Astrophysical evidence for dark matter

DPyC-SMF

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21 Jun 2007 / Reunión Anual de la DPyC

Outline

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1. Introduction
   - What are galaxies made of?
   - What is the universe made of?

2. Theoretical Cosmology
   - Homogeneity and Isotropy
   - Cosmological dynamics

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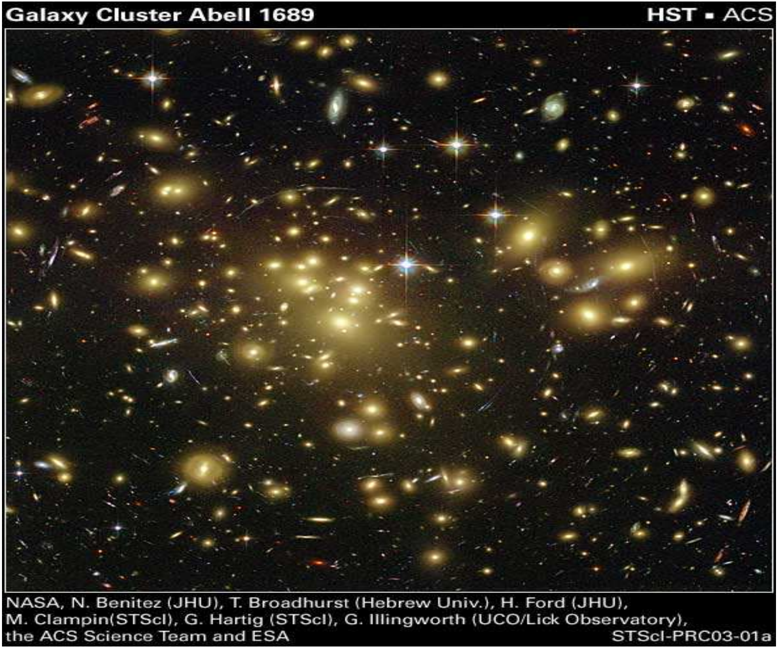
2. Theoretical Cosmology
   - Homogeneity and Isotropy
   - Cosmological dynamics
3. Big Bang Physics
   - CMB anisotropies
   - Nucleosynthesis
4. Dark Matters
   - Brief summary of matter contents
   - Dark energy
   - Cold dark matter
   - Candidates

