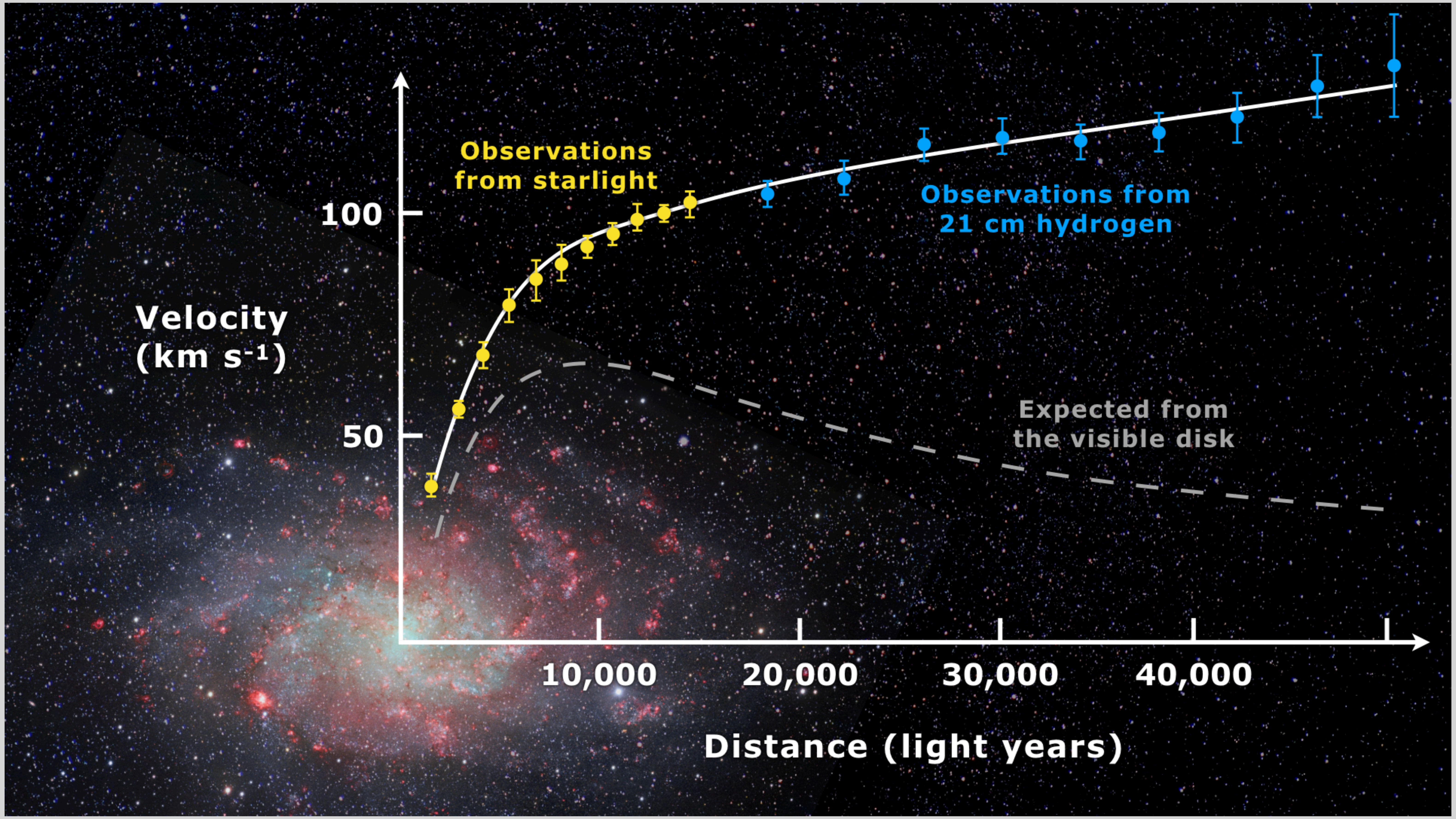
Constraints on Dark Matter from Galaxy Rotation Curves

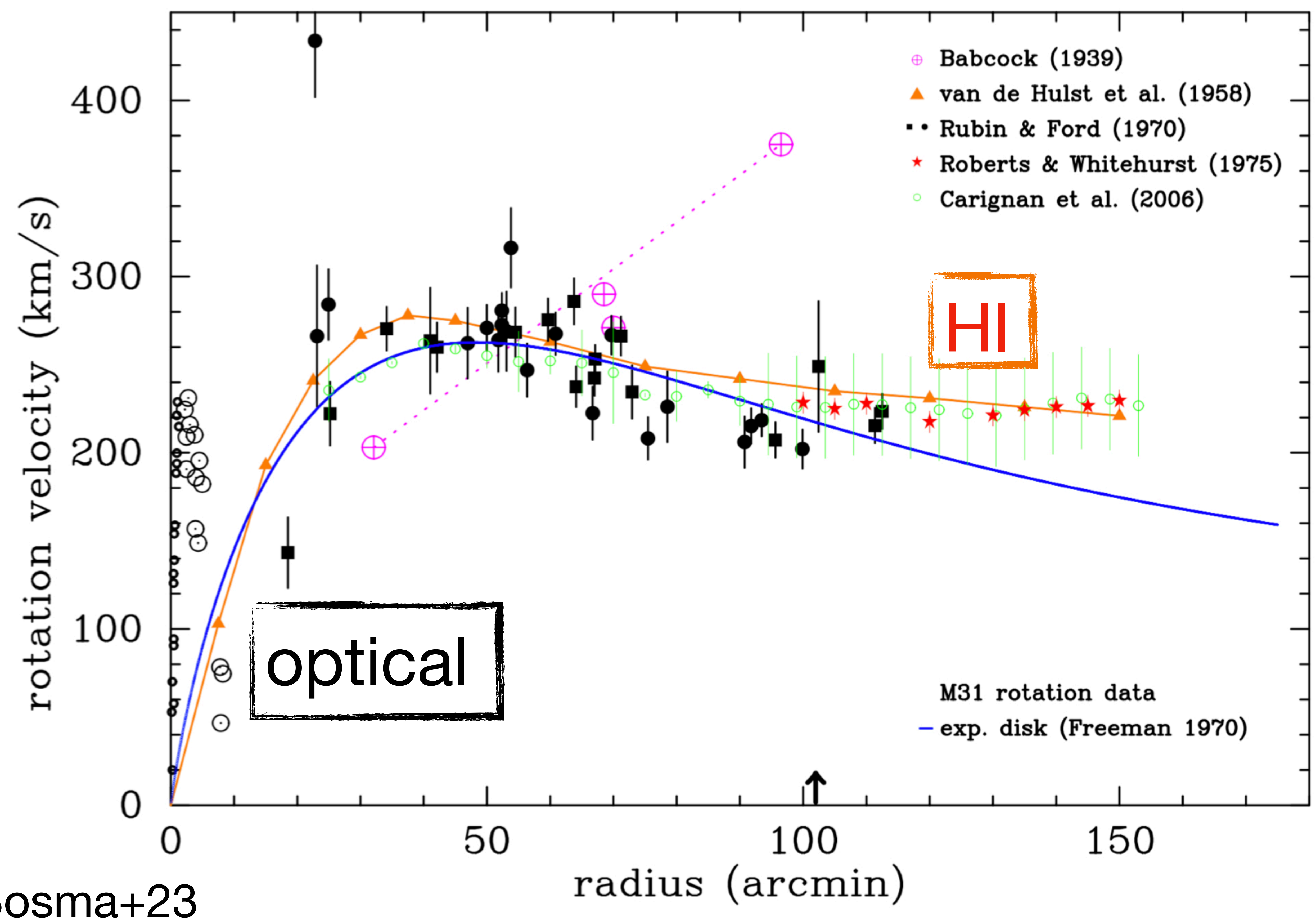
Bianca-Iulia Ciocan



CENTRE DE RECHERCHE ASTROPHYSIQUE DE LYON

Early Work

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



Bosma+23

- **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)

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).

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).

Nowadays

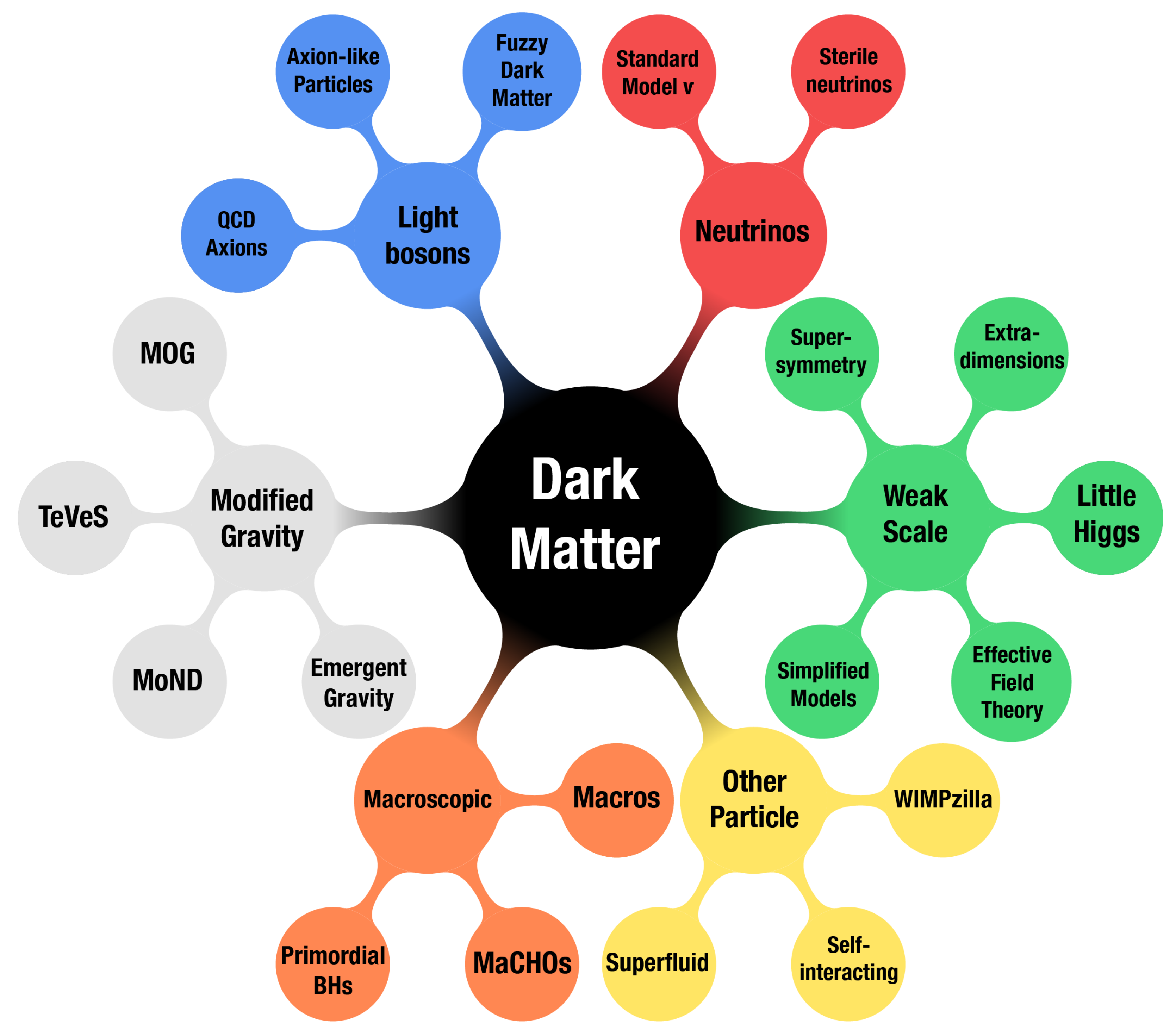


Image: Berton & Tait from here

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).

Nowadays

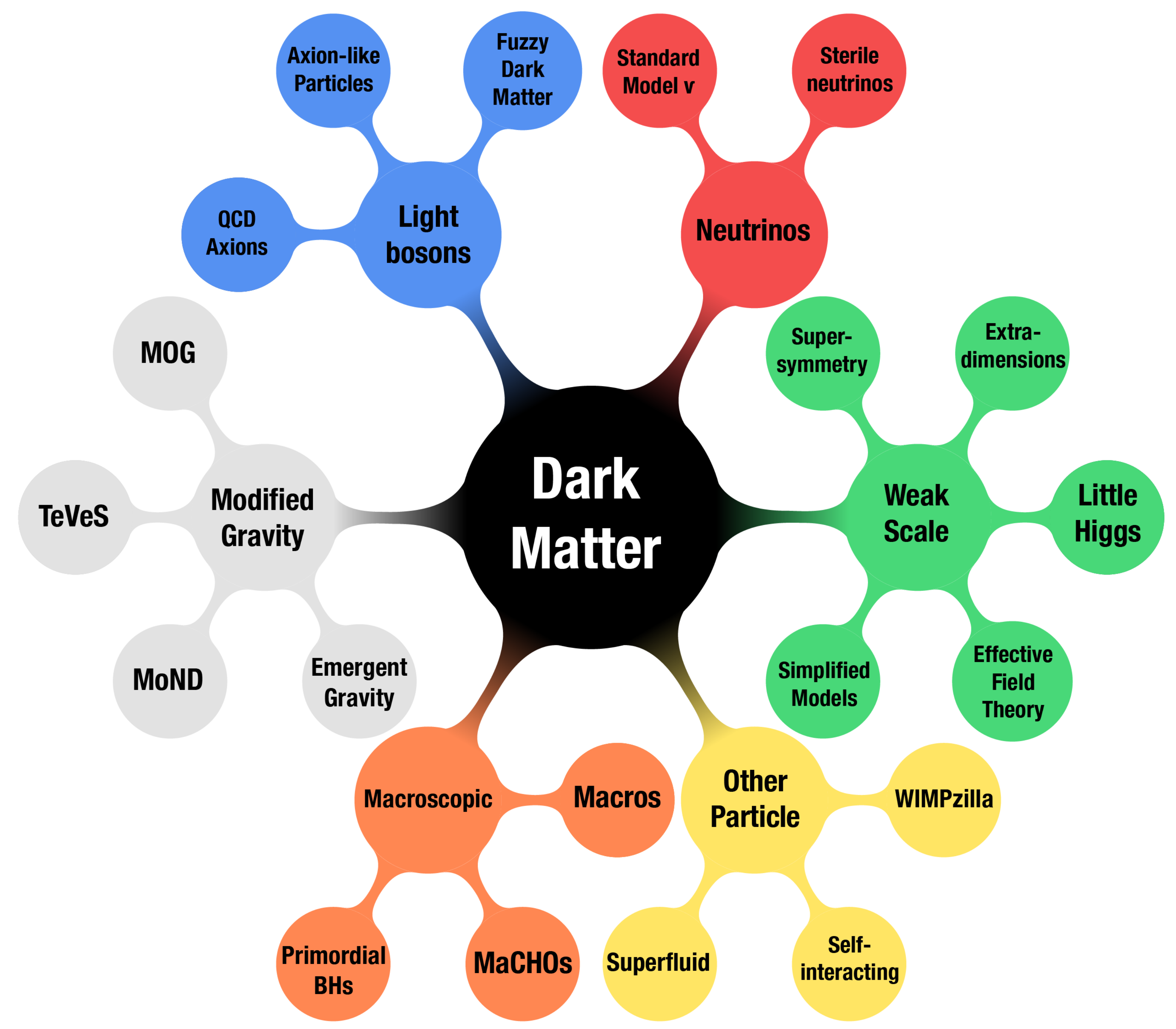
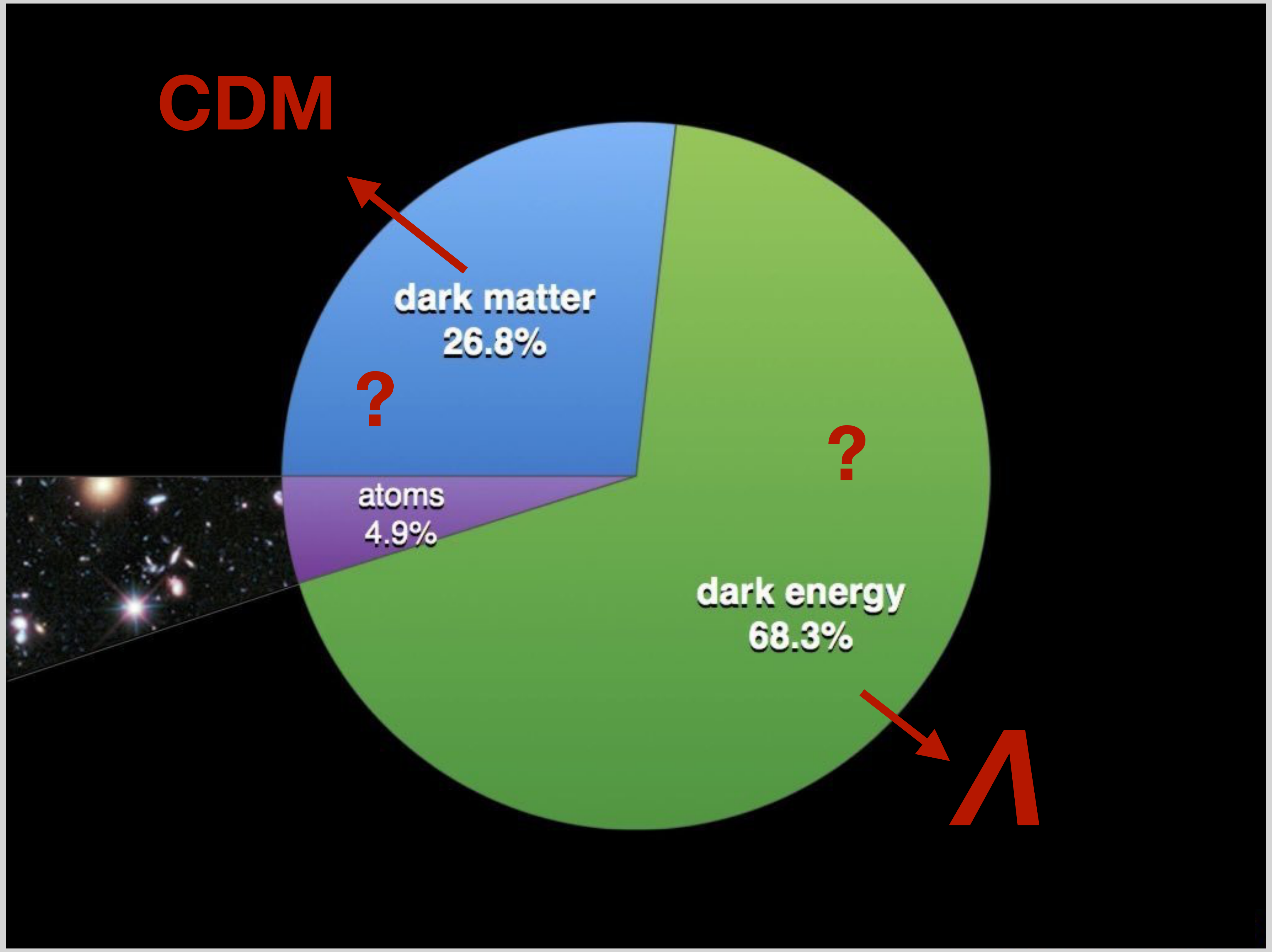


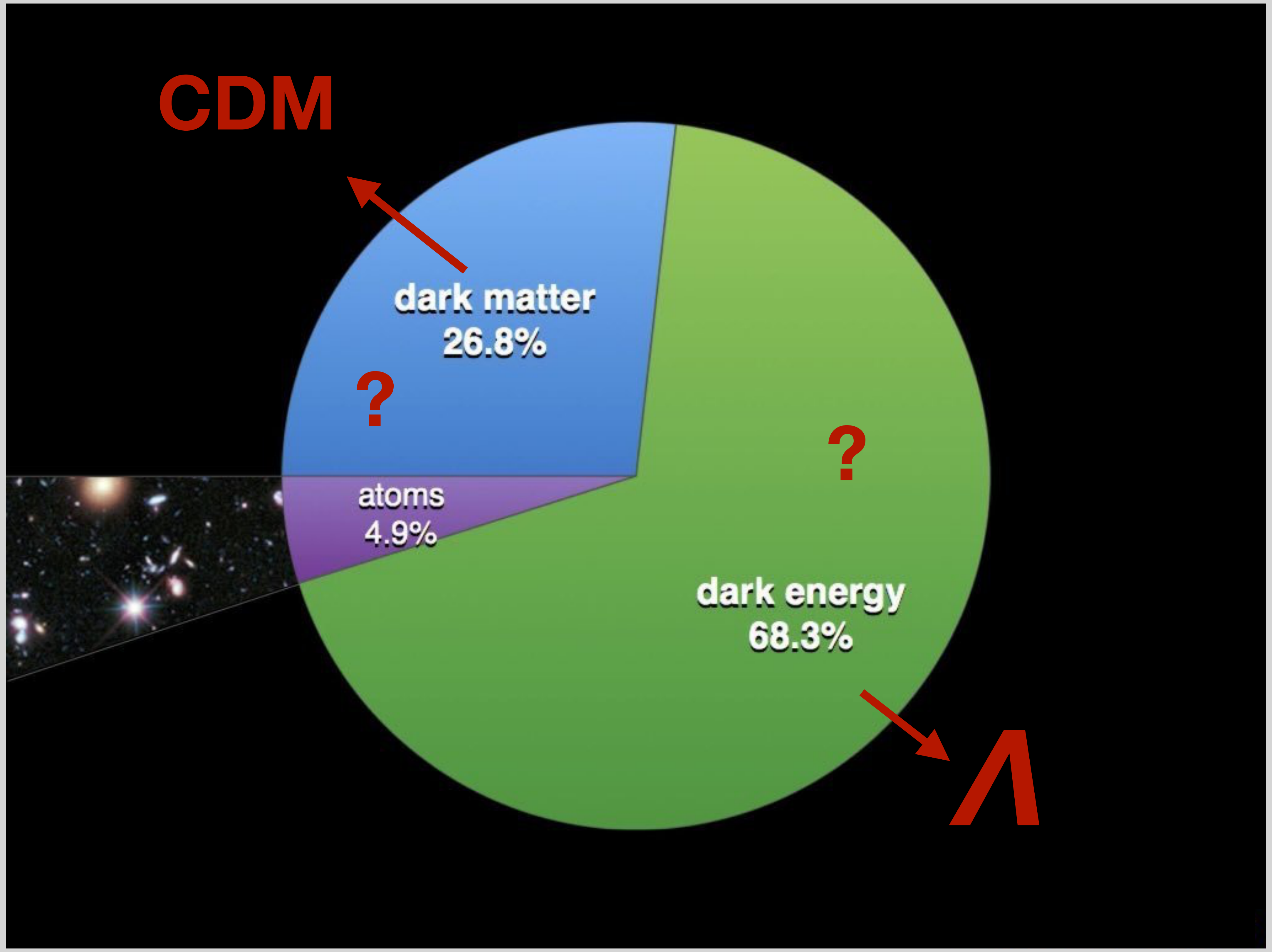
Image: Berton & Tait from here

??????

Concordance cosmological model: ΛCDM

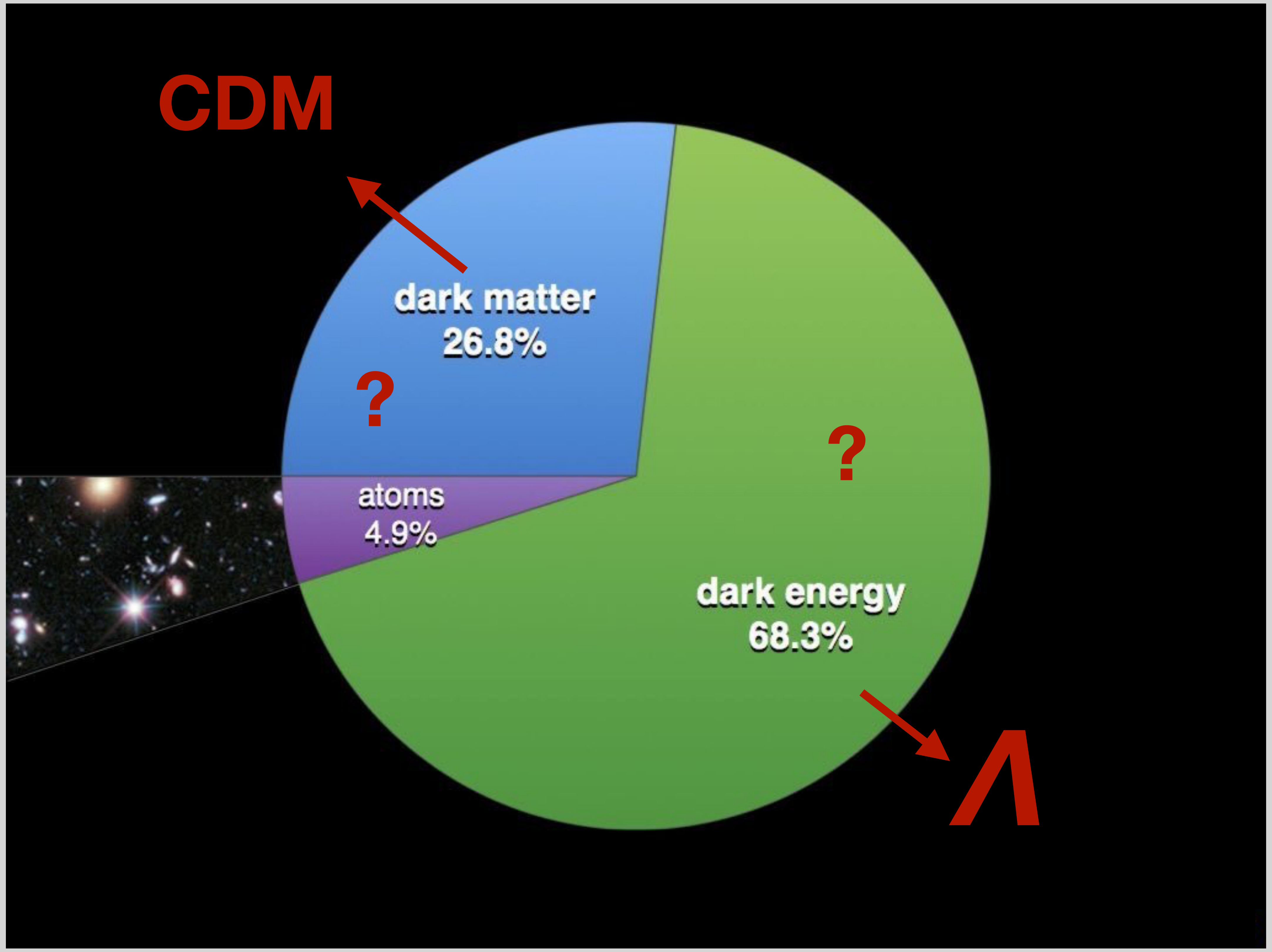


Concordance cosmological model: ΛCDM



- provides a good fit to cosmological observations:

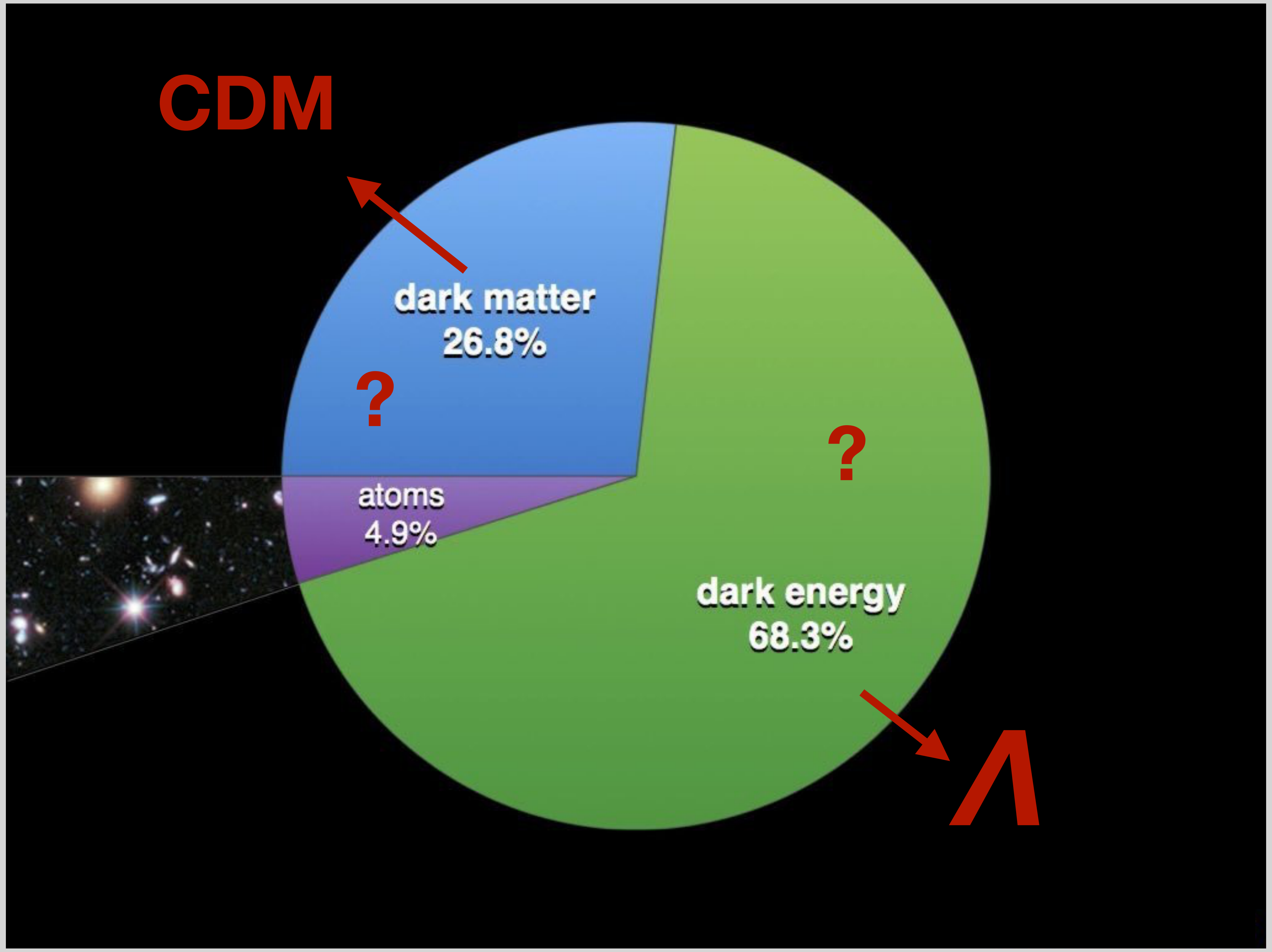
Concordance cosmological model: ΛCDM



- provides a good fit to cosmological observations:

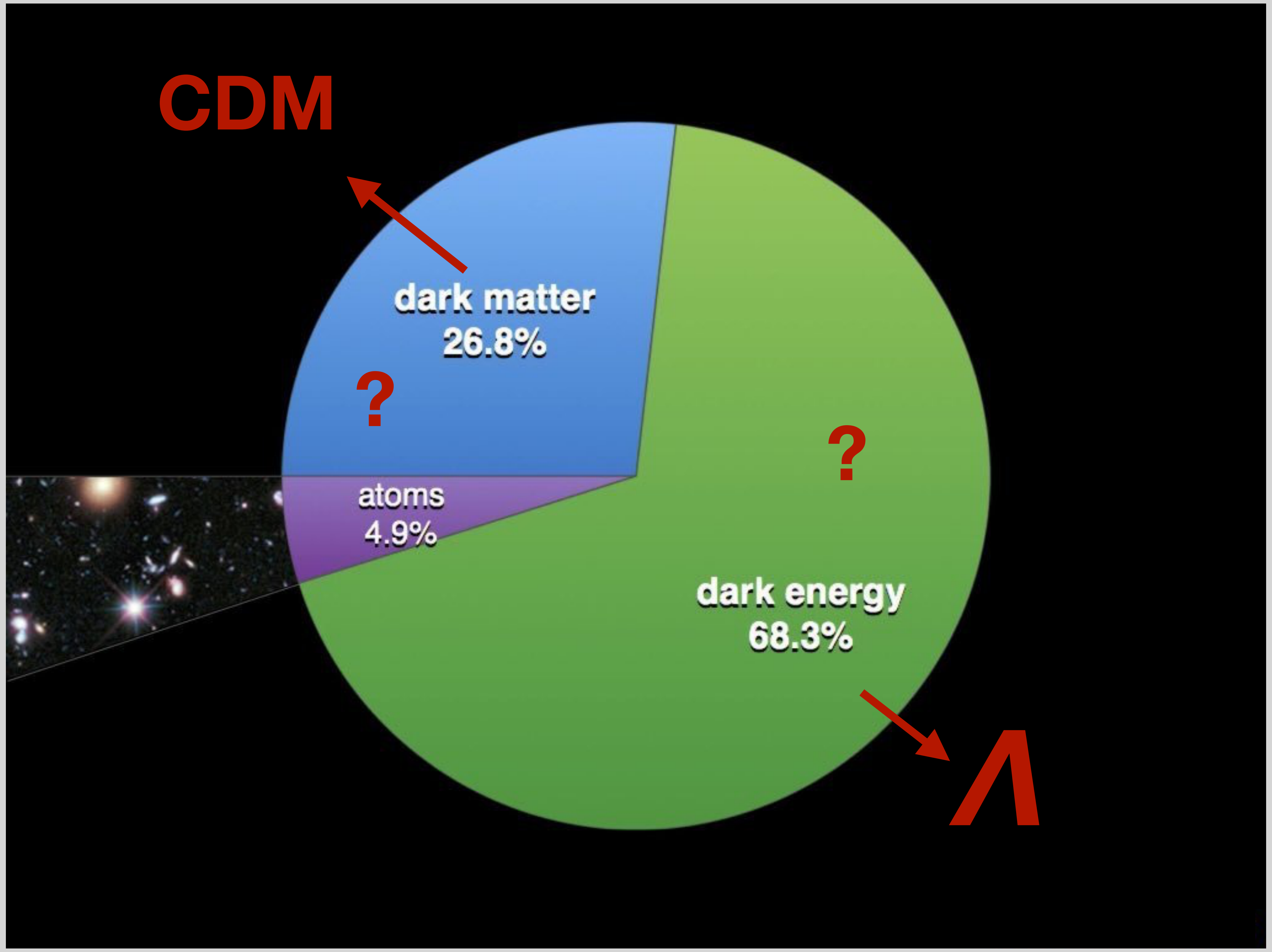
  ➡ expansion history of the Universe as inferred from Supernovae type Ia (Riess +1998)

Concordance cosmological model: ΛCDM



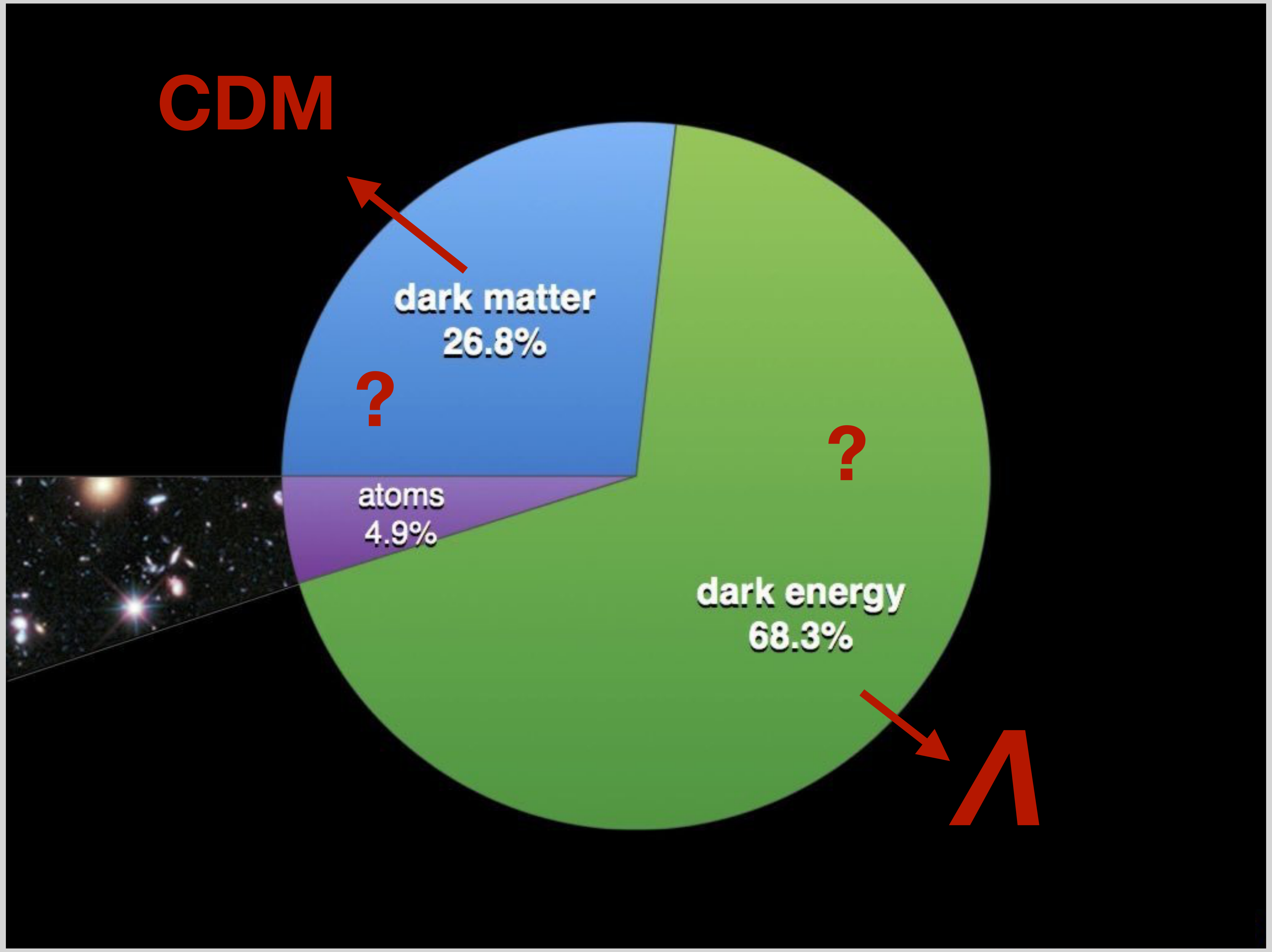
- provides a good fit to cosmological observations:
  - ➡ expansion history of the Universe as inferred from Supernovae type Ia (Riess +1998)
  - ➡the matter power spectrum (Gil-Marin+2015)

Concordance cosmological model: ΛCDM



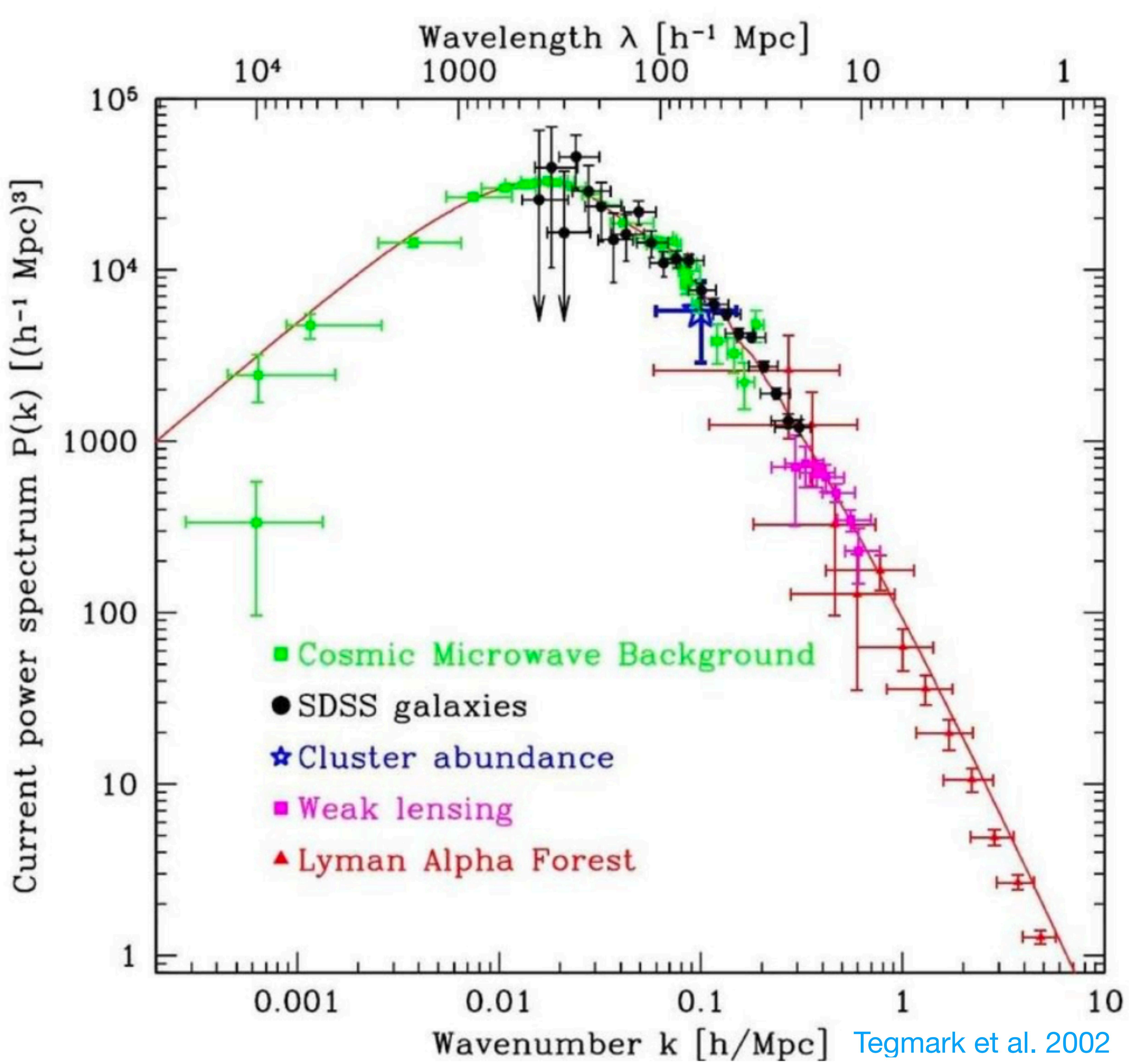
- provides a good fit to cosmological observations:
  - ➡ expansion history of the Universe as inferred from Supernovae type Ia (Riess +1998)
  - ➡the matter power spectrum (Gil-Marin+2015)
  - ➡the Cosmic Microwave Background data (Planck collaboration, 2020)

Concordance cosmological model: ΛCDM



- 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

- On scales <1Mpc: ‘small scale problems of ΛCDM’ (Bullock+2017, Sales+2022)

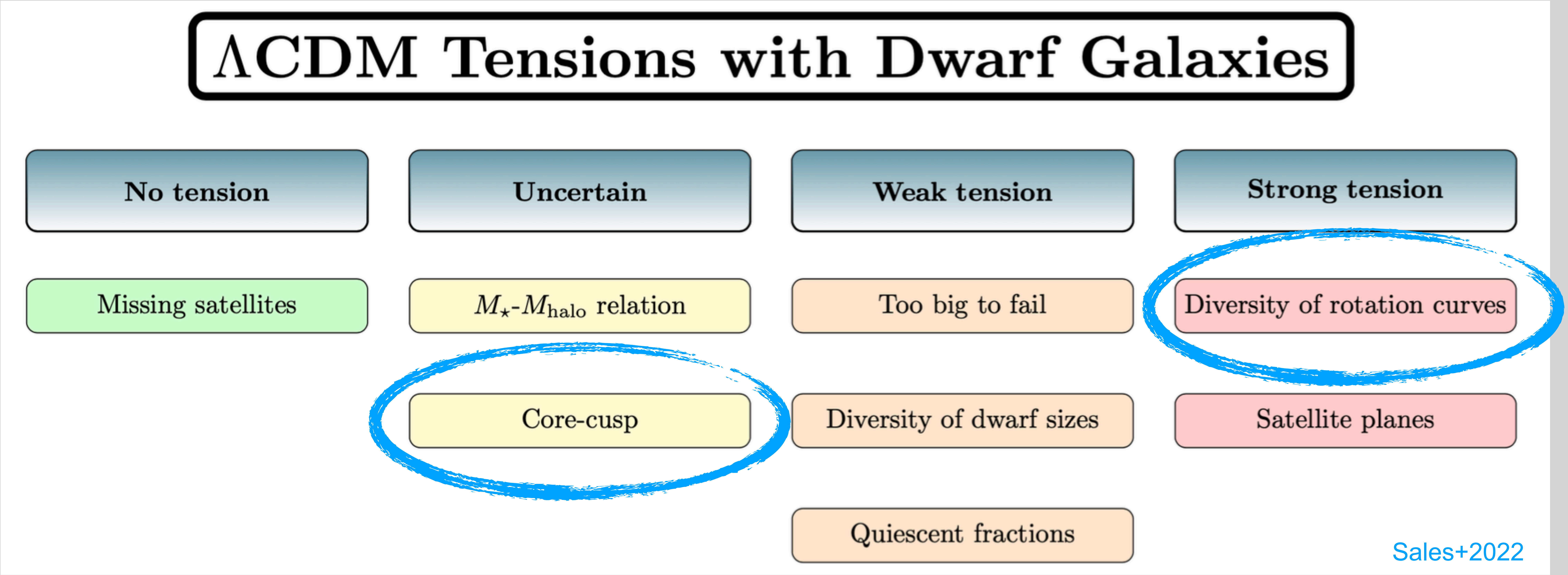
ΛCDM Tensions with Dwarf Galaxies

No tension	Uncertain	Weak tension	Strong tension
Missing satellites	$M_\star$-$M_{\rm halo}$ relation	Too big to fail	Diversity of rotation curves
	Core-cusp	Diversity of dwarf sizes	Satellite planes
		Quiescent fractions	

