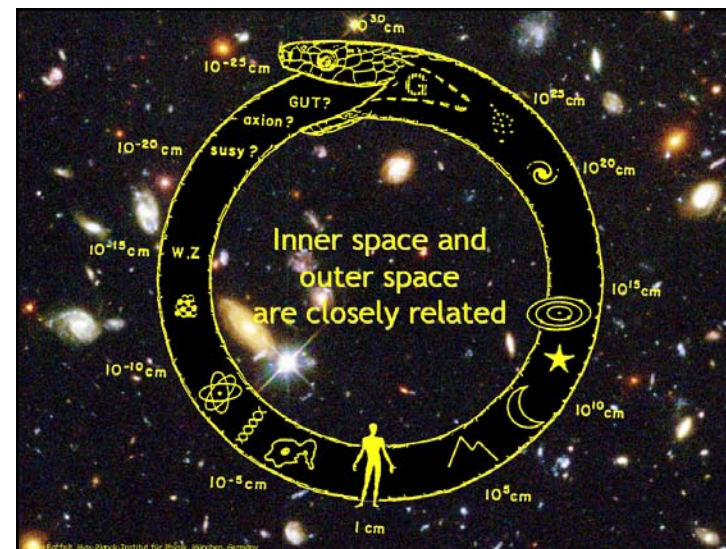


Georg Raffelt, Max-Planck-Institut für Physik, München

The Standard Model and Beyond: Frontiers of Cosmology



XVI Workshop "Beyond the Standard Model", 8-11 March 2004, Bad Honnef



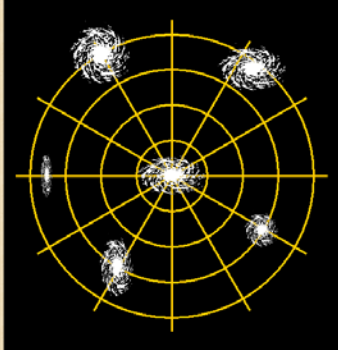
Expanding Universe and the Big Bang



Hubble's law $v_{\text{expansion}} = H_0 \times \text{distance}$
Hubble's constant $H_0 = h \, 100 \, \text{km s}^{-1} \, \text{Mpc}^{-1}$
Measured value $h = 0.72 \pm 0.04$
1 Mpc = $3.26 \times 10^6 \, \text{lyr}$ = $3.08 \times 10^{24} \, \text{cm}$
Expansion age of the universe $t_0 \approx H_0^{-1} \approx 14 \times 10^9 \, \text{years}$

Georg Raffelt, Max-Planck-Institut für Physik, München, Germany

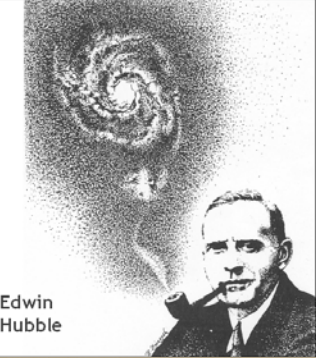
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Expanding Universe and the Big Bang



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 $v_{\text{expansion}} = H_0 \times \text{distance}$

Hubble's constant
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 $= 3.08 \times 10^{24} \, \text{cm}$**

Expansion age of the universe
 $t_0 \approx H_0^{-1} \approx 14 \times 10^9 \, \text{years}$

Source: Galileo - Max-Planck-Institut für Physik, München, Germany. Revised Big Bang Model, 8.11 March 2004, last revised: Germany

Expanding Universe and the Big Bang

- Photons
- Neutrinos
- Charged Leptons
- Quarks
- Gluons
- W- and Z-Bosons
- Higgs Particles
- Gravitons
- Dark-Matter Particles
- Topological defects
- ...

Hubble's law
 $v_{\text{expansion}} = H_0 \times \text{distance}$

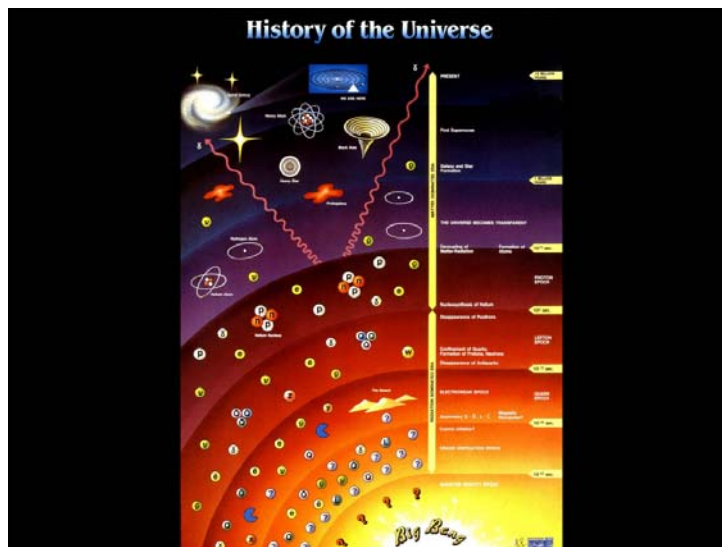
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Source: Galileo - Max-Planck-Institut für Physik, München, Germany. Revised Big Bang Model, 8.11 March 2004, last revised: Germany



Friedmann-Lemaître-Robertson-Walker Cosmology

- On scales $\geq 100 \, \text{Mpc}$, space is maximally symmetric (homogeneous & isotropic)
- The corresponding **Robertson-Walker metric** is

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

↑

Clock time of co-moving observer

↑

Cosmic scale factor

↑

Curvature $k = 0, \pm 1$

r, θ, ϕ , co-moving spherical coordinates
 r is dimensionless



$k = -1$



$k = 0$



$k = +1$

Source: Galileo - Max-Planck-Institut für Physik, München, Germany. Revised Big Bang Model, 8.11 March 2004, last revised: Germany

Einstein's "Greatest Blunder"

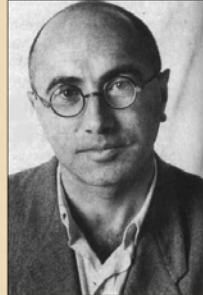
Density of gravitating mass & energy

Curvature term is very small or zero (Euclidean spatial geometry)

Newton's constant

Friedmann equation for Hubble's expansion rate

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G_N}{3} \rho - \frac{k}{a^2} + \frac{\Lambda}{3}$$



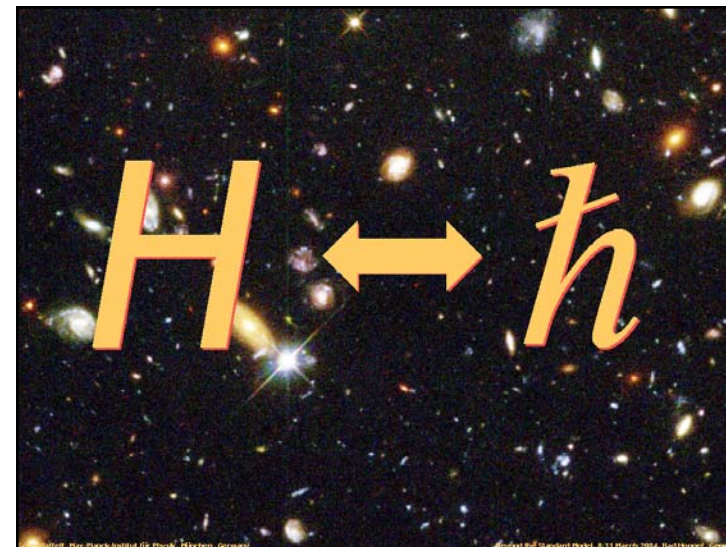
Yakov Borisovich Zeldovich
1914-1987



Cosmological constant Λ (new constant of nature) allows for a static universe by "global anti-gravitation"

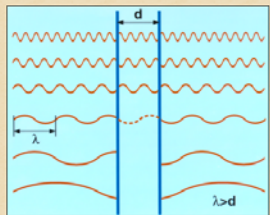
- Quantum field theory of elementary particles inevitably implies vacuum fluctuations because of Heisenberg's uncertainty relation, e.g. E and B fields can not simultaneously vanish
- Ground state (vacuum) provides gravitating energy
- Vacuum energy ρ_{vac} is equivalent to Λ

Source: Staffell, Max-Planck-Institut für Physik, München, Germany. Revised the Standard Model, 8-11 March 2004, Bad Honnef, Germany.



Casimir Effect (1948)

A measurable manifestation of the zero-point energy of the electromagnetic field



Long-wavelength field modes between the plates are "displaced," causing a reduction of the vacuum energy compared with free space



Hendrik Bogt Casimir
(1909 - 2000)

$F = \frac{\pi^2}{240} \frac{hc}{d^4} A \approx 1.3 \times 10^{-7} N \left(\frac{1 \mu m}{d} \right)^4 \left(\frac{A}{1 cm^2} \right)$

Casimir force between parallel plates (distance d, area A)

Bordag et al., New Developments in the Casimir Effect, Phys. Rept. 353 (2001)

Source: Staffell, Max-Planck-Institut für Physik, München, Germany. Revised the Standard Model, 8-11 March 2004, Bad Honnef, Germany.

Supersymmetric Extension of Particle Physics

In supersymmetric extensions of the particle-physics standard model, every boson has a fermionic partner and vice versa

Spin	Standard particle	Superpartner	Spin
1/2	Leptons (e, ν_e , ...) Quarks (u, d, ...)	Sleptons ($\tilde{e}$, $\tilde{\nu}_e$, ...) Squarks ($\tilde{u}$, $\tilde{d}$, ...)	0
1	Gluons $W^\pm$ Z^0 Photon (γ)	Gluinos Wino Zino Photino ($\tilde{\gamma}$)	1/2
0	Higgs	Higgsino	1/2
2	Graviton	Gravitino	3/2

Fermionic degree of freedom $\rho_{vac} = -\infty$
 Bosonic degree of freedom $\rho_{vac} = +\infty$
 Supersymmetry broken at a scale $\Lambda_{SUSY} \approx 1 \text{ TeV}$ (?)
 (Masses of particles and superpartners different)

$\rho_{vac} \approx \Lambda_{SUSY}^4$

Source: Staffell, Max-Planck-Institut für Physik, München, Germany. Revised the Standard Model, 8-11 March 2004, Bad Honnef, Germany.

Critical Density and Ω -Parameter

Evolution of cosmic scale factor $a(t)$ governed by **Friedmann equation**

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3} G_N \rho - \frac{k}{a^2}$$

In a flat universe ($k = 0$), there is a unique relationship between H and ρ , defining the **"critical density"**

$$\rho_{\text{crit}} = \frac{3H^2}{8\pi G_N} = \frac{3}{8\pi} (H_{\text{Mpl}})^2$$

Cosmic density always expressed in terms of

$$\Omega = \rho/\rho_{\text{crit}}$$

With the present-day Hubble parameter $H_0 = h \, 100 \, \text{km s}^{-1} \text{Mpc}^{-1}$ the critical density is

$$\rho_{\text{crit}} = h^2 \, 1.88 \times 10^{-29} \, \text{g cm}^{-3}$$

With the measured value $h = 0.72 \pm 0.04$ the critical density is

$$\rho_{\text{crit}} = (0.97 \pm 0.12) \times 10^{-29} \, \text{g cm}^{-3} = [(2.55 \pm 0.07) \text{meV}]^4 \approx 10^{-15} \Lambda_{\text{SUSY}}$$

Source: Baffert, Max-Planck-Institut für Physik, München, Germany. Revised the Standard Model, 8-11 March 2004, EastHolland, Germany.

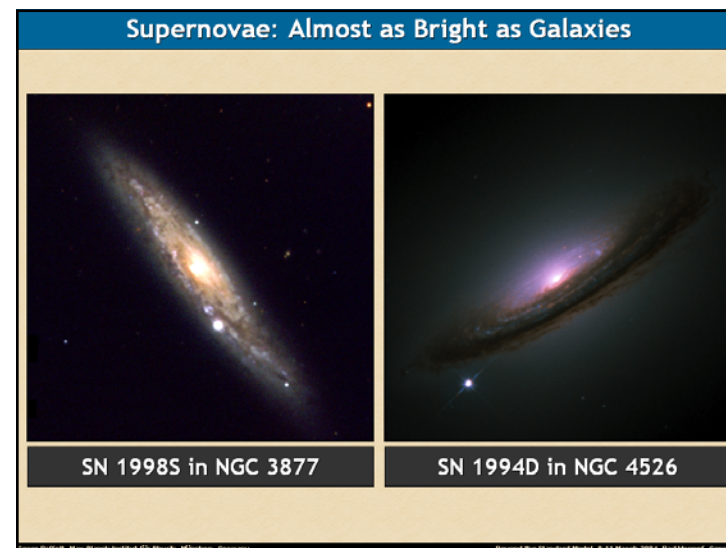
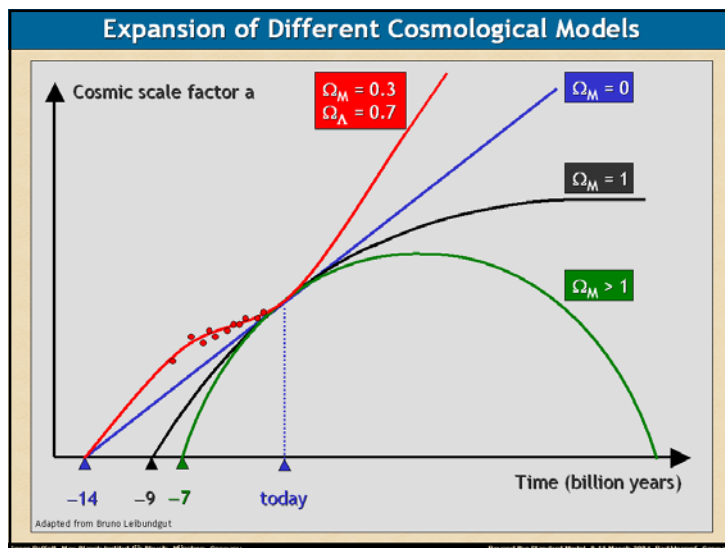
Generic Solutions of Friedmann Equation

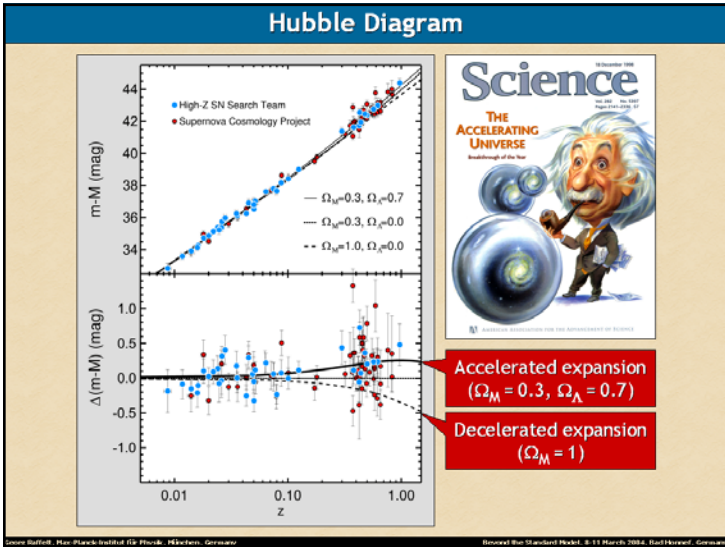
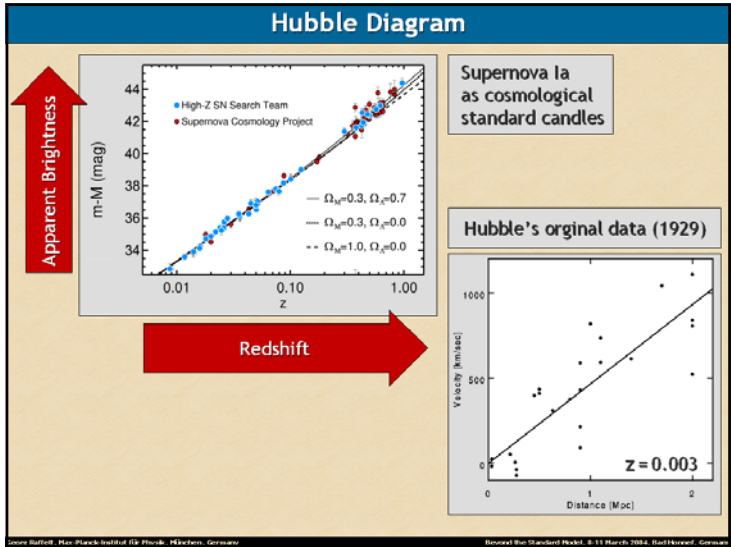
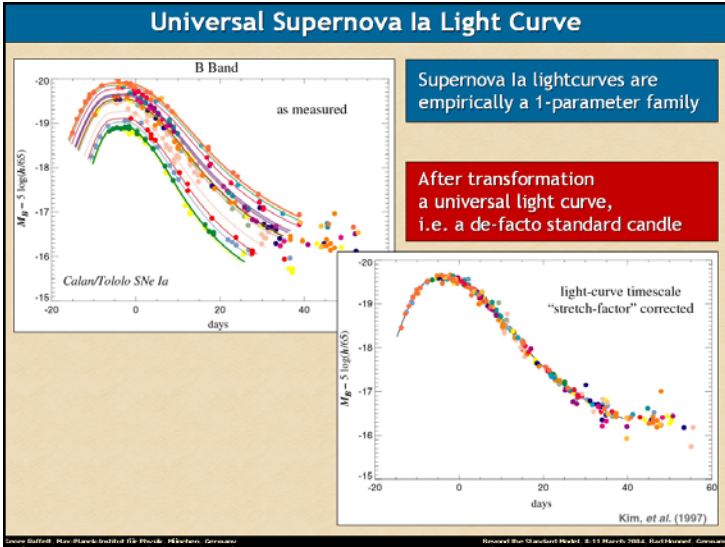
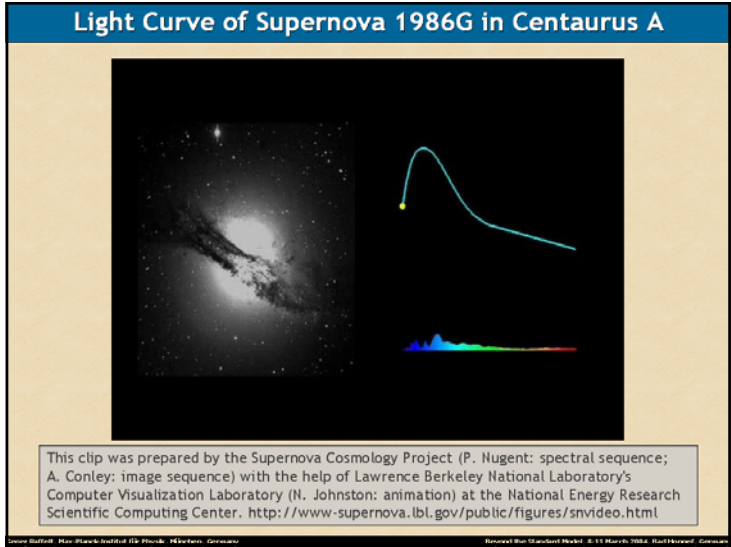
	Equation of state	Behavior of energy-density under cosmic expansion	Evolution of cosmic scale factor
Radiation	$p = \rho/3$	$\rho \propto a^{-4}$	Dilution of radiation and redshift of energy $a(t) \propto t^{1/2}$
Matter	$p = 0$	$\rho \propto a^{-3}$	Dilution of matter $a(t) \propto t^{2/3}$
Vacuum energy	$p = -\rho$	$\rho = \text{const}$	Vacuum energy not diluted by expansion $a(t) \propto \exp(\sqrt{\Lambda/3} t)$ $\Lambda = 8\pi G_N \rho_{\text{vac}}$

