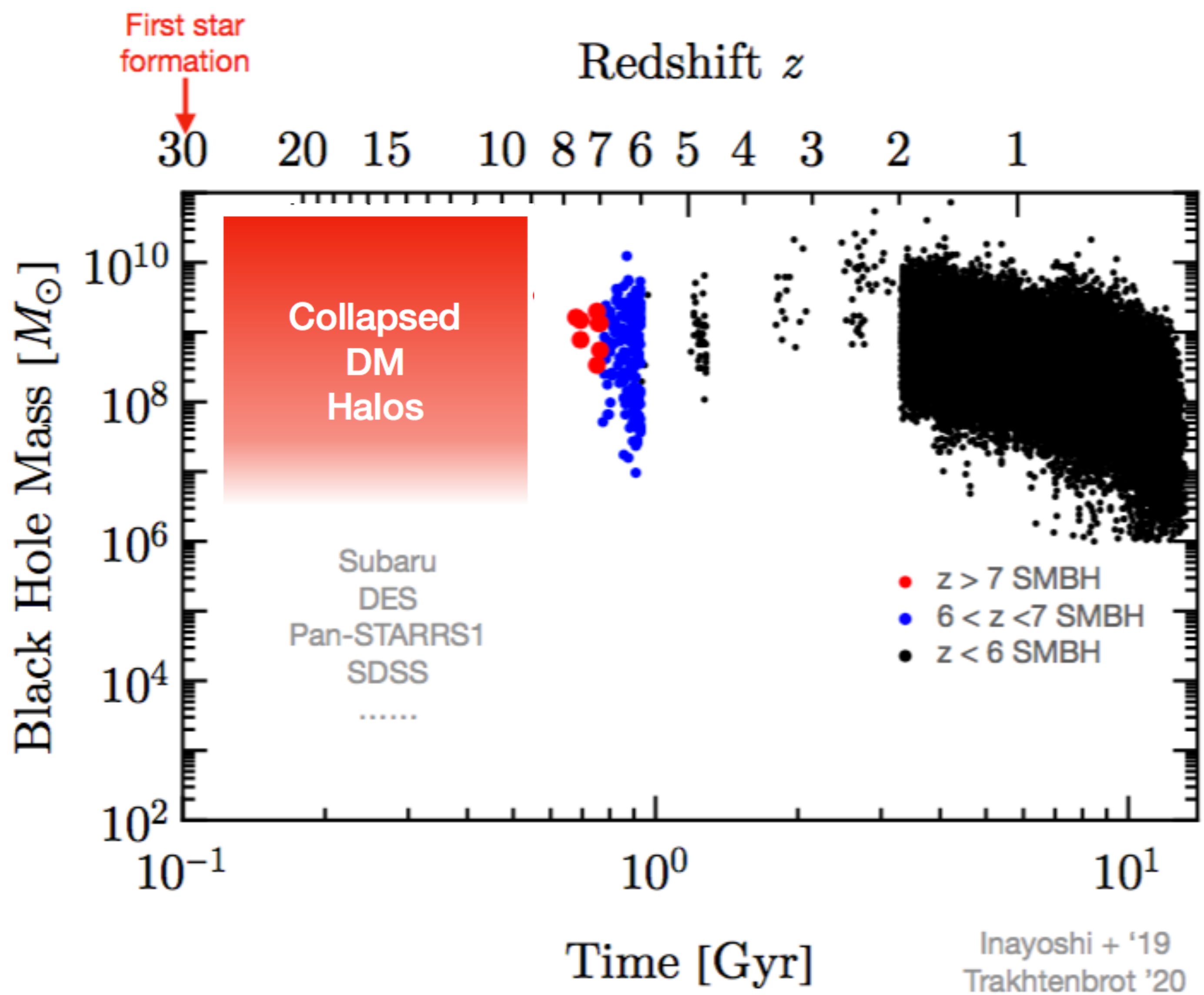
- Find stable configuration using the Tolman-Oppenheimer-Volkov (TOV) equation
- Calculate the critical adiabatic index and the adiabatic index
- Chandrasekhar's criterion.