Sales+2022

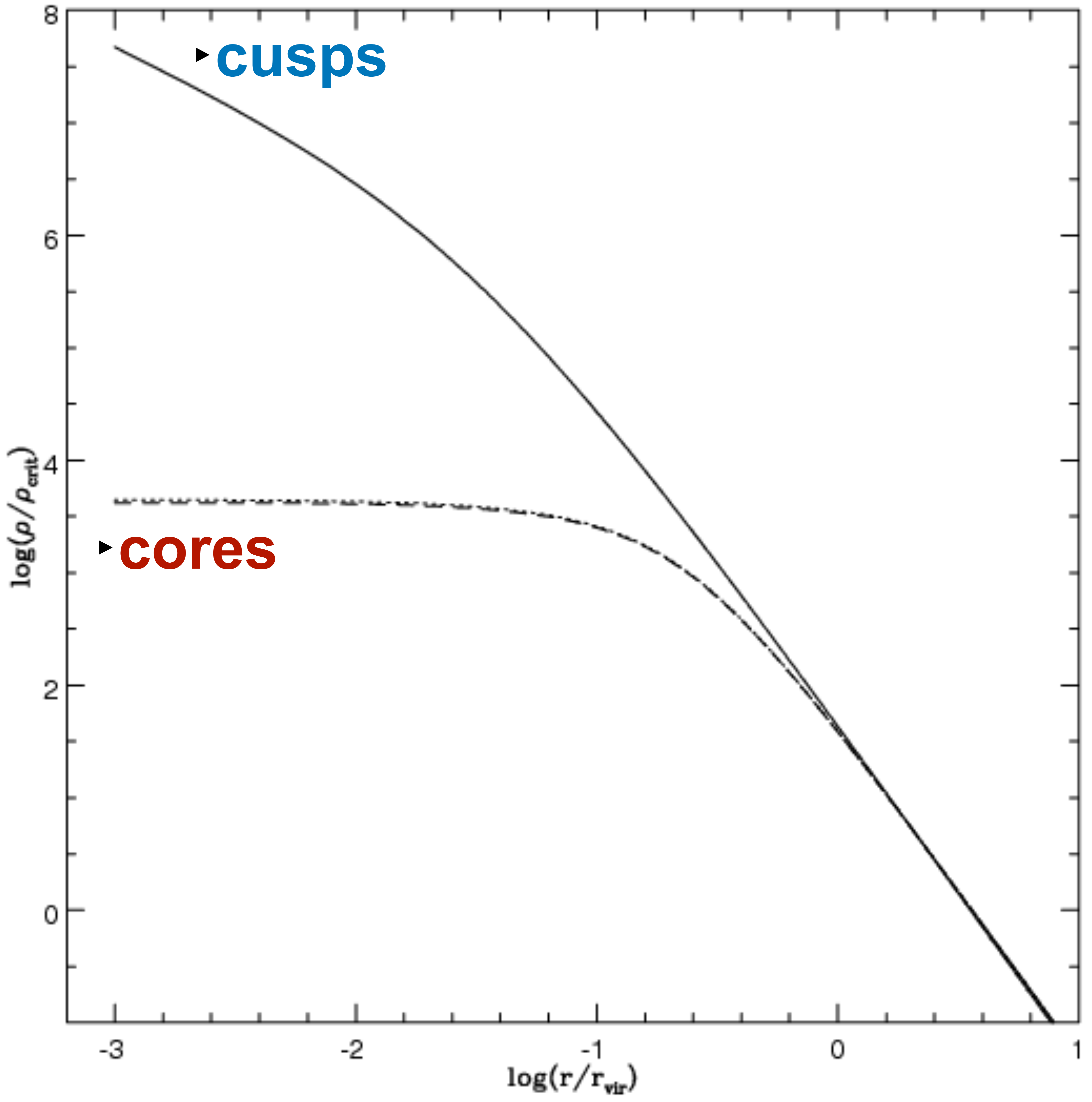
ΛCDM

On scales <1Mpc: ‘small scale problems of ΛCDM’
(Bullock+2017, Sales+2022)



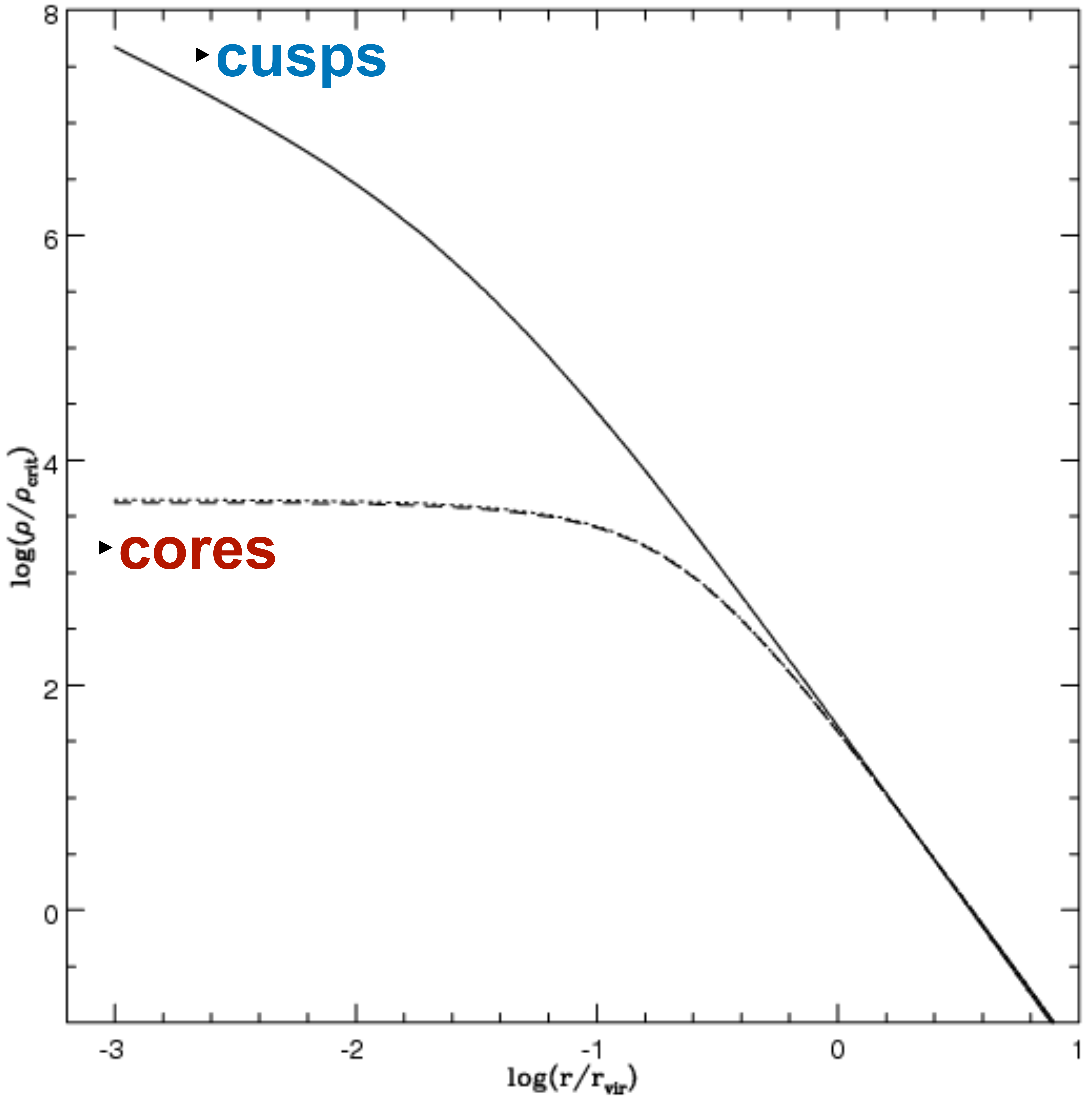
Sales+2022

Core - cusp problem



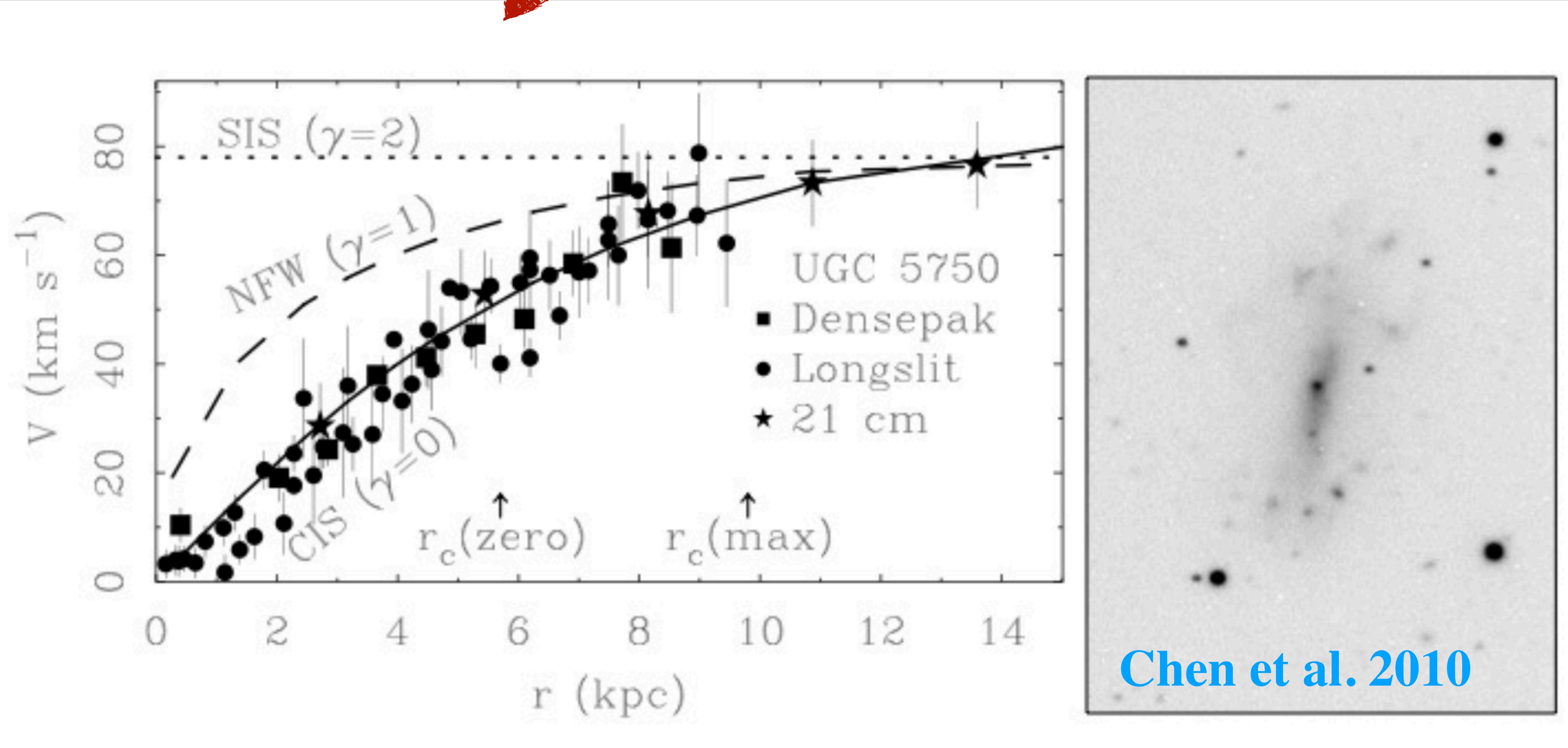
- N-body simulation predicts **cuspy** DM profiles (NFW, Navarro+1997)

Core - cusp problem



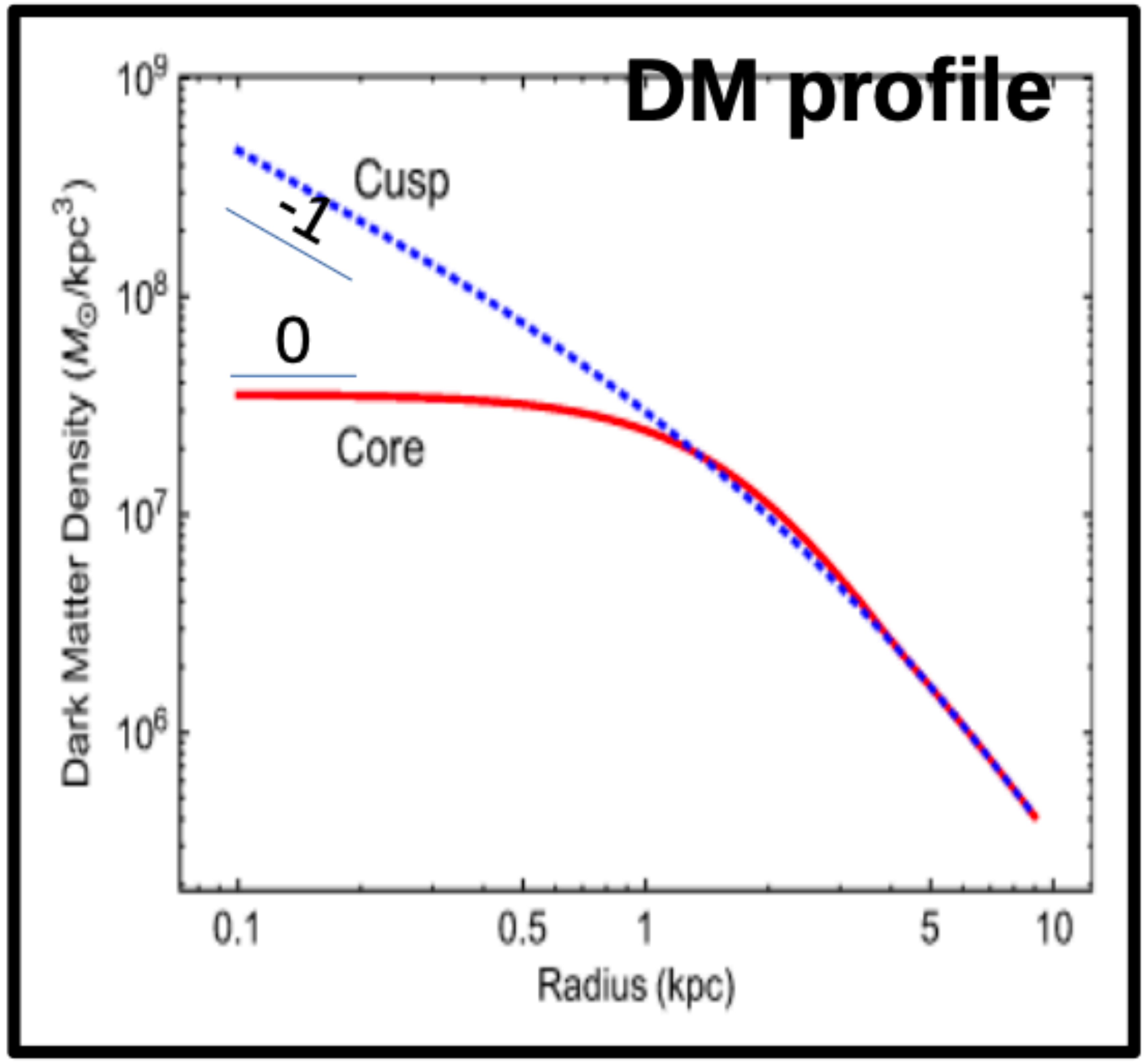
- N-body simulation predicts **cuspy** DM profiles (NFW, Navarro+1997)

- Rotation curves of low-surface brightness galaxies (e.g. de Blok et al. 2001) indicate constant-density **cores**

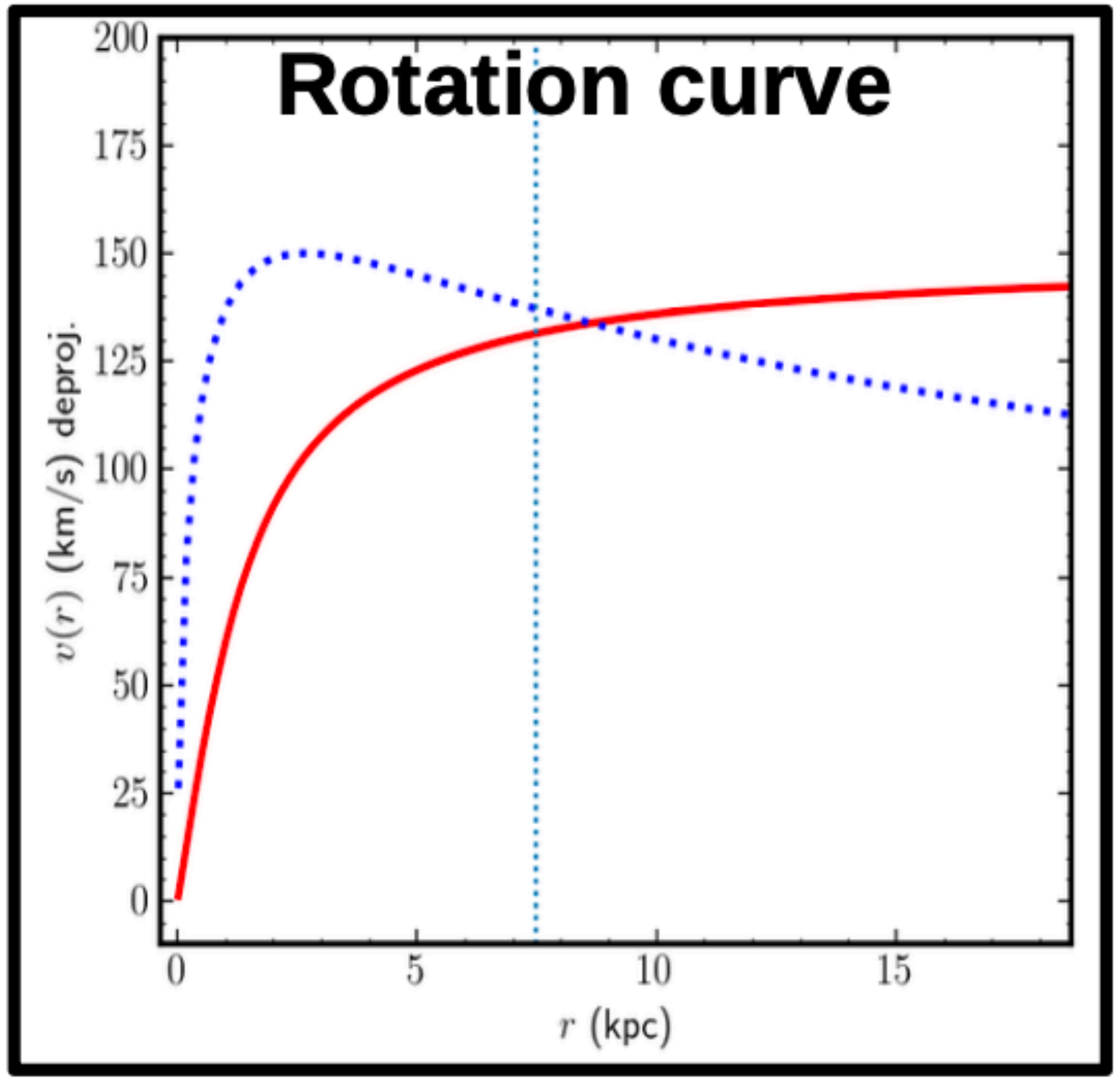


Chen et al. 2010

Core - cusp problem



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



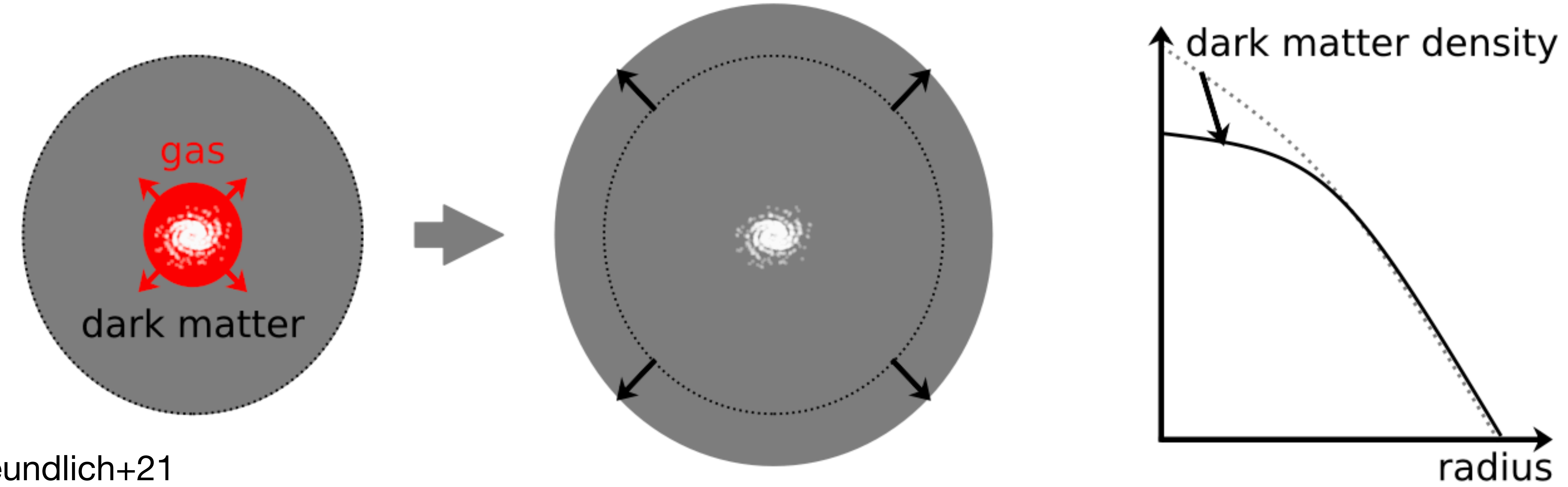
- A core on <1kpc → impact on several kpc

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

Core-cusp problem: solutions in ΛCDM

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

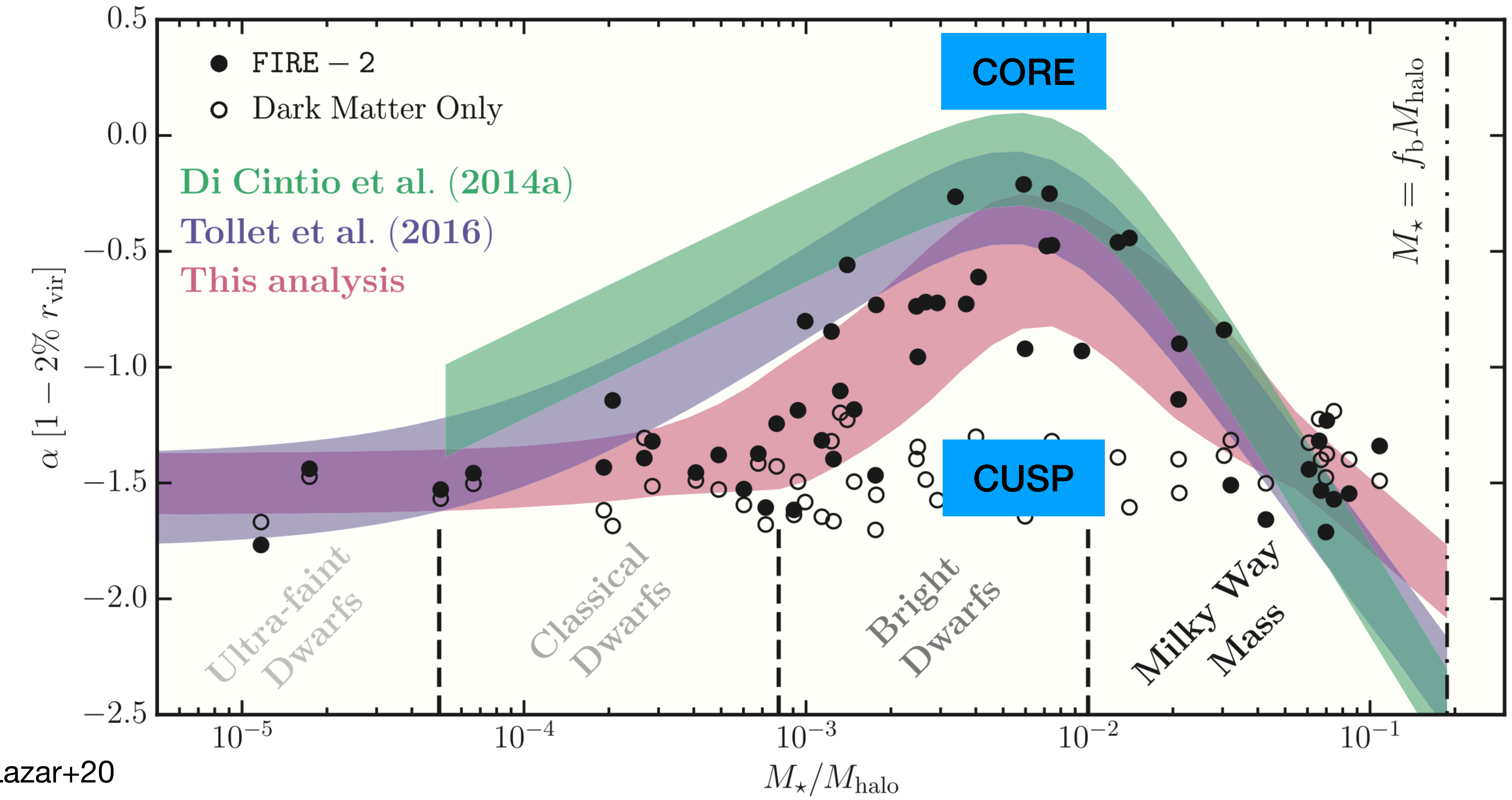
- rapid potential fluctuations



Freundlich+21

Core-cusp problem: solutions in ΛCDM

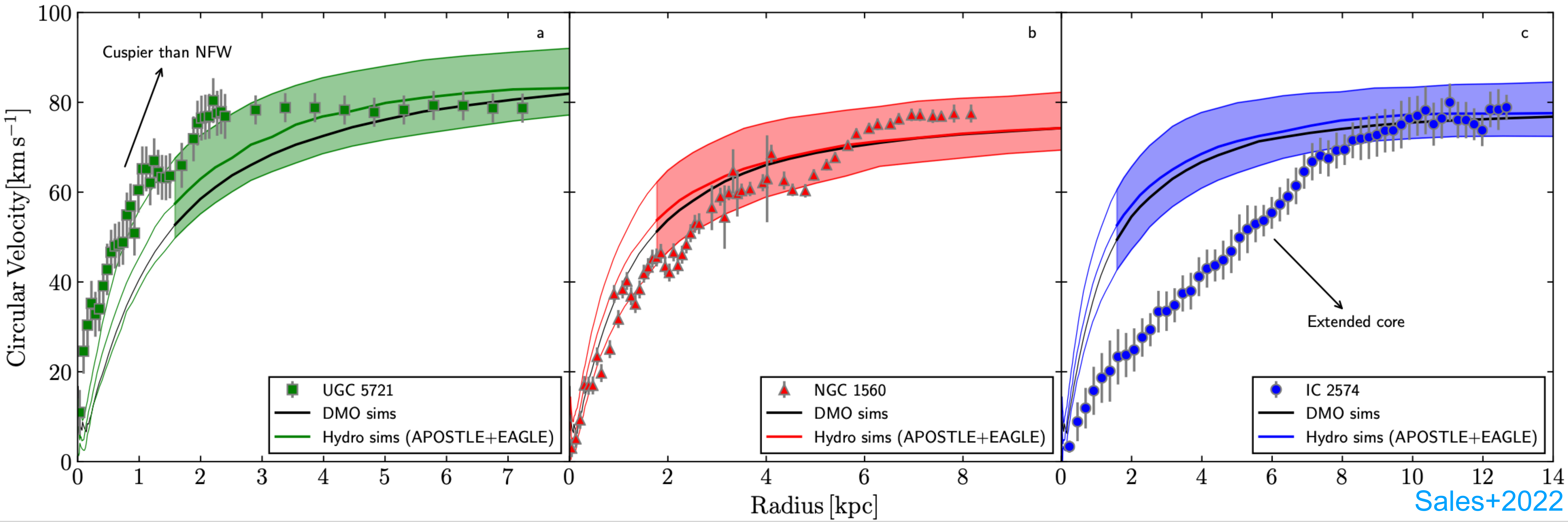
Hydrodynamical simulations with stellar feedback



Lazar+20

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

Diversity of Rotation Curves problem:

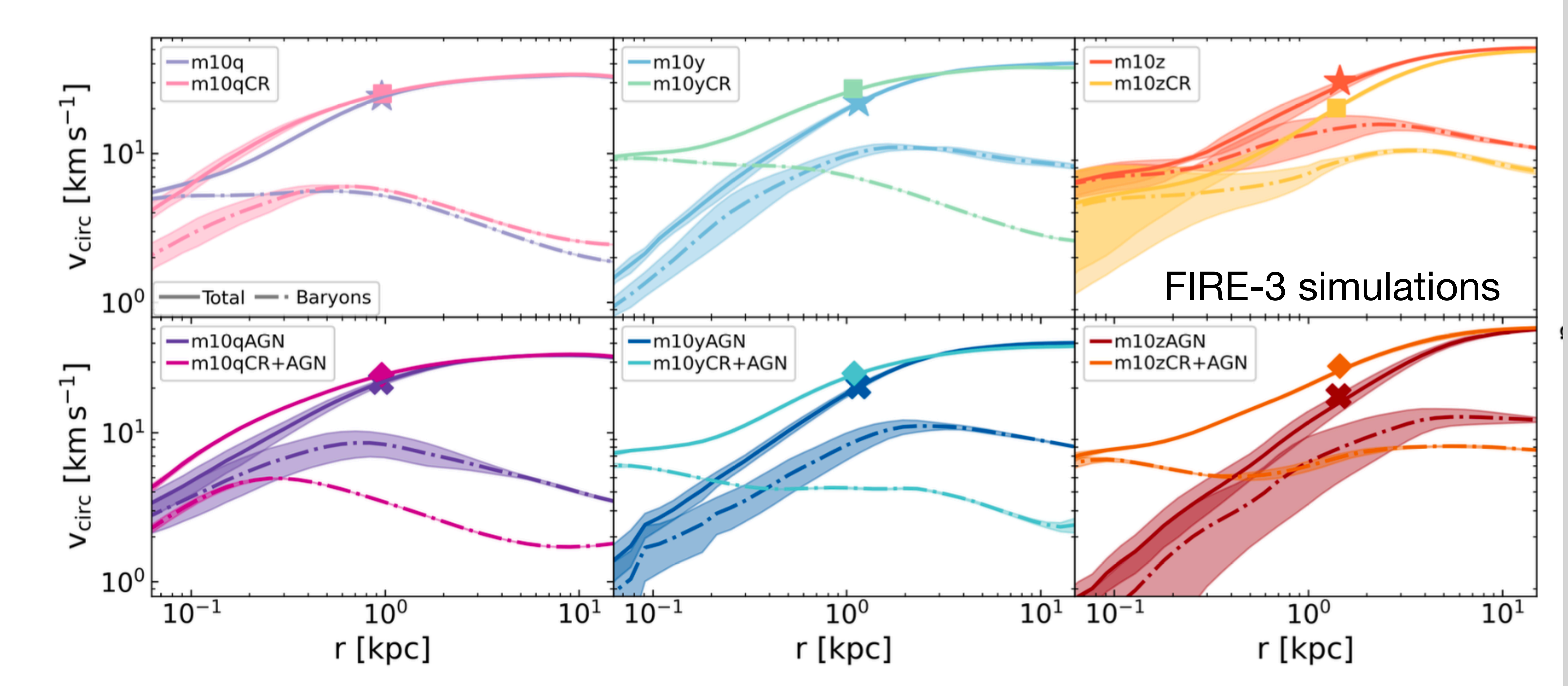


Sales+2022

- 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

▶baryonic processes to the rescue



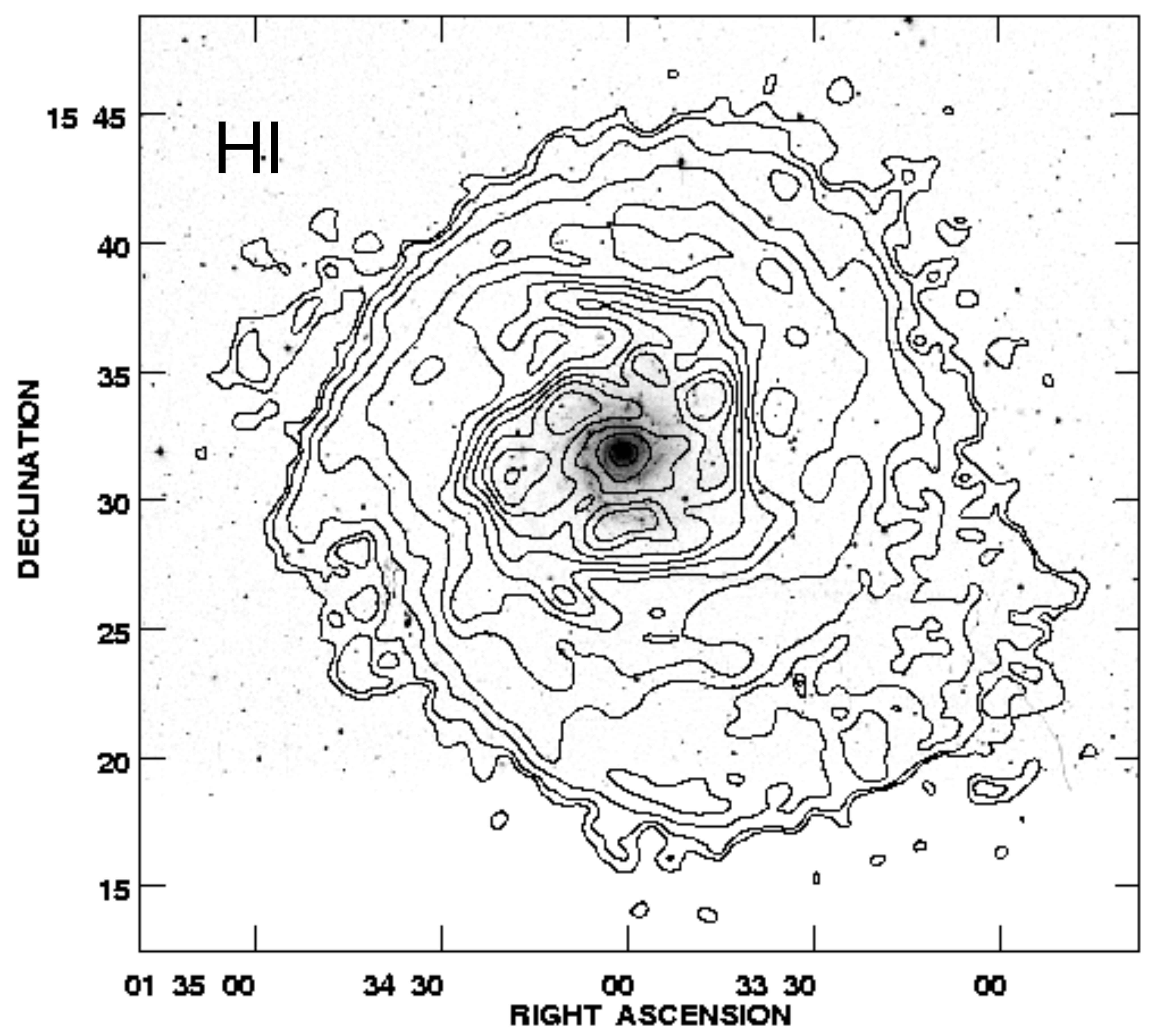
Koudmani et al. 2024

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

How to test this observationally?

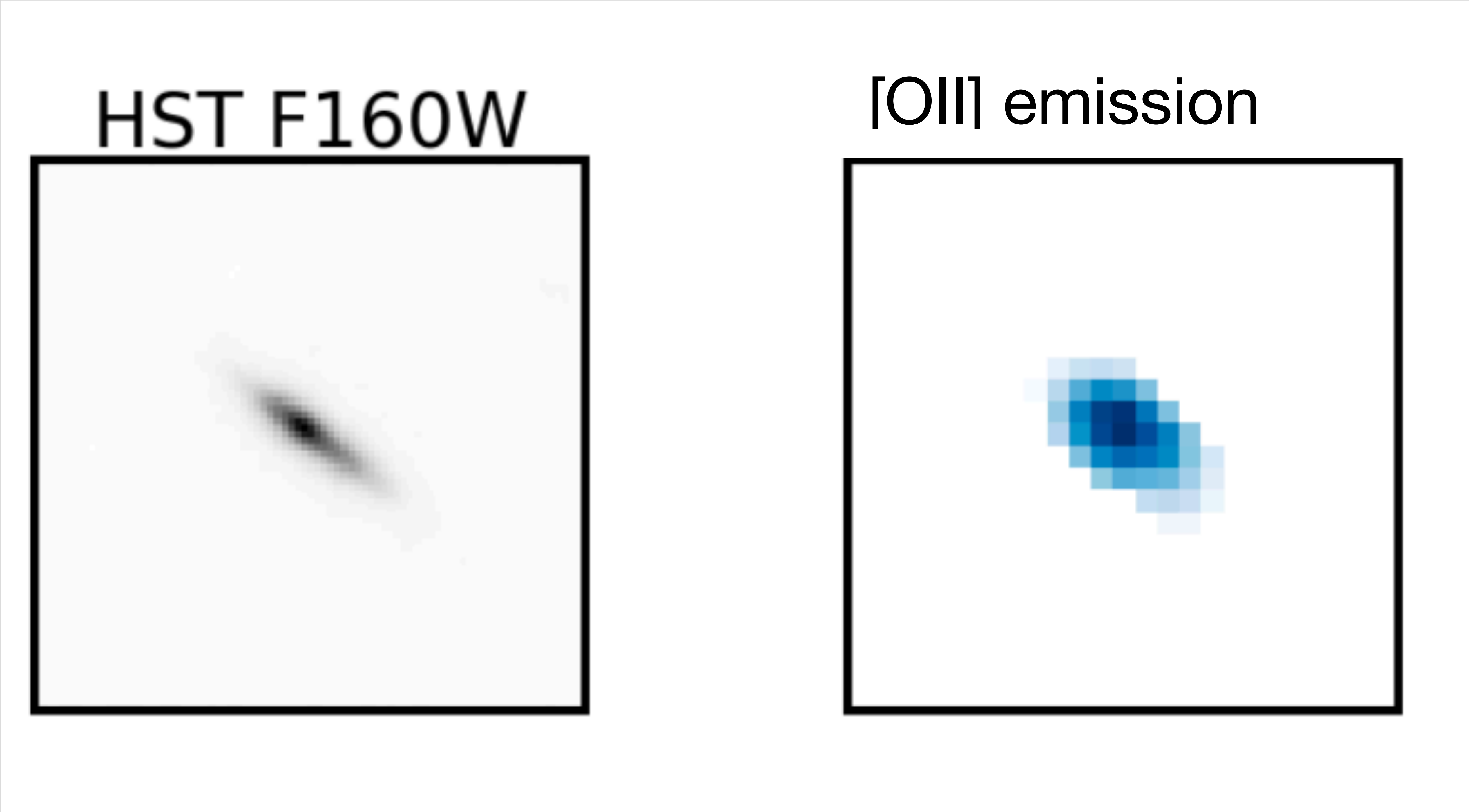
▶Need a kinematic tracer at large galactocentric radii, beyond 2xRe

z=0



Kamphuis and Briggs 1992

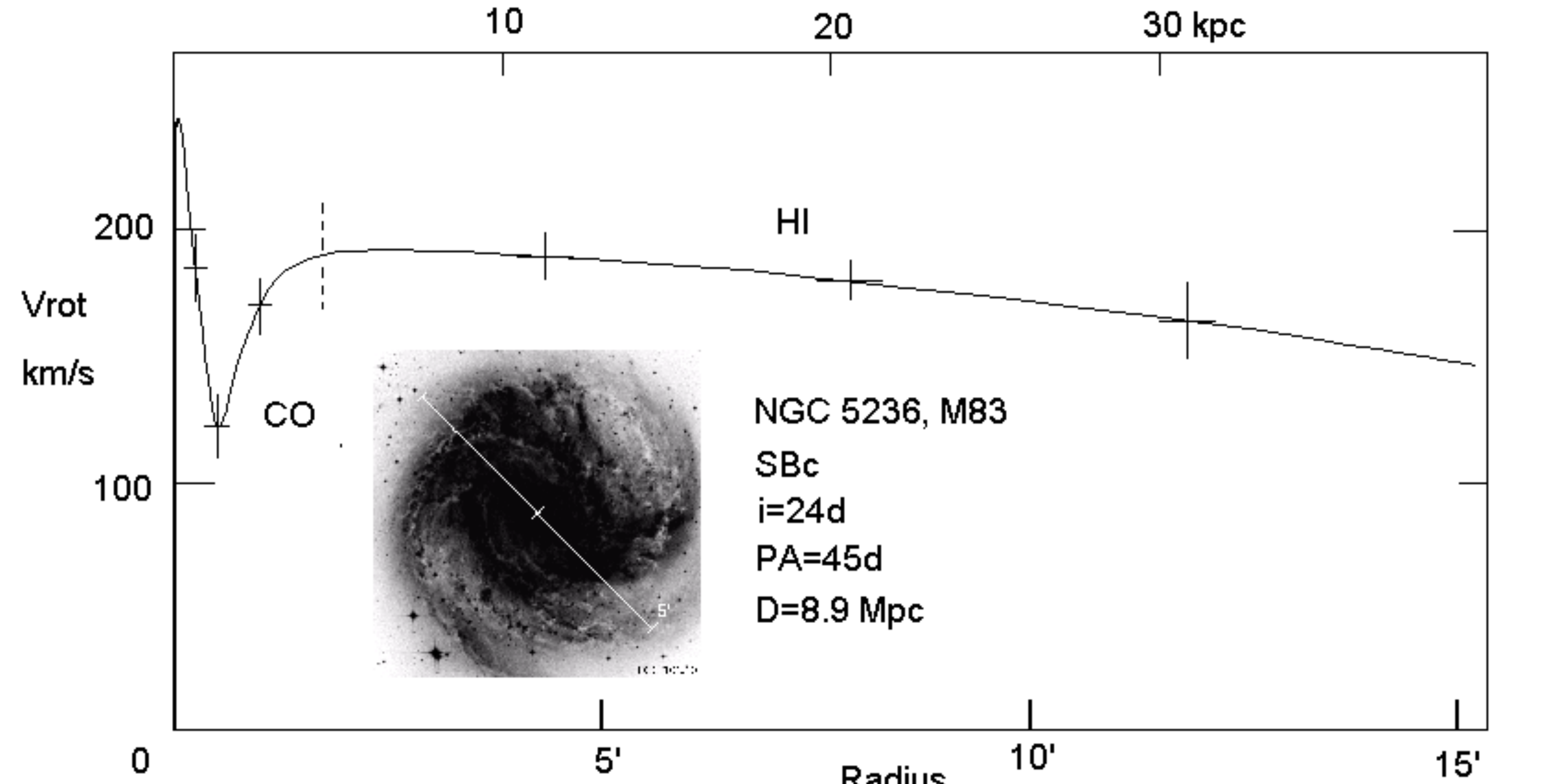
z~1



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



Honma+97

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):

