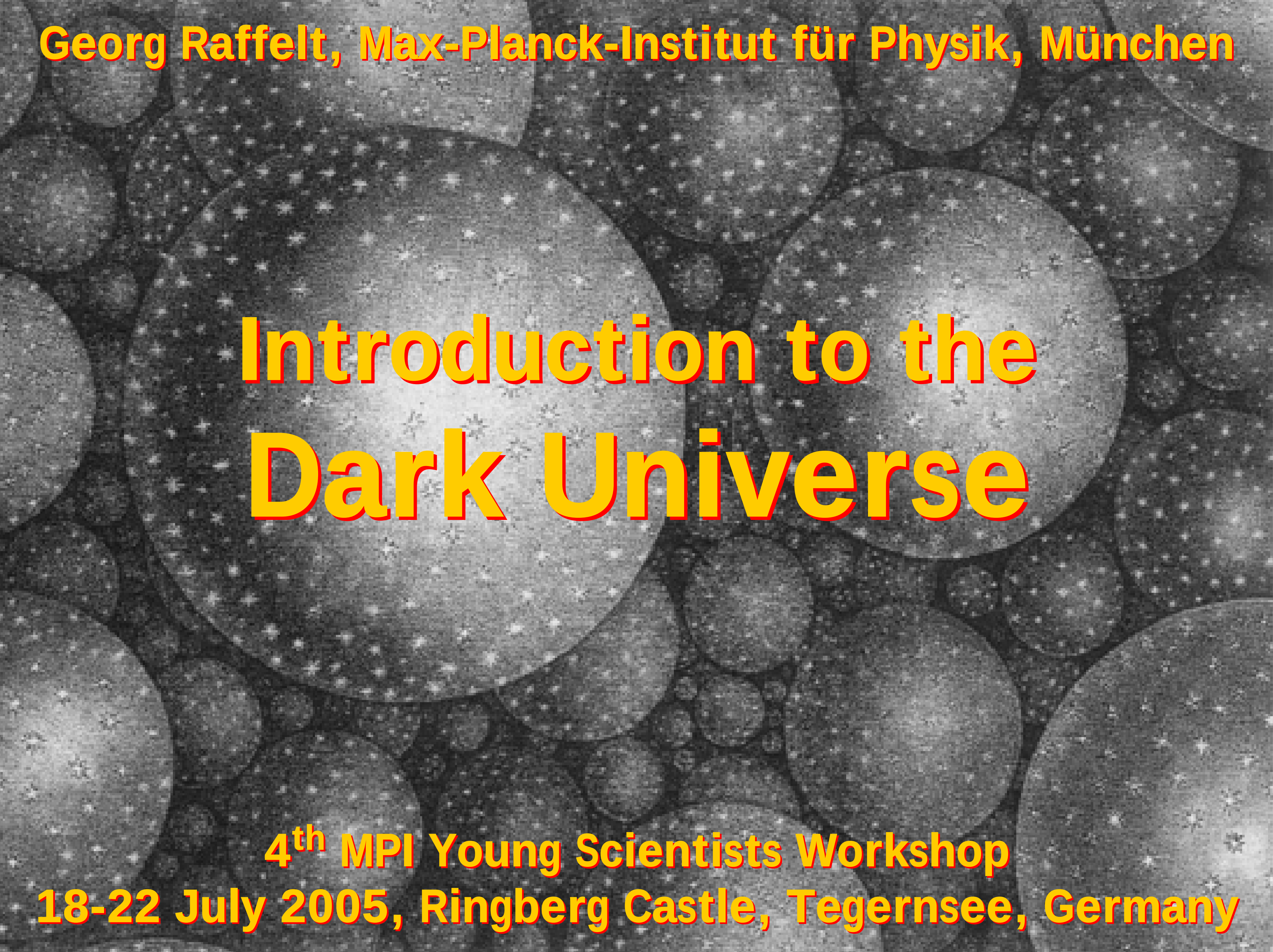
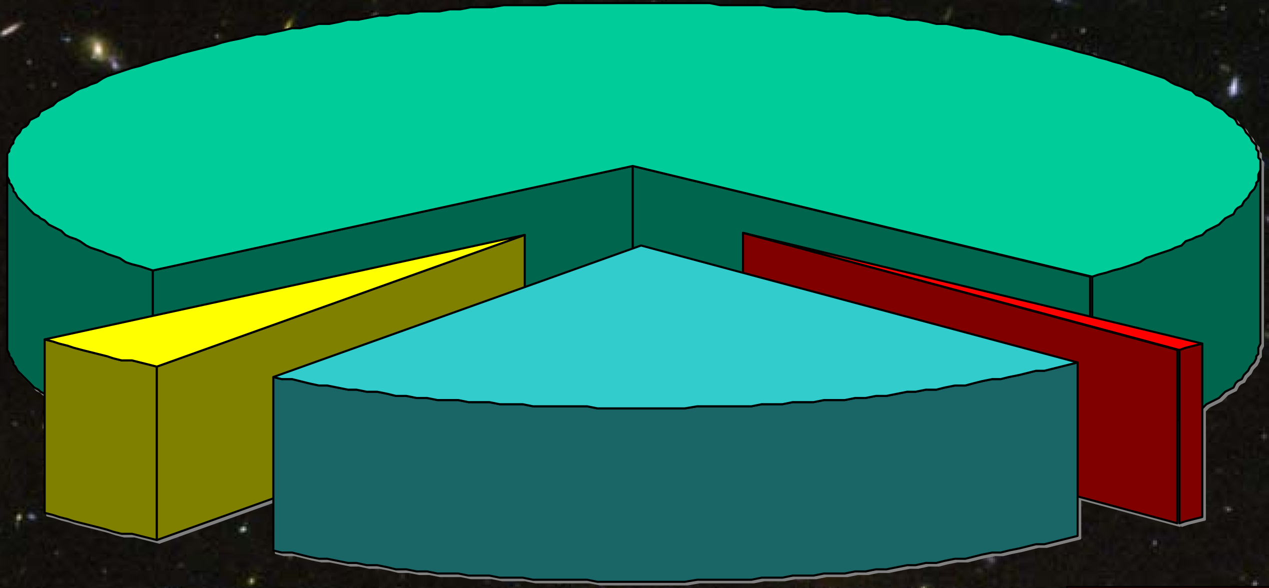


Georg Raffelt, Max-Planck-Institut für Physik, München

Introduction to the Dark Universe

4th MPI Young Scientists Workshop
18-22 July 2005, Ringberg Castle, Tegernsee, Germany

Portion of the Hubble Ultra Deep Field

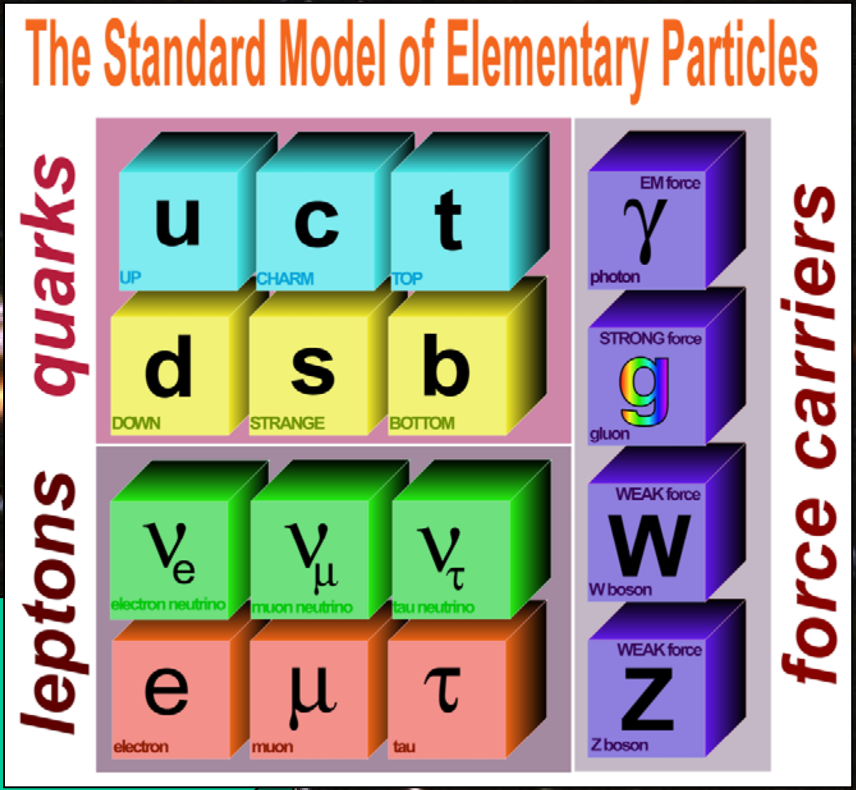


Dark Energy 73%
(Cosmological Constant)

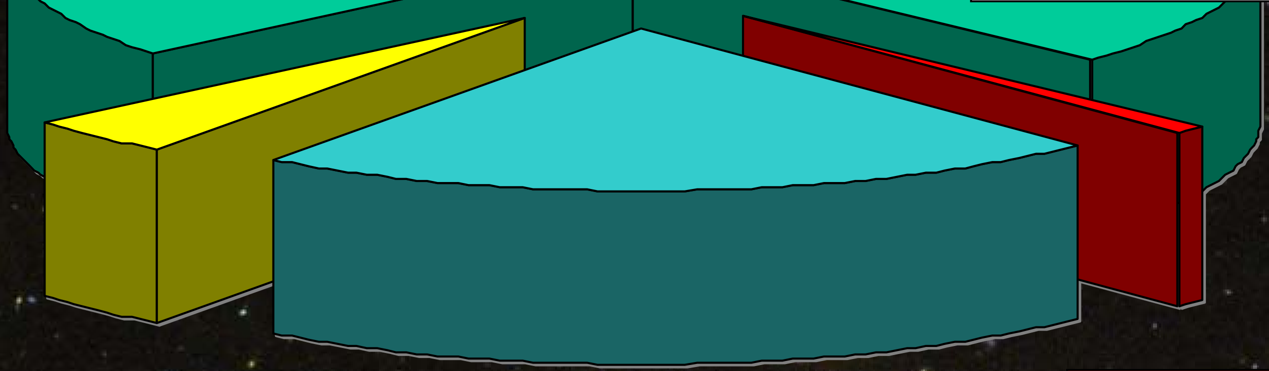
Ordinary Matter 4%
(of this only about
10% luminous)

Dark Matter
23%

Neutrinos
0.1–2%



**Dark Energy 73%
(Cosmological Constant)**



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

**Dark Matter
23%**

**Neutrinos
0.1–2%**

Baryogenesis in the Early Universe

Andrei Sakharov
1921–1989

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

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

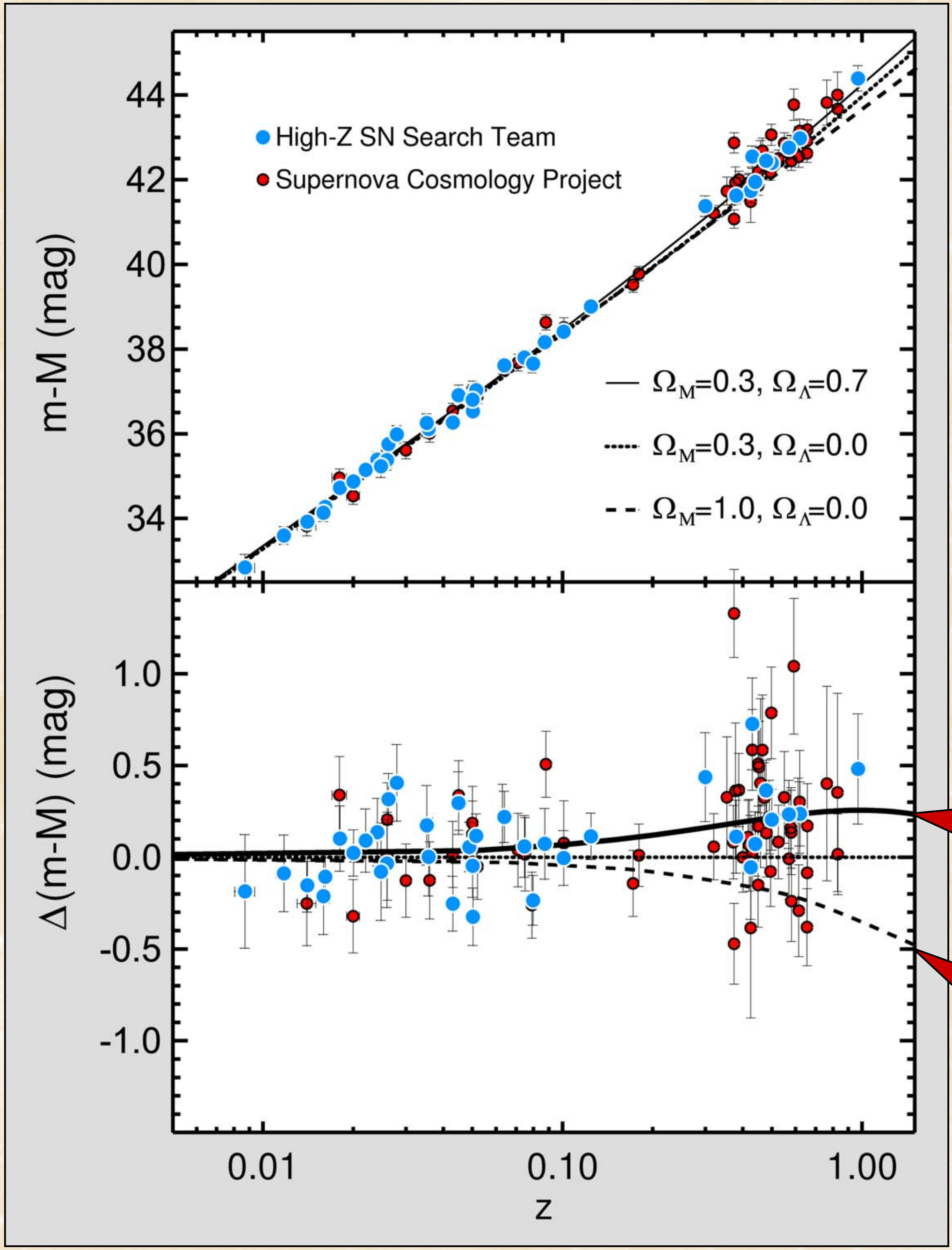
Particle-physics standard model

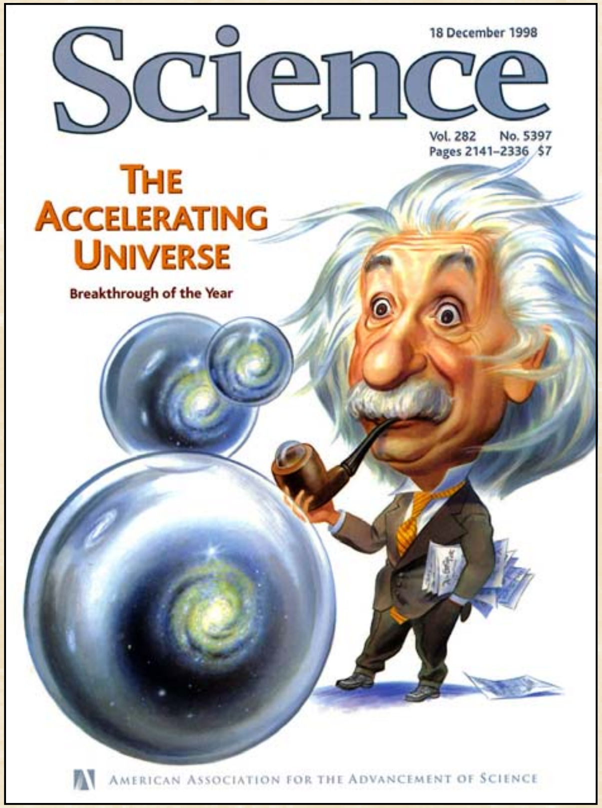
- Violates C and CP
- Violates B and L by EW instanton effects (B – L conserved)

- However, electroweak baryogenesis not quantitatively possible within particle-physics standard model
- Works in SUSY models for small range of parameters

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

Hubble Diagram





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

Decelerated expansion
($\Omega_M = 1$)

Einstein's "Greatest Blunder"

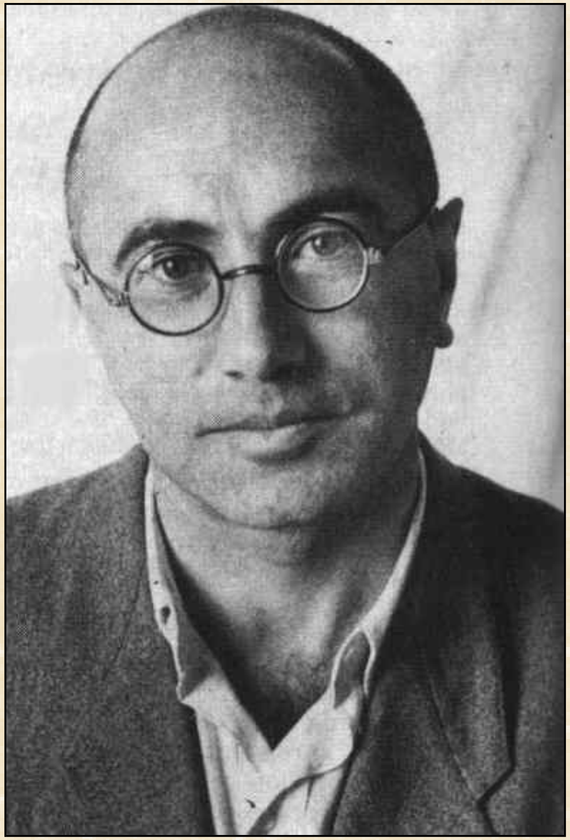
Density of gravitating mass & energy

Newton's constant

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

Friedmann equation for Hubble's expansion rate

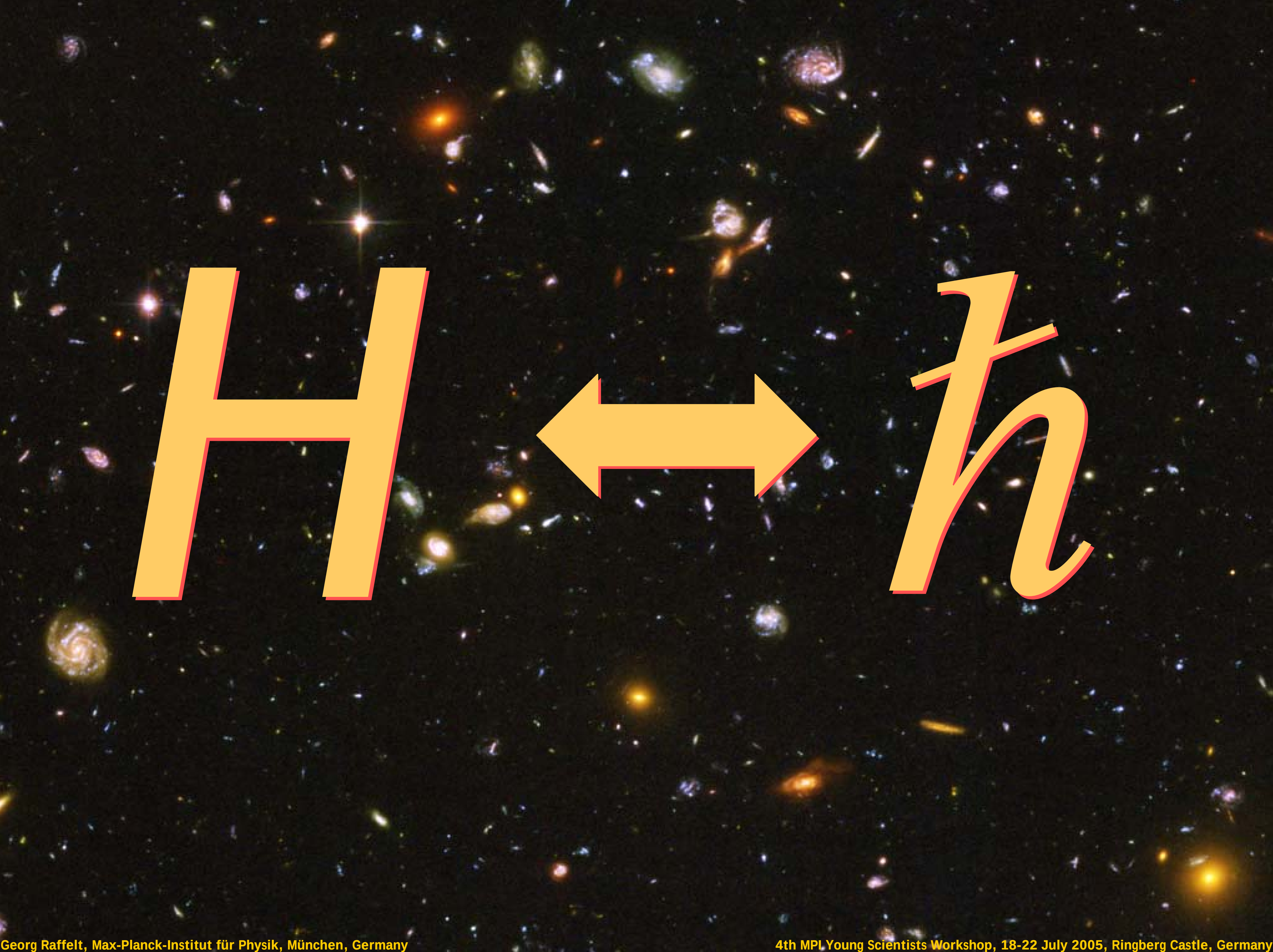
$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G_N}{3}\rho - \frac{k}{a^2} + \frac{\Lambda}{3}$$



**Yakov
Borisovich
Zeldovich
1914-1987**

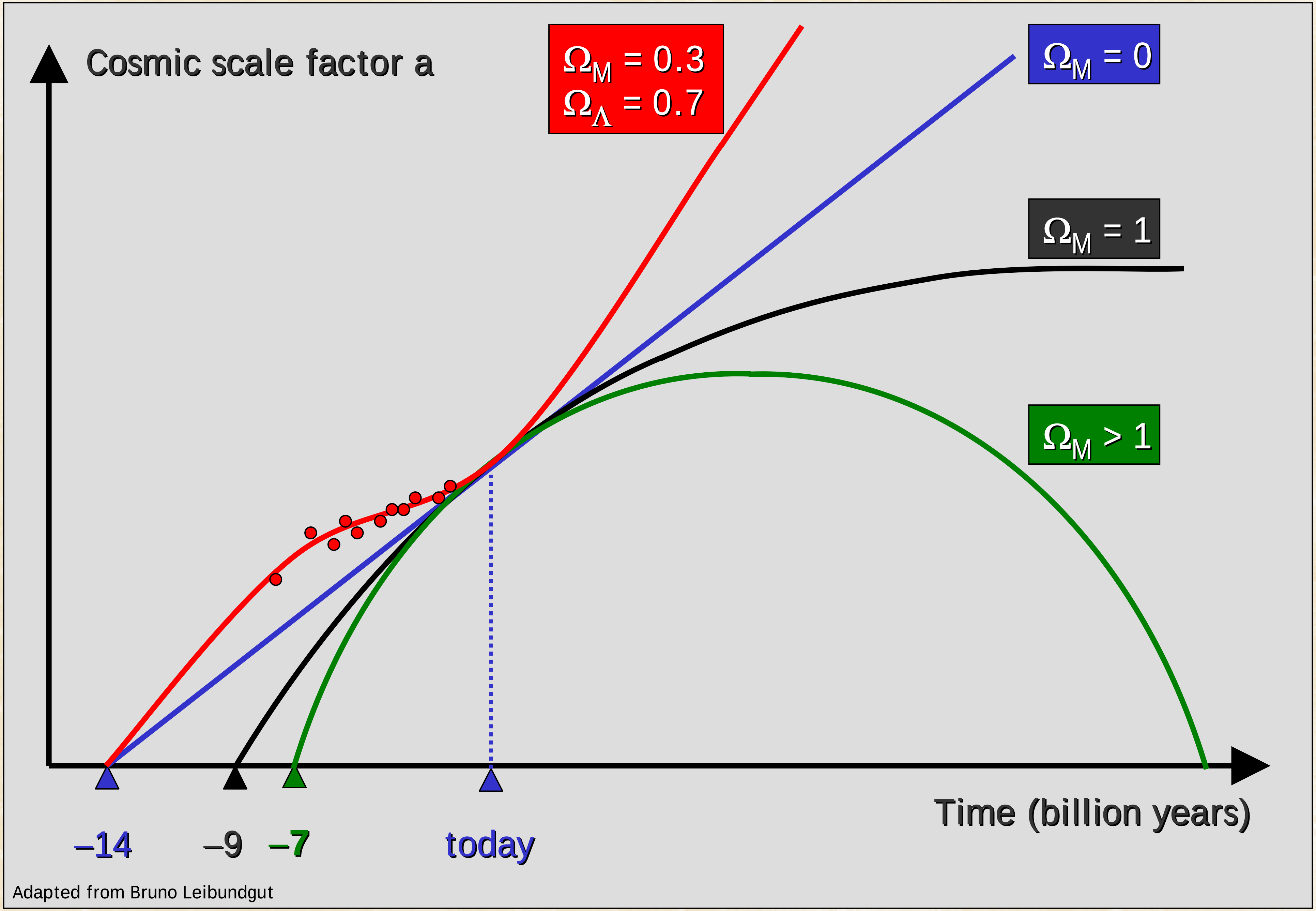
Cosmological constant Λ
(new constant of nature)
allows for a static universe
by "global anti-gravitation"

