DARK MATTER MODELING IN A ΛCDM UNIVERSE

[relevant for gamma-ray dark matter searches]

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MAGIC DM school

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Observational evidence of dark matter

Evidence has been reported at all scales.

Galactic scales

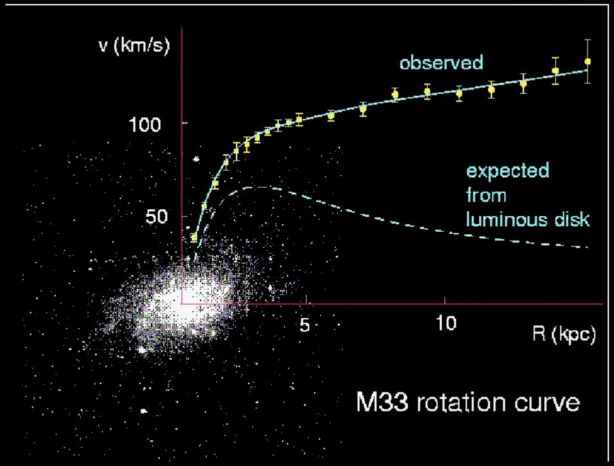
a) Rotation curves of spirals
b) Weak lensing
c) Velocity dispersions of satellite galaxies
d) Velocity dispersions in dSphs

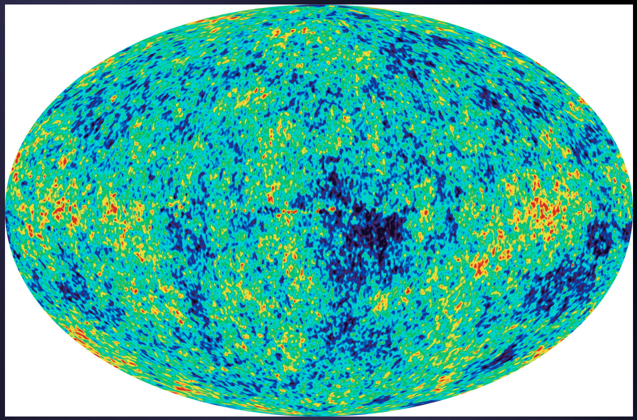
Galaxy clusters scales

a) Velocity dispersions of individual galaxies
b) Strong and weak lensing
c) Peculiar velocity flows
d) X-ray emission

Cosmological scales

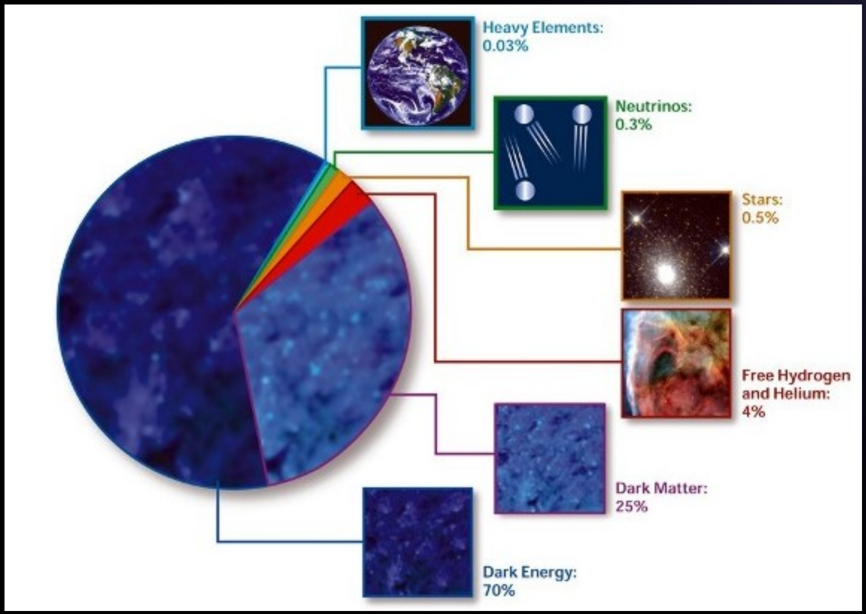
a) CMB anisotropies
b) Growth of structure
c) LSS distribution
d) BAOs
e) SZ effect

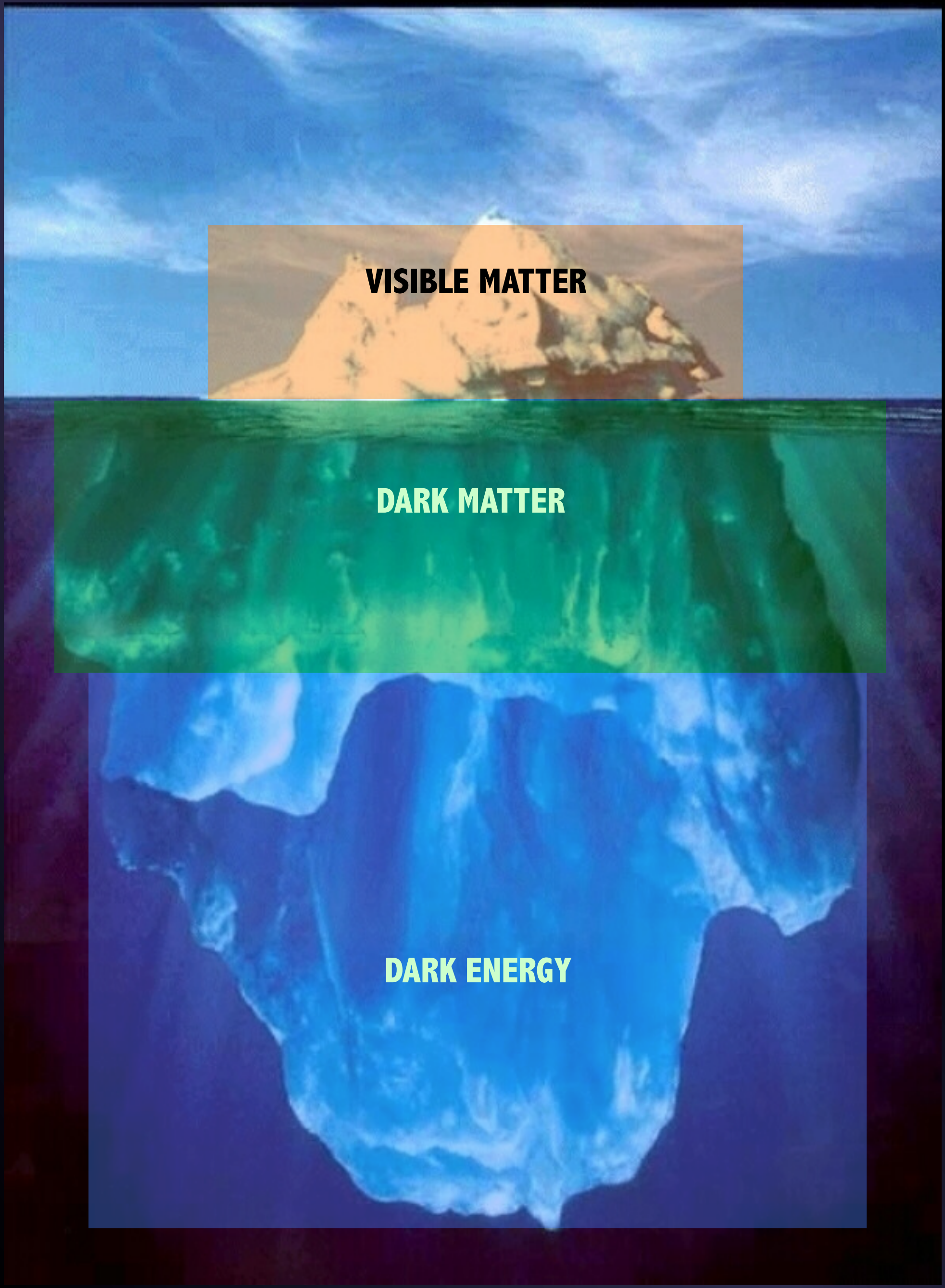




ΛCDM cosmology

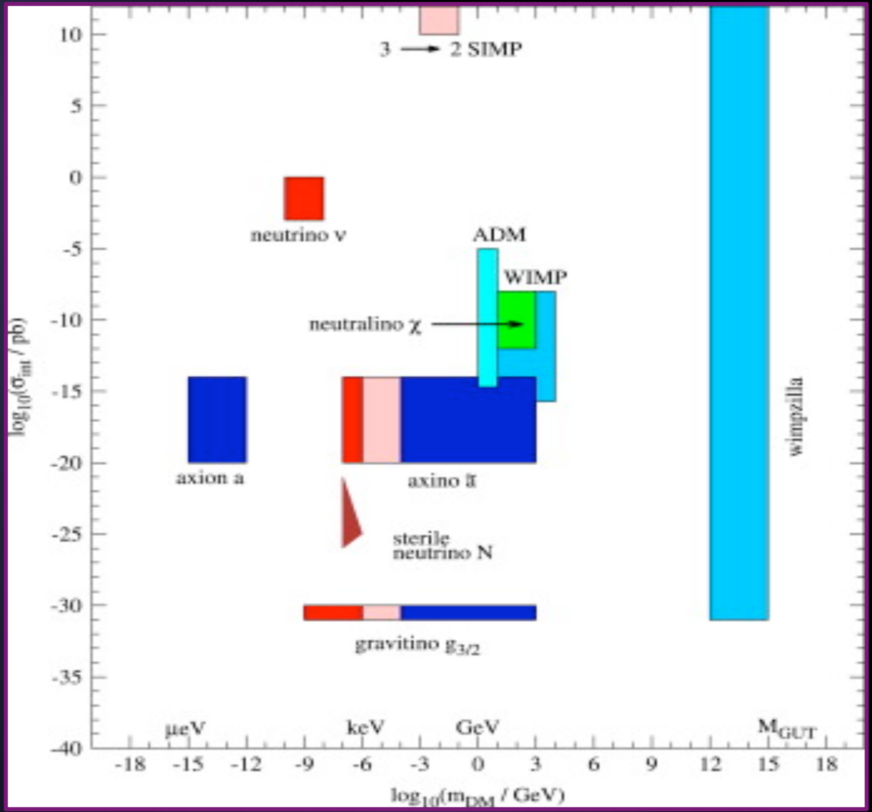
- ✓ Settled in the Big Bang scenario.
- ✓ Non-baryonic (dark) matter needed in order to explain observations.
- ✓ Cold DM to explain the Large Scale Structure
- ✓ Λ term to explain the accelerating Universe





What is the DM made of?
WIMP model

- ✓ No viable dark matter (DM) candidate within the Standard Model.
- ✓ Many DM particle candidates beyond the Standard Model.
- ✓ Weakly interacting massive particles (WIMPs) among the preferred ones.



Baer+14

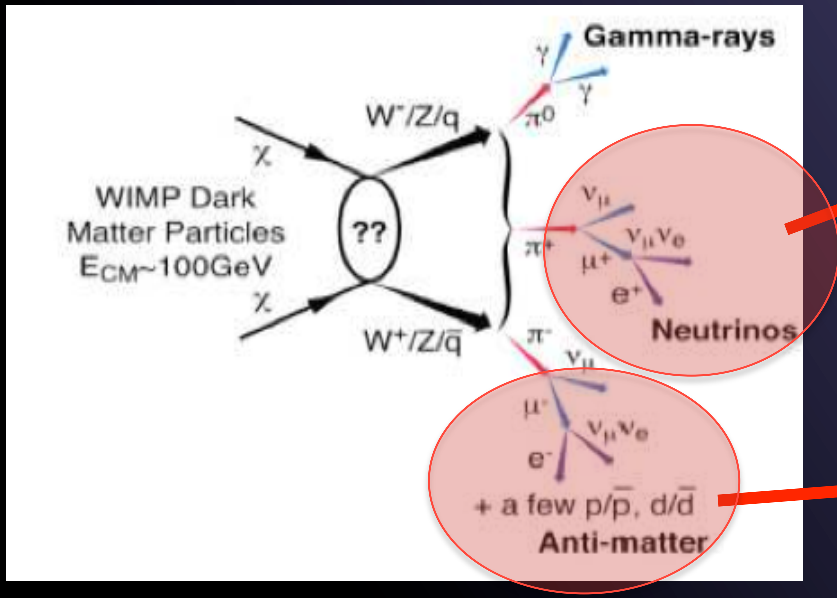
WIMP searches:

A. Direct detection: scattering of DM particles on target nuclei.

B. Direct production of DM particles at the lab.

C. Indirect detection: DM annihilation products (neutrinos, antimatter, gammas)

The 'golden channel': GAMMAS



Neutrinos
- ✓ No deflection
- ✓ No absorption
- ✓ BUT difficult to detect

Antimatter
- ✓ Low background in some cases
- ✓ BUT deflected by B fields
- ✓ BUT energy loses

Why gammas?
- ✓Energy scale of annihilation products set by DM particle mass
  - → favored models ~GeV-TeV
- ✓Gamma-rays travel following straight lines
  - → source can be known
- ✓[In the local Universe] Gamma-rays do not suffer from attenuation
  - → spectral information retained.

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

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

SMOOTH + SUBSTRUCTURE

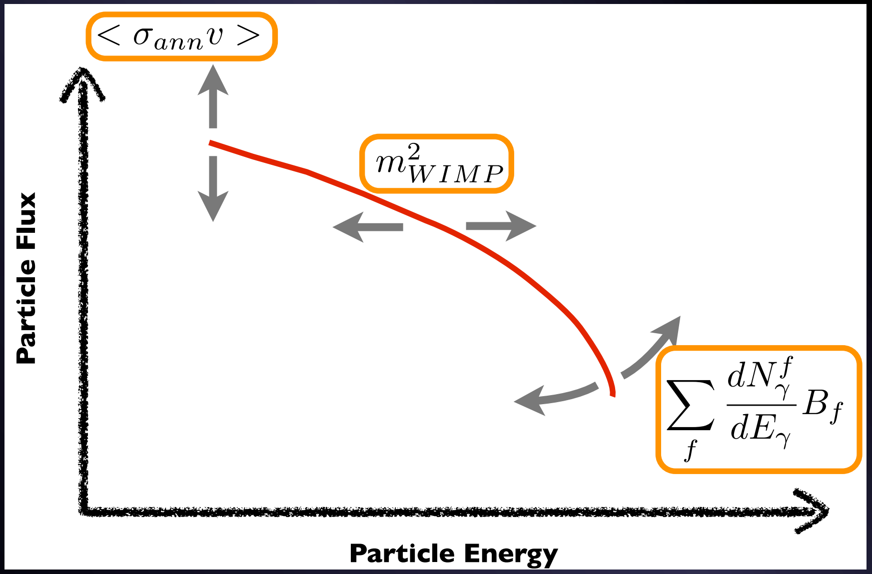
Where to search?

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

Particle physics

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

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



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THIS TALK

Astrophysics

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SMOOTH + SUBSTRUCTURE

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- Local galaxy clusters
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Particle physics

SOMEONE ELSE TALK

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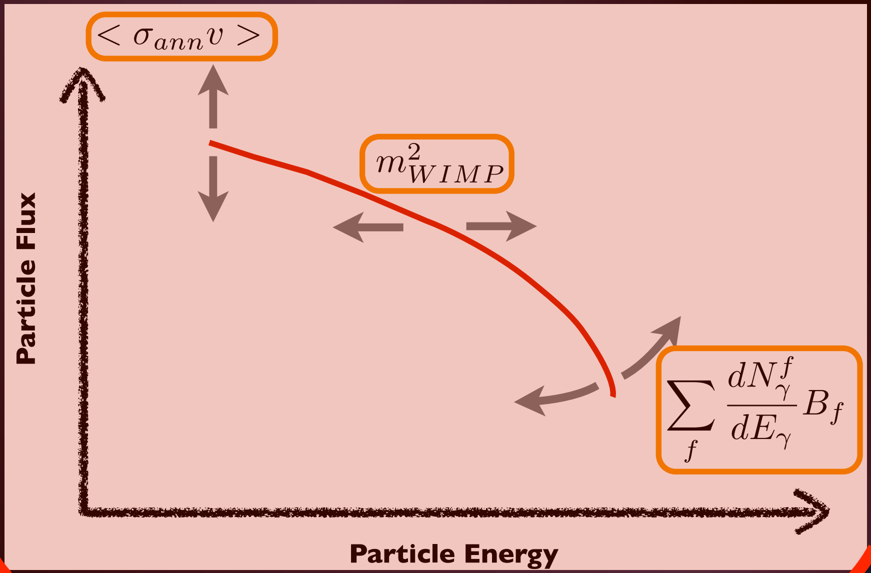
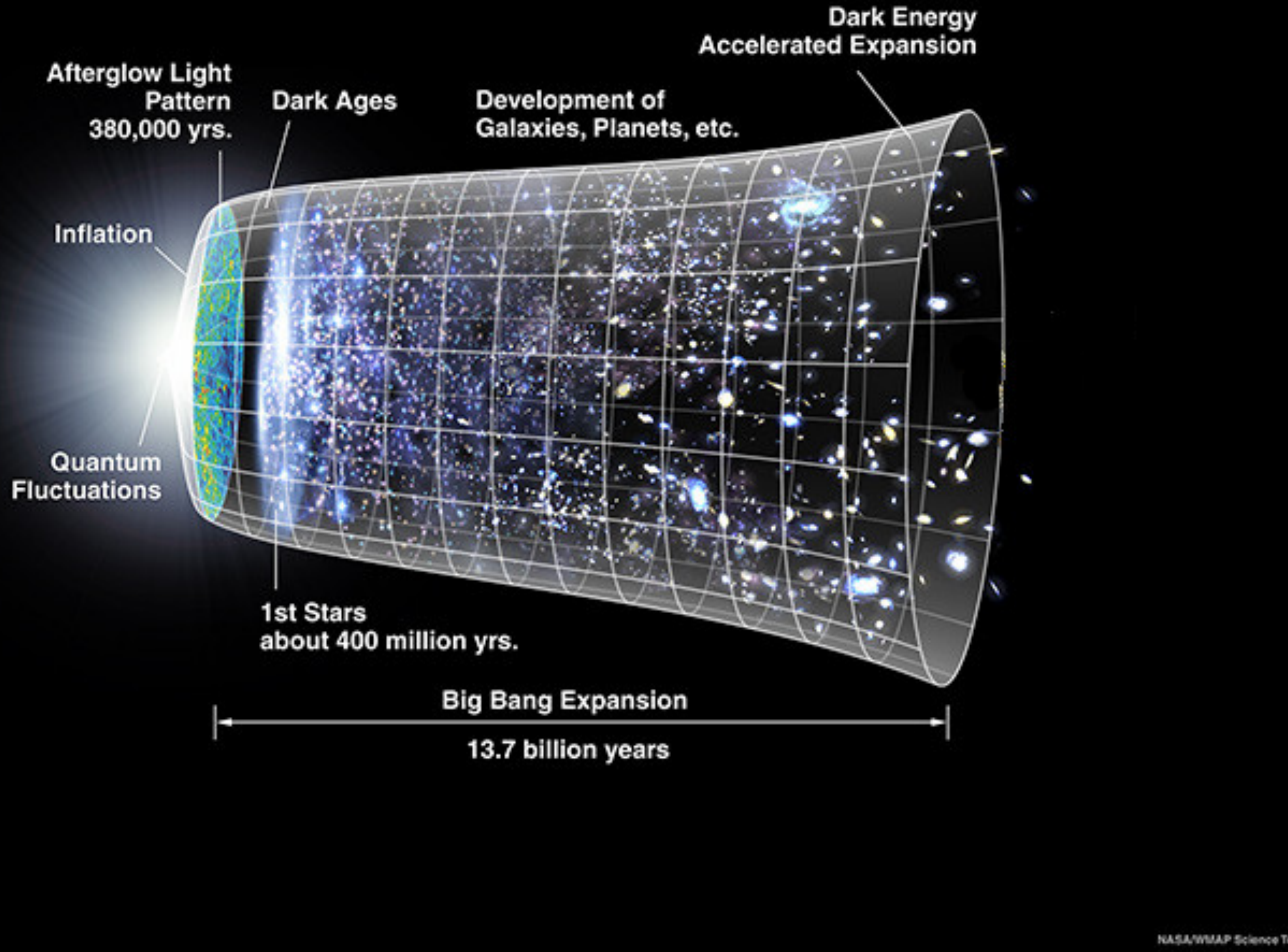


From the astrophysics point of view,
it's all about the J-factor.

