MULTIDARK
Multimessenger Approach for Dark Matter Detection

COLD DARK MATTER HALO CONCENTRATIONS

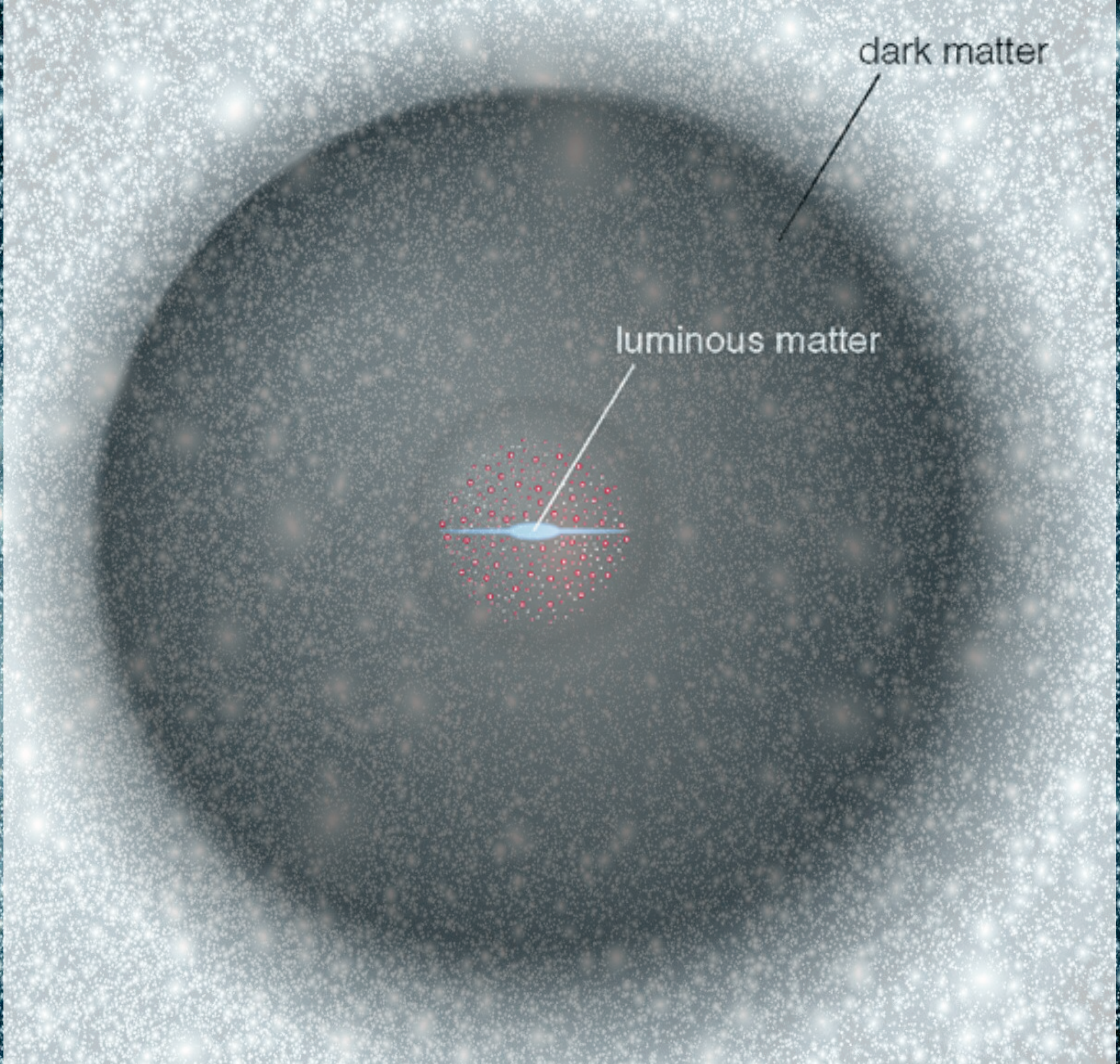
and their implications for
SUBSTRUCTURE ANNIHILATION BOOSTS

Miguel A. Sánchez-Conde

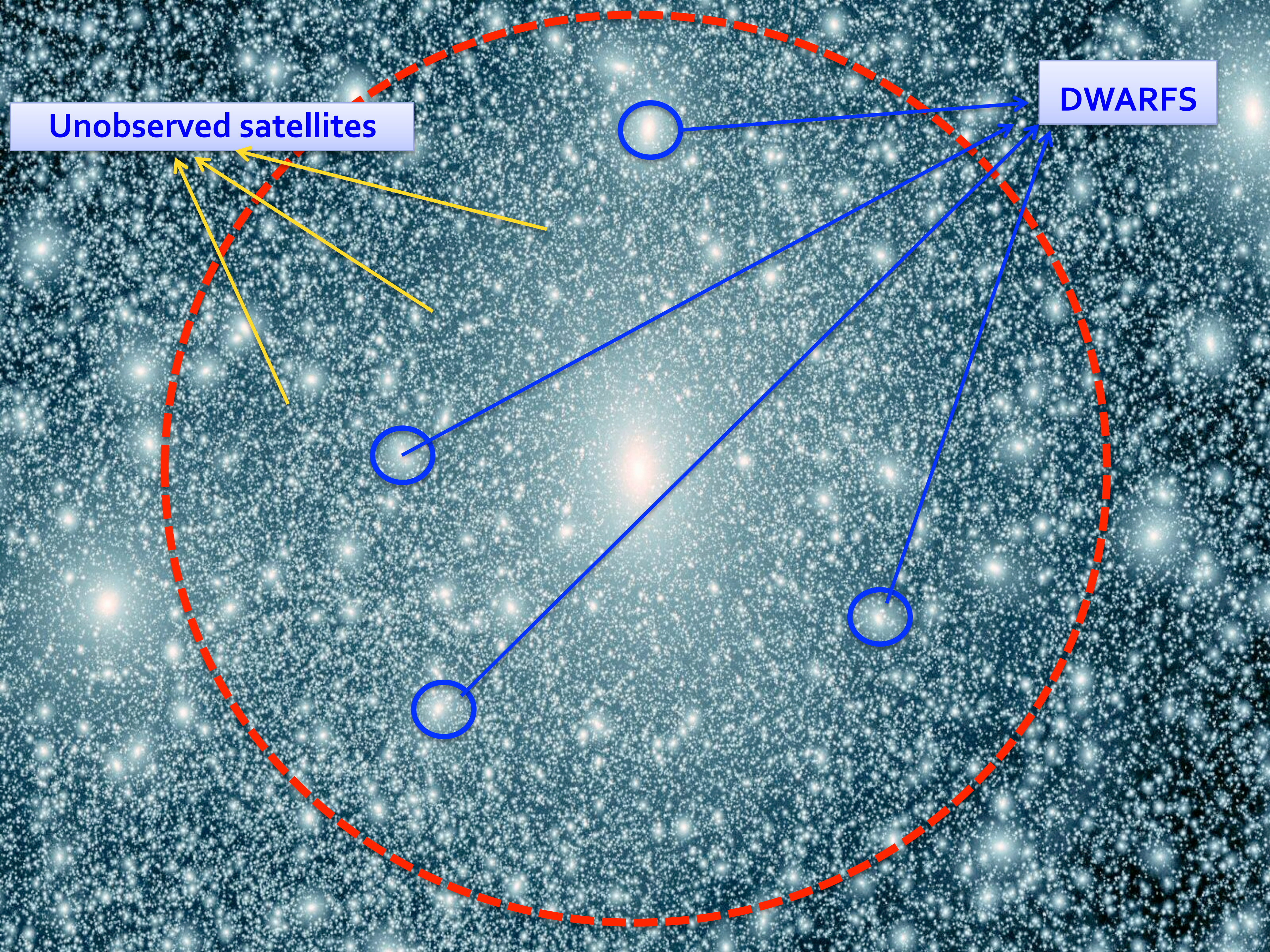
SLAC KIPAC STANFORD UNIVERSITY

What are we learning from the γ-ray sky? -- Minneapolis, October 10-12 2013

GHALO simulation [Stadel+09]



GHALO simulation [Stadel+09]


Unobserved satellites
DWARFS

The role of DM substructure in γ-ray 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

The role of DM substructure in γ-ray DM searches

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

→ GOOD TARGETS

THIS TALK

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

→ SUBSTRUCTURE BOOSTS

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

Particle physics

Integration of the squared DM density

J-FACTOR

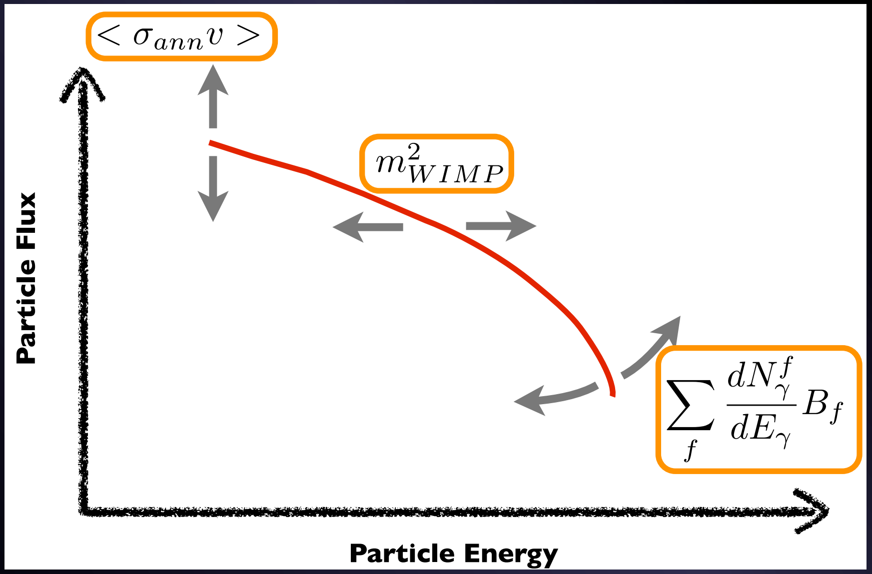
$$J(\Psi_0) = \frac{1}{4\pi}\int_{\Delta\Omega} d\Omega \int_{l.o.s.} \rho_{DM}^2[r(\lambda)]\,d\lambda$$

SMOOTH + SUBSTRUCTURE

J-factor can be expressed in terms of (v_{max},r_{max}) or (c,M) or (ρ_s,r_s)

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

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



DM annihilation boost factor from substructure

Since 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} x 2 due to subhalos

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

DM annihilation boost factor from substructure

Since 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} x 2 due to subhalos

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

Subhalo mass function

DM annihilation boost factor from substructure

Since 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

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

Subhalo luminosity

Subhalo mass function

DM annihilation boost factor from substructure

Since 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

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

Minimum halo mass

Subhalo mass function

Subhalo luminosity

DM annihilation boost factor from substructure

Since 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

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

Minimum halo mass

Subhalo mass function

Other levels of sub-substructure

Subhalo luminosity

DM annihilation boost factor from substructure

Since 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} x 2 due to subhalos

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

Host halo luminosity

Minimum
halo mass

Subhalo mass function

Other levels of
sub-substructure

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 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}

How can we know about the concentration of the smallest halos?

Two approaches taken so far:

1) Power-law extrapolations below the resolution limit.

