Dark Matter

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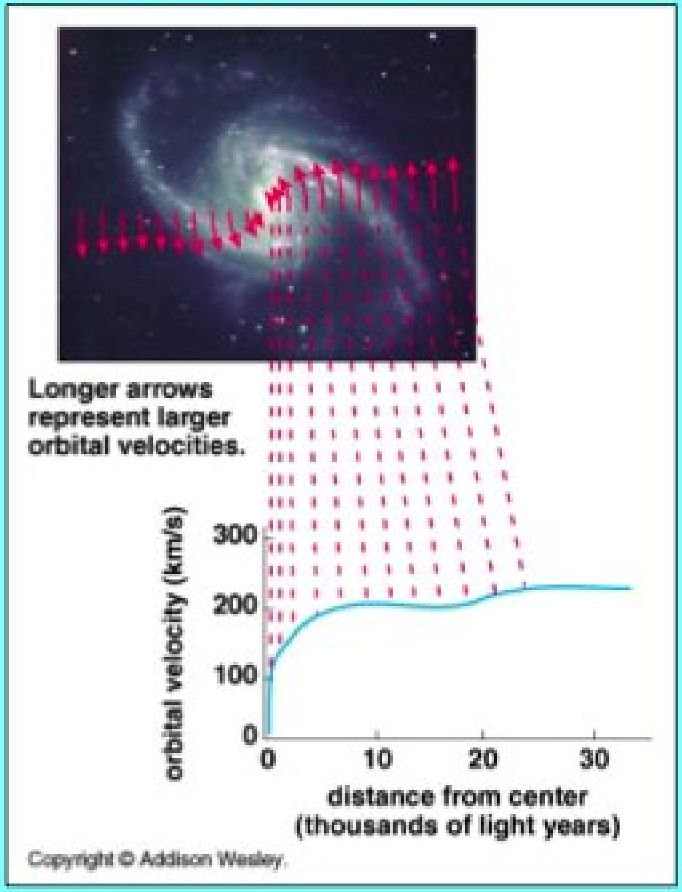
2020

Evidence for DM in galaxies: rotational curves

Look at the motion of visible stars and Hydrogen gas in galaxies (or galaxies in galactic clusters).

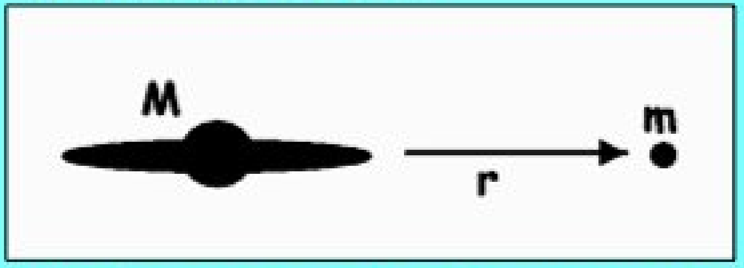
Measure velocities from redshifts.

Largely independent of their distance from the centre of the galaxy (or galactic cluster) – 'flat rotation curve'.



Evidence for DM in galaxies: rotational curves

If all the matter is concentrated near $r = 0$ where we see it:

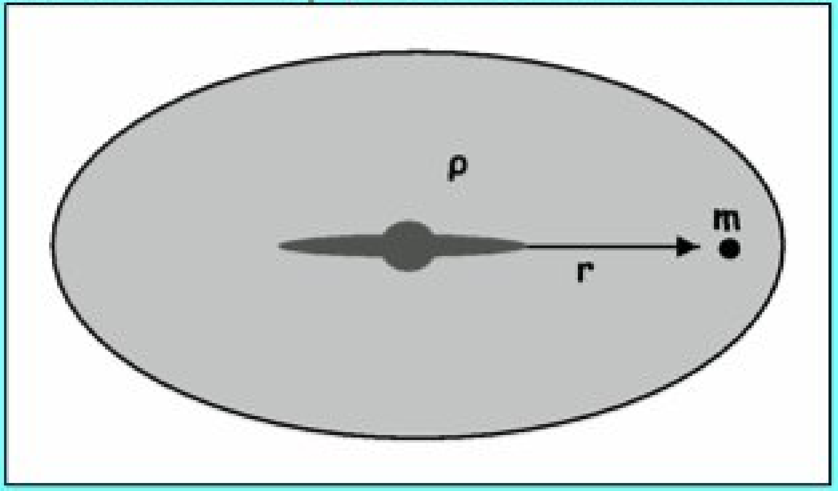


$$\frac{GMm}{r^2} = \frac{mv^2}{r}$$

$$v^2 = \frac{GM}{r}$$

$$\therefore v \propto r^{-\frac{1}{2}}$$

If the matter is distributed uniformly in a sphere with density ρ around the visible matter:

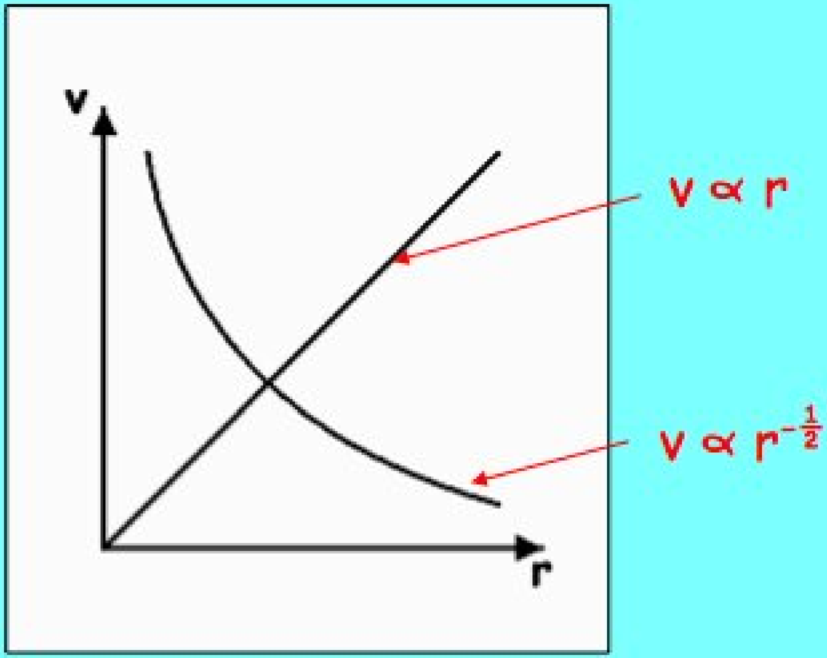


$$M = \frac{4}{3}\pi r^3 \rho \qquad v^2 = \frac{GM}{r}$$

$$v^2 = \frac{4}{3} G\pi r^2 \rho$$

$$\therefore v \propto r$$

Evidence for DM in galaxies: rotational curves



Flat is something like the sum of these two.

$$v^2 = \frac{GM}{r}$$

If v is to be constant then $M \propto r$.

Implies that there are roughly spherical halos of Dark Matter around the galaxies.

Evidence for DM in galaxies: rotational curves

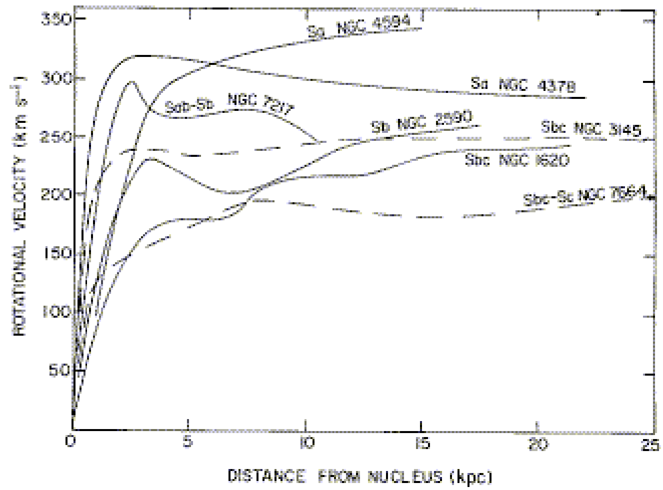


FIG. 3.—Rotational velocities for seven galaxies, as a function of distance from nucleus. Curves have been smoothed to remove velocity undulations across arms and small differences between major-axis velocities on each side of nucleus. Early-type galaxies consistently have higher peak velocities than later types.

(Rubin et al. 1978)

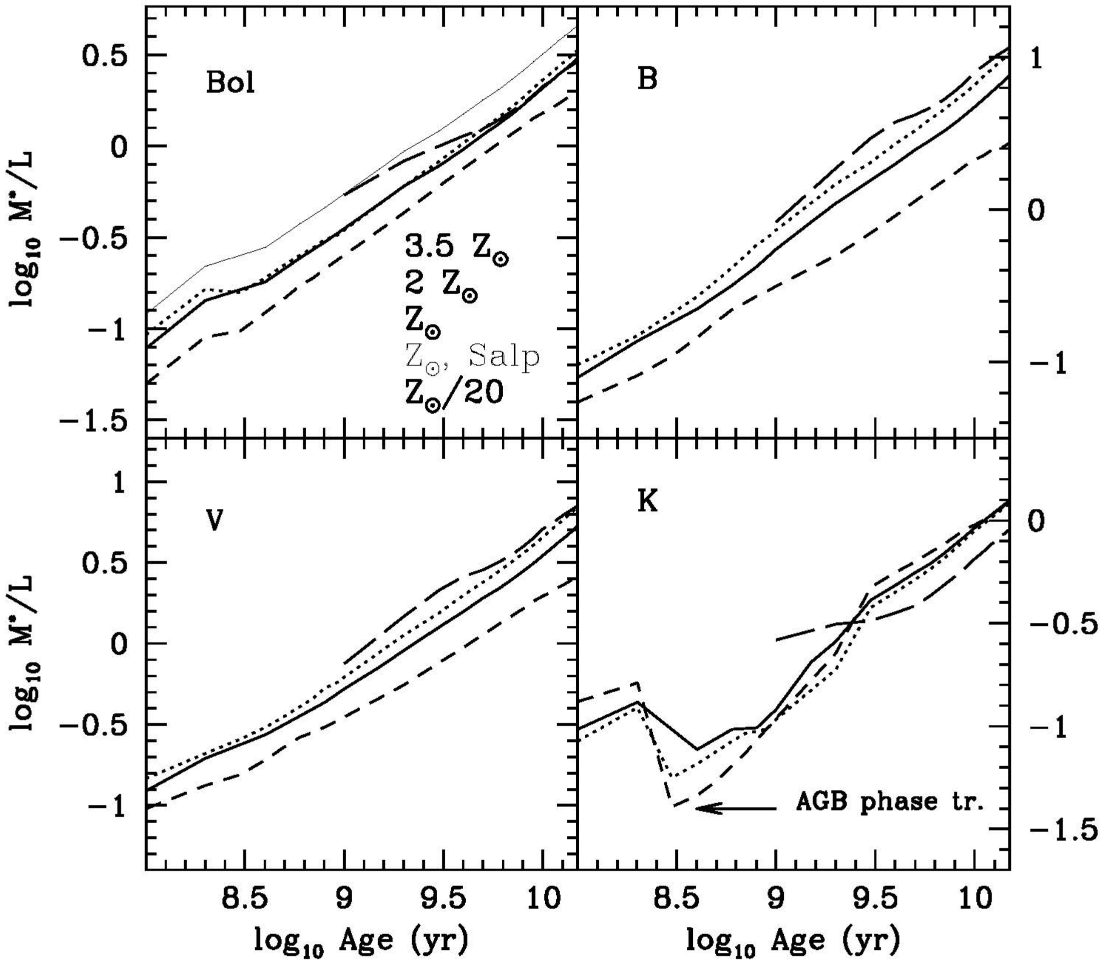
As Sofue & Rubin (2001) recount: flat curves first detected through HI (Roberts & Rots 1973), and theoreticians predicted them (e.g. Ostriker & Peebles 1973) . Faber & Gallager (1979) reviewed why DM halos should be common around spiral galaxies.