Outline

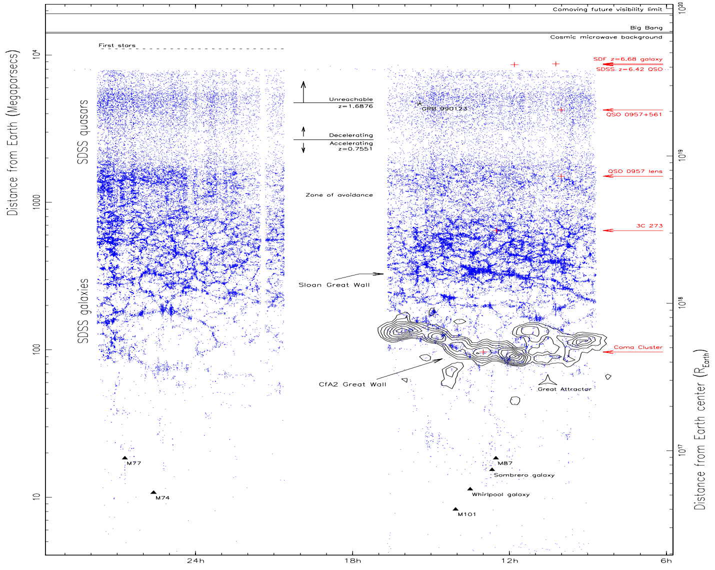
Typical galaxies

Outline

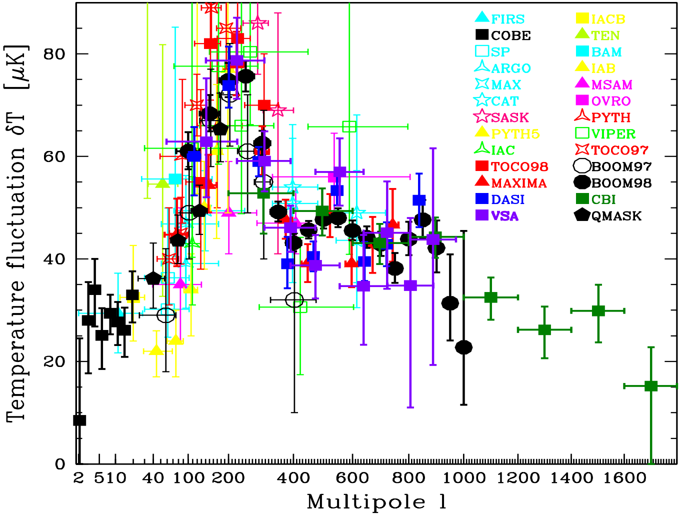
Clusters of galaxies



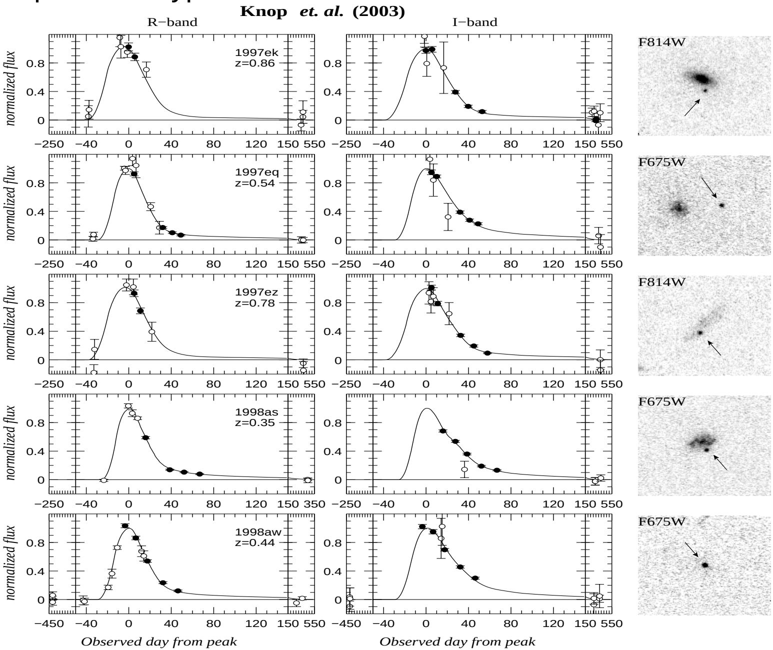
The whole observable universe



CMB anisotropies



Supernovae type Ia



Outline

Homogeneity and Isotropy (I)

- The universe is spatially homogeneous and isotropic
  - We are not priviledged observers (Copernican principle)
  - The universe is isotropic around us (CMB)
- Friedmann-Robertson-Walker-Lemaître (FRWL) metric

$$ds^2 = -dt^2 + a^2(t) \left[d\psi^2 + \begin{pmatrix} \sin^2\psi \\ \psi^2 \\ \sinh^2\psi \end{pmatrix} d\Omega^2 \right] \quad \begin{cases} k = \\ k = \\ k = \end{cases}$$

- Scale factor: $a(t)$; Hubble parameter: $H(t) = \dot{a}/a$
- (cosmological) Redshift: $a(z) = 1/(1+z)$

Homogeneity and Isotropy (II)

- Homogeneity: *extrapolation* from local measurements
- Isotropy *around any point* leads to homogeneity

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- Homogeneity: *extrapolation* from local measurements
- Isotropy *around any point* leads to homogeneity
- Sunyaev-Zeldovich effect: CMB scattering by hot gas in clusters of galaxies
- Expansion of the universe?
  - Dilation factor from SN Ia: $(1+z)^{1.07\pm0.06}$
  - CMB Temperature: $T(z) = 2.73(1+z)\,\mathrm{K}$

Outline

General Relativity Theory

- Energy-momentum tensor: $T^{\mu}_{\nu} = \mathrm{diag}(-\rho, p, p, p)$
  - Energy density: ρ
  - Isotropic pressure: p
  - Equation of state (EOS): $p = \omega\rho$
  - Conservation equation: $T^{\mu\nu}{}_{;\nu} = 0$

$$\dot{\rho} + 3H(\rho + p) = 0\,, \quad \rho = \rho_0 a^{-3(1+\omega)}$$

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- Main matter components
  - Relativistic: $\omega = 1/3$
  - non-Relativistic: $\omega = 0$
  - Cosmological constant: $\omega = -1$
  - Dark energy: $\omega < -2/3$

General Relativity Theory

- Einstein's equations: $R_{\mu\nu} - (1/2) g_{\mu\nu} R = 8\pi G \, T_{\mu\nu}$
  - Friedmann equation

$$H^2 = \frac{8\pi G}{3} \sum_i \rho_i - \frac{k}{a^2}$$

  - Acceleration equation

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3} \sum_i (\rho_i + 3p_i)$$

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- Cosmological parameters
  - Density parameters: $\Omega_i = \rho_i/\rho_c$, Feq: $1 = \sum_i \Omega_i - \Omega_k$
  - Age of the Universe: $\sim$ 13.7 Gy

$$T_0 = \int_{z_0}^{\infty} \frac{dz}{(1+z)H(z)}$$

  - Size of the Universe: $\sim$ 40 Gl-y ($\sim$ 12,000 Mpc)

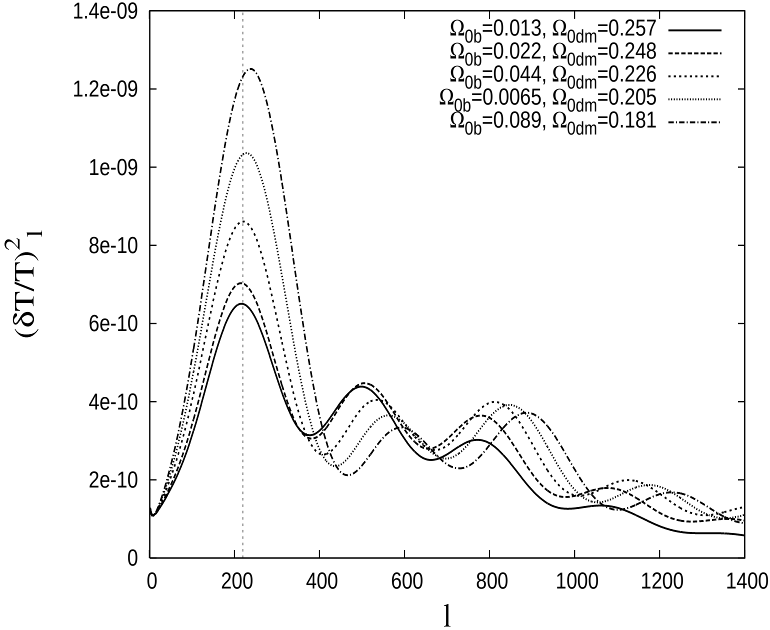
$$L_0 = \frac{1}{1+z_0} \int_{z_0}^{\infty} \frac{dz}{H(z)}$$