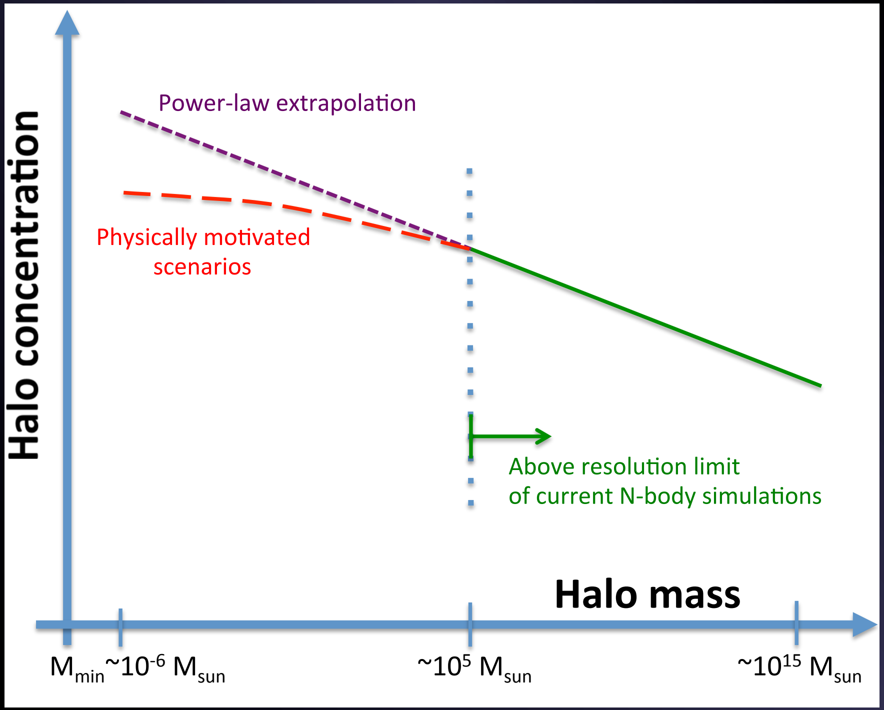
2) Physically motivated c(M) models that take into account the growth of structure in the Universe.

→ tuned to match simulations above resolution limit.

Power-law extrapolations, e.g.:
Springel+08, Zavala+10, Pinzke+11, Gao+11

Non power-law extrapolations, e.g.:
Kuhlen+08, Kamionkowski+10, Pieri+11

Large impact on boost factors!

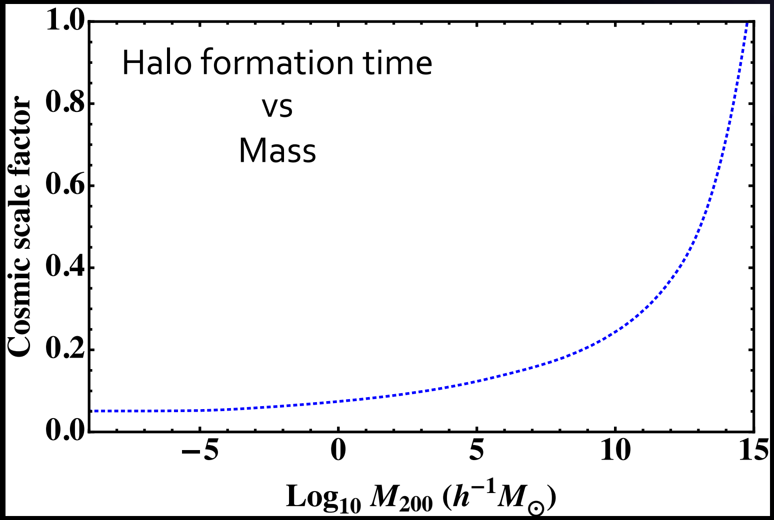


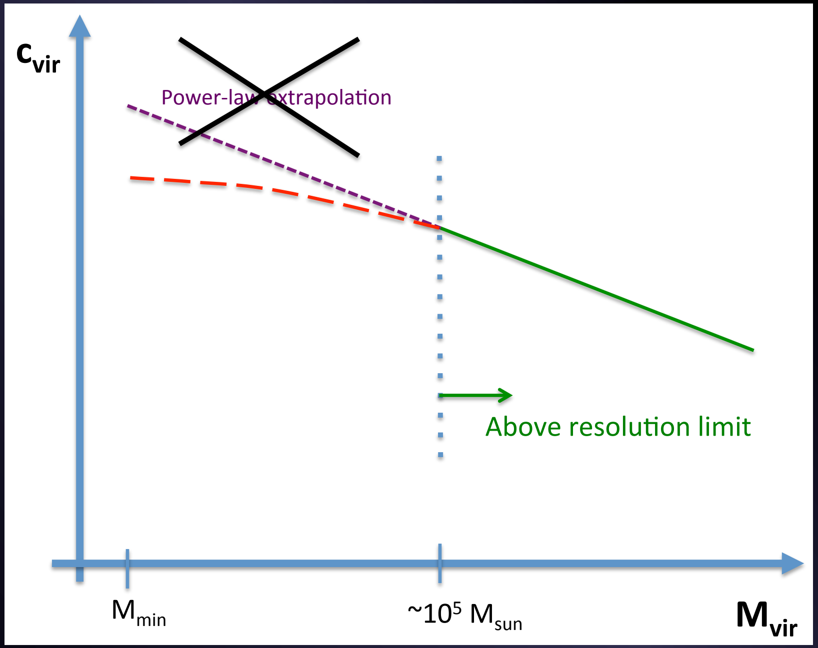
What does ΛCDM tell us about c(M) at the smallest scales?

- 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!

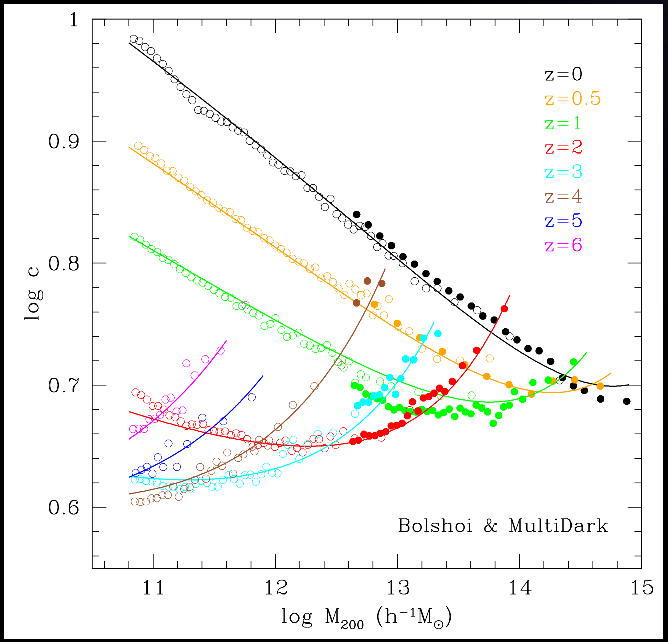


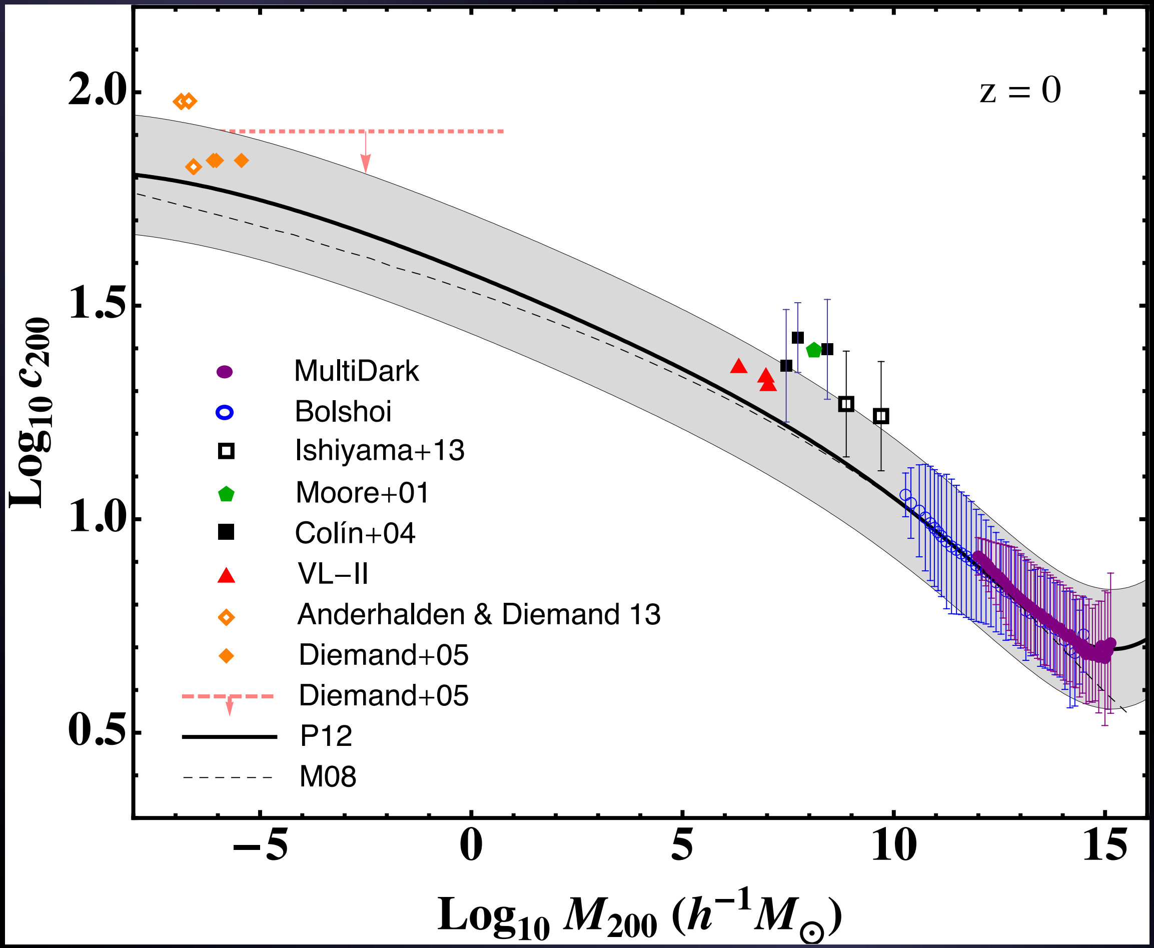


Current knowledge of the c(M) relation at z=0

Concentration $c = R_{vir} / r_s$

c scales with mass and redshift (e.g., Bullock+01, Zhao+03,08; Maccio+08, Gao+08, Prada+12)





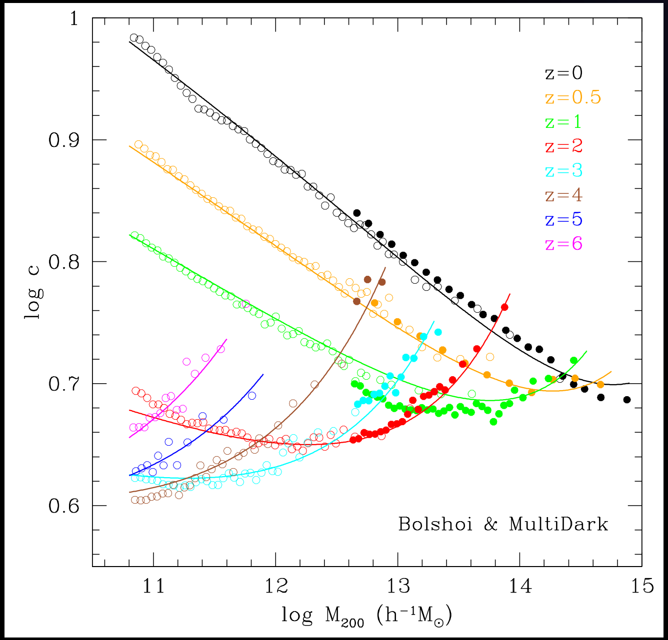
[MASC & Prada, in prep.]