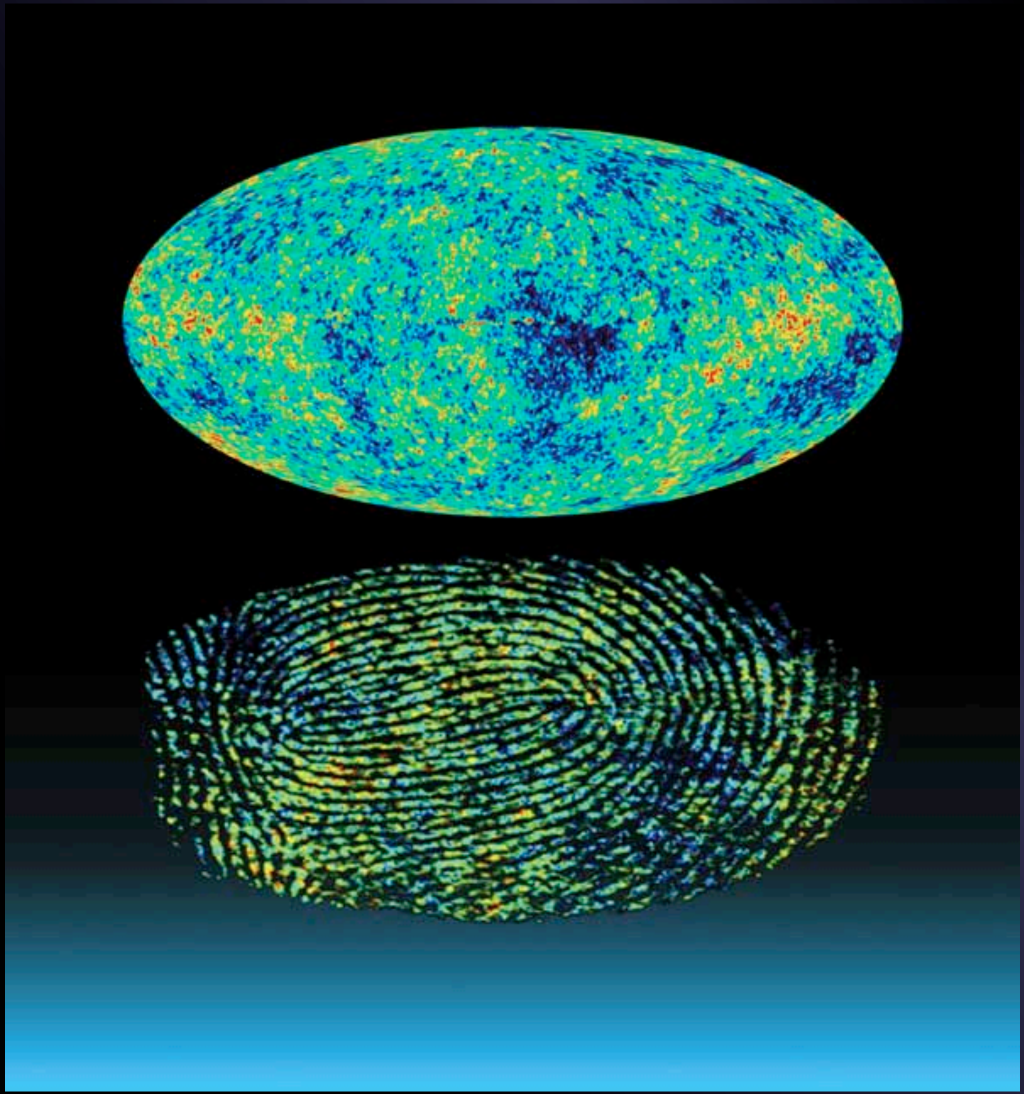
Observational uncertainties are large and typically prevent a precise J-factor determination.

Can ΛCDM help with accurate predictions?
(and are these compatible with current determinations of the DM distribution/content from data?)

The cosmic history in the standard cosmological model



The fluctuations in the Cosmic Microwave Background are the fingerprints of the right cosmological model!



“Concordance” cosmology

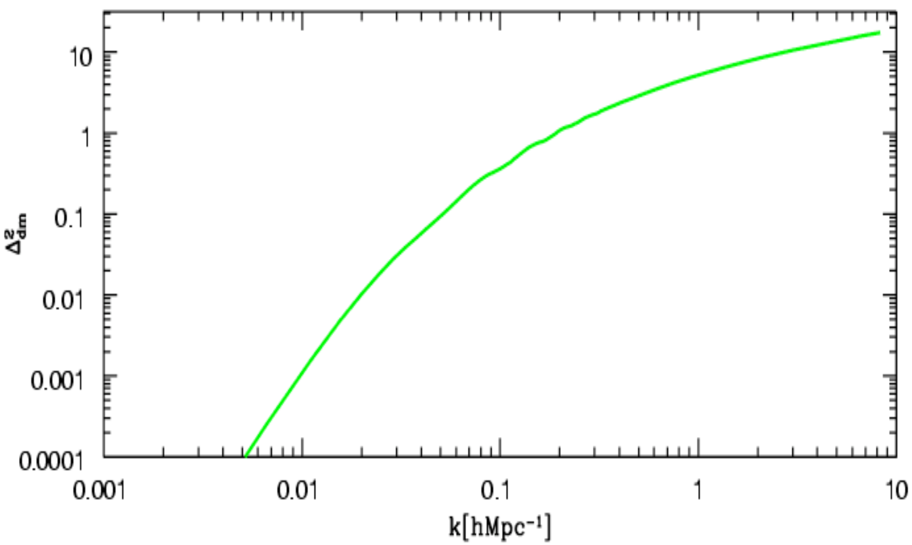
Six parameter ΛCDM model: $\{\Omega_b h^2, \Omega_c h^2, \Omega_\Lambda, \tau, n_s, \Delta_R^2\}$

	Planck (CMB+lensing)		*Planck*+WP+highL+BAO	
Parameter	Best fit	68 % limits	Best fit	68 % limits
$\Omega_b h^2$	0.022242	0.02217 ± 0.00033	0.022161	0.02214 ± 0.00024
$\Omega_c h^2$	0.11805	0.1186 ± 0.0031	0.11889	0.1187 ± 0.0017
$100\theta_{MC}$	1.04150	1.04141 ± 0.00067	1.04148	1.04147 ± 0.00056
τ	0.0949	0.089 ± 0.032	0.0952	0.092 ± 0.013
n_s	0.9675	0.9635 ± 0.0094	0.9611	0.9608 ± 0.0054
$\ln(10^{10} A_s)$	3.098	3.085 ± 0.057	3.0973	3.091 ± 0.025
Ω_Λ	0.6964	0.693 ± 0.019	0.6914	0.692 ± 0.010
σ_8	0.8285	0.823 ± 0.018	0.8288	0.826 ± 0.012
z_{re}	11.45	$10.8^{+3.1}_{-2.5}$	11.52	11.3 ± 1.1
H_0	68.14	67.9 ± 1.5	67.77	67.80 ± 0.77
Age/Gyr	13.784	13.796 ± 0.058	13.7965	13.798 ± 0.037
$100\theta_*$	1.04164	1.04156 ± 0.00066	1.04163	1.04162 ± 0.00056
r_{drag}	147.74	147.70 ± 0.63	147.611	147.68 ± 0.45
$r_{drag}/D_V(0.57)$	0.07207	0.0719 ± 0.0011		

(Planck Collaboration, 2013)

Initial conditions: matter power spectrum

- The PS describes the **density contrast** of the Universe as a function of scale.
- Initial conditions from inflation.



R. Wechsler

fluctuations in the density field

$$\delta(x,t) = \frac{\rho(x,t) - \overline{\rho}(t)}{\overline{\rho}(t)}$$

the Fourier transform is given by

$$\delta(\vec{k}) = \int \mathrm{d}^3x \; \delta(\vec{x}) e^{i\vec{k}\cdot\vec{x}}$$

the power spectrum is:

$$P(k) \equiv V^{-1} \langle |\delta(k)|^2 \rangle$$

which is often given in dimensionless units:

$$\Delta^2(k) \equiv k^3 P(k) / 2\pi^2$$

$\delta >> 1$ → linear regime
$\delta << 1$ → non-linear regime

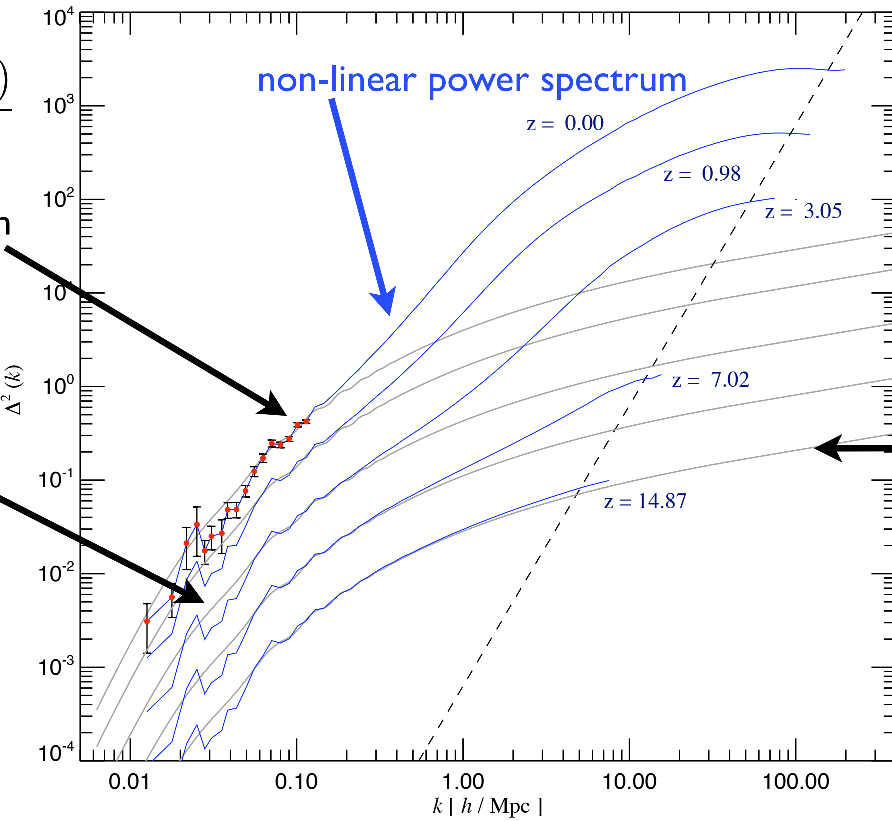
Evolution of the matter power spectrum

- On large scales, low density contrast → structures grow in the linear regime.
- On small scales, non-linear gravitational collapse:
  - → Simple analytical models (e.g. SIM)
  - → Higher order perturbation theory.
  - → N-body simulations.

$$\Delta^2(k) = \frac{k^3 P(k)}{2\pi^2}$$

largest scales are still in the linear regime

finite volume box; large modes have noise



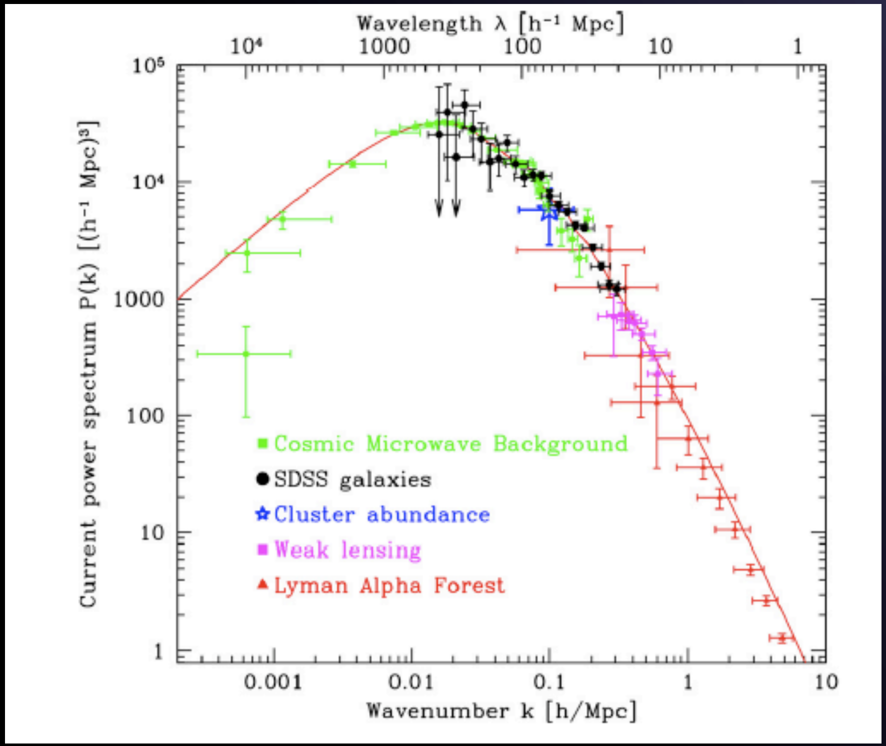
linear power spectrum

Springel et al 2005

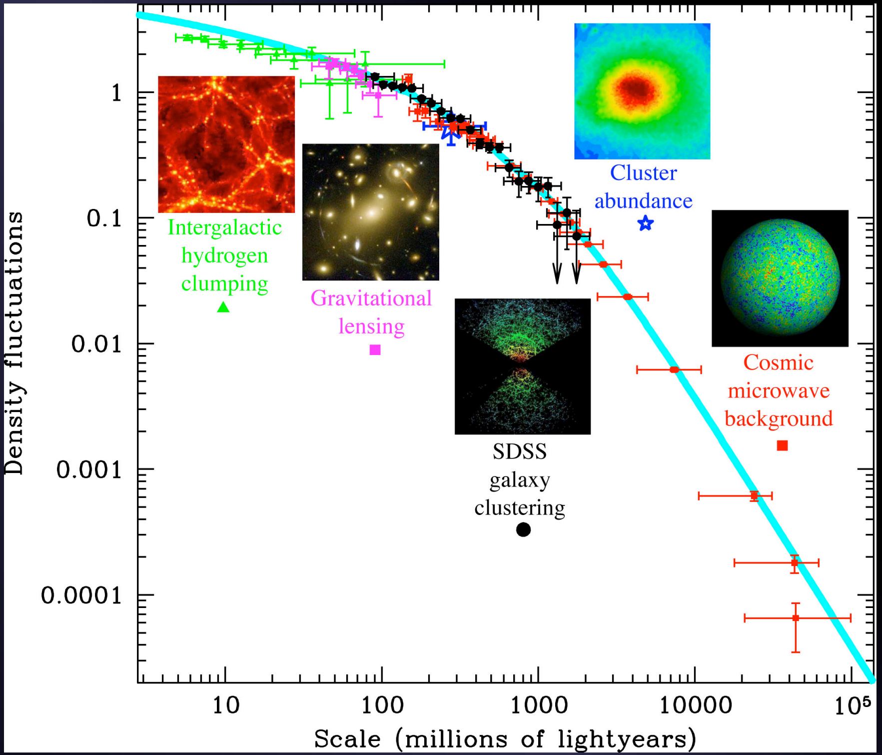
R. Wechsler

Matter power spectrum measurements

(Tegmark et al. 2004)



(M. Tegmark)



