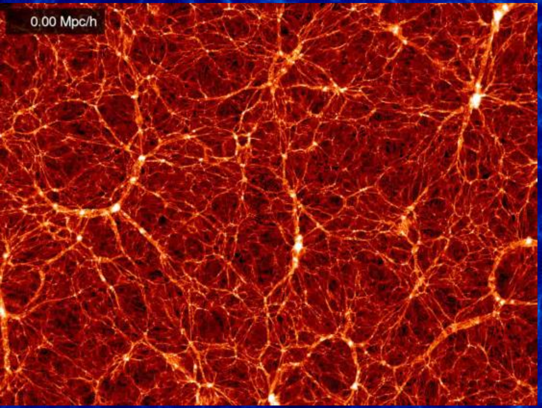

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A brief overview of Modern Cosmology:

Formation and evolution of structures in the Universe

Gustavo Yepes

Universidad Autónoma de Madrid

A Quick Review of Cosmology:

The purpouse of Cosmology:

a) Try to understand the origin, the structure, mass-energy content and the evolution of the universe as a whole.

b) To understand the emergence of structures and objects ranging from scales as small as stars (10^{10} m) to scales much larger than galaxies ($\sim 10^{26}$ m) through gravitational self-organization.

Foundations of Modern Cosmology

- Gravity is the dominant force at large scales:
  - Most accurate description of gravity as a metric theory.
    - *Gravity is a geometric phenomenon due to the curvature of space time produced by the matter-energy content.*

- The Cosmological principle:
  - The Universe is homogeneous and isotropic at sufficiently large scales
    - *Supported by observations: (isotropy of CMB; homogeity galaxy surveys*
    - *Generalization of the Copernican principle: no privileged observer in the Universe.*

Cosmological Models

- Choose a metric theory of gravity:
  - General Relativity is the most accurate theory with minimum fields content.

$$G_{\mu\nu} - \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

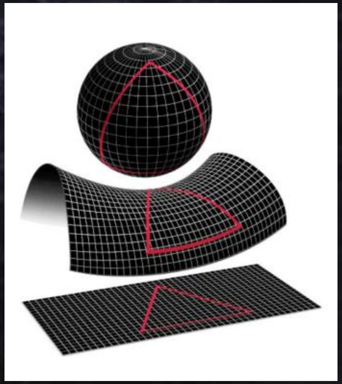
- Assume Cosmological Principle: *Robertson-Walker metric* of the space-time manifold (form of the metric tensor $g_{\mu\nu}$):

$$ds^2 = c^2 dt^2 - R(t)^2 \left(\frac{dr^2}{1 - kr^2} + r^2 (d\theta^2 + \sin^2\theta d\phi^2) \right)$$

•RW metric is the most general metric that satisfies homogeneity and isotropy in the 3 spatial dimensions and assumes a global evolution with time through the R(t) function.

κ accounts for the global curvature of the spatial hypersurface within the 4D manifold.

•K=+1 (spherical), k=-1(hyperbolic) and k=0 (eucledian)



•No physics in it. The form of the R(t) has to be computed from the Einsteins field equations.

Cosmological Models

$$G_{\mu\nu} - \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

+

$$ds^2 = c^2 dt^2 - R(t)^2 \left(\frac{dr^2}{1 - kr^2} + r^2 (d\theta^2 + \sin^2\theta d\phi^2) \right)$$

↓

Lemaitre-Friedman-Robertson-Walker models (LFRW)

$$\ddot{R} = -\frac{4\pi G R}{3}\left(\rho + \frac{3p}{c^2}\right) + \frac{\Lambda R}{3}$$

$$\frac{\dot{R}^2}{R^2} = \frac{8\pi G\rho}{3} + \frac{\Lambda}{3} - \frac{ck}{R^2}$$

Cosmological Models

$$G_{\mu\nu} - \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

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$$\frac{\dot{R}^2}{R^2} = \frac{8\pi G \rho}{3} + \frac{\Lambda}{3} - \frac{ck}{R^2}$$

- Solution depends on the equation of state of the matter content
  $P = f(c^2\rho(T))$; $P = \omega c^2 \rho(T)$
- No relativistic matter (dust model) $P=0$ ($\omega =0$)
- Relativistic matter $P= c^2\rho/3$ ($\omega=1/3$)

Solutions to the LFRW equations

First LFRW equation :

$$H^2 = H_0^2\left(\Omega_{r,0}(1+z)^4 + \Omega_{m,0}(1+z)^3 + \Omega_{k,0}(1+z)^2 + \Omega_{\Lambda,0}\right)$$

$a = \frac{1}{z+1}$

with

the cosmological parameters

- matter density $\Omega_{m,0} = \frac{\rho_{m,0}}{\rho_{crit,0}}$
- radiation density $\Omega_{r,0} = \frac{\rho_{r,0}}{\rho_{crit,0}}$
- vacuum energy $\Omega_{\Lambda,0} = \frac{c^2}{3H_0^2}\Lambda$
- curvature $\Omega_{k,0} = -\frac{c^2}{H_0^2 R_0^2}k$
- expansion rate $H_0 = \left(\frac{\dot{R}}{R}\right)_0$

•Note: $\rho_{crit} = \frac{3H_0^2}{8\pi G}$ $a(t) = \frac{R(t)}{R(t_0)}$

• $\rho_{mass} \sim a^{-3}$ $\rho_{radiation} \sim a^{-4}$ $\rho_{\Lambda} \sim a^0$

• redshift $z \equiv \frac{\nu_e}{\nu_o} - 1 = \frac{\lambda_o}{\lambda_e} - 1$

Second LFRW equation: Cosmic sum rule

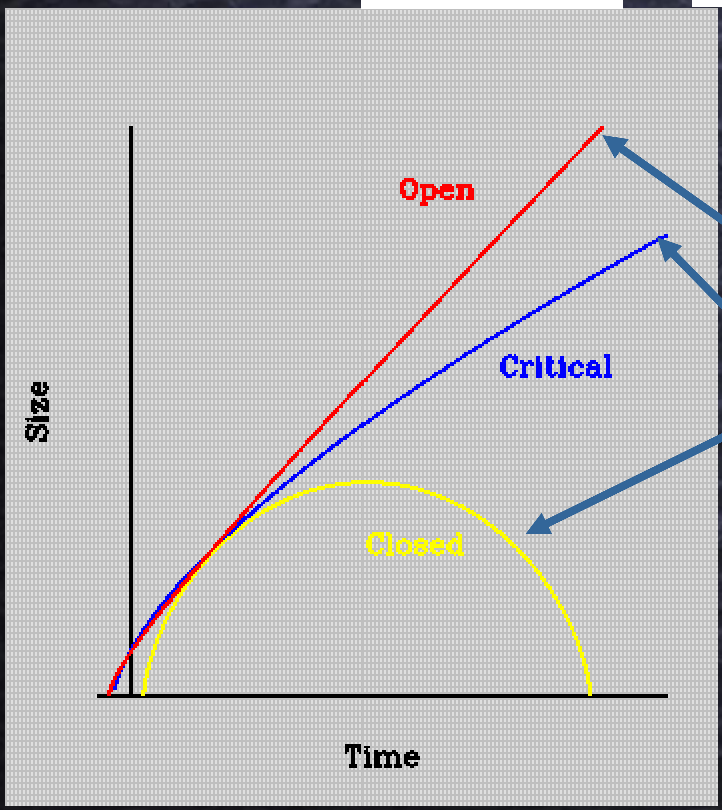
$$\Omega_{mass+radiation} + \Omega_k + \Omega_\Lambda = 1.$$

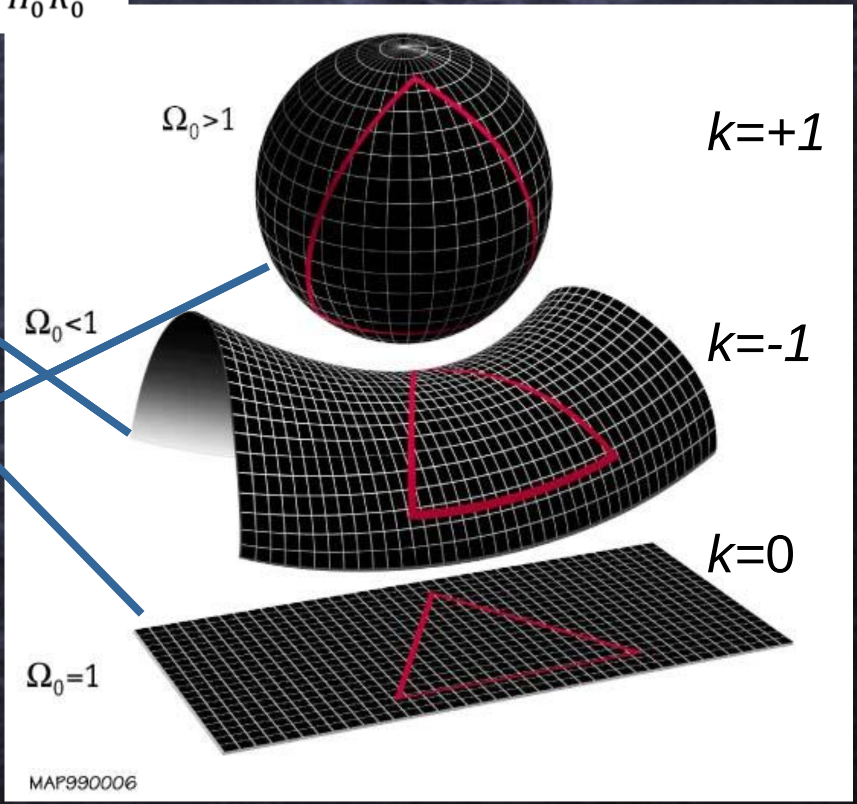
LFRW MODELS with Λ=0

$$\Omega_{\text{mass+radiation}} + \Omega_k = 1.$$

$$\Omega_{m,0} = \frac{\rho_{m,0}}{\rho_{crit,0}}$$

$$\Omega_{k,0} = -\frac{c^2}{H_0^2 R_0^2} k$$



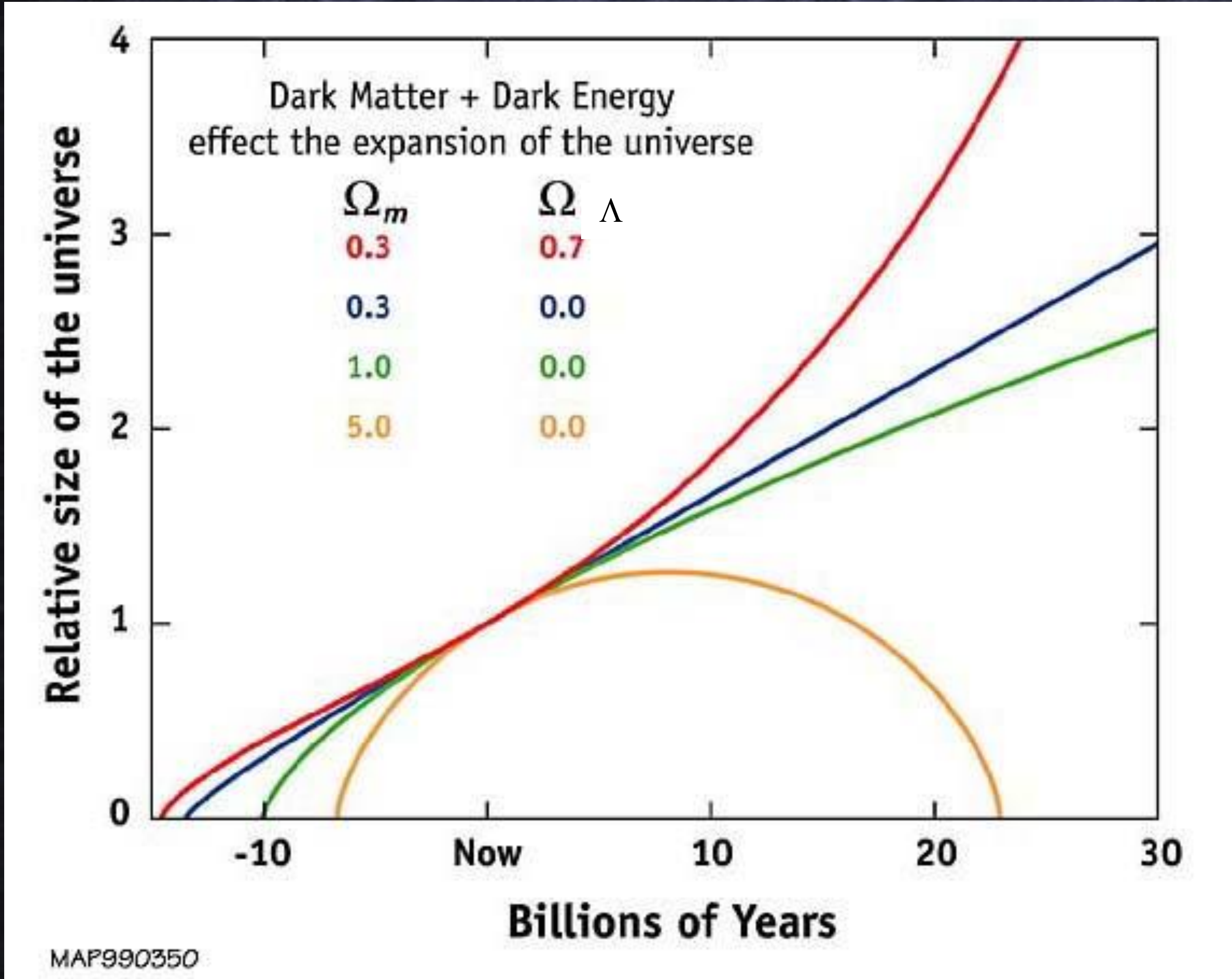


•Accelerated expansion in LFRW:

•Only if $\Lambda > 0$

•Decceleration parameter

$$q = -\frac{\ddot{R}R}{\dot{R}^2} = \frac{1}{2}\Omega_m(z) + \Omega_r(z) - \Omega_\Lambda(z)$$

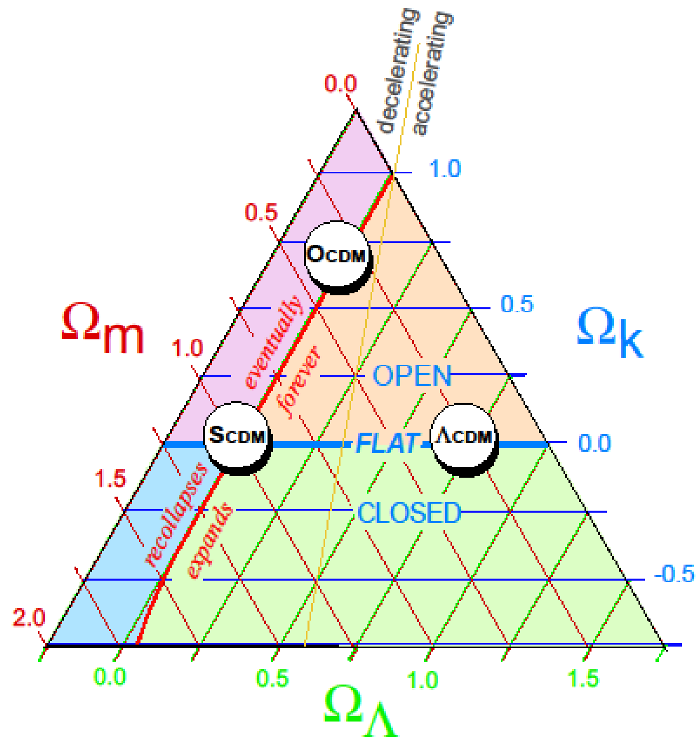


Which LFRW model best fit our Universe?

Observational determination of the cosmological parameters

THE COSMIC TRIANGLE

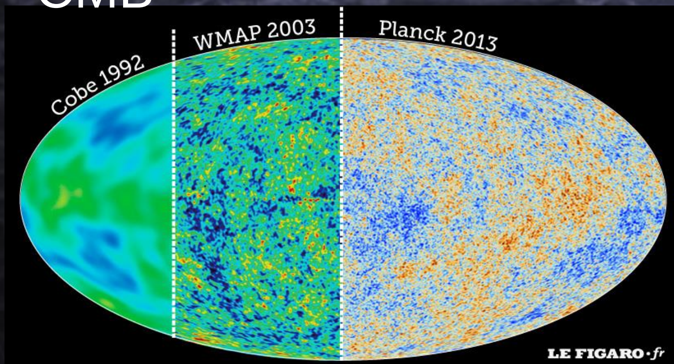
$$\frac{\dot{R}^2}{R^2} = \frac{8\pi G\rho}{3} + \frac{\Lambda}{3} - \frac{ck}{R^2}$$
$$\Downarrow$$
$$1 = \Omega_M + \Omega_\Lambda + \Omega_k$$

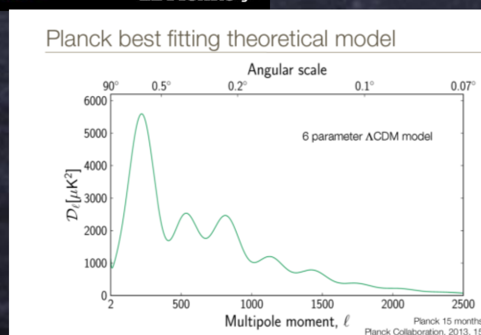


(From Bahcall et al 1999; astro-ph/9906463)

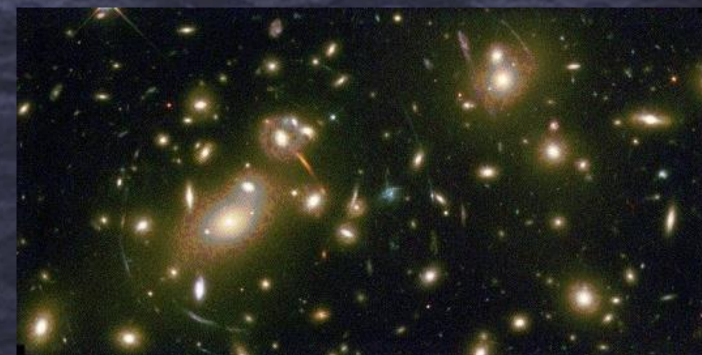
OBSEVATIONAL PROBES

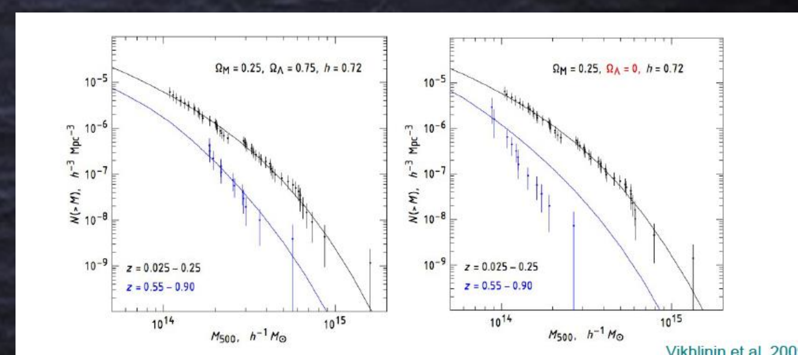
CMB



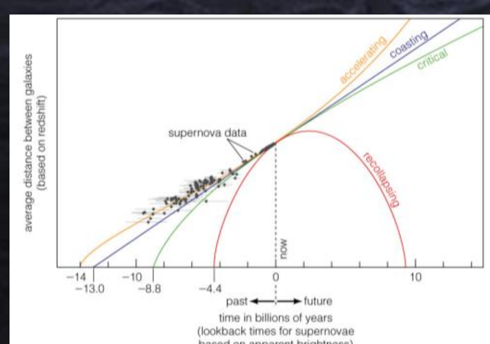


GALAXY CLUSTERS





SUPERNOVAS



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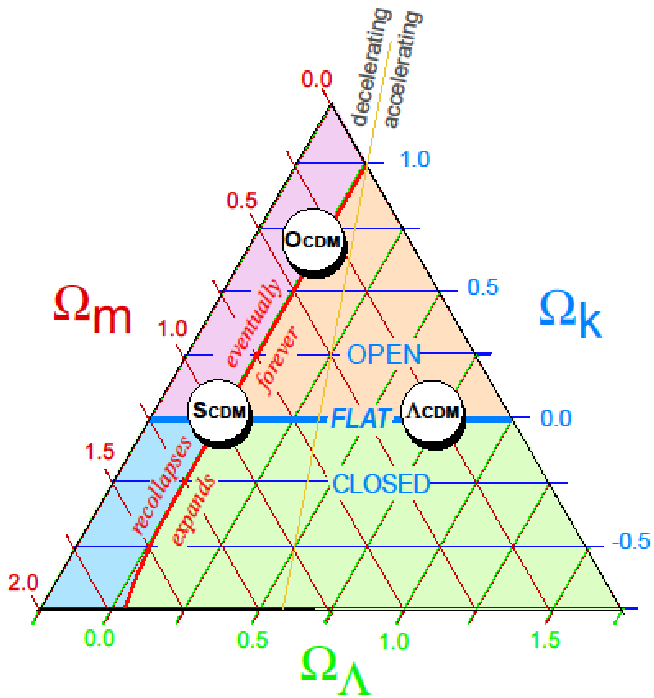
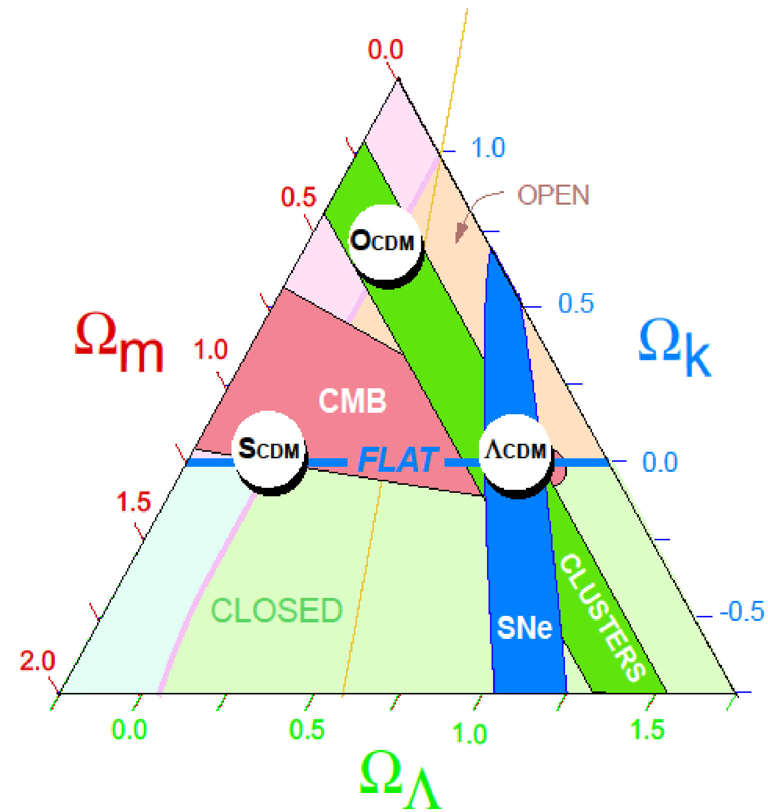
$$\Downarrow$$

$$1 = \Omega_M + \Omega_\Lambda + \Omega_k$$



(From Bahcall et al 1999; astro-ph/9906463)

