HALO SUBSTRUCTURE
and implications for
DARK MATTER ANNIHILATION SIGNALS

[arXiv: 1312.1729, **1603.04057**, 1703.06012]

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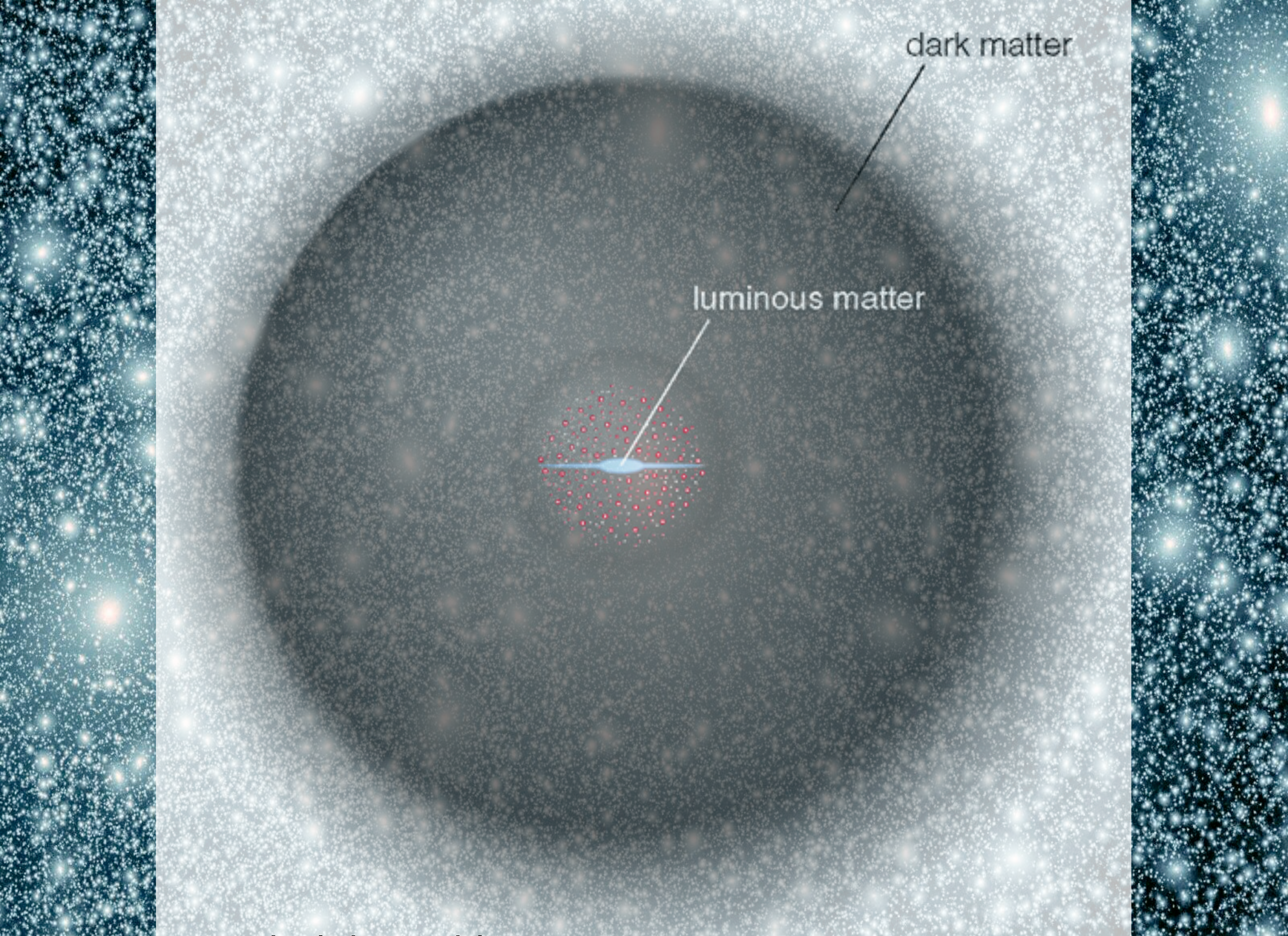
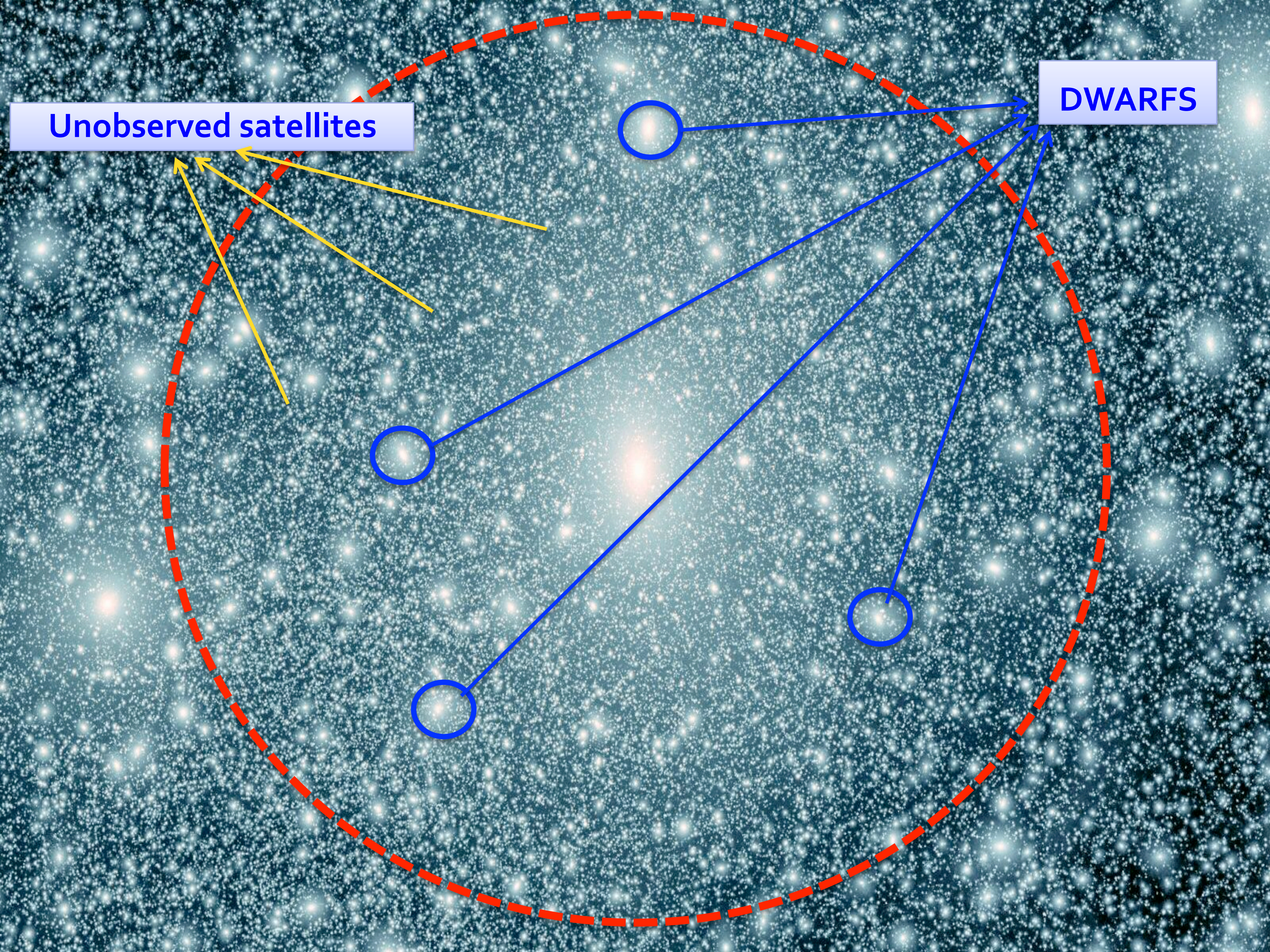
GHALO simulation [Stadel+09]



GHALO simulation [Stadel+09]


Unobserved satellites
DWARFS

The role of DM substructure in (indirect) DM searches

Both *dwarfs* and *dark satellites* are highly DM-dominated systems

→ GOOD TARGETS

The *clumpy distribution* of subhalos inside larger halos may boost the annihilation signal importantly.