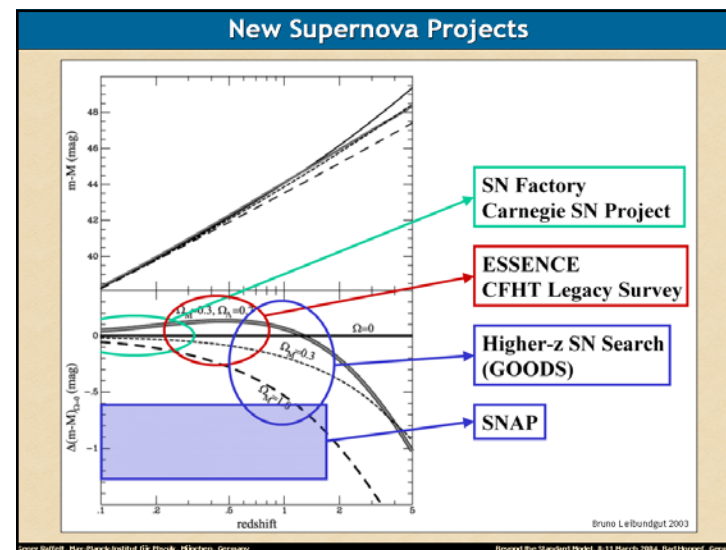
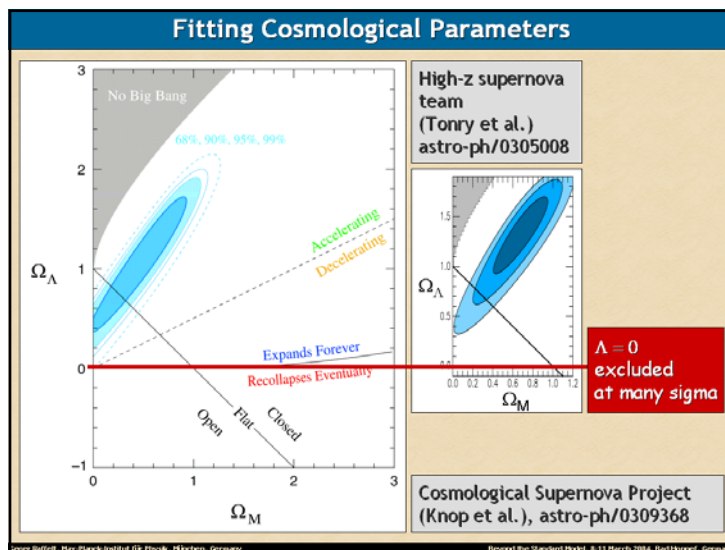
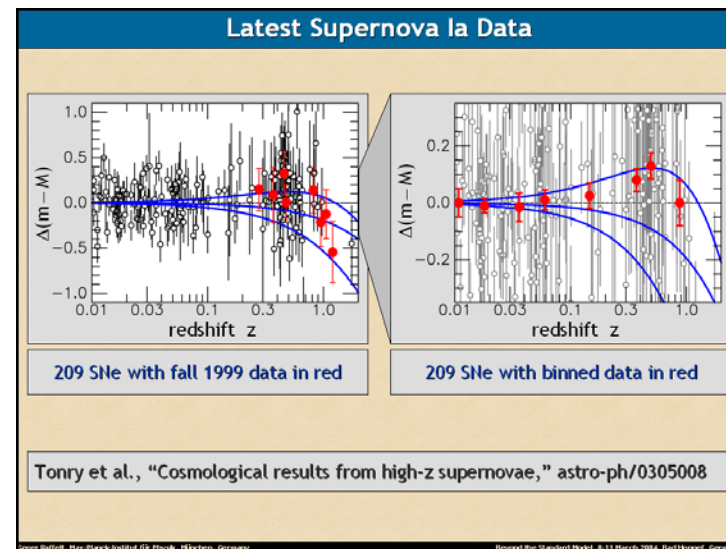
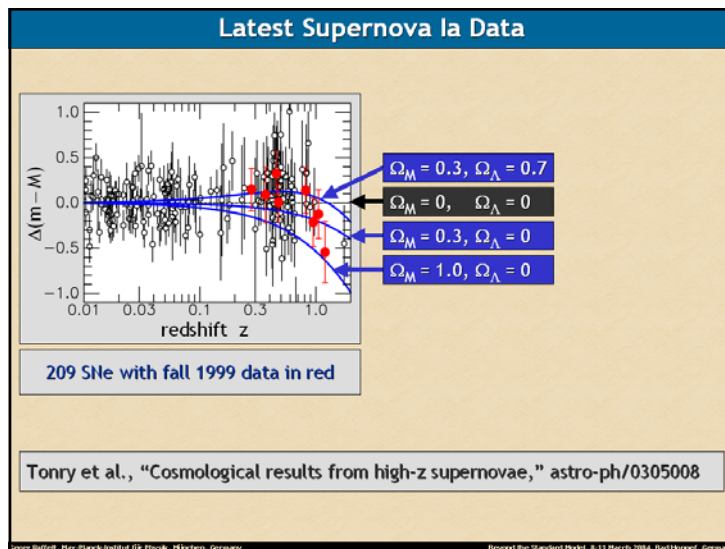
Energy-momentum tensor of perfect fluid with density ρ and pressure p

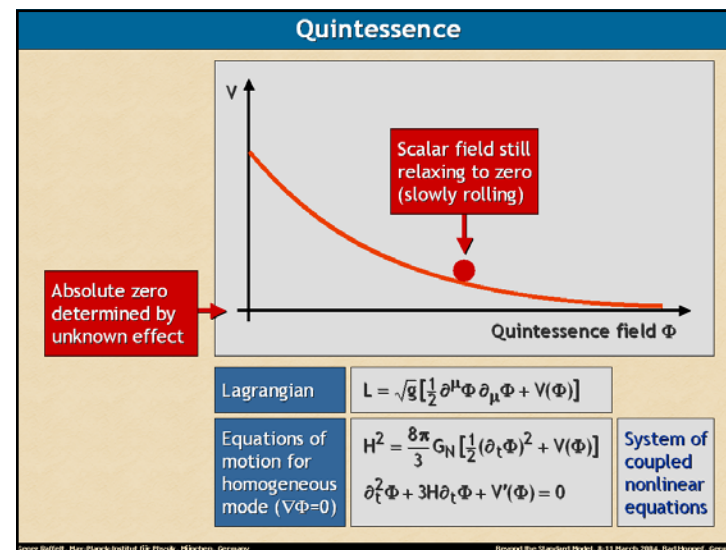
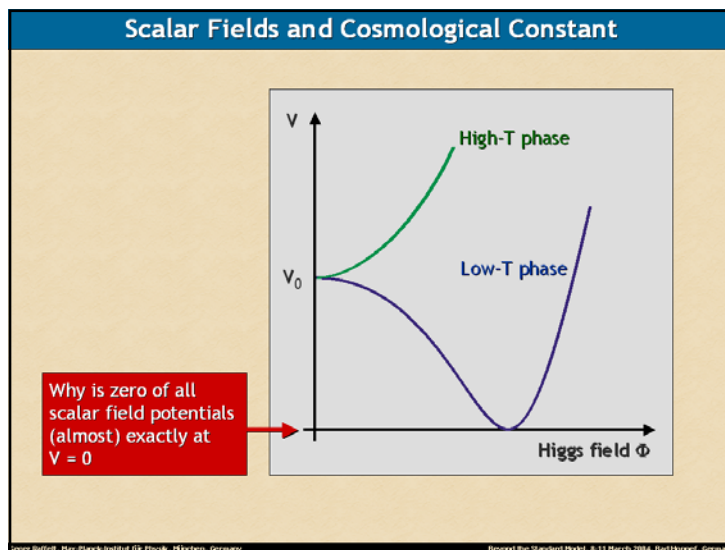
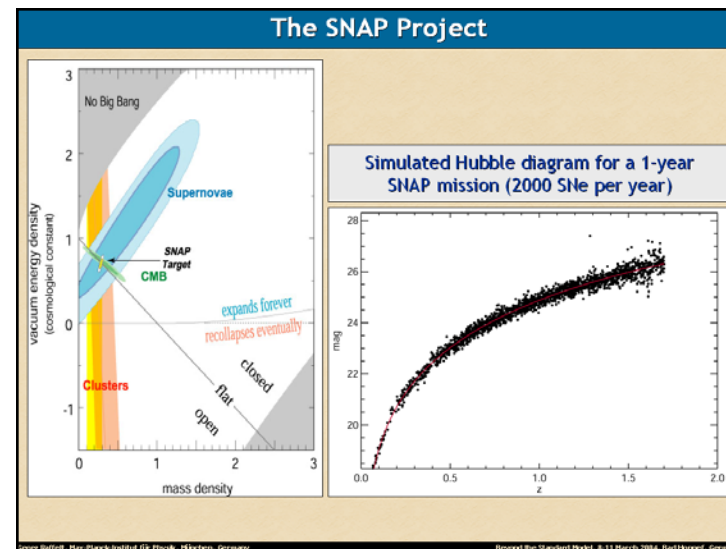
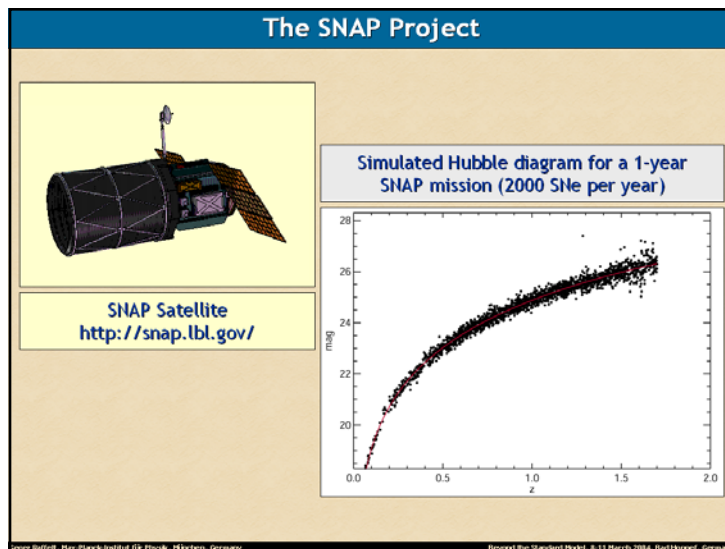
$$T^{\mu\nu} = \begin{pmatrix} \rho & & & \\ & p & & \\ & & p & \\ & & & p \end{pmatrix} \quad T_{\text{vac}}^{\mu\nu} = \rho g^{\mu\nu} = \begin{pmatrix} \rho & & & \\ & -\rho & & \\ & & -\rho & \\ & & & -\rho \end{pmatrix}$$

Source: Baffert, Max-Planck-Institut für Physik, München, Germany. Revised the Standard Model, 8-11 March 2004, EastHolland, Germany.







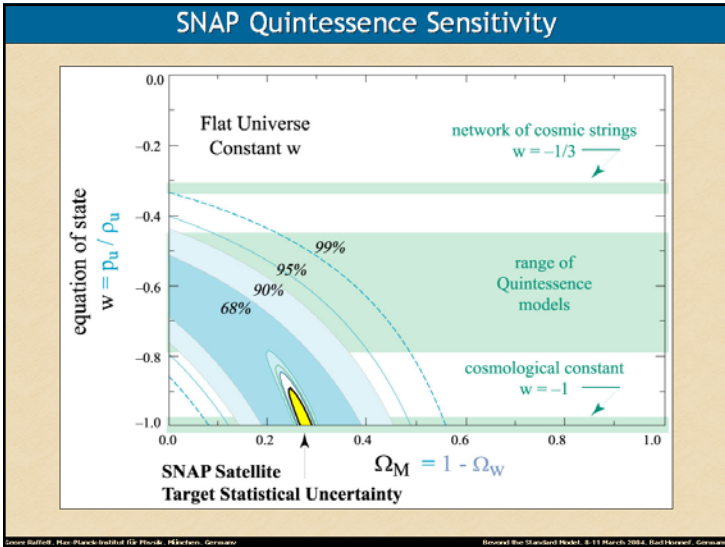
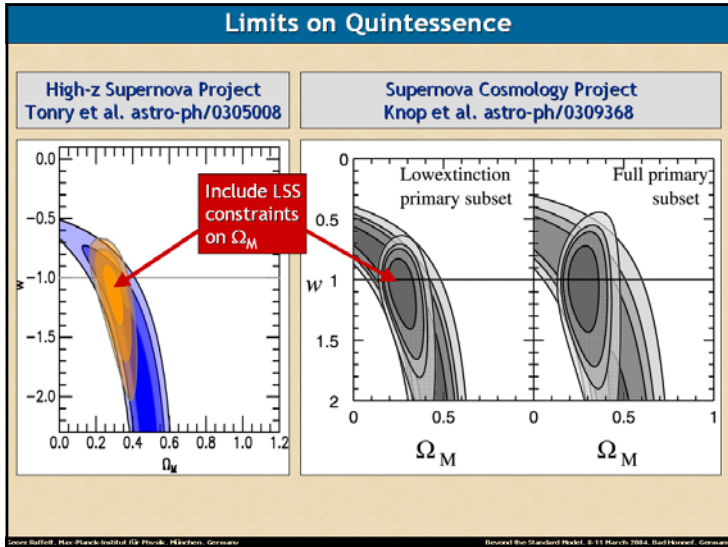
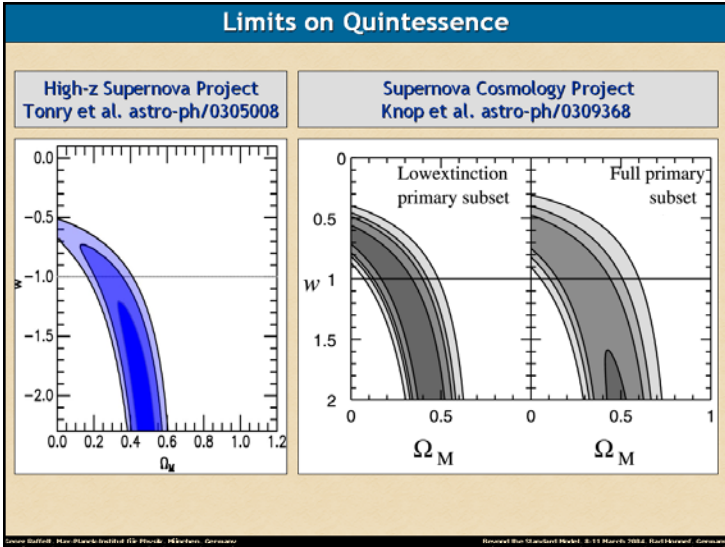