- 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



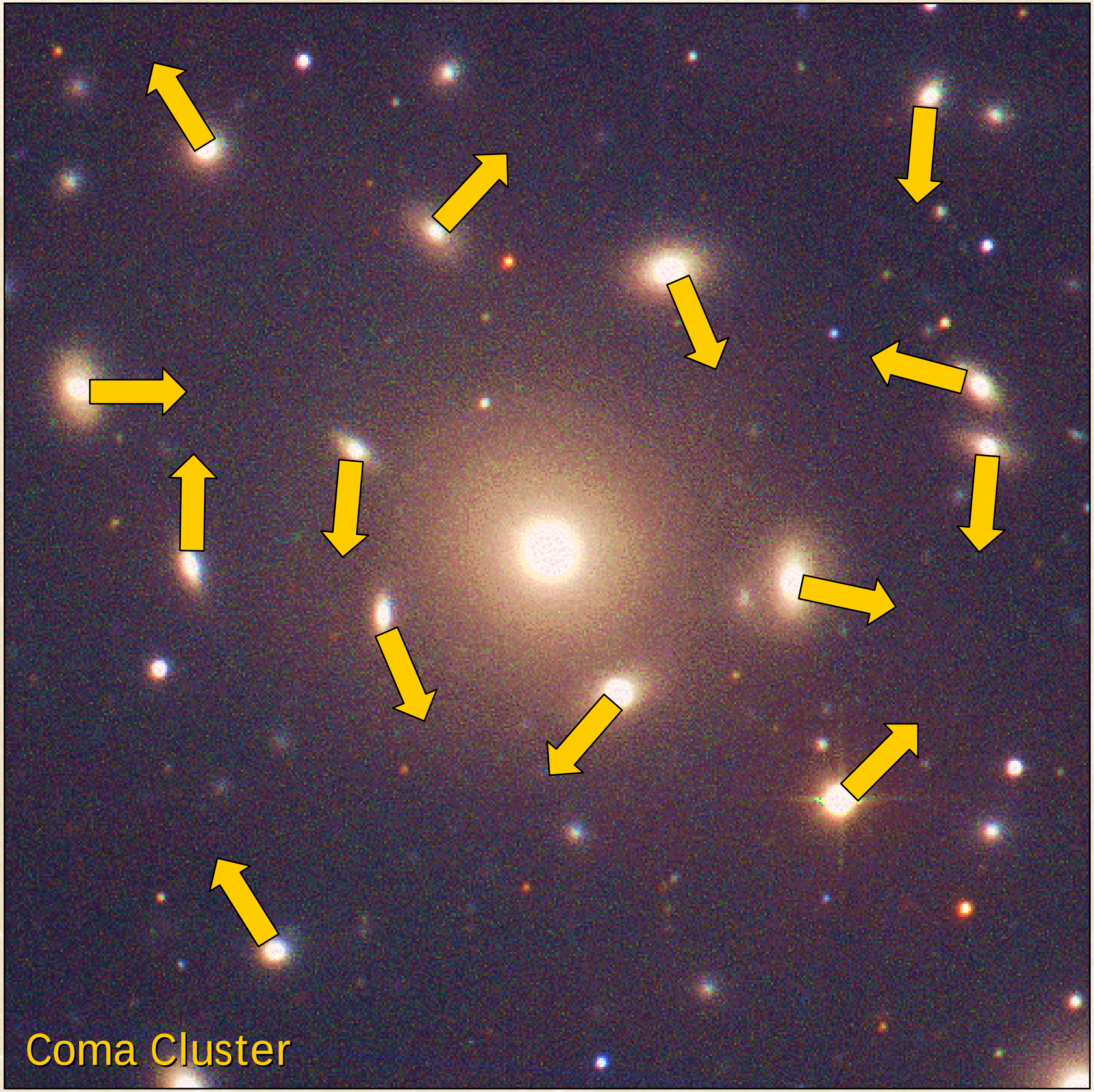
$$H \longleftrightarrow \hbar$$

Expansion of Different Cosmological Models



Adapted from Bruno Leibundgut

Dark Matter in Galaxy Clusters



A gravitationally bound system of many particles obeys the virial theorem

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

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

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

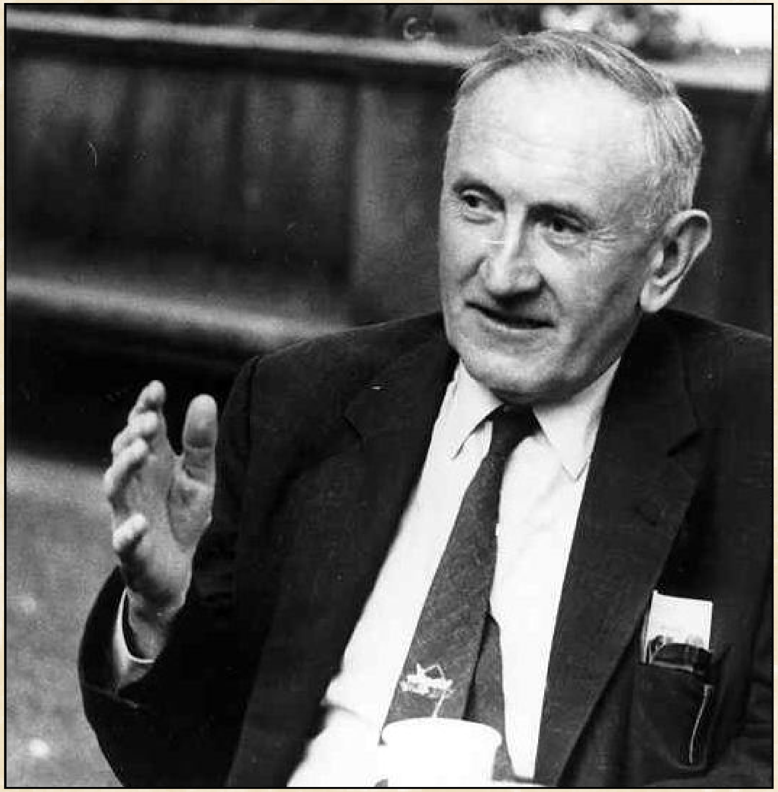
Velocity dispersion from Doppler shifts and geometric size

↓

Total Mass

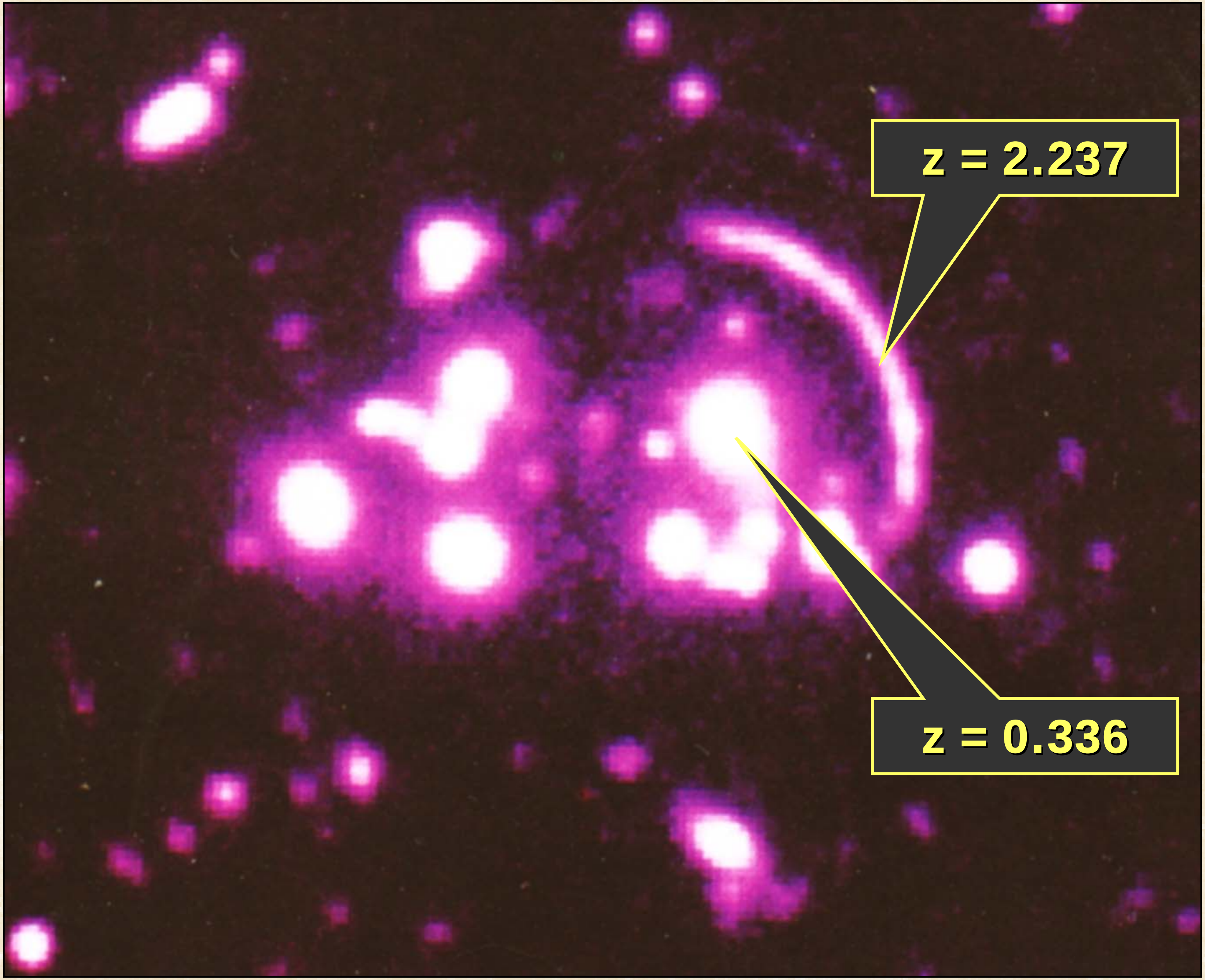
Dark Matter in Galaxy Clusters

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.

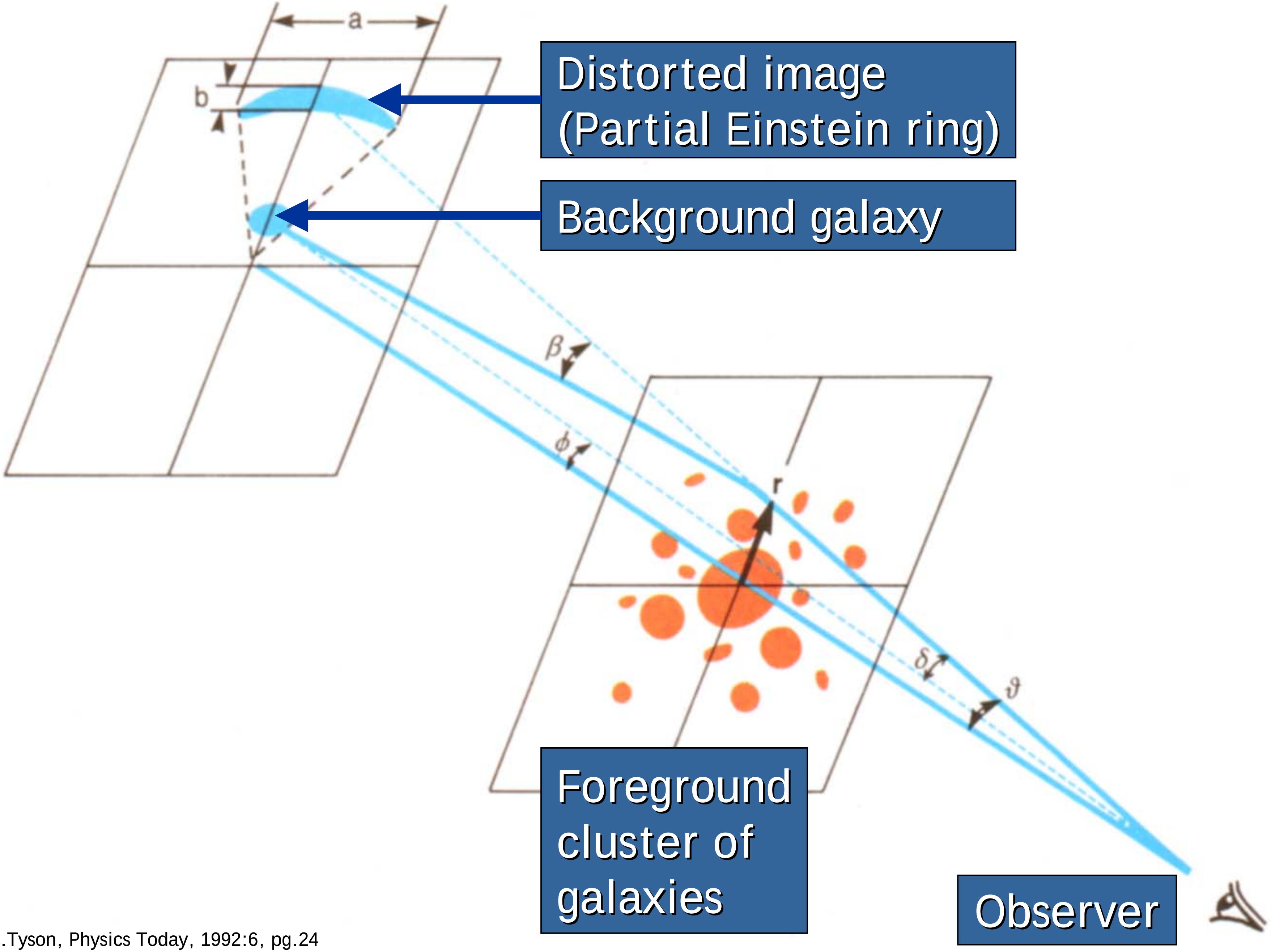
Giant Arc in Cluster Cl 2244-02



z = 2.237

z = 0.336

Giant Arcs – Gravitationally Lensed Background Galaxies



Distorted image
(Partial Einstein ring)

Background galaxy

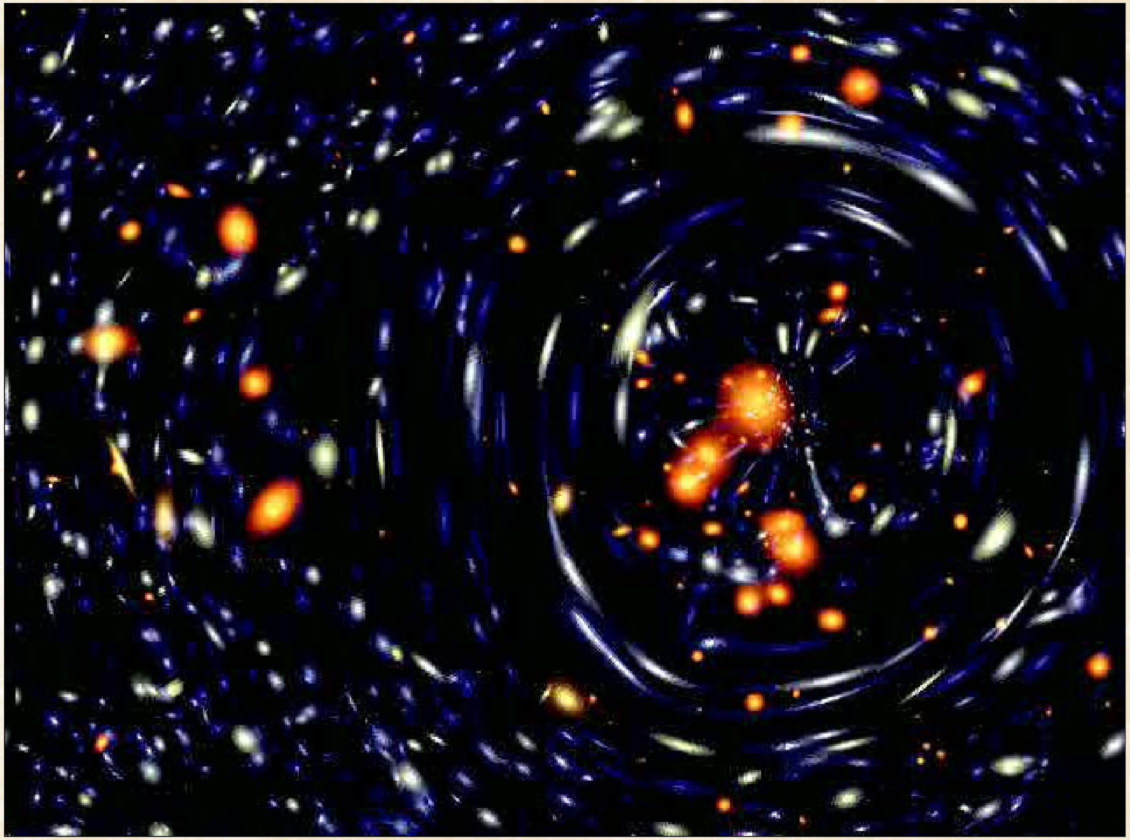
Foreground cluster of galaxies

Observer

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

Gravitational Lensing in Clusters of Galaxies

Galaxy cluster Cl 0024+1654
[Hubble Space Telescope]



