Structure Formation in Alternative Dark Matter

Oral candidacy presentation

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Committee members:
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Outline

- Personal background

- Background introduction
  - evidences for dark matter
  - classical candidates and experimental searches
  - alternative candidates
  - motivations from astrophysical observations
  - numeric simulations

- Alternative dark matter models & relevant projects
  - SIDM early studies
  - dissipative SIDM
  - SIDM beyond dwarf scale
  - other dark matter models

- Future plans/ projects

Personal background

- Third year graduate student in Physics
- Research interests: the nature of dark matter, numeric simulations of galaxy formation

- Previous work that are not directly related to the thesis
    - Radiative transfer post-processing and high redshift JWST predictions for IllustrisTNG

      Vogelsberger et al. 2020, https://ui.adsabs.harvard.edu/abs/2020MNRAS.492.5167V/abstract

      Shen et al. 2020, https://ui.adsabs.harvard.edu/abs/2020MNRAS.495.4747S/abstract

      Shen et al. 2021, https://arxiv.org/abs/2104.12788
    - First year project at Caltech: Observational constraints of bolometric quasar luminosity functions at z=0-7

      Shen et al. 2020, https://ui.adsabs.harvard.edu/abs/2020MNRAS.495.3252S/abstract

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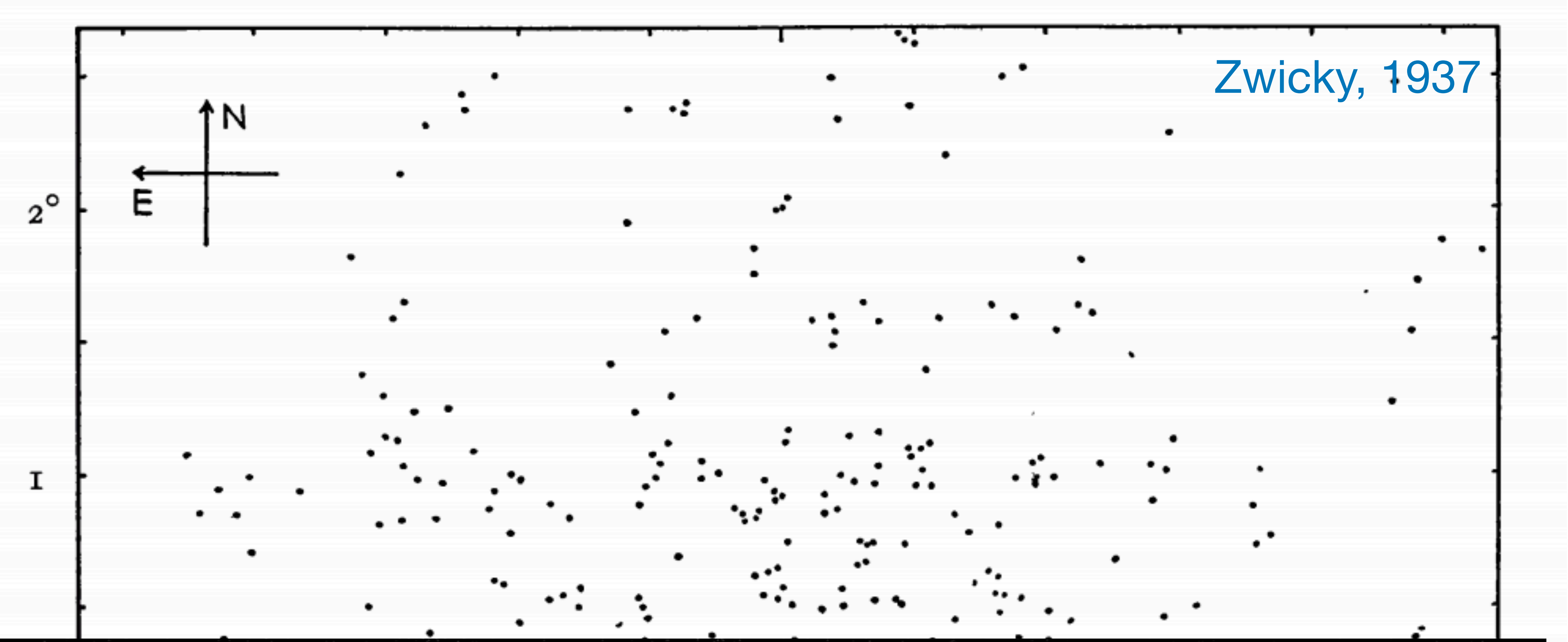
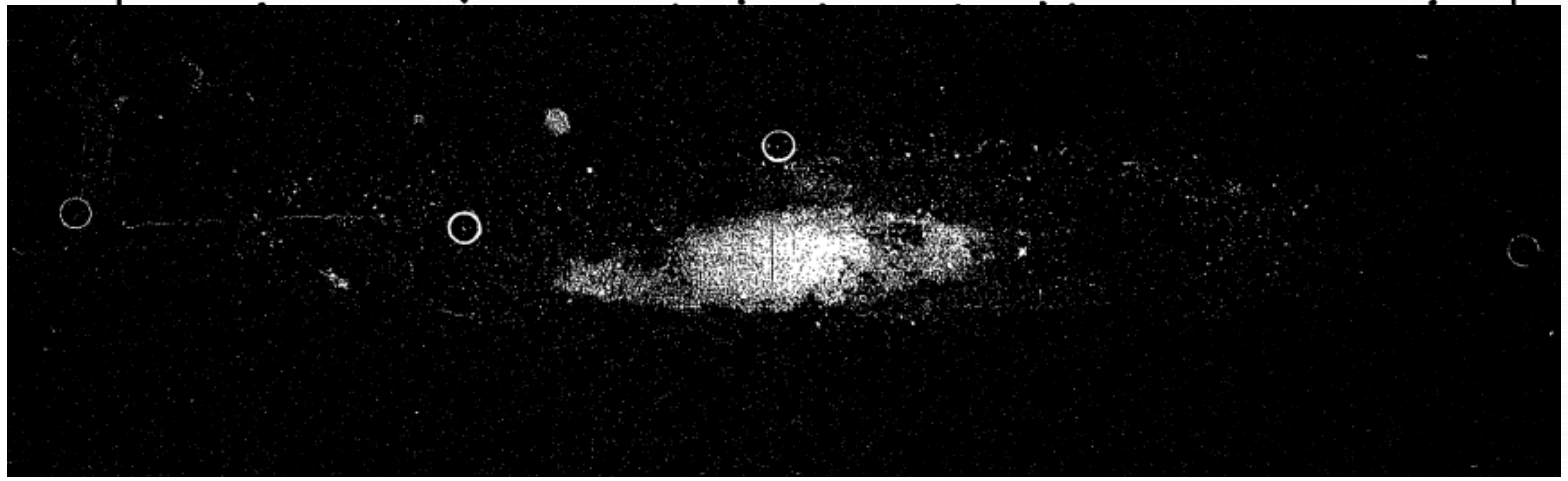
Early history

- Poincaré, 1906
- Kapteyn, 1922; Oort, 1932: stellar velocities in solar neighborhood
- Fritz Zwicky, 1933: applied the virial theorem to the Coma Cluster and obtained evidence for unseen mass
- Horace Babcock, 1939: the rotation curve for the Andromeda Galaxy (M31)





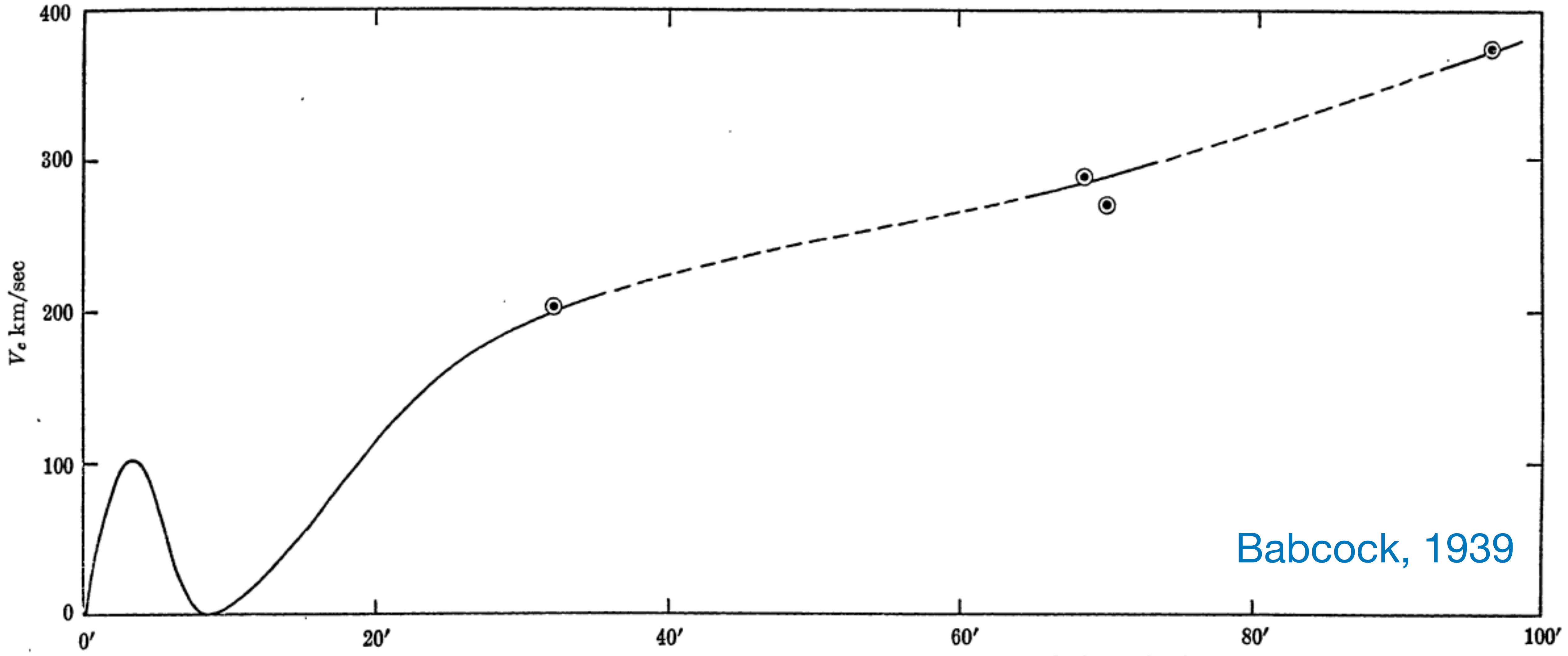
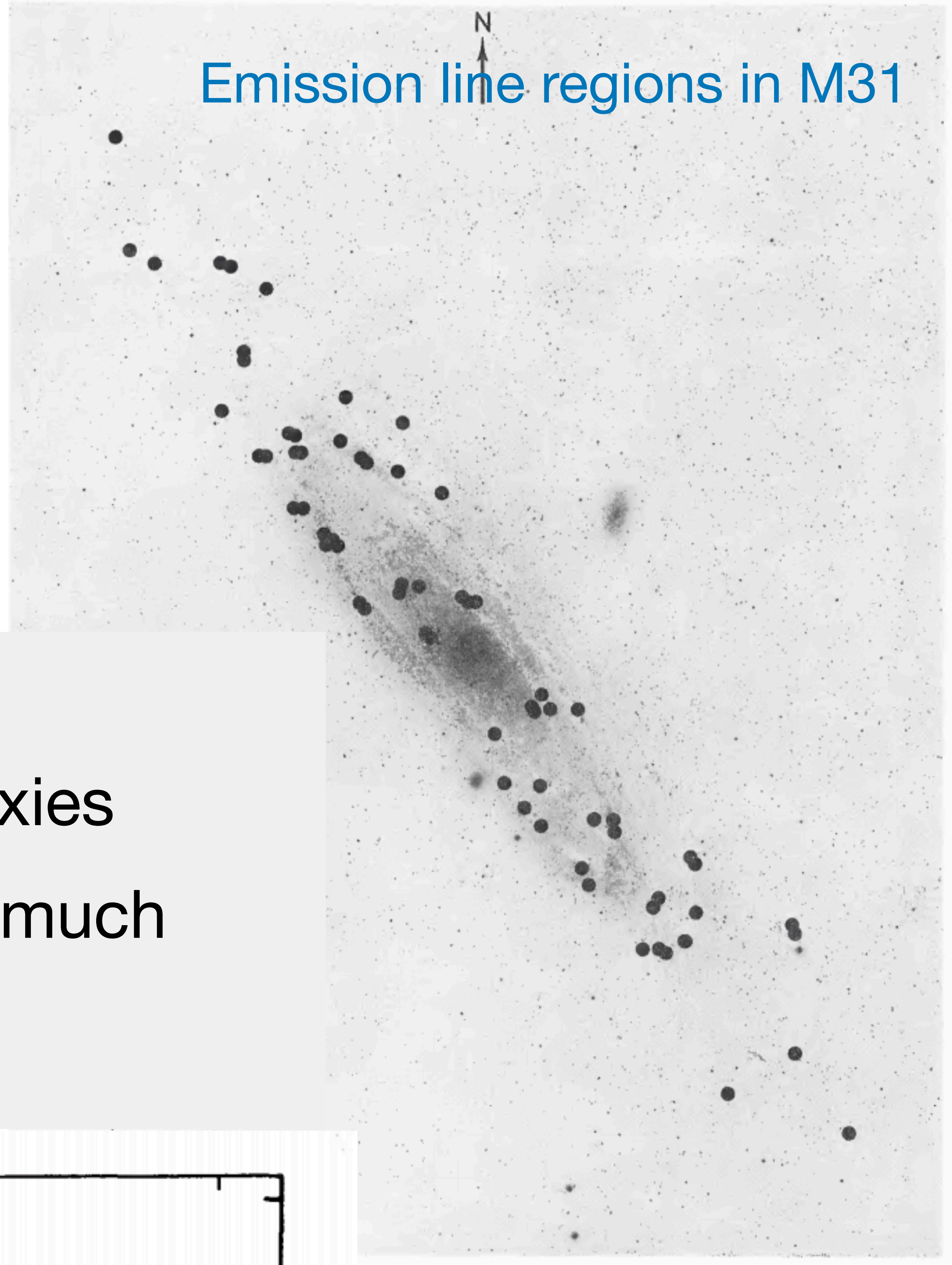
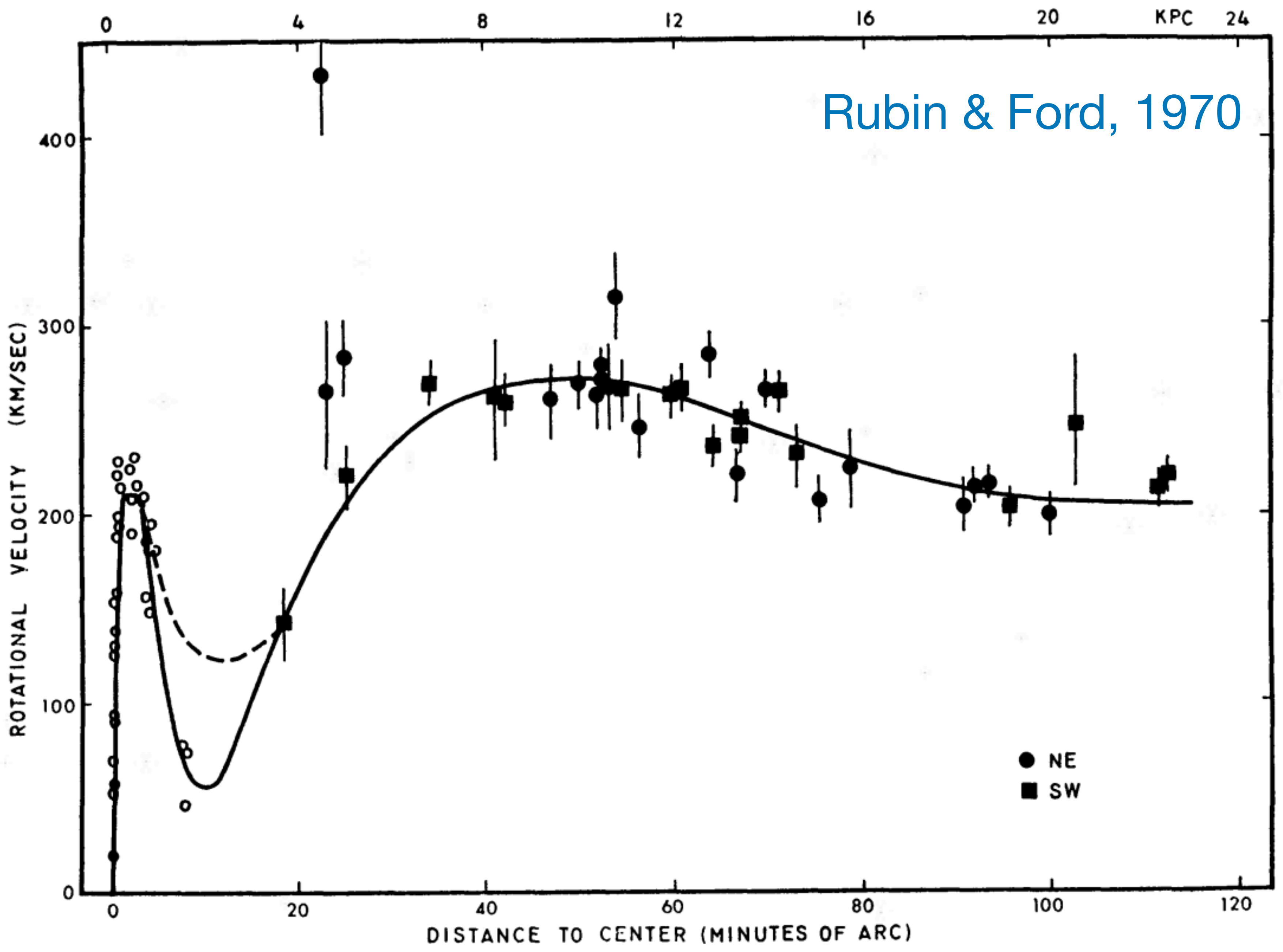


Fig. 4. Mean velocities of rotation in the plane of the spiral.

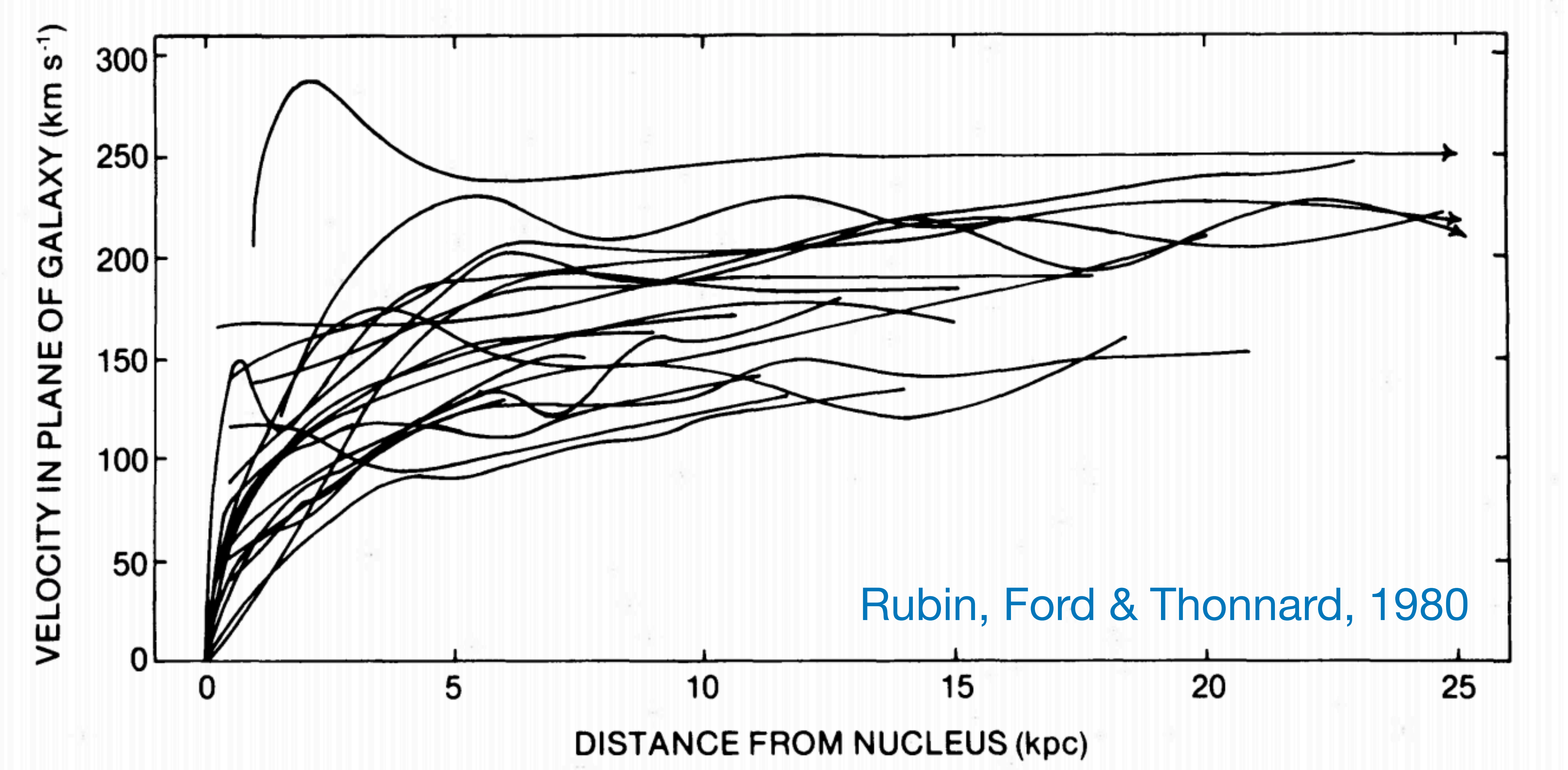
- 1970s: Vera Rubin, Kent Ford, Ken Freeman provide further strong evidences of dark matter through galaxy rotation curves

- Optical spectroscopy of HII regions in M31 (the Andromeda Galaxy)
- a “dark component” is required to explain the flatness of the rotation curves of M31





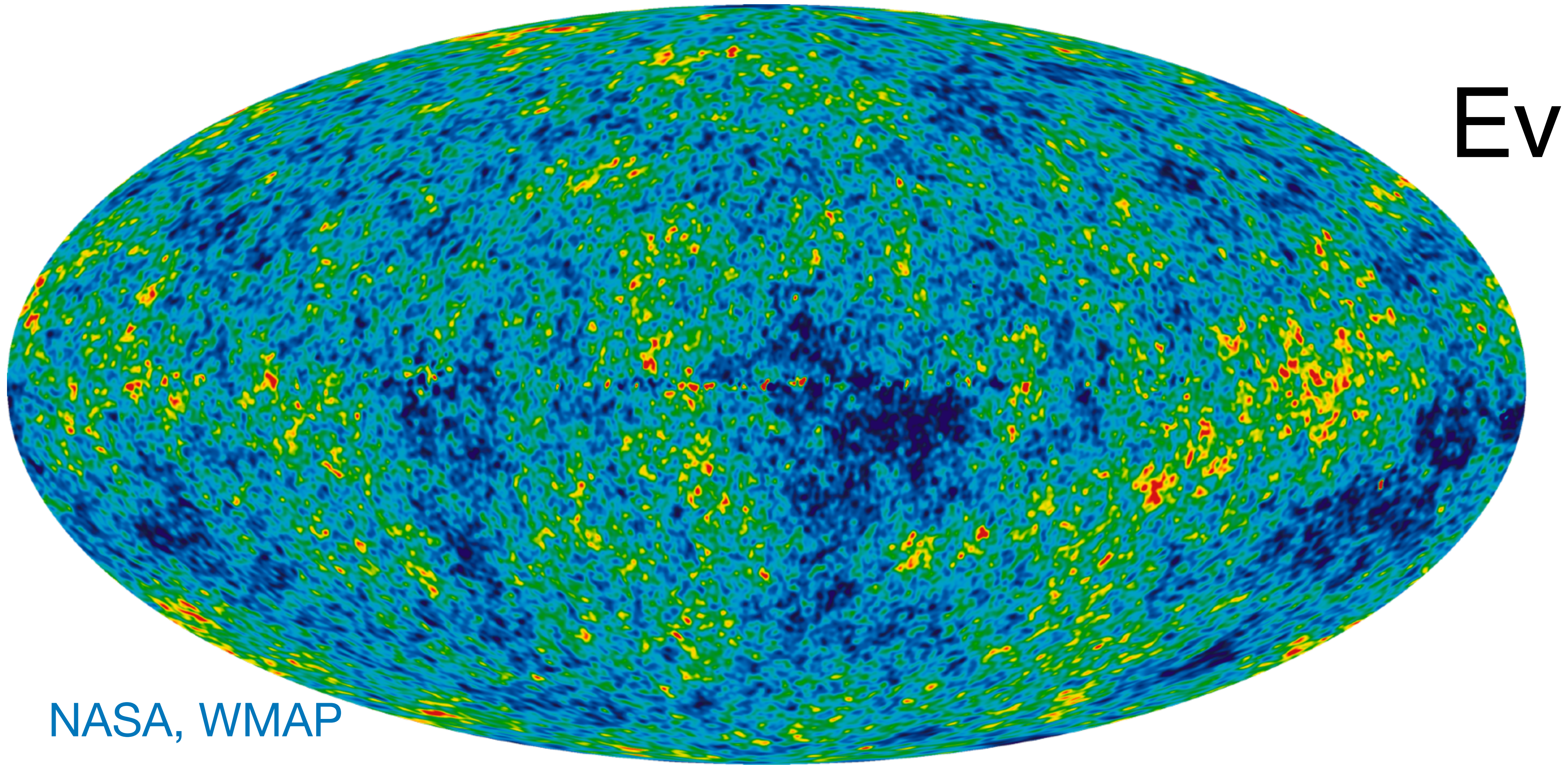
- measurements extend to more local sprial galaxies
- most galaxies must contain about six times as much dark as visible mass



