Cores and cusps with BlueMUSE
or
how can BlueMUSE help with Dark Matter

Davor Krajnović

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Dark matter / mass discrepancy puzzle

- **Dark Matter for astrophysicists†**:
  - observational evidence for discrepancies measured with different probes of the gravitational potential (rotation curves, gravitational lensing, hydrostatic temperatures)
- **Dark Matter for (particle) physicists†**:
  - a new particle (and a vast parameters space)
- "need" for DM comes from **astronomical observations** (galaxies, clusters of galaxies, lensign, CMB)
- how can BlueMUSE investigate DM?

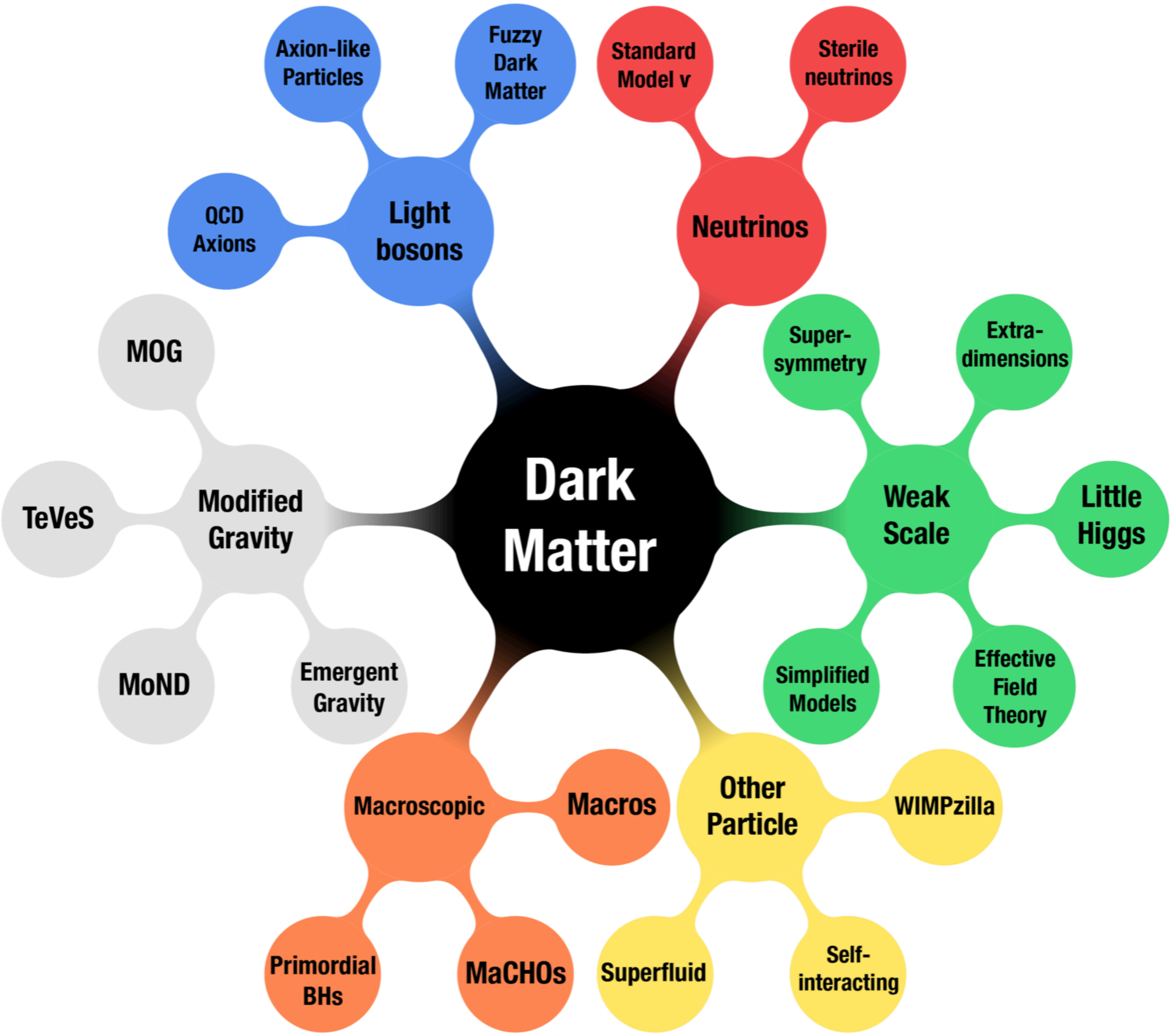


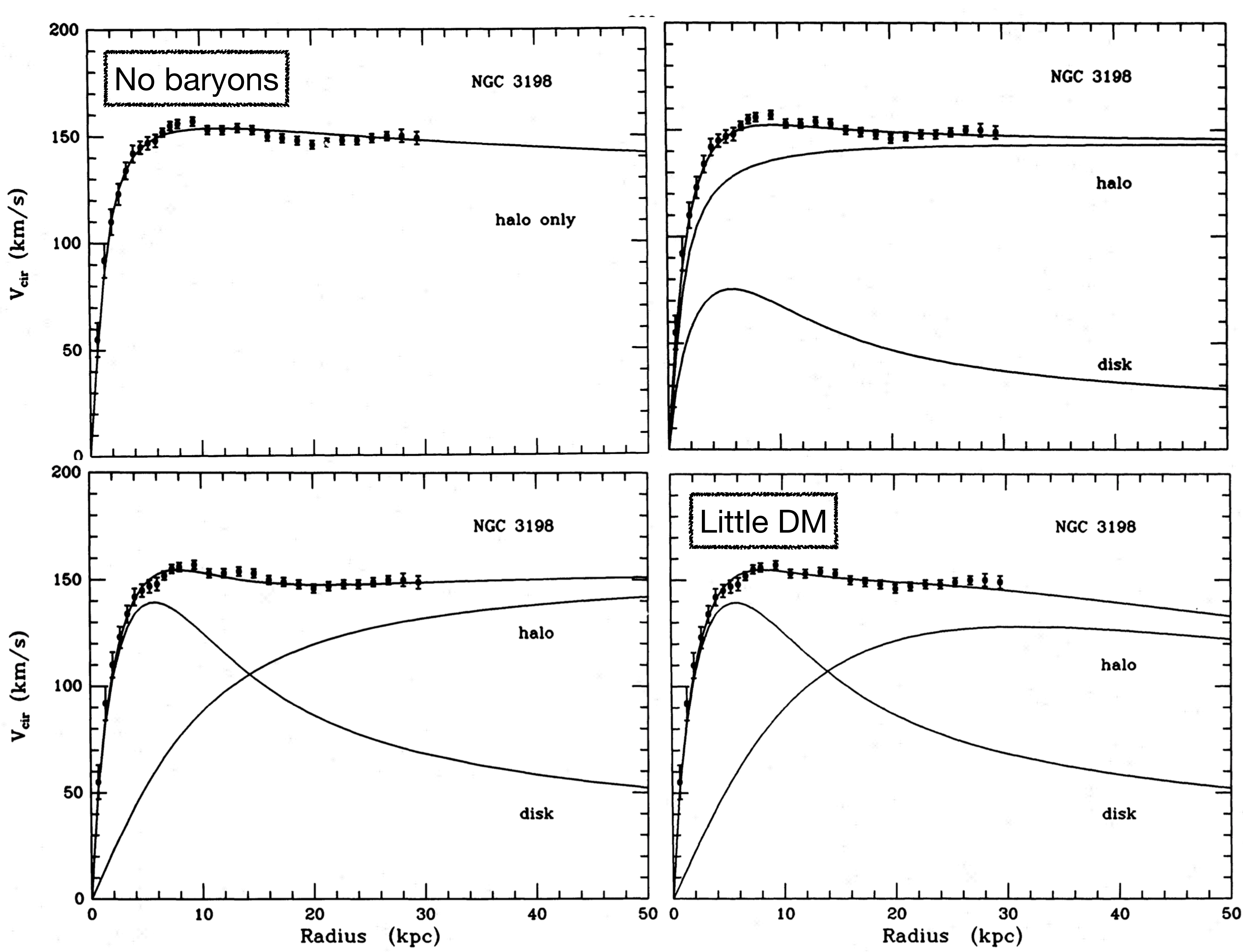
Image: Berton & Tait from here

† taken from Stacy McGaugh blog tritonstation

Rotation curves

- **observational fact**:
    - rotation curve stays (nearly) constant at large radii (far beyond the stellar body of the galaxy)
    - Oort; Shostak; Bosma; Rubin...
- **interpretation(s)**:
    - there is a certain amount of missing (unseen) mass
    - gravity law should change
- if mass is missing
    - **how much (unseen) mass is there**?
    - **how is it distributed**?

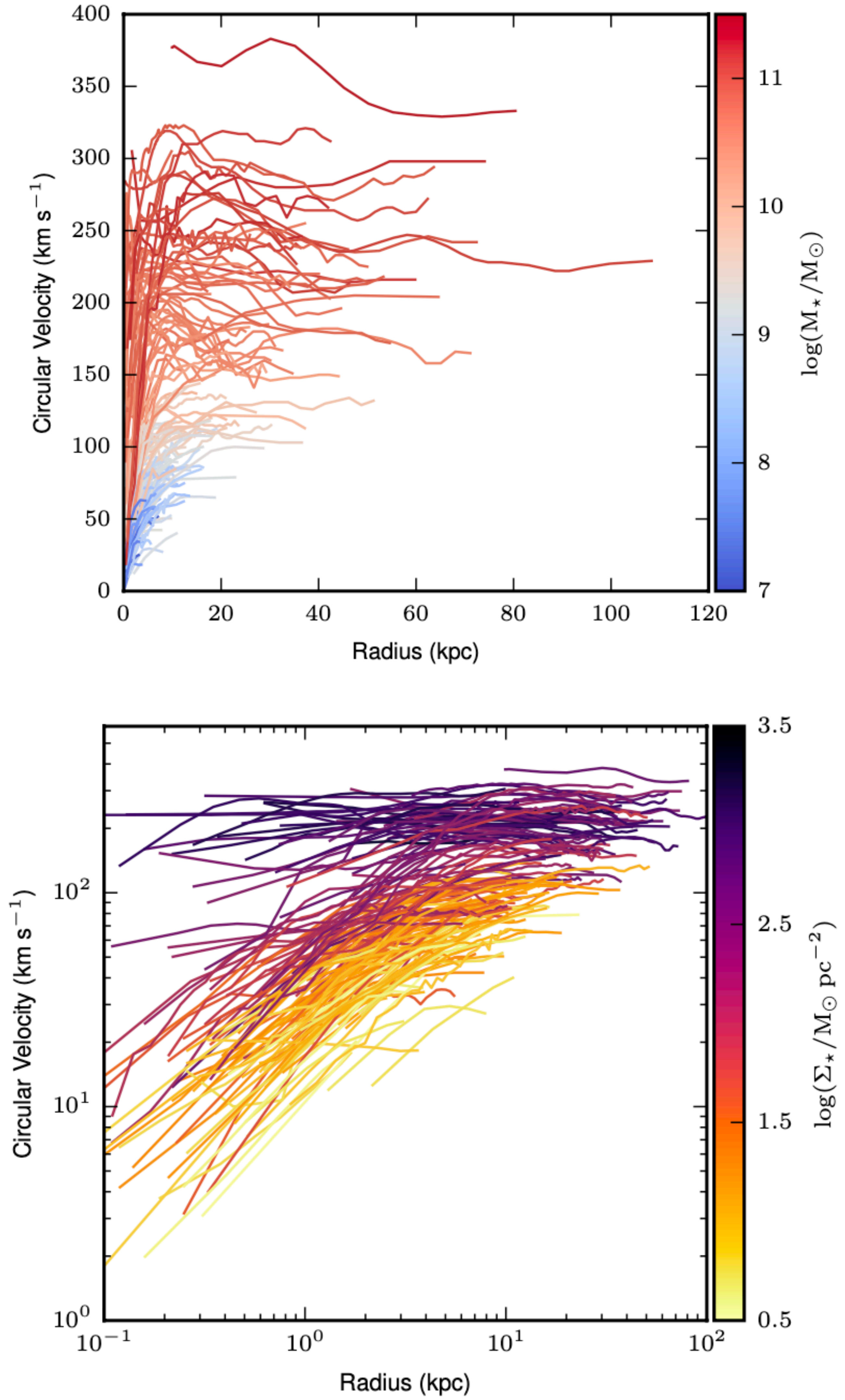
van Albada et al. (1985)



