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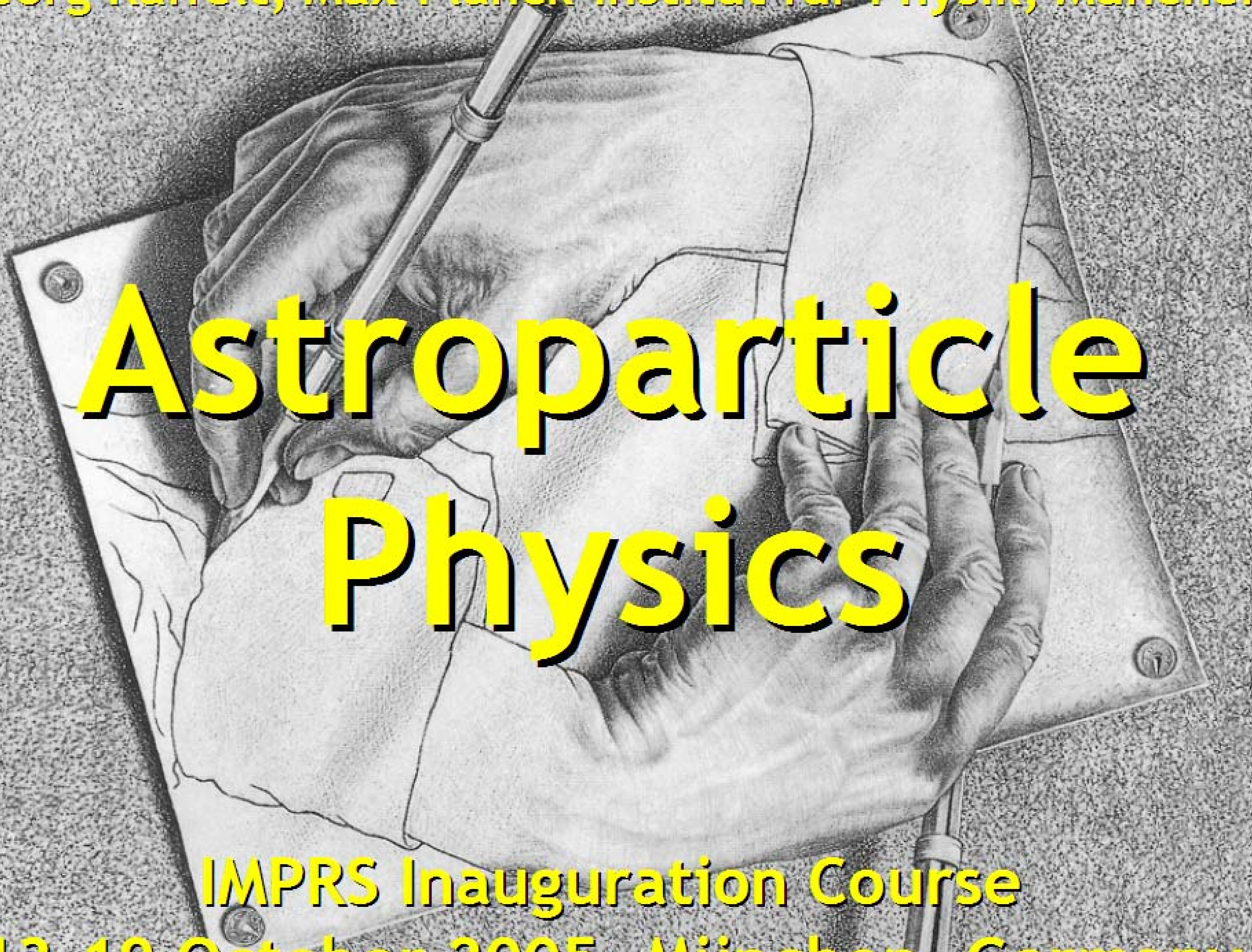
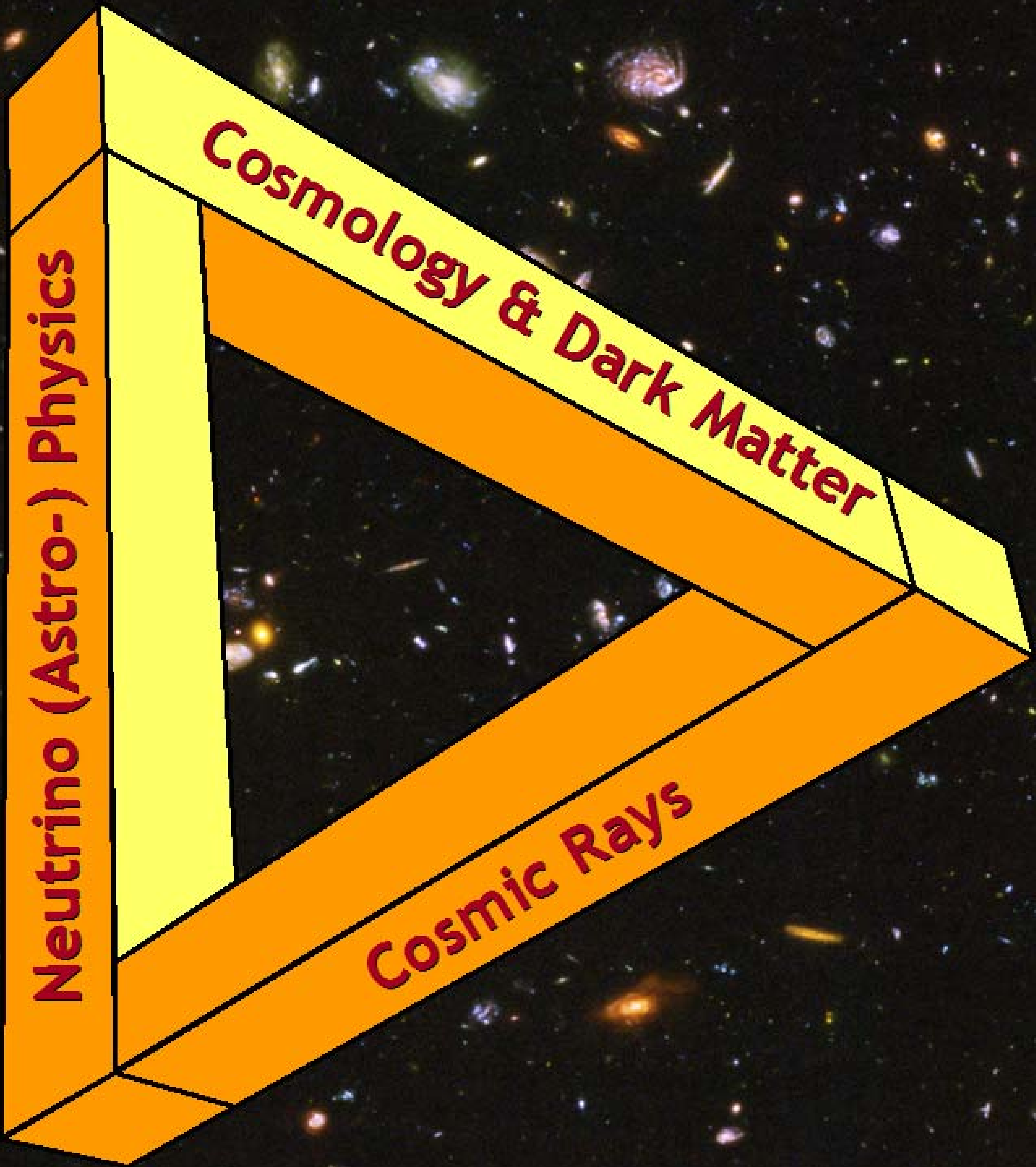


Astroparticle Physics

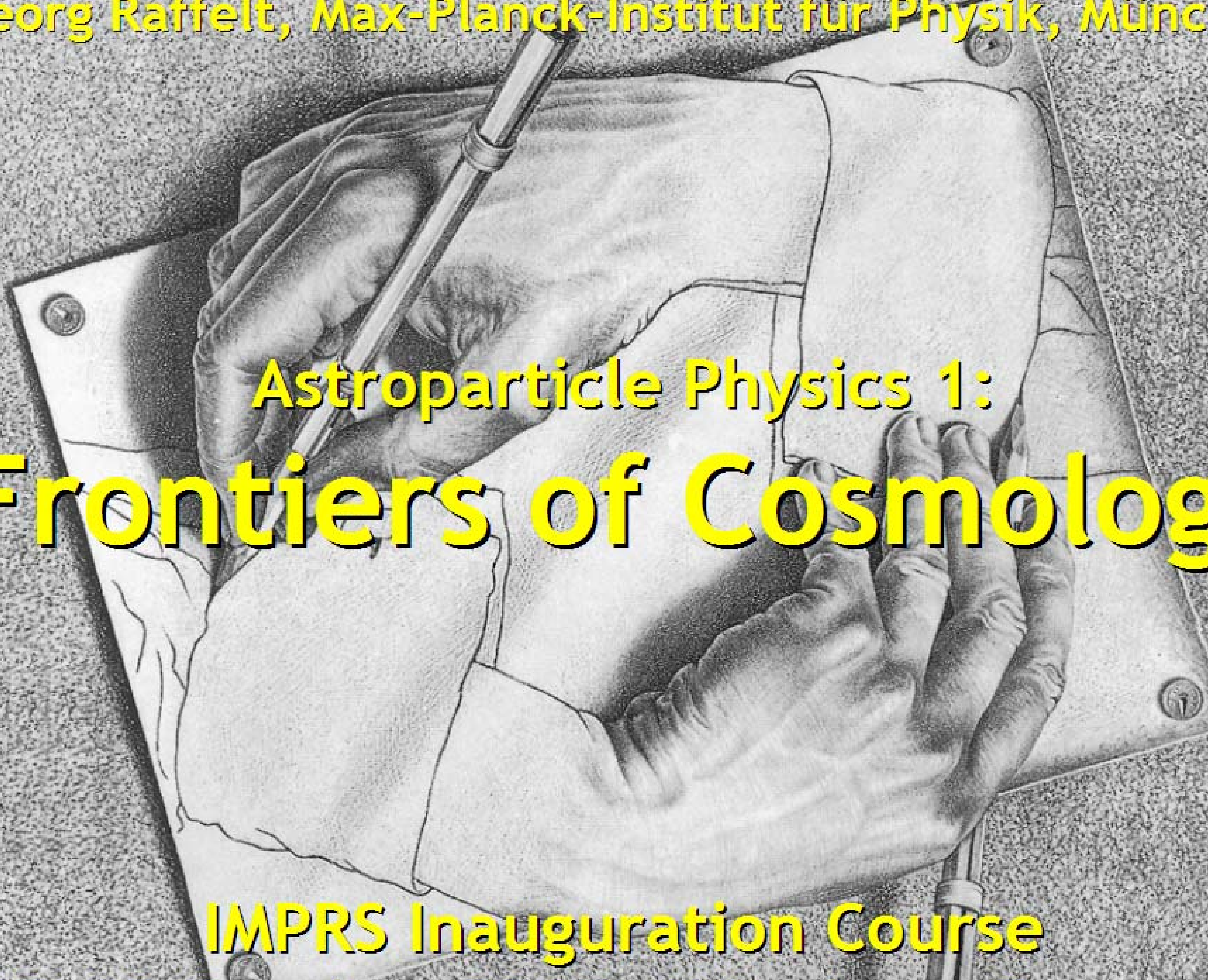
IMPRS Inauguration Course
13-19 October 2005, München, Germany



Cosmology & Dark Matter

Neutrino (Astro-) Physics

Cosmic Rays



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Astroparticle Physics 1:

Frontiers of Cosmology

IMPRS Inauguration Course

13-19 October 2005, München, 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

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

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

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

Friedmann-Lemaître-Robertson-Walker Cosmology

- On scales $\gtrsim$ 100 Mpc, space is maximally symmetric (homogeneous & isotropic)
- The corresponding Robertson-Walker metric is

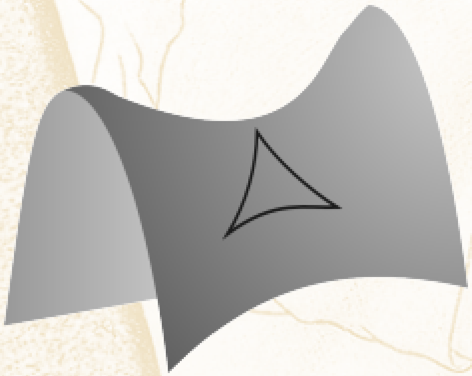
$$ds^2 = dt^2 + a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2(d\theta^2 + \sin^2\theta\, d\phi^2)\right]$$

Clock time of co-moving observer

Cosmic scale factor

Curvature $k = 0, \pm 1$

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



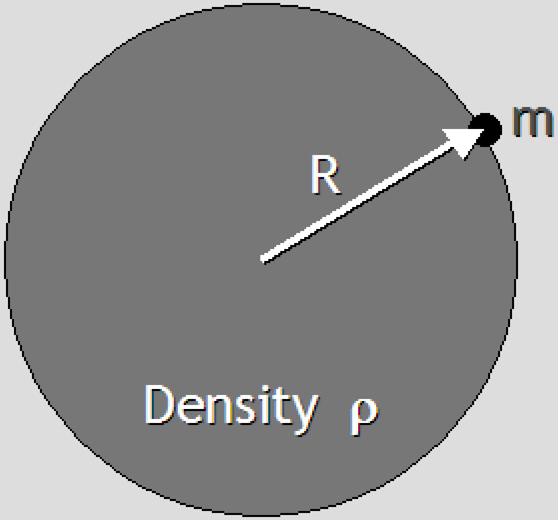
$k = -1$

$k = 0$

$k = +1$

Friedmann Equation - Newtonian Derivation

- Birkhoff’s theorem
  Spherical symmetry implies that only mass interior to radius R = ra is relevant for motion of a test mass m at R



- Energy conservation

$$-\frac{G_N \frac{4\pi}{3} R^3 \rho m}{R} + \frac{1}{2}\dot{R}^2 m = \text{const}$$

$$\left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi}{3} G_N \rho + \frac{\text{const}}{R^2}$$

- Rescale r = a/R with cosmic scale factor a

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3} G_N \rho - \frac{k}{a^2} \quad \text{with} \quad k = 0, \pm 1$$

Friedmann equation

Einstein's "Greatest Blunder"

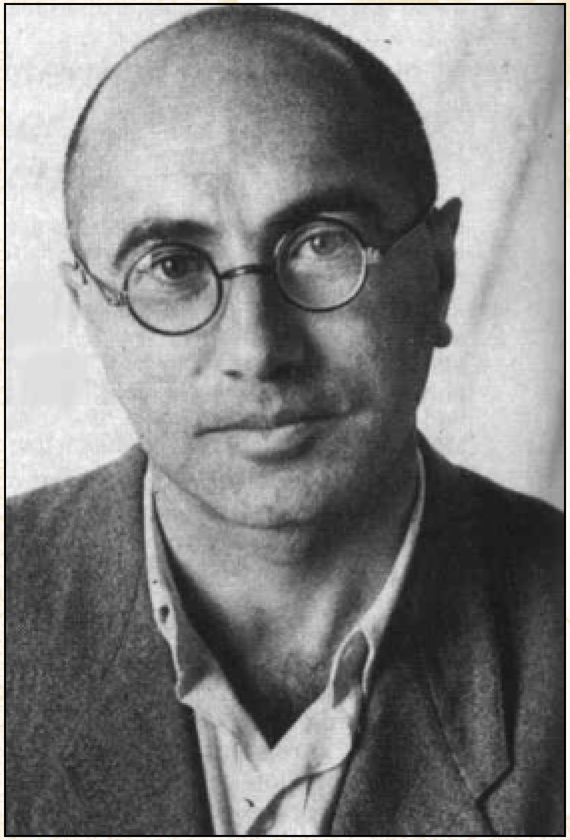
Density of gravitating mass & energy

Newton's constant

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

Friedmann equation for
Hubble's expansion rate

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



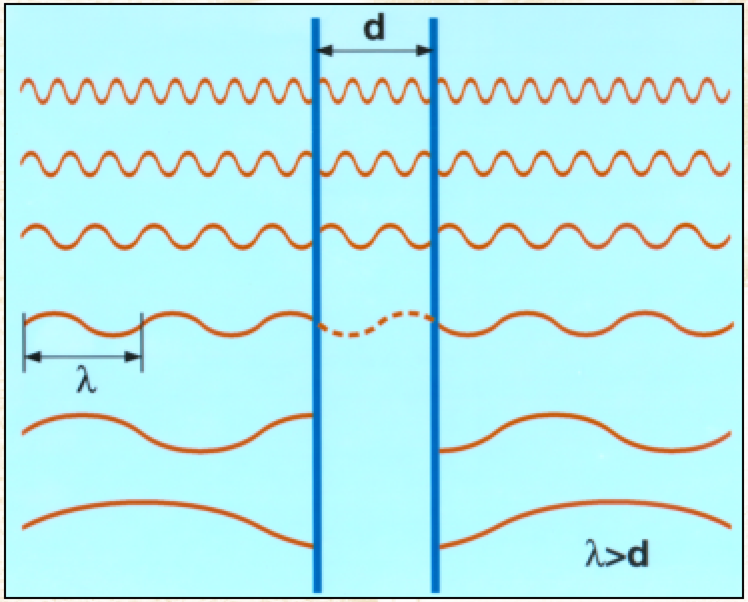
Yakov
Borisovich
Zeldovich
1914-1987

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

Casimir Effect (1948)

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



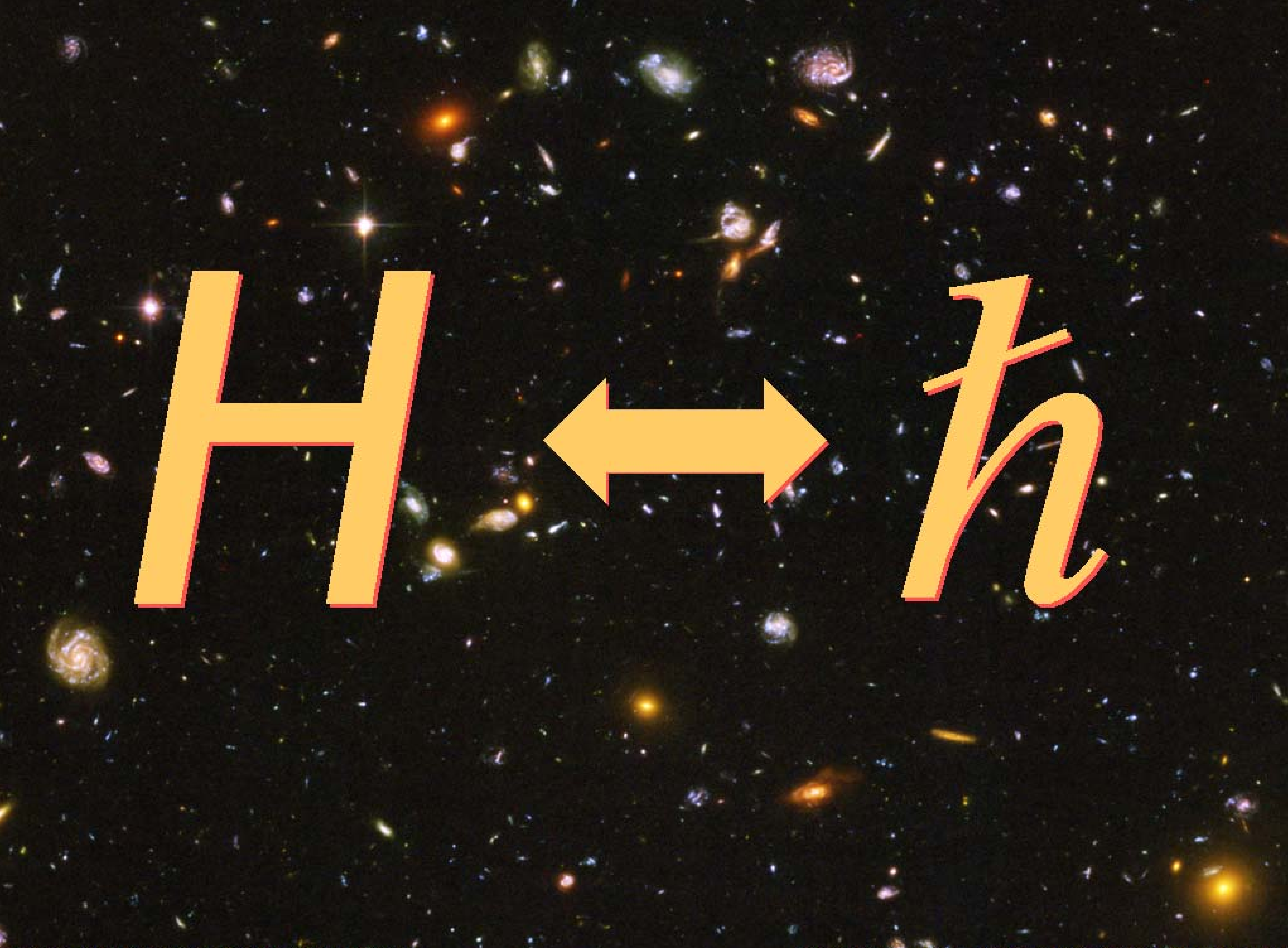
Long-wavelength field modes between the plates are "displaced," causing a reduction of the vacuum energy compared with free space

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)



$$H \leftrightarrow \hbar$$

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"

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

Cosmic density always expressed in terms of

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

With the present-day Hubble parameter

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

the critical density is

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

With the measured value

$$h = 0.72 \pm 0.04$$

the critical density is

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

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

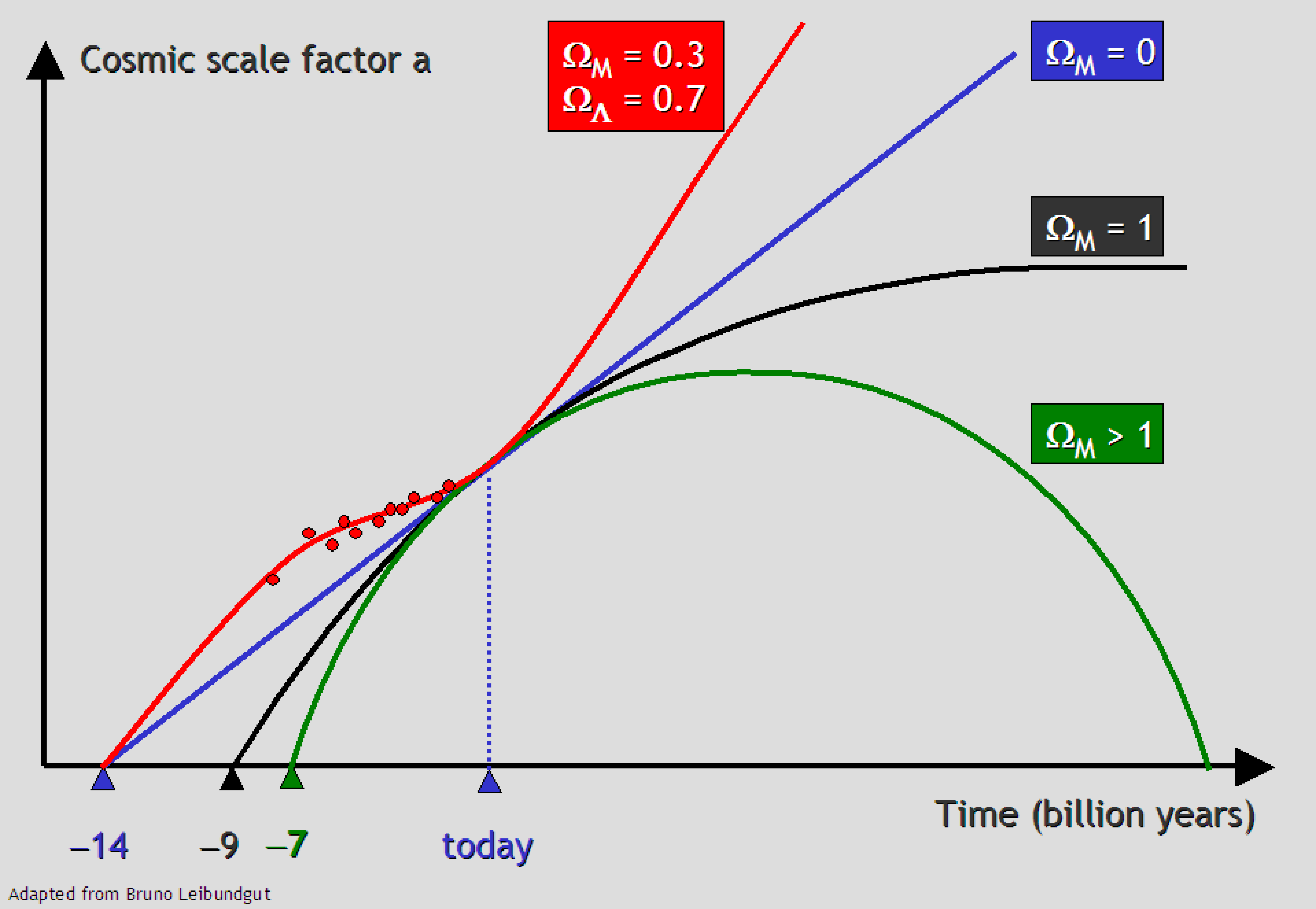
Generic Solutions of Friedmann Equation

	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	$a(t) \propto \exp\left(\sqrt{\Lambda/3}\,t\right)$ $\Lambda = 8\pi G_N \rho_{\rm vac}$

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

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

Expansion of Different Cosmological Models



Adapted from Bruno Leibundgut

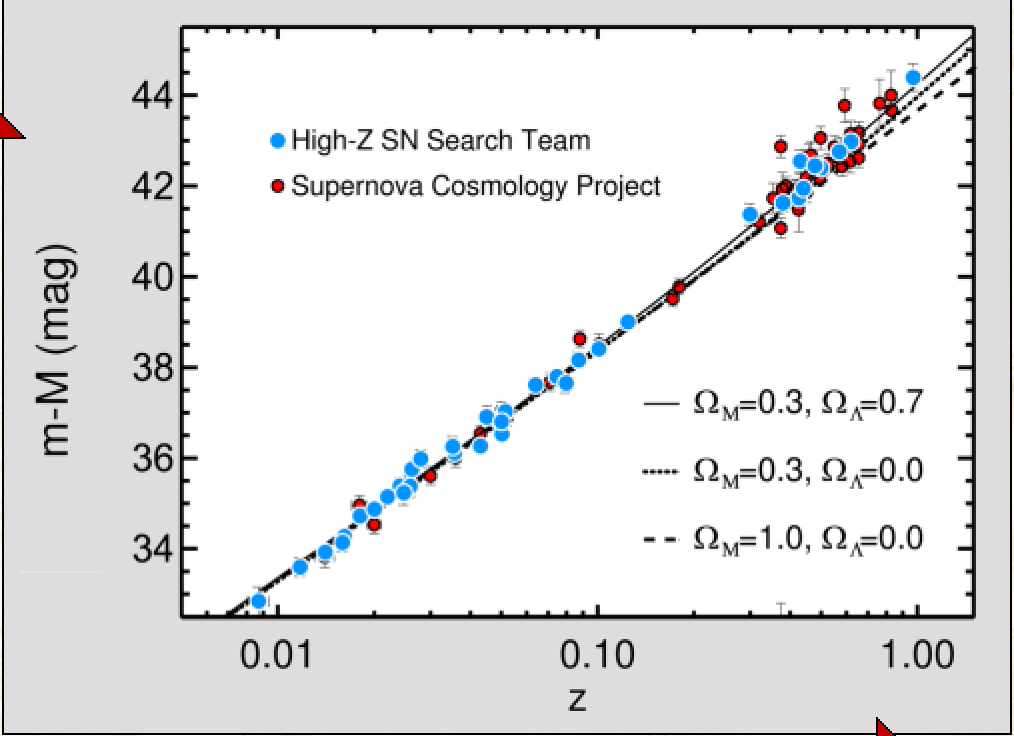
Supernovae: Almost as Bright as Galaxies

SN 1998S in NGC 3877

SN 1994D in NGC 4526

Hubble Diagram

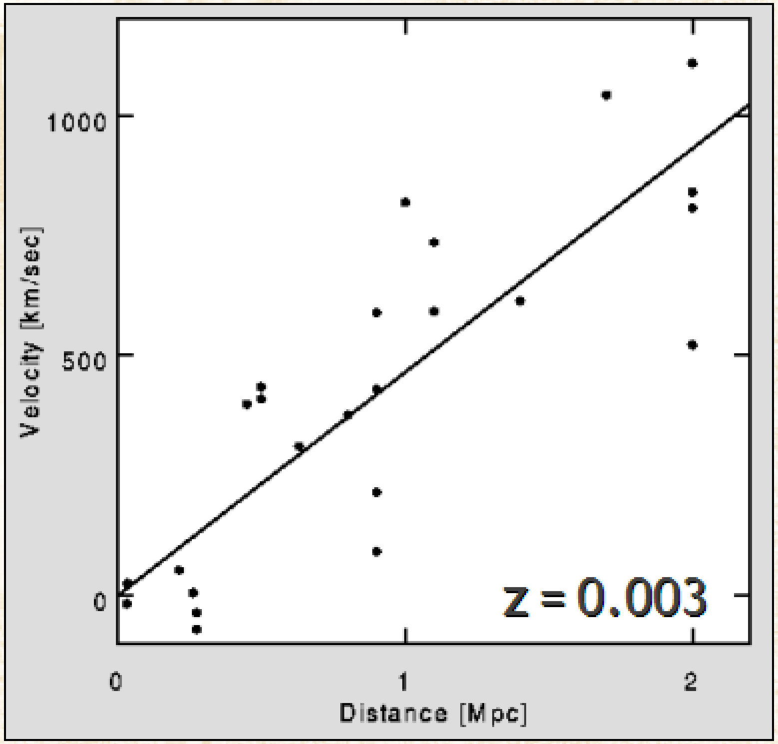
Apparent Brightness



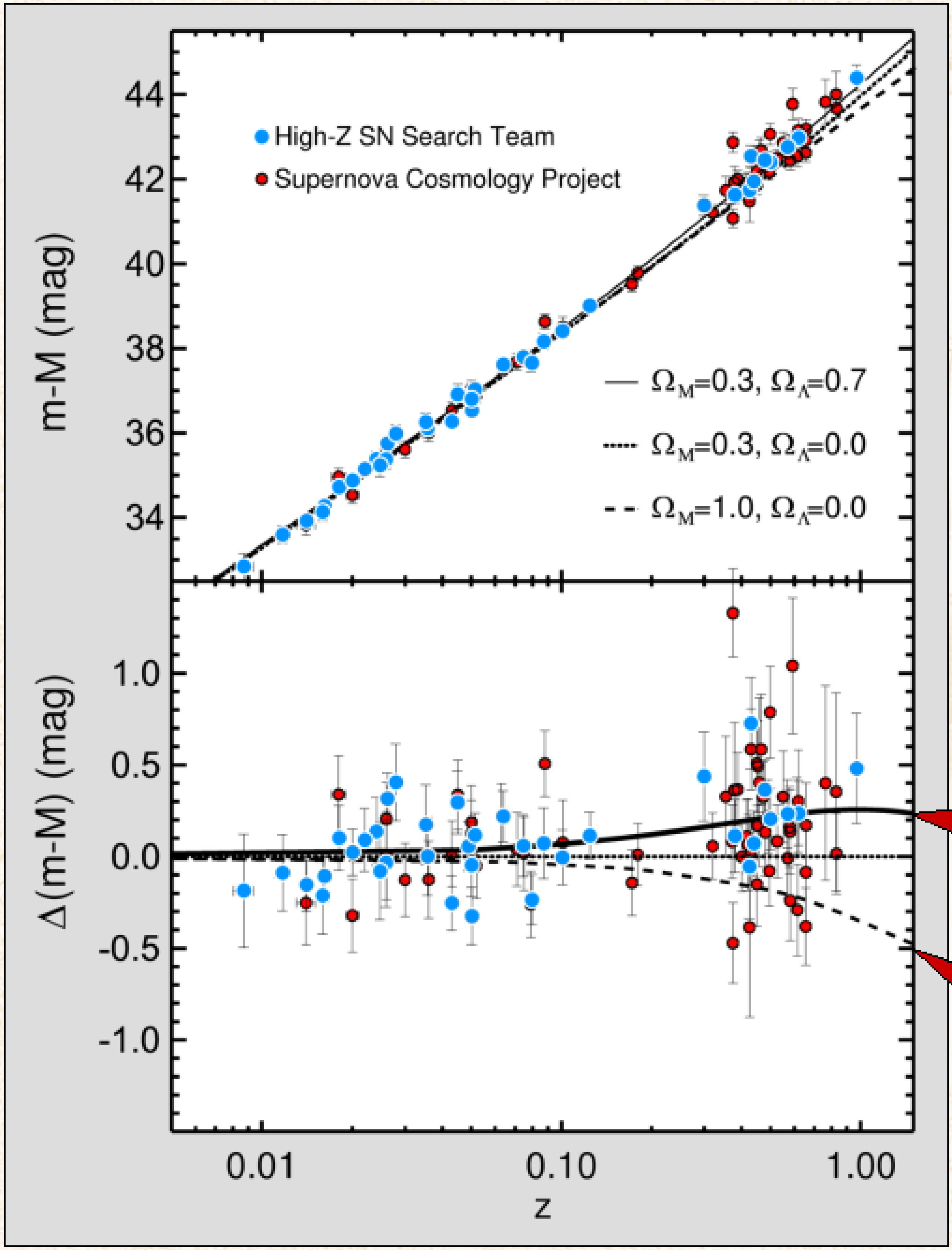
Redshift

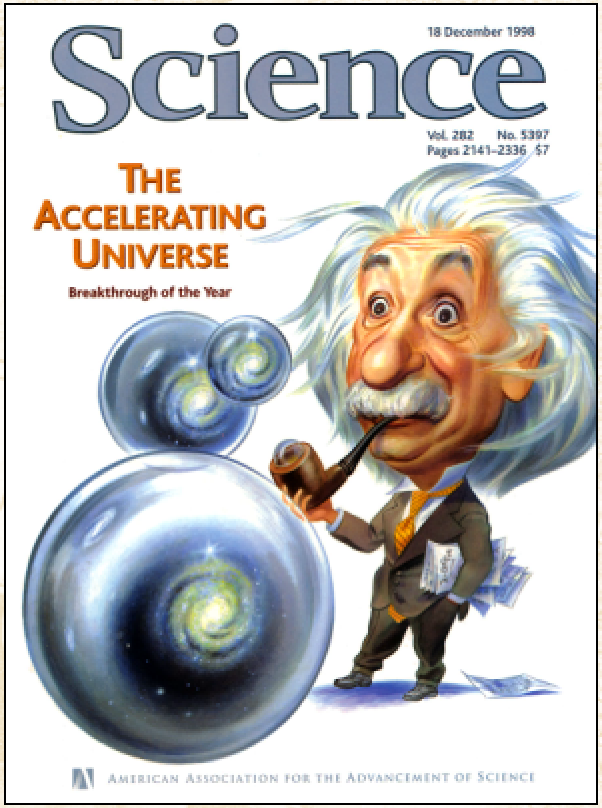
Supernova Ia
as cosmological
standard candles

Hubble’s orginal data (1929)



Hubble Diagram

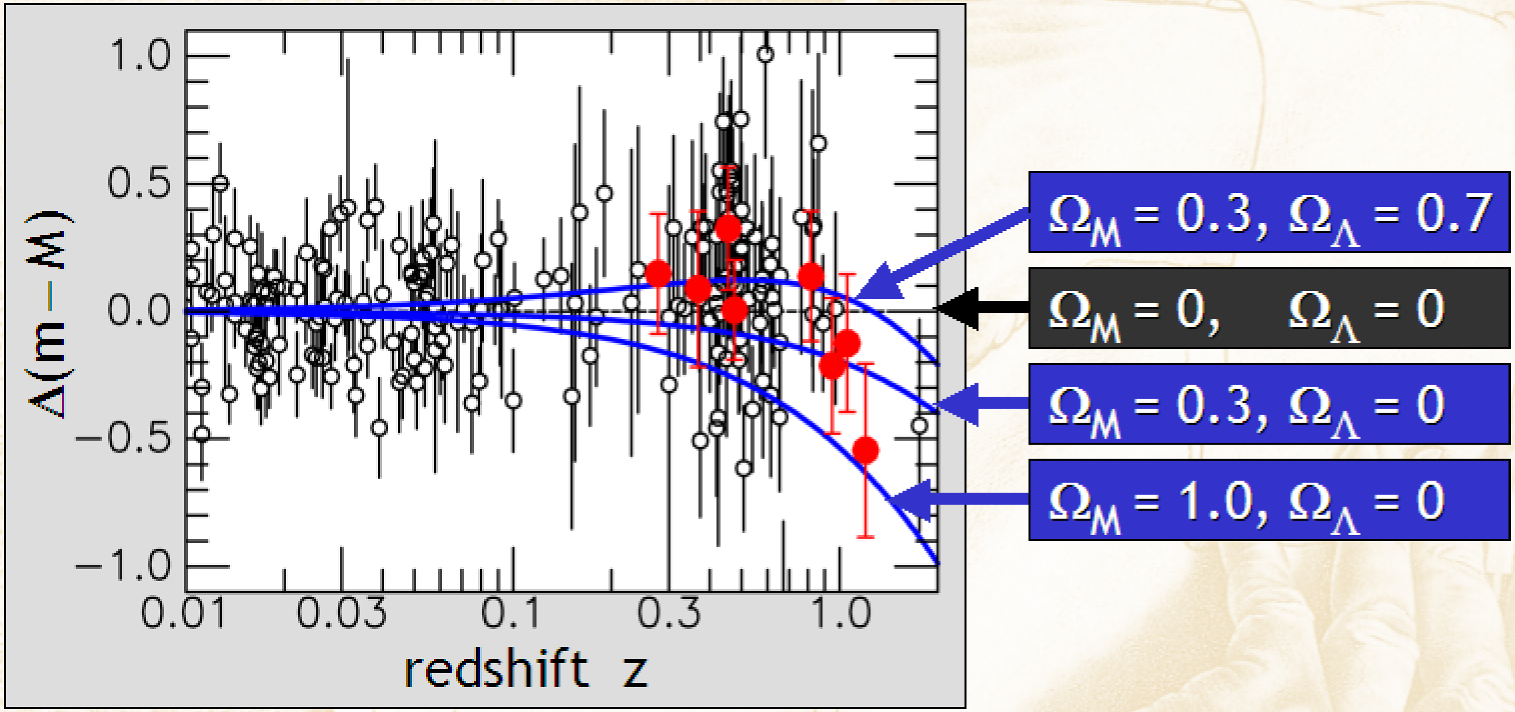




Accelerated expansion ($\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$)

Decelerated expansion ($\Omega_M = 1$)

