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Based on arXiv:2506.01152

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

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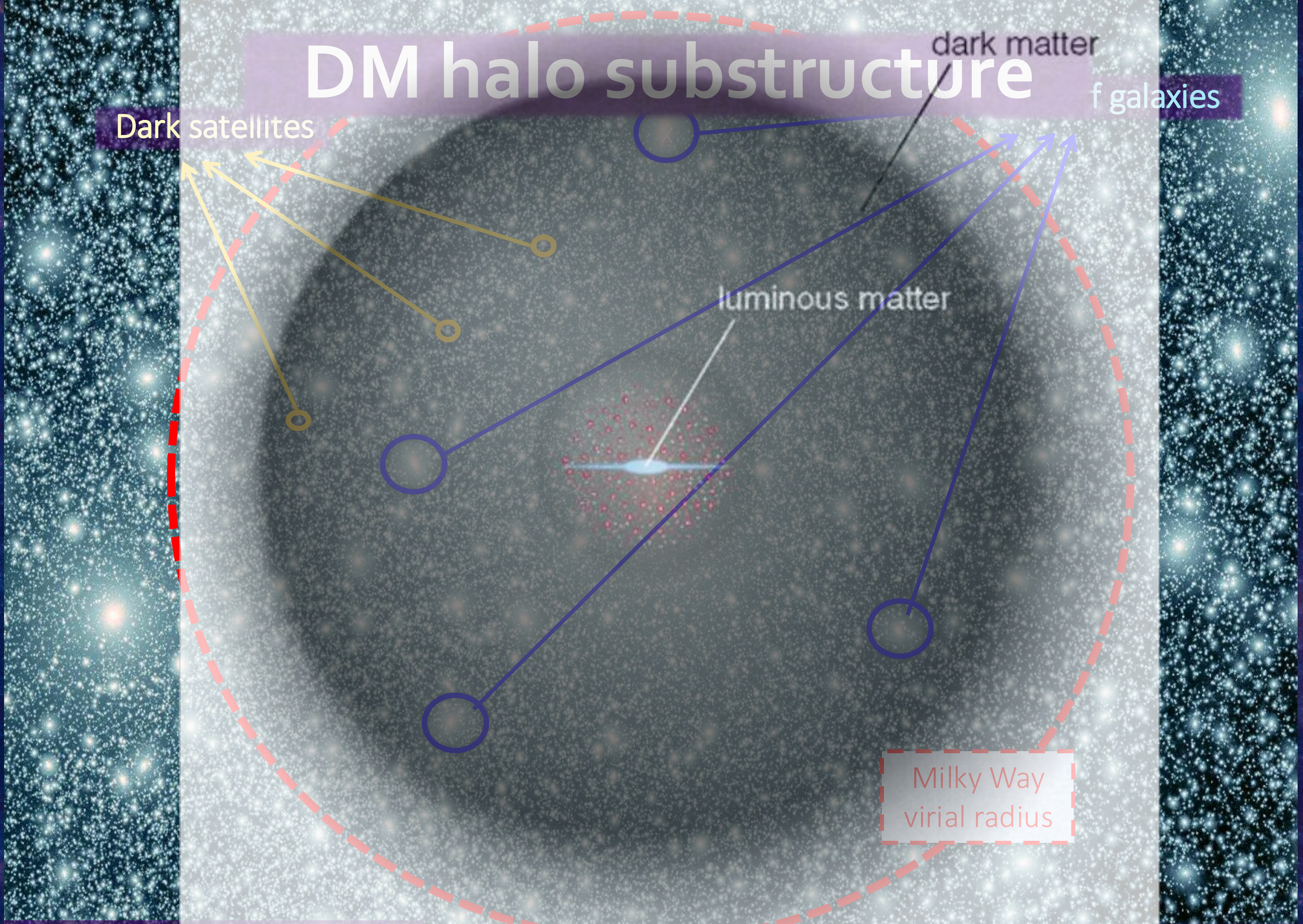
Vniversitat de València

DM halo substructure



GHALO simulation (Stadel+09)

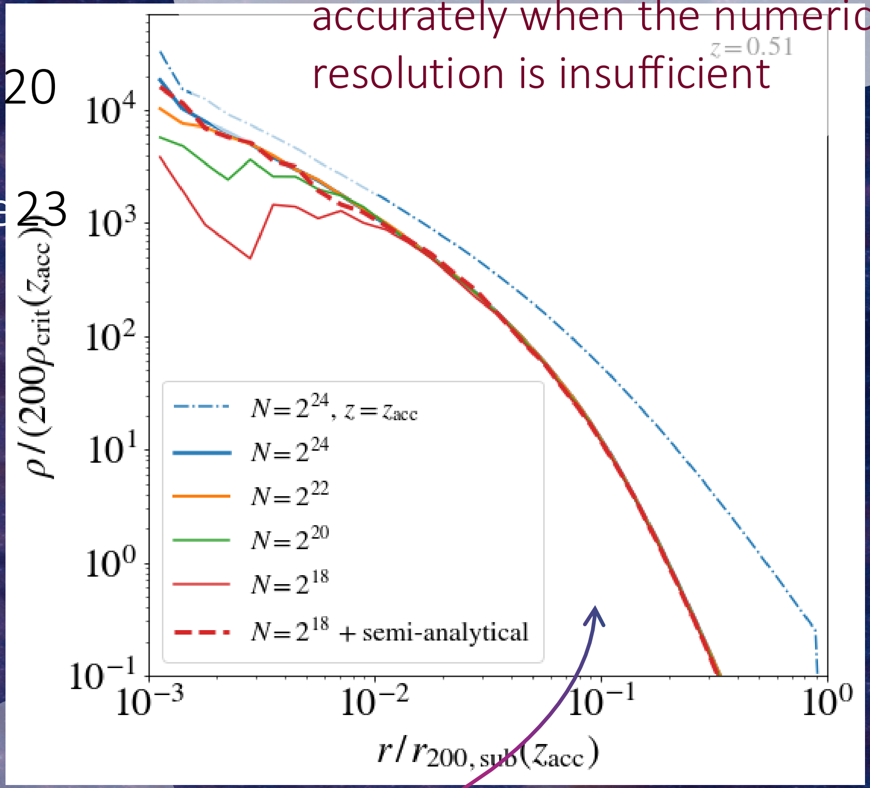
Credit: Sánchez-Conde

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



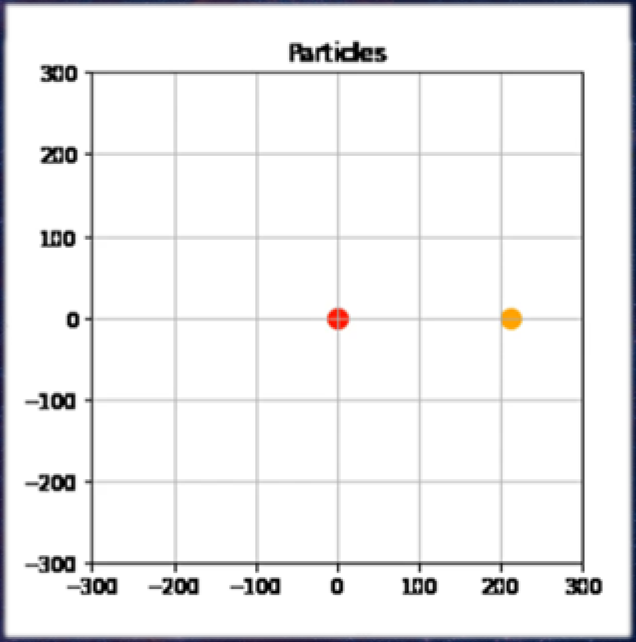
AAS+23

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

Alejandra Aguirre-Santaella

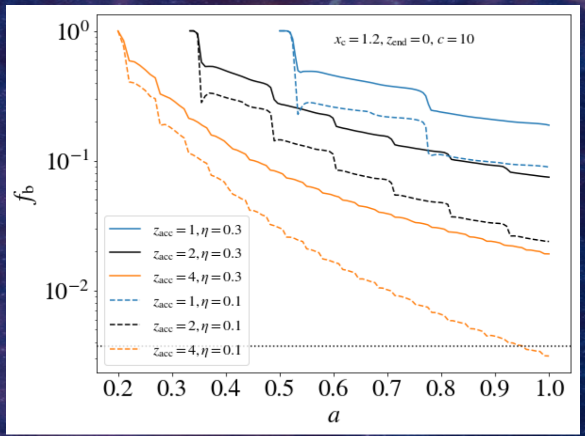
Focusing on individual subhaloes

- 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} ~ 3.3 x 10^7 particles in most cases