Outline

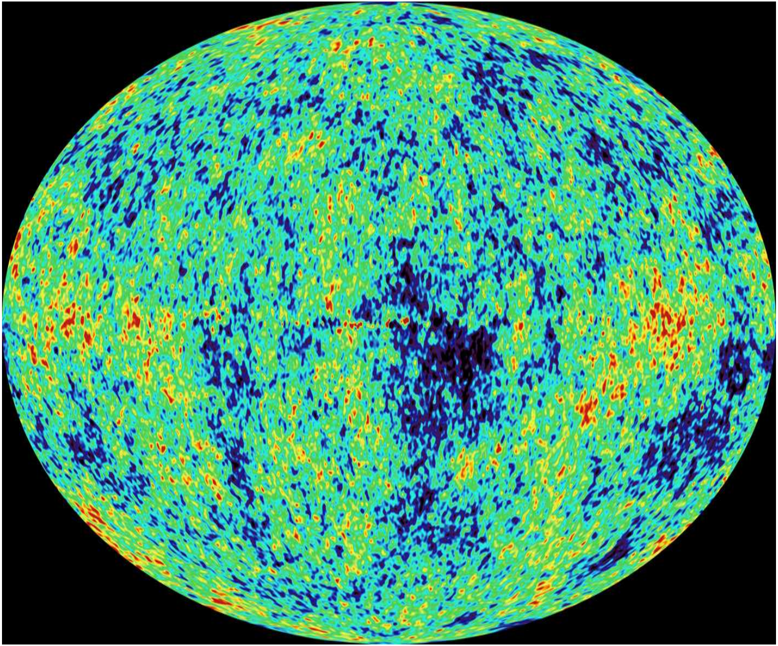
CMB anisotropies

- Acoustic peaks from primordial plasma[1]
- Origin at $z = 1100$
- Measurements:
  - Curvature of the universe: $\Omega_T = 1 - \Omega_k$ (flat)
  - Hubble parameter: $H_0 = 70.4^{+1.5}_{-1.6}\,\mathrm{km\,Mpc^{-1}\,s^{-1}}$
  - Baryonic component: $\Omega_{b,0}h^2 = 0.02186 \pm 00068$ $(\Omega_{b,0} = 0.044)$
  - Dark matter: $\Omega_{dm,0} = 0.268 \pm 0.018$
  - Dark energy: $\Omega_{de,0} = 0.732 \pm 0.018$
  - Inflation parameters: A_S, n_s

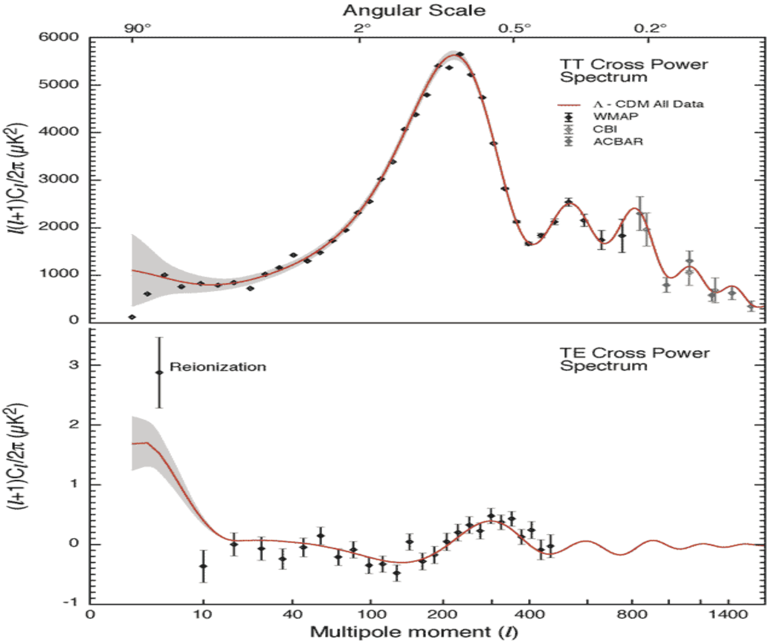
CMB anisotropies: Baryons and cold dark matter



CMB anisotropies: Anisotropy map



CMB anisotropies: WMAP3y

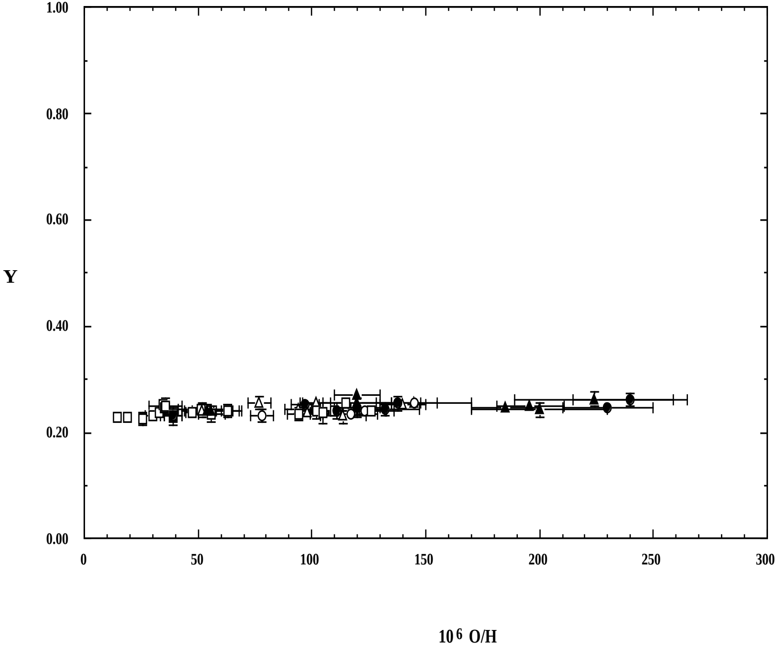


Outline

Nucleosynthesis, $z \sim 10^{10}$

- Particle Physics in an expanding universe[2, 3]
  - Protons + neutrons + electrons + photons
  - Baryon to photon ratio: $\eta_{10} = 10^{10}(n_b/n_\gamma) = 274\Omega_b h^2$
  - Primordial elements: H, D, ^{3}He, ^{4}He, ^{7}Li
- Dependency on parameters
  - Gravitational constant G
  - Neutron lifetime τ_n
  - Fine structure constant α
  - Electron mass m_e
  - Average nucleon mass $m_N \equiv (m_n + m_p)/2$
  - Neutron-proton mass difference $Q_N \equiv m_n - m_p$
  - Binding energies

