

Based on arXiv:2506.01152

New insights on low-mass dark matter subhalo tidal tracks via numerical simulations

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DM halo substructure

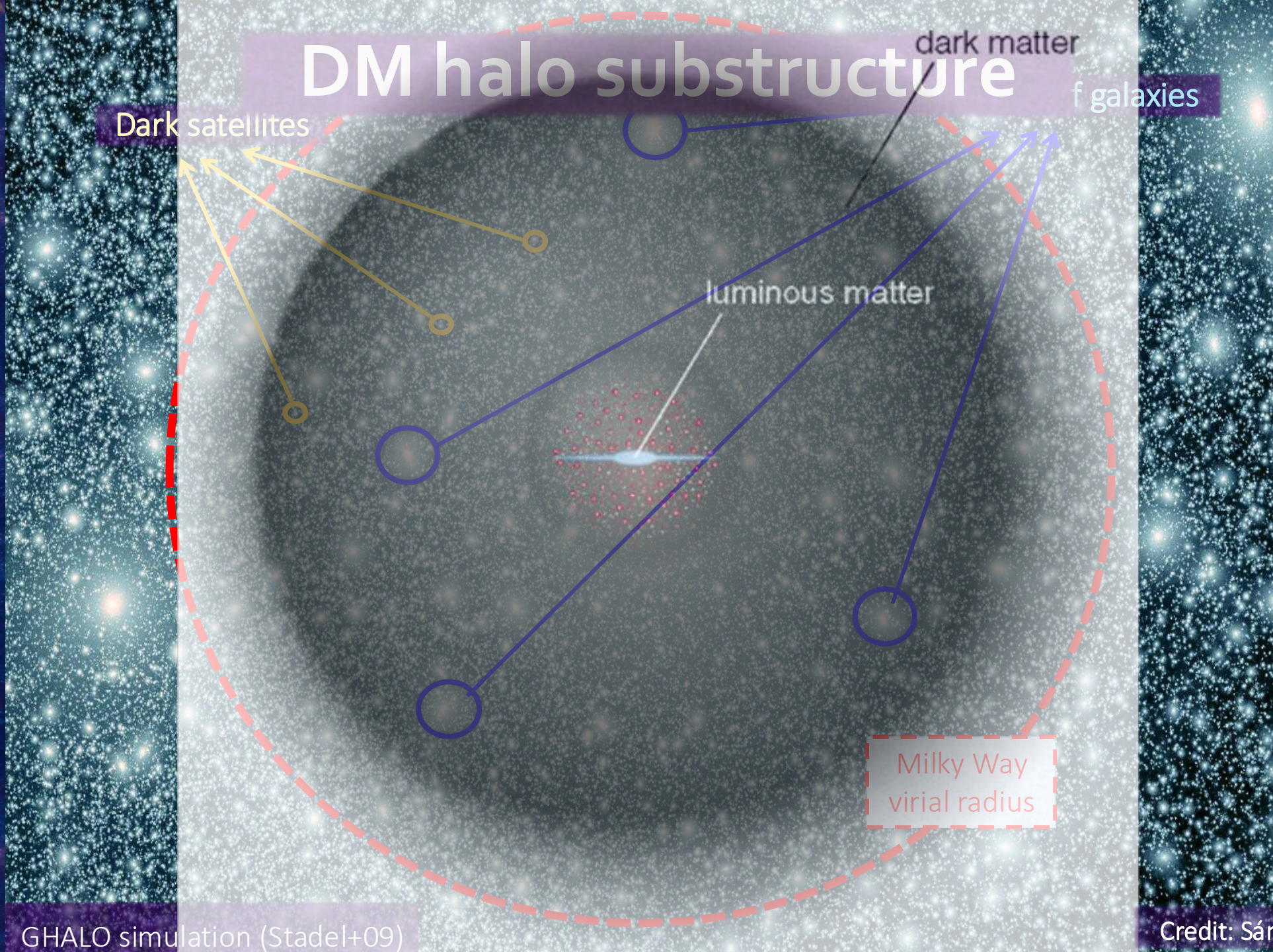
Dark satellites

dark matter

f galaxies

luminous matter

Milky Way
virial radius



Survival of CDM substructure

- Cuspy subhaloes are supposed to survive the host tidal forces: bound remnant
- Many are missing in (zoom-in) cosmological simulations: limited by numerical resolution
- A very high number of particles is needed to resolve the inner cusp properly
- How to overcome this?
 - Semianalytical approaches
 - Focusing the computational resources on an individual subhalo

van den Bosch+18

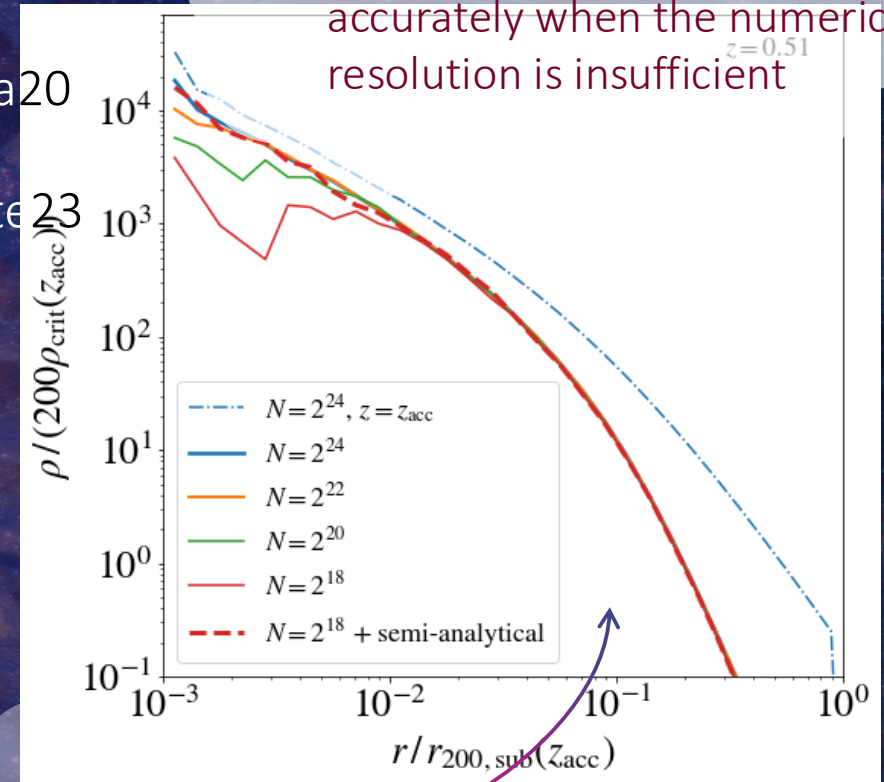
Ogiya+19

Errani+Peñarrubia20

Green+21

Delos+White23

The innermost part of the subhalo is not obtained accurately when the numerical resolution is insufficient

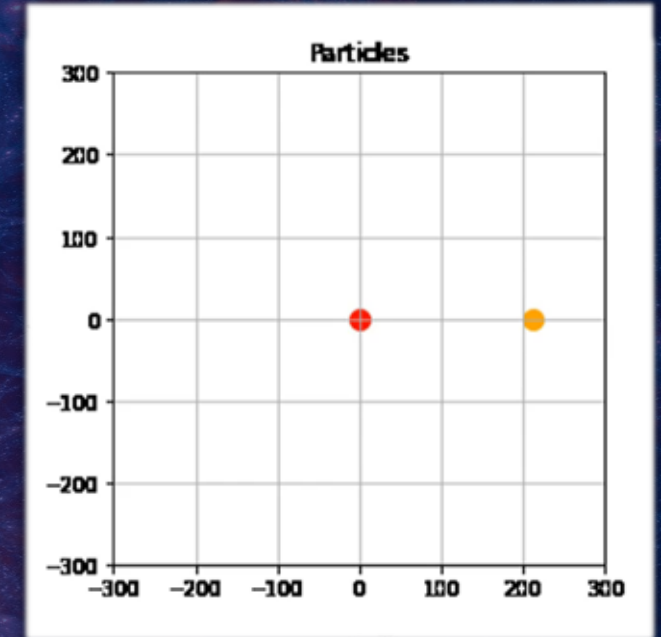


The subhalo DM density profile gets truncated as the mass loss takes place

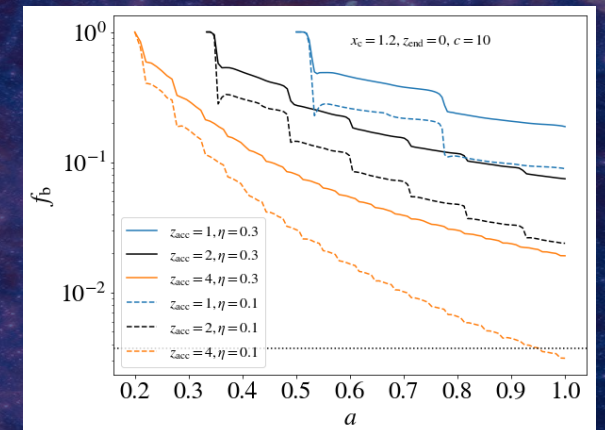
AAS+23

Focusing on individual subhaloes

- High-resolution numerical simulations (DASH, Ogiya+19) to follow the evolution of the subhalo
- Time-evolving host containing DM halo + baryonic disc + bulge
- Several subhalo initial parameters are varied:
 - Inner slope
 - Orbital configuration (circularity, orbital energy, inclination angle)
 - Accretion redshift
 - Concentration
- We already studied the evolution of the subhalo bound mass fraction (f_b) and annihilation luminosity (AAS+23)
- Previous work has also explored the evolution of the subhalo internal structure parameters: Peñarrubia+10 (P10), Errani & Navarro 21 (EN21), Du+24 (D24), Green & van den Bosch 19, Stücker+23 (including AAS), ... what do our simulations say?
- $N = 2^{25} \sim 3.3 \times 10^7$ particles in most cases



