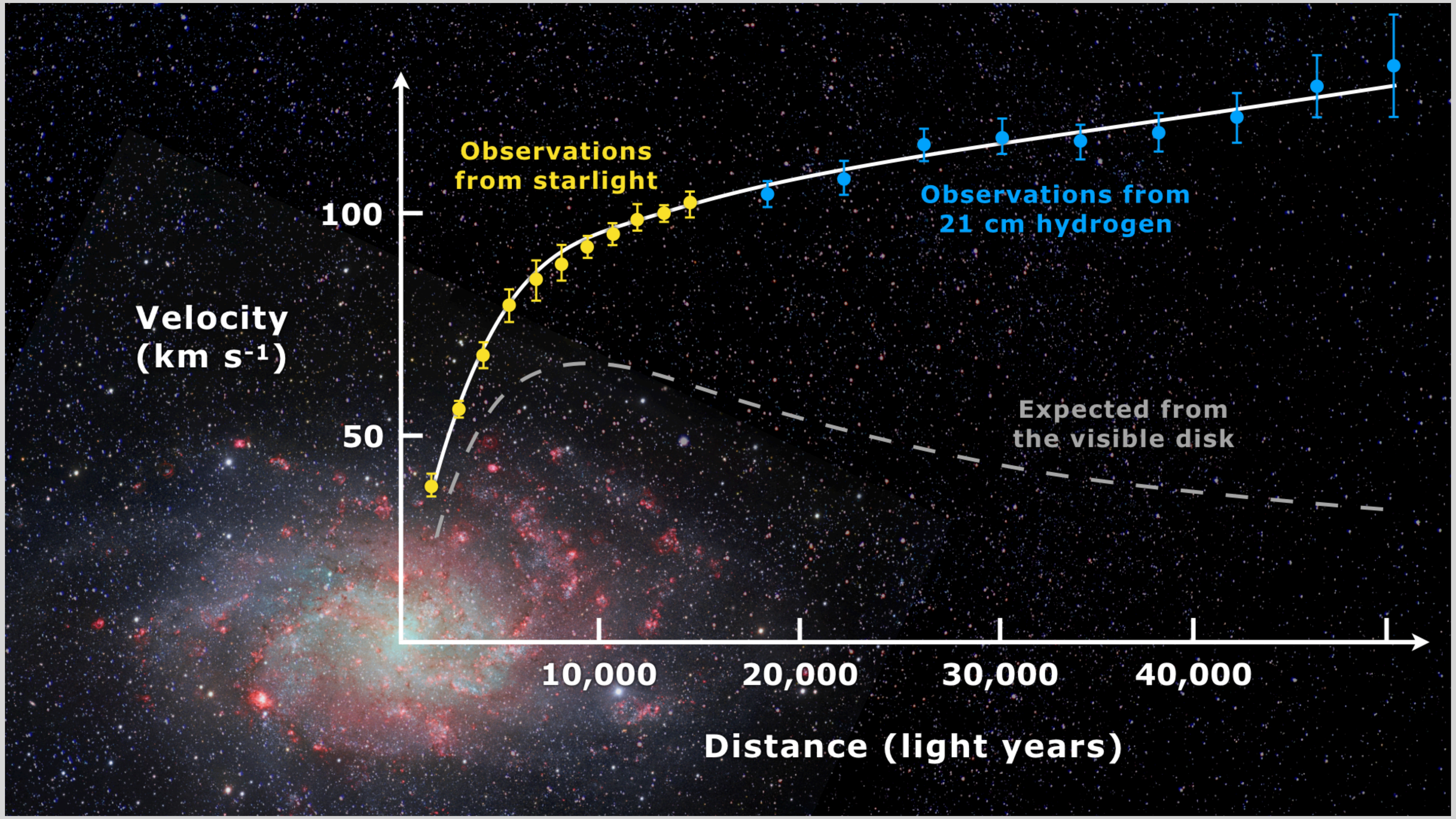
Constraints on Dark Matter from Galaxy Rotation Curves

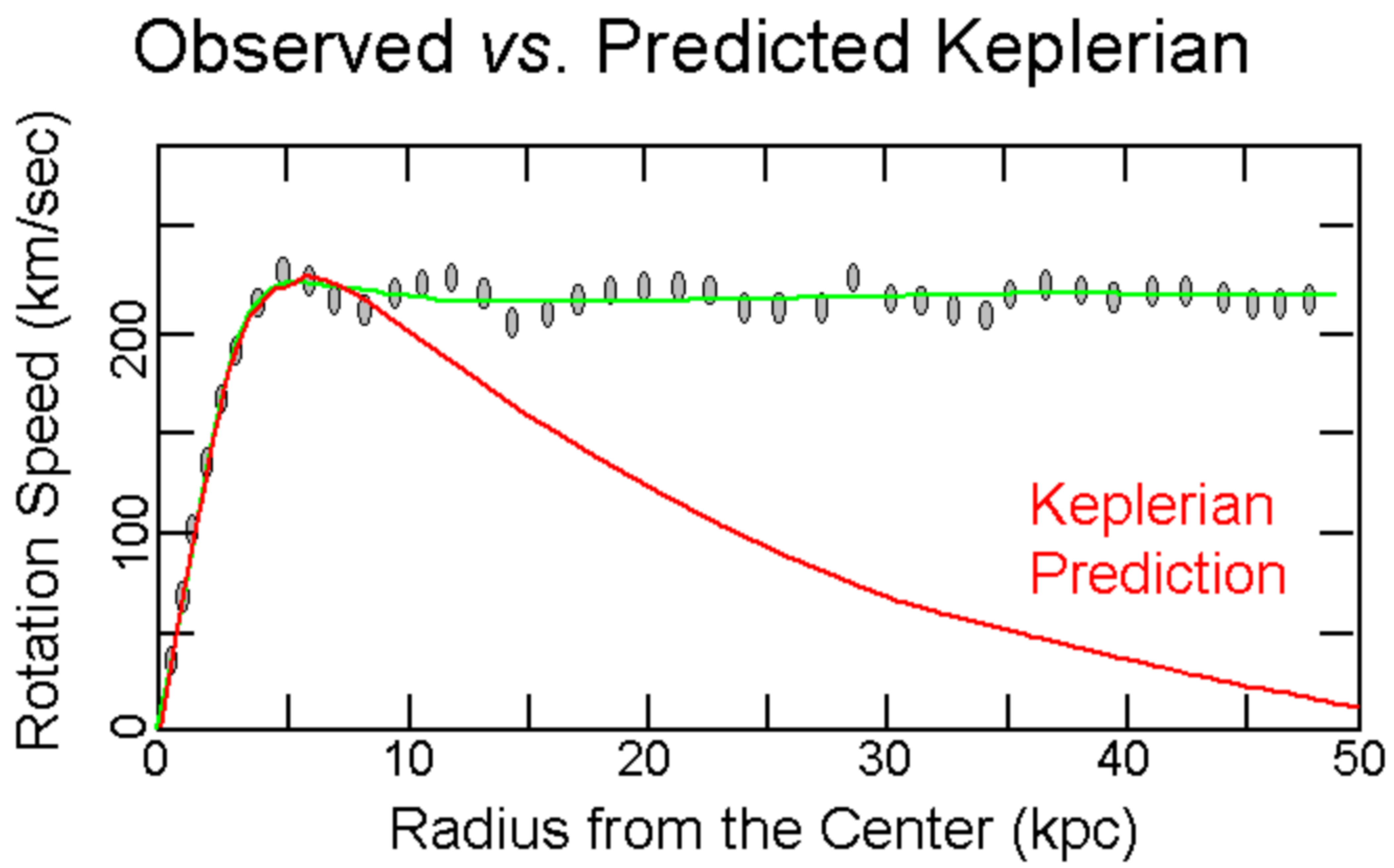


Outline

1. Early work
2. ΛCDM
3. Small scale problems of ΛCDM: core cusp problem & diversity of rotation curves
4. Solutions in ΛCDM
5. How to test this observationally?
6. Results from observational studies
7. Solutions beyond ΛCDM
8. Results from observational studies using alternative Dark Matter models
9. Outlook

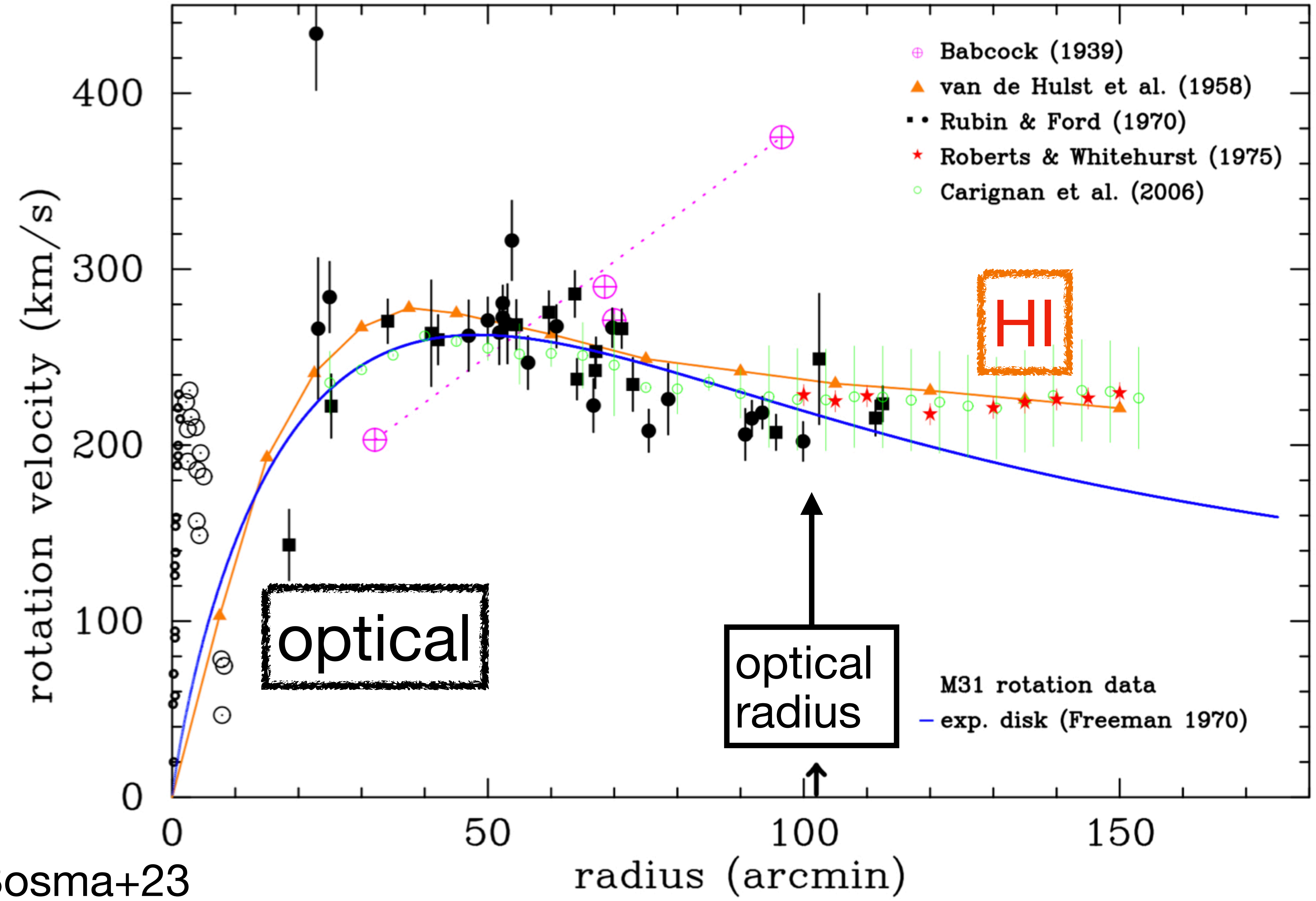
Early Work

- "**mass discrepancy problem**" in galaxies and cosmology has been around since ~1930 (Oort 1932 and Zwicky 1933).



- '**dark matter**' entered mainstream research in ~1970 when observations revealed that galaxy rotation curves remain flat at large galactocentric distances (van de Hulst +1957, Freeman 1970, Rubin & Ford 1970)

Early Work



Bosma+23

- rotation curves are amongst the only observables one can use to study the matter distribution on galactic scales

Dark Matter Candidates

Early work

- suggestions as to the identity of the unseen matter include **massive neutrinos** (Cowsik & McClelland 1972), **faint stars** (Ostriker, Peebles & Yahil 1974), **black holes** (Truran & Cameron 1971), and **comets** (Tinsley & Cameron 1974).

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Nowadays

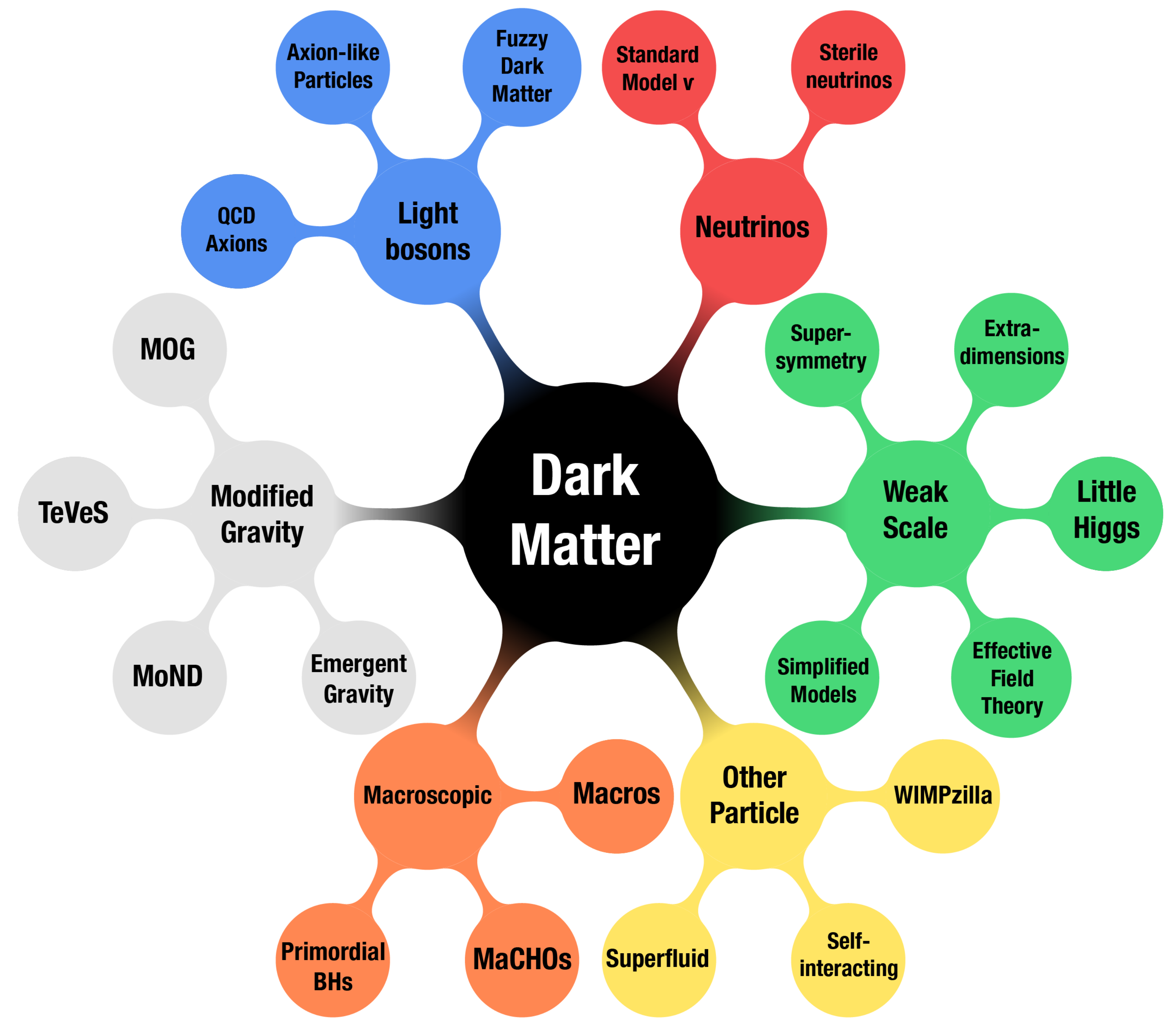

Image: Berton & Tait from here

Dark Matter Candidates

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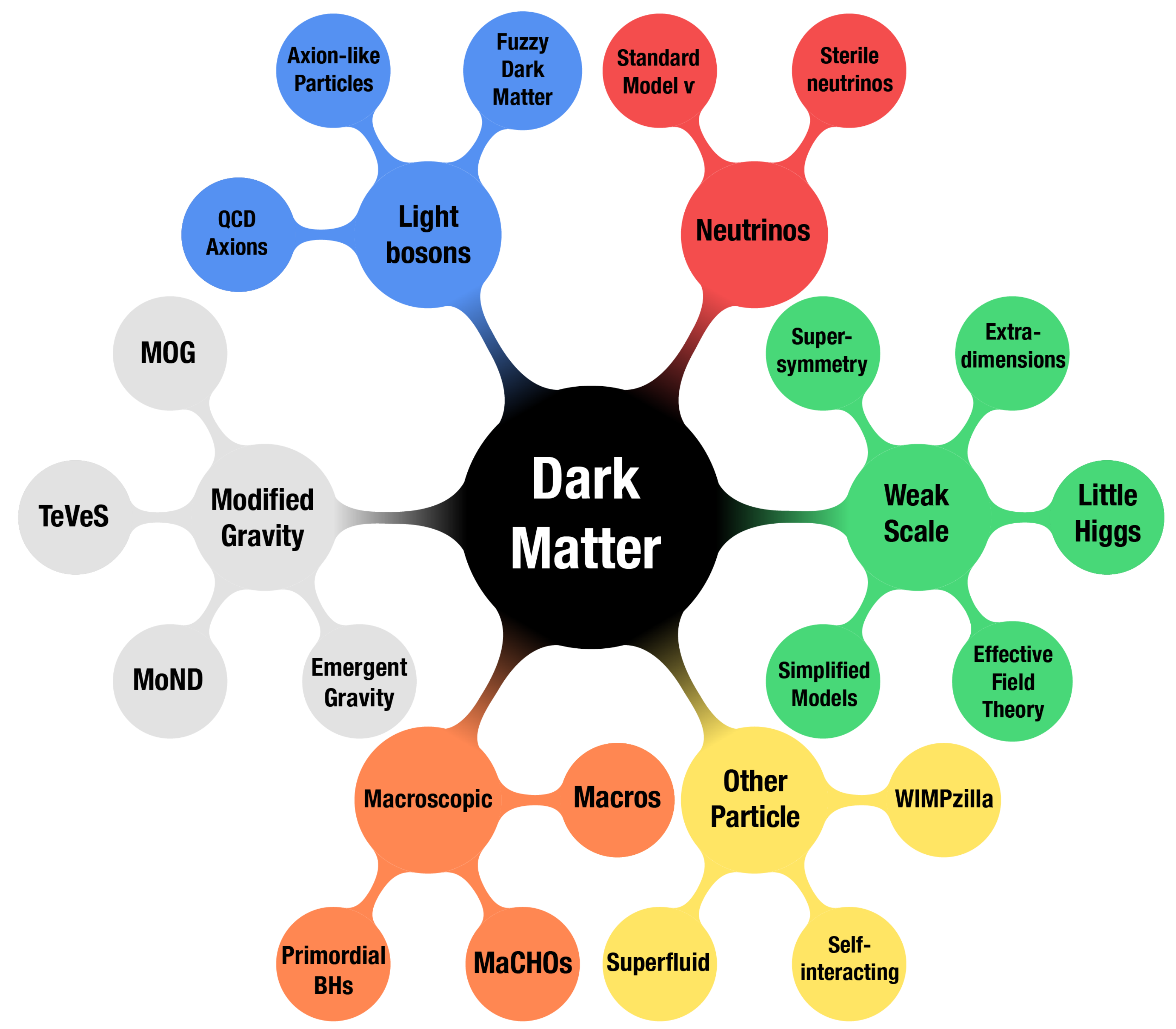
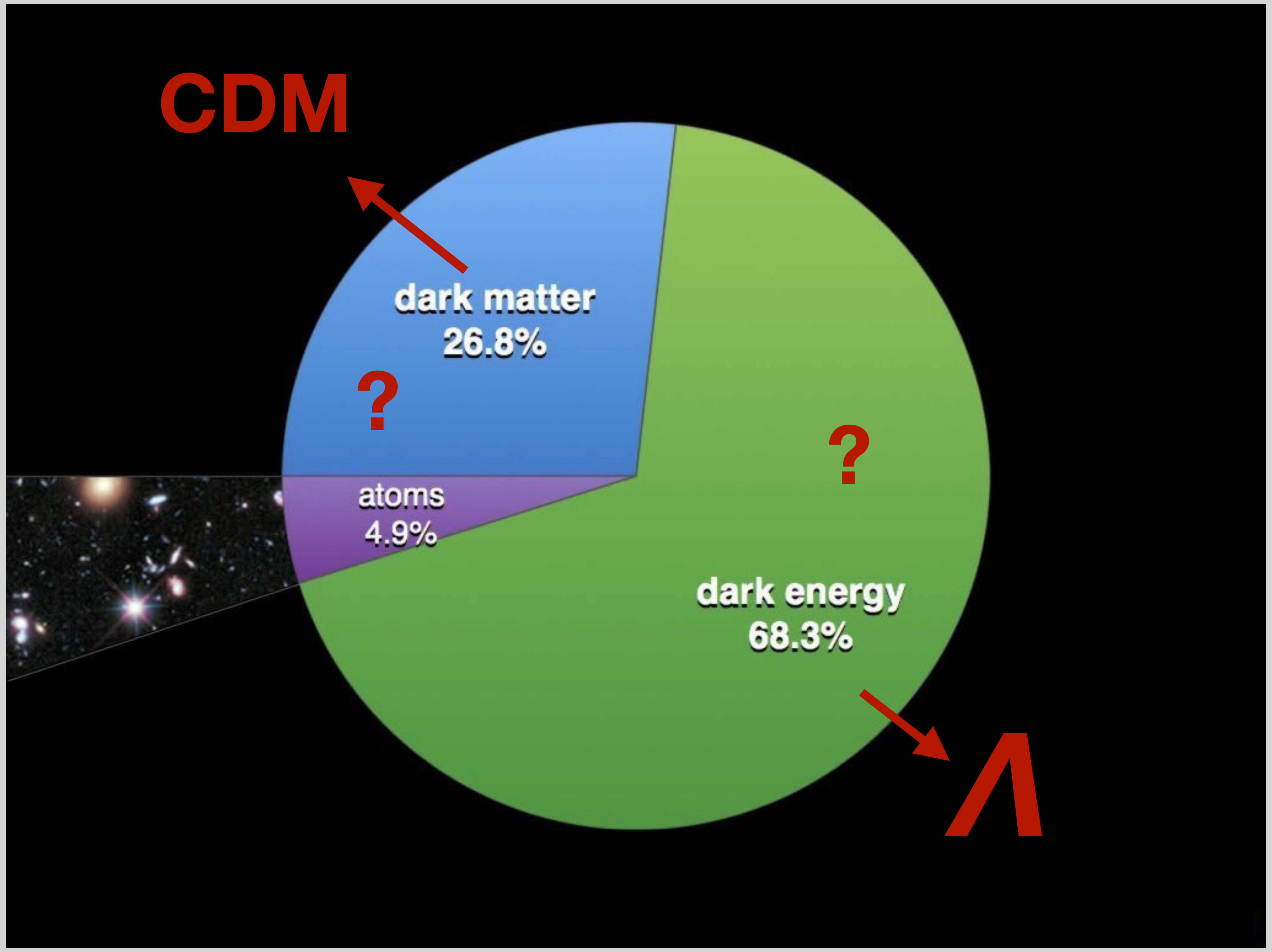


Image: Berton & Tait from here

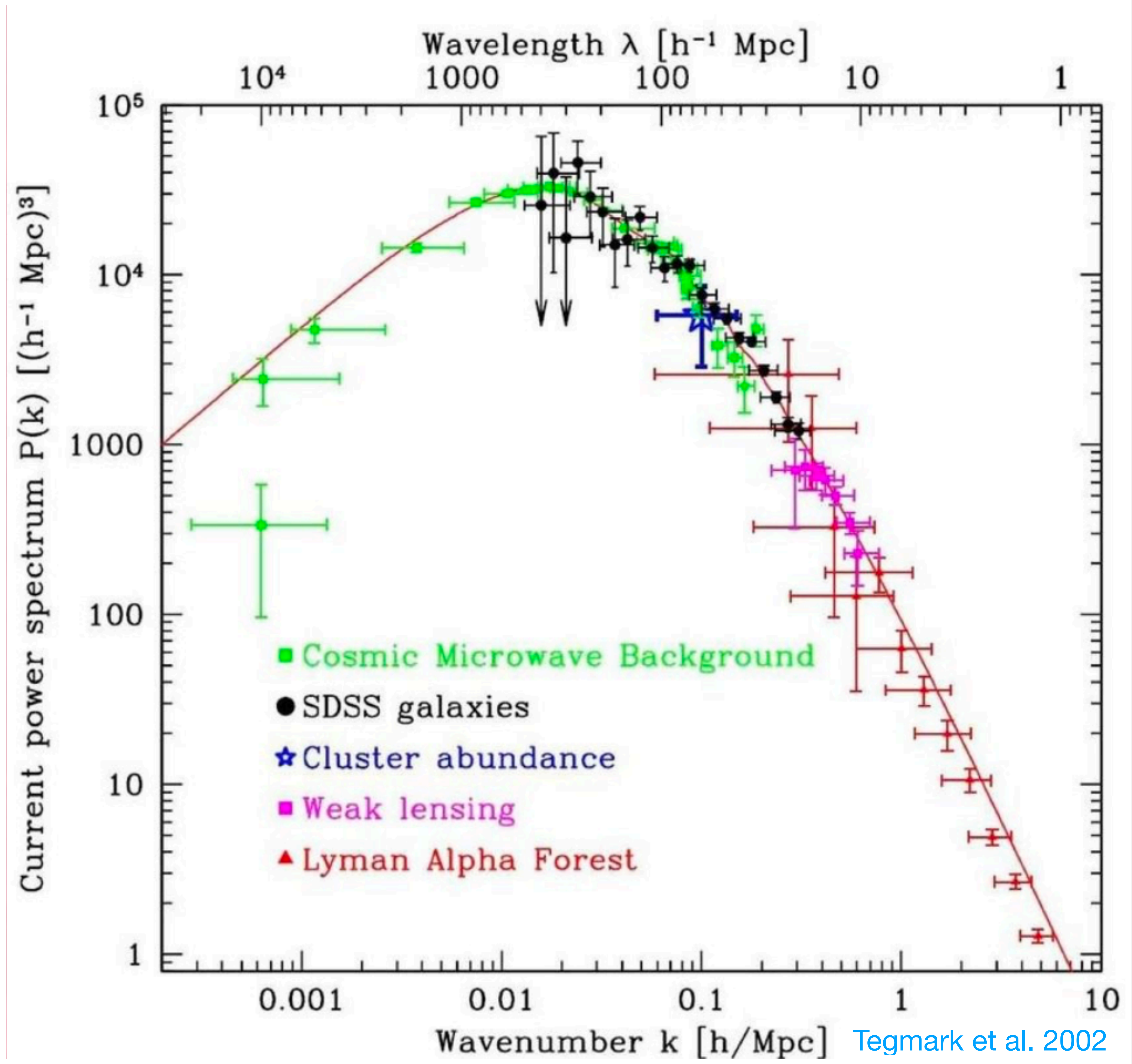
ΛCDM

- 3 main components:



- provides a good fit to cosmological observations:
  - ➡ expansion history of the Universe as inferred from Supernovae type Ia (Riess +1998)
  - ➡the matter power spectrum (Gil-Marin+2015)
  - ➡the Cosmic Microwave Background data (Planck collaboration, 2020)
  - ➡Baryon Acoustic Oscillation (Ross+2015)

ΛCDM



Tegmark et al. 2002

- Large scales: ΛCDM is a big success

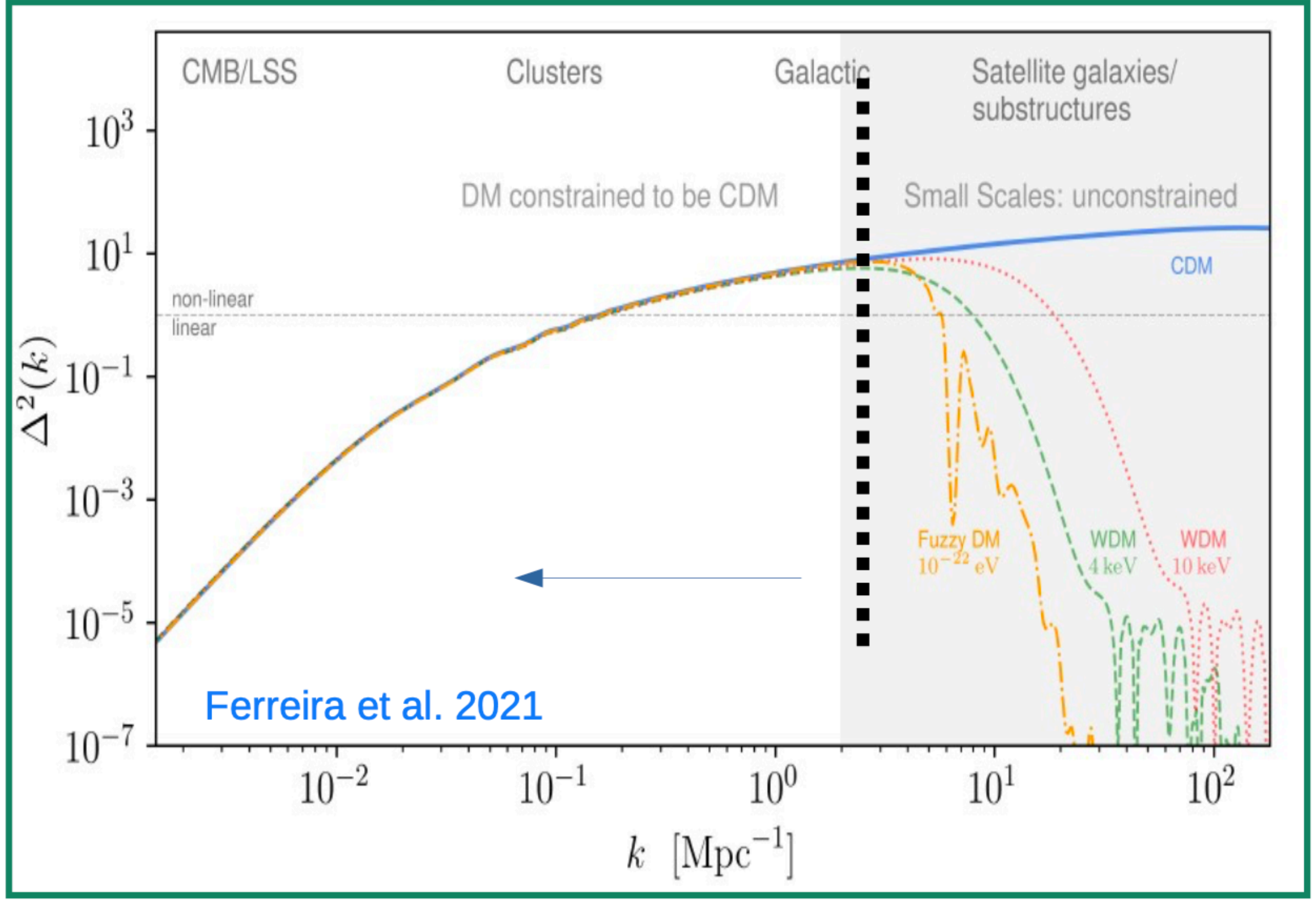
ΛCDM

Large scale (>>1 Mpc):

A big success

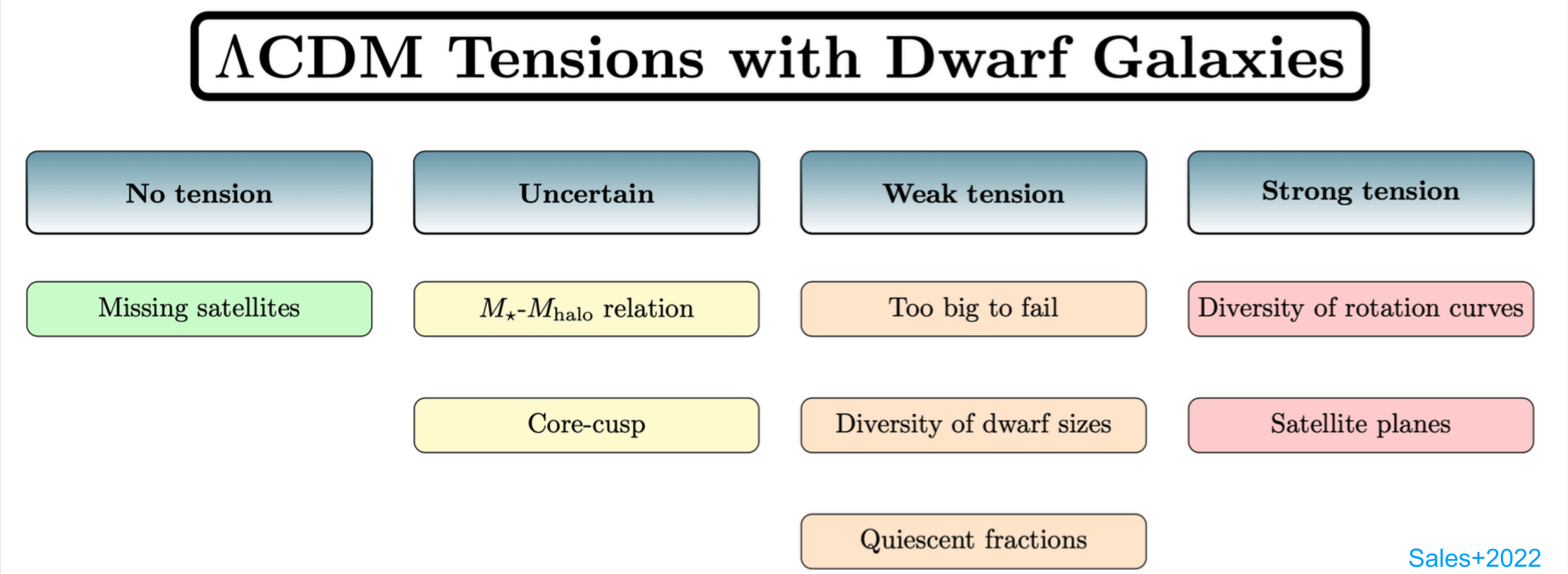
Small scale (<1 Mpc):

But baryons Can have an impact



Small scales: retain information about possible deviations from CDM

On small scales: small scale problems of ΛCDM (Bullock+2017, Sales+2022)



Sales+2022

ΛCDM

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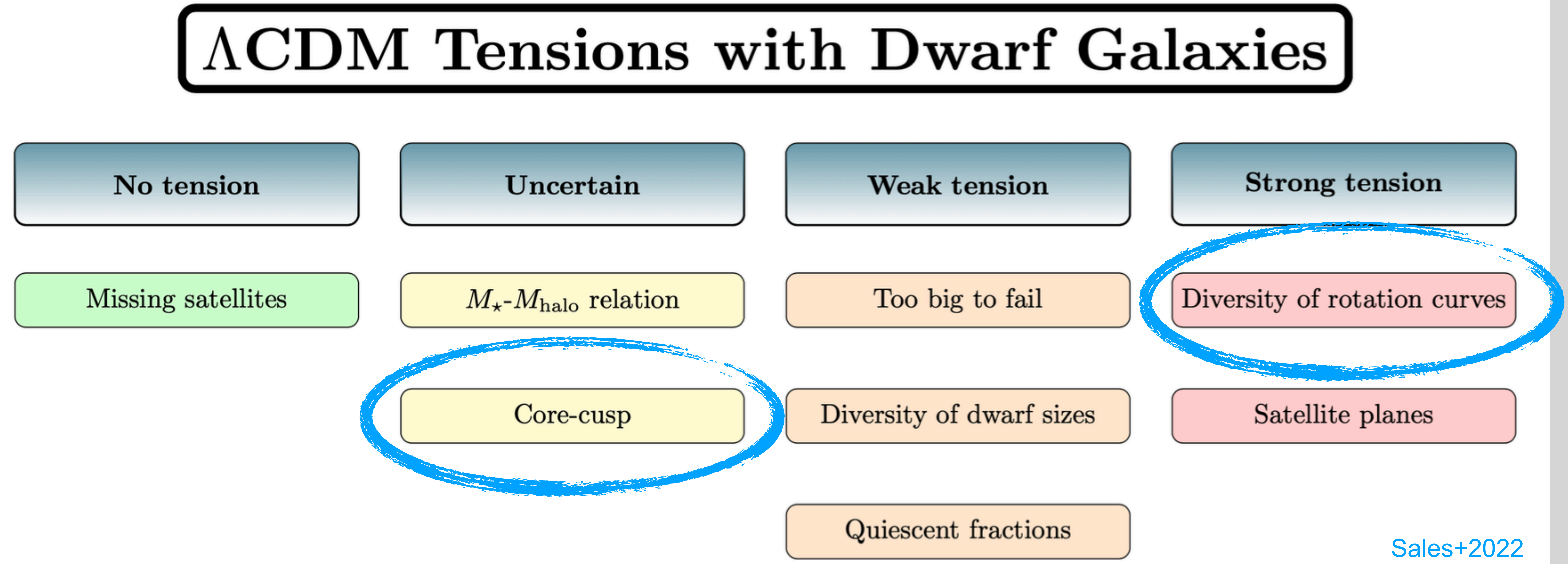
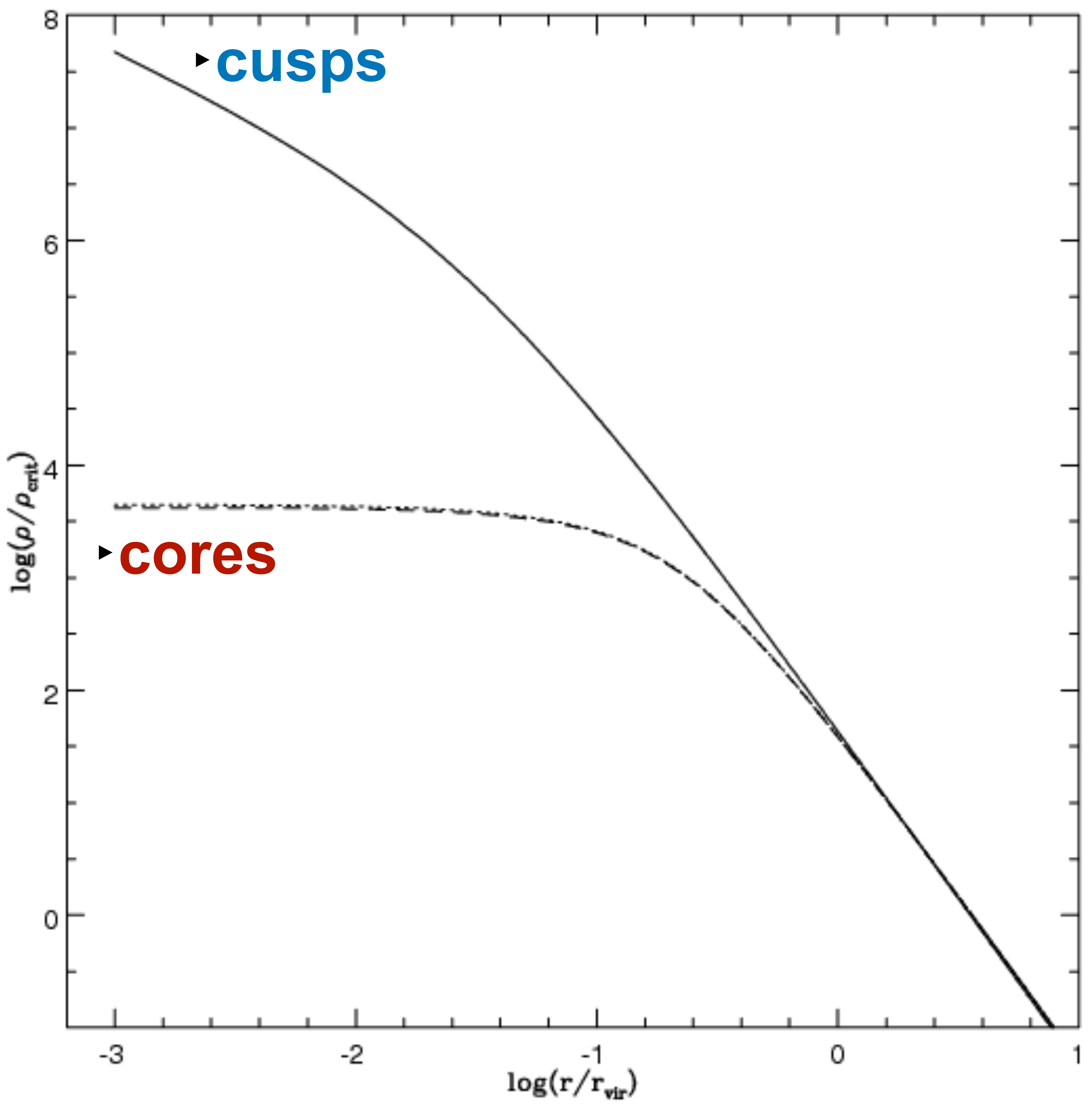