→ SUBSTRUCTURE BOOSTS

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→ SUBSTRUCTURE BOOSTS

DM annihilation boost factor from substructure

DM annihilation signal is proportional to the DM density squared
→ *Enhancement of the DM annihilation signal expected due to subhalos.*

Substructure **BOOST FACTOR**: $L = L_{host} * [1+B]$, so $B=0$ → no boost
$B=1$ → $L_{host} \times 2$ due to subhalos

$$B(M) = \frac{1}{L(M)} \int_{M_{min}}^{M} (dN/dm) \; [1 + B(m)] \; L(m) \; dm$$

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Subhalo mass function

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Subhalo luminosity

Subhalo mass function

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Minimum halo mass

Subhalo mass function

Subhalo luminosity

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Minimum halo mass

Subhalo mass function

Other levels of sub-substructure

Subhalo luminosity

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- $L(M)$: Host halo luminosity
- M_{min}: Minimum halo mass
- (dN/dm): Subhalo mass function
- $[1 + B(m)]$: Other levels of sub-substructure
- $L(m)$: Subhalo luminosity

B(M) depends on the internal structure of the subhalos and their abundance

→ N-body cosmological simulations

- Integration down to the minimum predicted halo mass ~10^{-6} Msun.
- Current Milky Way-size simulations "only" resolve subhalos down to ~10^5 Msun.

→ ***Extrapolations below the mass resolution*** *needed.*

Subhalo mass function

$$dN/dm = A/M(m/M)^{-\alpha}$$

α = -1.9 in Aquarius
α = -2 in VL-II

Subhalo annihilation luminosity

J-factor $\propto \rho_s^2 r_s^3 \propto M \frac{c^3}{f(c)^2}$ with

Concentration $c = R_{vir} / r_s$

$$f(c) = ln(1+c) - c/(1+c)$$

→ Results very sensitive to the c(M) extrapolations down to M_{min}

Subhalo concentrations? Yes.

- Difficulty in defining them:
  - More complex evolution compared to field halos.
  - Tidal forces modify the DM density profile (e.g. Kazantzidis+04)
  - Reduced R_{max}, i.e. the radius at which the maximum circular velocity V_{max} is reached (e.g. Bullock+01).

- Solution: choose a definition independent of the profile

$$c_{\rm V} = \frac{\bar{\rho}(R_{\rm max})}{\rho_c} = 2\left(\frac{V_{\rm max}}{H_0\, R_{\rm max}}\right)^2$$

See also Diemand+08

- Still useful to compare to the standard c_{200}:

For NFW:

$$c_{\rm V} = \left(\frac{c_\Delta}{2.163}\right)^3 \frac{f(R_{\rm max}/r_s)}{f(c_\Delta)}\,\Delta$$

c_v from N-body simulations

BOTH PUBLIC!

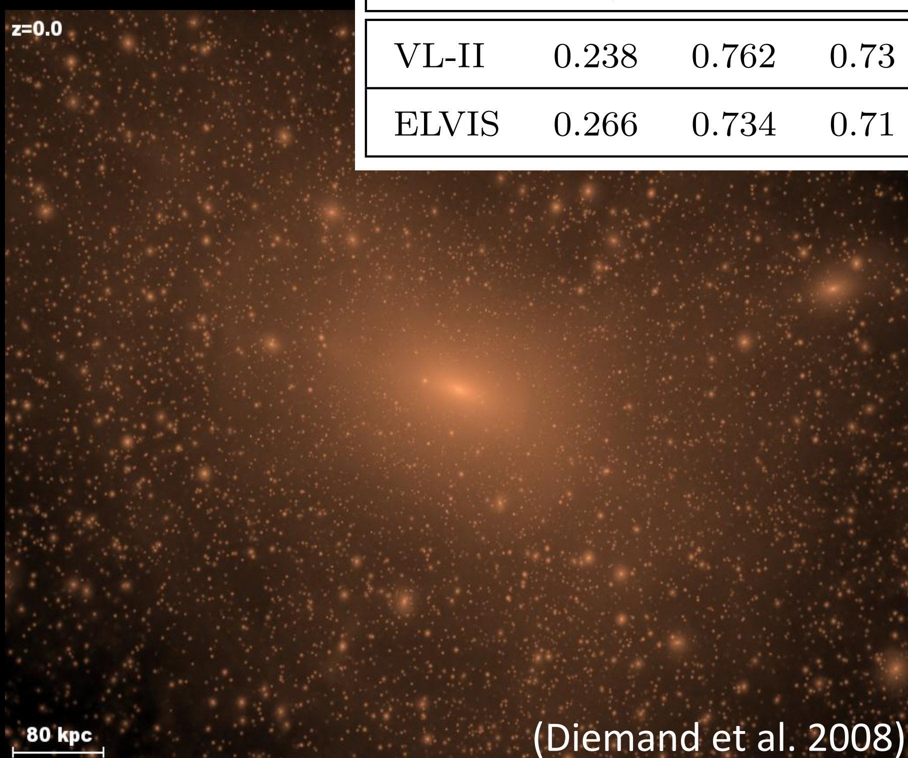
VIA LACTEA II

One MW-size halo.
WMAP3 cosmology.
4100 Msun mass resolution.
Over one billion particles.

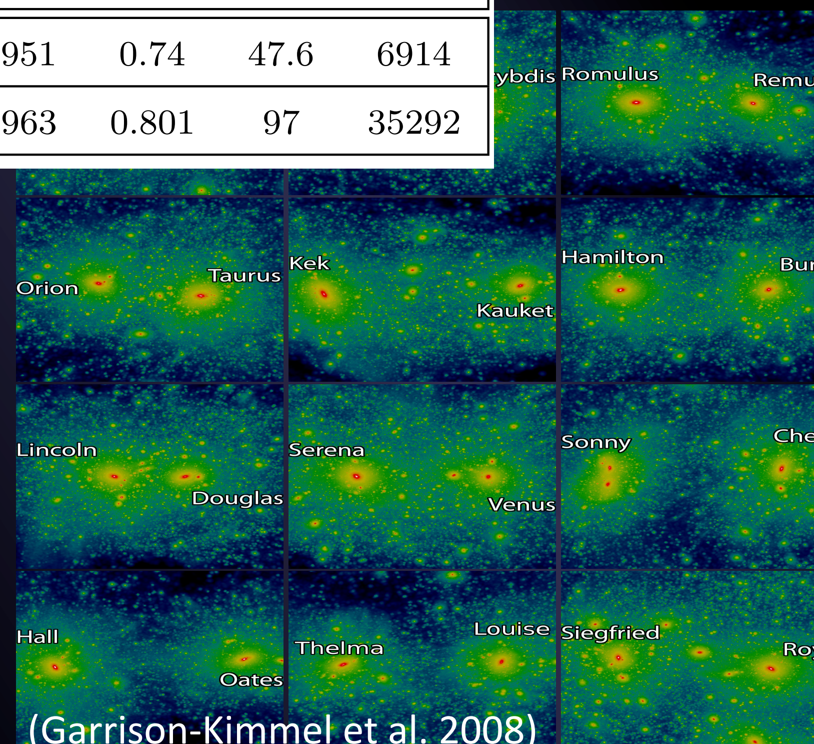
ELVIS

48 MW-size halos. Half in paired configurations.
3 additional MW with higher resolution.
WMAP7 cosmology.
10^5 Msun mass resolution for the 48 MW.