van den Bosch & Ogiya 18



AAS+23

Circular velocities

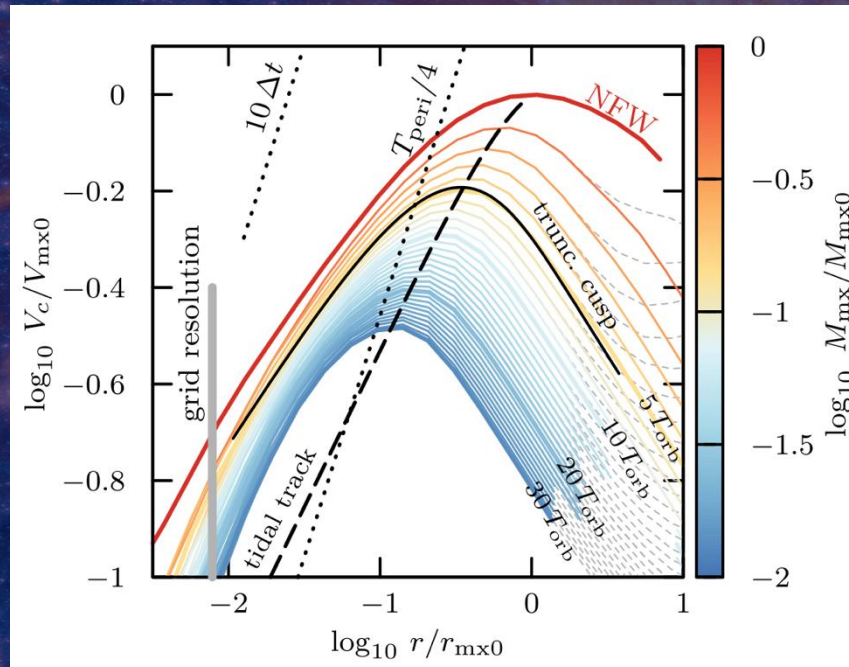
How do (maximum) circular velocities evolve as the subhalo loses mass?

What about the radius where this $V_{\max}$ is located ($r_{\max}$)?

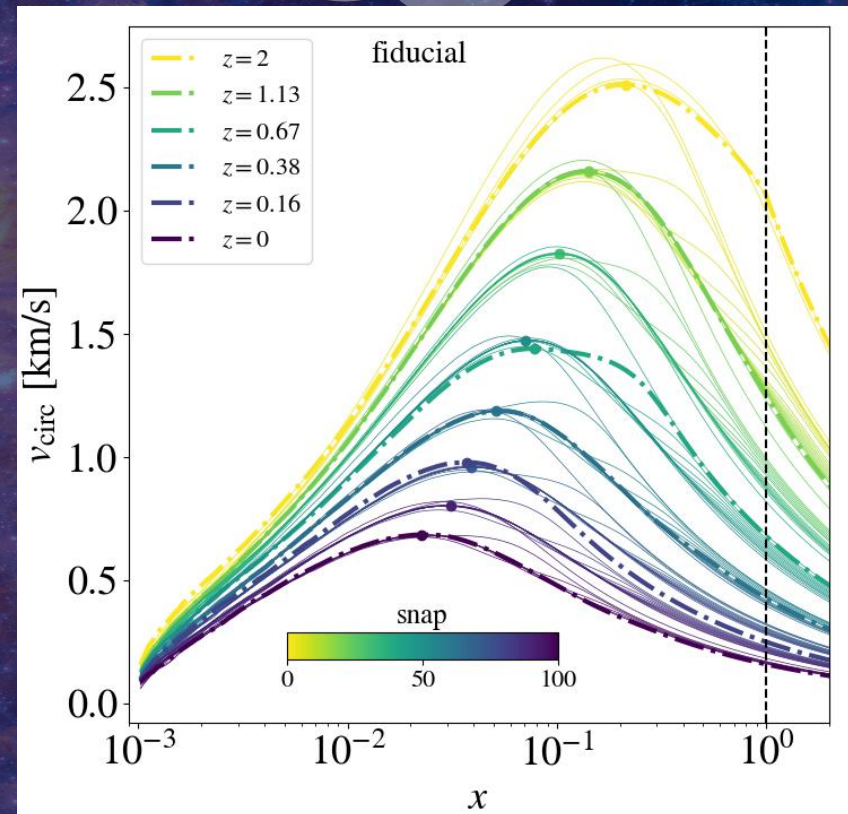
How does this evolution of $V_{\max}$ and $r_{\max}$ impact subhalo concentrations?