- Supported by radio observations of HI rotation curves (extend to larger radii)

e.g., Rogstad & Shostak, 1972; Roberts & Whitehurst, 1975

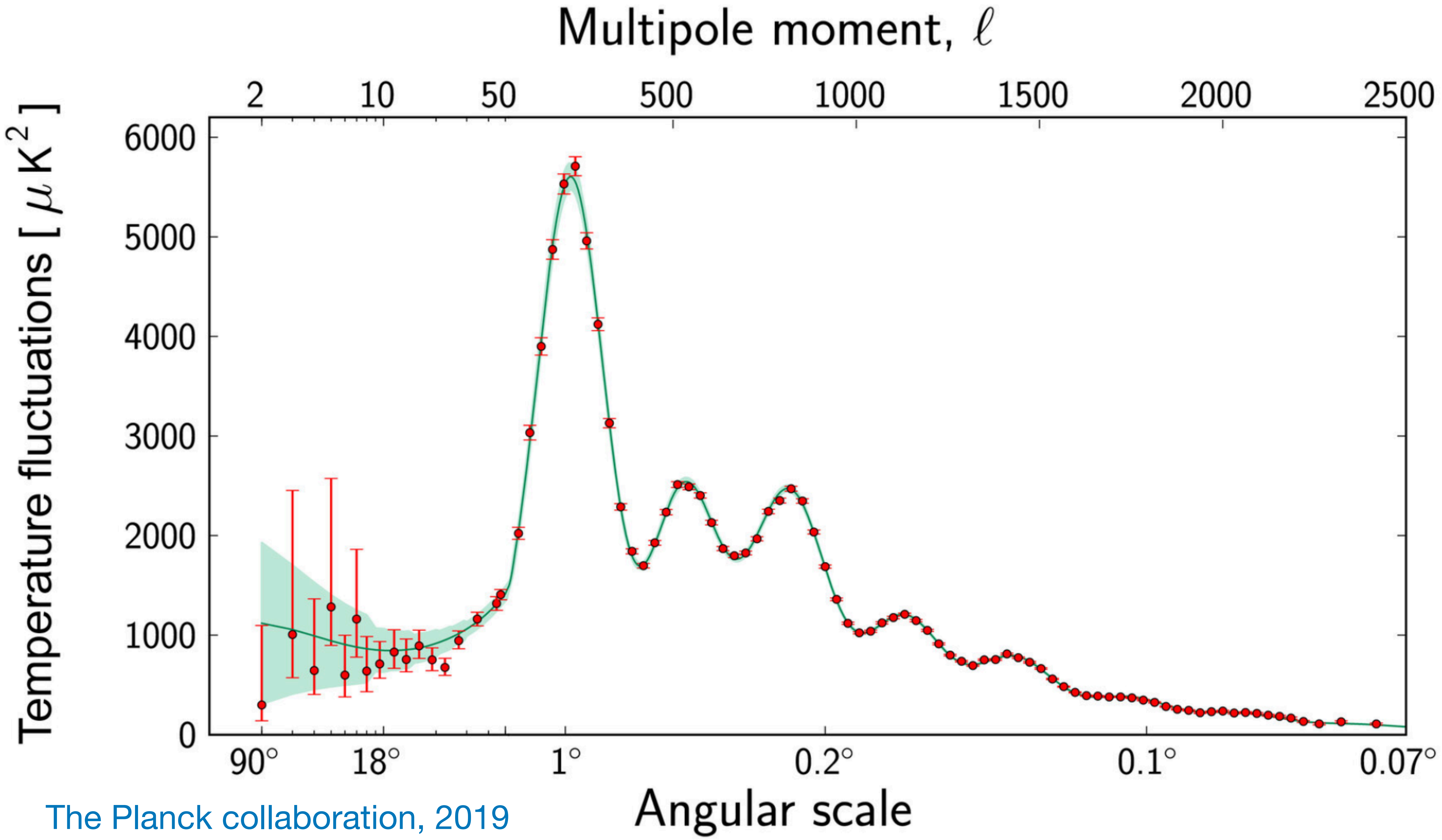
Evidences of dark matter beyond local galaxies



NASA, WMAP

- 1990s-2010s: CMB anisotropy measurements

  (COBE, 1992; WMAP, 2003-2012; Planck, 2013-present)



The Planck collaboration, 2019

- Baryon acoustic oscillation:

  radiation pressure versus gravity

  heights of the oscillation peaks

  $\rightarrow$ Ω_{dm}/Ω_b

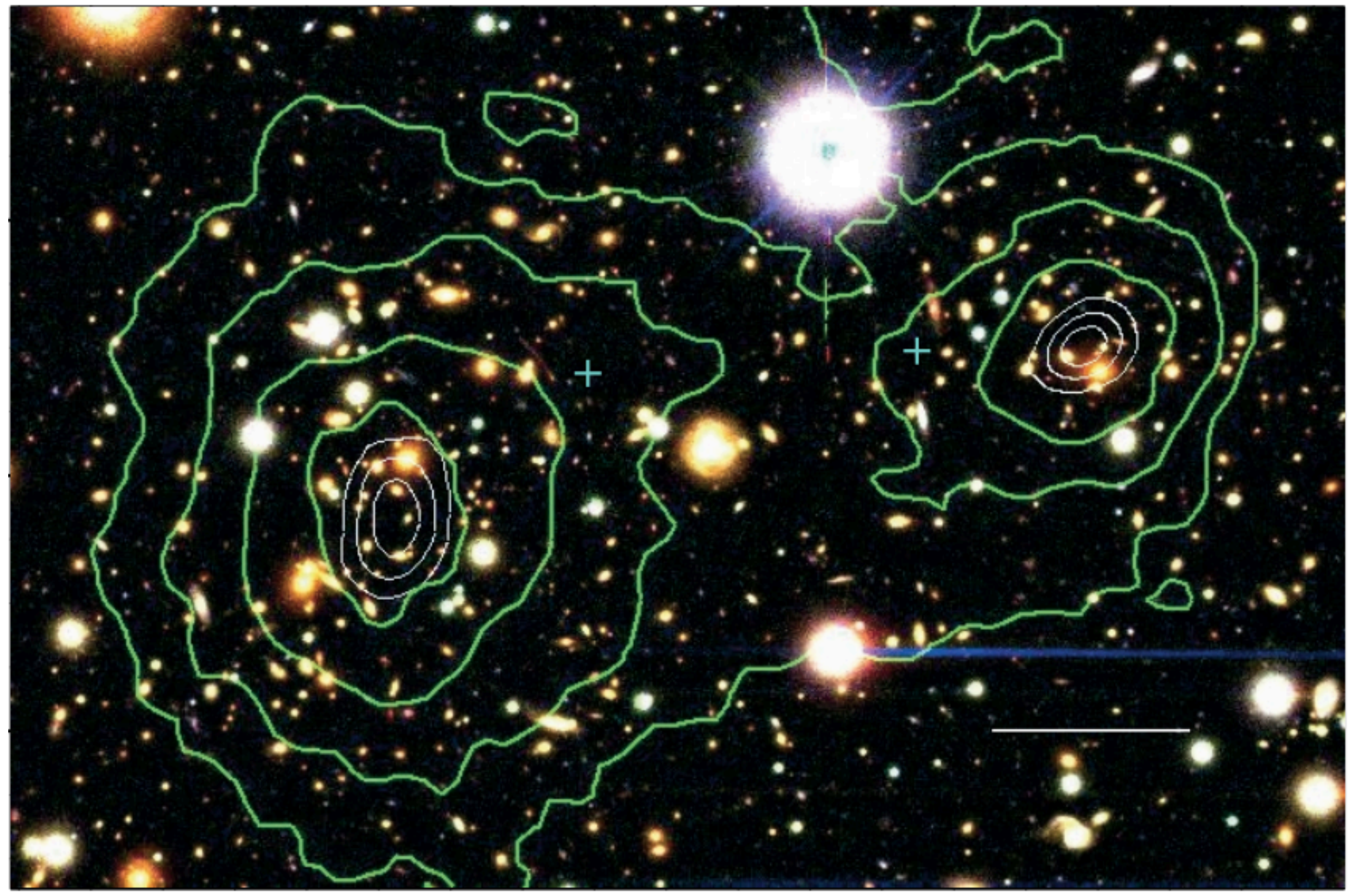
- Diffusion damping:

  hierarchy of structure formation

- The “bullet” cluster

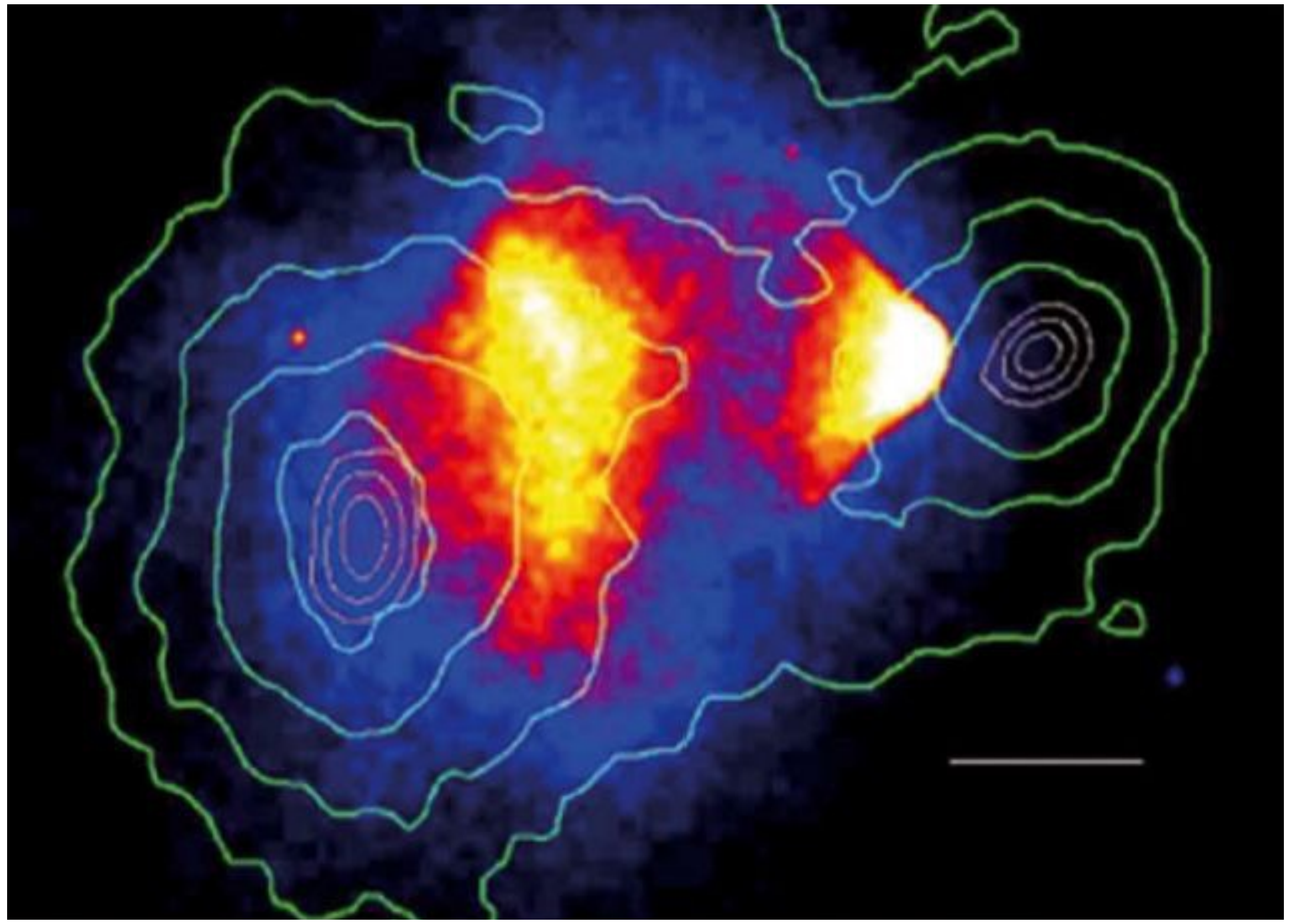
> - Clowe et al. 2006 found an 8-σ significance spatial offset of the center of the total mass from the center of the baryonic mass peaks
> - an empirical proof of dark matter that is hard to be explained with an alteration of the gravitational force law
>
> (also suggest that dark matter should be largely collisionless)

Weak lensing map

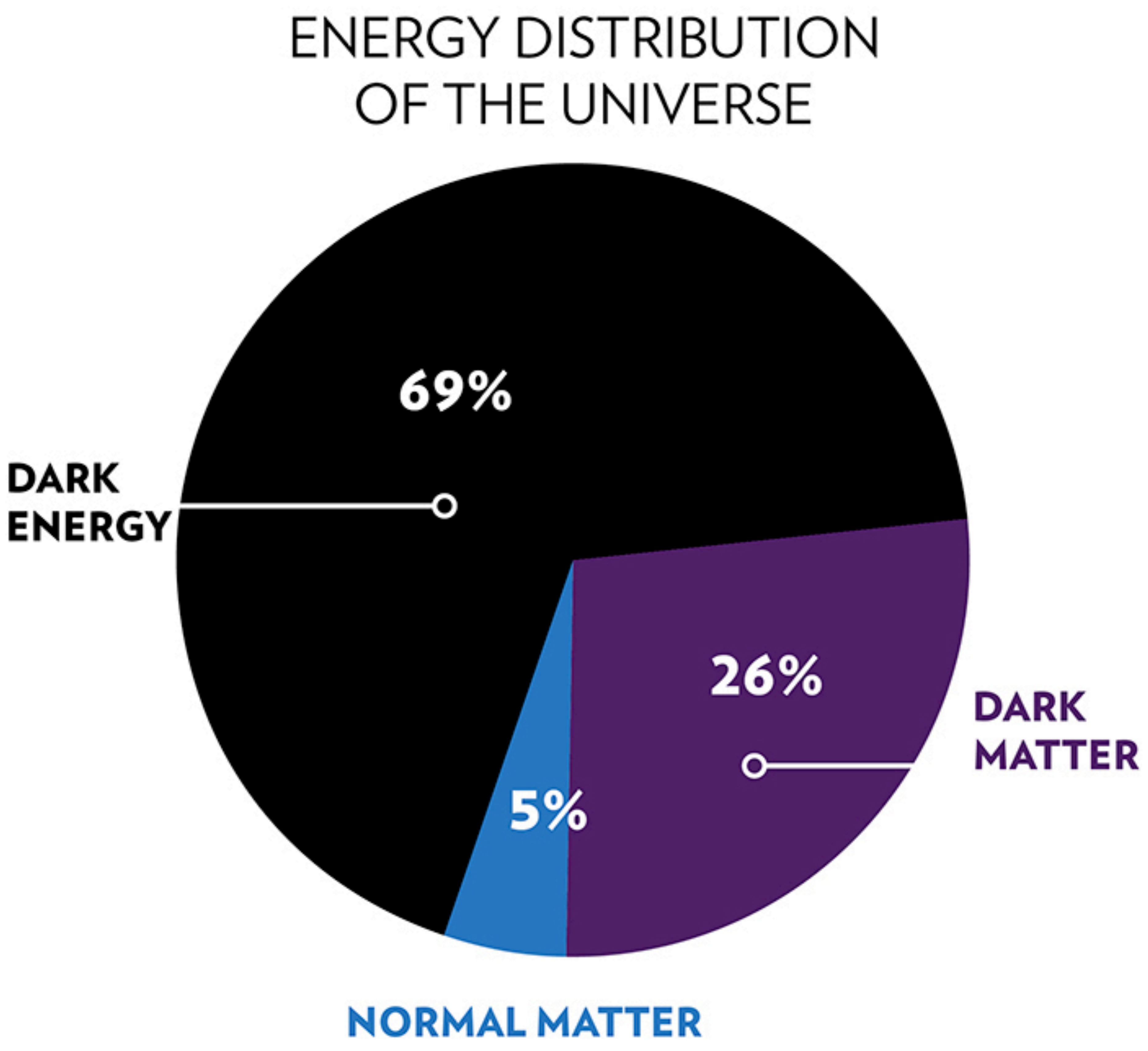


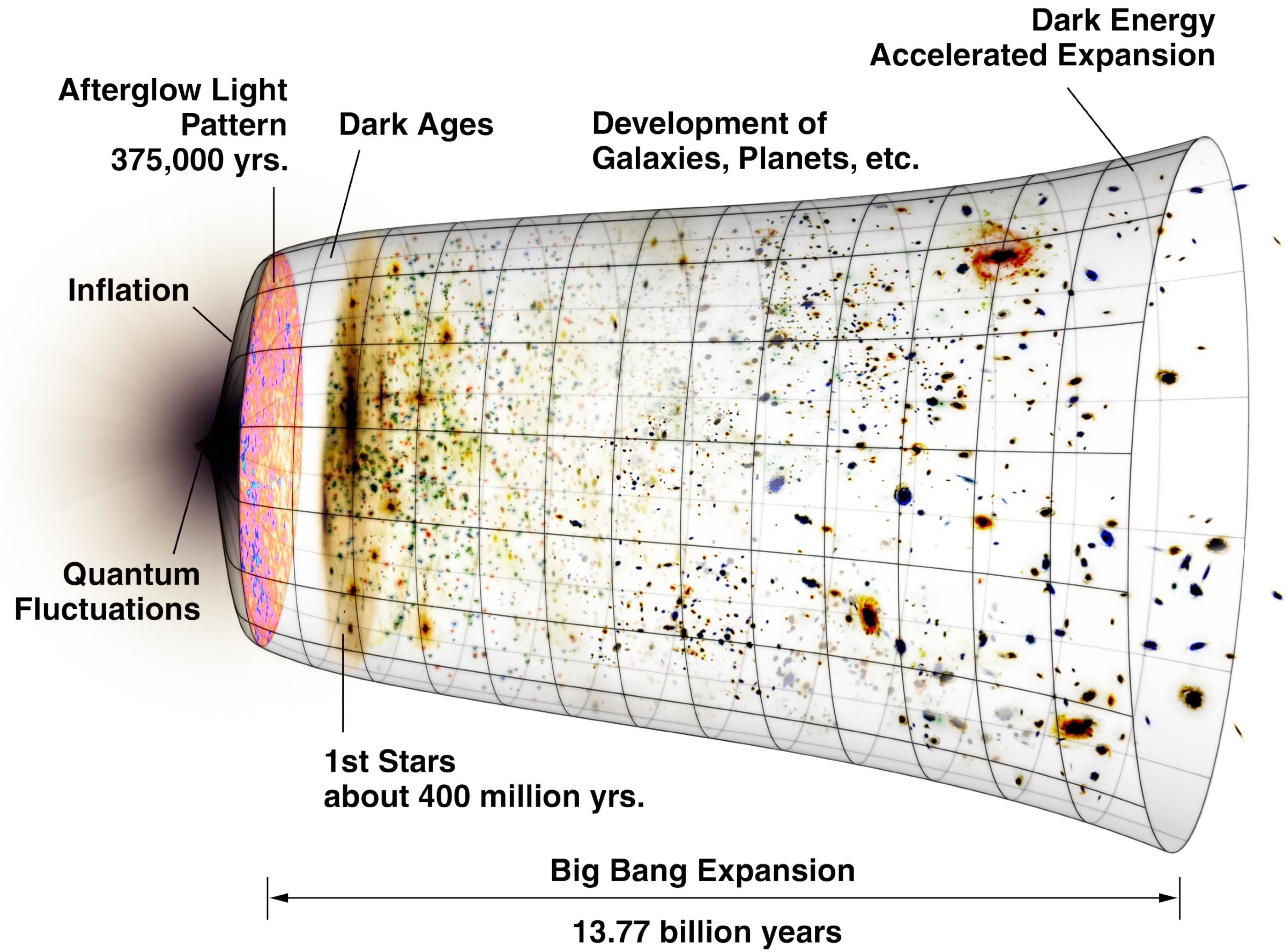
Chandra Xray image

Chandra Xray image overlay with weak lensing



The ΛCDM model

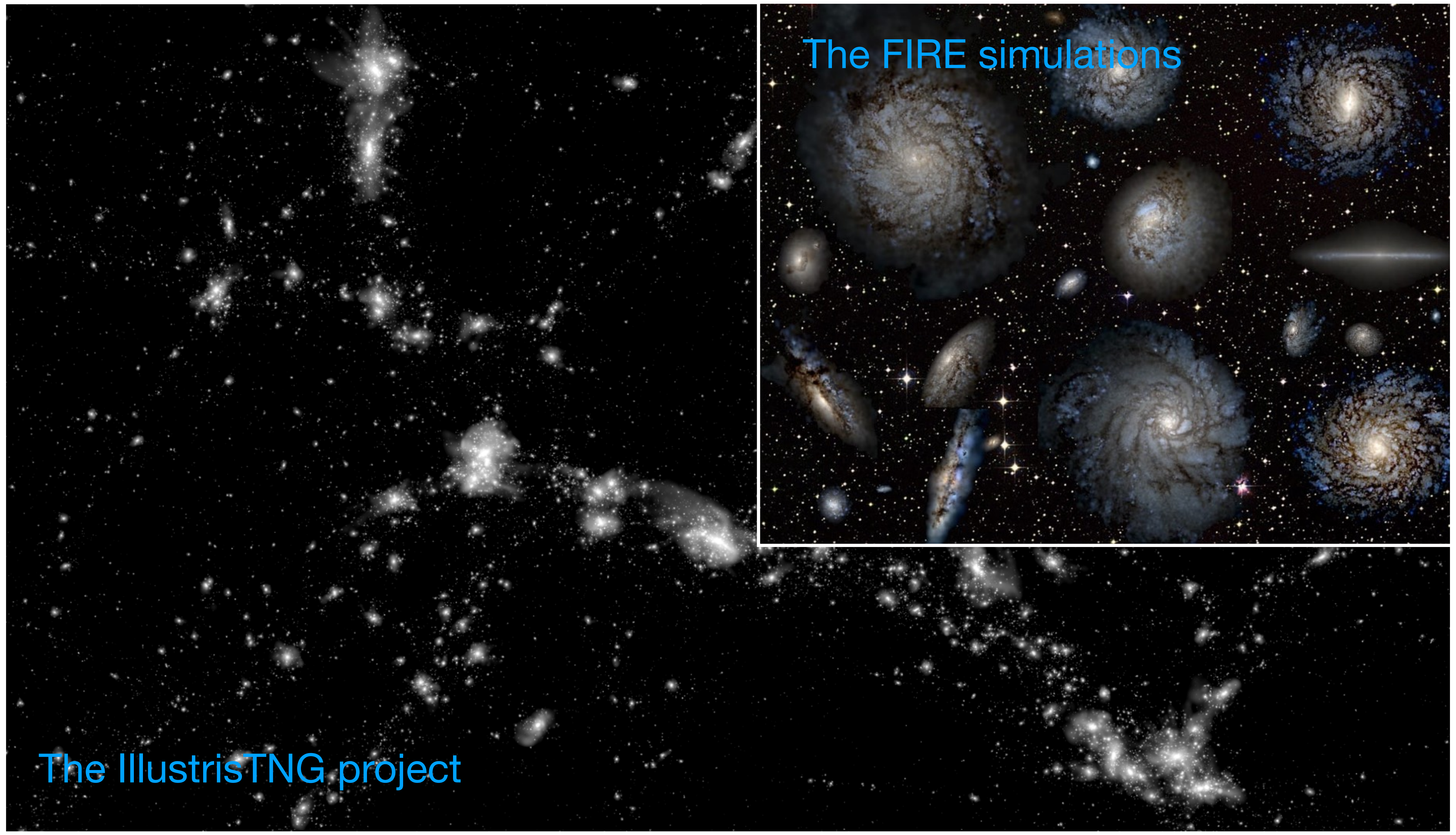


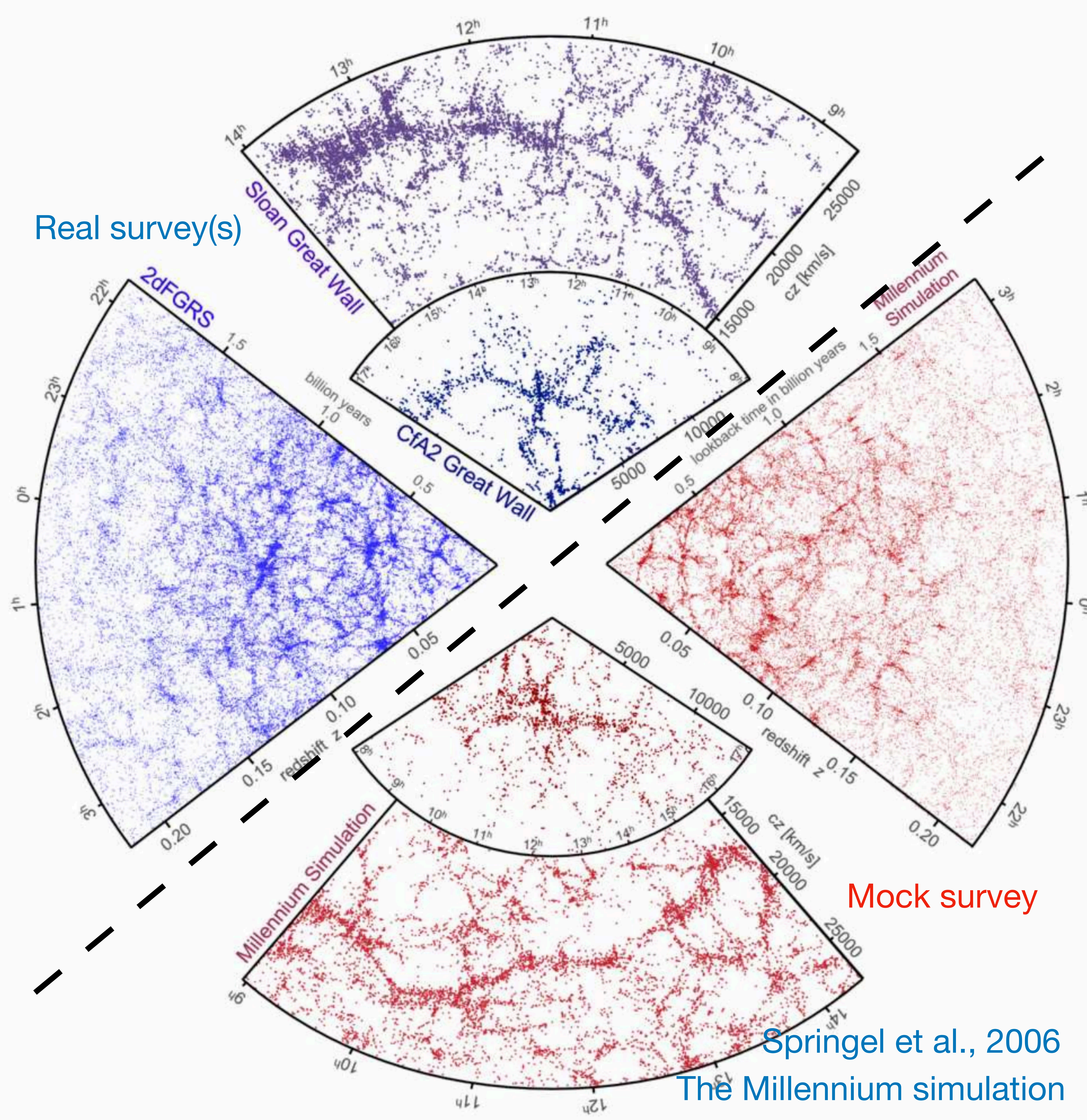


NASA, WMAP

- Dark matter as the driver for structure formation

- large-scale galaxy distribution
- galaxy-scale: dark matter halo as the host of formation of baryonic structures





