Testing dark matter with dwarf galaxies in cosmological simulations with baryons

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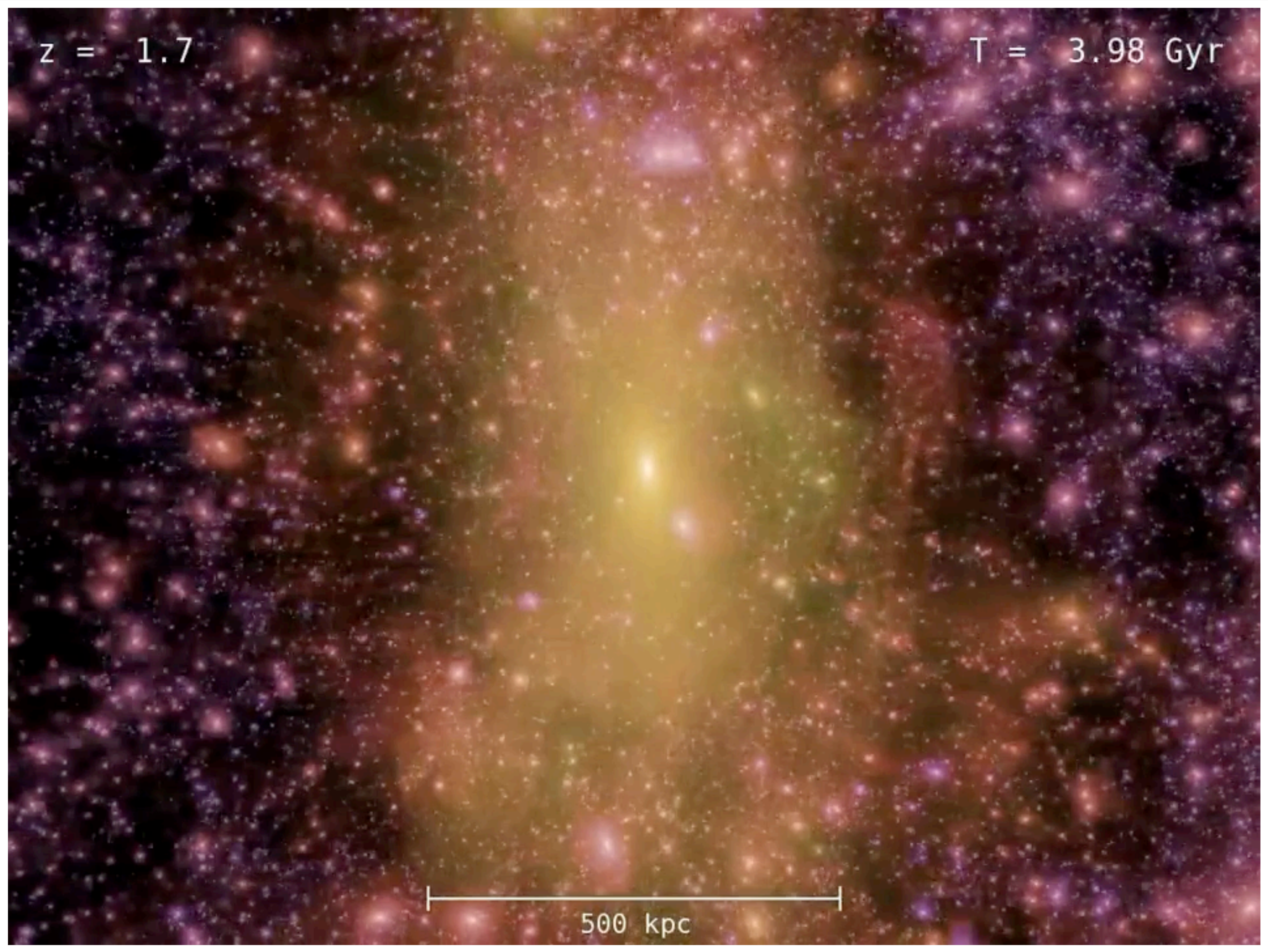
News from the Dark - Montpellier September 2025

Image Credit: McAlpine, Flamingo, Colibre

Substructure in Cold Dark Matter

Aquarius-A MW-mass halo simulation [Springel+08]



1 Well-defined mass function
→ More small halos than large ones

Self-similar abundance of substructure

2 Universal, "cuspy" halo density profiles
→ resilient to tidal effects

3 Orbits and accretion histories

[See e.g. Press&Schechter74; Bond+91; White&Rees78; White&Frenk91; NavarroFrenk&White97; Springel+08; Bullock&Boylan-Kolchin17].

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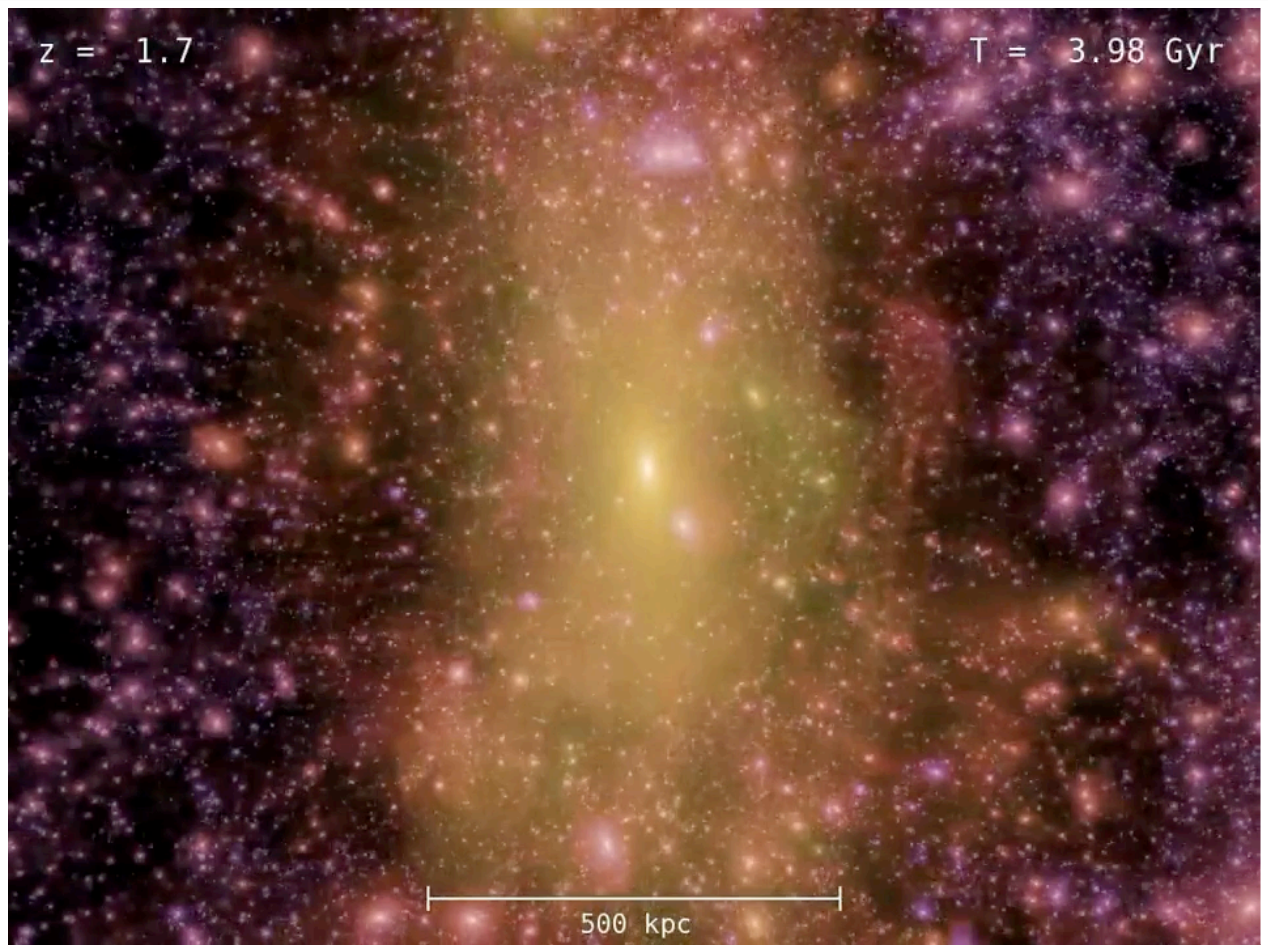

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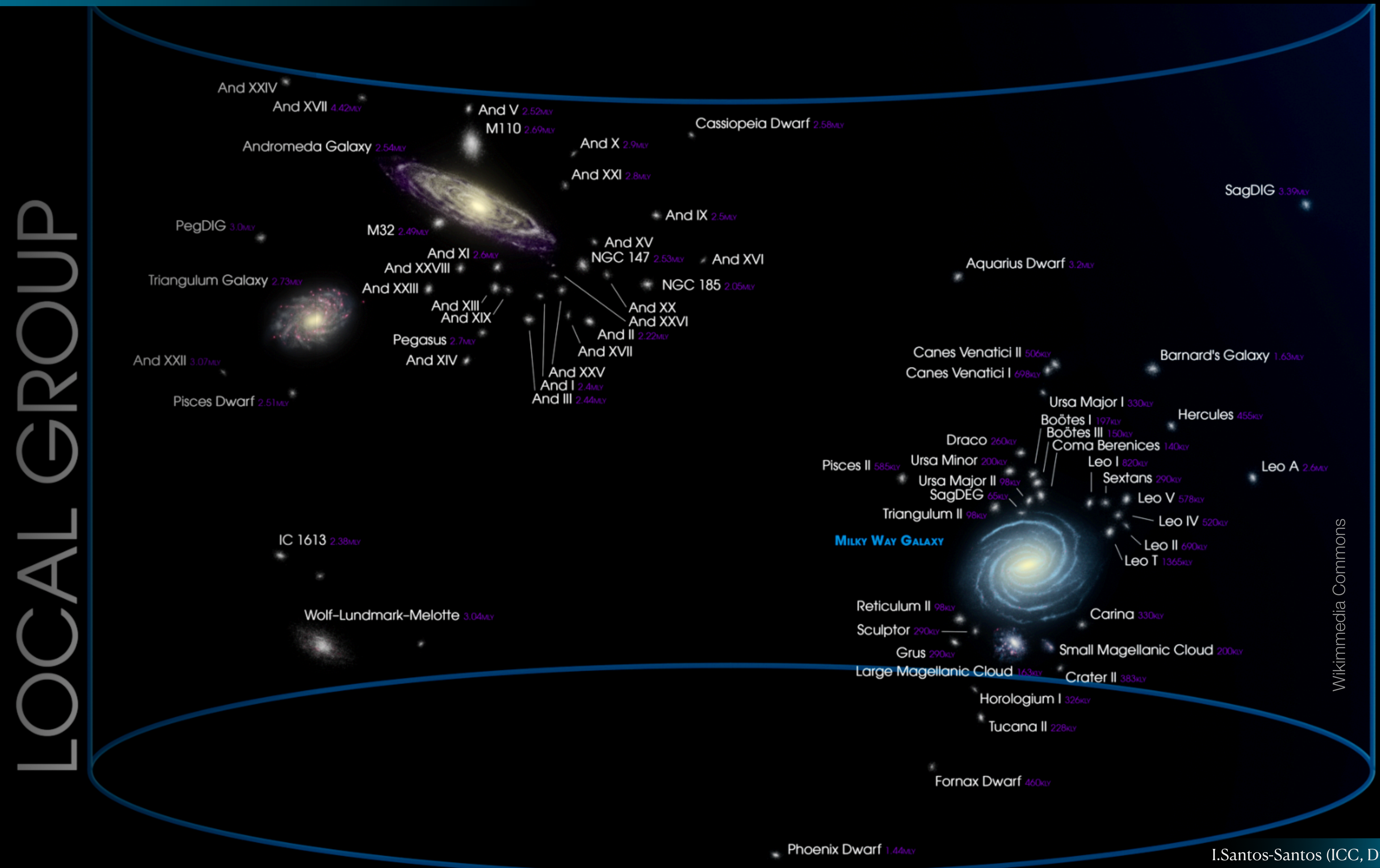
Substructure observed in the MW

**Not up-to-date



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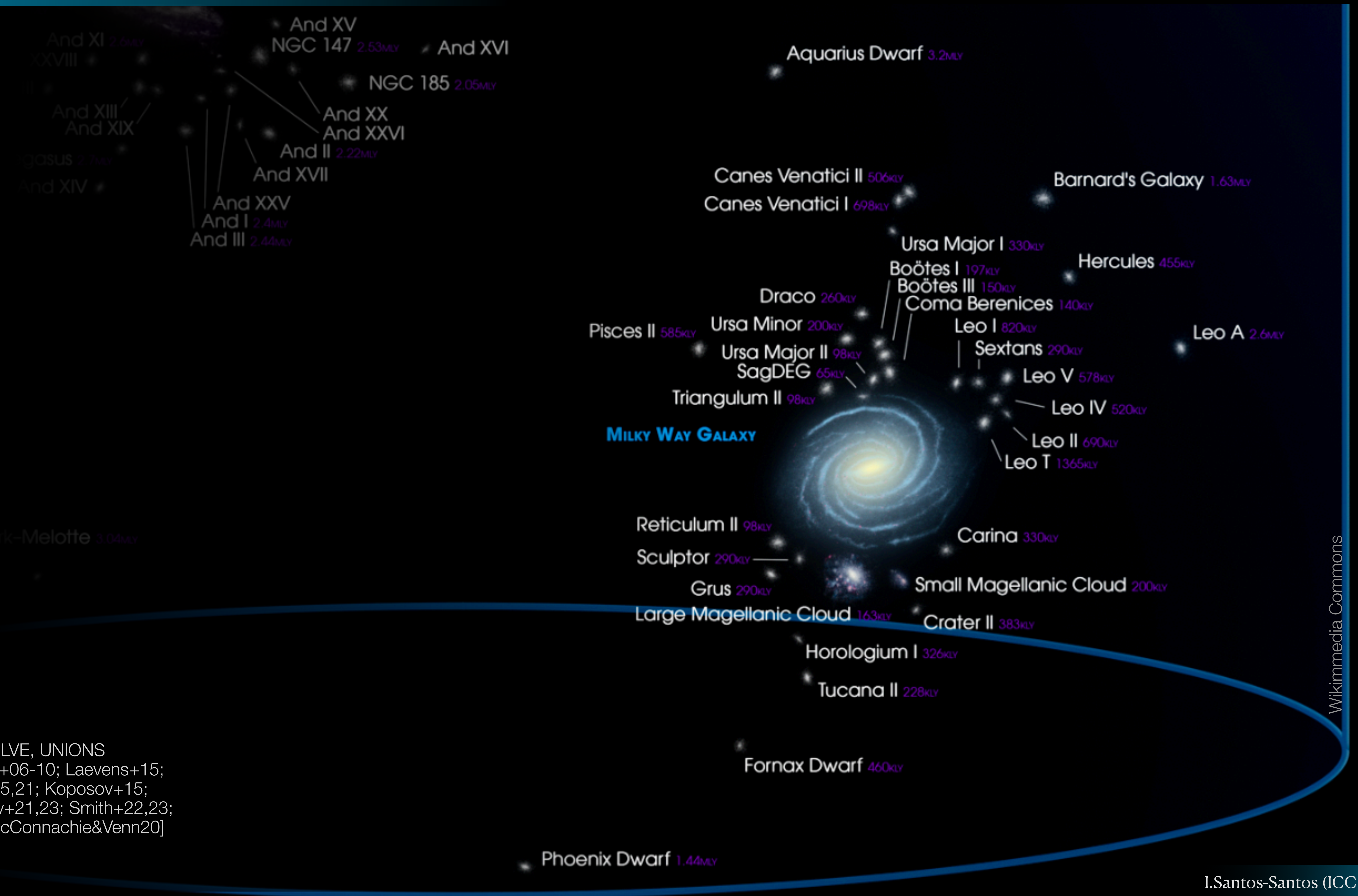

[SDSS, DES, HSC, Gaia, DELVE, UNIONS
e.g. Willman+05; Belokurov+06-10; Laevens+15; Bechtol+15; Drlica-Wagner15,21; Koposov+15; Homma+16; Mau+20; Cerny+21,23; Smith+22,23; Torrealba+19; Pace&Li19; McConnachie&Venn20]

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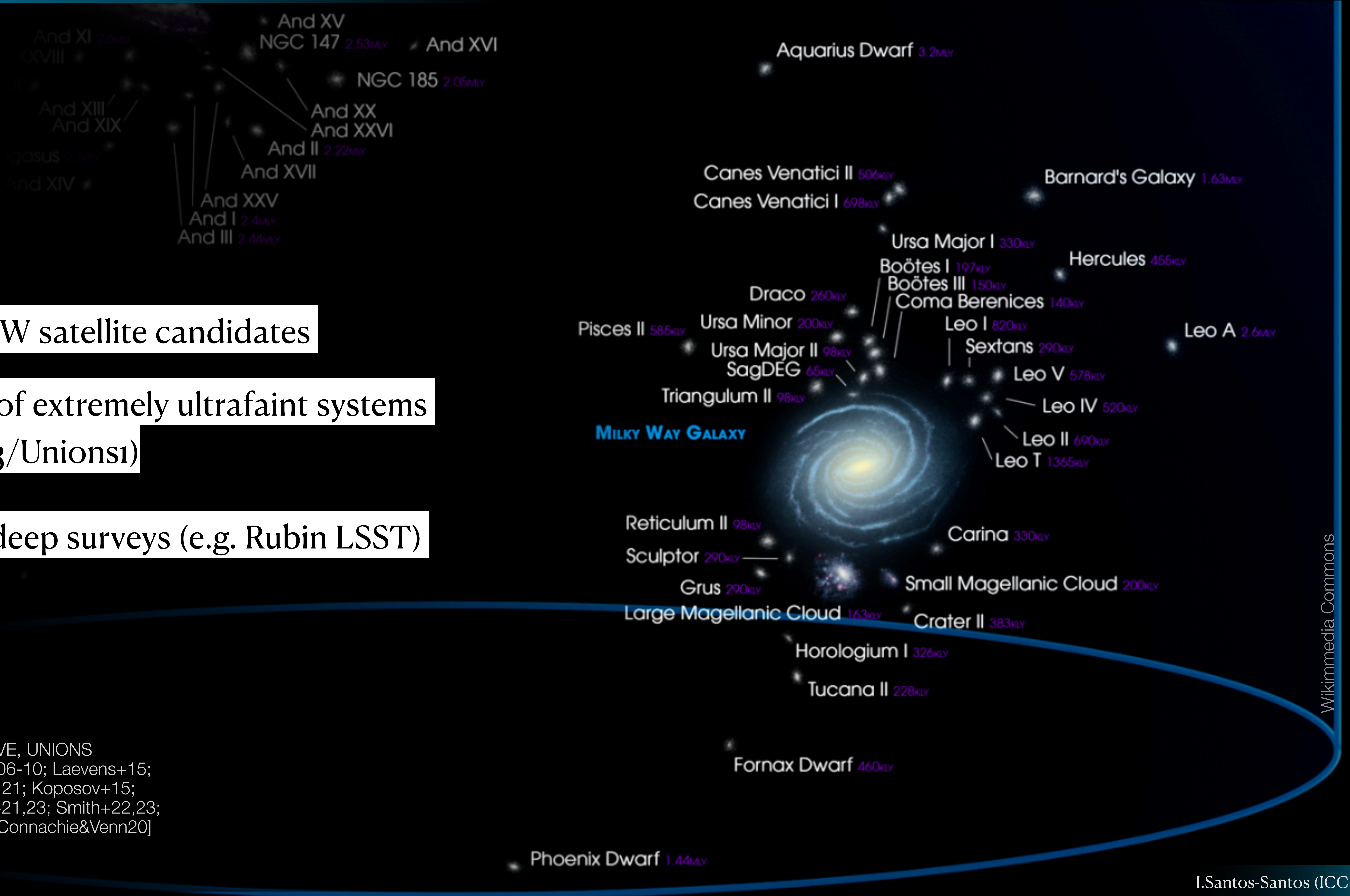

Currently ~60 MW satellite candidates

Recent findings of extremely ultrafaint systems (e.g. Tuc3, UMa3/Unions1)

New upcoming deep surveys (e.g. Rubin LSST)

[SDSS, DES, HSC, Gaia, DELVE, UNIONS
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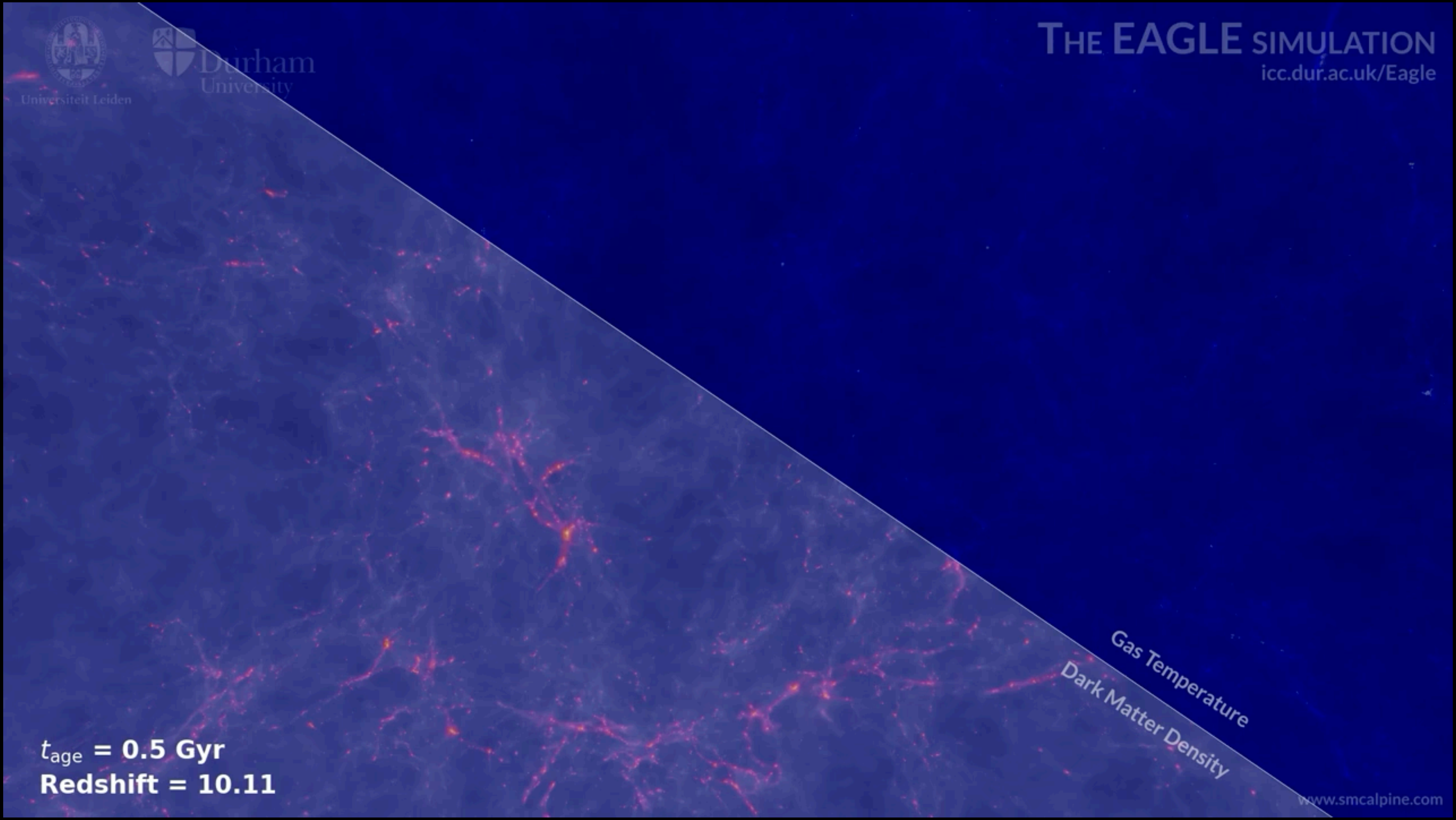
Cosmological simulations with baryons



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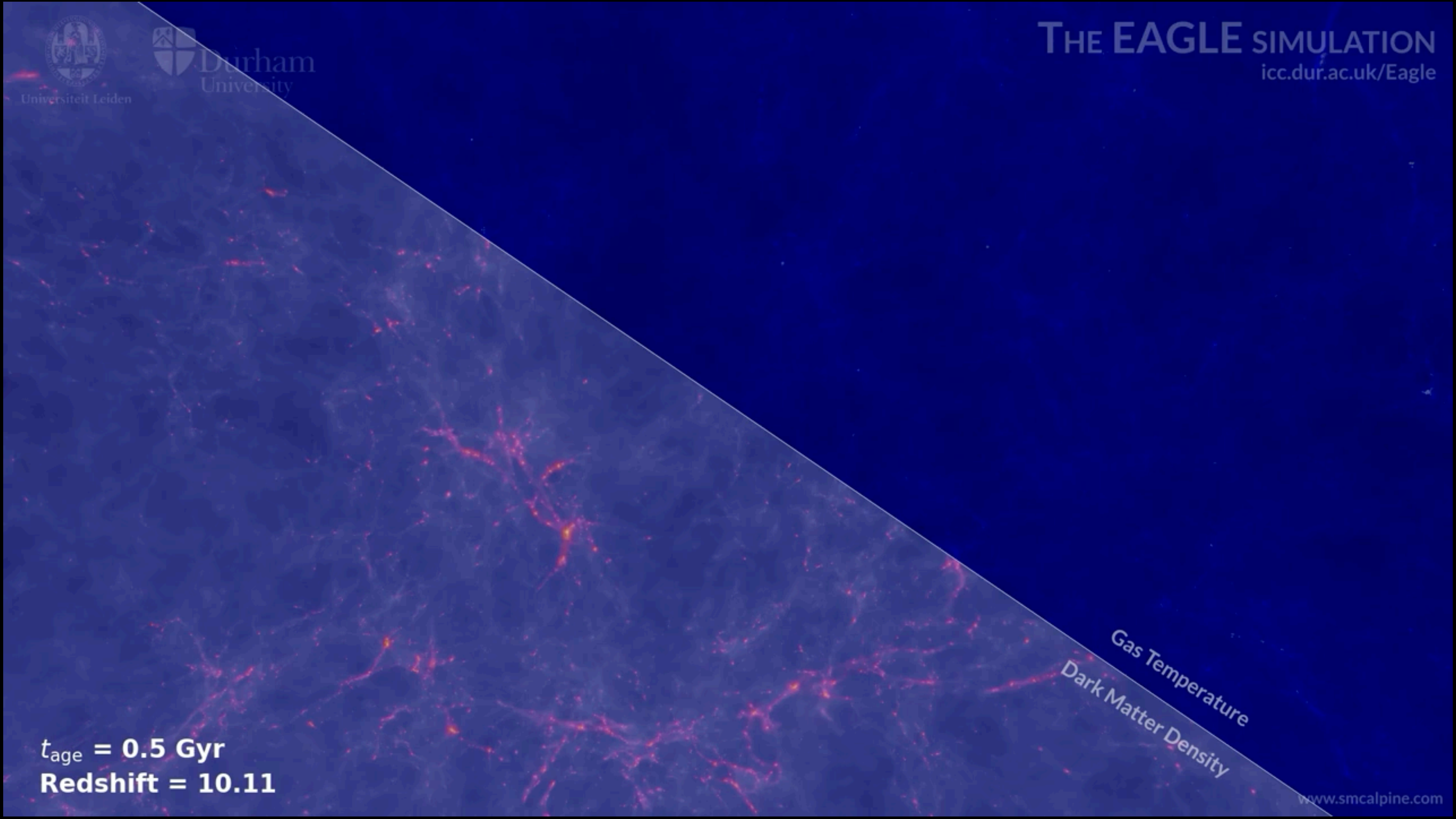
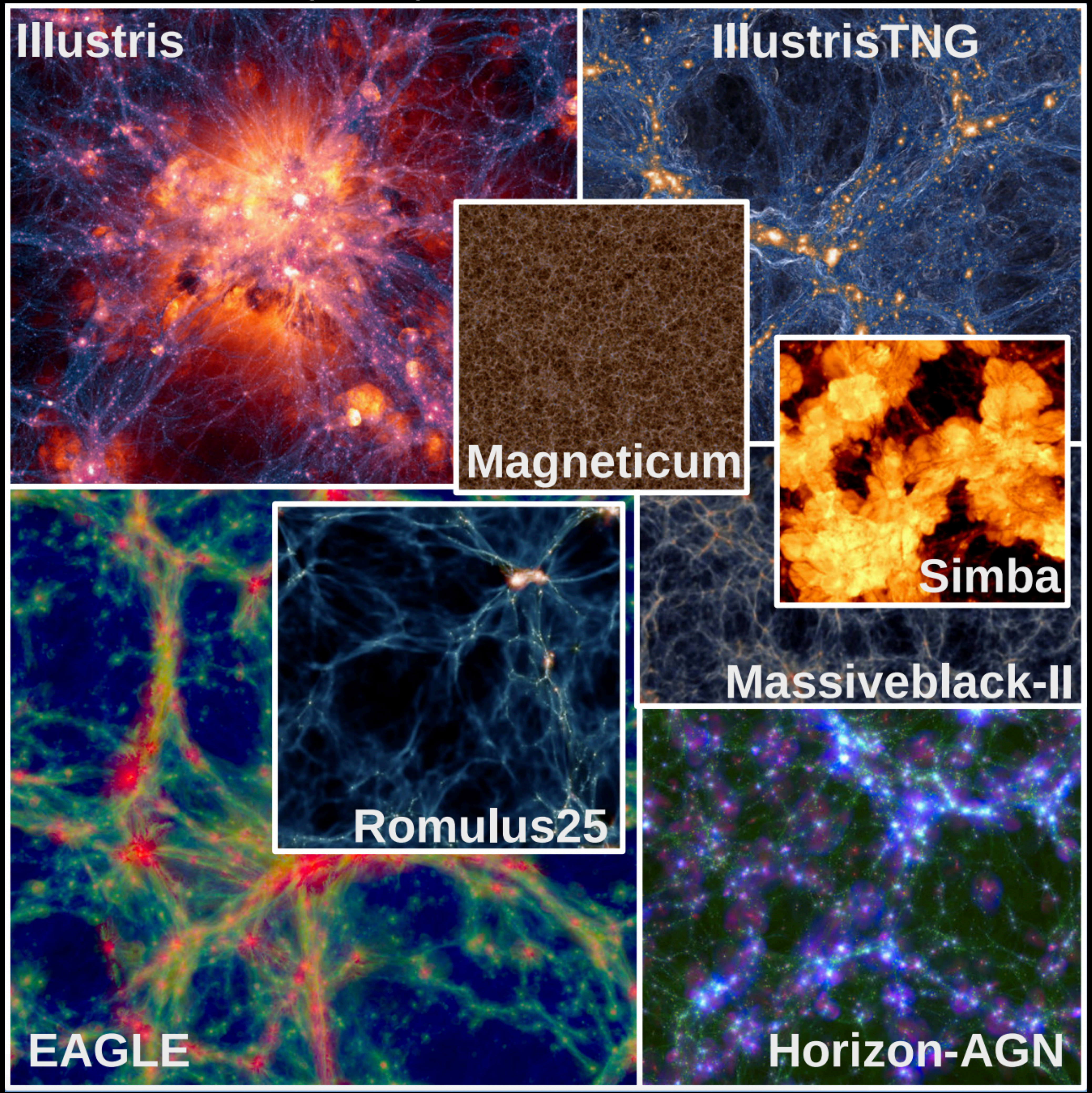
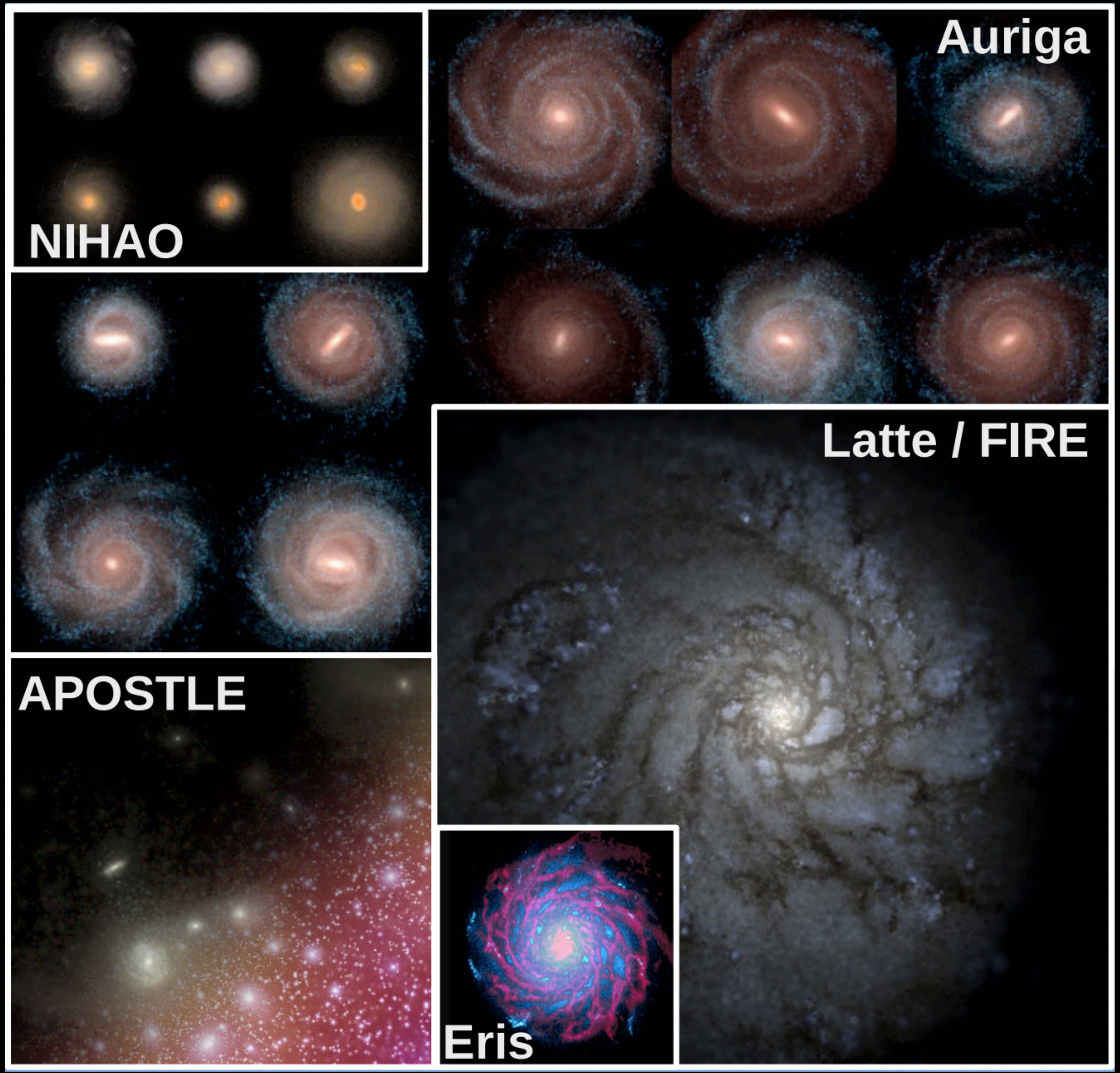


Cosmological simulations with baryons

Some examples [Vogelsberger+2020 and references therein]

Large volumes





Zoom-ins

+ e.g. EDGE, COLIBRE, NewHorizon, Lyra, Gear, DC Justice League, Hestia, FLAMINGO, …

Tests of Cold Dark Matter at small-scales

Dark Matter density profiles

Abundance of substructure

Tests of Cold Dark Matter at small-scales

Diversity of dwarf galaxy rotation curves

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Stellar mass-Halo mass relation in the low-mass end

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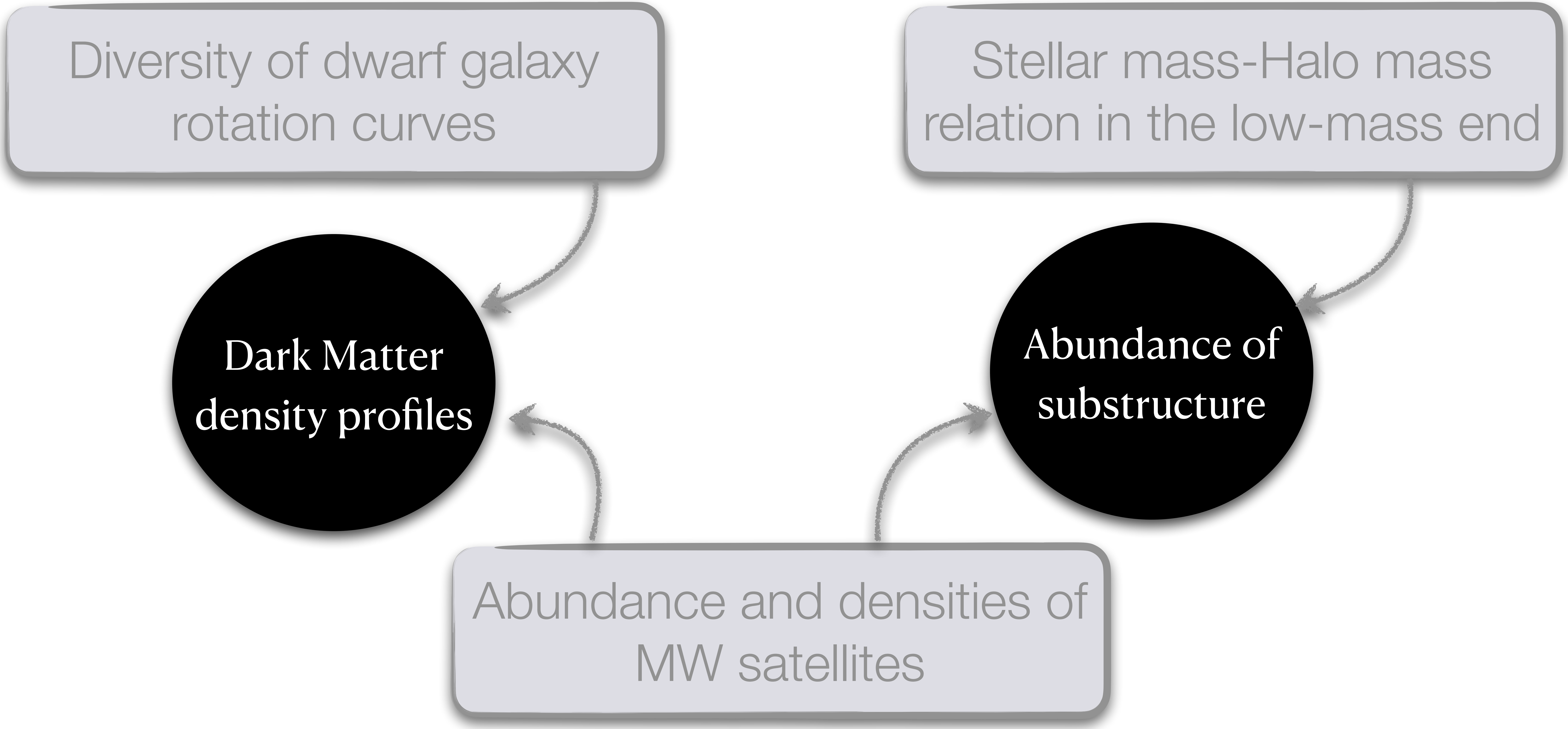
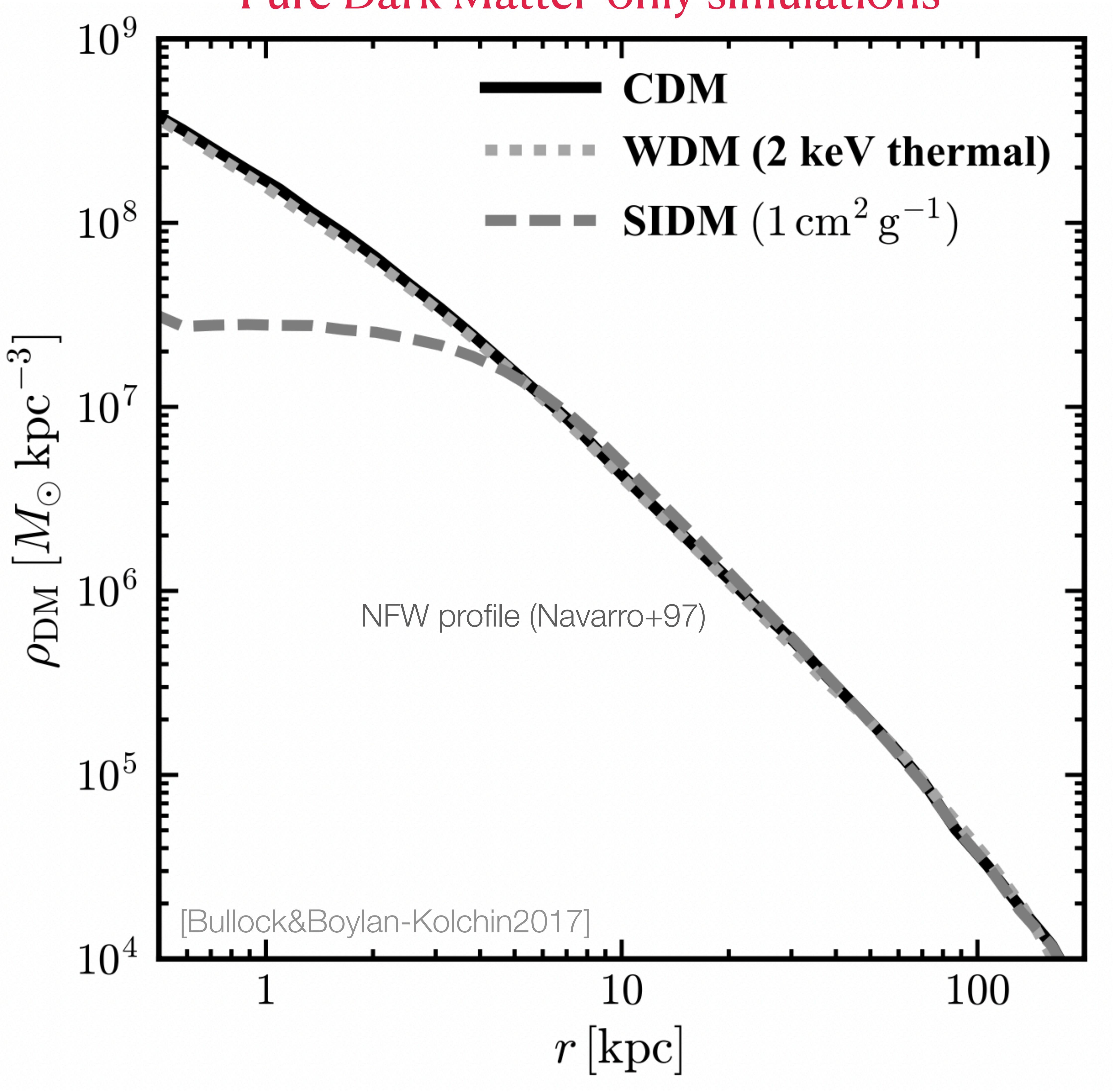


Dark matter density profiles

Pure Dark Matter-only simulations



[Read+2016]

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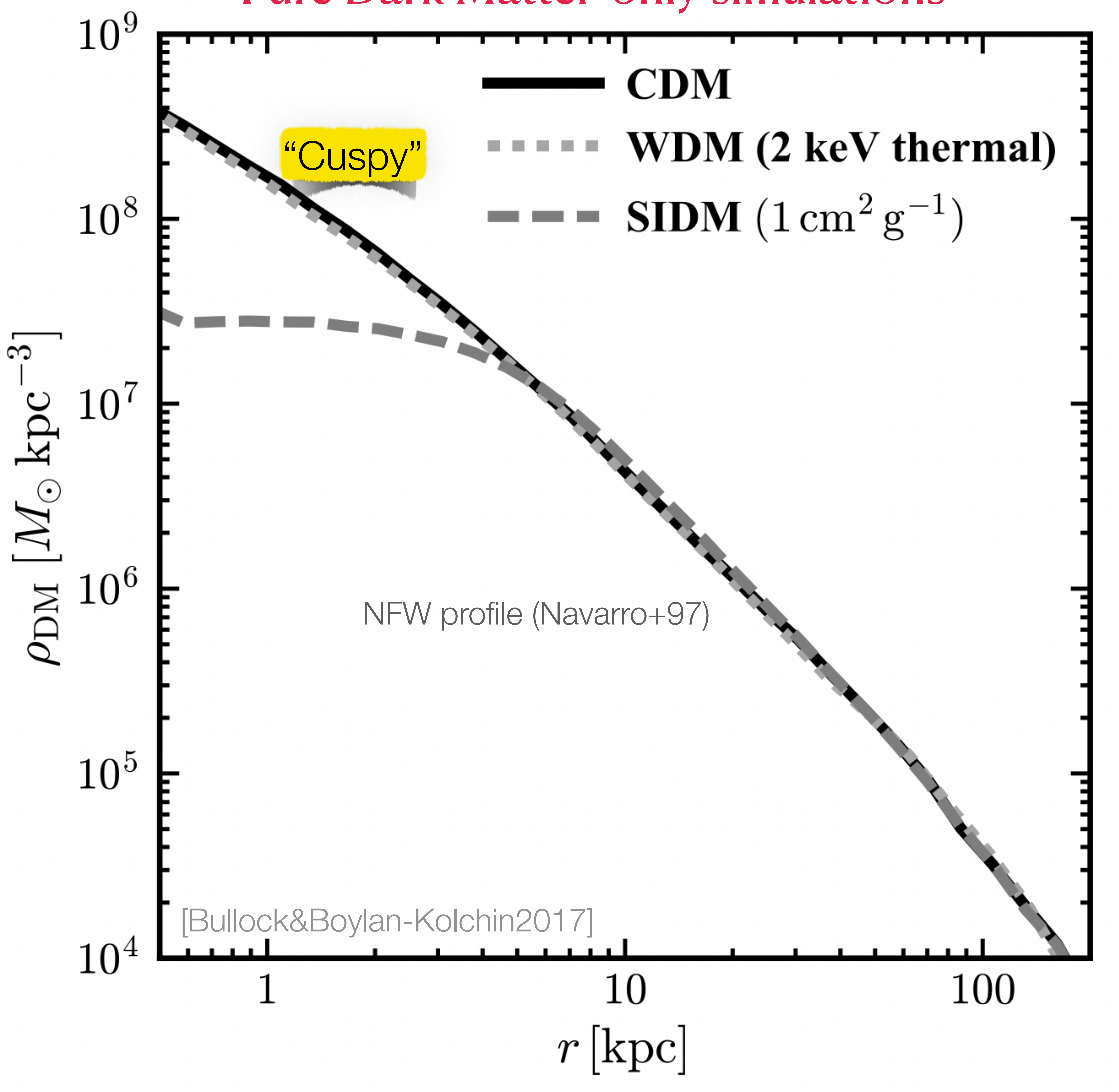

