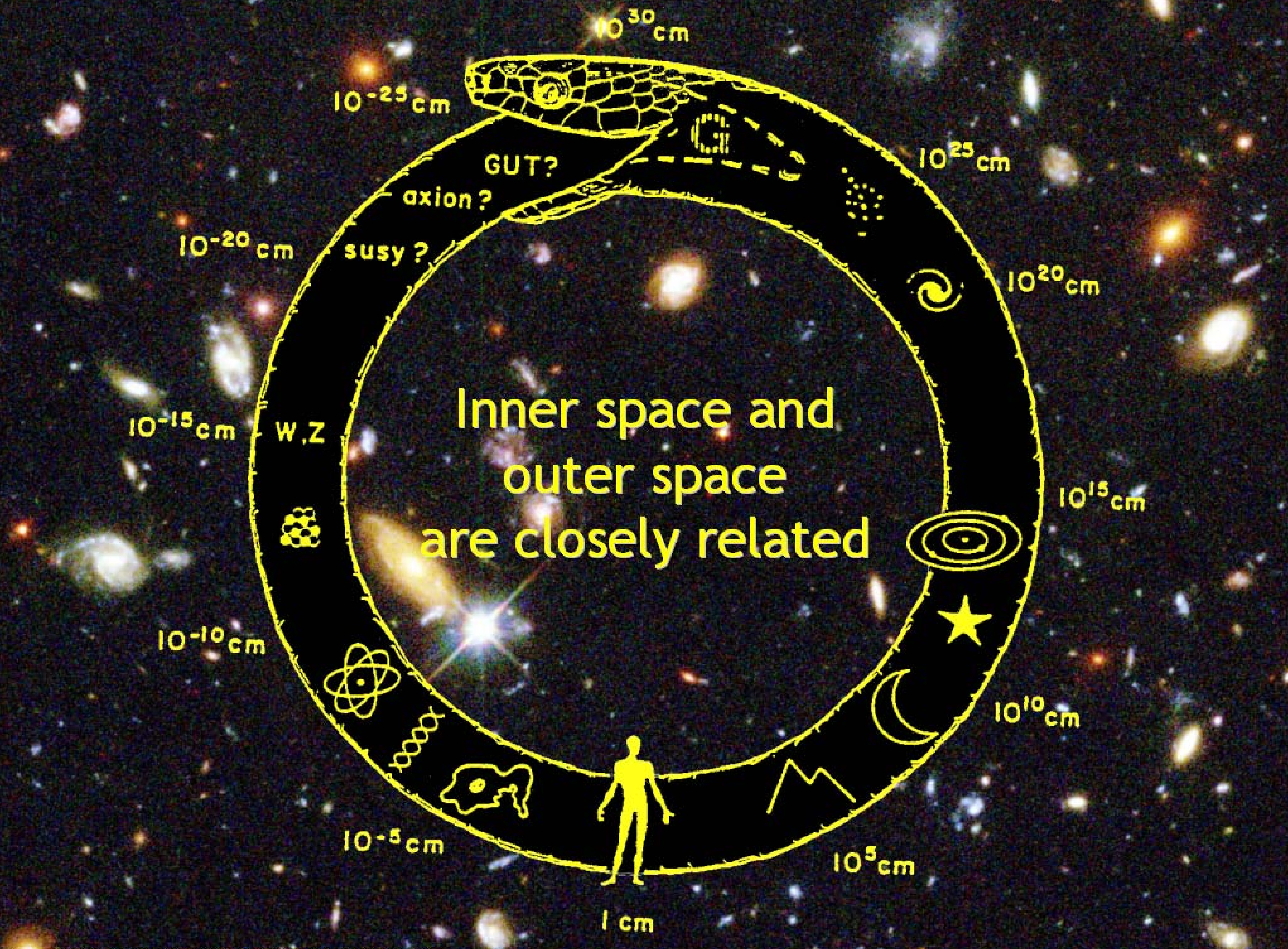
Georg Raffelt, Max-Planck-Institut für Physik, München

The Standard Model and Beyond: Frontiers of Cosmology

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



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

Expanding Universe and the Big Bang

Hubble's law

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

Hubble's constant

$H_0 = h\ 100\ \text{km s}^{-1}\ \text{Mpc}^{-1}$

Measured value

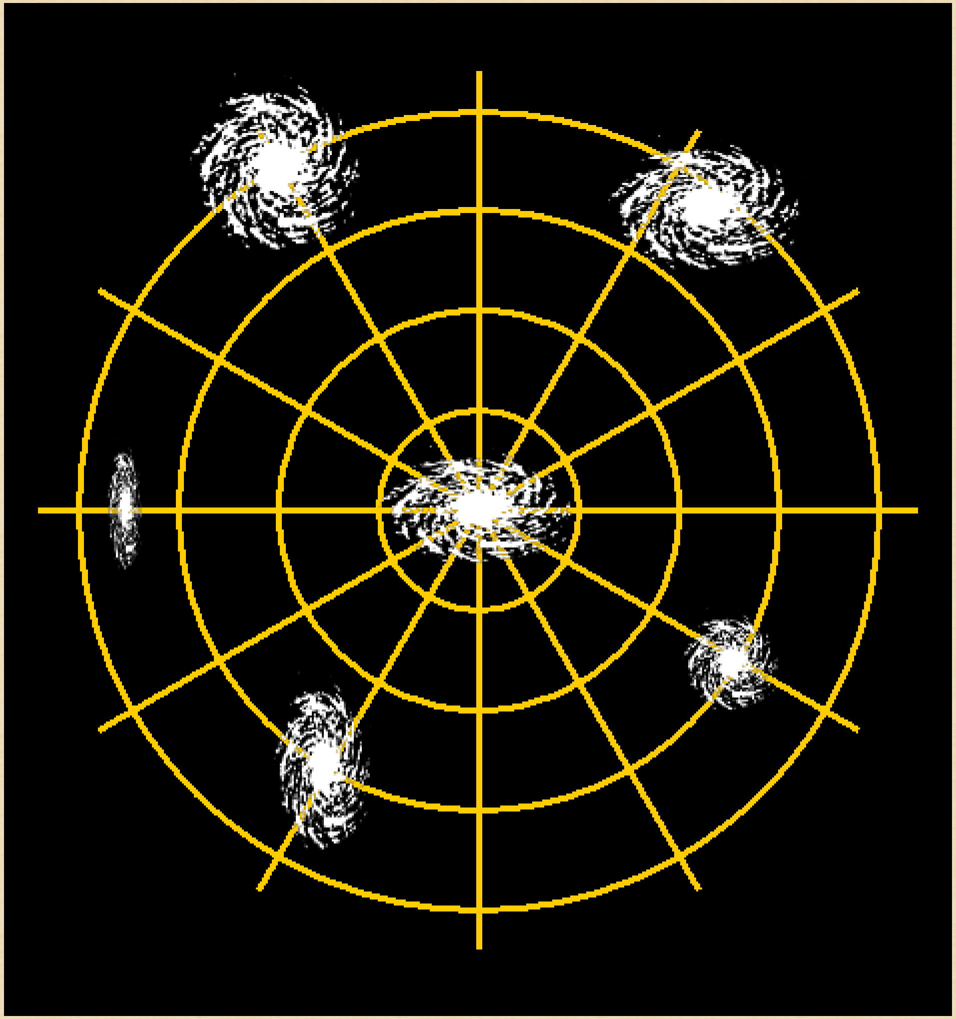
$h = 0.72 \pm 0.04$

$1\ \text{Mpc} = 3.26 \times 10^6\ \text{lyr}$
$= 3.08 \times 10^{24}\ \text{cm}$

Expansion age of the universe

$t_0 \approx H_0^{-1} \approx 14 \times 10^9\ \text{years}$

Expanding Universe and the Big Bang



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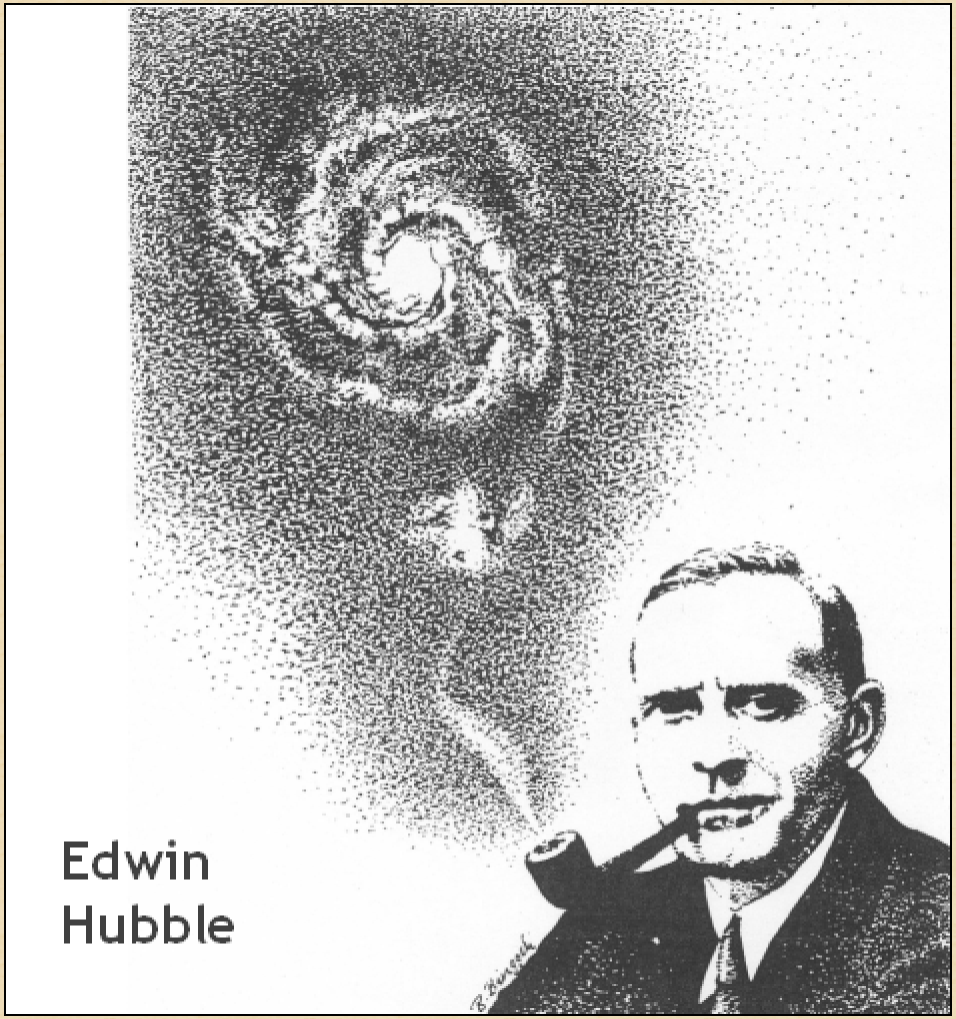

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Expanding Universe and the Big Bang

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

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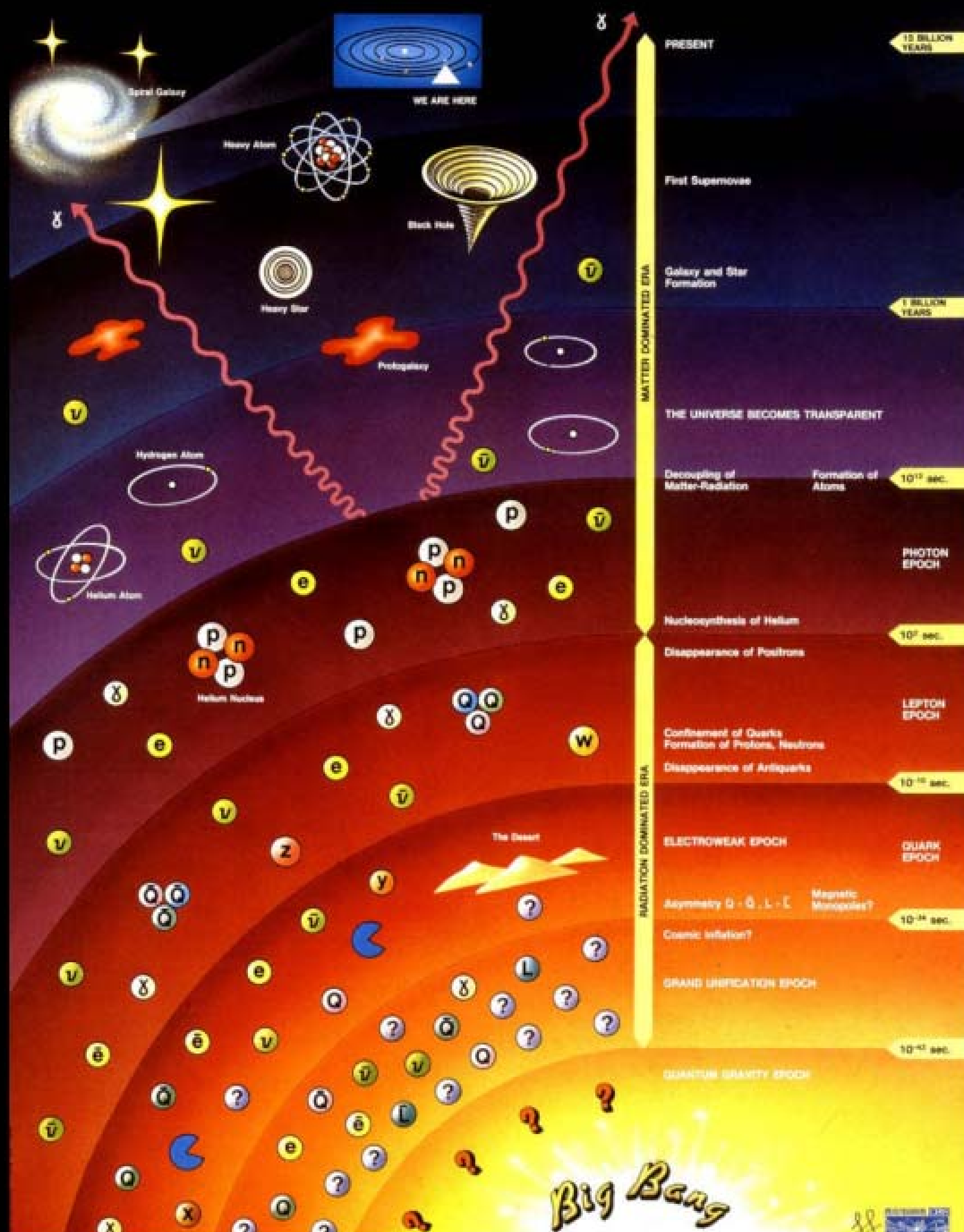
History of the Universe

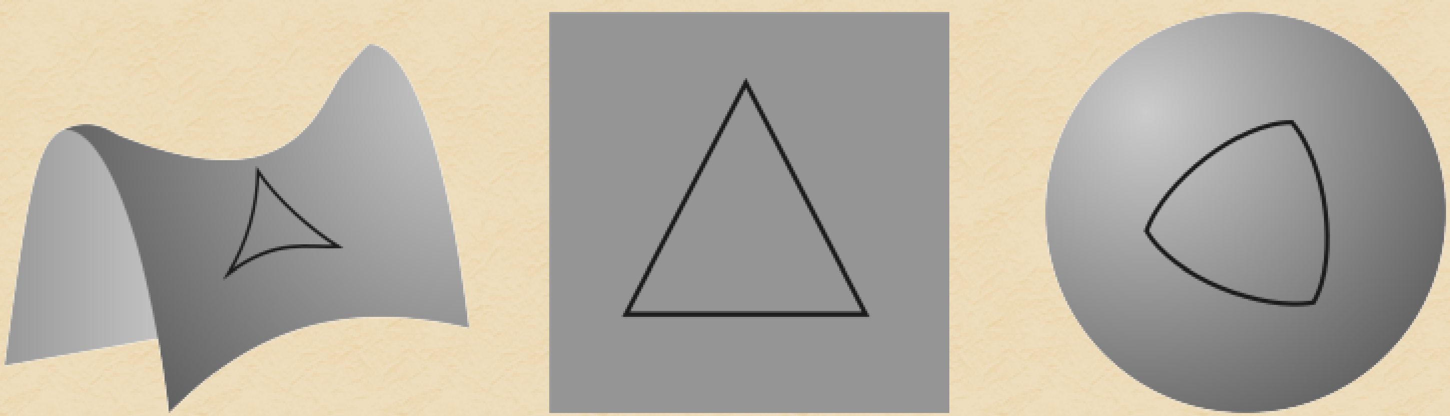


Friedmann-Lemaître-Robertson-Walker Cosmology

- On scales $\gtrsim$ 100 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



$k = -1$ | $k = 0$ | $k = +1$

Einstein's "Greatest Blunder"

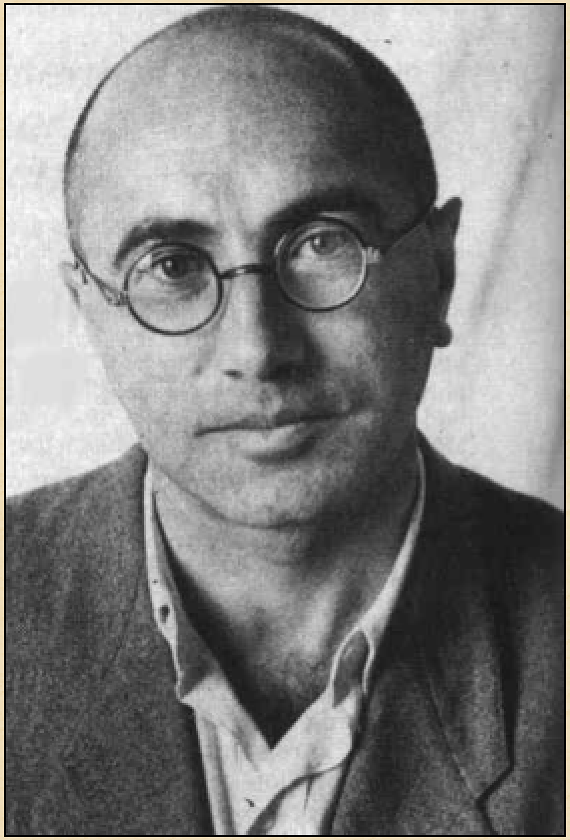
Density of gravitating mass & energy

Newton's constant

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

Friedmann equation for Hubble's expansion rate

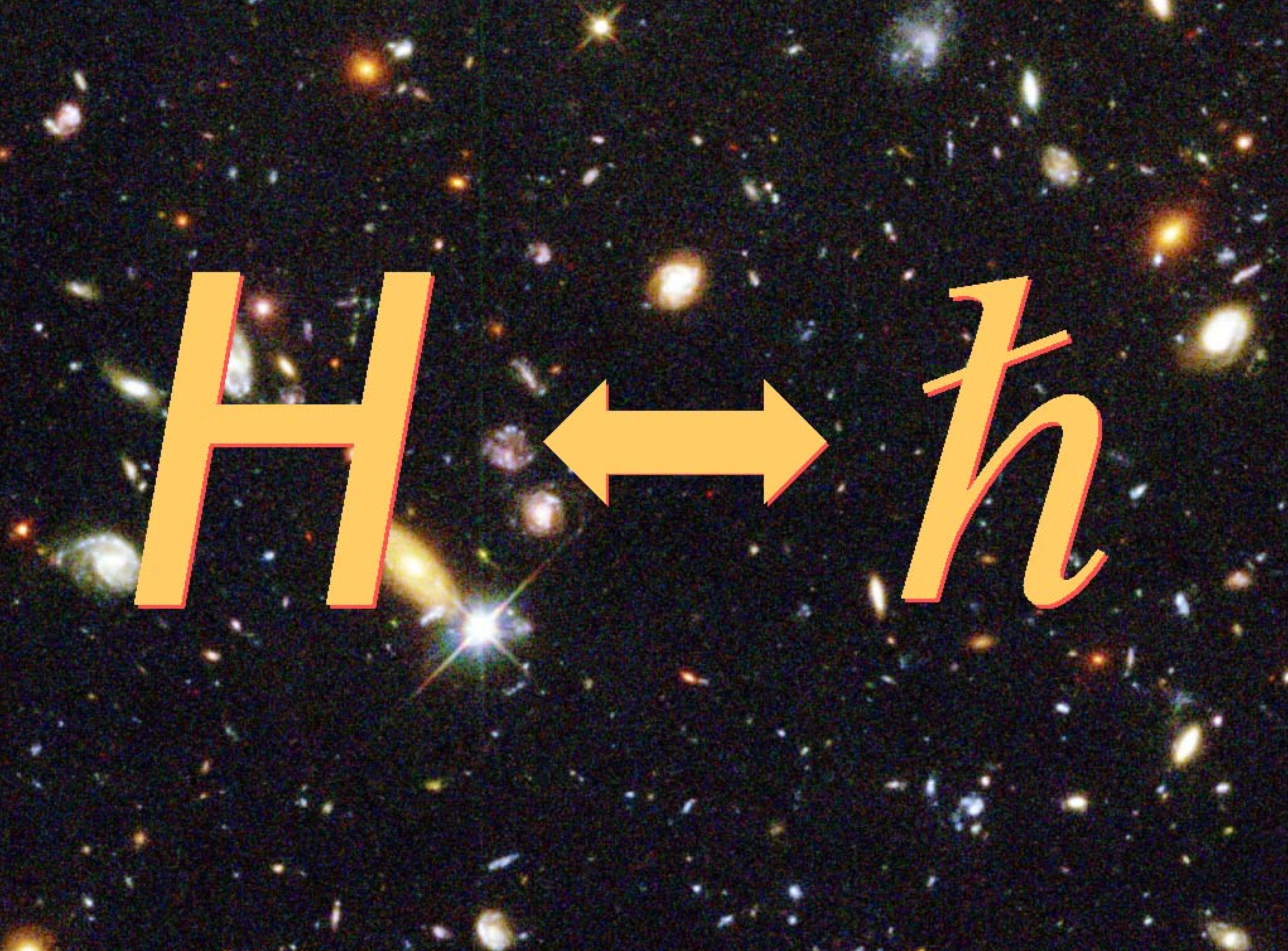
$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G_N}{3}\rho - \frac{k}{a^2} + \frac{\Lambda}{3}$$



Yakov Borisovich Zeldovich 1914-1987

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

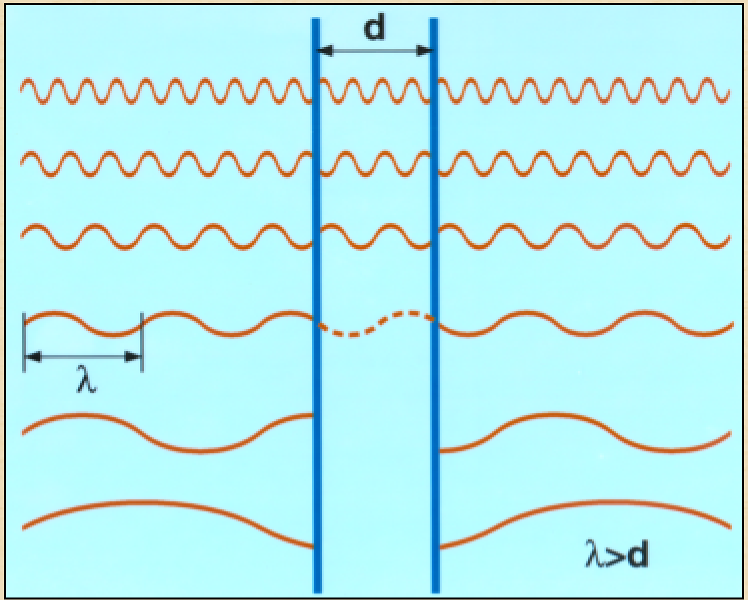
- Quantum field theory of elementary particles inevitably implies vacuum fluctuations because of Heisenberg's uncertainty relation, e.g. E and B fields can not simultaneously vanish
- Ground state (vacuum) provides gravitating energy
- Vacuum energy ρ_{vac} is equivalent to Λ



$$H \leftrightarrow \hbar$$

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 Bugt Casimir (1909 - 2000)

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

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

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

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 $\Lambda_{SUSY} \approx 1$ TeV (?)
(Masses of particles and superpartners different)

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

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"

$$\rho_{crit} = \frac{3H^2}{8\pi G_N} = \frac{3}{8\pi}(H m_{Pl})^2$$

Cosmic density always expressed in terms of

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

With the present-day Hubble parameter

$$H_0 = h\ 100\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$$

the critical density is

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

With the measured value

$$h = 0.72 \pm 0.04$$

the critical density is

$$\rho_{crit} = (0.97 \pm 0.12) \times 10^{-29}\ \mathrm{g\ cm^{-3}}$$

$$= [\underbrace{(2.55 \pm 0.07)\,\mathrm{meV}}_{\approx 10^{-15} \Lambda_{SUSY}}]^4$$

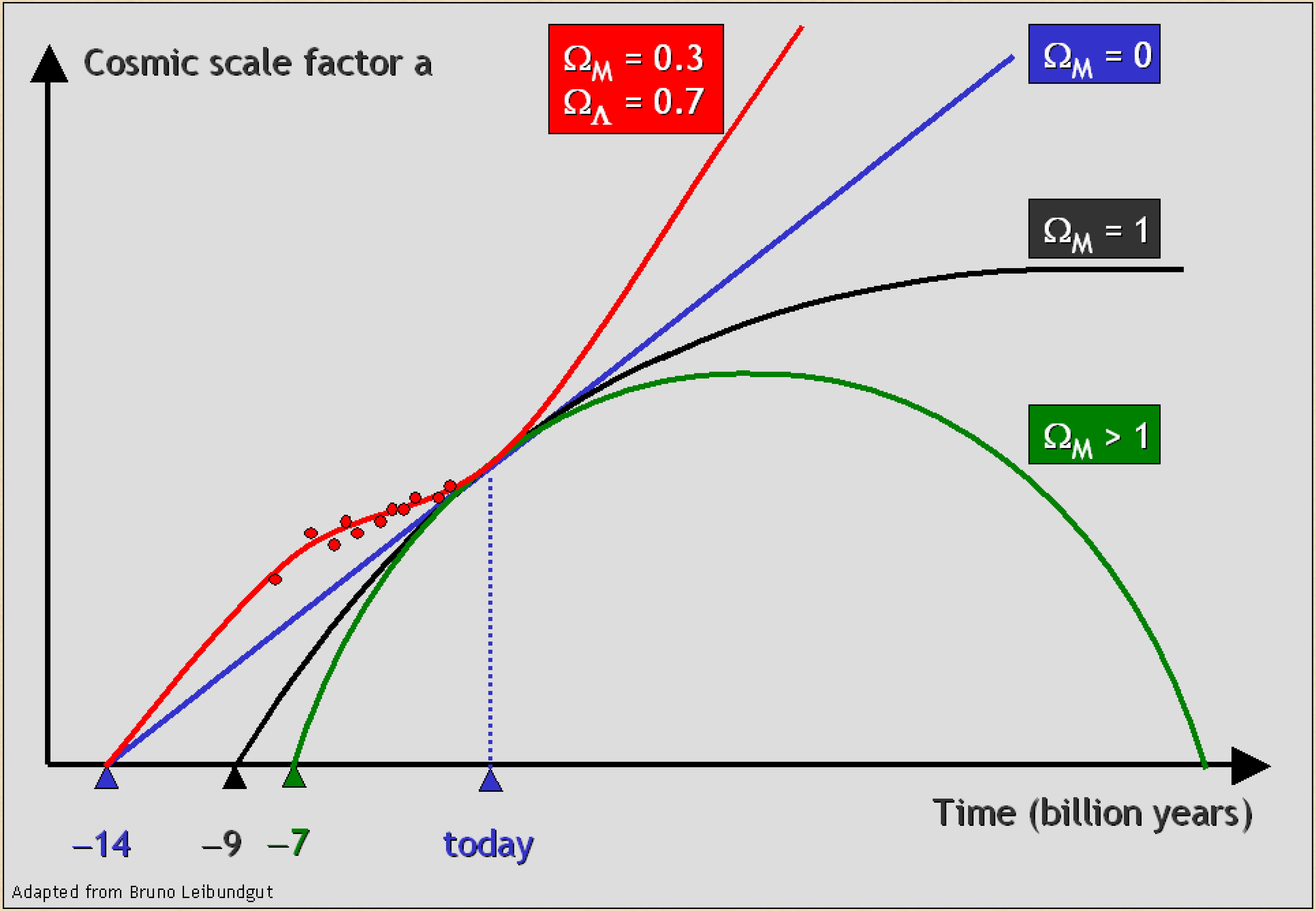
Generic Solutions of Friedmann Equation

	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	$p = -\rho$	ρ = const	Vacuum energy not diluted by expansion	$a(t) \propto \exp\left(\sqrt{\Lambda/3}\, t\right)$ $\Lambda = 8\pi G_N \rho_{vac}$

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

$$T^{\mu\nu} = \begin{pmatrix} \rho & & & \\ & p & & \\ & & p & \\ & & & p \end{pmatrix} \qquad T^{\mu\nu}_{vac} = \rho g^{\mu\nu} = \begin{pmatrix} \rho & & & \\ & -\rho & & \\ & & -\rho & \\ & & & -\rho \end{pmatrix}$$

Expansion of Different Cosmological Models

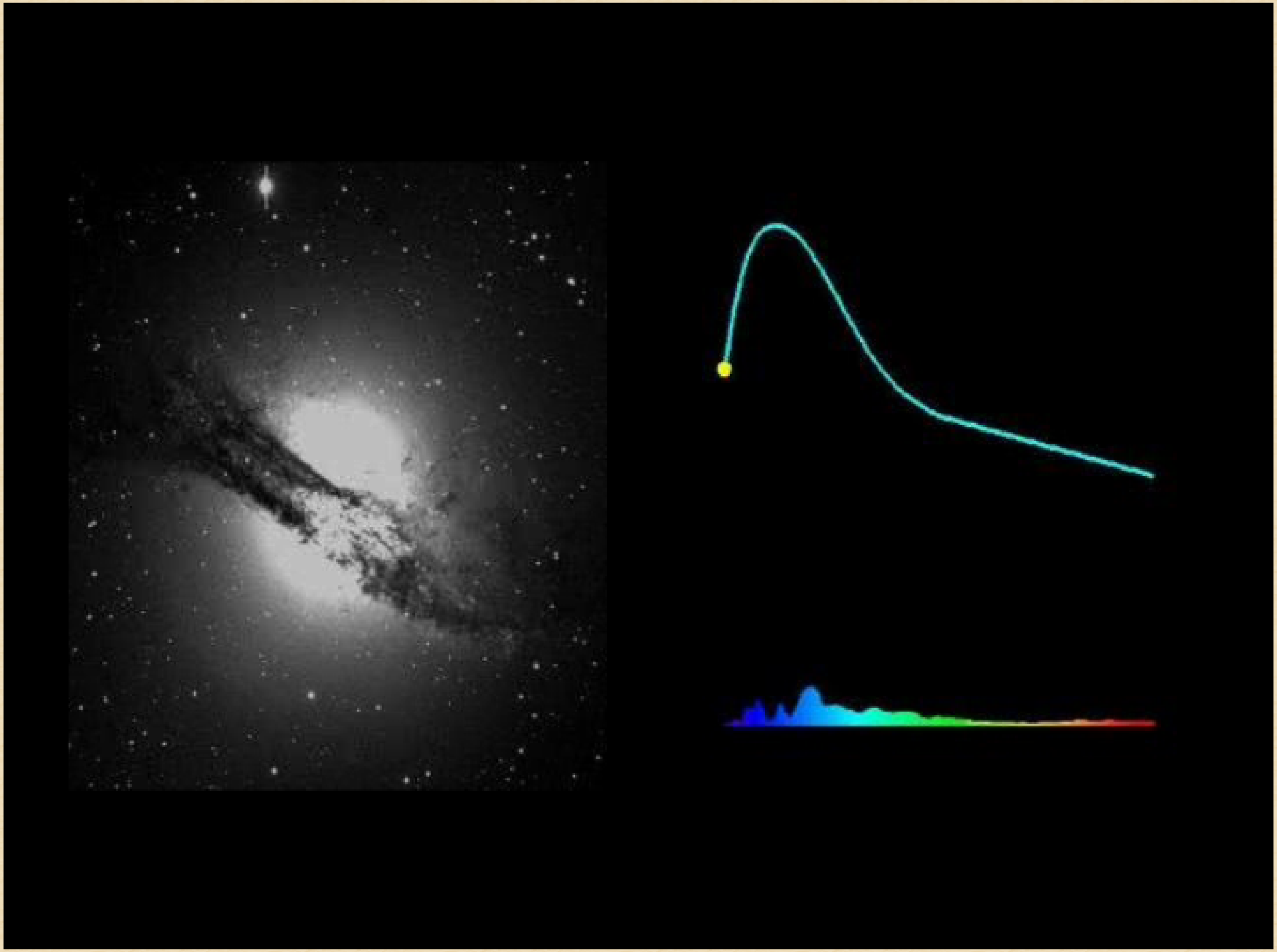


Supernovae: Almost as Bright as Galaxies

SN 1998S in NGC 3877

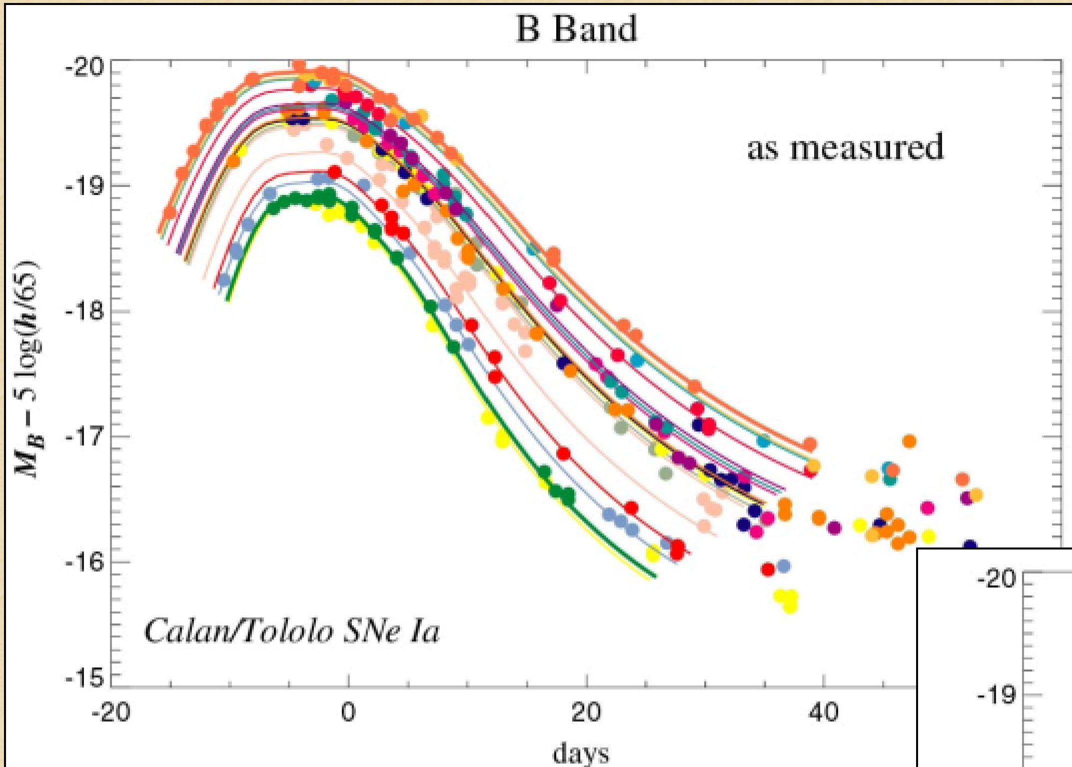
SN 1994D in NGC 4526

Light Curve of Supernova 1986G in Centaurus A



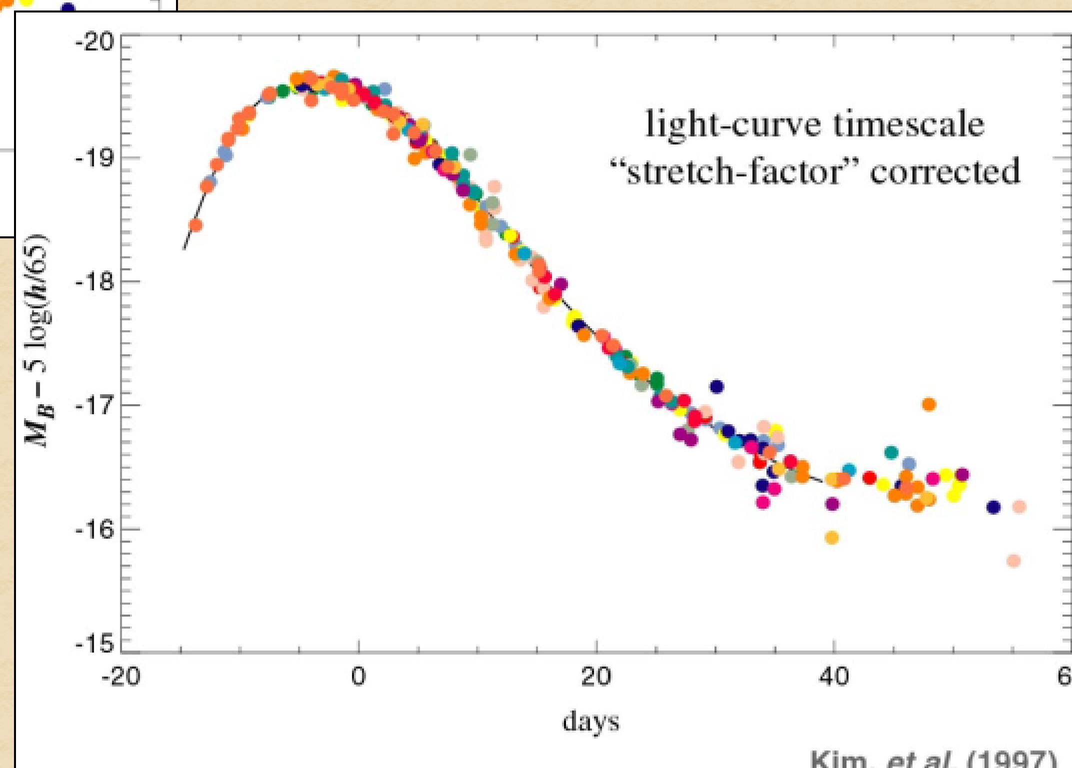
This clip was prepared by the Supernova Cosmology Project (P. Nugent: spectral sequence; A. Conley: image sequence) with the help of Lawrence Berkeley National Laboratory's Computer Visualization Laboratory (N. Johnston: animation) at the National Energy Research Scientific Computing Center. http://www-supernova.lbl.gov/public/figures/snvideo.html

Universal Supernova Ia Light Curve



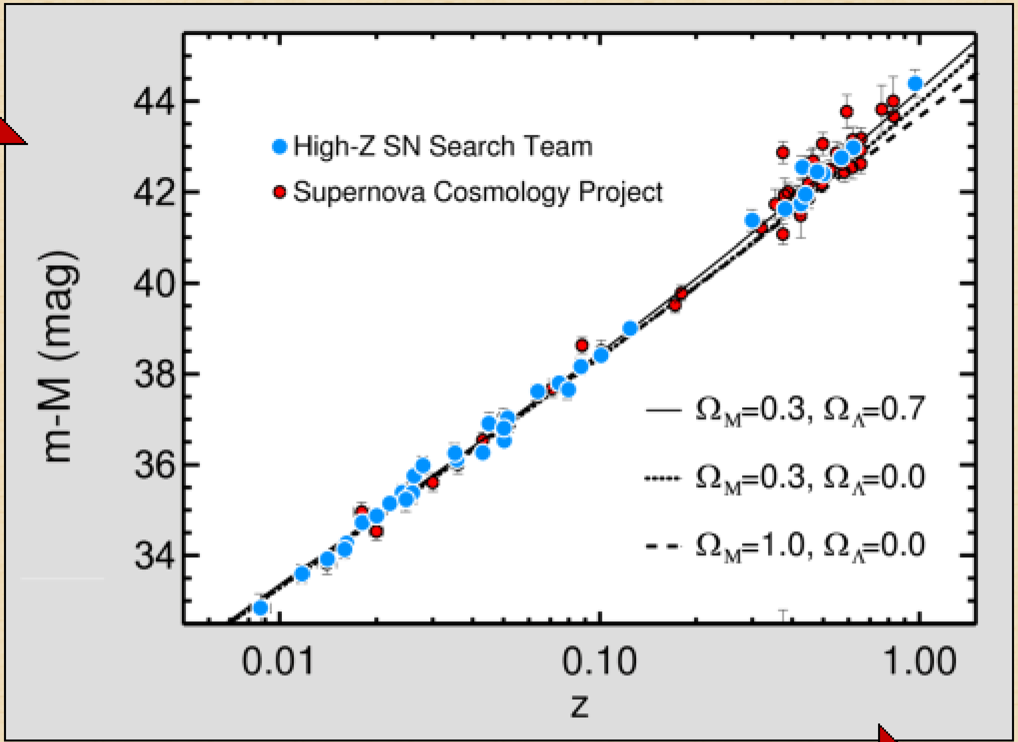
Supernova Ia lightcurves are empirically a 1-parameter family

After transformation
a universal light curve,
i.e. a de-facto standard candle



Hubble Diagram

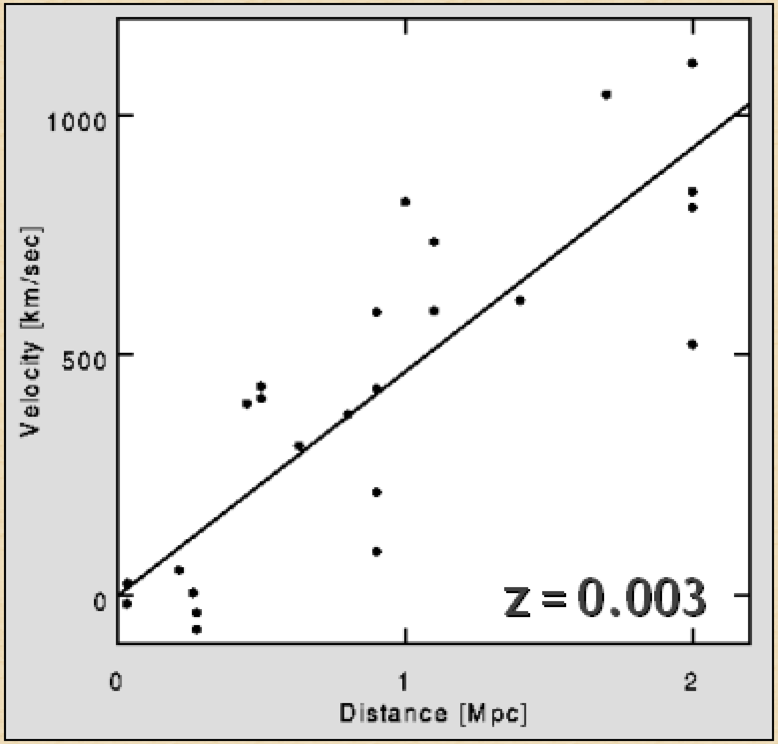
Apparent Brightness



Redshift

Supernova Ia
as cosmological
standard candles

Hubble's orginal data (1929)



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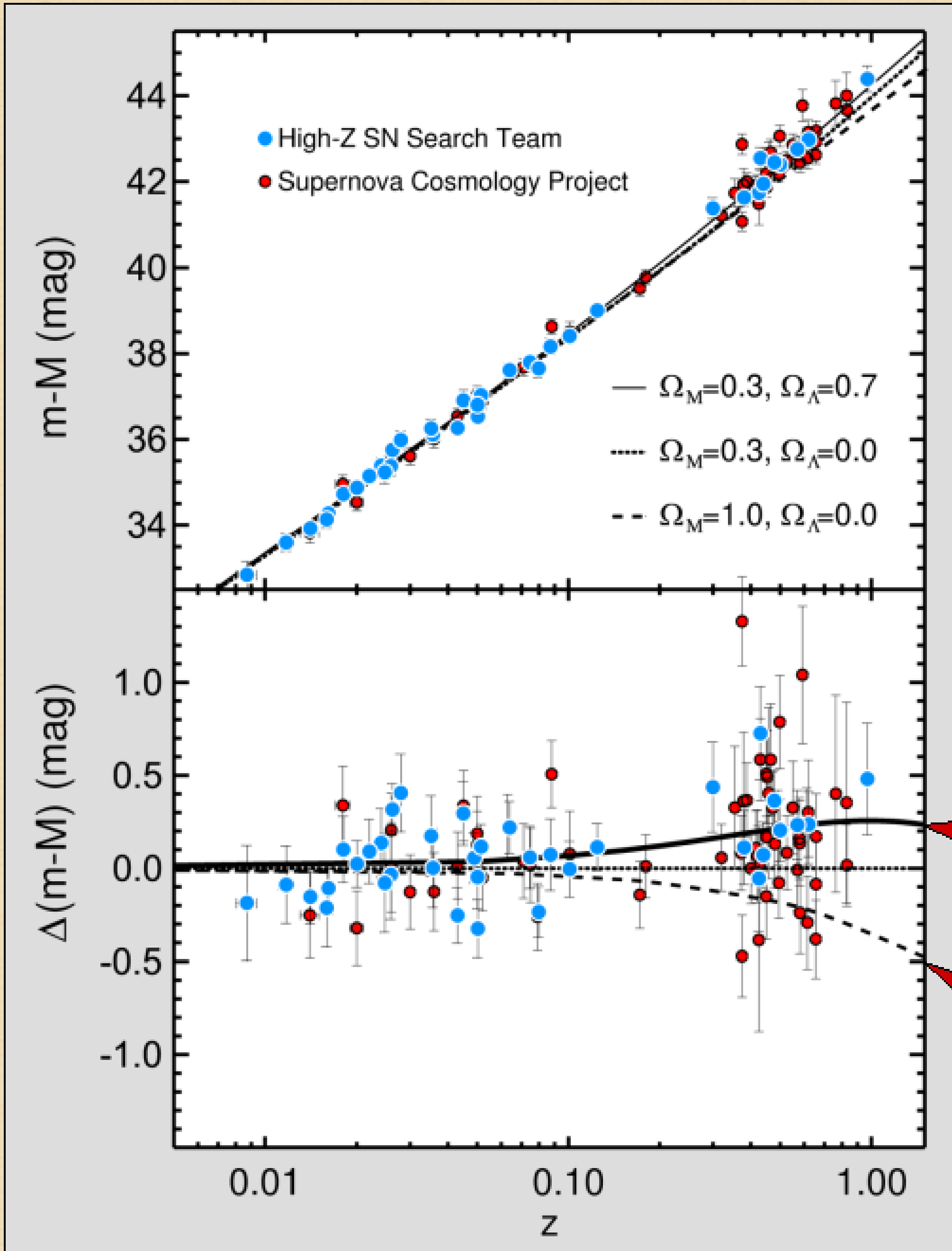
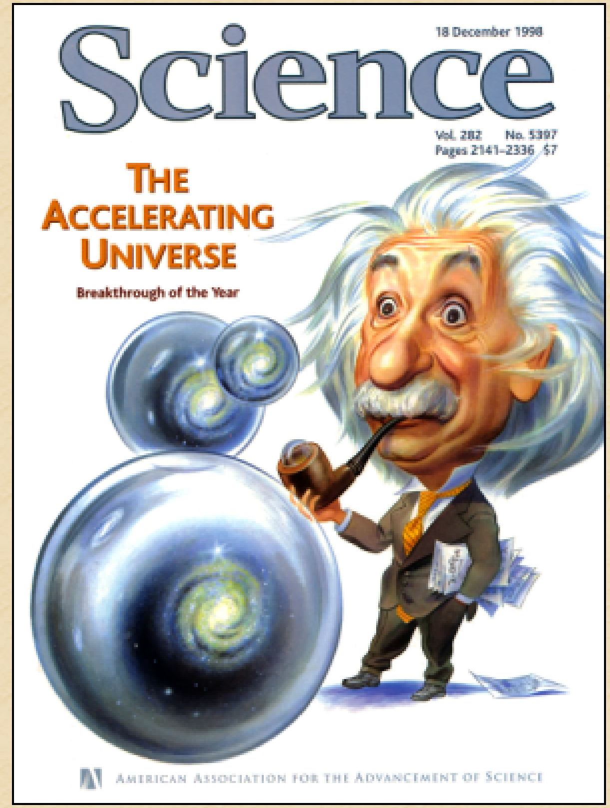
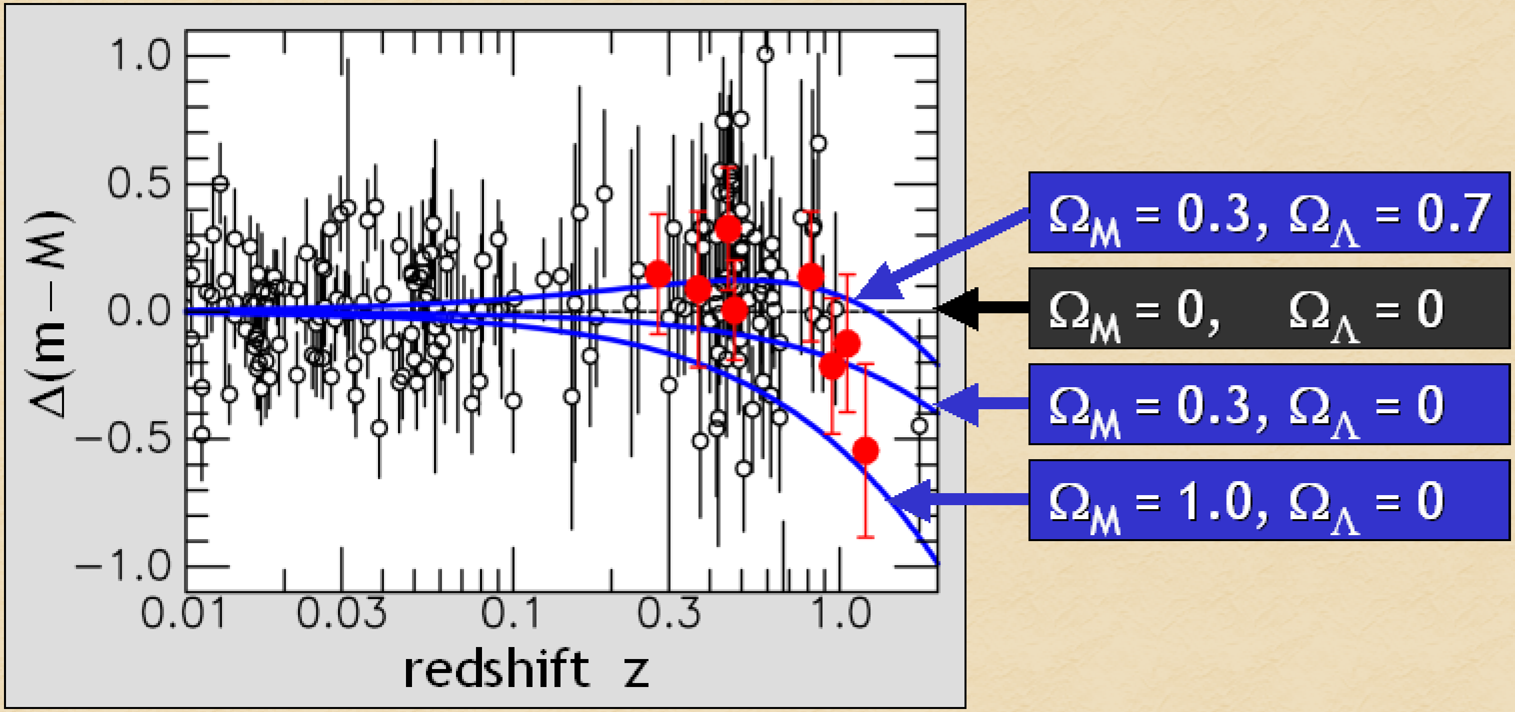




Accelerated expansion
($\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$)

Decelerated expansion
($\Omega_M = 1$)

