Self-Interacting Dark Matter & Structure Formation (III)

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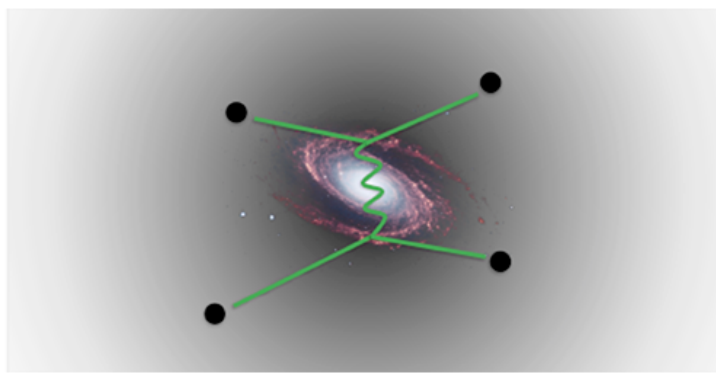


RESCEU Summer School, July 27-30, 2018

Review for Physics Reports: Tulin & HBY (2017)

Today's Plan

- Crisis on small scales: galactic scales, <10-100 kpc

  Core vs. Cusp ✓
  Diversity ✓
  Cores in Clusters ✓
  Missing Satellites
  Too-Big-To-Fail

  spiral galaxies and galaxy clusters in the field

  dwarf spheroidal galaxies in the Milky Way (Local Group)