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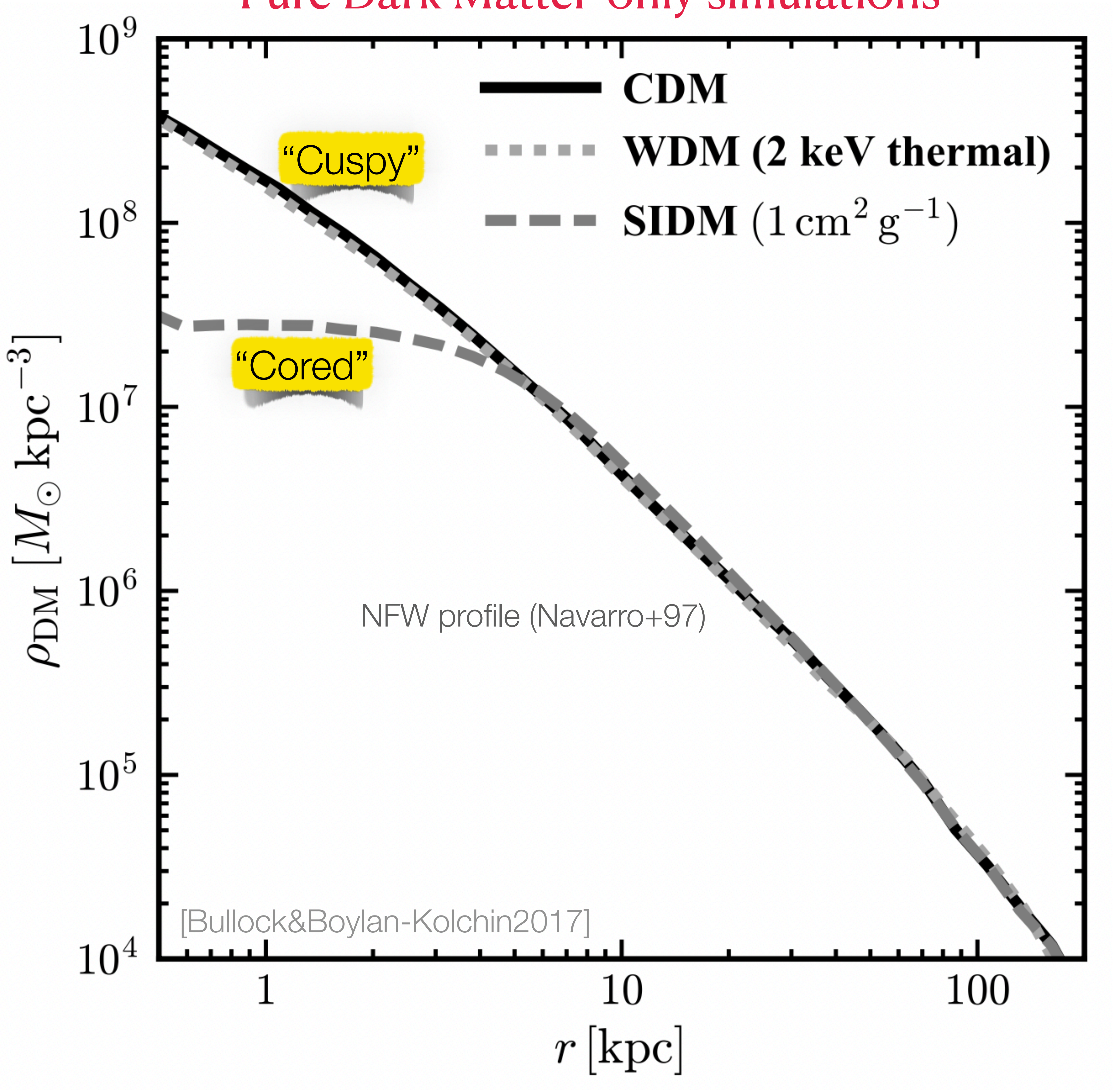

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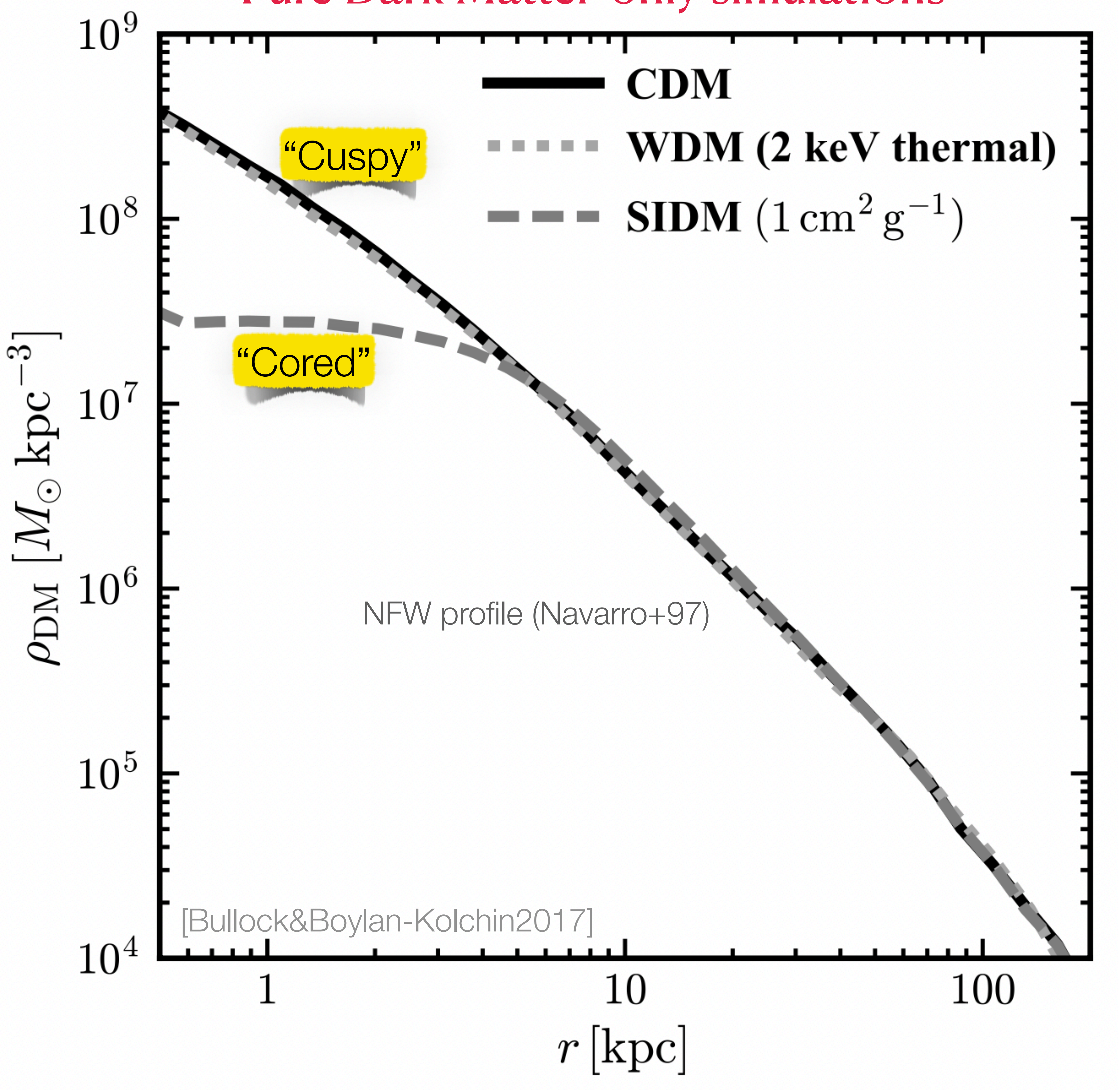
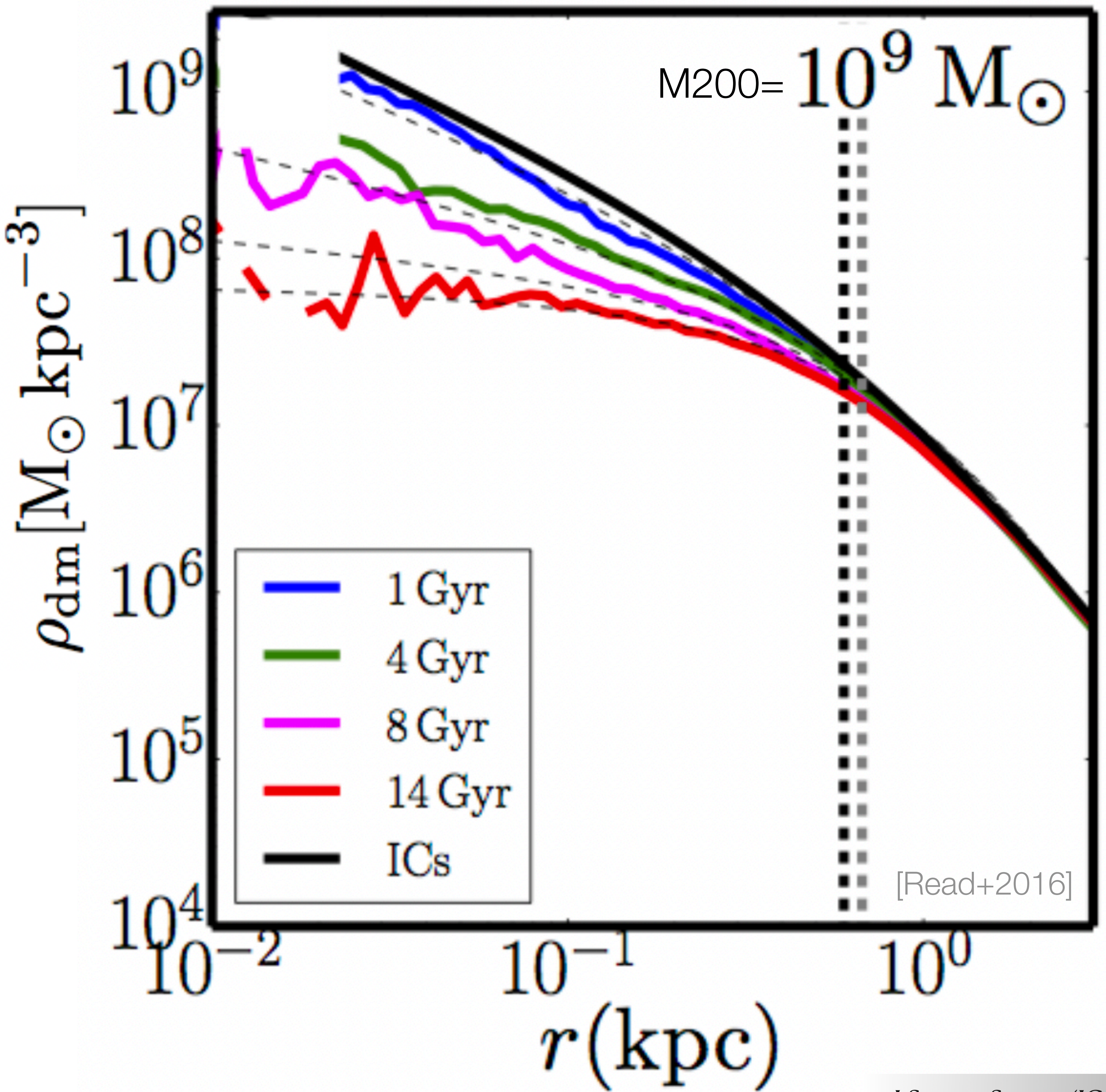


A simulation of Dark matter with baryons



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Dark matter density profiles

RAMSES code with feedback from Agertz+13
(~EDGE model)

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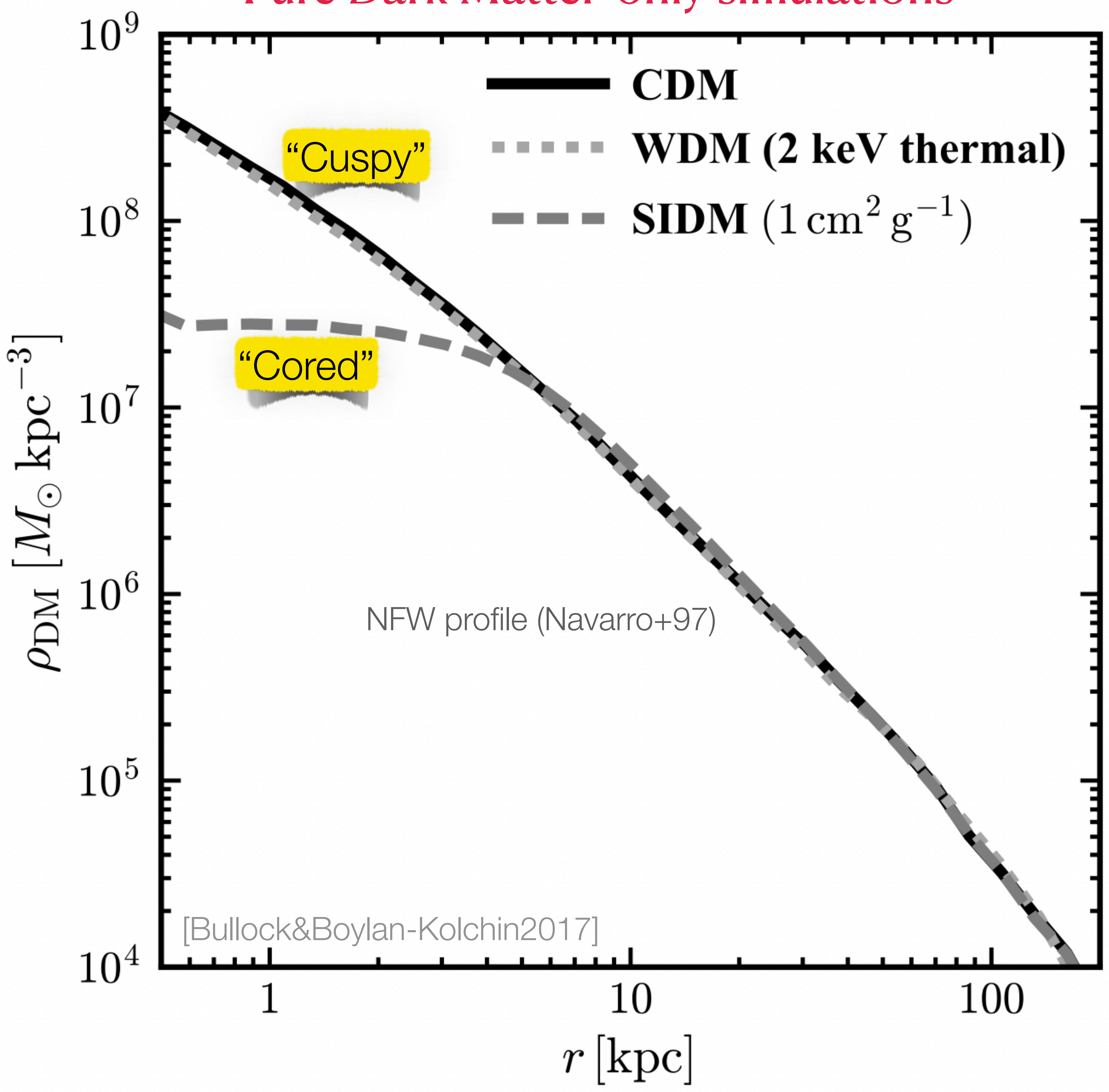

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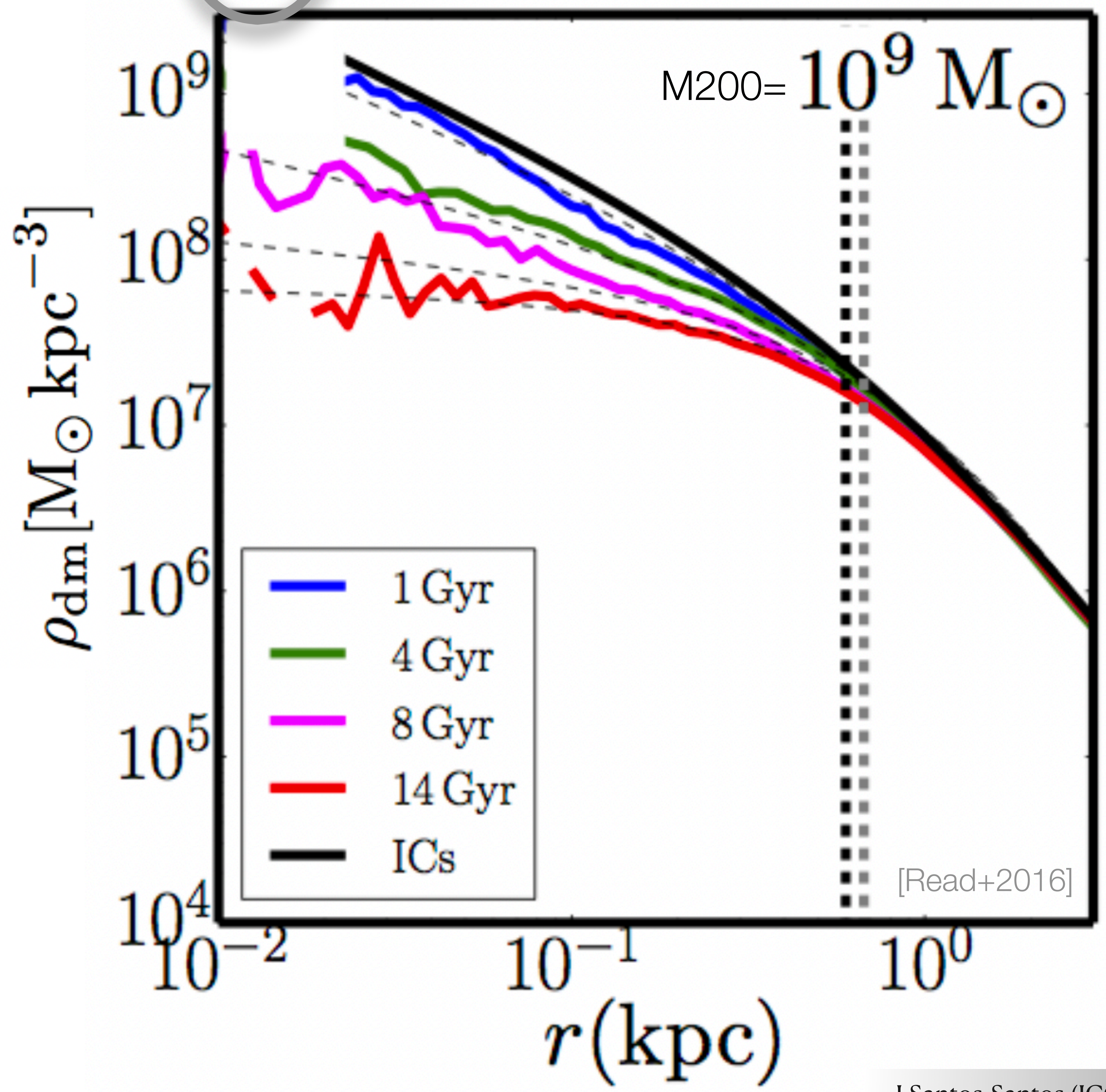

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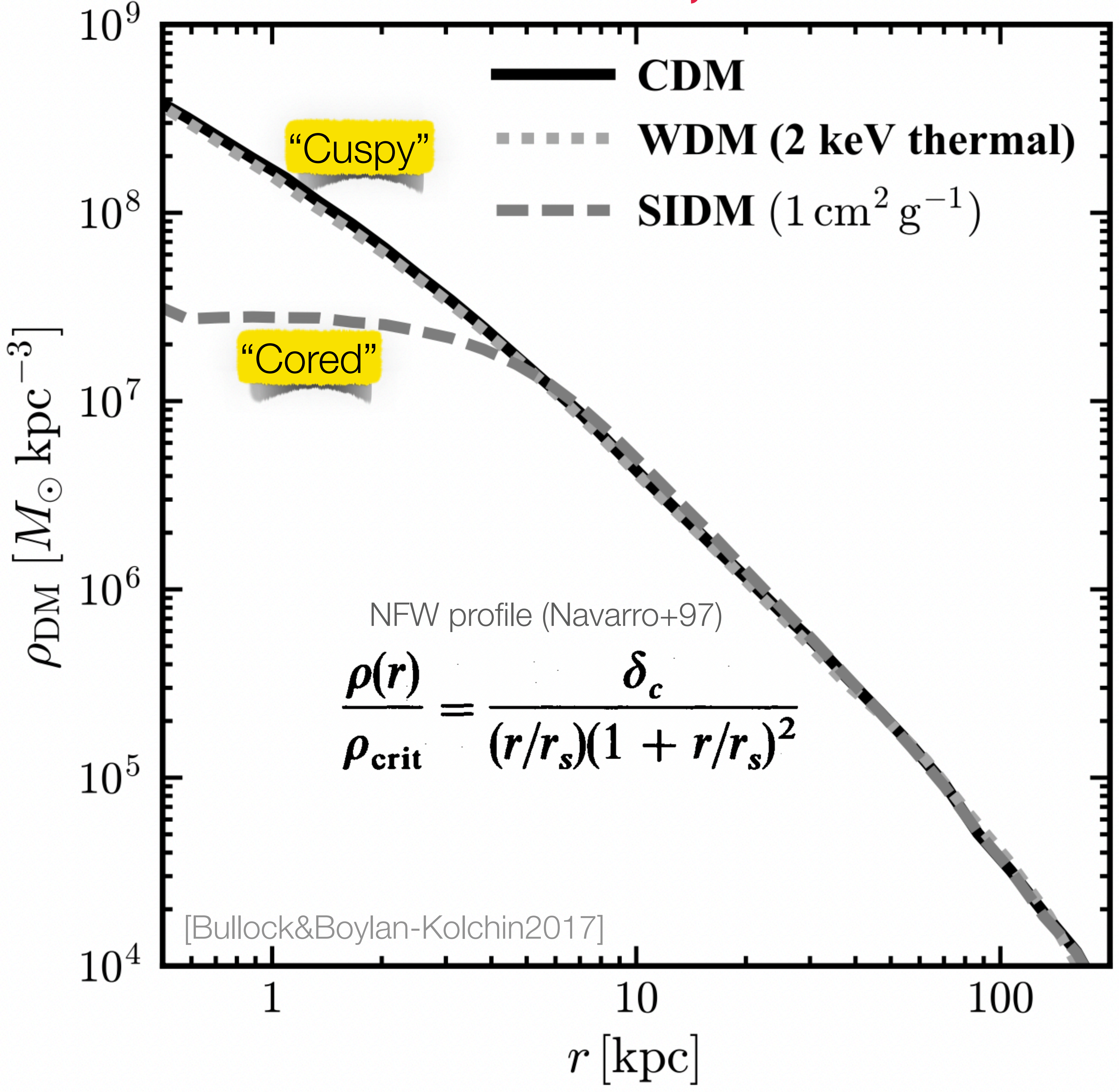

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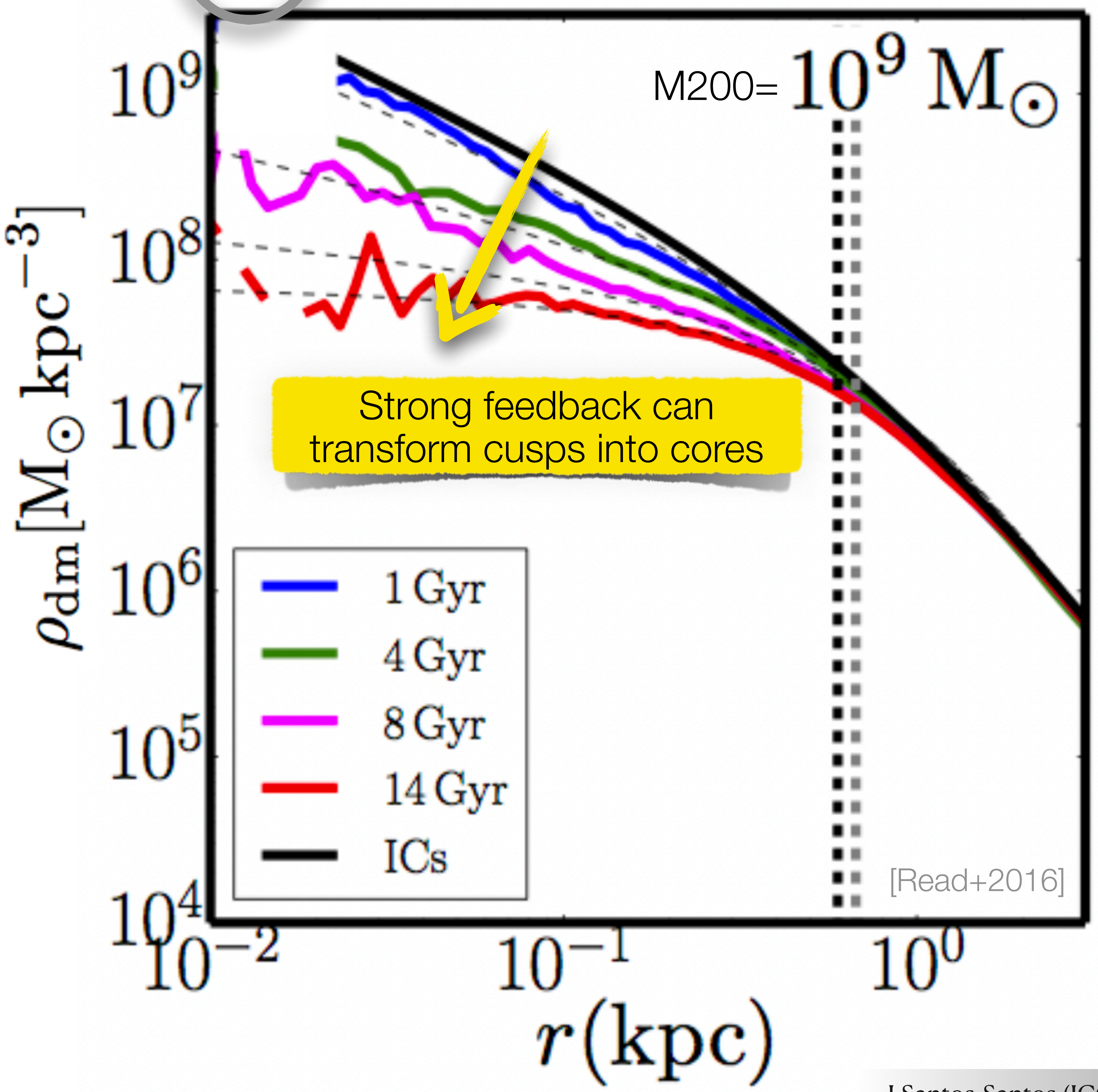
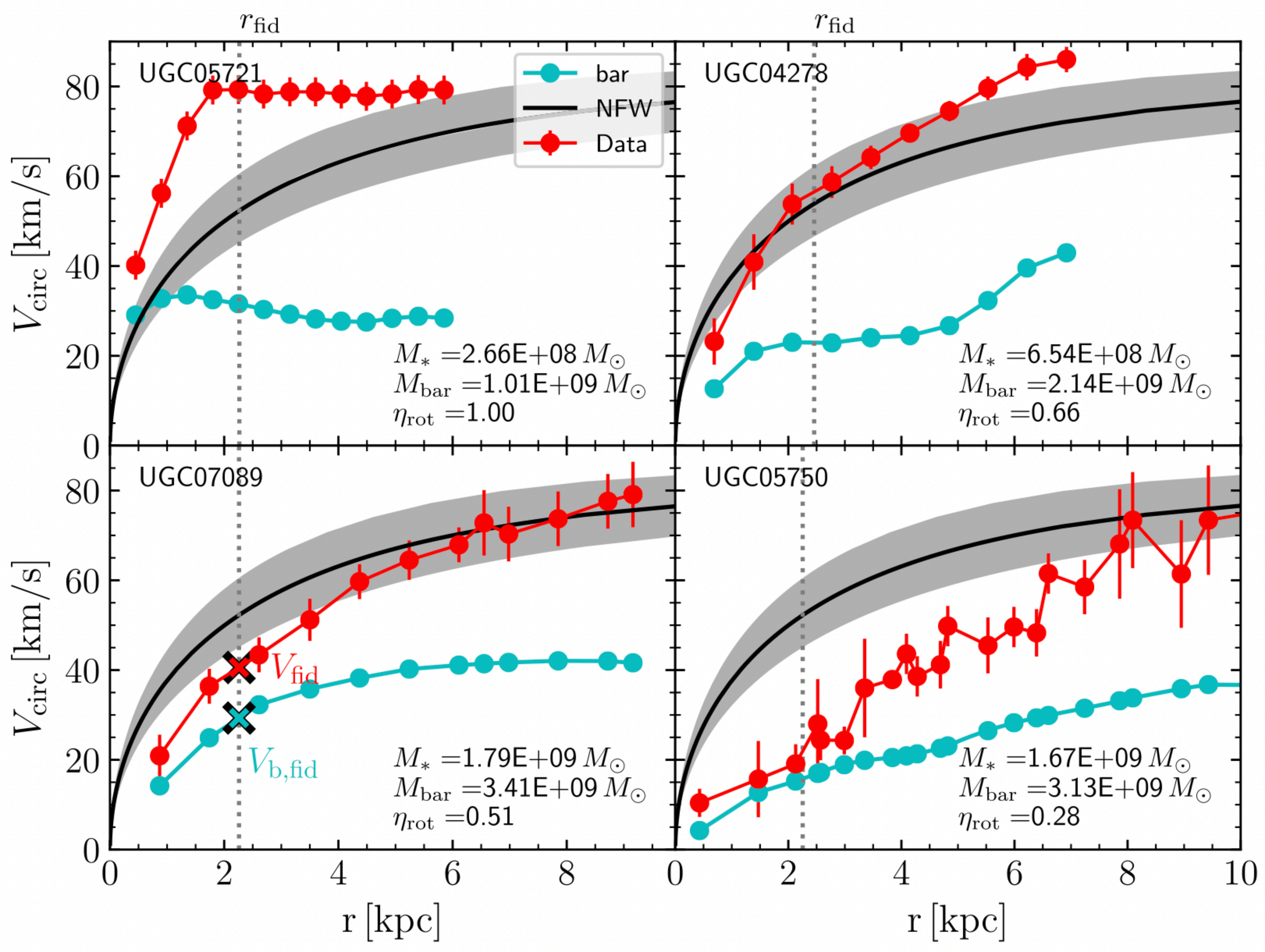


Diversity of dwarf rotation curves

[Santos-Santos+2020a, see also Oman+15]



CDM predicts fixed “cuspy” rotation curve shape at given mass.
Observations suggest diversity of shapes.

“Cusp-Core problem” e.g. Flores&Primack94; Moore1994; de Blok+2001; Gentile+2004; de Blok2010

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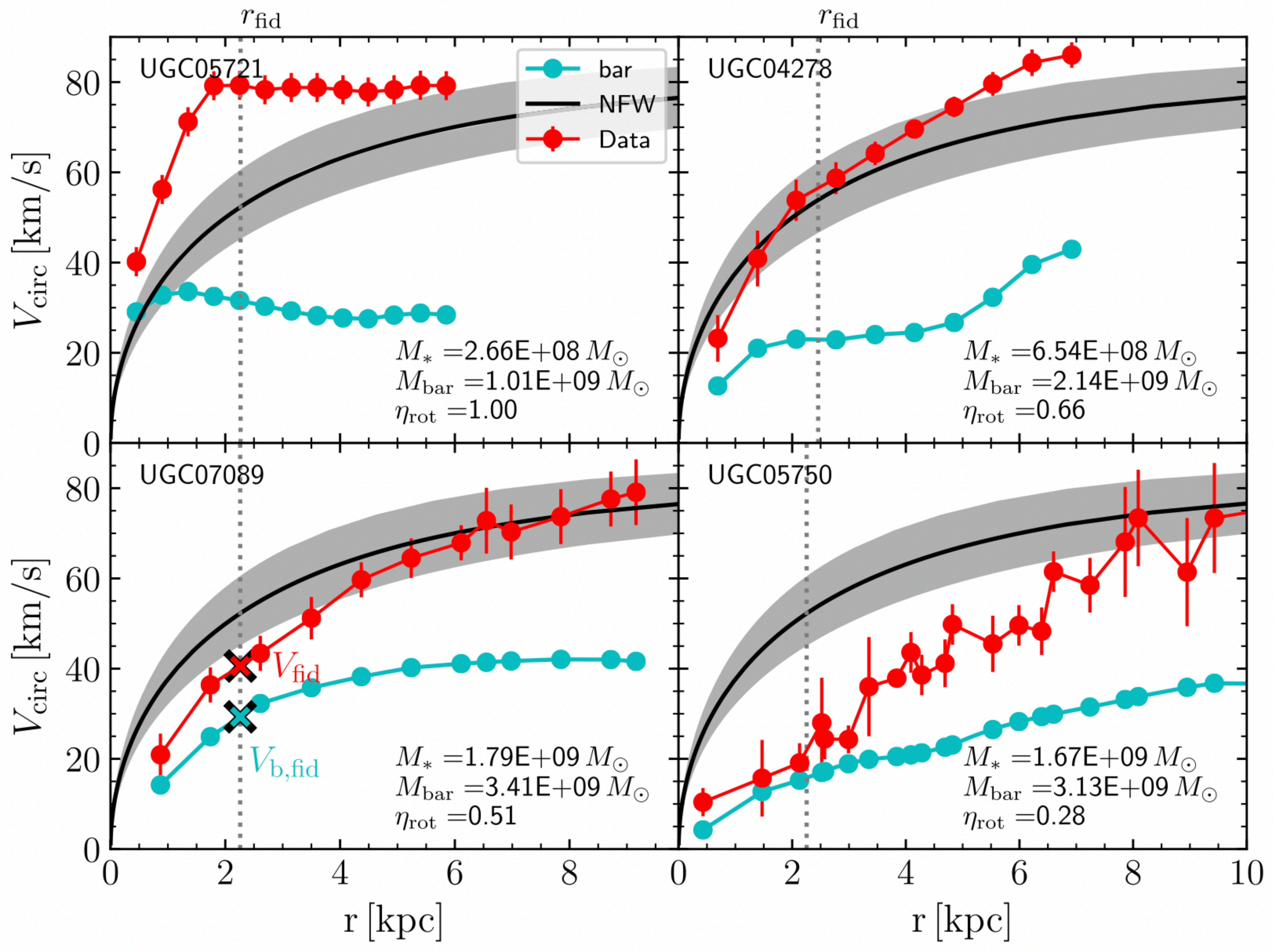

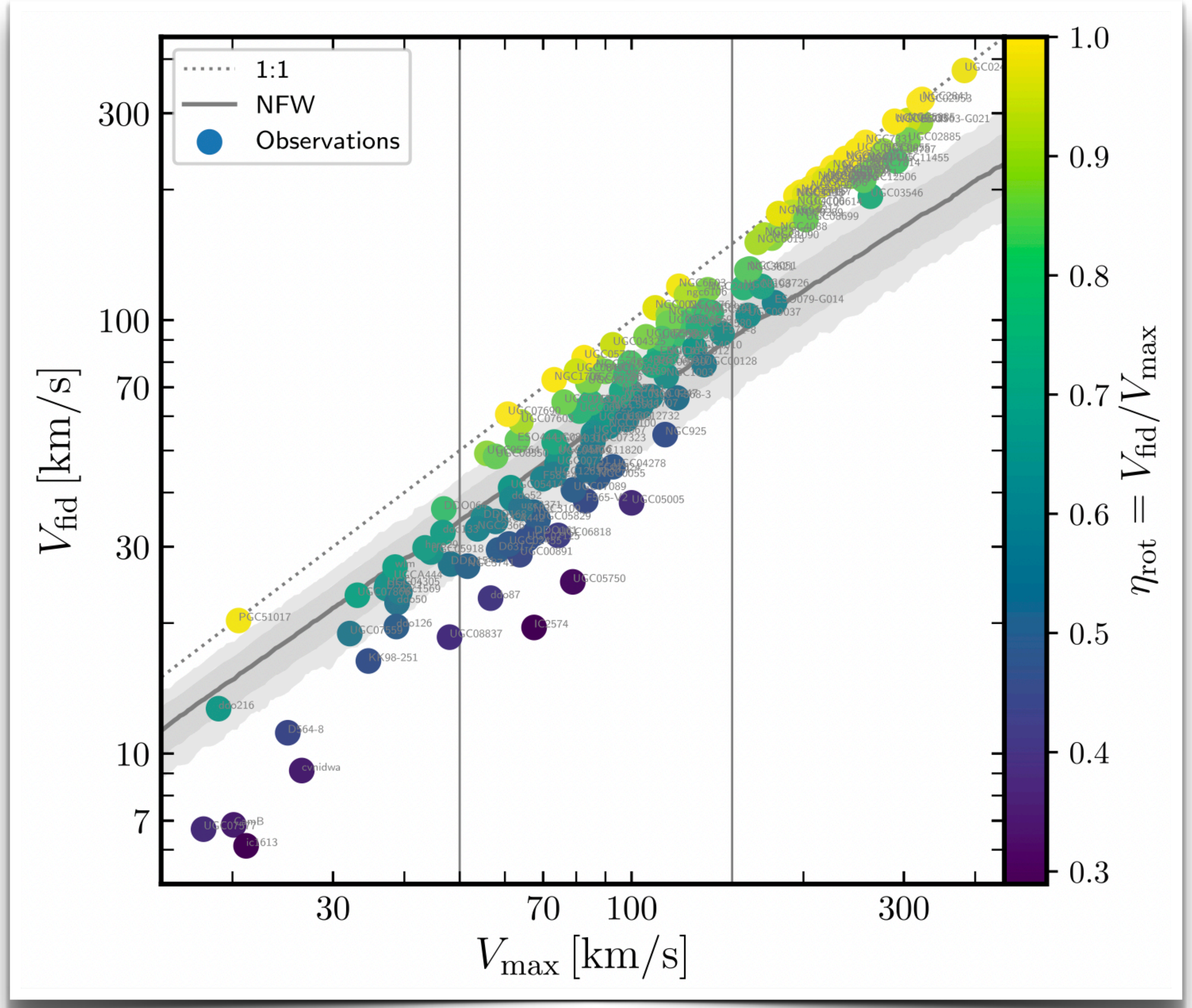

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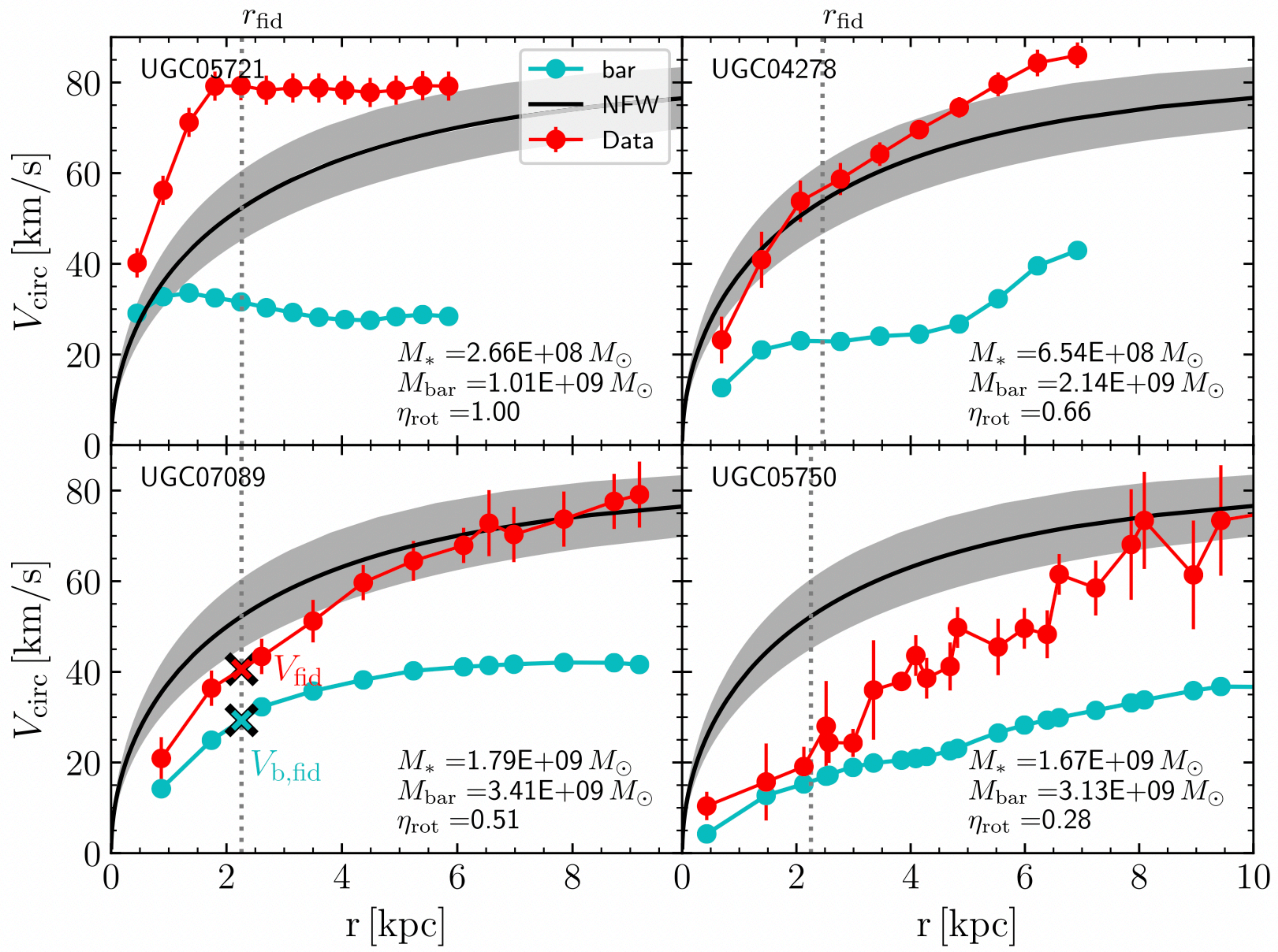

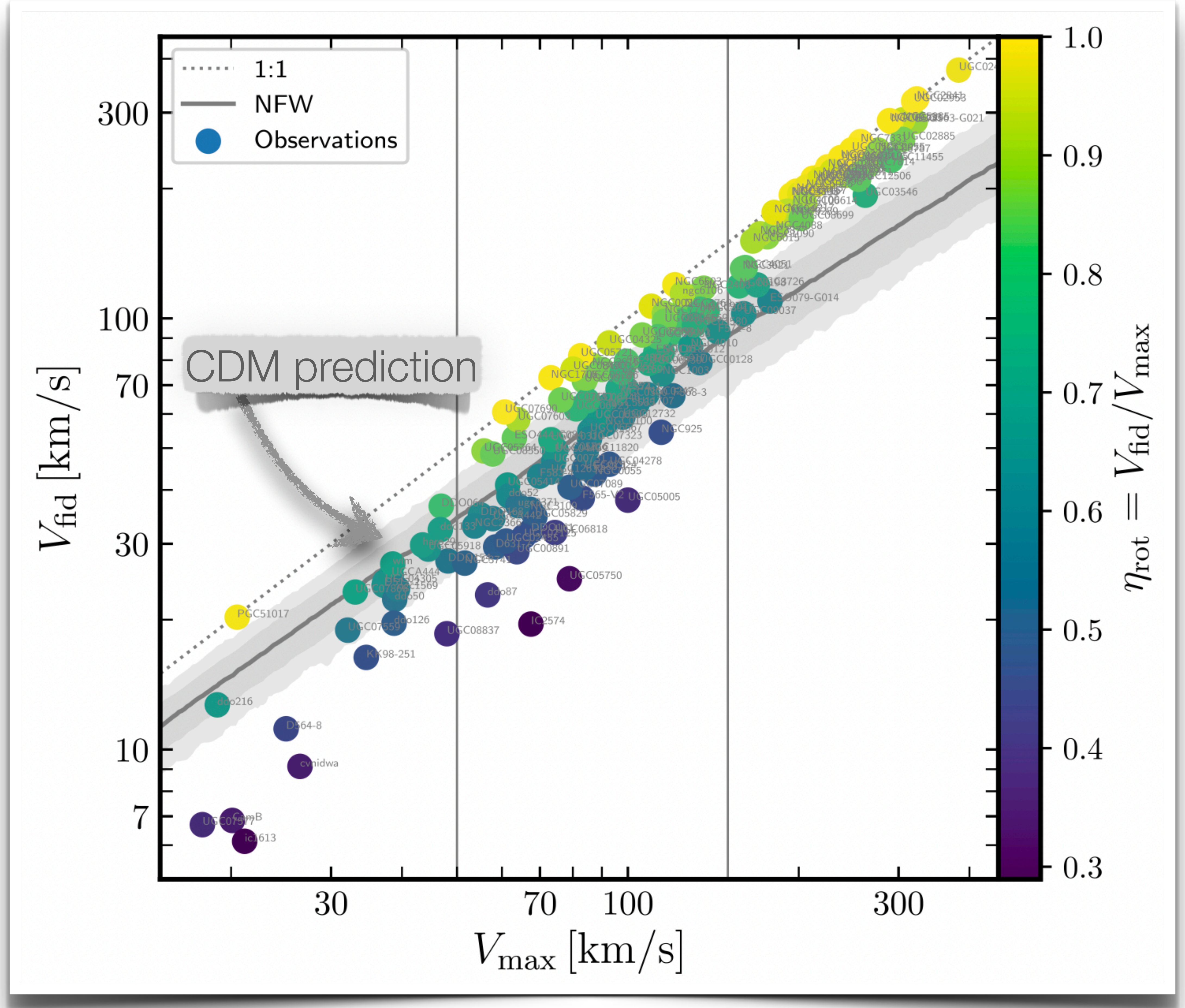

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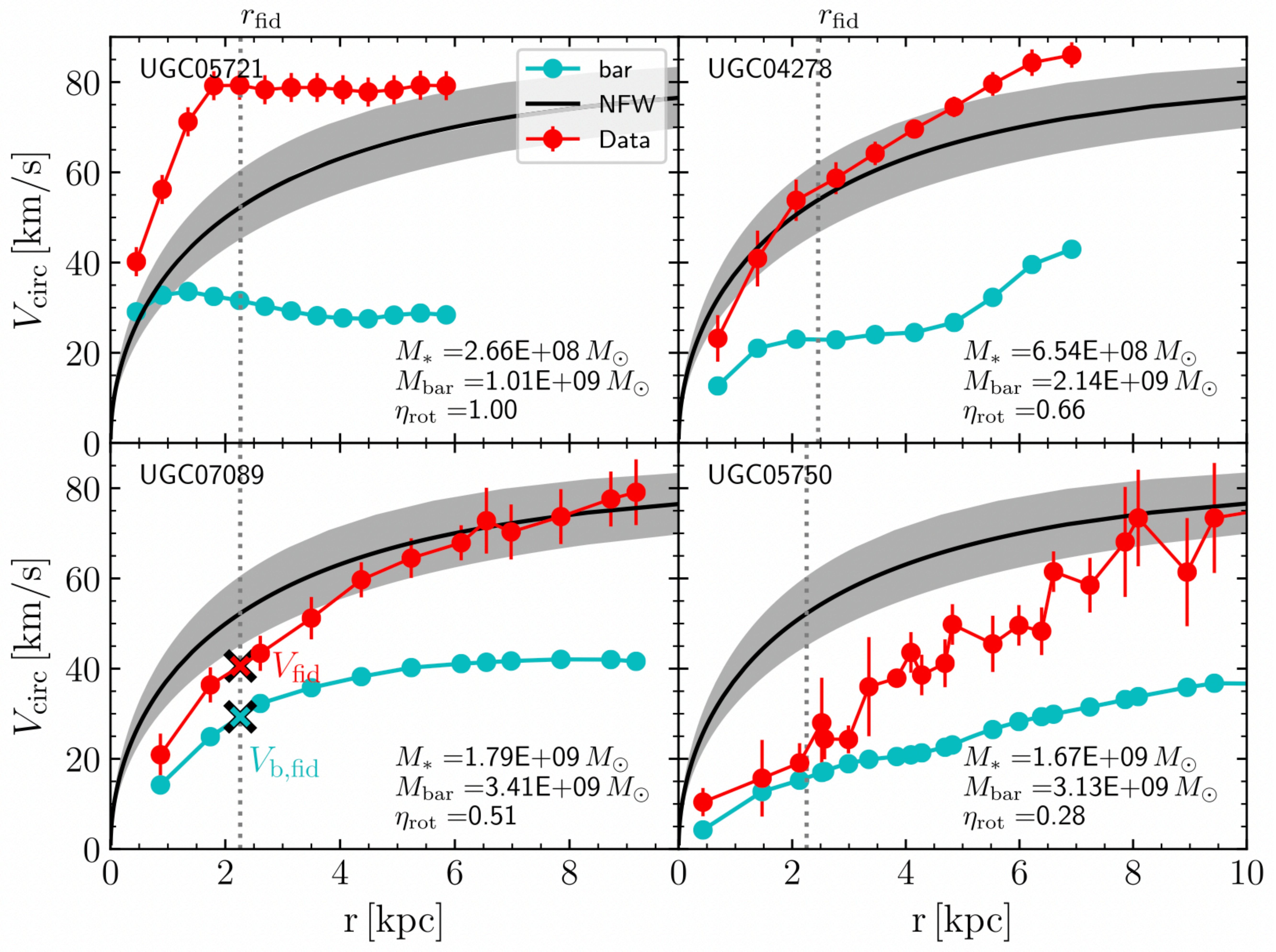