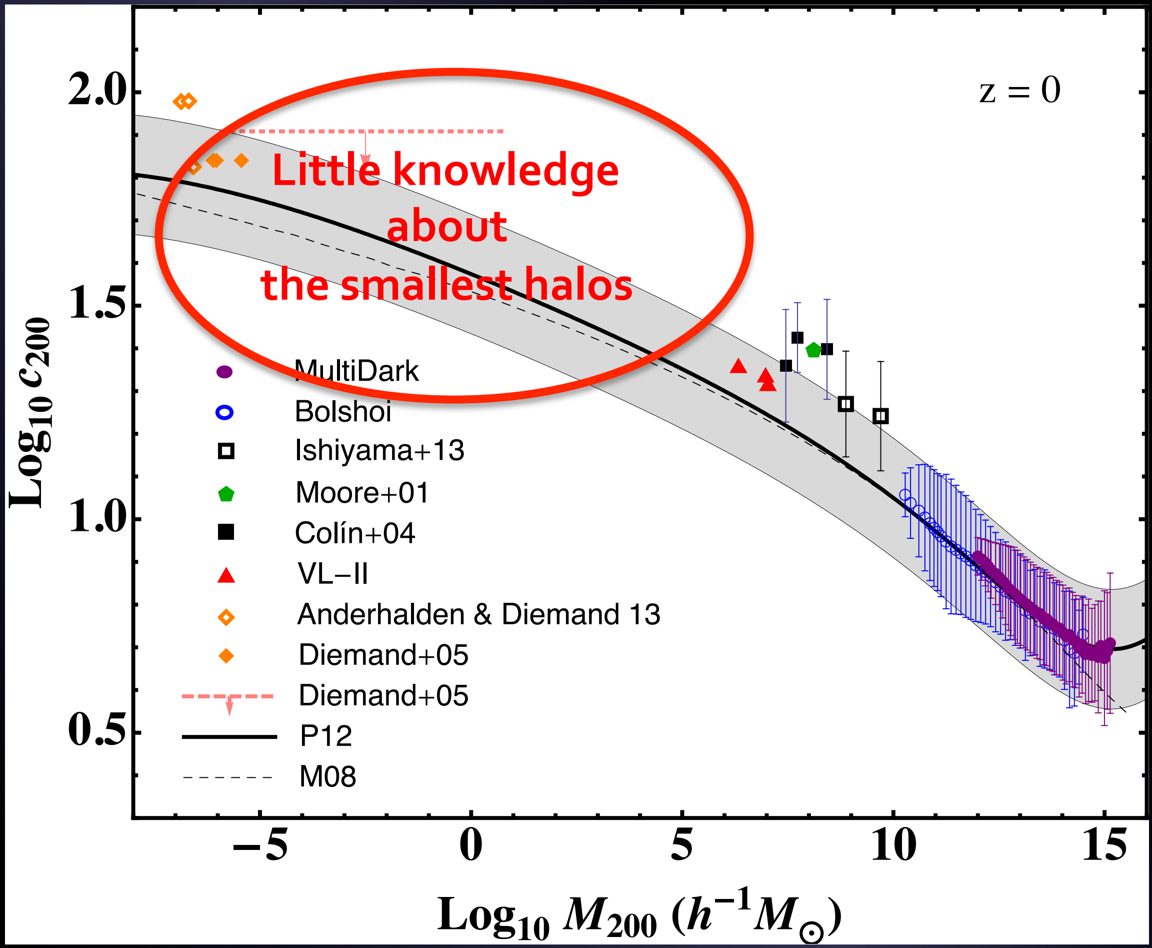
Prada+12 → P12

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

Concentration $c = R_{vir} / r_s$

c scales with mass and redshift (e.g., Bullock+01,Zhao+03,08; Maccio+08,Gao+08, Prada+12)



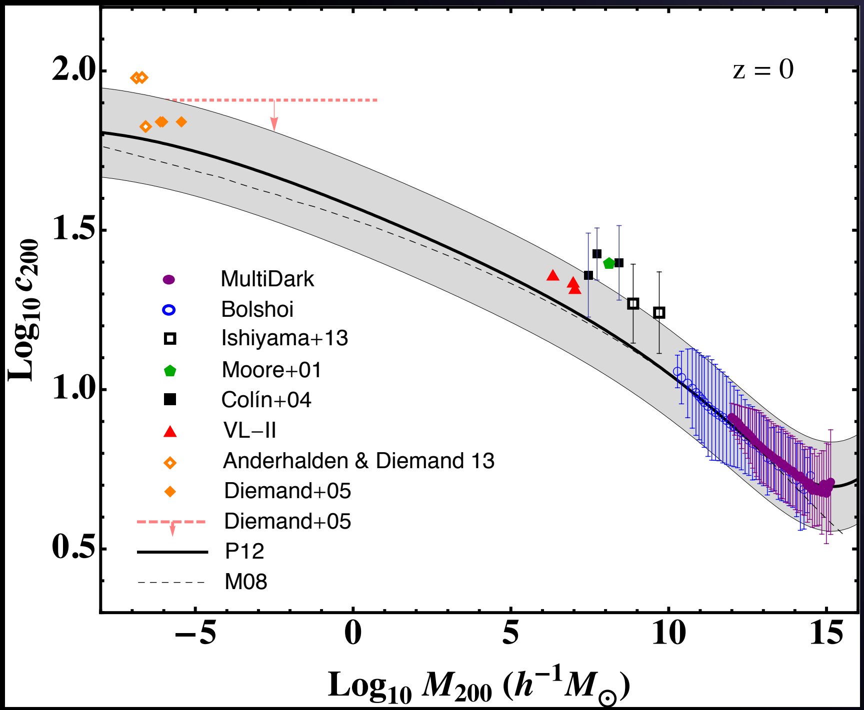


[MASC & Prada, in prep.]

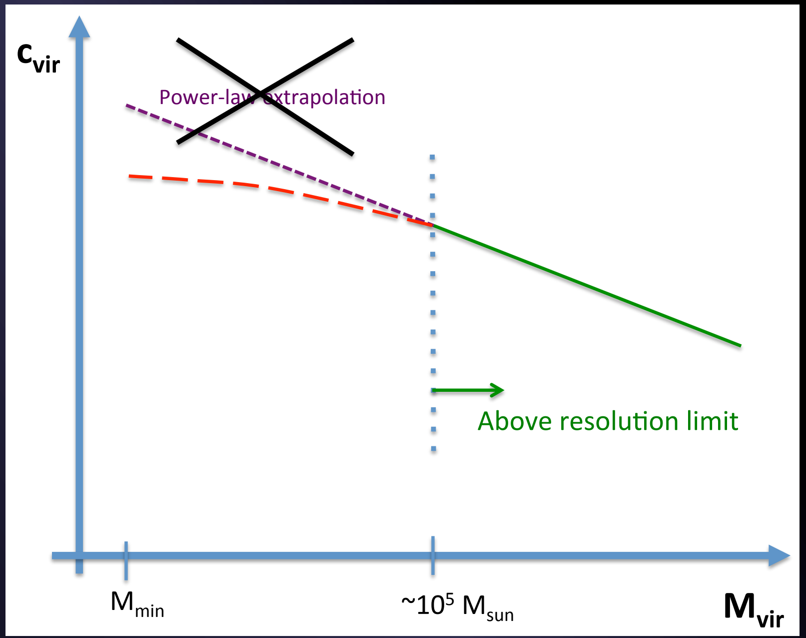
Prada+12 → P12

No more simple power-law c(M) extrapolations

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

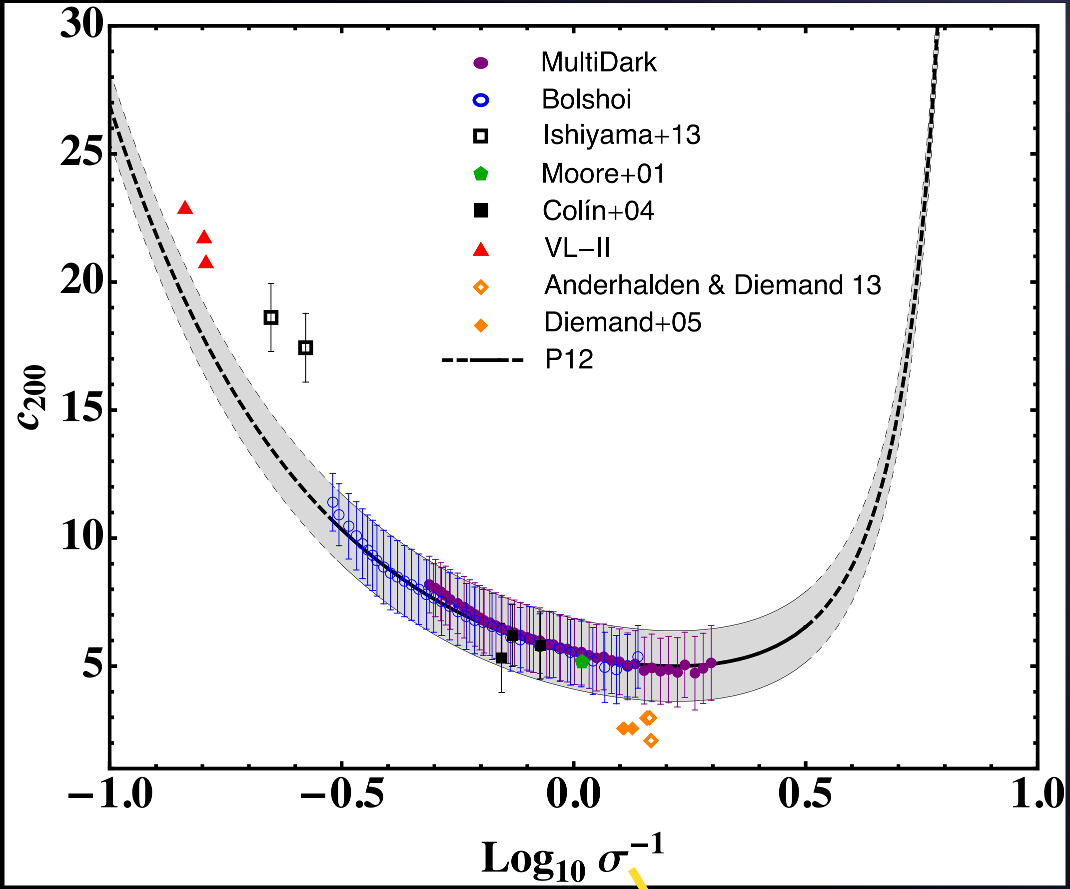


[MASC & Prada, in prep.]



The *U-shape plot*

[Is the use of P12 below the mass resolution entirely justified?]