Latest Supernova Ia Data



209 SNe with fall 1999 data in red

Tonry et al., “Cosmological results from high-z supernovae,” astro-ph/0305008

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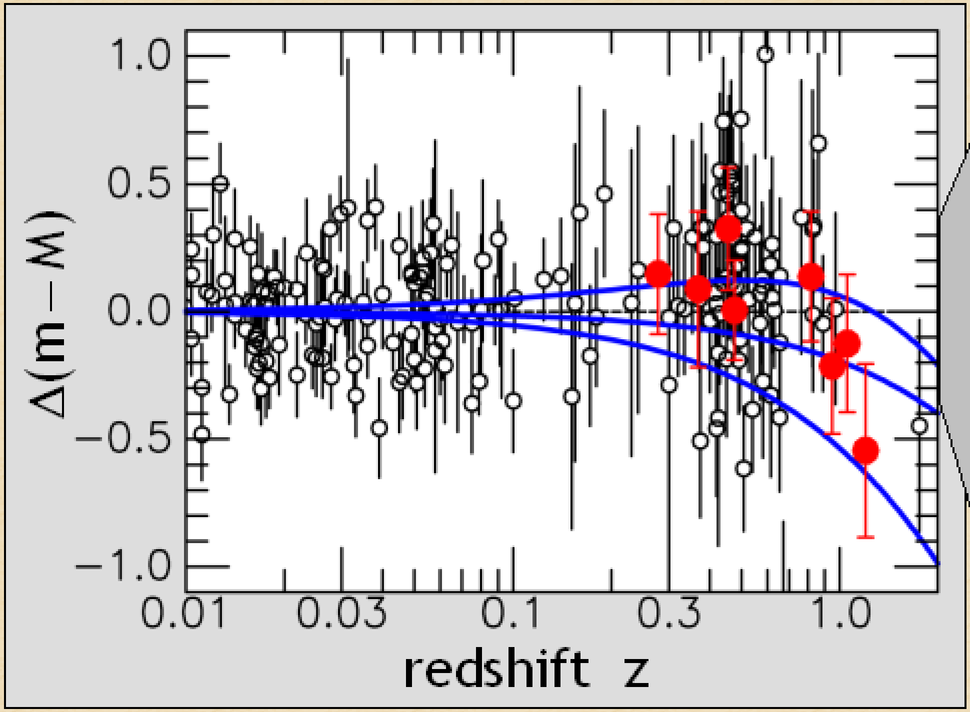
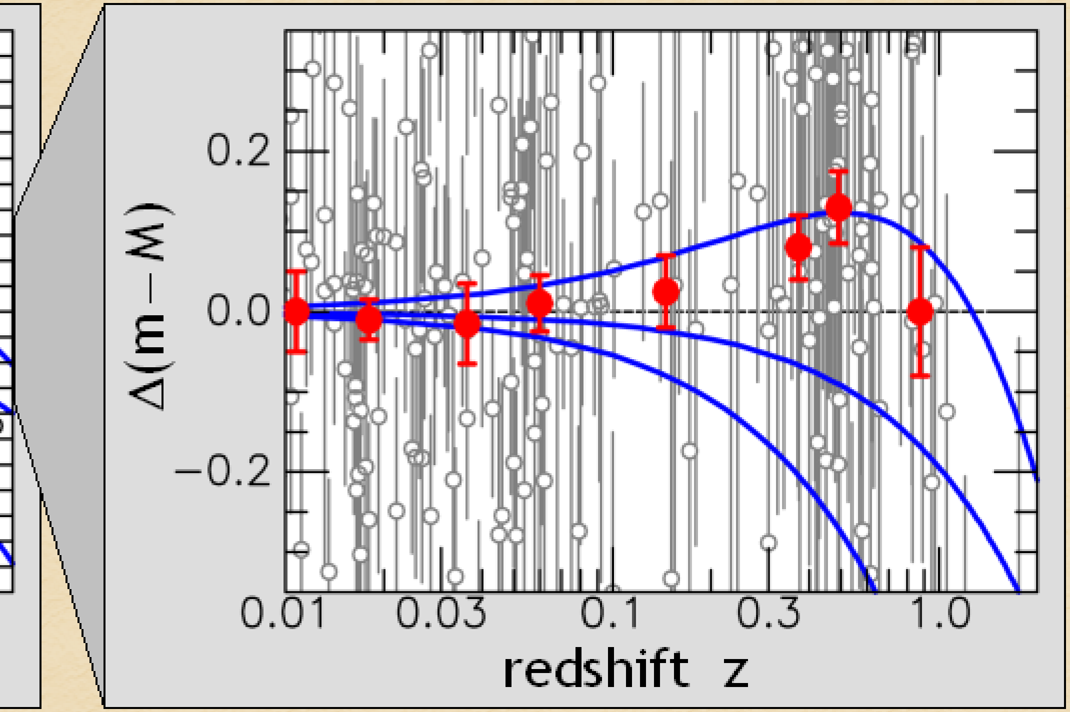


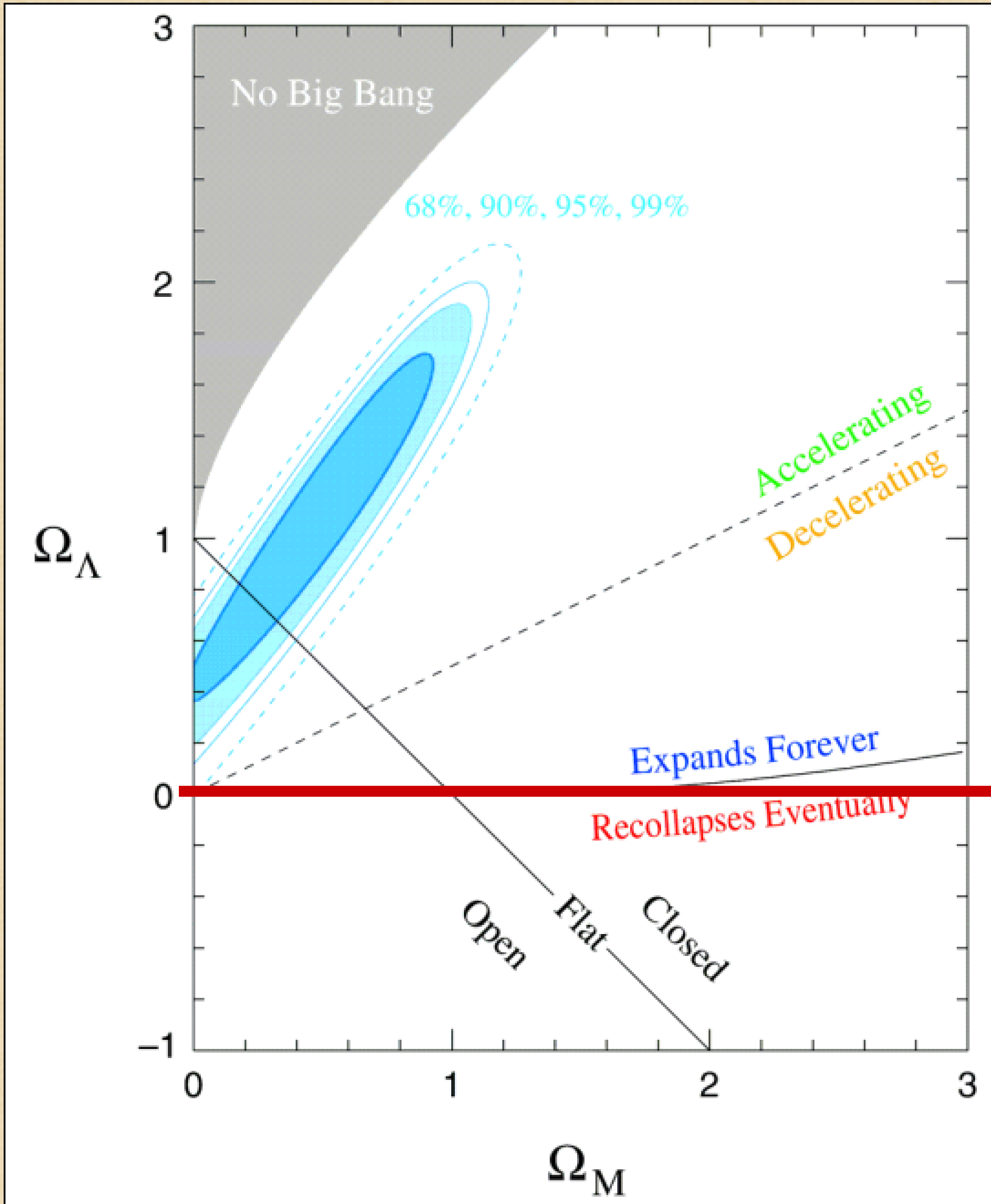
209 SNe with fall 1999 data in red



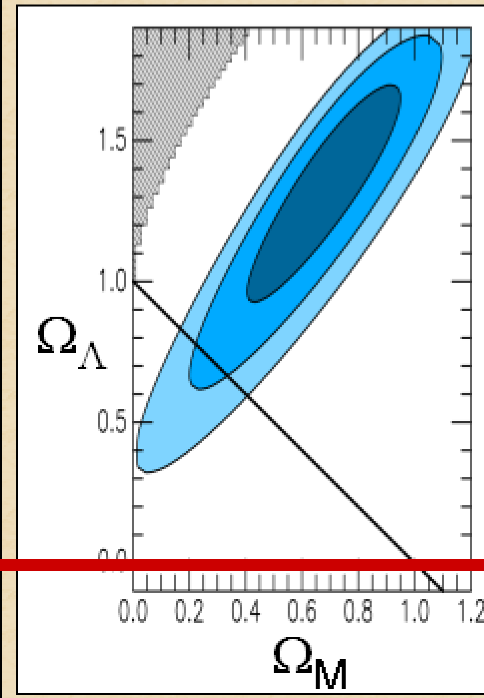
209 SNe with binned data in red

Tonry et al., "Cosmological results from high-z supernovae," astro-ph/0305008

Fitting Cosmological Parameters



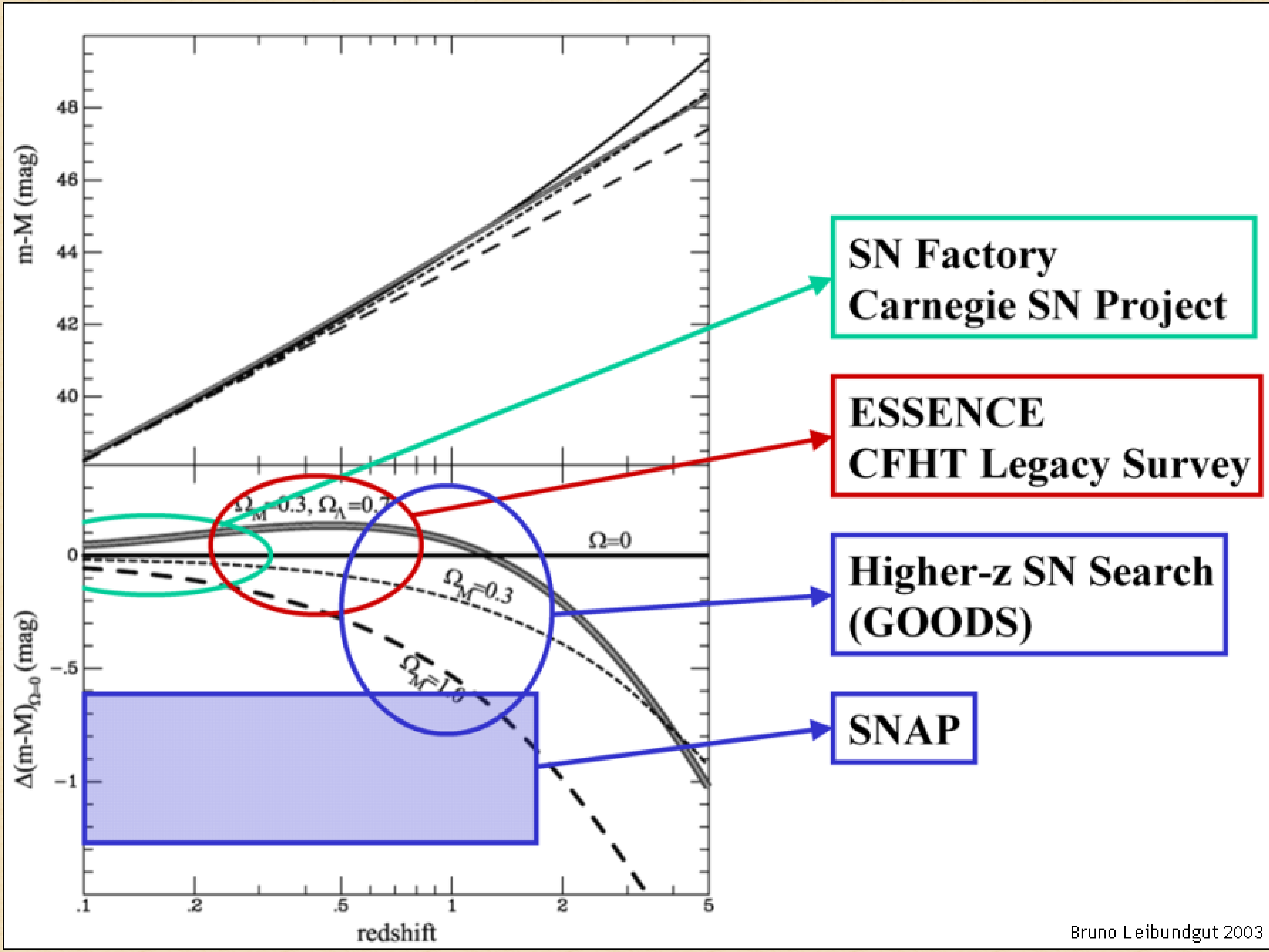
High-z supernova team (Tonry et al.) astro-ph/0305008



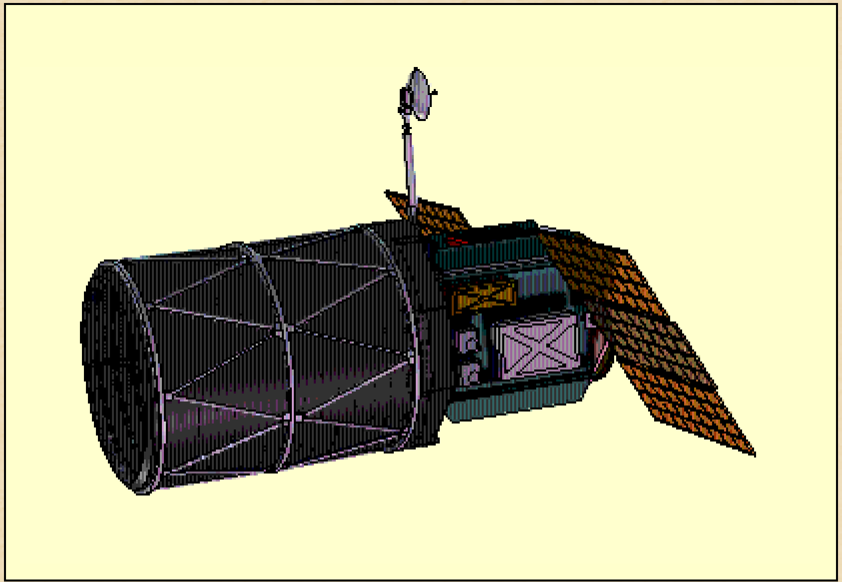
$\Lambda = 0$ excluded at many sigma

Cosmological Supernova Project (Knop et al.), astro-ph/0309368

New Supernova Projects

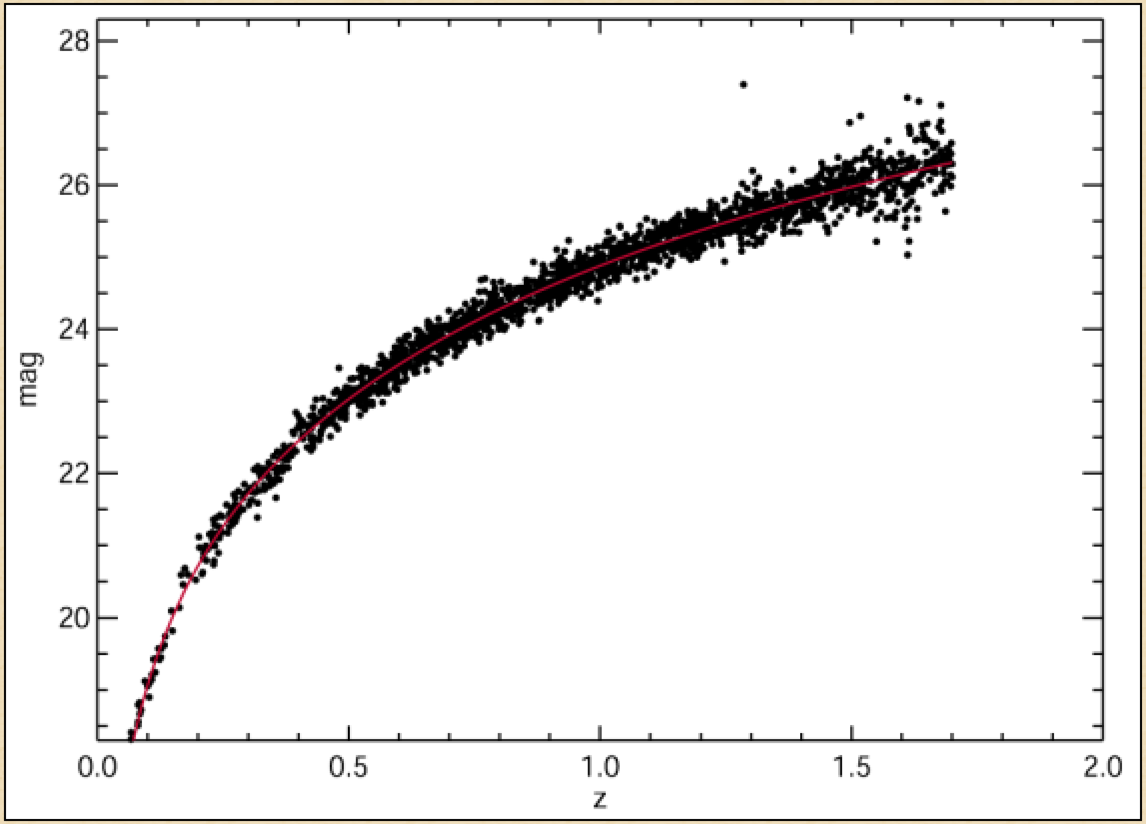


The SNAP Project



SNAP Satellite
http://snap.lbl.gov/

Simulated Hubble diagram for a 1-year SNAP mission (2000 SNe per year)



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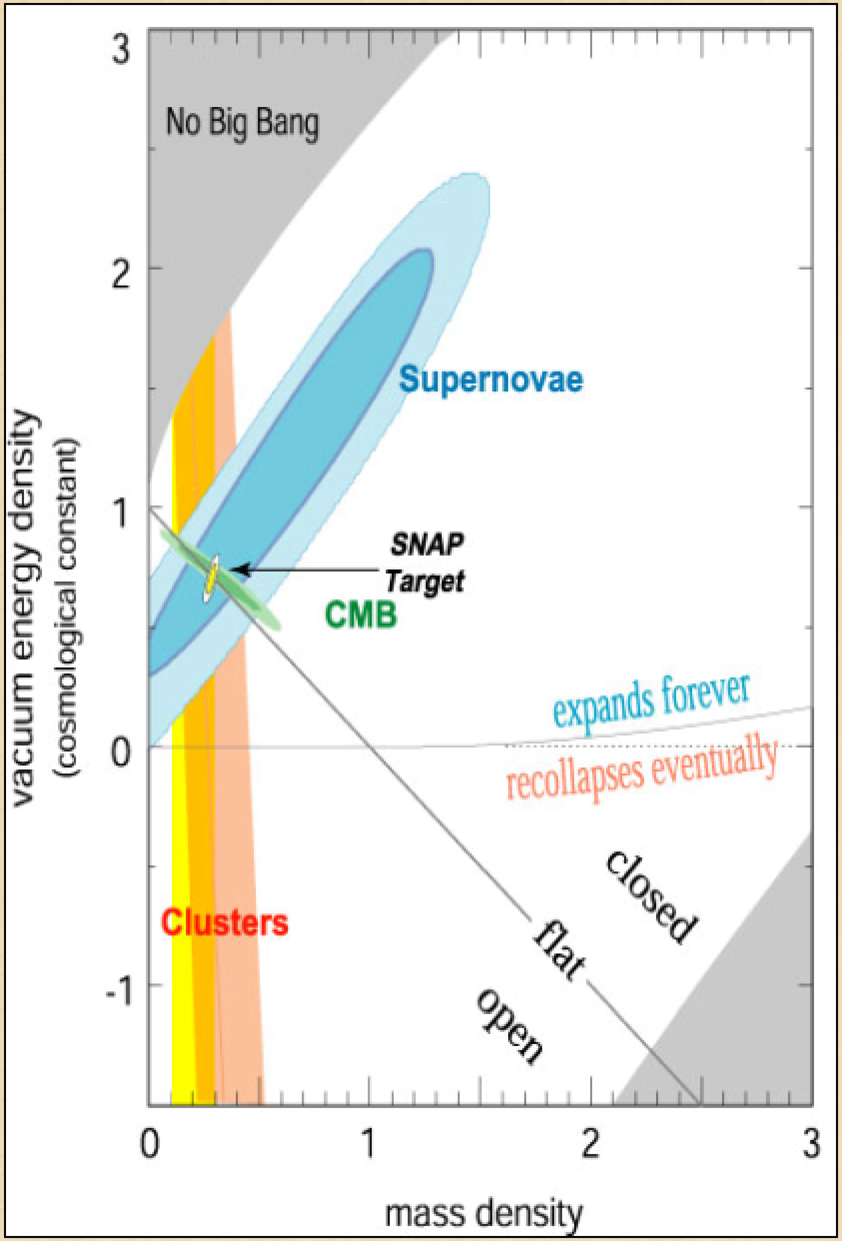

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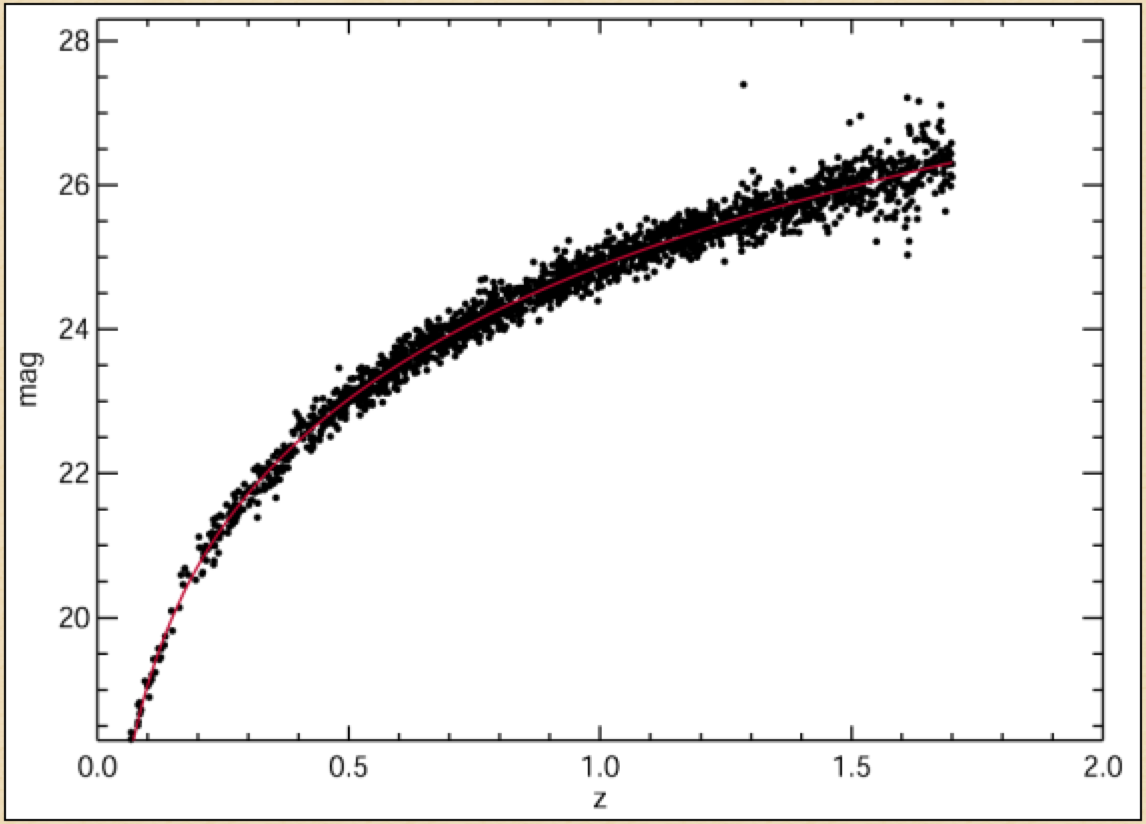
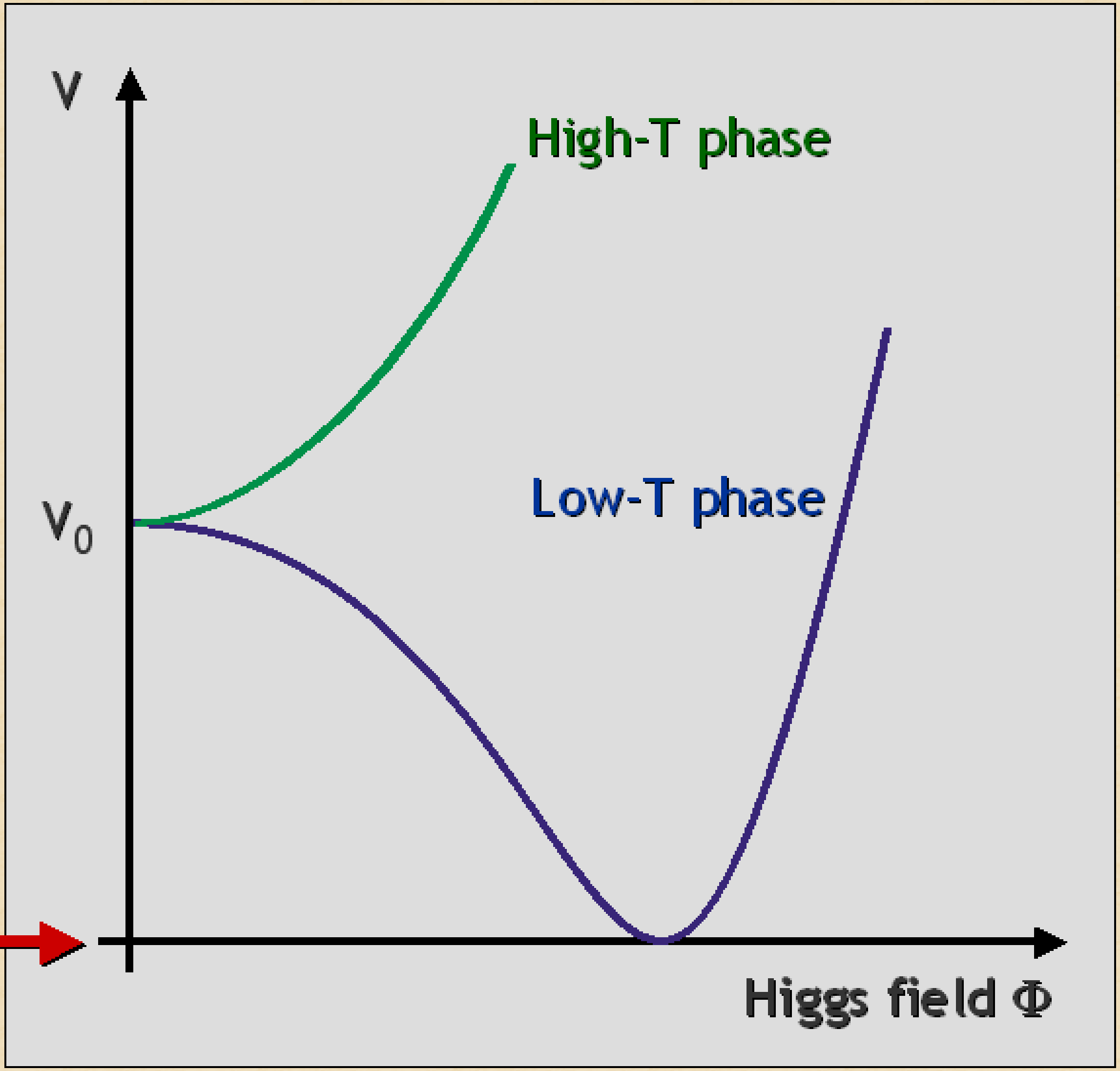
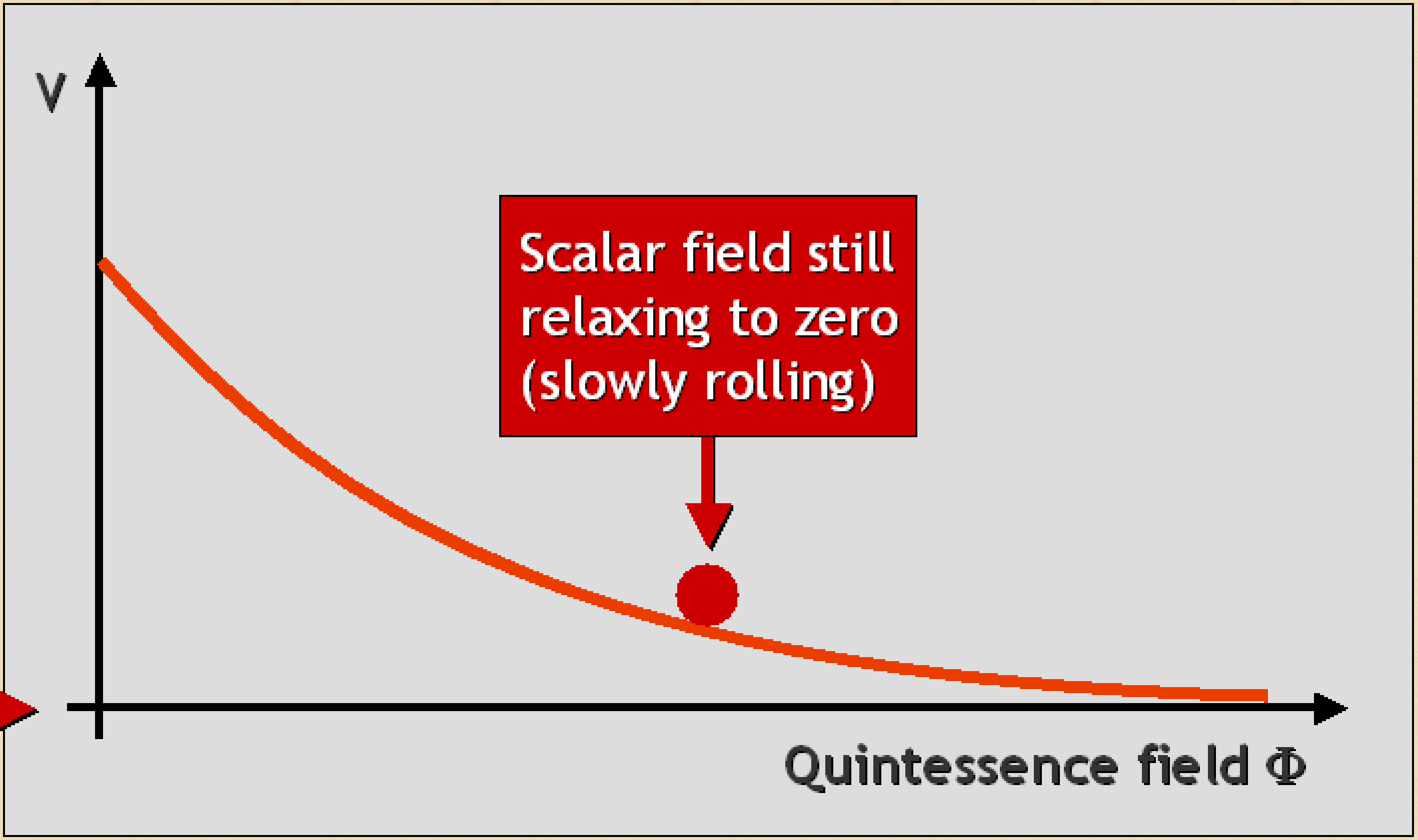


Scalar Fields and Cosmological Constant



Why is zero of all scalar field potentials (almost) exactly at V = 0

Quintessence



Absolute zero determined by unknown effect

Lagrangian	$L = \sqrt{g}\left[\frac{1}{2}\partial^\mu\Phi\,\partial_\mu\Phi + V(\Phi)\right]$
Equations of motion for homogeneous mode ($\nabla\Phi=0$)	$H^2 = \frac{8\pi}{3}G_N\left[\frac{1}{2}(\partial_t\Phi)^2 + V(\Phi)\right]$ $\partial_t^2\Phi + 3H\partial_t\Phi + V'(\Phi) = 0$

System of coupled nonlinear equations

Quintessence as a Perfect Fluid

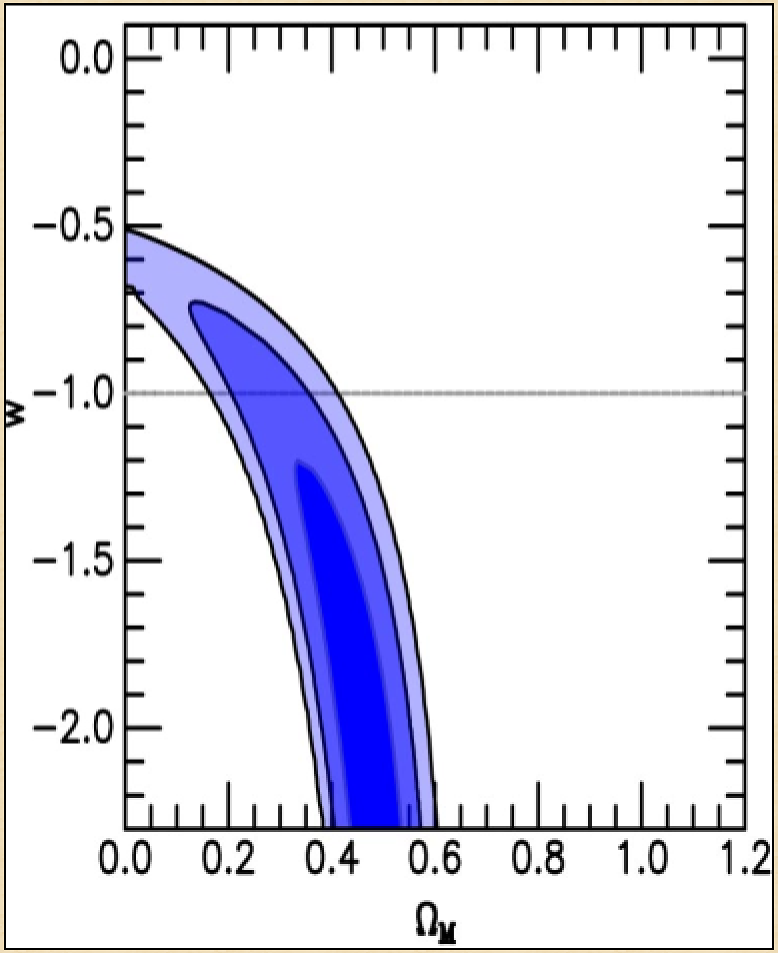
Energy-momentum tensor of homogeneous Φ-mode that of an isotropic perfect fluid	$\rho = \frac{1}{2}(\partial_t\Phi)^2 + V(\Phi)$ $p = \frac{1}{2}(\partial_t\Phi)^2 - V(\Phi)$
General equation of state	$p = w\,\rho$
Example: Exponential potential	$V(\Phi) = V_0\, e^{-\lambda 8\pi G_N \Phi}$
Explicit solution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

Like vacuum energy	$\lambda^2 = 0$	$w = -1$
Accelerated expansion	$\lambda^2 < 2$	$w < -1/3$
Like matter	$\lambda^2 = 3$	$w = 0$
Like radiation	$\lambda^2 = 4$	$w = 1$

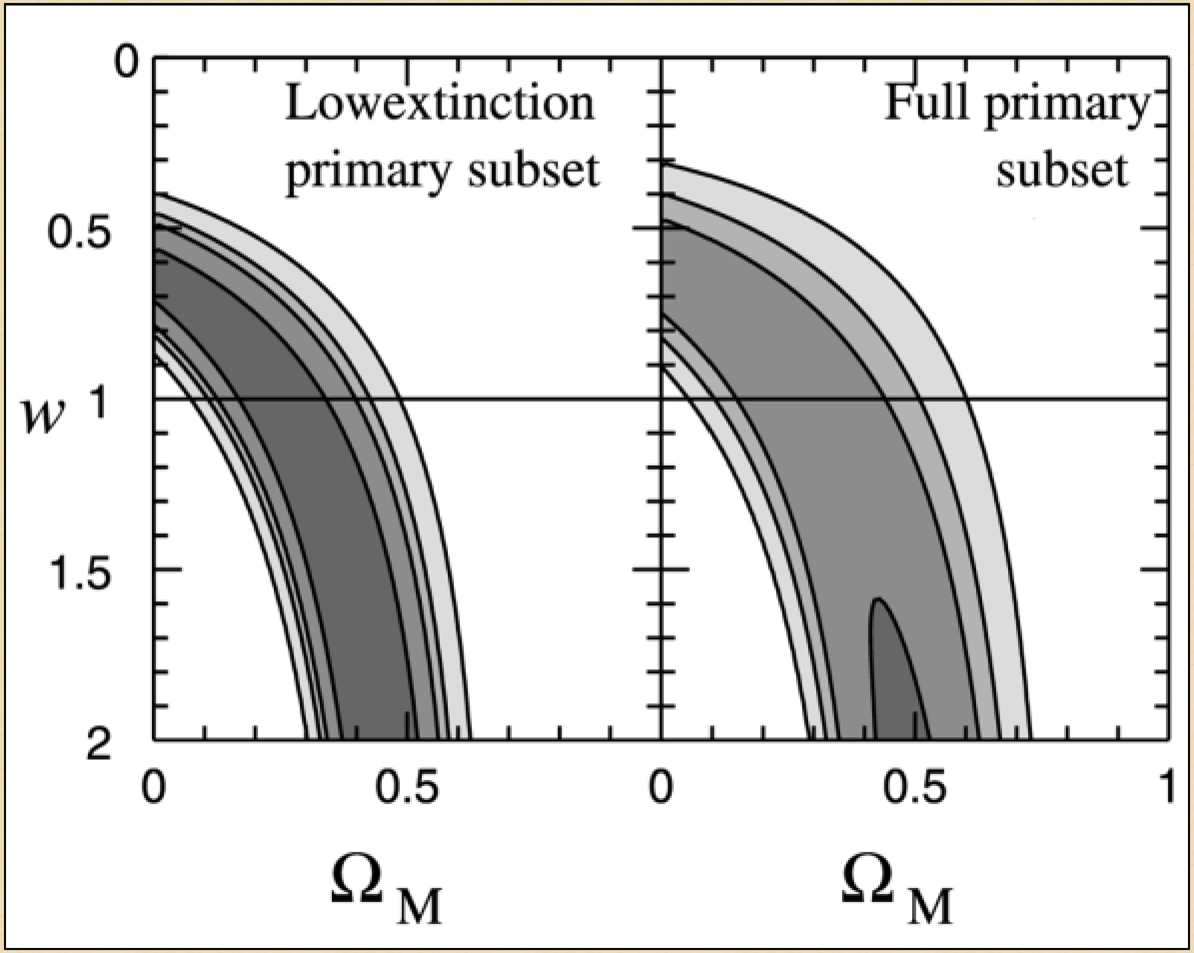
Observational evidence for equation of state with “nonstandard” w-parameter?

Limits on Quintessence

High-z Supernova Project
Tonry et al. astro-ph/0305008

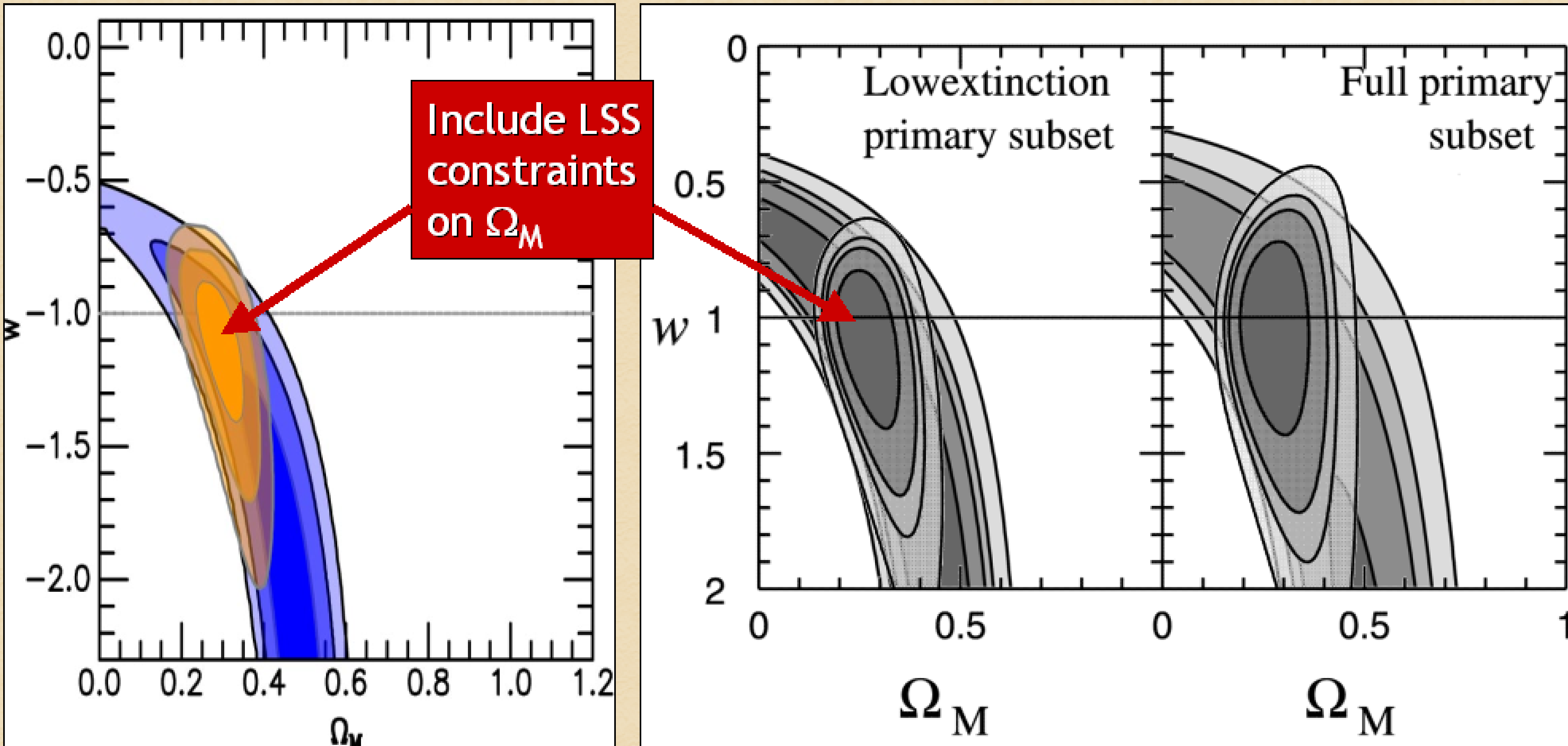


Supernova Cosmology Project
Knop et al. astro-ph/0309368

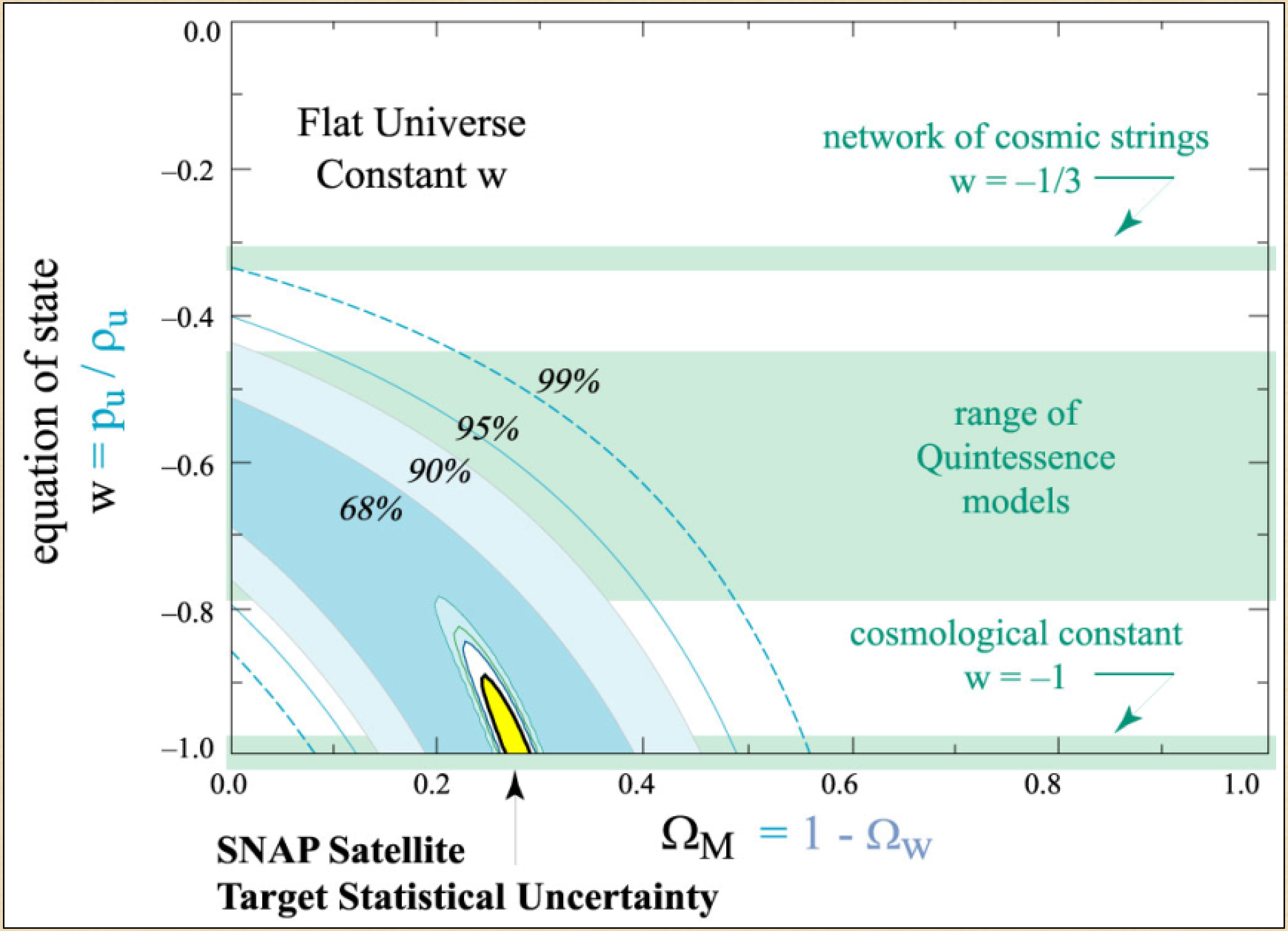


Limits on Quintessence

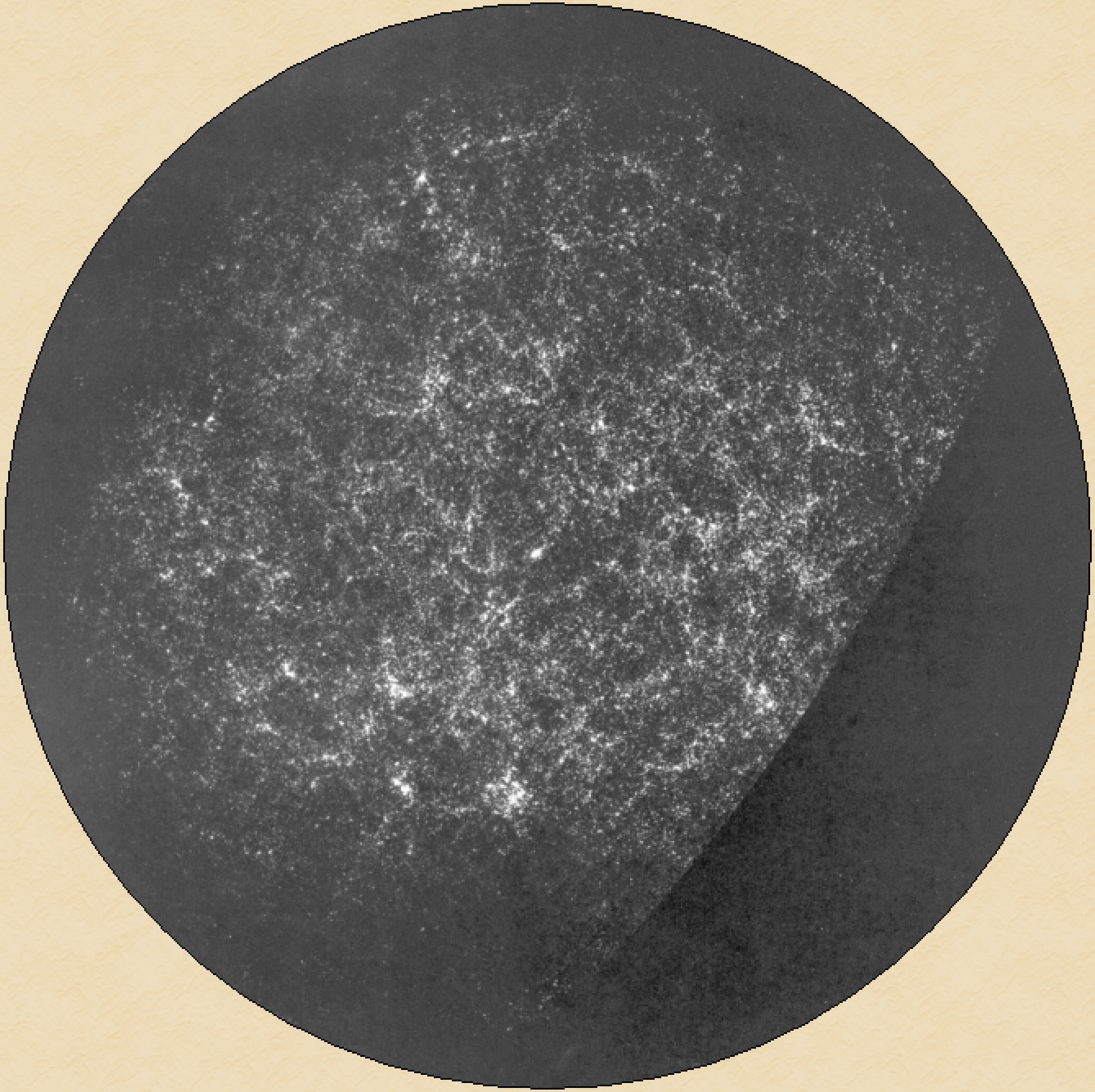
High-z Supernova Project Tonry et al. astro-ph/0305008	Supernova Cosmology Project Knop et al. astro-ph/0309368