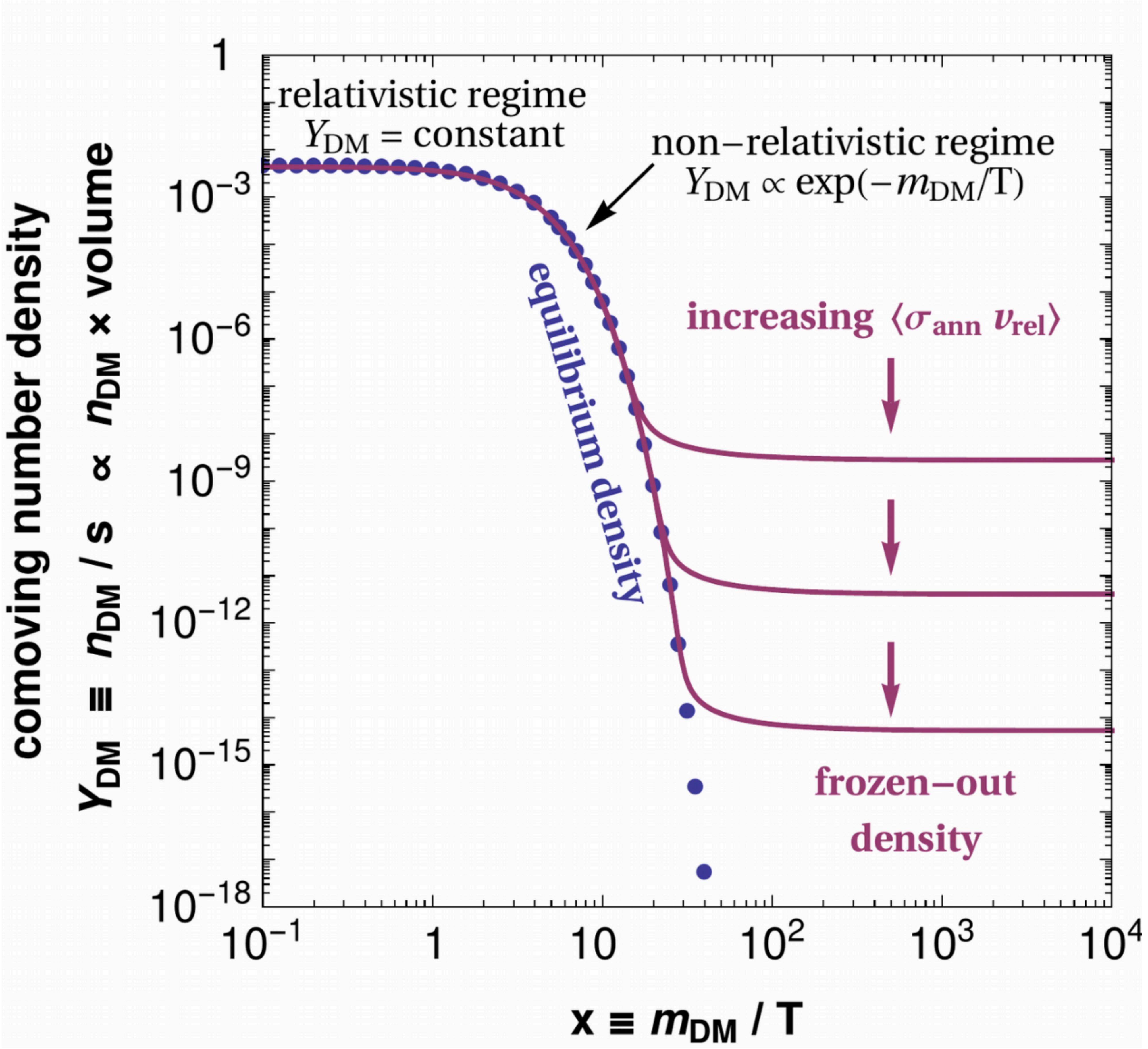
Classical candidate of dark matter

- Weakly Interacting Massive Particles (WIMPs)
  - thermal relic freeze out (the "WIMP miracle")

$$H \simeq \Gamma_{\text{eq}} = n_{\text{eq}}\langle\sigma v\rangle \qquad \Omega_X h^2 \sim \frac{0.1\text{pb}}{\langle\sigma v\rangle}$$

$$\langle\sigma v\rangle \sim \frac{g^4}{m^2} \simeq 1\text{pb}\left(\frac{200\,\text{Gev}}{m}\right)^2$$

  - an annihilation cross-section and mass pointing to the weak scale



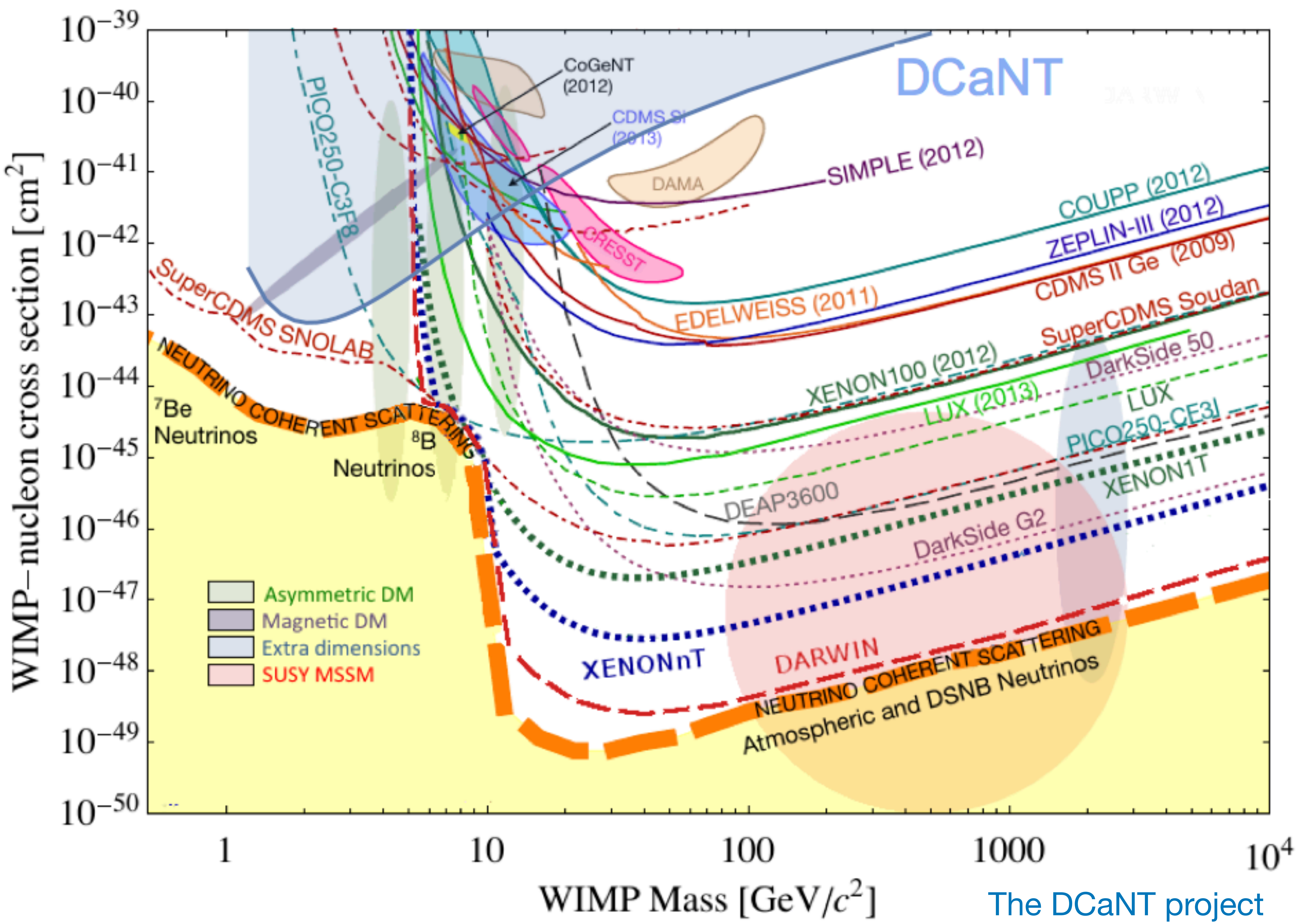
Petraki 2018 talk

- Natural candidates from beyond Standard Model theories
  - lightest supersymmetric particles (e.g. a neutralino) in the Minimal Supersymmetric Standard Model
  - WIMP-like particles also in Universal Extra-Dimension models, Little Higgs theories etc.

- Experimental searches for WIMPs

- Indirect detection
  - self-annihilation/decay
  - some signals, but contaminated with astrophysical processes

- Direct detection for WIMP-nucleon scattering
  - no established detection so far
  - some claims in contrast with follow-up experiments
  - null result in collider search



The DCaNT project

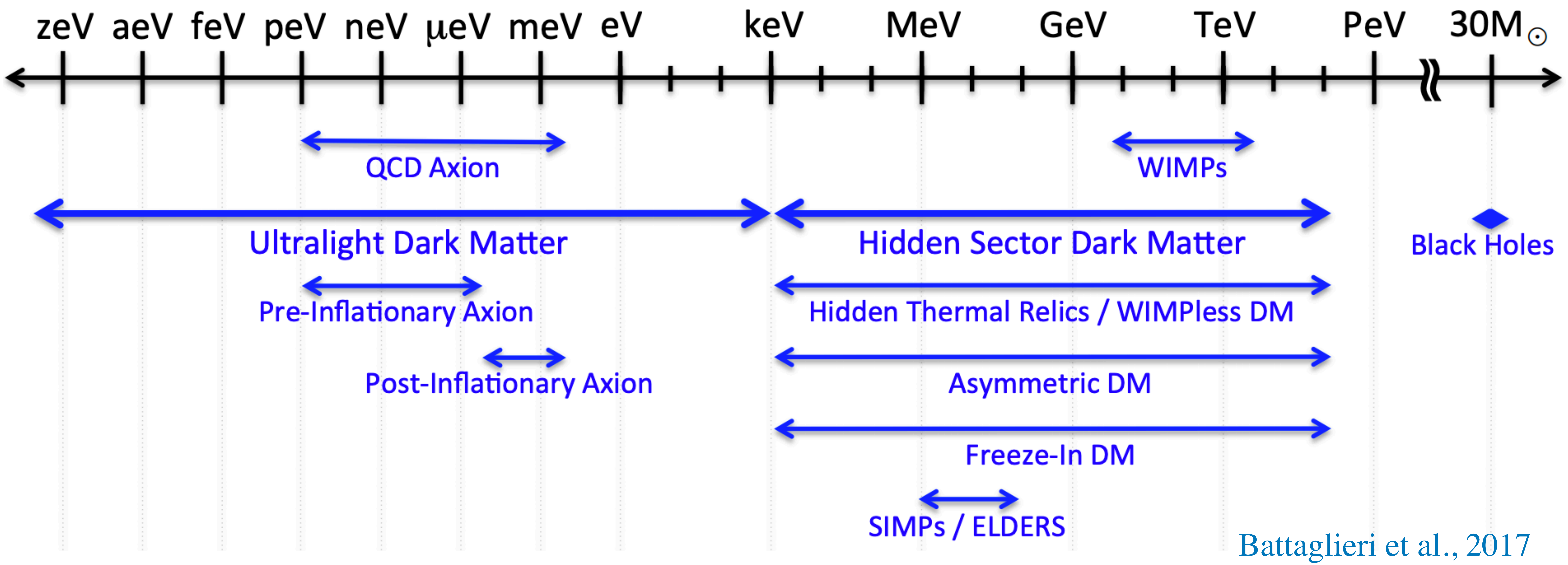
Broad spectrum of dark matter

- New production mechanisms
  - “freeze-out” (e.g. “SIMP miracle”)
  - “freeze-in” (feebly interacting particles)
  - asymmetric freeze-out
  - phase transition relics
  - from inflation etc.

- New types of interactions
  - hidden-sector interactions
  - coupling with SM particles other than the weak channel

Bertone & Tait 2018

Broad spectrum of dark matter



Battaglieri et al., 2017

from fuzzy dark matter of mass

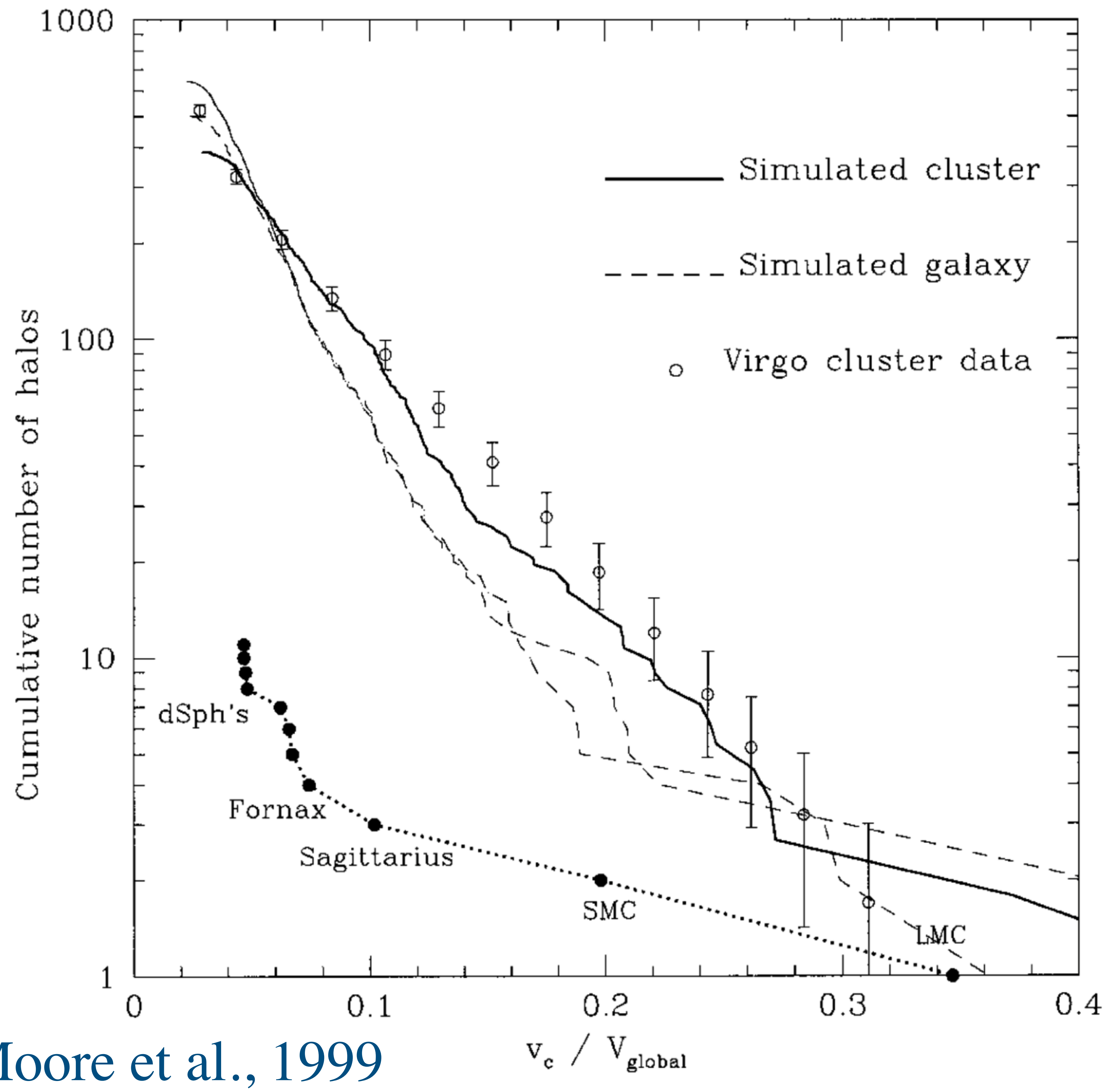
$\sim 10^{-22}$ ev

to primordial black holes of mass

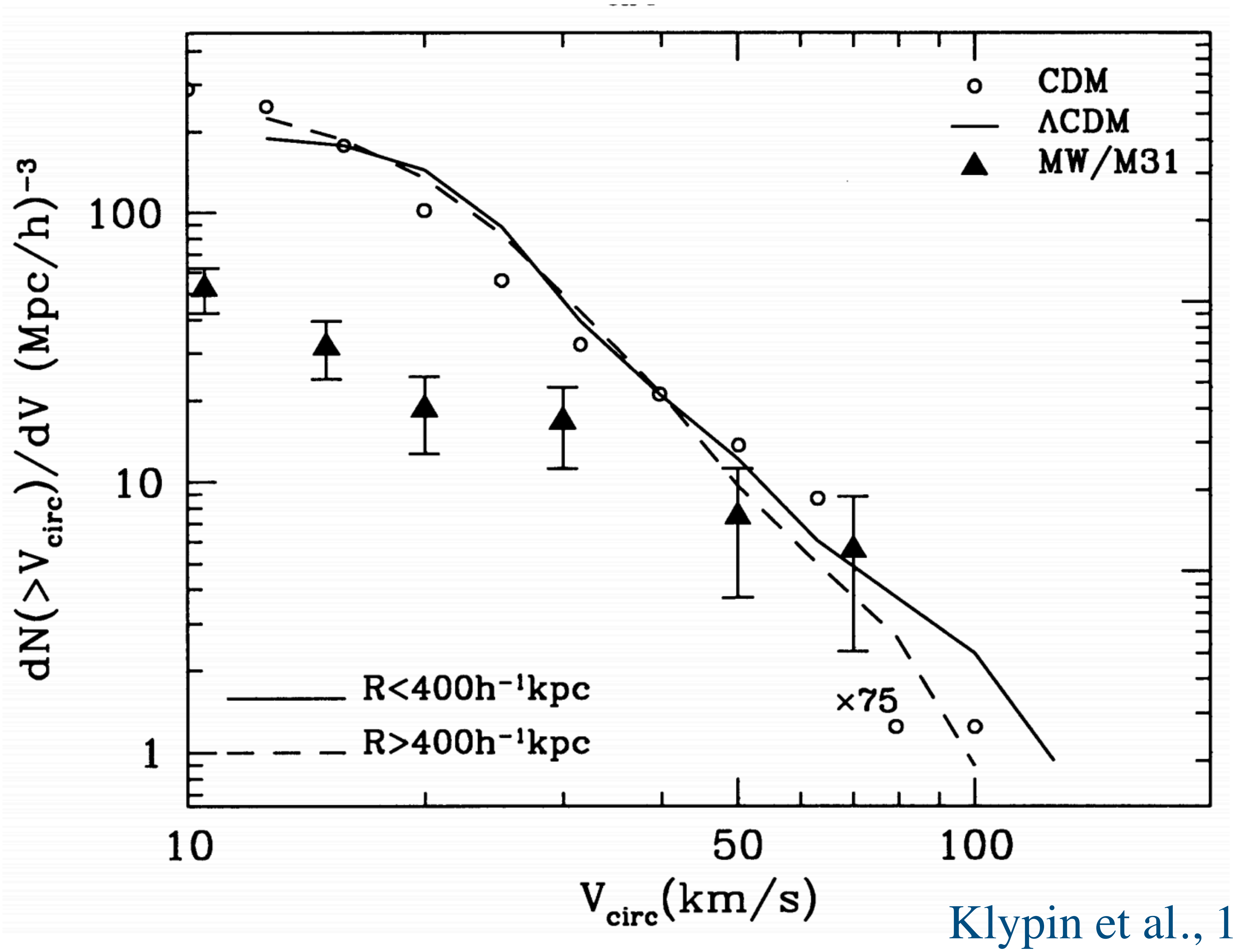
$\sim 10^{-10} M_{\odot} \sim 10^{56}$ ev

The “small-scale problems”

- The “Missing Satellite” (MS) problem
  - Dark-matter-only simulations of MW-mass host haloes in the ΛCDM model predict orders of magnitude more bound subhaloes than known luminous satellites of the Milky Way/M31

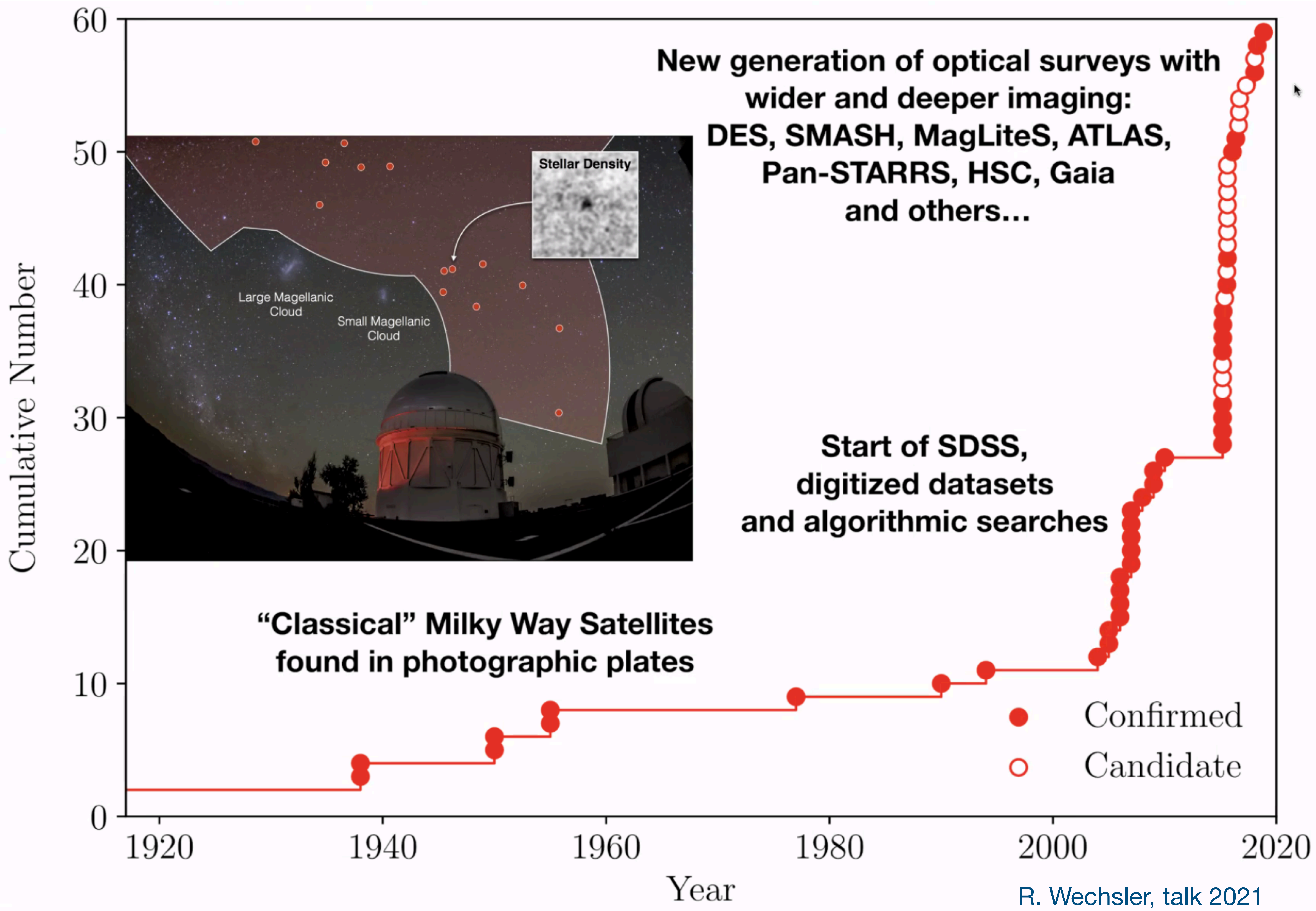


Moore et al., 1999



Klypin et al., 1999

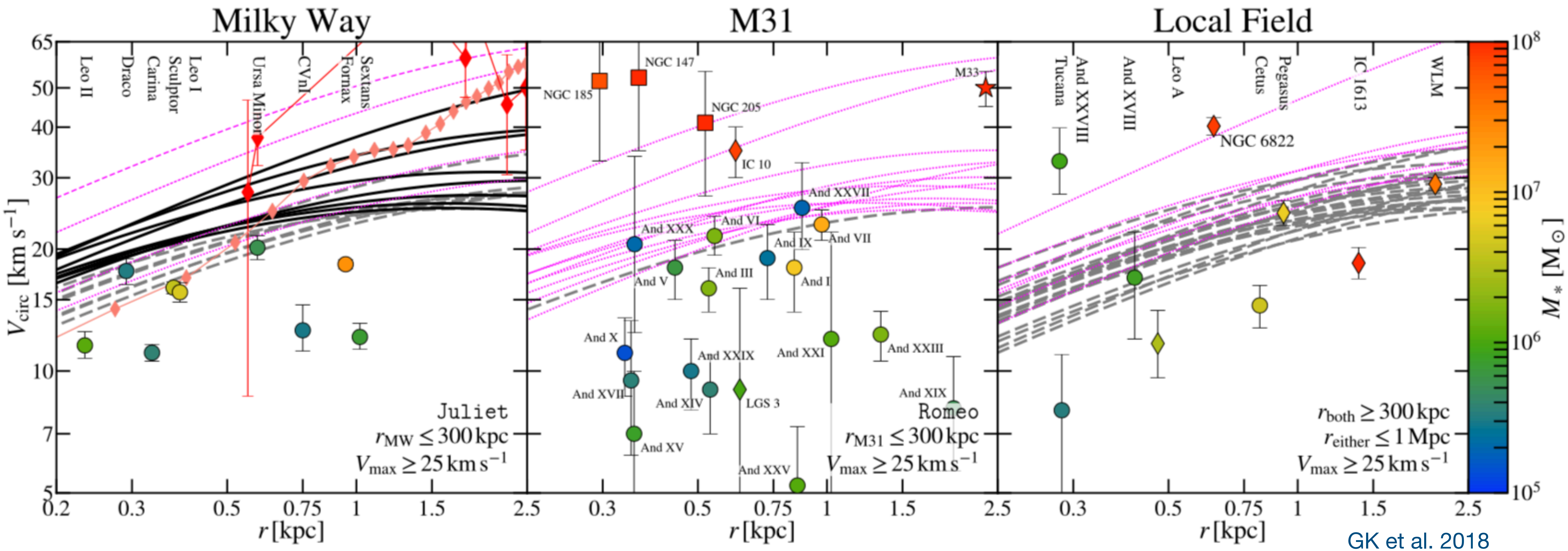
No longer a problem?



