DARK MATTER MODELING IN A ΛCDM UNIVERSE

[relevant for gamma-ray dark matter searches]

Miguel A. Sánchez-Conde

Instituto de Física Teórica IFT UAM/CSIC & Departamento de Física Teórica
Universidad Autónoma de Madrid

miguel.sanchezconde@uam.es

1st Thai-CTA workshop on Astroparticle Physics

Chiangmai, Thailand, February 18-22 2019

Hands-on session on DM modeling

I prepared a couple exercises on DM modeling for you.

Please download the sheet of problems from:

https://tinyurl.com/yywzqcsc

(and feel free to ask any questions)

BEFORE THAT…

The DM-induced gamma-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

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

Where to search?

- Galactic Center
- Dwarf spheroidal galaxies
- Local galaxy clusters
- Nearby galaxies...

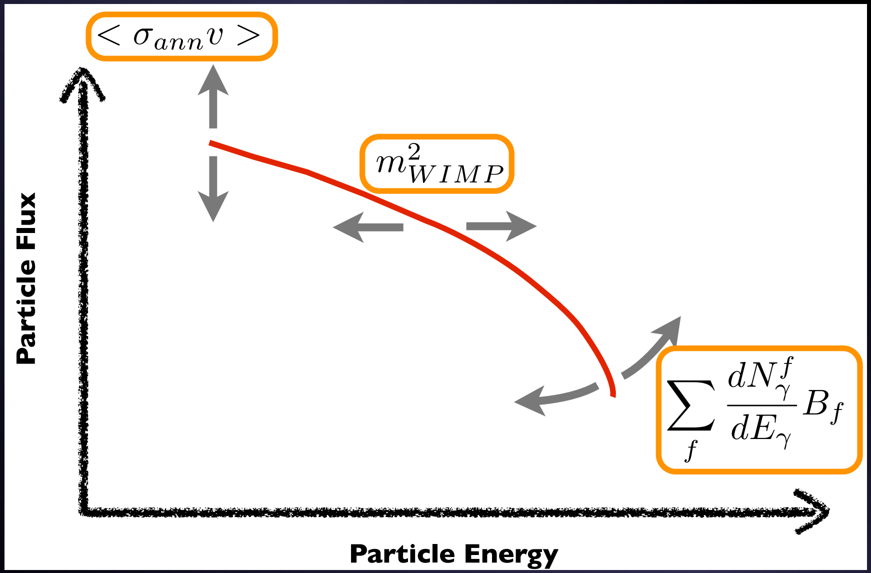
Particle physics

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

N$_g$: number of photons per annihilation above E$_{th}$

<σ v>: cross section

m$_\chi$: neutralino mass



The DM-induced gamma-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}

THIS TALK

Astrophysics

Integration of the squared DM density

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

SMOOTH + SUBSTRUCTURE

Where to search?

- Galactic Center
- Dwarf spheroidal galaxies
- Local galaxy clusters
- Nearby galaxies...