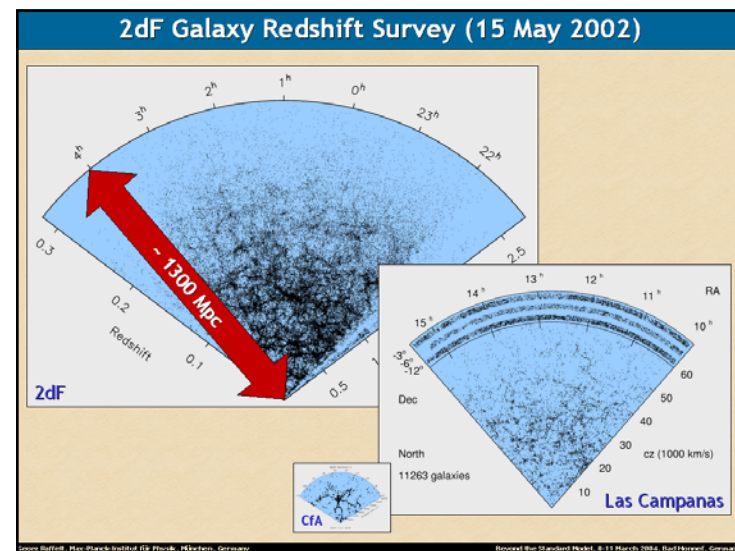
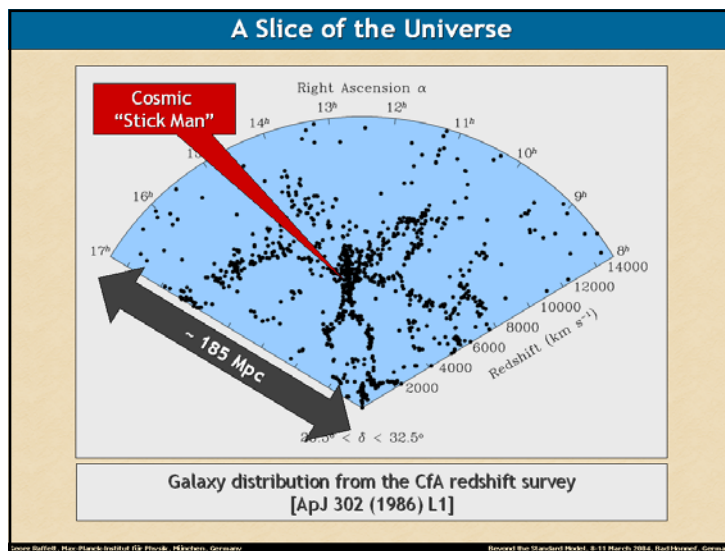
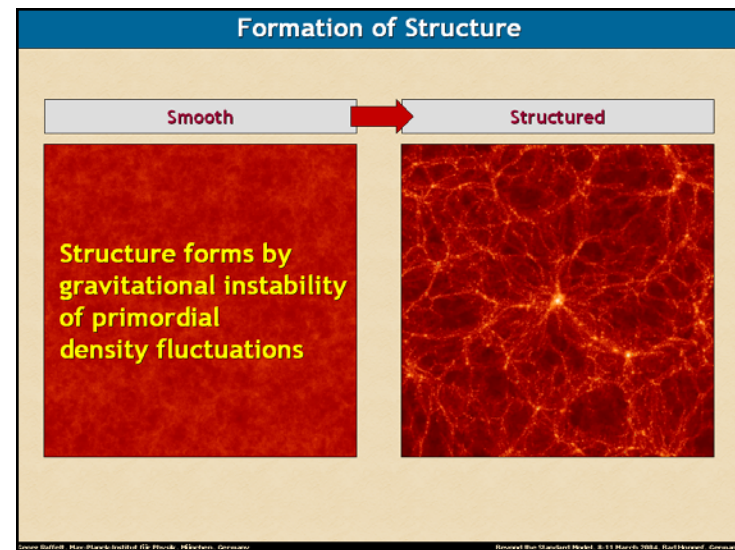
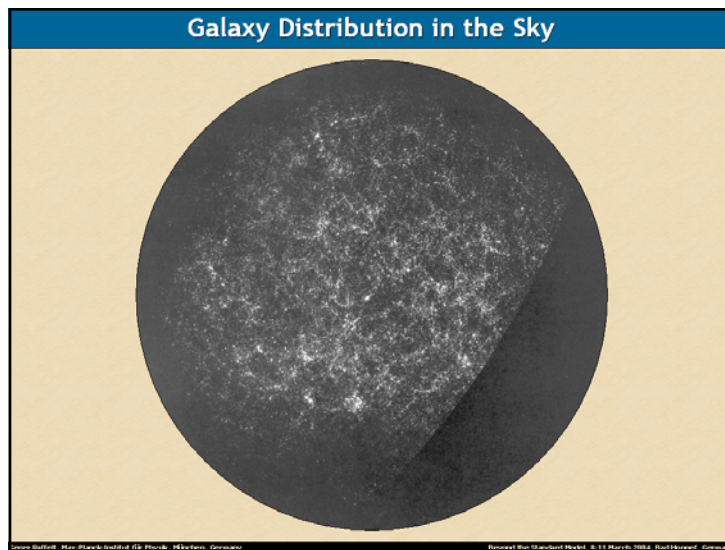
Quintessence as a Perfect Fluid

Energy-momentum tensor of homogeneous Φ -mode that of an isotropic perfect fluid	$\rho = \frac{1}{2}(\partial_t \Phi)^2 + V(\Phi)$ $p = \frac{1}{2}(\partial_t \Phi)^2 - V(\Phi)$
General equation of state	$p = w \rho$
Example: Exponential potential	$V(\Phi) = V_0 e^{-\lambda 8\pi G_M \Phi}$
Explicit solution of eqs of motion imply	$w = \frac{p}{\rho} = \frac{\lambda^2}{3} - 1$

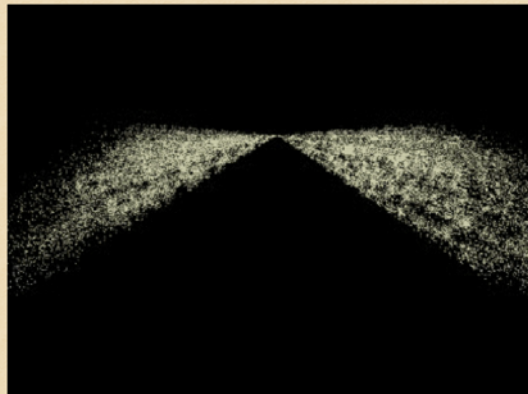
Like vacuum energy	$\lambda^2 = 0$	$w = -1$	Observational evidence for equation of state with "nonstandard" w-parameter?
Accelerated expansion	$\lambda^2 < 2$	$w < -1/3$	
Like matter	$\lambda^2 = 3$	$w = 0$	
Like radiation	$\lambda^2 = 4$	$w = 1$	

Source: Sudduth, Max-Planck-Institut für Physik, München, Germany. Revised Planck Standard Model, 8-11 March 2014, Euflora2014, Germany.





2dF Galaxy Redshift Survey



Animation from 2dFGRS homepage
<http://www.mso.anu.edu.au/2dFGRS/>

Source: Bauffert, Max-Planck-Institut für Physik, München, Germany

Revised Standard Model, 8-11 March 2004, EastHaven, Conn.

Power Spectrum of Density Fluctuations

Field of density fluctuations

$$\delta(x) = \frac{\delta\rho(x)}{\bar{\rho}}$$

Fourier transform

$$\delta_k = \int d^3x e^{-ik \cdot x} \delta(x)$$

Power spectrum essentially square of Fourier transformation

$$\langle \delta_k \delta_{k'} \rangle = (2\pi)^3 \delta(k - k') P(k)$$

with δ the δ -function

Power spectrum is Fourier transform of two-point correlation function ($x=x_2-x_1$)

$$\begin{aligned} \xi(x) &= \langle \delta(x_2) \delta(x_1) \rangle = \int \frac{d^3k}{(2\pi)^3} e^{ik \cdot x} P(k) \\ &= \int \frac{d\Omega}{4\pi} \frac{dk}{k} e^{ik \cdot x} \underbrace{k^3 P(k)}_{\Delta^2(k)} \end{aligned}$$

Gaussian random field (phases of Fourier modes δ_k uncorrelated) is fully characterized by the power spectrum

$$P(k) = |\delta_k|^2$$

or equivalently by

$$\Delta(k) = \left(\frac{k^3 P(k)}{2\pi^2} \right)^{1/2} = \frac{k^{3/2} |\delta_k|}{\sqrt{2\pi}}$$

Source: Bauffert, Max-Planck-Institut für Physik, München, Germany

Revised Standard Model, 8-11 March 2004, EastHaven, Conn.

Gravitational Growth of Density Perturbations

The dynamical evolution of small perturbations

$$\delta(x) = \frac{\delta\rho(x)}{\bar{\rho}} \ll 1$$

is independent for each Fourier mode δ_k

- For pressureless, nonrelativistic matter (cold dark matter) naively expect exponential growth
- Only power-law growth in expanding universe

	Sub-horizon $\lambda < H^{-1}$	Super-horizon $\lambda > H^{-1}$
Radiation dominates $a \propto t^{1/2}$	$\delta_k \approx \text{const}$	$\delta_k \propto a^2 \propto t$
Matter dominates $a \propto t^{2/3}$	$\delta_k \propto a \propto t^{2/3}$	

Source: Bauffert, Max-Planck-Institut für Physik, München, Germany

Revised Standard Model, 8-11 March 2004, EastHaven, Conn.

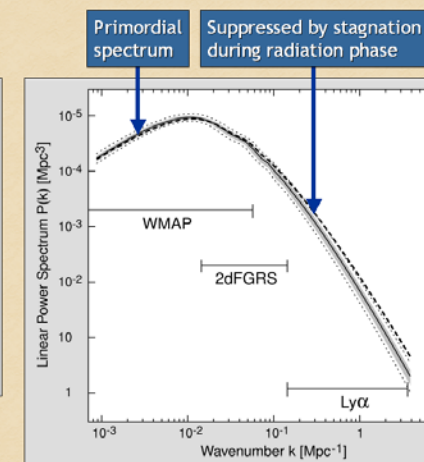
Processed Power Spectrum in Cold Dark Matter Scenario

Primordial spectrum usually assumed to be of power-law form

$$P(k) = |\delta_k|^2 \propto k^n$$

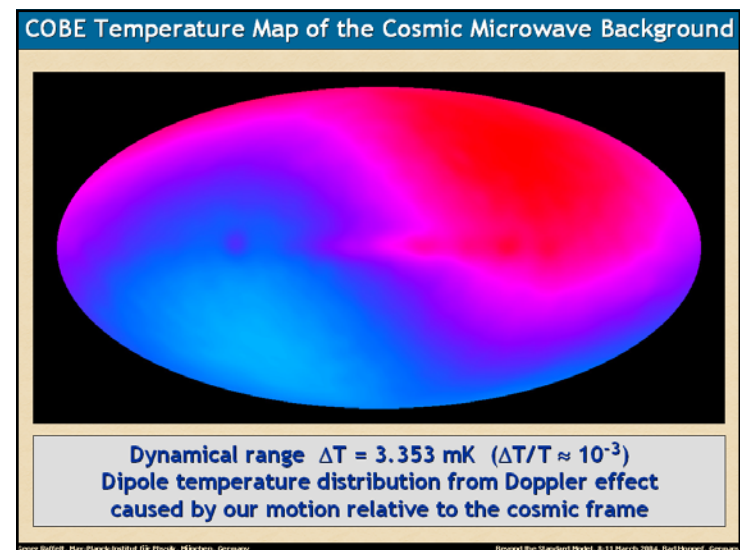
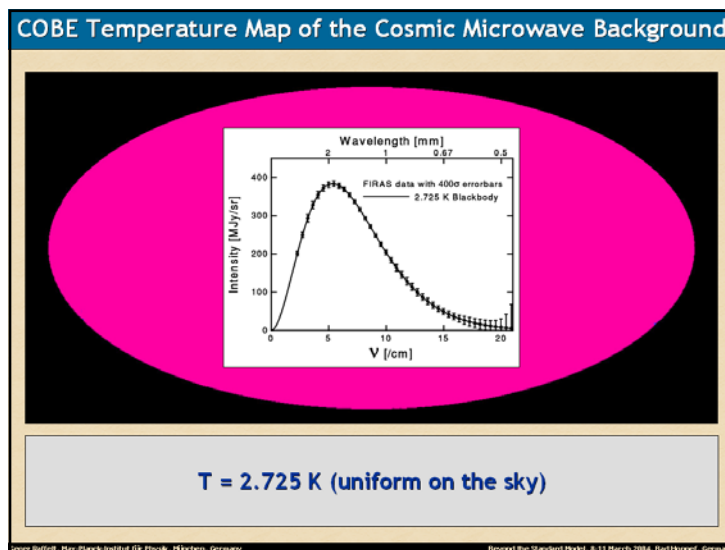
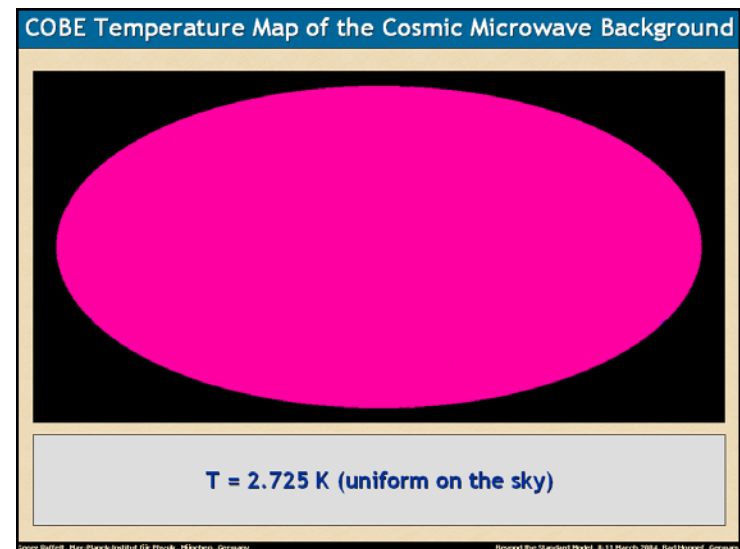
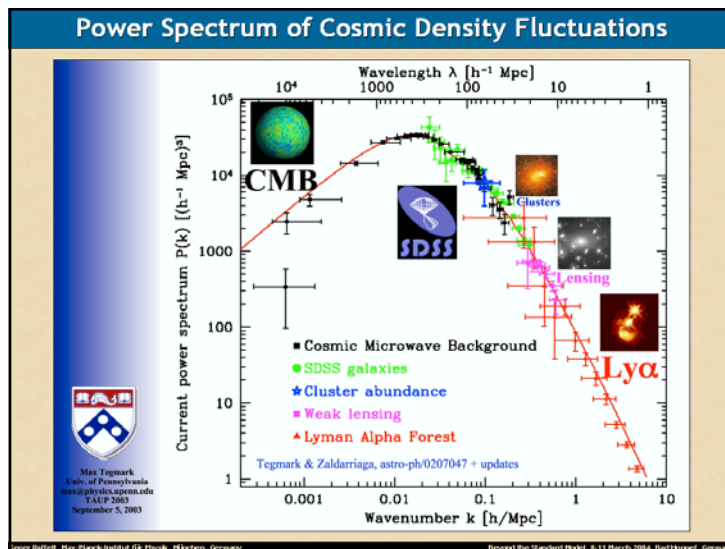
Harrison-Zeldovich ("flat") spectrum

$n = 1$
 expected from inflation (may be slightly less than 1, depending on details of inflationary phase)

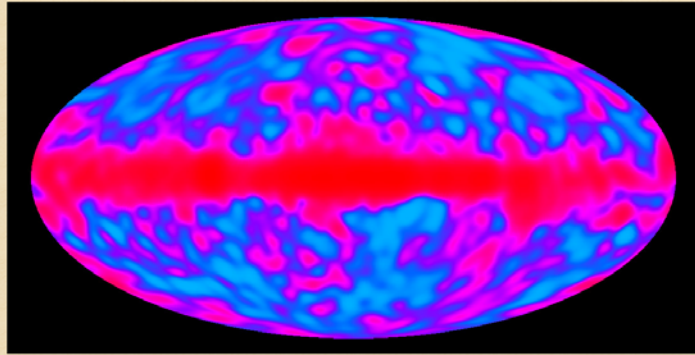


Source: Bauffert, Max-Planck-Institut für Physik, München, Germany

Revised Standard Model, 8-11 March 2004, EastHaven, Conn.