van den Bosch+Ogiya18

by J Stücker



AAS+23

Circular velocities

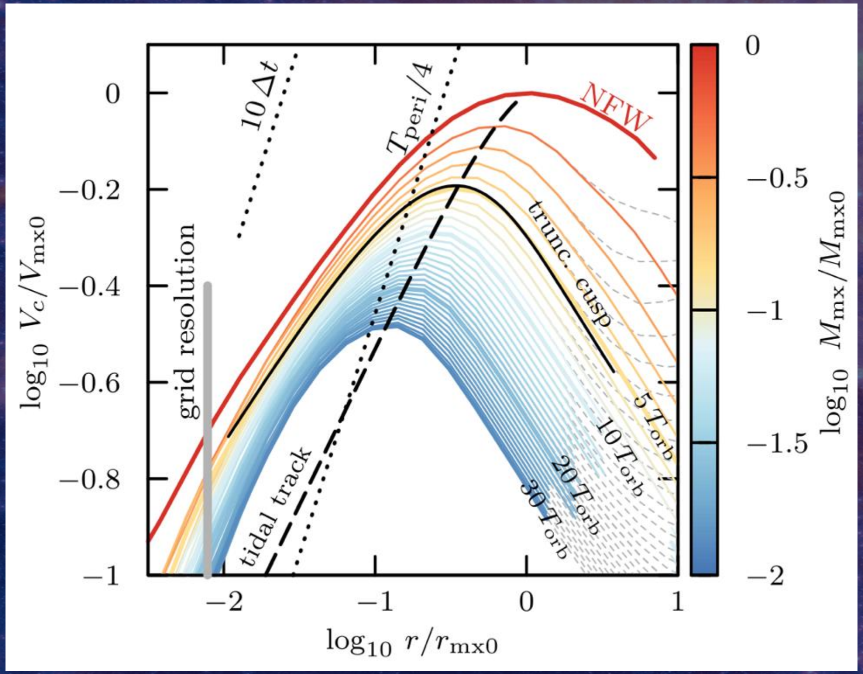
How do (maximum) circular velocities evolve as the subhalo loses mass?

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

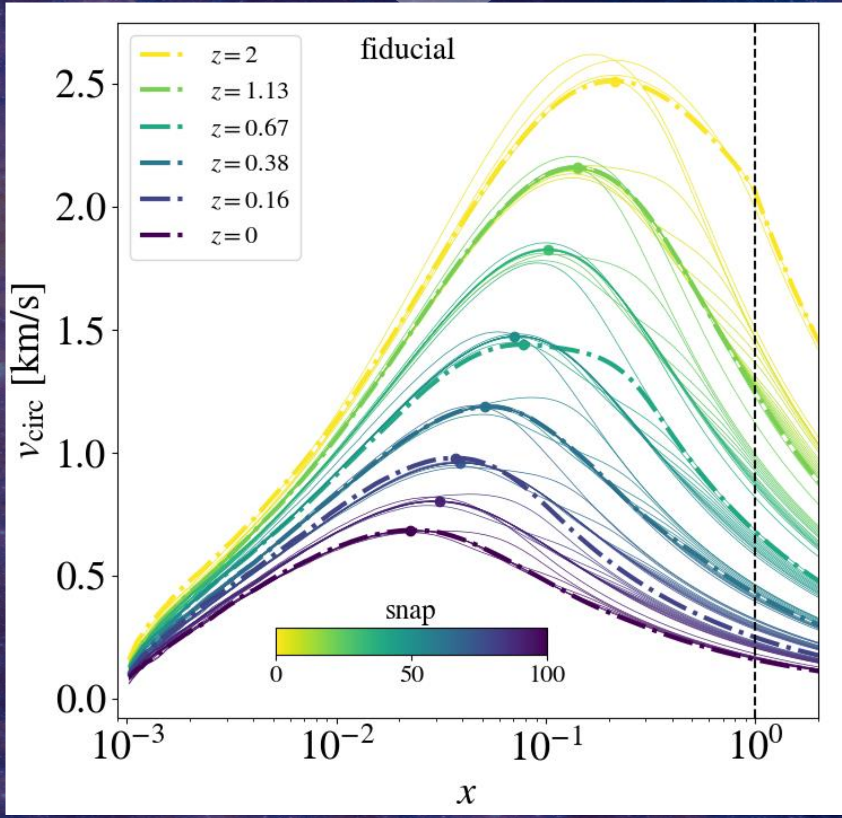
How does this evolution of V_{max} and r_{max} impact subhalo concentrations?