Latest Supernova Ia Data



$\Omega_M = 0.3, \Omega_\Lambda = 0.7$

$\Omega_M = 0, \quad \Omega_\Lambda = 0$

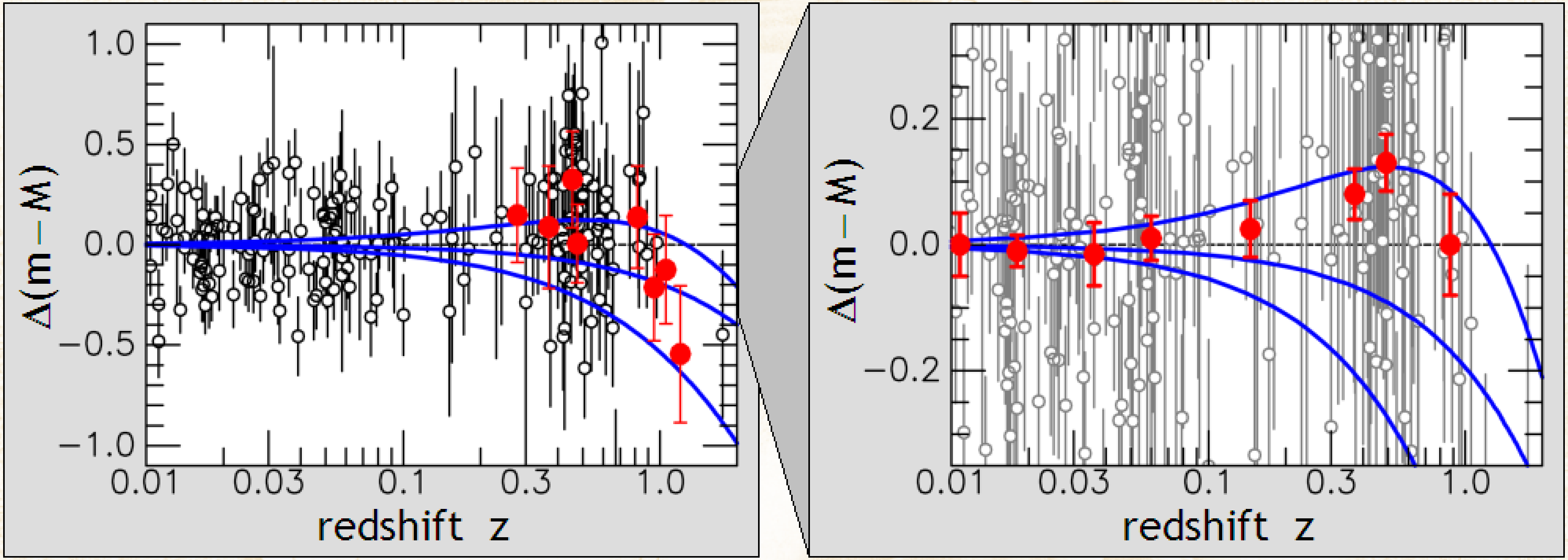
$\Omega_M = 0.3, \Omega_\Lambda = 0$

$\Omega_M = 1.0, \Omega_\Lambda = 0$

209 SNe with fall 1999 data in red

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

Latest Supernova Ia Data

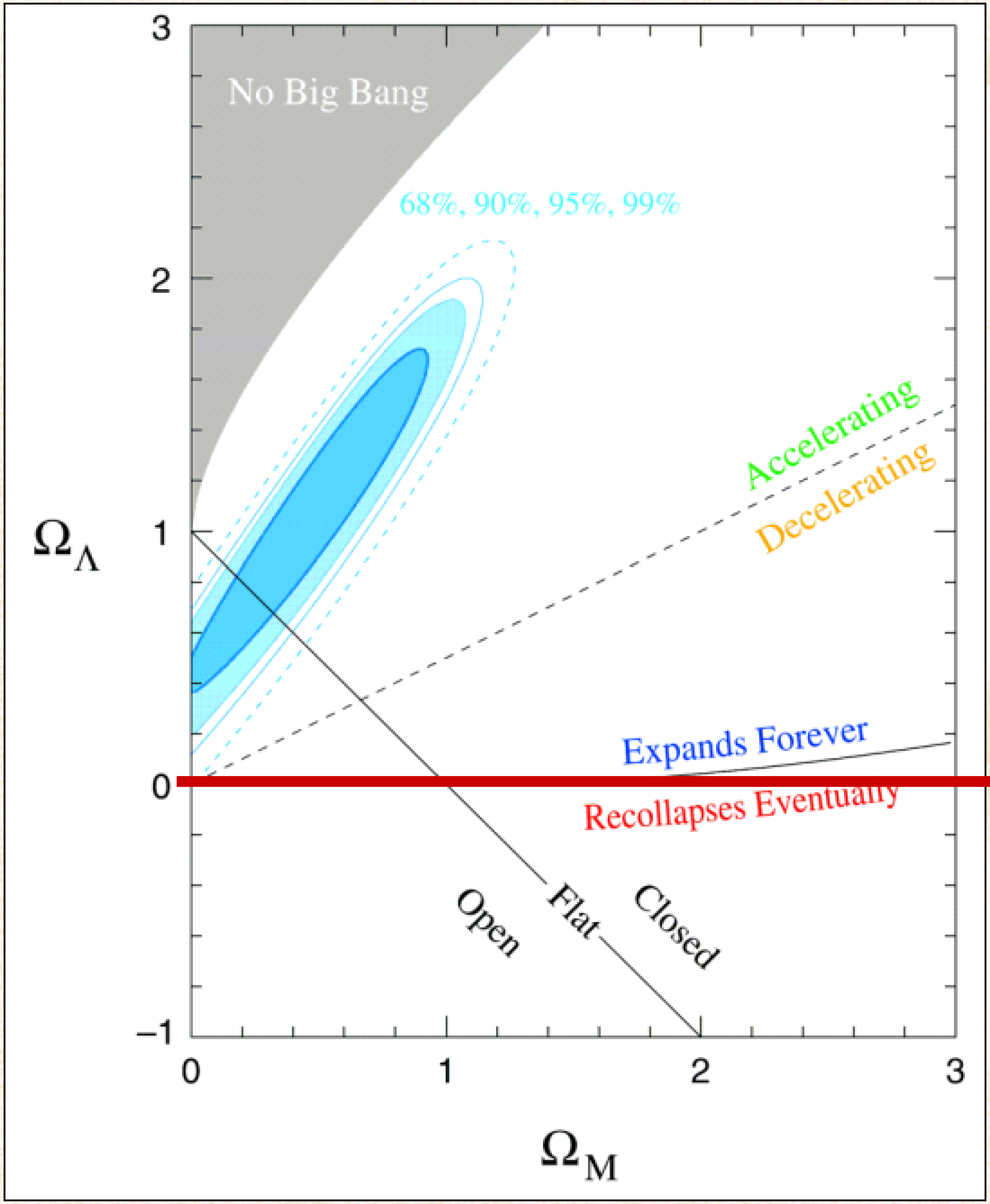


209 SNe with fall 1999 data in red

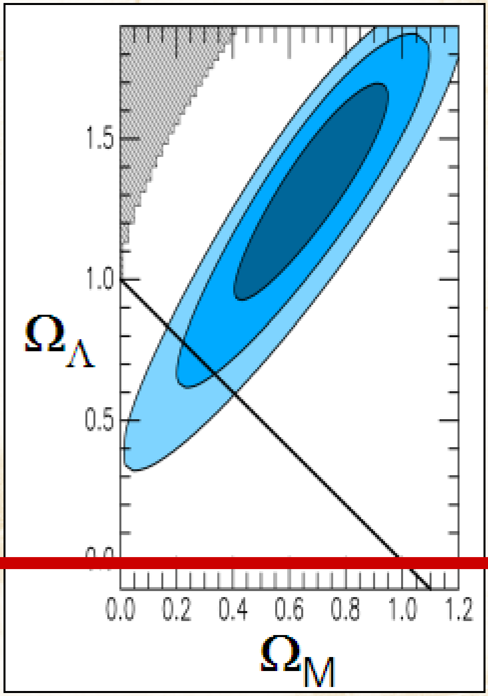
209 SNe with binned data in red

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

Fitting Cosmological Parameters



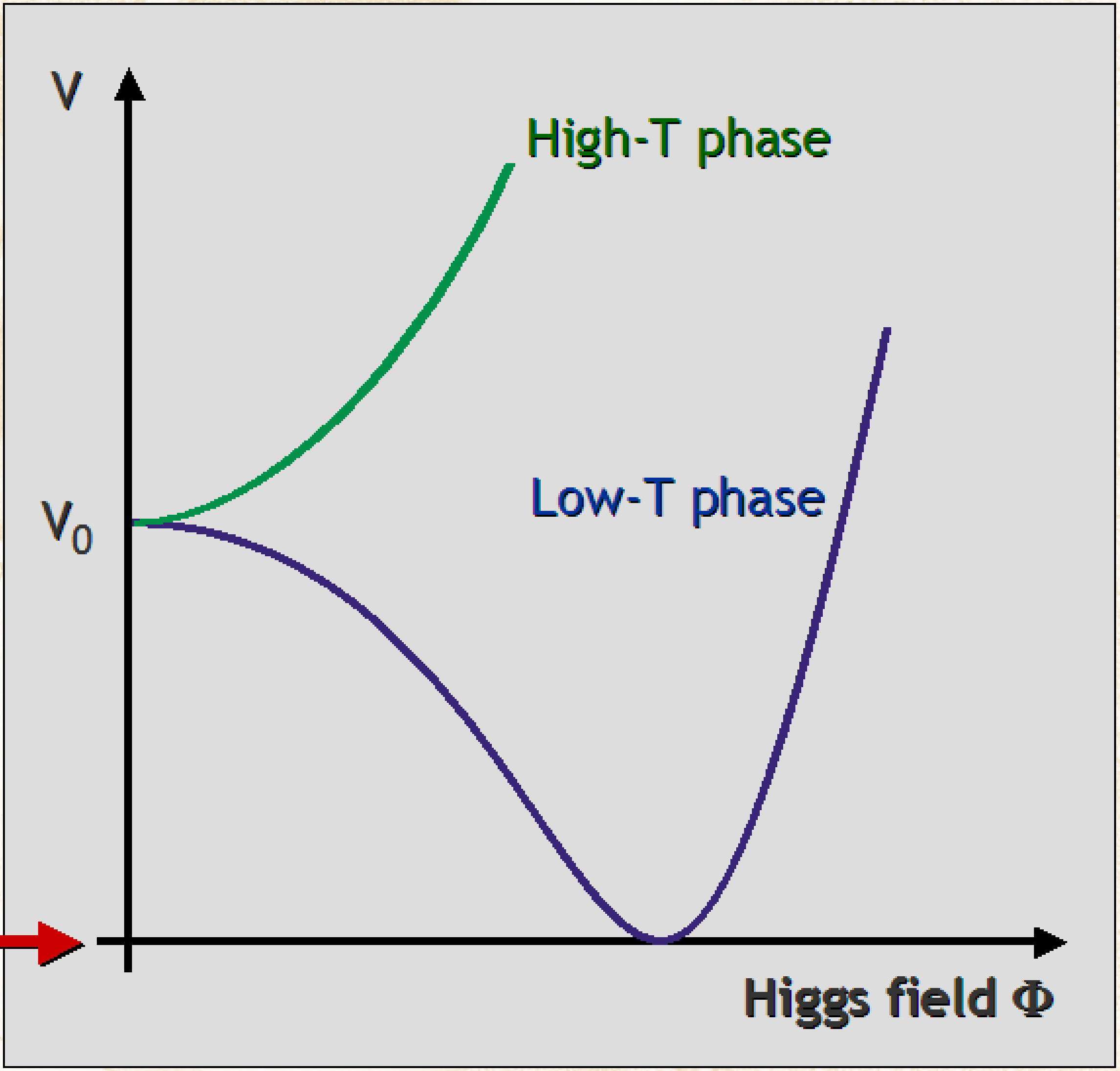
High-z supernova team
(Tonry et al.)
astro-ph/0305008



$\Lambda = 0$
excluded
at many sigma

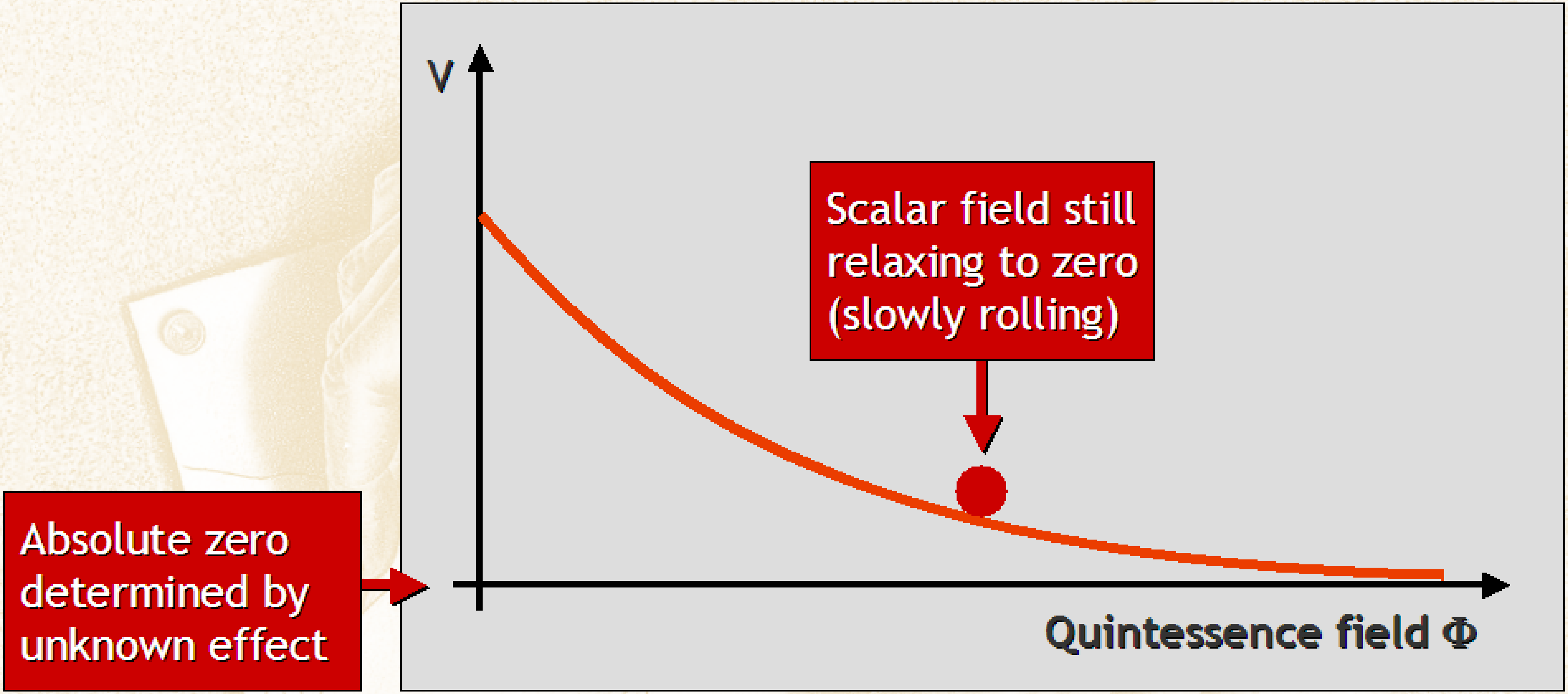
Cosmological Supernova Project
(Knop et al.), astro-ph/0309368

Scalar Fields and Cosmological Constant



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

Quintessence



Scalar field still relaxing to zero (slowly rolling)

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

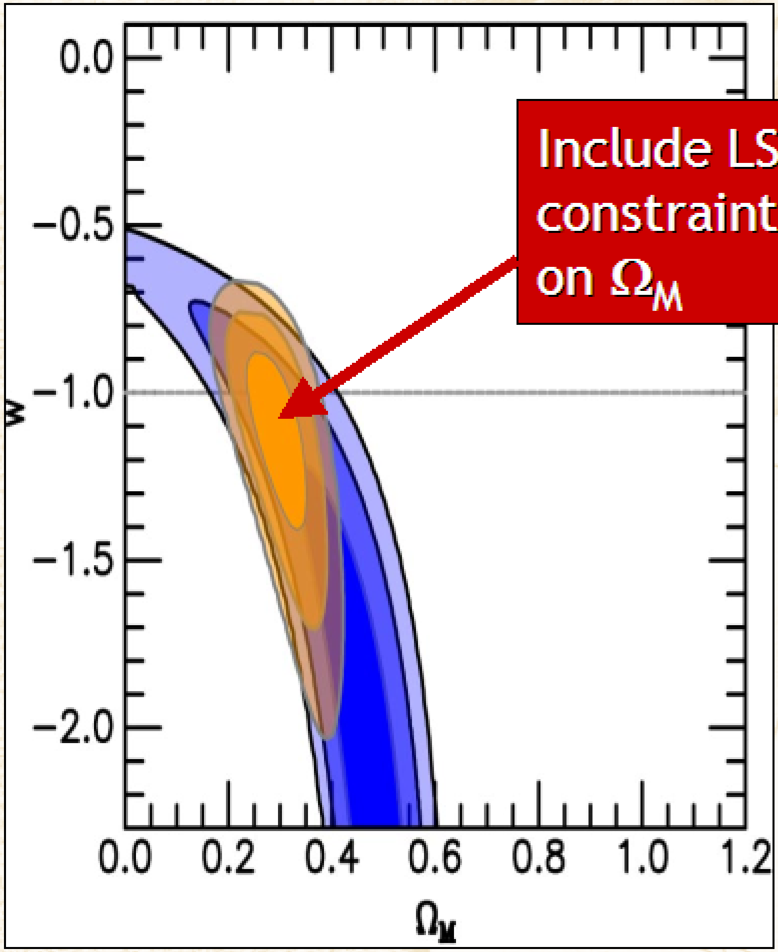
Energy-momentum tensor of homogeneous Φ-mode that of an isotropic perfect fluid	$\rho = \frac{1}{2}(\partial_t\Phi)^2 + V(\Phi)$ $p = \frac{1}{2}(\partial_t\Phi)^2 - V(\Phi)$
General equation of state	$p = w\,\rho$
Example: Exponential potential	$V(\Phi) = V_0\; e^{-\lambda 8\pi G_N \Phi}$
Explicit solution 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	$\lambda^2 = 4$	$w = 1$

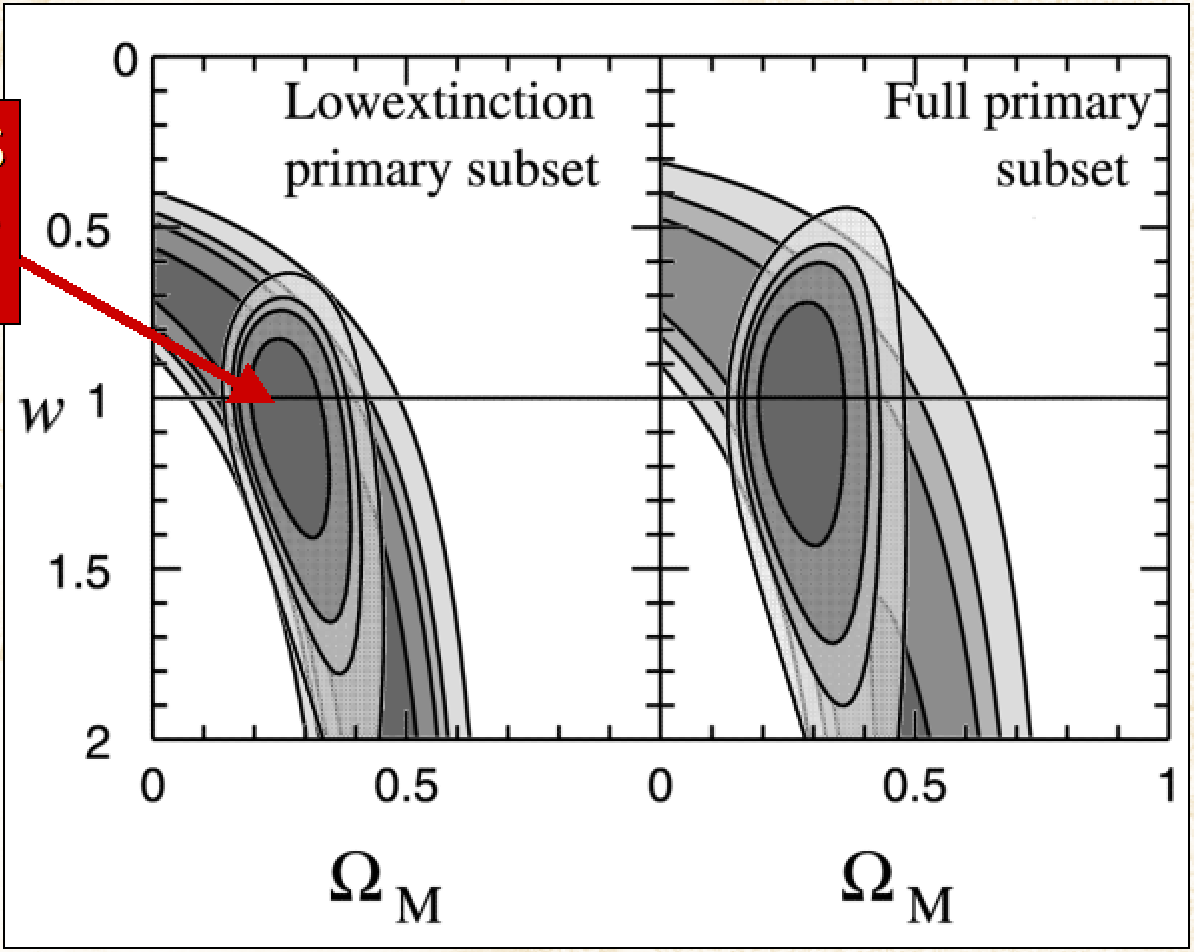
Observational evidence for equation of state with “nonstandard” w-parameter?

Limits on Quintessence

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



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



Include LSS constraints on Ω_M

$$w = -1.05^{+0.15}_{-0.20} \pm 0.09$$

Phantom Energy

What is the meaning of $w < -1$?

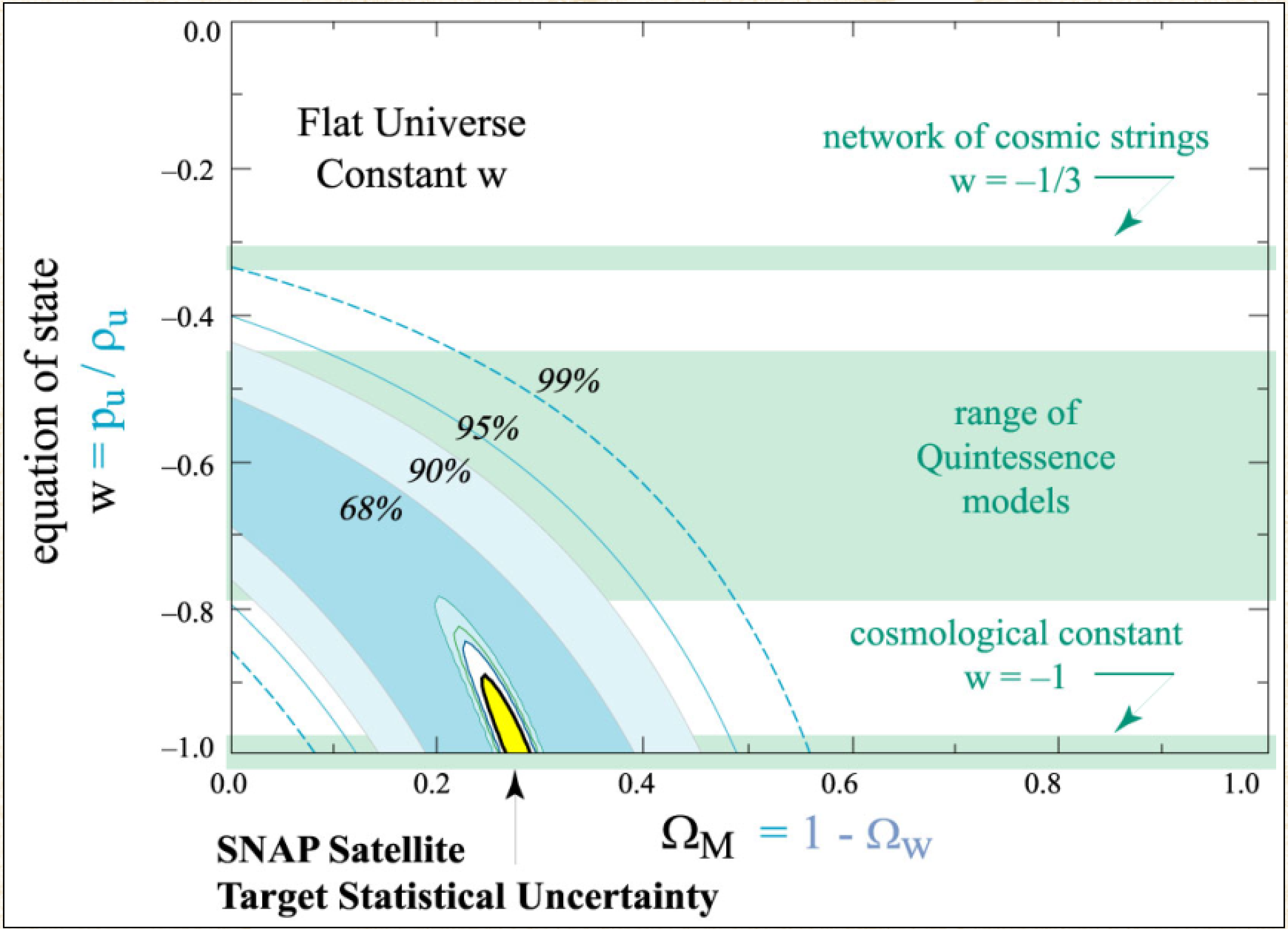
- Violates "dominant energy condition" $\rho + 3p > 0$
- Signals vacuum instability
  (e.g. Cline, Jeon & Moore, hep-ph/0311312)

Singularity of scale factor in the finite future ("big rip")

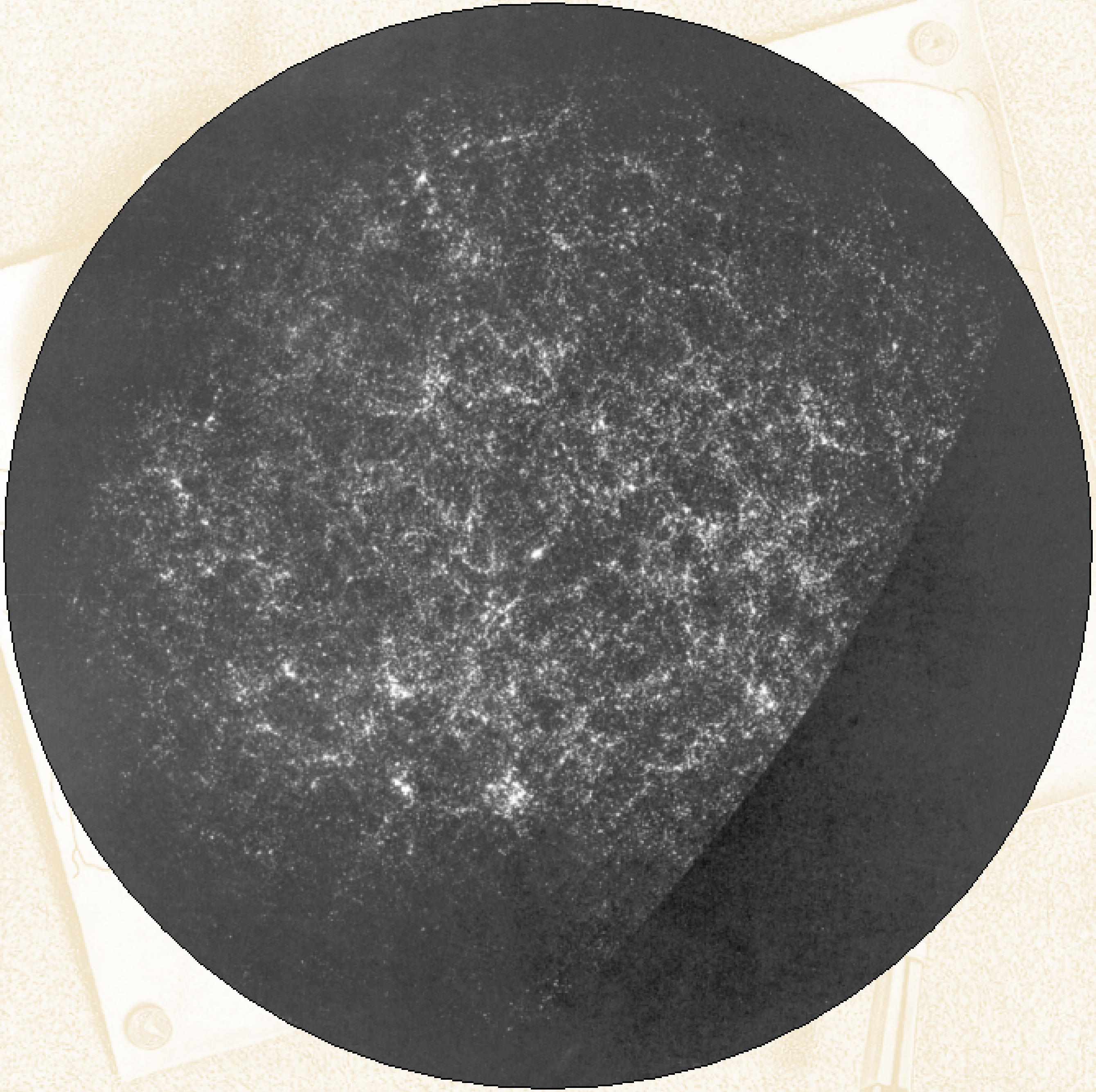
$$t \sim t_0 + \frac{2}{3}\frac{1}{H_0}\frac{1}{|1+w|}\frac{1}{(1-\Omega_M)^{1/2}}$$

(Caldwell, Kamionkowski & Weinberg, astro-ph/0302506)

SNAP Quintessence Sensitivity

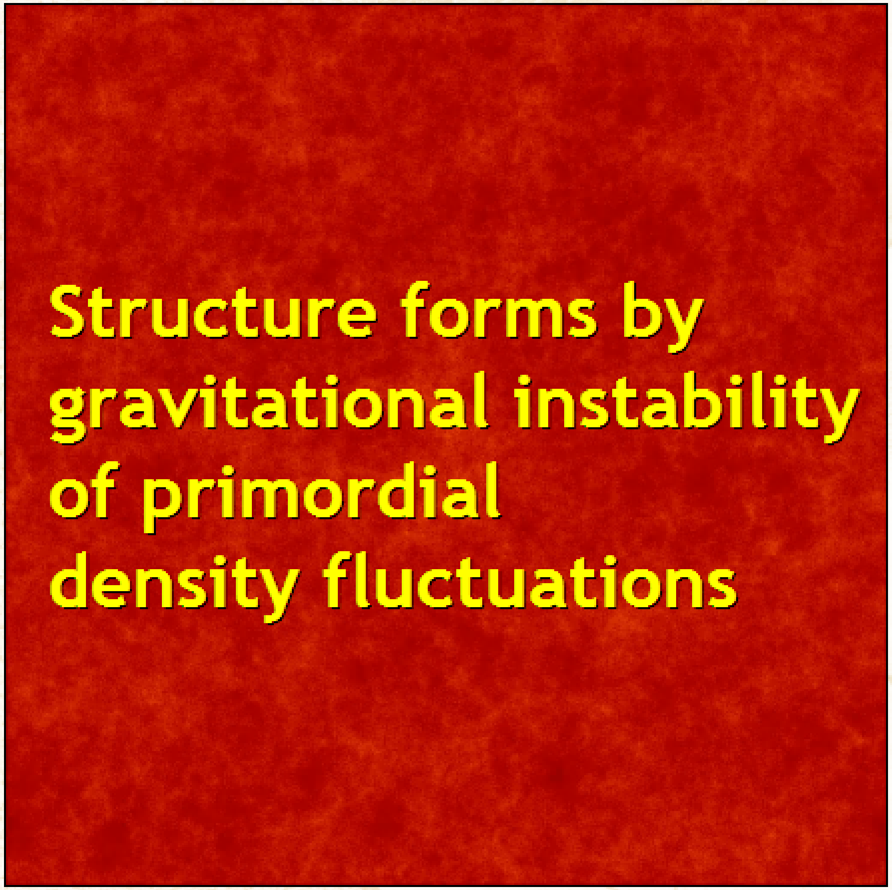


Galaxy Distribution in the Sky

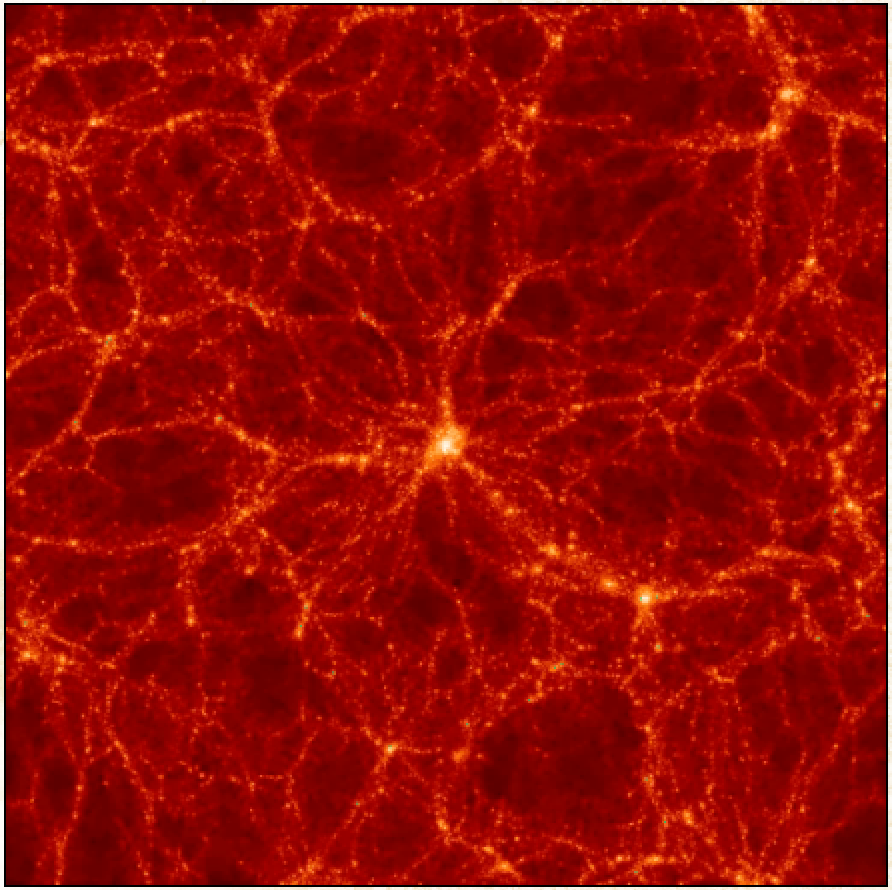


Formation of Structure

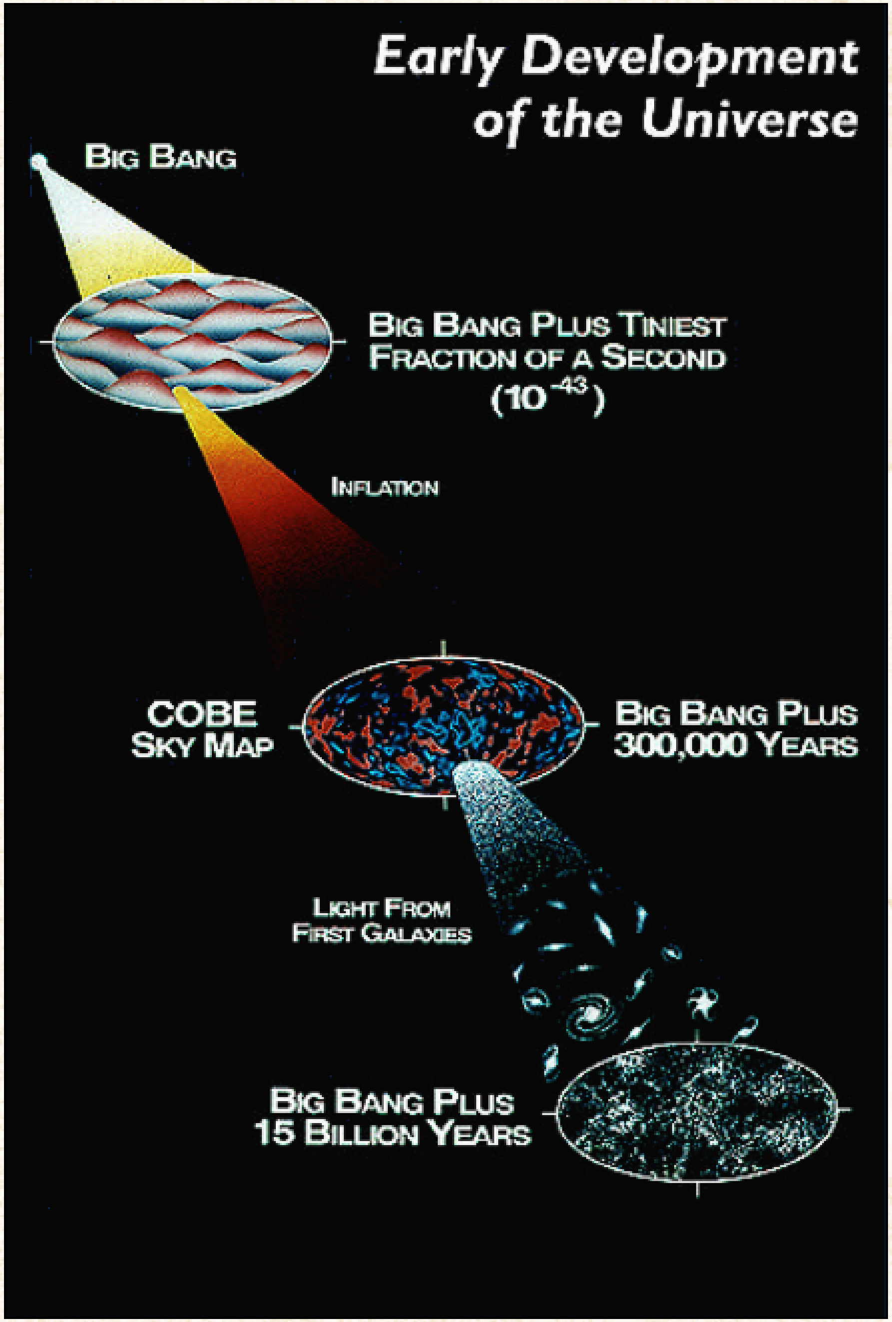
Smooth → **Structured**



Structure forms by gravitational instability of primordial density fluctuations



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

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

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

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 $\lambda \ll H^{-1}$	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