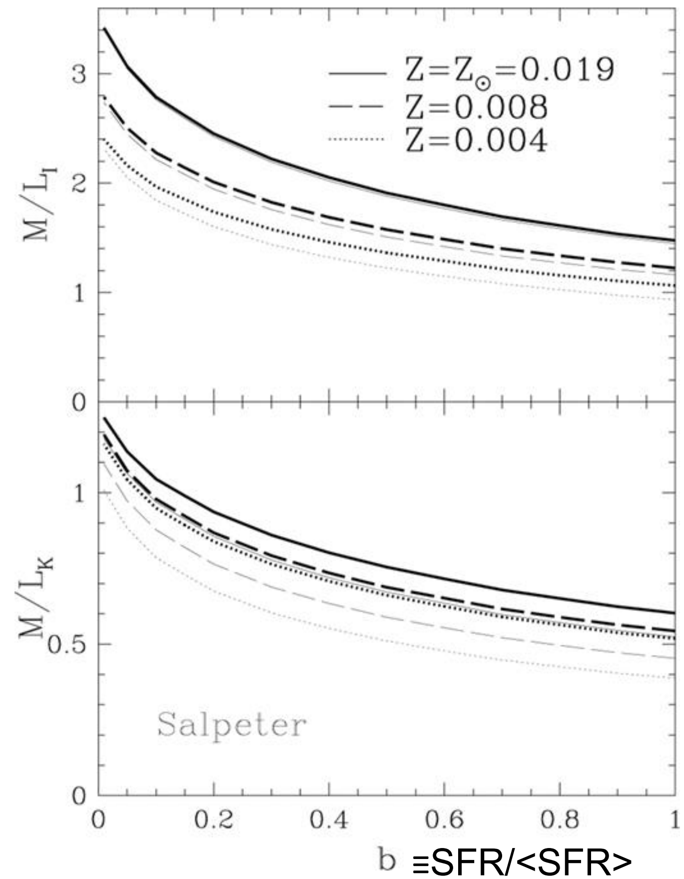
In the most extreme cases the curve can be flat to ~100 kpc

$M/L \sim 10 \pm 2\ M_{\odot} / L_{\odot}$ inside 20 kpc .
$M \sim 10^{14} M_{\odot}$ for Sp with v~250 km/s ($10^{13} M_{\odot}$ for MW)

Evidence for DM in galaxies: rotational curves

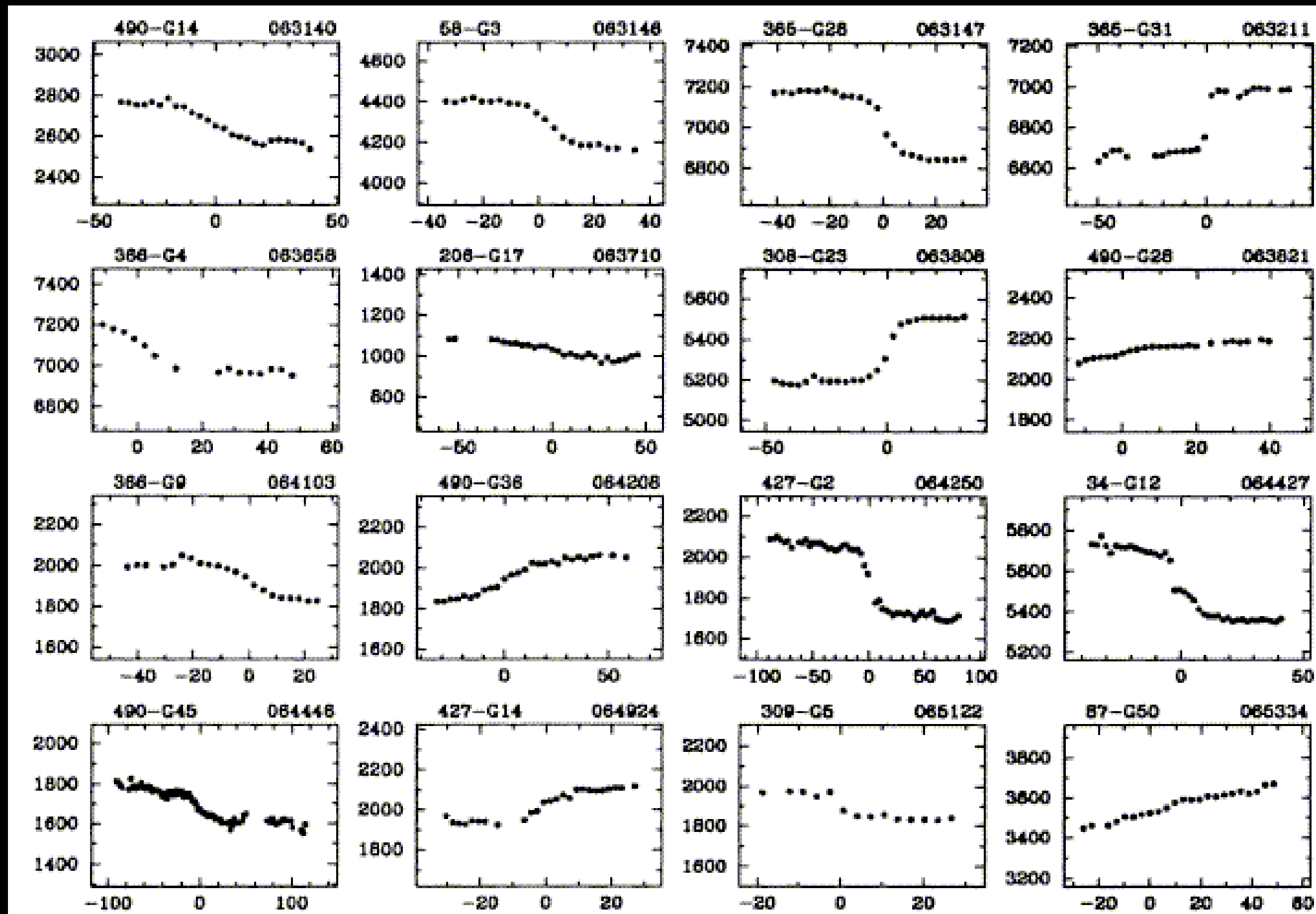
M/L for Single Stellar Populations (Maraston. 2005, see also Stéphane Courteau et al. Rev. Modern Phys., 2014: https://ned.ipac.caltech.edu/level5/Sept14/Courteau/Courteau1.html):





(Portinari et al. 2004)

Evidence for DM in galaxies: rotational curves



(Matthewson et al. 1992)

Not all spirals have flat rotation curves, but declining rotational curves are only a few cases (Sofue & Rubin 2001, ARAA)

Evidence for DM in galaxies: rotational curves

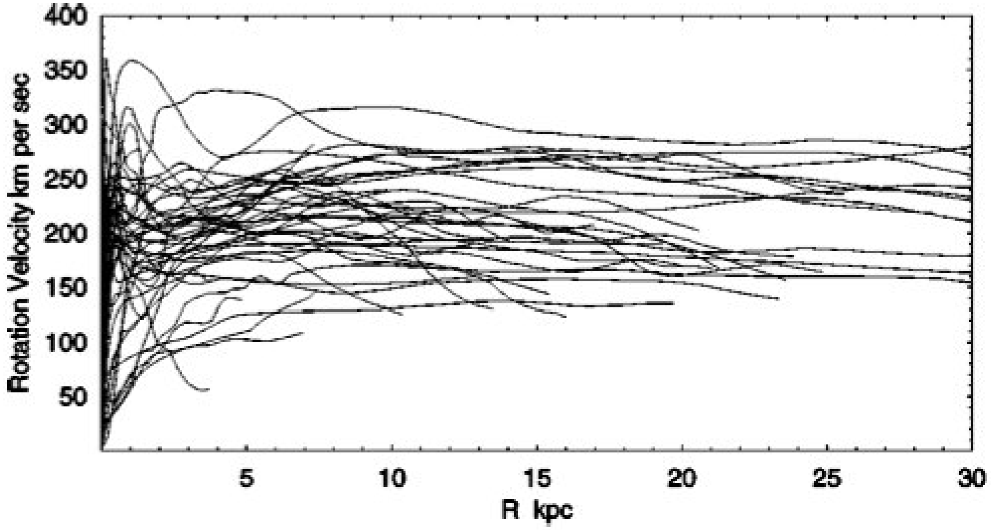


Figure 4 Rotation curves of spiral galaxies obtained by combining CO data for the central regions, optical for disks, and HI for outer disk and halo (Sofue et al. 1999a).

Not all spirals have flat rotation curves, but declining rotational curves are only a few cases (Sofue & Rubin 2001, ARAA)

Evidence for DM in galaxies: X-rays in E

Stellar kinematics can, in principle, be used, but complications due to anisotropies in orbits actually inhibits this method.

X-ray emission from $T \sim 5\times10^{6}$K ($\sim$10% of M_*), if in hydrodynamical equilibrium

$$\frac{dP}{dr} = -\frac{GM\rho}{r^2} \Rightarrow M = \frac{k_B T r}{\mu m_p G}\left(-\frac{d\ln\rho}{d\ln r} - \frac{d\ln T}{d\ln r}\right)$$

$M/L \sim 25 \pm 5\ M_\odot/L_\odot$ inside 20 kpc (Fabian et al. 1986).

There are extreme cases like M87 ($M/L \sim 200\ M_\odot/L_\odot$ at $r<270$kpc or $M \sim 6\times10^{13}\ M_\odot$)

Evidence for DM in groups of galaxies

Groups of galaxies (3-10) are usually considered bound.

Virial Theorem (2T+U=0), assuming isotropy ($v_i^2 = 3\langle u_i^2 \rangle$) and $m_i/L_i = M/L$ (Evrard 1987)

$$\sum_{i=1}^{N} m_i v_i^2 = \sum_{i=1}^{N} \sum_{j<i} \frac{G m_i m_j}{r_{ij}} \Rightarrow \frac{M}{L} = \frac{3\pi}{2G} \frac{\sum L_i u_i^2}{\sum \sum_{j<i} L_i L_j r_{ij}^{-1}}$$

$M/L \sim 180 \pm 50\ M_\odot/L_\odot$ (Ramella et al. 1989).

Evidence for DM in clusters of galaxies

Clusters of galaxies (>100) are usually considered bound.

Virial Theorem (2T+U=0), $M=2\sigma^2 r/G$

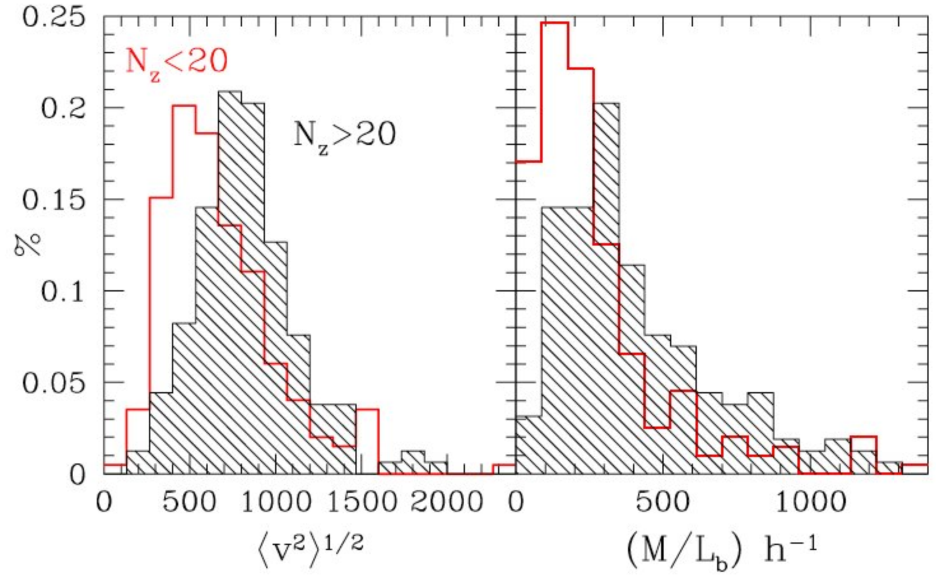


Figure 18: Left panel: Frequency distribution of ABELL/ACO cluster velocity dispersions based on $N_z < 20$ (empty histogram) and on $N_z > 20$ (shaded histogram). Right panel: The corresponding M/L distribution.

median(M/L)~320 $M_{\odot}/L_{\odot}$ (Carlberg et al. 1997).