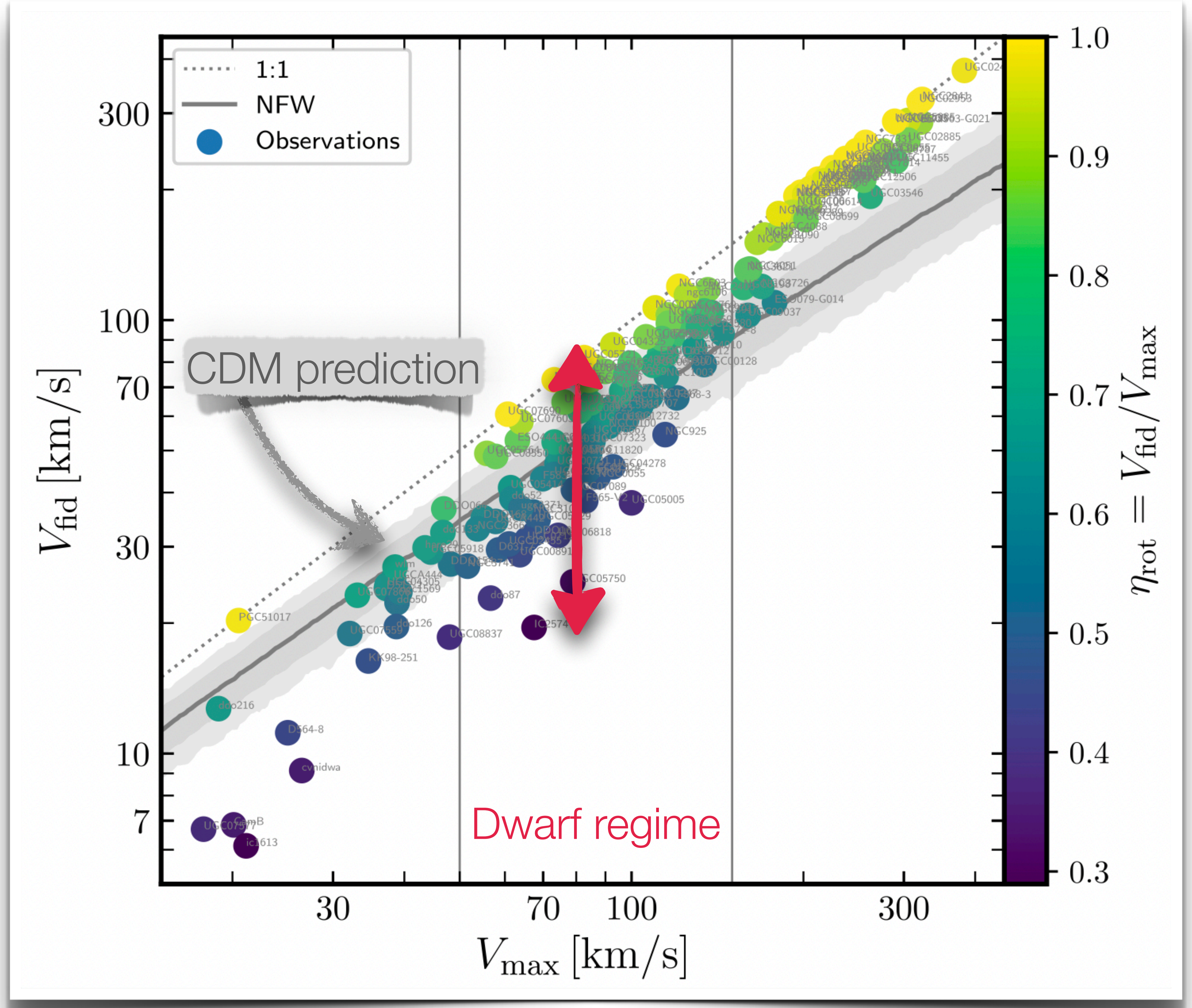

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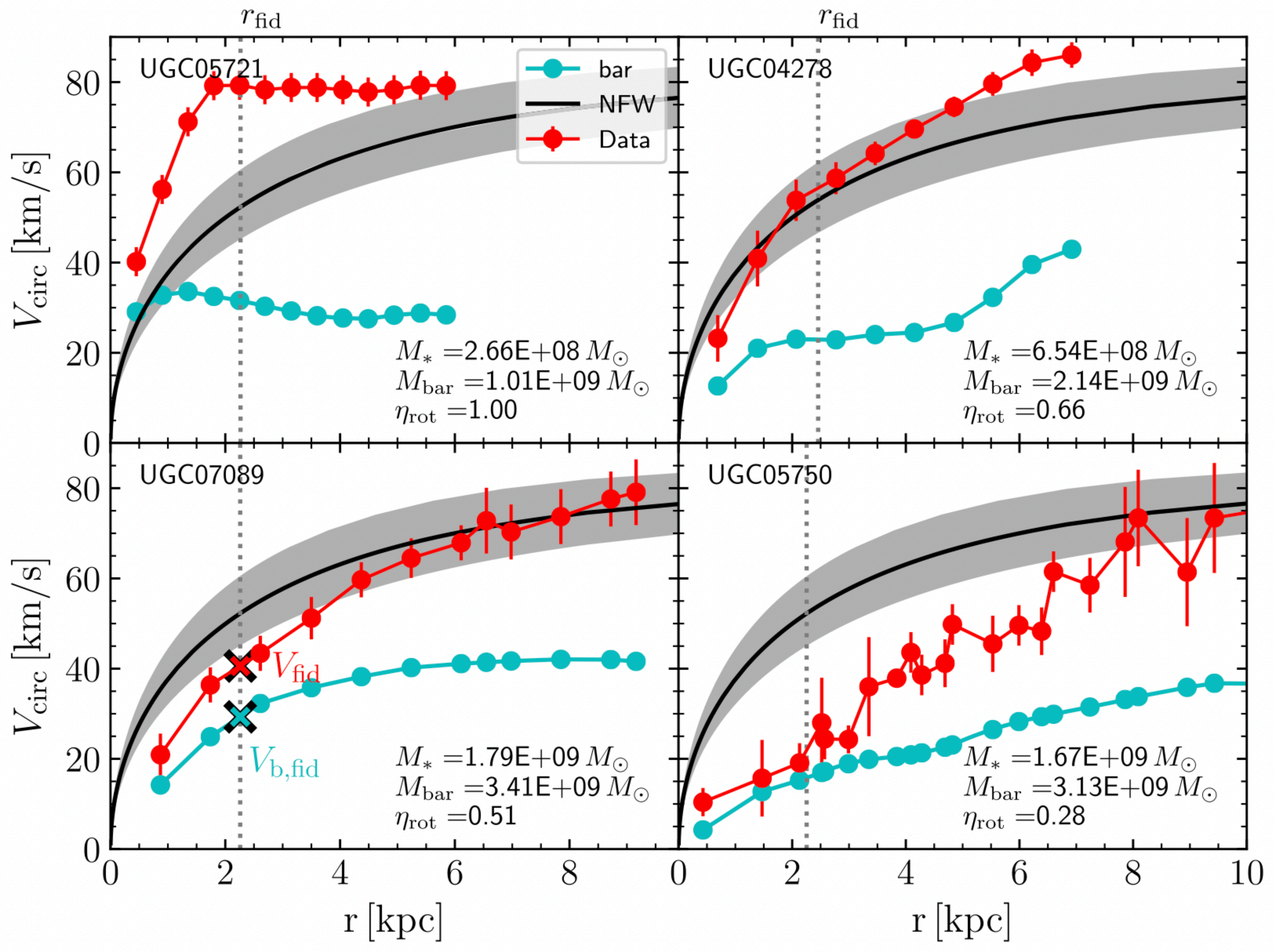

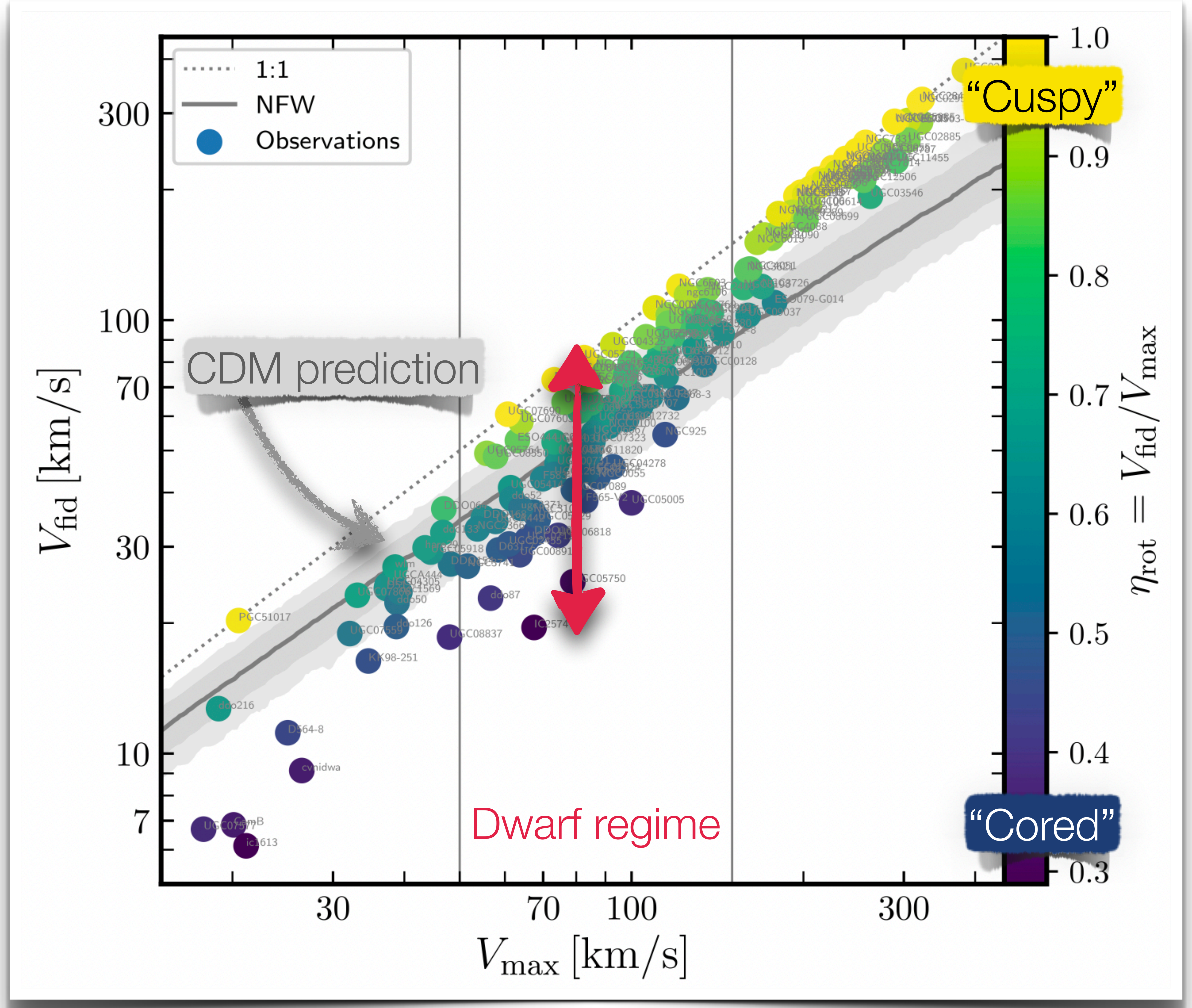

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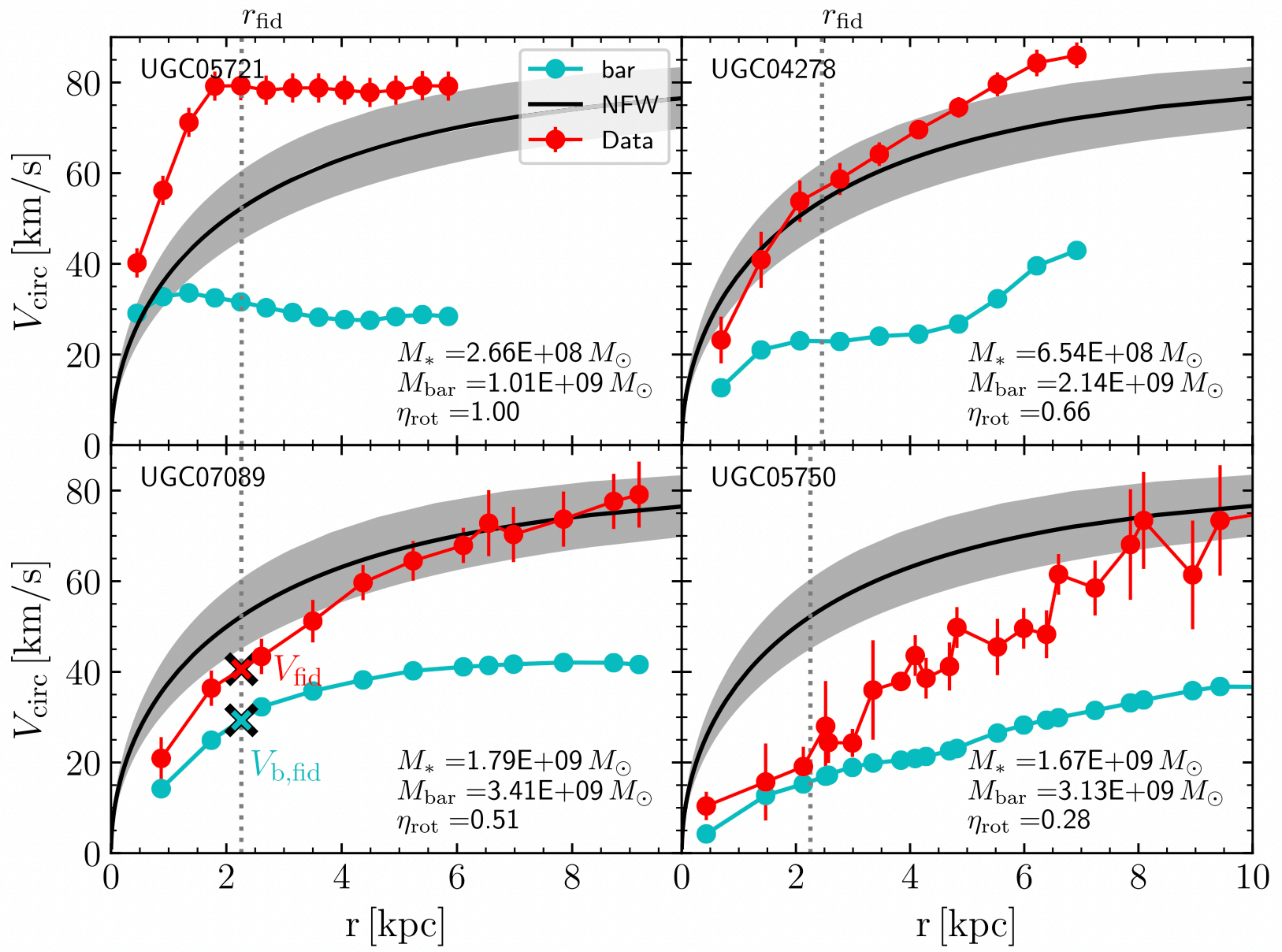

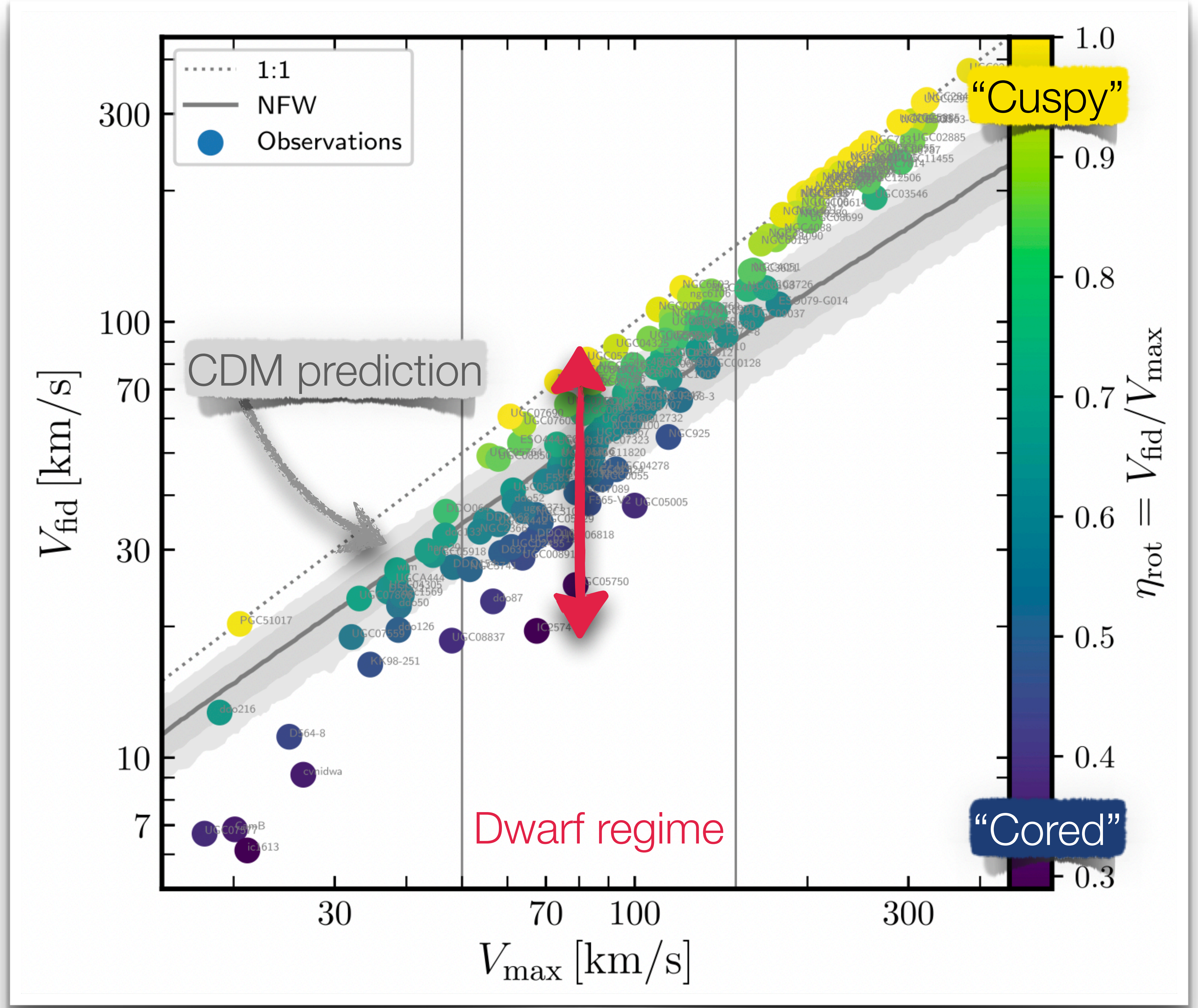

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- Baryon-induced cores+cusps?
  [e,g, Navarro+96, Pontzen&Governato12, Read+16, Benitez-Llambay+19]
- Self-interacting Dark Matter?
  [e,g, Spergel+2000, Rocha+2013, Tulin&Yu+2018Ren+2019, Kaplinghat+19]
- Observational uncertainties?
  [e,g, Marasco+2018, Oman+2019, Roper+23]

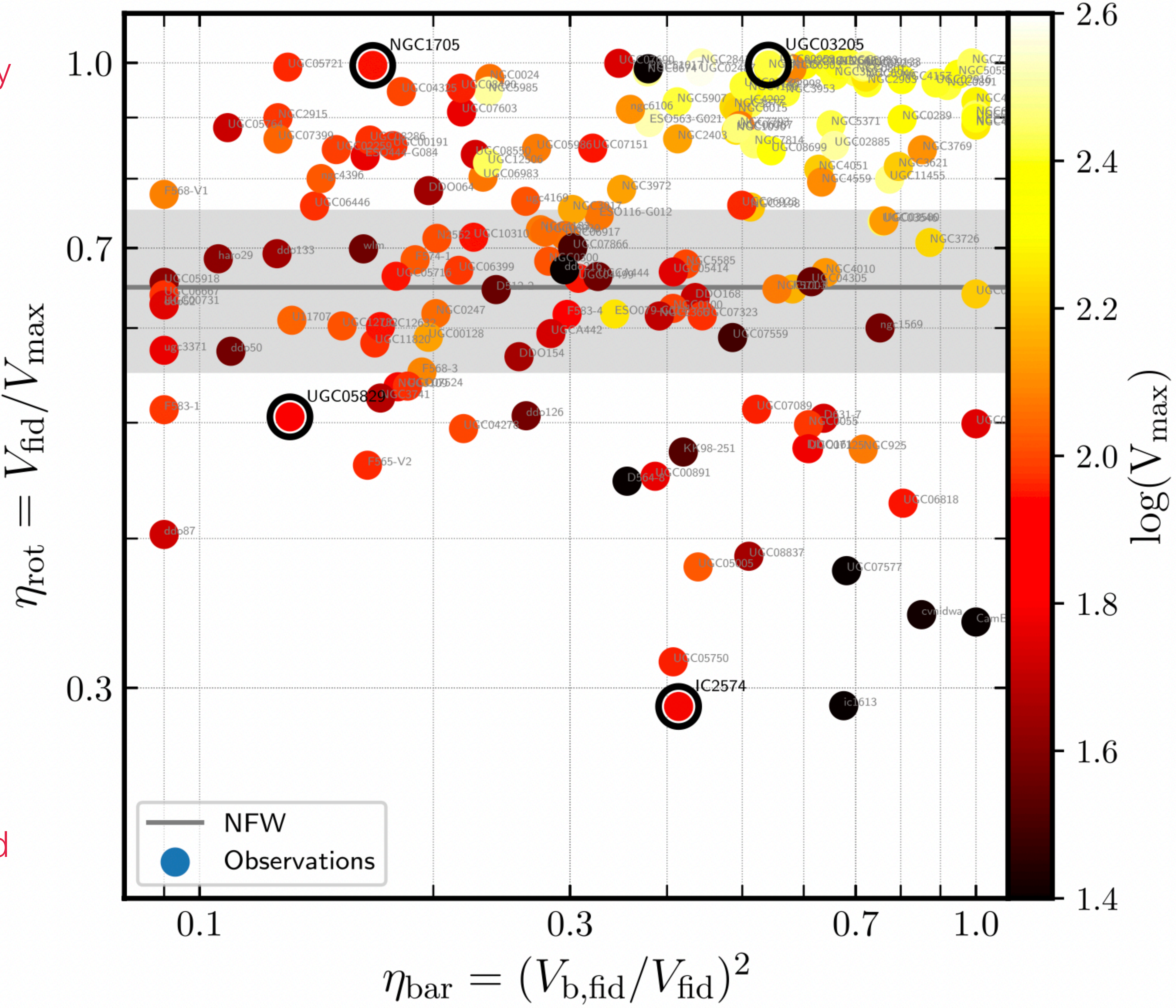
Diversity of dwarf rotation curves

[Santos-Santos+2020a]

Rotation curve shape
vs
Contribution of baryons to the inner mass budget

Cuspy

Cored



Baryons negligible

Baryons dominate

Diversity of dwarf rotation curves

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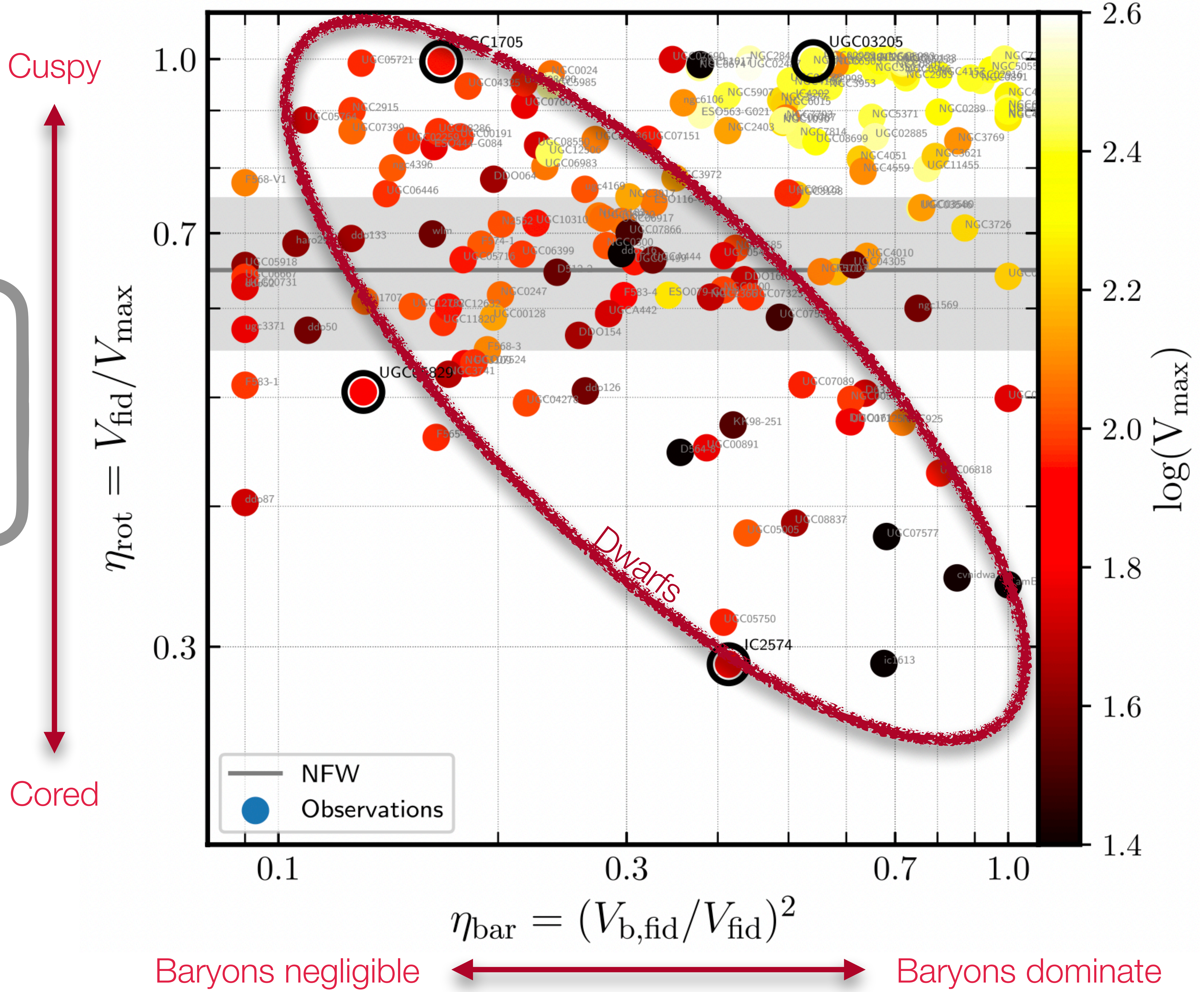

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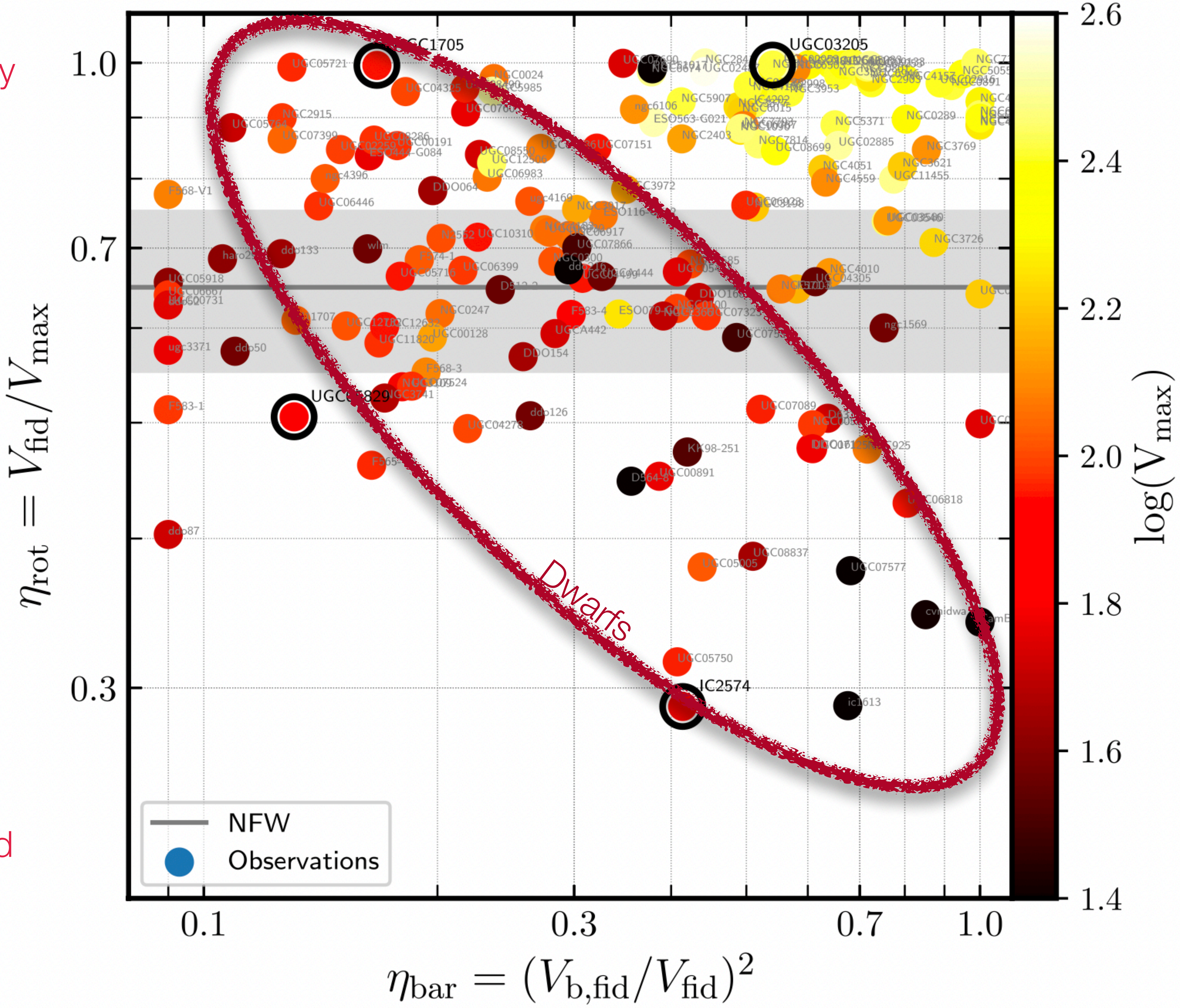

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Baryons are negligible in dwarfs with steeply-rising rotation curves.

Baryons dominate in dwarfs with cores.

Diversity of dwarf rotation curves

[Santos-Santos+2020a]

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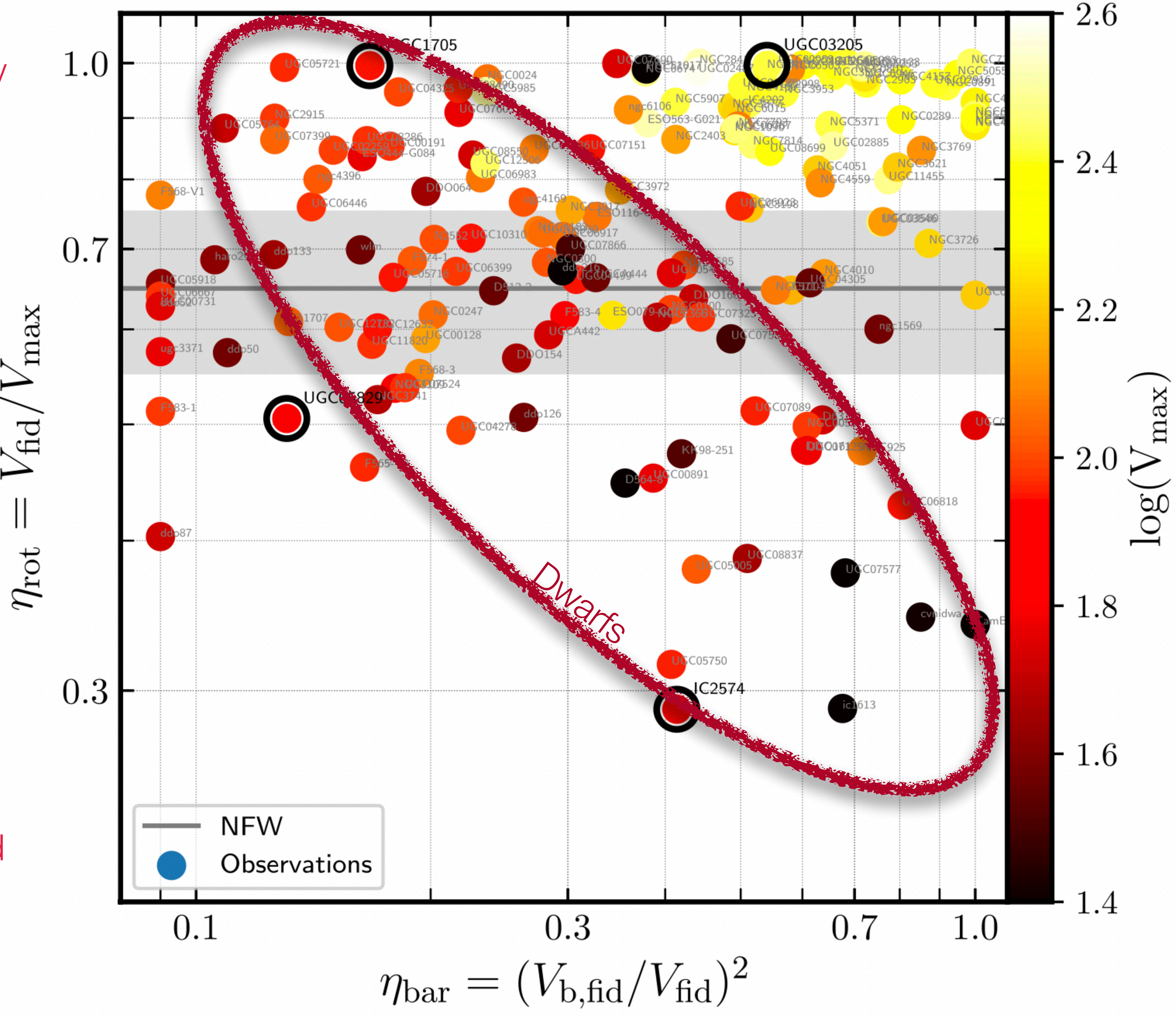

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↓

Counter-intuitive trend for models where baryonic feedback outflows produce dark matter cores

Diversity of dwarf rotation curves

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mDM~5e4Msun; mbar~1e4Msun
Fiducial EAGLE model with low density threshold (n=0.1 cm-3)

EAGLE-CHT10
mDM~4e5Msun; mbar~8e4Msun
EAGLE model with high density threshold (n=10 cm-3)

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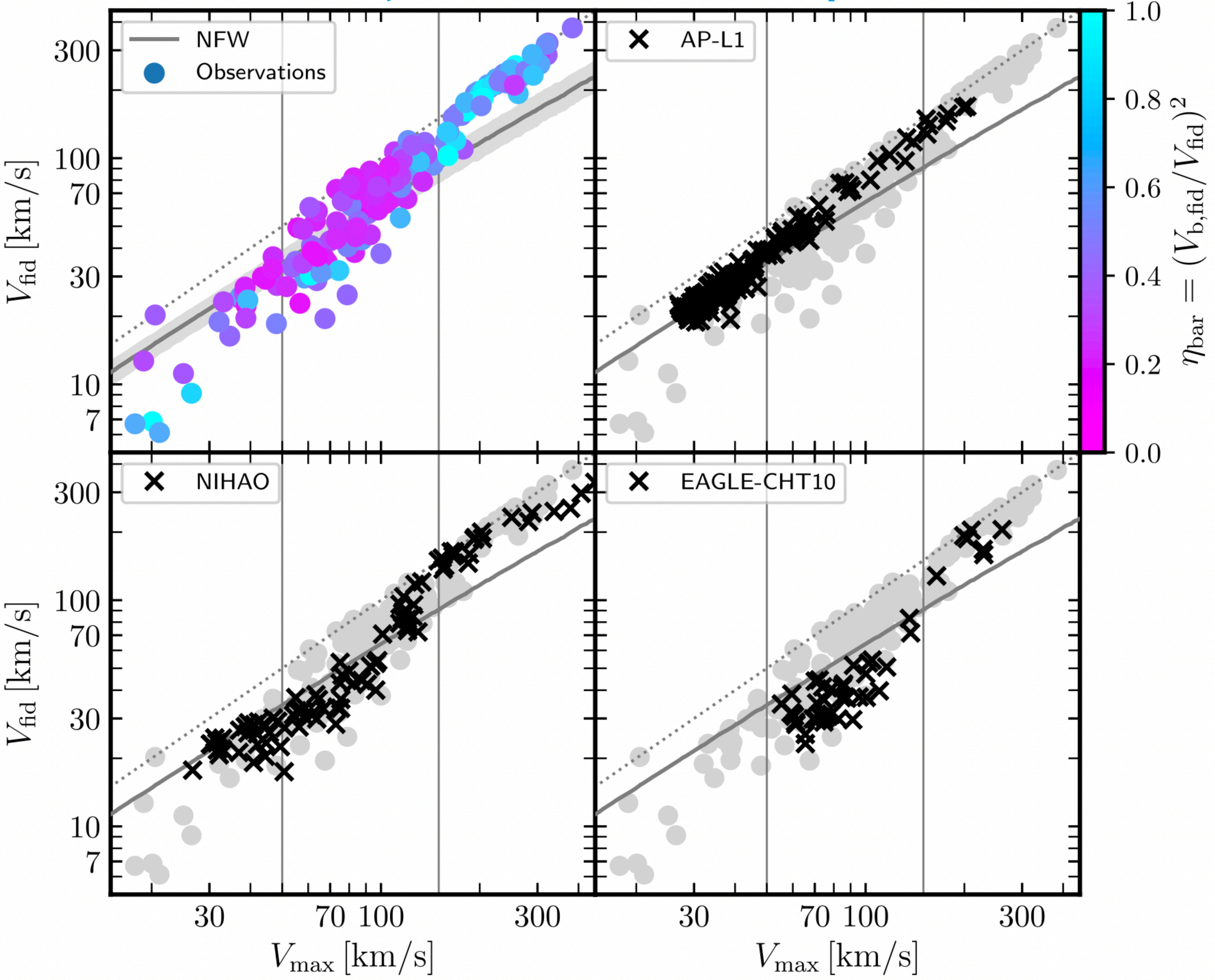
Gasoline model with high density threshold and strong SNe feedback (n>10.5 cm-3)

Baryon-induced cores+cusps?



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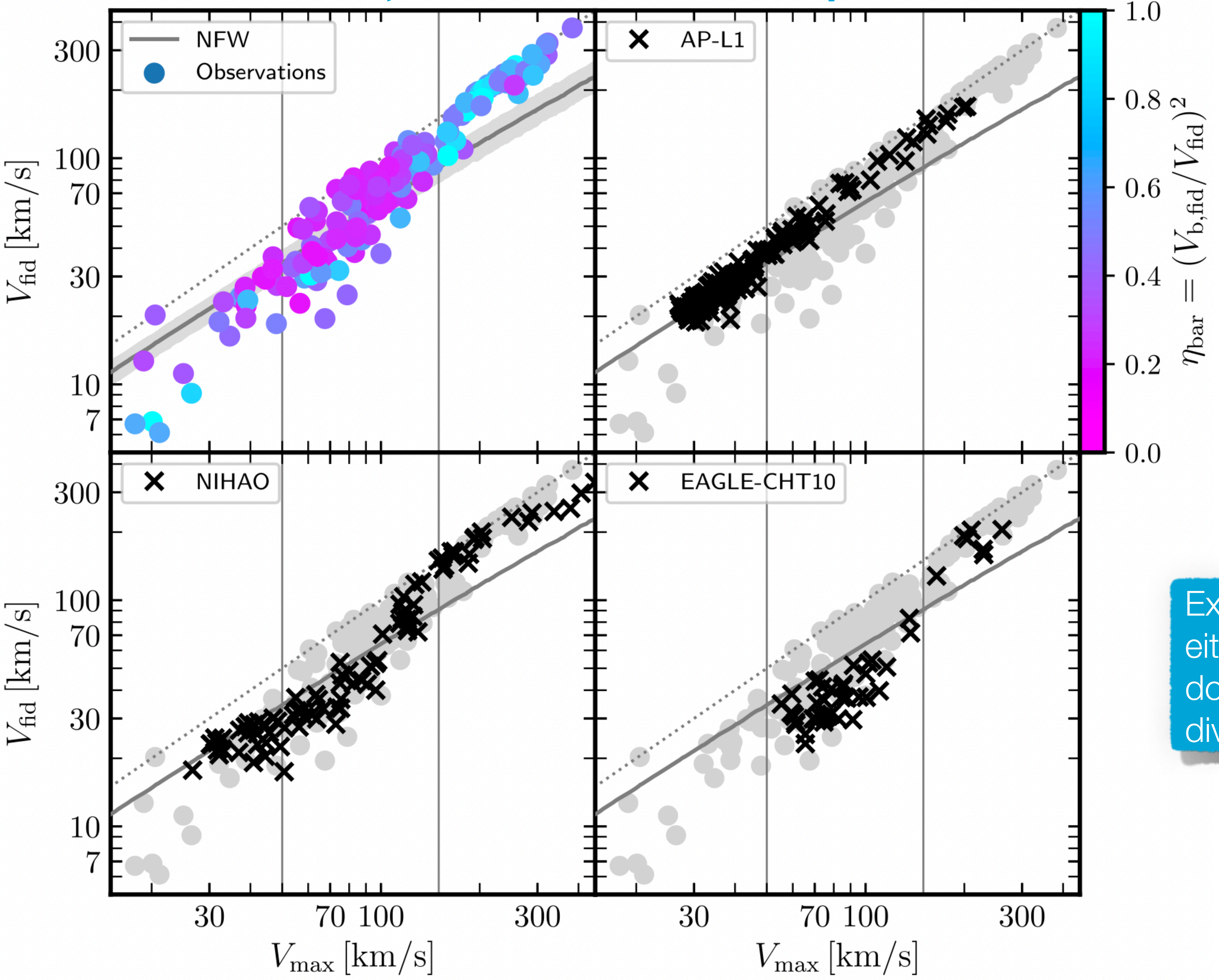

Existing models produce either cores or cusps, but do not reproduce the full diversity

Diversity of dwarf rotation curves

[Santos-Santos+2020a]

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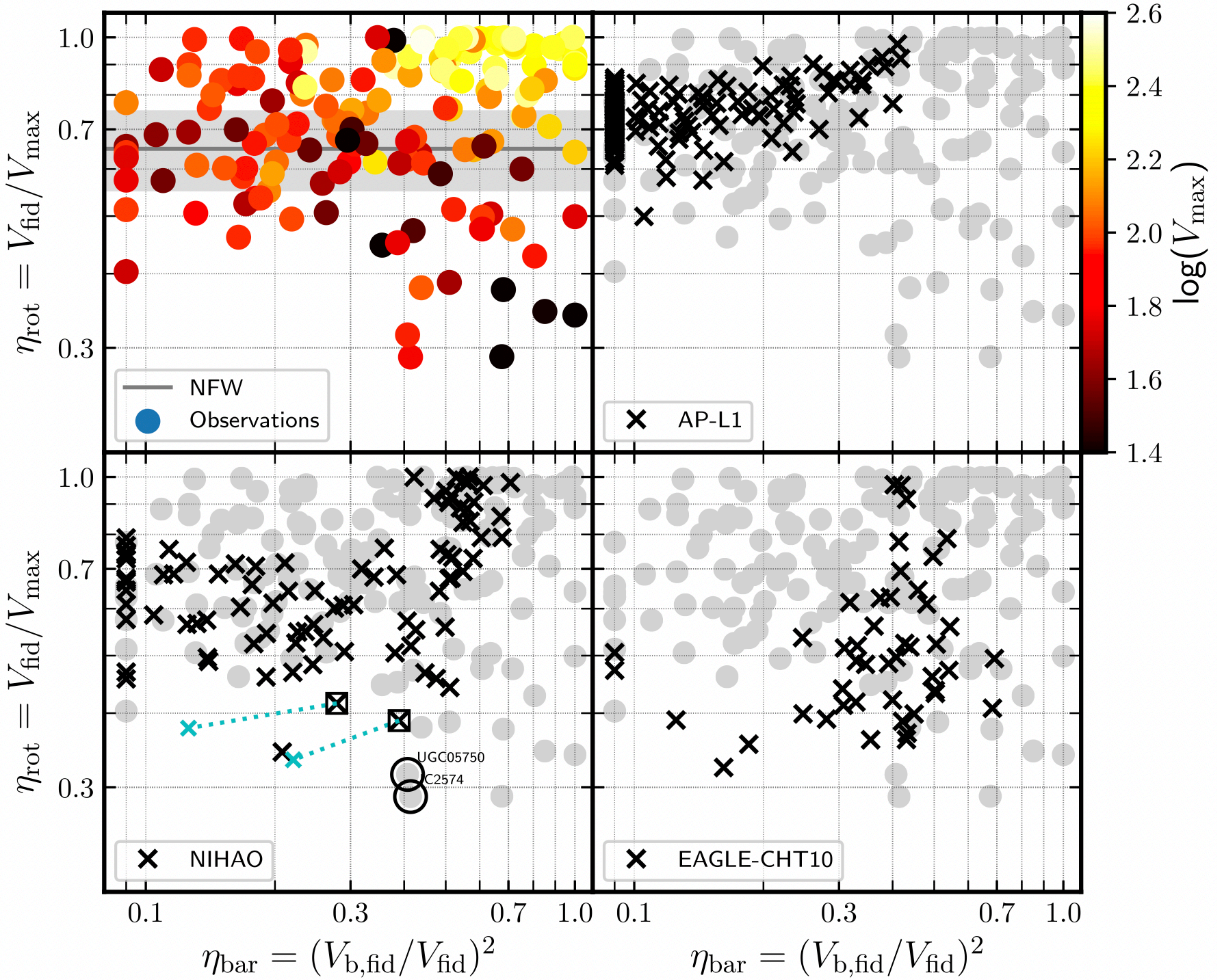

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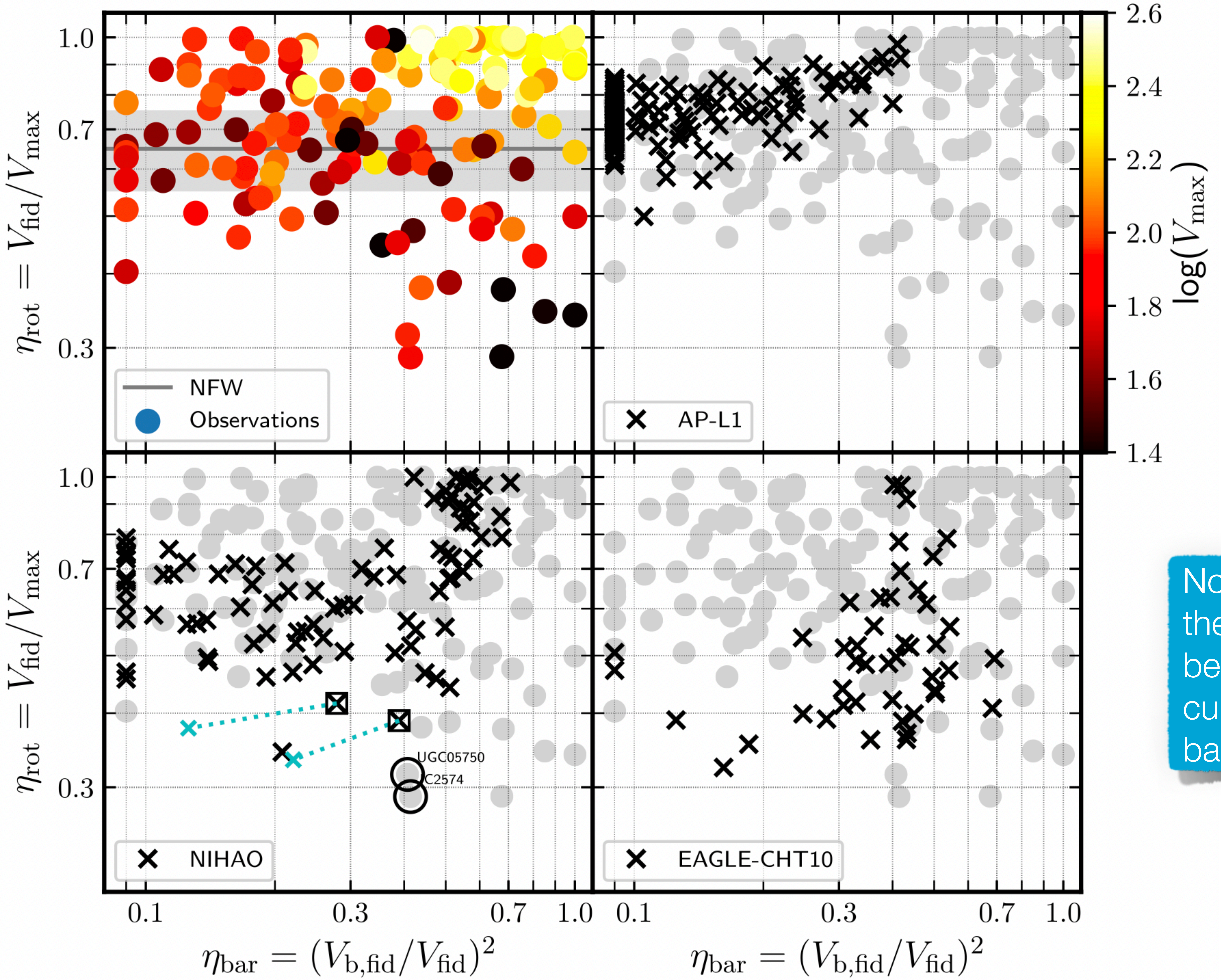


