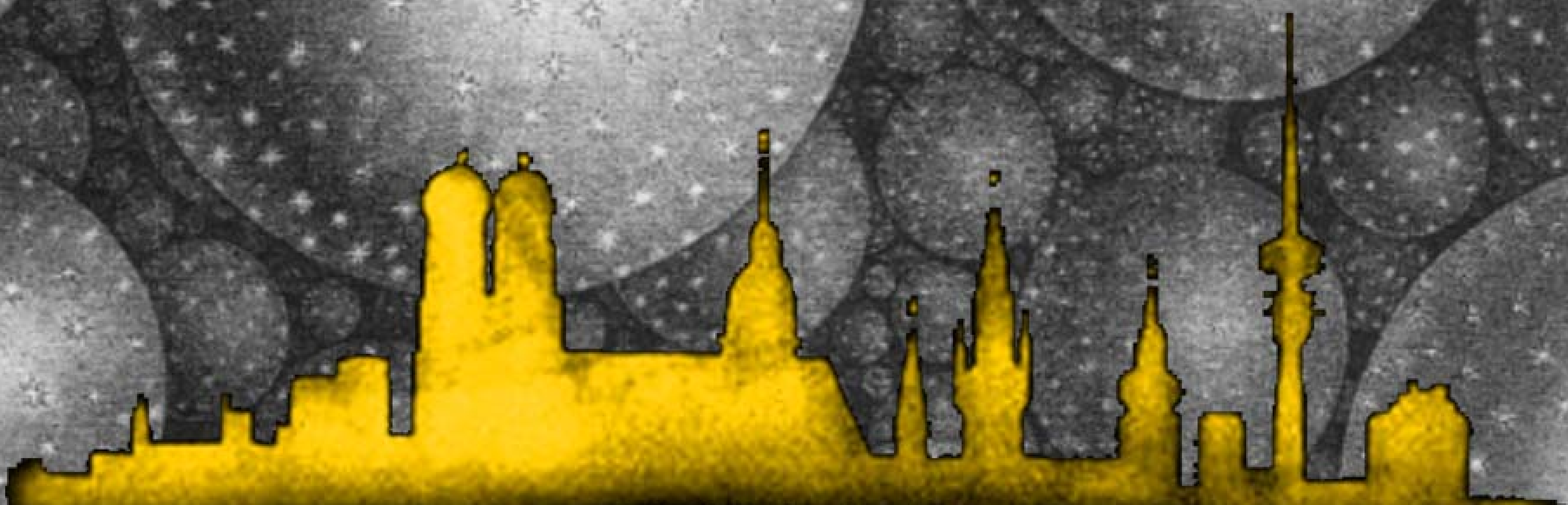
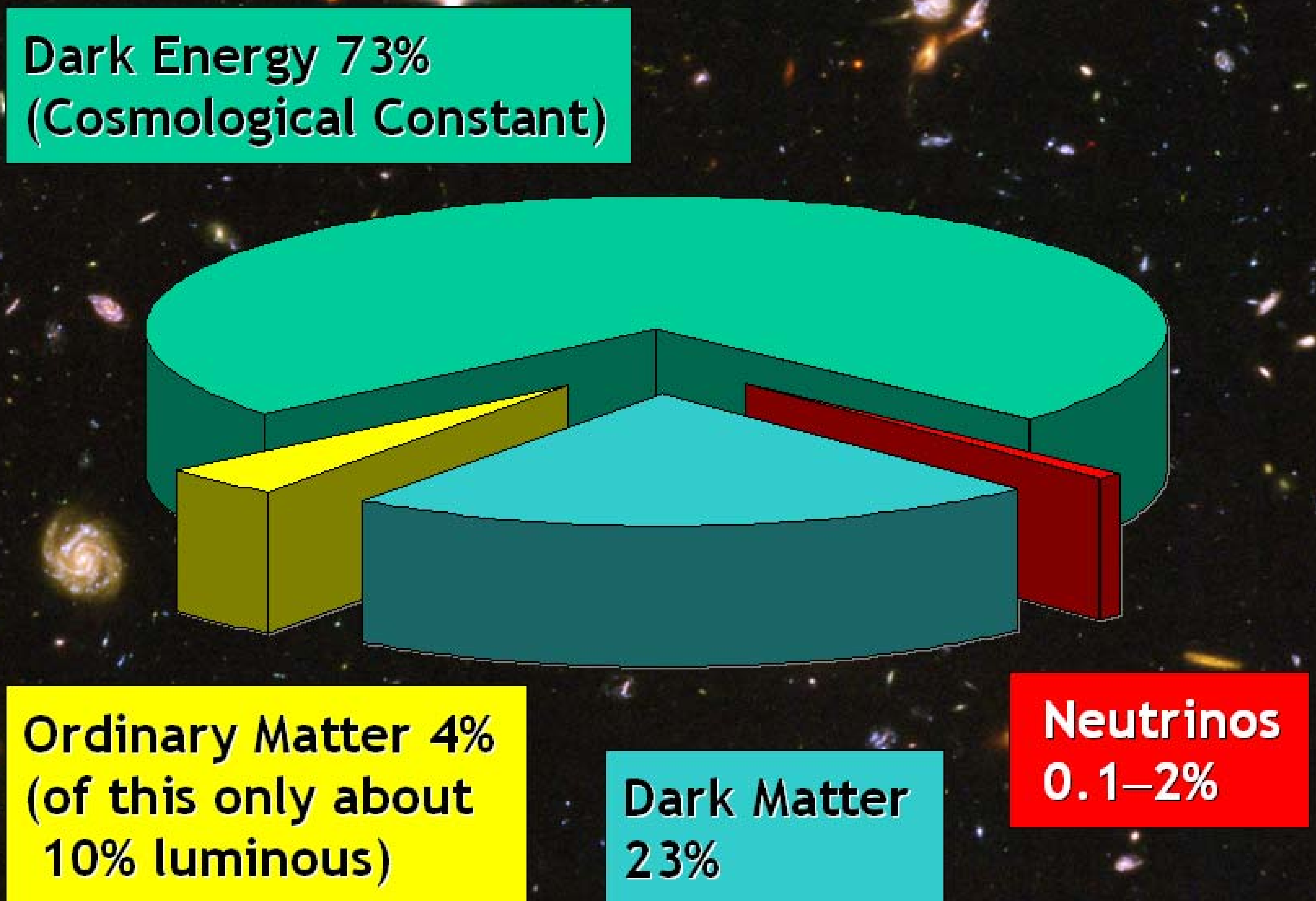
Georg Raffelt, Max-Planck-Institut für Physik, München

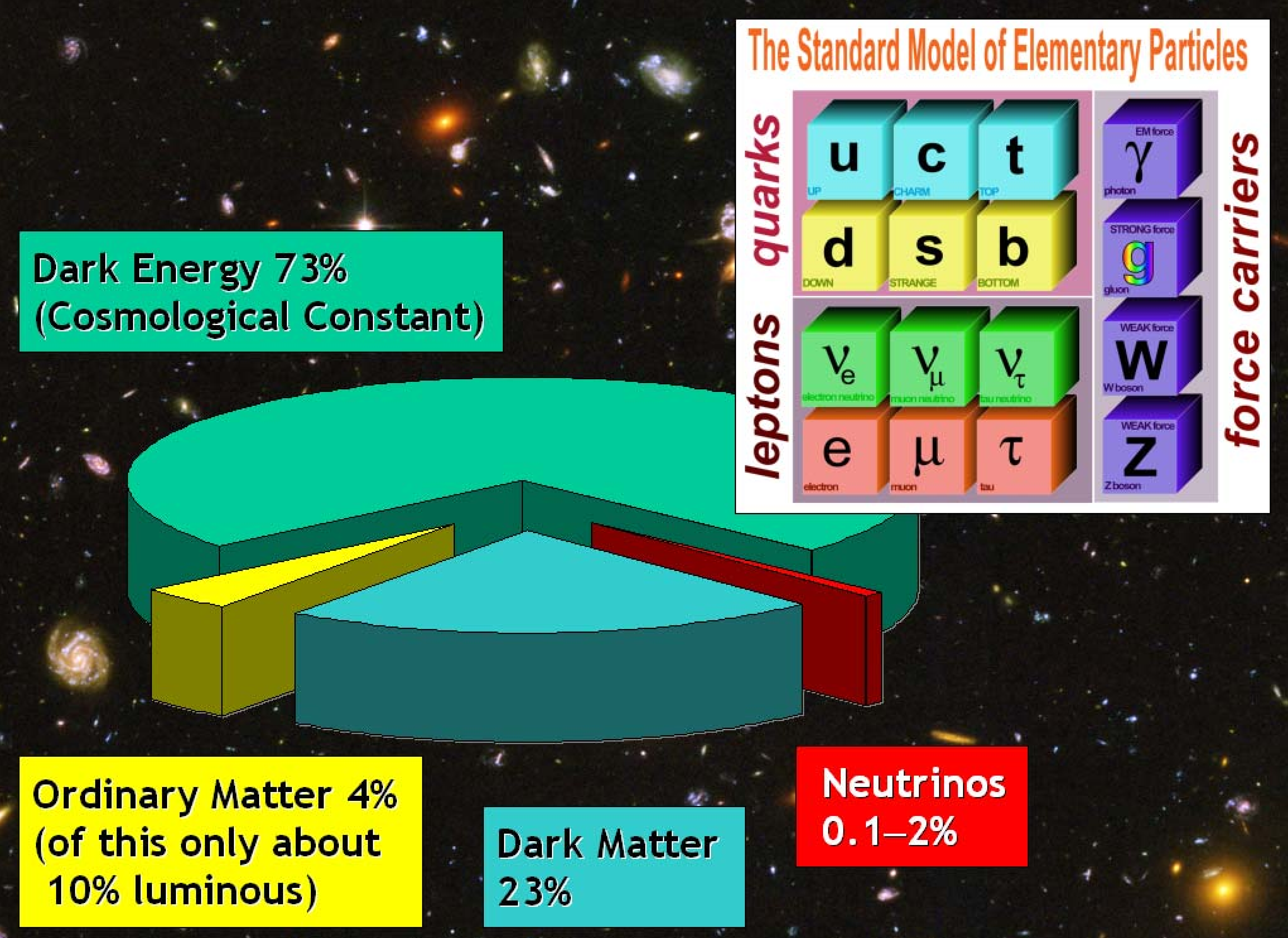
Introduction to the Dark Universe



The Dark Universe in Munich, 6-7 May 2004, Munich, 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%
The Standard Model of Elementary Particles
quarks
u
UP
c
CHARM
t
TOP
d
DOWN
s
STRANGE
b
BOTTOM
leptons
ν_e
electron neutrino
ν_μ
muon neutrino
ν_τ
tau neutrino
e
electron
μ
muon
τ
tau
force carriers
EM force
γ
photon
STRONG force
g
gluon
WEAK force
W
W boson
WEAK force
Z
Z boson