SNAP Quintessence Sensitivity

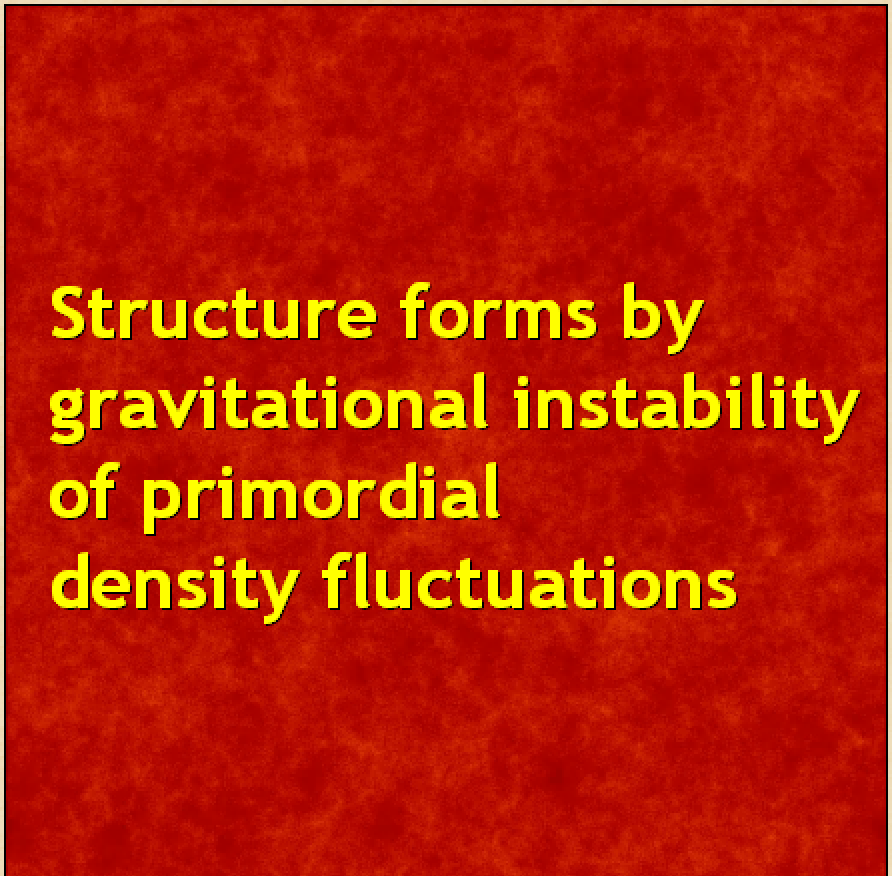


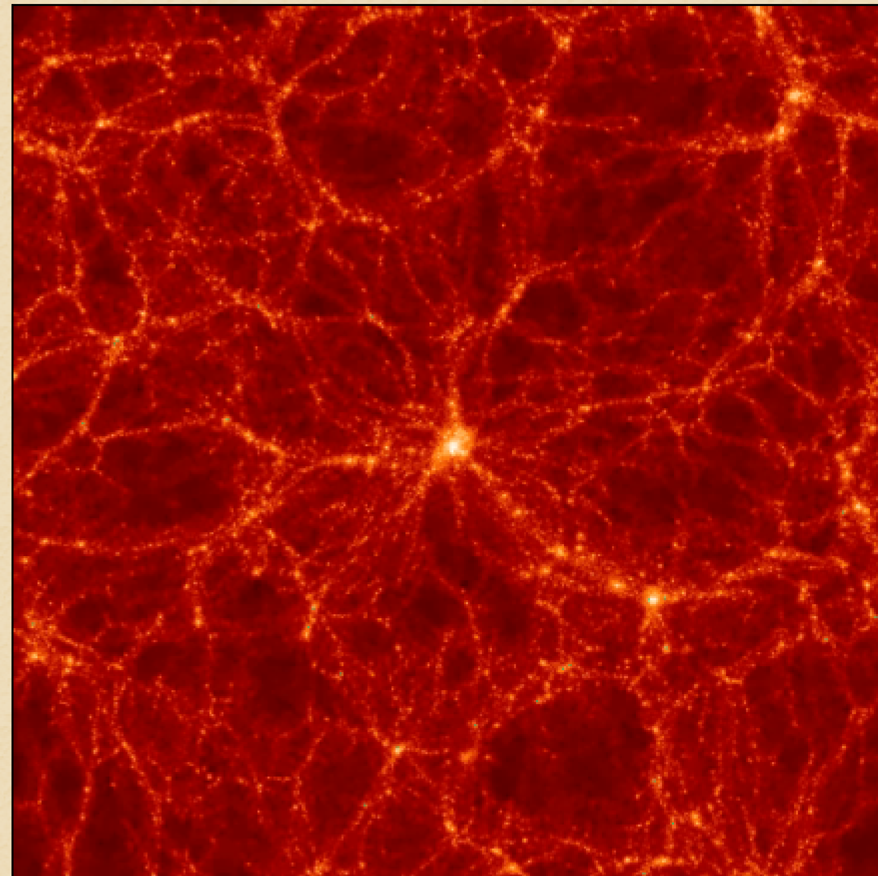
Galaxy Distribution in the Sky



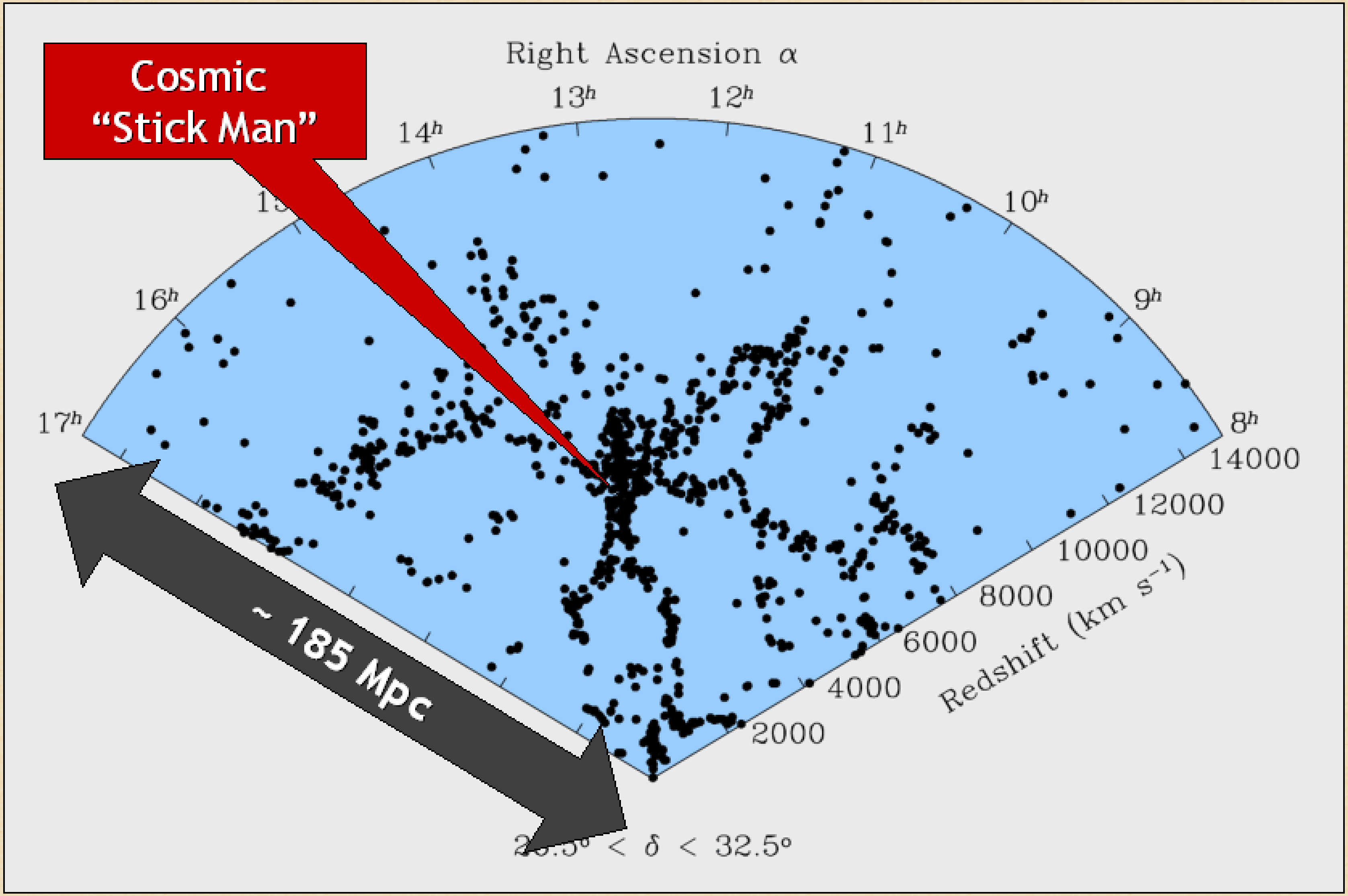
Formation of Structure

Smooth → Structured



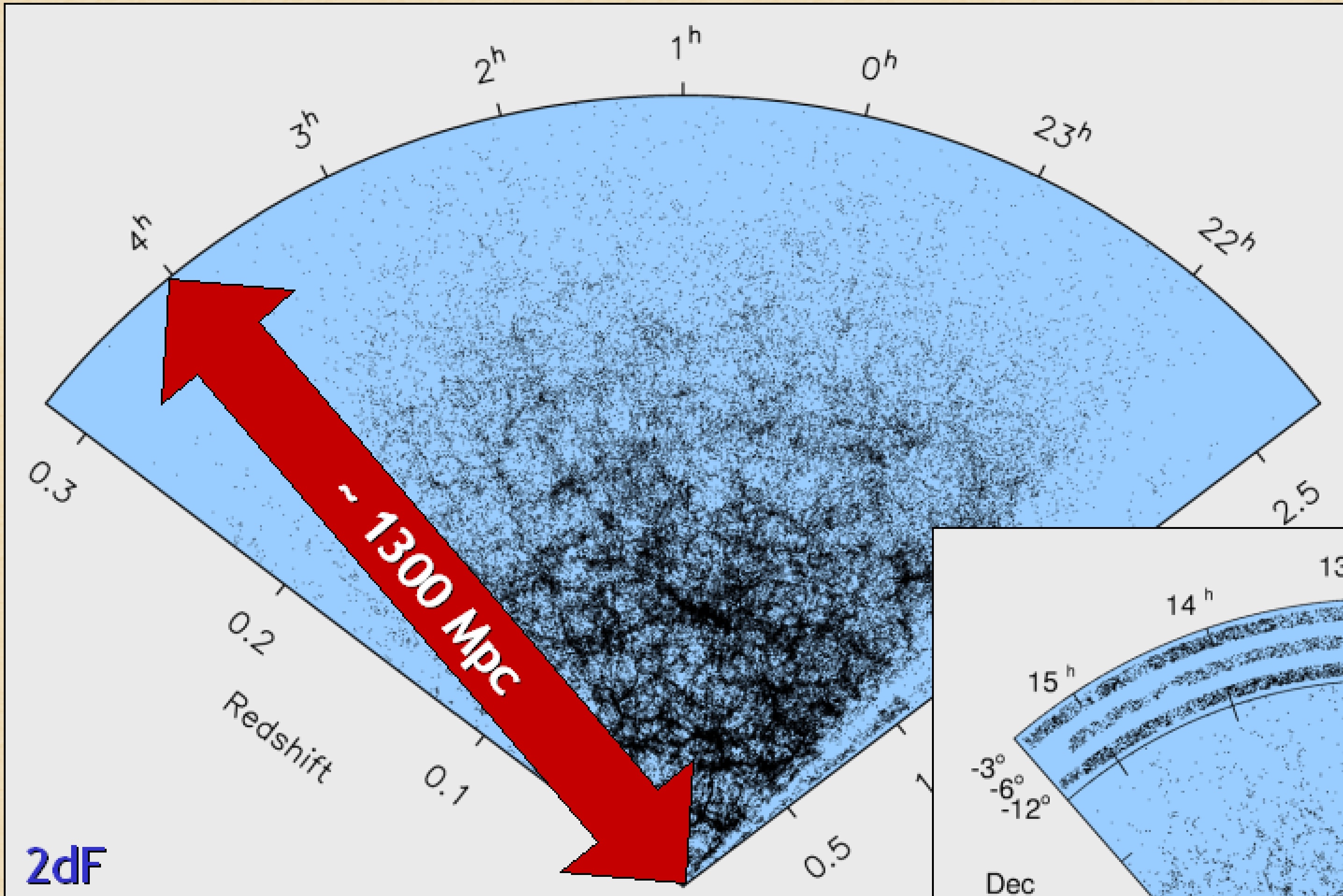


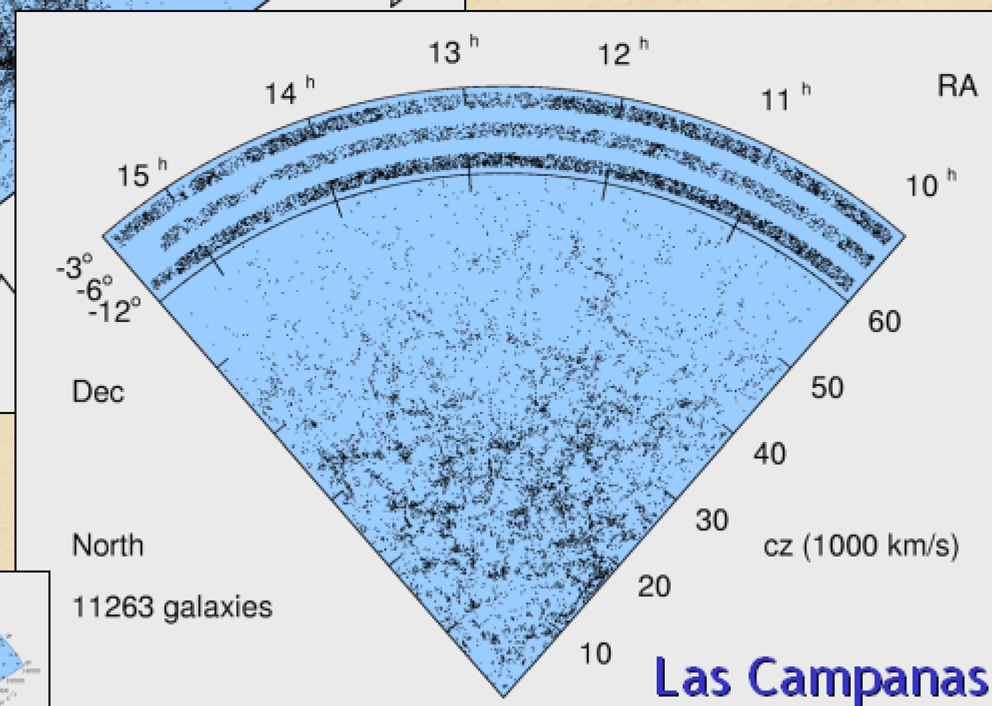
A Slice of the Universe

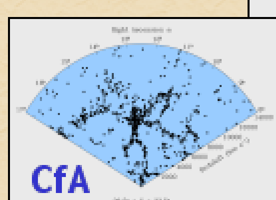


Galaxy distribution from the CfA redshift survey
[ApJ 302 (1986) L1]

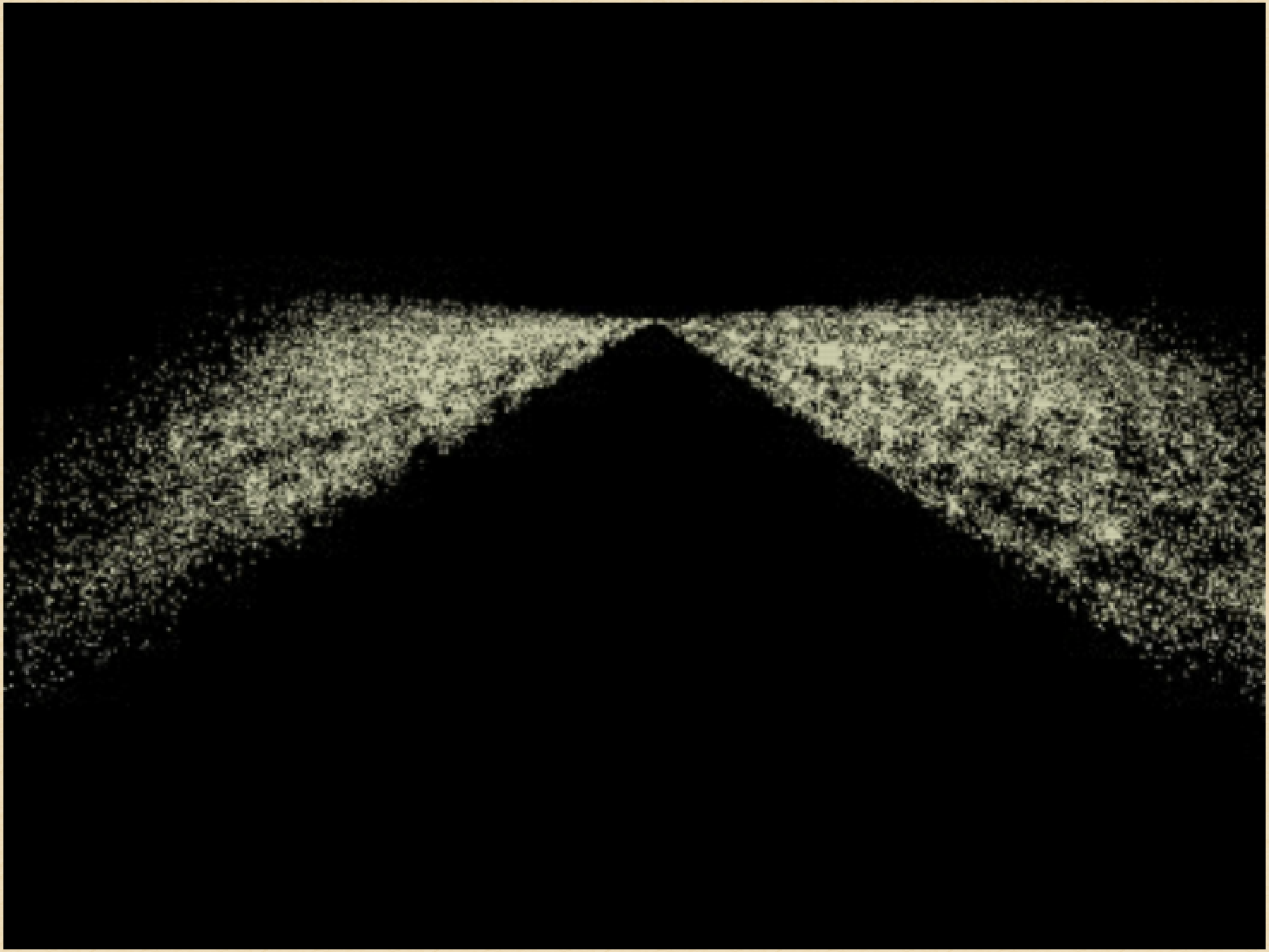
2dF Galaxy Redshift Survey (15 May 2002)







2dF Galaxy Redshift Survey



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

Power Spectrum of Density Fluctuations

Field of density fluctuations

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

Fourier transform

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

Power spectrum essentially square of Fourier transformation

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

with $\hat{\delta}$ the δ-function

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

$$\xi(x) = \langle \delta(x_2)\delta(x_1) \rangle = \int \frac{d^3k}{(2\pi)^3}\, e^{ik\cdot x}\, P(k)$$

$$= \int \frac{d\Omega}{4\pi} \frac{dk}{k}\, e^{ik\cdot x} \underbrace{\frac{k^3 P(k)}{2\pi^2}}_{\Delta^2(k)}$$

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

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

Gravitational Growth of Density Perturbations

The dynamical evolution of small perturbations

$$\delta(x) = \frac{\delta\rho(x)}{\overline{\rho}} << 1$$

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

Processed Power Spectrum in Cold Dark Matter Scenario

Primordial spectrum

Suppressed by stagnation during radiation phase

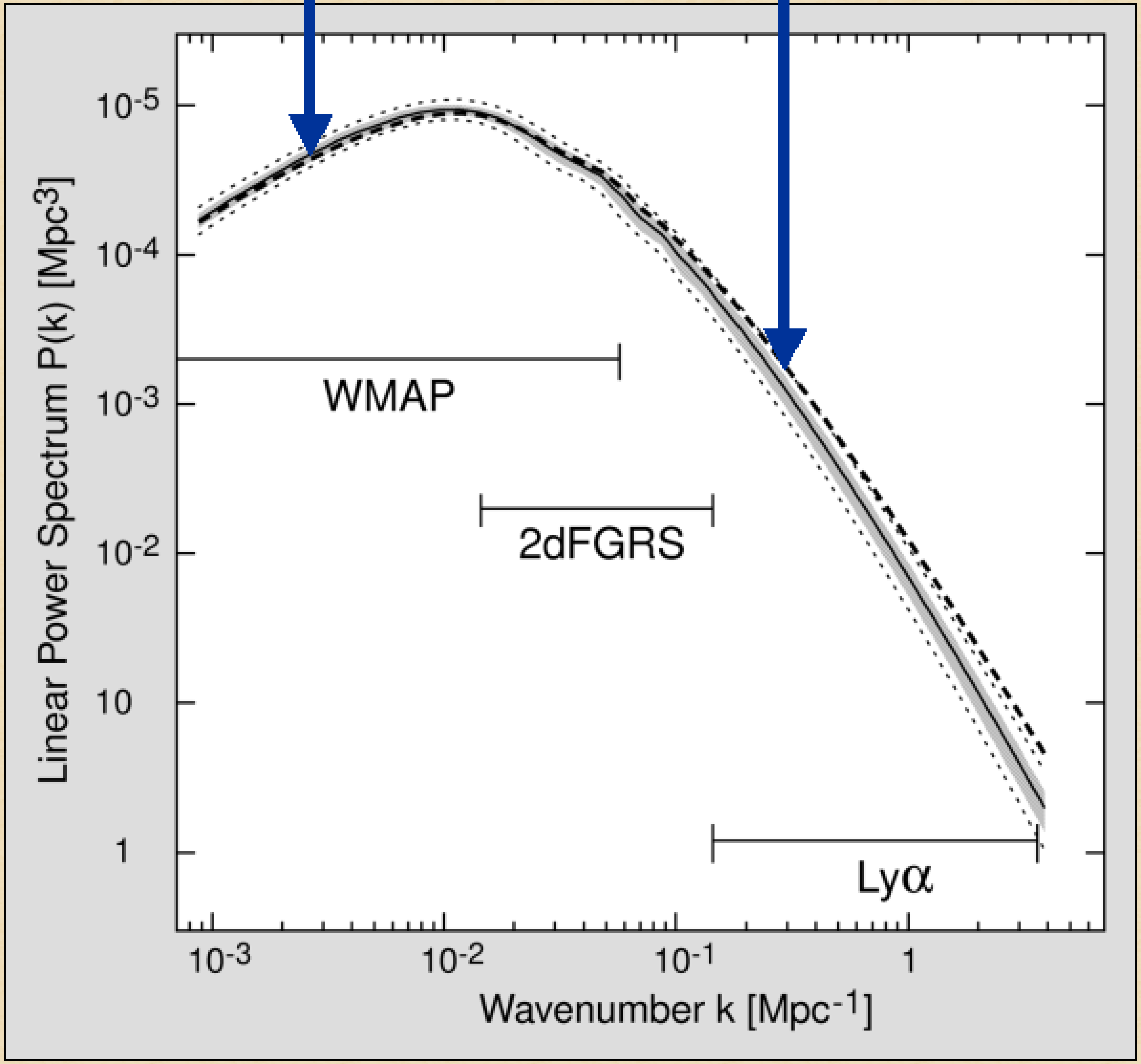
Primordial spectrum usually assumed to be of power-law form

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

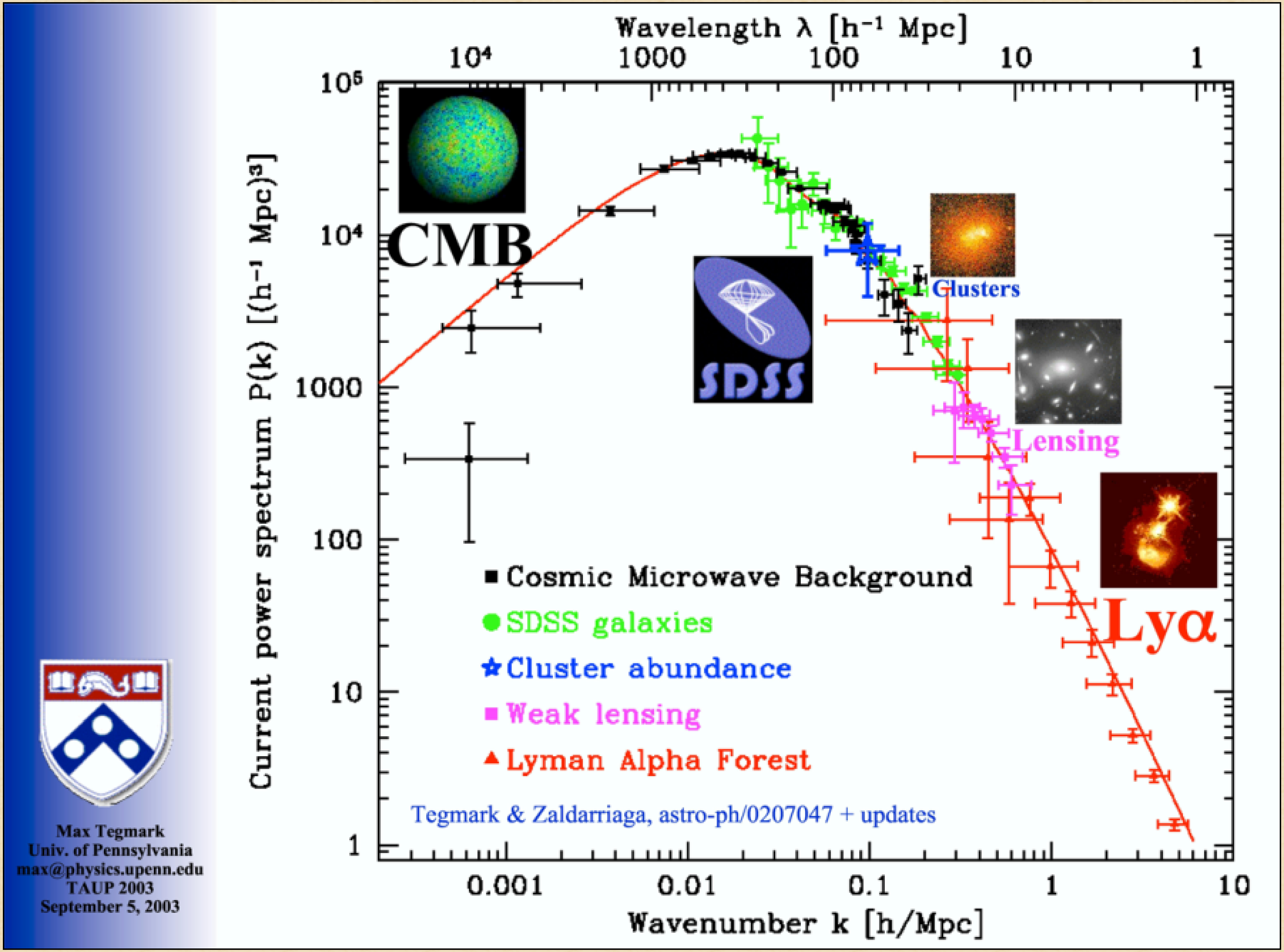
Harrison-Zeldovich ("flat") spectrum

$n = 1$

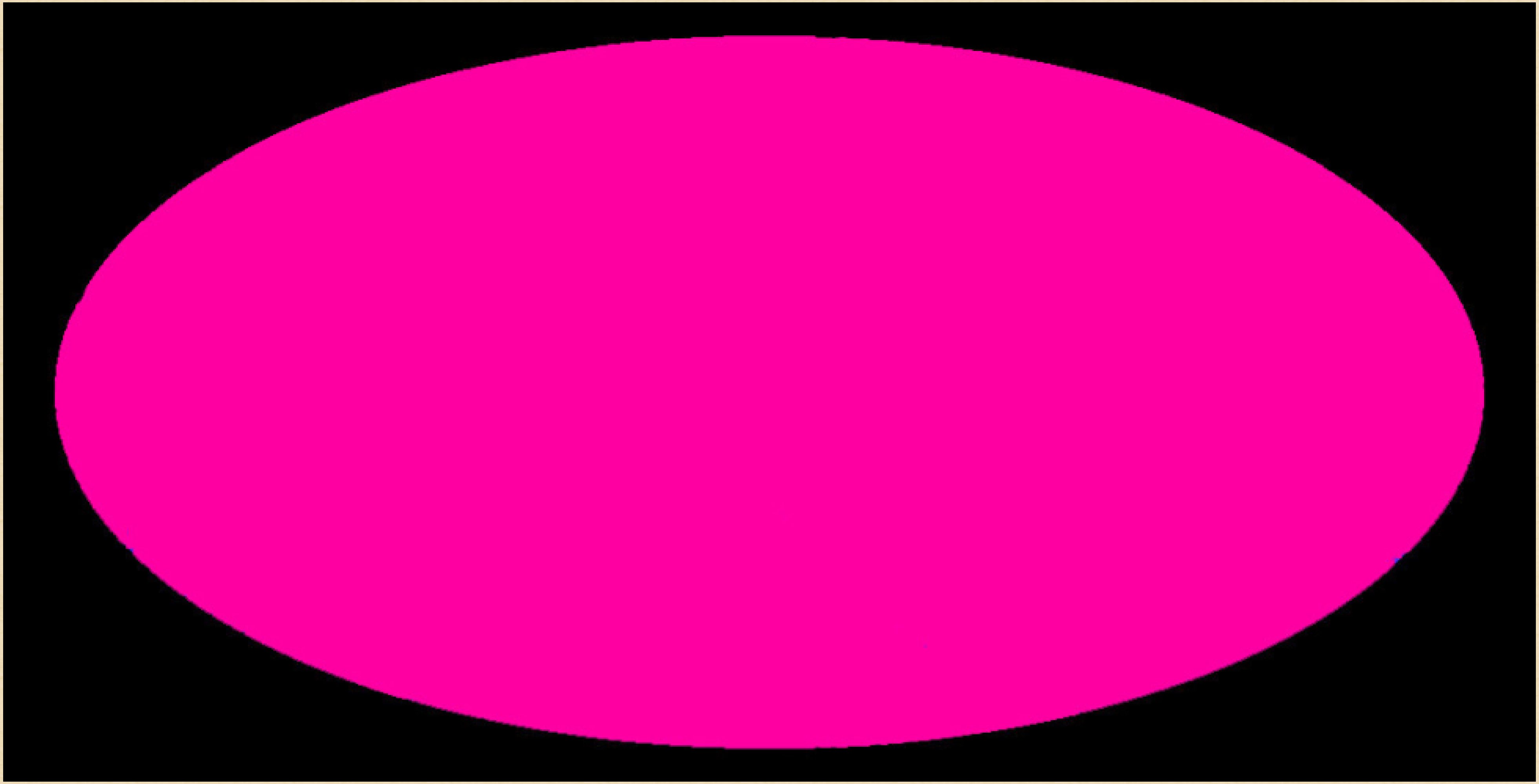
expected from inflation (may be slightly less than 1, depending on details of inflationary phase)



Power Spectrum of Cosmic Density Fluctuations

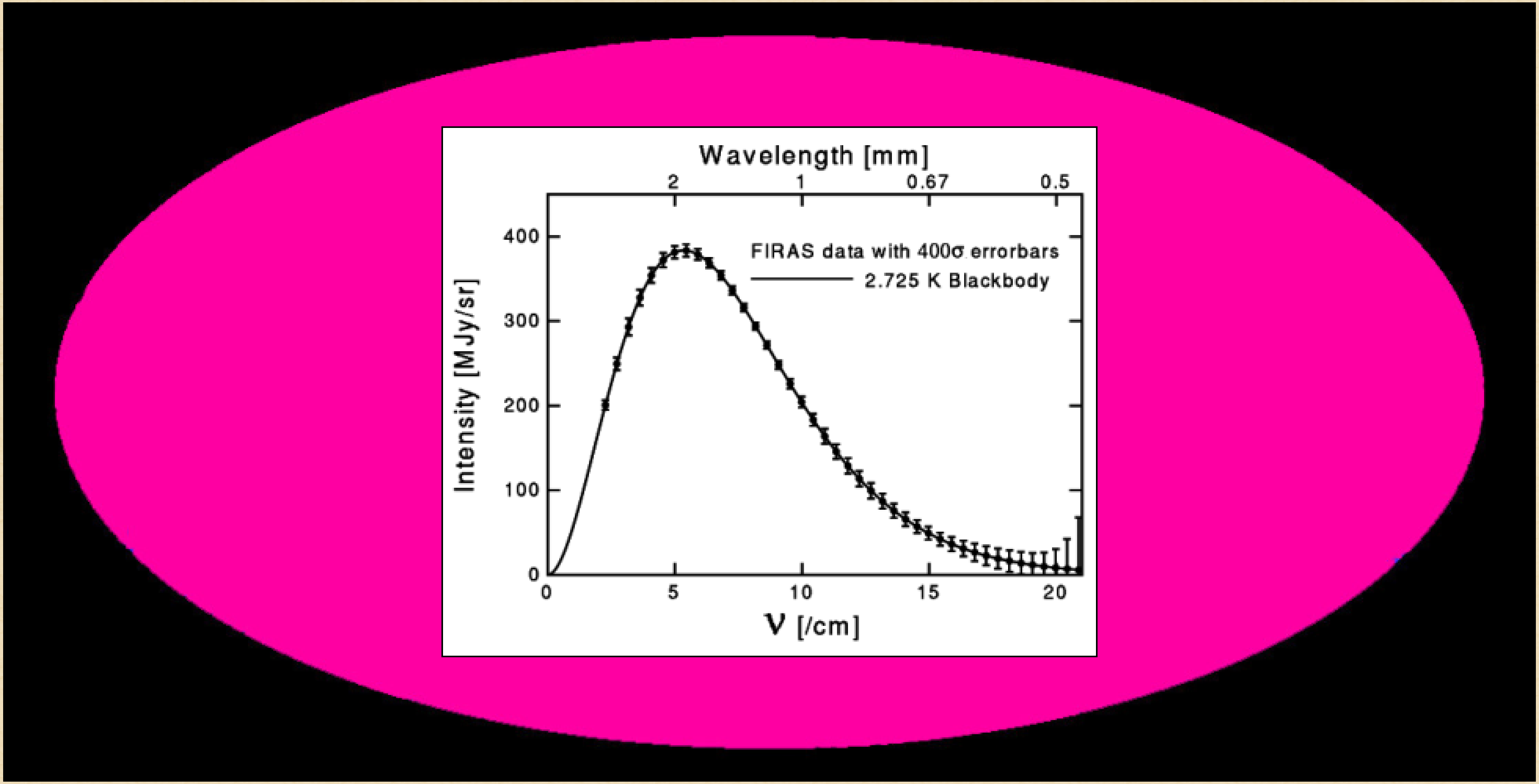


COBE Temperature Map of the Cosmic Microwave Background



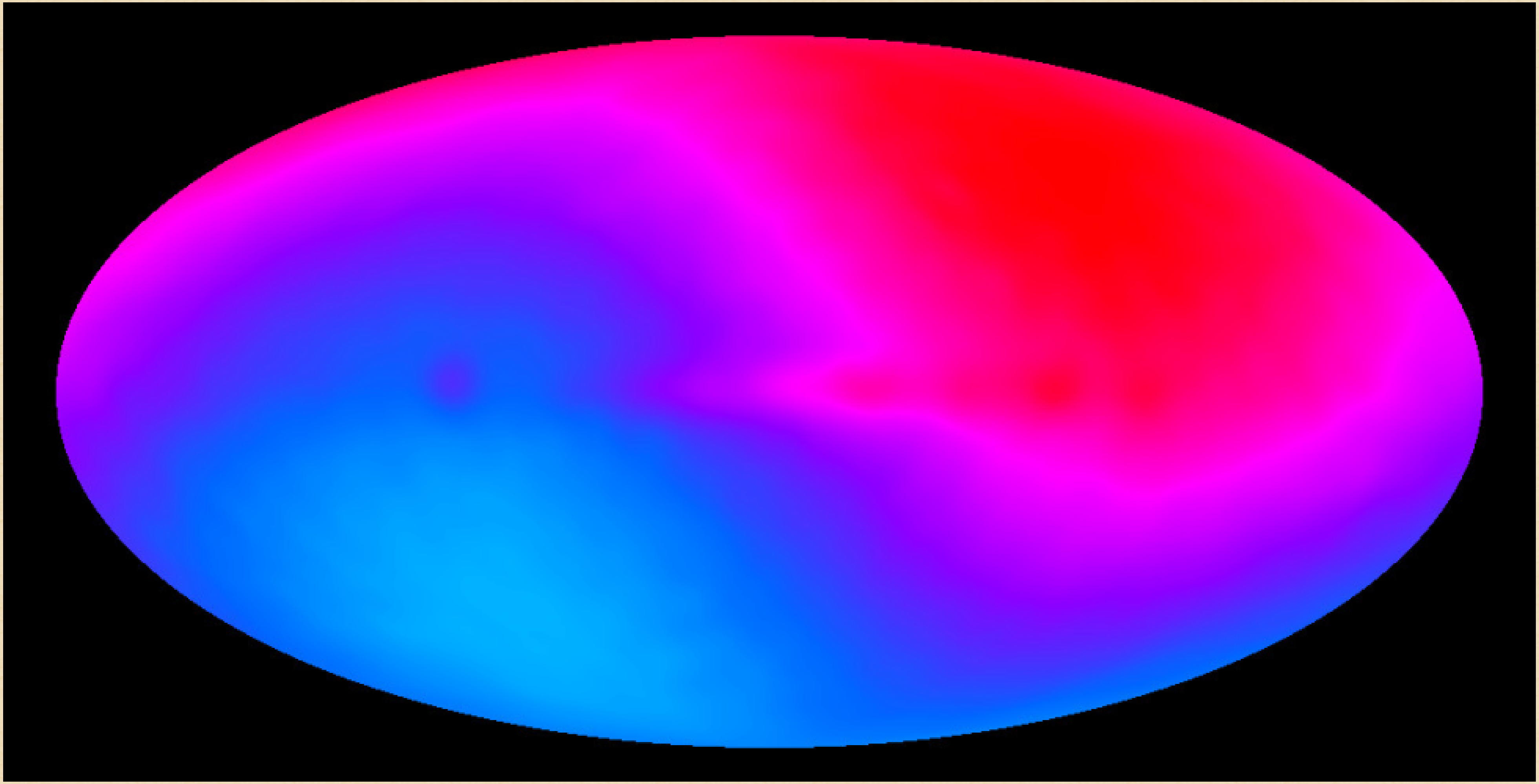
T = 2.725 K (uniform on the sky)

COBE Temperature Map of the Cosmic Microwave Background



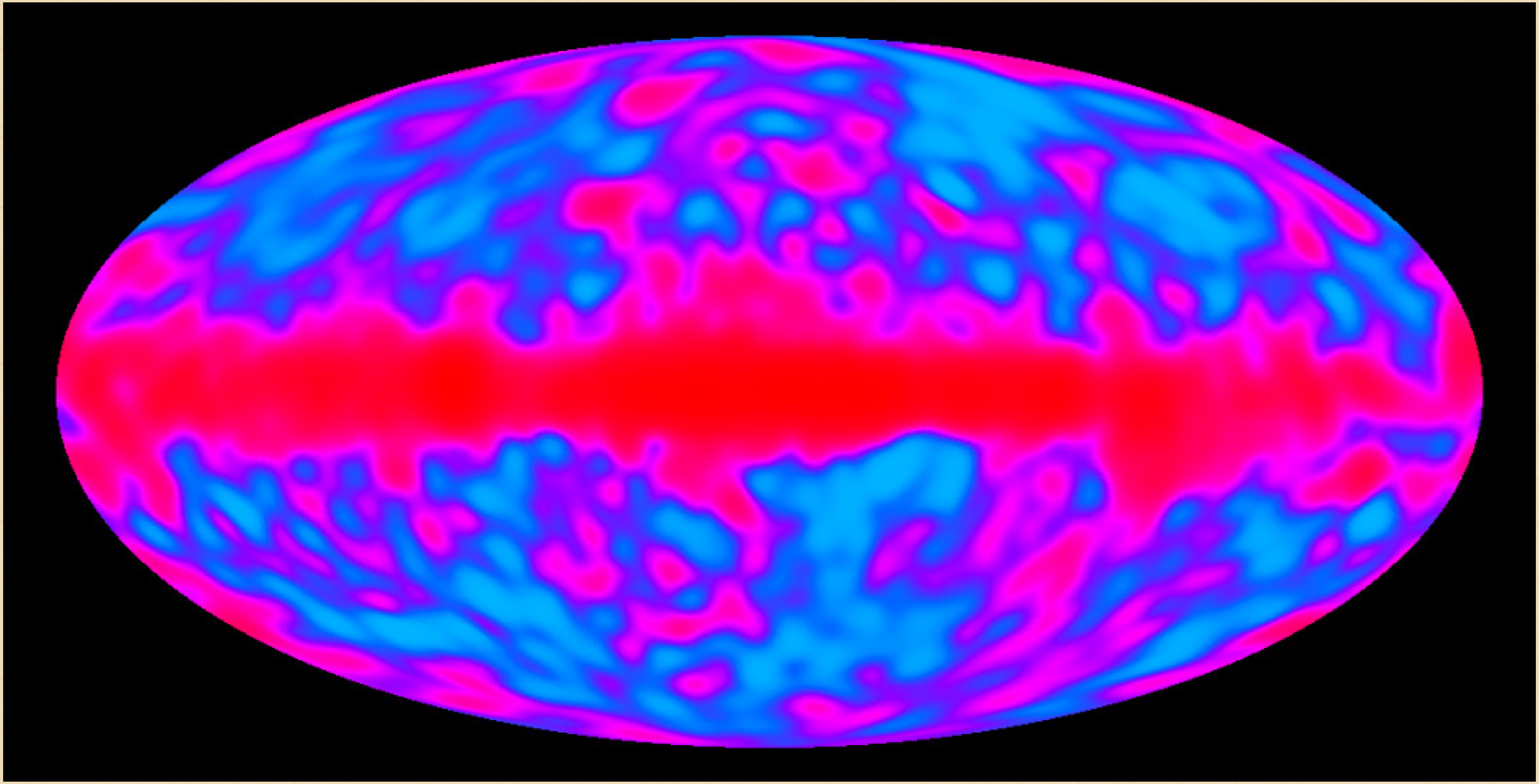
T = 2.725 K (uniform on the sky)

COBE Temperature Map of the Cosmic Microwave Background



Dynamical range $\Delta T = 3.353$ mK $(\Delta T/T \approx 10^{-3})$
Dipole temperature distribution from Doppler effect
caused by our motion relative to the cosmic frame

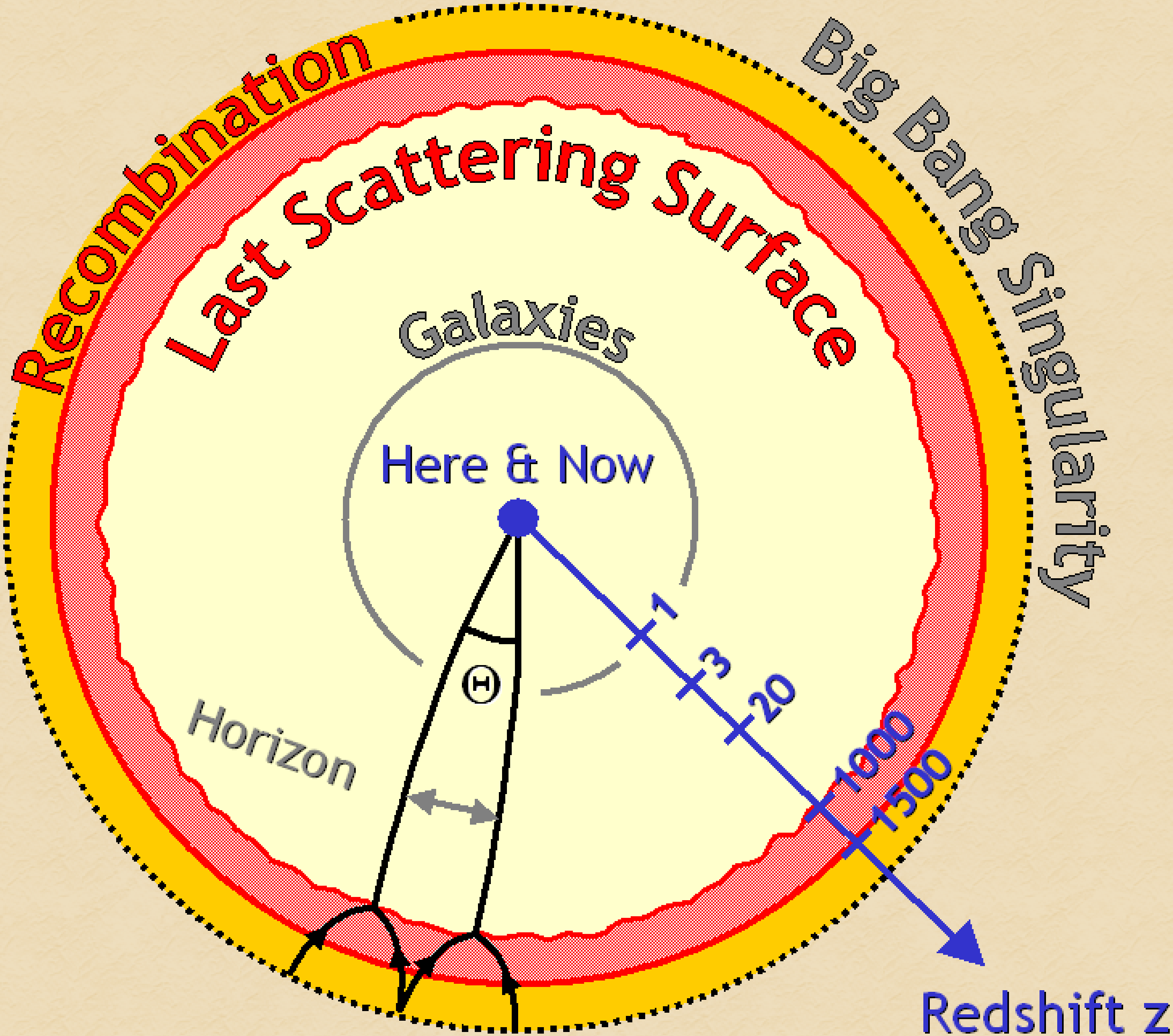
COBE Temperature Map of the Cosmic Microwave Background



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

Primordial temperature fluctuations

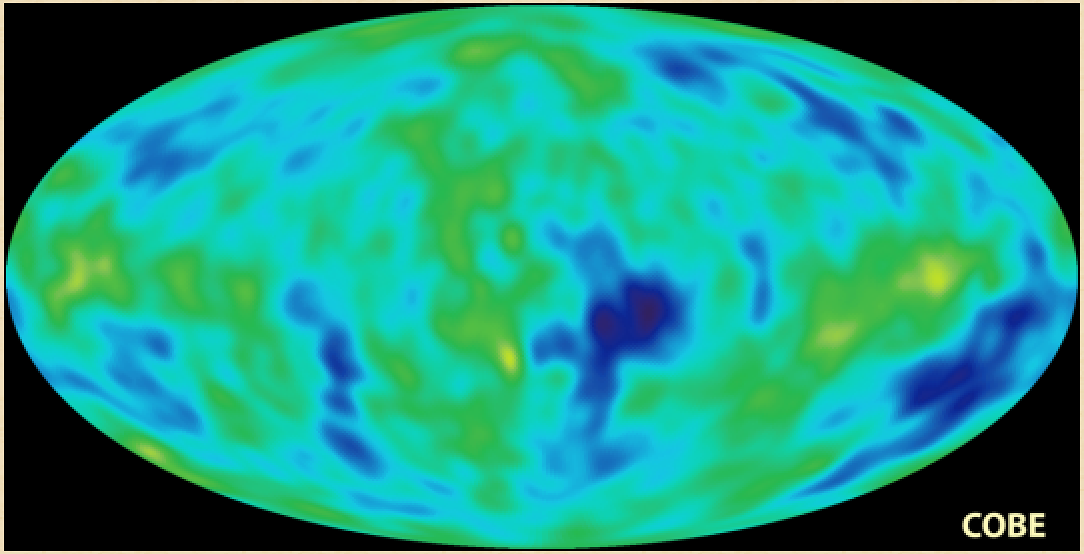
Last Scattering Surface



Power Spectrum of CMBR Temperature Fluctuations

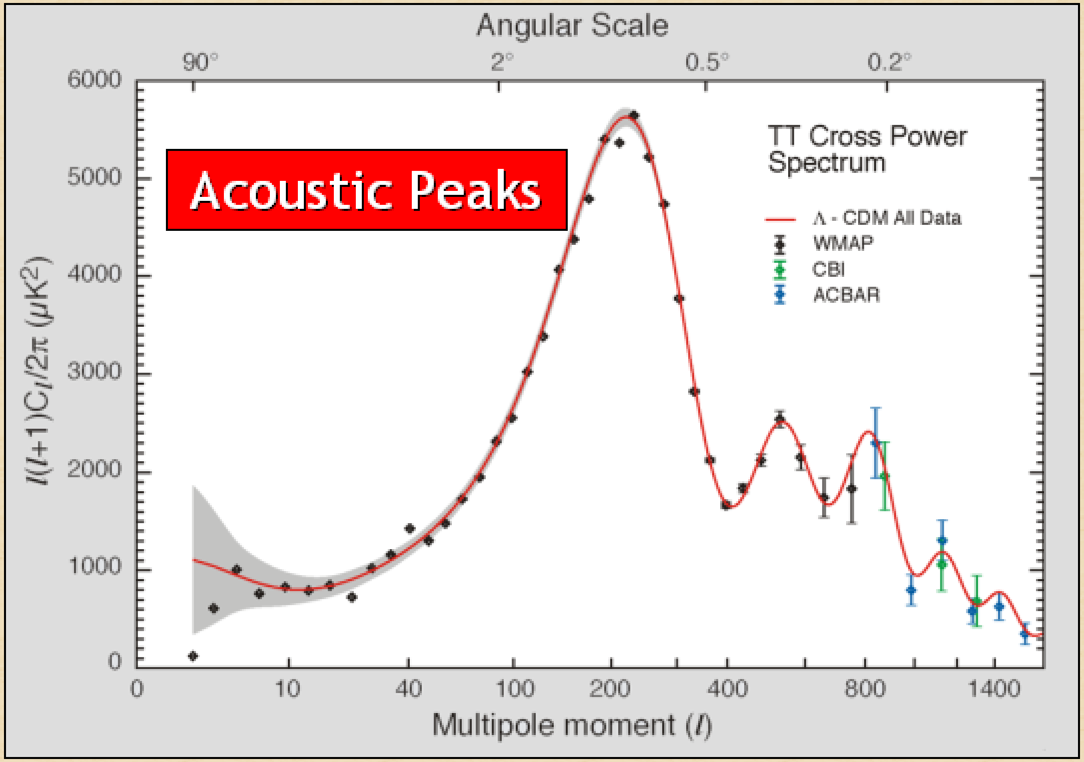
Sky map of CMBR temperature fluctuations