Particle physics

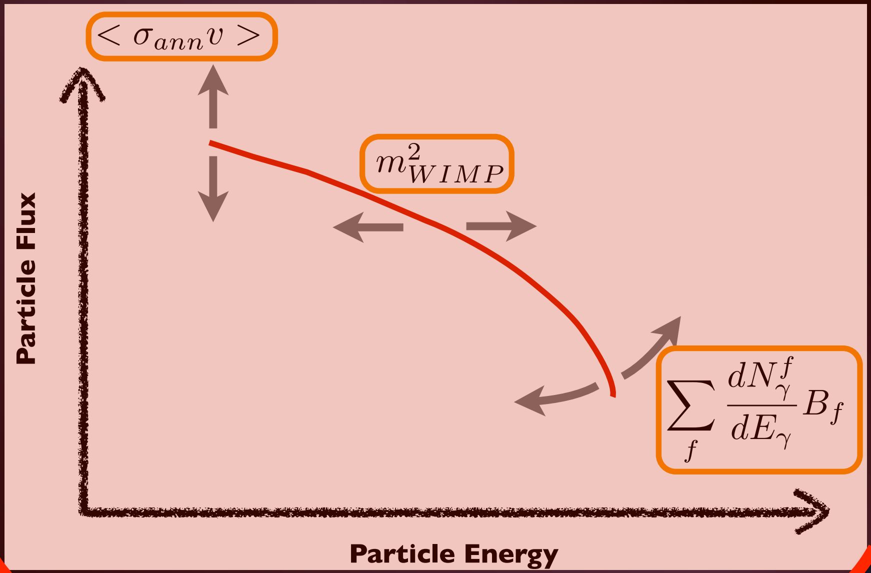
SOMEONE ELSE TALK

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

N_g : number of p
per annihilation
above E_{th}

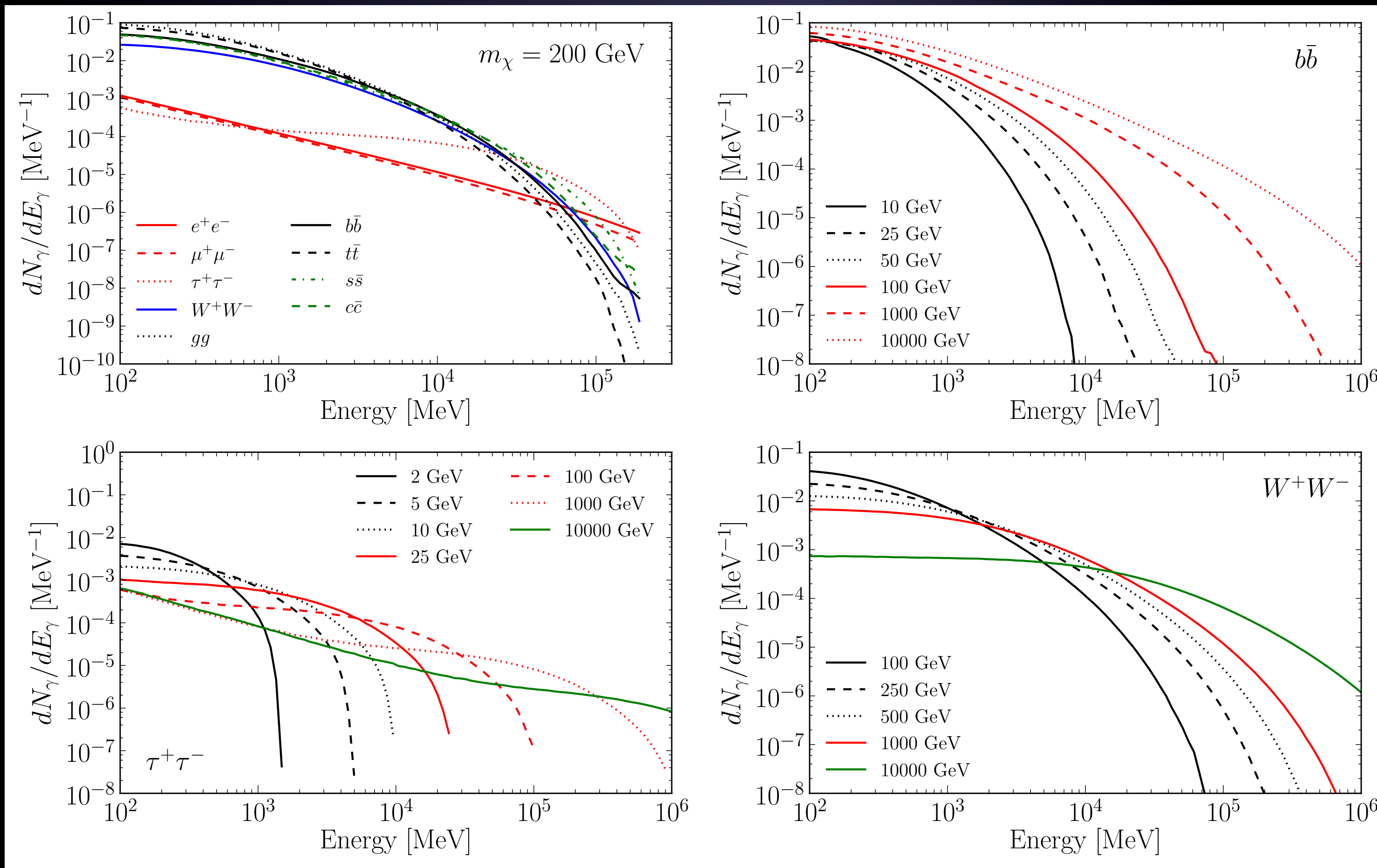
<σ v>: cross section

m_χ: neutralino mass



Annihilation spectra

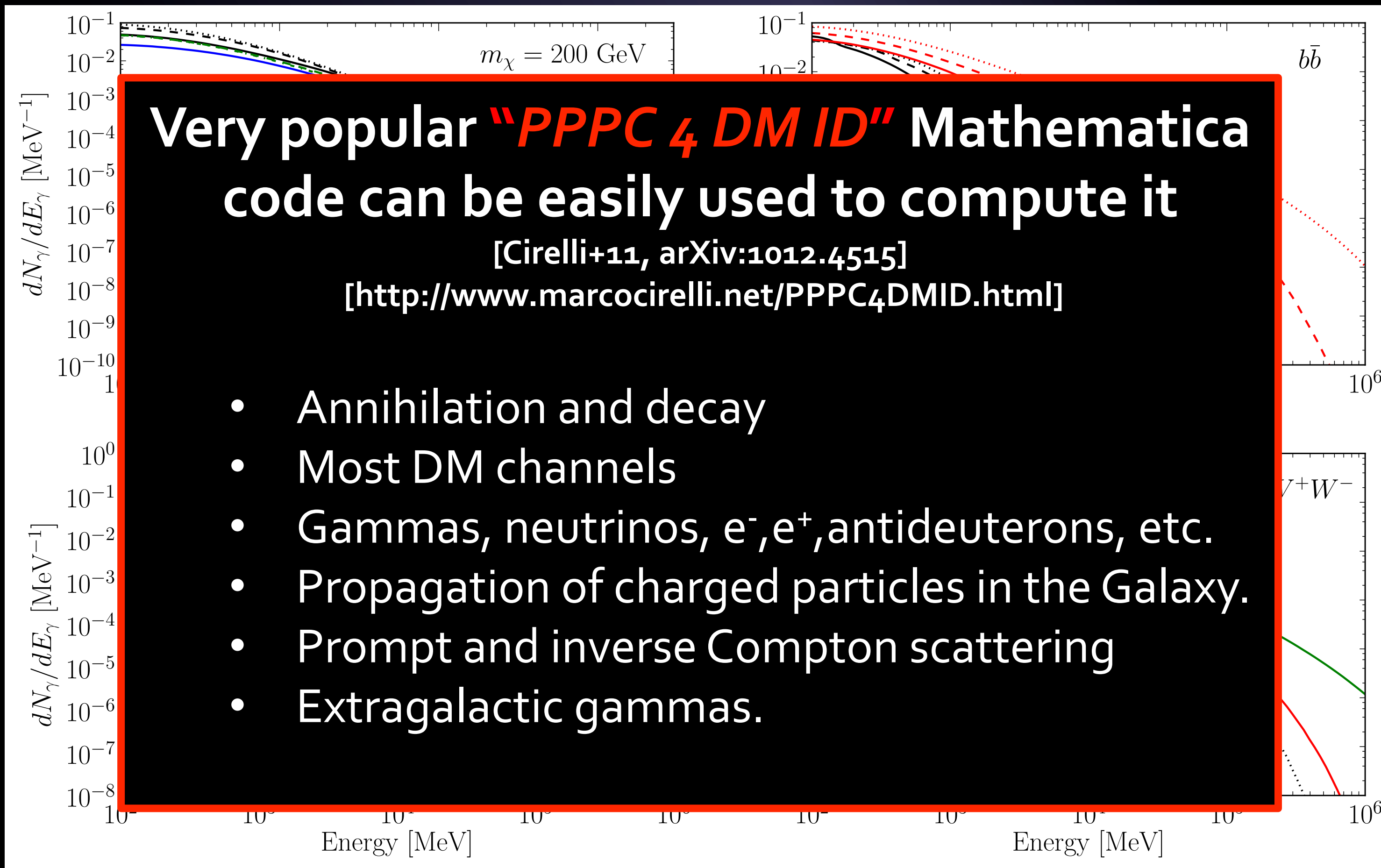
1. Cut-off at the DM particle mass
2. Spectra of leptonic channels “harder” (i.e., “fall slower”) than hadronic ones.



Charles, MASC+16, astro-ph/1605.02016

Annihilation spectra

1. Cut-off at the DM particle mass
2. Spectra of leptonic channels “harder” (i.e., “fall slower”) than hadronic ones.



Very popular *“PPPC 4 DM ID”* Mathematica code can be easily used to compute it

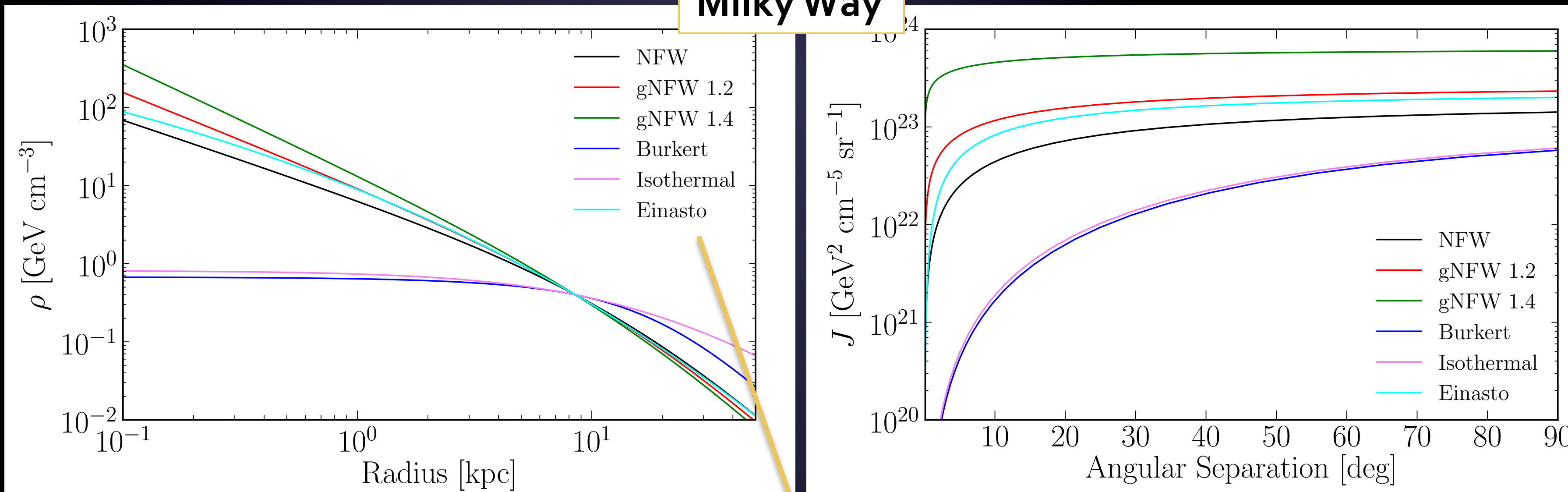
[Cirelli+11, arXiv:1012.4515]

[http://www.marcocirelli.net/PPPC4DMID.html]

- Annihilation and decay
- Most DM channels
- Gammas, neutrinos, e^-,e^+,antideuterons, etc.
- Propagation of charged particles in the Galaxy.
- Prompt and inverse Compton scattering
- Extragalactic gammas.

Charles, MASC+16, astro-ph/1605.02016

Milky Way



LCDM predictions crucial!

Typical J-factor values

Target	Distance (kpc)	J factor (GeV^2 cm^{-5})	Angular Extent (°)
Galactic center / halo (§4.4)	8.5	3×10^{22} to 5×10^{23}	> 10
Known Milky Way satellites (§4.5)	25 to 300	3×10^{17} to 3×10^{19}	< 0.5
Dark satellites (§4.6)	up to 300	up to 3×10^{19}	< 0.5
Galaxy Clusters (§4.7)	$> 5 \times 10^4$	up to 1×10^{18}	up to ~ 3
Cosmological DM (§4.8)	$> 10^6$	-	Isotropic

Charles, MASC+16, astro-ph/1605.02016

J-factor computation: CLUMPY

CLUMPY: multi-purpose code for indirect DM detection modelling and analysis

- Code distribution and usage:
  - Open-source: reproducible and comparable J-factor calculations
  - User-friendly Sphinx documentation, lots of examples & tests to run
  - All runs from single parameter file or command line (profiles, concentration, spectra…)
- Fast computation of:
  - Annihilation or decay astrophysical factors using any DM profile
  - Boost from substructures and its uncertainty
  - Integrated/differential fluxes in γ-rays and neutrinos, mixing user-defined branching ratios
- Four main modules / physics cases:
  I. DM emission from list of objects (dSph galaxies, galaxy clusters)
  II. Full-sky map mode for Galactic DM emission with substructure + additional objects from list
  III. Jeans module: full analysis from kinematic data to J-factors for dSph
  IV. Full-sky map mode for extragalactic DM emission

Growing use in the community for state-of-the-art DM studies for many targets (dSphs, cluster, dark clumps…) and by various collaborations (MAGIC, CTA, HAWC)

Download from **https://lpsc.in2p3.fr/clumpy/**

[Courtesy of M. Hütten]

From the astrophysics point of view,
it's all about the J-factor.