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

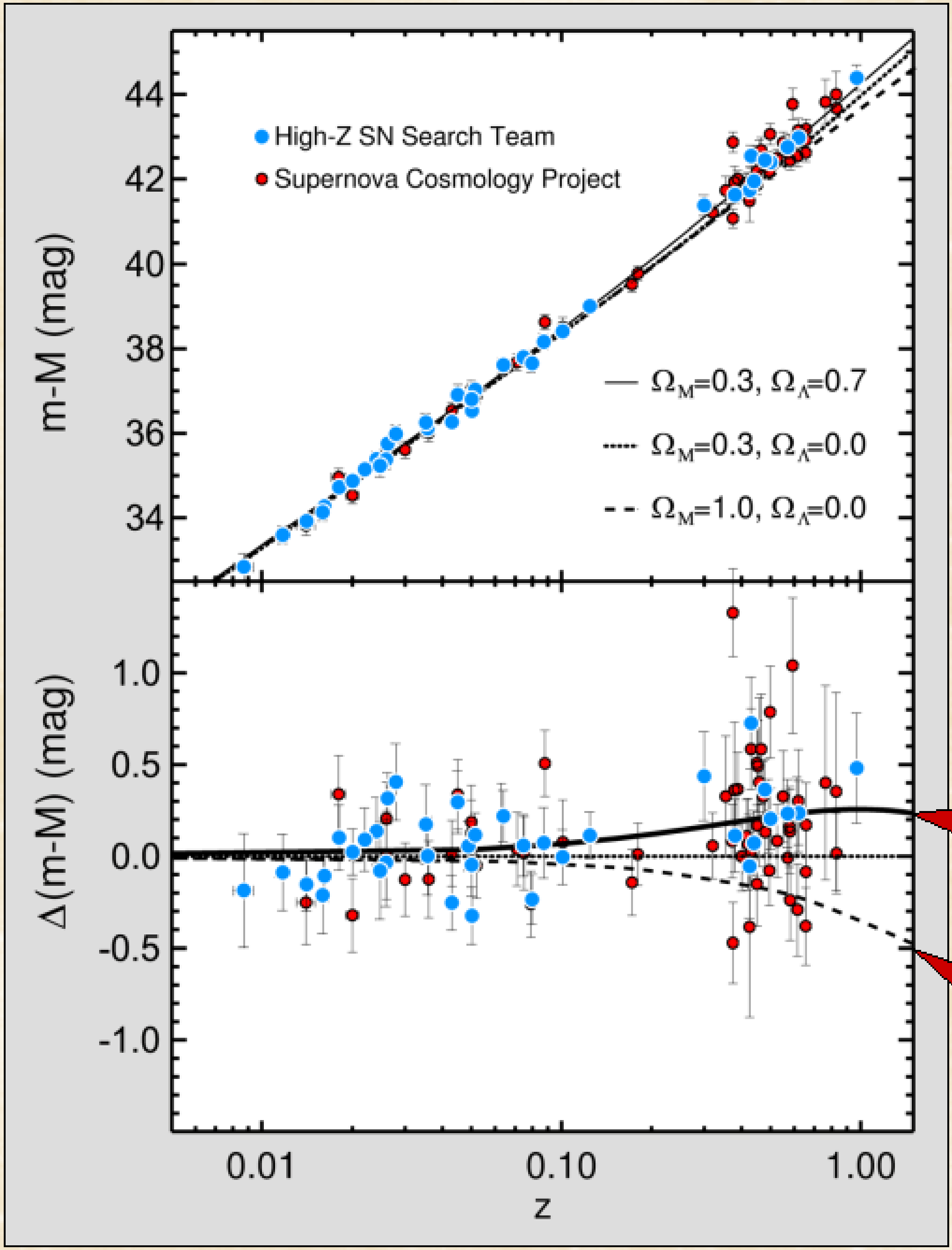
Particle-physics standard model

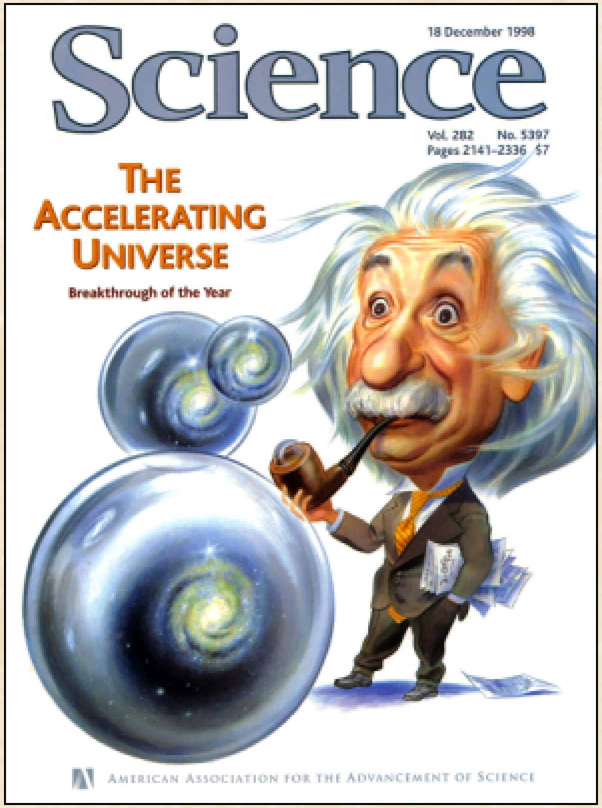
- Violates C and CP
- Violates B and L by EW instanton effects (B – L conserved)

- 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"

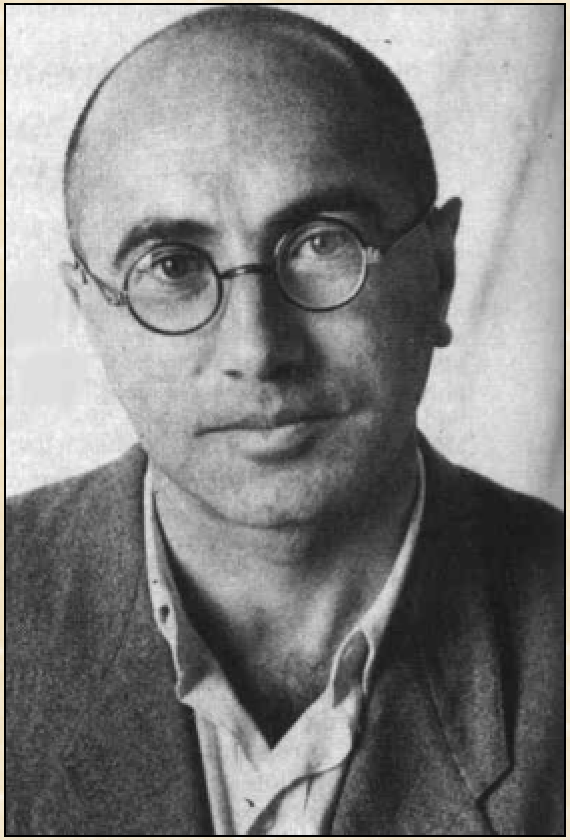
Density of gravitating mass & energy

Newton's constant

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

Friedmann equation for
Hubble's expansion rate

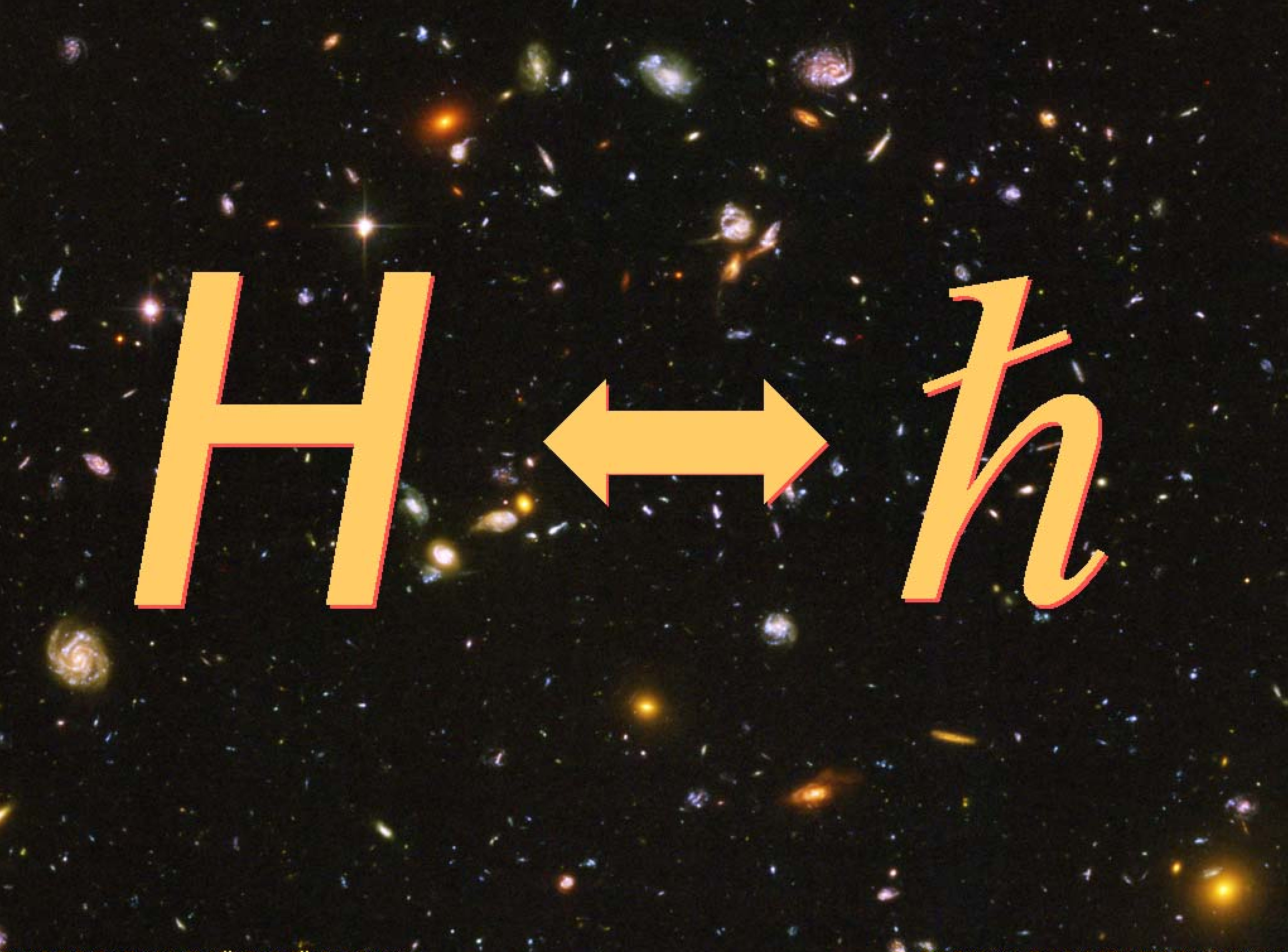
$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G_N}{3}\rho - \frac{k}{a^2} + \frac{\Lambda}{3}$$



Yakov
Borisovich
Zeldovich
1914-1987

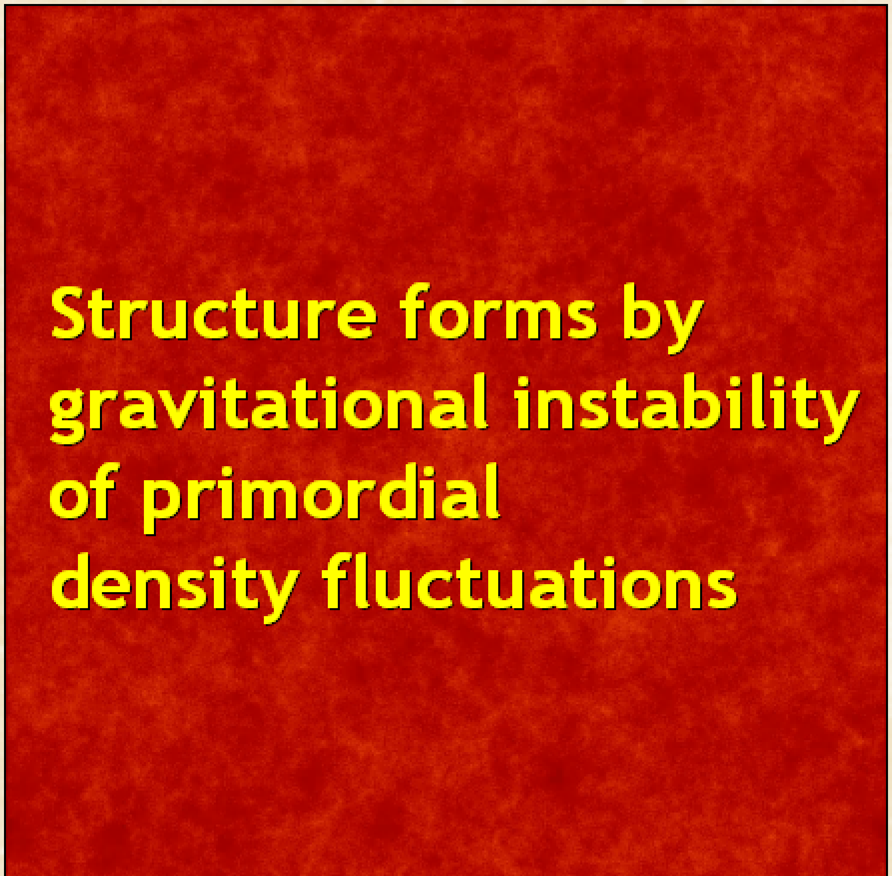
Cosmological constant Λ
(new constant of nature)
allows for a static universe
by "global anti-gravitation"