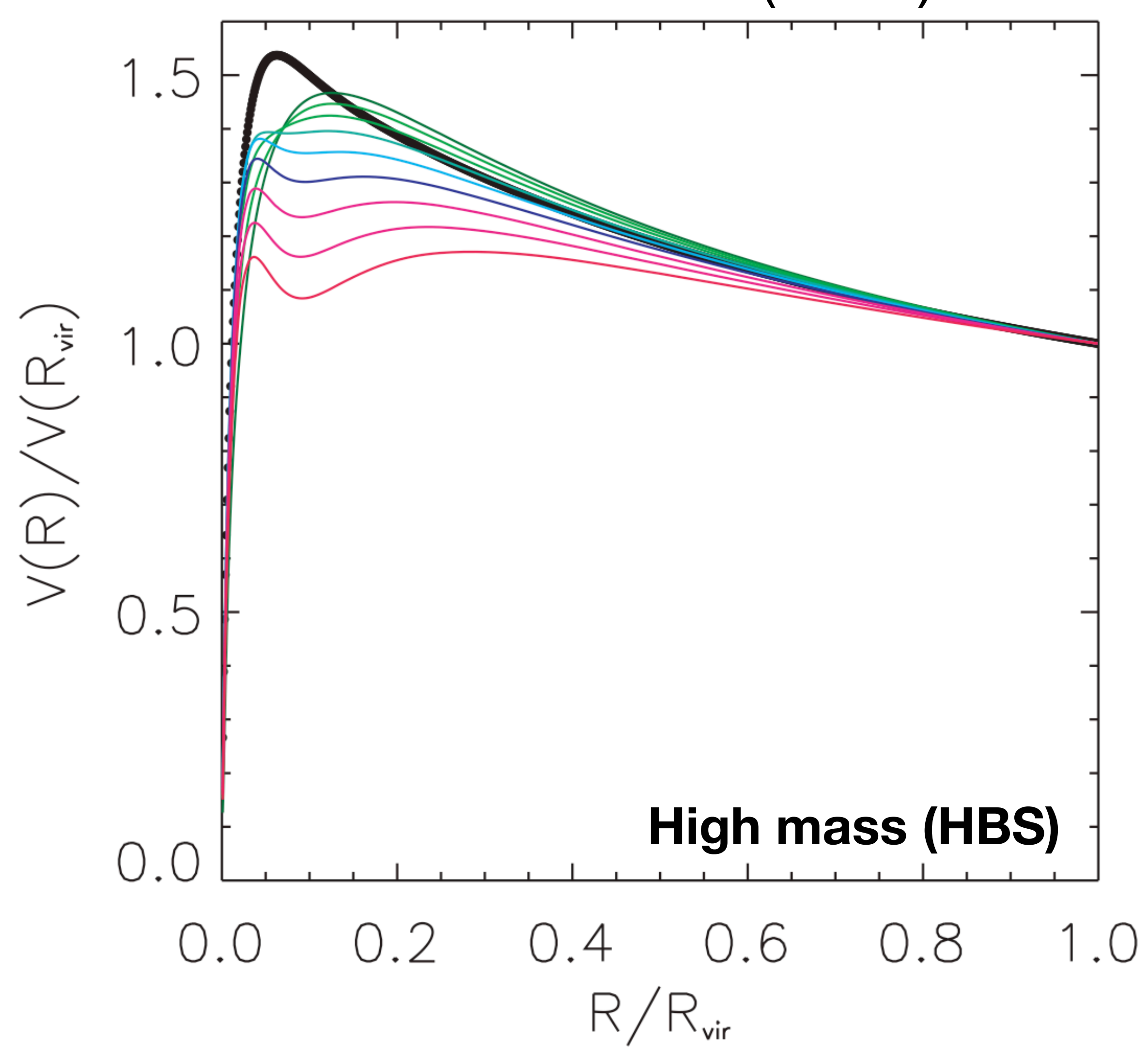
A few facts about rotation curves

- **Fact 1 (large spatial scales)**:
  - the amplitude of the rotation curve depends on the galaxy mass (Tully - Fisher relation)
- **Fact 2 (small spatial scales)**:
  - the steepness of the rotation curve depends on the stellar surface density (central density relation)
- **Fact 3 (different mass scales)**:
  - remarkable regularity of rotation curves (once divided by mass)
  - strong local baryon-DM coupling

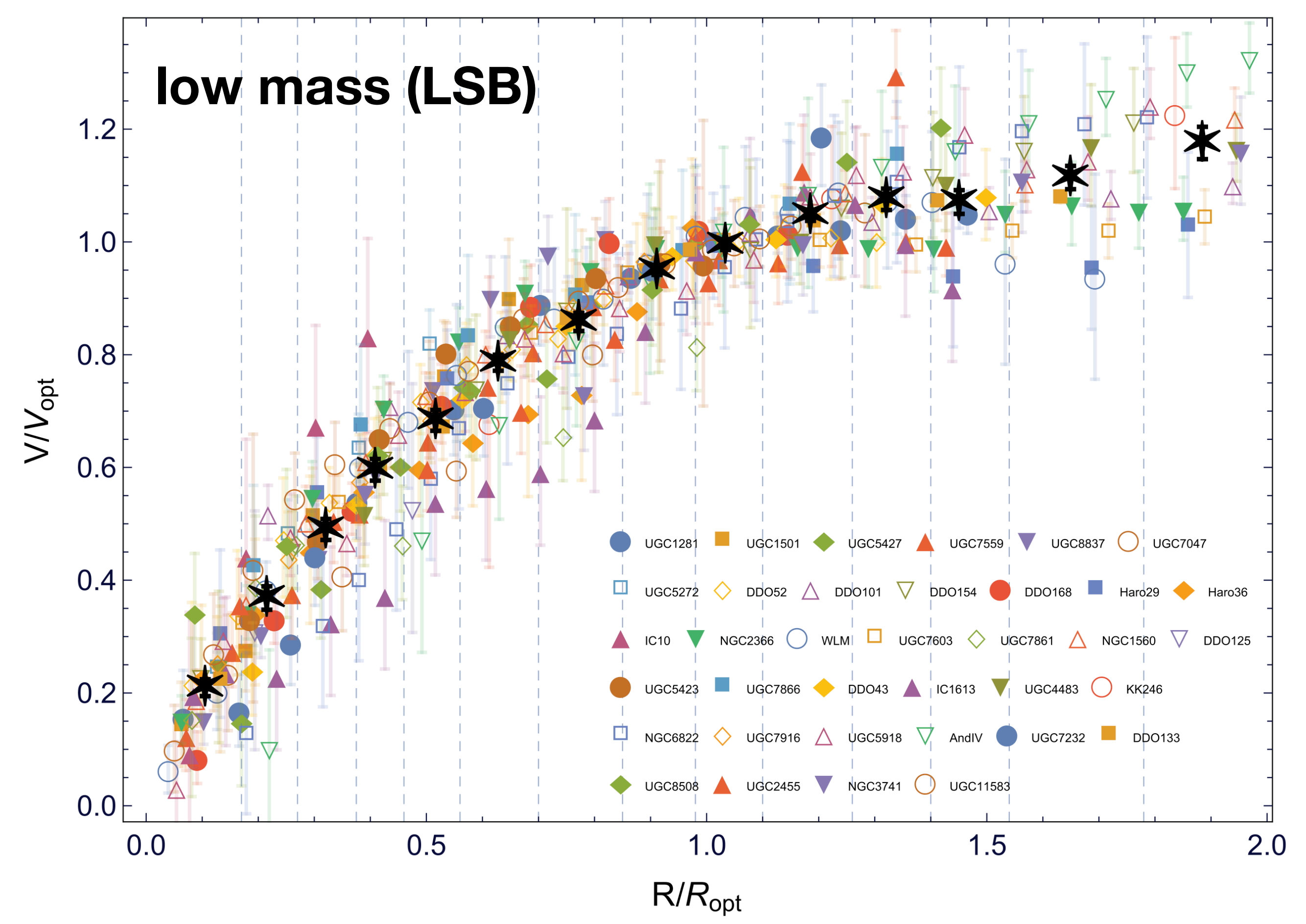
Lelli et al. (2022)



Salucci et al. (2007)

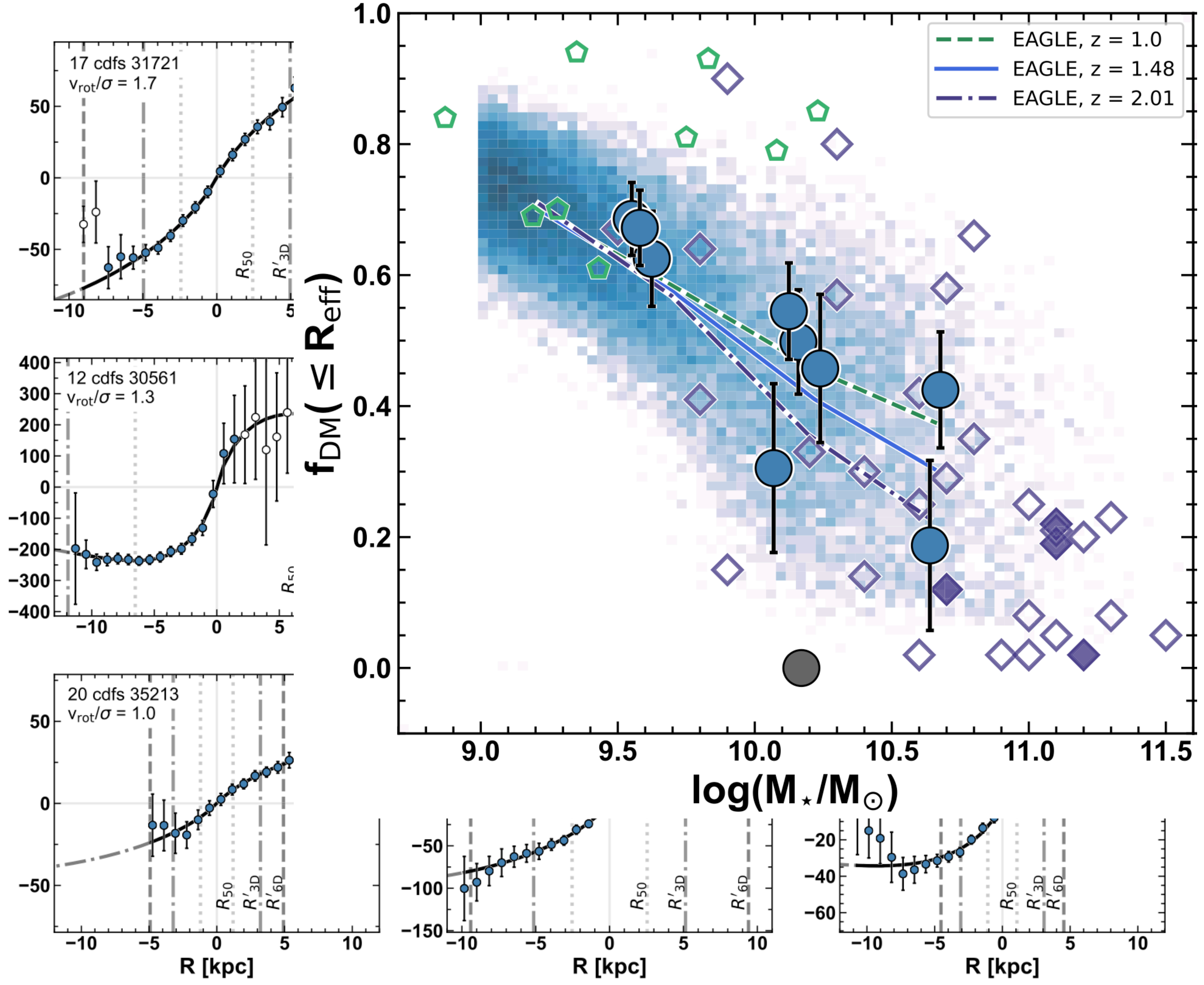


Karukes et al. (2017)