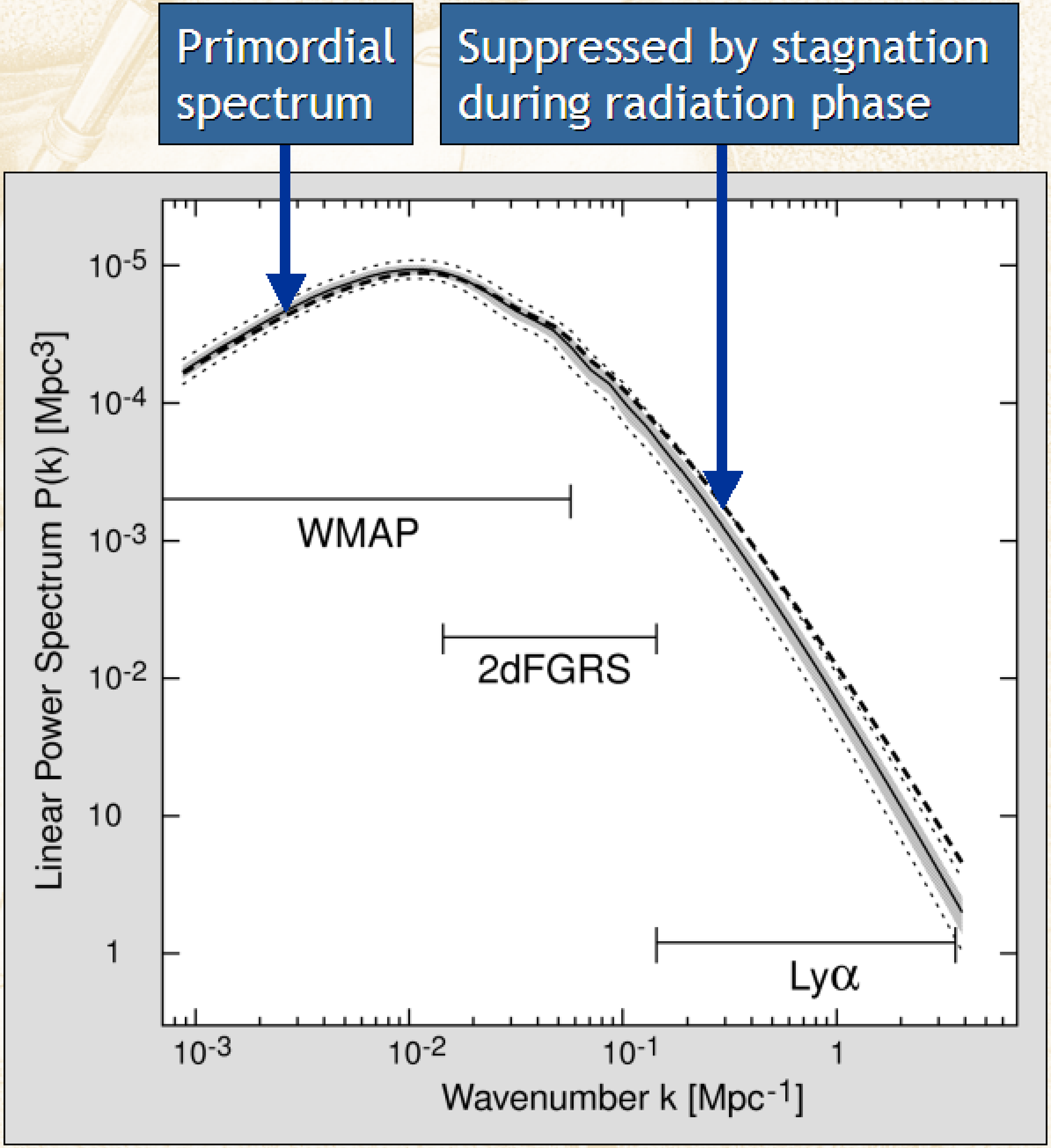
Primordial spectrum usually assumed to be of power-law form

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

Harrison-Zeldovich (“flat”) spectrum

$n = 1$

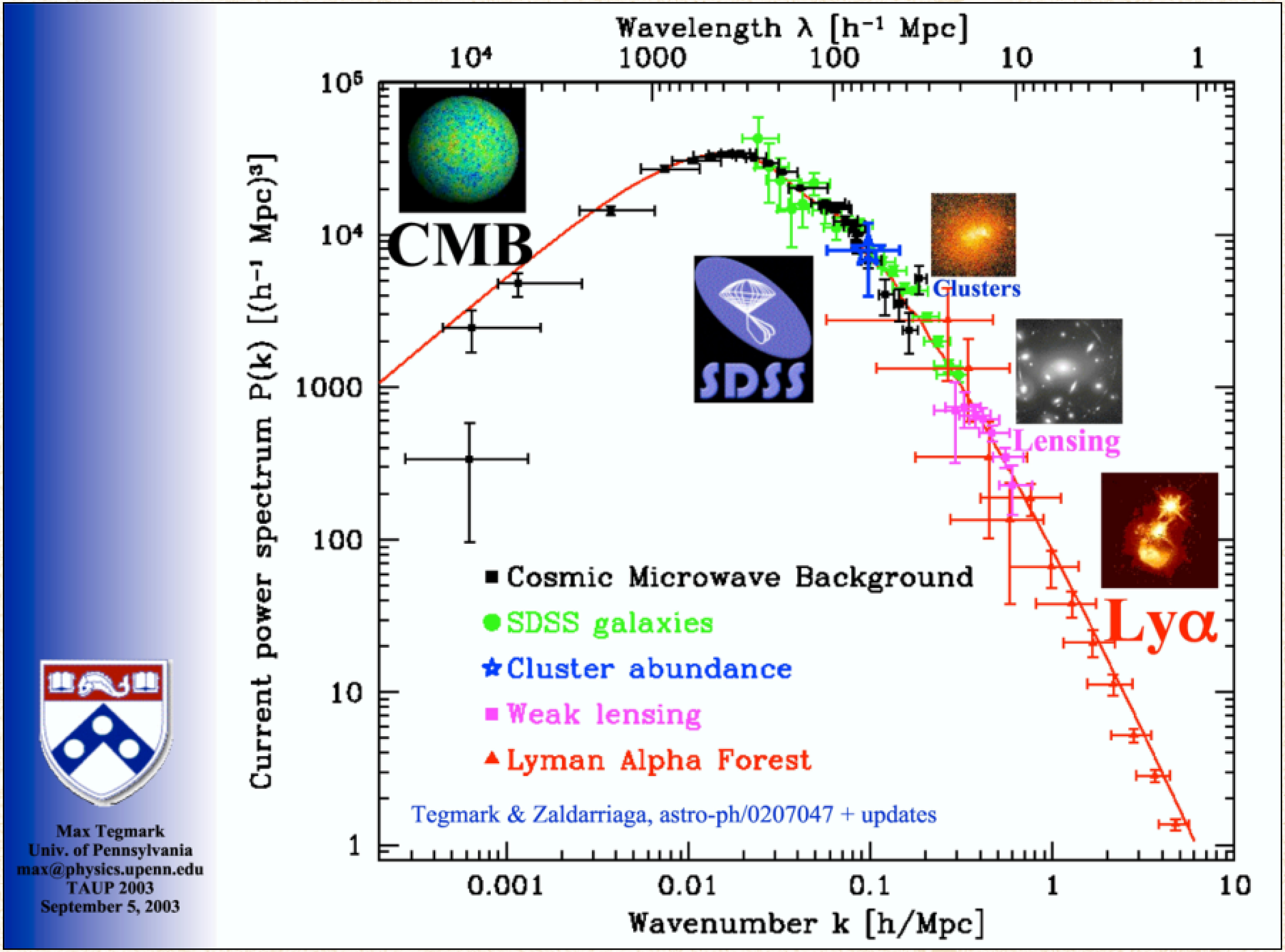
expected from inflation (may be slightly less than 1, depending on details of inflationary phase)



Primordial spectrum

Suppressed by stagnation during radiation phase

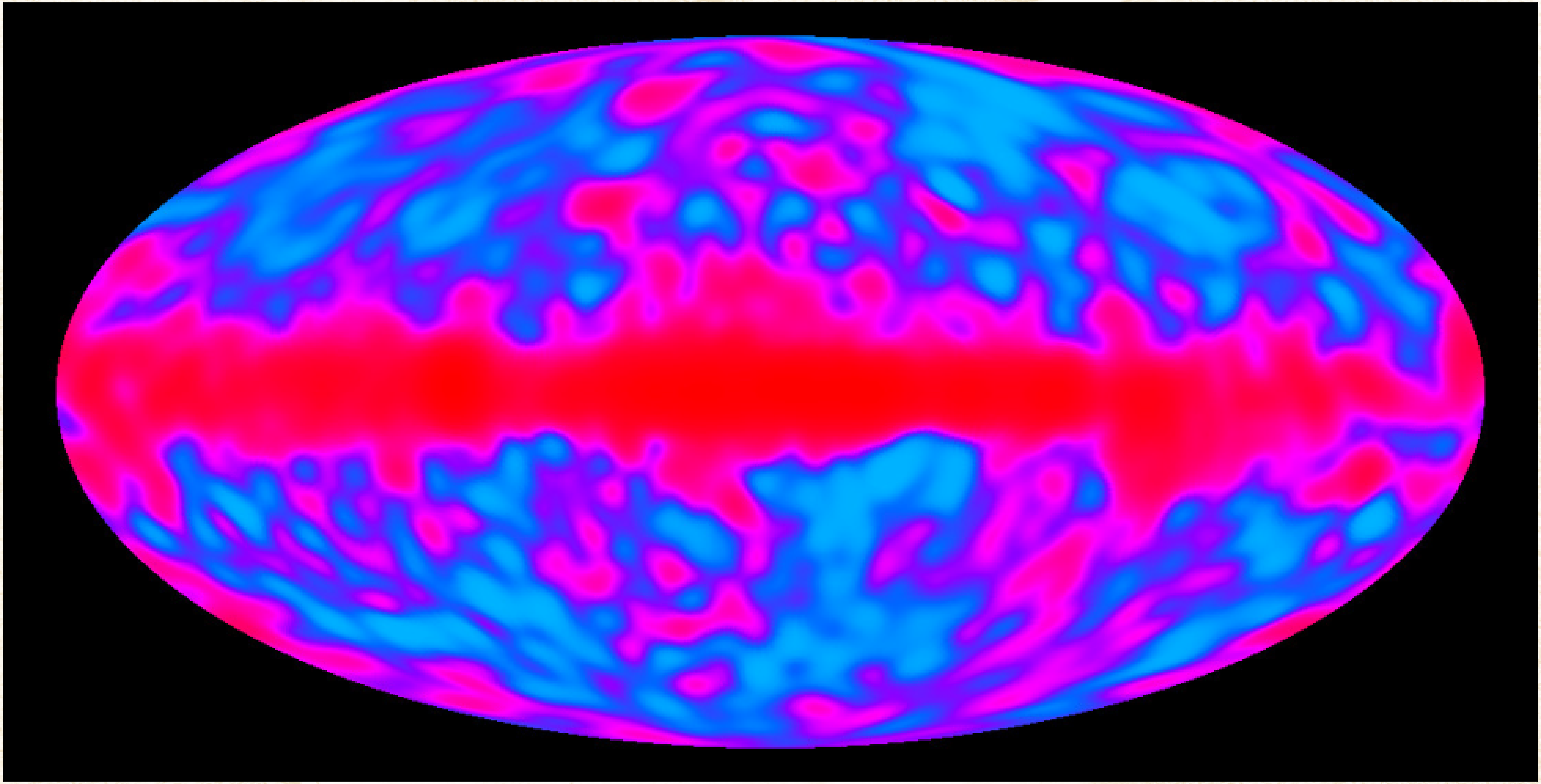
Power Spectrum of Cosmic Density Fluctuations



Tegmark & Zaldarriaga, astro-ph/0207047 + updates

Max Tegmark
Univ. of Pennsylvania
max@physics.upenn.edu
TAUP 2003
September 5, 2003

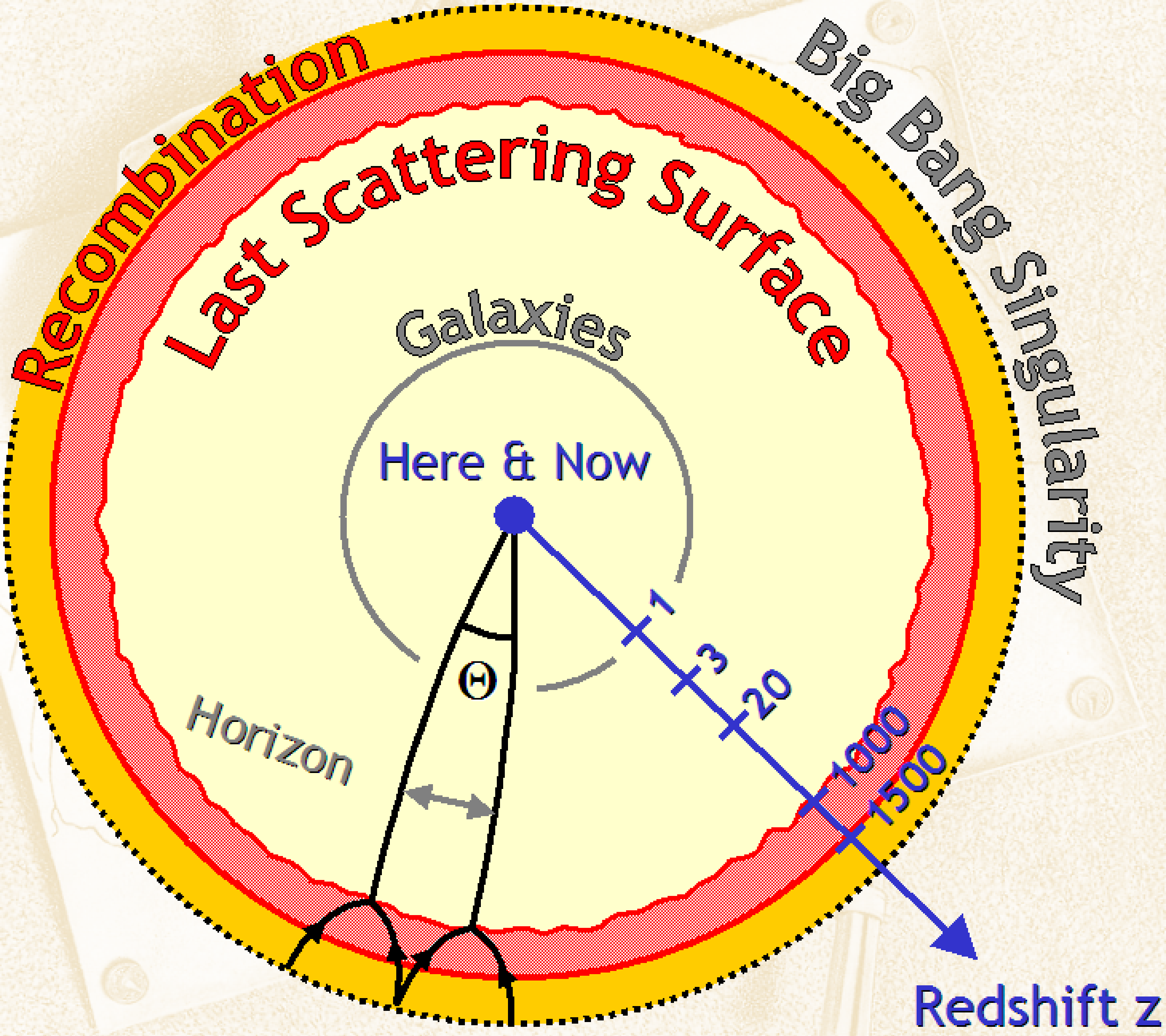
COBE Temperature Map of the Cosmic Microwave Background



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

Primordial temperature fluctuations

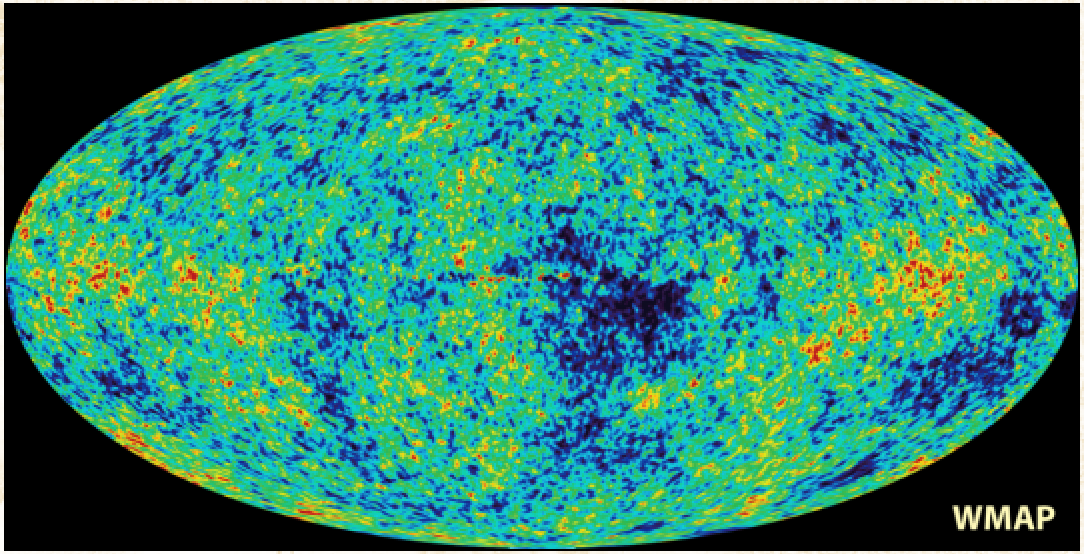
Last Scattering Surface



Power Spectrum of CMBR Temperature Fluctuations

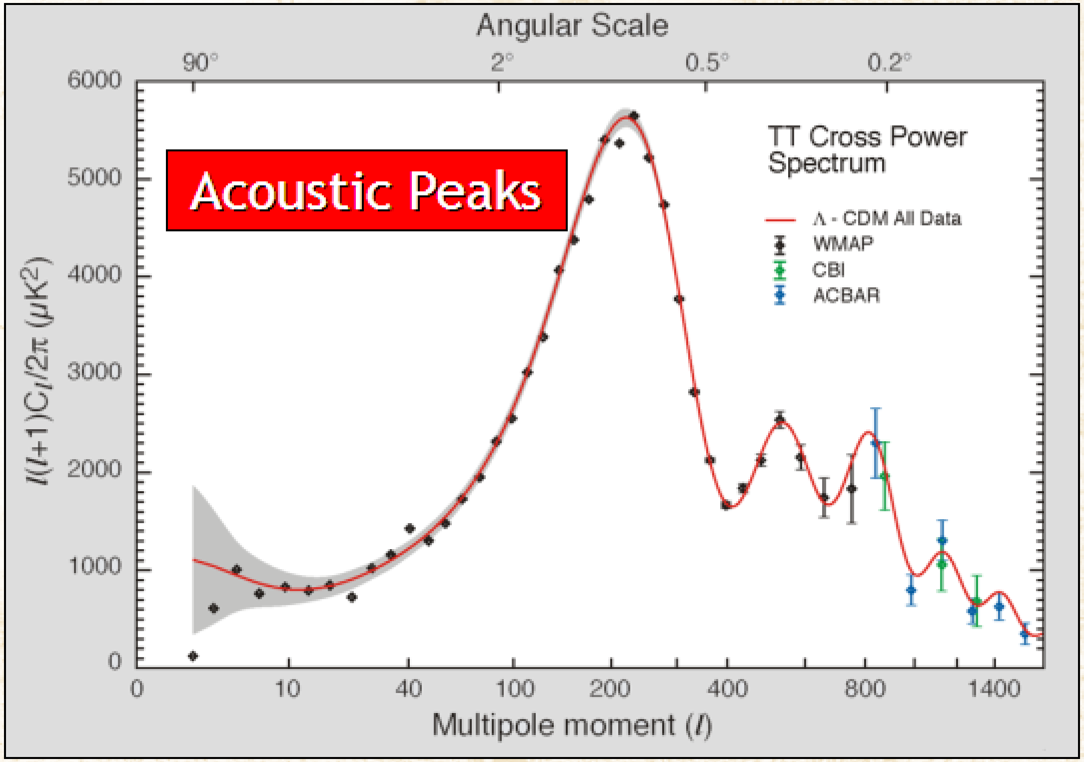
Sky map of CMBR temperature fluctuations

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



Multipole expansion

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

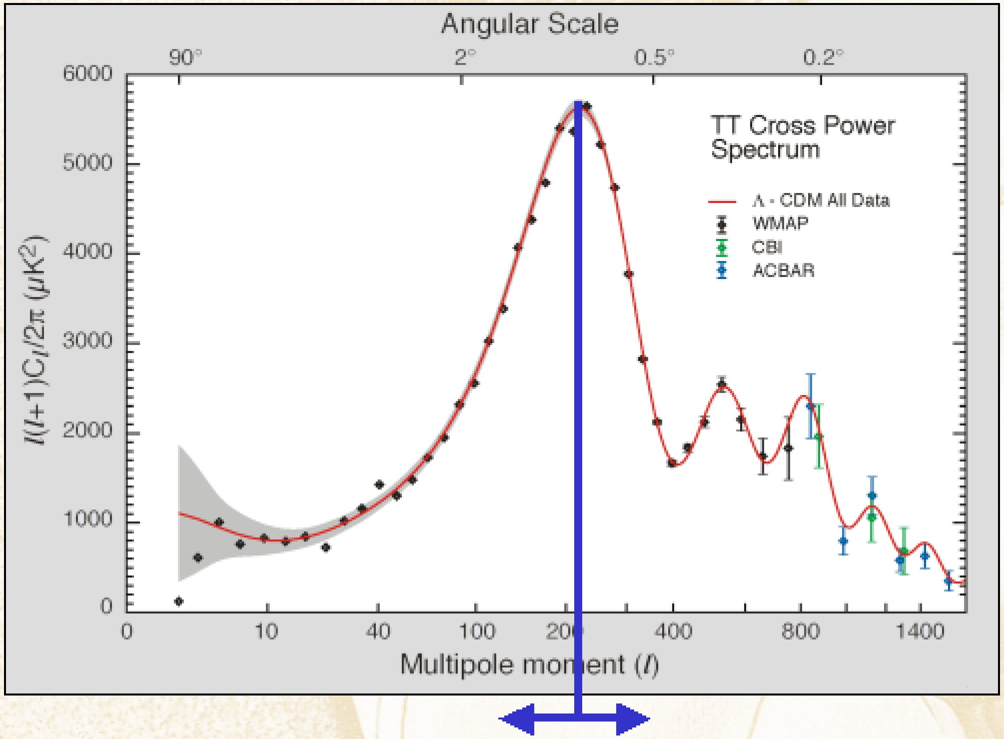


Angular power spectrum

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

Flat Universe from CMBR Angular Fluctuations

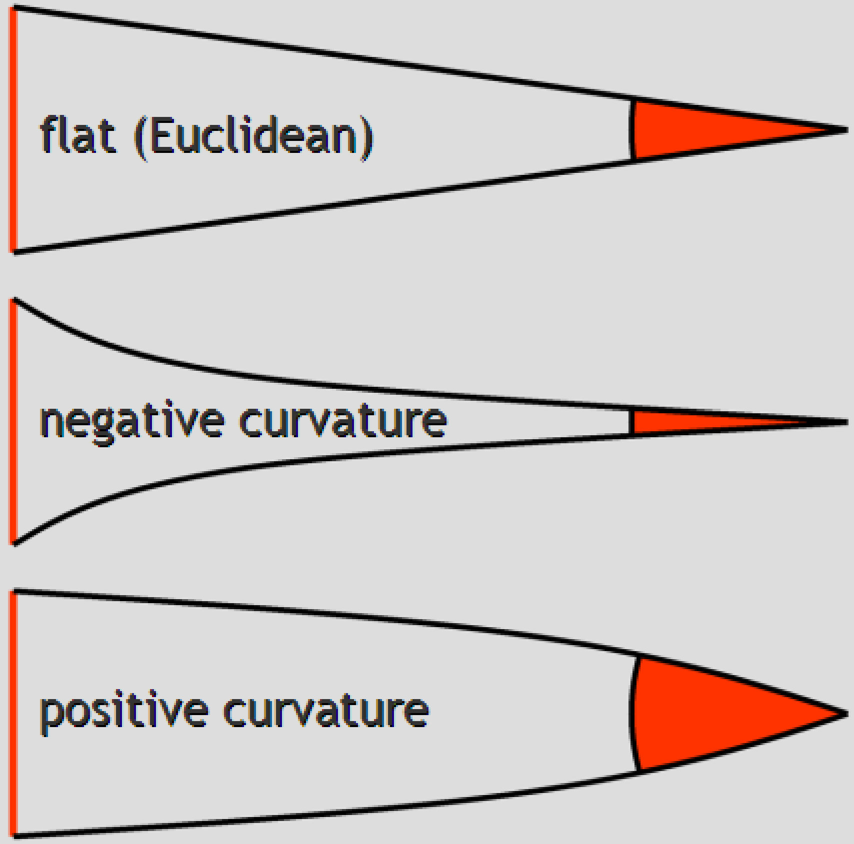
Spergel et al. (WMAP Collaboration)
astro-ph/0302209



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

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

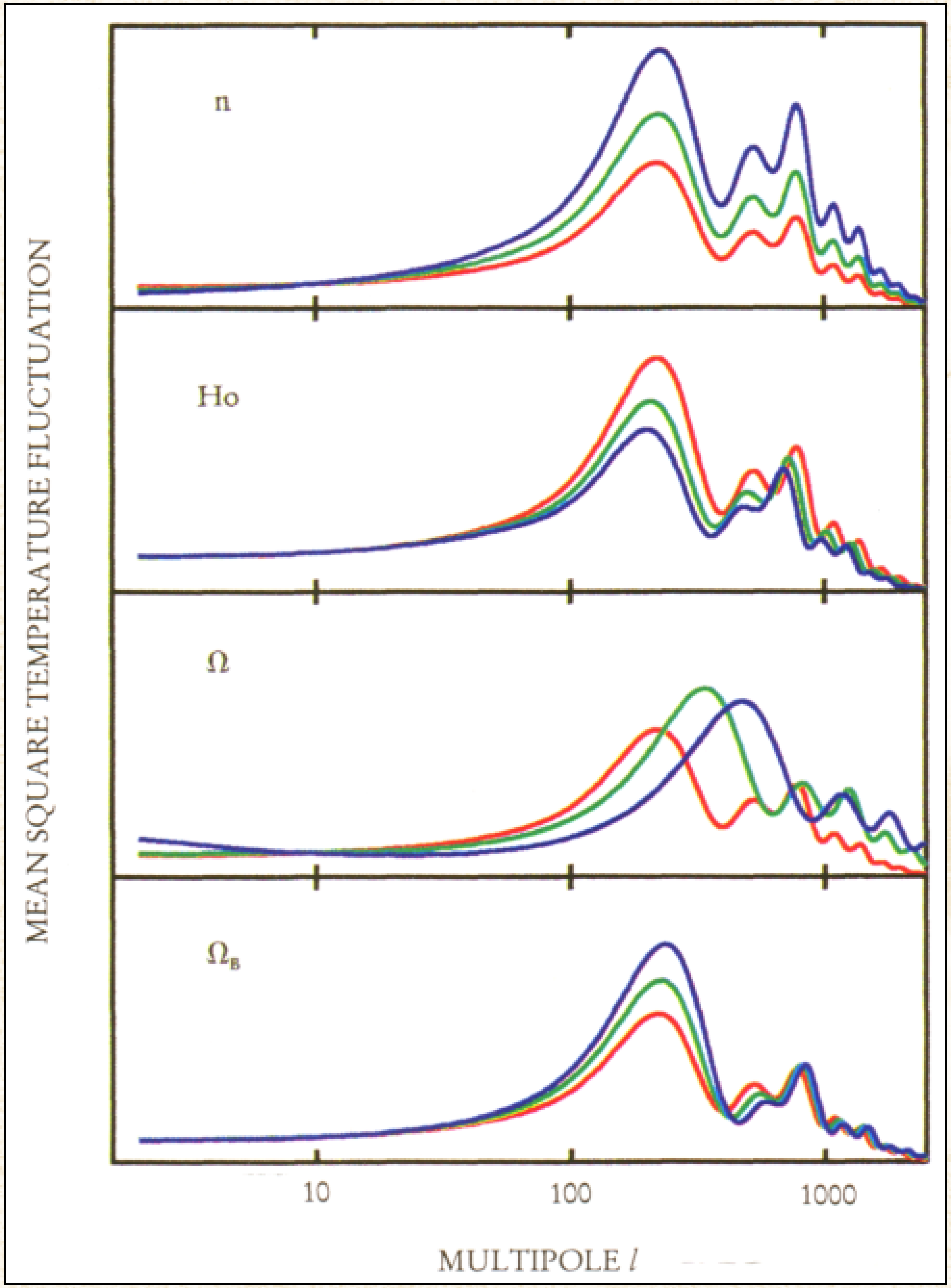
Triangulation with acoustic peak



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

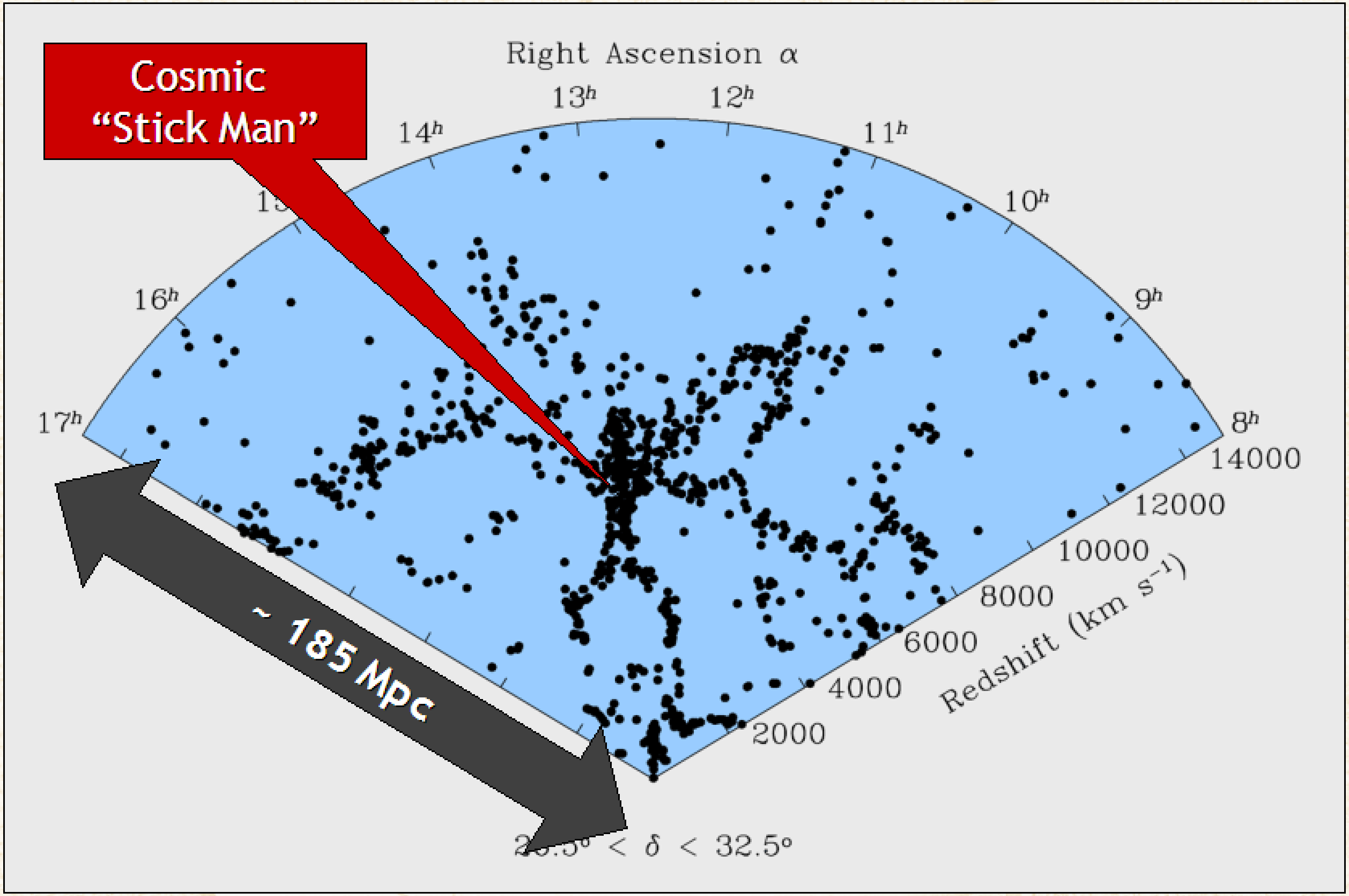
Hubble constant
H_0 = 50, 60, 70

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

A Slice of the Universe

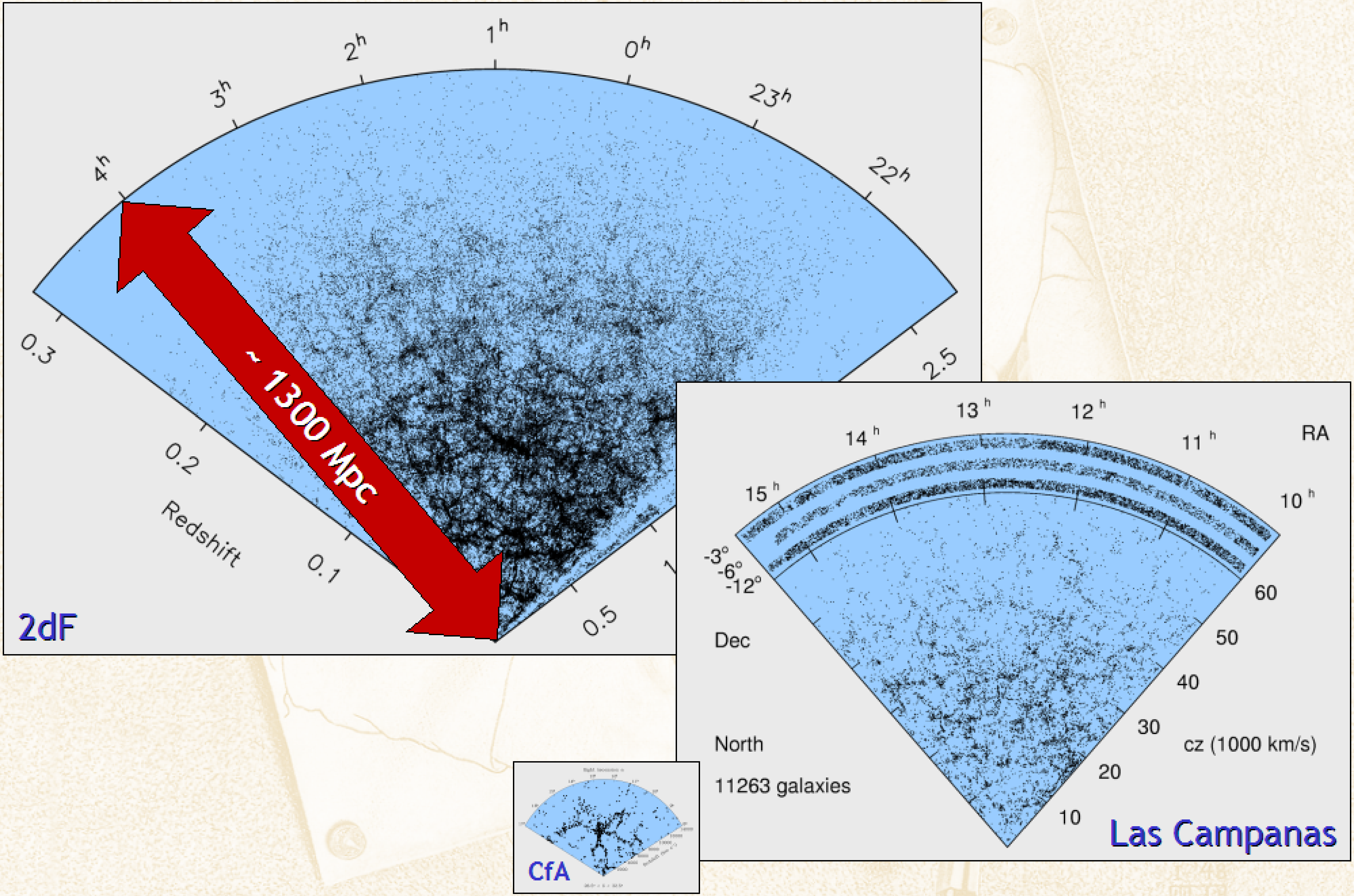


Cosmic "Stick Man"

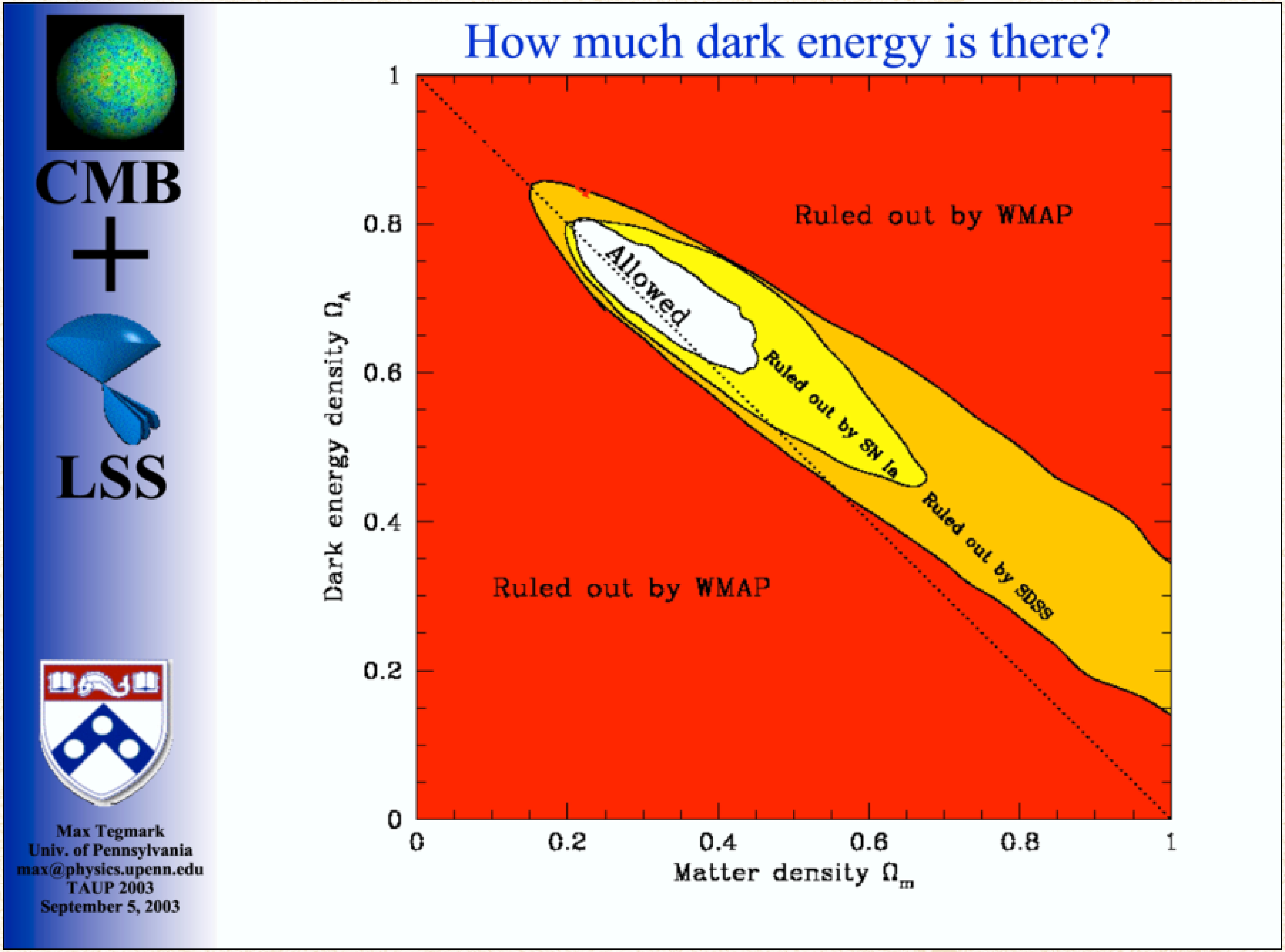
~ 185 Mpc

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

2dF Galaxy Redshift Survey (15 May 2002)



Cosmological Parameter Fitting



How much dark energy is there?