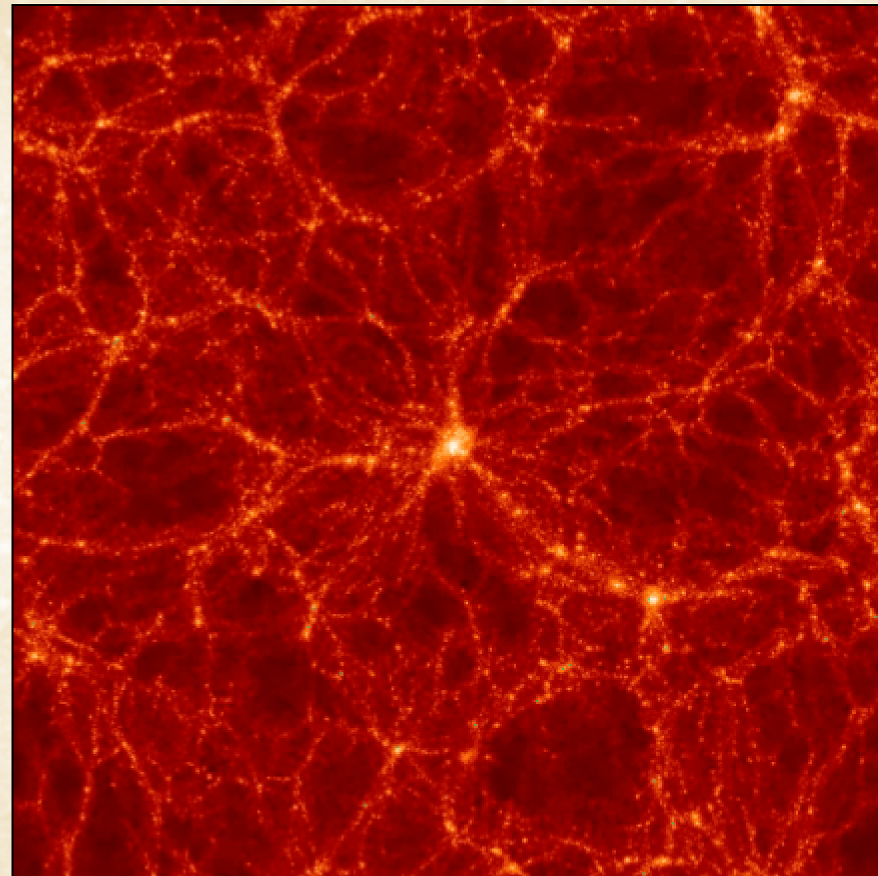
- Quantum field theory of elementary particles inevitably implies vacuum fluctuations because of Heisenberg's uncertainty relation, e.g. E and B fields can not simultaneously vanish
- Ground state (vacuum) provides gravitating energy
- Vacuum energy ρ_{vac} is equivalent to Λ


$H \leftrightarrow \hbar$

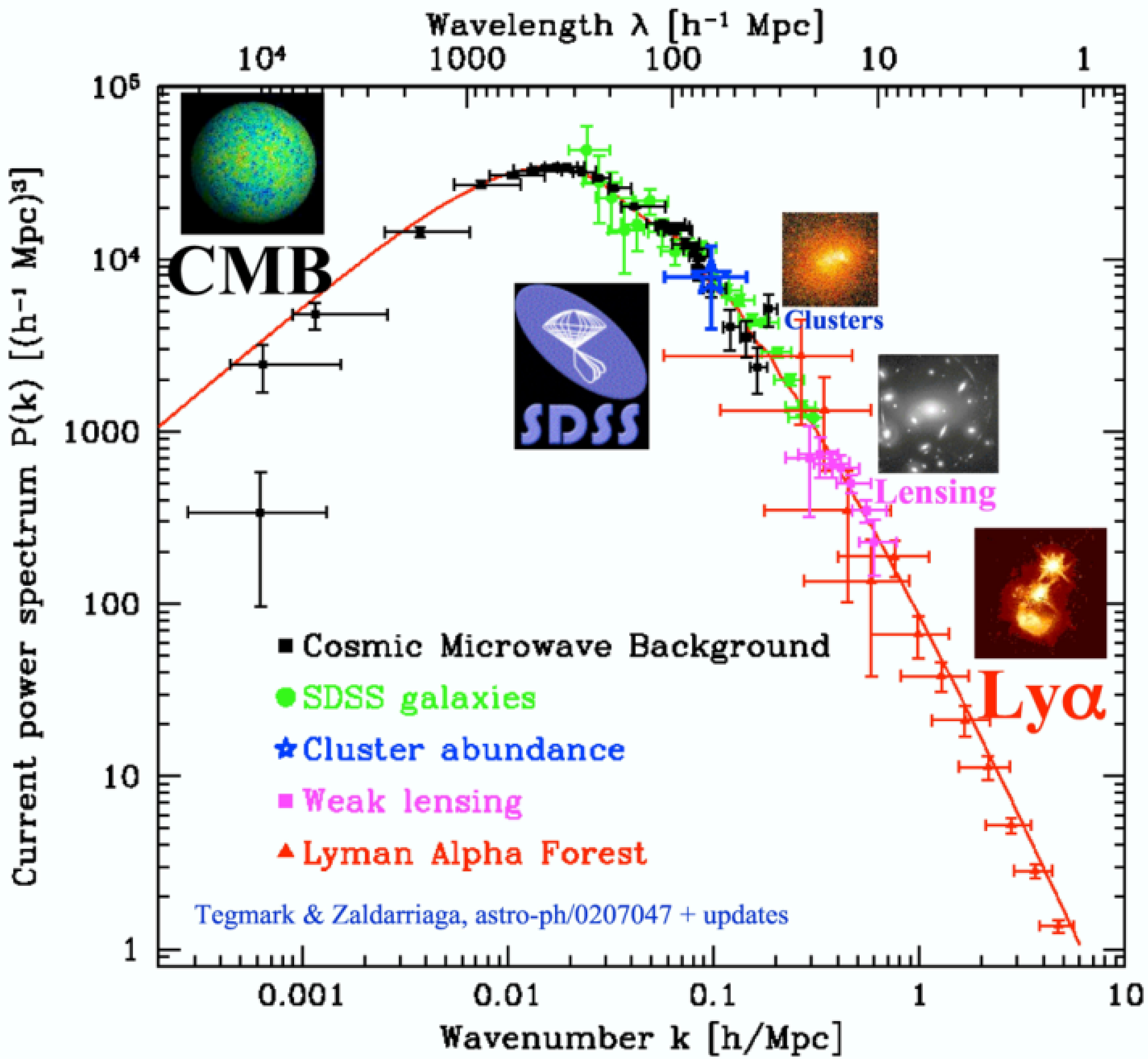
Formation of Structure

Smooth	Structured



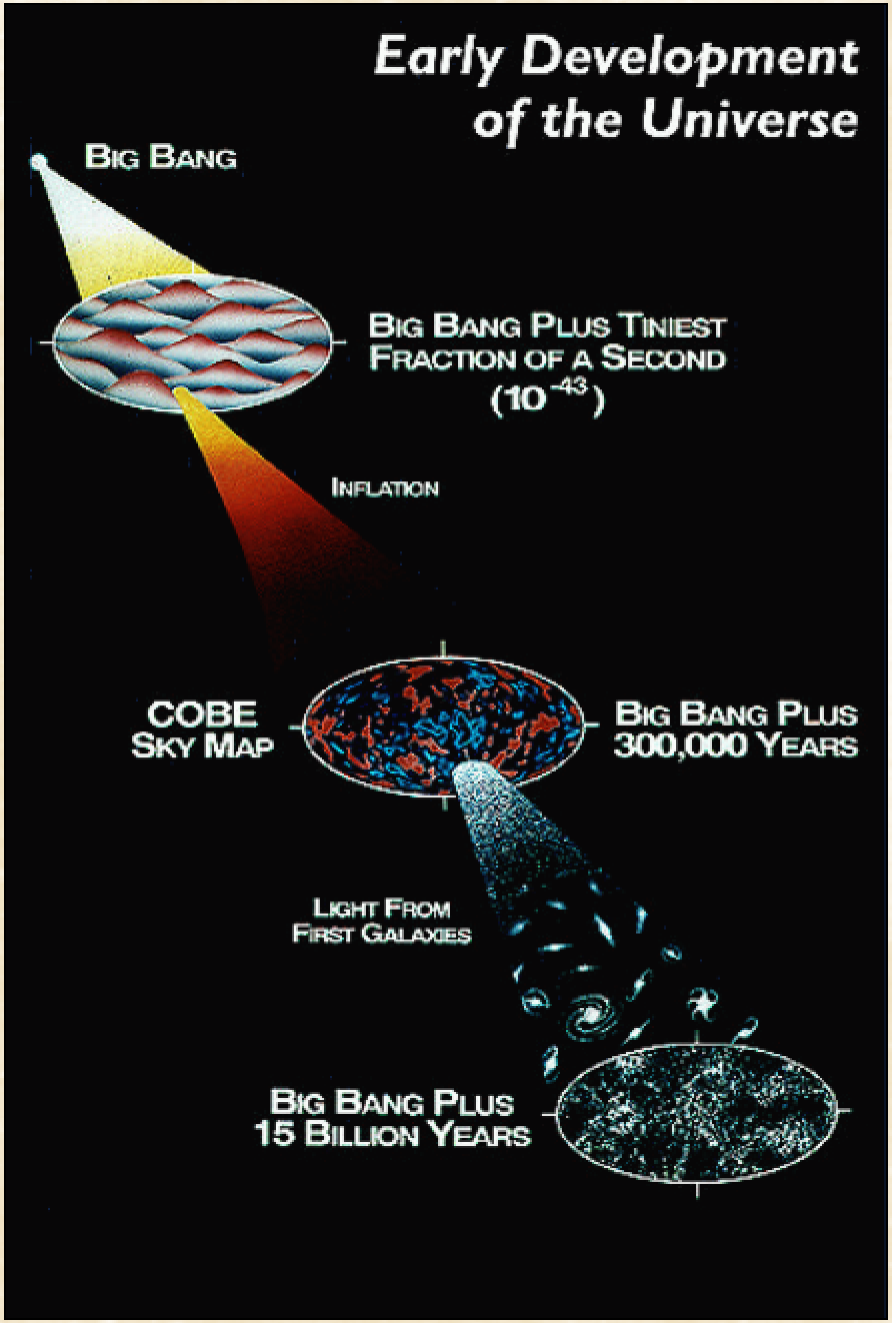


Power Spectrum of Cosmic Density Fluctuations



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

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

Weakly Interacting Particles as Dark Matter

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

GRAVITY OF NEUTRINOS OF NONZERO MASS IN ASTROPHYSICS

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

ABSTRACT

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

Subject headings: cosmology — galaxies, clusters of — neutrinos

The possibility of a finite rest mass for the neutrinos has fascinated astrophysicists (Kuchowicz 1969). A recent discussion of such a possibility has been in the context of the solar-neutrino experiments (Bahcall, Cabibbo, and Yahil 1972). Here we wish to point out some interesting consequences of the gravitational interactions of such neutrinos. These considerations become particularly relevant in the framework of big-bang cosmologies which we assume to be valid in our discussion here.

In the early phase of such a Universe when the temperature was ~ 1 MeV, several processes of neutrino production (Ruderman 1969) would have led to copious production of neutrinos and antineutrinos (Steigman 1972; Cowsik and McClelland 1972). Conditions of thermal equilibrium allow an easy estimate of their number densities (Landau and Lifshitz 1969):

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

Here $n_{\nu i}$ = number density of neutrinos of the ith kind (notice that in writing this expression we have assumed that both the helicity states are allowed for the neutrinos because of finite rest mass); $E = c(p^2 + m^2c^2)^{1/2}$; k = Boltzmann's constant; $T(z_{eq}) = T_r(z_{eq}) = T_\nu(z_{eq}) = T_e(z_{eq}) \cdots =$ the common temperature of radiation, neutrinos, electrons, etc., at the latest epoch characterized by redshift z_{eq} when they may be assumed to have been in thermal equilibrium; $kT(z_{eq}) \simeq 1$ MeV.