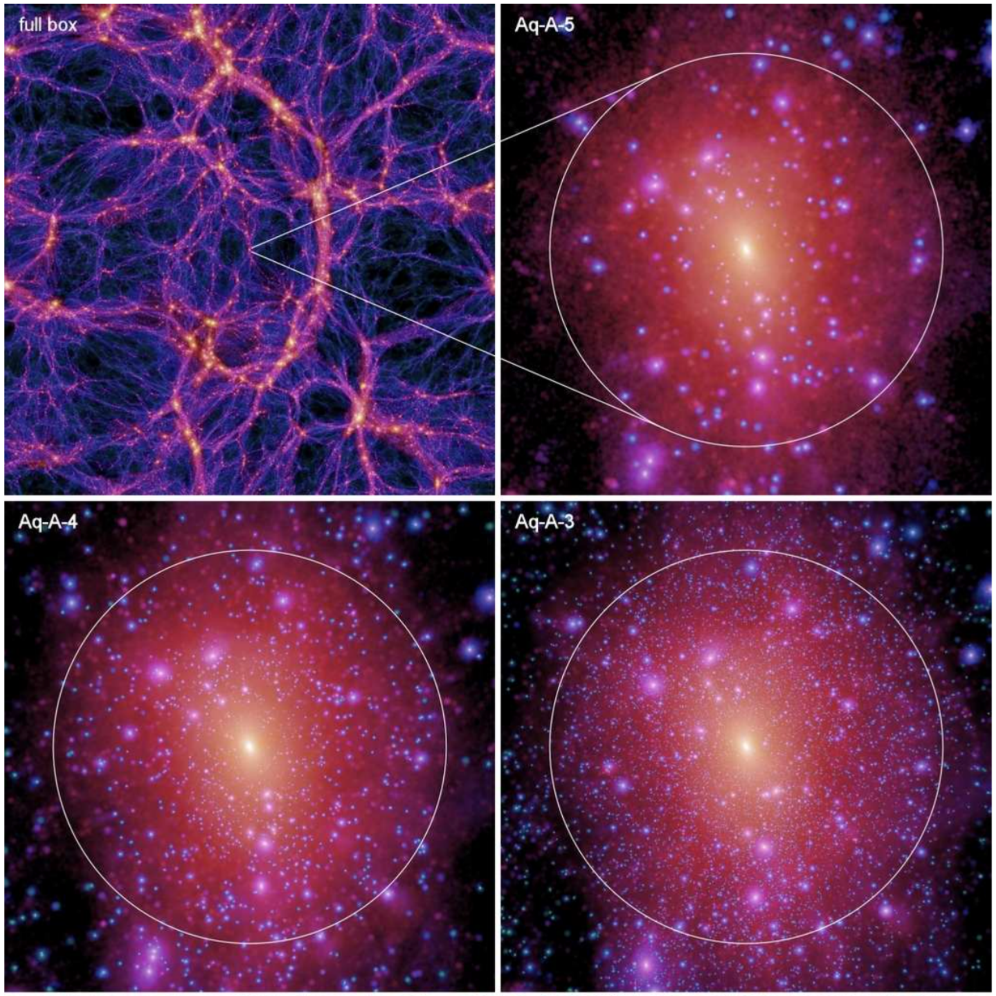
- Additional topics

  Halo shapes

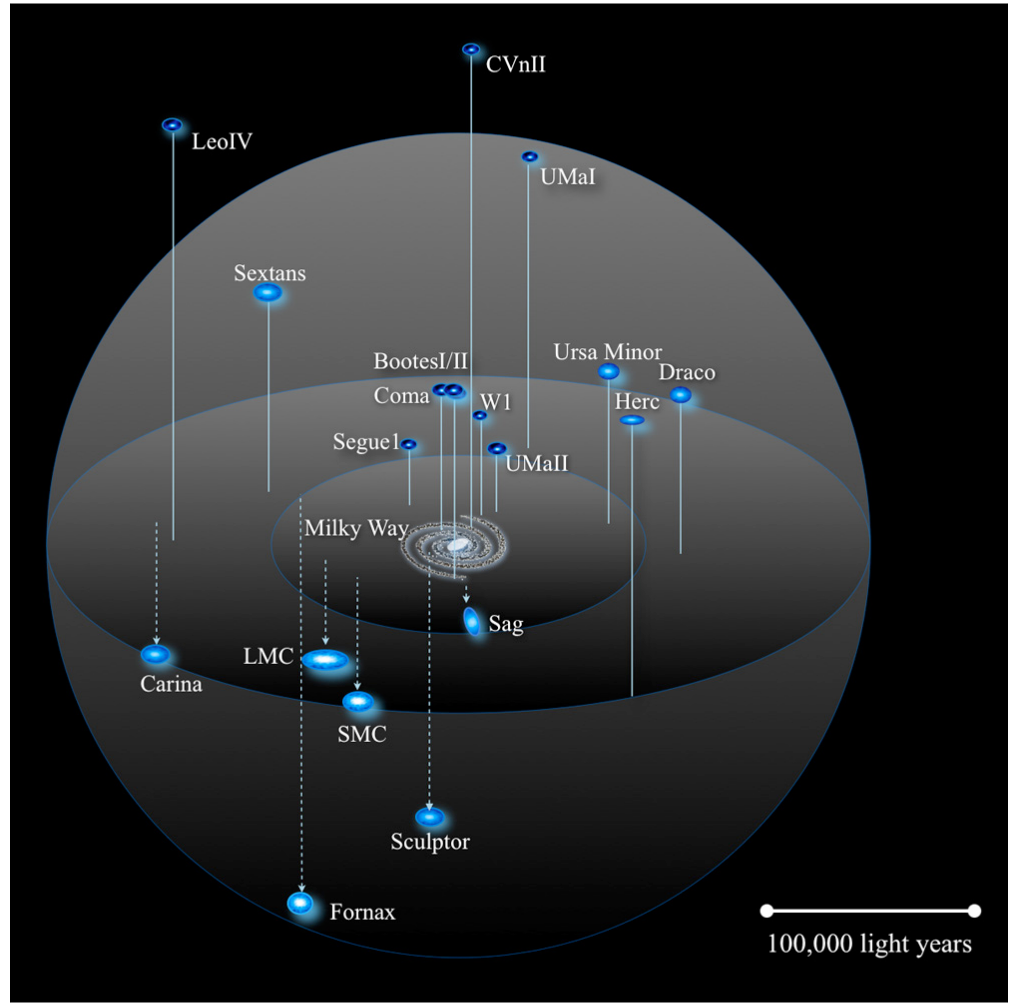
  Cosmological signatures/constraints

  Direct detection and collider searches

From Simulations to Observations

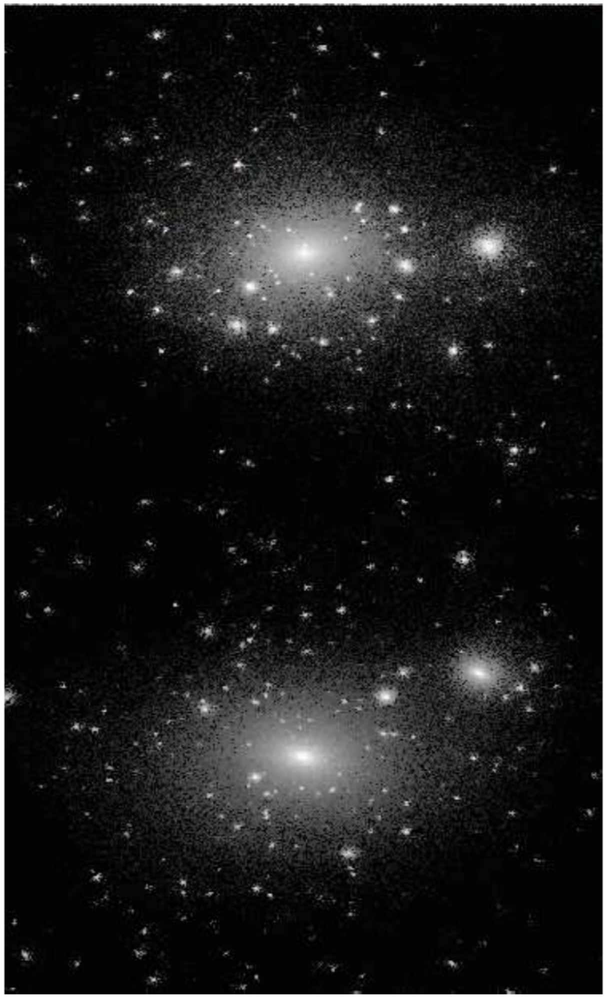


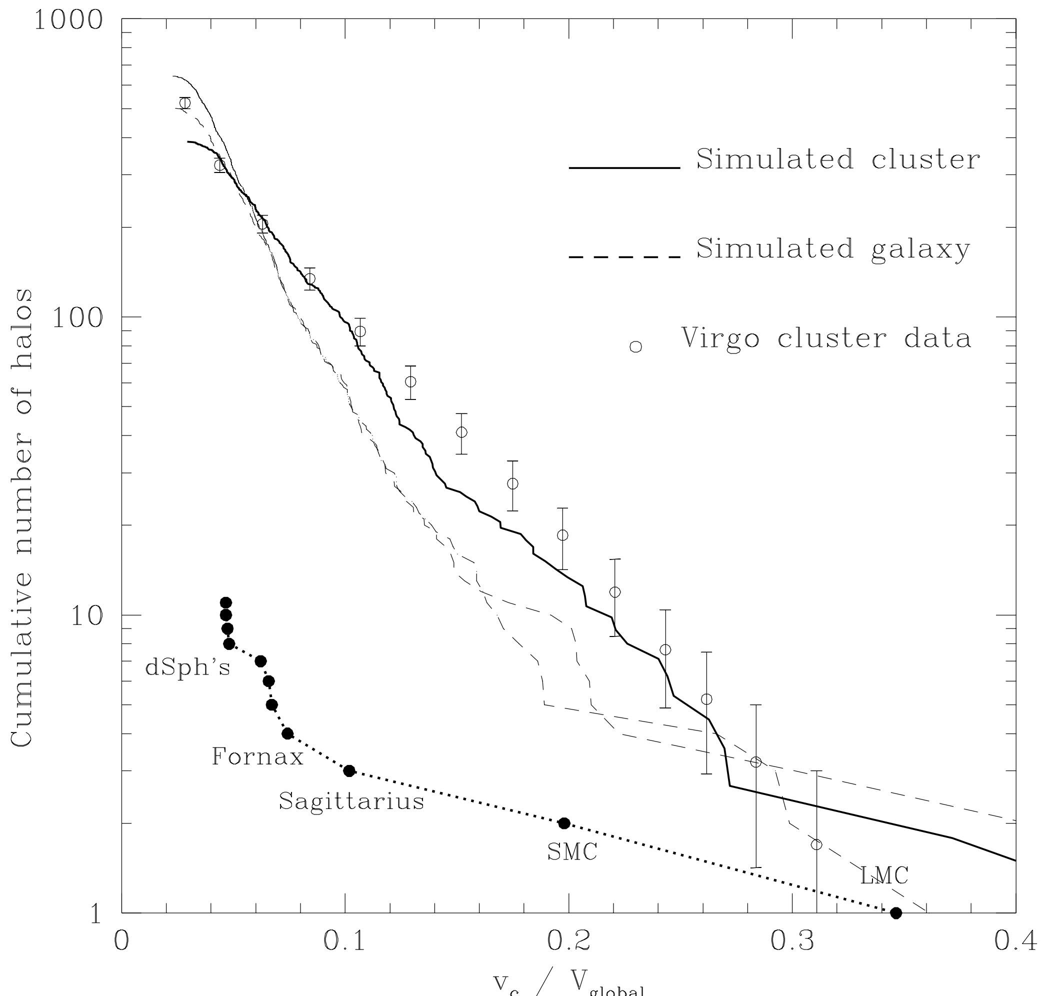
Aquarius Project, Springel et al. (2008)



Bullock et al.

Missing Satellites Problem

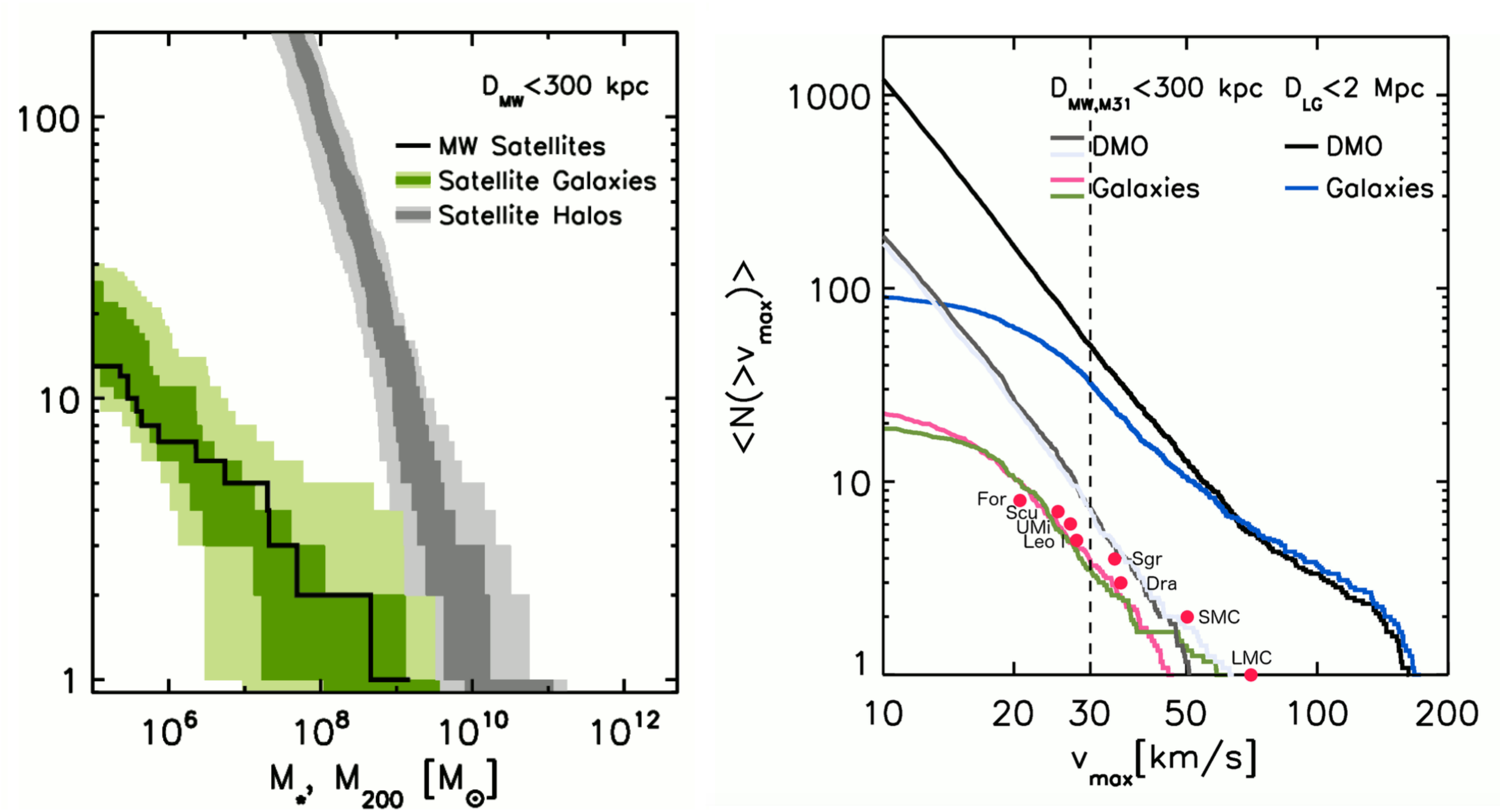




Moore et al. (1999)

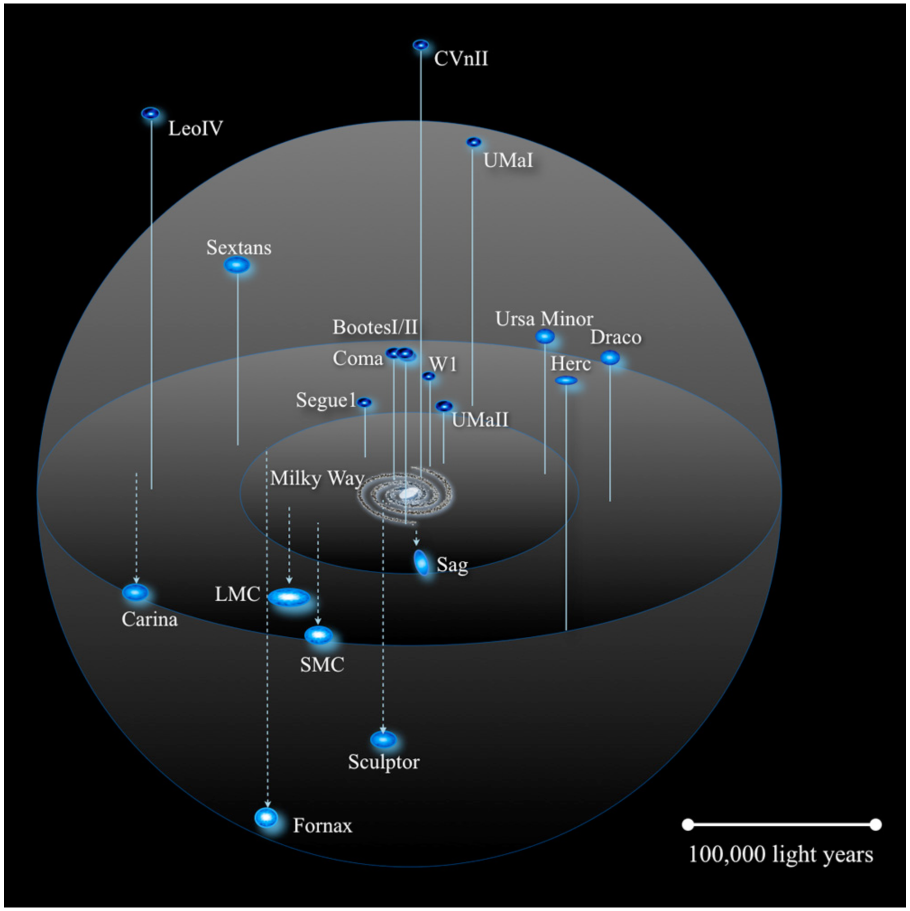
Predicted: ~O(100) subhalos with V~10-30 km/s within its viral radius
Observed: 11 by 1999, 15 SDSS satellites, expected more from LSST
Expected to have a factor of ~5-20 more, due to faintness, limited sky coverage…

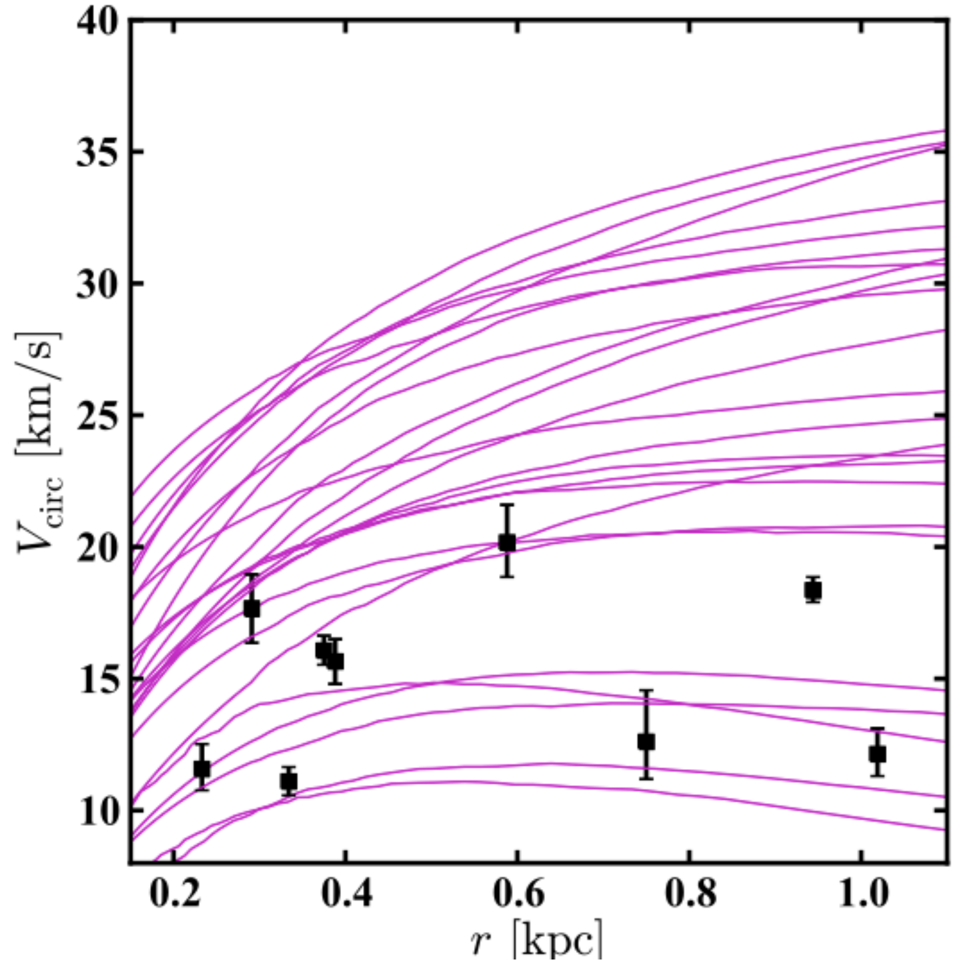
Feedback+Environment Effect?