Max Tegmark
Univ. of Pennsylvania
max@physics.upenn.edu
TAUP 2003
September 5, 2003

Concordance Model of Cosmology

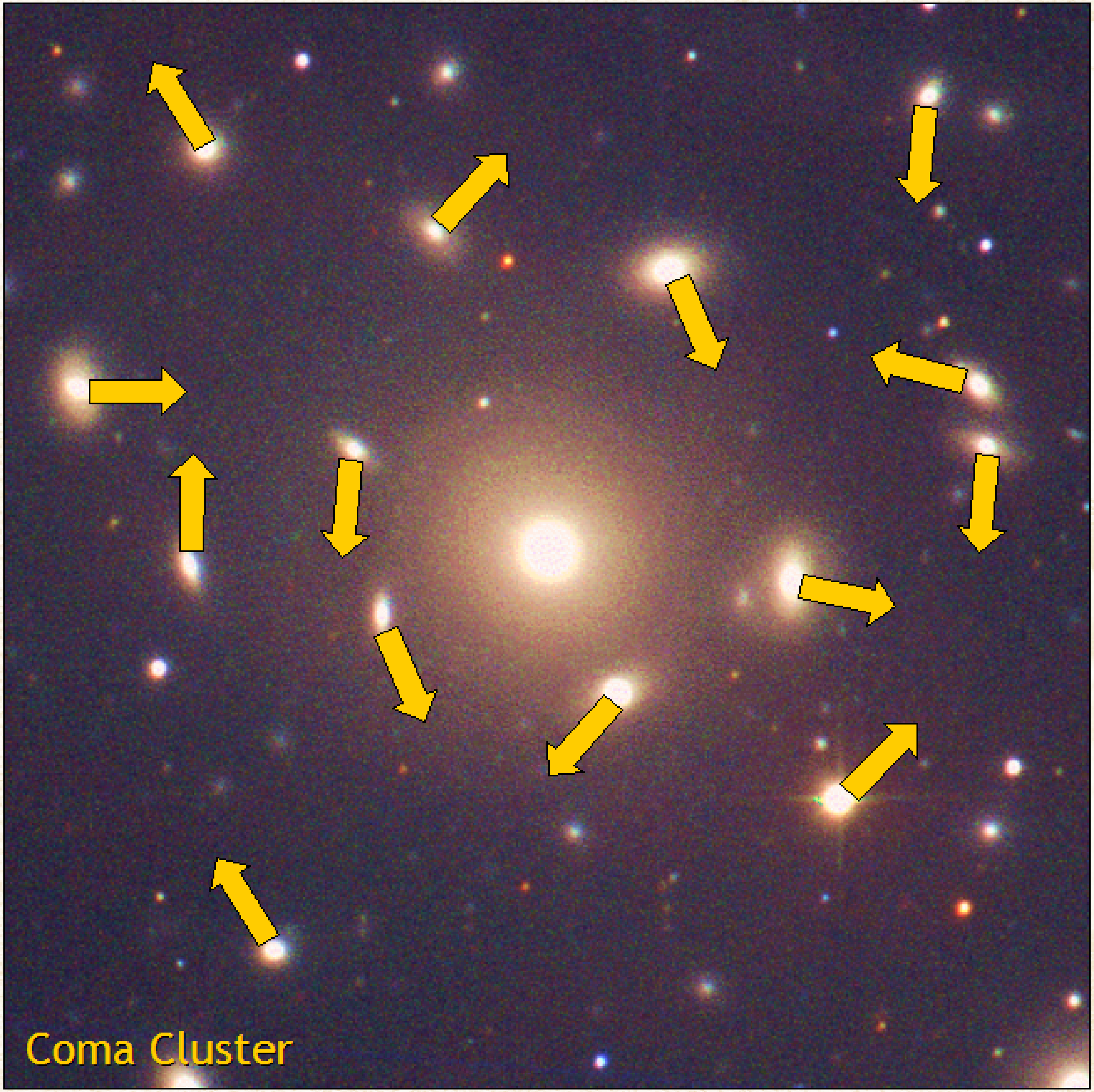
A Friedmann-Lemaître-Robertson-Walker model with the following parameters perfectly describes the global properties of the universe

Expansion rate	$H_0 = (72 \pm 4)\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$	
Spatial curvature	$\lvert R_{\mathrm{curv}} \rvert > 5 H_0^{-1}$	$\Omega_{\mathrm{tot}} = 1.02 \pm 0.02$
Age	$t_0 = (13.7 \pm 0.2) \times 10^9\ \mathrm{years}$	
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	$n = 0.93 \pm 0.03$

Dark Matter in Galaxy Clusters



A gravitationally bound system of many particles obeys the virial theorem

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

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

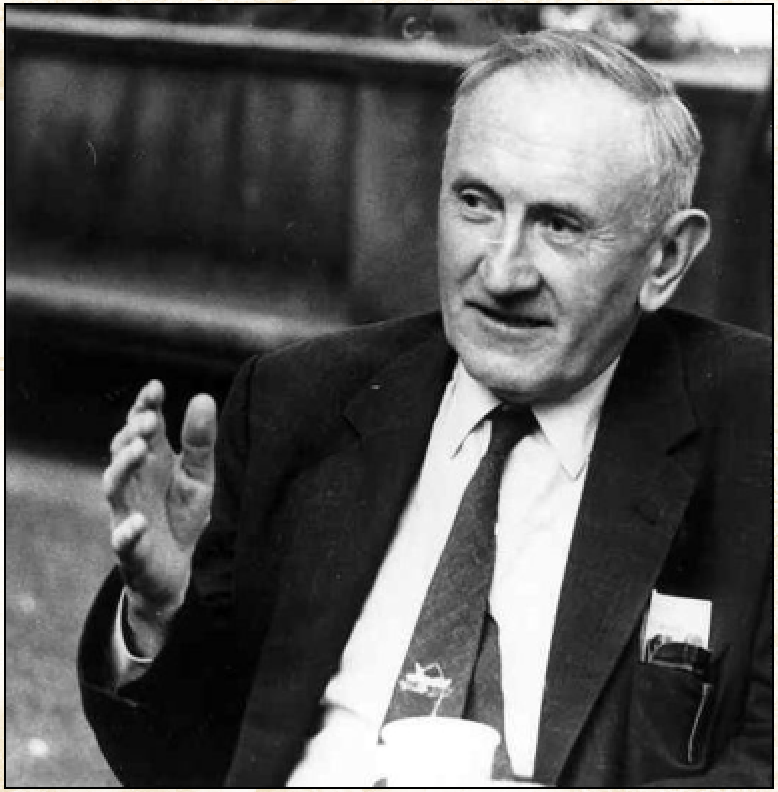
$$\langle v^2\rangle \approx G_N M_r \langle r^{-1}\rangle$$

Velocity dispersion from Doppler shifts and geometric size

Total Mass

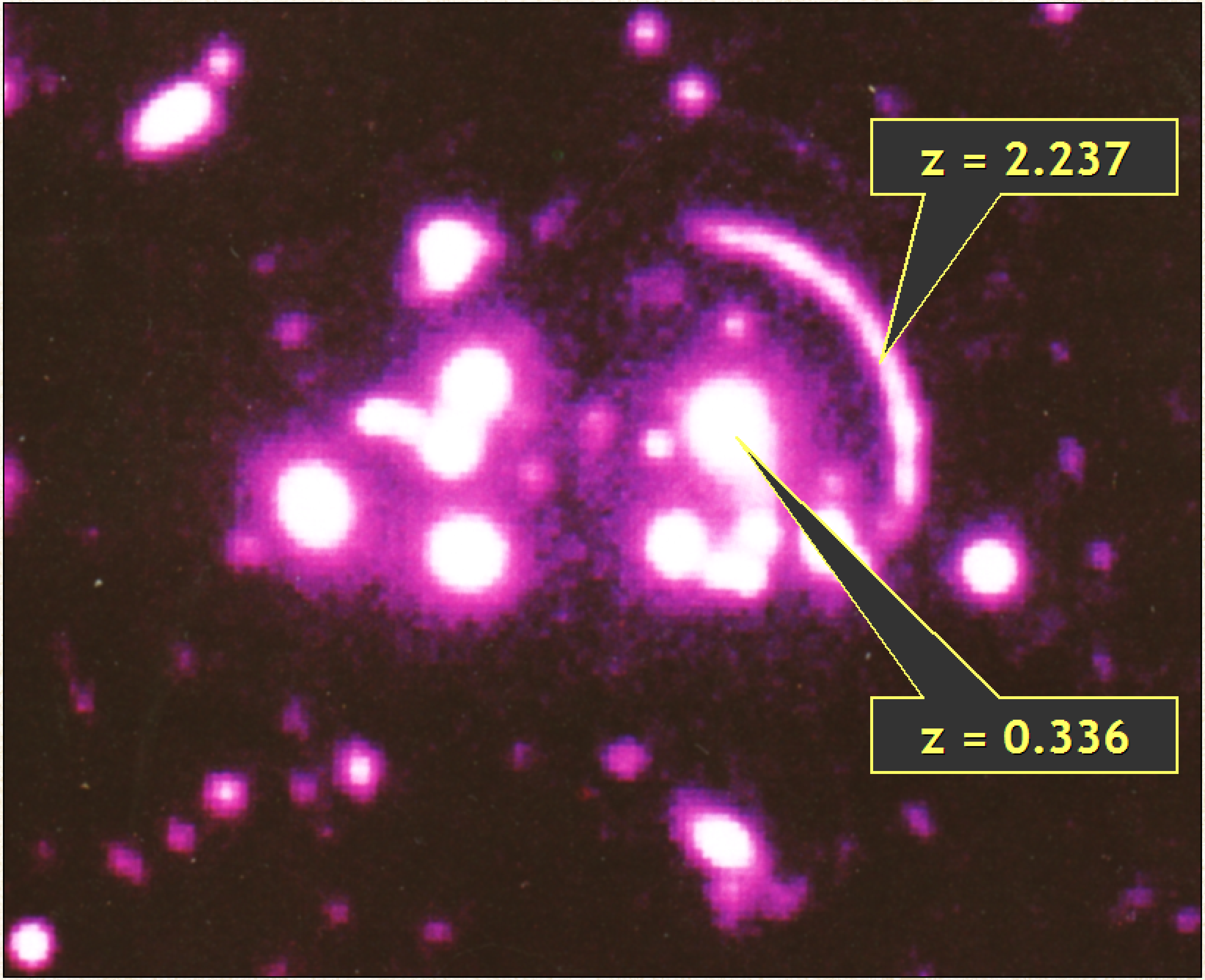
Dark Matter in Galaxy Clusters

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

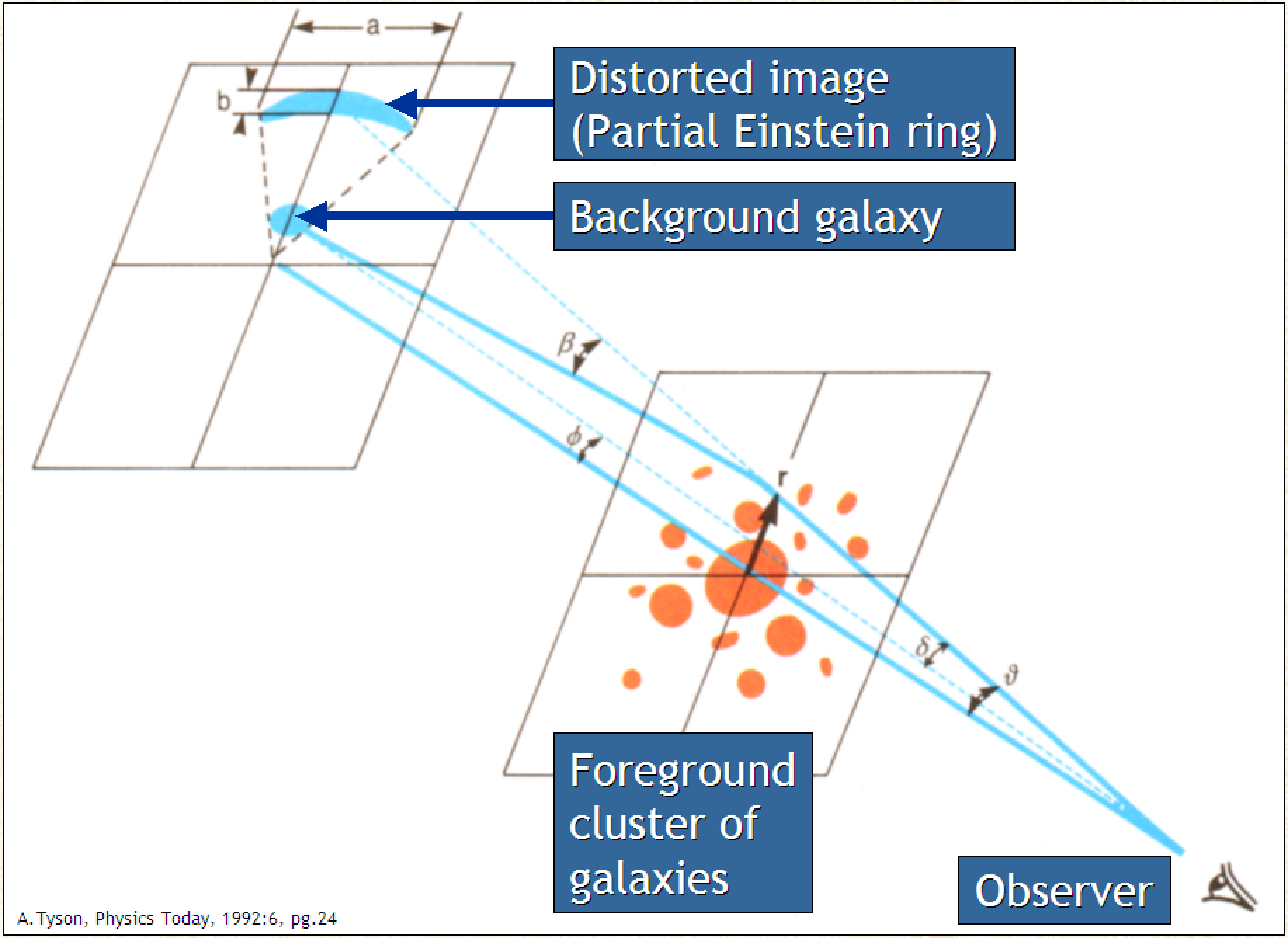


In order to obtain the observed average Doppler effect of 1000 km/s or more, the average density of the Coma cluster would have to be at least 400 times larger than what is found from observations of the luminous matter.
Should this be confirmed one would find the surprising result that dark matter is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

Giant Arc in Cluster Cl 2244-02



Giant Arcs – Gravitationally Lensed Background Galaxies



Distorted image (Partial Einstein ring)

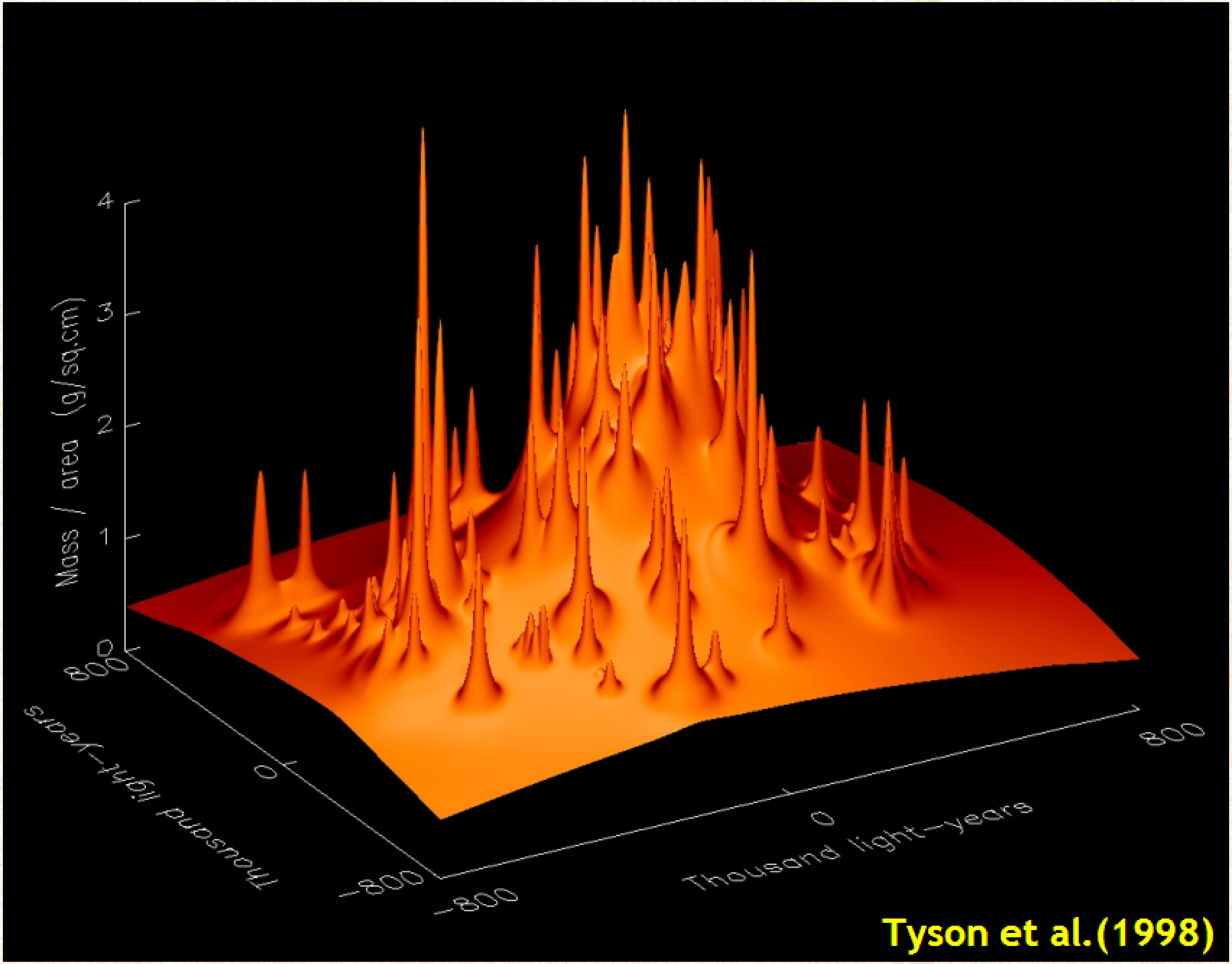
Background galaxy

Foreground cluster of galaxies

Observer

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

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



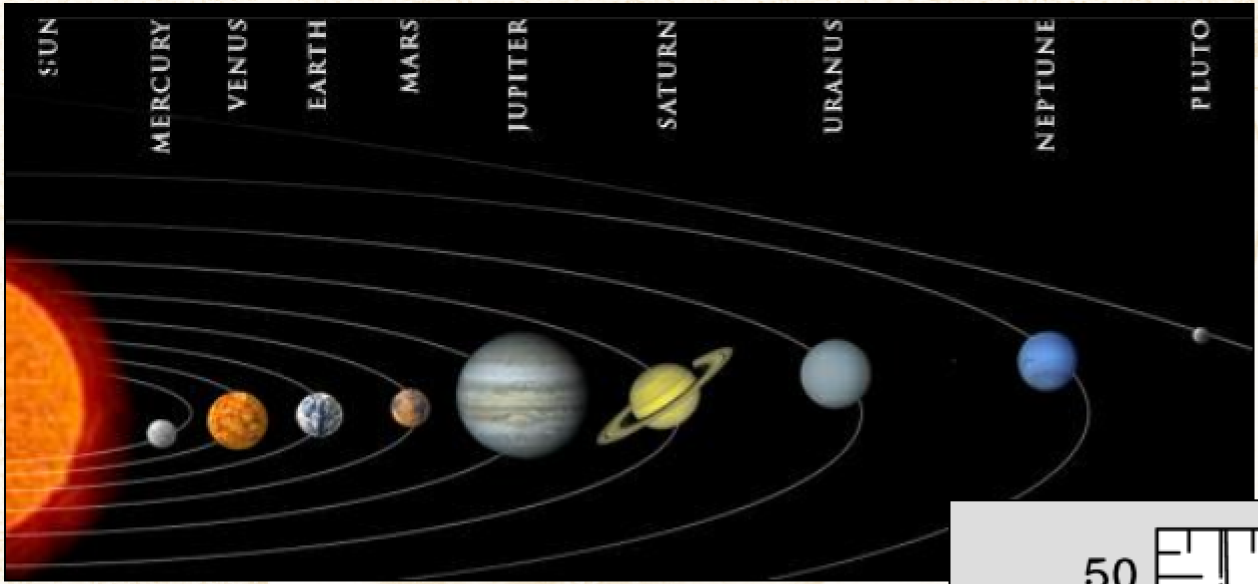
Tyson et al.(1998)

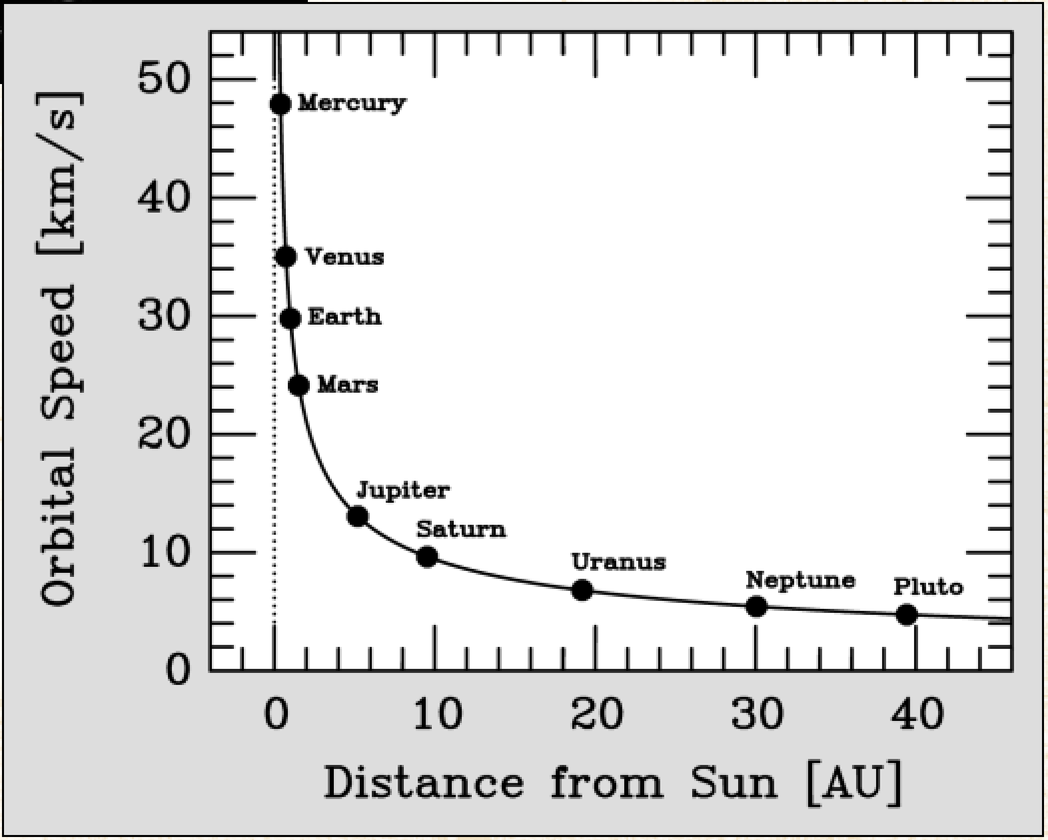
Structure of Spiral Galaxies

Spiral Galaxy NGC 2997

Spiral Galaxy NGC 891

"Rotation Curve" of the Solar System

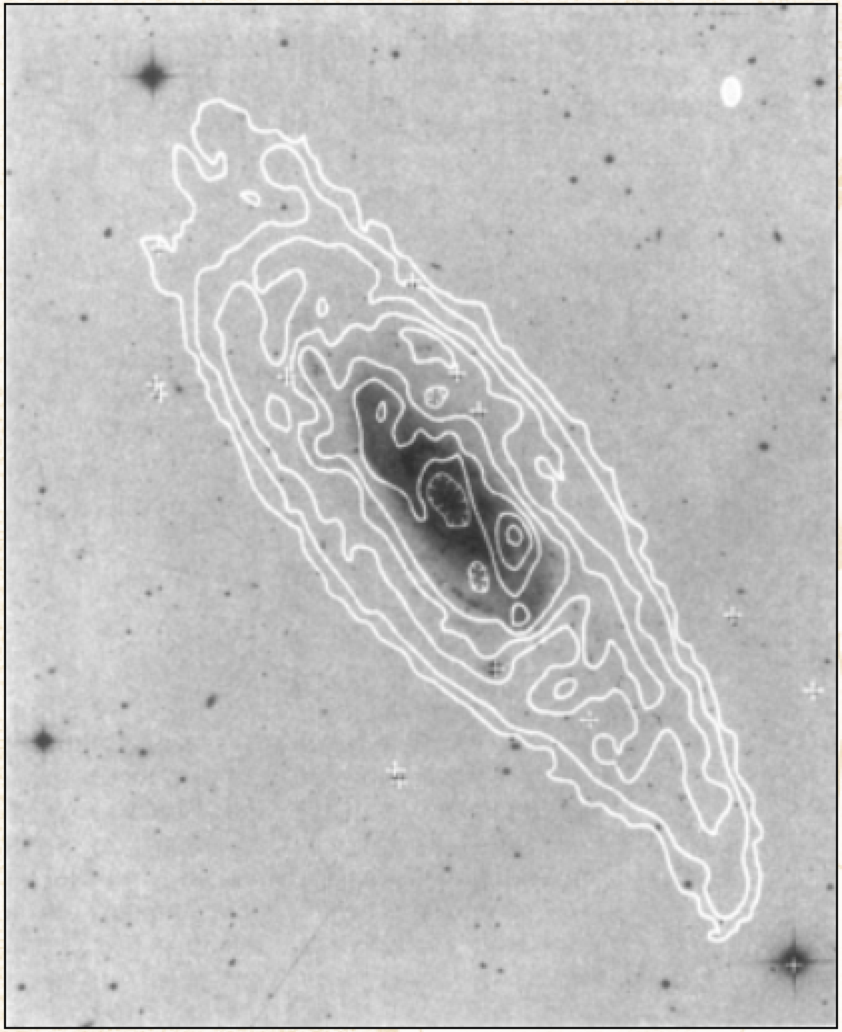




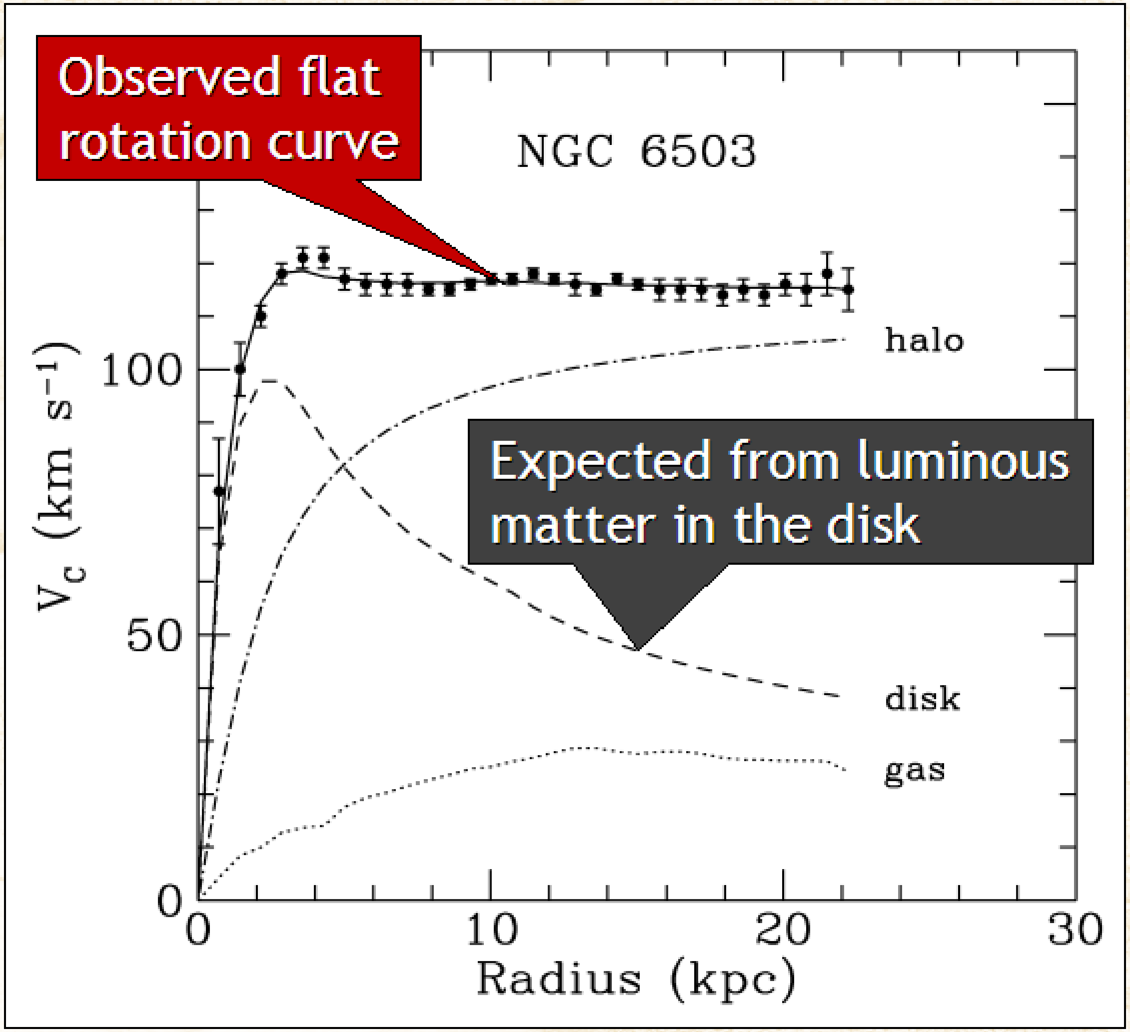
Kepler's Law

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

Galactic Rotation Curve from Radio Observations



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

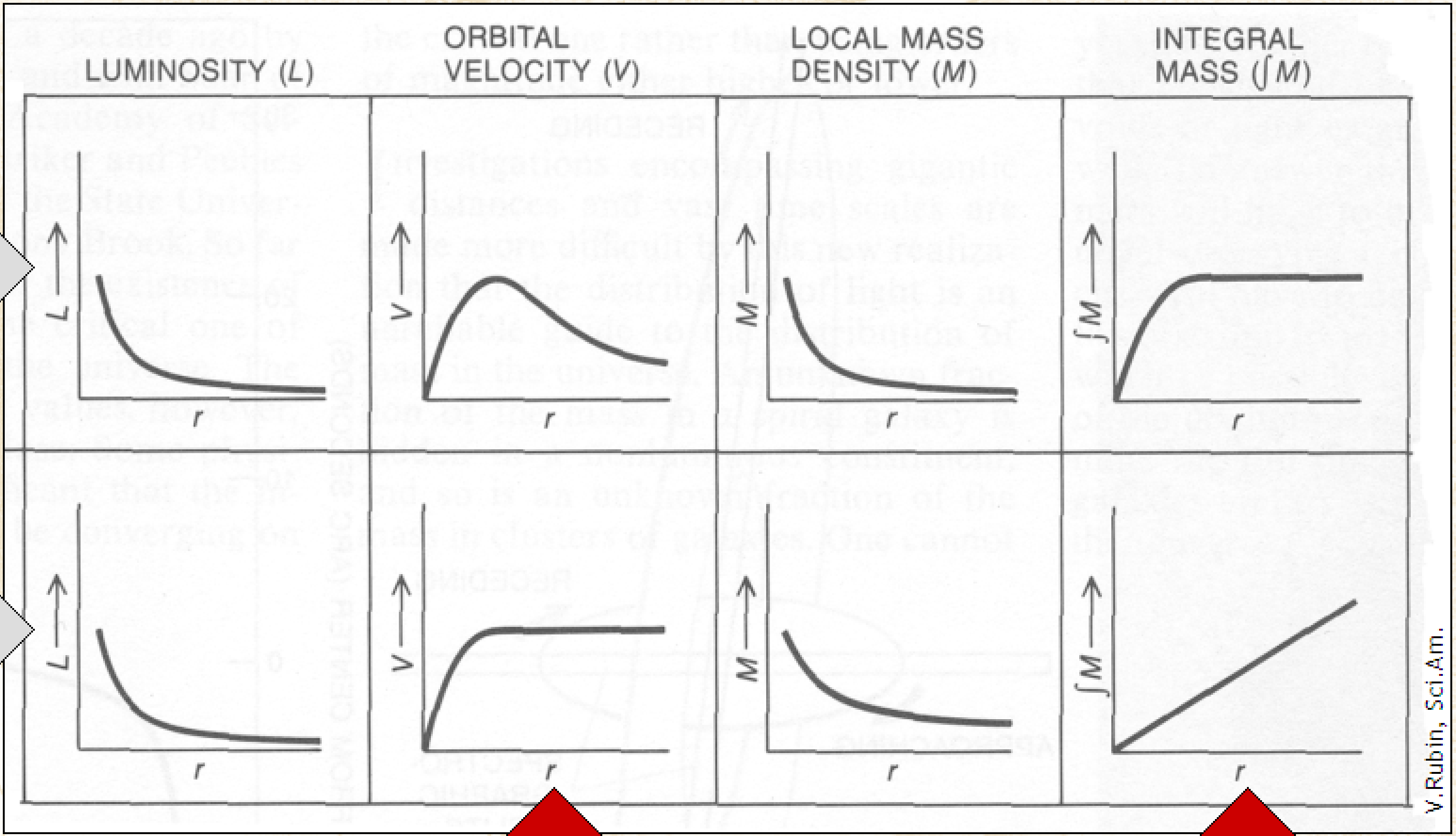


Observed flat rotation curve

Expected from luminous matter in the disk

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

Dark Matter in Spiral Galaxies - Summary



V.Rubin, Sci.Am.