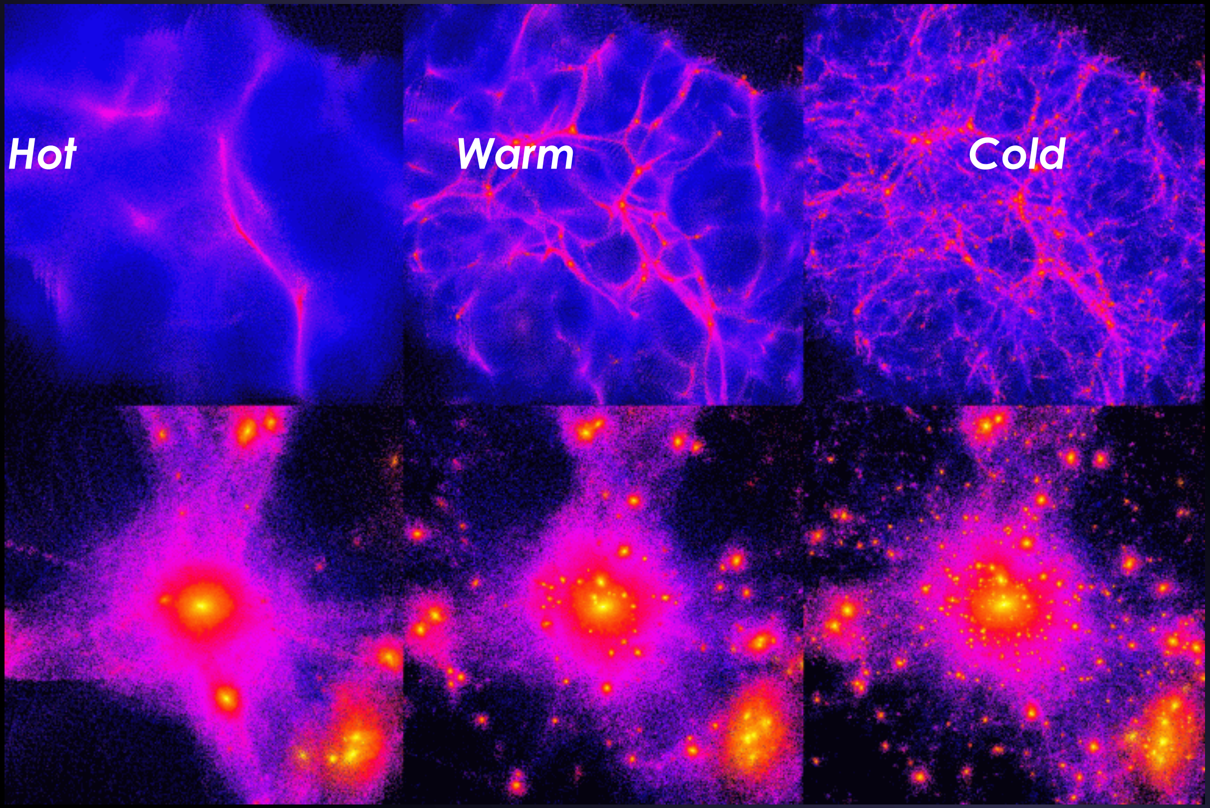
P(k) at present epoch

¿Why cold?

- $\delta \sim M^{-(n+3)/6}$
- for n=1 spectrum: $\delta \sim M^{-2/3}\, t^{2/3}$
- smaller fluctuations at bigger mass scales.

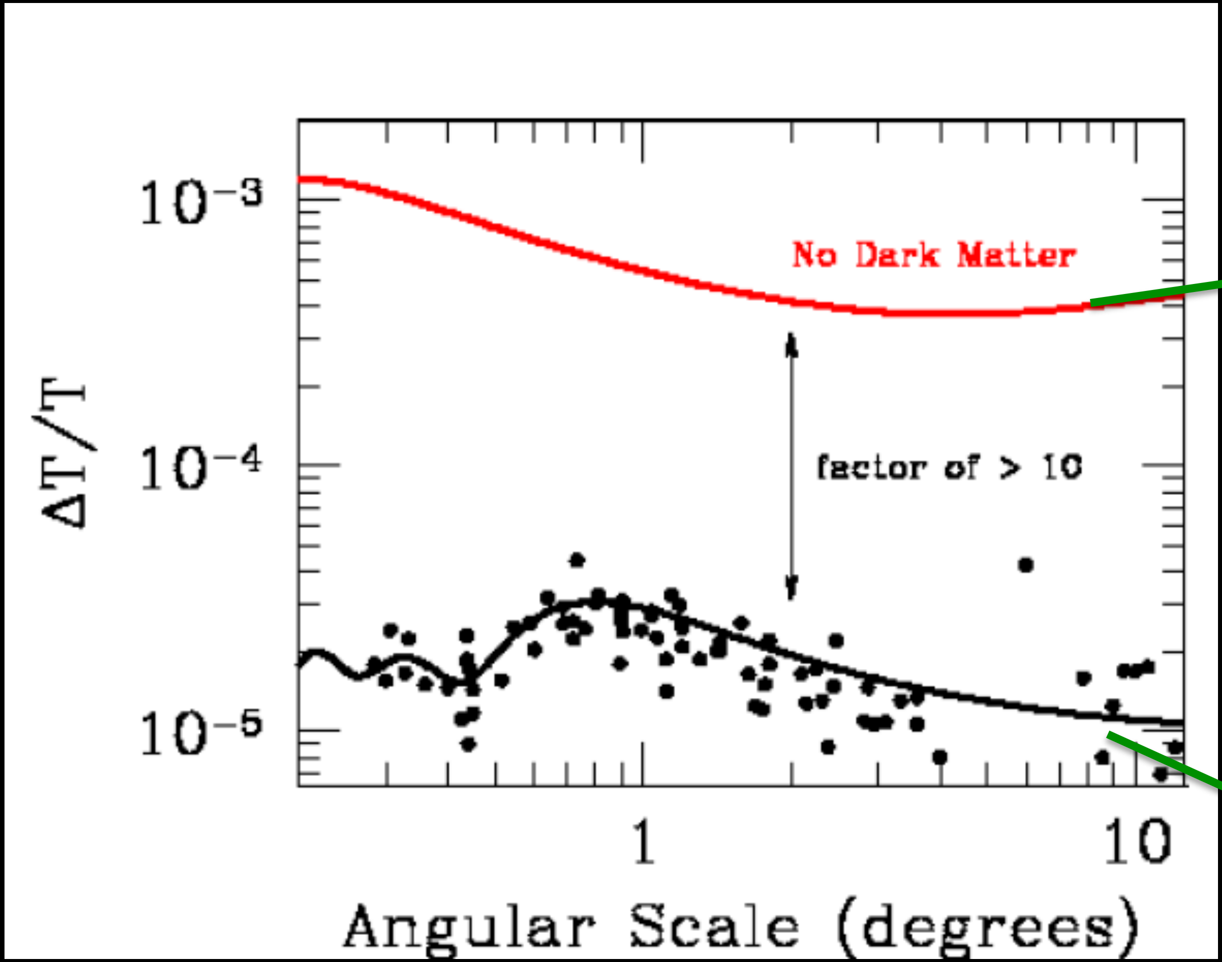
Small structures form first and merge to form large structures

BOTTOM-UP hierarchical structure formation and **abundance of substructure** favored by present observations.



Credit: Ben Moore http://www.nbody.net

¿Why CDM?



Amplitude of fluctuations **needed** to account for the structure we see today if there was no DM

Actual CMB data

CMB fluctuations ARE NOT large enough to produce the observed Large Scale Structure without the help of CDM

DARK MATTER HALOS

- Basics:
  - Collapsed structures.
  - Self-bound.
  - "Virialized" (i.e. in equilibrium) → Virial radius and mass.
- Halos are the basic building blocks of LSS. Galaxies also reside in them.
- Halos come from peaks in the initial density field
  - → 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.

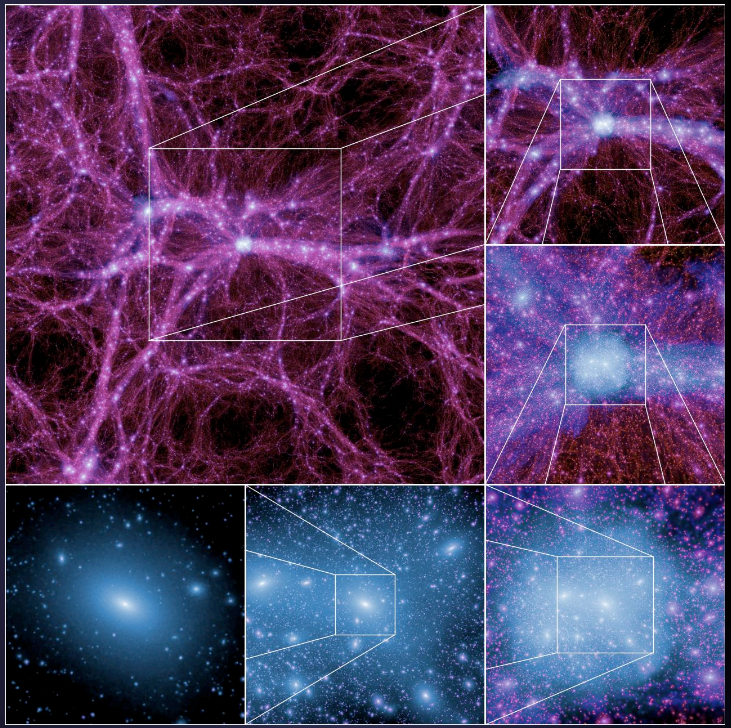
Non-linear evolution: N-body cosmological simulations

- ✓ 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

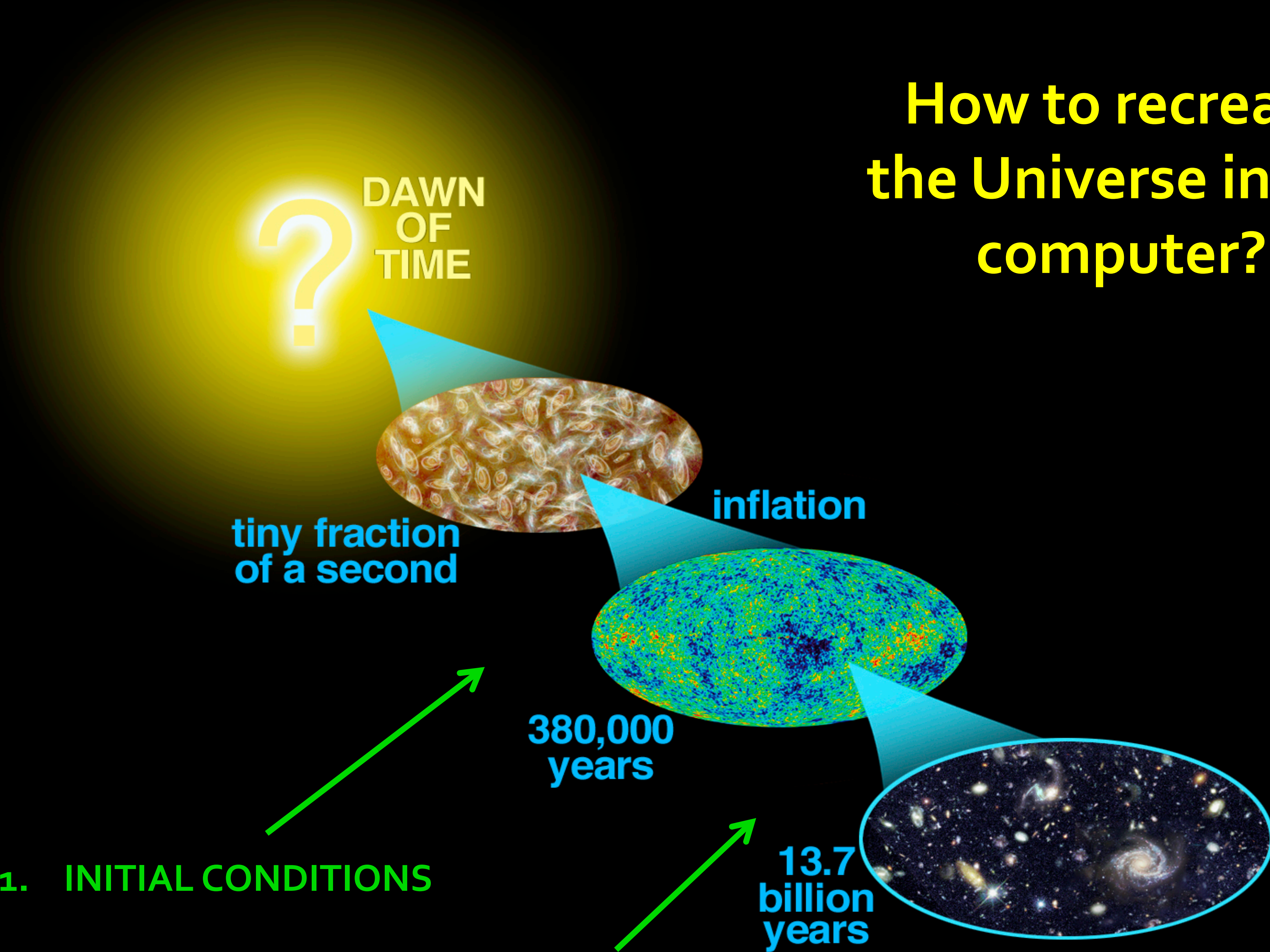
Some applications…

- ✓ 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?

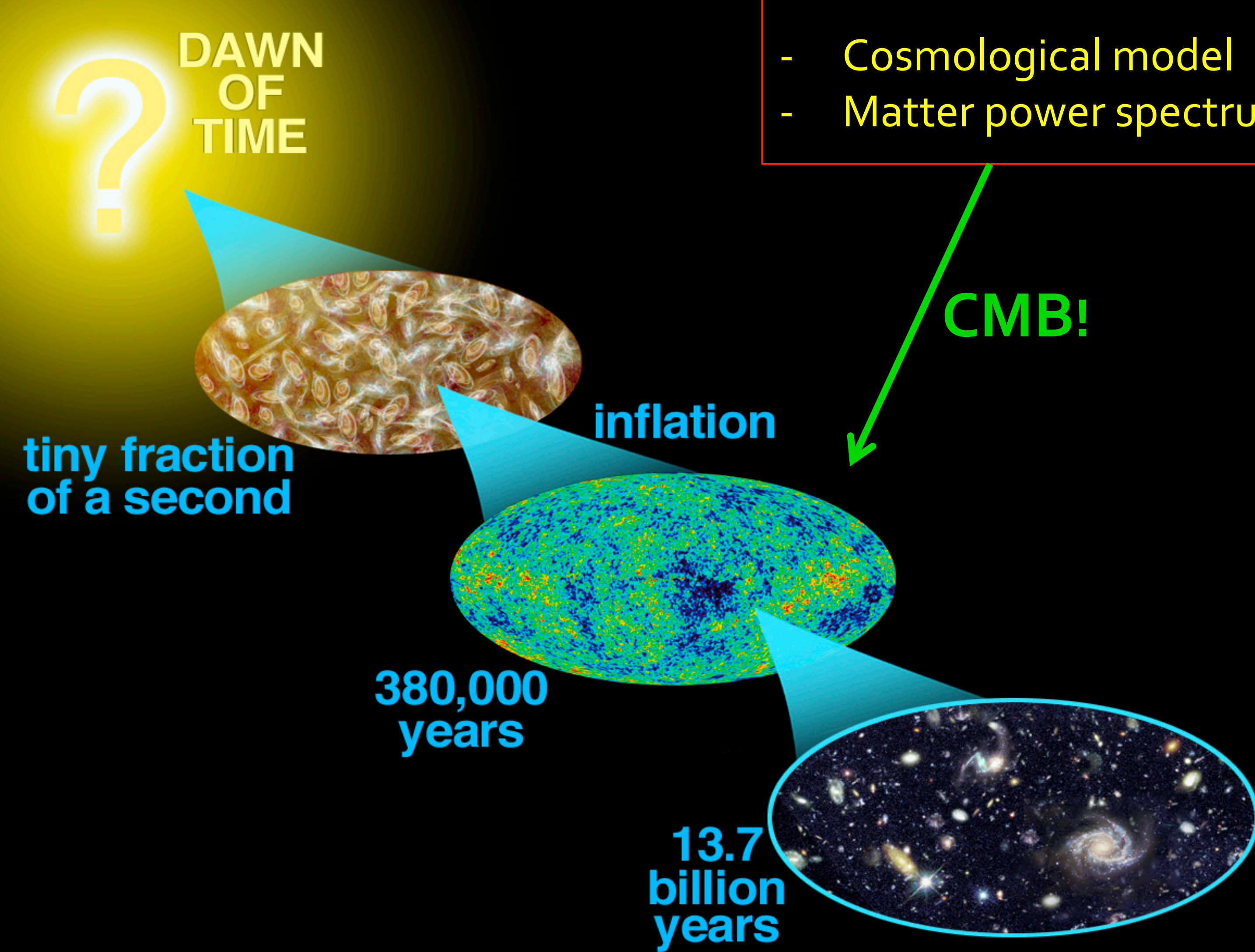


1. INITIAL CONDITIONS

2. EVOLUTION

1. INITIAL CONDITIONS

- Cosmological model
- Matter power spectrum



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.

2. Evolution: structure formation

- Growth of density perturbations in an expanding universe.

- Newtonian gravity (size of the region << R_{Hubble}; non-relativistic matter)
  (Other forces may be included depending on composition and scales considered.)