Sawala et al. (2015)

Too-Big-to-Fail Problem





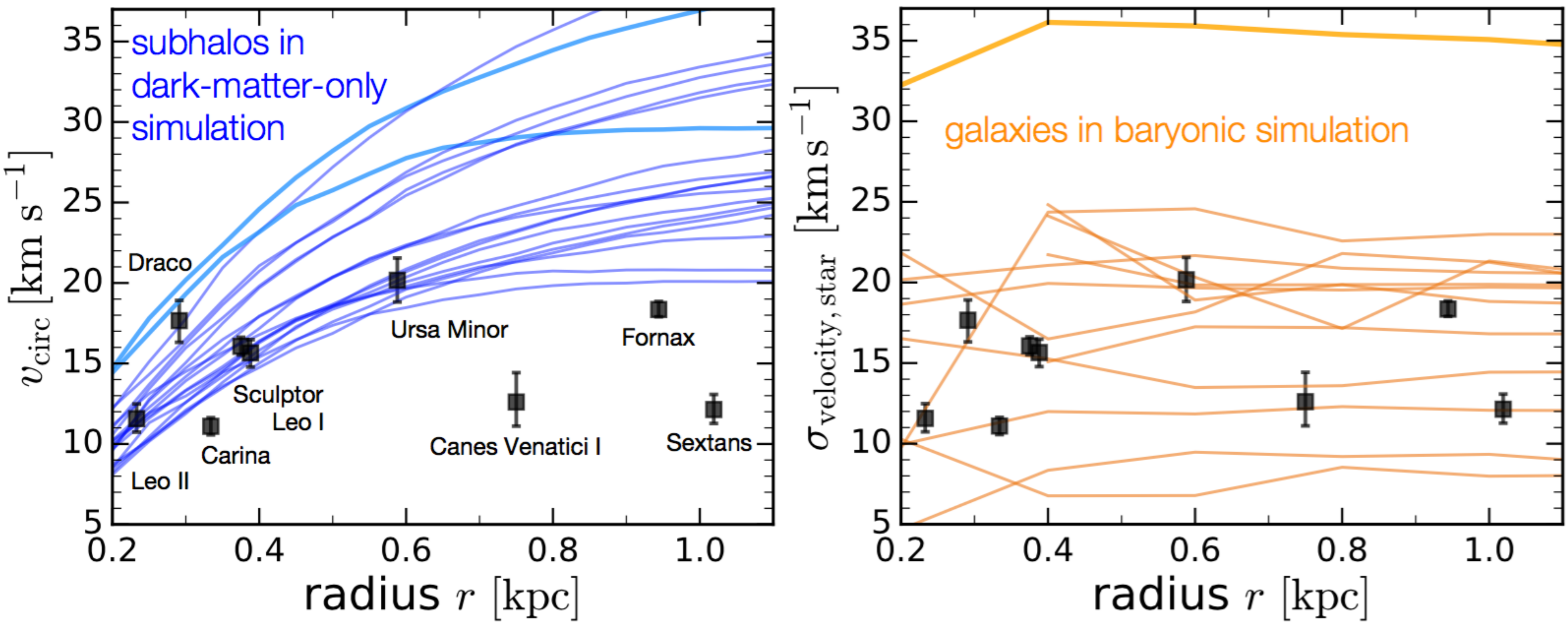
Boylan-Kolchin, Bullock, Kaplinghat (2011)

$$M_{1/2} = 3\, G^{-1} \langle \sigma_{\rm los}^2 \rangle\, r_{1/2}$$

$$V_{\rm circ}(r_{1/2}) = \sqrt{3\, \langle \sigma_{\rm los}^2 \rangle}\,.$$

subhalos in Andromeda, field dwarfs in Local Group, and field galaxies

Feedback+Environment Effect?

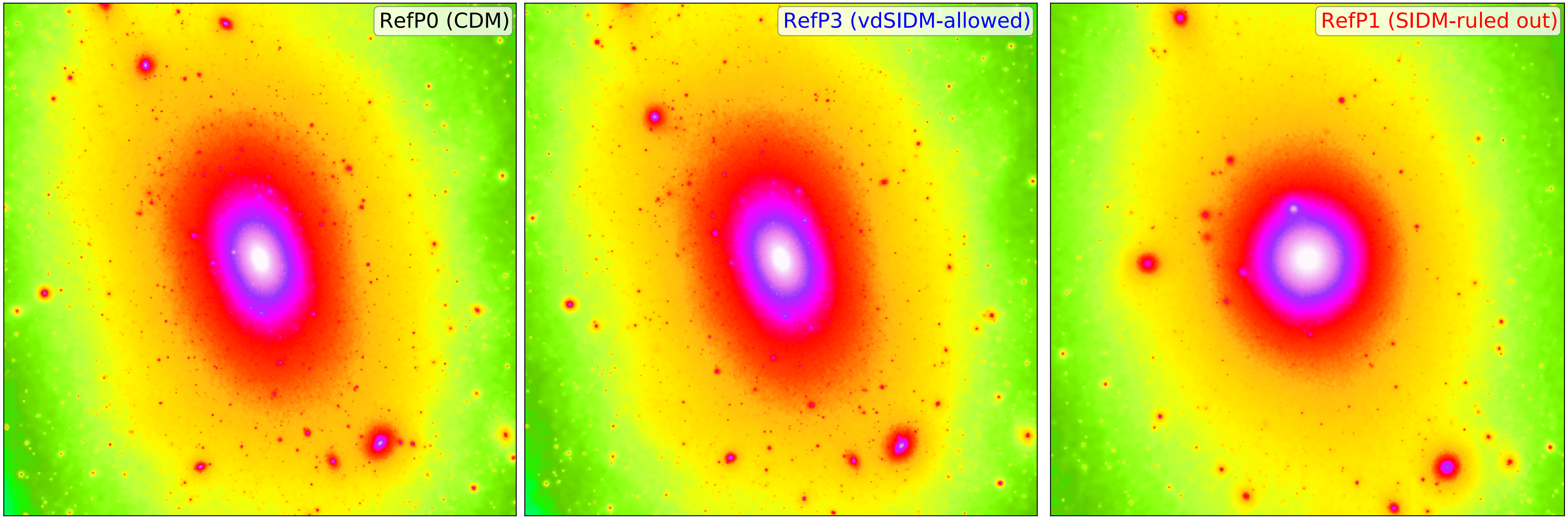


Strong feedback generates cores
DM mass loss due to tidal stripping from the stellar disk

Wetzel et al. (2016)

FIRE simulations

Substructure in SIDM



CDM

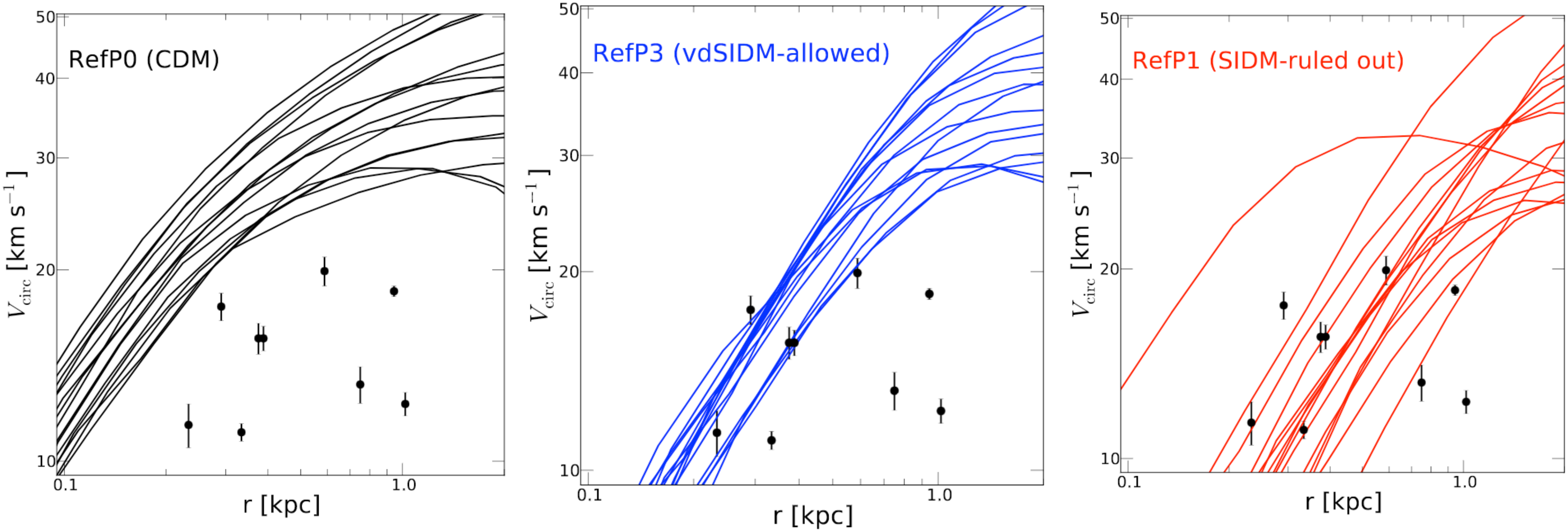
$\sigma/m \sim 3\ cm^2/g$ ($v \sim 30$ km/s)
$\sigma/m \sim 0.1\ cm^2/g$ ($v \sim 100$ km/s)

$\sigma/m = 10\ cm^2/g$

- DM-only simulations, no baryons
- For $\sigma/m \sim 1\ cm^2/g$, the halo mass function does not change
- The minimal SIDM model does not solve the missing satellites problem (?!)