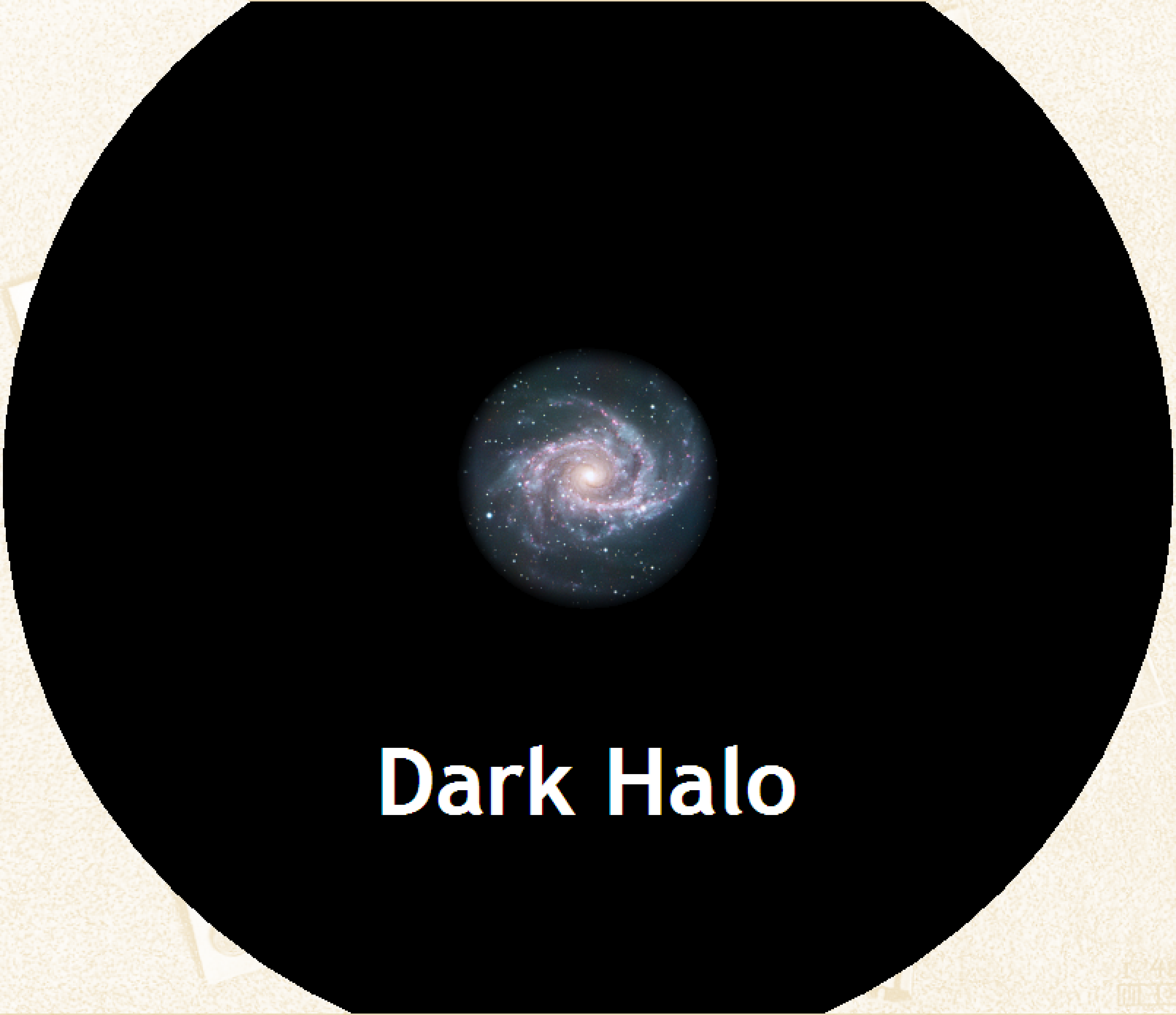
Expected from luminosity distribution

Infered from rotation curve

Flat rotation curve instead of Keplerian

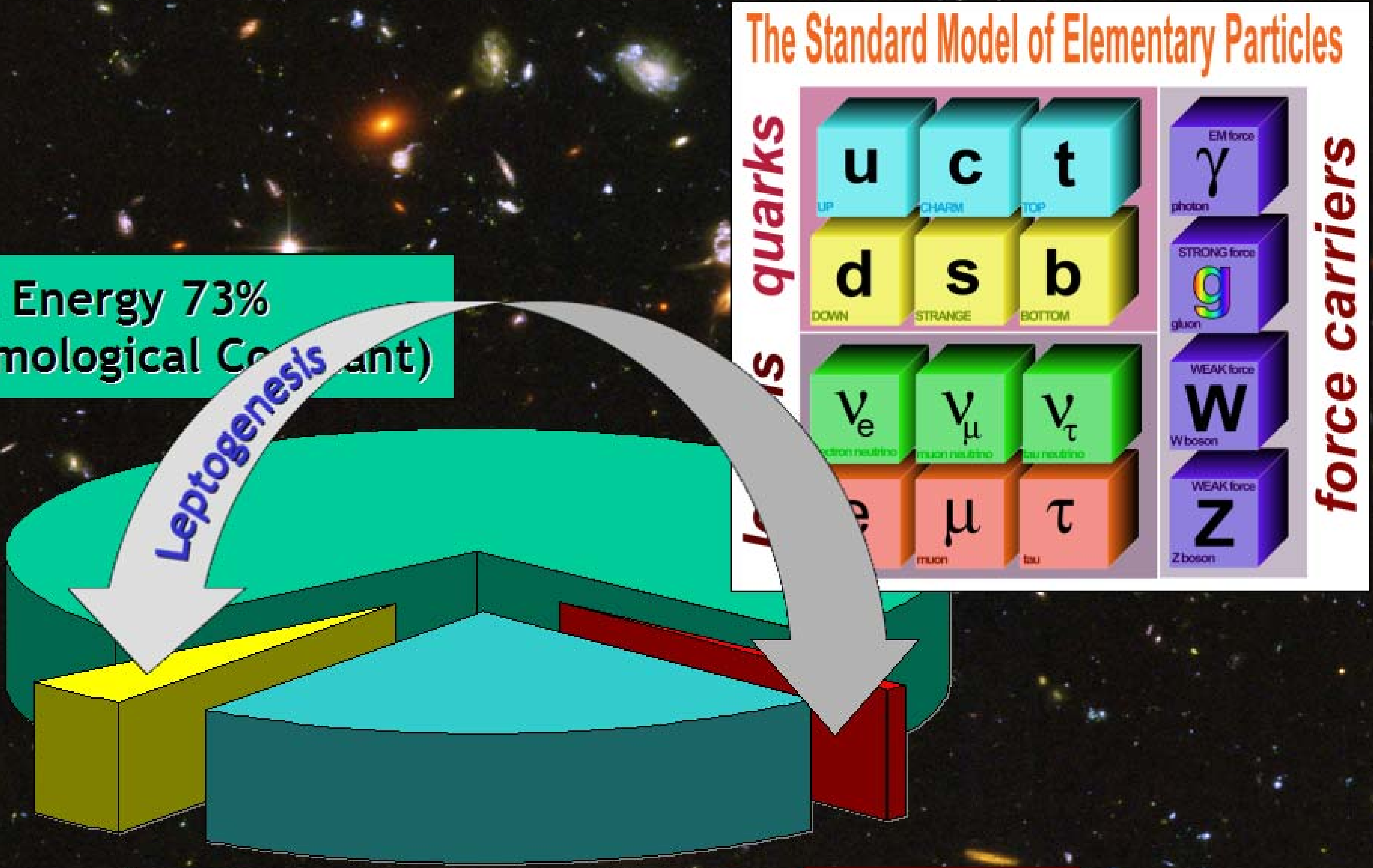
No obvious limit to total mass

Structure of a Spiral Galaxy



A Galaxy is a Strange Animal …

Dark Energy 73%
(Cosmological Constant)

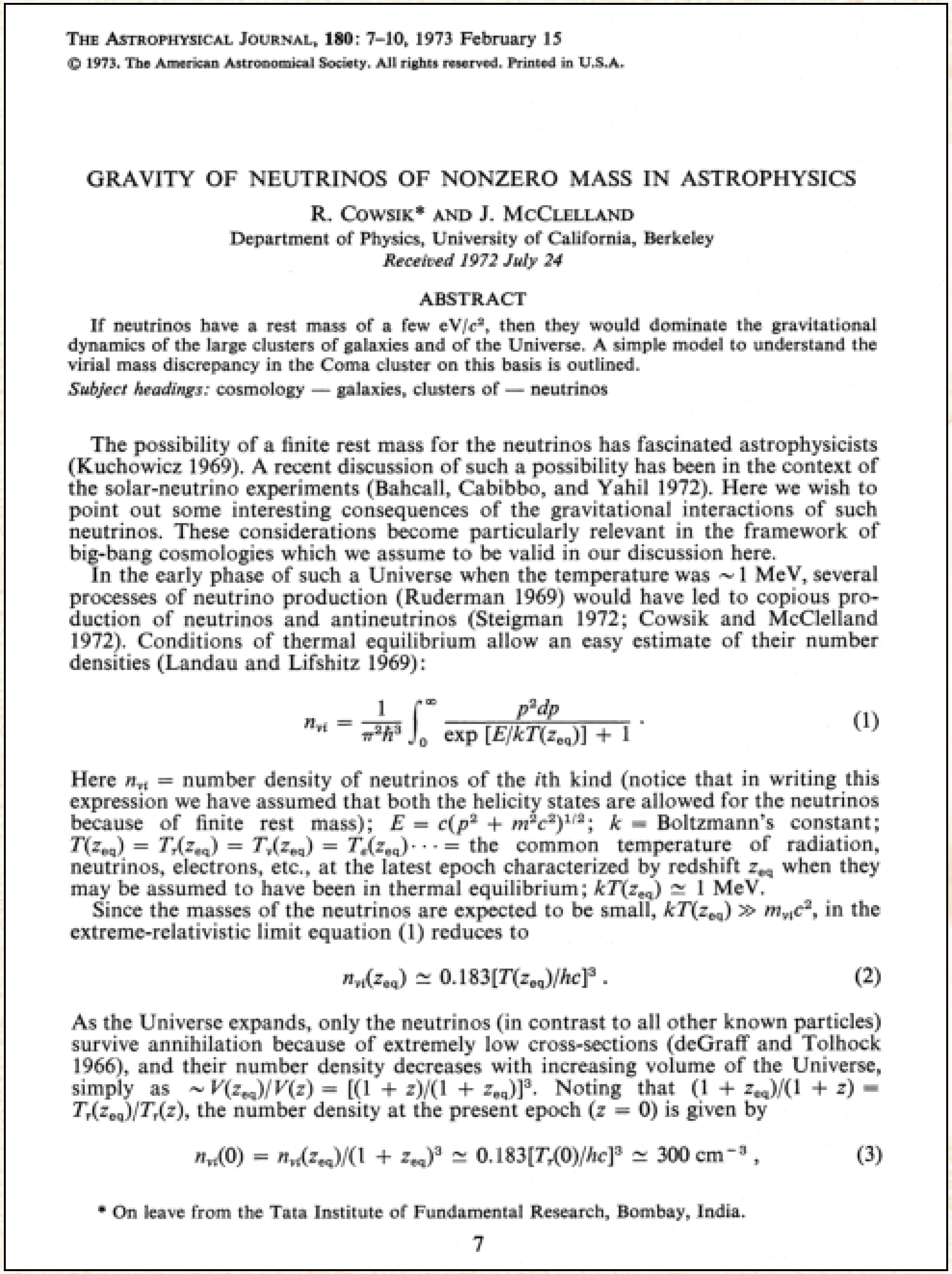


Ordinary Matter 4%
(of this only about
10% luminous)

Dark Matter
23%

Neutrinos
0.1–2%

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):

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

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; $T(z_{\rm eq}) = T_r(z_{\rm eq}) = T_\nu(z_{\rm eq}) = T_e(z_{\rm eq}) \cdots =$ the common temperature of radiation, neutrinos, electrons, etc., at the latest epoch characterized by redshift $z_{\rm eq}$ when they may be assumed to have been in thermal equilibrium; $kT(z_{\rm eq}) \simeq 1$ MeV.

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

$$n_{\nu i}(z_{\rm eq}) \simeq 0.183[T(z_{\rm eq})/\hbar c]^3\,. \tag{2}$$

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 $\sim V(z_{\rm eq})/V(z) = [(1 + z)/(1 + z_{\rm eq})]^3$. Noting that $(1 + z_{\rm eq})/(1 + z) = T_r(z_{\rm eq})/T_r(z)$, the number density at the present epoch ($z = 0$) is given by

$$n_{\nu i}(0) = n_{\nu i}(z_{\rm eq})/(1 + z_{\rm eq})^3 \simeq 0.183[T_r(0)/\hbar c]^3 \simeq 300\ {\rm cm}^{-3}\,, \tag{3}$$

---

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

7

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")

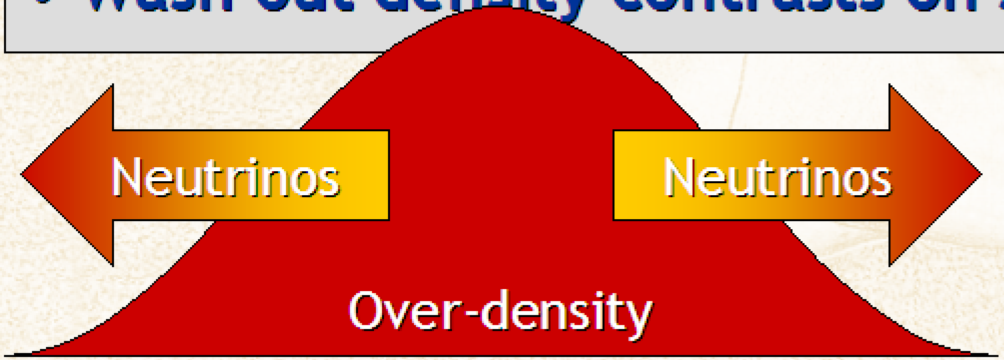
Maximum mass density of a degenerate Fermi gas

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

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

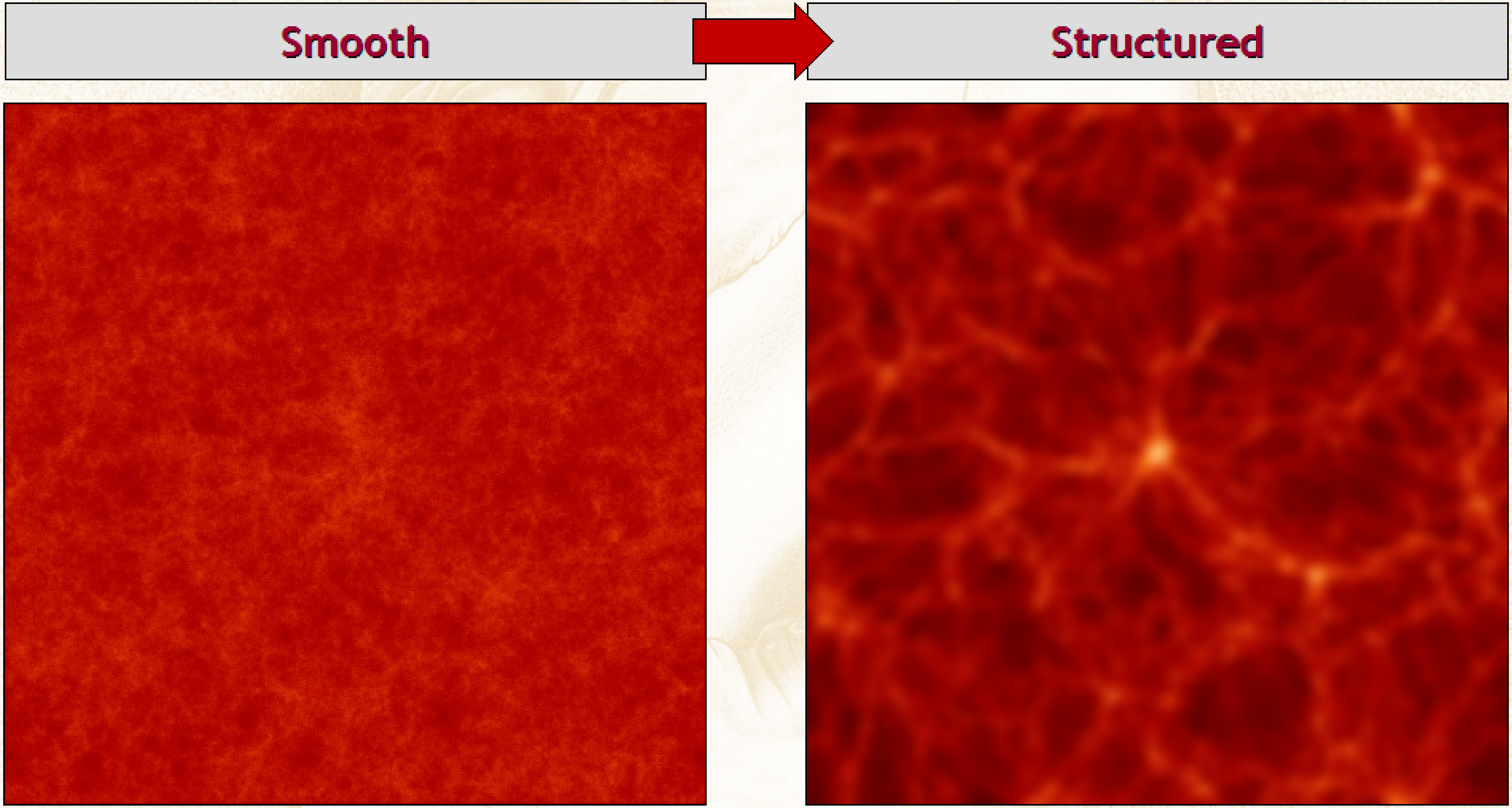
Neutrino Free Streaming (Collisionless Phase Mixing)

- 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

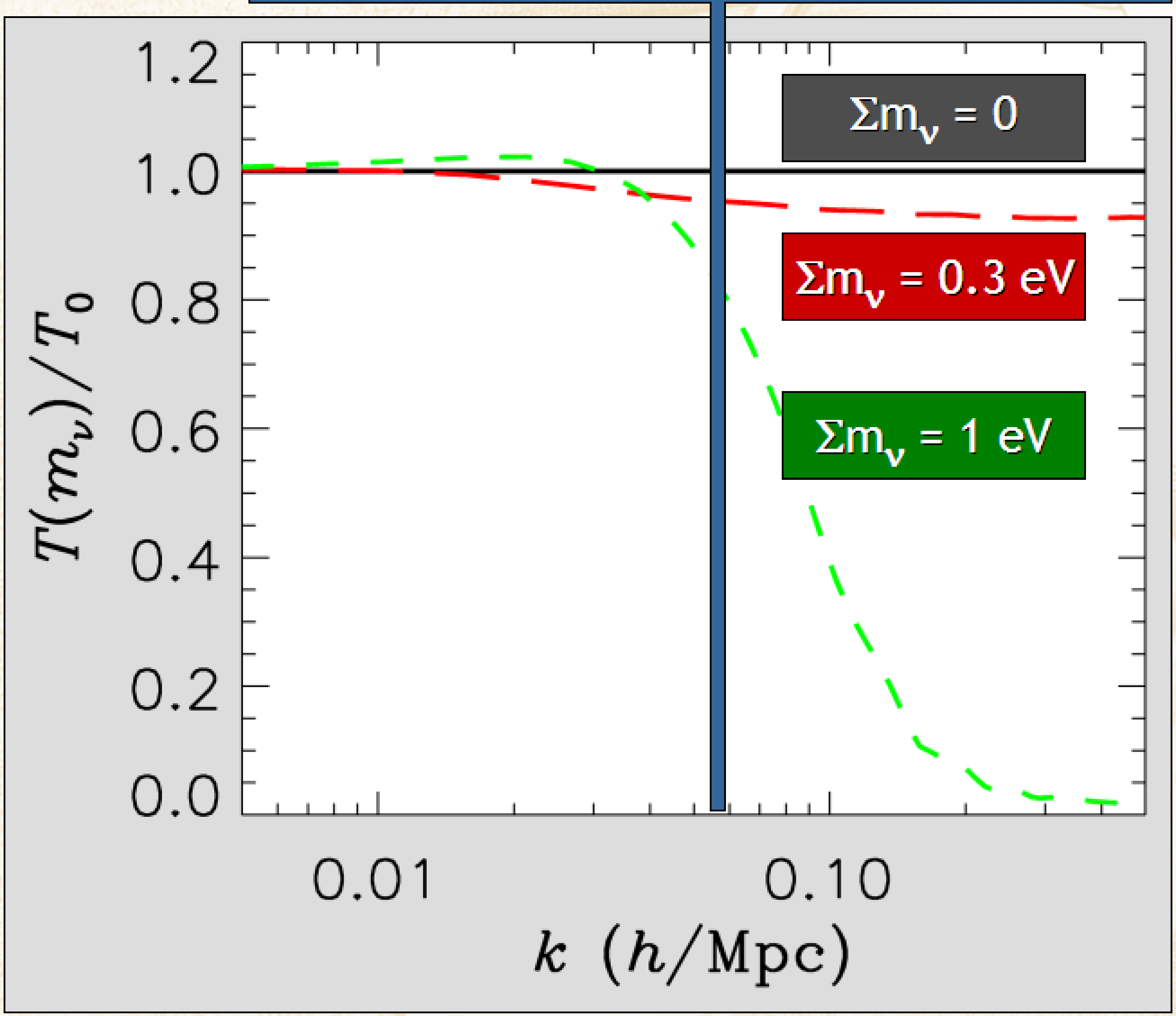
Formation of Structure



A fraction of hot dark matter suppresses small-scale structure

Neutrino Free Streaming - Transfer Function

Power suppression for $\lambda_{FS} \lesssim 100$ Mpc/h



Transfer function

$P(k) = T(k)\, P_0(k)$

Effect of neutrino free streaming on small scales

$T(k) = 1 - 8\Omega_\nu/\Omega_M$

valid for

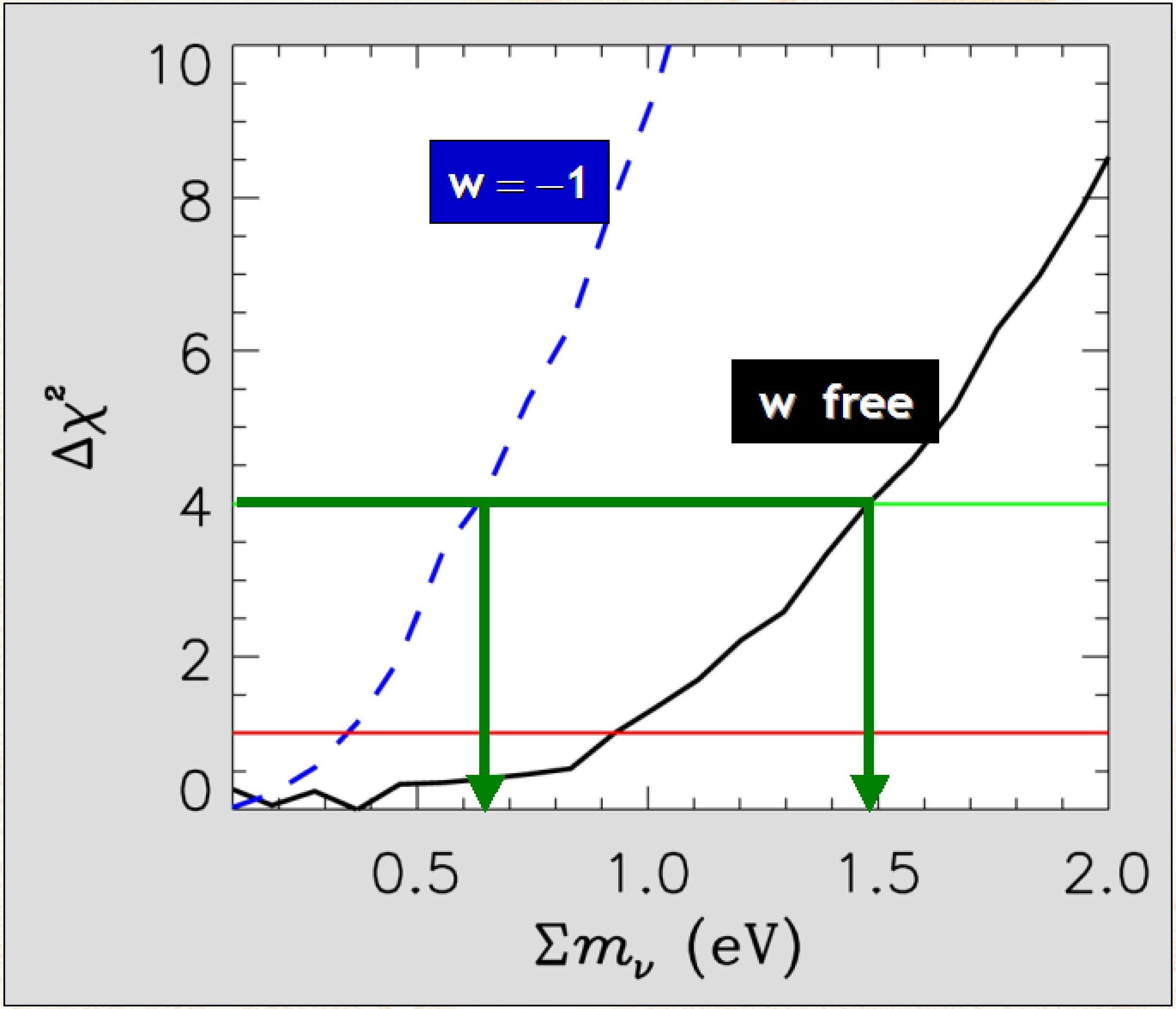
$8\Omega_\nu/\Omega_M \ll 1$

Hannestad, Neutrinos in Cosmology, hep-ph/0404239

Recent Cosmological Limits on Neutrino Masses

	Σm_ν/eV (limit 95%CL)	Data / Priors
Ichikawa, Fukugita, Kawasaki 2004 [astro-ph/0409768]	2.0	WMAP
Tegmark et al. 2003 [astro-ph/0310723]	1.8	WMAP, SDSS
Hannestad 2003 [astro-ph/0303076]	1.01	WMAP, CMB, 2dF, HST
Spergel et al. (WMAP) 2003 [astro-ph/0302209]	0.69	WMAP, CMB, 2dF, HST, σ_8
Barger et al. 2003 [hep-ph/0312065]	0.75	WMAP, CMB, 2dF, SDSS, HST
Crotty et al. 2004 [hep-ph/0402049]	1.0 0.6	WMAP, CMB, 2dF, SDSS & HST, SN
Hannestad 2004 [hep-ph/0409108]	0.65	WMAP, SDSS, SN Ia gold sample, Ly-α data from Keck sample
Seljak et al. 2004 [astro-ph/0407372]	0.42	WMAP, SDSS, Bias, Ly-α data from SDSS sample

Degeneracy with Dark Energy Equation of State



Used data:
WMAP, SDSS, HST, SNIa

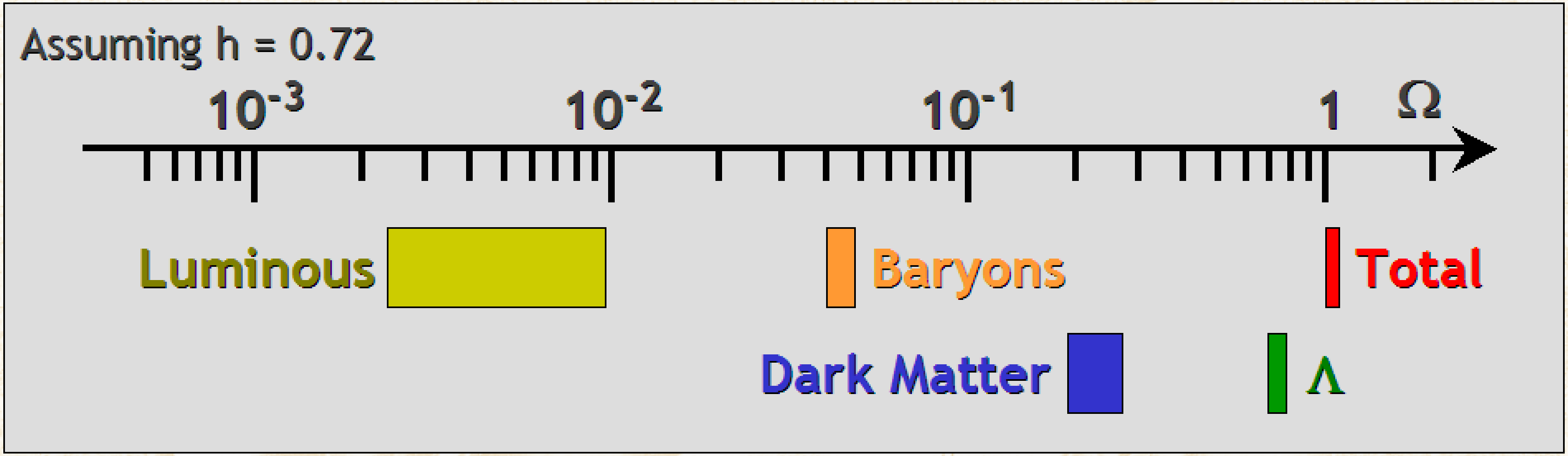
Fixed or variable EOS
of dark energy
w = p/ρ

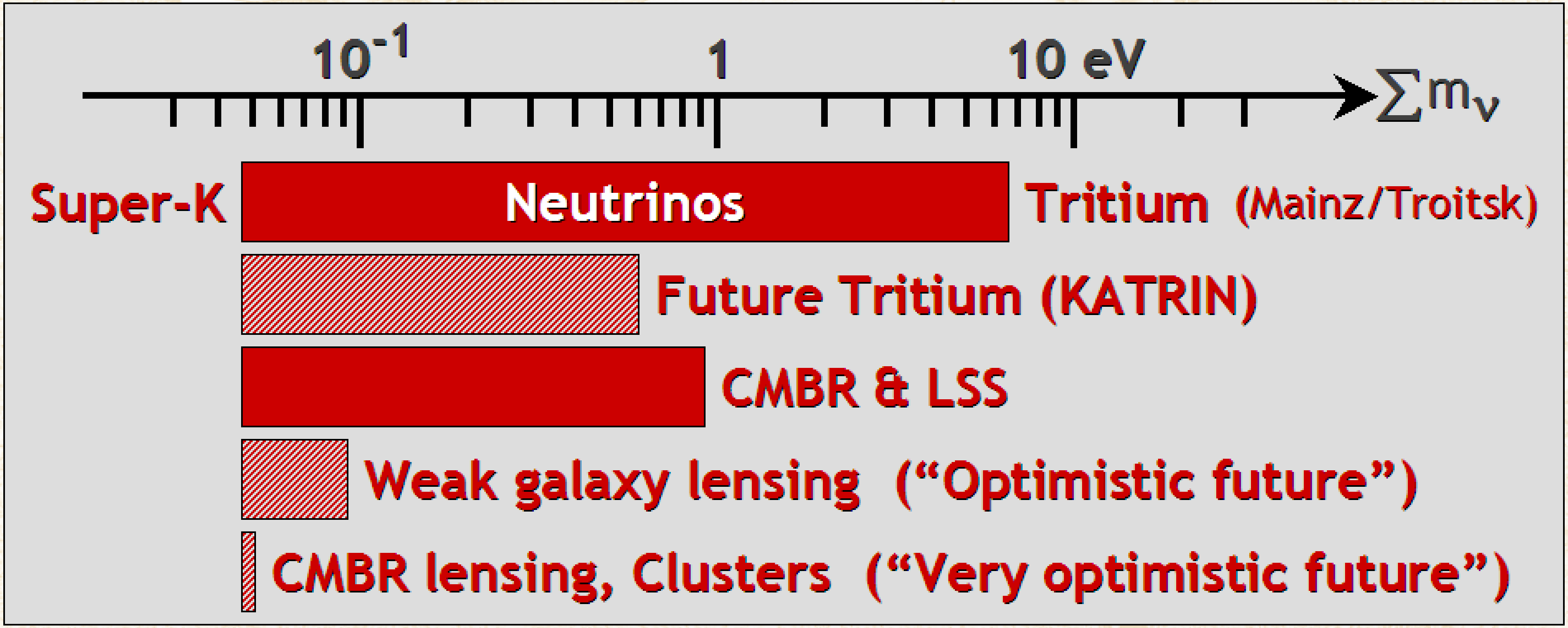
Hannestad,
astro-ph/0505551

Sensitivity Forecasts for Future LSS Observations

Lesgourgues, Pastor & Perotto, hep-ph/0403296	Planck & SDSS	$\Sigma m_\nu > 0.21$ eV detectable at 2σ
	Ideal CMB & 40 x SDSS	$\Sigma m_\nu > 0.13$ eV detectable at 2σ
Abazajian & Dodelson astro-ph/0212216	Future weak lensing survey 4000 deg^2	$\sigma(m_\nu) \sim 0.1$ eV
Kaplinghat, Knox & Song, astro-ph/0303344	CMB lensing	$\sigma(m_\nu) \sim 0.15$ eV (Planck) $\sigma(m_\nu) \sim 0.044$ eV (CMBpol)
Wang, Haiman, Hu, Khoury & May, astro-ph/0505390	Weak-lensing selected sample of > 10^5 clusters	$\sigma(m_\nu) \sim 0.03$ eV

Mass-Energy-Inventory of the Universe

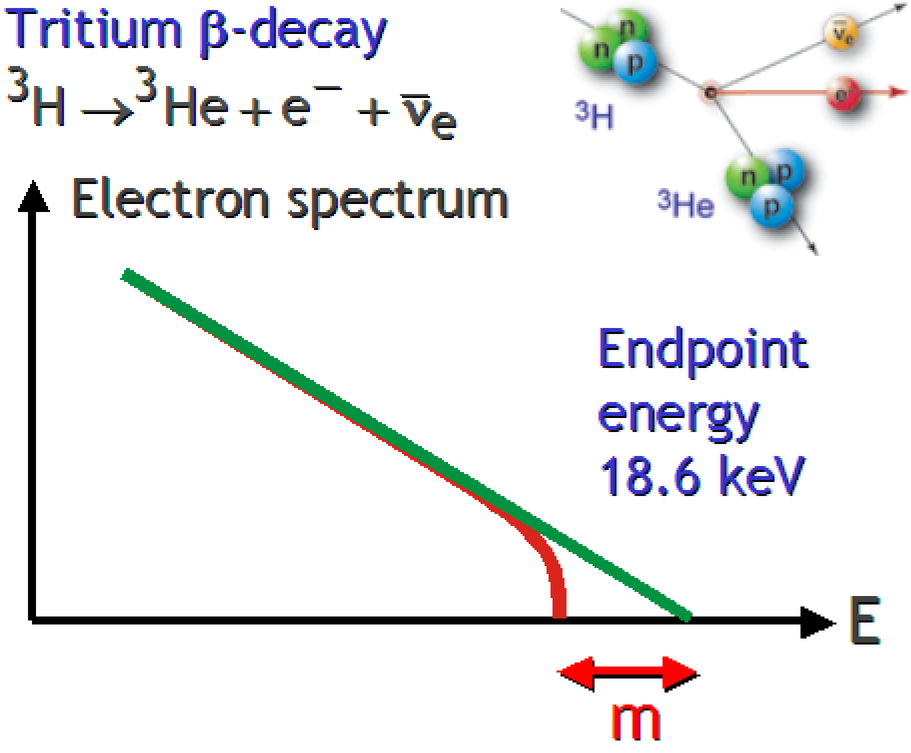




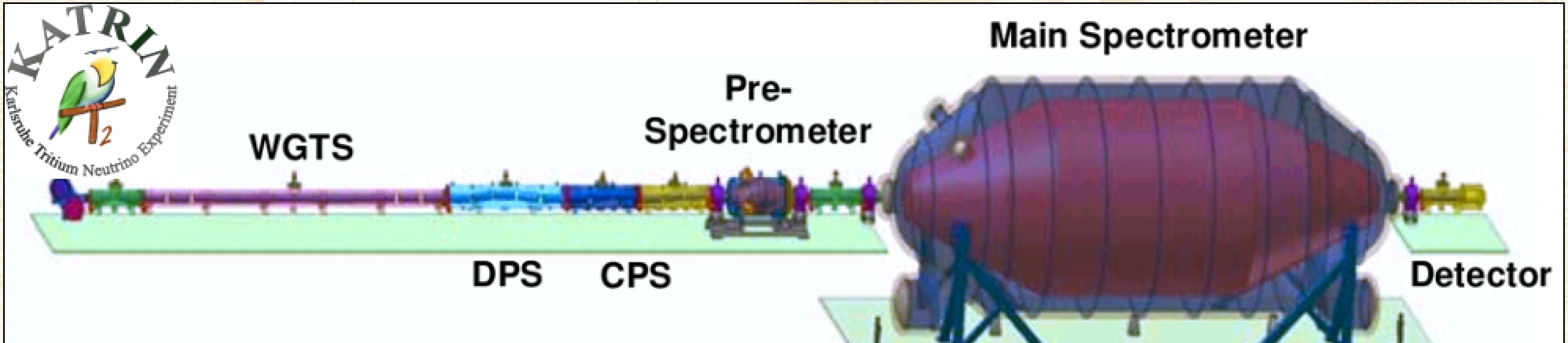
“Weighing” Neutrinos with KATRIN

Tritium β-decay

$${}^3\mathrm{H} \rightarrow {}^3\mathrm{He} + e^- + \bar{\nu}_e$$

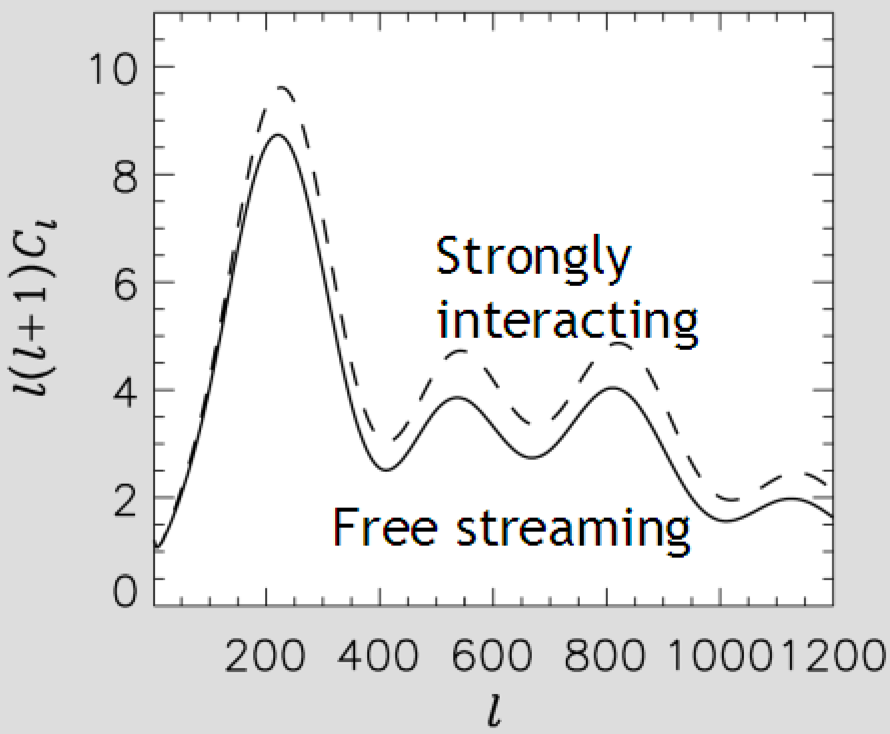


- Sensitive to common mass scale m for all flavors because of small mass differences from oscillations
- Best limit from Mainz und Troitsk
  m < 2.2 eV (95% CL)
- KATRIN can reach 0.2 eV
- Under construction
- Data taking foreseen to begin in 2007



http://www-ik.fzk.de/katrin/

“Strongly” Interacting Neutrinos



- If neutrinos are not freely streaming at the time of photon decoupling, acoustic oscillations in neutrino fluid leave an imprint in CMB temperature fluctuations
- Observations imply neutrinos must be freely streaming at the time of photon decoupling at $z \approx 1100$

[Hannestad, astro-ph/0411475,
Chacko et al., hep-ph/0312267]

Implies most restrictive interactions on neutrino decays of the “Majoron” type

$\nu \to \nu' + \phi$

Limit on Yukawa coupling

$g < 1 \times 10^{-11}\ (0.05\ \mathrm{eV}/m)^2$

Neutrino decays not important for high-energy cosmic ray neutrinos

[Hannestad & Raffelt, hep-ph/0509278]

Extending the Mass Bound to Other Low-Mass Particles

Assume a generic hot dark matter particle that was in thermal equilibrium at some cosmological epoch

- Internal particle degrees of freedom (e.g. spin states) g_X
- Mass m_X
- Effective number of thermal degrees of freedom at freeze-out g_*

Contribution to cosmic mass density

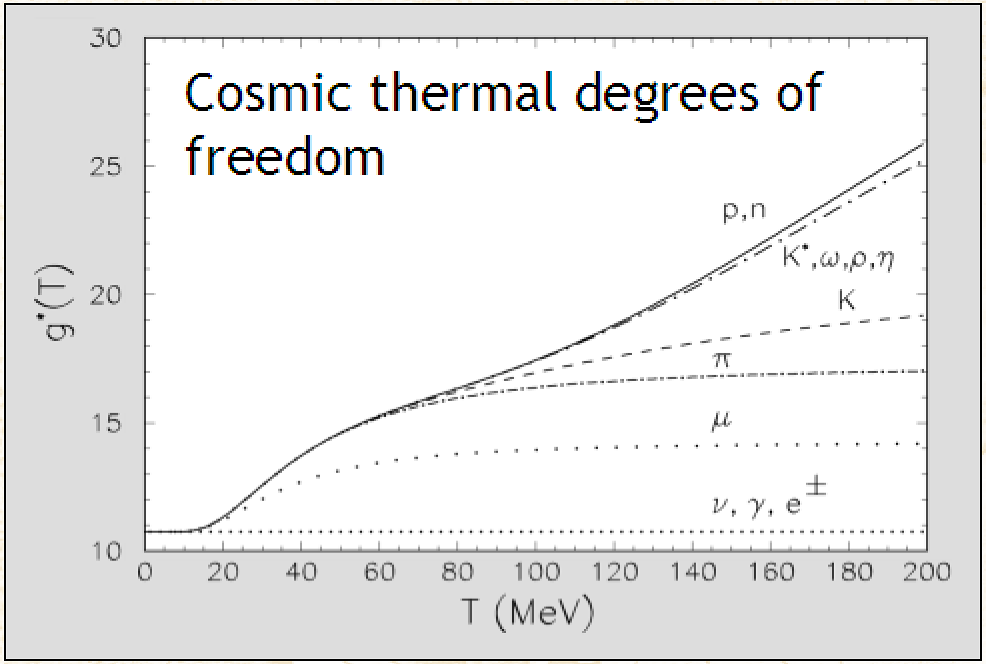
$$\Omega_X h^2 = \frac{m_X g_X}{183\ \text{eV}} \, \frac{10.75}{g_{*X}} \times \begin{cases} 1 & \text{for fermions} \\ 4/3 & \text{for bosons} \end{cases}$$

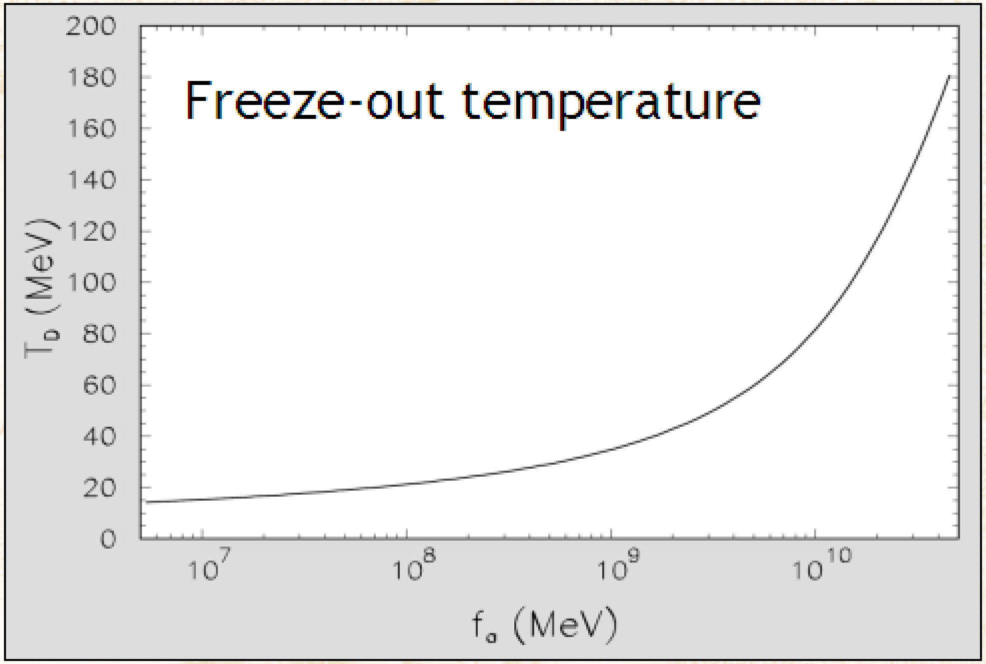
Free-streaming length

$$\lambda_{FS} \approx \frac{20\ \text{Mpc}}{\Omega_X h^2} \left(\frac{T_X}{T_\nu} \right)^4 \left[1 + \log\left(3.9 \, \frac{\Omega_X}{\Omega_m} \, \frac{T_\nu^2}{T_X^2} \right) \right]$$