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



Multipole expansion

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



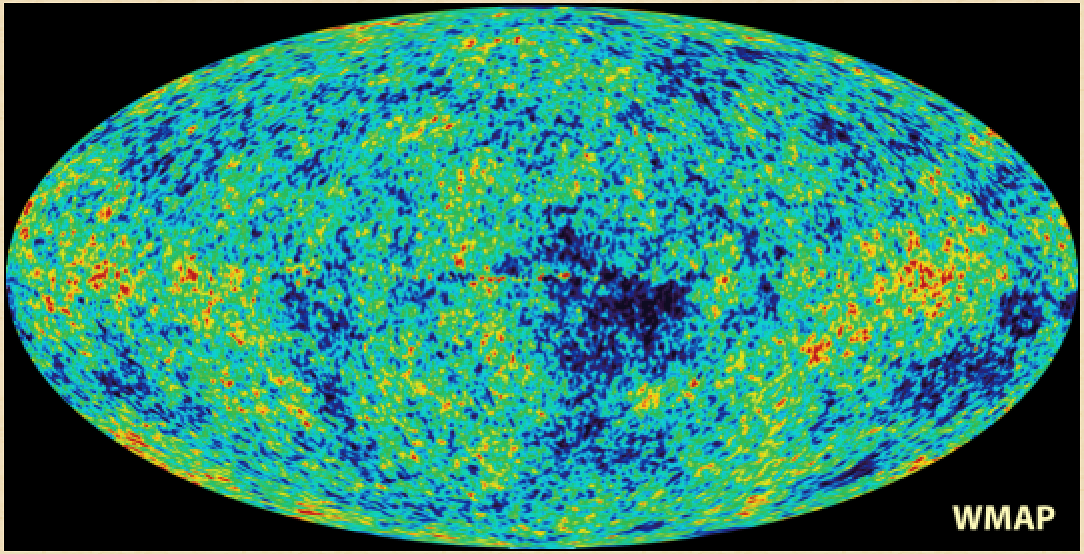
Angular power spectrum

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

Power Spectrum of CMBR Temperature Fluctuations

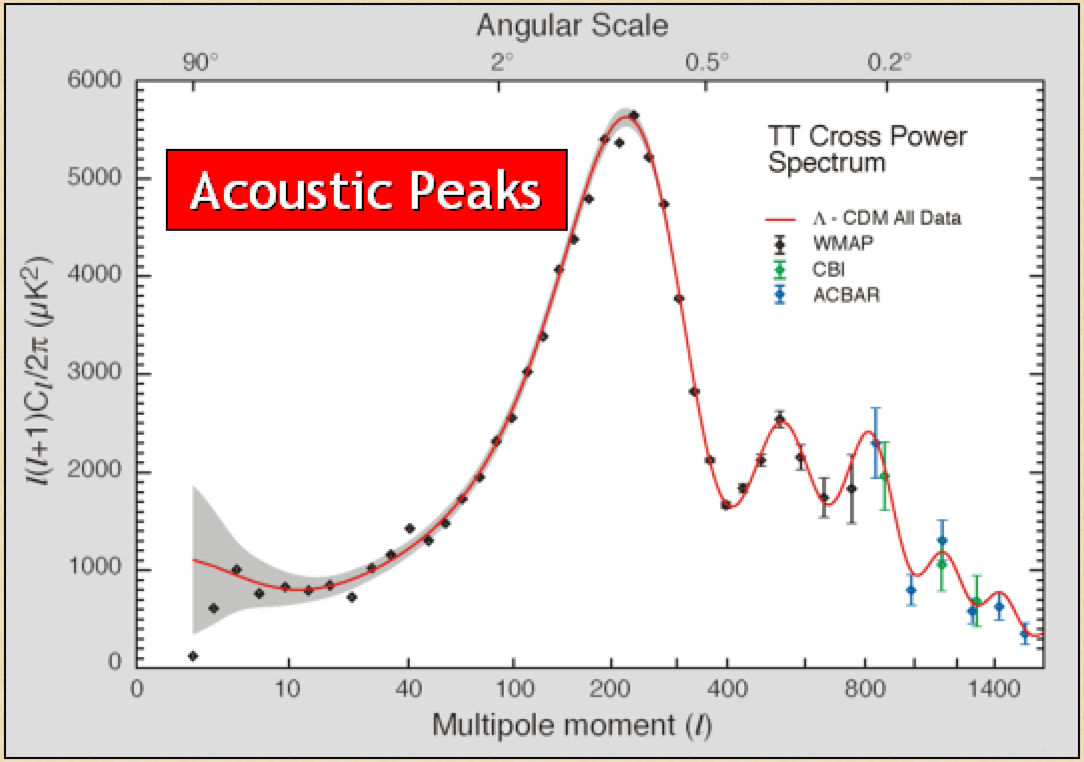
Sky map of CMBR temperature fluctuations

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



Multipole expansion

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

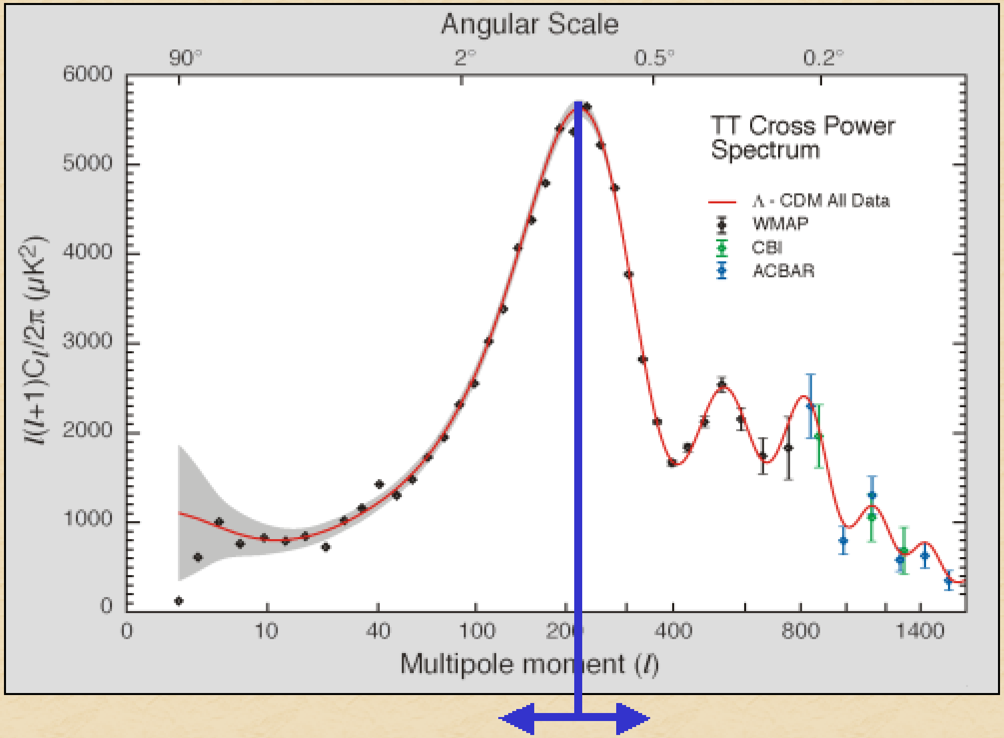


Angular power spectrum

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

Flat Universe from CMBR Angular Fluctuations

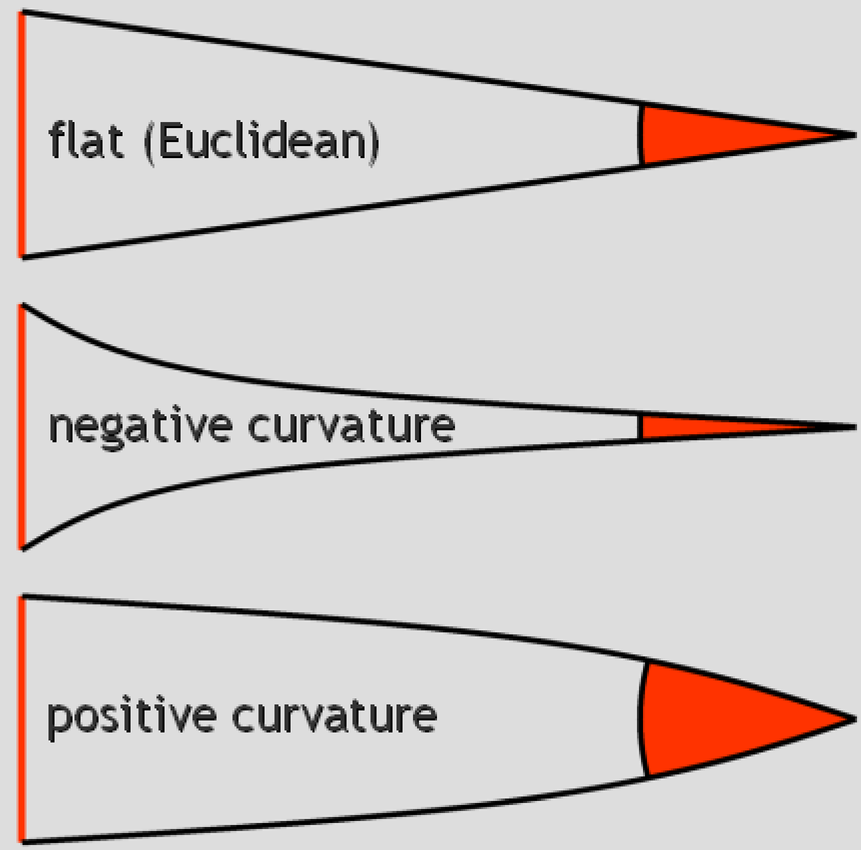
Spergel et al. (WMAP Collaboration)
astro-ph/0302209



$$\ell_{max} \approx 200/\sqrt{\Omega_{tot}}$$

$$\Omega_{tot} = 1.02 \pm 0.02$$

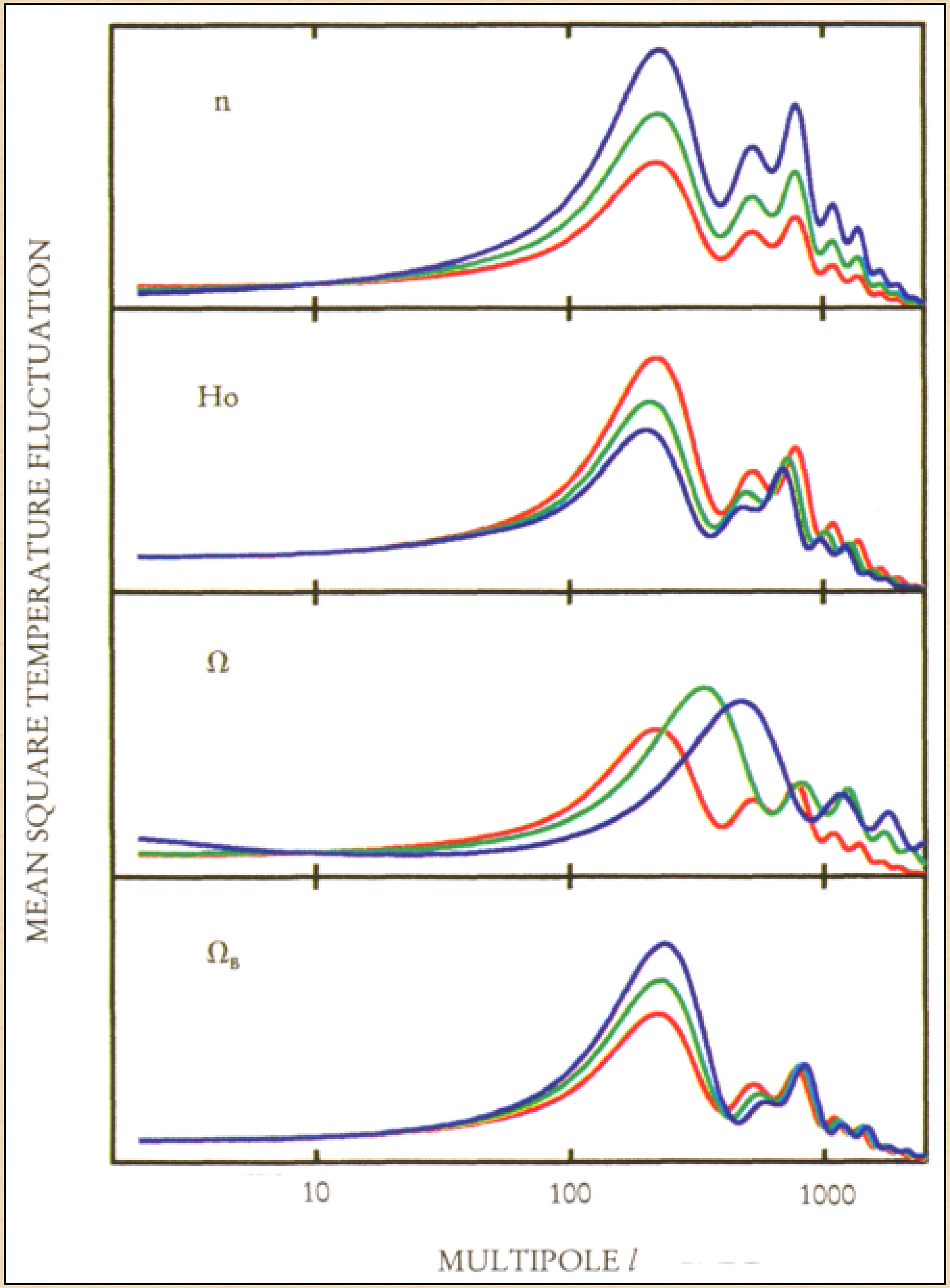
Triangulation with acoustic peak



Known physical size of acoustic peak at decoupling ($z \approx 1100$)

Measured angular size today ($z = 0$)

CMBR - The Cosmic Rosetta Stone



Power-law index (tilt)
n = 1.0, 1.1, 1.2

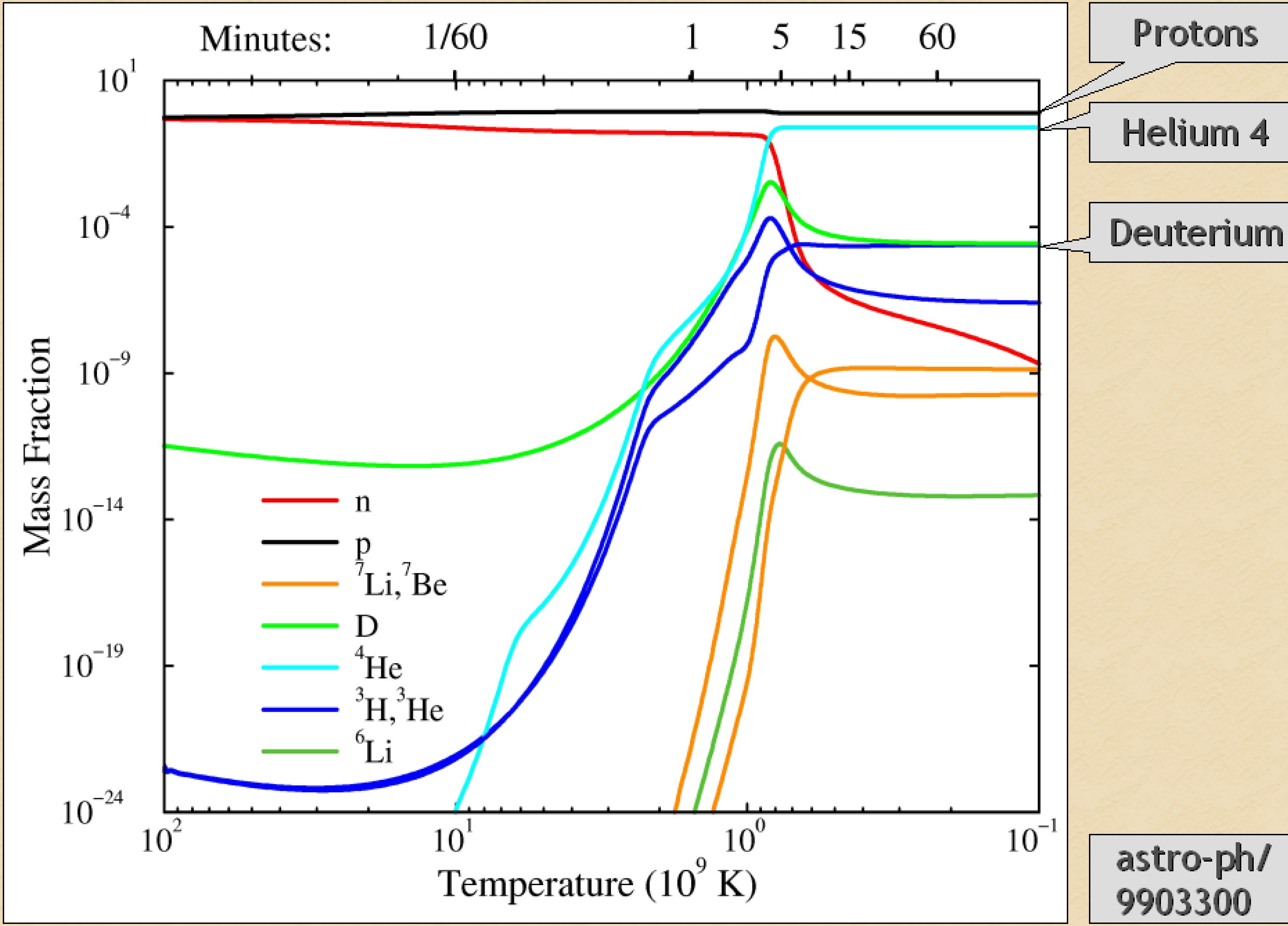
Hubble constant
H_0 = 50, 60, 70

Total density
Ω_{tot} = 1.0, 0.5, 0.3

Baryon density
Ω_B = 5, 7.5, 10×10^{-3}

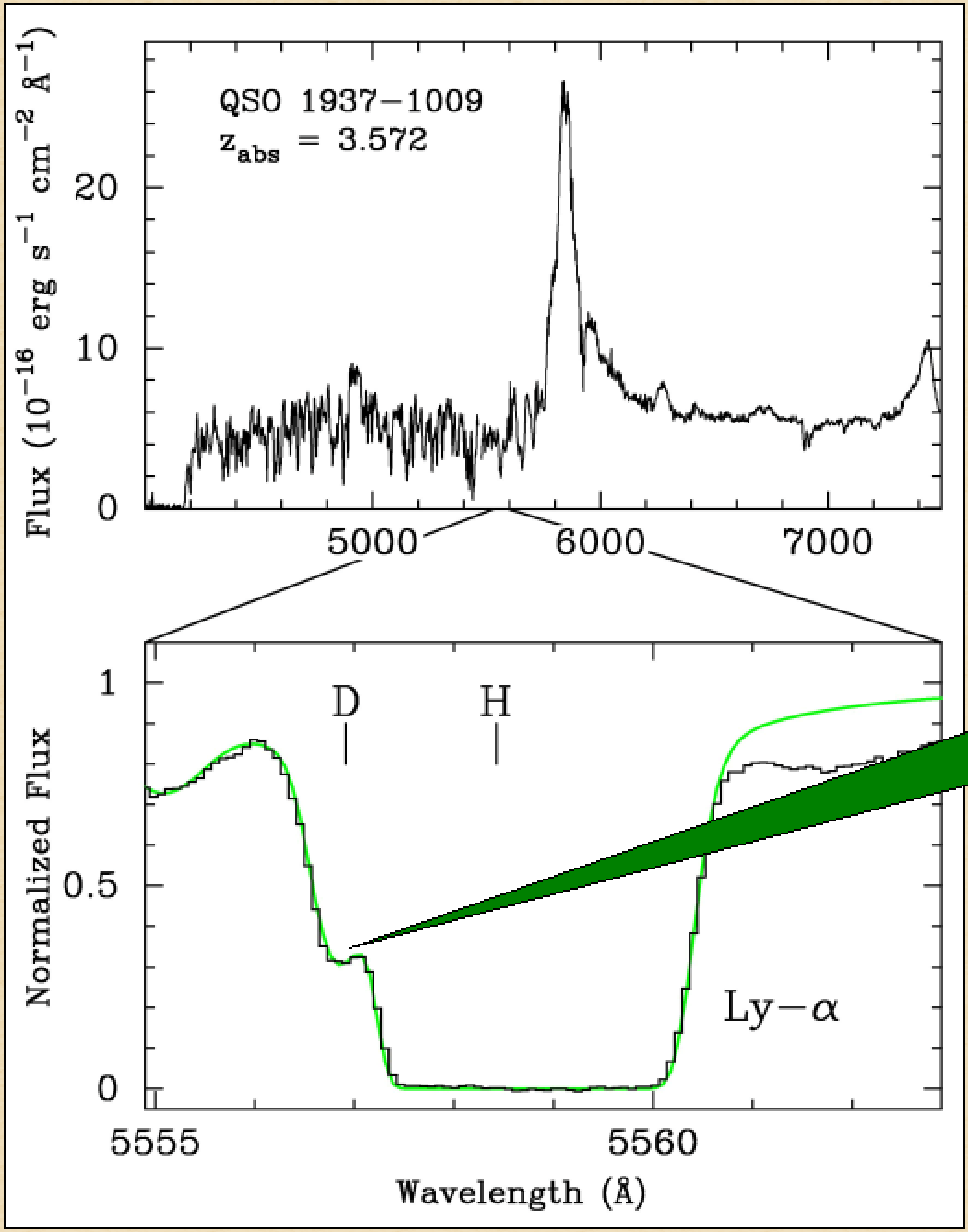
Physics Today 1997:11, 32

Formation of Light Elements (Big Bang Nucleosynthesis)



astro-ph/9903300

Measuring Primordial Deuterium



Hydrogen absorption spectrum of a background quasar in high-redshift hydrogen clouds

Deuterium Lyman-α in the flank of the saturated hydrogen Lyman-α line

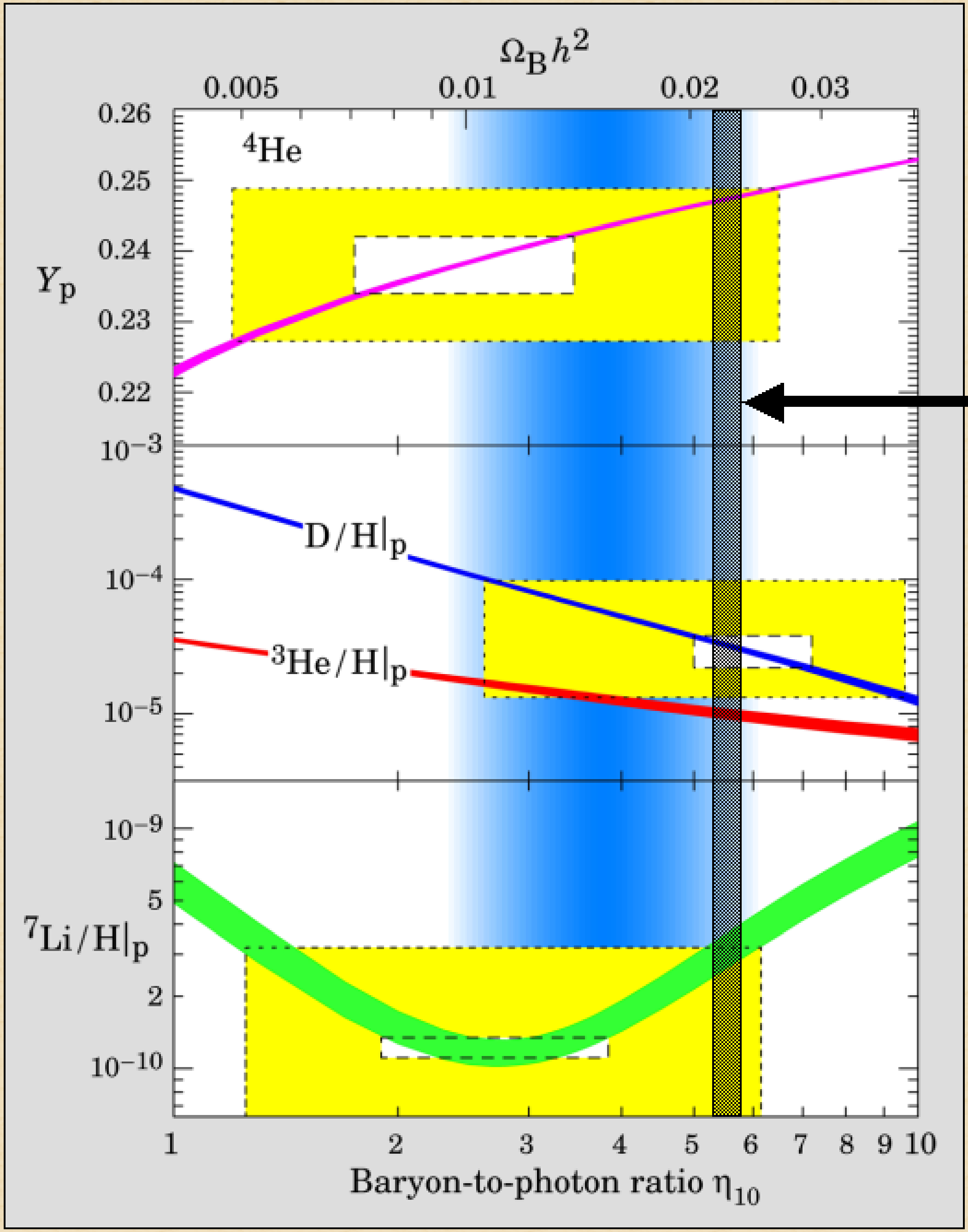
astro-ph/9903300

BBN Concordance

Helium

Deuterium

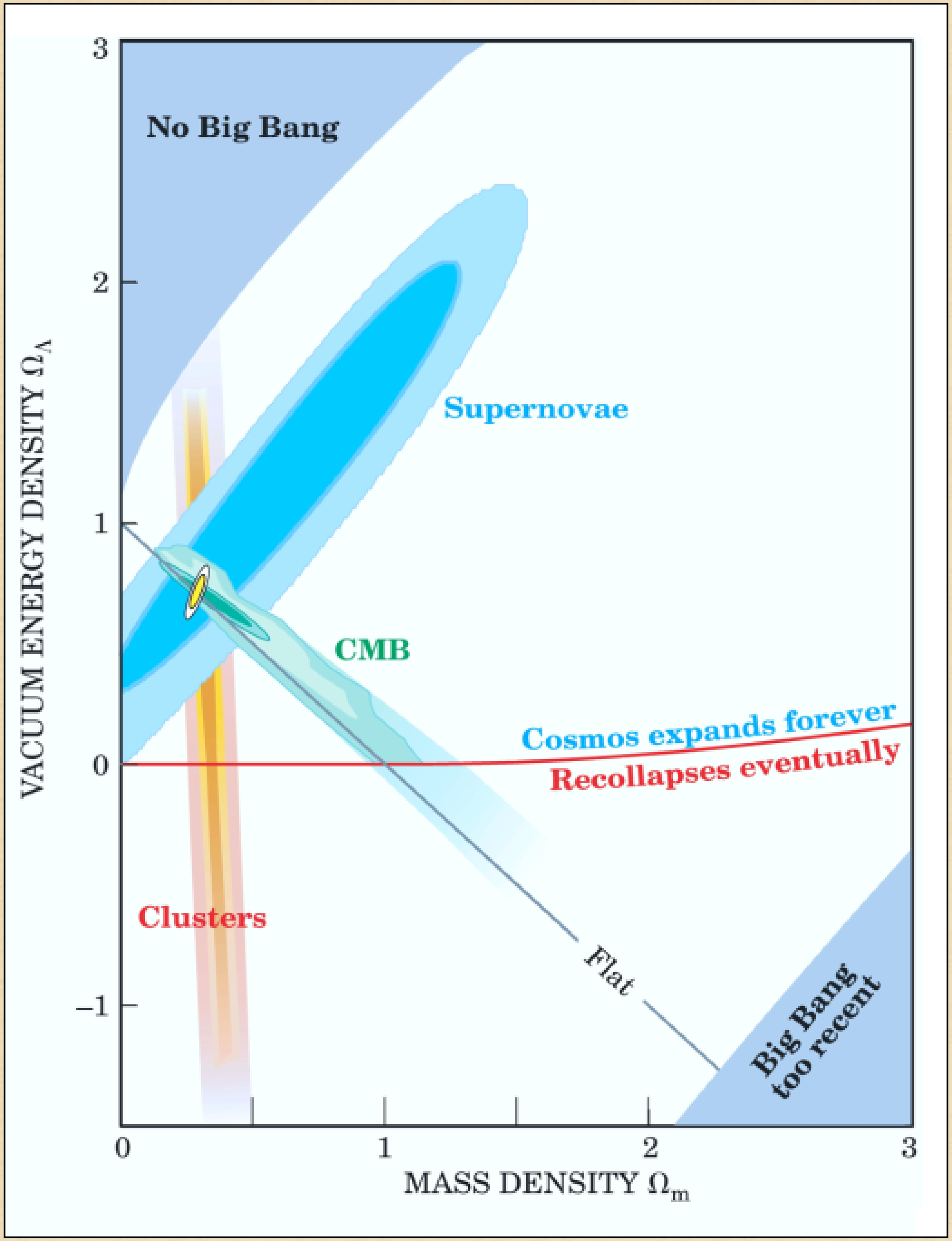
Lithium



Implied by CMBR and large-scale structure

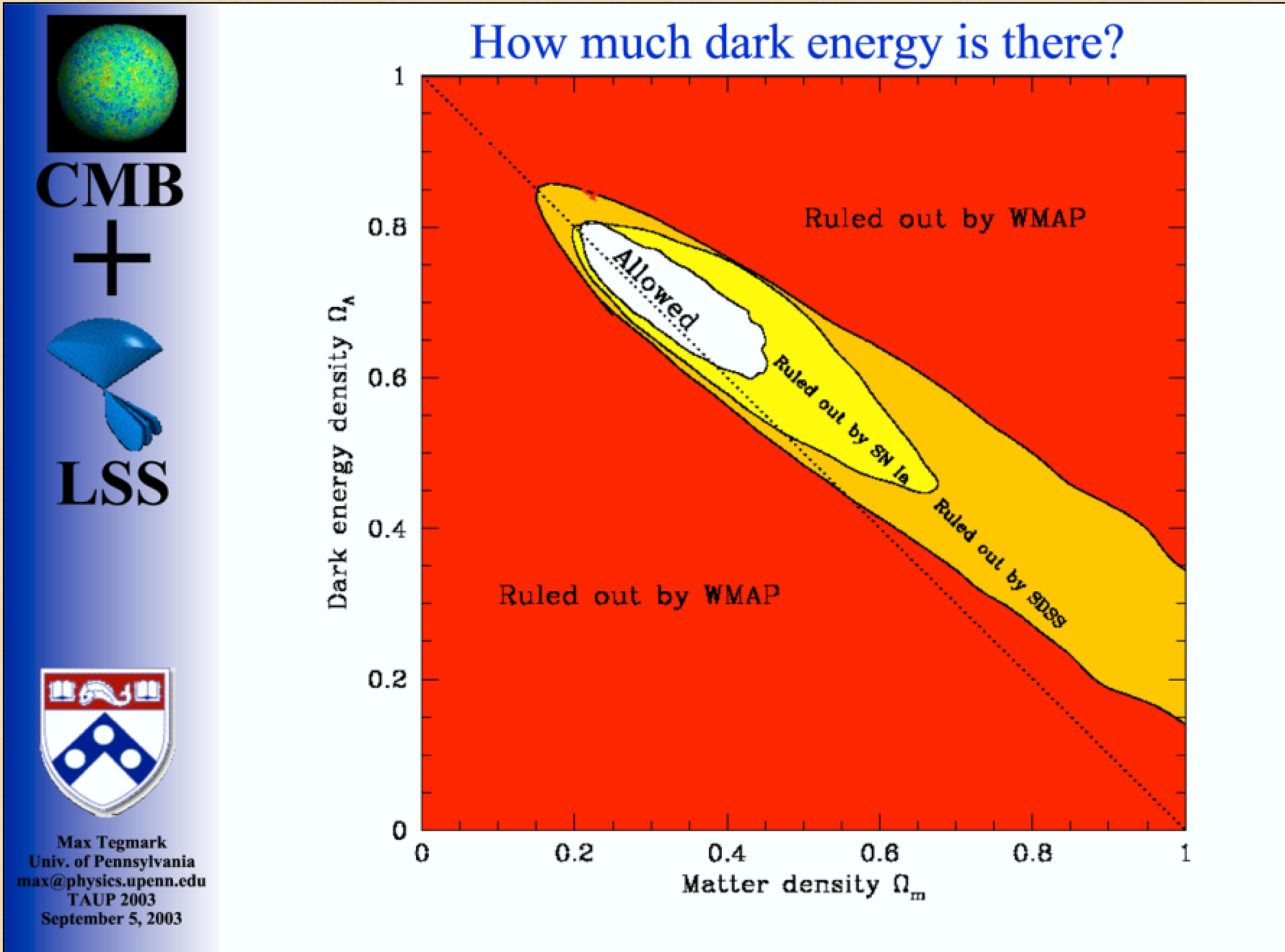
Review of Particle Properties

Best-Fit Universe



S. Perlmutter
Physics Today, April 2003, p.53

Cosmological Parameter Fitting



Concordance Model of Cosmology

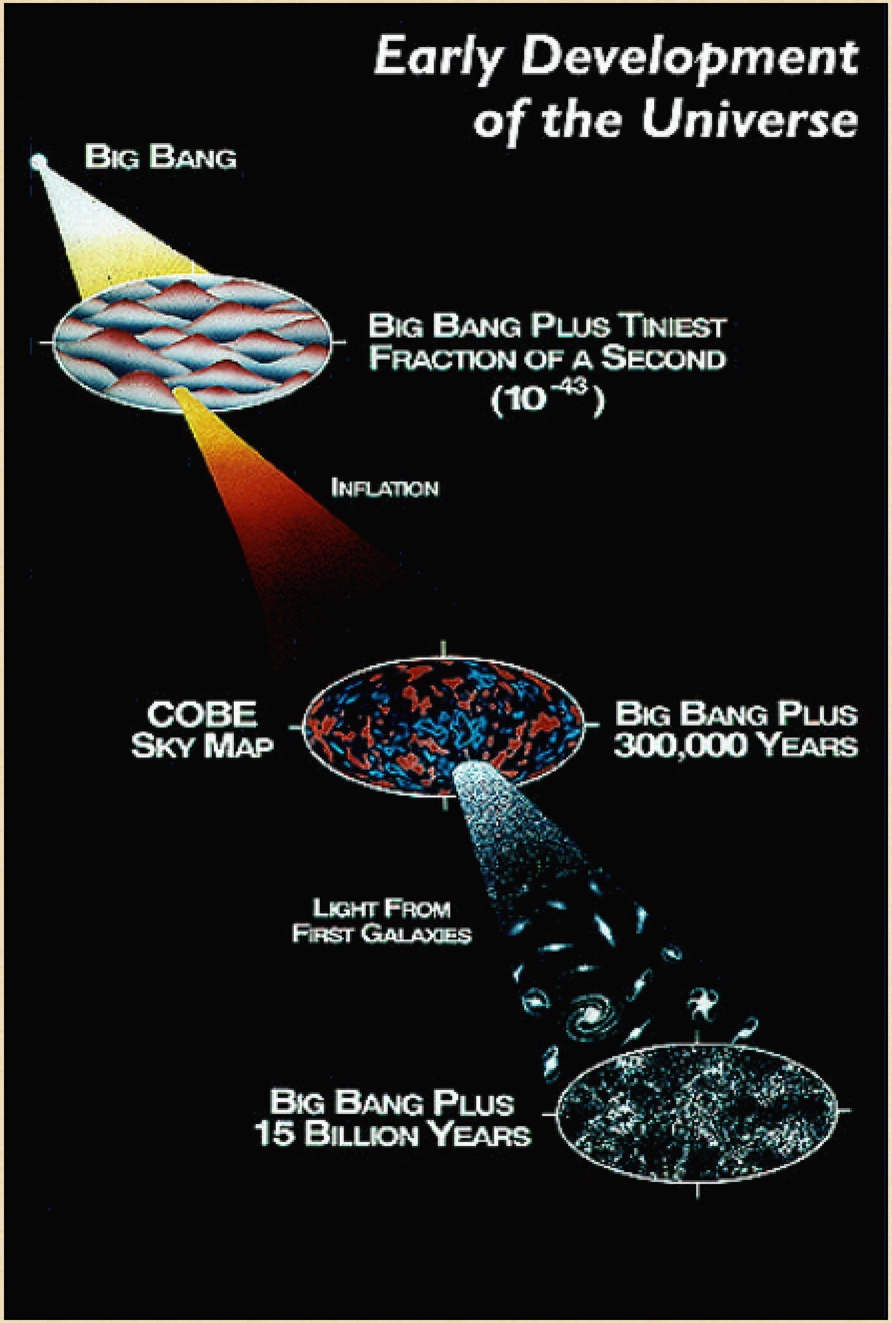
A Friedmann-Lemaître-Robertson-Walker model with the following parameters perfectly describes the global properties of the universe

Expansion rate	$H_0 = (72 \pm 4)\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$	
Spatial curvature	$\lvert R_{curv} \rvert > 5 H_0^{-1}$	$\Omega_{tot} = 1.02 \pm 0.02$
Age	$t_0 = (13.7 \pm 0.2) \times 10^9$ years	
Vacuum energy	$\Omega_\Lambda = 0.73 \pm 0.04$	$\Omega_\Lambda + \Omega_M = 1.02 \pm 0.02$
Matter	$\Omega_M = 0.27 \pm 0.04$	
Baryonic matter	$\Omega_B = 0.044 \pm 0.004$	

The observed large-scale structure and CMBR temperature fluctuations are perfectly accounted for by the gravitational instability mechanism with the above ingredients and a power-law primordial spectrum of adiabatic density fluctuations (curvature fluctuations) $P(k) \propto k^n$

Power-law index	$n = 0.93 \pm 0.03$

Generating the Primordial Density Fluctuations



Early phase of exponential expansion (Inflationary epoch)

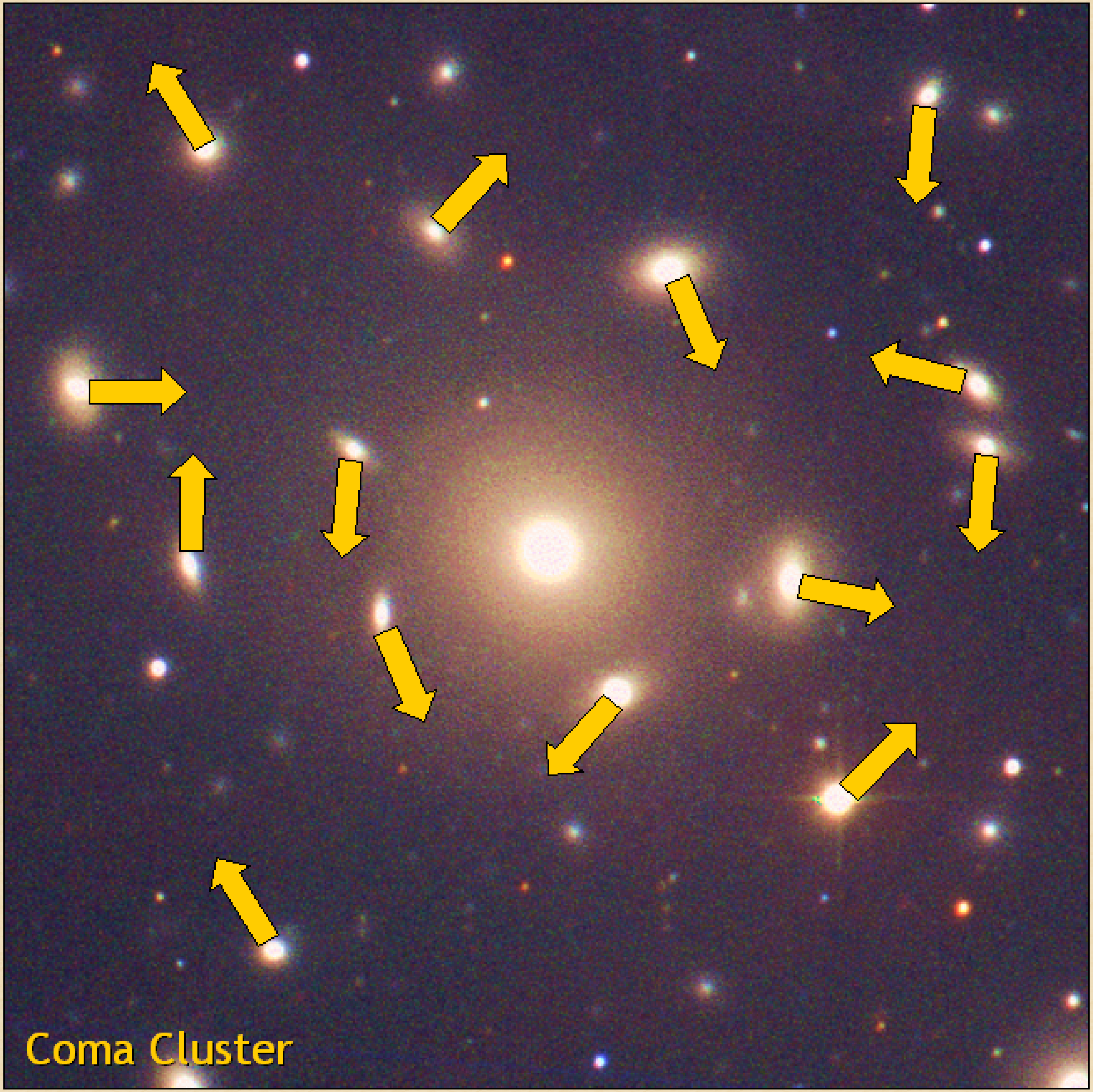
↓

Zero-point fluctuations of quantum fields are stretched and frozen

↓

Cosmic density fluctuations are frozen quantum fluctuations

Dark Matter in Galaxy Clusters



A gravitationally bound system of many particles obeys the virial theorem

$$2\langle E_{kin} \rangle = -\langle E_{kin} \rangle$$

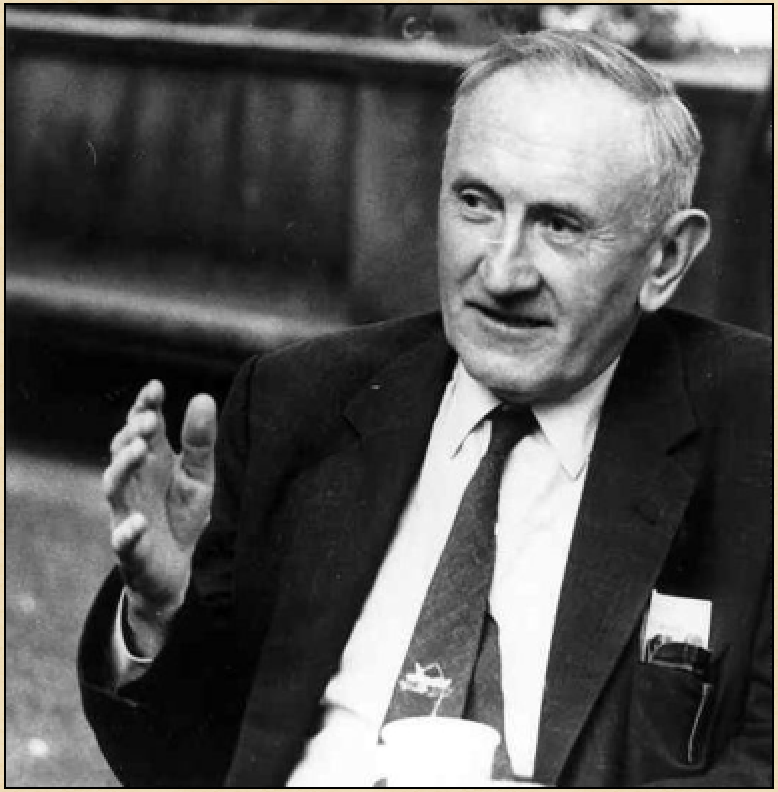
$$2\left\langle \frac{mv^2}{2} \right\rangle = \left\langle \frac{G_N M_r m}{r} \right\rangle$$

$$\langle v^2 \rangle \approx G_N M_r \langle r^{-1} \rangle$$

Velocity dispersion from Doppler shifts and geometric size

Total Mass

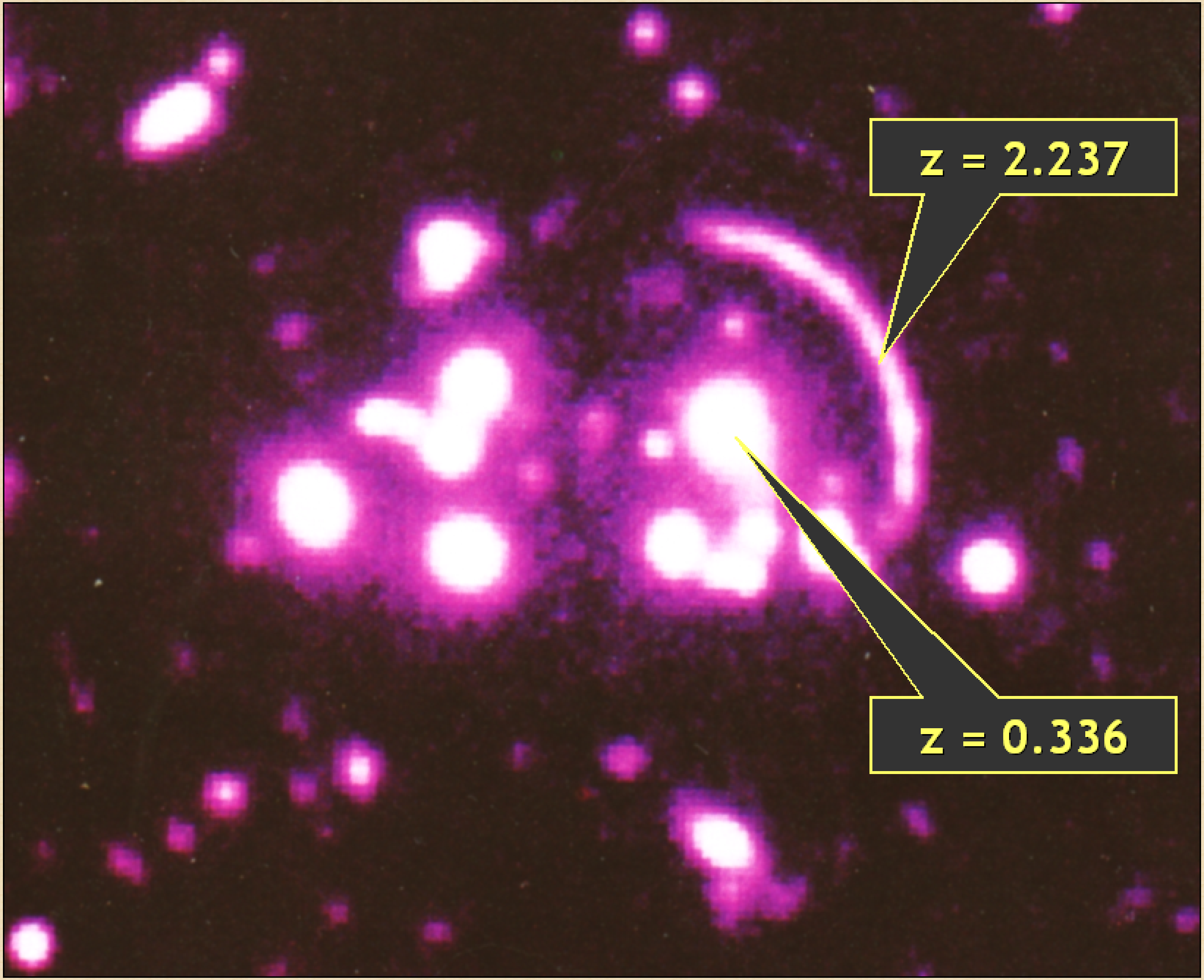
Dark Matter in Galaxy Clusters



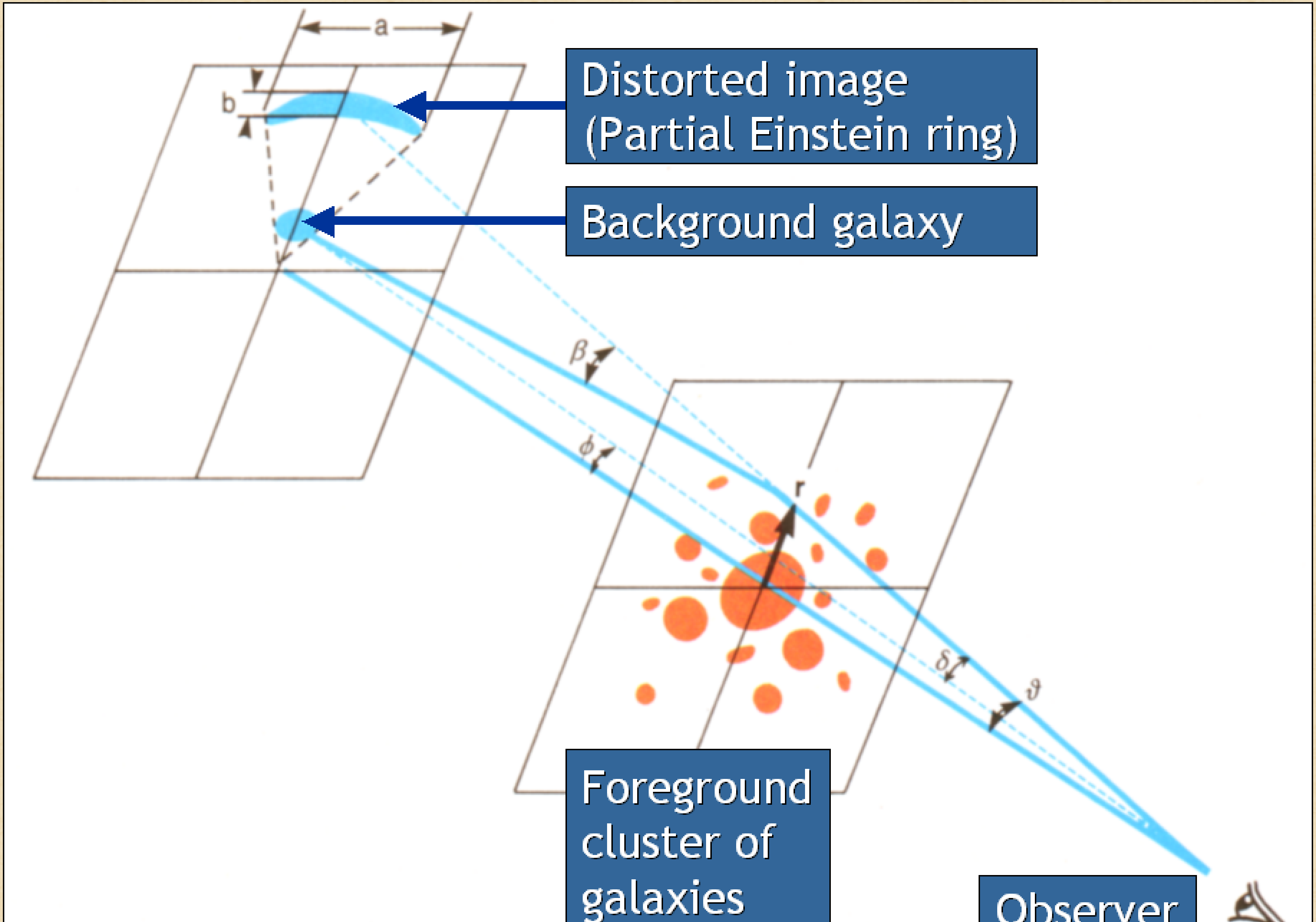
Fritz Zwicky:
Die Rotverschiebung von Extragalaktischen Nebeln
(The redshift of extragalactic nebulae)
Helv. Phys. Acta 6 (1933) 110

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.