- The equations are solved in an expanding system of coordinates.

$$\begin{aligned} \text{Equation of Continuity} &: \quad \frac{\partial \varrho}{\partial t} + \nabla \cdot (\varrho \boldsymbol{v}) = 0 \; ; \\ \text{Equation of Motion} &: \quad \frac{\partial \boldsymbol{v}}{\partial t} + (\boldsymbol{v} \cdot \nabla)\boldsymbol{v} = -\frac{1}{\varrho}\nabla p - \nabla \phi \; ; \\ \text{Gravitational Potential} &: \quad \nabla^2 \phi = 4\pi G \varrho \; . \end{aligned}$$

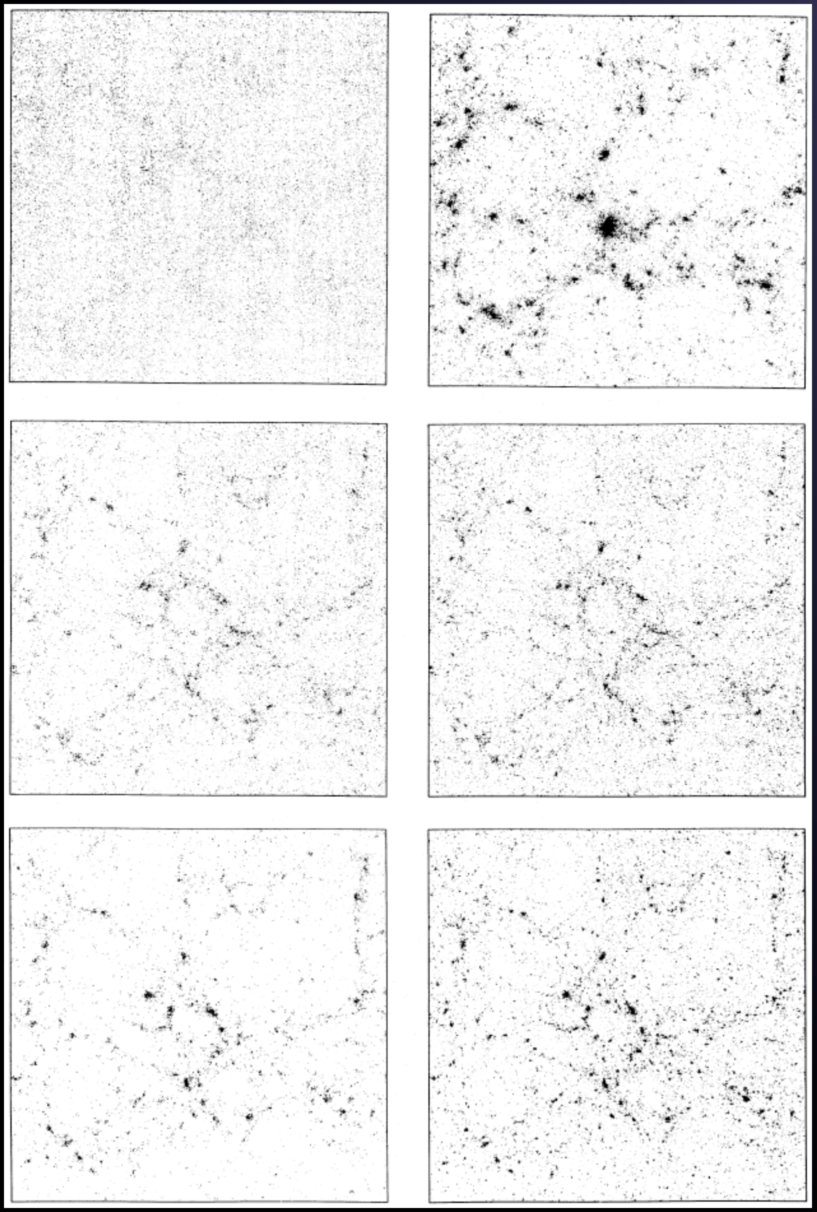
- We perturb the system around the uniform expansion $v_o = H_o r$:

$$\boldsymbol{v} = \boldsymbol{v}_0 + \delta \boldsymbol{v}, \quad \varrho = \varrho_0 + \delta\varrho, \quad p = p_0 + \delta p, \quad \phi = \phi_0 + \delta\phi \; .$$

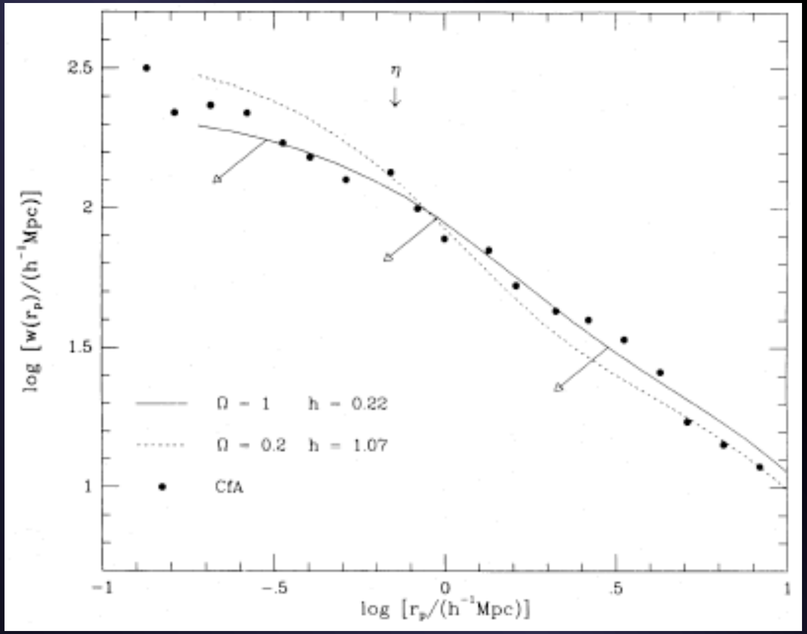
$$\frac{\mathrm{d}^2\Delta}{\mathrm{d}t^2} + 2\left(\frac{\dot{a}}{a}\right)\frac{\mathrm{d}\Delta}{\mathrm{d}t} = \Delta(4\pi G\varrho - k^2 c_\mathrm{s}^2) \; .$$

Evolution of the density contrast, $\Delta = \delta\rho/\rho_0$

First large scale structure (LSS) simulations



$N_p = 32768$



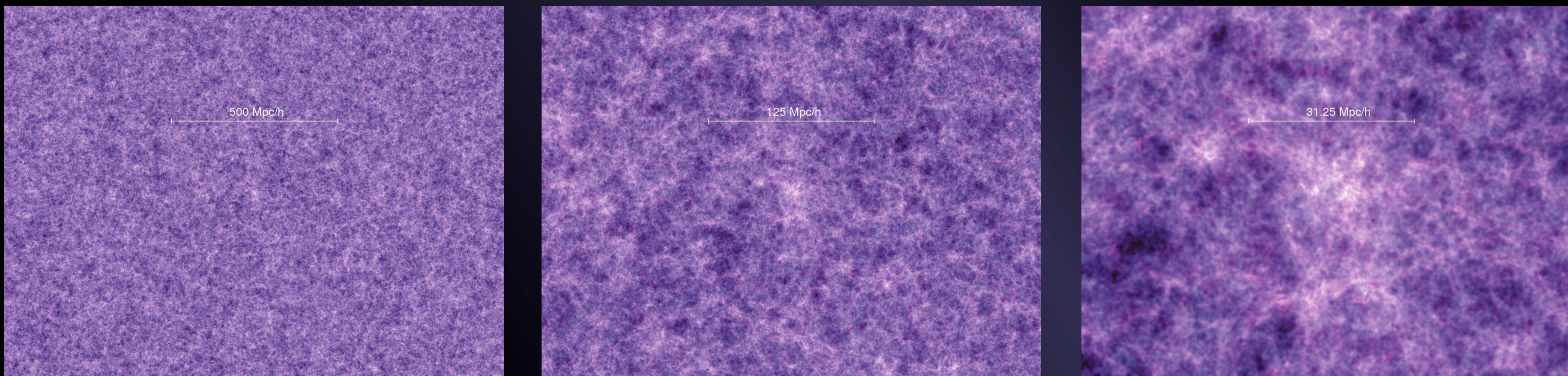
Klypin & Shandarin 1983
Davis et al. 1985

The Millennium Simulation

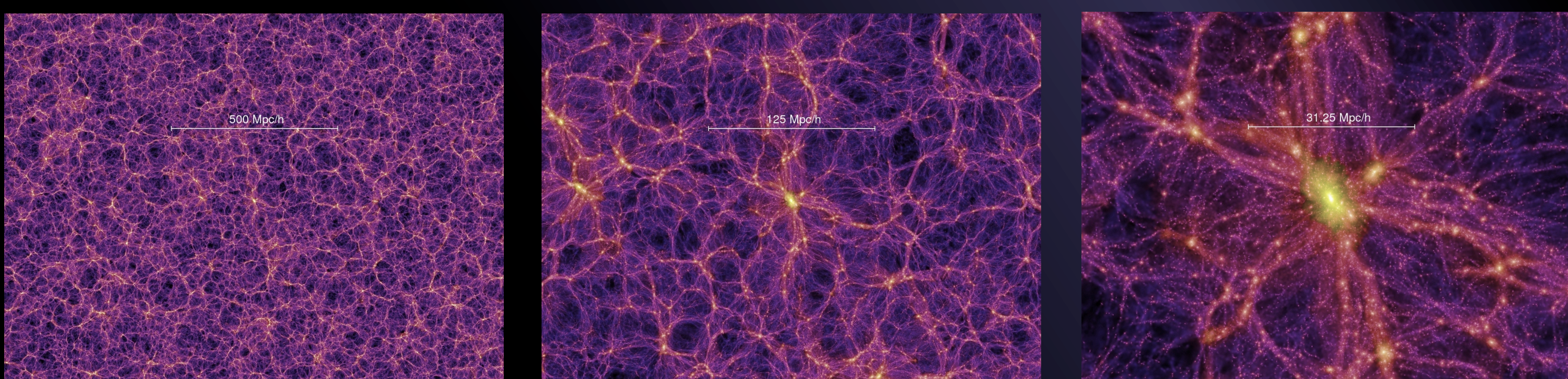
The Millennium Run used more than 10 billion particles to trace the evolution of the matter distribution in a cubic region of the Universe over 2 billion light-years on a side.

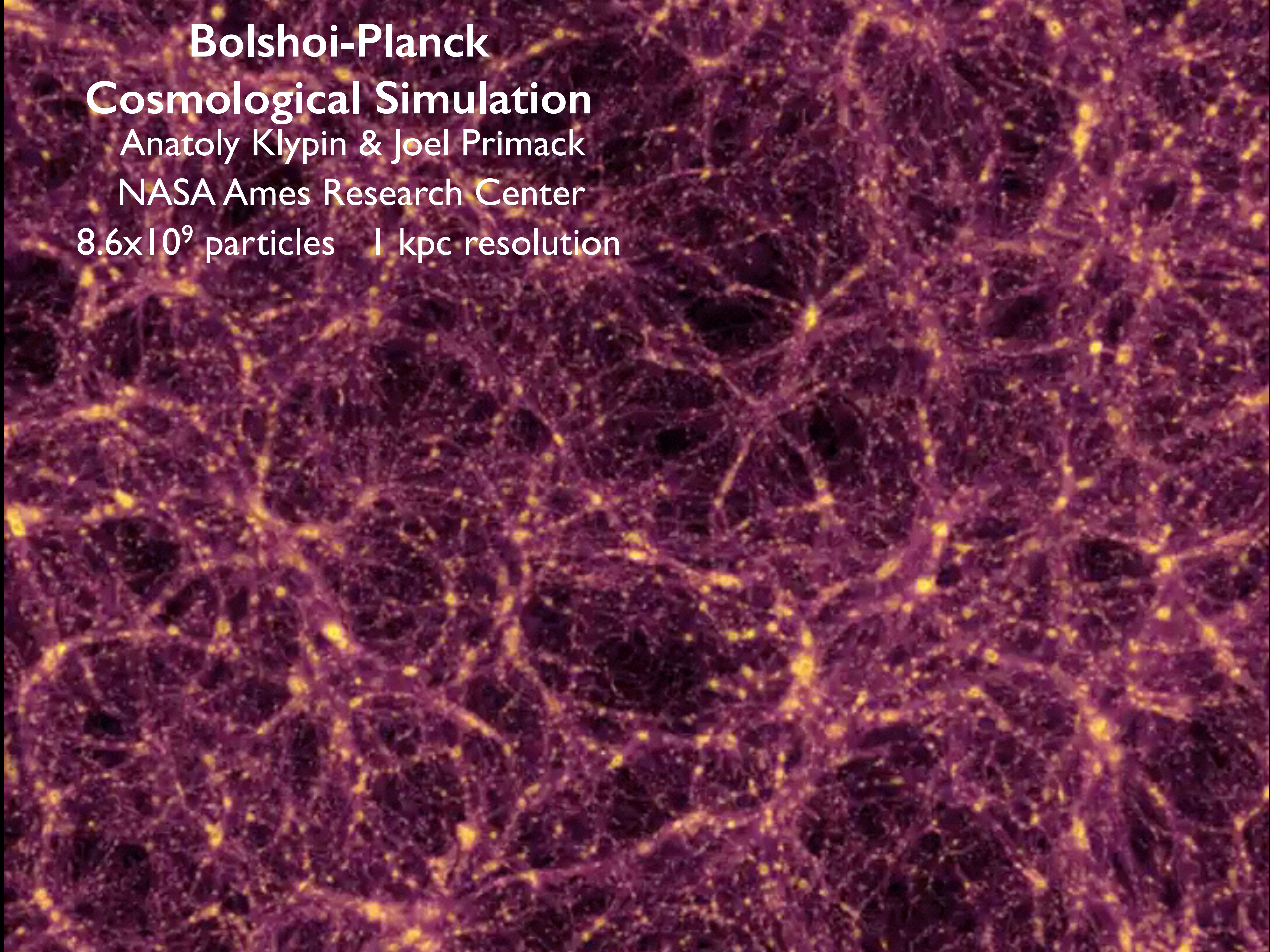
Redshift z=18.3 (t = 0.21 Gyr):

Springel et al. 2005



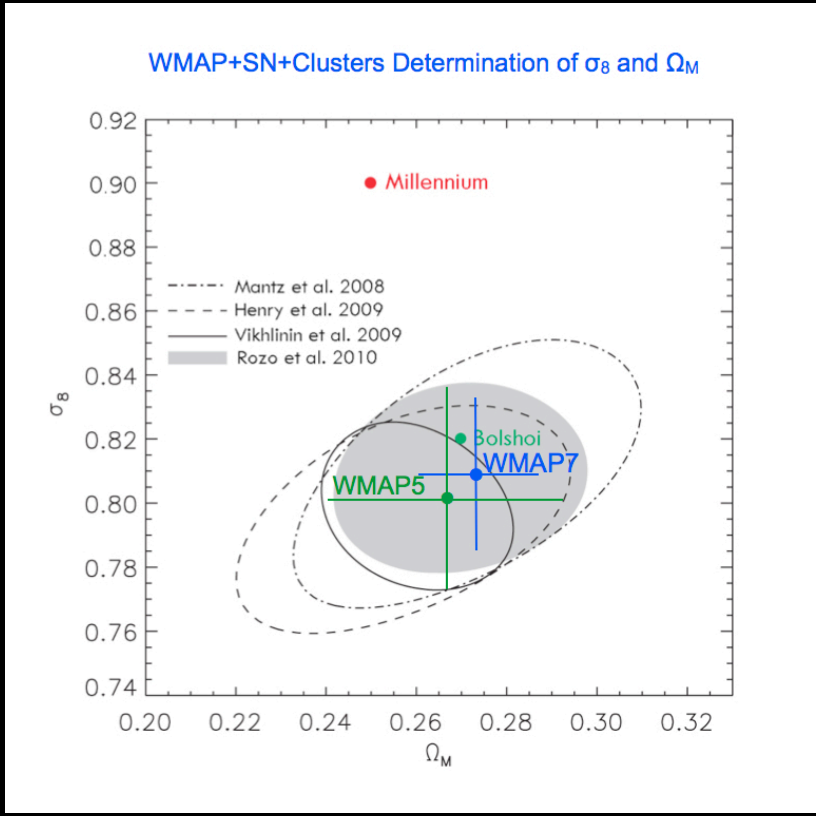
Redshift z=0 (t = 13.6 Gyr):




Bolshoi-Planck
Cosmological Simulation
Anatoly Klypin & Joel Primack
NASA Ames Research Center
8.6x10^9 particles   1 kpc resolution

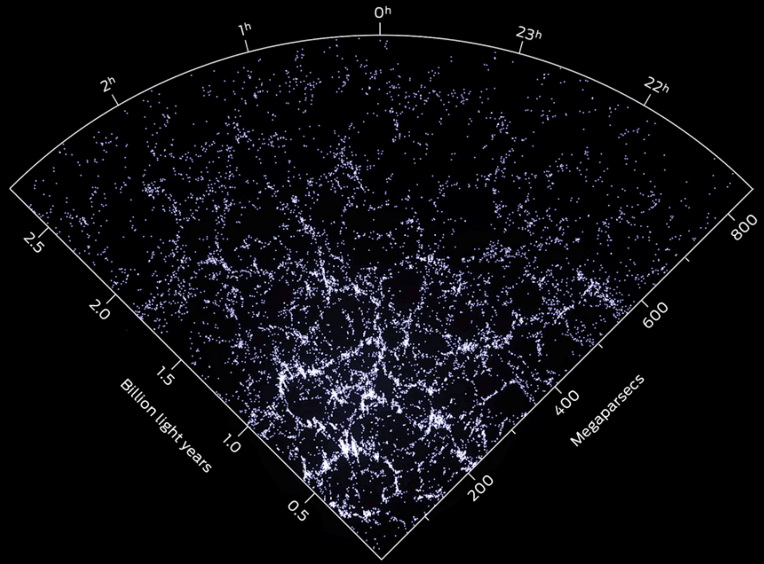
The LSS is well reproduced by simulations

Also a good statistical match
(important to use the right cosmological parameters)