COBE Temperature Map of the Cosmic Microwave Background

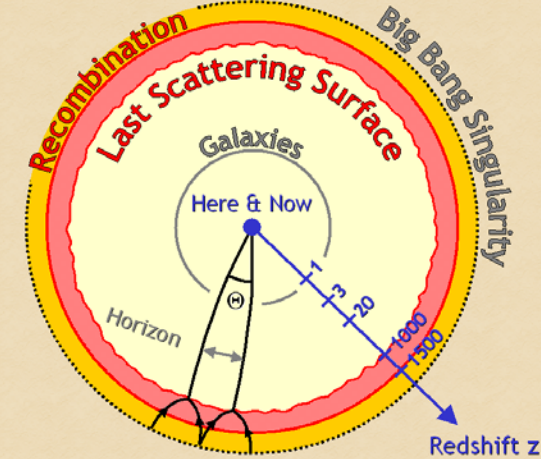


Dynamical range $\Delta T = 18 \mu\text{K}$ ($\Delta T/T \approx 10^{-5}$)
Primordial temperature fluctuations

Source: Battelli, Max-Planck-Institut für Physik, München, Germany

Revised Big Bang Model, 8-11 March 2004, Bad Honnef, Germany

Last Scattering Surface



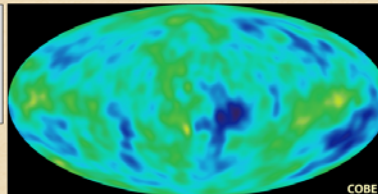
Source: Battelli, Max-Planck-Institut für Physik, München, Germany

Revised Big Bang Model, 8-11 March 2004, Bad Honnef, Germany

Power Spectrum of CMBR Temperature Fluctuations

Sky map of CMBR temperature fluctuations

$$\Delta(\theta, \varphi) = \frac{T(\theta, \varphi) - \langle T \rangle}{\langle T \rangle}$$

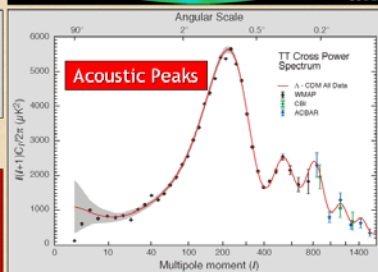


Multipole expansion

$$\Delta(\theta, \varphi) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\theta, \varphi)$$

Angular power spectrum

$$C_{\ell} = \langle a_{\ell m}^* a_{\ell m} \rangle = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} a_{\ell m}^* a_{\ell m}$$



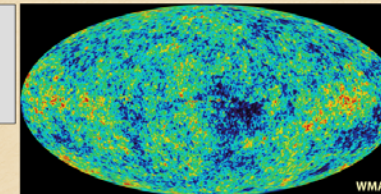
Source: Battelli, Max-Planck-Institut für Physik, München, Germany

Revised Big Bang Model, 8-11 March 2004, Bad Honnef, Germany

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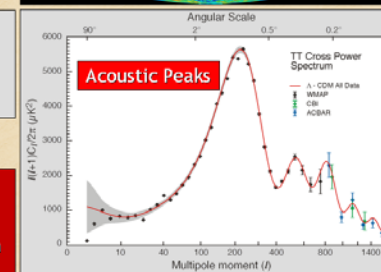


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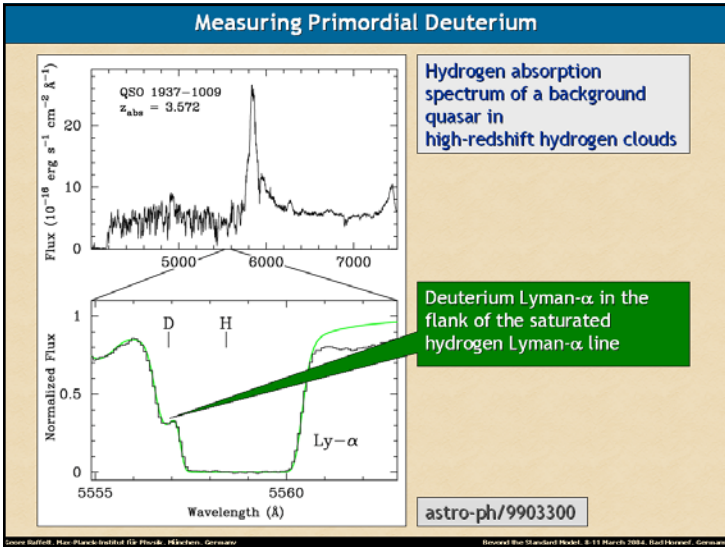
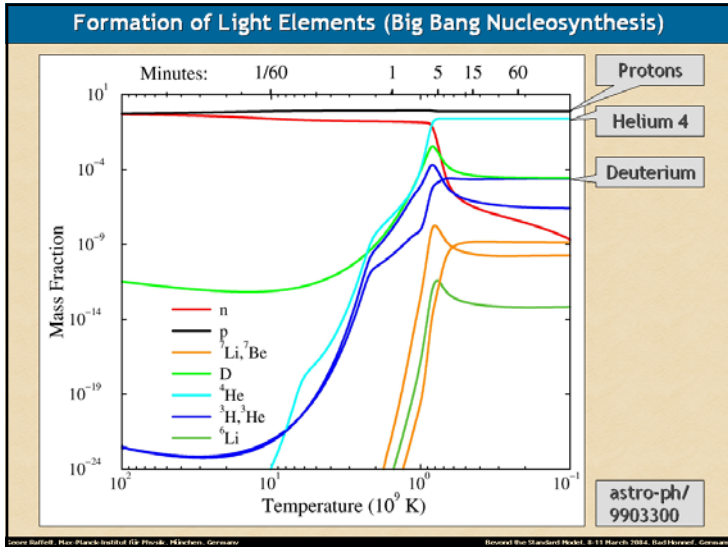
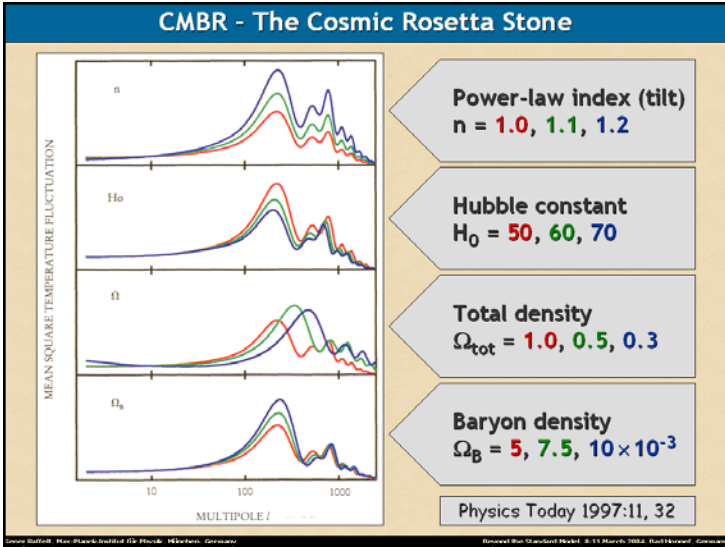
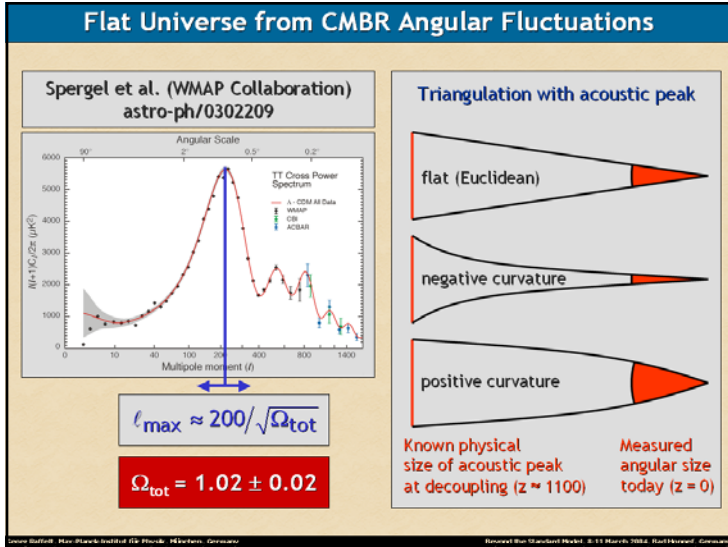
Angular power spectrum

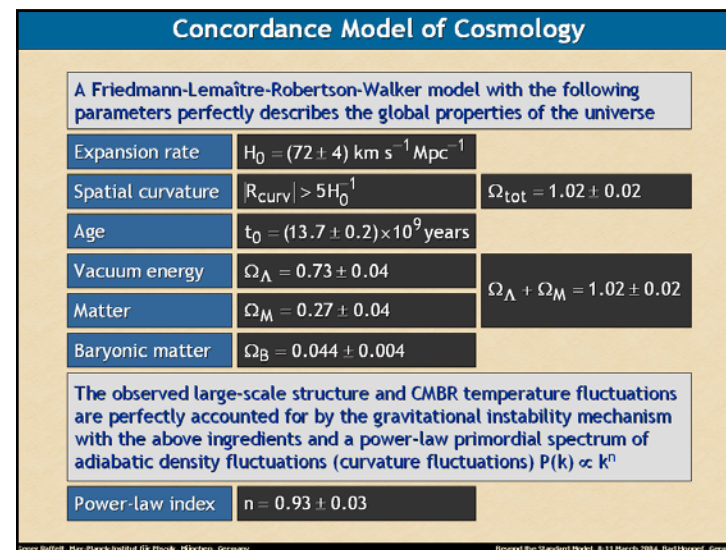
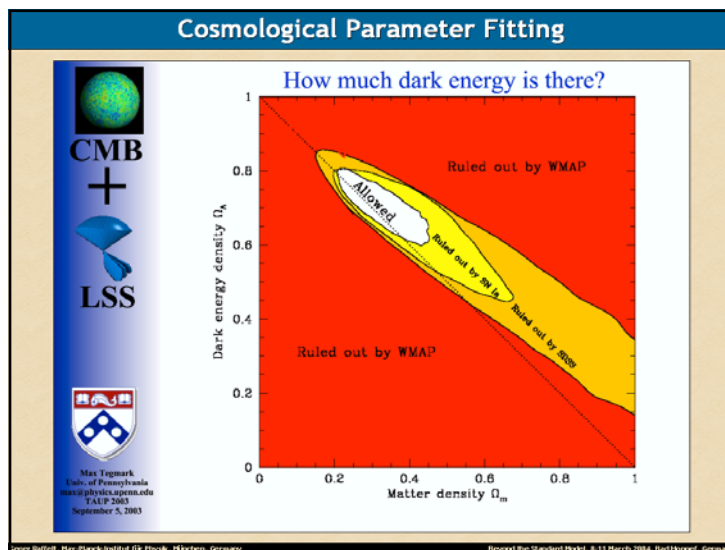
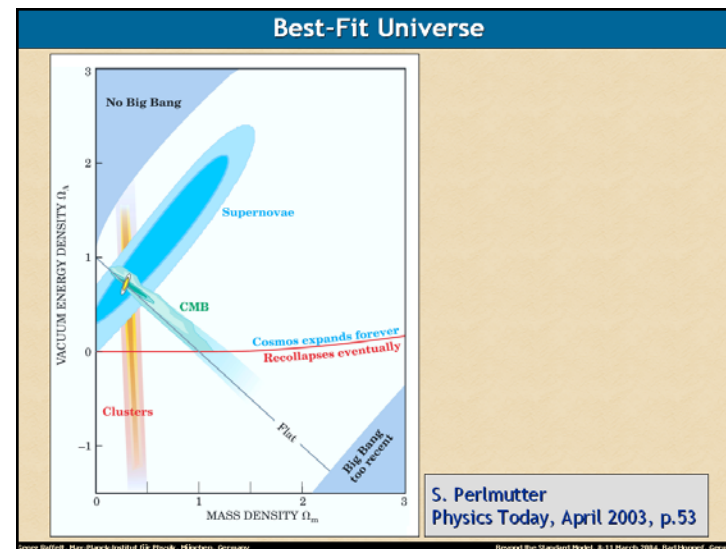
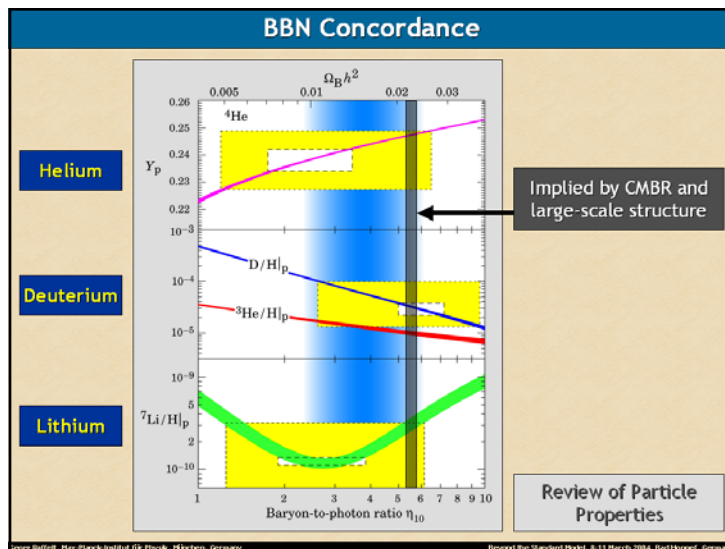
$$C_{\ell} = \langle a_{\ell m}^* a_{\ell m} \rangle = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} a_{\ell m}^* a_{\ell m}$$

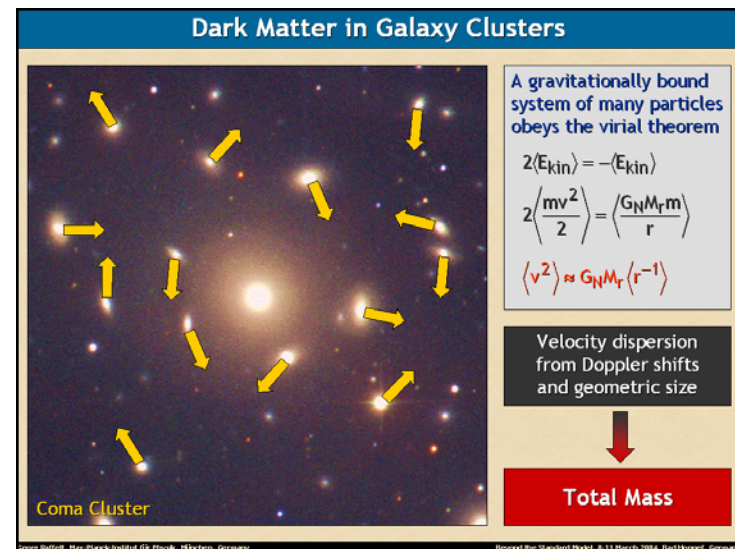
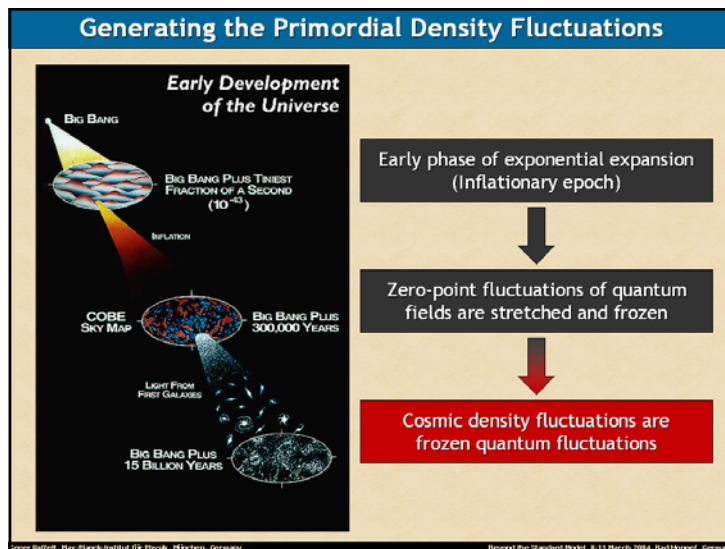


Source: Battelli, Max-Planck-Institut für Physik, München, Germany

Revised Big Bang Model, 8-11 March 2004, Bad Honnef, Germany





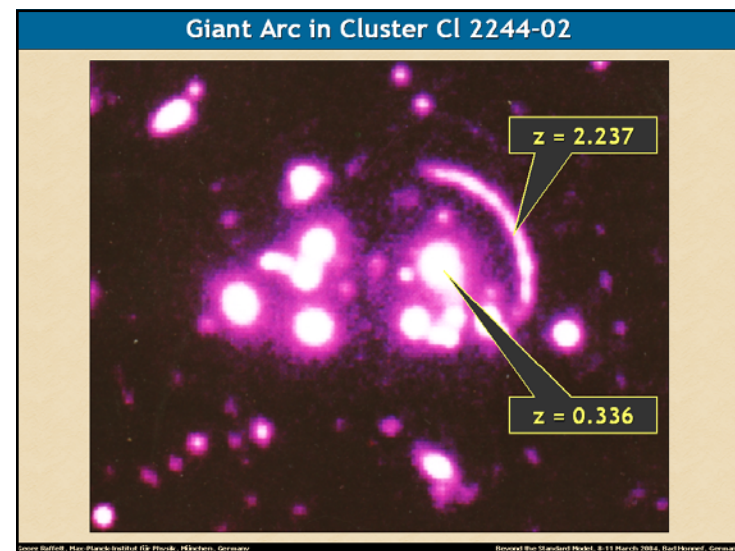


Dark Matter in Galaxy Clusters

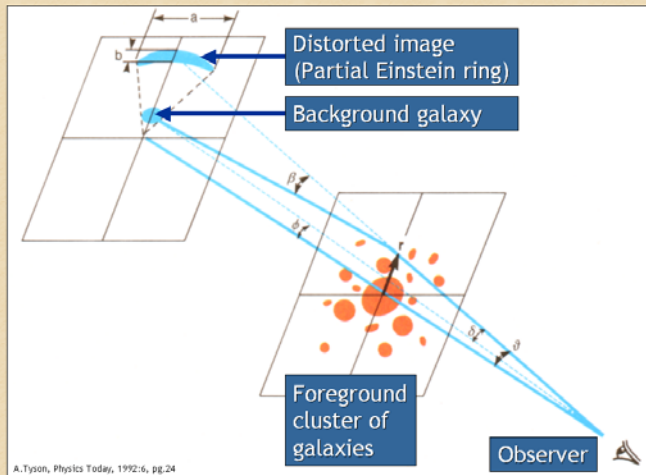
Fritz Zwicky:
Die Rotverschiebung von Extragalaktischen Nebeln
(The redshift of extragalactic nebulae)
Helv. Phys. Acta 6 (1933) 110

In order to obtain the observed average Doppler effect of 1000 km/s or more, the average density of the Coma cluster would have to be at least 400 times larger than what is found from observations of the luminous matter. Should this be confirmed one would find the surprising result that **dark matter** is far more abundant than luminous matter.

Source: Staffell, Max-Planck-Institut für Physik, München, Germany. Revised Ben Standard Model, 8-11 March 2004, EastHaven, Conn.