Vogelsberger, Zavala, Loeb (2012)

Addressing the TBTF Problem



CDM

σ/m~3 cm²/g (v~30 km/s)
σ/m~0.1 cm²/g (v~100 km/s)

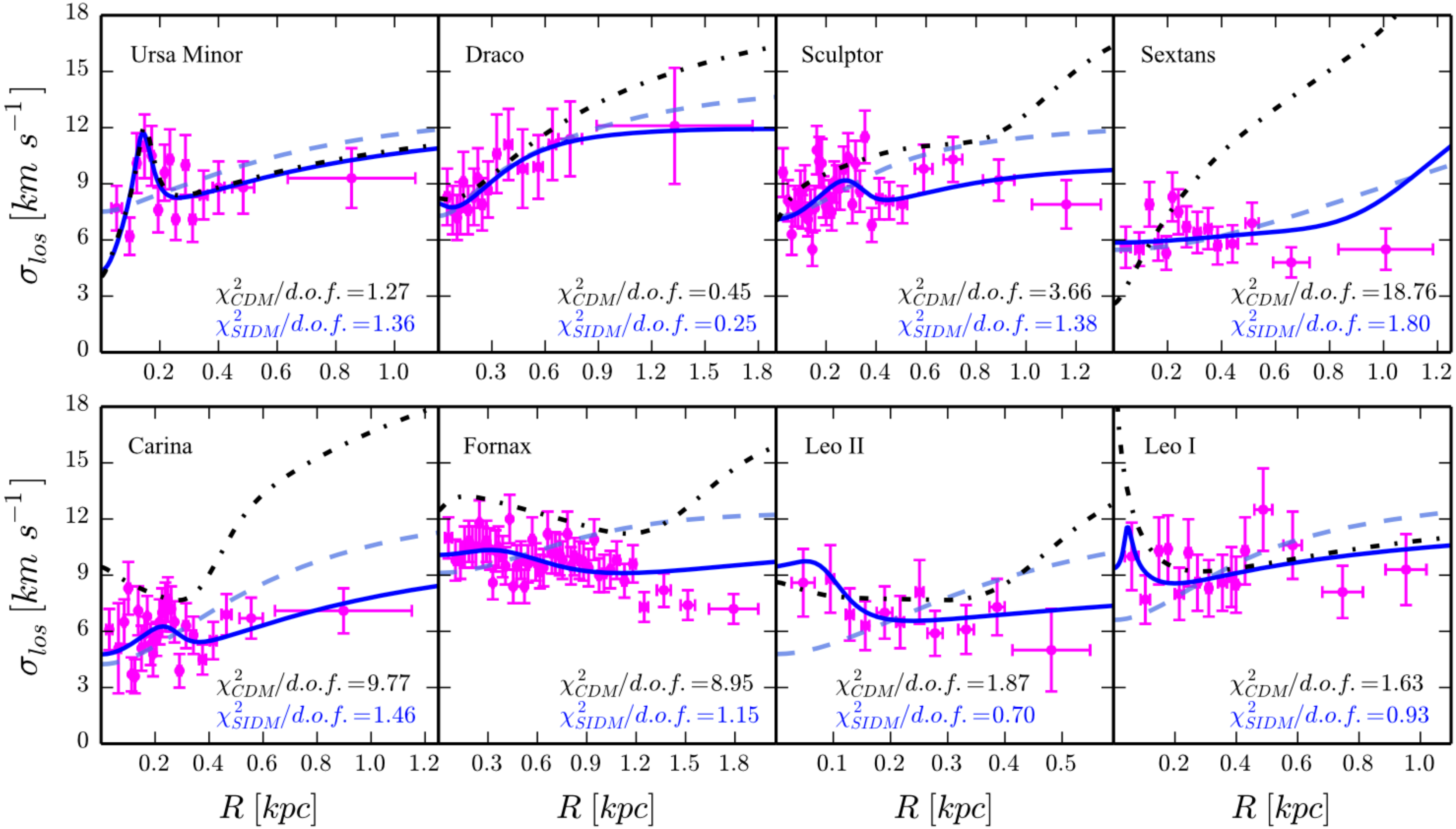
σ/m=10 cm²/g

$$M_{1/2} = 3\,G^{-1}\langle\sigma_{\rm los}^2\rangle\,r_{1/2}$$

$$V_{\rm circ}(r_{1/2}) = \sqrt{3\,\langle\sigma_{\rm los}^2\rangle}\,.$$

Vogelsberger, Zavala, Loeb (2012)

To fully understand the dynamics, we need SIDM simulations with the stellar disk



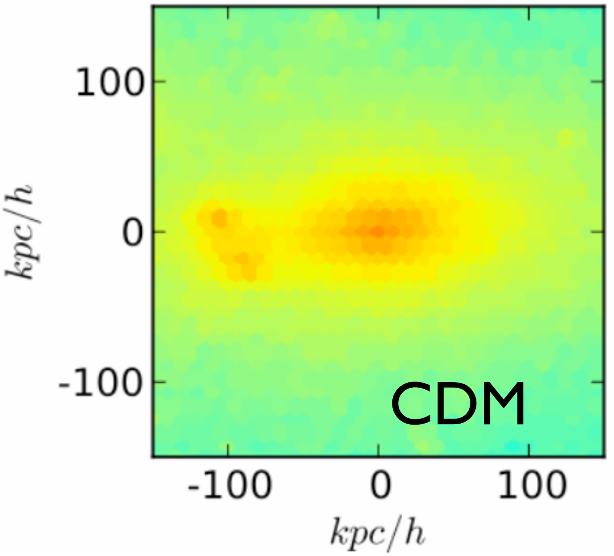
Dot-dashed black: CDM (best fit)

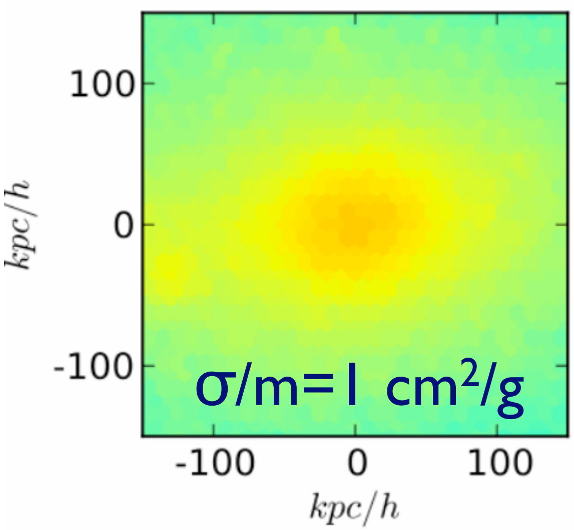
Solid blue: SIDM (spatially varying stellar anisotropy)

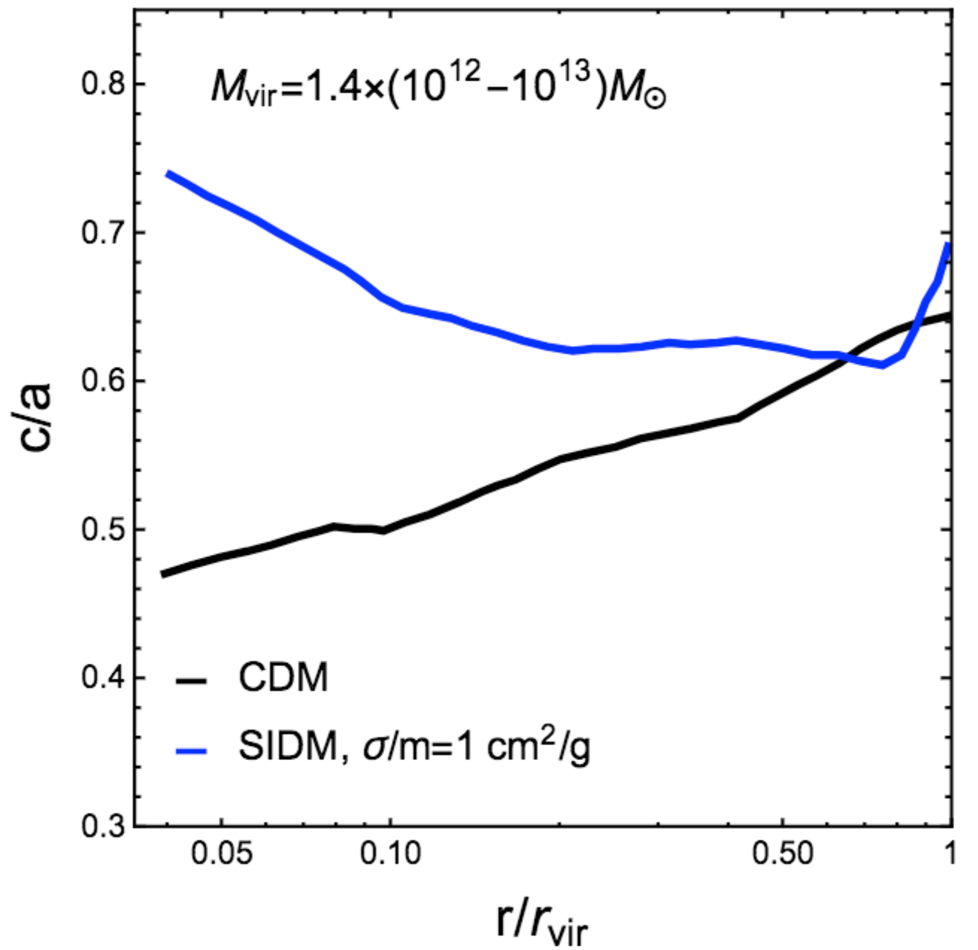
Dashed blue: SIDM (spatially constant stellar anisotropy)

Valli & HBY (Nature Astronomy, 2017)

Halo Shapes







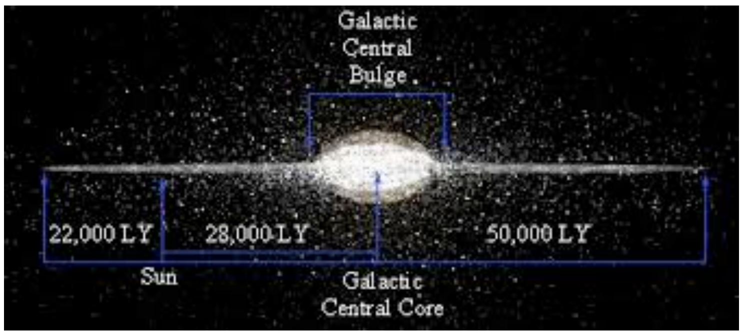
median halo shapes

Peter et al. (2013)

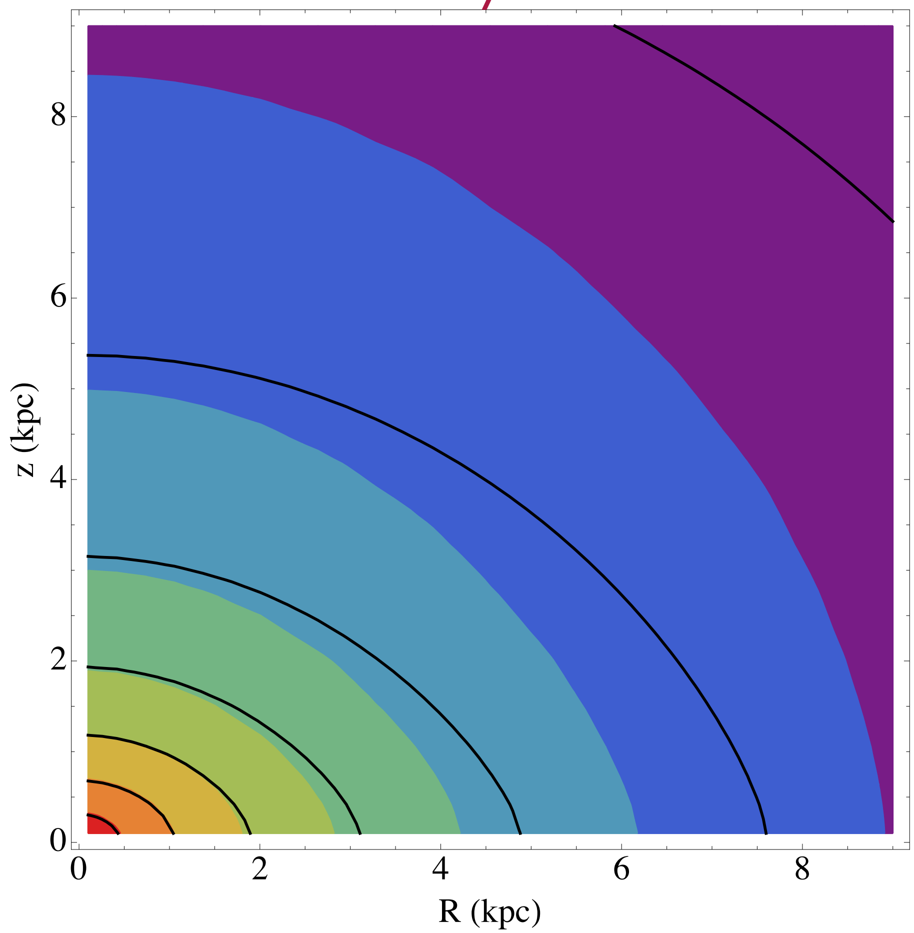
- CDM halos are triaxial, Jing & Suto (2002)
- Dark matter self-interactions make the halo rounder