	$\Omega_{m,0}$	Ω_Λ	h	n_s	σ_8	Δ	N_{sub}
VL-II	0.238	0.762	0.73	0.951	0.74	47.6	6914
ELVIS	0.266	0.734	0.71	0.963	0.801	97	35292



(Diemand et al. 2008)



(Garrison-Kimmel et al. 2008)

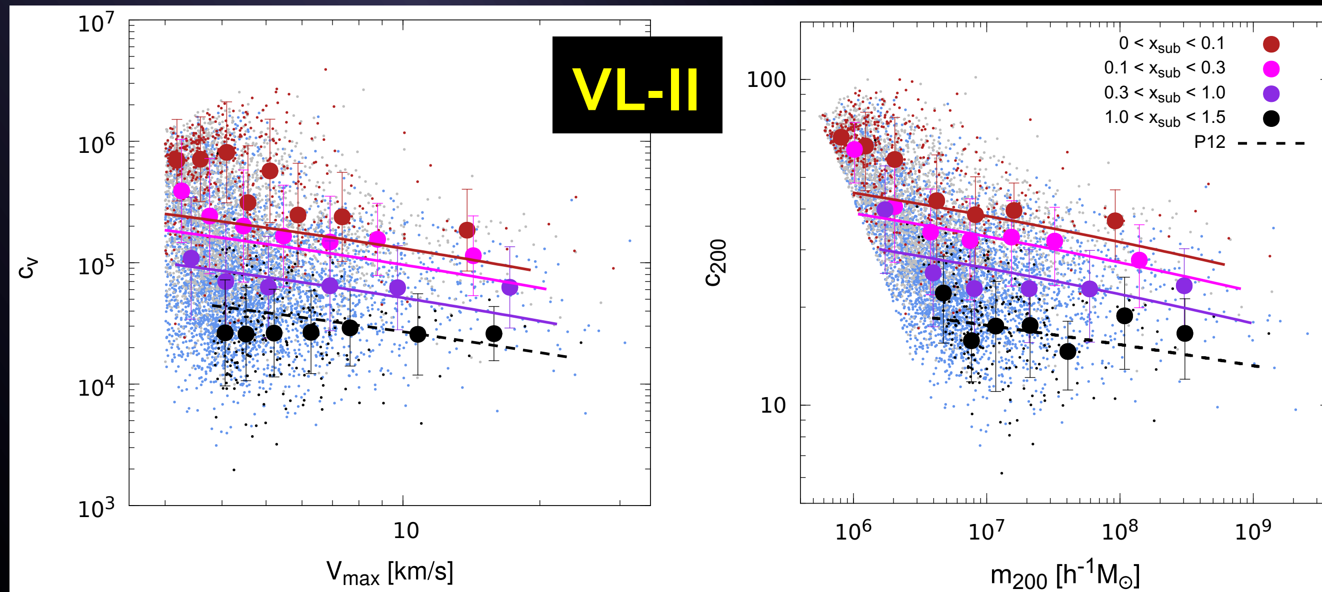
c_v results from VL-II and ELVIS

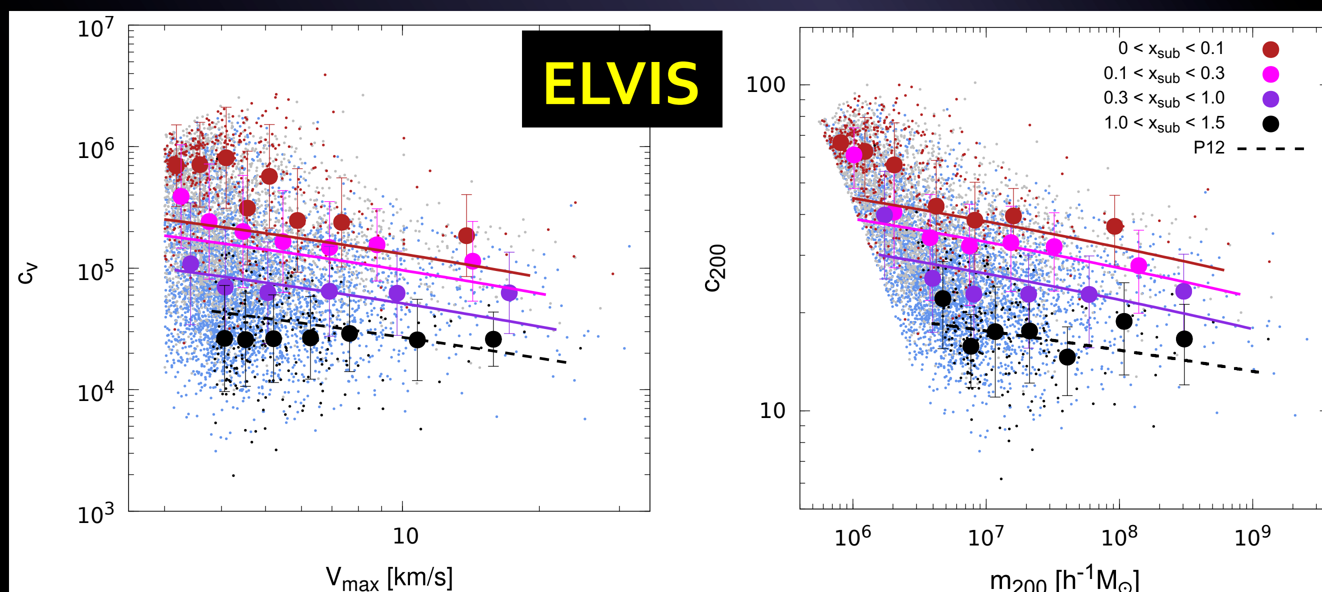
Median values

Four radial bins

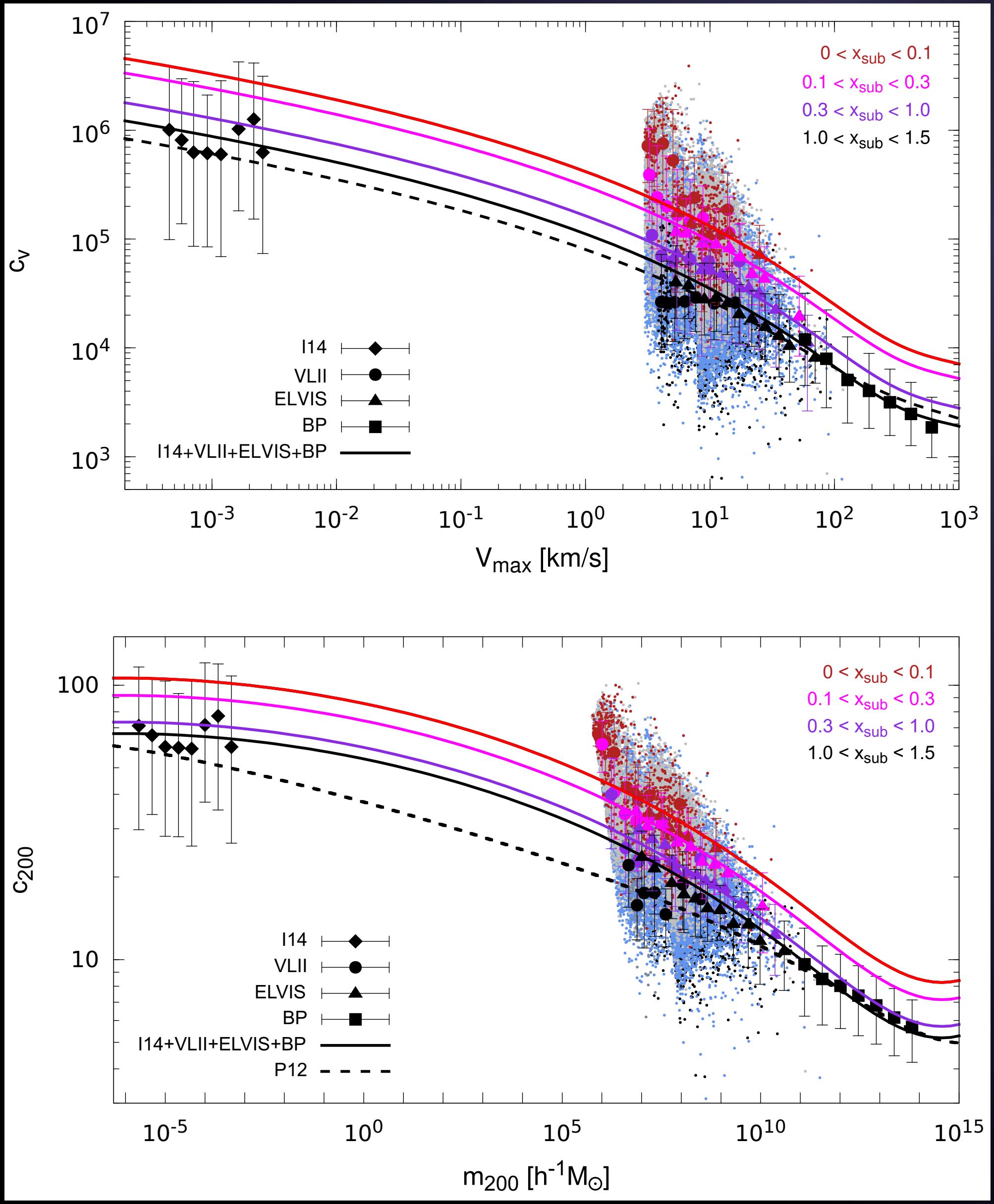
Clear **increase** of subhalo concentration as we approach the host halo center