Tidal tracks

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

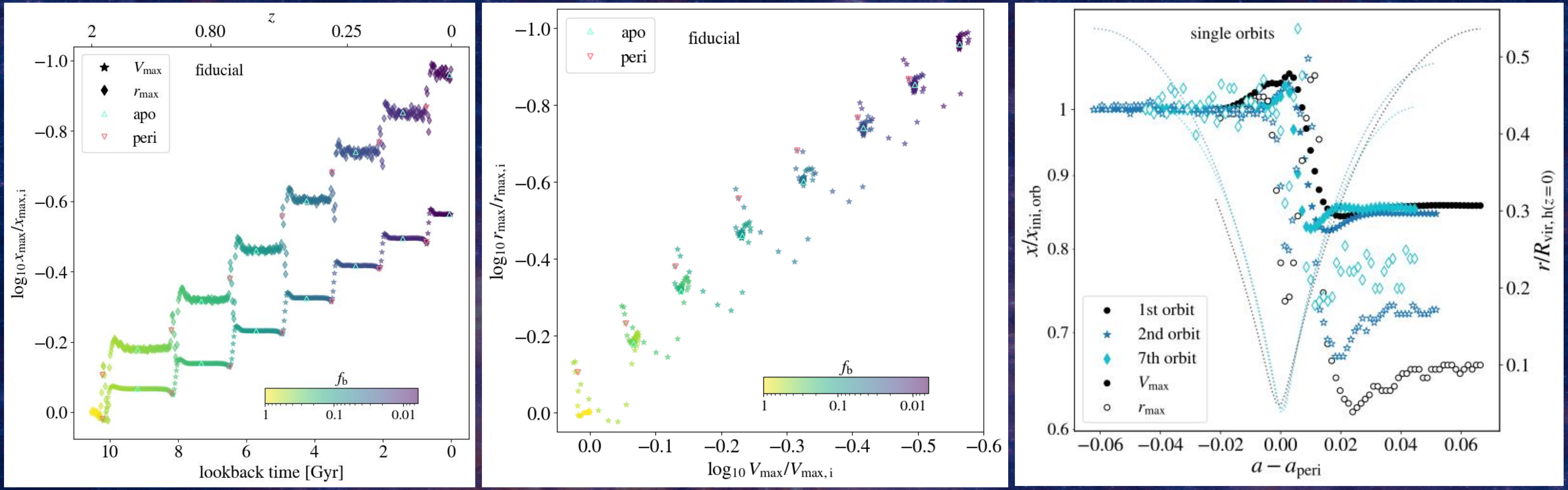


Errani+22



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

AAS+25

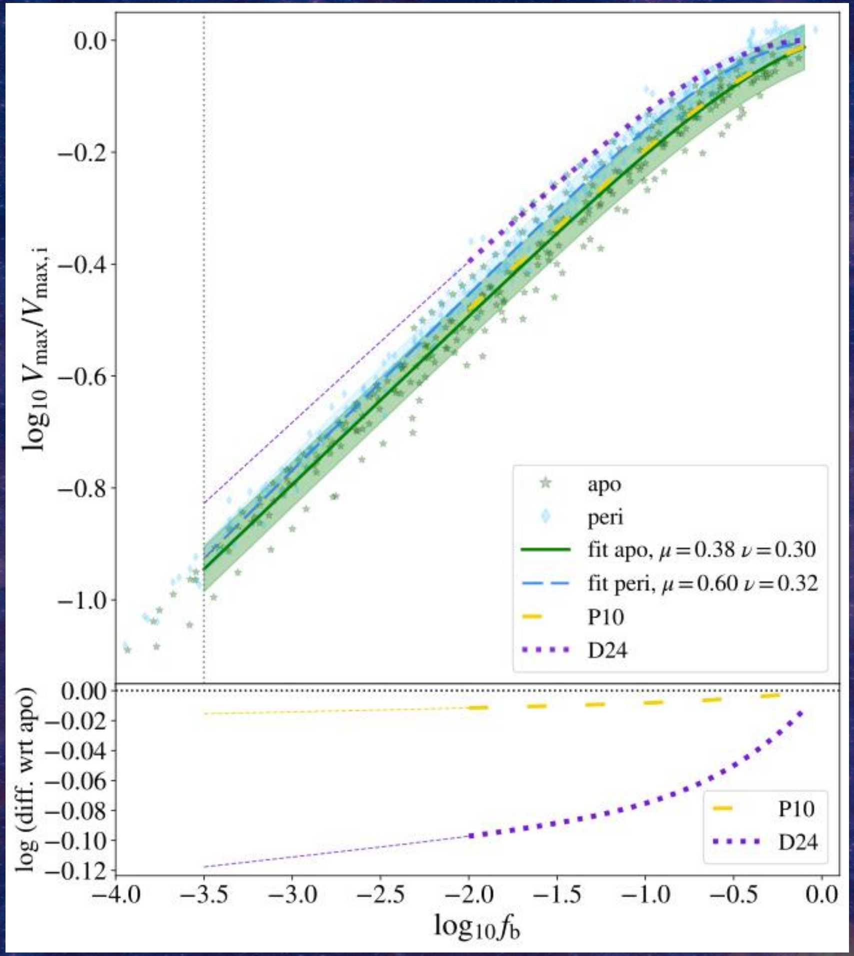
Tidal tracks for NFW subhaloes

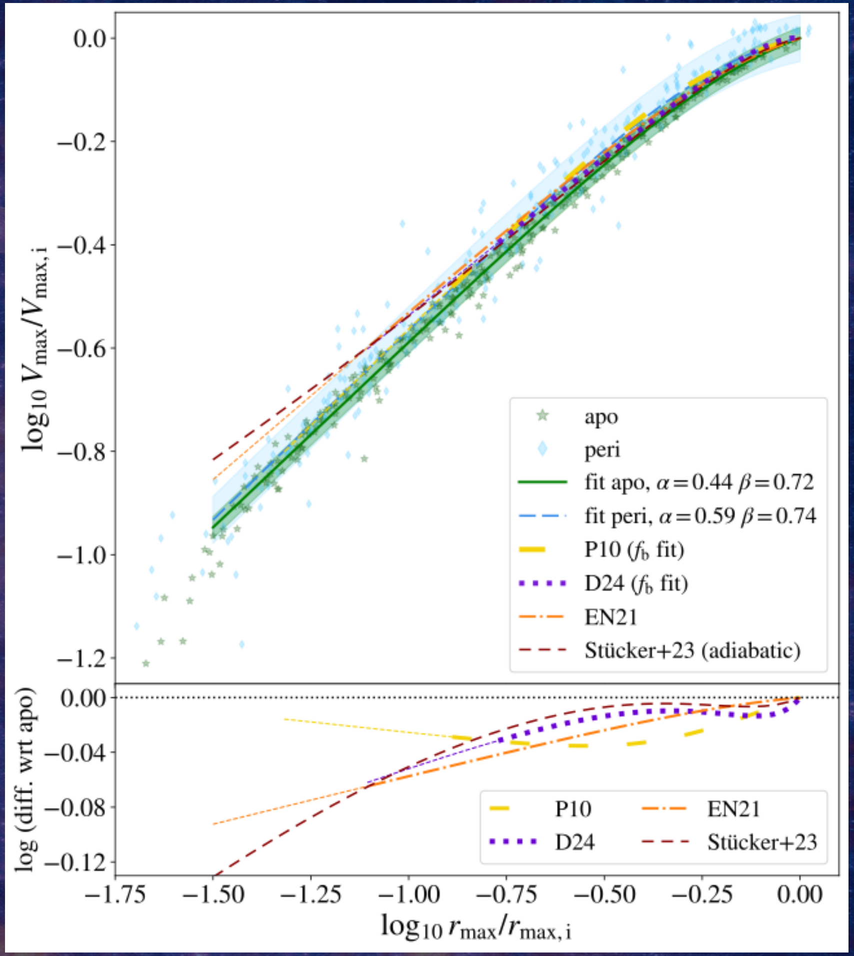
- Apocentre tidal track V_{max} - f_b below pericentre curve reflects V_{max} increase at pericentre
- Apocentre tidal track consistent with P10
- Peñarrubia+10 (left):

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

- EN21 (right):

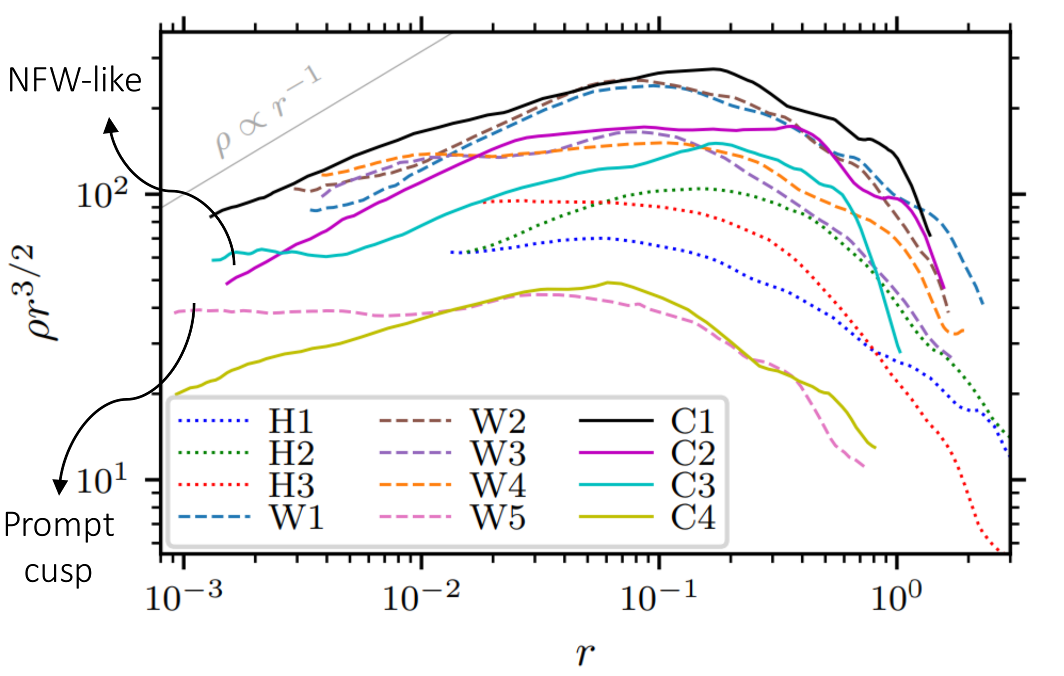
$$g(x) = 2^{\alpha} x^{\beta} [1 + x^2]^{-\alpha}$$



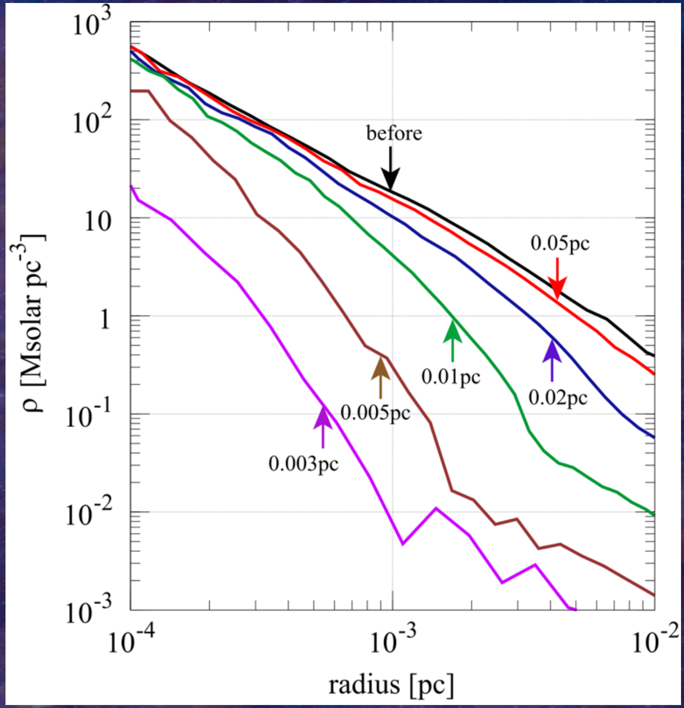


Steeper than NFW: prompt cusps

- The first DM haloes (~Earth mass in CDM) formed from density peaks (Ishiyama+10)
- Their density profile is supposed to exhibit a prompt cusp: $\rho \propto r^{-3/2}$ (Delos+White23)
- Even stellar encounters can have an impact on such small structures!