BBN observations



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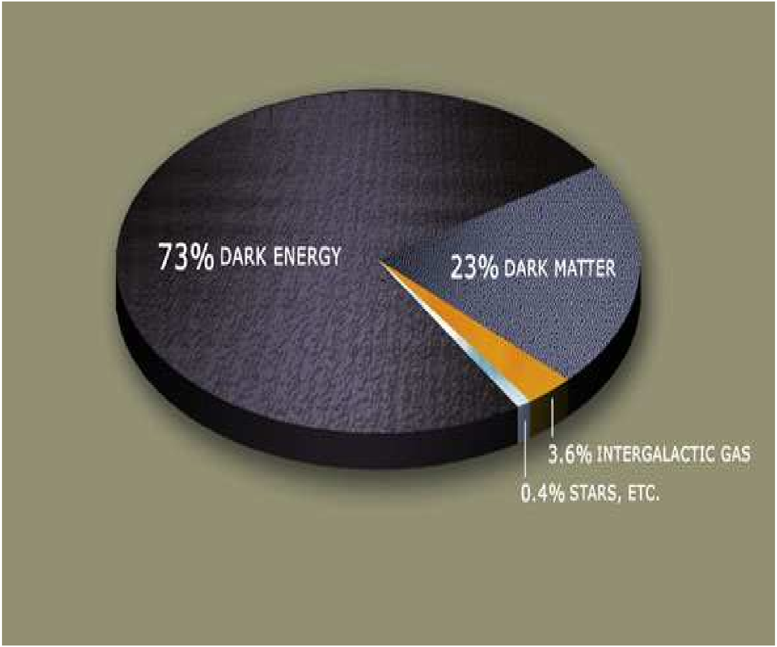
  - Baryon to photon ratio: $\eta_{10} = 10^{10}(n_b/n_\gamma) = 274\Omega_b h^2$
  - Primordial elements: H, ^{3}He
- Baryons: $\Omega_{b,0}h^2 = 0.0224$ (WMAP 0.02186 ± 0.00068)

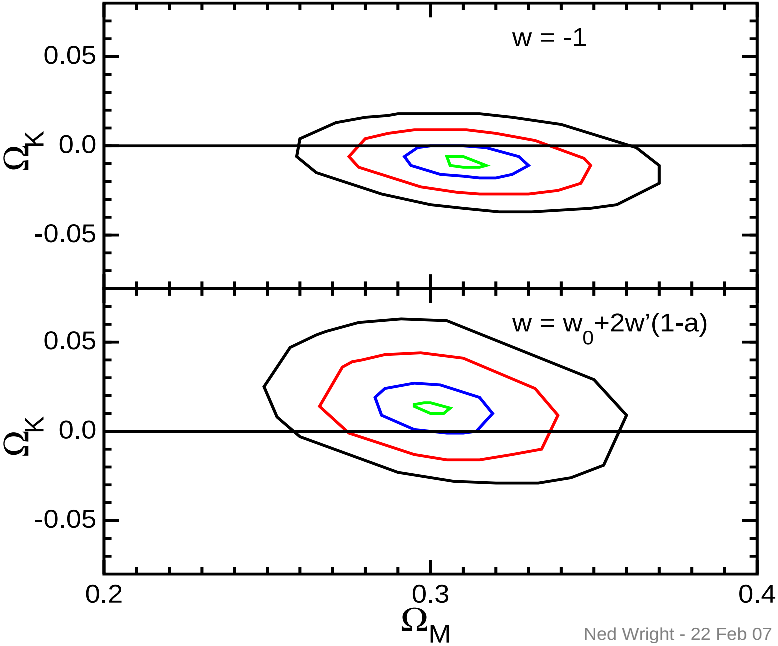
Abundances	*Observed*	Predictions
^{4}He/H	0.249 ± 0.009	0.2478 ± 0.0002
^{3}He/H	$(1.1 \pm 0.2) \times 10^{-5}$	$(1.03 \pm 0.03) \times 10^{-5}$
^{7}Li/H	$(1.5 \pm 0.5) \times 10^{-10}$	$(4.5 \pm 0.4) \times 10^{-10}$

Outline

Dark universe!



Degeneracy: Believe it or not! (All together)[2]