First evidence of DM noticed by Zwicky (1933) in Coma, after having taken only 9 z's!.

Matter in the Universe

Table 2: Mass-to-light ratios and contribution to $\Omega_{\rm m}$ for the different scales.

Object	scale (h^{-1} Mpc)	$\langle M/L \rangle\, h^{-1}$	$\Omega_{\rm m}$
Spirals	0.02	10 ± 2	0.0071 ± 0.0015
Ellipticals	0.02	25 ± 5	0.018 ± 0.004
Galaxy pairs	0.1	80 ± 20	0.057 ± 0.012
Groups	0.8	180 ± 60	0.13 ± 0.09
Clusters	1.5	320^{+170}_{-85}	$0.23^{+0.12}_{-0.06}$

where

$$\rho_{\rm cr} = \frac{3H_0}{8\pi G} = 1.88 \times 10^{-29} h^2 \ {\rm gcm^{-3}}$$

$$\Omega_{\rm m} \equiv \frac{\rho_{\rm m}}{\rho_{\rm cr}}$$

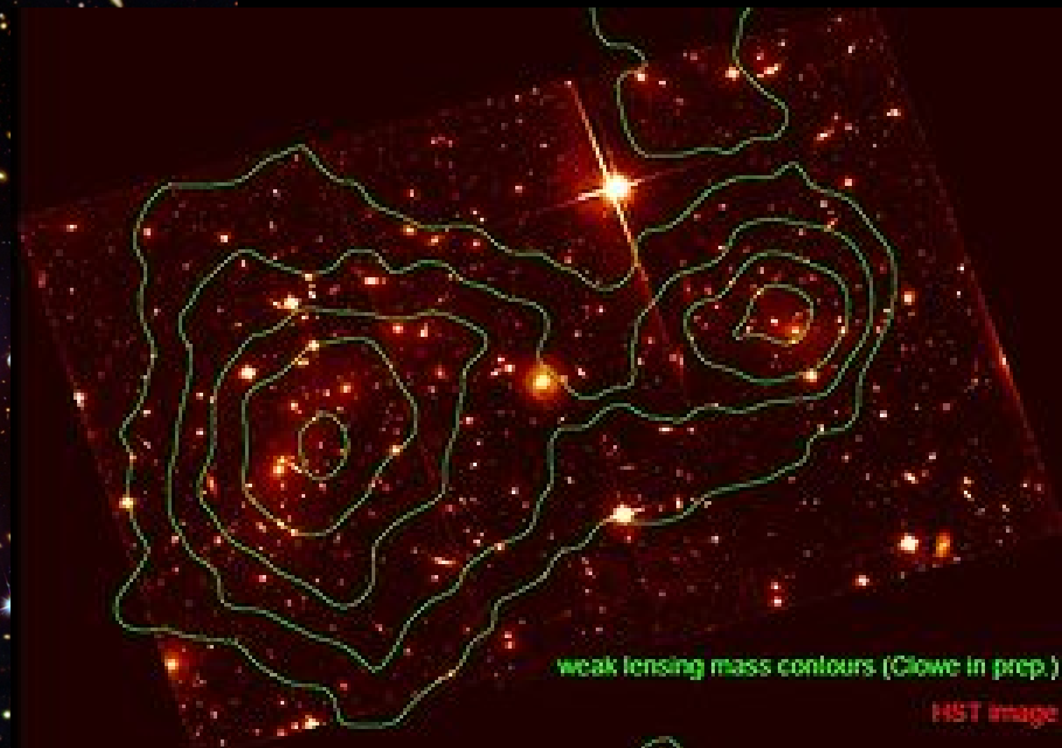
Since clusters are the deepest potential wells in the Universe, it is expected that their M/L represents that of the Universe.

Summary of DM evidences

- proper velocities in Coma and other clusters and groups of gals, from Zwicky onwards
- Flat rotation curves of S gals
- Content of X-rays in E gals
- Lensing map in Bullet Cluster
- Amplitude of peaks in power-spectra of CMB
- Big Bang Nucleosynthesis implied baryon density $\Omega_B \sim 0.04$

Bullet Cluster weak lensing map

Merger of 2 clusters about 4500km/s, spacial separation of dark and (hot gas) baryonic matter



Red, X-ray: NASA/CXC/CfA/ Markevitch et al. (2004)
Blue Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/ Clowe et al. (2004)
Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al

Types of Dark Matter

Dark Matter can be classified as

- Baryonic

- Non-baryonic: - cold (non-relativistic, heavy), > 1 keV

  - hot (relativistic, light)

Baryonic DM (no larger than 4% of E-m content of the Universe)

- Remnants of dead-stars

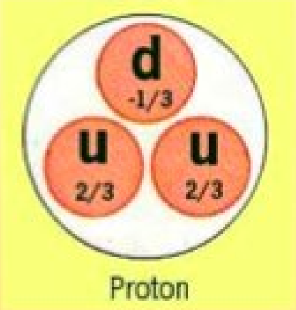
- H ice, that could gassify

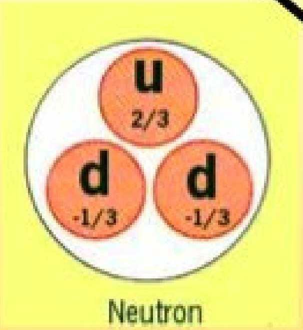
- Comets

- MACHOs (Massive Compact Halo Objects): very dim low mass stars, brown dwarfs and planets.

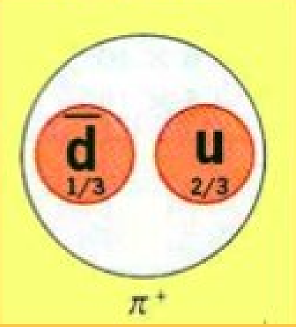
What is a Baryon?

Baryons are made from three quarks





Mesons (unstable) are made from quark-antiquark pairs



Hadrons

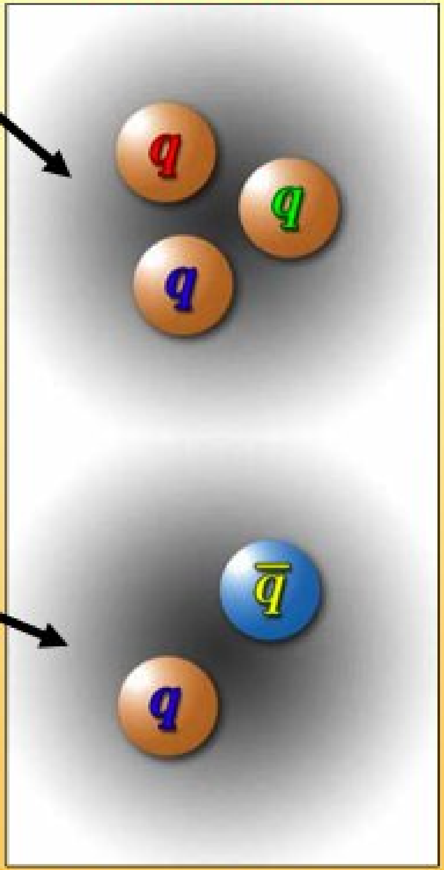


image from hands-on-cern.physto.se/.../ani_paty1.html

Flavor	Charge
Up	+ 2/3
Down	- 1/3
Charm	+ 2/3
Strange	- 1/3
Top	+ 2/3
Bottom	- 1/3

Flavor	Charge
Anti-Up	- 2/3
Anti-Down	+ 1/3
Anti-Charm	- 2/3
Anti-Strange	+ 1/3
Anti-Top	- 2/3
Bottom	+ 1/3

For reasons not well understood, hadrons only comes in colorless composites

Sub-particle charts (ParticleAdventure.org)

FERMIONS
matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

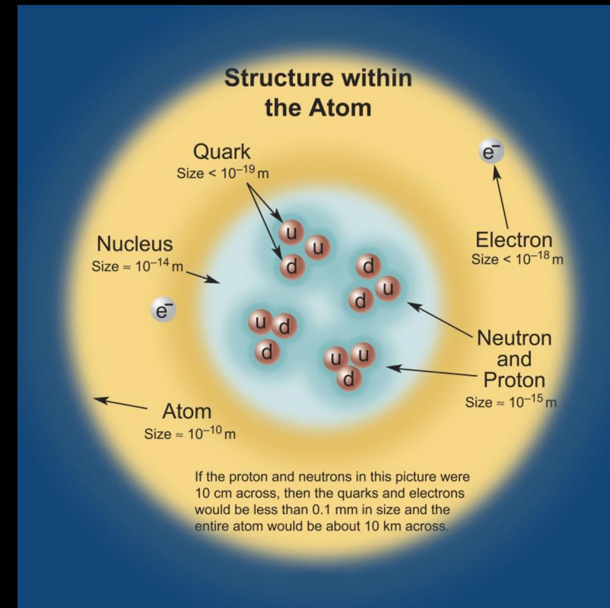
Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ tau	1.777	–1

Quarks spin =1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

Ordinary matter

At high-E



Hadrons

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$
Baryons are fermionic hadrons.
These are a few of the many types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	antiproton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Mesons $q\bar{q}$
Mesons are bosonic hadrons
These are a few of the many types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.776	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2.980	0

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BOSONS
force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^- W bosons	80.39	–1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin =1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Hadrons

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$
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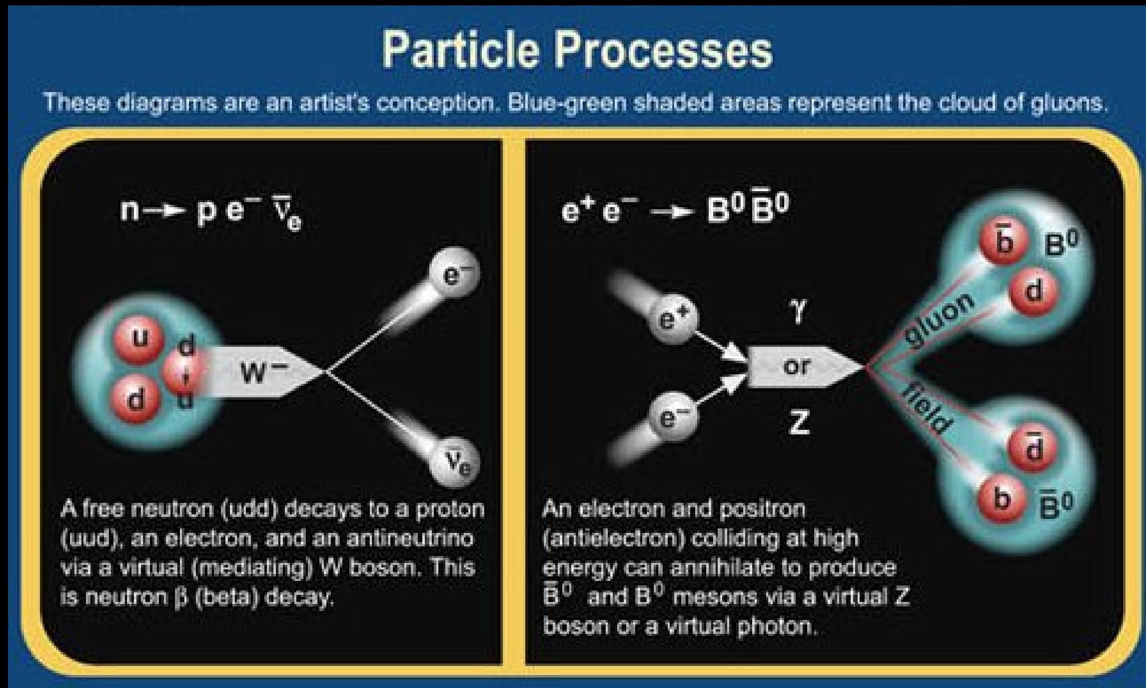
Sub-particle charts (ParticleAdventure.org)