No model reproduces the observed trend between rotation curve shape and baryonic contribution

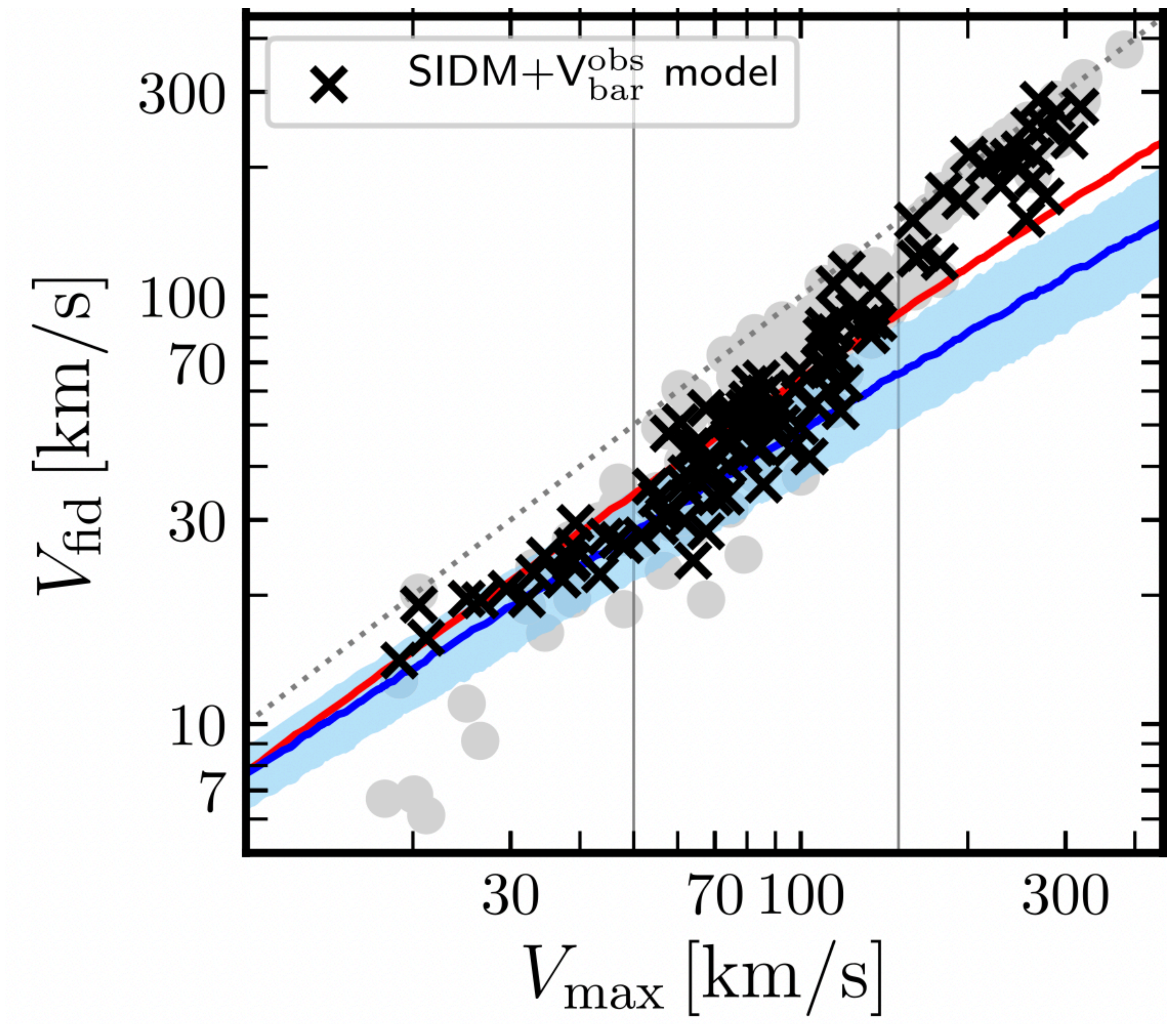
Diversity of dwarf rotation curves

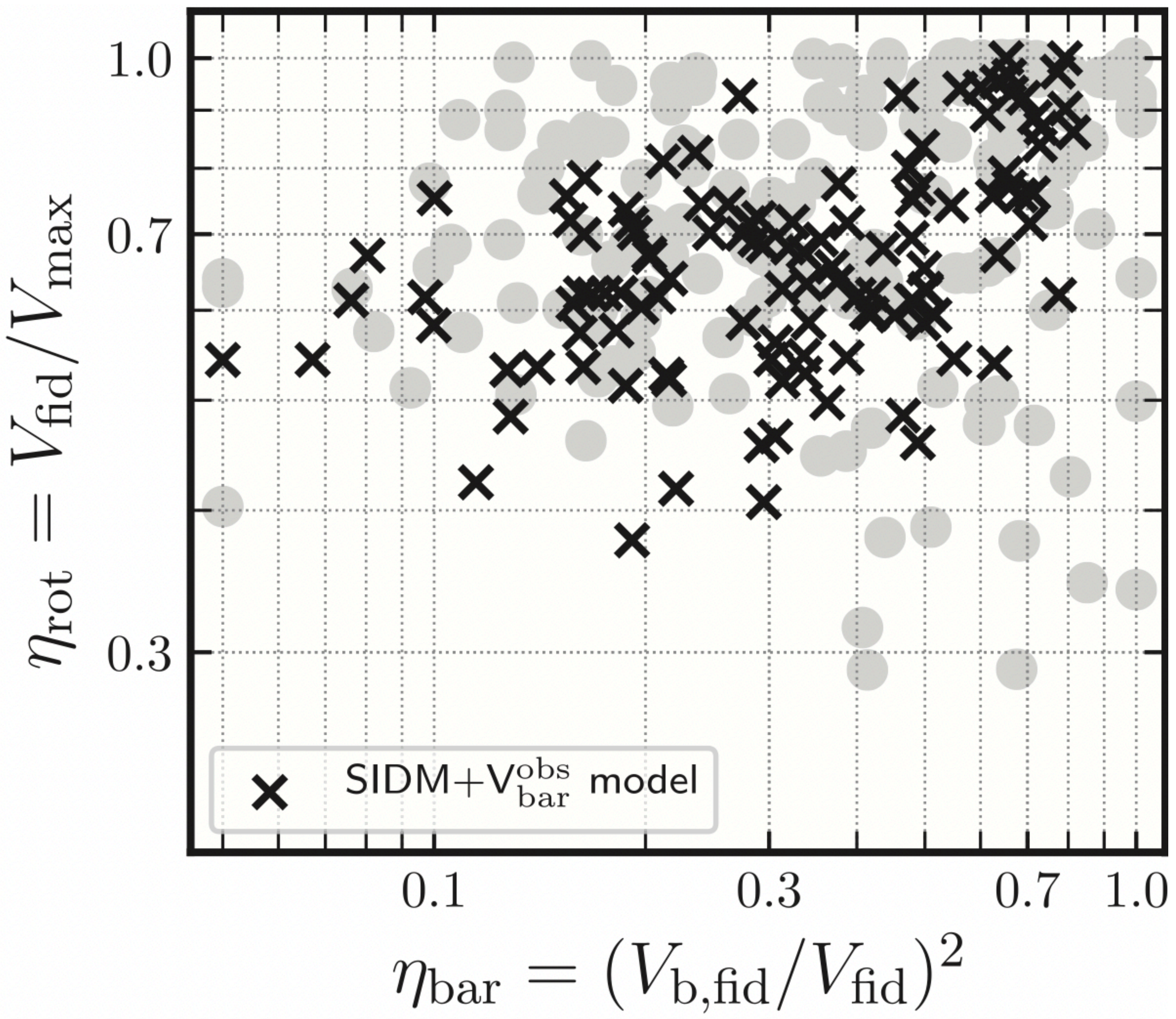
[Santos-Santos+2020a]

In it's simplest version:
elastic velocity-independent
cross-section

Self-interacting Dark Matter?

SIDM + Vbar^obs model
SIDM DM-only simulation σ=10 cm2/g
+ Analytical model to add baryon effects following observed Vbar data





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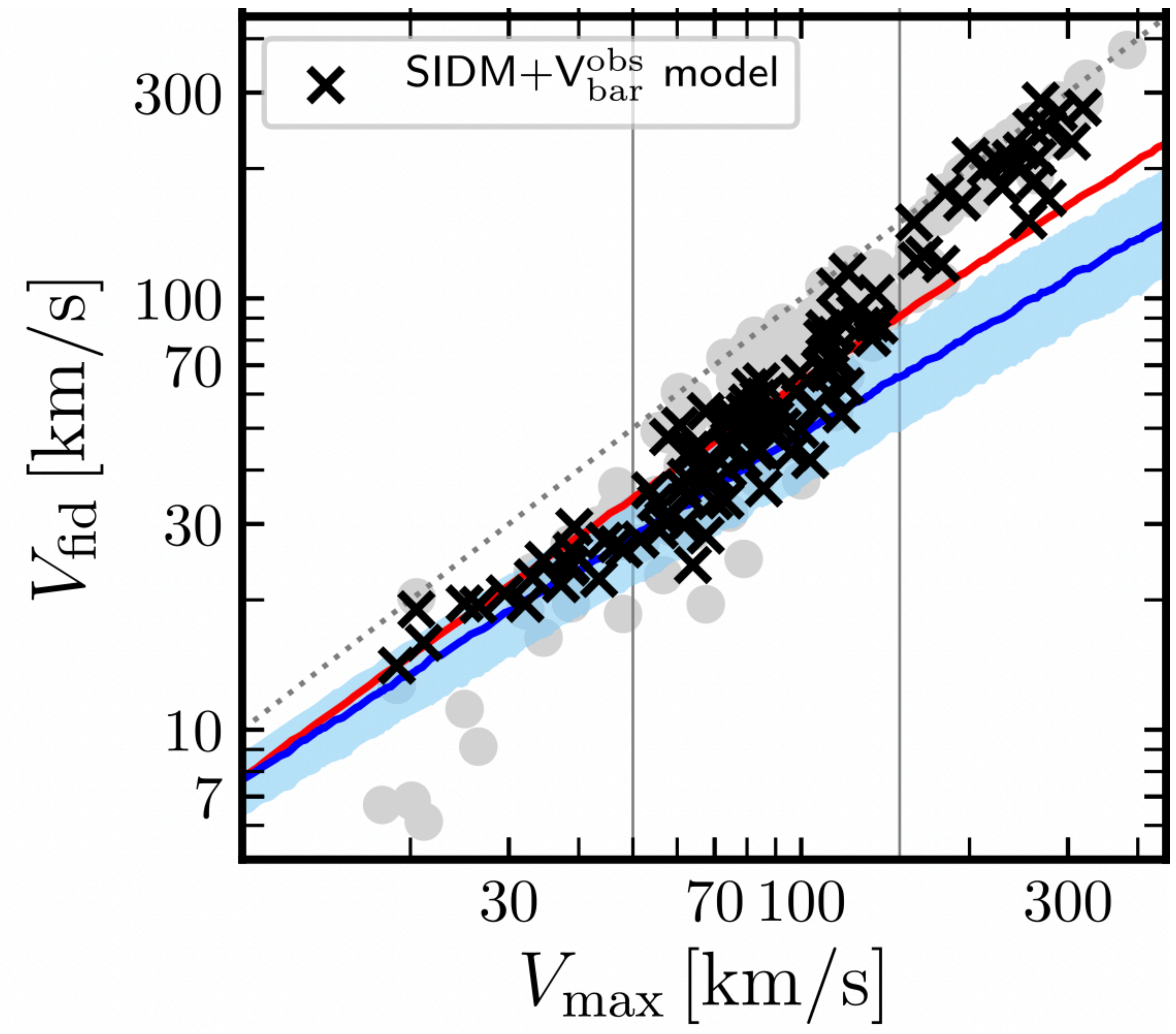

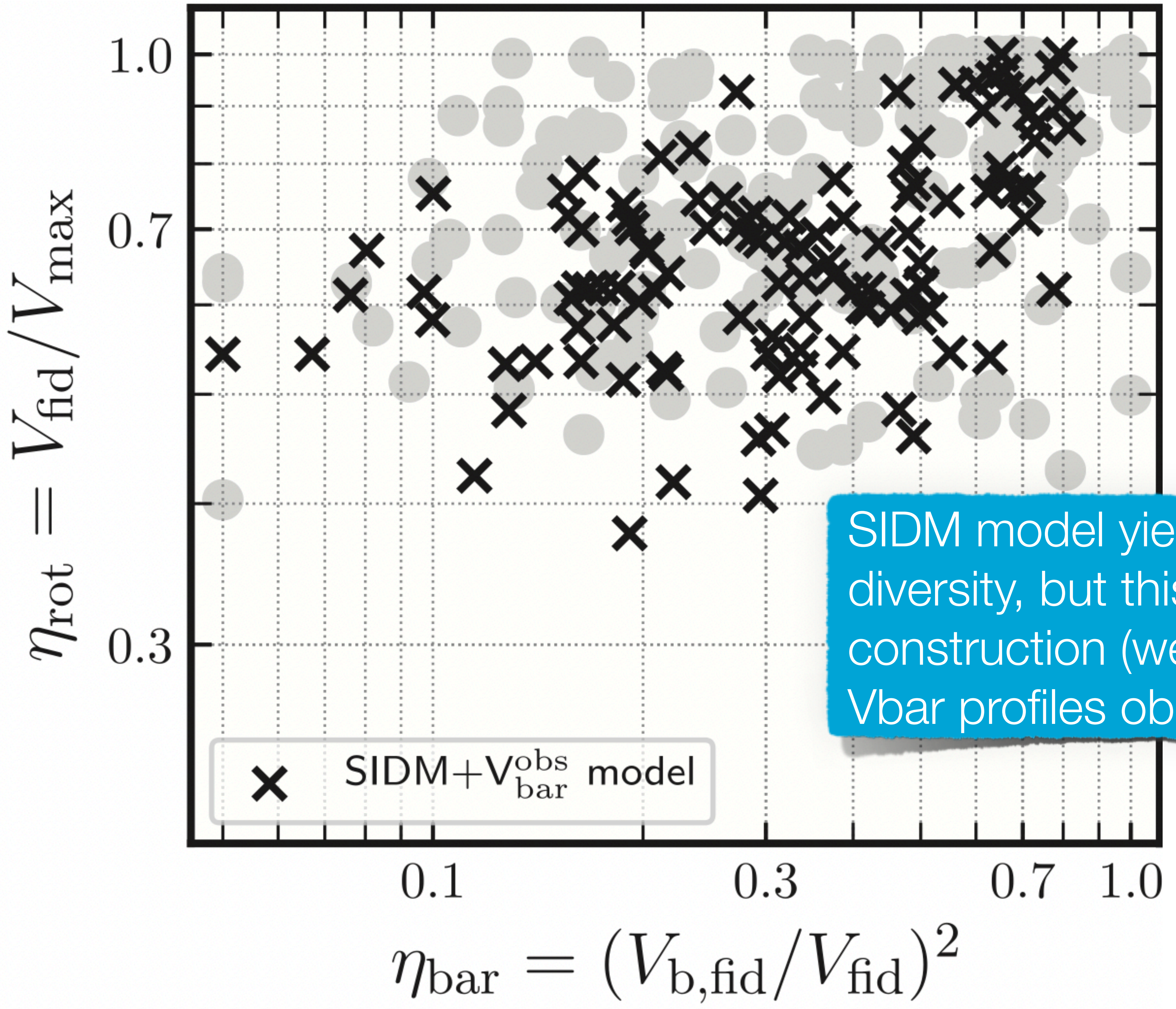

SIDM model yields more diversity, but this is by construction (we input the Vbar profiles observed)

Diversity of dwarf rotation curves

[Santos-Santos+2020a]

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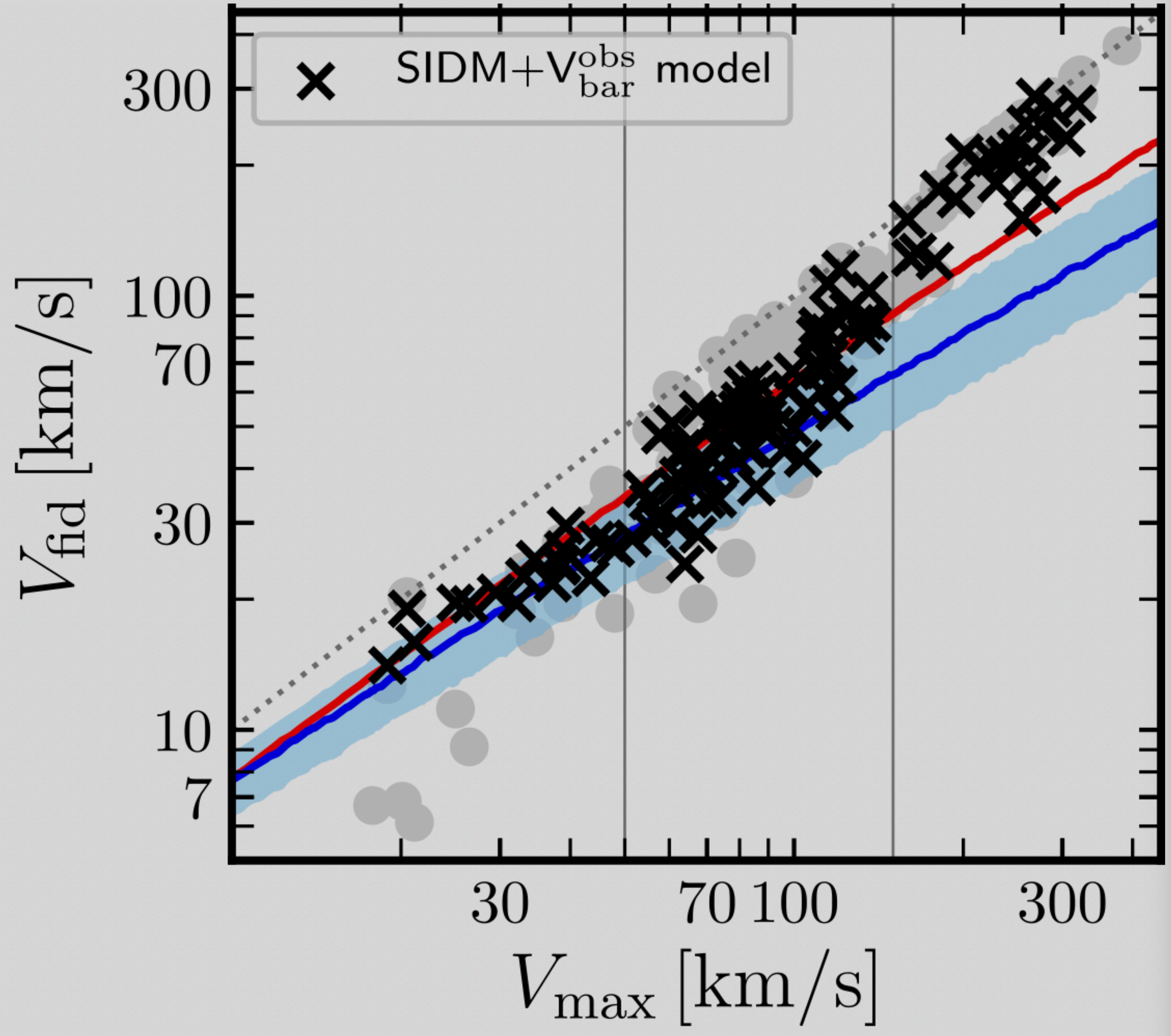

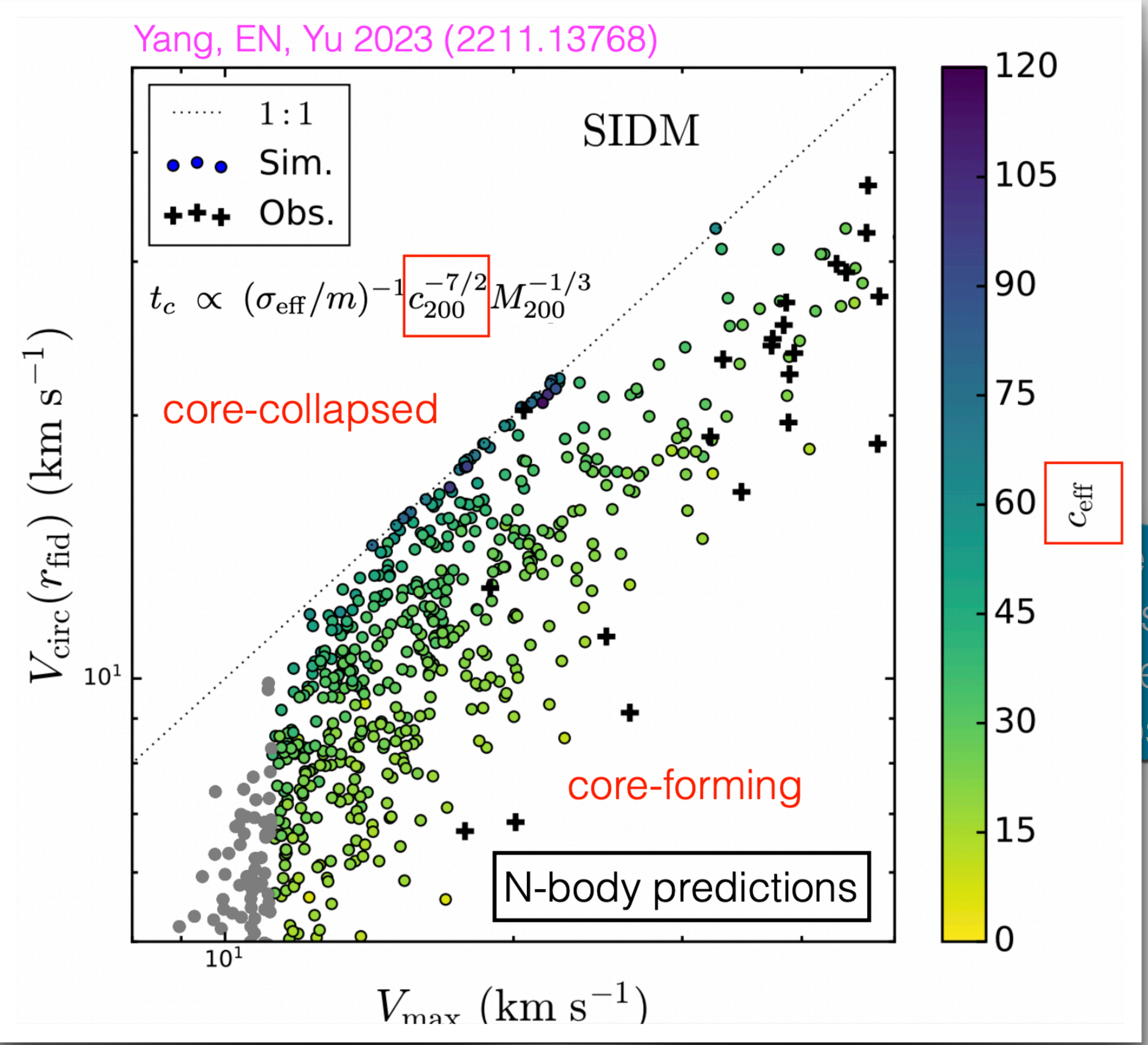

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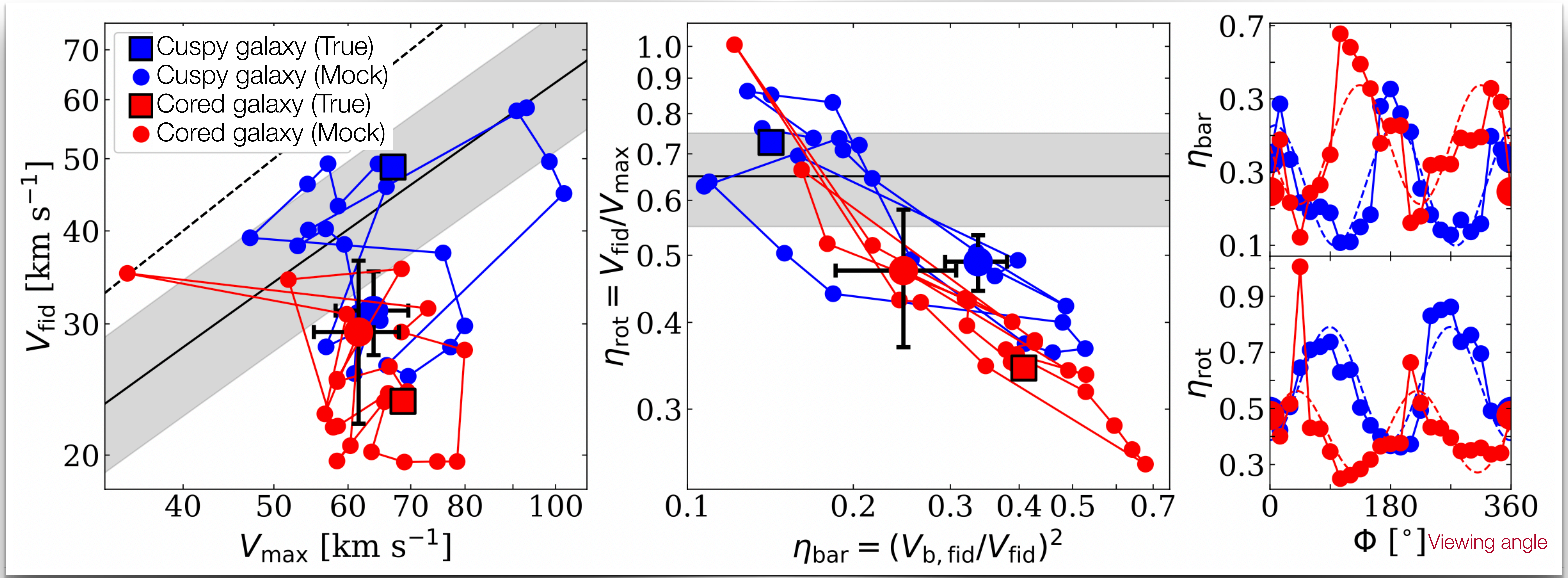
Diversity of dwarf rotation curves

[see also Oman+19, Santos-Santos+2020a]

Observational uncertainties?

[Roper, SS, +2023]



If we analyse simulated galaxies using **same methods as observers use**, inferred gas rotational velocities are biased towards the presence of a 'core', even when the galaxy truly hosts a 'cusp'.

Diversity of dwarf rotation curves

[see also Oman+19, Santos-Santos+2020a]

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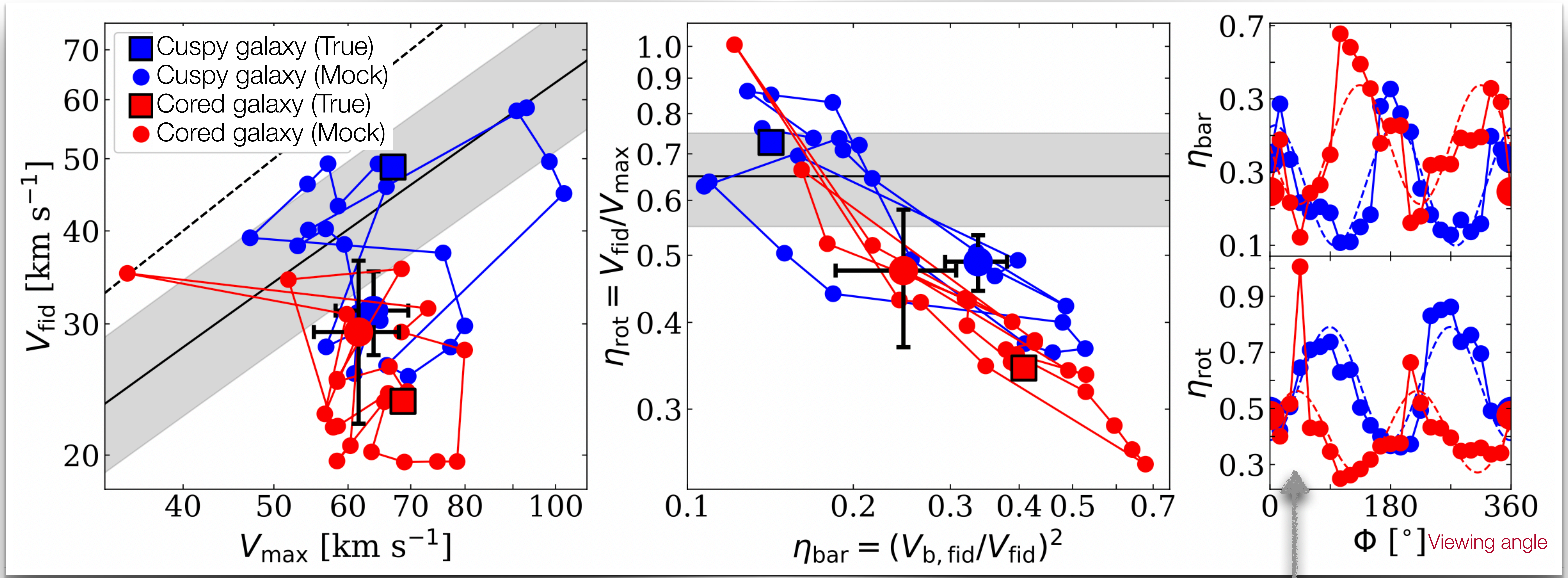

Bisymmetric non-circular motions

If we analyse simulated galaxies using **same methods as observers use**, inferred gas rotational velocities are biased towards the presence of a 'core', even when the galaxy truly hosts a 'cusp'.

Diversity of dwarf rotation curves: status

- ✦ No existing model can reproduced the full diversity of observed dwarf rotation curve shapes

- ✦ Observations suggest baryons are negligible in ‘cuspy’ galaxies, and dominant in ‘cored’ galaxies. No existing model can reproduce this trend.

- ✦ Simulations suggest that gas rotational velocities measured near the centres of galaxies are affected by non-circular motions. Therefore, rotation curves derived from HI data do not follow the true circular velocity, and cannot be used to infer the underlying dark matter density profile.

- ✦ The presence of non-circular motions, plus HI thick disks, biases rotation curves to look more like “cores”.

- ✦ Do real galaxies also present such ubiquitous non-circular motions? Or is this an issue with our current limited modelling of galaxies?

Diversity of dwarf rotation curves: status

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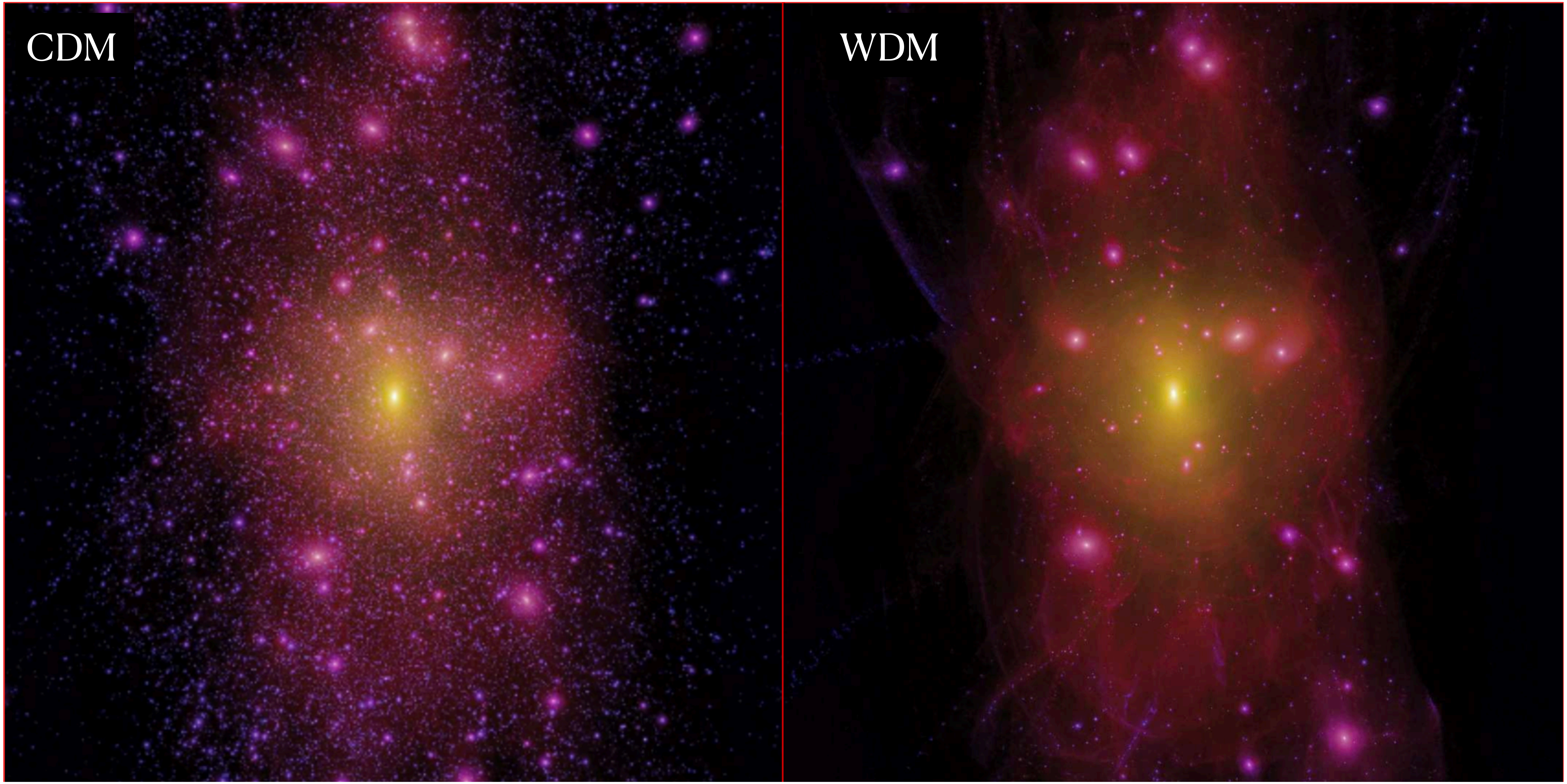
✦ The presence of non-circular motions, plus HI thick disks
more like "cores".

. If the rotation curves of observed late-type dwarfs are similarly impacted – which seems likely – a late-type dwarf population where most galaxies have DM cusps is easier to reconcile with the available data than one where most galaxies have sizeable DM cores.

✦ Do real galaxies also present such ubiquitous non-circular motions? Or is this an issue with our current limited modelling of galaxies?

Abundance of substructure

[Lovell+2014]



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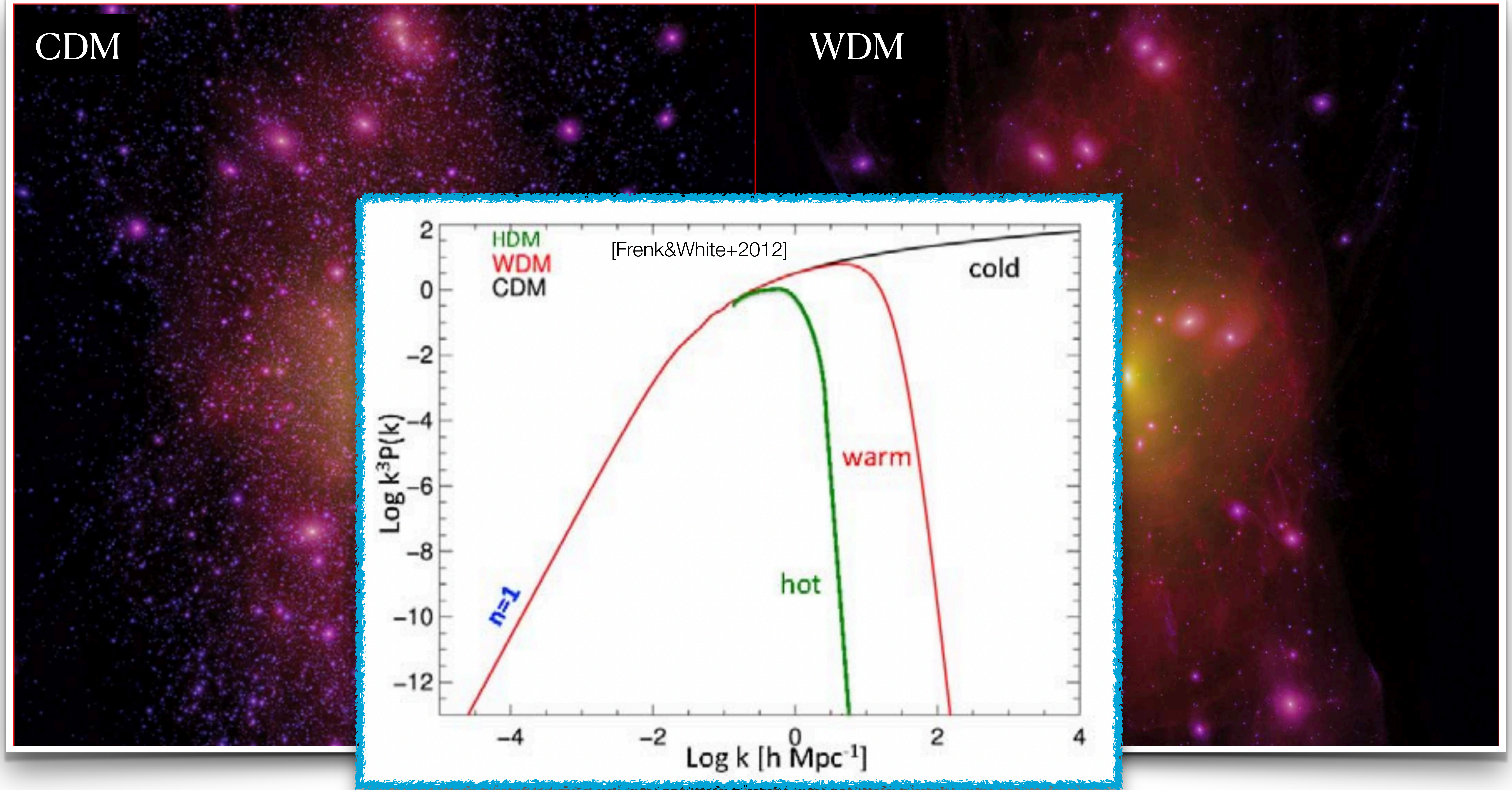

I.Santos-Santos (ICC, Durham)

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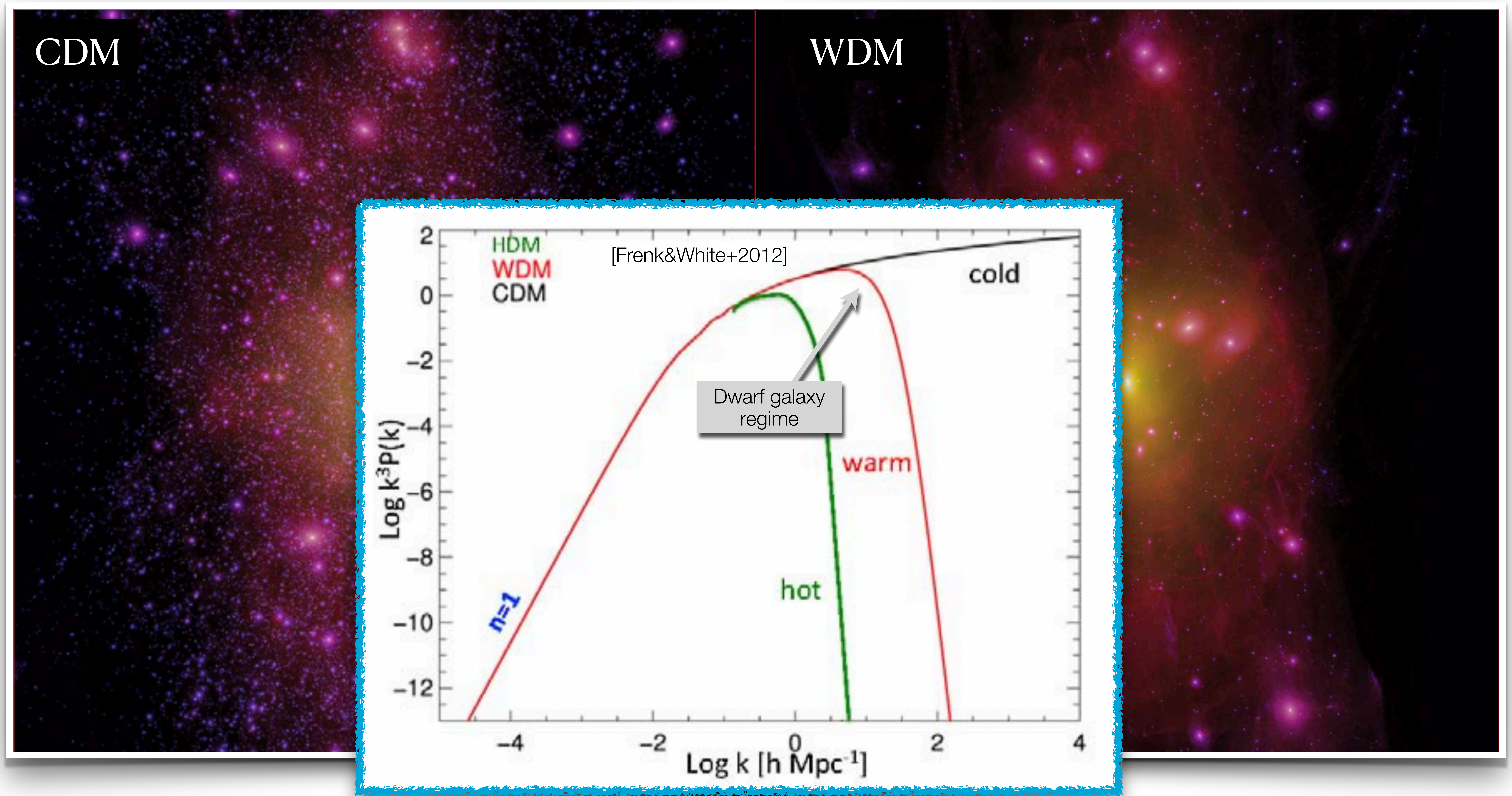

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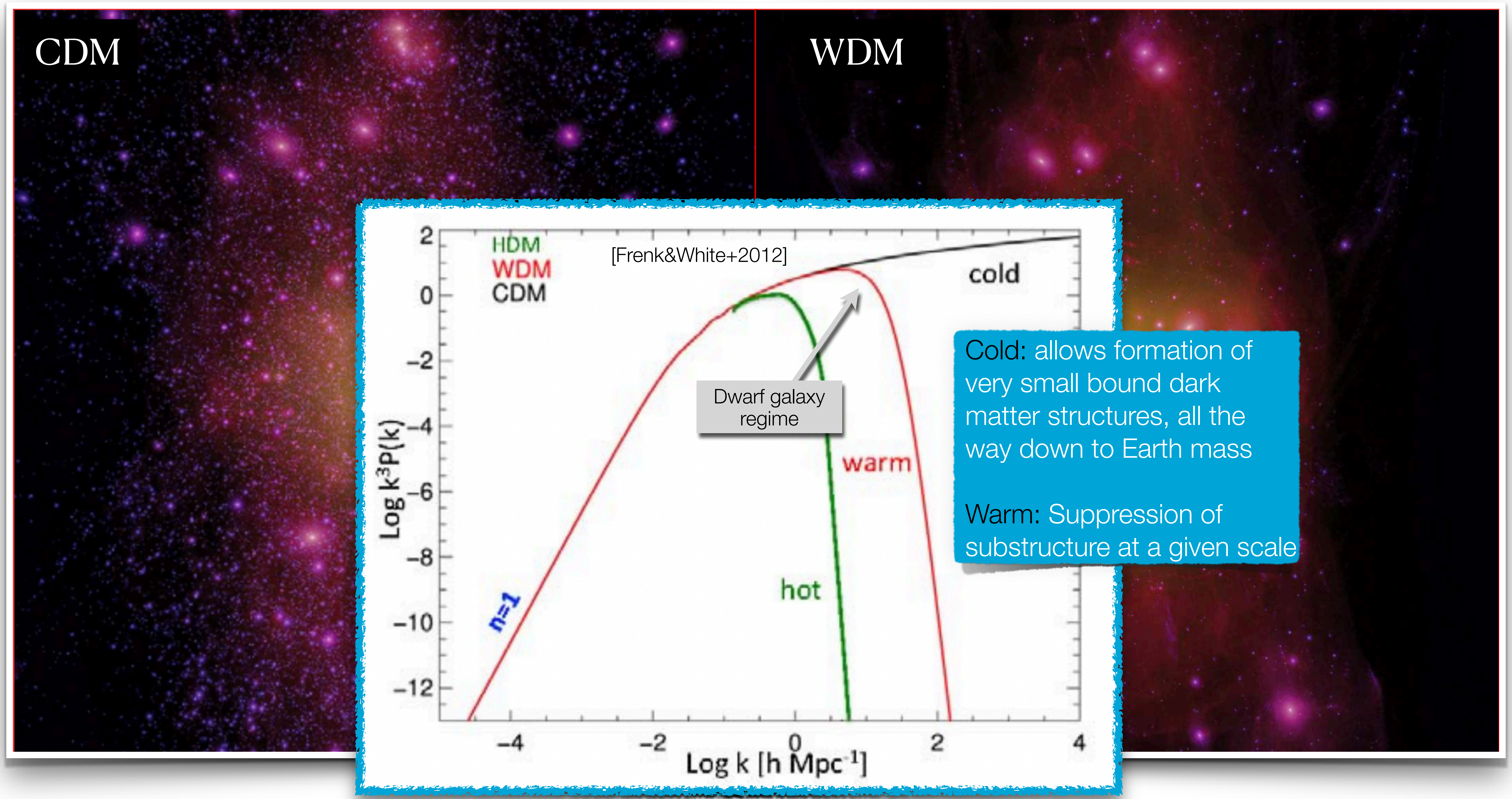