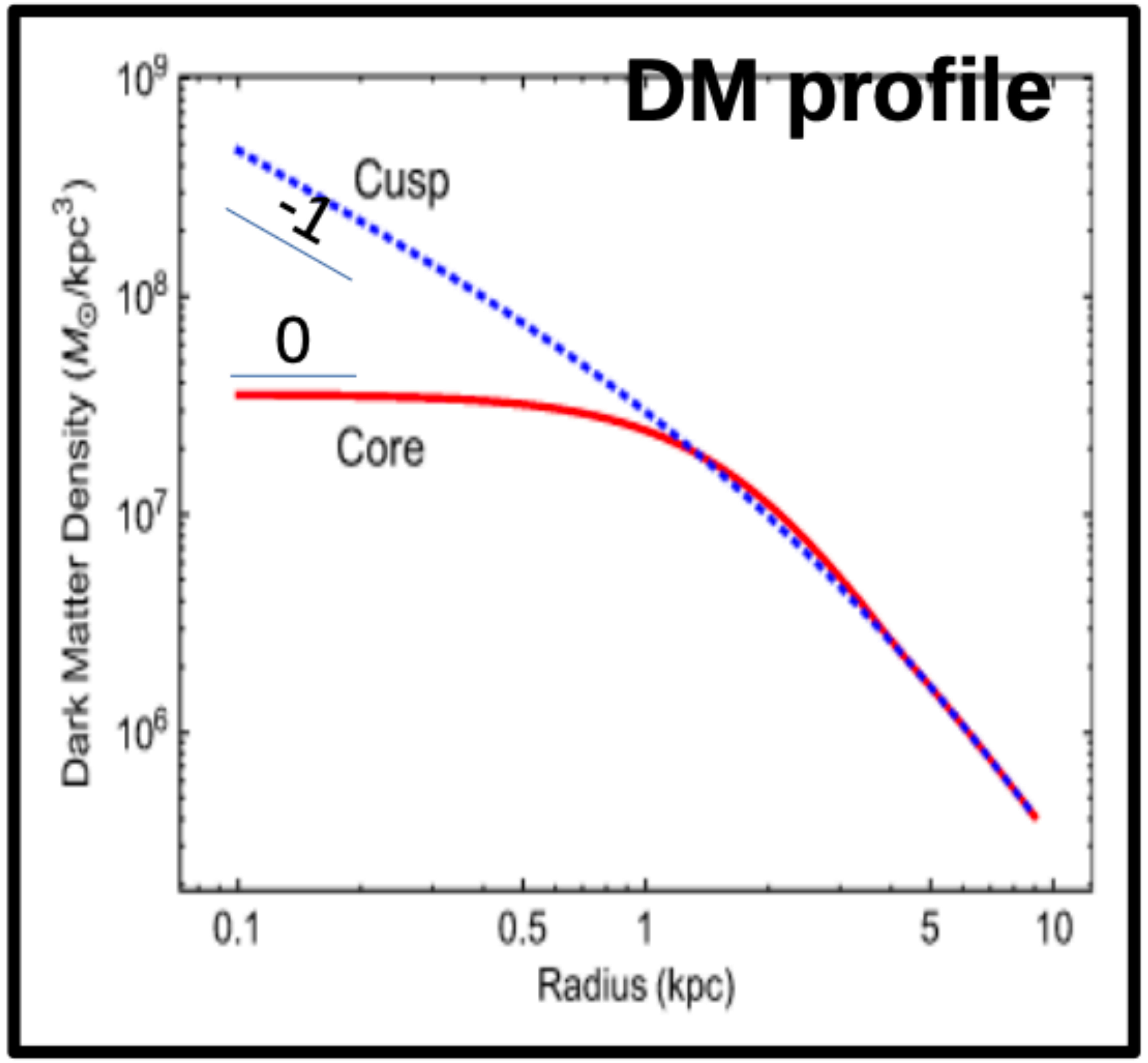
Sales+2022

Core - cusp problem

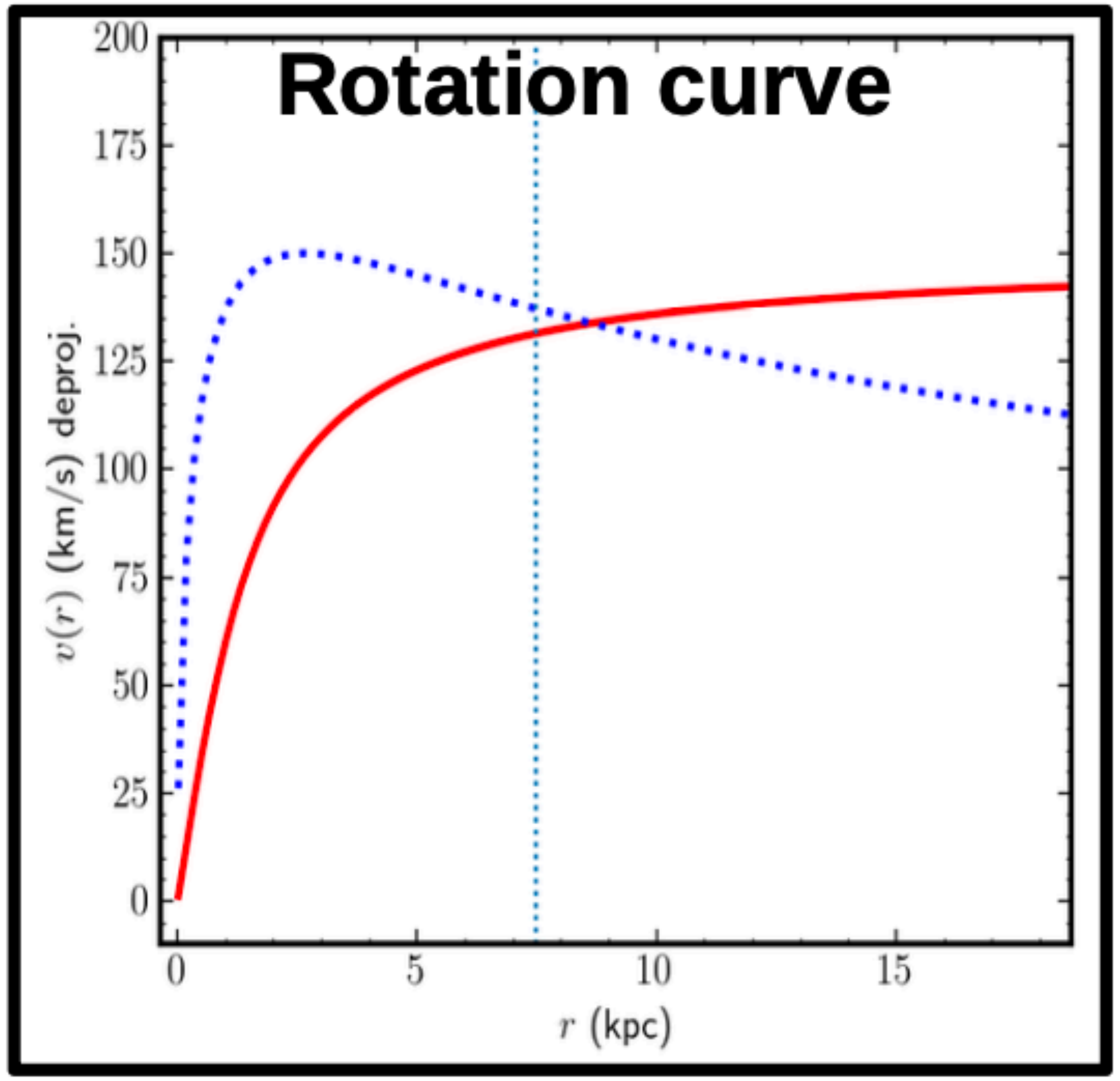


- N-body simulation predicts **cuspy** DM profiles (NFW, Navarro+1997)
- Rotation curves of low-surface brightness galaxies (e.g. de Blok et al. 2001) indicate constant-density **cores**

Core - cusp problem



$$v_c = \sqrt{\frac{GM}{r}}$$

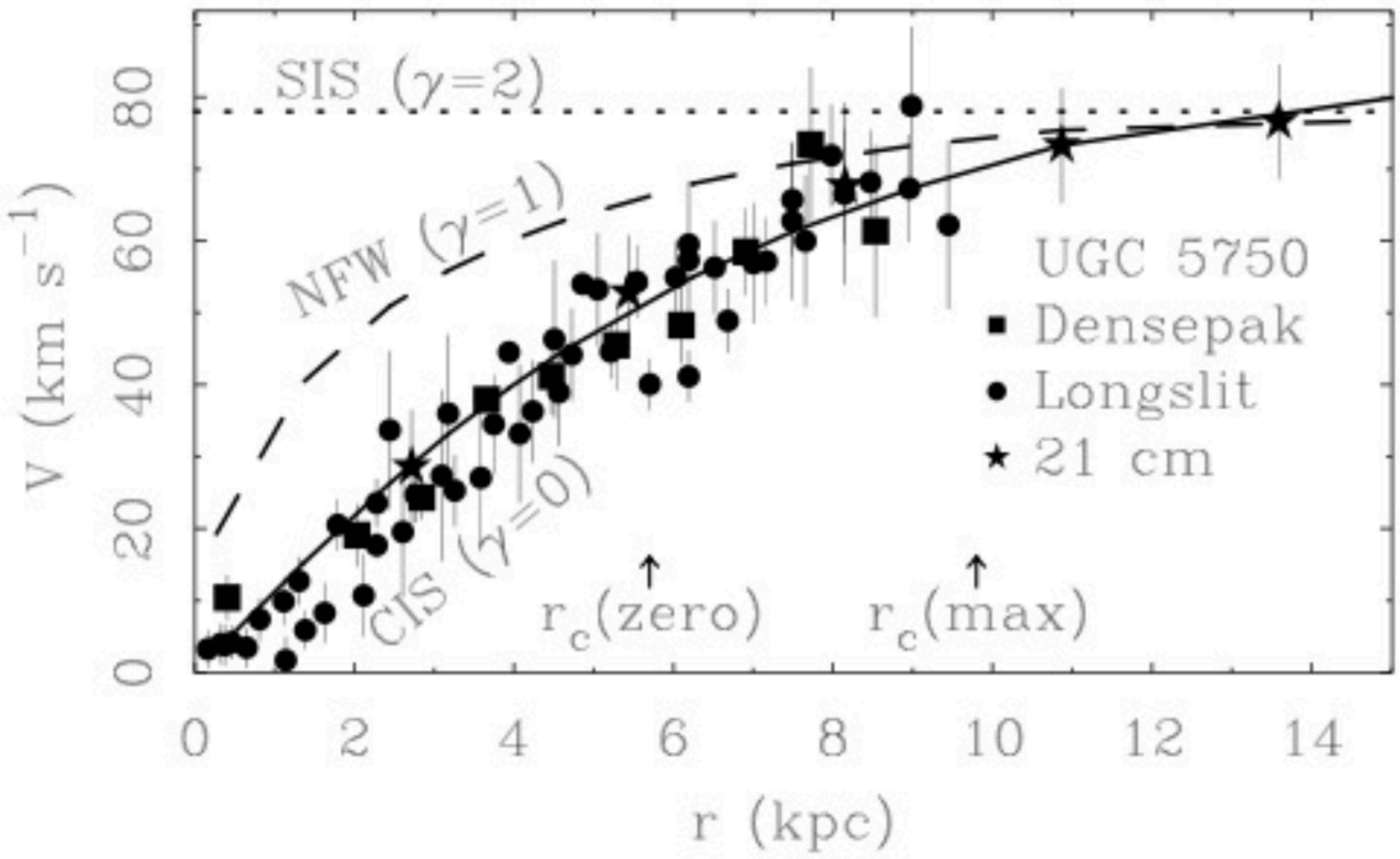


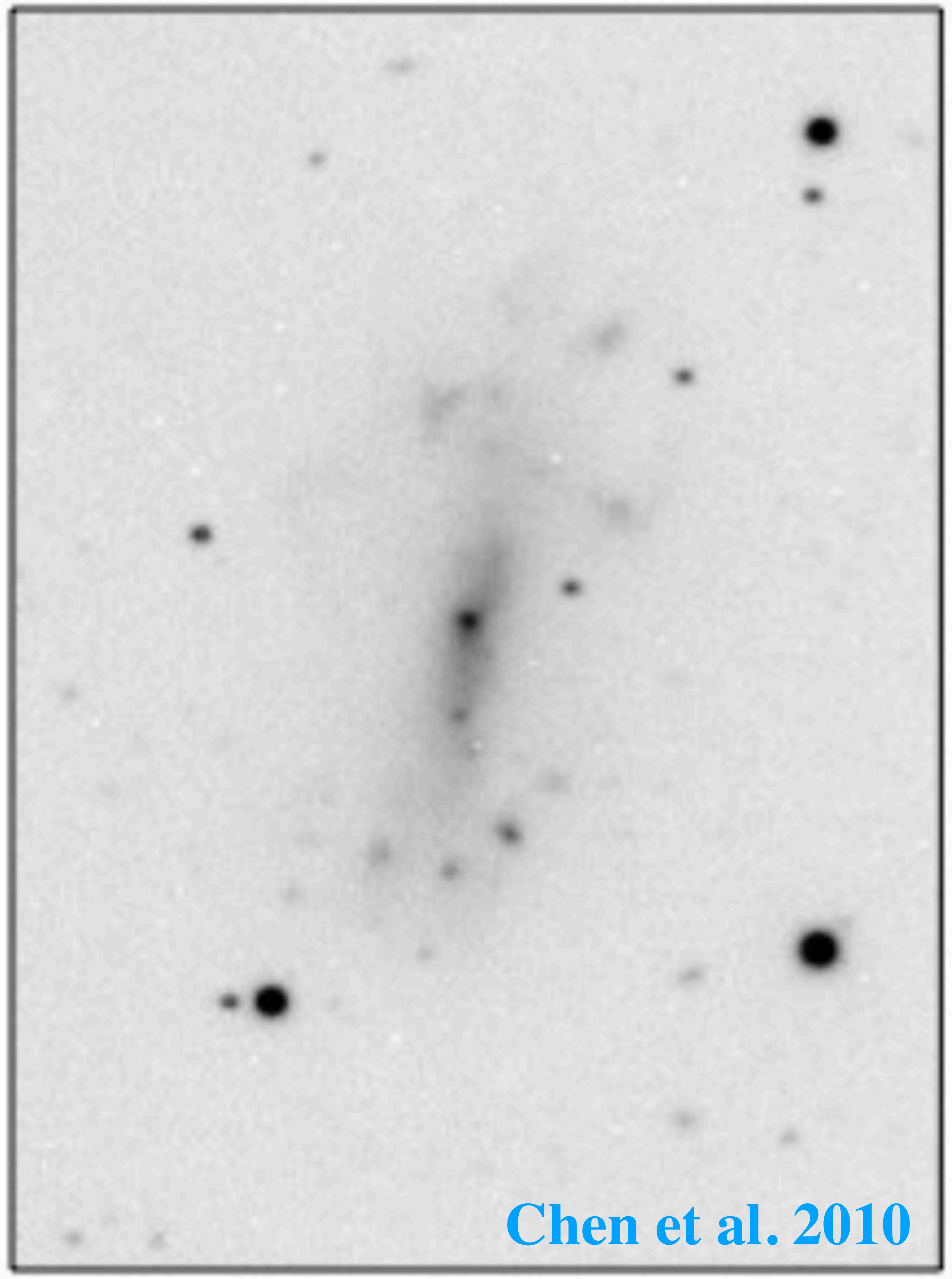
- A core on <1kpc → impact on several kpc

→ the curvature of v(r) relates to inner DM density profiles (CDM, SIDM, FDM, WDM, etc)

Examples:

Cored galaxy UGC5750; z~0.013



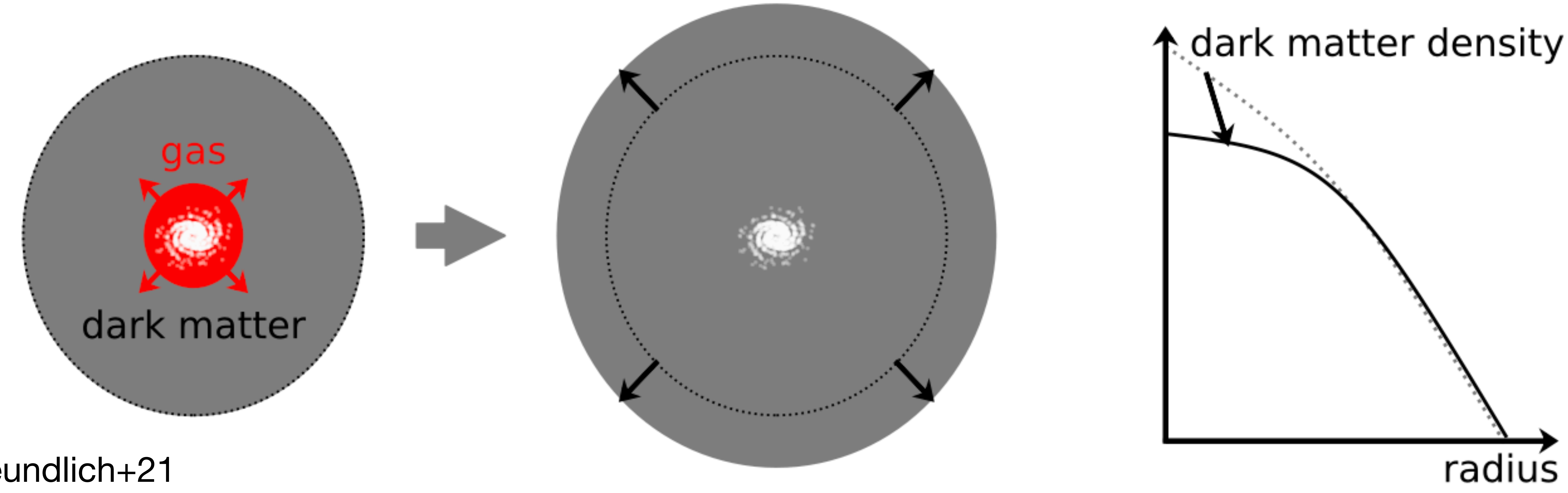


Chen et al. 2010

Core-cusp problem: solutions in ΛCDM

- **baryonic processes to the rescue:** stellar feedback, AGN feedback, central stellar bar, infalling clumps

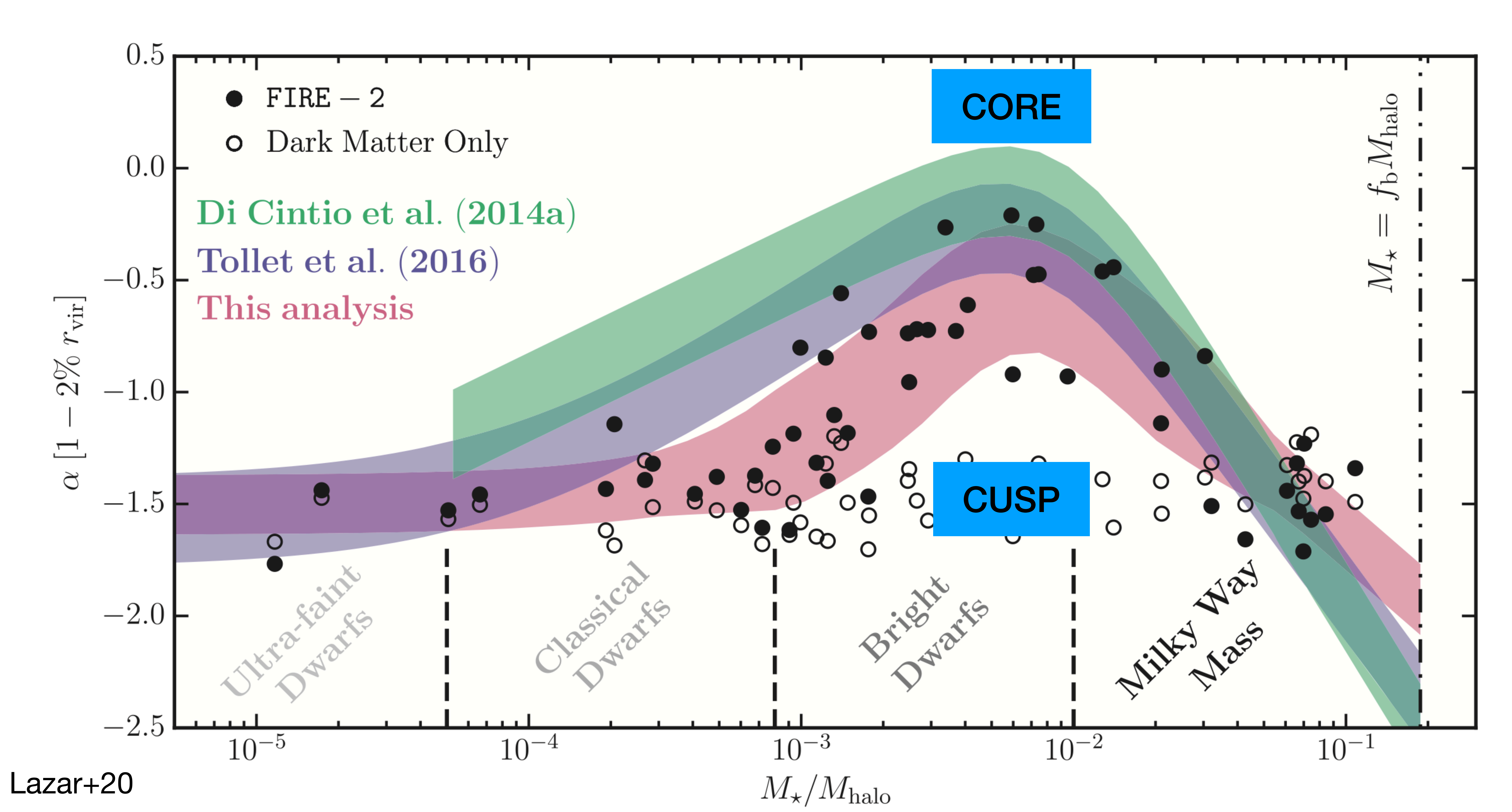
- rapid potential fluctuations



Freundlich+21

Core-cusp problem: solutions in ΛCDM

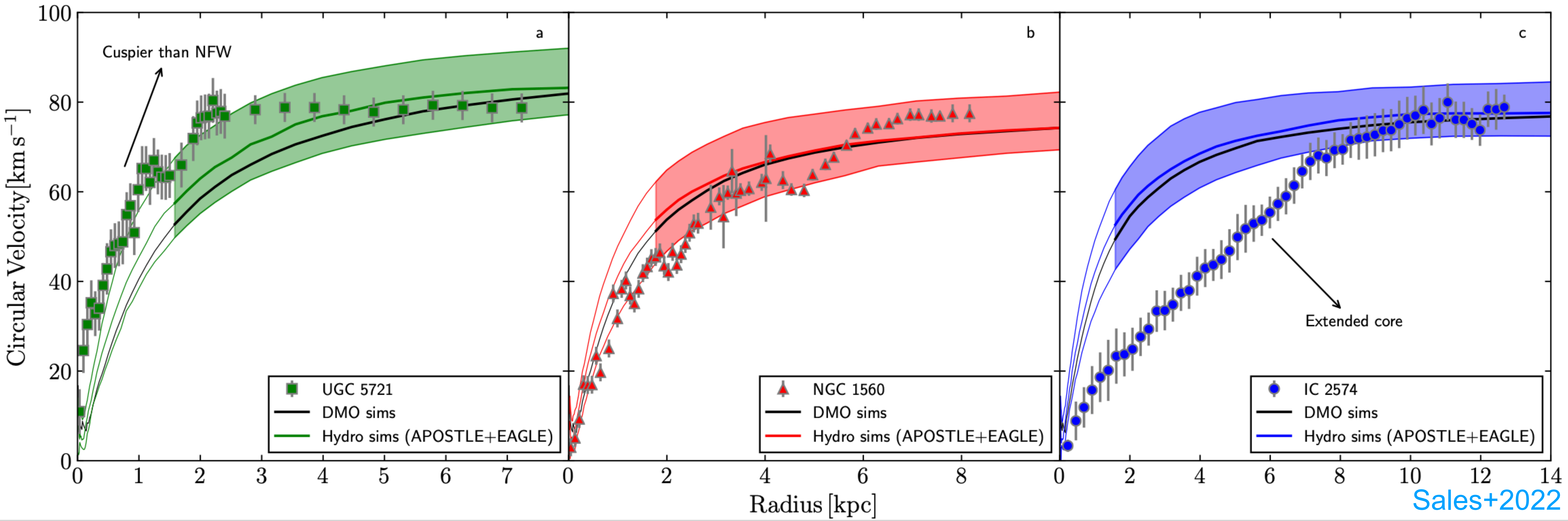
Hydrodynamical simulations with stellar feedback



Lazar+20

- core formation most efficient for galaxies with 9<log(M*/M☉)<10

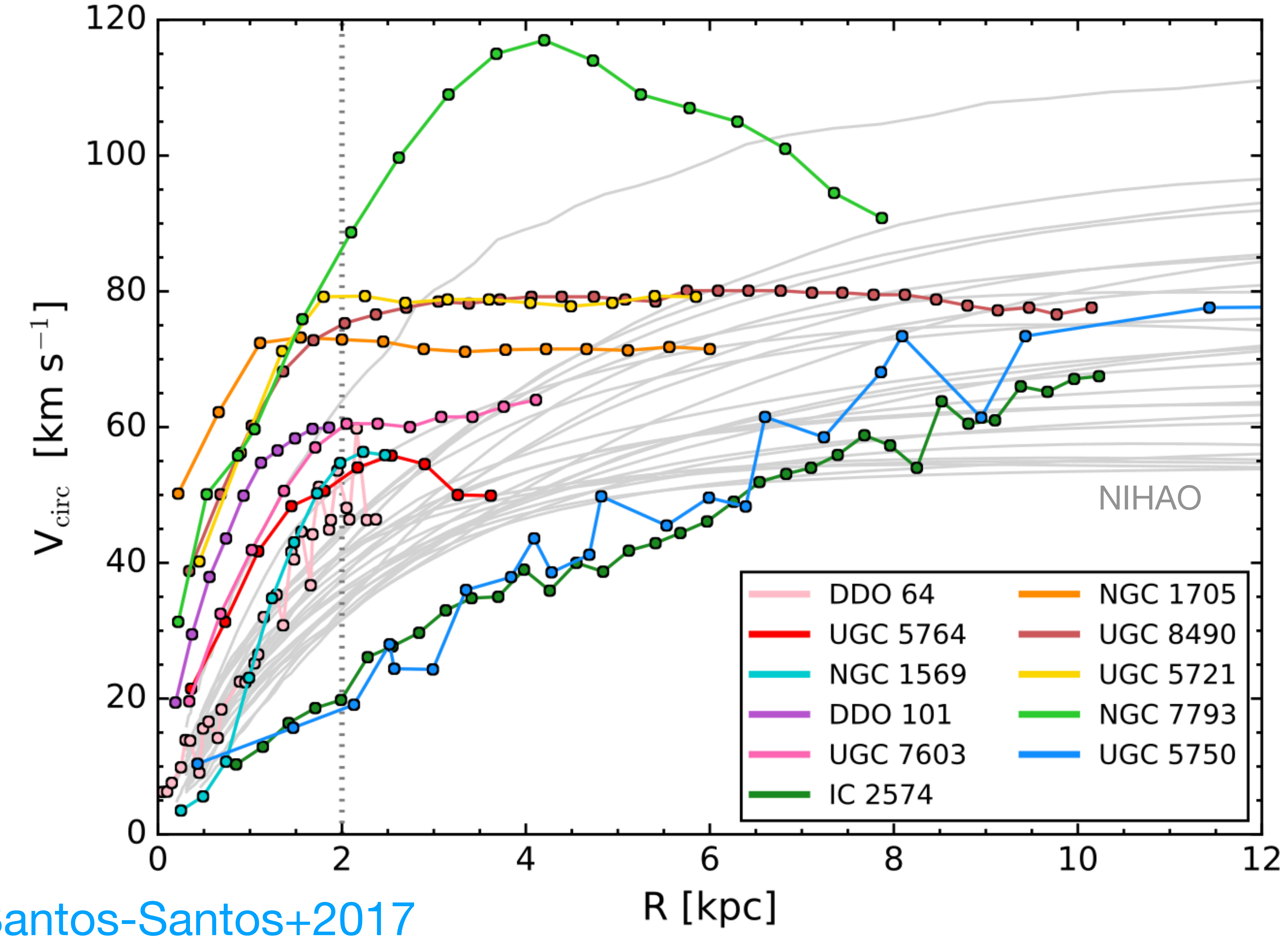
Diversity of Rotation Curves problem:



Sales+2022

- in dark matter only simulations, haloes have a universal **cuspy** density profile that results in self-similar rotation curve shapes
- observed dwarfs of similar masses show a large diversity in the rotation curve shapes

Diversity of Rotation Curves: solutions in ΛCDM



Santos-Santos+2017

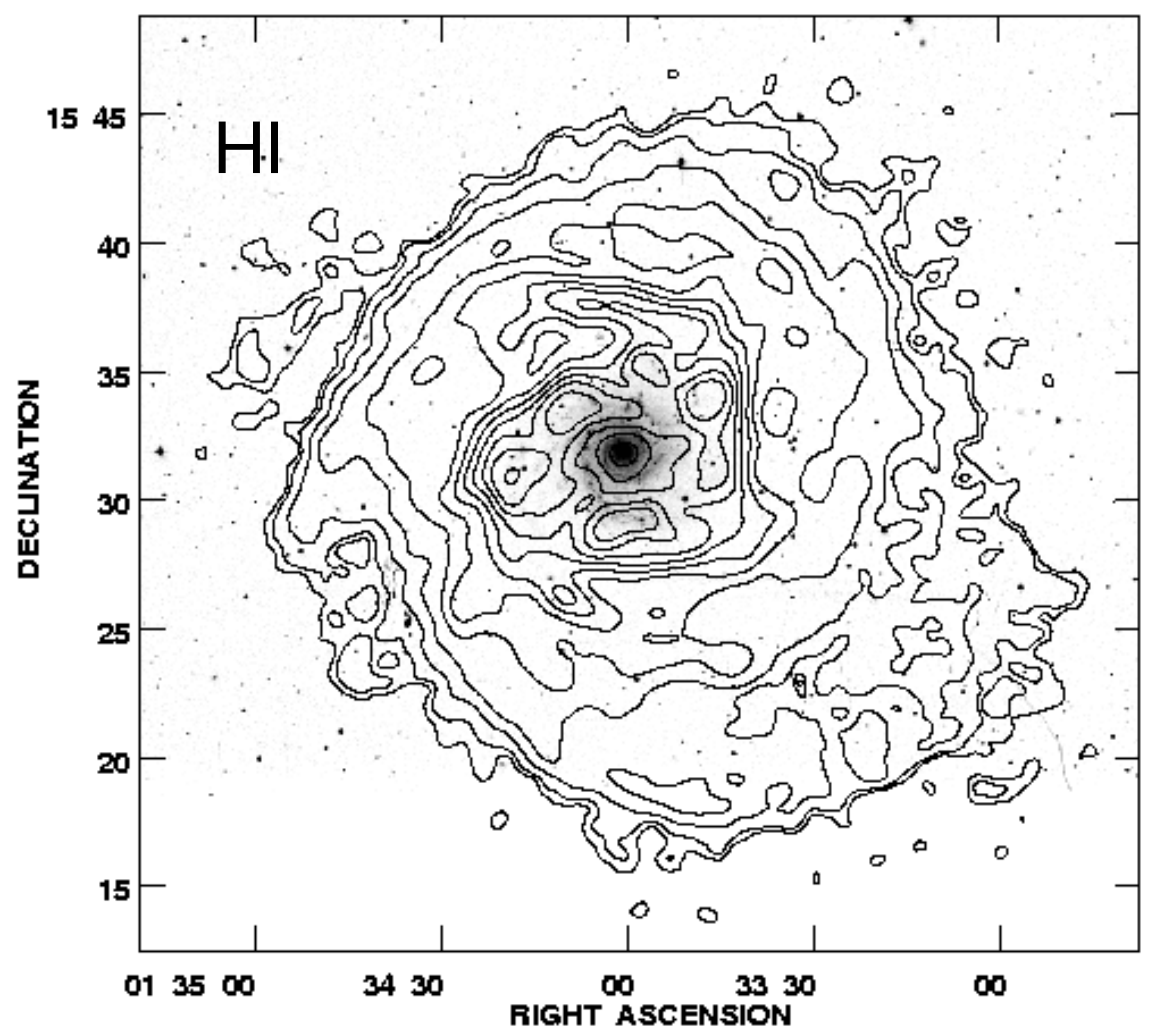
- **baryonic processes to the rescue**

- Some hydrodynamical **ΛCDM** simulations ~reproduce the observed diversity

How to test this observationally?

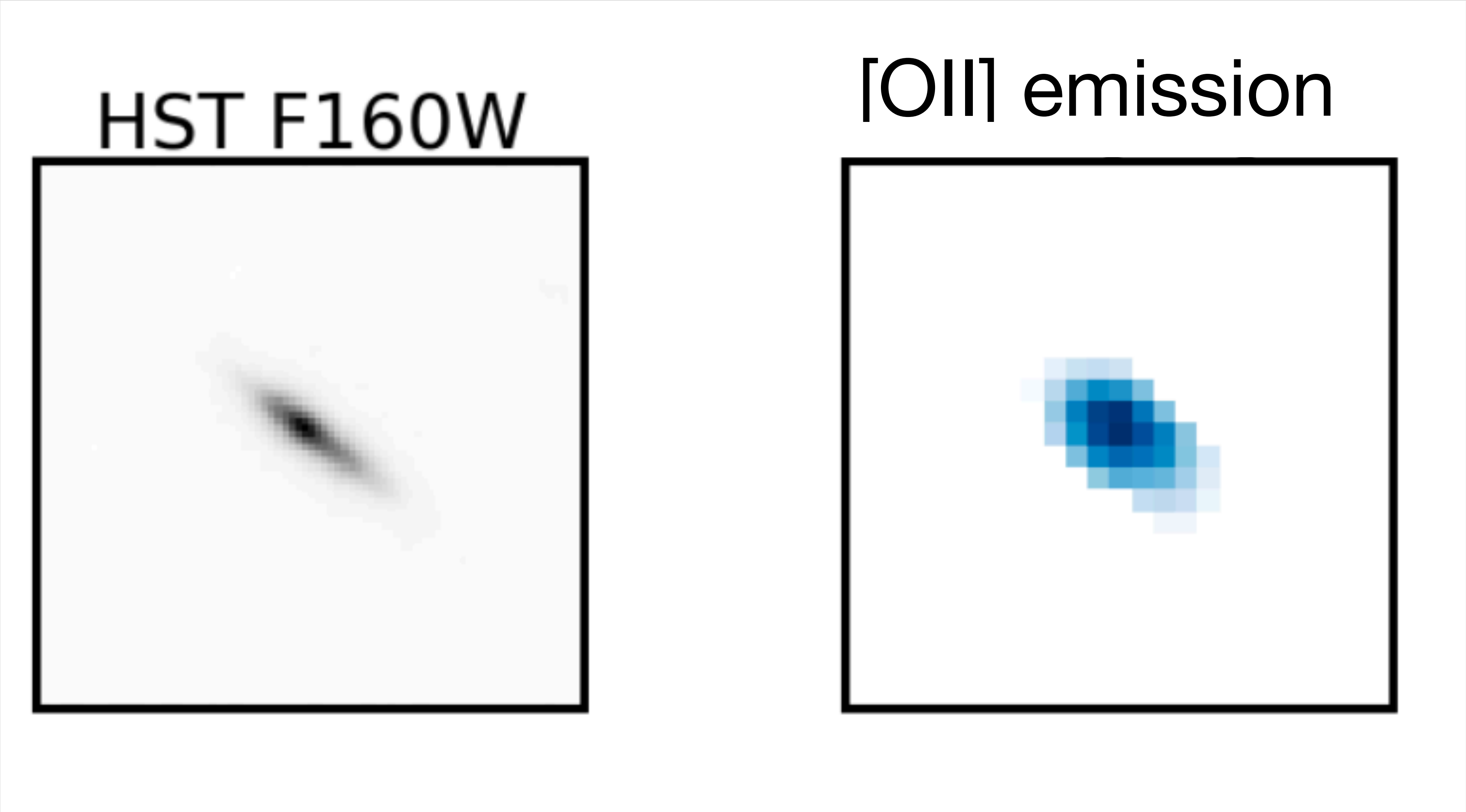
Need a kinematic tracer at large galactocentric radii, beyond 2xRe

z=0



Kamphuis and Briggs 1992

z~1



optical

How to test this observationally?

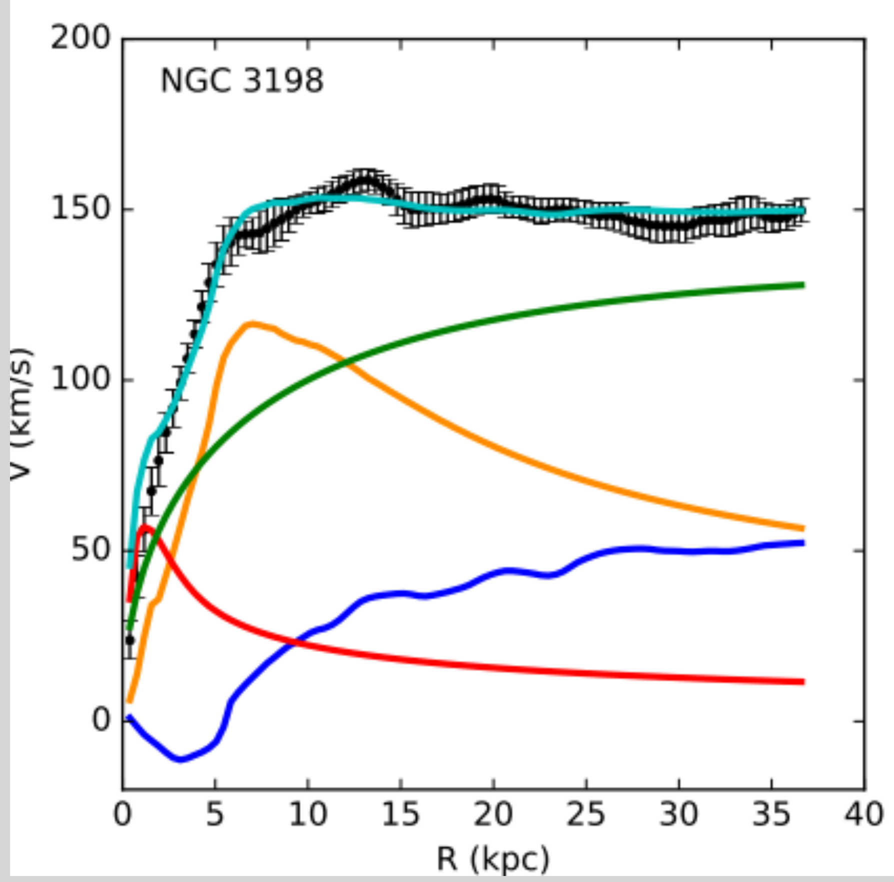
- Need a kinematic tracer at large galactocentric radii, beyond 2xRe
- Precise determination of the rotation curves, from the innermost to the outermost parts of galaxy discs

Using 1D methods for disk-halo decomposition:

Tilted ring method (e.g. Rogstad, Lockhart & Wright 1974, Schoenmakers 1999, Simon et al. 2003, Krajnović et al. 2006, Spekkens & Sellwood 2007; Sellwood & Sánchez 2010, Di Teodoro et al. 2015):

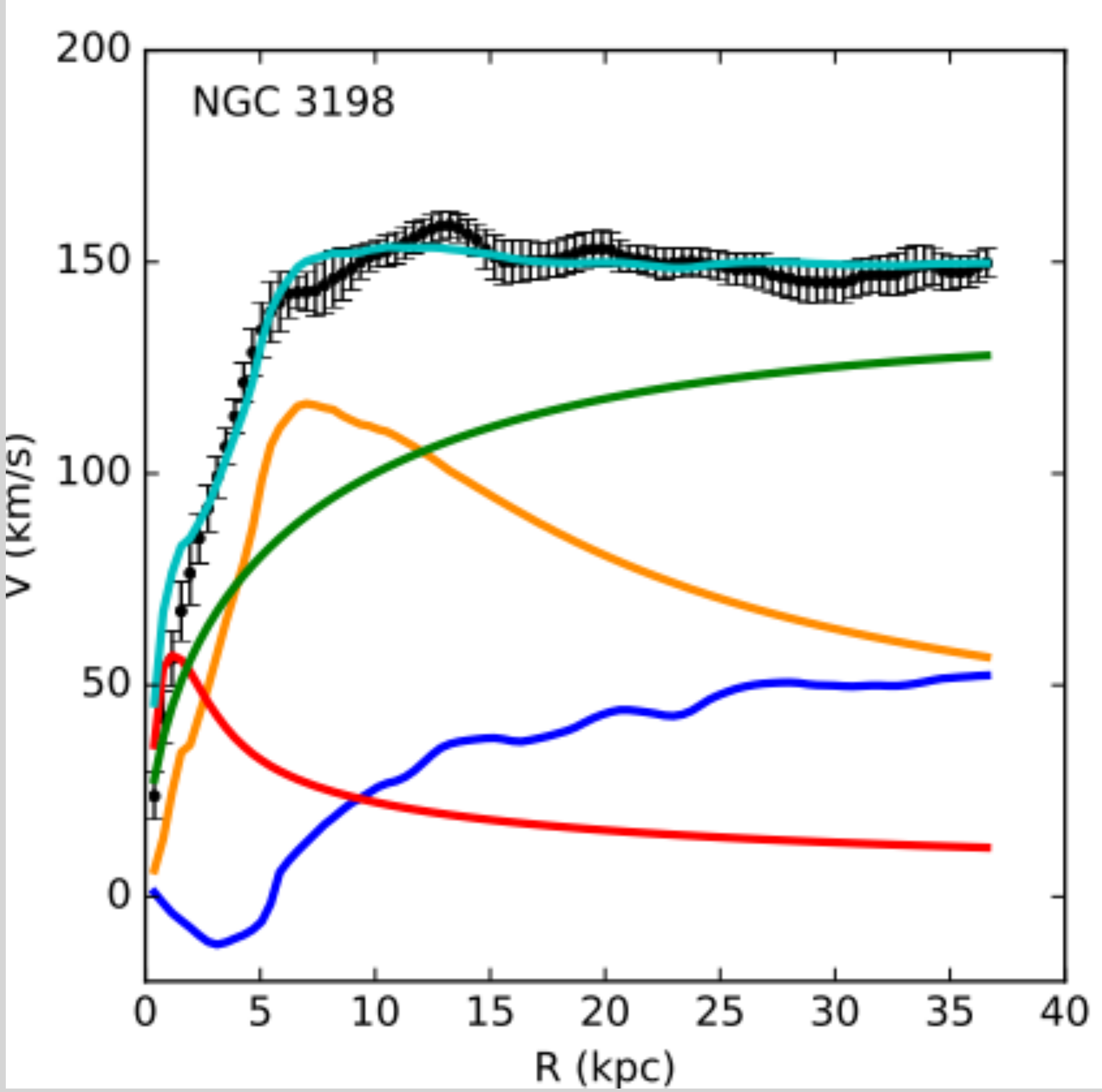
- **Assumptions:** the galaxy's gas is confined to a series of concentric rings, each with its own orientation and rotational velocity
- **Fitting the Velocity Field:** for each ring at radius r, fit for rotational velocity, inclination, position angle
- **Reconstructing the Rotation Curve:** the rotation curve is extracted from the fitted rotational velocities V(r) for each ring

The resulting 1D rotation curve is used for the decomposition



How to test this observationally at z>0?