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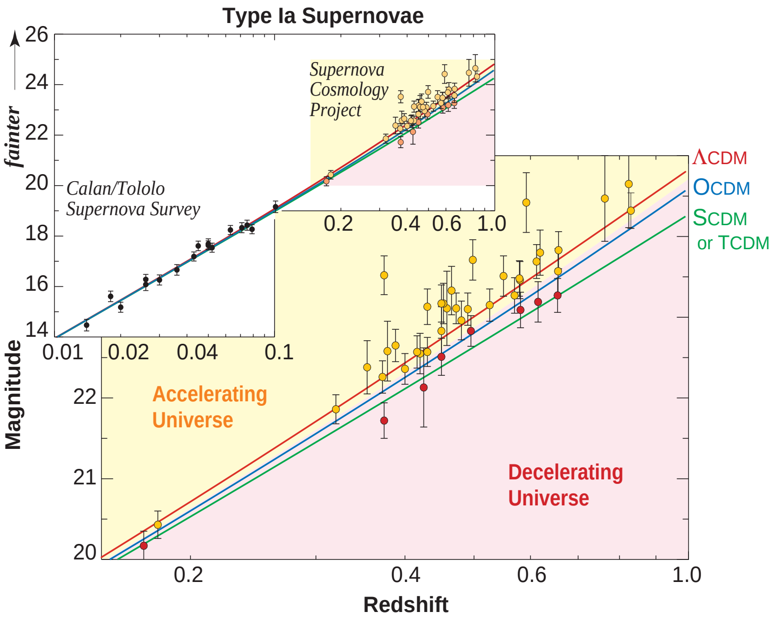
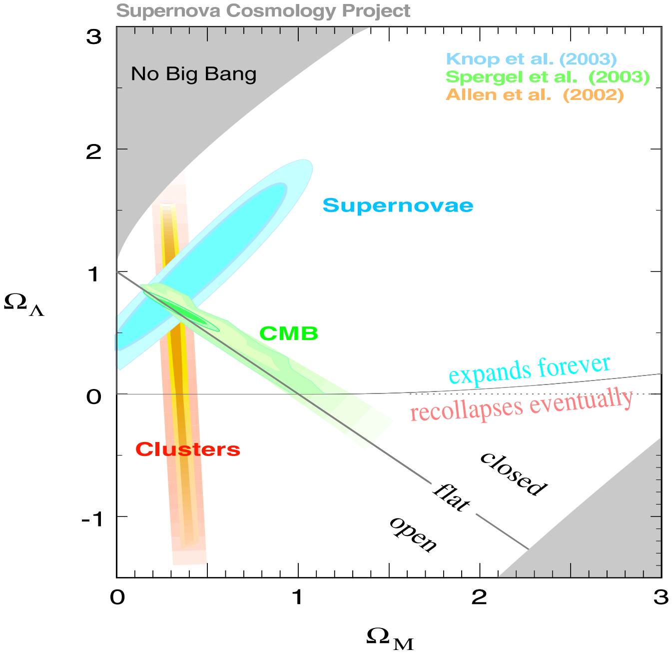
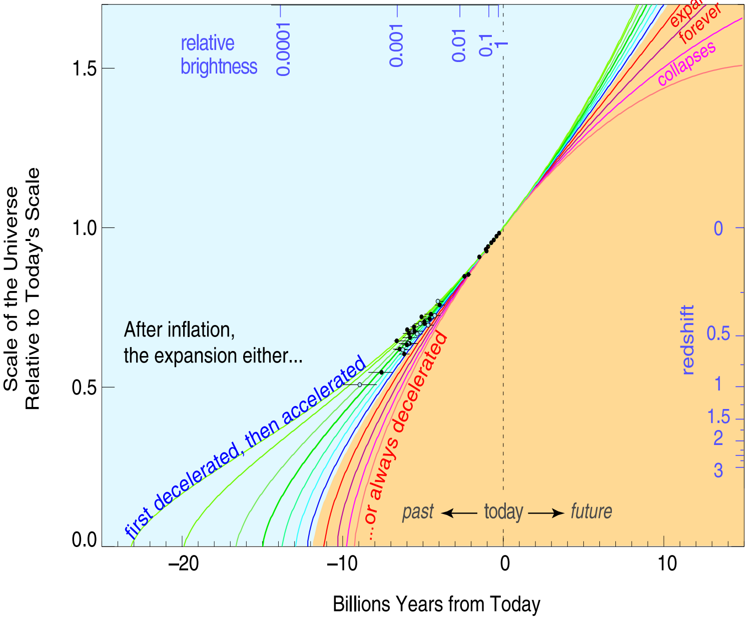

Type Ia Supernovae
Supernova Cosmology Project
Calan/Tololo Supernova Survey
fainter
Magnitude
Redshift
Accelerating Universe
Decelerating Universe
ΛCDM
OCDM
SCDM or TCDM
26
24
22
20
18
16
14
0.01
0.02
0.04
0.1
0.2
0.4
0.6
1.0
22
21
20
0.2
0.4
0.6
1.0


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

Expansion History of the Universe

Perlmutter, Physics Today (2003)



Cosmological constant

- Origin: by hand $T^{\Lambda}_{\mu\nu} = (\Lambda/\kappa^2)g_{\mu\nu}$
- Nernst 1916; Lemaître 1934; Zel'dovich 1967
- Ideas:
  - Adjustments mechanisms
  - Anthropic considerations
  - Changing gravity
  - Quantum gravity
  - Supergravity
  - Degenerate vacua
  - Higher dimensional gravity
  - Space-time foam
  - Vacuum fluctuations
  - String landscape

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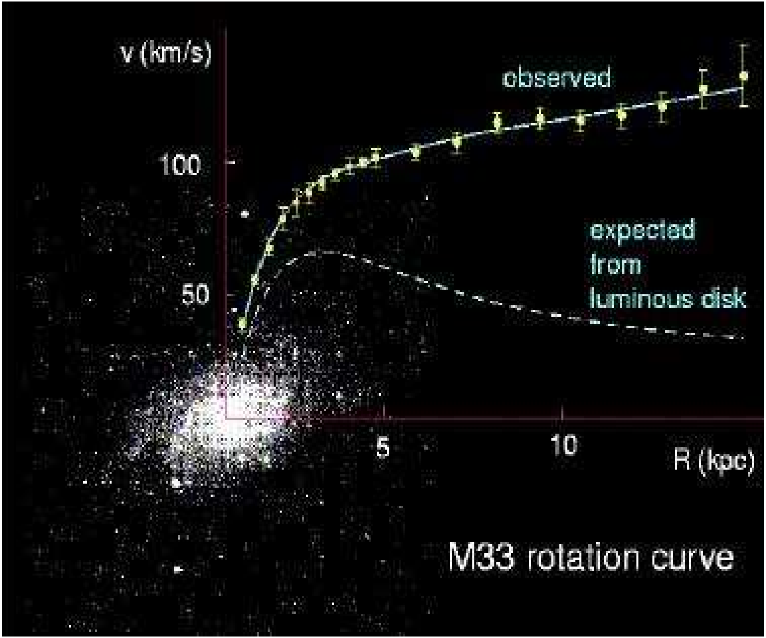
- Laboratory test of Newton's Gravitational Inverse-Square Law [4]
  - Valid for distances $\lambda > 56 \mu m$
  - Size of extra dimensions: $R < 44 \mu m$
  - Fundamental scale: $M_{Pl}^2 = M^{n+2} R^n$ [5]