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

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

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

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

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

7

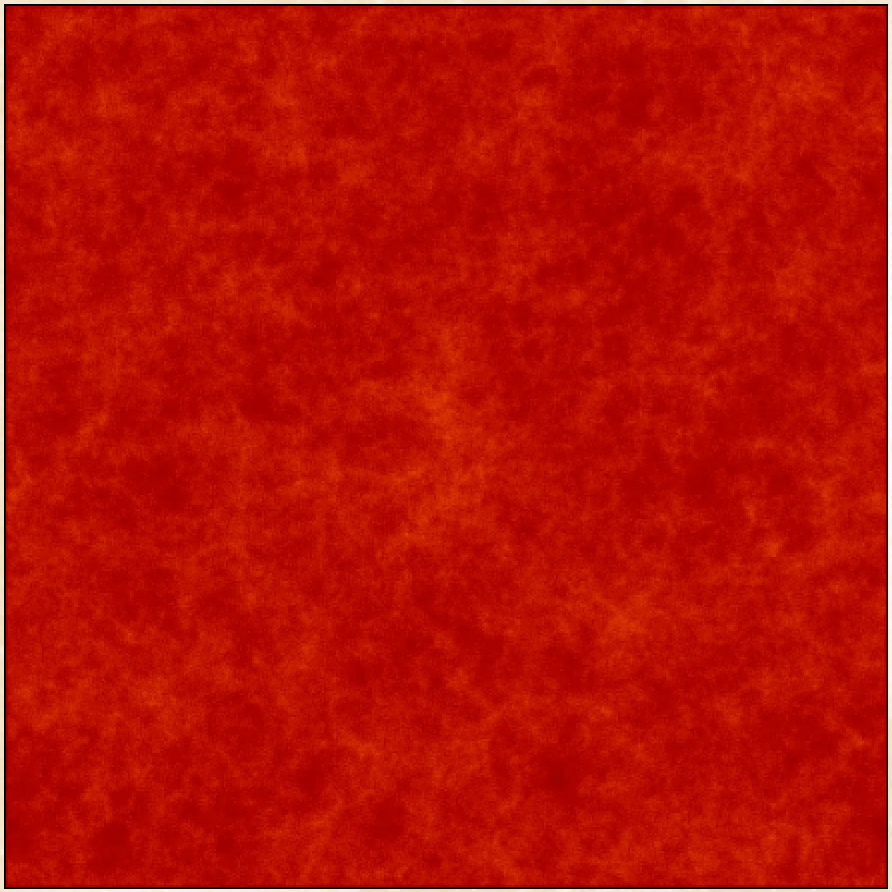
More than 30 years ago, beginnings of the idea of weakly interacting particles (neutrinos) as dark matter

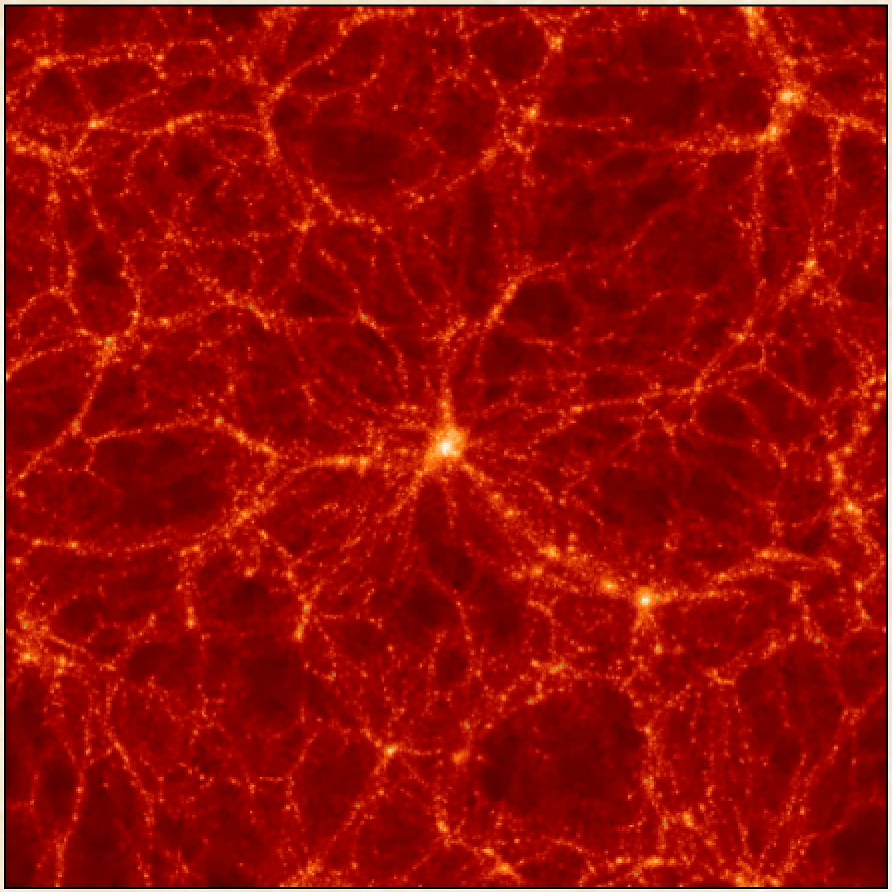
Massive neutrinos are no longer a good candidate (hot dark matter)

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

Formation of Structure

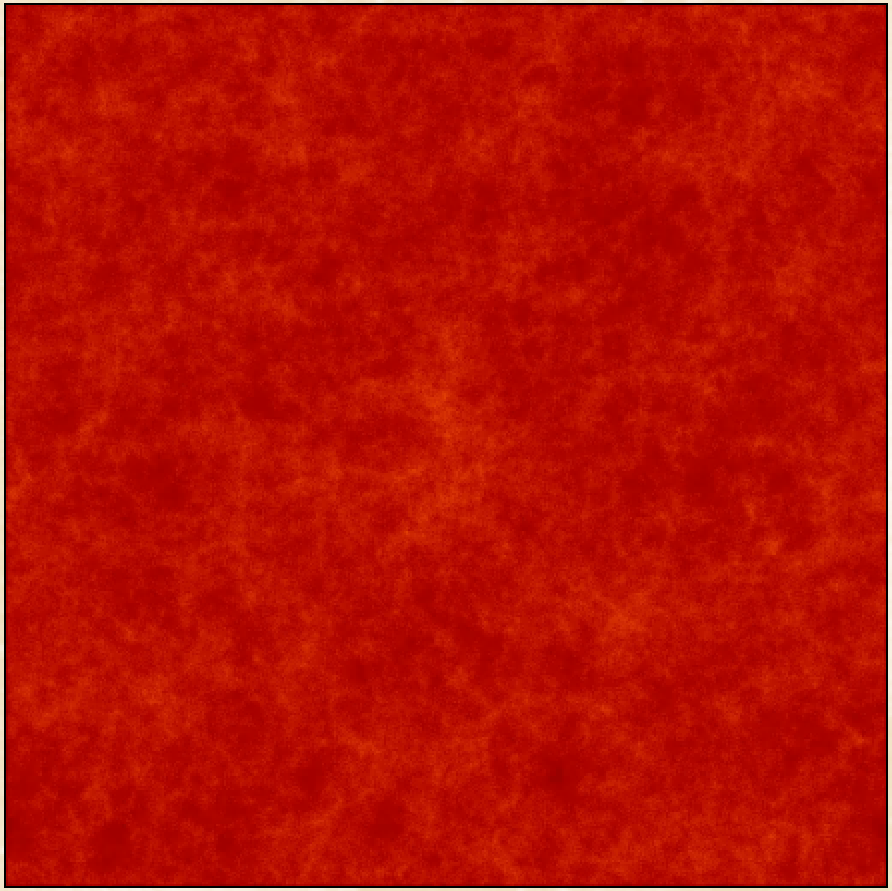
Smooth → **Structured**

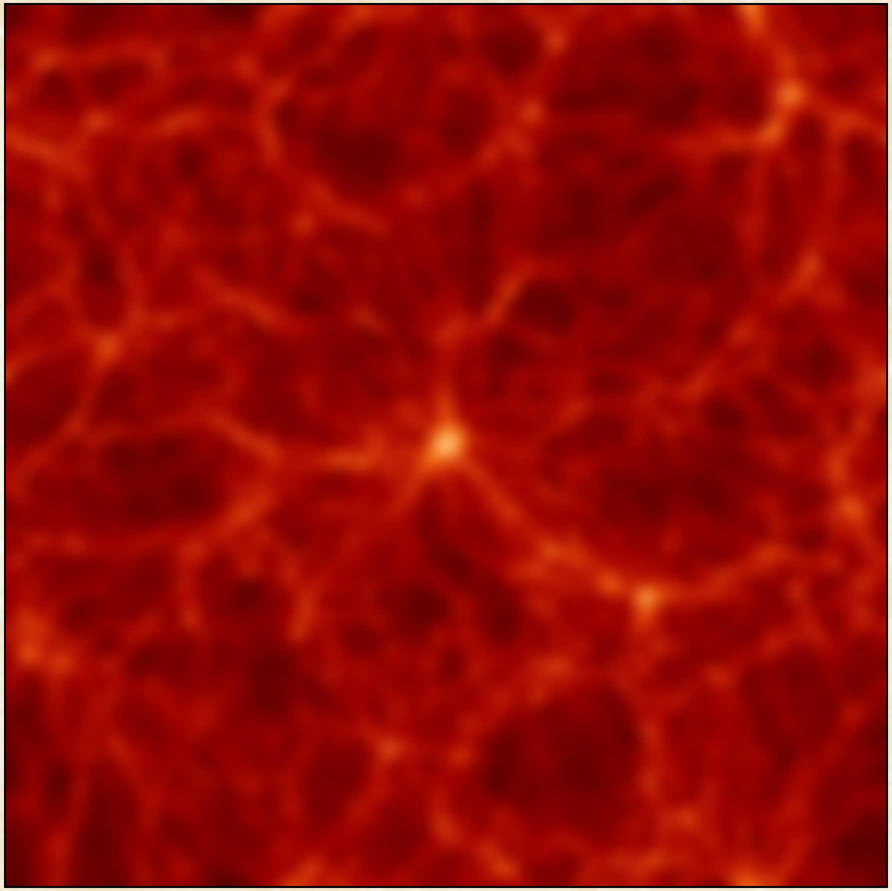




Formation of Structure

Smooth → Structured





A fraction of hot dark matter suppresses small-scale structure

Neutrino Mass Limits from Large-Scale Structure

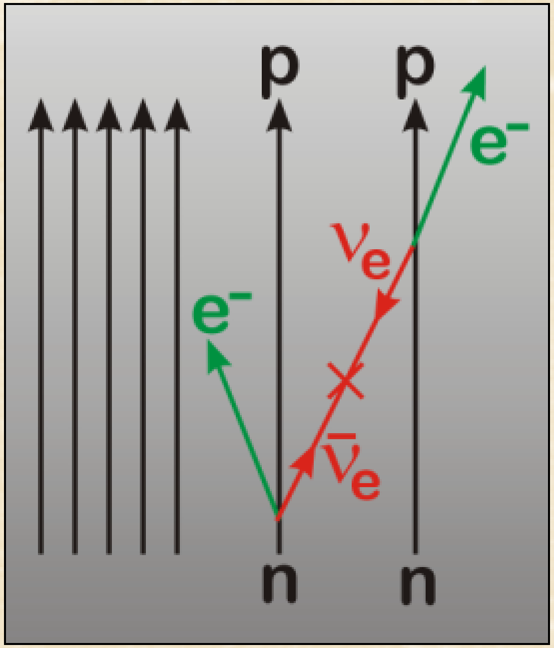
Statistical 95% C.L. limits depend on used data and on priors for other parameters. For detailed analyses see

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

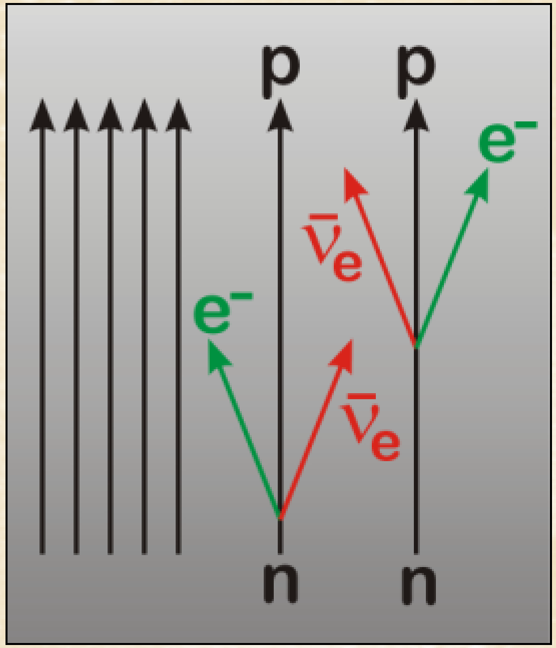
$\Sigma m_\nu < 2.1$ eV	2dF (Galaxy-galaxy correlation) + WMAP (Cosmic microwaves)
$\Sigma m_\nu < 1.2$ eV	+ Small-scale CMBR (breaks degeneracy with bias)
$\Sigma m_\nu < 1.0$ eV	+ Priors (1σ) $h = 0.72 \pm 0.08$, $\Omega_M = 0.28 \pm 0.14$