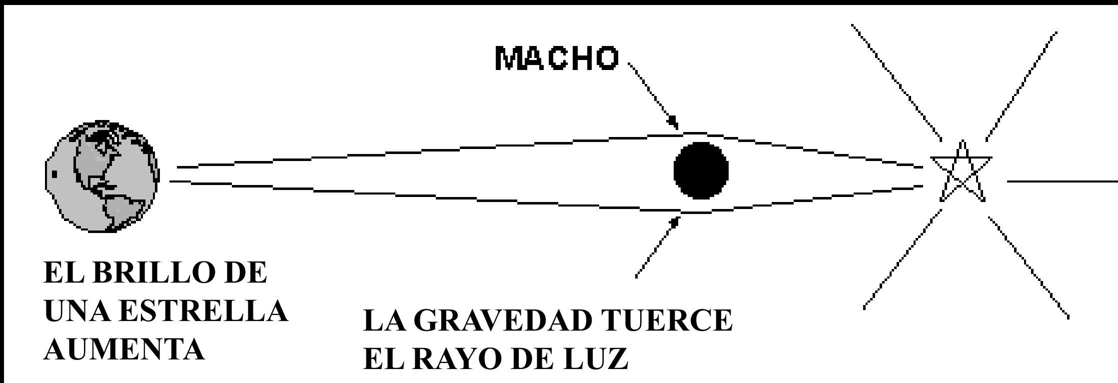


Properties of the Interactions

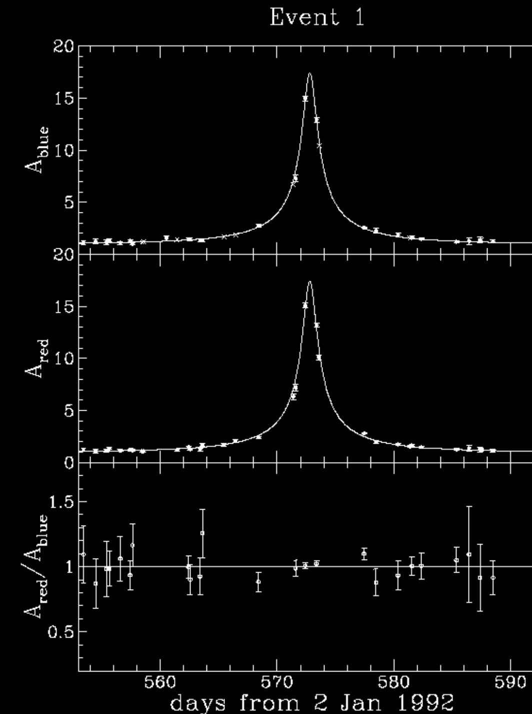
The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

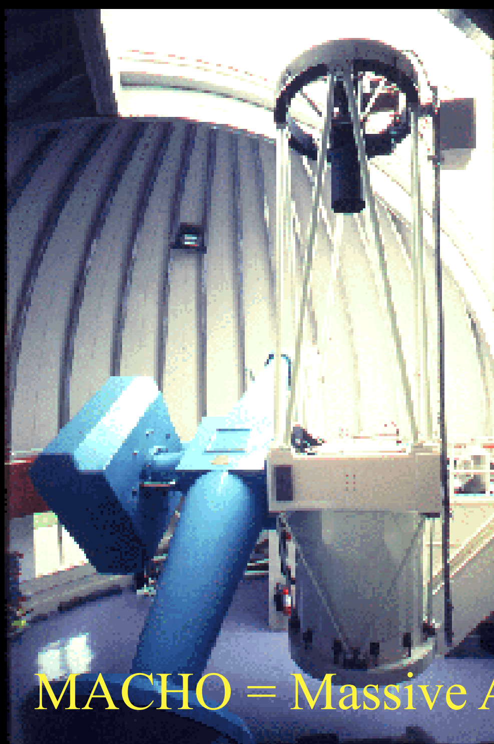
Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction (Electroweak)	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at 10^{-18} m	10^{-41}	0.8	1	25
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60

En busca de la materia perdida

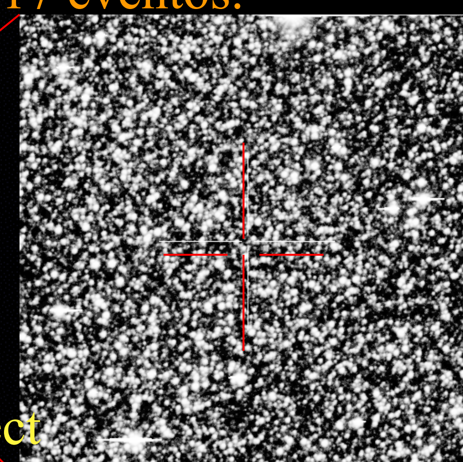


$$A = \frac{1}{2}\left[\frac{\sqrt{1+r^2}}{r} + \frac{r}{\sqrt{1+r^2}}\right] \approx (2r)^{-1} (r << 1)$$



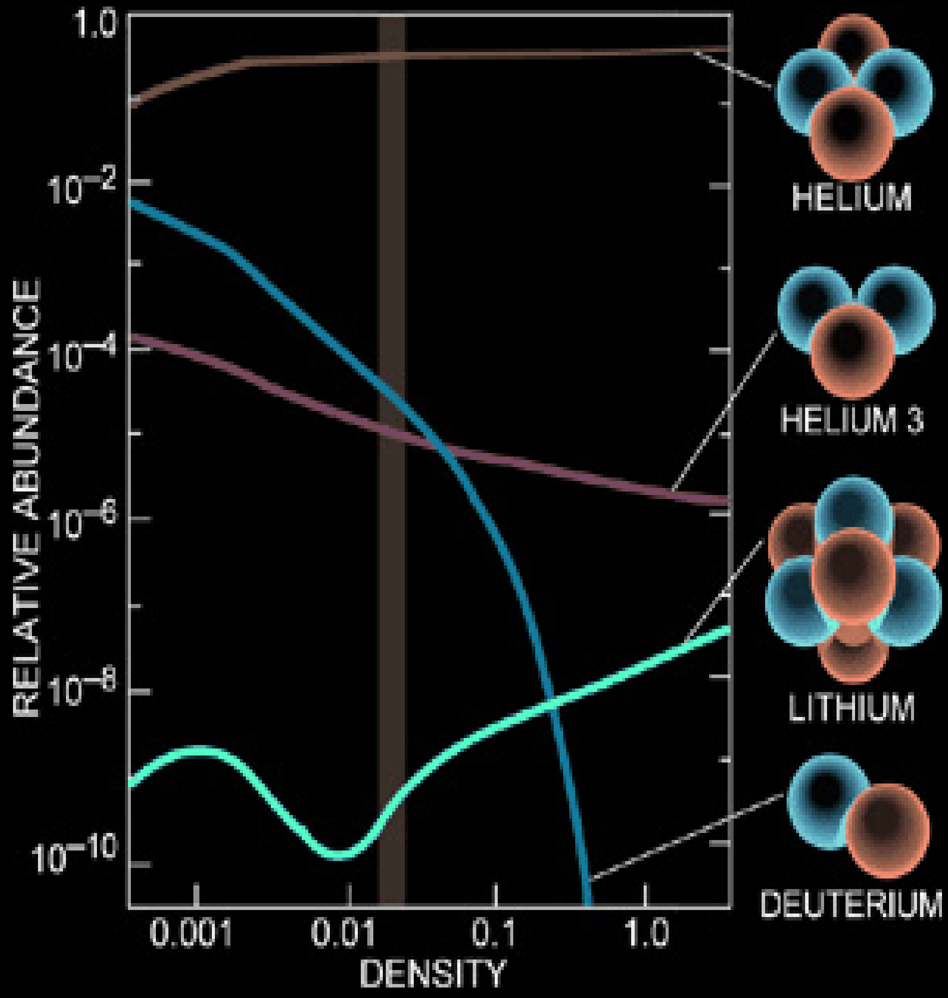


búsqueda de MACHOs hacia la Gran Nube de Magallanes y el Halo de la Vía Láctea © *Consorcio MACHO*: masa bariónica en 0.1-0.9$M_\odot$ sólo 20% de la masa dinámica. Tras seguimiento de $12x10^6$ estrellas, 17 eventos.



MACHO = Massive Astrophysical Compact Halo Object

Resultados del cálculo de abundancias primordiales



La materia bariónica (que constituye los átomos de los que estamos formados) tiene una densidad promedio en el Universo de

1 átomo / 4 m^3

t ~ 1 min

Properties of Dark Matter

Non-baryonic Dark Matter is

- Massive $w \approx 0 \Rightarrow \rho = \rho_0 a^{-3}$

- Neutral No radiation now, but also, if, for instance +1, could have formed "heavy water". In sea water for $5m_p < m_{DM} < 16m_p$ $\Omega_{DM} < 10^{-17}$

If it were milicharged, it would be tightly coupled with baryons, and the amplitudes in PS of CMB would be wrong.

- Cold i.e. non-relativistic, at least by z~10000 (t~7000 yr) -- see later, LSS of gals.

- non interactive on itself <1 scattering in a t_H ➡ $\sigma < 10^{-4}$ cm^2

- not a large-scale new force of nature

β = new-force/gravity < 0.2

Types of Dark Matter

Non-Baryonic DM (at least 22%!!!)