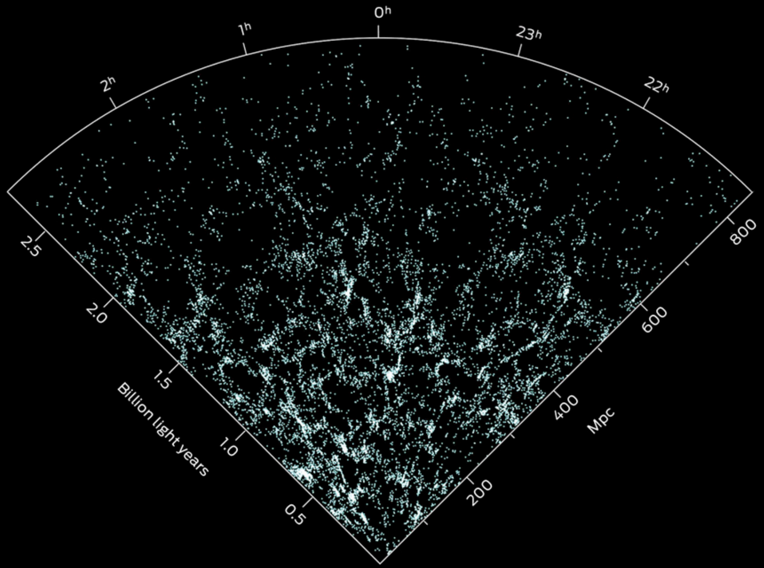


e.g. Bolshoi in better agreement with current data

Sloan Digital Sky Survey

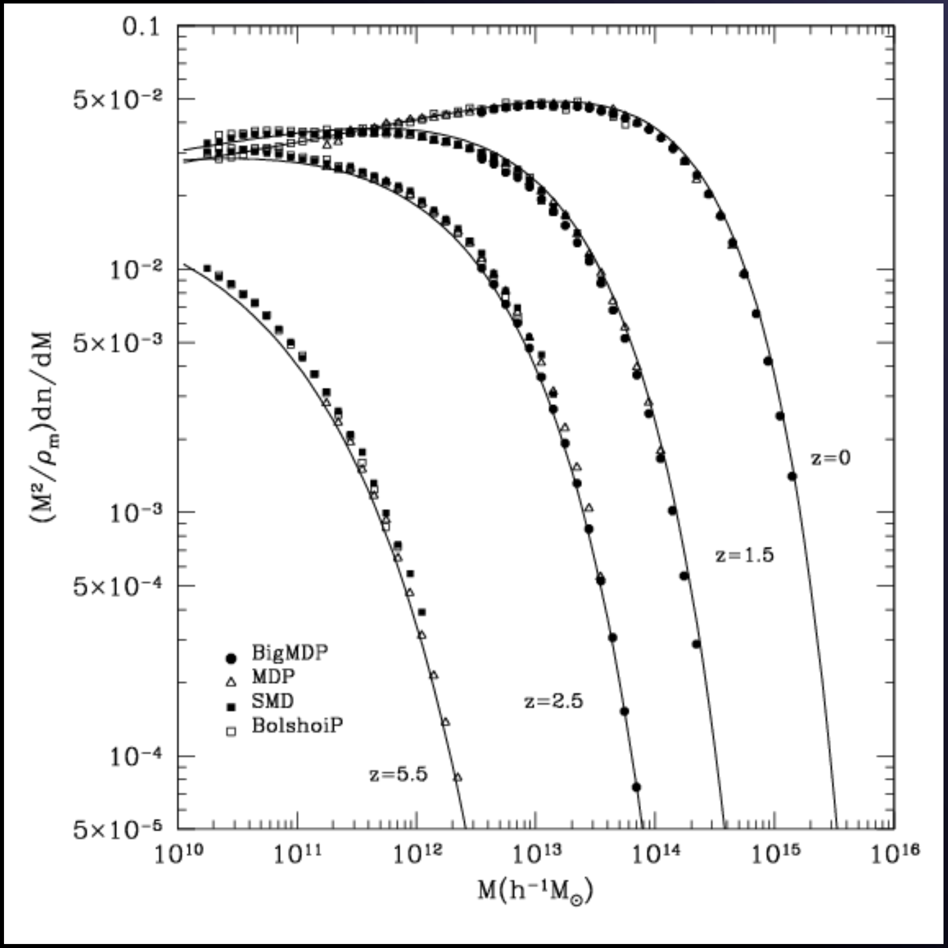


Bolshoi Simulation



DM halo mass function (HMF)

HMF gives the number of dark matter halos of a given mass.



Points: MultiDark set of simulations (Klypin+16)
Lines: Tinker+08 HMF

$$\frac{dn}{dM} = f(\sigma)\,\frac{\bar{\rho}_m}{M}\,\frac{d\ln\sigma^{-1}}{dM}.$$

with:

$$\sigma^2 = \int P(k)\hat{W}(kR)k^2\,dk,$$

r.m.s. of amplitude fluctuations

HMF one of the most fundamental statistics in Cosmology.

It controls the number of galaxies, clusters, etc.

Its evolution tells how fast objects grow.

Two-point correlation function

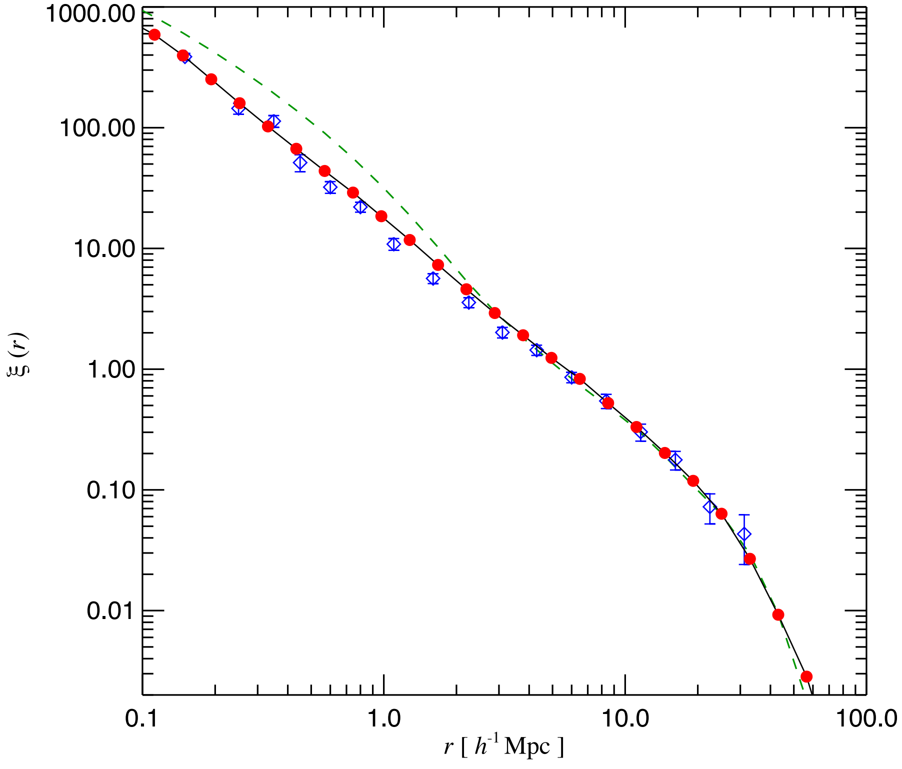


Figure 4: Galaxy 2-point correlation function at the present epoch. Red symbols (with vanishingly small Poisson error-bars) show measurements for model galaxies brighter than $M_K = -23$. Data for the large spectroscopic redshift survey 2dFGRS[28] are shown as blue diamonds. The SDSS[34] and APM[31] surveys give similar results. Both, for the observational data and for the simulated galaxies, the correlation function is very close to a power-law for $r \leq 20\,h^{-1}$Mpc. By contrast the correlation function for the dark matter (dashed line) deviates strongly from a power-law.

(Springel et al. 2005)

Given a random galaxy in a location, the correlation function describes the probability that another galaxy will be found within a given distance.

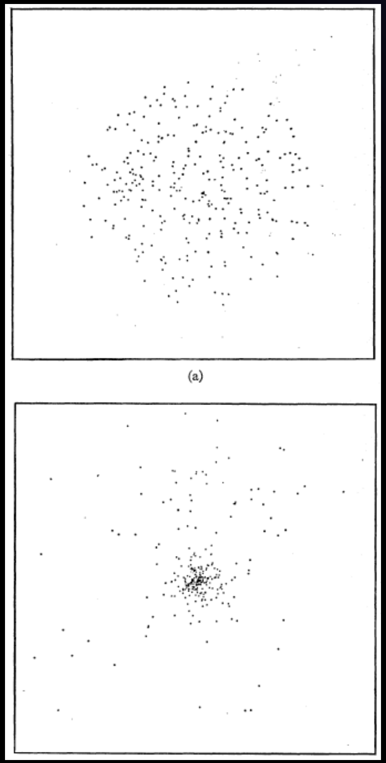
(Peebles 1980)

It can be calculated from P(k):

$$\xi(r) = \frac{1}{2\pi^2} \int dk\, k^2 P(k) \frac{\sin(kr)}{kr}$$

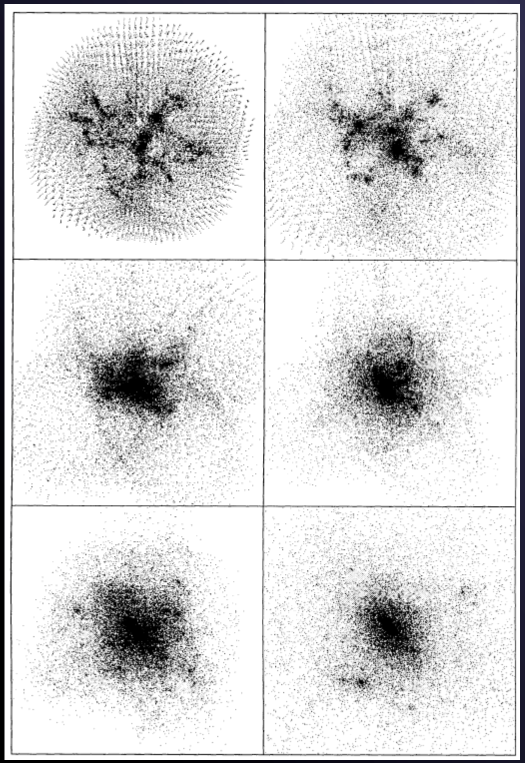
The structure of Cold Dark Matter halos

Structure of the Coma cluster
$N_p = 300$



Peebles 1970

Structure of DM halos
$N_p = 32000/250000$



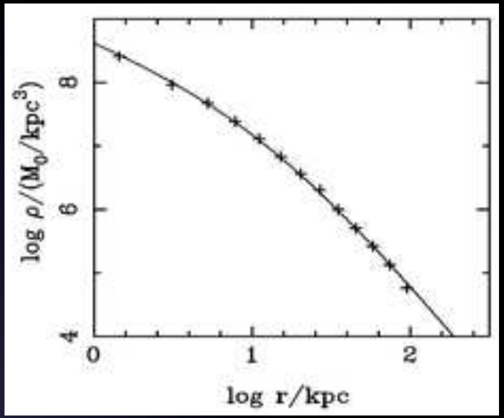
Dubinski & Carlberg 1991

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

Stadel et al. 2009

Dark Matter density profiles from N-body simulations

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

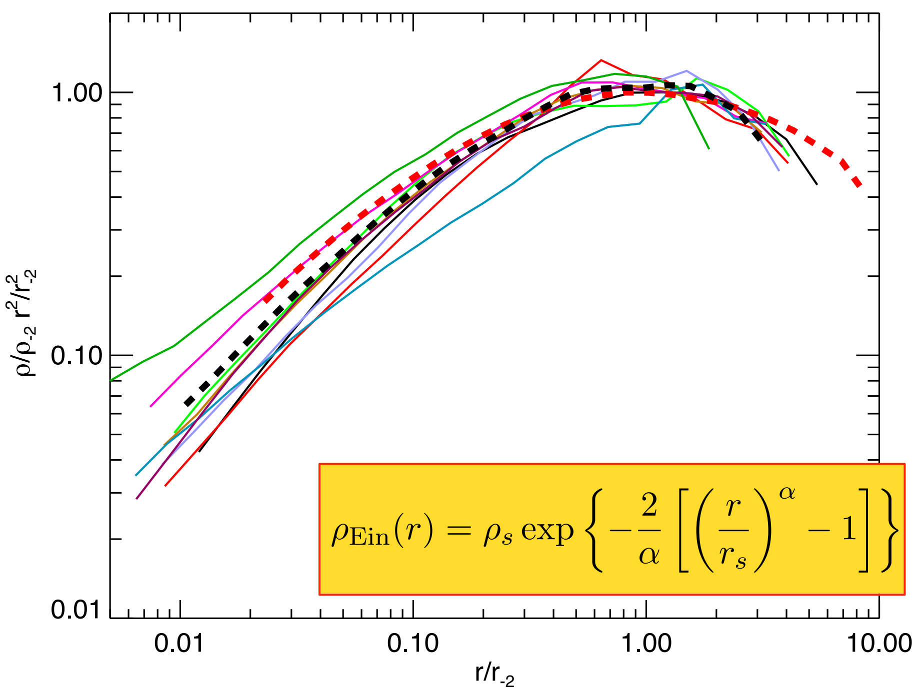


Dubinsky&Carlberg 90

$$\rho(r) = \frac{4\rho_s}{(r/r_s)(1+r/r_s)^2}$$

Navarro-Frenk-White (1996)
[NFW]

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



$$\rho_{\rm Ein}(r) = \rho_s \exp\left\{-\frac{2}{\alpha}\left[\left(\frac{r}{r_s}\right)^\alpha - 1\right]\right\}$$

Phoenix + Aquarius simulations [Frenk & White 2012]

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

The origin of these profiles is not well understood.

CDM halo concentrations

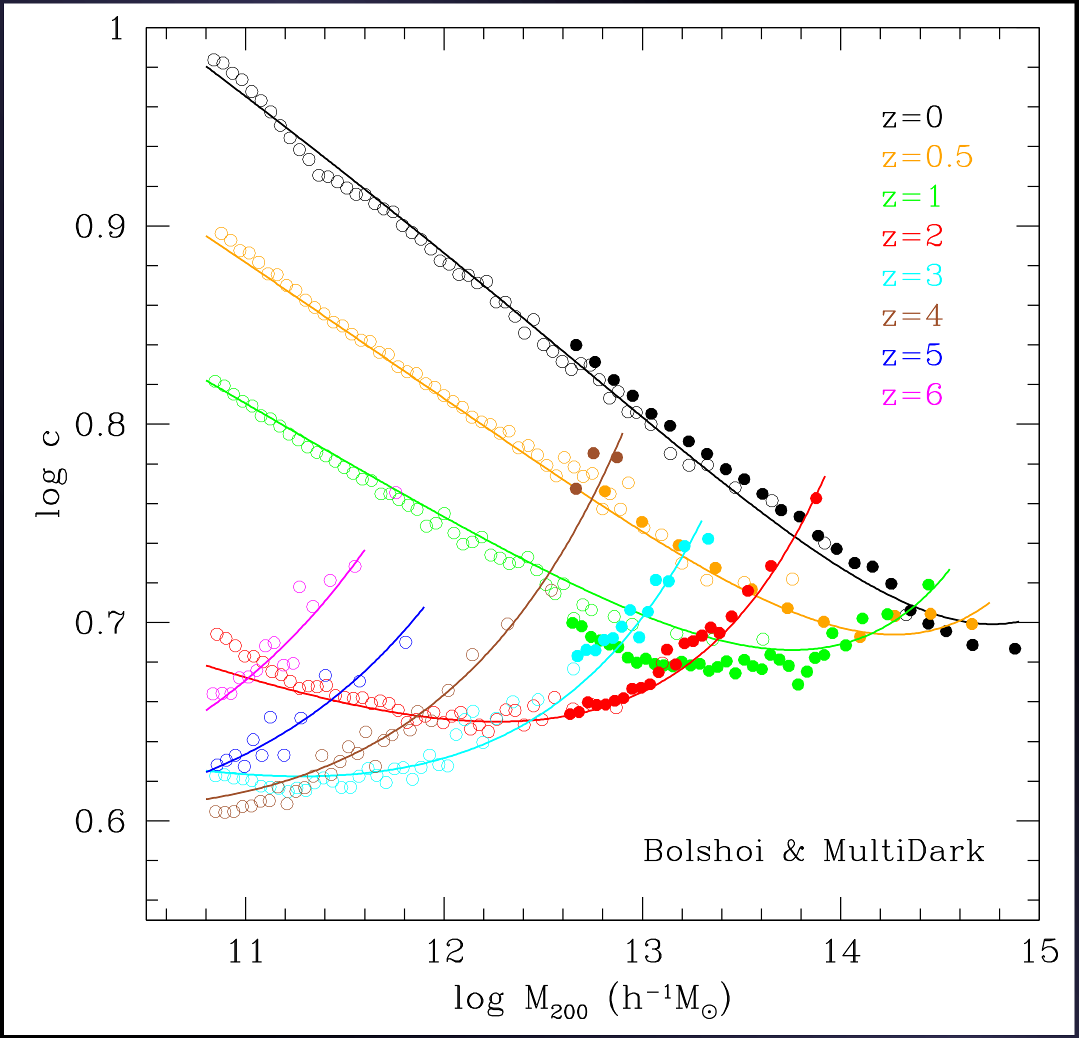
Concentration c = R_{vir} / r_s

Describes the structural halo properties.