[MASC & Prada, in prep.]

r.m.s. of the matter power spectrum

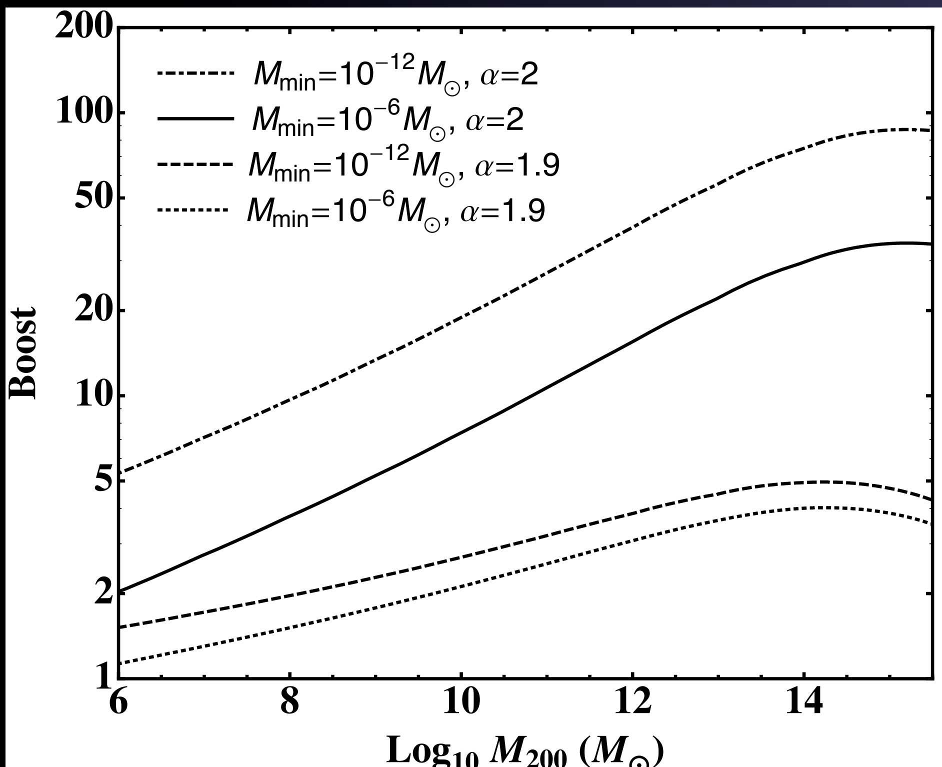
P12 links the concentration with the r.m.s. of the matter power spectrum.

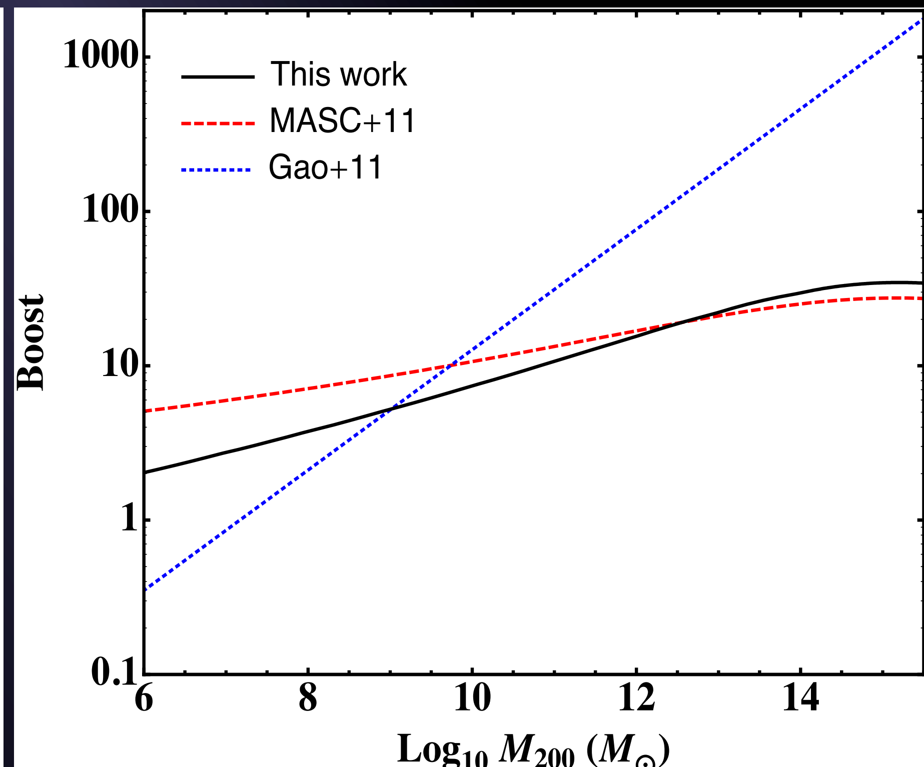
Most data sets used lie within the range fully tested by P12

→ No extrapolations indeed

Substructure boosts

[MASC & Prada, in prep.]





Variation with M_{min} and α

(only the first two substructure levels included)

Comparison with previous boosts in the literature

O(1000) boost factors for galaxy clusters given by simple power-law c(M) extrapolations clearly ruled out.

SUMMARY

- ΛCDM substructure key component for planning gamma-ray search strategies:
  - Some of them excellent targets.
  - Boost to the DM annihilation signal expected.

- Substructure boosts factors:
  - Very sensitive to extrapolations below the mass resolution.
  - Specially relevant for clusters; moderate values <50.
  - O(10) for MW-sized halos.

- Halo concentrations:
  - P12 c(M) model in remarkable agreement with N-body simulations at all halo masses.
  - Power-law extrapolations to low masses clearly ruled out.

MULTIDARK

Multimessenger Approach for Dark Matter Detection

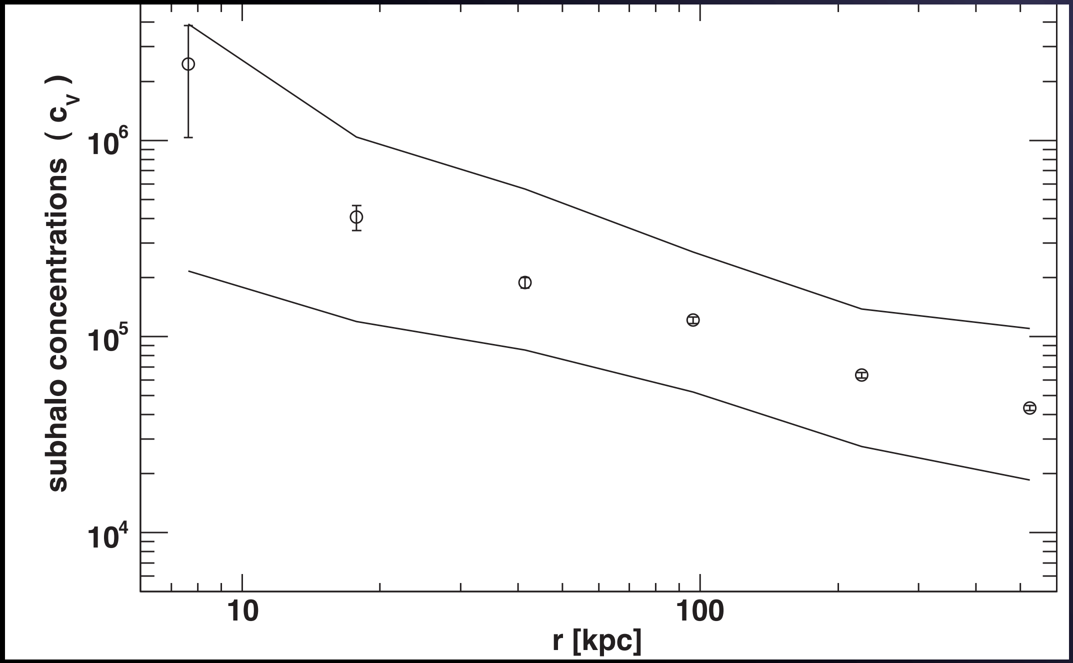
STAY TUNED

masc@stanford.edu

KIPAC

ADDITIONAL MATERIAL

Subhalo c(M) = halo c(M)?



VL-II (Diemand+08)

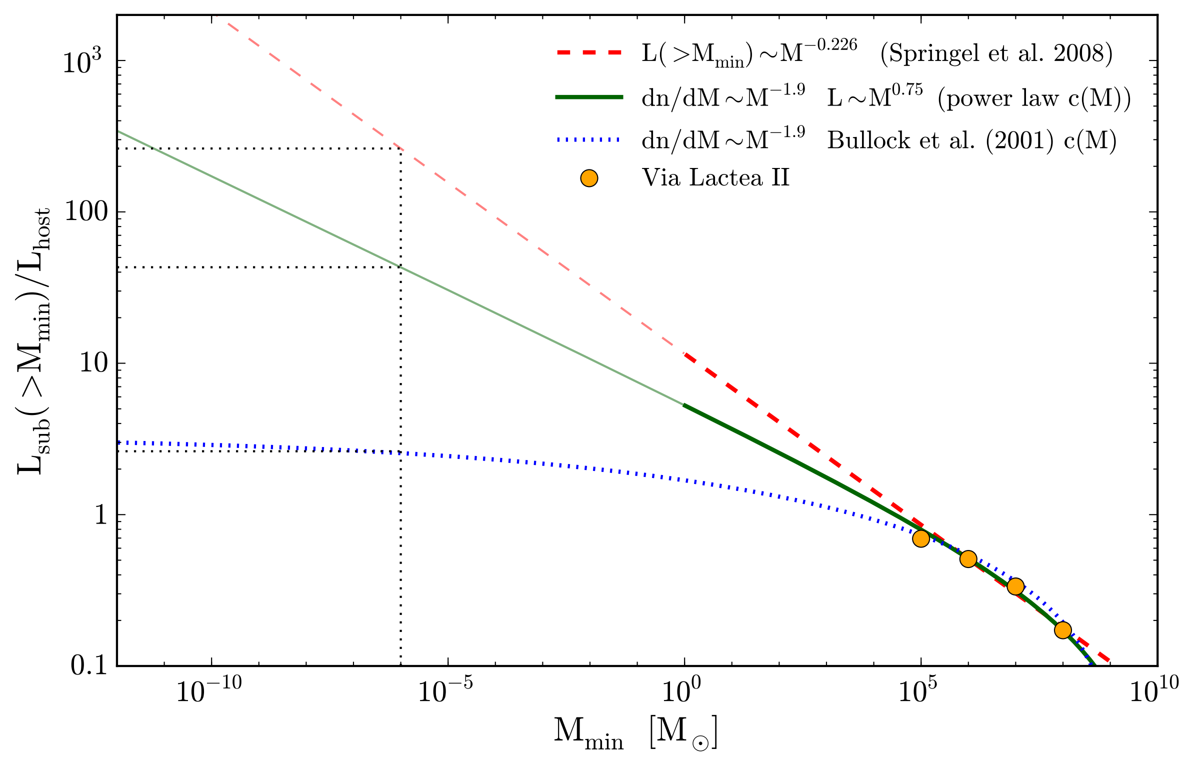
Subhalo c(M) is actually c(M,R)
→P12 boosts are a lower limit!