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

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

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

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

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

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

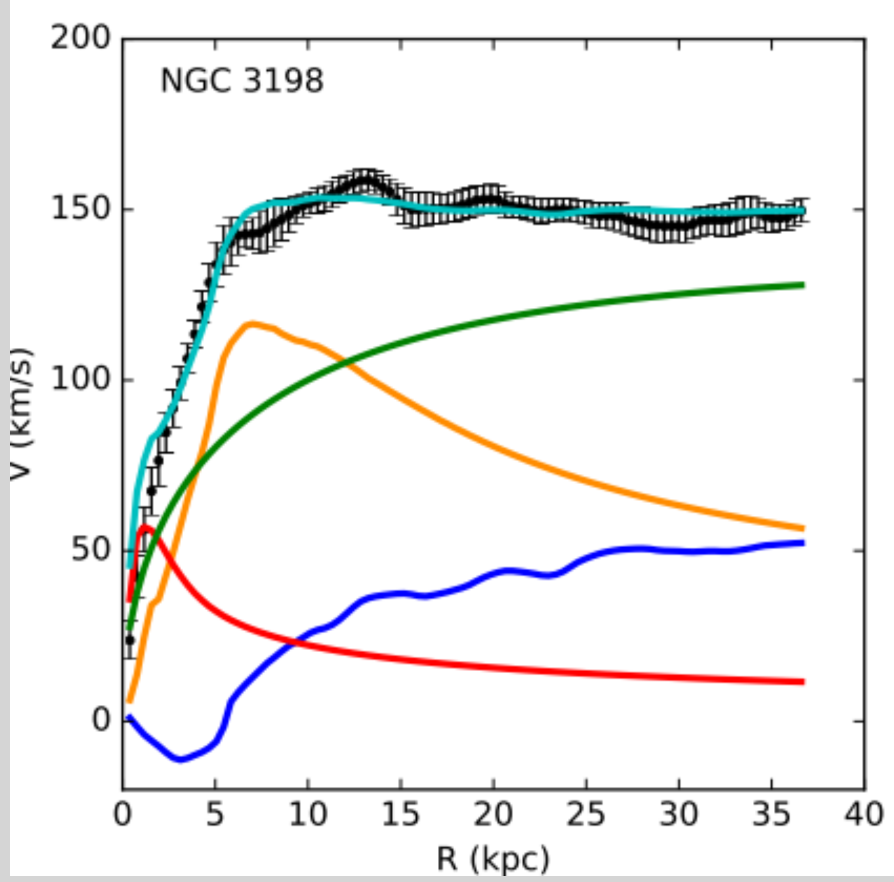
The resulting 1D rotation curve is used for the decomposition →

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):

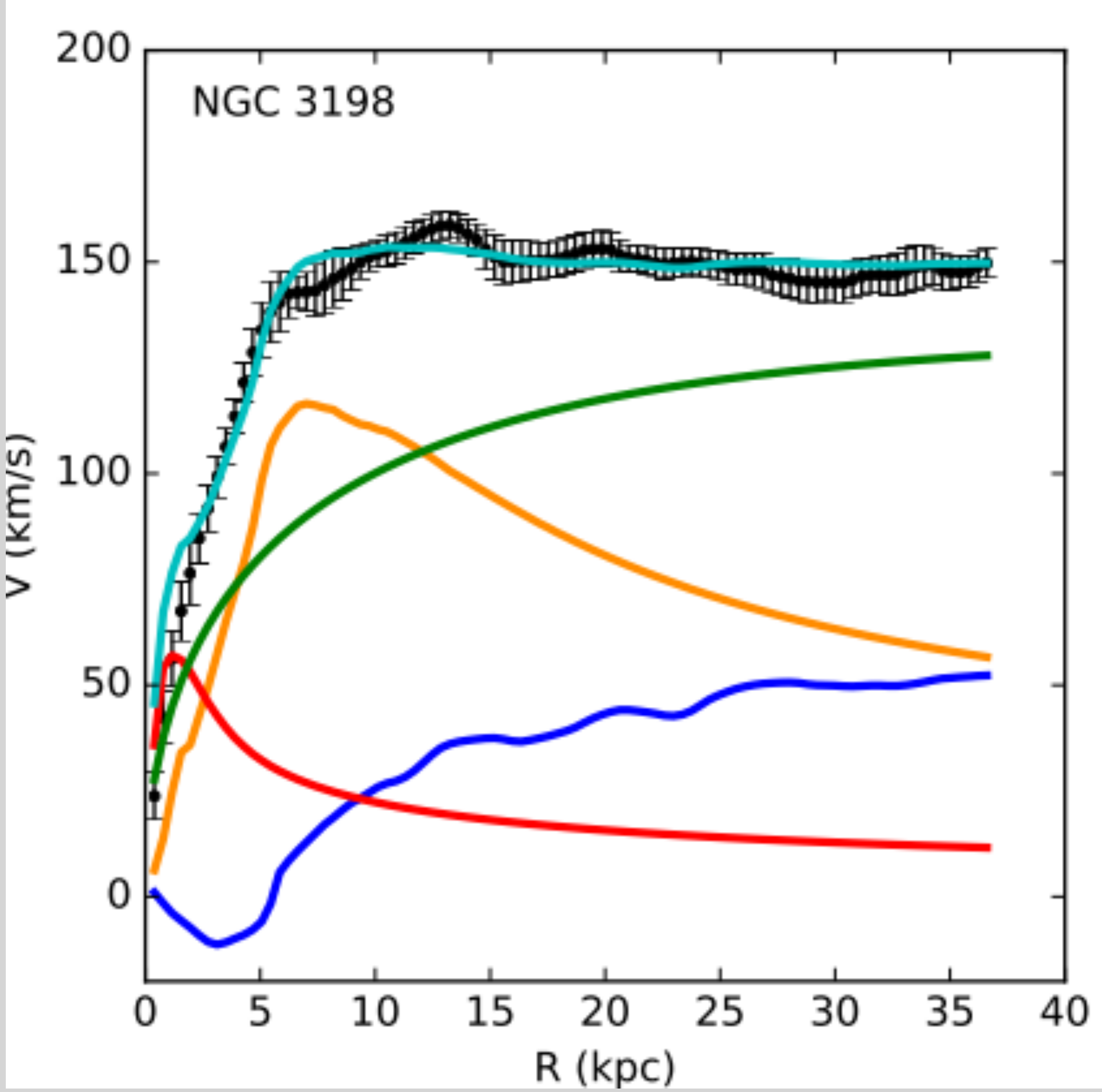
- **Assumptions:** the galaxy's gas is confined to a series of concentric rings, each with its own orientation and rotational velocity
- **Fitting the Velocity Field:** for each ring at radius r, fit for rotational velocity, inclination, position angle
- **Reconstructing the Rotation Curve:** the rotation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

The resulting 1D rotation curve is used for the decomposition



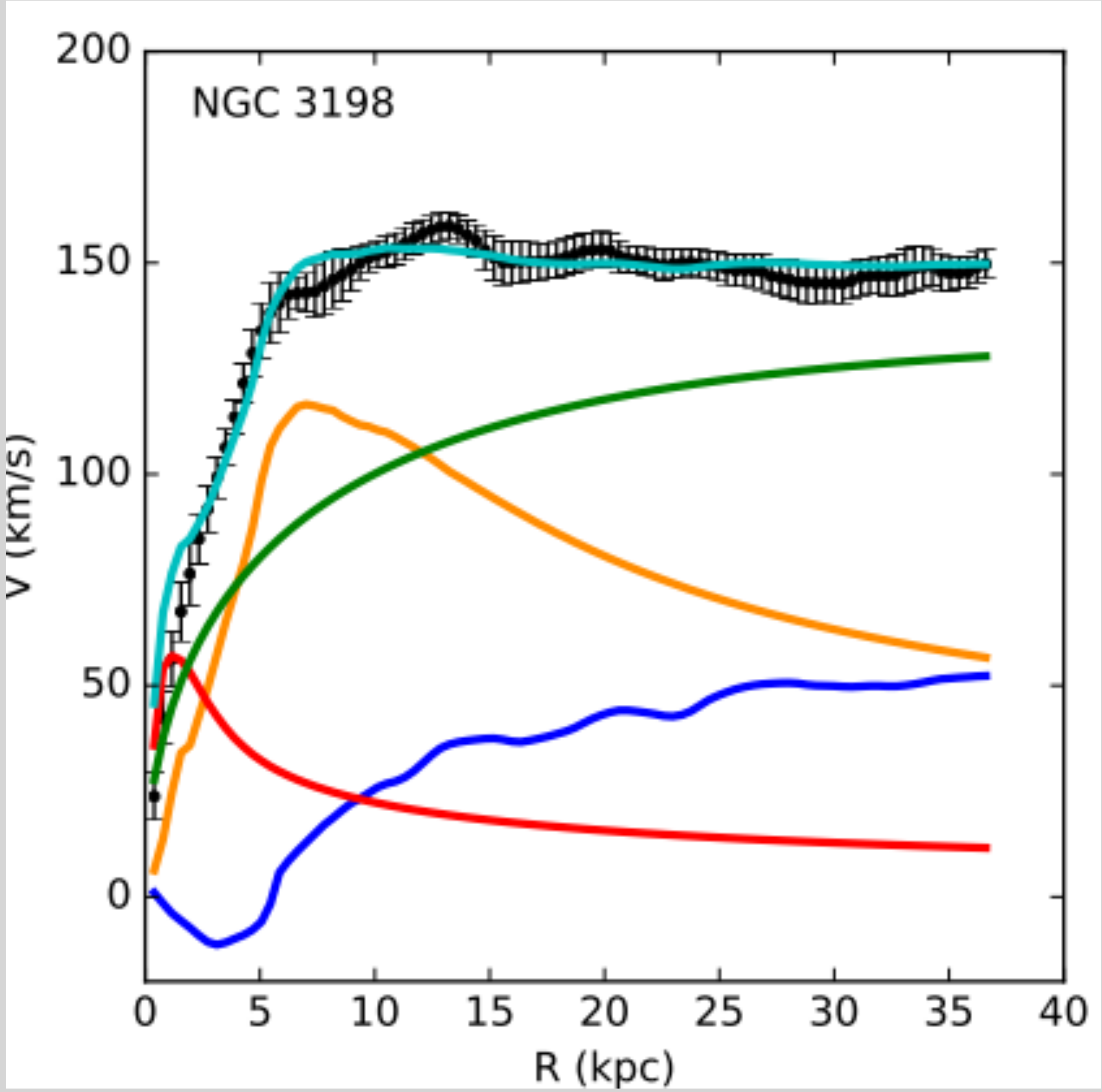
How to test this observationally at z>0?

- At z=0: « easy » ?



How to test this observationally at z>0?

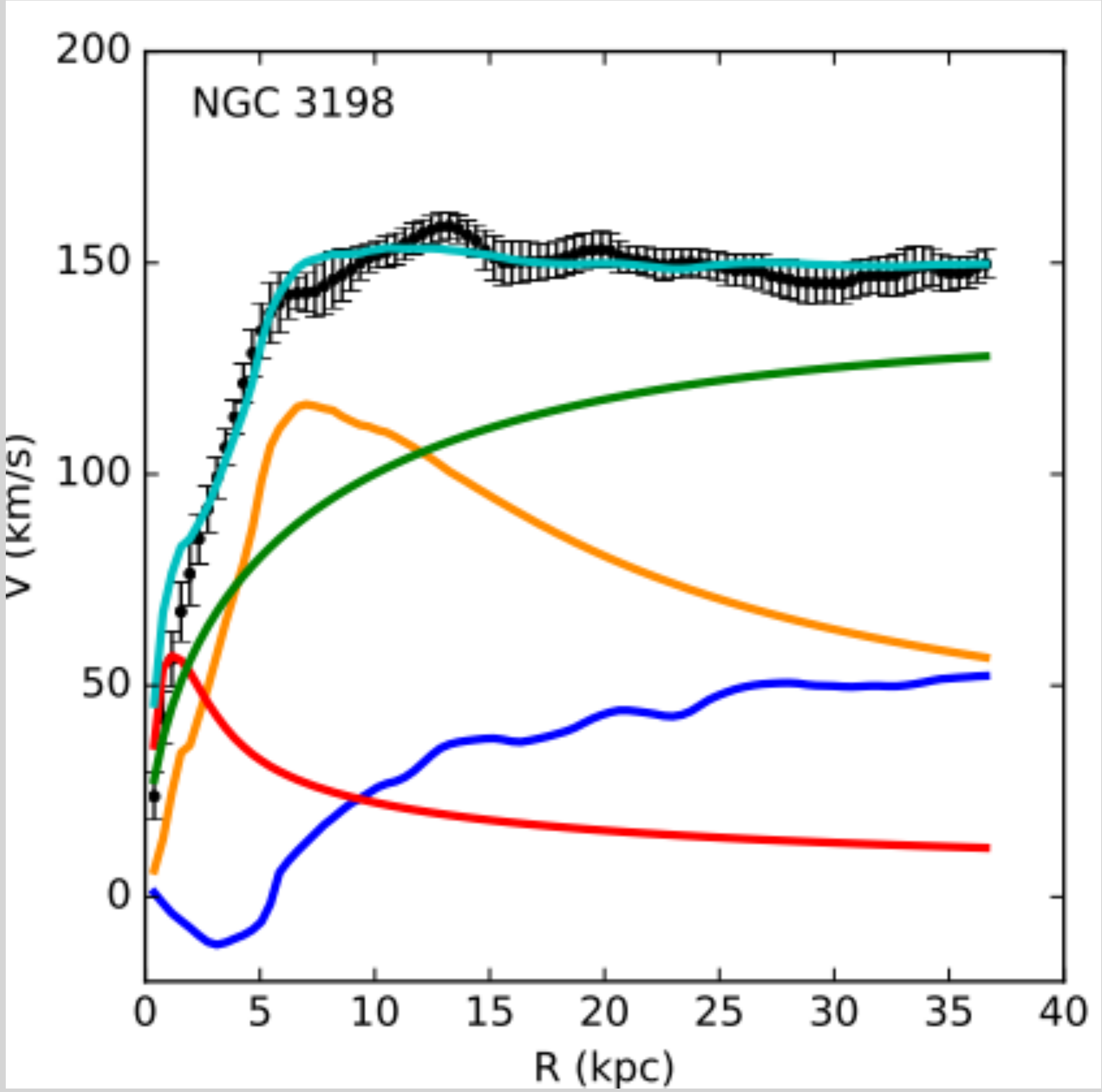
- At z=0: « easy » ?



- At z=1: « hard » ?

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

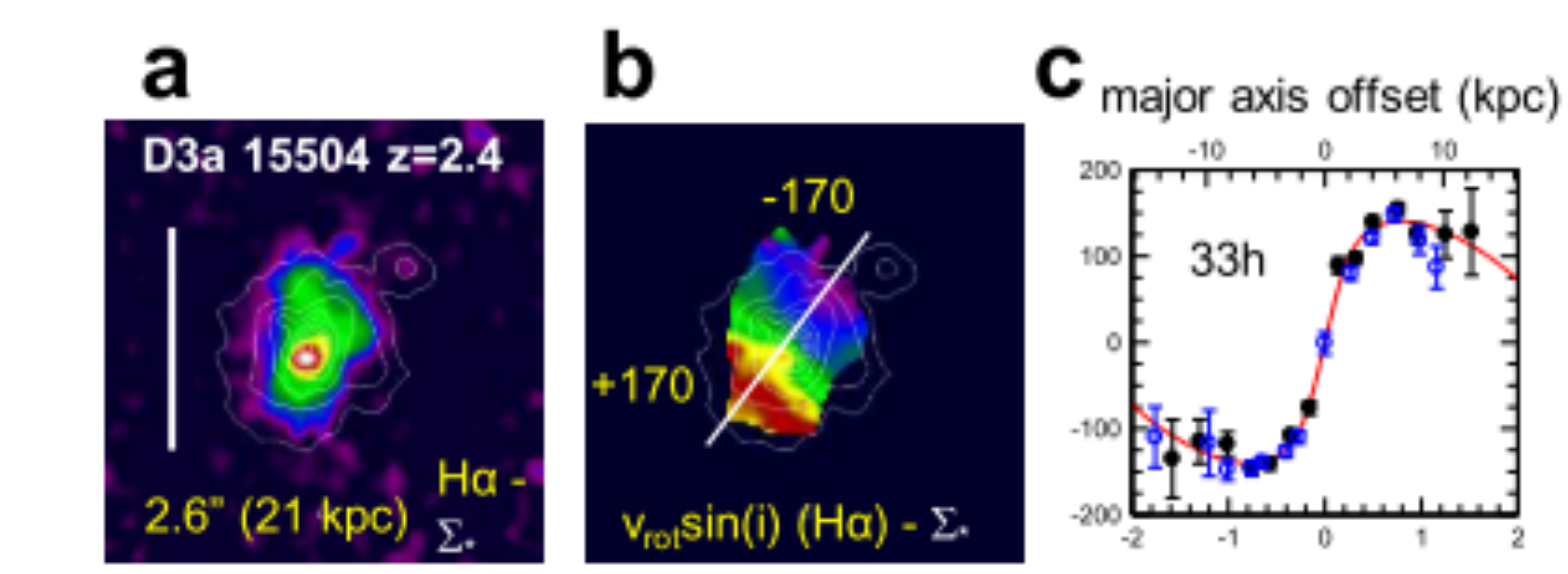
How to test this observationally at z>0?

- At z=1: « hard » ?

There are only 3 options:

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

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



Genzel +17

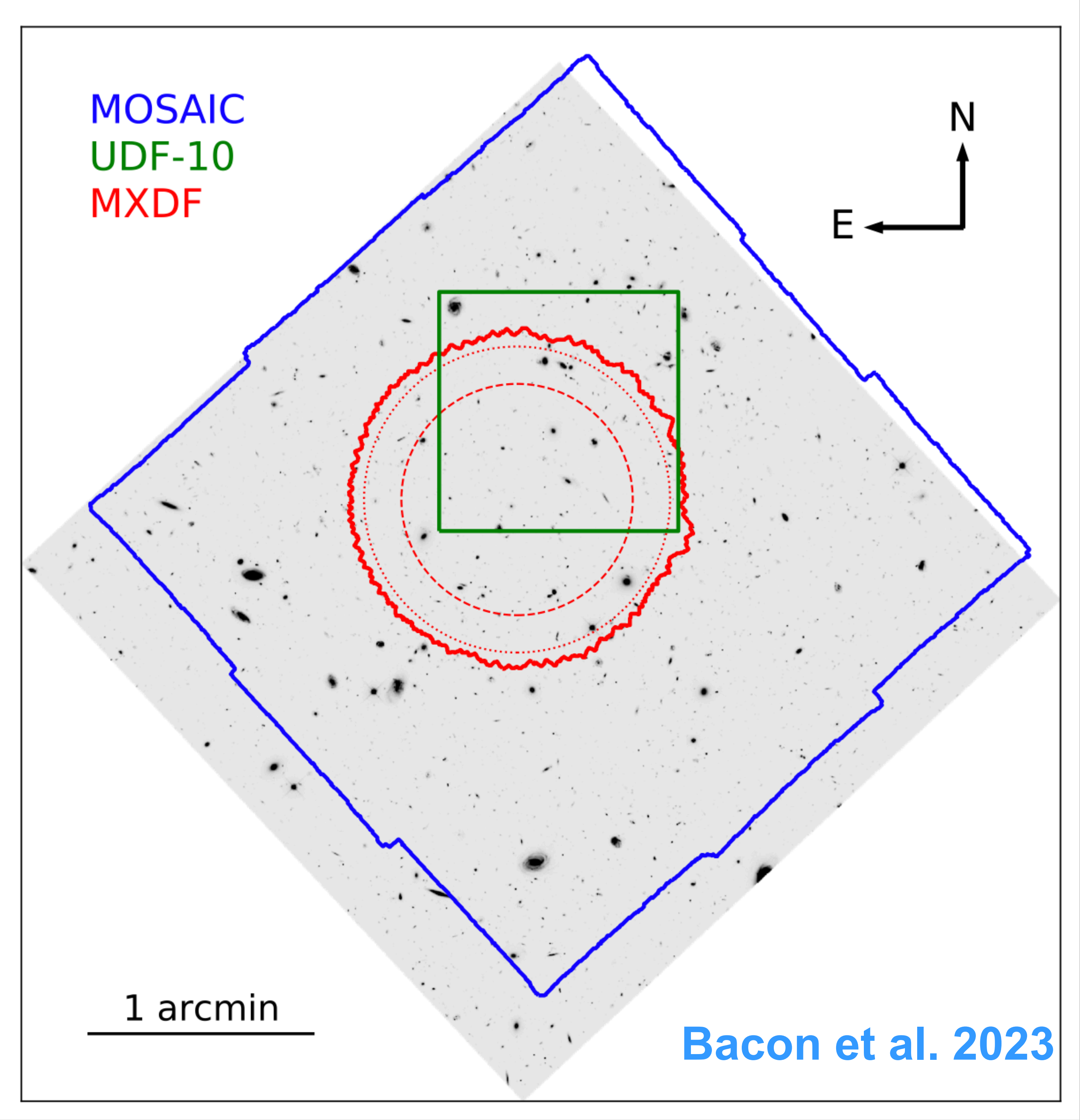
How to test this observationally at z>0?

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



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)**
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

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

GalPaK
galaxy parameters and kinematics

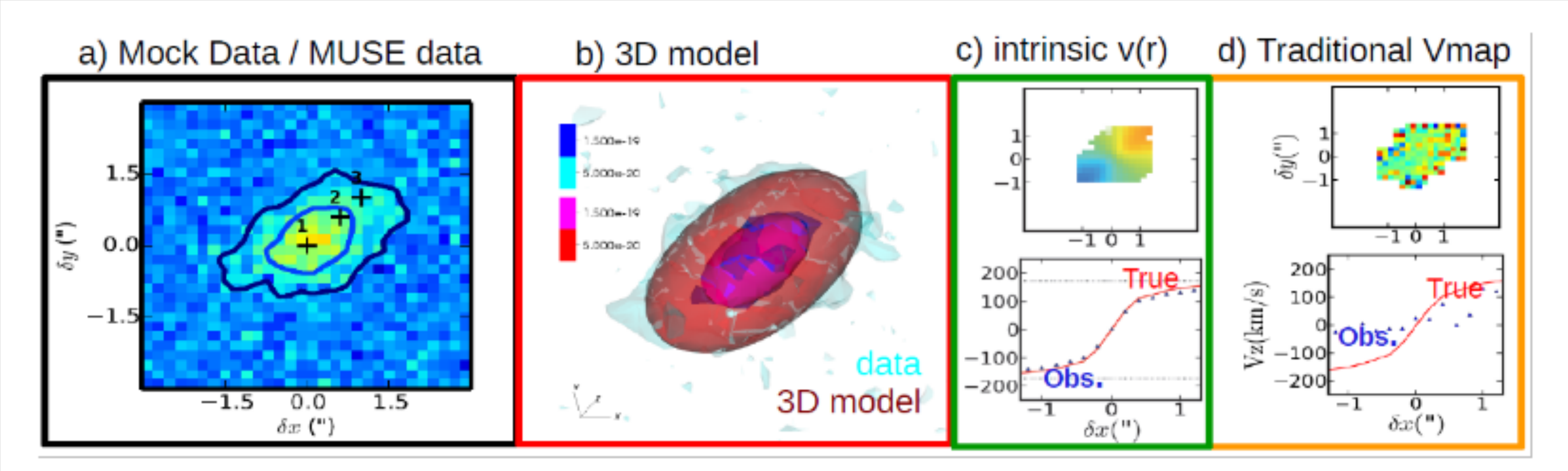
Bouché et al. 2015

this work

Using 3D forward modelling for disk-halo decomposition

GalPaK
galaxy parameters and kinematics

Bouché et al. 2015

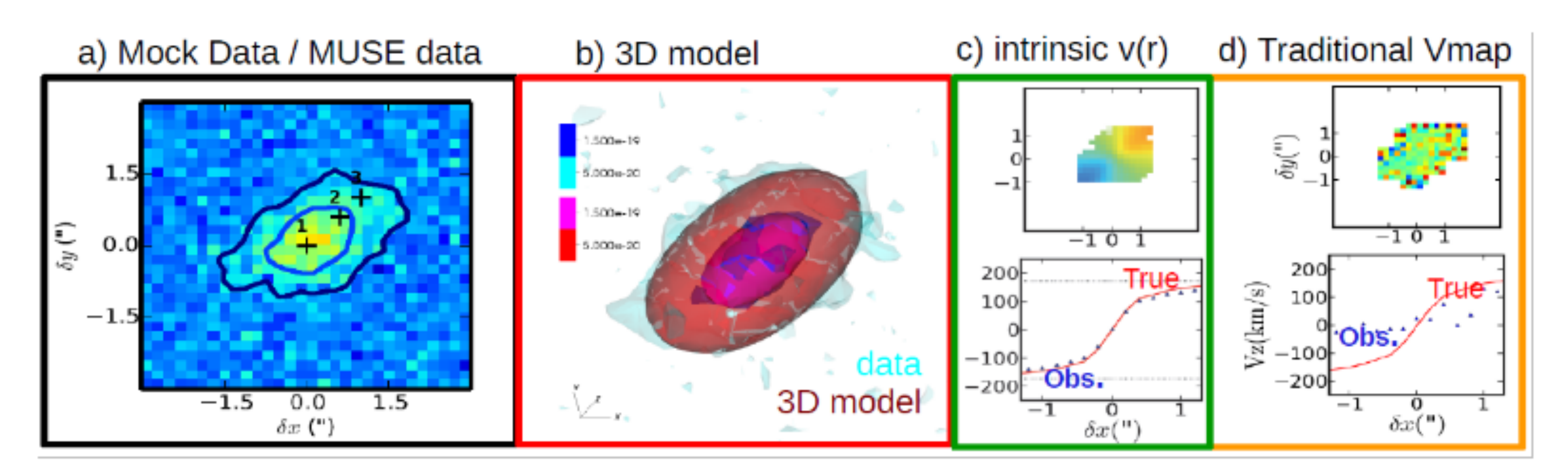


- **Compares 3D parametric models directly to the IFU data-cube, taking into account the LSF and PSF**
- **Primary assumption: axisymmetric disk**

Using 3D forward modelling for disk-halo decomposition

GalPaK — galaxy parameters and kinematics

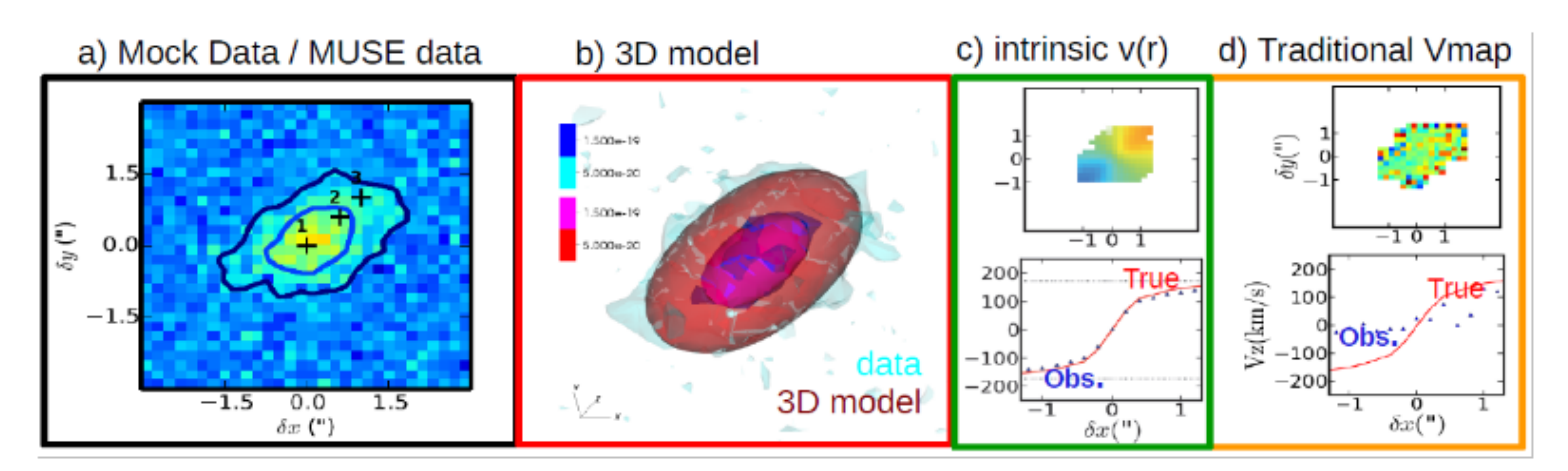
Bouché et al. 2015



Advantages :

Using 3D forward modelling for disk-halo decomposition

Bouché et al. 2015



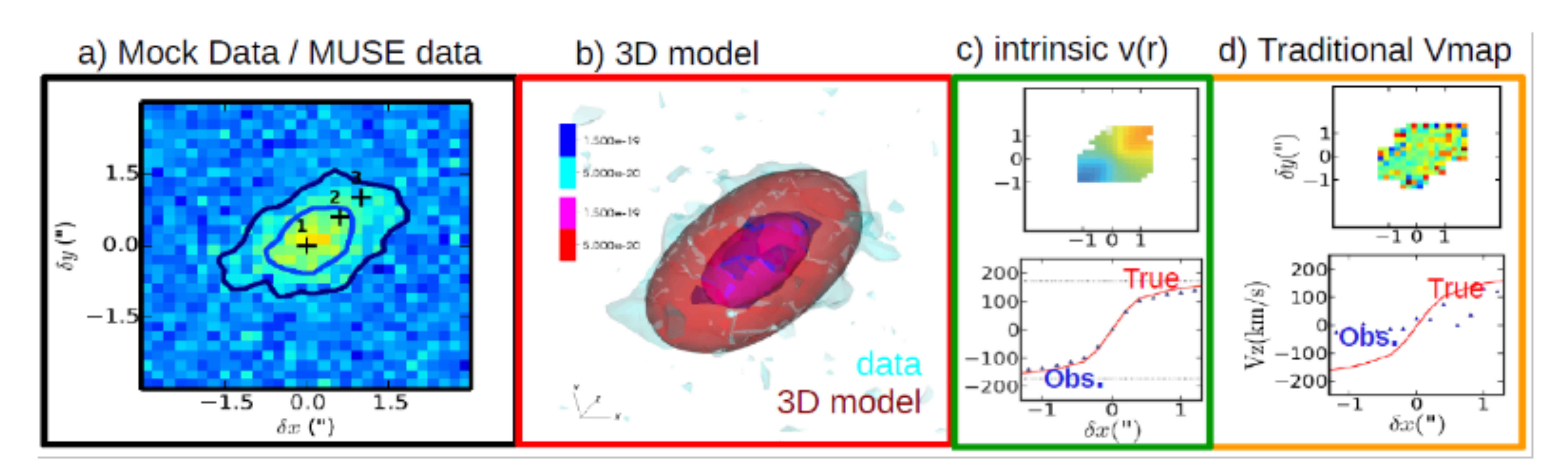
Advantages :

✦Morpho-kinematics yielded simultaneously

Using 3D forward modelling for disk-halo decomposition

GalPaK galaxy parameters and kinematics

Bouché et al. 2015



Advantages :

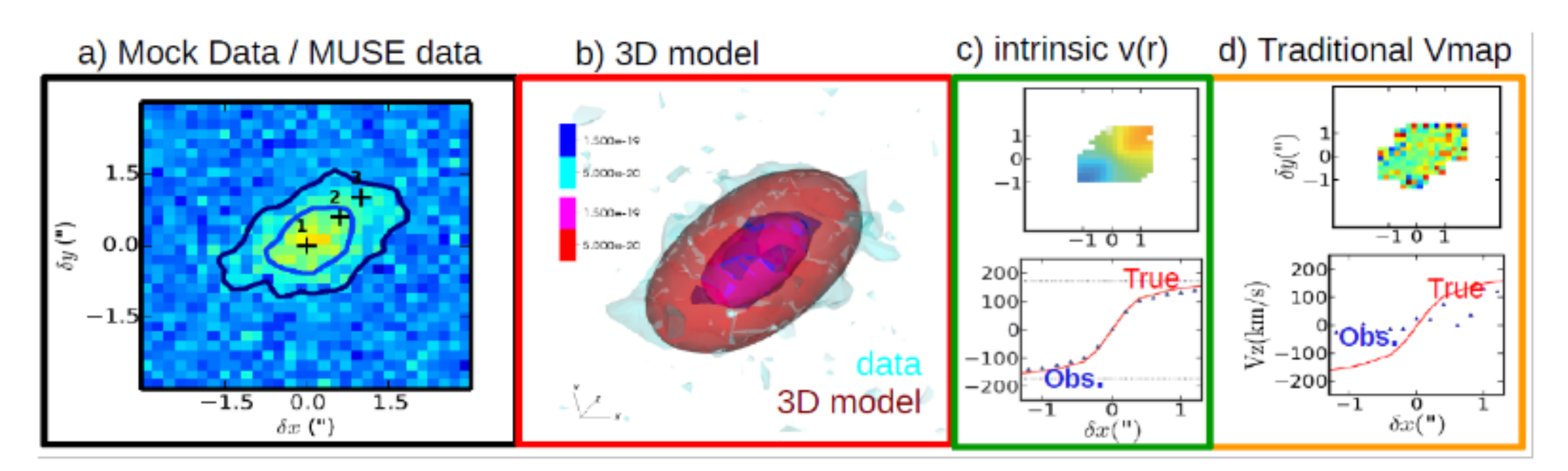
✦Morpho-kinematics yielded simultaneously

✦yields intrinsic parameters (by taking into account LSF & PSF)

Using 3D forward modelling for disk-halo decomposition

GalPaK
galaxy parameters and kinematics

Bouché et al. 2015



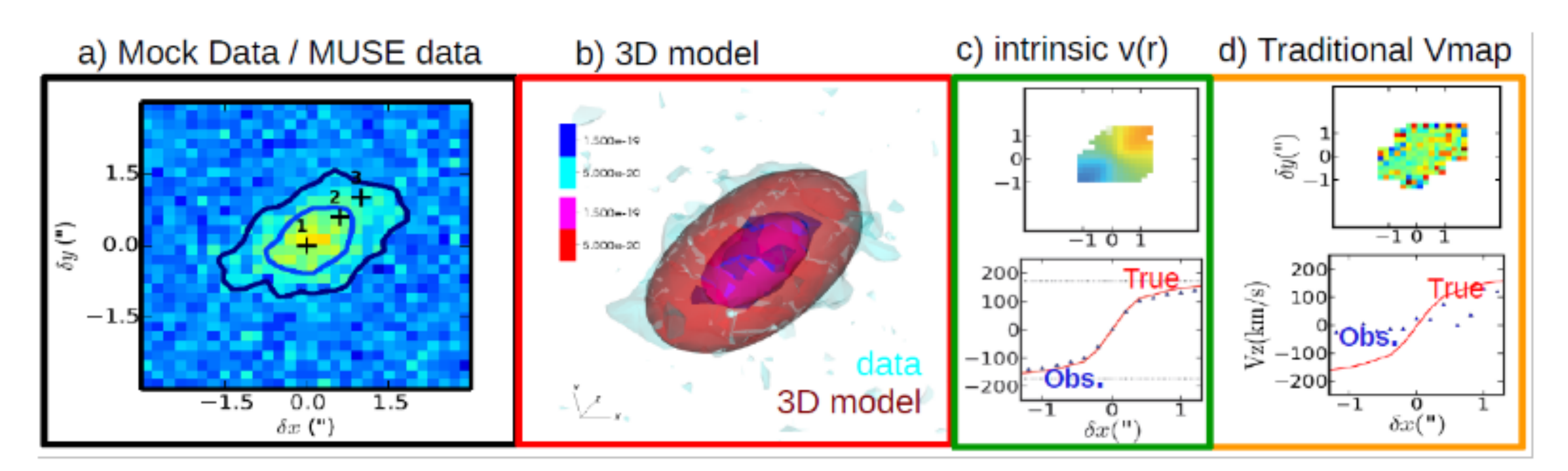
Advantages :

- ✦Morpho-kinematics yielded simultaneously
- ✦yields intrinsic parameters (by taking into account LSF & PSF)
- ✦Works on all spaxels

Using 3D forward modelling for disk-halo decomposition

GalPaK
galaxy parameters and kinematics

Bouché et al. 2015



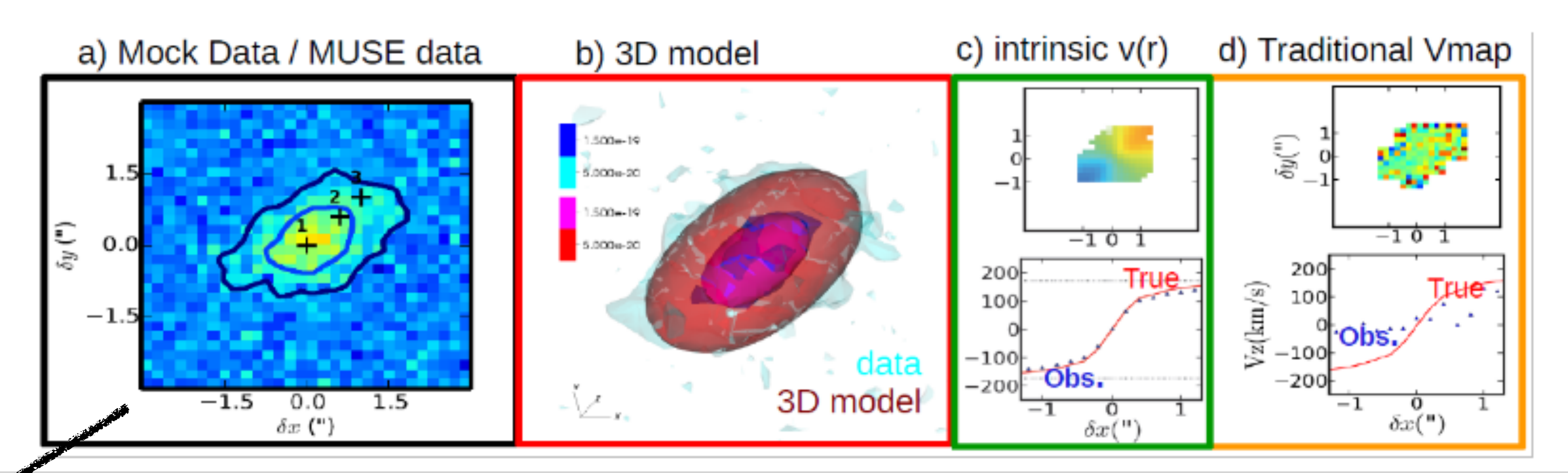
Advantages :

- ✦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]

Using 3D forward modelling for disk-halo decomposition

GalPaK
galaxy parameters and kinematics

Bouché et al. 2015



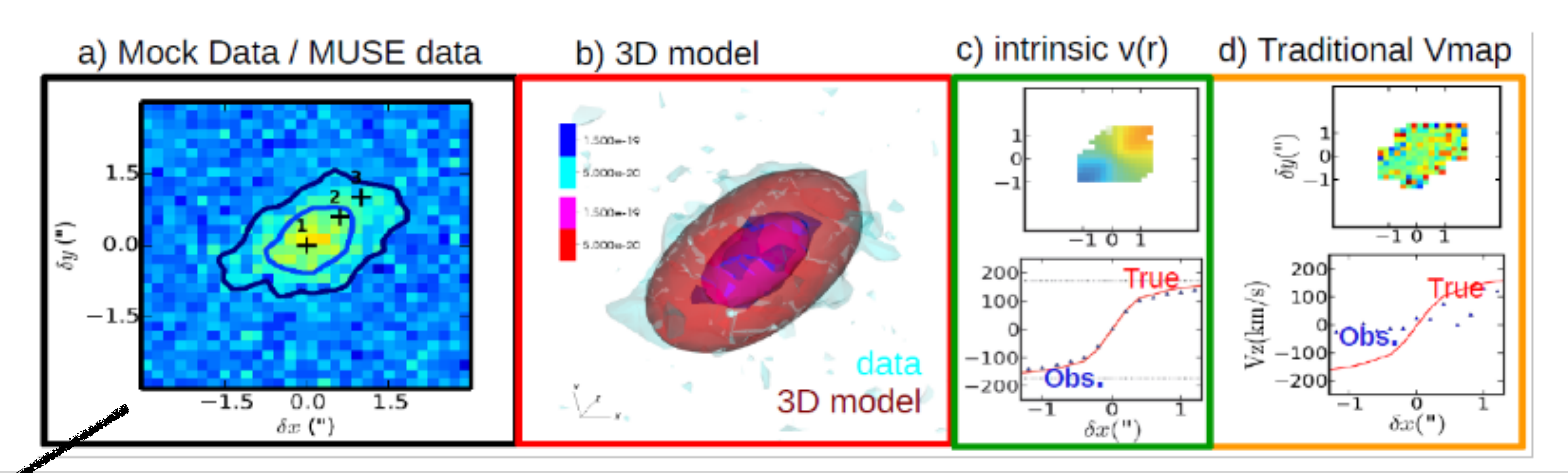
Advantages :

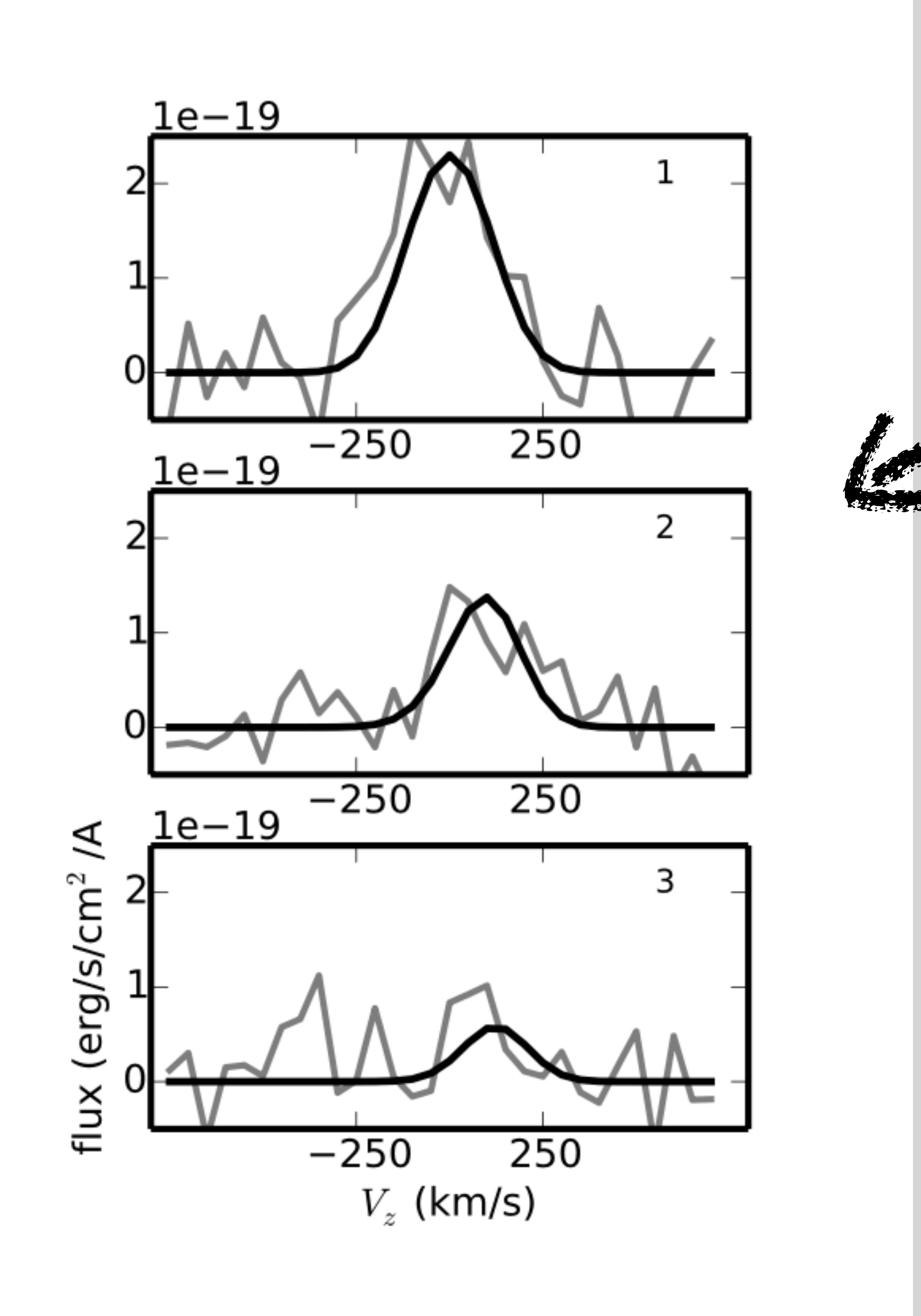
✦Morpho-kinematics yielded simultaneously
✦yields intrinsic parameters (by taking into account LSF & PSF)
✦Works on all spaxels
✦Well suited for low S/N regime [good for R>Re]