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

Important quantity directly related to the formation time of the halo

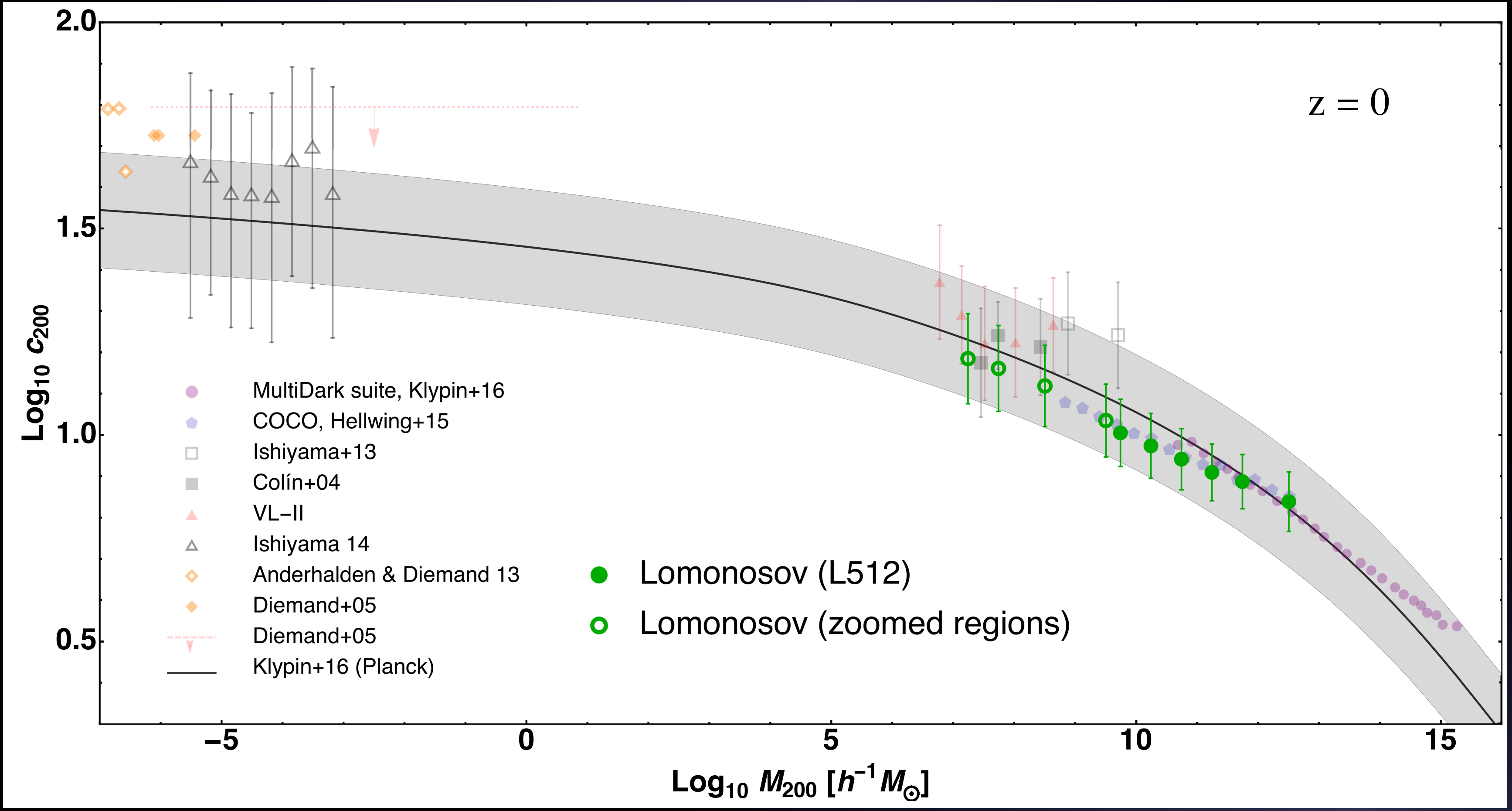
Once the halo is formed, r_s varies very little.



Prada+12

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

Concentration $c = R_{vir} / r_s$



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

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

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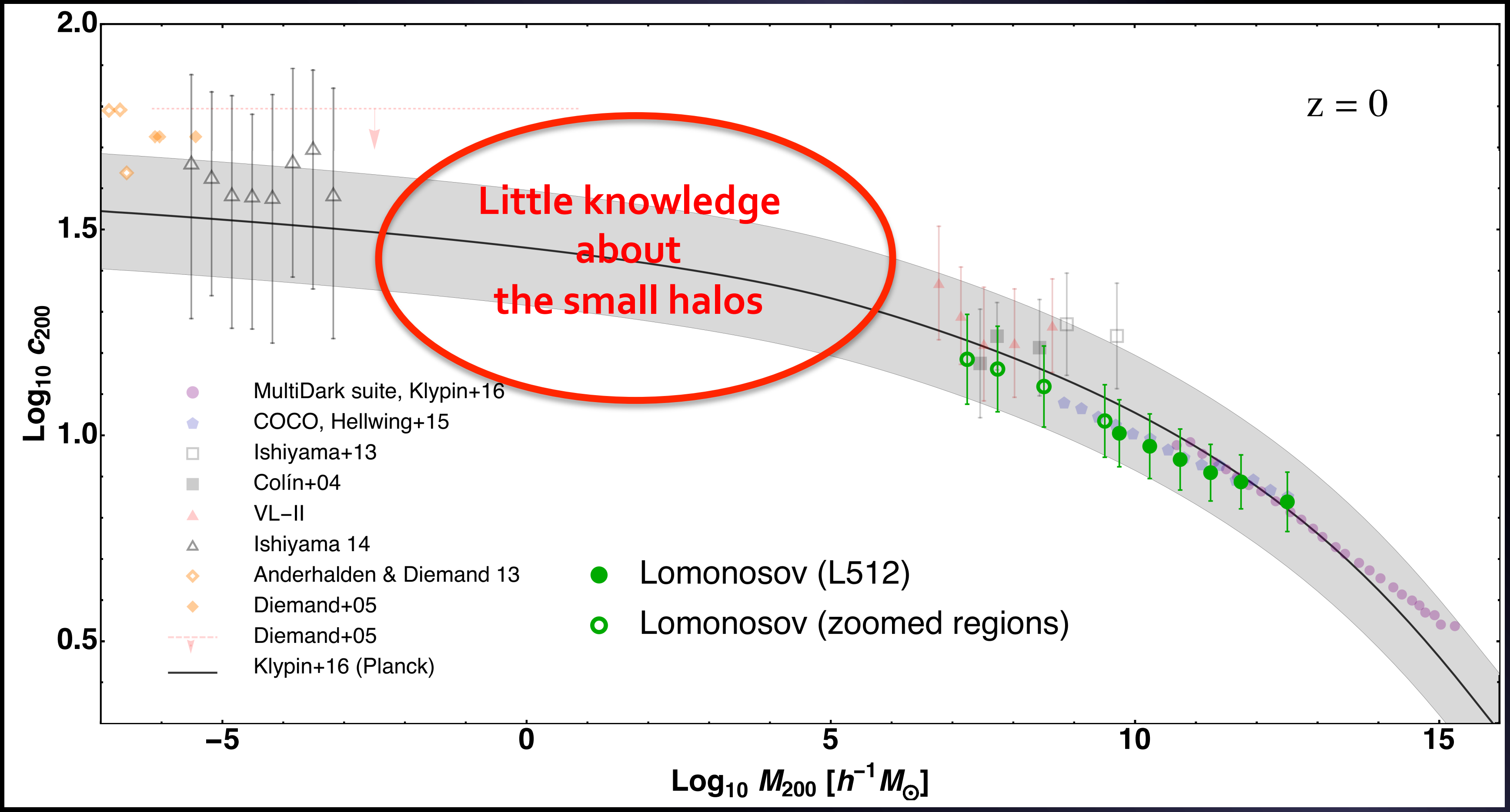


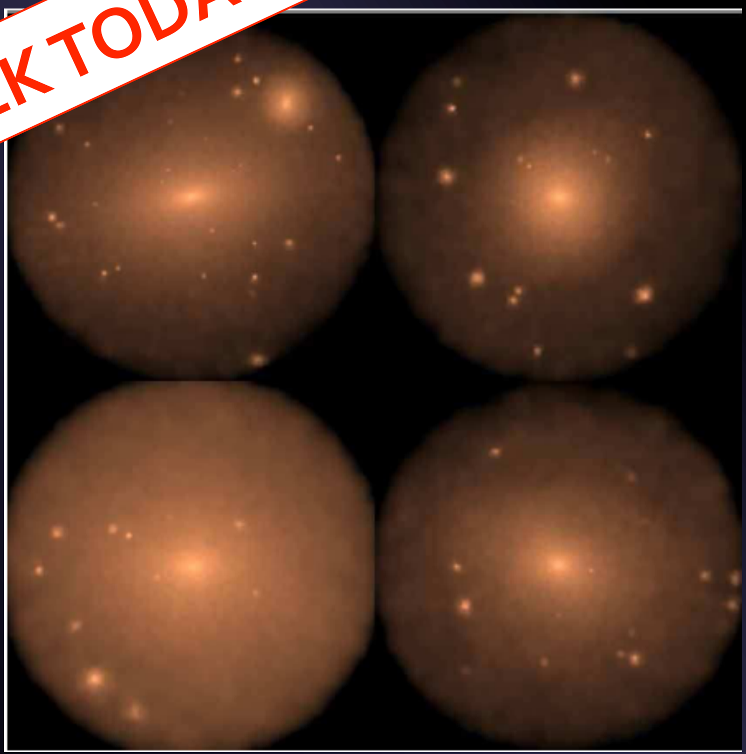
Pilipenko, MASC+17 [astro-ph/1703.06012]

CDM halo substructure

In ΛCDM, smallest structures collapse first and then merge to form the largest ones.

Substructure expected at all scales down to a minimum halo mass set by DM particle mass and decoupling temperature.

MW-sized halo, Aquarius simulations (Springel+08)



~10^9 Msun subhalos, Via Lactea (Diemand+06)

MY NEXT TALK TODAY!

State-of-the-art DM-only simulations

No baryons

Collisionless DM particles

Mature

Mostly computational resource limited

Extremely high resolution

DM-only simulations

Cosmic

Name	Code	L_{box} $[h^{-1}\mathrm{Mpc}]$	N_p $[10^9]$	m_p $[h^{-1}\,M_\odot]$	ϵ_{soft} $[h^{-1}\mathrm{kpc}]$	$N_{halo}^{>100p}$ $[10^6]$
DEUS FUR	Ramses-Deus	21000	550	1.2×10^{12}	$40.0^\dagger$	145
Horizon Run 3	GOTPM	10815	370	2.5×10^{11}	150.0	~190
Millennium-XXL	Gadget-3	3000	300	6.2×10^{9}	10.0	170
Horizon-4Π	Ramses	2000	69	7.8×10^{9}	$7.6^\dagger$	~40
Millennium	Gadget-2	500	10	8.6×10^{8}	5.0	4.5
Millennium-II	Gadget-3	100	10	6.9×10^{6}	1.0	2.3
MultiDark Run1	Art	1000	8.6	8.7×10^{9}	$7.6^\dagger$	3.3
Bolshoi	Art	250	8.6	1.4×10^{8}	$1.0^\dagger$	2.4

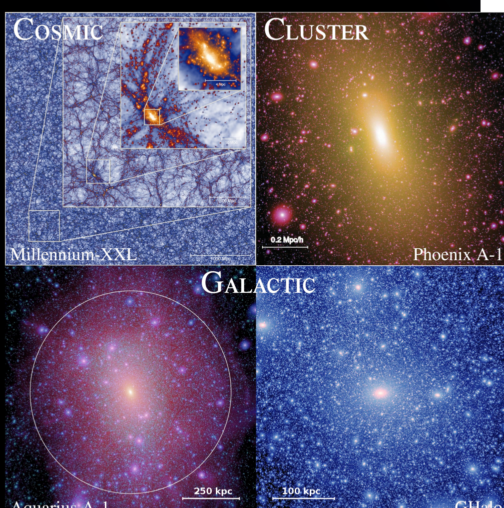
†For AMR simulations (Ramses, Art) ϵ_{soft} refers to the highest resolution cell width.

Cluster

Name	Code	L_{hires} $[h^{-1}\mathrm{Mpc}]$	$N_{p,hires}$ $[10^9]$	$m_{p,hires}$ $[h^{-1}\,M_\odot]$	ϵ_{soft} $[h^{-1}\mathrm{kpc}]$	$N_{sub}^{>100p}$ $[10^3]$
Phoenix A-1	Gadget-3	41.2	4.1	6.4×10^{5}	0.15	60

Galactic

Name	Code	L_{hires} $[\mathrm{Mpc}]$	$N_{p,hires}$ $[10^9]$	$m_{p,hires}$ $[M_\odot]$	ϵ_{soft} $[\mathrm{pc}]$	$N_{sub}^{>100p}$ $[10^3]$
Aquarius A-1	Gadget-3	5.9	4.3×10^{9}	1.7×10^{3}	20.5	82
GHalo	PKDGRAV2	3.89	2.1×10^{9}	1.0×10^{3}	61.0	43
Via Lactea II	PKDGRAV2	4.86	1.0×10^{9}	4.1×10^{3}	40.0	13



Kuhlen+12

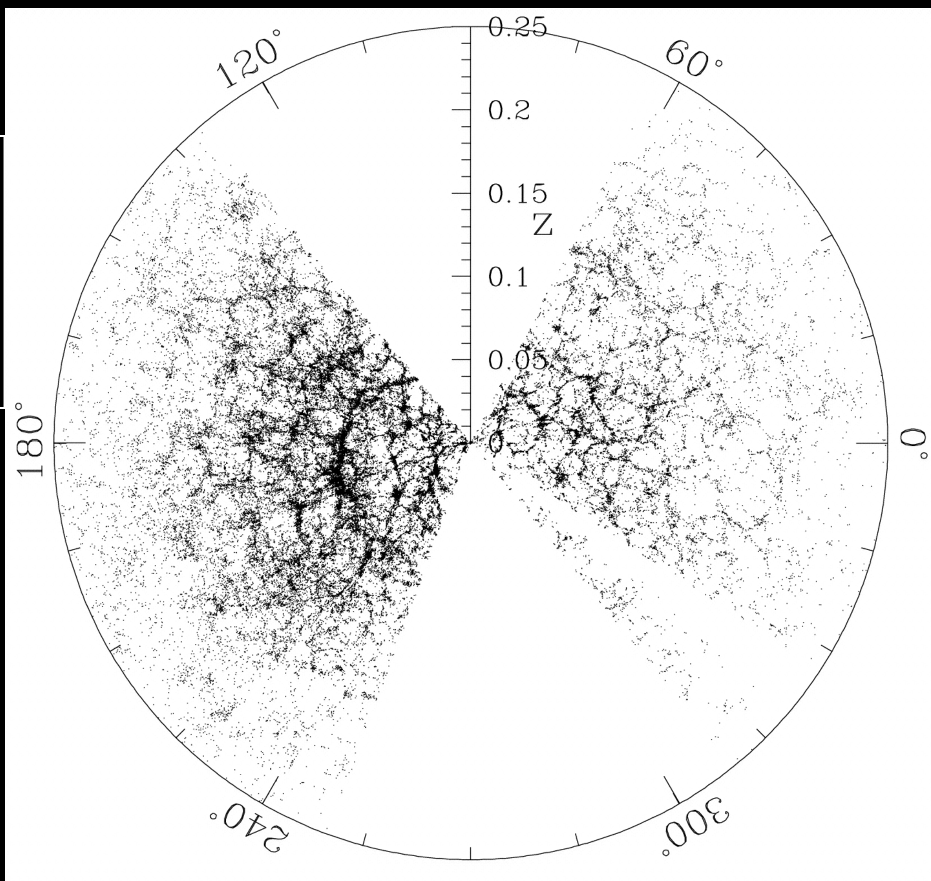
Galaxy formation: Challenges in computational cosmology

Realistic simulations would require inclusion of baryons.