R. Wechsler, talk 2021

- The Too-big-to-fail (TBTF) problem

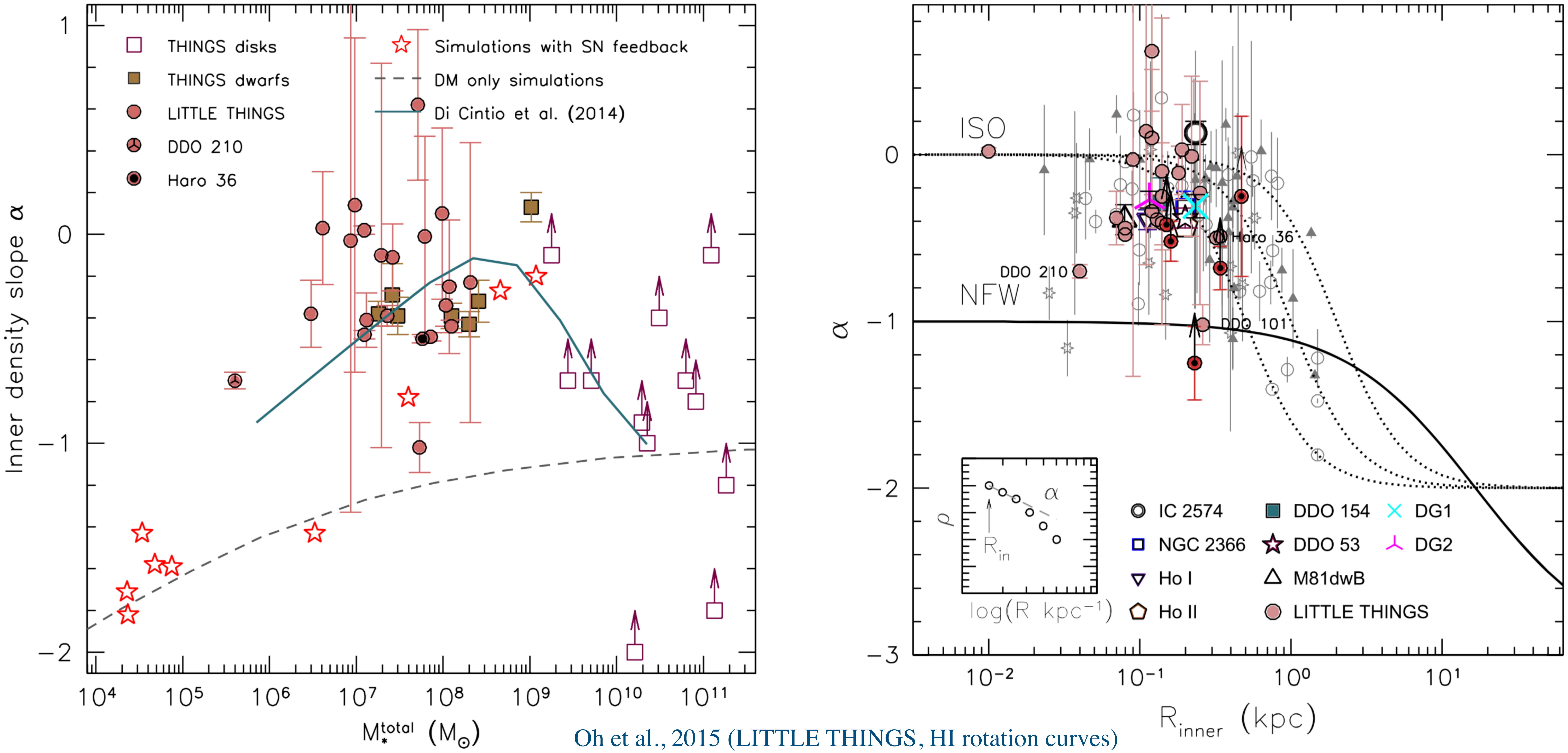
- Relation to MS: What if some subhaloes found in simulations are just not qualified to host stars?
- A substantial population of massive, concentrated subhaloes found in DMO simulations are incompatible with the stellar kinematics of observed satellite galaxies (MW & M31 satellites: Boylan-Kolchin et al. 2011, 2012; Tollerud et al. 2014; Local Group field dwarfs: Garrison-Kimmel et al. 2014; Kirby et al. 2014).



GK et al. 2018

- The Core-Cusp problem

- the central profiles of dark matter dominated systems are cored, in contrast to the universal cuspy central density profile found in dark matter only (DMO) simulations

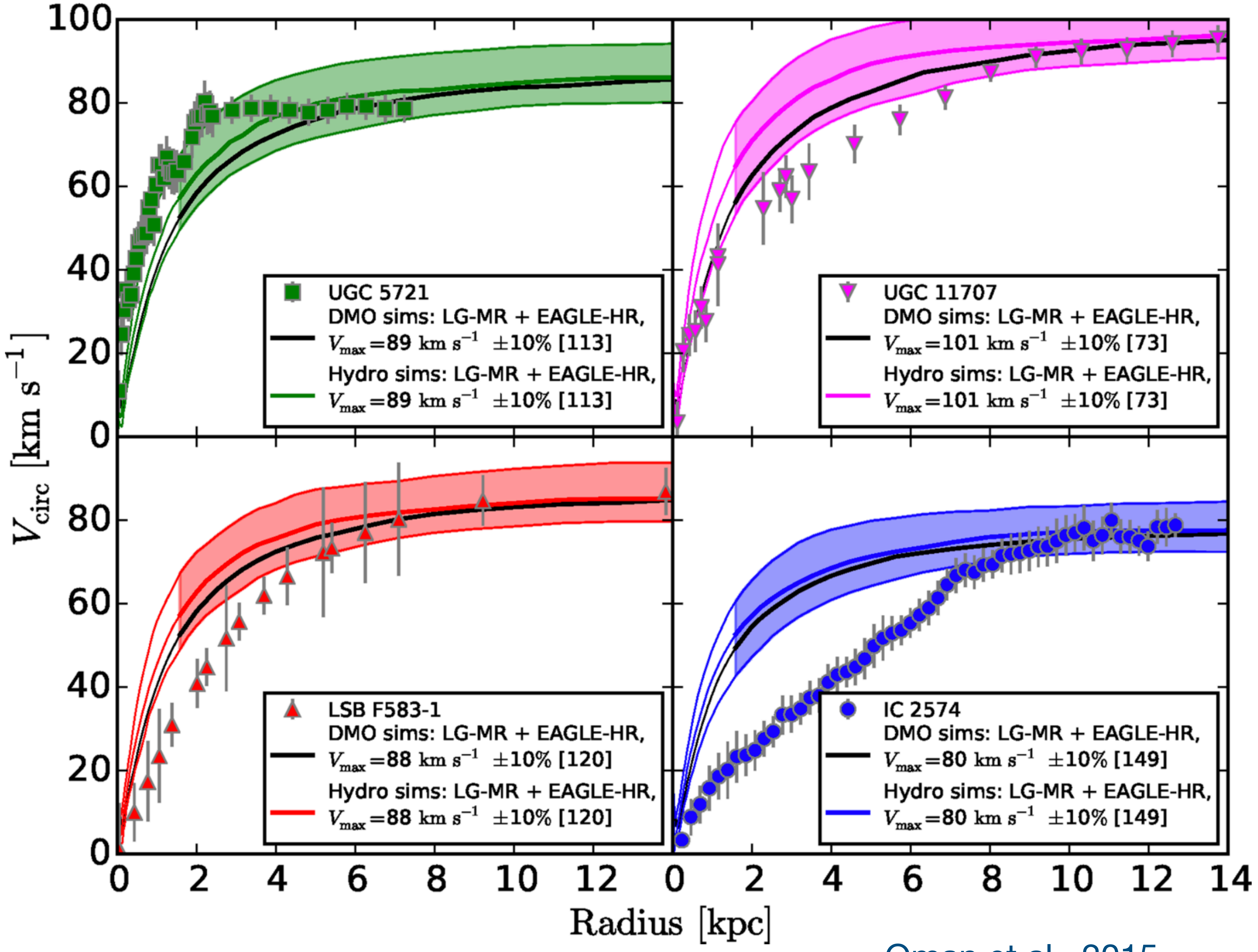


Oh et al., 2015 (LITTLE THINGS, HI rotation curves)

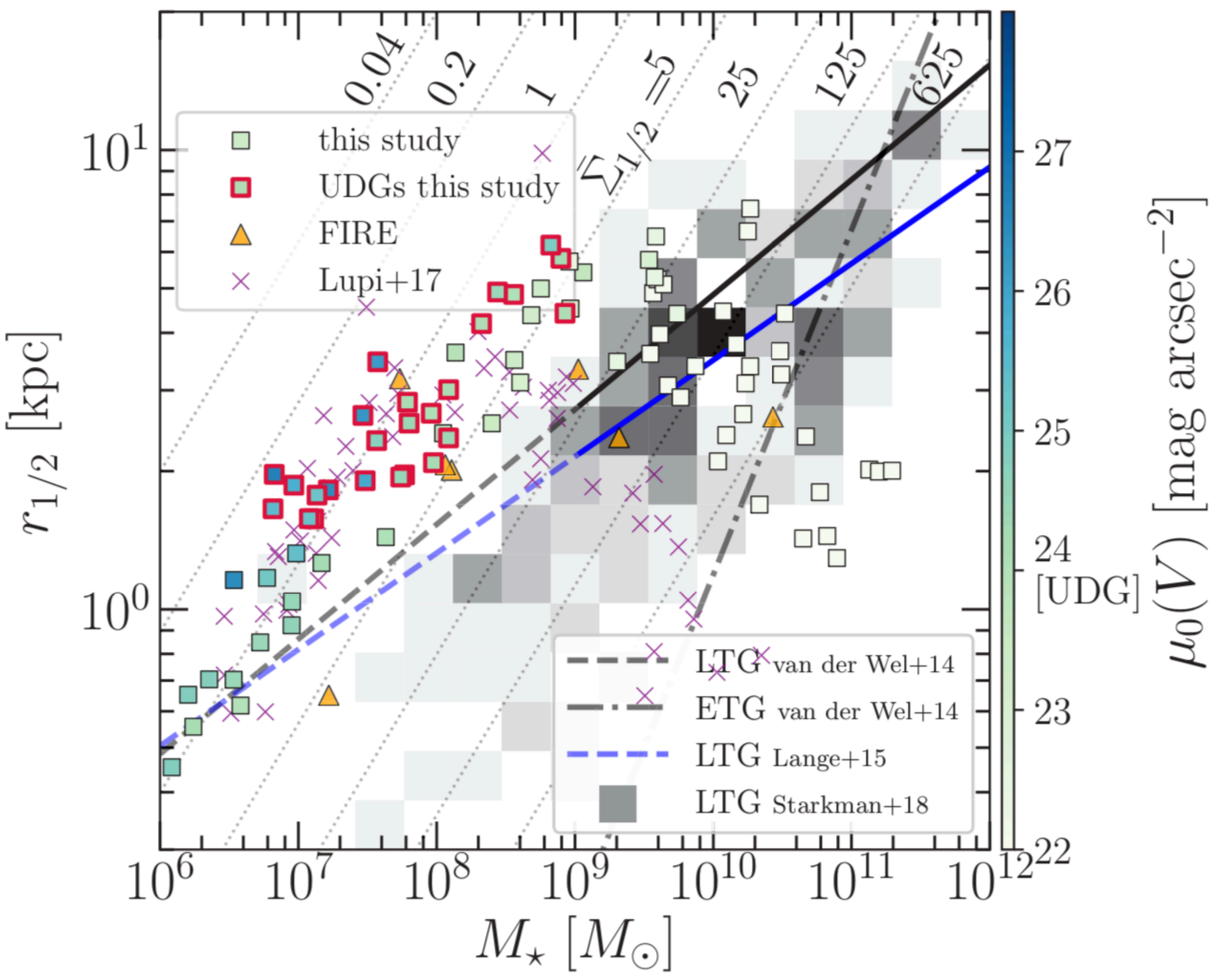
- Beyond

- Diversity of rotation curves at the mass scale of LSBs

  observed dwarf LSBs have more diverse rotation curves than analogs in simulations that include baryons

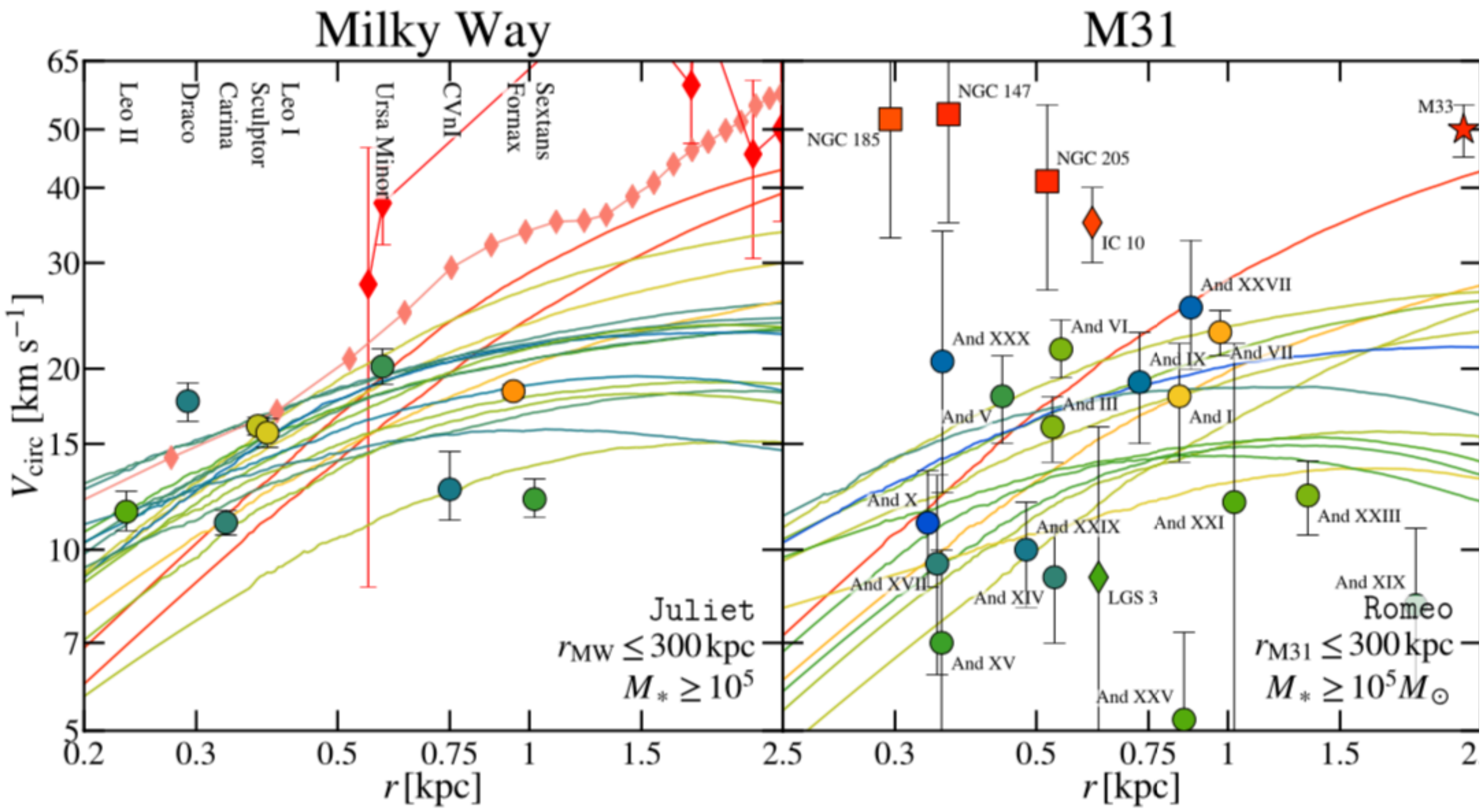


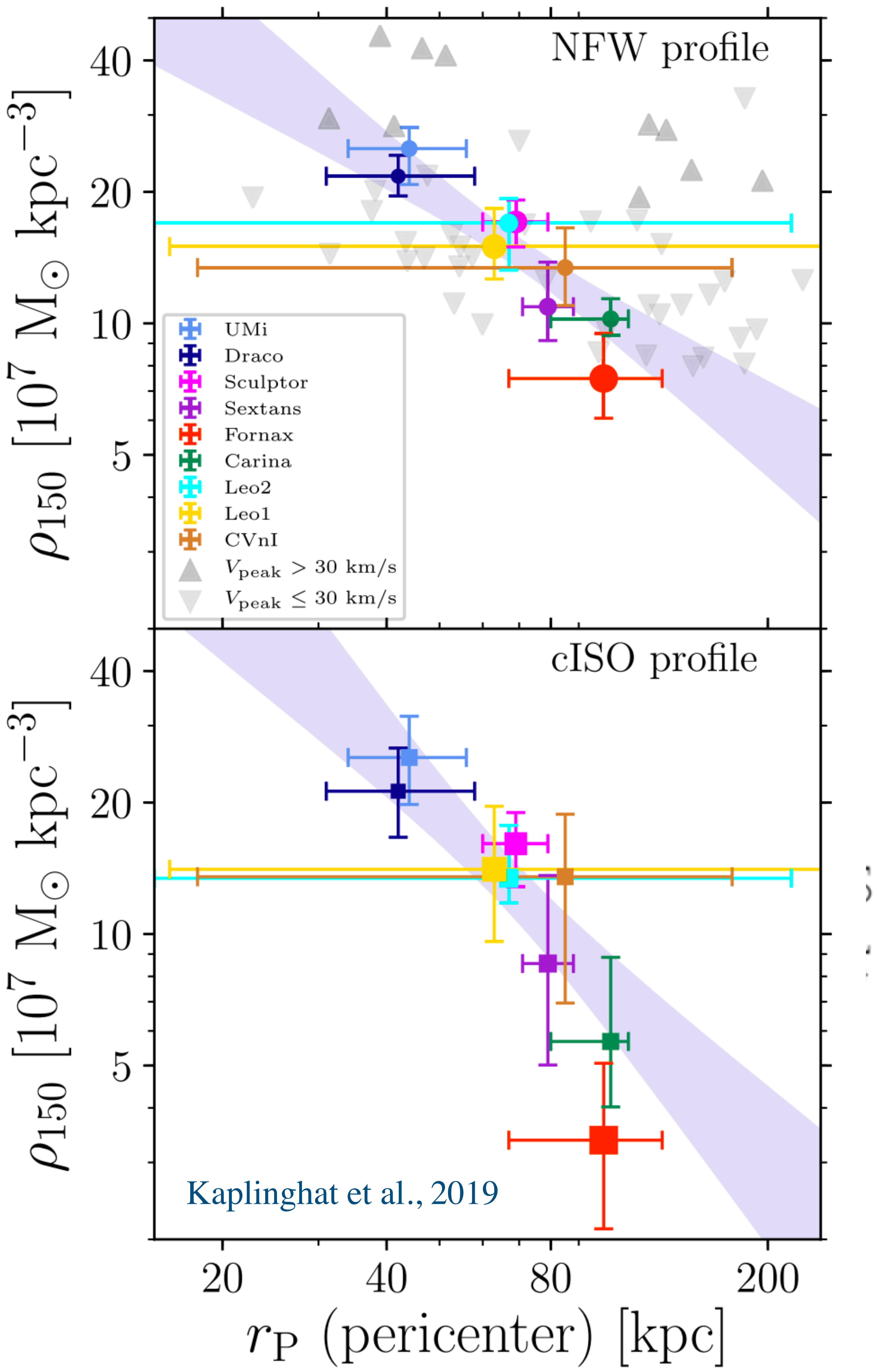
Oman et al., 2015



Jiang et al. 2018

- The diversity problem extended to the Local Group
    - Local Group dwarfs show big diversity in central density
    - the central densities of MW satellites anti-correlates with pericenter distances

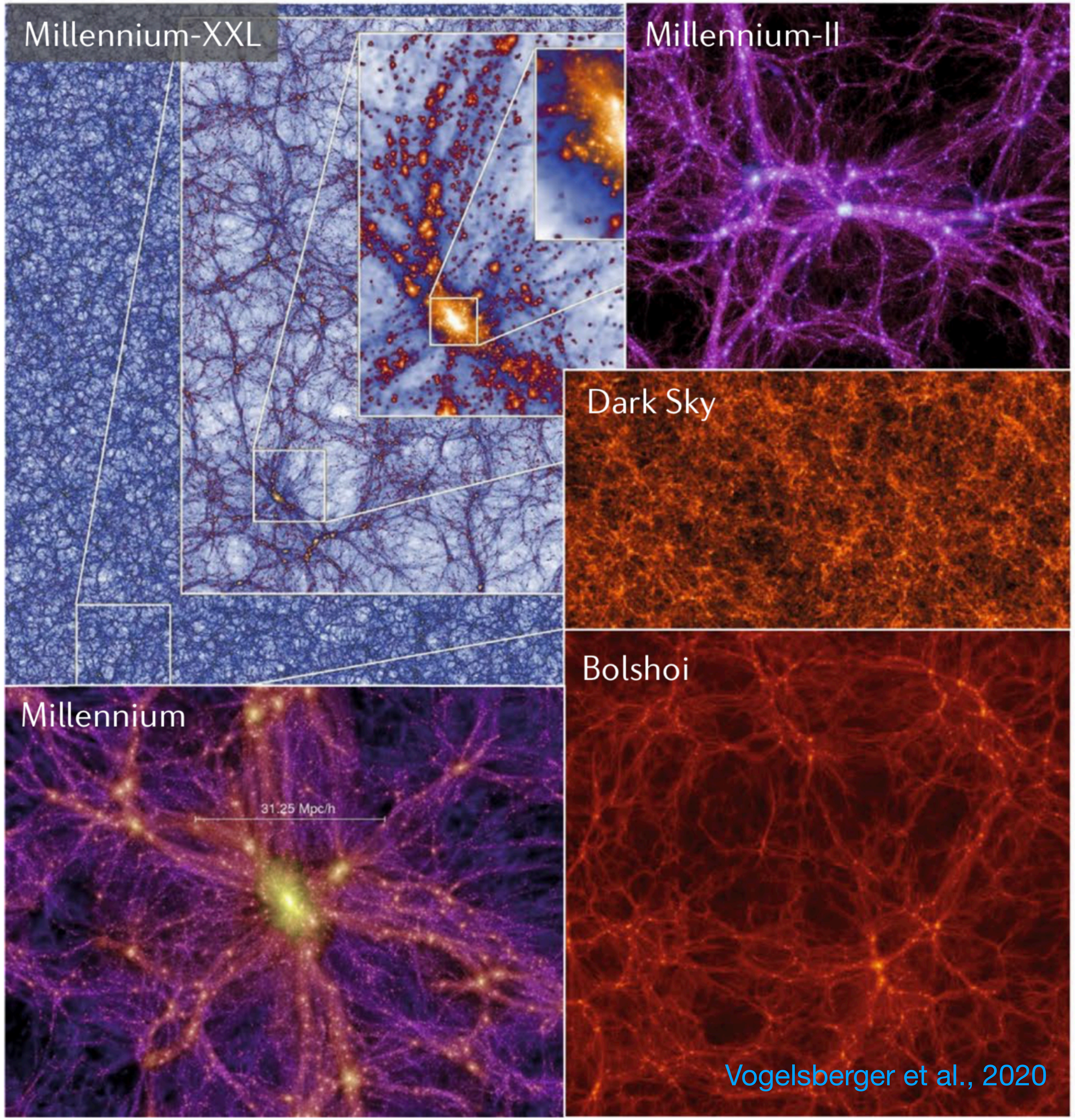




Numeric simulation

N-body simulations: dark matter only, gravity

- self-consistent initial conditions; cosmological integrations
- key predictions:
  - large scale structure
  - internal mass distribution of dark matter halo
  - halo substructures