Cold DM

Several theoretical particles, including WIMPS (Weakly Interacting Massive Particles)

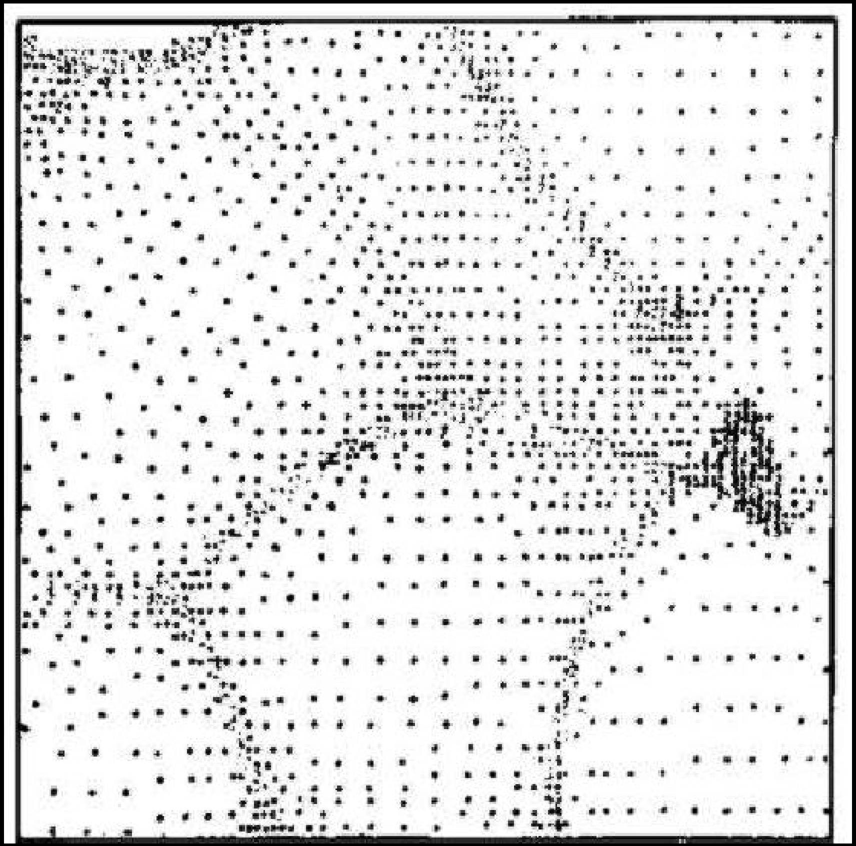
Hot DM

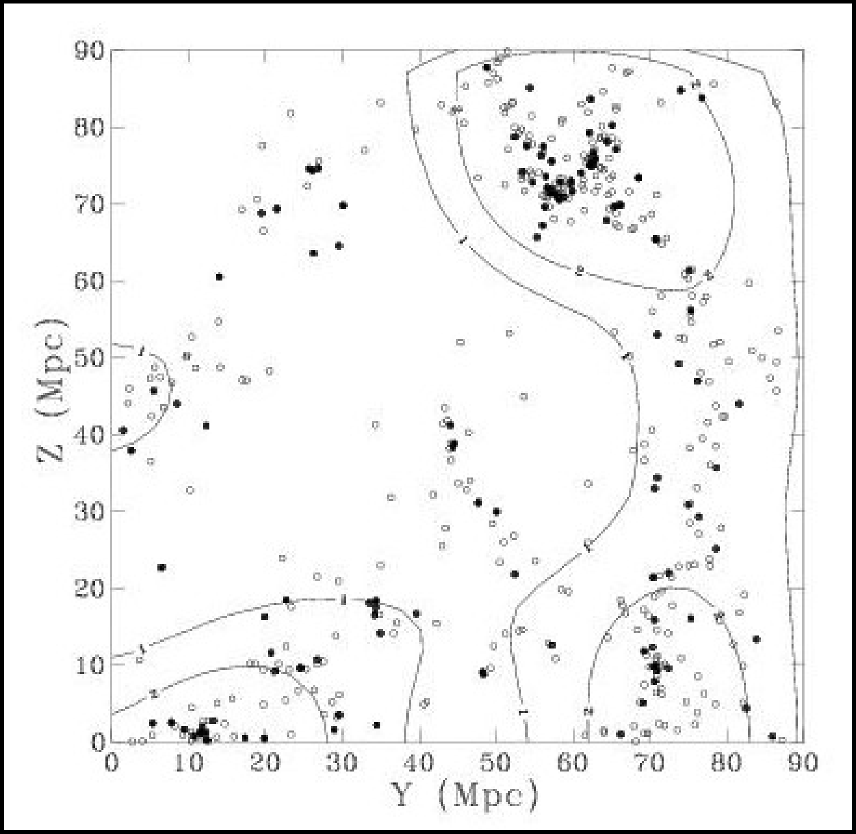
Unlikely mayor contributor due to LSS hierarchical growth

- neutrinos with mass 1-10 eV/c^2 not ruled out
- neutrinos with mass ~45GeV/c^2 ruled out by LEP
- very heavy neutrinos already ruled out

Hot Dark Matter

Zeldovich's original suggestion was that DM is made of massive neutrinos (hot dark matter). But in this case the structure forms too late and there is no fine structure in voids (Zeldovich, Einasto, Shandarin 1982).



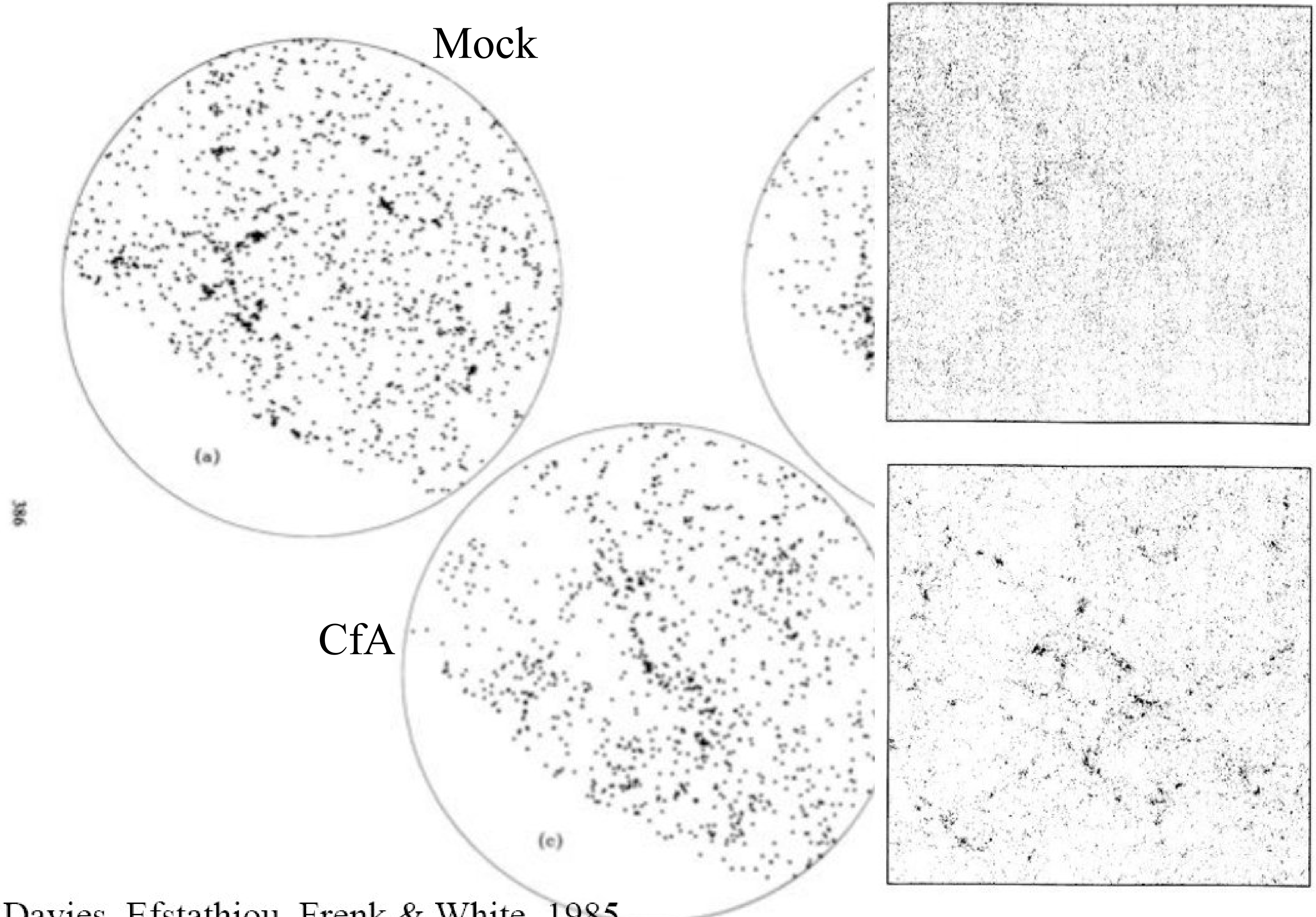


Cold Dark Matter

As an alternative to neutrinos axions and other weakly interactive particles were suggested (Peebles 1982, Bond, Szalay, Turner 1982, Sciama 1982

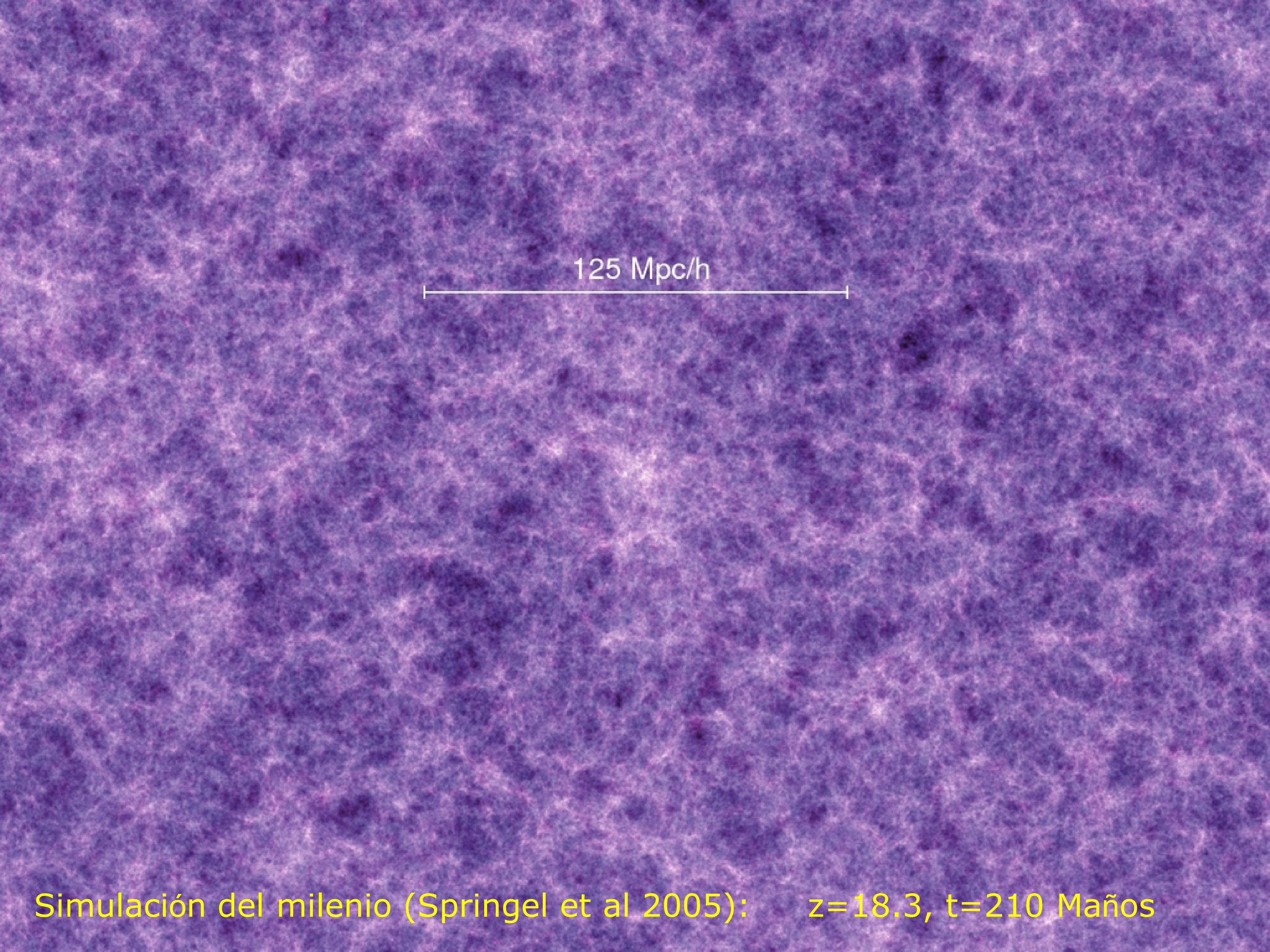
This new model yields a distribution of galaxies with very good agreement with observations, producing both massive and faint galaxy filaments with good percolation; the structure forms early (Melott et al. 1983).