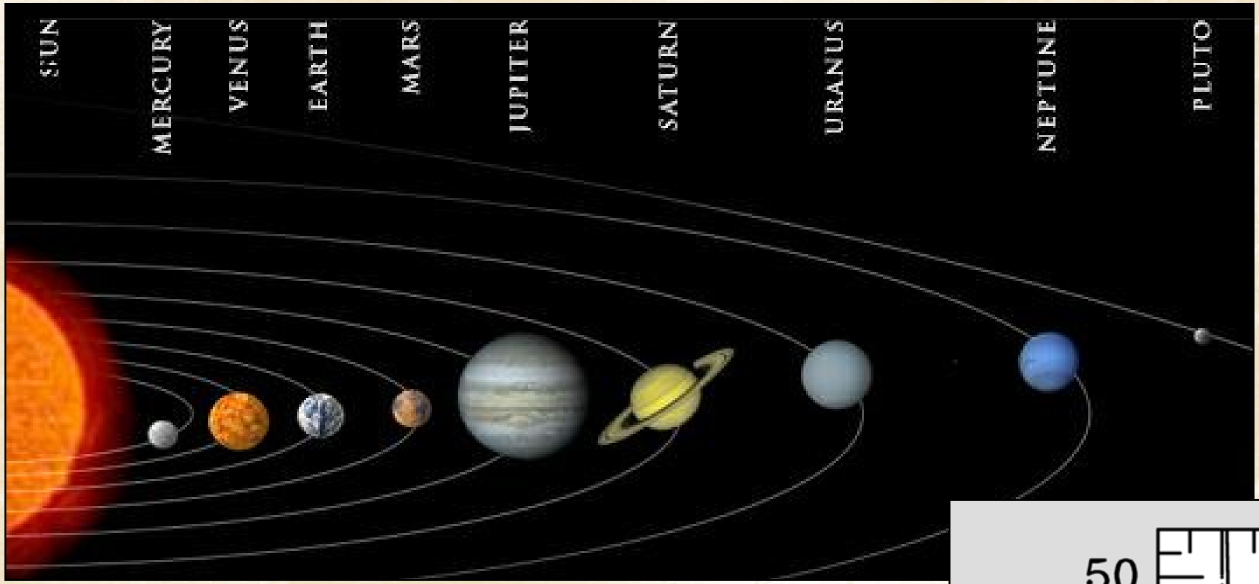
Numerical Simulation

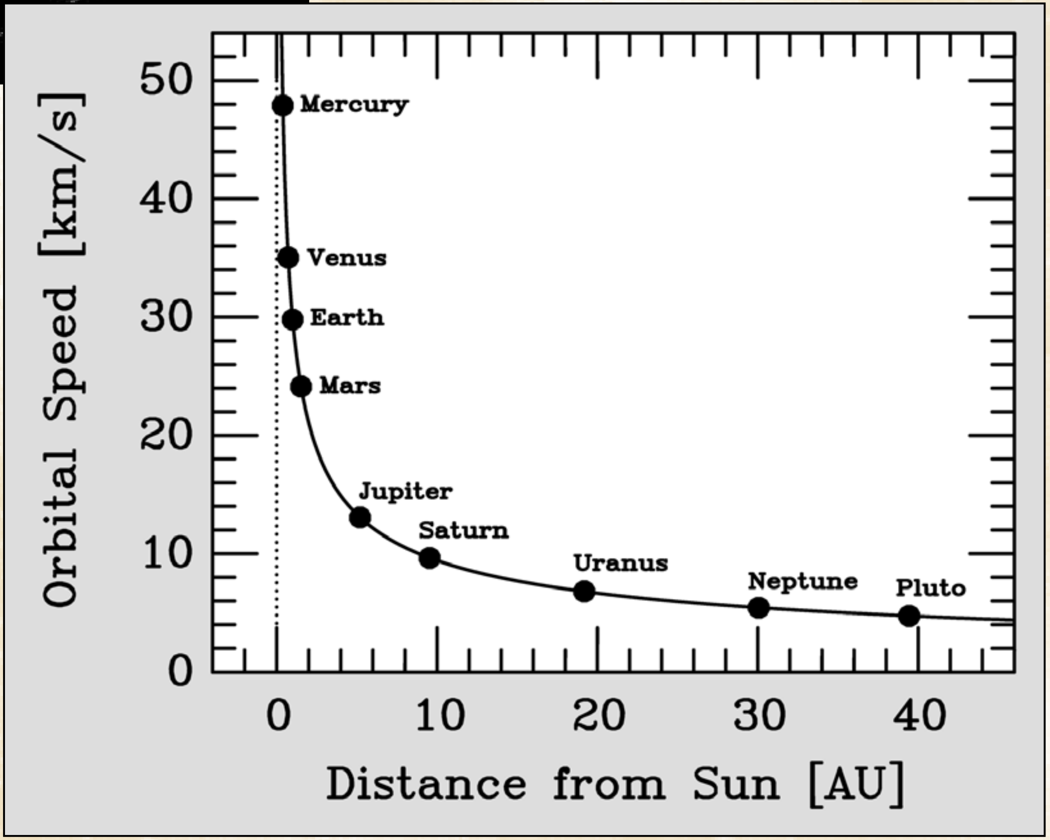
Structure of Spiral Galaxies

Spiral Galaxy NGC 2997

Spiral Galaxy NGC 891

“Rotation Curve” of the Solar System

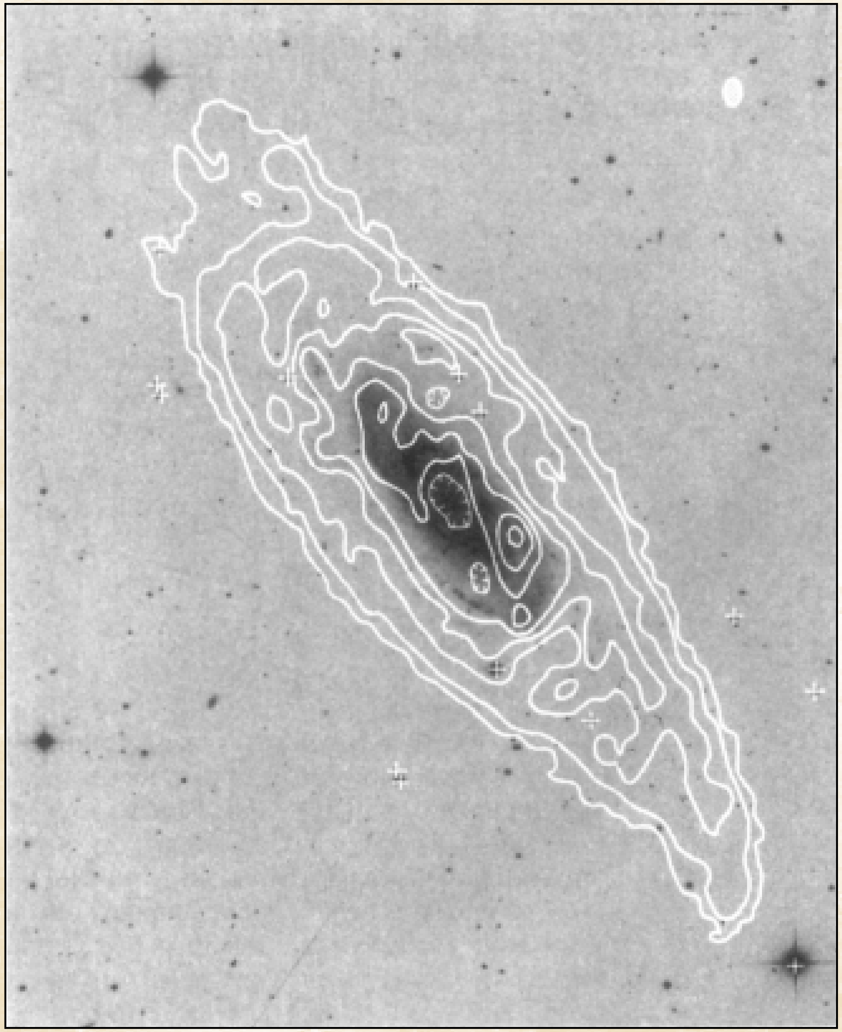


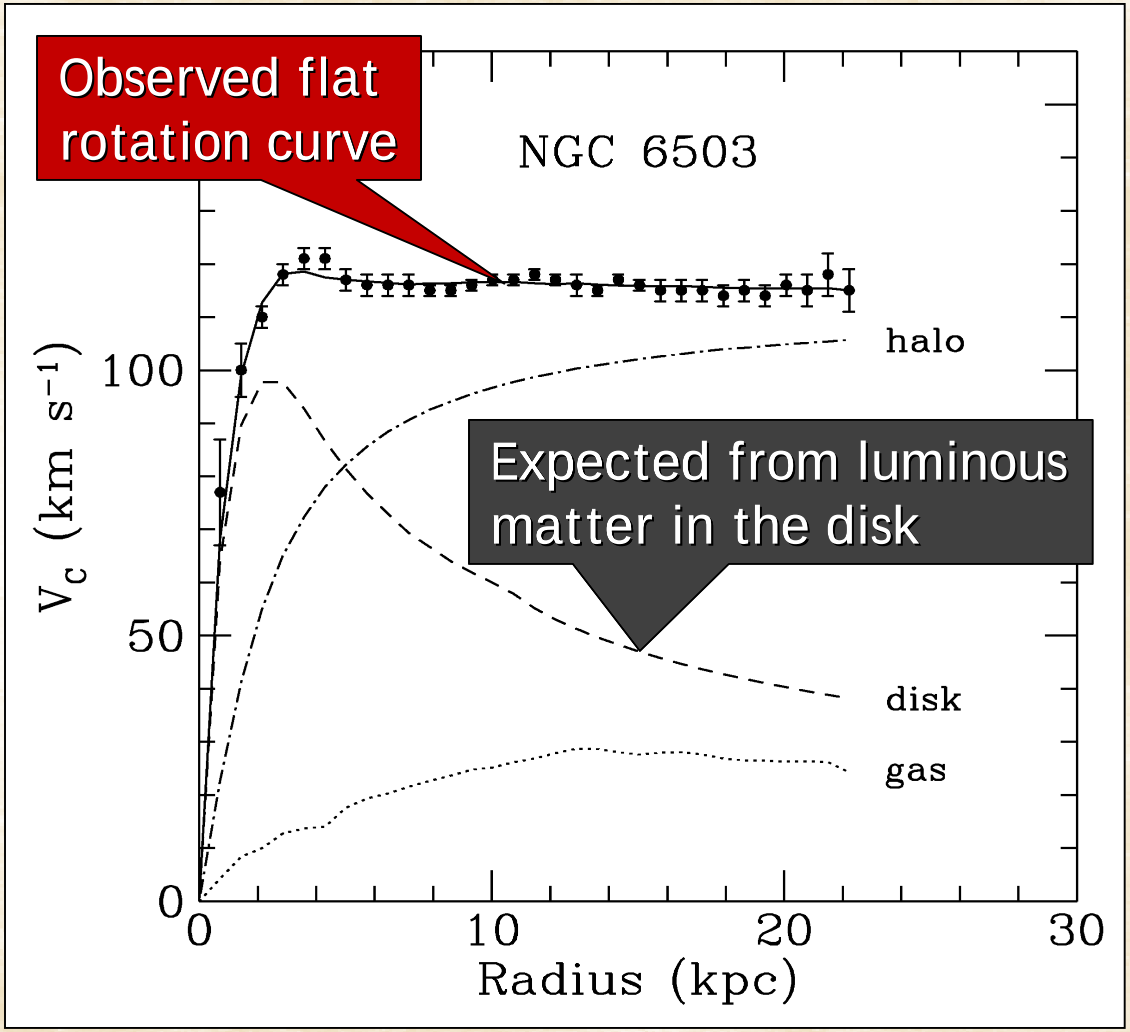


Kepler’s Law

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

Galactic Rotation Curve from Radio Observations





Observed flat rotation curve

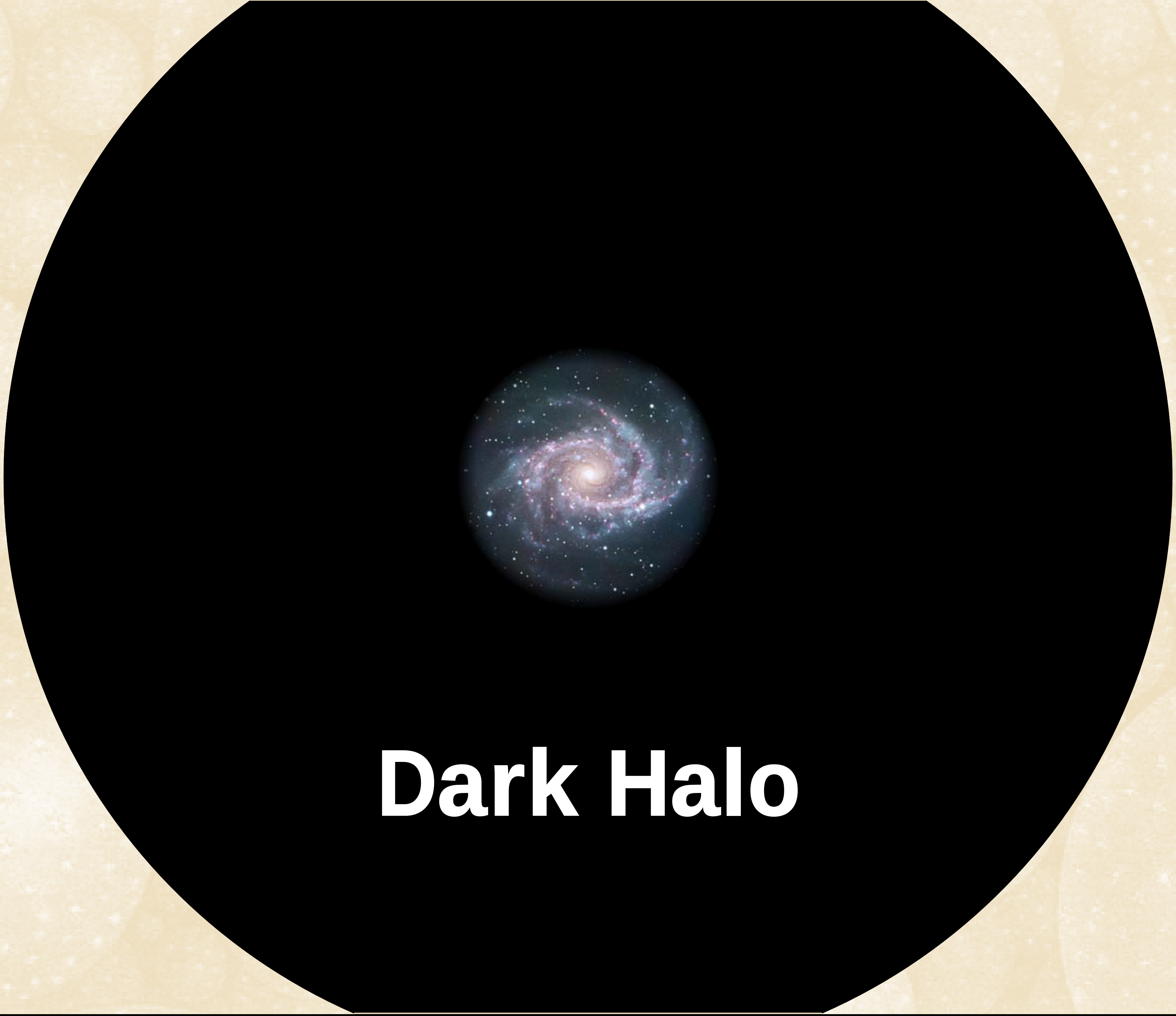
Expected from luminous matter in the disk

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]

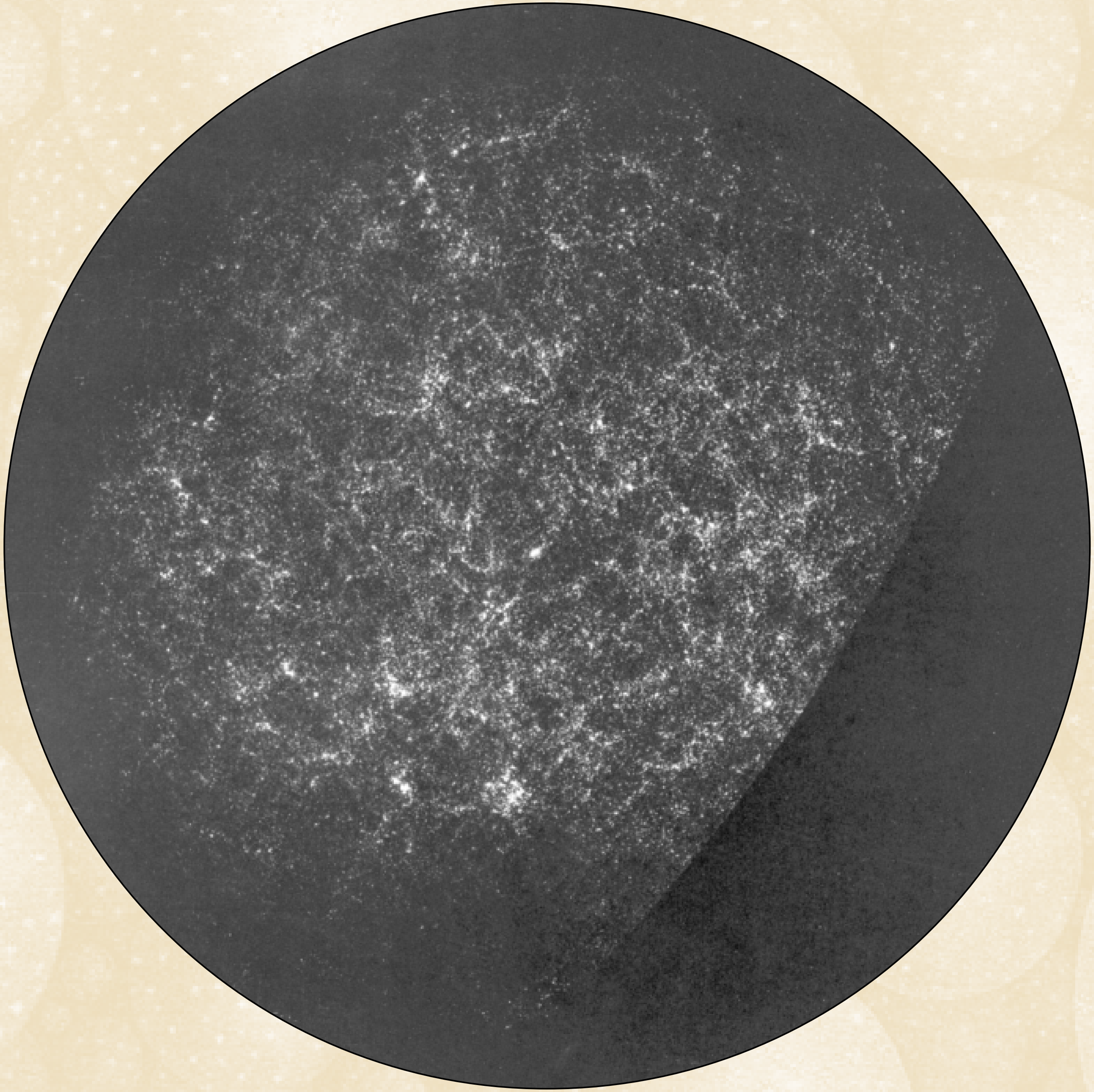
Structure of a Spiral Galaxy

Structure of a Spiral Galaxy



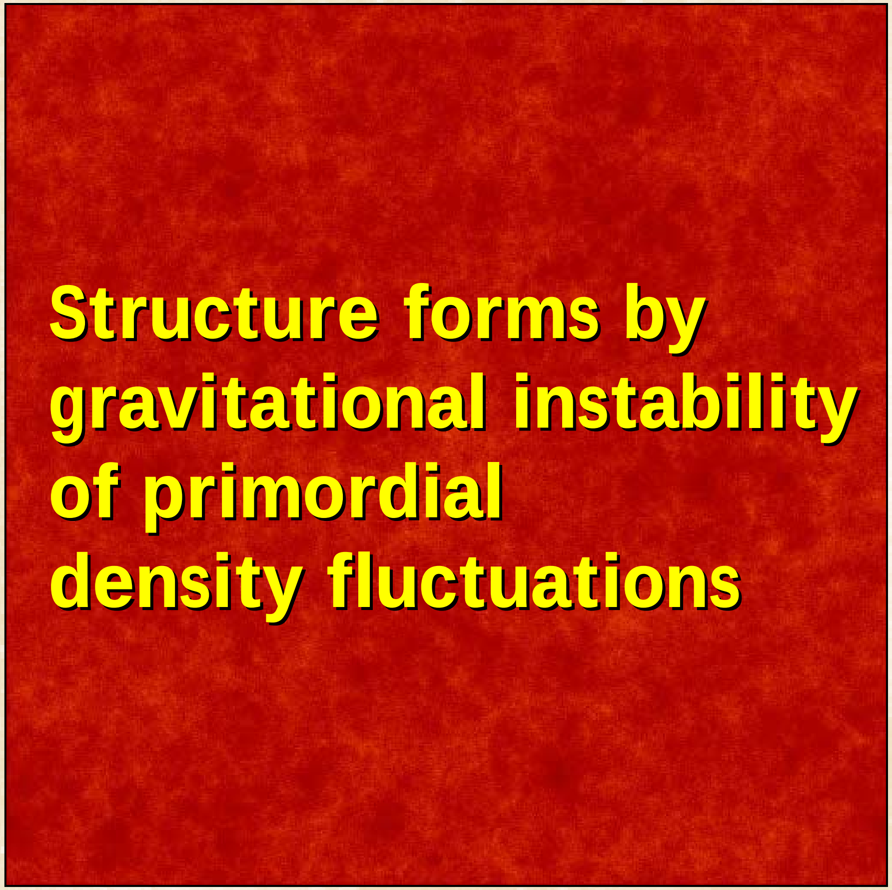
Dark Halo

Galaxy Distribution in the Sky

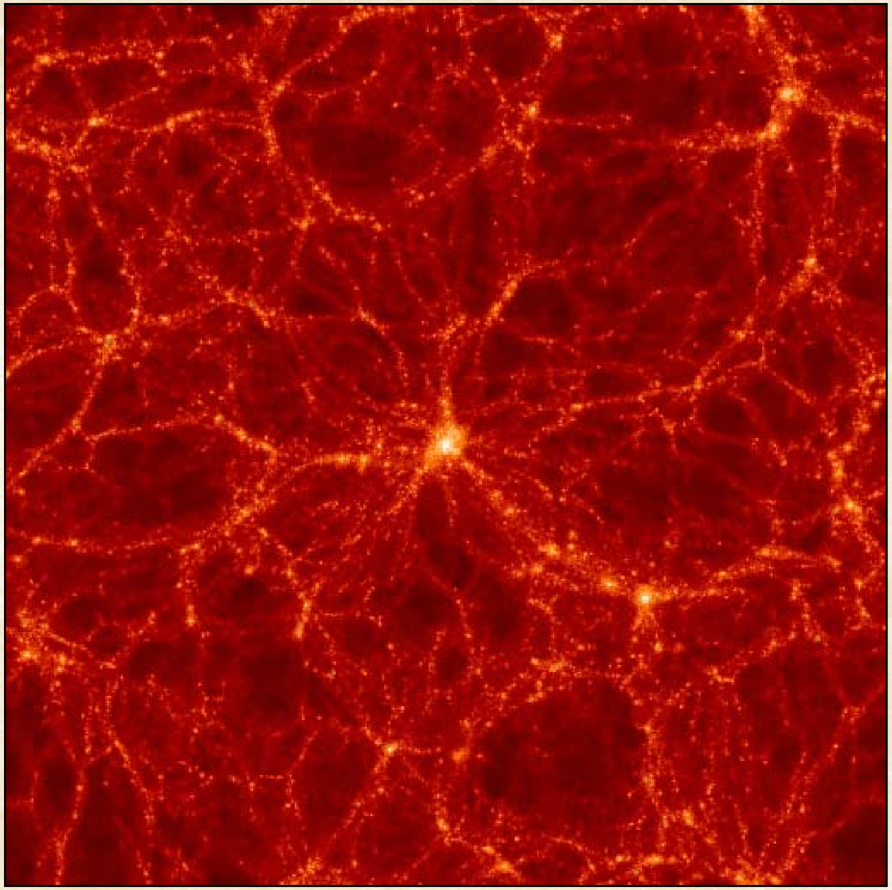


Formation of Structure

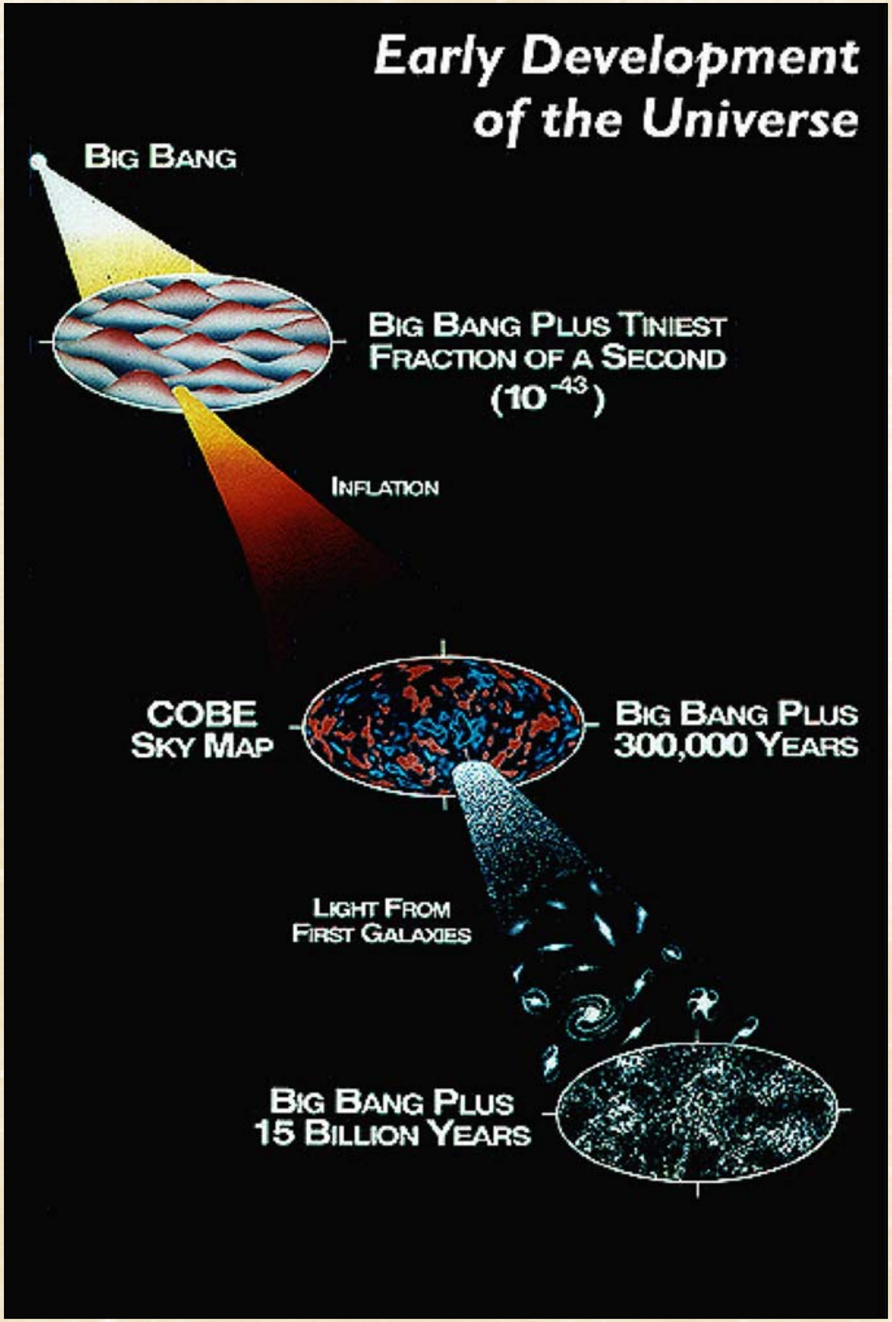
Smooth → **Structured**



Structure forms by gravitational instability of primordial density fluctuations



Generating the Primordial Density Fluctuations



Early phase of exponential expansion (Inflationary epoch)