- At z=0: « easy » ?



- At z=1: « hard » ?

- Galaxies have small angular sizes
- Outer disks are too faint

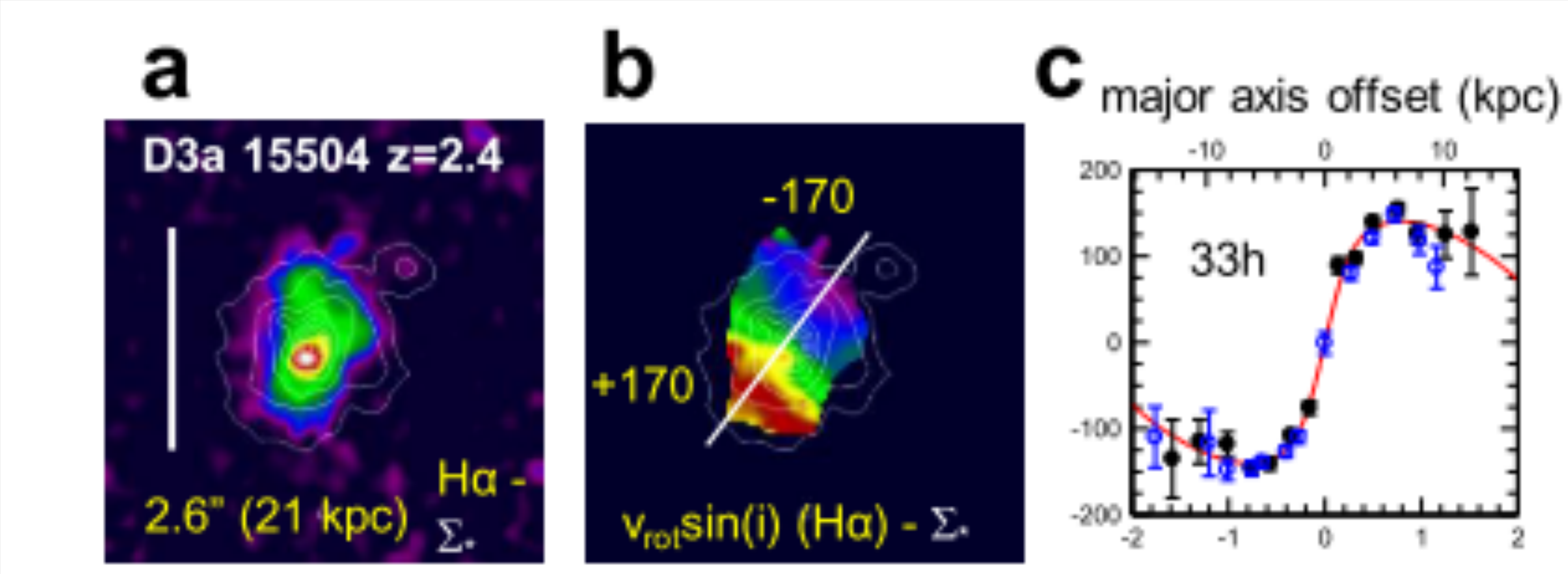
How to test this observationally at z>0?

- At z=1: « hard » ?

> - Galaxies have small angular sizes
> - Outer disks are too faint

There are only 3 options:

1. **Using deep observations (10h-40h exposure times)**



Genzel +17

How to test this observationally at z>0?

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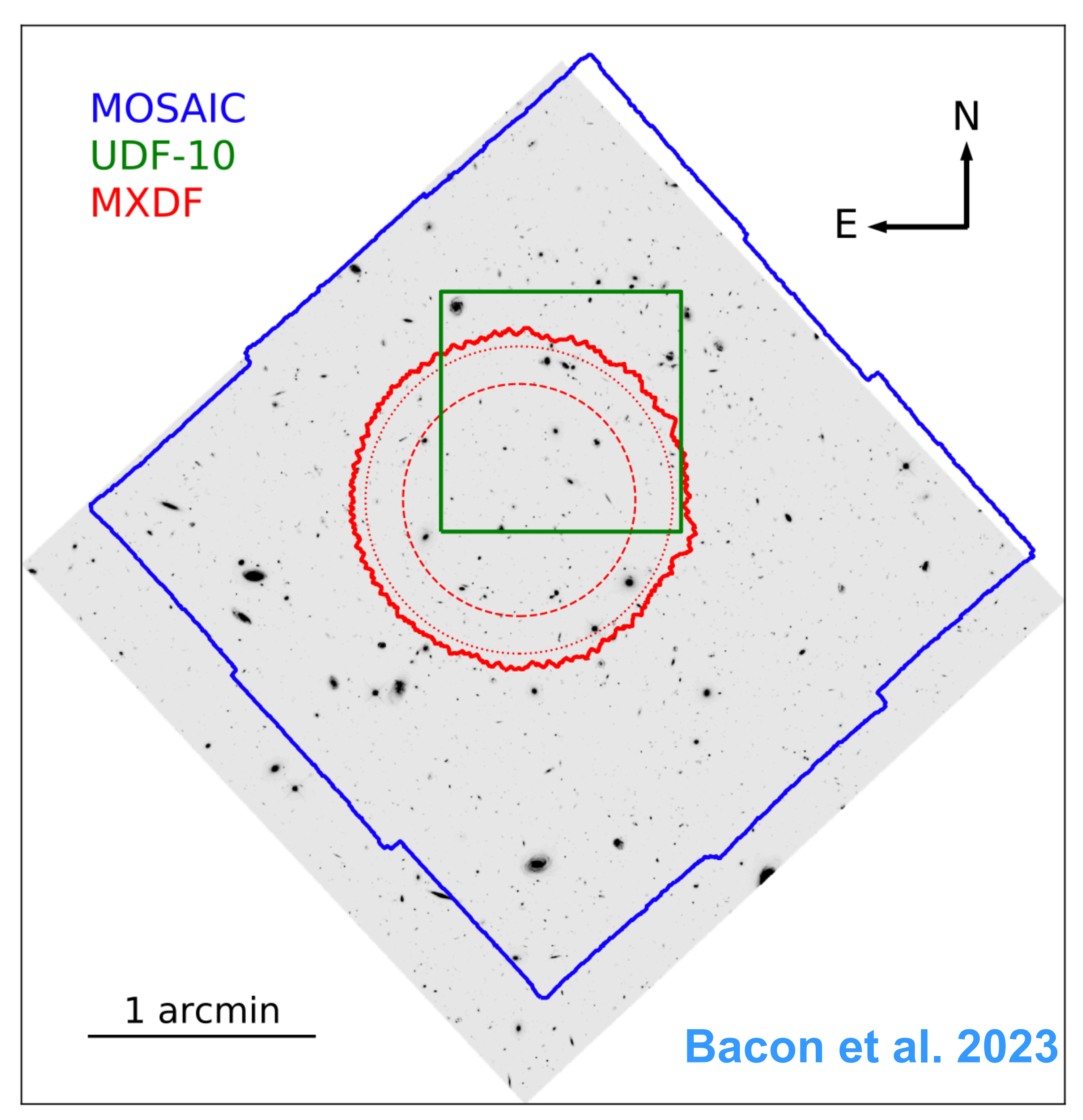
There are only 3 options:

1. **Using deep observations (10h-40h exposure times)**
2. **Using very deep observations (140h exposure times)**



Bacon et al. 2023

How to test this observationally at z>0?

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- Outer disks are too faint

There are only 3 options:

1. **Using deep observations (10h-40h exposure times)**
2. **Using very deep observations (140h exposure times)**
3. **Use all information available (3D forward modelling)**

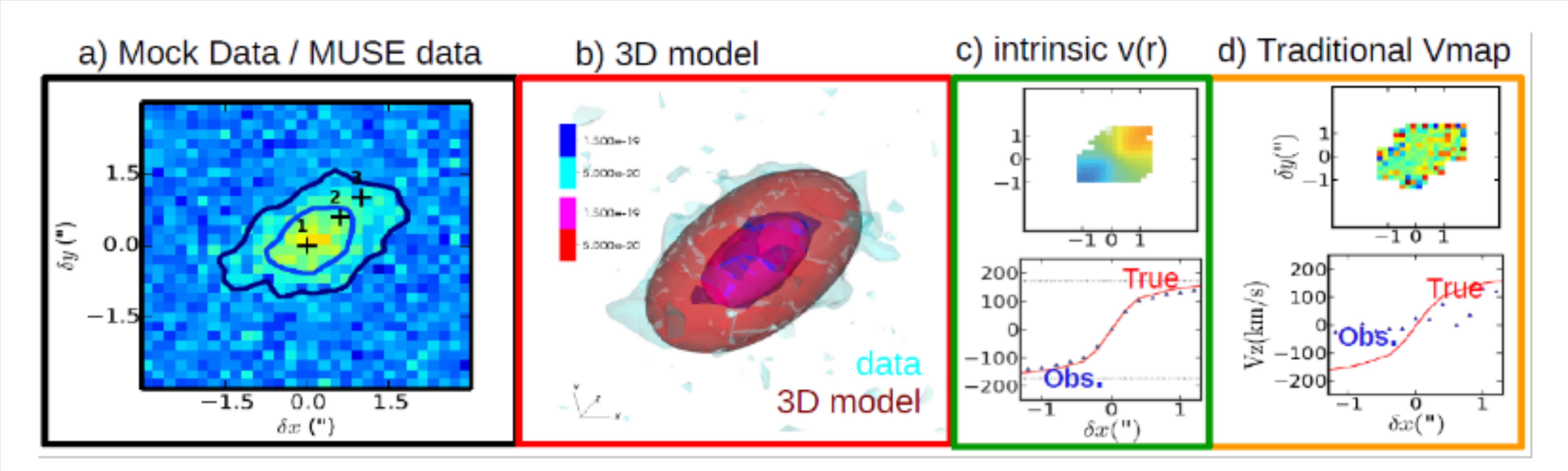
GalPaK
galaxy parameters and kinematics

Bouché et al. 2015

Using 3D forward modelling for disk-halo decomposition

GalPaK galaxy parameters and kinematics

Bouché et al. 2015



- Compares 3D parametric models directly to the IFU data-cube, taking into account the LSF and PSF

- Primary assumption: axisymmetric disk

Using 3D forward modelling for disk-halo decomposition

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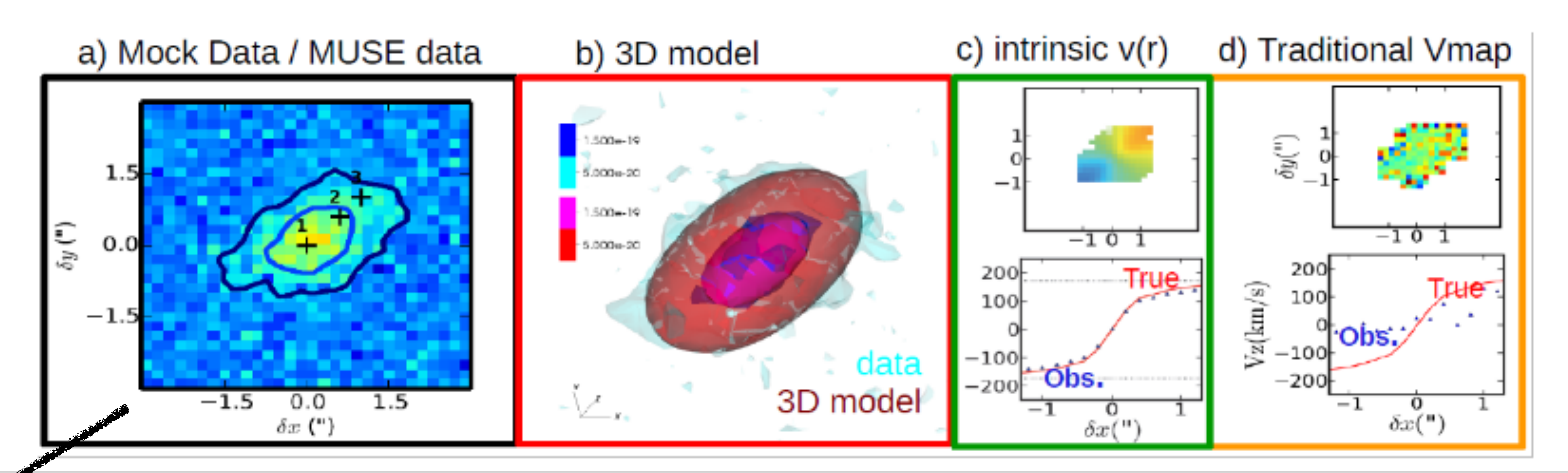
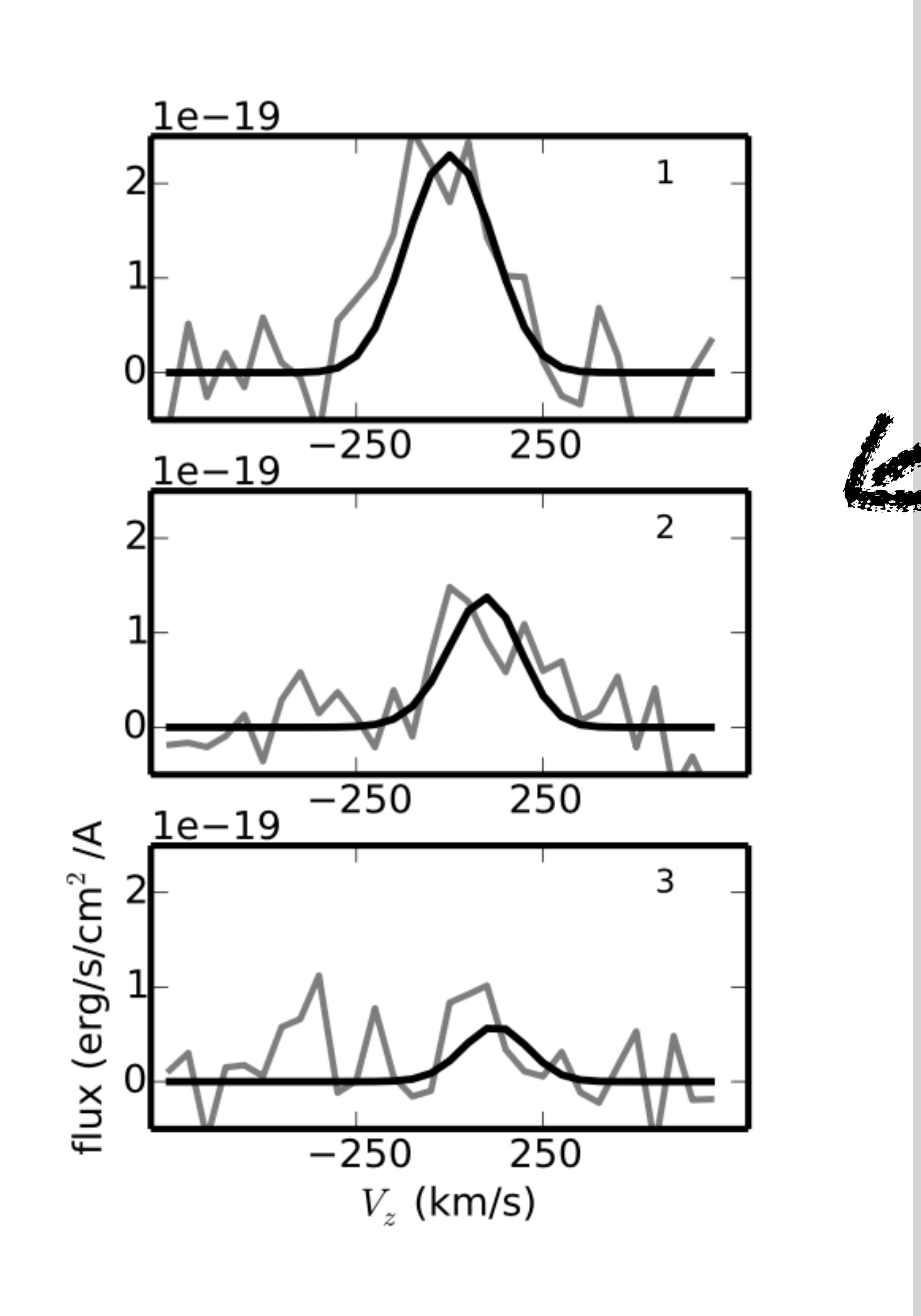
Bouché et al. 2015



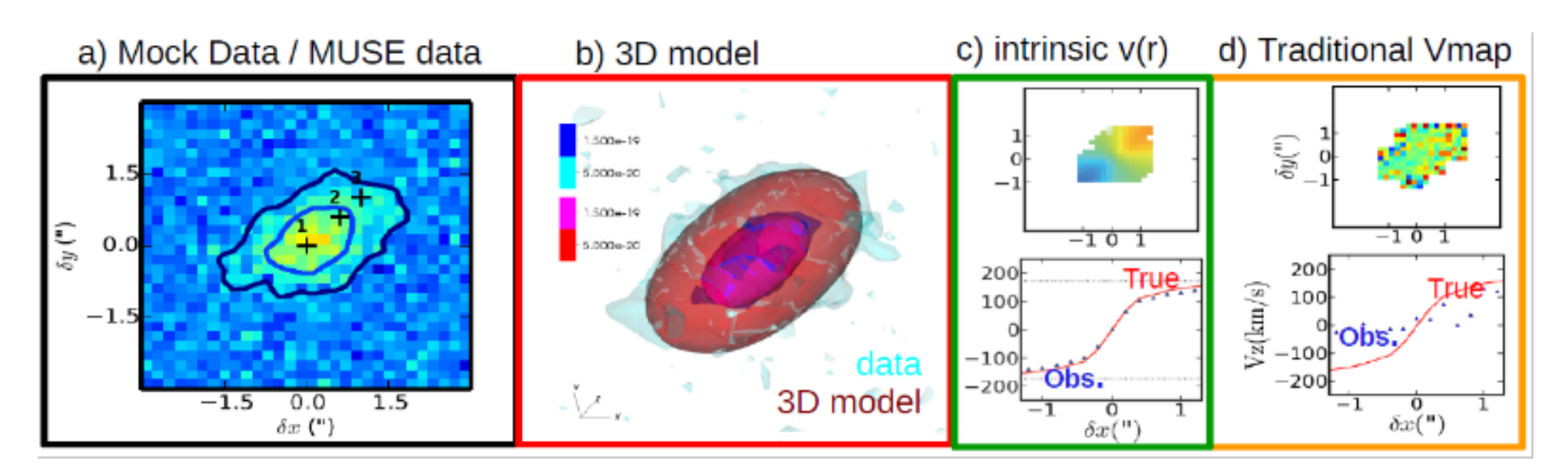


Advantages :

✦Morpho-kinematics yielded simultaneously
✦yields intrinsic parameters (by taking into account LSF & PSF)
✦Works on all spaxels
✦Well suited for low S/N regime [good for R>Re]
✦Breaks inclination-Vmax degeneracy
✦Flexible parametric models & MCMC

Using 3D forward modelling for disk-halo decomposition

Bouché et al. 2015



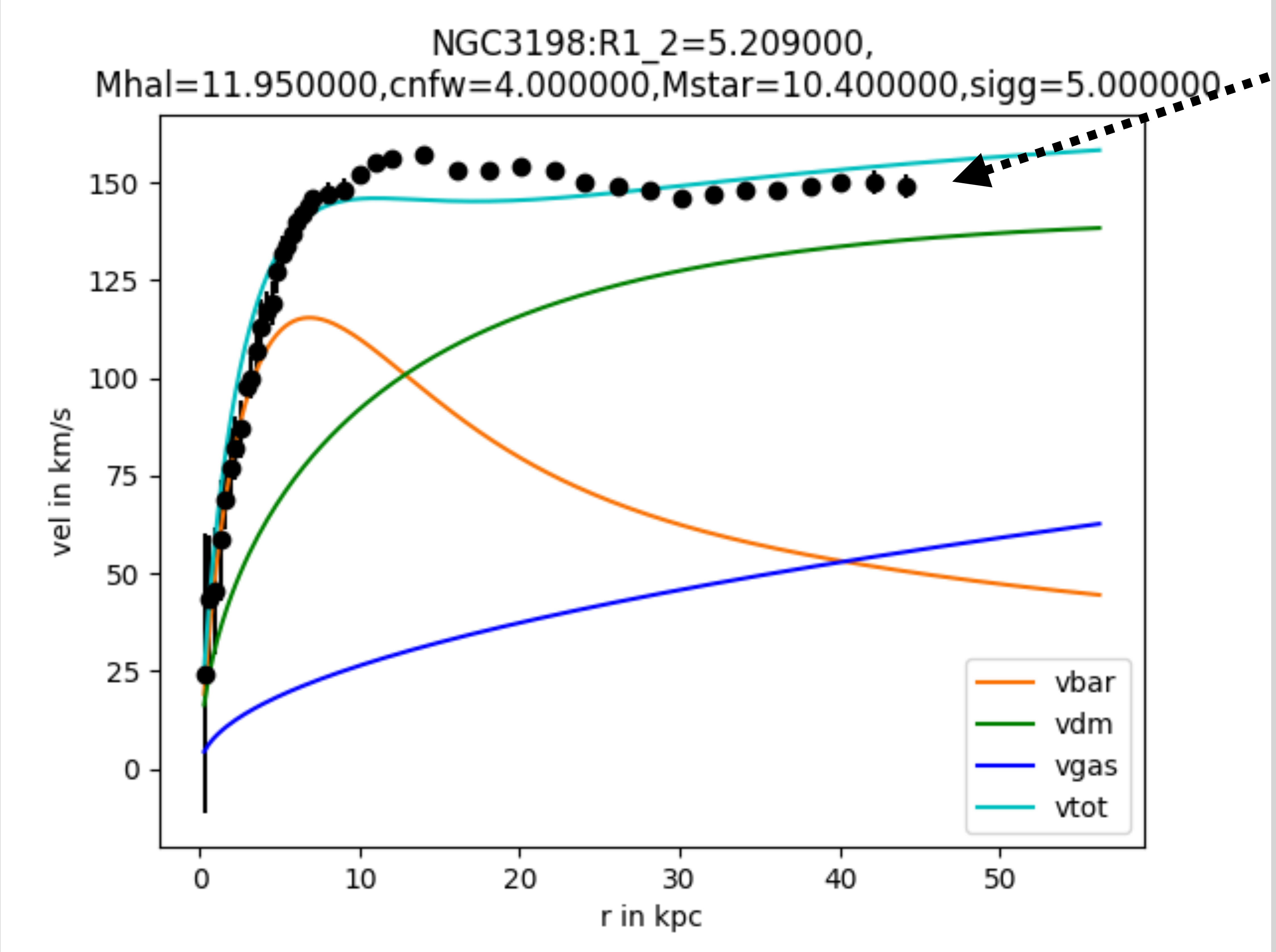
Compare to state-of-the-art :

- ✦ 3D method (vs. 1D)
- ✦ No priors (M*, inclination)
- ✦ computes the likelihood directly on the 3D data giving us thousands of degrees of freedom

Using 3D forward modelling: Under the hood

GalPaK galaxy parameters and kinematics

Bouché et al. 2015



$$v_c(r)^2 = v_{DM}(r)^2 + v_{disk}(r)^2 + v_{HI}(r)^2$$

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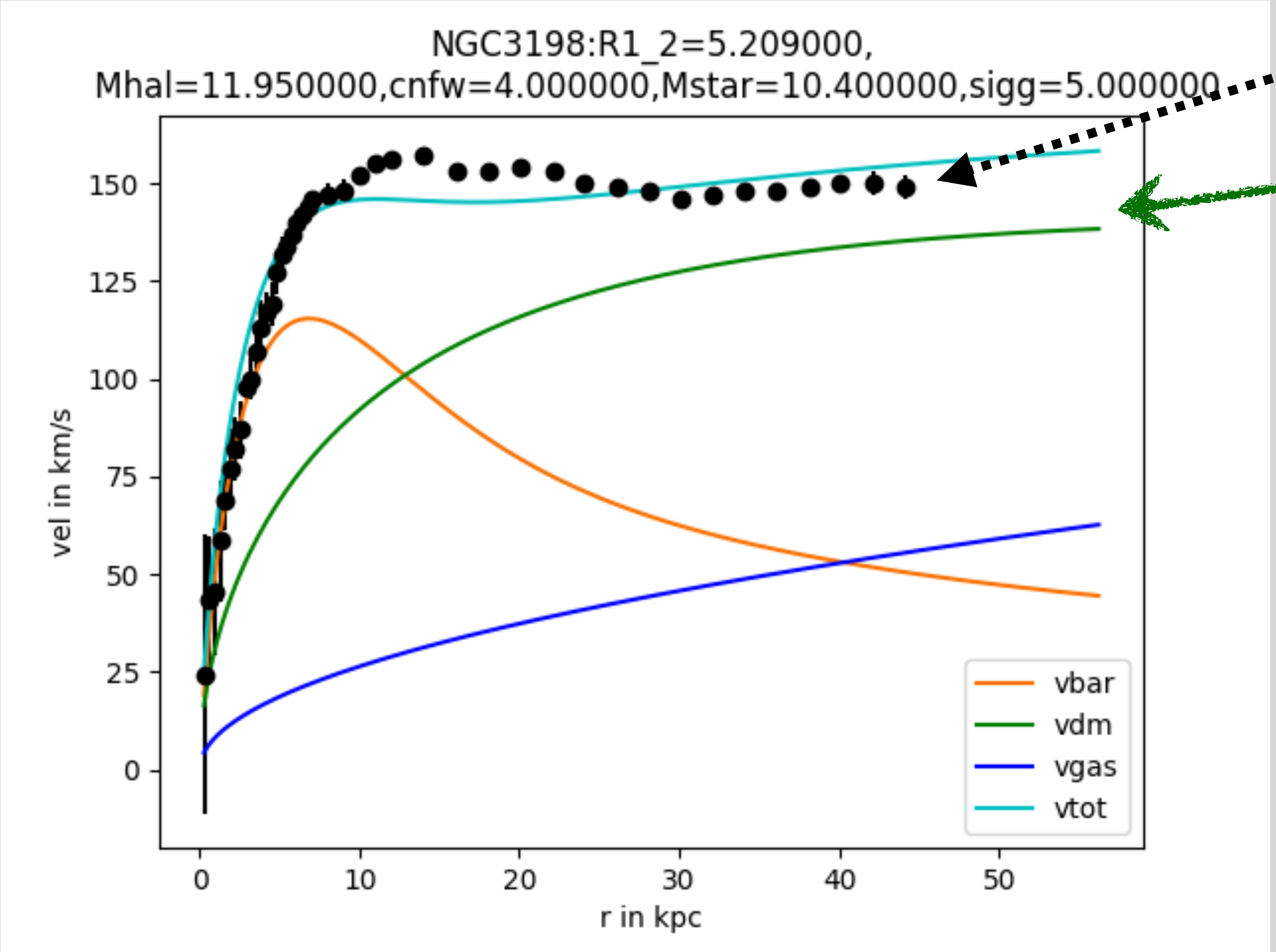

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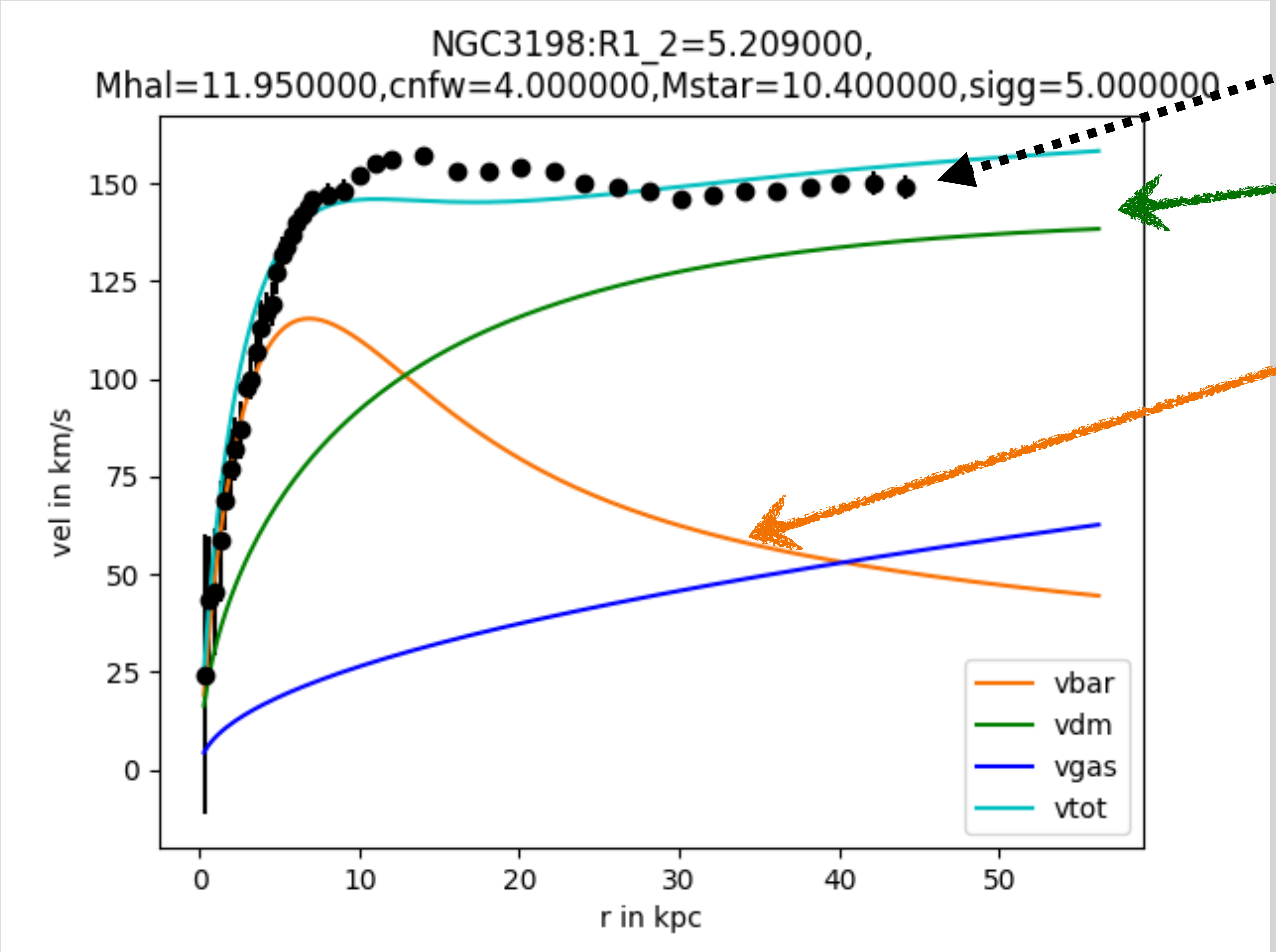

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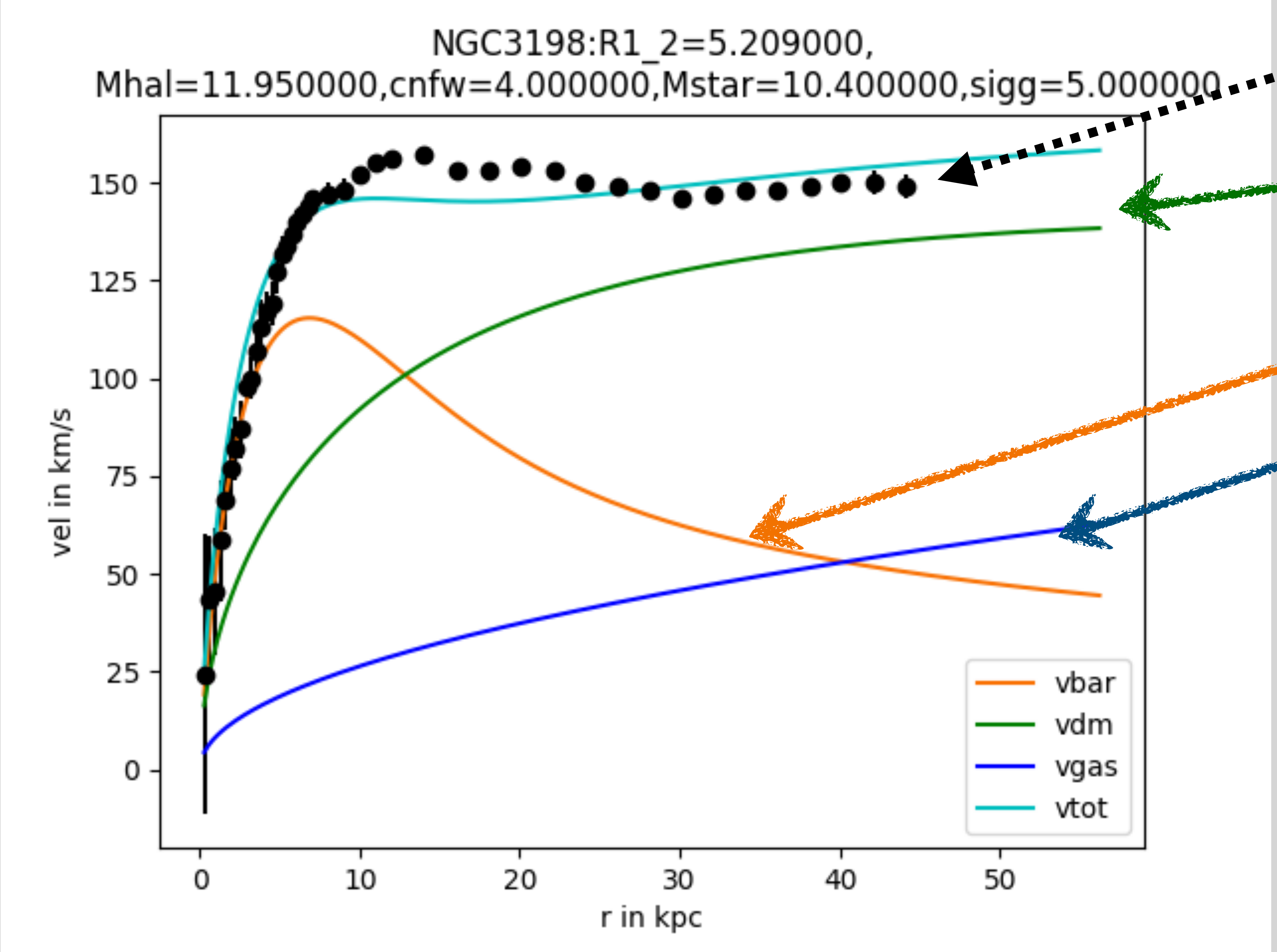

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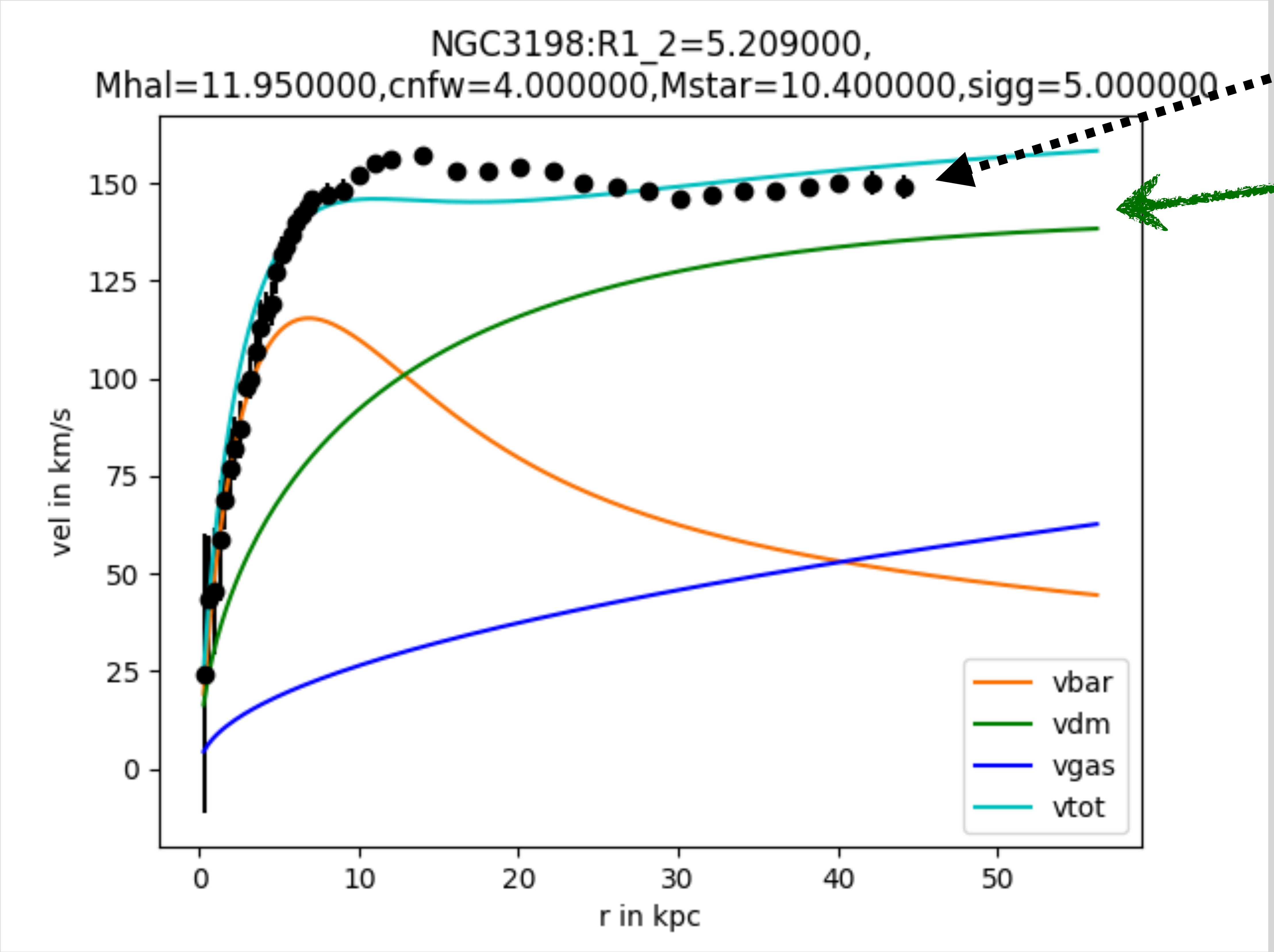