Scatter similar to that of main halos





Subhalo concentrations at all masses



Subhalo **data**:

- VL-II and ELVIS between $10^6 - 10^{10}$ Msun.
- Ishiyama (2014) main halos at the lowest masses
- BolshoiP main halos at the largest masses

Clear **increase** of subhalo concentrations as we approach the host halo center.

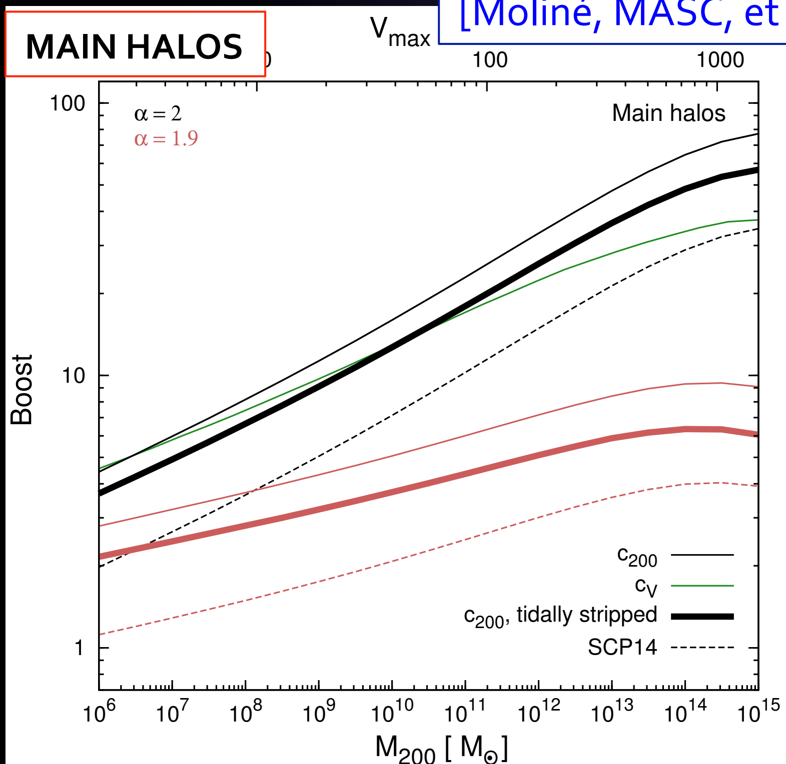
Future: add BolshoiP, MultidDark, Lomonosov, 'Ishiyama'…

(Improved) subhalo boost model

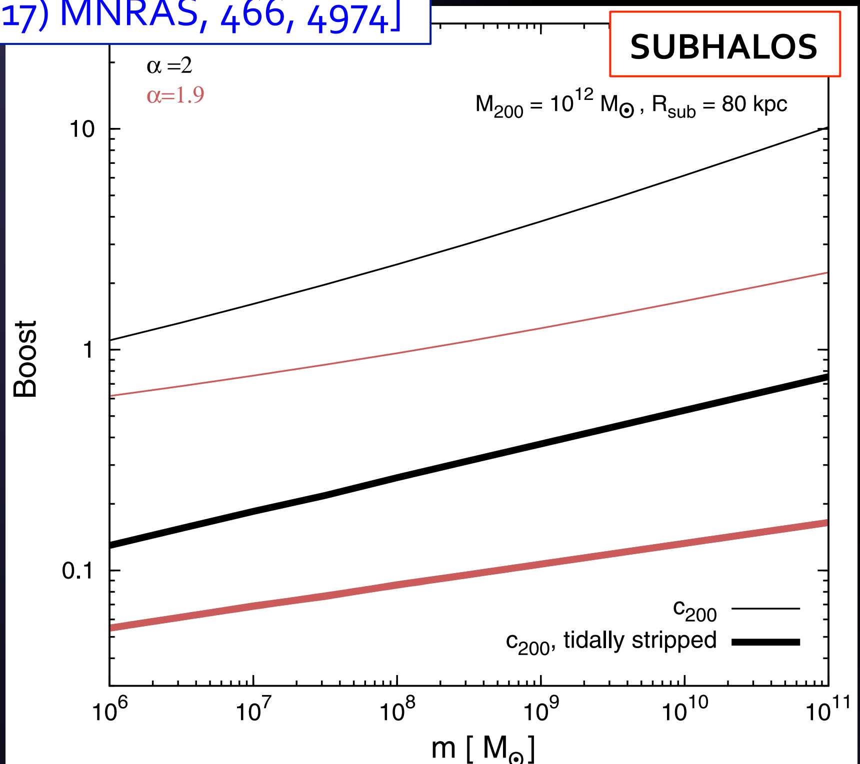
1. Make use of our best knowledge on subhalo concentrations.
2. Tidal stripping included (Roche criterium).

[Moliné, MASC, et al., (2017) MNRAS, 466, 4974]

MAIN HALOS



SUBHALOS



O(30) boost for MW-size halos
(factor ~2 higher than SCP14)

Very small boost for subhalos, e.g. **dwarfs**

[Agrees also with Bartels & Ando (2015) and Zavala & Afshordi (2015)]

Remarks

- Subhalo concentrations:
  - Used VL-II and ELVIS.
  - Used a concentration parameter independent of the profile.
  - The closer to the host halo center the more concentrated.
  - Substantially larger (factor ~2) than field halos.

- Substructure boosts factors:
  - Improved the model in Sánchez-Conde & Prada (2014).
  - More accurate subhalo concentrations + tidal stripping.
  - About a factor 2-3 larger than before (main halos).
  - Negligible for dwarf galaxies of the Milky Way.

Thanks!