Rotation curves at high - z

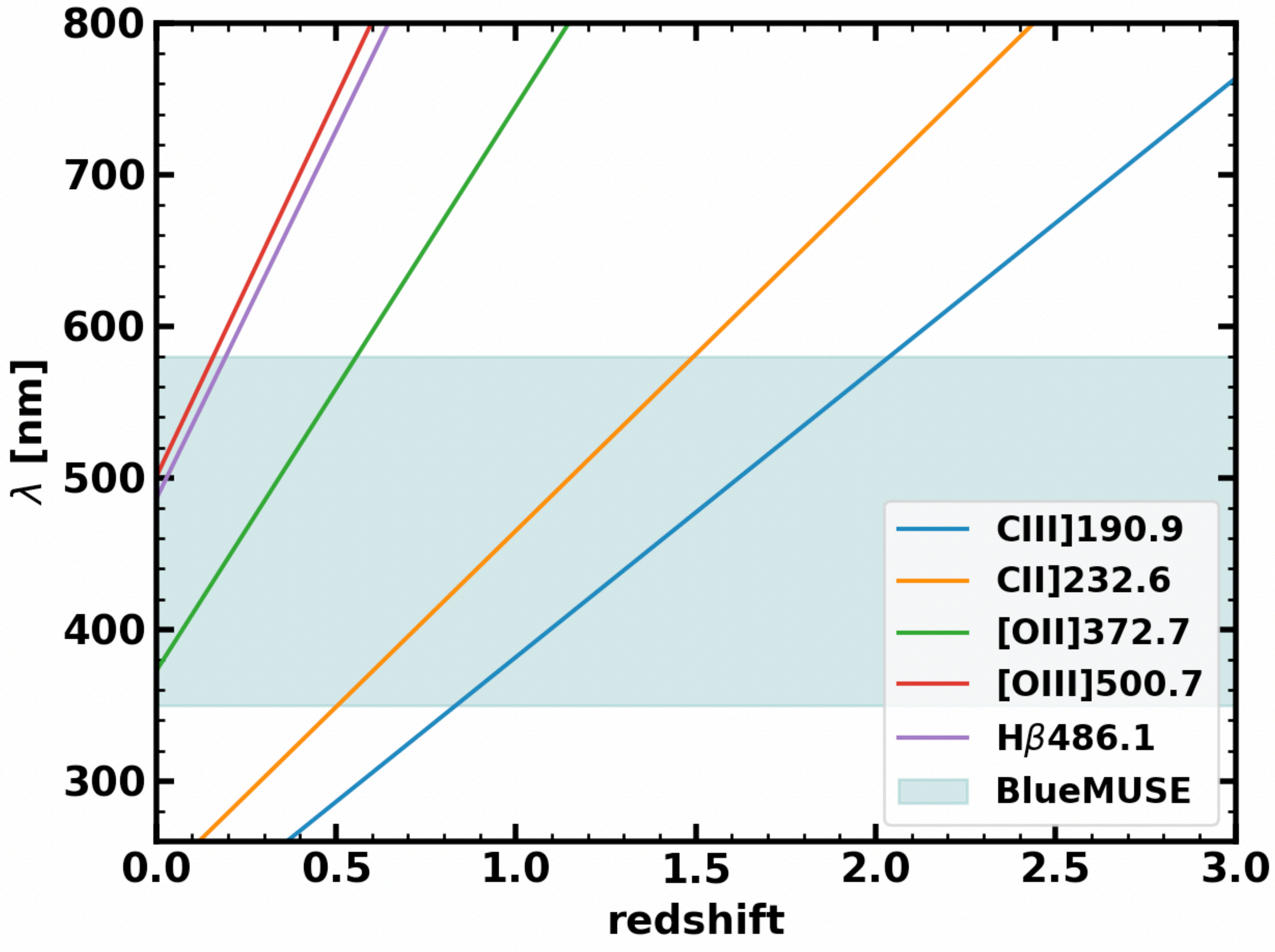
- flat rotational curves are **not yet well established** for high-z
  - with some (deep) exceptions
- samples of galaxies with DM estimates are growing (e.g. Genzel et al. 2017, 2020, Lang et al. 2017, Tiley et al. 2018, Übler et al. 2018, Rizzo et al. 2020,2021, Price et al. 2021, Sharma et al. 2022, Bouche et al. 2022, Lelli et al. 2023, Puglisi et al. 2023, Roman-Oliviera et al. 2024)
- fraction of DM changes with stellar mass (roughly as predicted)
- ALMA, NIR -IFU (Sinfoni), MUSE, ELT (Harmoni, MOSAIC)
  - waiting for SKA



Puglisi et al. (2023)

What could BlueMUSE target?

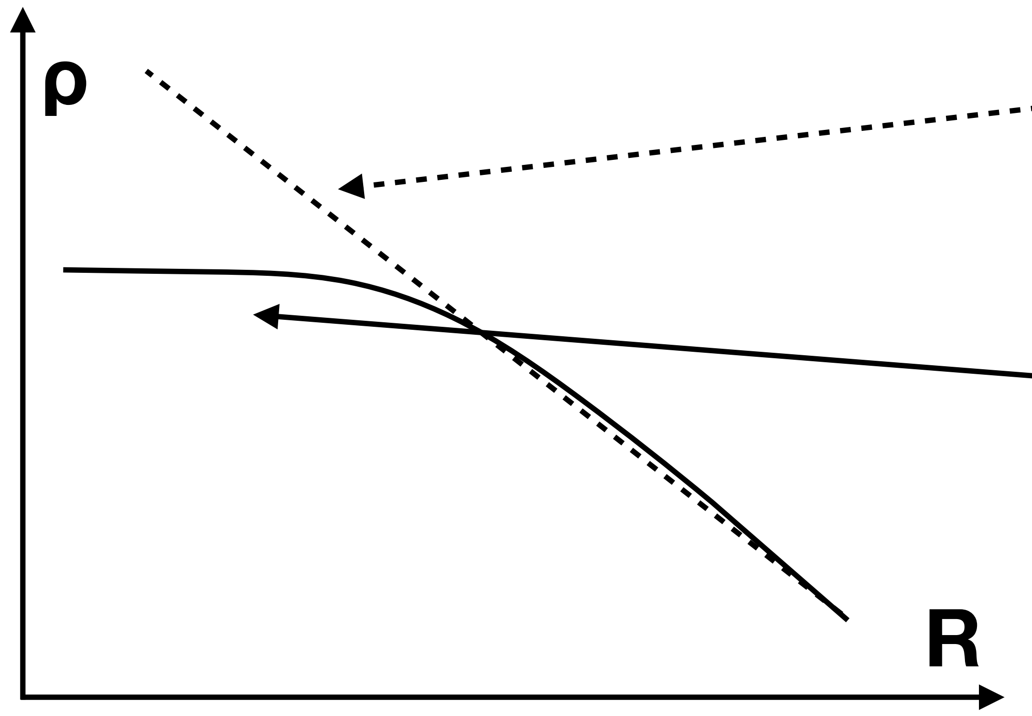
- **DM content and properties**
  - as MUSE in medium + deep fields (e.g. Abril-Melgarejo et al. (2021); Mercier et al. (2022, 2023), Bouché et al. (2021, 2022)
  - + angular momentum, TFR, environment, emission-line properties...
- **limited by spatial resolution** (galaxies are small)
  - targeting large scale kinematics (outer rotation curves)
  - targeting galaxies with large discs
- (less?) **limited by the obs time** (galaxies are faint)
  - emission-line kinematics
  - (absorption-line kinematics)
- **better spectral resolution**
  - MUSE σ ~ 40 - 65 km/s
  - BlueMUSE σ ~ 30 - 45 km/s



Cusps or cores?

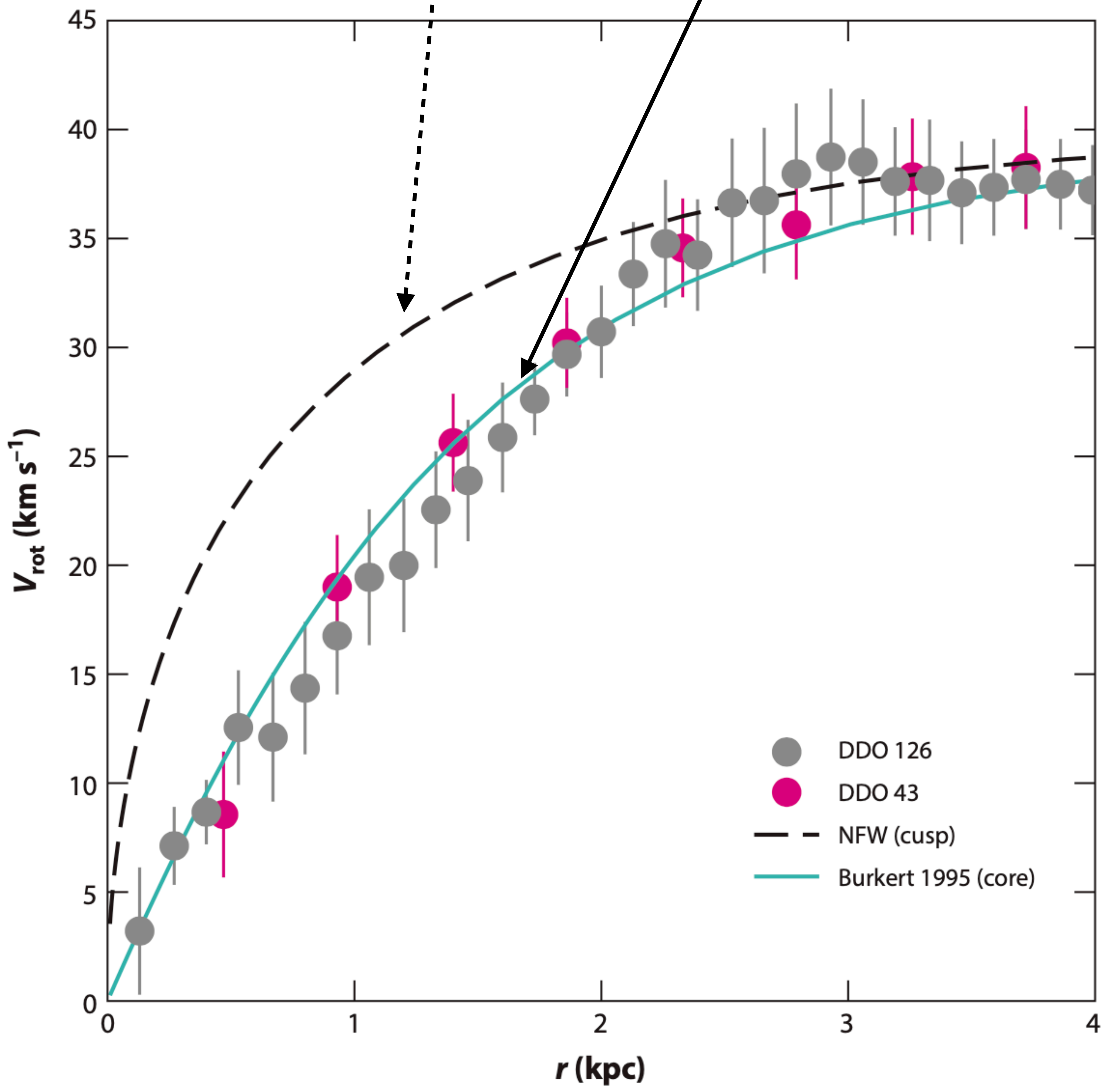
- what is the **dark matter distribution**
  - observations imply a strong link between baryons and DM
- the (historic?) **core problem**?
  - some galaxies have cusps, some have cores
  - based on the V_{rot} shape: more massive galaxies will have cusps, less massive will have cores
- the **inner slope** of the mass distributions
  - double-power law: γ (Jaffe 1983, Hernquist 1990, Zhao 1996)
- proposed solution (ΛCDM)
  - **stellar feedback**

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



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

$$\rho_{Bur}(r) = \frac{\rho_0 r_{core}^3}{(r+r_{core})(r^2+r_{core}^2)}$$

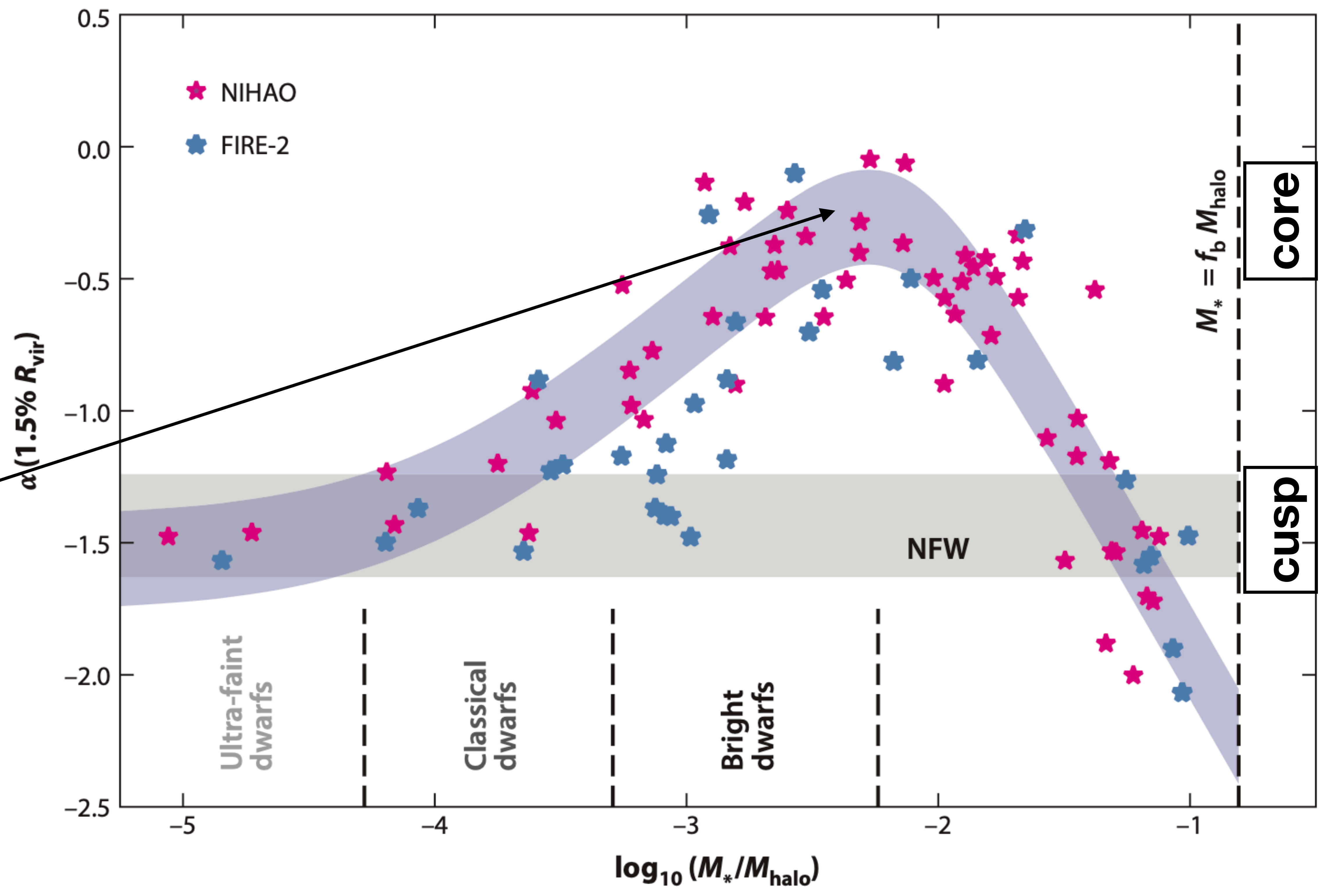


Bullock & Boylan-Kolchin (2017)