Neutrinoless ββ Decay

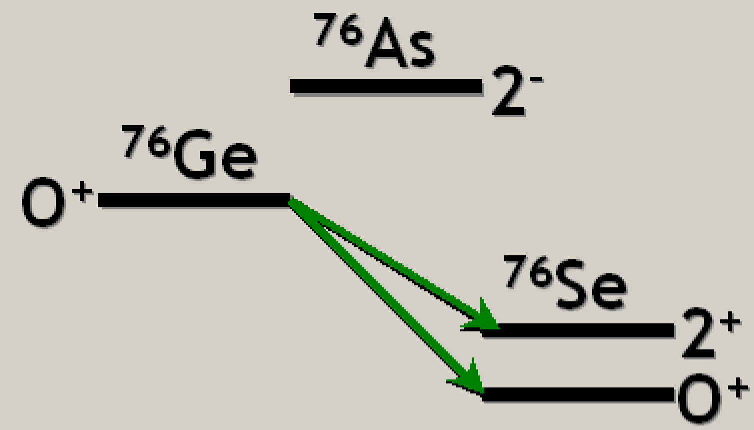
0ν mode, enabled by Majorana mass



Standard 2ν mode



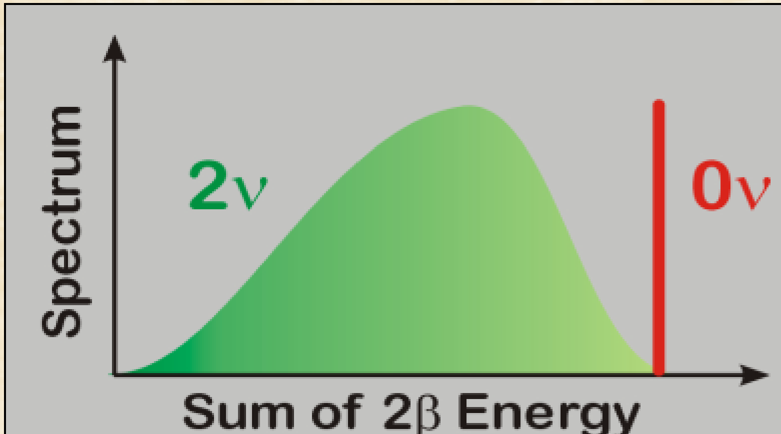
Some nuclei decay only by the ββ mode, e.g.



Half life ~ 10^{21} yr

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

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



Improved Evidence for 0ν2β Decay

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

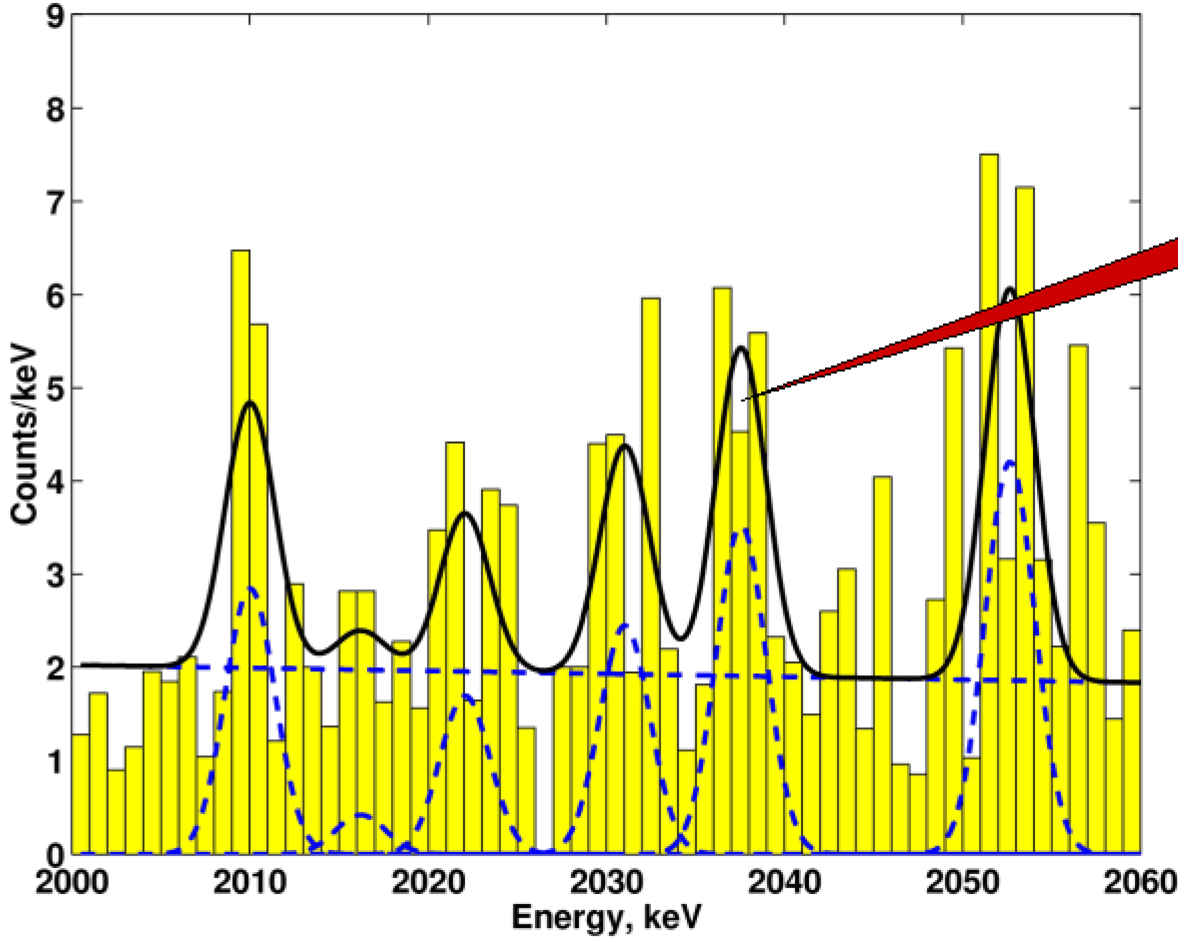


Fig. 31. The single site sum spectrum of the four detectors 2,3,4,5 for the period November 1995 to May 2003 (51.389 kg y), and its fit (see section 3), in the range 2000 - 2060 keV.

Possible evidence for 0ν2β line now ~ 4σ

Leptogenesis by Majorana Neutrino Decays

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

Cosmological evolution

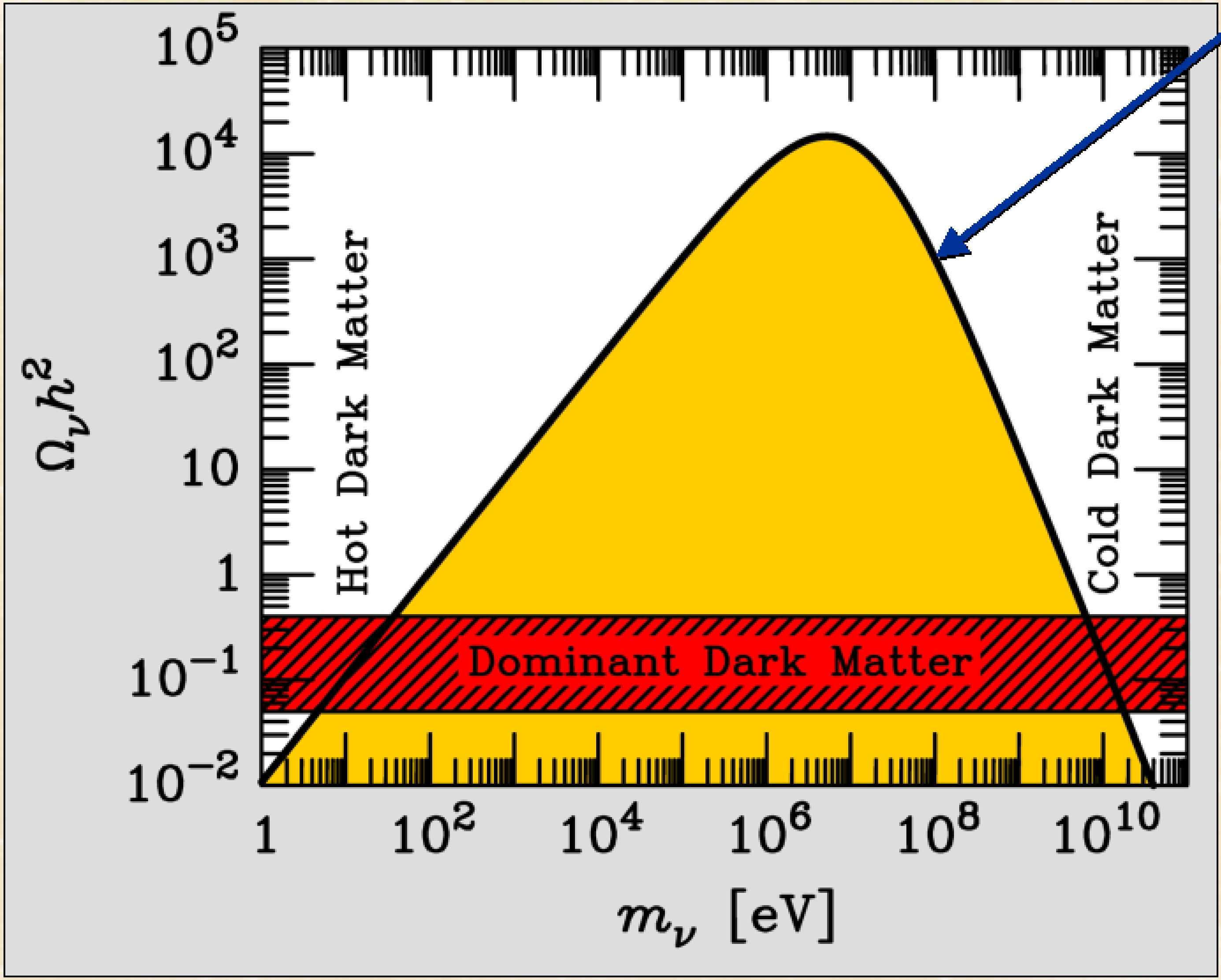
- B = L = 0 early on
- Thermal freeze-out of heavy Majorana neutrinos
- Out-of-equilibrium CP-violating decay creates net L
- Shift L excess into B by sphaleron effects

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

Requires Majorana neutrino masses below 0.1 eV

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

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

The WIMP miracle:
Typical gauge couplings and masses of order the electroweak scale
→ roughly DM density

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

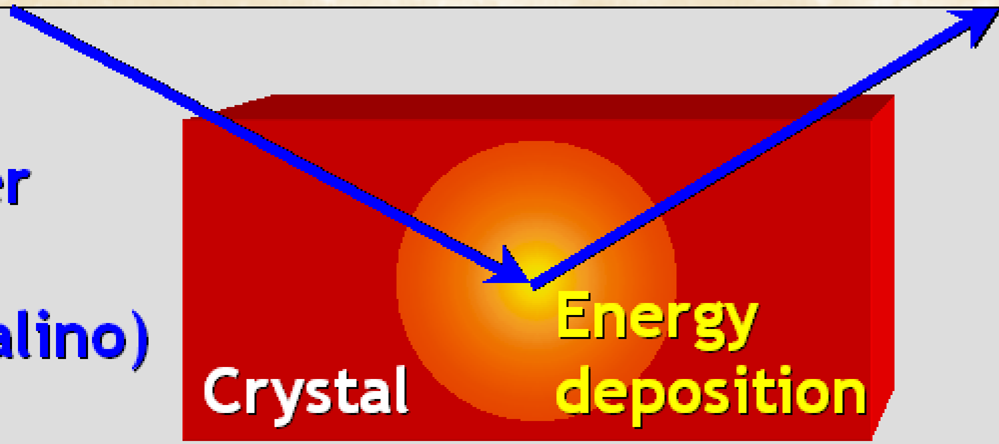
- If R-Parity is conserved, the lightest SUSY-particle (LSP) is stable
- Most plausible candidate for dark matter is the neutralino, similar to a massive Majorana neutrino