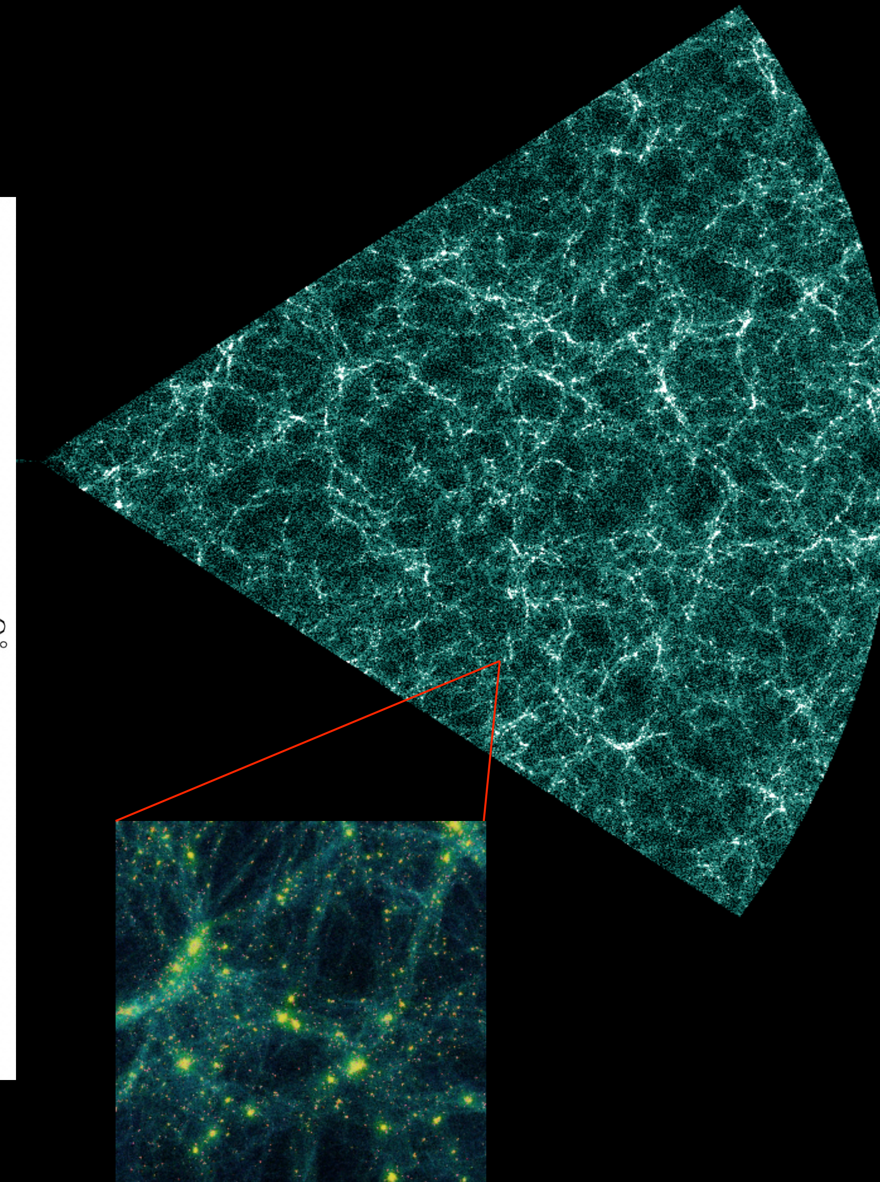
Galaxy formation involves not only gravity but also gas dynamics and complex physics (cooling, heating, star formation, SN feedback…)

→ **Extreme computing intensive simulations**
(Multi-billion particle simulations with N-body and gas dynamics in large volumes)

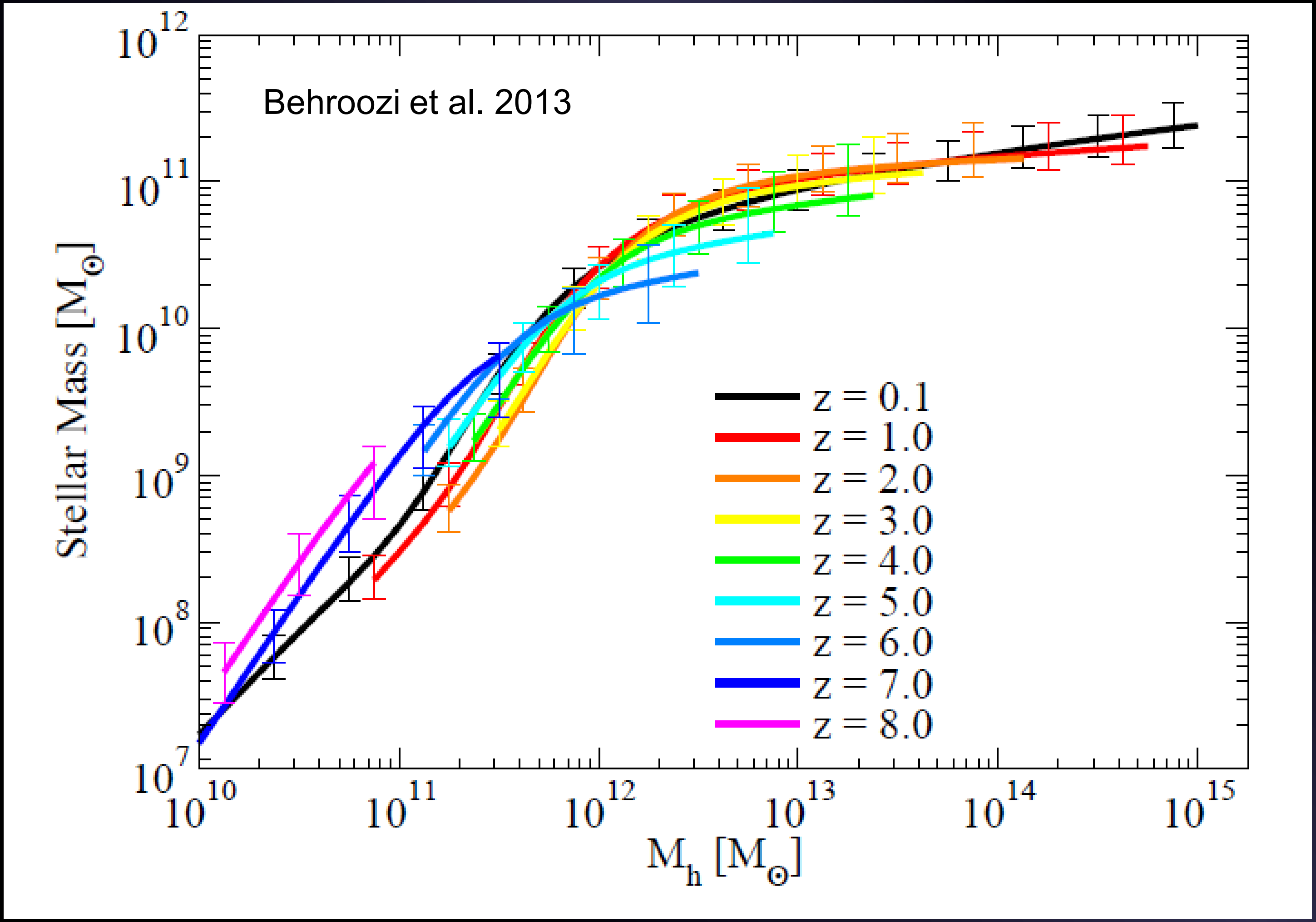
Galaxies - DM halos connection



SDSS



Galaxies - DM halos connection

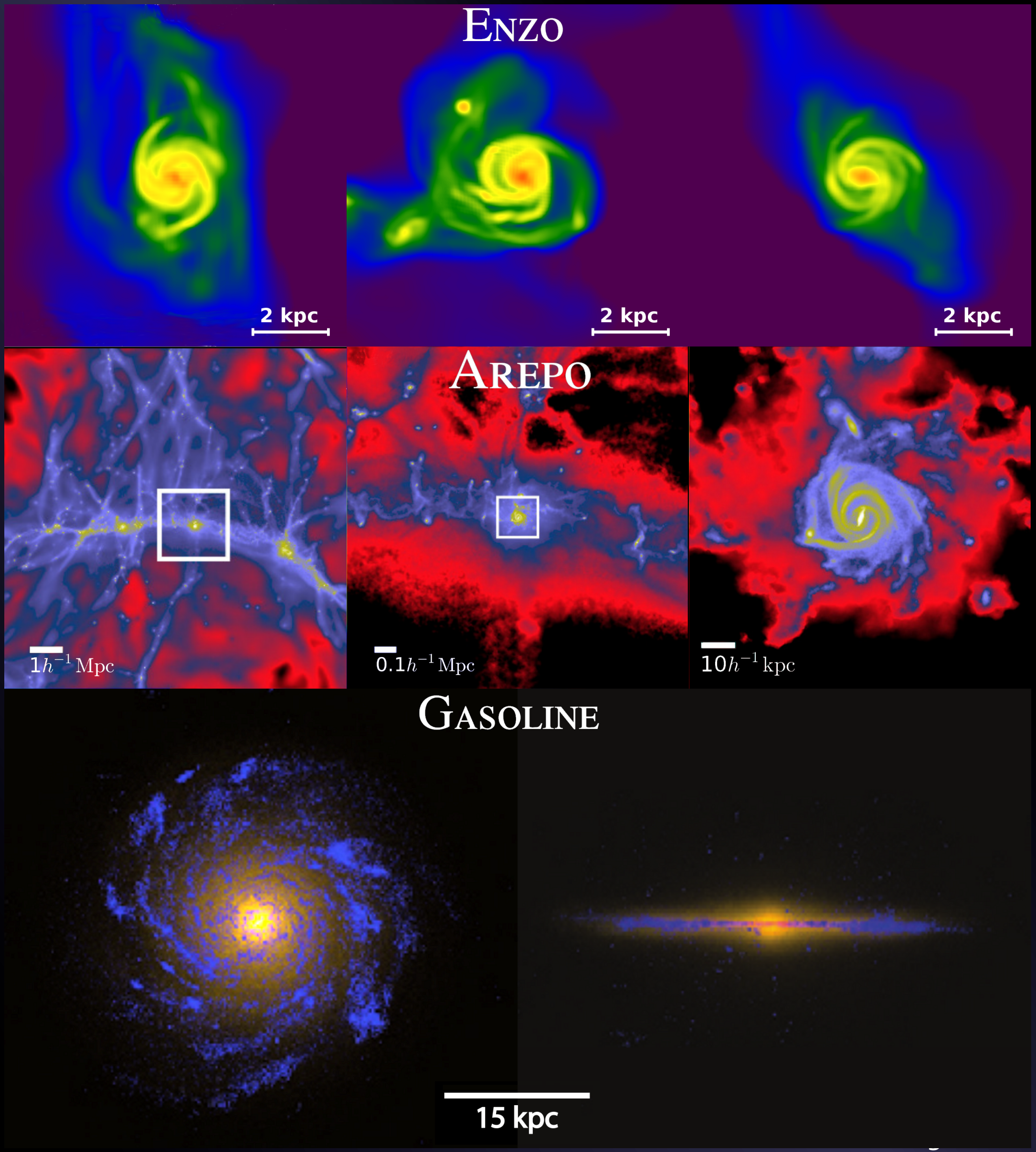


Hydrodynamical simulations

Including baryons dramatically increases the complexity of simulations

These simulations are limited by both memory and speed

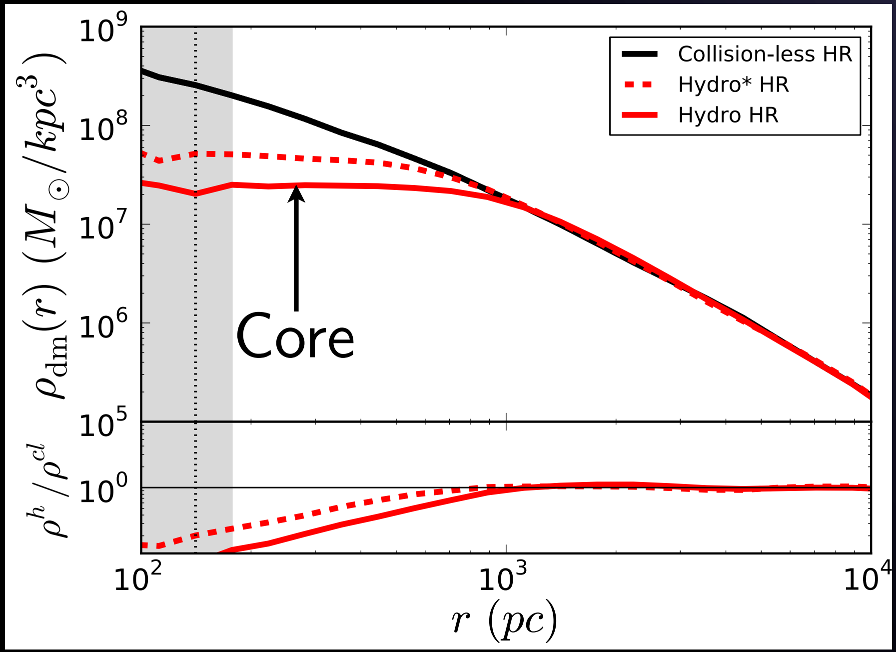
Simplifications on baryonic physics can be dangerous
E.g.: cusps or cored profiles?



Impact of baryons: one example

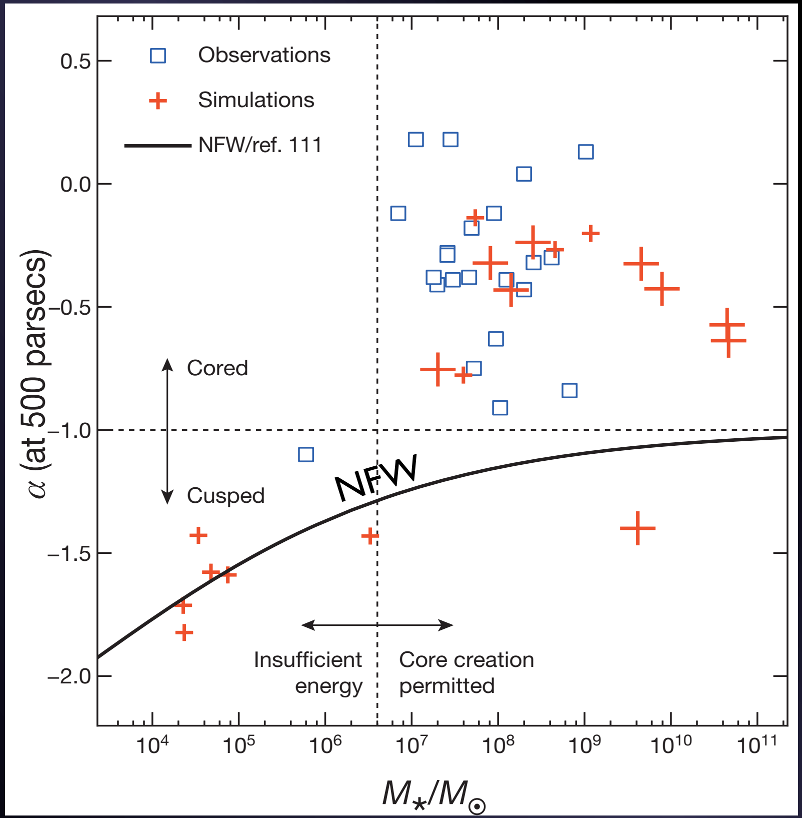
DM-only simulations predict cusps. Observations seem to prefer cores in some cases.
→ Baryons expected to play a role!
→ Baryonic contraction at work, but other baryonic physics counter balancing?
→ Cores from observations is controversial…

FIRE simulations:
$M_{vir}=10^{10}\,M_{sun}$; $M_*=4\cdot 10^6\,M_{sun}$; z=0



[Oñorbe+ 14]

[Pontzen & Governato 14]

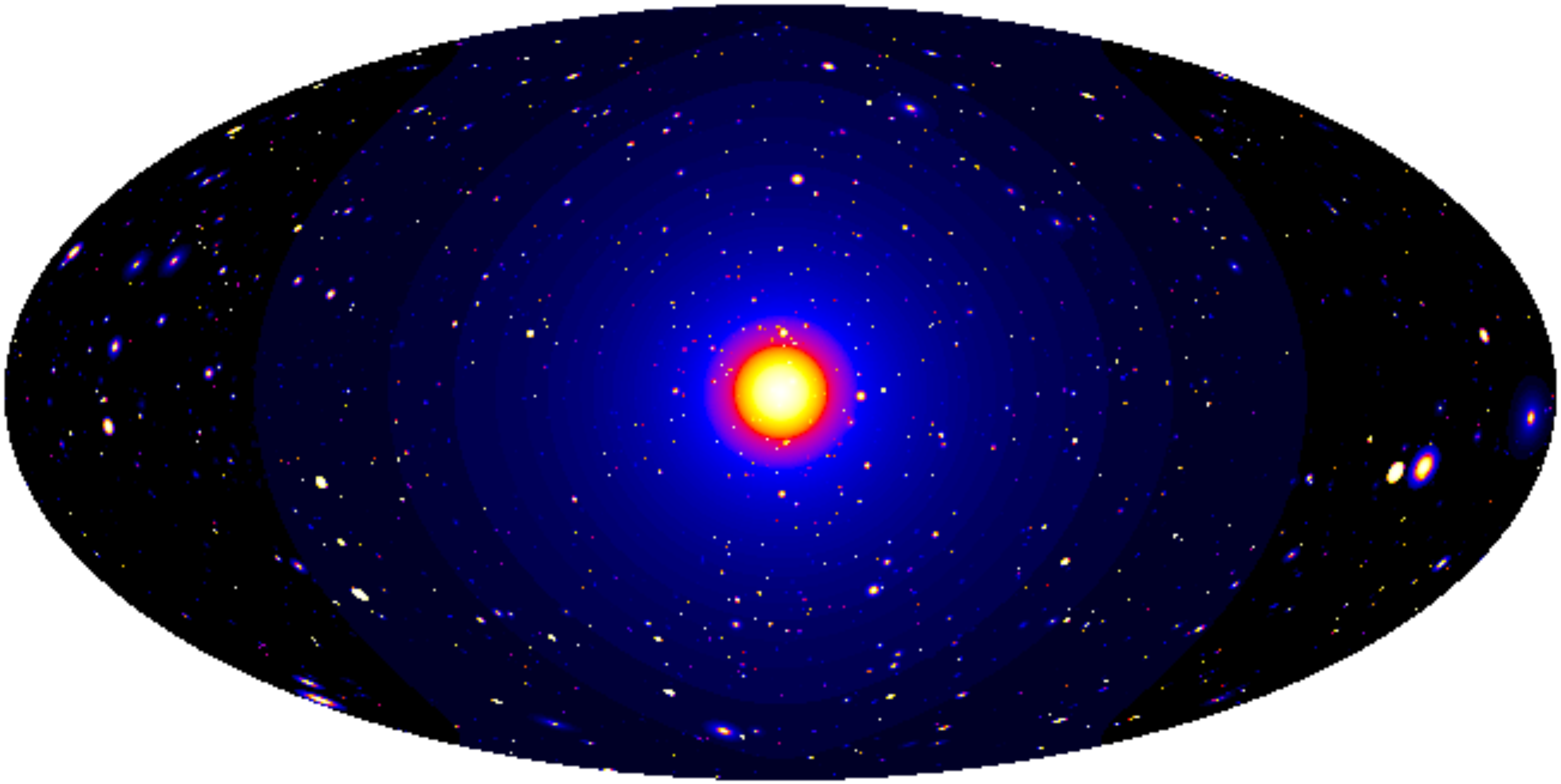


From the astrophysics point of view,
it's all about the J-factor.