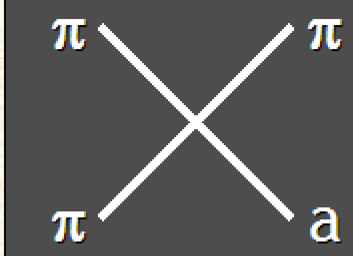
Perform maximum likelihood analysis for different choices of g_X and g_* to derive cosmological limit on m_X

Axion Freeze-Out


Cosmic thermal degrees of freedom

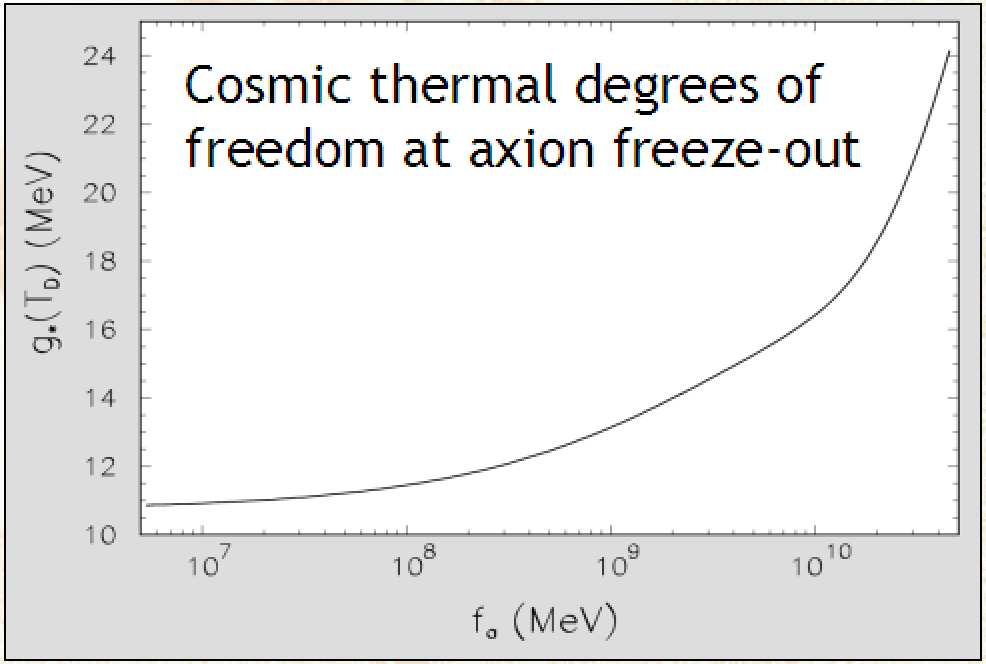

Freeze-out temperature

$$L_{a\pi} = \frac{C_{a\pi}}{f_a f_\pi}(\pi^0\pi^+\partial_\mu\pi^- + \pi^0\pi^-\partial_\mu\pi^+ - 2\pi^+\pi^-\partial_\mu\pi^0)\partial^\mu a$$

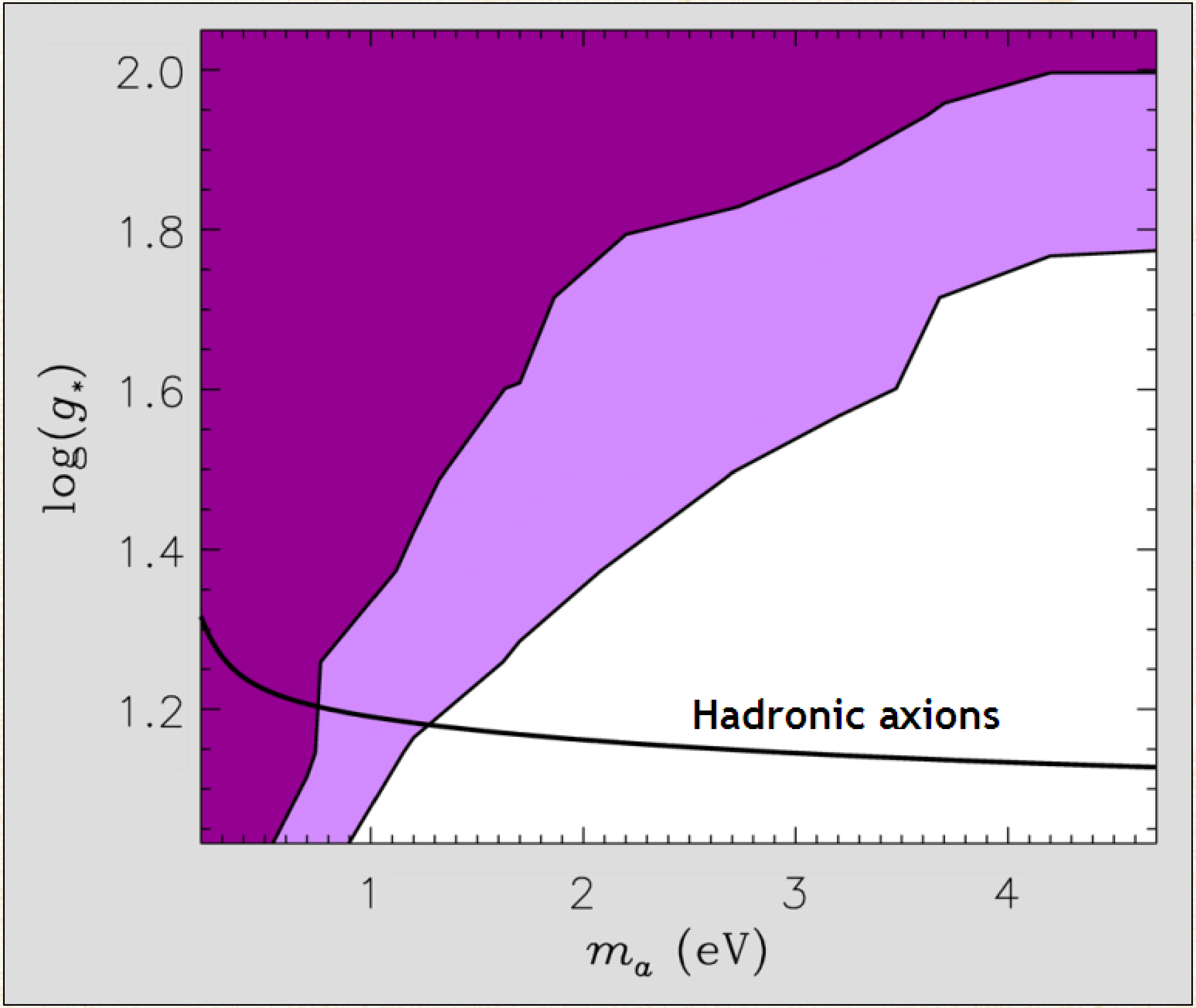


$$C_{a\pi} = \frac{1-z}{3(1+z)} \approx 0.094$$

Chang & Choi, PLB 316 (1993) 51


Cosmic thermal degrees of freedom at axion freeze-out

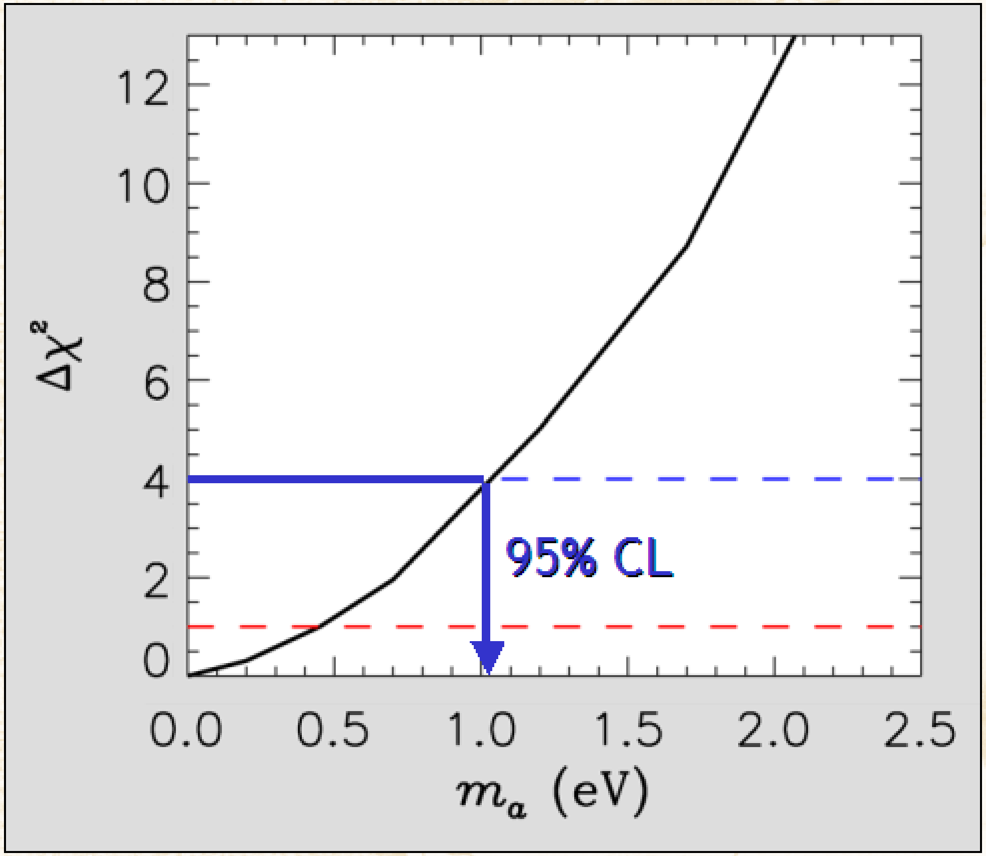
Structure-Formation Exclusion Range for Axions



Hannestad,
Mirizzi &
Raffelt,
hep-ph/0504059

Mass Limits on Hot Dark Matter Axions and Neutrinos

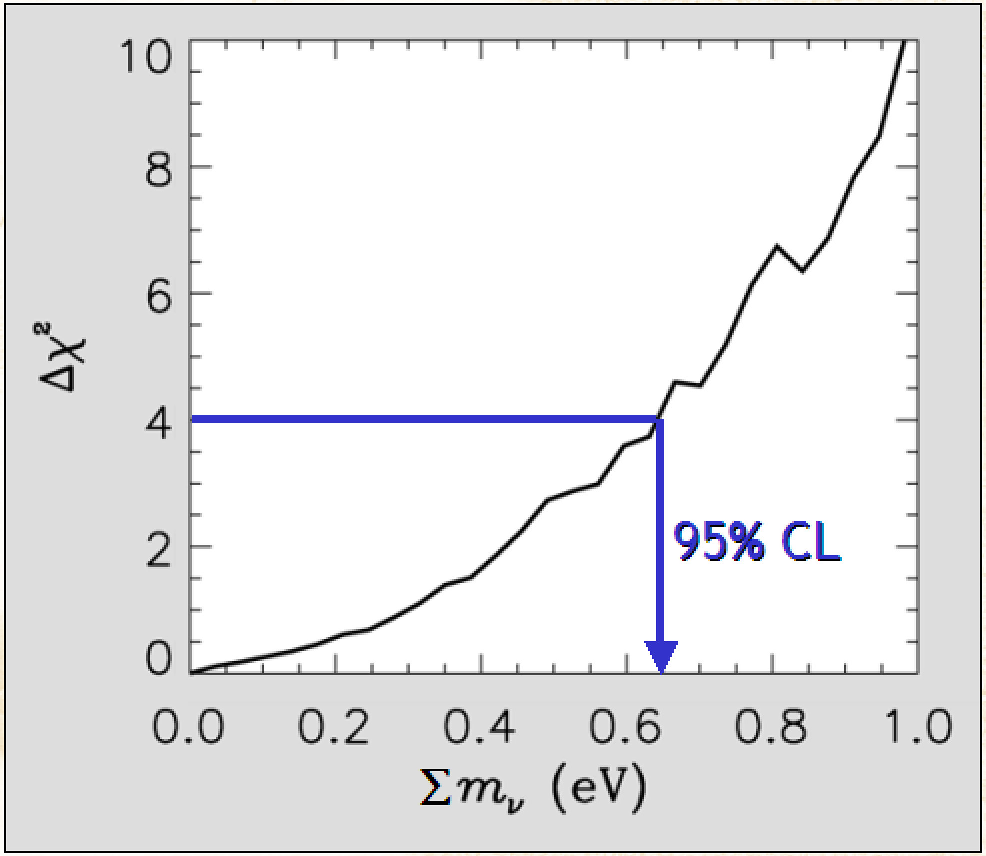
Hannestad, Mirizzi & Raffelt
hep-ph/0504059



Axions

$m_a < 1.05$ eV (95% CL)

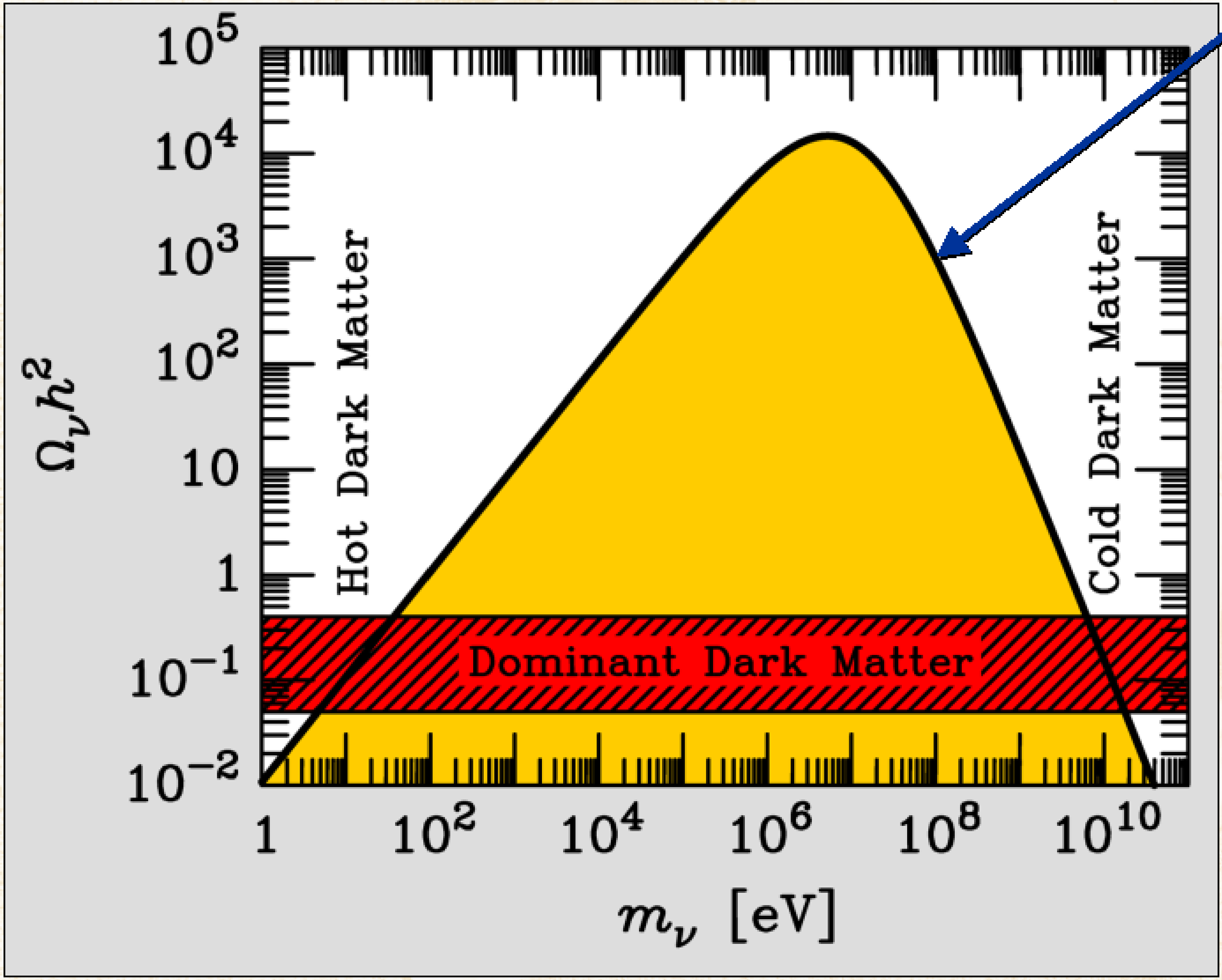
Hannestad, astro-ph/0409108
(Seesaw proceedings, Paris, 2004)



Neutrinos

$\Sigma m_\nu < 0.65$ eV (95% CL)

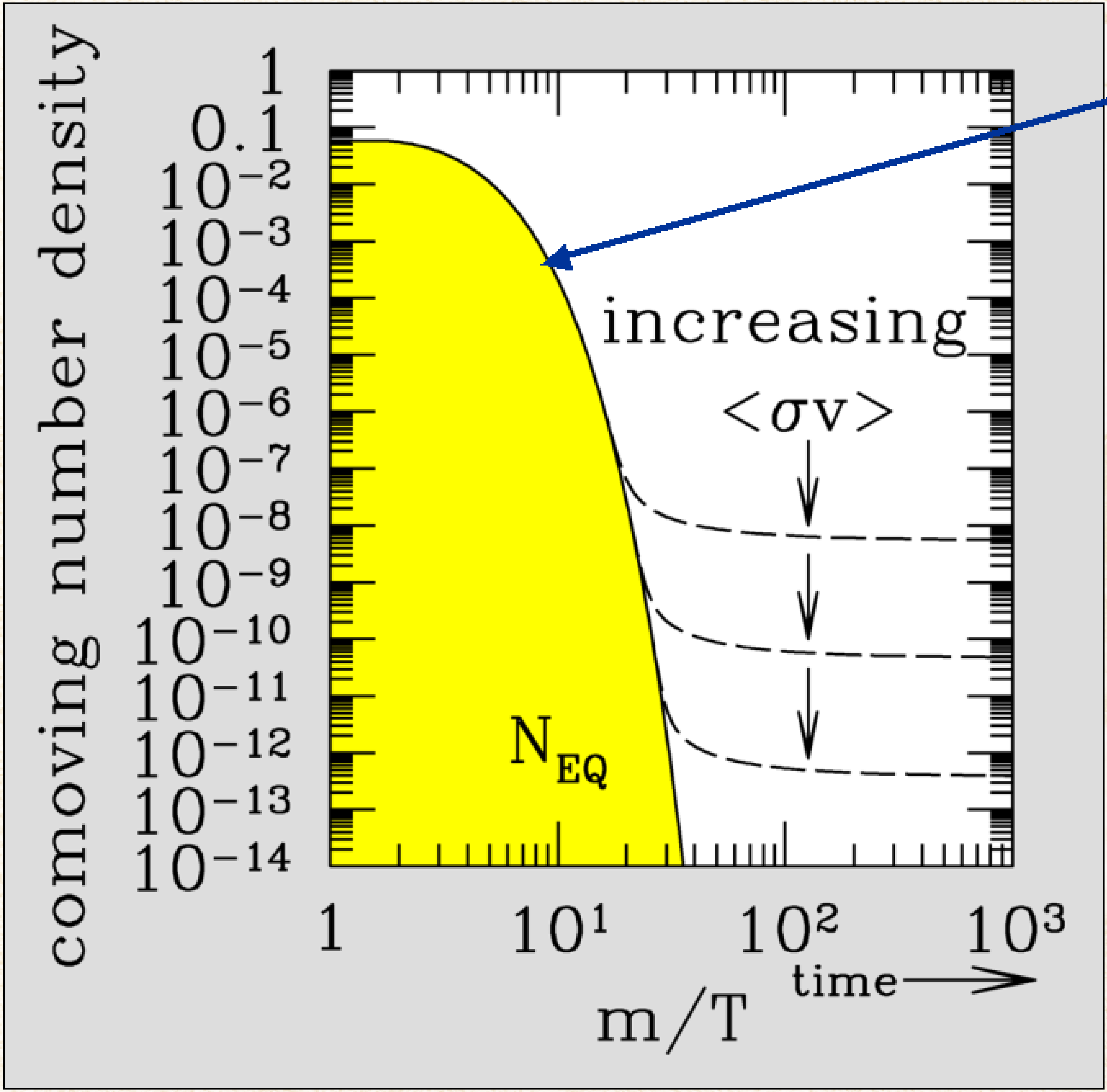
Lee-Weinberg-Curve



- 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

Survival of the Weakest



Boltzmann suppression of equilibrium density $n \propto \exp(-m/T)$

Number density freezes out when annihilation rate is slower than cosmic expansion rate

Gondolo
astro-ph/0403064

Electroweak Scale Favored?

Boltzmann collision equation for number density n of particles with annihilation cross section σ_A

$$\frac{dn}{dt} + 3Hn = -\langle\sigma_A v\rangle(n^2 - n_{eq}^2)$$

Resulting cosmic mass density

$$\Omega h^2 = \text{factors} \times \frac{\text{logarithmic terms}}{\langle\sigma_A v\rangle}$$

With electroweak cross section (Majorana neutrino)

$$\Omega h^2 \approx 0.11 \left(\frac{10\,\text{GeV}}{m}\right)^2$$

Concordance dark matter density

$$\Omega h^2 = 0.110 \pm 0.006$$

Mass for Weakly Interacting Massive Particle (WIMP) as dark matter

$$m \approx 10\,\text{GeV}$$

Cosmic dark matter density of thermal relics
and approximate electroweak gauge coupling strength
favor electroweak scale for scale of new physics

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

SUSY Particles Natural as Dark Matter ?

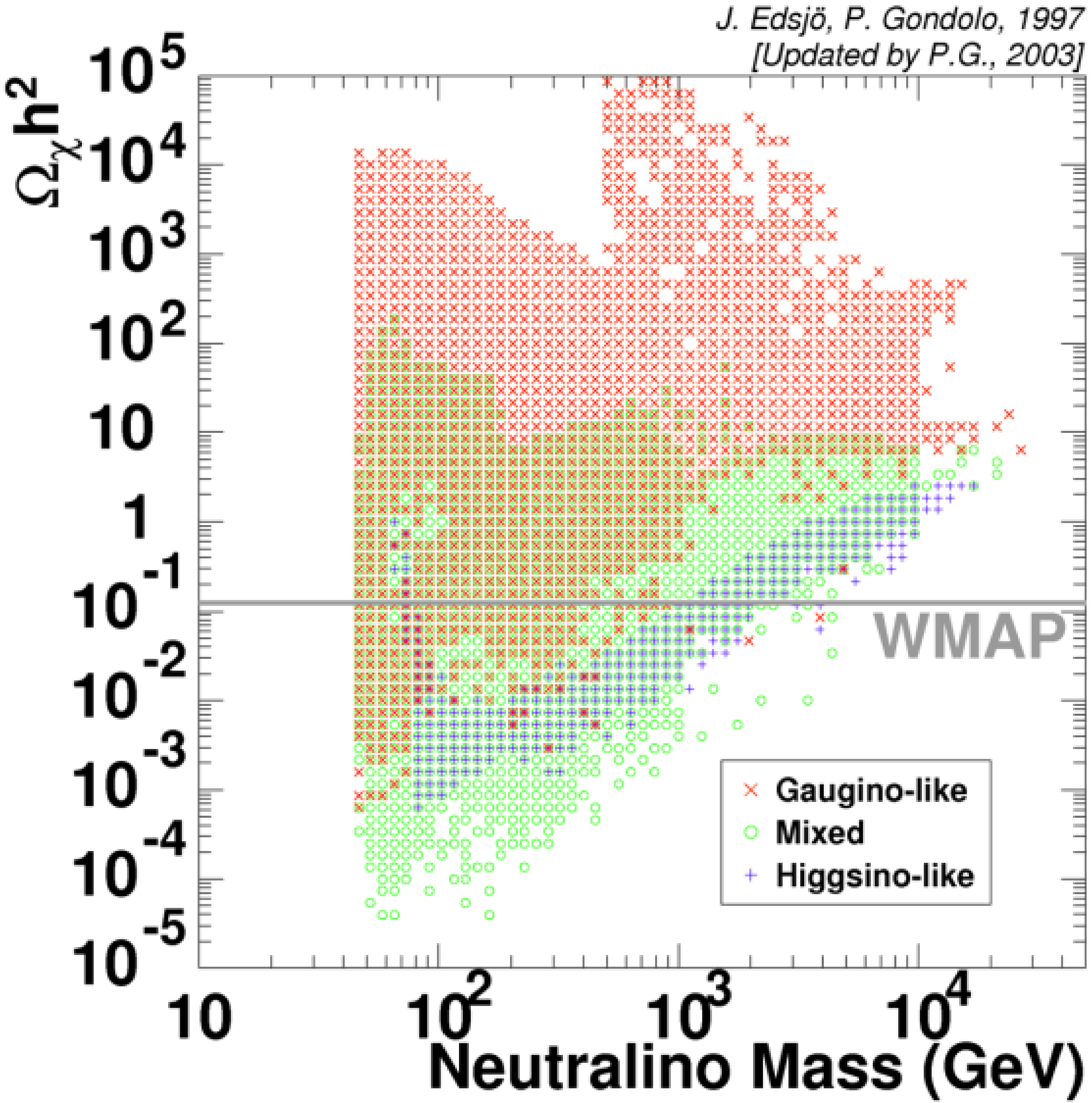
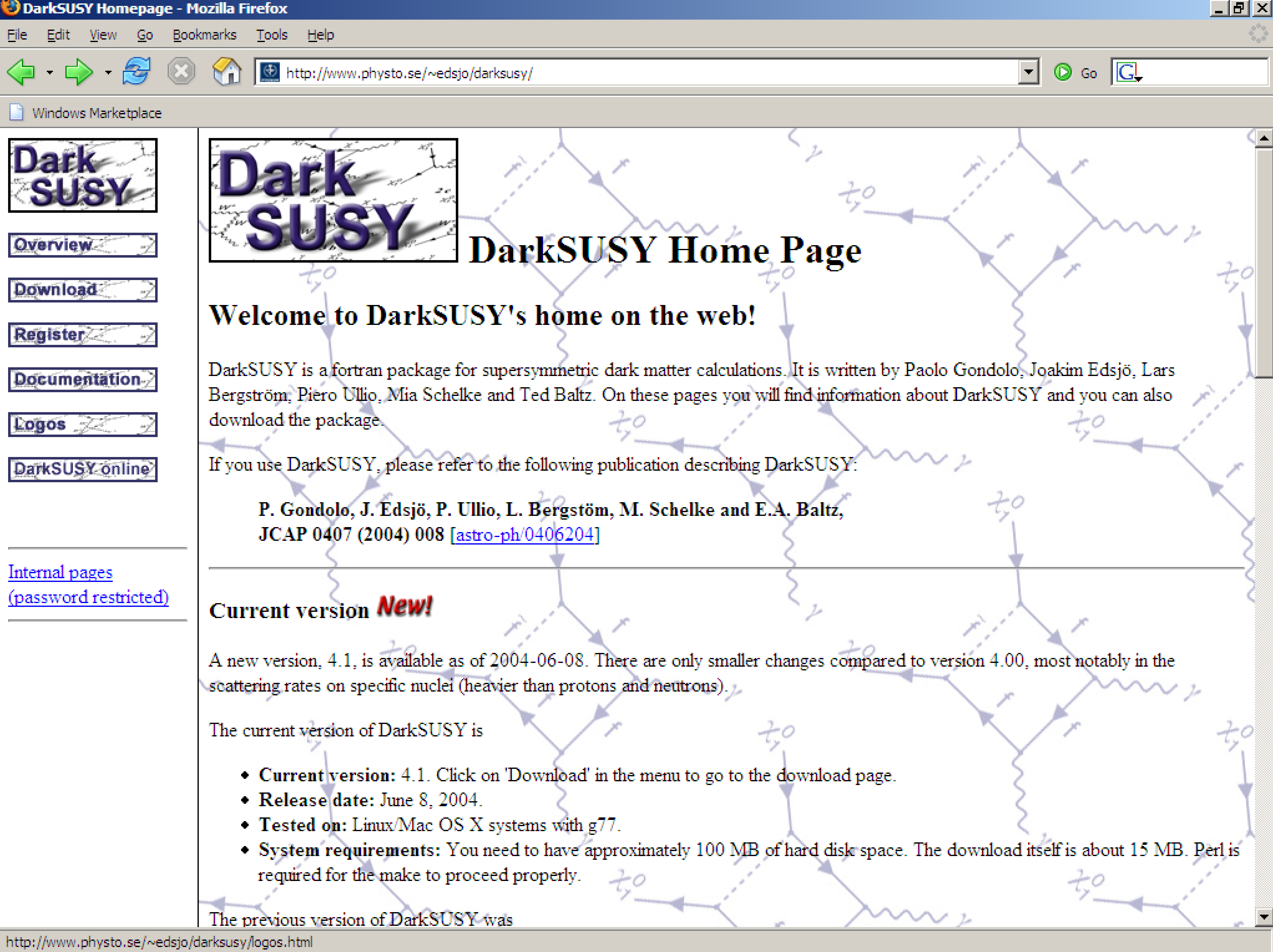


Figure 4: Relic density of the lightest neutralino as a function of its mass. For each mass, several density values are possible depending on the other supersymmetric parameters (seven in total in the scenario plotted). The color code shows the neutralino composition (gaugino, higgsino or mixed). The gray horizontal line is the current error band in the WMAP measurement of the cosmological cold dark matter density. (Figure adapted from Edsjö & Gondolo, 1997.)

Gondolo, astro-ph/0403064



DarkSUSY Home Page

Internal pages (password restricted)

Welcome to DarkSUSY's home on the web!

DarkSUSY is a fortran package for supersymmetric dark matter calculations. It is written by Paolo Gondolo, Joakim Edsjö, Lars Bergström, Piero Ullio, Mia Schelke and Ted Baltz. On these pages you will find information about DarkSUSY and you can also download the package.

If you use DarkSUSY, please refer to the following publication describing DarkSUSY:

> **P. Gondolo, J. Edsjö, P. Ullio, L. Bergstöm, M. Schelke and E.A. Baltz,**
> **JCAP 0407 (2004) 008** [astro-ph/0406204]

Current version *New!*

A new version, 4.1, is available as of 2004-06-08. There are only smaller changes compared to version 4.00, most notably in the scattering rates on specific nuclei (heavier than protons and neutrons).

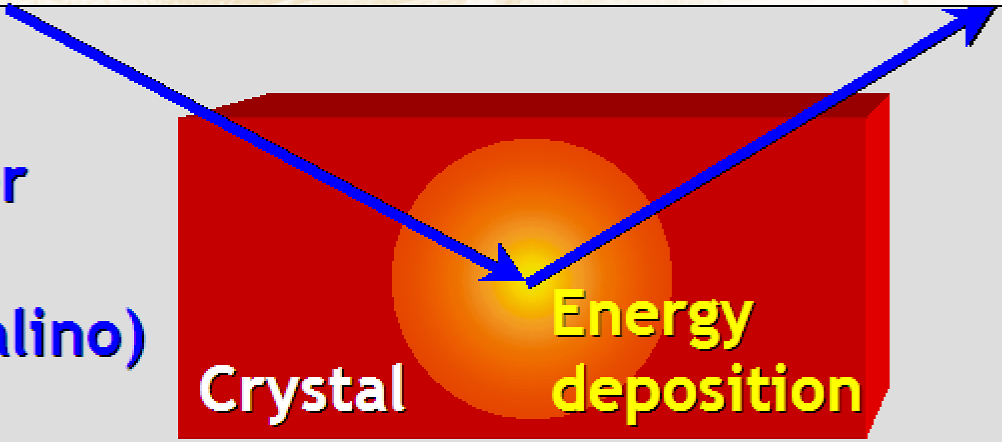
The current version of DarkSUSY is

- **Current version:** 4.1. Click on 'Download' in the menu to go to the download page.
- **Release date:** June 8, 2004.
- **Tested on:** Linux/Mac OS X systems with g77.
- **System requirements:** You need to have approximately 100 MB of hard disk space. The download itself is about 15 MB. Perl is required for the make to proceed properly.

The previous version of DarkSUSY was

Search for Neutralino Dark Matter

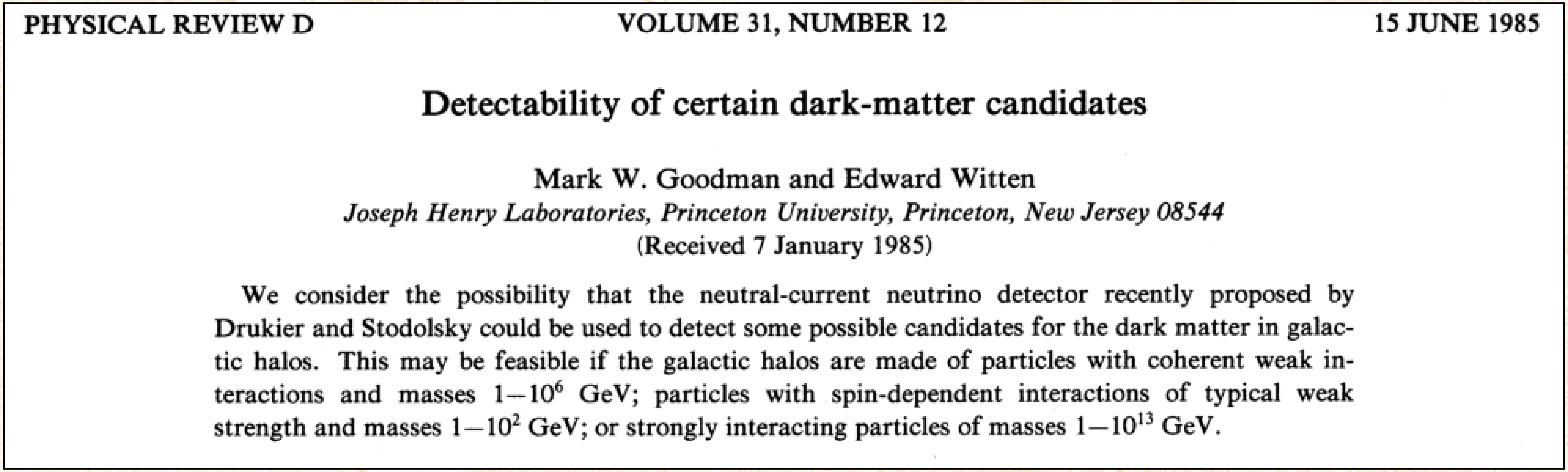
Direct Method (Laboratory Experiments)



Galactic dark matter particle (e.g.neutralino)

Recoil energy (few keV) is measured by

- Ionisation
- Scintillation
- Cryogenic



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

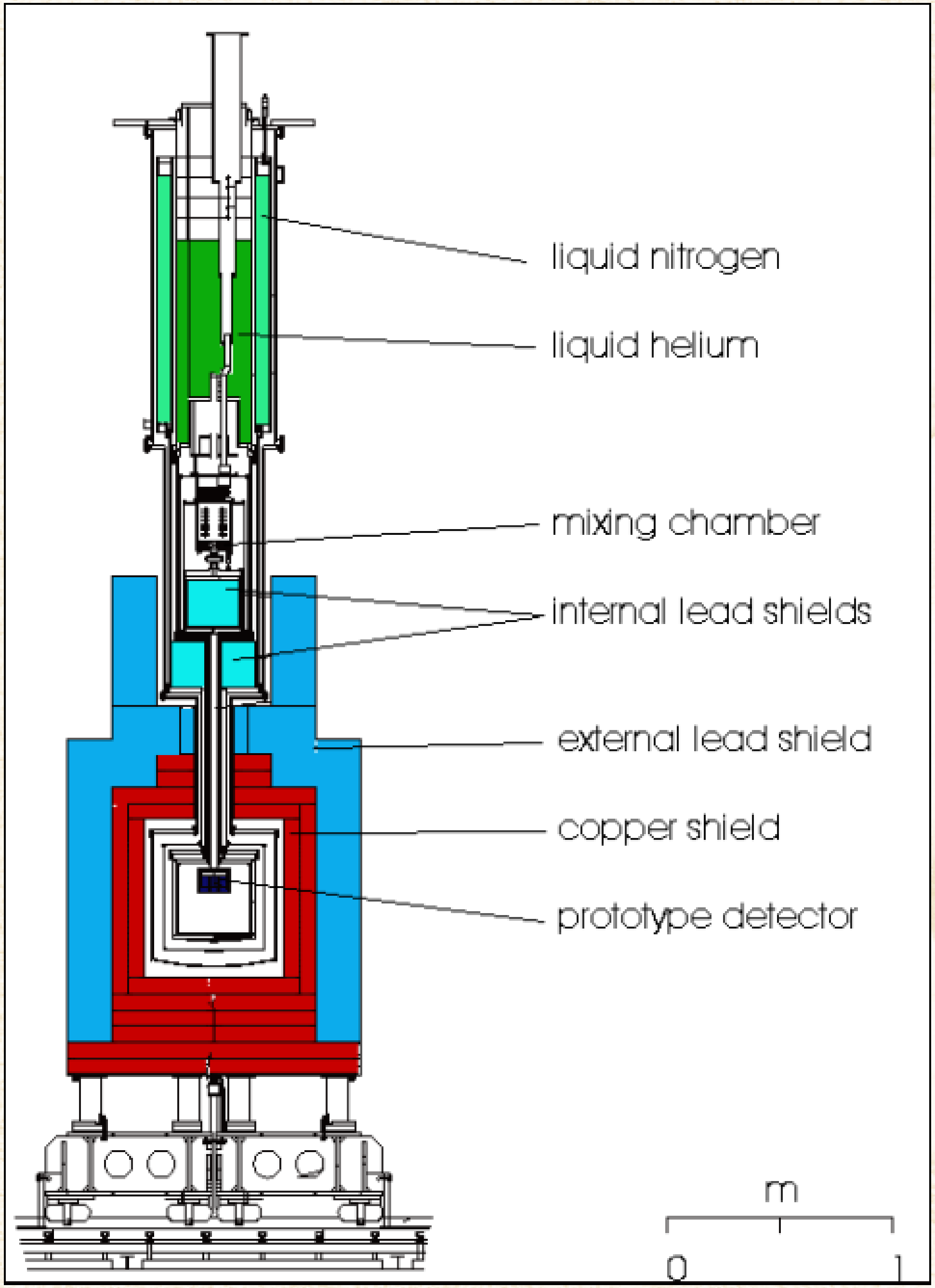
(Received 7 January 1985)

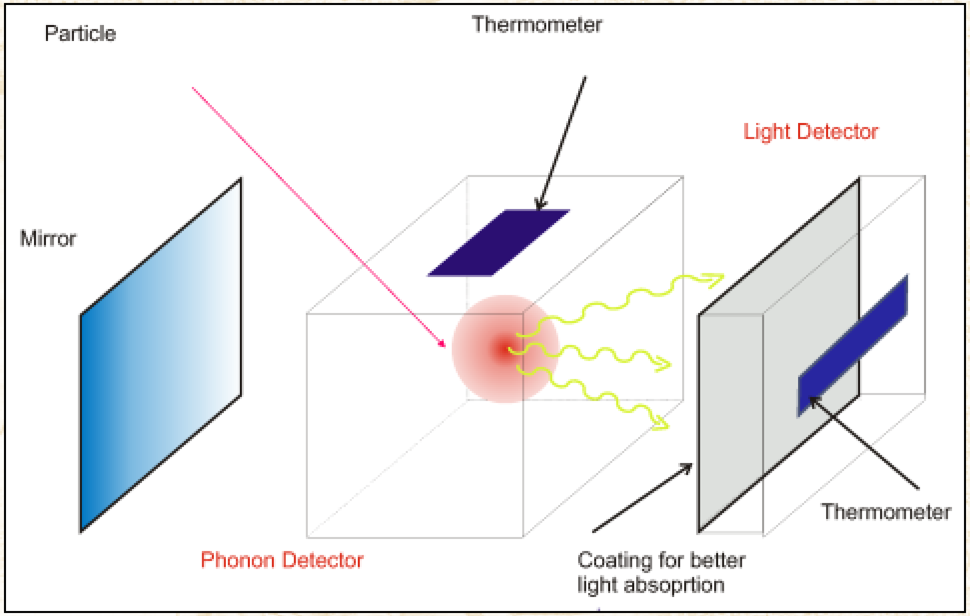
We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses $1-10^6$ GeV; particles with spin-dependent interactions of typical weak strength and masses $1-10^2$ GeV; or strongly interacting particles of masses $1-10^{13}$ GeV.