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ADDITIONAL MATERIAL

The DM annihilation γ-ray flux

$$F(E_\gamma > E_{th}, \Psi_0) = J(\Psi_0) \times f_{PP}\left(E_\gamma > E_{th}\right)$$

photons cm^{-2} s^{-1}

Astrophysics

Integration of the squared DM density

J-FACTOR

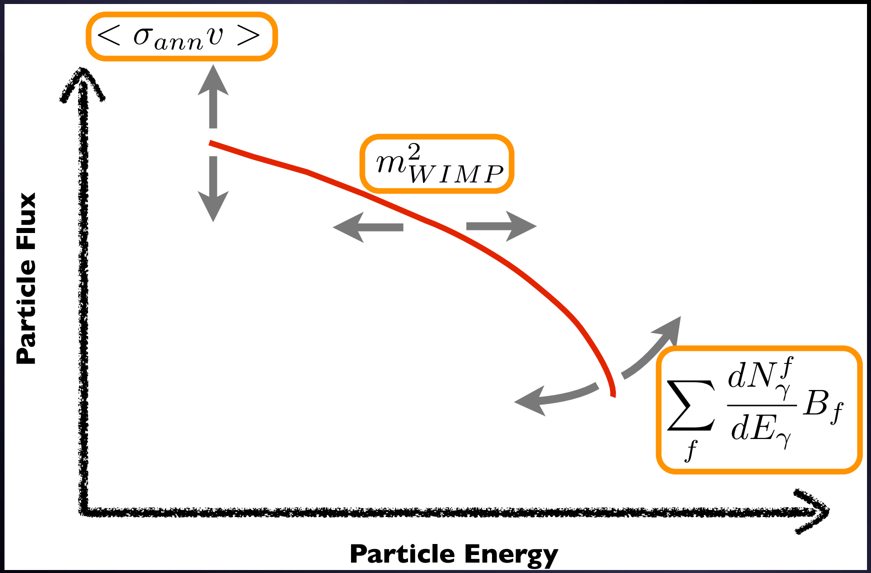
$$J(\Psi_0) = \frac{1}{4\pi} \int_{\Delta\Omega} d\Omega \int_{l.o.s.} \rho^2_{DM}[r(\lambda)]\, d\lambda$$

SMOOTH + SUBSTRUCTURE

Particle physics

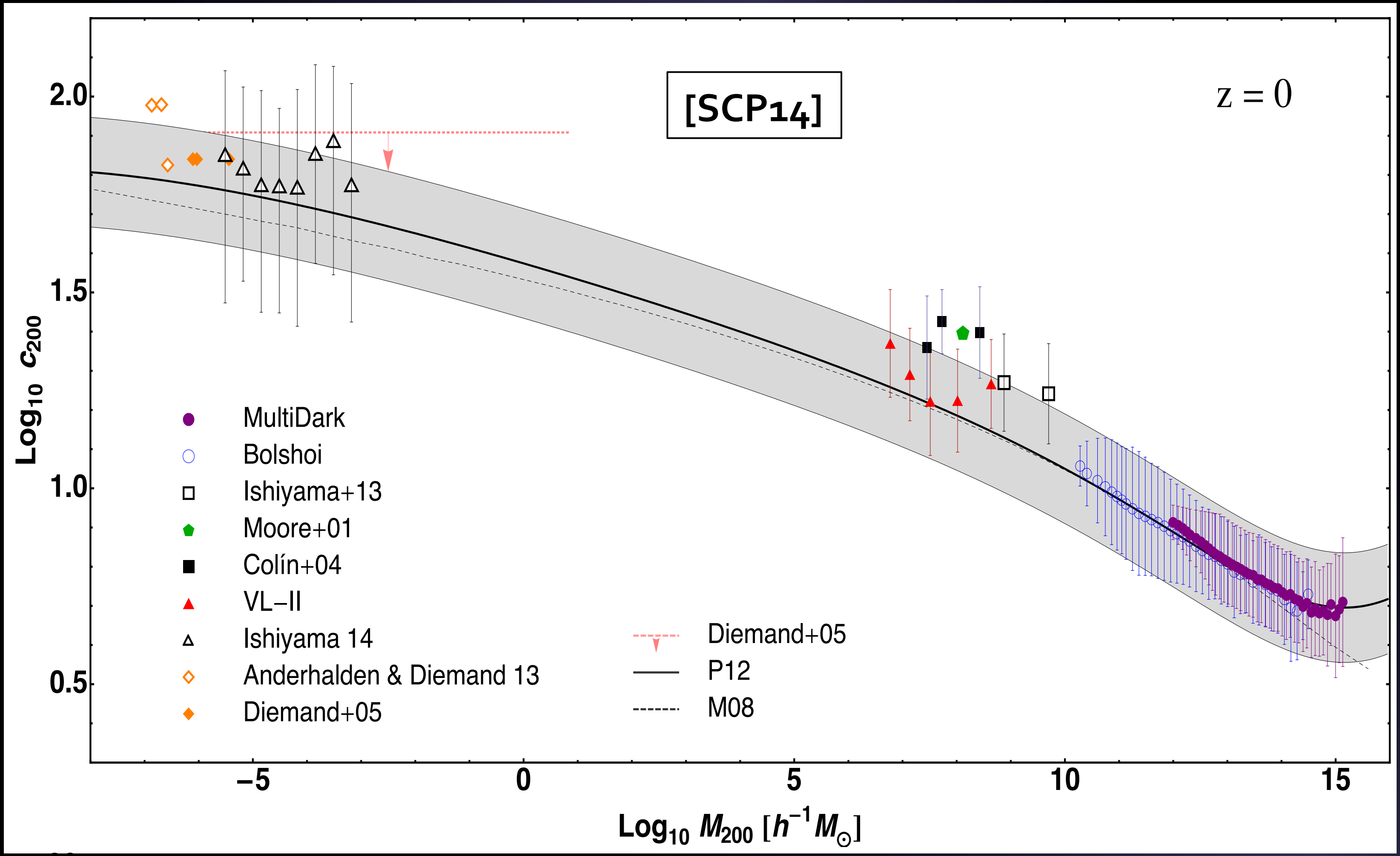
$$f_{PP} \propto \sum_f \frac{dN_\gamma^f}{dE_\gamma} B_f \frac{\langle \sigma \cdot v \rangle}{m_\chi^{\ 2}}$$

- N_g : number of photons per annihilation, E >E_{th}
- <σ v>: cross section
- m_χ: neutralino mass