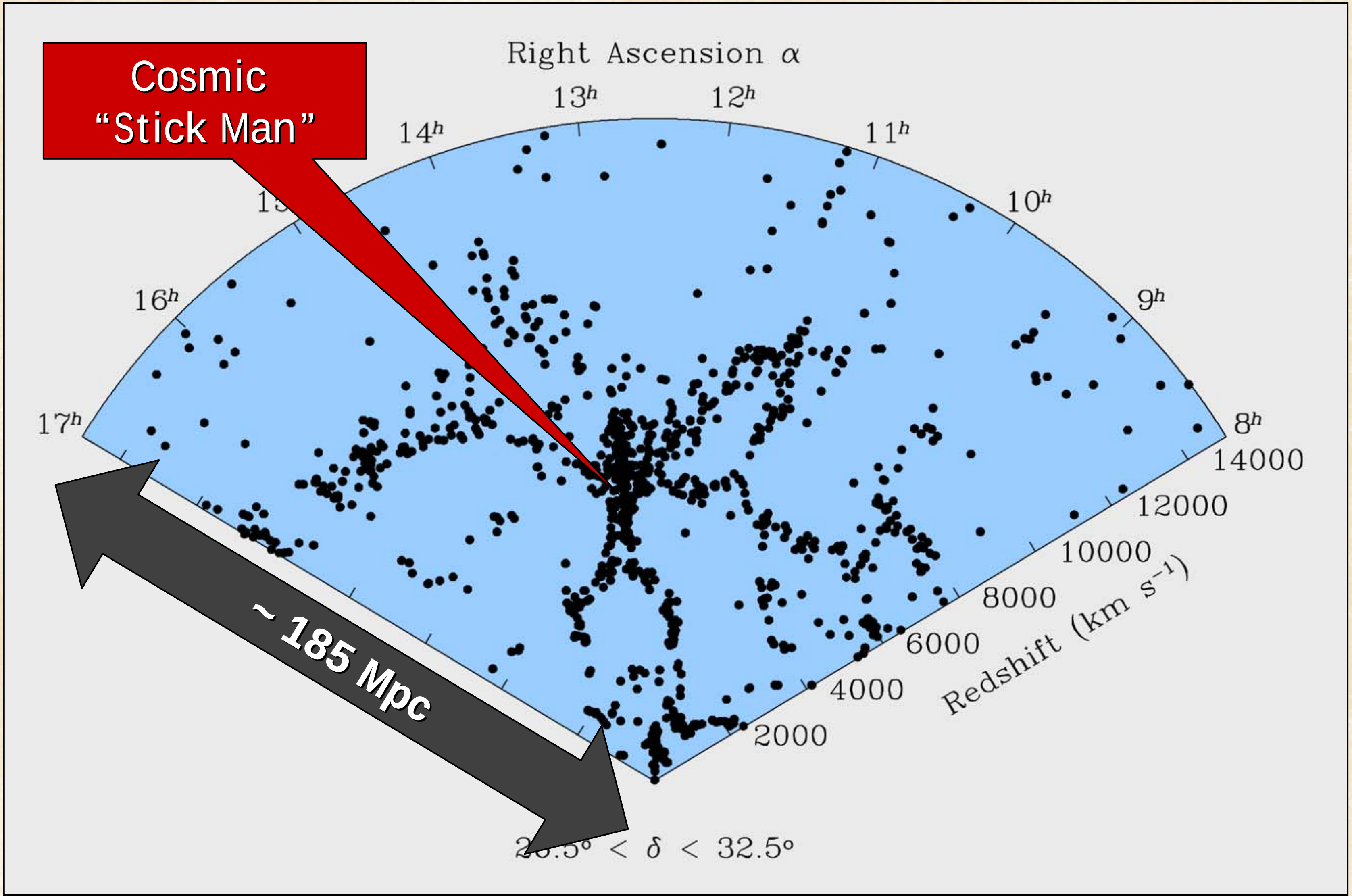
↓

Zero-point fluctuations of quantum fields are stretched and frozen

↓

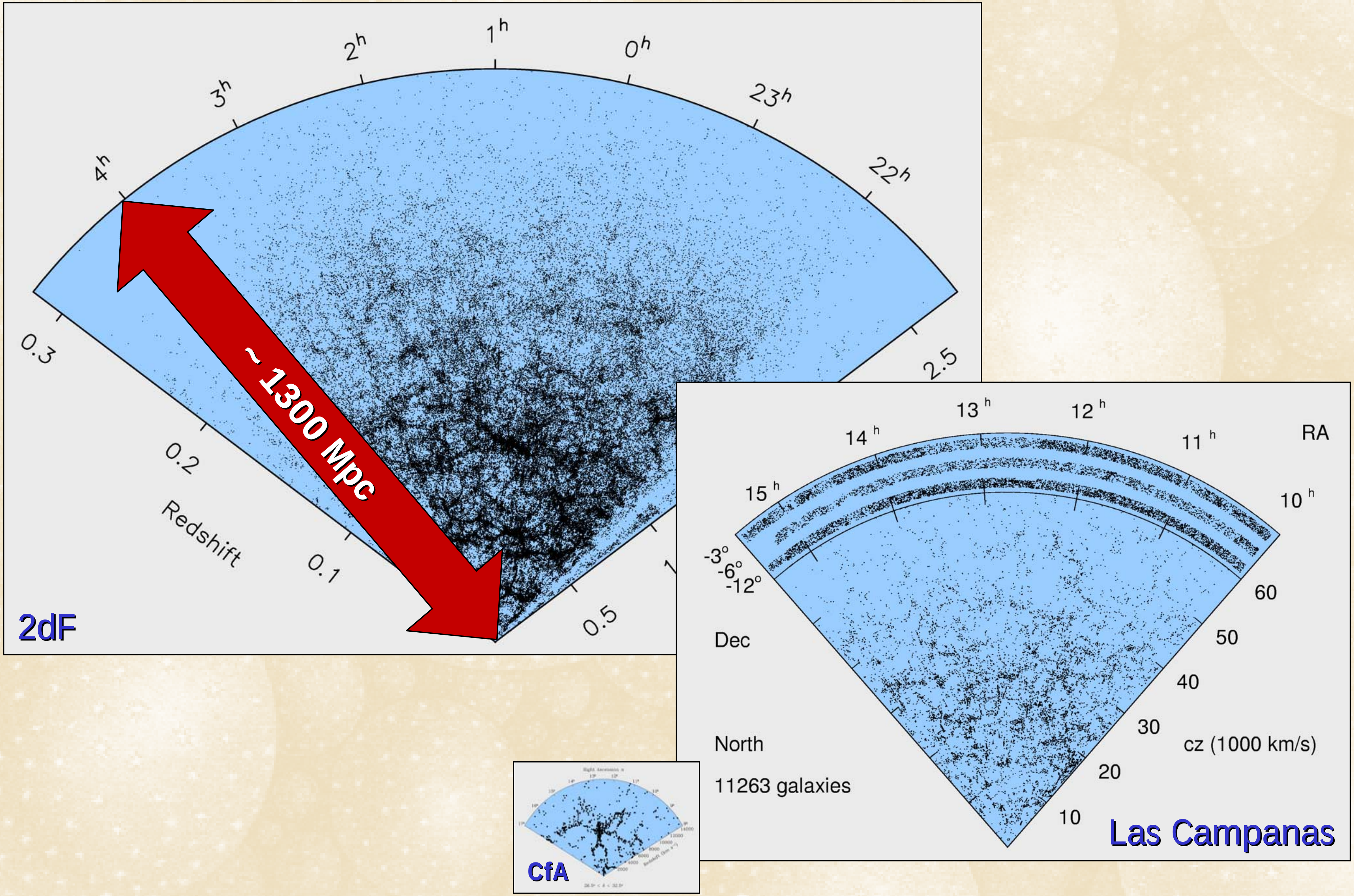
Cosmic density fluctuations are frozen quantum fluctuations

A Slice of the Universe



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

2dF Galaxy Redshift Survey (15 May 2002)



Power Spectrum of Density Fluctuations

Field of density fluctuations

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

Fourier transform

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

Power spectrum essentially square of Fourier transformation

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

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

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

is independent for each Fourier mode δ_k

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

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

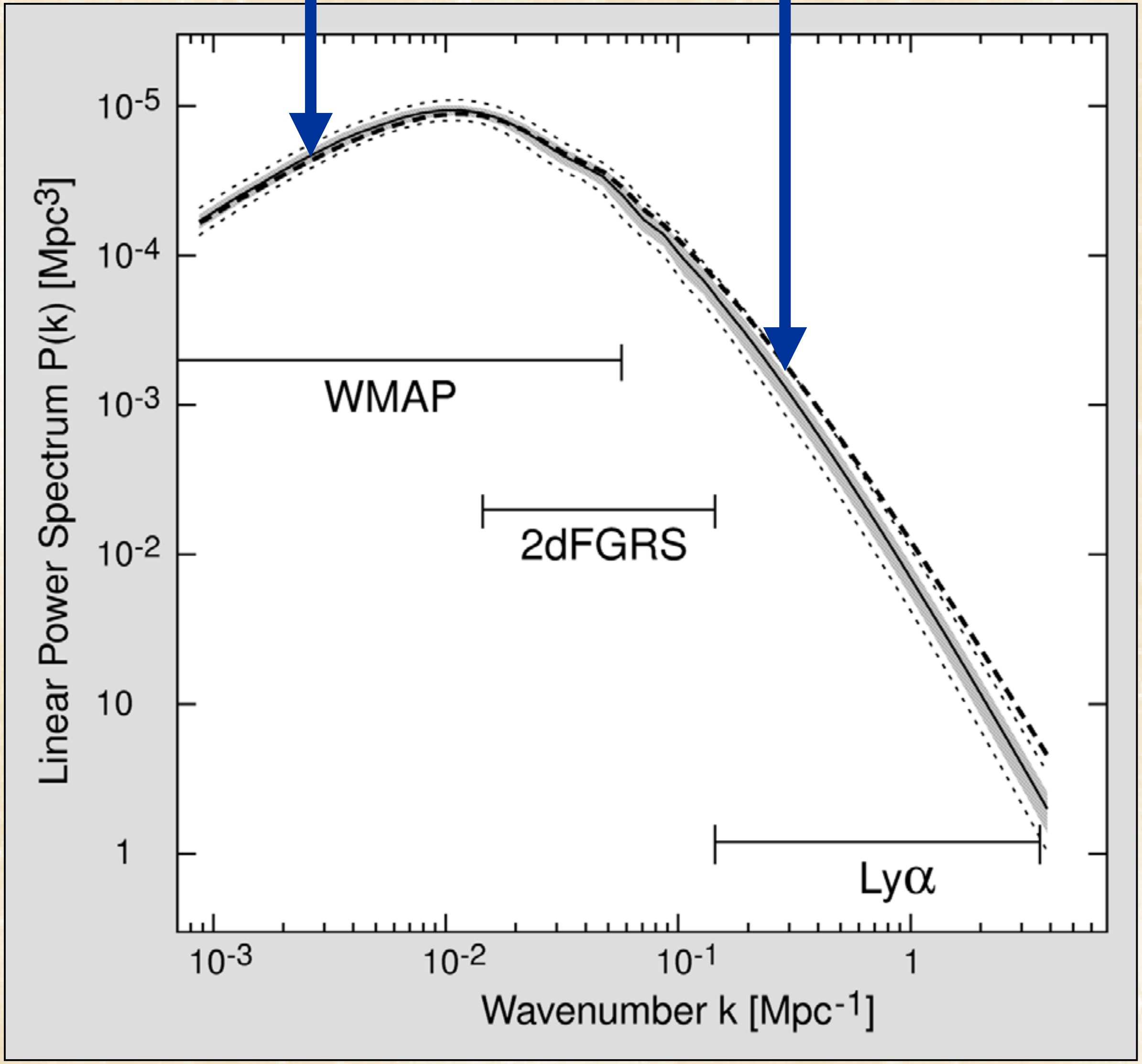
Primordial spectrum usually assumed to be of power-law form

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

Harrison-Zeldovich ("flat") spectrum

$n = 1$

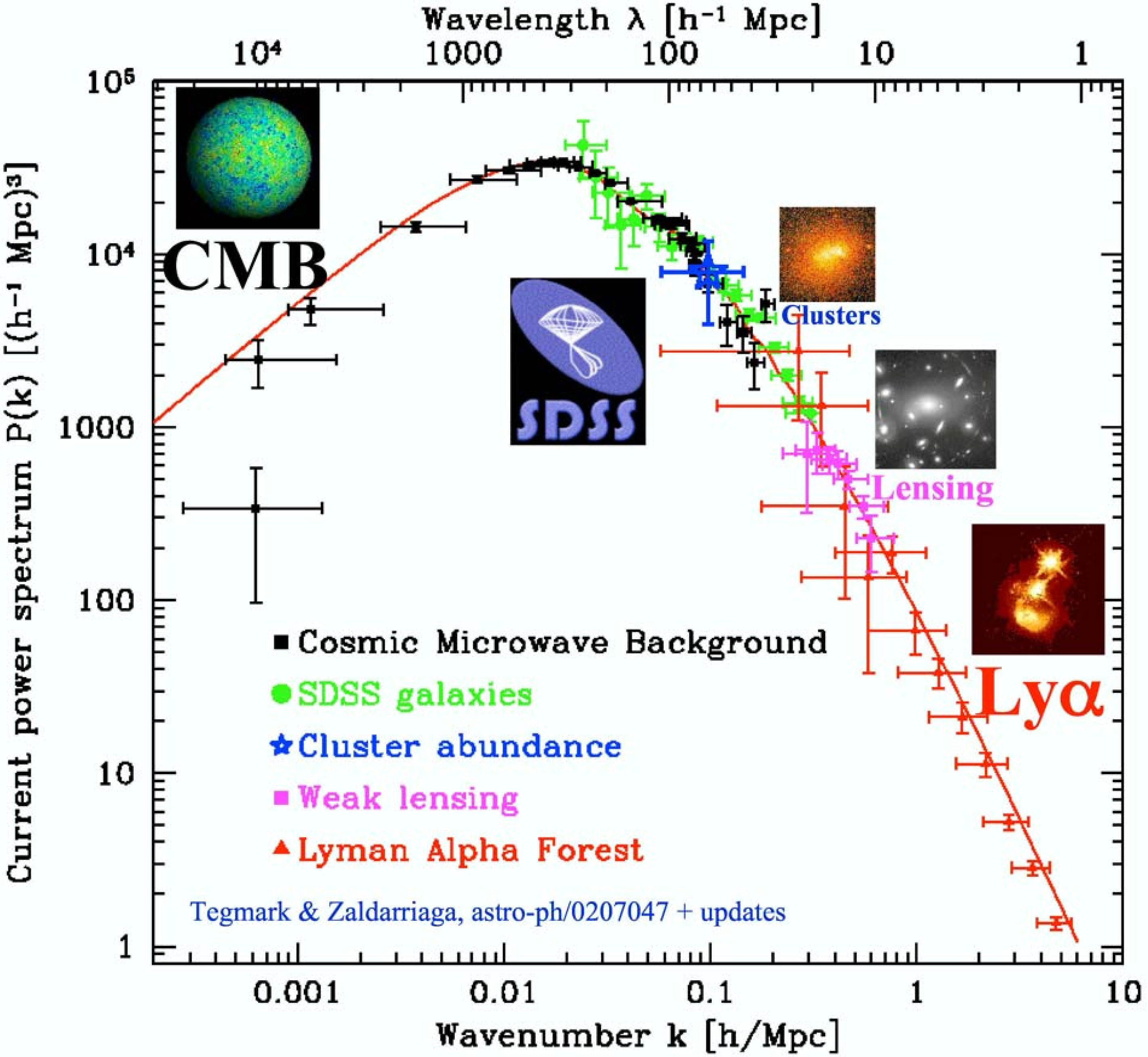
expected from inflation (n may be slightly less than 1, depending on details of inflationary phase)



Primordial spectrum

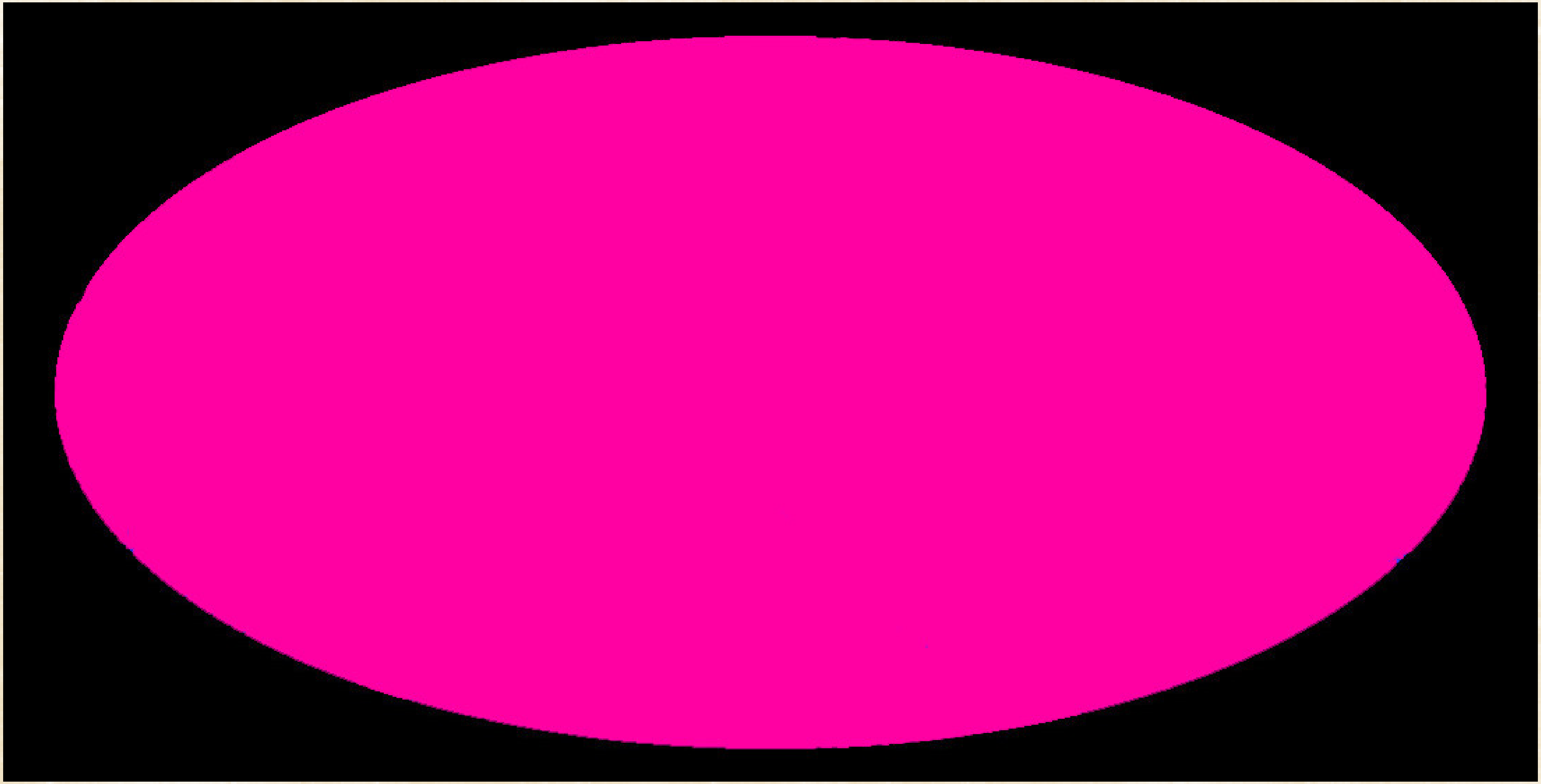
Suppressed by stagnation during radiation phase

Power Spectrum of Cosmic Density Fluctuations



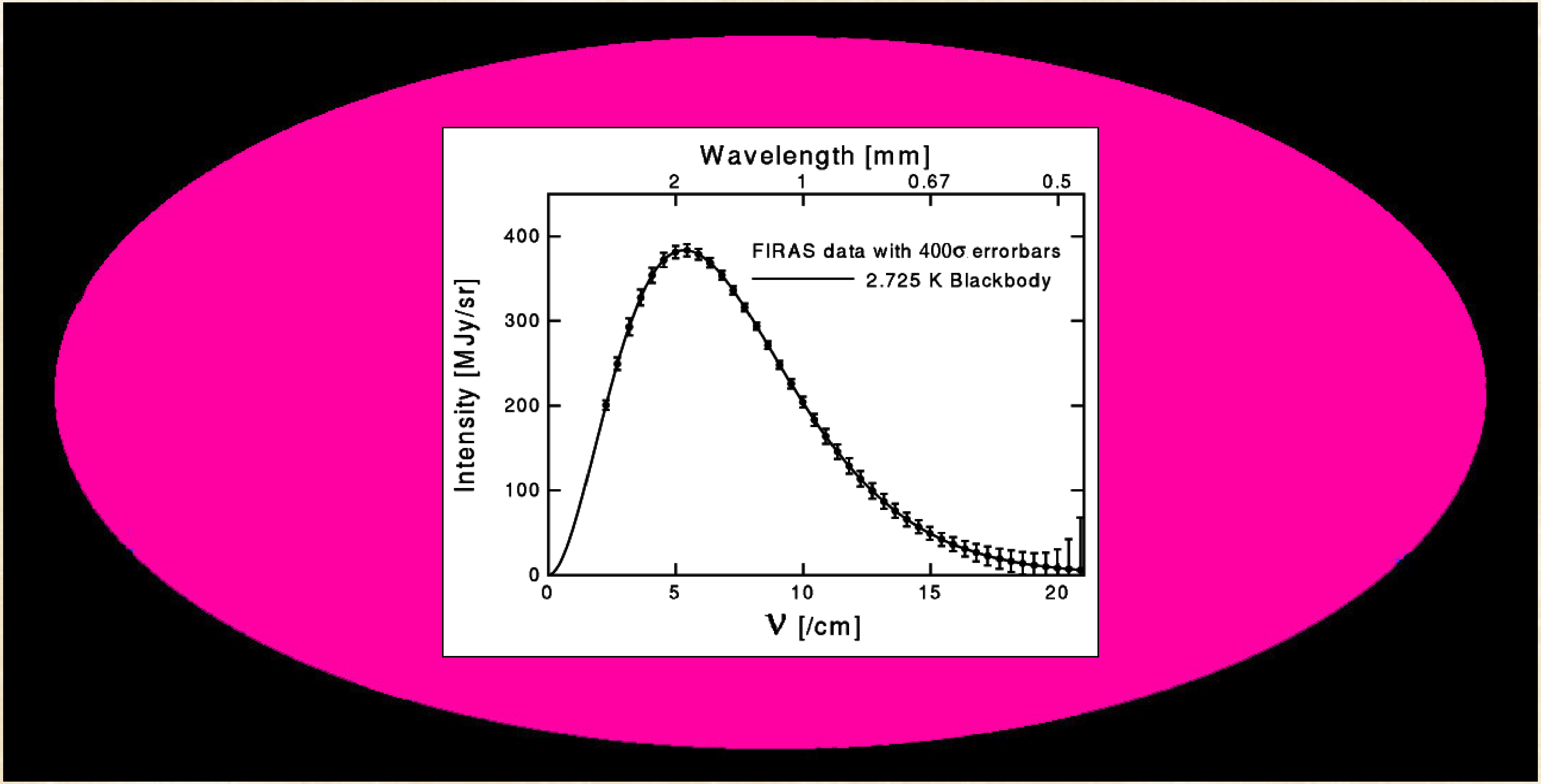
Max Tegmark
Univ. of Pennsylvania
max@physics.upenn.edu
TAUP 2003
September 5, 2003