Giant Arc in Cluster Cl 2244-02

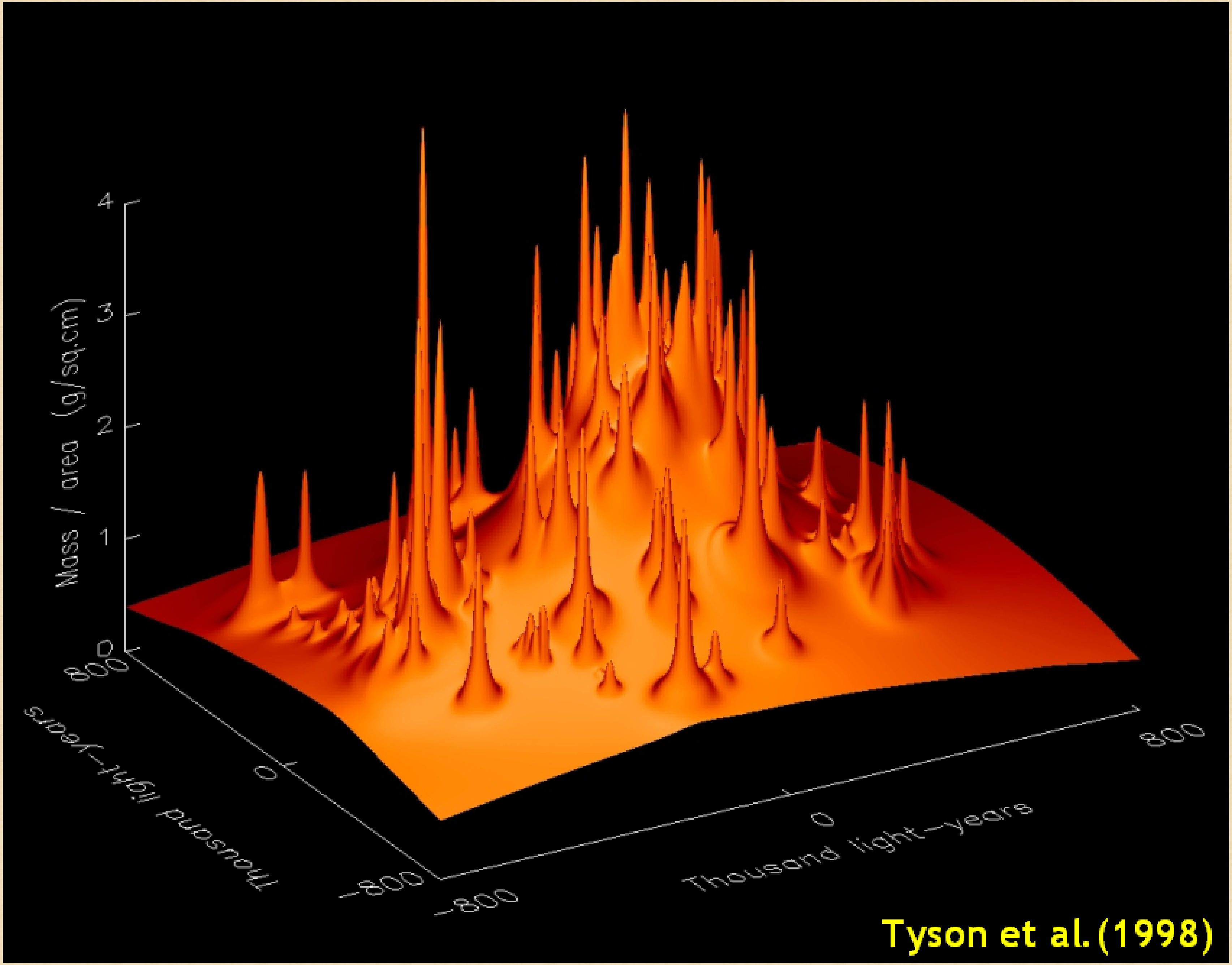


Giant Arcs – Gravitationally Lensed Background Galaxies



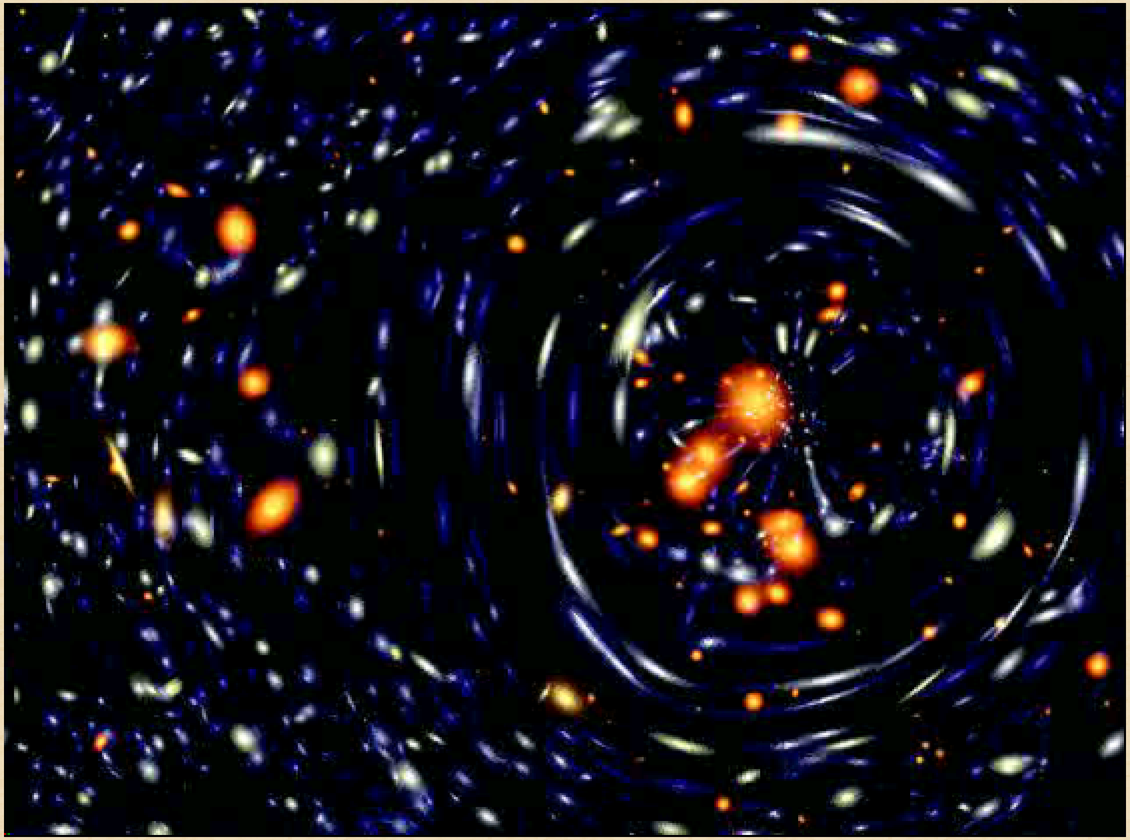
A.Tyson, Physics Today, 1992:6, pg.24

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



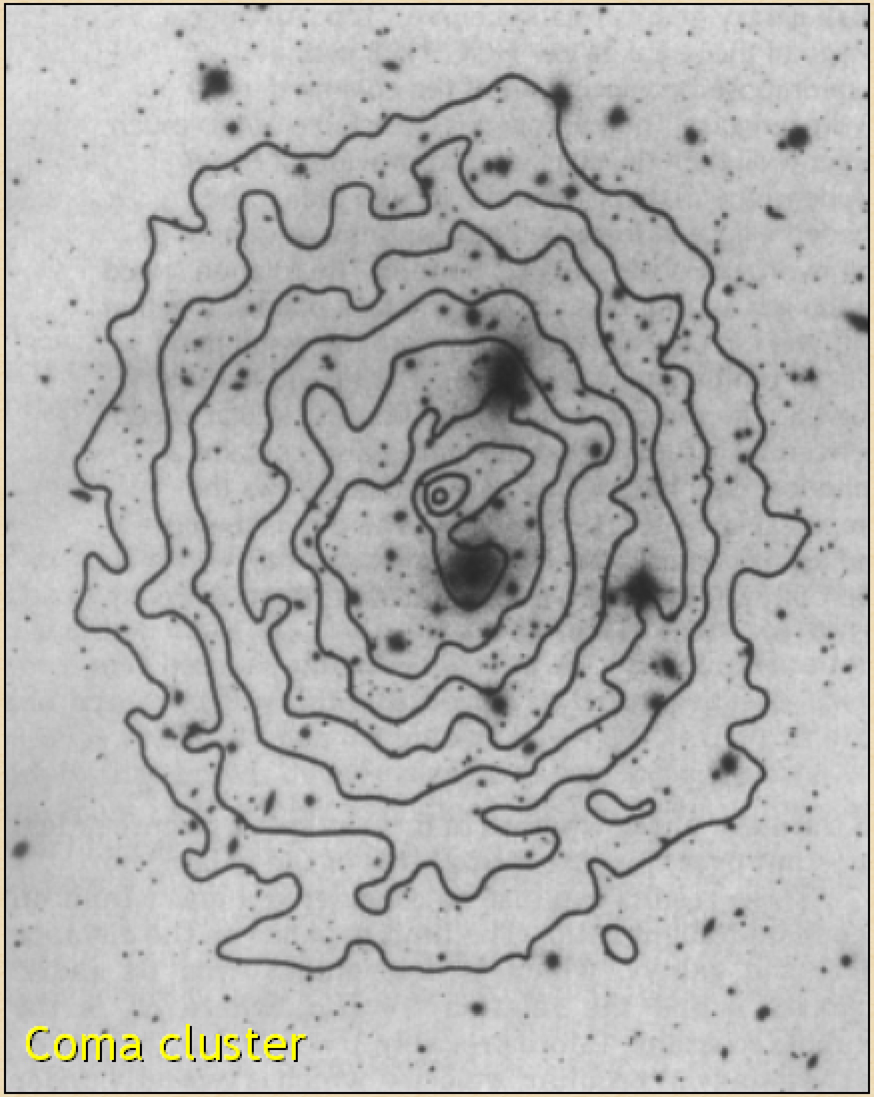
Gravitational Lensing in Clusters of Galaxies

Galaxy cluster Cl 0024+1654
[Hubble Space Telescope]

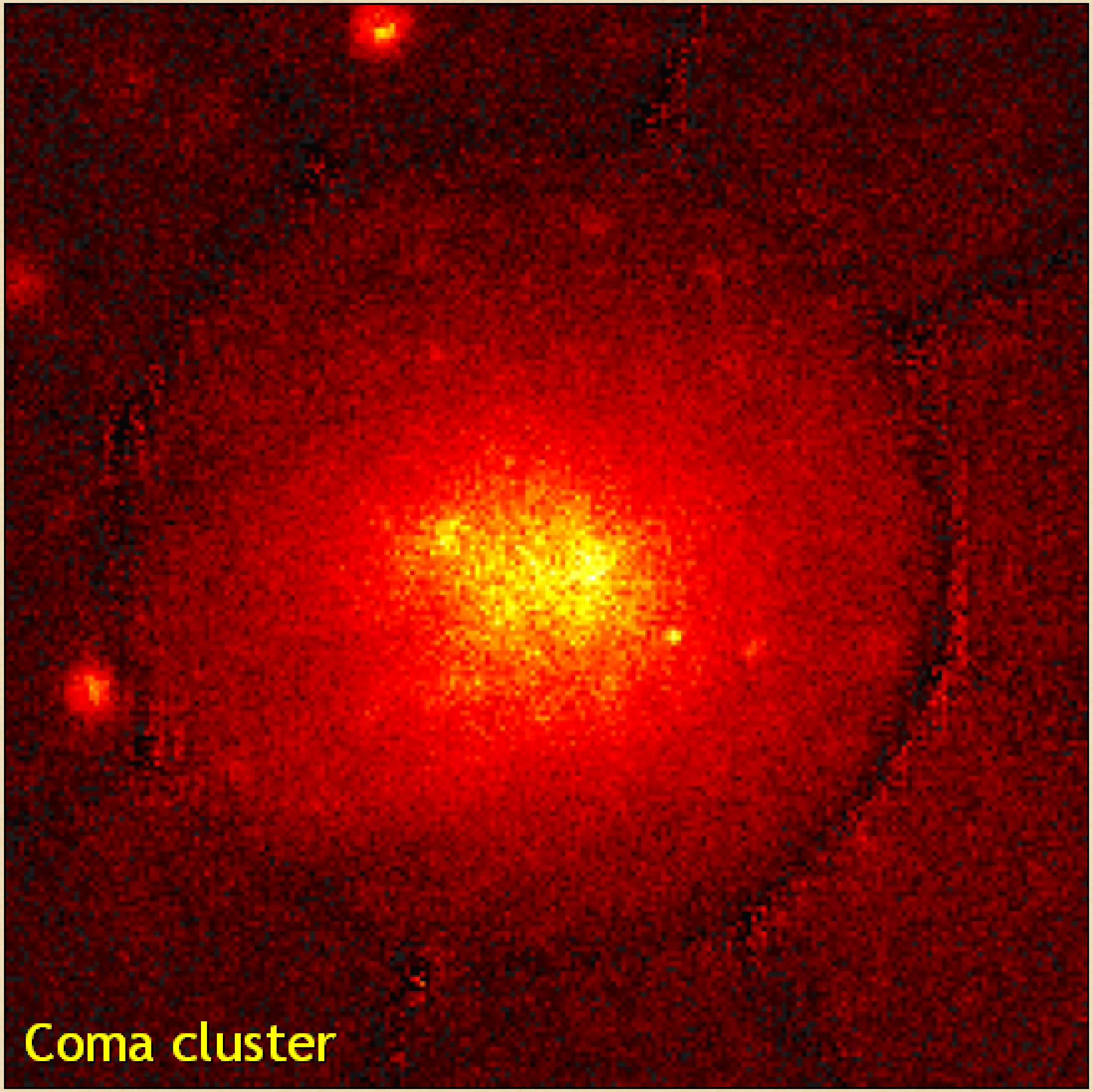


Numerical Simulation

X-Ray Emission from Galaxy Clusters

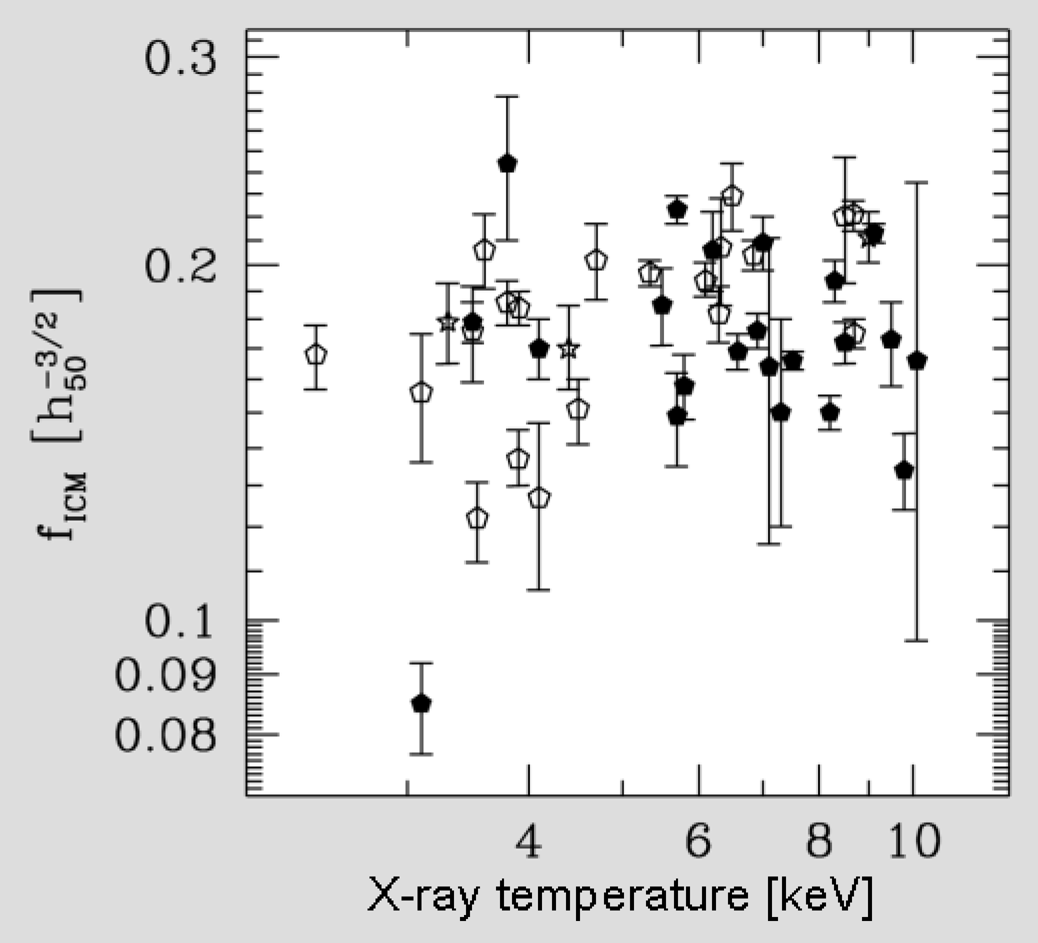


Contours of x-ray emission (Einstein satellite)



ROSAT x-ray image

Cluster Gas Fraction



Mohr et al., astro-ph/9901281

Gas fraction in clusters

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

- 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

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

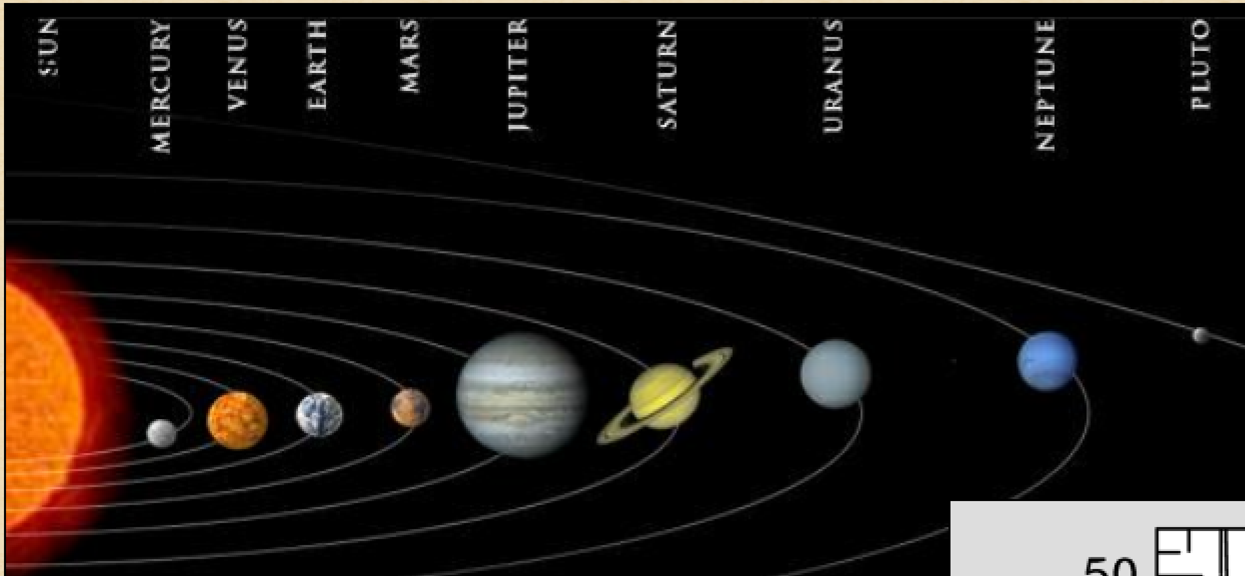
(Fabian, astro-ph/0304020)

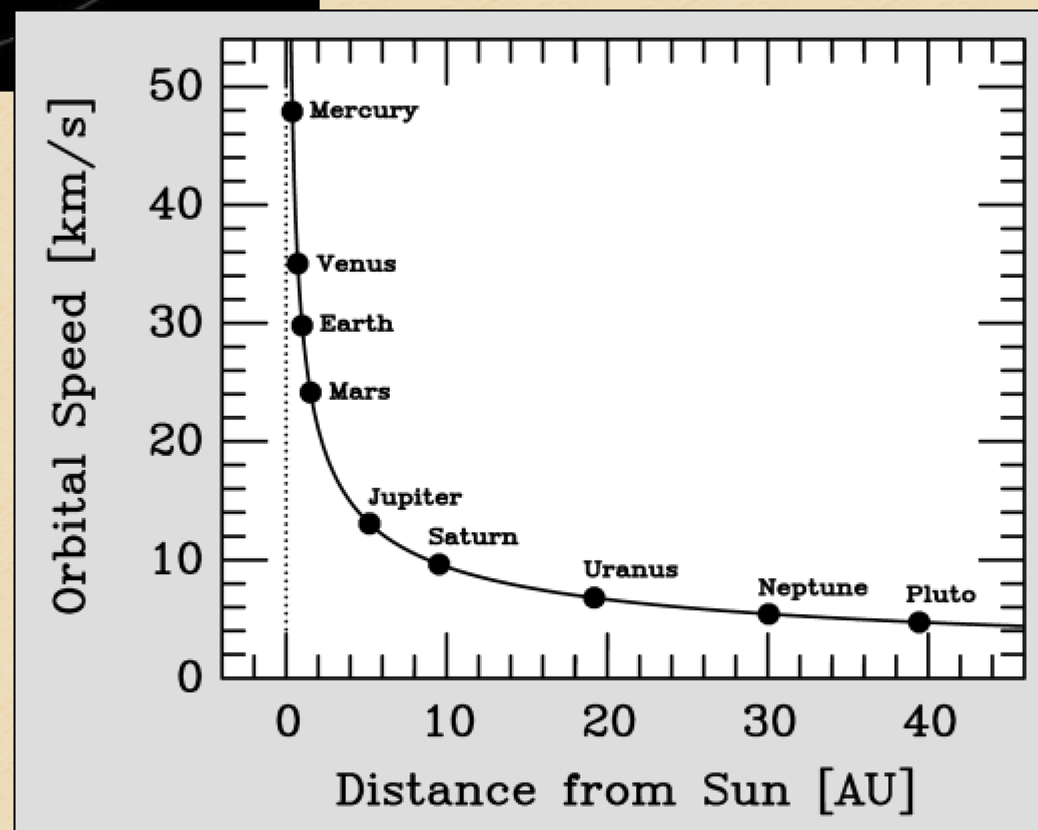
Structure of Spiral Galaxies

Spiral Galaxy NGC 2997

Spiral Galaxy NGC 891

"Rotation Curve" of the Solar System

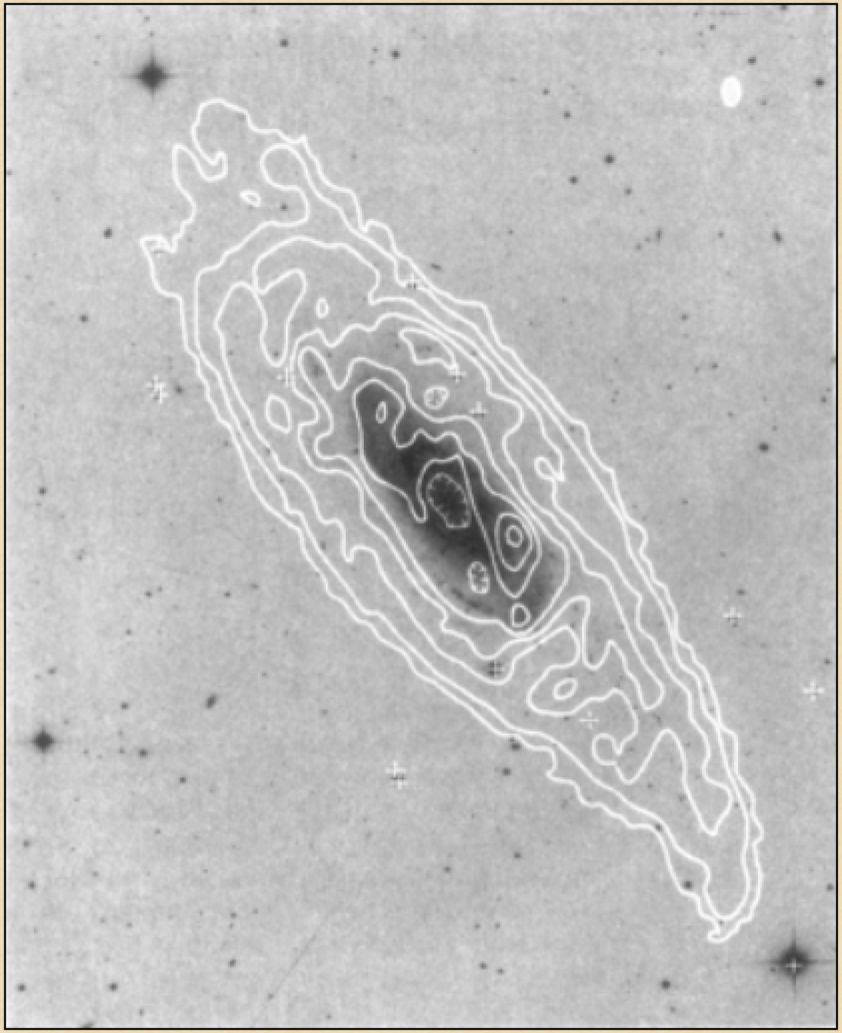




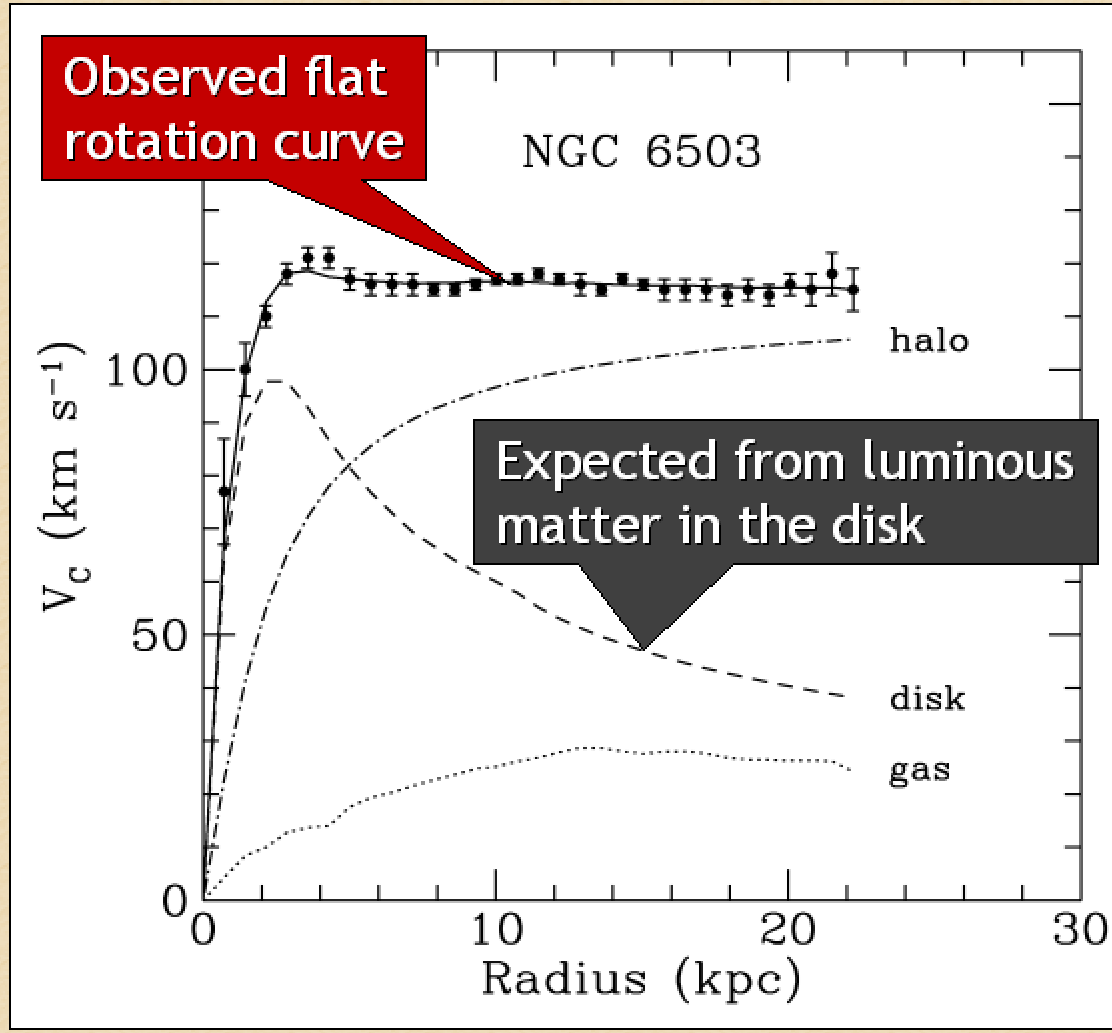
Kepler's Law

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

Galactic Rotation Curve from Radio Observations

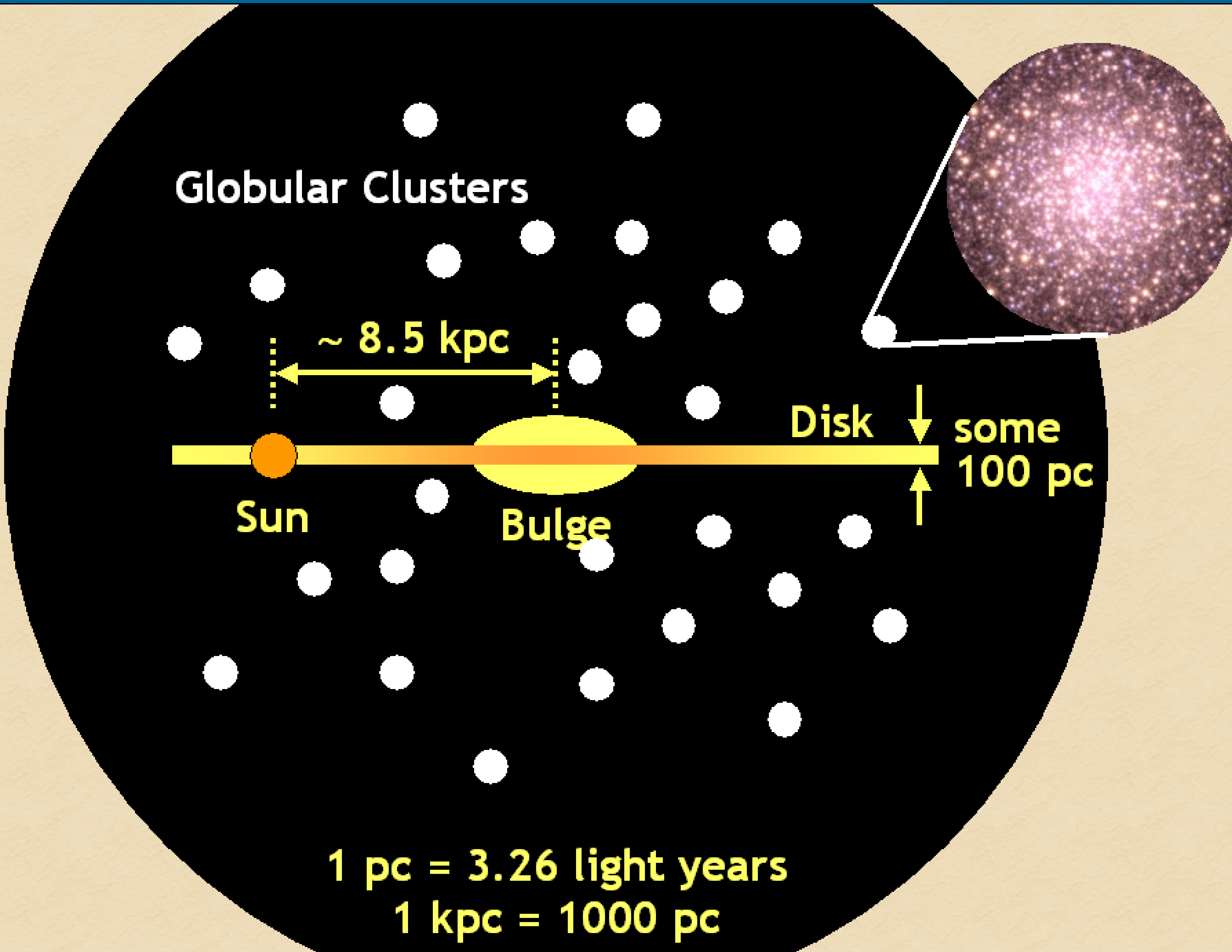


Spiral galaxy NGC 3198 overlaid with hydrogen column density [ApJ 295 (1985) 305]

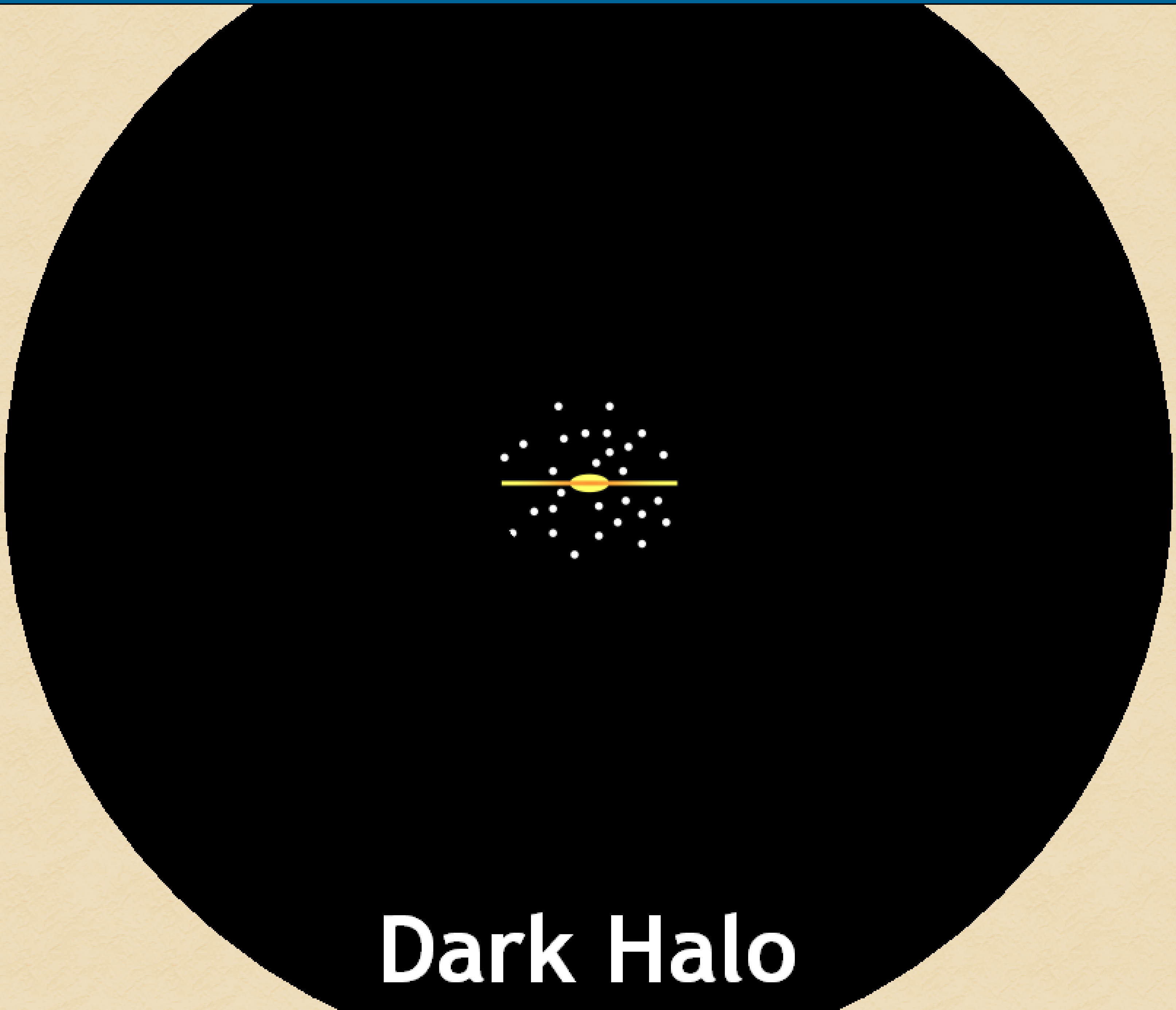


Rotation curve of the galaxy NGC 6503 from radio observations of hydrogen motion [MNRAS 249 (1991) 523]

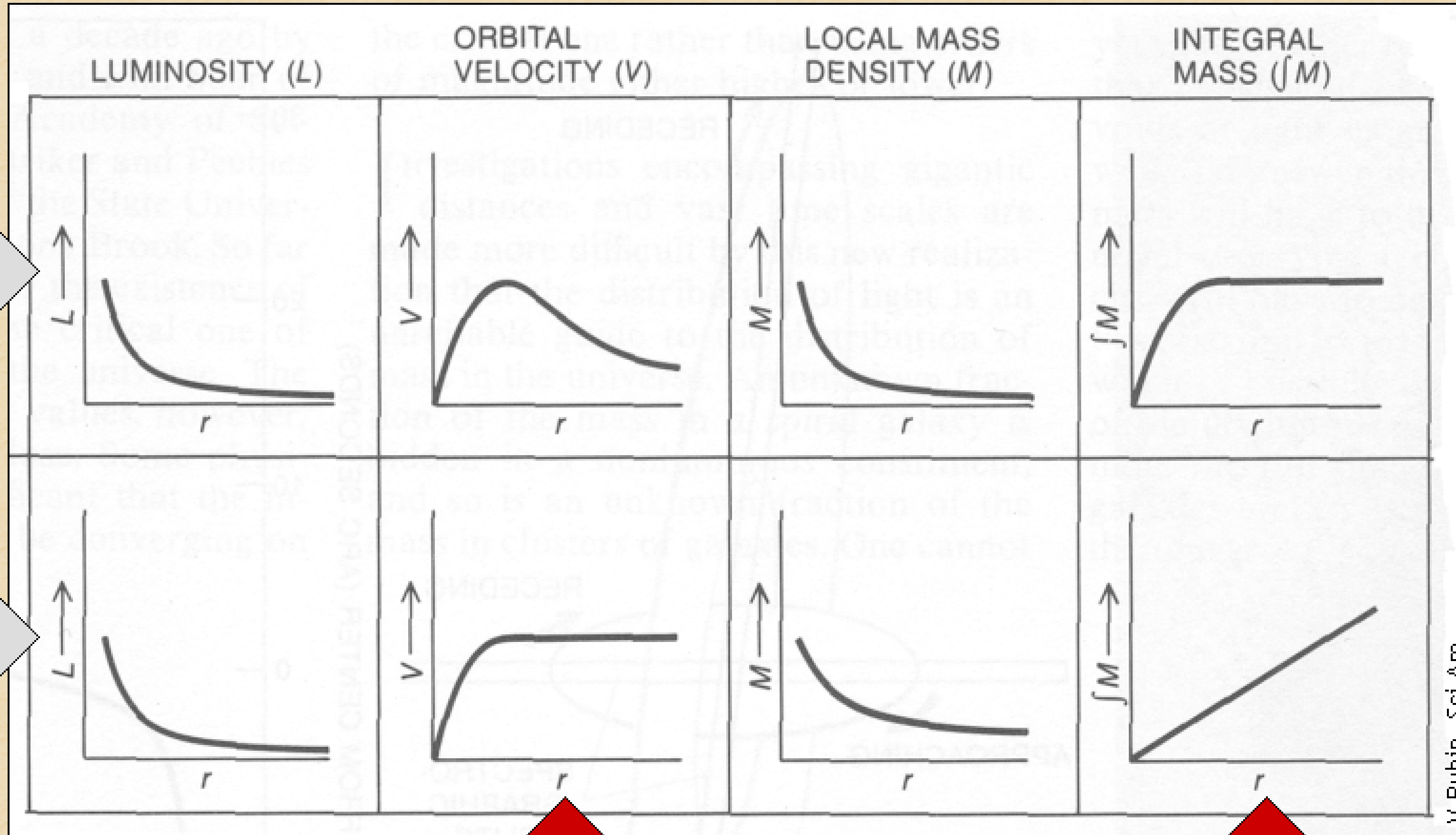
Structure of a Spiral Galaxy



Structure of a Spiral Galaxy



Dark Matter in Spiral Galaxies - Summary



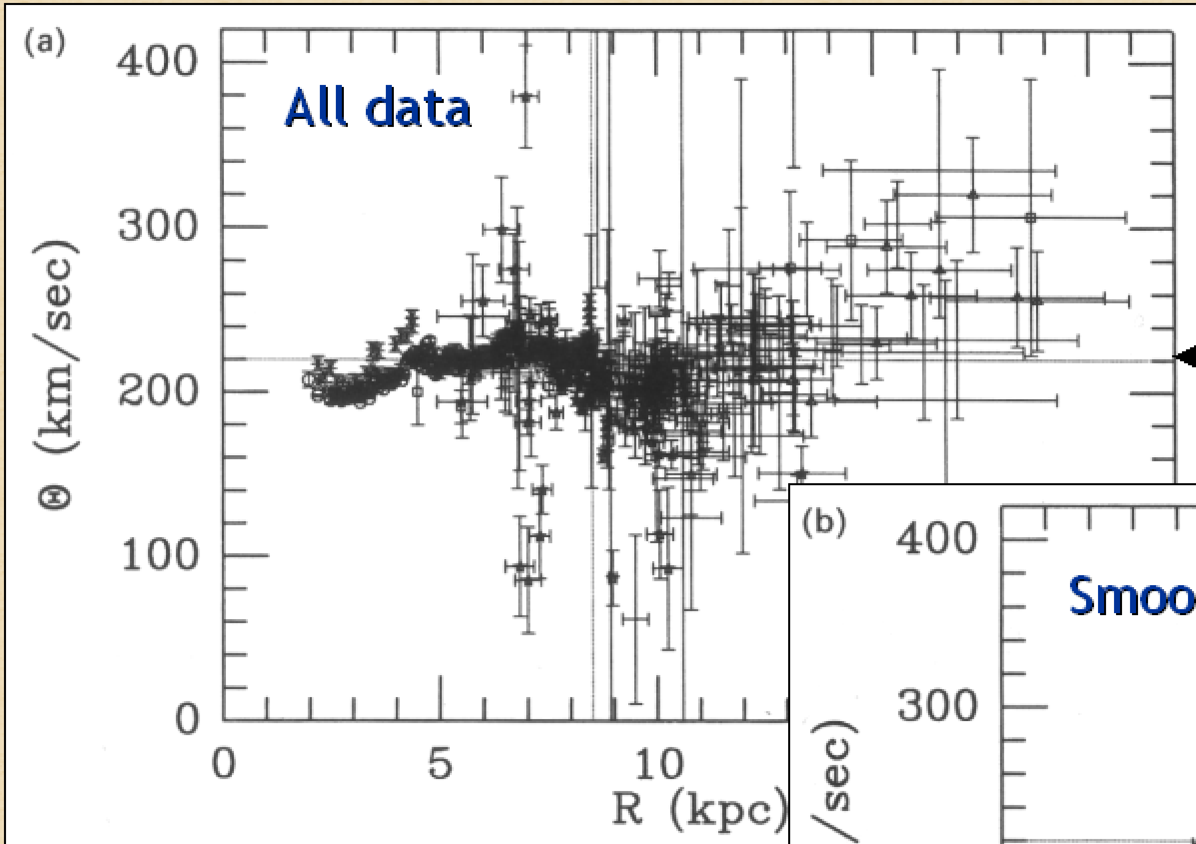
Expected from luminosity distribution

Infered from rotation curve

Flat rotation curve instead of Keplerian

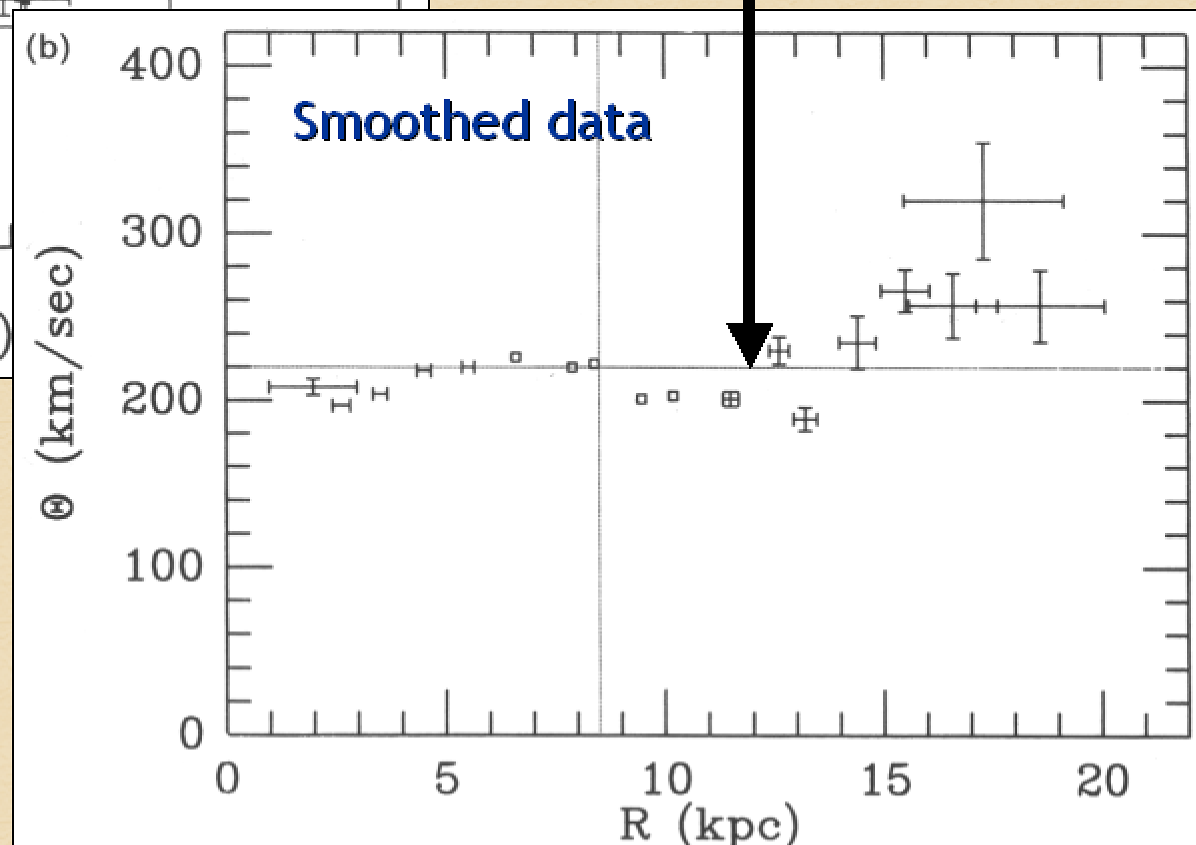
No obvious limit to total mass

Rotation Curve of the Milky Way



Finch & Tremaine
ARAA 29 (1991) 409

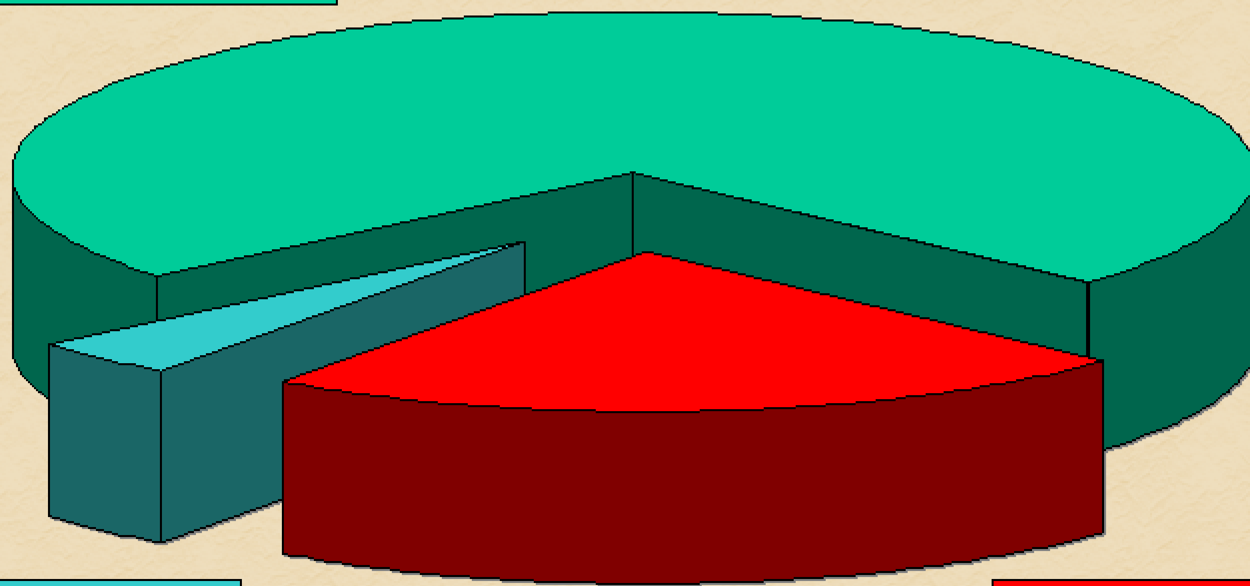
$v_{rot} \approx 220$ km/s



Expect dark matter density near solar system of about 300 MeV cm^{-3}

Mass-Energy-Inventory of the Universe

Dark energy 73%
(Cosmological constant)



Baryonic matter 4%
(only 10% of this is
luminous)

Dark matter
23%

Cosmological Limit on Neutrino Masses

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

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

m_ν < 40 eV For all stable flavors

REST MASS OF MUONIC NEUTRINO AND COSMOLOGY

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

Low-accuracy experimental estimates of the rest mass of the neutrino [1] yield $m(\nu_e) < 200\ \mathrm{eV}/c^2$ for the electronic neutrino and $m(\nu_\mu) < 2.5 \times 10^6\ \mathrm{eV}/c^2$ 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-Mparsec $= (13 \times 10^9\ \text{years})^{-1}$. It follows therefore that the density of all types of matter in the Universe is at the present time [1)]

$$\rho < 2 \times 10^{-28}\ \mathrm{g/cm^3}.$$

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

Weakly Interacting Particles as Dark Matter

THE ASTROPHYSICAL JOURNAL, 180: 7–10, 1973 February 15

GRAVITY OF NEUTRINOS OF NONZERO MASS IN ASTROPHYSICS

R. COWSIK* 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 virial 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 (Kuchowicz 1969). A recent discussion of such a possibility has been in the context of the solar-neutrino experiments (Bahcall, Cabibbo, and Yahil 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 ~1 MeV, several processes of neutrino production (Ruderman 1969) would have led to copious production of neutrinos and antineutrinos (Steigman 1972; Cowsik and McClelland 1972). Conditions of thermal equilibrium allow an easy estimate of their number densities (Landau and Lifshitz 1969):

$$n_{\nu i} = \frac{1}{\pi^2 \hbar^3} \int_0^\infty \frac{p^2 dp}{\exp\,[E/kT(z_{eq})] + 1} \,. \qquad (1)$$

Here $n_{\nu i}$ = number density of neutrinos of the ith 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); $E = c(p^2 + m^2c^2)^{1/2}$; k = Boltzmann's constant; $T(z_{eq}) = T_r(z_{eq}) = T_\nu(z_{eq}) = T_e(z_{eq}) \cdots =$ the common temperature of radiation, neutrinos, electrons, etc., at the latest epoch characterized by redshift z_{eq} when they may be assumed to have been in thermal equilibrium; $kT(z_{eq}) \simeq 1$ MeV.

Since the masses of the neutrinos are expected to be small, $kT(z_{eq}) \gg m_{\nu i}c^2$, in the extreme-relativistic limit equation (1) reduces to

$$n_{\nu i}(z_{eq}) \simeq 0.183[T(z_{eq})/hc]^3 \,. \qquad (2)$$

As the Universe expands, only the neutrinos (in contrast to all other known particles) survive annihilation because of extremely low cross-sections (deGraff and Tolhock 1966), and their number density decreases with increasing volume of the Universe, simply as $\sim V(z_{eq})/V(z) = [(1 + z)/(1 + z_{eq})]^3$. Noting that $(1 + z_{eq})/(1 + z) = T_r(z_{eq})/T_r(z)$, the number density at the present epoch ($z = 0$) is given by

$$n_{\nu i}(0) = n_{\nu i}(z_{eq})/(1 + z_{eq})^3 \simeq 0.183[T_r(0)/hc]^3 \simeq 300 \text{ cm}^{-3} \,, \qquad (3)$$

* 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

What is wrong with neutrino dark matter?