Delos+White23



Ishiyama+10

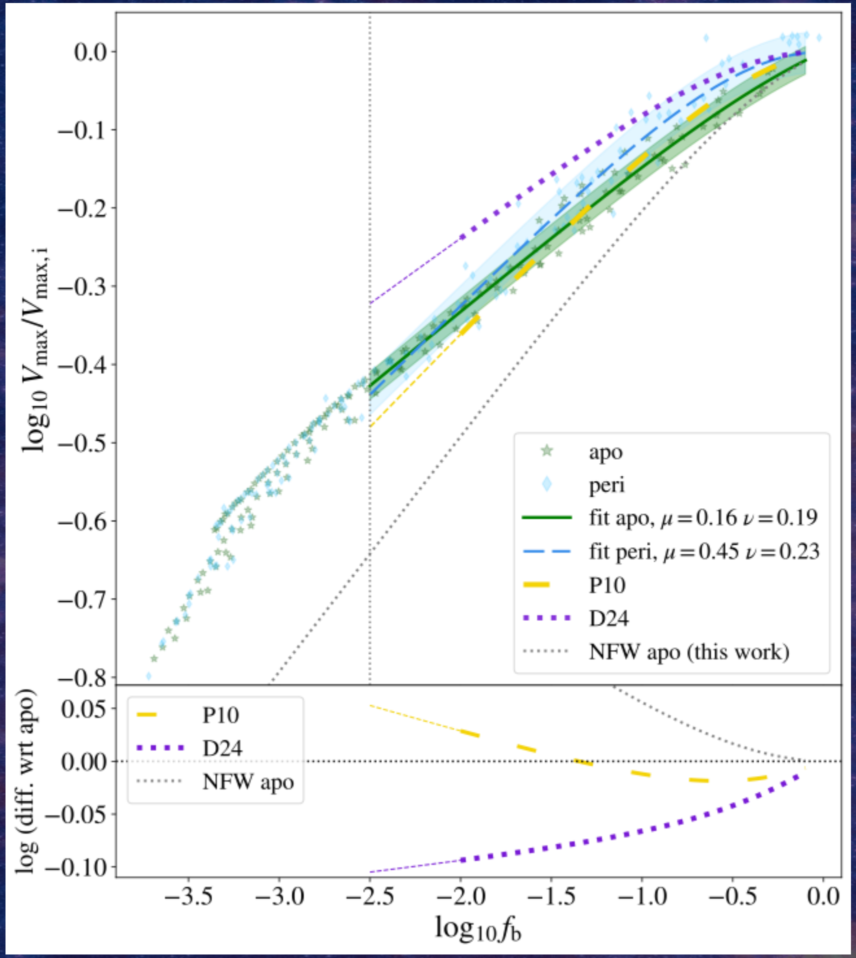
Tidal tracks for prompt cusps

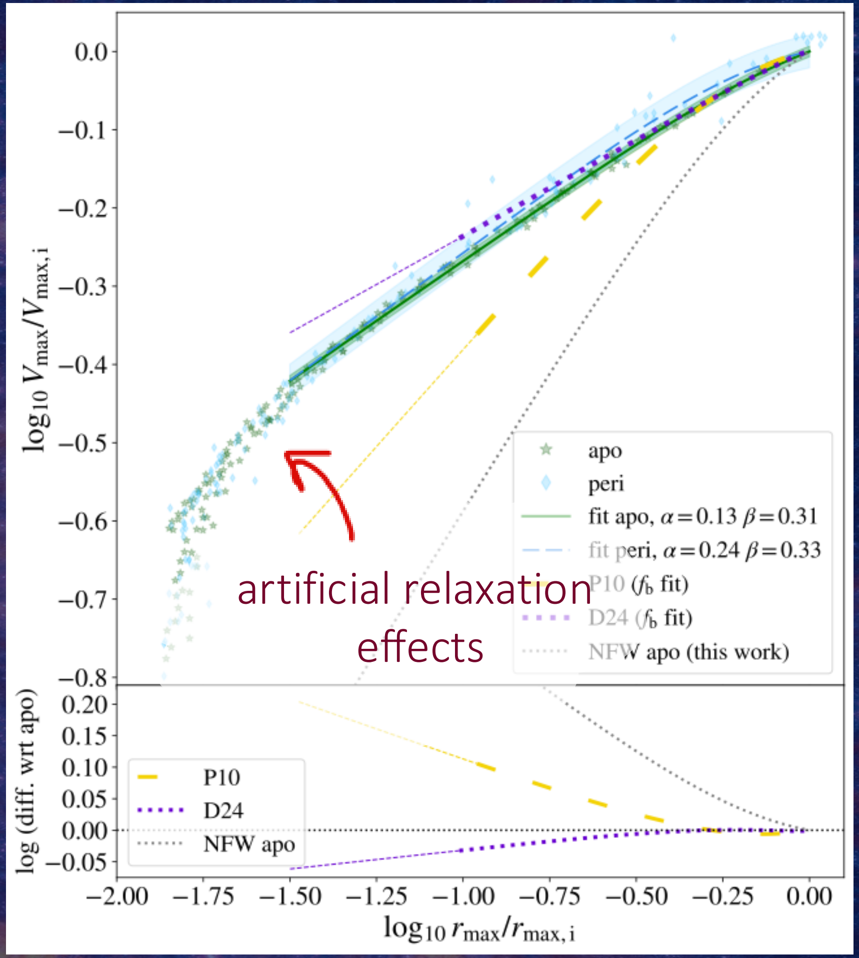
- V_{max} decreases less wrt NFW subhaloes
- Pericentre tidal track reaches the apocentre tt faster
- Our fits lie between D24 and P10
- Peñarrubia+10 (left):

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

- EN21 (right):