Using 3D forward modelling for disk-halo decomposition

GalPaK
galaxy parameters and kinematics

Bouché et al. 2015





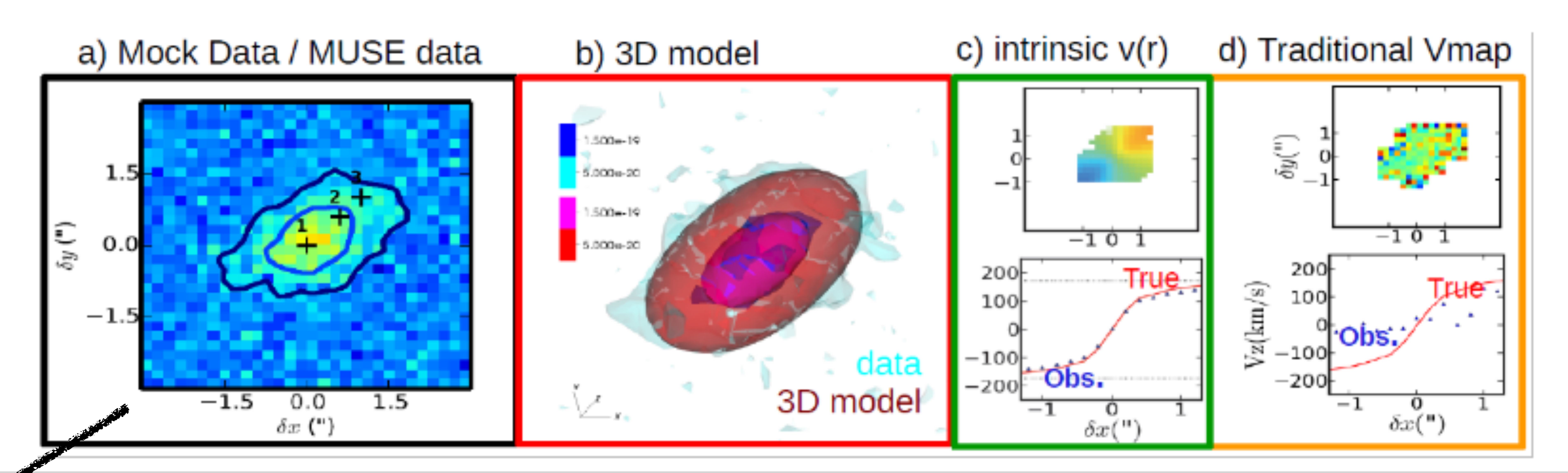
Advantages :

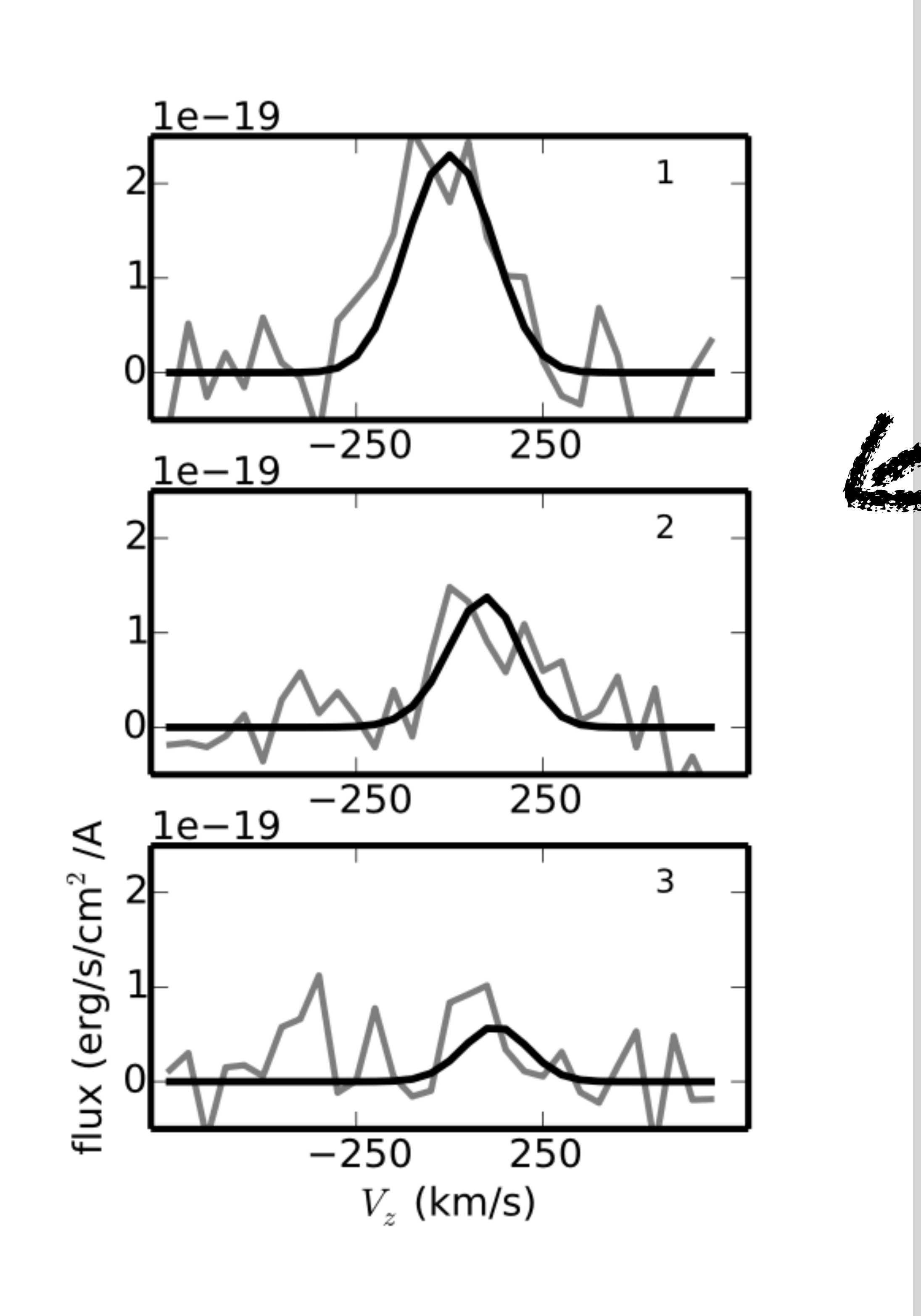
✦Morpho-kinematics yielded simultaneously
✦yields intrinsic parameters (by taking into account LSF & PSF)
✦Works on all spaxels
✦Well suited for low S/N regime [good for R>Re]

Using 3D forward modelling for disk-halo decomposition

GalPaK
galaxy parameters and kinematics

Bouché et al. 2015





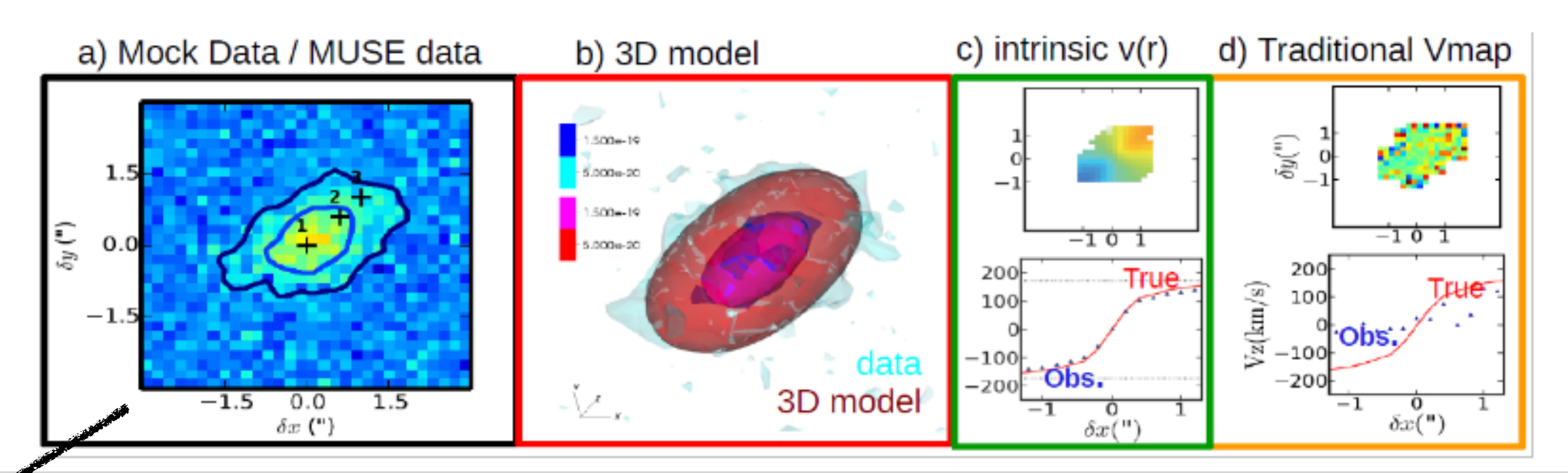
Advantages :

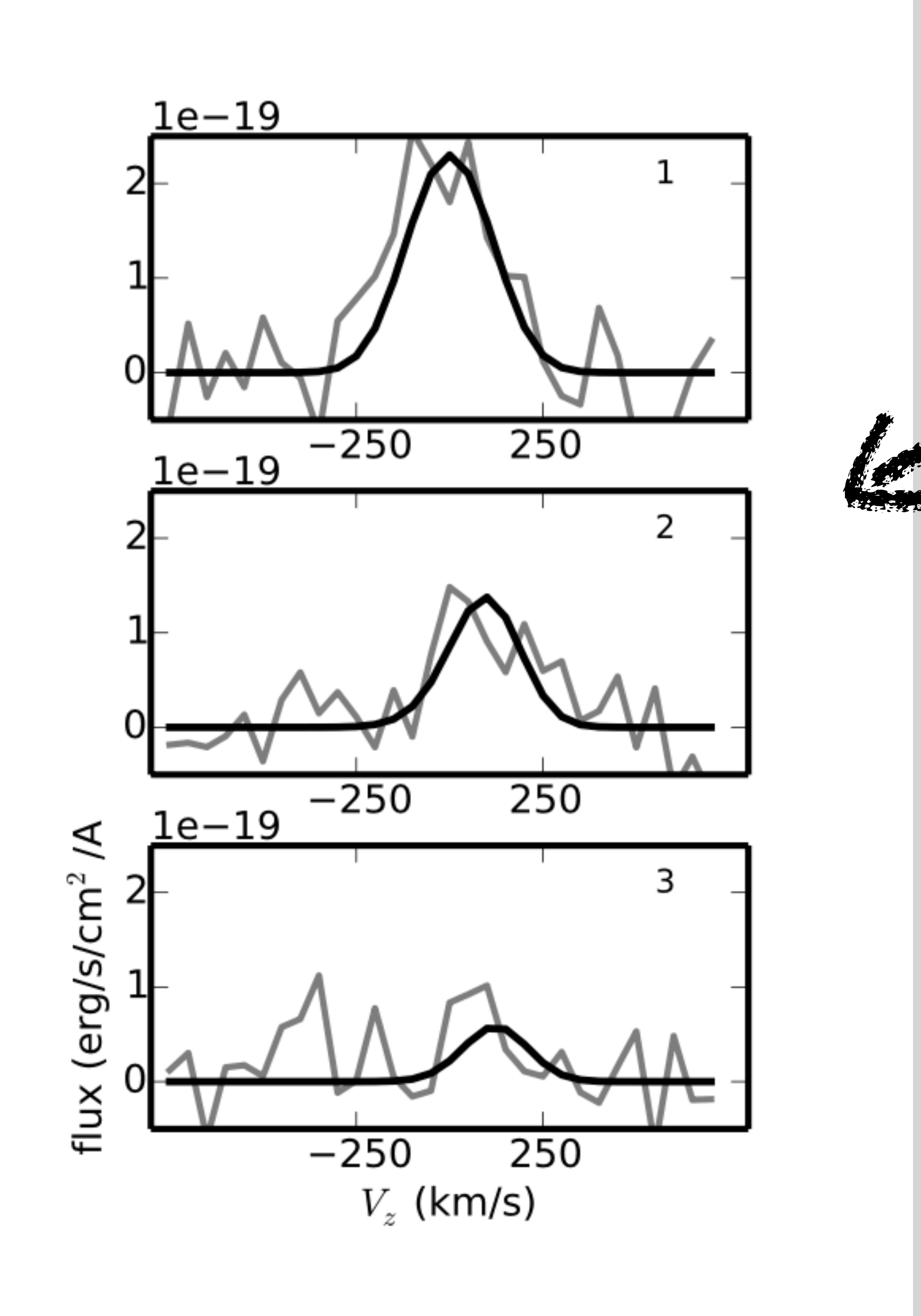
✦Morpho-kinematics yielded simultaneously
✦yields intrinsic parameters (by taking into account LSF & PSF)
✦Works on all spaxels
✦Well suited for low S/N regime [good for R>Re]
✦Breaks inclination-Vmax degeneracy

Using 3D forward modelling for disk-halo decomposition

GalPaK
galaxy parameters and kinematics

Bouché et al. 2015





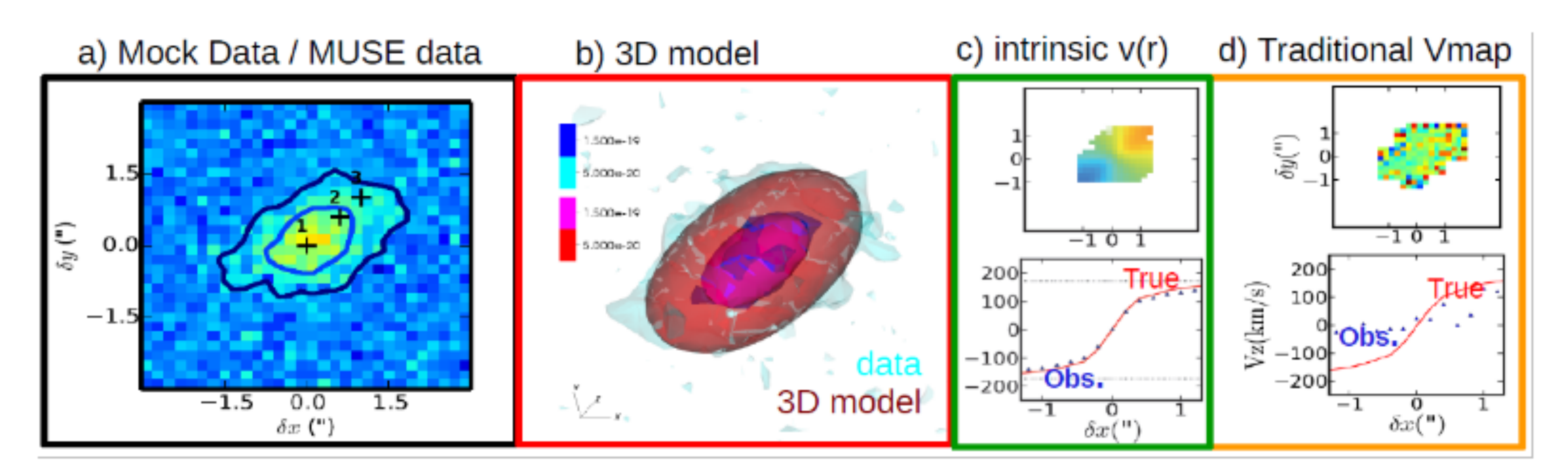
Advantages :

- ✦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

Using 3D forward modelling for disk-halo decomposition

GalPaK
galaxy parameters and kinematics

Bouché et al. 2015

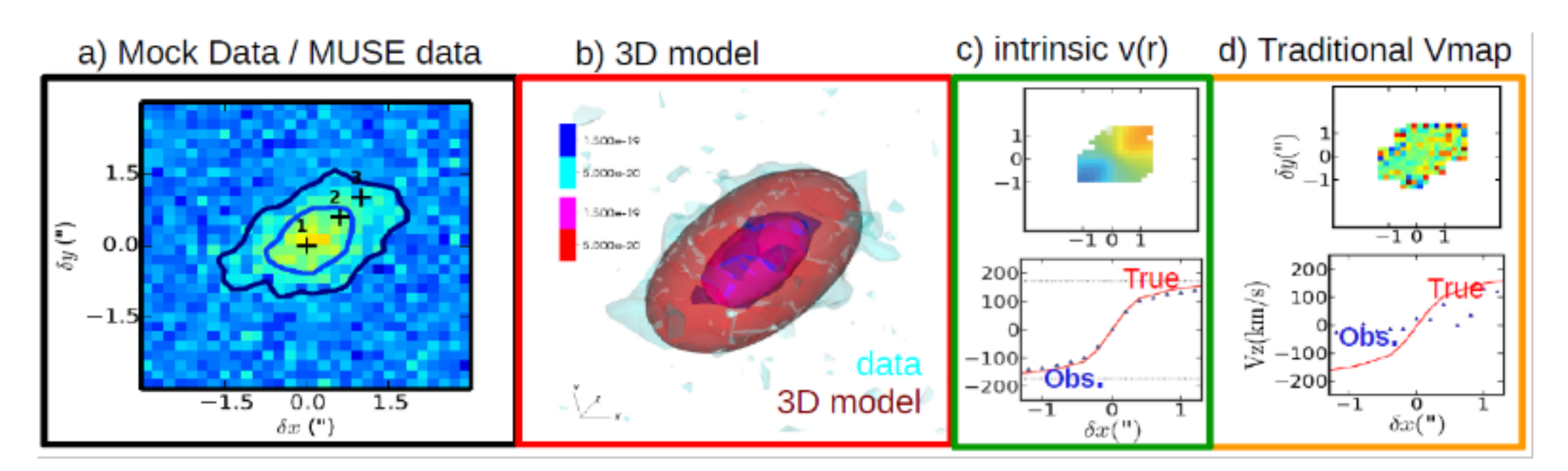


Compare to state-of-the-art :

Using 3D forward modelling for disk-halo decomposition

GalPaK
galaxy parameters and kinematics

Bouché et al. 2015

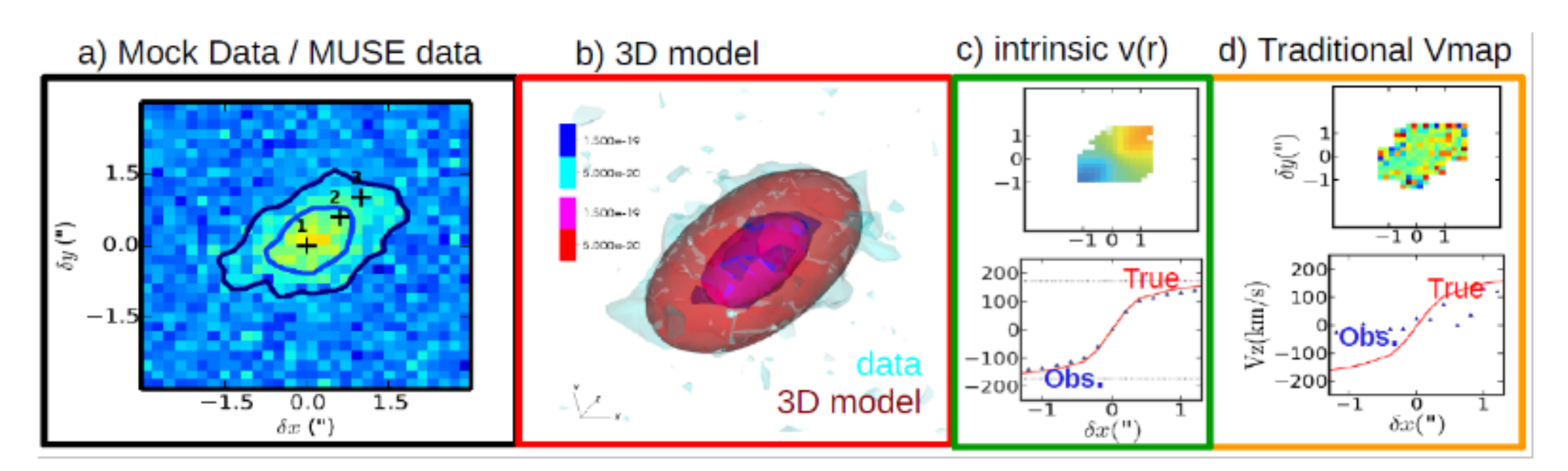


Compare to state-of-the-art :

Using 3D forward modelling for disk-halo decomposition

GalPaK
galaxy parameters and kinematics

Bouché et al. 2015



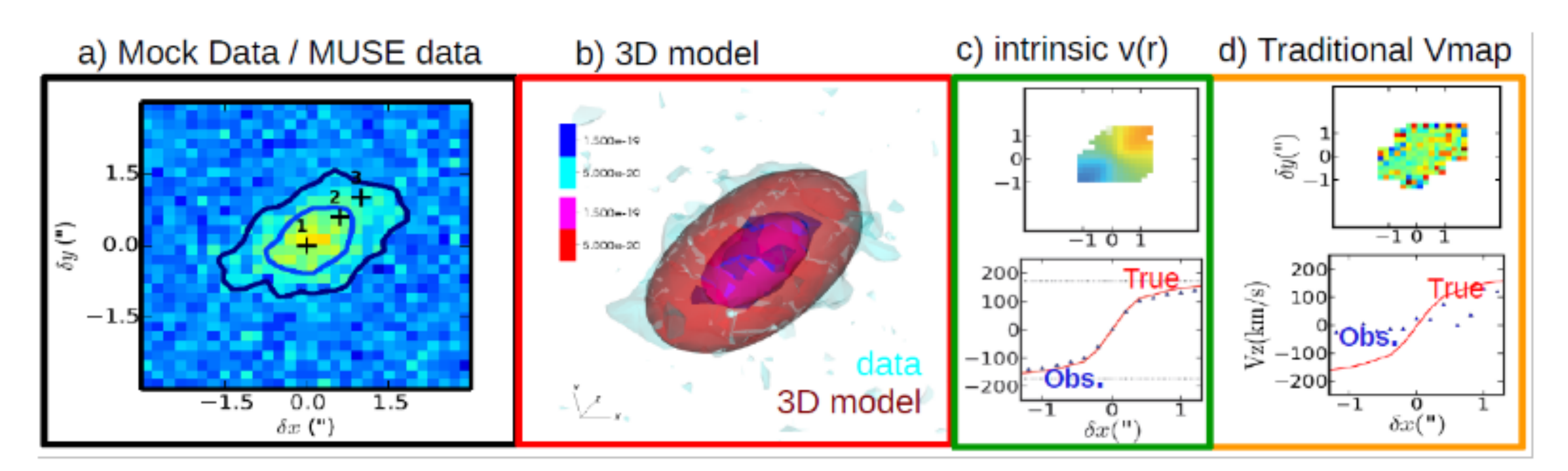
Compare to state-of-the-art :

✦ 3D method (vs. 1D)

Using 3D forward modelling for disk-halo decomposition

GalPaK
galaxy parameters and kinematics

Bouché et al. 2015



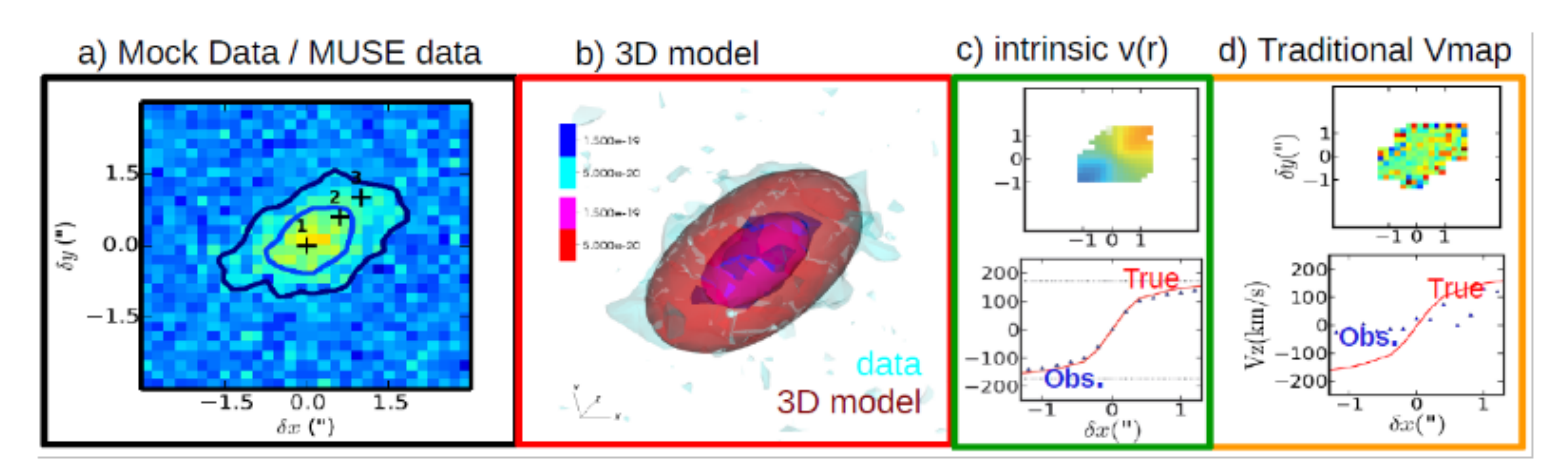
Compare to state-of-the-art :

- ✦ 3D method (vs. 1D)
- ✦ No priors (M*, inclination)

Using 3D forward modelling for disk-halo decomposition

GalPaK
galaxy parameters and kinematics

Bouché et al. 2015



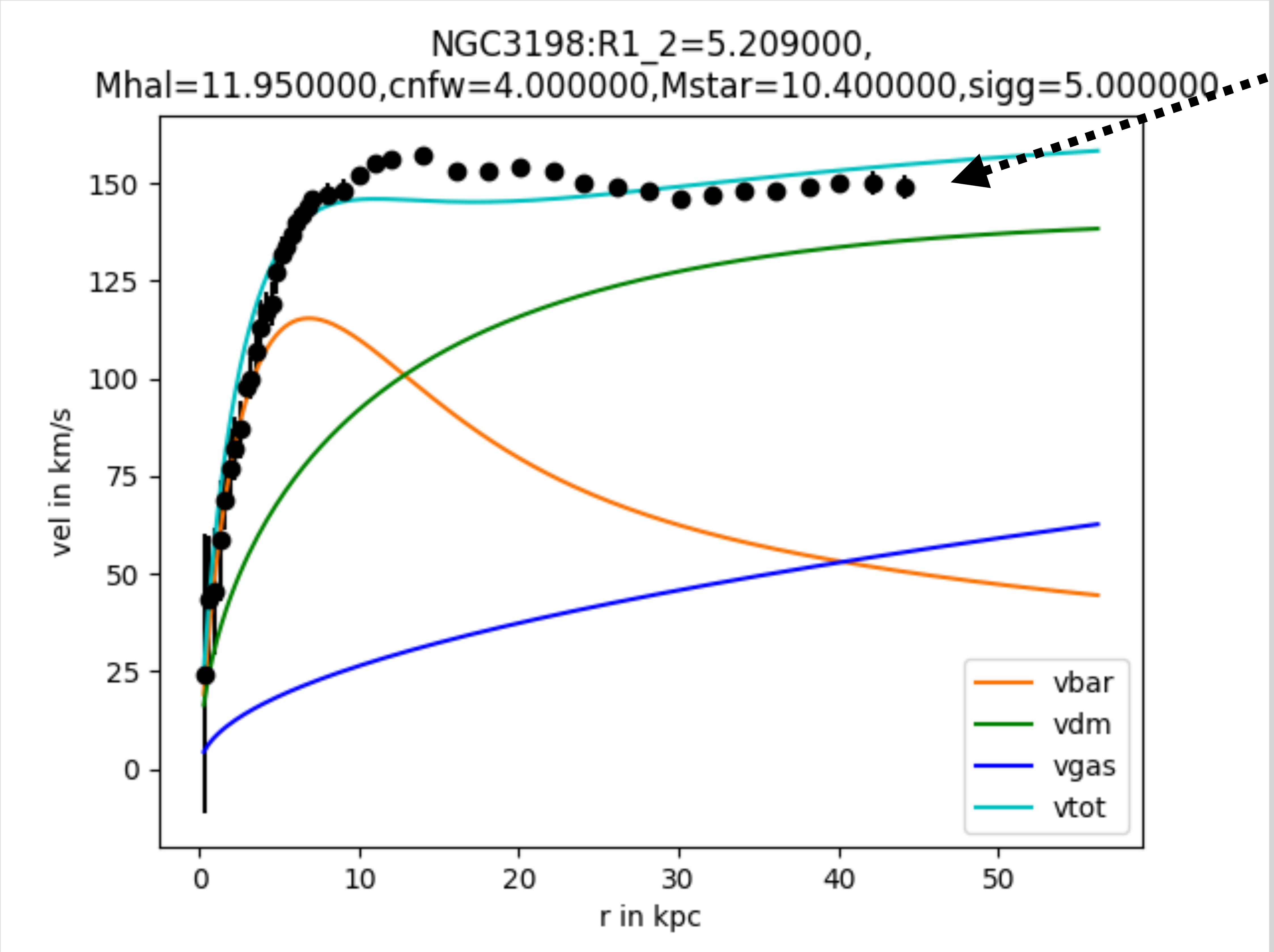
Compare to state-of-the-art :

- ✦ 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

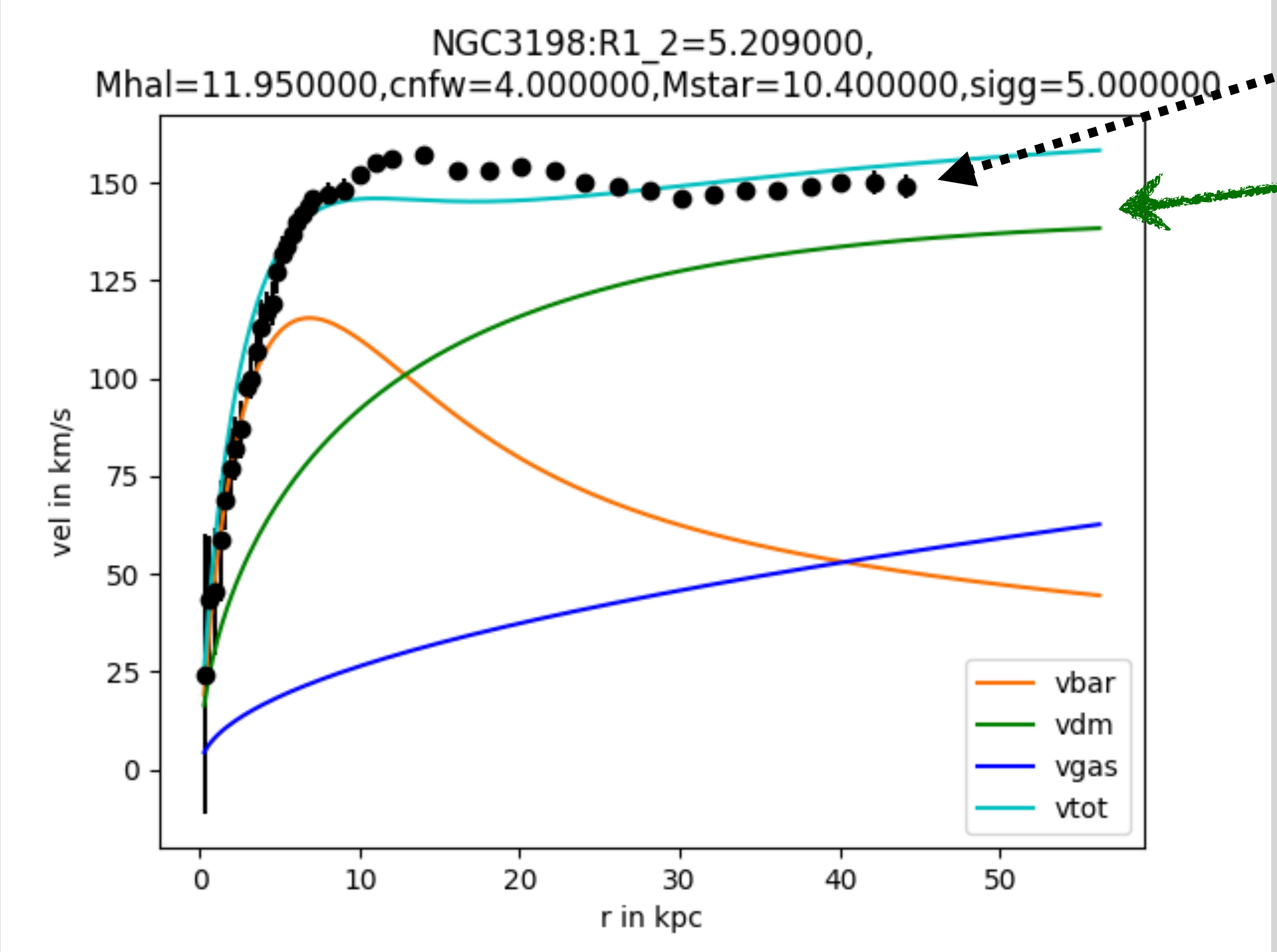


$$v_c(r)^2 = v_{DM}(r)^2 + v_{disk}(r)^2 + v_{HI}(r)^2$$

Using 3D forward modelling: Under the hood

GalPaK galaxy parameters and kinematics

Bouché et al. 2015

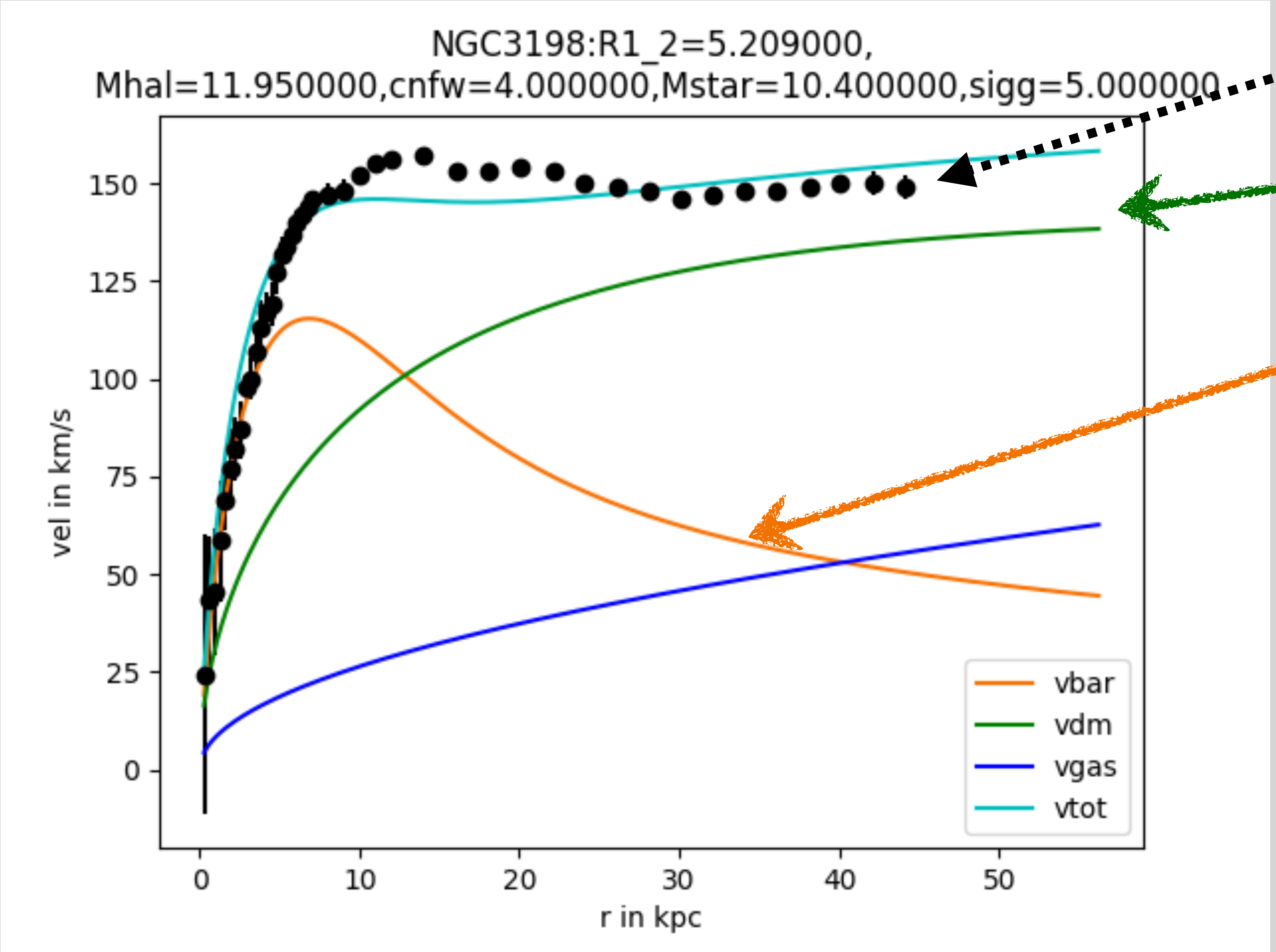


$$v_c(r)^2 = v_{DM}(r)^2 + v_{disk}(r)^2 + v_{HI}(r)^2$$

Using 3D forward modelling: Under the hood

GalPaK — galaxy parameters and kinematics

Bouché et al. 2015

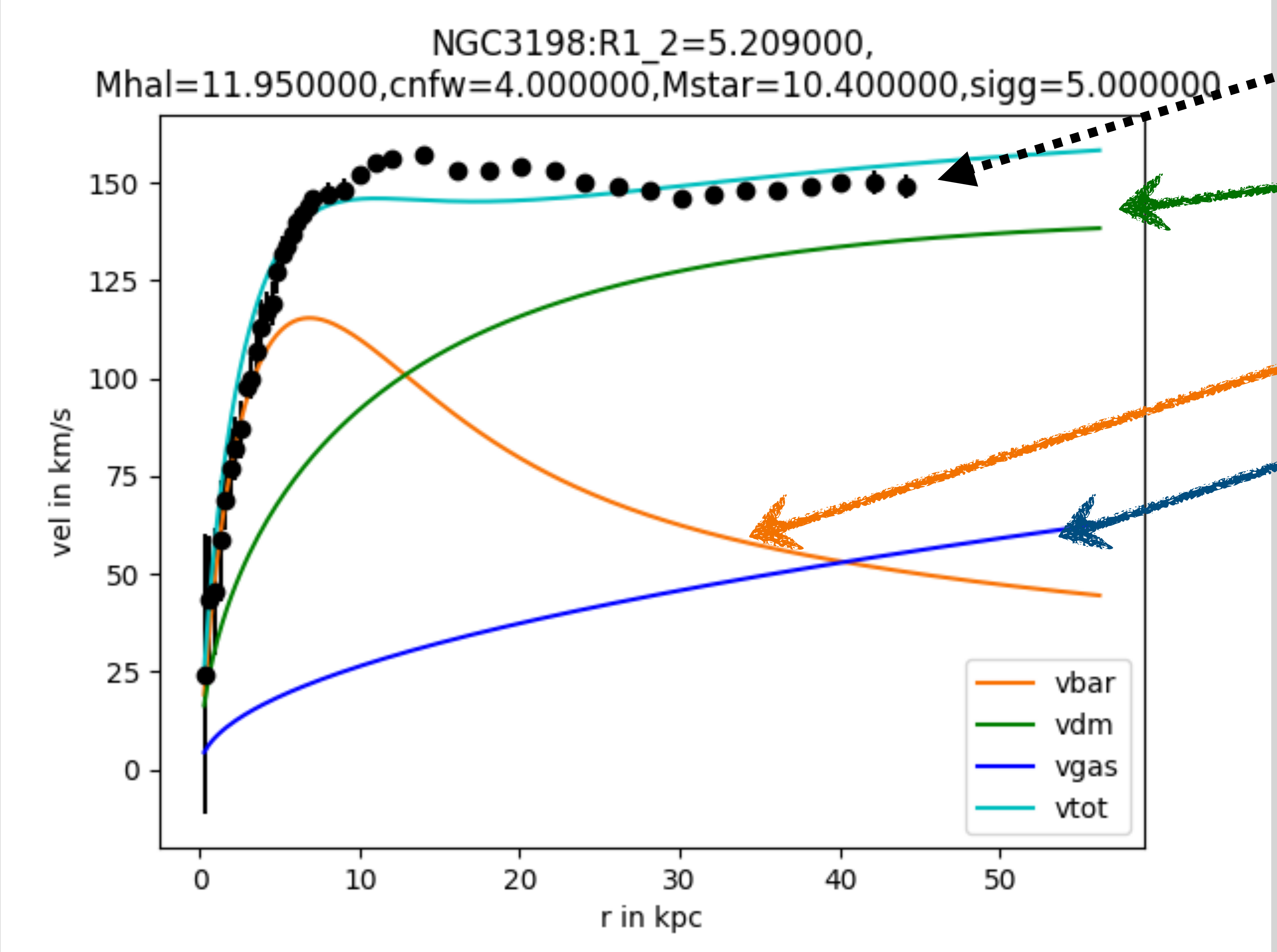


$$v_c(r)^2 = v_{DM}(r)^2 + v_{disk}(r)^2 + v_{HI}(r)^2$$

Using 3D forward modelling: Under the hood

GalPaK galaxy parameters and kinematics

Bouché et al. 2015

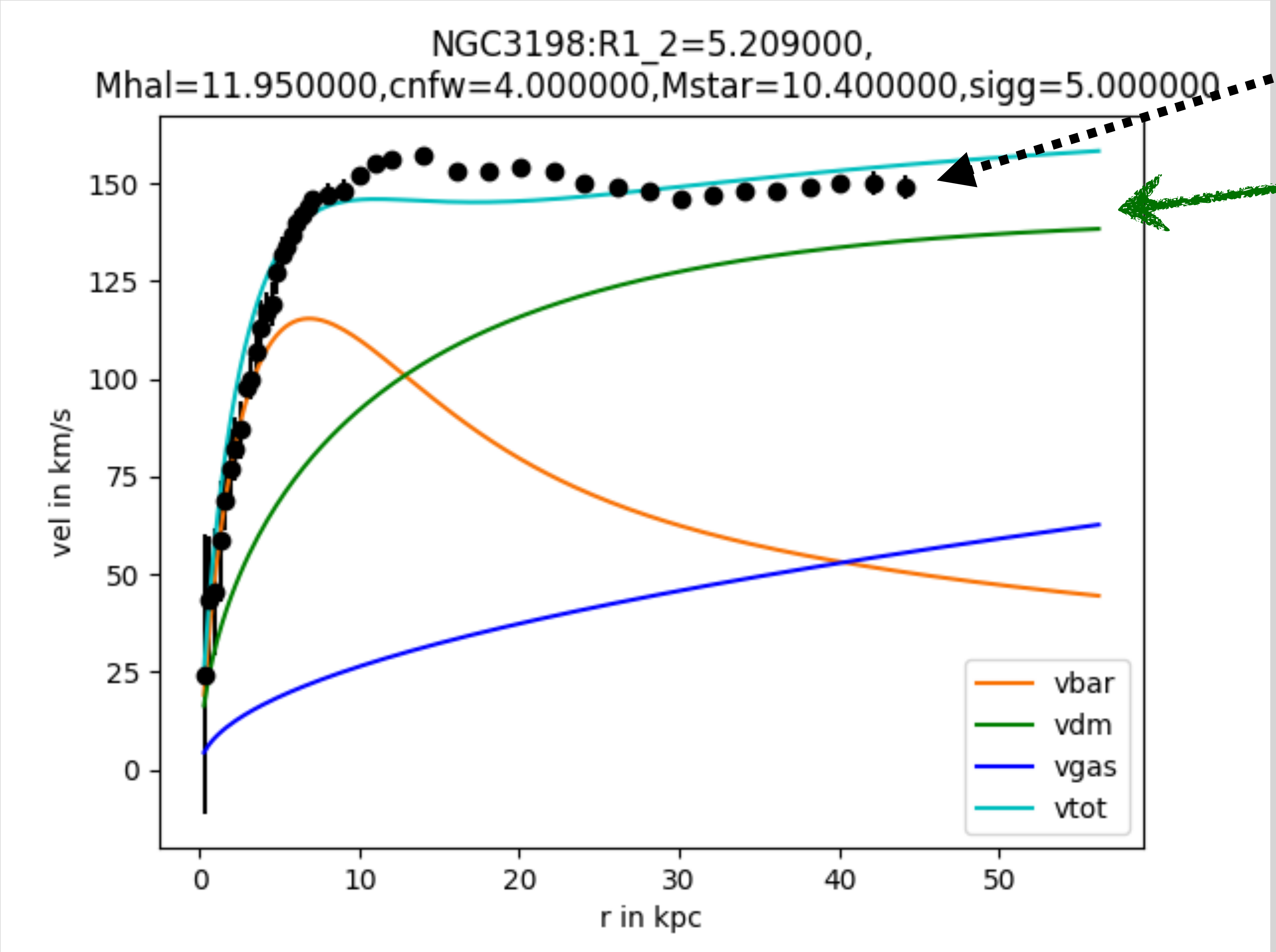


$$v_c(r)^2 = v_{DM}(r)^2 + v_{disk}(r)^2 + v_{HI}(r)^2$$

Using 3D forward modelling: Under the hood

GalPaK galaxy parameters and kinematics

Bouché et al. 2015



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

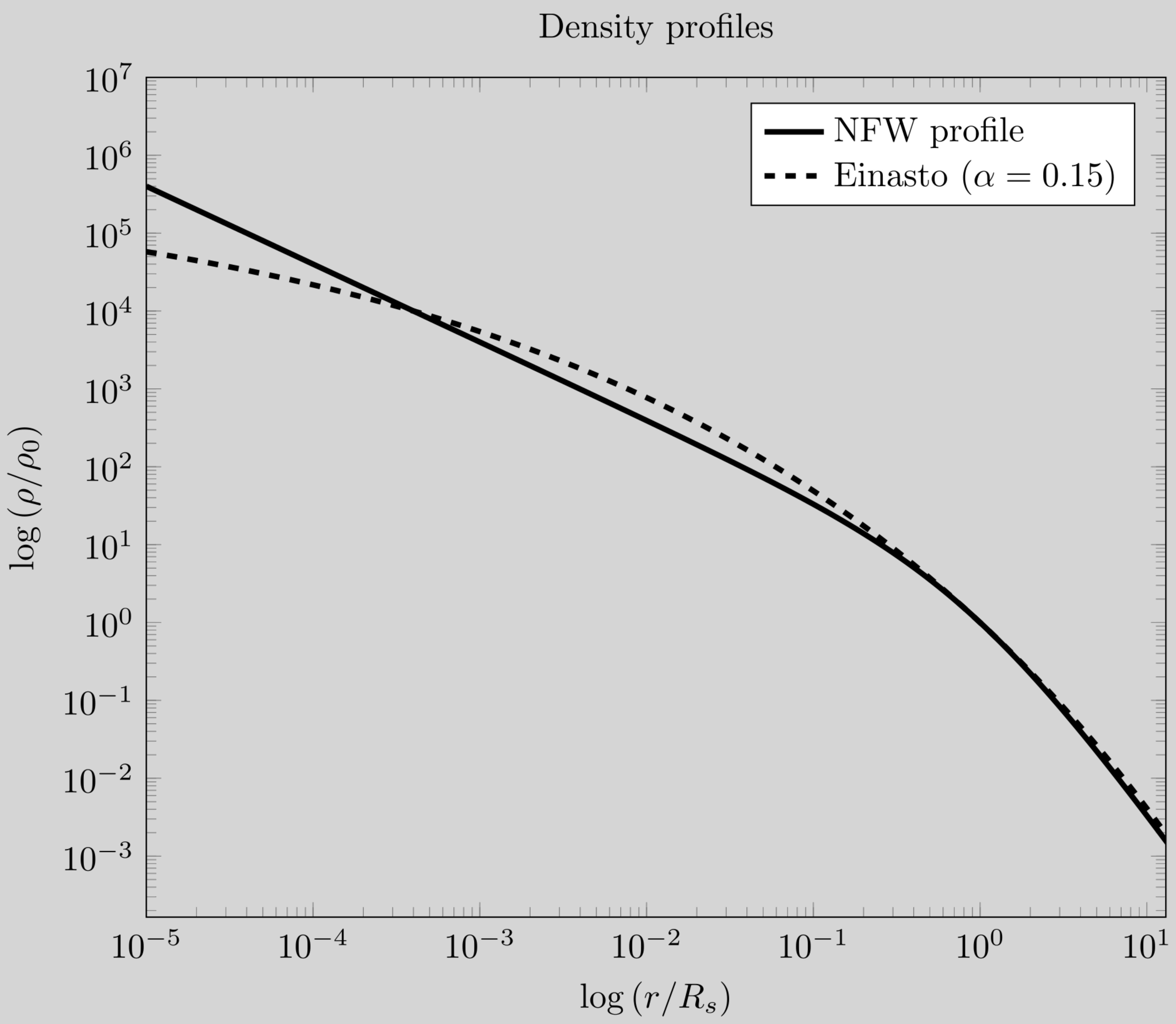
1) DM: different Dark Matter density profiles