Tying SIDM to Baryons

- SIDM may follow the stellar distribution; halo morphology

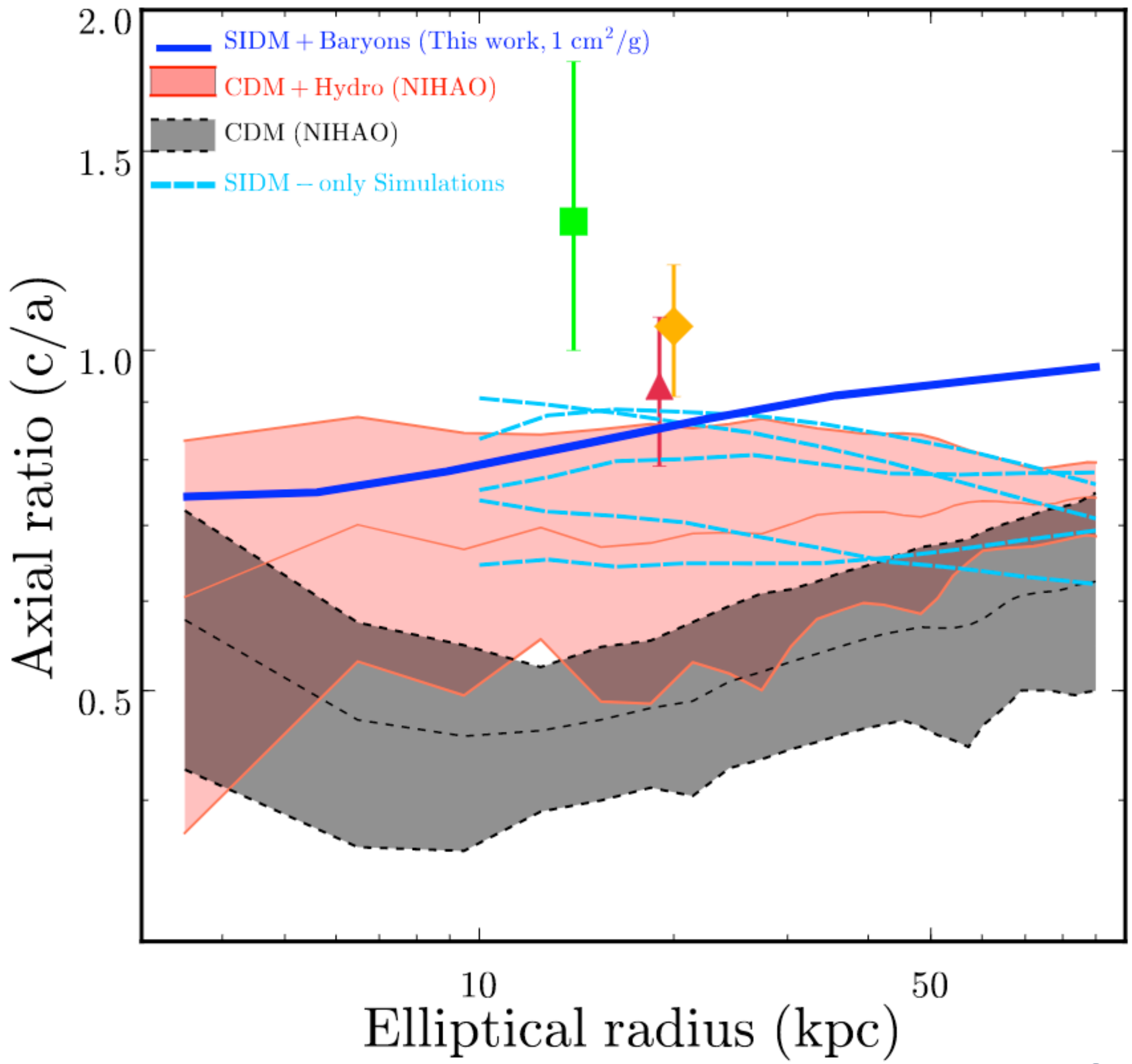


SIDM density contour



with Kaplinghat, Keeley, Linden (2013)

A Milky-Way SIDM Model

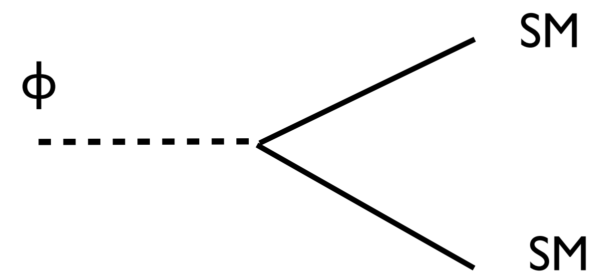


With Omid et al. (2018)

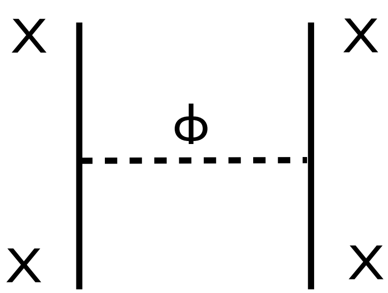
Cosmological Constraints

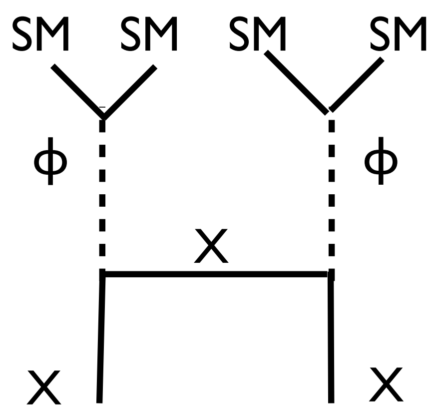
- The mediator may dominate the energy density of the Universe