DM annihilation boost factor from substructure

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

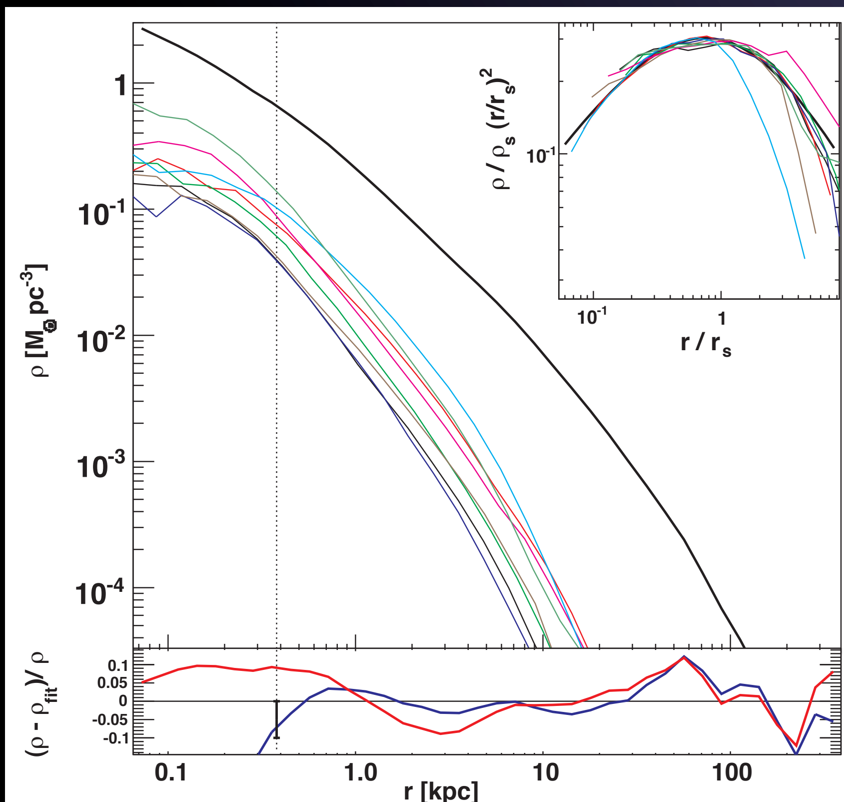
Depending on the extrapolations below the mass resolution limit in simulations, one may get completely different answers.

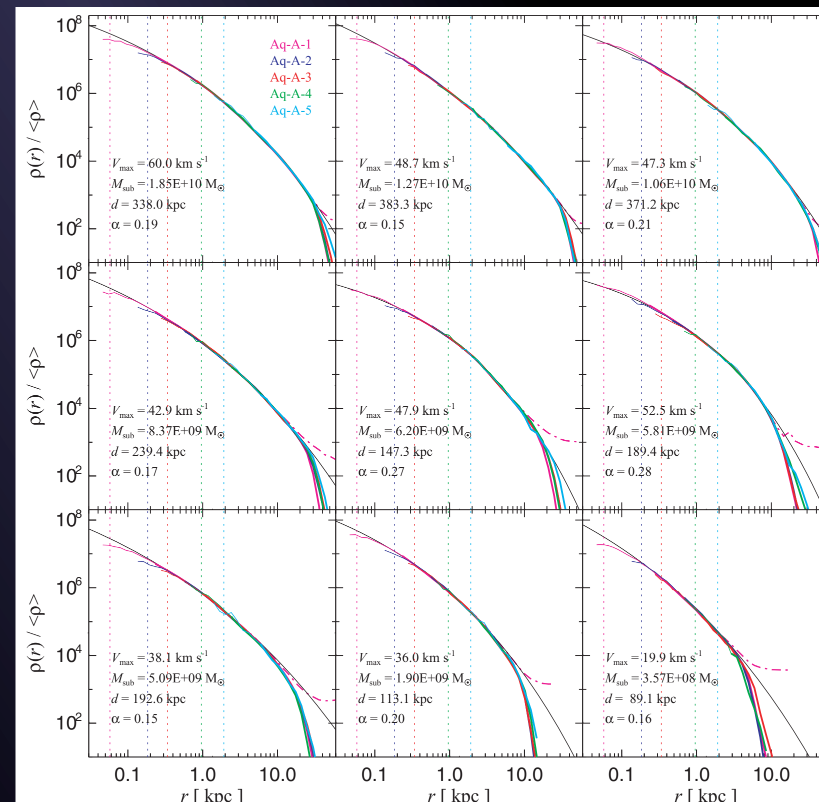
Boost for a
Milky Way-size halo



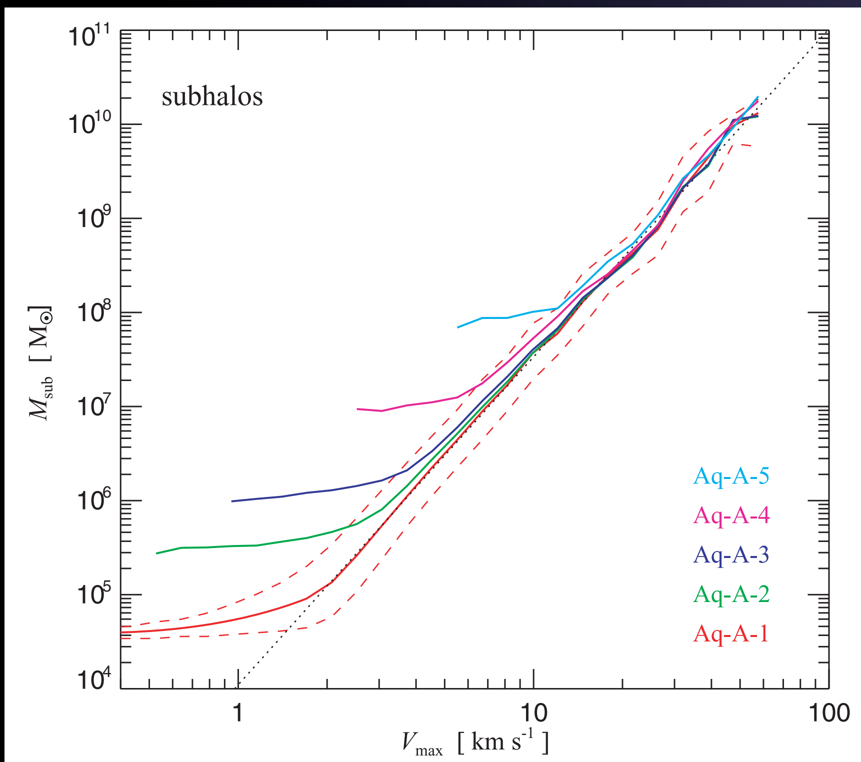
Kuhlen+12

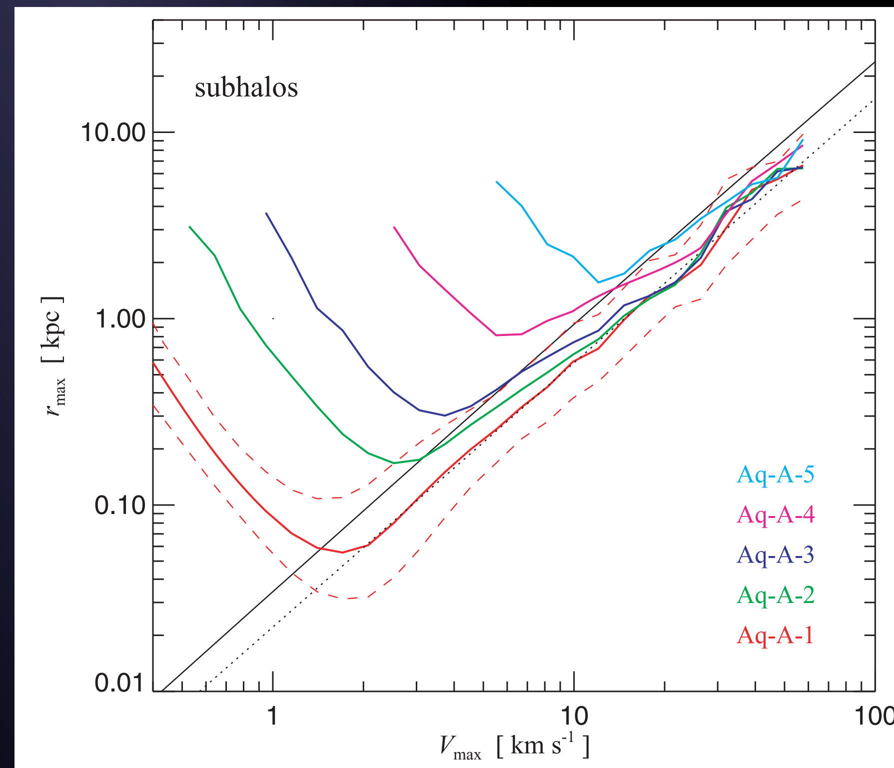
Subhalo DM density profiles





Resolution effects in V_{max} and r_{max} in Aquarius

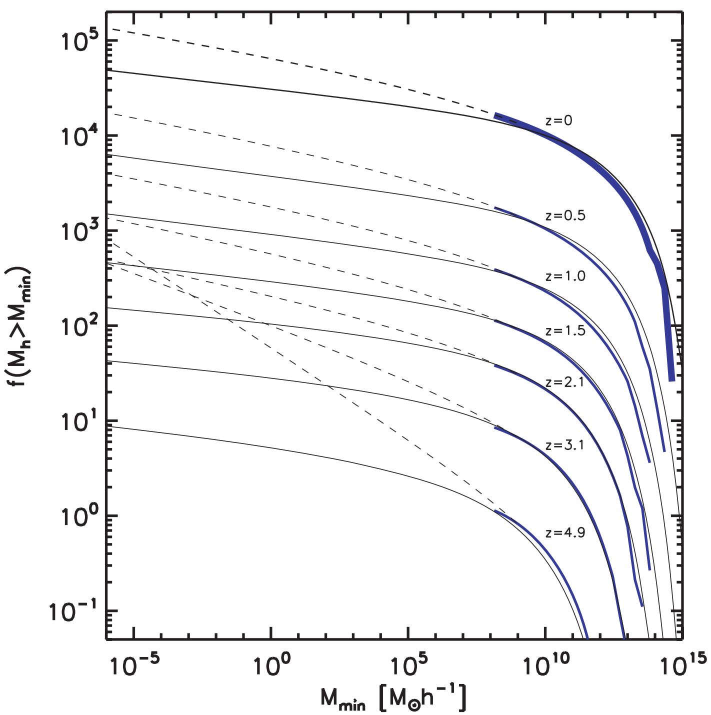




c-M power-law extrapolations?

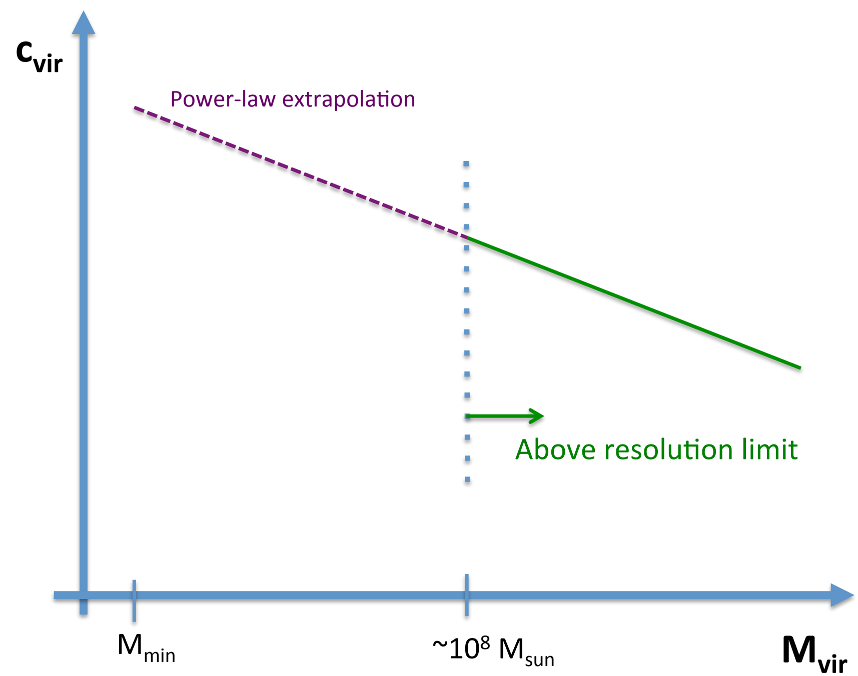
- Power-laws assign very high concentrations for the smallest halos:

  → As flux prop. c^3, v**ery high substructure boosts** expected (and very dependent on the extrapolation)
  - Springel+08 (Aquarius simulations) found B~200 for MW halos.
  - Pinzke+11 and Gao+11 find B~1300 for clusters.
  - Zavala+11 find B to be between 2 and 1821 for MW sized halos, depending on the extrapolation.