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

Examples of Halo profiles - from hydrodynamical simulations

CORE-CUSP

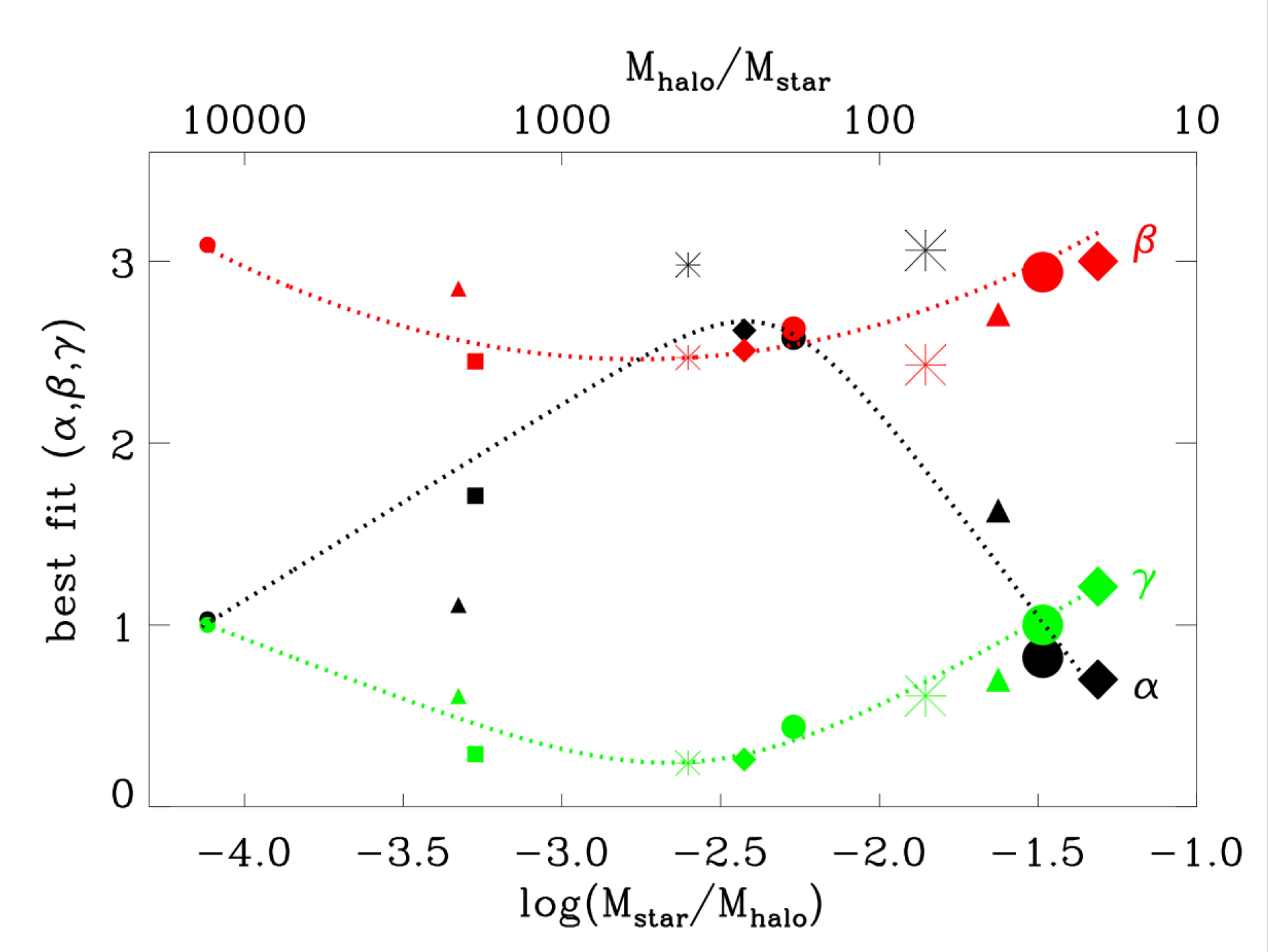
$$\rho_{\rm DC14}(r) = \frac{\rho_s}{\left(\frac{r}{r_s}\right)^{\gamma}\left(1+\left(\frac{r}{r_s}\right)^{\alpha}\right)^{(\beta-\gamma)/\alpha}}$$

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

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

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

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



Di Cintio et al. 2014

➡takes into account the response of dark matter to baryonic processes

Examples of Halo profiles - from hydrodynamical simulations

CORE-CUSP

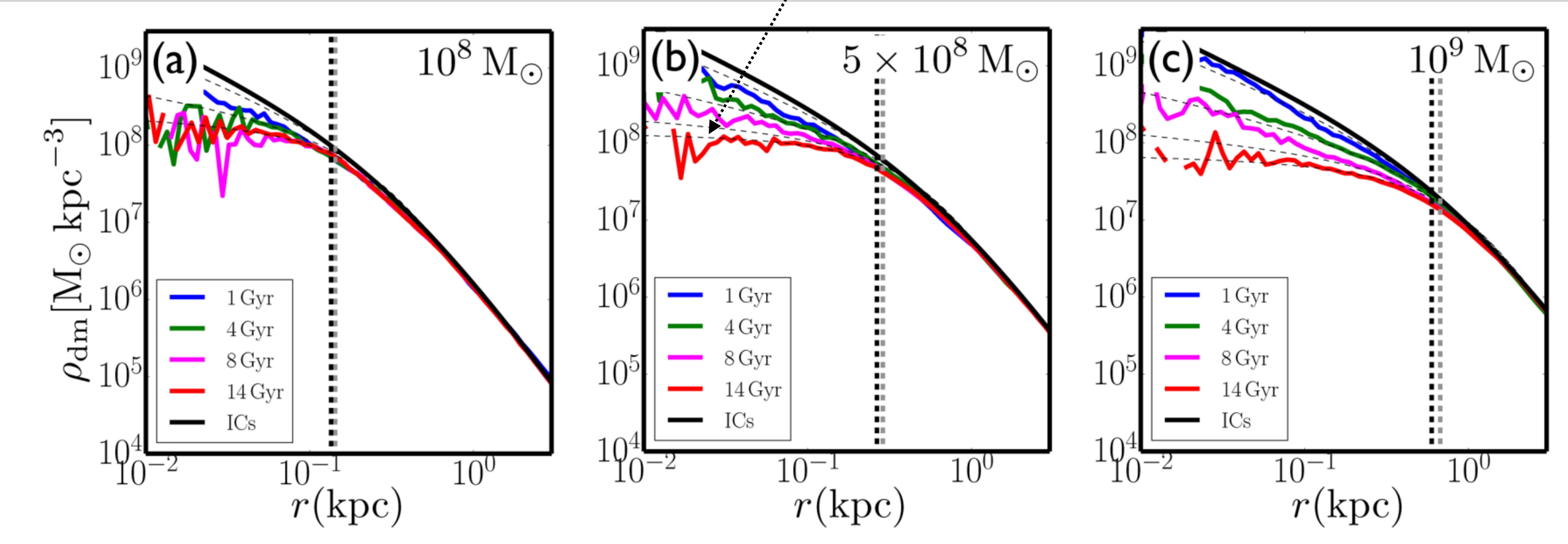
$$\rho_{\mathrm{cNFW}} = f^n(r)\rho_{\mathrm{NFW}} + \frac{n f^{n-1}(r)(1 - f^2(r))}{4\pi r^2 r_c} M_{\mathrm{NFW}}$$

where

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

Read et al. 2016

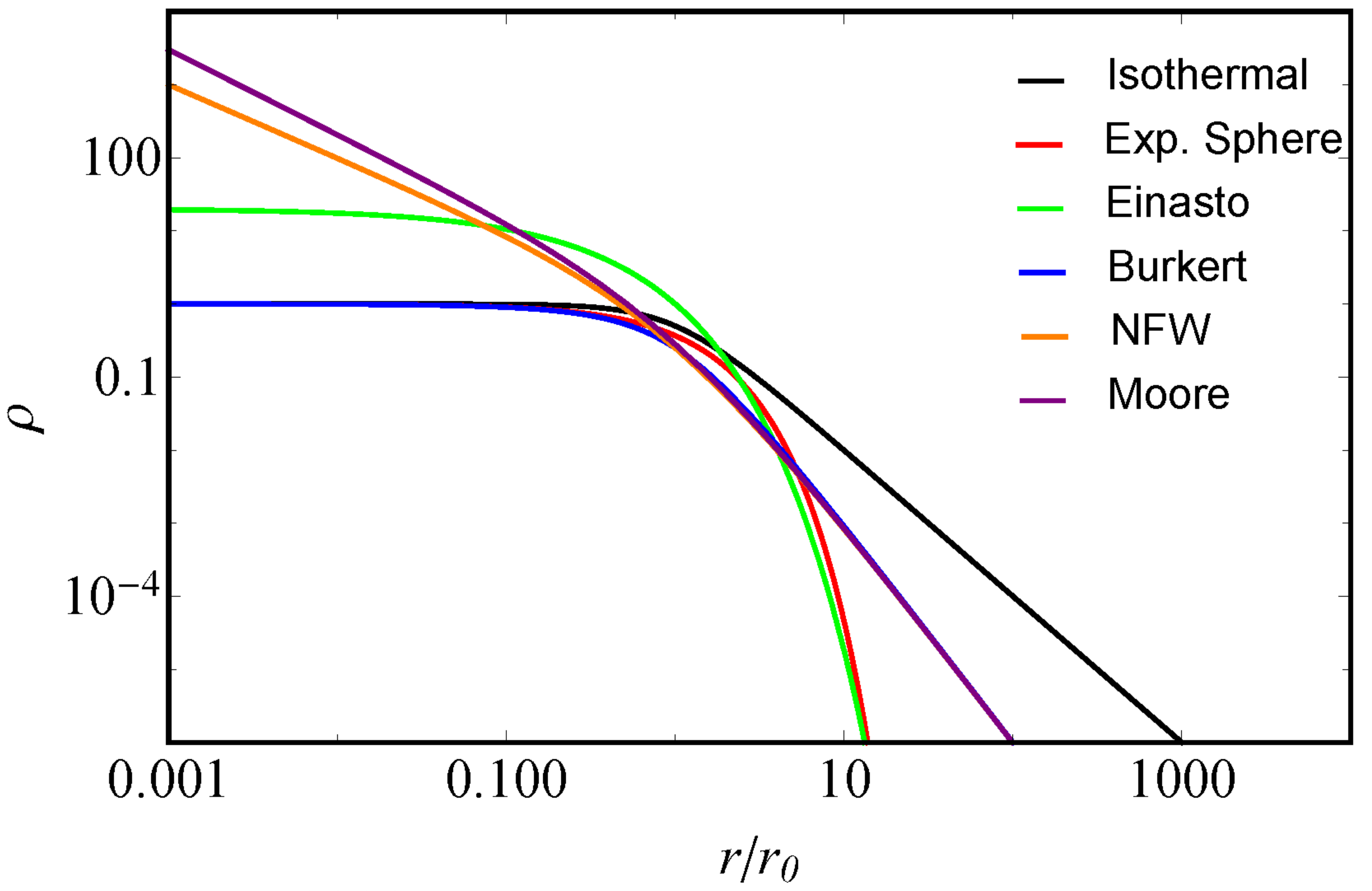
coreNFW fits



➡captures the dark matter core growth as a function of star formation time

Examples of Halo profiles - many more

- ➡Einasto (Navarro et al. 2004)
- ➡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 Profile (Freundlich et al. 2020)
- ➡cNFW Profile(Peñarrubia et al. 2012)
- ➡coreEinasto Profile (Lazar et al. 2020)
- ➡etc

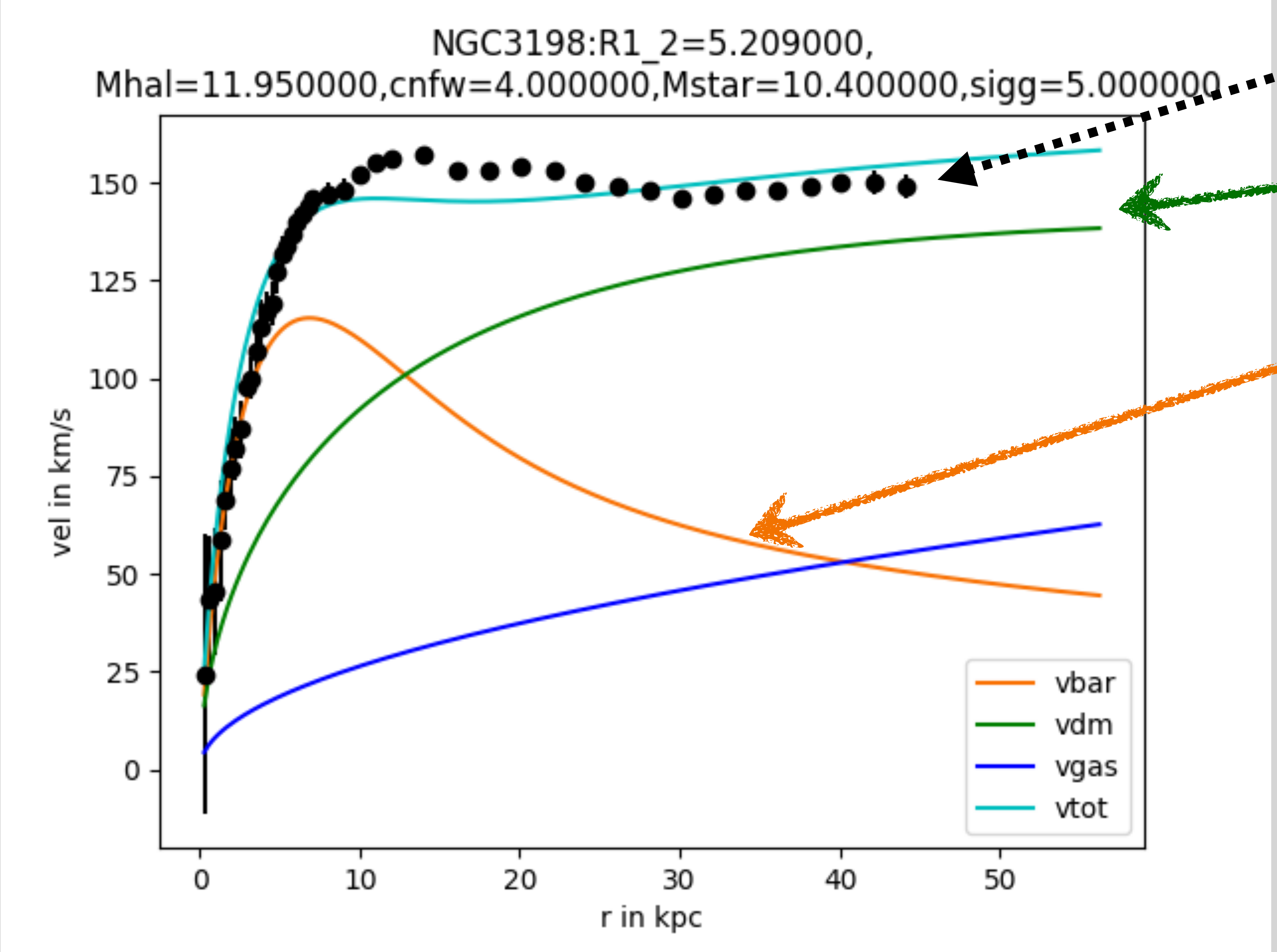


Boshkaye +2020

Using 3D forward modelling: Under the hood

GalPaK
galaxy parameters and kinematics

Bouché et al. 2015



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

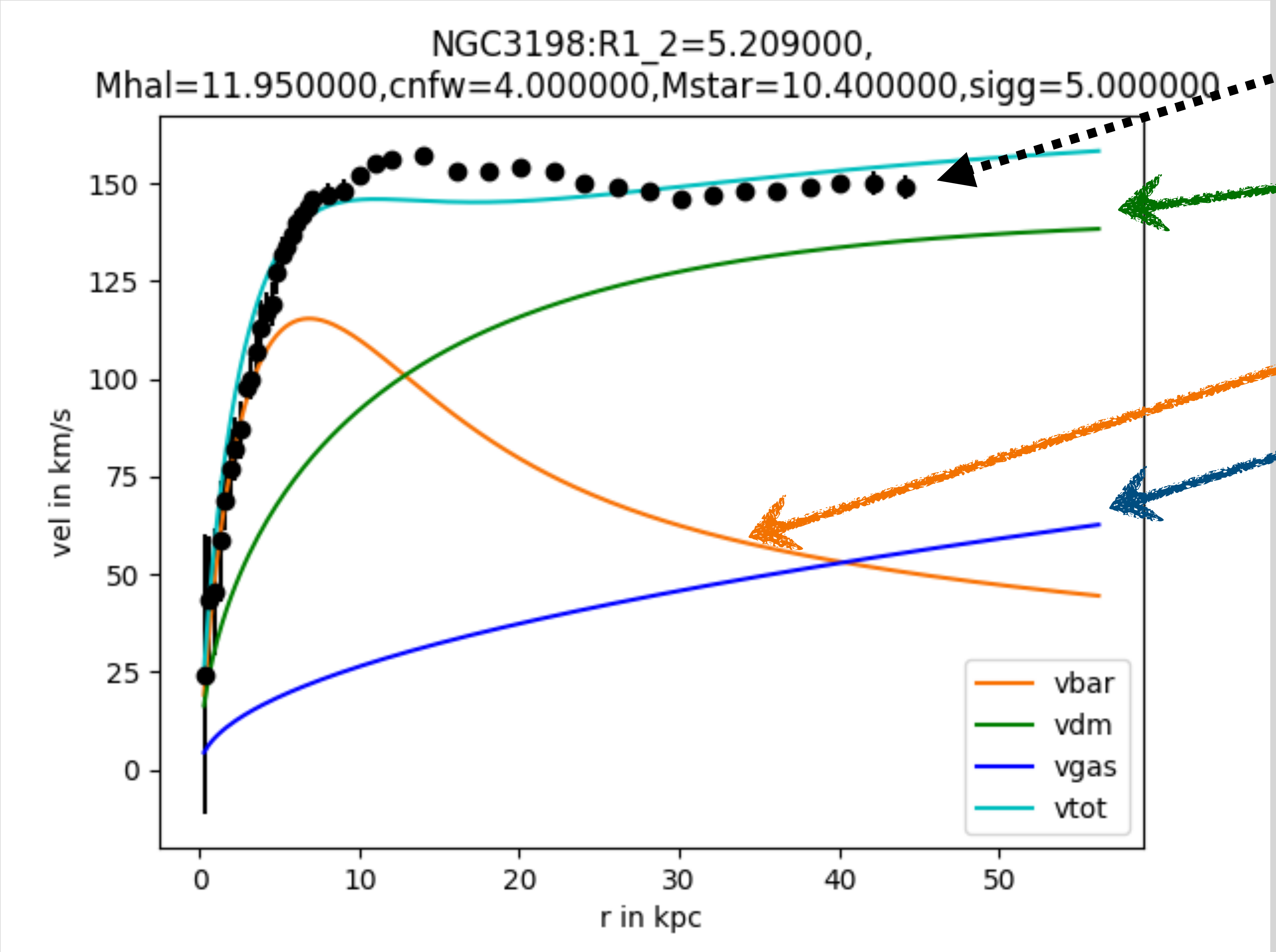
1) DM: different Dark Matter halo profiles

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

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)

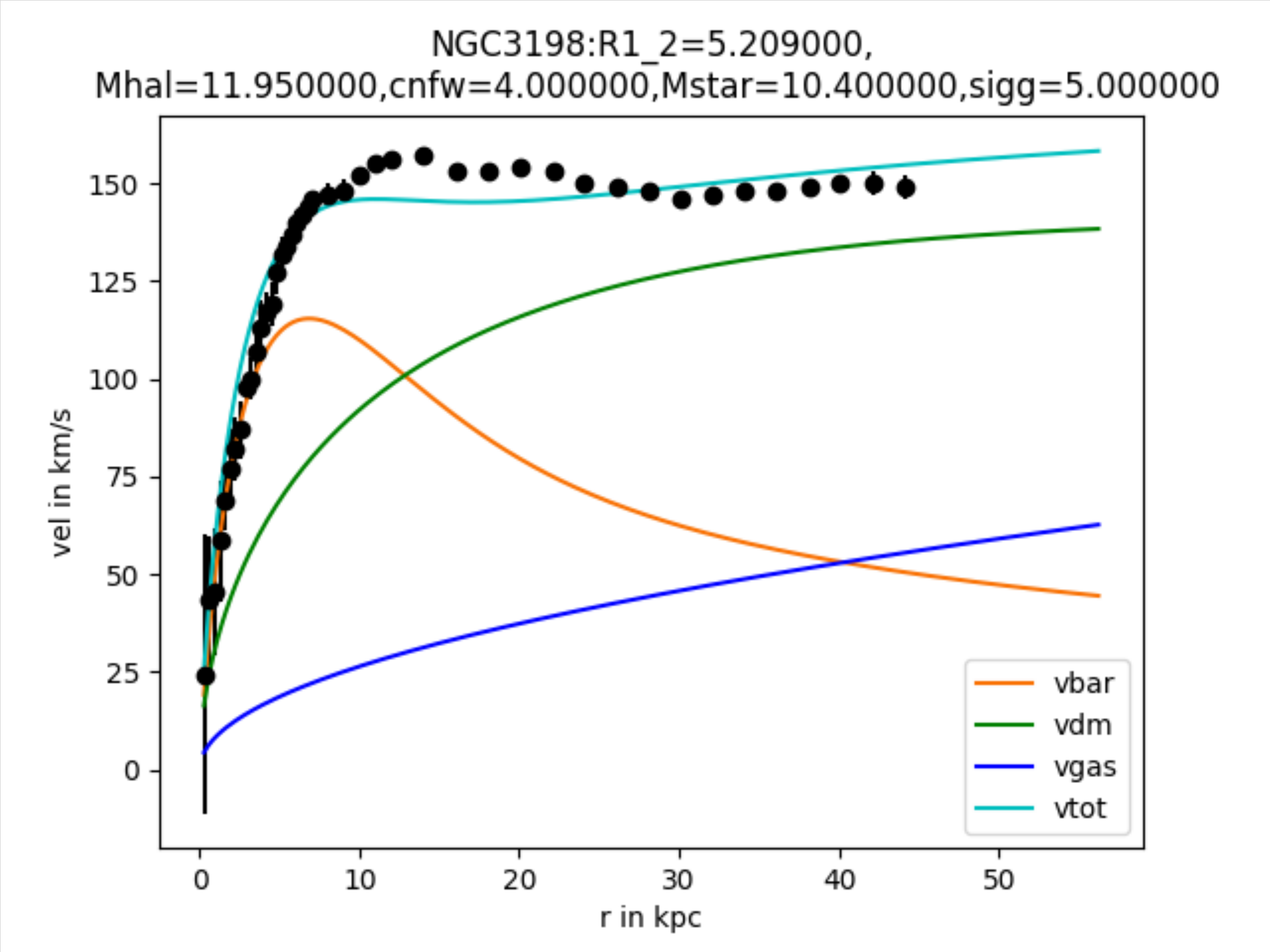
$$v_{HI}(r) \propto \sqrt{\Sigma_g r}$$

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)

→ **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:

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)

Validation of the methodology:

GalPaK galaxy parameters and kinematics

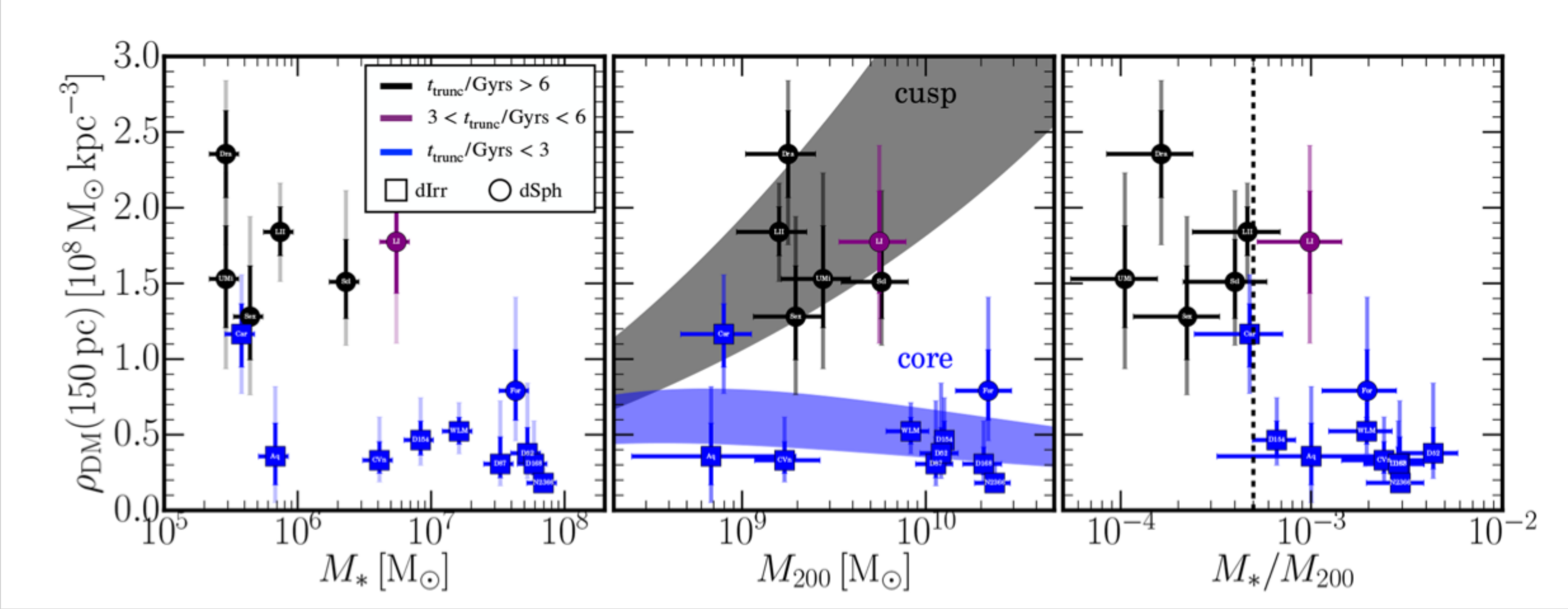
- Apply 3D disk-halo decomposition on mock observations (using DC14 halo profile)

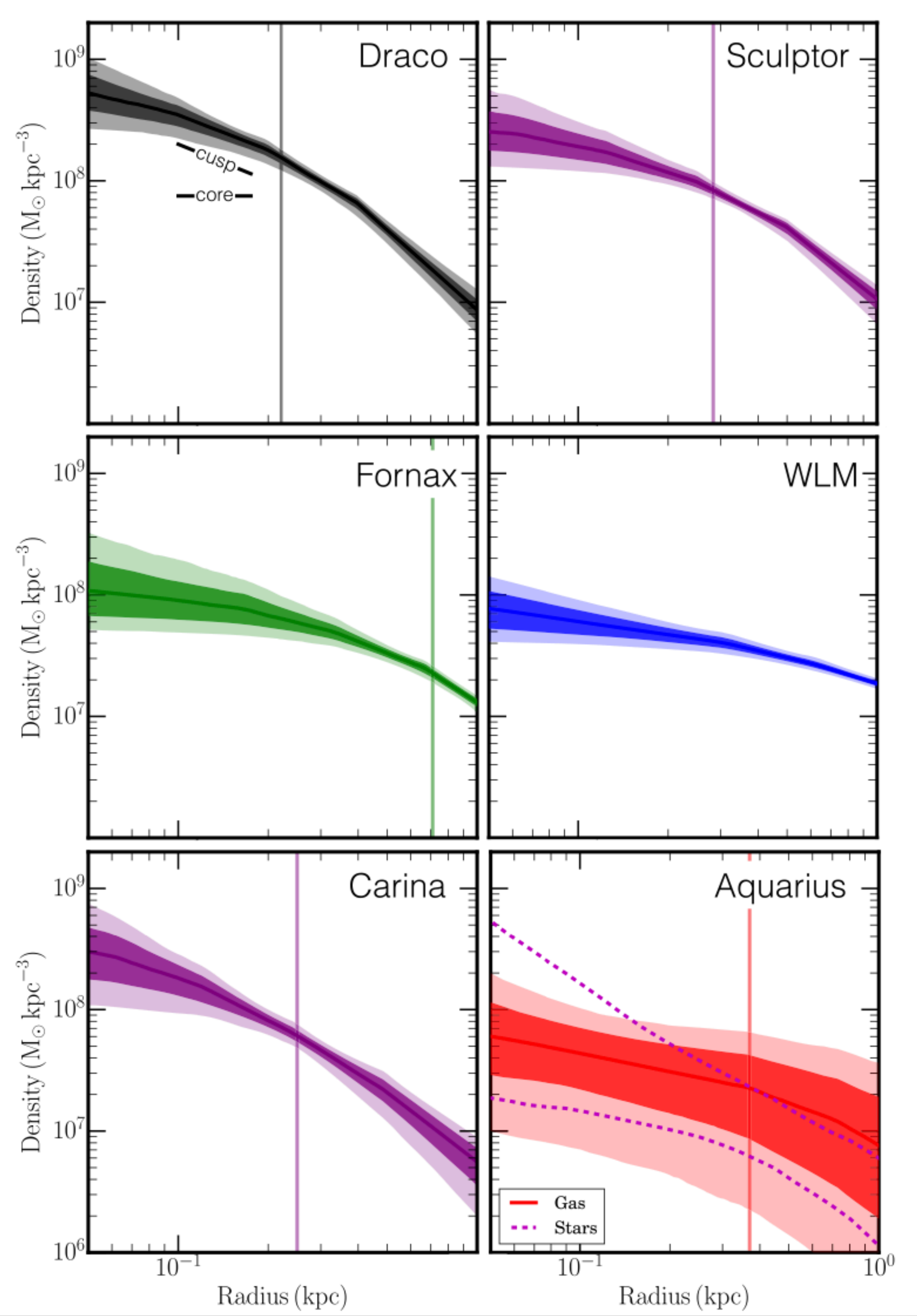
State-of-the-art (z=0): Read et al. 2019

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

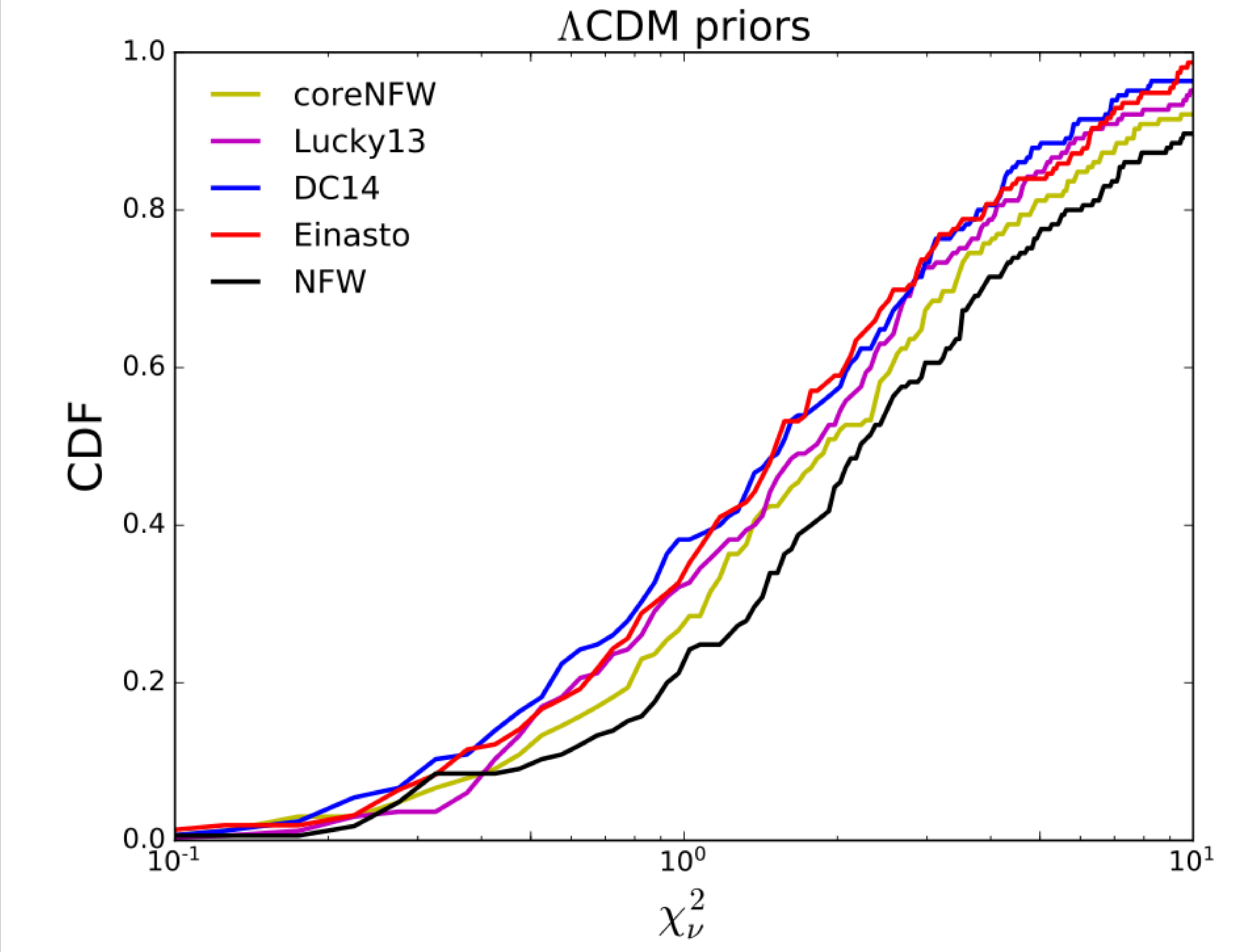




State-of-the-art (z=0): SPARC sample - Li+2020

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

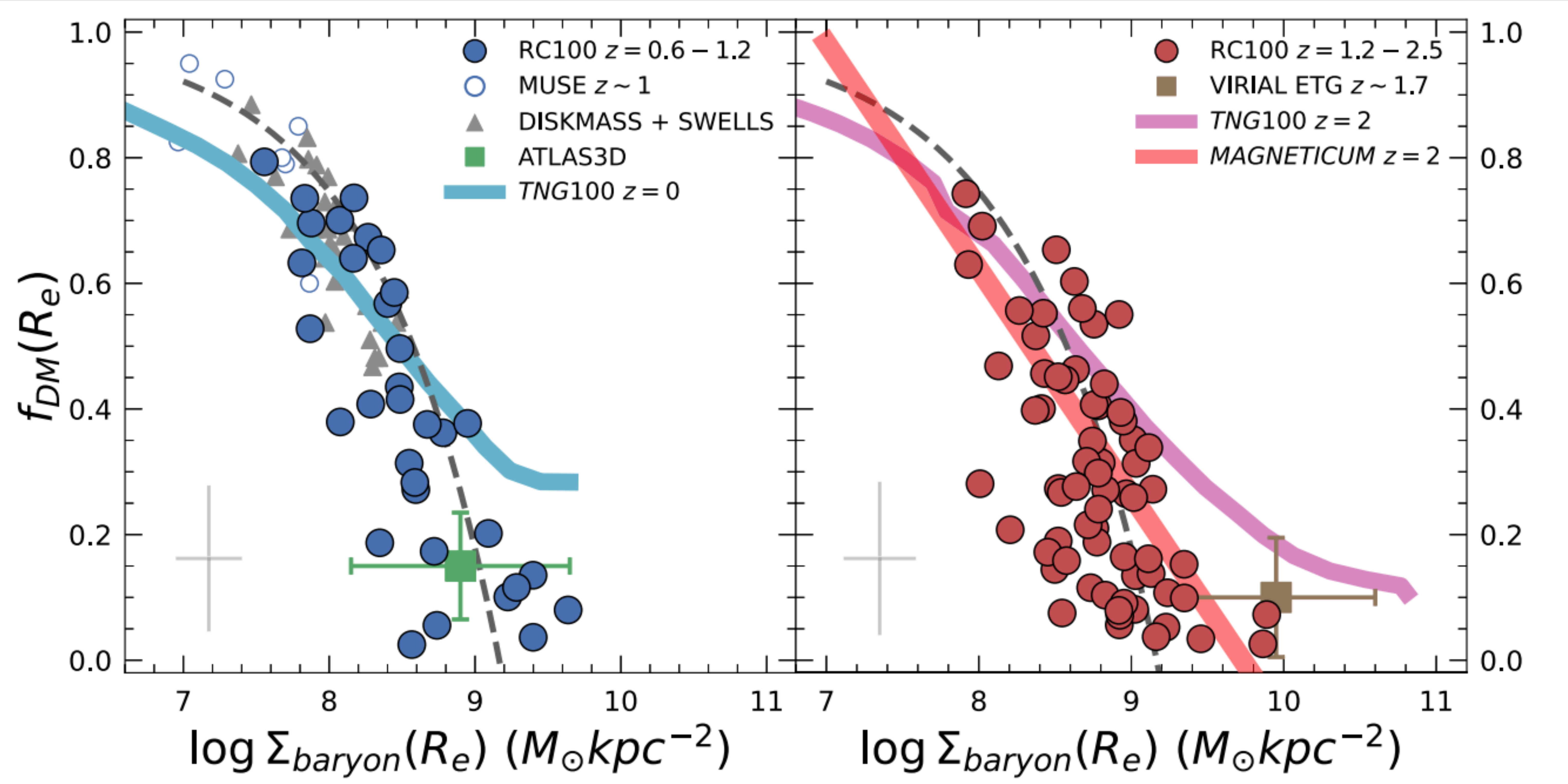
State-of-the-art (z~1-2): Genzel+17, Nestor Shachar+2023