OBSERVATIONAL CONSTRAINTS



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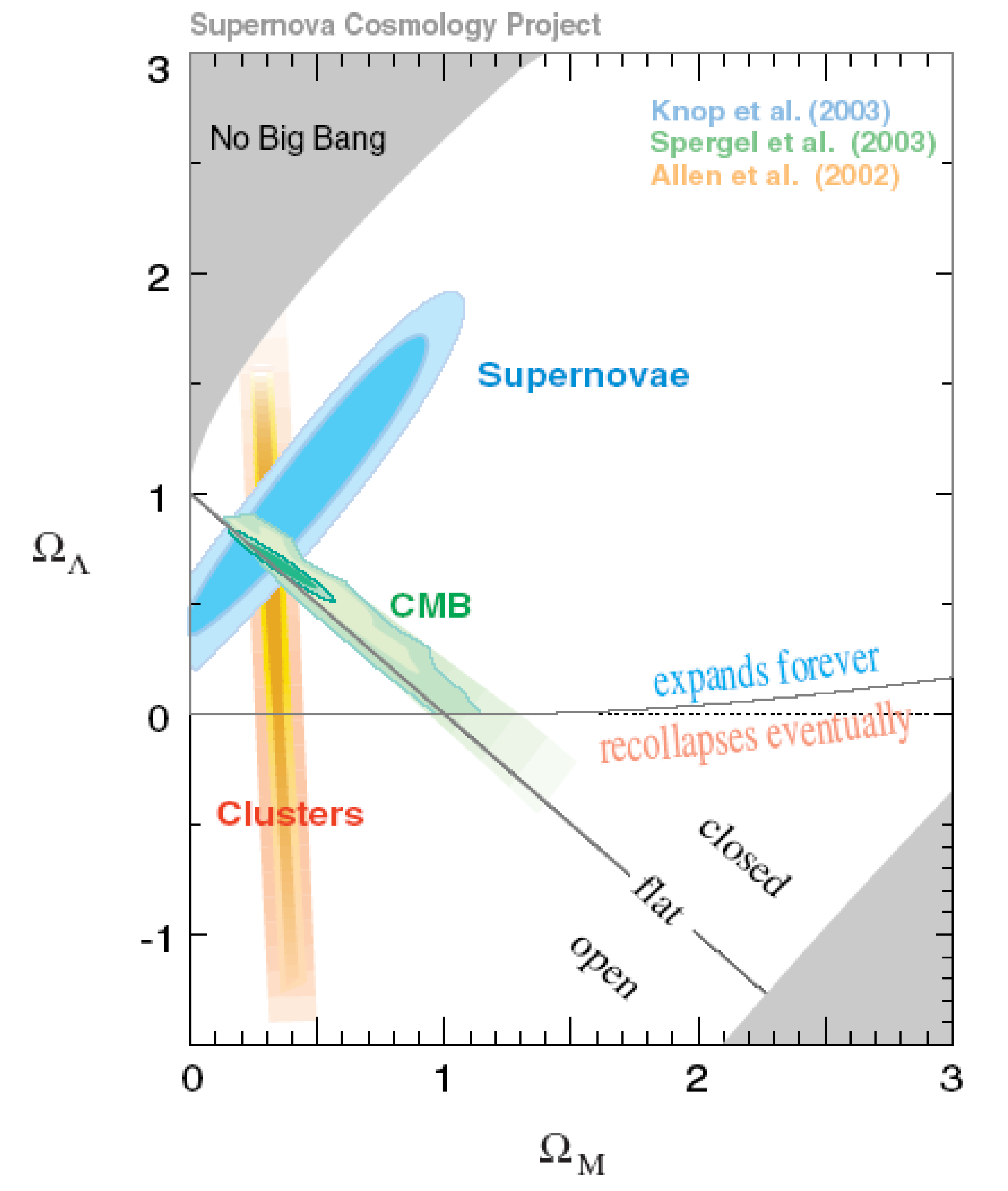
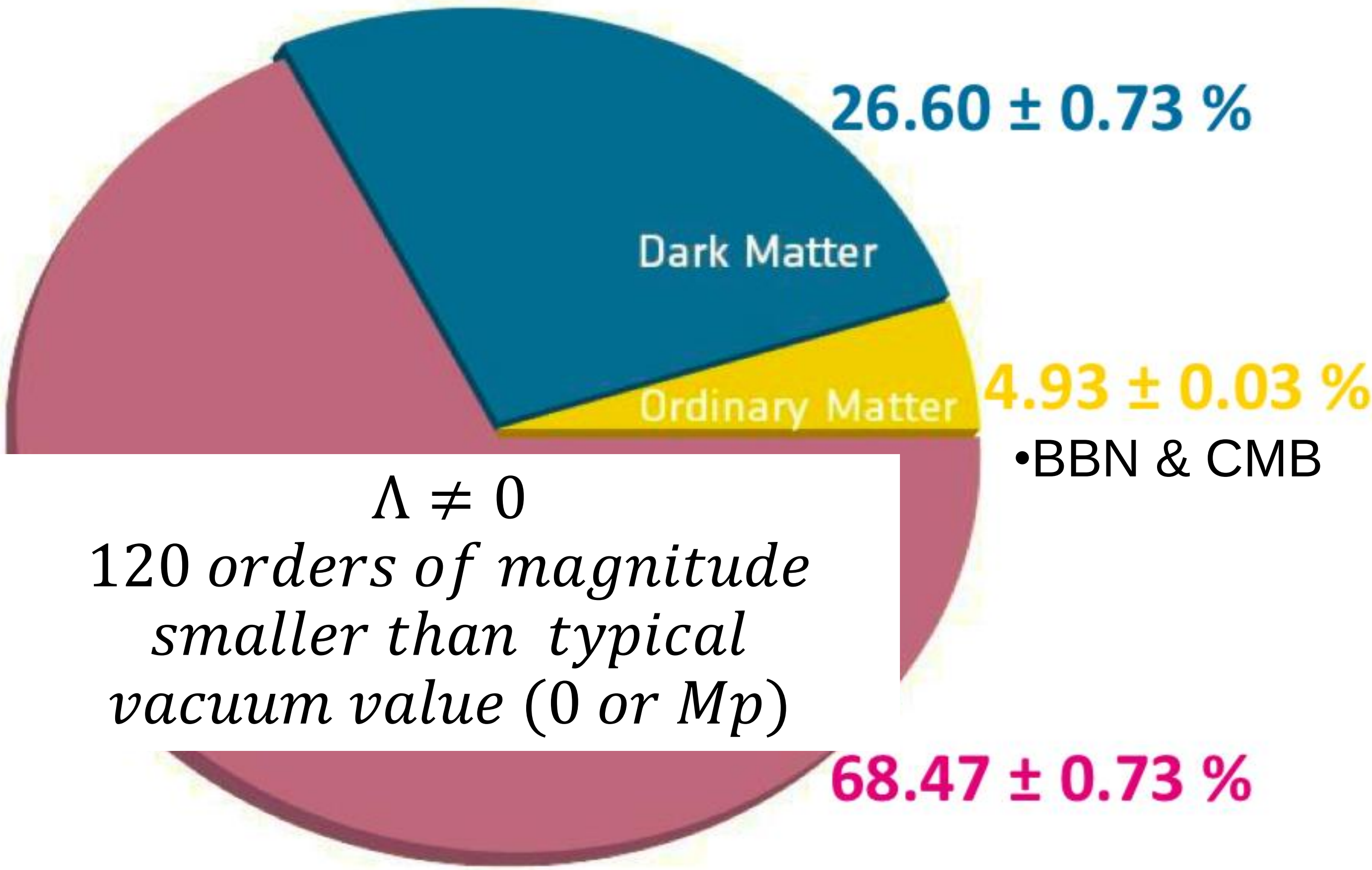

Supernova Cosmology Project
Knop et al. (2003)
Spergel et al. (2003)
Allen et al. (2002)
No Big Bang
Supernovae
CMB
Clusters
expands forever
recollapses eventually
closed
flat
open
3
2
1
0
-1
0
1
2
3
Ω_Λ
Ω_M

THE COSMIC PIE

PLANCK 2018



- BBN & CMB

$\Lambda \neq 0$

$120\ orders\ of\ magnitude\ smaller\ than\ typical\ vacuum\ value\ (0\ or\ Mp)$

FLAT UNIVERSE Ω_k=0

Alternative Cosmological Models

- Addition of exotic fields (scalar, vector) to the Einstein's equations (dark energy models parametrized by EOS $\omega = P/\rho$)
- Modified Gravity models: $S = -\frac{1}{2}\int d^4x\,\sqrt{-g}\,f(R)$
  - $f(R)=R$ in GR.
- Breaking the Cosmological principle: Univere not homogeneus. Underdense region (Bondi-Tolman models)

Alternative Cosmological Models

- Dark energy models:
  - *Quintessence*: adding an homogeneous scalar field $\phi(t)$ to the Einstein-Hilbert action describing gravity.
    - Contribution to the LFRW equation with an additional fluid with a negative EoS ($P_{\phi} = \omega c^2 \rho_{\phi}$) with $\omega<0$.
    - Contrary to Λ, ω can change with cosmic time.
    - Fine tuning: so w~ -1 at z=0 (supported by observations $\Lambda>0$; $P_{\Lambda}=-\rho_{\Lambda}$)

Dark energy models

- How can dark energy fluid be distinguished from Cosmological constant?
  - Measure the expansion rate H(z) or Ω(z) at different epochs with enough accuracy to constrain the EoS of dark energy field ($\omega > -1$).
  - Time variation of fundamental constants G., α
  - Apparent violation of the Equivalence Principle ($M_g = M_i$)

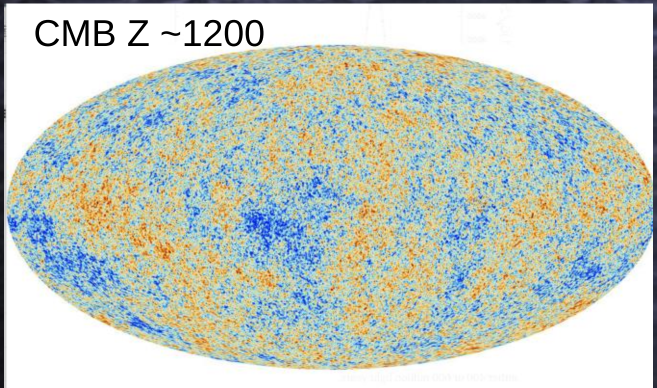
Dark energy models

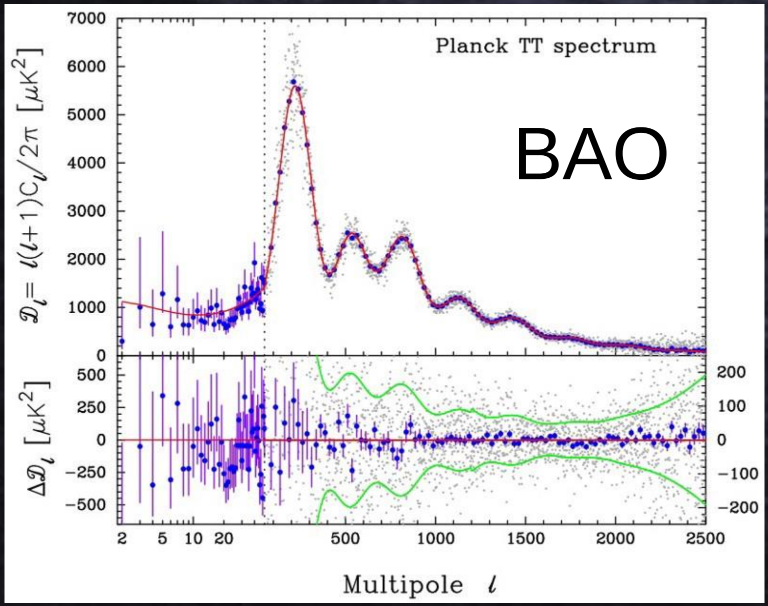
- How can dark energy quintessence be distinguished from Cosmological constant?
  - Measure the expansion rate H(z) or Ω(z) at different epochs with enough accuracy to constrain the EoS ($P= \omega \rho$) of the dark energy field ($\omega > -1$).

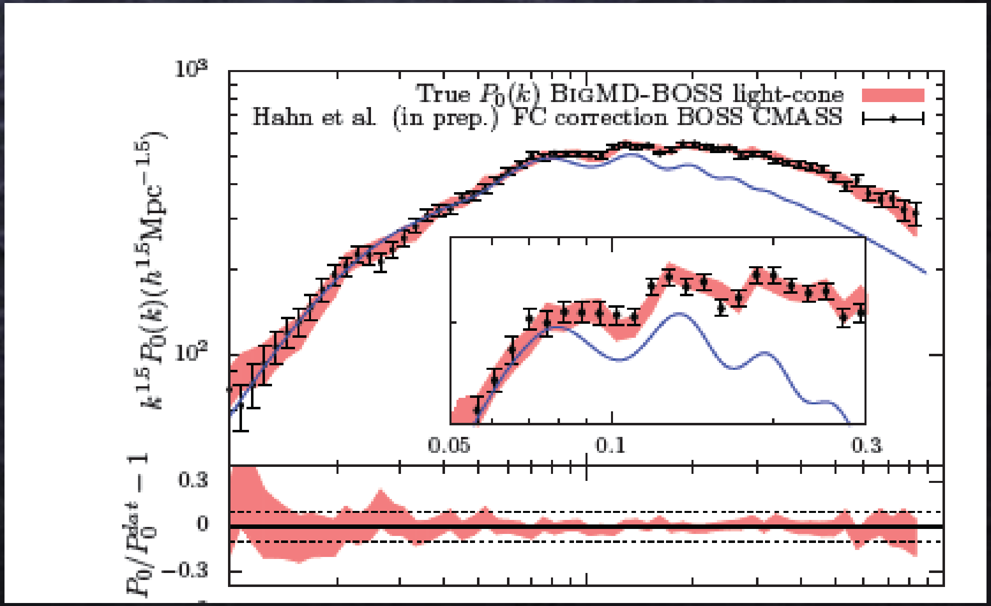
    Using a standard ruler (e.g. **Baryonic Accoustic Oscillation (BAO)** feature of the power spectrum of galaxy clustering from large redshift surveys BOSS, DESI, Euclid…)

    Or redshift space distortions due to peculiar velocities.

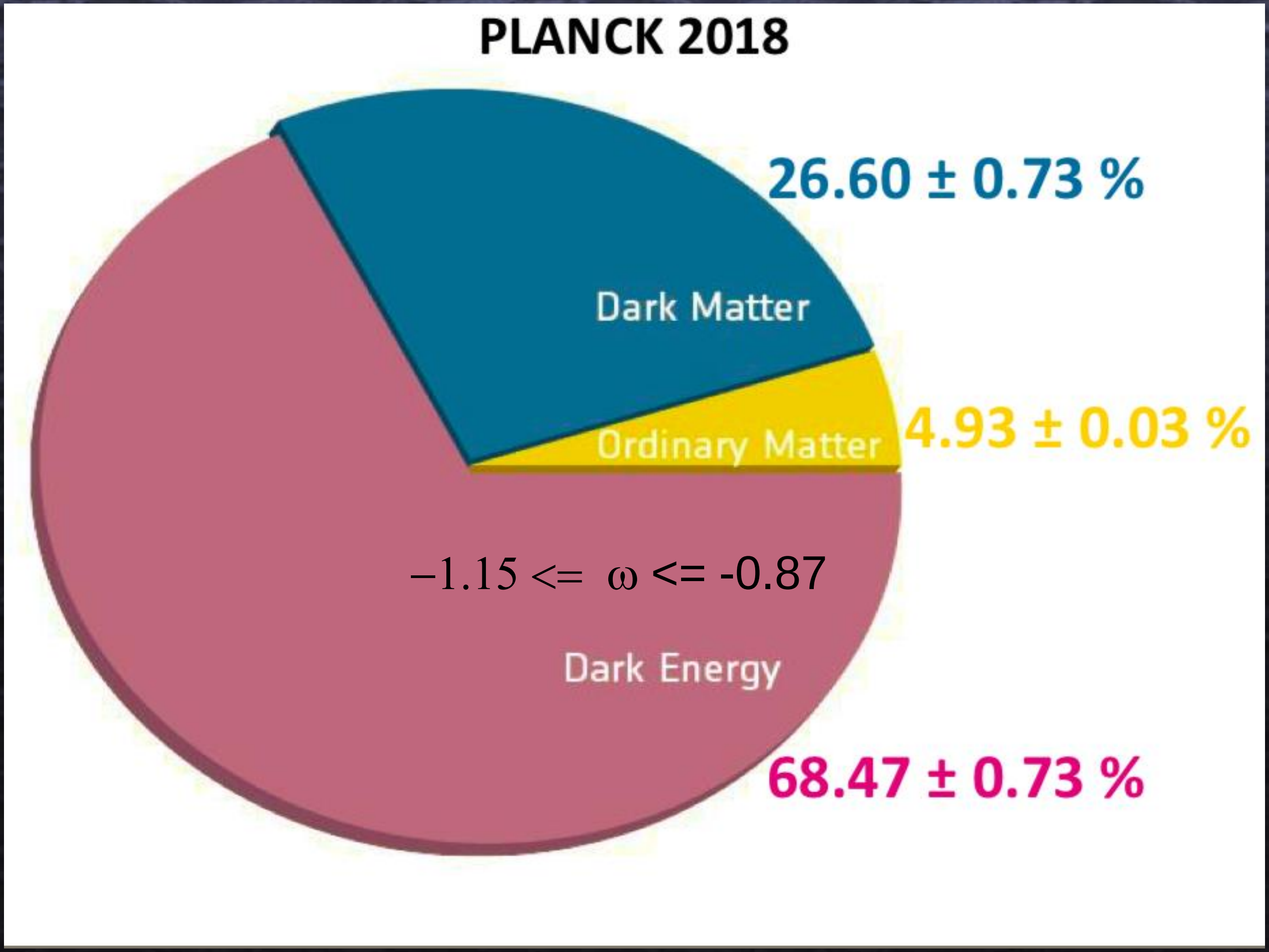
Dark energy models







THE COSMIC PIE



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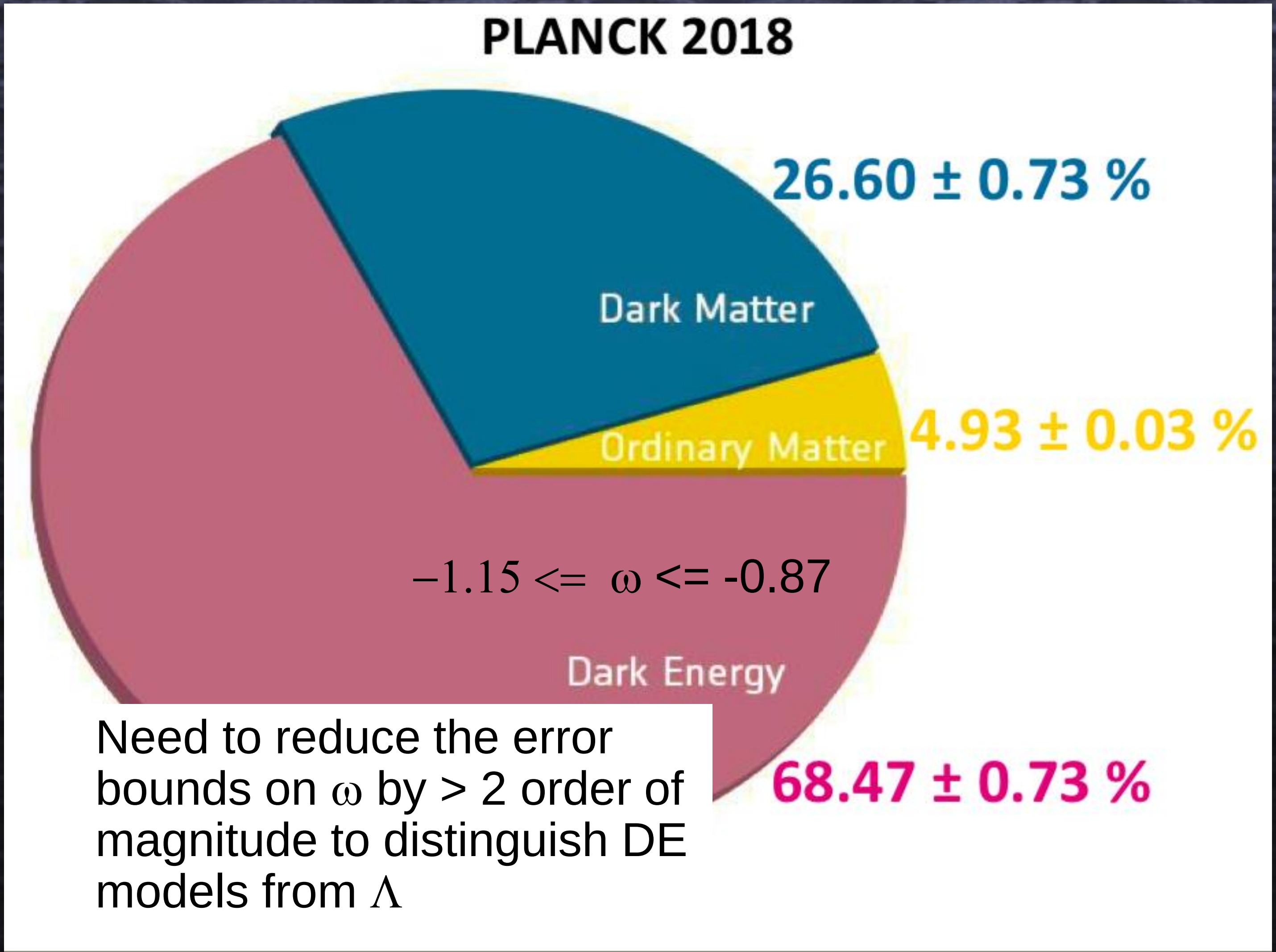


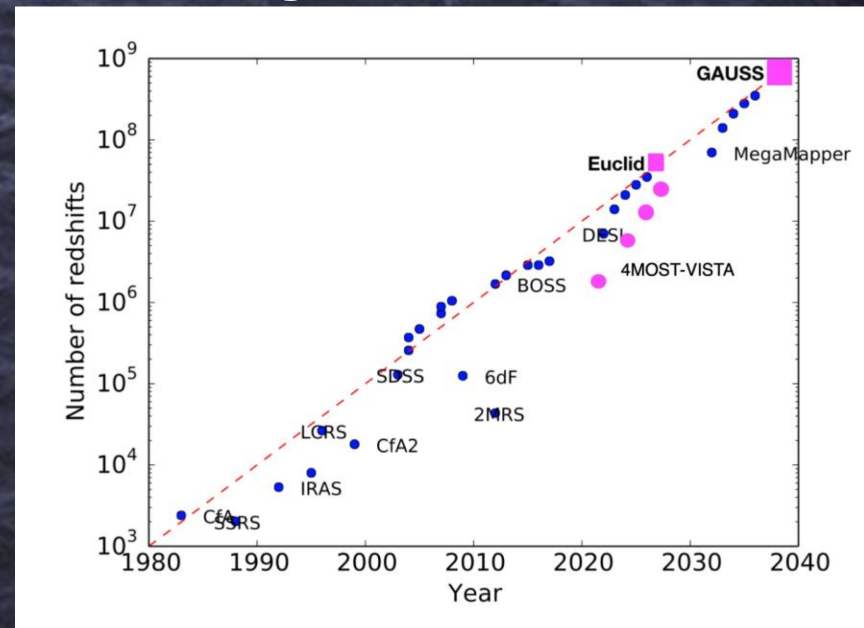
$-1.15 <= \omega <= -0.87$

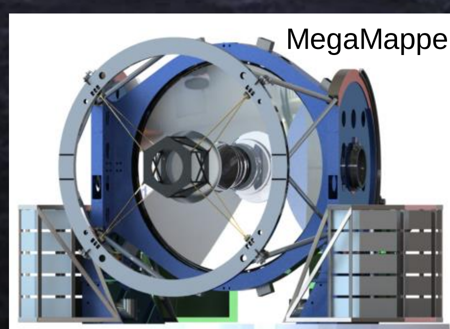
Need to reduce the error bounds on ω by > 2 order of magnitude to distinguish DE models from Λ

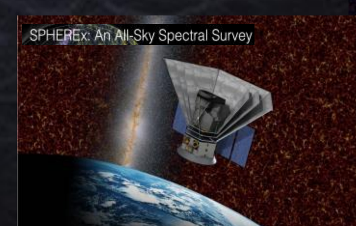
Future optical/IR Galaxy Redshift Surveys

The mapping of the galaxy distribution will dramatically increase in the next years

It will allow us to determine the value of the cosmological parameters, including the EoS of dark energy with < **1% accuracy**



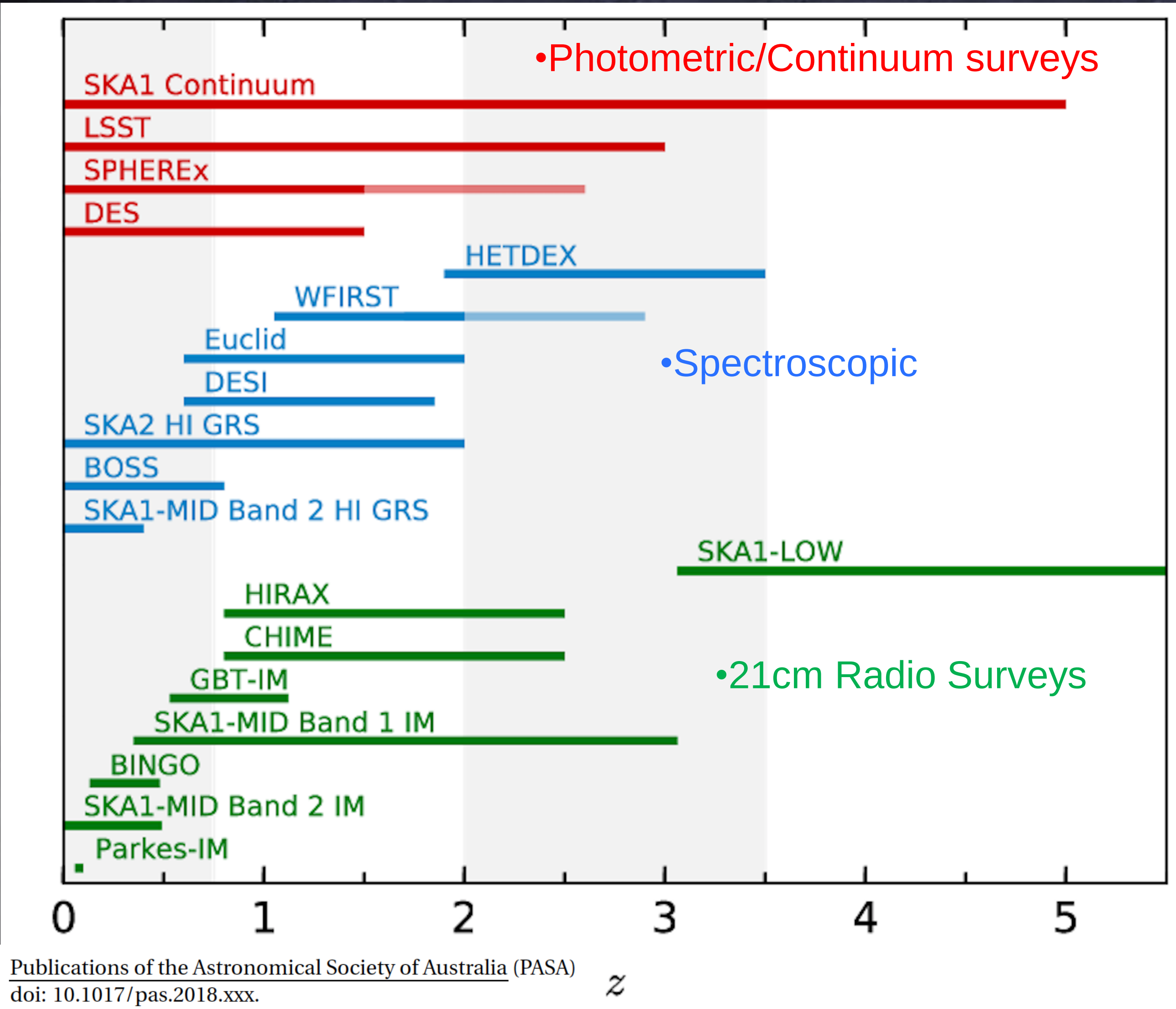




Euclid consortium

GAUSS

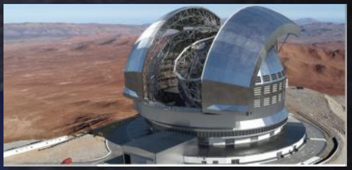
Redshift coverage of Galaxy surveys



Publications of the Astronomical Society of Australia (PASA)
doi: 10.1017/pas.2018.xxx.