Tidal tracks

$$c_V = 2 \left(\frac{V_{\max}}{H(z)R_{\max}} \right)^2$$

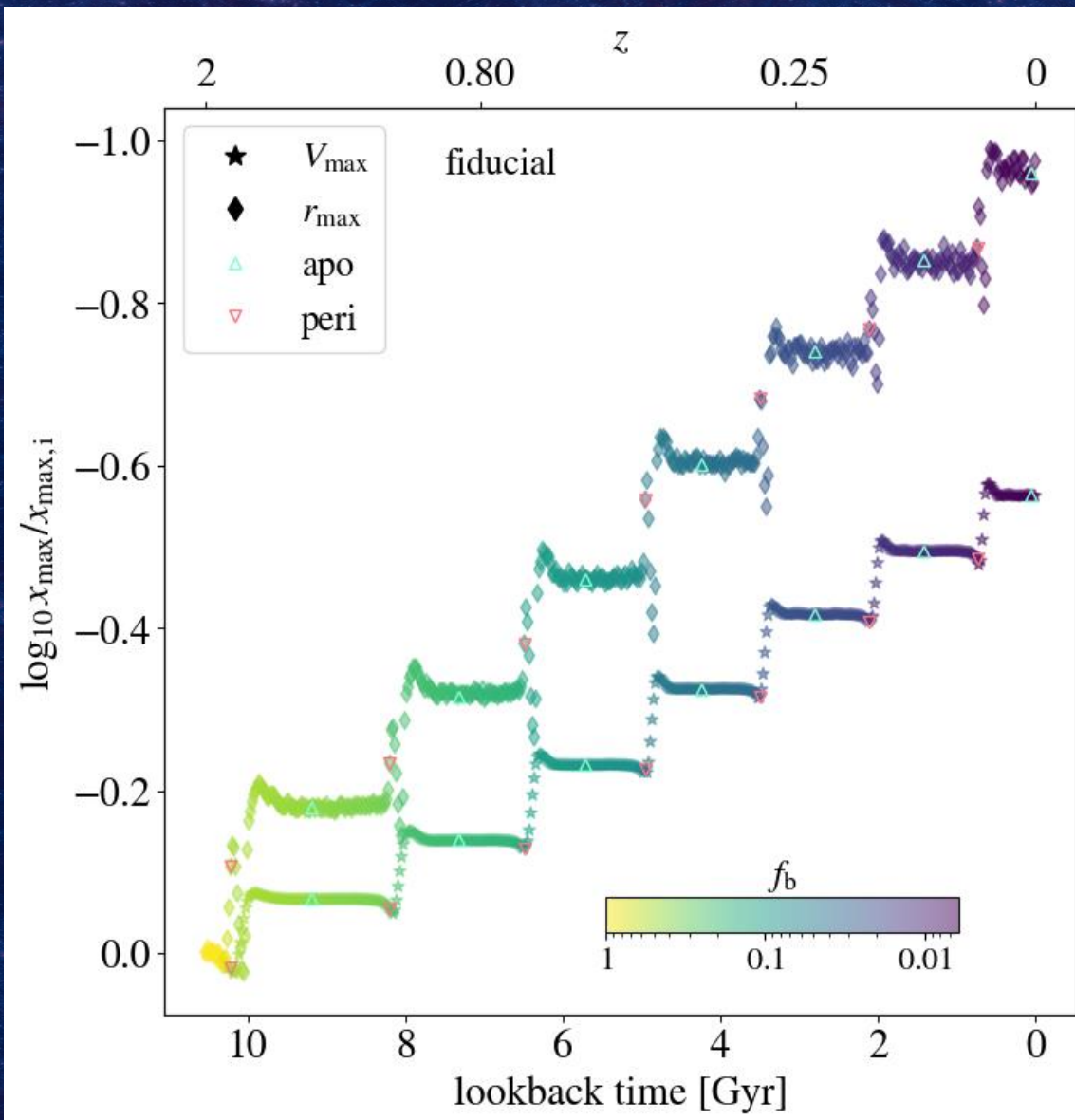


Errani+22



AAS+25

Evolution of internal structure

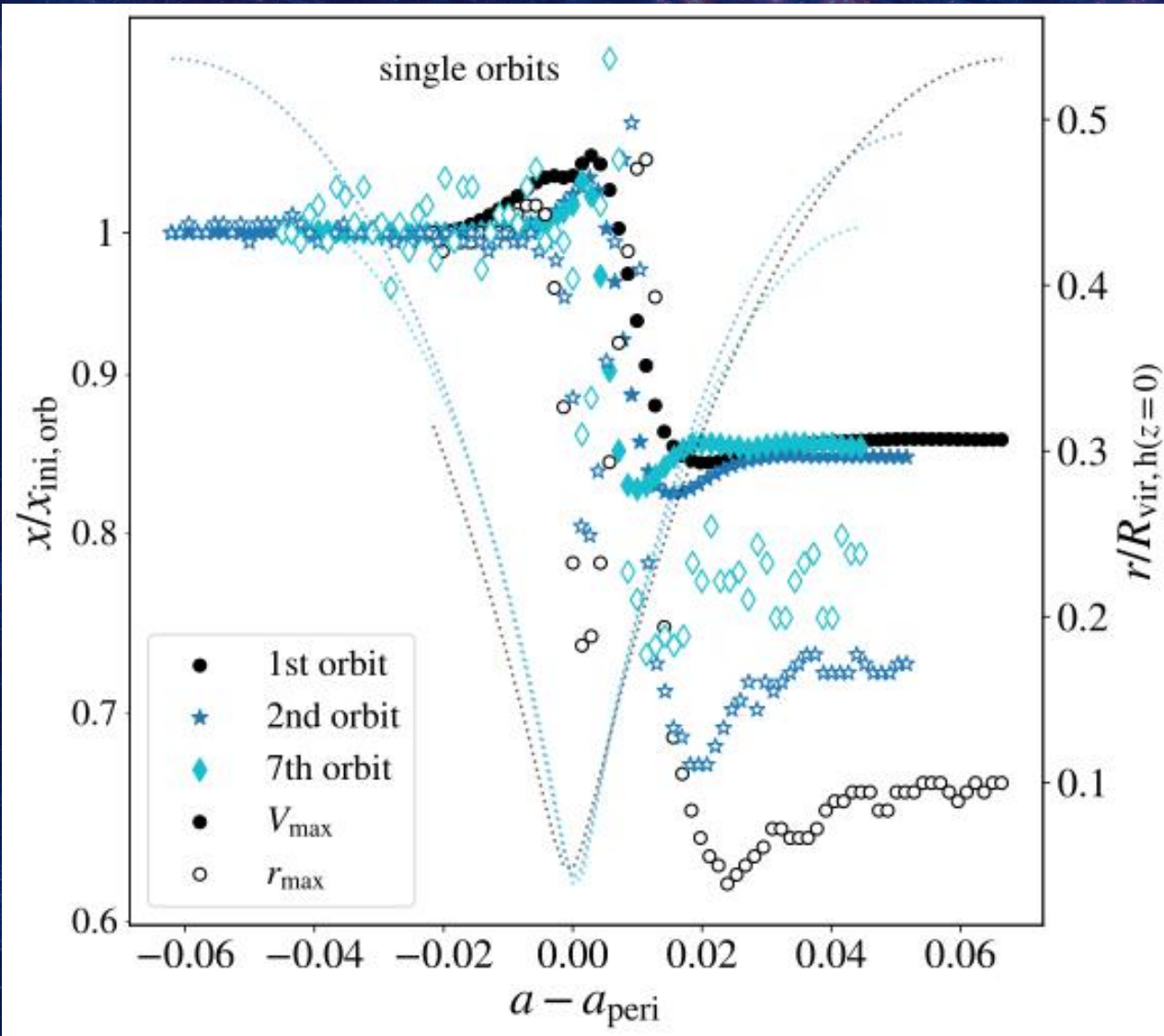


Both $V_{\max}$ and $r_{\max}$ decrease mainly at the pericentre (stronger tidal forces)

A stable tidal track can be found looking at the apocentre, but we want to explore the behaviour at the pericentre as well

$V_{\max}$ decreases less than $r_{\max}$; $r_{\max}$ becomes more stable with time

Evolution of internal structure



Both V_{max} and r_{max} decrease mainly at the pericentre (stronger tidal forces)

A stable tidal track can be found looking at the apocentre, but we want to explore the behaviour at the pericentre as well

V_{max} decreases less than r_{max} ; r_{max} becomes more stable with time

Tidal tracks for NFW subhaloes

- Apocentre tidal track $V_{\max} - f_b$ below pericentre curve reflects $V_{\max}$ increase at pericentre

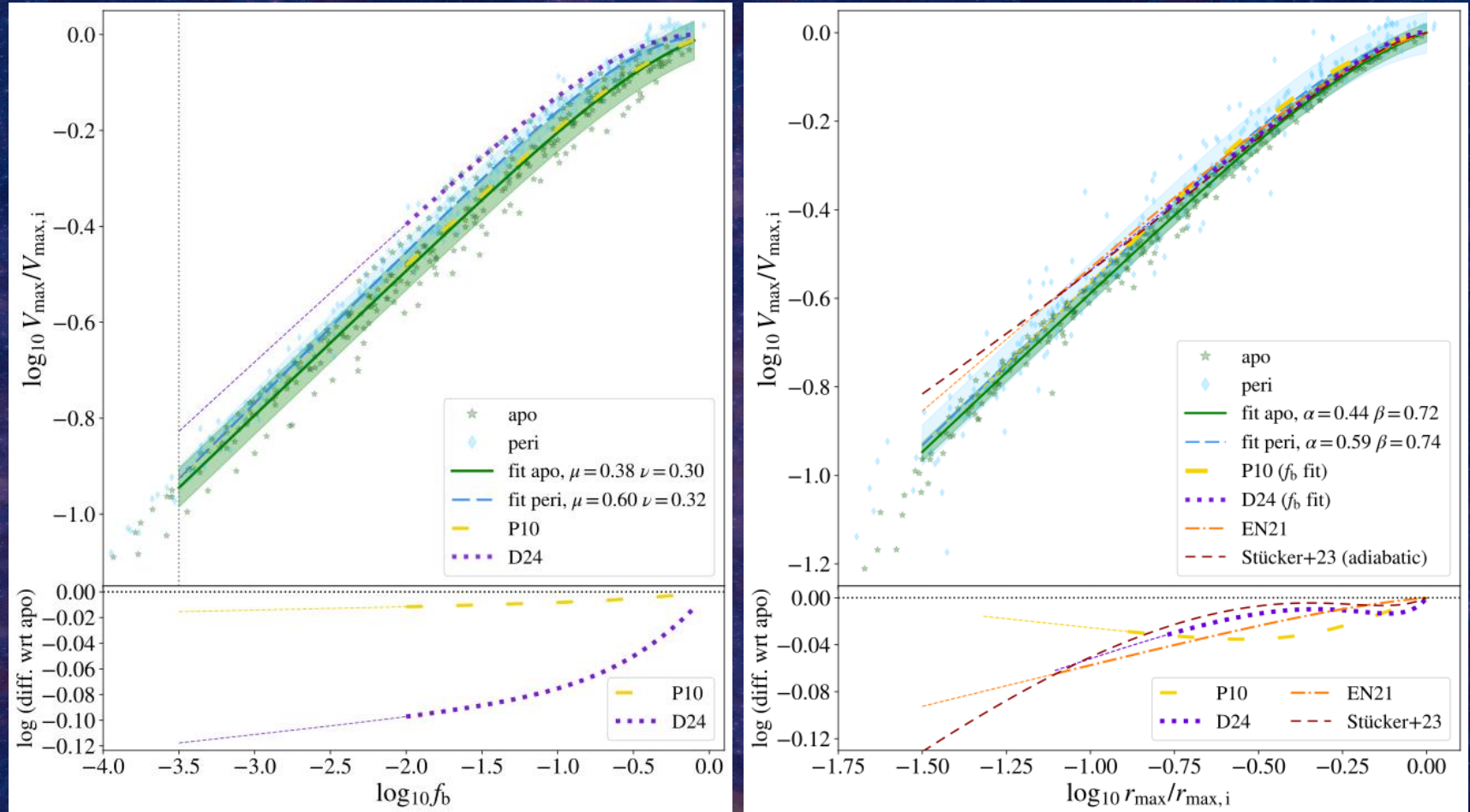
- Apocentre tidal track consistent with P10

- Peñarrubia+10 (left):

$$g(x) = \frac{2^\mu x^\nu}{(1+x)^\mu}$$

- EN21 (right):