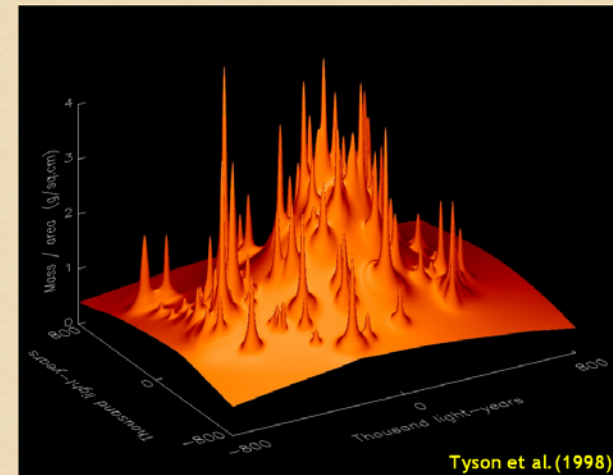
Giant Arcs - Gravitationally Lensed Background Galaxies



Source: Baffert, Max-Planck-Institut für Physik, München, Germany

Revised: Ben Staudert Model, 8.11 March 2004, Bad Homburg, Germany

Mass Map of the Cluster Cl 0024+1645 from Strong Lensing



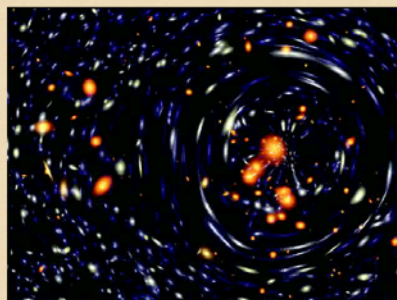
Source: Baffert, Max-Planck-Institut für Physik, München, Germany

Revised: Ben Staudert Model, 8.11 March 2004, Bad Homburg, Germany

Gravitational Lensing in Clusters of Galaxies



Galaxy cluster Cl 0024+1654
[Hubble Space Telescope]

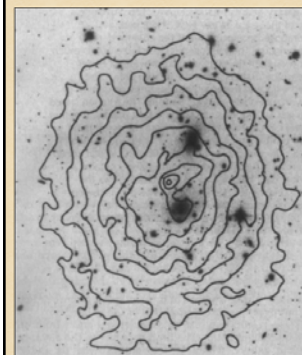


Numerical Simulation

Source: Baffert, Max-Planck-Institut für Physik, München, Germany

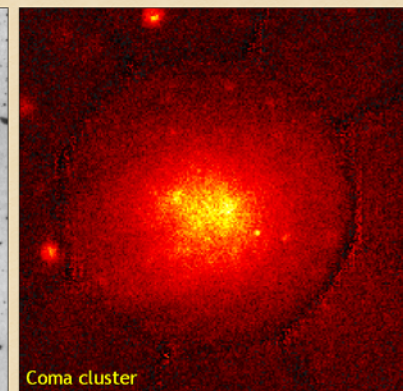
Revised: Ben Staudert Model, 8.11 March 2004, Bad Homburg, Germany

X-Ray Emission from Galaxy Clusters



Coma cluster

Contours of x-ray emission
(Einstein satellite)



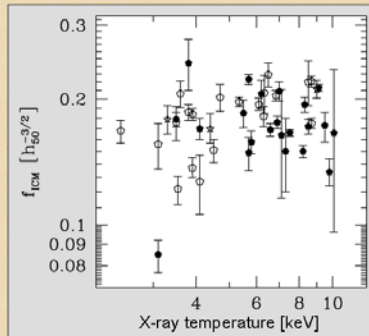
Coma cluster

ROSAT x-ray image

Source: Baffert, Max-Planck-Institut für Physik, München, Germany

Revised: Ben Staudert Model, 8.11 March 2004, Bad Homburg, Germany

Cluster Gas Fraction



Mohr et al., astro-ph/9901281

Gas fraction in clusters

$$f_{\text{gas}} h^{3/2} = 0.075 \pm 0.002$$

- Assume the cluster matter inventory represents a fair sample of the universe
- Use the measured baryon content Ω_B (BBN, CMBR)
- $h = 0.72 \pm 0.08$

Cosmic matter content

$$\Omega_M = \Omega_B / f_{\text{gas}} = 0.325 \pm 0.034$$

(Fabian, astro-ph/0304020)

Structure of Spiral Galaxies

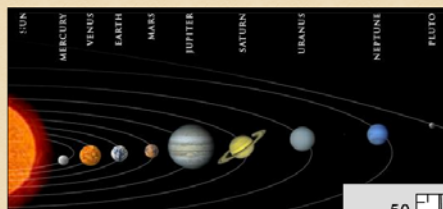


Spiral Galaxy NGC 2997



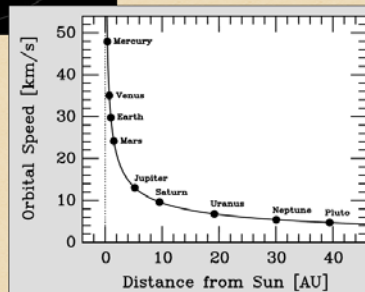
Spiral Galaxy NGC 891

"Rotation Curve" of the Solar System



Kepler's Law

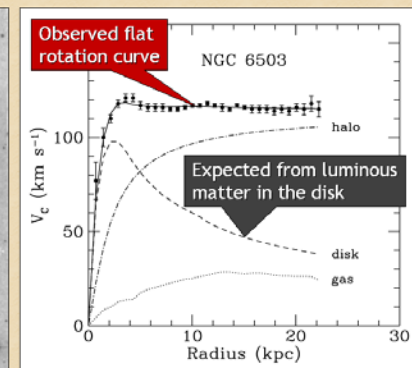
$$v_{\text{rotation}} = \sqrt{\frac{G_{\text{Newton}} M_{\text{central}}}{\text{radius}}}$$



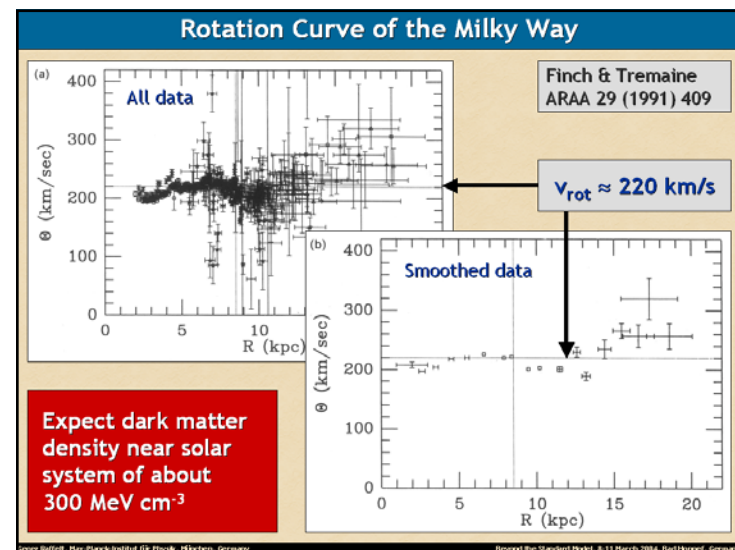
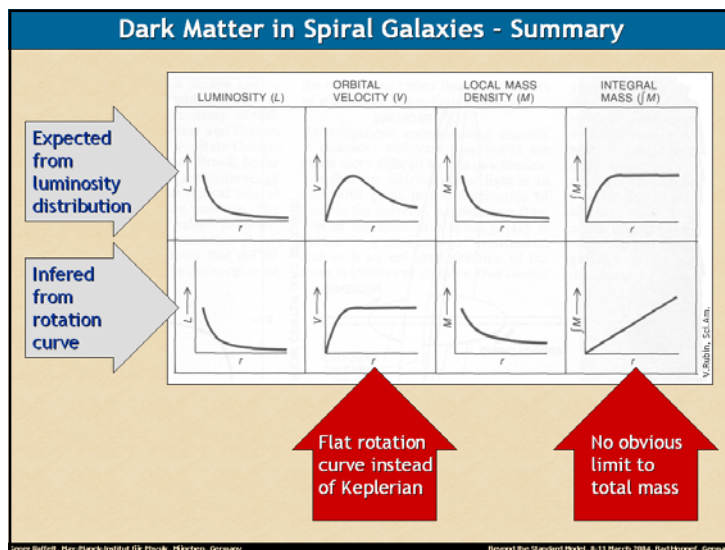
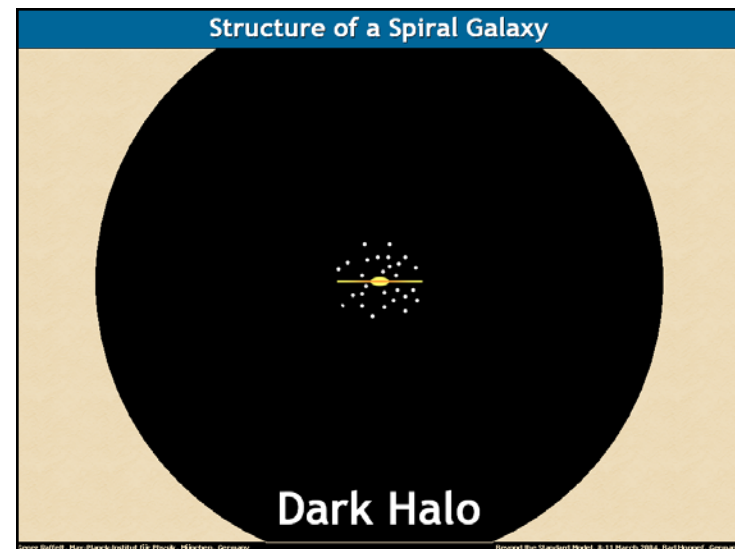
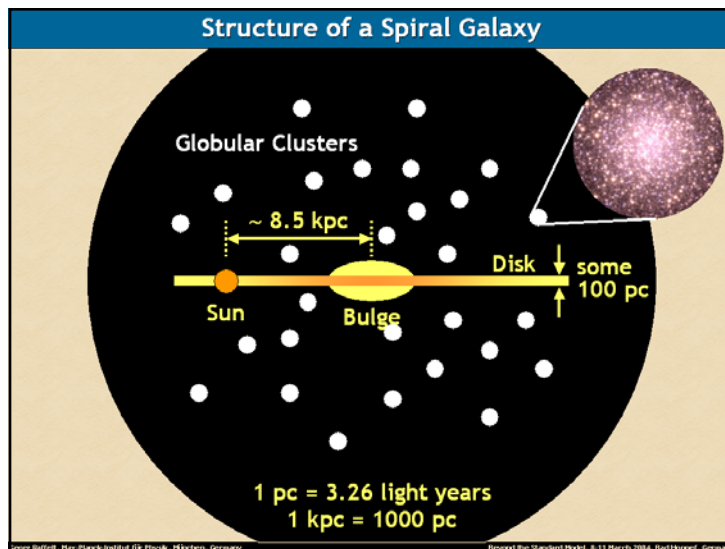
Galactic Rotation Curve from Radio Observations

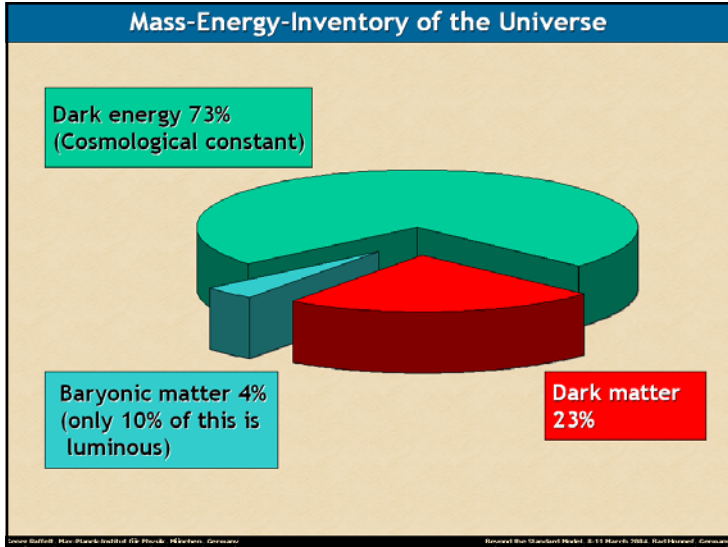


Spiral galaxy NGC 3198 overlaid with hydrogen column density [ApJ 295 (1985) 305]



Rotation curve of the galaxy NGC 6503 from radio observations of hydrogen motion [MNRAS 249 (1991) 523]





Cosmological Limit on Neutrino Masses

Cosmic neutrino "sea" - 112 cm^{-3} neutrinos + anti-neutrinos per flavor

$$\Omega_\nu h^2 = \sum \frac{m_\nu}{94 \text{ eV}} < 0.4$$

$m_\nu < 40 \text{ eV}$ For all stable flavors

BEST MASS OF MUONIC NEUTRINO AND COSMOLOGY

G. S. Gershtein and Ya. B. Zel'dovich
Submitted 4 June 1966
ZhETF Pis'ma 2, No. 5, 174-177, 1 September 1966

A classic paper:
Gershtein & Zeldovich
JETP Lett. 4 (1966) 120

Low-accuracy experimental estimates of the rest mass of the neutrino [1] yield $m(\nu_e) < 200 \text{ eV}/c^2$ for the electronic neutrino and $m(\nu_\mu) < 2.5 \times 10^6 \text{ eV}/c^2$ for the muonic neutrino. Cosmological considerations connected with the hot model of the Universe [2] make it possible to strengthen greatly the second inequality. Just as in the paper by Ya. B. Zel'dovich and Ya. A. Smorodinskii [3], let us consider the gravitational effect of the neutrinos on the dynamics of the expanding Universe. The age of the known astronomical objects is not smaller than 5×10^9 years, and Hubble's constant H is not smaller than 75 km/sec-Mpc $= (13 \times 10^9 \text{ years})^{-1}$. It follows therefore that the density of all types of matter in the Universe is at the present time ¹⁾

$$\rho < 2 \times 10^{-26} \text{ g/cm}^3.$$

Source: Baffert, Max-Planck-Institut für Physik, München, Germany. Received for Standard Model: 8.11 March 2004. Last Revised: Germany.

Weakly Interacting Particles as Dark Matter

The Astrophysical Journal, 180: 7-10, 1973 February 15
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GRAVITY OF NEUTRINOS OF NONZERO MASS IN ASTROPHYSICS

R. COWIE* and J. MCCLELLAND
Department of Physics, University of California, Berkeley
Received 1972 July 24

ABSTRACT

If neutrinos have a rest mass of a few eV/c^2 , then they would dominate the gravitational dynamics of the large clusters of galaxies and of the Universe. A simple model to understand the vital mass discrepancy in the Coma cluster on this basis is outlined.

Subject headings: cosmology — galaxies, clusters of — neutrinos

The possibility of a finite rest mass for the neutrinos has fascinated astrophysicists (Okuniewicz 1965). A recent discussion of such a possibility has been in the context of the solar-neutrino experiments (Bahcall, Cabibbo, and Vahni 1972). Here we wish to point out some interesting consequences of the gravitational interactions of such neutrinos. These considerations become particularly relevant in the framework of big-bang cosmologies which we assume to be valid in our discussion here.

In the early phase of such a Universe when the temperature was $\sim 1 \text{ MeV}$, several processes of neutrino production (Ruderman 1969) would have led to copious production of neutrinos and antineutrinos (Nagman 1972; Cowie and McClelland 1972). Conditions of thermal equilibrium offer an easy estimate of their number density (Landau and Lifshitz 1969):

$$n_\nu = \frac{1}{2\pi^2} \int_0^\infty \frac{p^2 dp}{\exp [kT(\nu_{\text{max}})/kT] + 1} \quad (1)$$

Here n_ν = number density of neutrinos of the k th kind (notice that in writing this expression we have assumed that both the helicity states are allowed for the neutrinos because of finite rest mass); $k = e^2/k^2 = m^2 c^4/\hbar^2$; k = Boltzmann's constant; $T(\nu_{\text{max}}) = T(L_{\text{max}}) = T(L_{\text{min}}) = T(L_{\text{min}}) = T(L_{\text{min}})$ = the common temperature of radiation, neutrinos, electrons, etc., at the latest epoch characterized by redshift ν_{max} when they may be assumed to have been in thermal equilibrium; $kT(\nu_{\text{max}}) \approx 1 \text{ MeV}$.

Since the masses of the neutrinos are expected to be small, $kT(\nu_{\text{max}}) \approx m_\nu c^2$, in the extreme-relativistic limit equation (1) reduces to

$$n_\nu(\nu_{\text{max}}) \approx 0.183 [T(\nu_{\text{max}})/kT]^3 \quad (2)$$

As the Universe expands, only the neutrinos (in contrast to all other known particles) survive annihilation because of extremely low cross-sections (deGroot and Tolkachev 1966), and their number density decreases with increasing volume of the Universe, simply as $n_\nu \propto T(\nu_{\text{max}})^3 \propto (1+z)^3 \propto a^{-3}$. Noting that $(1+z) = a_0/(1+z) = a_0/a$, the number density at the present epoch ($z=0$) is given by

$$n_\nu(0) = n_\nu(\nu_{\text{max}})(1+z)^3 \approx 0.183 [T(0)/kT]^3 \approx 300 \text{ cm}^{-3} \quad (3)$$

* On leave from the Tata Institute of Fundamental Research, Bombay, India.

More than 30 years ago, beginnings of the idea of weakly interacting particles (neutrinos) as dark matter

Massive neutrinos are no longer a good candidate (hot dark matter)

However, the idea of weakly interacting massive particles as dark matter is now standard

Source: Baffert, Max-Planck-Institut für Physik, München, Germany. Received for Standard Model: 8.11 March 2004. Last Revised: Germany.

What is wrong with neutrino dark matter?