SKAO and next generation of 30m telescopes ELT, TMT +

JWST, and WFIRST space telescopes will also probe the galaxies and gas distributions during the EOR (**6 < z <10**)



Observational cosmology as a driver of technological developments

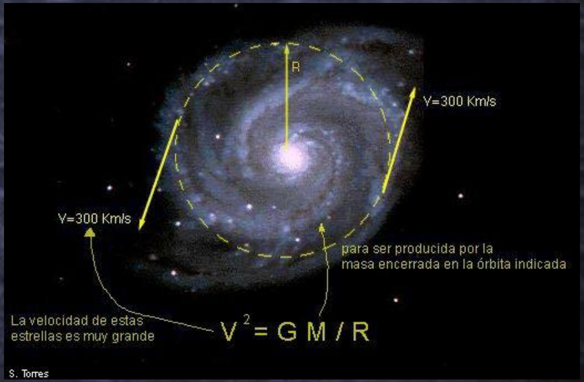
- The quest for measuring the EoS of dark energy through the study of the galaxy distribution in space and time has triggered a huge observational effort that will continue in the coming decades.
- This will provide us with Hexa Bytes of data that will have to be processed.
  - Just the SKA alone will need of hexaflop supercomputers.
- So, despite the very important physical interest in understanding the nature of dark energy, the technological information developments will benefit the society in many different ways.
  - Investing in basic research IS NOT a waste of money!

DARK MATTER

- Total matter in the Universe is of order 30% of the critical density. (Ω_m ~0.3)
- Visible matter (particles of the Standard Model) accounts for only 5% of critical density (Ω_b = 0.049)
- Multiple evidence of the existence of collisionless, non interacting, non baryonic matter, negligible thermal velocities ("cold").

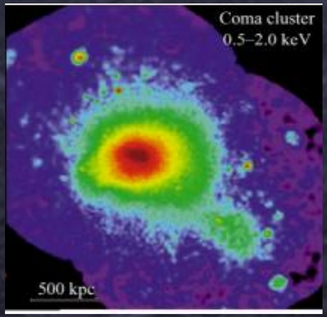
Evidences of Dark matter

- Rotation curves of spiral galaxies



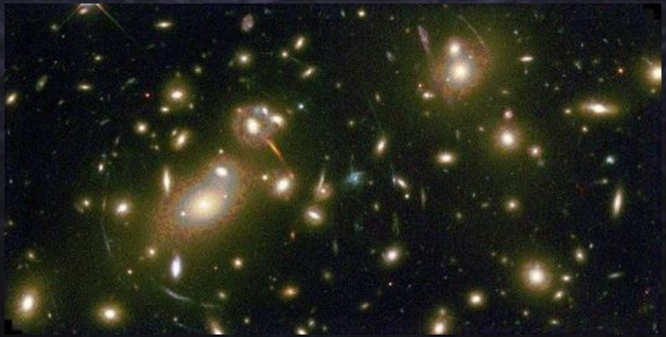
Velocity dispersion of stars in elliptical galaxies.

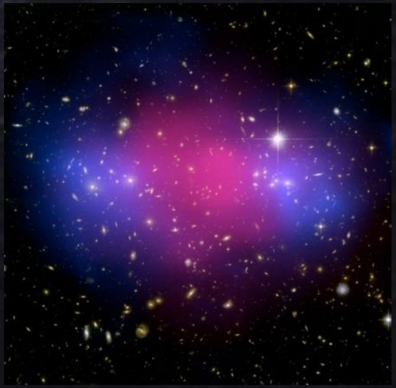
- X-ray and SZ signal in clusters



- Bullet Cluster

- Gravitational lensing in clusters and larger structures





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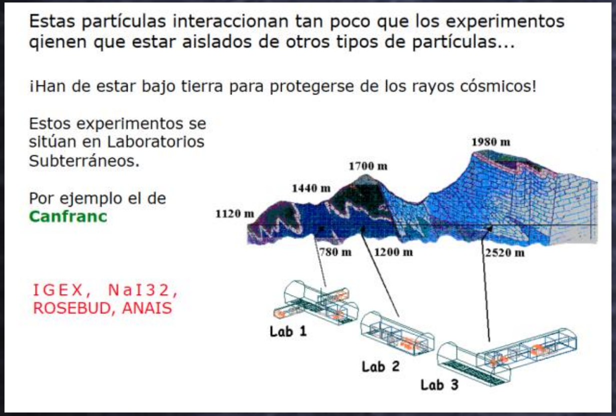
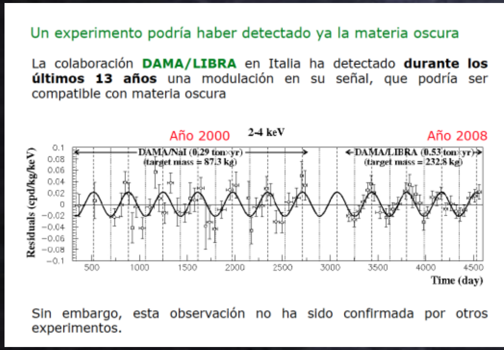
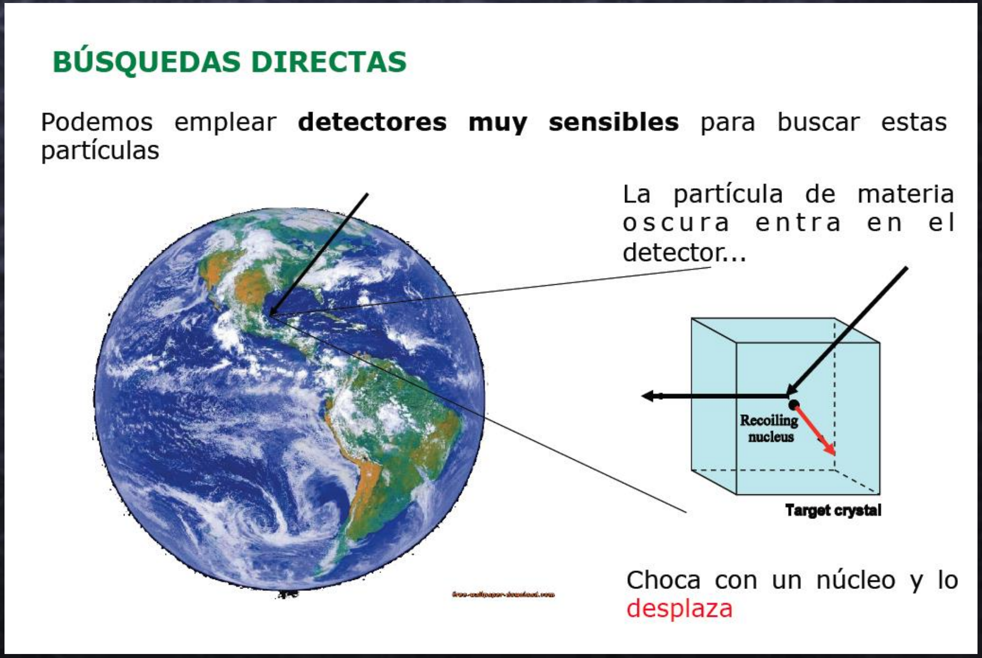
- Visible matter (particles of the Standard Model) accounts for only 5% of critical density (Ω_b = 0.049)
- Multiple evidence of the existence of collisionless, non interacting, non baryonic matter, negligible thermal velocities ("cold").
- Not any physical detection of the nature of the particles forming the DM fluid..

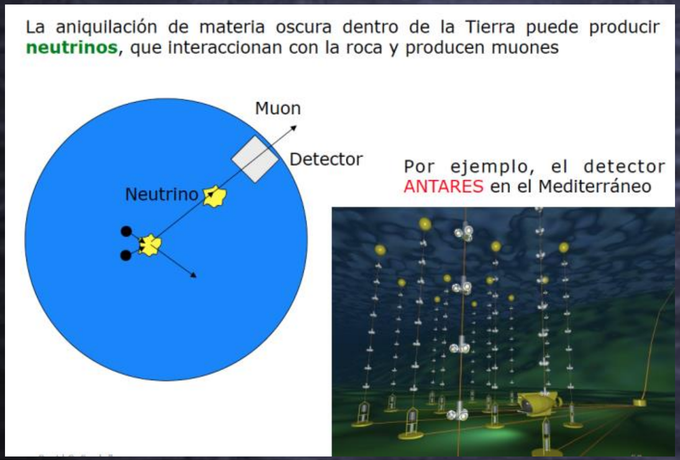
•DIRECT DARK MATTER DETECTION EXPERIMENTS

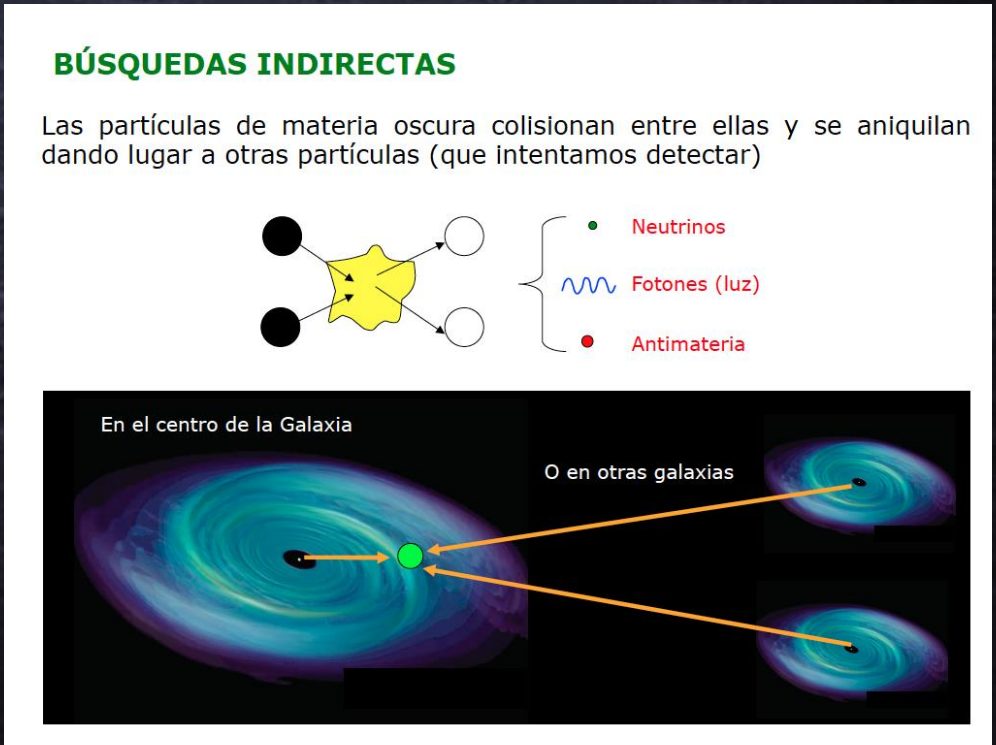






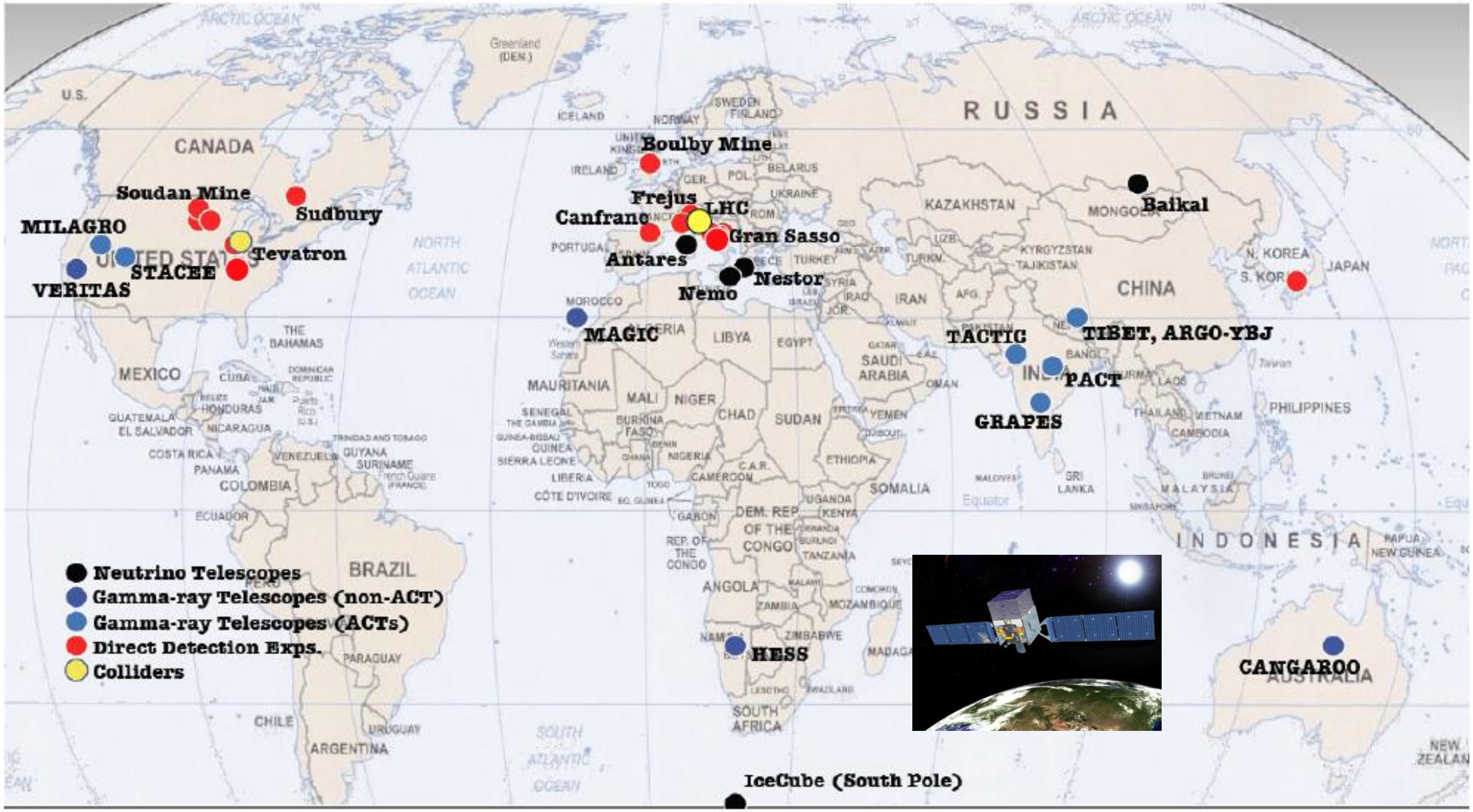
•INDIRECT DARK MATTER DETECTION EXPERIMENTS





•FERMI

Experimentos de materia oscura alrededor del mundo



DESPITE ALL EFFORTS WE STILL DO NOT KNOW THE NATURE OF THE DARK MATTER PARTICLES. WE ONLY HAVE ASTROPHYSICAL EVIDENCES UNDER THE ASSUMPTION THAT GRAVITY IS DESCRIBED BY GENERAL RELATIVITY (AND NEWTON'S THEORY AS THE SHORT SCALE APPROXIMATION OF GR).

NATURE OF THE DARK MATTER
Cold DM vs Warm DM

•Substructures in galaxies

And early formation of galaxies and QSO at high redshift put strong contrains on the nature of the DM particles.

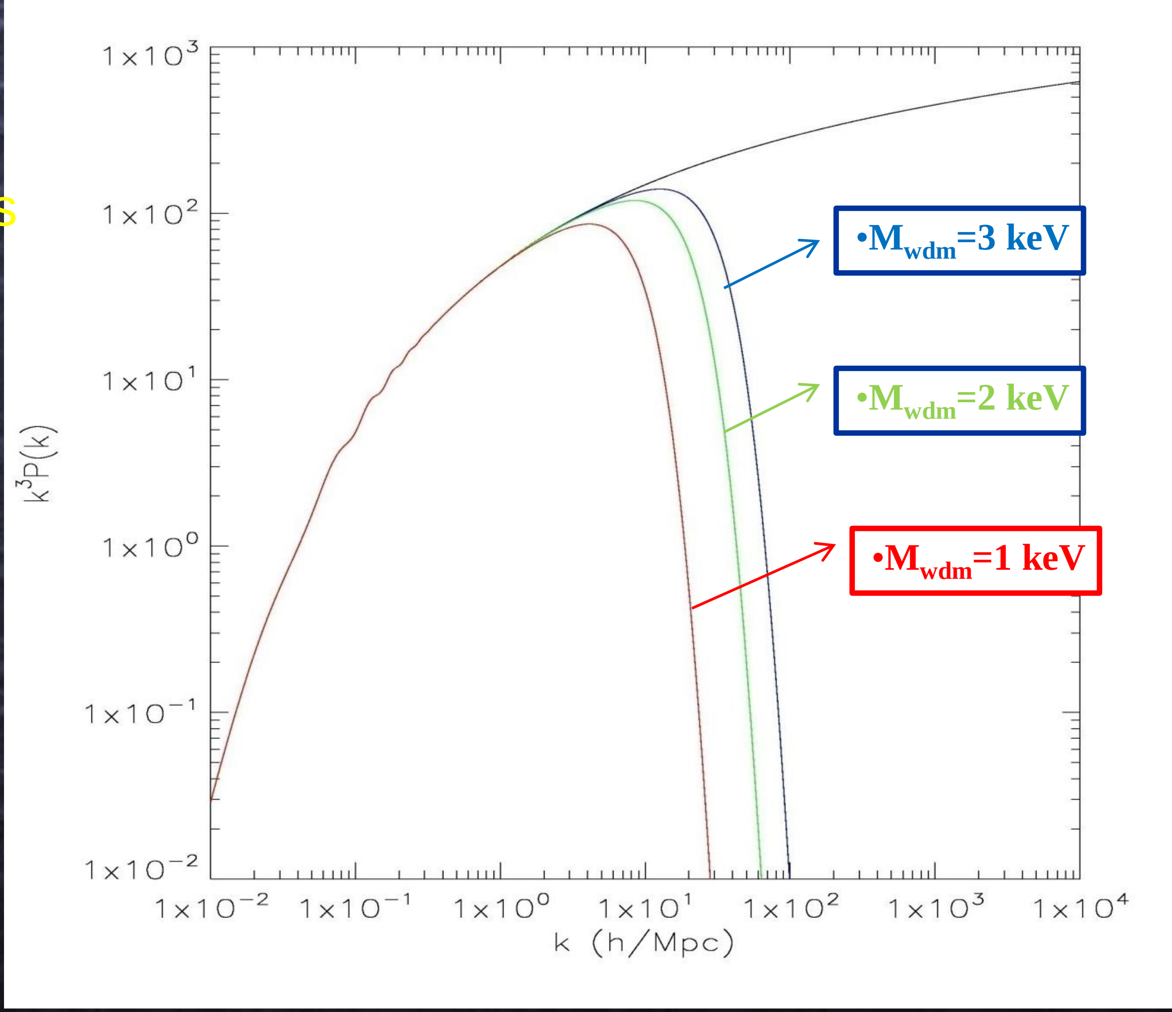
DM has to be **cold.** Negligible kinetic energy versus rest particle mass

For thermally produced particles (WIMPS or Sterile ν

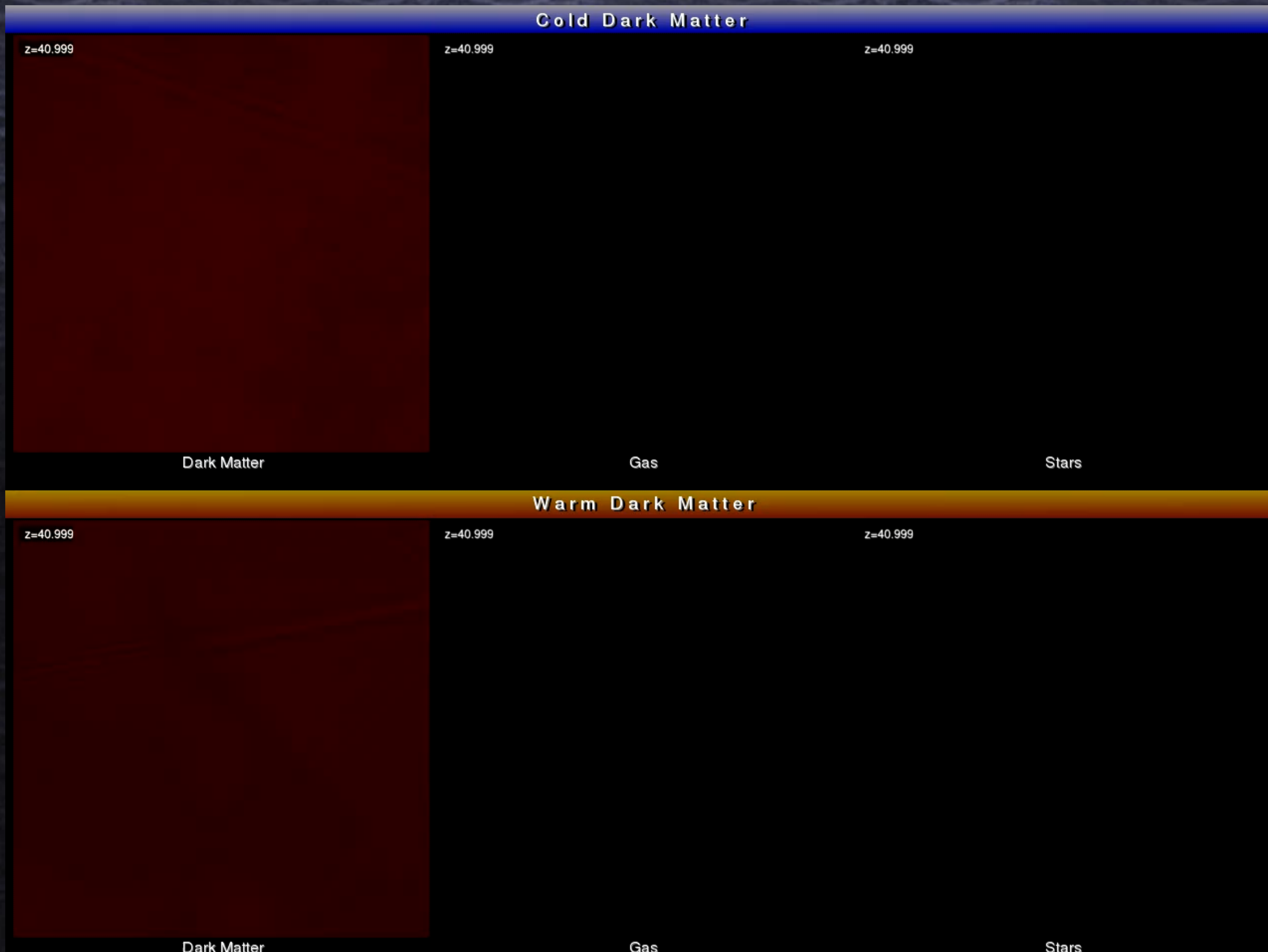
•M_{dm} >1 keV

•Other candidates:

•Primordial BH or Axions



THE MILKY WAY SEEN IN CDM vs WDM



From the Homogeneous to the in-homogeneous Universe

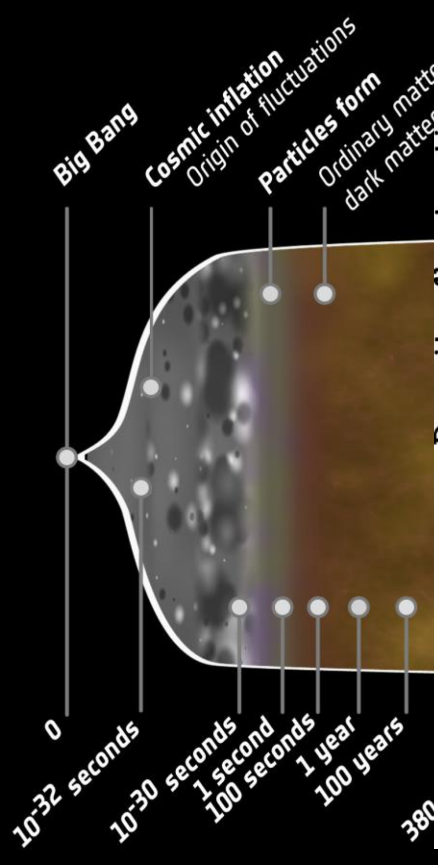
- LFRW models assume that the Universe is homogeneous, namely that $\rho(T)$ only.
- But most of the cosmological probes to determine the parameters of the cosmological models are based on observations of highly non-homogeneous and non-linear objects
  - Galaxies, galaxy clusters, and cosmic web of galaxies are biased objects objects with respect to the mean matter density field of the Universe.
- **Question:** *How can we make predictions from models about the non-homogeneous Universe?*

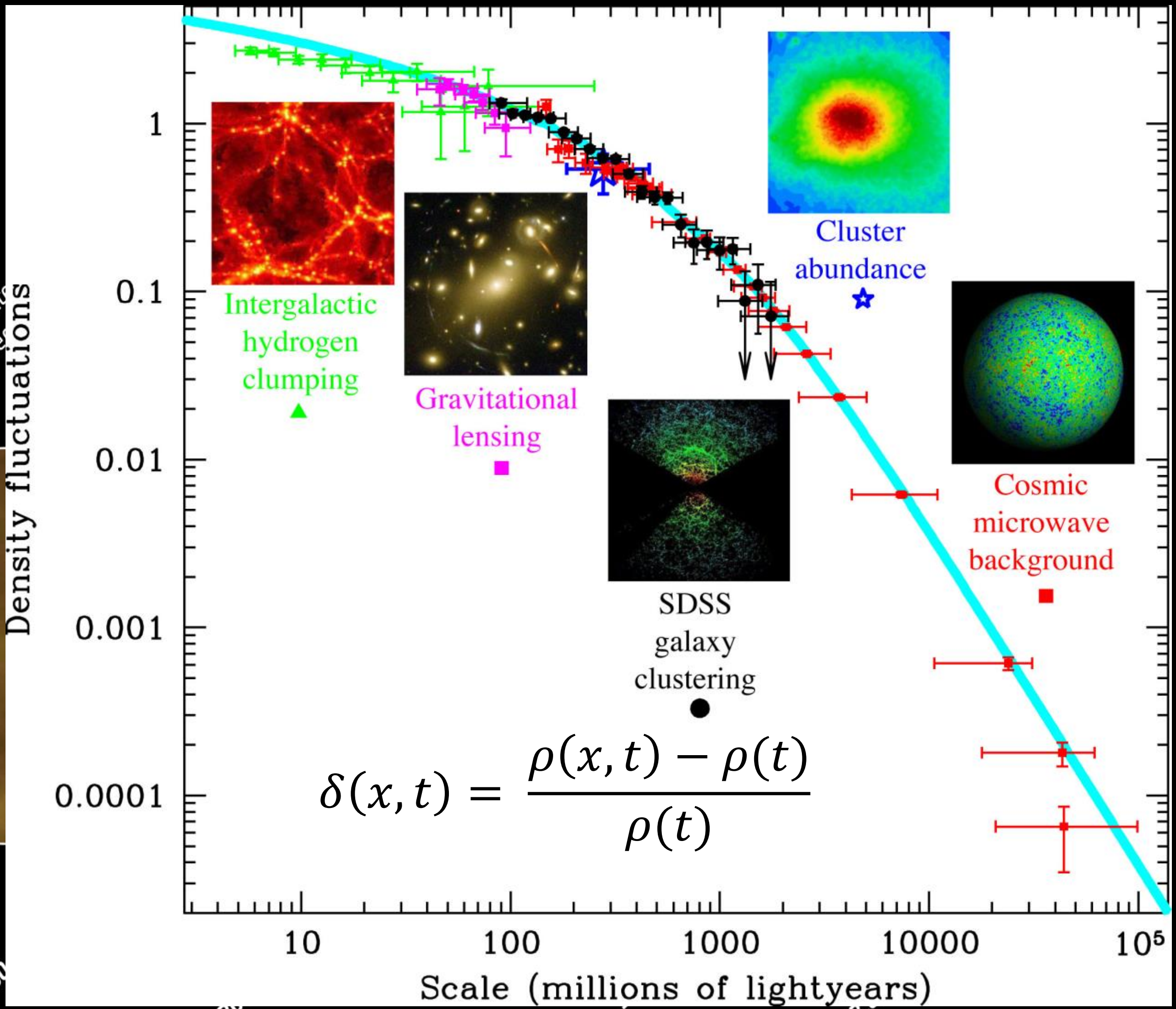
THE INHOMOGENEOUS UNIVERSE

Formation and evolution of structures in the matter distribution

The emergence of structure in the Universe

Structures in the matter distribution has grown across cosmic times:





•Credit: ESA

THE INHOMOGENEOUS UNIVERSE

- GOAL:
  - How can we explain quantitatively the observed "structure" (galaxies, galaxy clusters, superclusters, their abundance and spatial distribution, and the Lyman-α forest) as arising from small fluctuations in the nearly homogeneous early universe?
  - How can we make theoretical predictions from cosmological models   to be contrasted against observations of the large scale structure in the Universe?

THE INHOMOGENEOUS UNIVERSE

- The driving mechanism of structure formation:
  - *Gravitational growth of density fluctuations generated after the inflationary epoch*:
  - Density fluctuation $$\delta(r,t) = \frac{\rho(r,t) - \rho(t)}{\rho(t)}$$
  - $\rho(t)$ is the background density that enters in the LFRW models.
  - As any other physical process with a stochastic random field, we can use perturbation theory to linearize the equations of motion and simplify the problem.
    - Linear theory predictions valid when $\delta(r,t) \ll 1$

LINEAR THEORY OF DENSITY FLUCTUATIONS

- Based on the previous works of Jeans Theory (1910) of density fluctuations of a self-gravitating gas cloud.
- Extended to a FRW universe model by Lifshitz (1946).
- For scales smaller than the Horizon, RG can be approximated by Newton's theory (action at a distance)
- For scales larger than Horizon, perturbation theory in GR (pertubations in the metric)

Follow Jeans theory:

We start with the continuity equation and neglect radiation and any pressure forces for now:

$$\left(\frac{\partial\rho}{\partial t}\right)_p + \vec{\nabla}_p\left(\rho\,\vec{v}_p\right) = 0$$

and the equation of motion:

$$\left(\frac{\partial\vec{v}}{\partial t}\right)_p + \left(\vec{v}_p \cdot \vec{\nabla}_p\right)\vec{v}_p = -\frac{\vec{\nabla}_p P}{\rho} - \vec{\nabla}_p\Phi$$

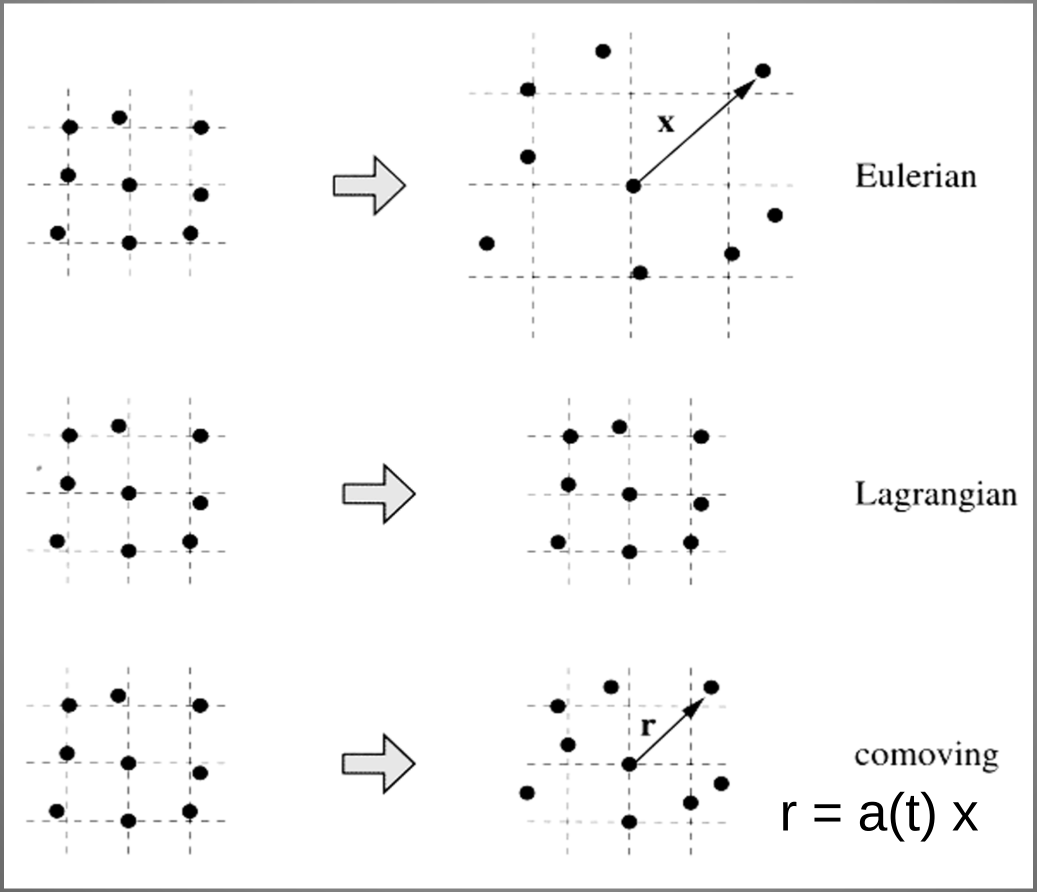
∇_p is the derivative with respect to the proper (not co-moving) coordinate.

- In addition, we have Poisson's Equation:

$$\nabla_p^2\Phi = 4\pi G\rho$$

•...But there is a significant difference with respect to Jeans. In an expanding universer, spatial coordinates depend on time through the a(t) scale factor given by the LFRW equations...

- At this point, we have the choice of a co-ordinate system that simplifies the analysis.



LINEAR THEORY OF DENSITY FLUCTUATIONS

- After applying change of variables to comoving coordinates and simplifying 2nd order terms we arrive to the master equation that describe the evolution of a density perturbation δ(x,t) in Newtonian linear theory

$$\frac{\partial^2 \delta}{\partial t^2} + 2\frac{\dot{a}}{a}\frac{\partial \delta}{\partial t} = 4\pi G\bar{\rho}\delta + \frac{c_s^2}{a^2}\nabla^2\delta + \frac{2}{3}\frac{\bar{T}}{a^2}\nabla^2 S$$

Fourier Transform

"Master equation"

$$\frac{d^2\delta_{\vec{k}}}{dt^2} + 2\frac{\dot{a}}{a}\frac{d\delta_{\vec{k}}}{dt} = \left[4\pi G\bar{\rho} - \frac{k^2 c_s^2}{a^2}\right]\delta_{\vec{k}} - \frac{2}{3}\frac{\bar{T}}{a^2}k^2 S_{\vec{k}}$$

LINEAR THEORY OF DENSITY FLUCTUATIONS

$$\frac{\partial^2 \delta}{\partial t^2} + 2\frac{\dot{a}}{a}\frac{\partial \delta}{\partial t} = 4\pi G\bar{\rho}\delta + \frac{c_{\rm s}^2}{a^2}\nabla^2\delta + \frac{2}{3}\frac{\bar{T}}{a^2}\nabla^2 S$$

Fourier Transform

"Master equation"

$$\frac{{\rm d}^2\delta_{\vec{k}}}{{\rm d}t^2} + 2\frac{\dot{a}}{a}\frac{{\rm d}\delta_{\vec{k}}}{{\rm d}t} = \left[4\pi G\bar{\rho} - \frac{k^2 c_{\rm s}^2}{a^2}\right]\delta_{\vec{k}} - \frac{2}{3}\frac{\bar{T}}{a^2}k^2 S_{\vec{k}}$$

- Complemented with the equation of state of the matter (eg. Ideal gas or relativistic matter, or collisionless matter ($P=c_s=0$)

ideal gas $P = \frac{k_{\rm B}T}{\mu m_{\rm p}}\rho$ $\varepsilon = \frac{1}{\gamma - 1}\frac{k_{\rm B}T}{\mu m_{\rm p}}$

sound speed $c_{\rm s} = (\partial P/\partial\rho)_S^{1/2}$

•The Baryonic Universe

The Jeans Mass

Prior to recombination: photon-baryon fluid $c_s = \frac{c}{\sqrt{3}}\left[\frac{3}{4}\frac{\rho_b(t)}{\rho_r(t)} + 1\right]^{-1/2}$

$$\left.\begin{matrix}\rho_b \propto a^{-3} \\ \rho_r \propto a^{-4}\end{matrix}\right\} \Longleftrightarrow \left\{\begin{matrix} t < t_{eq} \Rightarrow c_s = c/\sqrt{3} \propto a^0 \\ t > t_{eq} \Rightarrow c_s \propto a^{-1/2}\end{matrix}\right.$$

After recombination: baryon fluid is `ideal gas' $c_s = (\partial P/\partial \rho)^{1/2} \propto T^{1/2}$

$$T \propto a^{-2} \Rightarrow c_s \propto a^{-1}$$

Using Jeans length, we can also define Jeans mass: $M_J = \frac{4\pi}{3}\bar{\rho}\left(\frac{\lambda_J}{2}\right)^3 = \frac{\pi}{6}\bar{\rho}\,\lambda_J^3$

- Immediately after recombination, $M_J = 1.5 \times 10^5 (\Omega_{b,0} h^2)^{-1/2} M_\odot$ while at matter-radiation equality, $M_J = 1.5 \times 10^{16} (\Omega_{b,0} h^2)^{-2} M_\odot$
- At recombination, photons decouple from baryons,which dramatically reduces the pressure, causing a huge drop in the Jeans mass...

Non linear gravitational evolution

- Structure formation in the Universe can be studied using Linear Perturbation theory when $\delta\rho \ll 1$.
- Lagrangian Perturbation Theory (1LPT, 2LPT) can be used to study the quasi-linear regime $\delta\rho \gtrsim 1$)
- But for the strong non-linear regimen when $\delta\rho \gg 1$, there is no analytical approximations for the gravitational evolution of density perturbations…

Non linear gravitational evolution

- Therefore…
- One has to resort to numerically integrate the equations governing the dynamical evolution of self gravitating systems.
- Since they are made of a large number elements (stars, or dark matter particles) one can treat them as statistical mechanical systems that are described by a **distribution function in phase space.**

Basic Equations

The Boltzmann equation is then

$$\frac{\partial f}{\partial t} + \nabla_x f \cdot \nabla_p H_{sm} - \nabla_p f \cdot \nabla_x H_{sm} = \left(\frac{\delta f}{\delta t}\right)_c$$

or, for $H_{sm} = \frac{p^2}{2\mathrm{m}} + \Phi(\boldsymbol{x})$

$$\frac{\partial f}{\partial t} + \frac{\boldsymbol{p}}{m} \cdot \nabla_x f - \nabla_x \Phi \cdot \nabla_p f = \left(\frac{\delta f}{\delta t}\right)_c$$

For self-gravity as a potential source we have

$$\nabla^2 \phi = 4\pi G \rho$$

where ρ = space density.

$$\rho(\mathbf{x}) = \int f(\mathbf{x}, \mathbf{p}) d^3 p$$

The Vlasov-Poisson Equation

- For pure collisionless gravitational systems

$$\left.\frac{\delta f}{\delta t}\right|_c = 0$$

..and the equation to integrate is the integro-differential Vlasov-Poisson equations:

$$\frac{\partial f}{\partial t} + \frac{\mathbf{p}}{m} \cdot \nabla_x f - \nabla_x \phi \cdot \nabla_p f = 0$$

$$\nabla^2 \phi = 4\pi G \int f(x,p,t) d^3 p$$

The N-body method

- How can we solve de collisionless Bolzmann (Vlasov) equation?.
- **Method of the characteristics**: f(x,p,t) is constant along the characteristics.
- Discretize the f(x,p,t) in N phase space volume elements (pseudo particles).
- For systems where f(x,p,t) only depens on positions, the N tracers of the distribution function can be just subvolumes of 3D space variables such $\sum_{i=1}^{N} m_i = \int_V \rho(x) d^3x$

The N-body method

- If f(x,p) has a dependence on momentum, (eg. Neutrinos, or other relativistic particles following Fermi-Dirac statistics, there must be a sampling of the velocity distribution for each subvolume of the space variables.
- The equations of the characteristics of each of these pseudo-particles representing one phase space element will be just the equations of motion of N bodies subject to their mutual gravity forces.

The N-body method in Cosmology

For cosmological problems, space coordinates depend on time through the Friedman equations.

Therefore, it is better to work in comoving coordinates: **r** = a(t) **x**; $\mathbf{u} = \dot{\mathbf{r}} = \dot{a}\mathbf{x} + a\dot{\mathbf{x}} = H(t)\mathbf{r} + \mathbf{v}$

In addition, we also transform t -> a(t)

$$\frac{d\mathbf{x}}{da} = \frac{\mathbf{p}}{a^3 H}, \quad \frac{d\mathbf{p}}{da} = -\frac{\nabla\phi}{aH}, \quad \mathbf{p} \equiv \mathbf{a}^2\dot{\mathbf{x}}$$

$$\nabla^2\phi = \frac{3}{2}\frac{H_0^2\Omega_0\delta_{\rm dm}}{a}, \qquad \Phi(\mathbf{x}) = -G\sum_{j=1}^{N}\frac{m_j}{[(\mathbf{x}-\mathbf{x}_j)^2+\epsilon^2]^{1/2}}$$

$$H^2 = H_0^2\left(\frac{\Omega_0}{a^3} + \Omega_{\Lambda,0}\right), \quad \Omega_0 + \Omega_{\Lambda,0} = 1.$$

Numerical Methods

- PARTICLE-BASED
  - Particle-particle
  - Tree codes
- GRID-BASED
  - Particle-Mesh
  - ART (Adaptive Refinement Mesh tree)
- HYBRID
  - Particle-Particle-Particle-Mesh (P3M)
  - Tree + PM

Moore's Law for Cosmological N-body Simulations

Moore`s Law:

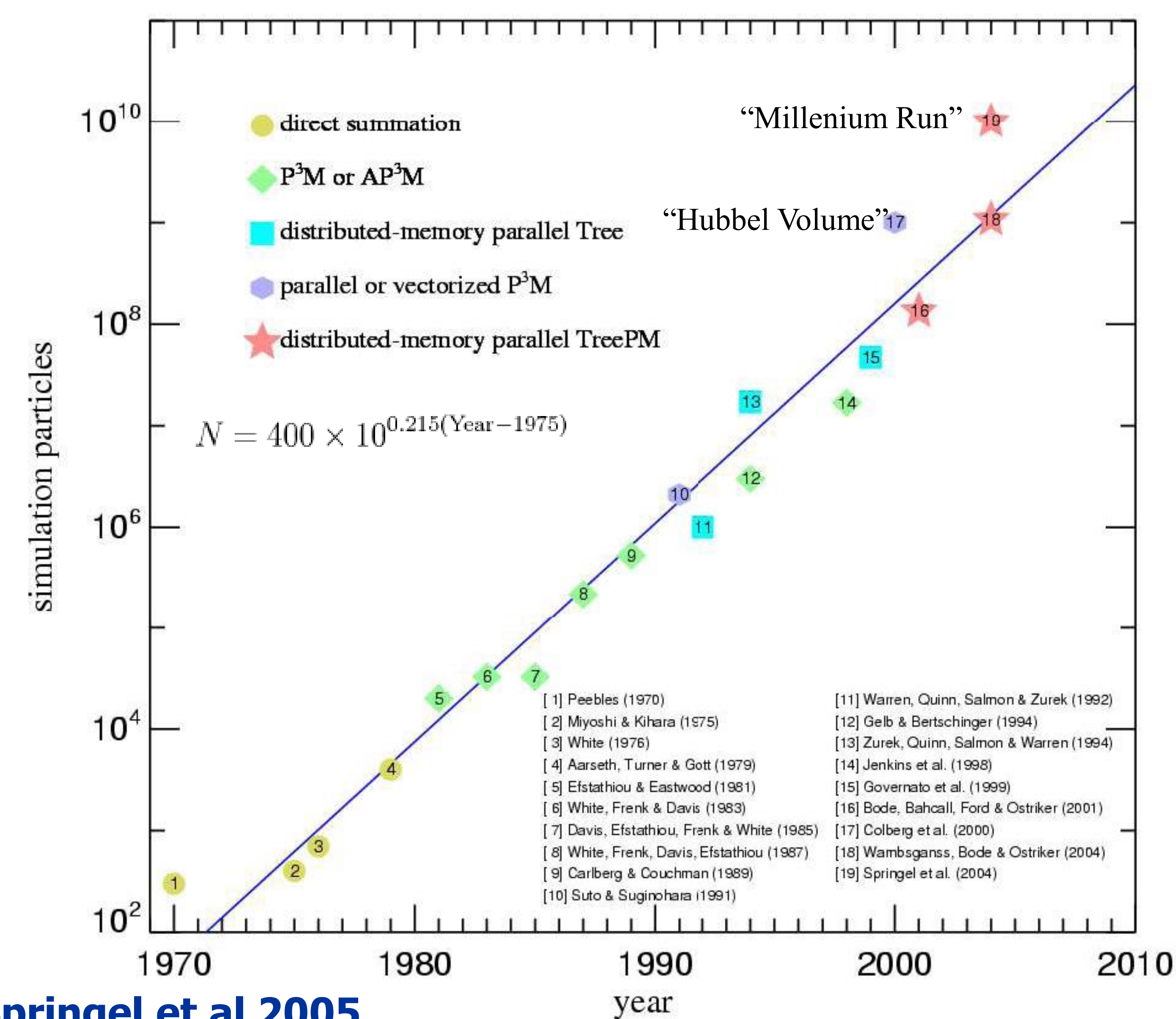
Capacity of processors double every 18 months