Neutralino = C_1 Photino + C_2 Zino + C_3 Higgsino

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

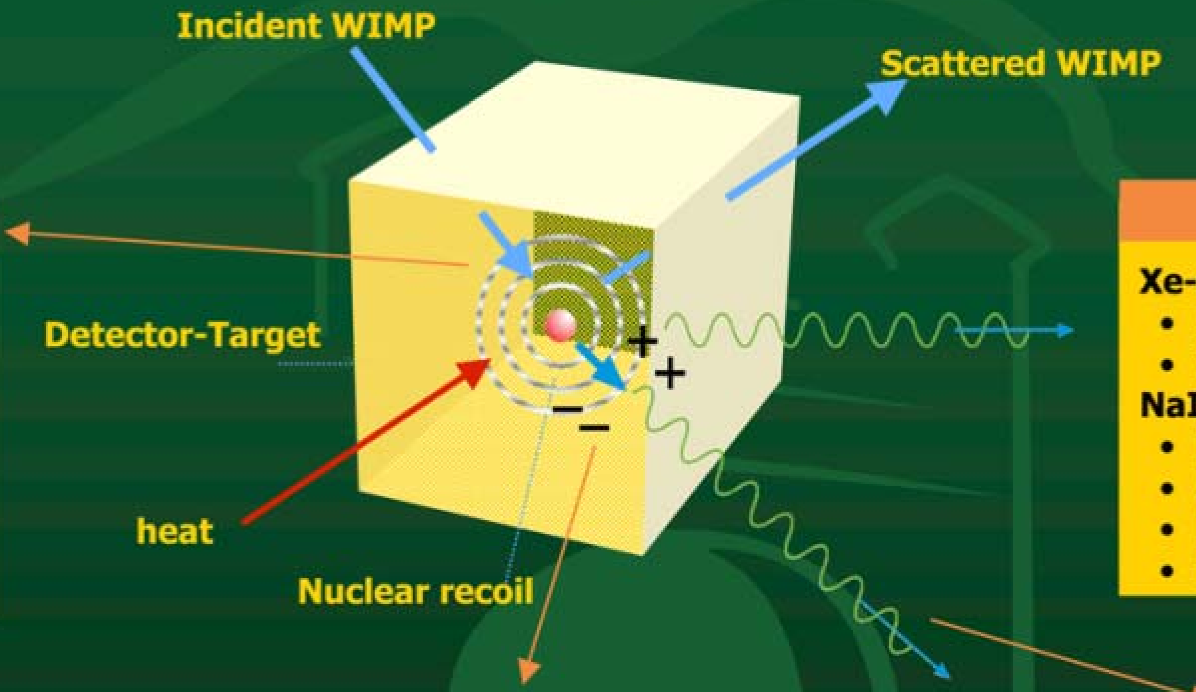
PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

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

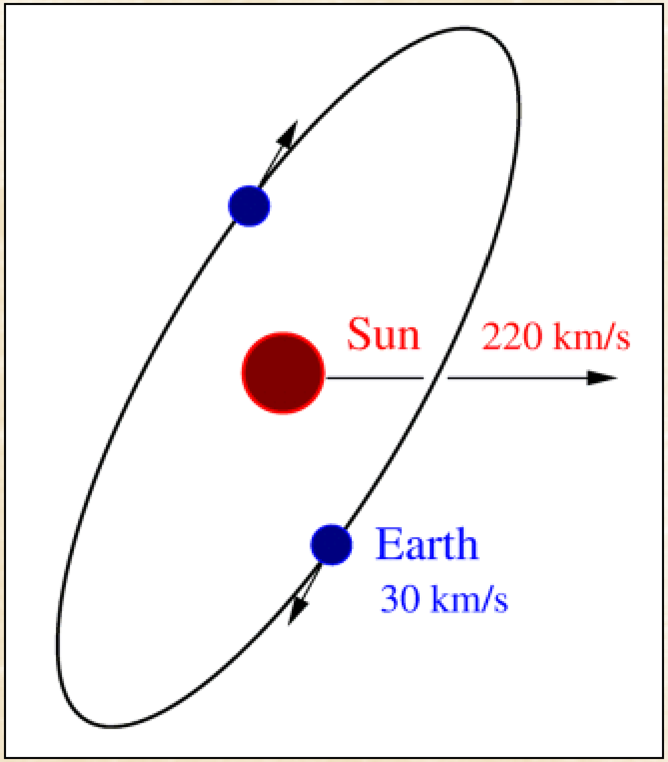
Ge-experiments:
- H/M
- IGEX
- GENIUS-TF

Tracking Chambers:
- DRIFT

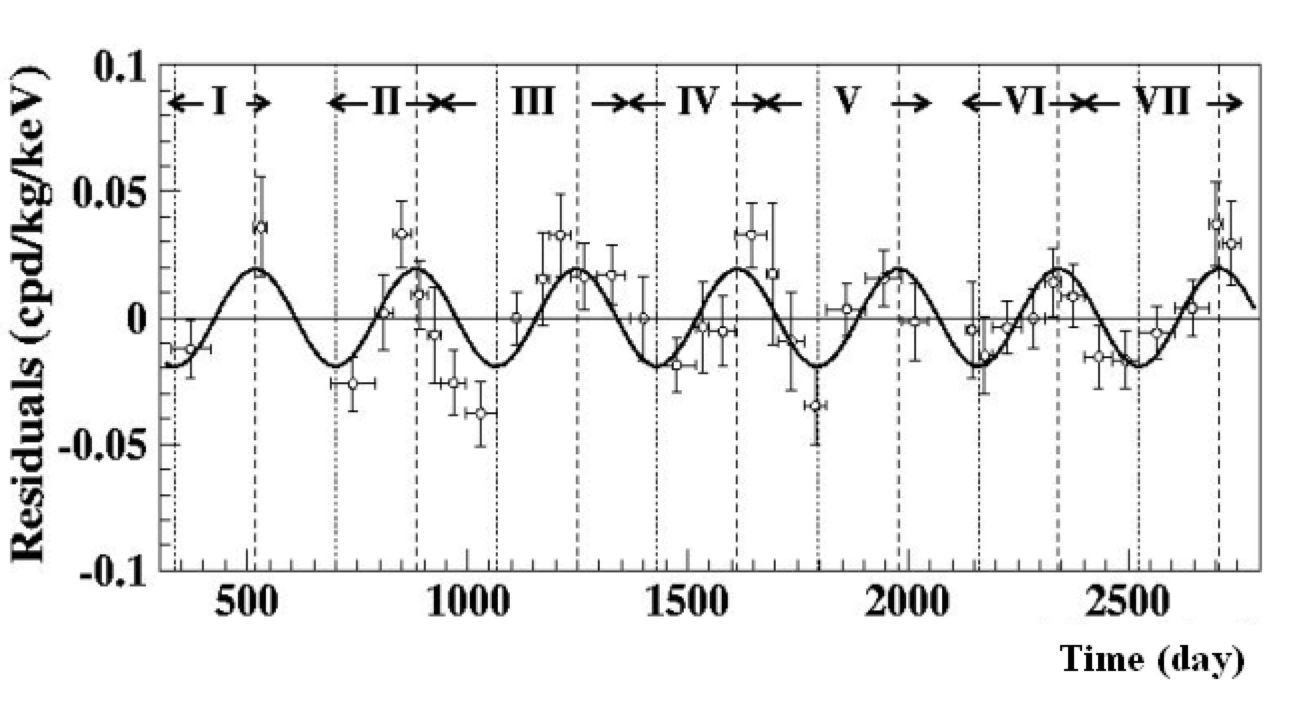
HEAT+LIGHT
- ROSEBUD-II
- CRESST-II

LIGHT+CHARGE
- ZEPLIN-II
- X-MASS

DAMA Evidence for WIMP Detection



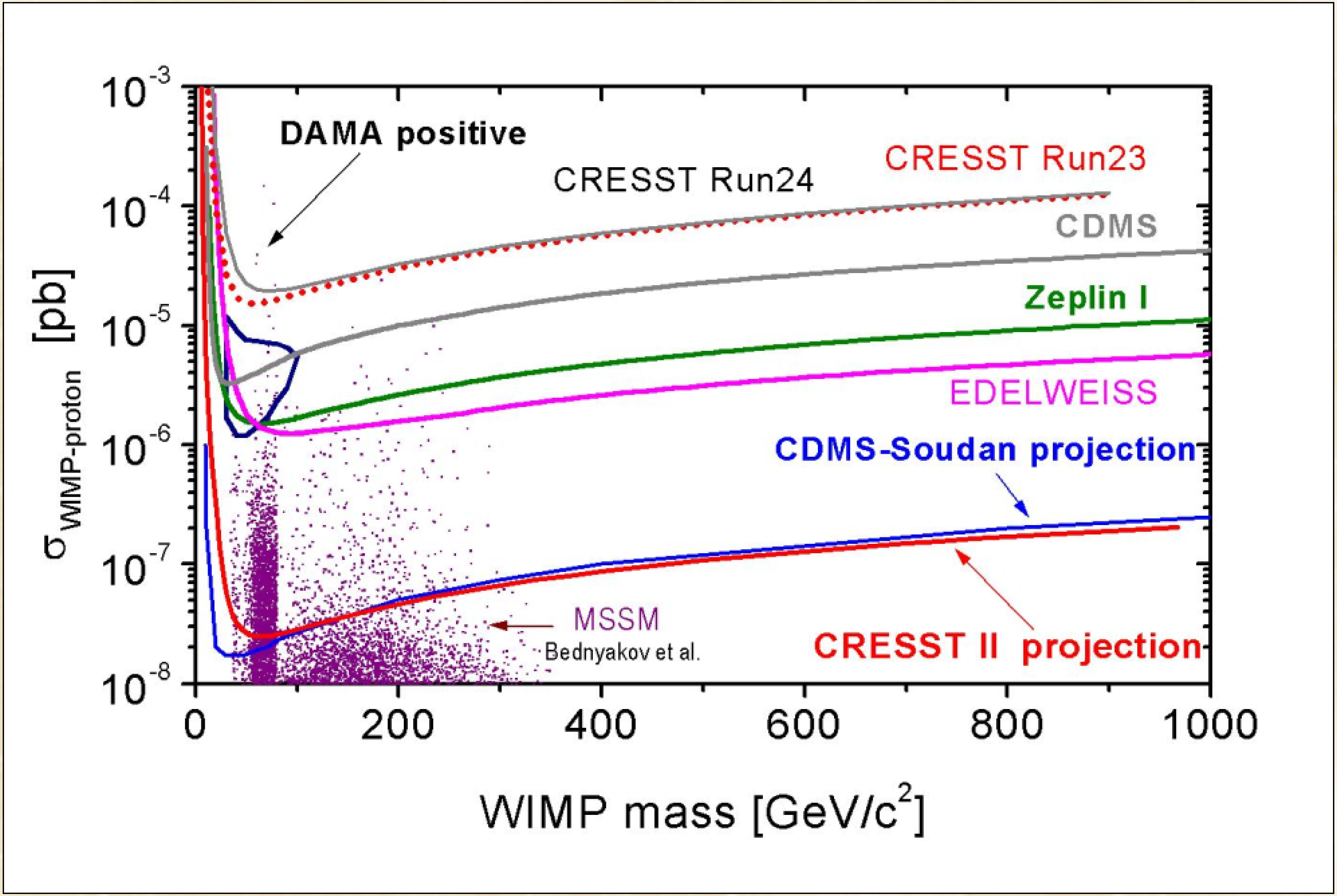
DAMA experiment in Gran Sasso (NaI scintillation detector) observes an annual modulation at a 6.3σ statistical CL, based on 110 ton-days of data [Riv. N. Cim. 26 (2003) 1–73]



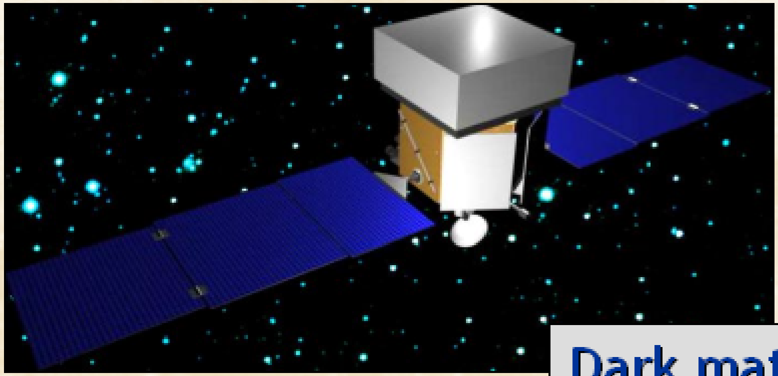
Annual modulation of WIMP signal a "smoking gun" signature

- Detector stability ?
- „Background stability" ?