$$g(x) = 2^\alpha x^\beta [1+x^2]^{-\alpha}$$

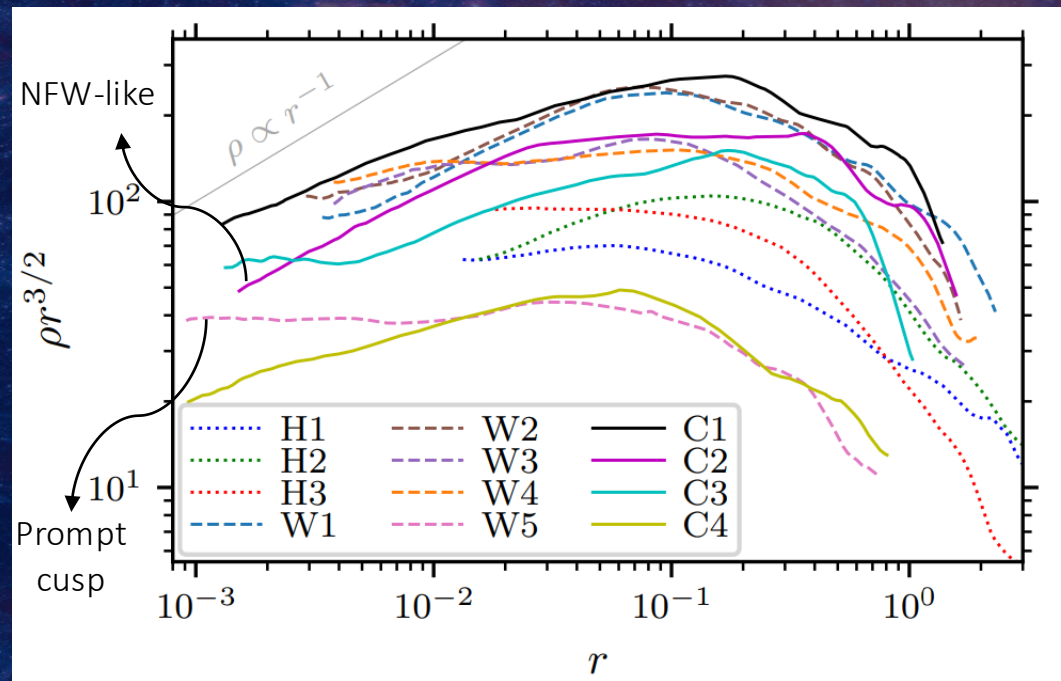


Steeper than NFW: prompt cusps

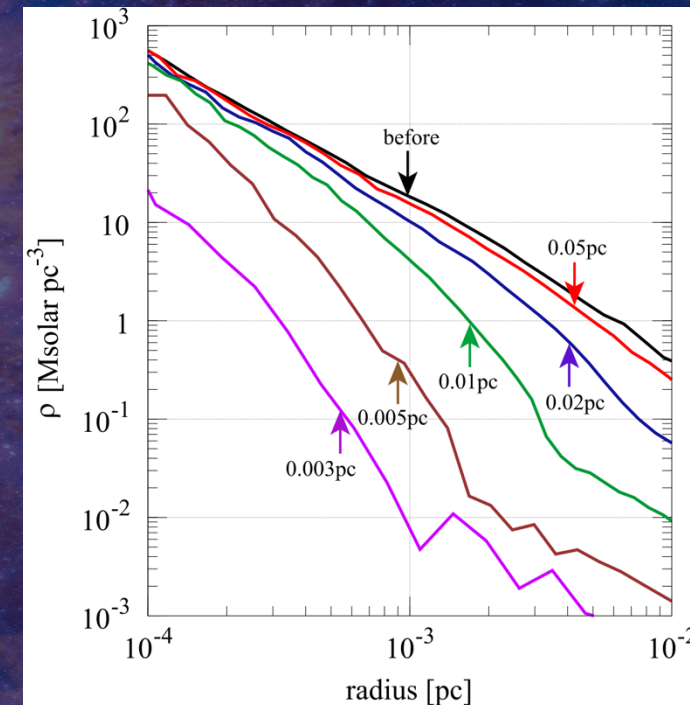
- The first DM haloes (~Earth mass in CDM) formed from density peaks
- Their density profile is supposed to exhibit a prompt cusp: $\rho \propto r^{-3/2}$
- Even stellar encounters can have an impact on such small structures!

(Ishiyama+10)

(Delos+White23)



Delos+White23



Ishiyama+10

Tidal tracks for prompt cusps

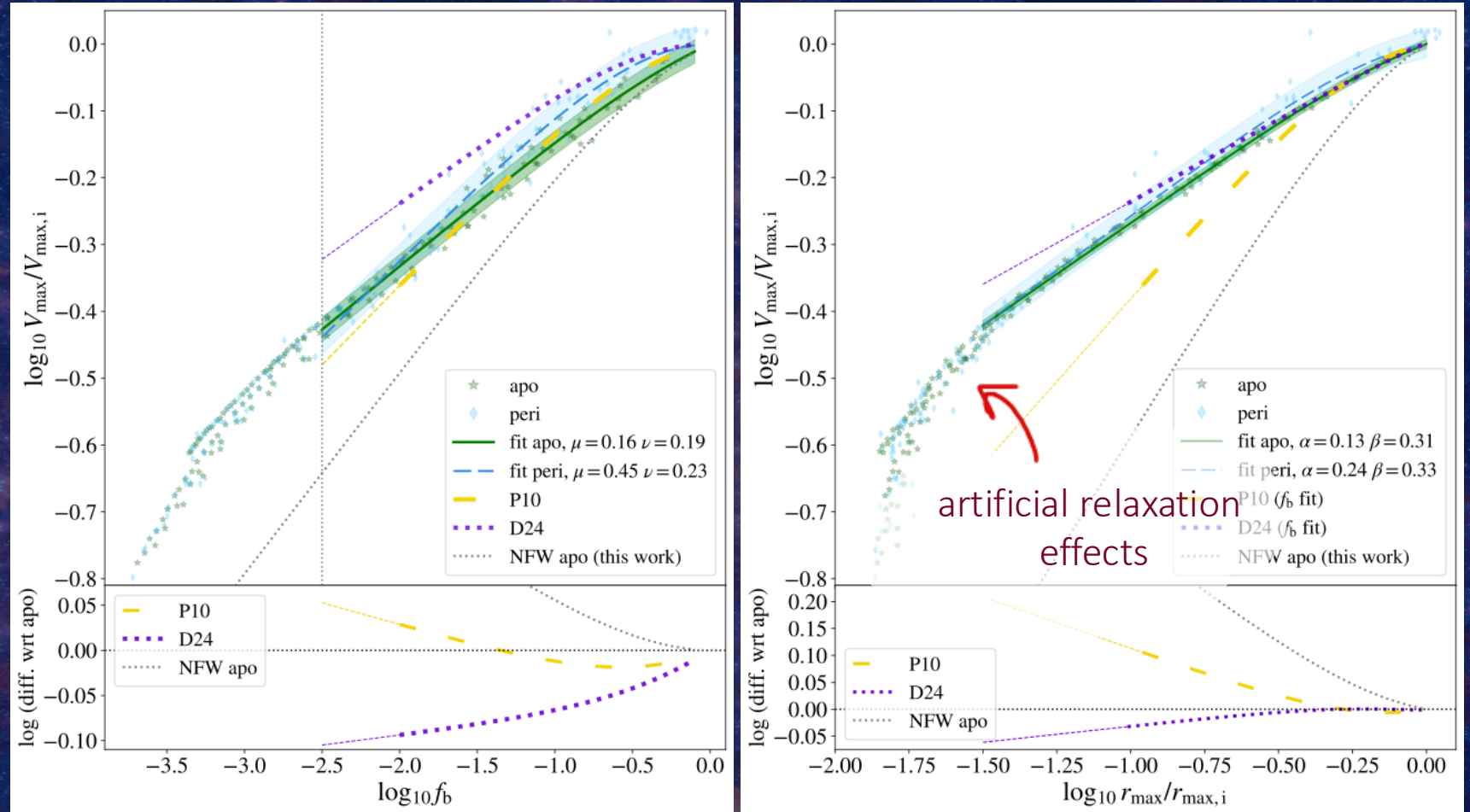
- $V_{\max}$ decreases less wrt NFW subhaloes
- Pericentre tidal track reaches the apocentre faster
- Our fits lie between D24 and P10

- Peñarrubia+10 (left):

$$g(x) = \frac{2^\mu x^\nu}{(1+x)^\mu}$$

- EN21 (right):

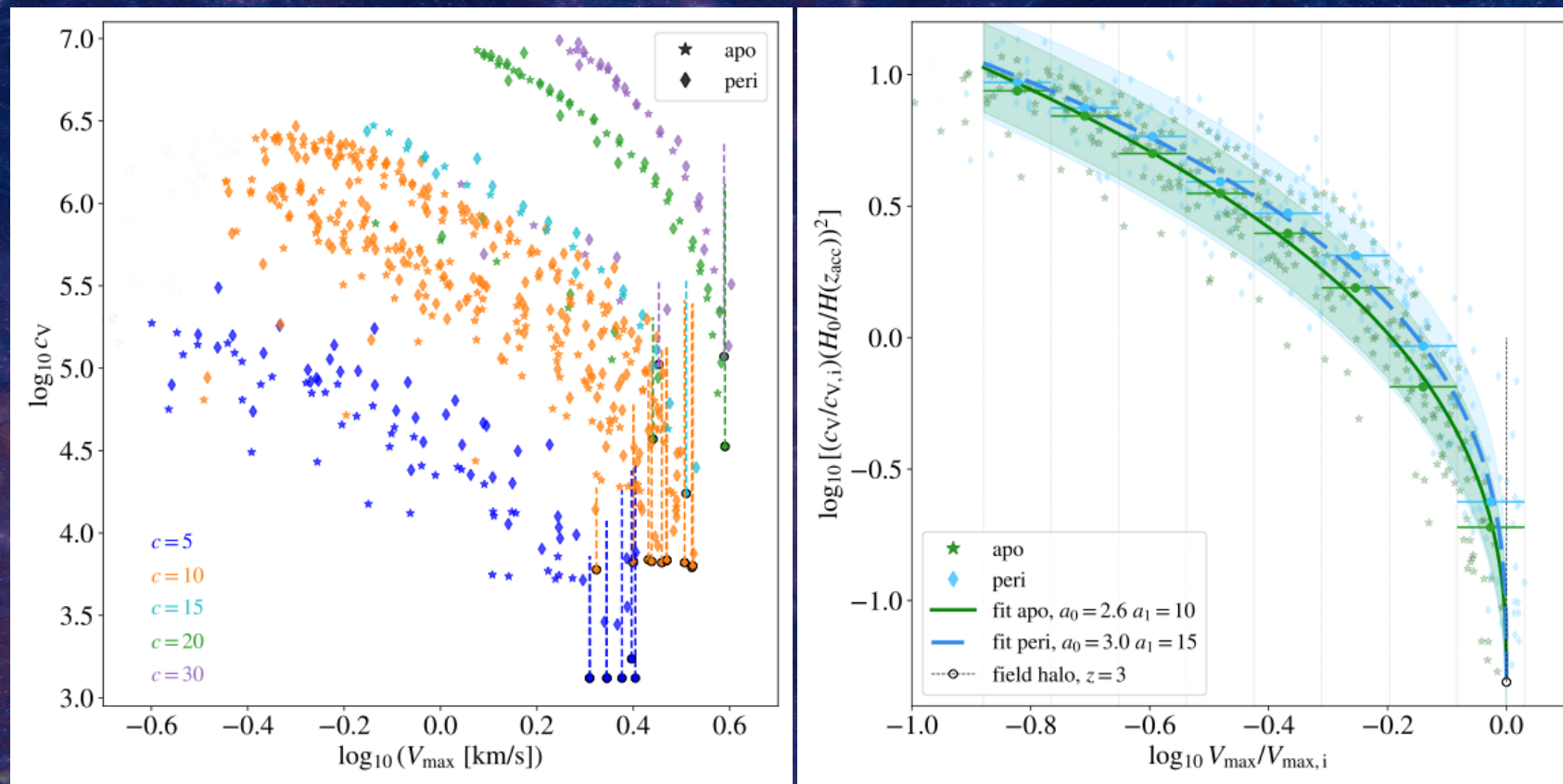
$$g(x) = 2^\alpha x^\beta [1+x^2]^{-\alpha}$$