COBE Temperature Map of the Cosmic Microwave Background



T = 2.725 K (uniform on the sky)

COBE Temperature Map of the Cosmic Microwave Background



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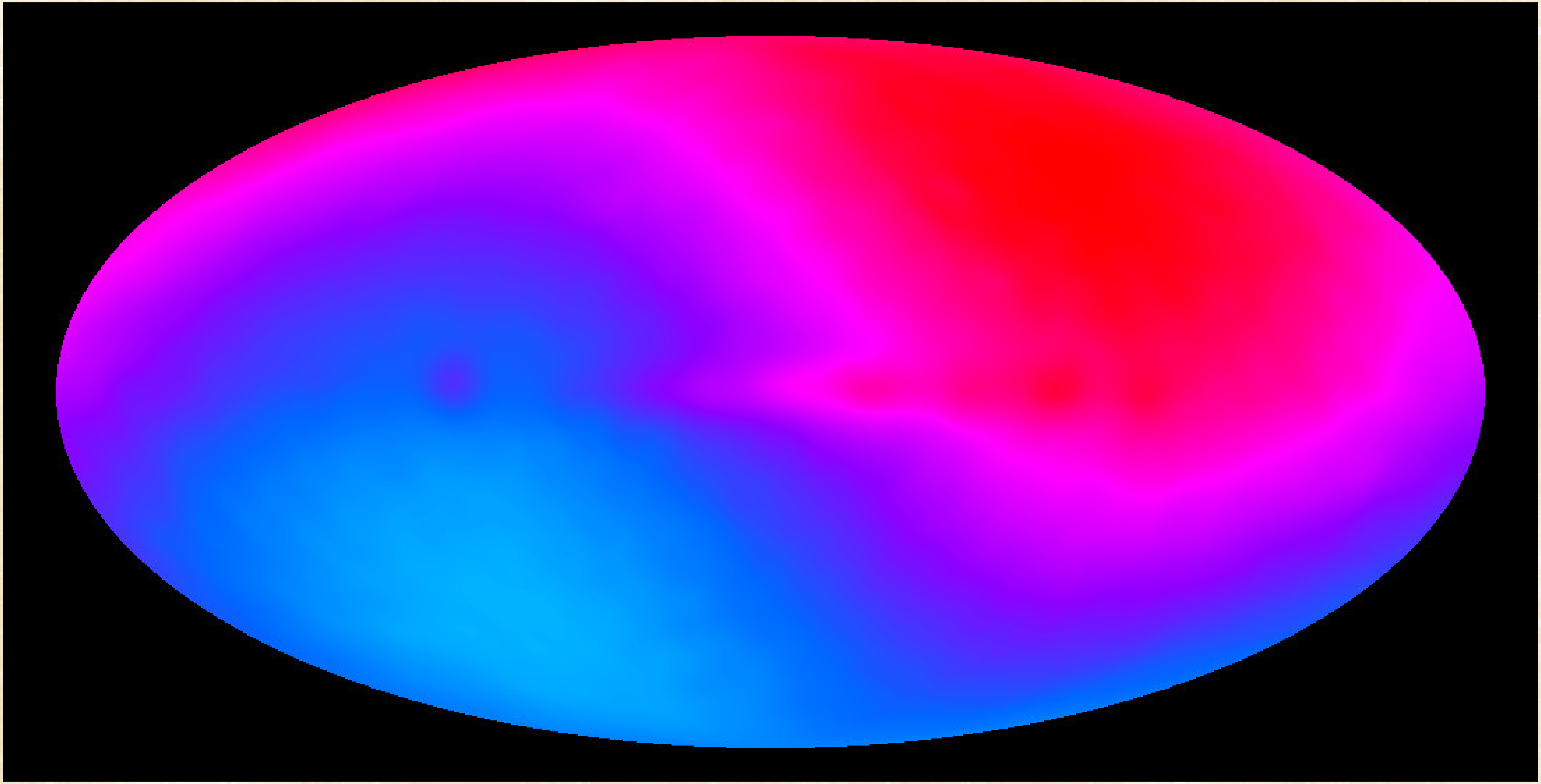
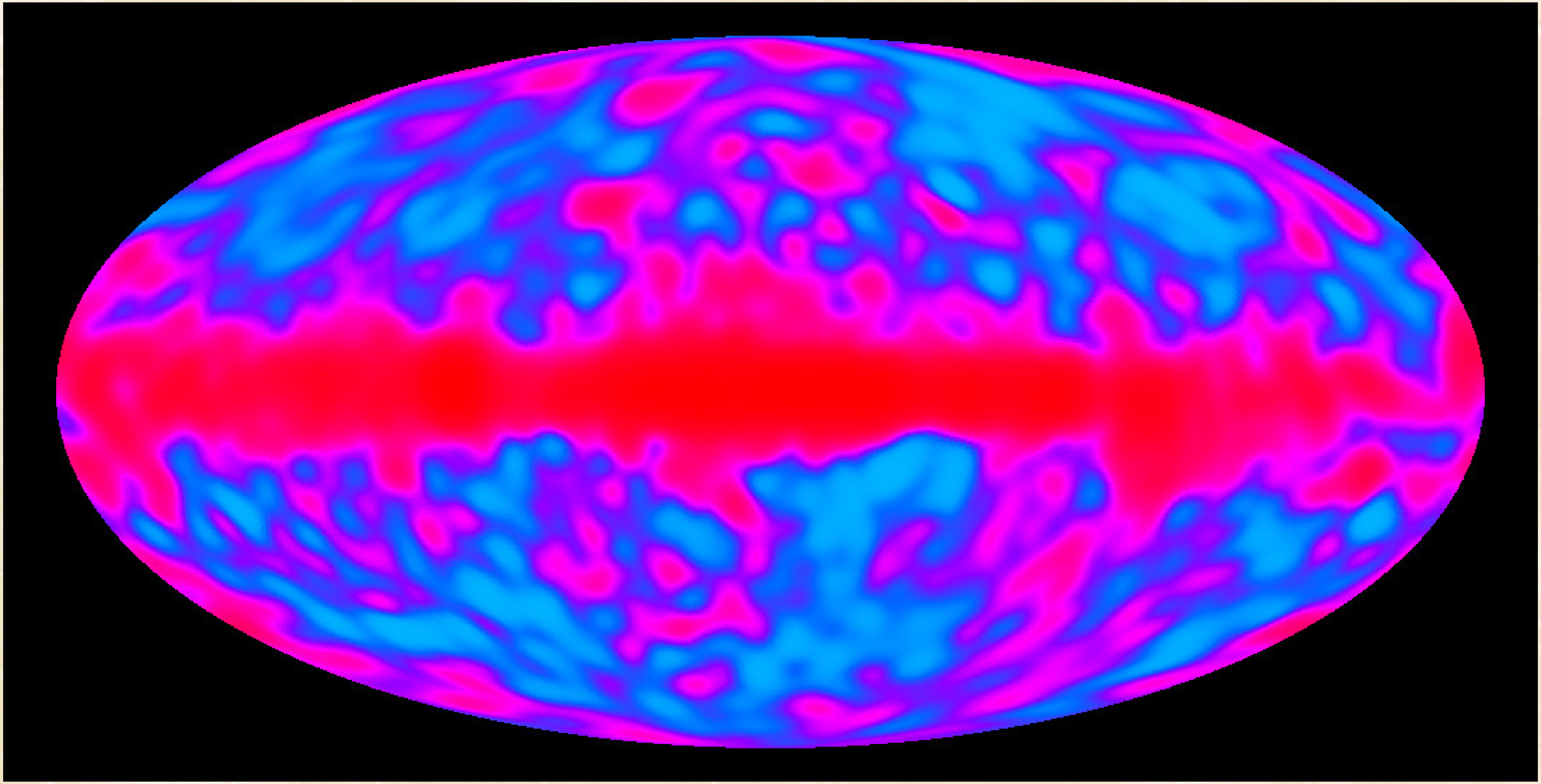


Dynamical range $\Delta T = 3.353$ mK ($\Delta T/T \approx 10^{-3}$)
Dipole temperature distribution from Doppler effect caused by our motion relative to the cosmic frame

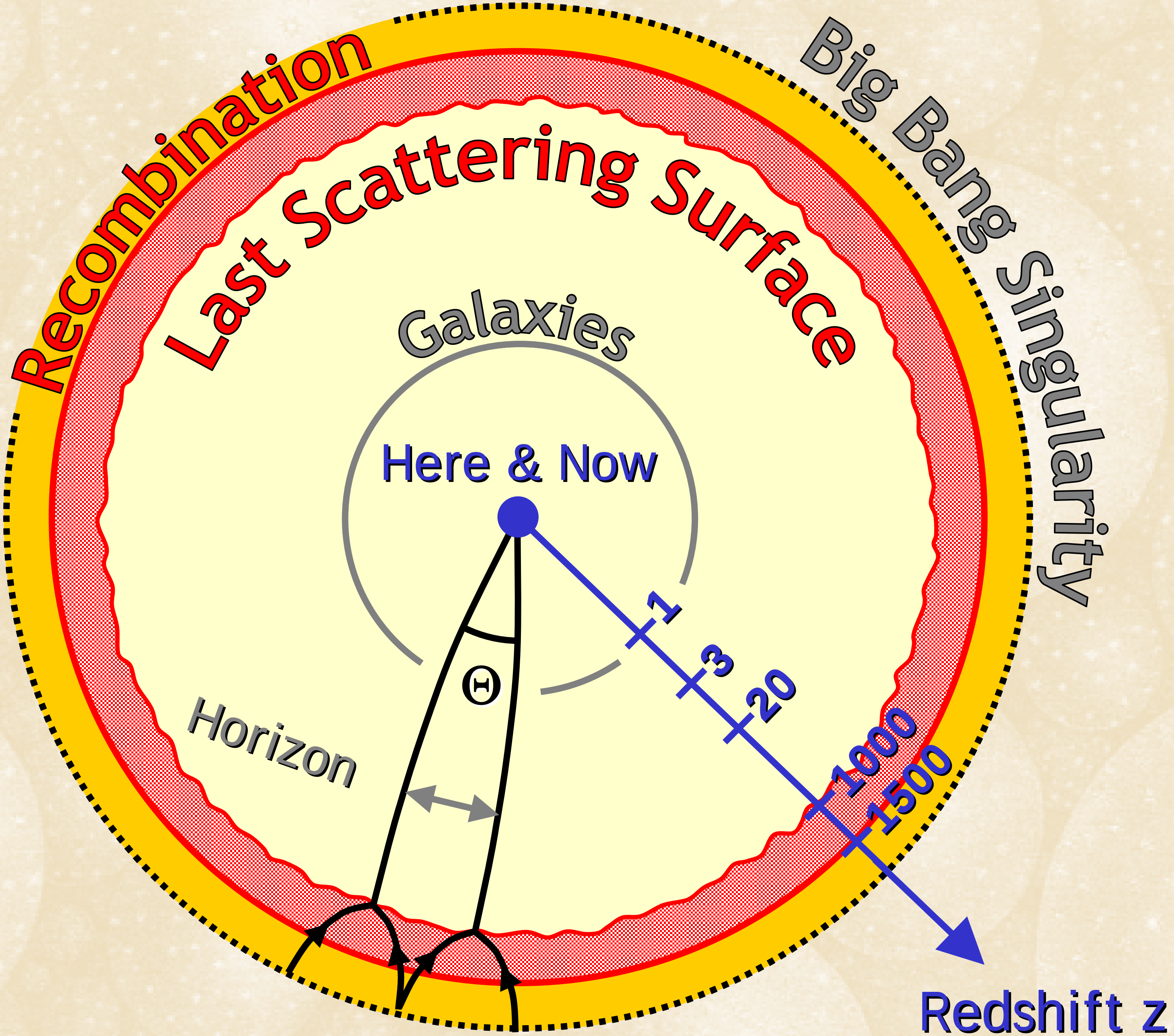
COBE Temperature Map of the Cosmic Microwave Background



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

Primordial temperature fluctuations

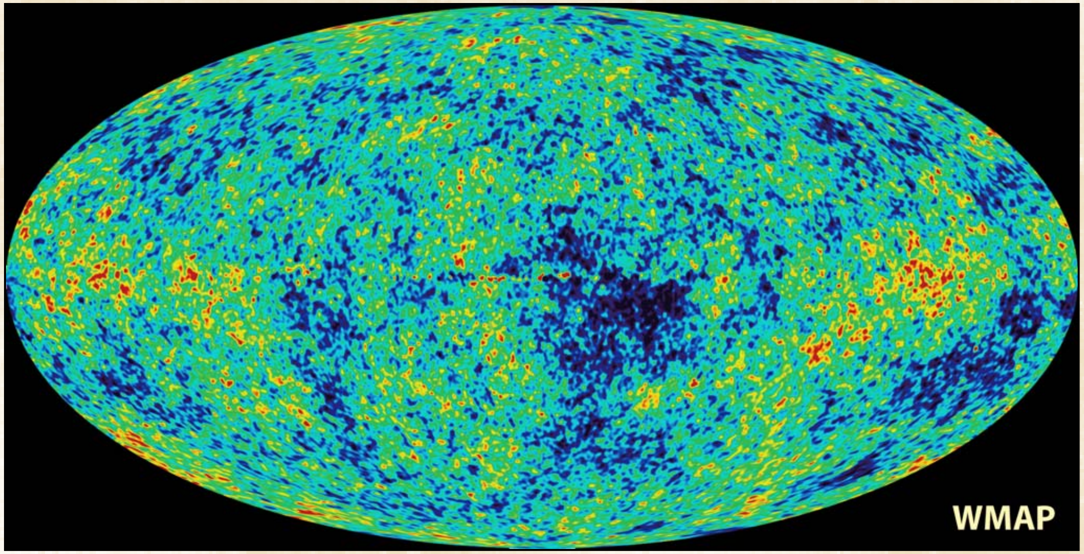
Last Scattering Surface



Power Spectrum of CMBR Temperature Fluctuations

Sky map of CMBR temperature fluctuations

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

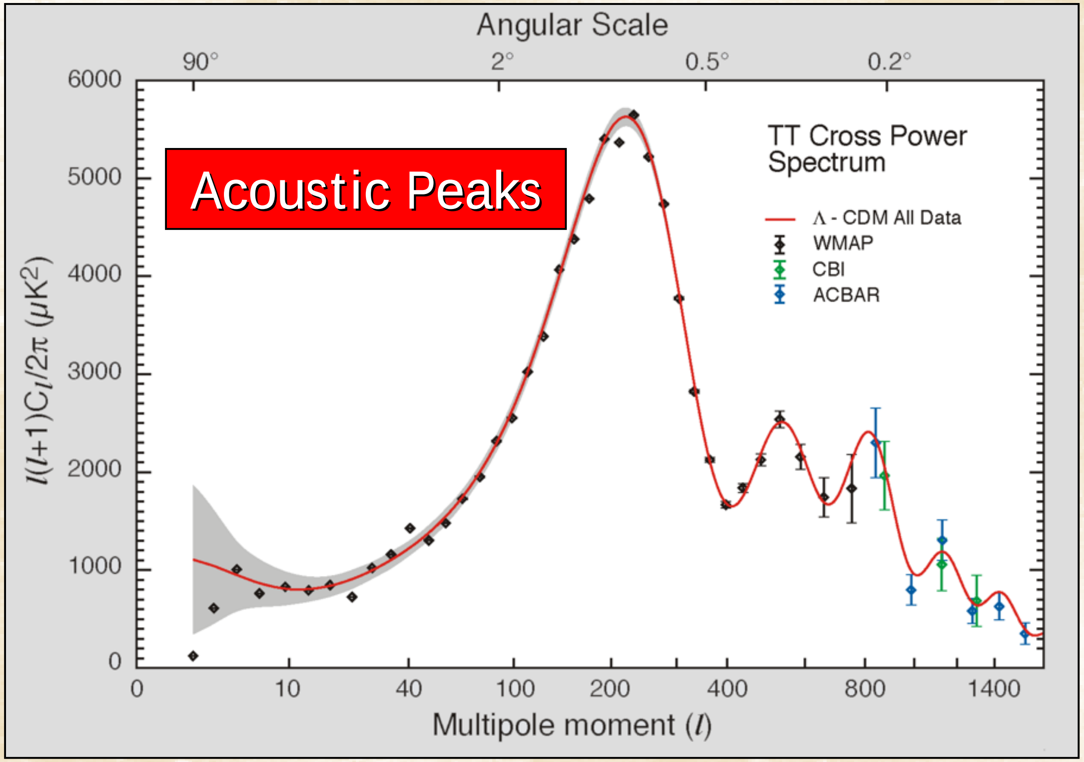


Multipole expansion

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

Angular power spectrum

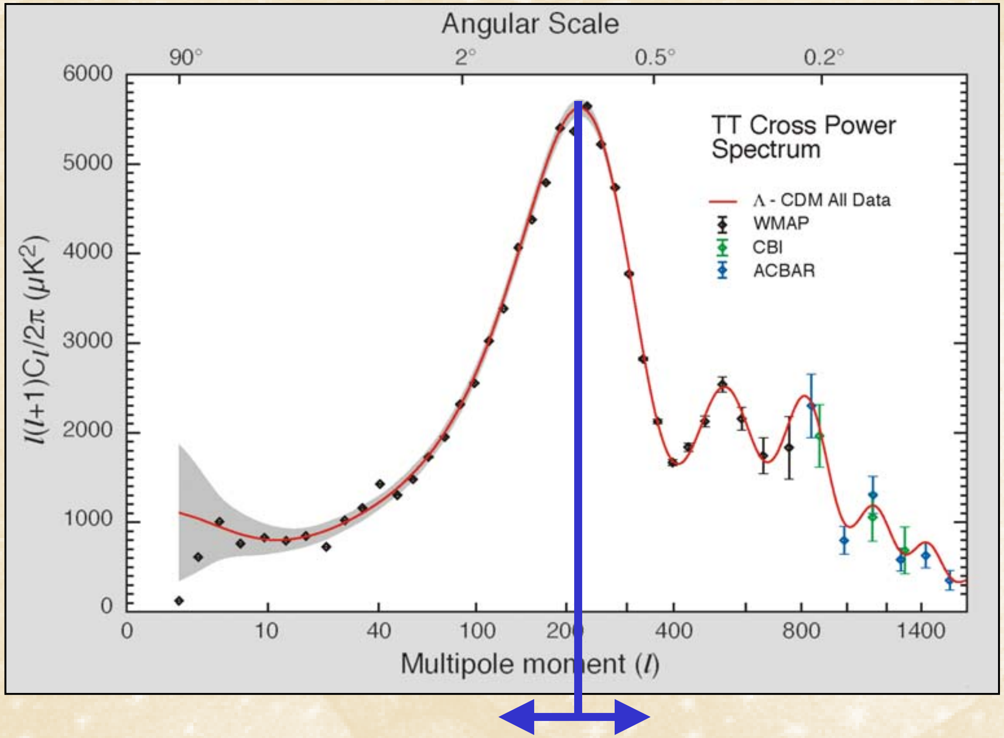
$$C_\ell=\left\langle a_{\ell m}^{*}a_{\ell m}\right\rangle=\frac{1}{2\ell+1}\sum_{m=-\ell}^{\ell}a_{\ell m}^{*}a_{\ell m}$$



Acoustic Peaks

Flat Universe from CMBR Angular Fluctuations

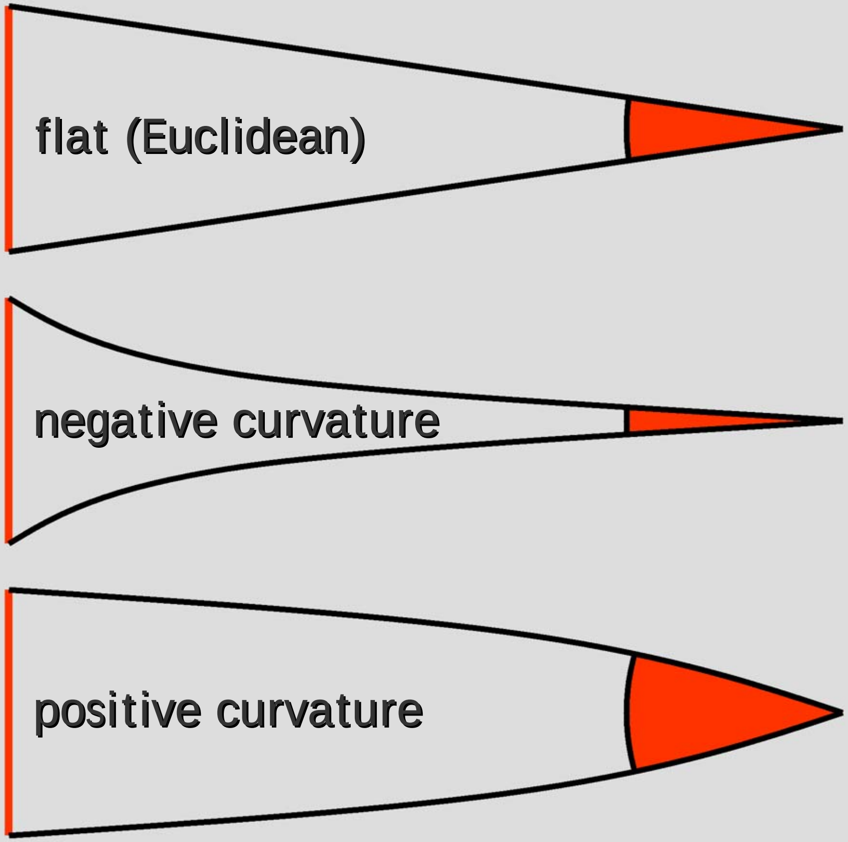
Spergel et al. (WMAP Collaboration)
astro-ph/0302209



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

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

Triangulation with acoustic peak



flat (Euclidean)