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

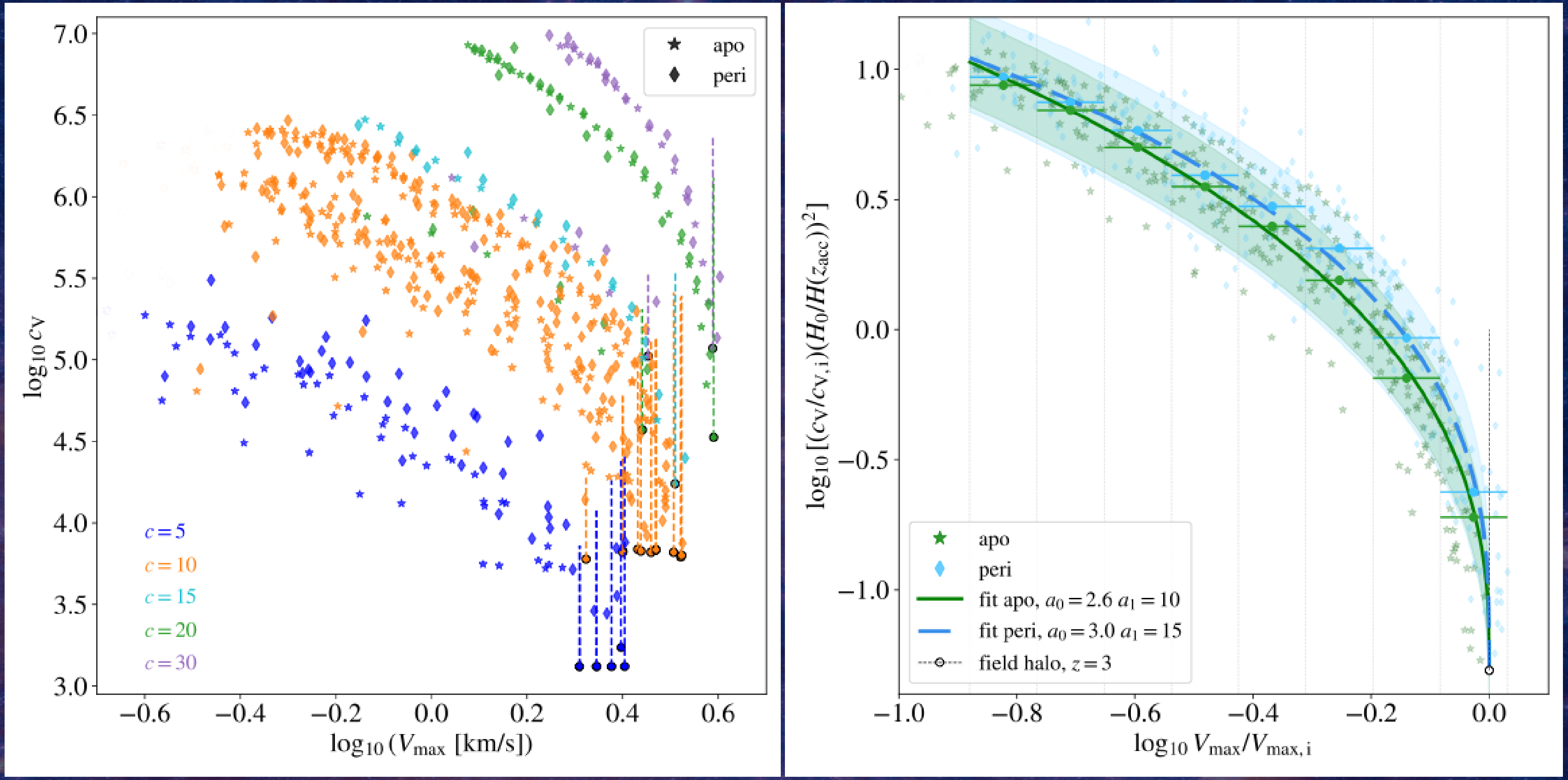




Subhalo concentrations

- Concentrations increase with time since r_{max} decreases more than V_{max}
- c_V increase ~ two orders of magnitude (vs ~ 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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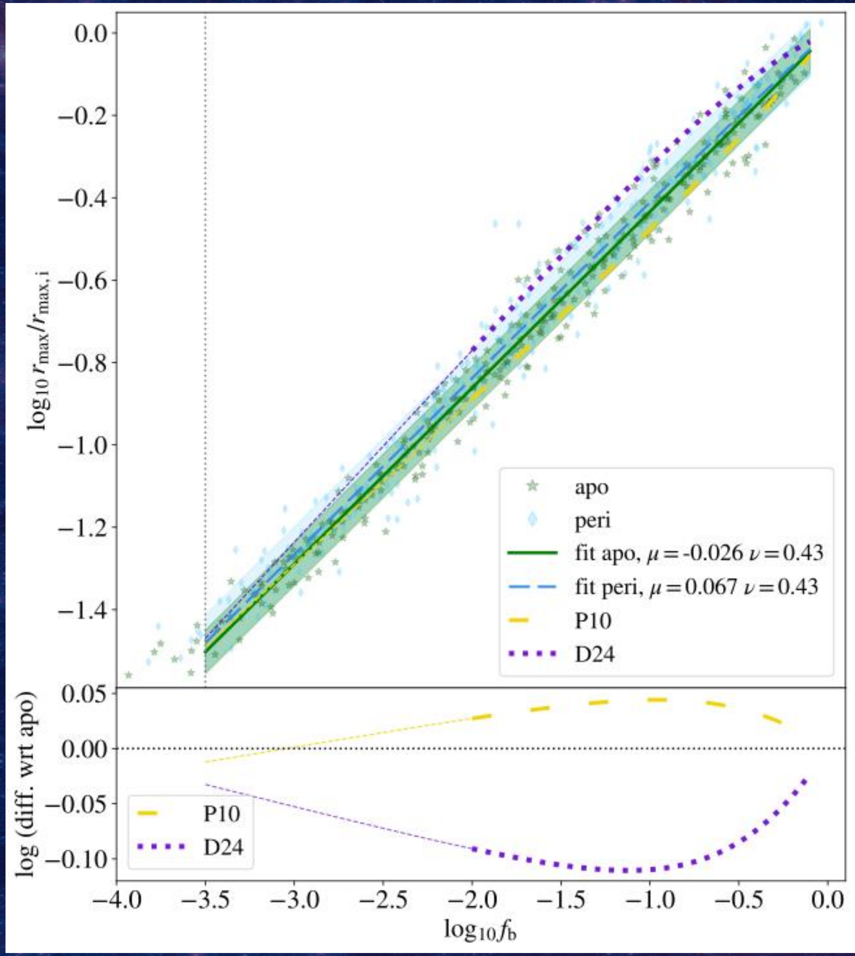
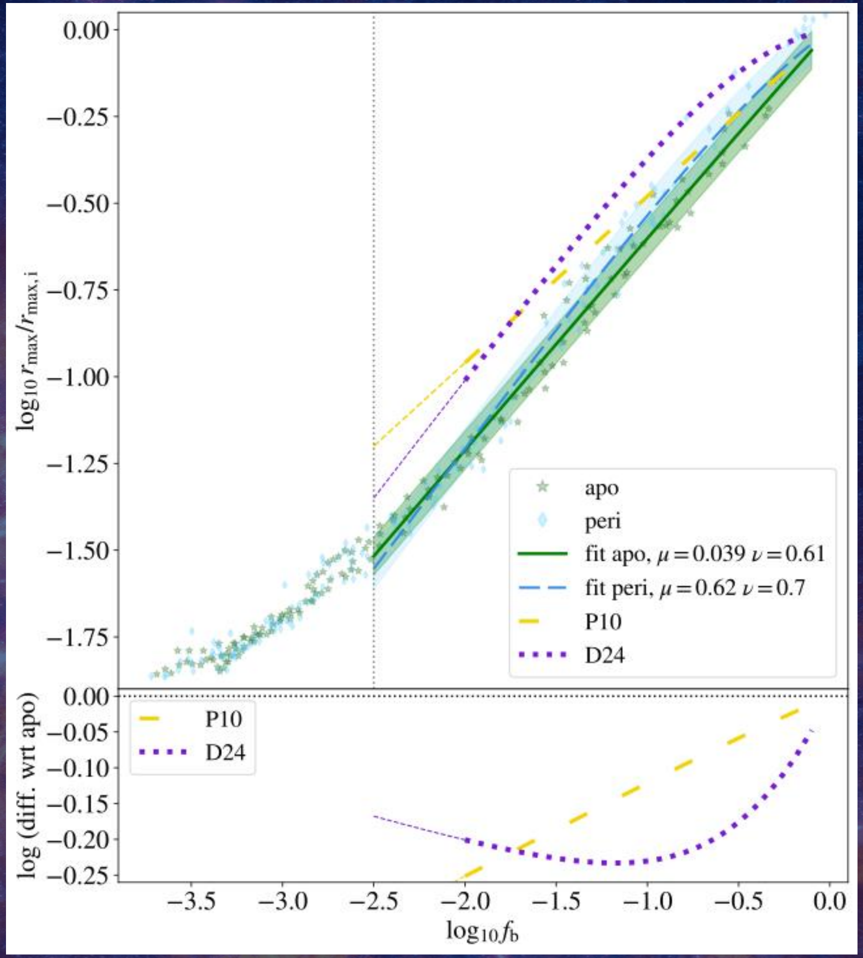
Back-up slides