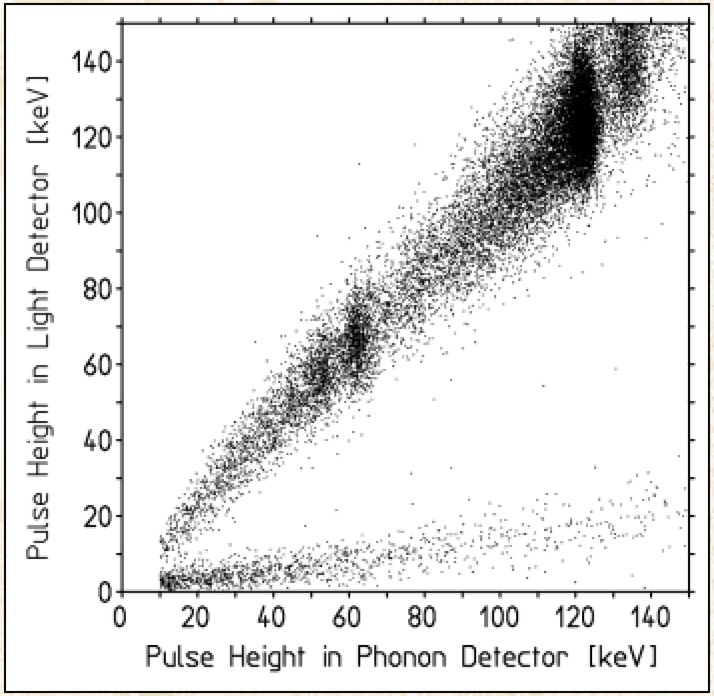
WIMP direct detection in underground facilities experiments currently running (or in preparation)

LABORATORY	EXPERIMENT	TECHNIQUE
Bern (Switzerland)	ORPHEUS	(SSD) Tin Superconducting Superheated Detector
Boulby (UK)	NAIAD	NaI scintillators (46-65 Kg)
	ZEPLIN I	Liquid Xe scintillator (4 Kg)
	ZEPLIN II	Liquid-Gas Xe (scintillation/ionization) (30 Kg) (R+D)
	DRIFT	Low pressure Xe TPC 1m^3 (R+D)
Canfranc (Spain)	IGEX	Ge ionization detector (2.1 Kg)
	GEDEON	Set of Ge ionization detector (in project) (4x7x2 Kg)
	ANAIS	NaI scintillators (110 kg)
	ROSEBUD	$CaWO_4$ 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	Ge ionization detector (2.7 Kg)
	HDMS	Ge ionization in Ge well
	GENIUS-TF	Set of Ge crystals in LN_2 (40 Kg)
	DAMA	NaI scintillators (~100 Kg)
	LIBRA	NaI scintillators 250 kg (starting)
	Liquid-Xe	Liquid Xe scintillator (6 Kg)
	CaF_2	Scintillator
	CRESST	Set of $CaWO_4$ scintillating bolometers (n x 300 g)
	CUORICINO	Set of TeO_2 thermal detector (41 Kg)
	CUORE	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	Large set of massive NaI scintillators (670 kg)
	ELEGANTS VI	CaF_2 scintillators

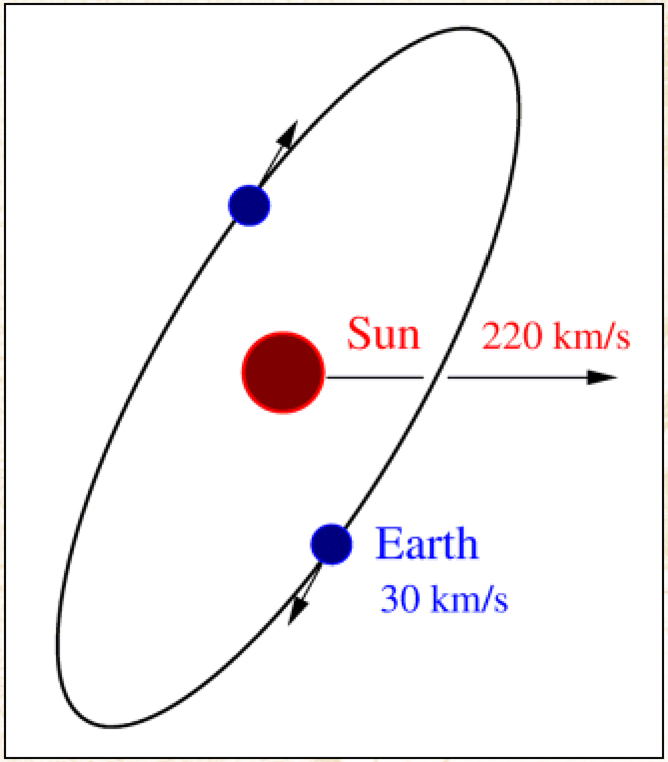
CRESST Experiment to Search for Dark Matter





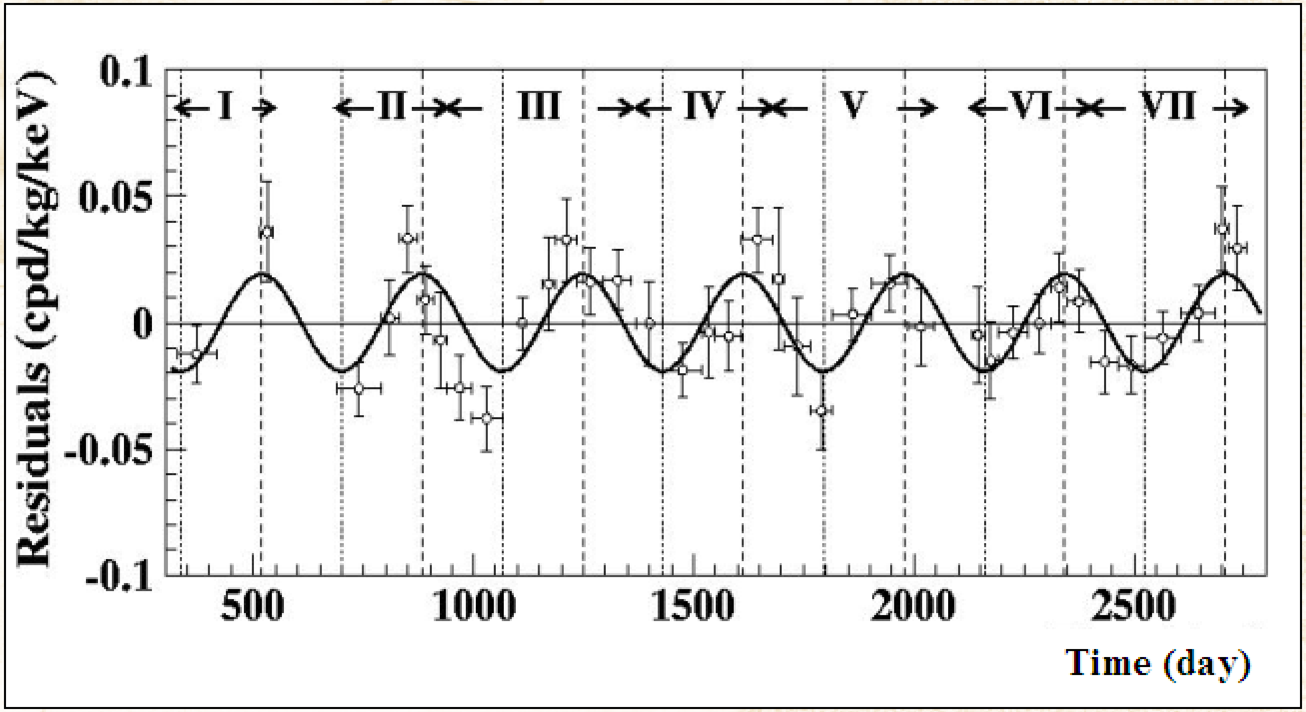


DAMA Evidence for WIMP Detection



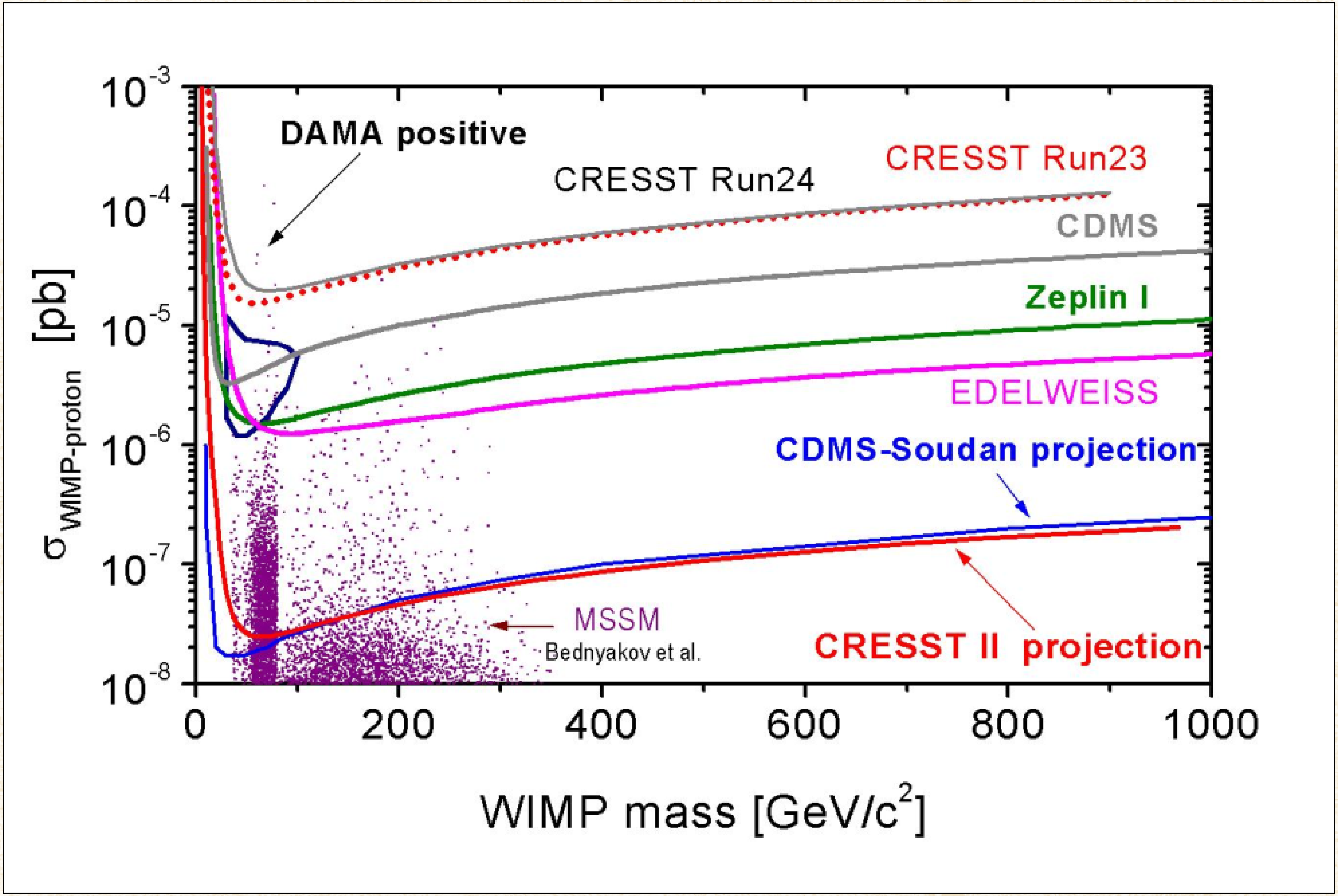
Annual modulation of WIMP signal a “smoking gun” signature

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]

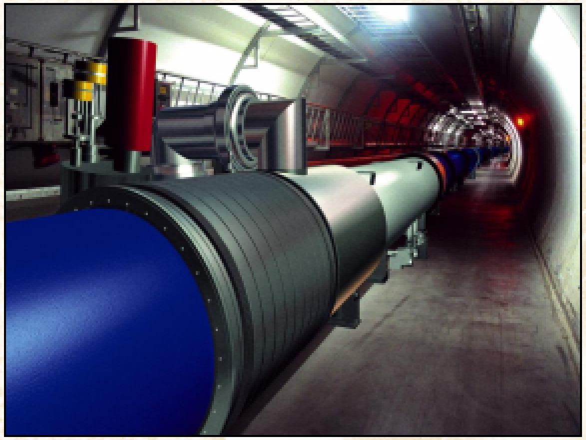


- Detector stability ?
- „Background stability“ ?

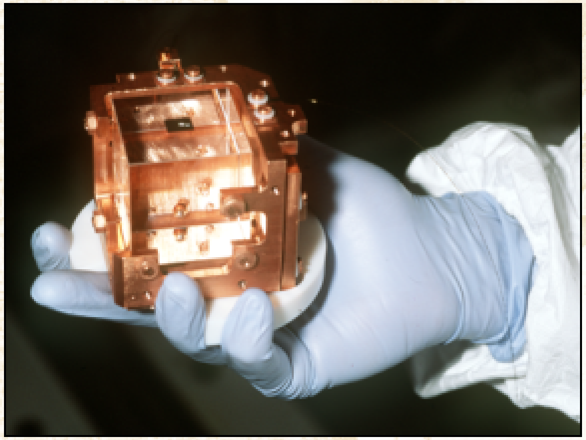
Projected WIMP Sensitivities

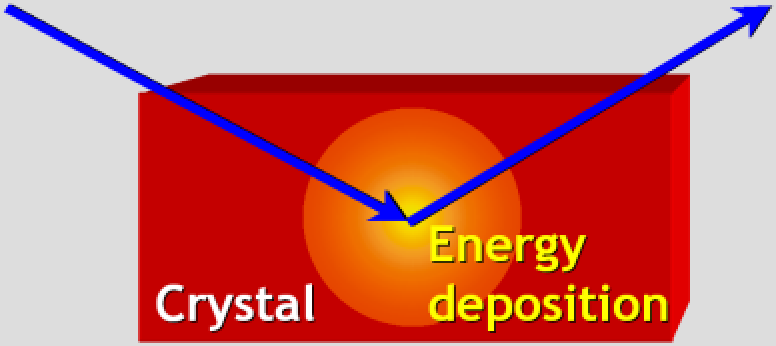


Hunting WIMPs



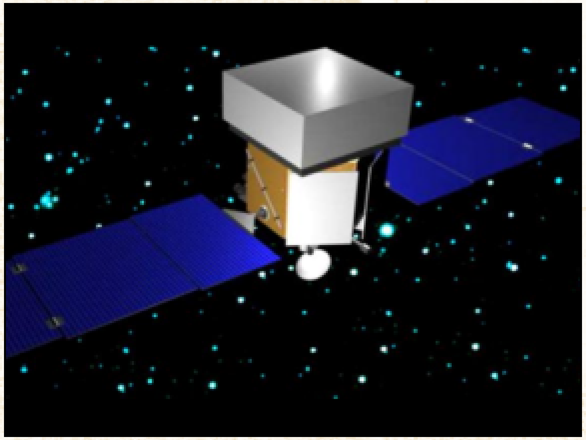
Search for new particles at accelerators, notably the Large Hadron Collider (LHC) at CERN (> 2007)





Recoil energy (few keV) is measured by

- Ionisation
- Scintillation
- Cryogenically

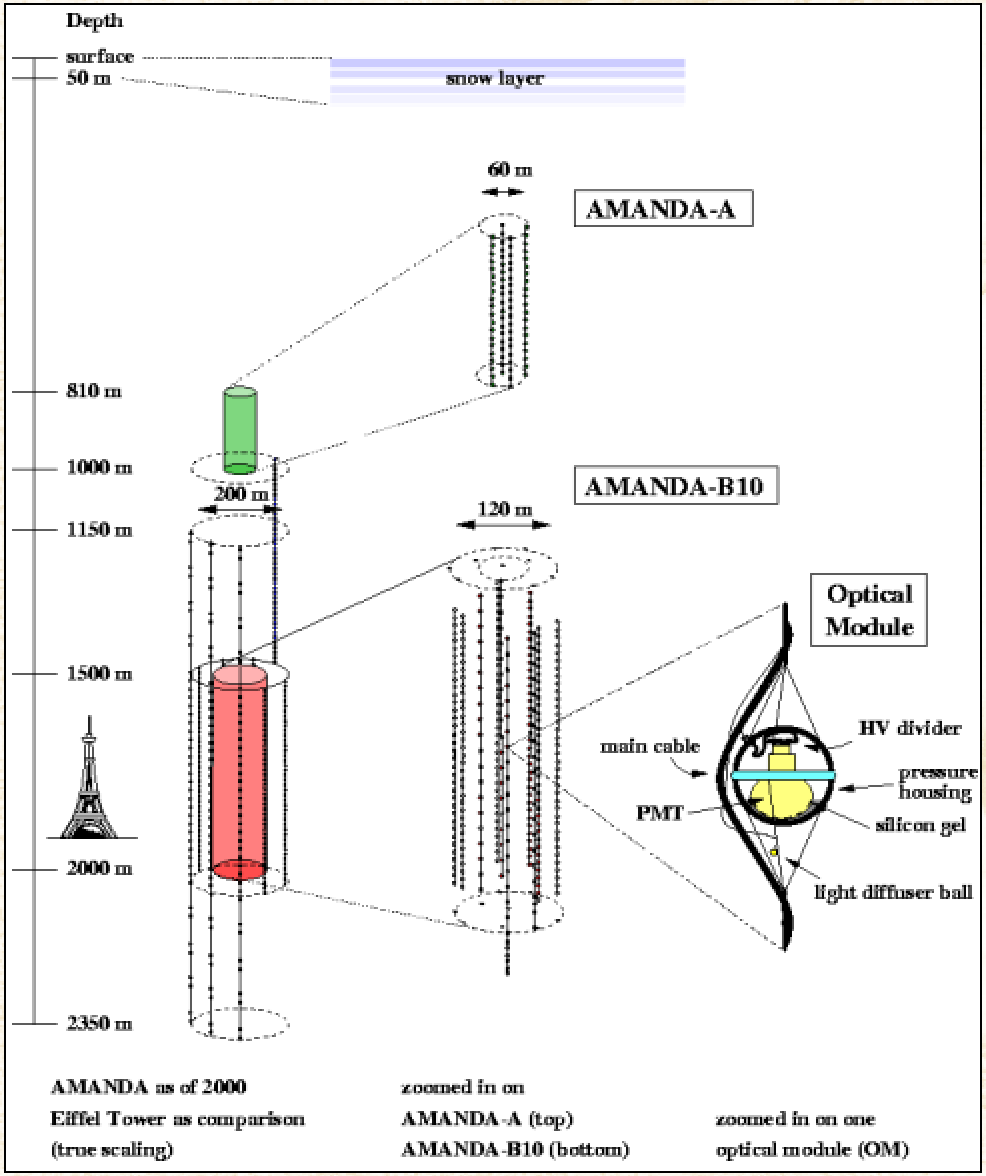


Search for WIMP annihilation products in the form of

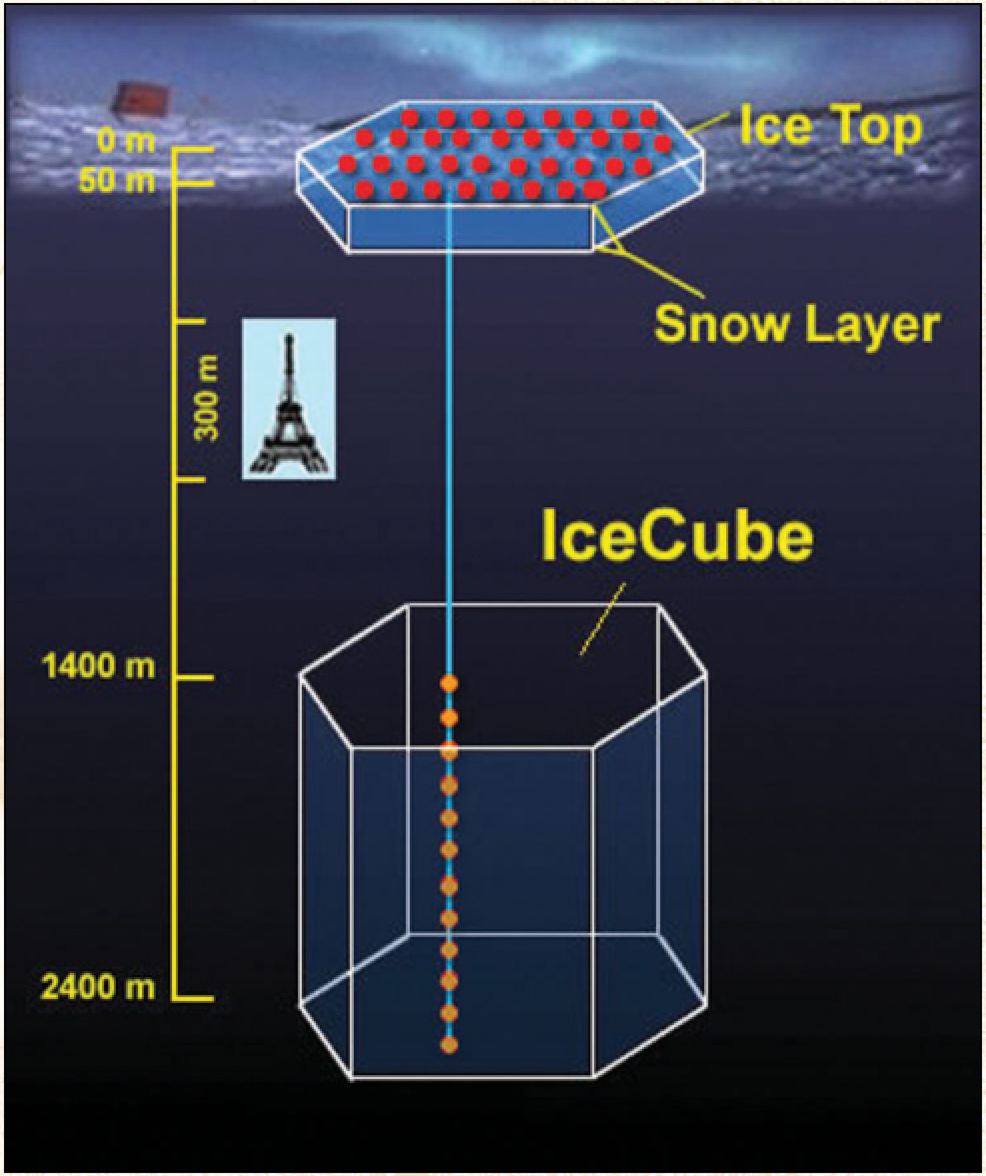
- Gamma rays (e.g. EGRET, HESS, MAGIC, GLAST)
- Anti-protons (AMS)
- Positrons
- High-energy neutrinos from the Sun or Earth (e.g. Super-K, Amanda/IceCube, Antares, …)

Southpole Ice-Cherenkov Neutrino Detectors

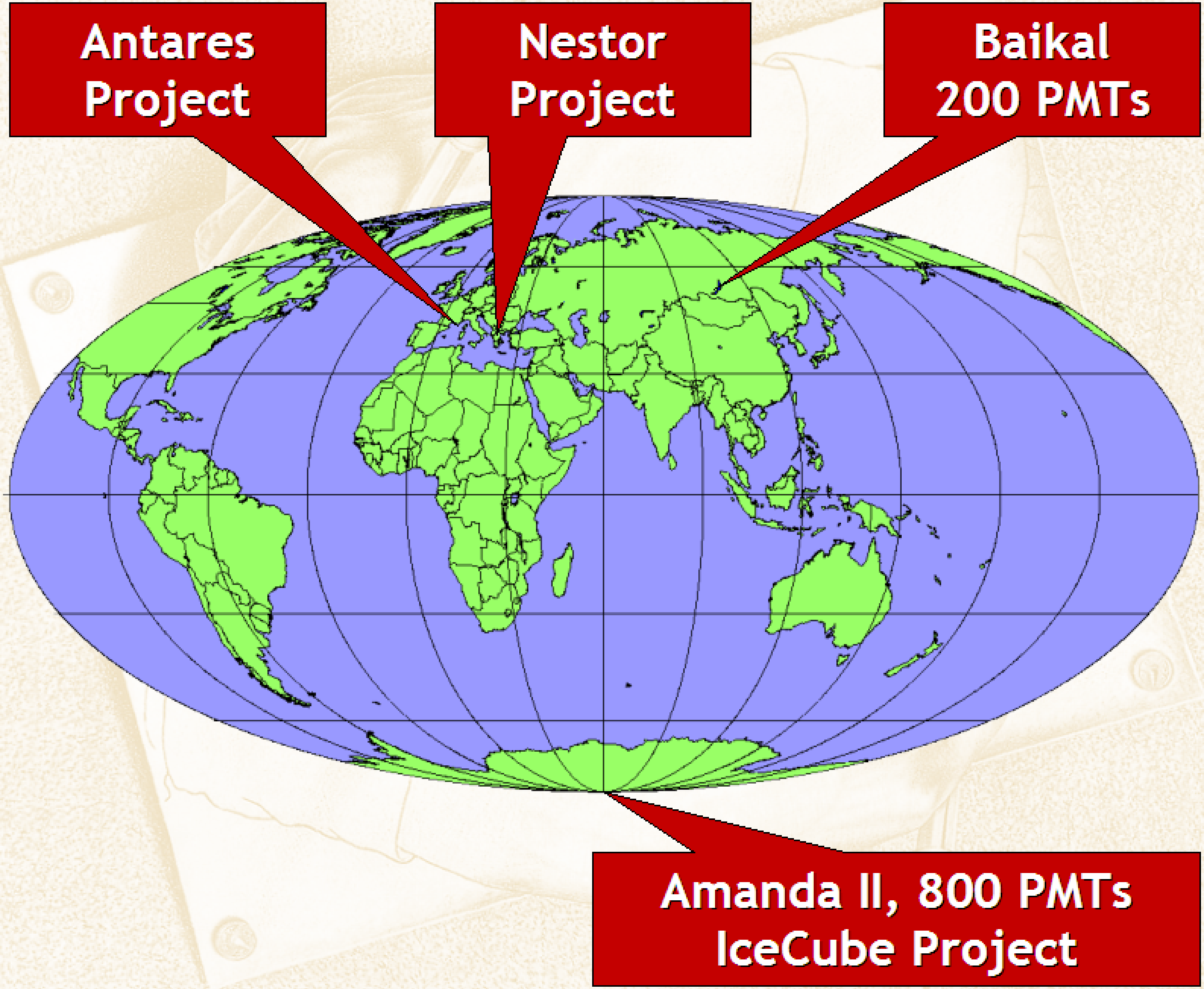
AMANDA II (0.1 km^3, 800 PMTs)



Future IceCube (1 km^3, 4800 PMTs)



High-Energy Neutrino Telescopes



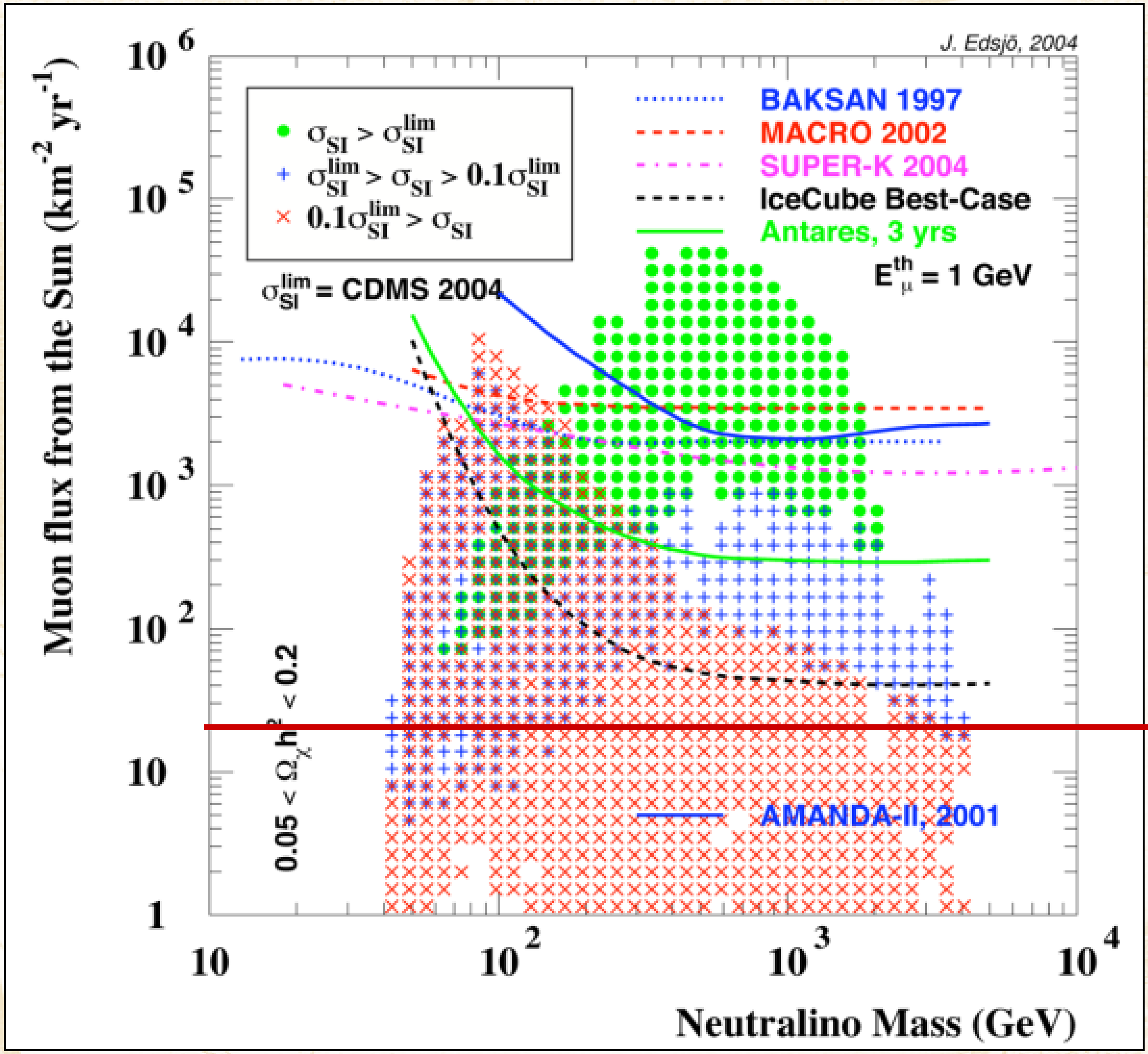
Antares Project

Nestor Project

Baikal 200 PMTs

Amanda II, 800 PMTs IceCube Project

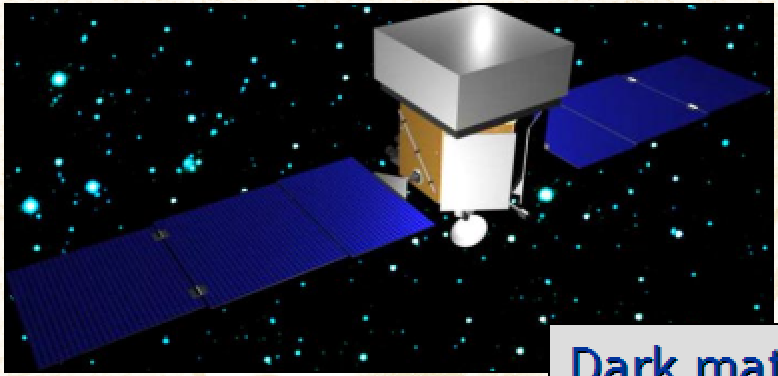
Muon Flux from WIMP Annihilation in the Sun



Background from Sun

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

Can We See the Dark Matter?



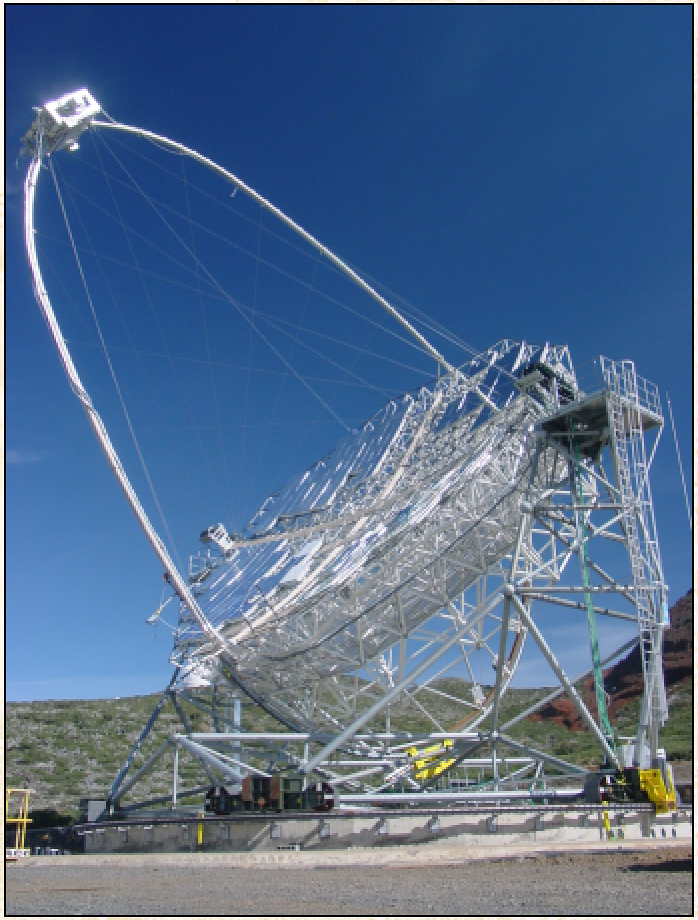
GLAST Project

Dark matter particles can directly annihilate

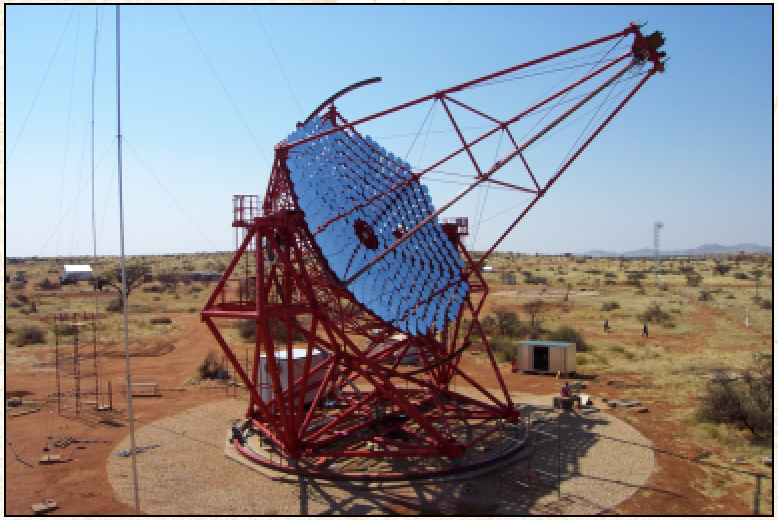
$$\chi\chi \rightarrow \gamma\gamma$$

The dark halo of our galaxy can slightly glow in high-energy gamma rays

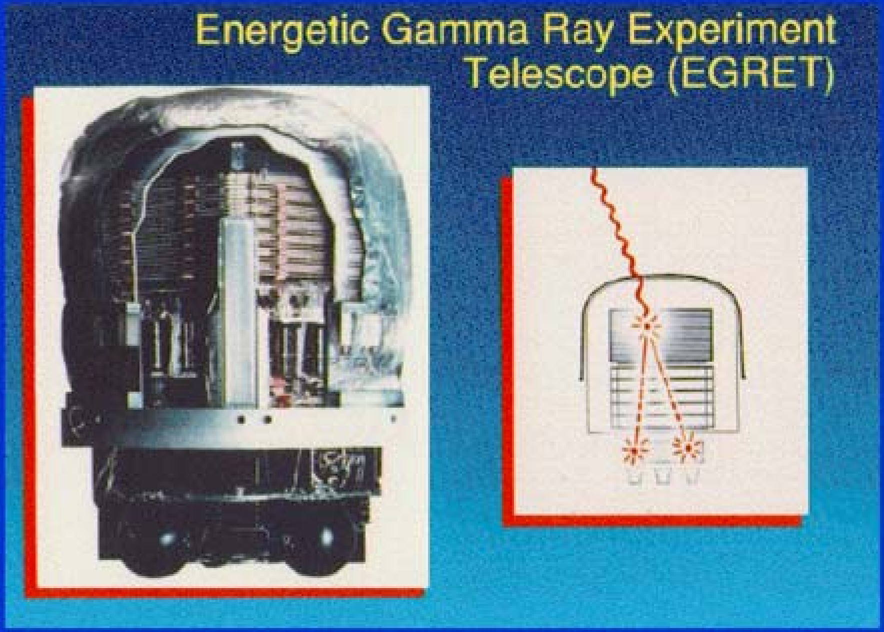
MAGIC airshower telescope, La Palma

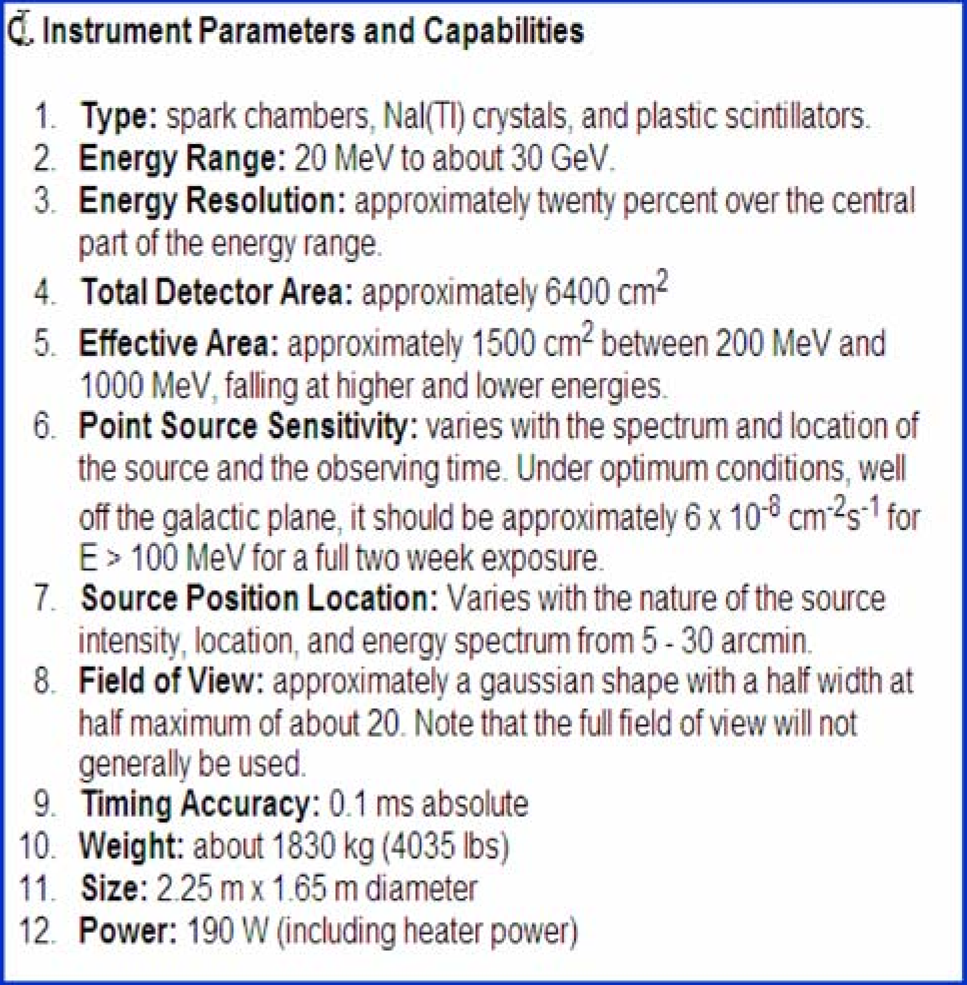


HESS airshower telescope, Namibia



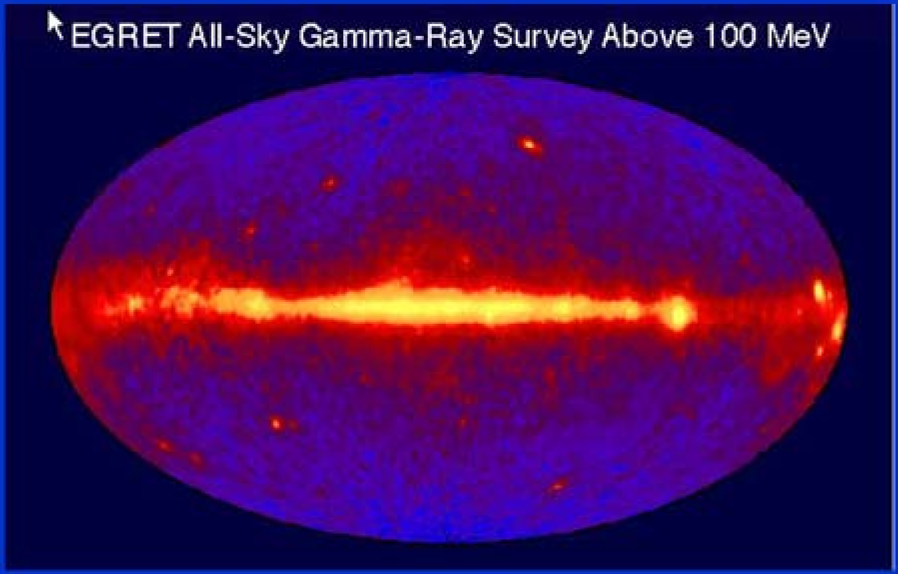
EGRET on CGRO (Compton Gamma Ray Observ.)