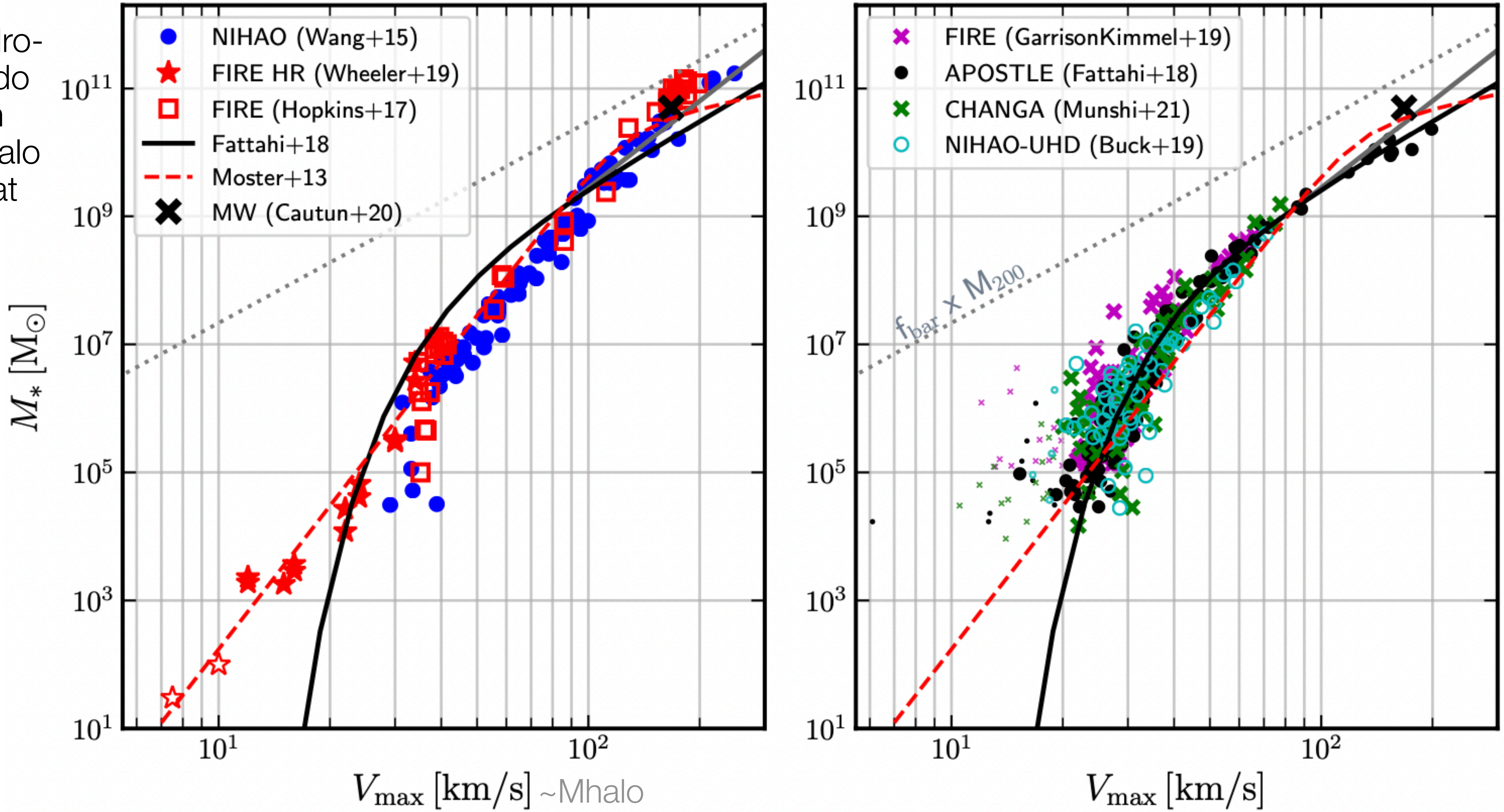
Cold: allows formation of very small bound dark matter structures, all the way down to Earth mass

Warm: Suppression of substructure at a given scale

M_{star}-M_{halo} in the low-mass end

[Santos-Santos+2022]

Different hydro-simulations do not agree on the galaxy-halo connection at low masses



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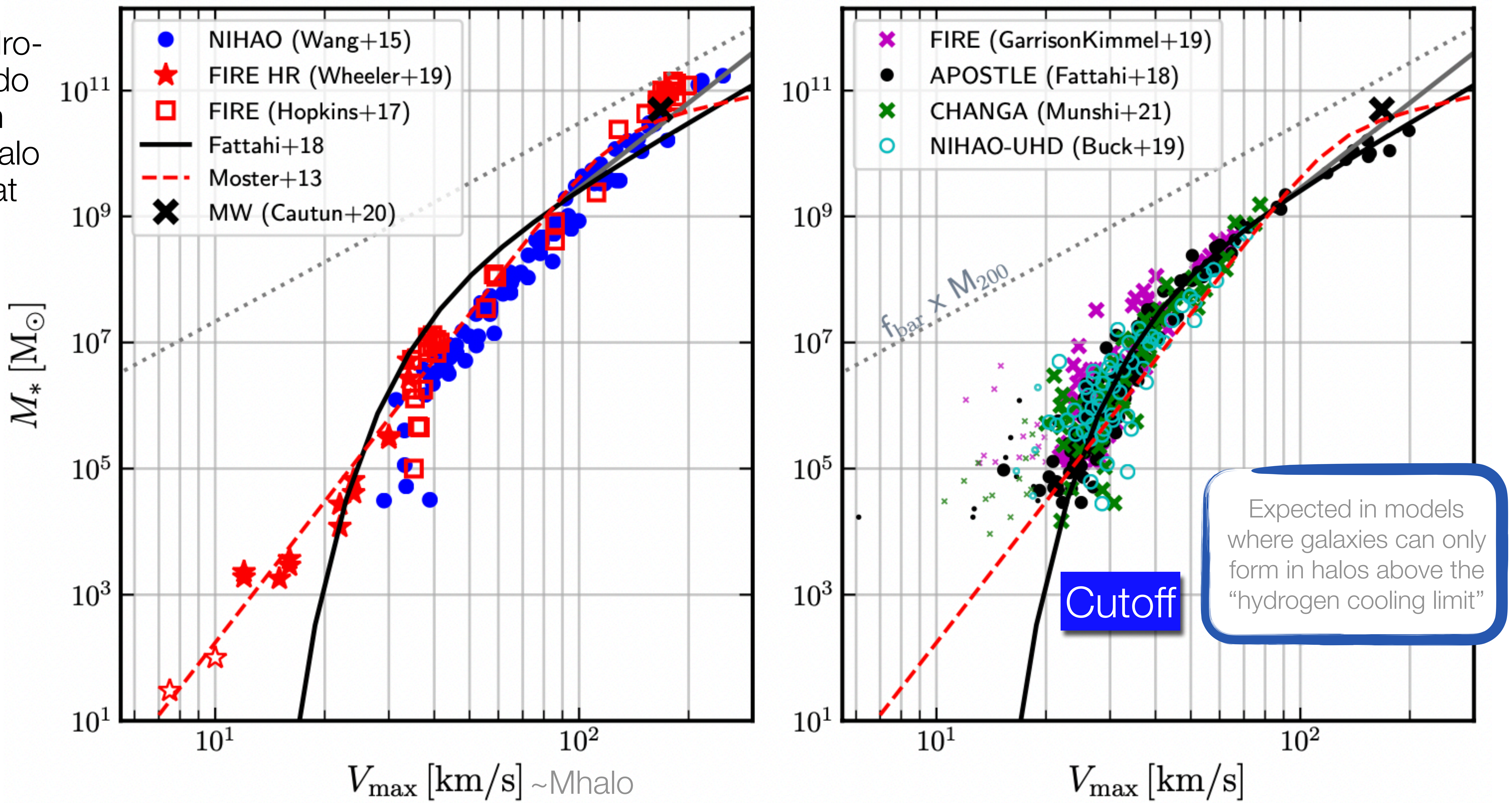

[Okamoto&Frenk09; Benitez-Llambay&Frenk+20]

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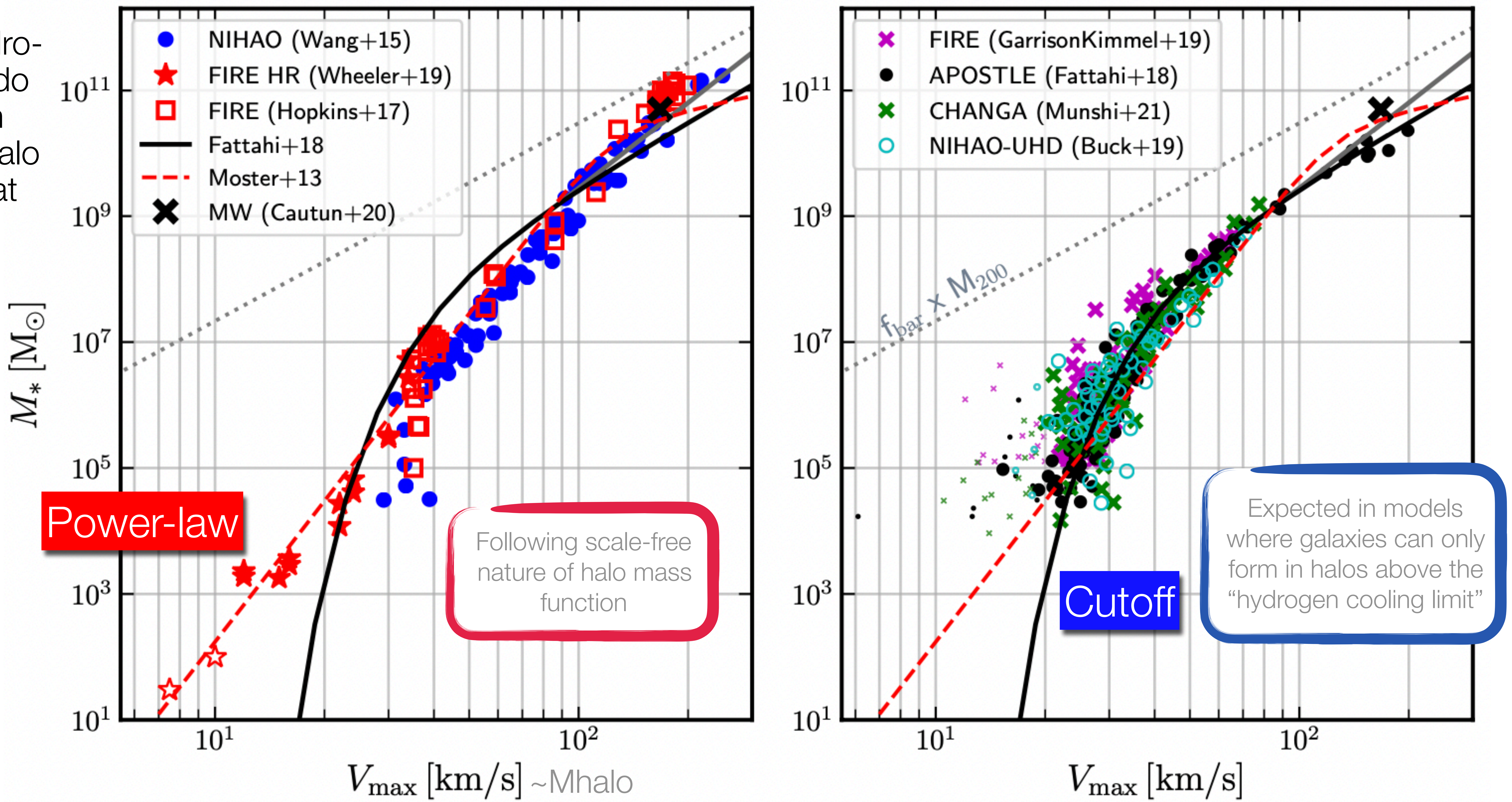

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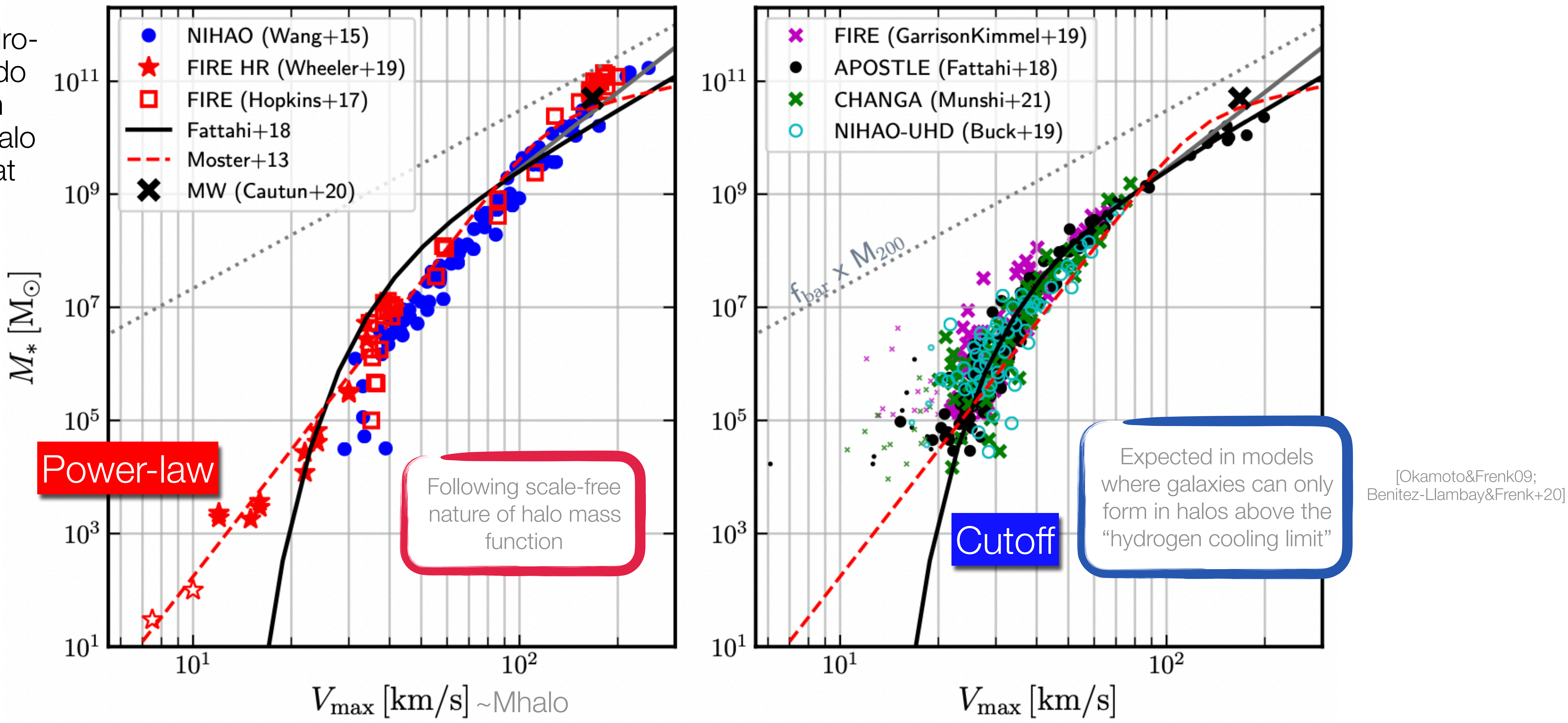

CDM subhalo mass function + M*-Mhalo relation w/ scatter = Satellite luminosity function

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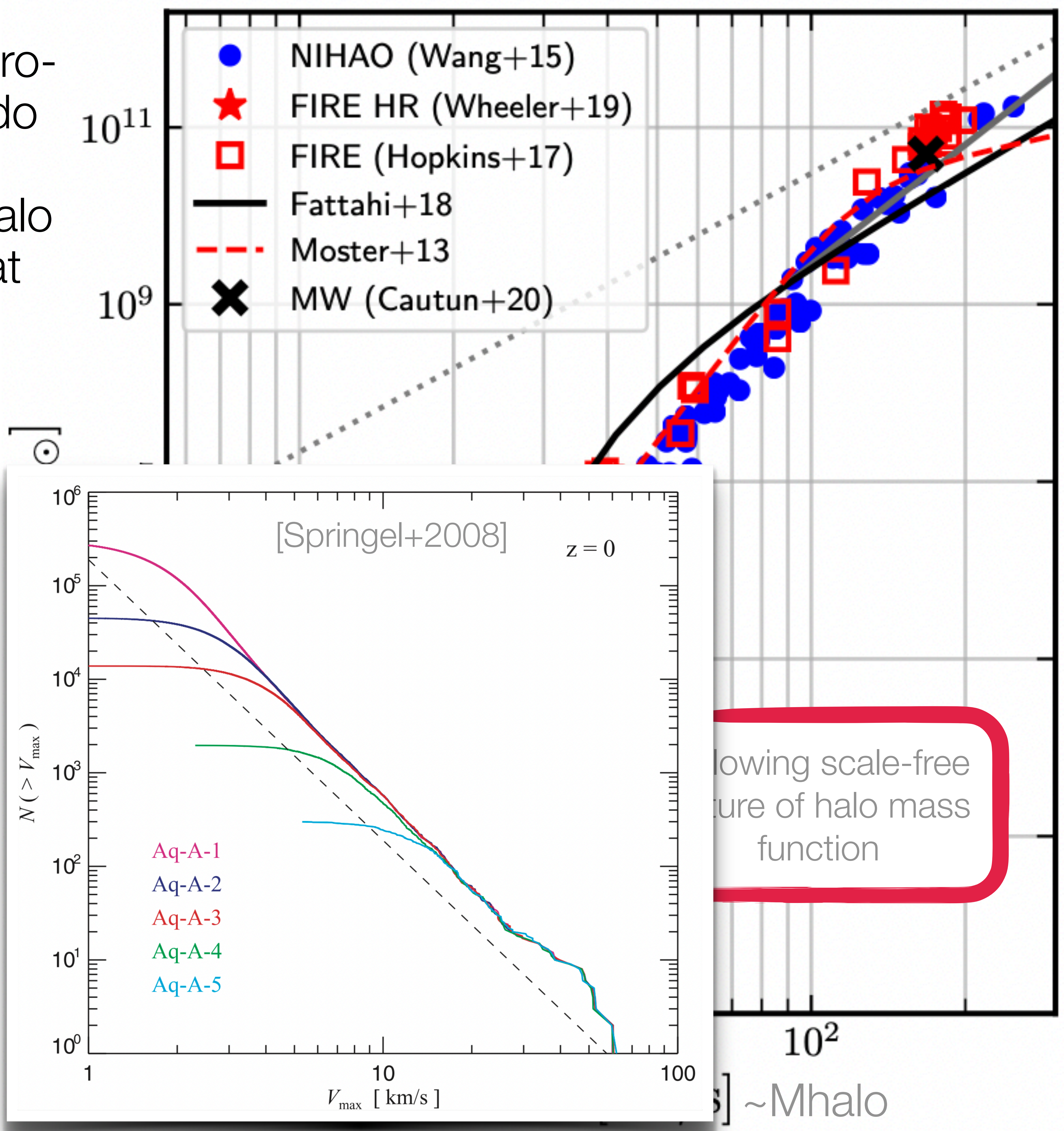
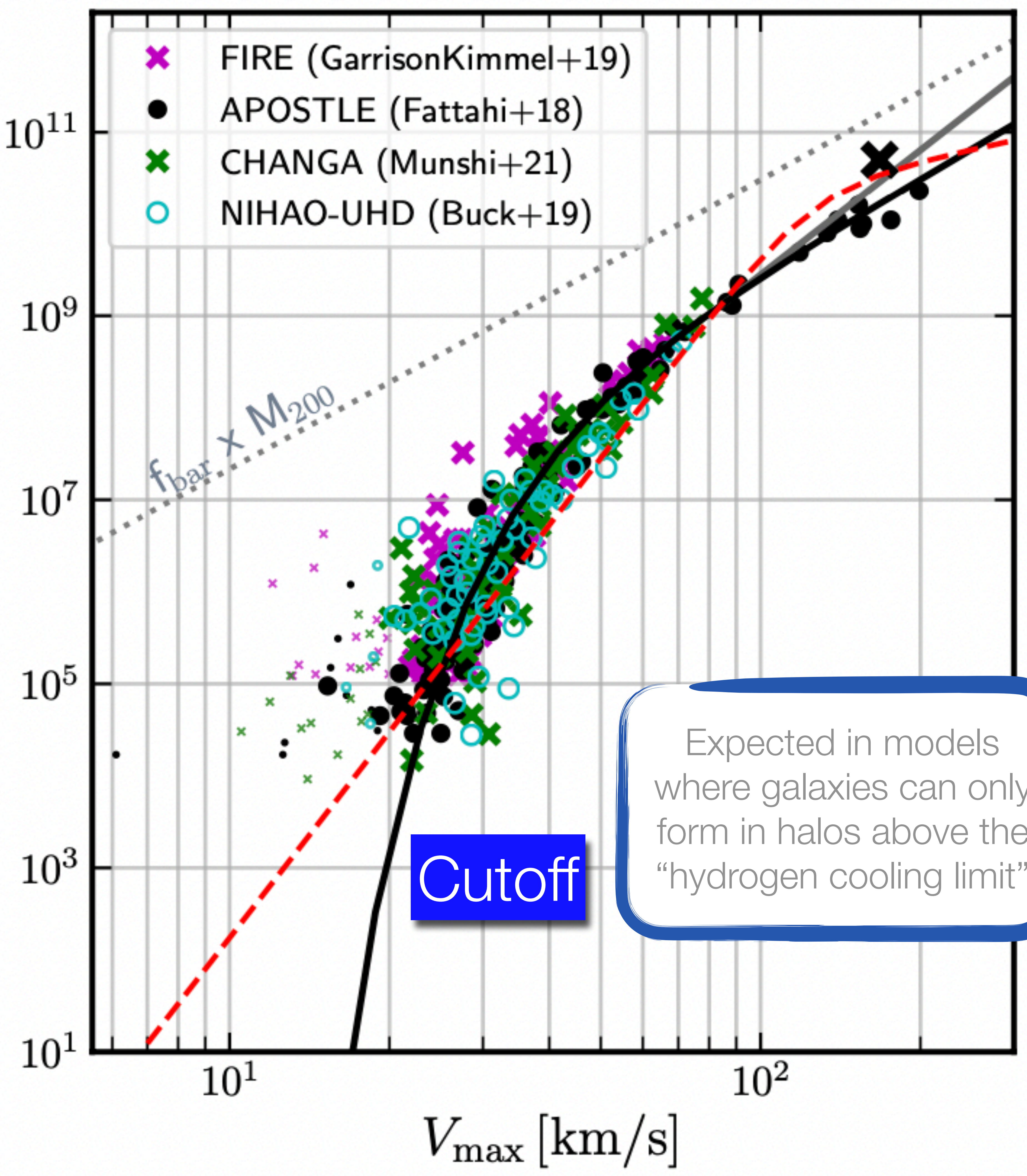


…lowing scale-free …ure of halo mass function

…] ~Mhalo



Cutoff

Expected in models where galaxies can only form in halos above the "hydrogen cooling limit"

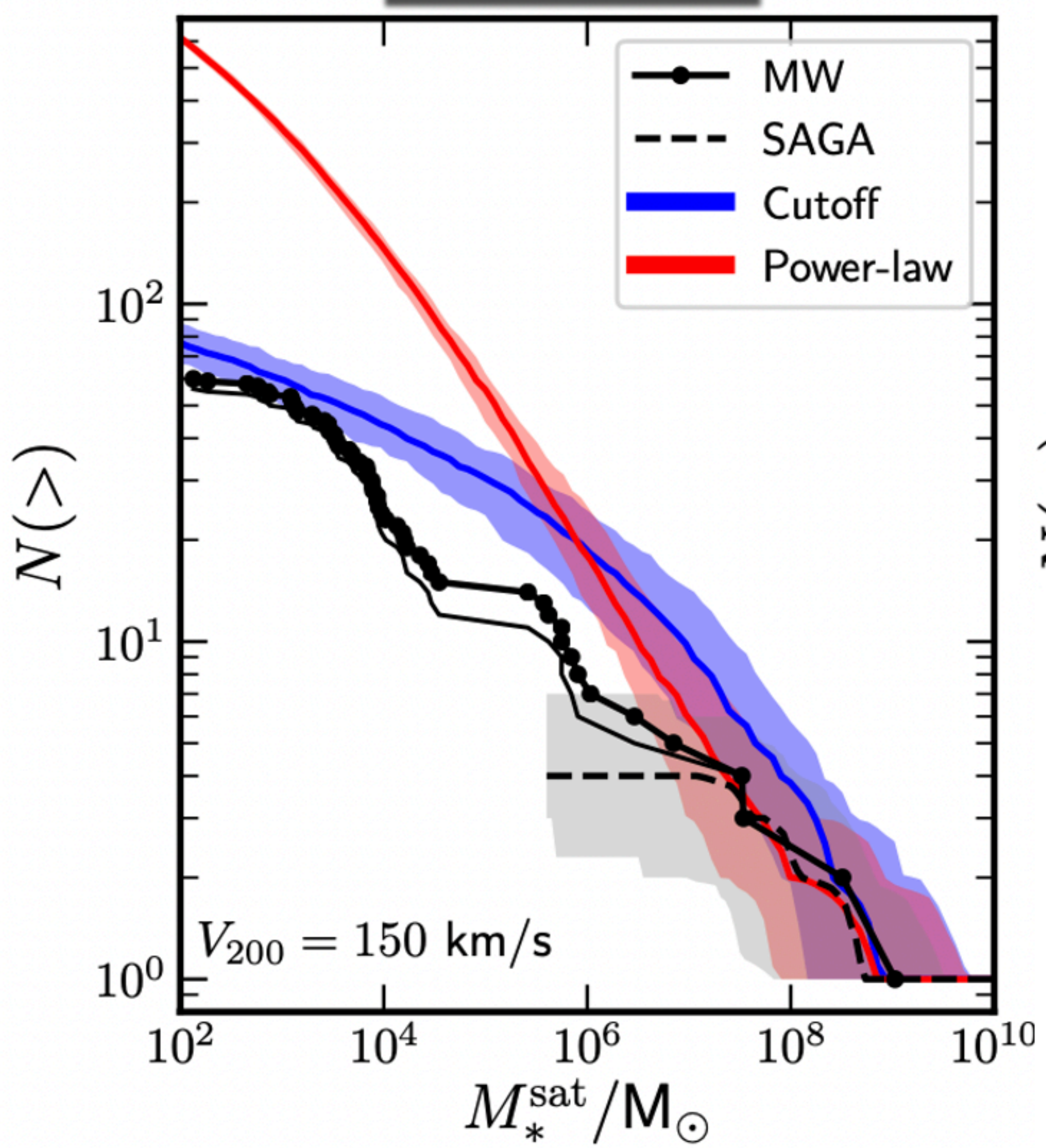
[Okamoto&Frenk09; Benitez-Llambay&Frenk+20]

CDM subhalo mass function + M*-Mhalo relation w/ scatter = Satellite luminosity function

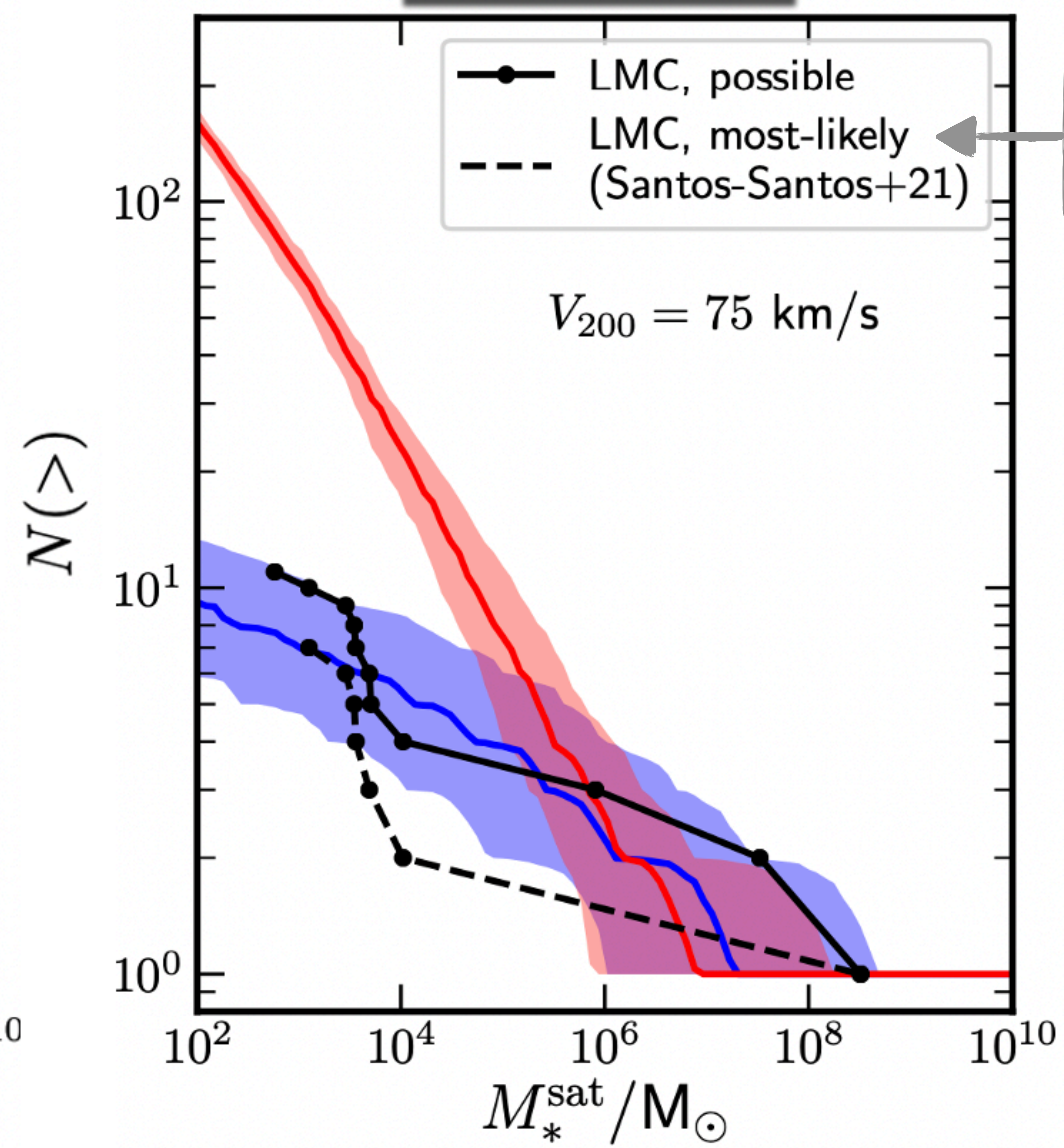
M_{star}-M_{halo} in the low-mass end

[Santos-Santos+2022]

MW-mass host



LMC-mass host

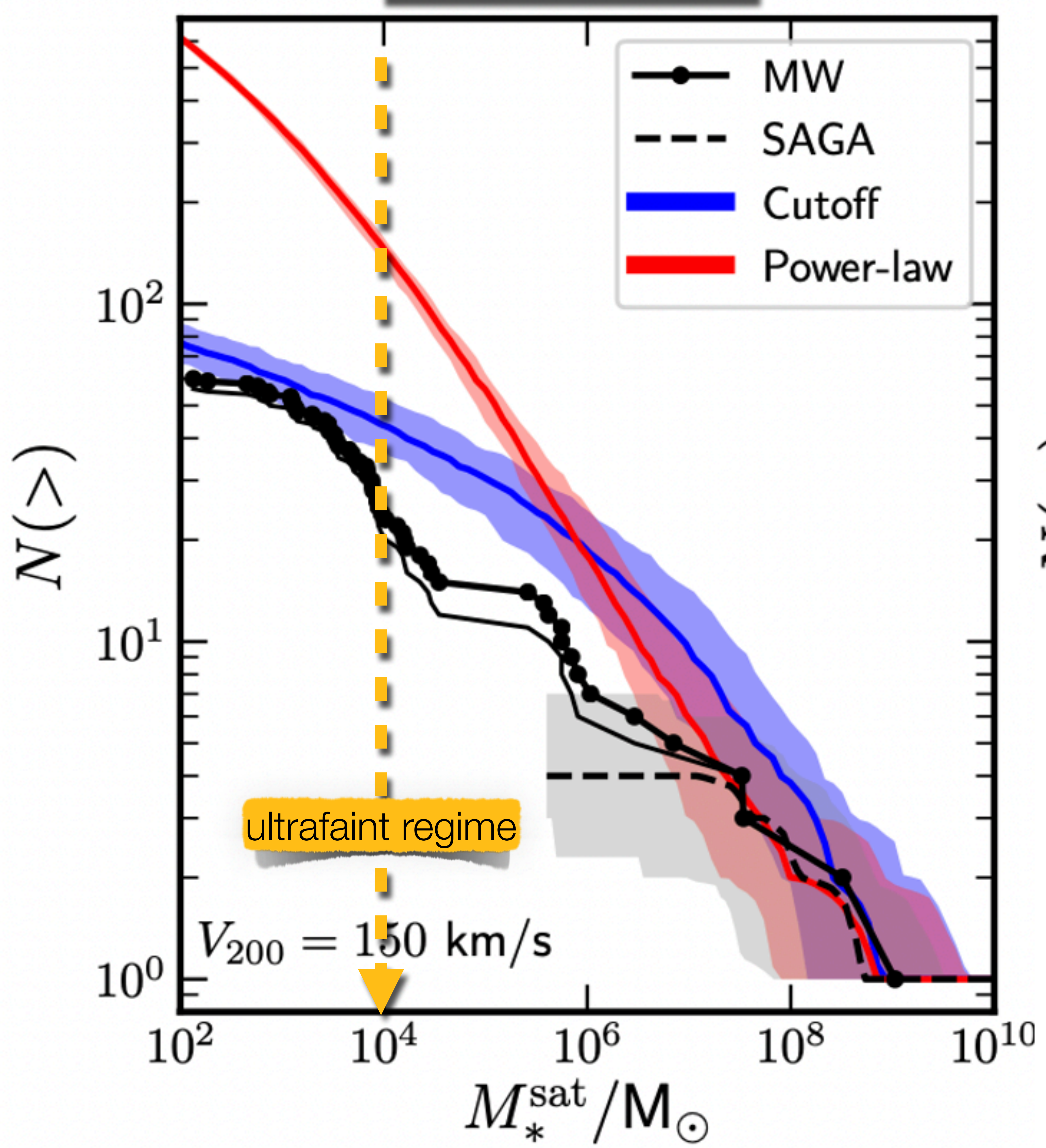


Estimates of which MW satellites were contributed by LMC

M_{star}-M_{halo} in the low-mass end

[Santos-Santos+2022]

MW-mass host



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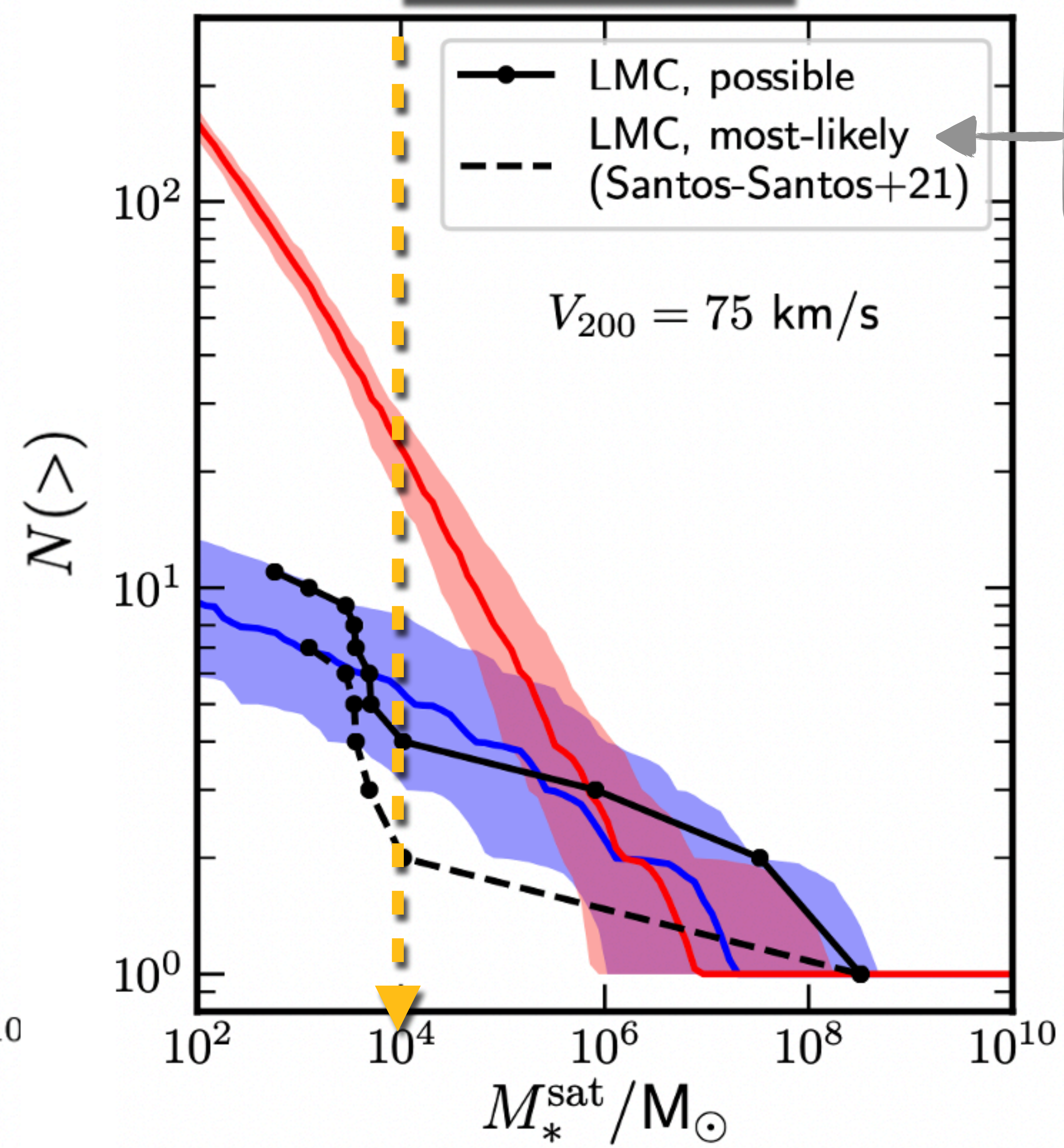

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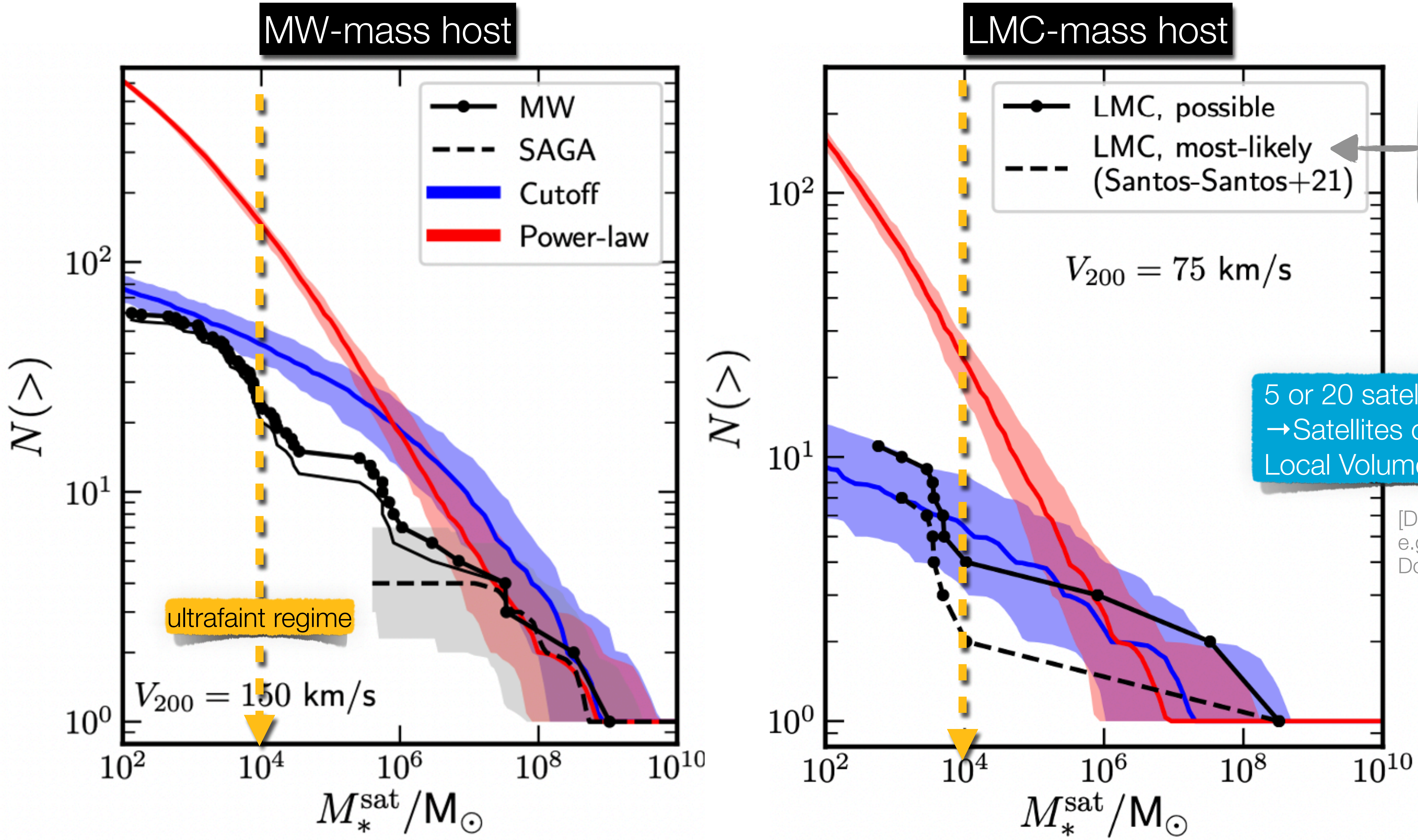


Estimates of which MW satellites were contributed by LMC

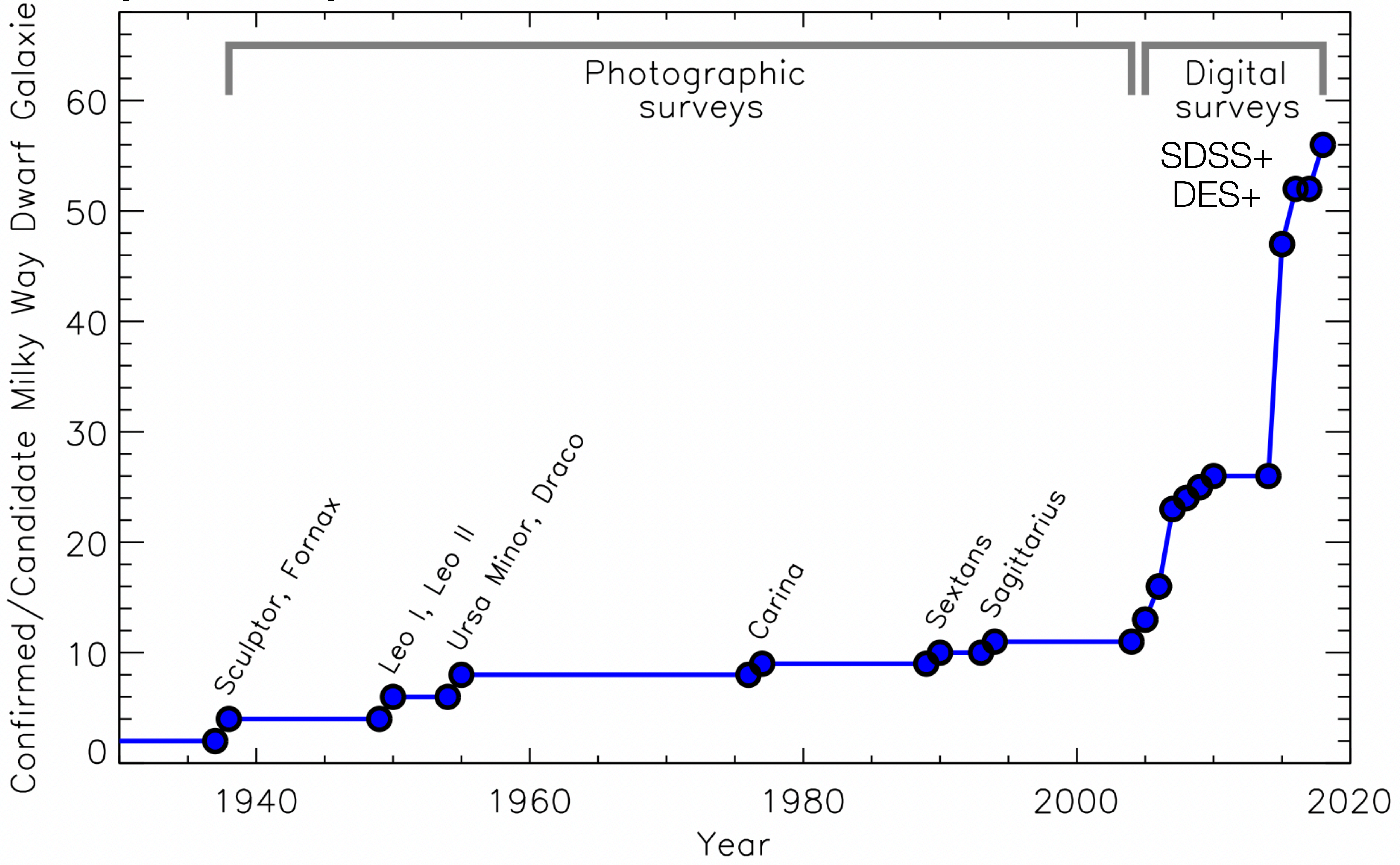
5 or 20 satellites?
→Satellites of Dwarfs in the Local Volume are promising

[DELVE-DEEP survey, e.g. Medoff+2025, Doliva-Dolinsky+2025]

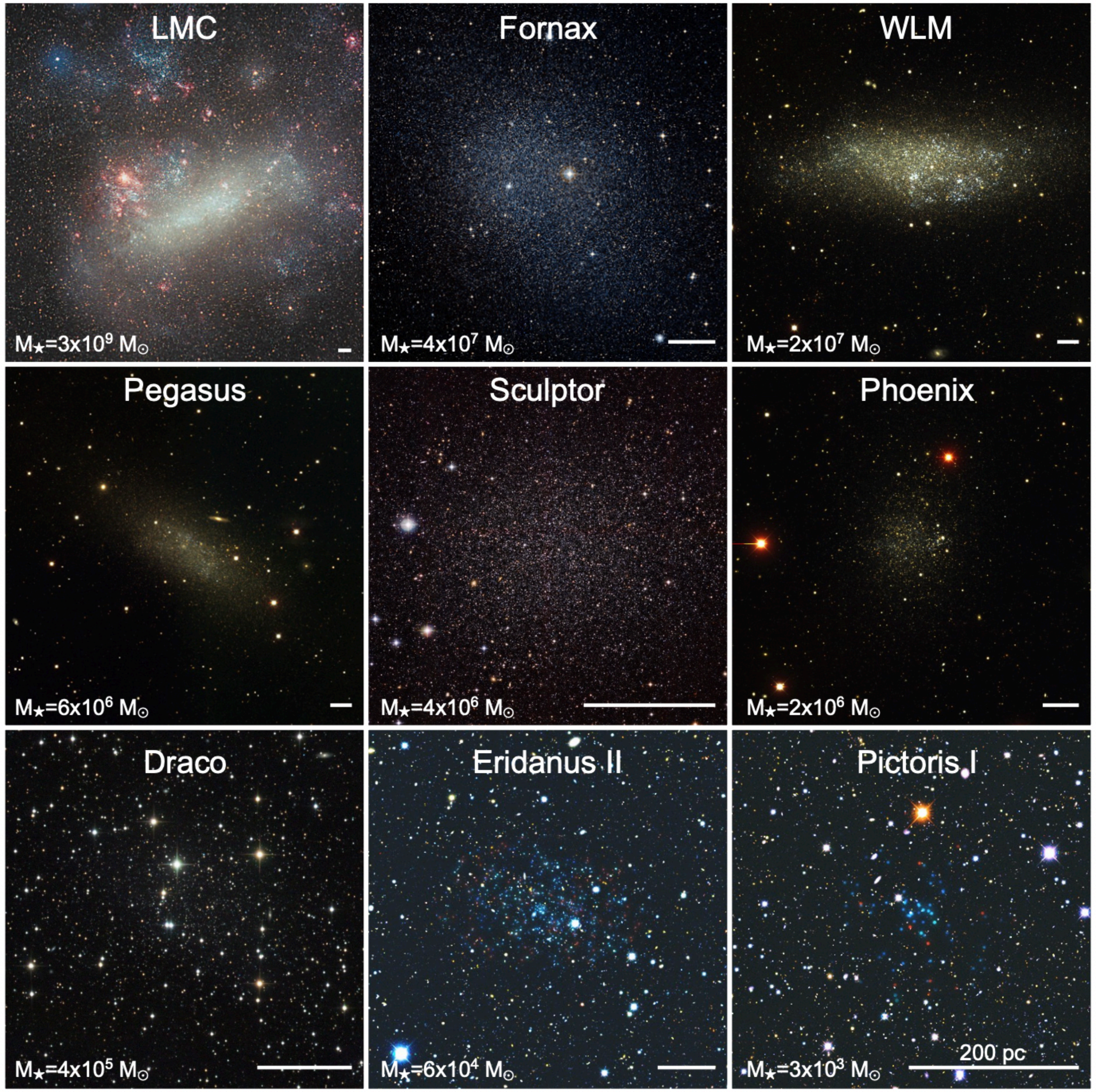
M_{star}-M_{halo} in the low-mass end: status

- Hydrodynamical models do not agree on the galaxy-halo connection on the low-mass end.
- Whatever assumption is chosen will have a strong impact on the predicted satellite luminosity function.
- Observations of satellites around massive dwarfs could help discriminate between Mstar-Mhalo models.
- Remaining caveats: Different dark matter models predict different underlying subhalo mass functions (CDM vs WDM) precisely in the dwarf regime of interest here.
- **What are the physical mechanisms driving galaxy formation in the smallest halos?** E.g. Impact of the photoionizing background / atomic hydrogen cooling dominates, or molecular cooling is also important? / Lyman-Werner radiation can dissociate molecular gas?