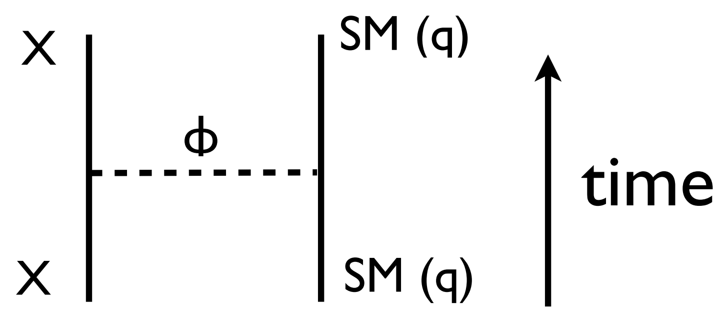
mediator mass: ~10 MeV



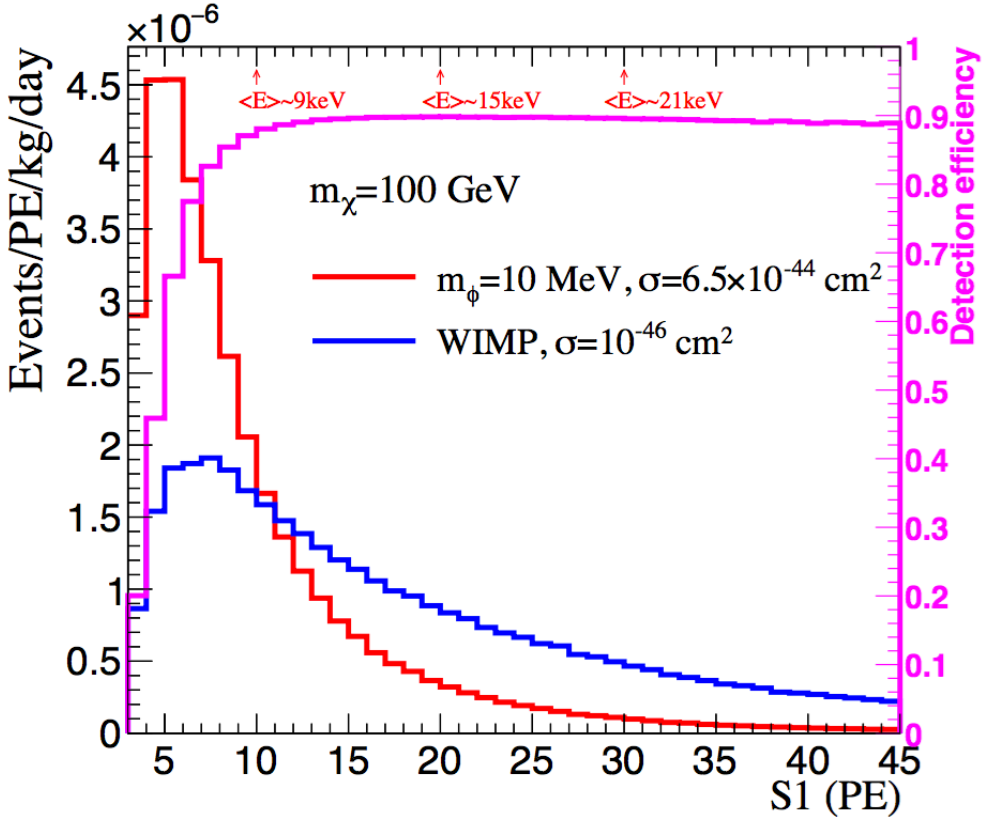
A simple (super) model

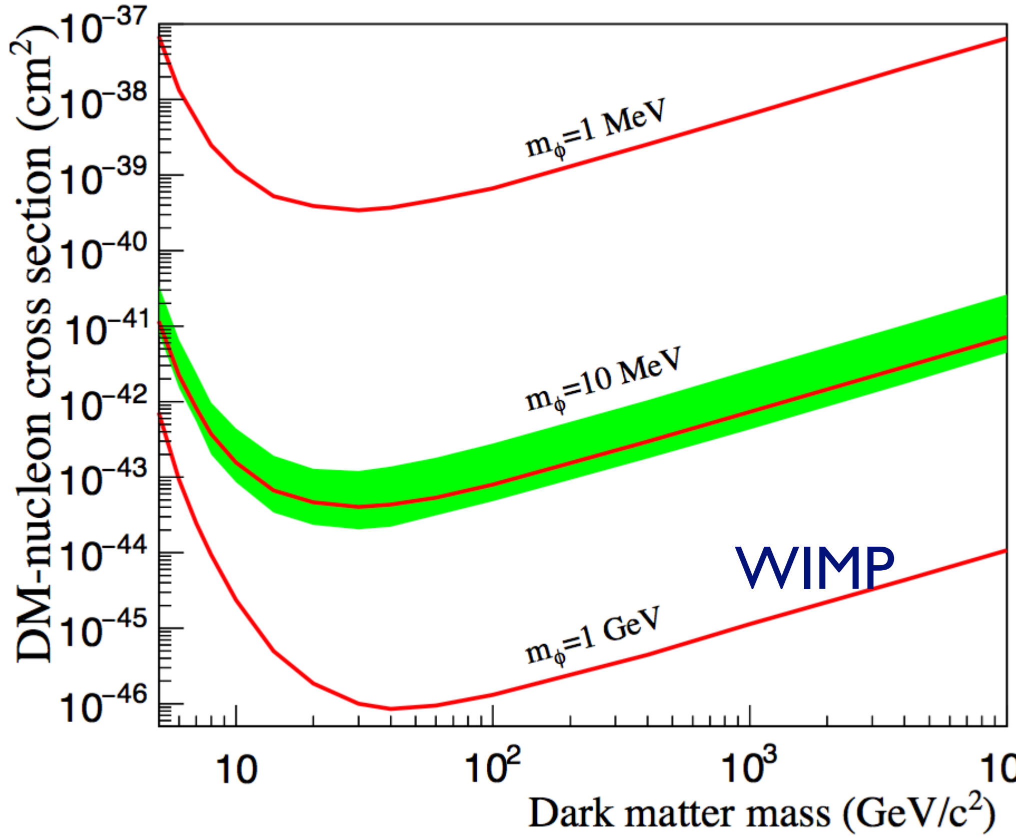




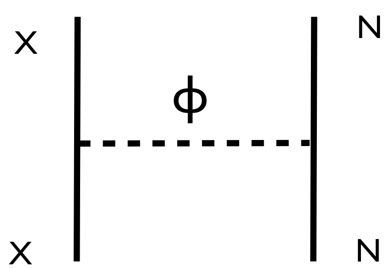


Direct Detection





Smoking-gun signature

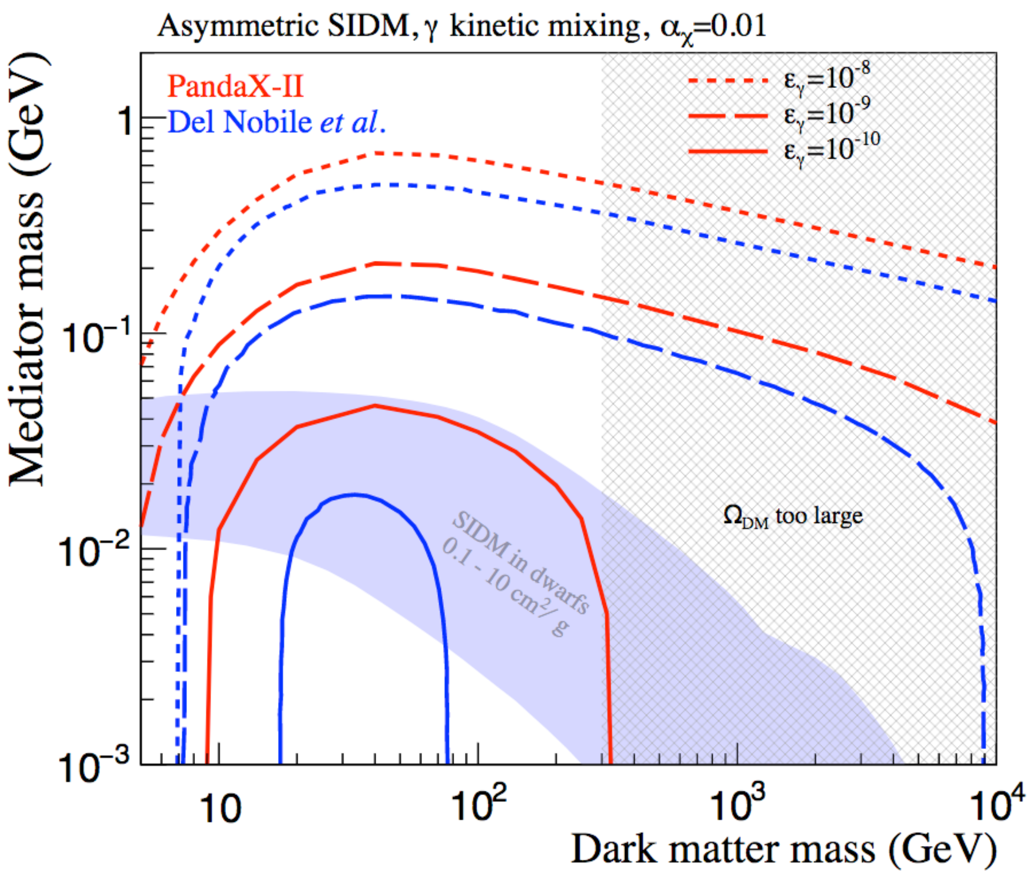


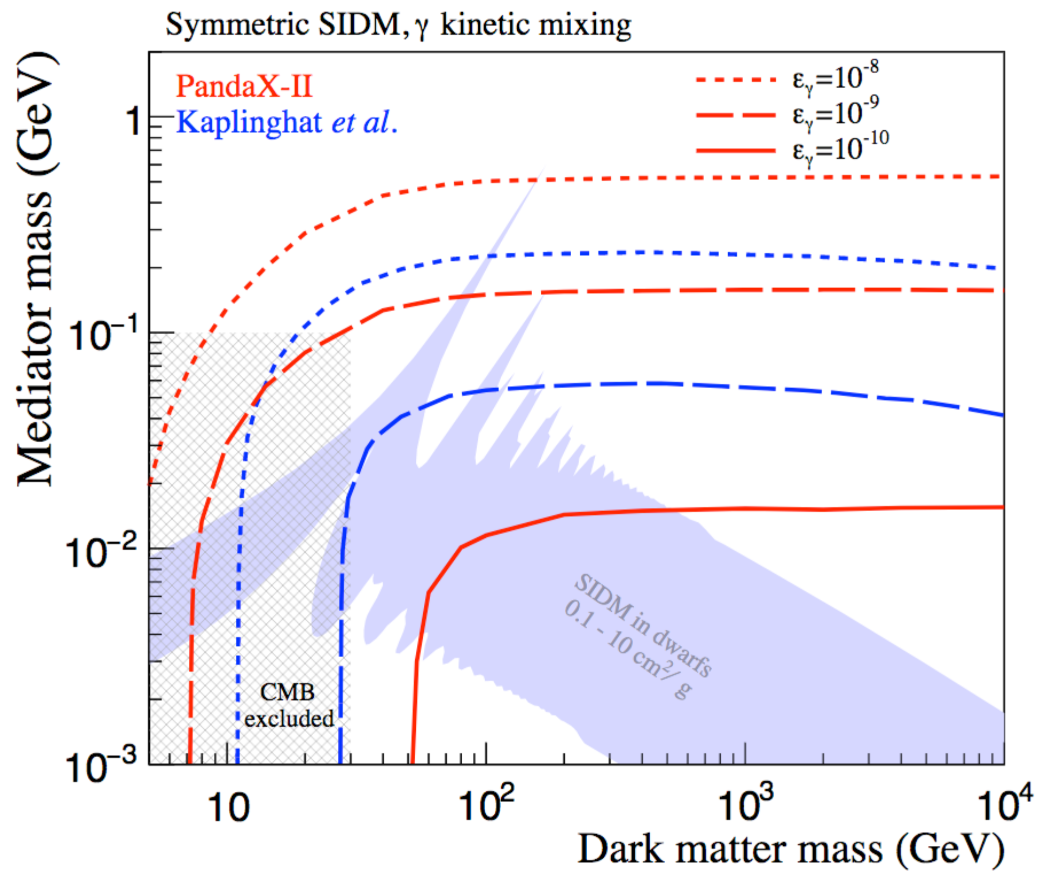
$$\sigma_{\chi N} \propto \frac{1}{(q^2 + m_\phi^2)^2}$$

WIMP: m_ϕ~1 TeV>>q
SIDM: m_ϕ~10 MeV~q

With Ren et al., the PandaX-II collaboration (PRL, 2018)

Direct Detection Constraints



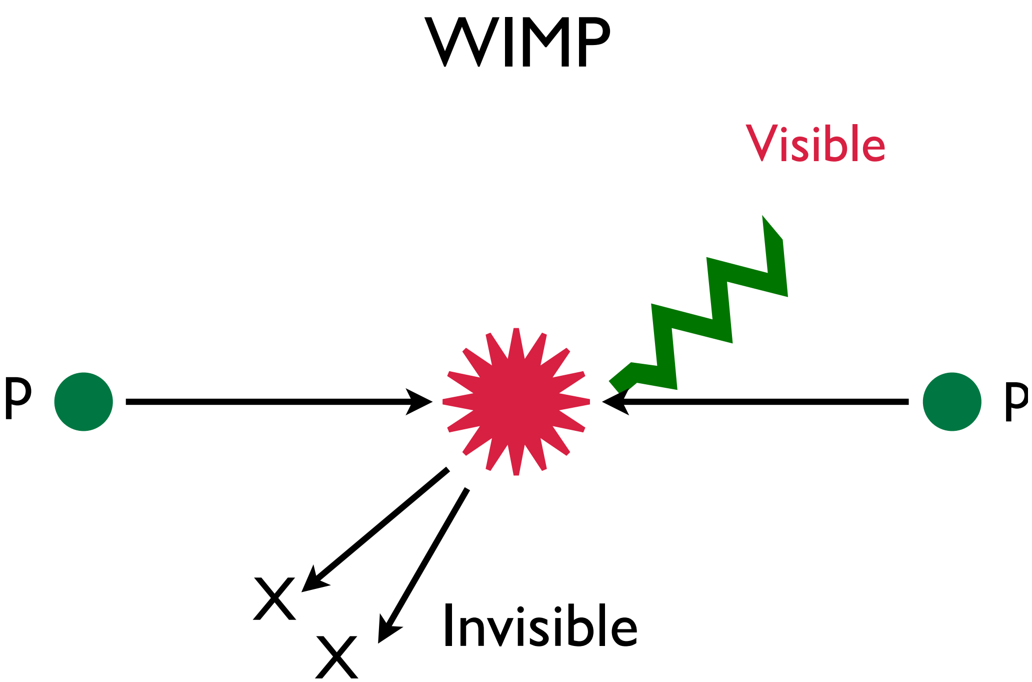


$$\epsilon_\gamma F^{\mu\nu}\phi_{\mu\nu}$$

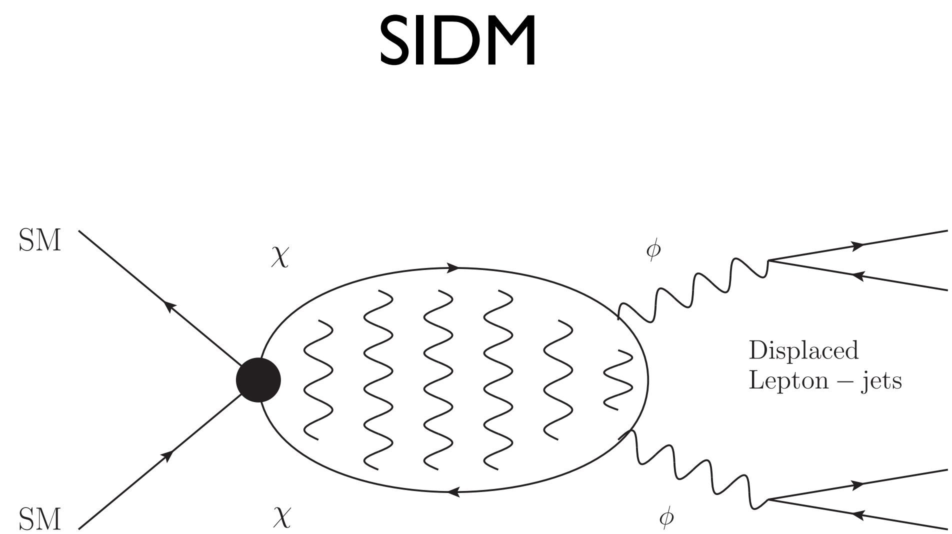
With Ren et al., the PandaX-II collaboration (PRL, 2018)