$\langle\gamma\rangle > \gamma_{\rm cr}$ stable

$\langle\gamma\rangle = \gamma_{\rm cr}$ marginal

$\langle\gamma\rangle < \gamma_{\rm cr}$ unstable

Seeding SMBHs with SIDM

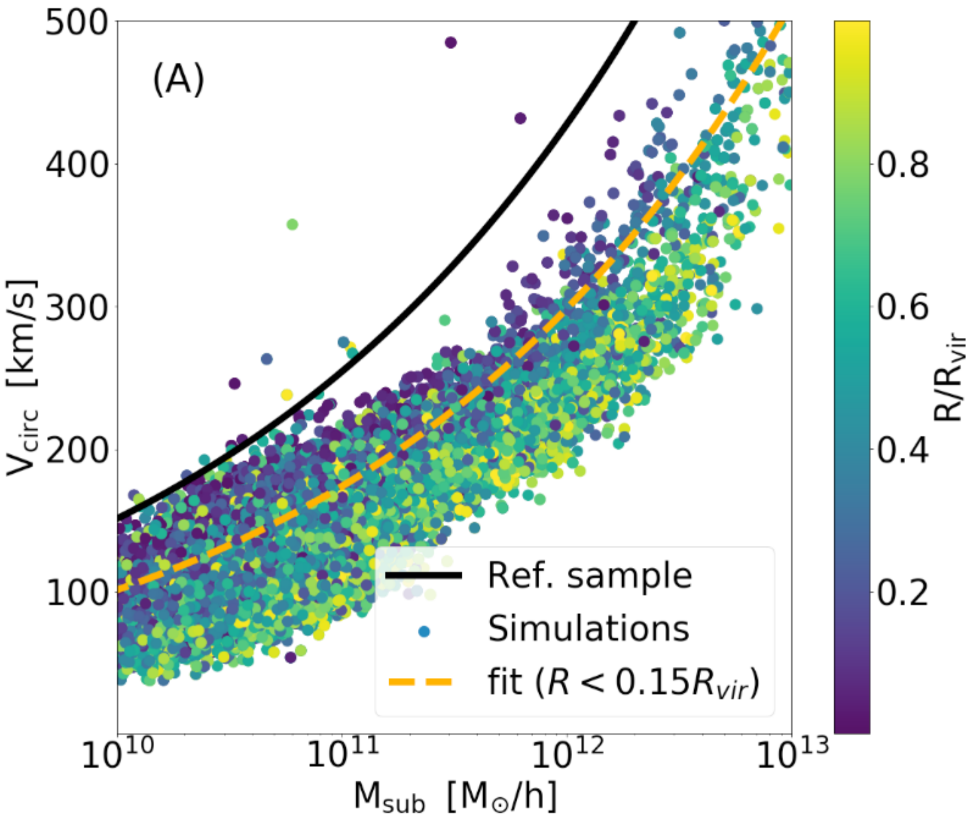


REPORT

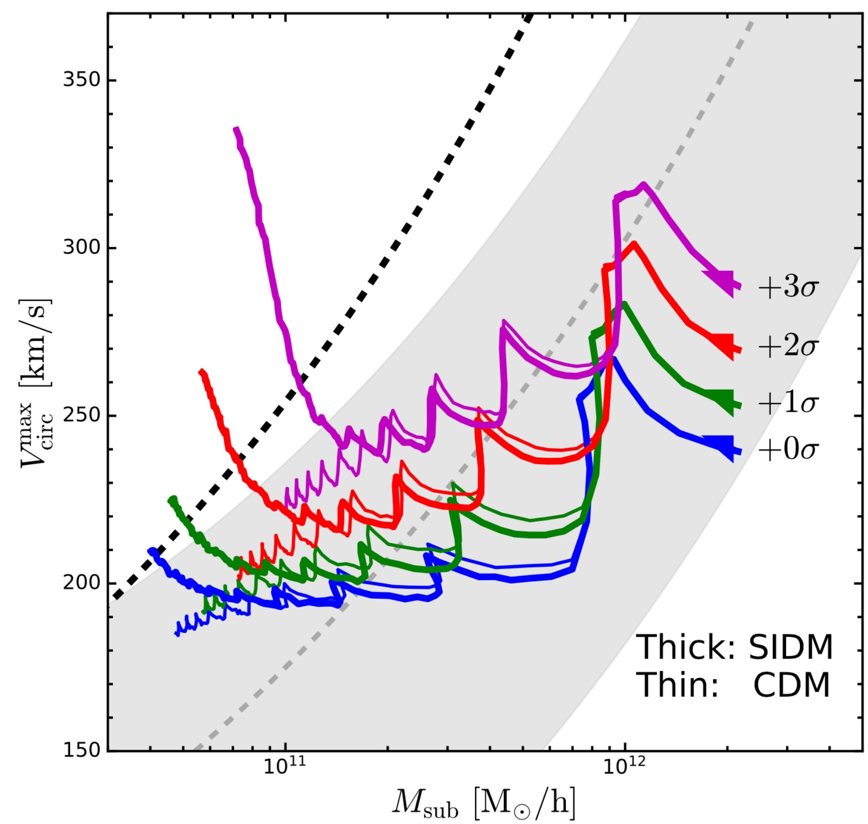
An excess of small-scale gravitational lenses observed in galaxy clusters

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...