Abundance and densities of MW satellites



[Bullock&Boylan-Kolchin+2017]



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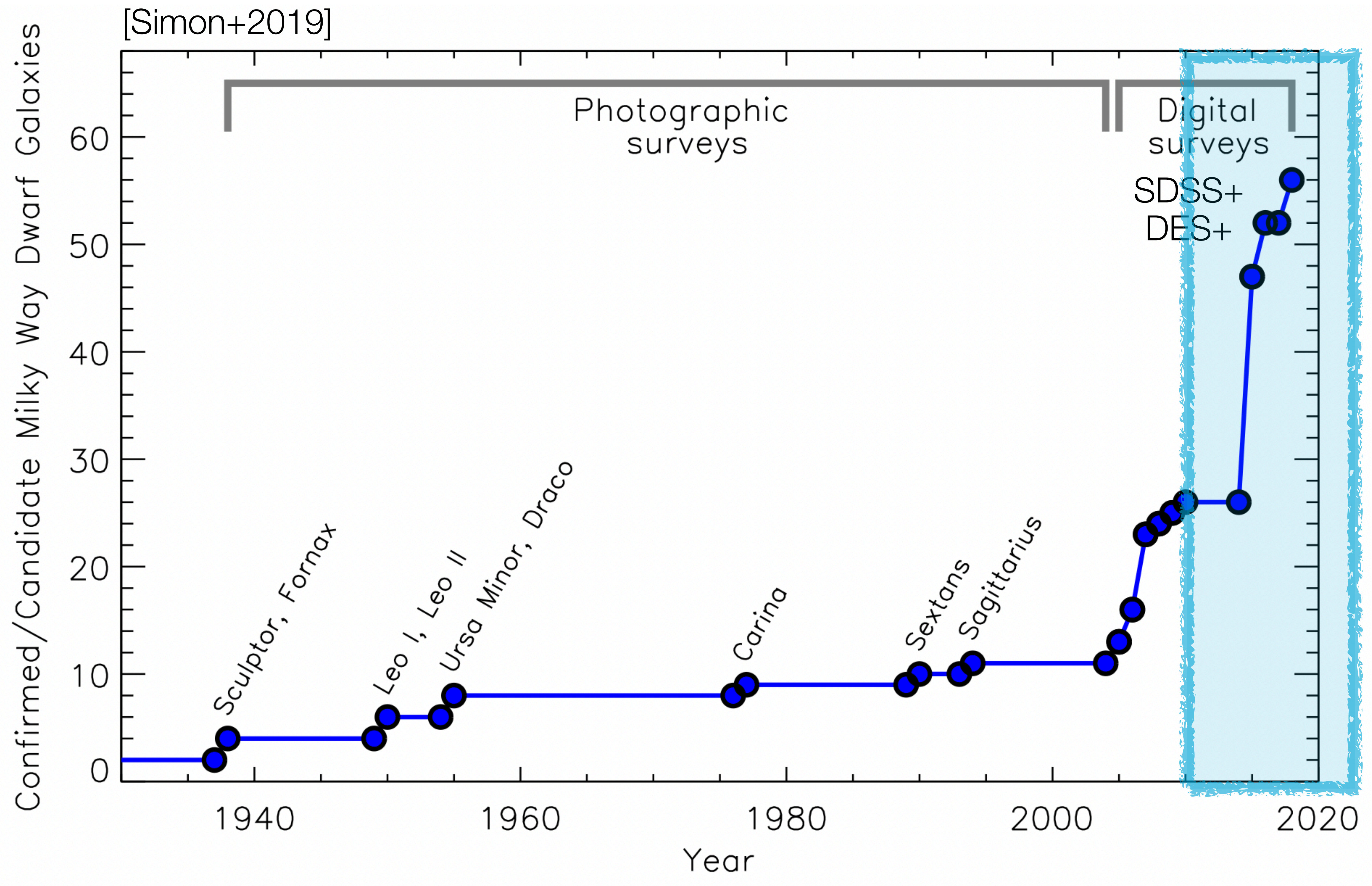

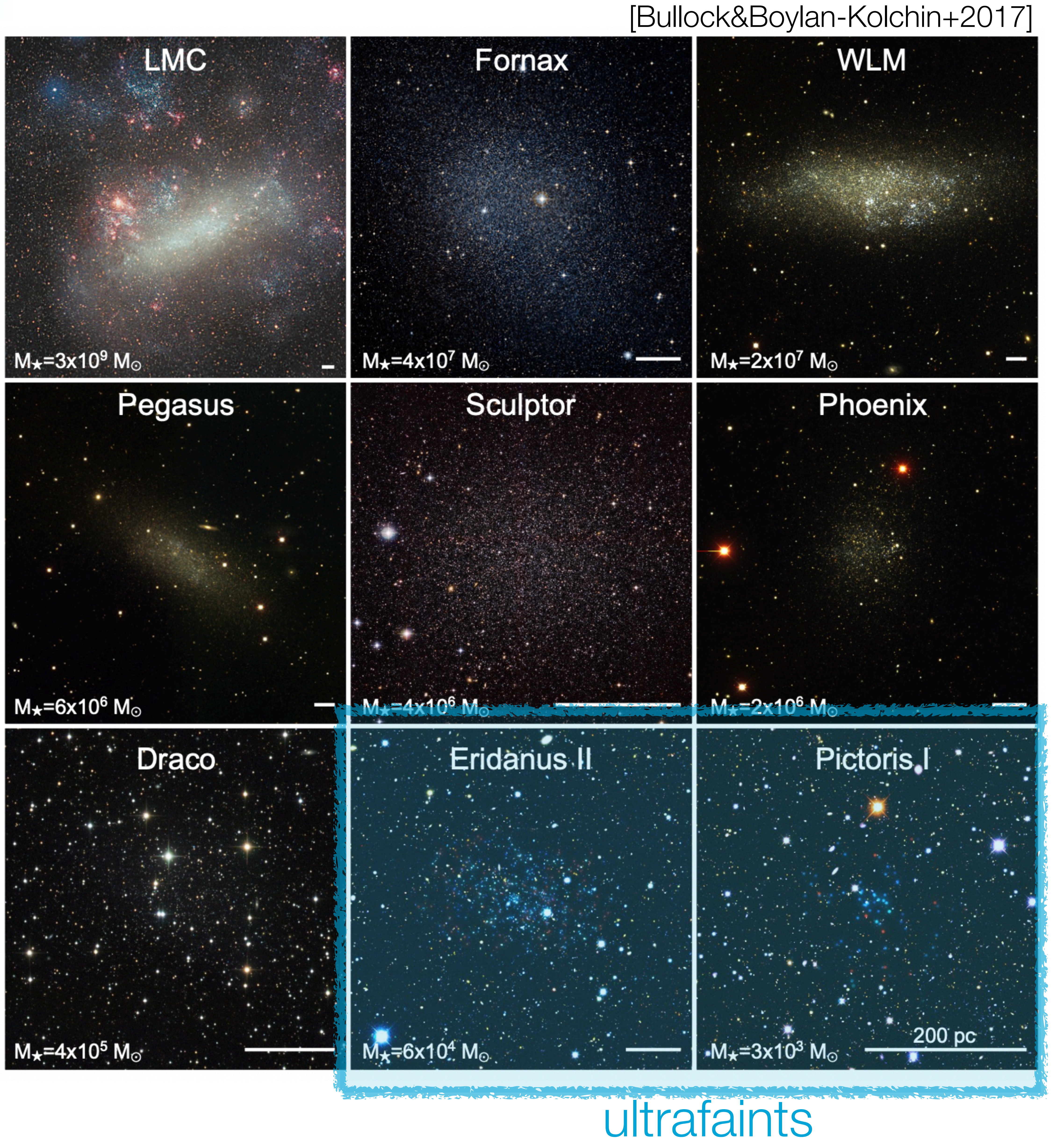

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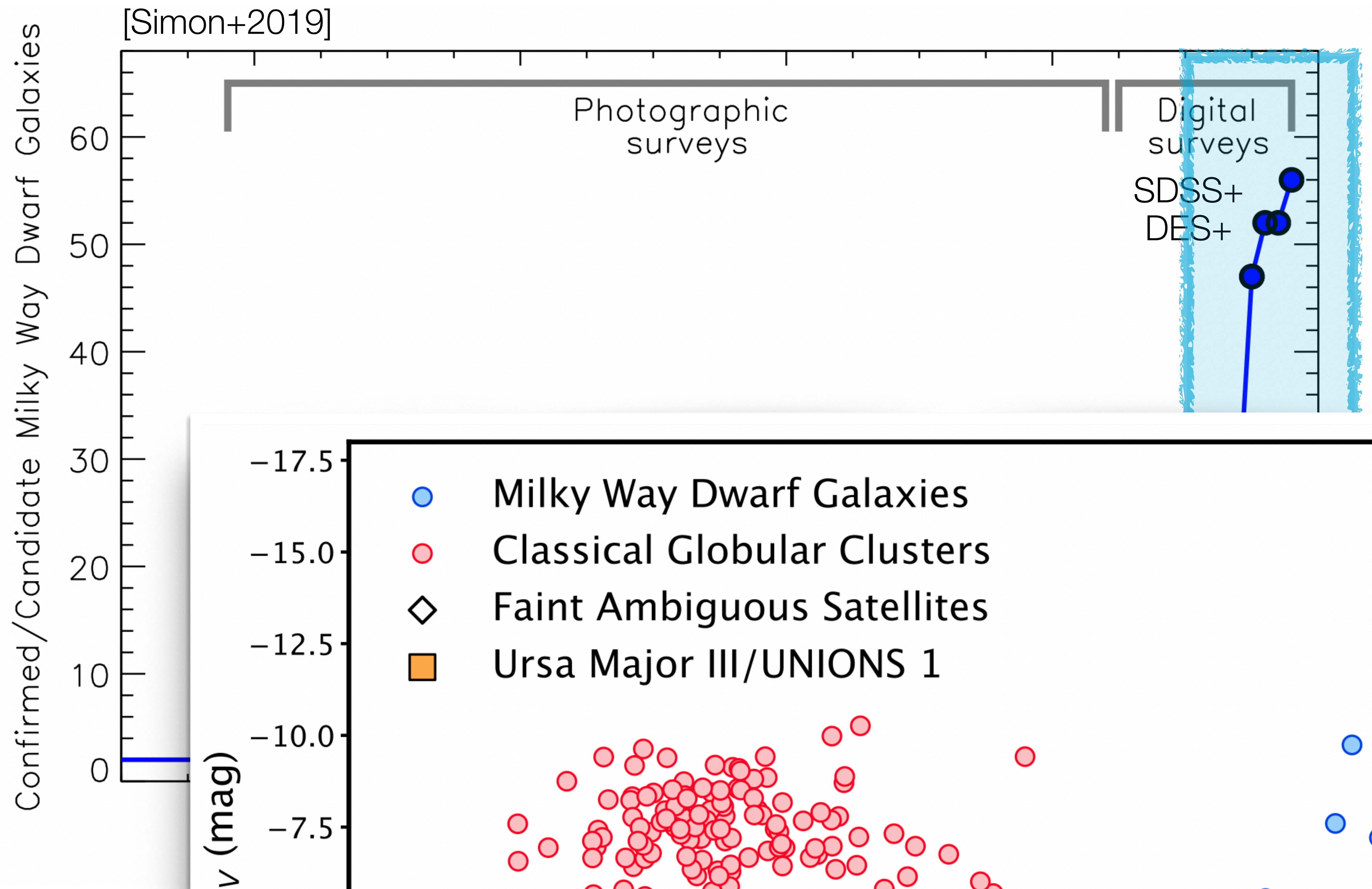

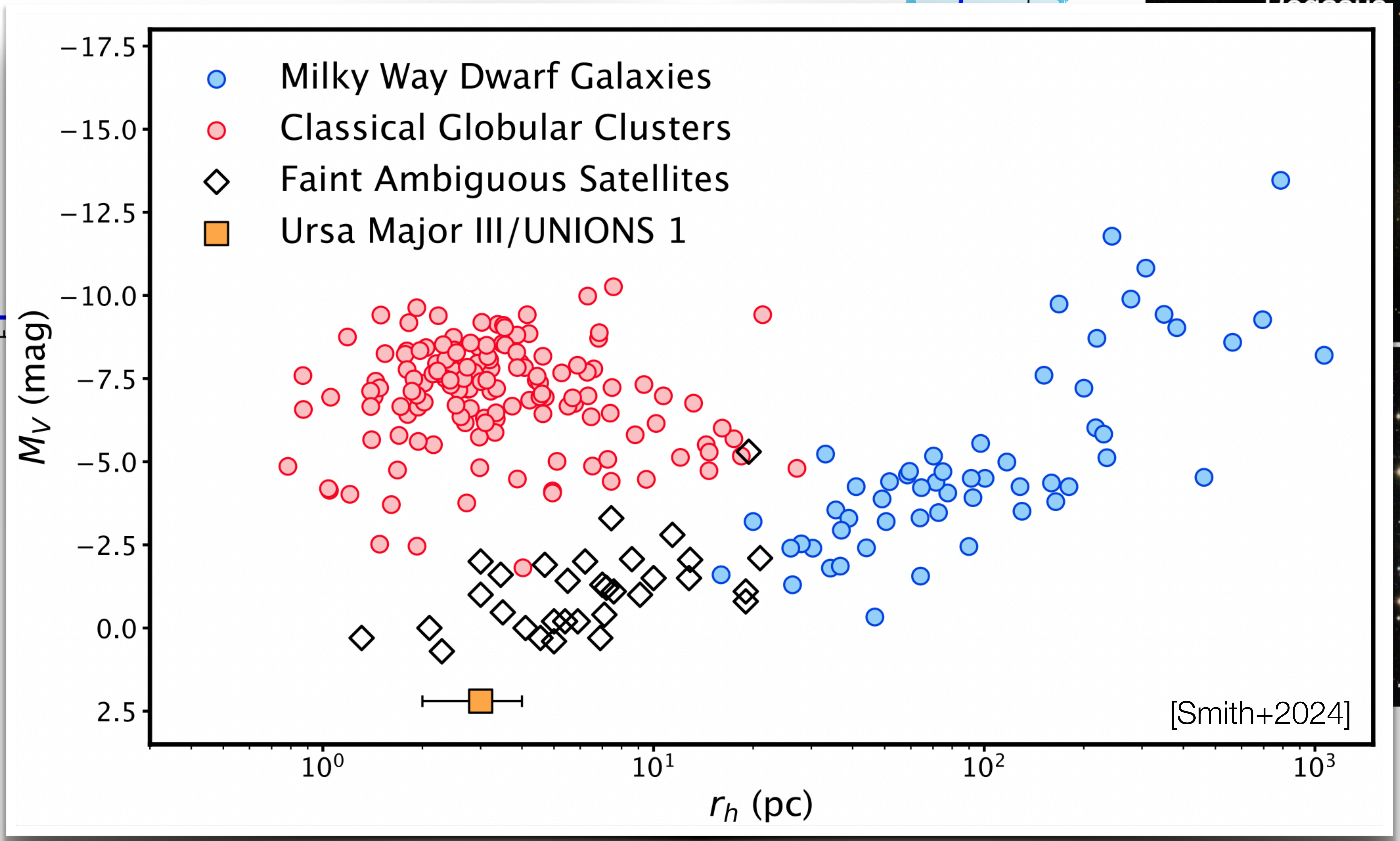

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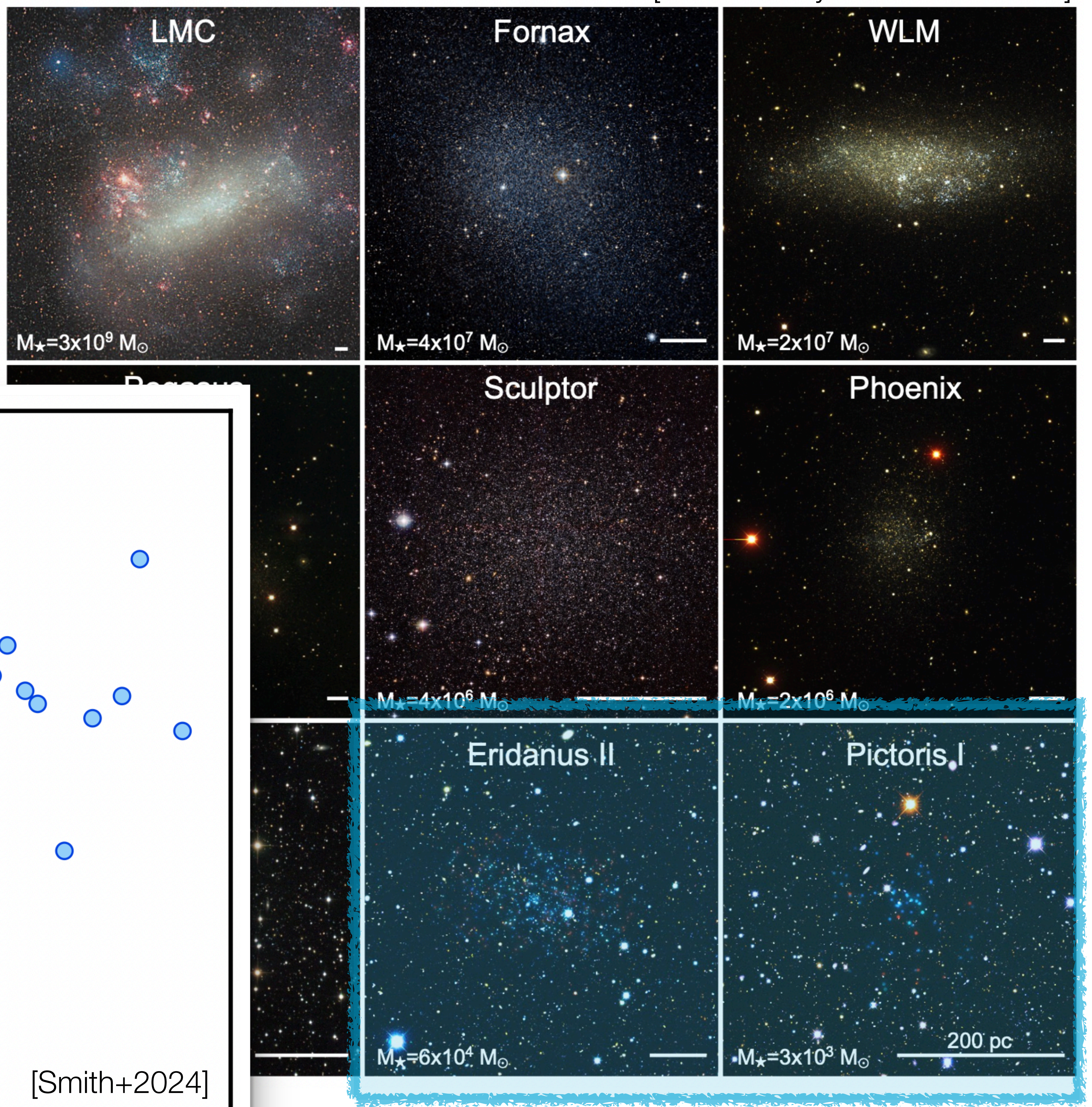
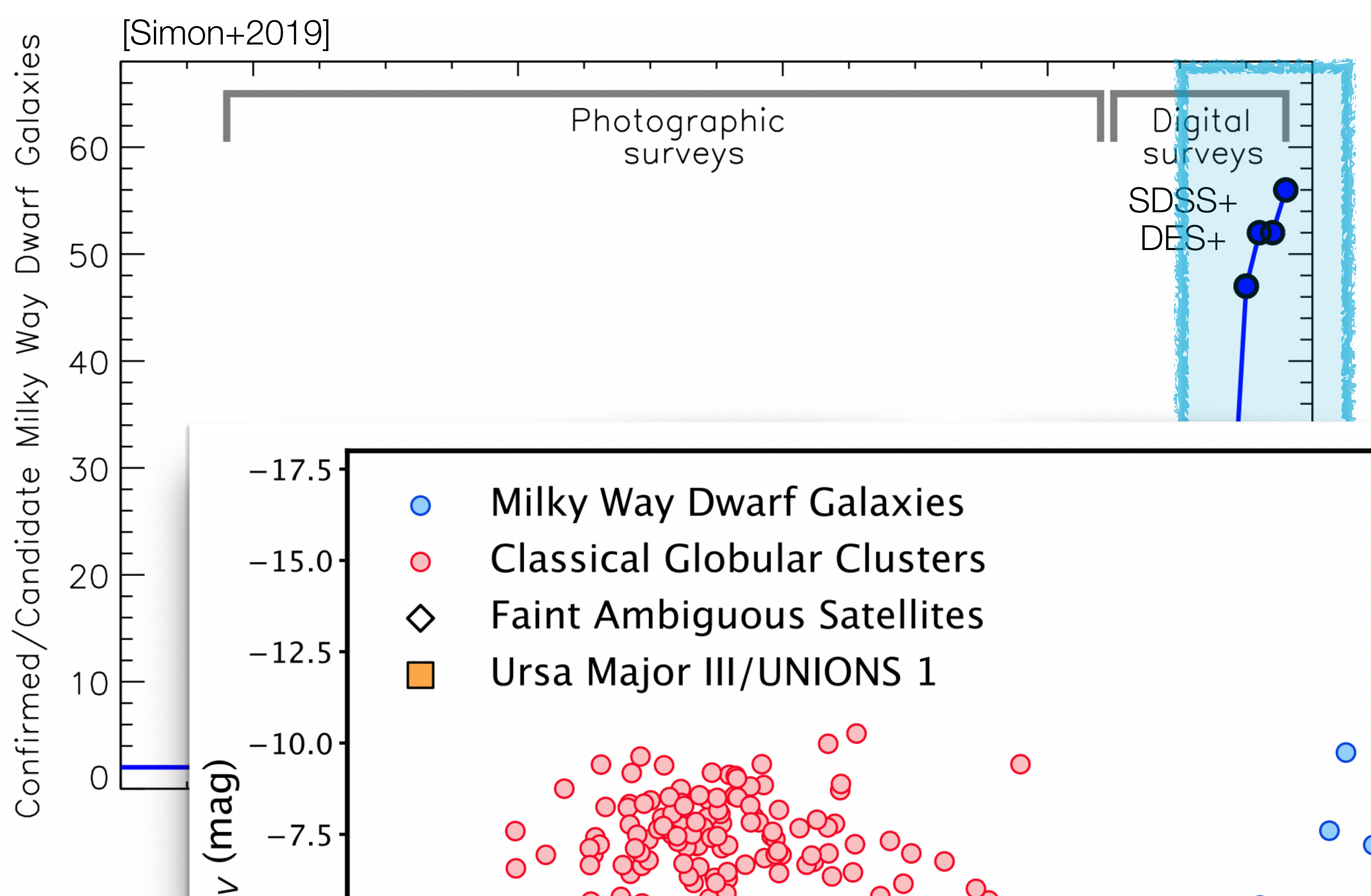
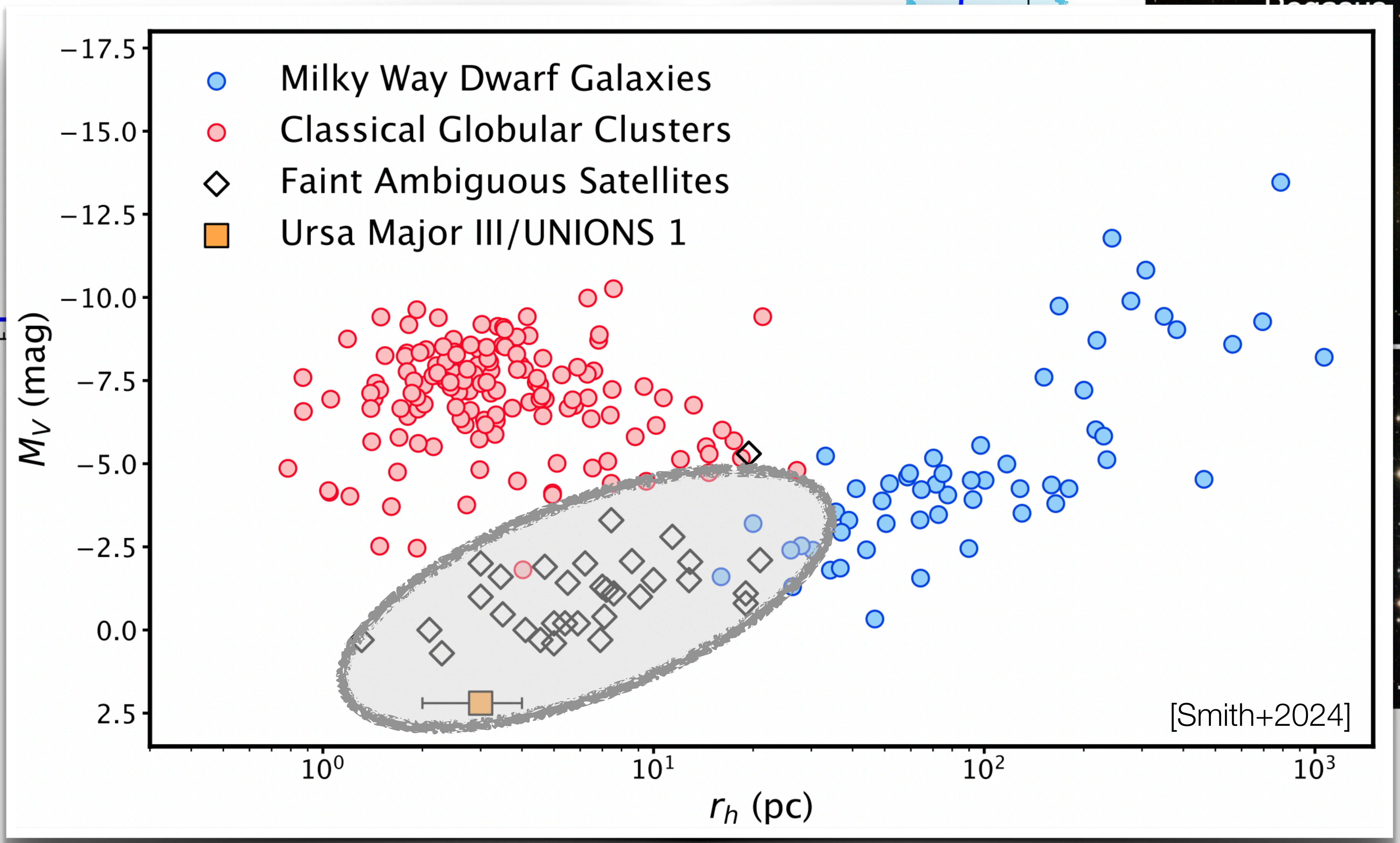
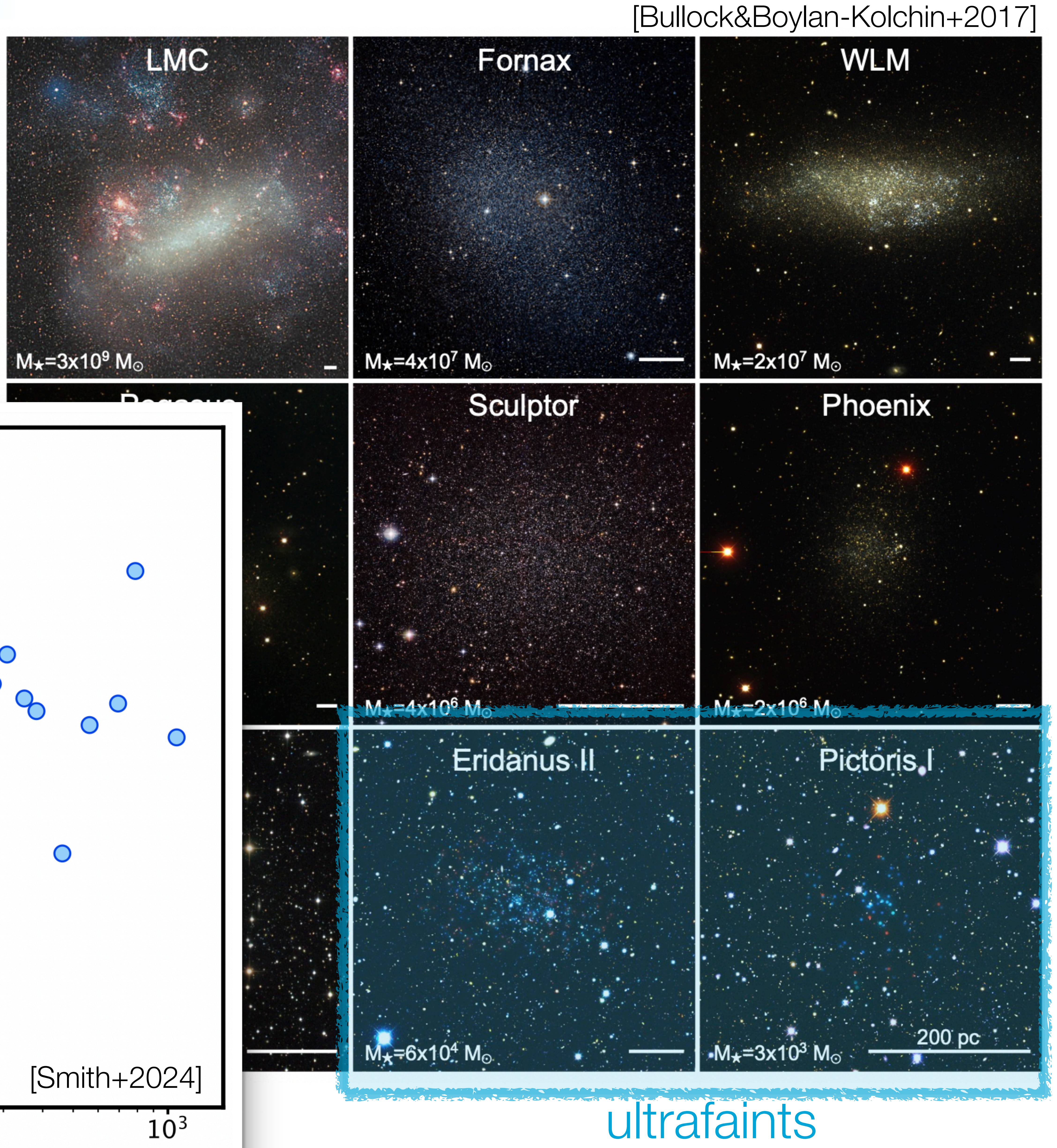


ultrafaints

Abundance and densities of MW satellites







Credit: Daniel Boyea / Gaia

Abundance and densities of MW satellites

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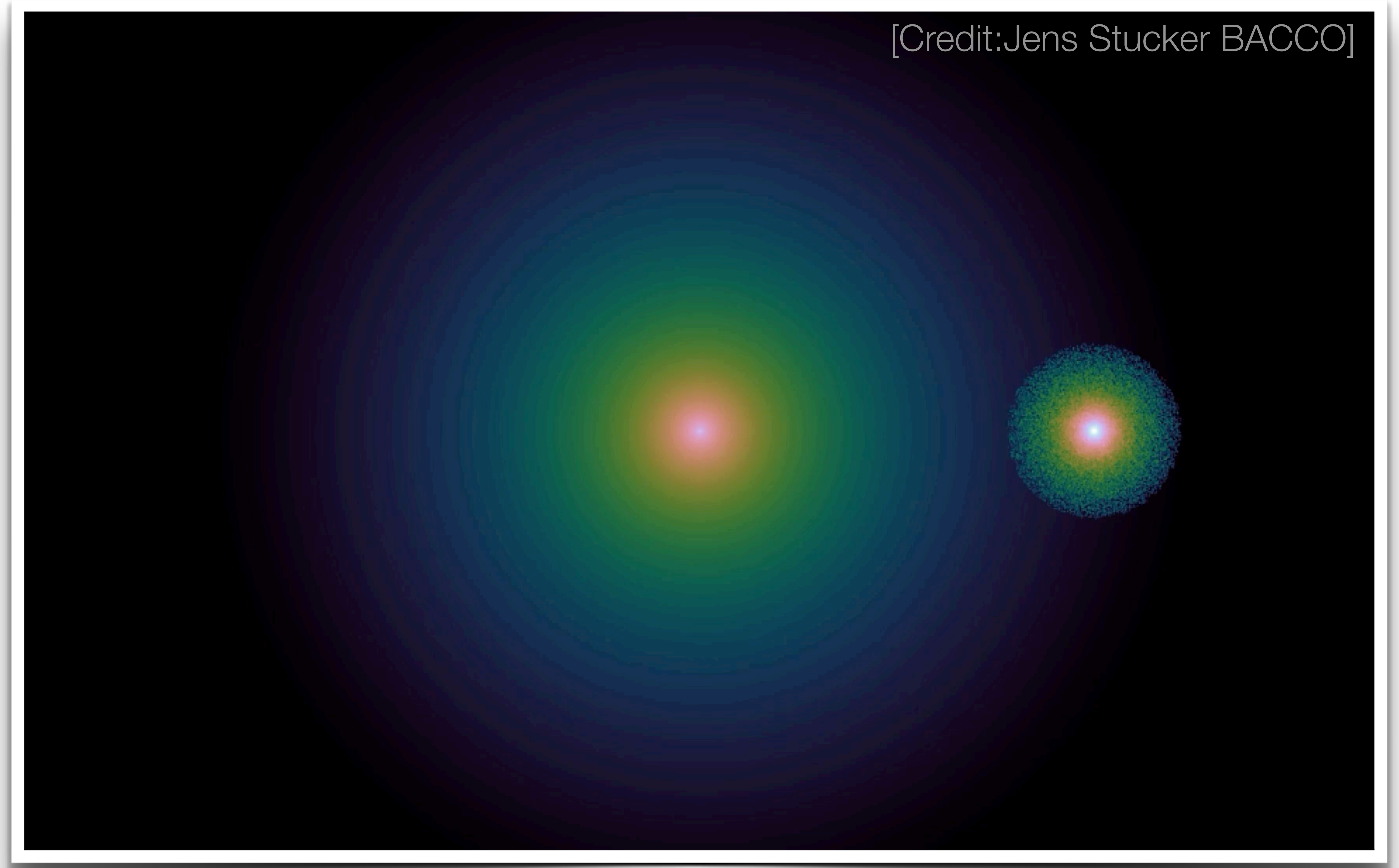
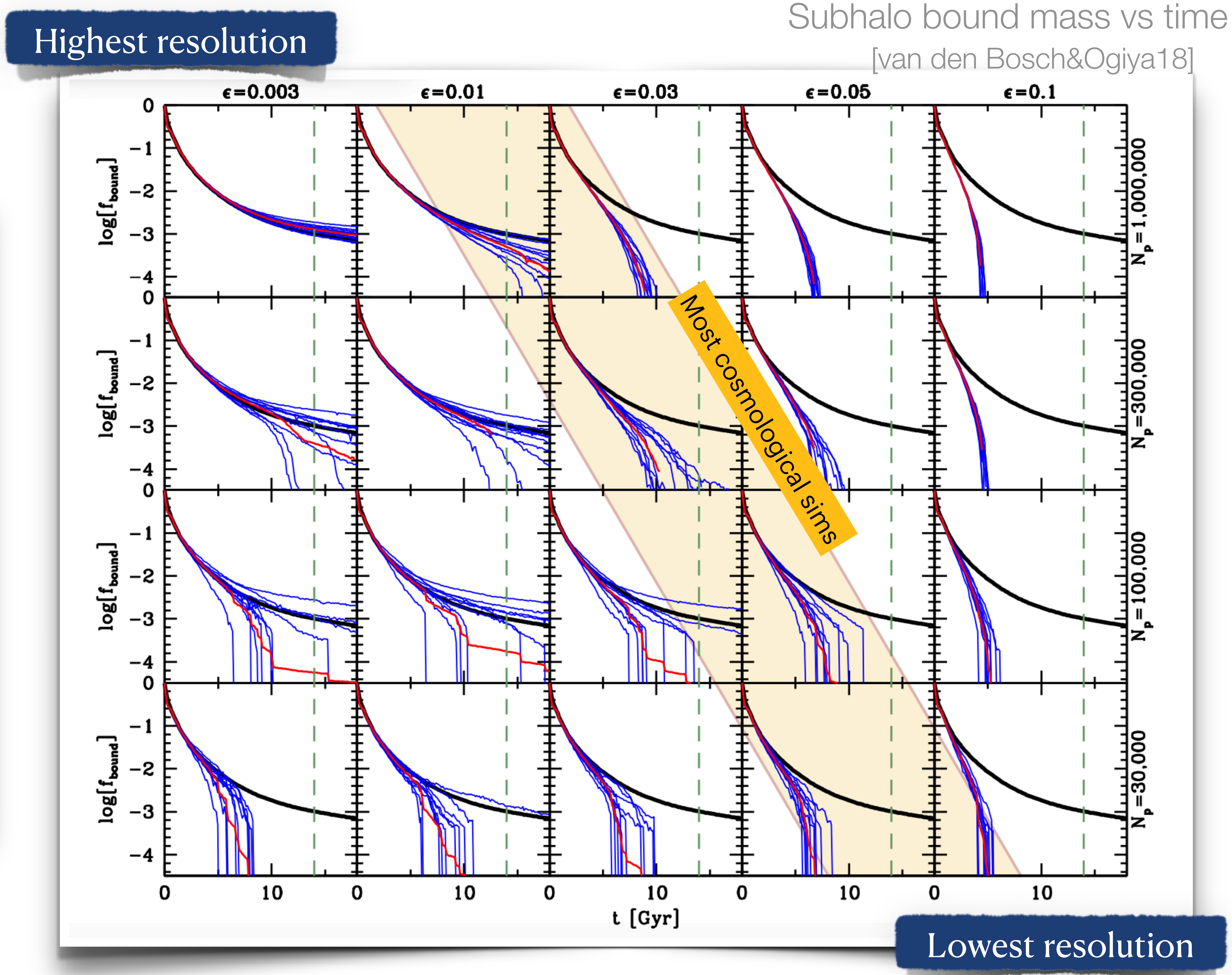


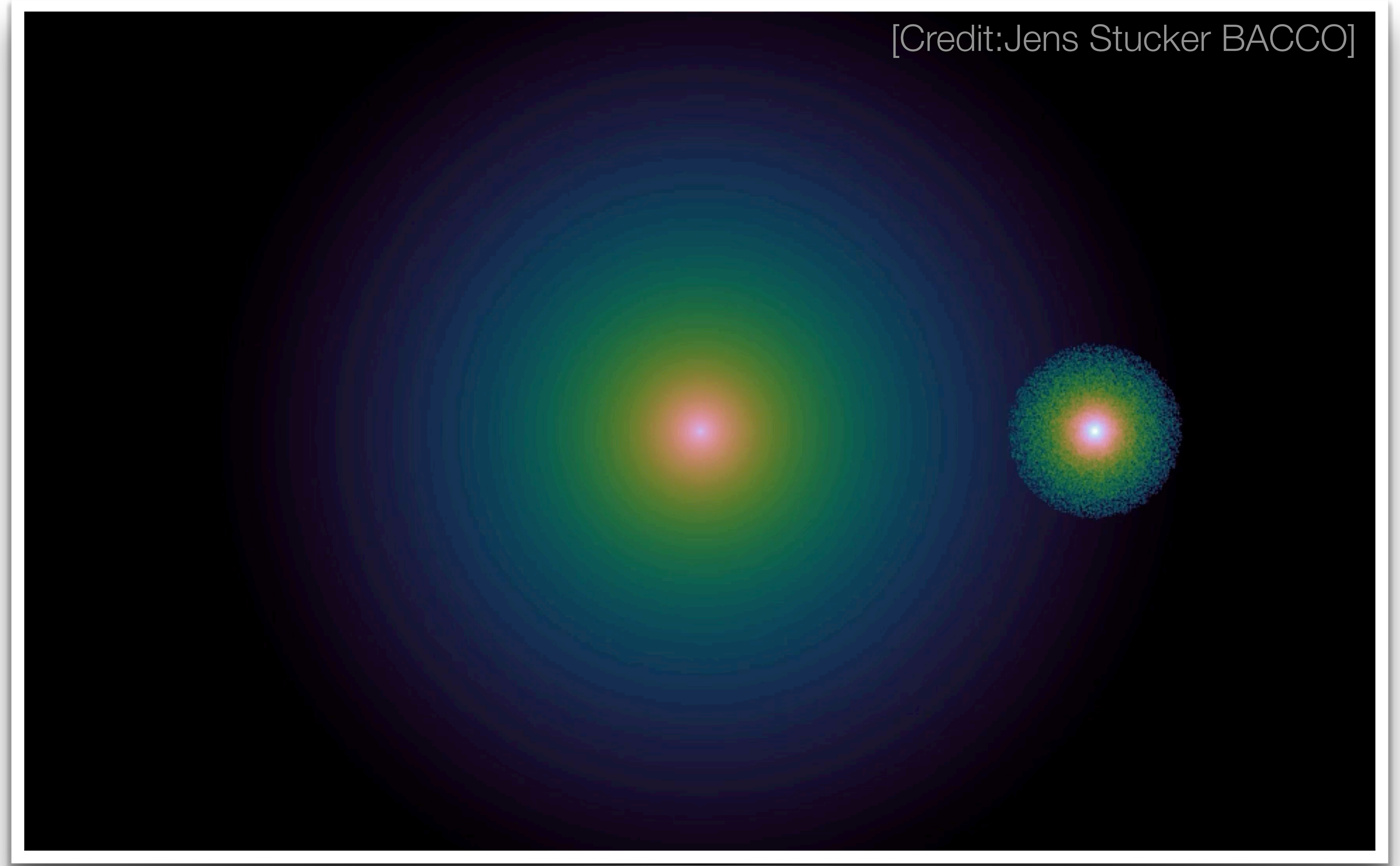
Subhalo bound mass vs time
[van den Bosch&Ogiya18]



[see e.g. Peñarrubia+08,10; van den Bosch & Ogiya18; Han+18; Green&van den Bosch 19; Jiang+21; Stucker+23; He+25; Errani+20,21,22,24]

Abundance and densities of MW satellites

Cosmological simulations suffer from artificial disruption of subhalos



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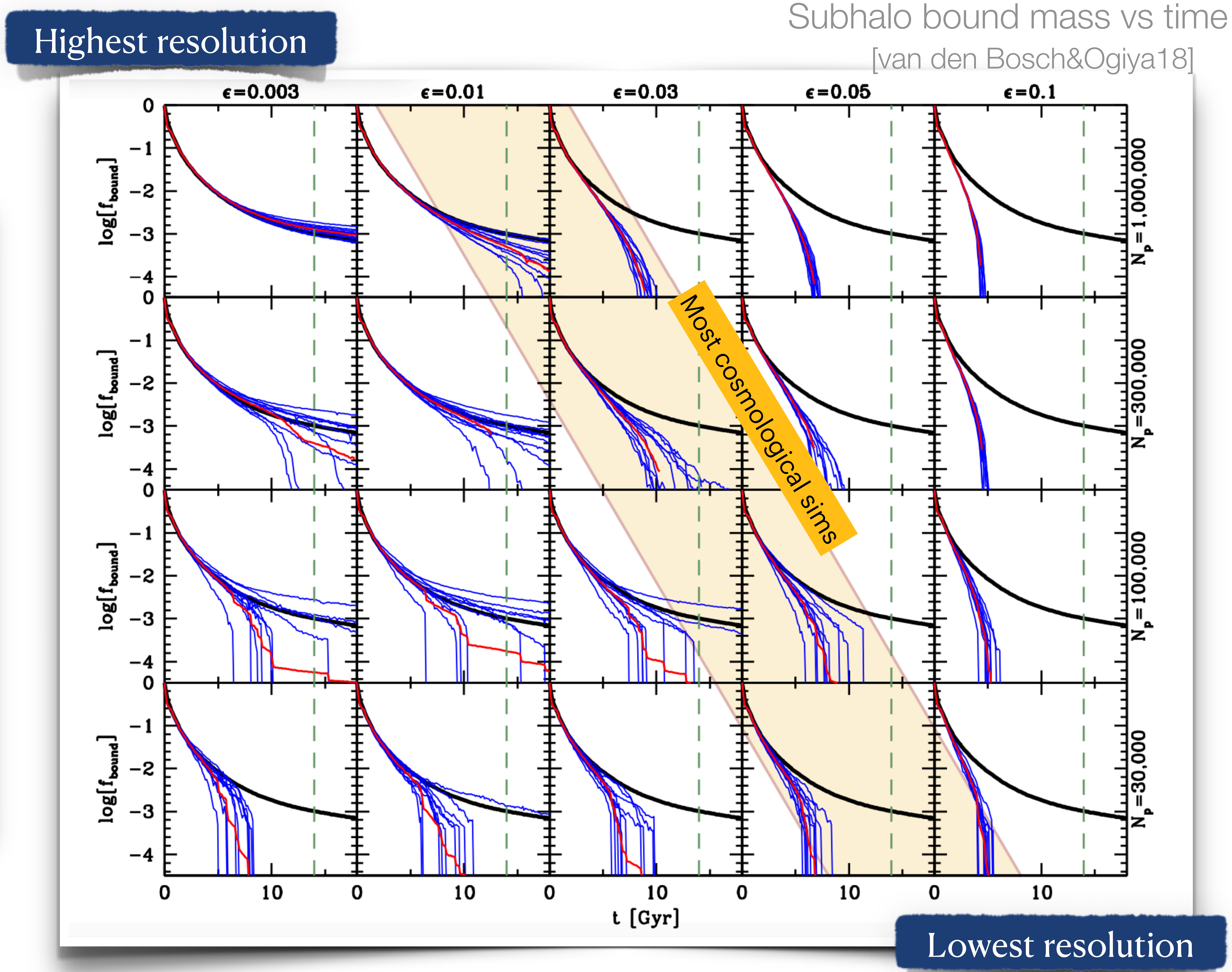