Outline

Rotation curves [6]



Modified Newtonian Dynamics: What if ..?[7]

- Universal acceleration limit $a_0 \simeq 10^{-10}\, m/s^2$

$$\mathbf{F} = m\mathbf{a} \times \begin{cases} 1 & a \gg a_0 \\ \mu(a/a_0) & a \ll a_0 \end{cases}$$

- Predicts Tully-Fischer relation
- No-dark matter at all!

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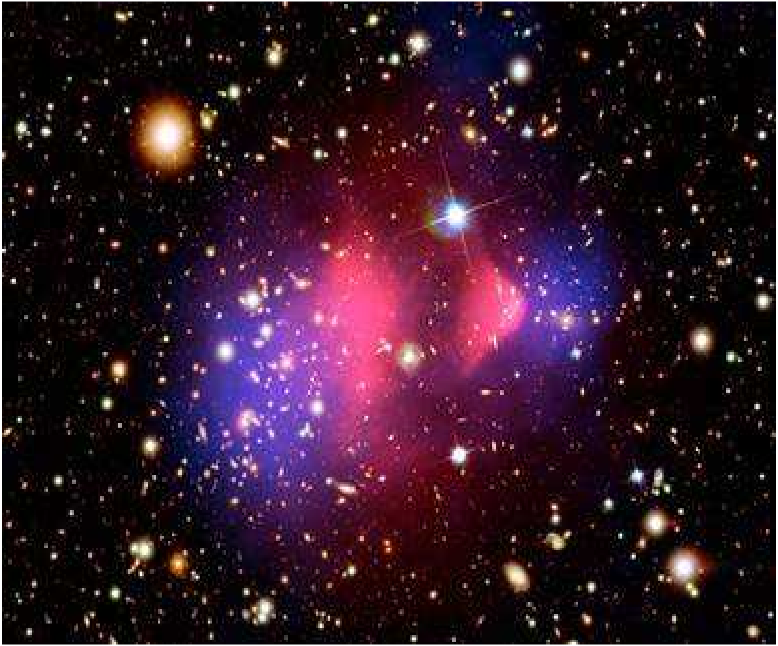
  - Predicts Tully-Fischer relation
  - No-dark matter at all!
- Laboratory test of Newton's Second Law
  - Valid for $a > 5 \times 10^{-14}\, m/s^2$

Weak gravitational lensing (Bullet cluster 1E 0657-56)[8]



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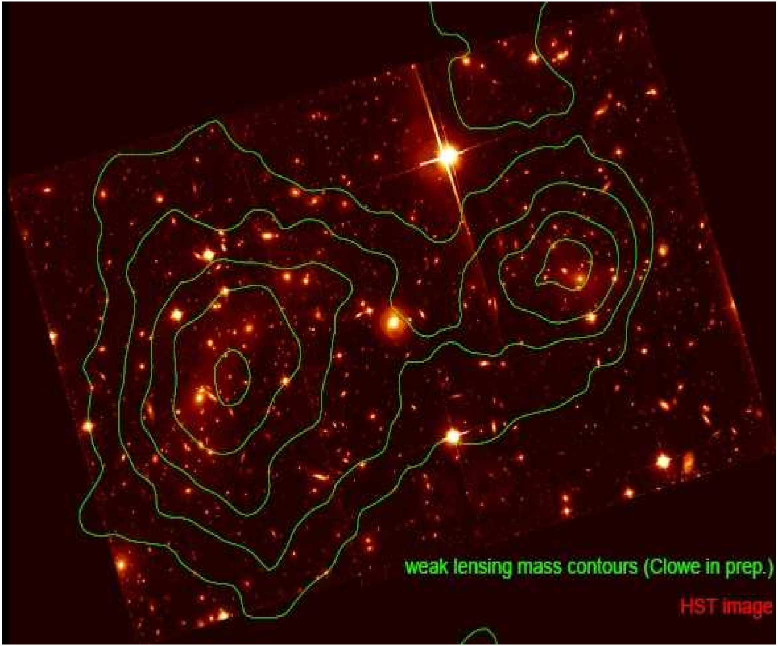

Weak gravitational lensing (CL0024+17)[9]