Feedback

- DM - baryon link through star formation feedback (e.g. Di Cintio et al. 2014, Reed et al. 2016)
  - how "deep" the core will be, depends on the mass of formed stars
  - energy from SN redistributes DM and creates core
  - too few stars: not enough energy to move DM
  - too many stars: excess central mass attracts DM (back)
  - as long as there is SF, cores will form
- stochastic SF induced fast changes of gravitational potential: inducing gas to expand (outflow) and collapse (inflow) rapidly (e.g. Pontzen & Governato 2012) --> transfer of energy to DM
- peak core formation:
  - 0.005 M_{vir} or $M_s \sim 10^{8-9} M_{SUN}$
- inefficient:
  - below $M_s/M_{vir} \sim 10^{-4}$, or for $M_s < 10^6 M_{SUN}$ (too few SN)
  - high stellar masses: it takes longer than the Hubble time to form a core

Bullock & Boylan-Kolchin (2017)

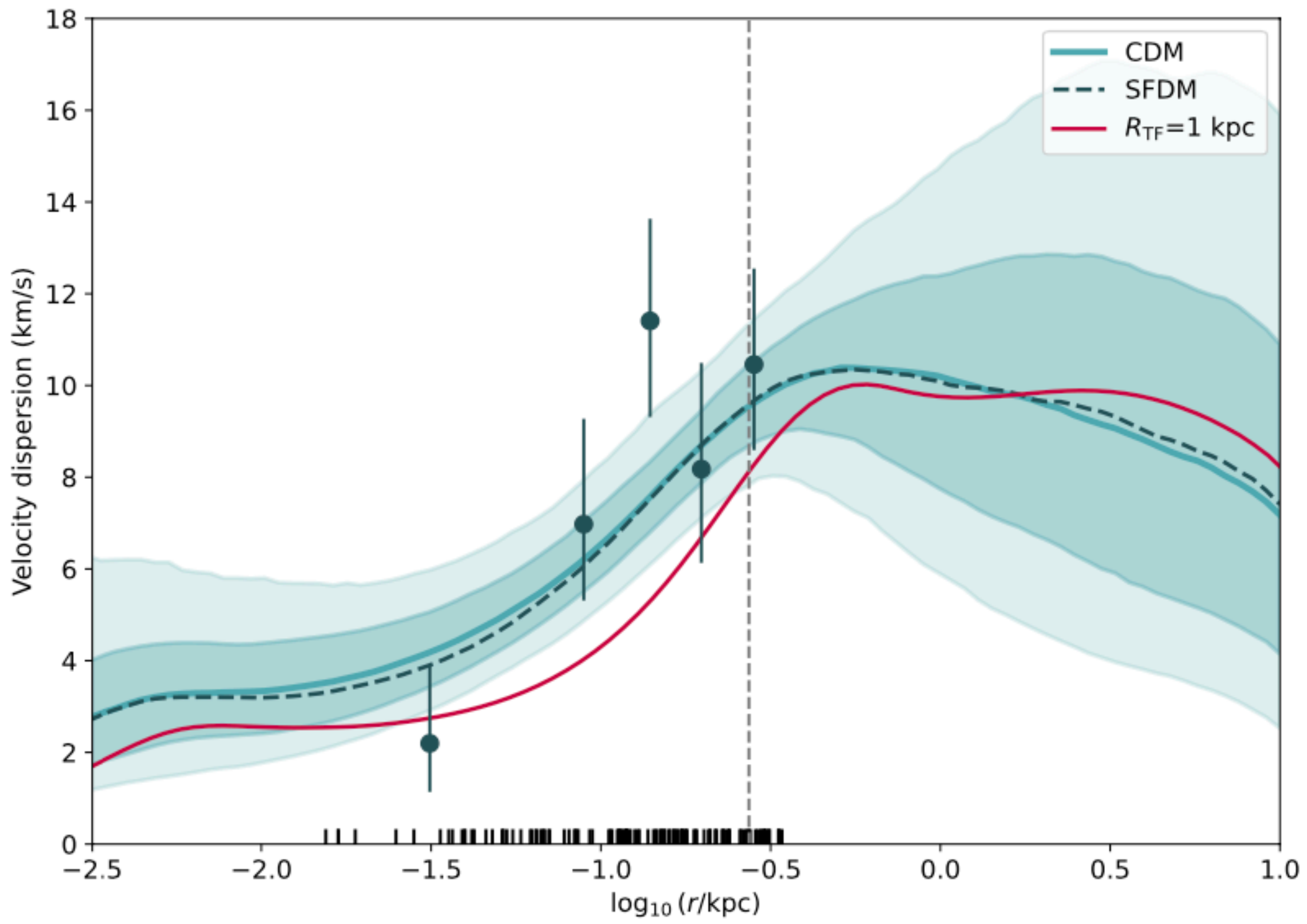


galaxies with "original" DM cores:
- truncated SF
- small galaxies

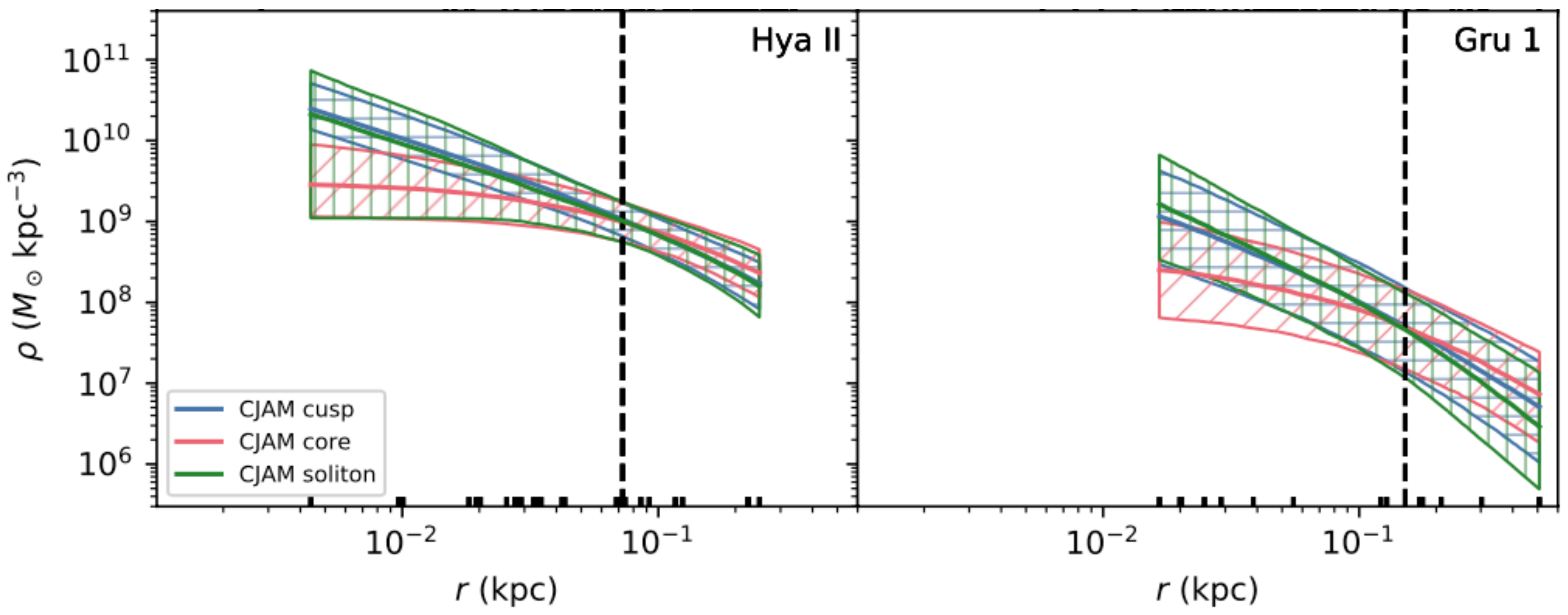
Different DM flavours

- a few DM possibilities - same as CDM on large scales, but diverge on small scales
- **CDM** - collisionless Boltzmann equation
- **WDM** - Warm Dark Matter
  - free streaming suppress small-scale fluctuations (and keeps cusps)
- **FDM** - "Fuzzy" DM (axion-like)
  - - ultra light bosons (10^{-22} eV) (Bose-Einstein condensate)
  - 1kpc soliton cores
- **SIDM** - Scalar Field DM (or Self-Interacting DM) -
  - ultralight bosons (Bose-Einstein condensate)
  - self-interaction + repulsive self-interaction
  - cores (kpc scale) caused by self interaction

Júlio et al. (2023)



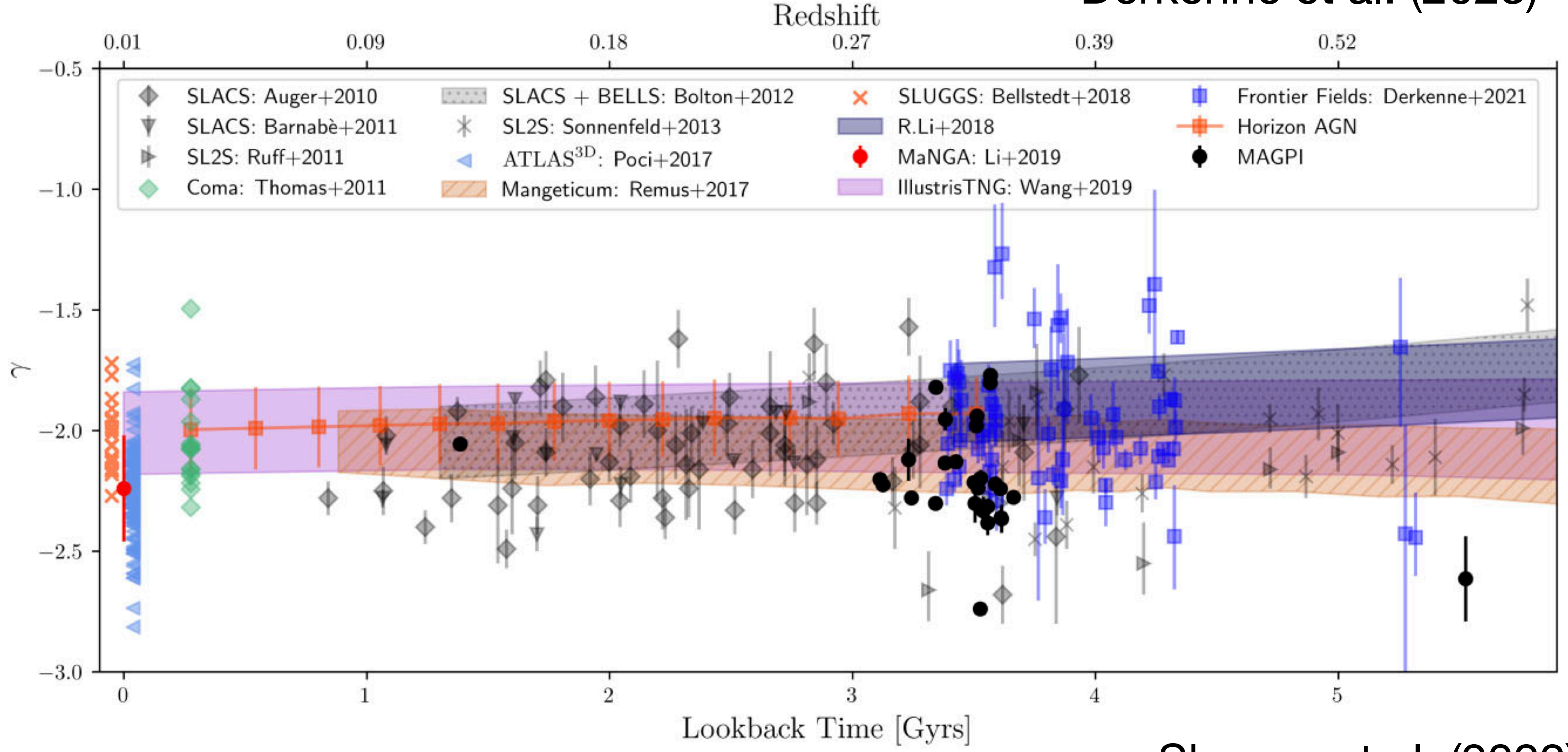
Zoutendijk et al. (2021)