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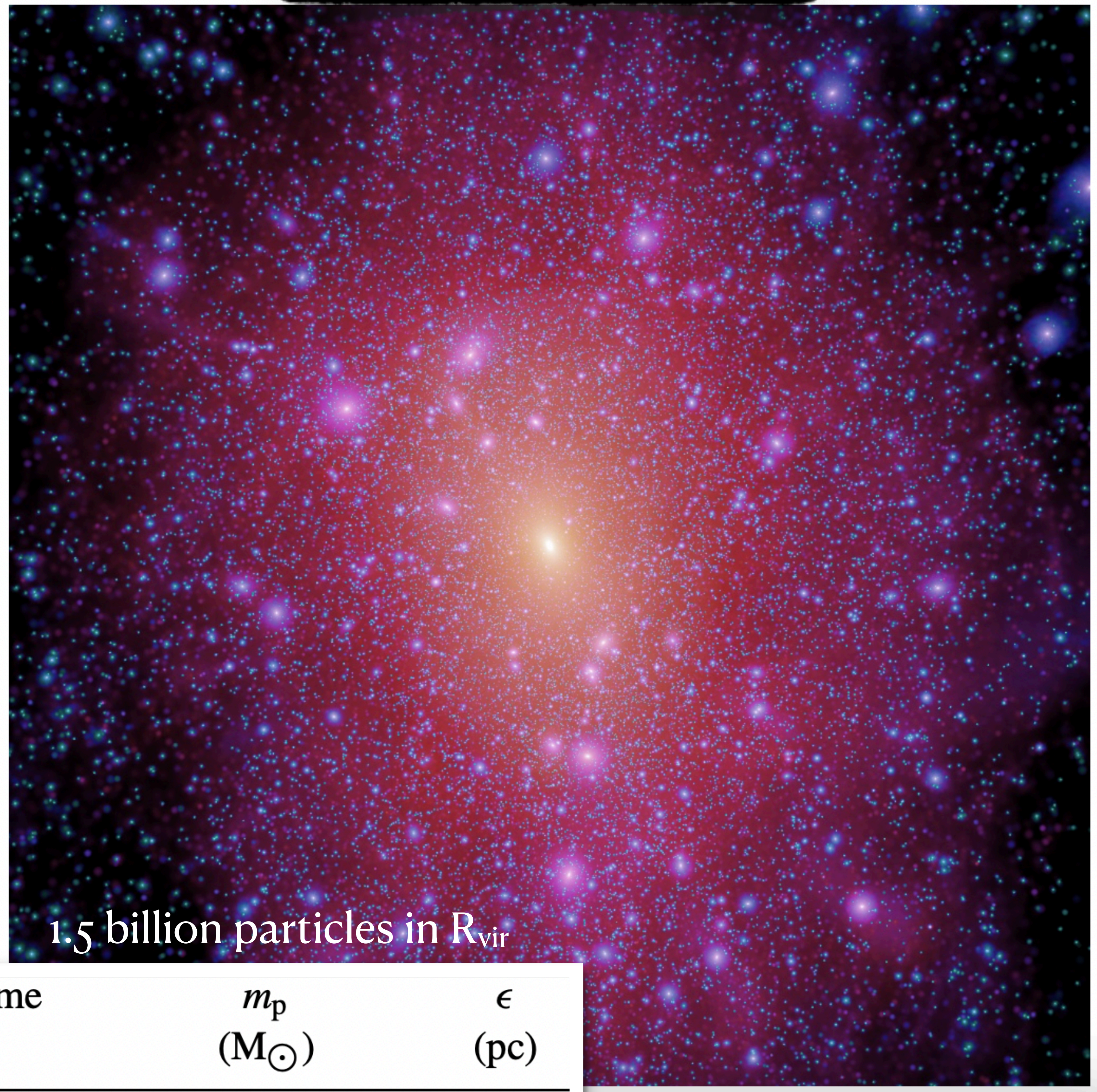
Abundance and densities of MW satellites

[Santos-Santos+2025]

Aquarius project



Name	m_p ($M_\odot$)	ϵ (pc)
Aq-A-1	1.712×10^3	20.5

Highest-resolution MW halo simulation (DM-only)

Abundance and densities of MW satellites

[Santos-Santos+2025]

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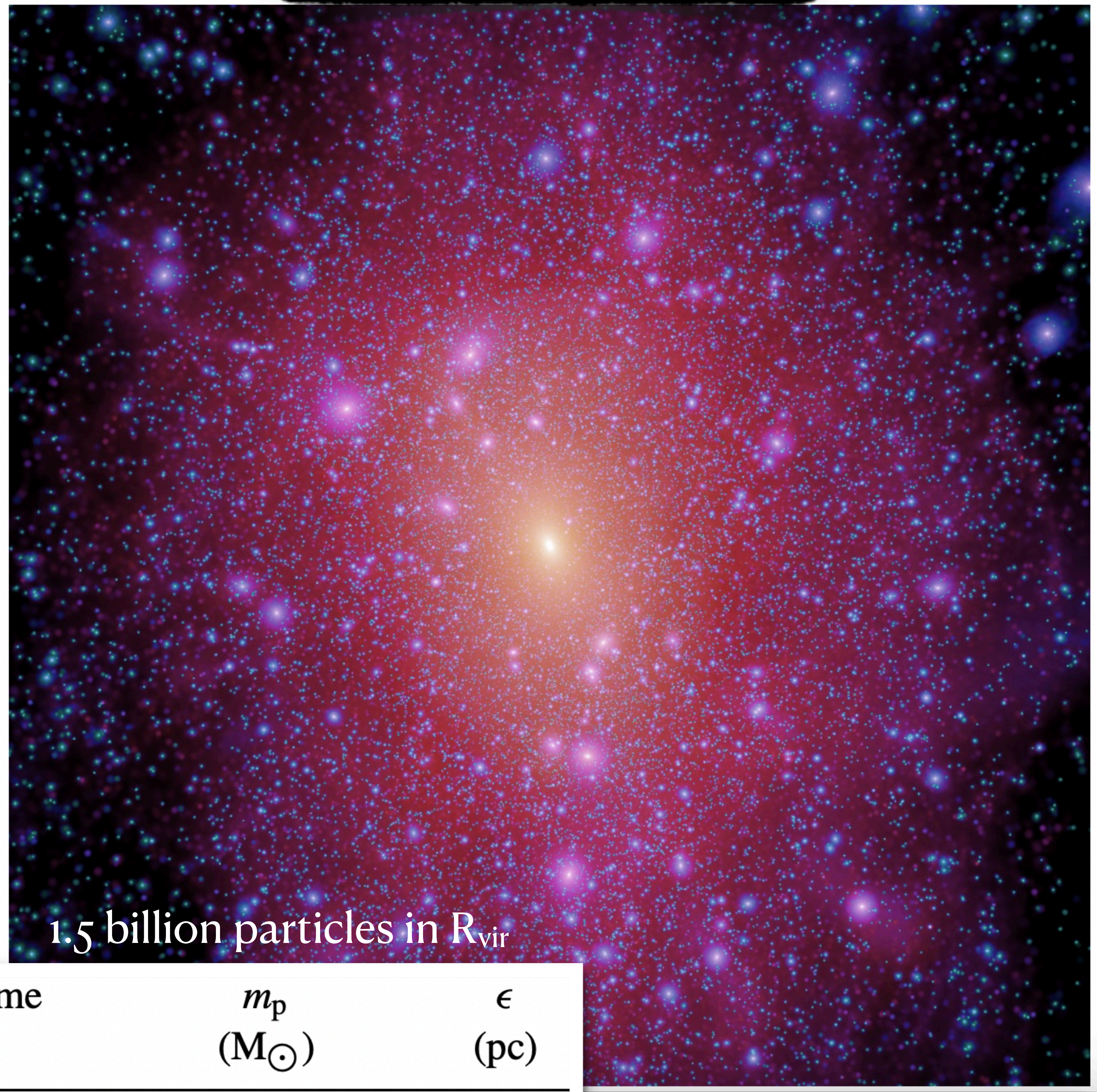

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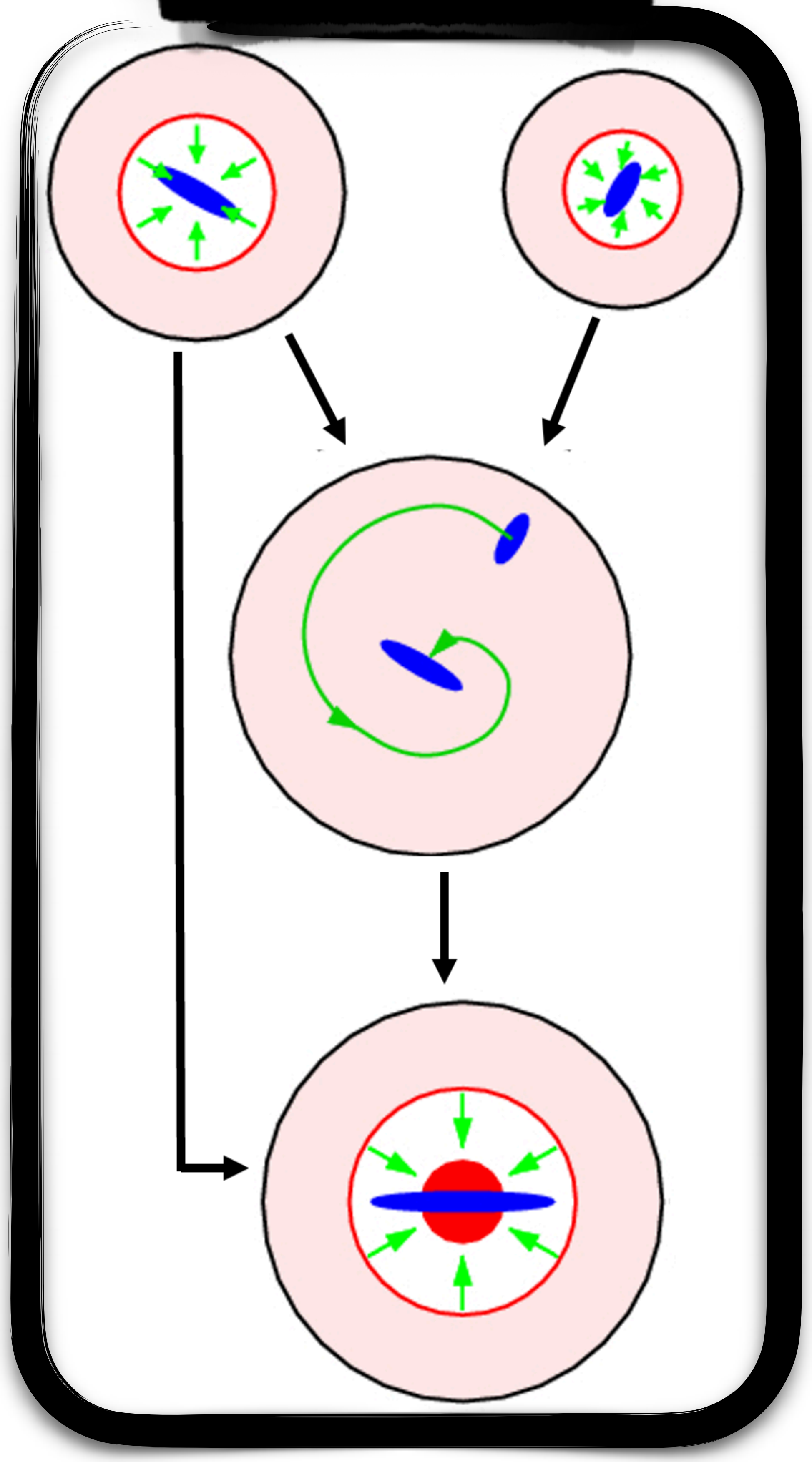

Semi-analytic model for galaxy formation

Abundance and densities of MW satellites

[Santos-Santos+2025]

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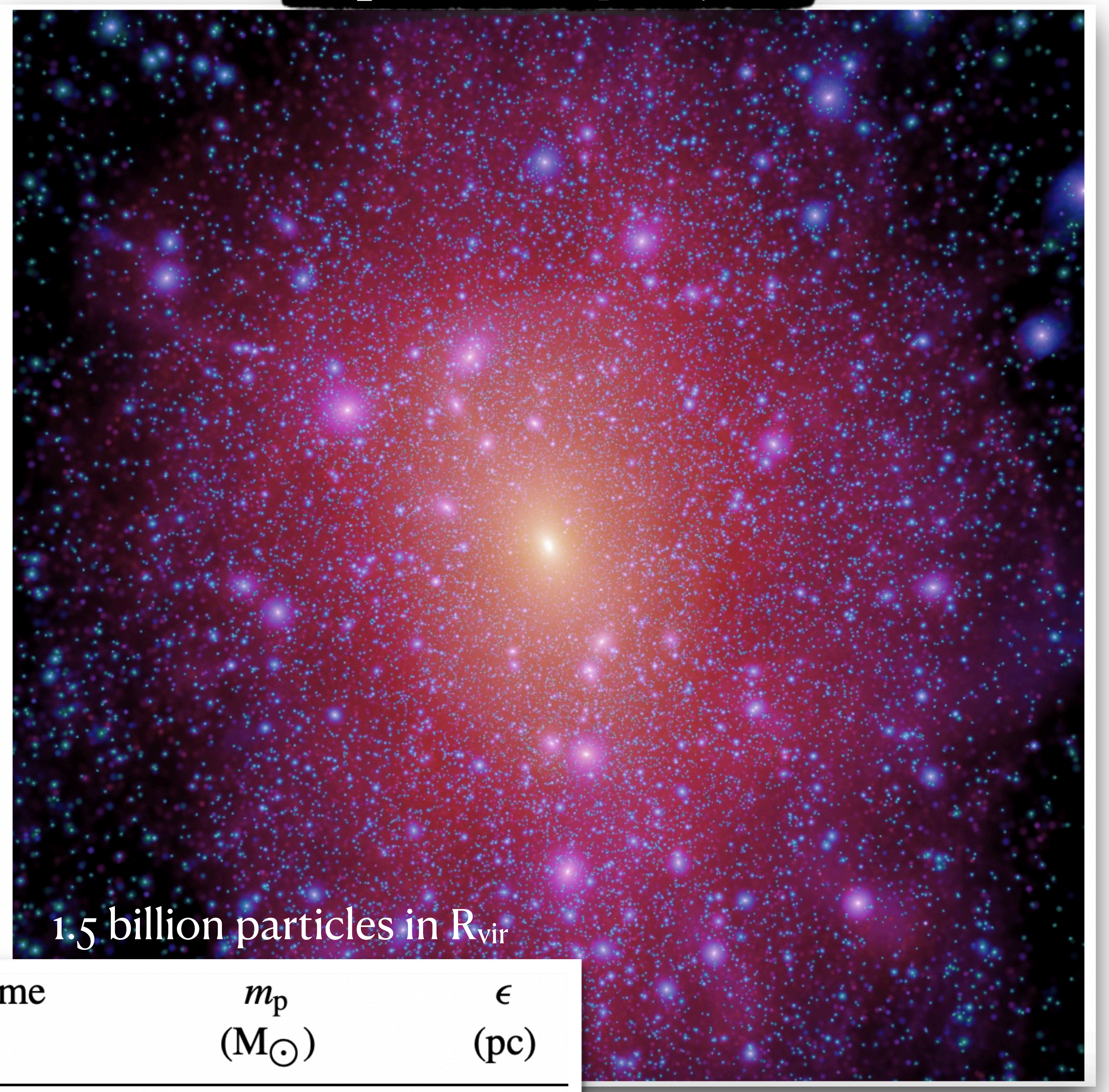

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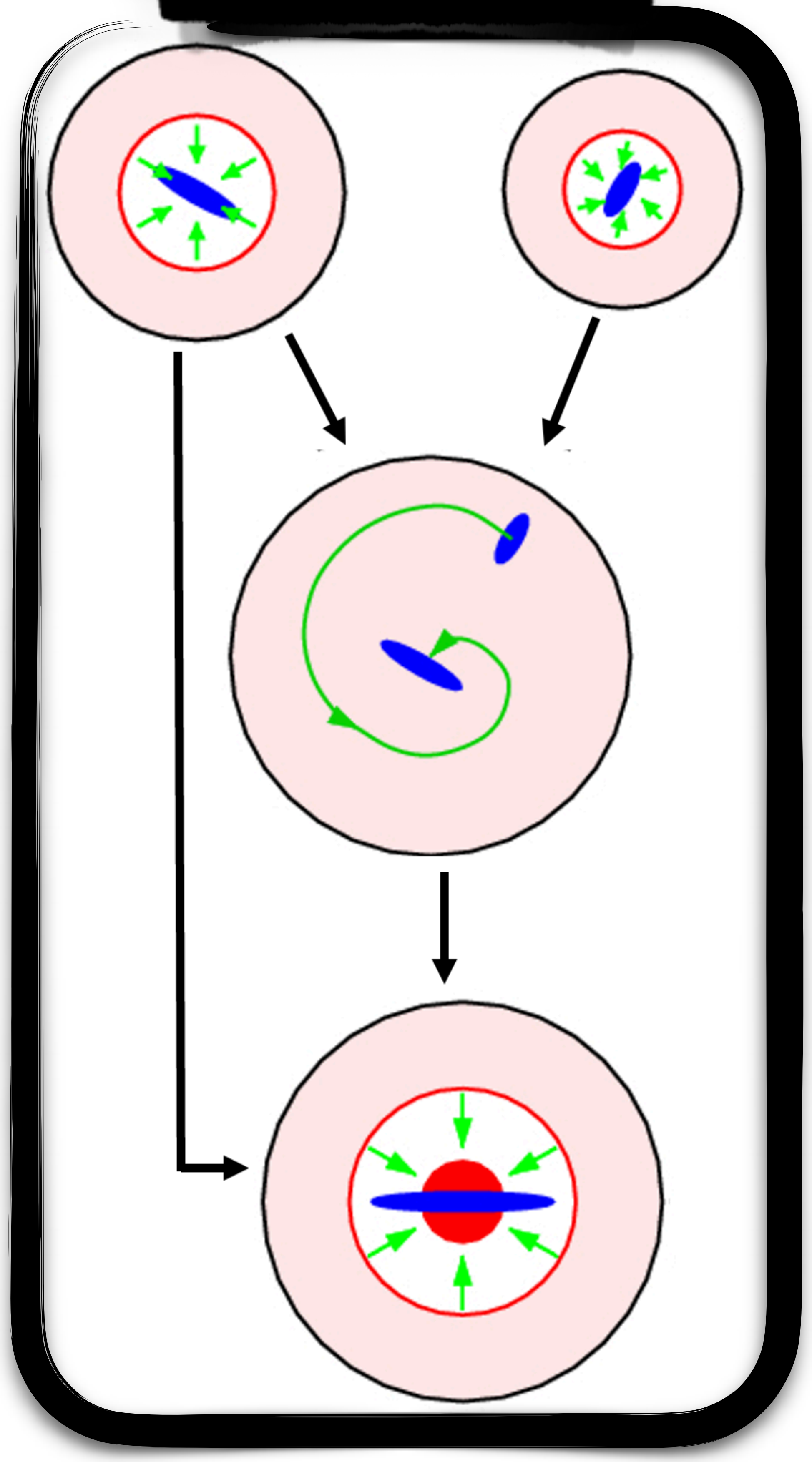


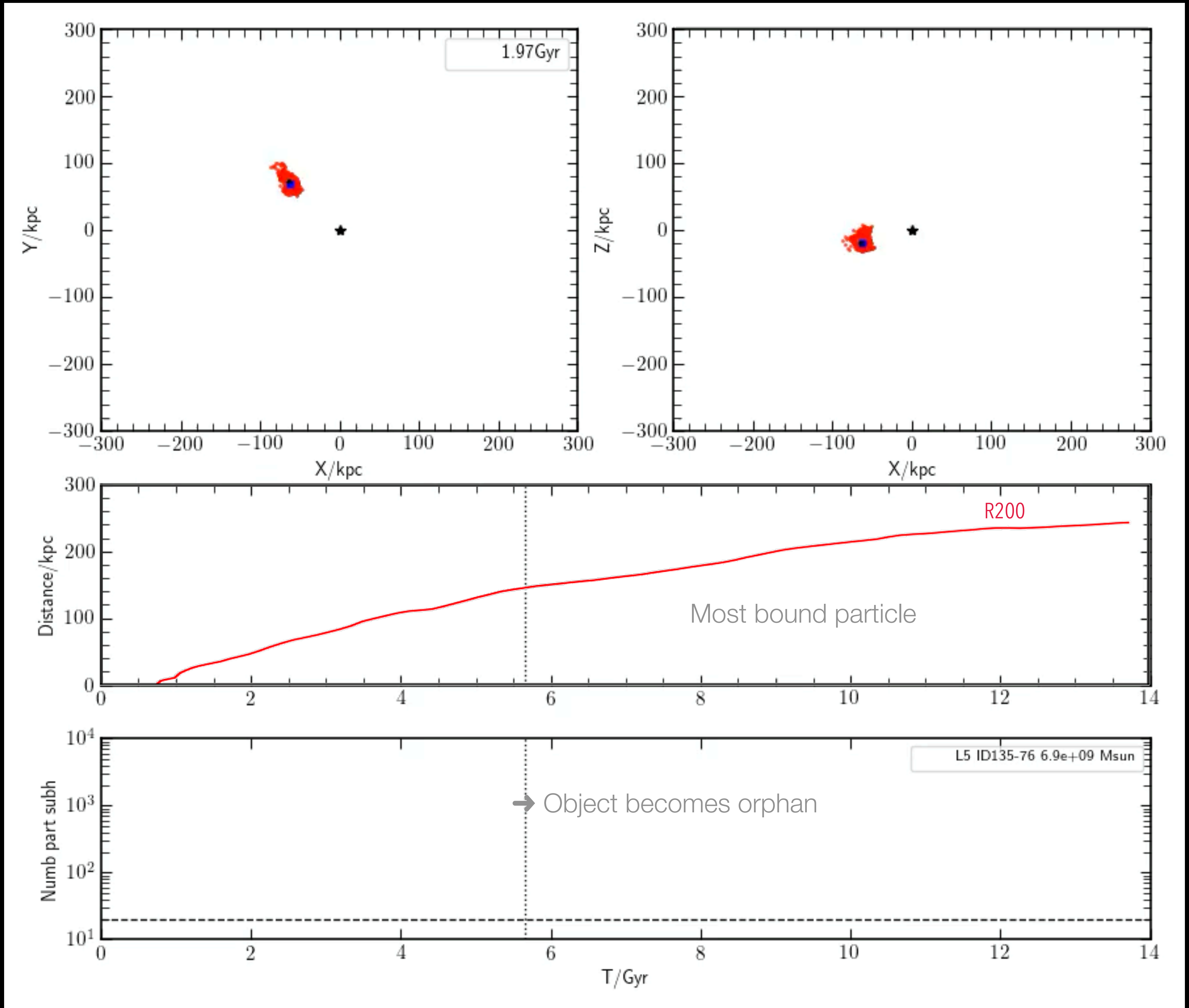
Semi-analytic model for galaxy formation

- Galform reads Aquarius merger trees and particle data, and is able to track the evolution of a galaxy after it disrupts (following the most-bound particle).
- “Type-1s” (satellites in “resolved” subhalos)
- “Type-2s/orphans” (satellites in “unresolved” subhalos).

“Orphans”: sub-resolution galaxies

[Santos-Santos+2025]

Starts at time when M=M$_{peak}$
Subfind data
“Orphan” phase



- Very early infall times
- Small pericentres
- Short orbital periods

20 particles

“Orphans”: sub-resolution galaxies

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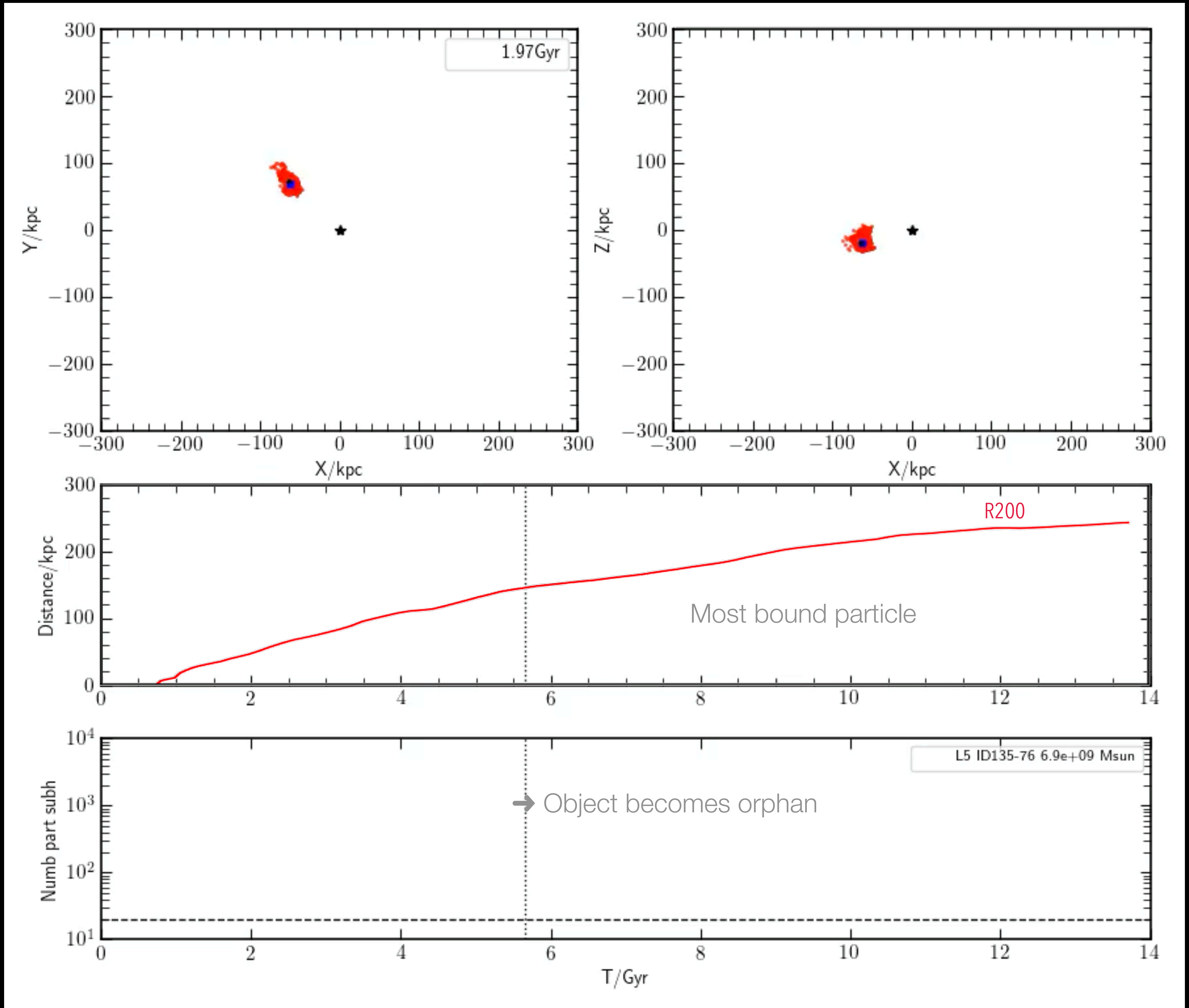

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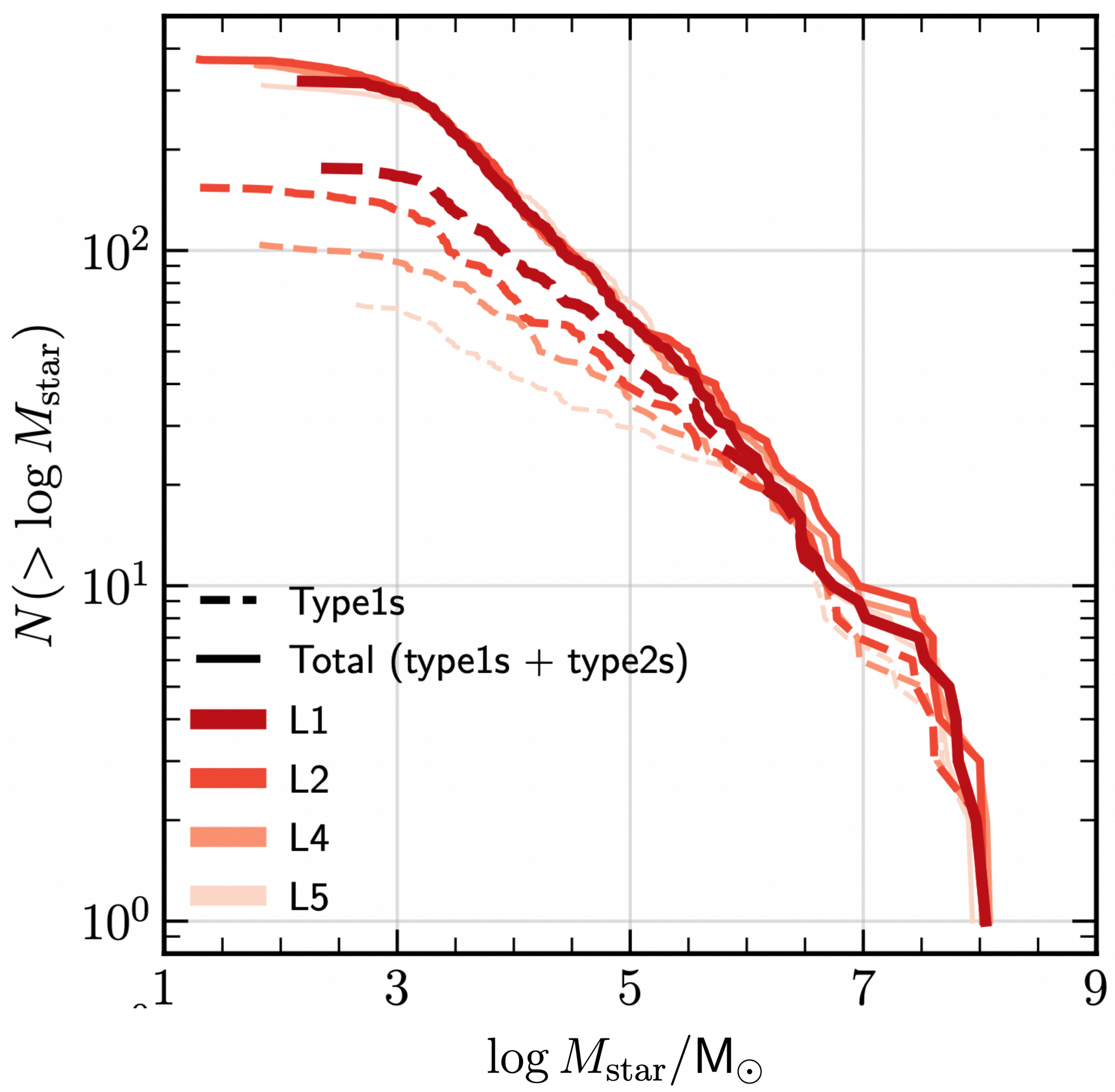
I.Santos-Santos (ICC, Durham)

Abundance and densities of MW satellites

[Santos-Santos+2025]



Peak stellar mass (no stripping)

I.Santos-Santos (ICC, Durham)

Abundance and densities of MW satellites

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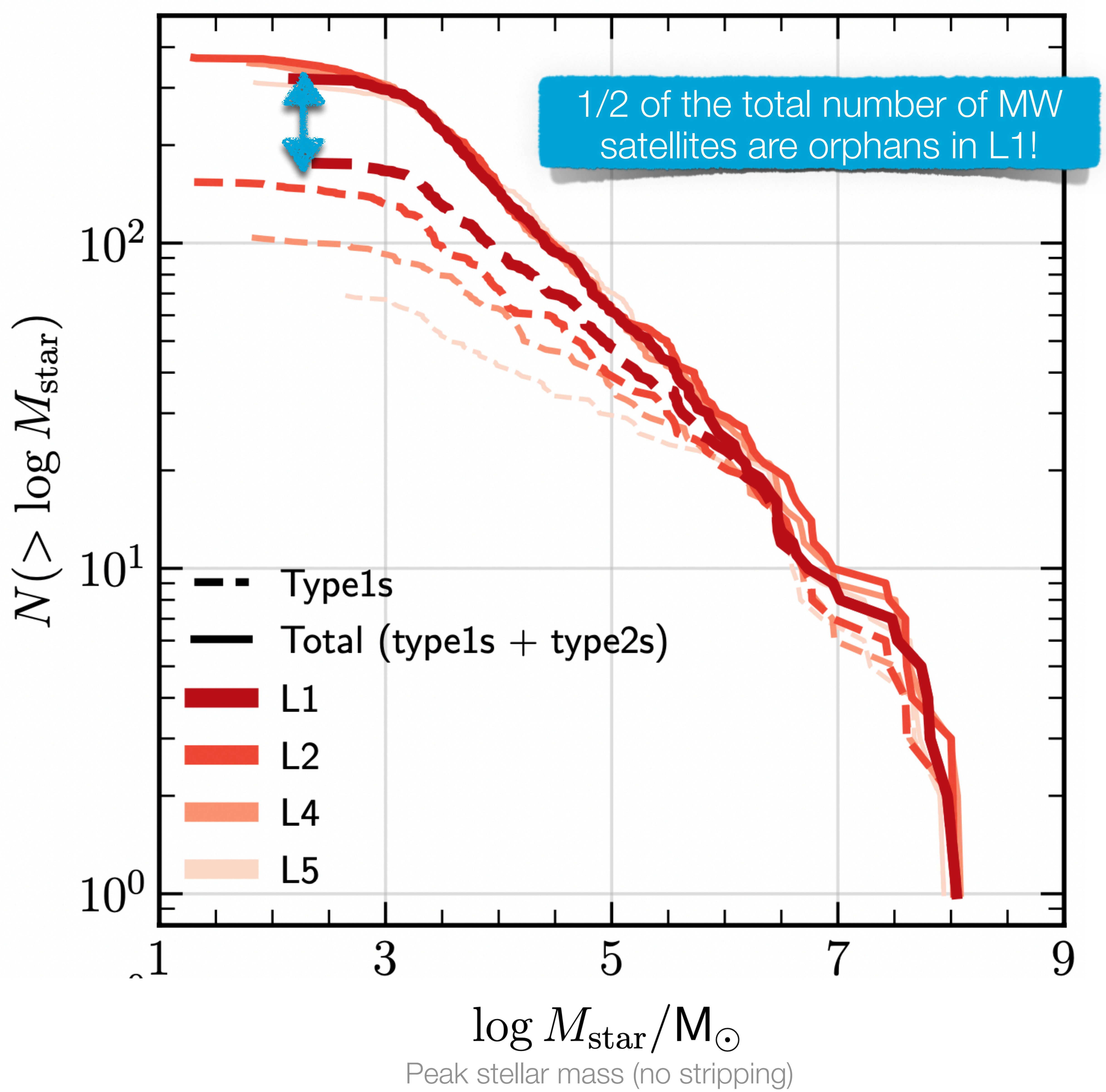

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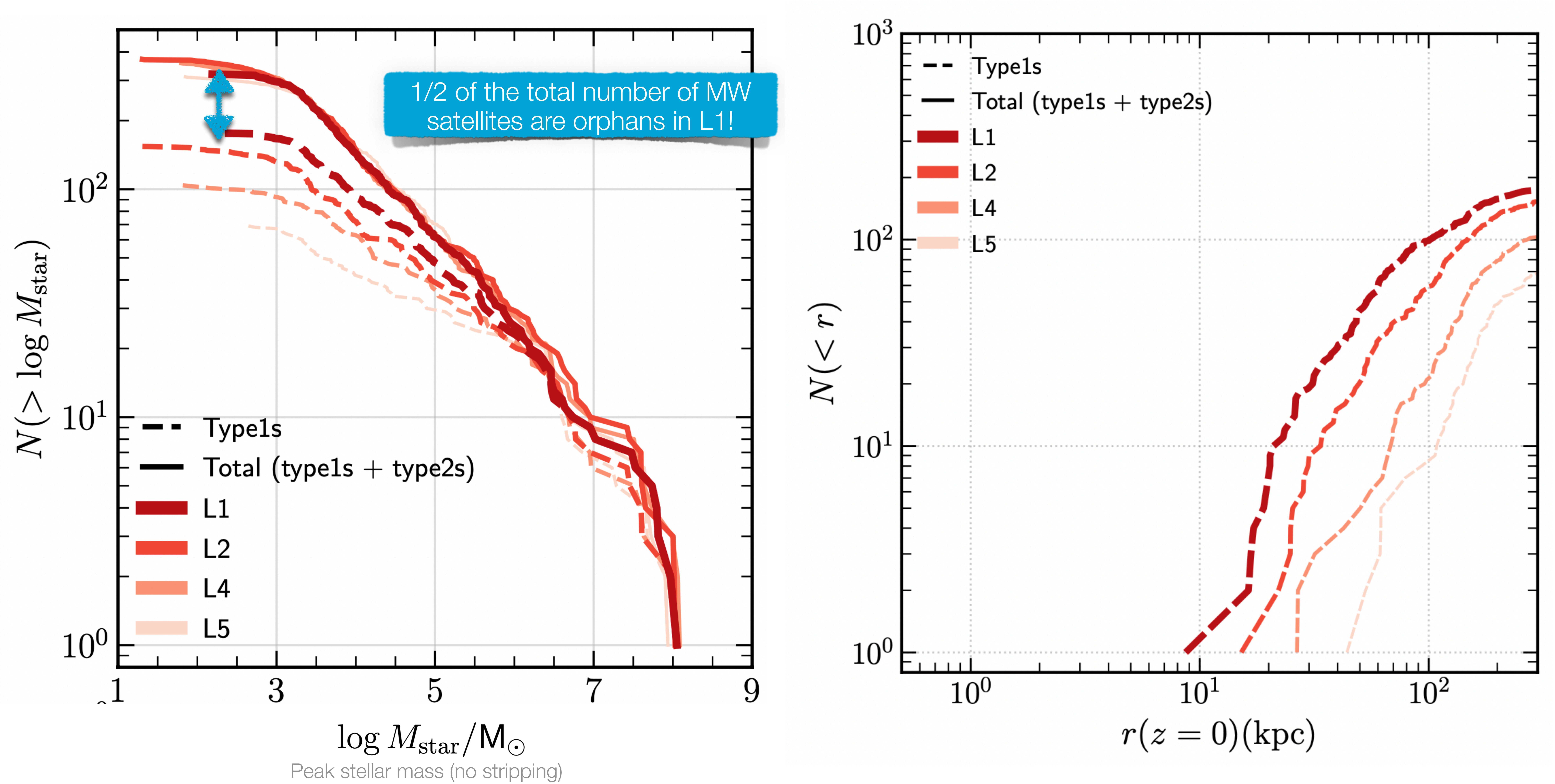

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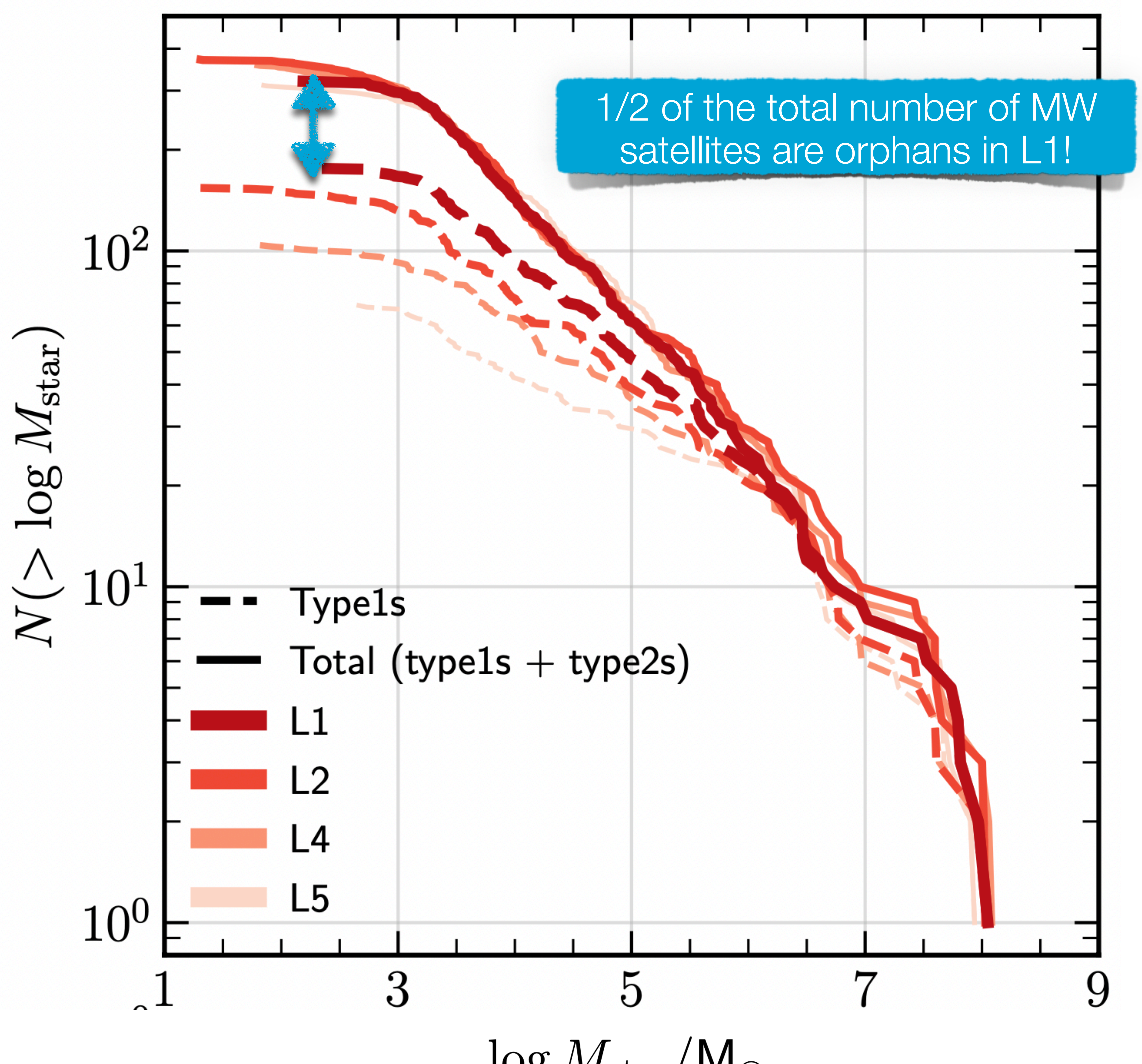

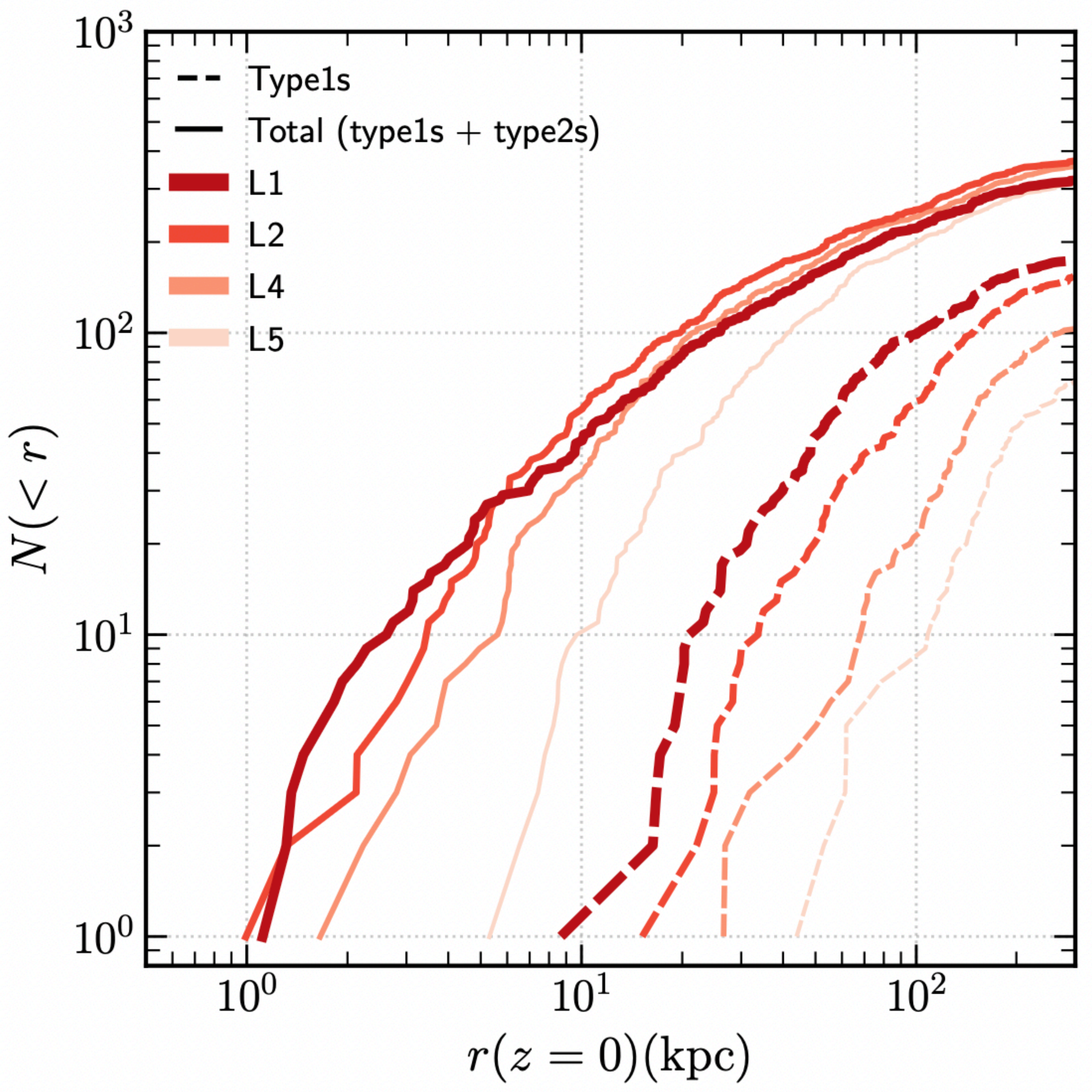

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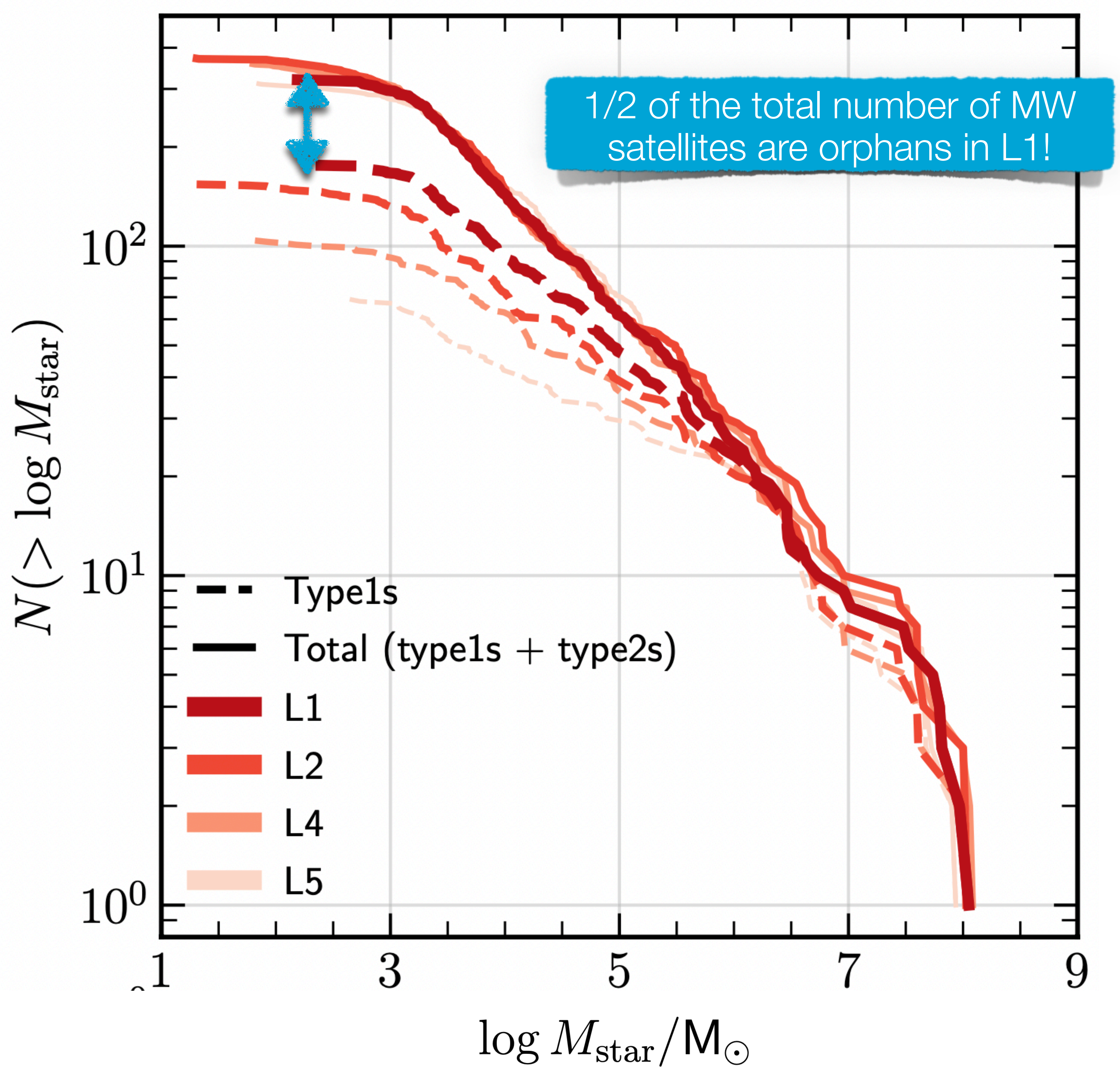