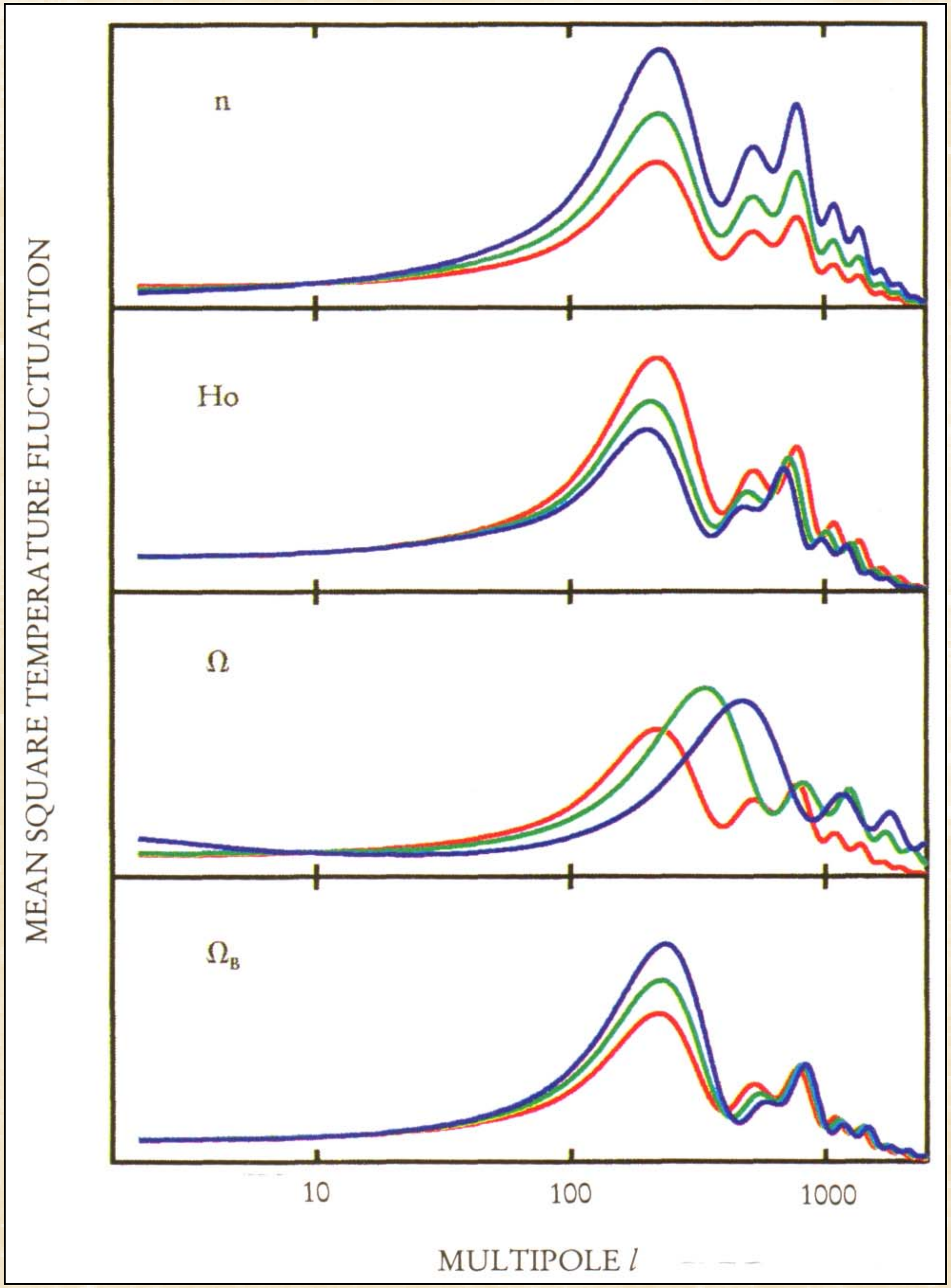
negative curvature

positive curvature

Known physical
size of acoustic peak
at decoupling (z ≈ 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
$\Omega_{tot} = 1.0, 0.5, 0.3$

Baryon density
$\Omega_B = 5, 7.5, 10 \times 10^{-3}$

Physics Today 1997:11, 32

Concordance Model of Cosmology

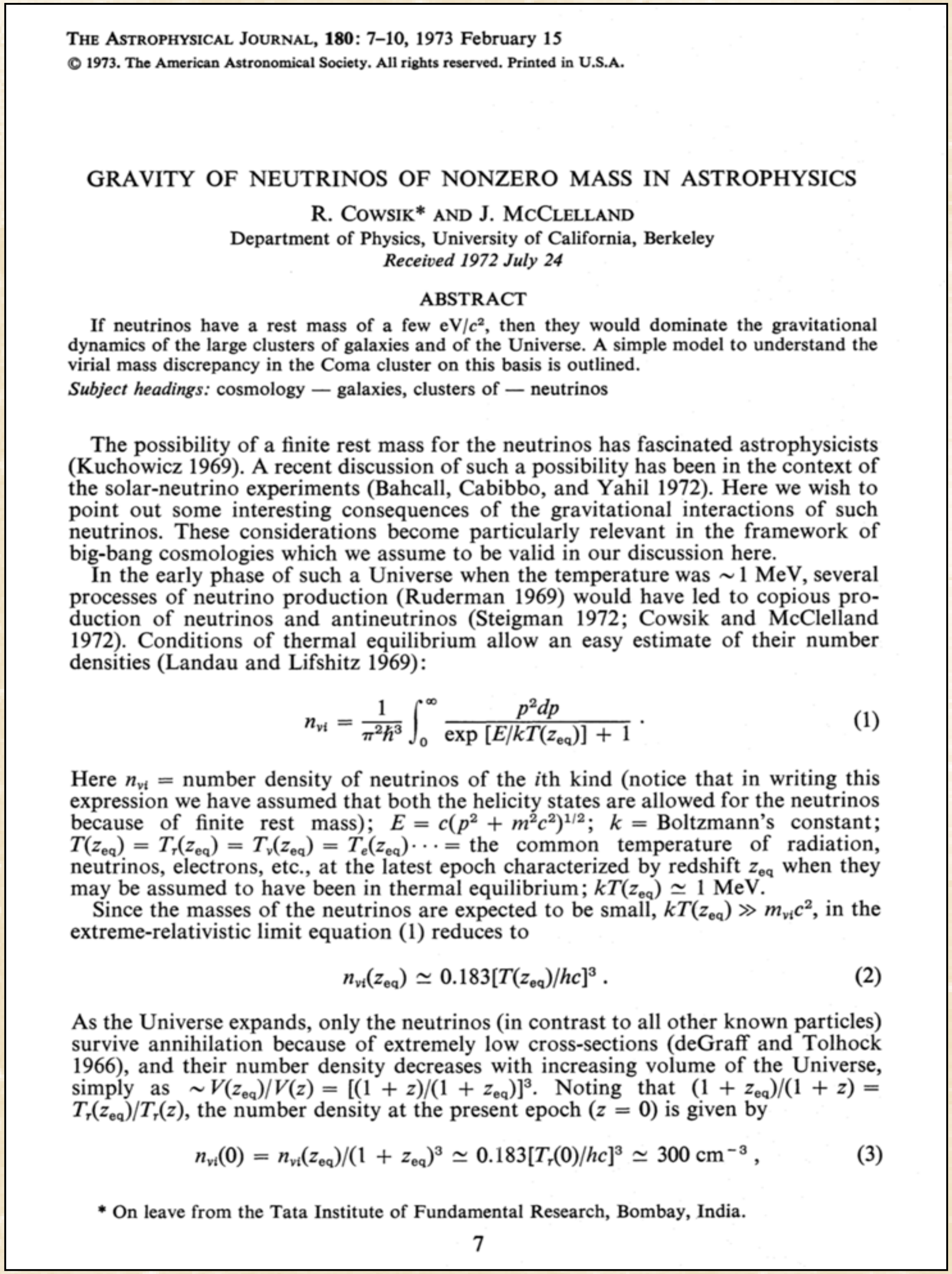
A Friedmann-Lemaître-Robertson-Walker model with the following parameters perfectly describes the global properties of the universe

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	$n = 0.93 \pm 0.03$

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):

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

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; $T(z_{eq}) = T_r(z_{eq}) = T_\nu(z_{eq}) = T_e(z_{eq})\cdots =$ 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

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

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 $\sim V(z_{eq})/V(z) = [(1 + z)/(1 + z_{eq})]^3$. 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

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

---

* 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")

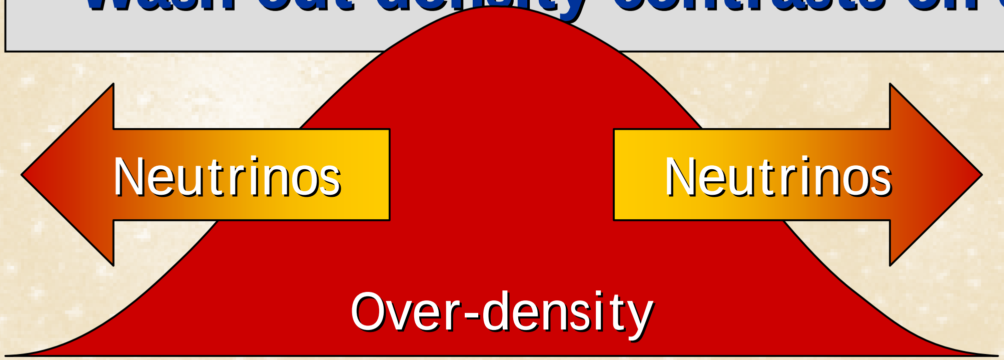
Maximum mass density of a degenerate Fermi gas

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

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

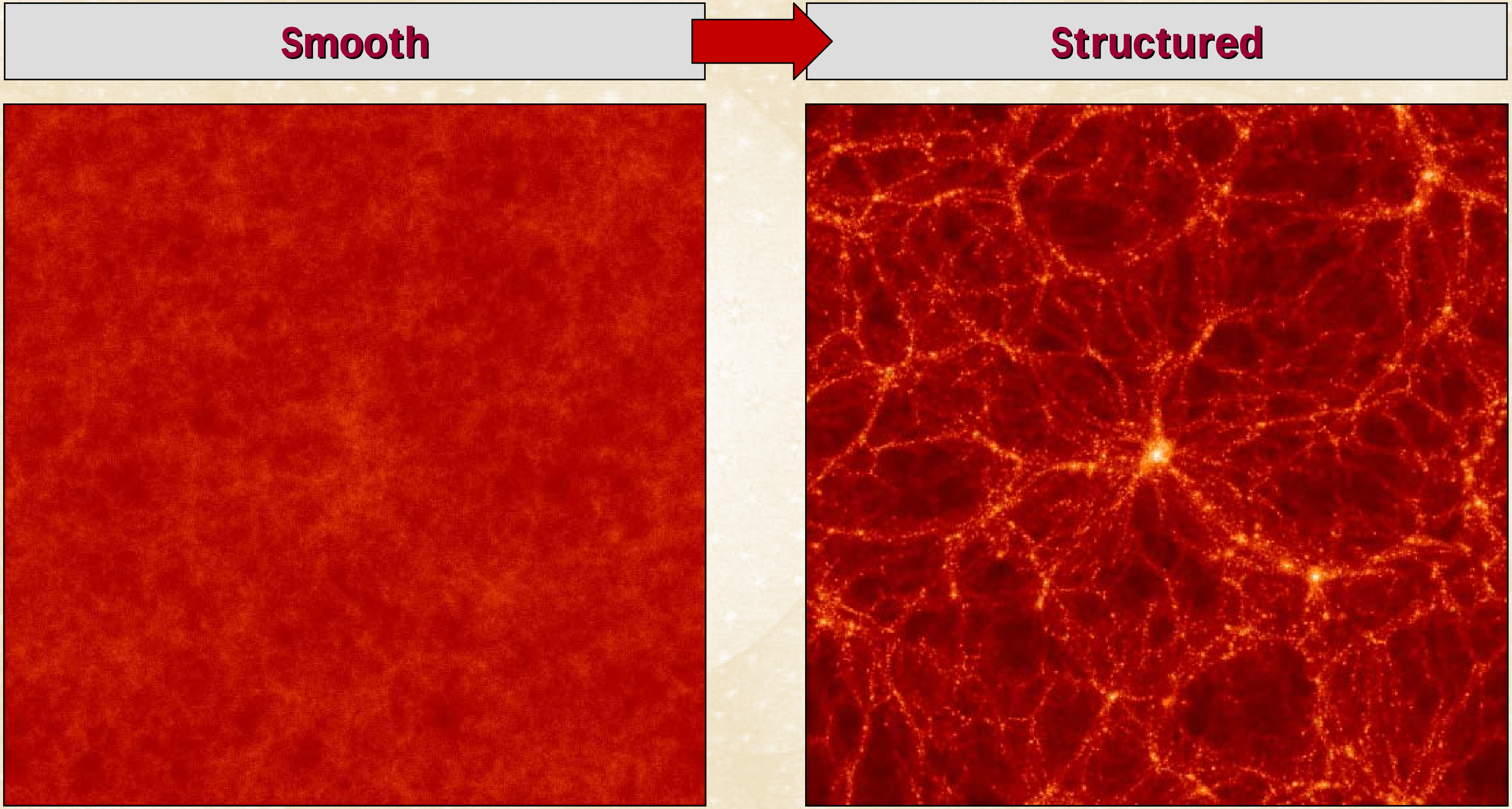
Neutrino Free Streaming (Collisionless Phase Mixing)

- **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

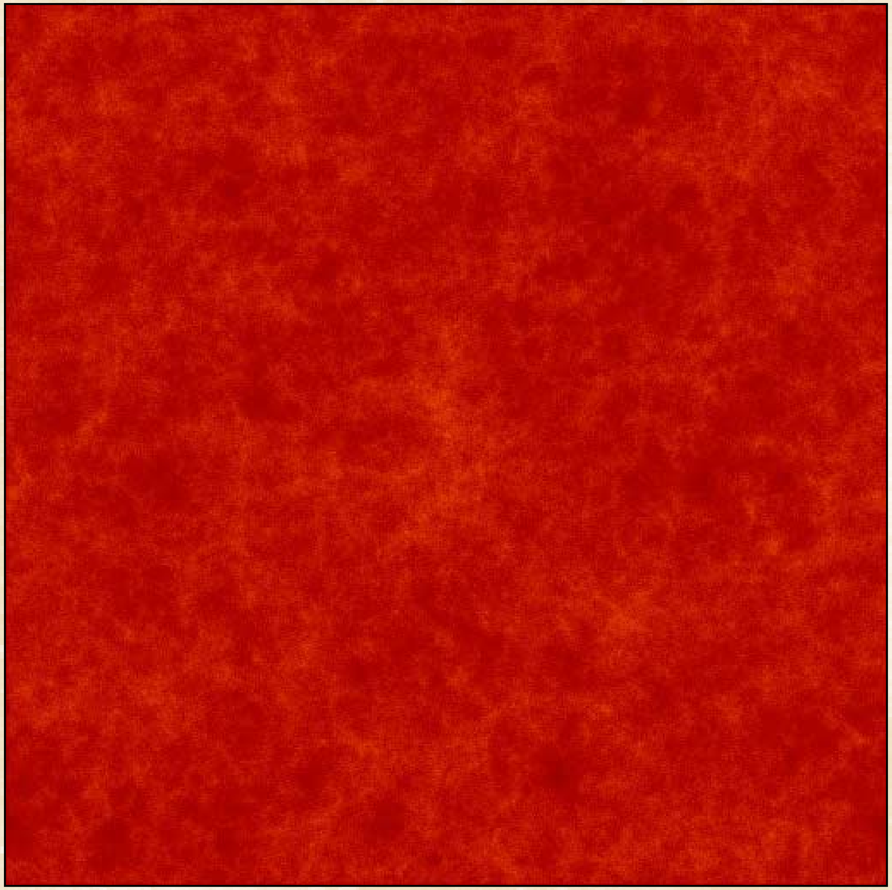


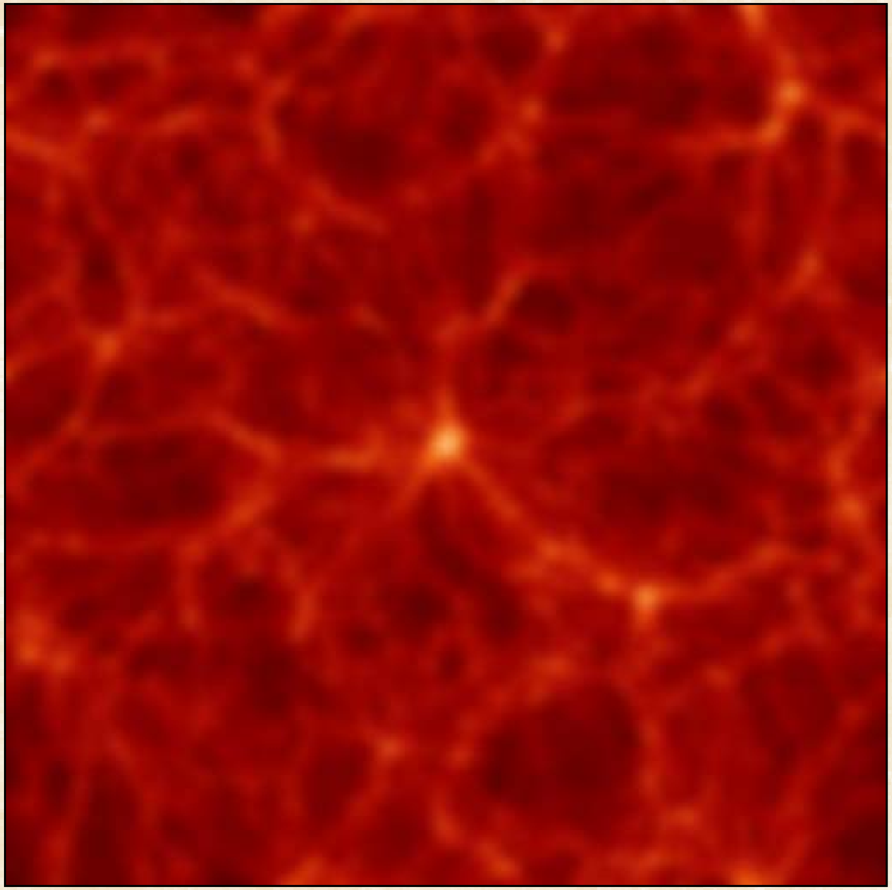
Smooth

Structured

Formation of Structure

Smooth → **Structured**

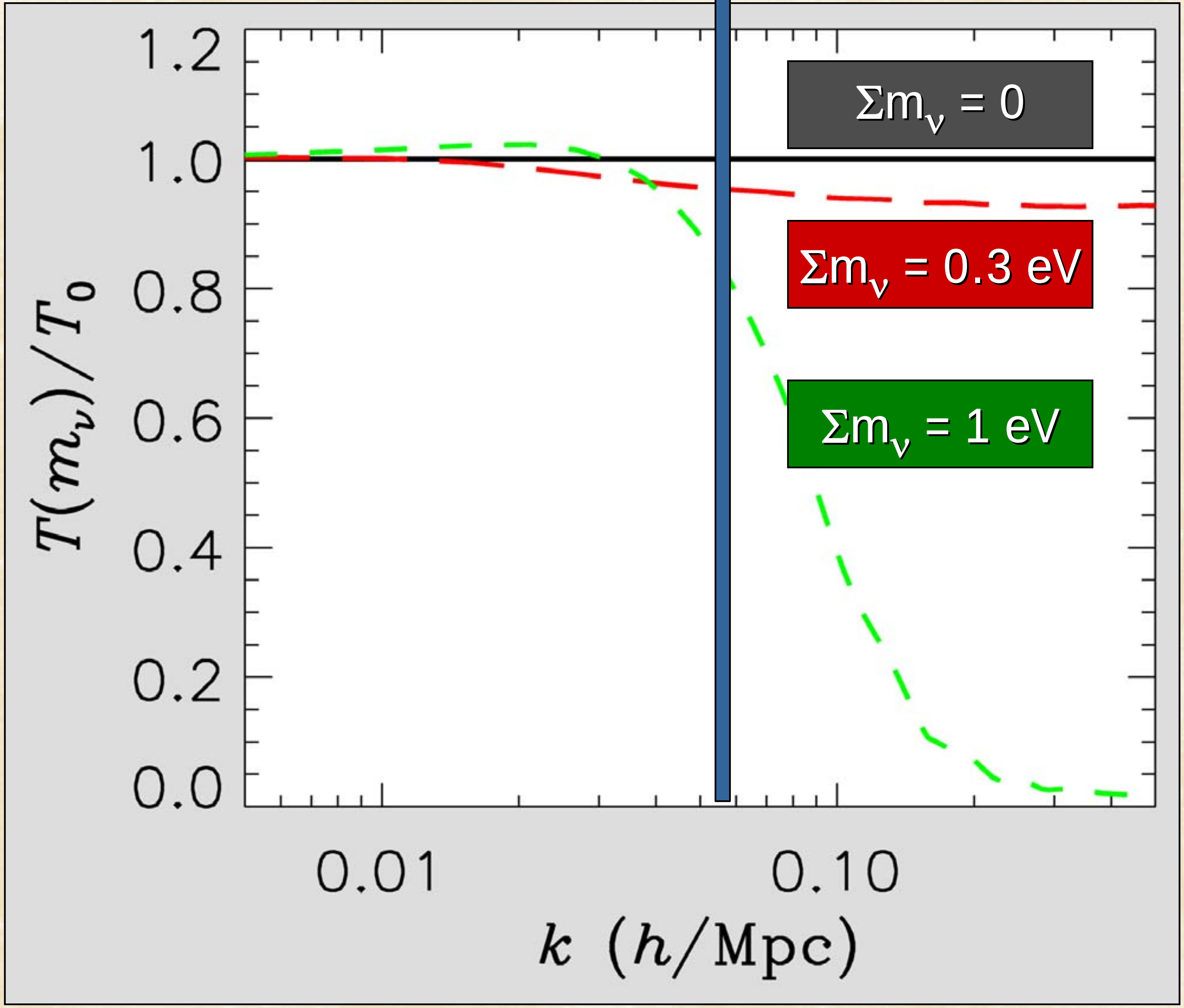




A fraction of hot dark matter suppresses small-scale structure

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

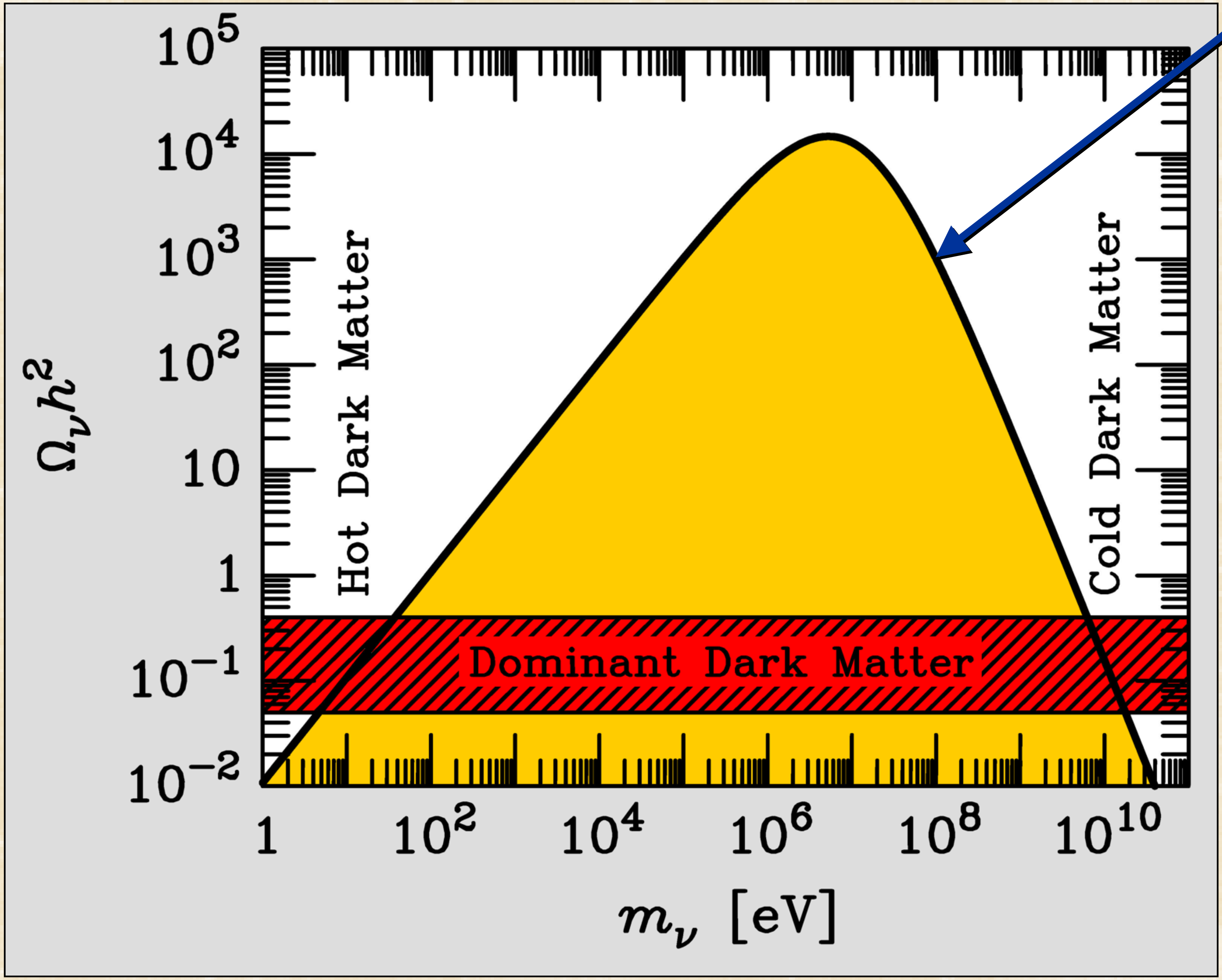
$$8\Omega_\nu/\Omega_M \ll 1$$

Hannestad, Neutrinos in Cosmology, hep-ph/0404239

Recent Cosmological Limits on Neutrino Masses

Authors	Σm_ν/eV (limit 95%CL)	Data / Priors
Spergel et al. (WMAP) 2003 [astro-ph/0302209]	0.69	WMAP, CMB, 2dF, σ_8, HST
Hannestad 2003 [astro-ph/0303076]	1.01	WMAP, CMB, 2dF, HST
Tegmark et al. 2003 [astro-ph/0310723]	1.8	WMAP, SDSS
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