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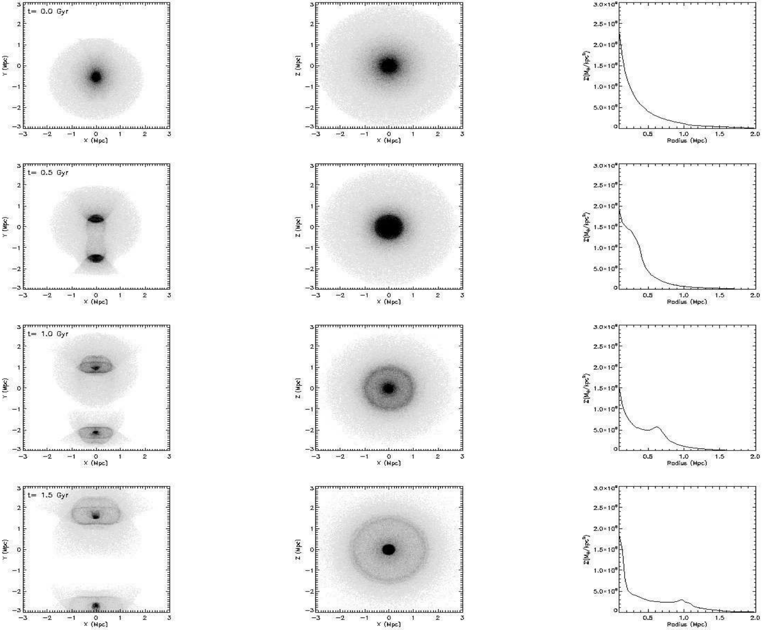
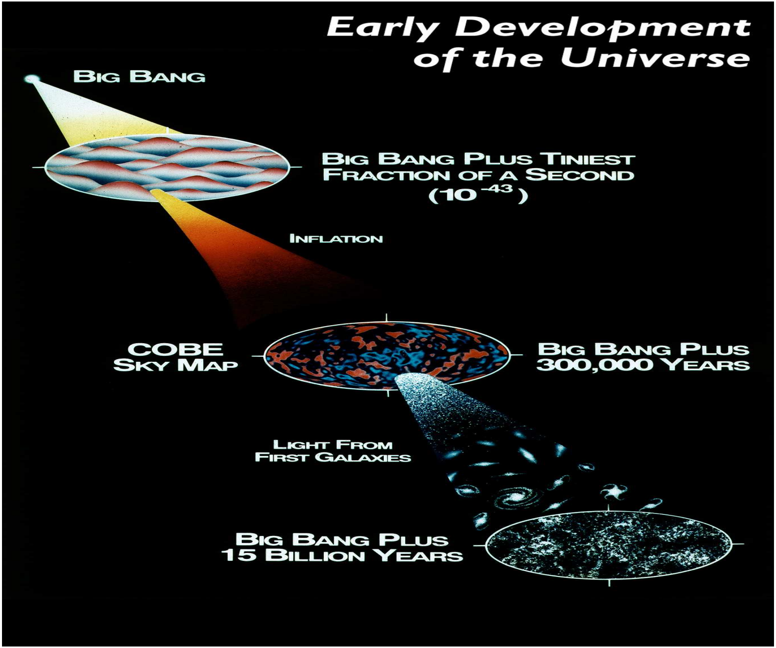
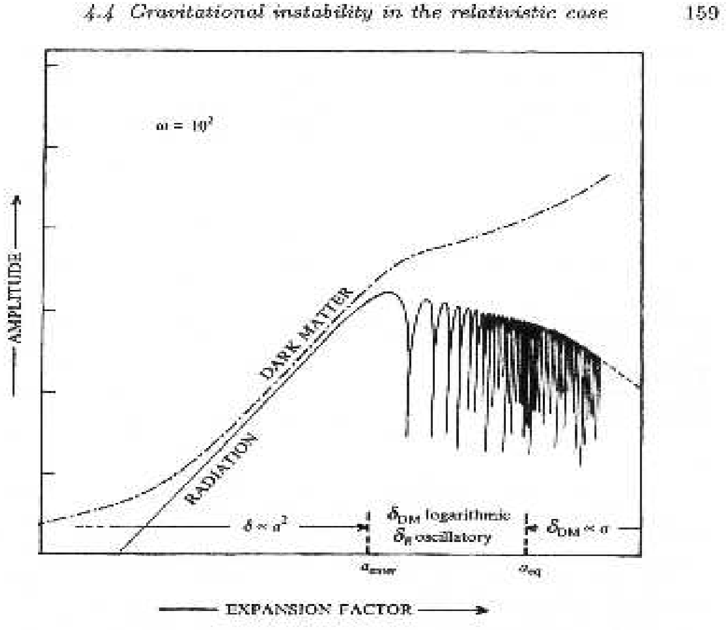


Structure formation



Weakly self-interacting dark matter



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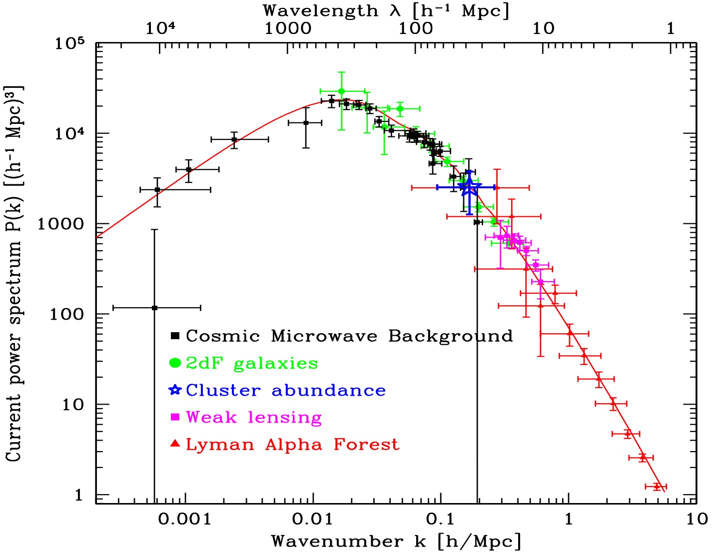

Outline

WIMP's

- Boltzmann equation and *freeze out*
- Neutral particle
- Stable particle (lightest!)
- Standard result

$$\Omega_X h^2 \simeq 0.3 \frac{10^{-39} cm^2}{\langle \sigma v \rangle}$$

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- Neutralino, gravitino, etc.