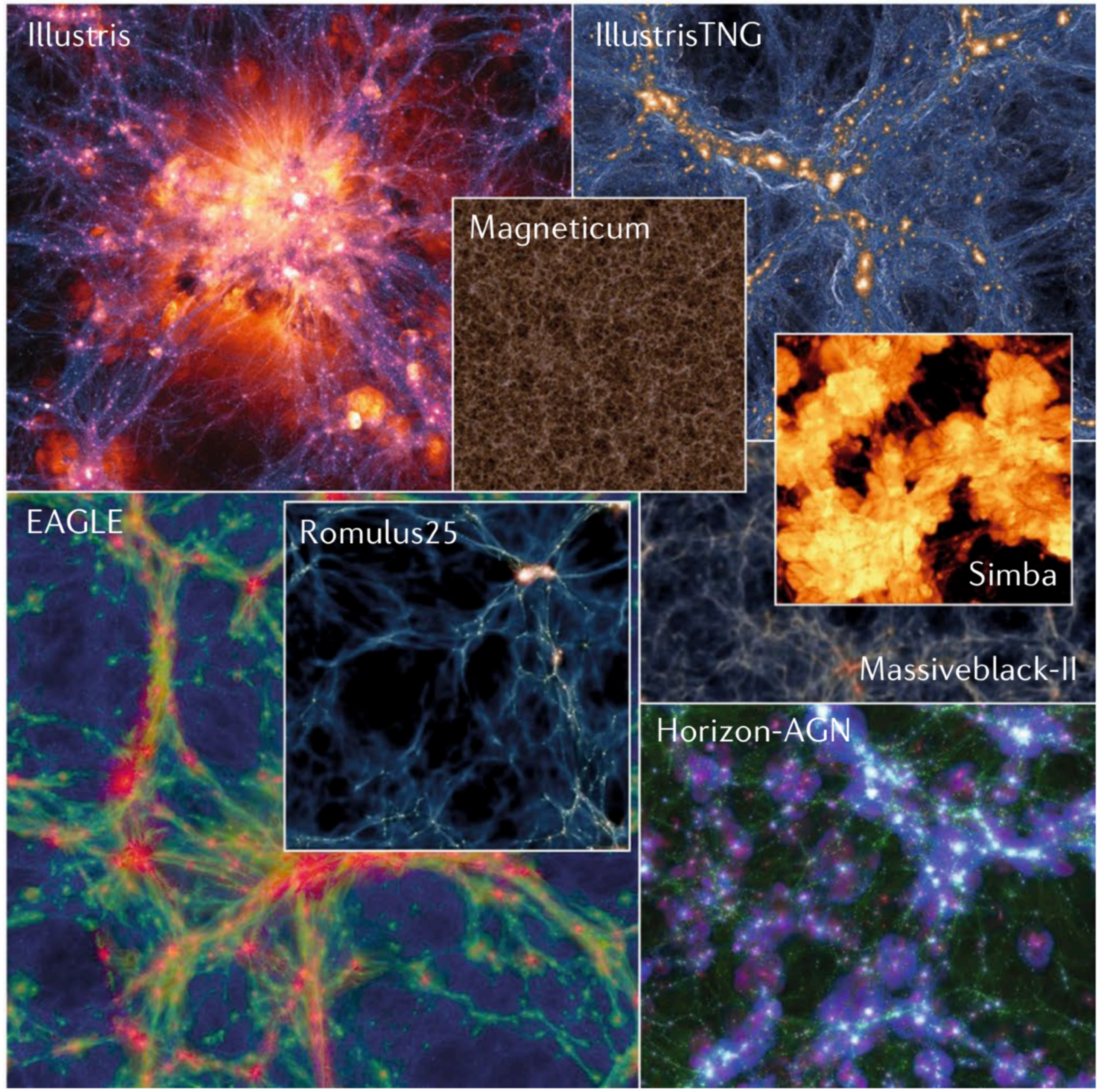
Vogelsberger et al., 2020

Hydrodynamical (baryonic) simulations

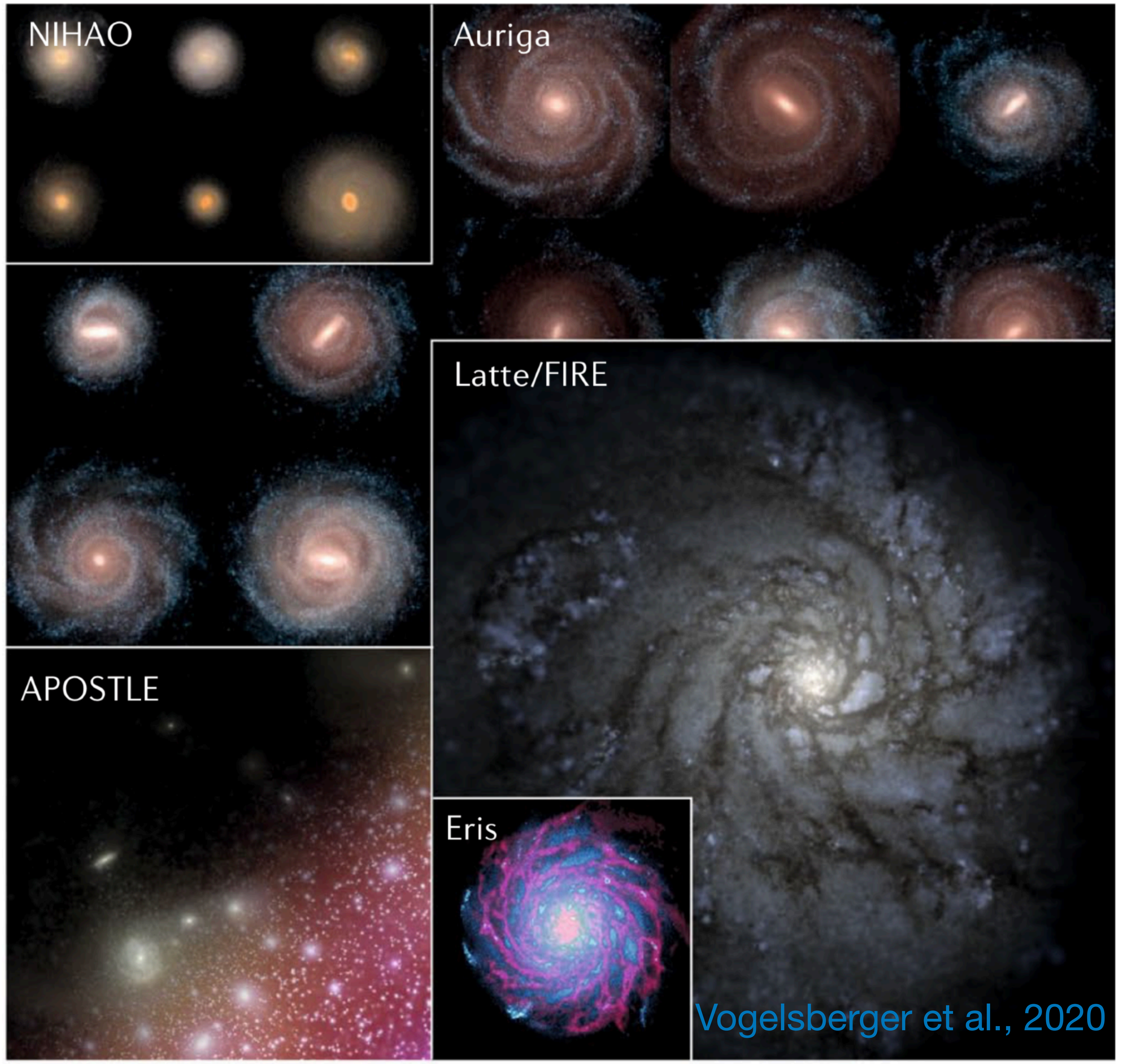
The Feedback-In-Realistic-Environments (FIRE) simulations

- hydrodynamics: quasi-Lagrangian Godunov Meshless-Finite-Mass method
- baryonic physics input: gas cooling; UV background; multiphase ISM, star formation, feedback. metal enrichment, magnetic fields, cosmic rays, dust etc

Large volume simulation



Zoom-in simulation



Vogelsberger et al., 2020

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- Future plans/ projects

Self-interacting dark matter (SIDM)

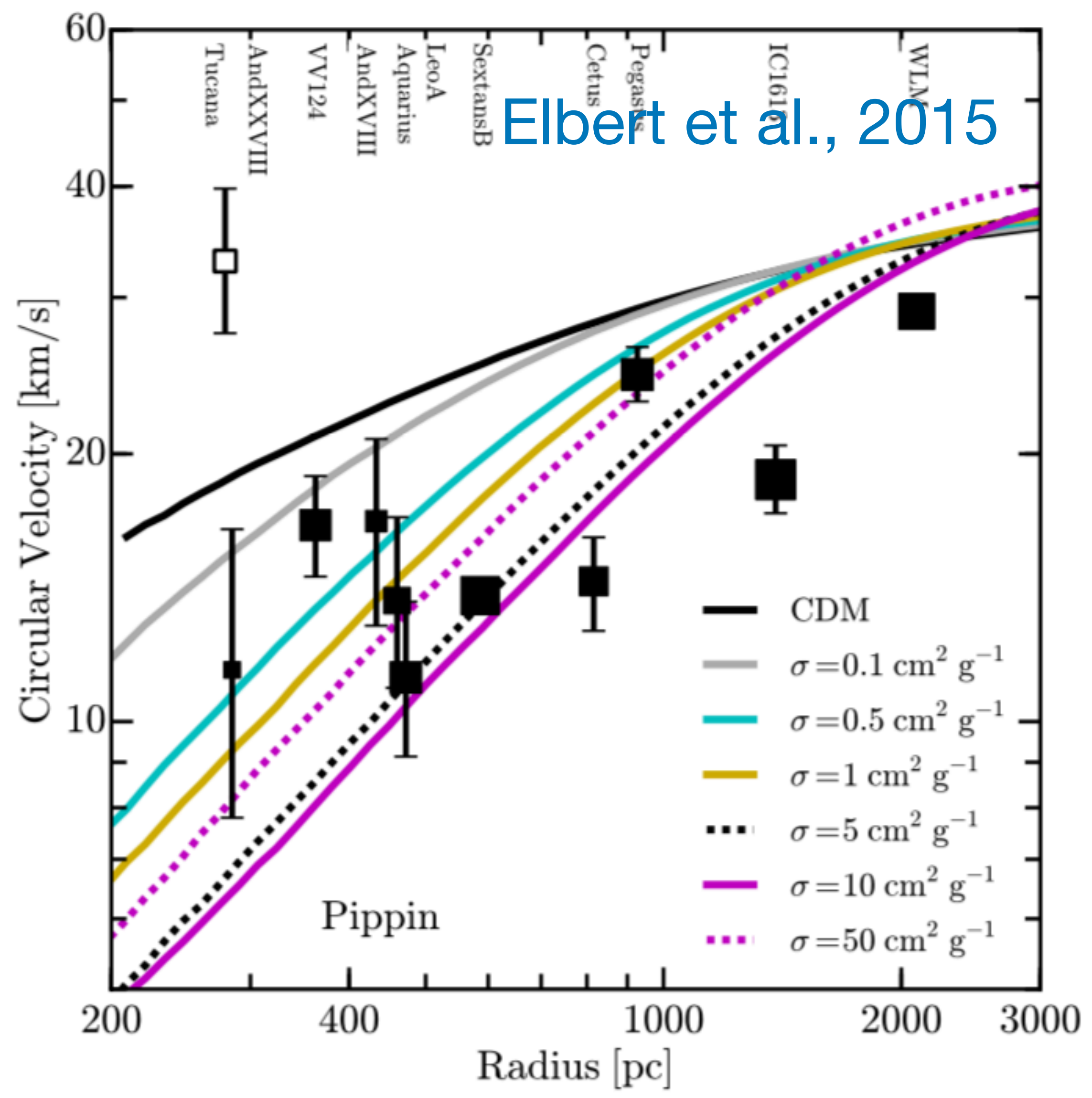
- Early propositions

first proposed in the 90's (e.g., Carlson et al. 1992; de Laix et al. 1995)
later argued as the solution to the "small-scale problems" (Firmani et al. 2000; Spergel & Steinhardt 2000)

- elastic, weakly collisional $\Gamma_{\rm sidm} = n\langle \sigma v \rangle \gtrsim H_0$ $\longleftrightarrow$ O(1) collision per Hubble time
- most effective in dense environments, e.g. galaxy centers
- conduction due to self-interaction help form thermalized cores

- Early numeric studies

DMO simulations have found that a self-interaction cross-section of $\sim 1 {\rm cm}^2/{\rm g}$ could solve the core-cusp and the TBTF problem simultaneously (e.g., Vogelsberger et al. 2012; Rocha et al. 2013; Zavala et al. 2013; Elbert et al. 2015)

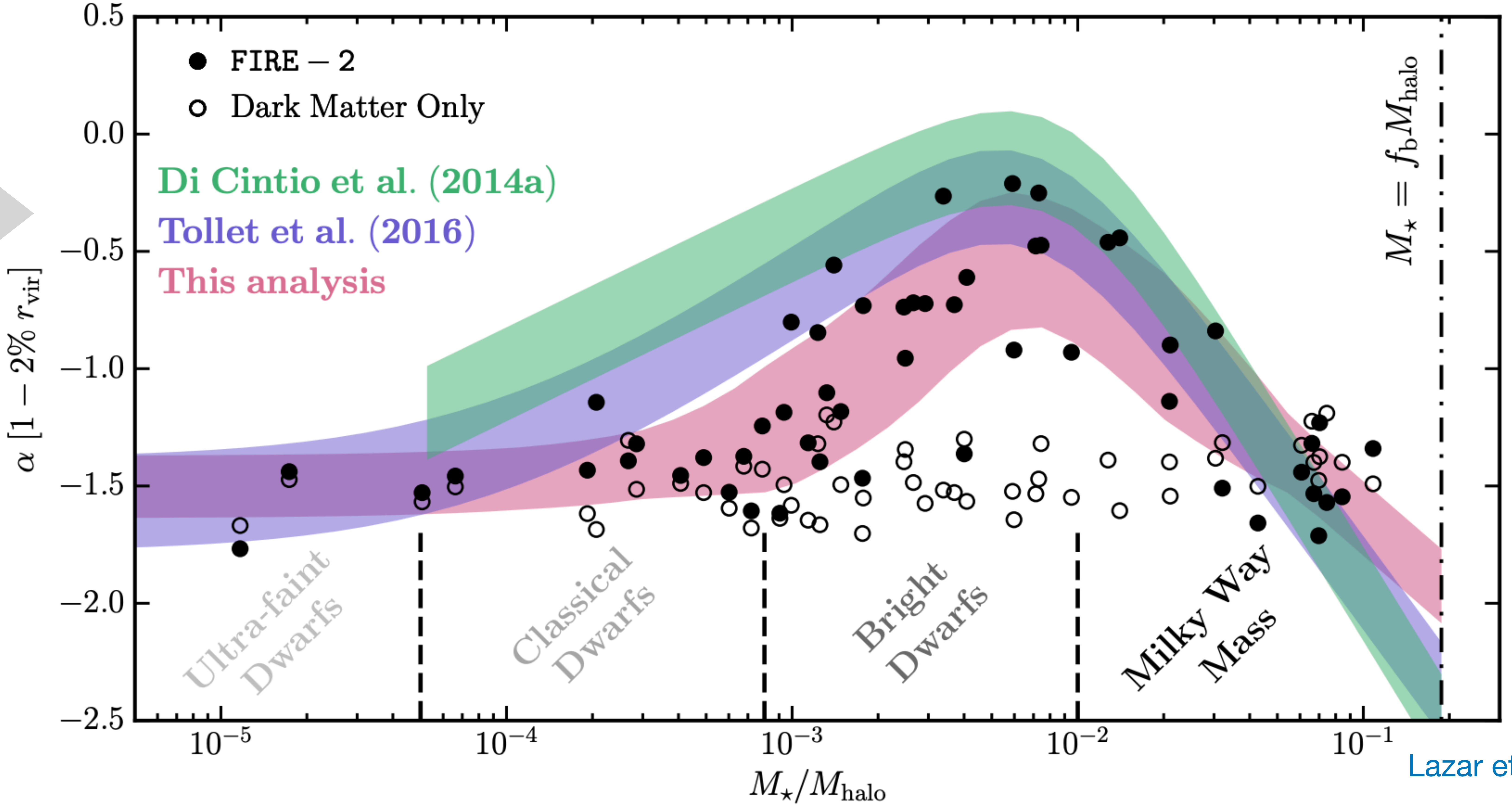


- The inclusion of baryons

Gas outflows driven by stellar/supernovae feedback could create fluctuations in the central potential, which irreversibly transfer energy to CDM particles and generate dark matter cores (Governato et al. 2010, 2012; Pontzen & Governato 2012; Madau et al. 2014)

CDM + baryon simulations e.g.,
Brooks & Zolotov 2014;
Dutton et al. 2016;
Fattahi et al. 2016;
Sawala et al. 2016;
Wetzel et al. 2016;
Garrison-Kimmel et al. 2019;
Buck et al. 2019

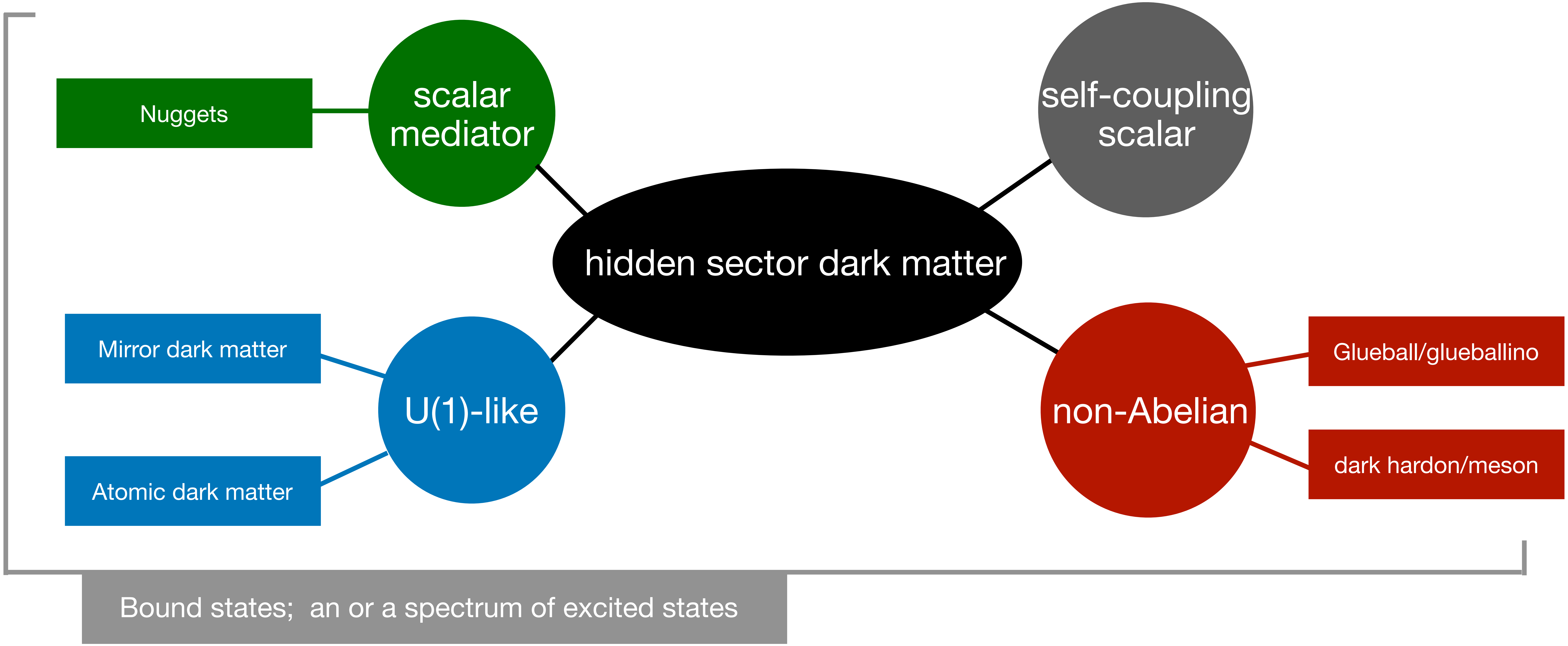
SIDM + baryon simulations e.g.,
Vogelsberger et al. 2014;
Robles et al. 2017, 2019;
Despali et al. 2019;
Fitts et al. 2019



Lazar et al., 2020

- Bursty star formation and feedback reduce the distinct signatures of SIDM, especially in bright dwarfs.
- In low-mass dwarfs, SIDM is still the appealing mechanism to decrease galaxy central densities.

- particle physics realization with hidden sectors
    - a U(1)-like sector: hidden charge, low-mass or massless mediator, bound states "dark atoms" (e.g. Ackerman 2009; Arkani-Hamed 2009 ; Feng 2009; Cyr-Racine & Sigurdson 2013; Cline 2014; Boddy 2016)
    - non-Abelian sector: glueballs, composite "hardons", "meson" (e.g. Arkani-Hamed 2009; Boddy 2014; Cline 2014)
    - scalar mediators, large states nuggets (e.g. Wise & Zhang 2014, Gresham et al. 2017,2018)



- Less explored ideas

- dissipative self-interactions

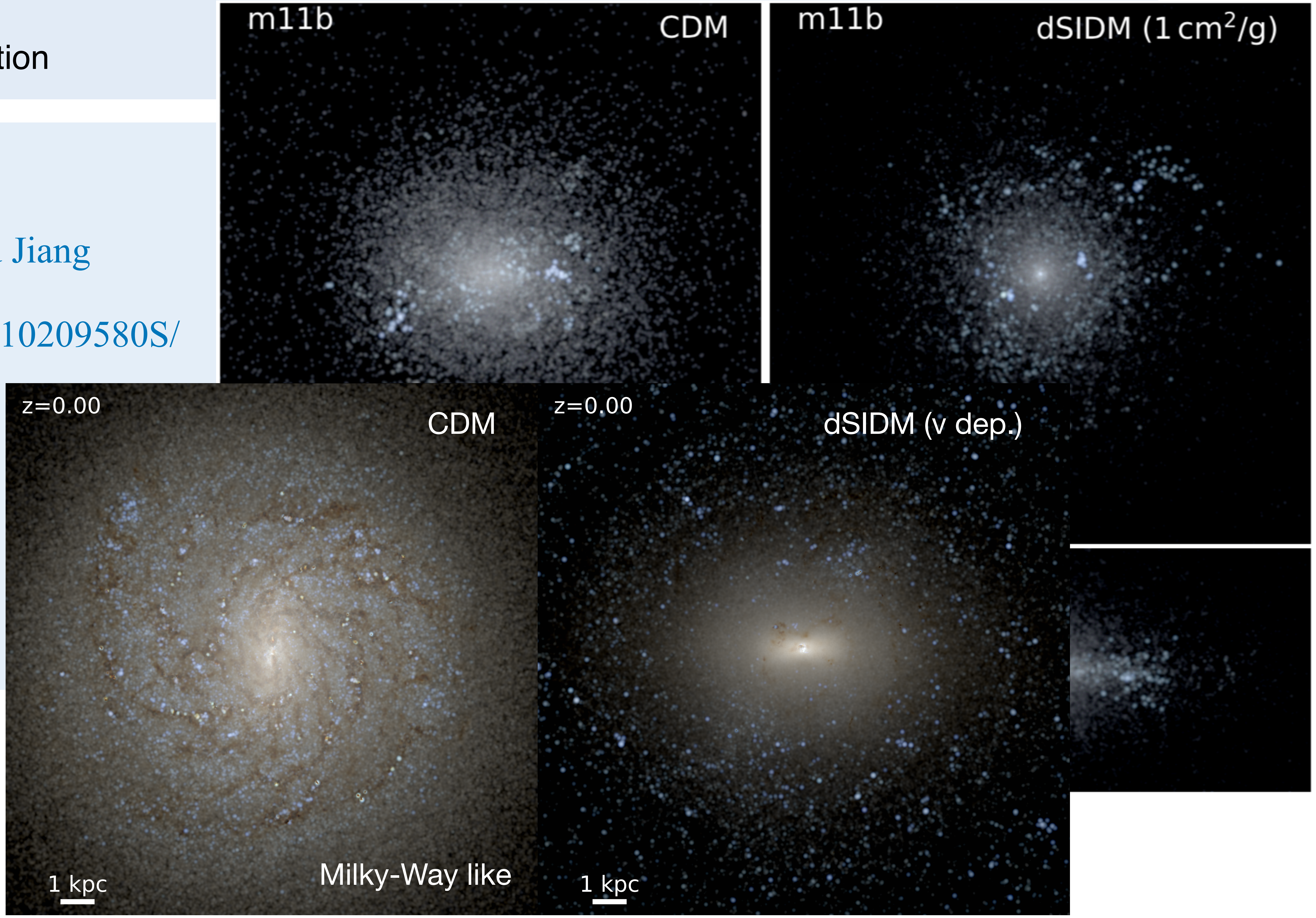
  - Many particle physics realizations of SIDM, dark matter have inelastic (or specifically dissipative) self-interactions (e.g., Kaplan et al. 2010; Cyr-Racine & Sigurdson 2013; Cline et al. 2014; Boddy et al. 2014; Wise & Zhang 2014; Foot & Vagnozzi 2015; Schutz & Slatyer 2015; Boddy et al. 2016; Finkbeiner & Weiner 2016; Zhang 2017; Blennow et al. 2017; Gresham et al. 2018)

  - Less explored in the context of structural formation

- Dissipative dark matter on FIRE

Supervised by Philip Hopkins, Lina Necib and Fangzhou Jiang (Caltech and Carnegie Observatories)
first paper: https://ui.adsabs.harvard.edu/abs/2021arXiv210209580S/abstract

- The first suite of cosmological baryonic simulations of galaxies in dissipative SIDM
- Incorporates the standard FIRE-2 model for hydrodynamic and baryonic physics