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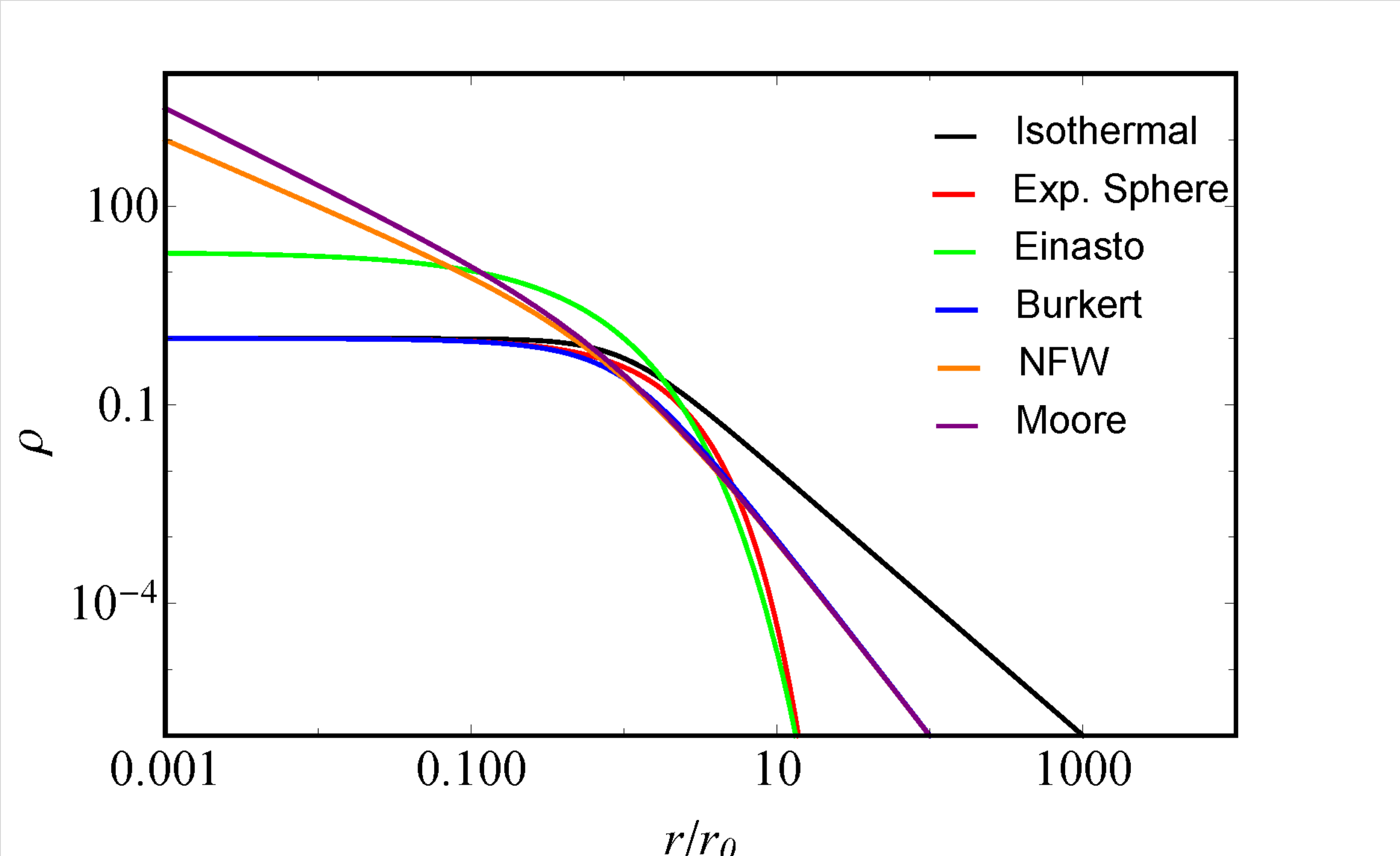
1) DM: different Dark Matter density profiles



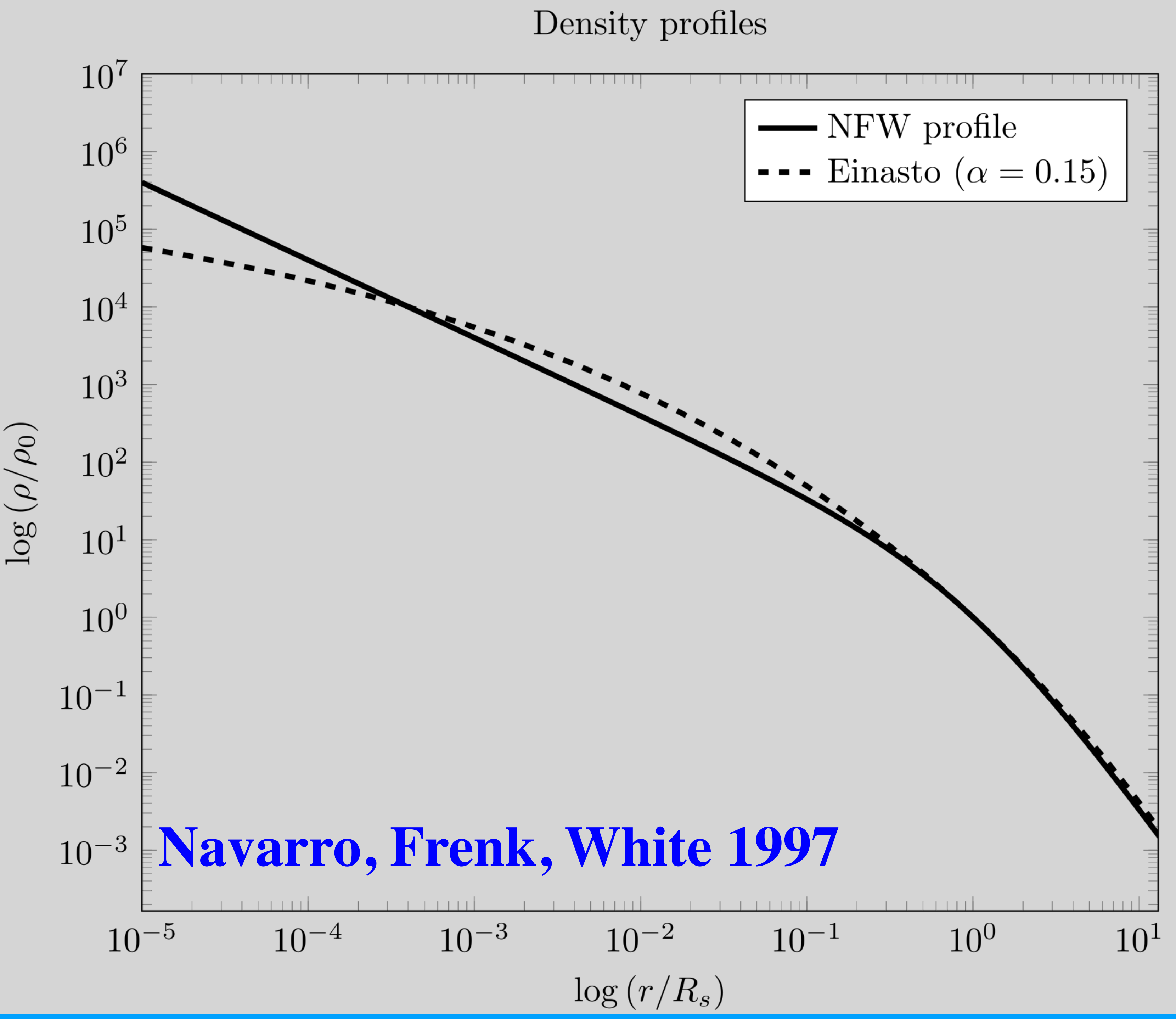
Boshkaye +2020

Examples of Halo profiles - from N-body simulations

CUSP

$$\rho_{\mathrm{NFW}}(r) = \frac{\rho_s}{\left(\frac{r}{r_s}\right)\left(1+\left(\frac{r}{r_s}\right)\right)^2}$$

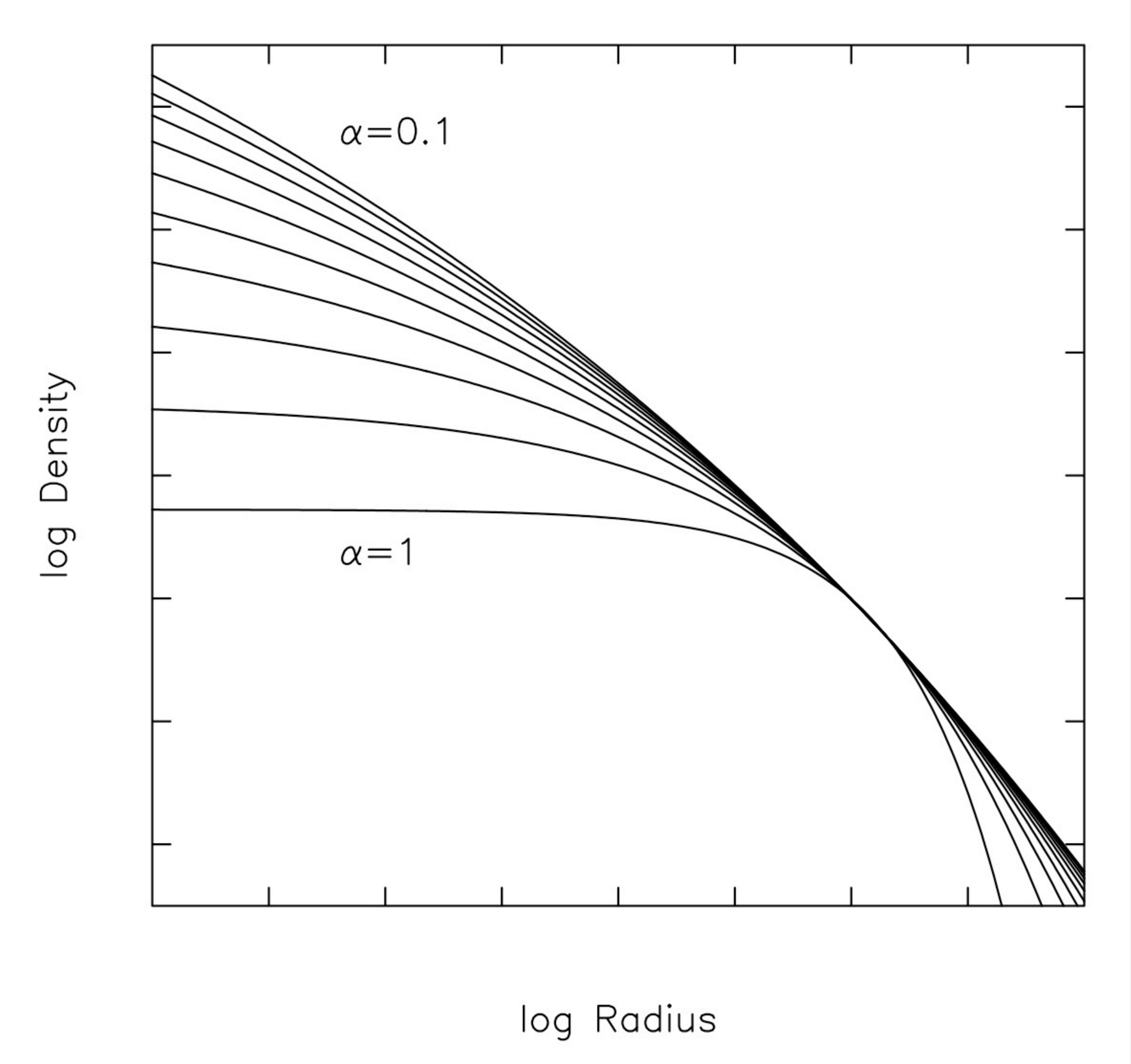
$$C_{200} = r_{200}/r_s$$



Navarro, Frenk, White 1997

CORE-CUSP

$$\rho_{\mathrm{Einasto}}(r) = \rho_s e^{-\frac{2}{\alpha\epsilon}\left(\left(\frac{r}{r_s}\right)^{\alpha\epsilon}-1\right)}$$



Navarro et al. (2004)

Examples of Halo profiles - from hydrodynamical simulations

CORE-CUSP

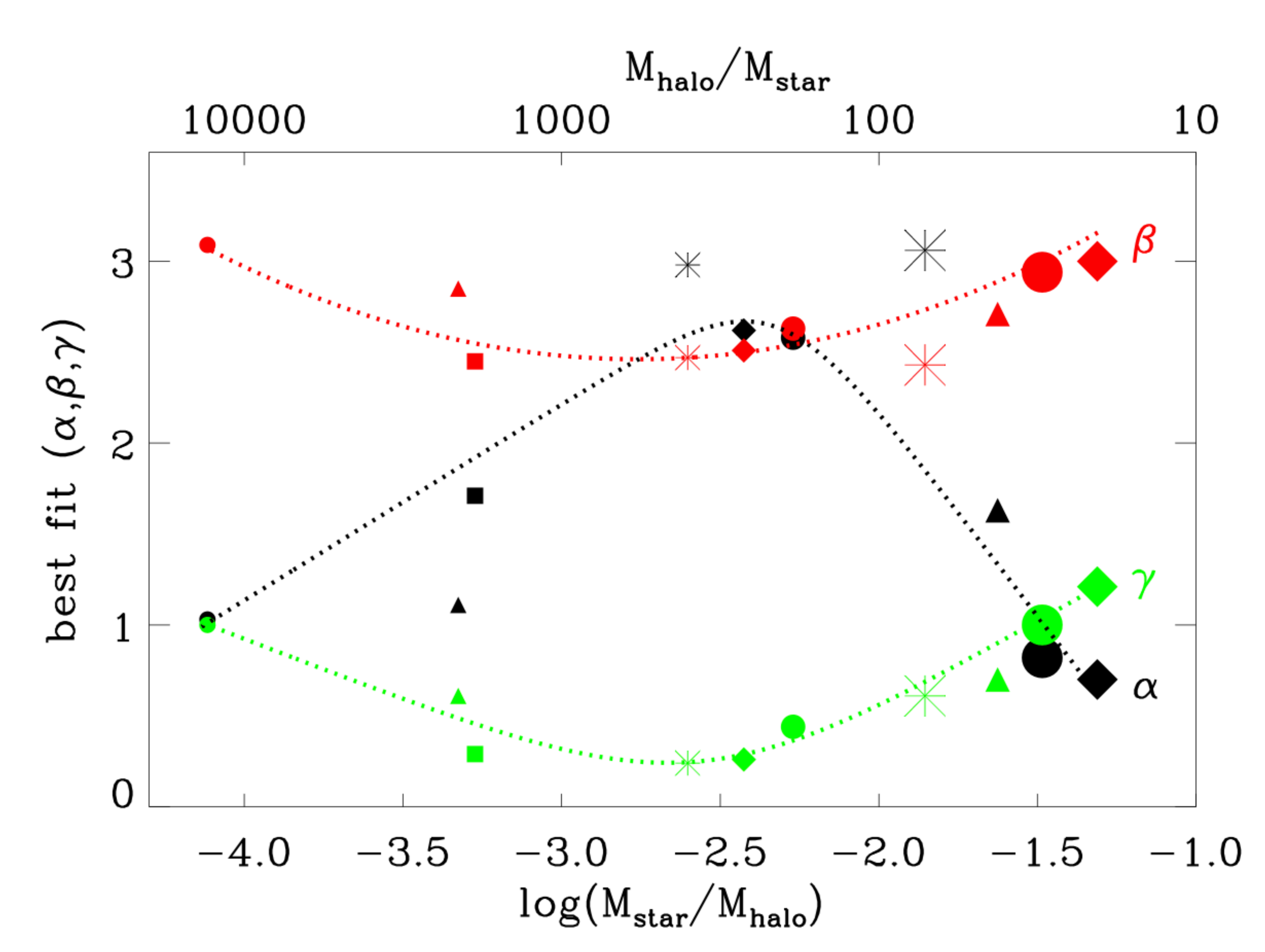
$$\rho_{DC14}(r) = \frac{\rho_s}{\left(\frac{r}{r_s}\right)^{\gamma}\left(1+\left(\frac{r}{r_s}\right)^{\alpha}\right)^{(\beta-\gamma)/\alpha}}$$

$$\alpha = 2.94 - log[(10^{X+2.33})^{-1.08} + (10^{X+2.33})^{2.29}],$$

$$\beta = 4.23 + 1.34X + 0.26X^2,$$

$$\gamma = -0.06 + log[(10^{X+2.56})^{-0.68} + 10^{X+2.56}].$$

$$X = \log(M_\star/M_{halo})$$



Di Cintio et al. 2014

➡takes into account the stellar-to-halo mass dependence of the response of dark matter to baryonic processes

Examples of Halo profiles - from hydrodynamical simulations

CORE-CUSP

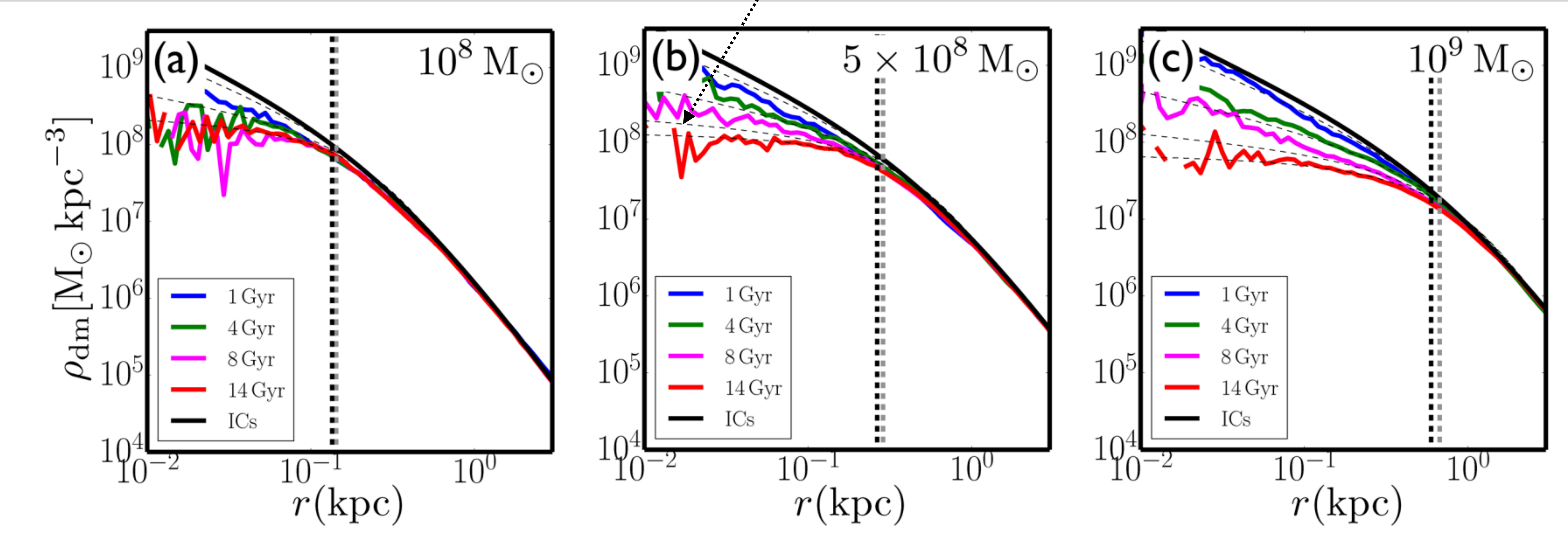
$$\rho_{\rm cNFW} = f^n(r)\rho_{\rm NFW} + \frac{n f^{n-1}(r)(1 - f^2(r))}{4\pi r^2 r_c} M_{\rm NFW}$$

where

$$f^n(r) = \tanh(r/r_c)^n$$

Read et al. 2016

coreNFW fits



➡captures the dark matter core growth as a function of star formation time and the projected stellar half-mass radius

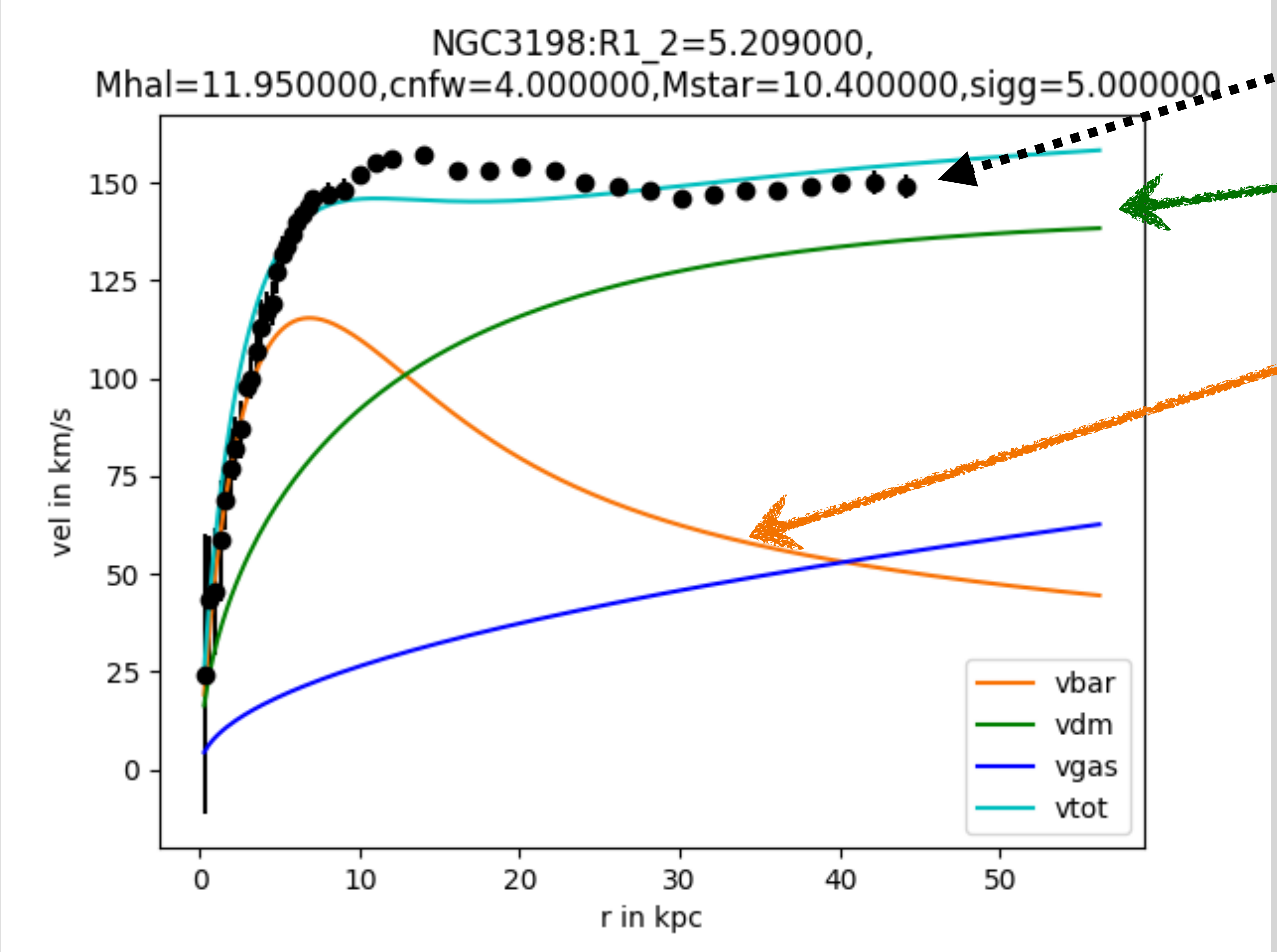
Examples of Halo profiles - many more

- ➡Burkert Profile (Burkert 1995)
- ➡Moore Profile (Moore et al. 1999)
- ➡Isothermal Profile (Binney & Tremaine 1987)
- ➡Hernquist Profile (Hernquist 1990)
- ➡Zhao Profile (Zhao 1996)
- ➡Dekel-Zhao (Freundlich et al. 2020)
- ➡cNFW (Peñarrubia et al. 2012)
- ➡coreEinasto (Lazar et al. 2020)
- ➡Etc

Using 3D forward modelling: Under the hood

GalPaK — galaxy parameters and kinematics

Bouché et al. 2015



$$v_c(r)^2 = v_{DM}(r)^2 + v_{disk}(r)^2 + v_{HI}(r)^2$$

1) DM: different Dark Matter halo profiles

2) Disk: I(r) - Freeman Disk; Sersic n (OII, Ha)

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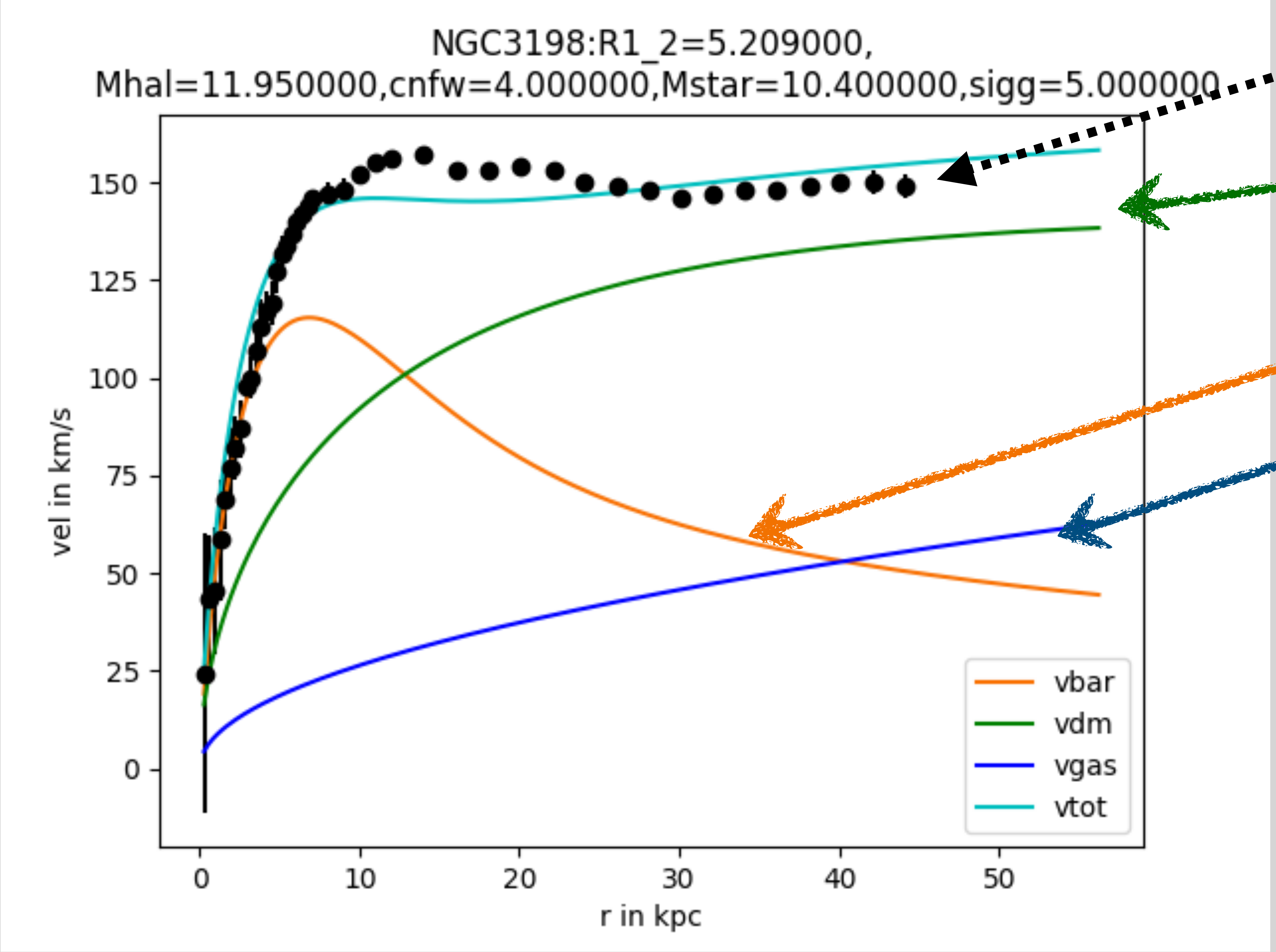

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1) DM: different Dark Matter halo profiles

2) Disk: I(r): Sersic n (OII,Ha); Freeman Disk

3) gas: HI gas (marginalized)

$$v_{HI}(r) \propto \sqrt{\Sigma_g r}$$

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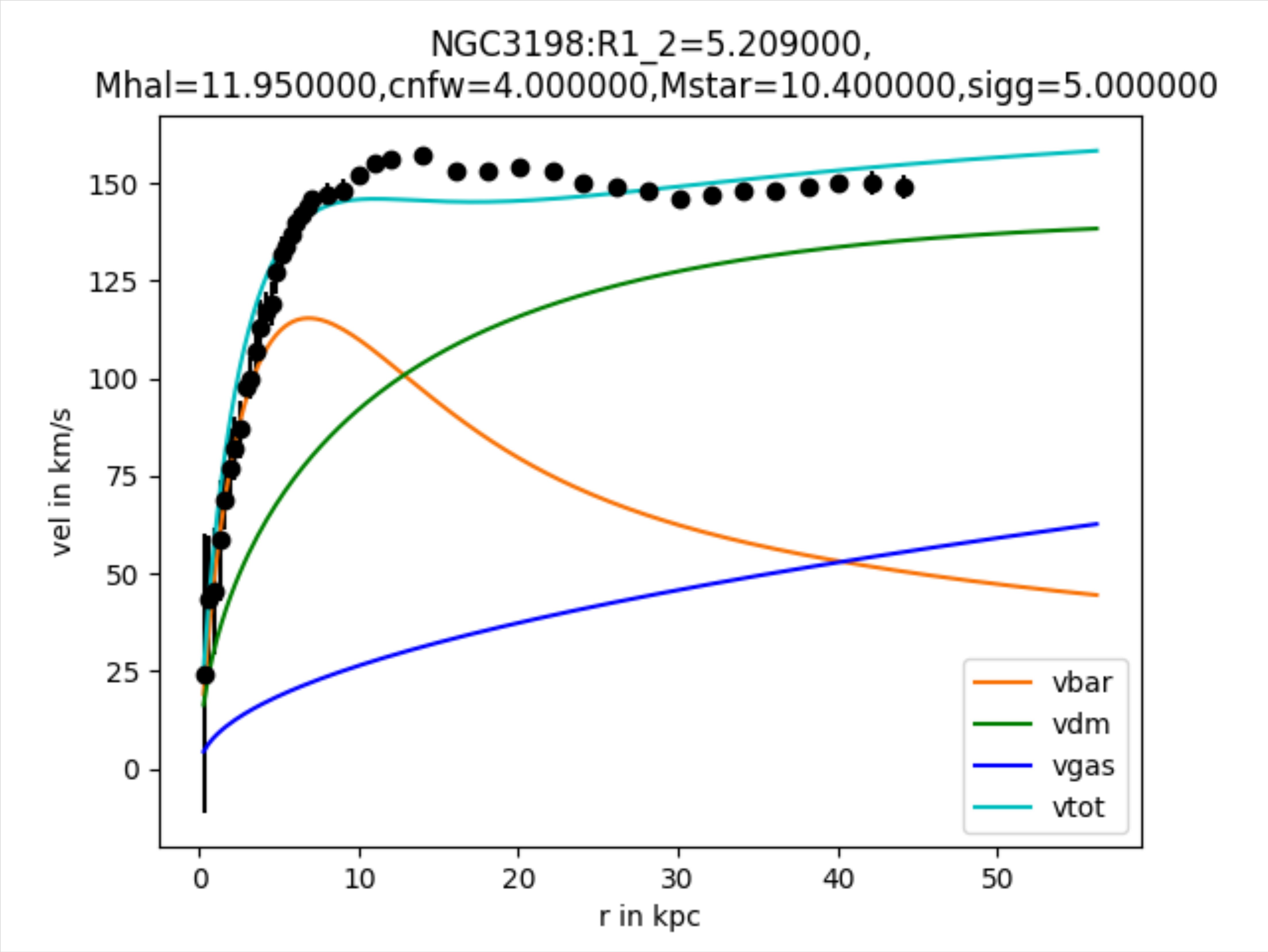
Bouché et al. 2015

$$v_c(r)^2 = v_{DM}(r)^2 + v_{disk}(r)^2 + v_{HI}(r)^2$$



1) DM: different Dark Matter halo profiles

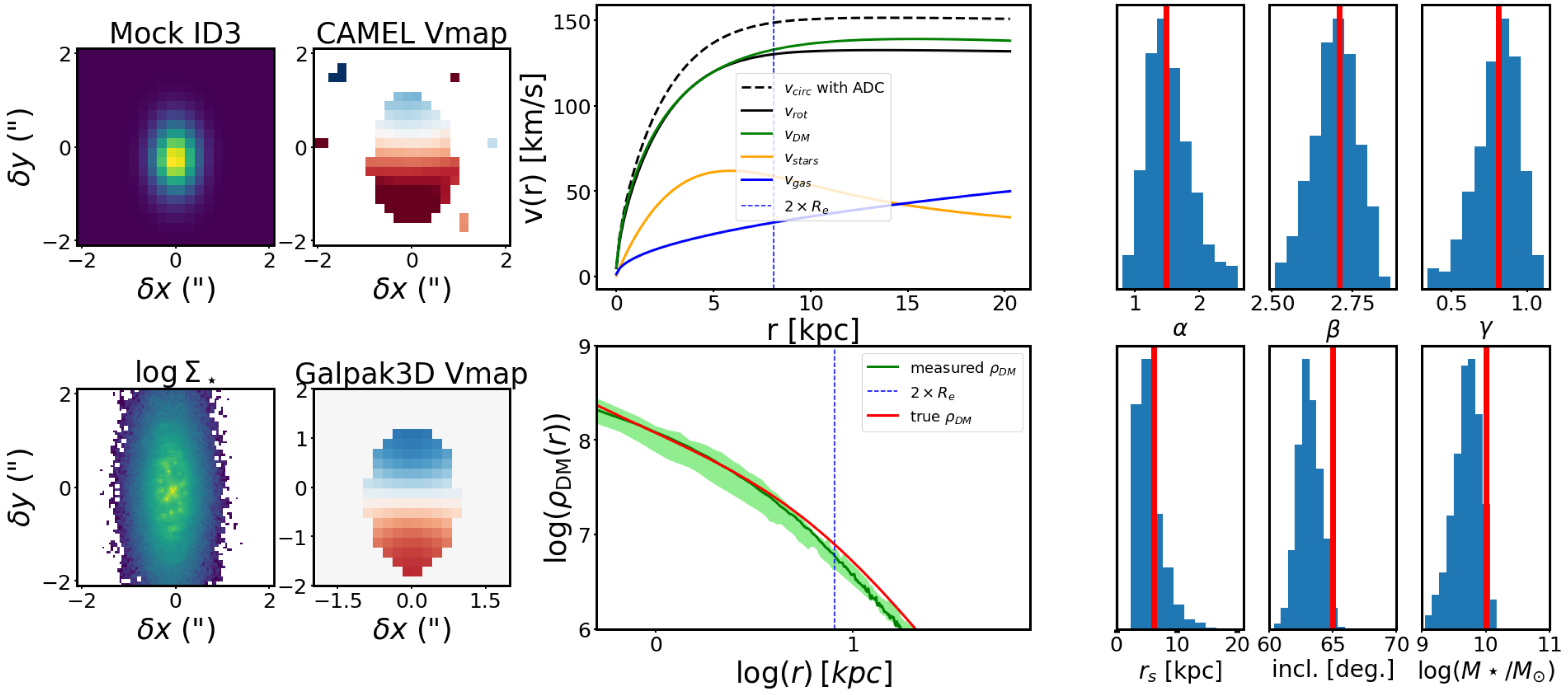
2) Disk: I(r): Sersic n (OII,Ha); Freeman Disk

3) gas: HI gas (marginalized)

→ **13 - 15 free parameters**
(x,y,z,incl,PA,**M**$_*$,M_{vir},c_{vir},sig0,Re,n,…)
→ all optimised simultaneously directly on the 3D IFU cube

Validation of the methodology:

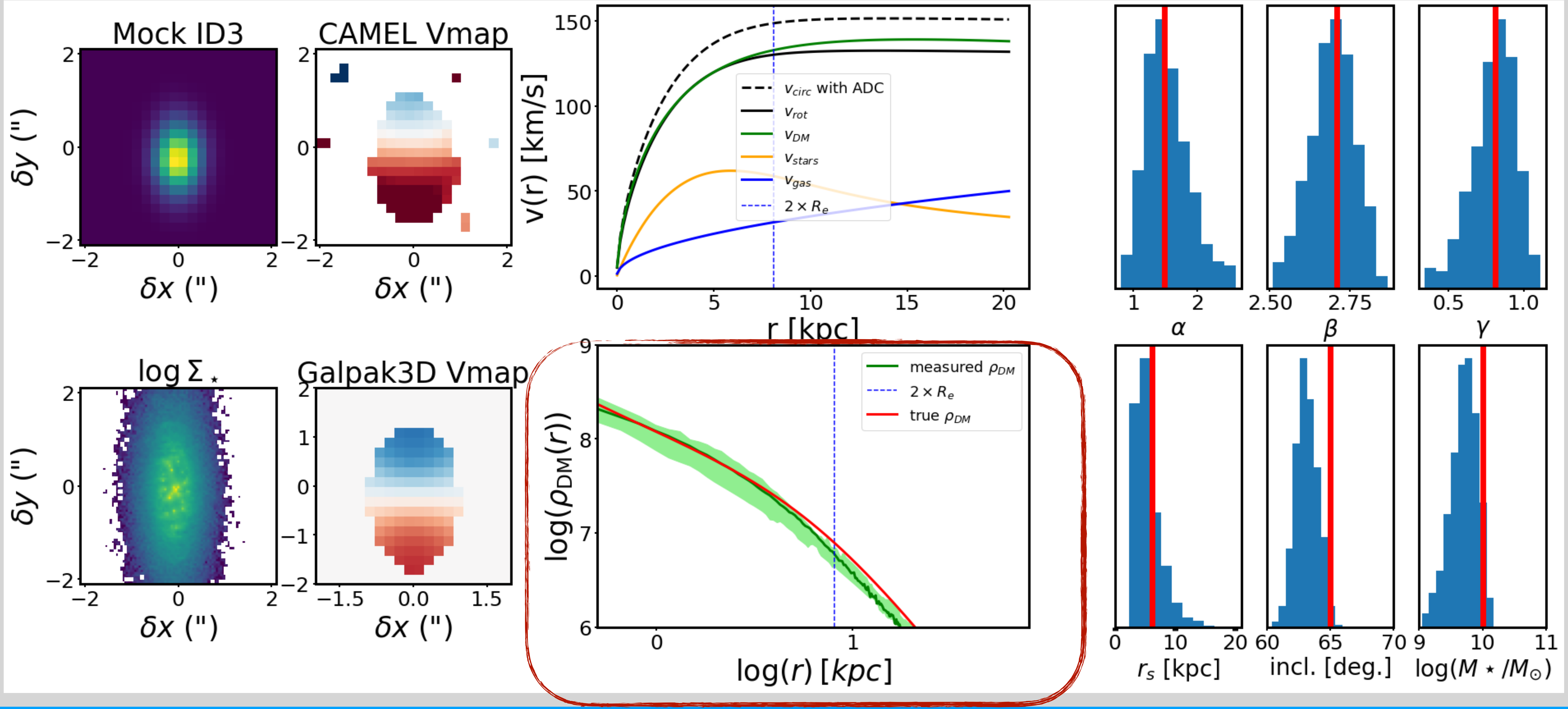
- Apply 3D disk-halo decomposition on mock observations



Validation of the methodology:

GalPaK
galaxy parameters and kinematics

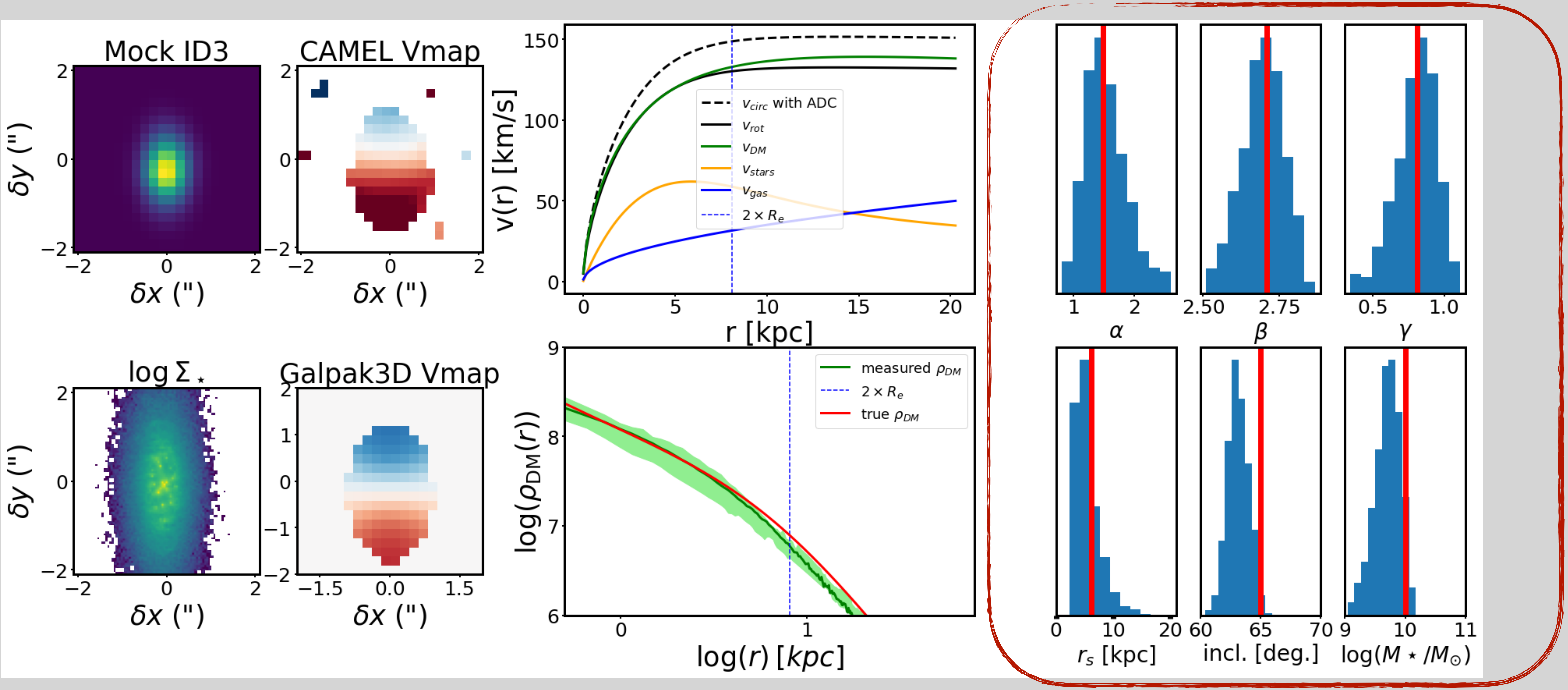
- Apply 3D disk-halo decomposition on mock observations



Validation of the methodology:

GalPaK galaxy parameters and kinematics

- Apply 3D disk-halo decomposition on mock observations (using DC14 halo profile)