Subhalo concentrations

- Concentrations increase with time since $r_{\max}$ decreases more than $V_{\max}$
- c_V increase $\sim$ two orders of magnitude (vs $\sim$ one oom for field halos)
- We find a significant scatter driven by z_{acc}
- Higher c_V at pericentre
- We propose:

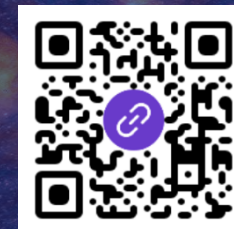
$$\log_{10} g(x) = (a_1 |\log_{10} x|)^{1/a_0}$$



$$c_V = 2 \left(\frac{V_{\max}}{H(z)R_{\max}} \right)^2$$

Summary & conclusions

- After our survival work AAS+23, now we characterise subhalo tidal tracks with great particle resolution ($O(10^7)$ particles)
- Extensive initial configuration parameter space: inner slopes (NFW & prompt cusps), concentrations, orbital parameters, accretion redshift. The host is described with a time-evolving analytical potential including baryons
- Our results show:
 - Both $V_{\max}$ and $r_{\max}$ decrease with time
 - While $r_{\max}$ shrinks more than $V_{\max}$, its rate of decrease diminishes with time
 - First prompt cusps tidal track $V_{\max} - r_{\max}$ and pericentre tidal tracks
 - Prompt cusps remain more stable (larger $V_{\max}$) than NFW
 - Velocity concentrations increase with time up to 2 orders of magnitude, this way enhancing concentrations wrt field haloes
- Relevant for lensing, streams, indirect DM searches
- Check it out! arXiv:2506.01152

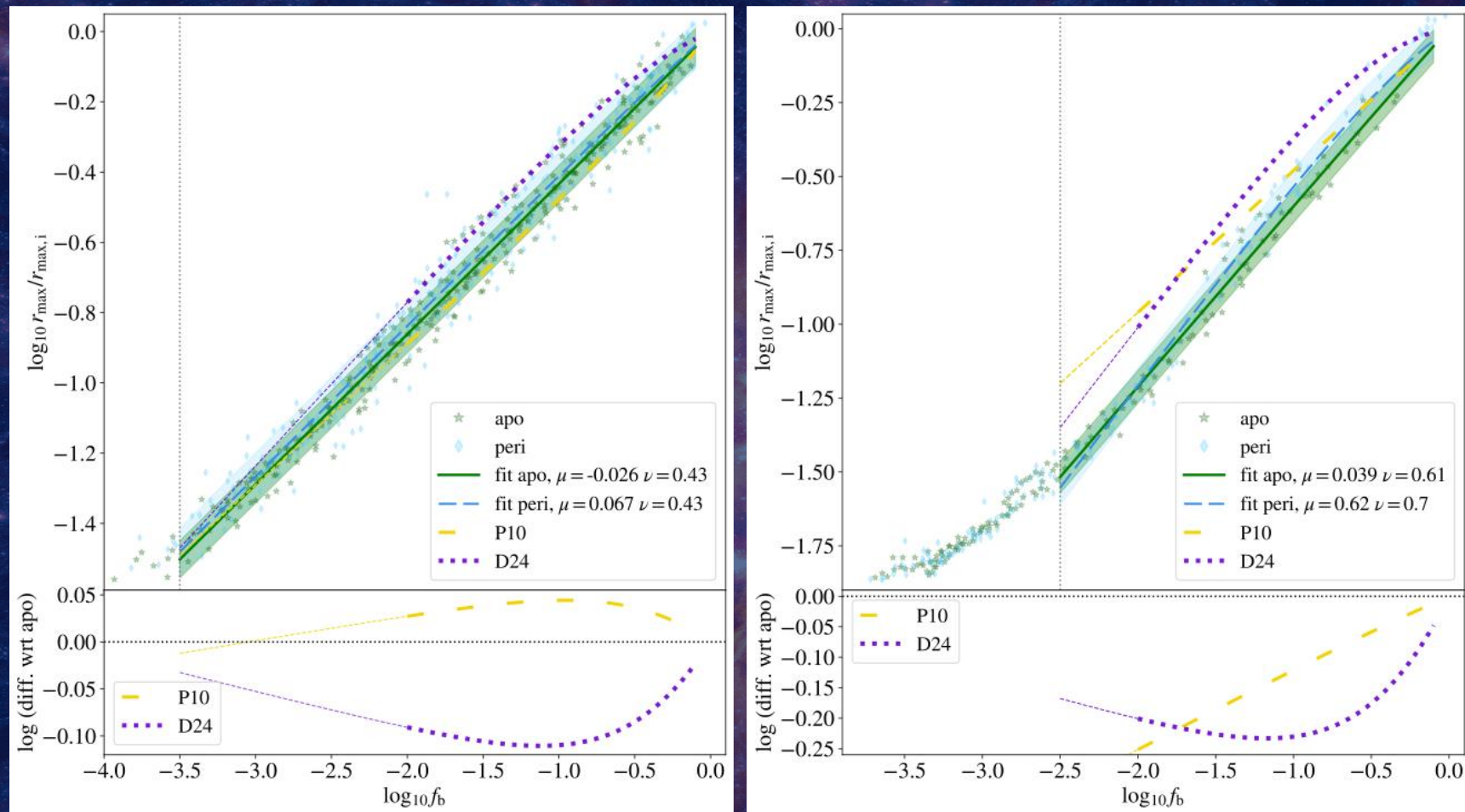


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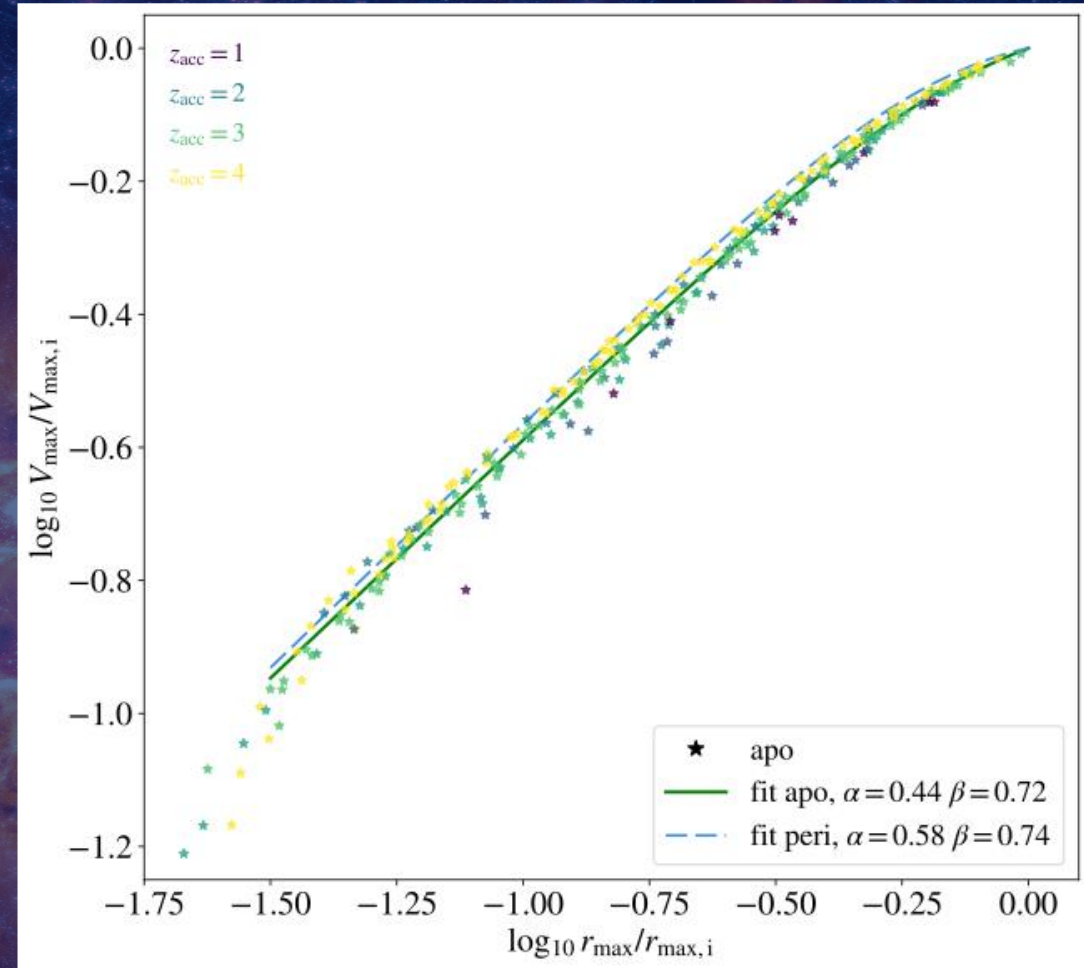
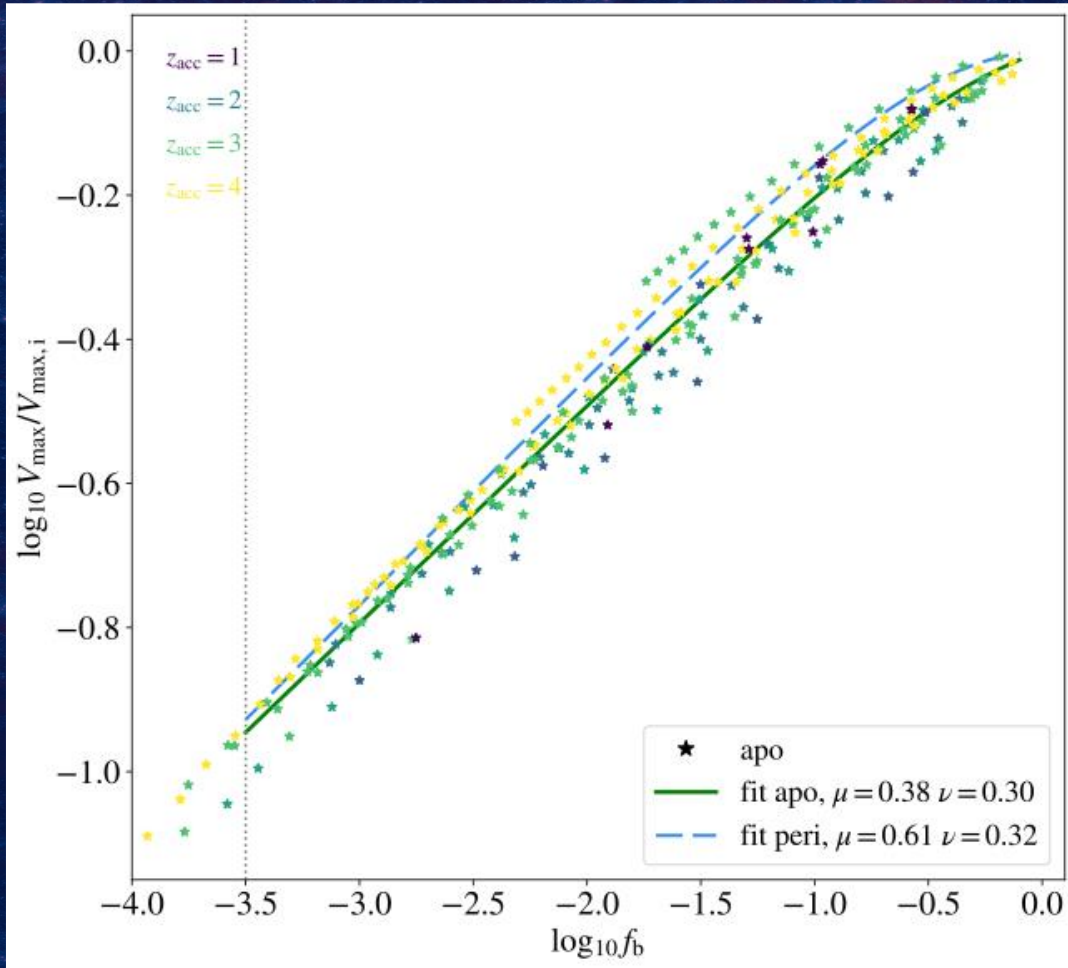
Thank you!