Wikipedia candidates

- Scalar Field Dark Matter (SFDM, Matos, Guzmán & Ureña-López)[10]
- Strongly Interacting Massive Particle (SIMP)
- Light Dark Matter
- Self-interacting dark matter
- Mirror matter

Summary

- Pillars of BBC: GR (1915), BBN (1950's), CMB (1992), SN Ia (1998), BAO (2005)

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How odd it is that anyone should not see that all observation must be for or against some view if it is to be of any service!

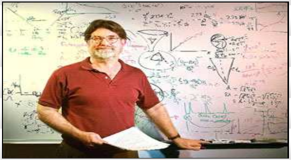
Charles Darwin
(George Smoot, private communication)

Presidente: Jorge Kahwagi Gastine / Vicepresidente: Jorge Kahwagi Macari / Director Gral.: Guillermo Ortega Ruiz 20 de Junio 2007 | Añ

LA CRÓNICA DE HOY

Nobel de Física apadrina al Instituto Avanzado de Cosmología en México

Por: Ingridh Vega | Academia Sabado 9 de Junio de 2007 | Hora de publicación: 01:34



Inauguracion. Smoot señaló que el IAC permitirá a México una participación adicional en proyectos para entender el universo.

"El Instituto Avanzado de Cosmología será la herramienta que permitirá a México una participación adicional en proyectos que contribuyan significativamente a la comprensión del cosmos", enfatizó el Premio Nobel de Física, George Smoot.

El profesor de la Universidad de California refrendó su apoyo para el desarrollo de la cosmología en México, donde existen, dijo, científicos del más alto nivel en este campo.

Acompañado por el físico Octavio Novaro, miembro de El Colegio Nacional, Smoot ofreció la conferencia "Cuando el universo llamó" para apadrinar el nacimiento del Instituto Avanzado de Cosmología (IAC), un grupo de 48 científicos mexicanos de más de 18 instituciones académicas del país, que buscan cohesionar e intercambiar ideas sobre la cosmología en México.

El director del IAC, Axel de la Macorra Pettersson, informó que, hasta el momento, el instituto se conforma a investigadores, científicos y expertos de diversas áreas de la física como teoría cuántica, astronomía y astrofísica.

POCAS DUDAS SOBRE EL BIG BANG. Durante su conferencia en el Colegio Nacional, Smoot dio detalles sobre la teoría que le hiciera ganar en el 2006, junto con el científico John C. Mather, el Premio Nobel de Física, por el estudio de radiación de fondo de microondas, que refuerza la teoría del big bang.

Aseguró que el satélite artificial COBE (Cosmic Background Explorer) de la NASA, fue lo que les permitió mostrar la primera imagen representativa del universo 300 mil años después de la gran explosión, demostrando que el cosmos ha pasado por diferentes etapas, y que desde hace algunos años, el universo crece de manera acelerada.

Simplificó que COBE contribuyó a asentar la teoría del big bang con tres experimentos. El primero, analizar el espectro de la radiación de fondo, "Los resultados muestran que esta radiación tiene exactamente las propiedades que se esperaban de acuerdo con la teoría, que supone que esta radiación procede de un universo mucho más denso y caliente…"

"… El segundo experimento, mapeaba el universo temprano. El resultado fue que existen diferencias en el cielo, que unas partes son levemente más calientes en una dirección y otras levemente más frías en otra dirección"

Estos resultados lo llevaron a creer que al principio el universo era perfectamente homogéneo e isotrópico, pero estas fluctuaciones, que explica la mecánica cuántica, llevaron a la creación de las galaxias.

El último experimento estudió la radiación infrarroja que emiten las estrellas de primera generación y se comprobó que los datos que aportaba confirman las expectativas de la teoría del big-bang

"El cosmos comenzó pequeño y a temperaturas altas. Los avances científicos permiten hacer un censo preciso de las galaxias, y determinar la velocidad de rotación de estrellas en ella. Sabemos que el cosmos se

For further reading

WMAP Collaboration, D. N. Spergel *et al.*, "Wilkinson microwave anisotropy probe (wmap) three year results: Implications for cosmology," `astro-ph/0603449`.

E. L. Wright, "Constraints on dark energy from supernovae, gamma ray bursts, acoustic oscillations, nucleosynthesis and large scale structure and the hubble constant," `astro-ph/0701584`.

T. Dent, S. Stern, and C. Wetterich, "Primordial nucleosynthesis as a probe of fundamental physics parameters," `arXiv:0705.0696 [astro-ph]`.

D. J. Kapner *et al.*, "Tests of the gravitational inverse-square law below the dark-energy length scale," *Phys. Rev. Lett.* **98** (2007) 021101, `hep-ph/0611184`.

- A. Perez-Lorenzana, “An introduction to extra dimensions,” *J. Phys. Conf. Ser.* **18** (2005) 224–269, `hep-ph/0503177`.
- V. C. Rubin, N. Thonnard, and J. Ford, W. K., “Rotational properties of 21 sc galaxies with a large range of luminosities and radii, from ngc 4605 /r = 4kpc/ to ugc 2885 /r = 122 kpc/,” *Astrophys. J.* **238** (1980) 471.
- M. Milgrom, “Mond–a pedagogical review,” *Acta Phys. Polon.* **B32** (2001) 3613, `astro-ph/0112069`.
- D. Clowe, A. Gonzalez, and M. Markevitch, “Weak lensing mass reconstruction of the interacting cluster 1e0657-558: Direct evidence for the existence of dark matter,” *Astrophys. J.* **604** (2004) 596–603, `astro-ph/0312273`.

M. J. Jee *et al.*, "Discovery of a ringlike dark matter structure in the core of the galaxy cluster cl 0024+17," `arXiv:0705.2171 [astro-ph]`.

T. Matos and L. A. Urena-Lopez, "On the nature of dark matter," *Int. J. Mod. Phys.* **D13** (2004) 2287–2292, `astro-ph/0406194`.