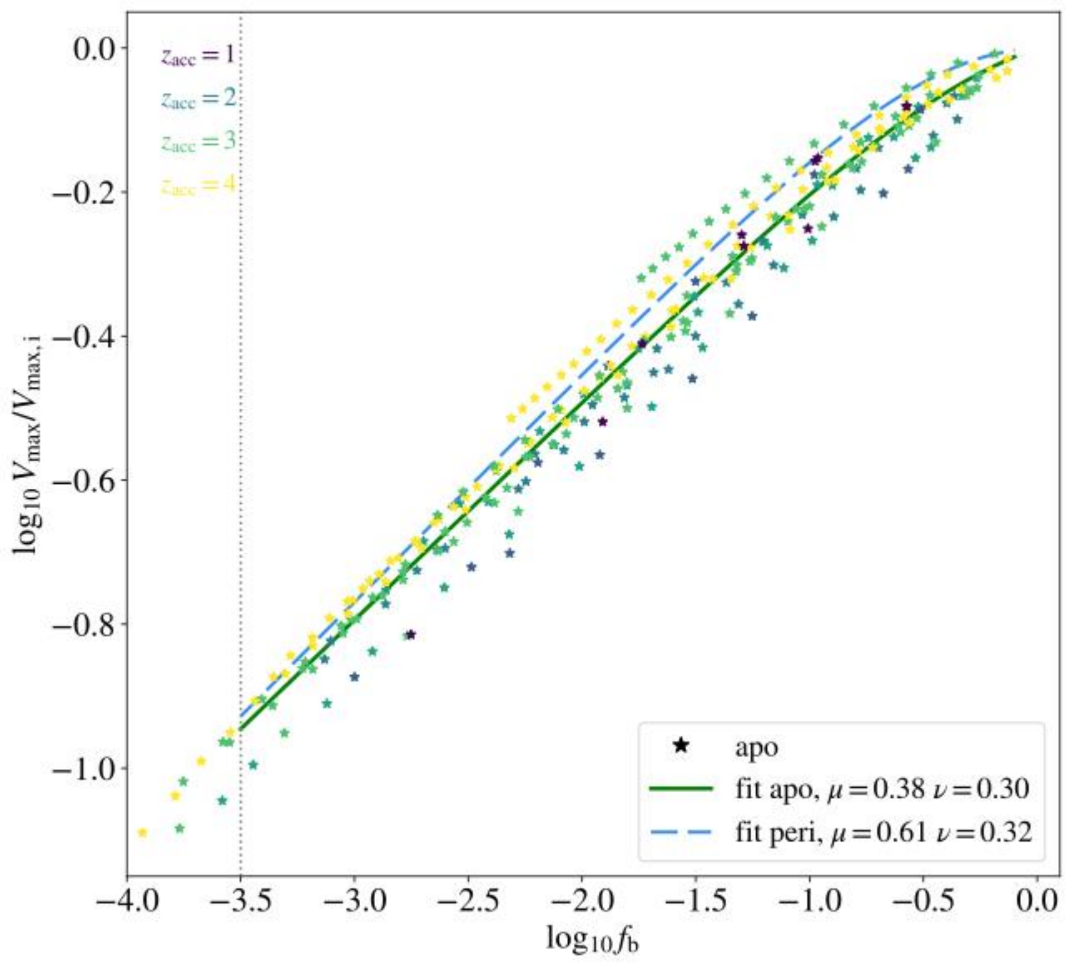
Tidal tracks r_{max} - f_b

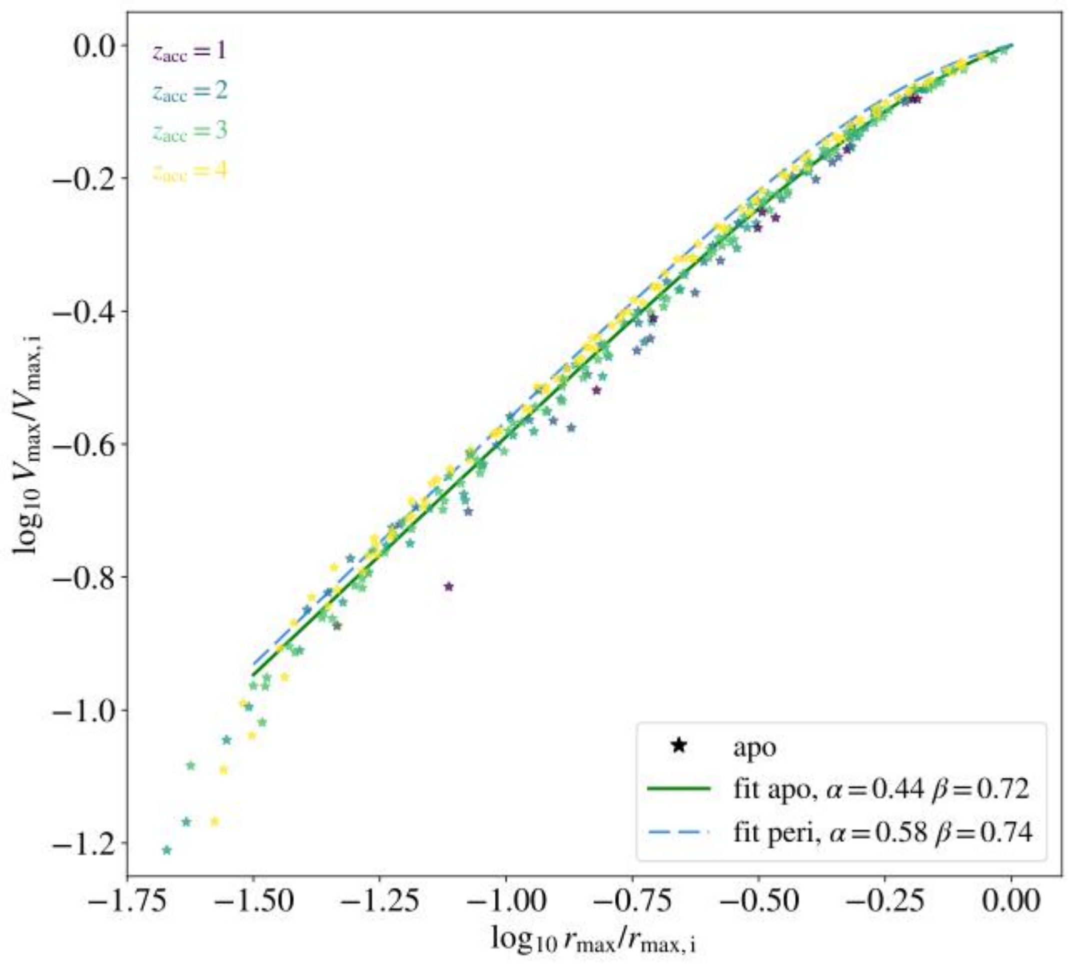




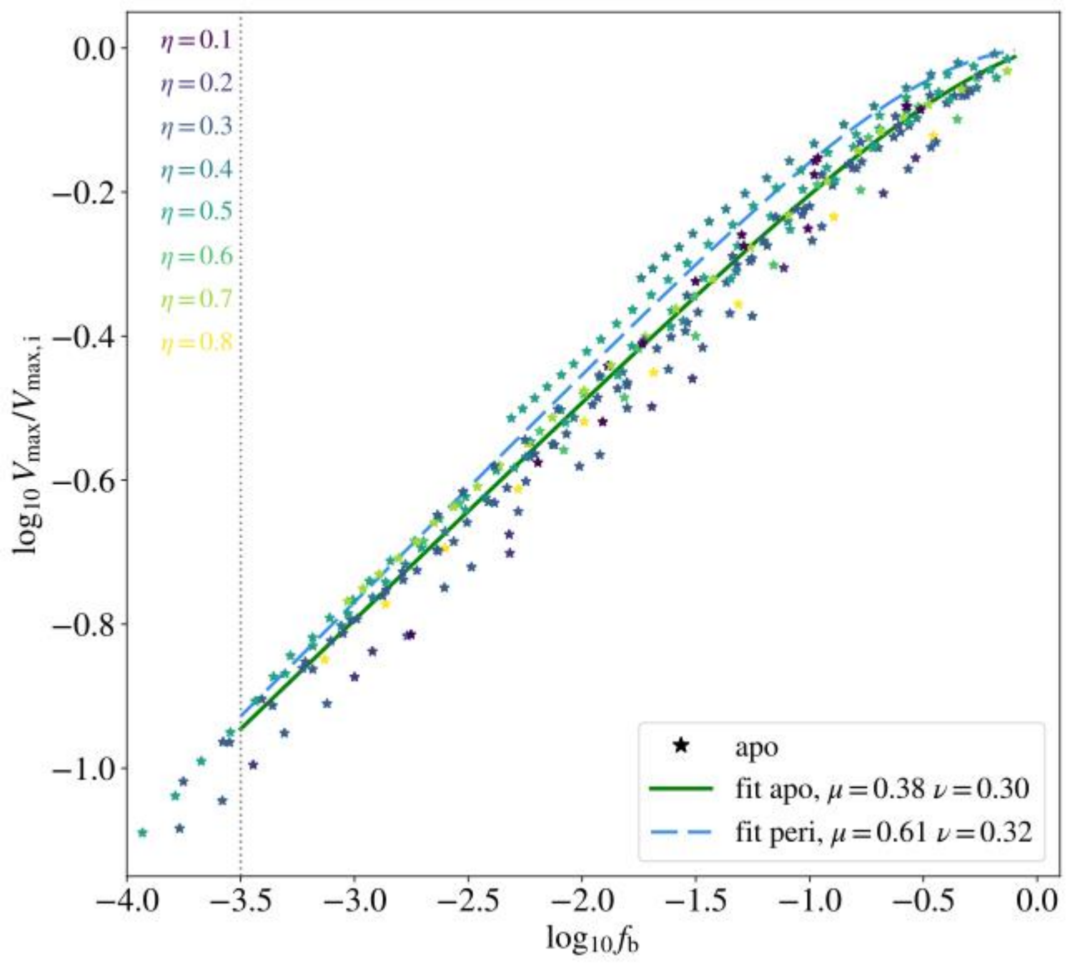
AAS+25 (in prep)