Observational uncertainties are large and typically prevent a precise J-factor determination.

We can use ΛCDM cosmological simulations to shed light on J-factor values

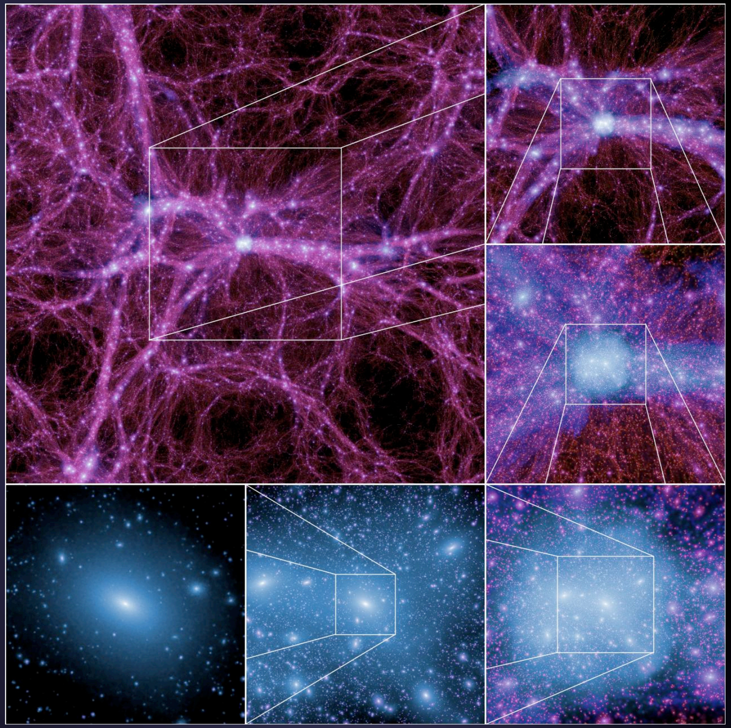
N-body cosmological simulations

- ✓ Great theoretical advances in cosmic structure and galaxy formation in the last 40 years.
  (e.g. Spherical Collapse + Press-Schechter formalism)

- ✓ **BUT**… Structure formation highly non-linear process
  → N-body simulations needed

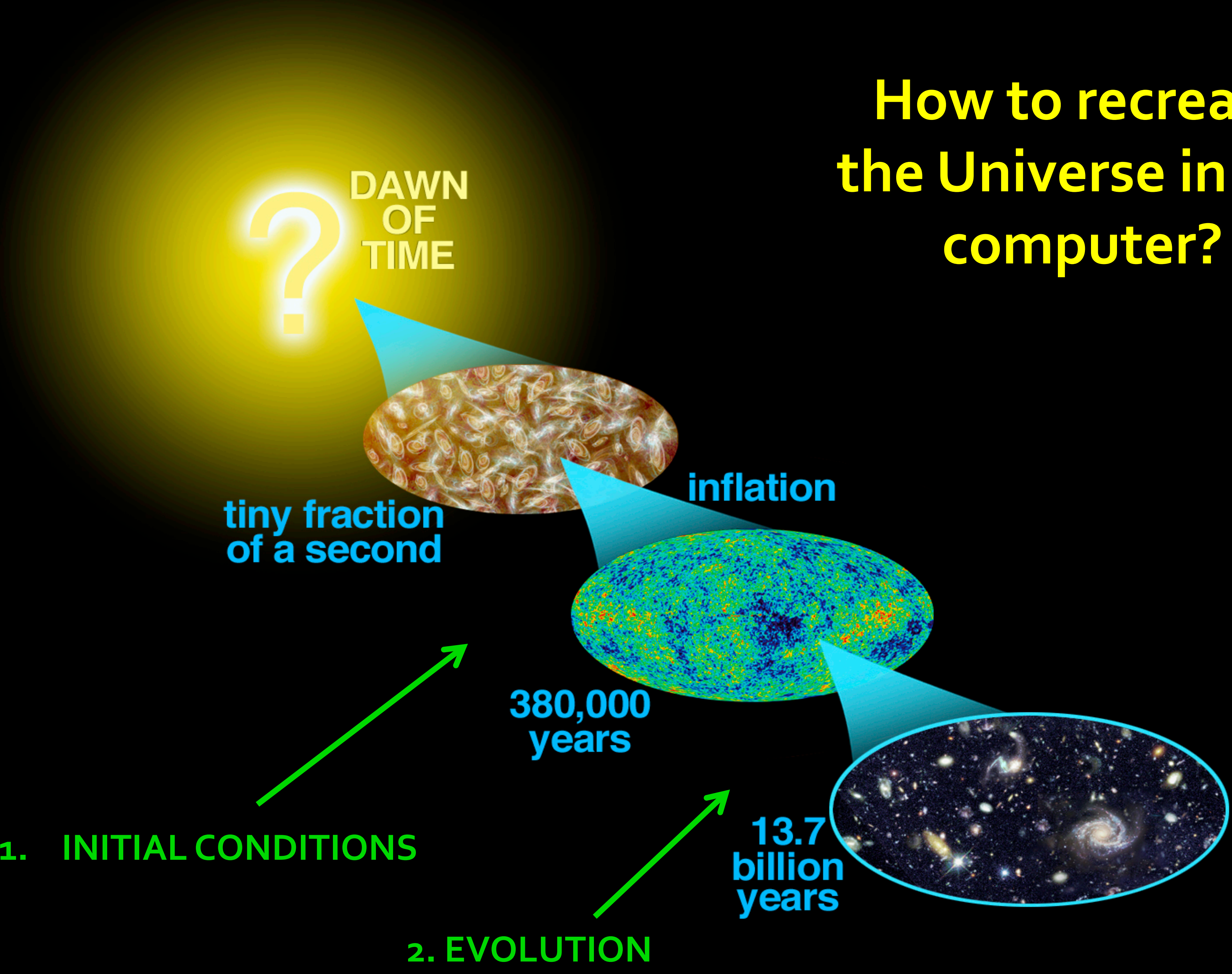
Some applications…

- ✓ Large Scale Structure studies.
- ✓ Internal structure of CDM halos.
- ✓ Substructures.
- ✓ Galaxy formation and evolution.
- ✓ Strong/weak lensing
- ✓ Near-field cosmology
- ✓ Streams.
- ✓ Dark matter detection.



Zoom sequence from 100 to 0.5 Mpc/h
Millenium-II simulation (Boylan-Kolchin+09)

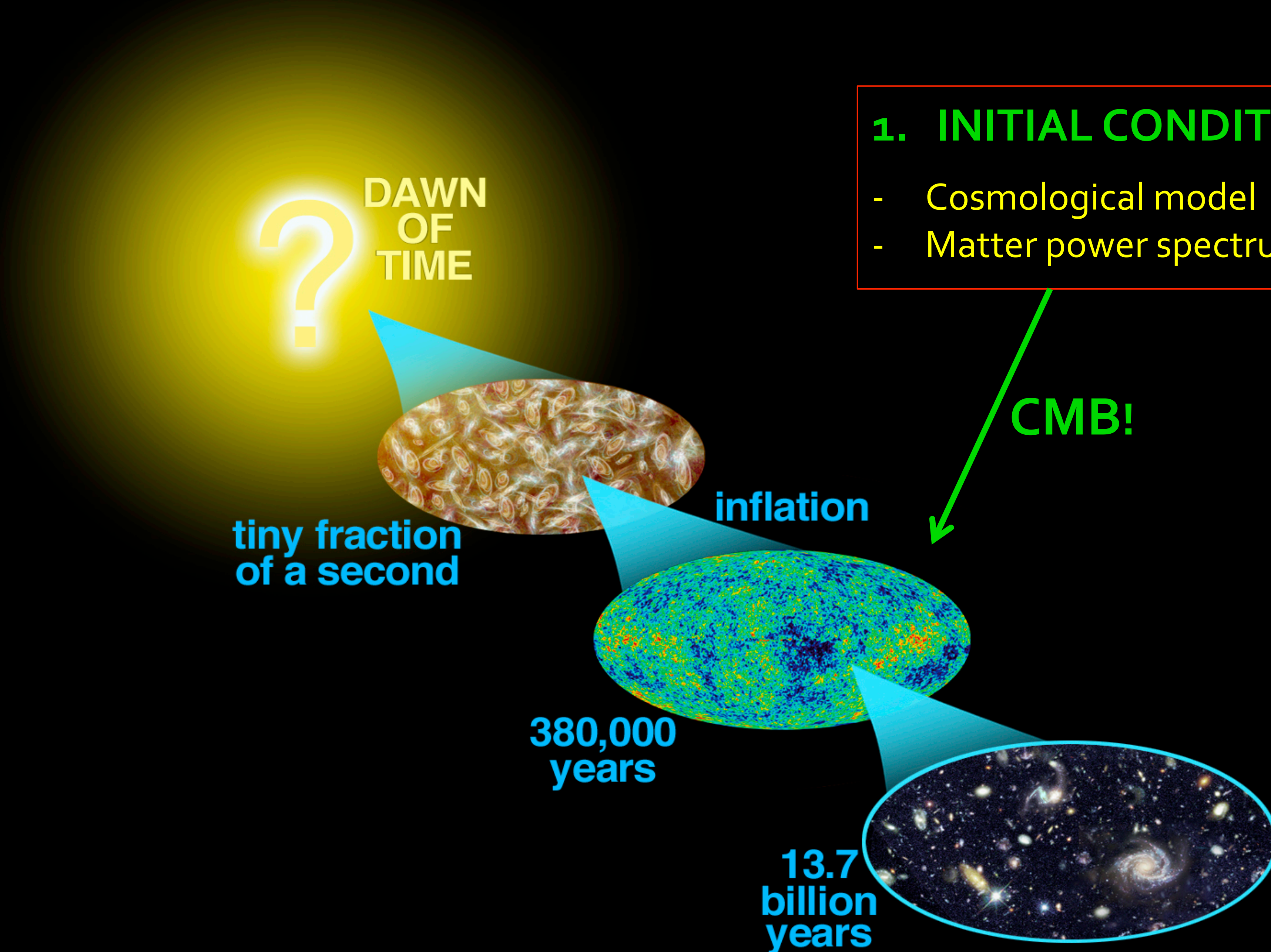
How to recreate the Universe in the computer?