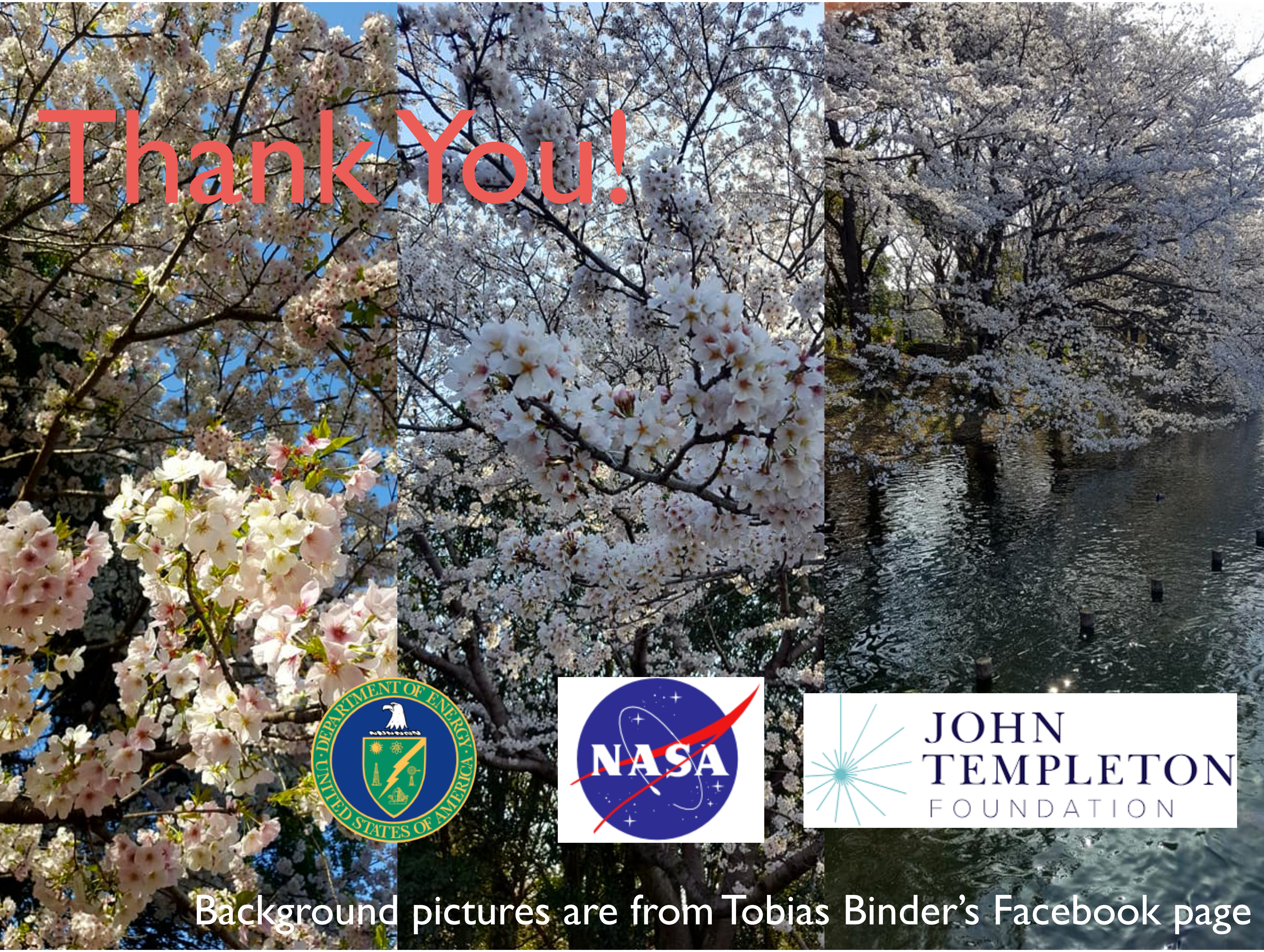
Meneghetti+(2020)



w/ Yang (2021)

Testing "gravothermal catastrophe" with strong gravitational lensing observations!


Hope for the best,
but prepare for the ~~worst~~.
unexpected


Thank You!
JOHN TEMPLETON FOUNDATION
Background pictures are from Tobias Binder's Facebook page