Zavala+10, MNRAS 405, 593

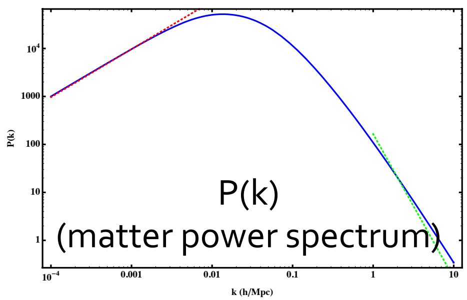
=

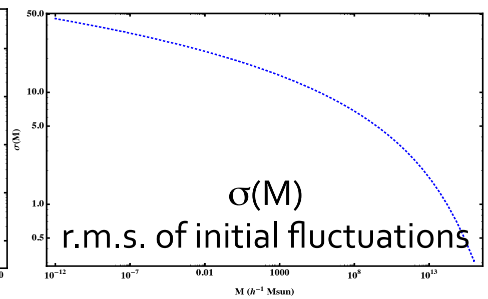


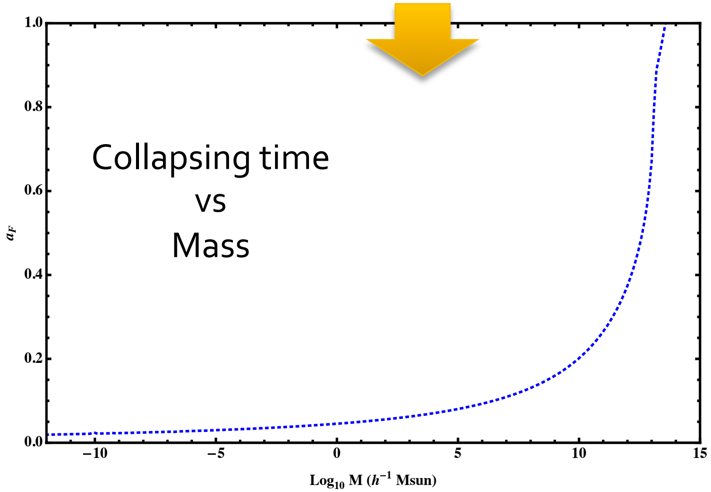
KIPAC

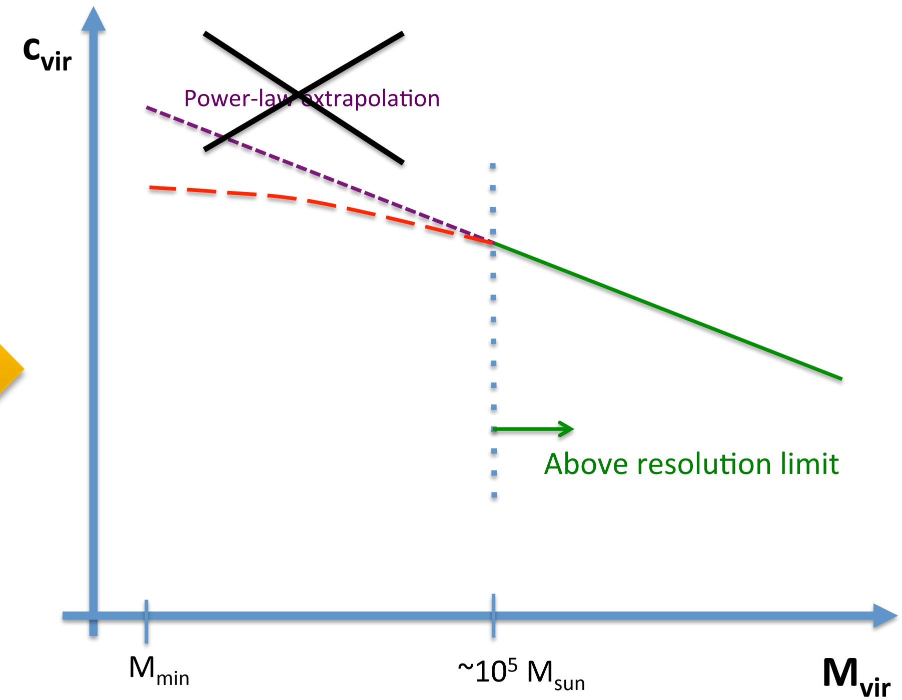
What does LCDM tell us about c(M)?

- Natal concentrations are mainly set by the collapse time.
- Assuming spherical collapse model: $\sigma(M)*D(z_c) = d_c$
- Given the shape of P(k) in CDM, the smallest halos collapse nearly at the same redshift:
  - → Concentration is nearly the same for the smallest halos!
  - → **c(M) flattening at low mass → power-law extrapolations not correct!**









3K10 substructure formalism

- Semi-analytical treatment presented in Kamionkowski+10 for MW sized halos.
  → Slight modification to extend the formalism to halos of different masses (MASC+11)

- Two crucial parameters:
  - **f_s**, that controls the amount of substructure.
    → Calibrated using VL-II simulations above the resolution limit.
  - ρ_{max}, which depends on the natal concentration of the earliest virialized objects
    → fixed to **c = 4** following e.g. Diemand+06 and Zhao+09 findings at high z.

- Radial distribution of subhalos from VL-II.

DIFFERENTIAL BOOST

$$B(r) = f_s e^{\Delta^2} + (1 - f_s)\frac{1+\alpha}{1-\alpha}\left[\left(\frac{\rho_{max}}{\rho(r)}\right)^{1-\alpha} - 1\right]$$

$$1 - f_s(r) = 7 \times 10^{-3}\left(\frac{\rho(r)}{\rho(r = 3.56 \times r_s \ \mathrm{kpc})}\right)^{-0.26}.$$

MASC+11 recipe

INTEGRATED BOOST

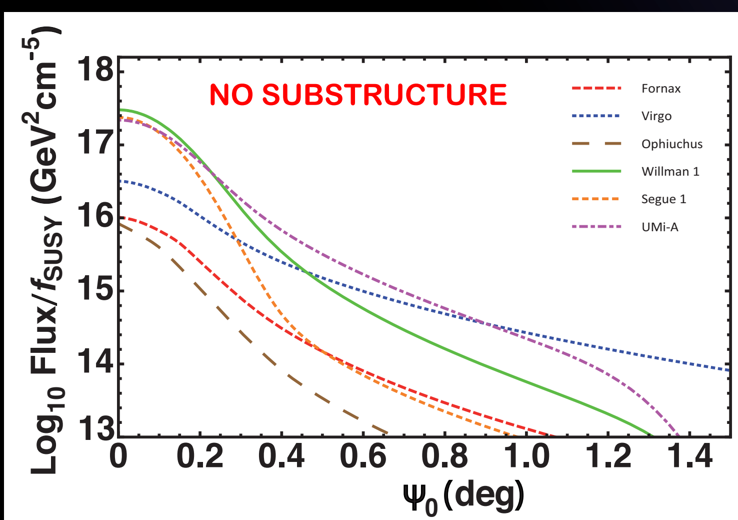
$$B(<R) = \frac{\int_0^R B(r)\,\rho^2(r)\,r^2\,dr}{\int_0^R \rho^2(r)\,r^2\,dr}.$$

3K10 boosts

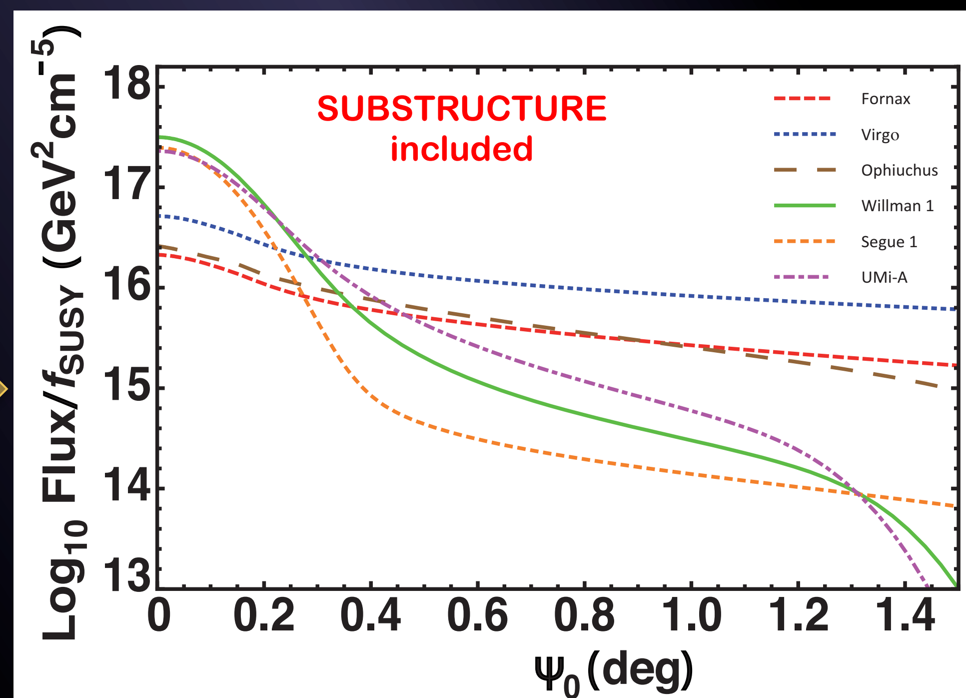
[also based on well motivated c(M) extrapolations]

- **B ≈ 1.1-1.3 for dwarf galaxies** (vs ≈ 20 found by Pinzke+11)
- **B ≈15-20 for MW**-sized halos (vs ≈ 200 found by Springel+08).
- **B ≈ 40-50 for galaxy clusters** (vs ≈ 1300 found by Pinzke+11, Gao+11, Han+12).

Substructure modifies the annihilation flux importantly



3K10 boosts



[MASC+11]

3K10 boost values

(based on well motivated c-M extrapolations)

CLUSTERS boosted

Cluster	$B(< R_{vir})$ BOOSTS	$\mathrm{Log}_{10}\ J_T$ ($\mathrm{GeV^2 cm^{-5}}$)	ψ_{90} (deg)	r_{90}/r_s	J_{01}/J_T	r_{01}/r_s	ψ_{r_s} (deg)	J_{r_s}/J_T	Rank_{01}	Rank_{90}
Perseus	34.0	17.73	1.22	4.24	0.037	0.135	0.29	0.19	3	5
Coma	51.6	17.84	1.41	4.08	0.028	0.29	0.34	0.20	4	4
Ophiuchus	54.0	17.89	1.38	3.89	0.028	0.28	0.36	0.21	2	3
Virgo	55.0	19.11	7.29	4.55	0.004	0.06	1.61	0.18	1	1
Fornax	39.9	18.17	2.97	5.11	0.013	0.17	0.58	0.16	5	2
NGC5813	34.8	17.33	1.36	5.69	0.035	0.42	0.24	0.14	7	7
NGC5846	36.1	17.51	1.59	5.54	0.028	0.35	0.29	0.15	6	6

MASC+11, 1104.3530

90% of the annihilation flux comes from this radius

- **B ≈ 1.1-1.3 for dwarf galaxies** (vs ≈ 20 found by Pinzke+11)
- **B ≈15-20 for MW**-sized halos (vs ≈ 200 found by Springel+08).
- **B ≈ 40-50 for galaxy clusters** (vs ≈ 1300 found by Pinzke+11, Gao+11, Han+12).