1. INITIAL CONDITIONS

- Cosmological model
- Matter power spectrum

CMB!



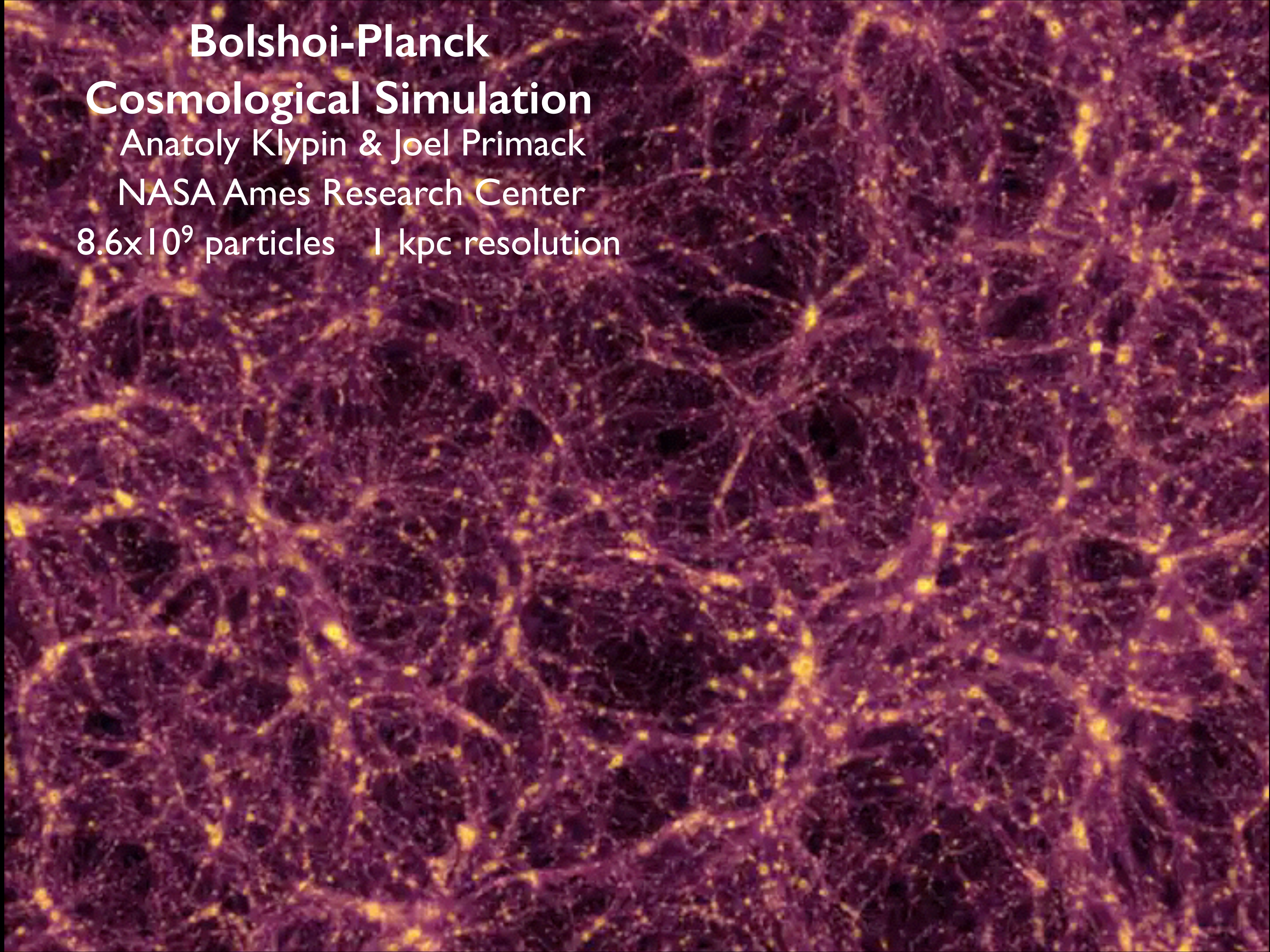
CMB is a snapshot of primordial density fluctuations in matter at z=1000. These fluctuations later collapse under gravity to form structures in the Universe.

Bolshoi-Planck Cosmological Simulation

Anatoly Klypin & Joel Primack

NASA Ames Research Center

8.6×10^9 particles   1 kpc resolution



DARK MATTER HALOS

- Basics:
  - Collapsed structures.
  - Self-bound.
  - "Virialized" (i.e. in equilibrium) → Virial radius and mass, R_{vir} and M_{vir}.

- Halos are the basic building blocks of Large Scale Structure.
  - Galaxies also reside in them.

- Halos come from peaks in the initial density field

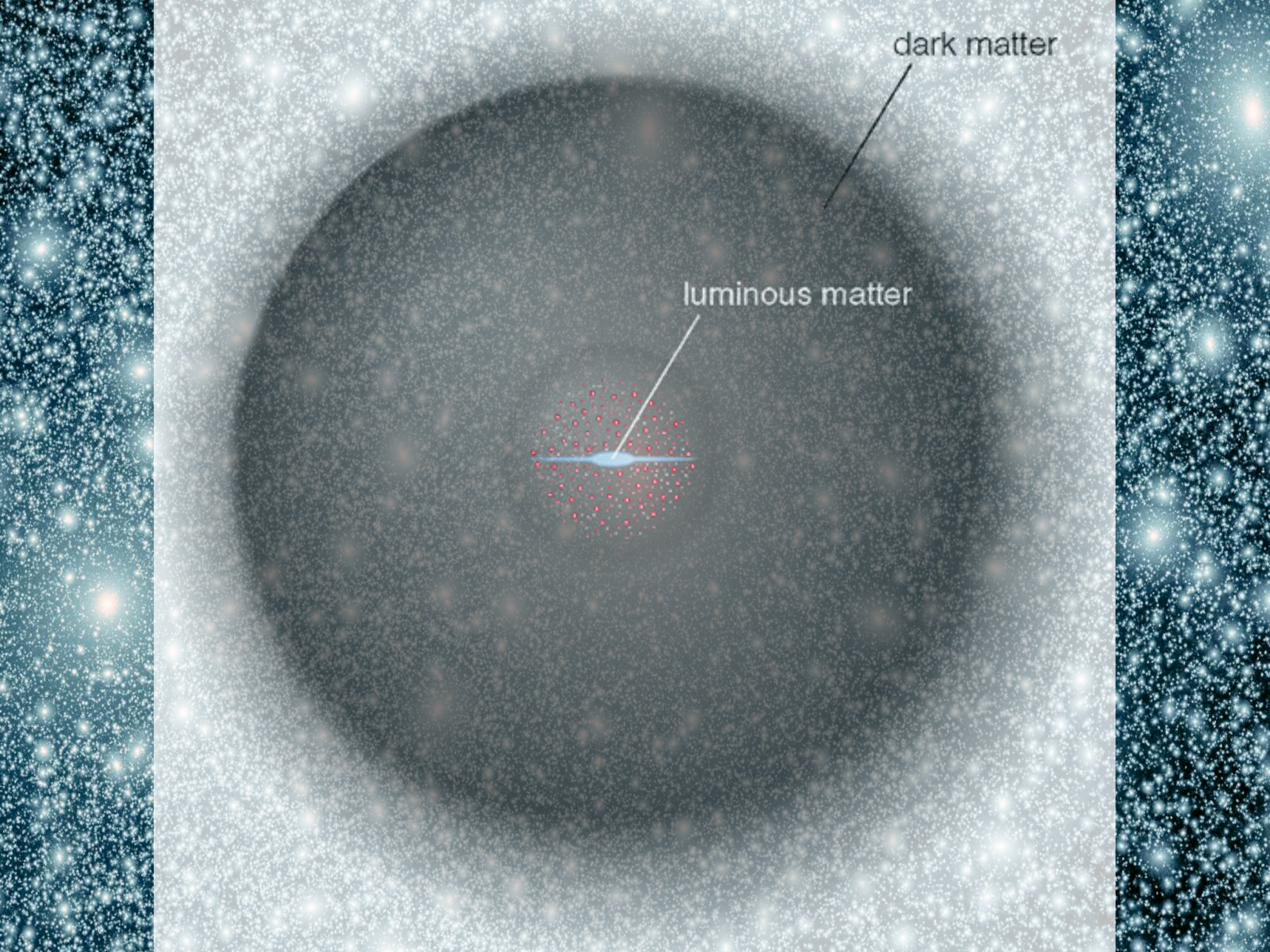
  → theoretical study of initial peaks' properties

  → final halo properties (density profiles, abundance, clustering…)

  → starting point for semi-analytical models, e.g. Spherical Collapse.