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

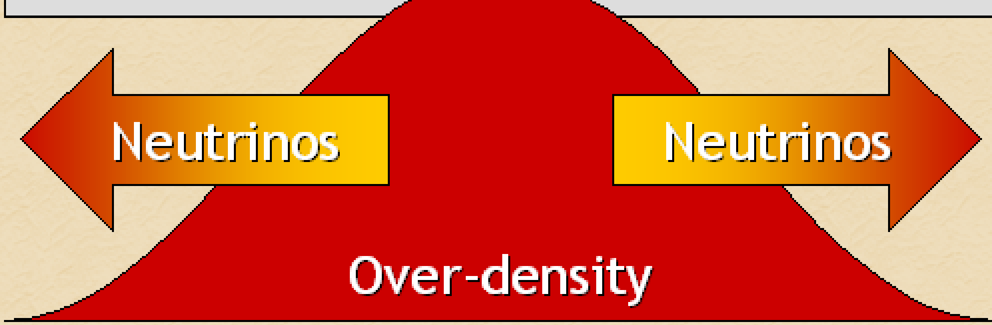
Maximum mass density of a degenerate Fermi gas

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

$m_\nu > 20 - 40$ eV	Spiral galaxies
$m_\nu > 100 - 200$ eV	Dwarf galaxies

Neutrino Free Streaming (Collisionless Phase Mixing)

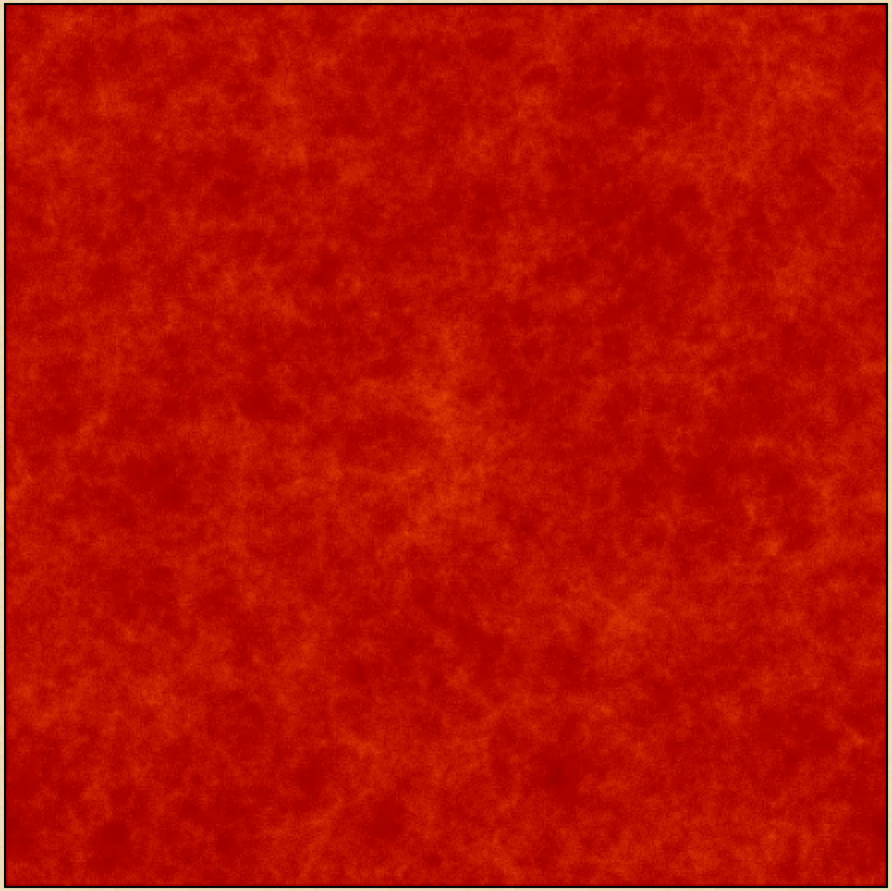
- At $T < 1$ MeV neutrino scattering in early universe ineffective
- Stream freely until non-relativistic
- Wash out density contrasts on small scales

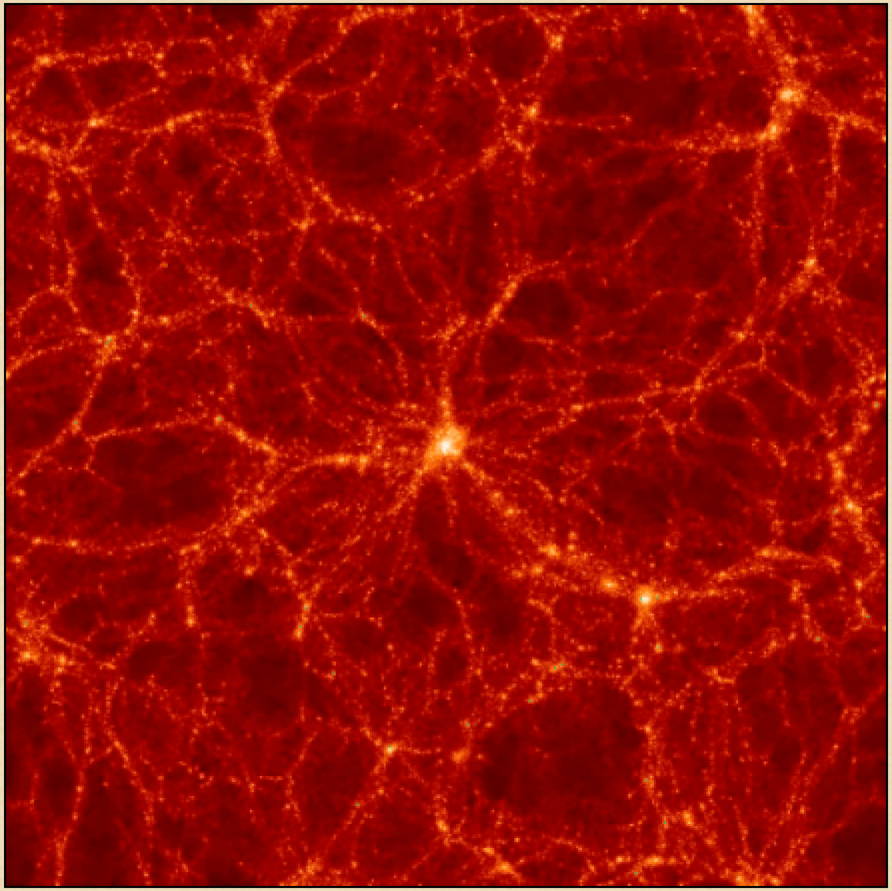


- Nus are "Hot Dark Matter"
- Ruled out
  by structure formation

Formation of Structure

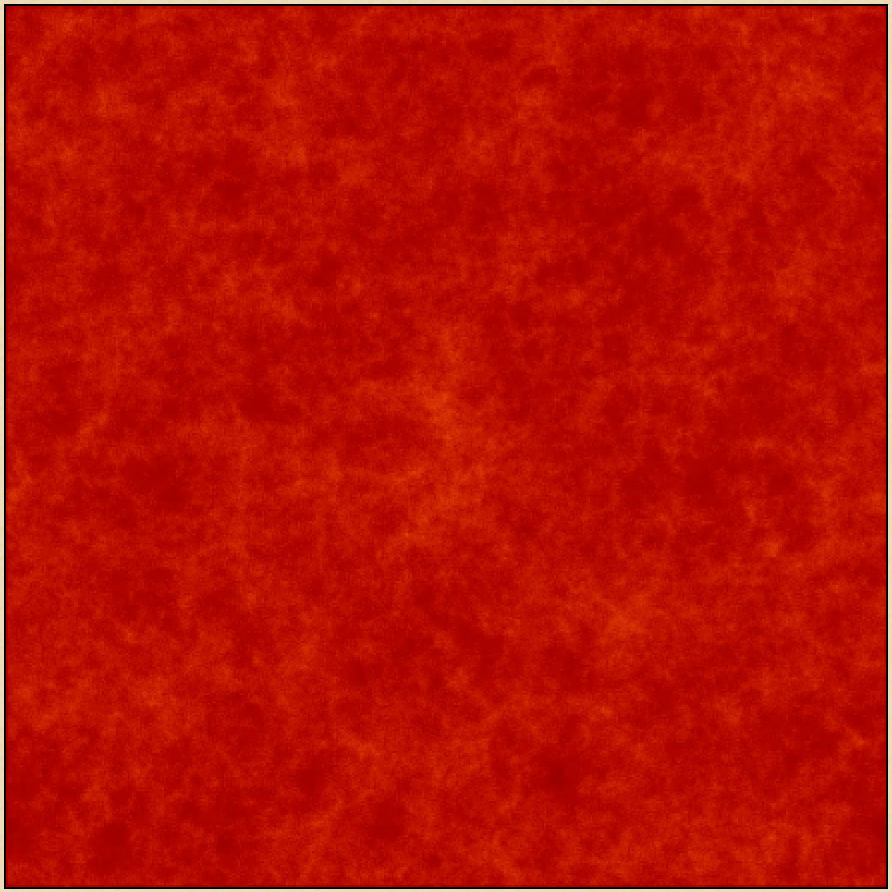
Smooth → Structured



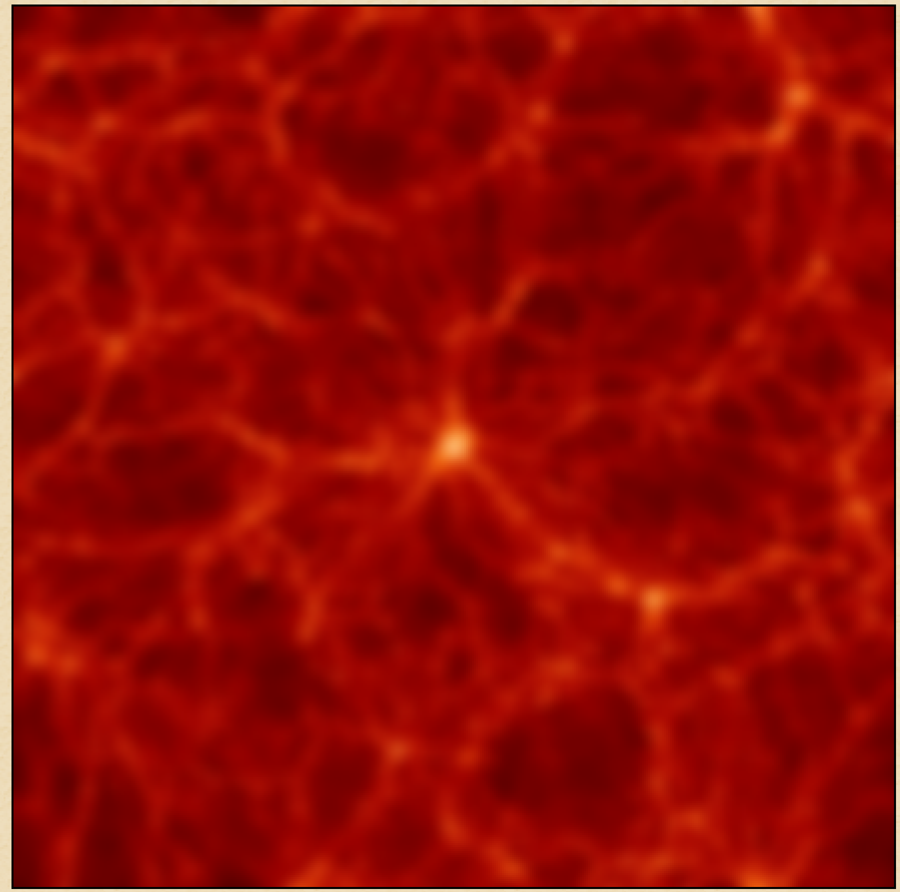


Formation of Structure

Smooth



Structured

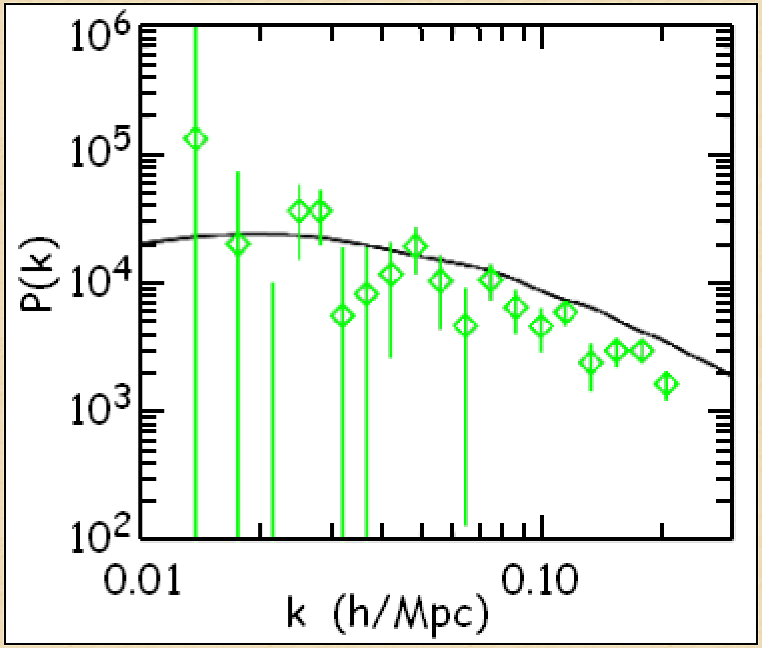


A fraction of hot dark matter suppresses small-scale structure

Cosmic Structure Modified by Hot Dark Matter

Galaxy Distribution (2dF, PSCz)

Scales 1–200 Mpc



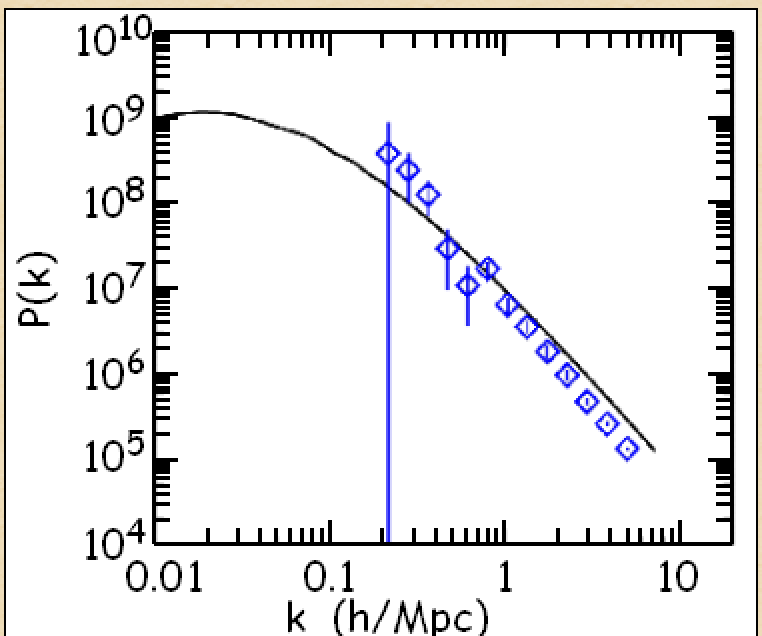
$\Omega_0 = 1$
$\Omega_\Lambda = 0.66$
$\Omega_B = 0.04$
$H_0 = 72$
$n_S = 0.94$

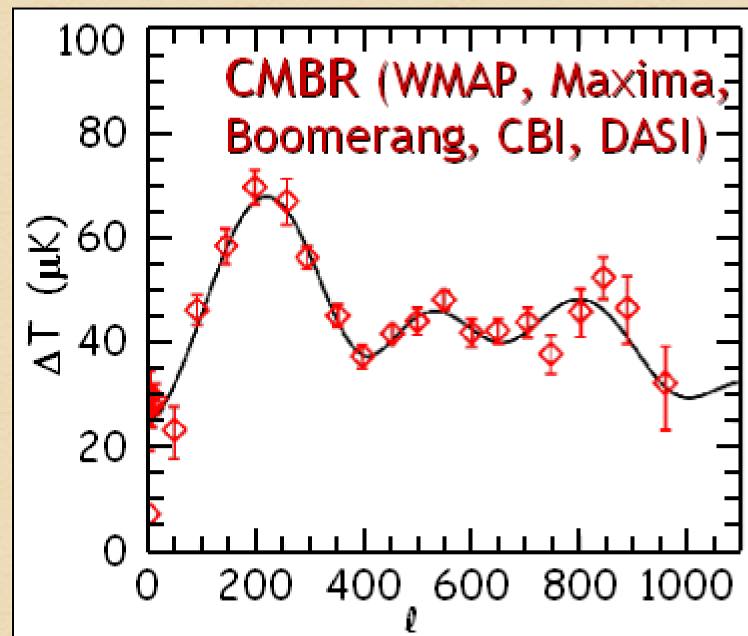
Adapted from S.Hannestad

$\Omega_\nu = 0.00$

Lyman-a forest at large redshift $\langle z \rangle = 2.72$

Scales 0.1–10 Mpc

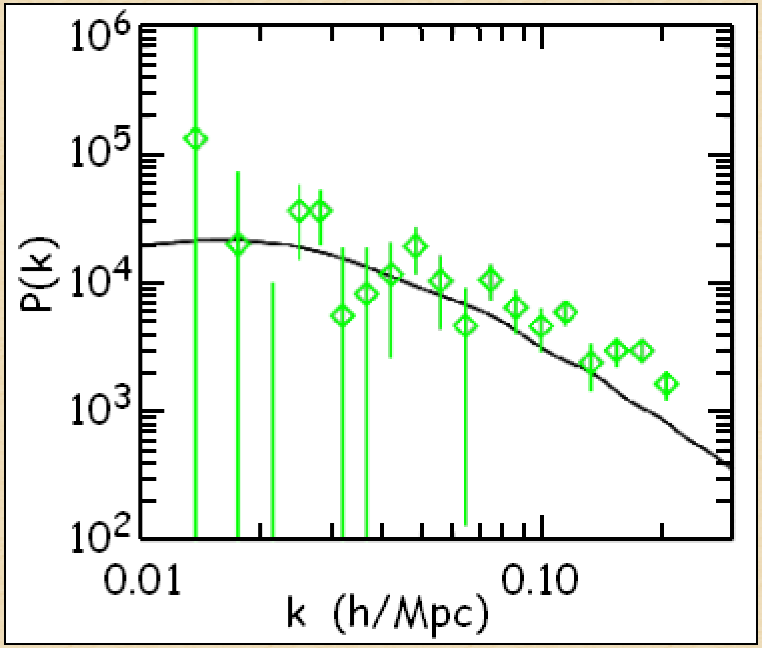




Cosmic Structure Modified by Hot Dark Matter

Galaxy Distribution (2dF, PSCz)

Scales 1–200 Mpc



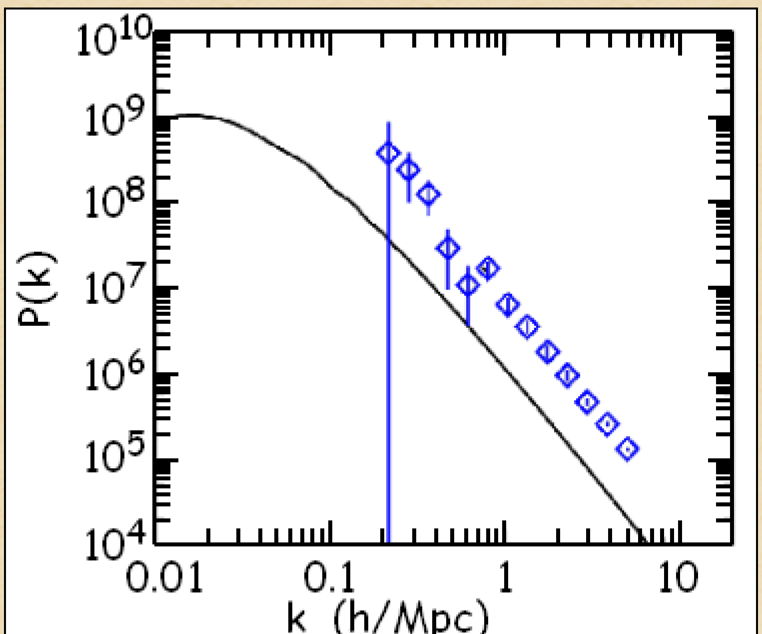
$\Omega_0 = 1$
$\Omega_\Lambda = 0.66$
$\Omega_B = 0.04$
$H_0 = 72$
$n_s = 0.94$

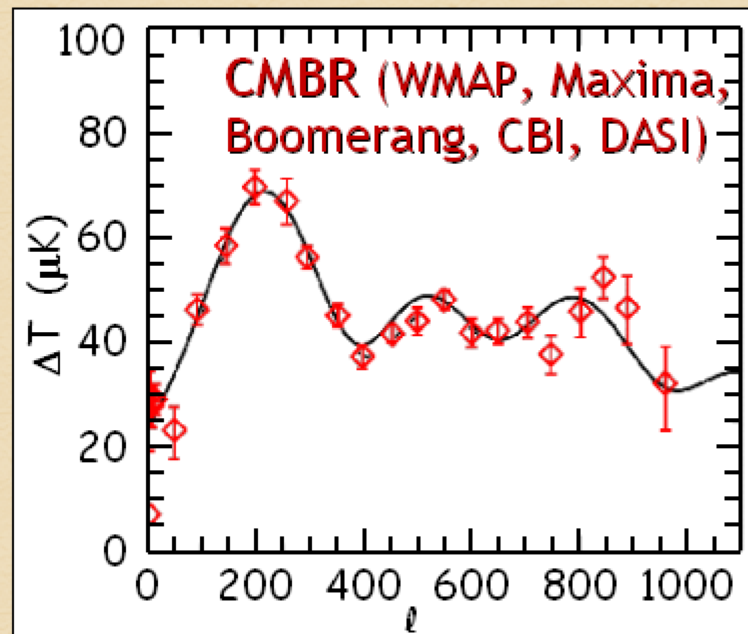
$\Omega_\nu = 0.05$

Adapted from S.Hannestad

Lyman-a forest at large redshift $\langle z \rangle = 2.72$

Scales 0.1–10 Mpc

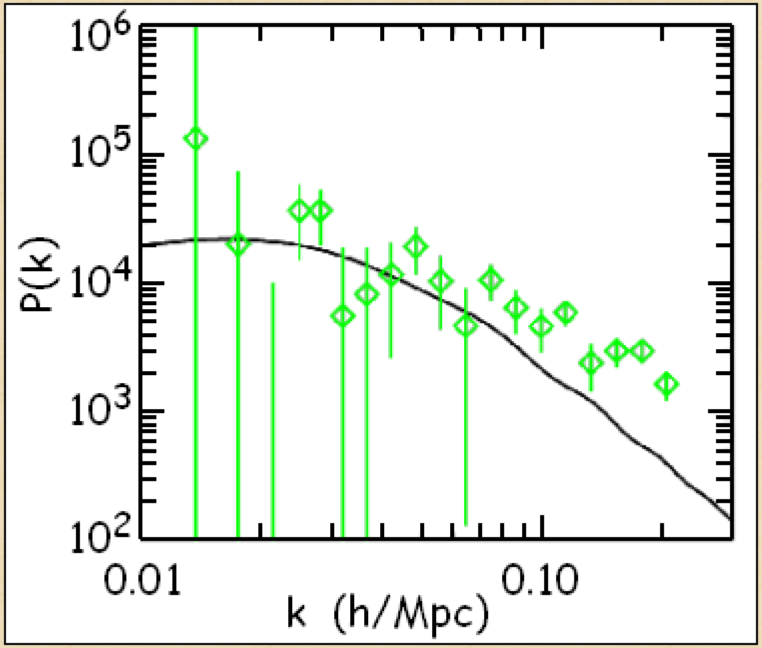




Cosmic Structure Modified by Hot Dark Matter

Galaxy Distribution (2dF, PSCz)

Scales 1–200 Mpc



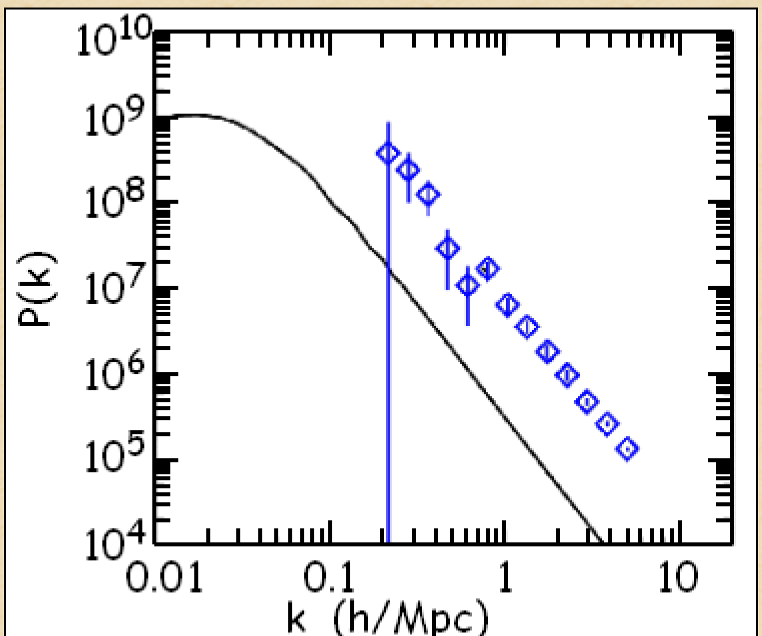
$\Omega_0 = 1$
$\Omega_\Lambda = 0.66$
$\Omega_B = 0.04$
$H_0 = 72$
$n_s = 0.94$

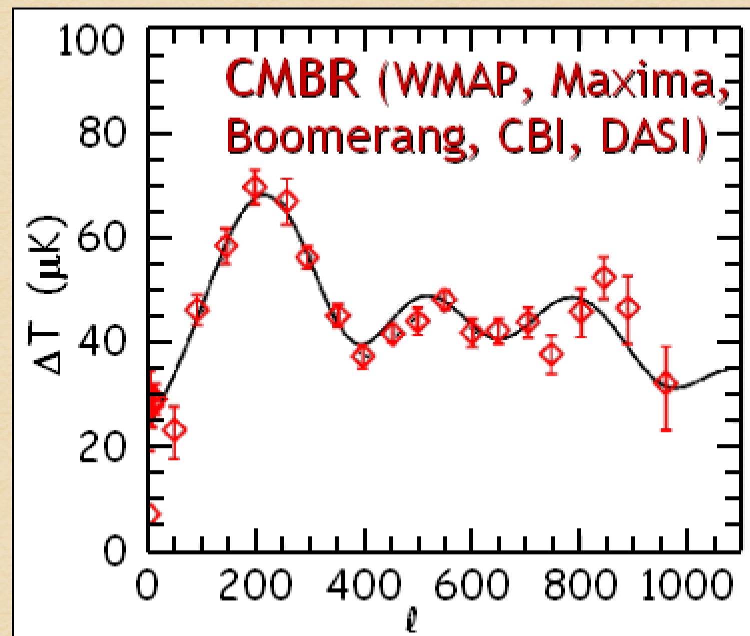
$\Omega_\nu = 0.10$

Adapted from S.Hannestad

Lyman-a forest at large redshift $\langle z \rangle = 2.72$

Scales 0.1–10 Mpc

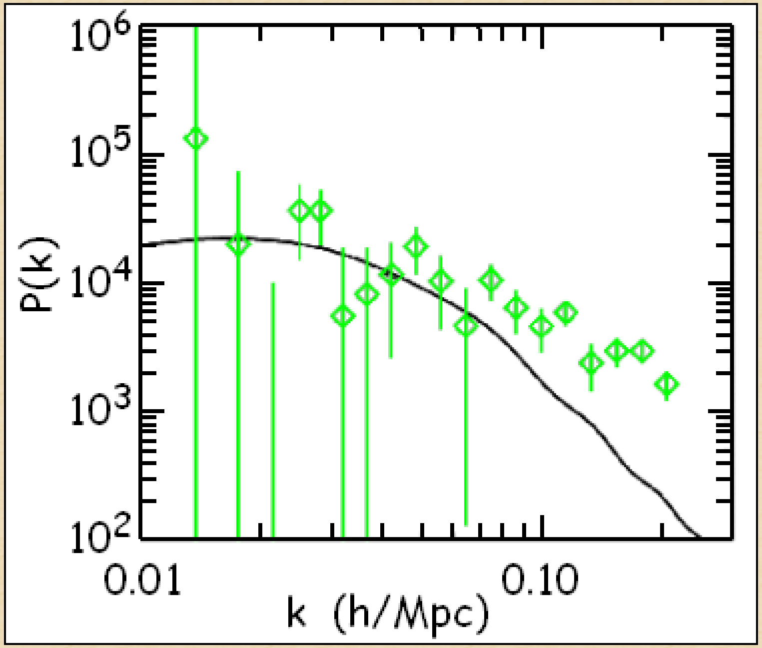




Cosmic Structure Modified by Hot Dark Matter

Galaxy Distribution (2dF, PSCz)

Scales 1–200 Mpc



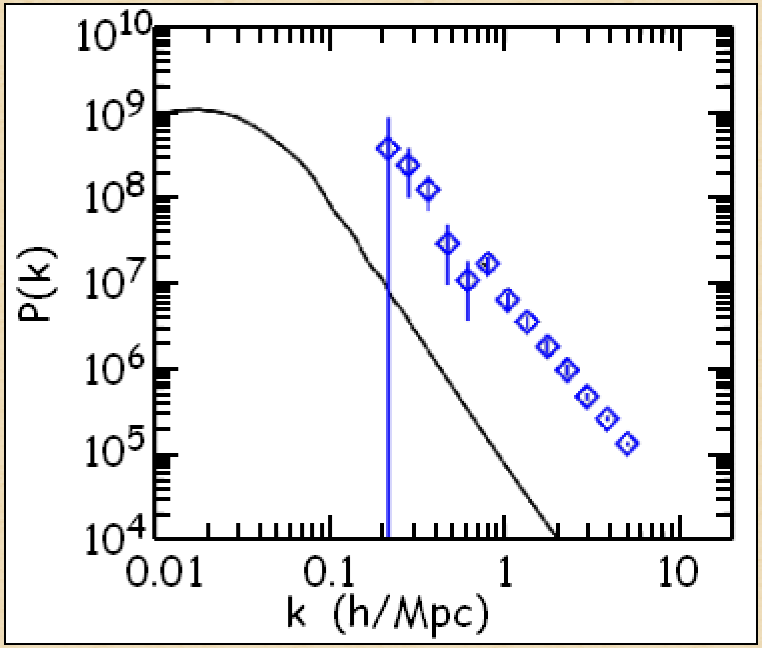
$\Omega_0 = 1$
$\Omega_\Lambda = 0.66$
$\Omega_B = 0.04$
$H_0 = 72$
$n_s = 0.94$

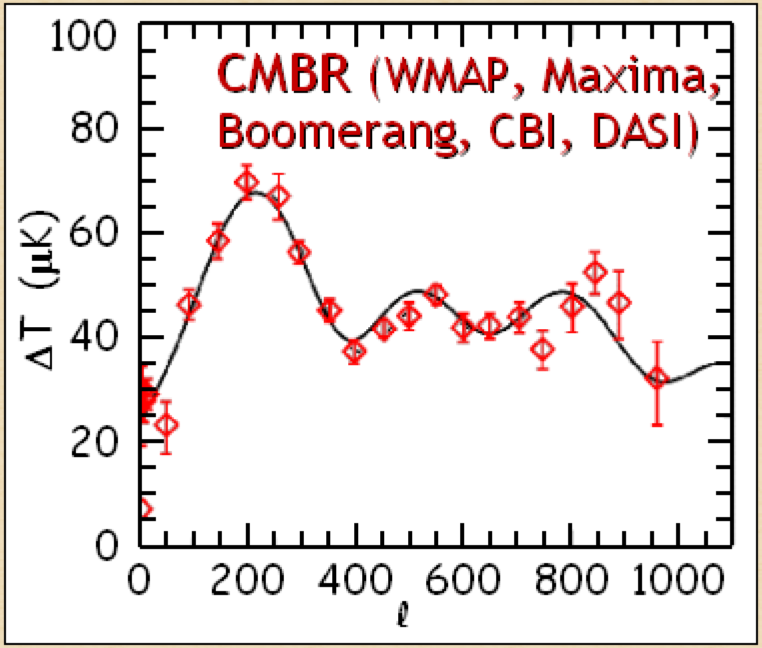
$\Omega_\nu = 0.15$

Adapted from S.Hannestad

Lyman-a forest at large redshift $\langle z \rangle = 2.72$

Scales 0.1–10 Mpc





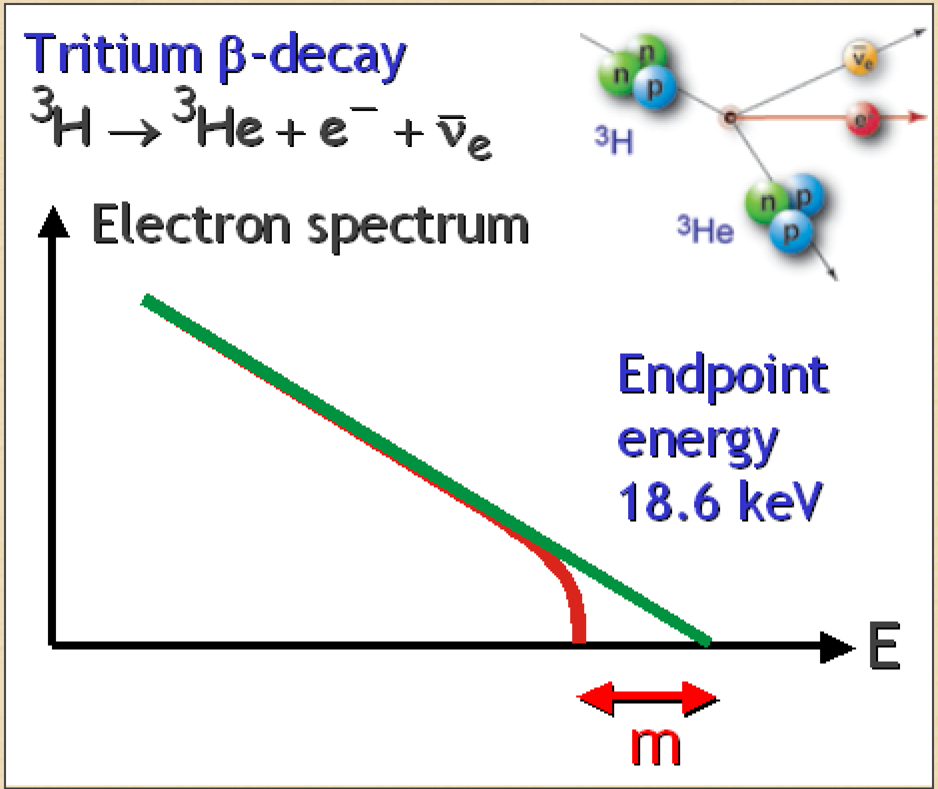
Neutrino Mass Limits from Large-Scale Structure

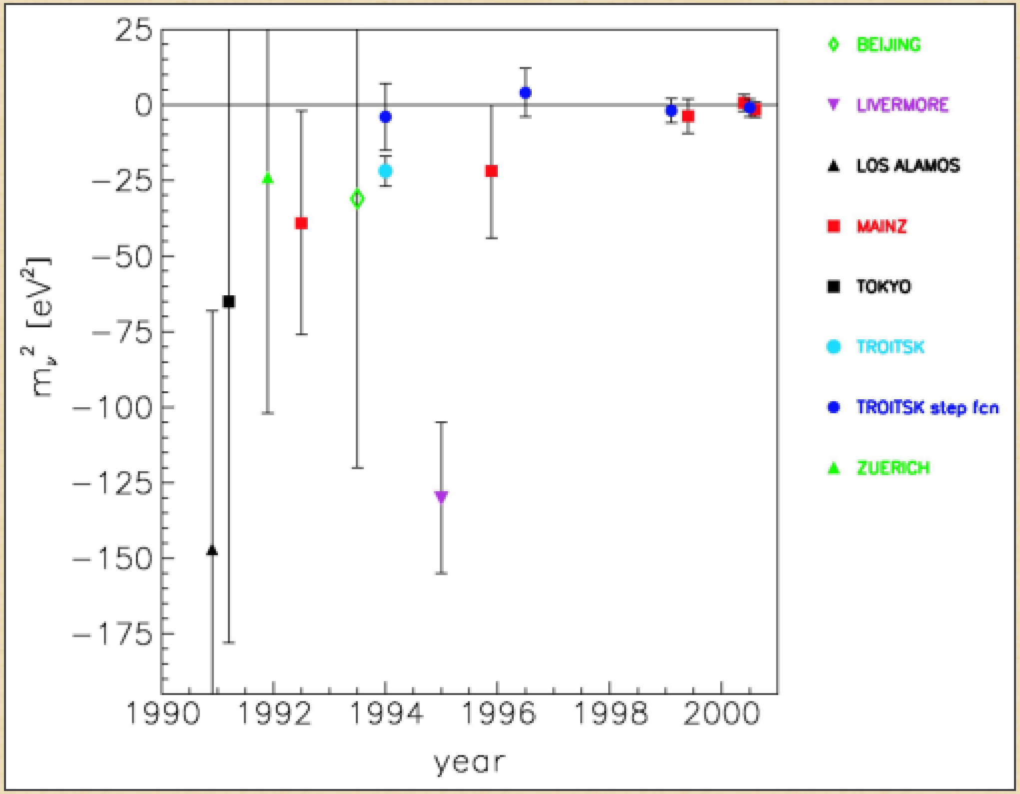
Statistical 95% C.L. limits depend on used data and on priors for other parameters. For detailed analyses see

- Hannestad, astro-ph/0303076
- Elgaroy & Lahav, astro-ph/0303089

$\Sigma m_\nu < 2.1$ eV	2dF (Galaxy-galaxy correlation) + WMAP (Cosmic microwaves)
$\Sigma m_\nu < 1.2$ eV	+ Small-scale CMBR (breaks degeneracy with bias)
$\Sigma m_\nu < 1.0$ eV	+ Priors (1σ) $h = 0.72 \pm 0.08$, $\Omega_M = 0.28 \pm 0.14$

Tritium Endpoint Spectrum





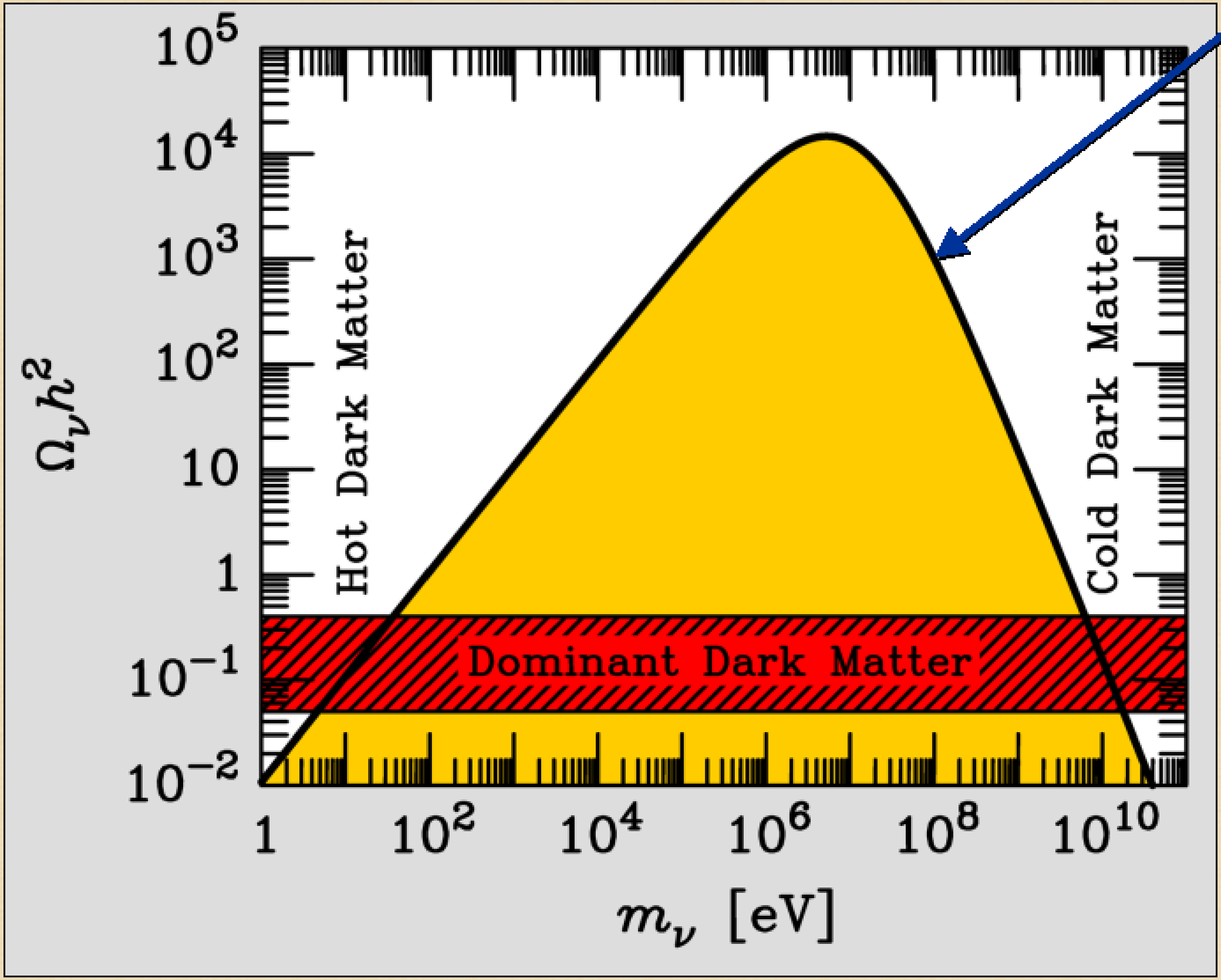
Currently best limits from Mainz and Troitsk experiments

$m < 2.2$ eV (95% CL)

- Scaled-up spectrometer (KATRIN) should reach 0.2 eV
- Currently under construction
- Measurements to begin 2007

http://ik1au1.fzk.de/~katrin

Lee-Weinberg-Curve



- For $m_\nu \gtrsim 1$ MeV neutrinos freeze out nonrelativistically
- Density suppressed by annihilation before freeze-out

Weakly interacting massive particles (WIMPs) possible as cold dark matter

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

- 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

(With permission of David Simmonds ©)

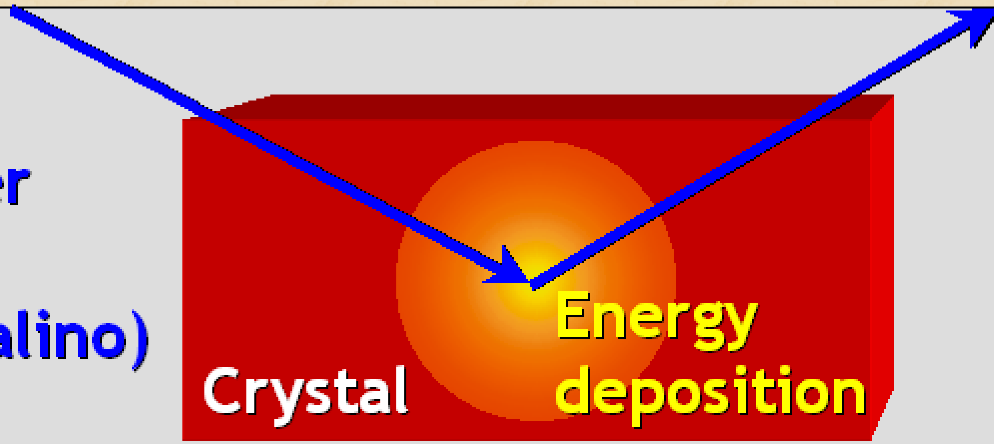
Direct search experiments exist for

- 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)

Search for Neutralino Dark Matter

Direct Method (Laboratory Experiments)

Galactic dark matter particle (e.g.neutralino)



Recoil energy (few keV) is measured by
- Ionisation
- Scintillation
- Cryogenic

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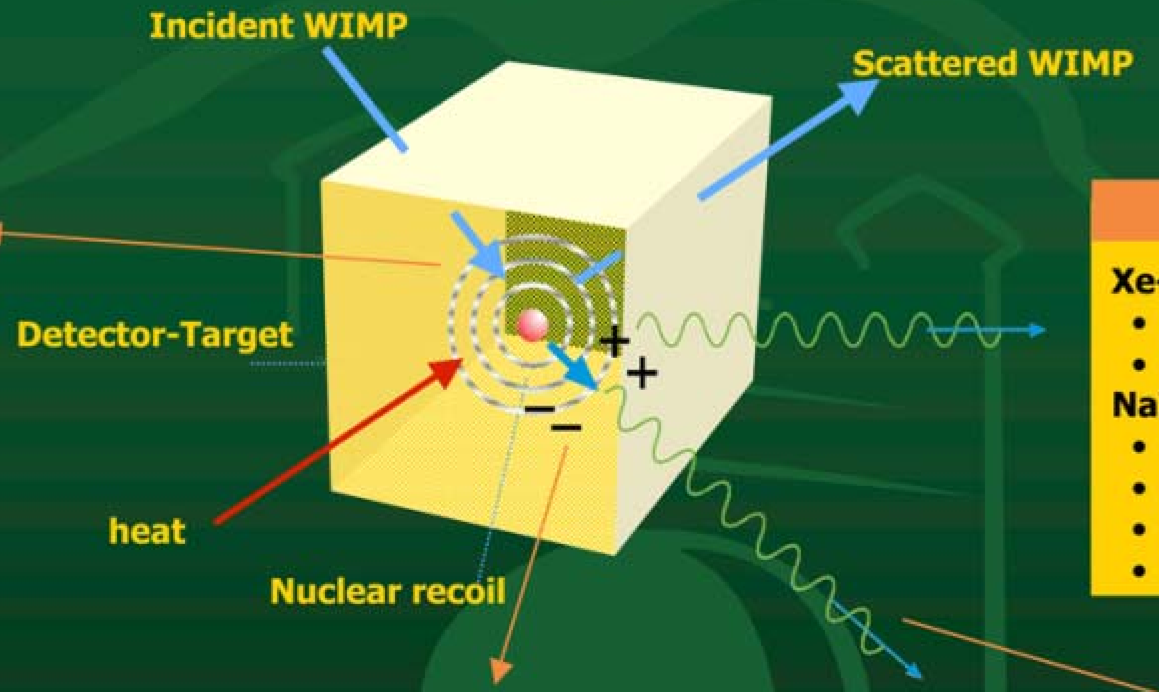
Detectability of certain dark-matter candidates

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 $1-10^2$ GeV; or strongly interacting particles of masses $1-10^{13}$ GeV.