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

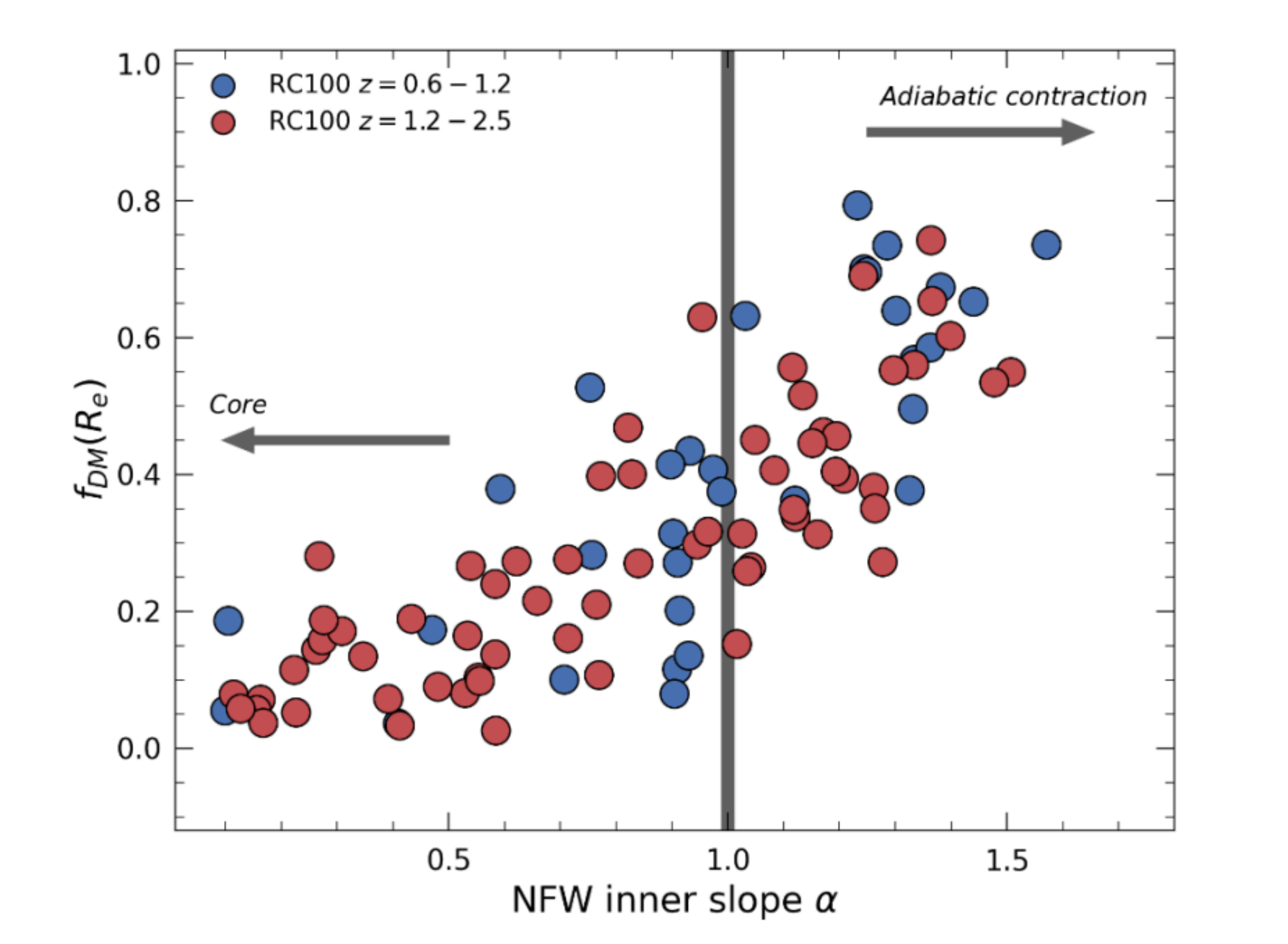
1D

- 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 Survey: Ciocan, Bouché +2024

submitted

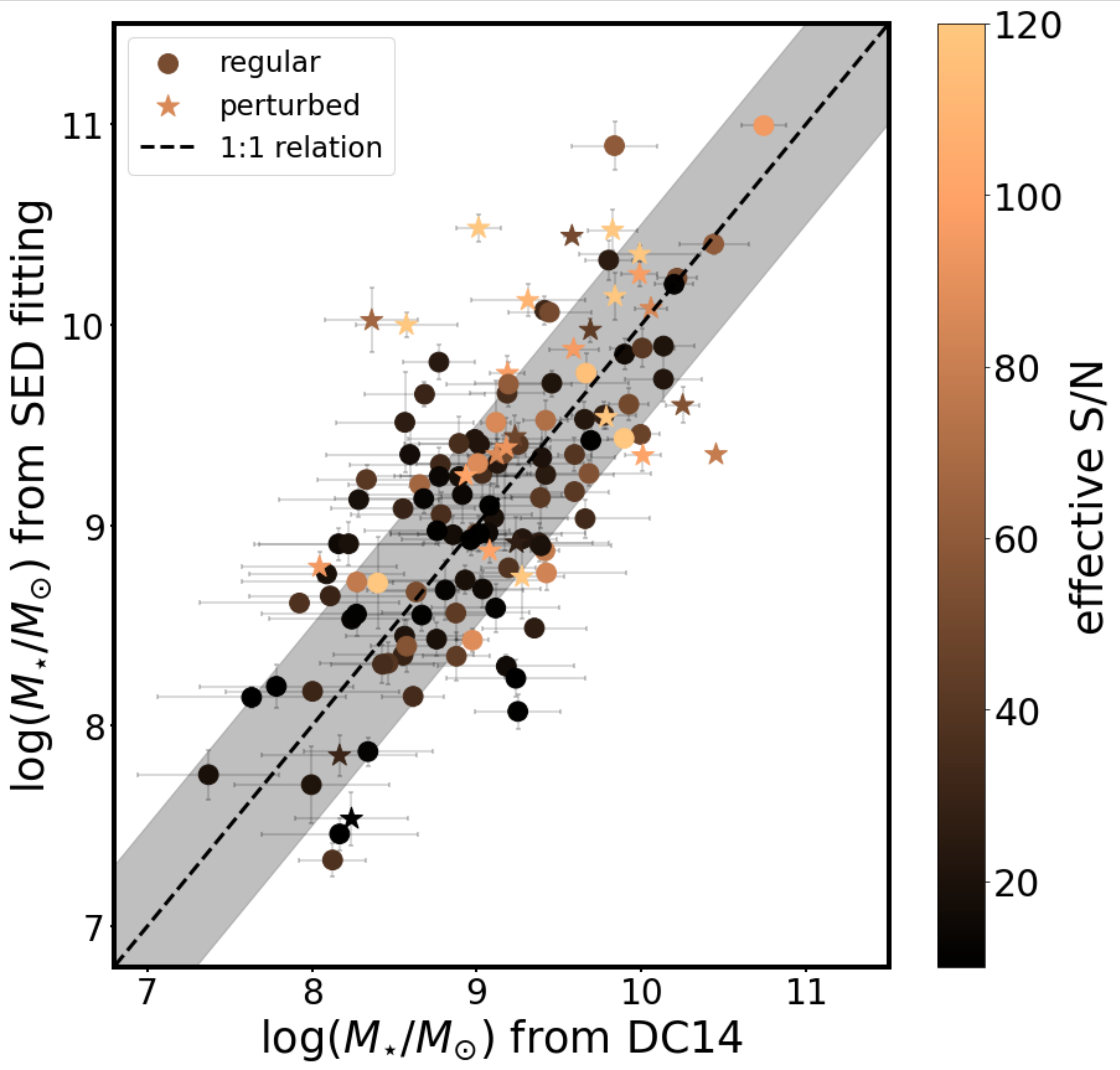
- Rotation curve decomposition for 136 galaxies with $0.3 < z < 1.5$ and $7 < \log(M_\star/M_\odot) < 11$
- Model DM halos with: (1) NFW; (2) Di Cintio +2014 profile; (3)Burkert (Burkert 1995); (4) Dekel-Zhao (Freundlich et al. 2020b); (5) Einasto (Navarro et al. 2004); and (6) coreNFW (Read et al. 2016)

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

3D GalPaK galaxy parameters and kinematics

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

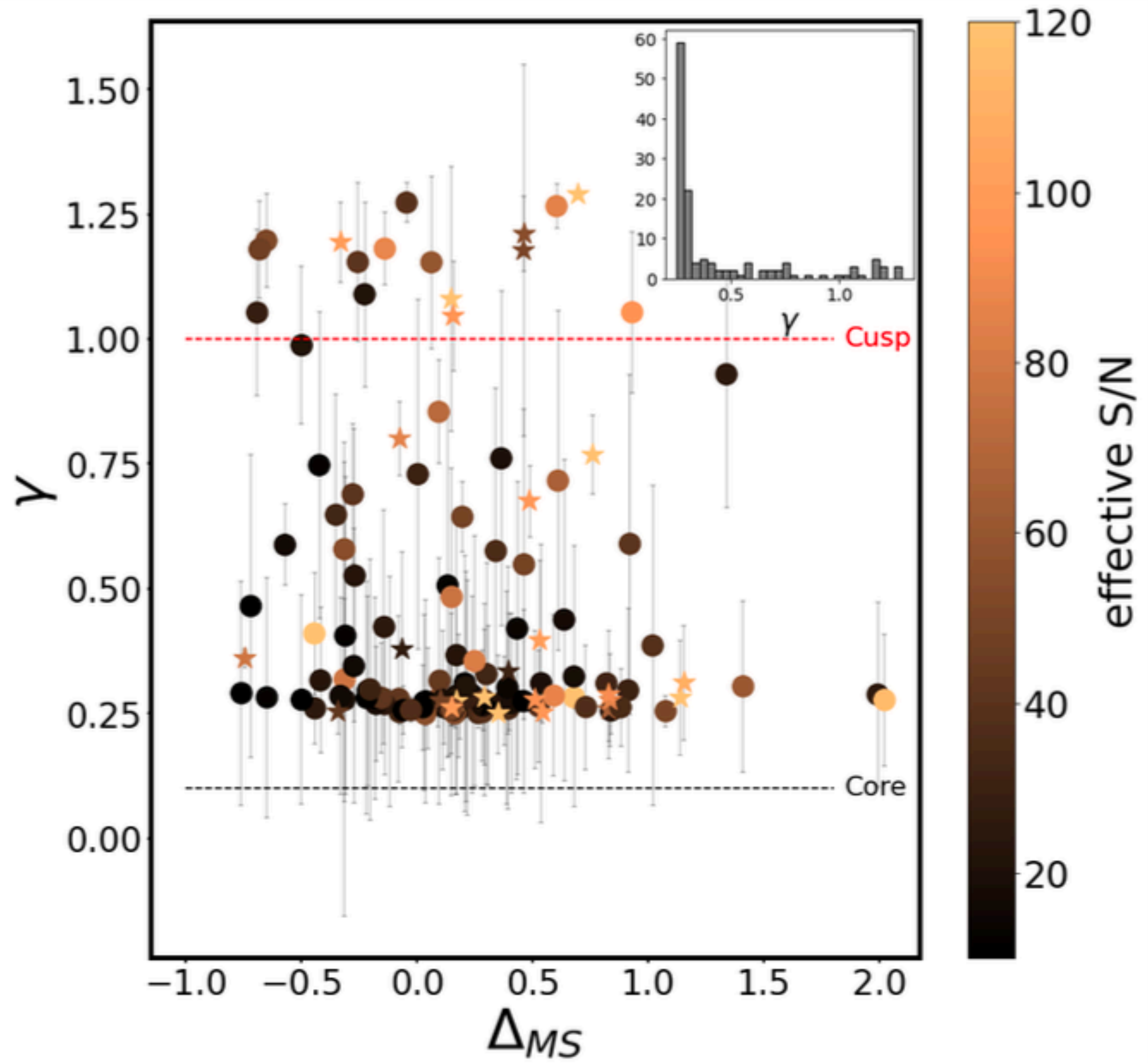
- **Consistency checks for DC14**



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

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

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

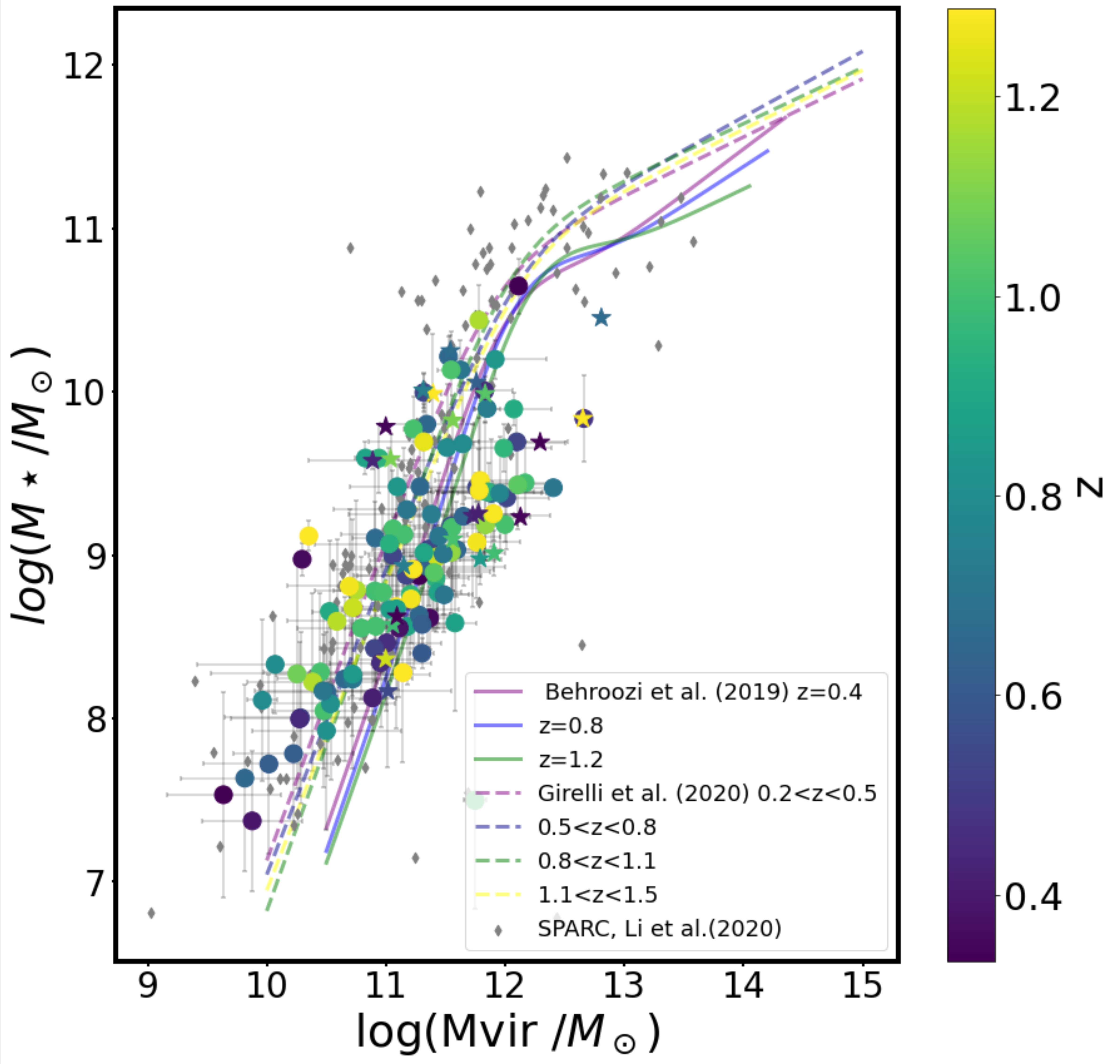


➡66% shows cored dark matter density profiles
➡No correlation between the dark matter inner slope and the star formation activity of the sample

3D GalPaK galaxy parameters and kinematics

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

- Stellar mass - halo mass relation

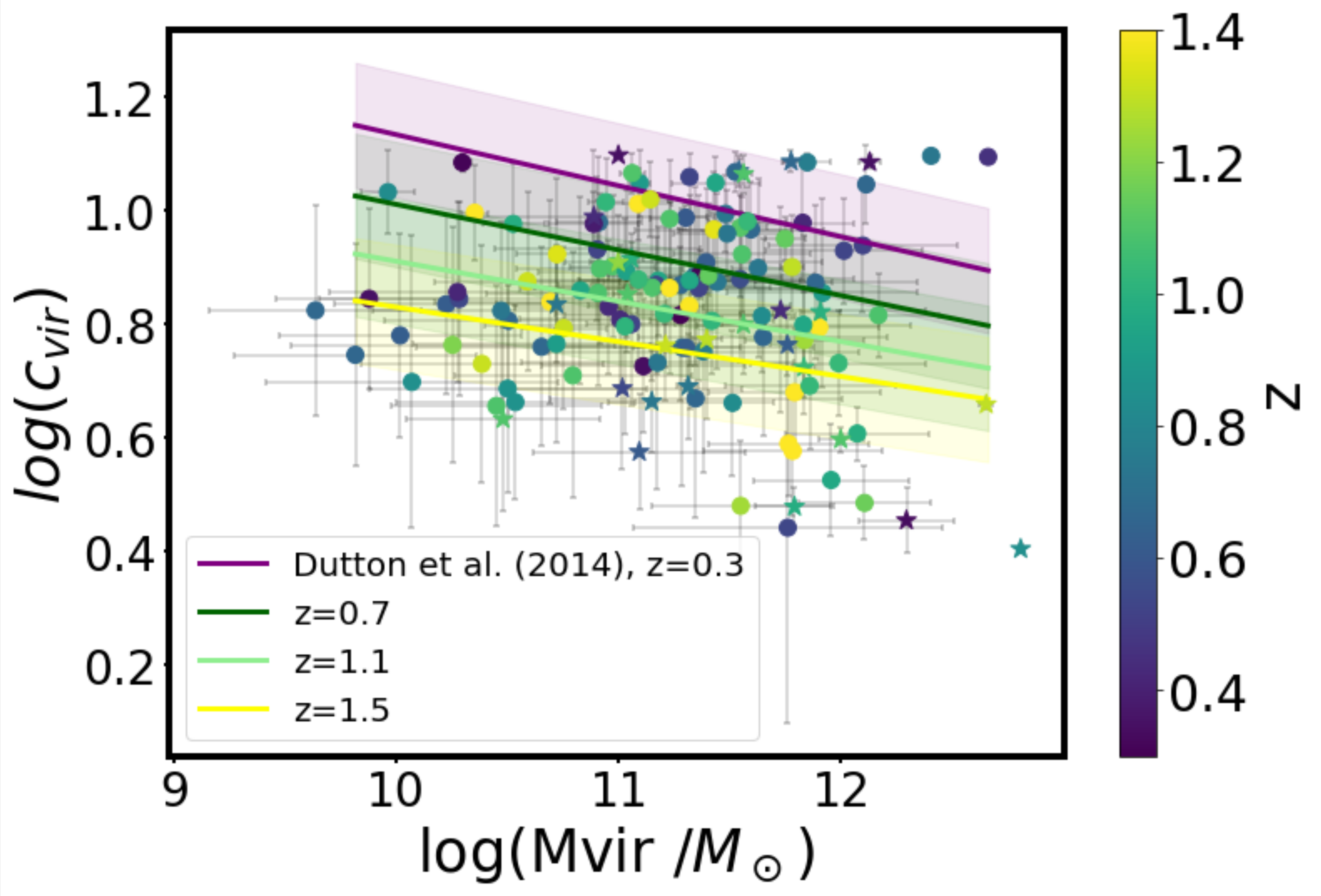


➡in agreement with the predictions from Behroozi+2019 and Girelli+2020

3D GalPaK galaxy parameters and kinematics

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

- **Concentration - halo mass relation**

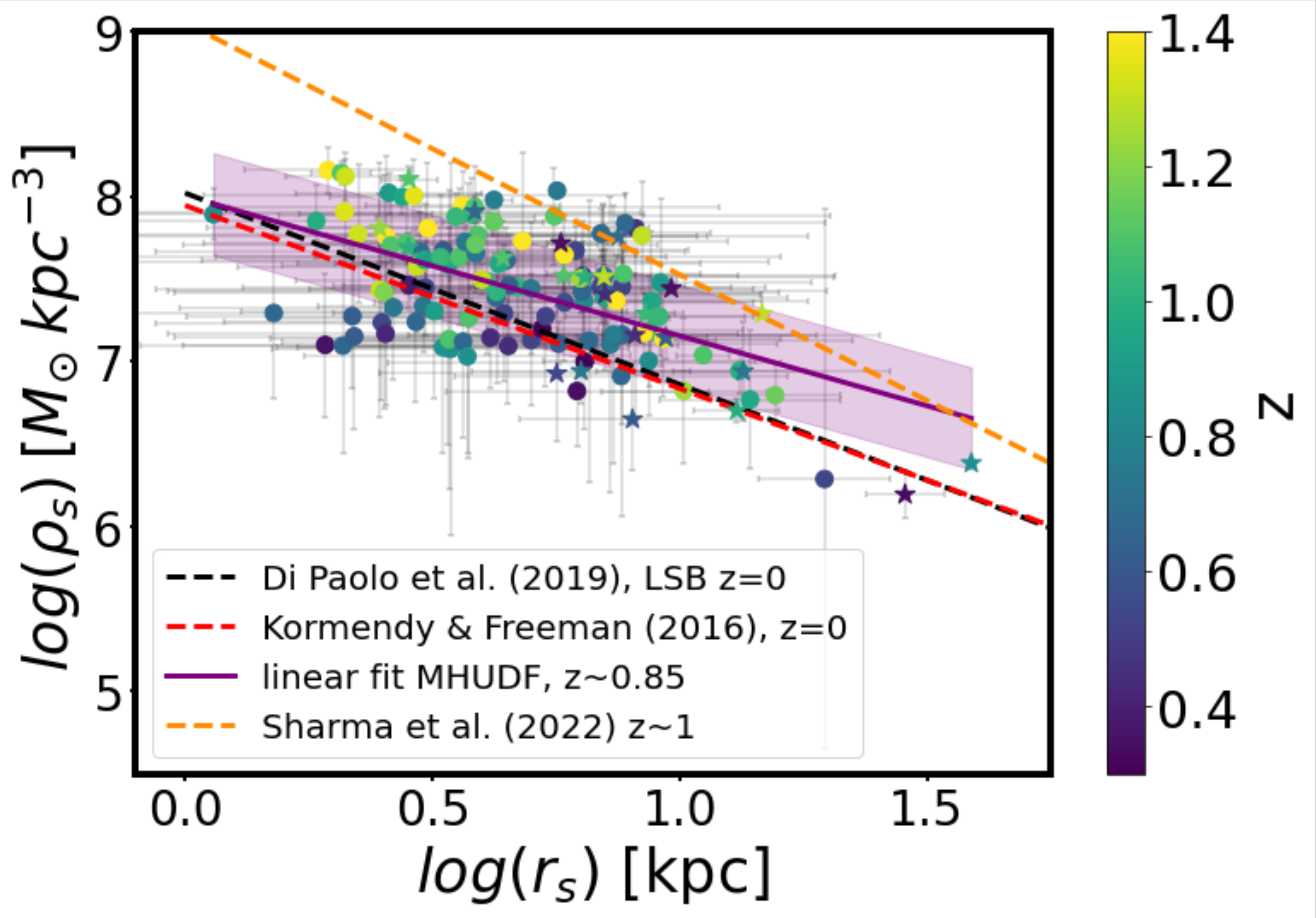


➡in agreement with the predictions from Dutton et al. 2014, but with larger scatter

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

- **Halo scale radius - density relation**

3D GalPaK galaxy parameters and kinematics



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

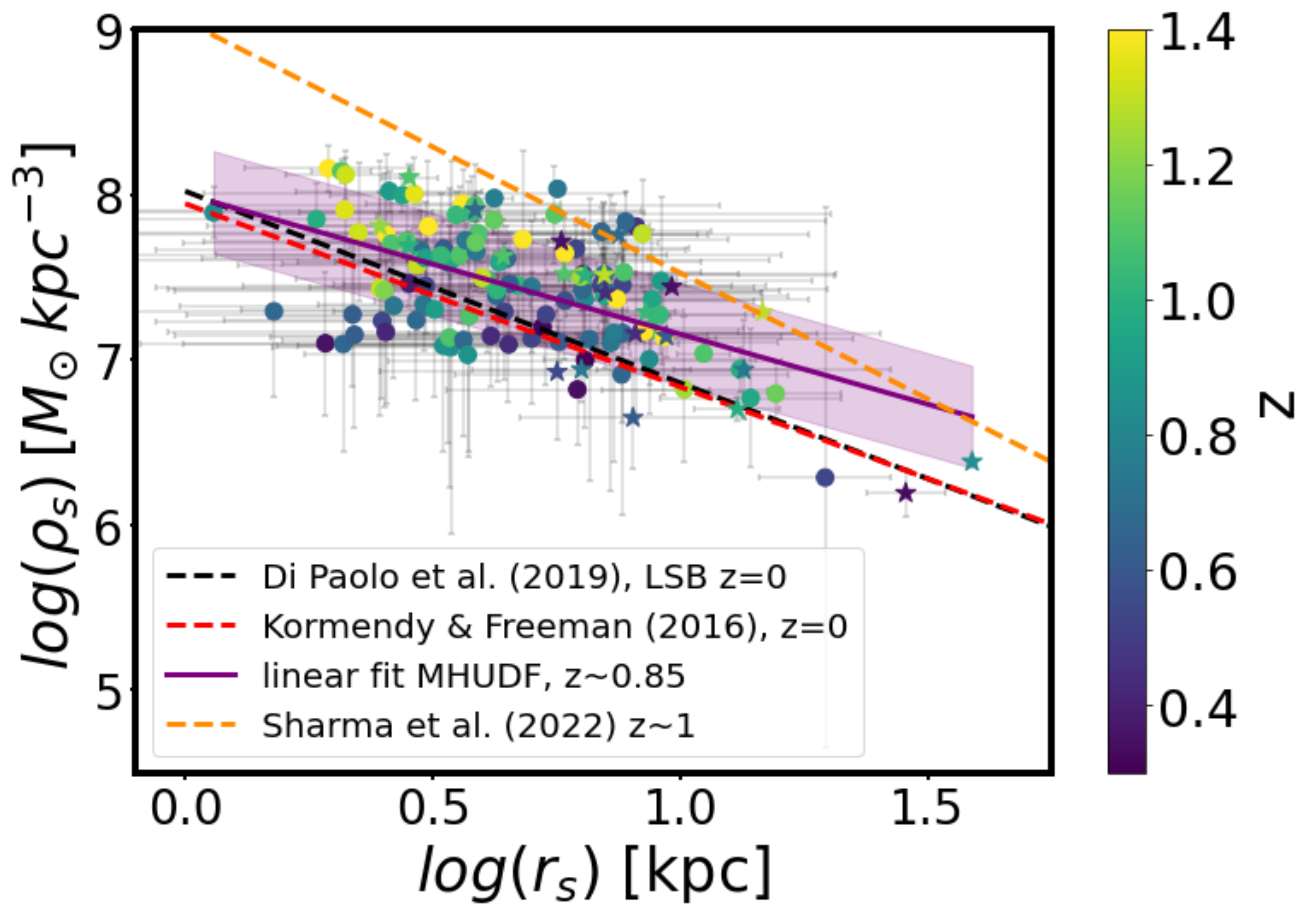
(Djorgovski 1992)

$n \sim -2$

➡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

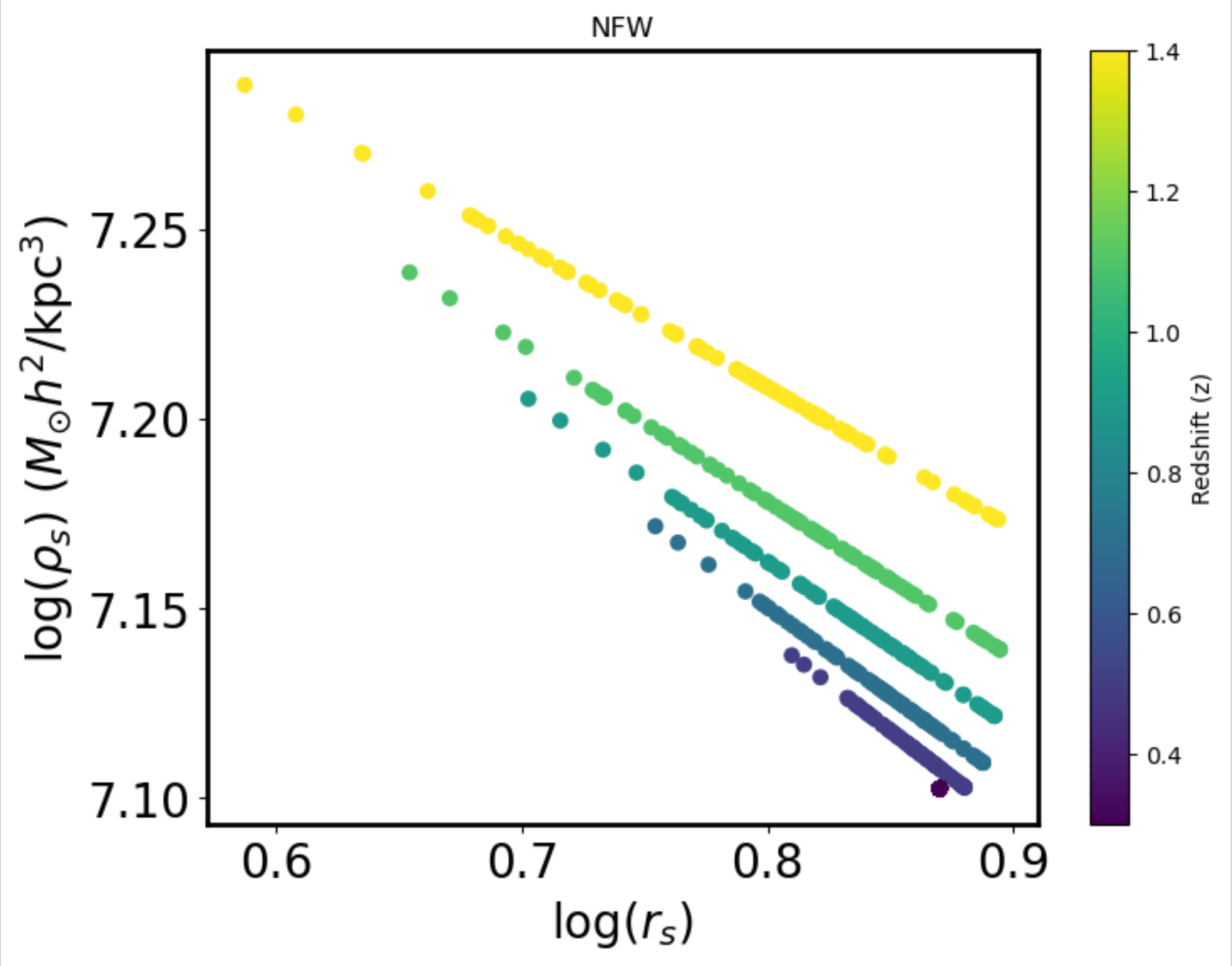
▸ **Halo scale radius - density relation**



predicted?

Diffmah (Hearin+21)

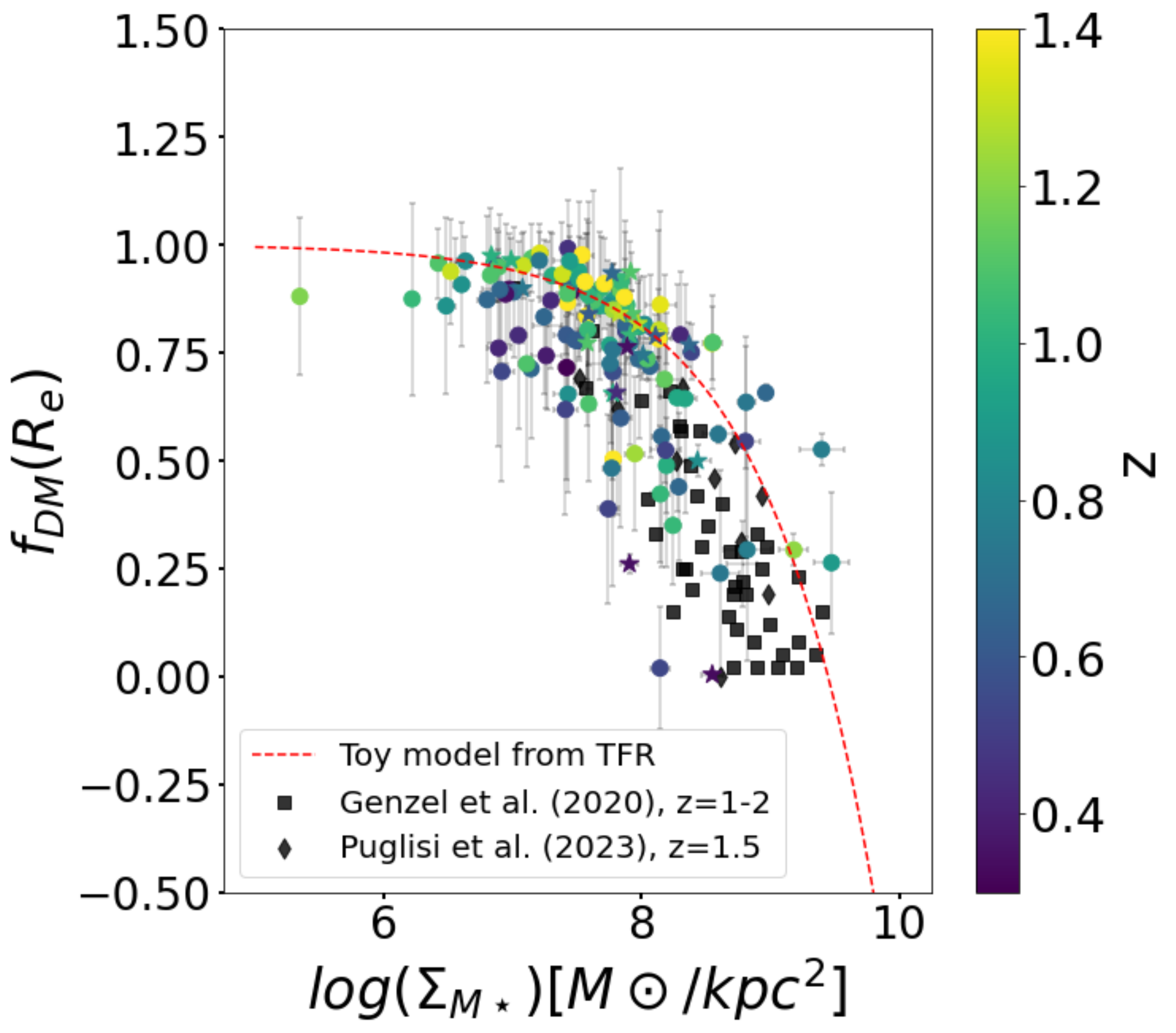
Colossus (Diemer+2018)



➡evolution of halo characteristic density with z

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

- Dark matter fraction - stellar mass surface density relation

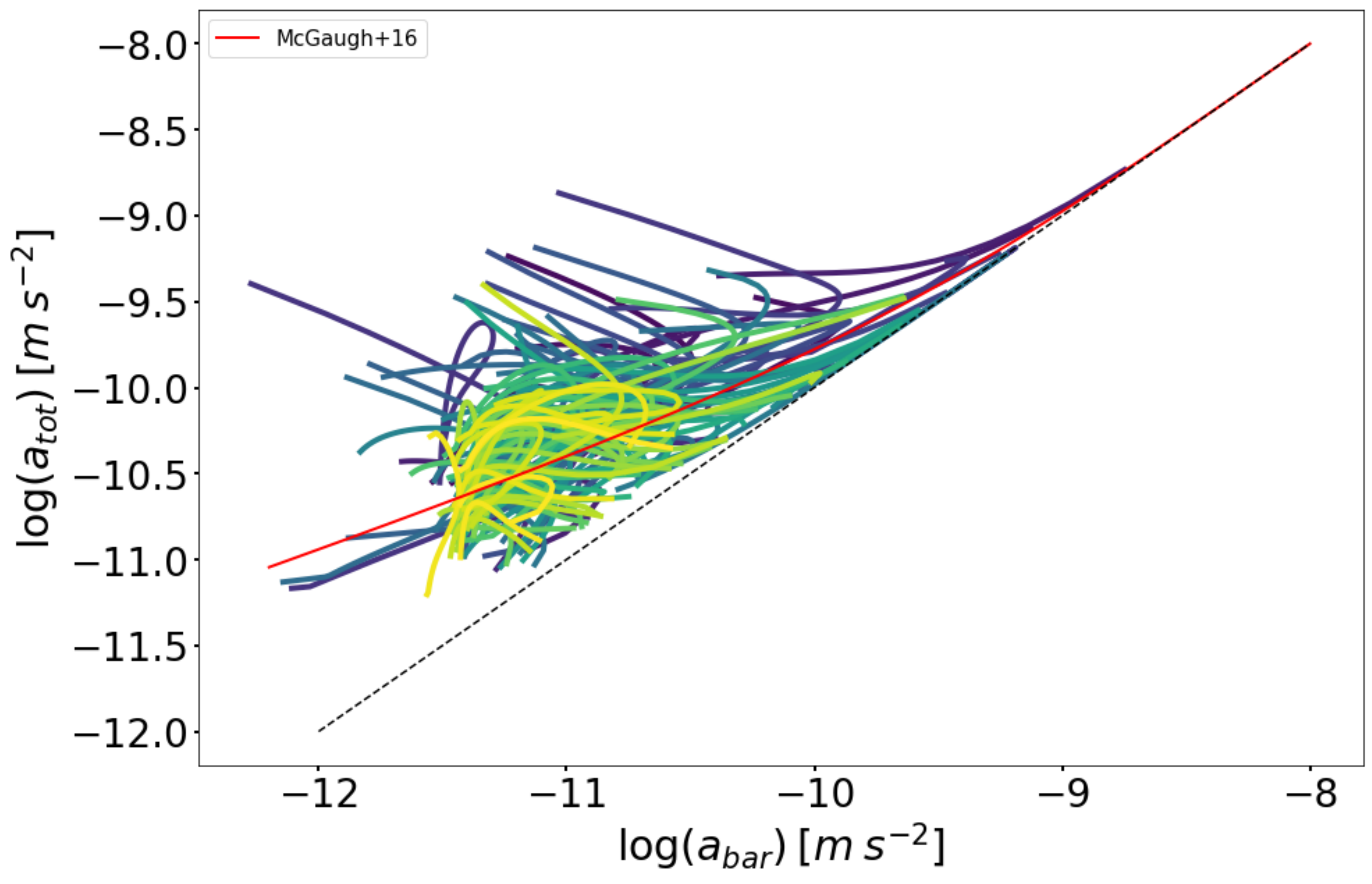


➡89% of the sample has dark matter fractions larger than 50% within Re

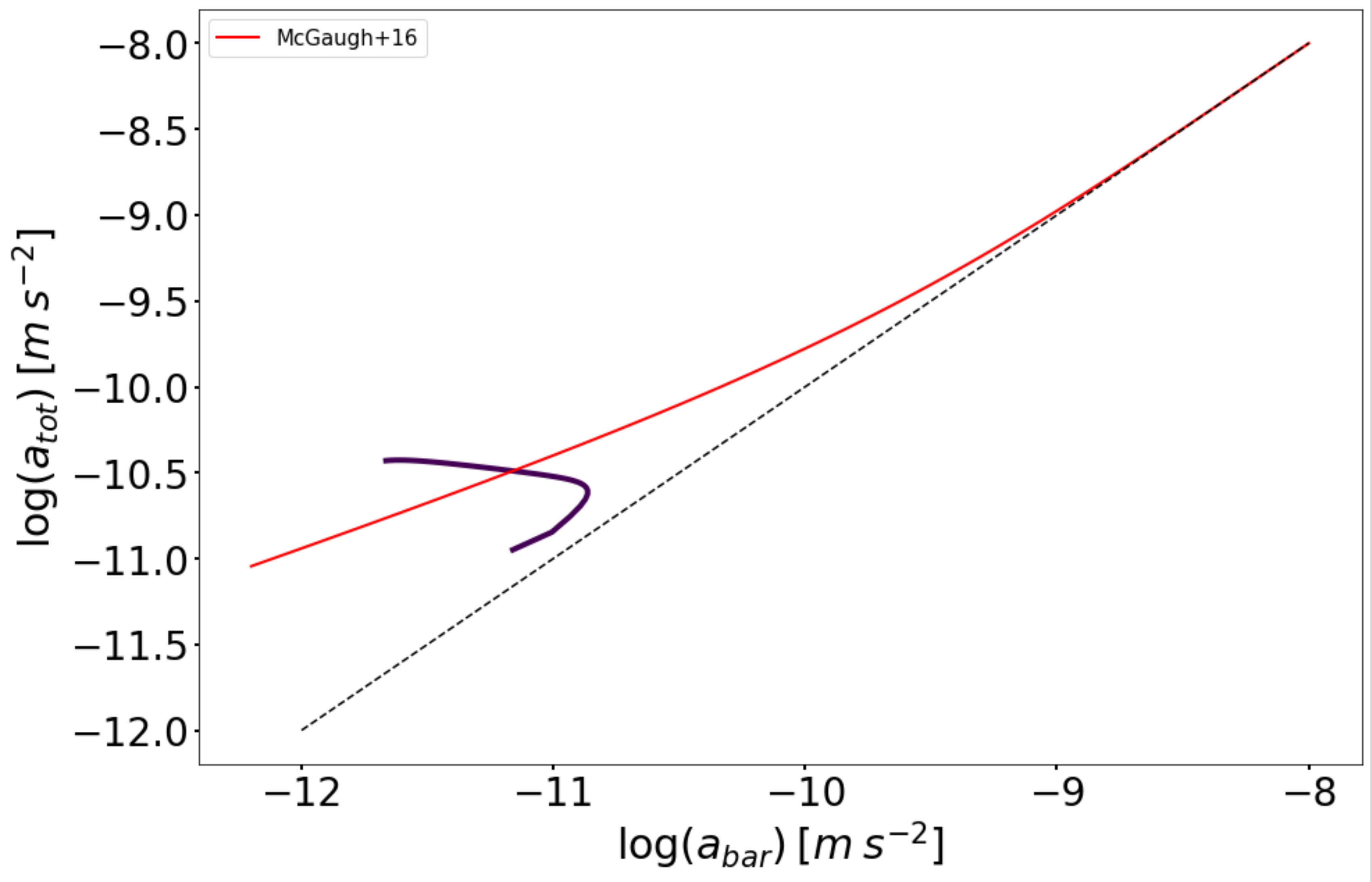
3D GalPaK galaxy parameters and kinematics

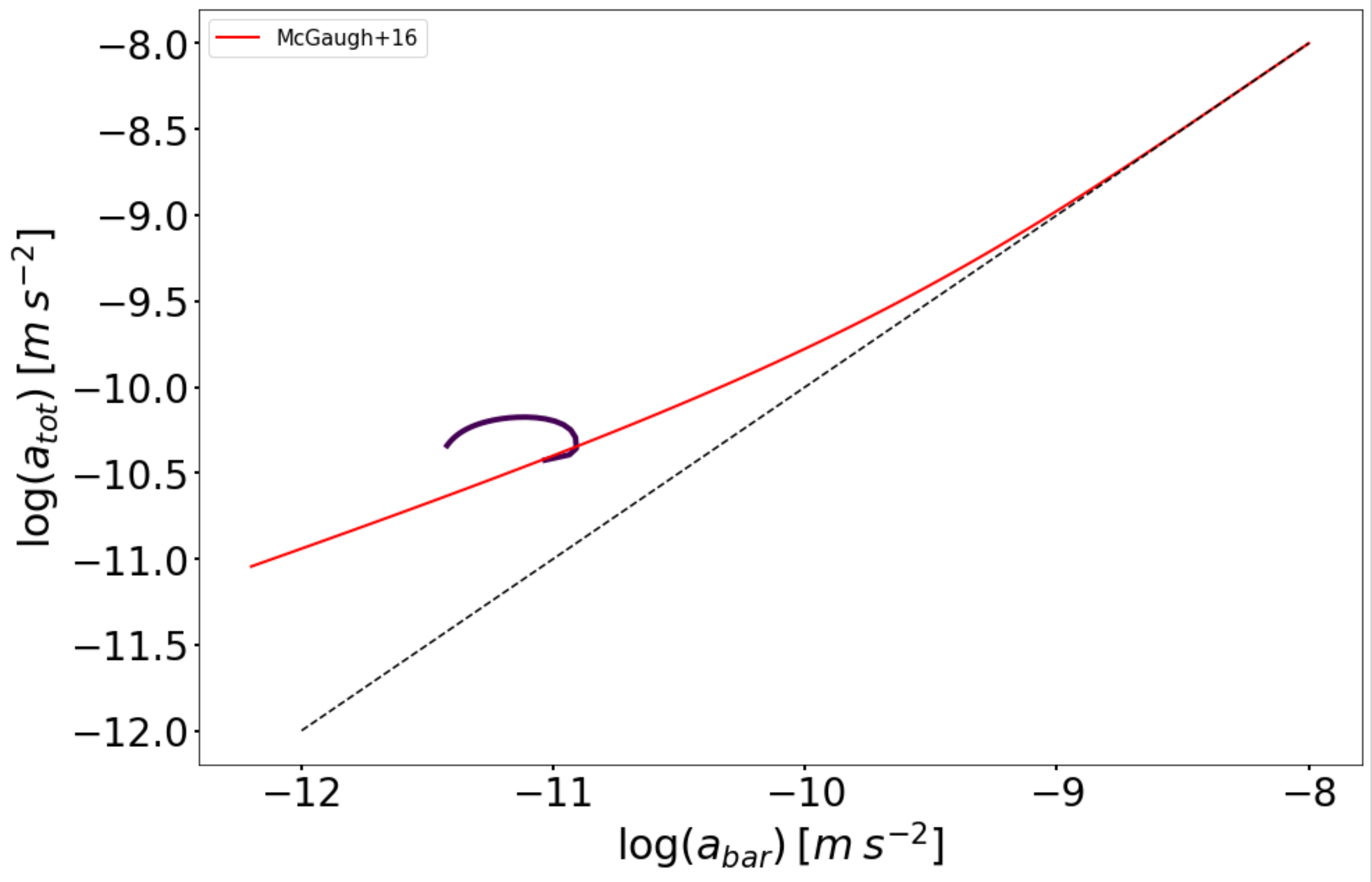
At z~1 - MUSE Hubble Ultra Deep Field Survey: Ciocan, Bouché +2024