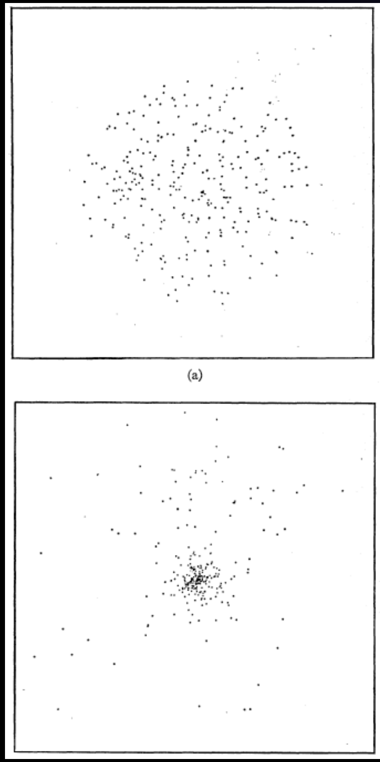
  → complicated.

  → N-body simulations.


dark matter
luminous matter

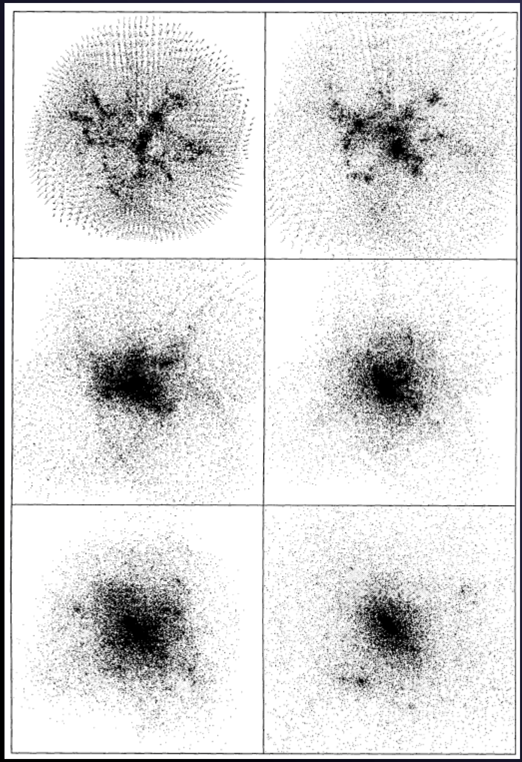
The structure of Cold Dark Matter halos

Structure of the Coma cluster
$N_p = 300$



Peebles 1970

Structure of DM halos
$N_p = 32000/250000$



Dubinski & Carlberg 1991

GHALO Milky Way
$N_p = 2 \cdot 10^9$

Stadel et al. 2009

The structure of CDM halos

Virialized DM halos of all masses seem to exhibit a nearly universal DM density profile, e.g. Einasto or NFW.

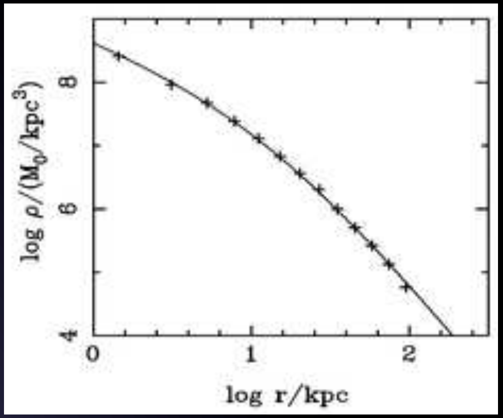
$$\rho(r) = \frac{\rho_0}{(r/r_s)(1+r/r_s)^2}$$

Navarro-Frenk-White (1996)
[NFW]

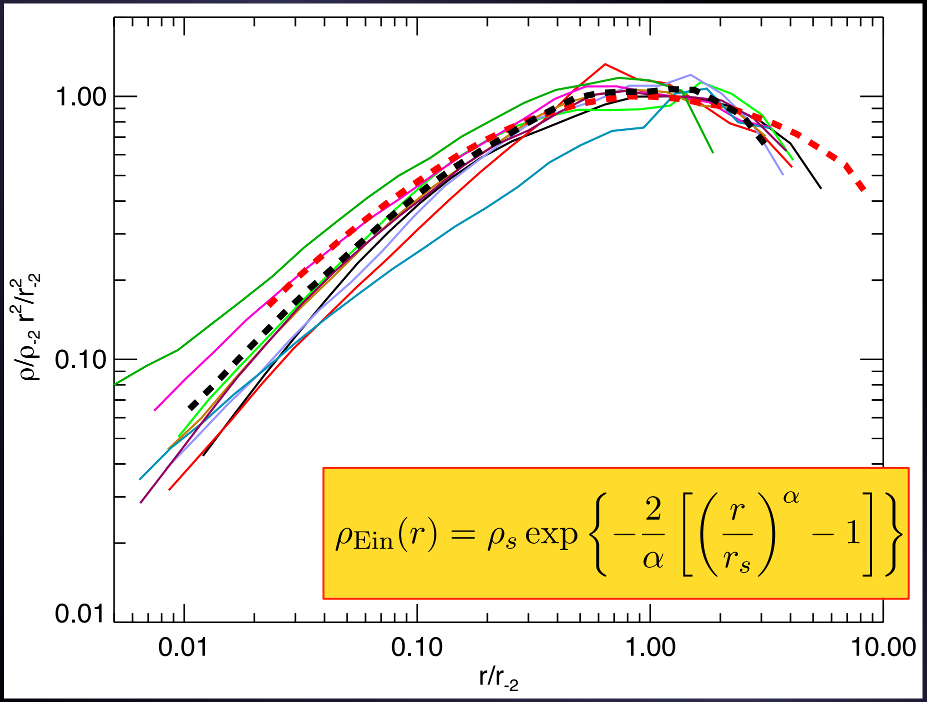
Parameters:
(ρ_o , r_s) or (c_{vir}, M_{vir}) or (v_{max}, r_{max})
Concentration $c_{vir} = R_{vir} / r_s$

DM-only simulations predict cusps with log slopes of -1 in the center of DM halos

The origin of these profiles is not well understood.



Dubinsky&Carlberg 90



Phoenix + Aquarius simulations [Frenk & White 2012]