Direct Detection Methods



HEAT

Bolometers:
- MiDBD
- ROSEBUD-I
- CRESST-I
- CUORICINO

Metastable p.det:
- SSD Micrograins
- SDD Droplets

LIGHT

Xe-scintillators:
- DAMA-Xe
- ZEPLIN-I

NaI scintillators:
- NAIAD
- ANAIS
- DAMA, LIBRA
- ELEGANTS

HEAT+CHARGE
- CDMS
- EDELWEISS

CHARGE

Ge-experiments:
- H/M
- IGEX
- GENIUS-TF

Tracking Chambers:
- DRIFT

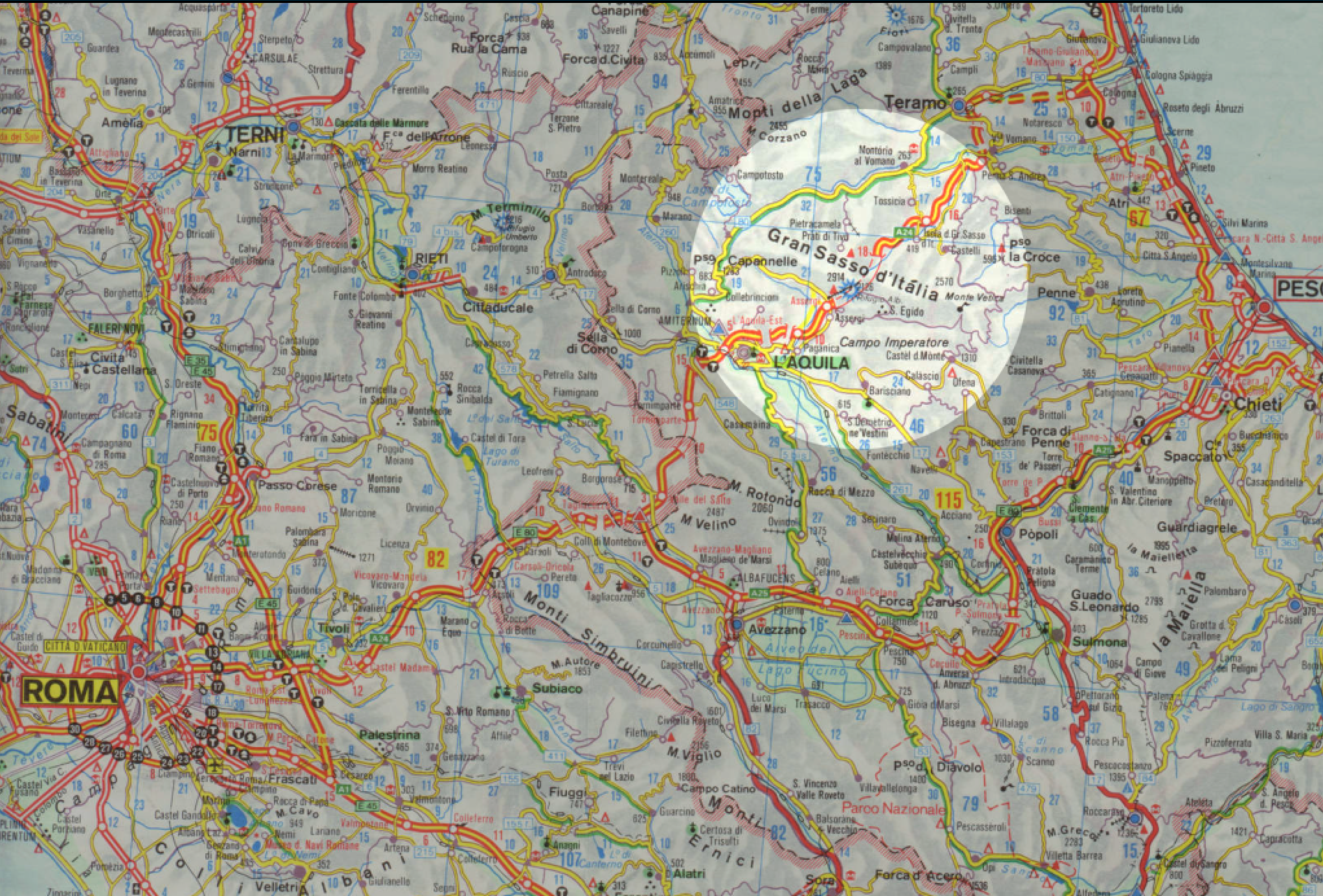
HEAT+LIGHT
- ROSEBUD-II
- CRESST-II

LIGHT+CHARGE
- ZEPLIN-II
- X-MASS

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

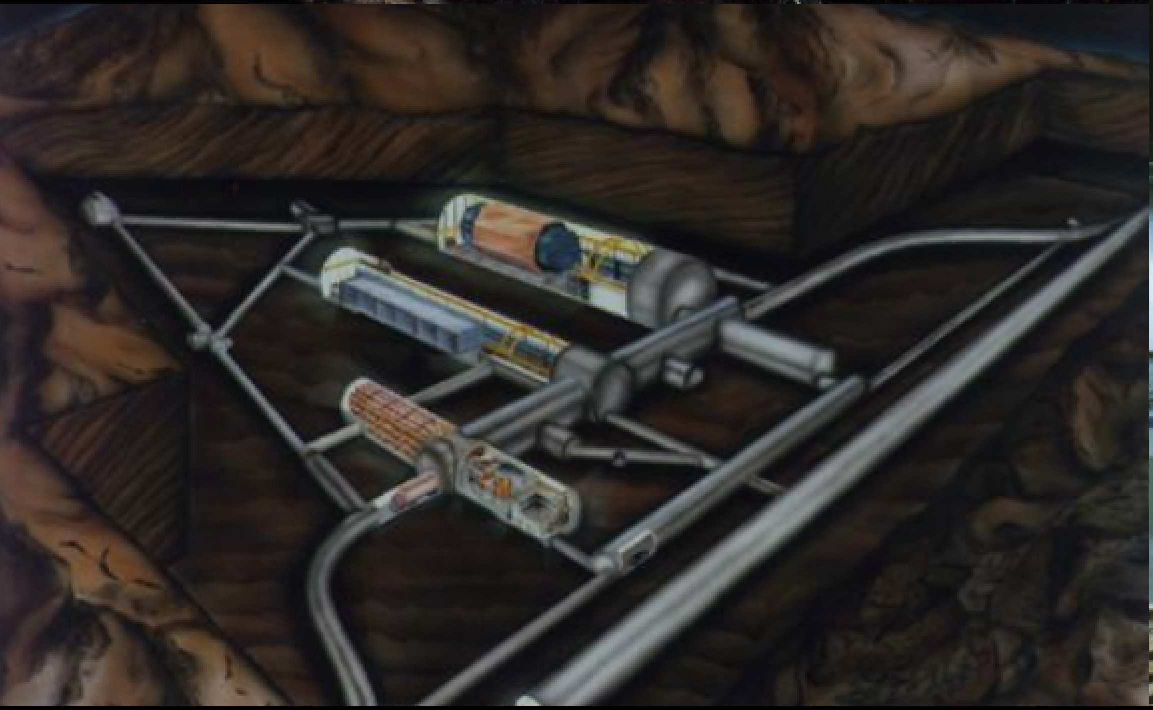
LABORATORY	EXPERIMENT	TECHNIQUE
Bern (Switzerland)	ORPHEUS	(SSD) Tin Superconducting Superheated Detector
Boulby (UK)	NAIAD ZEPLIN I ZEPLIN II DRIFT	NaI scintillators (46-65 Kg) Liquid Xe scintillator (4 Kg) Liquid-Gas Xe (scintillation/ionization) (30 Kg) (R+D) Low pressure Xe TPC $1m^3$ (R+D)
Canfranc (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)
Frejus/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 CUORICINO 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

CRESST Experiment in the Gran Sasso Laboratory

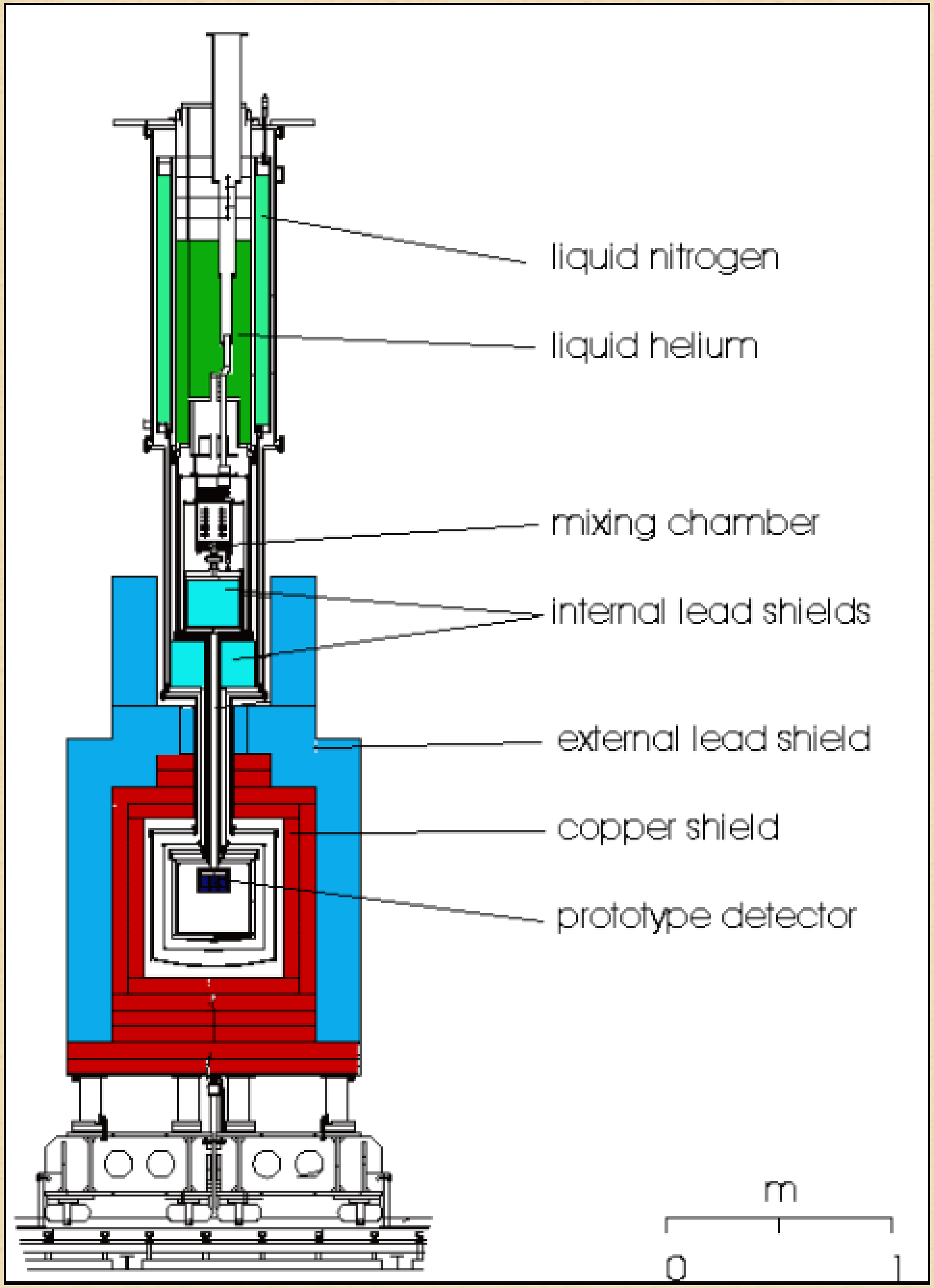


CRESST Experiment in the Gran Sasso Laboratory

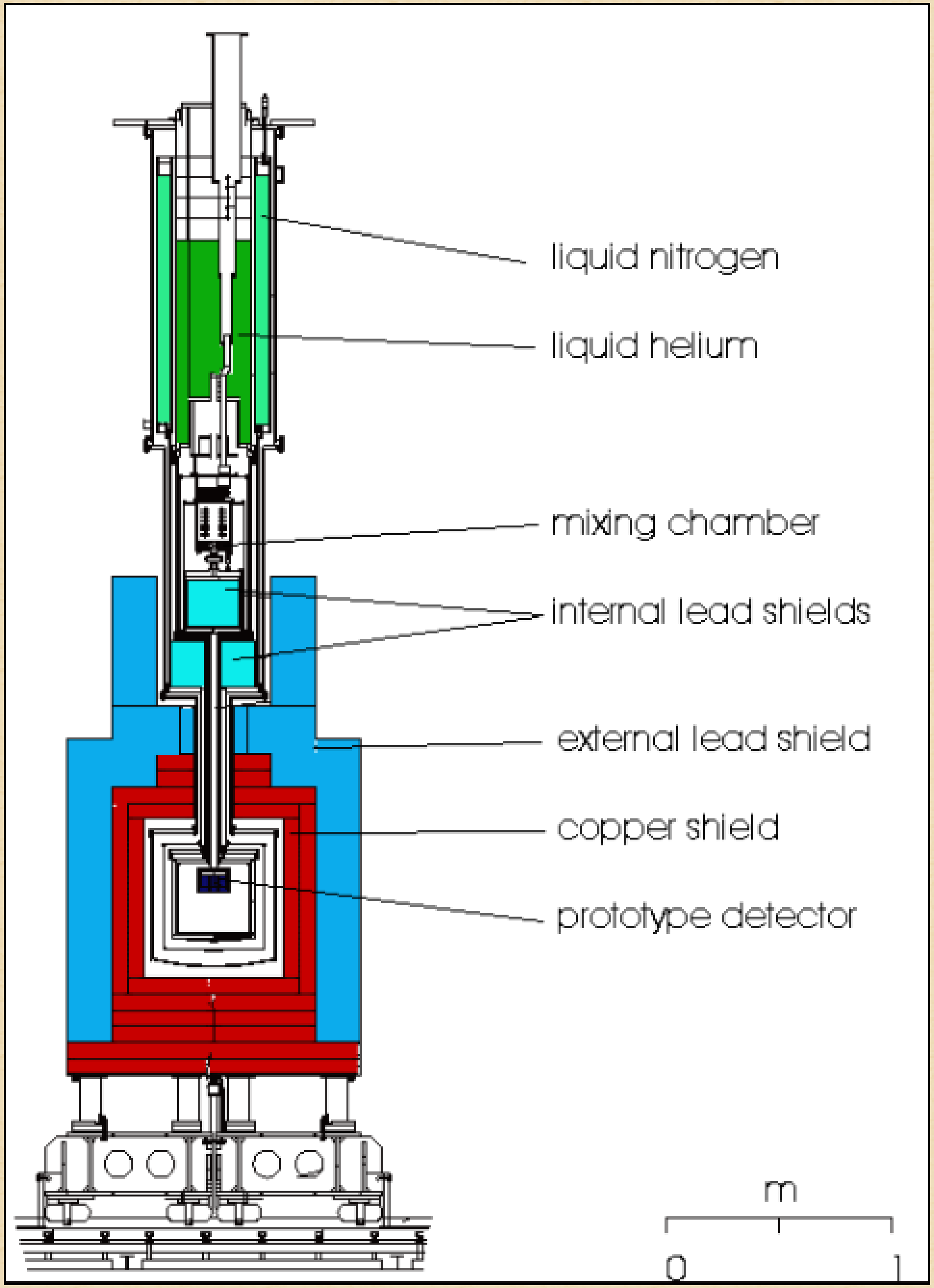
Cryogenic
Rare
Event
Search with
Superconducting
Thermometers

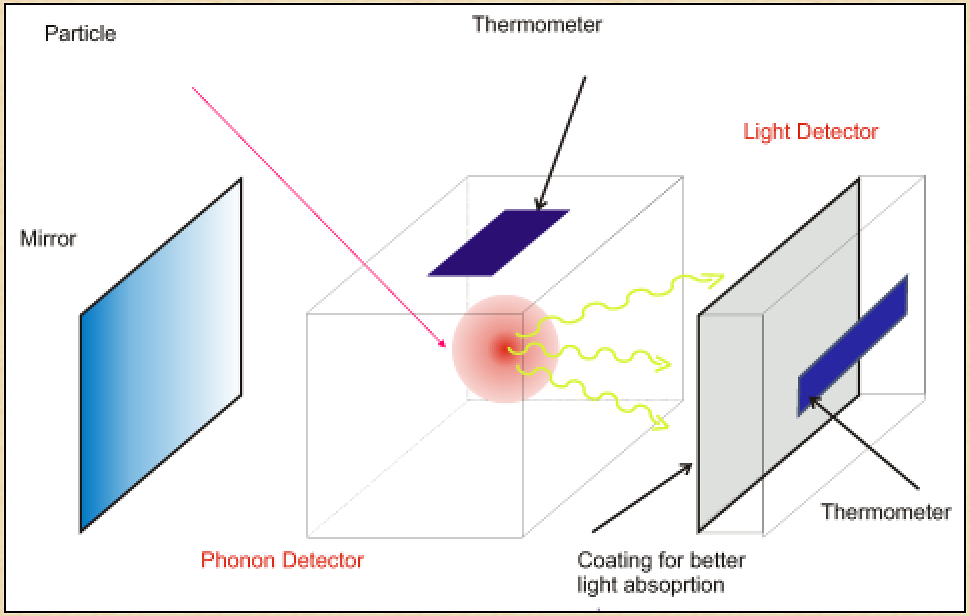


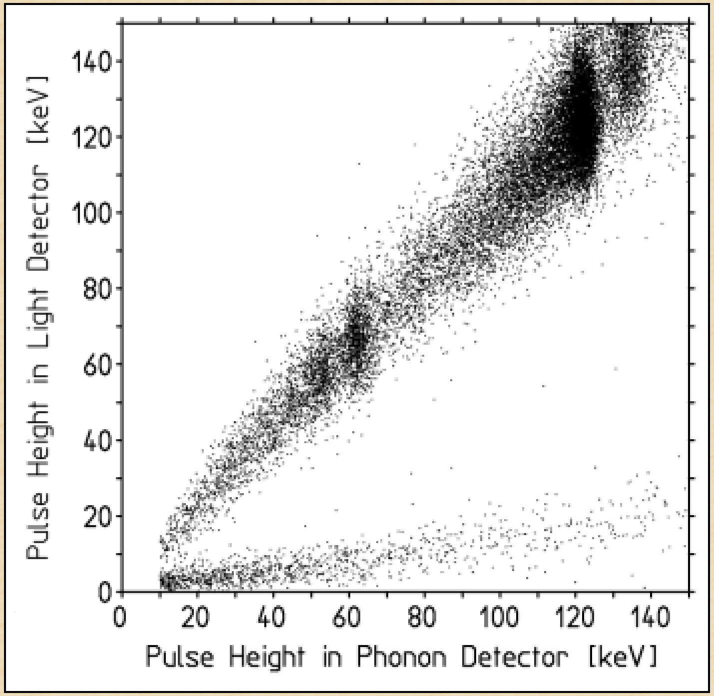
CRESST Experiment to Search for Dark Matter



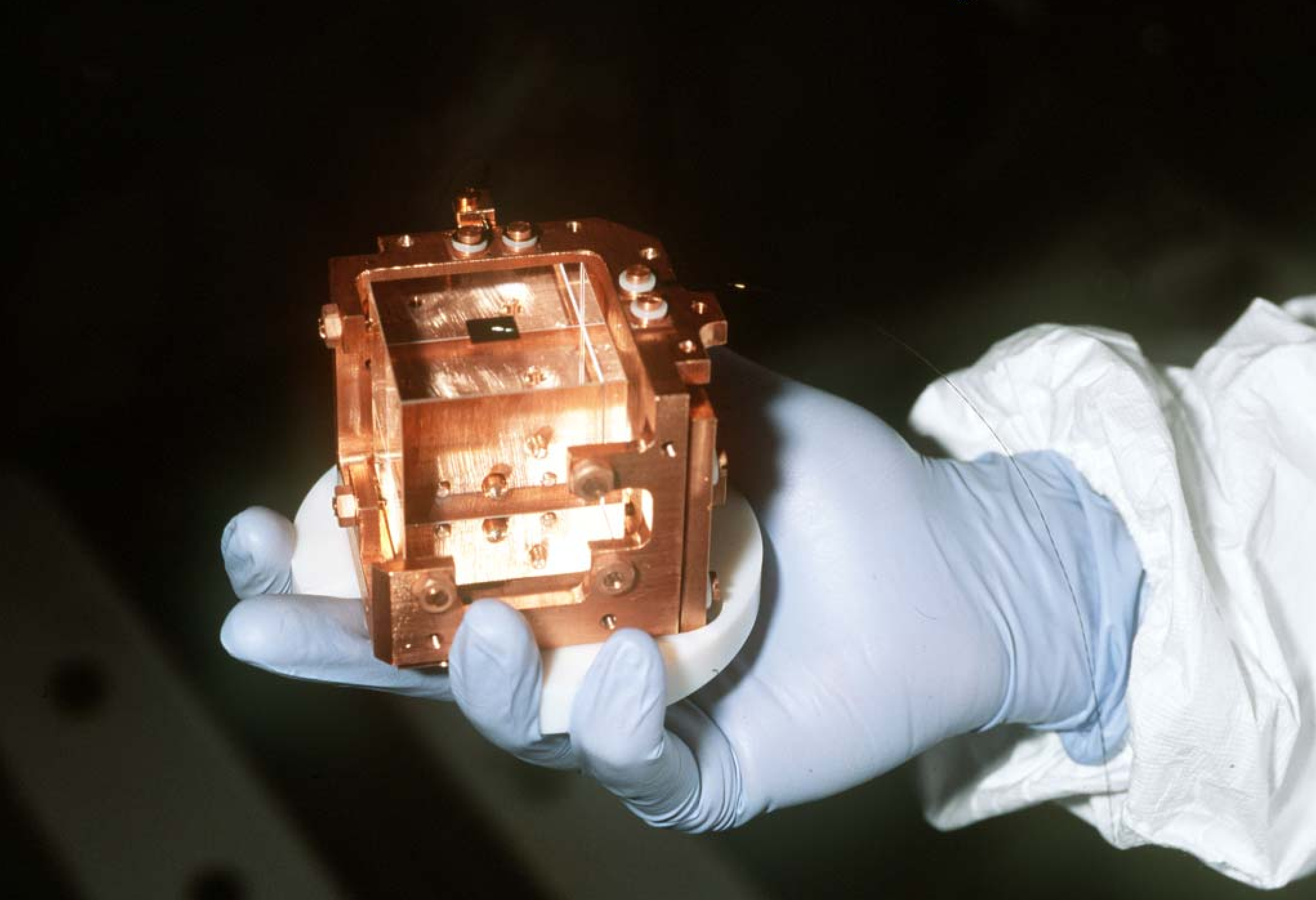
CRESST Experiment to Search for Dark Matter



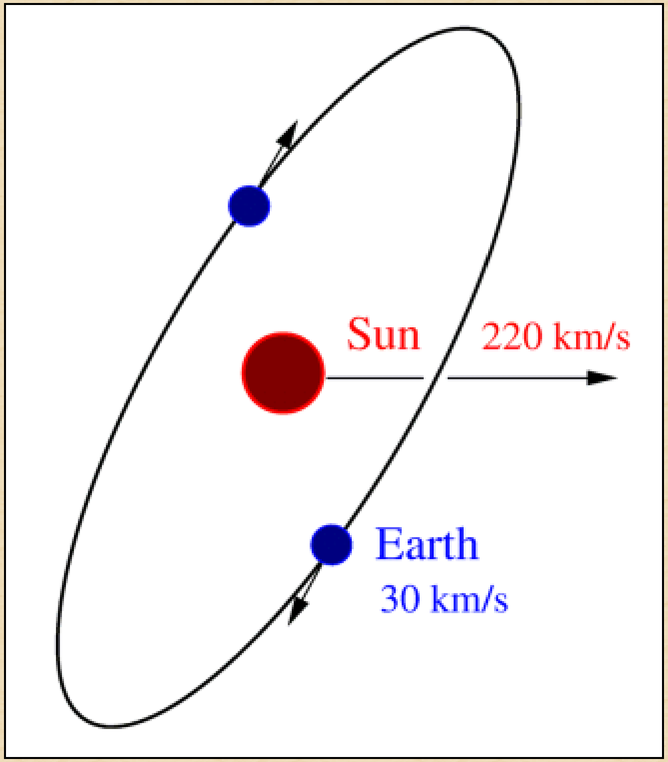




One of the CRESST Detector Crystals

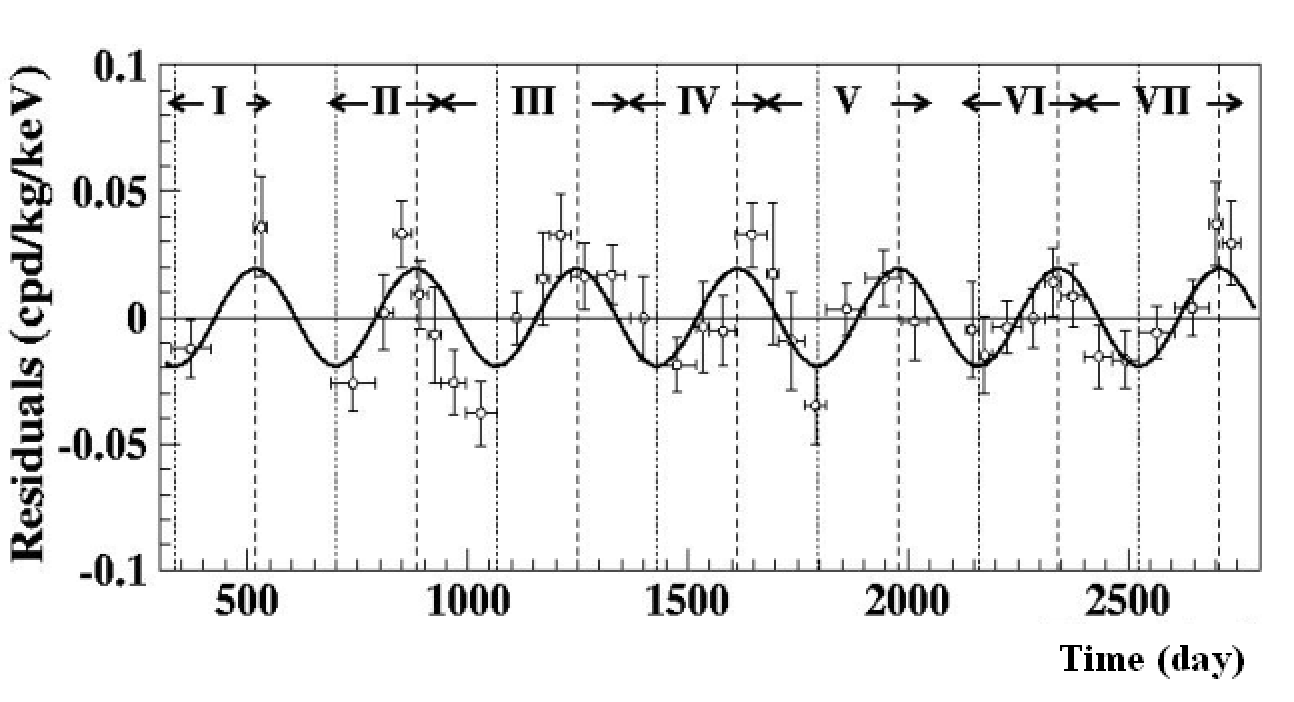


DAMA Evidence for WIMP Detection



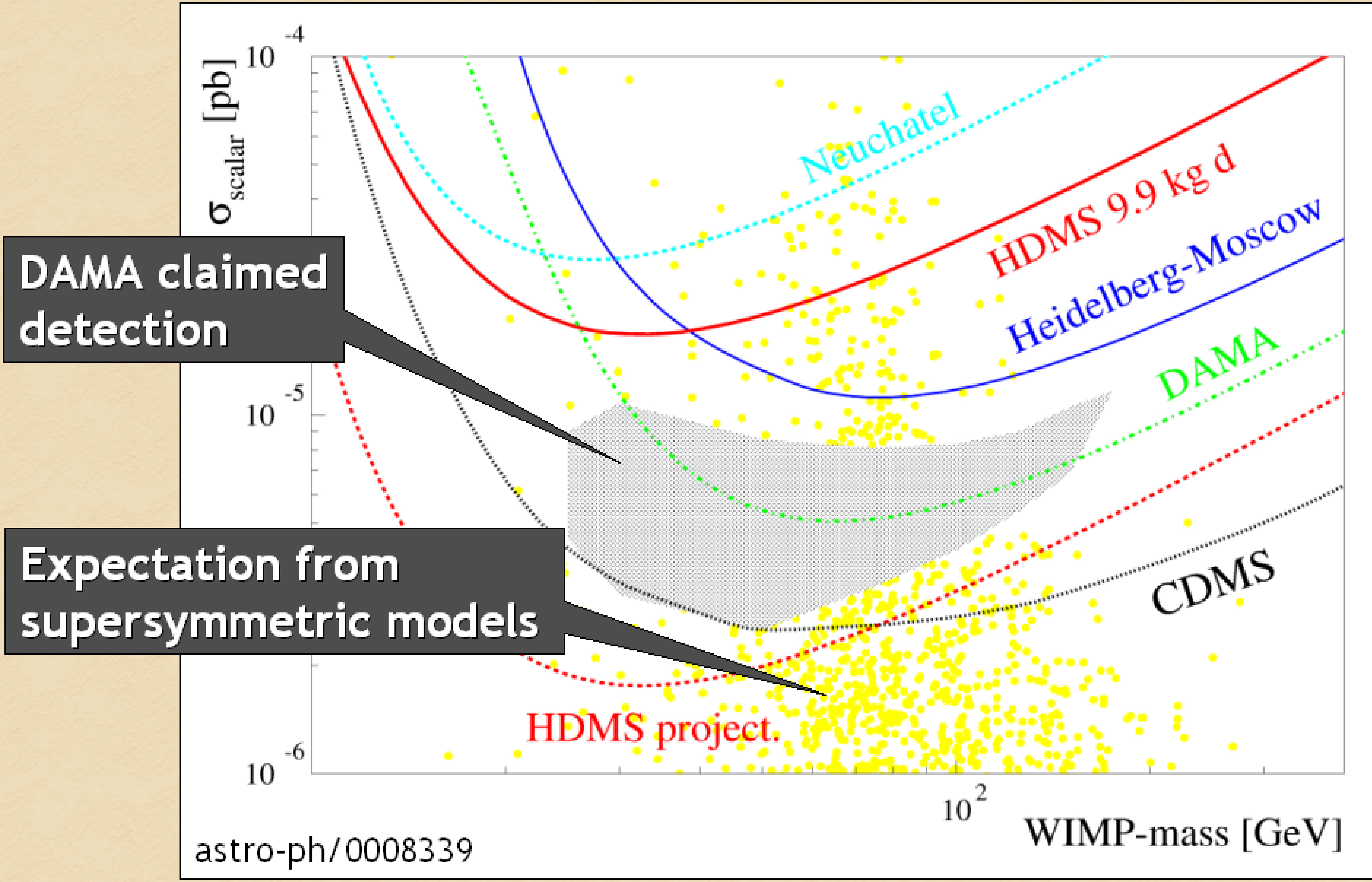
Annual modulation of WIMP signal a “smoking gun” signature

DAMA experiment in Gran Sasso (NaI scintillation detector) observes an annual modulation at a 6.3σ statistical CL, based on 110 ton-days of data [Riv. N. Cim. 26 (2003) 1–73]

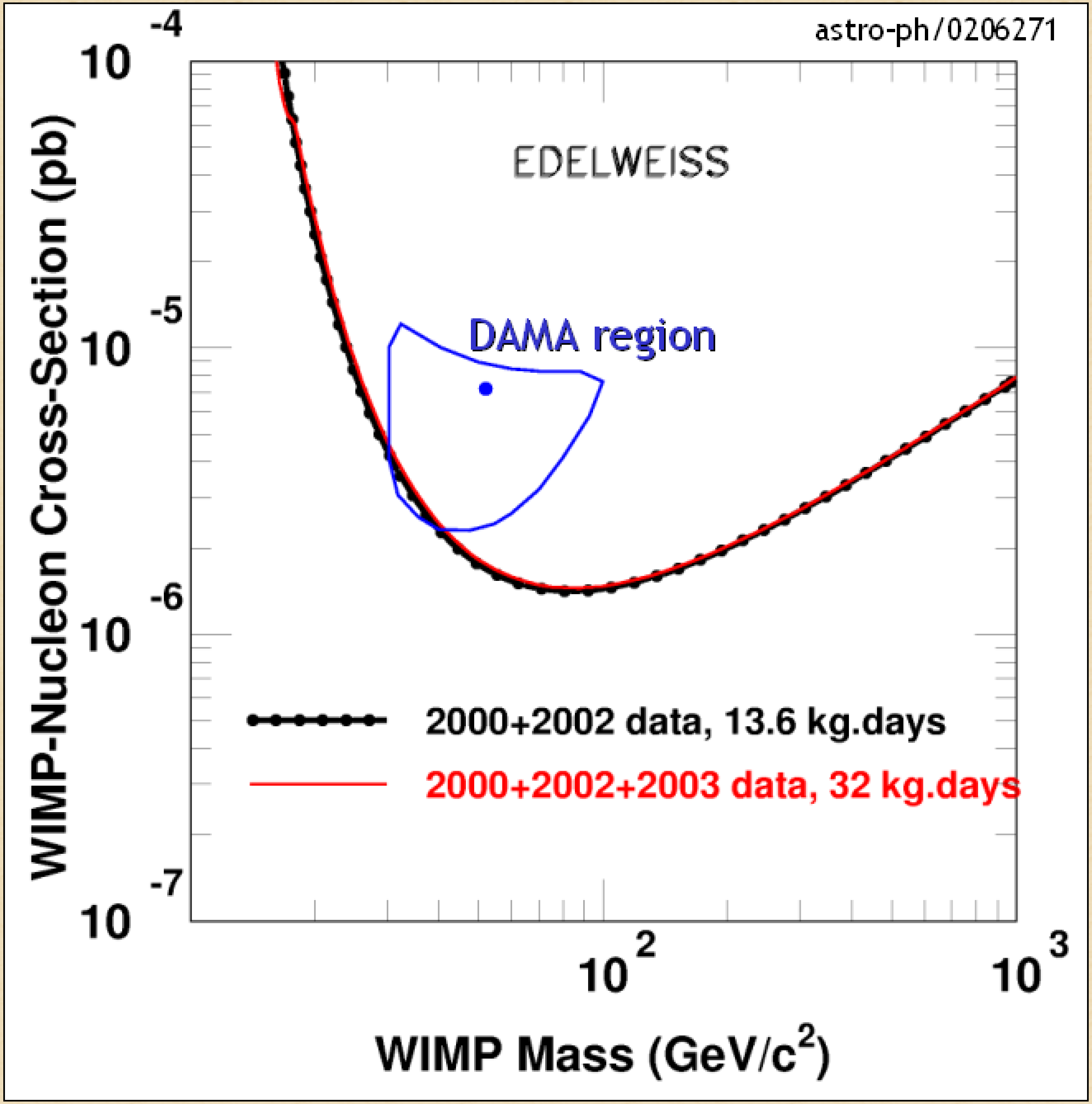


- Detector stability ?
- „Background stability“ ?

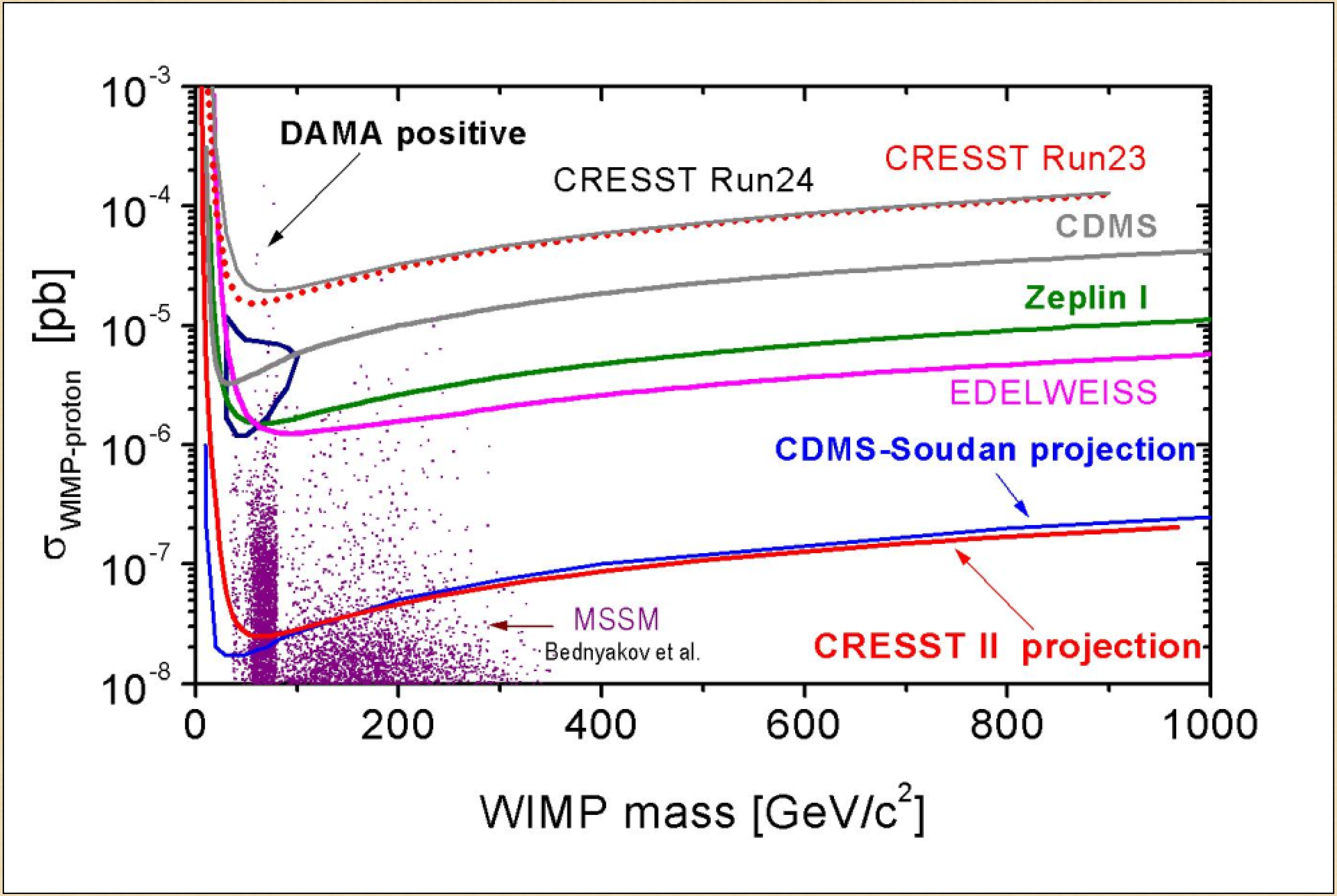
Limits from WIMP Search Experiments



EDELWEISS Limits



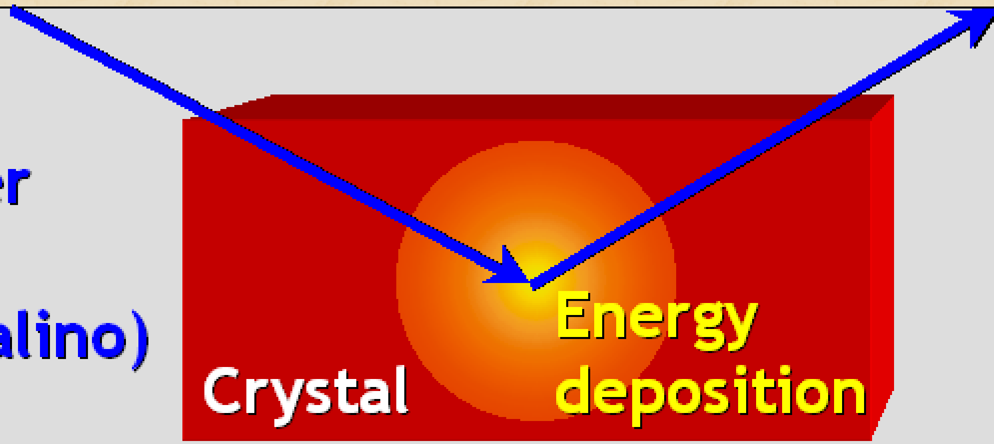
Projected WIMP Sensitivities



Search for Neutralino Dark Matter

Direct Method (Laboratory Experiments)

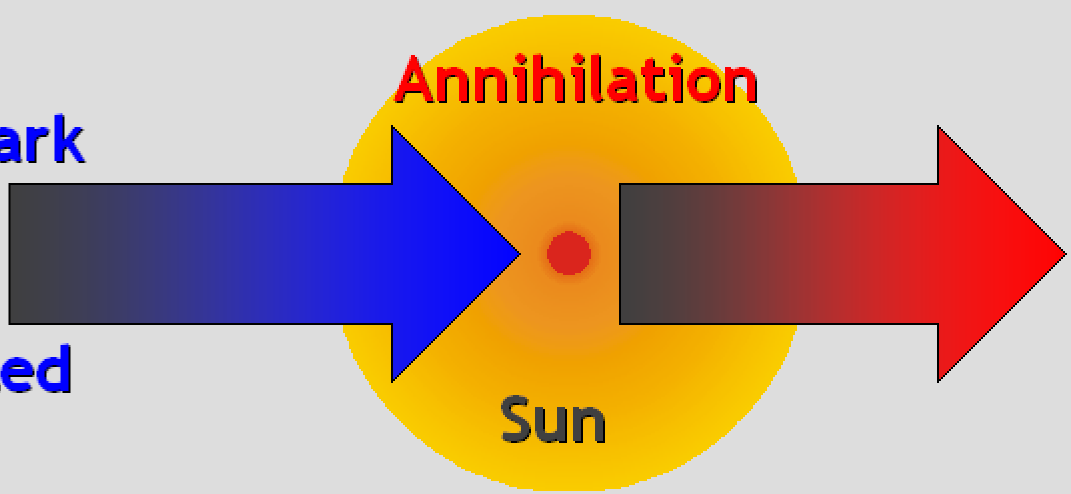
Galactic dark matter particle (e.g.neutralino)



Recoil energy (few keV) is measured by
- Ionisation
- Scintillation
- Cryogenic

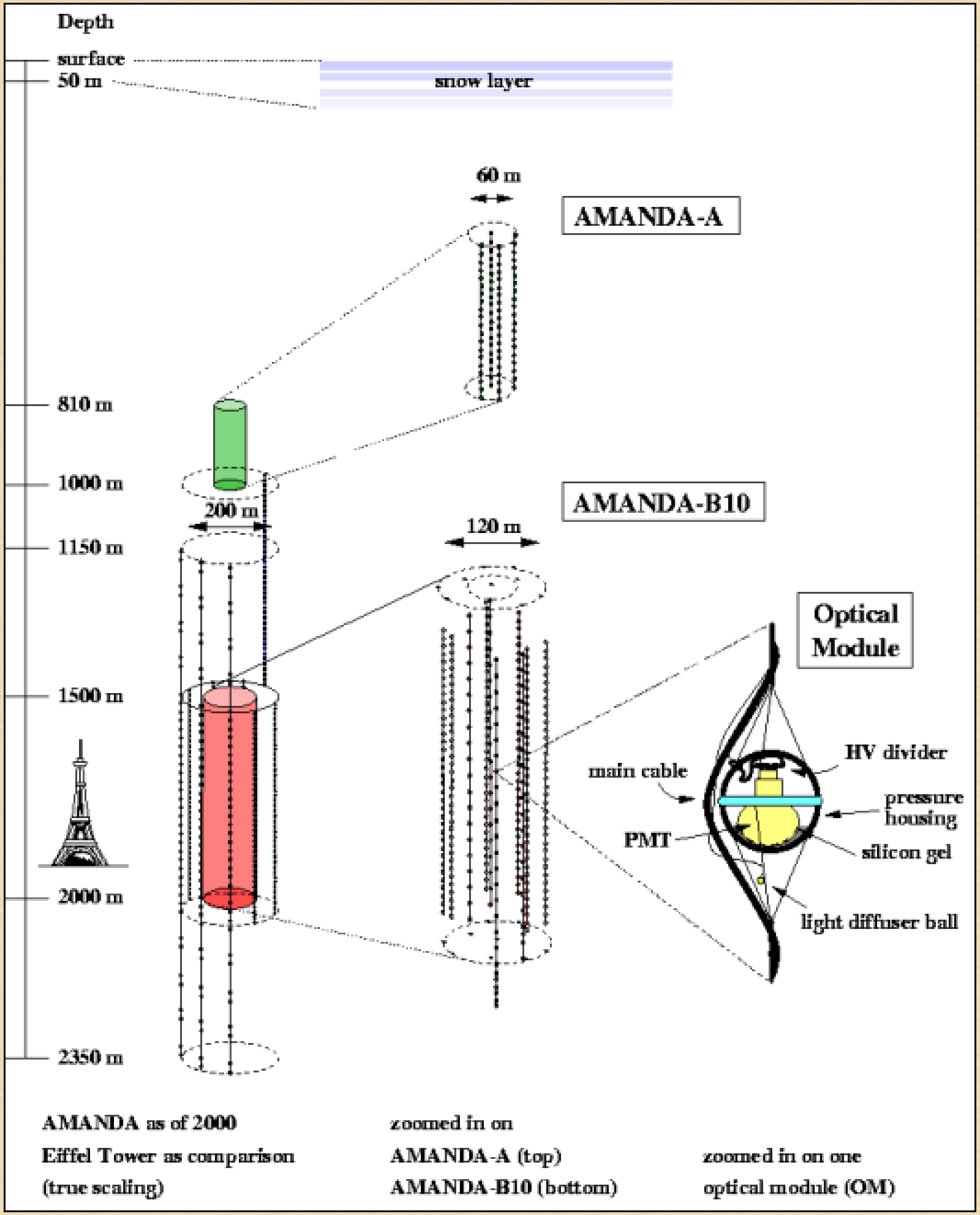
Indirect Method (Neutrino Telescopes)

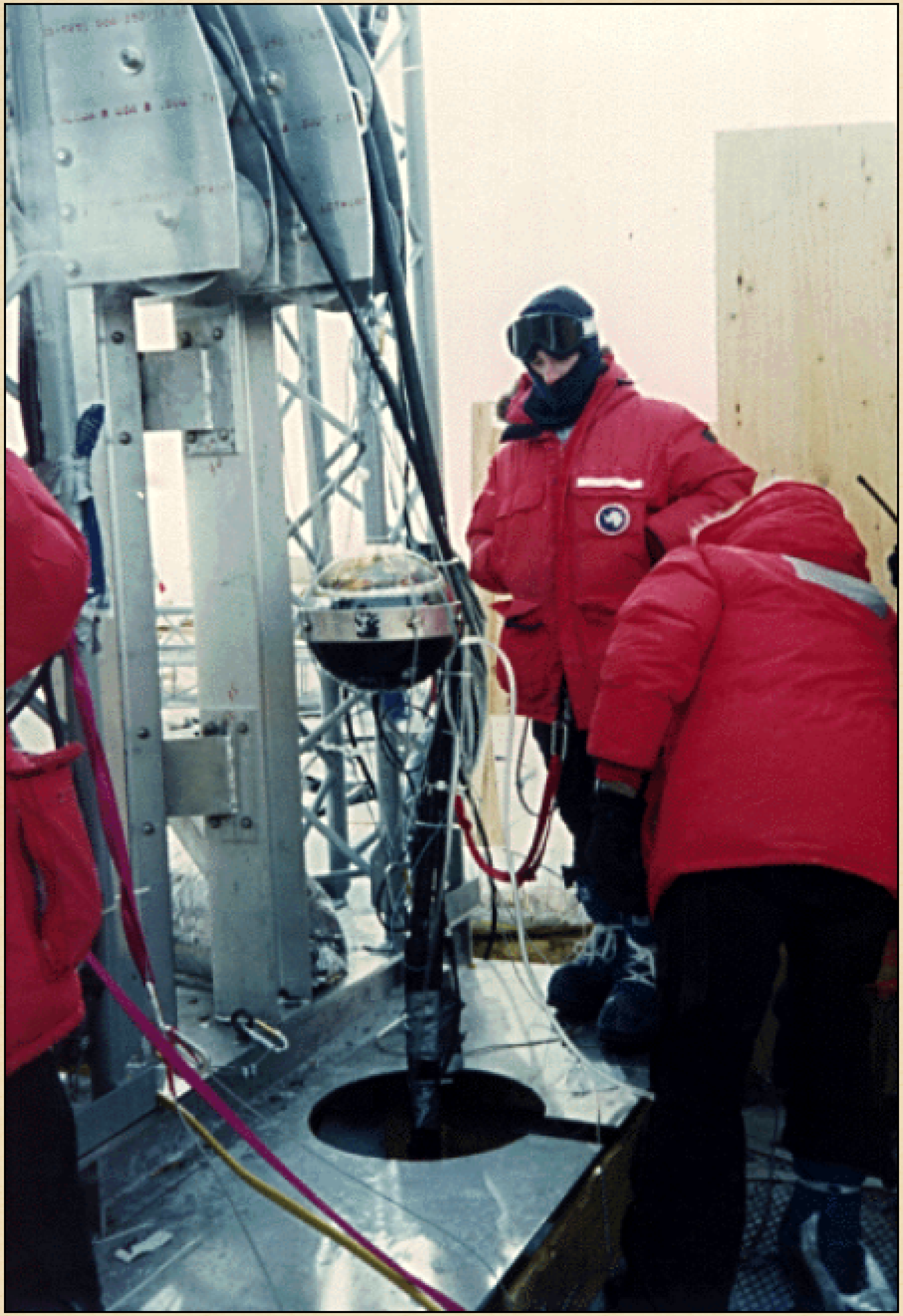
Galactic dark matter particles are accreted



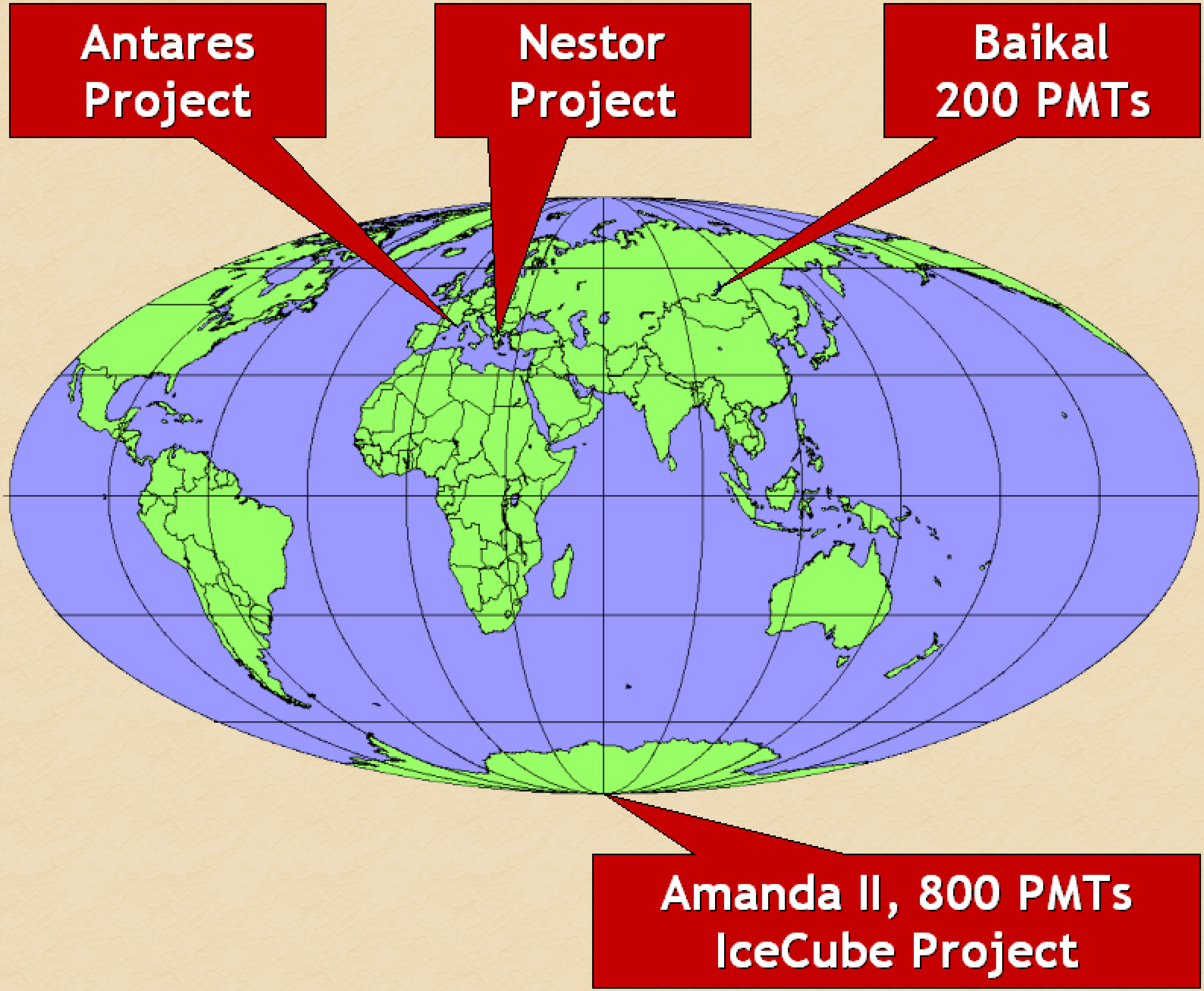
High-energy neutrinos (GeV-TeV) can be measured

AMANDA - South Pole Neutrino Telescope

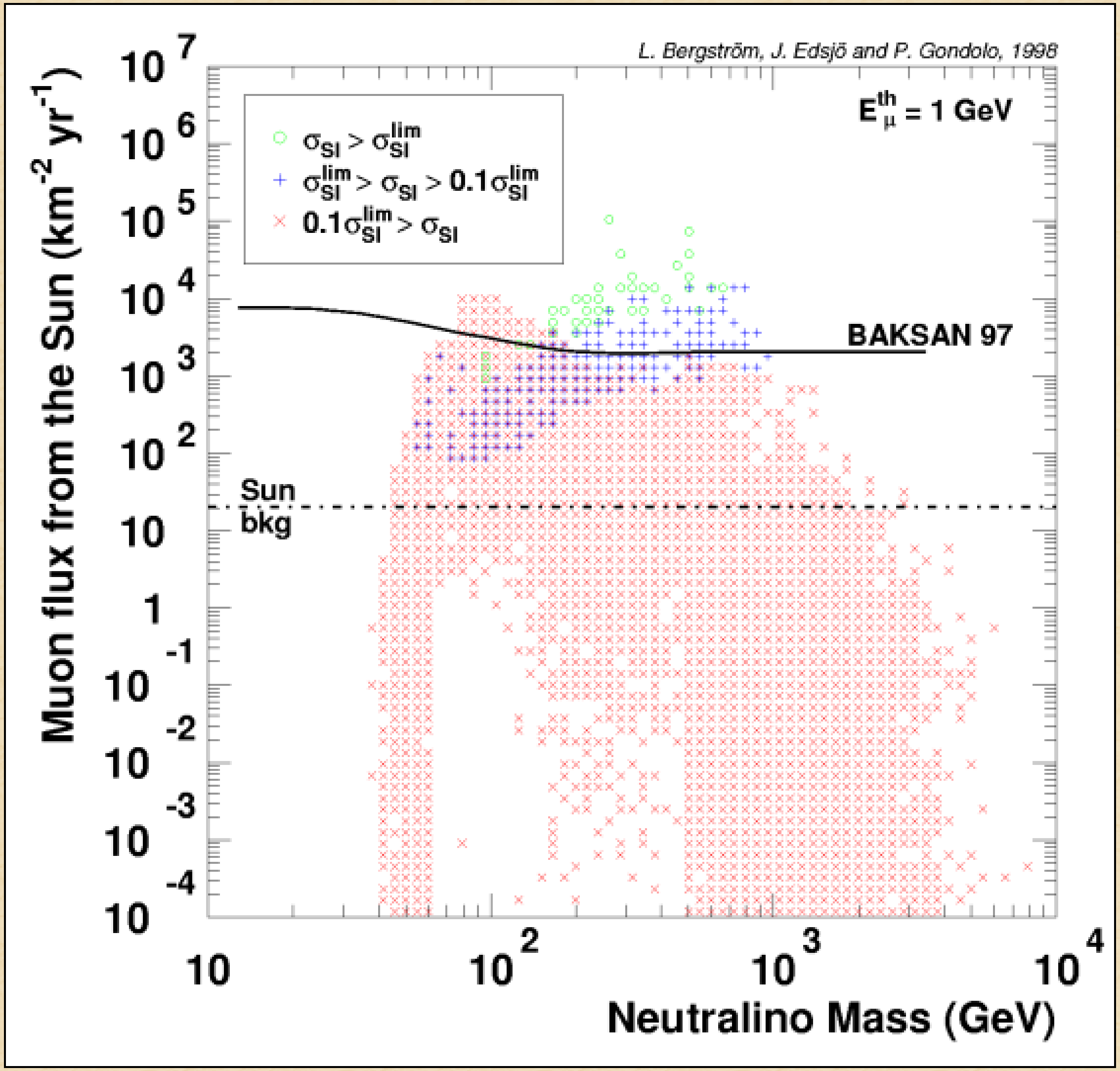




High-Energy Neutrino Telescopes



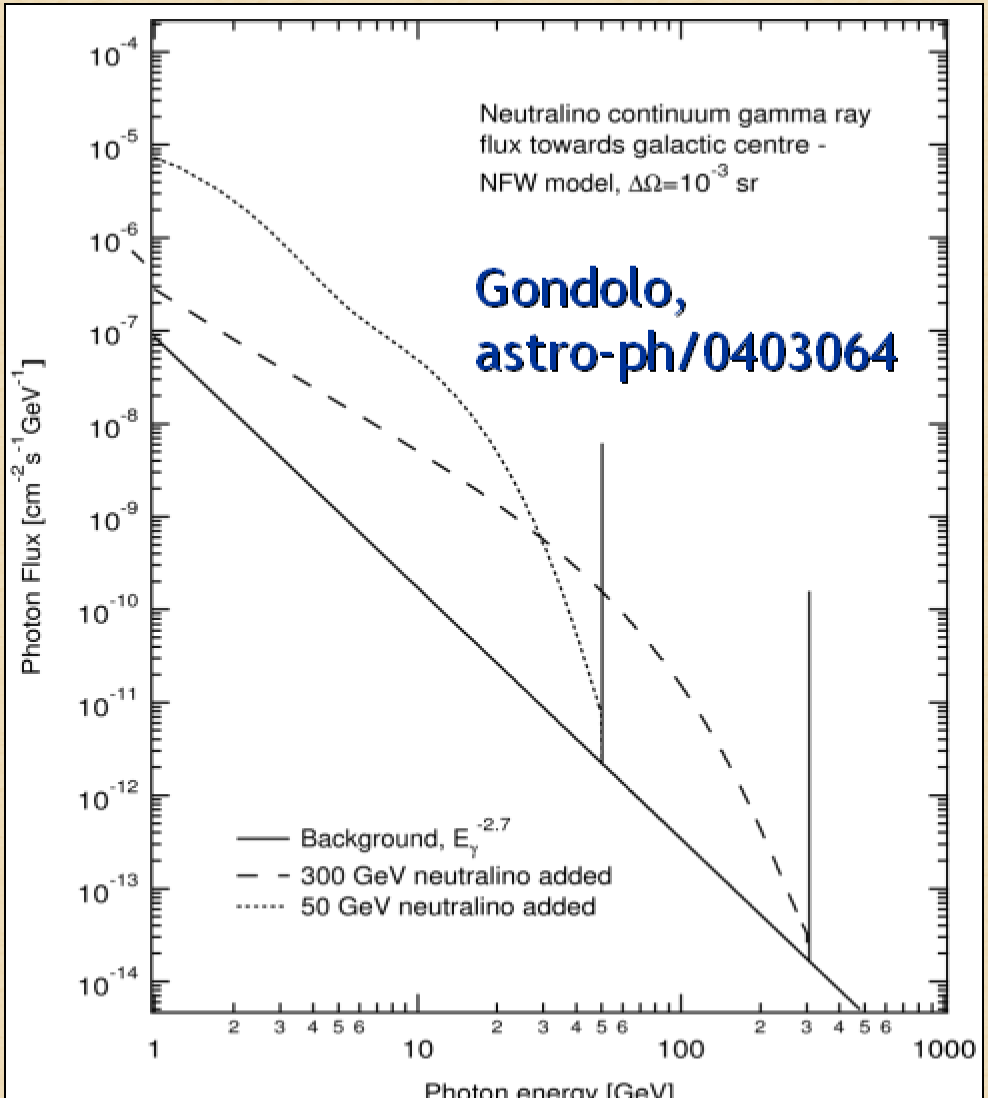
Muon Flux from WIMP Annihilation in the Sun