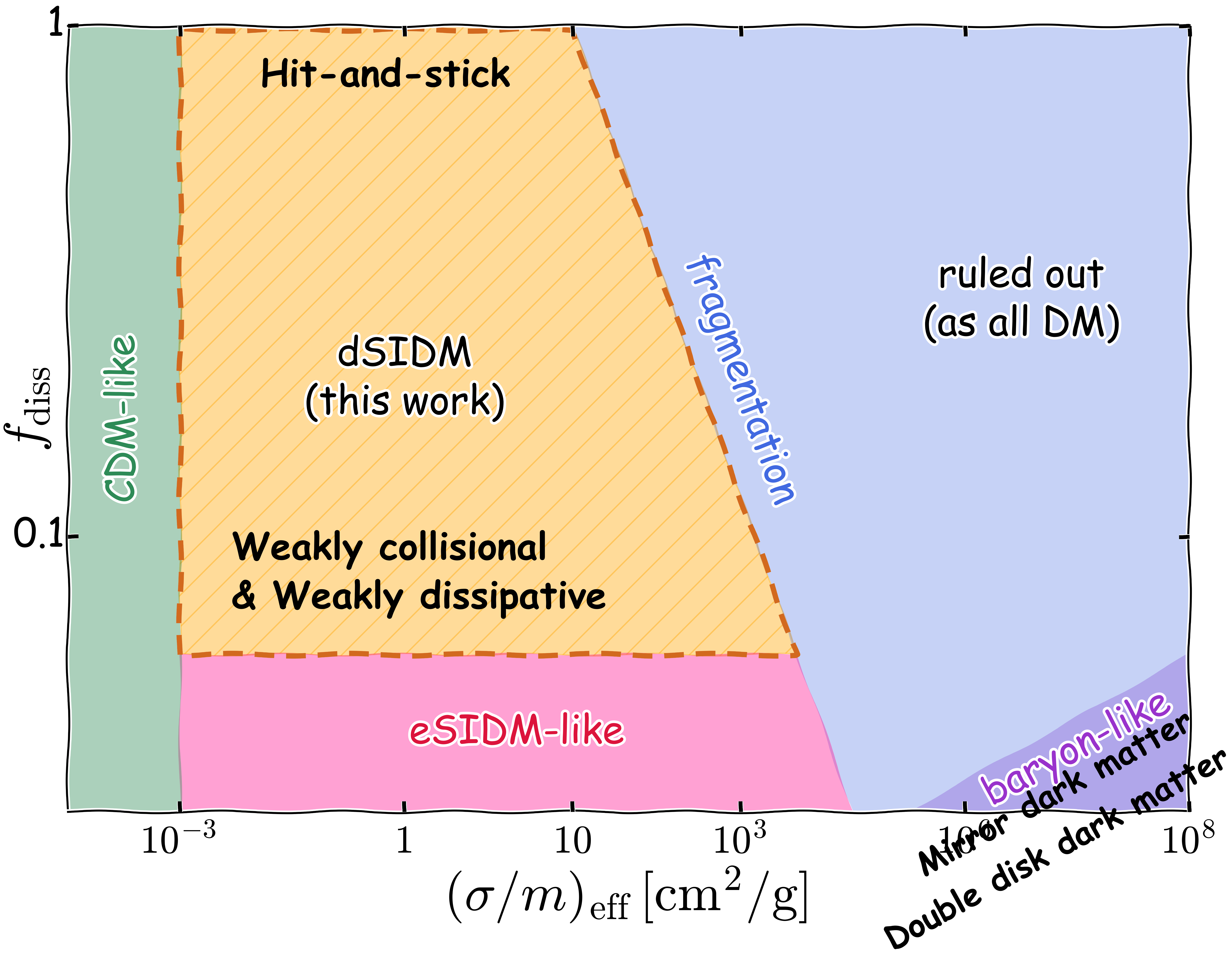
- Parameter space

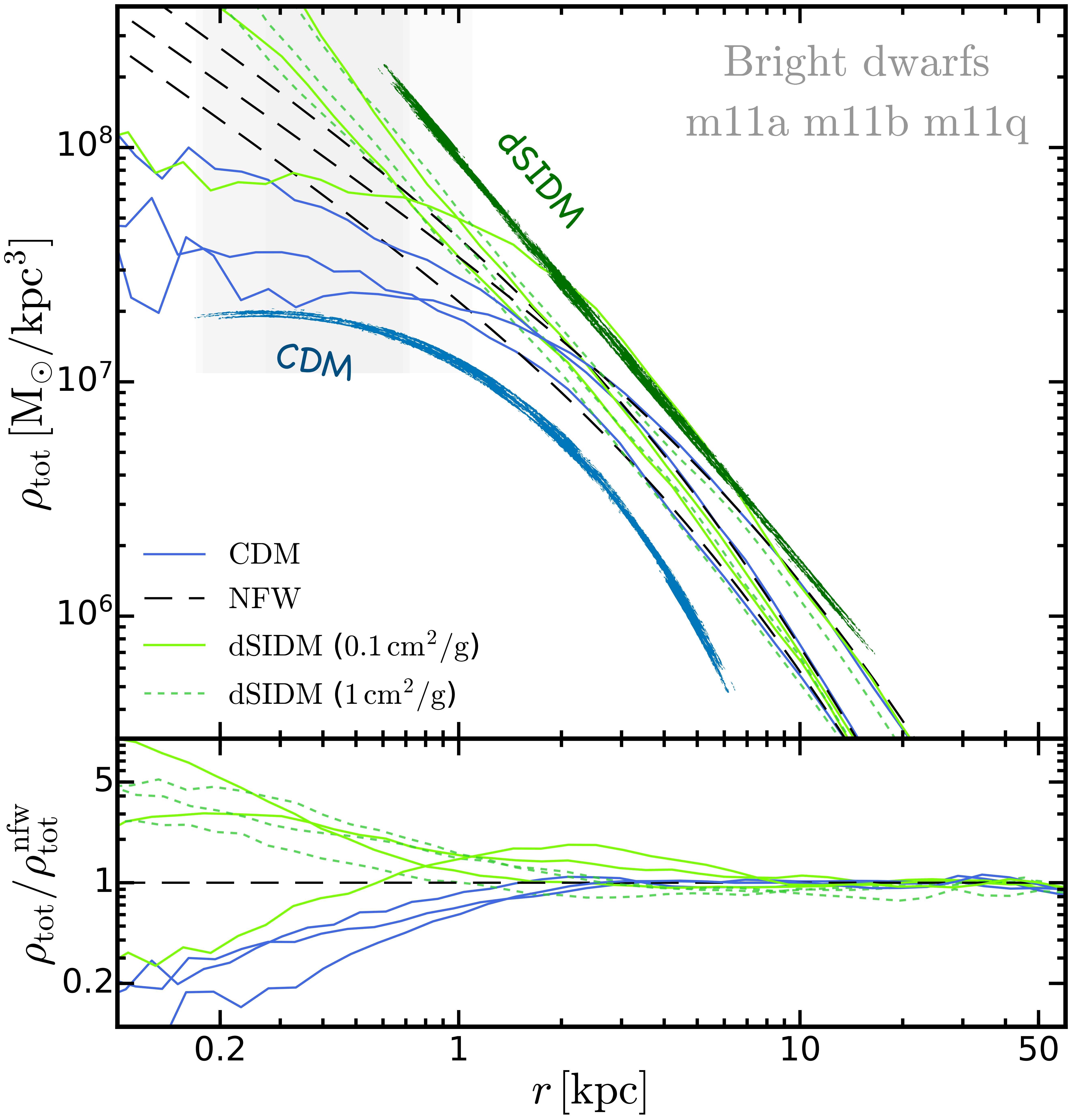
- a constant fraction $f_{\rm diss}$ of kinetic energy loss per collision
- other behavior of cooling can be realized through $f_{\rm diss}(v)$ or $f_{\rm diss}(T_{\rm dm})$

$$t_{\rm diss} \simeq \mathrm{O}(1)\,\frac{t_{\rm coll}}{f_{\rm diss}}$$

$$t_{\rm ff} \sim t_{\rm dyn} \ll t_{\rm diss} \underset{f_{\rm diss}\sim \mathrm{O}(1)}{\sim} t_{\rm coll} \lesssim t_{\rm H}$$

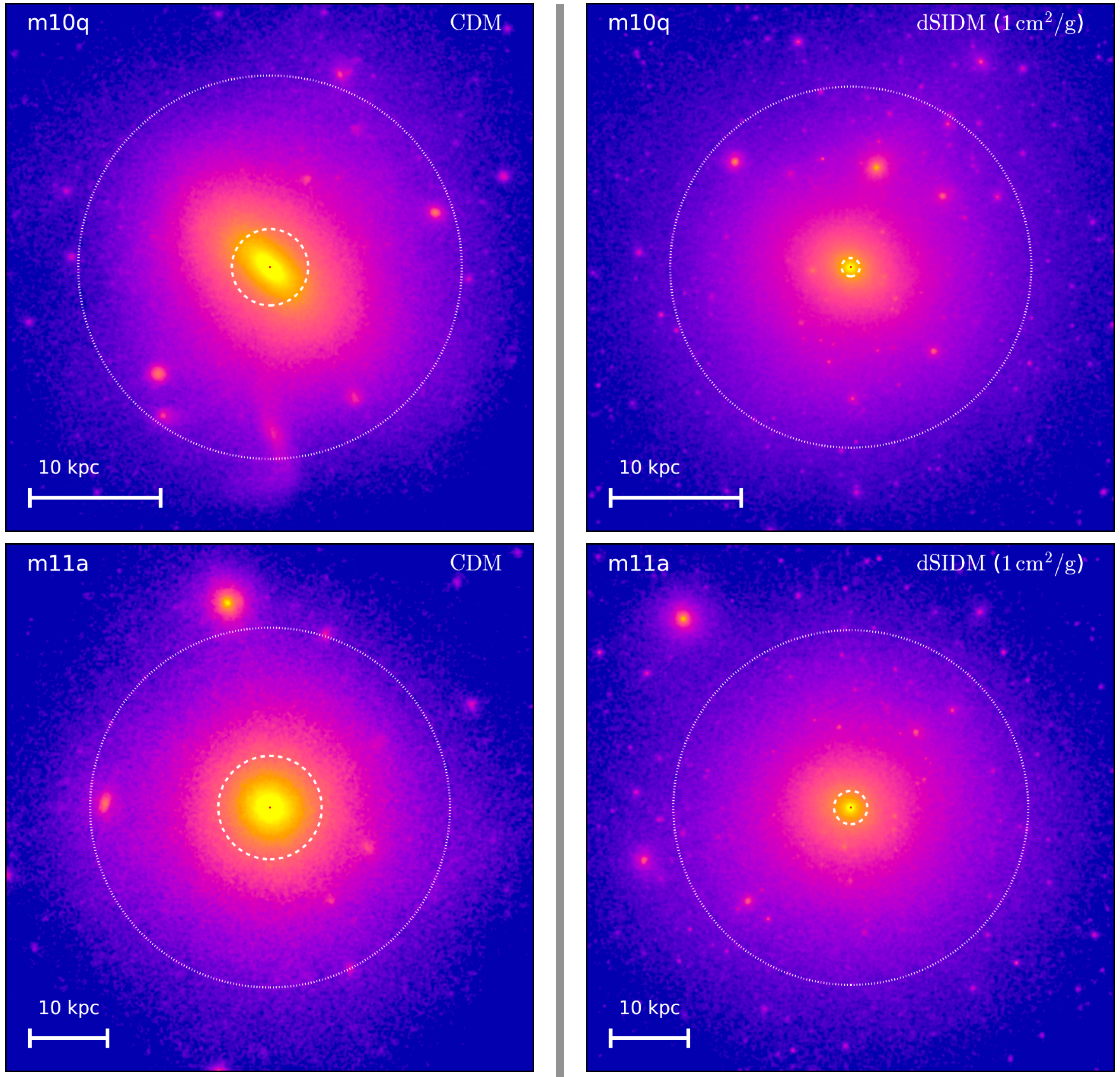
- qualitative different from baryonic gas
- and previously proposed baryon-like dissipative dark matter





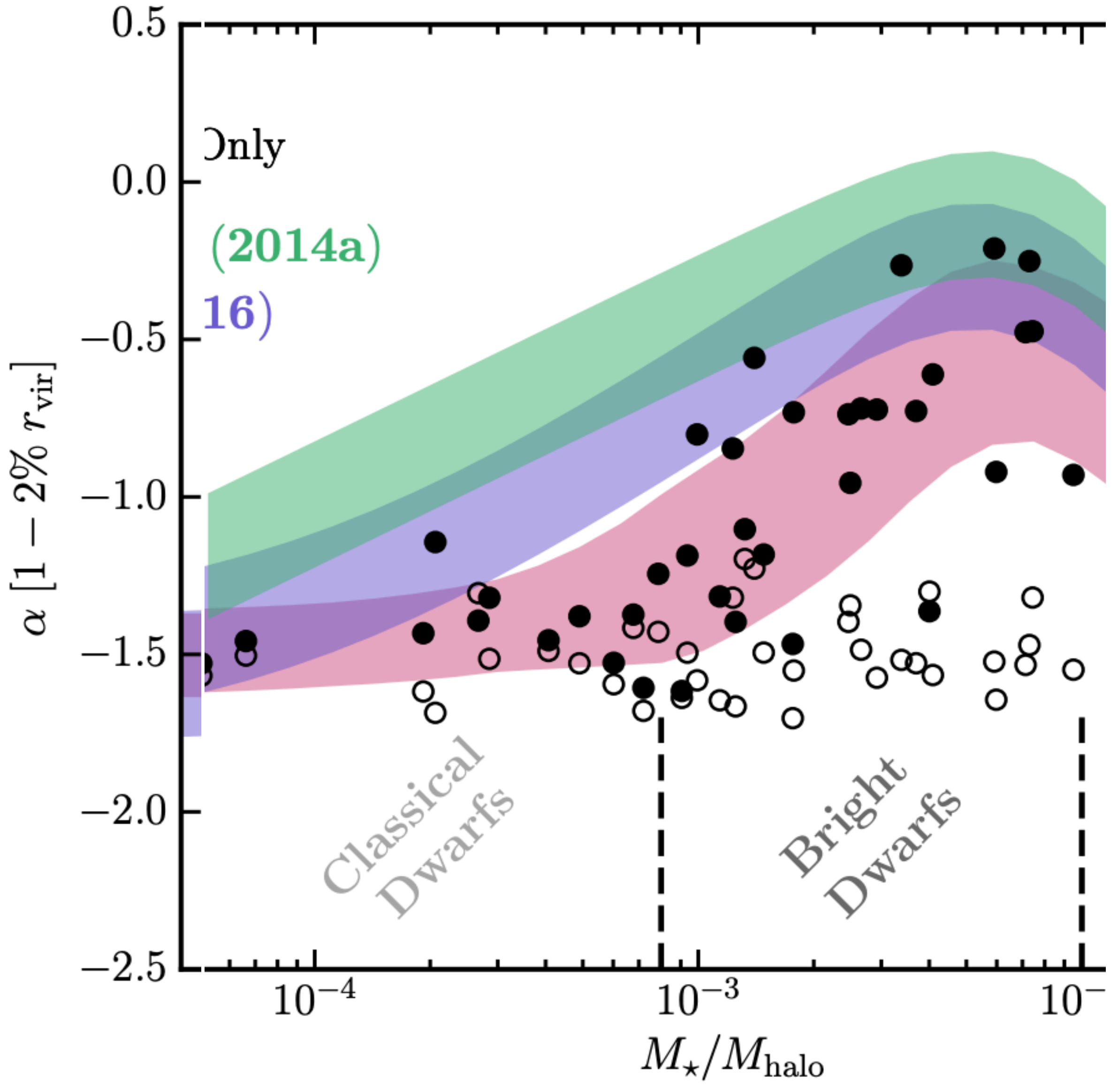
- Dwarfs

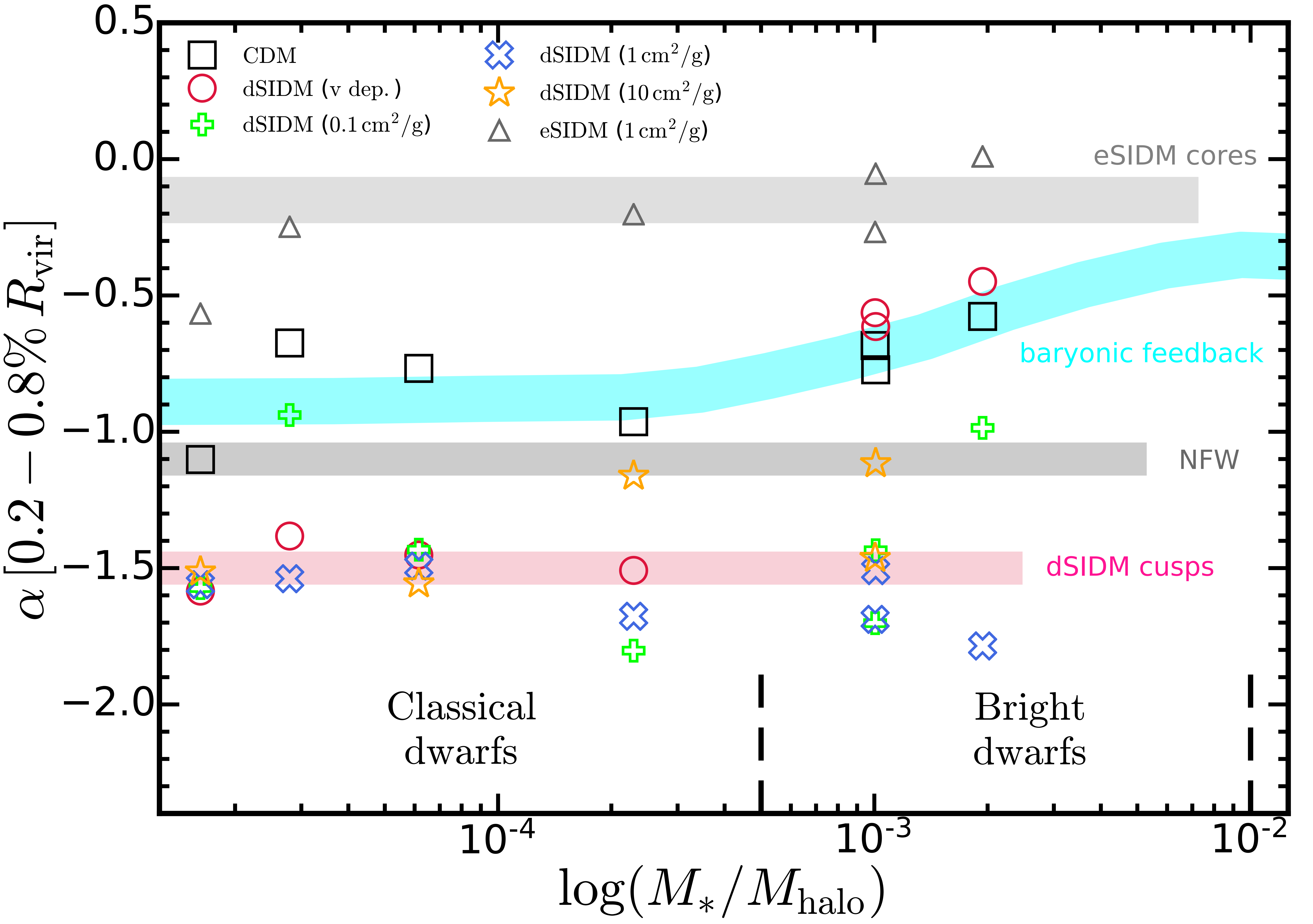
- haloes are more concentrated in dSIDM
- central density profiles become cuspy
- the cusp slope shows little dependence on SIDM cross-section



- the slope asymptotes to $\alpha \sim -3/2$
- spherical cooling flow of ideal fluid in steady state
- qualitatively different from eSIDM/feedback induced cores and NFW cusps

Lazar et al., 2020





- Observation constraints

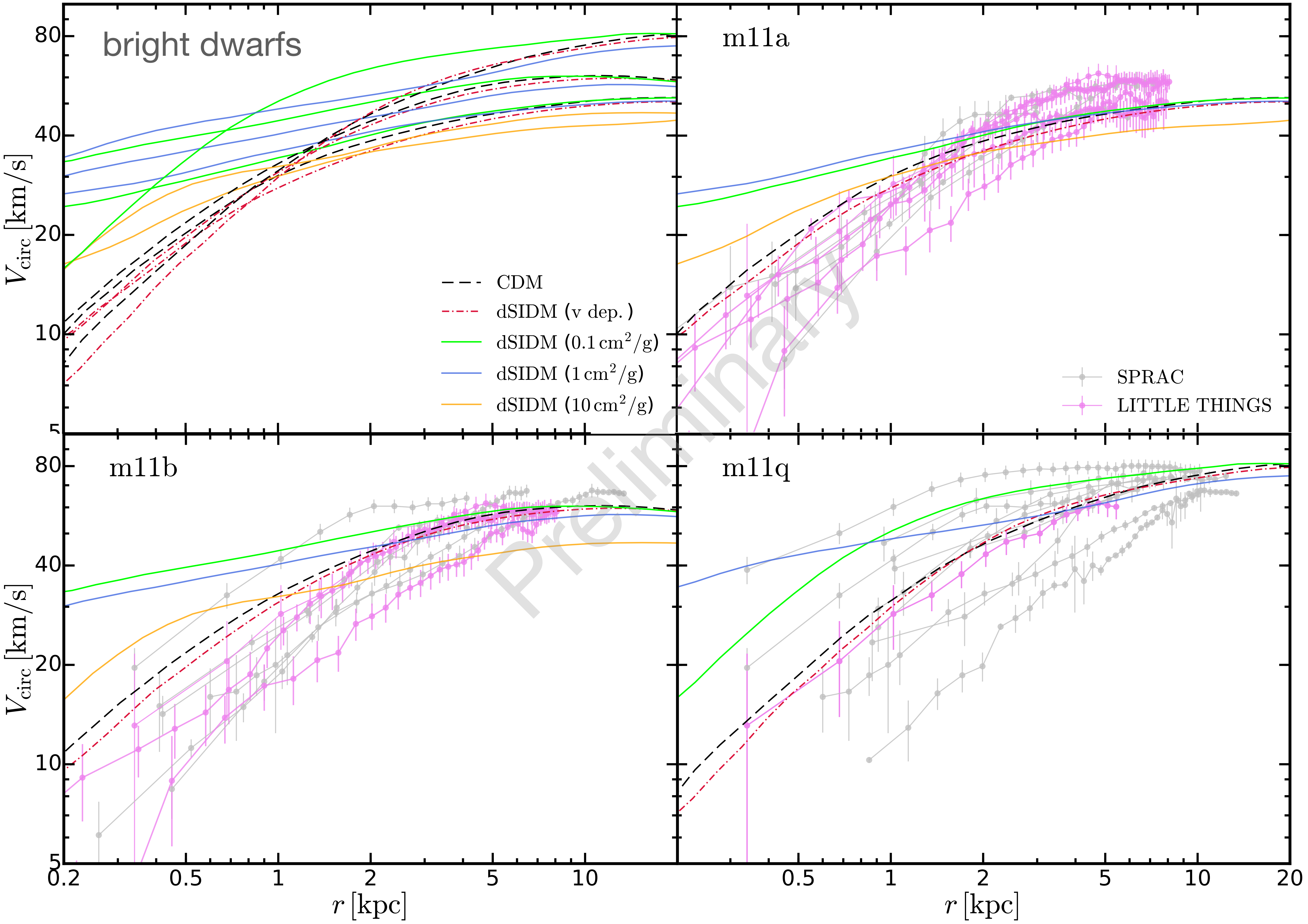
  - still consistent with Local Group observations
  - strongest constraints come from bright dwarfs (LSBs and UDGs as analogs in observations)

$$t_{\rm diss} \sim t_{\rm coll} \sim \frac{1}{\rho\,(\sigma/m)\,\nu}$$

$$\sim \frac{1}{\rho\,(\sigma/m)\,V_{\rm circ}^{\rm max}}$$

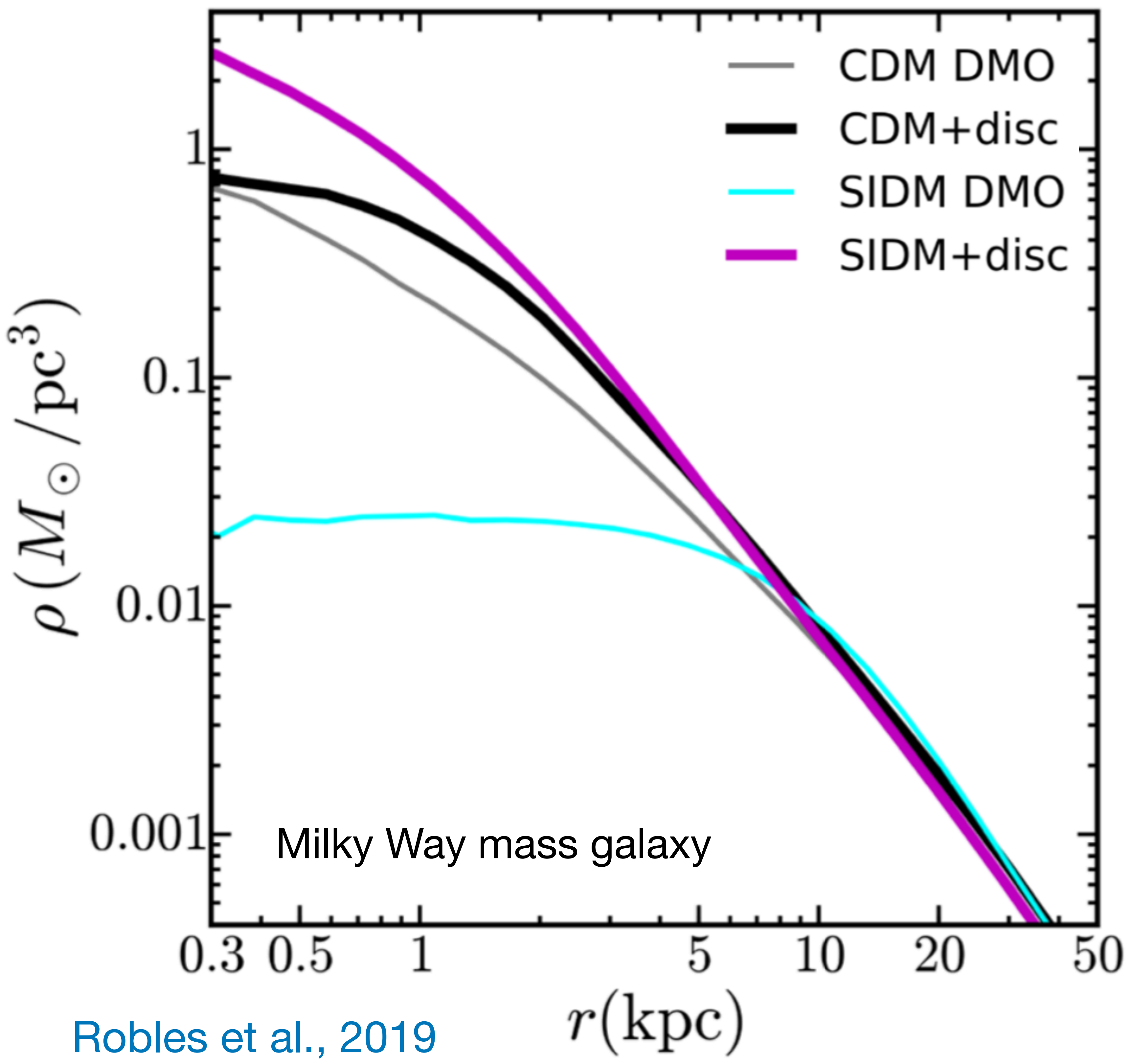
$$\sim \frac{1}{\rho\,(\sigma/m)\,M_{\rm vir}^{1/3}}$$

  - dSIDM cusps result too high rotation velocities at $r \lesssim 1\mathrm{kpc}$ when $(\sigma/m) \gtrsim 0.1\,\mathrm{cm}^2/\mathrm{g}$