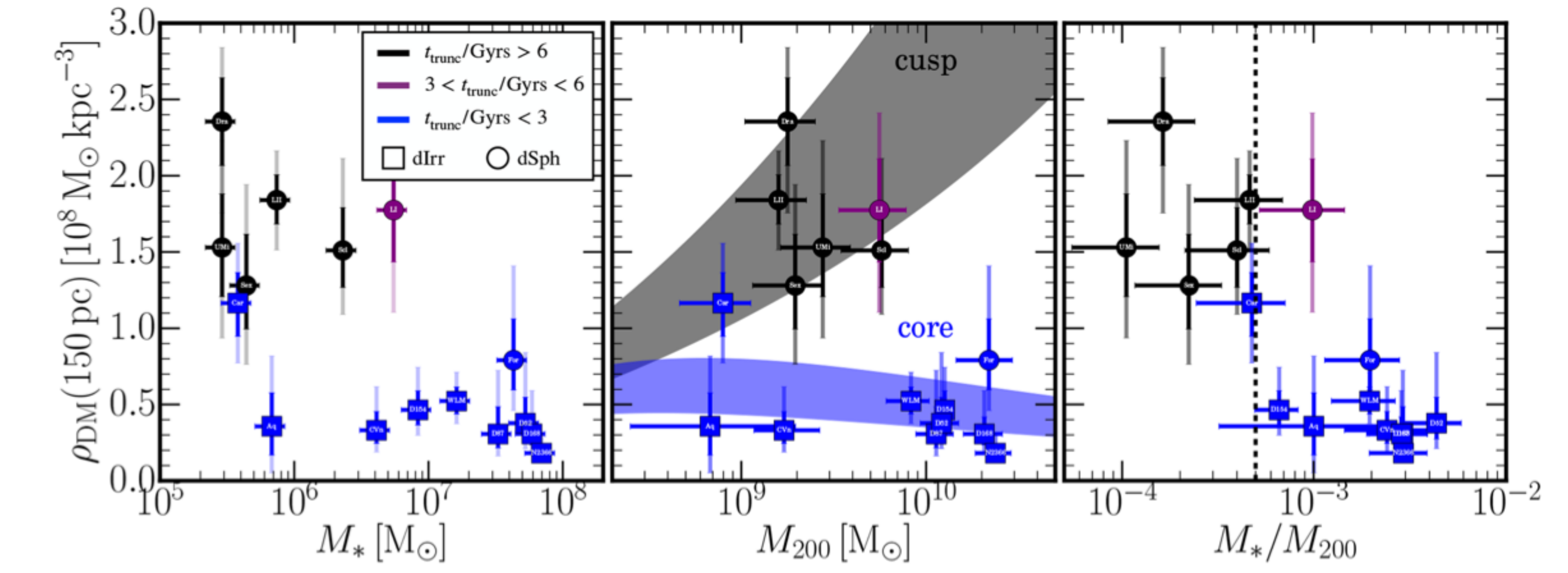


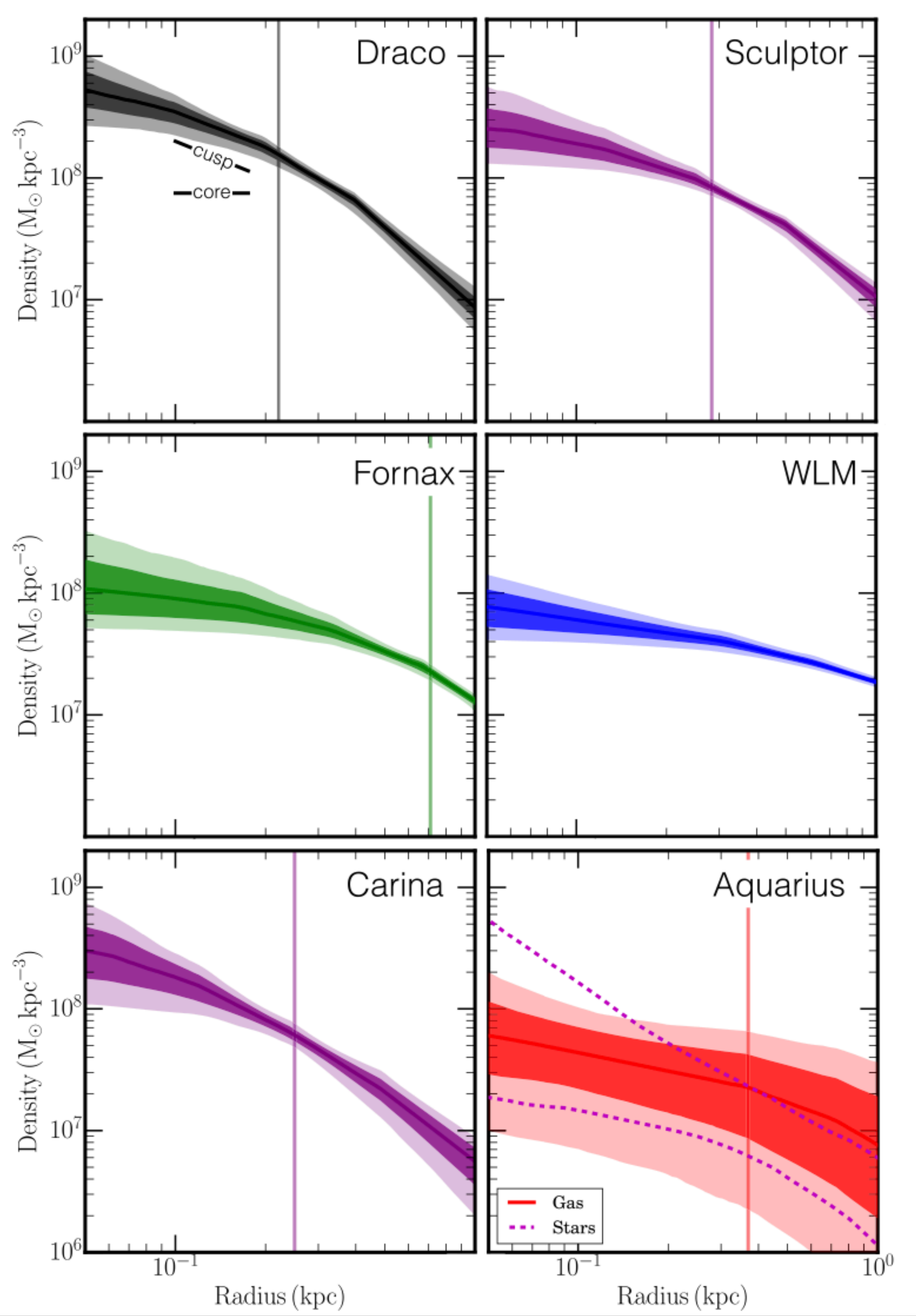
State-of-the-art (z=0): Read et al. 2019

1D

- Dynamical modelling of 8 dwarf spheroidal and 8 dwarf irregular galaxies
- Use NFW & coreNFW
- Investigate SFHs

➡ **Find evidence that galaxies which stopped forming stars over 6 Gyr ago show cusps, while those with more extended star formation cores**





State-of-the-art (z=0): SPARC sample - Katz+2017

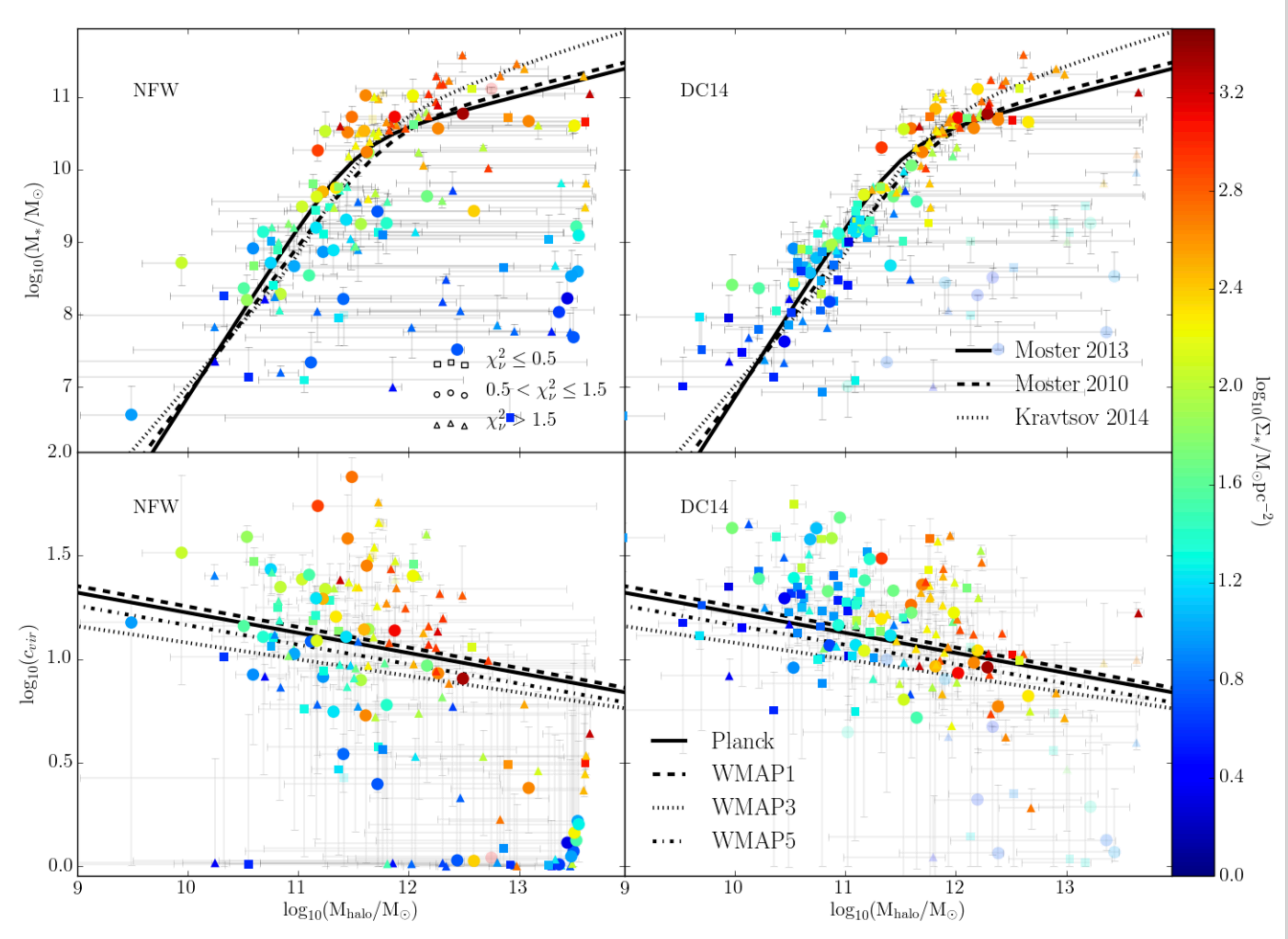
1D

- Rotation curve decomposition for 147 local galaxies (SPARC sample - Ha+HI)

- Model DM halo with (1) Navaro, Frenk, White +1997 profile; and (2) Di Cintio +2014 profile

➡Di Cintio halo profile provides better fits to the data

➡Recover halo mass–concentration & stellar mass–halo mass relations

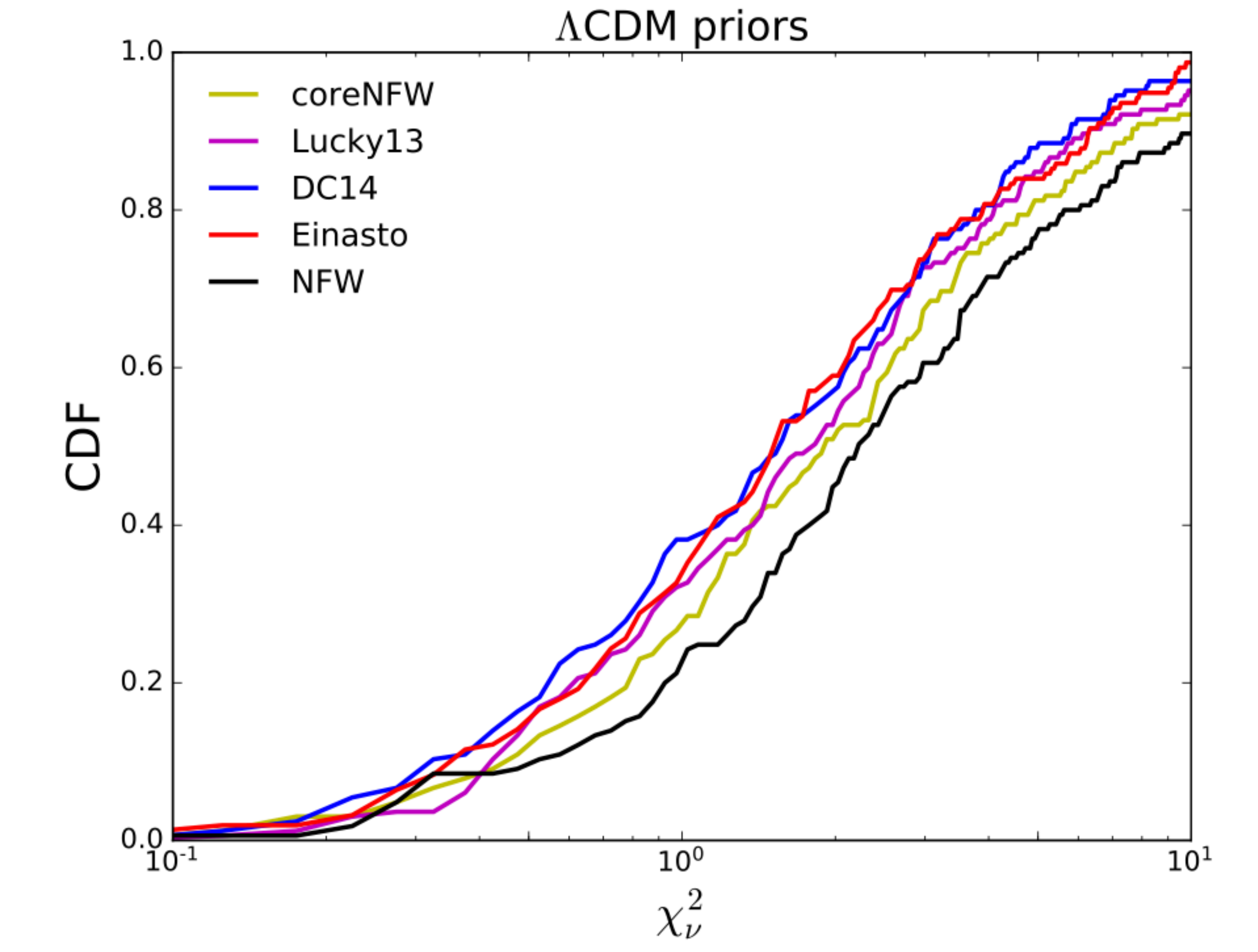


State-of-the-art (z=0): SPARC sample - Li+2020

1D

- Rotation curve decomposition for 175 local galaxies (SPARC sample - Ha+HI)

- Model DM halo with: (1) NFW; (2) Di Cintio +2014 profile; (3) pseudo-isothermal; (4) Burkert; (5) Einasto; (6)cored-NFW; and (7) Lucky13



➡**Find evidence that cored profiles, such as Burkert, coreNFW, DC14, Einasto, and pISO, provide better rotation curve fits than the cuspy NFW profile**

➡Recover halo mass–concentration & stellar mass–halo mass relations

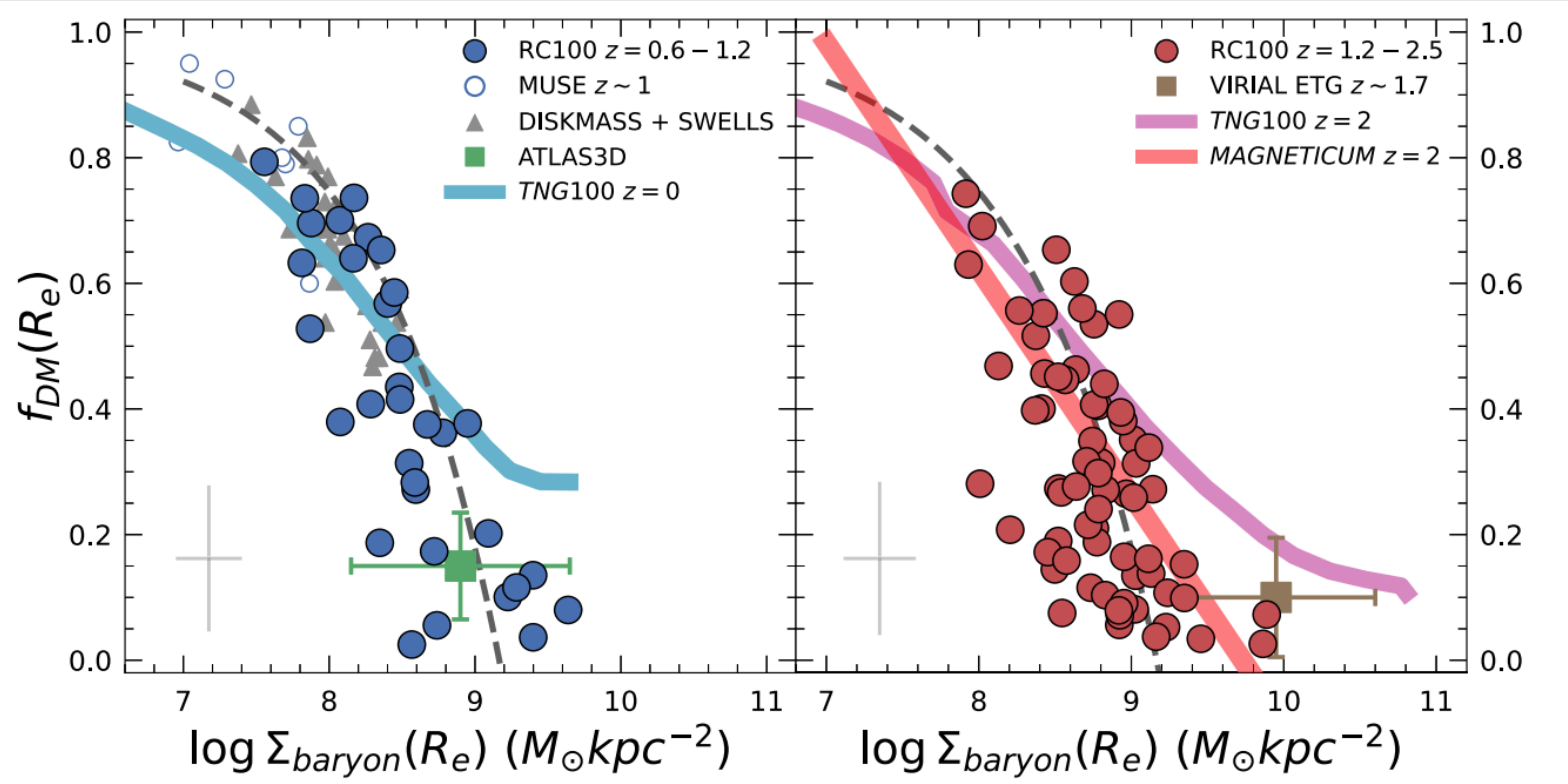
State-of-the-art (z~1-2): Genzel+17, Nestor Shachar+2023

1D

‣Rotation curve decomposition for 100 z=0.6-2.5 massive galaxies (CO, Ha)

➡fraction of dark to total matter decreases with z

➡DM deficit is more evident at high star formation rate surface densities and galaxies with massive bulges



State-of-the-art (z~1-2): Genzel+17, Nestor Shachar+2023

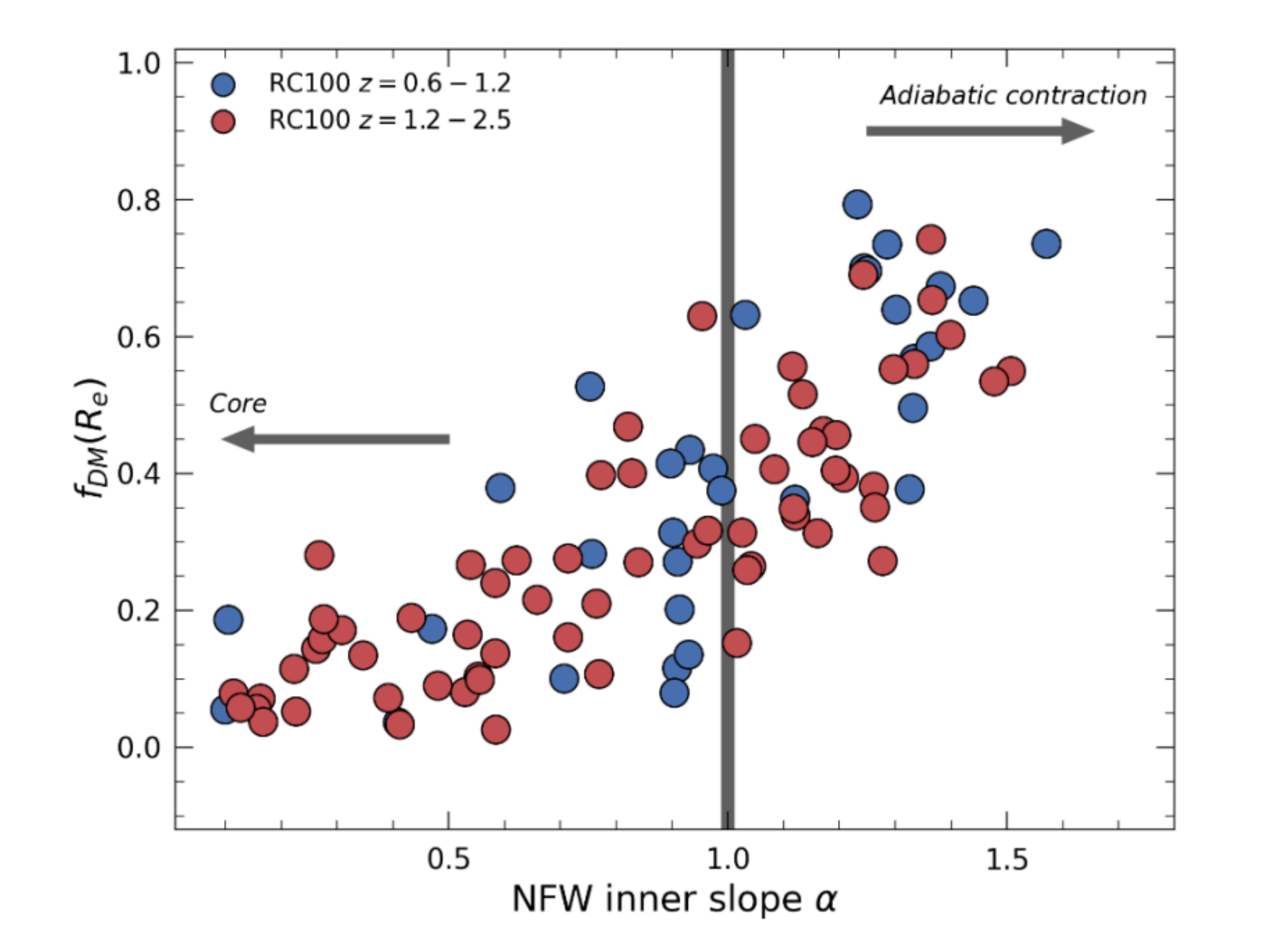
1D

- Rotation curve decomposition for 100 z=0.6-2.5 massive galaxies (CO, Ha)

➡fraction of dark to total matter decreases with z

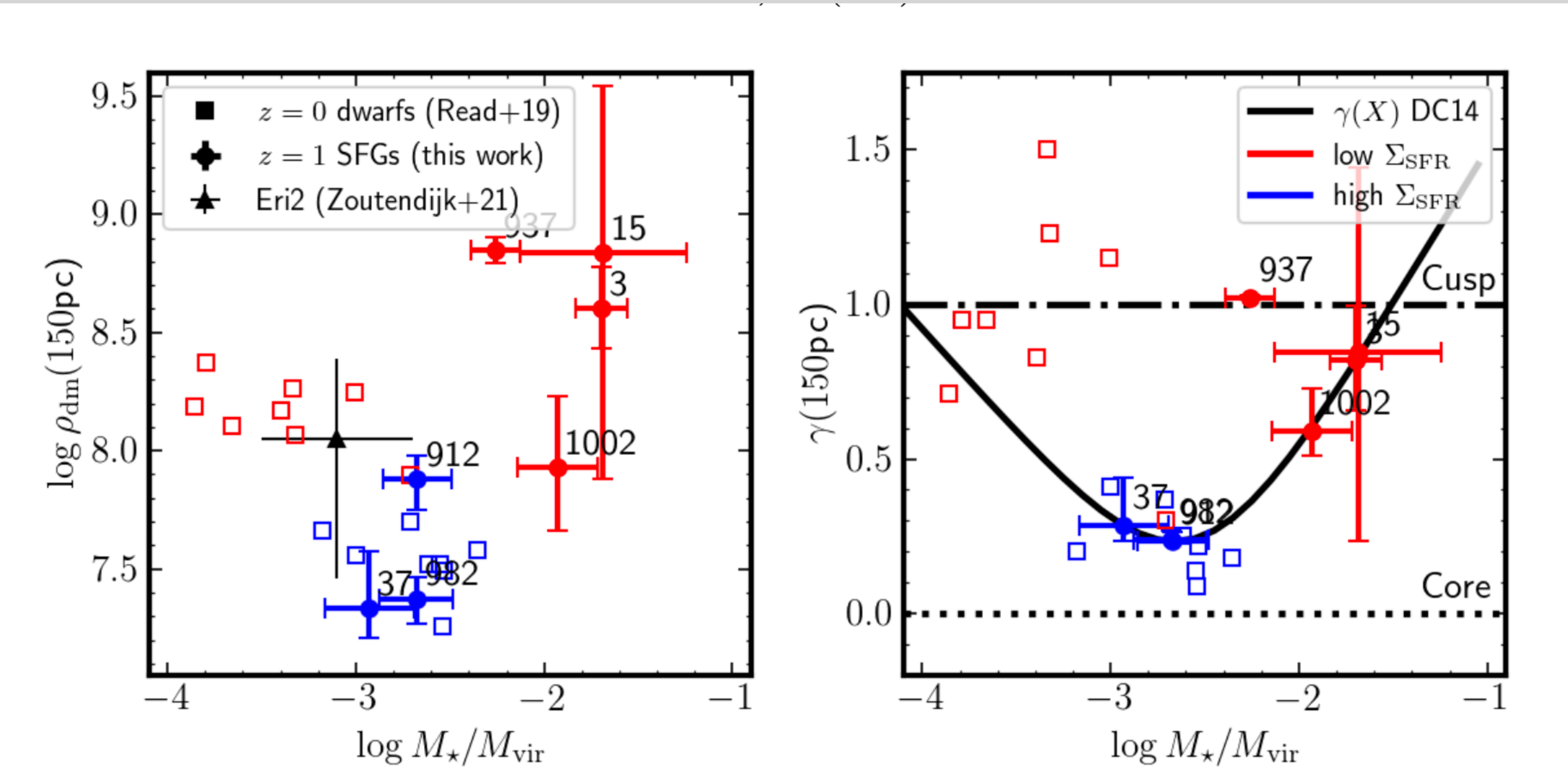
➡DM deficit is more evident at high star formation rate surface densities and galaxies with massive bulges

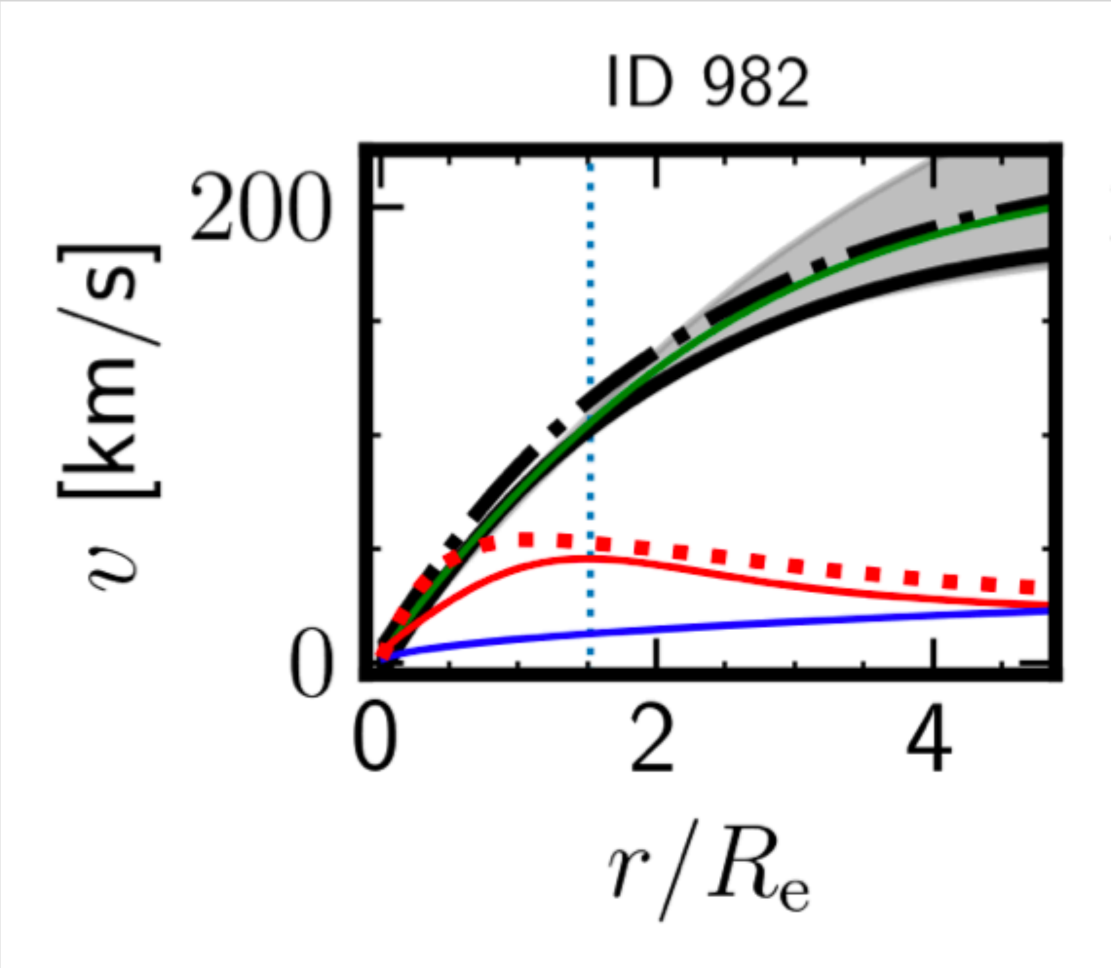
➡low DM fractions can be explained with cored inner DM density

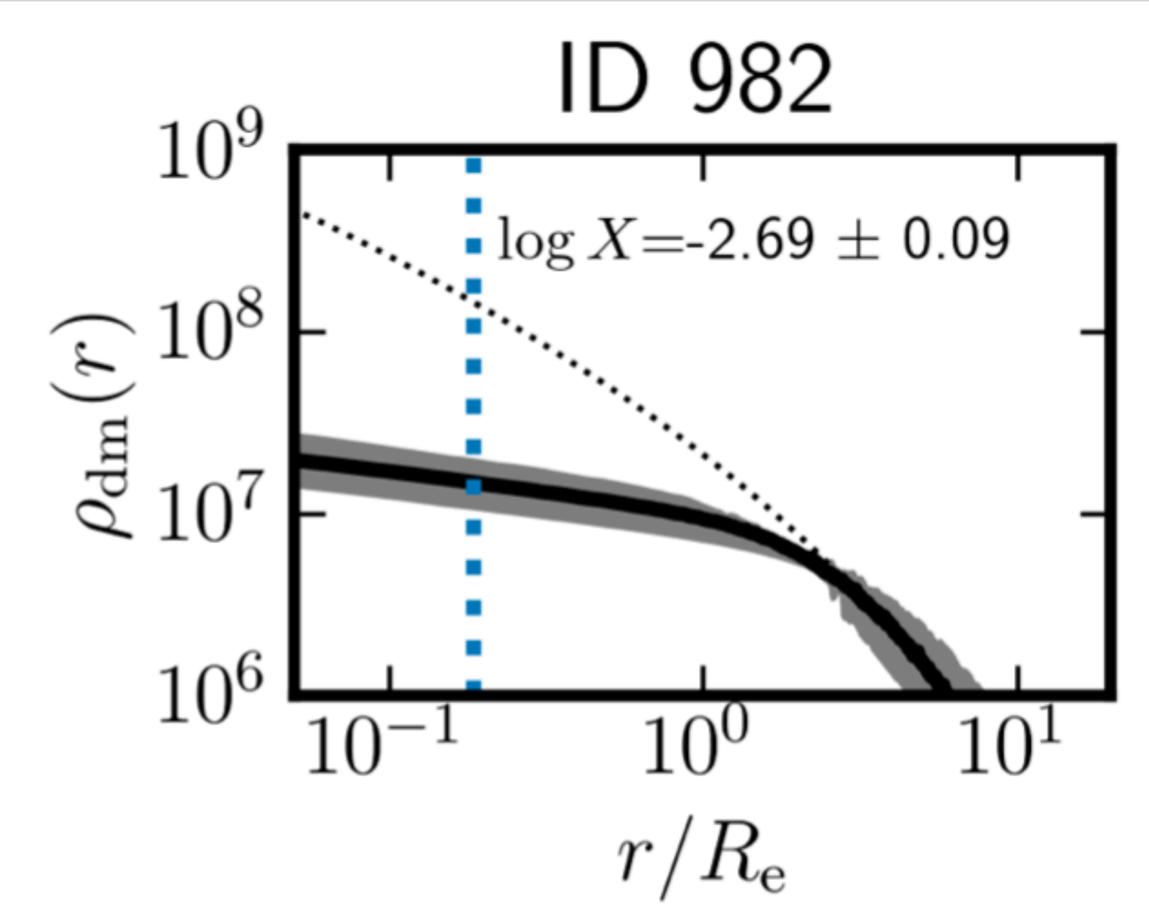


At z~1 - MUSE Hubble Ultra Deep Field: Bouché +2022

- Rotation curve decomposition for 10 z~1 lower mass galaxies
- Model DM halo with: (1) NFW; (2) Di Cintio +2014 profile







➡Di Cintio +2014 profile represents the data better
➡Halo parameters agree with expectations
➡Evidence for stellar feedback induced cores

3D GalPaK galaxy parameters and kinematics

At z~1 - MUSE Hubble Ultra Deep Field Survey: Ciocan, Bouché +2024

submitted

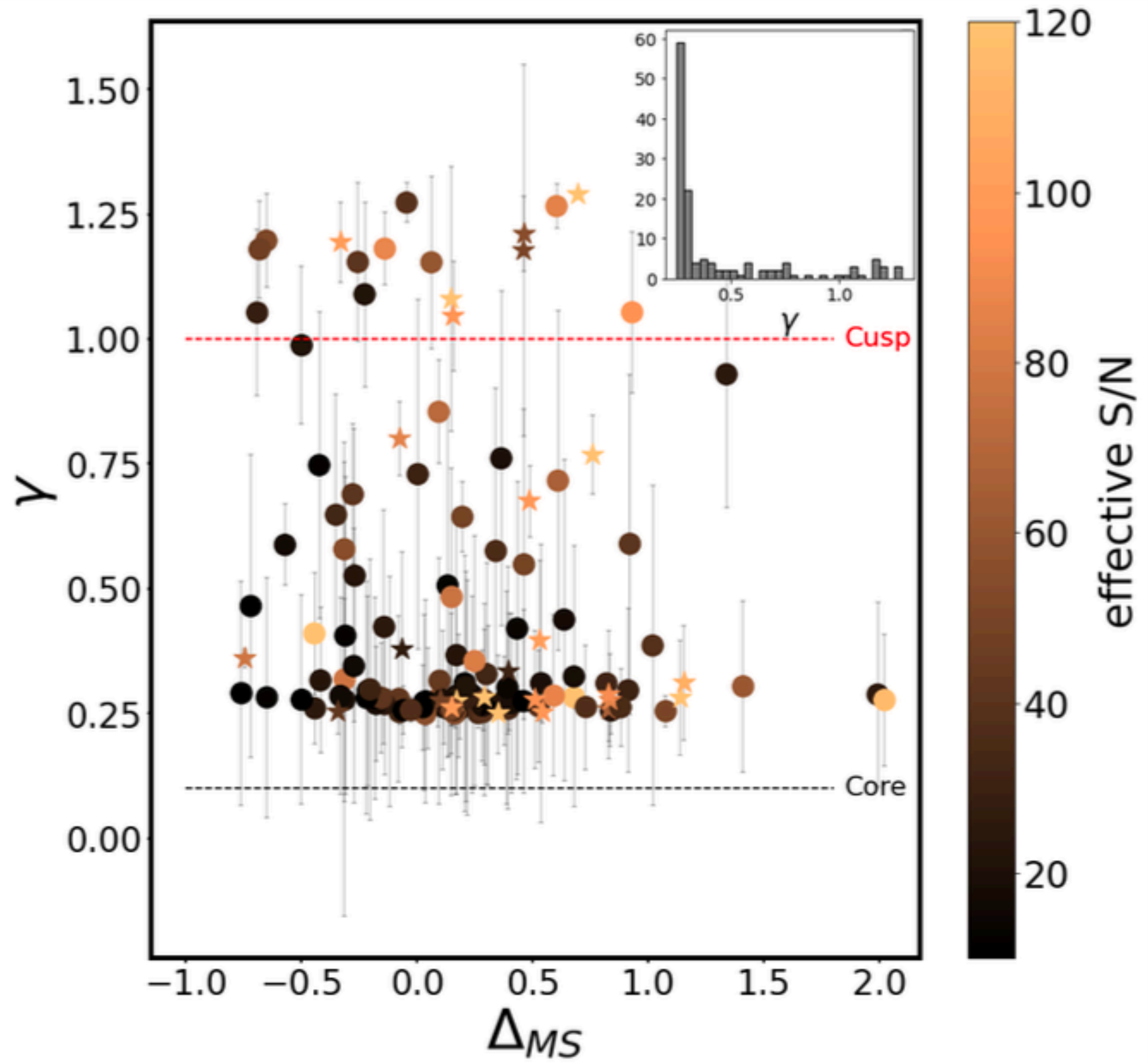
- Rotation curve decomposition for 136 galaxies with $0.3 < z < 1.5$ and $7 < \log(M_\star/M_\odot) < 11$

- Model DM halos with: (1) NFW; (2) Di Cintio +2014 profile; (3)Burkert (Burkert 1995); (4) Dekel-Zhao (Freundlich et al. 2020b); (5) Einasto (Navarro et al. 2004); and (6) coreNFW

➡Bayesian model comparison: Di Cintio +2014 profile represents the data better

At z~1 - MUSE Hubble Ultra Deep Field Survey: Ciocan, Bouché +2024

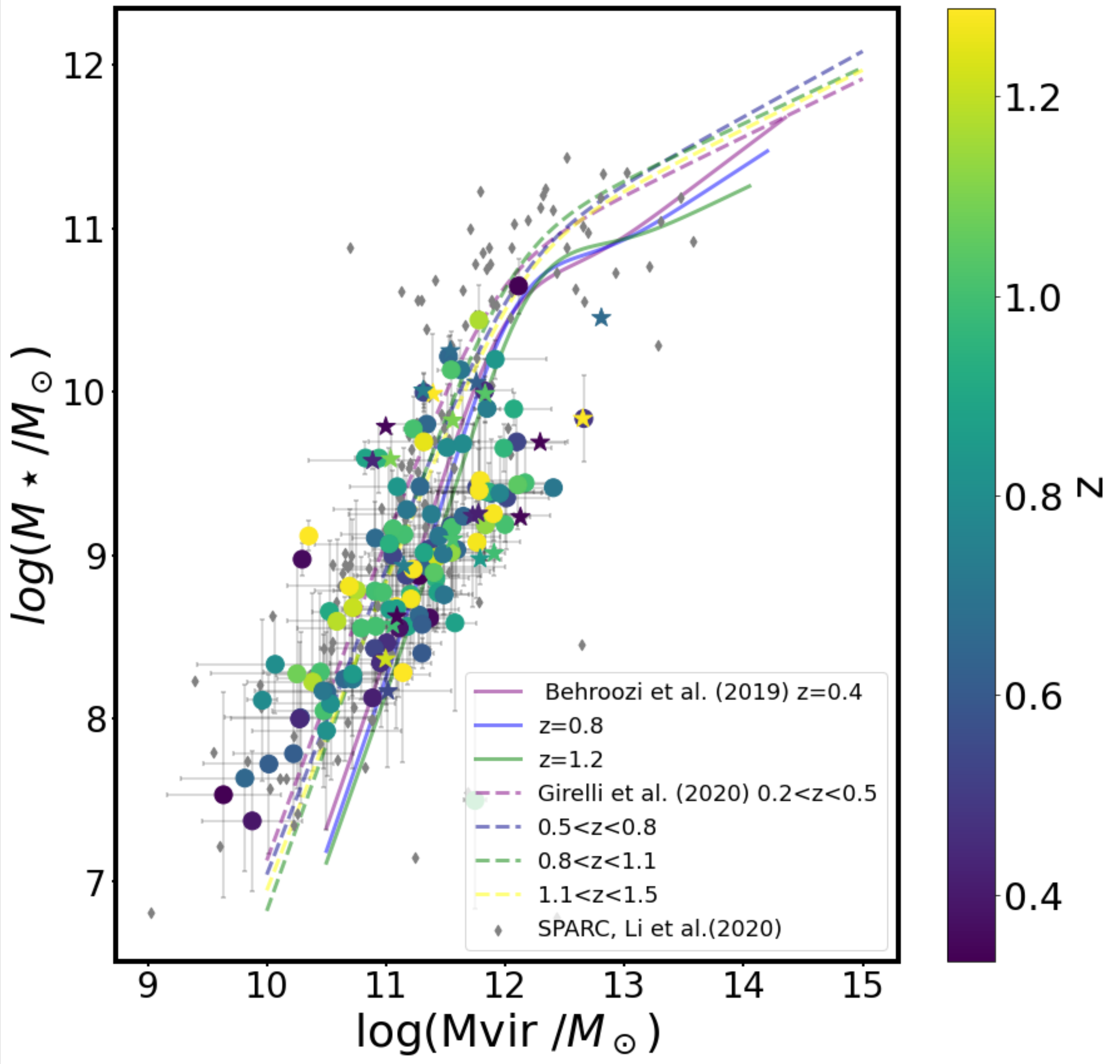
- Dark matter inner slope vs offset from star forming main sequence