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

High-Energy Gamma Rays from Neutralino Annihilation

$$\chi\chi \rightarrow \gamma\gamma \text{ or } Z\gamma$$



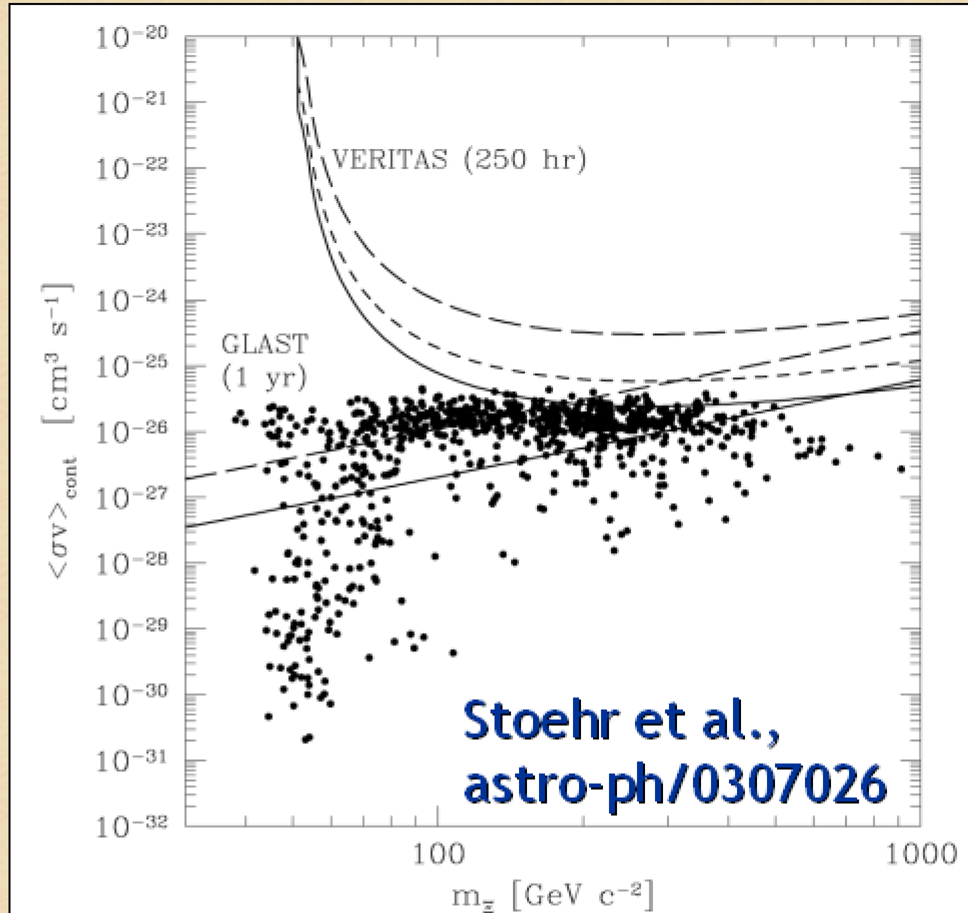


Figure 8. MSSM models of cosmological interest (dots) and 3-σ detection limits for VERITAS and GLAST. For VERITAS the limits are shown for a pointing at the centre of the Milky Way, assuming an NFW profile (solid) and an SWTS profile (short dashes). The lower solid line gives estimated limits for GLAST 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

Characterizes degenerate QCD ground state (Θ vacuum)

Phase of Quark Mass Matrix

Standard QCD Lagrangian contains a CP violating term

$$L_{CP} = -\frac{\alpha_s}{8\pi}\underbrace{(\Theta - \arg\det M_q)}_{0\leq\overline{\Theta}\leq 2\pi}\,\mathrm{Tr}\,\tilde{G}_{\mu\nu}G^{\mu\nu}$$

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

$$d_n \approx \overline{\Theta}\,10^{-16}\,\mathrm{e\,cm} \approx \frac{\overline{\Theta}}{10^2}\,\mu_n < 10^{-25}\,\mathrm{e\,cm}$$

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

Dynamical Solution

Peccei & Quinn 1977 - Wilczek 1978 - Weinberg 1978

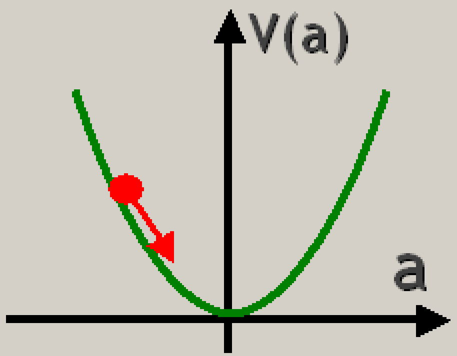
Re-interpret $\bar{\Theta}$ as a dynamical variable (scalar field)

$$\bar{\Theta} \to \frac{a(x)}{f_a}$$

Pseudo-scalar axion field

Peccei-Quinn scale, Axion decay constant

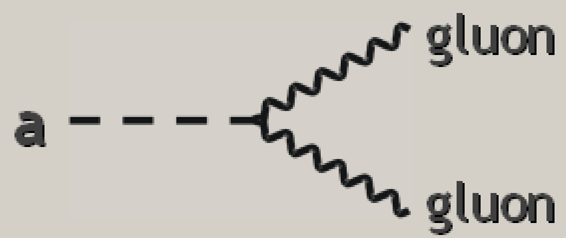
$$L_{CP} = -\frac{\alpha_s}{8\pi}\bar{\Theta}\,\mathrm{Tr}\tilde{G}G \quad \Rightarrow \quad -\frac{\alpha_s}{8\pi}\frac{a(x)}{f_a}\,\mathrm{Tr}\tilde{G}G$$



$\bar{\Theta} = 0$

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

$$\begin{pmatrix}\text{Axion mass}\\ \text{\& couplings}\end{pmatrix} \sim \begin{pmatrix}\text{Pion mass}\\ \text{\& couplings}\end{pmatrix} \times \frac{f_\pi}{f_a}$$

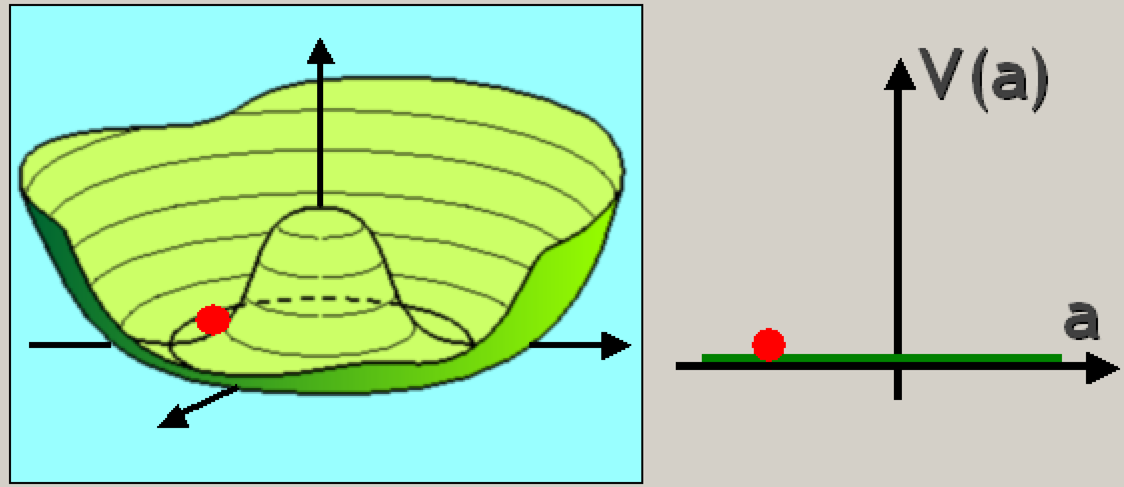
$f_\pi \approx 93$ MeV
Pion decay constant

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

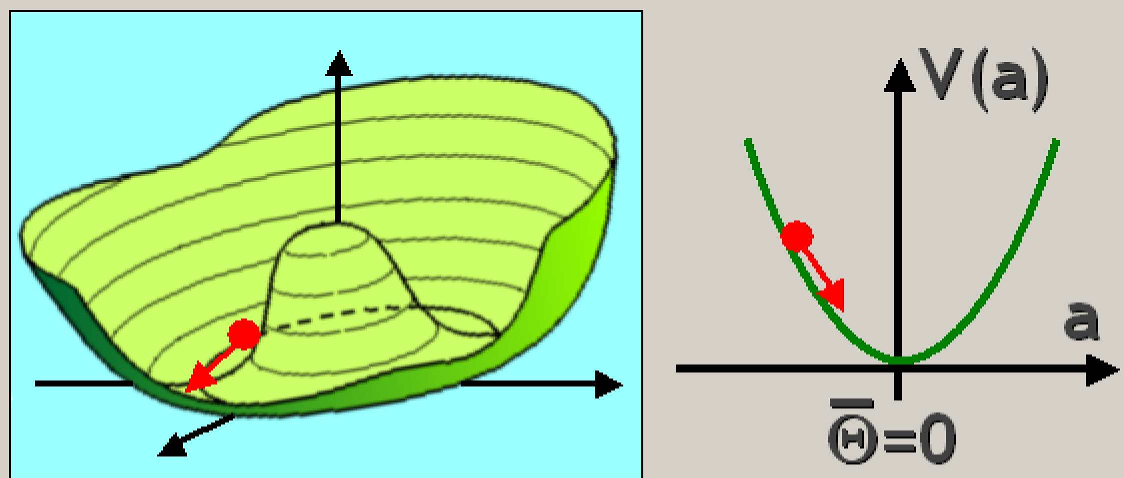
$E \approx f_a$

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



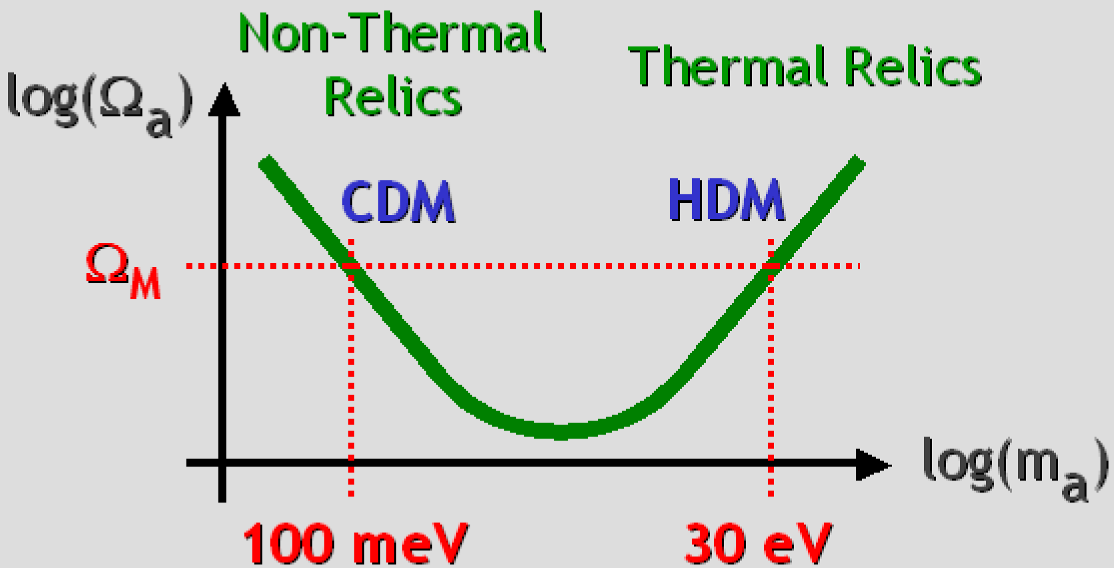
$E \approx \Lambda_{QCD} = f_a$

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

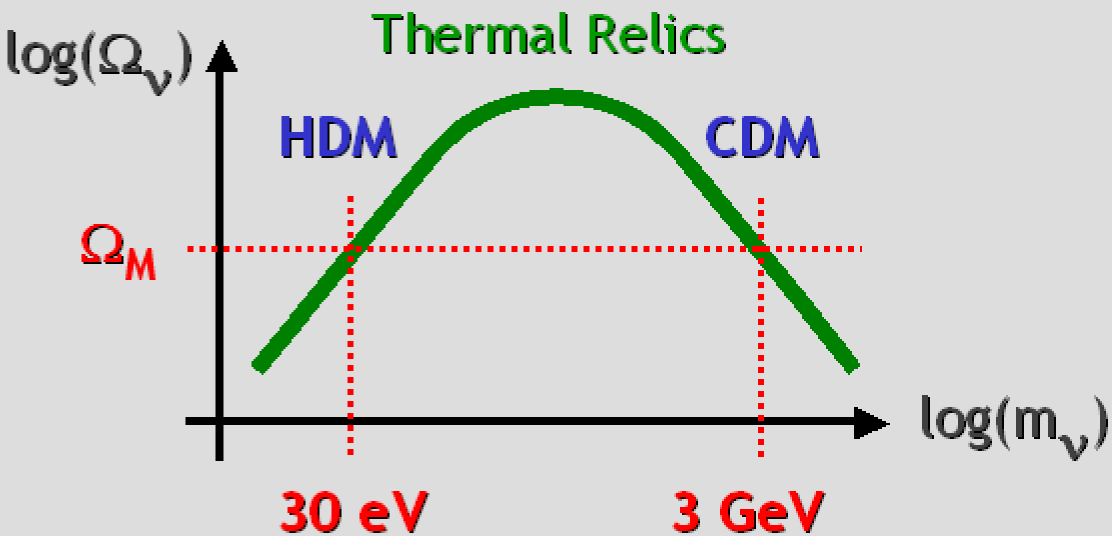


Lee-Weinberg Curve for Neutrinos and Axions

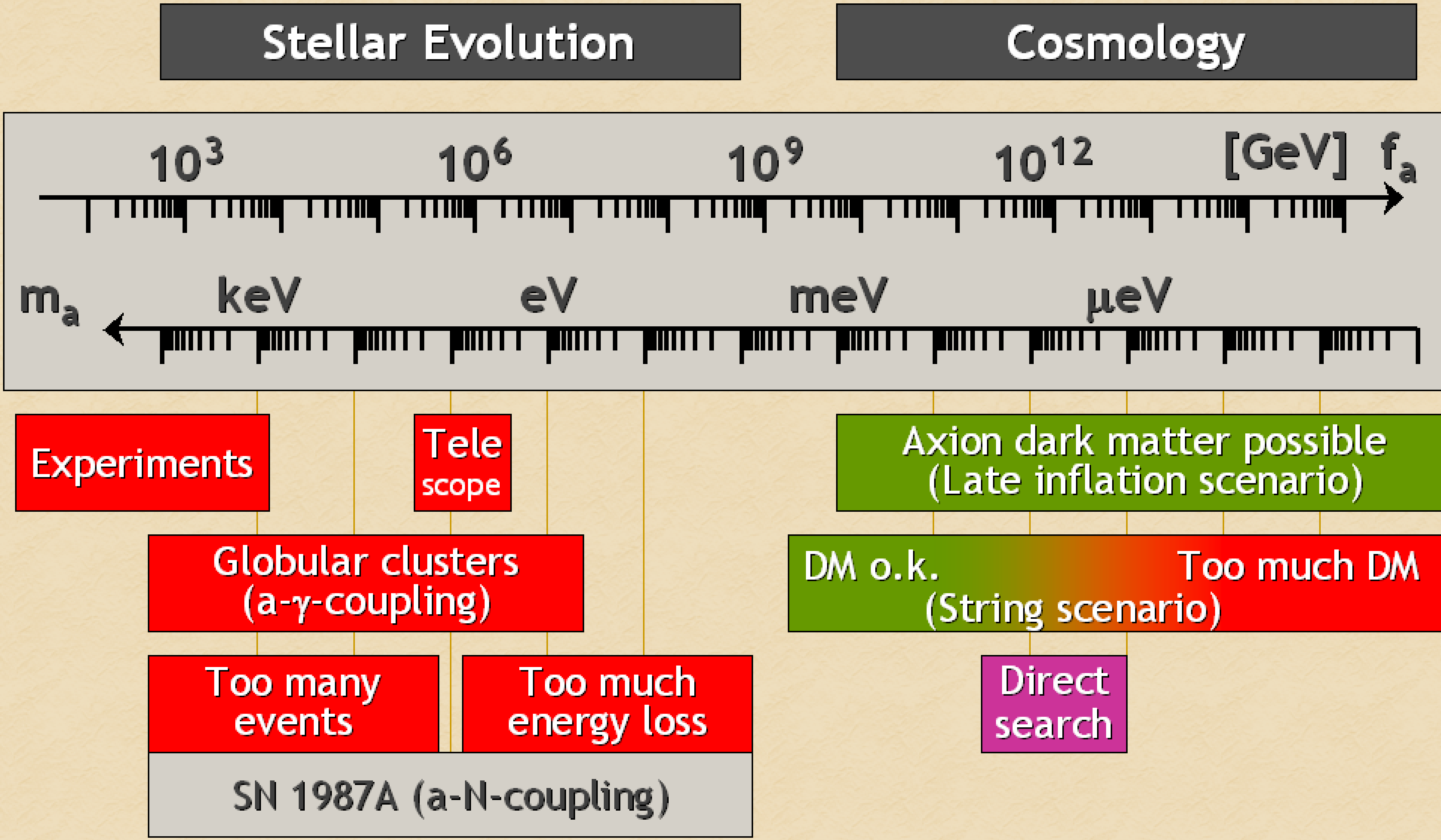
Axions



Neutrinos



Astrophysical Axion Bounds

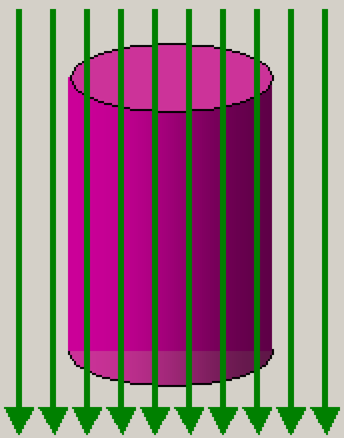


Experimental Search for Galactic Axions

DM axions	m_a = 10-3000 μeV
Velocities in galaxy	$v_a \approx 10^{-3}$ c
Energies therefore	$E_a \approx (1 \pm 10^{-6})\, m_a$

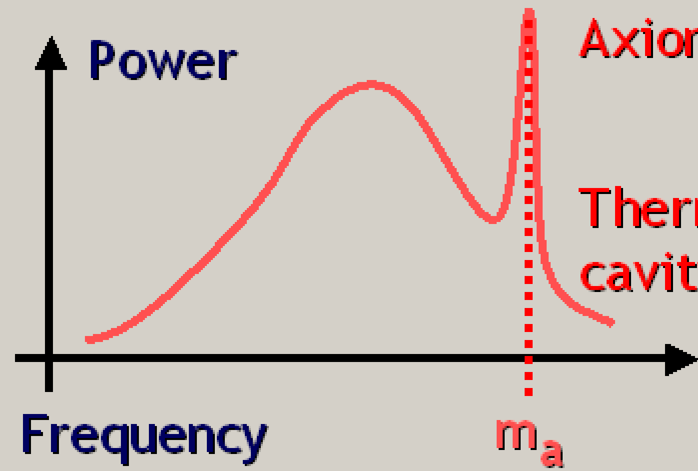
→ **Microwave Energies (1 GHz ≈ 4 μeV)**

Axion Haloscope (Sikivie 1983)



$B_{ext} \approx$ 8 Tesla

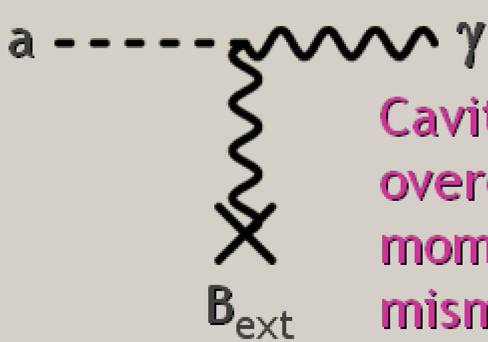
Microwave Resonator $Q \approx 10^5$



Axion Signal

Thermal noise of cavity & detector

Primakoff Conversion



Cavity overcomes momentum mismatch

Power of galactic axion signal

$$4\times10^{-21}\,\mathrm{W}\,\frac{V}{0.22\,\mathrm{m}^3}\left(\frac{B}{8.5\,\mathrm{T}}\right)^2\frac{Q}{10^5}\times\left(\frac{m_a}{2\pi\,\mathrm{GHz}}\right)\left(\frac{\rho_a}{5\times10^{-25}\,\mathrm{g/cm}^3}\right)$$

Experimental Search for Galactic Axions

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Microwave Energies
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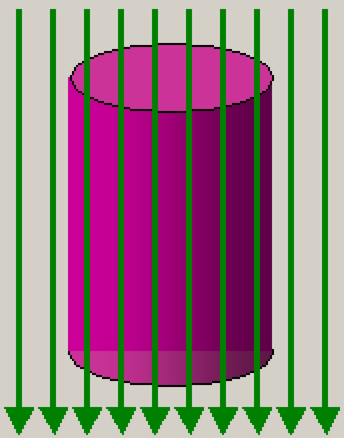

$B_{ext} \approx 8$ Tesla

Microwave
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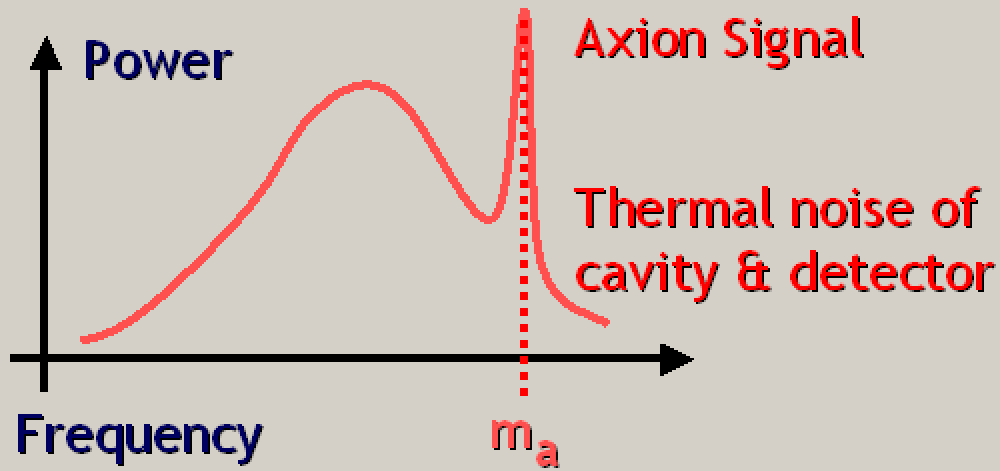
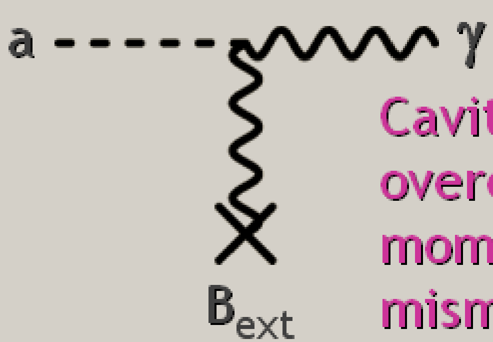
$Q \approx 10^5$



Primakoff Conversion



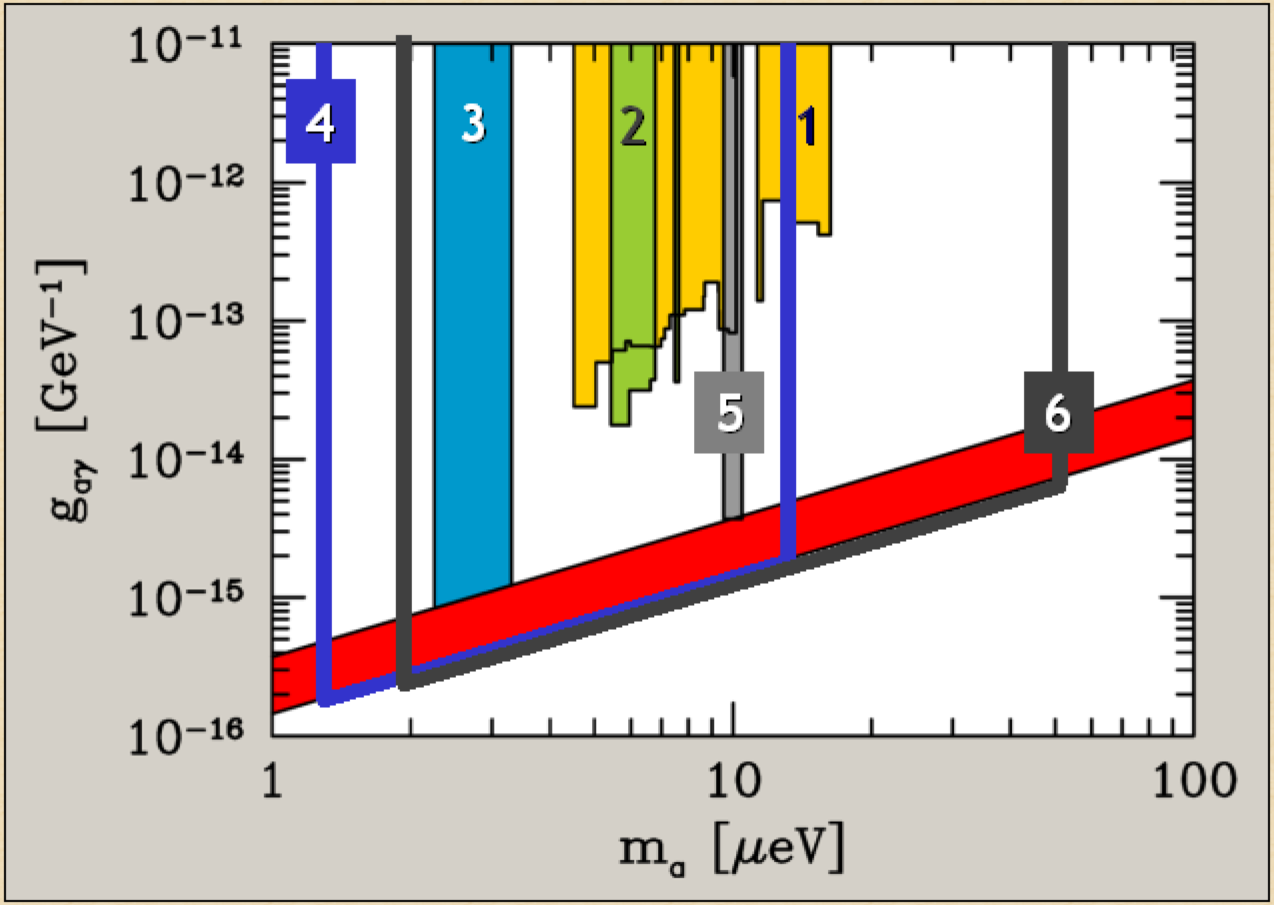
Cavity
overcomes
momentum
mismatch

2 Experiments in Operation

- Axion Dark Matter Experiment (ADMX), Livermore, US
- CARRACK II, Kyoto, Japan

Axion Dark Matter Searches

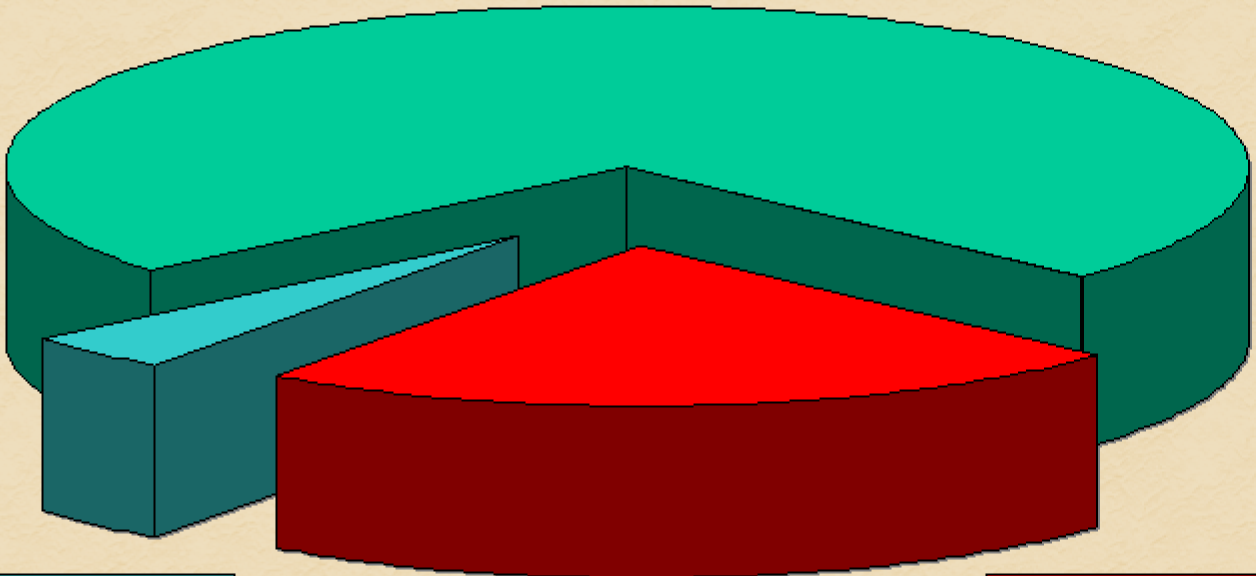
Limits/sensitivities assume axions are the galactic dark matter



1. Rochester-Brookhaven-Fermilab
   PRD 40 (1989) 3153
2. University of Florida
   PRD 42 (1990) 1297
3. US Axion Search (Livermore)
   ApJL 571 (2002) L27
4. ADMX (Livermore)
   Phys Repts 325 (2000) 1
5. CARRACK I (Kyoto)
   preliminary
   hep-ph/0101200
6. CARRACK II (Kyoto)
   hep-ph/0101200

Mass-Energy-Inventory of the Universe

Dark energy 73%
(Cosmological constant)



Baryonic matter 4%
(only 10% of this is luminous)

Dark matter 23%

Baryogenesis in the Early Universe

Andrei Sakharov
1921–1989

Sakharov conditions for creating the
Baryon **A**symmetry of the **U**niverse (**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

Leptogenesis by Majorana Neutrino Decays

A classic paper

Volume 174, number 1 PHYSICS LETTERS B 26 June 1986

BARYOGENESIS WITHOUT GRAND UNIFICATION

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and

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Institute of Physics, College of General Education, Tohoku University, Sendai 980, Japan
and Deutsches Elektronen-Synchrotron DESY, D-2000 Hamburg, Fed. Rep. Germany

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.

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_1	N_1
ν_2	N_2
ν_3	N_3

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

Lagrangian for particle masses

$$L_{mass} = -\bar{\ell}_L \phi g_\ell e_R - \bar{\ell}_L \phi g_\nu N_R - \frac{1}{2}\overline{N_R^c} M N_R + h.c.$$

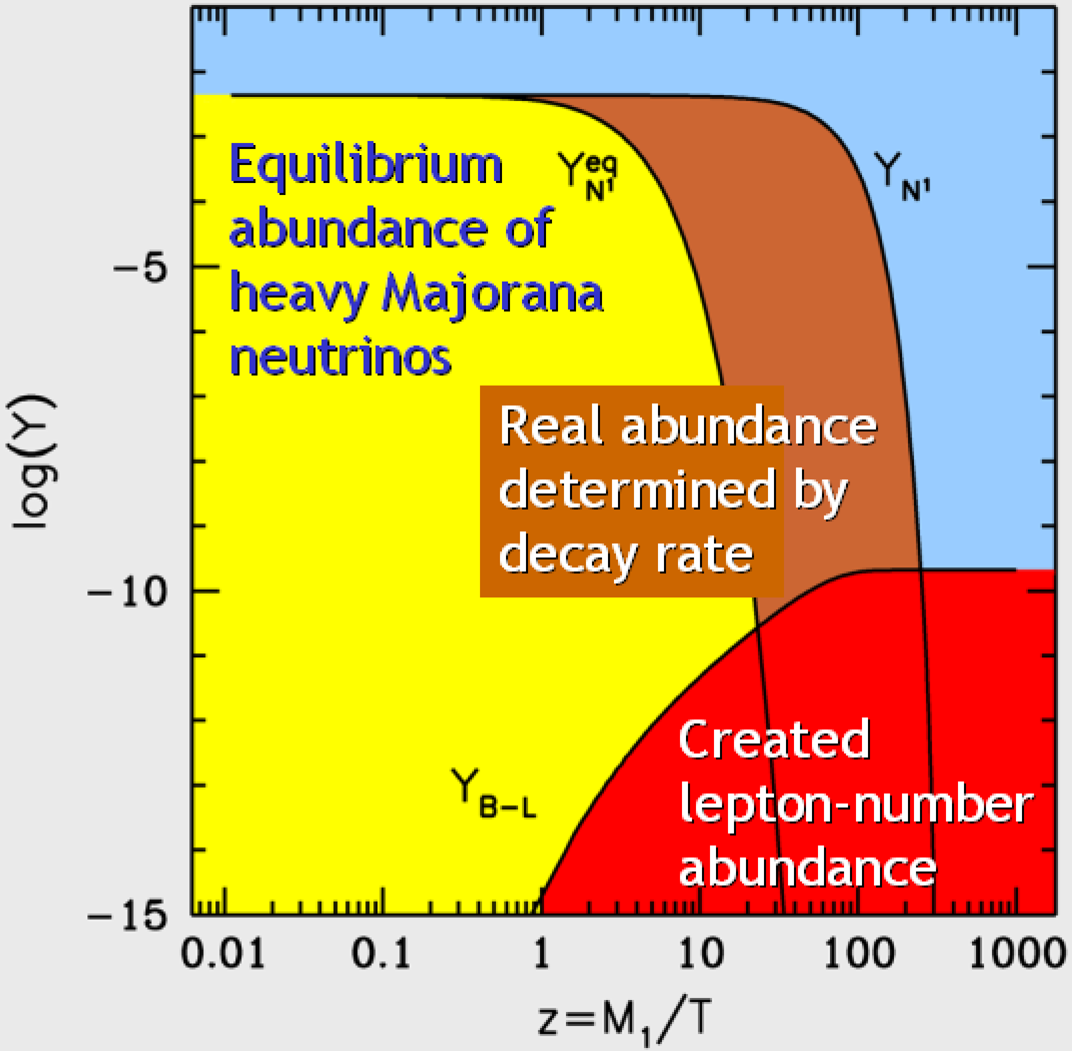
$$\begin{pmatrix} \bar{\nu}_L & \bar{N}_R \end{pmatrix} \begin{pmatrix} 0 & g_\nu \langle\phi\rangle \\ g_\nu \langle\phi\rangle & M \end{pmatrix} \begin{pmatrix} \nu_L \\ N_R \end{pmatrix}$$

Diagonalize

Light Majorana mass

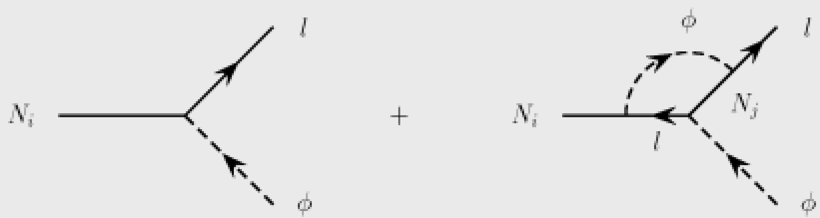
$$\begin{pmatrix} \bar{\nu}_L & \bar{N}_R \end{pmatrix} \begin{pmatrix} \frac{g_\nu^2 \langle\phi\rangle^2}{M} & 0 \\ 0 & M \end{pmatrix} \begin{pmatrix} \nu_L \\ N_R \end{pmatrix}$$

Leptogenesis by Out-of-Equilibrium Decay



M. Fukugita & T. Yanagida:
Baryogenesis without Grand Unification
Phys. Lett. B 174 (1986) 45

CP-violating decays by interference of tree-level with one-loop diagram



$$\Gamma_{Decay} = g_\nu^2 \frac{M}{8\pi}$$

W. Buchmüller & M. Plümacher: Neutrino masses and the baryon asymmetry
Int. J. Mod. Phys. A15 (2000) 5047-5086

Leptogenesis by Majorana Neutrino Decays

In see-saw models for neutrino masses, out-of-equilibrium decays of right-handed heavy Majorana neutrinos provide source for CP- and L-violation

Cosmological evolution
- B = L = 0 early on
- Thermal freeze-out of heavy Majorana neutrinos
- Out-of-equilibrium CP-violating decay creates net L
- Shift L excess into B by sphaleron effects

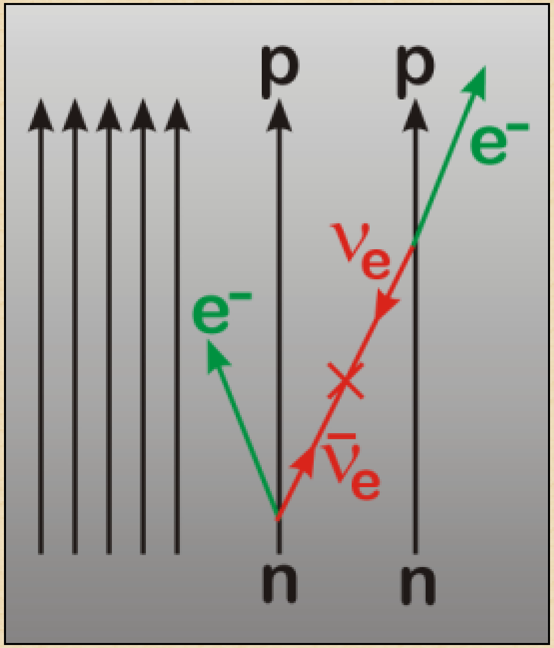
Sufficient deviation from equilibrium distribution of heavy Majorana neutrinos at freeze-out → Limits on Yukawa couplings → Limits on masses of ordinary neutrinos

Requires Majorana neutrino masses below 0.1 eV

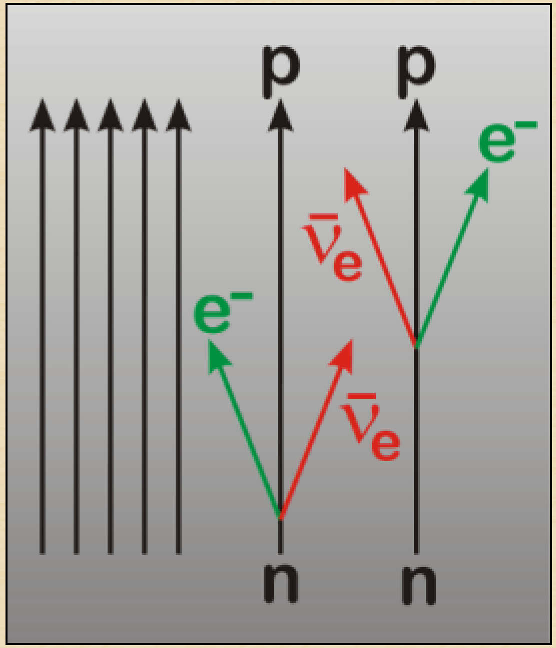
Buchmüller, Di Bari & Plümacher, hep-ph/0209301 & hep-ph/0302092

Neutrinoless ββ Decay

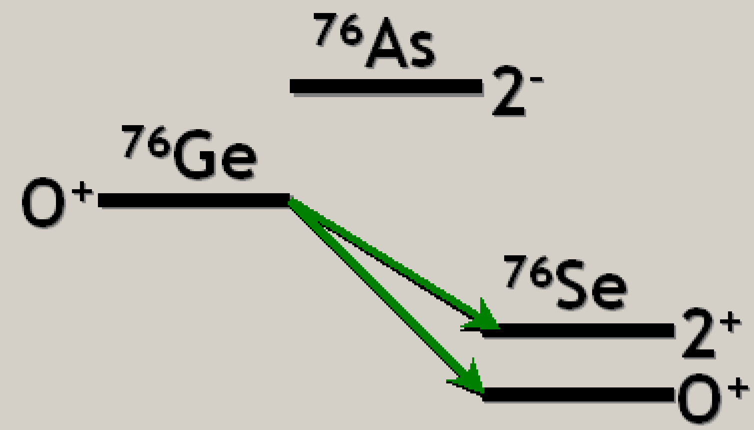
0ν mode, enabled by Majorana mass



Standard 2ν mode



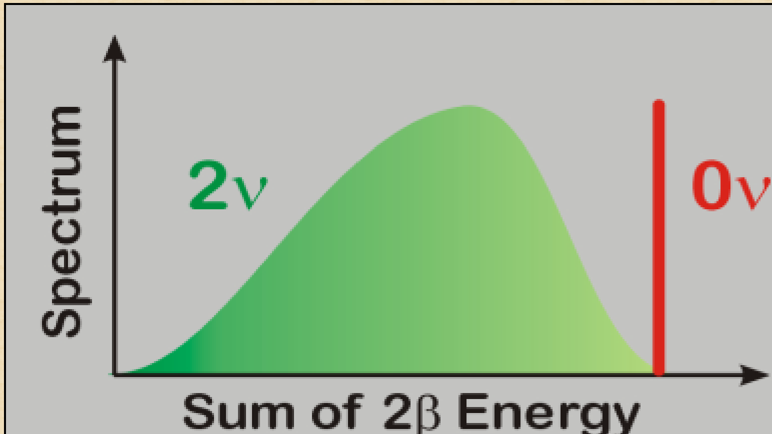
Some nuclei decay only by the ββ mode, e.g.



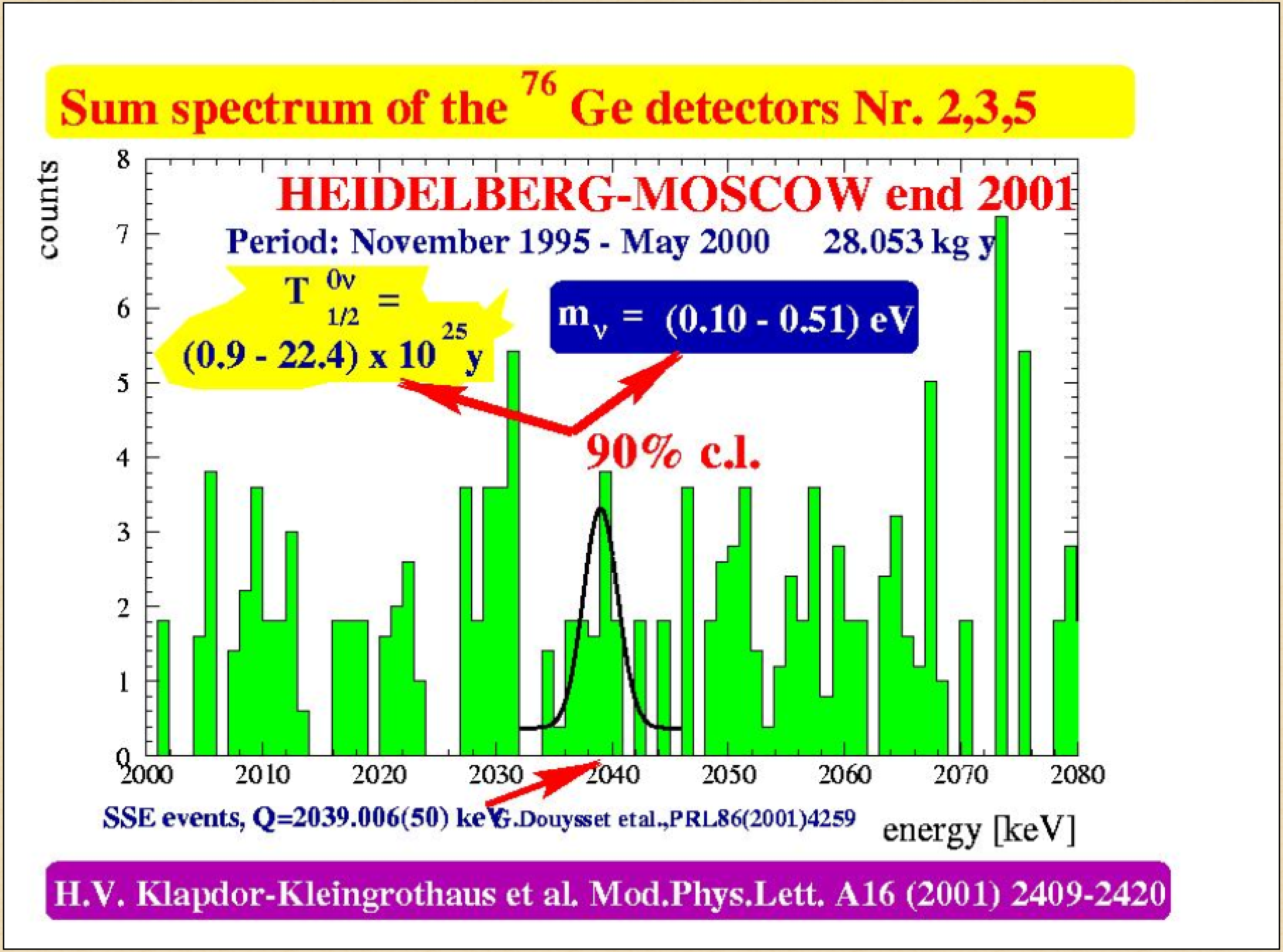
Half life ~ 10^{21} yr

Measured quantity $$|m_{ee}| = \left|\sum_{i=1}^{N} \lambda_i |U_{ei}|^2 m_i\right|$$

Best limit from ^{76}Ge $$|m_{ee}| < 0.35\,\mathrm{eV}$$



Evidence for $0\nu2\beta$ Decay from Heidelberg-Moscow



Improved Evidence for $0\nu2\beta$ Decay

H.V. Klapdor-Kleingrothaus et al.: Data Acquisition and Analysis of the 76Ge Double Beta Experiment in Gran Sasso 1990-2003, arXiv:hep-ph/0403018

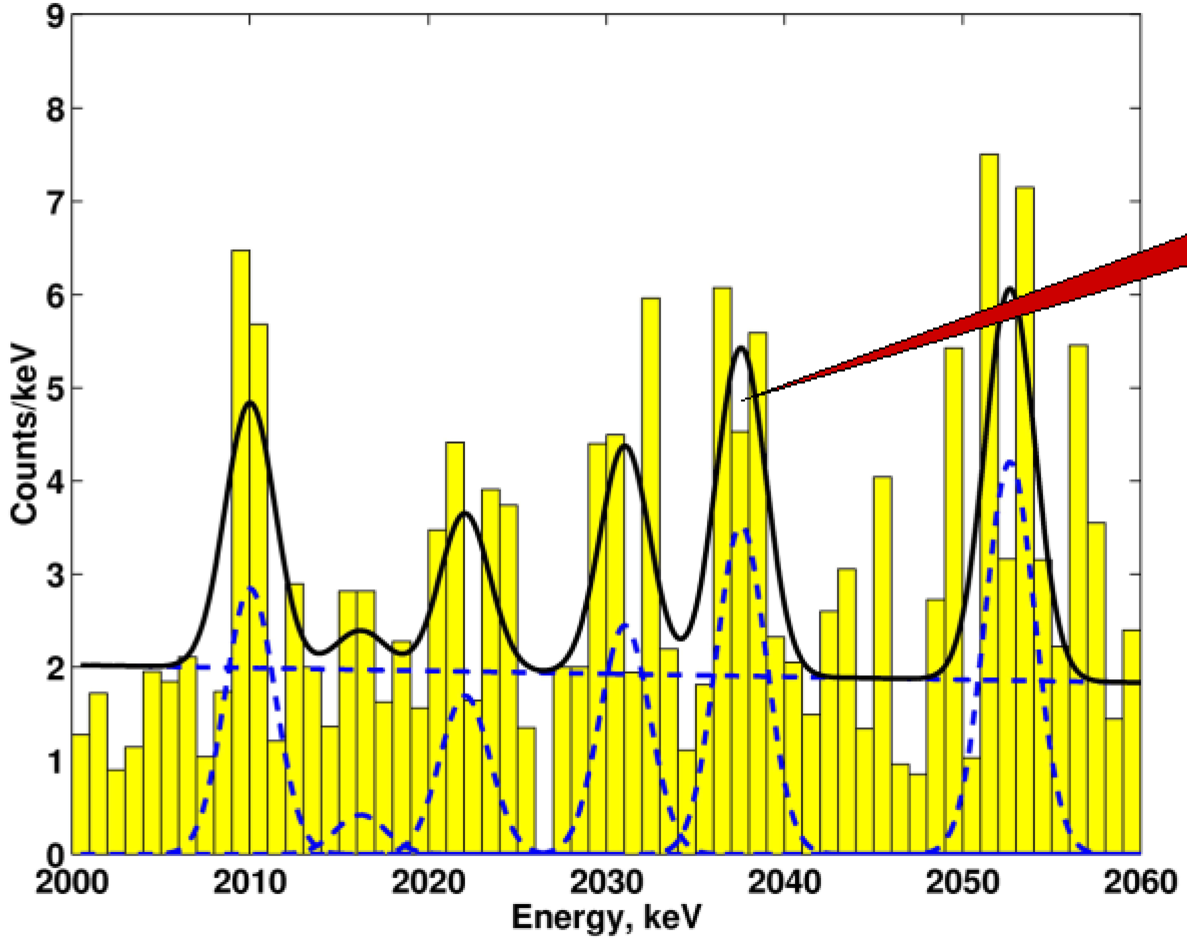


Fig. 31. The single site sum spectrum of the four detectors 2,3,4,5 for the period November 1995 to May 2003 (51.389 kg y), and its fit (see section 3), in the range 2000 - 2060 keV.

Claimed evidence for $0\nu2\beta$ line now ~ 4σ

Frontiers of Cosmology

Missing pieces of 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
($0\nu2\beta$ decay $\leftrightarrow$ leptogenesis)

Search for physics beyond the concordance model

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, ...)


DENNIS the MENACE
(Dennis the Menace® used by permission of Hank Ketcham and ©North America Syndicate)
"LOTS OF THINGS ARE INVISIBLE, BUT WE DON'T KNOW HOW MANY BECAUSE WE CAN'T SEE THEM."