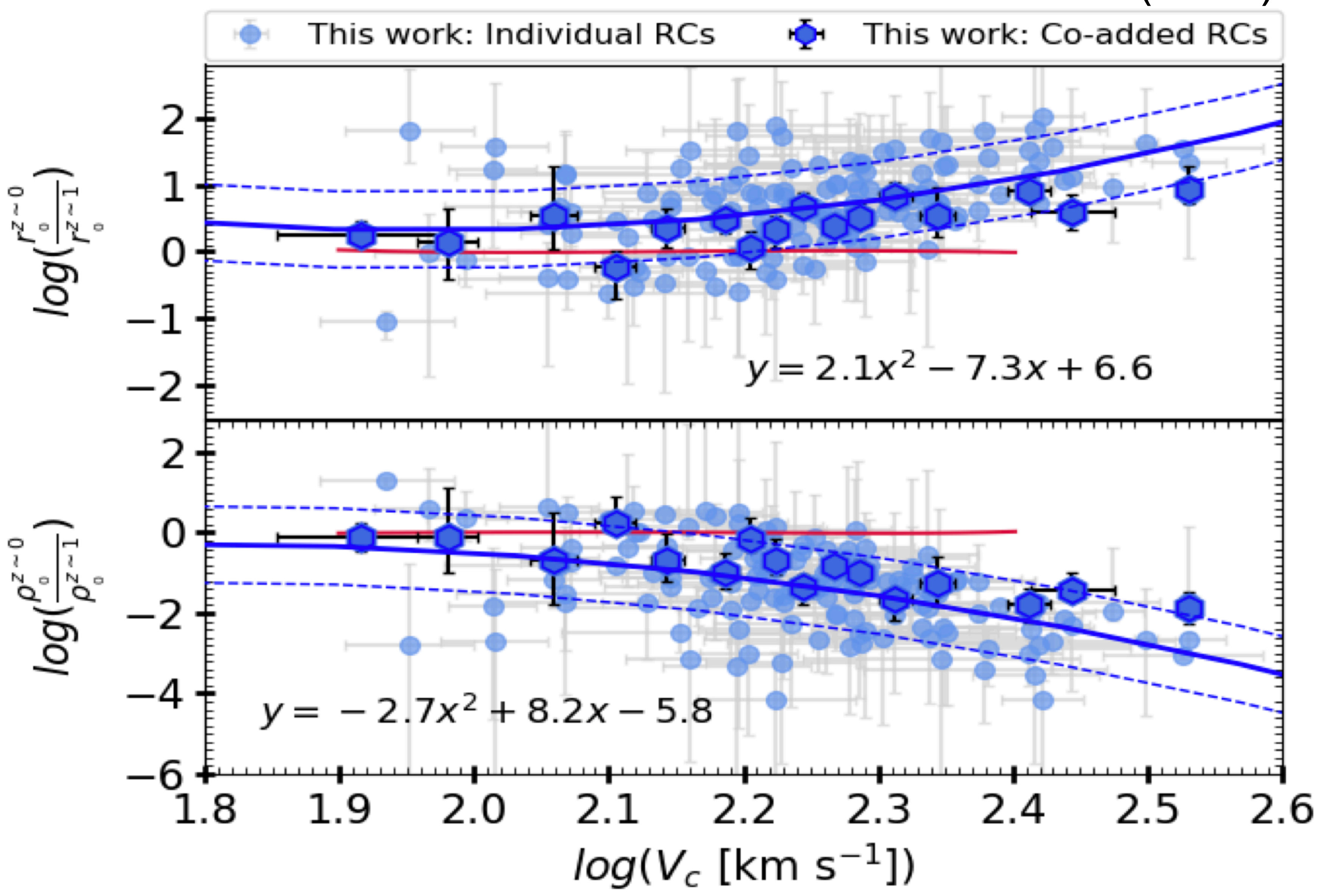
Evolution of DM properties

- how do DM properties evolve ith time
  - DM fraction
  - total mass density slope
  - size of cores
- numerical simulations predict a change of total density slopes due to merging, converging to an isothermal sphere value (e.g. Remus et al. 2013)
  - time evolution
  - environment influence
- observational evidence suggest DM properties (i.e. size of cores) change with redshift

Derkenne et al. (2023)



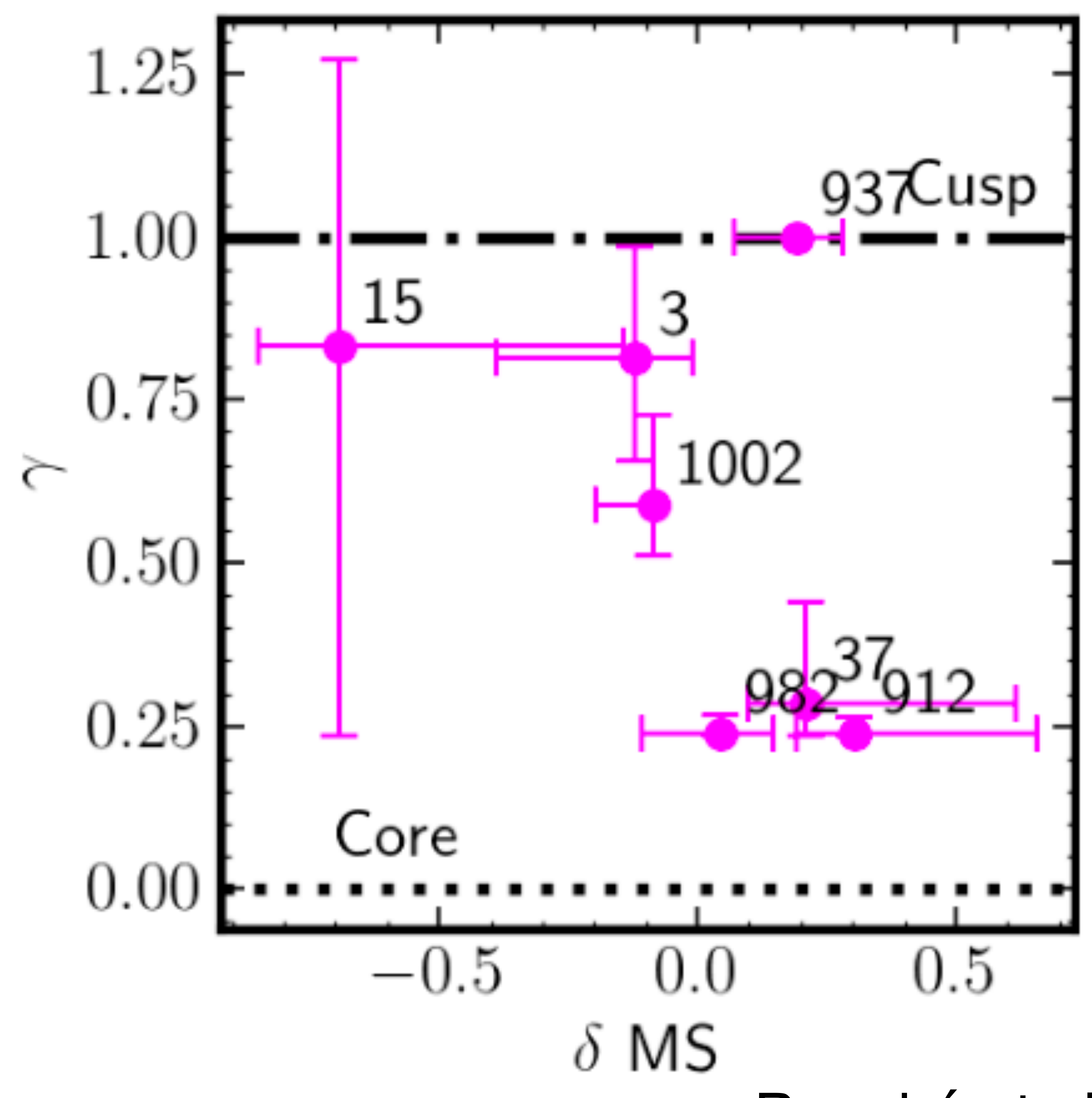
Sharma et al. (2022)



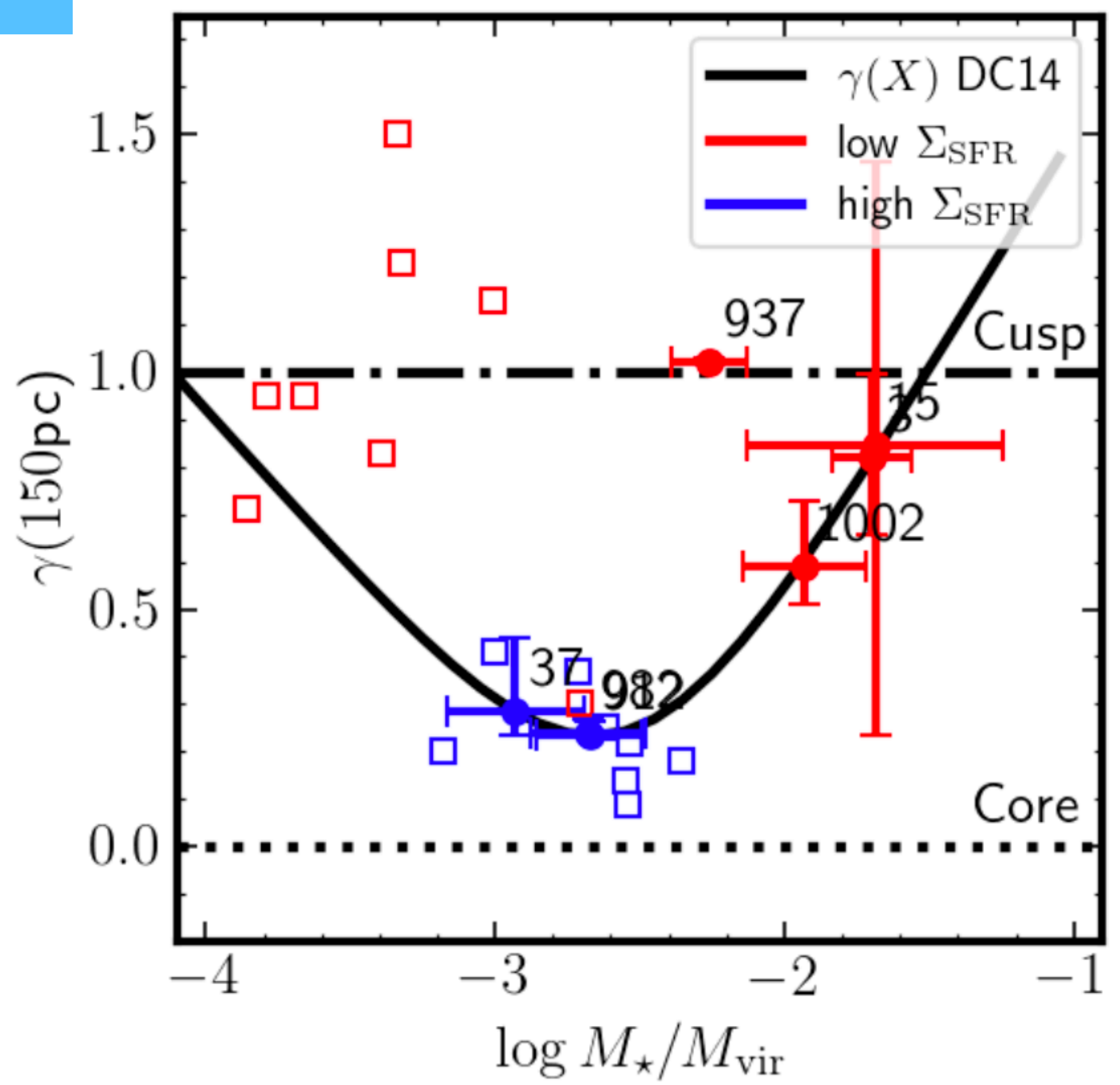
Cusps and SF

- **theory**: DM cores due to baryonic feedback
  - star formation / AGN
  - minor mergers (major mergers remake cusps)
- **observations**: cusps and cores
  - local dwarf galaxies (<$10^7 M_{SUN}$; Read et al. 2019)
    - truncated SF -- cusps
    - extended SF -- cores
  - star forming z~1 galaxies (logM~10^9 M_{SUN})
    - cores
- linking the **star formation history** with **core formation**?
  - complications with merger history and DM properties
  - SFH depend on halo masses (Scholz-Díaz et al. 2023)
- investigating **local sample** of SF and quenched (dwarf) galaxies