SIDM at Colliders

- Striking collider signals



pp→Monojet+Missing Energy



With Ren, Tsai, Xu (in prep)

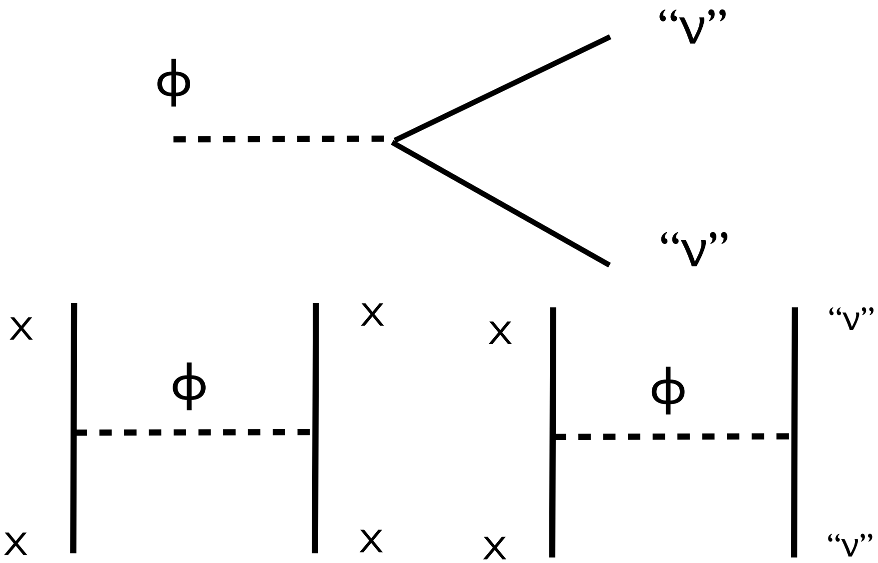
Shepherd, Tait, Zaharijas (PRD 2009)

An, Echenard, Pospelov, Zhang (PRL 2015)

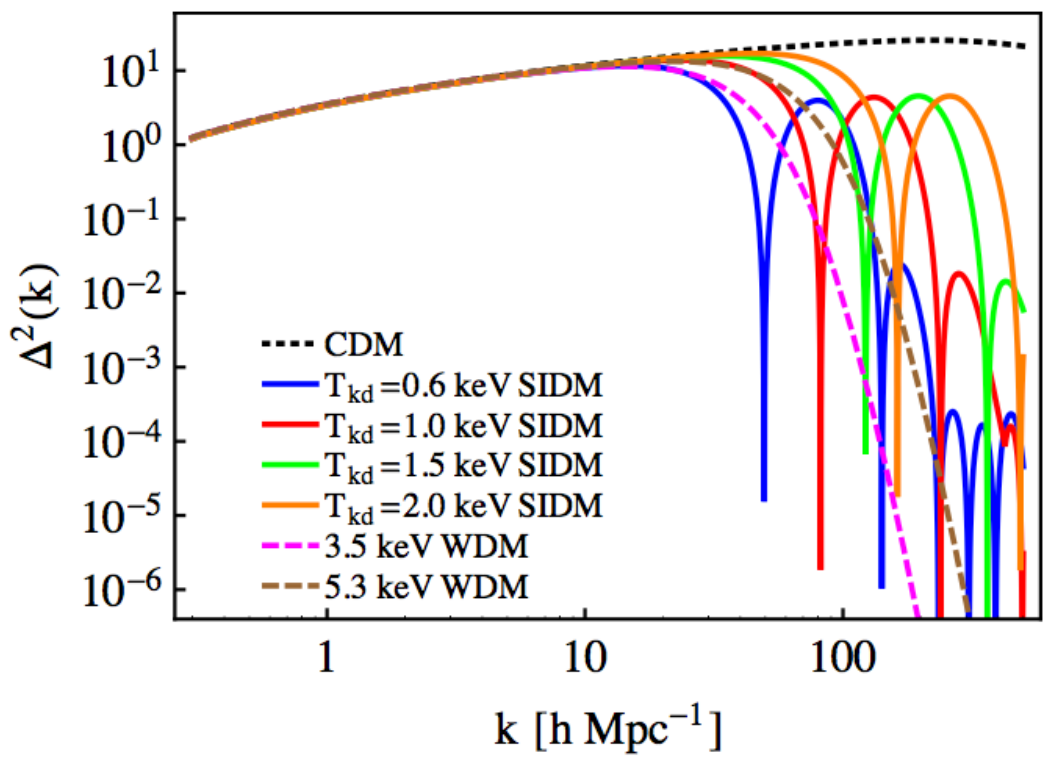
Tsai, Wang, Zhao (PRD 2015)

Cosmological Signatures

- The mediator has to decay to massless particles



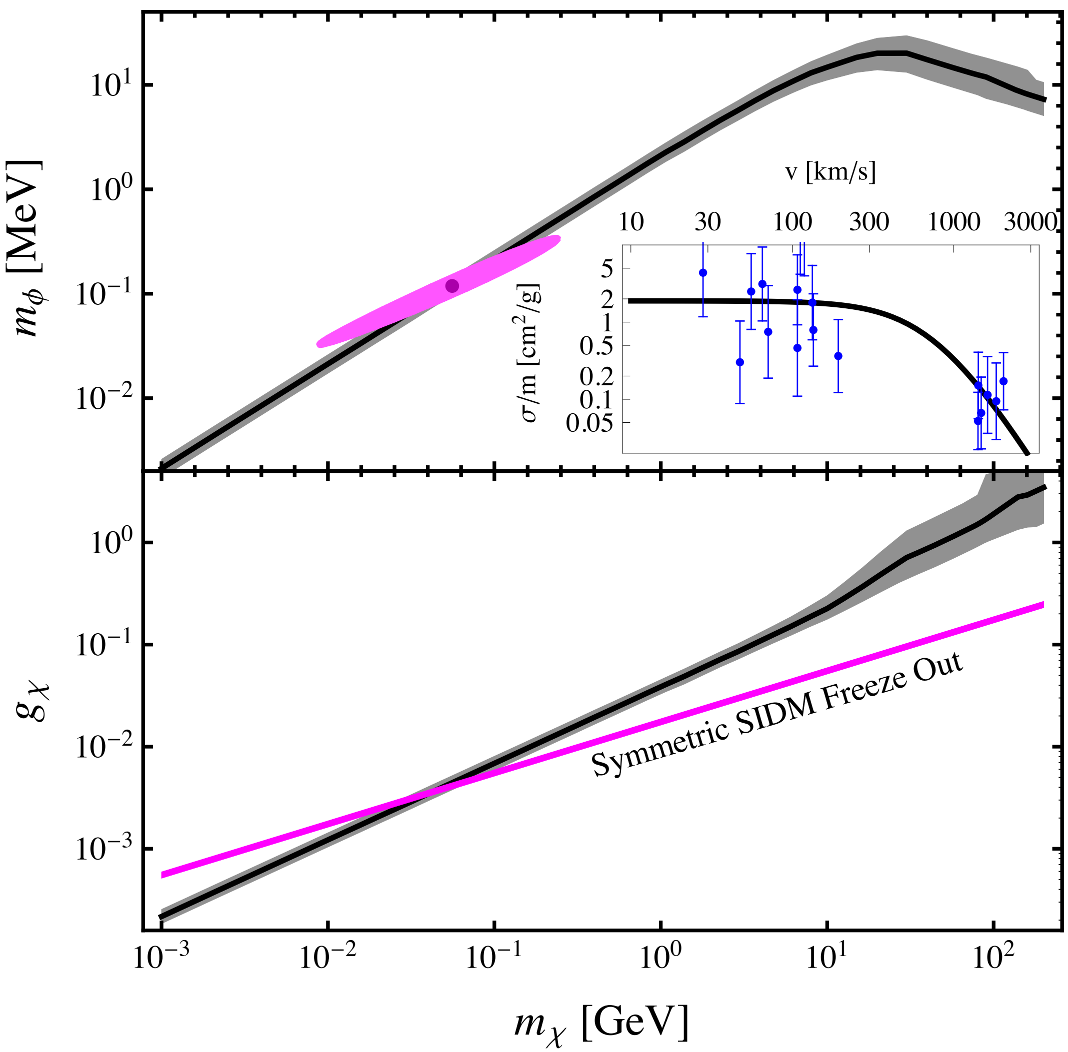
$$T_{\rm kd} \approx \frac{1.38\ \text{keV}}{\sqrt{g_\chi g_f}} \left[\frac{m_\chi}{100\ \text{GeV}}\right]^{\frac{1}{4}} \left[\frac{m_\phi}{10\ \text{MeV}}\right] \left[\frac{g_*}{3.38}\right]^{\frac{1}{8}} \left[\frac{0.5}{\xi}\right]^{\frac{3}{2}}$$



- Damped dark matter matter power spectrum
- Additional massless degrees of freedom, CMB Stage-IV
- Lyman-alpha constraints

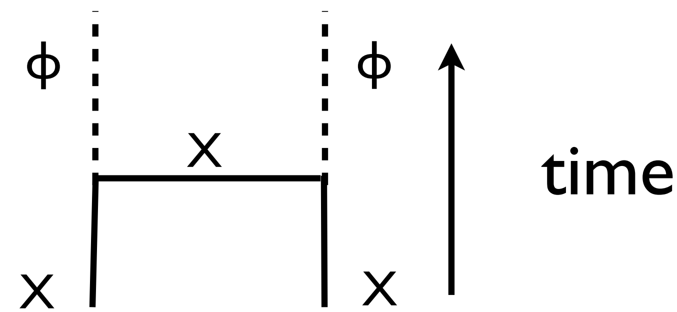
with Huo, Kaplinghat, Pan (PLB, 2017)