This model was named Cold Dark Matter, in contrast to neutrino model named Hot Dark Matter (Blumenthal & Primack 1984, Blumenthal, Faber, Primack, Rees 1984, Davies et al. 1985). The last two are classical Cold Dark Matter papers.

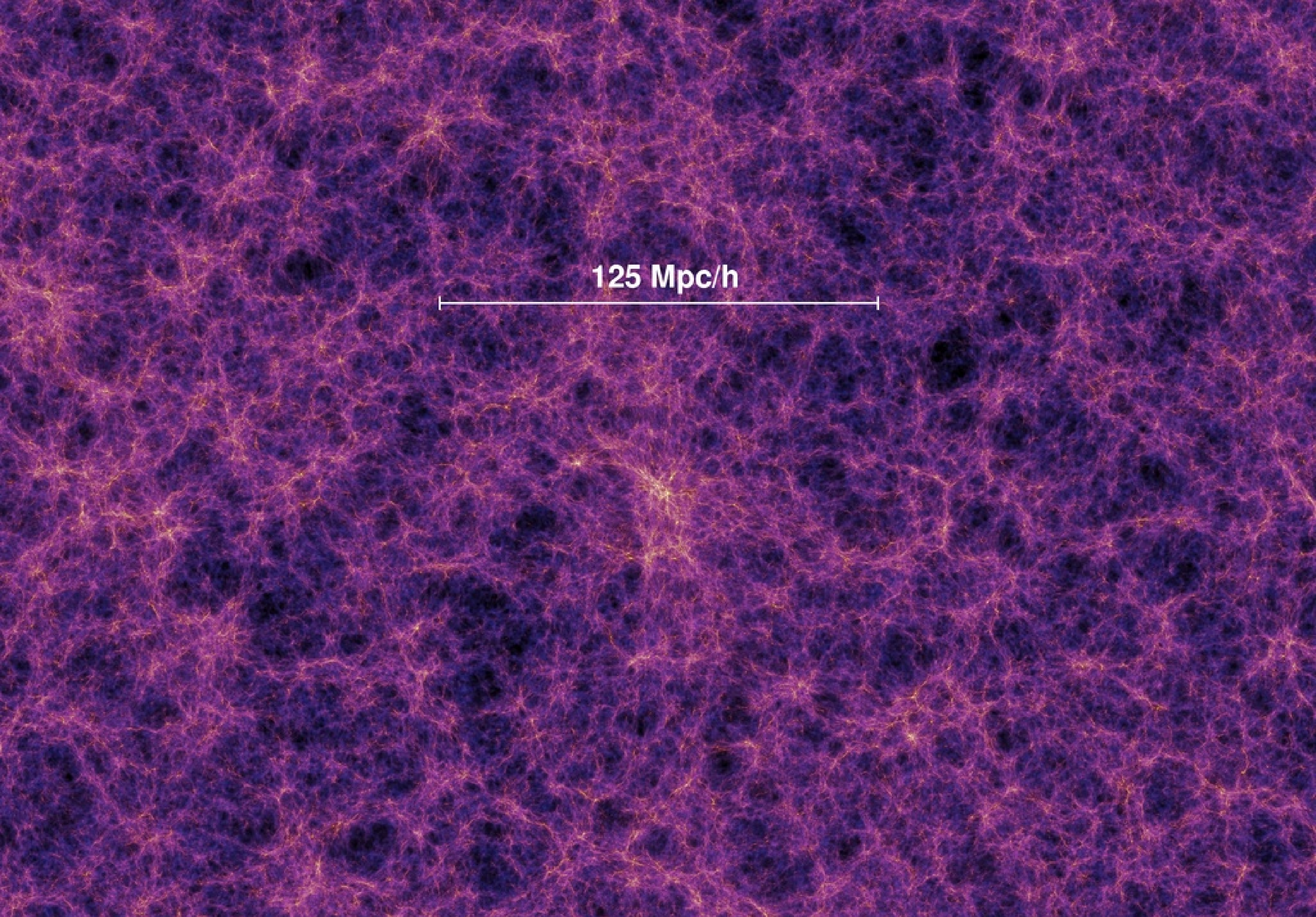


Davies, Efstathiou, Frenk & White, 1985

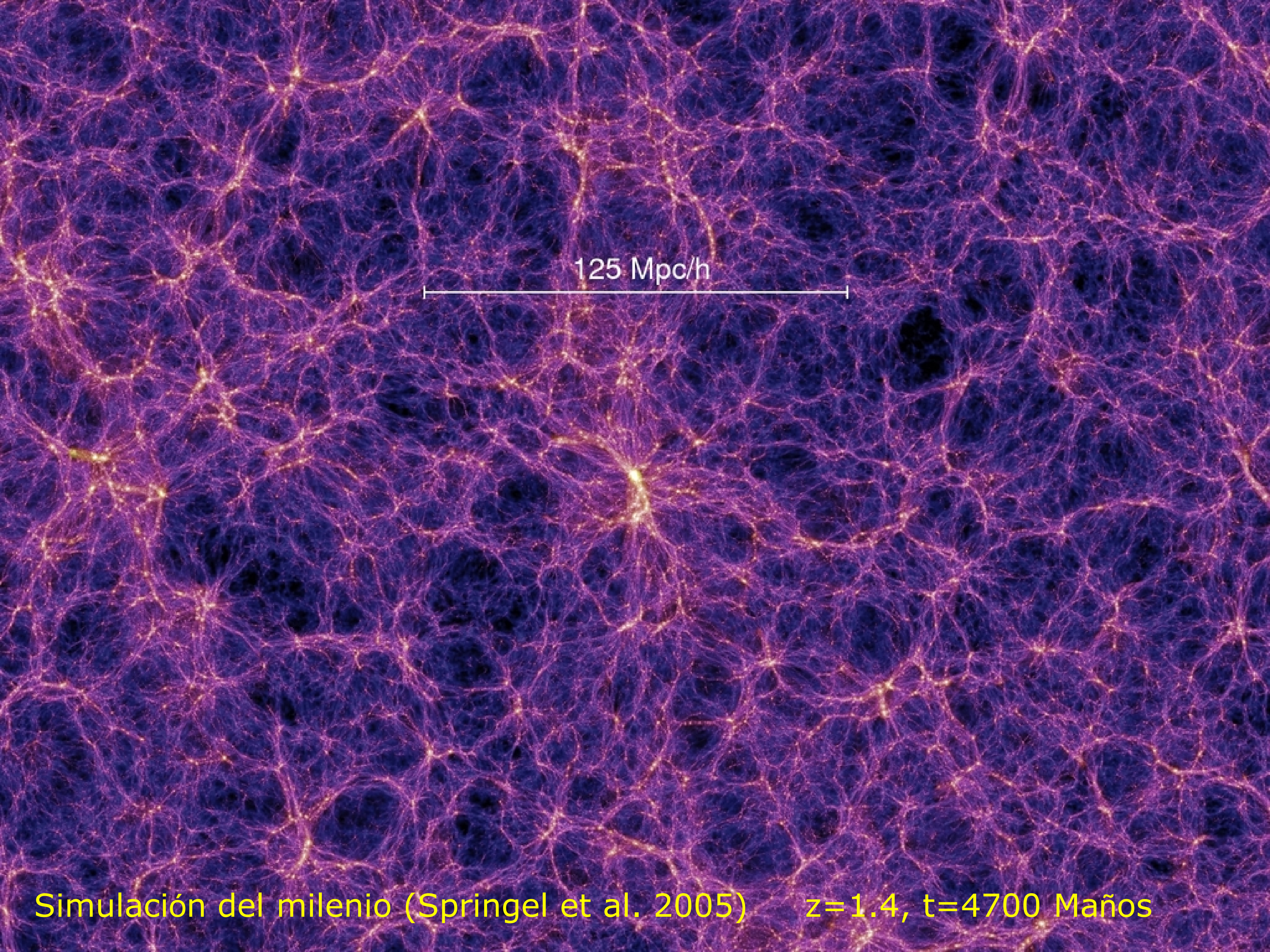
FIG. 12.—Redshift catalogs constructed from two open models (O2 and O3) are shown in (a) and (b) as projections onto the "sky." Particles were selected for inclusion in these catalogs in such a way as to mimic the northern CfA survey. The real data are shown in the same format in (c). These are equal area plots of the sky; the outer circle corresponds to Galactic latitude +40°, while the empty regions correspond to declinations below 0°. In constructing the catalog from O3 shown in (b), the "observer" was purposely sited near a prominent cluster.



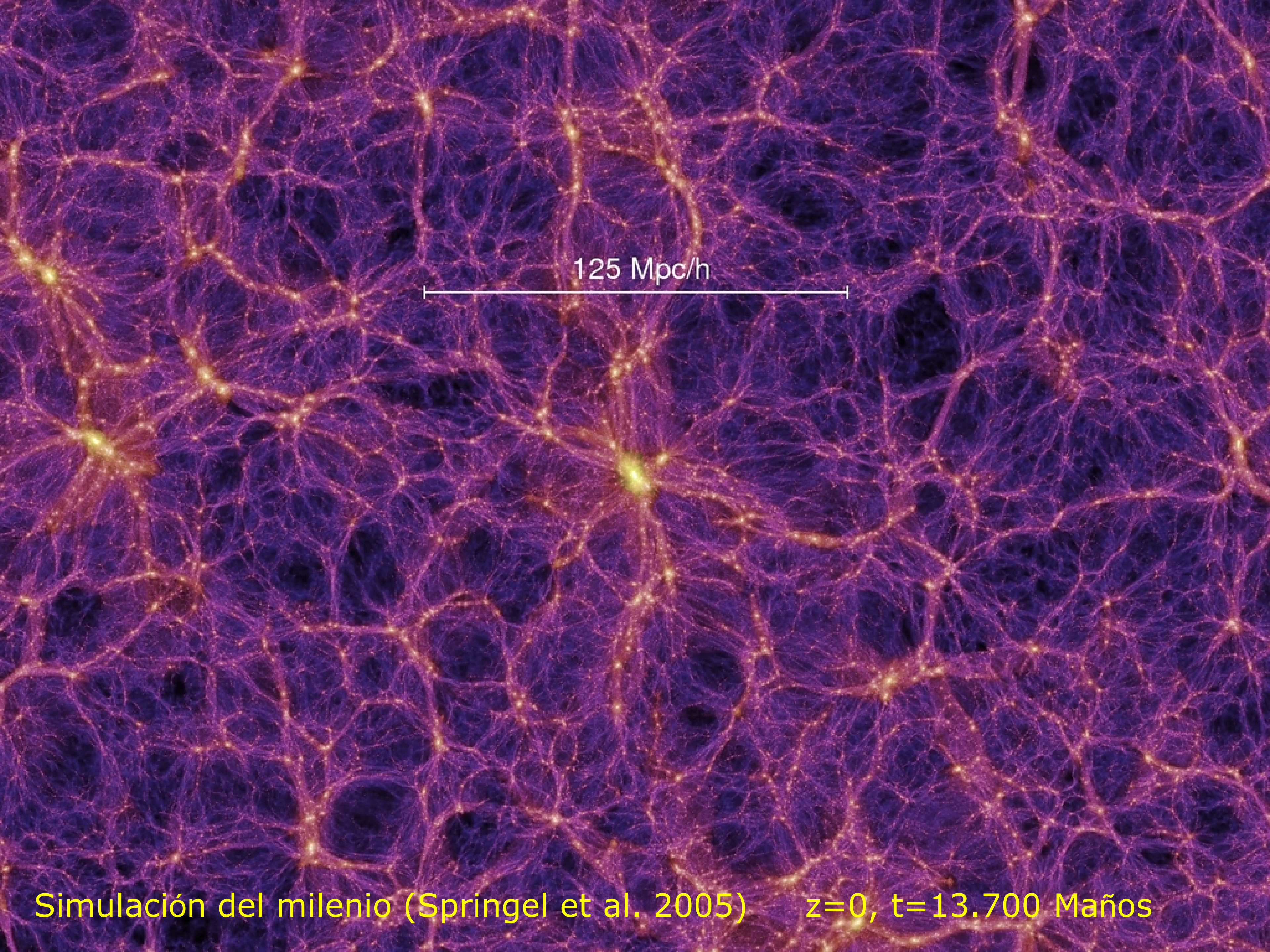
Simulación del milenio (Springel et al 2005):   z=18.3, t=210 Maños