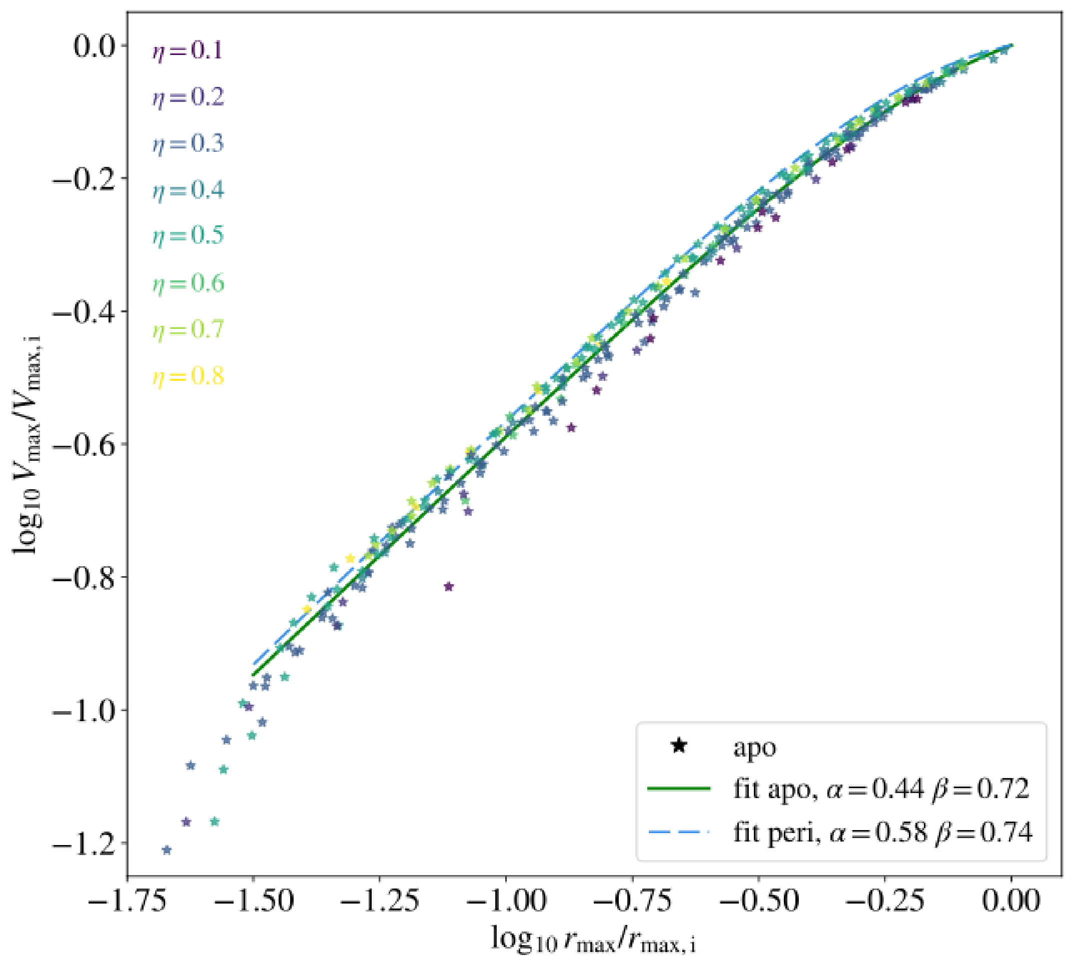
Tidal track dependence on z_{acc}



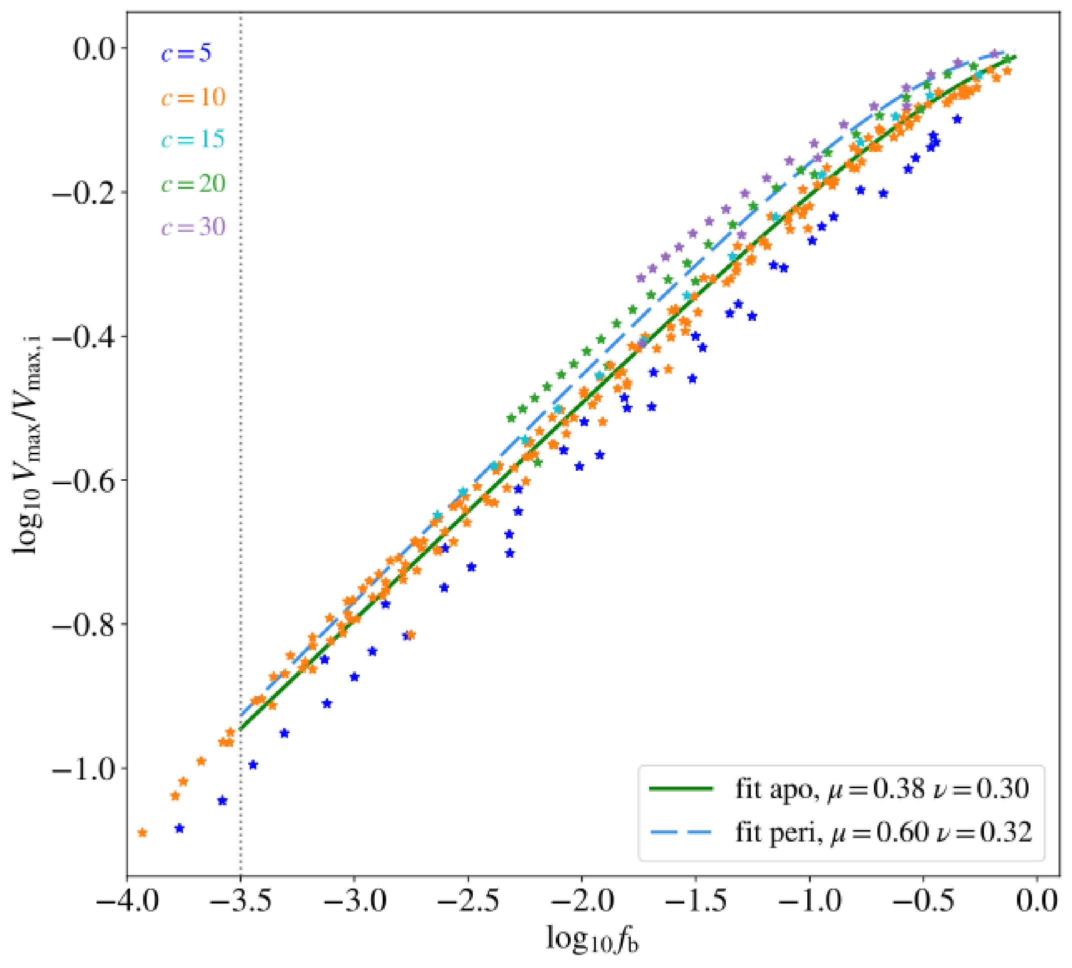


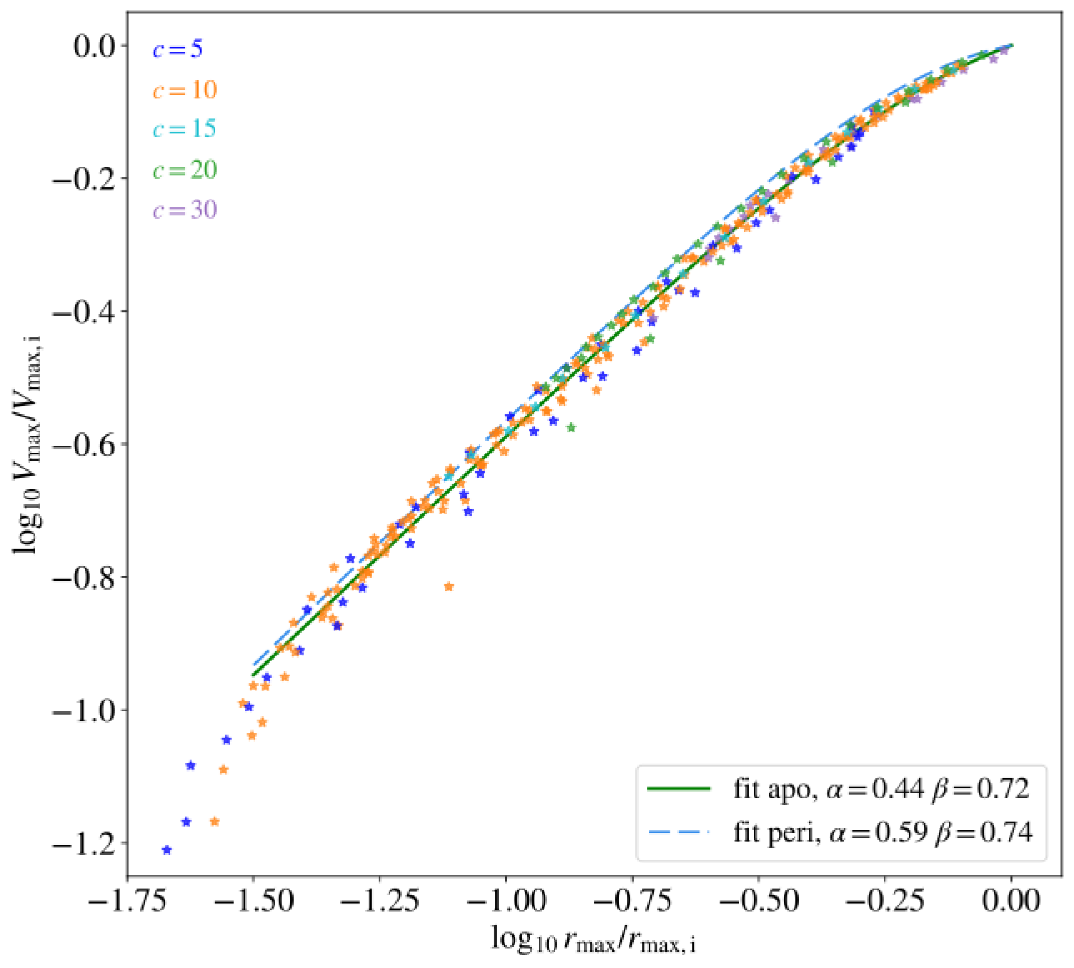
Tidal track dependence on η





Tidal track dependence on *c*

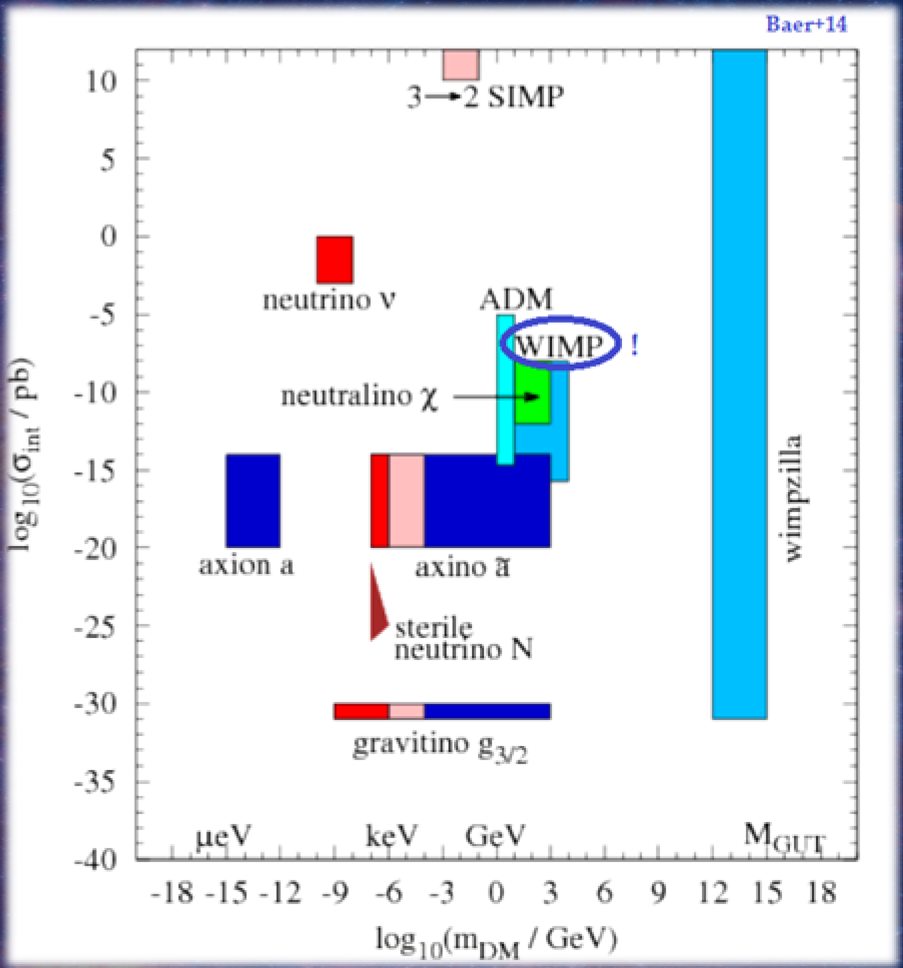




The nature of DM

- 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:

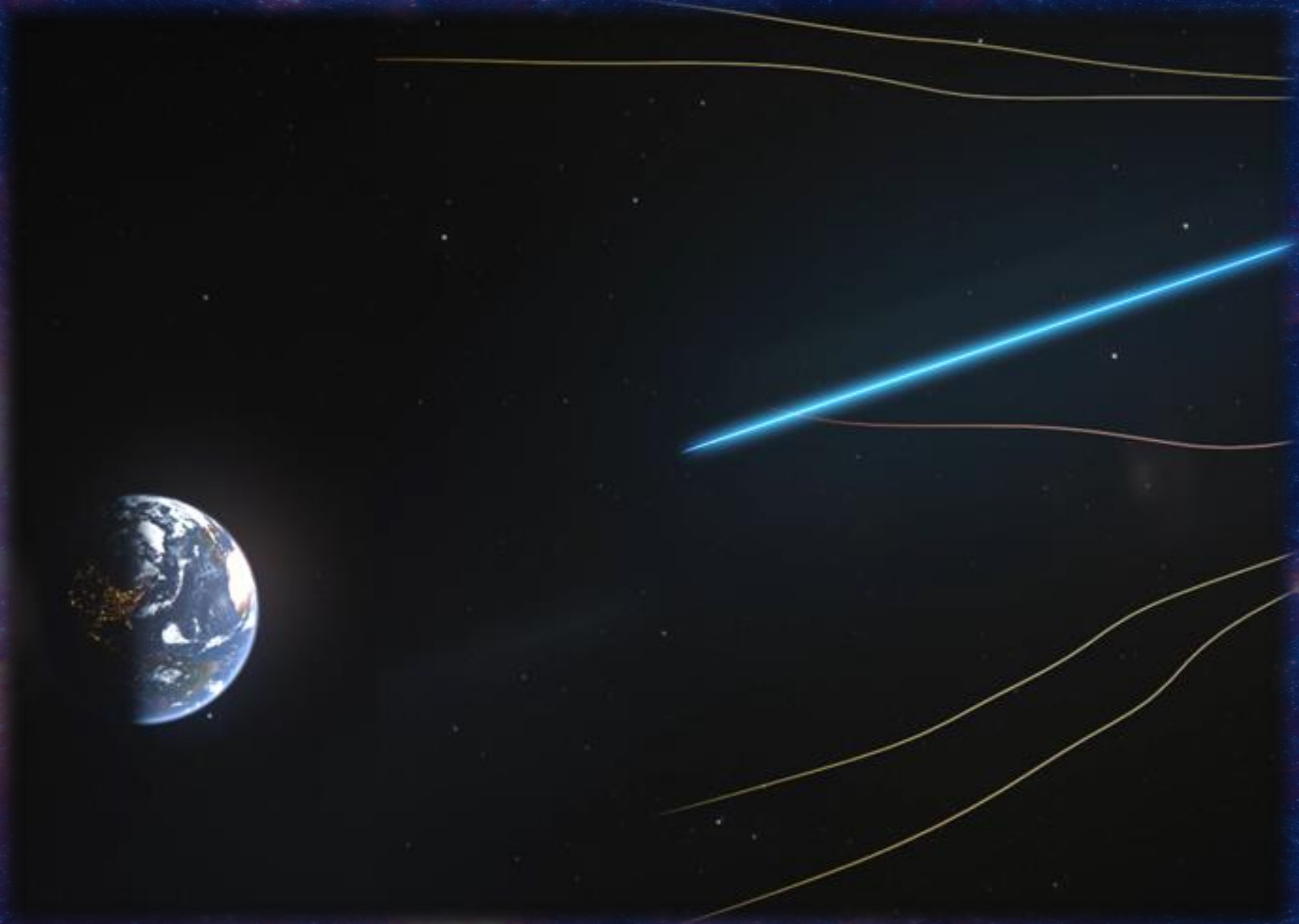


The 'golden channel': gamma rays