Both approaches were used in Abdo+10 to bracket the uncertainties:

- Millenium II simulations, with power-law extrapolations to lower masses.
- Bullock+01 semi-analytical model for halo concentrations, which gives softer extrapolation.

FLUX from DM-induced extragalactic photons

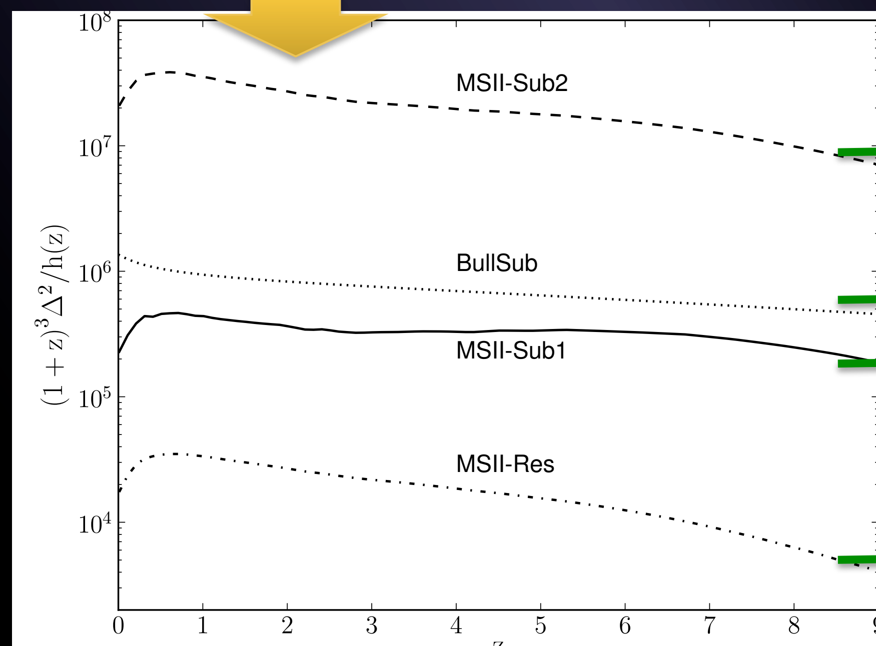
$$\frac{d\phi_\gamma}{dE_0} = \underbrace{\frac{\langle \sigma v \rangle}{8\pi} \frac{c}{H_0} \frac{\bar{\rho}_0^2}{m_{DM}^2}}_{\text{Constant for a particular DM model}} \int dz \underbrace{(1+z)^3 \frac{\Delta^2(z)}{h(z)}}_{\text{“Flux multiplier”}} \underbrace{\frac{dN_\gamma(E_0(1+z))}{dE}}_{\text{Redshifted DM spectrum}} \underbrace{e^{-\tau(z,E_0)}}_{\text{EBL}}$$

1) N-body simulations:

$\Delta^2(z)$ calculated from MSII (Zavala+10)

2) Halo models:

$$\Delta^2(z) = \int dM \underbrace{\frac{dn}{dM}}_{\text{Halo mass function (S\&T)}} \int dc \underbrace{P(c) \frac{\langle \rho^2(M,c) \rangle}{\langle \rho(M,c) \rangle^2}}_{\text{Density profiles and concentration}}$$



Most optimistic power-law extrapolation

Semi-analytical

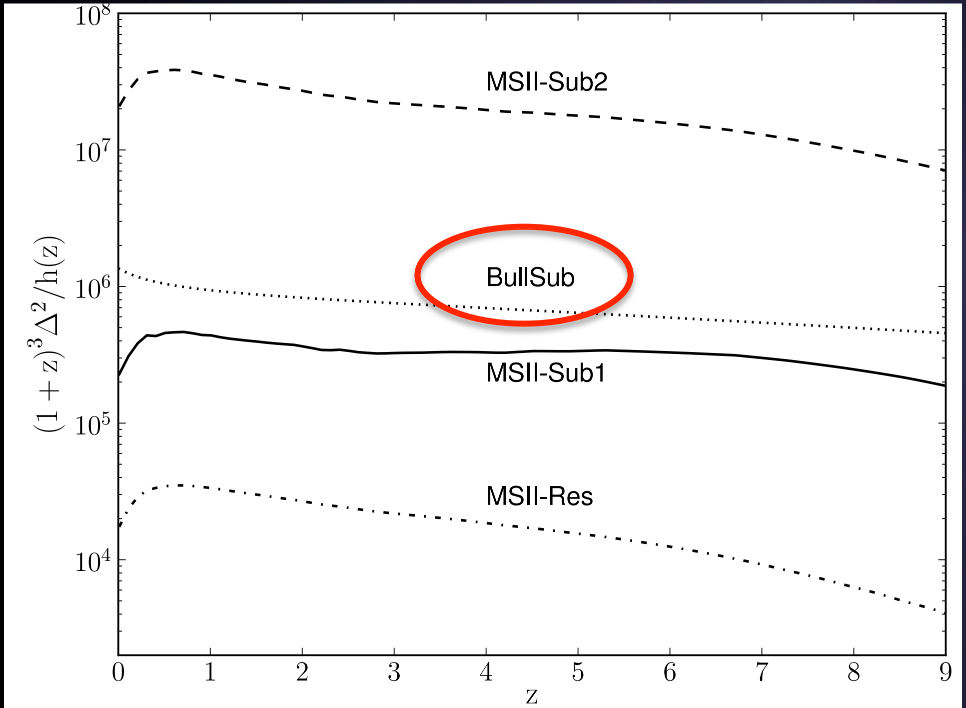
Conservative power-law extrapolation

Only resolved halos in MSII

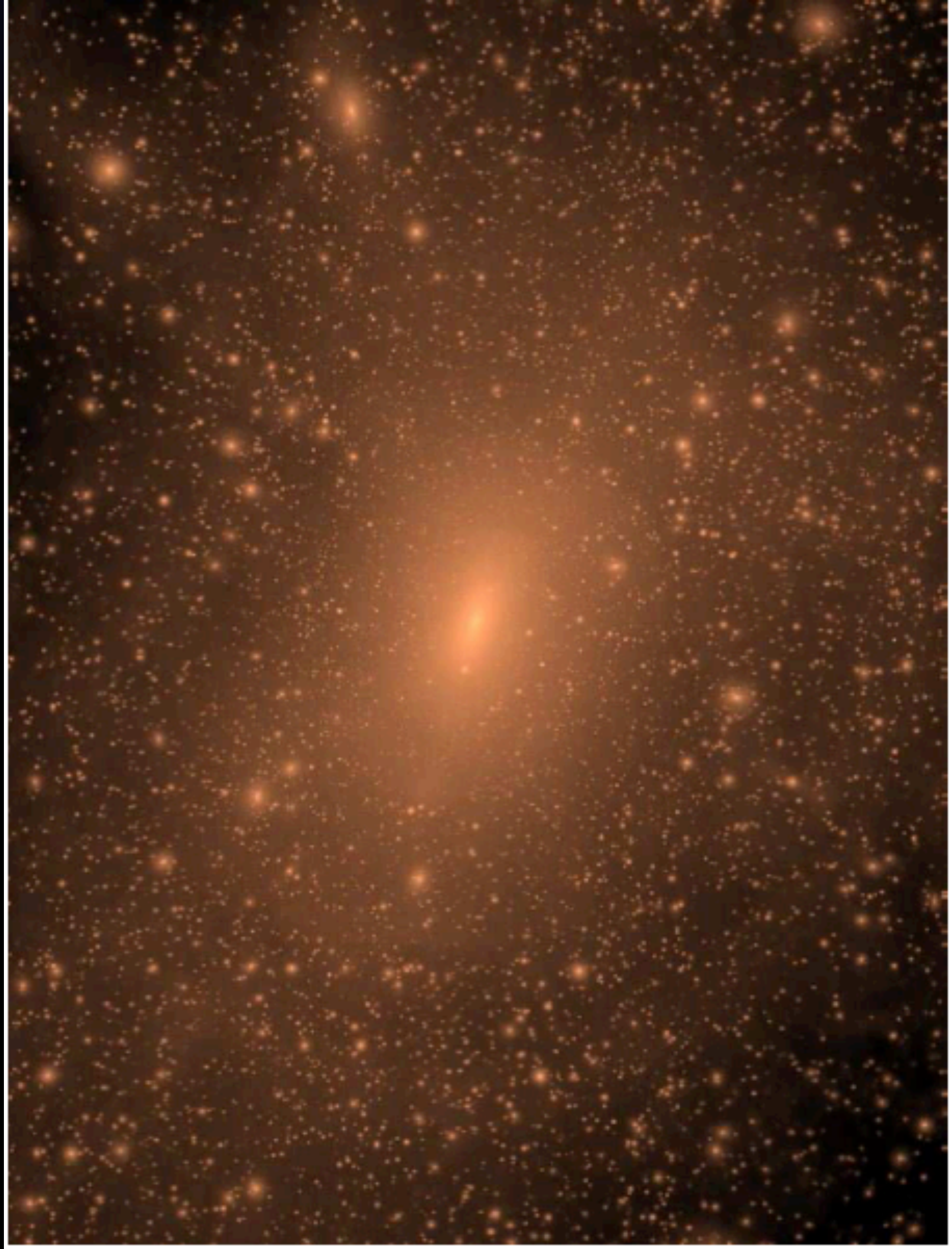
Abdo+10

Halo substructure and the IGRB

- DM halo evolution and halo substructure play a critical role in the determination of the contribution of DM annihilation to the IGRB.
- However, **very large uncertainties**! e.g.: 3 orders of magnitude uncertainty in the cross section was quoted in the Fermi-LAT paper on the interpretation of the IGRB in terms of DM.
- Working on this: results will be probably close to the "BullSub" model.



Abdo+10, JCAP 04, 014



3-year WMAP cosmology.

Initial z = 48.4.

Mvir = 1.8 x 10^{12} Msun

234 x 10^6 particles
(SUSY CDM)

Each particle 2x10^4 Msun.