Current knowledge of the c(M) relation at z=0

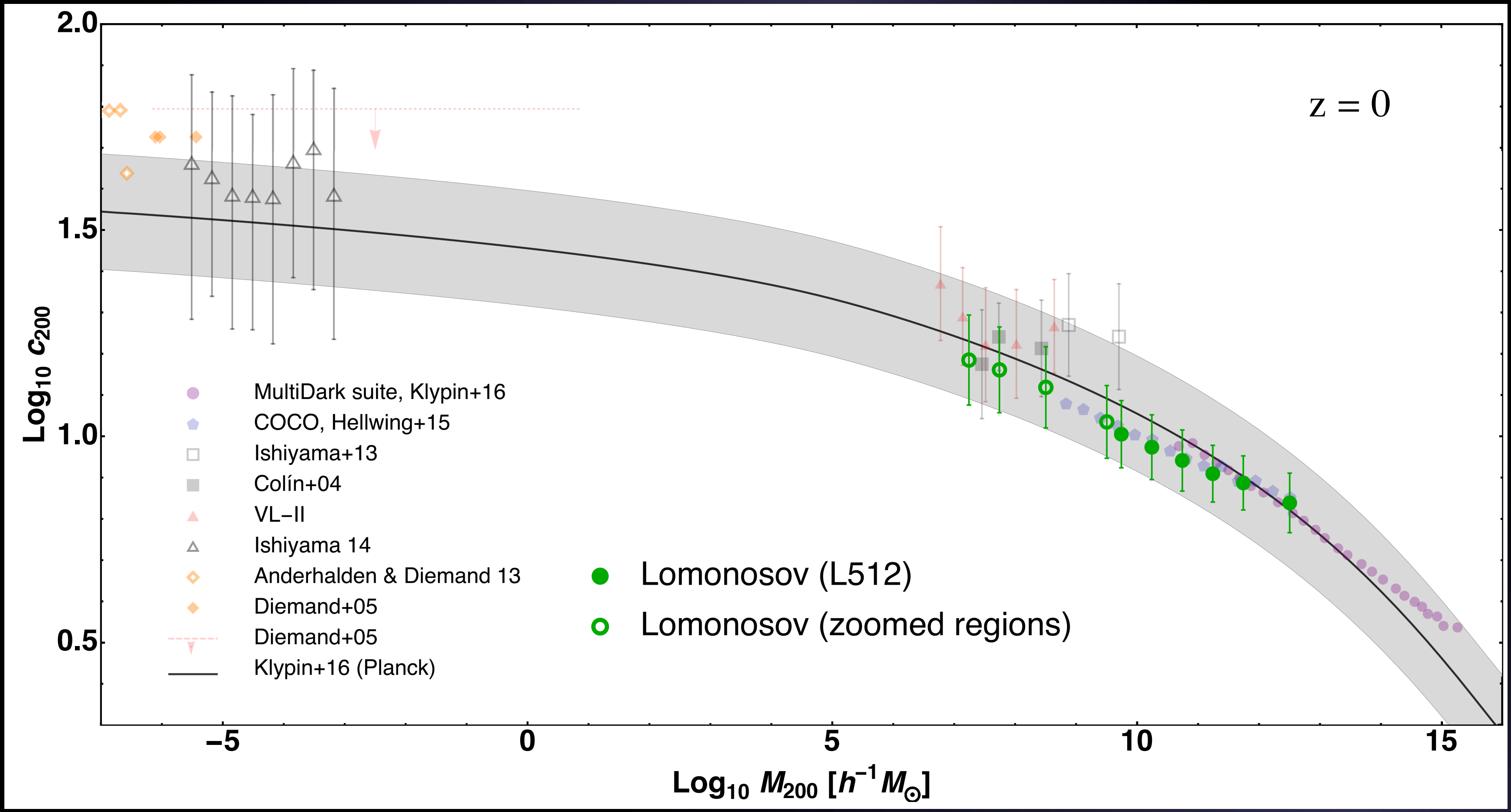
Concentration $c = R_{vir} / r_s$



MASC & Prada, MNRAS, 442, 2271 (2014) [astro-ph/1312.1729]

New LOMONOSOV simulations

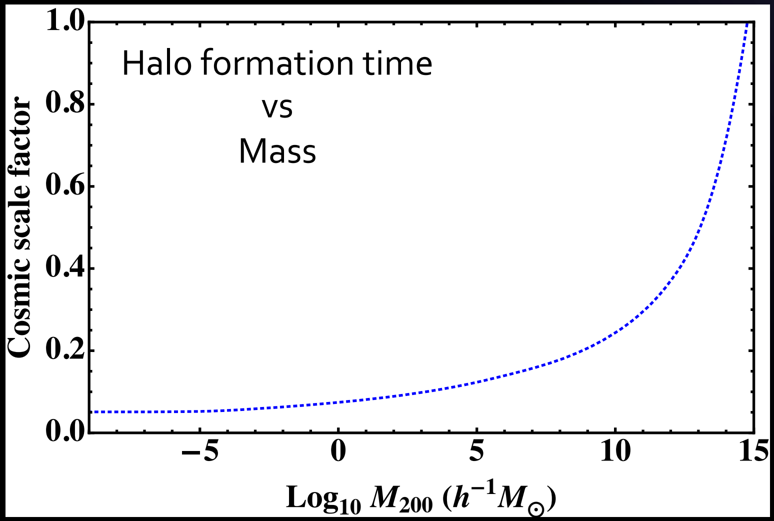
Concentration $c = R_{vir} / r_s$

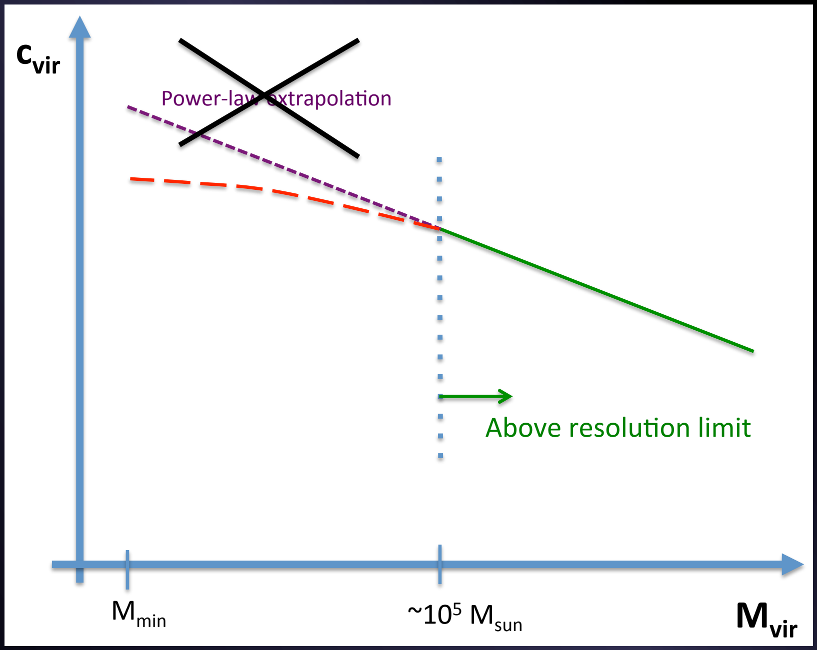


Pilipenko, MASC+17 [astro-ph/1703.06012]

What does ΛCDM tell us about c(M) at the smallest scales?

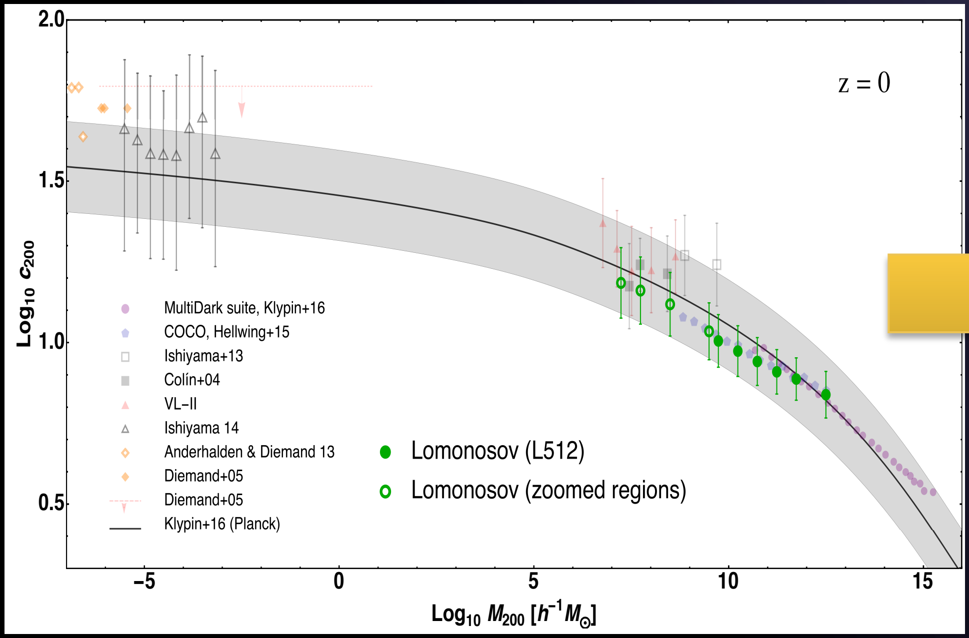
- Natal concentrations are mainly set by the halo formation time.
- Given the CDM power spectrum , the smallest halos typically collapse *nearly* at the same time:
  - → Concentration is nearly the same for the smallest halos over a wide range of masses.
  - → power-law c(M) extrapolations not correct!