Back-up slides

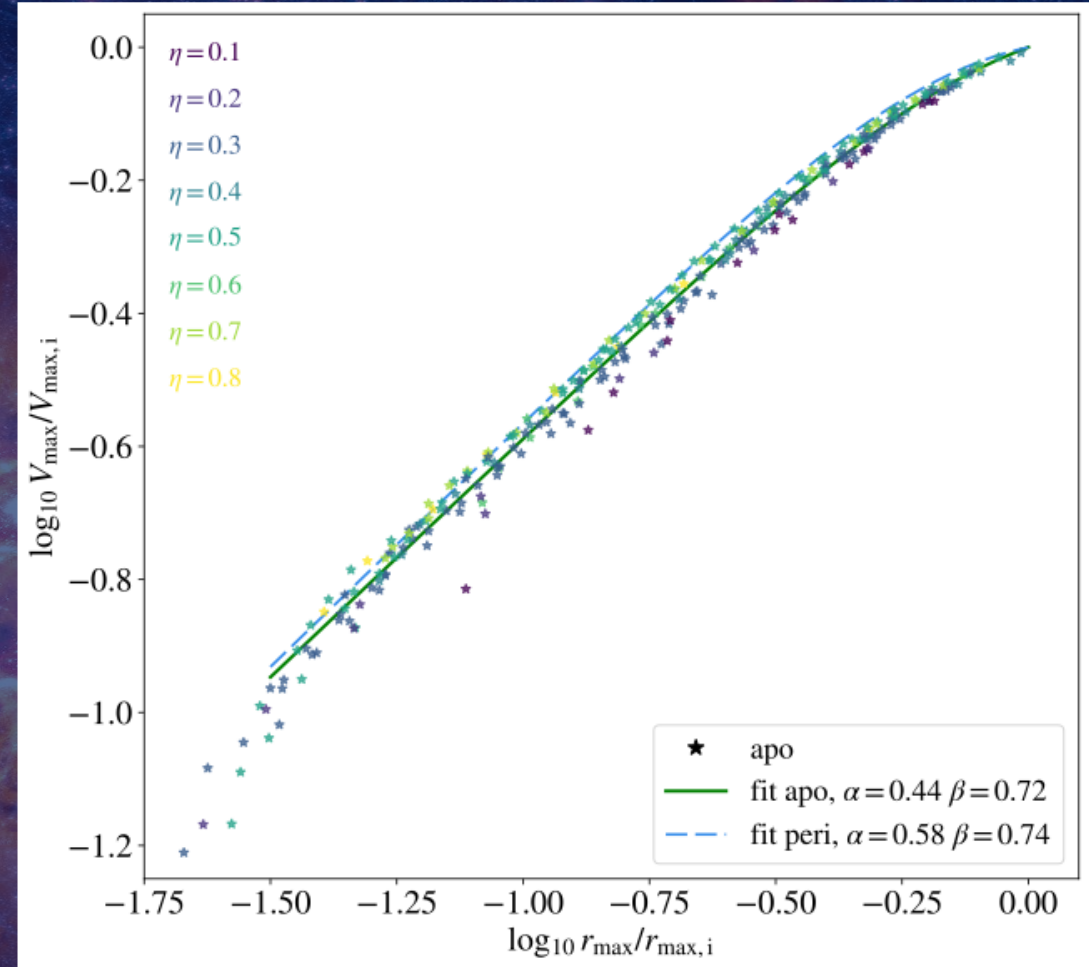
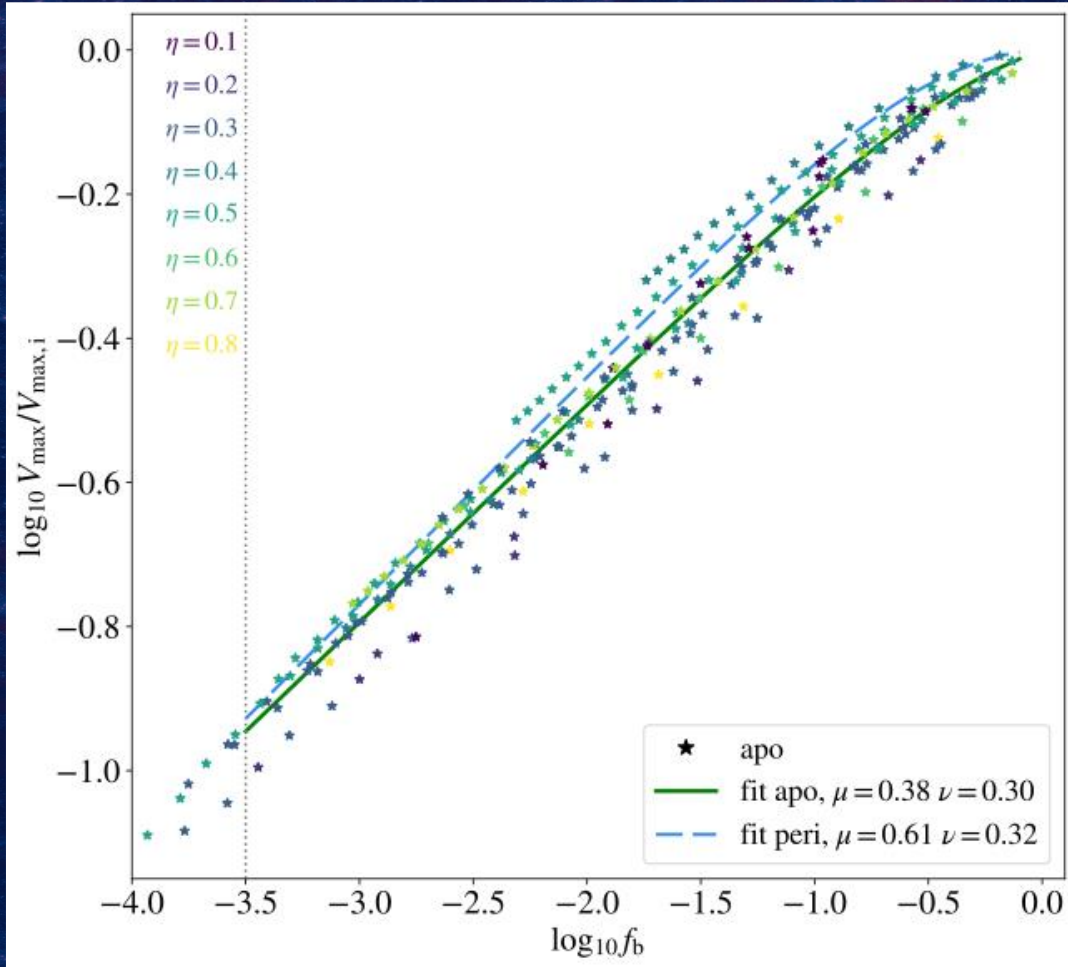
Tidal tracks $r_{\max} - f_b$