rotation curves of galaxies at z~1 based on MXDF 140h



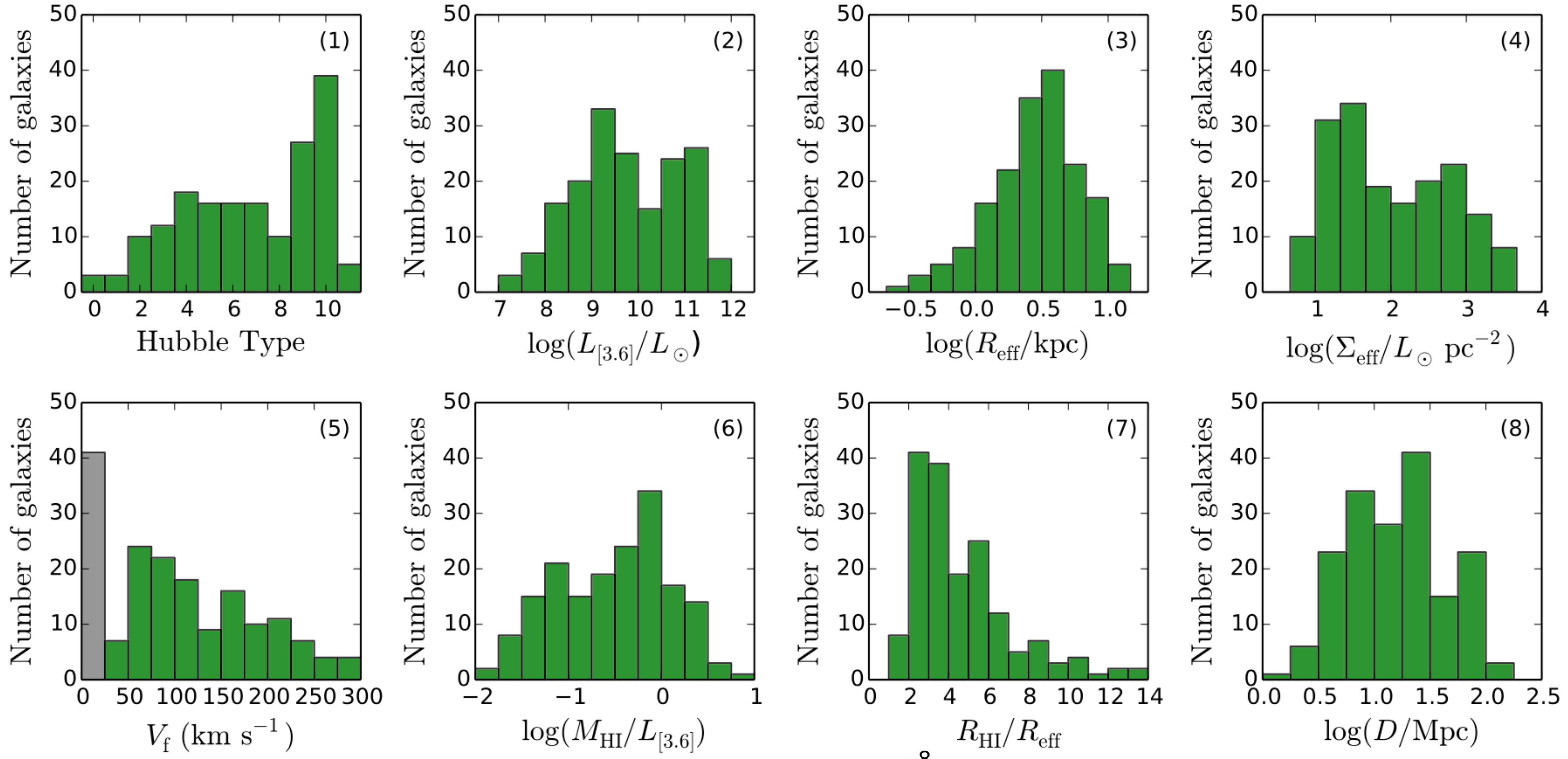
Bouché et al. (2022)

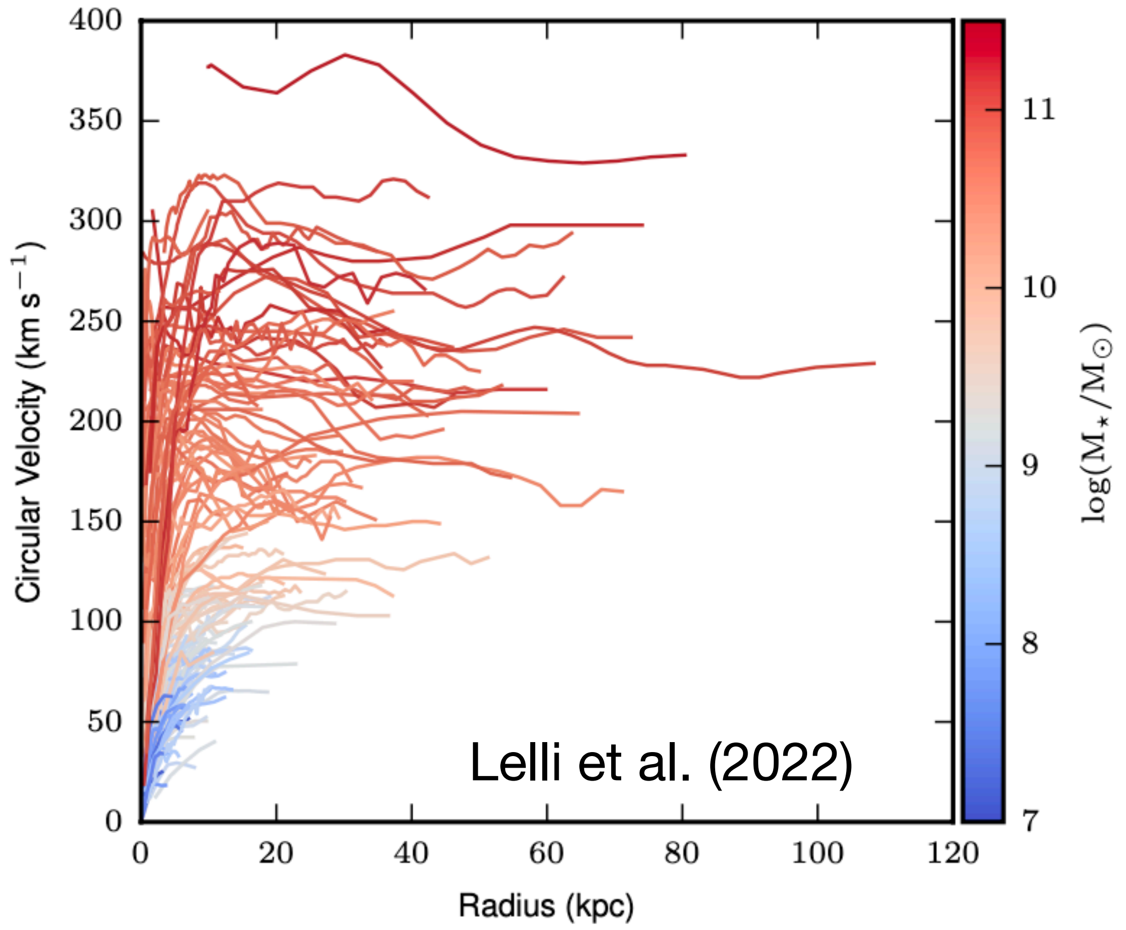


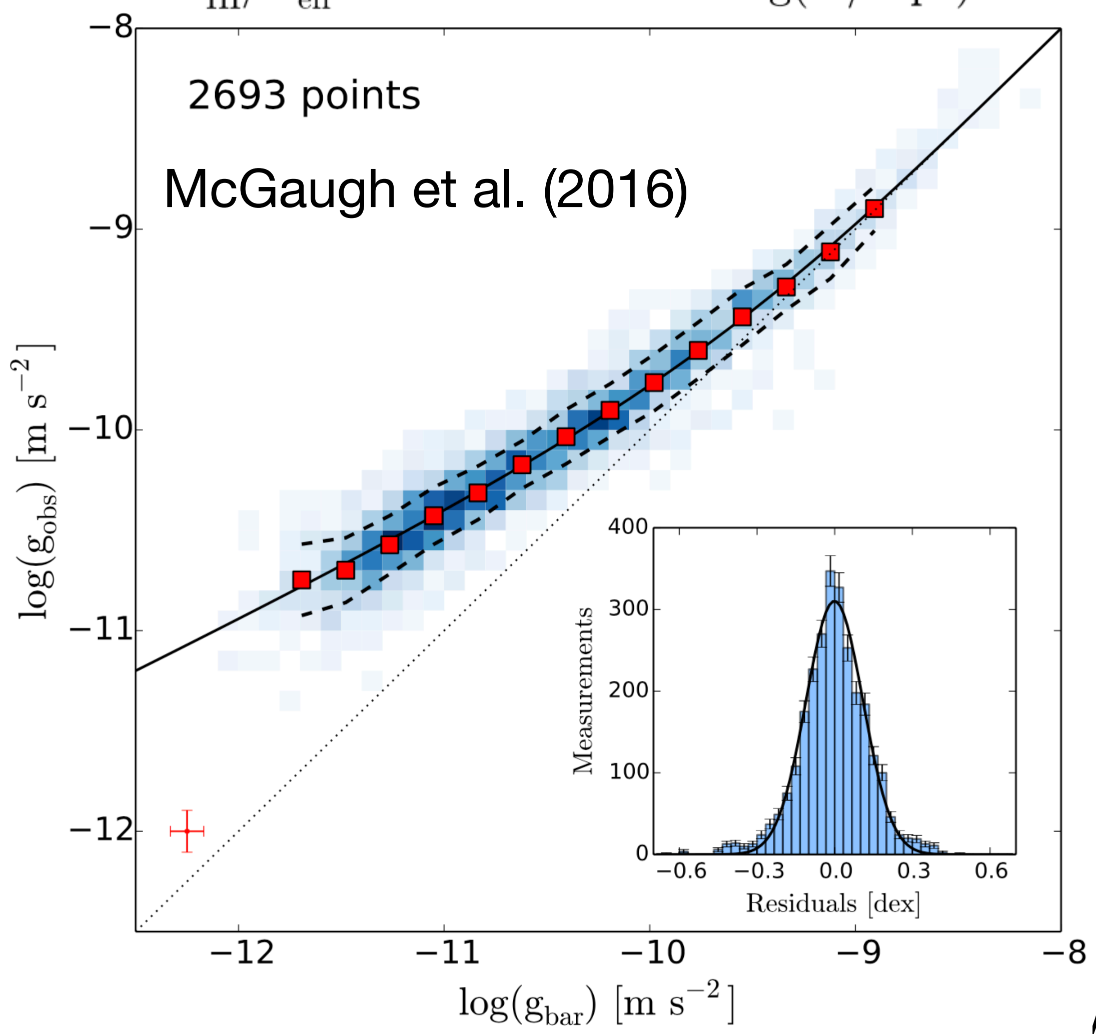
A ready sample - SPARC

- 175 disk galaxies with extended HI rotation curves and 3.6 μm photometry
- high(er) resolution Hα rotation curves
- broad range of surface brightness, rotation velocity (mass)
- not so much work on stellar population (beyond photometry)

Lelli et al. (2016)