➡66% shows cored dark matter density profiles
➡No correlation between the dark matter inner slope and the star formation activity of the sample

At z~1 - MUSE Hubble Ultra Deep Field Survey: Ciocan, Bouché +2024

- **Stellar mass - halo mass relation**



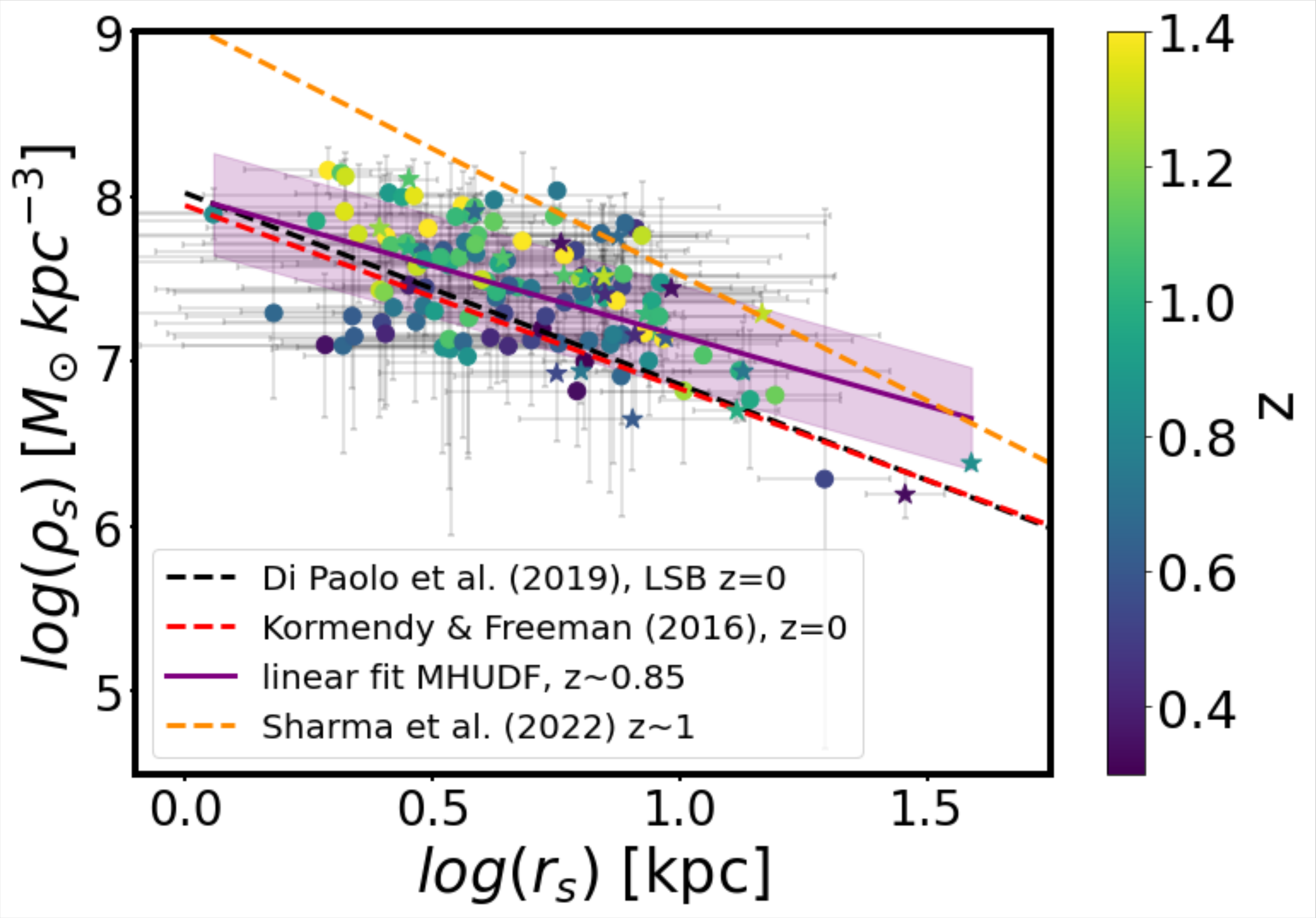
➡in agreement with the predictions from Behroozi+2019 and Girelli+2020

3D GalPaK galaxy parameters and kinematics

At z~1 - MUSE Hubble Ultra Deep Field Survey: Ciocan, Bouché +2024

▸ Halo scale radius - density relation

3D GalPaK
galaxy parameters and kinematics



$\rho \propto R^{-3(3+n)/(5+n)}$ (Djorgovski 1992)

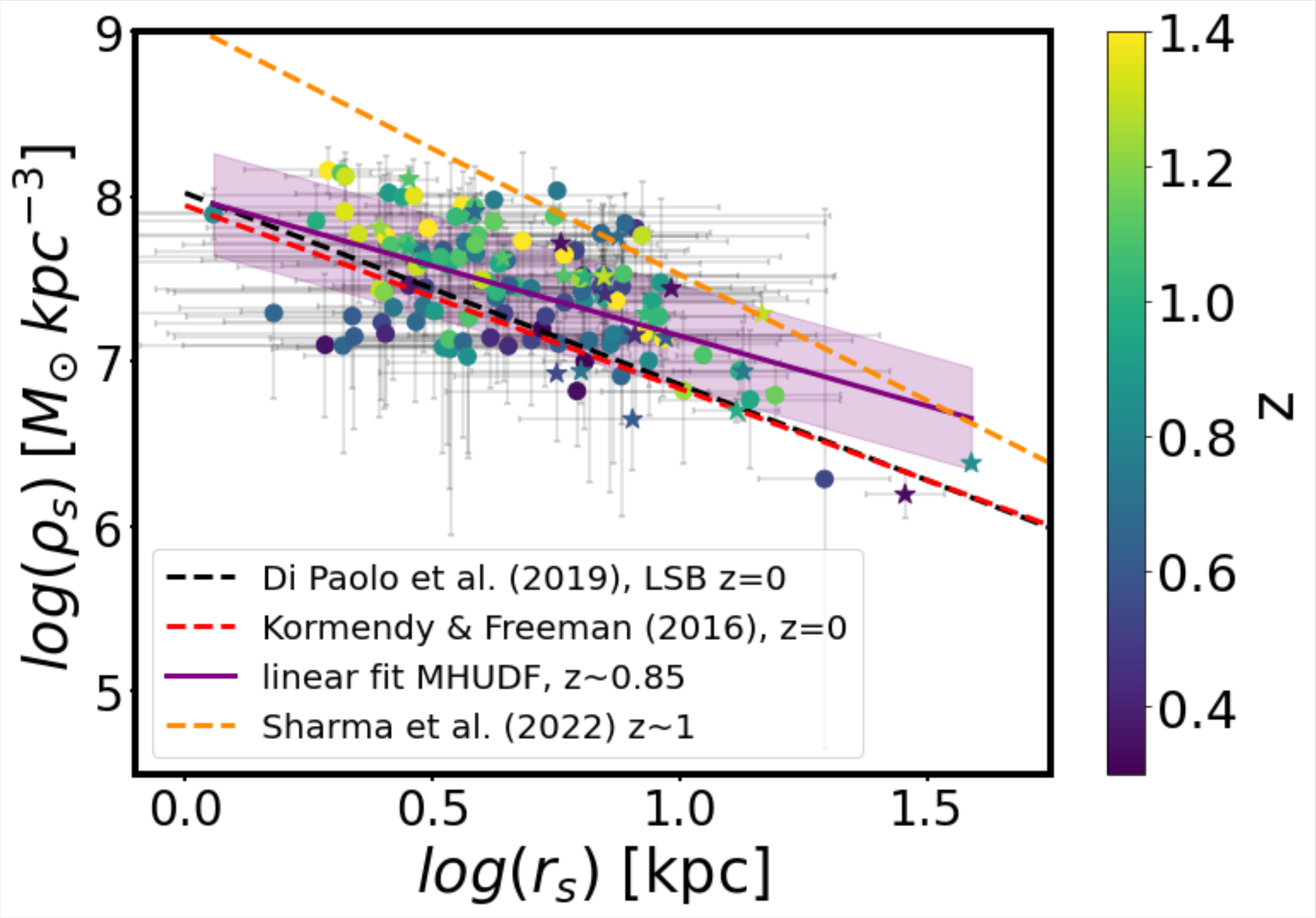
$n \sim -2$

➡anticorrelation results from the expected scaling relation of DM predicted by hierarchical clustering

At z~1 - MUSE Hubble Ultra Deep Field Survey: Ciocan, Bouché +2024

▸ Halo scale radius - density relation

3D GalPaK galaxy parameters and kinematics



➡evolution of halo characteristic density with z

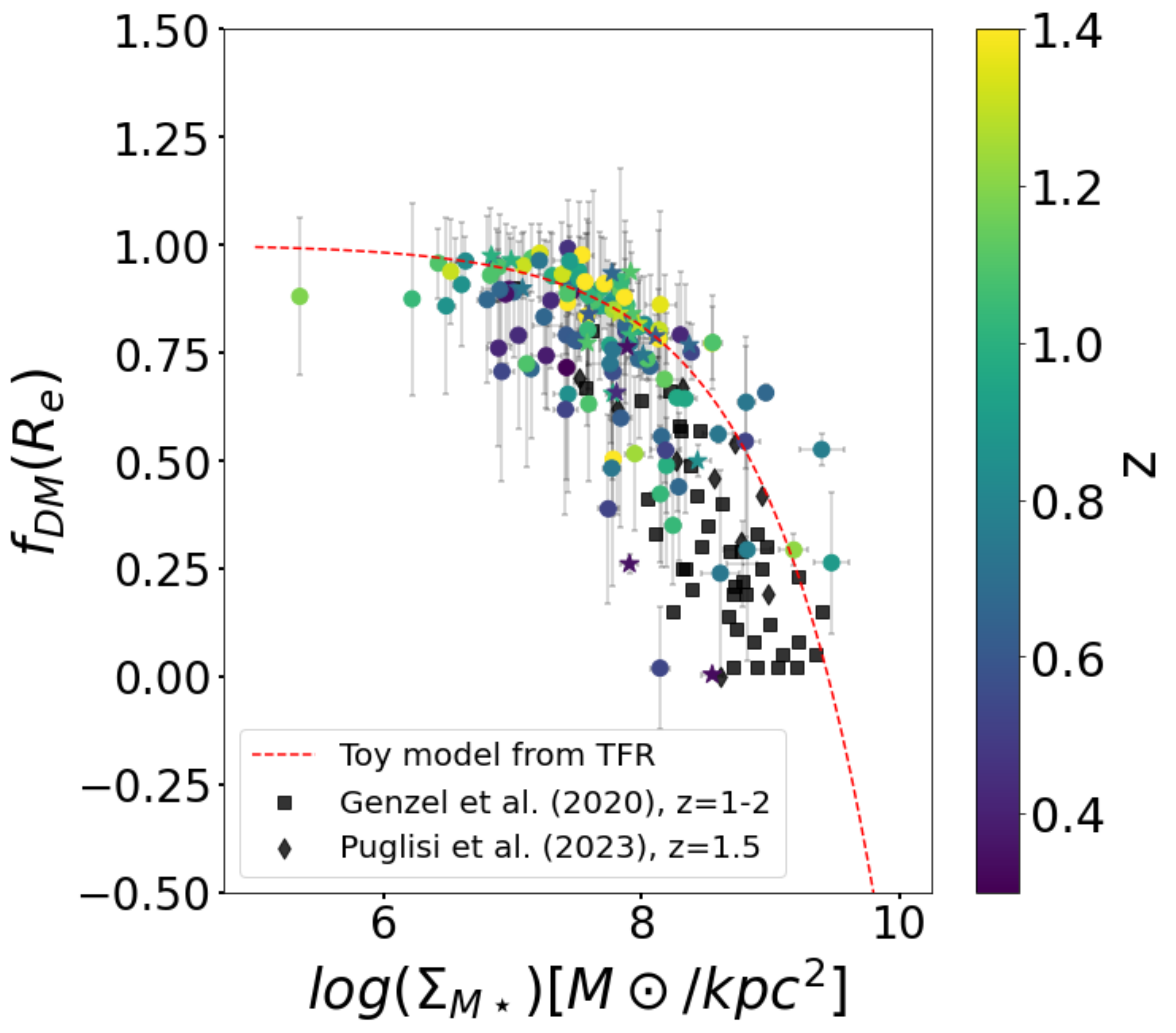
$\rho \propto R^{-3(3+n)/(5+n)}$ $n \sim -2$

(Djorgovski 1992)

➡anticorrelation results from the expected scaling relation of DM predicted by hierarchical clustering

At z~1 - MUSE Hubble Ultra Deep Field Survey: Ciocan, Bouché +2024

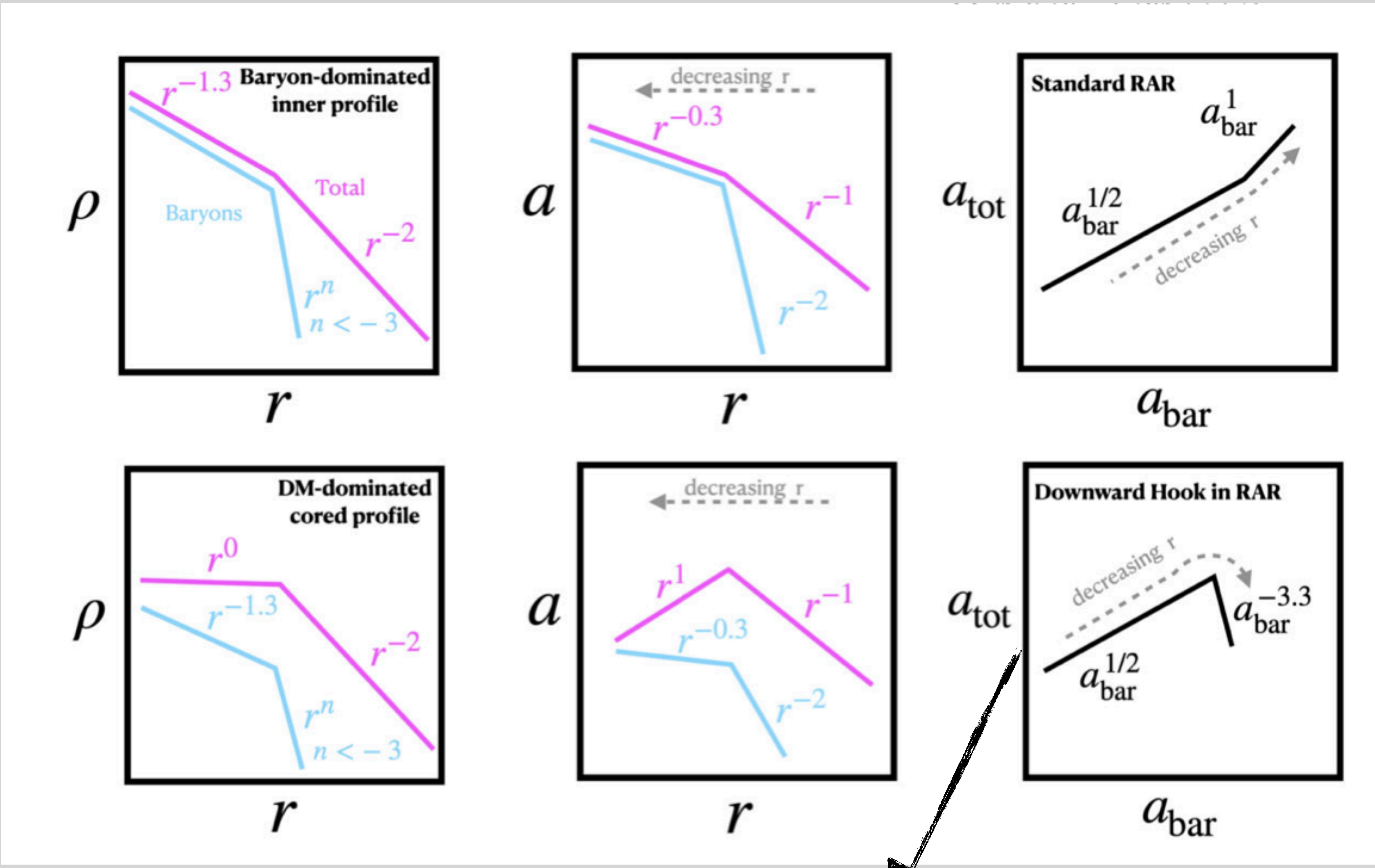
- Dark matter fraction - stellar mass surface density relation

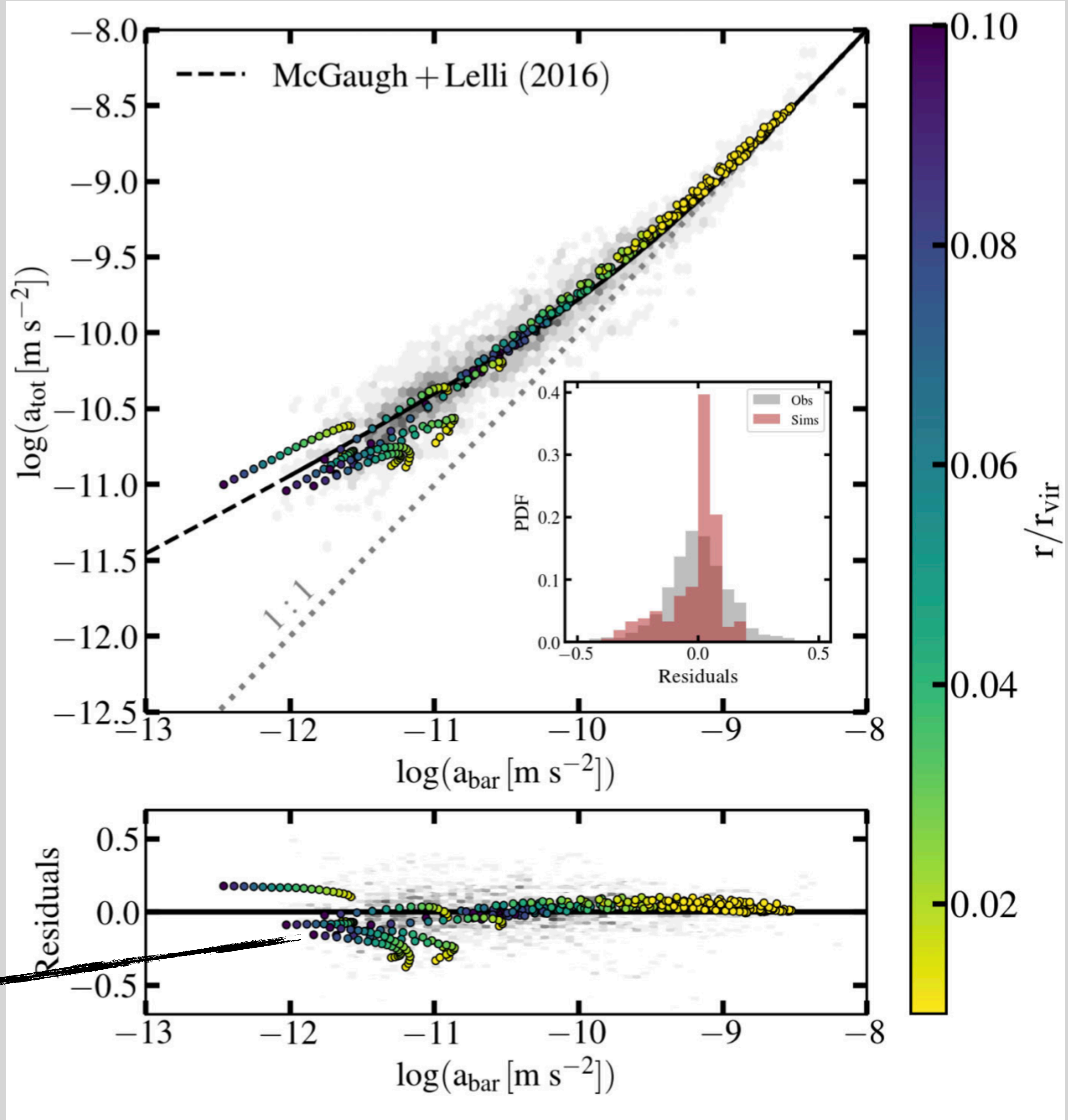


➡89% of the sample has dark matter fractions larger than 50% within Re

(At z~1 - MUSE Hubble Ultra Deep Field Survey: Ciocan, Bouché +2024)

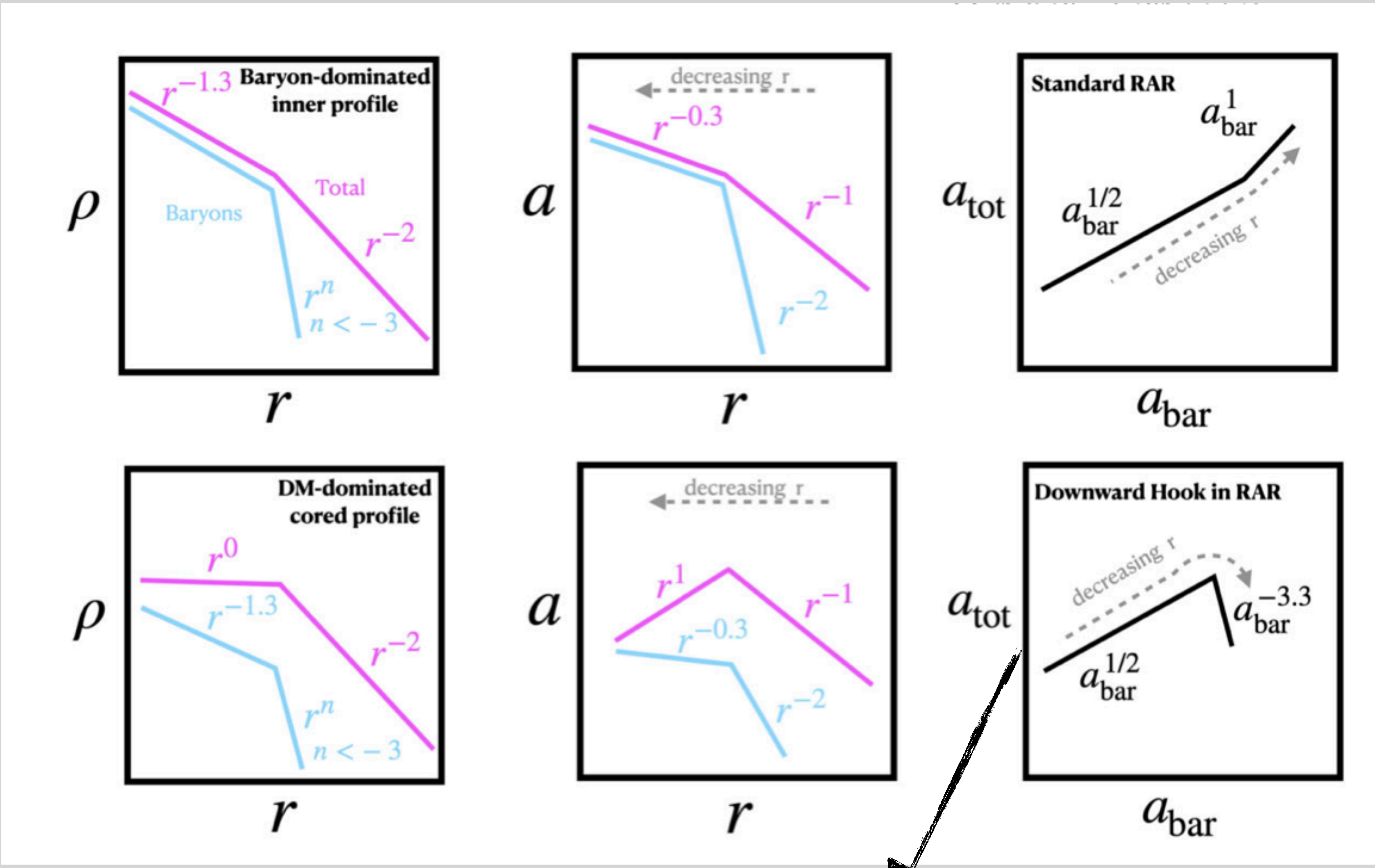
- **RAR relation -predictions from FIRE-2 simulations (Mercado+24)**

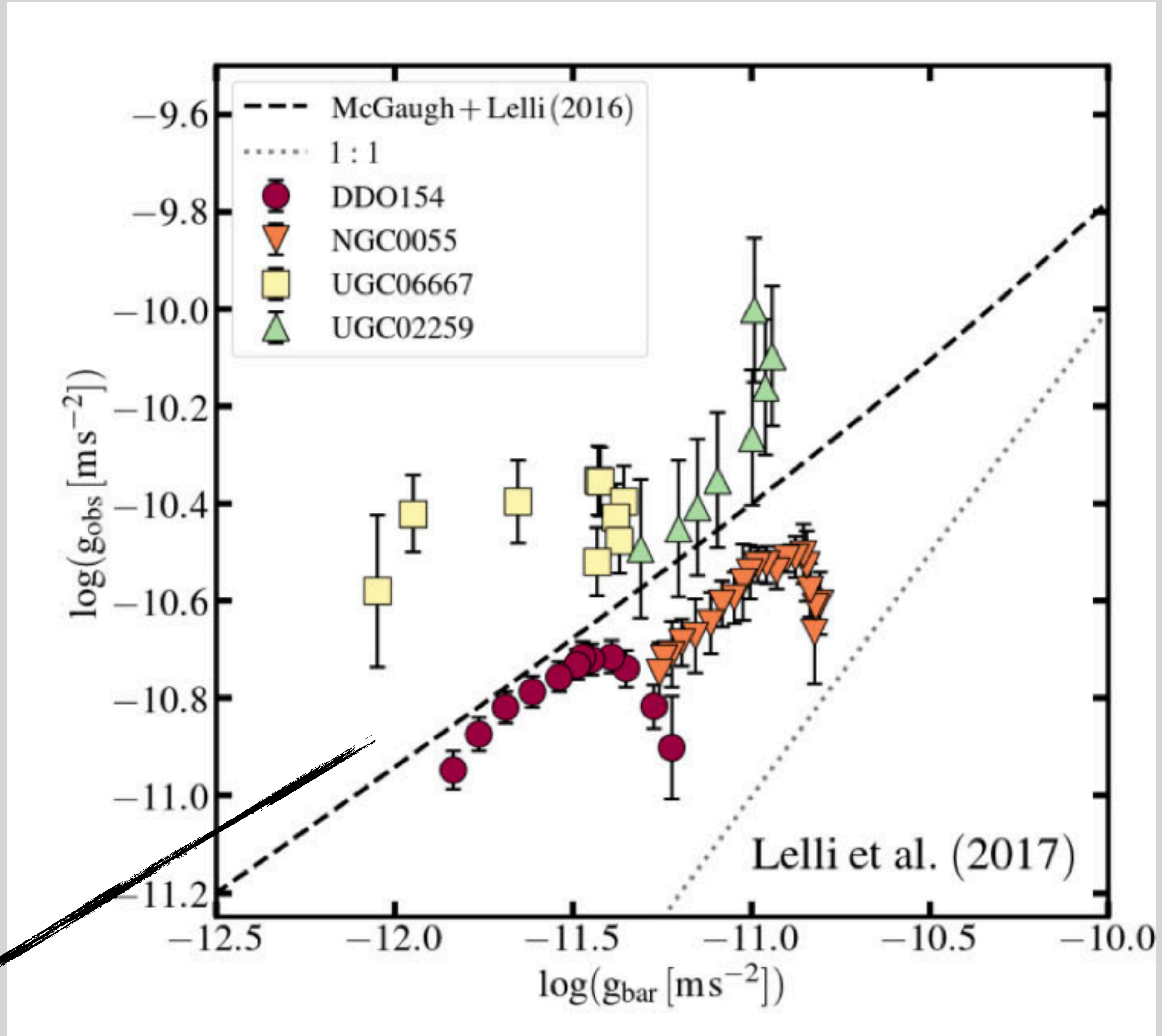




expected in ΛCDM but not in MOND

- **RAR relation -predictions from FIRE-2 simulations (Mercado+24)**



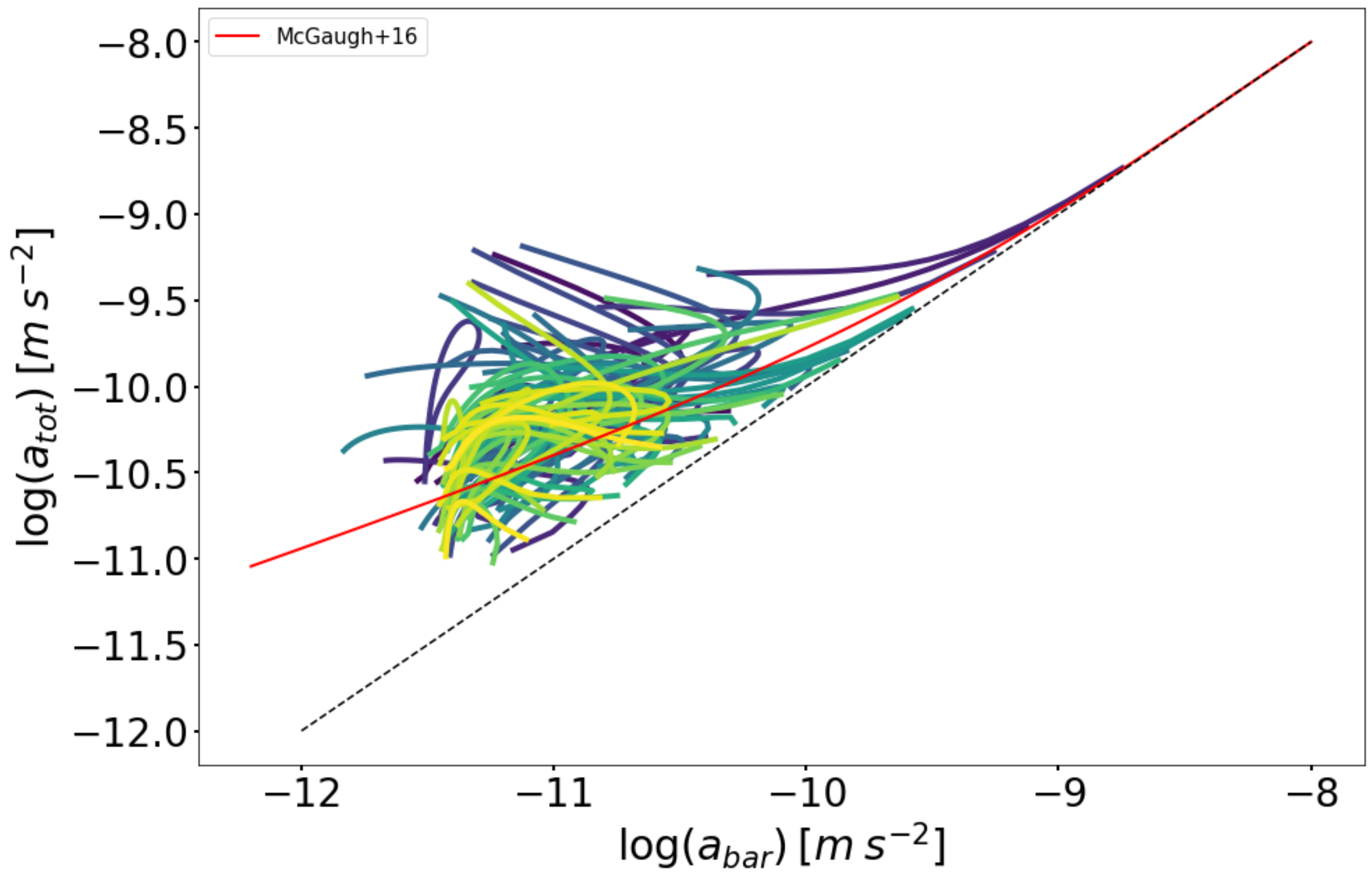


SPARC galaxies

expected in ΛCDM but not in MOND

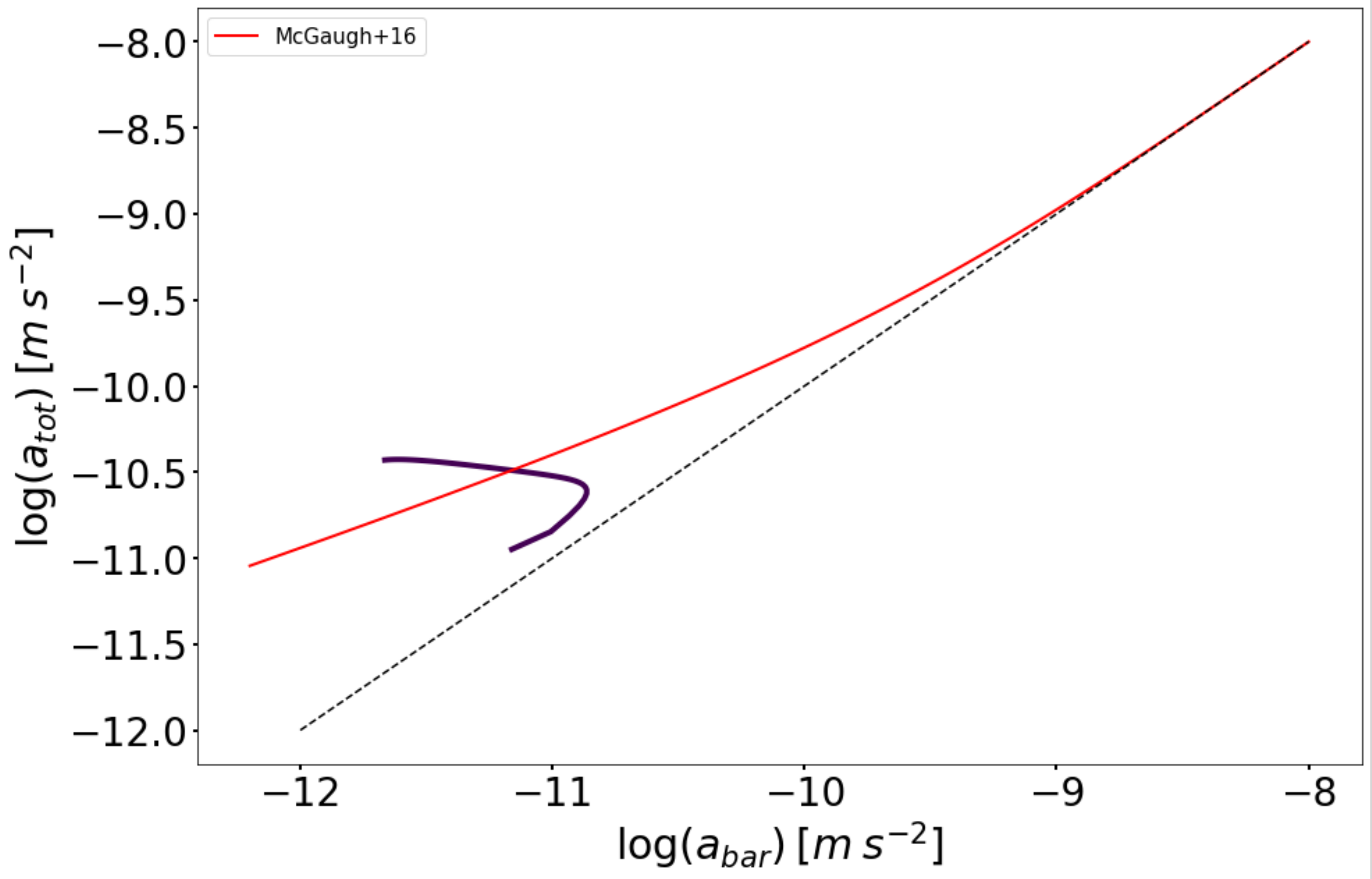
At z~1 - MUSE Hubble Ultra Deep Field Survey: Ciocan, Bouché +2024