CDM halo concentrations

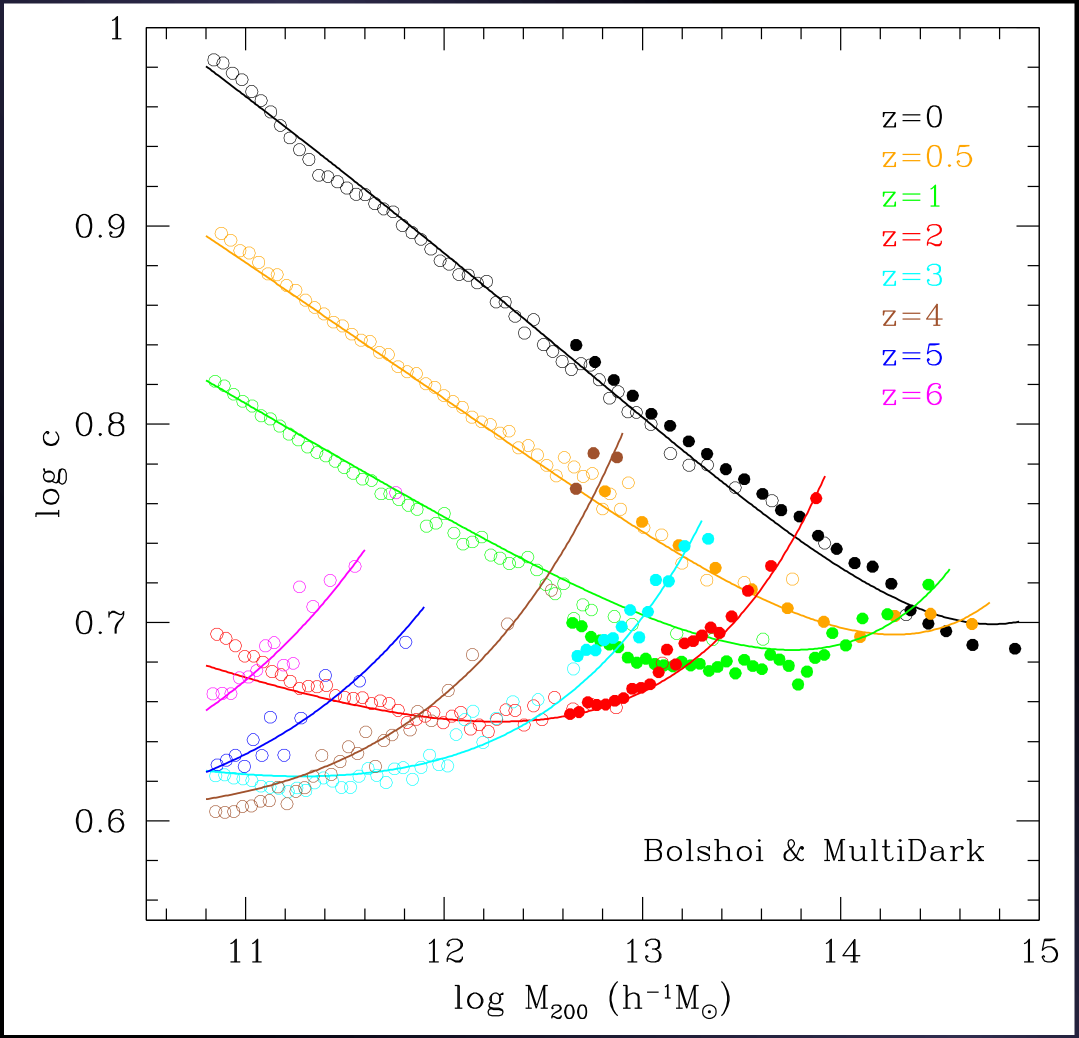
Concentration c = R_{vir} / r_s

Describes the structural halo properties.

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

Related to the formation time of the halo

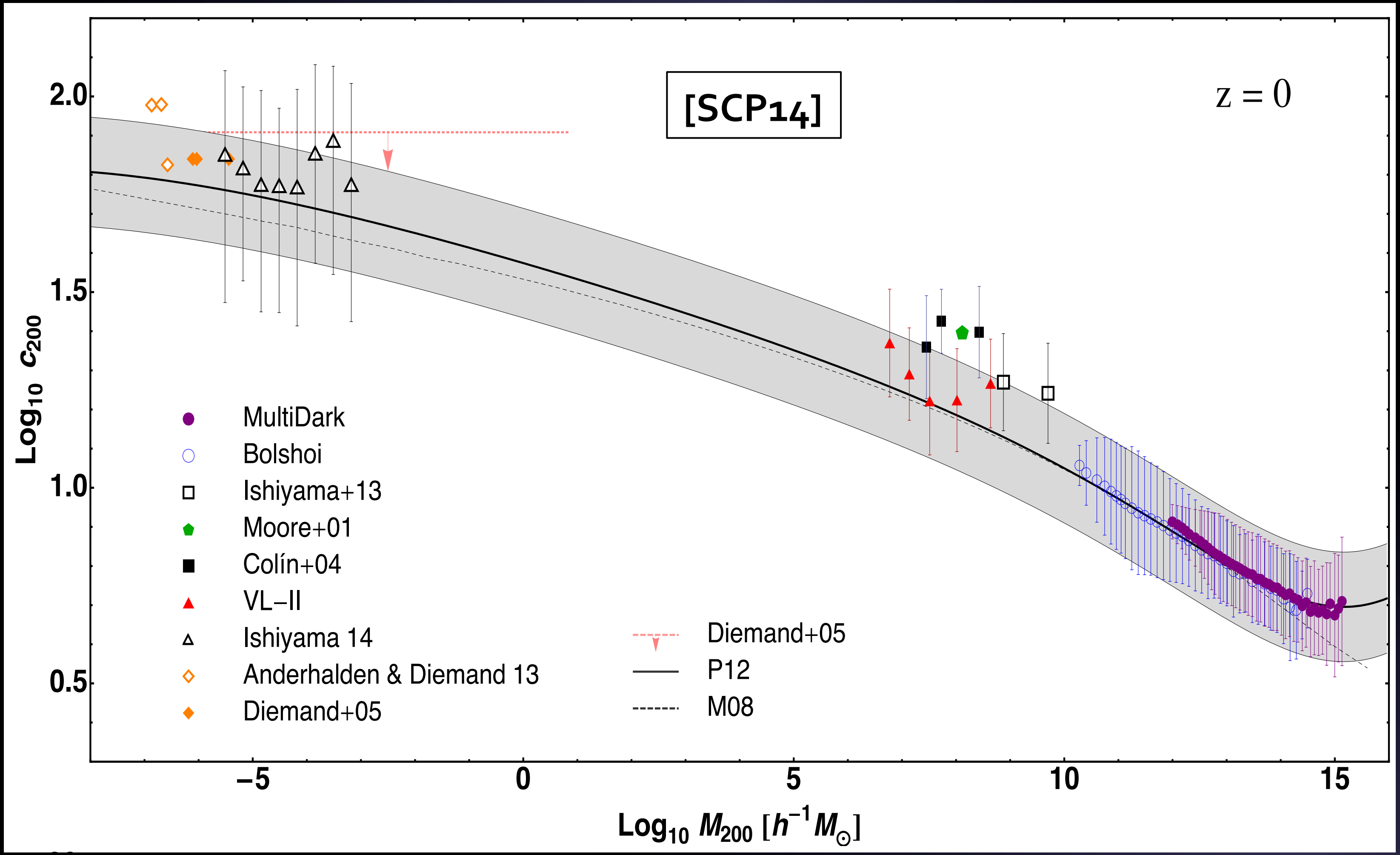
Different c(M) models



Prada+12

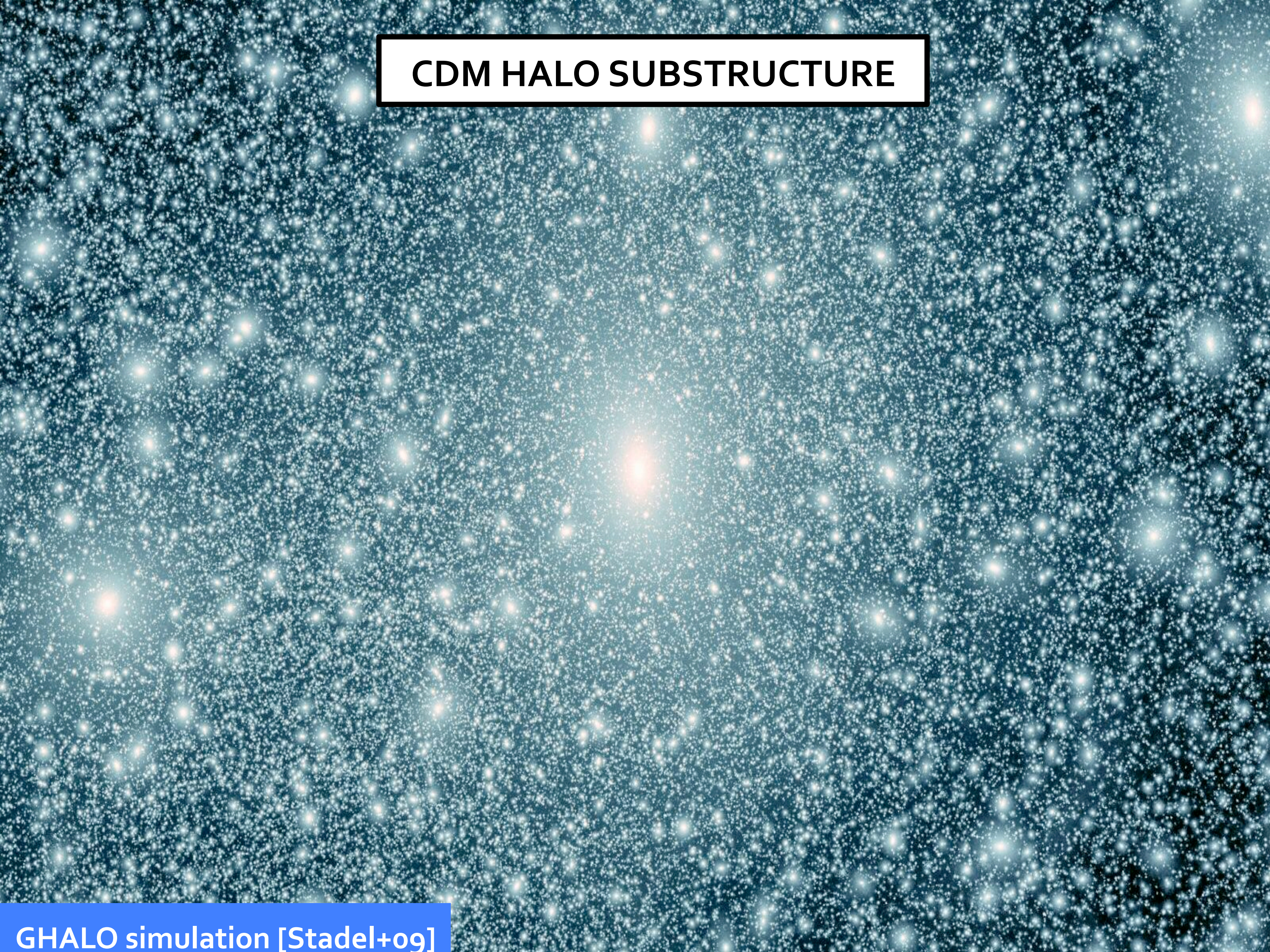
Current knowledge of the c(M) relation at z=0