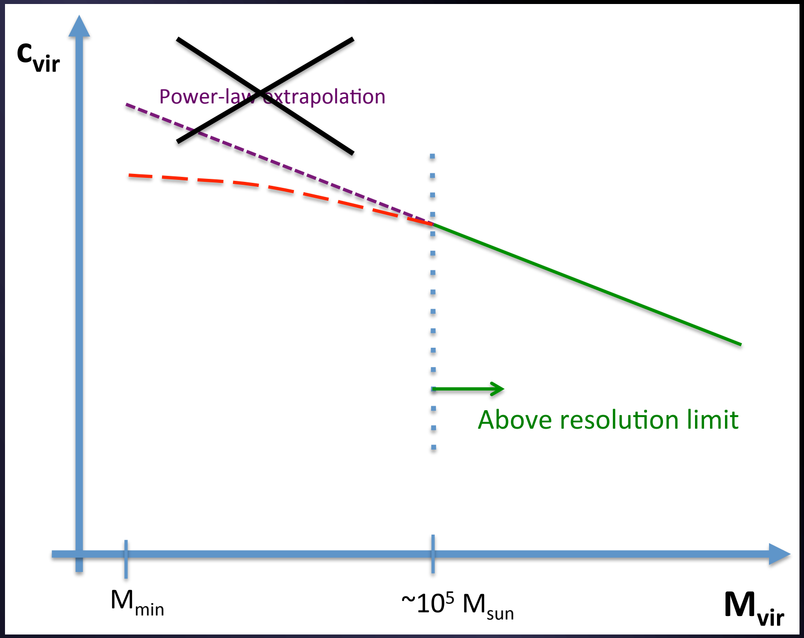




No more simple power-law c(M) extrapolations!

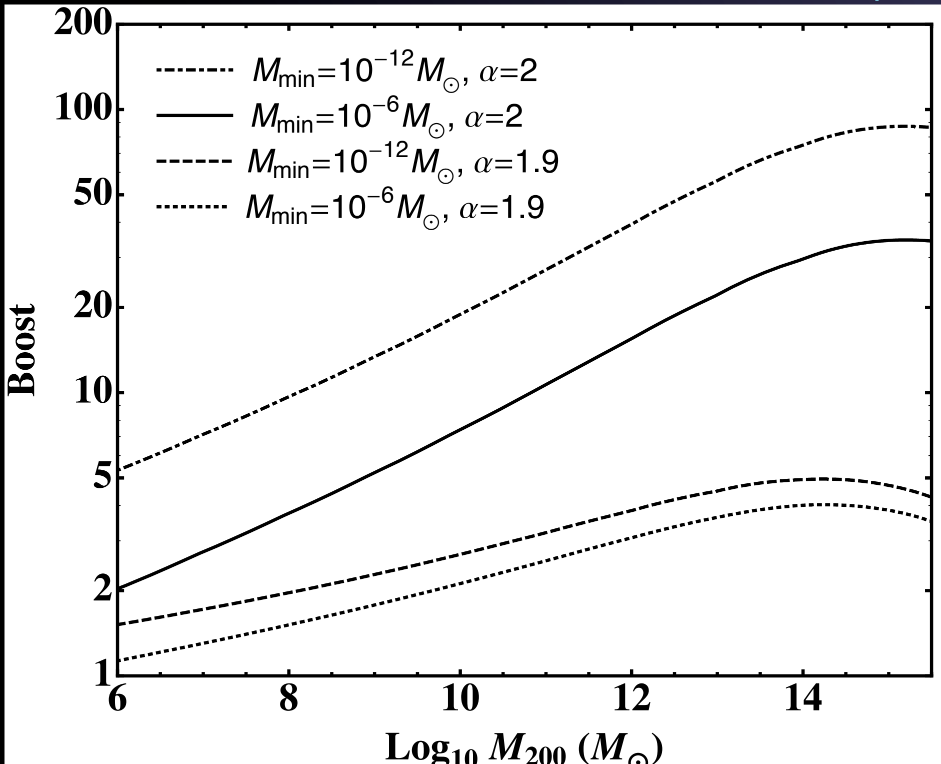
Our current knowledge of the c(M) relation from simulations also support the theoretical expectations.

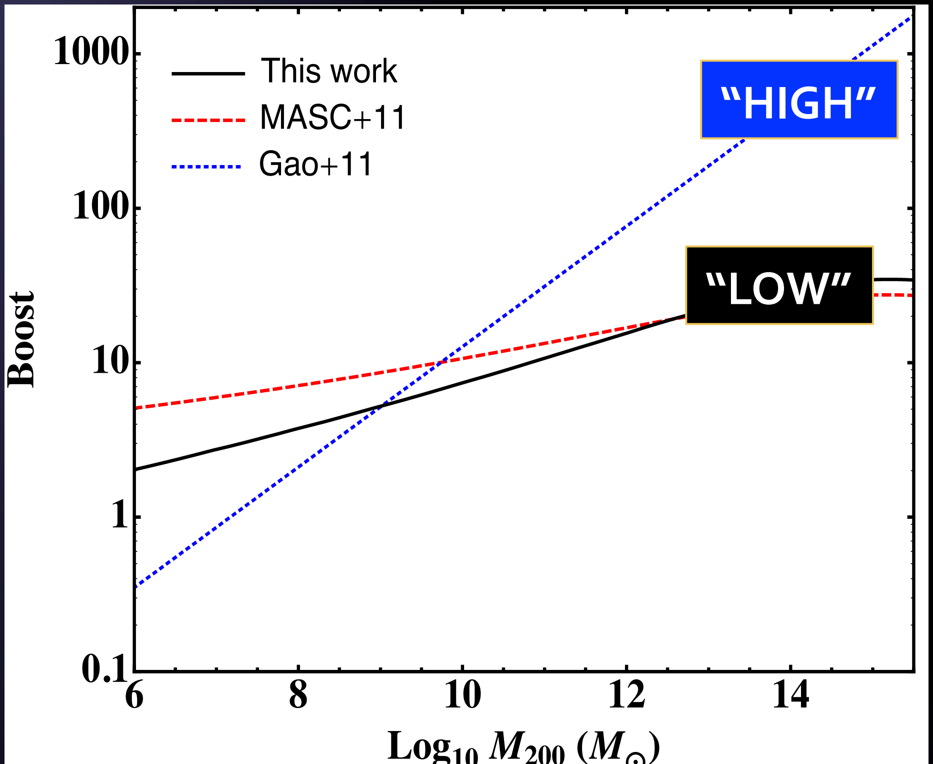




SCP14 substructure boosts

MASC & Prada, MNRAS, 442, 2271 (2014) [astro-ph/1312.1729]





Variation with M_{min} and α
[only first two substructure levels included]

Comparison with previous boost models

Reminder: they all assume that both main halos and subhalos possess similar structural properties!

SCP14: caveats

1) Strictly valid only for field DM halos (i.e., no subhalos).