N.Body simulations double the number of particles every 16.4 months

Extrapolating:

10^{10} partículas in 2008

...but it was done in 2004



Springel et al 2005

Moore's Law for Cosmological N-body Simulations

Moore`s Law:

Capacity of processors double every 18 months

N.Body simulations double the number of particles every 16.4 months

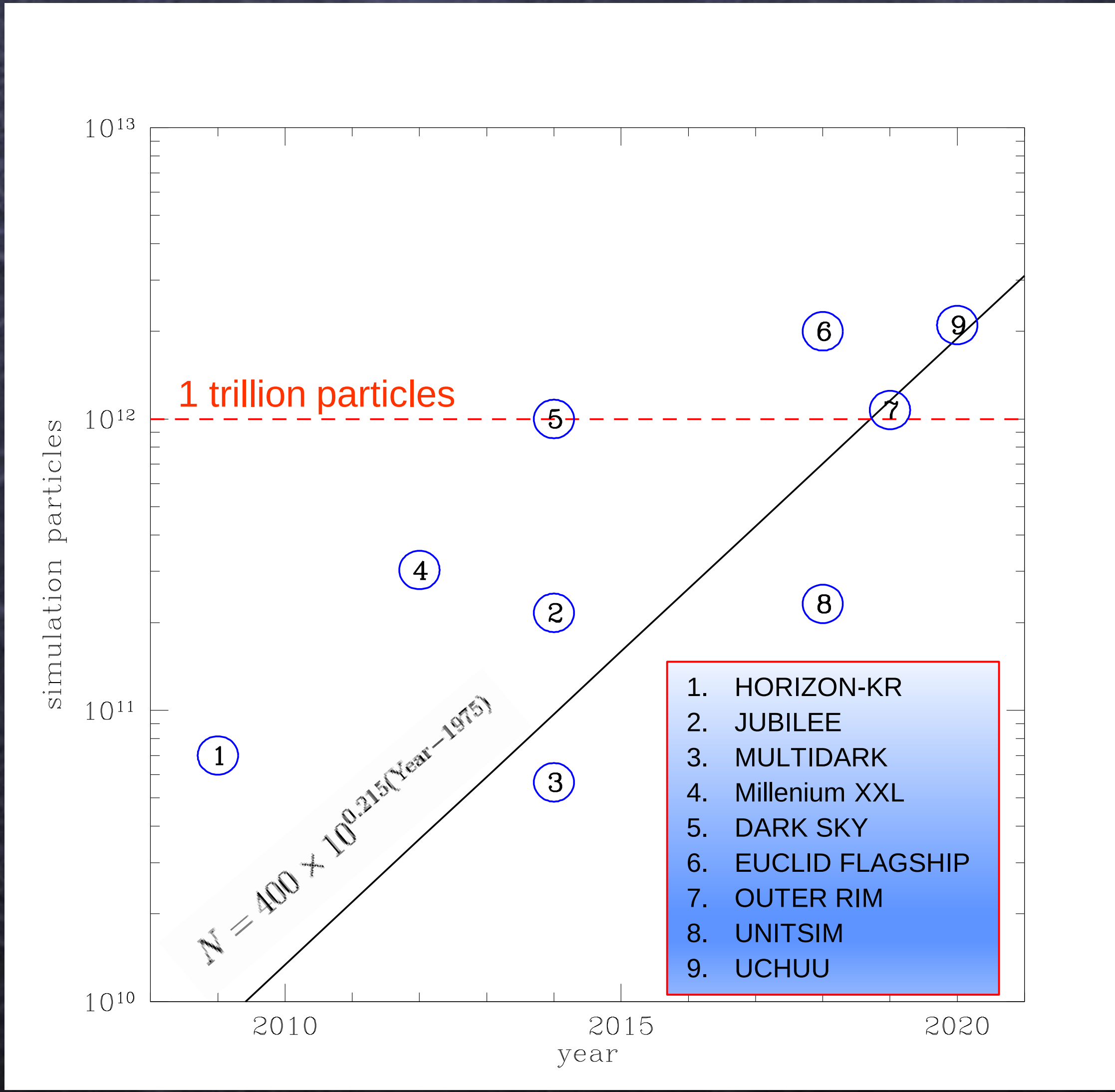
Extrapolating:

10^{12} partículas in 2020

...but it was done in 2014

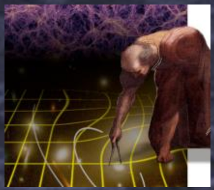
Computer technology allows to run much larger simulations. But the Moore's law is flattening since 6 years ago.

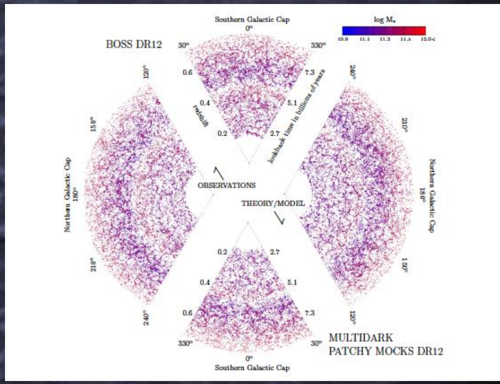
The reason is how data management mostly and the increasing resilience problems when using > 100K processors...



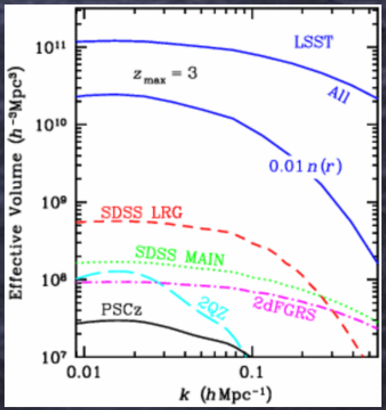
Why Large N-body simulations are needed?

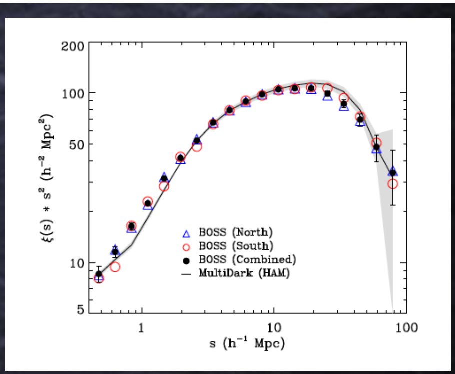
- **Plenty of Large Volume Galaxy Surveys (**DES, BOSS, eBOSS DESI, JPAS, Euclid, LSST, WFIRST





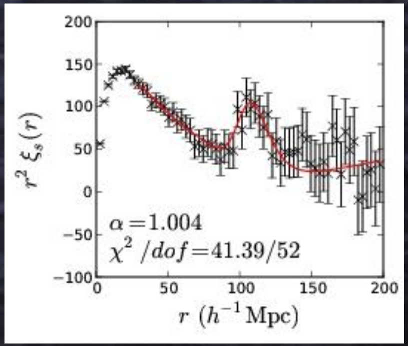
- They will probe 10-100 Gpc^3 volumes





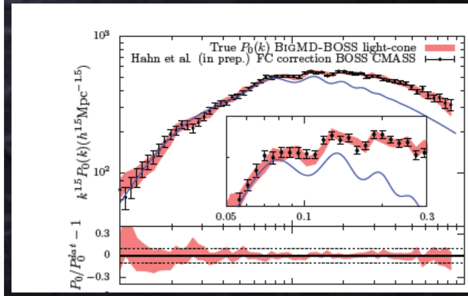
- Need to resolve halos hosting the faintest galaxies of these surveys to produce realistic mock catalogues. Higher z surveys imply smaller galaxies and smaller halos->more mass resolution.

- Fundamental tool to compare clustering properties of galaxies with theoretical predictions from cosmological models at few % level. Not possible only with LPT. Must do the full non-linear evolution for scales 100+ Mpc (BAO, P(k), RSD, 2pcf of galaxies)



•BAO in BOSS,

•100Mpc scale



• P(k) from Dr12 and BiGMD

•Rodriguez-Torres et al 2015

•**Galaxy Biases**: Large mass resolution is needed if internal sub-structure of dm halos has to be properly resolved to map halos to galaxies.

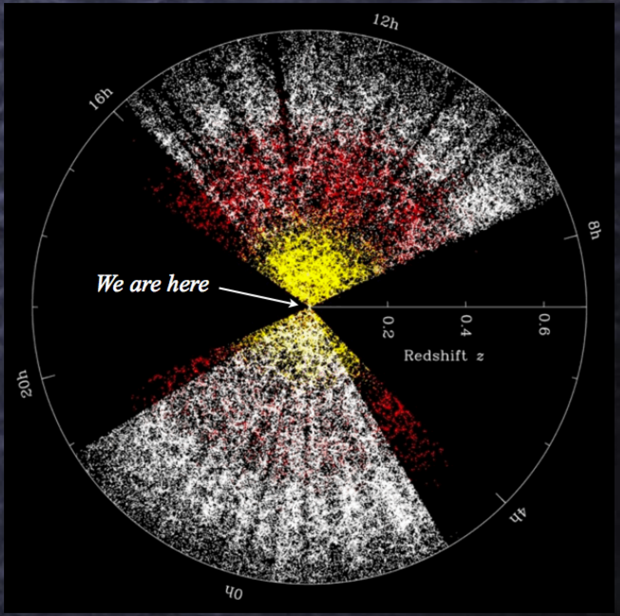
•e.g. Using the *Halo Abundance Matching* technique (e.g. Trujillo et al 2011).

Why Large N-body simulations are needed

- **Large Volume Galaxy Surveys**

•A real example: BOSS (z=0.1..0.7)

•Box size to host full BOSS survey : 3.5 h^{-1} Gpc



•BOSS completed down to LRG galx with

•V_{cir} >350 km/s -> M_{vir} ~5x10^12 Msun.

•To properly resolve the peak of the Vrot in a dark matter halo we need a minimum of few 100 particles. High-force resolution to properly model halos and subhalos hosting LRG's

Dark Energy Spectroscopic Instrument

•Then, a proper representation N-body realization of a BOSS survey will need

> 7000^3 particles.

•DESI, Euclid , LSST will probe to z>1.5

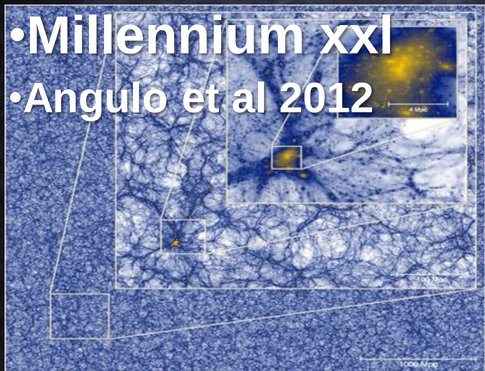
•Larger Boxes: > 4/h Gpc

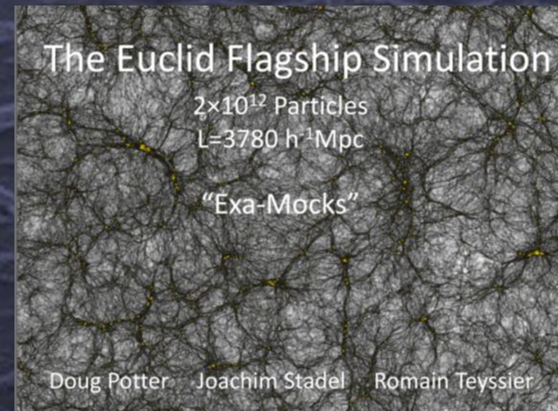
•Npart > 10,000^3

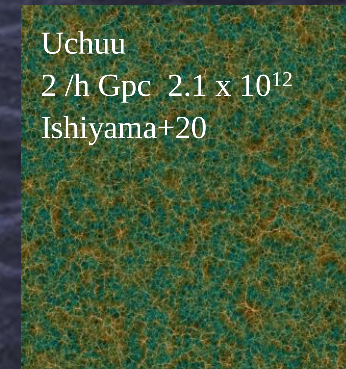
•Smaller host halos (~10^12) for ELG's

LSST
Large Synoptic Survey Telescope

Dark Matter Cosmological Simulations

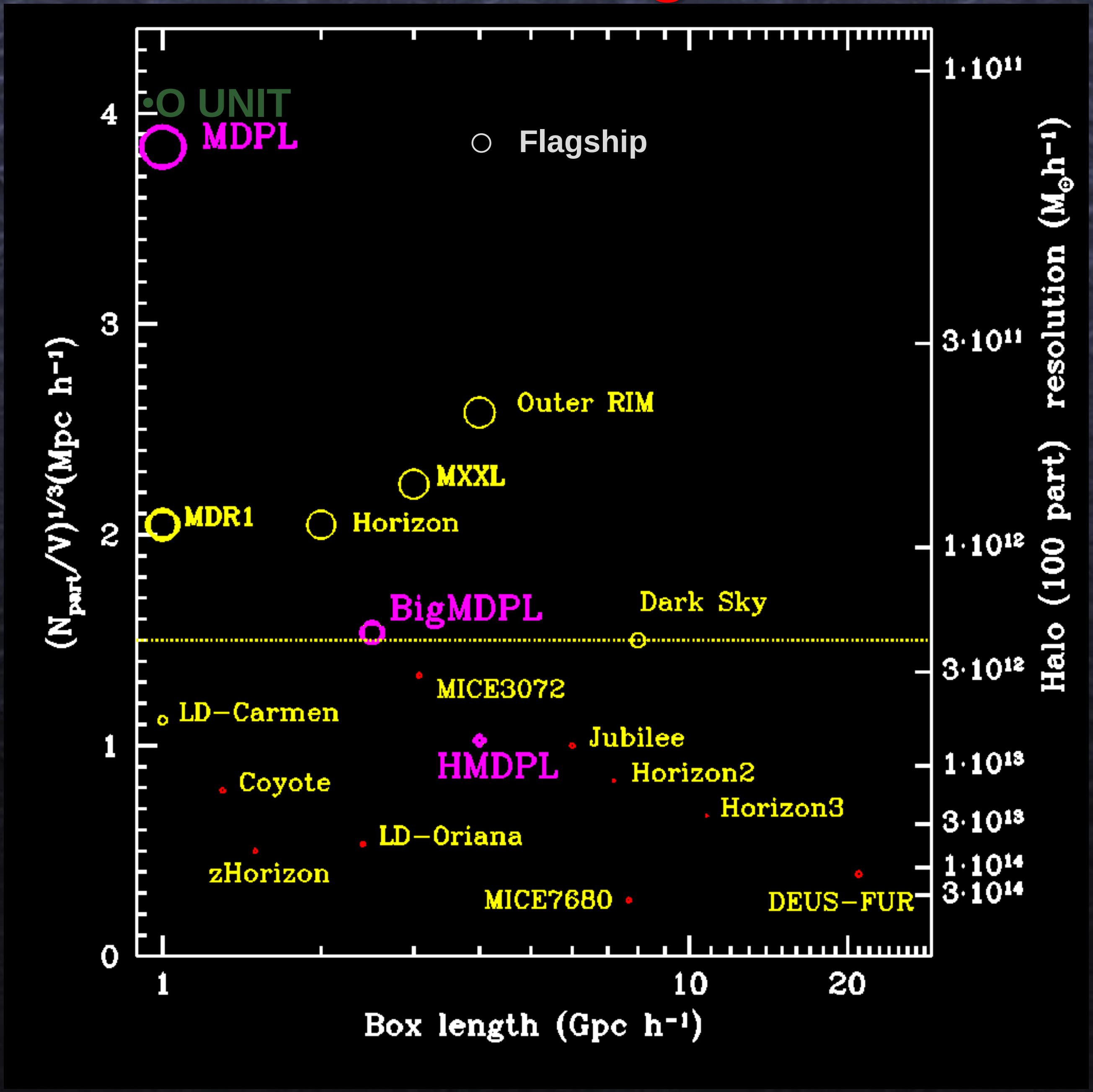




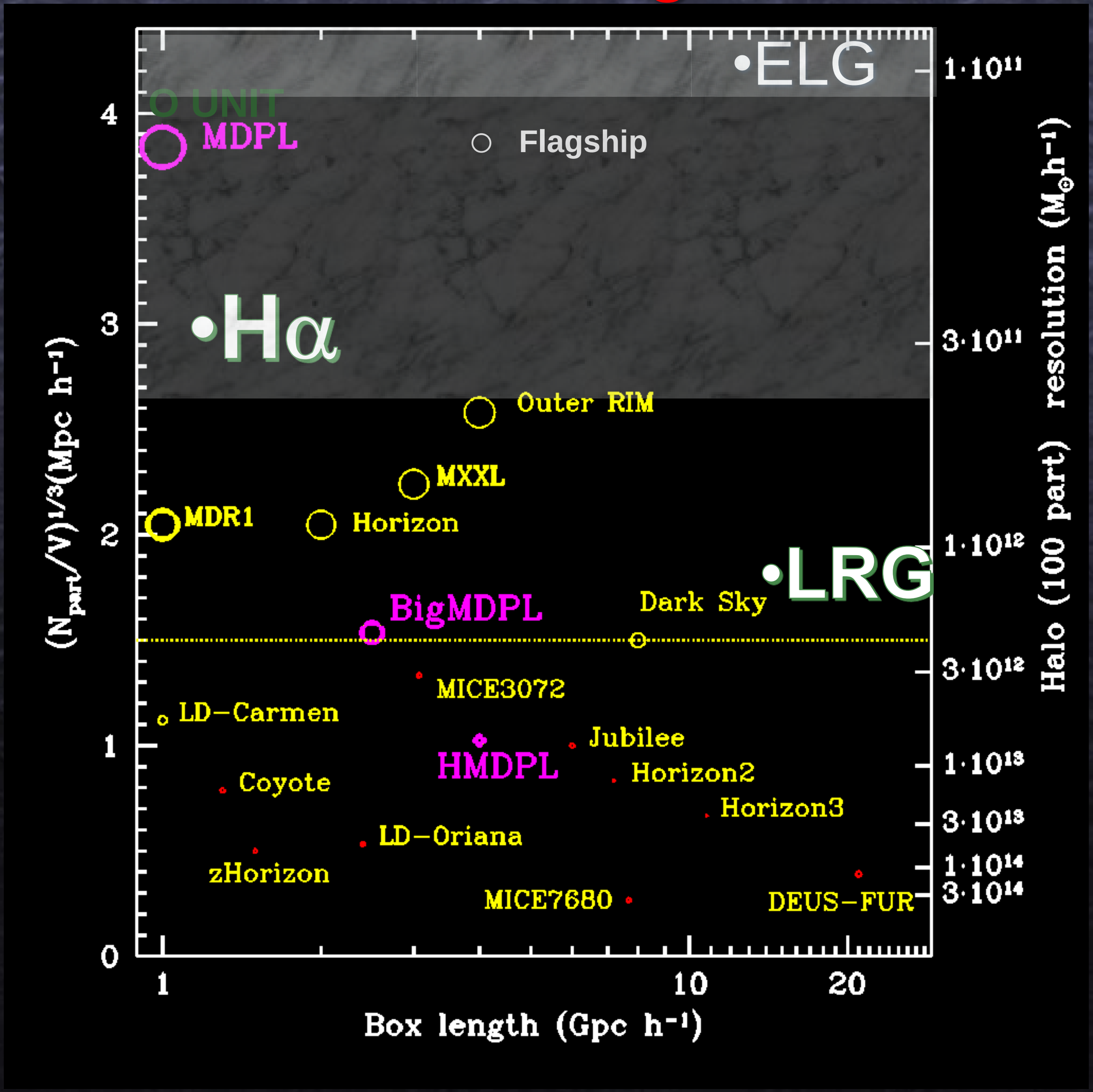


- •Bolshoi (WMAP7-ART) 250/h Mpc 8 billion particles
- •Multidark (WMAP7-ART) 1 /h Gpc 8 billion particles
- •MICE -GC (WMAP5-GAD) 3 /h Gpc 68 billion particles
- •Horizon (FR) (WMAP3-RAMSES) 2 /h Gpc 68 billion particles
- •Millenium XXL (WMAP1-GAD) 3 /h Gpc 303 billion particles
- •Horizon (KR) (WMAP5-GOTPM) 10.7 /h Gpc 372 billion.
- •DEUS (FR) (WMAP7-RAMSES) 21/h Gpc 550 billion particles
- •JUBILEE (WMAP7-CP3M) 6/h Gpc 216 billion particles
- •BigMD (PLANCK-GAD) 2.5/h Gpc 56.6 billion particles
- •MultiDark (PLANCK-GAD) 1.0/h Gpc 56.6 billion particles
- •UNITSIMS (PLANCK-GAD) 3/h Gpc 232 bliion particles
- ***•OUTER RIM ((PLANCK-HAAC) 4.0/h Gpc 1.1 trillion particles***
- ***•DARK SKY (PLANCK-2HOT) 8.0/h Gpc 1.1 Trillion particles***
- ***•Euclid FLAGSHIP (PLANCK-PKDGRAV) 3.7 /h Gpc 2 trillion particles.***
- ***•UCHUU (PLANCK-GREEM) 2/h Gpc 2.1 Trillion particles.***

Current S.o.A Cosmological Simulations

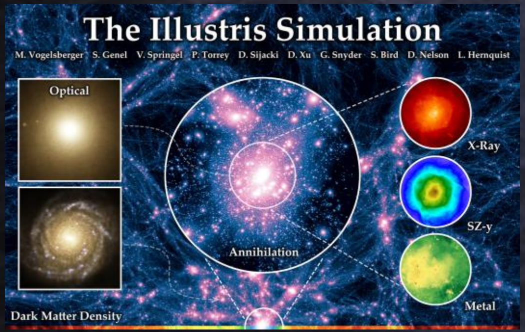


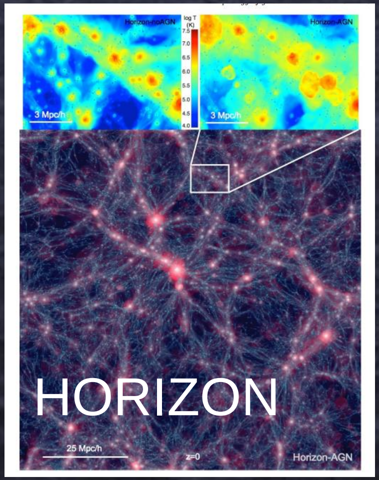
Current S.o.A Cosmological Simulations

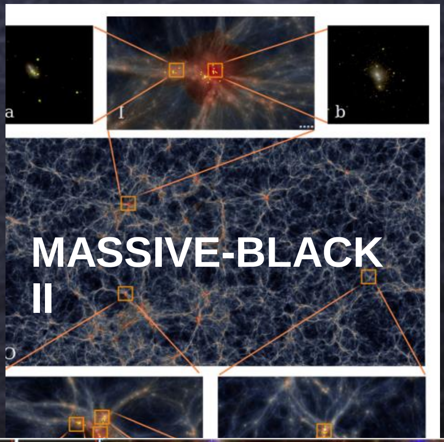


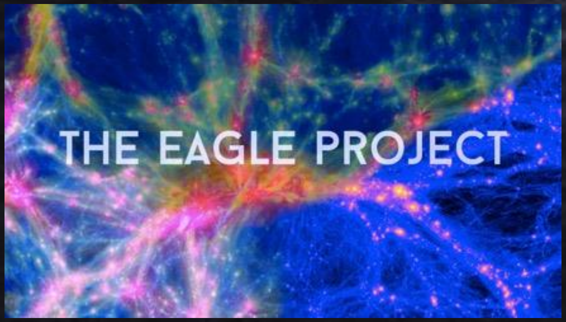
From dark halos to galaxies

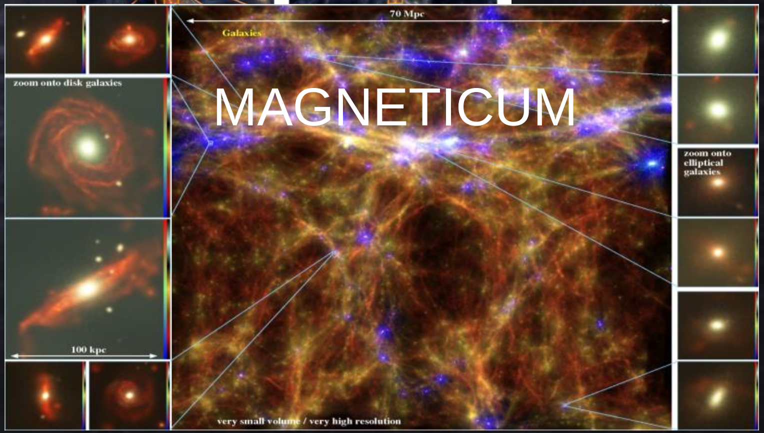
- A Full self-consistent galaxy formation simulation is orders of magnitudes more computationally expensive than dark matter only simulations.