Concentration $c = R_{vir} / r_s$

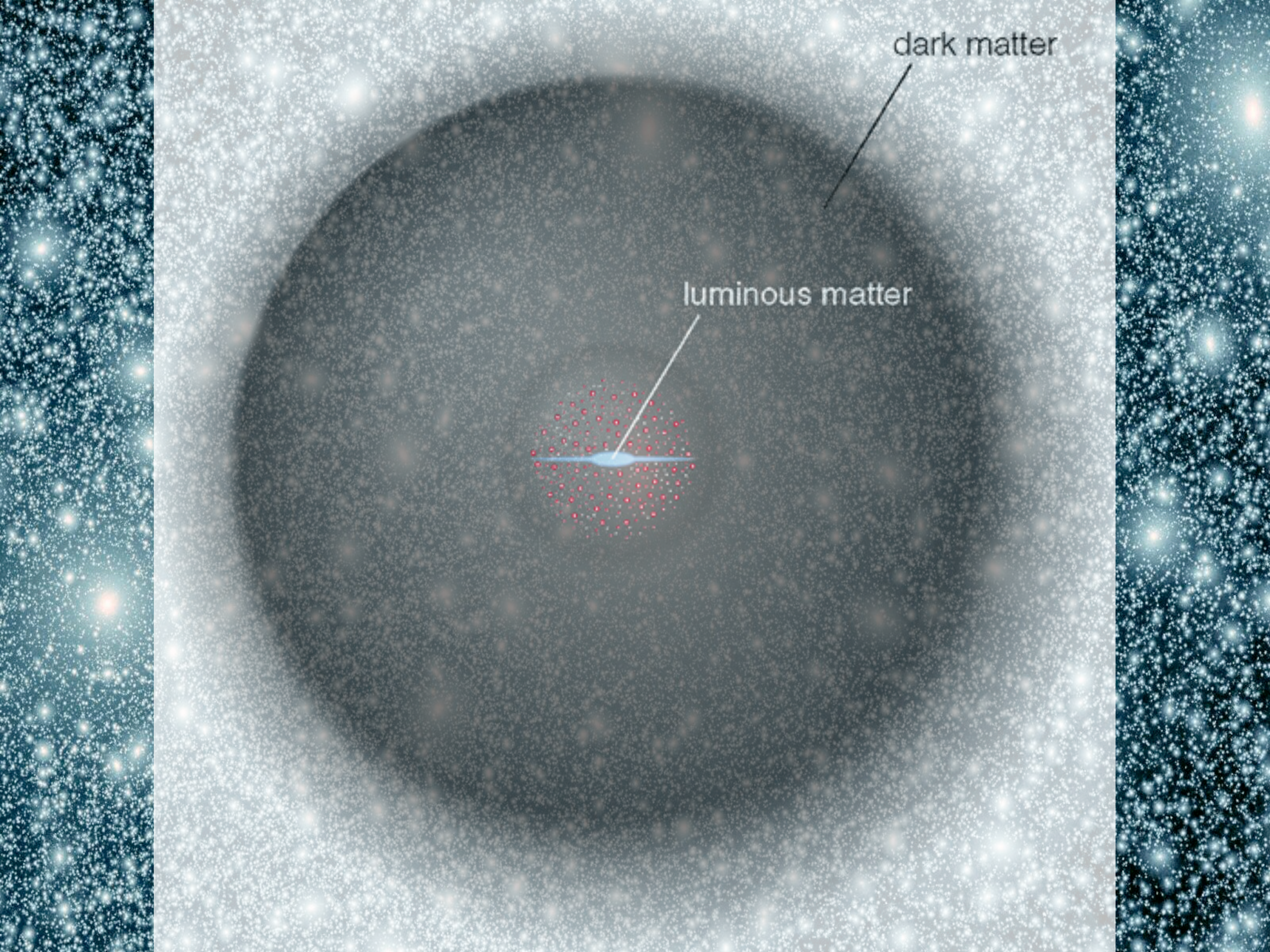


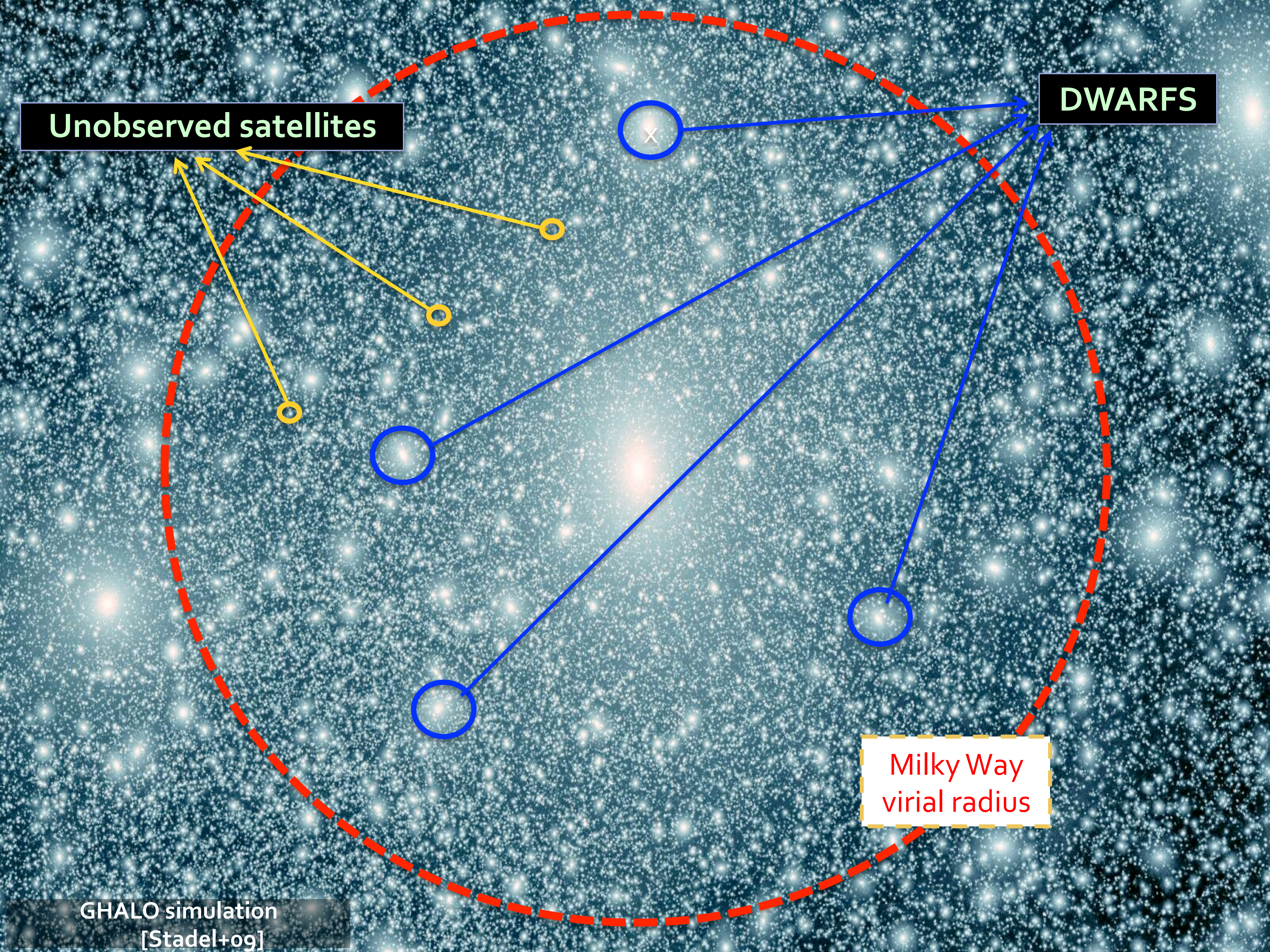
MASC & Prada, MNRAS, 442, 2271 (2014) [astro-ph/1312.1729]