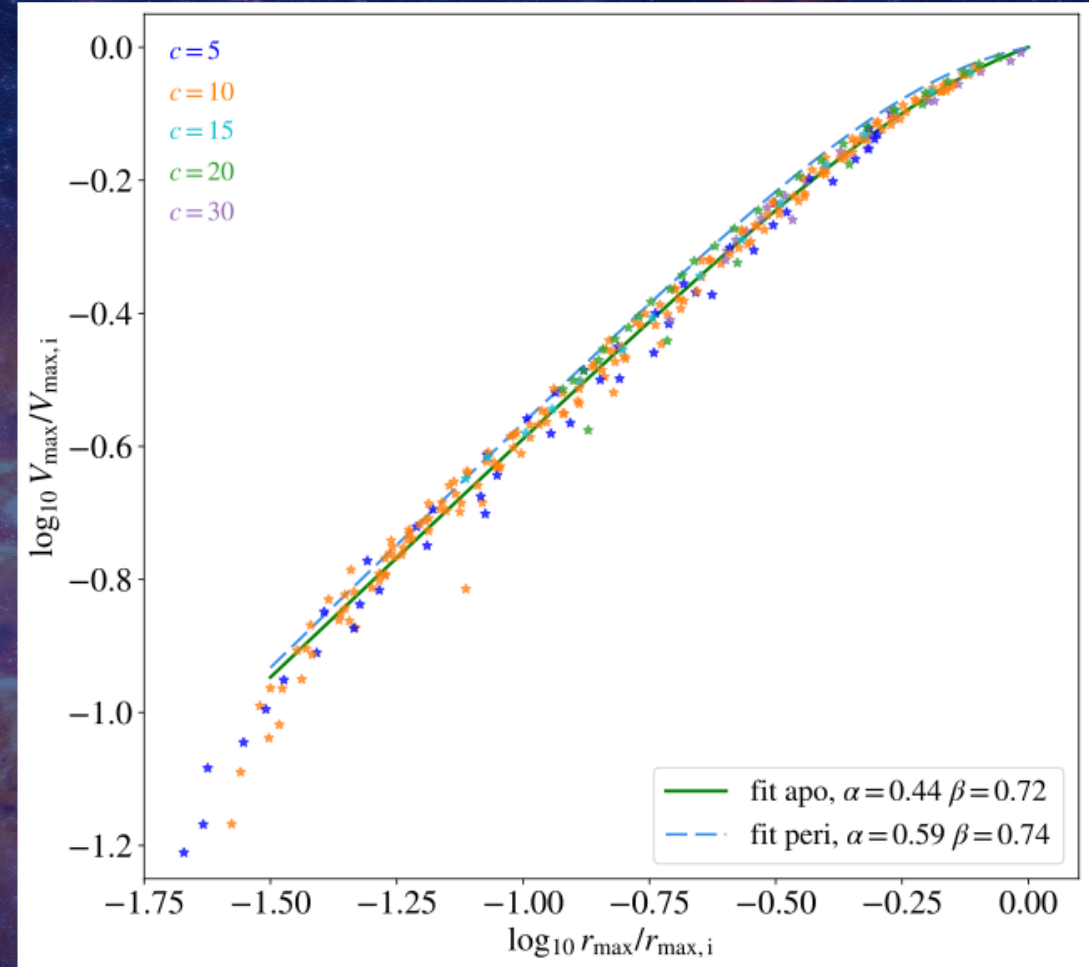
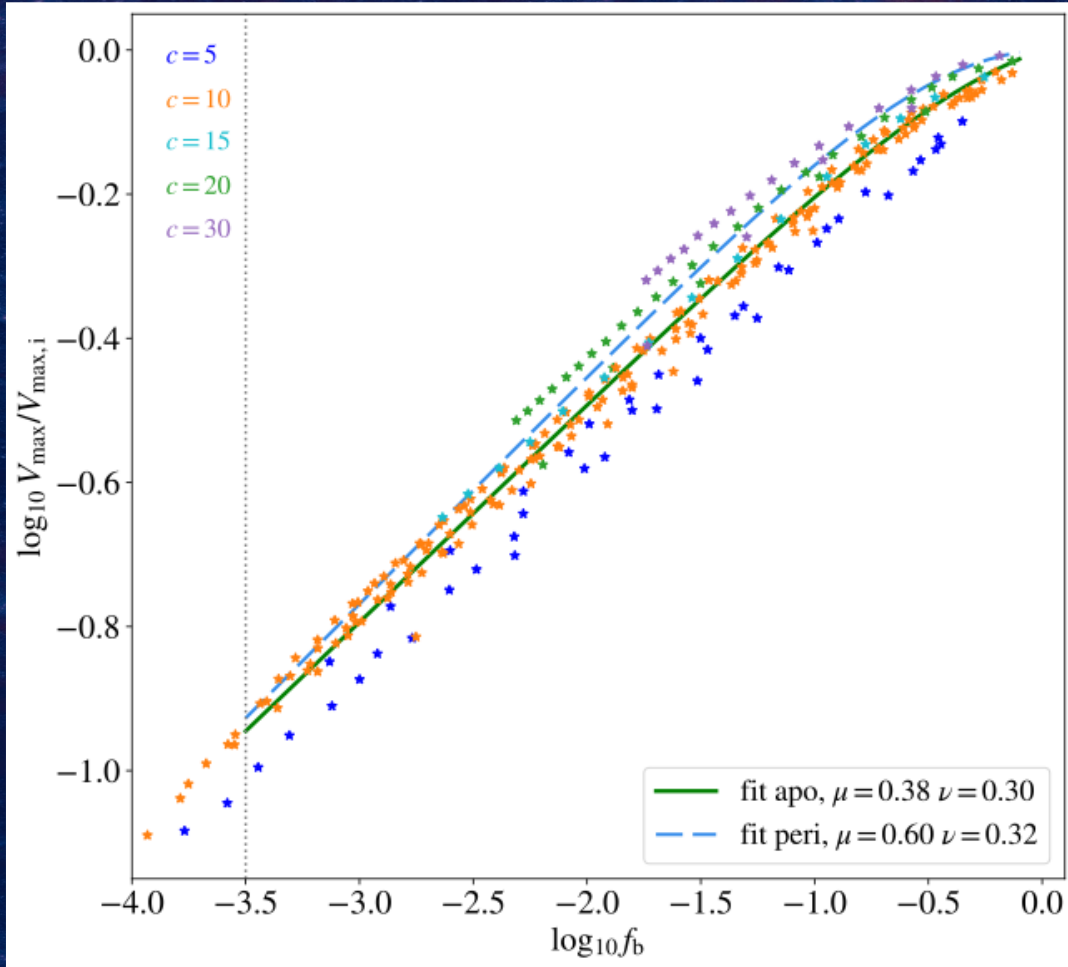
Tidal track dependence on z_{acc}



Tidal track dependence on η

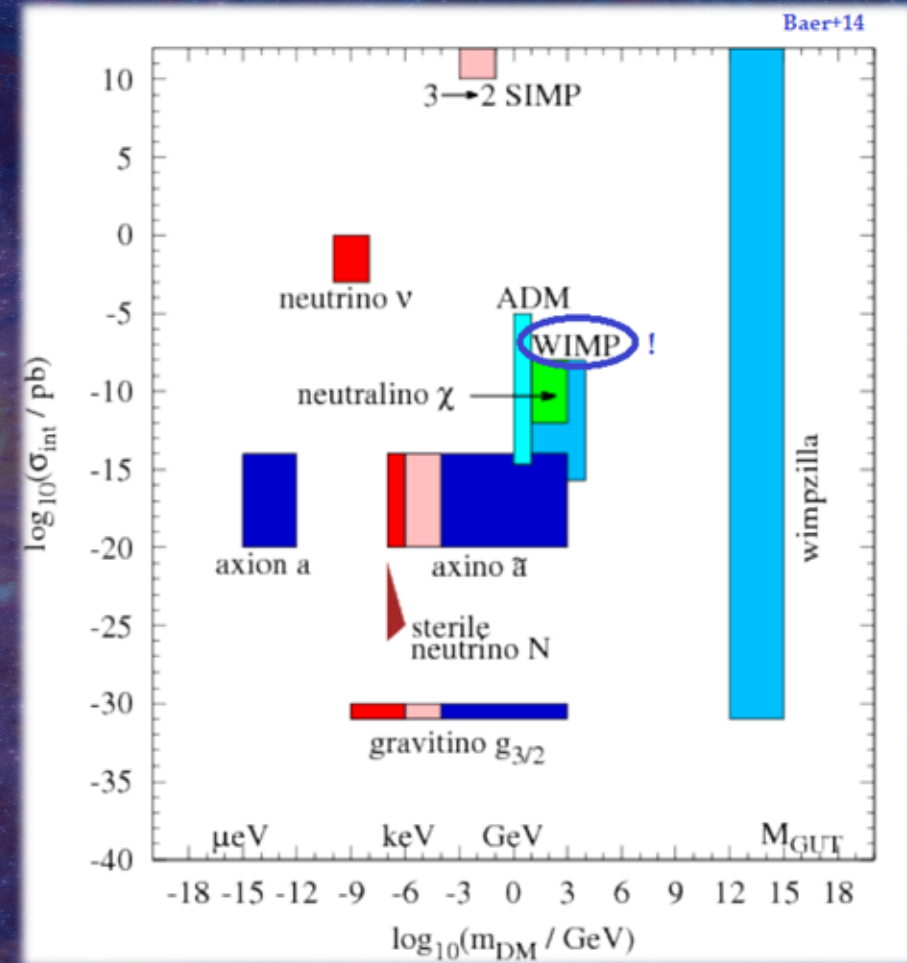
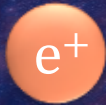