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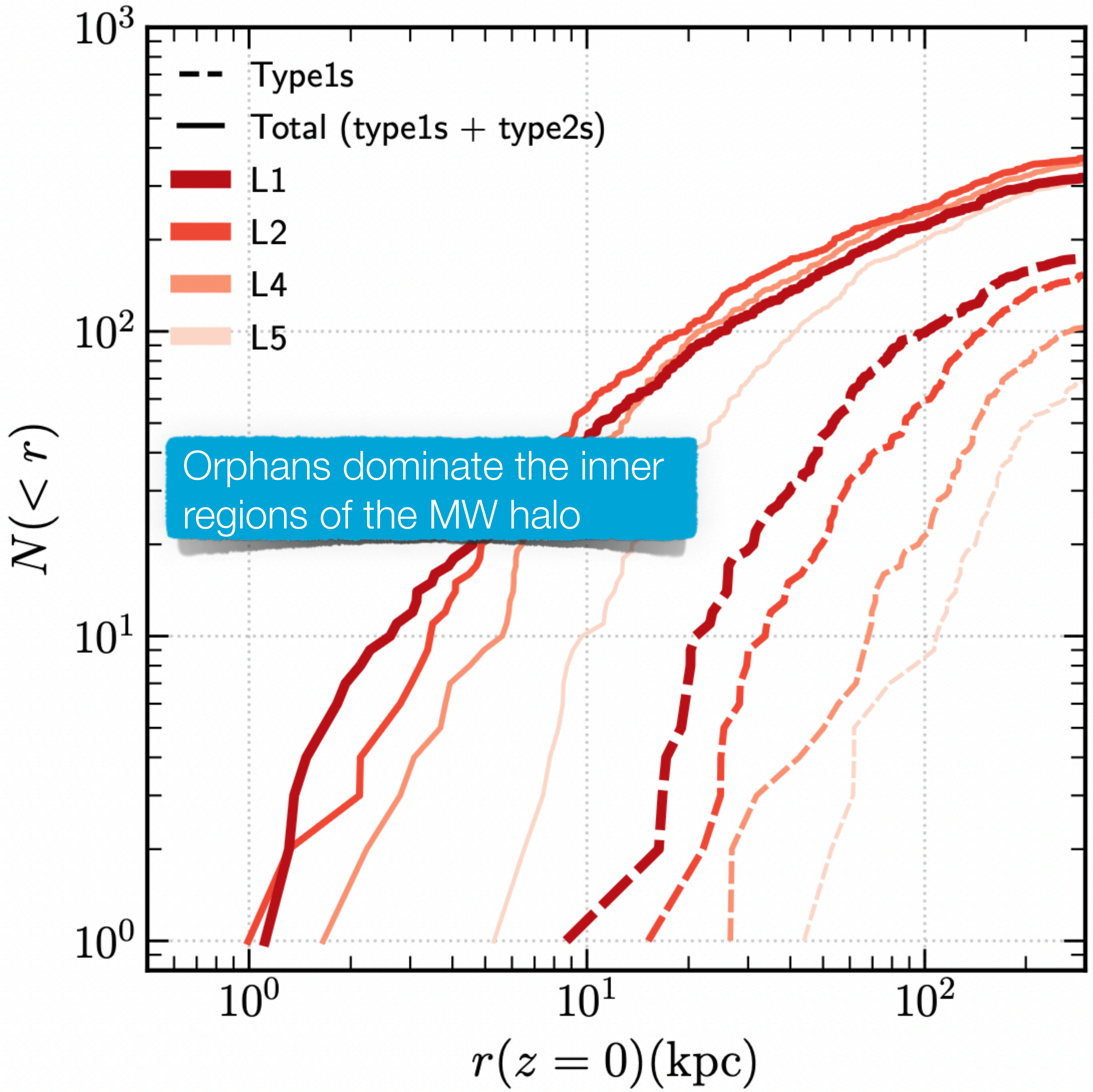
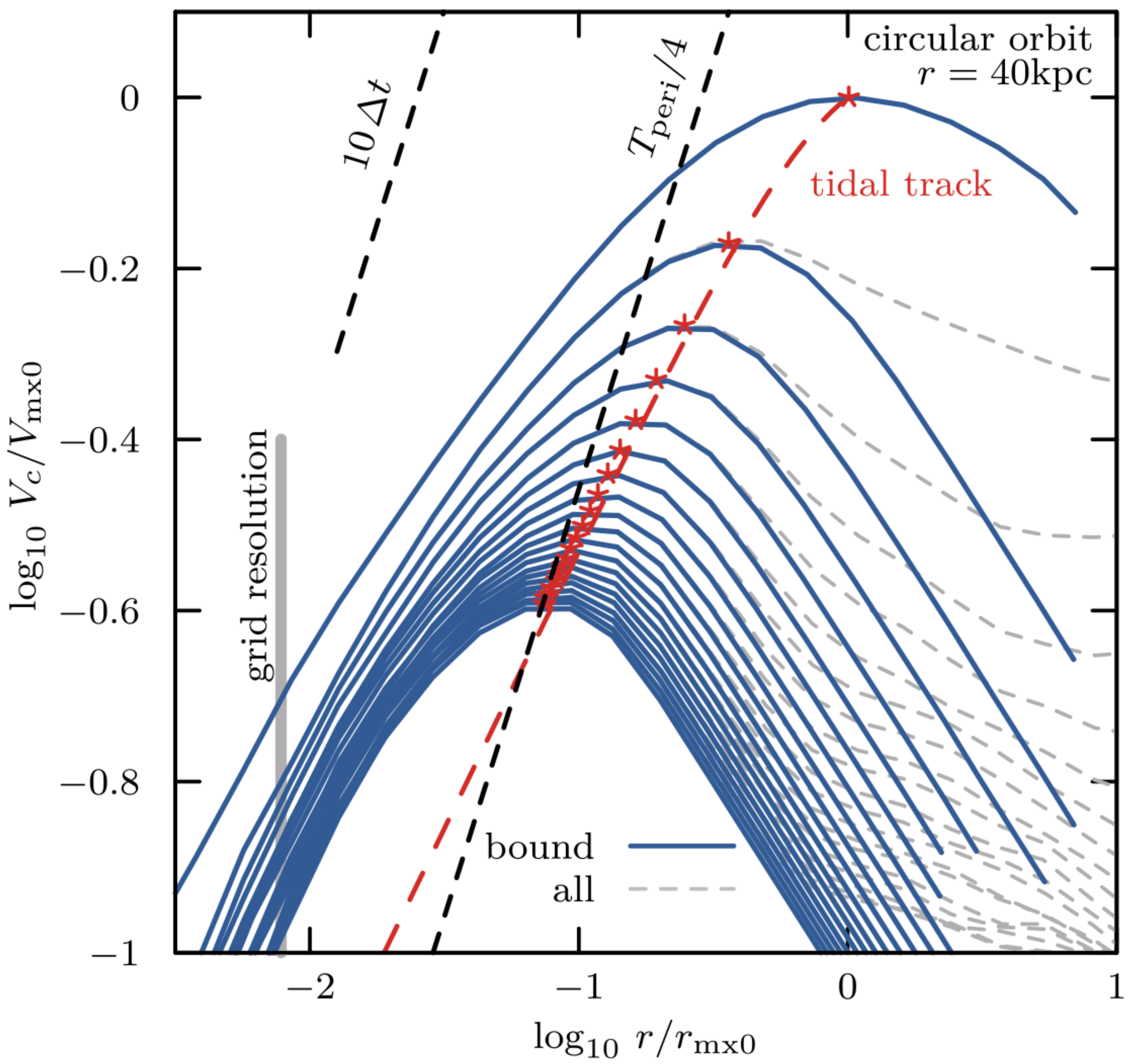


Abundance and densities of MW satellites

[Santos-Santos+in prep]

Dark matter tidal stripping

"Tidal Tracks" [Errani+21]



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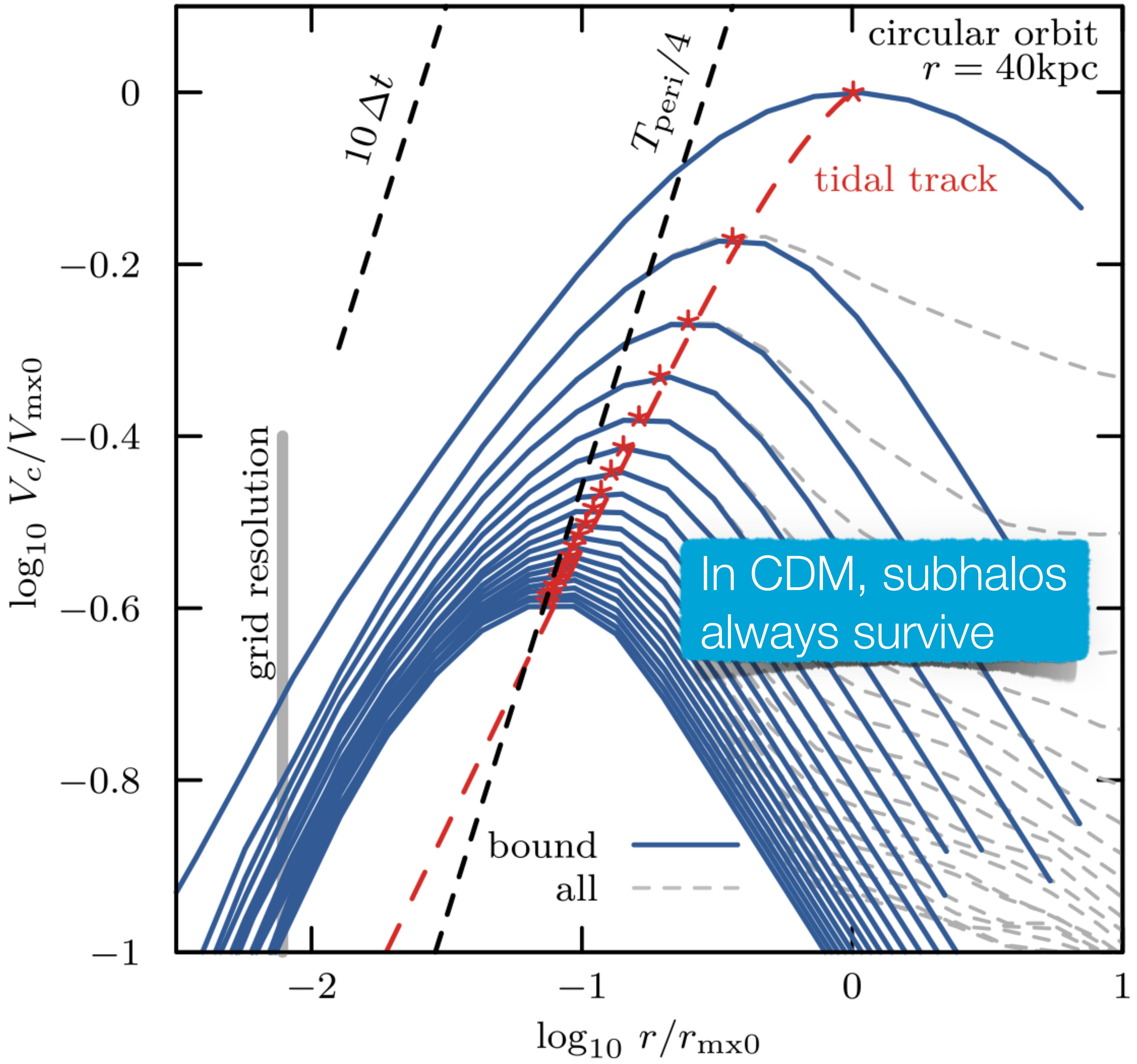

In CDM, subhalos always survive

Abundance and densities of MW satellites

[Santos-Santos+in prep]

Dark matter tidal stripping

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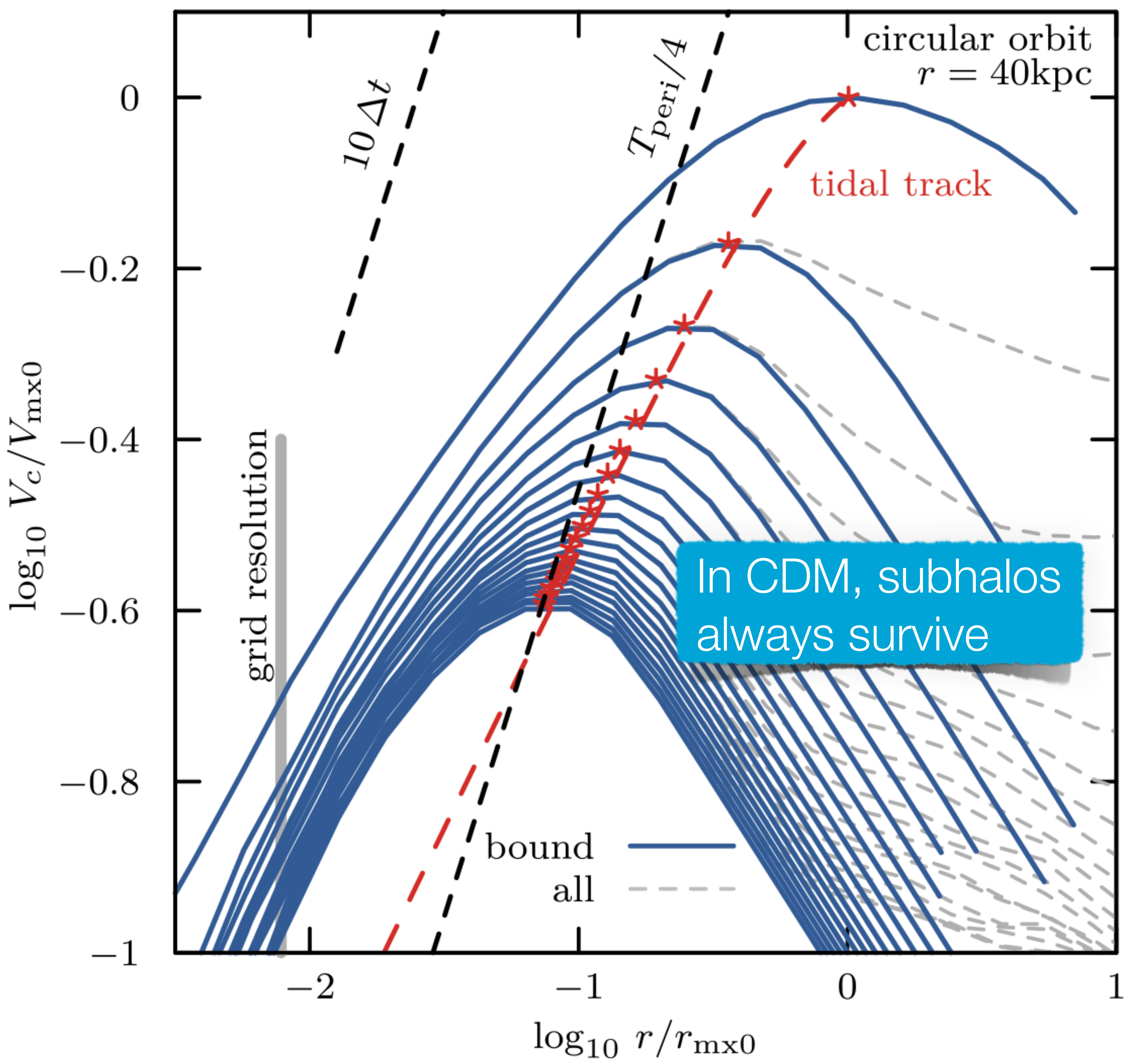

In CDM, subhalos always survive

Subhalo stripping in WDM, SIDM,…?

Abundance and densities of MW satellites

[Santos-Santos+in prep]

Dark matter tidal stripping

Stellar tidal stripping?

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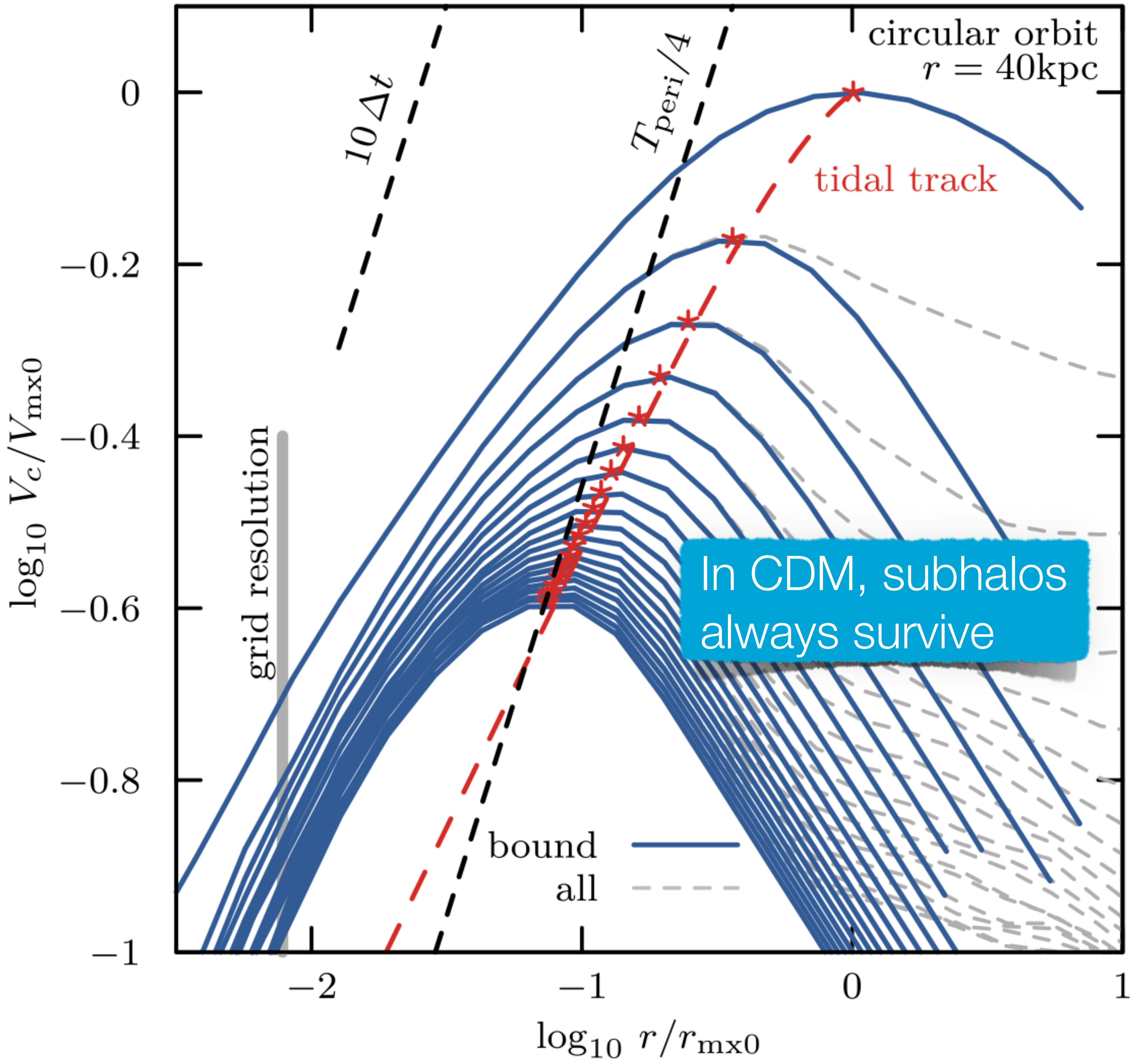

Subhalo stripping in WDM, SIDM,…?

Abundance and densities of MW satellites

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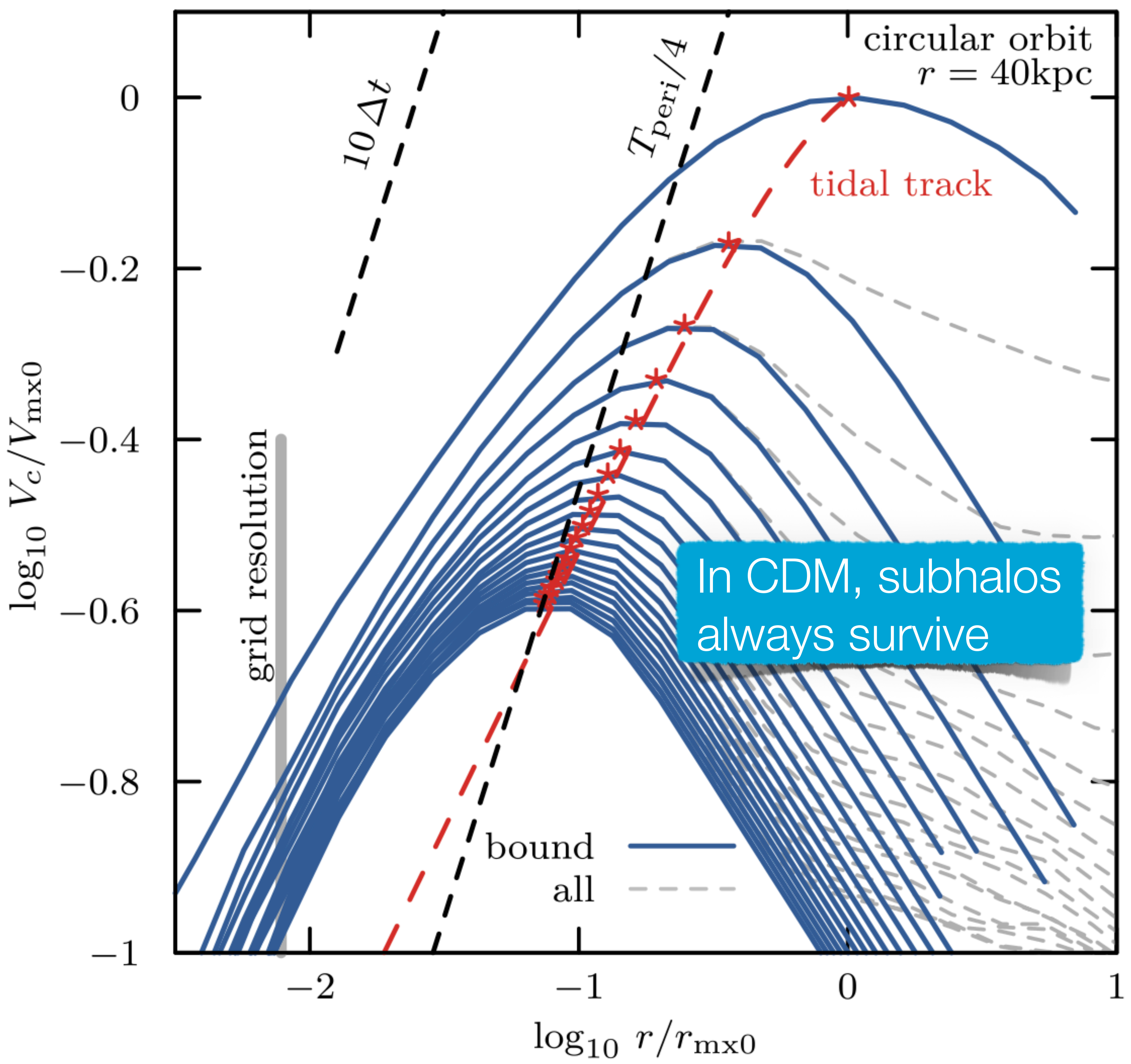


Subhalo stripping in WDM, SIDM,…?

Stellar tidal stripping?

What is the initial energy distribution of stars?

What is the initial size of the stellar component?

[See Errani+22,24]

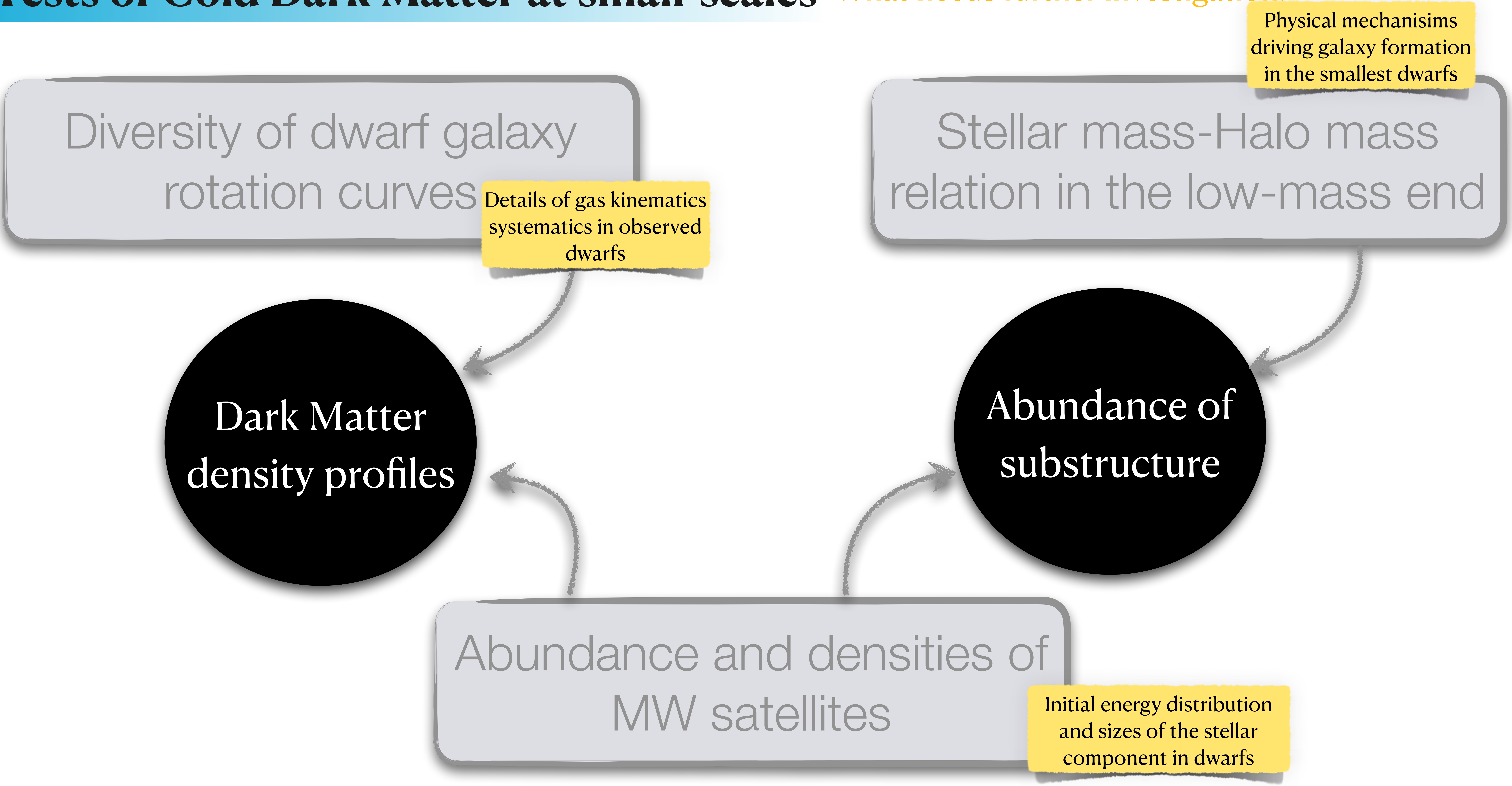
Abundance and densities of MW satellites: status

- ✦ The number of known MW satellites has rapidly increased in the last decade.
- ✦ Some confirmed galaxies, other whose nature remains “ambiguous”.
- ✦ Cosmological simulations at even the highest resolution suffer artificial subhalo fragmentation. This needs to be corrected for if we want robust predictions in the ultrafaint regime.
- ✦ Models including “orphan” galaxy tracking show that half of the total population of MW satellites are “orphans”. These are located at close distances (similar to “ambiguous” population observed).
- ✦ Comparison to z=0 data requires modelling dark matter and stellar stripping. CDM stripping well understood. However, **what are the expected energy distributions of stars in dwarf galaxies?** Advanced hydrodynamical models may help respond this question.

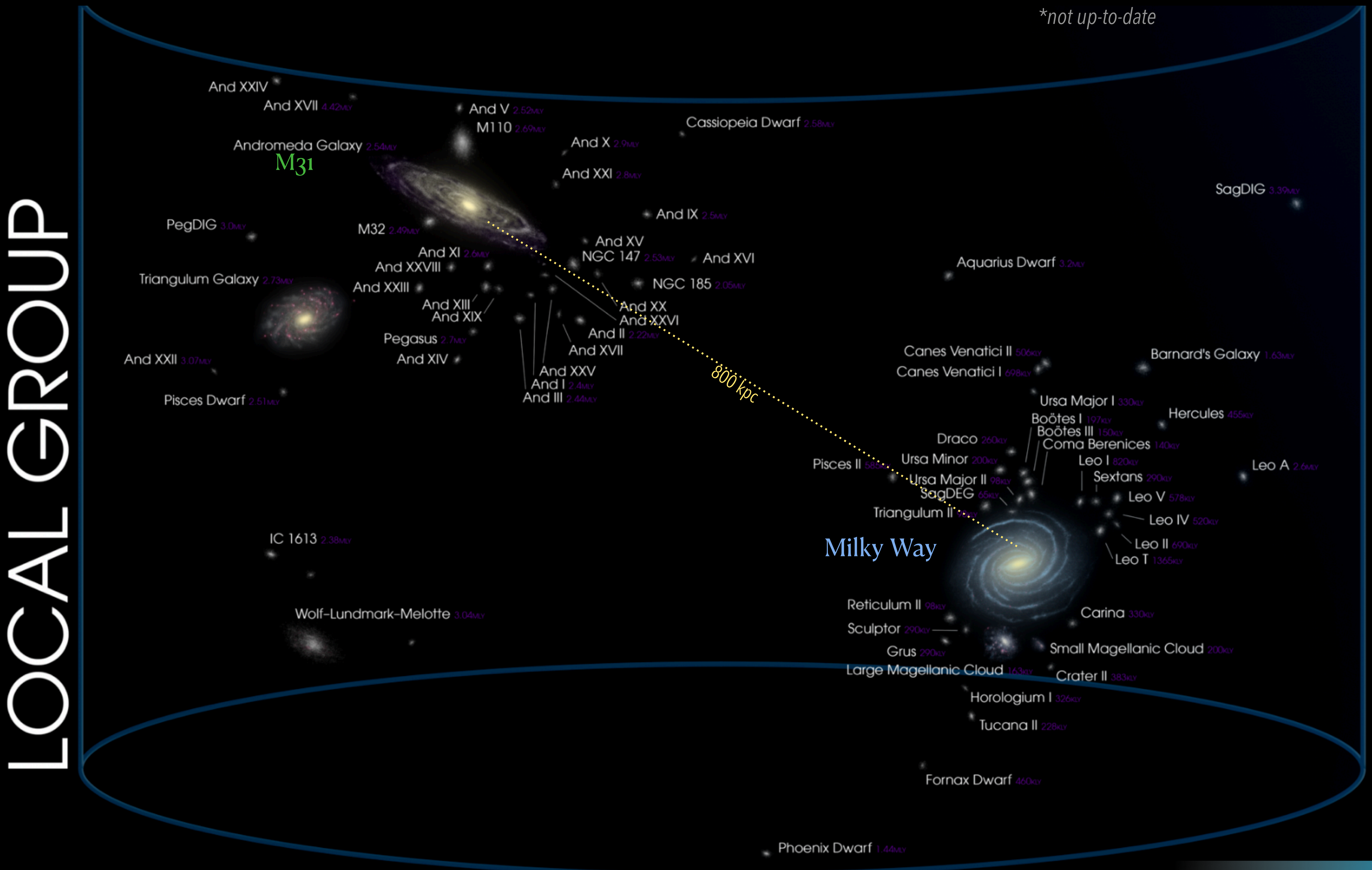
I.Santos-Santos (ICC, Durham)

Tests of Cold Dark Matter at small-scales

What needs further investigation:

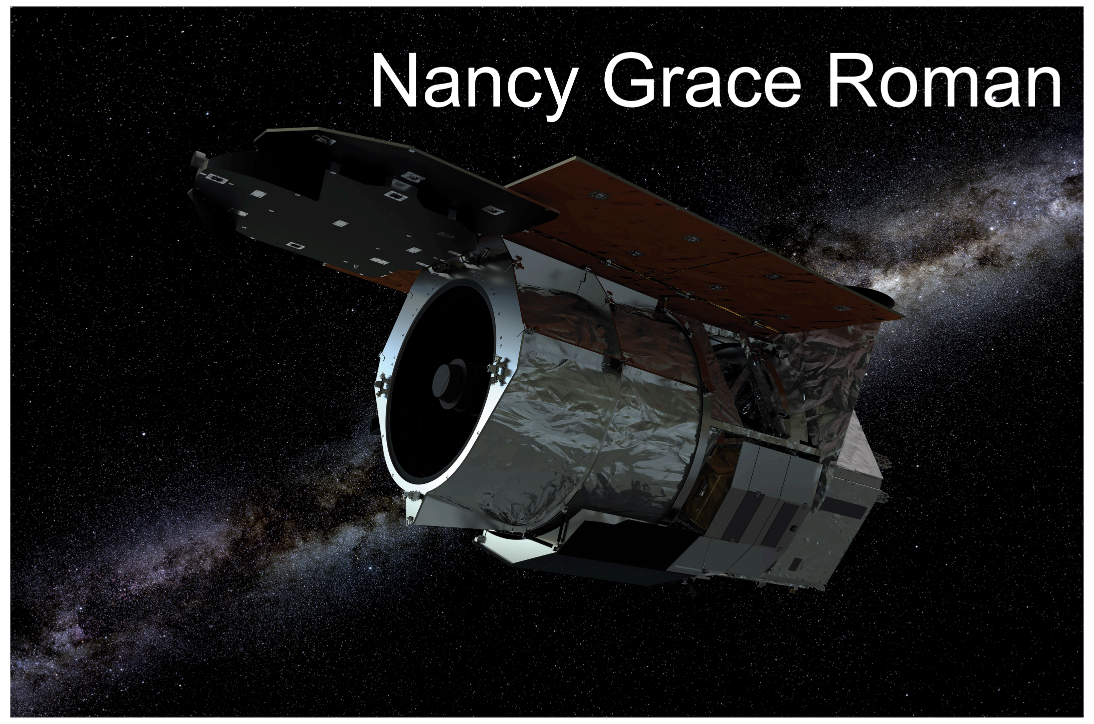


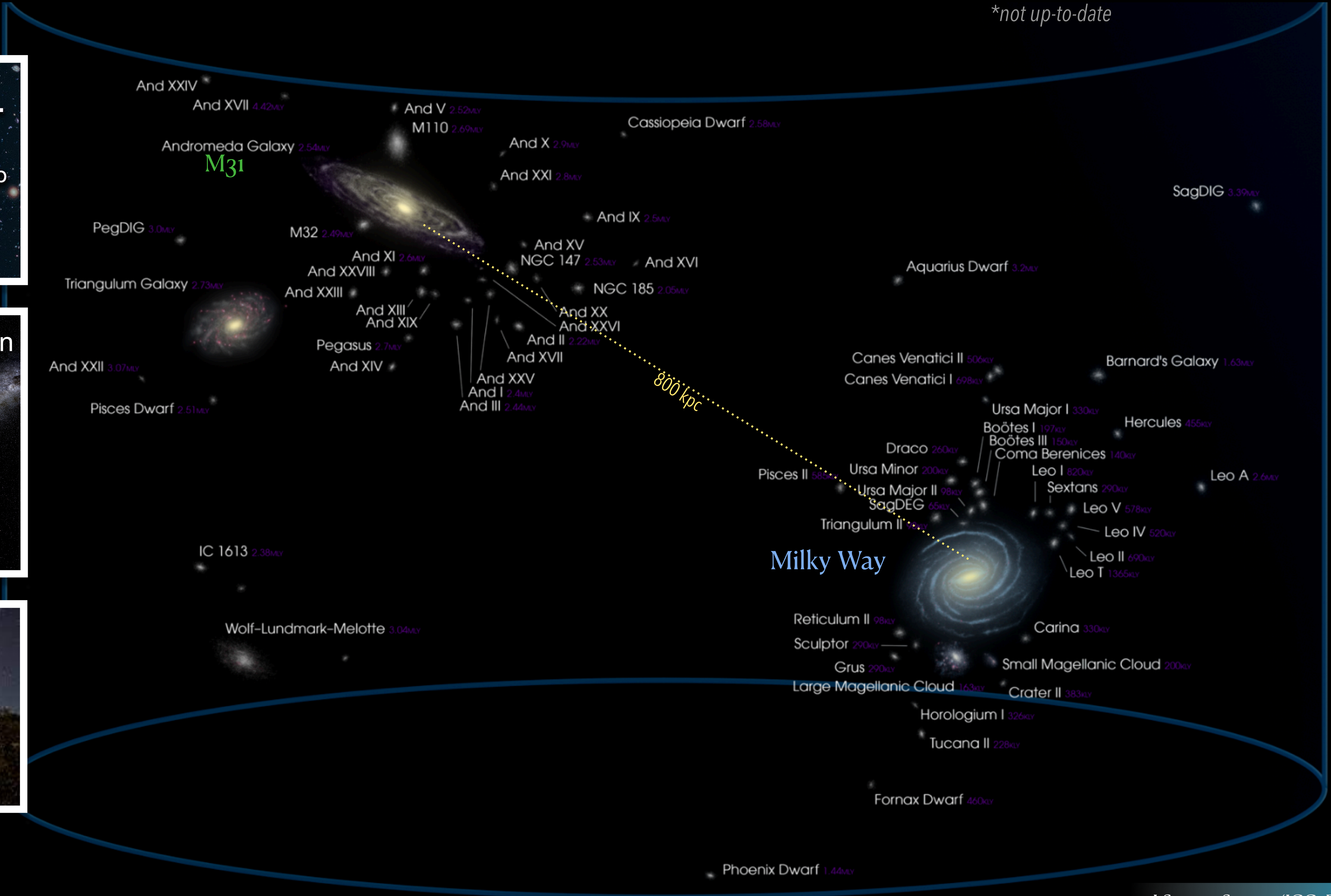
Upcoming surveys will unveil faint galaxies



I.Santos-Santos (ICC, Durham)

Upcoming surveys will unveil faint galaxies





I.Santos-Santos (ICC, Durham)

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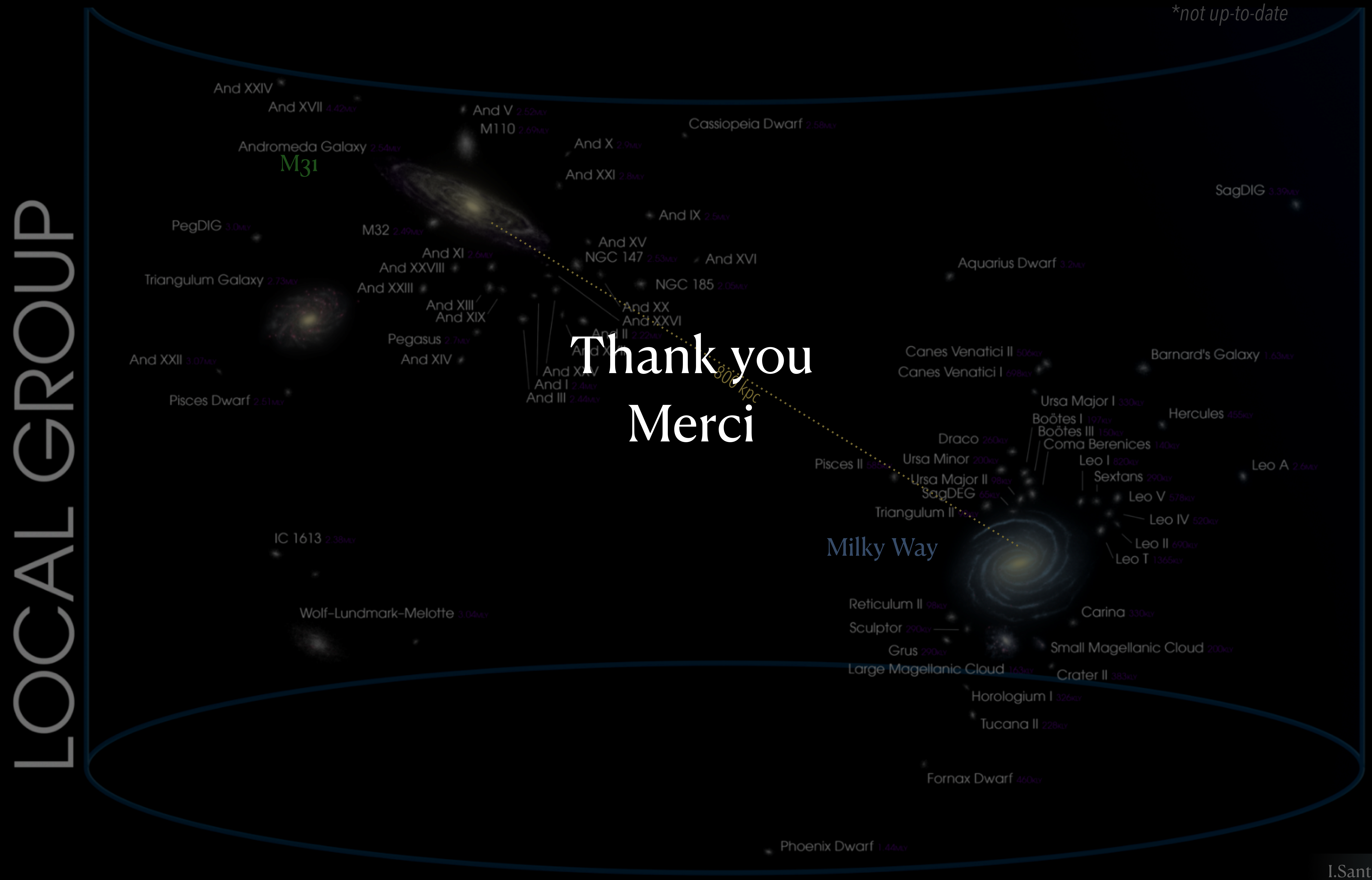
*not up-to-date

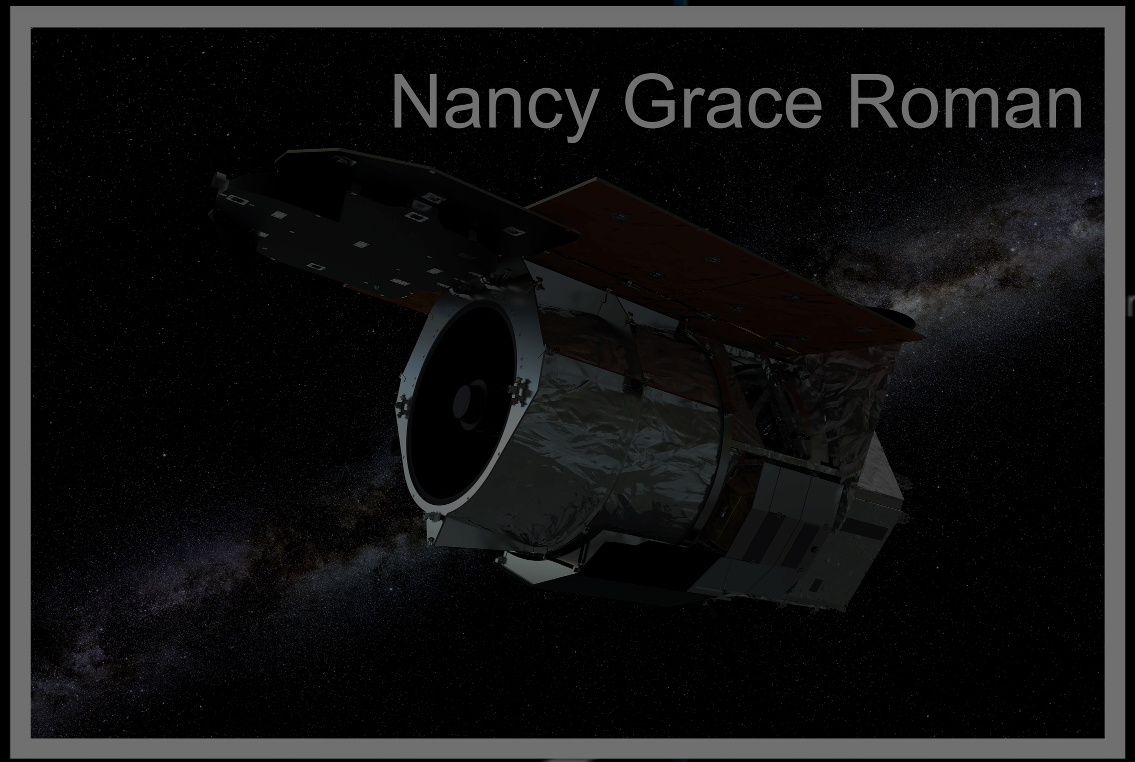


Thank you

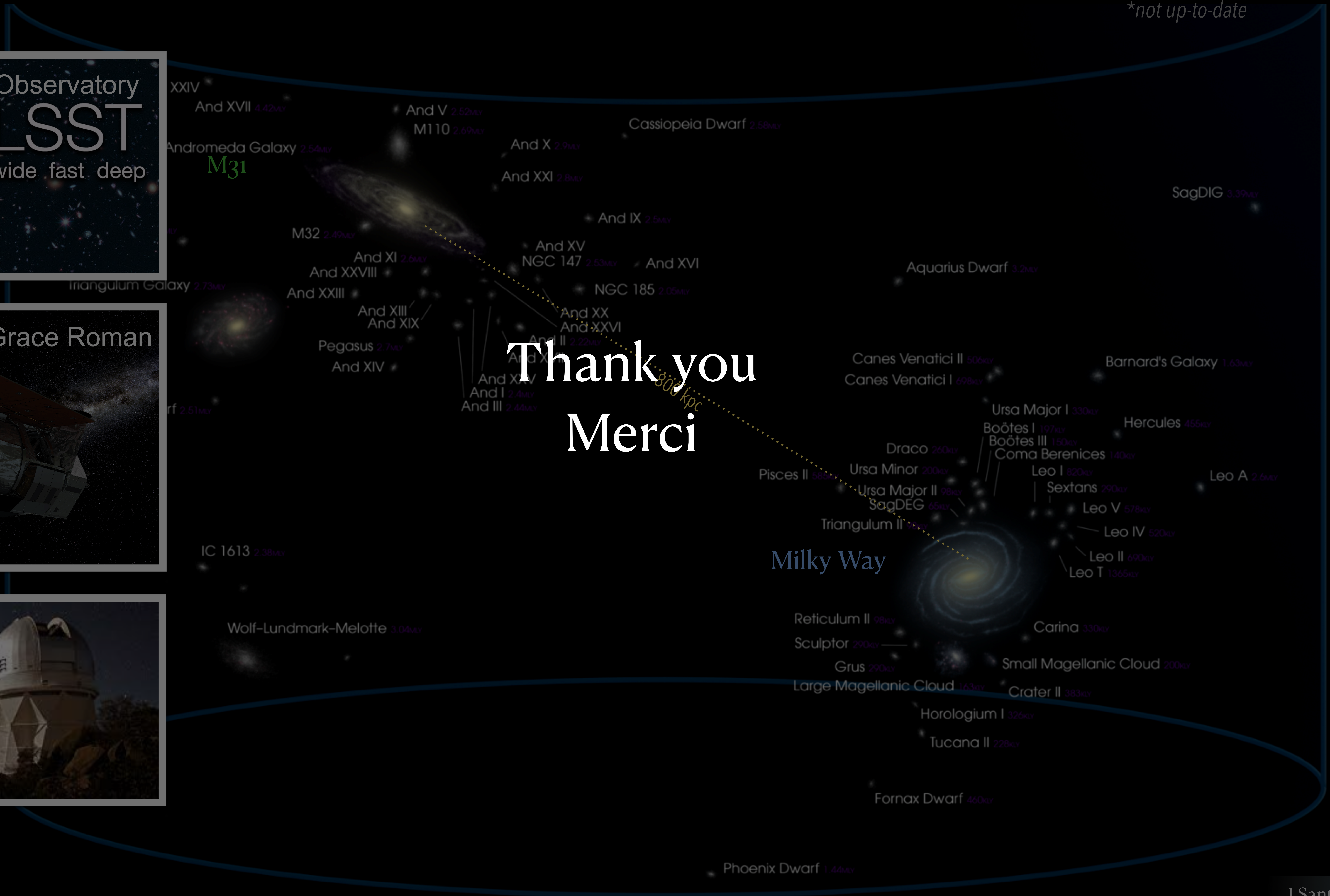
Merci

I.Santos-Santos (ICC, Durham)

Upcoming surveys will unveil faint galaxies



*not up-to-date



Thank you
Merci