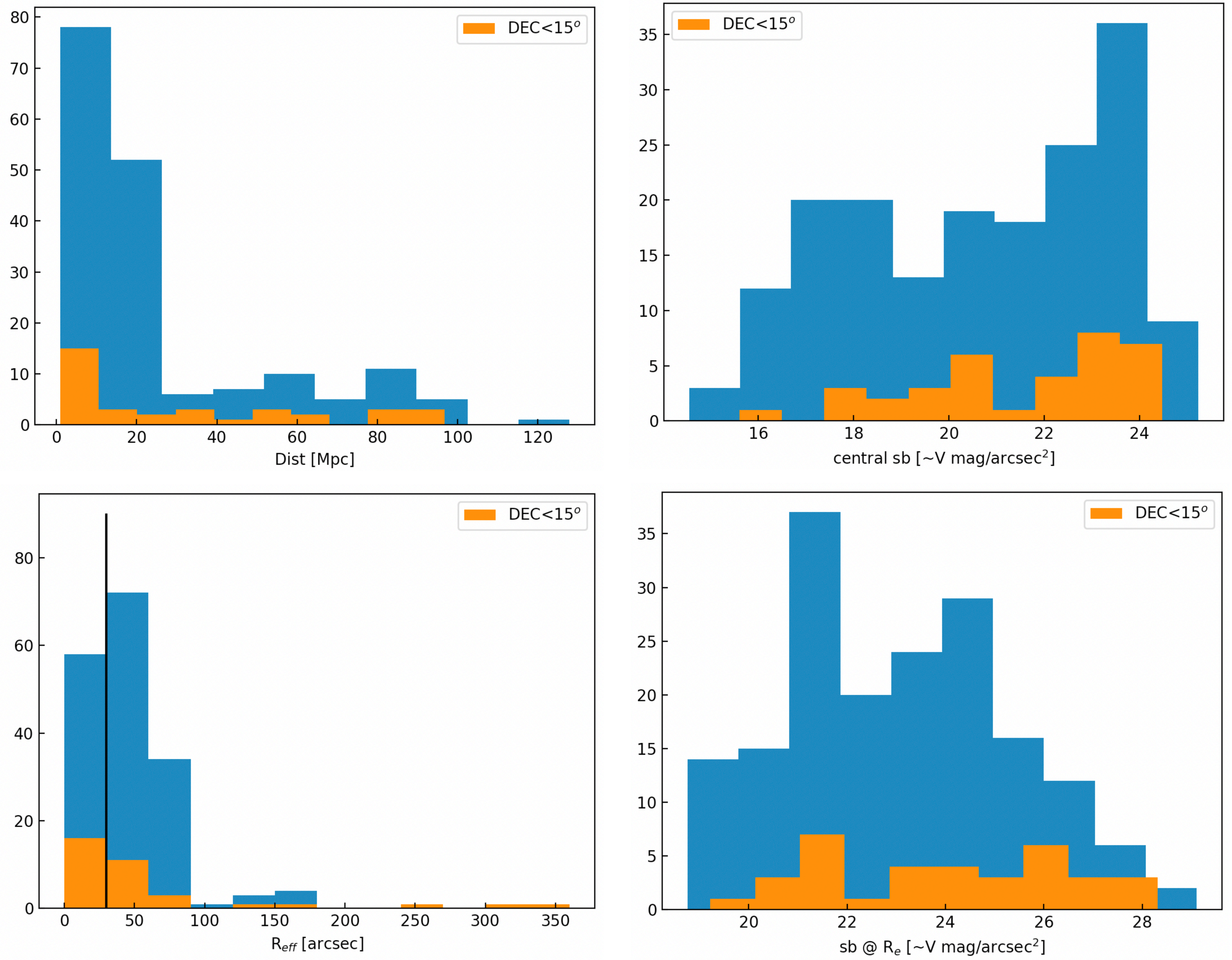






Observing SPARC(s) with BlueMUSE

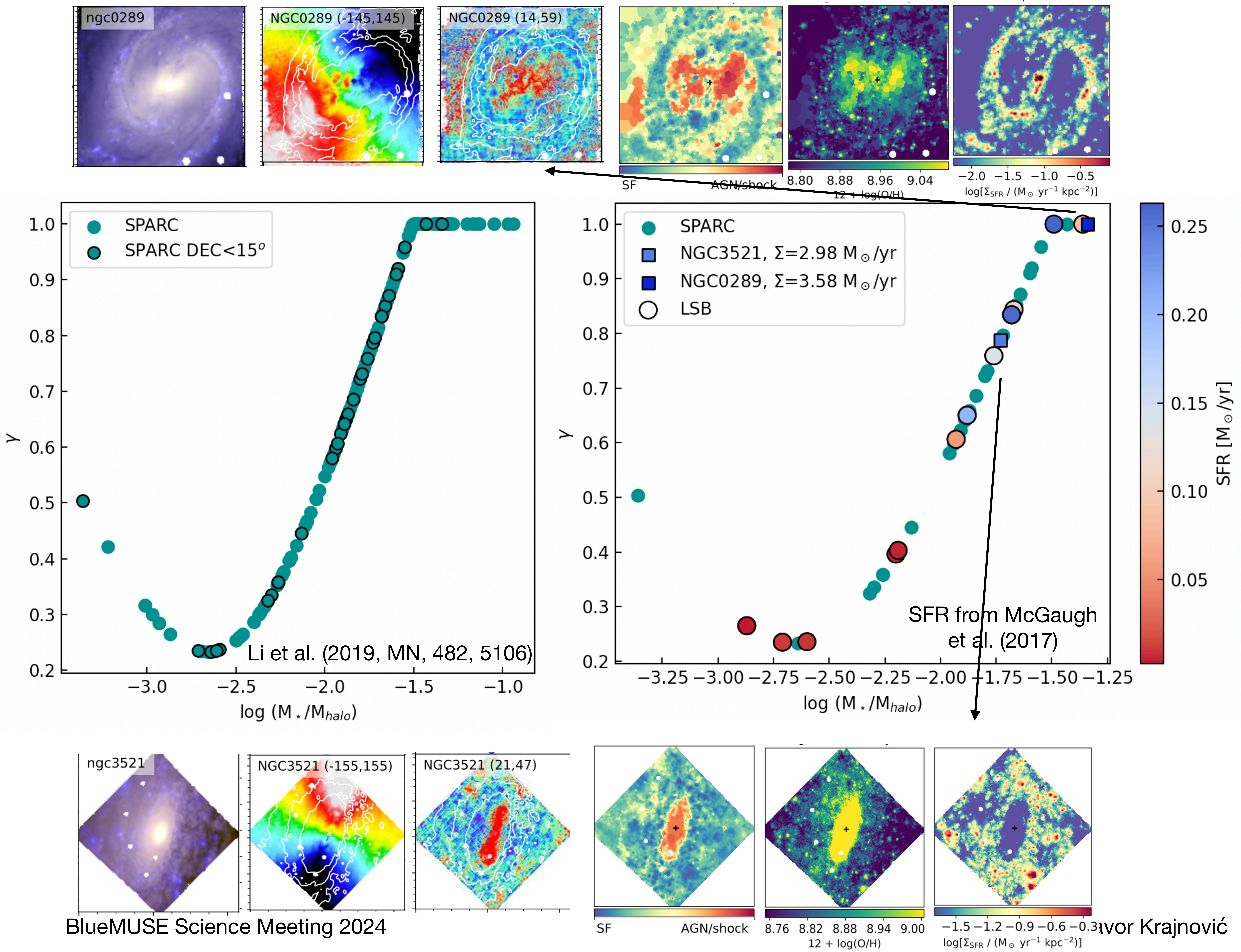
- mostly northern galaxies
    - 20% accessible from Paranal
- nearby (unresolved stellar pops)
    - well suited for natural seeing
- range of sizes suitable for BlueMUSE
- relatively bright



What to expect?

- halo models are/can be derived
- **is there a link with SF?**
  - not really (for LSB)
  - quiescent galaxies with a range of slopes
- what about stellar ages and metallicities?
- **case for BlueMUSE**
  - general star formation history
  - how episodic was the star formation?
  - evidence for past mergers?

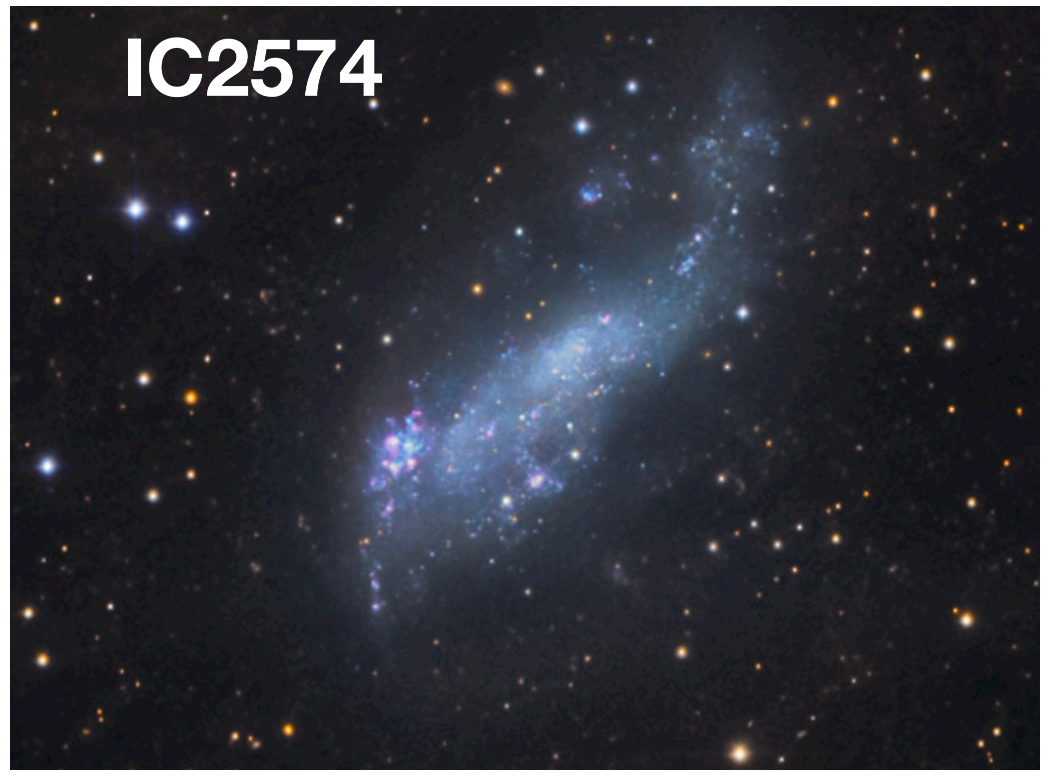
(Erroz-Ferrer et al. 2020, den Brok et al. 2021)

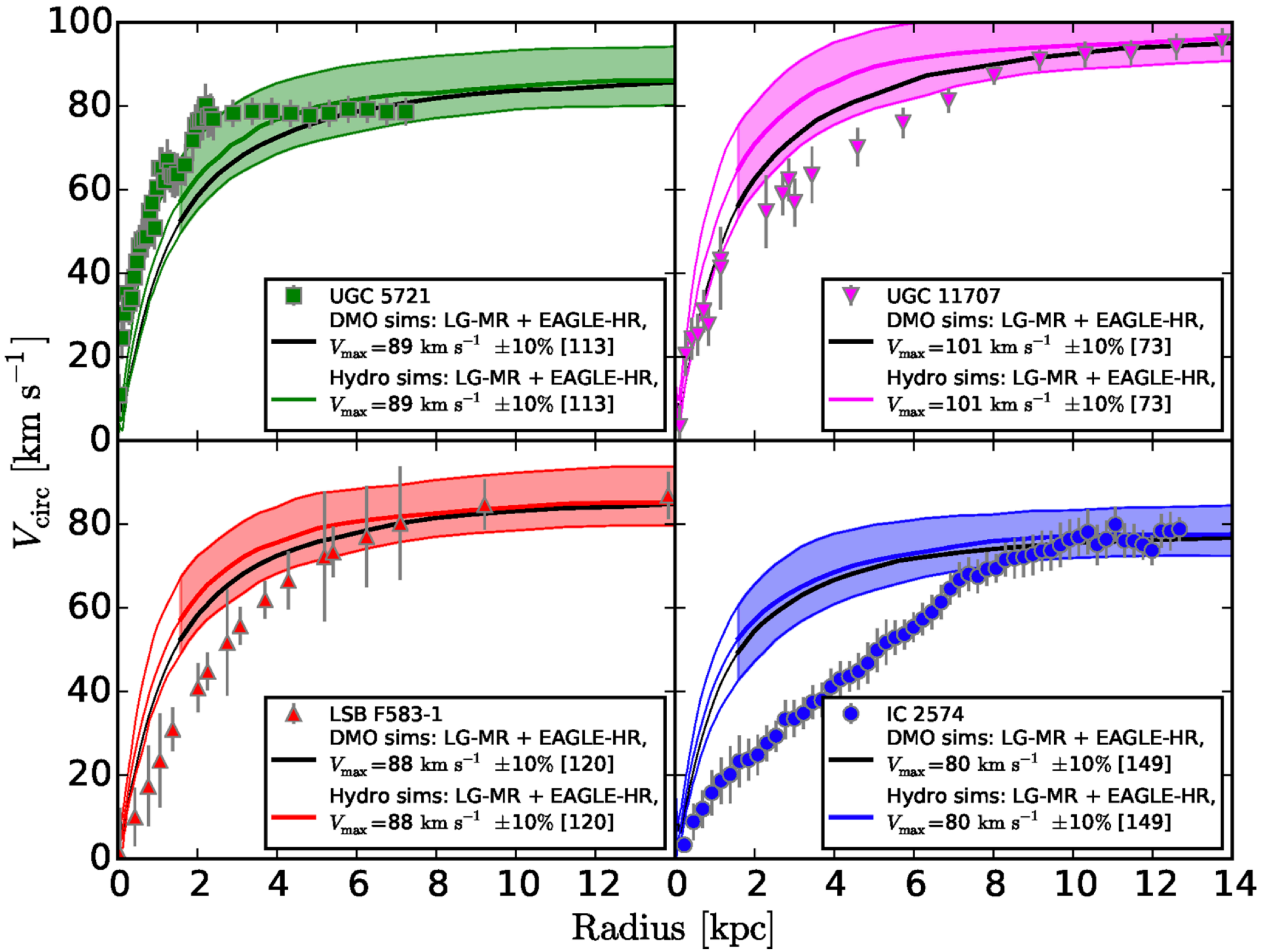


BlueMUSE targets

Oman et al. (2015)

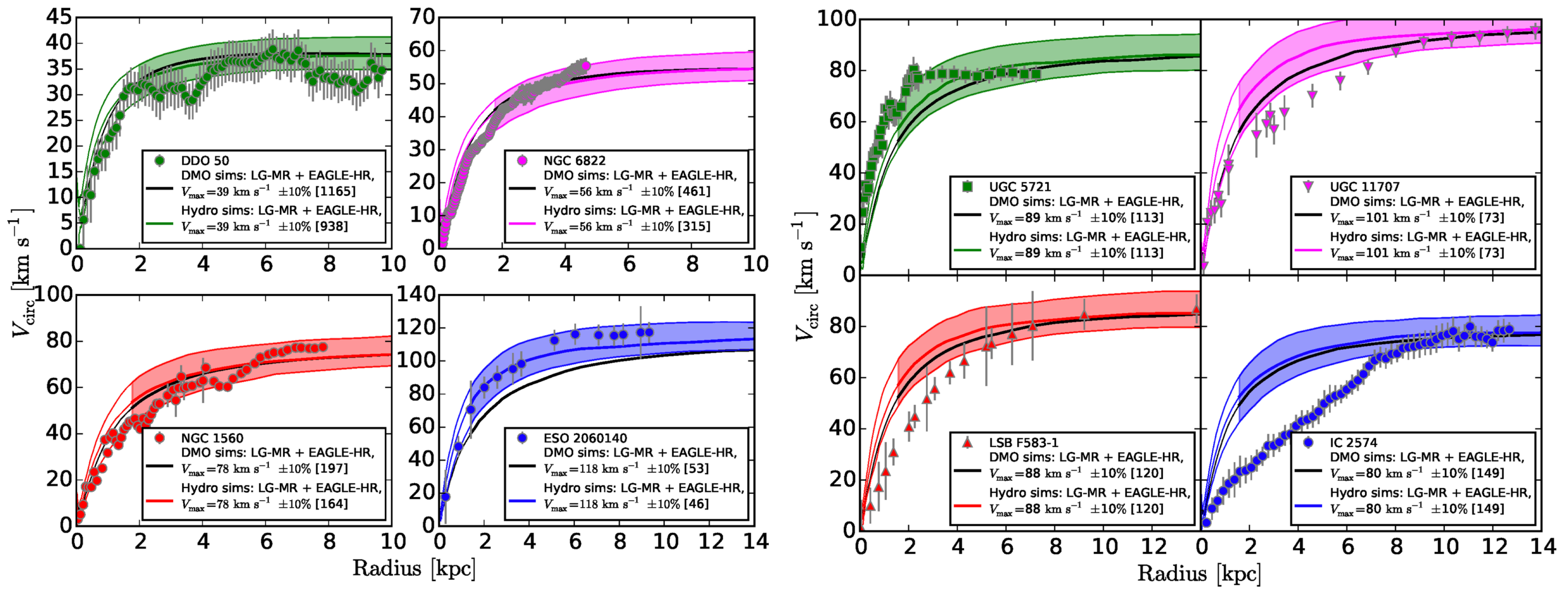
- focus on galaxies with "unusual" HI rotation curves
  - are they unusual due to non-gravitational processes (e.g. turbulence, non circular motions)?
- prototypes: Magellanic Clouds, IC2574, UGC5721
- what will BlueMUSE bring:
  - SFH
  - inner rotation curves from emission-lines
  - turbulence, noncircular motions (spectral resolution)