- 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: $F = J \cdot f_{\mathrm{pp}}$

J-factor: astrophysical factor: DM density squared

particle physics: depends on DM particle mass and cross section

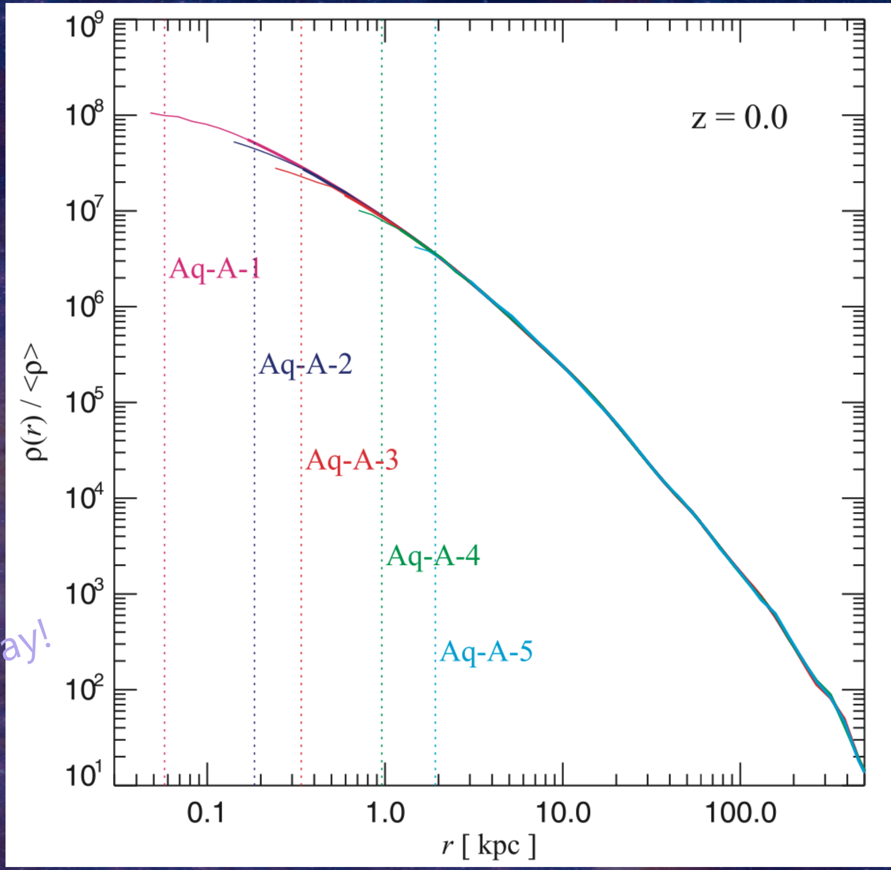


Cosmological simulations are great

Simulations are great until they are not

- 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

IAC seminar next Tuesday!



Springel+08

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