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

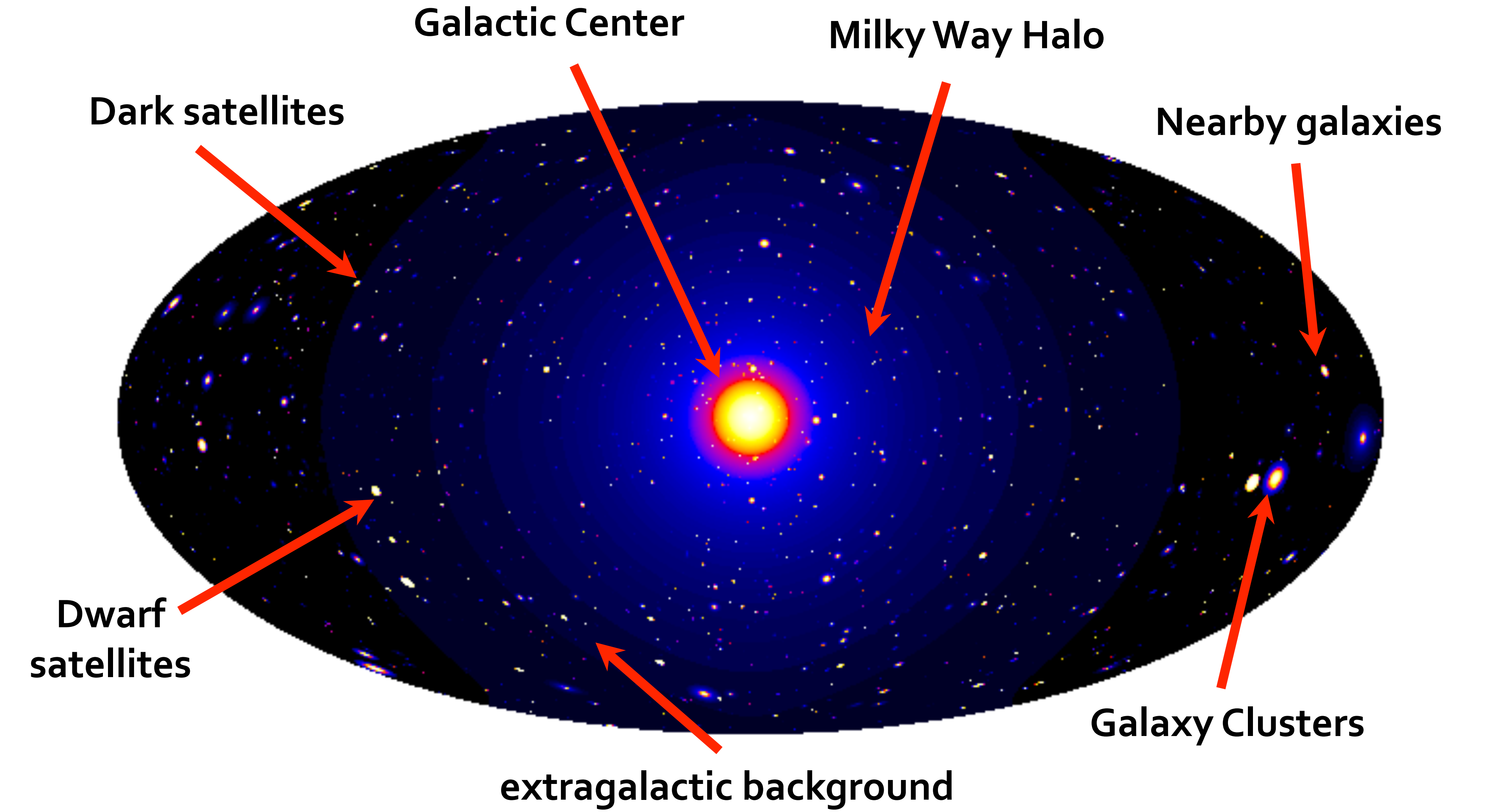
Can ΛCDM help with accurate predictions?
(and are these compatible with current determinations of the DM distribution/content from data?)

The (simulated) DM-induced gamma-ray sky



Dark Matter simulation:
Pieri+09, arXiv:0908.0195

DM search strategies



+ Spectral Lines

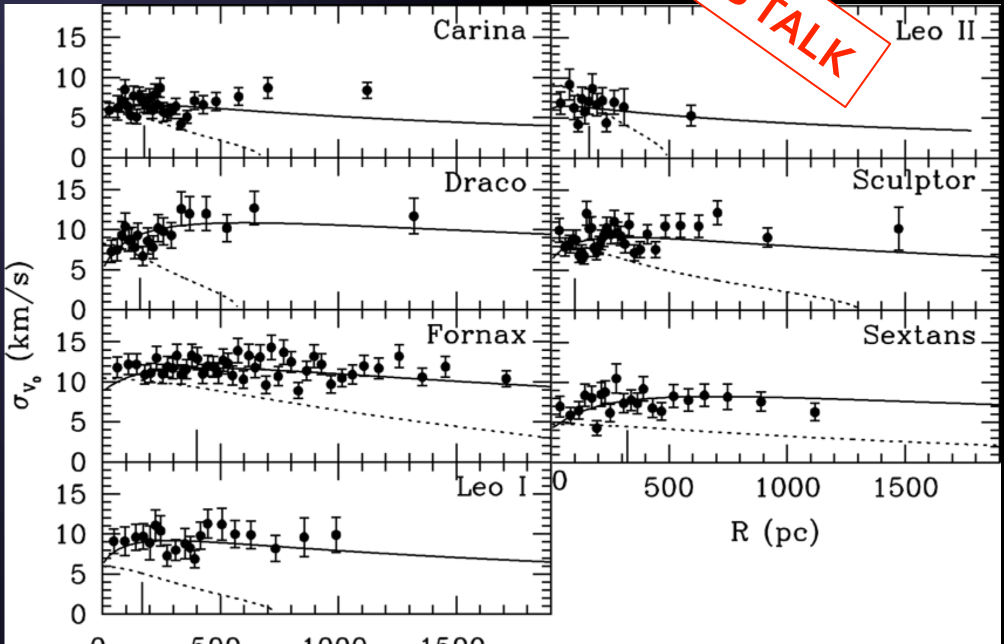
Dark Matter simulation:
Pieri+(2009) arXiv:0908.0195

EXAMPLE: DM content in dwarfs

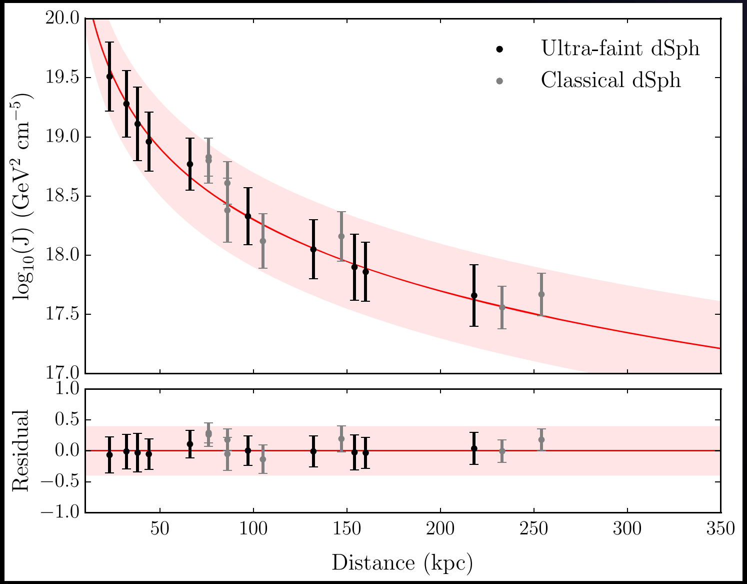
SATURNI'S TALK

- Determined spectroscopically from **stellar velocity dispersions**:
  - O(100) in classical dwarfs.
  - O(10) in ultra-faint dwarfs.

- Dispersion profiles generally remain flat up to large radii
  → **highly DM dominated**



Wilkinson et al 2009



Albert+15

"J-factor" of MW dwarf satellite galaxies inferred from:
- l.o.s. velocity dispersion profiles
- DM density profile (e.g. NFW)

→ **LCDM predictions crucial!**

EXAMPLE: Cosmological DM annihilation

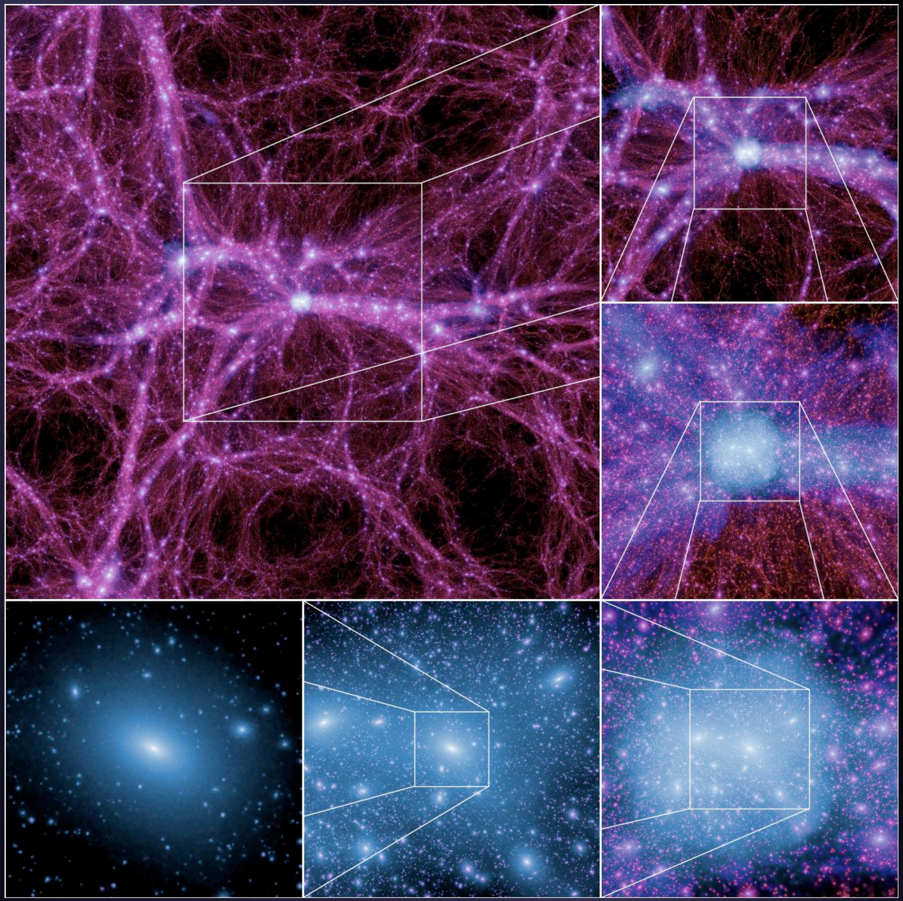
DM halos and substructure *expected* at all scales down to a $M_{min} \sim 10^{-6}\ M_{sun}$.

DM annihilation signal from all DM halos at all redshifts contribute to the IGRB.

Ingredients: HMF, DM profiles and subhalos at all redshifts.

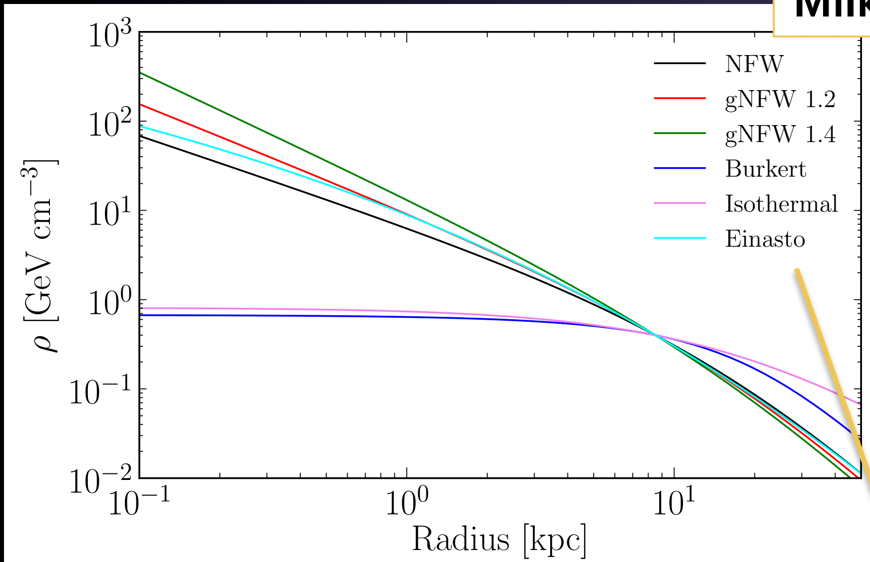
→ **LCDM predictions crucial!**

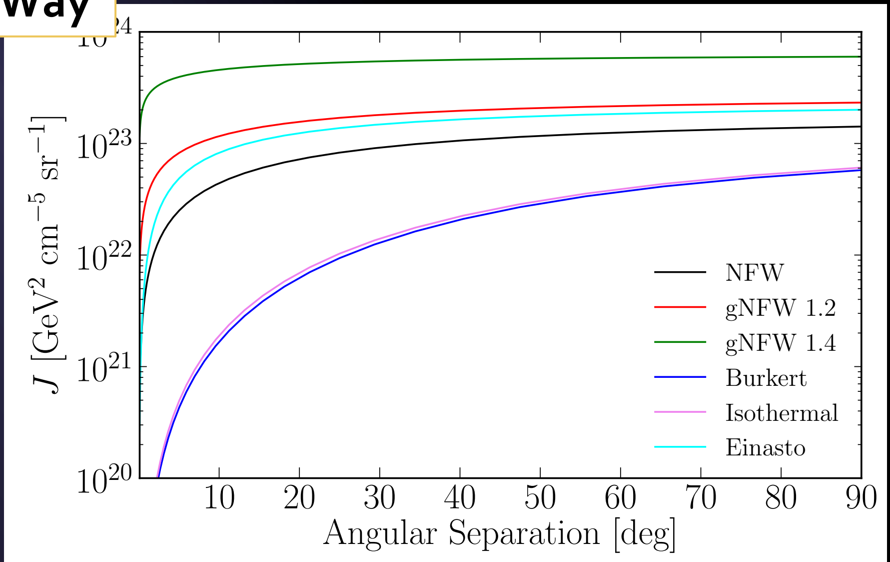
[see.e.g. 1501.05464]



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

Milky Way





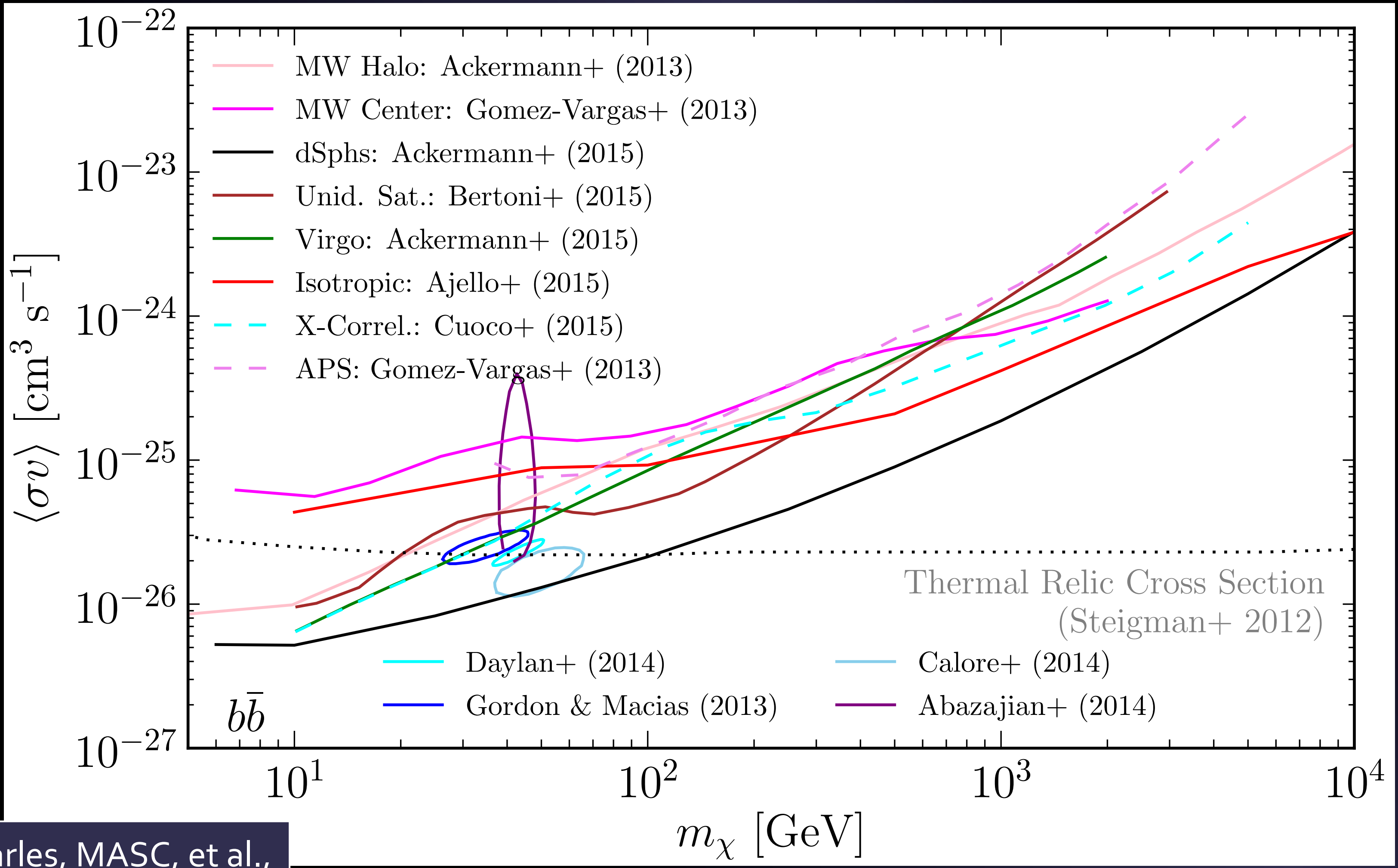
LCDM predictions crucial!

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

DM modeling in ΛCDM critical to set all limits



Charles, MASC, et al., [1605.02016]

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ift Instituto de Física Teórica UAM-CSIC

MULTIDARK Multimessenger Approach for Dark Matter Detection

Thanks!

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