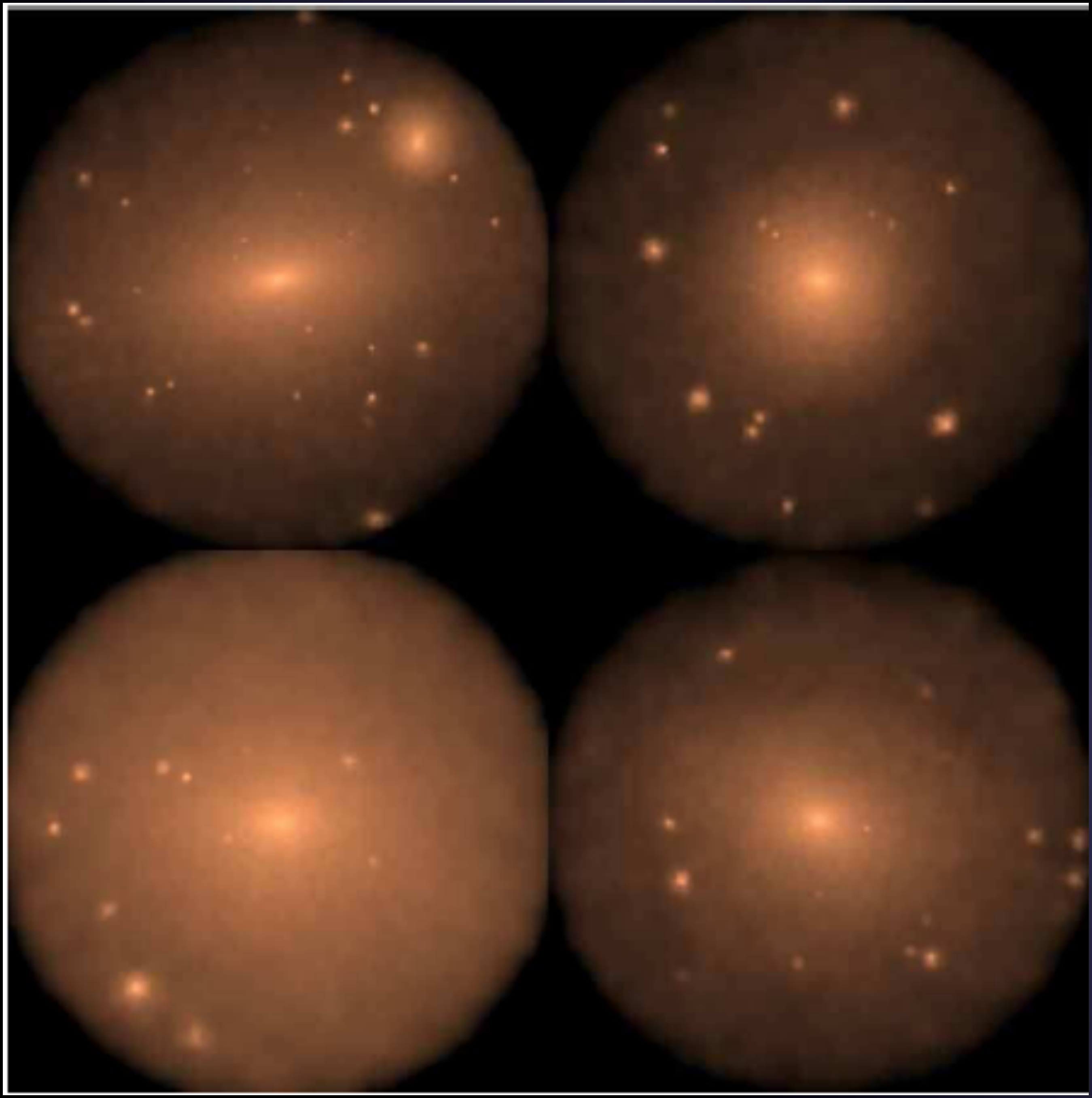
800 x 600 kpc

600 kpc depth

10,000 subhalos

110 million particles

(Diemand et al. 2006)

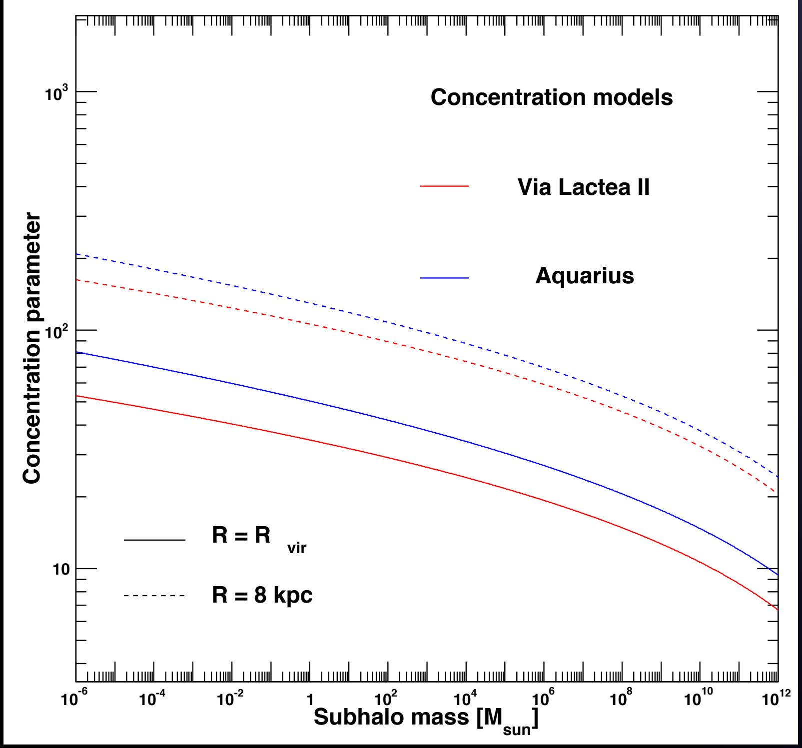


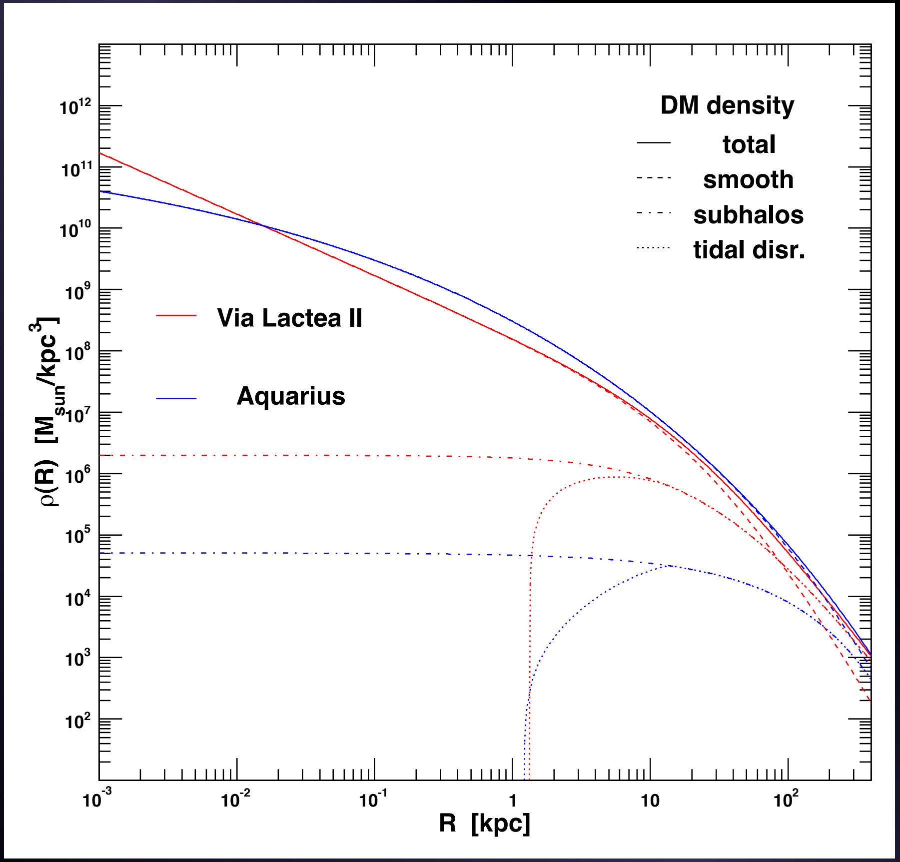
The 4 most massive subhalos (~10^9 Msun)

Sub-substructure clearly visible.

(Diemand et al. 2006)

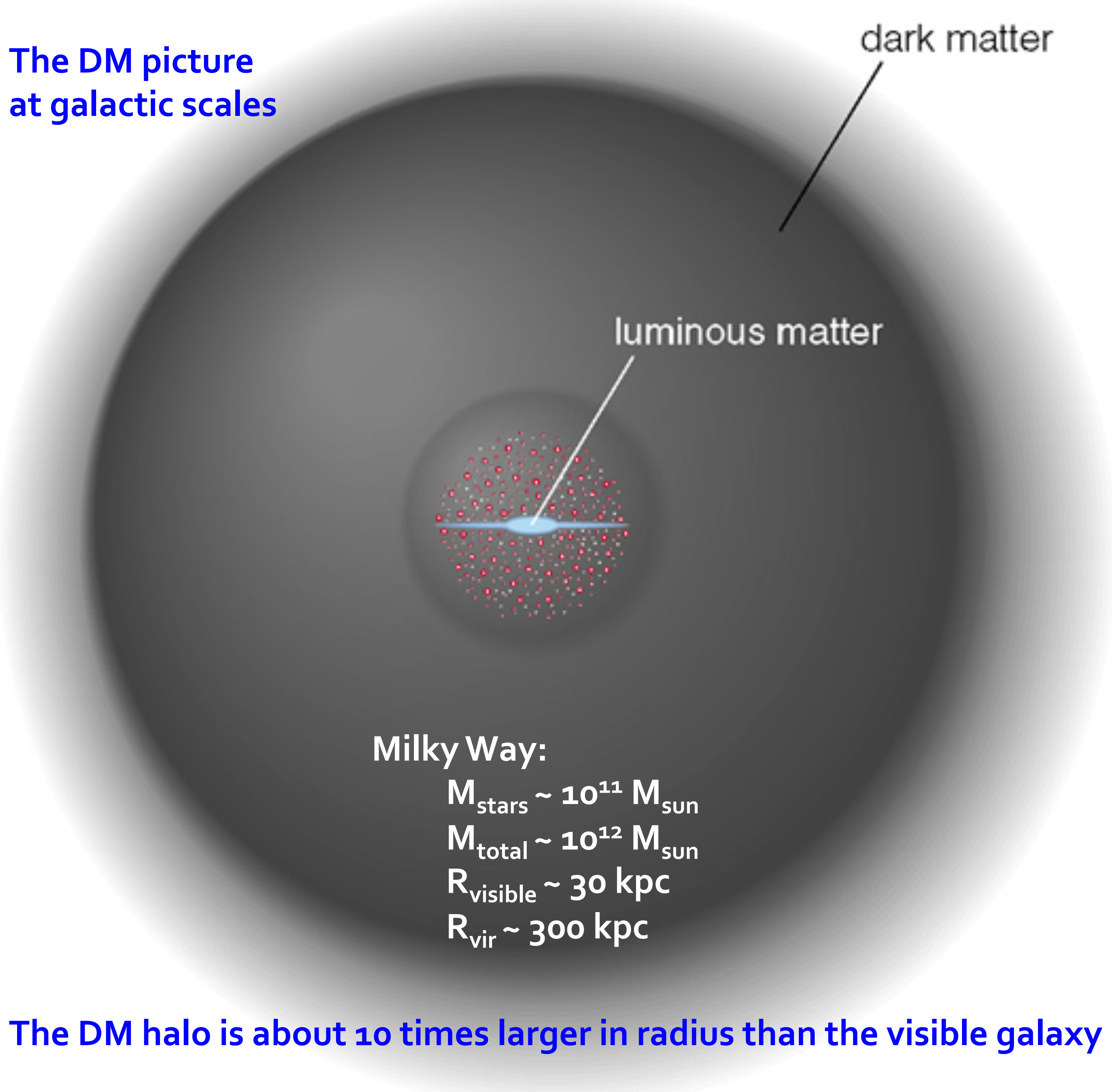
Aquarius – VLII comparison





Pieri+09

The DM picture at galactic scales



Milky Way:

$M_{stars} \sim 10^{11}\ M_{sun}$

$M_{total} \sim 10^{12}\ M_{sun}$

$R_{visible} \sim 30$ kpc

$R_{vir} \sim 300$ kpc

The DM halo is about 10 times larger in radius than the visible galaxy