Galactic Phase Space ("Tremaine-Gunn-Limit")

Maximum mass density of a degenerate Fermi gas

$$\rho_{\text{max}} = m_\nu \frac{p_{\text{max}}^3}{3\pi^2} = \frac{m_\nu (m_\nu v_{\text{escape}})^3}{3\pi^2}$$

$m_\nu > 20 - 40 \text{ eV}$ Spiral galaxies

$m_\nu > 100 - 200 \text{ eV}$ Dwarf galaxies

Neutrino Free Streaming (Collisionless Phase Mixing)

- At $T < 1 \text{ MeV}$ neutrino scattering in early universe ineffective
- Stream freely until non-relativistic
- Wash out density contrasts on small scales

Neutrinos

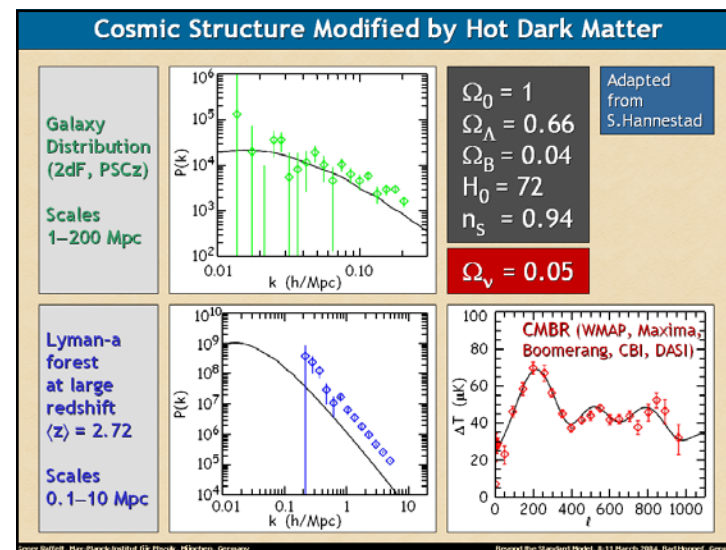
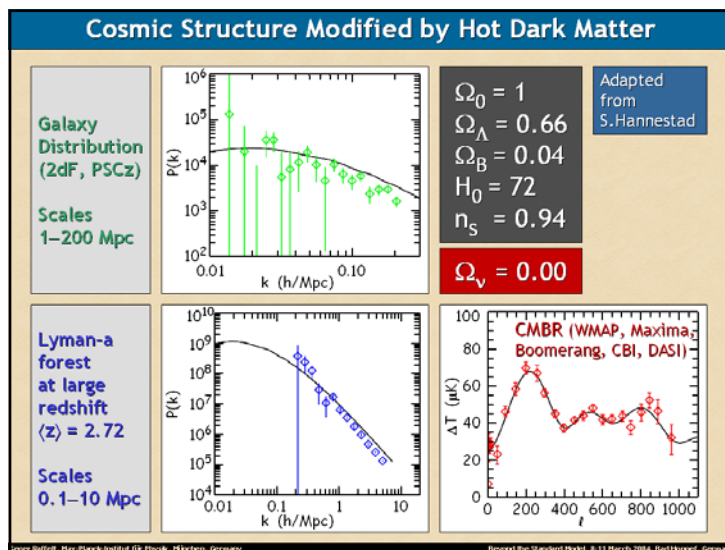
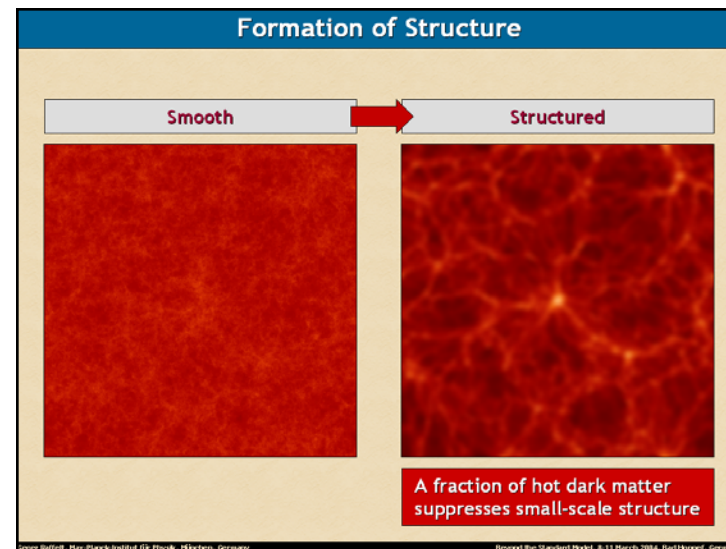
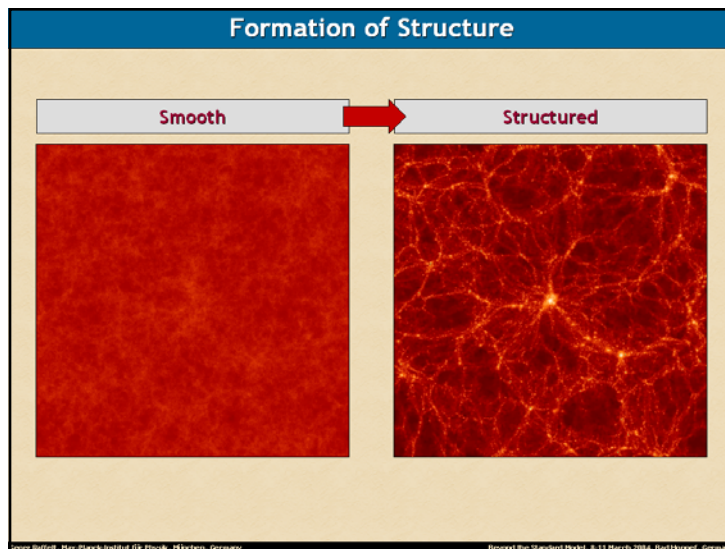
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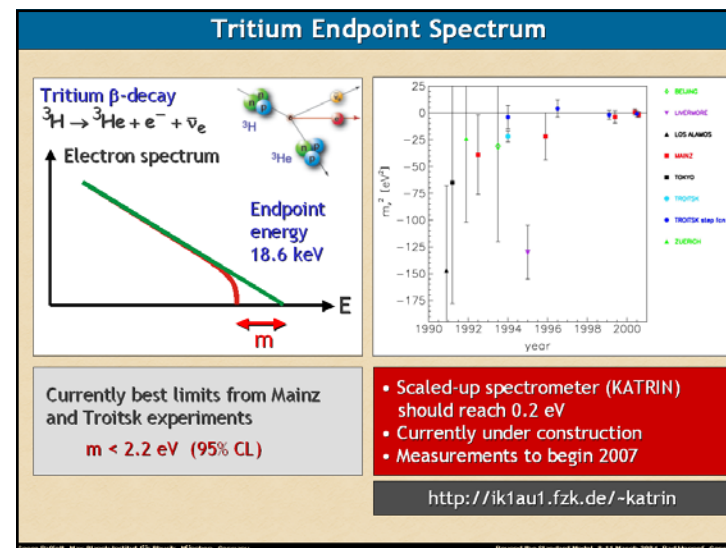
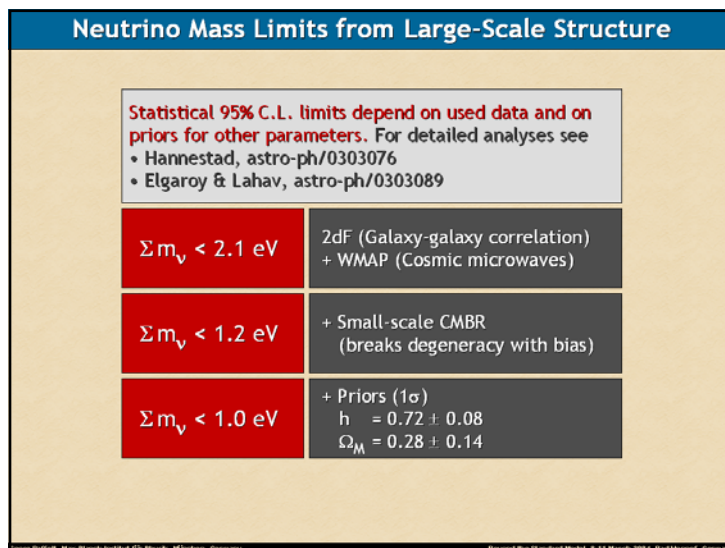
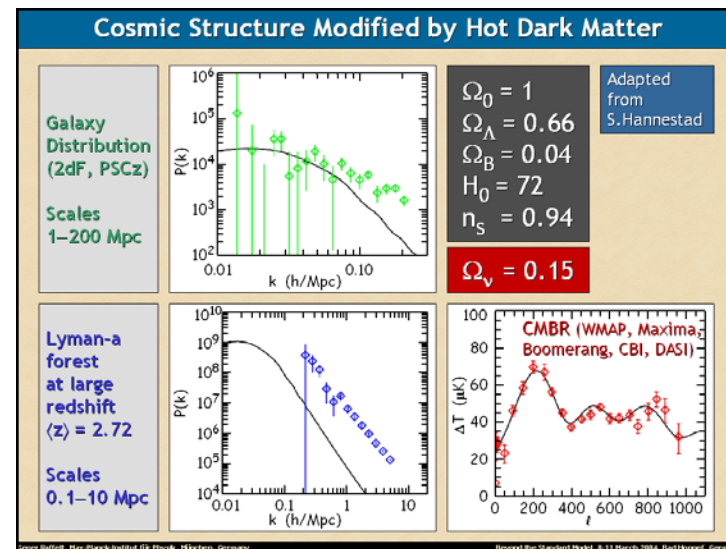
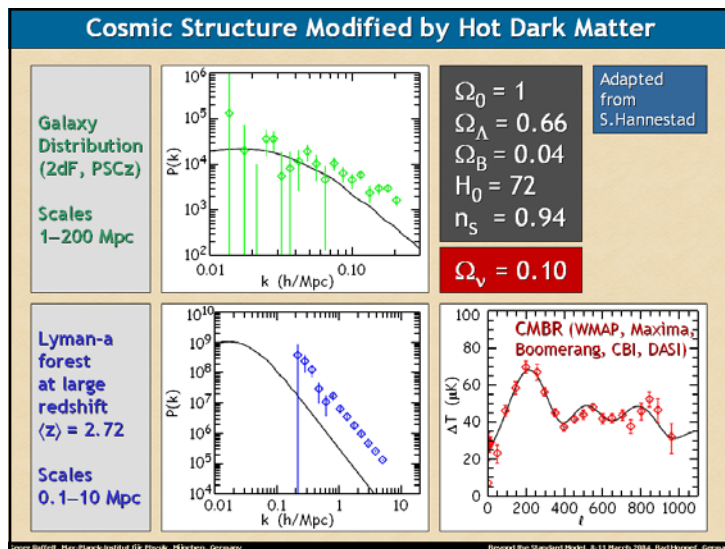
Neutrinos

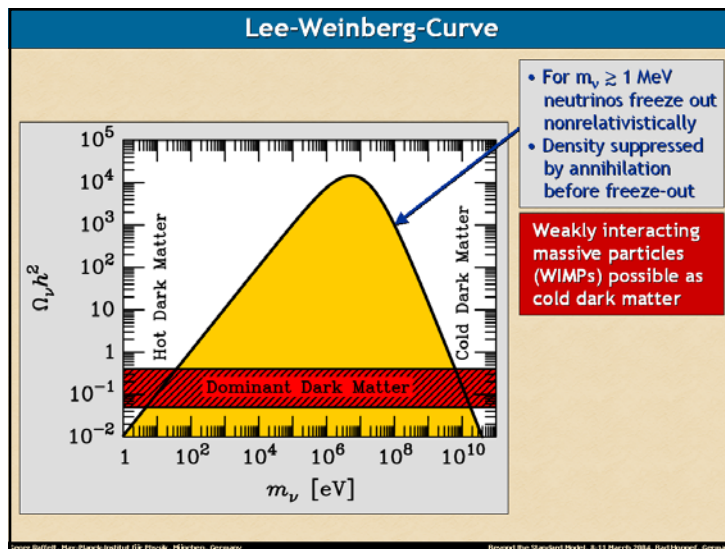
Over-density

- Nus are "Hot Dark Matter"
- Ruled out by structure formation

Source: Baffert, Max-Planck-Institut für Physik, München, Germany. Received for Standard Model: 8.11 March 2004. Last Revised: Germany.







Supersymmetric Extension of Particle Physics

In supersymmetric extensions of the particle-physics standard model, every boson has a fermionic partner and vice versa

Spin	Standard particle	Superpartner	Spin
1/2	Leptons ($e, \nu_e, \dots$) Quarks ($u, d, \dots$)	Sleptons ($\tilde{e}, \tilde{\nu}_e, \dots$) Squarks ($\tilde{u}, \tilde{d}, \dots$)	0
1	Gluons $W^\pm$ Z^0 Photon (γ)	Gluinos Wino Zino Photino ($\tilde{\gamma}$)	1/2
0	Higgs	Higgsino	1/2
2	Graviton	Gravitino	3/2

• If R-Parity is conserved, the lightest SUSY-particle (LSP) is stable

• Most plausible candidate for dark matter is the neutralino, similar to a massive Majorana neutrino

Neutralino = C_1 Photino + C_2 Zino + C_3 Higgsino

The Search for Dark Matter in our Galaxy

Direct search experiments exist for

- **WIMPs**
(Weakly Interacting Massive Particles, often assumed to be supersymmetric neutralinos)
- **Axions**
(Very low-mass very weakly interacting bosons, motivated by CP problem of QCD)

(With permission of David Simmonds ©)

Search for Neutralino Dark Matter

Direct Method (Laboratory Experiments)

Galactic dark matter particle (e.g. neutralino)

Crystal

Recoil energy (few keV) is measured by

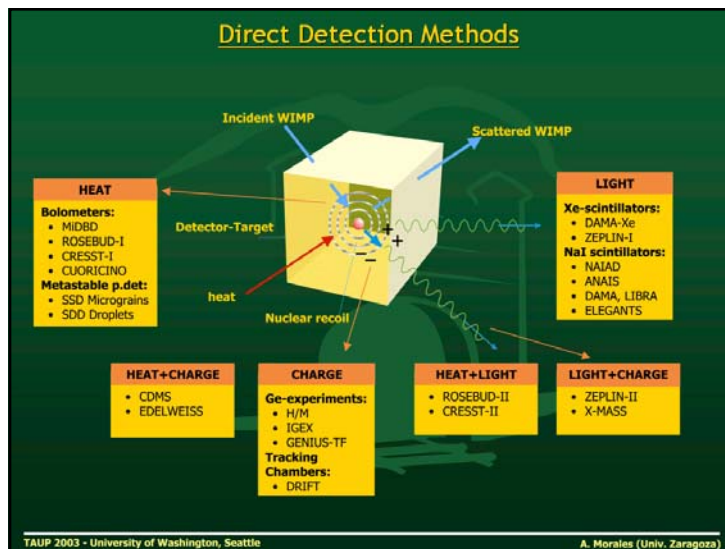
- Ionisation
- Scintillation
- Cryogenic

PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)

We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses $1-10^6$ GeV; particles with spin-dependent interactions of typical weak strength and masses $1-10^7$ GeV; or strongly interacting particles of masses $1-10^{13}$ GeV.

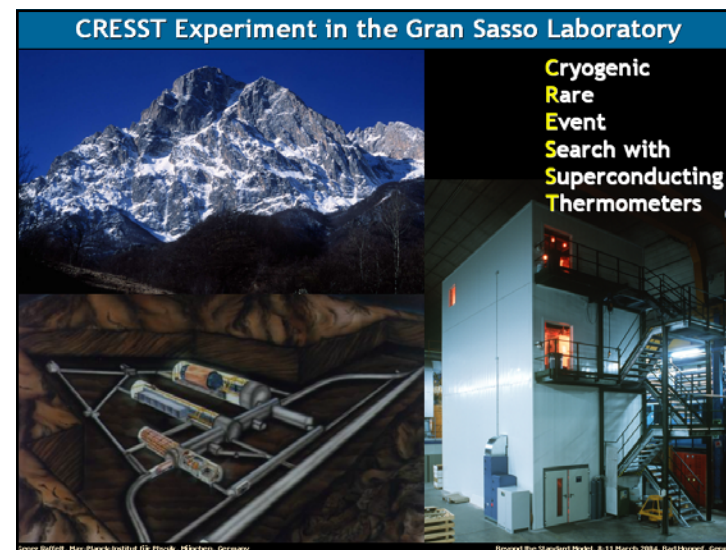
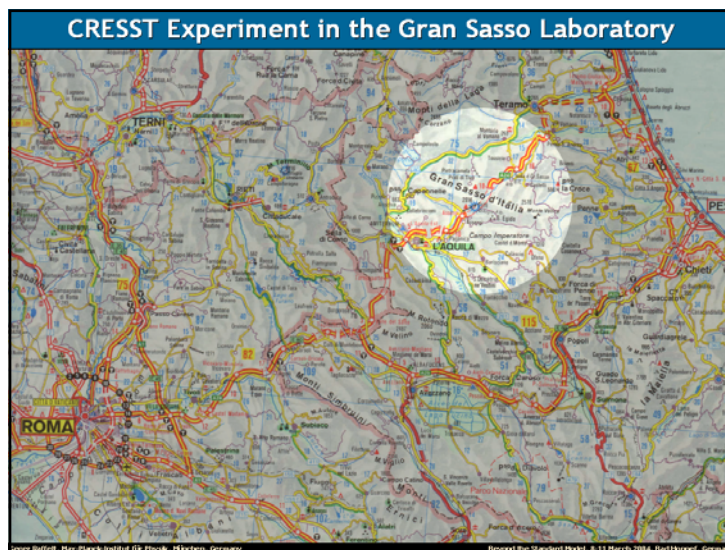