Projected WIMP Sensitivities



Can We See the Dark Matter?



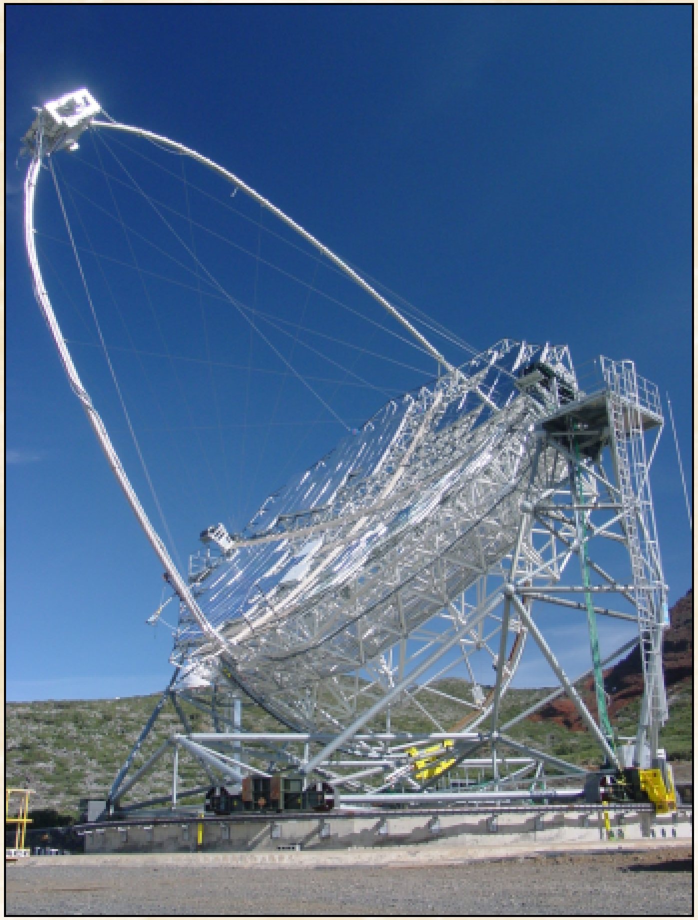
GLAST Project

Dark matter particles can directly annihilate

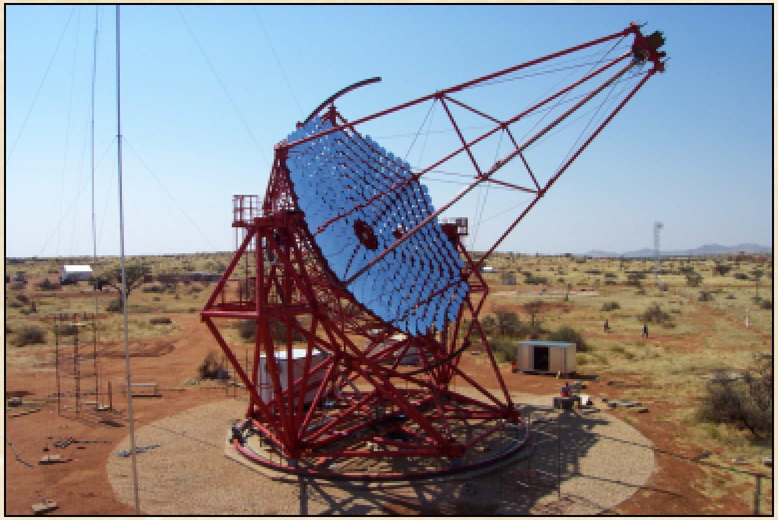
$$\chi\chi \to \gamma\gamma$$

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

MAGIC airshower telescope, La Palma

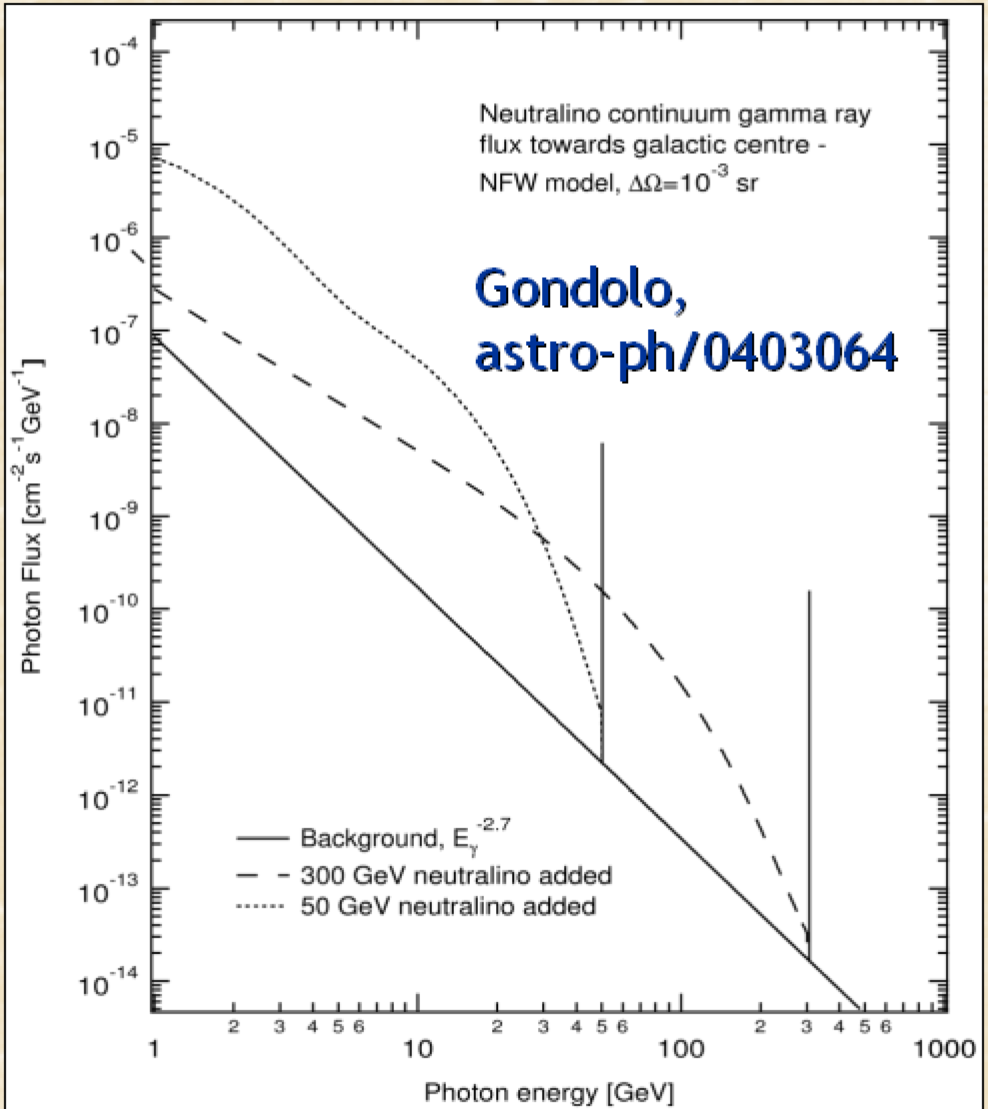


HESS airshower telescope, Namibia



High-Energy Gamma Rays from Neutralino Annihilation

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



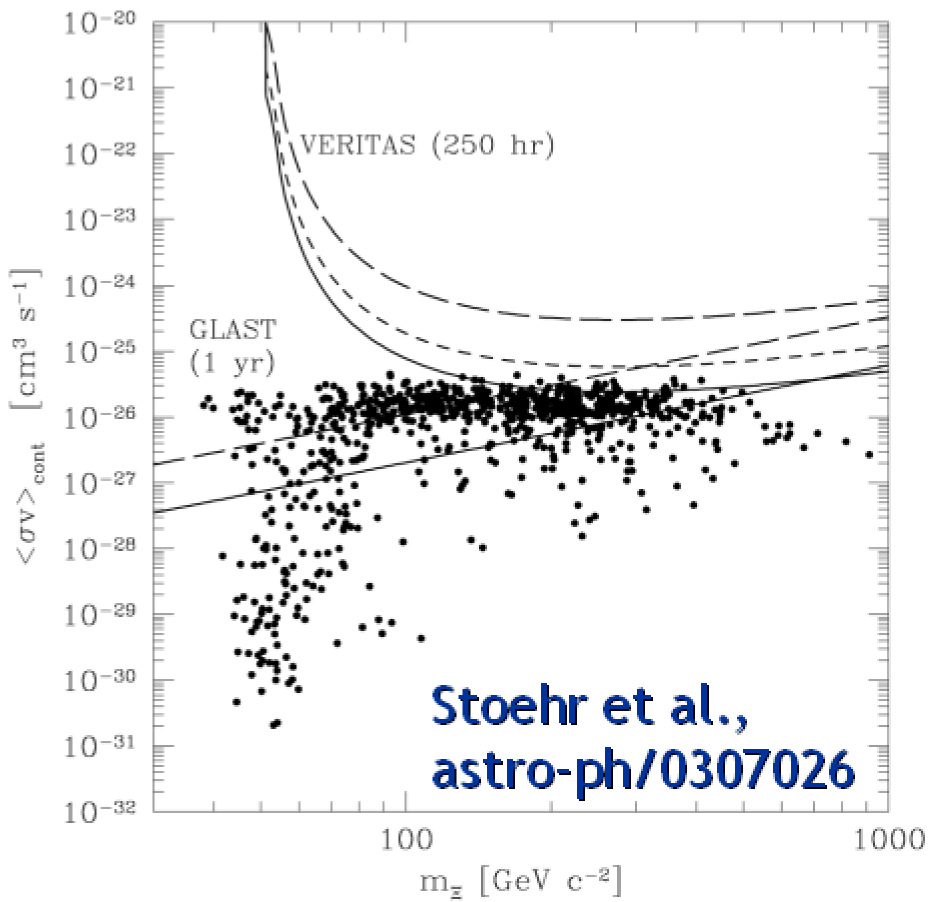


Figure 8. MSSM models of cosmological interest (dots) and 3-σ detection limits for VERITAS and GLAST. For VERITAS the limits are shown for a pointing at the centre of the Milky Way, assuming an NFW profile (solid) and an SWTS profile (short dashes). The lower solid line gives estimated limits for GLAST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

TeV Gammas from the Galactic Center

Whipple (astro-ph/0403422)