Simulated volumes
100 Mpc- 500 Mpc

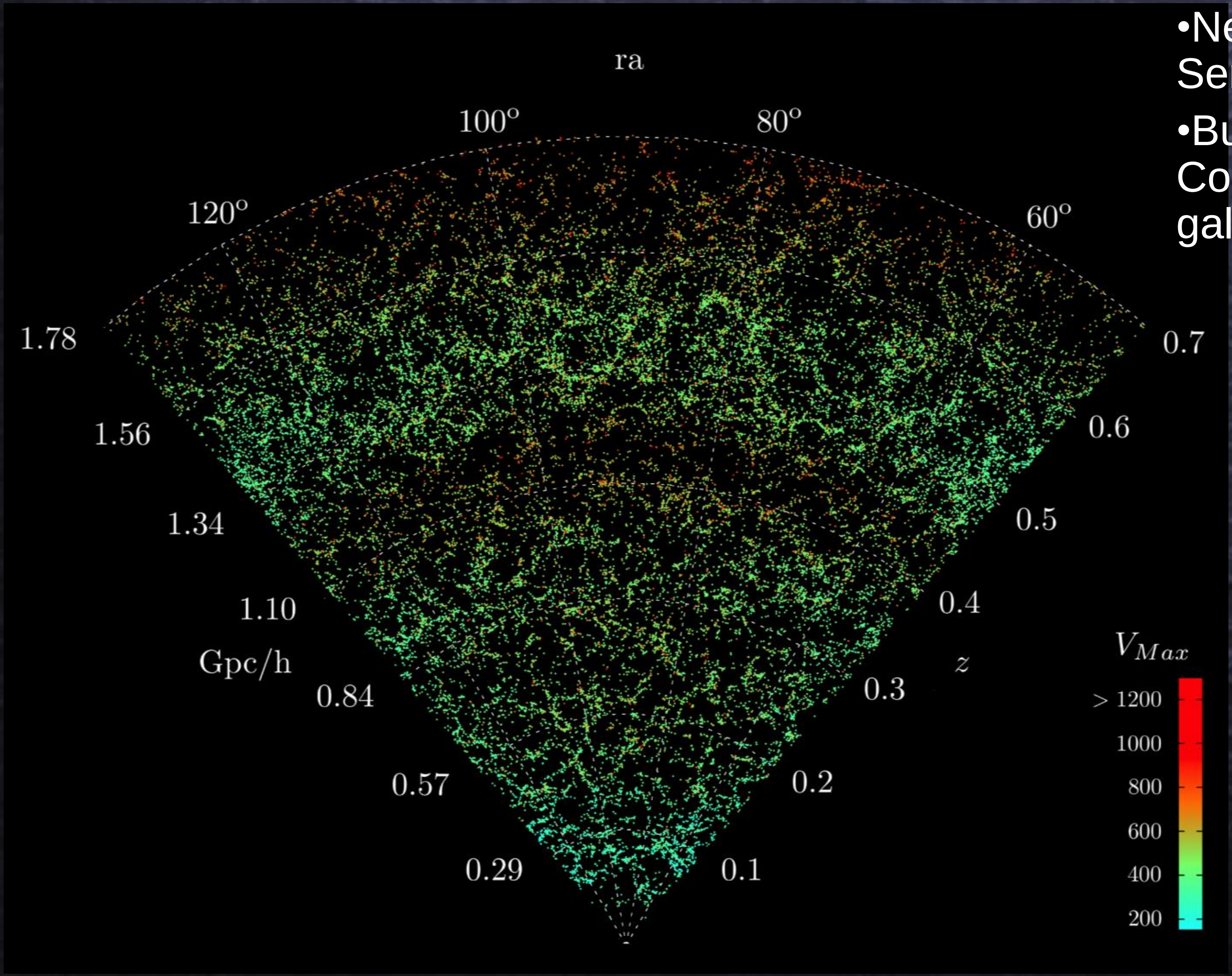
From dark halos to galaxies

- A Full self-consistent galaxy formation simulation is orders of magnitudes more computationally expensive than dark matter only simulations.

- Not possible to simulate large computational volumes
  - (>> $1 Gpc^3$) with baryons and proper resolution

- Need to map halos to galaxies using approx. models:
  - ✓ Halo Occupation Distribution (HOD)
  - ✓ Halo Abundance Matching (HAM)
  - ✓ Semi Analytical Modelling (SAM)
  - ✓ Machine Learning Techniques (ML)

•SUGAR: creating Realistic Light cone mocks for BOSS LRG's

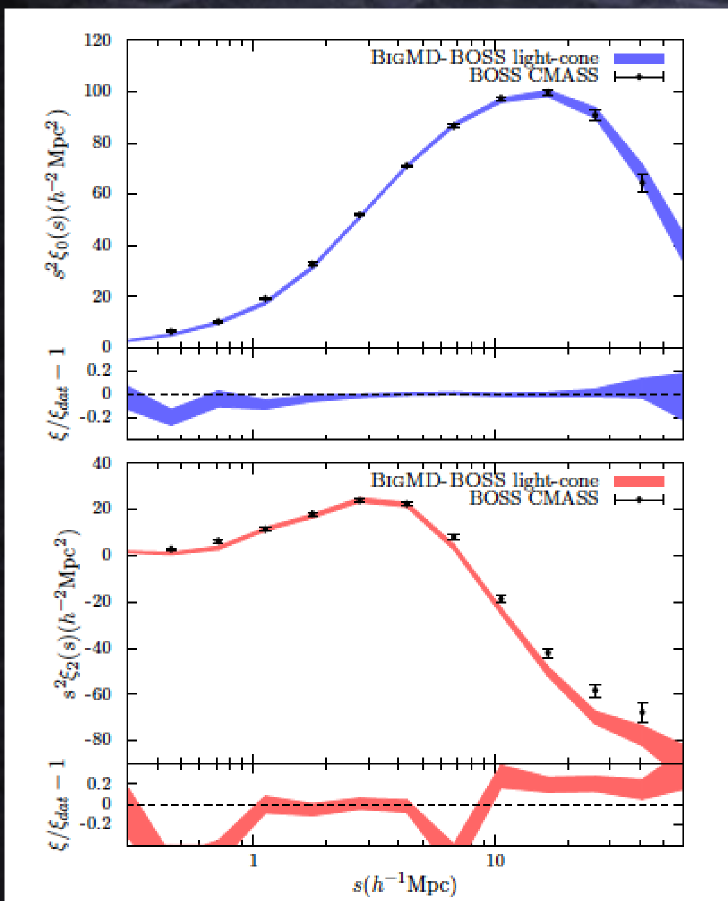


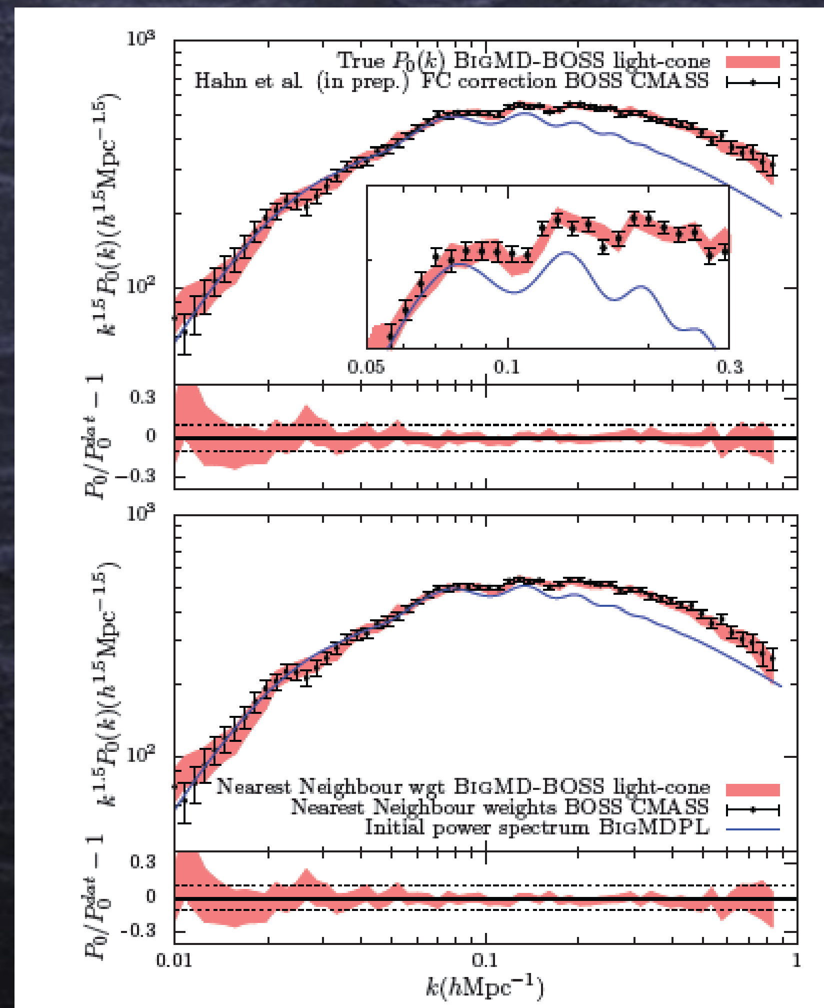
- SUrvey GenerAtoR :
- New code developed by Sergio Rodriguez to
- Build high fidelity Light Cone mocking BOSS LRG galaxies

The clustering of galaxies in the SDSS-III Baryon Oscillation Spectroscopic Survey: Modeling the clustering and halo occupation distribution of BOSS-CMASS galaxies in the Final Data Release

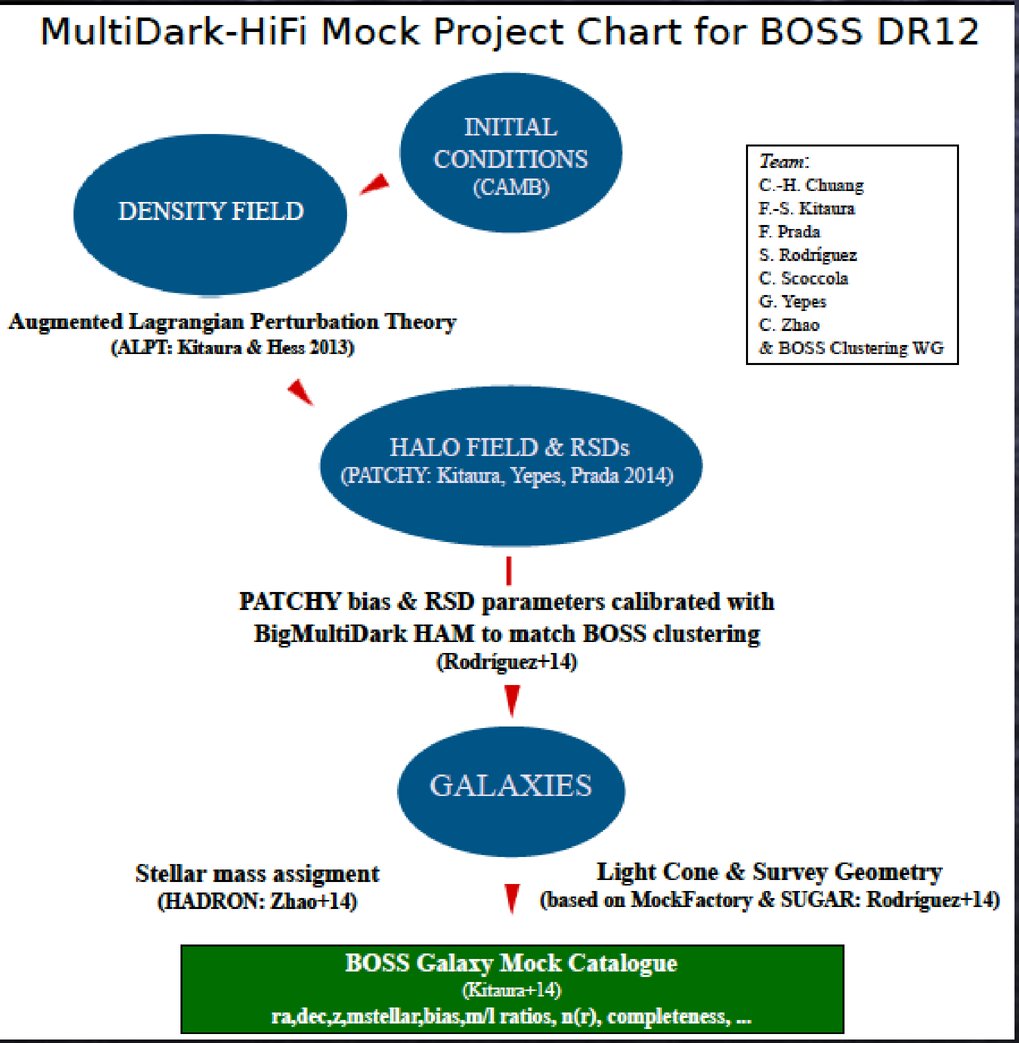
Arxiv-1509.06404

Rodriguez-Torres, et al 2015

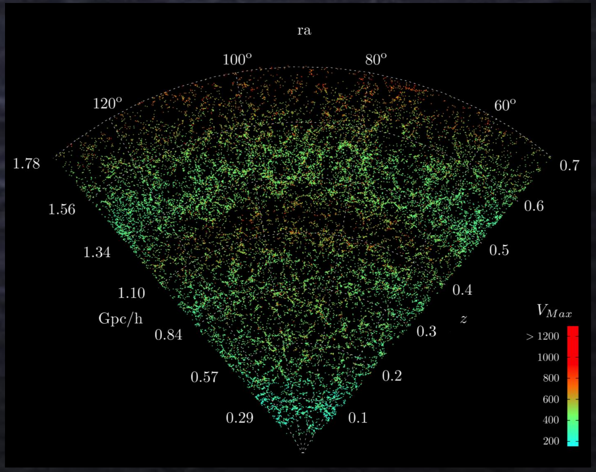




The Mock Factory for BOSS LRG's



- Generation of high-fidelity mocks for final data release DR12 of BOSS Survey:
  - More than 2000+ light-cones for CMASS North and South + LOWz North and South.



BOSS Galaxy Mocks Massive Production

The clustering of galaxies in the SDSS-III Baryon Oscillation Spectroscopic Survey:
Mock galaxy catalogues for the final BOSS Data Release

Kitaura et al, 2015 , Arxiv/1509.06400

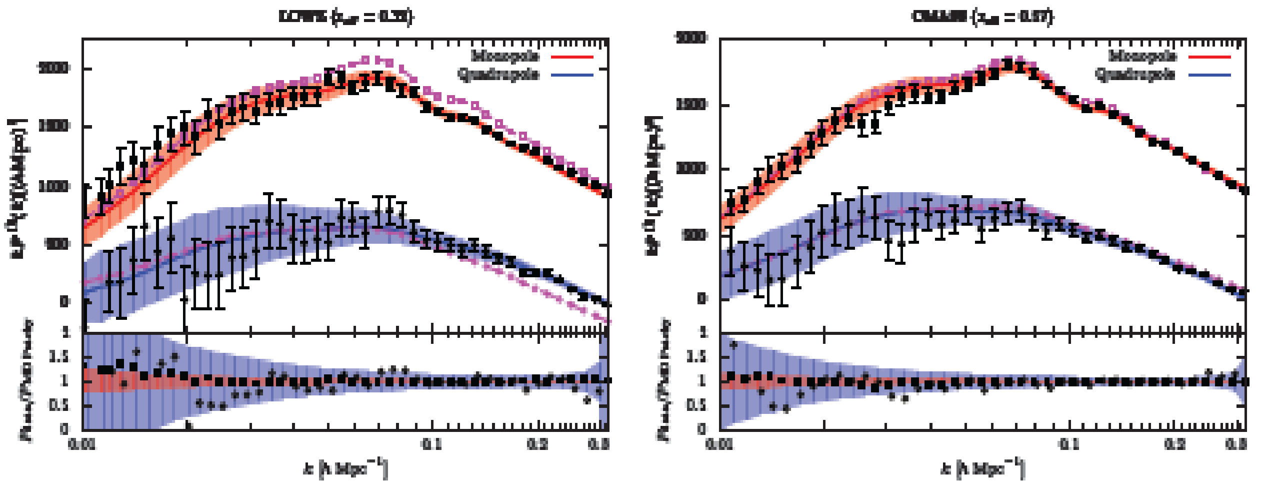


Figure 7. Monopole (red) and quadrupole (blue) in Fourier space for the LOWZ (left) and CMASS galaxies (right) for the mean over 2048 MD PATCHY mocks for both southern and northern galactic caps, the average and 1-σ uncertainties are shown. The results for QPM (1000 mocks for each LOWZ/CMASS, and north/south) are shown with dashed magenta lines. The error bars assigned to the data points have been computed based on 2048 MD PATCHY mocks. The ratio plots in the bottom panels have been only done for the MD PATCHY mocks.

More than 2000 BOSS Light-cone mocks:

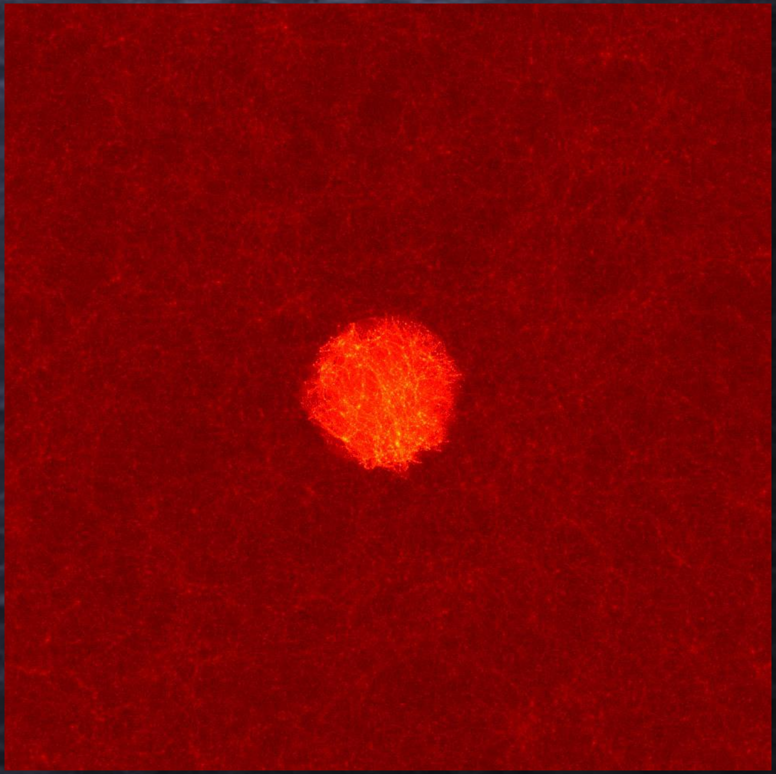
192,000 /h^3 Gpc^3

SIMULATIONS OF INDIVIDUAL COSMIC STRUCTURES

THE ZOOMING TECHNIQUE

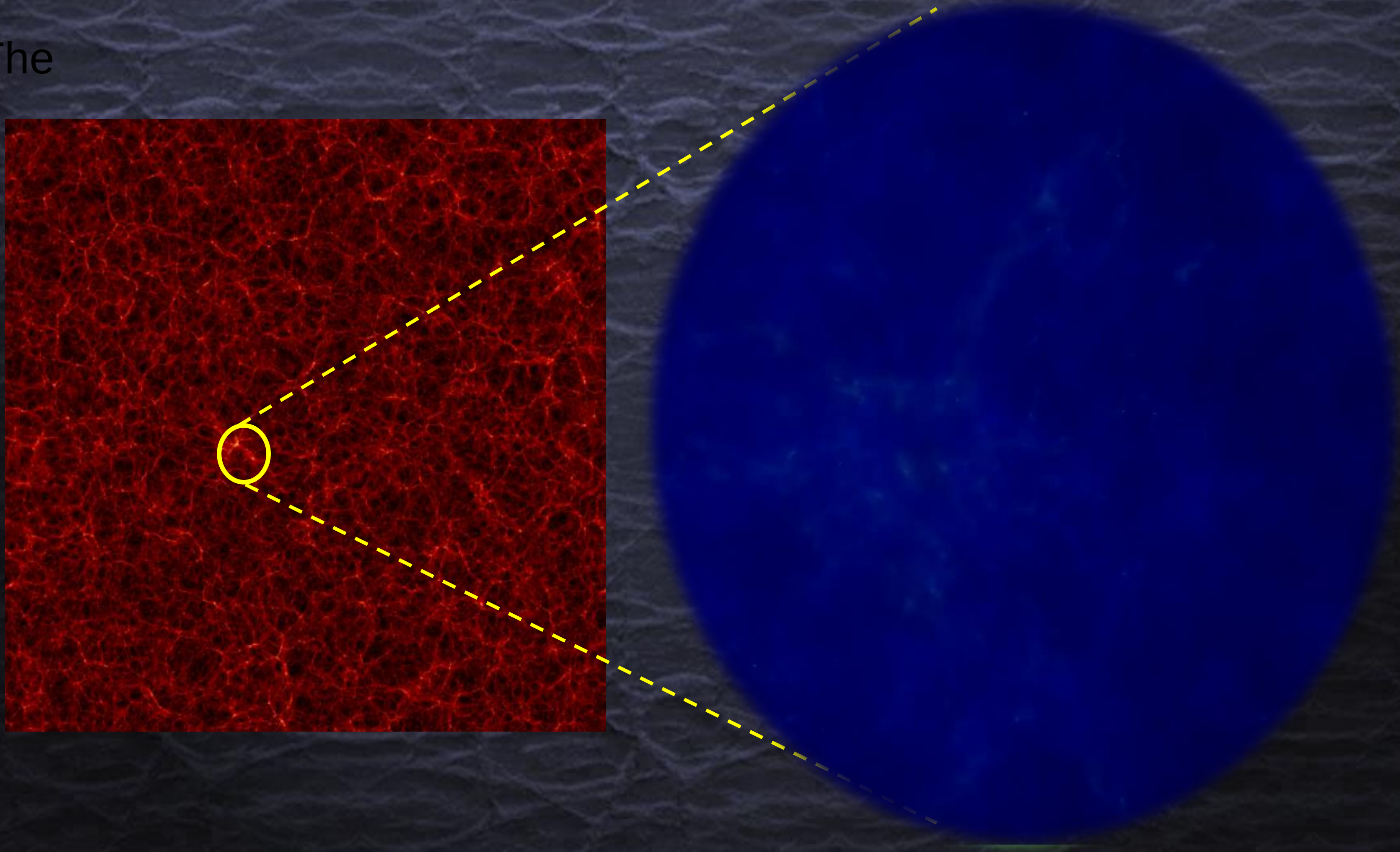
MULTIMASS TECHNIQUE

- Adaptive multi-mass to achieve high resolution:
- Re-Simulated areas from large computational boxes by resampling particles of increasing mass away from the refined region:
  - Original initial conditions up to 4096^3 particles in a big box.
  - Trace back particles of selected objects to identify the Lagrangiang region to be resimulated with very high resolution and degrade resolution elsewhere in spherical shells
  - **Very easy way of parallelization.**