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

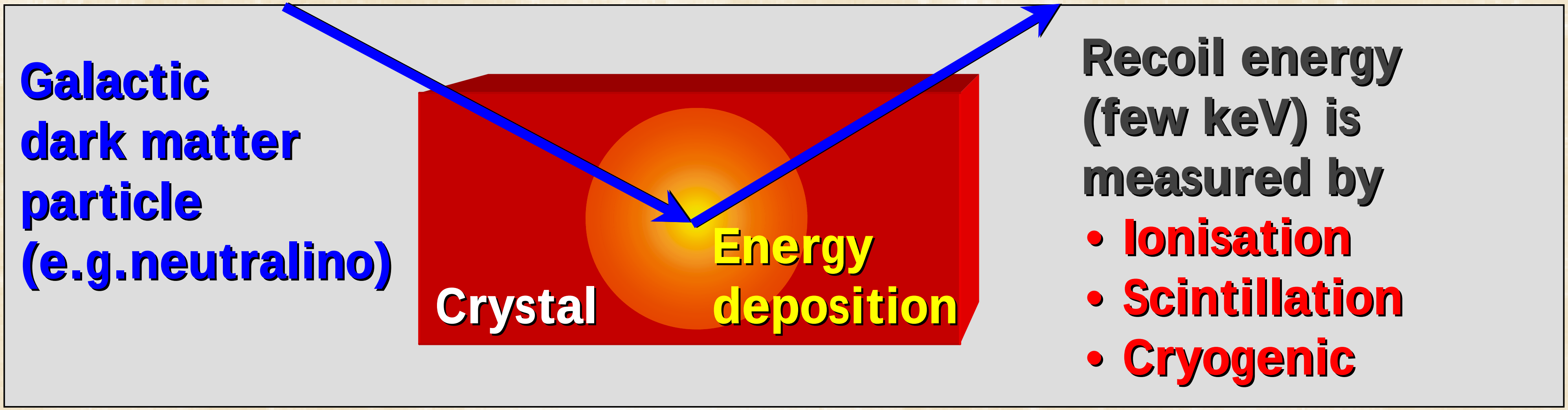
(With permission of David Simmonds ©)

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

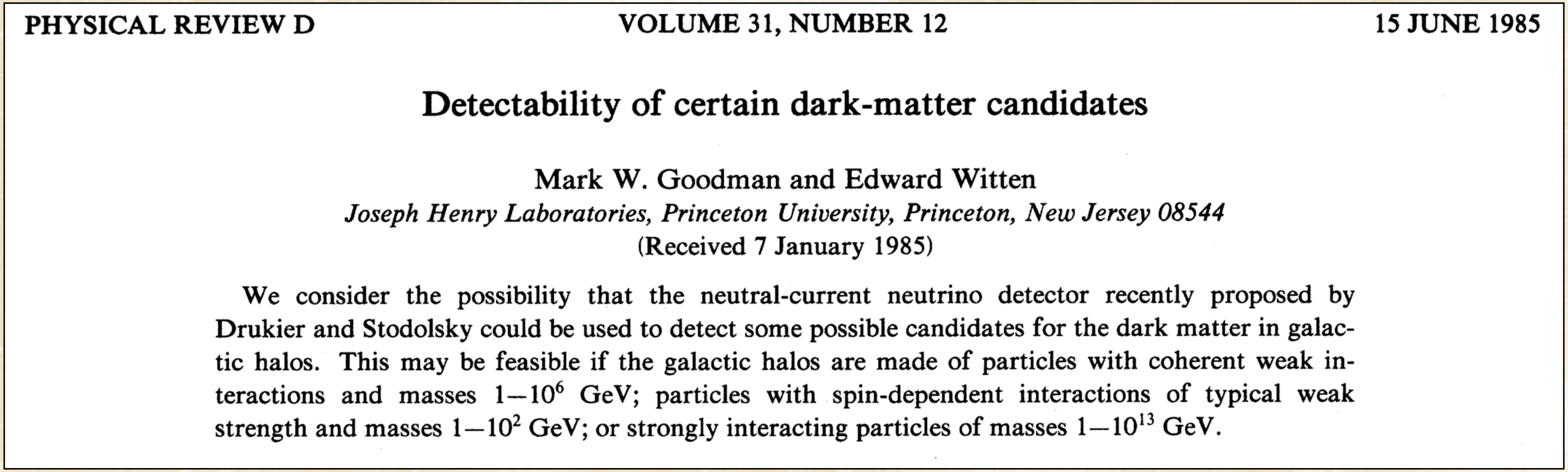
Direct Method (Laboratory Experiments)



Galactic dark matter particle (e.g.neutralino)

Recoil energy (few keV) is measured by

- **Ionisation**
- **Scintillation**
- **Cryogenic**



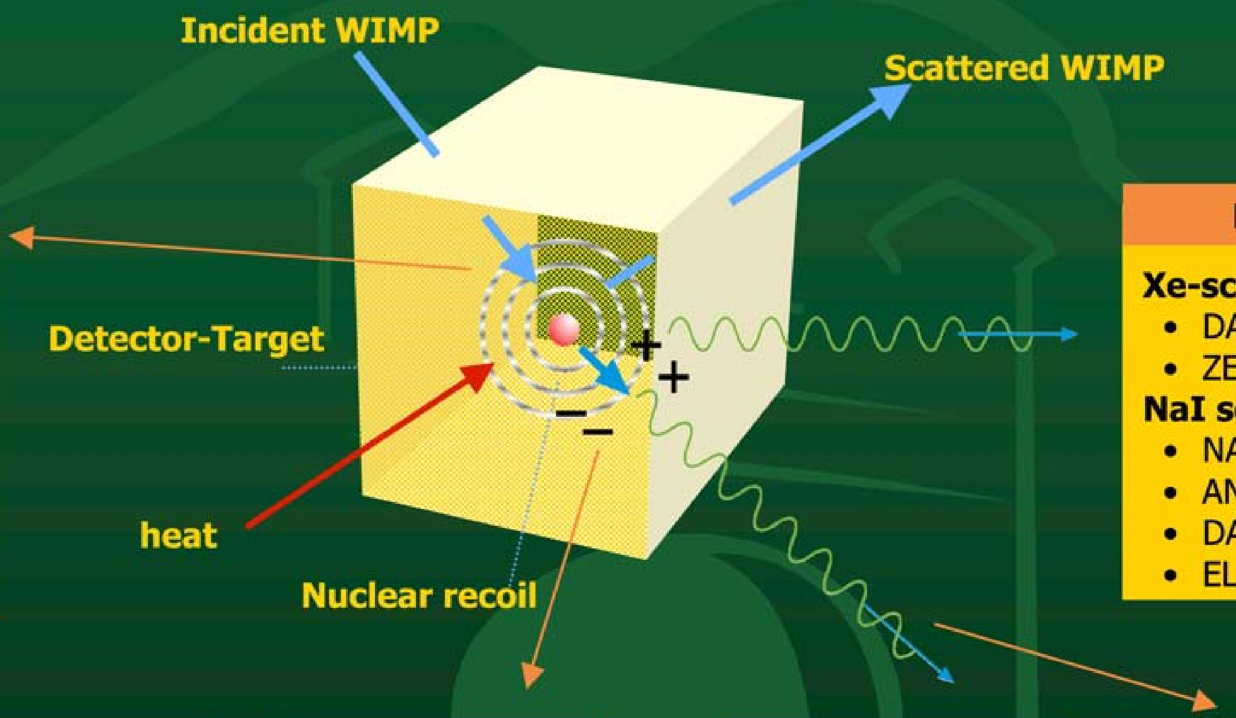
PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

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.

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

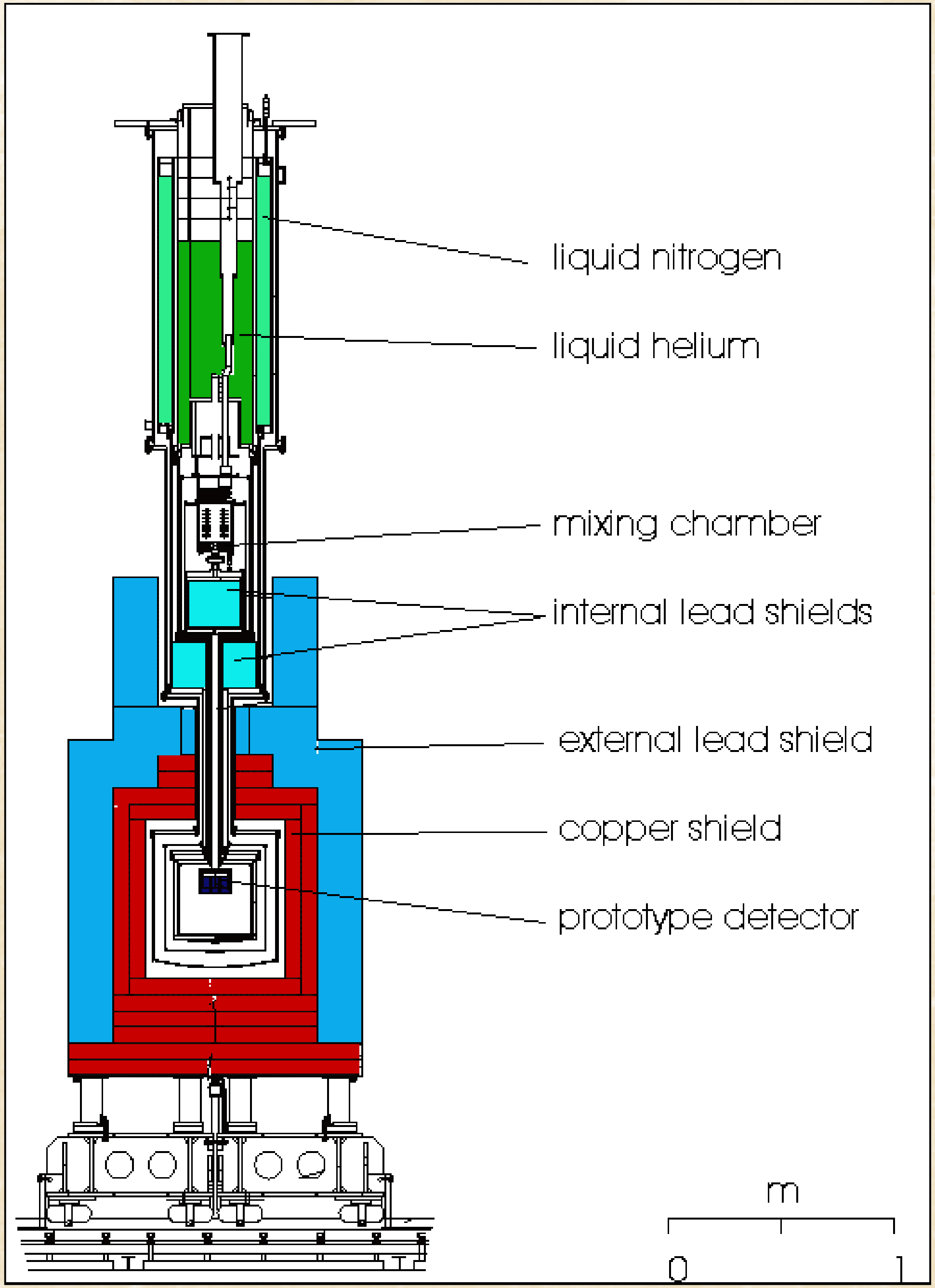
LIGHT+CHARGE

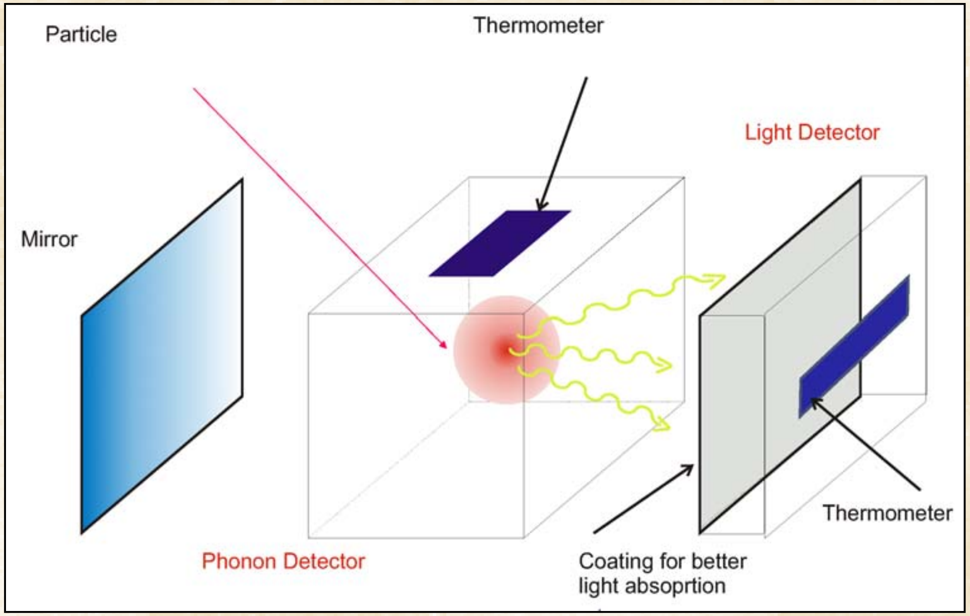
- ZEPLIN-II
- X-MASS

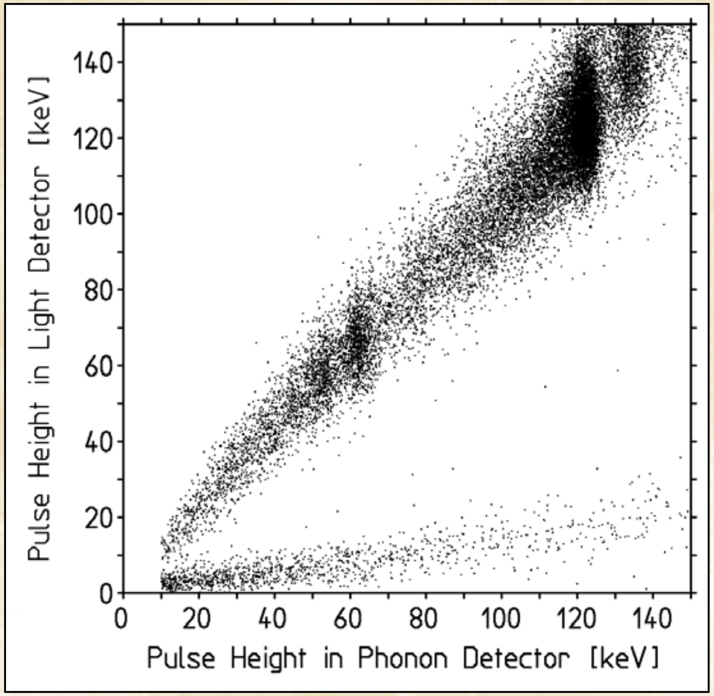
WIMP direct detection in underground facilities experiments currently running (or in preparation)

LABORATORY	EXPERIMENT	TECHNIQUE
Bern (Switzerland)	ORPHEUS	(SSD) Tin Superconducting Superheated Detector
Boulby (UK)	NAIAD	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

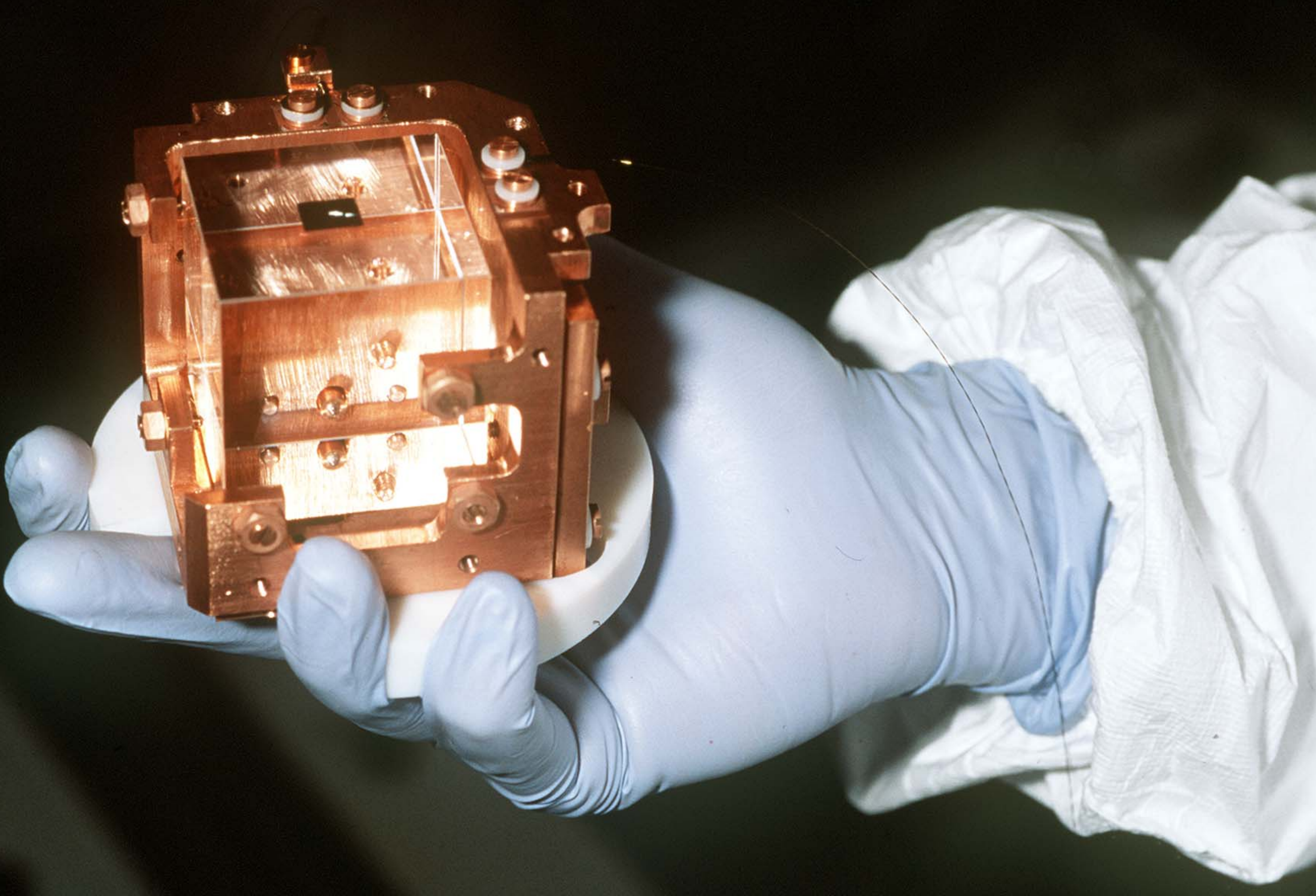
CRESST Experiment to Search for Dark Matter