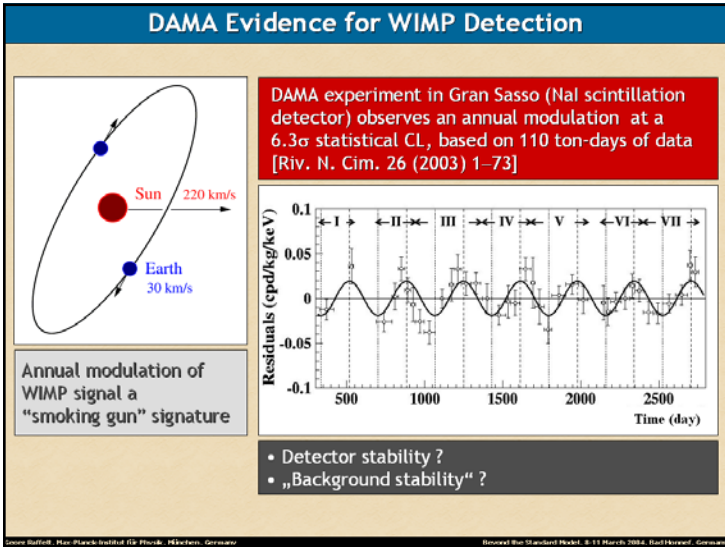
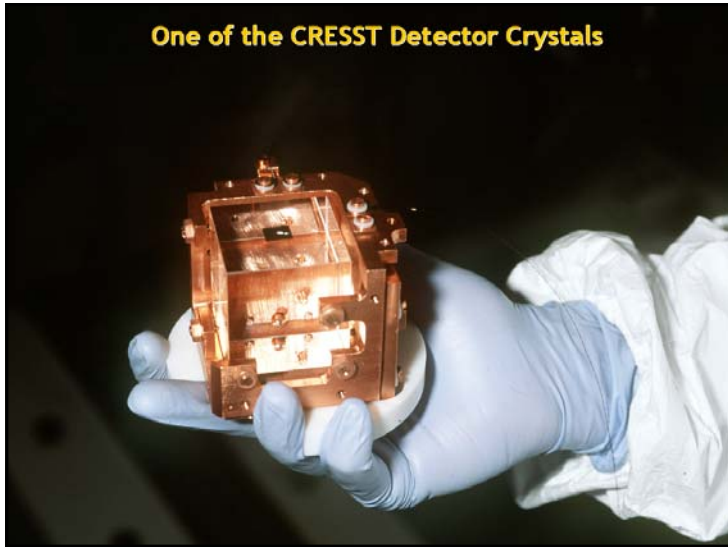
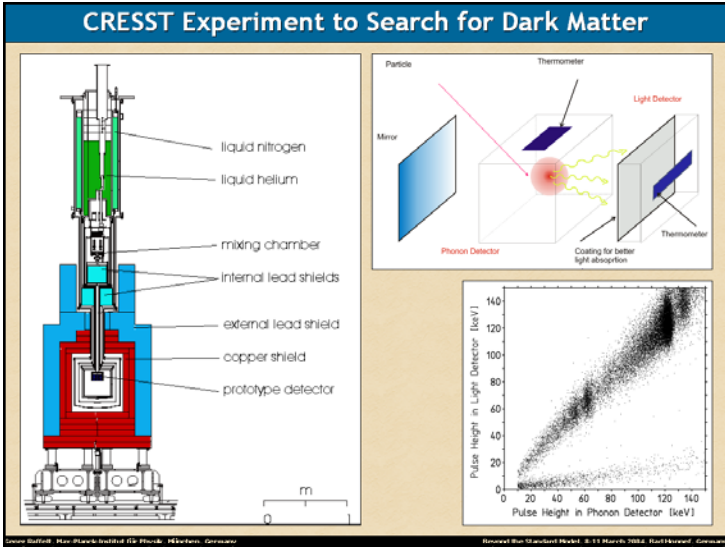
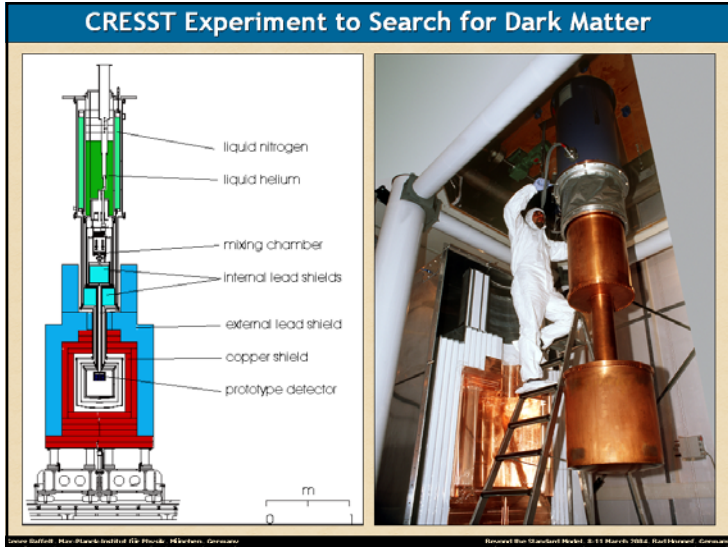
WIMP direct detection in underground facilities experiments currently running (or in preparation)

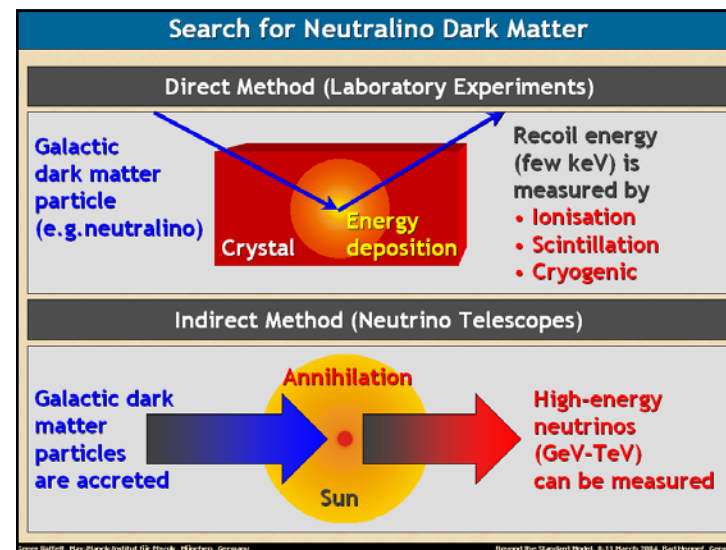
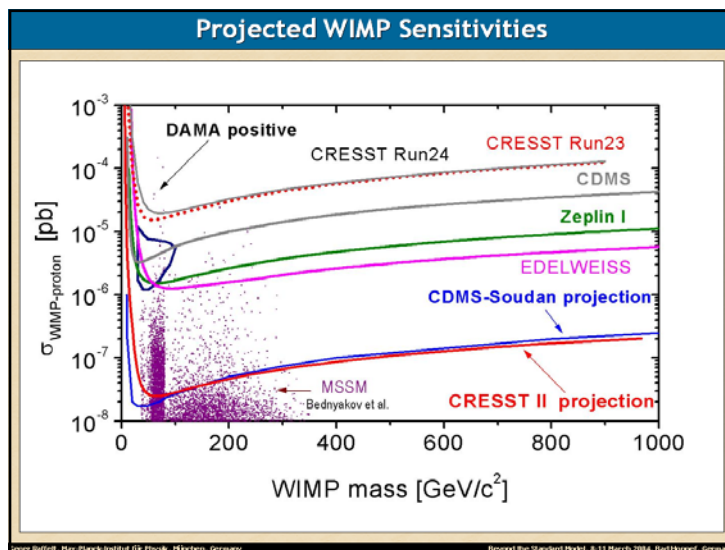
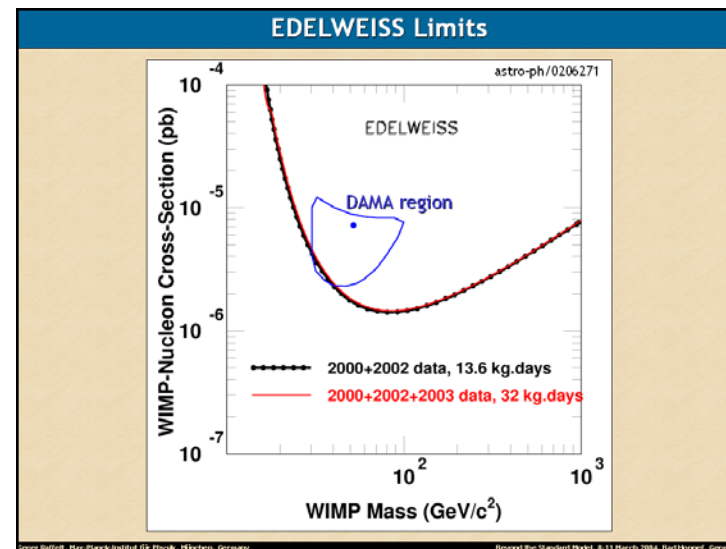
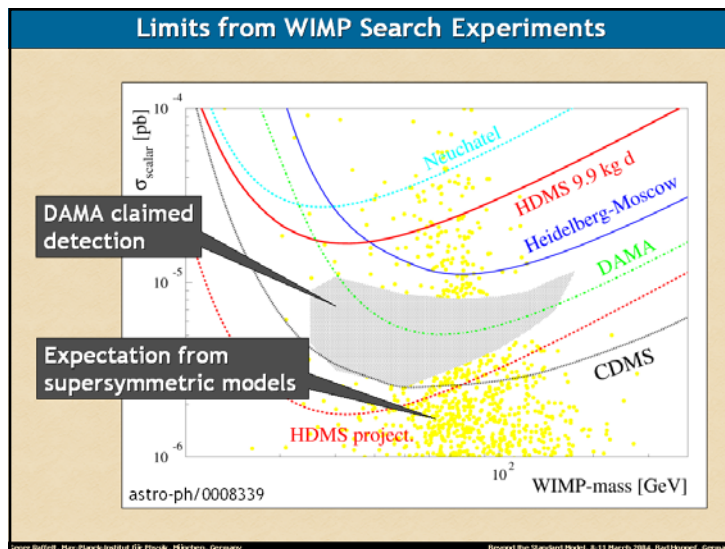
LABORATORY	EXPERIMENT	TECHNIQUE
Bern (Switzerland)	ORPHEUS	(SSD) Tin Superconducting Superheated Detector
Boulby (UK)	NAJAD ZEPLIN I ZEPLIN II DRIFT	NaI scintillators (46-65 Kg) Liquid Xe scintillator (4 Kg) Liquid-Gas Xe (scintillation/ionization) (30 Kg) (R+D) Low pressure Xe TPC (m) (R+D)
Carrifran (Spain)	IGEX GEDEON ANAIS ROSEBUD	Ge ionization detector (2.1 Kg) Set of Ge ionization detector (in project) (4x7x2 Kg) NaI scintillators (110 kg) CaWO ₄ and BGO scintillating bolometers (50-200 g)
Frojus/Modane (France)	EDELWEISS	Sets of Ge thermal-ionization detectors (n x 320 g)
Gran Sasso (Italy)	H/M HDMS GENIUS-TF DAMA LIBRA Liquid-Xe CaF ₂ CRESST CLORICINO CUORE	Ge ionization detector (2.7 Kg) Ge ionization in Ge well Set of Ge crystals in LN ₂ (40 Kg) NaI scintillators (~100 Kg) NaI scintillators 250 kg (starting) Liquid Xe scintillator (6 Kg) Scintillator Set of CaWO ₄ scintillating bolometers (n x 300 g) Set of TeO ₂ thermal detector (41 Kg) 1000x760 g TeO ₂ (in project)
KAMIOKA (Japan)	XMASS	Large mass Xe scintillators (R+D)
Rustrel (France)	SIMPLE	(SDD) Superheated Droplets Detectors (Freon)
Soudan (USA)	CDMS	Sets of Ge and Si thermal + ionization detectors
SNO (Canada)	PICASSO	(SDD) Superheated Droplets Detectors (Freon)
OTO (Japan)	ELEGANTS V ELEGANTS VI	Large set of massive NaI scintillators (670 kg) CaF ₂ scintillators

TAUP 2003 - University of Washington, Seattle

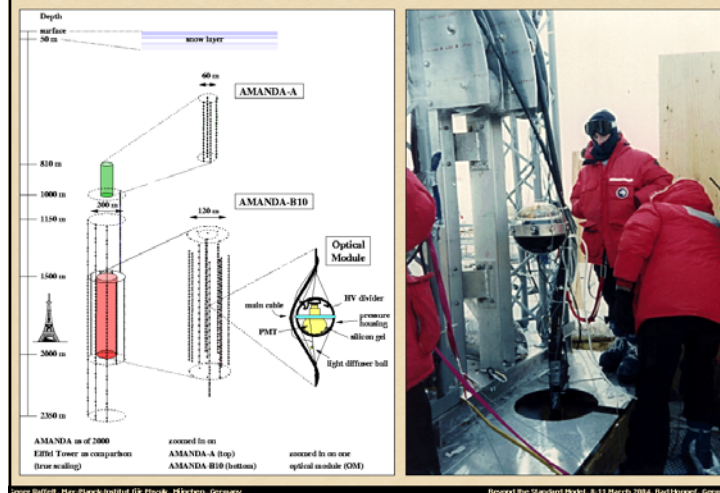
A. Morales (Univ. Zaragoza)



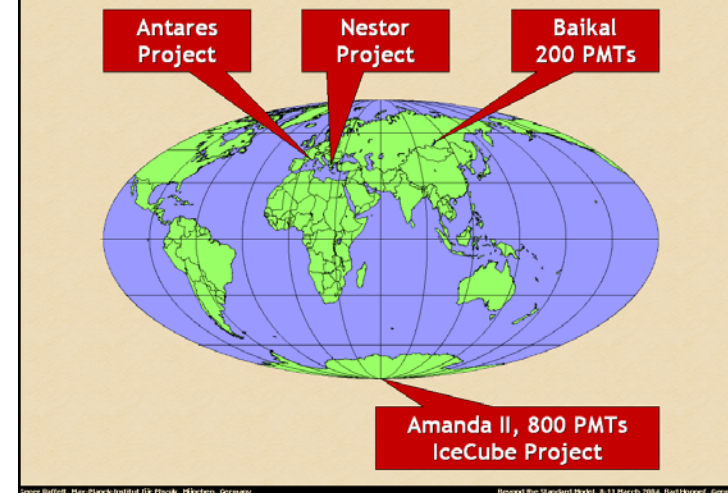




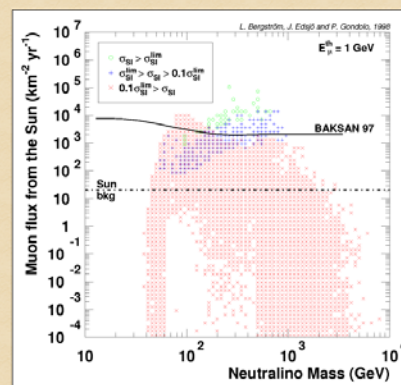
AMANDA - South Pole Neutrino Telescope



High-Energy Neutrino Telescopes



Muon Flux from WIMP Annihilation in the Sun



Need a km^3 water Cherenkov detector to reach solar background

High-Energy Gamma Rays from Neutralino Annihilation

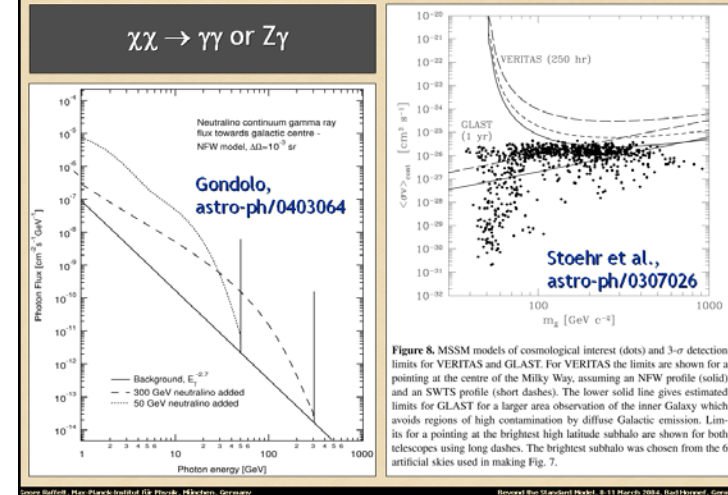


Figure 8. MSSM models of cosmological interest (dots) and $3\text{-}\sigma$ detection limits for VERITAS and GLAST. For VERITAS the limits are shown for a pointing at the centre of the Milky Way, assuming an NFW profile (solid) and an SWTS profile (short dashes). The lower solid line gives estimated limits for GLAST for a larger area observation of the inner Galaxy which avoids regions of high contamination by diffuse Galactic emission. Limits for a pointing at the brightest high latitude subhalo are shown for both telescopes using long dashes. The brightest subhalo was chosen from the 6 artificial skies used in making Fig. 7.

The CP Problem of Strong Interactions

Standard QCD Lagrangian contains a CP violating term

Induces a neutron electric dipole moment (EDM) much in excess of experimental limits

Characterizes degenerate QCD ground state (Θ vacuum)

Phase of Quark Mass Matrix

$$L_{CP} = -\frac{\alpha_s}{8\pi} (\Theta - \arg \det M_q) \text{Tr} \tilde{G}_{\mu\nu} G^{\mu\nu}$$

$0 \leq \Theta \leq 2\pi$

$$d_n \approx \Theta \cdot 10^{-16} \text{ e cm} \approx \frac{\Theta}{10^2} \mu_n < 10^{-25} \text{ e cm}$$

$\Theta < 10^{-9}$ Why so small?