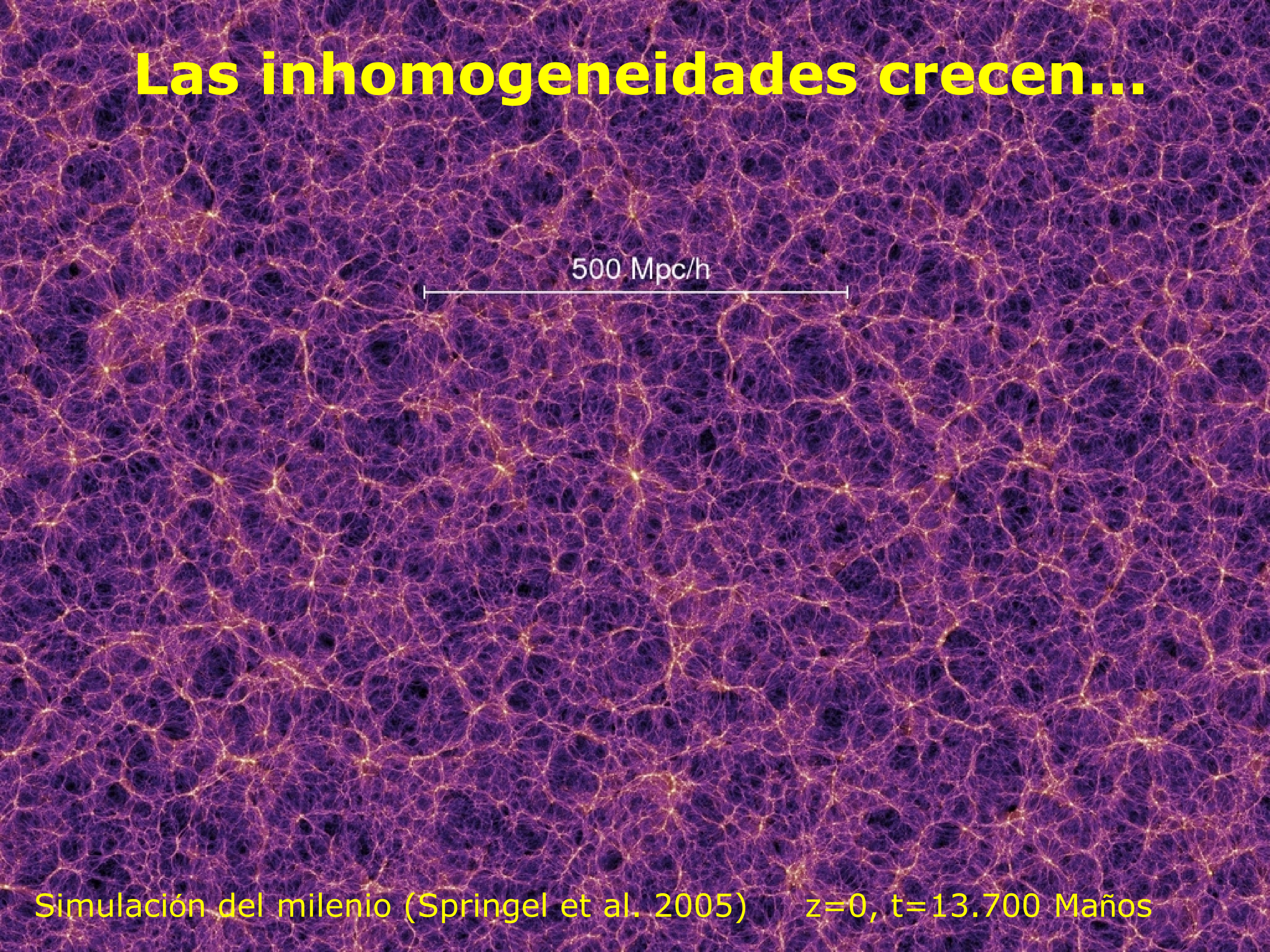
Simulación del milenio (Springel et al. 2005):   z=5.7, t=1000 Maños



Simulación del milenio (Springel et al. 2005) z=1.4, t=4700 Maños

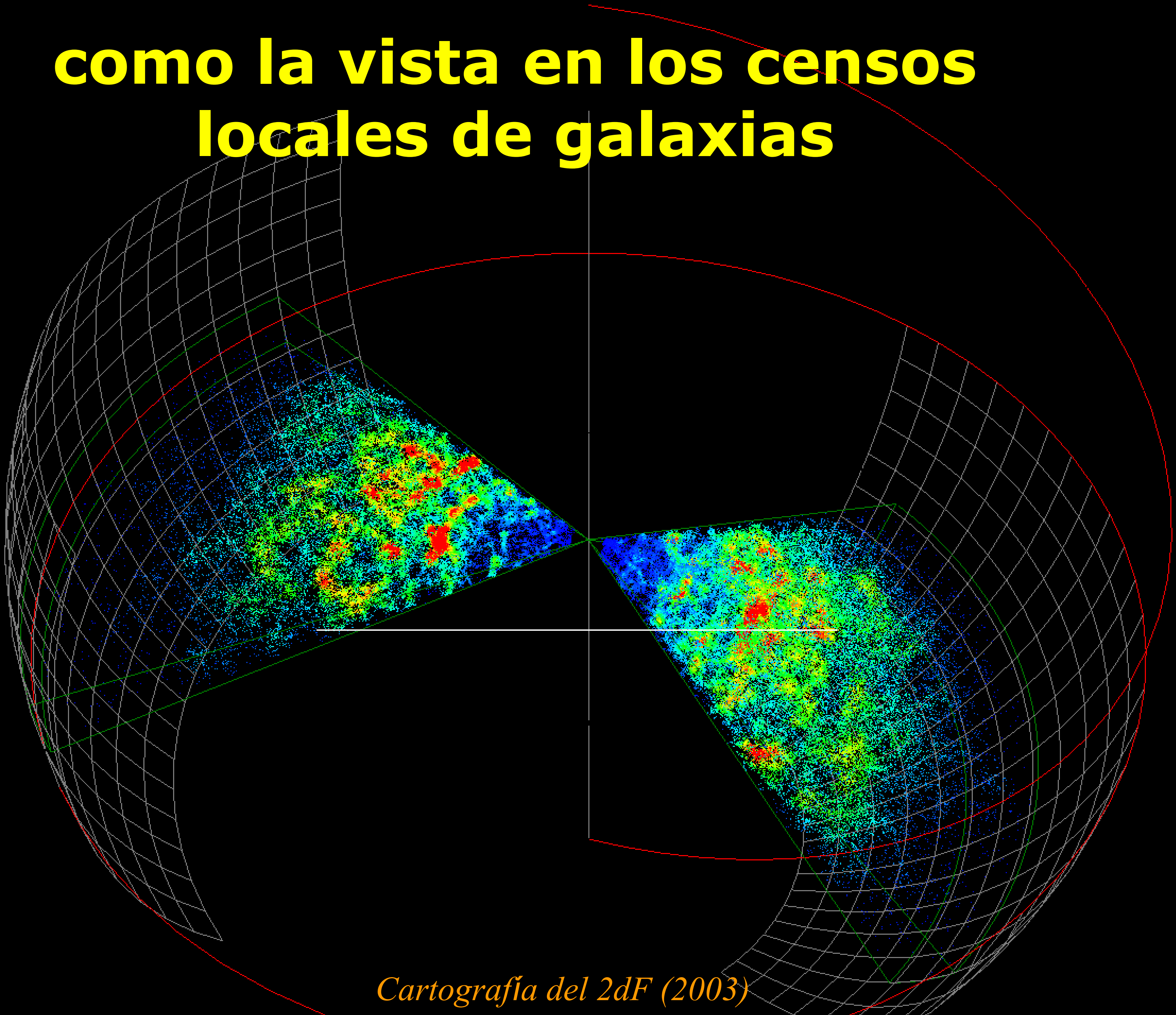

125 Mpc/h
Simulación del milenio (Springel et al. 2005)
z=0, t=13.700 Maños

Las inhomogeneidades crecen...



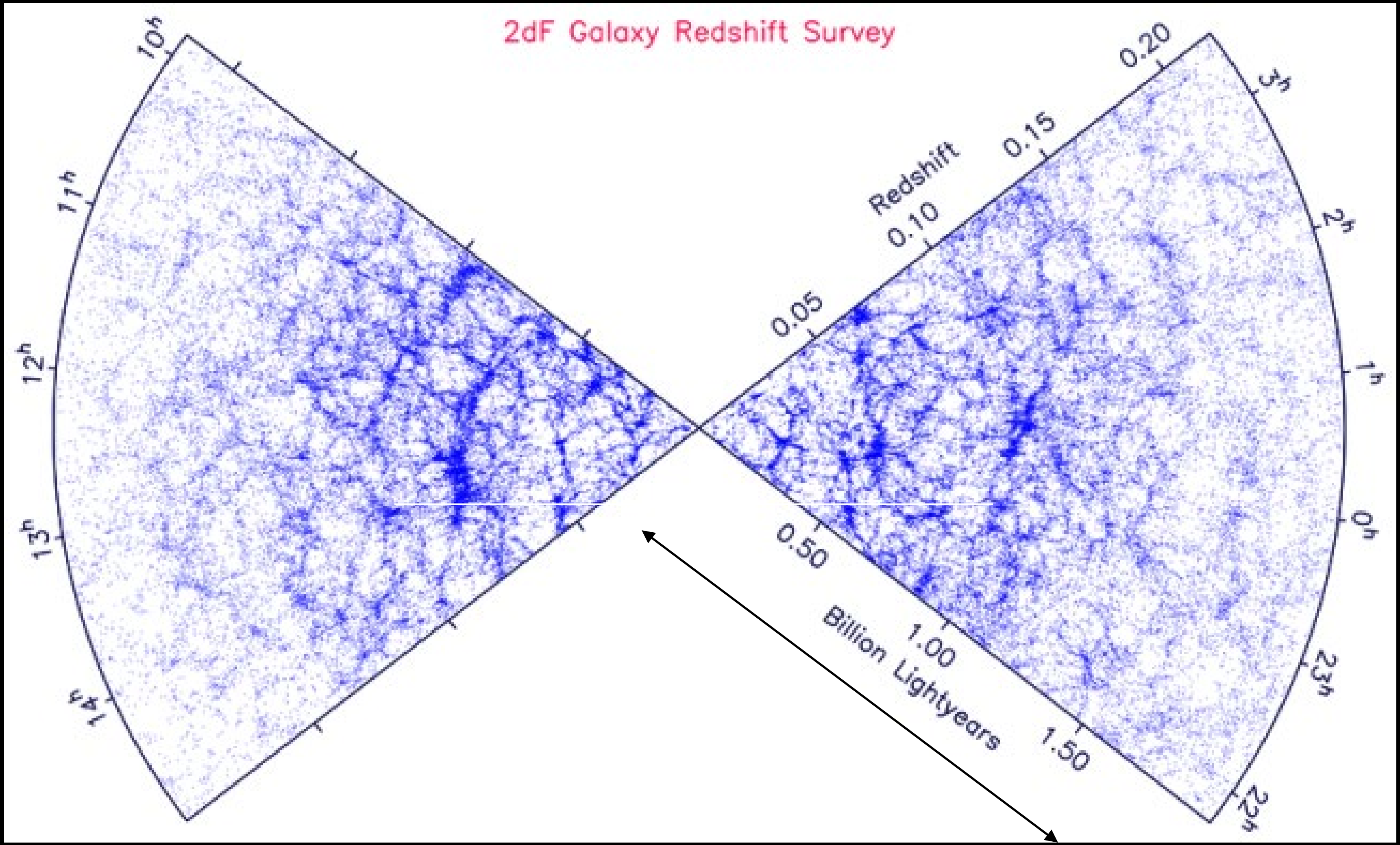
Simulación del milenio (Springel et al. 2005)   z=0, t=13.700 Maños