CDM HALO SUBSTRUCTURE



GHALO simulation [Stadel+09]


dark matter
luminous matter



Unobserved satellites
DWARFS
Milky Way virial radius
GHALO simulation [Stadel+09]

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} 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

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} x 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} x 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} x 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

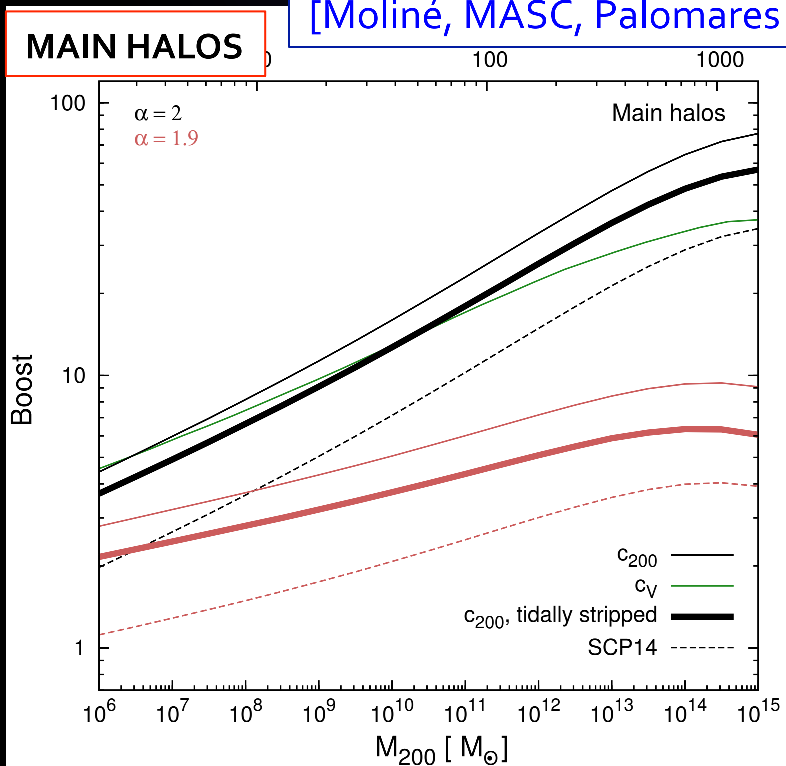
B(M) depends on the internal structure of the subhalos and their abundance

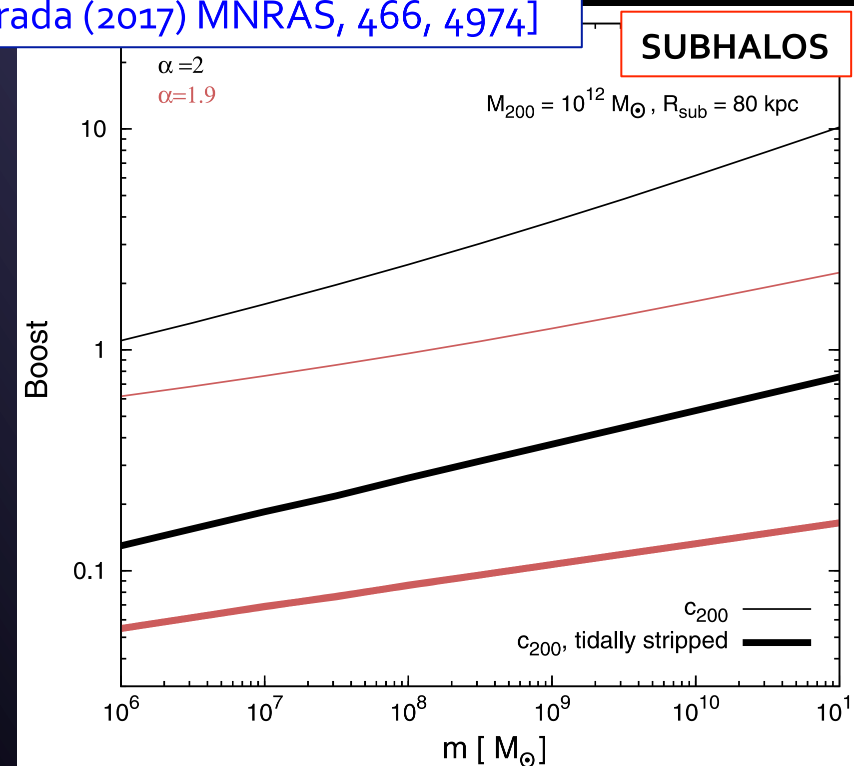
→ N-body cosmological simulations

Subhalo boost model

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

[Moliné, MASC, Palomares and Prada (2017) MNRAS, 466, 4974]





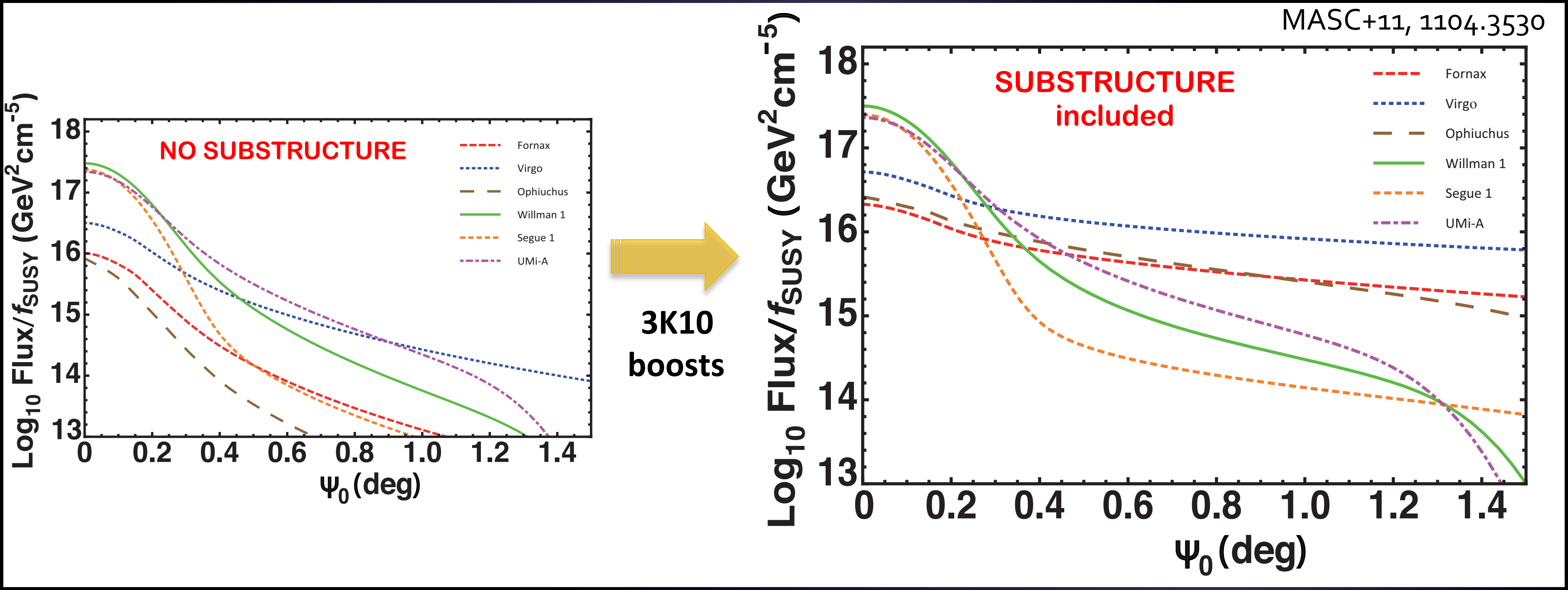
O(30) boost for MW-size halos
(factor ~2 higher than SCP14)

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

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

Substructure modifies the annihilation flux profile

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



Annihilation signal becomes *more spatially extended*.

Hands-on session on DM modeling

I prepared a couple exercises on DM modeling for you.

Please download the sheet of problems from:

https://tinyurl.com/yywzqcsc

(and feel free to ask any questions)

BEFORE THAT…

UAM UNIVERSIDAD AUTONOMA DE MADRID

ift Instituto de Física Teórica UAM-CSIC

MULTIDARK
Multimessenger Approach for Dark Matter Detection

Thanks!

Miguel A. Sánchez-Conde
miguel.sanchezconde@uam.es
www.miguelsanchezconde.com