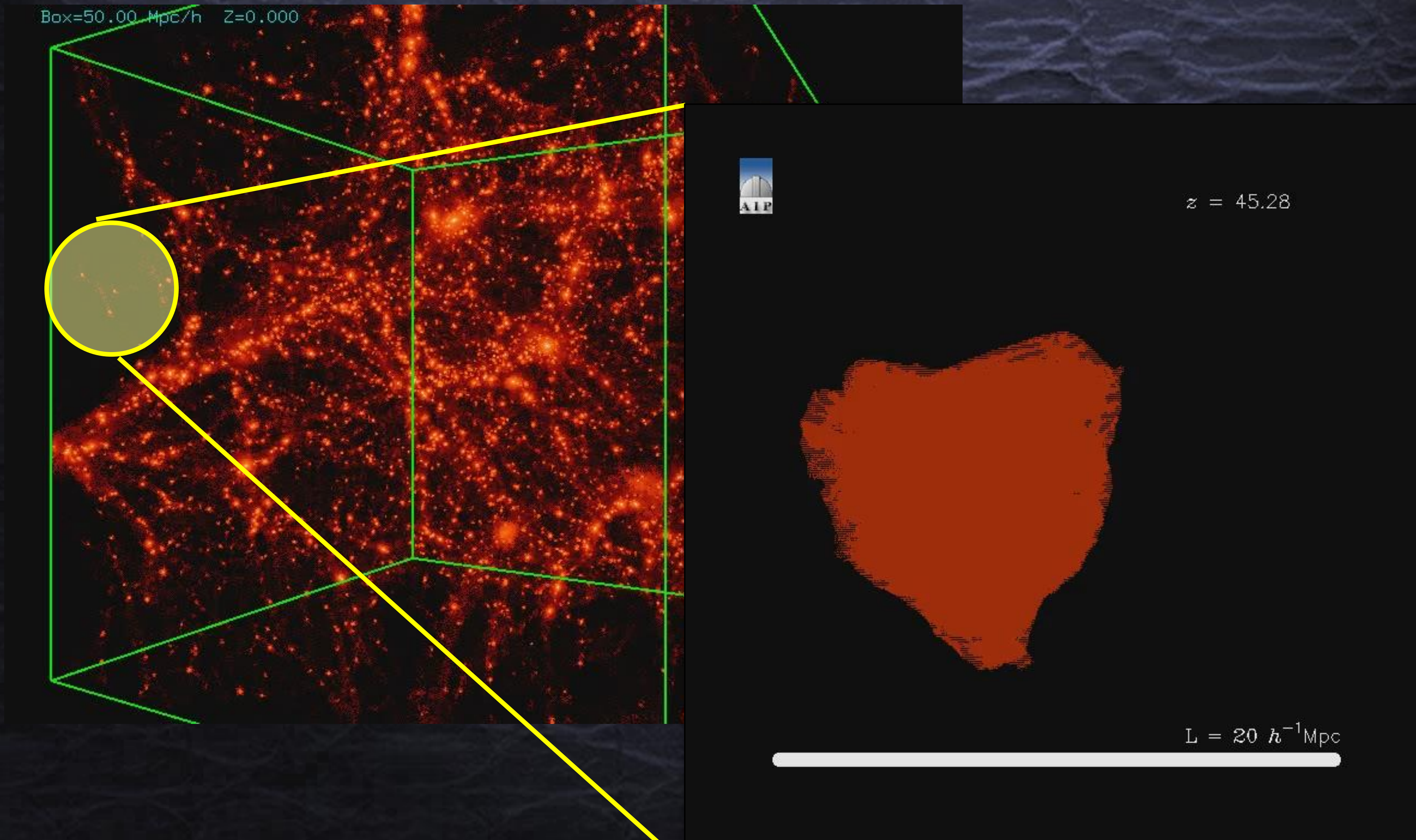
ZOOMED CLUSTER SIMULATIONS

•The

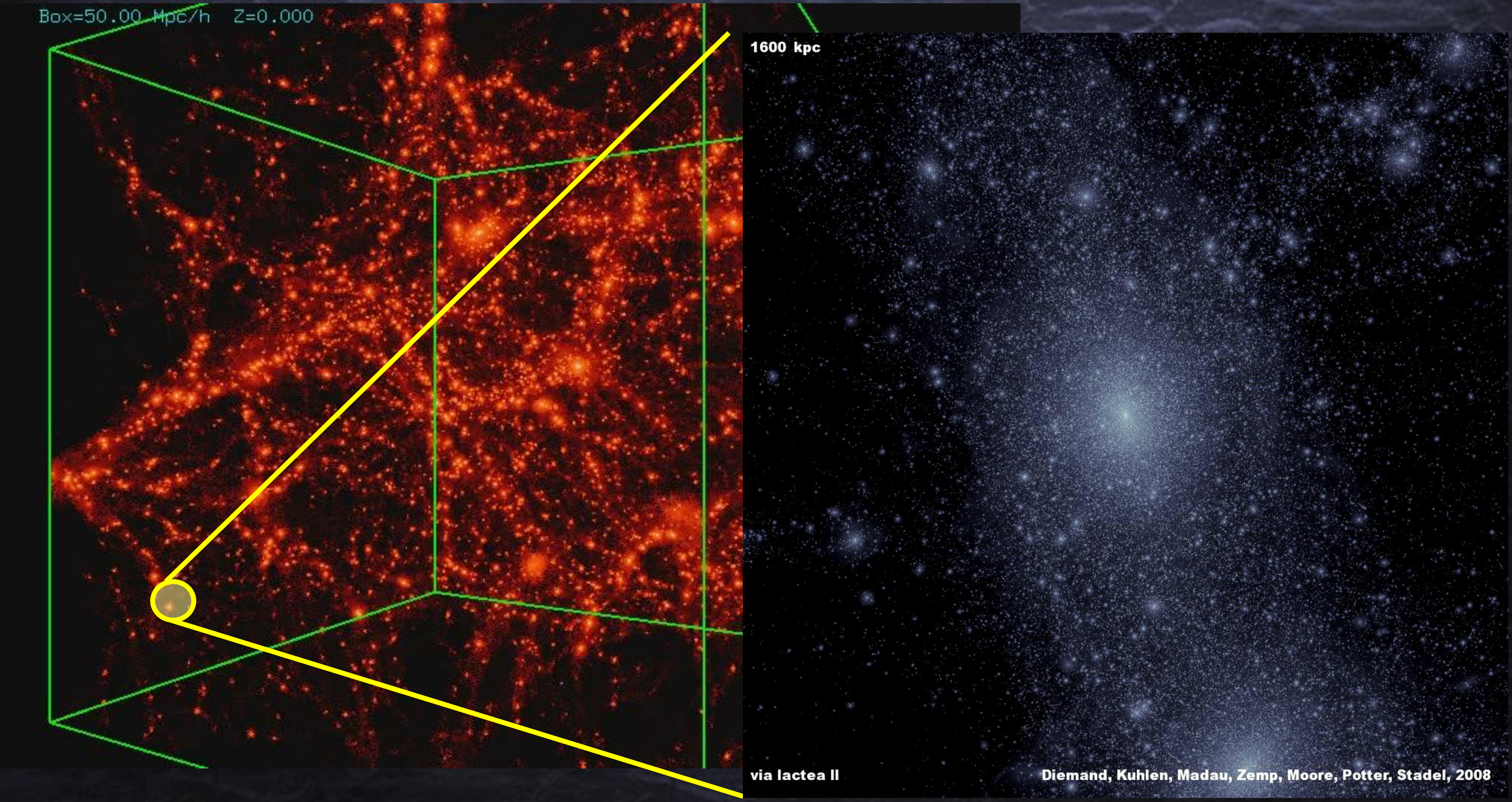


- We selected all the cluster-size halos more massive than $M > 10^{15}\ h^{-1}\ M_{sun}$ (*282*) at z=0

COSMIC VOIDS:

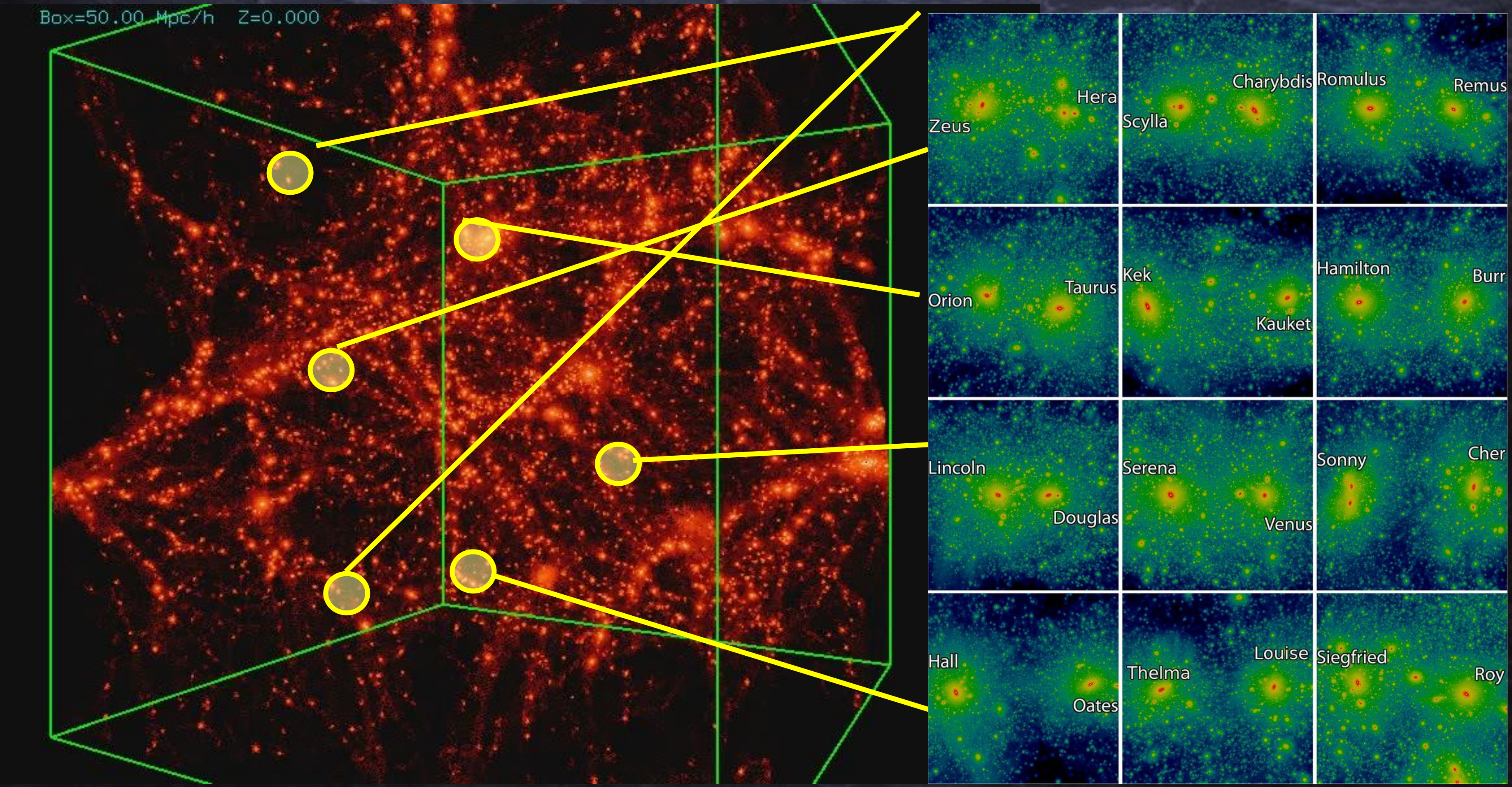


Individual MW Halos



Via láctea II Simulation

Local Group halos



ELVIS LG N-BODY SIMULATIONS

PROBLEMS OF ΛCDM AT SHORT SCALES

FROM RESULTS OF N-BODY SIMULATIONS

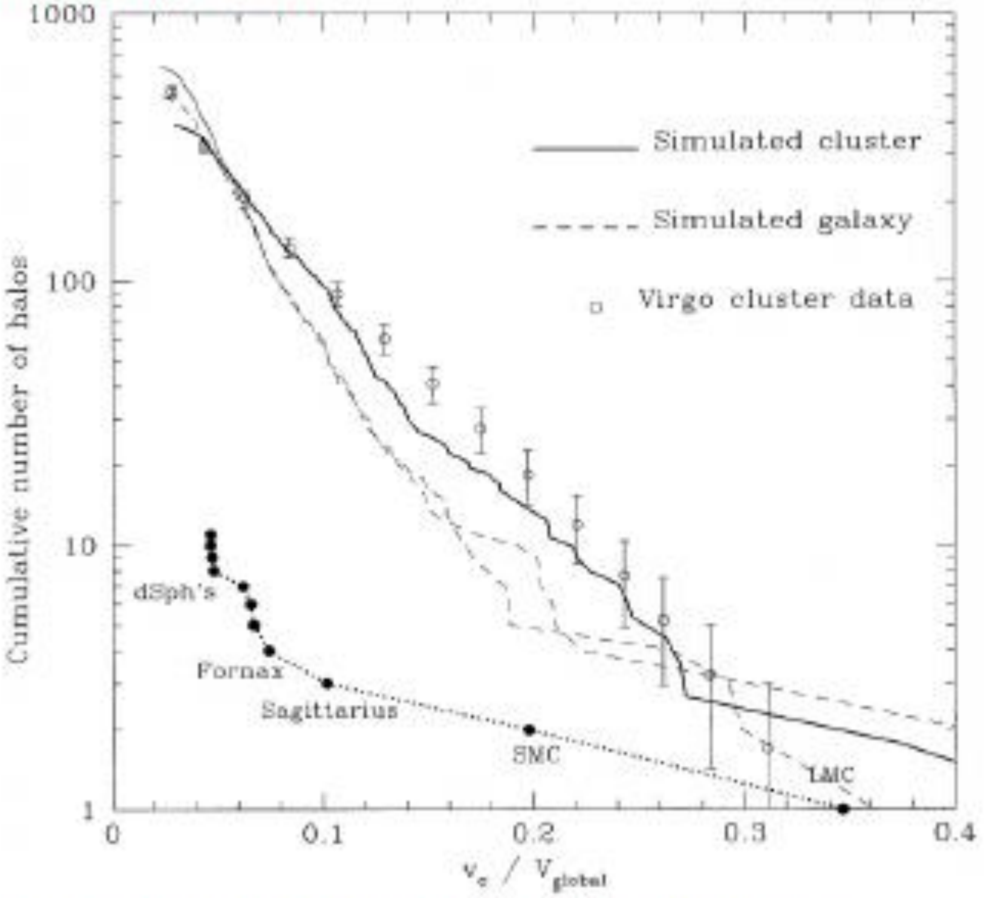
PROBLEMS OF ΛCDM AT SHORT SCALES

- The standard cosmological model with the best fit cosmological parameters from Planck and other probes, works extremely well to describe the large scale structure of matter in our Universe.
- But when looking at the properties of structures at short scales < 1 Mpc, the predictions of the model (from N-body simulations) are at odds with observations…

Substructure in dark matter halos hardly depends on mass

SUBHALOS IN A RICH CLUSTER AND A MILKY WAY-SIZED HALO

Moore et al. (1999)



Halo with $5x10^{14}$ $M_{\odot}$

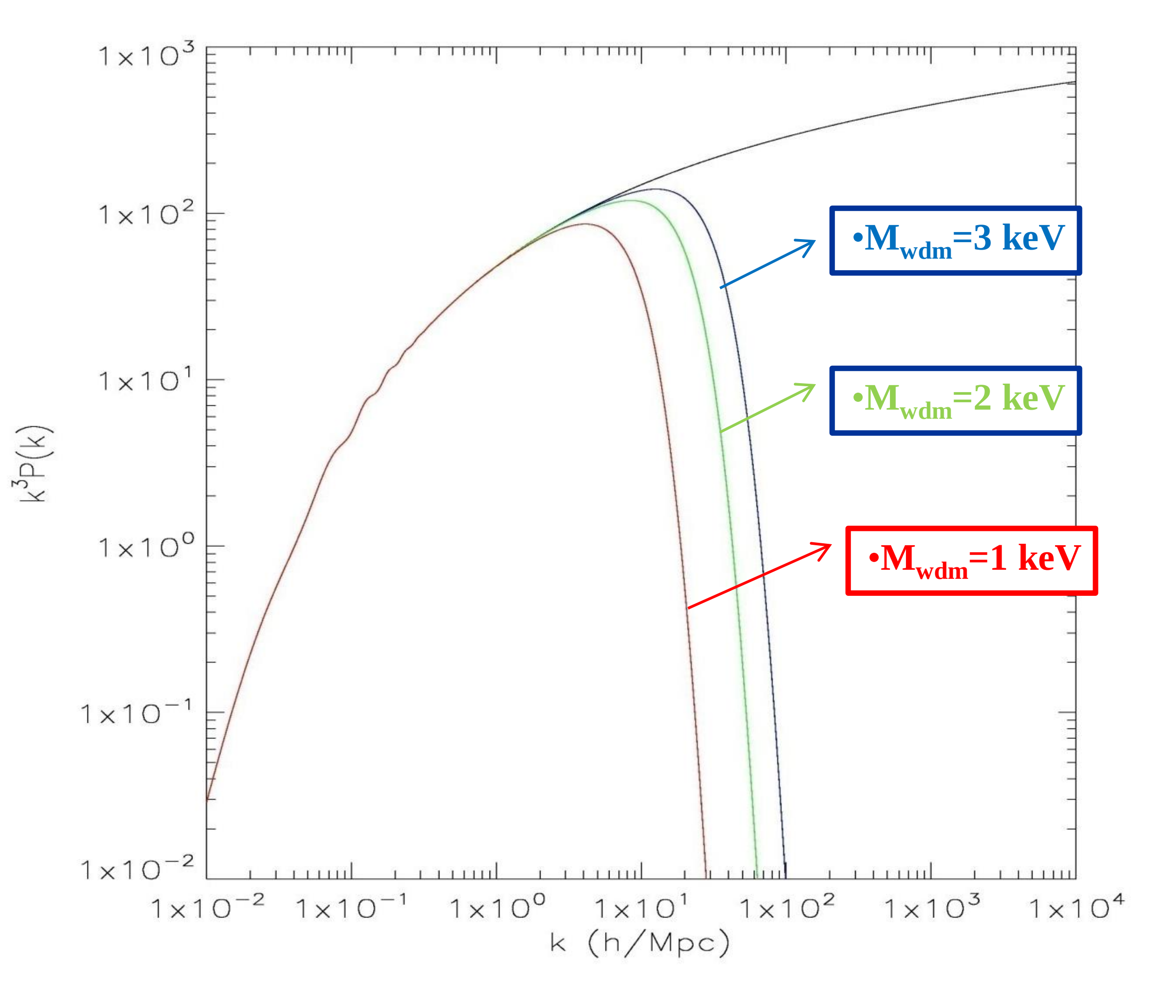
Halo with $2x10^{12}$ $M_{\odot}$

Klypin et al. (1999), Moore et al. (1999): **Where are all the missing satellites?**

NATURE OF THE DARK MATTER
Cold DM vs Warm DM

- WDM particles:
- M_{wdm} = 3keV – 1 keV

- Comparison with ΛCDM:
    - density profiles
    - substructure mass functions
-



Missing Satellite Problem nearby

•Springel et al. 2001

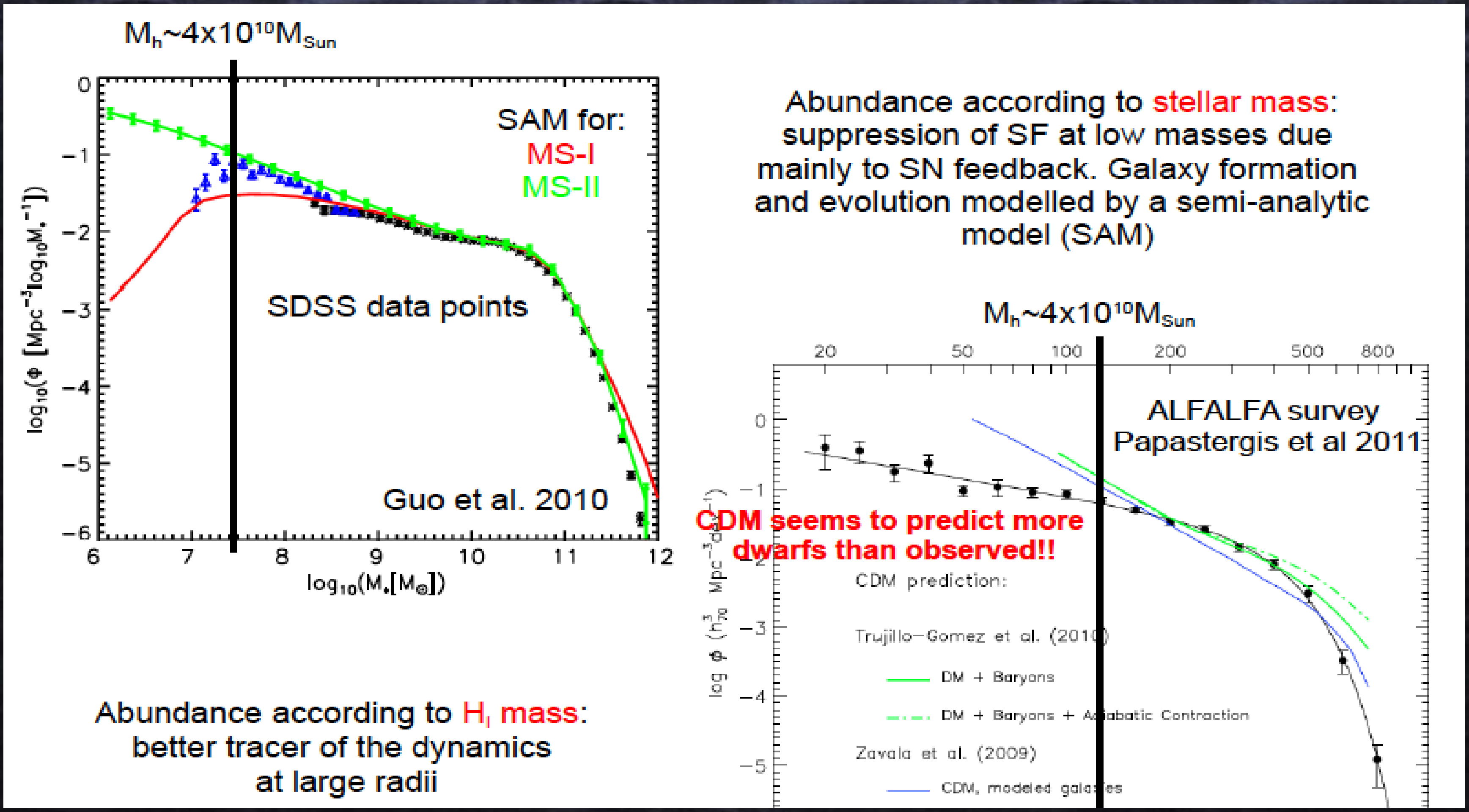
- CDM predicts large numbers of subhalos (~100-1000 for a Milky Way-sized galaxy)
- Milky Way only has 23 known satellites
- What happened to the rest of them?

Missing Satellite Problem nearby

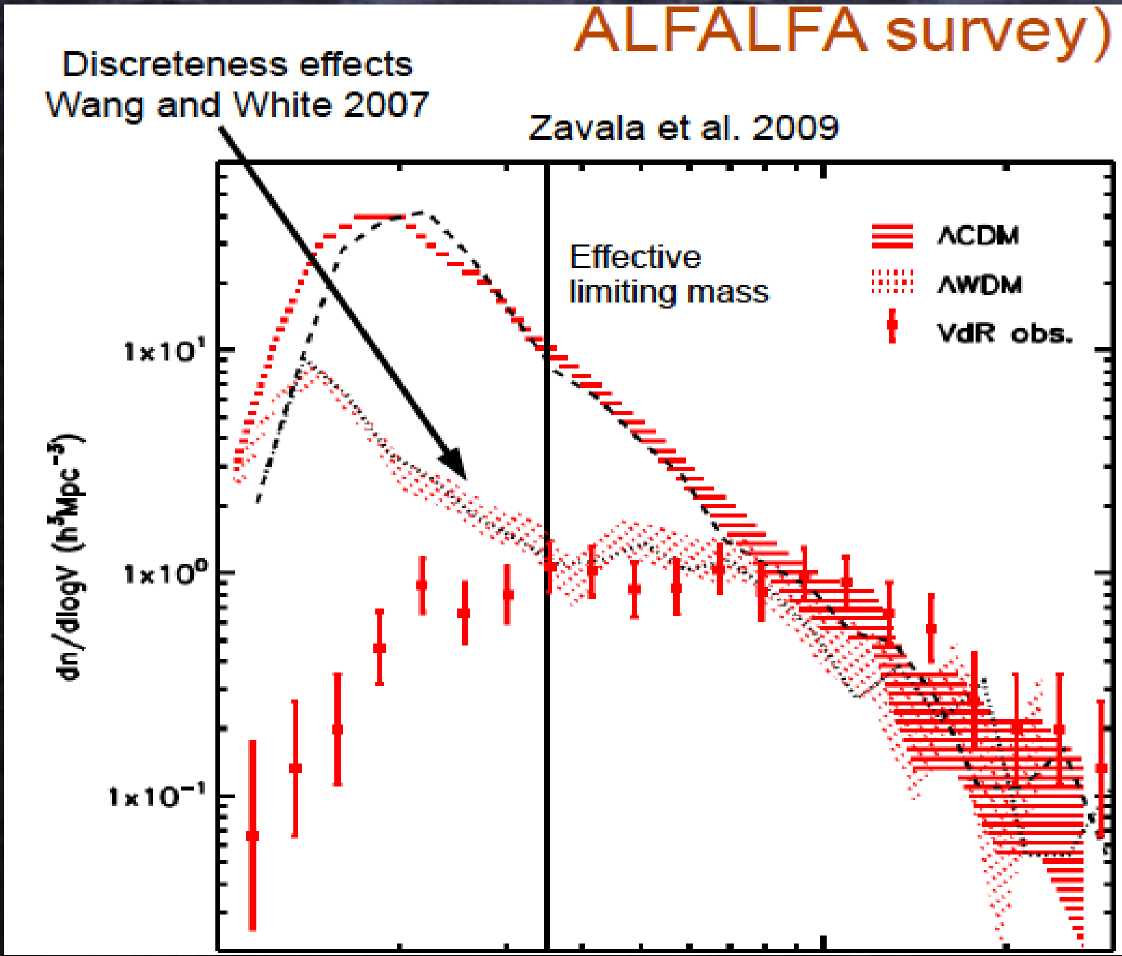
•Springel et al. 2001

- CDM predicts large numbers of subhalos (~100-1000 for a Milky Way-sized galaxy)
- Milky Way only has 23 known satellites
- What happened to the rest of them?