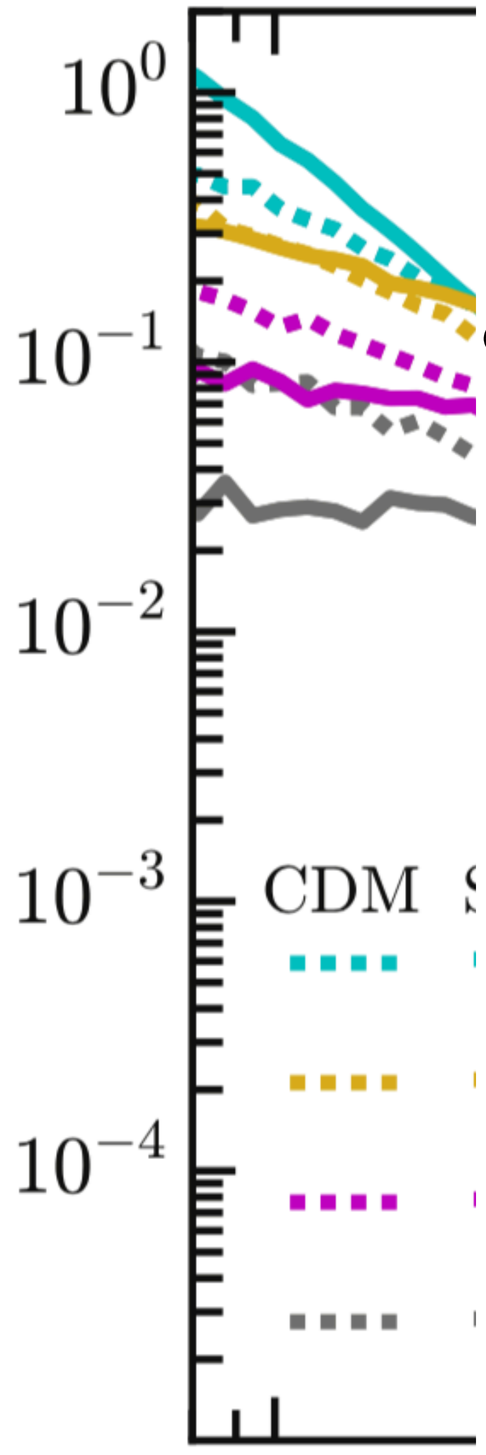


- Beyond dwarf scale - transition of baryon dominated system

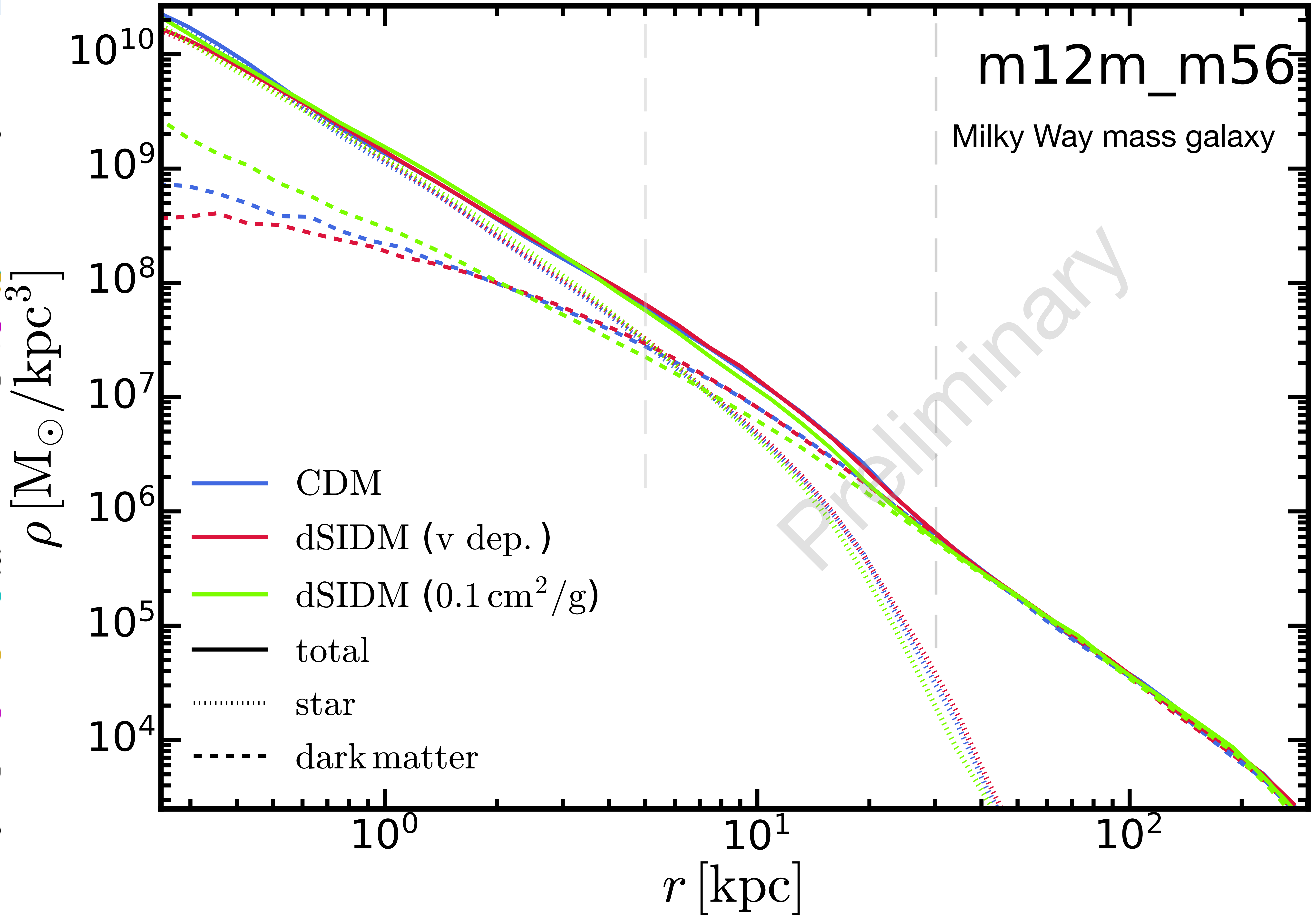
  - adiabatic contraction (stronger response from SIDM)
  - enhanced thermal conduction and gravothermal contraction
  - self-regulation of baryons



Robles et al., 2019



Elbert



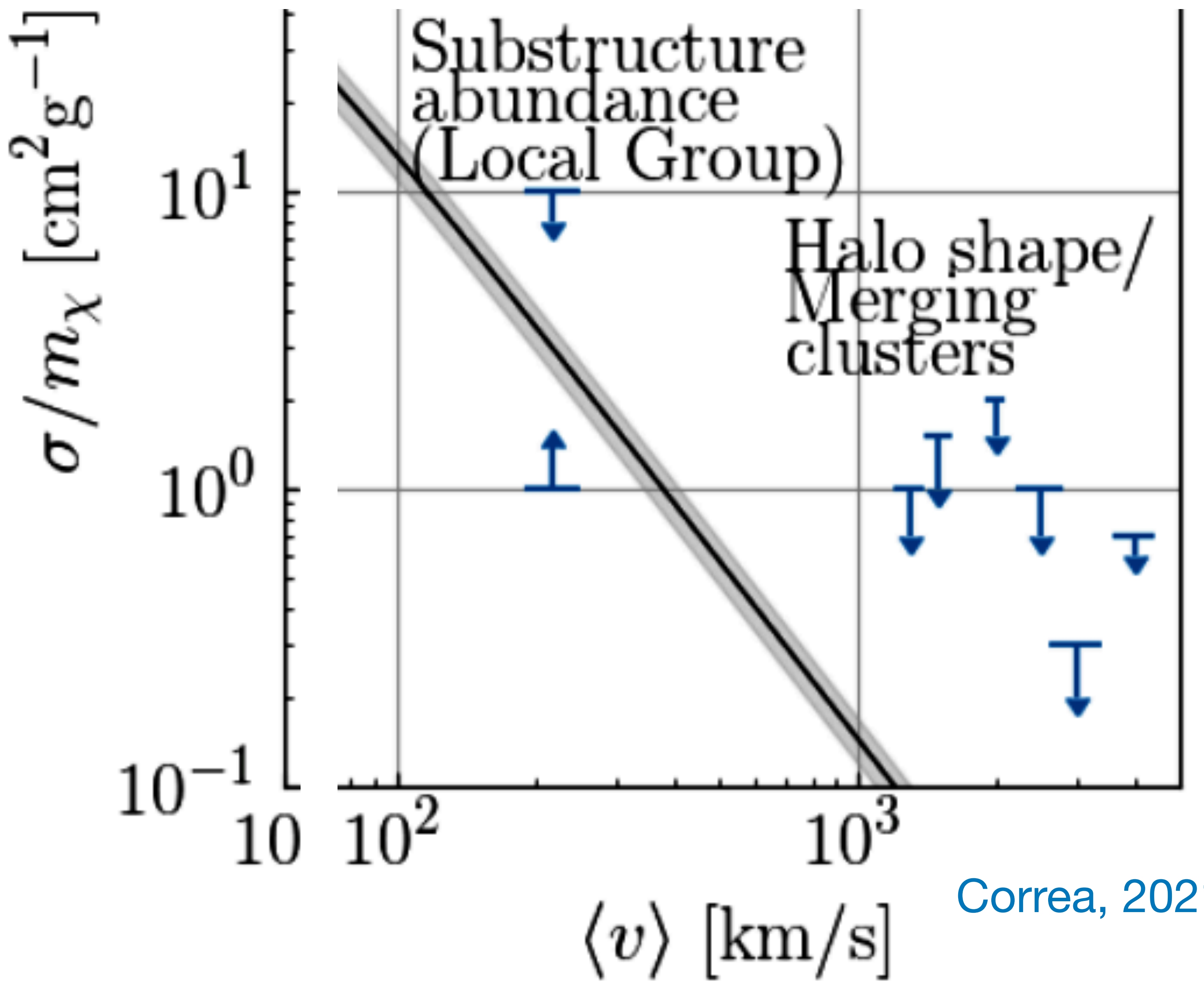
- Galaxy clusters

- Strongest constraints, hints for velocity-dependent model
    - shape and central density of clusters (Peter et al. 2013)
    - measurements of the offset between the DM and galaxy centre (e.g. Kahlhoefer et al. 2015; Harvey et al. 2015; Wittman et al. 2018; Harvey et al. 2019)
    - measurements of the mass-to-light ratio of the Bullet Cluster (Randall et al. 2008)

- baryonic processes ?

  fueling of cold gas, quenching of star formation
  growth and feedback from massive BHs

- substructures ?
    - An excess of small-scale gravitational lenses observed in galaxy clusters (Meneghetti et al., 2020)
    - Unexpected concentrated substructures in galaxy cluster (Minor et al., 2020)

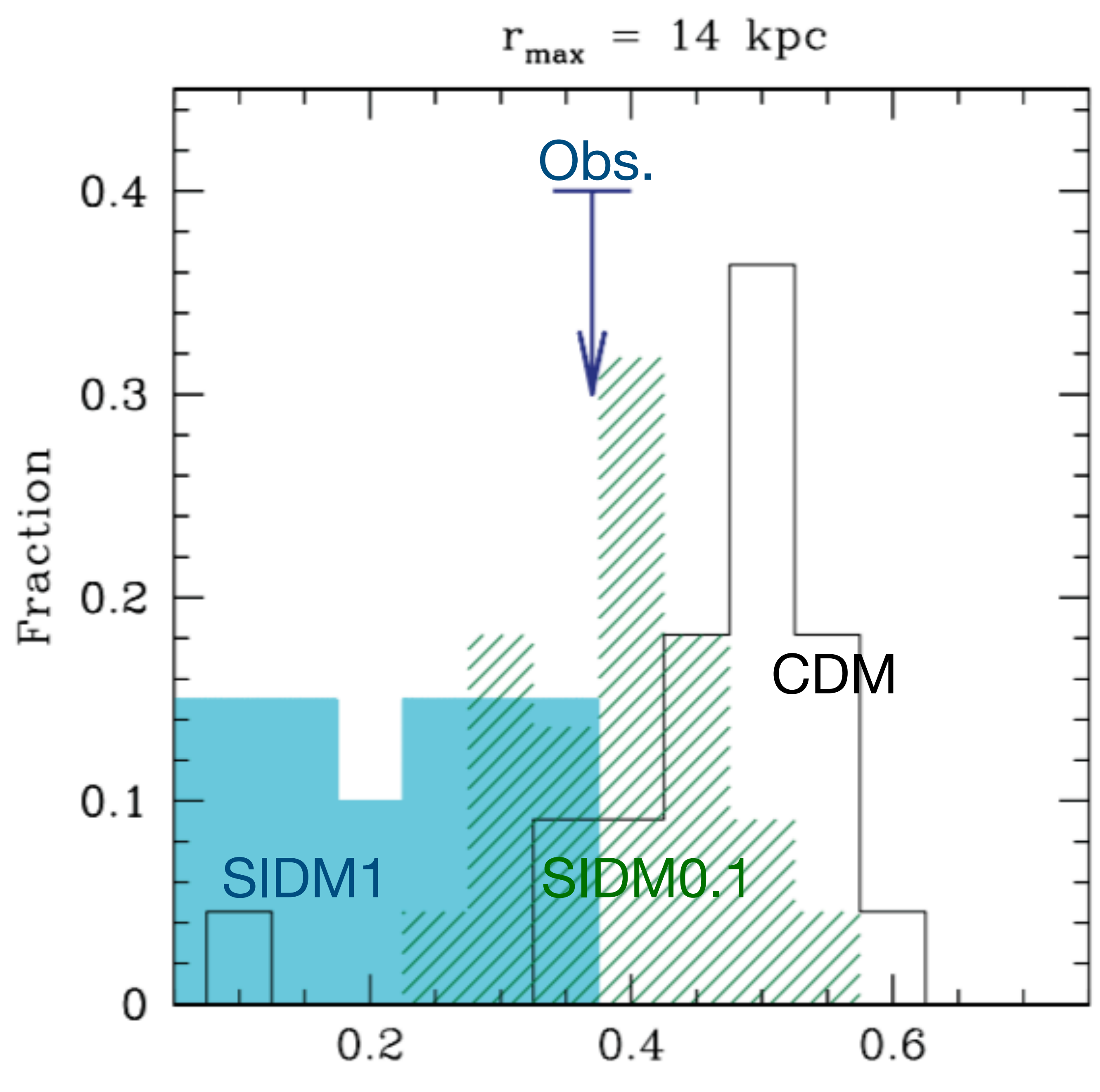


Correa, 2021

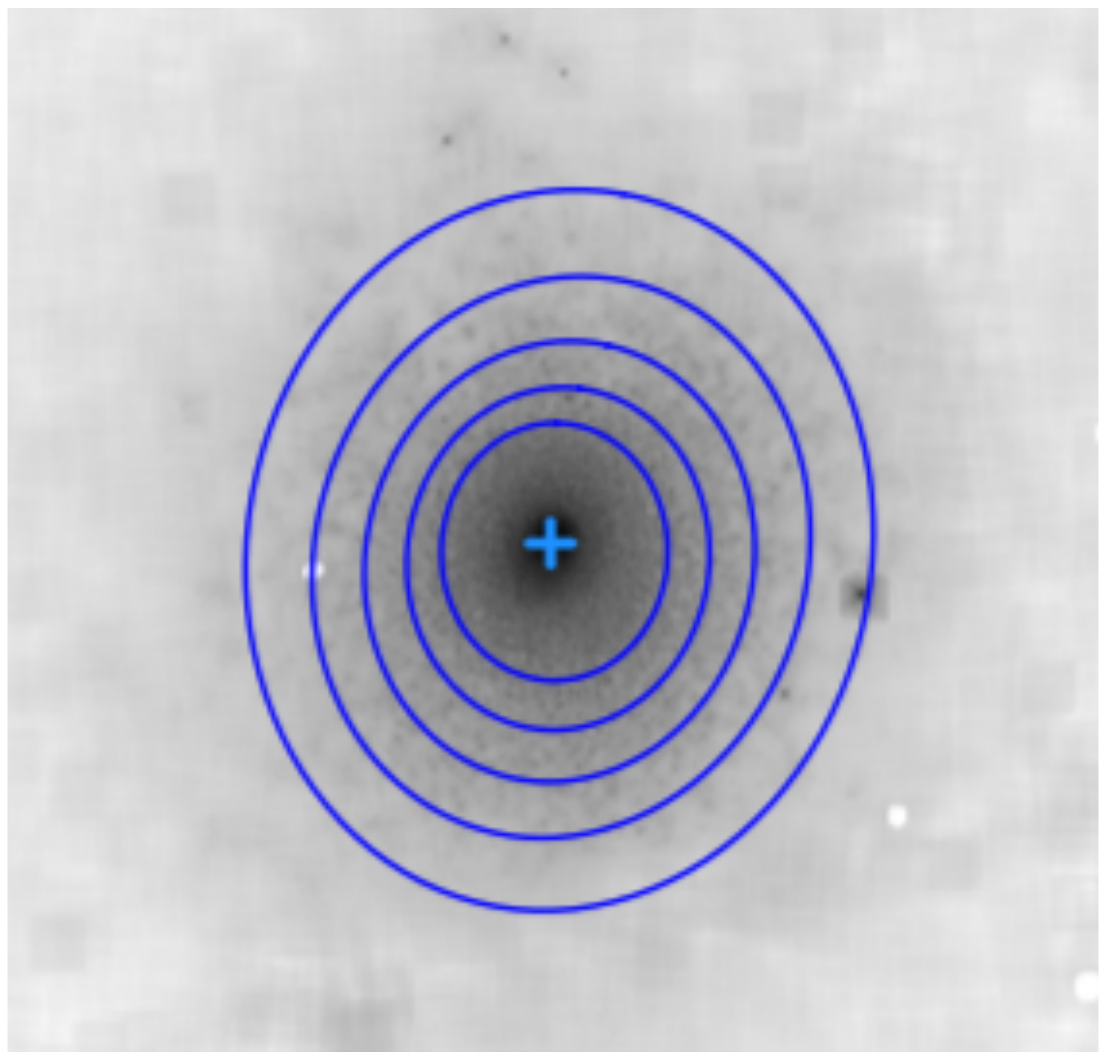
- X-ray morphology of clusters in SIDM

In collaboration with Thejs Brinckmann, Jesús Zavala (University of Iceland), David Rapetti (CU Boulder) and Mark Vogelsberger (MIT), in prep.

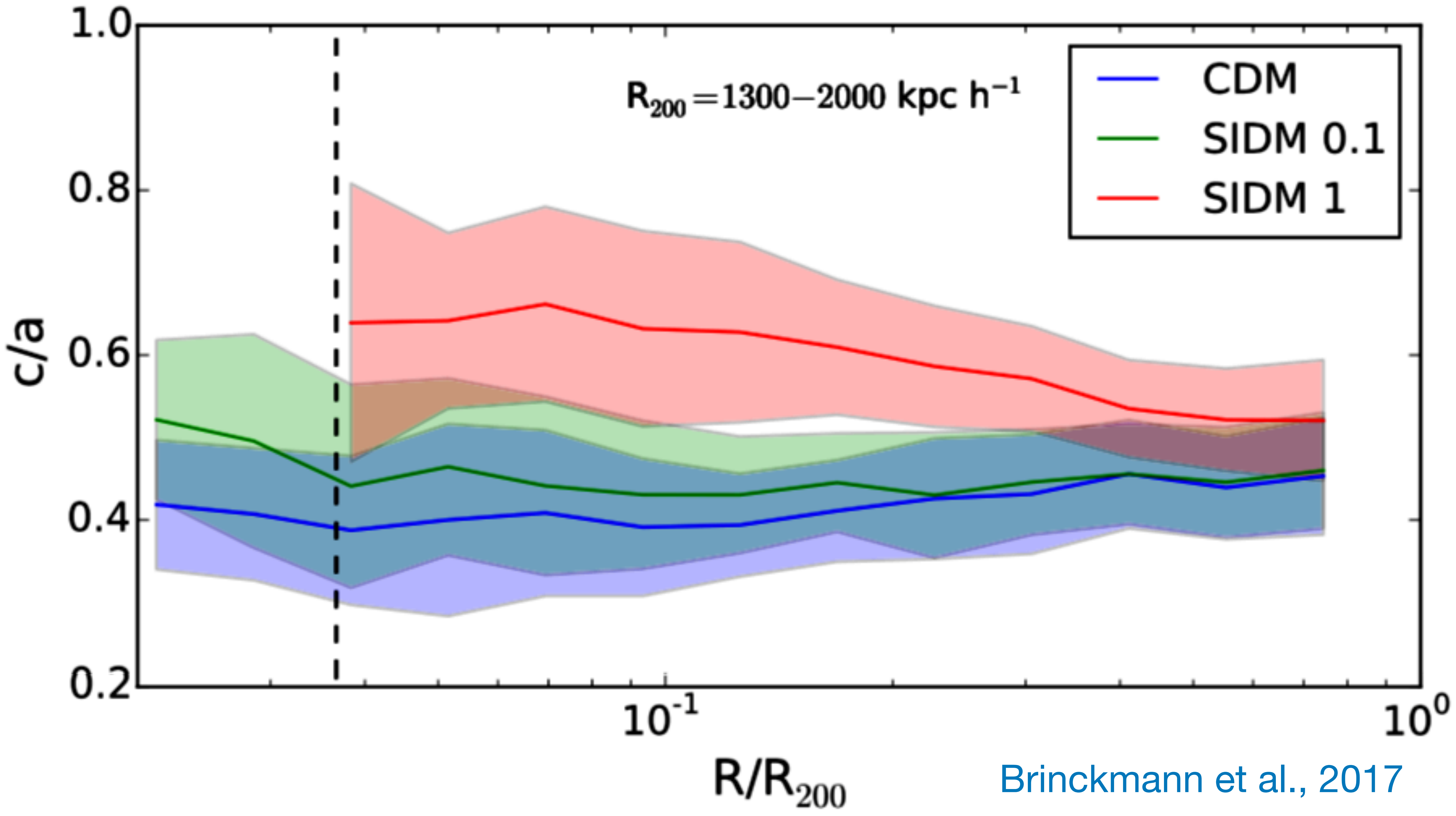
- A series of cosmological zoom-in simulations of cluster-mass haloes in CDM/eSIDM with the inclusion of adiabatic gas
- Mock X-ray images generated by modeling the emission of hot intra-cluster gas
- The 2D morphology of X-ray images (shapes of the isophotes) can be used to constrain SIDM