Instrument Parameters and Capabilities

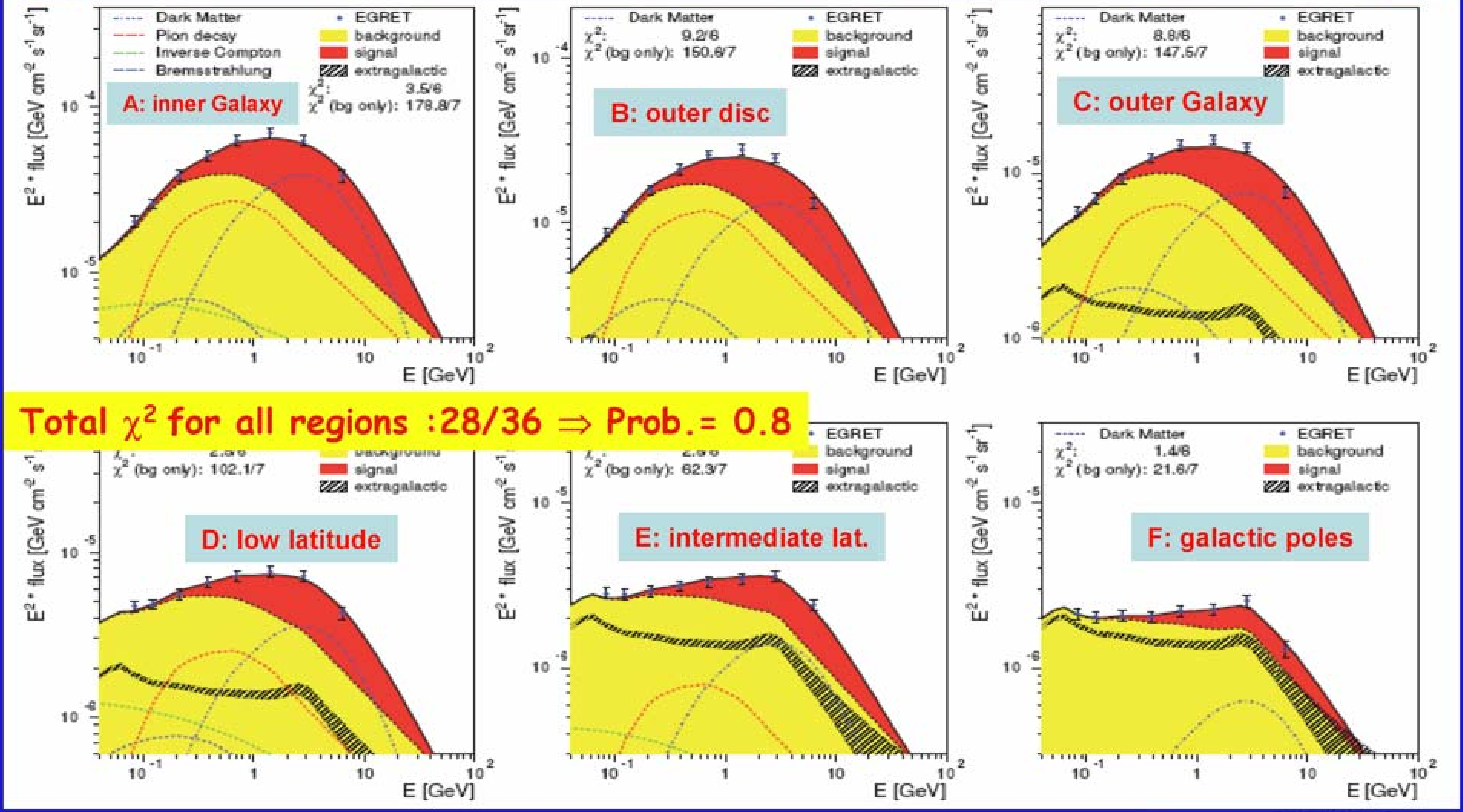
1. **Type:** spark chambers, NaI(Tl) crystals, and plastic scintillators.
2. **Energy Range:** 20 MeV to about 30 GeV.
3. **Energy Resolution:** approximately twenty percent over the central part of the energy range.
4. **Total Detector Area:** approximately 6400 cm^2
5. **Effective Area:** approximately 1500 cm^2 between 200 MeV and 1000 MeV, falling at higher and lower energies.
6. **Point Source Sensitivity:** varies with the spectrum and location of the source and the observing time. Under optimum conditions, well off the galactic plane, it should be approximately 6 x 10^{-8} cm^{-2}s^{-1} for E > 100 MeV for a full two week exposure.
7. **Source Position Location:** Varies with the nature of the source intensity, location, and energy spectrum from 5 - 30 arcmin.
8. **Field of View:** approximately a gaussian shape with a half width at half maximum of about 20. Note that the full field of view will not generally be used.
9. **Timing Accuracy:** 0.1 ms absolute
10. **Weight:** about 1830 kg (4035 lbs)
11. **Size:** 2.25 m x 1.65 m diameter
12. **Power:** 190 W (including heater power)



EGRET All-Sky Gamma-Ray Survey Above 100 MeV

9 yrs of data taken in space!
(1991-2000)

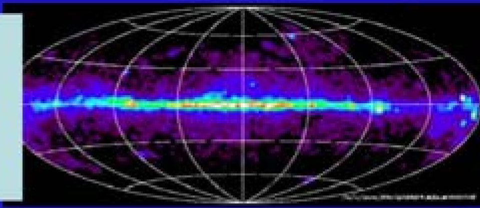
Analysis of EGRET Data in 6 sky directions



Total χ^2 for all regions :28/36 ⇒ Prob.= 0.8

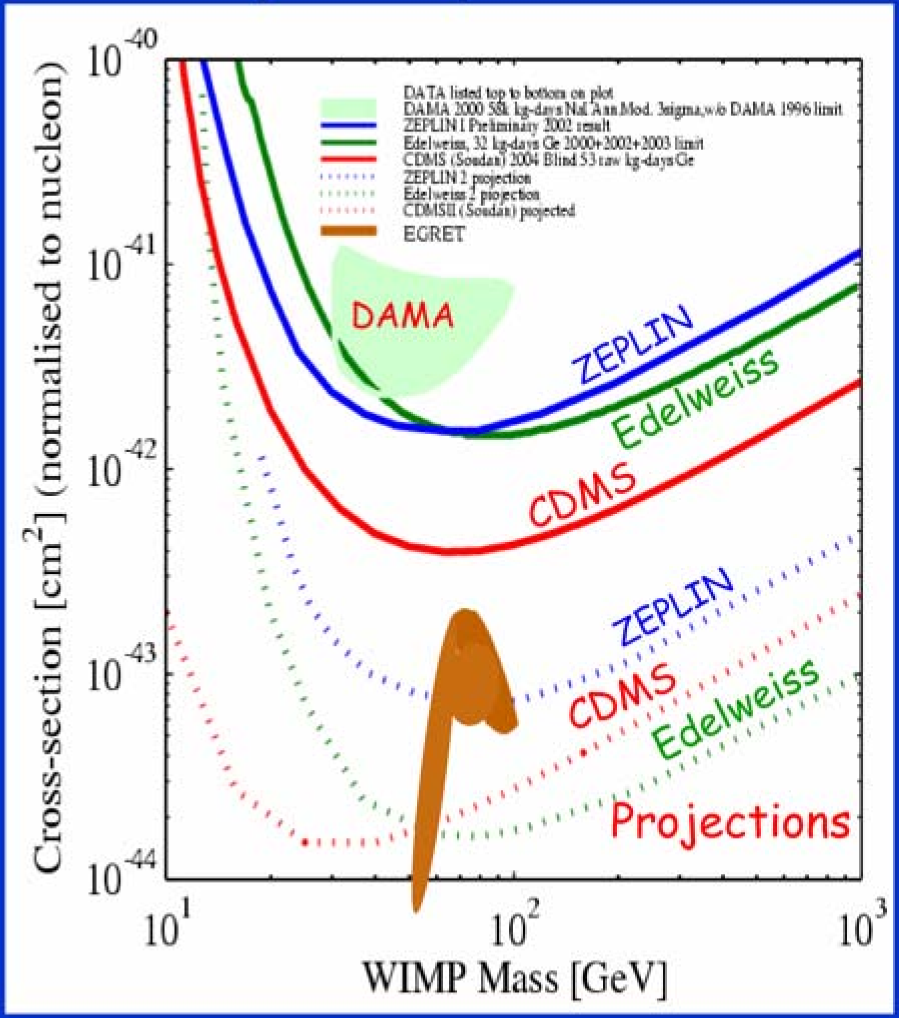
A: inner Galaxy (l=±30^0, |b|<5^0)
B: Galactic plane avoiding A
C: Outer Galaxy

D: low latitude (10-20^0)
E: intermediate lat. (20-60^0)
F: Galactic poles (60-90^0)

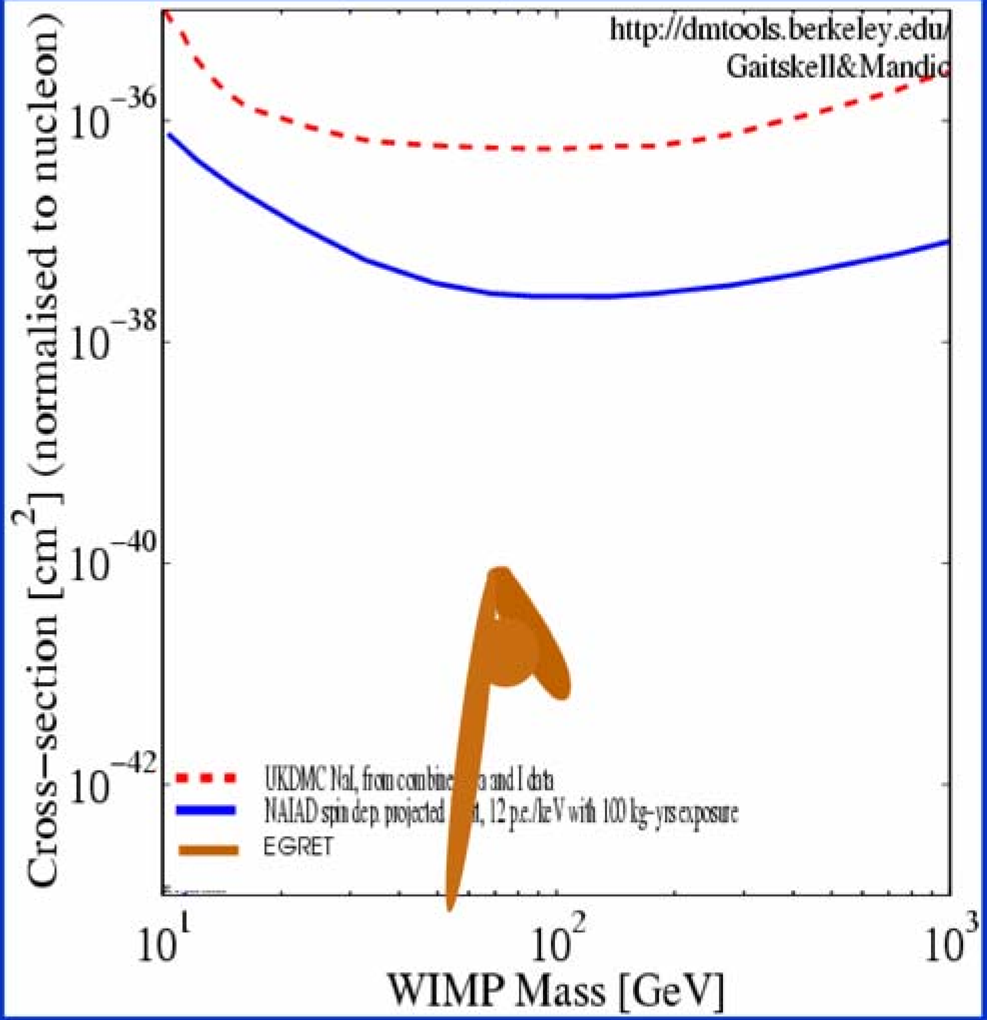


Future: Direct DM Searches

Spin-independent



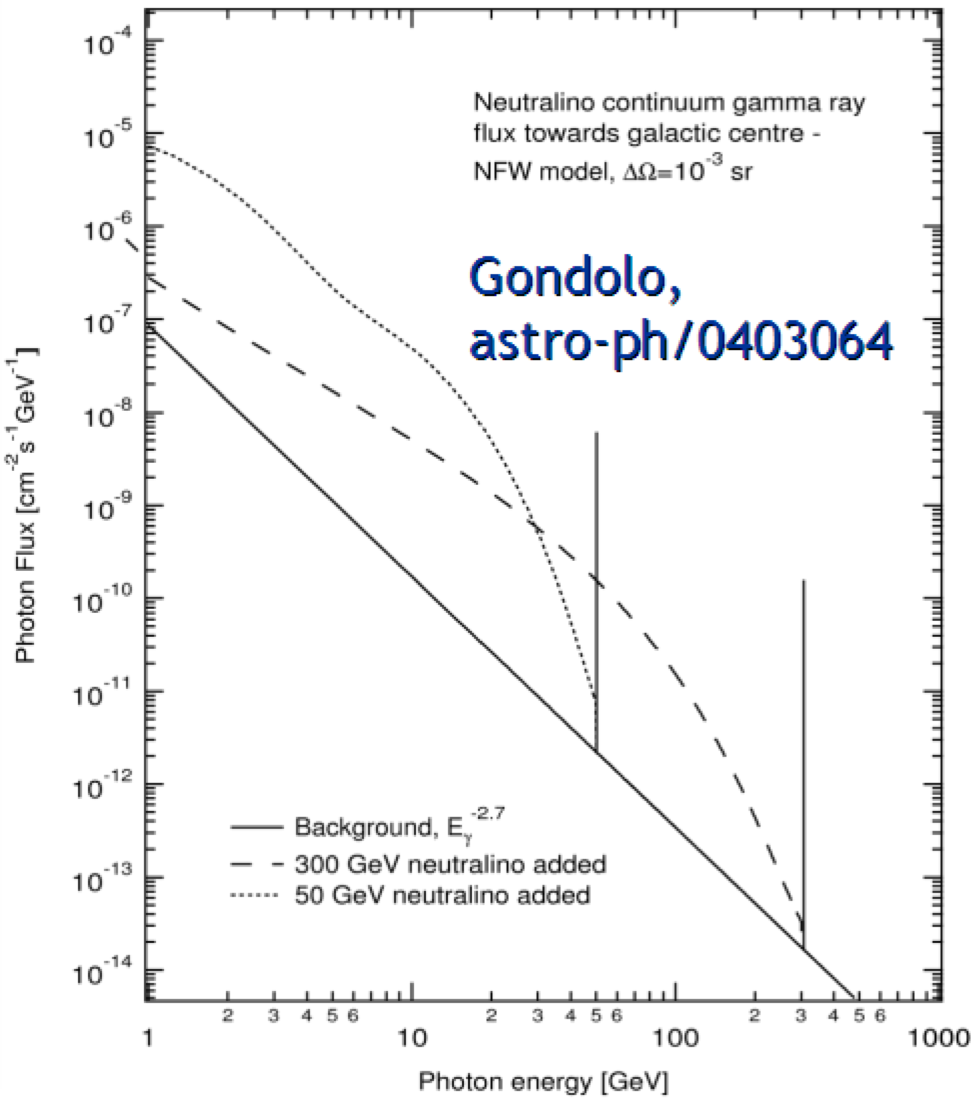
Spin-dependent



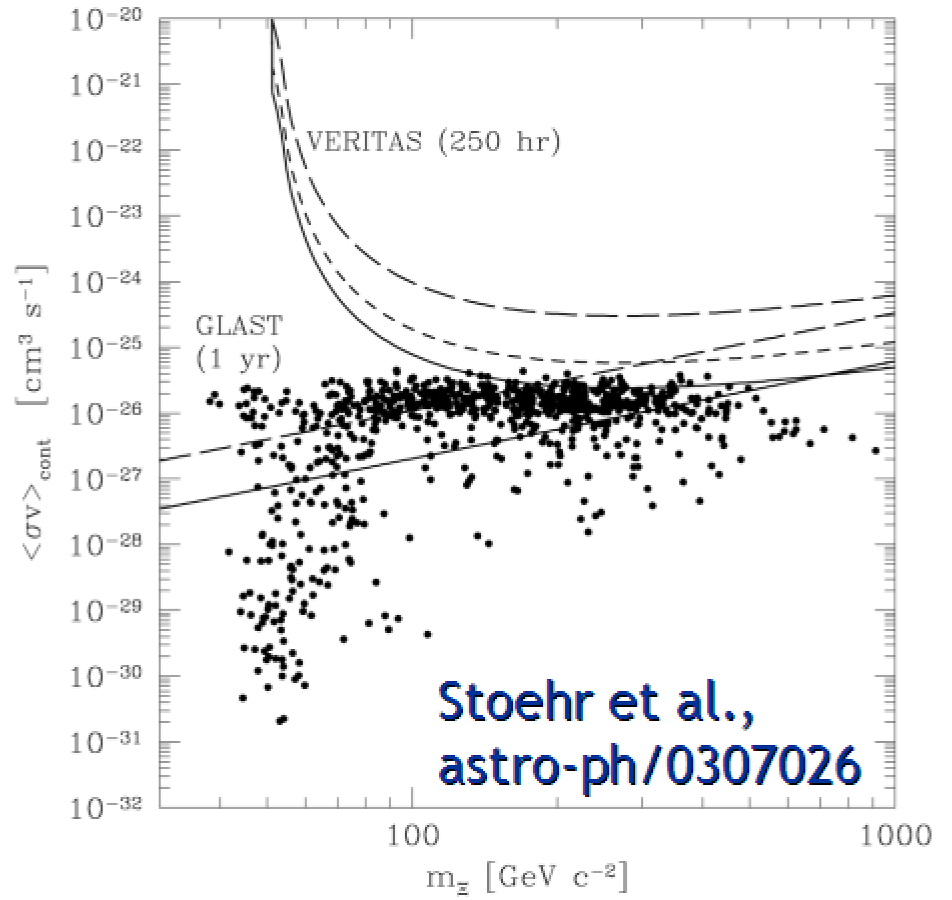
● Predictions from EGRET data assuming Supersymmetry

High-Energy Gamma Rays from Neutralino Annihilation

$\chi\chi \to \gamma\gamma$ or $Z\gamma$



Gondolo, astro-ph/0403064



Stoehr et al., astro-ph/0307026

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.

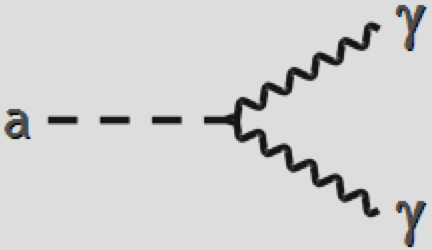
Axion Physics in a Nut Shell

Particle-Physics Motivation

CP conservation in QCD by Peccei-Quinn mechanism

→ Axions $a \sim \pi^0$

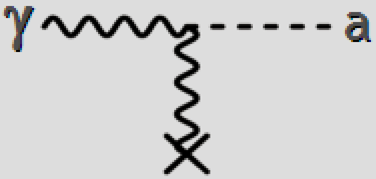
$m_\pi f_\pi \approx m_a f_a$



For $f_a \gg f_\pi$ axions are "invisible" and very light

Solar and Stellar Axions

Axions thermally produced in stars, e.g. by Primakoff production

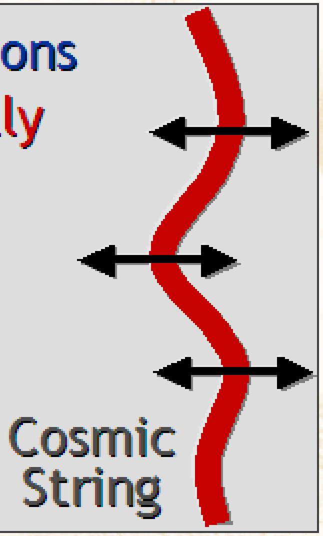


- Limits from avoiding excessive energy drain
- Search for solar axions (CAST)

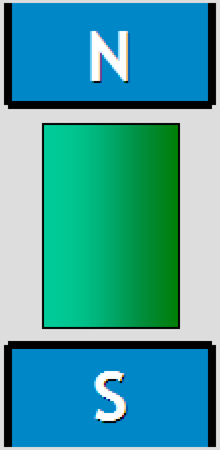
Cosmology

In spite of small mass, axions are born non-relativistically ("non-thermal relics")

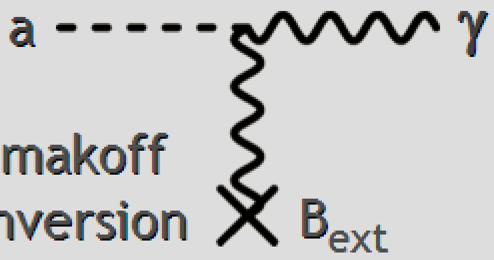
→ "Cold dark matter" candidate
$m_a \sim 1\text{-}1000\ \mu\text{eV}$



Search for Axion Dark Matter



Microwave resonator (1 GHz = 4 μeV)

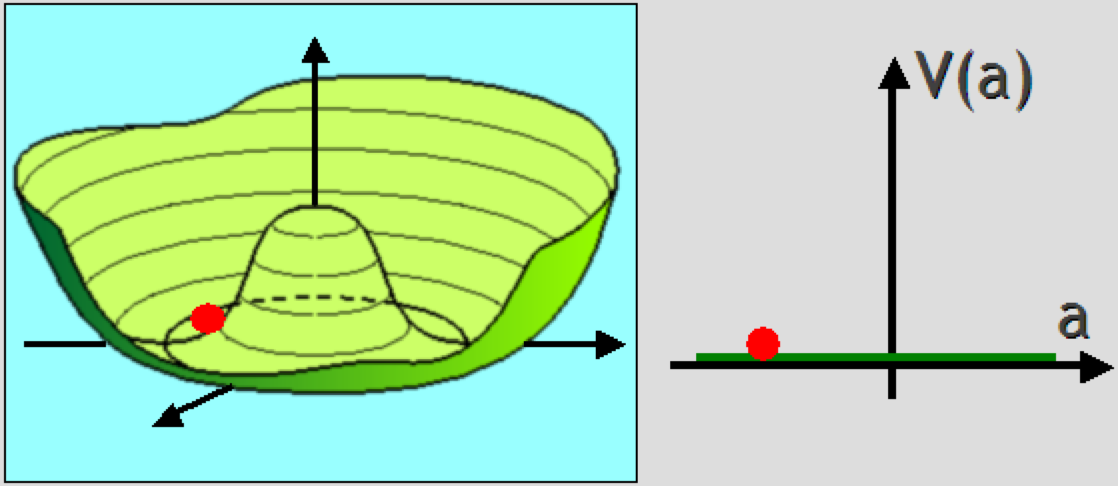


Primakoff conversion

Axions as Pseudo Nambu-Goldstone Bosons

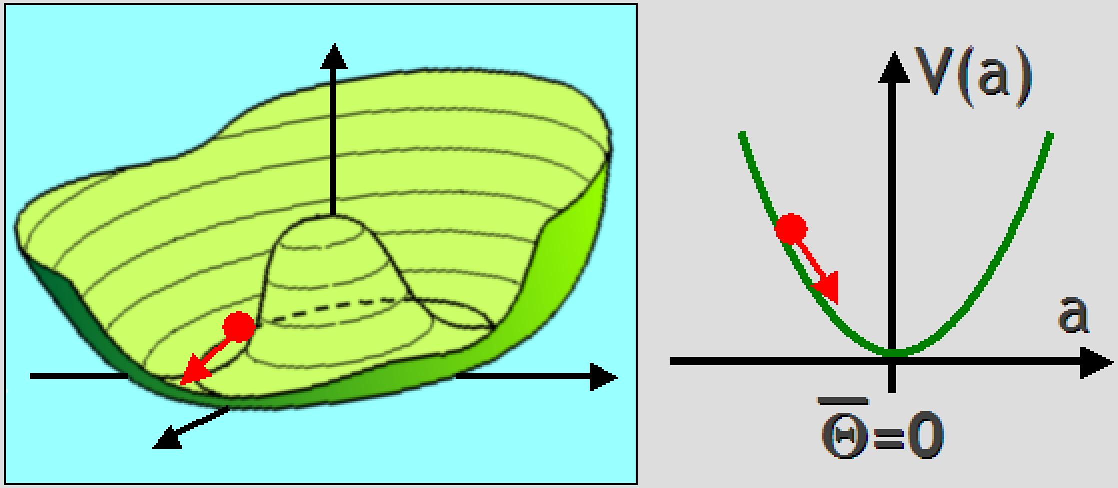
- The realization of the Peccei-Quinn mechanism involves a new chiral U(1) symmetry, spontaneously broken at a scale f_a
- Axions are the corresponding Nambu-Goldstone mode

$E \approx f_a$



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

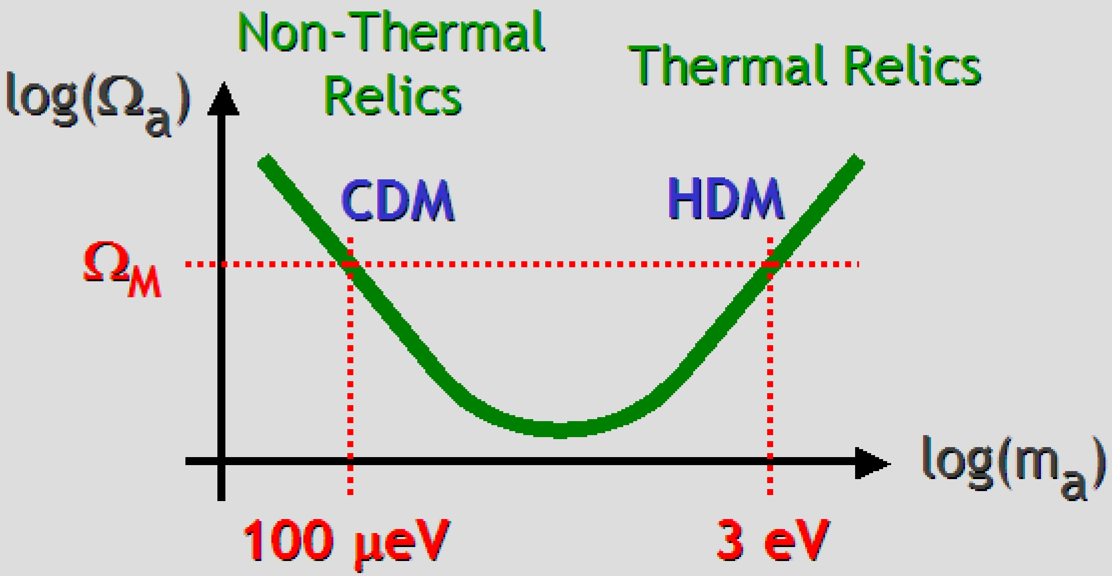
$E \approx \Lambda_{QCD} \ll f_a$



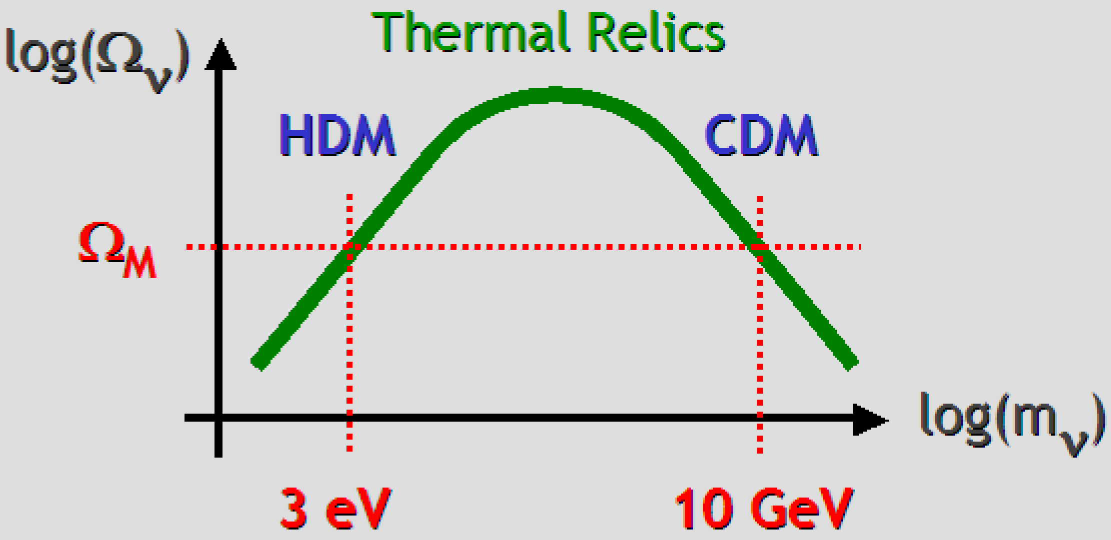
- $U_{PQ}(1)$ explicitly broken by instanton effects
- Mexican hat tilts
- Axions acquire a mass

Lee-Weinberg Curve for Neutrinos and Axions

Axions



Neutrinos

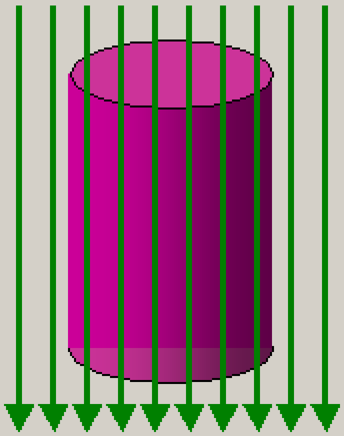


Experimental Search for Galactic Axions

DM axions $m_a = 10\text{-}3000~\mu\mathrm{eV}$
Velocities in galaxy $v_a \approx 10^{-3}~c$
Energies therefore $E_a \approx (1 \pm 10^{-6})~m_a$

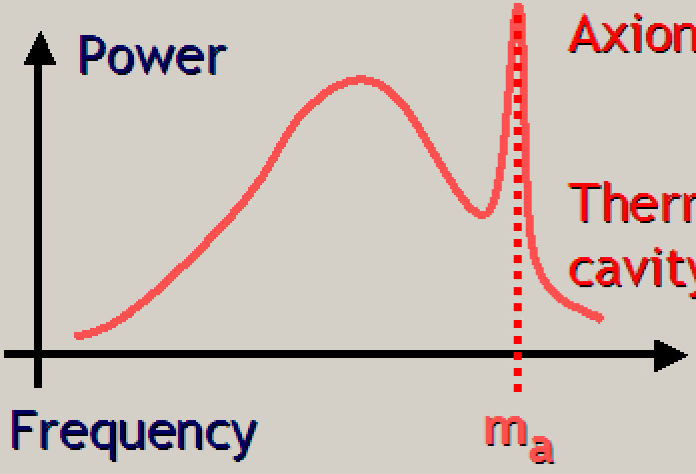
Microwave Energies
(1 GHz ≈ 4 μeV)

Axion Haloscope (Sikivie 1983)

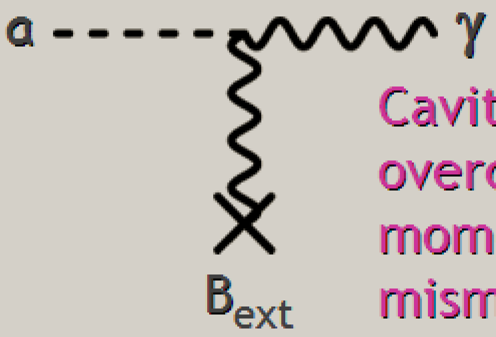


$B_{\mathrm{ext}} \approx 8$ Tesla

Microwave
Resonator
$Q \approx 10^5$



Primakoff Conversion



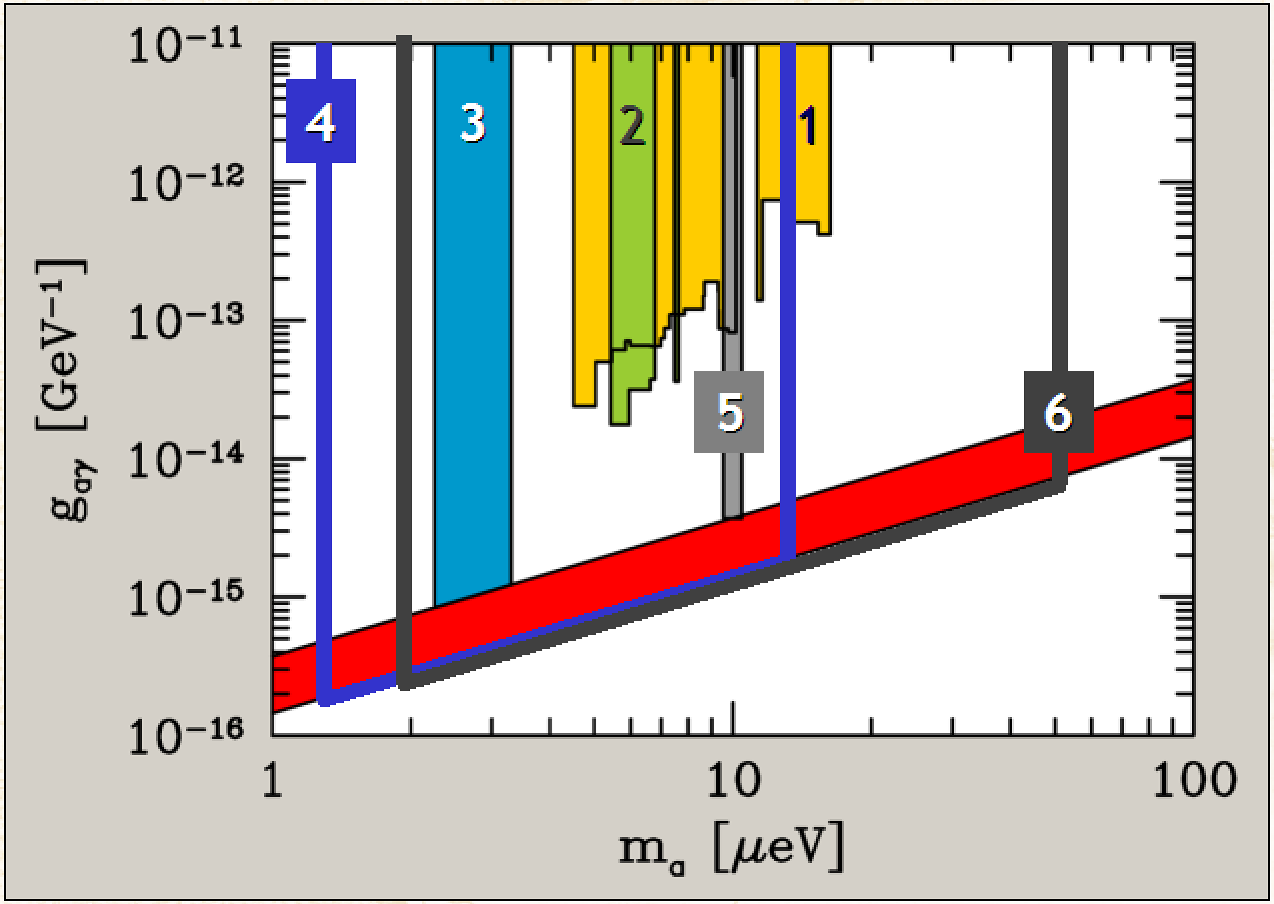
Cavity
overcomes
momentum
mismatch

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

Some Dark Matter Candidates

Supersymmetric particles • Neutralinos • Axinos • Gravitinos	Gauge hierarchy problem
Little Higgs models	
Axions	CP Problem of strong interactions
Kaluza-Klein excitations	Large extra dimensions
Mirror matter	Exact parity symmetry
Sterile neutrinos	Right-handes states should exist
Wimpzillas (superheavy particles)	Super GZK cosmic rays
MeV-mass dark matter	Explain cosmic-ray positrons
Q-balls	Why not ?
Primordial black holes	

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 ↔ 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, ...)