- **RAR relation**



- **For cored galaxies**

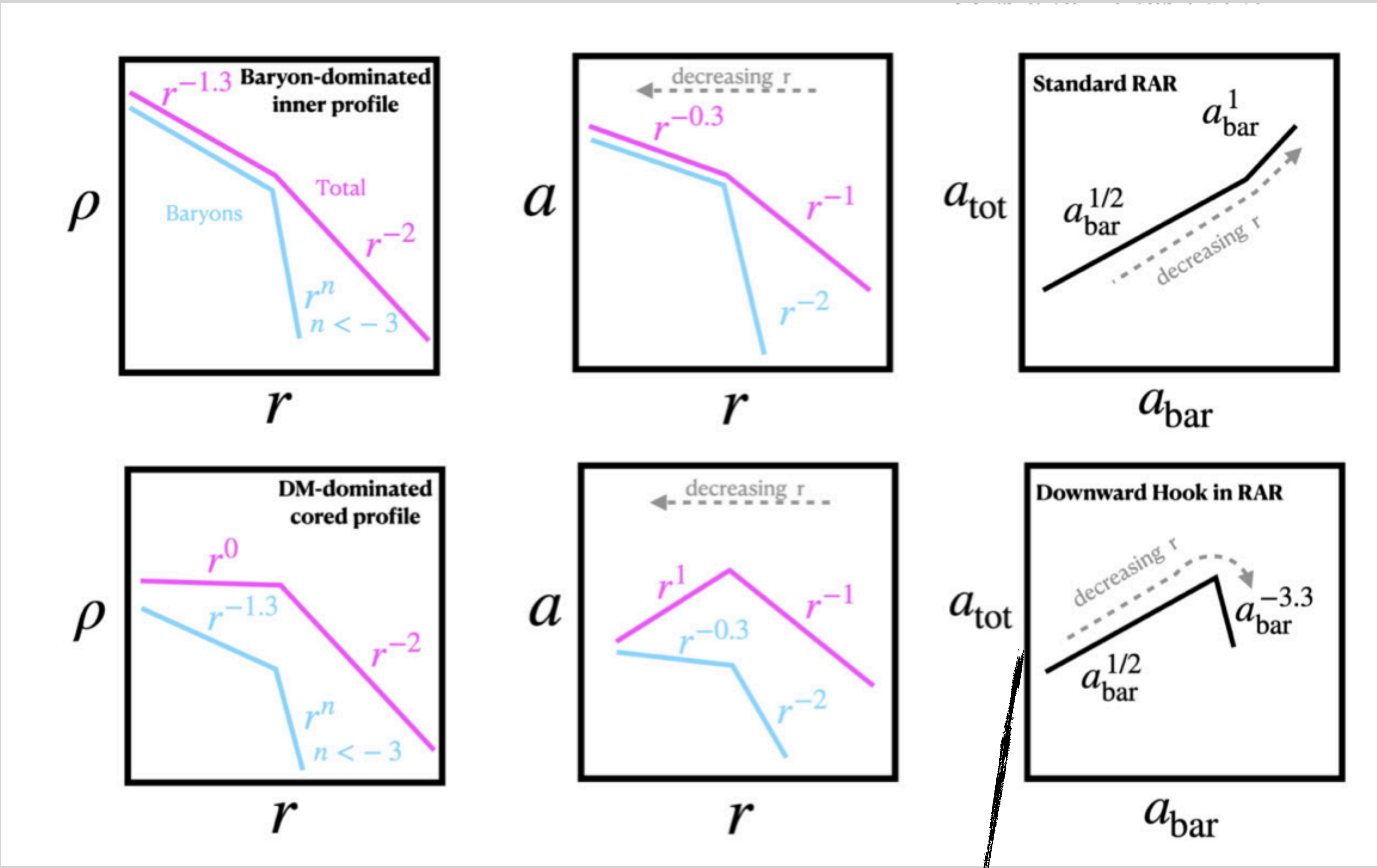


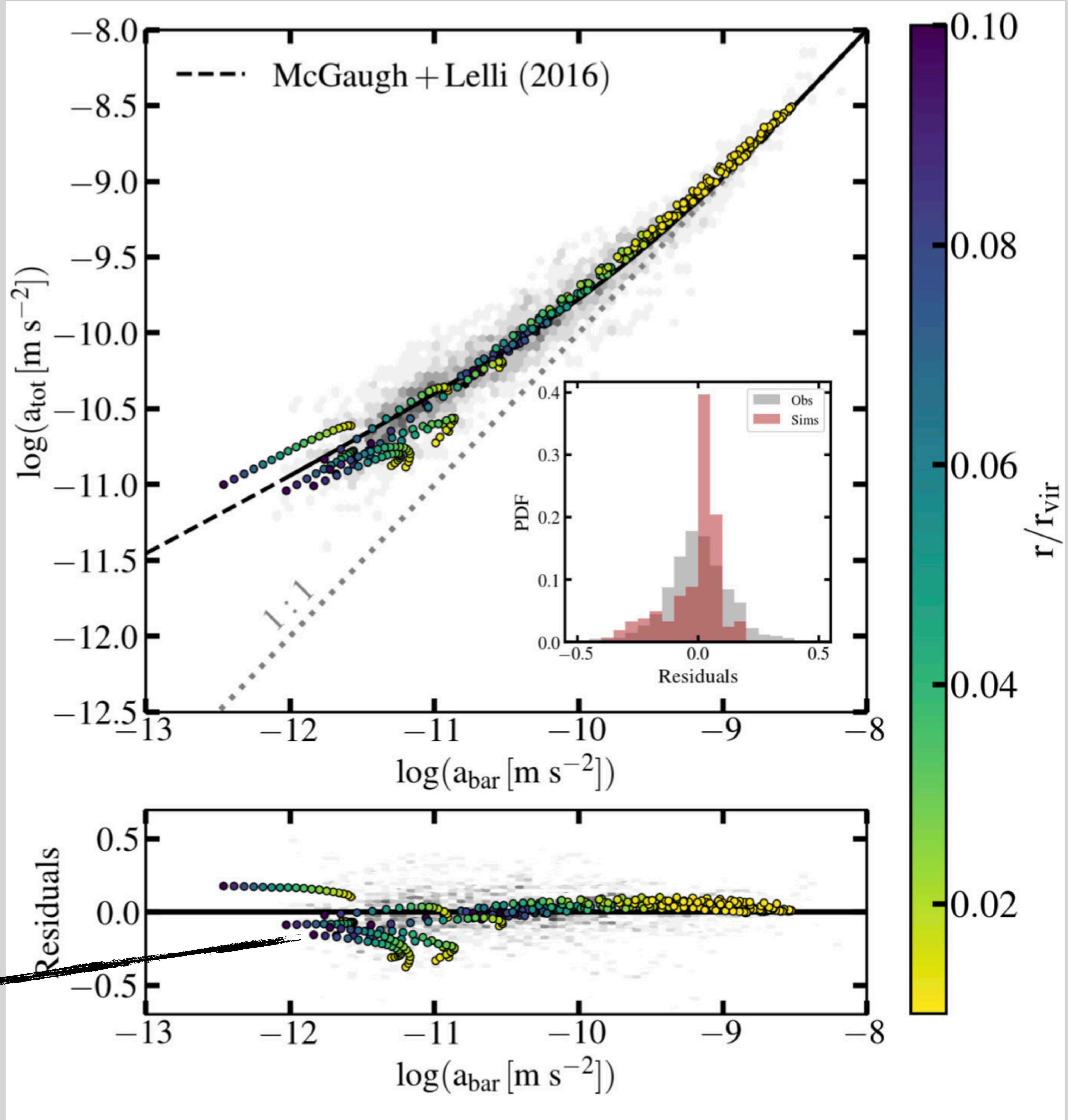


galaxy parameters and kinematics

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

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

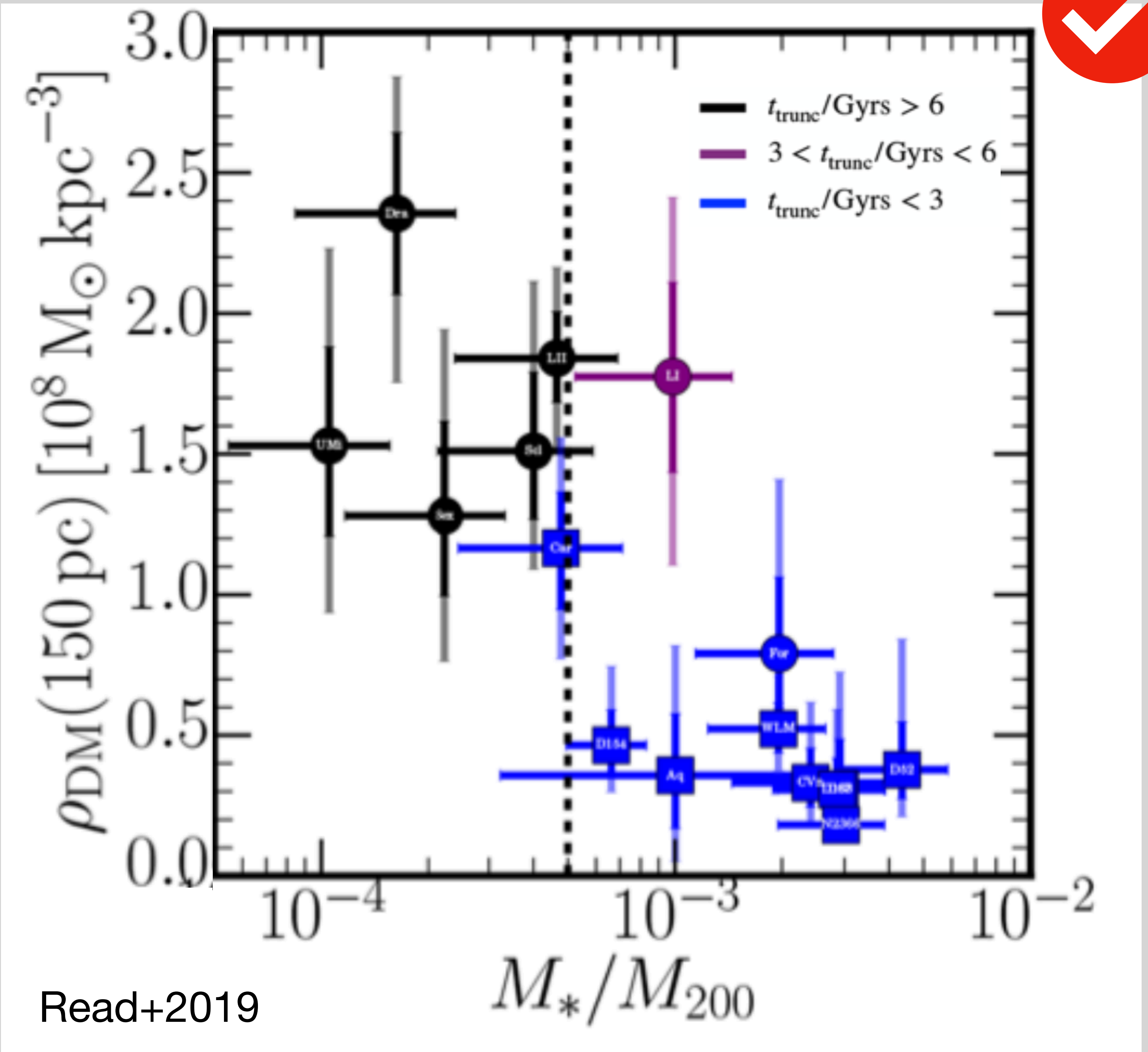


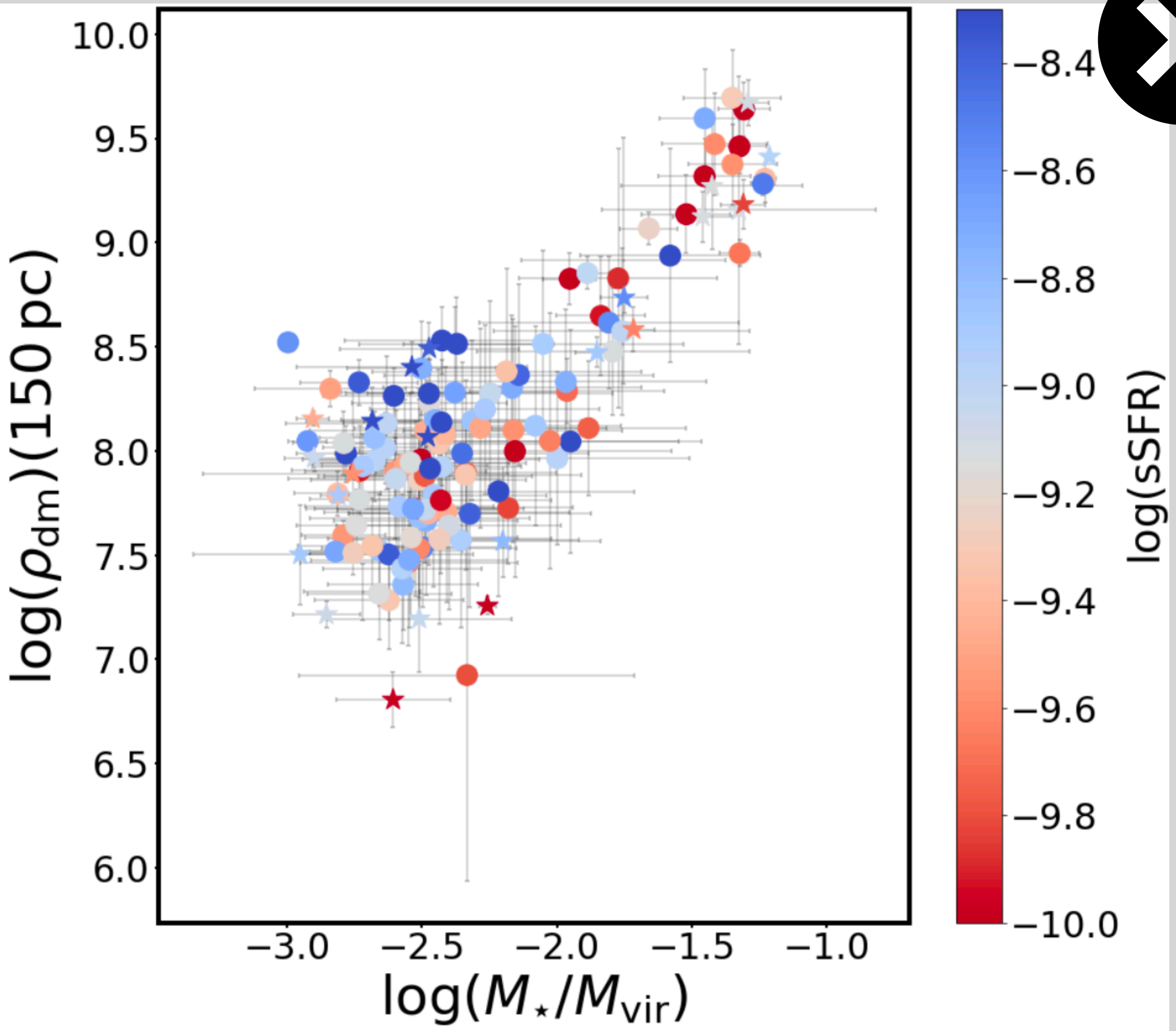


expected in ΛCDM but not in MOND

Is baryonic feedback the answer to the core cusp problem?

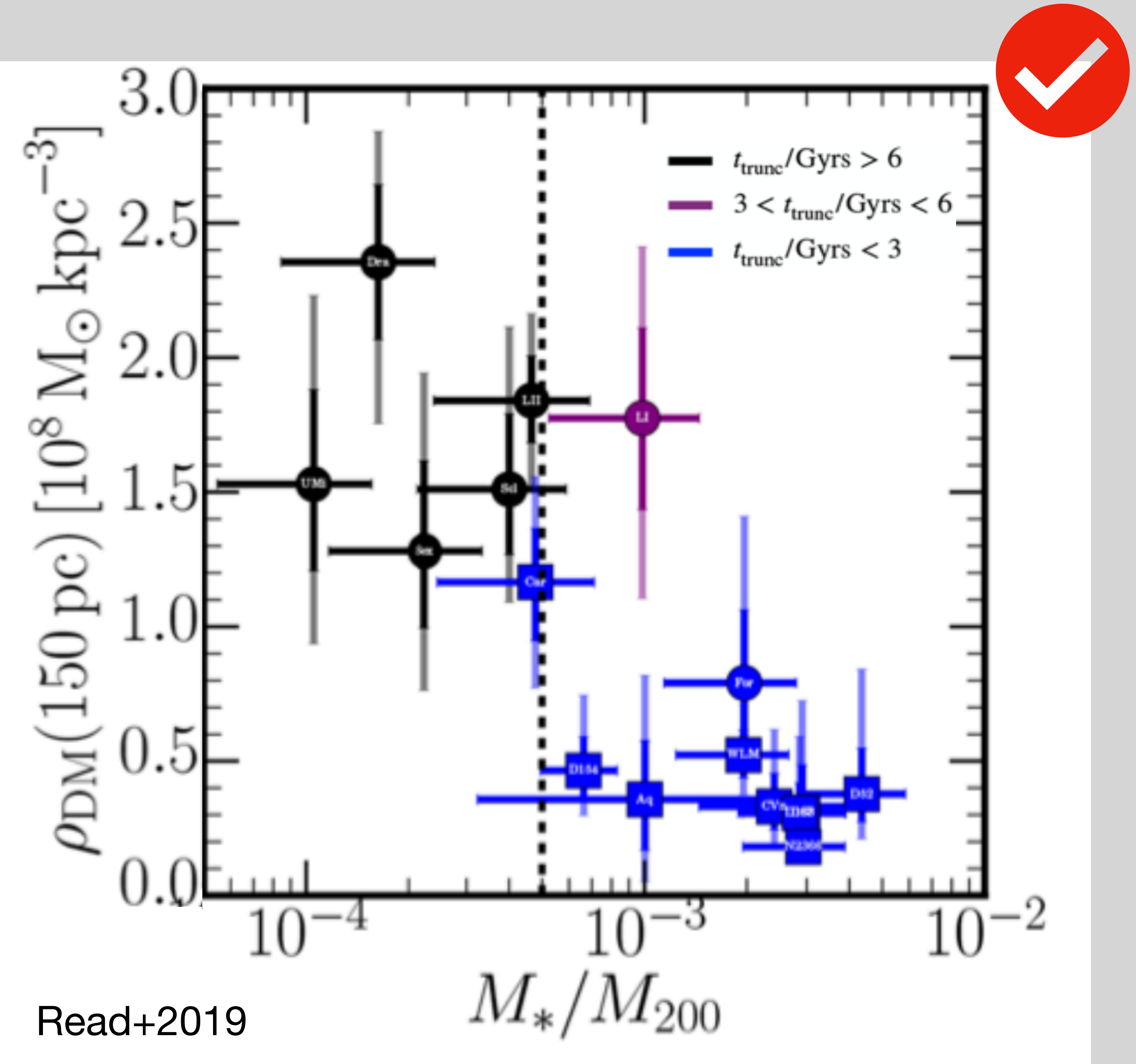
- Observationally, cores have been detected up to z ~ 2
- No clear correlation between core formation and stellar feedback yet



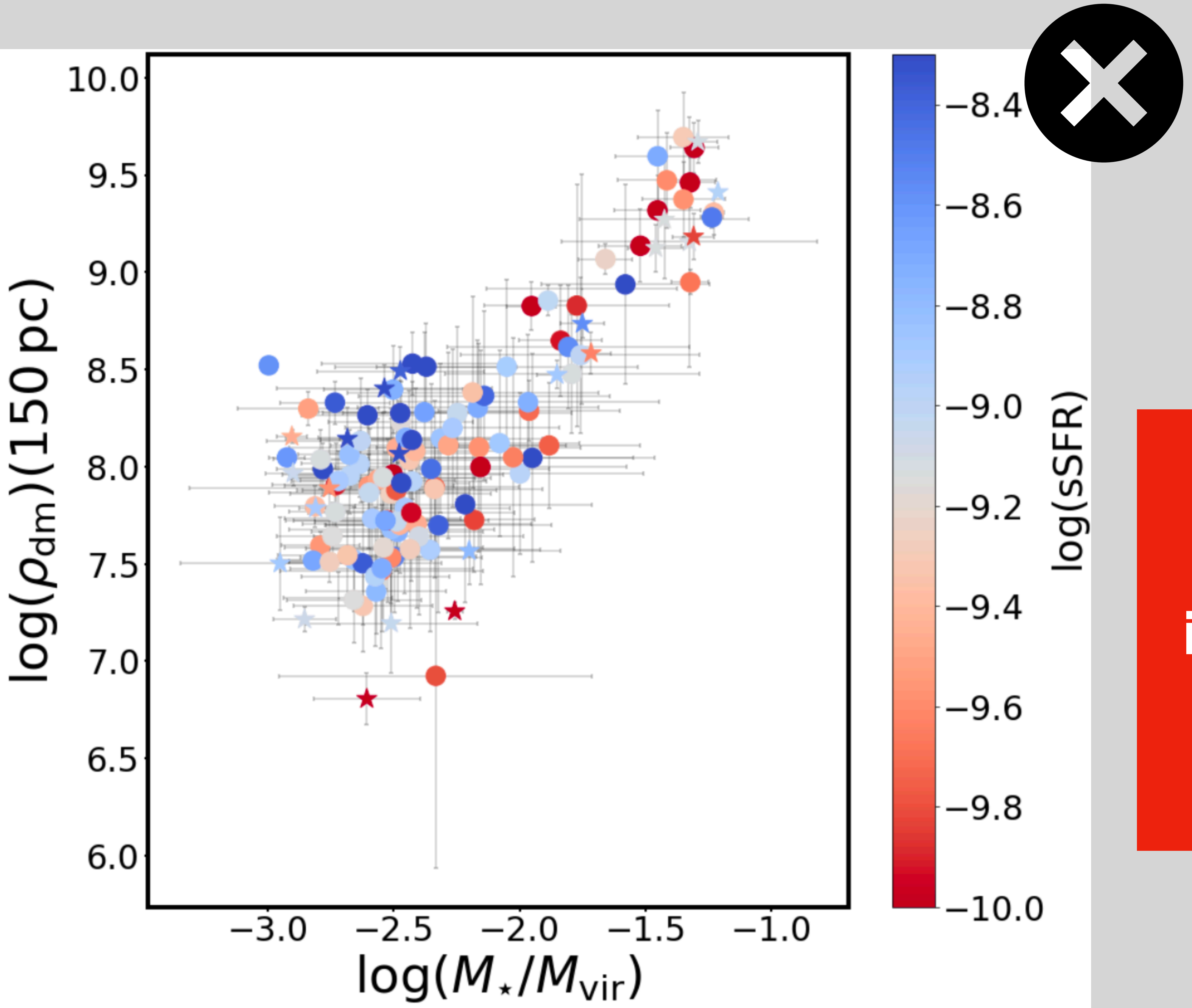


Is baryonic feedback the answer to the core cusp problem?

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

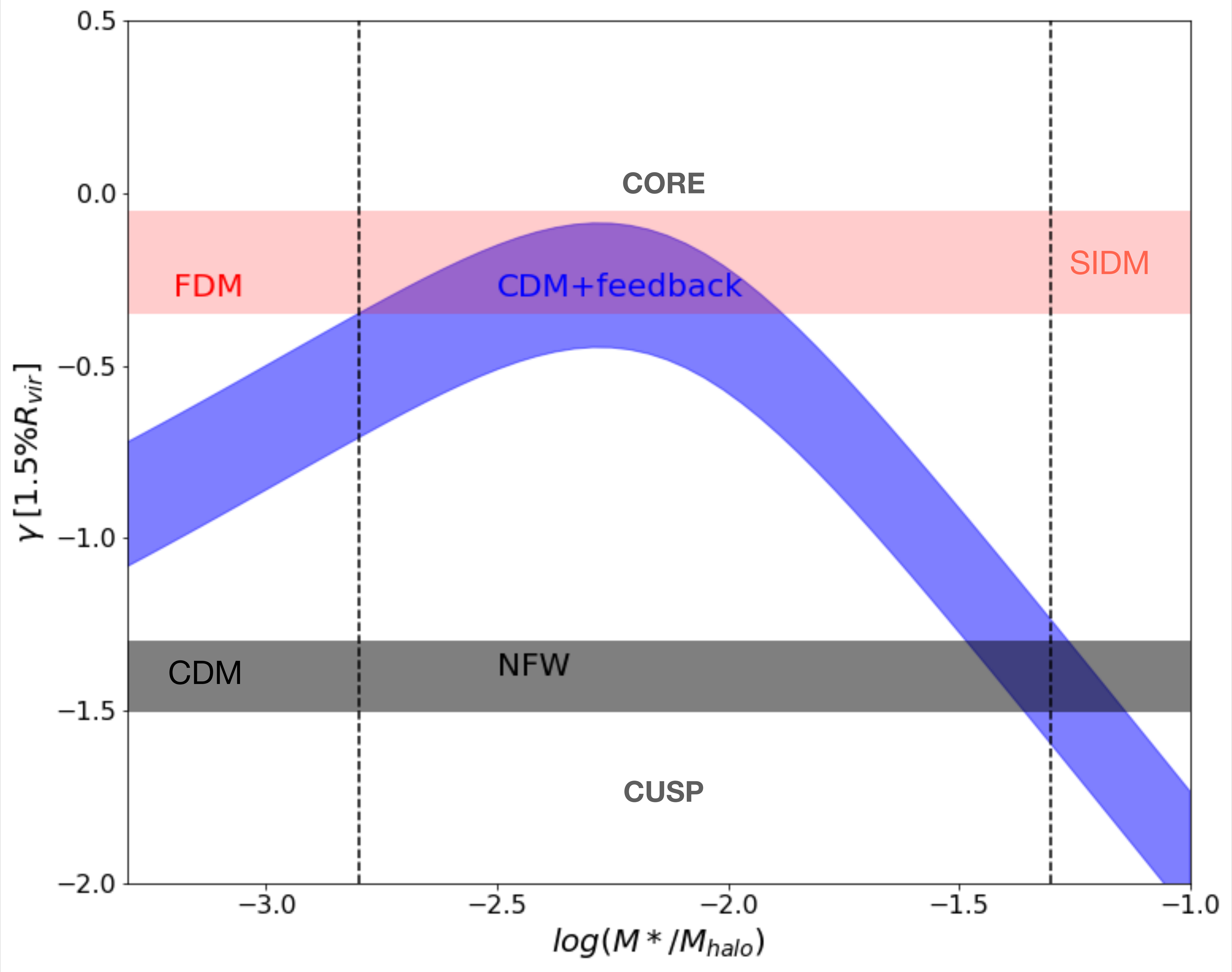


Read+2019



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

Core-cusp problem: alternative solutions

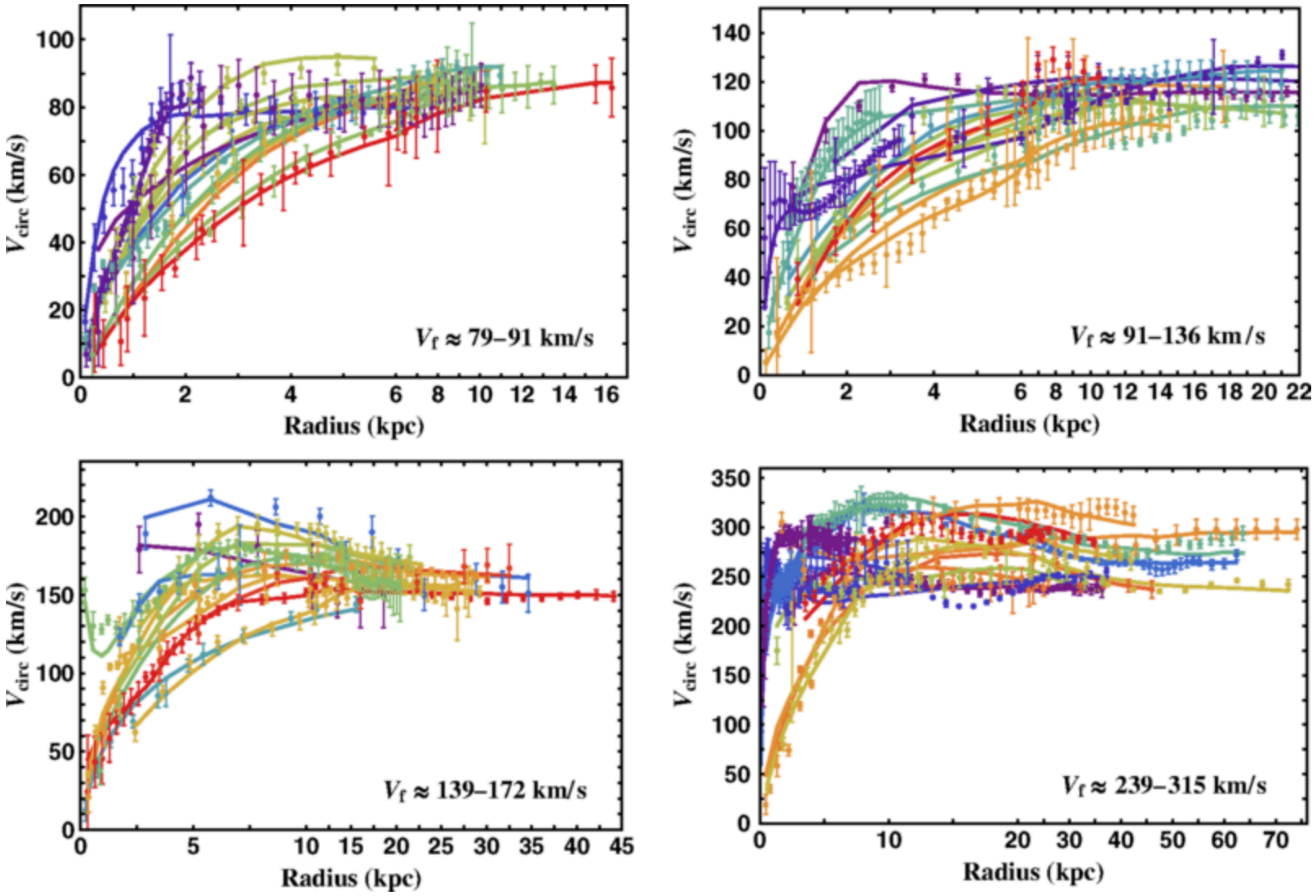


➡alternative models of dark matter:

- **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.



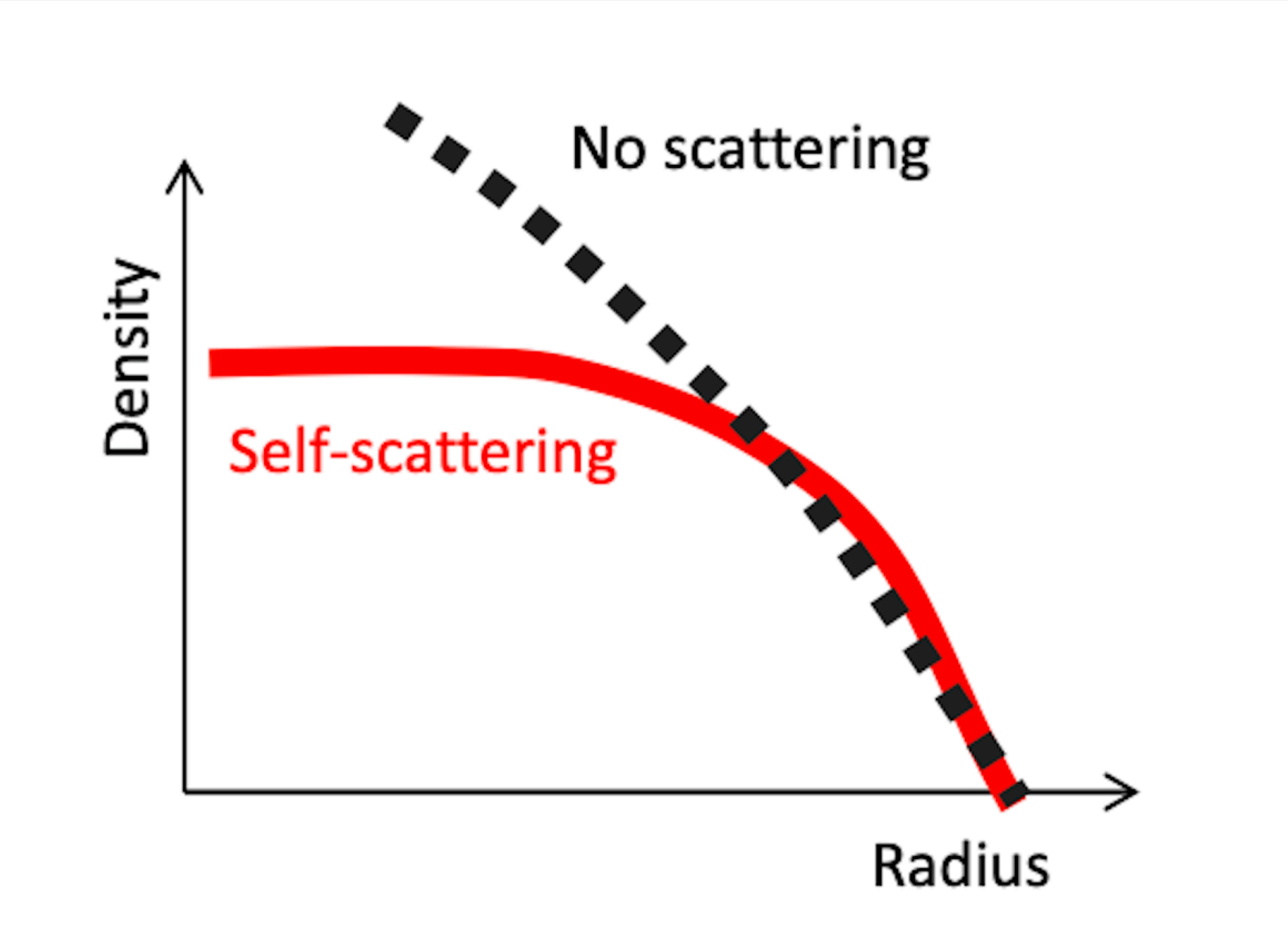
Ren +2019, Kamada+2017

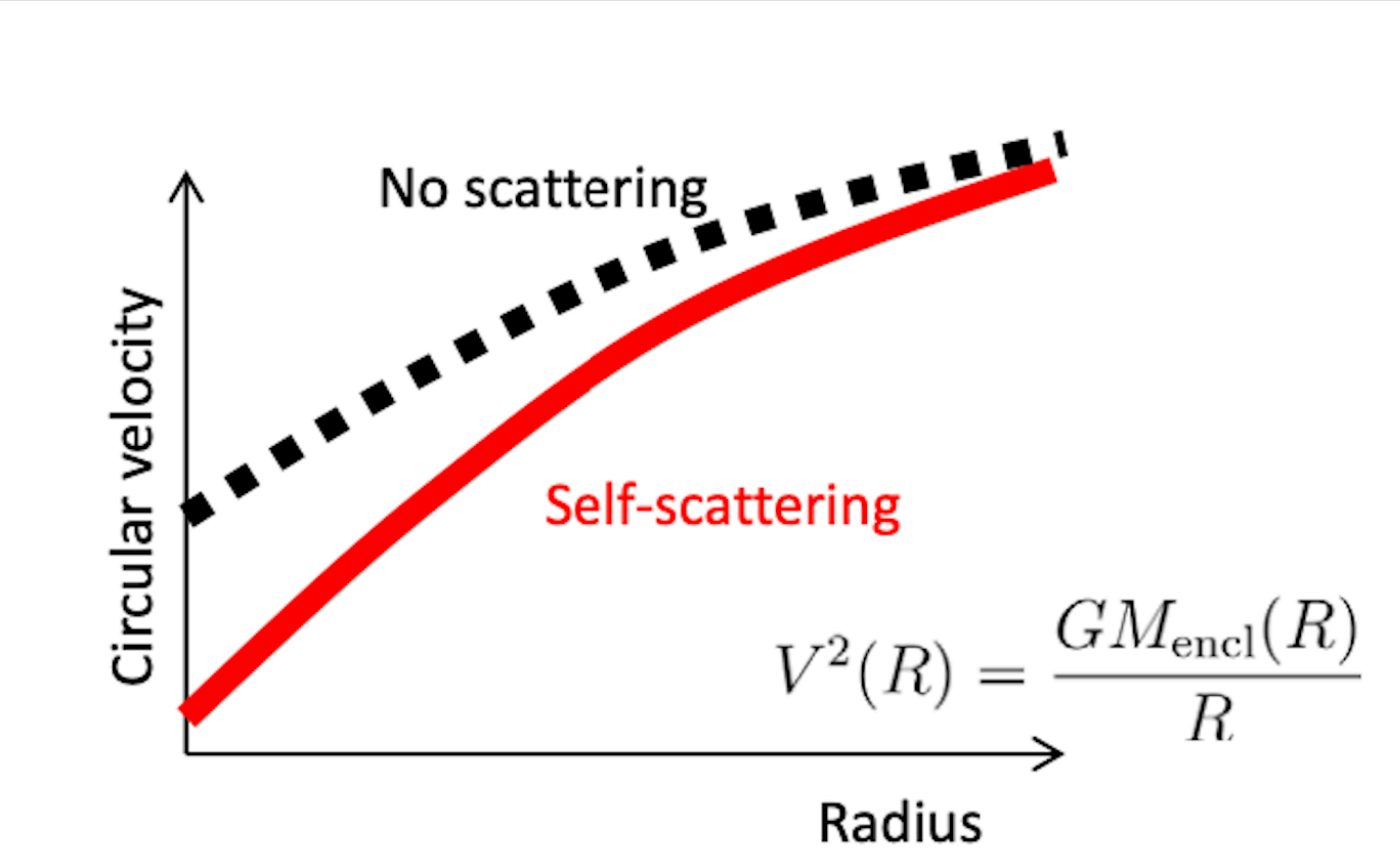
➡alternative models of DM:

- **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

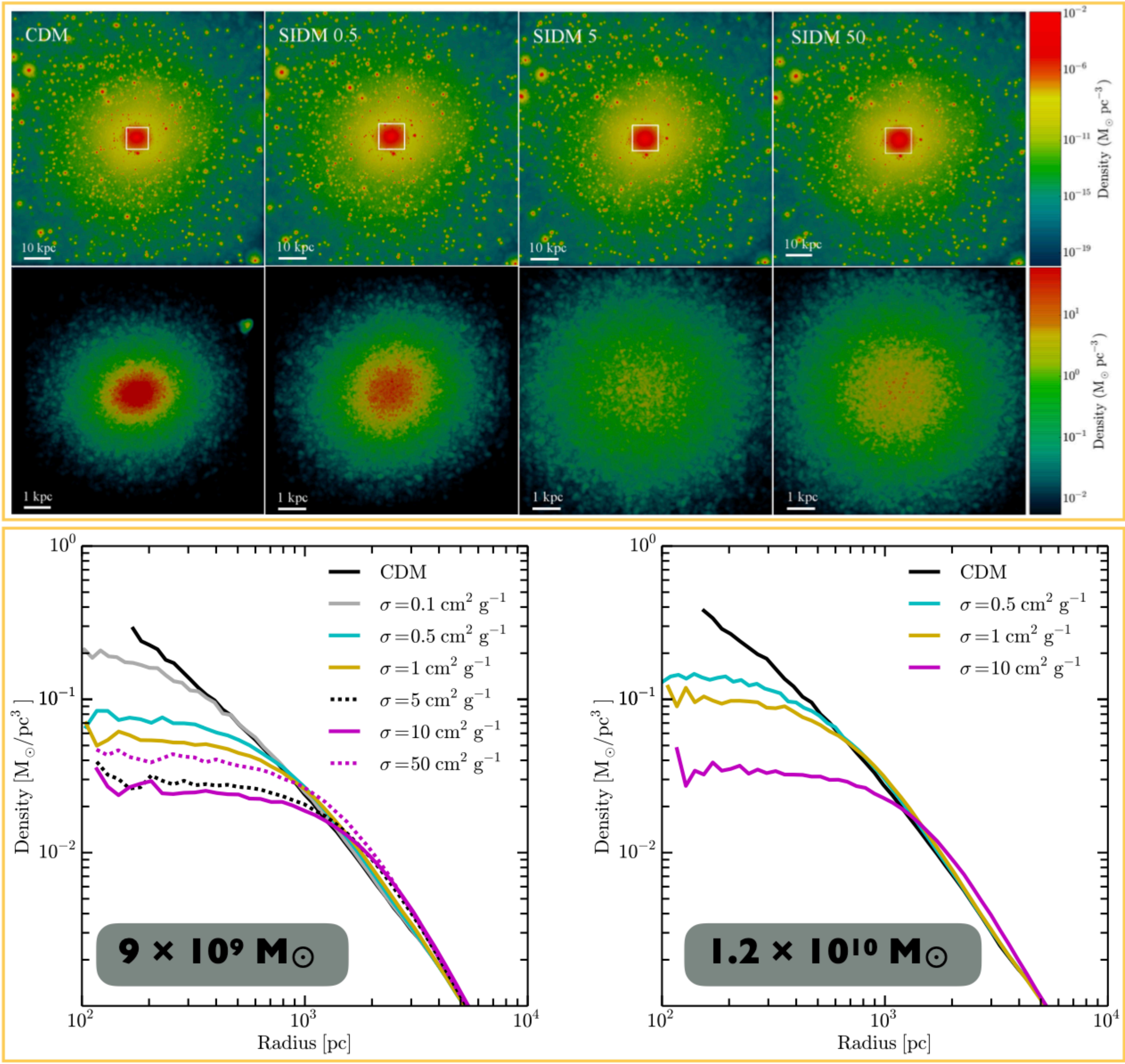
Self Interacting Dark Matter

➡ 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

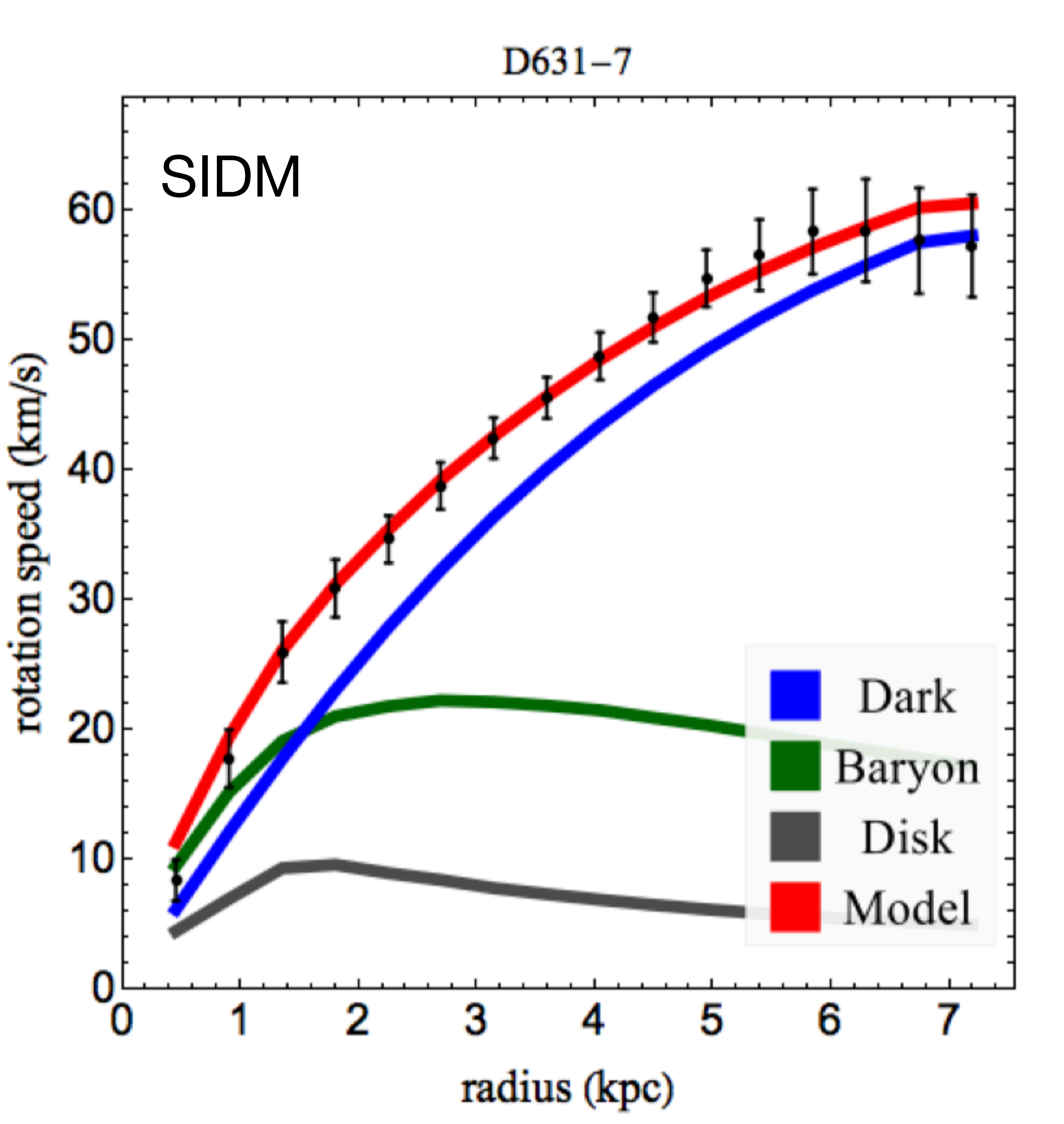
➡ shares the success of ΛCDM on large scales