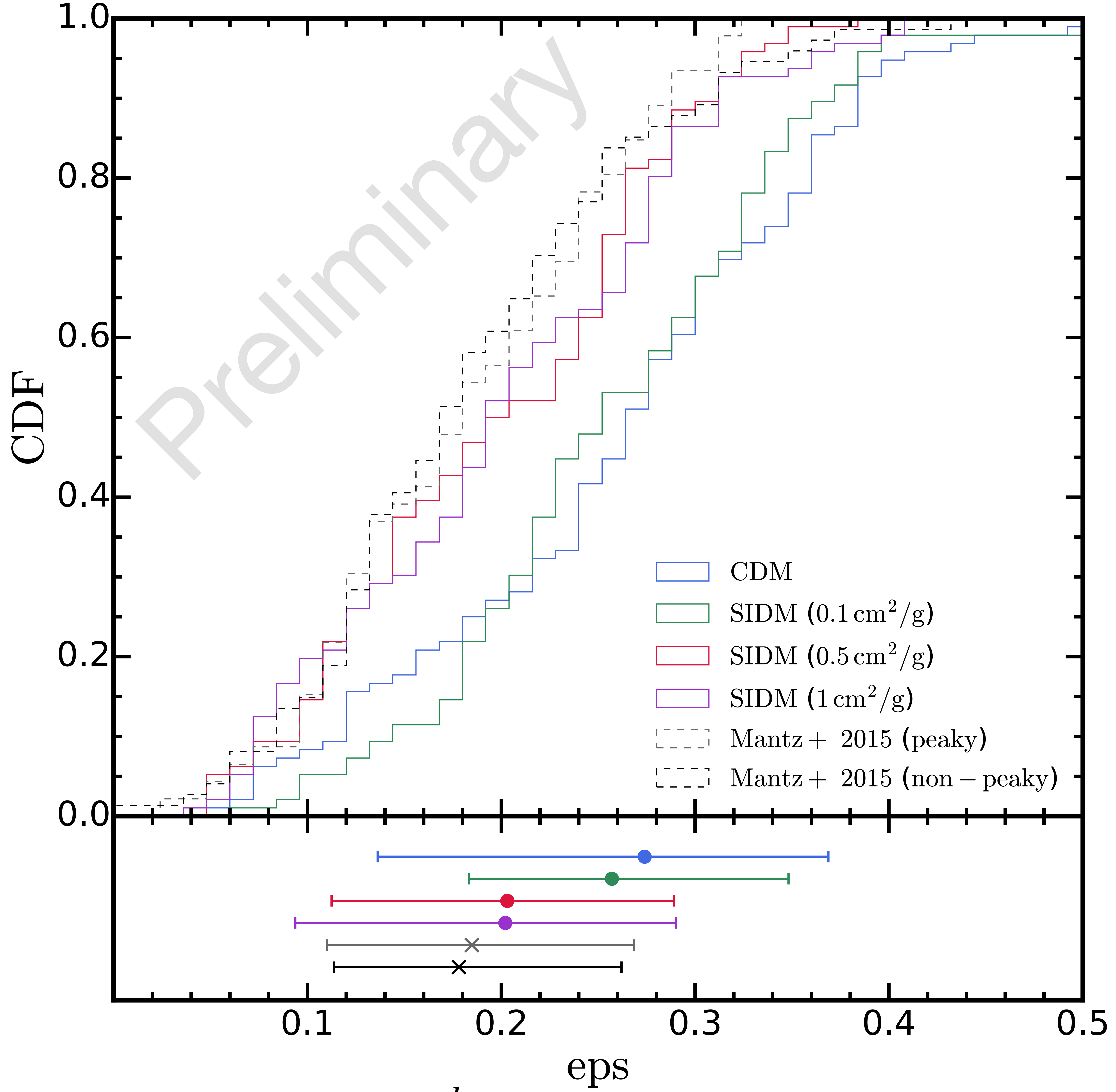
Peter et al., 2013



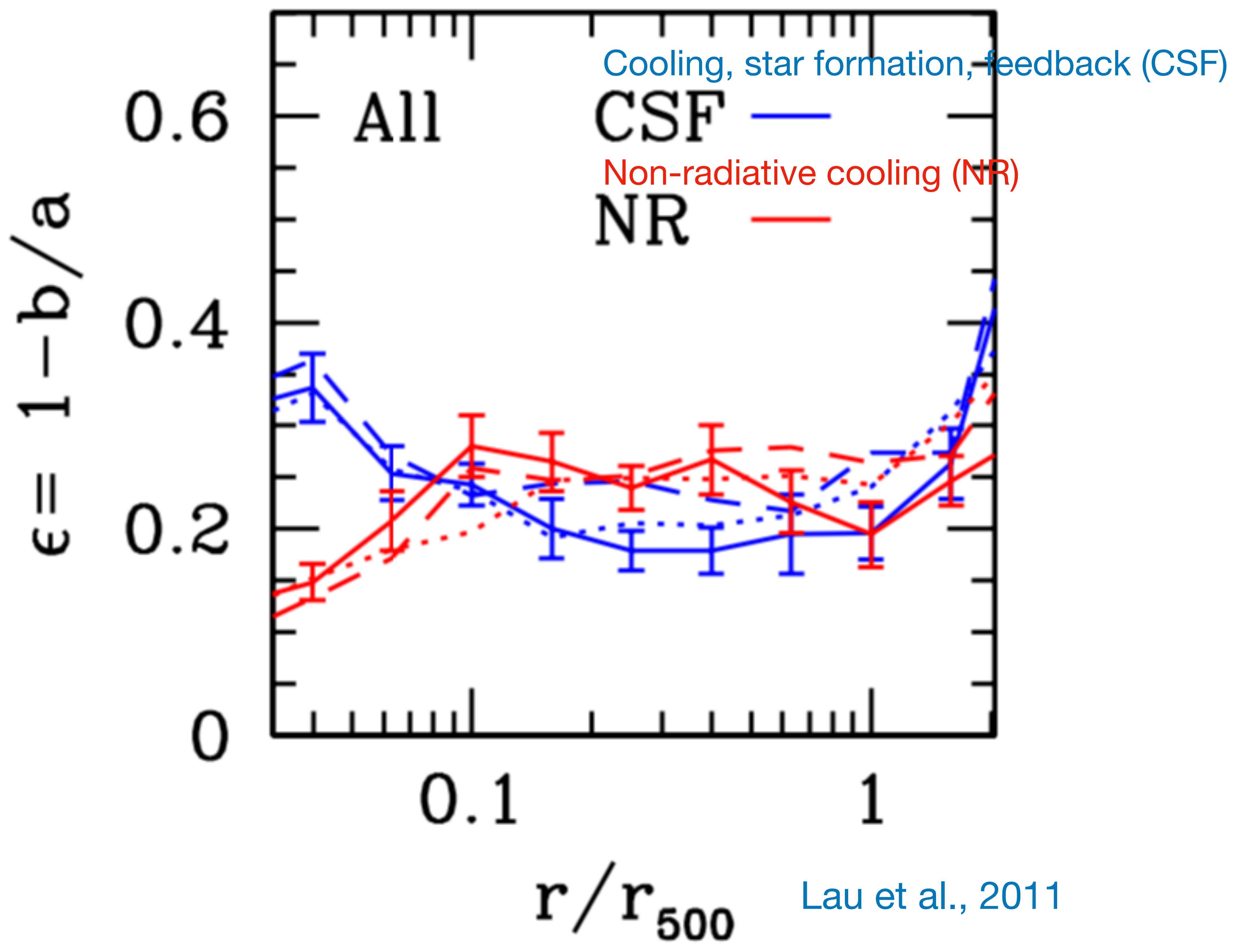
Chandra Xray
Mantz et al., 2015



Brinckmann et al., 2017



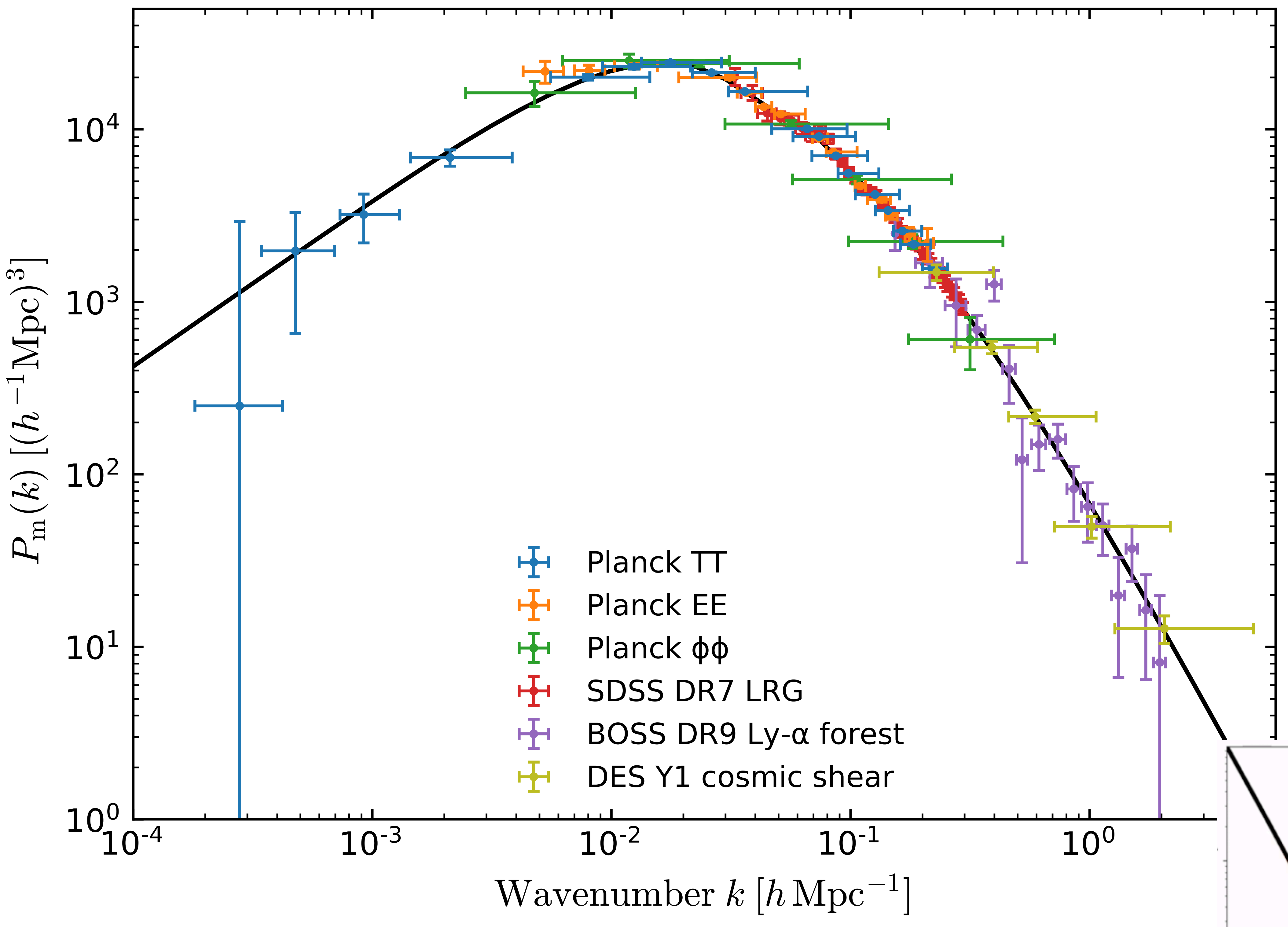
$$eps \equiv 1 - \frac{b}{a} \quad \text{at} \quad r \sim 10\% - 20\,\%\, R_{200}$$

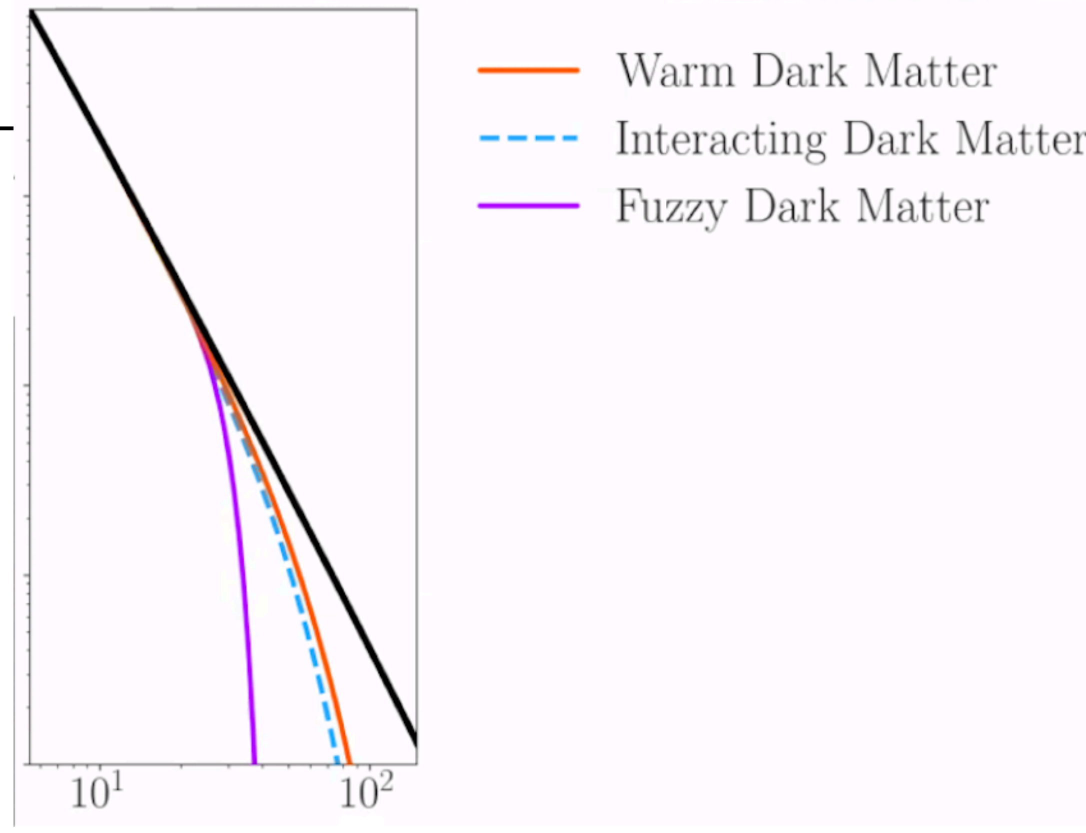


- more realistic modelling of physics at cluster-scale
- higher resolution

- beyond Local Universe
- & beyond SIDM

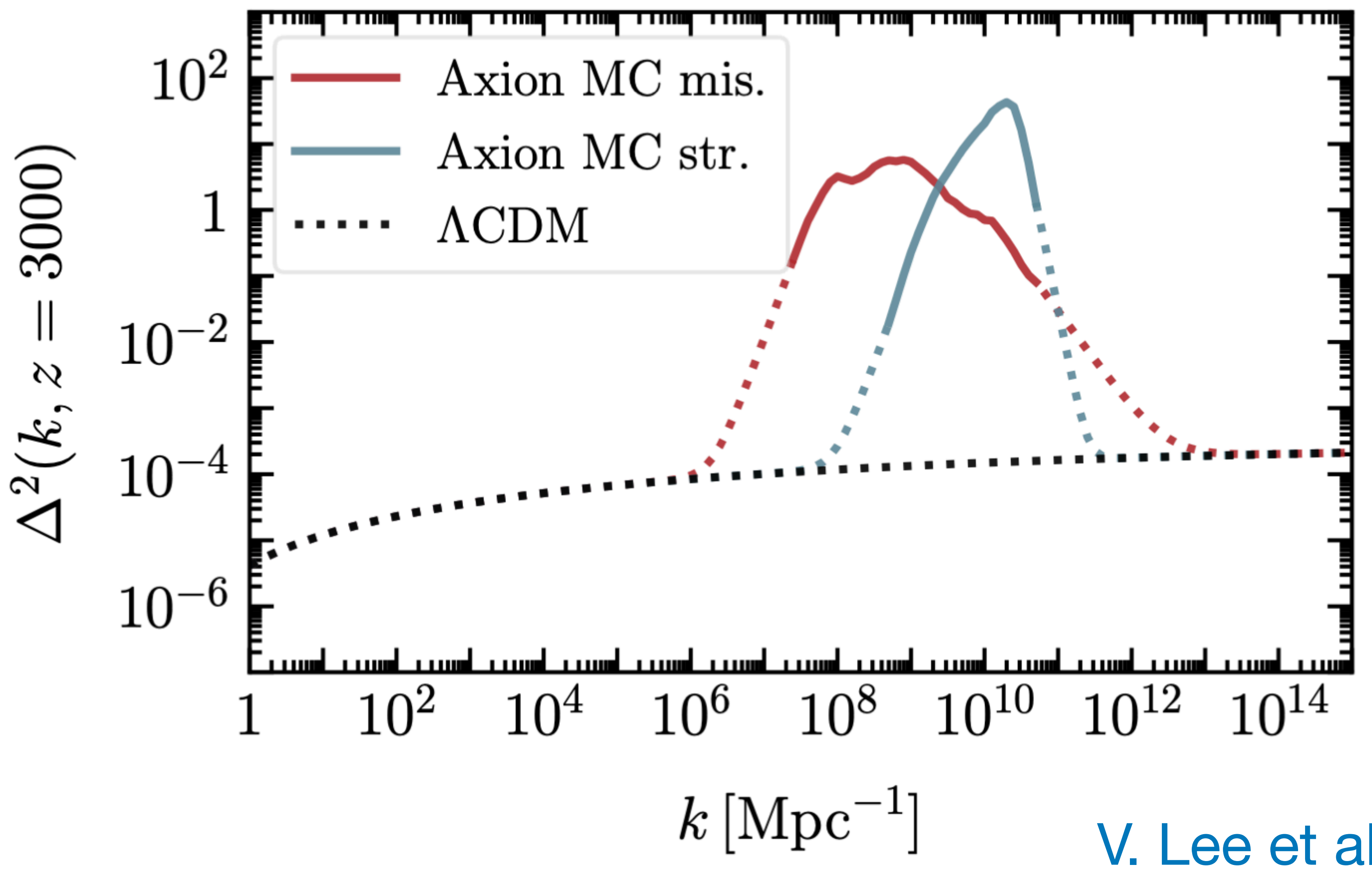
- Initial power-spectrum
  - cut-off in power spectrum at sub-galactic scale $k \gtrsim 1 h\mathrm{Mpc}^{-1}$
    - warm dark matter
    - fuzzy dark matter
    - SIDM with dark acoustic oscillation
  - enhanced clustering at small scale $k \gtrsim 1\mathrm{pc}^{-1}$
    - axion miniclusters





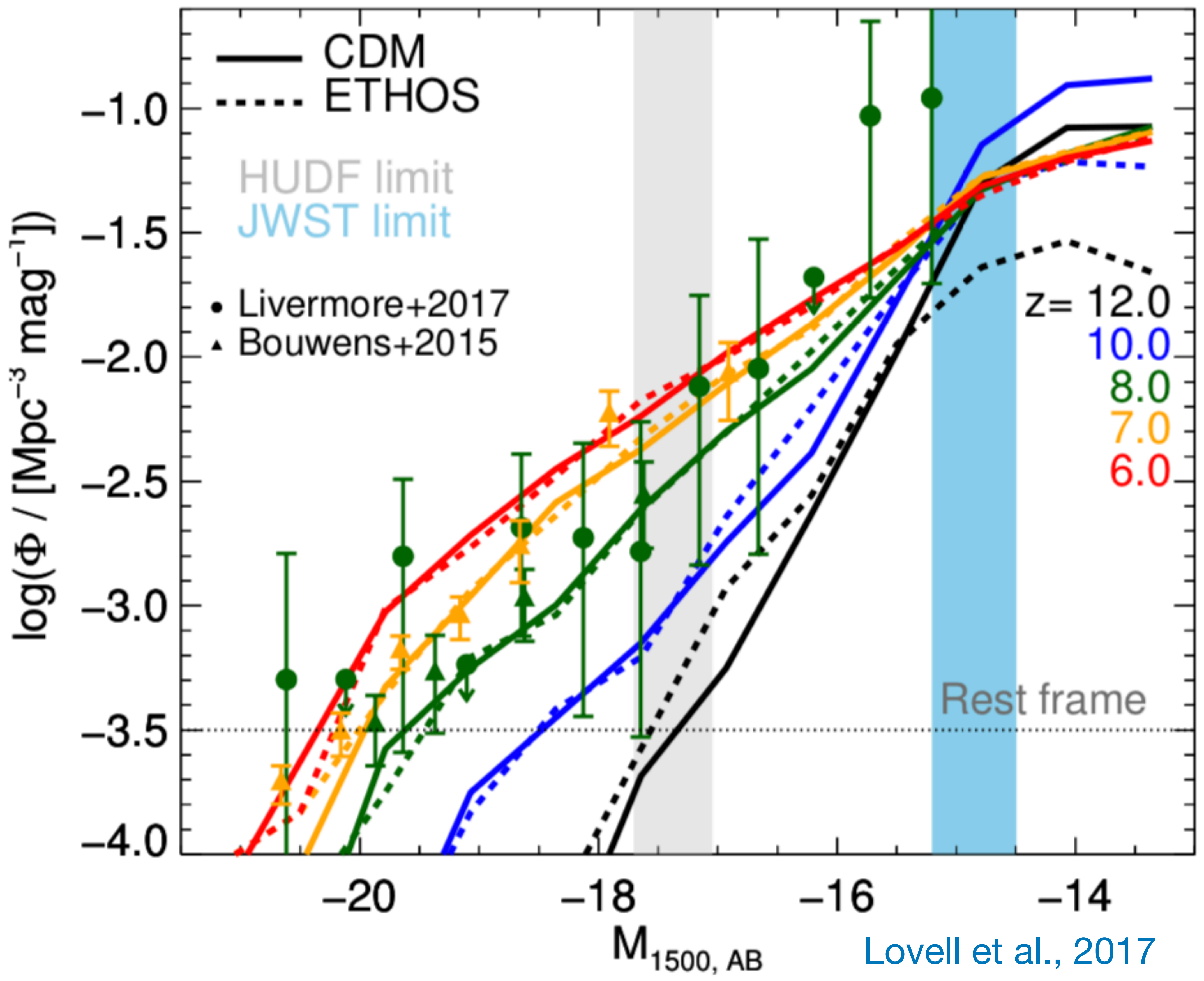
The Planck collaboration, 2019

E. Nadler, 2019/2020



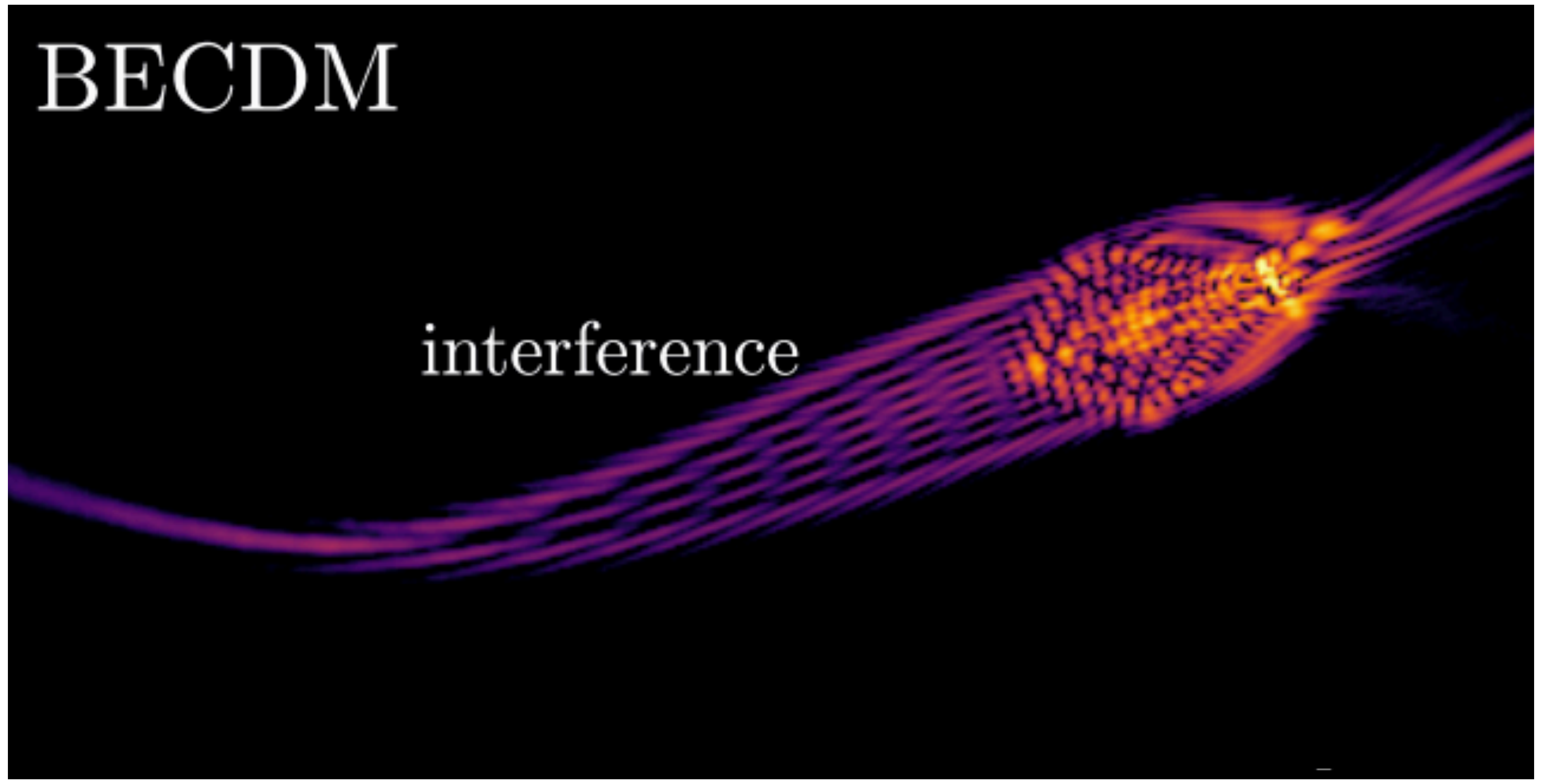
V. Lee et al., 2020

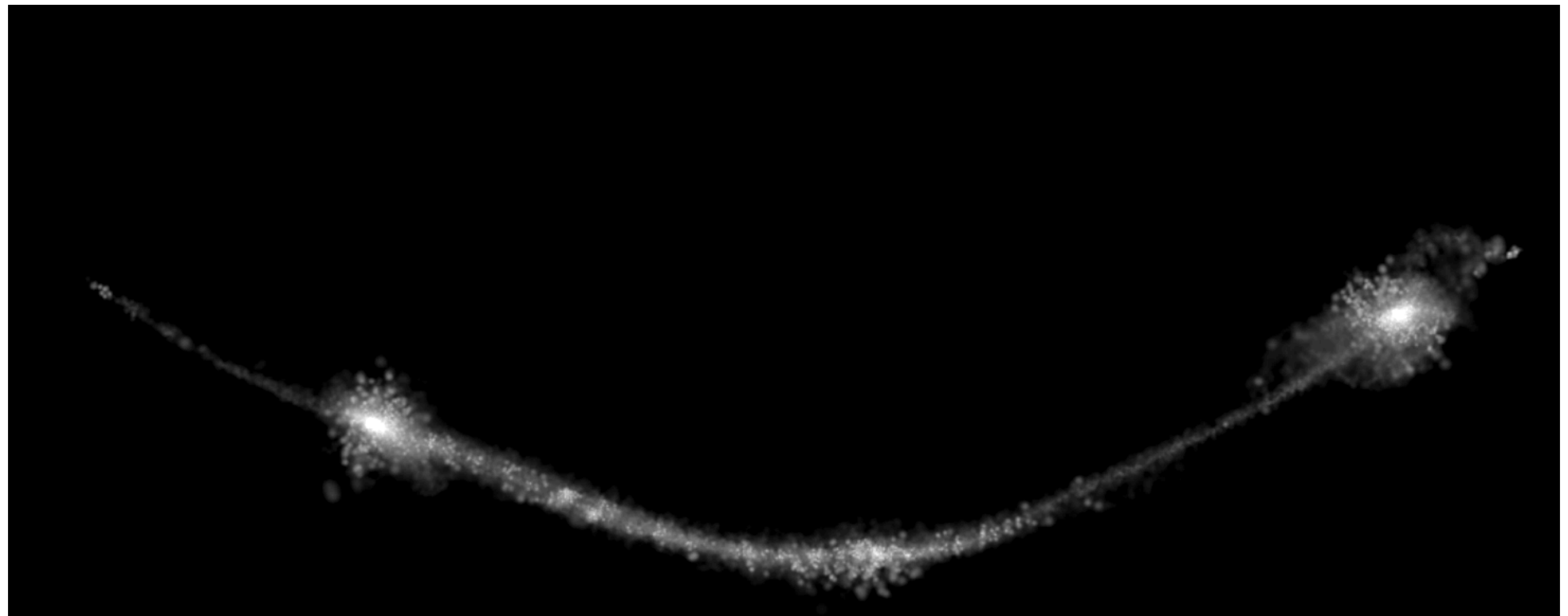
- dark ages to reionization ($6 \lesssim z \lesssim 30$)
    - abundance of faint galaxies at cosmic dawn
    - reionization history & CMB optical depth



Lovell et al., 2017

- unique structures (e.g. filaments in fuzzy dark matter/BECDM)





Filamentary structure at z=5.5 in BECDM

Mocz et al. 2020

Outline

- Personal background

- Background introduction
  - evidences for dark matter
  - classical candidates and experimental searches
  - alternative candidates
  - motivations from astrophysical observations
  - numeric simulations

- Alternative dark matter models & relevant projects
  - SIDM early studies
  - dissipative SIDM
  - SIDM beyond dwarf scale
  - other dark matter models

- Future plans/ projects

Future plans/projects

Planned (2021- early 2022)

dSIDM follow-up(s)

II. observational constraints from dwarfs

III. Milky Way mass galaxies

cluster X-ray morphology

disruption of axion-minicluster

Future plans/projects

Ideas in mind (2022-)

more realistic dSIDM/multi-state SIDM setup

- exothermic and endothermic processes
- bound states, cooling function

fuzzy dark matter

- numeric implementation
- Local Group & high redshift implications

epoch of reionization predictions