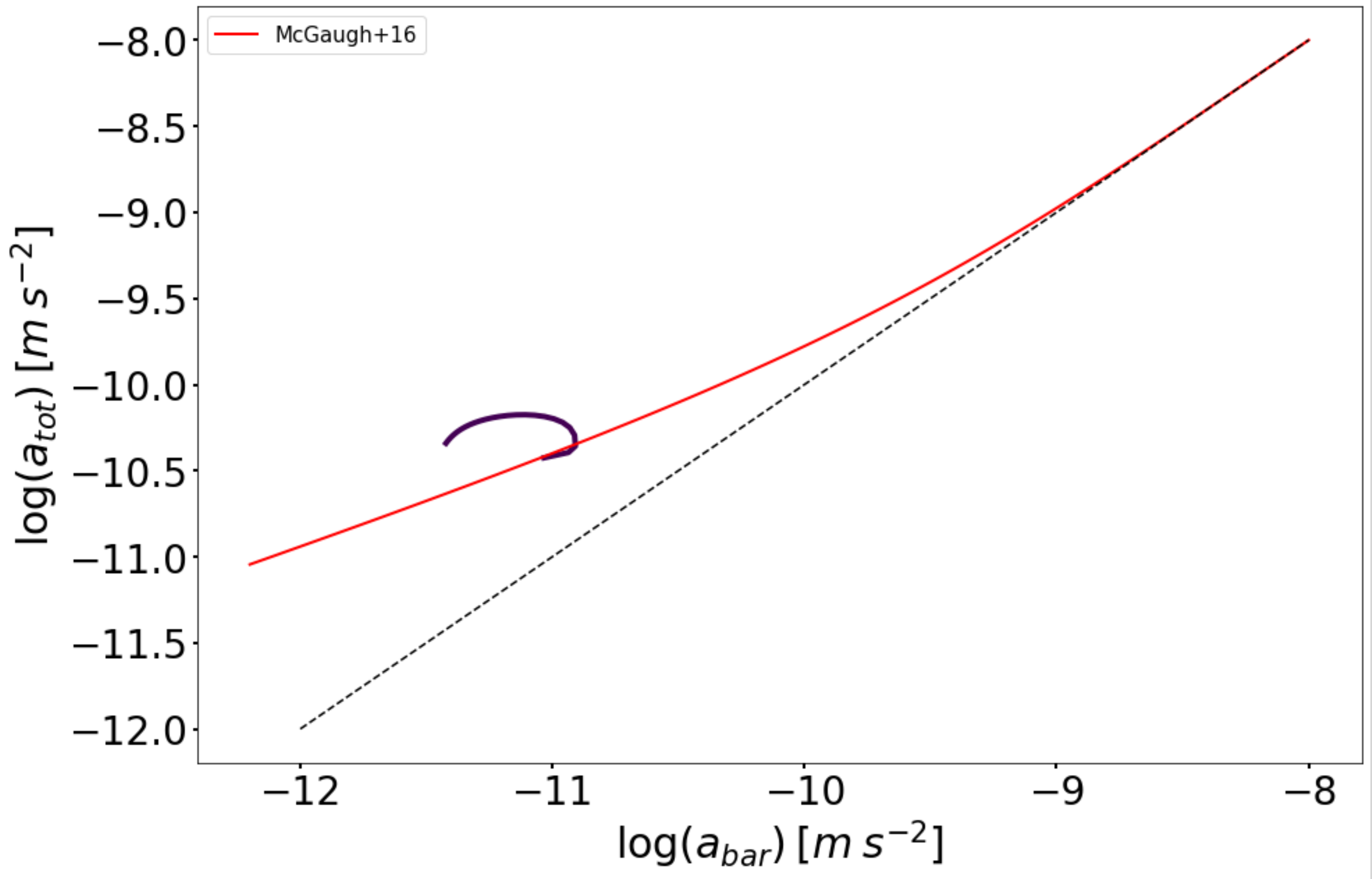
- **RAR relation**



Rules out MOND **???**

- **For cored galaxies**



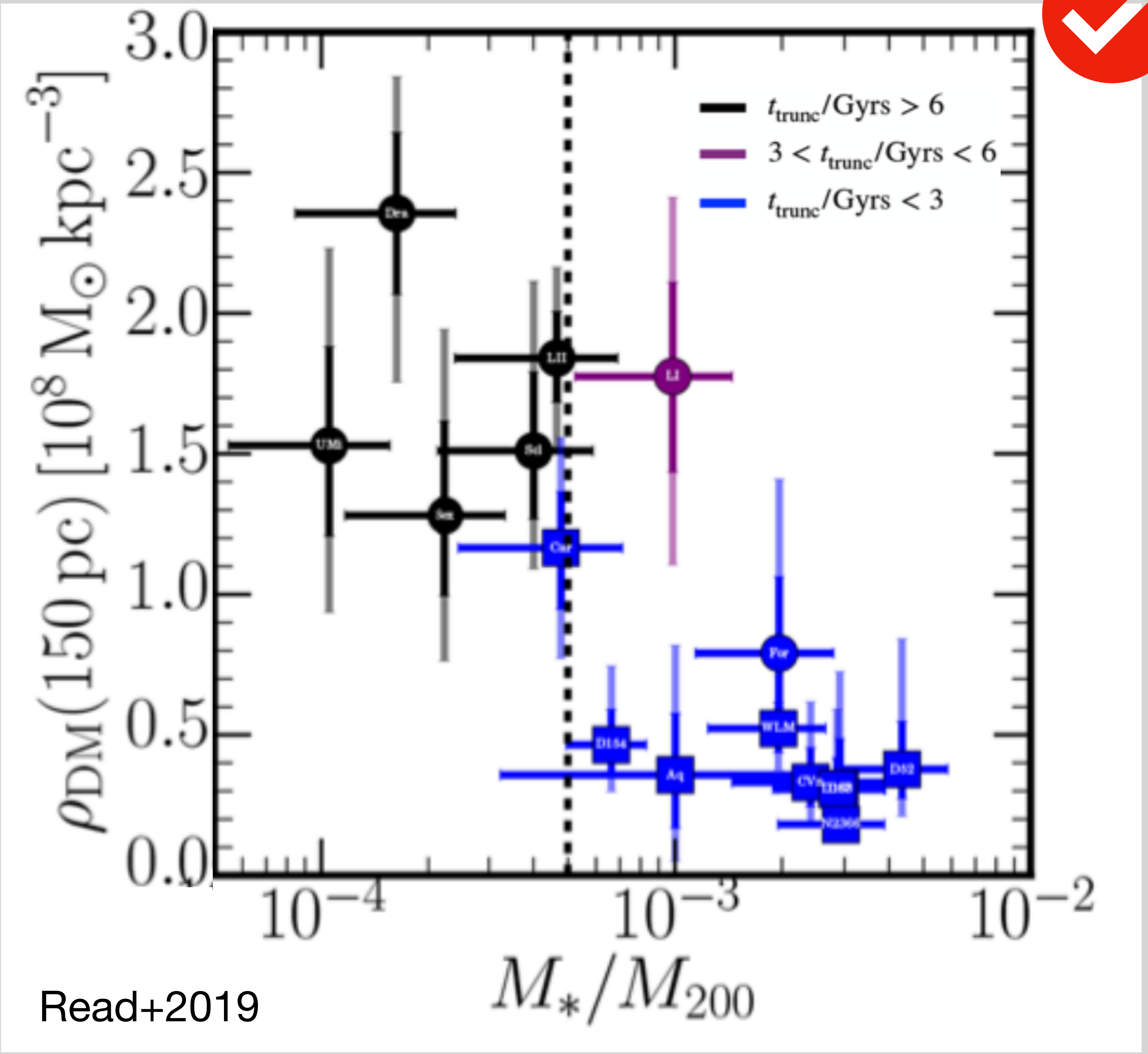


work in progress 0% 100%

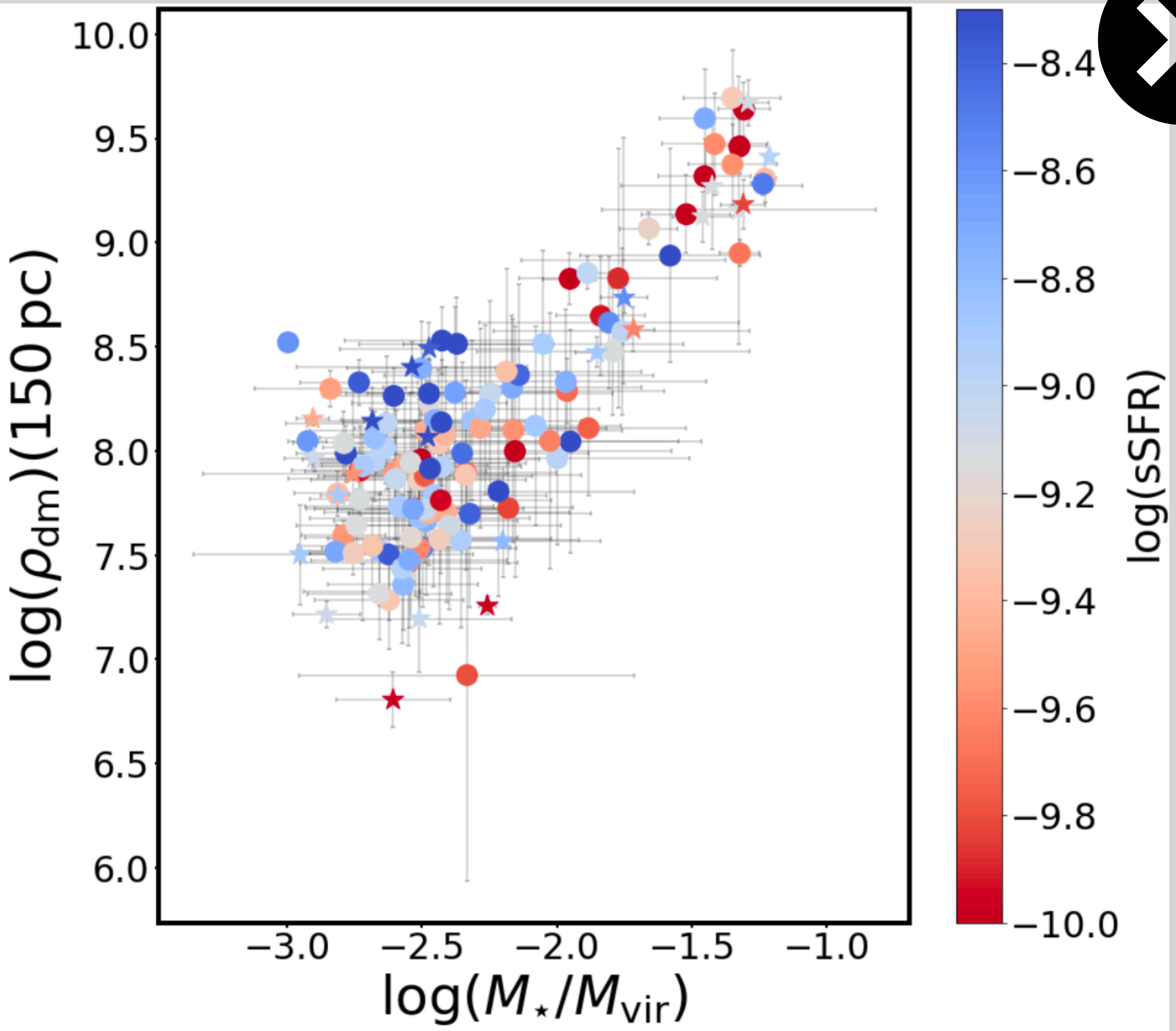
GalPaK galaxy parameters and kinematics

Is baryonic feedback the answer?

- Observationally, cores have been detected up to z ~ 2
- No clear correlation between core formation and stellar feedback yet



Read+2019



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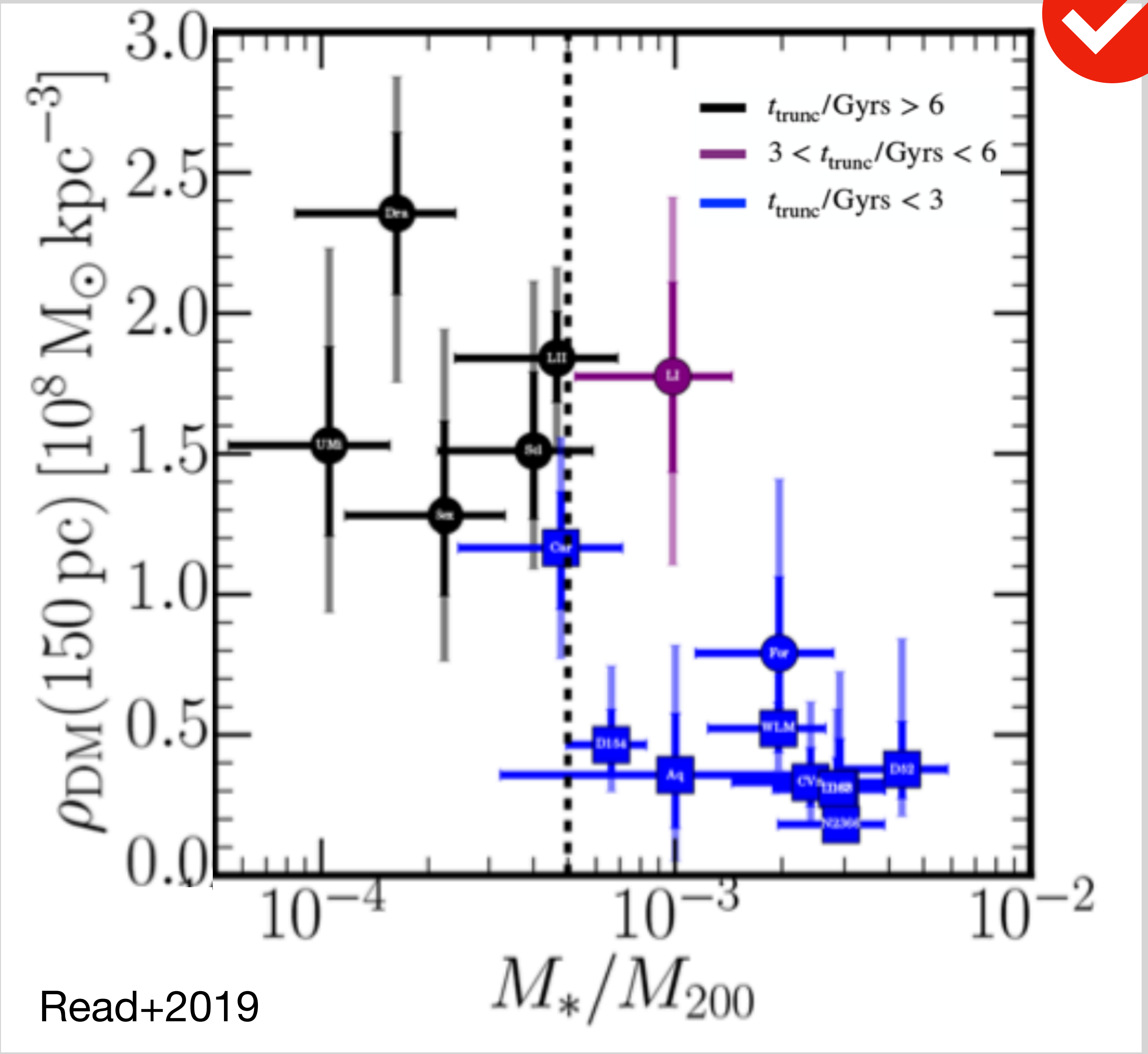
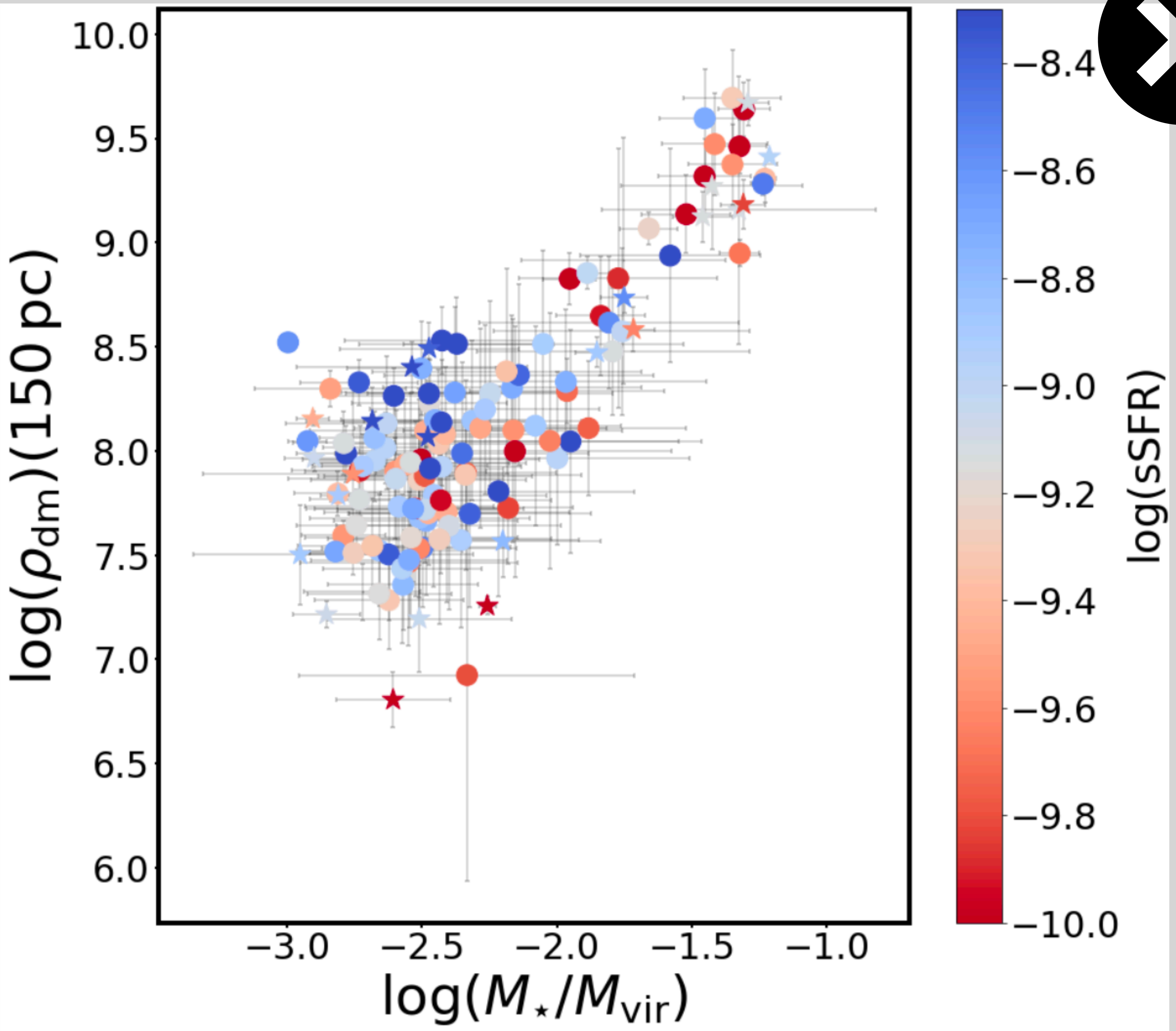
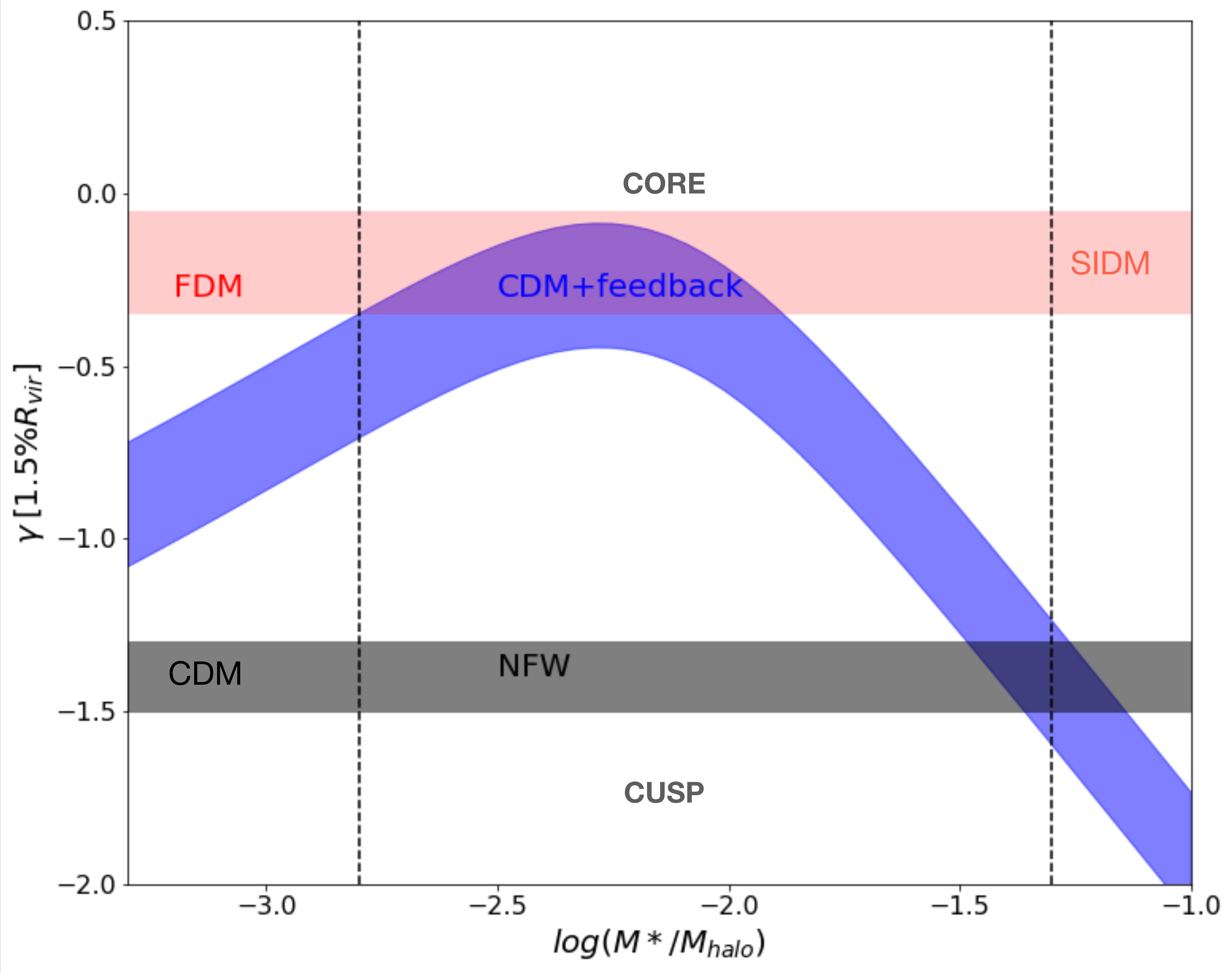




- **Need to link dark matter densities / inner slopes to the star formation histories**

Core-cusp problem: alternative solutions

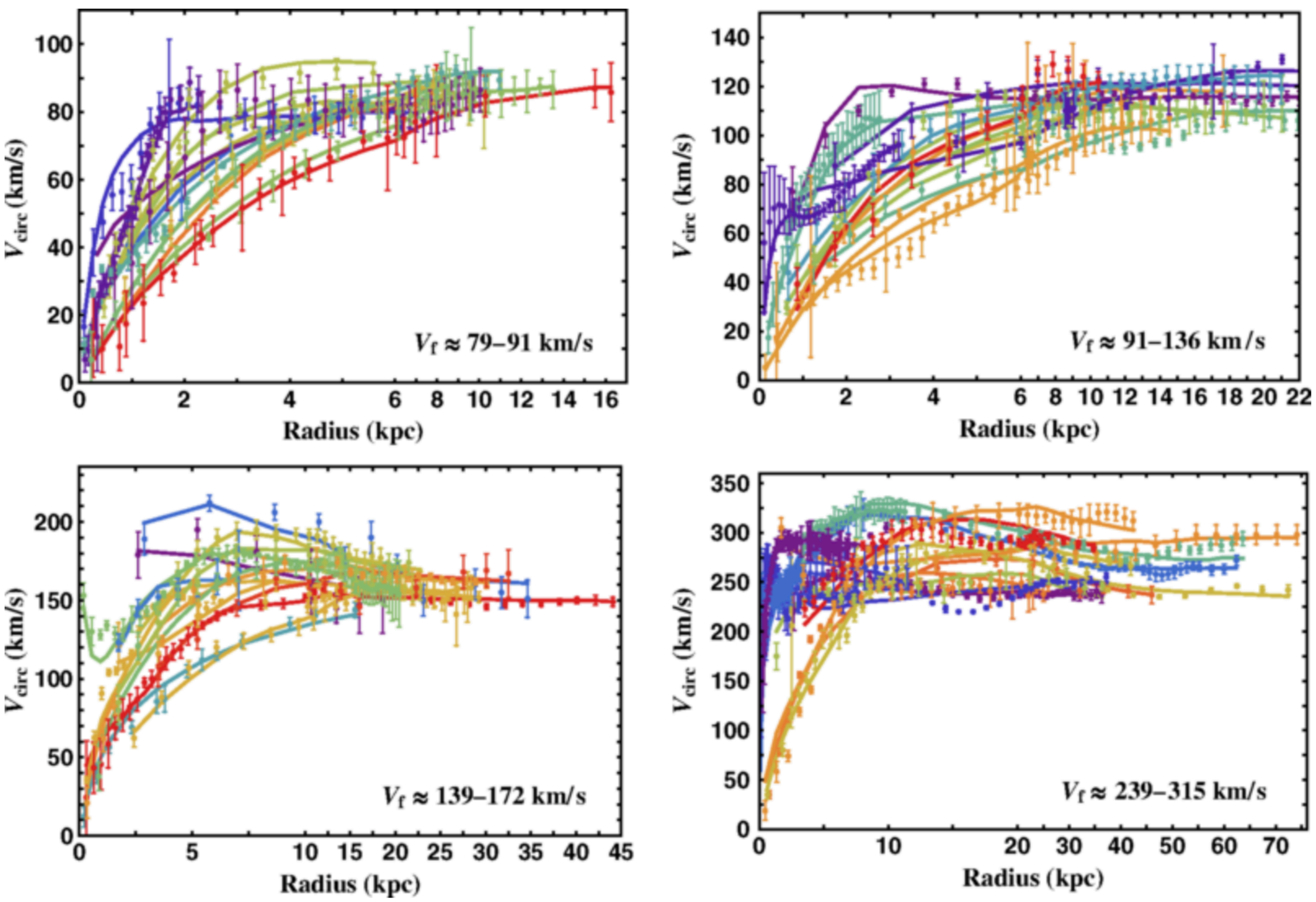


➡alternative models of dark matter:

- **self-interacting dark matter** (Spergel +2000)
- **axion-like fuzzy dark matter** (Hu+2000)
- **warm dark matter** (Bode+2001)

Diversity of Rotation Curves: alternative solutions

FIG. 1.



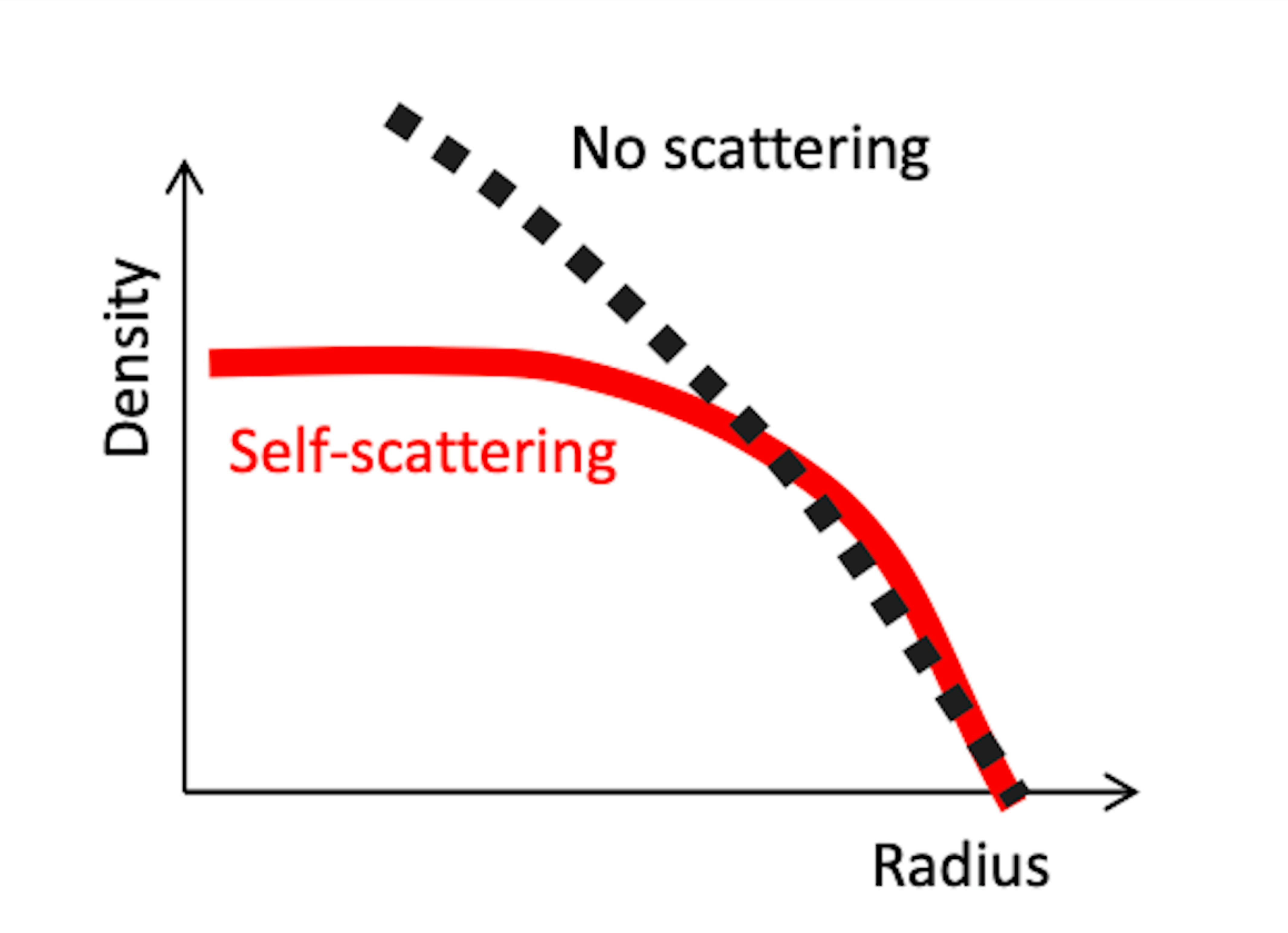
Ren +2019, Kamada+2017

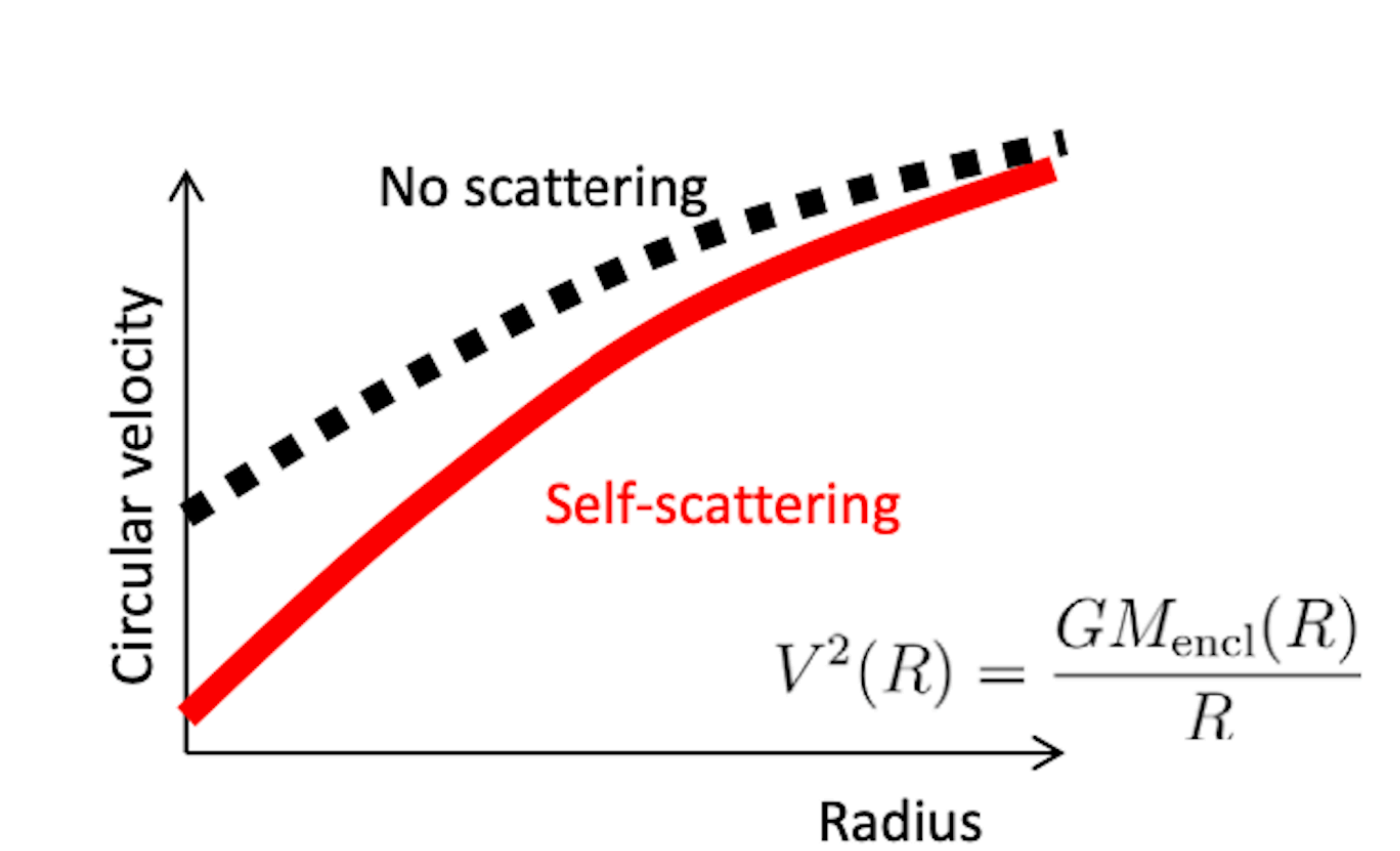
➡alternative models of DM:

- **self-interacting dark matter**

Self Interacting Dark Matter

➡the particles have a significant self-interaction cross section





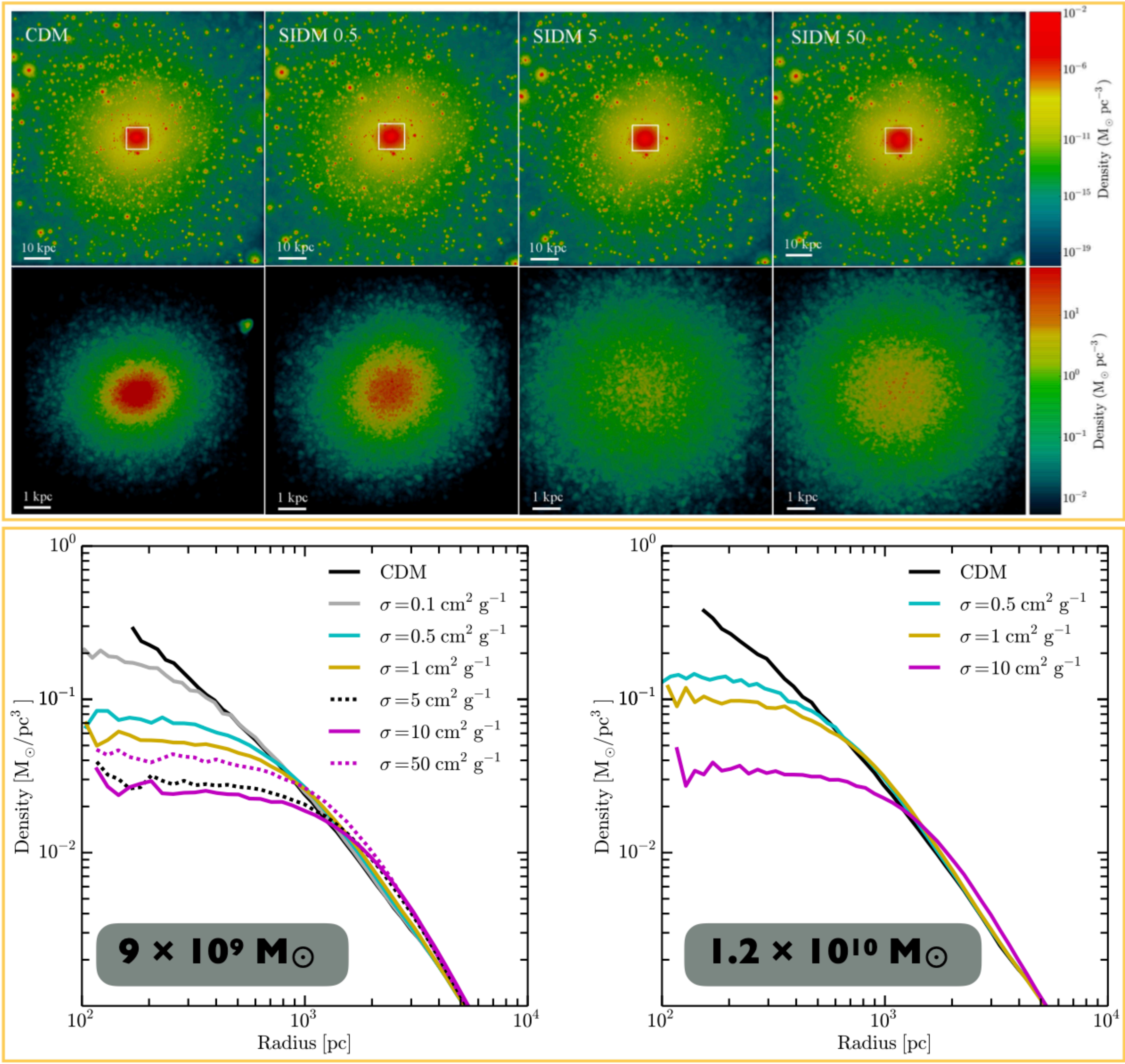
Self-interactions solve core-vs-cusp
Particles get scattered out of dense halo centers

Self Interacting Dark Matter

- ➡parameter governing the rate of DM particle interactions is the cross section per unit mass: σ/m_χ
- ➡σ/m_χ : velocity dependent

σ/m ~ 0.5 – 50 cm²/g to form kpc core in dwarf galaxy

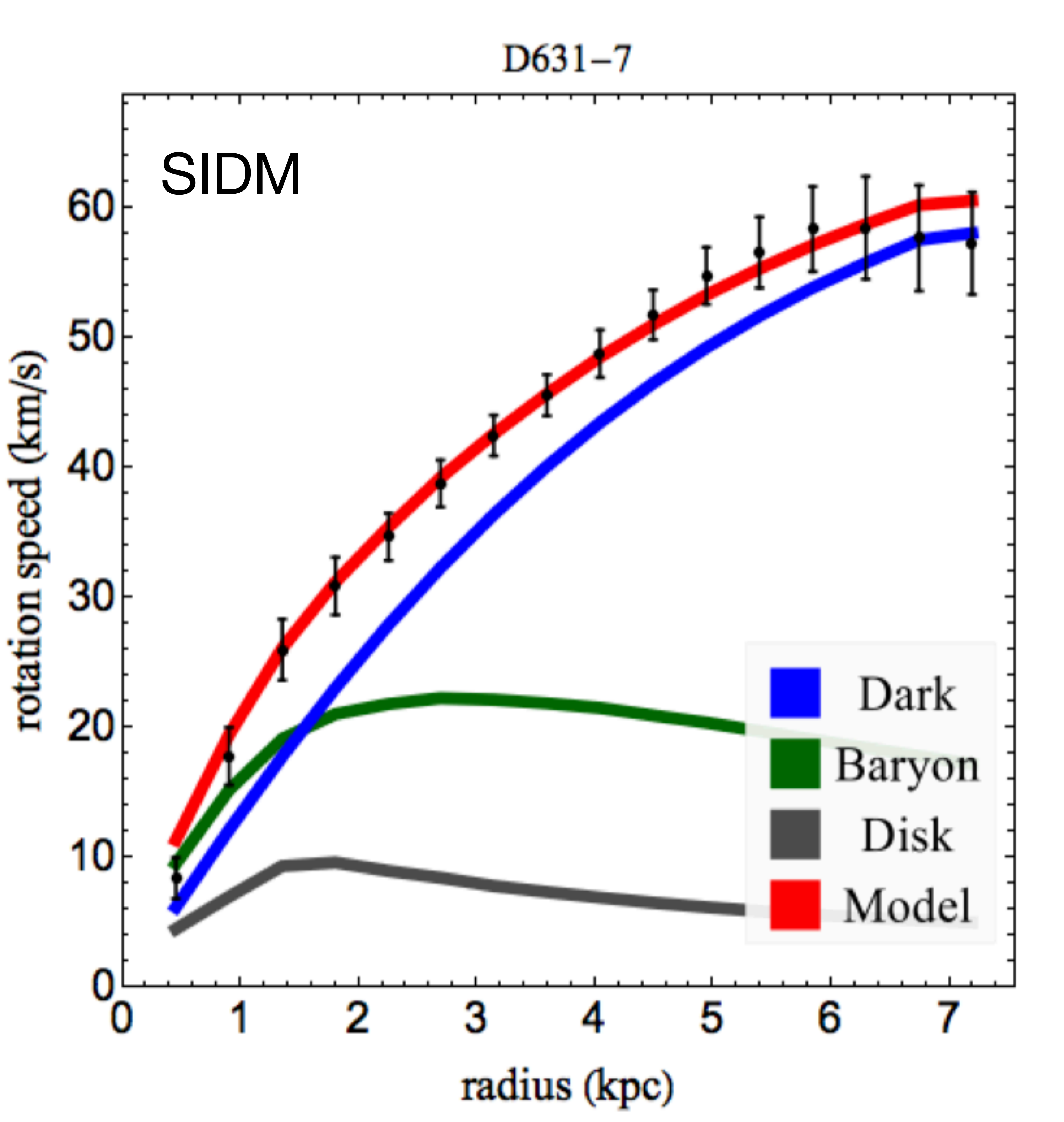
- ➡shares the success of ΛCDM on large scales

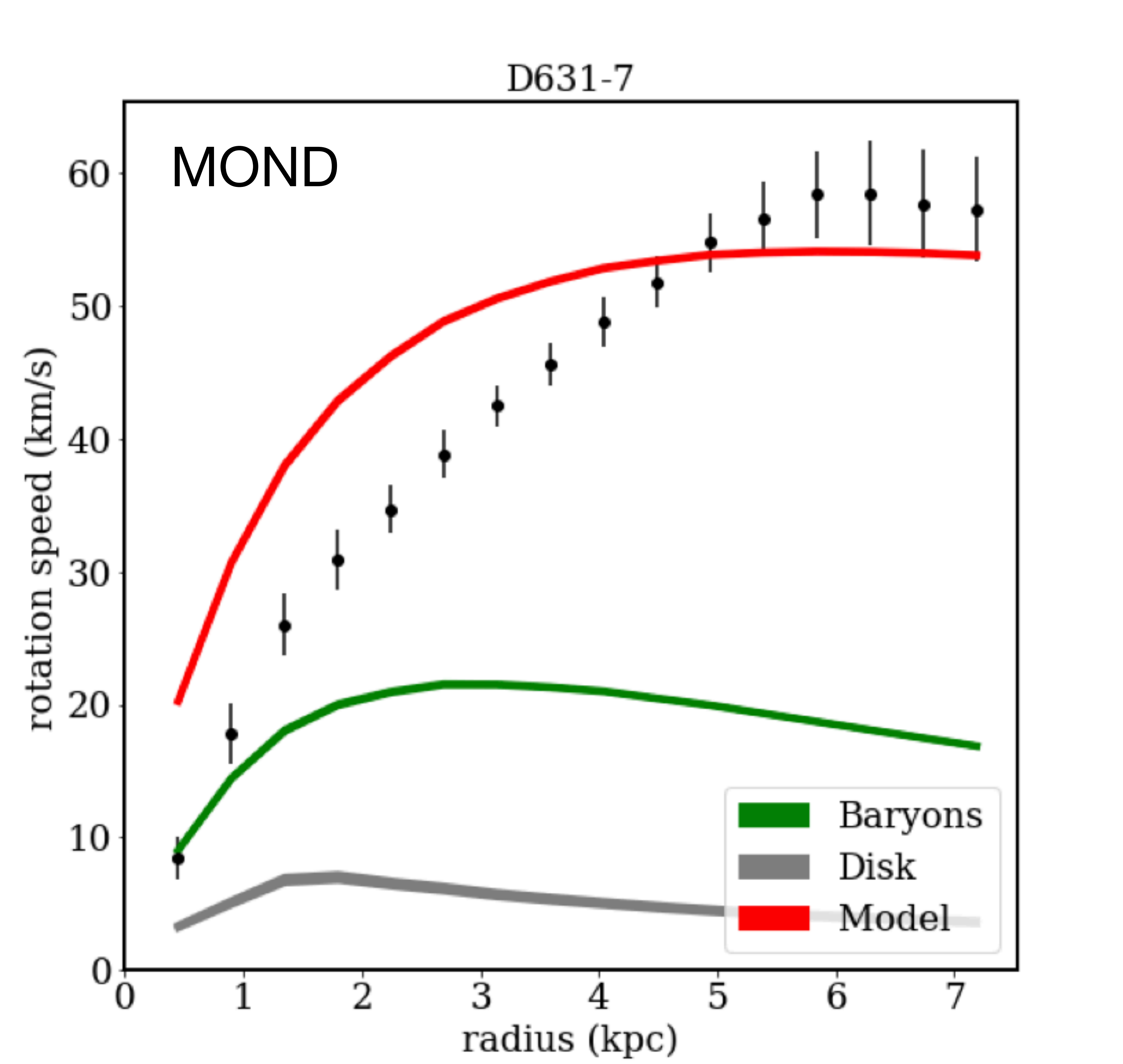


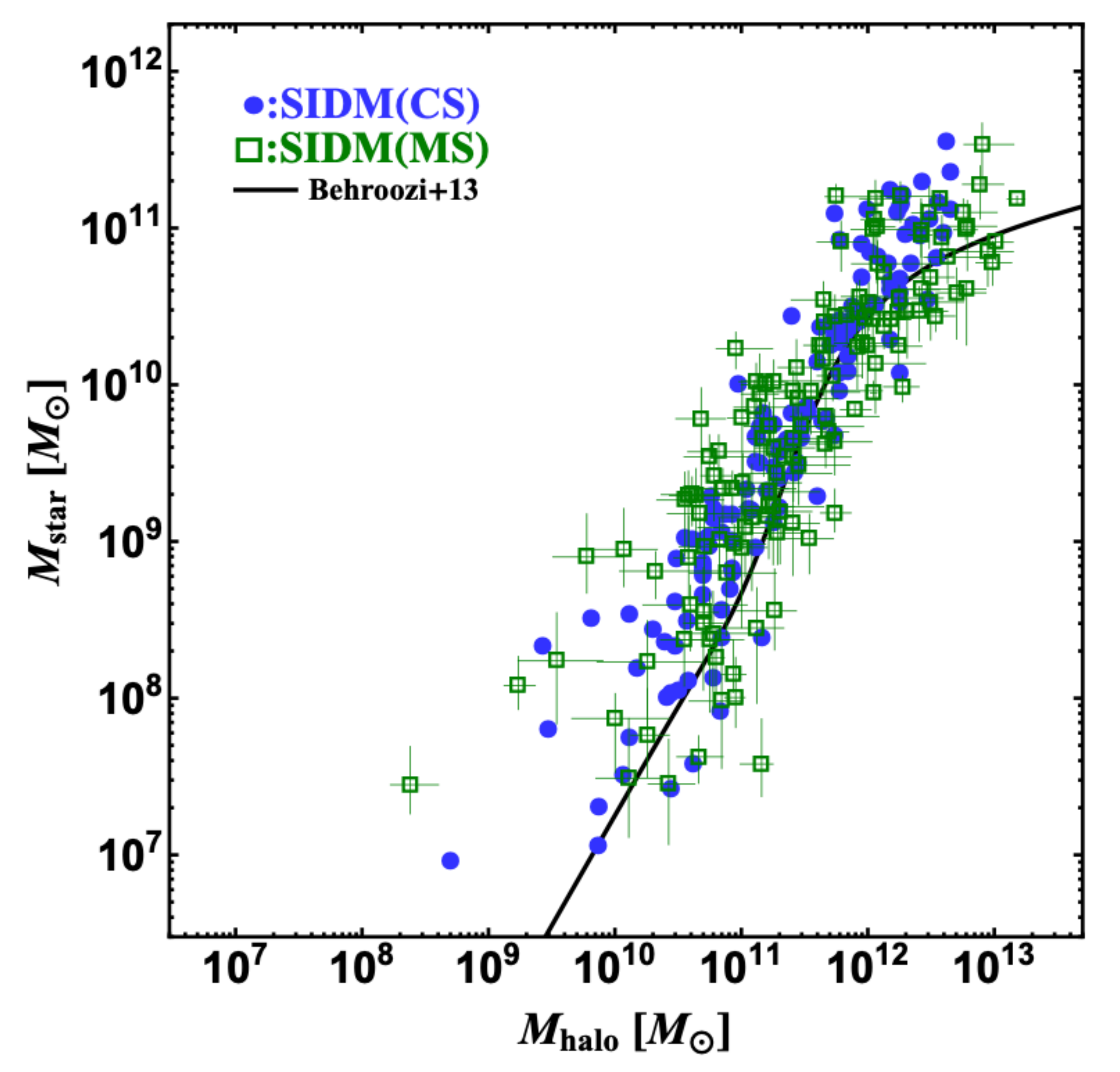
Elbert et al.2015

Self interacting Dark Matter and rotation curves: Ren +2018

- Rotation curve decomposition for 135 local galaxies (SPARC sample - Ha+HI)
- Constant $\sigma/\mathrm{m} = 3\ \mathrm{cm}^2/\mathrm{g}$