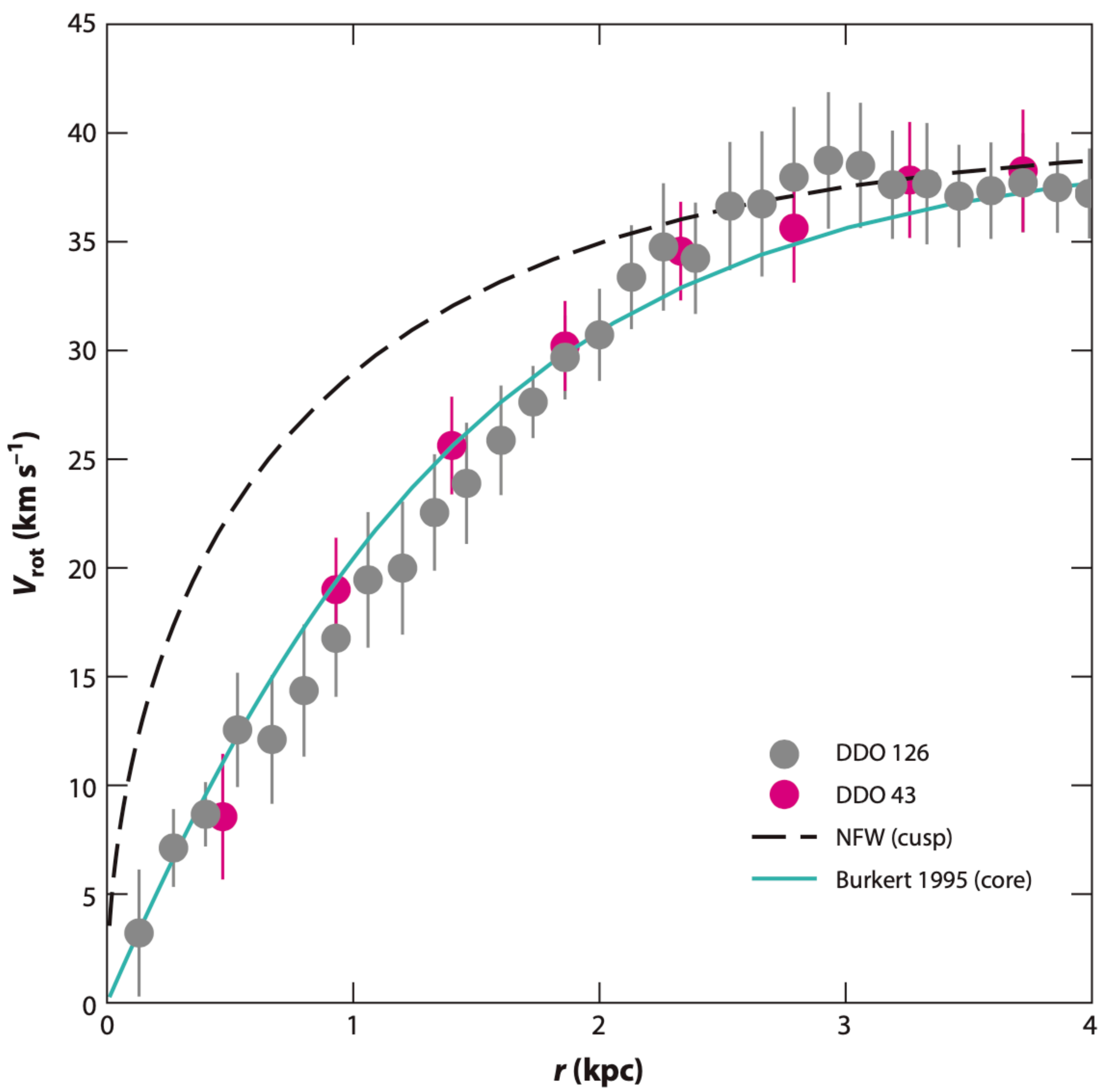
Conclusions

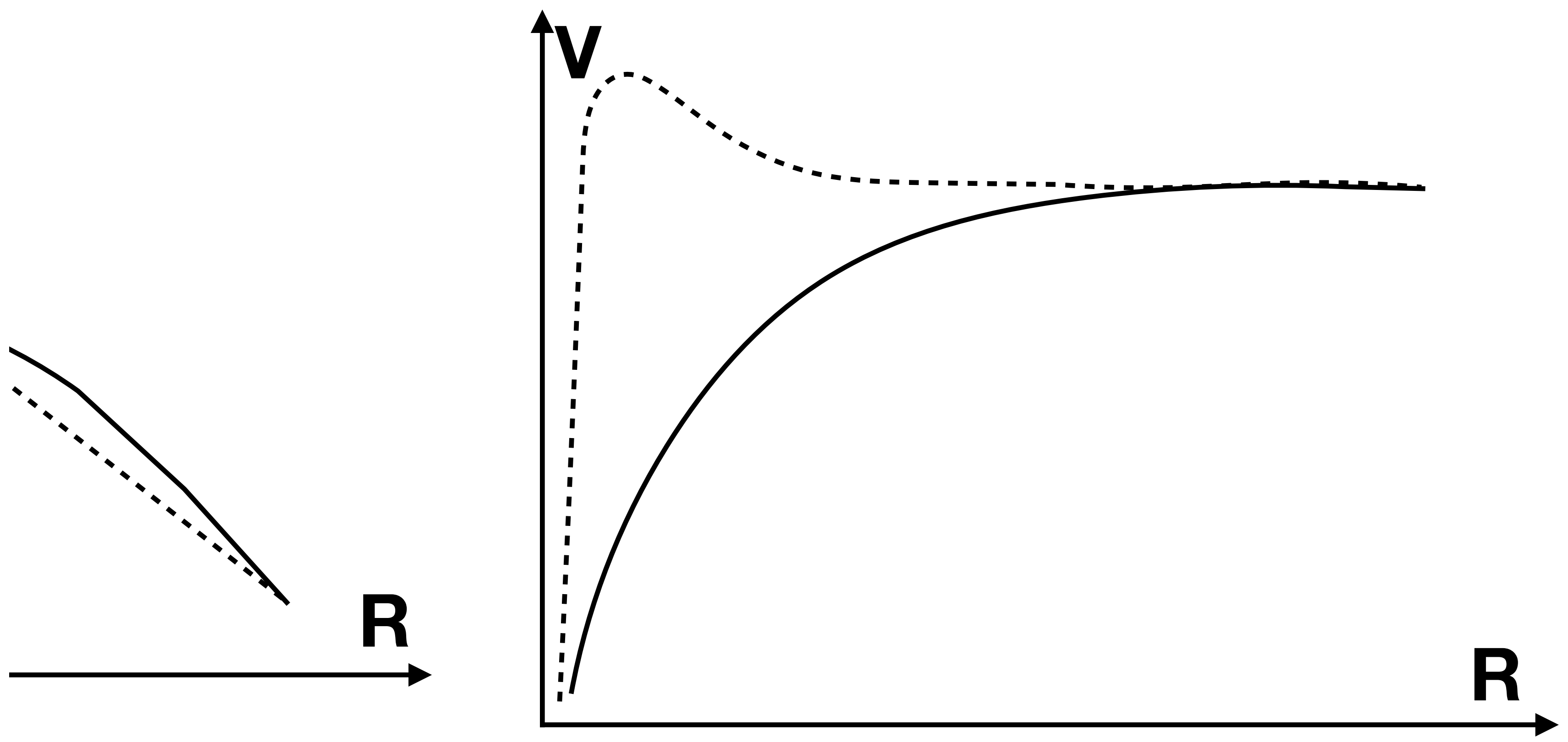
- a sample of dwarf galaxies ($<10^9$ M_{SUN}) with well characterised rotation curves
  - star formation histories
  - inner rotation curves / density slopes (for local dwarfs)
  - relating cores/cusps with stellar properties
- differentiating between dark matter models
- testing the evolution of dark matter properties
- Synergies:
  - MeerKAT, SKA
  - ALMA
  - ELT: MOSAIC, HARMONI

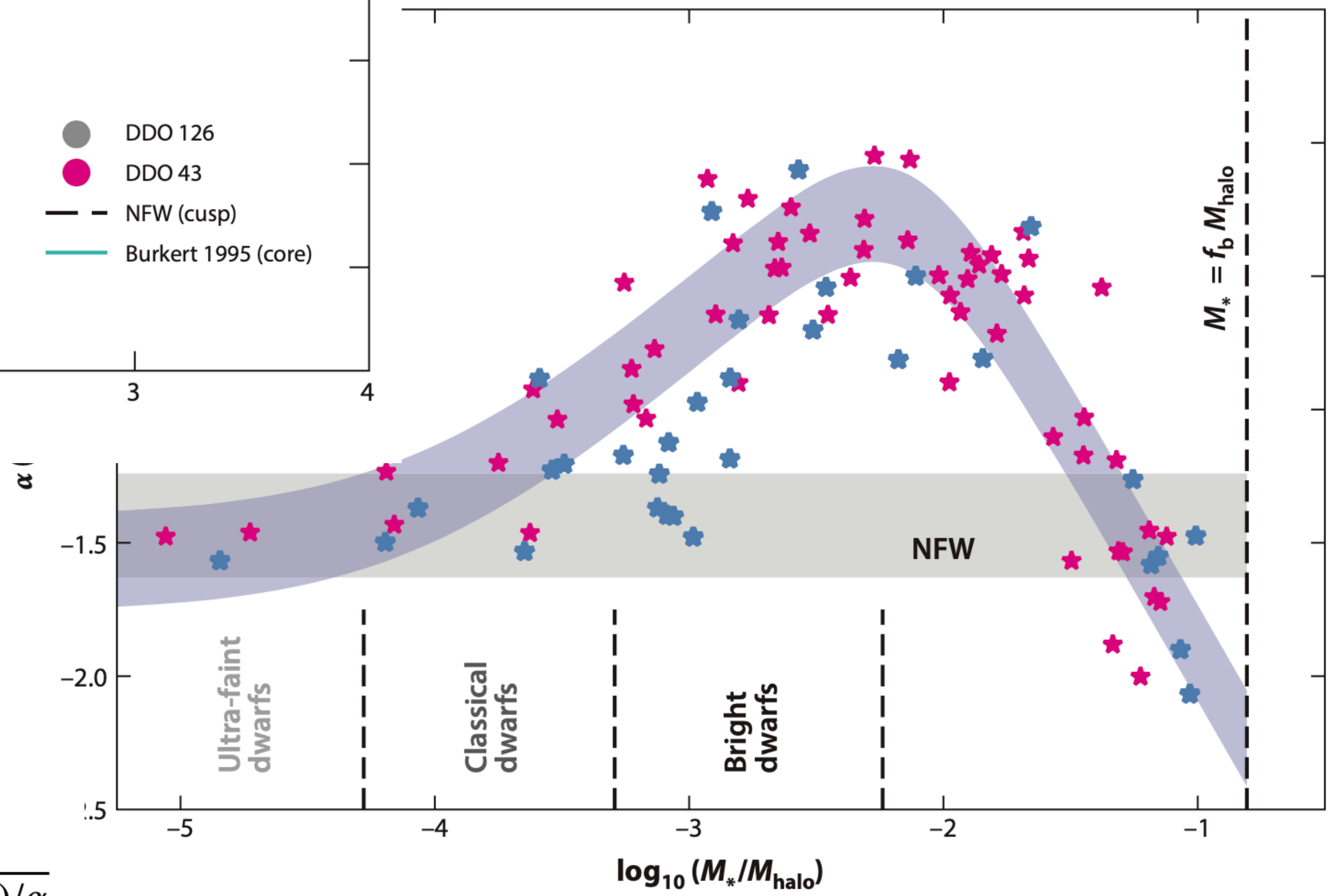


Cusps or cores?

- only exist in case DM exis
- the core problem?
- and its proposed solution







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

Bullock & Boylan-Kolchin (2017)