Tidal track dependence on c



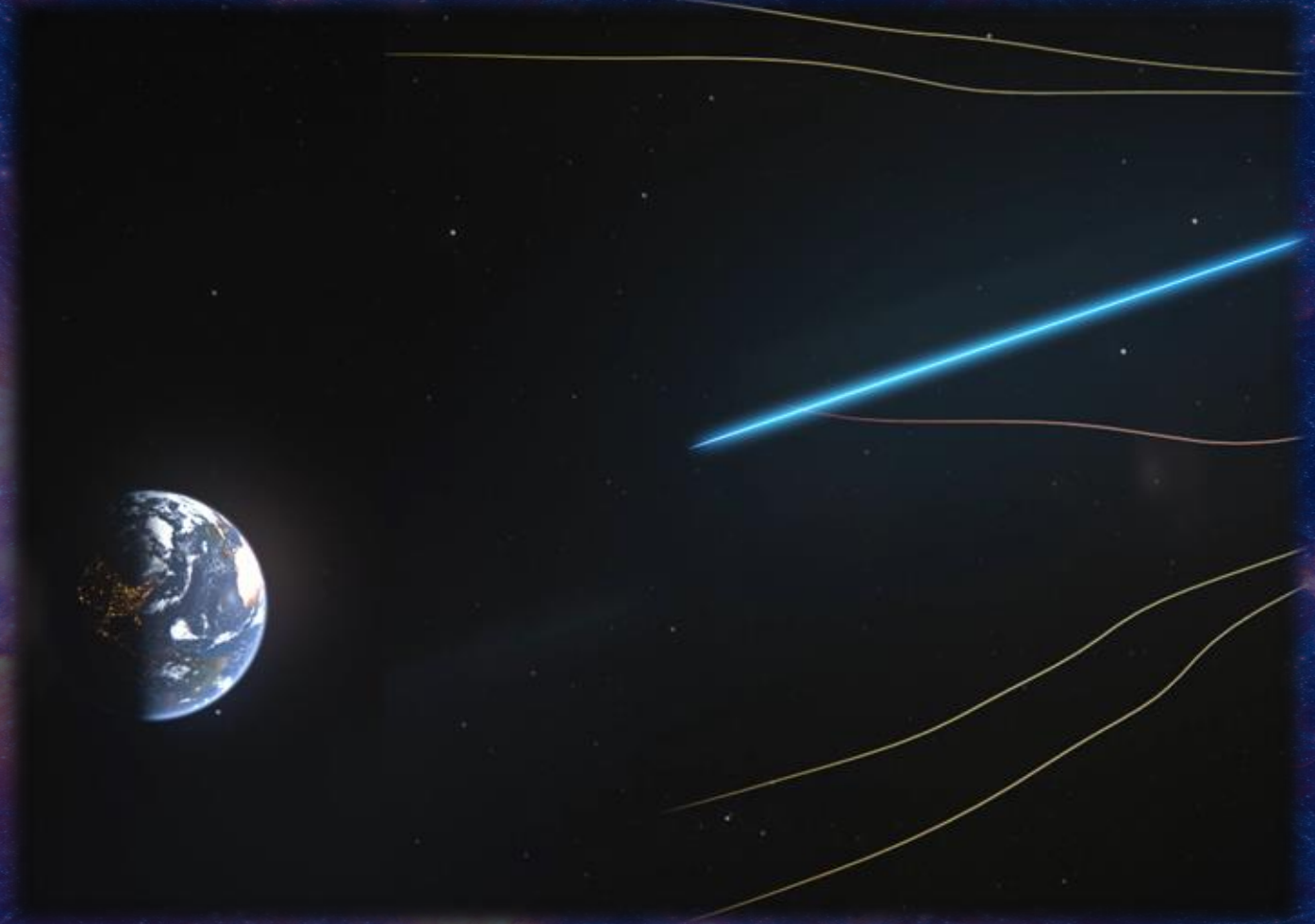
The nature of DM

- We still do not know what DM is made of: particle zoo
 - Weakly Interacting Massive Particles (WIMPs) among the preferred ones
 - ❖ direct production at colliders
 - ❖ direct detection through scattering
 - ❖ indirect detection
- possible annihilation products:



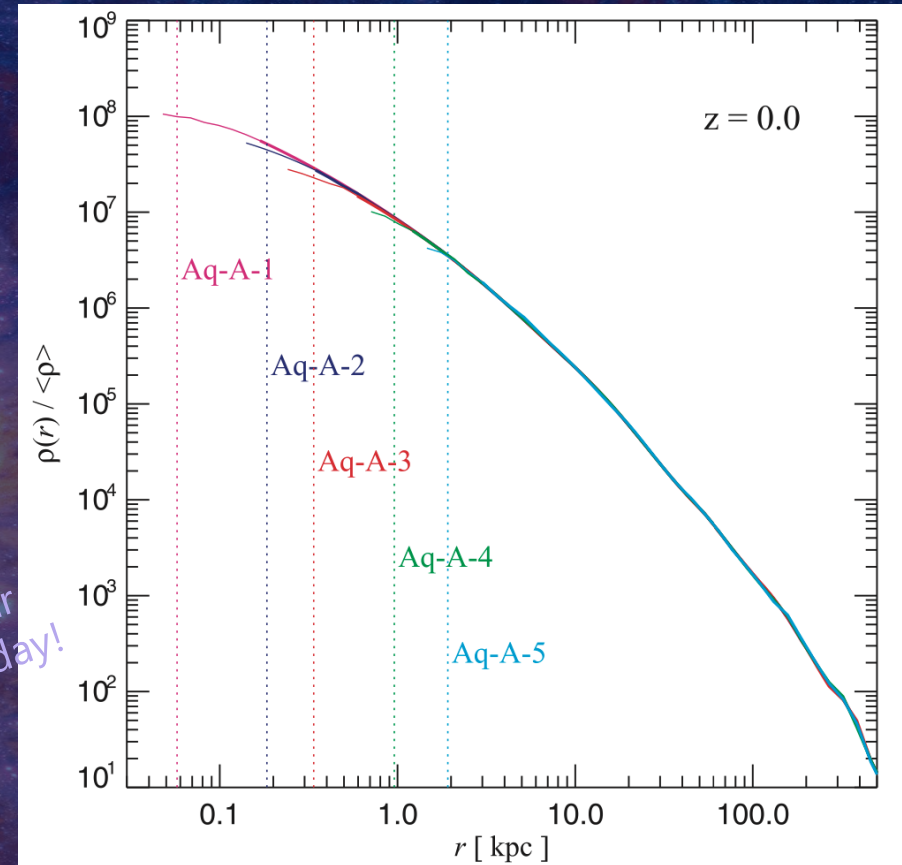
The 'golden channel': gamma rays

- **Neutrinos** are difficult to detect
- **Antimatter** can be deflected by magnetic fields and loses energy
- ✓ **Gamma rays** travel following straight lines and do not undergo attenuation
- Energy of annihilation products depends on DM particle mass:
~GeV-TeV
- γ -ray flux: $F = J \cdot f_{pp}$
 - J -factor: astrophysical factor:
DM density squared and particle mass
 - f_{pp} : particle physics factor:
DM density squared and particle mass and cross section



Simulation of galaxy formation is a very hot topic

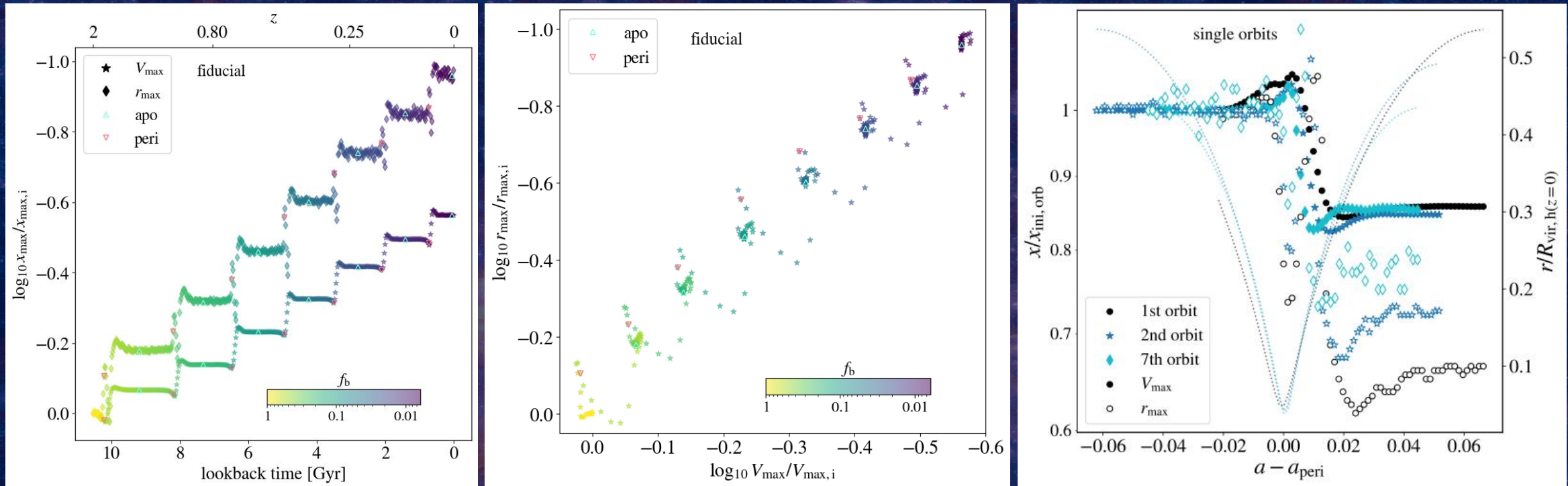
- Best tools in the non-linear regime
- Zoom-in simulations help analyse the details and substructure of haloes
- Limited by numerical resolution
- Subhaloes with masses smaller than several times the particle mass cannot be simulated
- How to overcome this?
 - Repopulation procedure: generating subhaloes below the resolution limit of the parent simulation via extrapolation
 - Focusing the computational resources on an individual subhalo



Springel+08

IAC seminar
next Tuesday!

Evolution of internal structure



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