Production Mechanism



Three free parameters: m_χ, m_ϕ, $g_\chi(\alpha_\chi)$

magenta: symmetric DM



fix the coupling by the relic density

Narrow mass range: 10 MeV-300 MeV

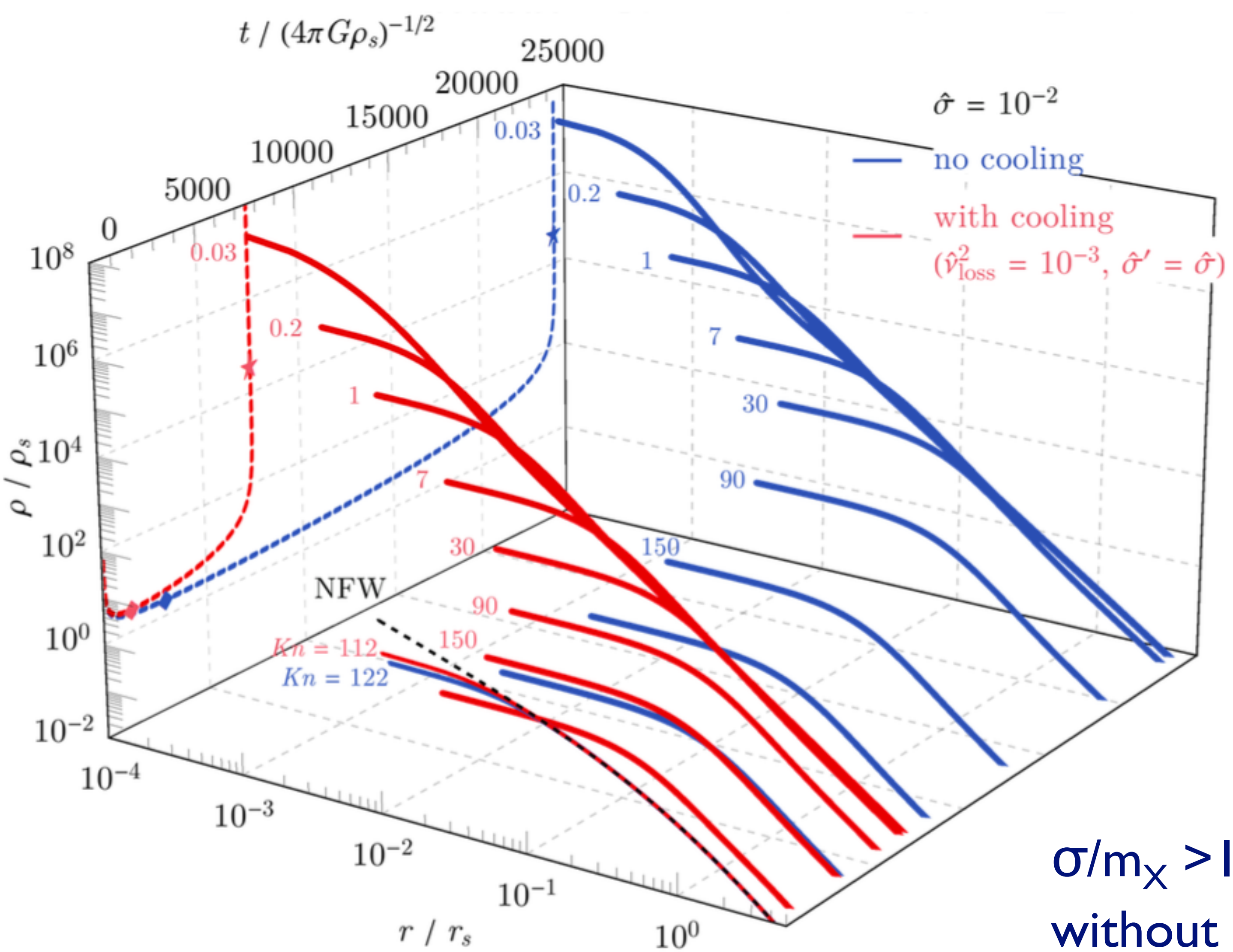
gray: asymmetric DM

Large mass range

For given m_χ, the stellar kinematics fixes both $g_\chi(\alpha_\chi)$ and m_ϕ

With Ran, Kaplinghat, Pan (PLB, 2017)

Gravothermal Catastrophe?

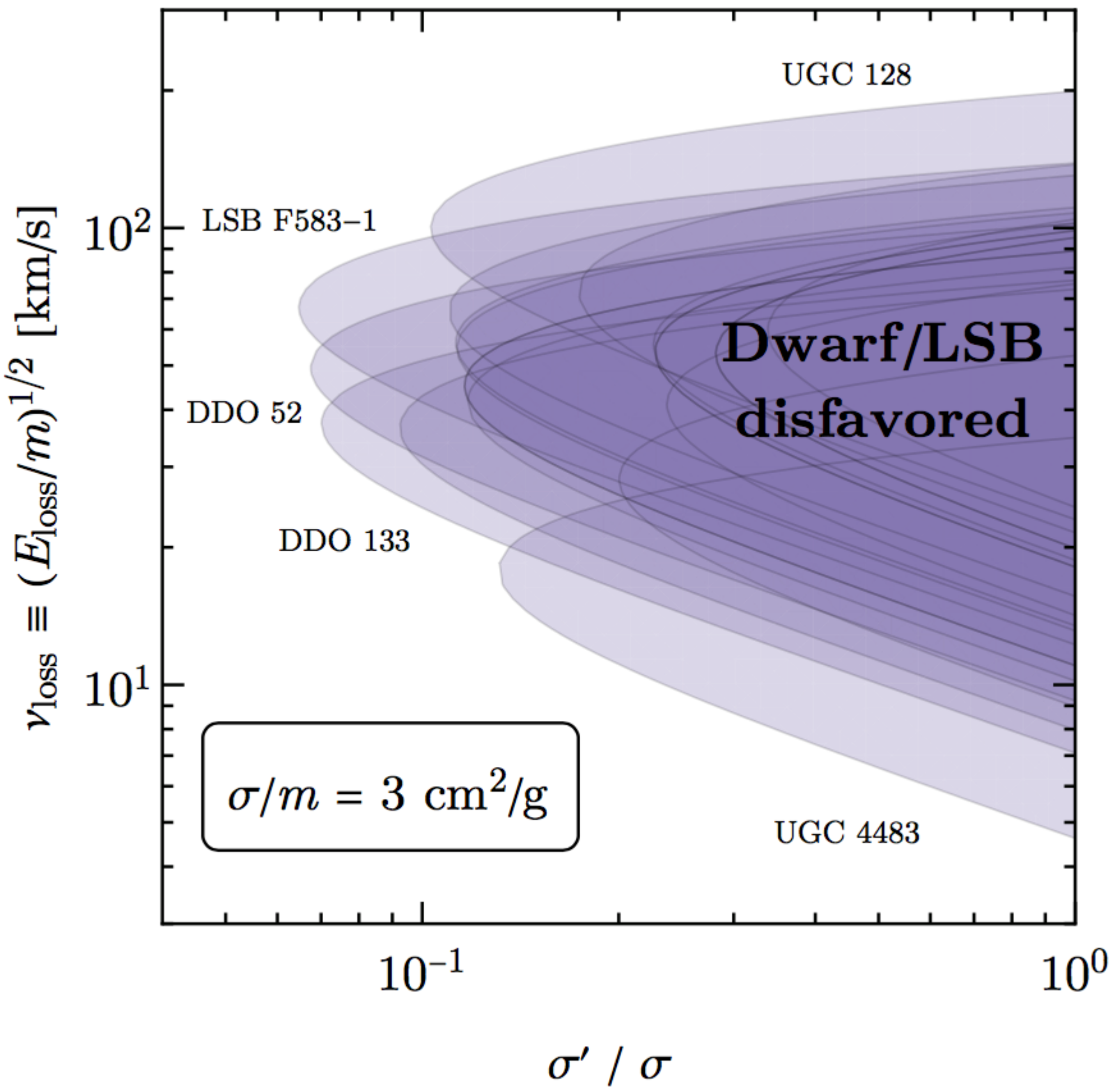


$\sigma/m_X > 10\ cm^2/g$
without cooling

Balberg & Shapiro (2001)

with Essig, McDermott, Zhong (in prep)

Constraining Dissipative DM Scattering



with Essig, McDermott, Zhong (in prep)

Summary

- For dwarf spheroidal galaxies in the Milky Way, the environment effect becomes important.

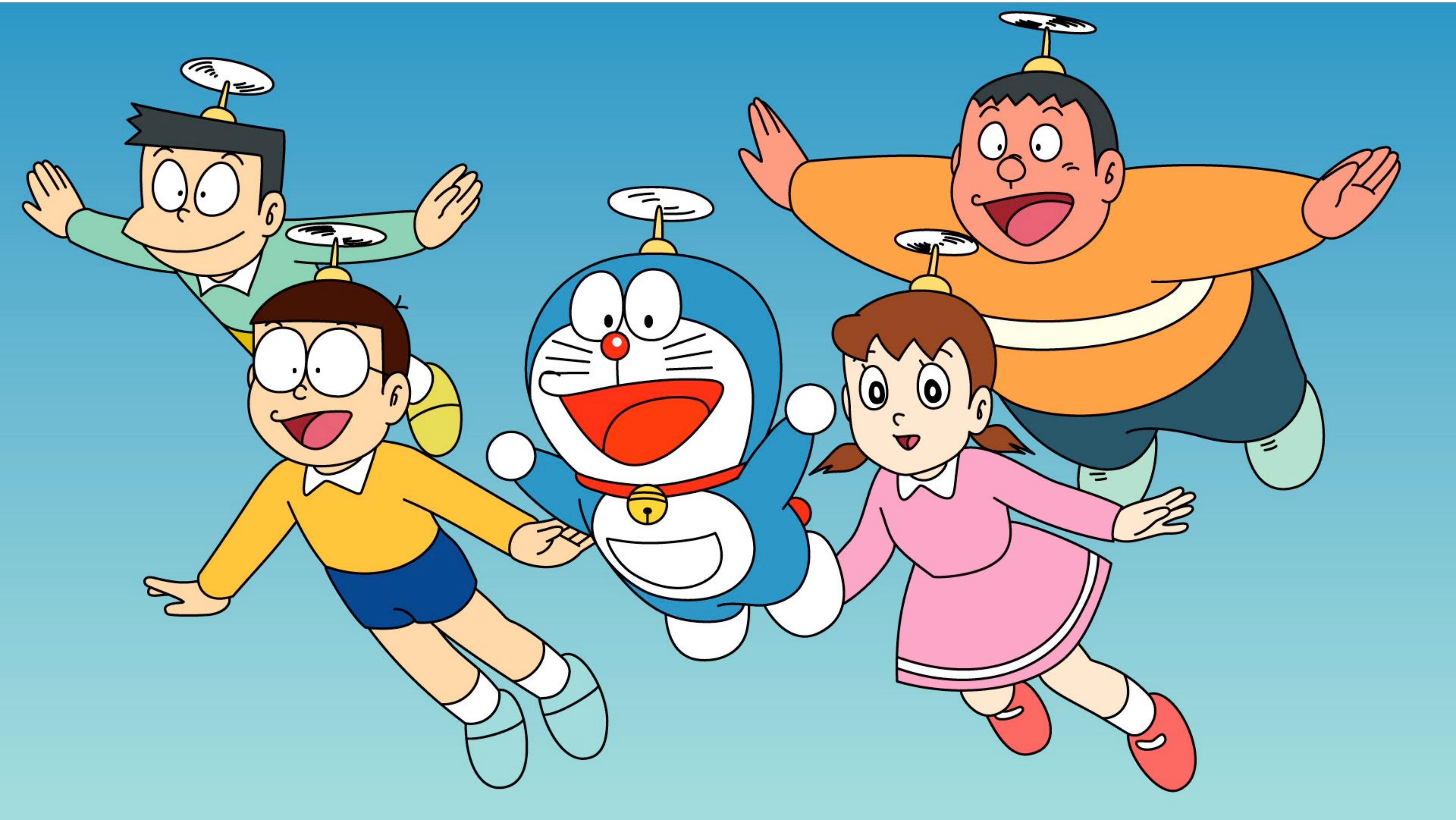
- To fully address the issues (MS & TBTF) in the SIDM framework, we need to include both SIDM and baryon physics in simulations.

- The SIDM halo shape and the baryon distribution are correlated.

- SIDM has other novel signals in terrestrial experiments, cosmological and astrophysical observations.

Large scales: ΛSIDM~ΛCDM

Small scales: ΛSIDM>ΛCDM



Have a lot of fun. Thank you!