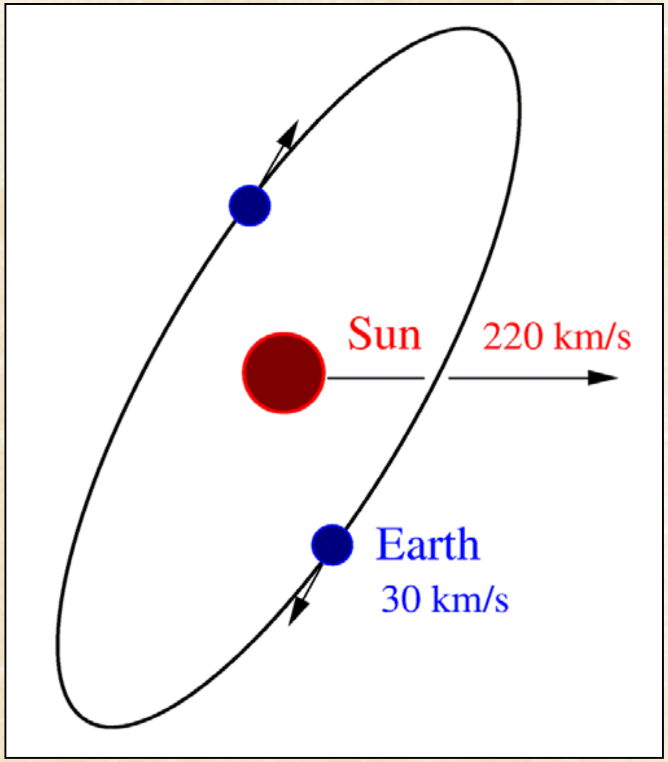




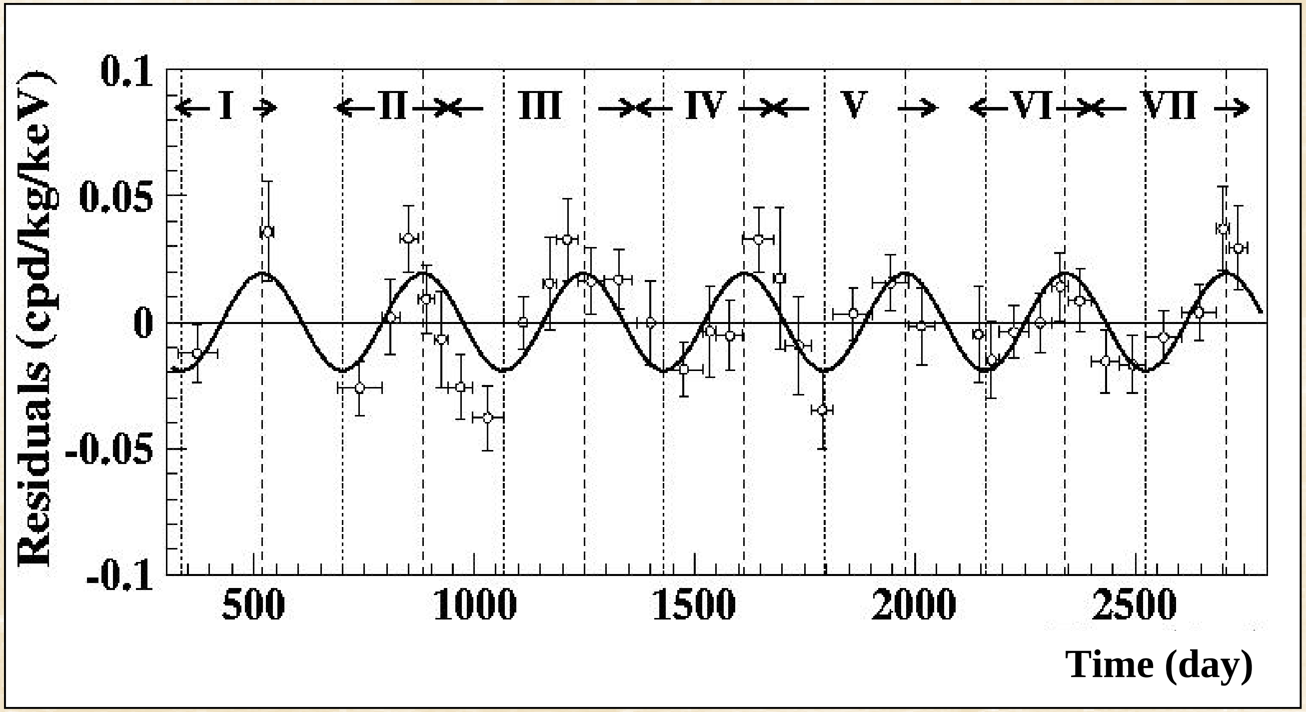
One of the CRESST Detector Crystals



DAMA Evidence for WIMP Detection



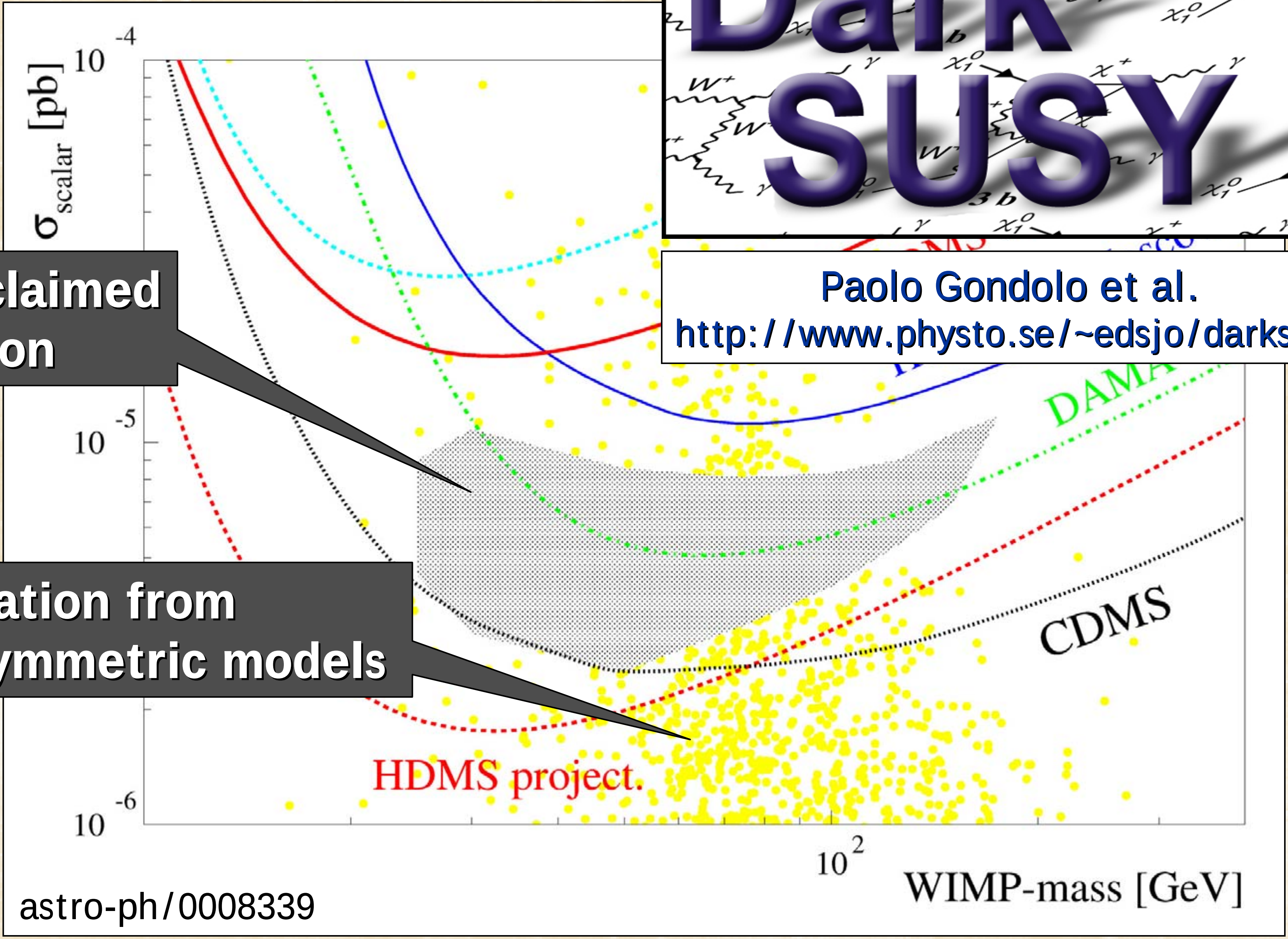
DAMA experiment in Gran Sasso (NaI scintillation detector) observes an annual modulation at a 6.3σ statistical CL, based on 110 ton-days of data [Riv. N. Cim. 26 (2003) 1–73]



Annual modulation of WIMP signal a “smoking gun” signature

- Detector stability ?
- „Background stability“ ?

Limits from WIMP Search Experiments



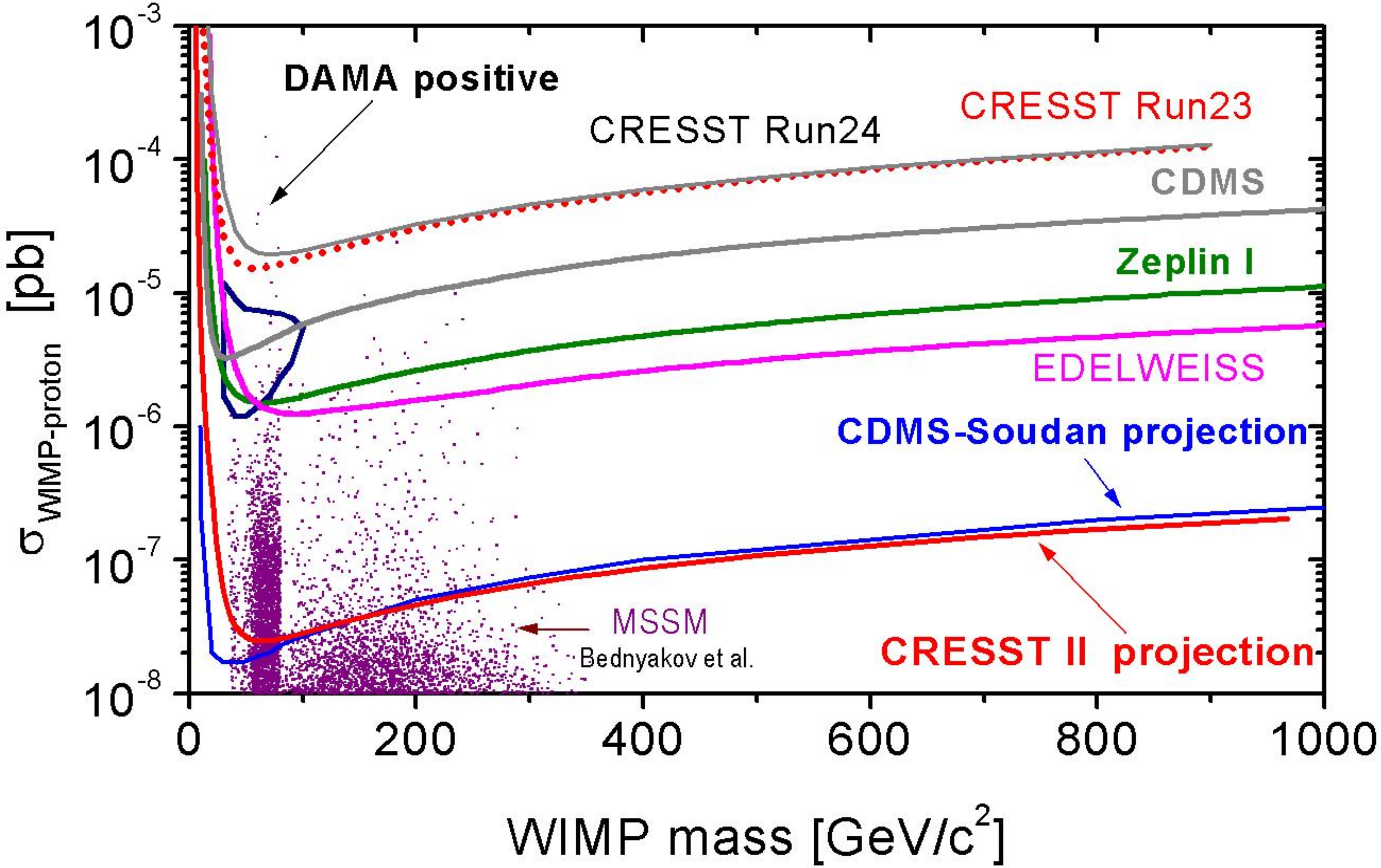
astro-ph/0008339

DAMA claimed detection

Expectation from supersymmetric models

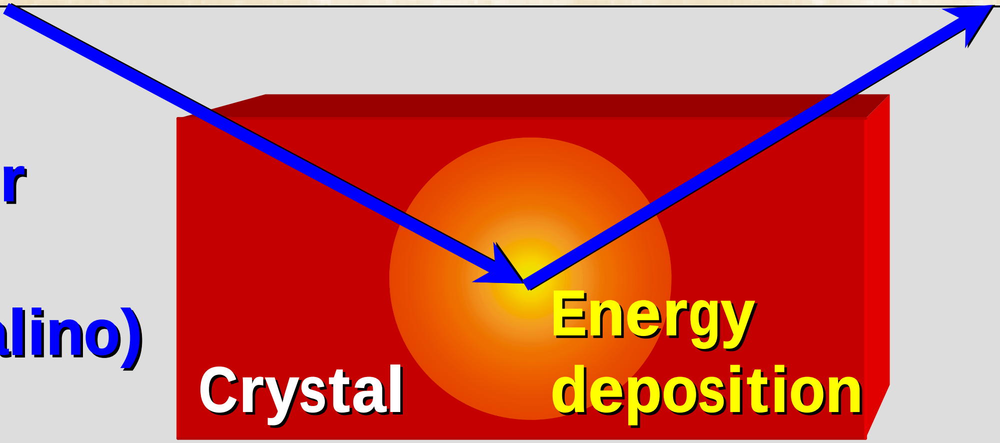
Paolo Gondolo et al.
http://www.physto.se/~edsjo/darksusy

Projected WIMP Sensitivities



Search for Neutralino Dark Matter

Direct Method (Laboratory Experiments)

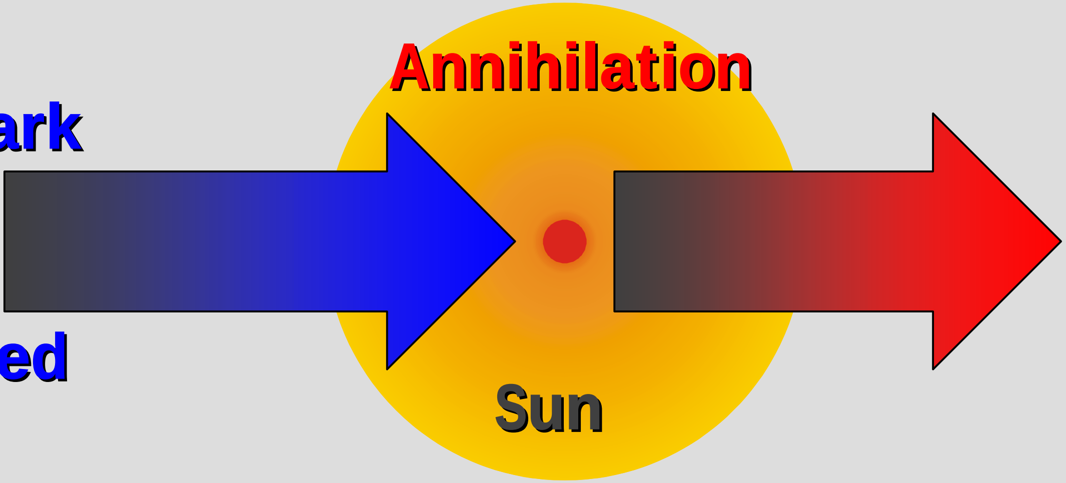


Galactic dark matter particle (e.g.neutralino)

Recoil energy (few keV) is measured by

- Ionisation
- Scintillation
- Cryogenic

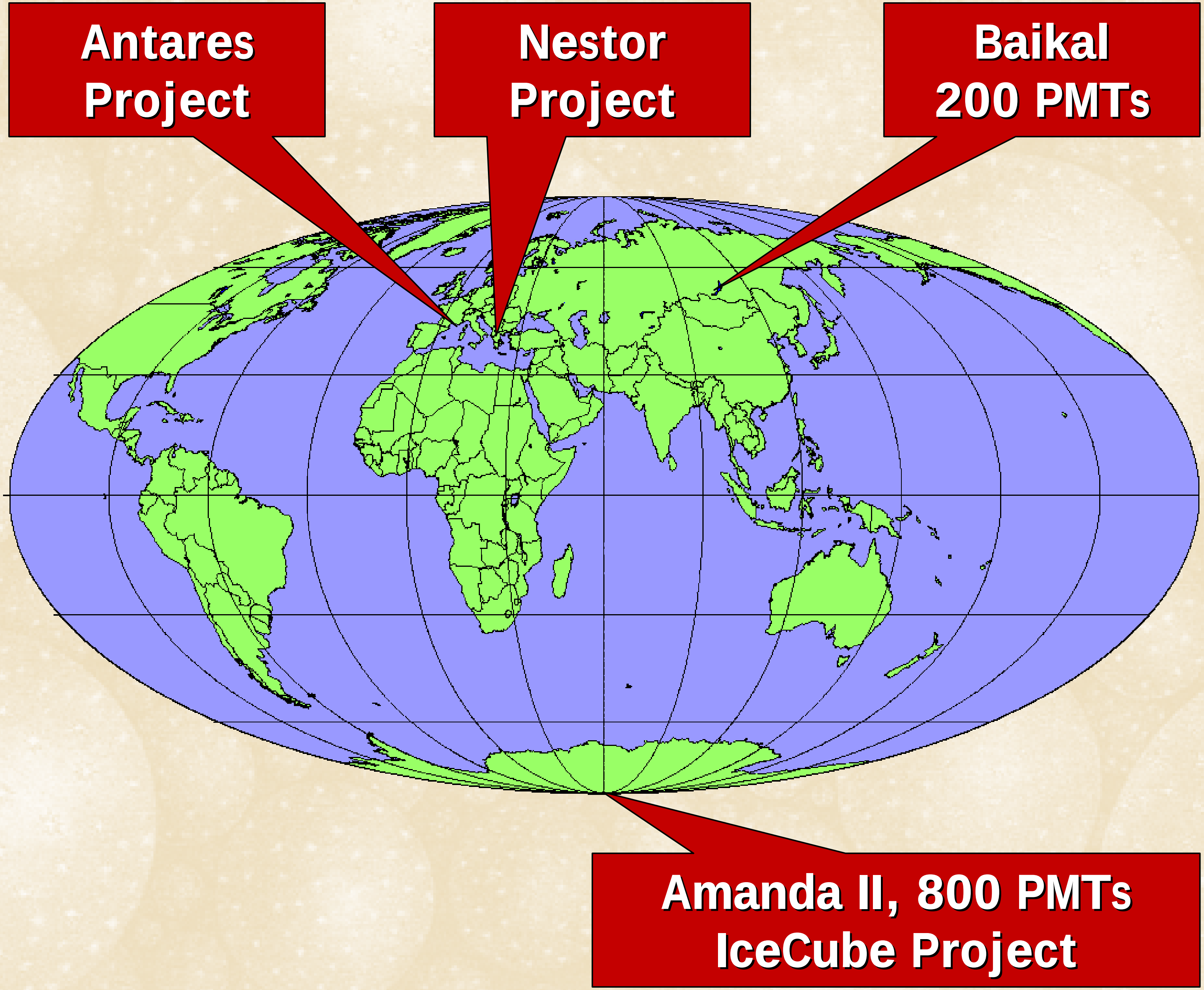
Indirect Method (Neutrino Telescopes)



Galactic dark matter particles are accreted

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

High-Energy Neutrino Telescopes



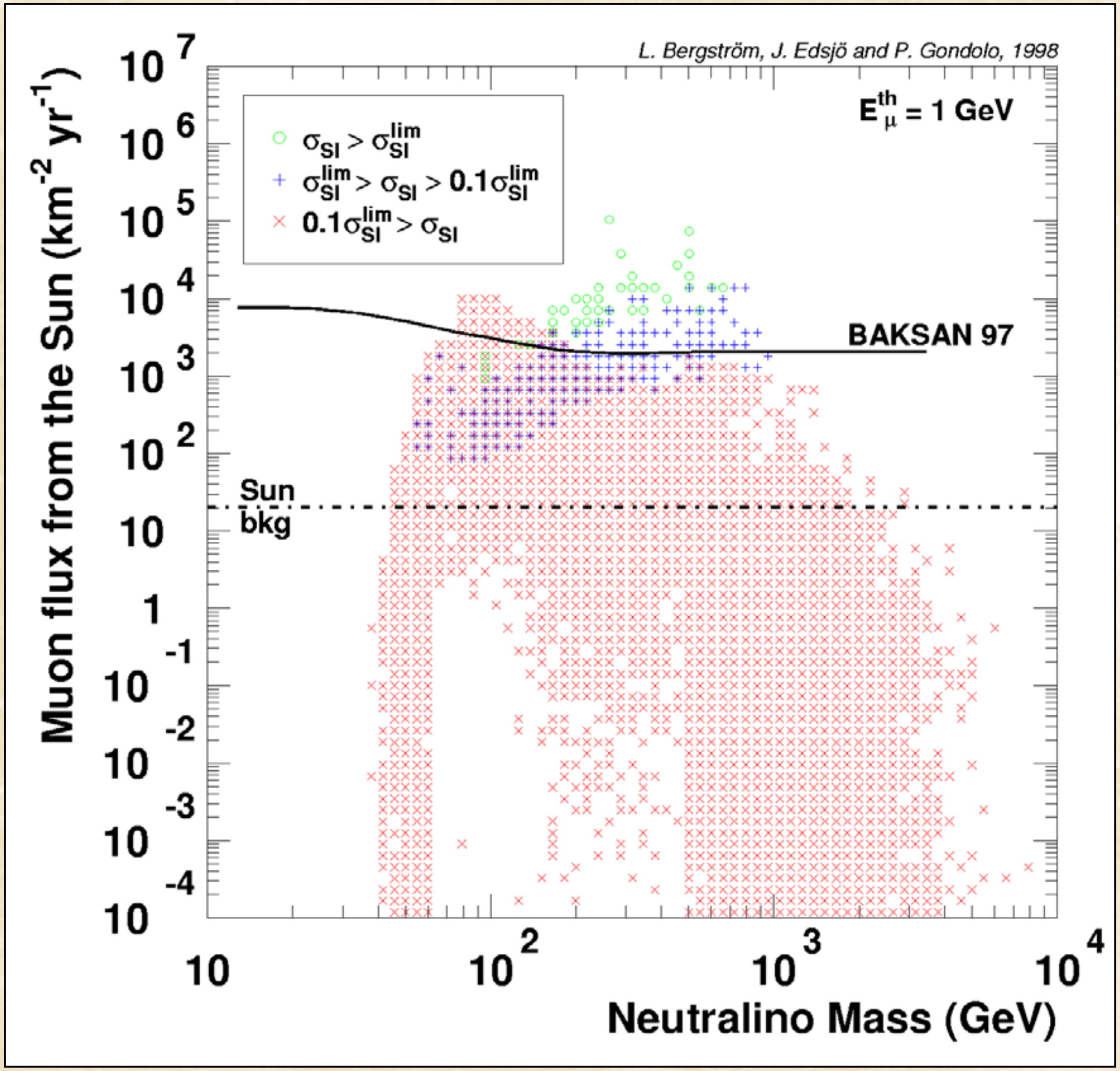
Antares Project

Nestor Project

Baikal 200 PMTs

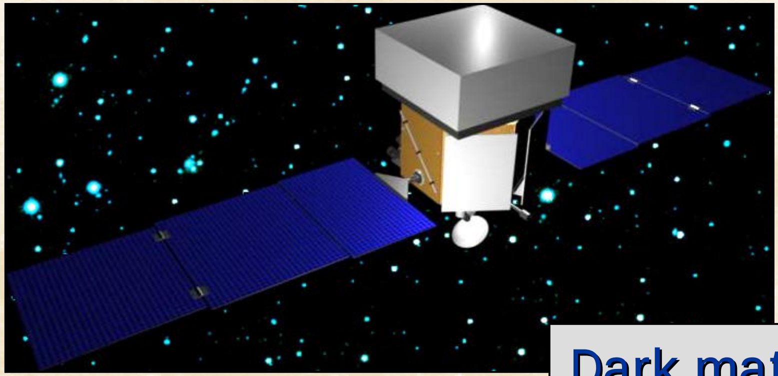
Amanda II, 800 PMTs IceCube Project

Muon Flux from WIMP Annihilation in the Sun



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

Can We See the Dark Matter?



GLAST Project

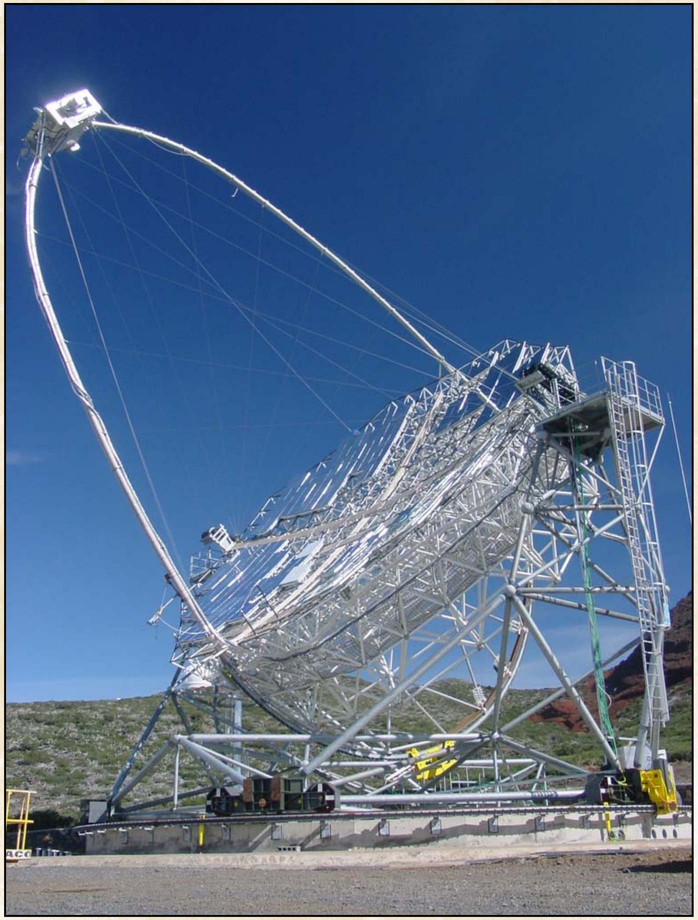
Dark matter particles can directly annihilate

$$\chi\chi \to \gamma\gamma$$

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

HESS airshower telescope, Namibia

MAGIC airshower telescope, La Palma



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	

"LOTS OF THINGS ARE INVISIBLE, BUT WE DON'T KNOW HOW MANY BECAUSE WE CAN'T **SEE** THEM."

(Dennis the Menace® used by permission of Hank Ketcham and ©North America Syndicate)