Dynamical Solution

Peccei & Quinn 1977 - Wilczek 1978 - Weinberg 1978

Re-interpret Θ as a dynamical variable (scalar field)

$$L_{CP} = -\frac{\alpha_s}{8\pi} \Theta \text{Tr} \tilde{G}G$$

$\Theta \rightarrow \frac{a(x)}{f_a}$

Pseudo-scalar axion field

Peccei-Quinn scale, Axion decay constant

$L_{CP} = -\frac{\alpha_s}{8\pi} \Theta \text{Tr} \tilde{G}G \rightarrow -\frac{\alpha_s}{8\pi} \frac{a(x)}{f_a} \text{Tr} \tilde{G}G$

Potential (mass term) induced by L_{CP} drives $a(x)$ to CP-conserving minimum

CP-symmetry dynamically restored

Axions generically couple to gluons and thus mix with π^0

(Axion mass & couplings) = (Pion mass & couplings) $\times \frac{f_\pi}{f_a}$

$f_\pi \approx 93 \text{ MeV}$ Pion decay constant

Axions as Pseudo Nambu-Goldstone Bosons

- The realization of the PQ mechanism involves a new chiral U(1) symmetry, spontaneously broken at a scale f_a
- Axions are the corresponding Nambu-Goldstone mode

$E \approx f_a$

- $U_{PQ}(1)$ spontaneously broken
- Higgs field settles in "Mexican hat"

$E \approx \Lambda_{QCD} = f_a$

- $U_{PQ}(1)$ explicitly broken by instanton effects
- Mexican hat tilts
- Axions acquire a mass

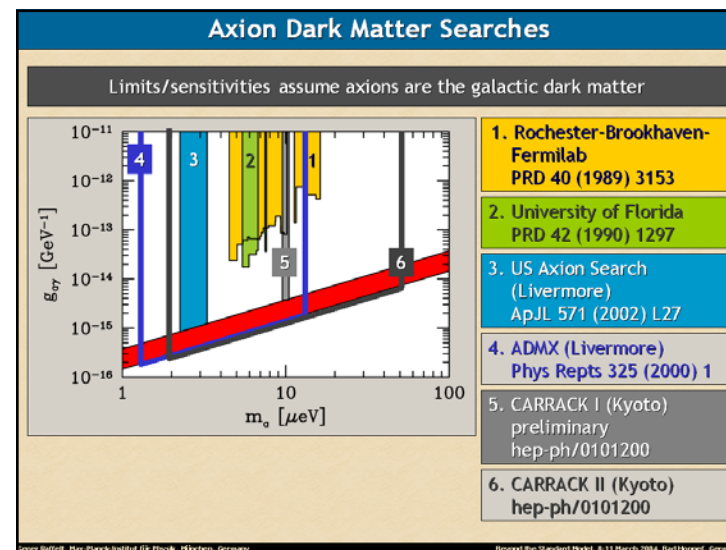
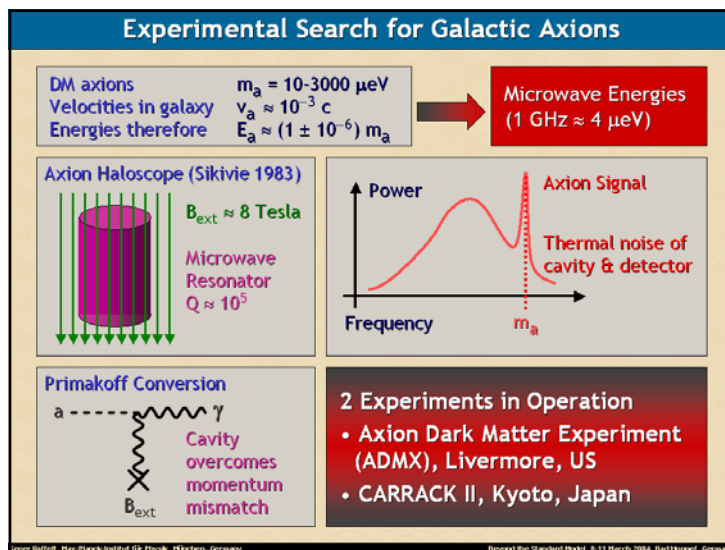
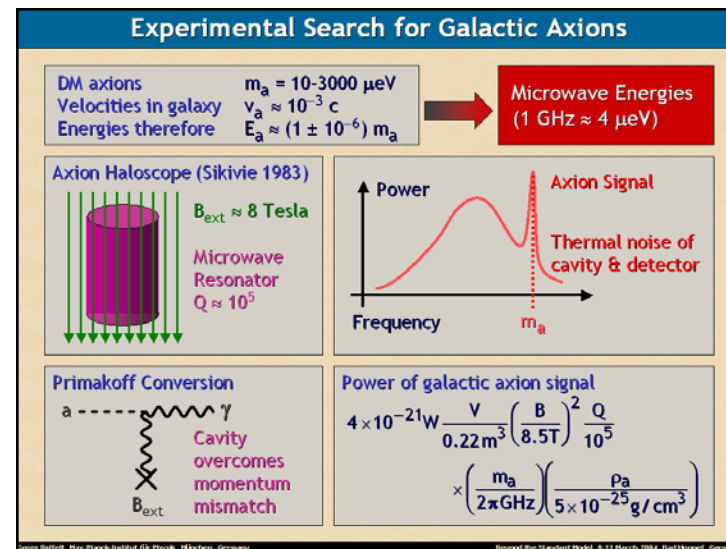
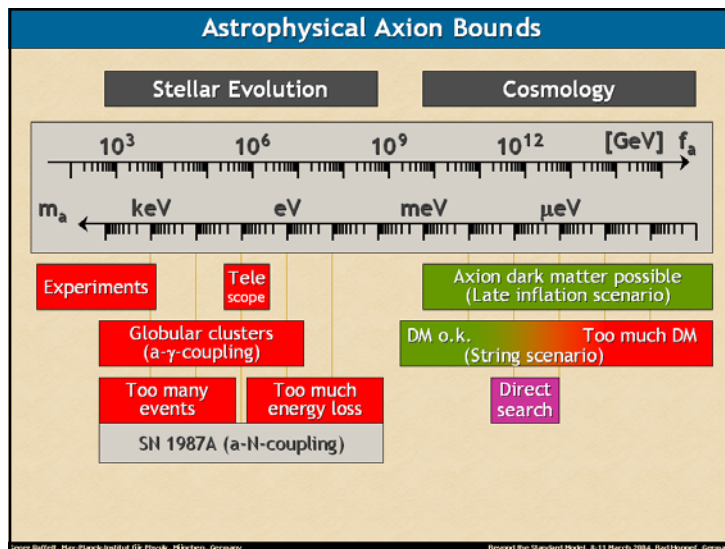
Lee-Weinberg Curve for Neutrinos and Axions

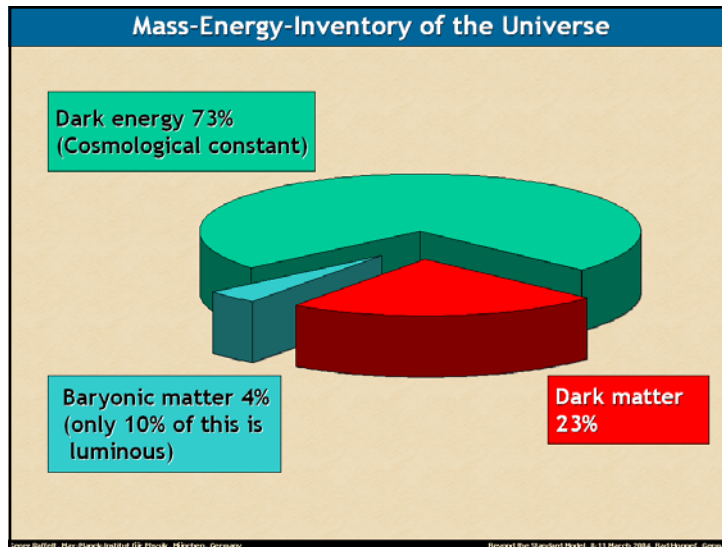
Axions

Non-Thermal Relics (CDM) and Thermal Relics (HDM) regions.

Neutrinos

Thermal Relics (HDM) and Non-Thermal Relics (CDM) regions.





Baryogenesis in the Early Universe

Sakharov conditions for creating the Baryon Asymmetry of the Universe (BAU)

- C and CP violation
- Baryon number violation
- Deviation from thermal equilibrium

Particle-physics standard model

- Violates C and CP
- Violates B and L by EW instanton effects (B – L conserved)

• However, electroweak baryogenesis not quantitatively possible within particle-physics standard model

• Works in SUSY models for small range of parameters

A. Riotto & M. Trodden: Recent progress in baryogenesis
Ann. Rev. Nucl. Part. Sci. 49 (1999) 35

Source: Baffert, Max-Planck-Institut für Physik, München, Germany. Revised the Standard Model, 8.11 March 2004, last revised: Germany

Leptogenesis by Majorana Neutrino Decays

A classic paper

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BARYOGENESIS WITHOUT GRAND UNIFICATION

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Received 8 March 1986

A mechanism is pointed out to generate cosmological baryon number excess without resorting to grand unified theories. The lepton number excess originating from Majorana mass terms may transform into the baryon number excess through the unsuppressed baryon number violation of electroweak processes at high temperatures.

Source: Baffert, Max-Planck-Institut für Physik, München, Germany. Revised the Standard Model, 8.11 March 2004, last revised: Germany

See-Saw Model for Neutrino Masses

Dirac masses from coupling to standard Higgs field ϕ

Charged Leptons	
e_L	e_R
μ_L	μ_R
τ_L	τ_R

Neutrinos	
ν_L	ν_R
ν_L	ν_R
ν_L	ν_R

Heavy Majorana masses
 $M_j > 10^{10}$ GeV

Lagrangian for particle masses

$$L_{\text{mass}} = -\bar{e}_L \phi g_e e_R - \bar{\nu}_L \phi g_\nu \nu_R - \frac{1}{2} \bar{N}_R^c M N_R + \text{h.c.}$$

$$(\bar{\nu}_L \quad \bar{N}_R) \begin{pmatrix} 0 & g_\nu \langle \phi \rangle \\ g_\nu \langle \phi \rangle & M \end{pmatrix} \begin{pmatrix} \nu_L \\ N_R \end{pmatrix}$$

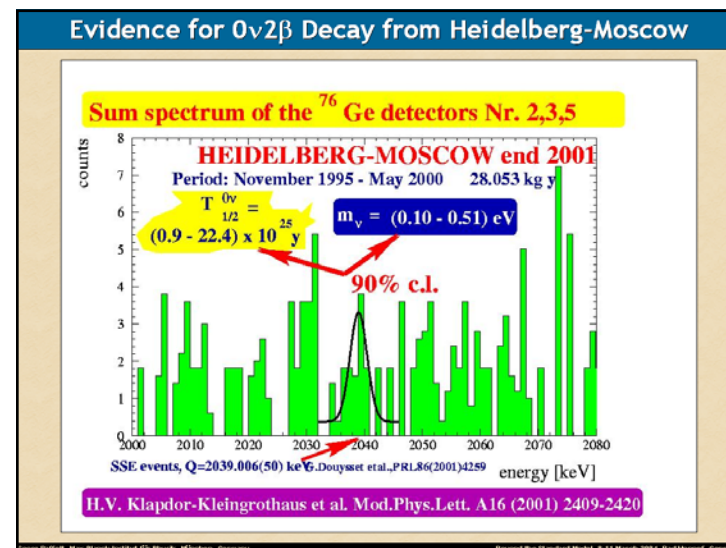
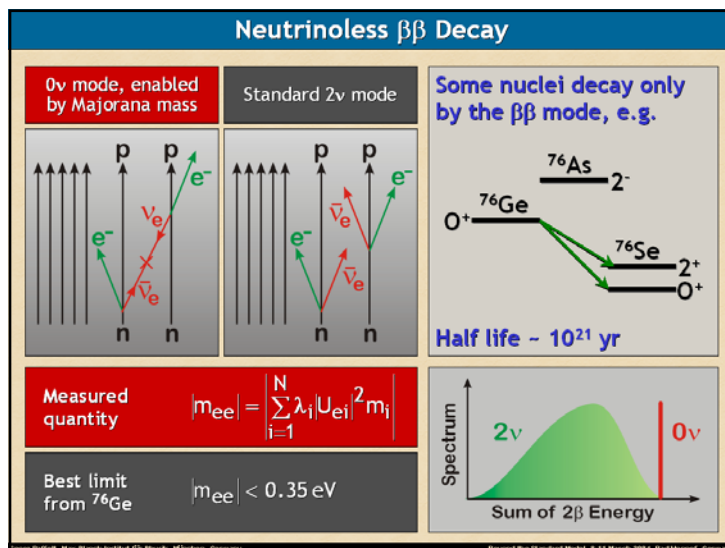
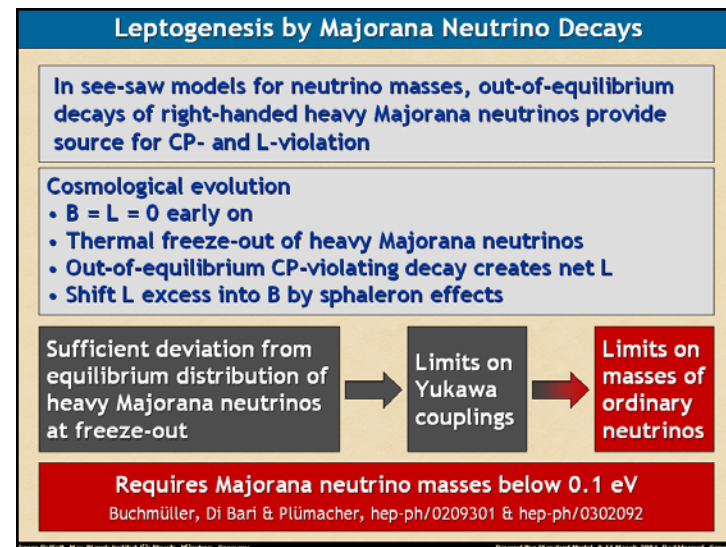
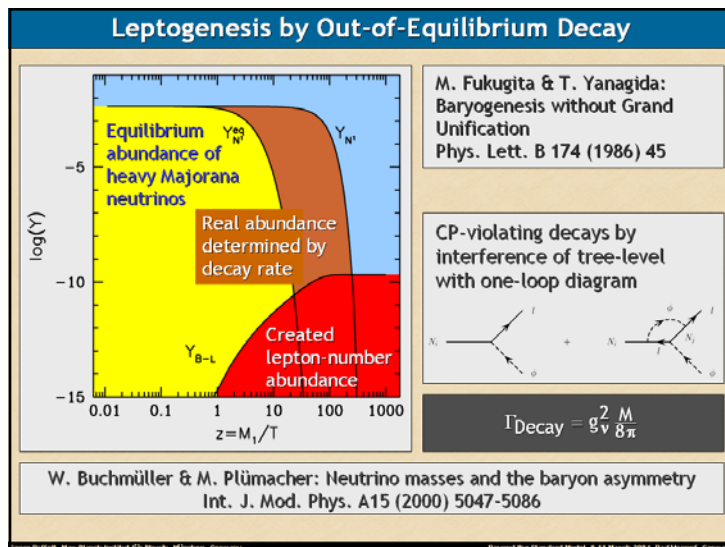
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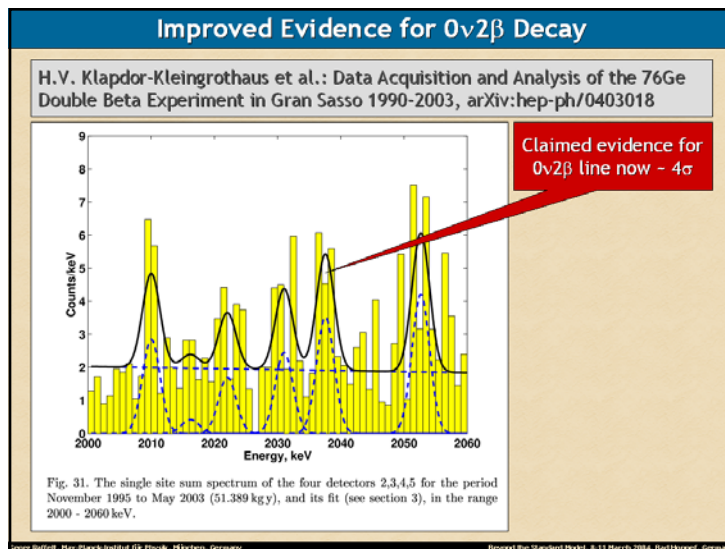
Light Majorana mass

$$(\bar{\nu}_L \quad \bar{N}_R) \begin{pmatrix} \frac{g_\nu^2 \langle \phi \rangle^2}{M} & 0 \\ 0 & M \end{pmatrix} \begin{pmatrix} \nu_L \\ N_R \end{pmatrix}$$

Diagonalize

Source: Baffert, Max-Planck-Institut für Physik, München, Germany. Revised the Standard Model, 8.11 March 2004, last revised: Germany





Frontiers of Cosmology	
Missing pieces of the concordance model	Search for physics beyond the concordance model
Astrophysical understanding of cosmic dark ages: Epoch between decoupling and first luminous objects (e.g. quasars) Identification of dark matter particles • Accelerator search for SUSY particles • Direct search for galactic dark matter • Neutrino telescopes • Cosmic ray signatures Neutrino masses and Majorana nature ($0\nu 2\beta$ decay $\leftrightarrow$ leptogenesis)	Precision cosmology • CMBR, in particular polarization • Galaxy redshift surveys • SN Ia Hubble diagram • Weak lensing • ... ↓ • Some fundamental inconsistency • Nontrivial equation of state $w \neq -1$ or even $w(t)$ • Running spectral index $P(k) \propto k^{n(k)}$ • Tensor modes
Theoretical break-through, for example concerning • Nature of dark energy or cosmological constant • Early-universe physics (inflation, origin of density fluctuations, baryogenesis, alternative theories, e.g. brane-worlds, string cosmology, ...)	