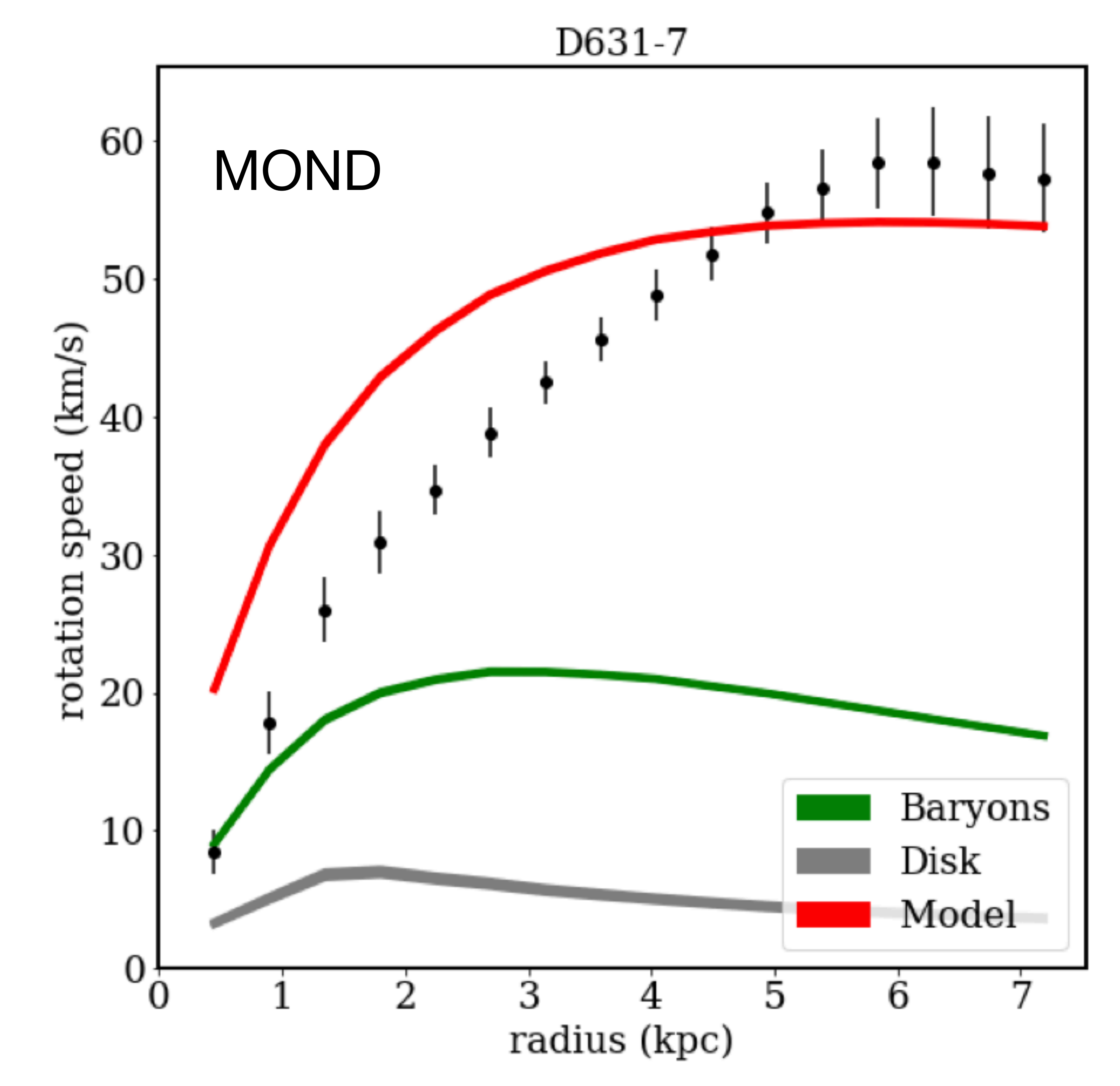


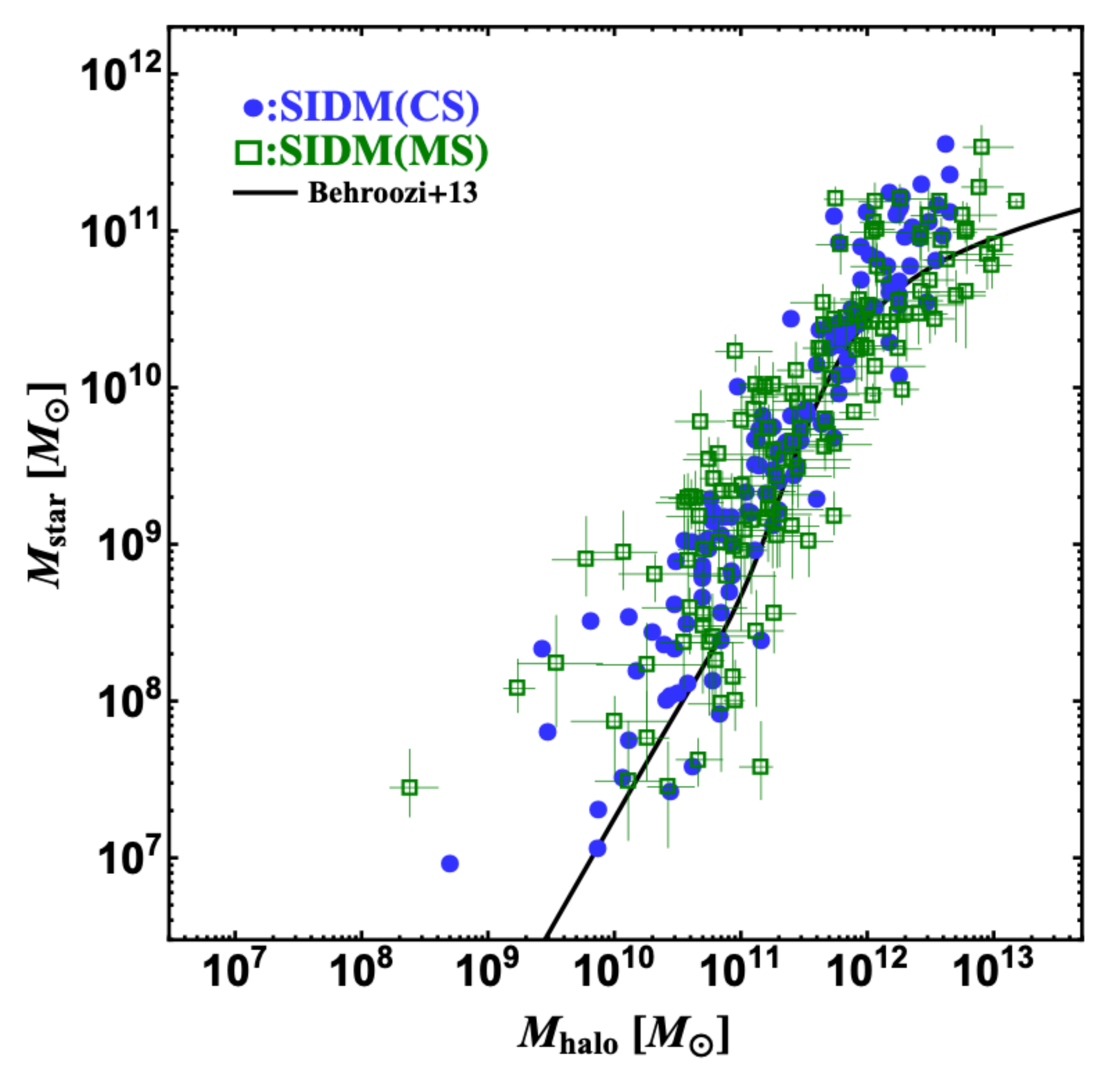
Elbert et al.2015

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 offers better fits to the RCs than MOND
➡halos are fully consistent with the Planck cosmology

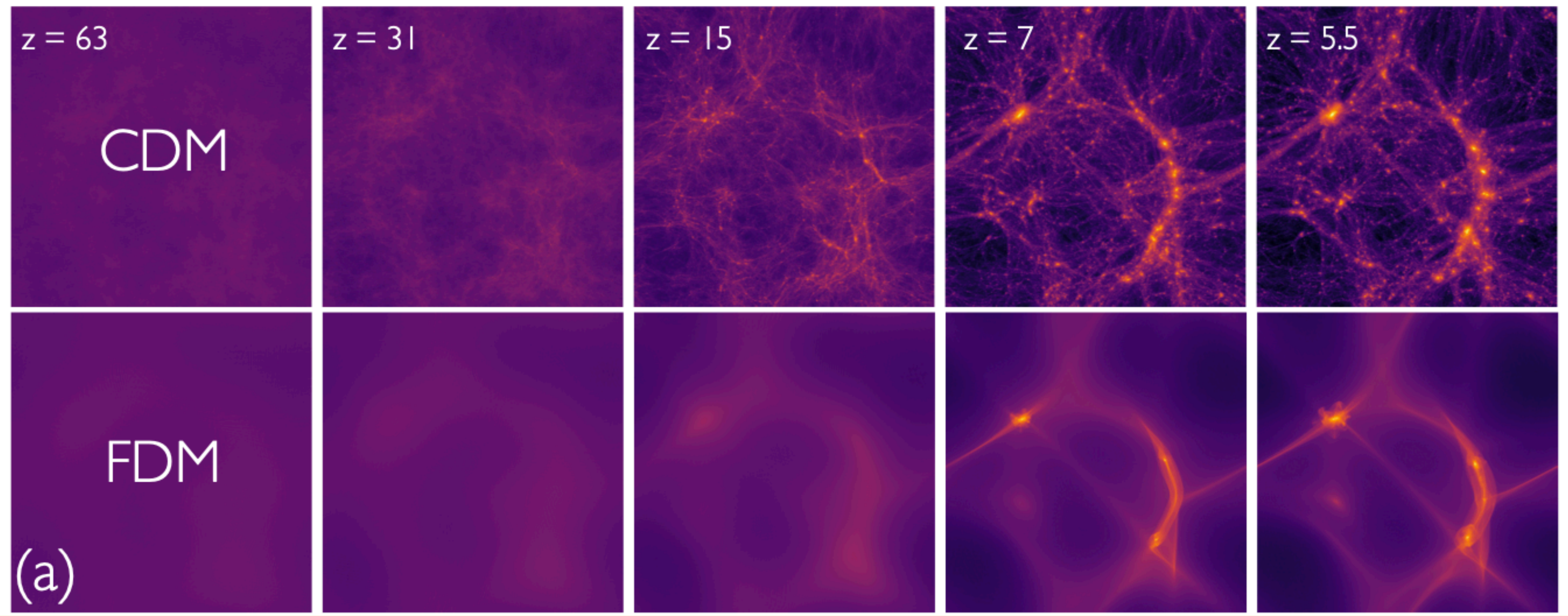
Fuzzy dark matter

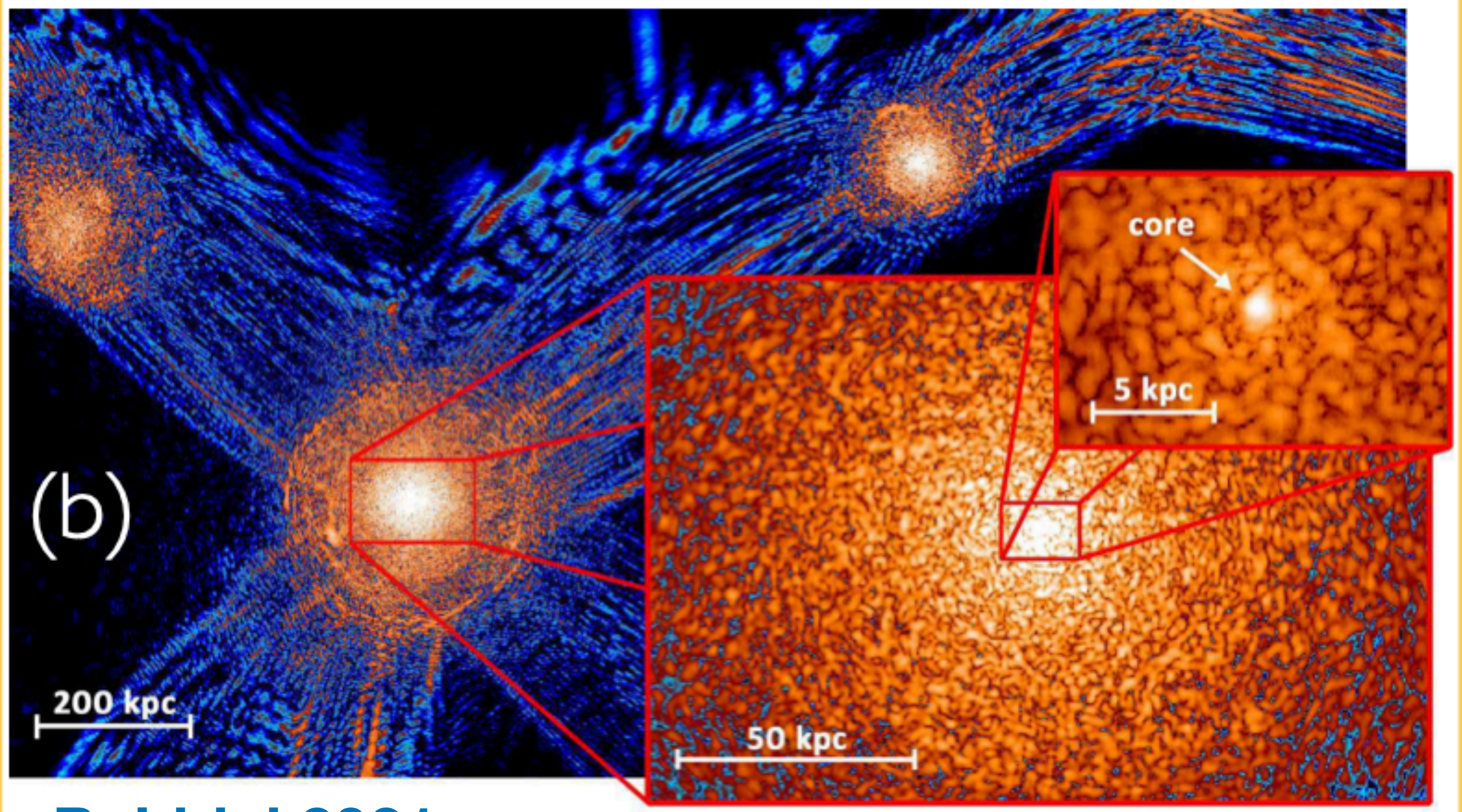
➡Ultralight scalar field with no self-interactions in the non-relativistic limit

➡suppresses structure formation on small scales

➡wave nature leads to quantum pressure, preventing cusps

➡form a Bose-Einstein condensate soliton

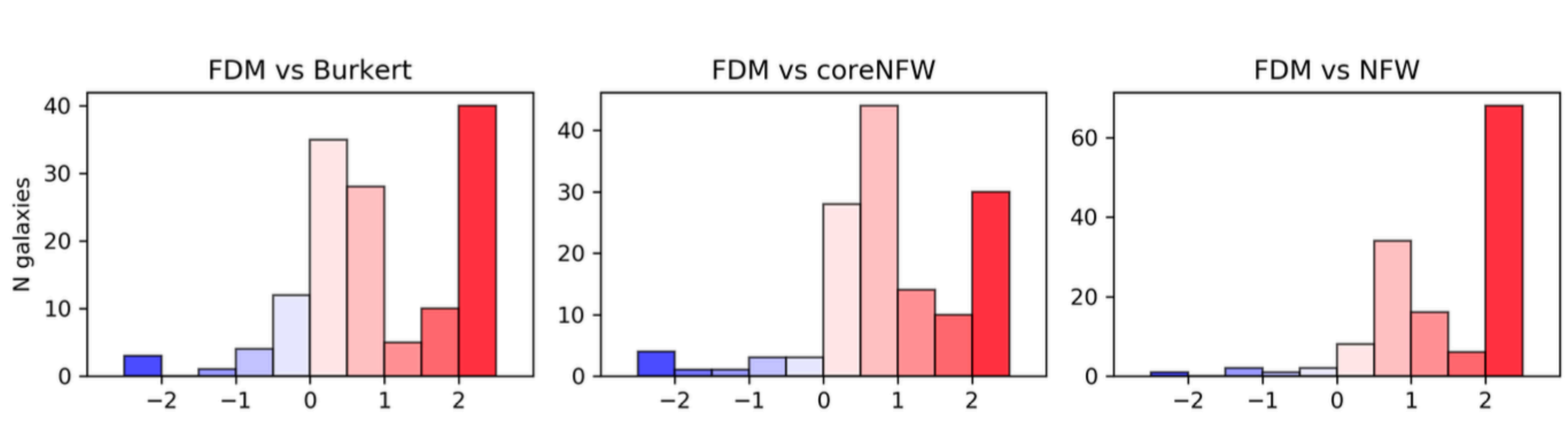




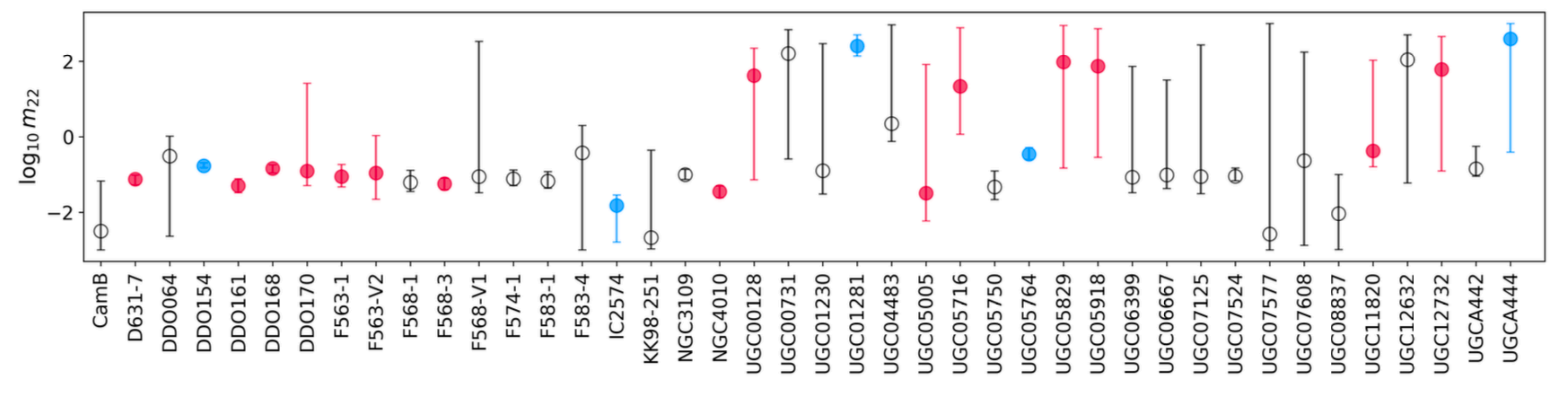
Boldrini 2021

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; (3) Burkert and (4) fuzzy DM



➡Fuzzy DM preferred by >50% of the sample



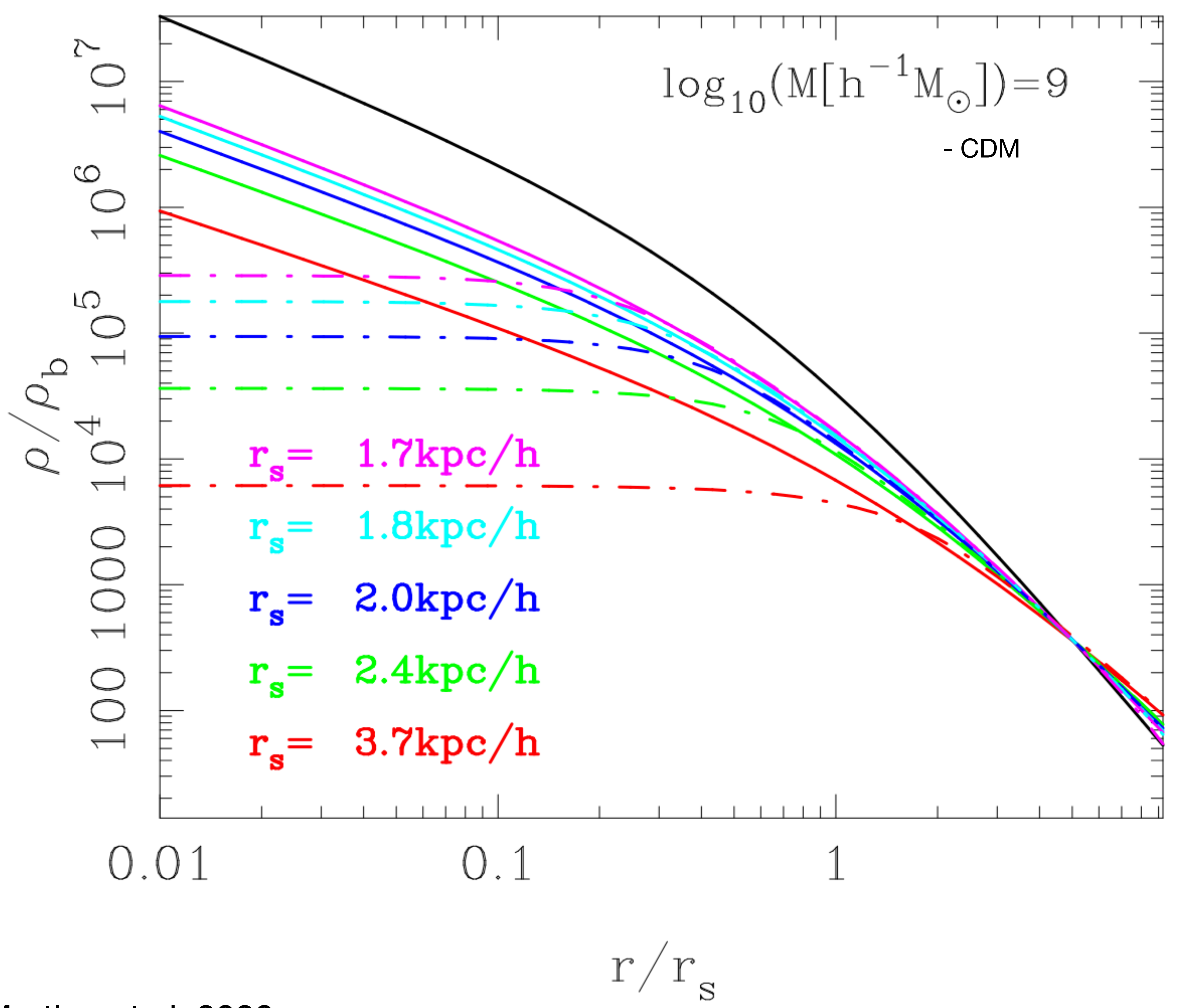
➡**No** single value for the particle mass that provides a good fit for all galaxies

Warm Dark Matter

➡WDM particles decouple when they are still relativistic

➡erase primordial fluctuations on subgalactic scales

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



Martino et al. 2020

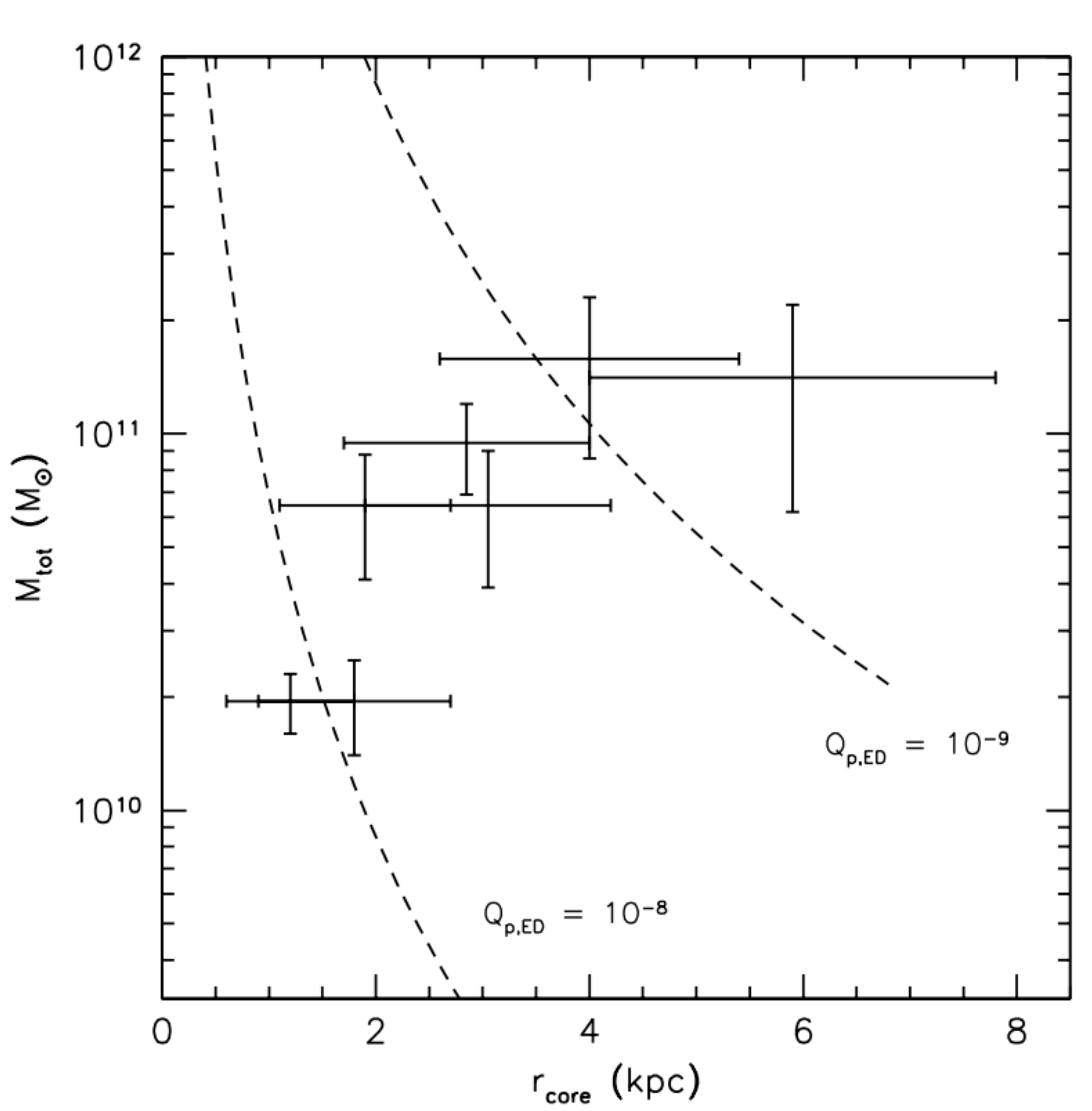
Warm Dark Matter and Rotation Curves: Kuzio de Naray+2010

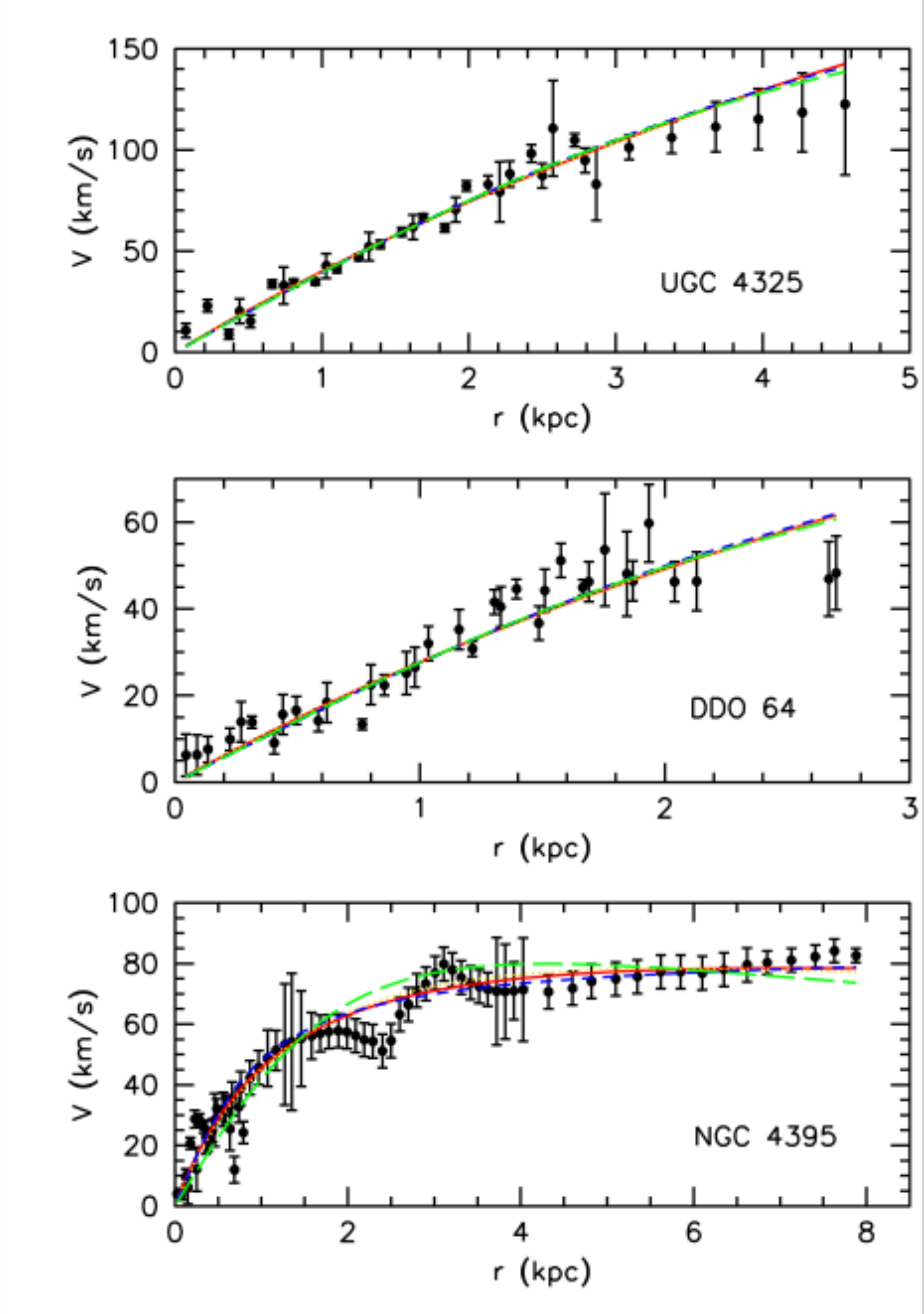
- use rotation curves of 9 local low surface brightness galaxies
- test WDM, non-thermal WDM, and SIDM

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





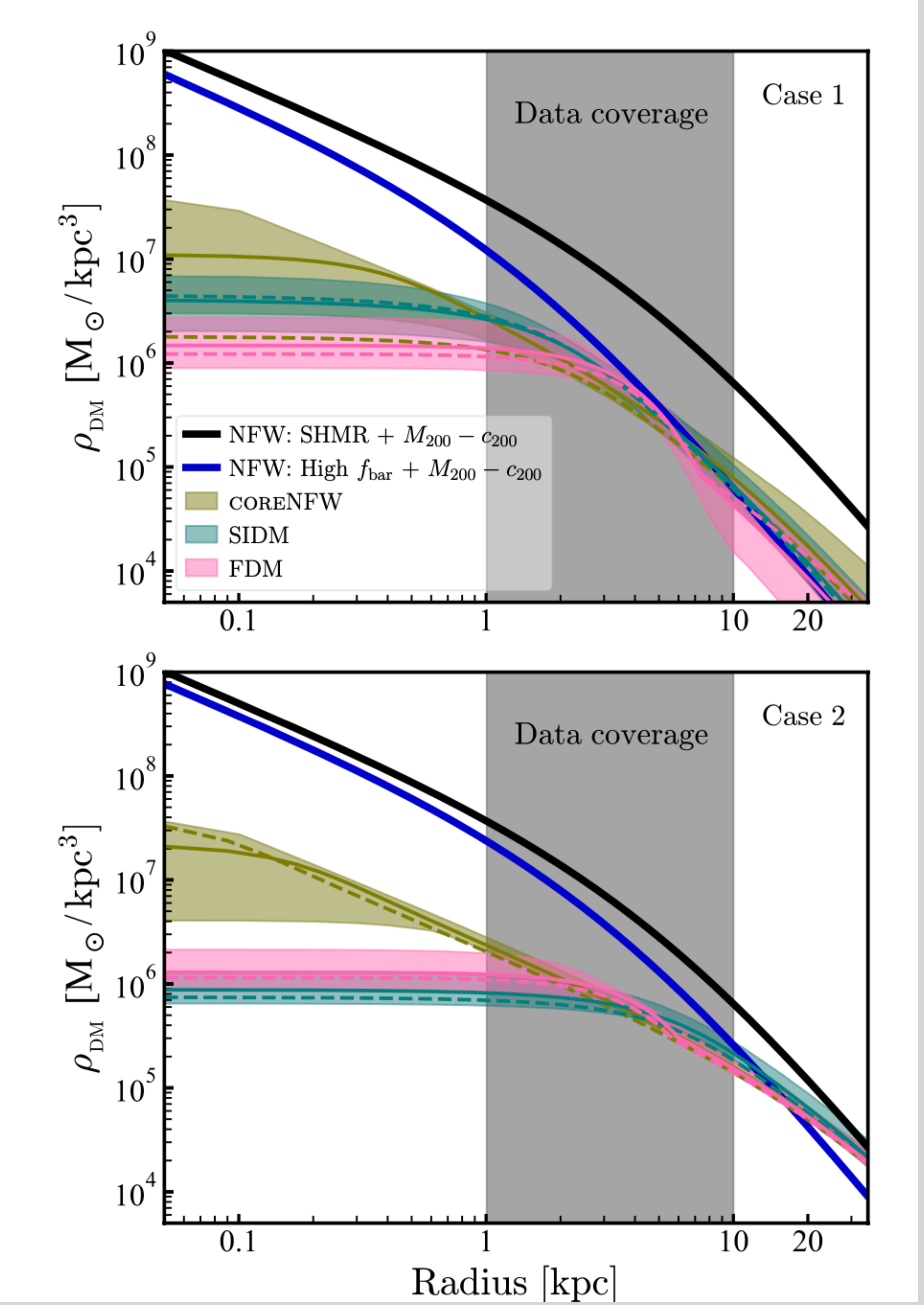
Can we constrain the DM flavour from RCs?

- **Answer is: <u>Probably not?</u>**

☑ **Disk-halo decomposition in <u>1D</u>**

- similar BIC, chi2 values for CDM, SIDM, FDM, etc.

- Need high resolution data to resolve central regions to discriminate between different DM models!



Mancera Piña et al.(2024)

Can we constrain the DM flavour from RCs?

▶ **Answer is: Possibly!**

☑ **Disk-halo decomposition in 3D**

- discriminate between different halo profiles if all available information is used

Outlook

Outlook

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

Outlook

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

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

Outlook

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

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

- **Test alternative DM models:** SIDM, FDM, WDM etc models need to be tested for larger galaxy samples and compared against LCDM.

Outlook

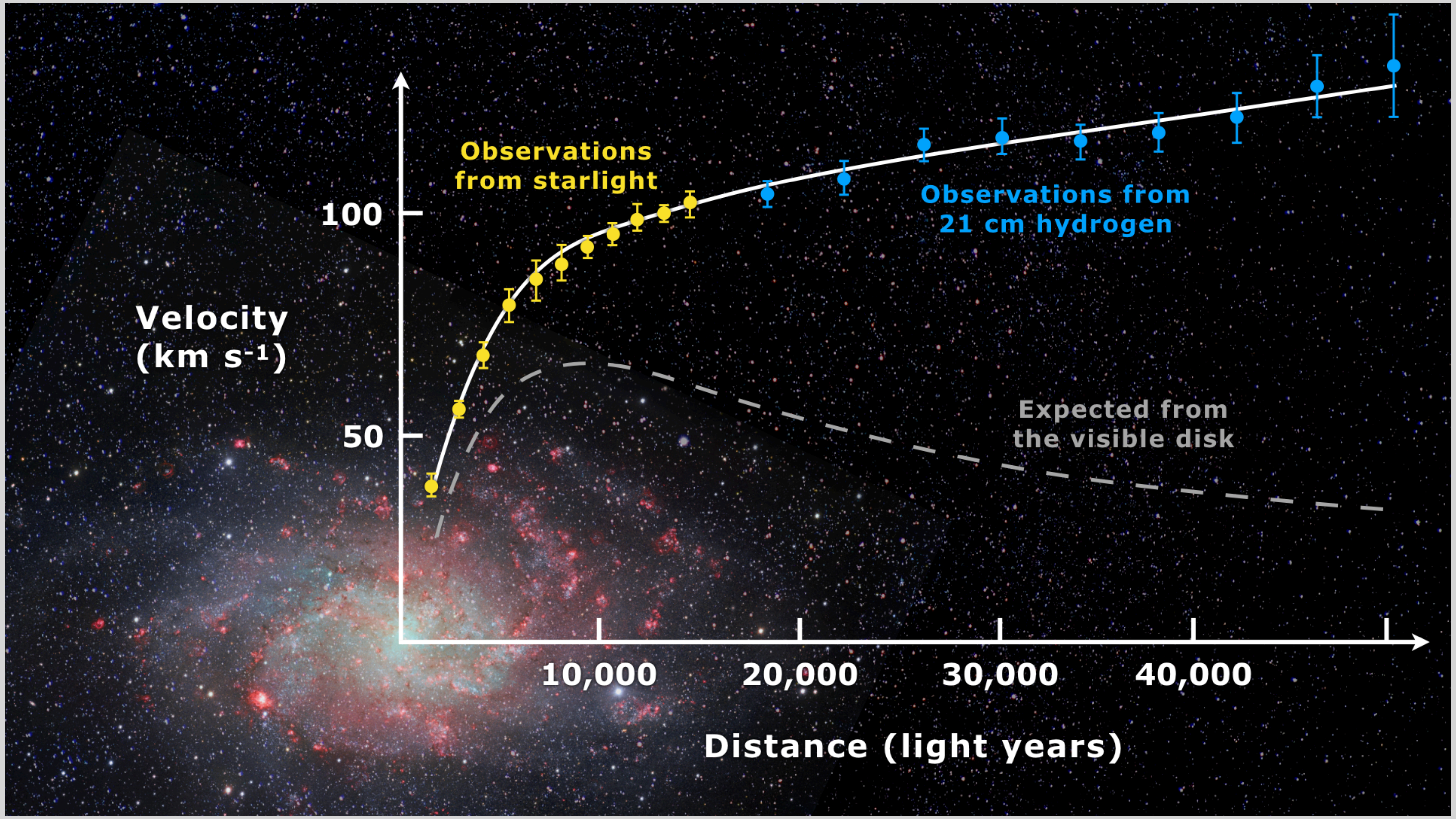
- **Probe larger samples (at z > 1):** With more observational data from next generation instruments, we can extend rotation curve studies beyond the local Universe and explore the evolution of dark matter properties over cosmic time.

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

- **Test alternative DM models:** SIDM, FDM, WDM etc models need to be tested for larger galaxy samples and compared against LCDM.

- **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

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

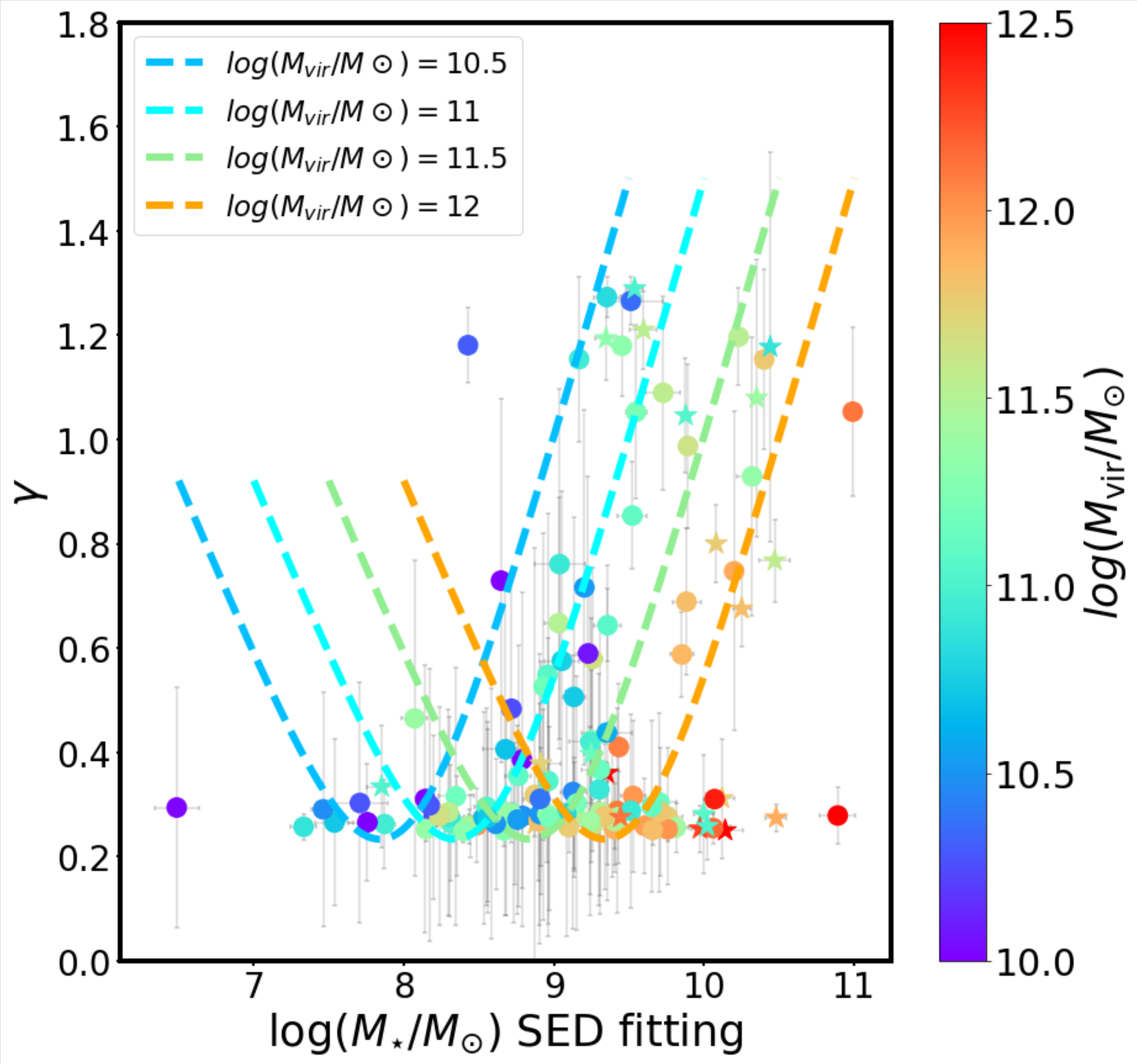
1) DM: different Dark Matter halo profiles
2) Disk: I(r): Sersic n (OII,Ha); Freeman Disk
3) gas: HI gas (marginalized)
4) **pressure support correction (asymmetric drift correction)** →

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

→ **13 - 15 free parameters** (x,y,z,incl,PA,**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



➡Inferred DM inner slopes in accordance with the expectations