Missing dwarf galaxies in the field



Missing galaxies in LCDM



CDM is overabundant by a factor of ~10 at V_{max}~30 km/s
WDM (1keV) fits nicely but:

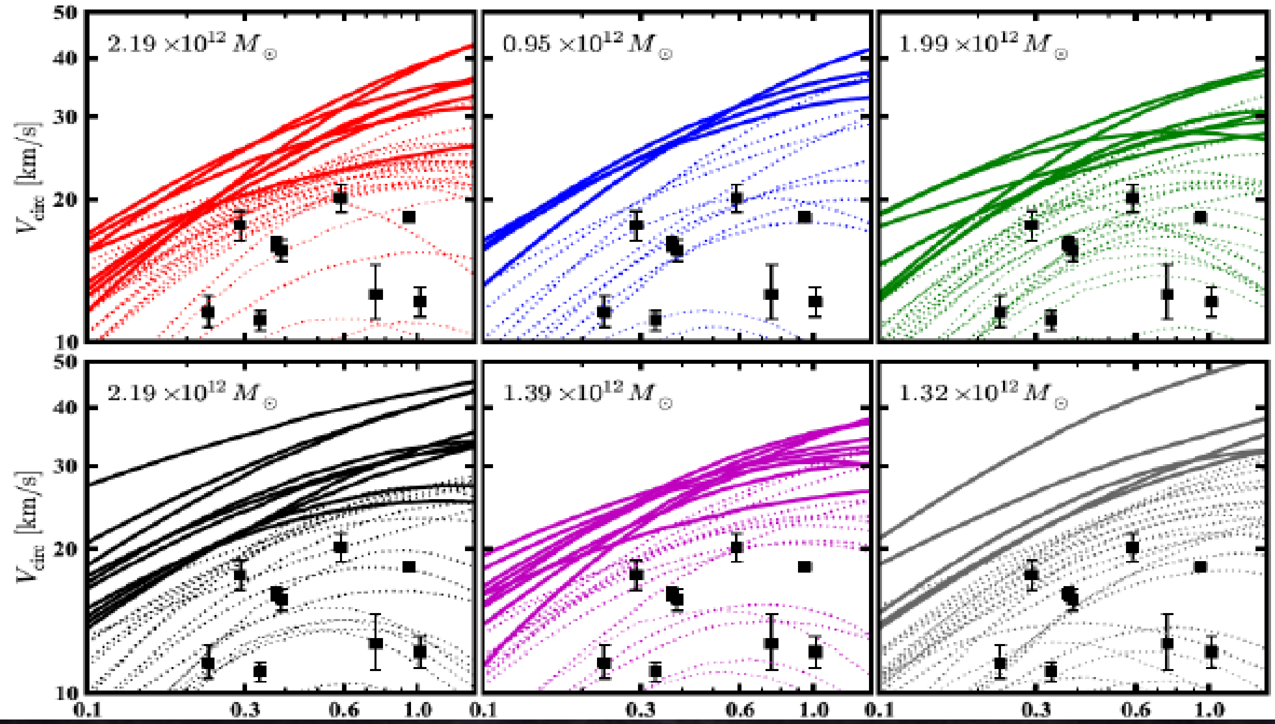
In marginal tension with current Ly-α forest constraints

Too Big to fail problem

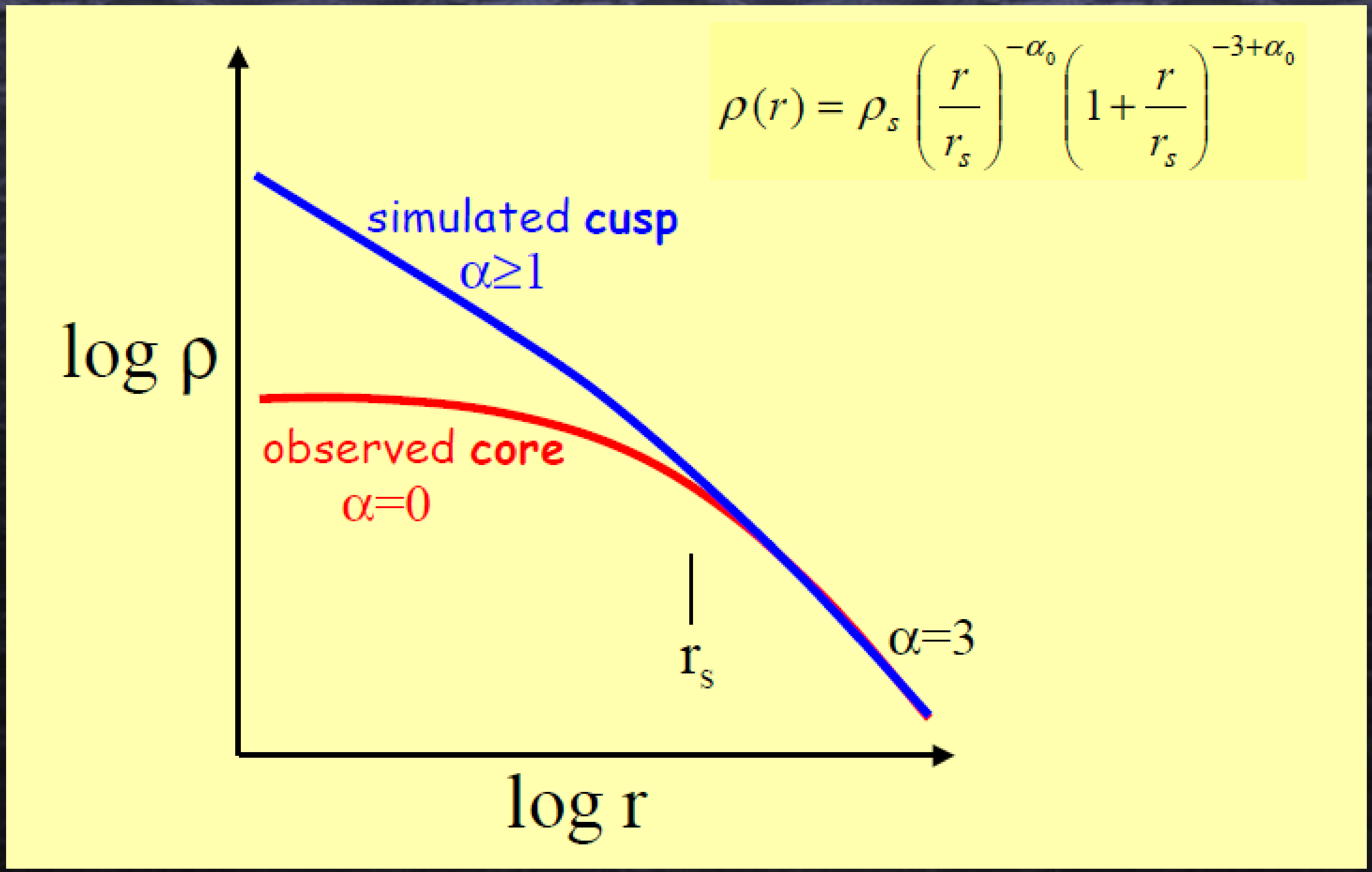
Independent(?) of the core-cusp problem, recent analysis of high resolution simulations of MW-size halos find that:

The most massive CDM subhalos seem to be too dense to host the MW dSphs!!

DM satellites of six MW-size halos (Aquarius project)



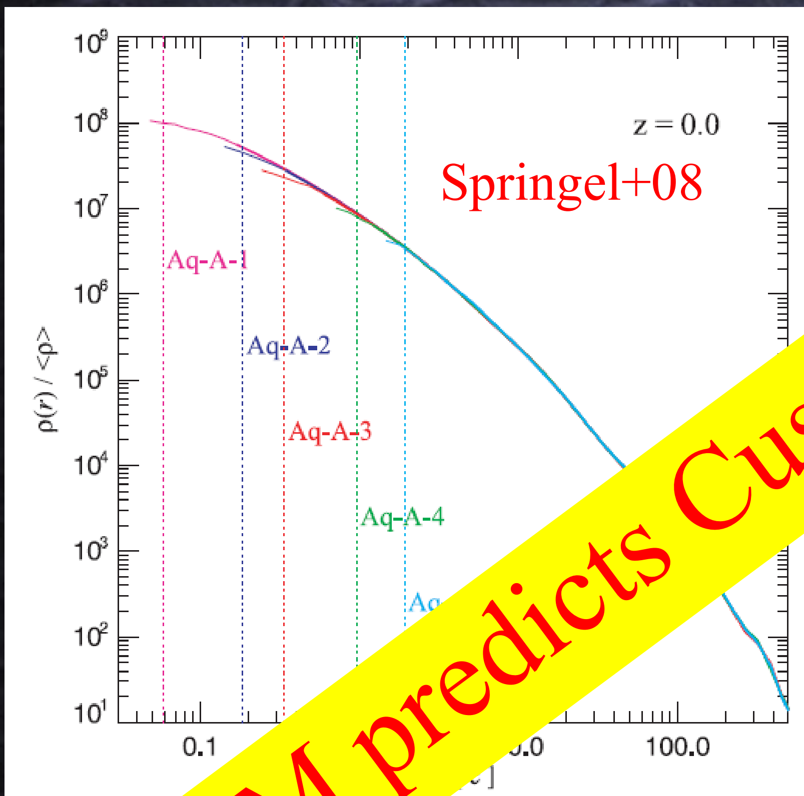
THE CUSP-CORE PROBLEM

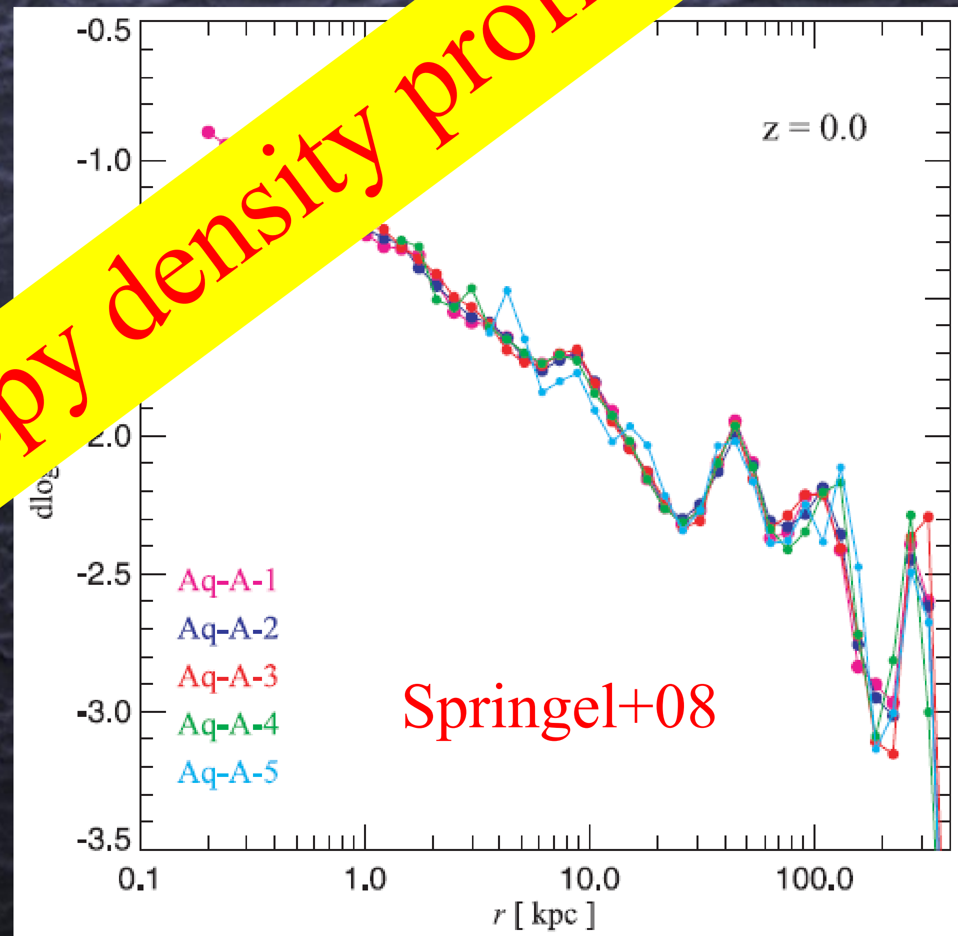


• Inner density slope

Navarro, Frank & White (1997) : $\alpha = -1.0$ $\quad \frac{\rho(r)}{\rho_{cr}} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}$

Moore et al. (1999) : $\alpha = -1.5$





CDM predicts Cuspy density profiles

No asymptotic slope detected so far

•Observational Results

Observations provide velocity profiles that are then converted in density profiles

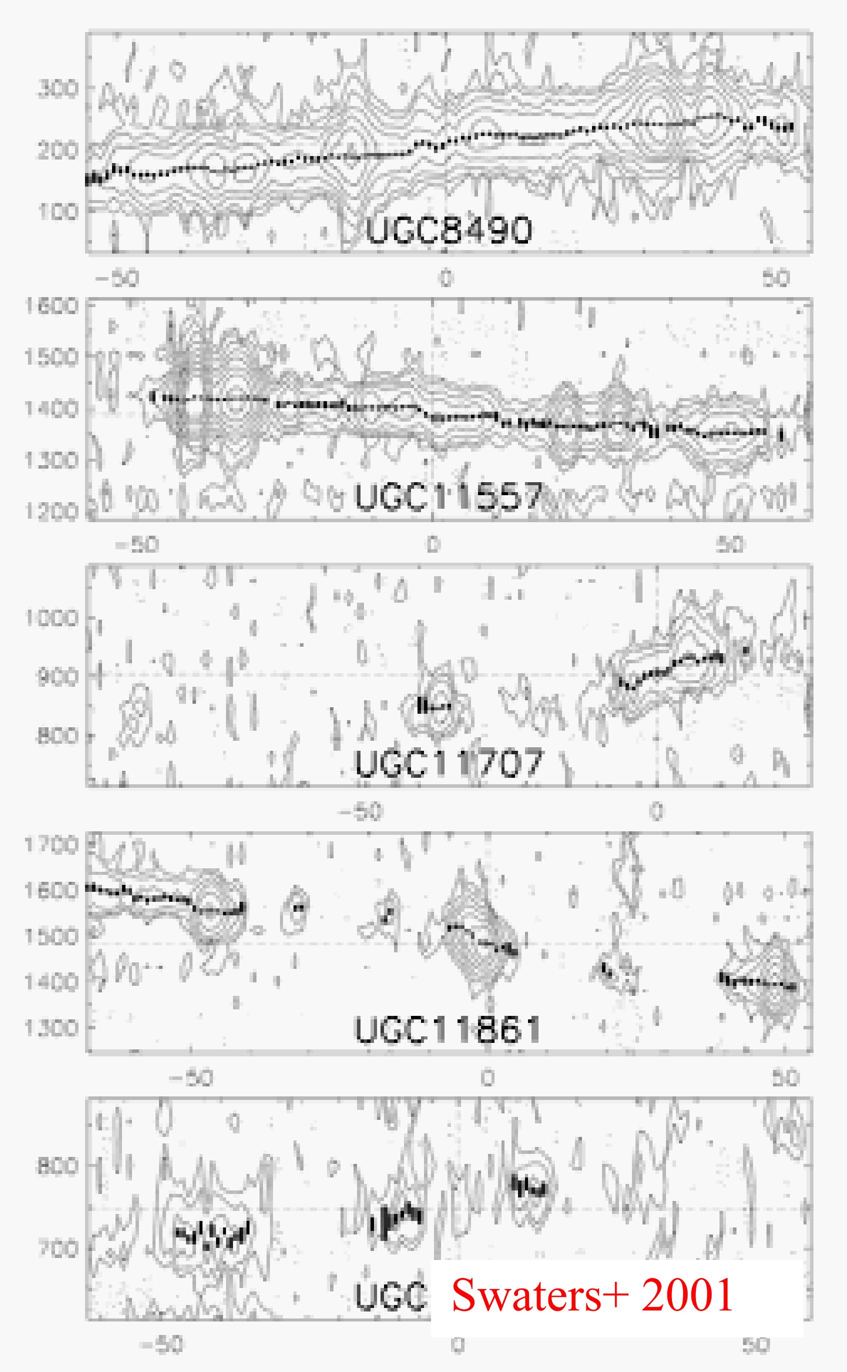
•Low Surface Brightness Galaxies

LSB: Dark matter dominated, stellar population make only a small contribution to the observed rotation curve

Rotational velocity from HI and Hα

Rotational velocity proportional to enclosed mass

$$V_c(<R) = \sqrt{\frac{GM(<R)}{R}}$$



Swaters+ 2001

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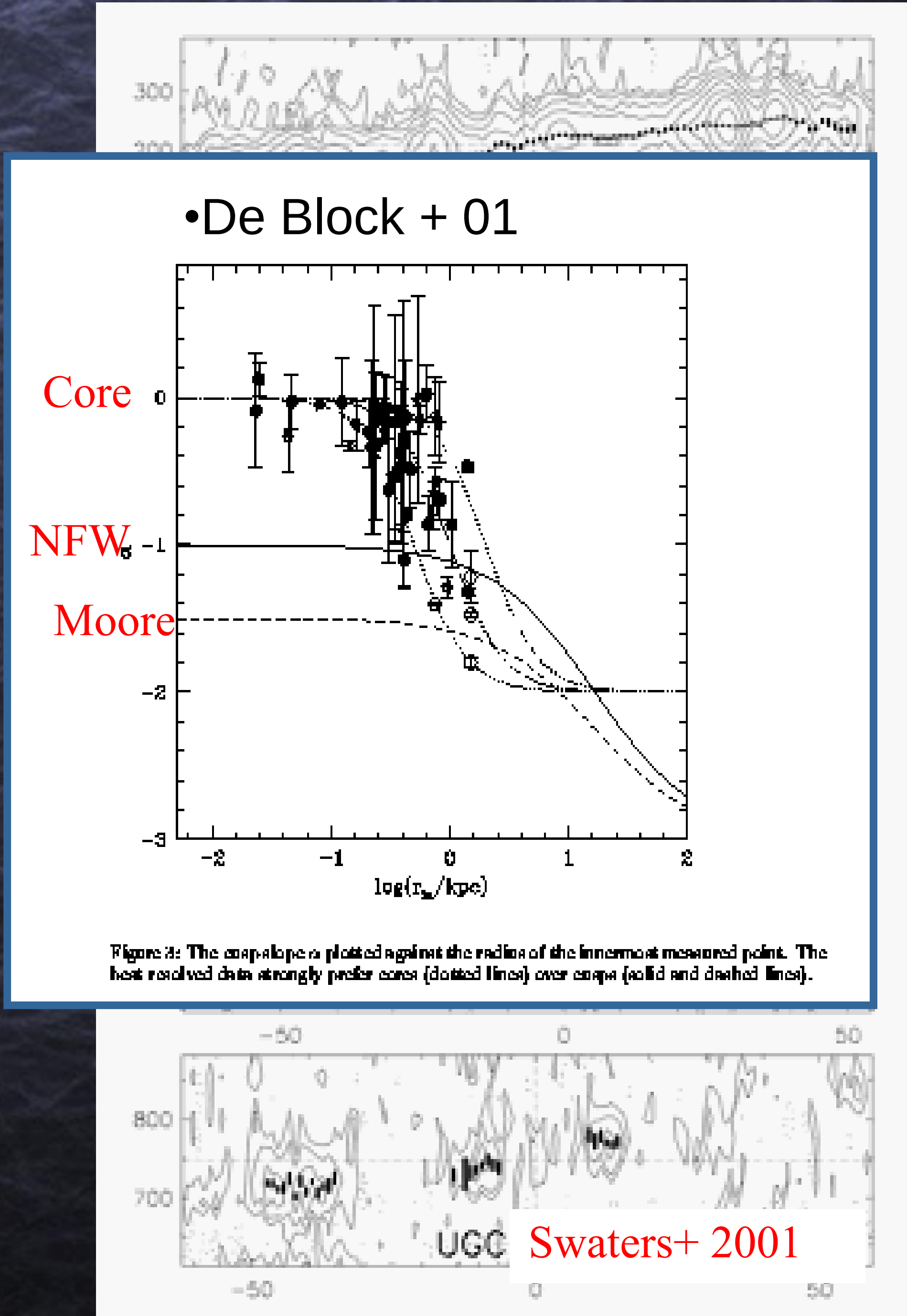

Figure 3: The core-slope α plotted against the radius of the innermost measured point. The best resolved data strongly prefer cores (dotted lines) over cusps (solid and dashed lines).

How can we explain these observations?

- In general, N-body simulations of ΛCDM on scales < 1 Mpc are at odds with observations.
- Two basic possible solutions:
  - Modifications to CDM hypothesis:
    - DM particle mass/decay/interaction cross-section?
      - Plenty of alternatives: SIDM, fuzzy dm, ultralight scalars, Bose-Einstein condensates…
  - GasAstrophysics: Effects of baryon physics
    - What astrophysics? AGN and SN feedback, winds?
    - Hydrodynamical simulations + subgrid physics can shed light on these problems at least until a dark matter particles is detected…

SUMMARY

- Modern Cosmology can be considered a real science now like any other are in which the Scientific Method (observations, measurements, experiments, and formulation of theories and constrast of predictions against data) can be applied in its full extent, thanks to the incredible developments both in astronomical observations and in numerical developments.
- Numerical simulations have become an indispensable tool in Cosmology. They are the cosmic laboratories in which we can create universe models that can be observed by the same observational tools as the real universe and compare their results.
- Therefore we can test the viability of the different hypothesis about the abundance and nature of the dark matter and dark energy in the Universe.
- There is still a lot of work to in the modelling of the complex physical processes of normal matter (gas, stars and Black holes). A self-consistent picture of the galaxy formation process needs of hydrodynamical simulations coupled with sub-grid modelling of unresolved processes associated to star formation and feedbacks for large enough volumes to compare with observations of galaxy distribution.

Some Useful Reading

- **GENERAL**
  - “Modern Cosmology”. Scott Dodelson (online)
  - “Cosmological Physics” by John Peacock (available online)
  - Extragalactic Astronomy and Cosmology”. P. Schneider (online)
- **LINEAR PERTURBATION THEORY**
  - “Large Scale Structure of the Universe” by Peebles
  - “Structure formation in the Universe”. T. Padmanabhan (online)
  - **LARGE-SCALE SURVEYS AND COSMIC STRUCTURE (ONLINE)**
    - https://ned.ipac.caltech.edu/level5/Sept03/Peacock/Peacock_contents.html
- **GALAXY FORMATION**:
  - “Galaxy Formation Theory”, A. Benson, Phys.Rep 2010. (online)
    - Arxiv:1006.5394
  - “Galaxy Formation and Evolution”. Mo, van den Boch, White 2010, Cambridge Univ. Press. (online)