➡SIDM preferred over MOND
➡recover stellar mass-halo mass relation, i.e. host halos are fully consistent with the Planck cosmology

Fuzzy dark matter

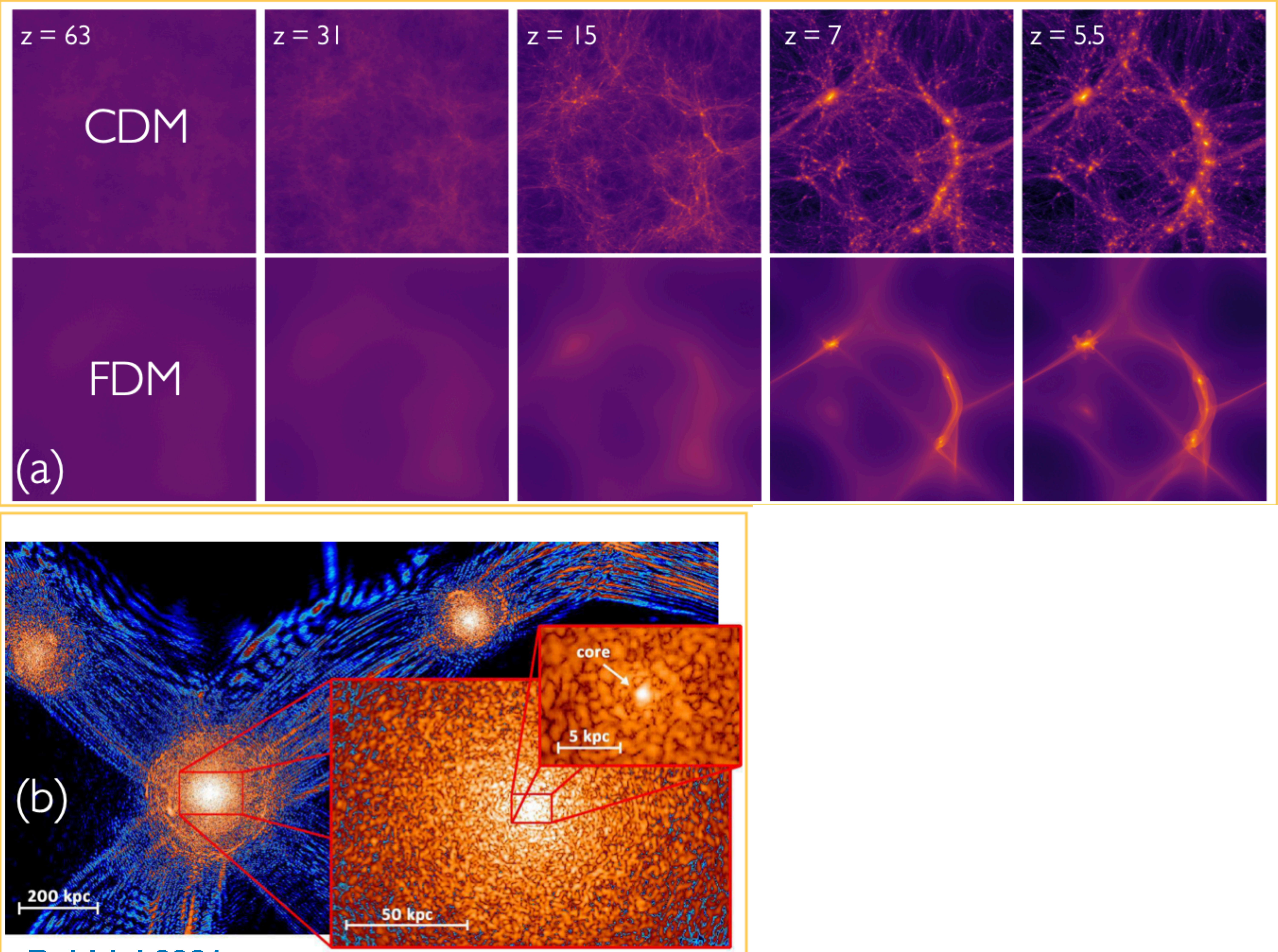
➡Ultralight scalar field with no self-interactions in the non-relativistic limit

➡low masses: ~10^-24 to 10^−19 eV

➡suppresses structure formation on small scales

➡wave nature of FDM leads to quantum pressure, preventing cusps

➡form a Bose-Einstein condensate soliton

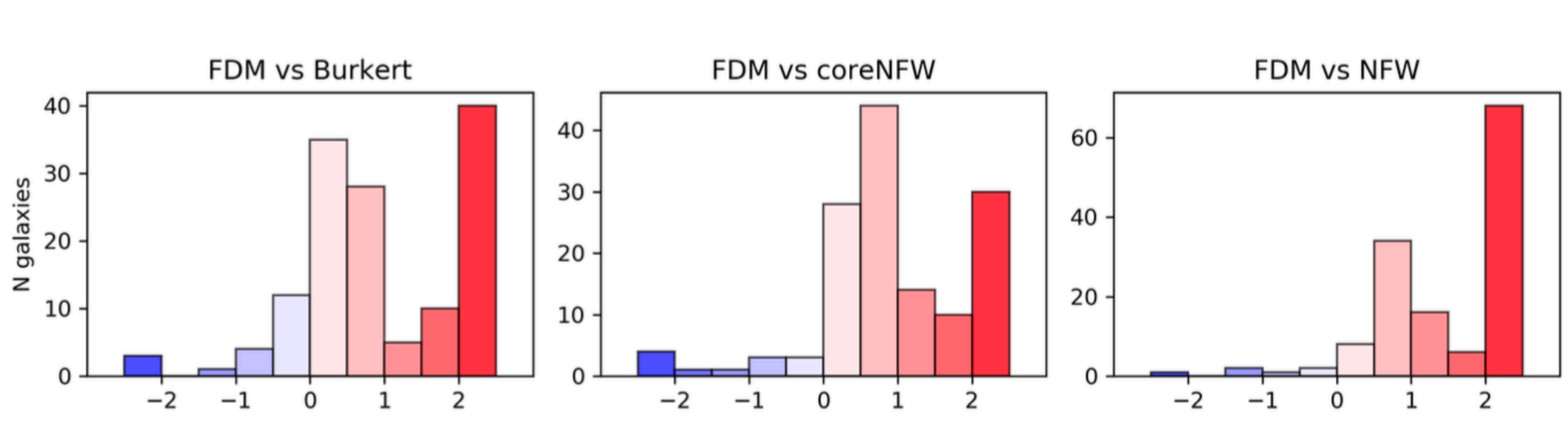


Boldrini 2021

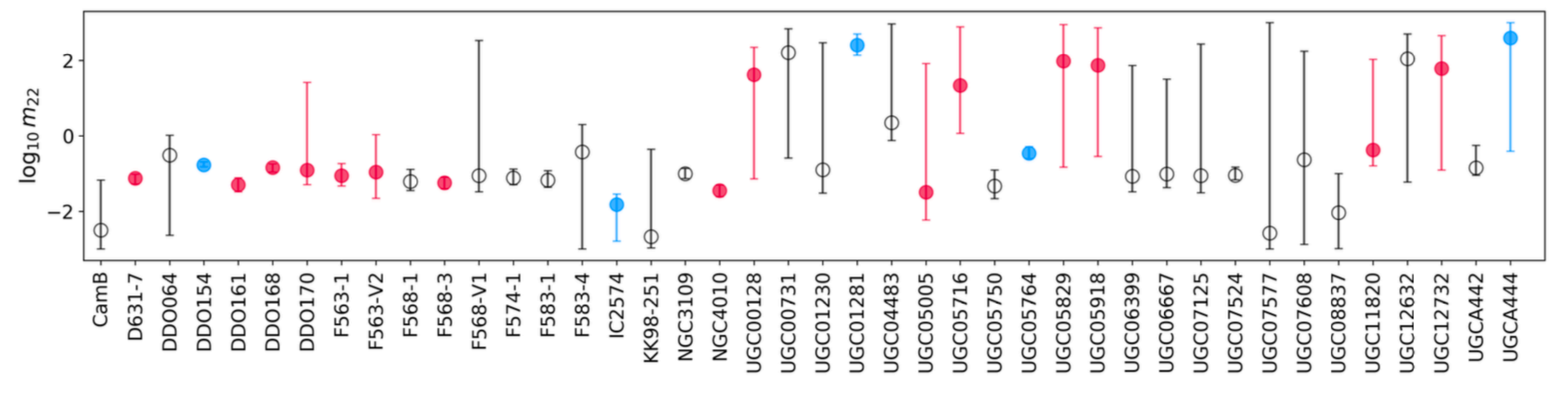
Fuzzy dark matter and Rotation Curves: Khelashvili+23

- Rotation curve decomposition for 175 local galaxies (SPARC sample - Ha+HI)

- Model DM halo with (1) NFW; (2) coreNFW; and (3) fuzzy DM



➡Fuzzy DM preferred by >50% of the sample



➡**No** single value for the particle mass that provides a good fit for all galaxies

Warm Dark Matter

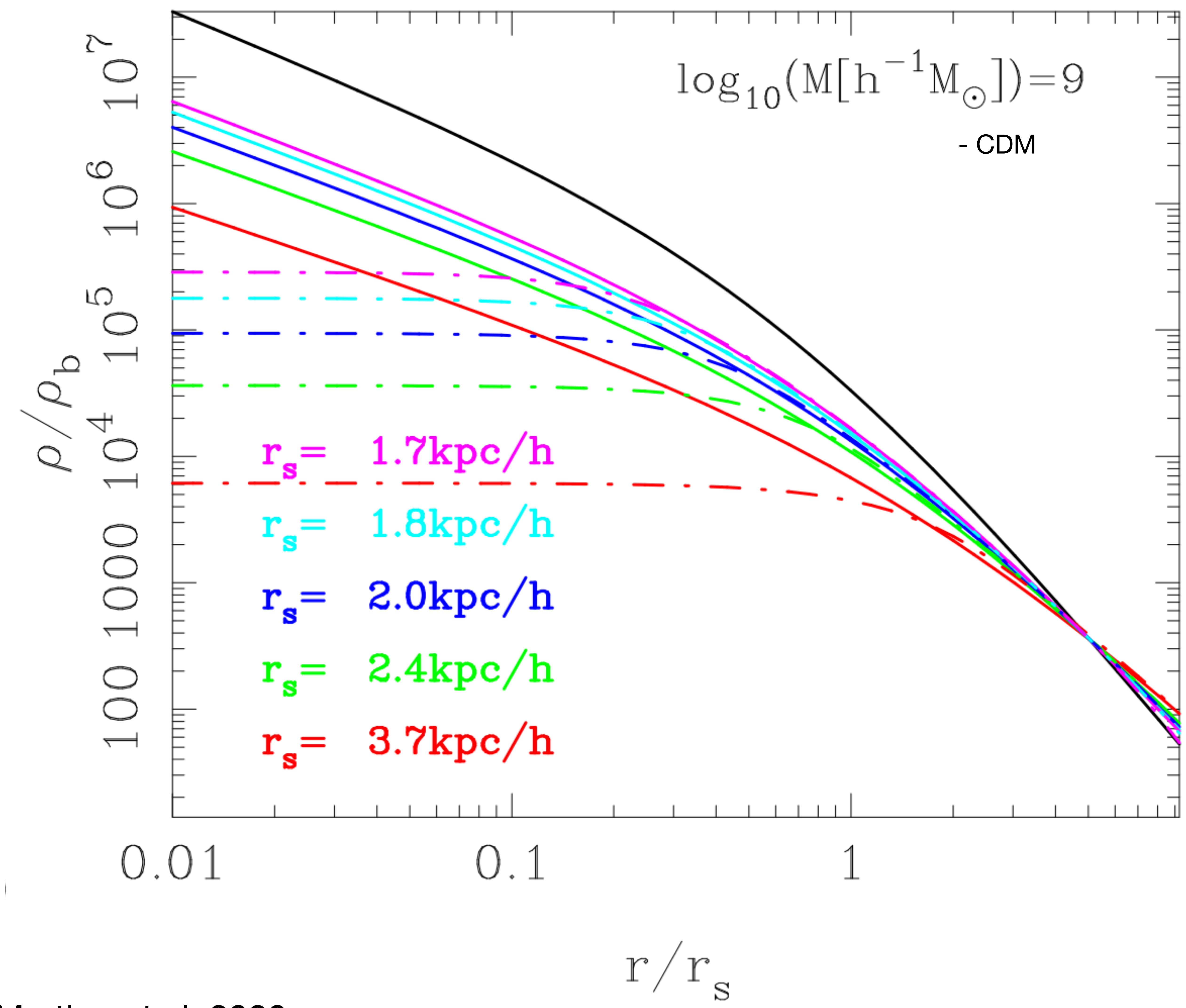
➡WDM particles decouple when they are still relativistic

➡erase primordial fluctuations on subgalactic scales

➡ produce a cut-off in the primordial power spectrum

➡ reduce phase-space density resulting in the formation of cores

➡observations of strong gravitational lensing / Lyman-α forest: particle mass of > 5.58 keV / > 3.5 keV



Martino et al. 2020

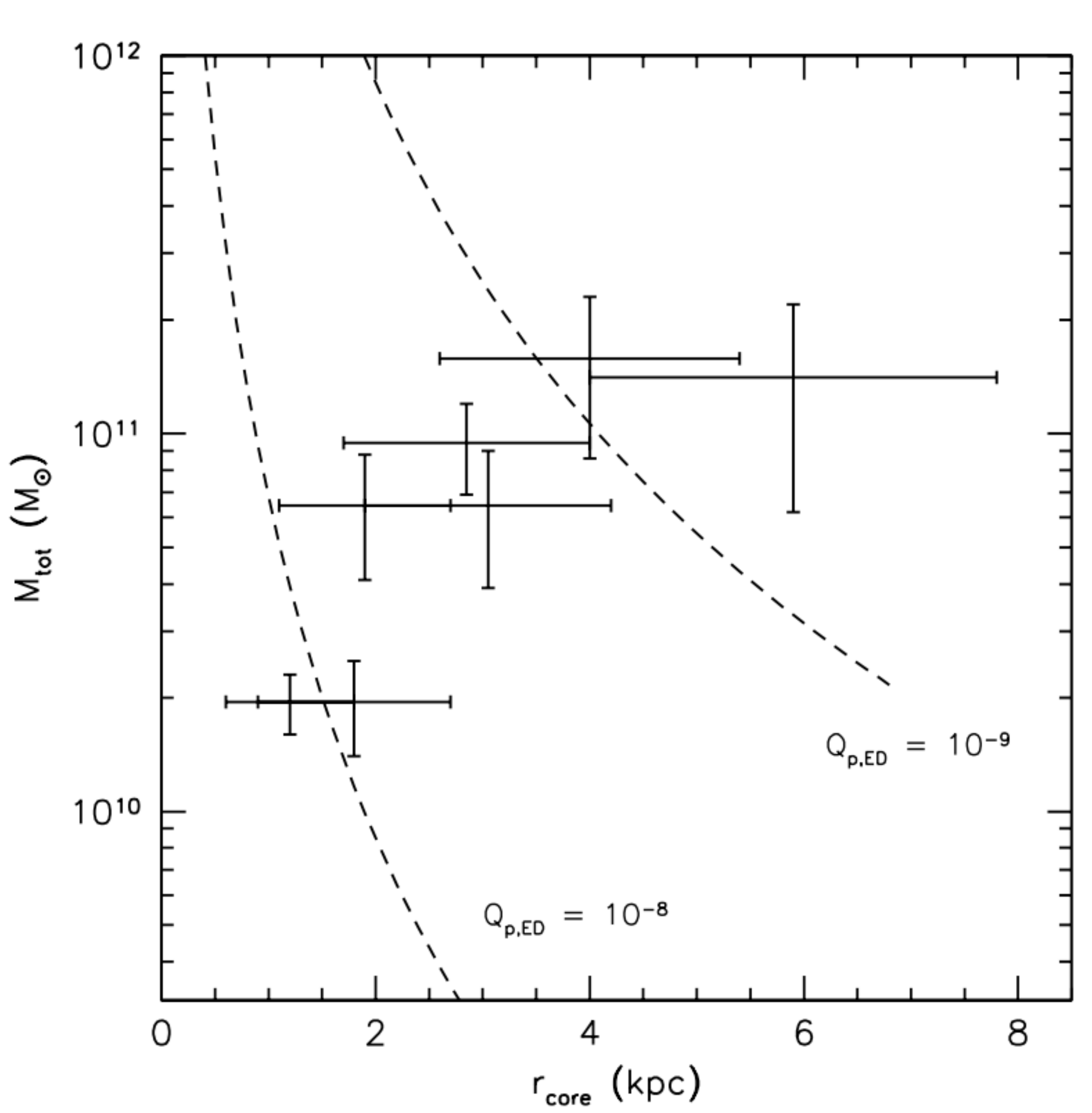
Warm Dark Matter and Rotation Curves: Kuzio de Naray+2010

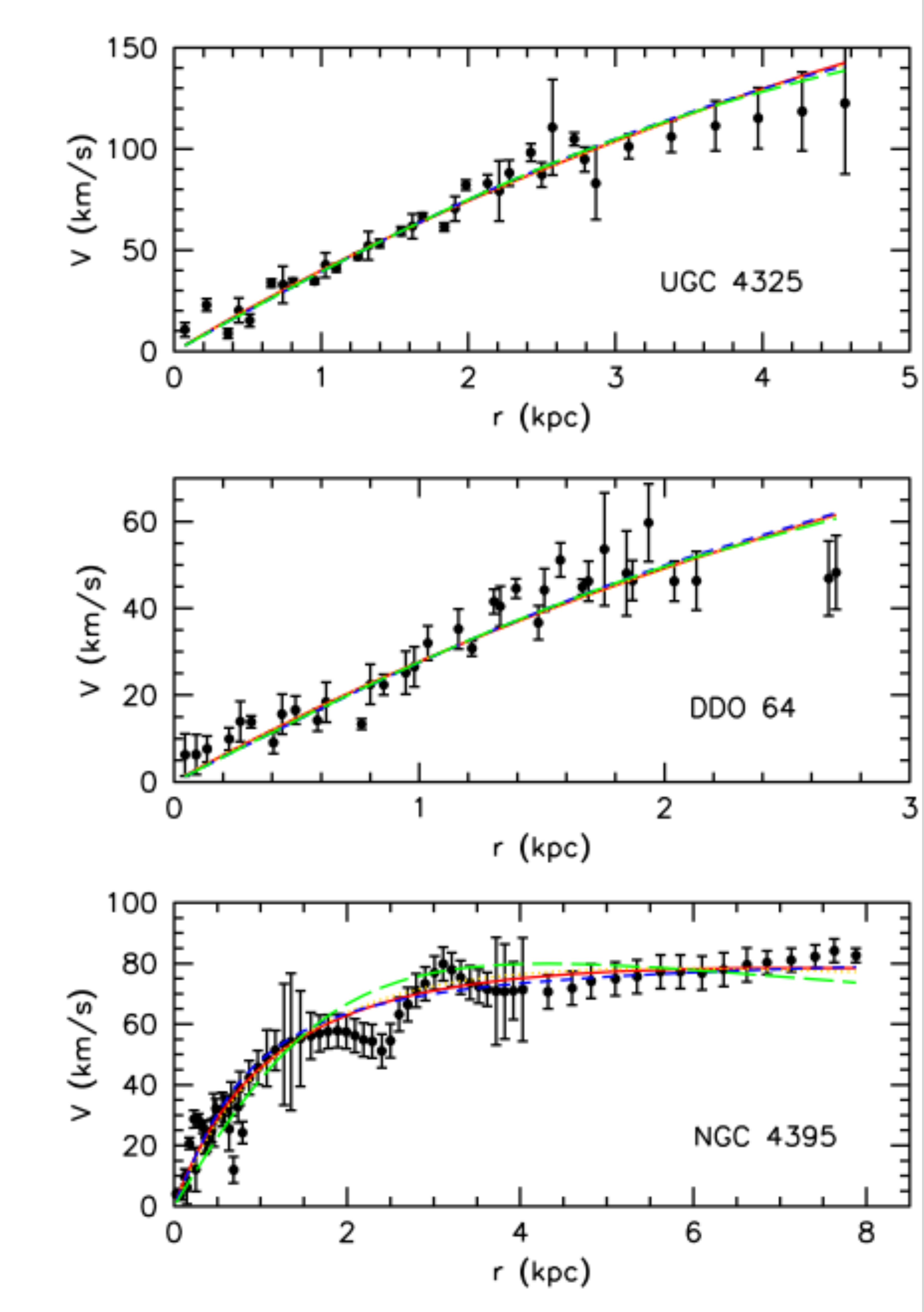
- use rotation curves of 9 local low surface brightness galaxies
- test WDM, non-thermal WDM, and SIDM

Problems for WDM:

➡does not manage to solve core-cusp problem with one particle mass for all galaxies

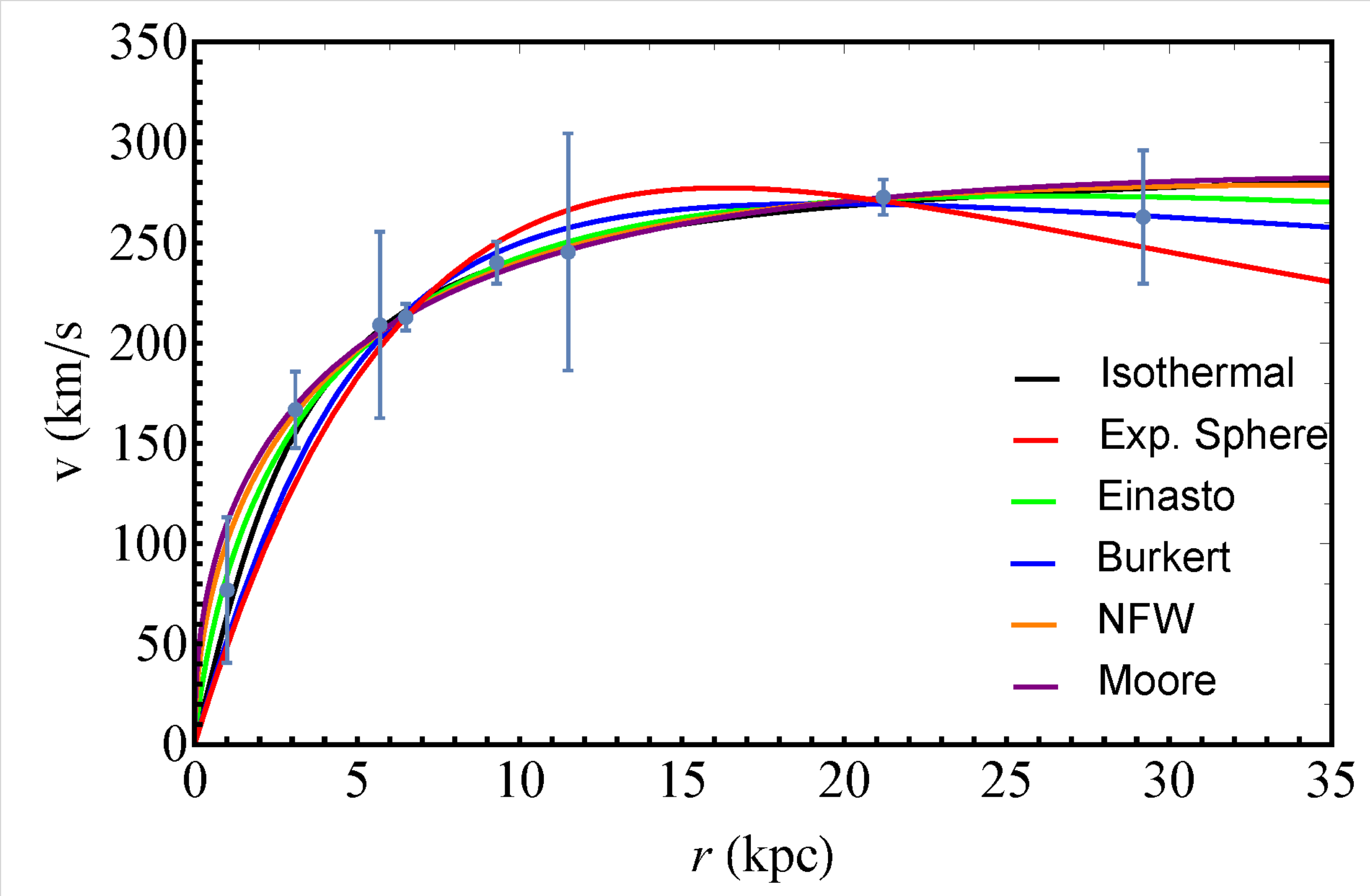
➡inferred r_core increase with halo mass while predictions state the opposite





Can we constrain the Dark Matter flavour from RCs?

- Answer is: <u>possibly</u>
- Disk-halo decomposition in 3D



- the curvature pf the RC is different for different halo profiles
- discriminate if all pixels are used

Outlook

- **Improving precision of rotation curve measurements**: Higher resolution, deep IFU data and advancements in 3D modelling techniques can help improving dark matter profile constraints.

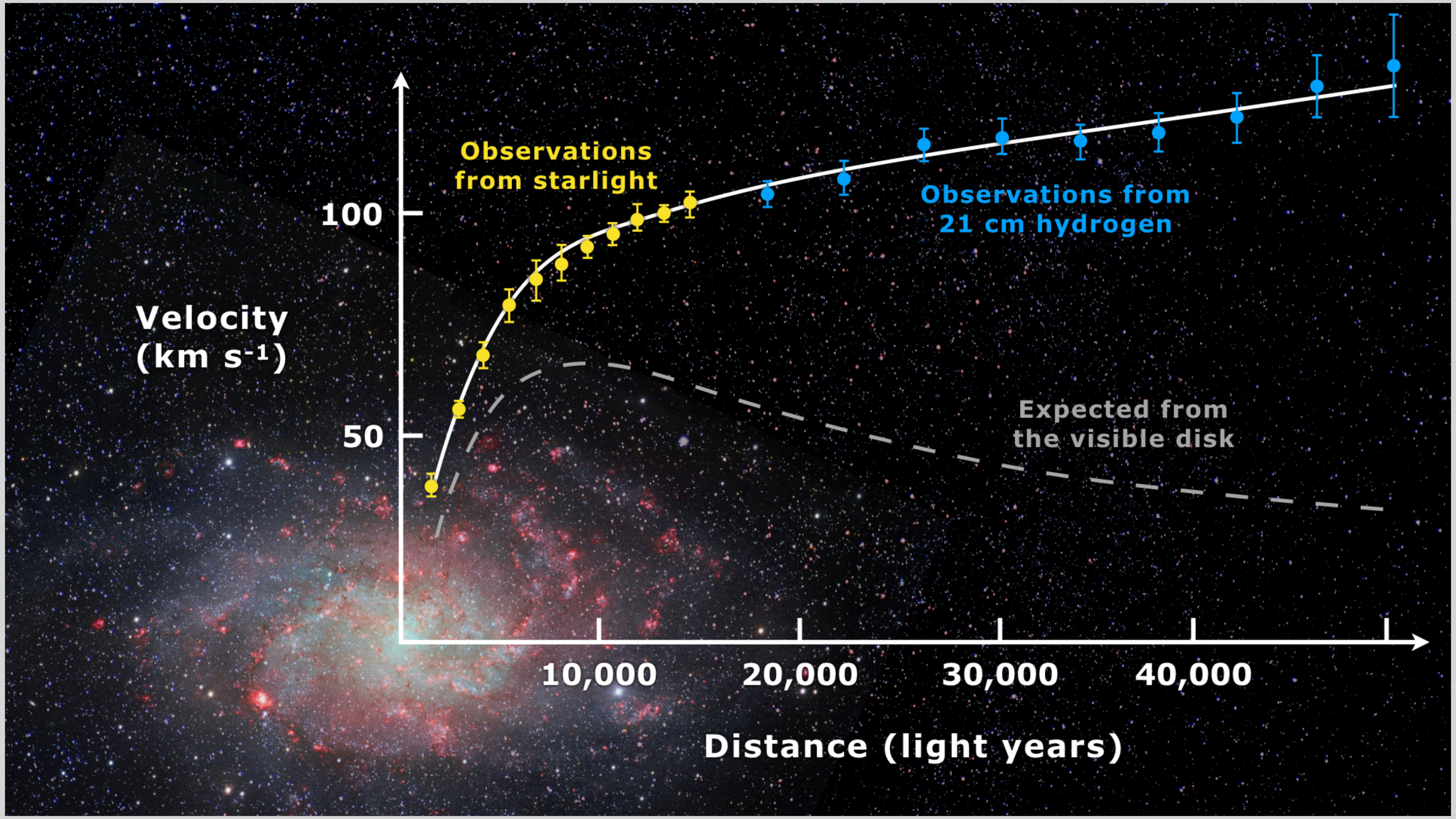
- **Probing larger samples (at high redshift $z > 1$):** With more observational data from next generation instruments, we can extend rotation curve studies beyond the local Universe to explore the evolution of dark matter properties over cosmic time.

- **Linking DM profiles to galaxy star formation histories:** Combining star formation histories and DM profiles will offer further insights into the connection between baryonic feedback and DM distribution.

- **Testing alternative DM models:** SIDM, FDM, WDM models need to be tested against larger datasets and a wider variety of galaxy types to refine their viability in addressing small-scale structure problems.

- **Need for simulations:** High-resolution cosmological simulations that incorporate baryonic physics will be crucial to further testing predictions of the alternative DM models.

Thank you for your attention!



Extra

Using 3D forward modelling: Under the hood

GalPaK
galaxy parameters and kinematics

Bouché et al. 2015

$$v_c(r)^2 = v_{DM}(r)^2 + v_{disk}(r)^2 + v_{HI}(r)^2$$

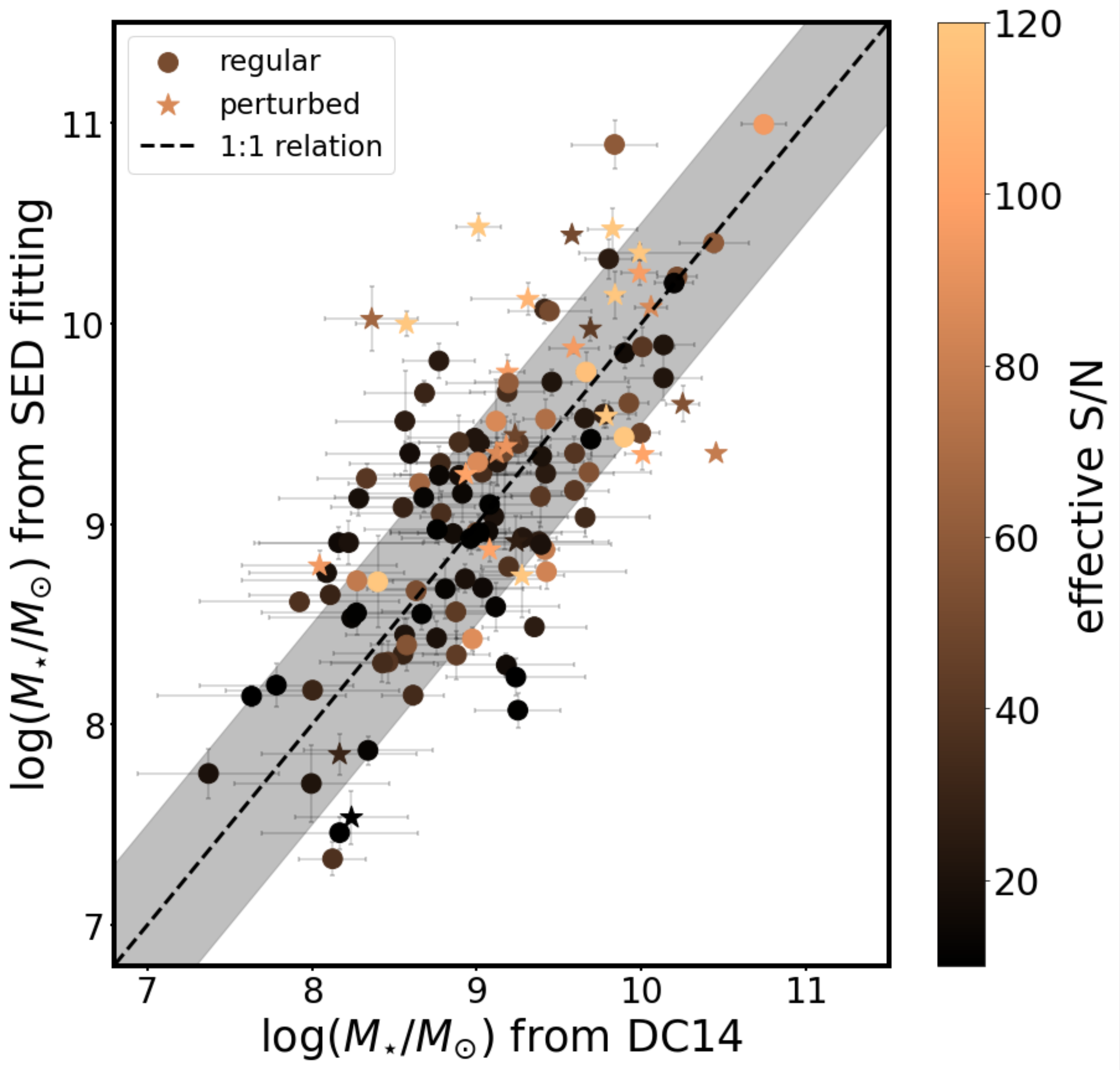
1) DM: different Dark Matter halo profiles
2) Disk: I(r): Sersic n (OII,Ha); Freeman Disk
3) gas: HI gas (marginalized)
4) **pressure support correction (asymmetric drift correction)** →

$$v_c(r)^2 = v_\perp(r)^2 + v_{AD}(r)^2$$

→ **13 - 15 free parameters** (x,y,z,incl,PA,$\mathbf{M_*}$,M_{vir},c_{vir},sig0,Re,n,…)
→ all optimised simultaneously directly on the 3D IFU cube

At z~1 - MUSE Hubble Ultra Deep Field Survey: Ciocan, Bouché +2024

- Consistency checks for DC14

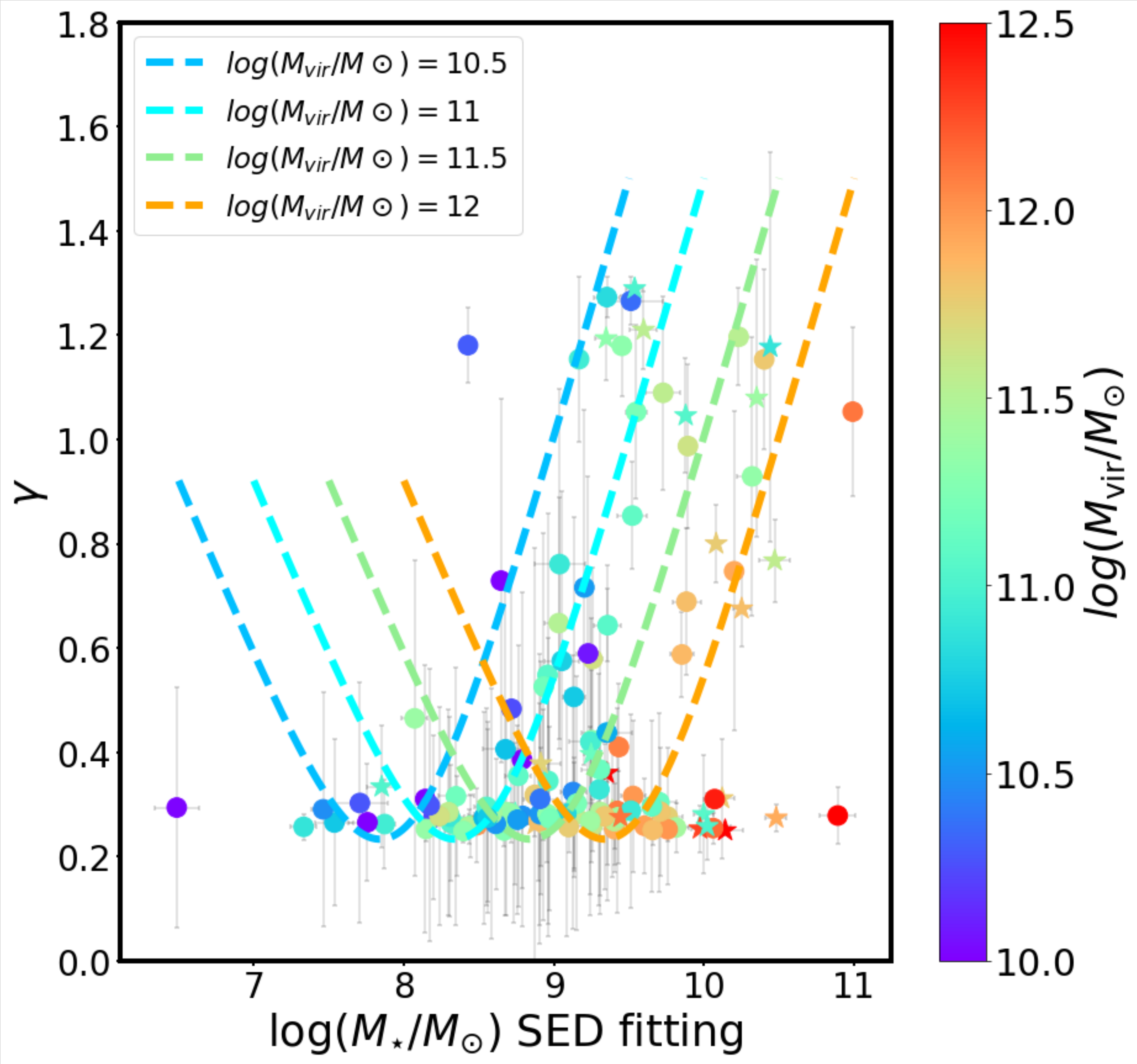


➡The kinematically inferred M* agree with the ones derived from photometry

3D GalPaK galaxy parameters and kinematics

At z~1 - MUSE Hubble Ultra Deep Field Survey: Ciocan, Bouché +2024

- Consistency checks for DC14



➡Inferred DM inner slopes in accordance with the expectations