como la vista en los censos locales de galaxias

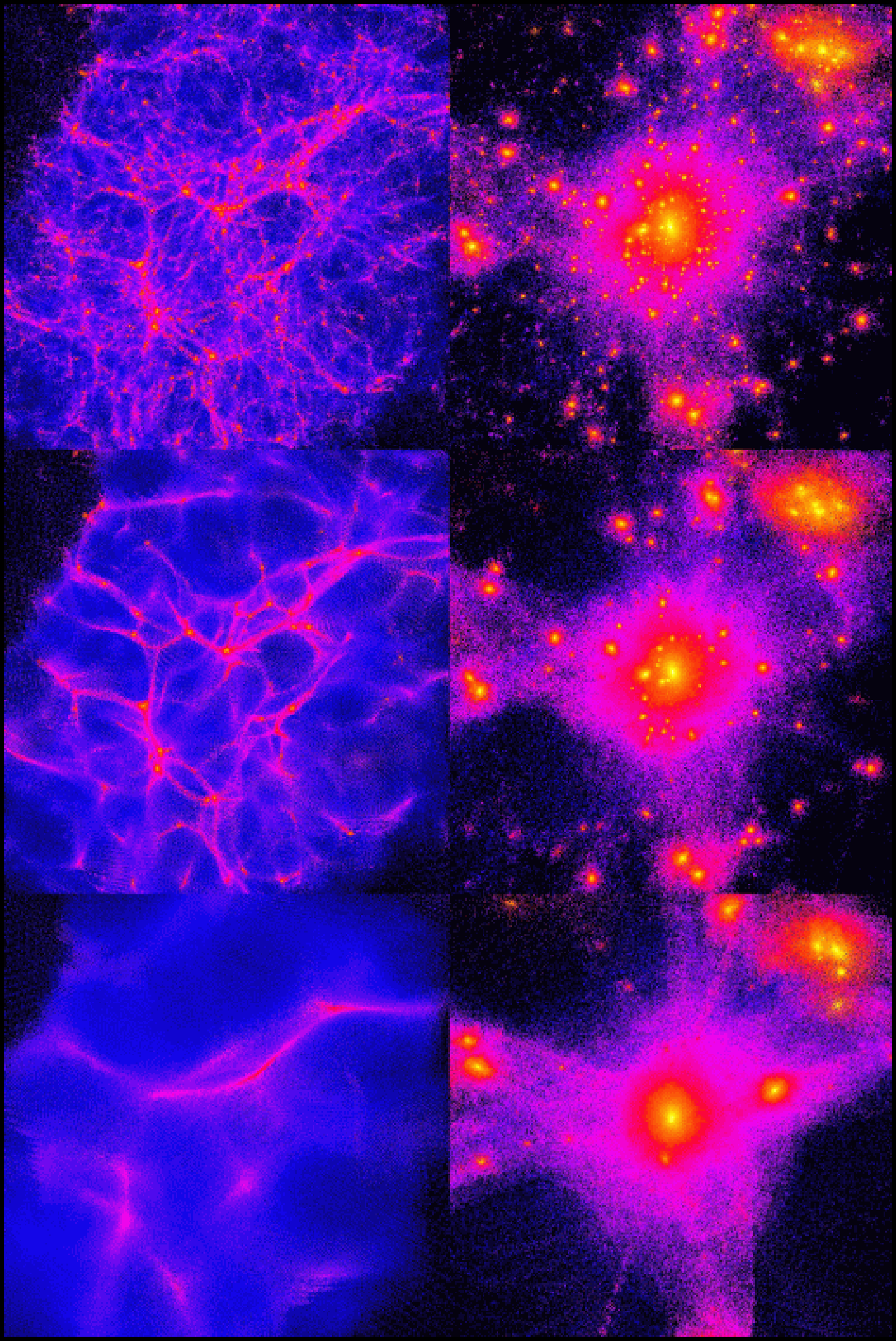


Cartografía del 2dF (2003)

como la vista en los censos locales de galaxias



Cartografía del 2dF (2003)



A dominant contribution of hot DM is ruled out:
- LSS appears later in time
- LSS is smoothed out
- there is little substructure

However, mixes of CDM and HDM are still in fashion in the literature.

(Moore et al.)

Types of Dark Matter

Cold DM

Several theoretical particles, including WIMPS (Weakly Interacting Massive Particles)

- Axions (1977): to solve the strong Charge Conjugation-Parity problem in Quantum Cromodynamics.

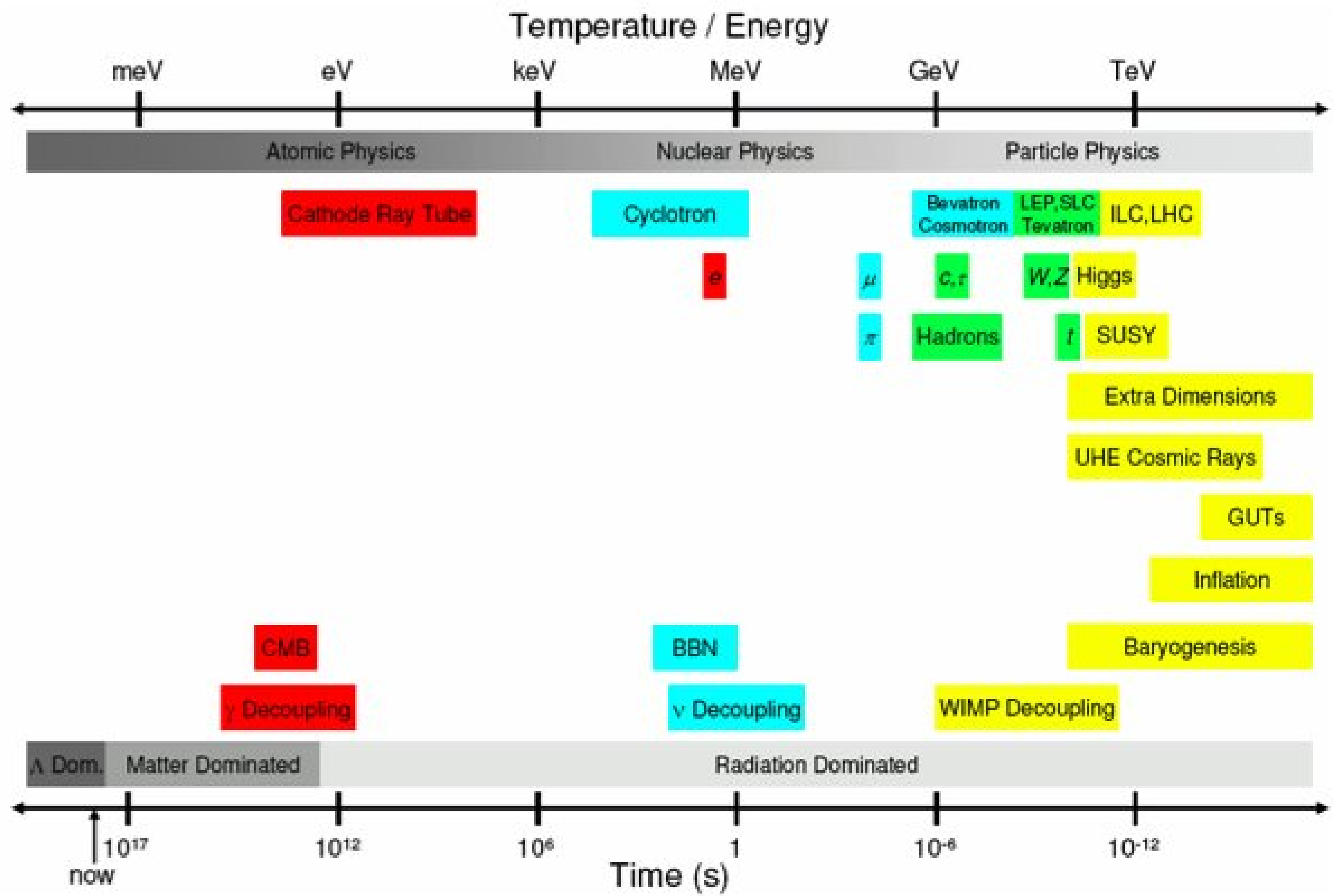
- Neutralino to solve hierarchy problem in Standard Model of particles (why is gravity 10^{32} times weaker than the weak force) -> Supersymetry. 10-10000 GeV.

- Axino: super particle of axion, solves both the hierarchy and CP problem

- 4th neutrino, as might be suggestive from CMB and BBN

- gravitino, the supersymetric particle of graviton,

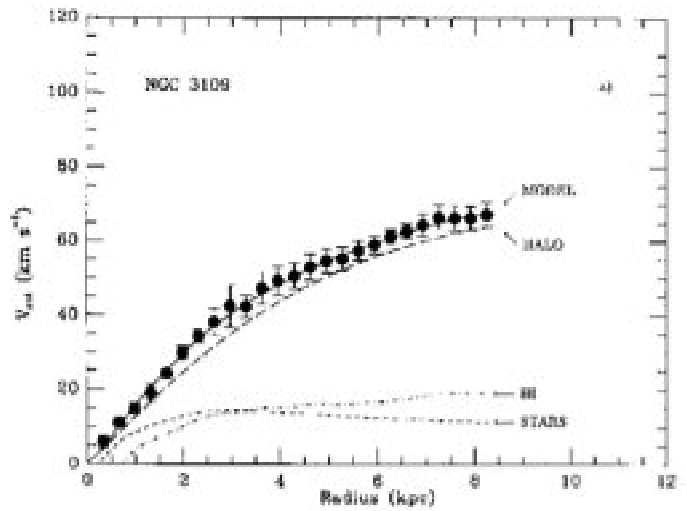
PARTICLE PHYSICS AT THE ENERGY FRONTIER



COMPOSITION OF THE UNIVERSE

MATERIAL	REPRESENTATIVE PARTICLES	TYPICAL PARTICLE MASS OR ENERGY (ELECTRON VOLTS)	NUMBER OF PARTICLES IN OBSERVED UNIVERSE	PROBABLE CONTRIBUTION TO MASS OF UNIVERSE	SAMPLE EVIDENCE
Ordinary ("baryonic") matter	Protons, electrons	10^6 to 10^9	10^{78}	5%	Direct observation, inference from element abundances
Radiation	Cosmic microwave background photons	10^{-4}	10^{87}	0.005%	Microwave telescope observations
Hot dark matter	Neutrinos	≤ 1	10^{87}	0.3%	Neutrino measurements, inference from cosmic structure
Cold dark matter	Supersymmetric particles?	10^{11}	10^{77}	25%	Inference from galaxy dynamics
Dark energy	"Scalar" particles?	10^{-33} (assuming dark energy comprises particles)	10^{118}	70%	Supernova observations of accelerated cosmic expansion

Dark Matter “laboratories”



“Low Surface Brightness” dwarf galaxies have become an important laboratory- they are dark matter dominated at all radii

- The most DM dominated objects we know, baryonic component dynamically negligible
- DM halo probes down to 20-30pc!
- The number of dwarf satellites sets constrains on warm DM contribution
- They are being monitores for DM candidate detection (Strigari et al. 2018)