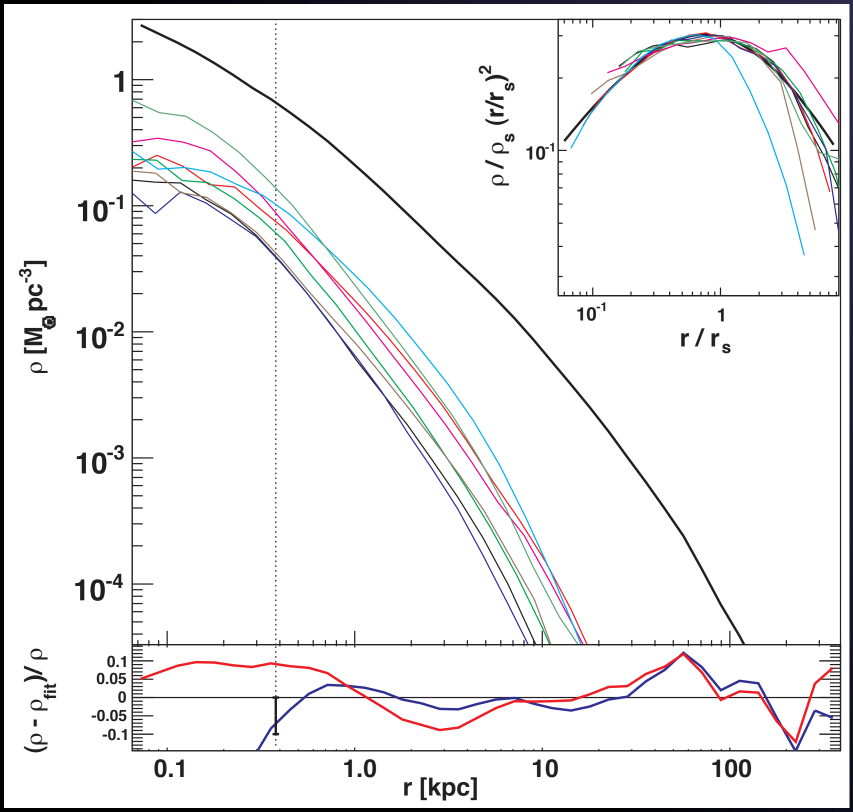
→ Not easily applicable to e.g. Milky Way satellites.
→ Subhalo concentrations are larger → *lower limits* to actual boost values.
→ Tidal forces will remove material from the outskirts → *upper limits*

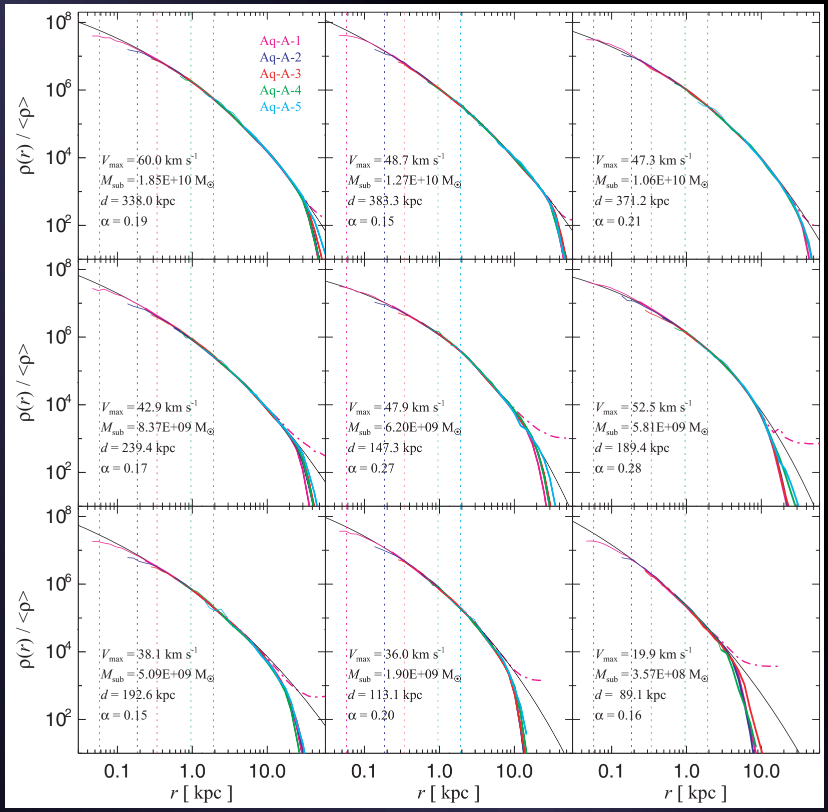
2) Total integrated boosts for the whole object.

→ No radial information.
→ *Suggestion*: follow 3k10 formalism (Kamionkowski+10) with the recipe in MASC+11, assuming the total boost given by MASC+14.

[Slide taken from my presentation at the UCLA DM 14]

Subhalo DM density profiles





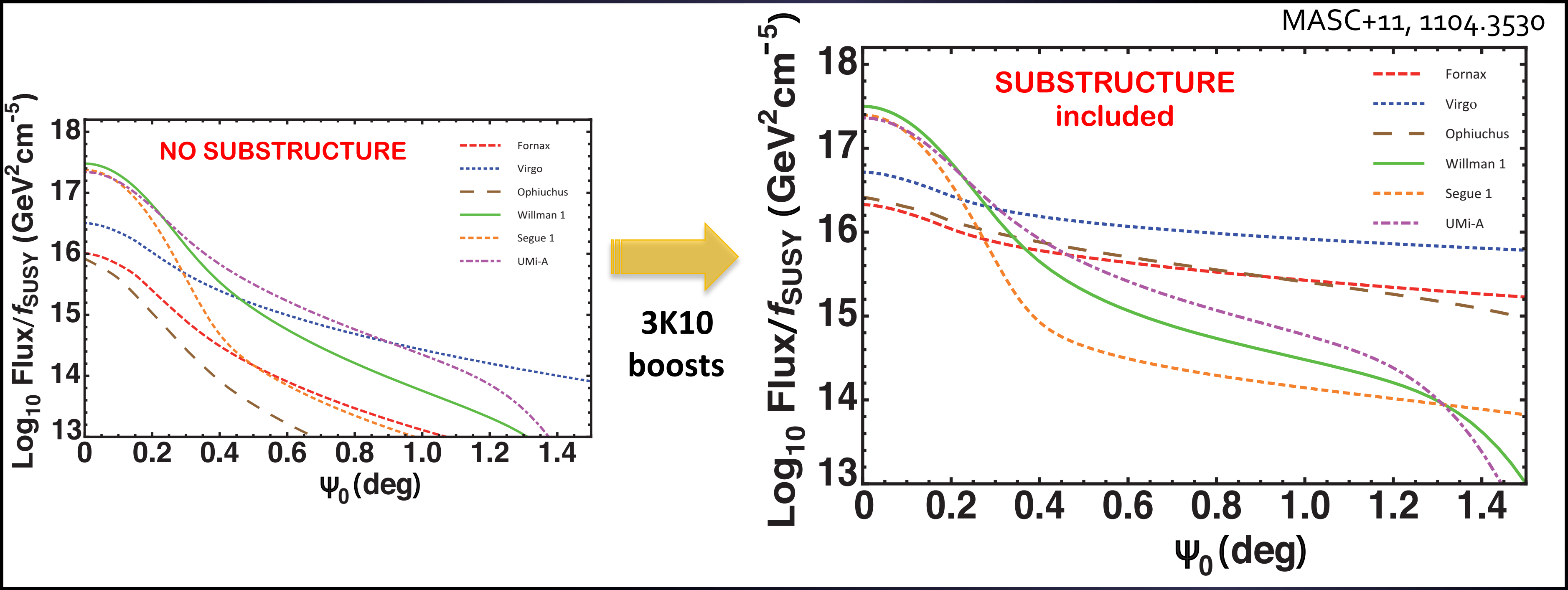
Springel+08

Similar to those of main halos but in the outermost regions, where they exhibit a exponential cut-off (tidal stripping)

→ 'standard' virial radius definition not valid → concentration??

Substructure modifies the annihilation flux profile

[MASC, Cannoni, Zandanel et al., JCAP 12 (2011) 011]



Annihilation signal becomes *more spatially extended*.

→ Instrumental sensitivity is worse for extended sources.

→ More relevant for galaxy clusters; irrelevant for dwarfs.