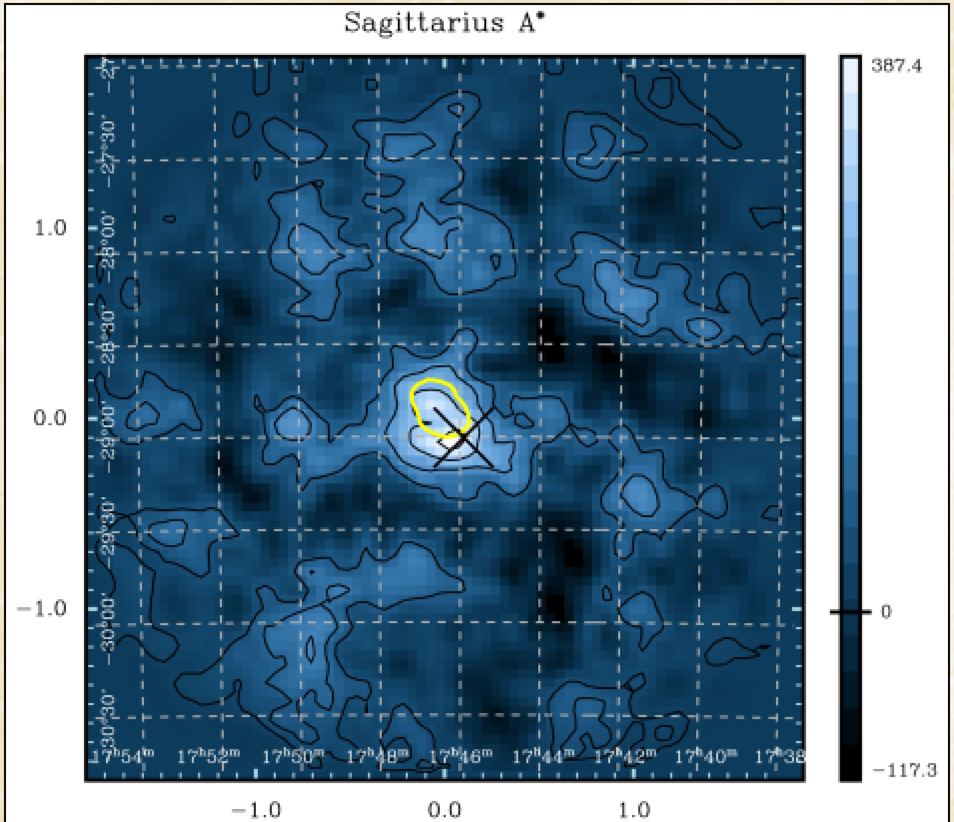


Fig. 3.— A gamma-ray image of the region around Sgr A*. The image is of excess counts with overlaid significance contours (1 standard deviation per contour). The axes are labeled in degrees from the assumed camera center. The true center position of the camera, which is not exactly at (0,0) due to flexing of the telescope at low elevation, is marked with a cross. The dashed lines are the RA and Dec contours at this position. Also shown (as a light contour) is the 99% confidence region for the EGRET observations (Hooper & Dingus 2002).

CANGAROO-II (astro-ph/0403592)

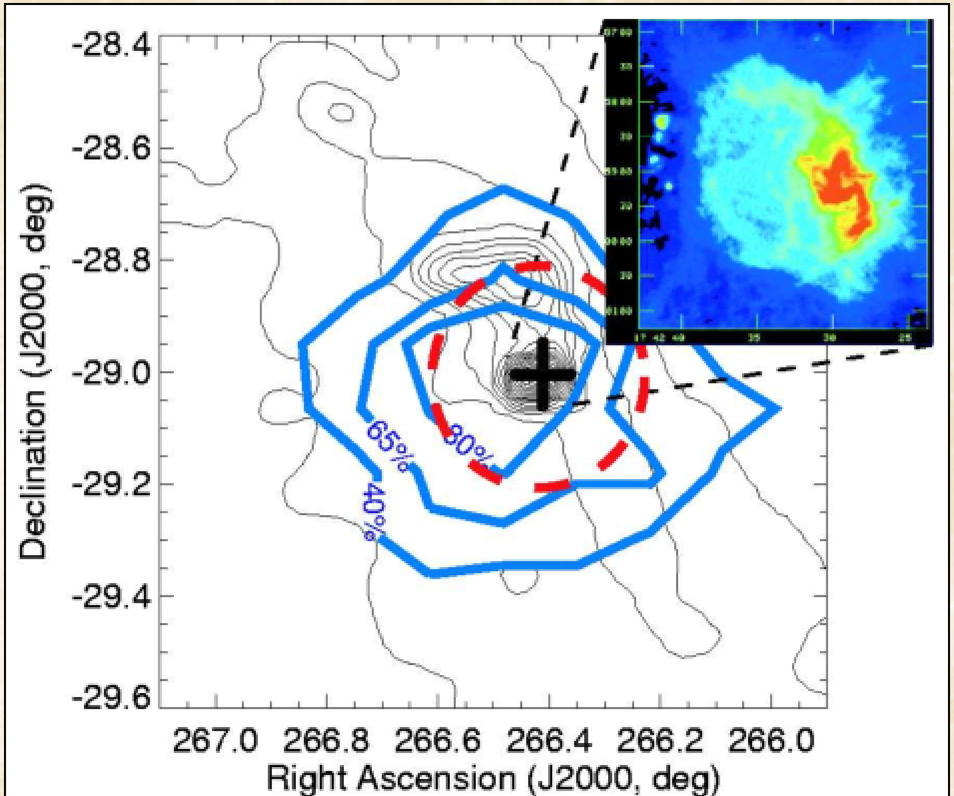


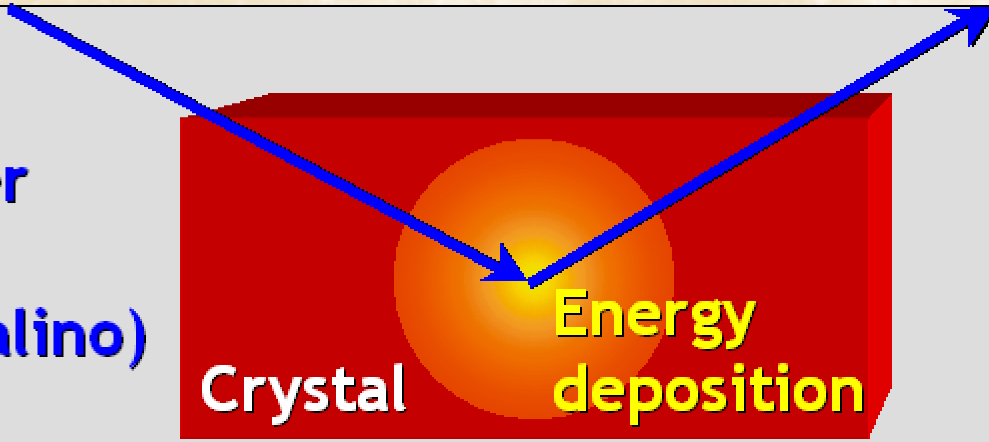
Fig. 2.— The "significance map" obtained by the CANGAROO-II telescope is shown by the blue contours. The thin contours are a 12μ IRAS image. The position of Sgr A* (the telescope tracking center) is given by the cross. The inset is a 5 GHz VLA image showing Sgr A* and Sgr A East (Yusef-Zadeh & Morris 1987). The uncertainty in the position for 3EG J1746−2851 analysed by Mayer-Hasselwander et al. (1998) is indicated by the orange dashed contour.

Hooper et al., Have atmospheric Cherenkov telescopes observed dark matter? astro-ph/0404205

Search for Neutralino Dark Matter

Direct Method (Laboratory Experiments)

Galactic dark matter particle (e.g.neutralino)

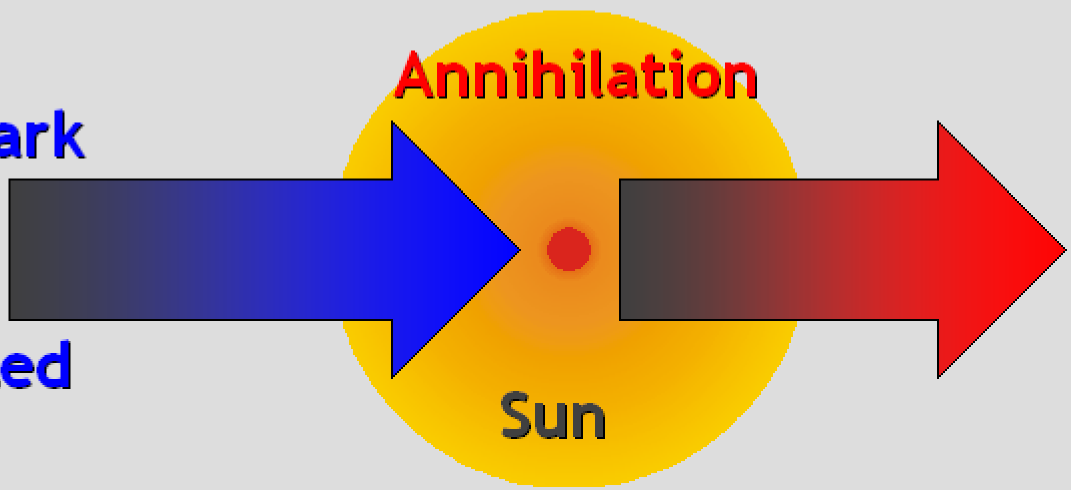


Recoil energy (few keV) is measured by

- Ionisation
- Scintillation
- Cryogenic

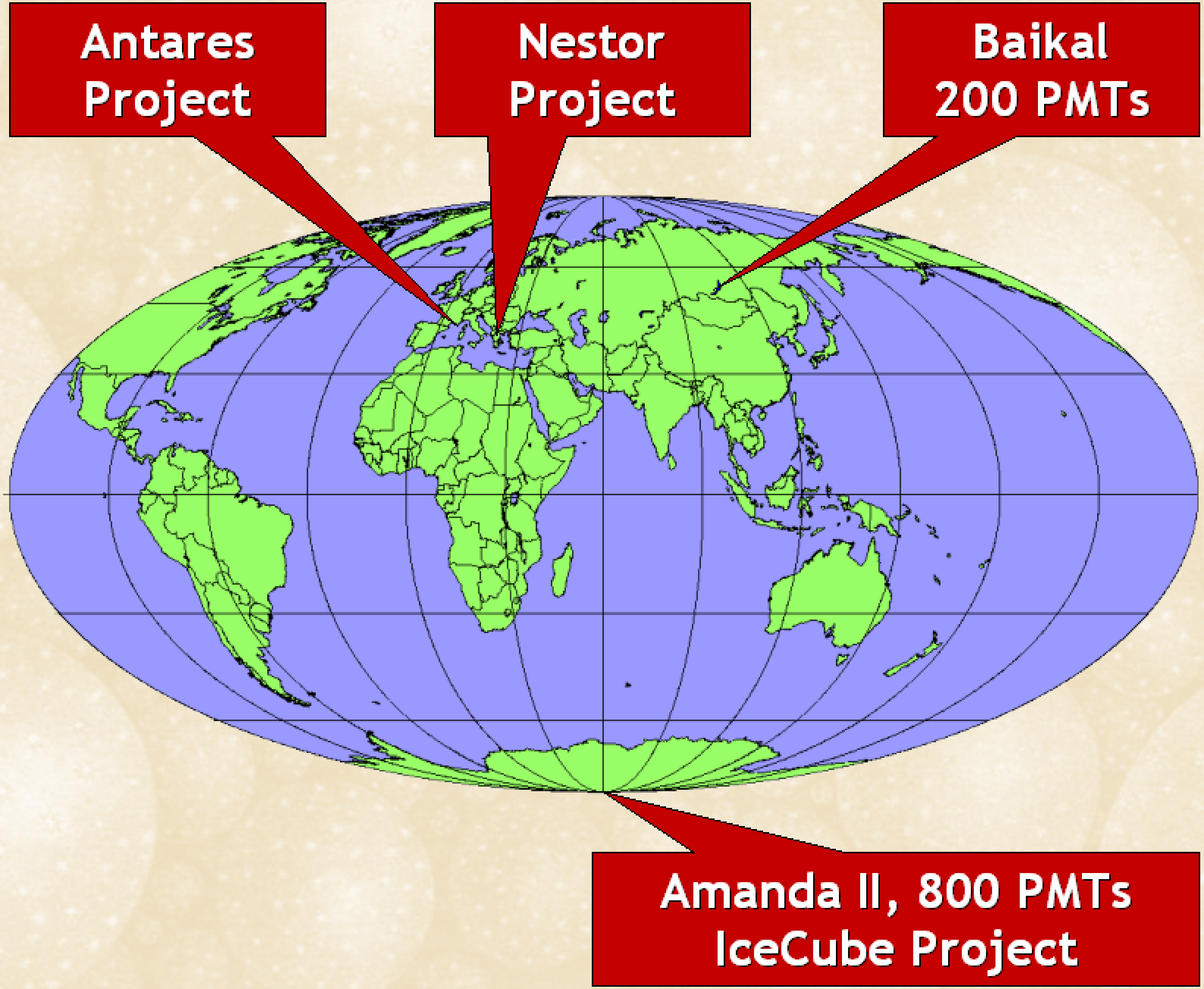
Indirect Method (Neutrino Telescopes)

Galactic dark matter particles are accreted



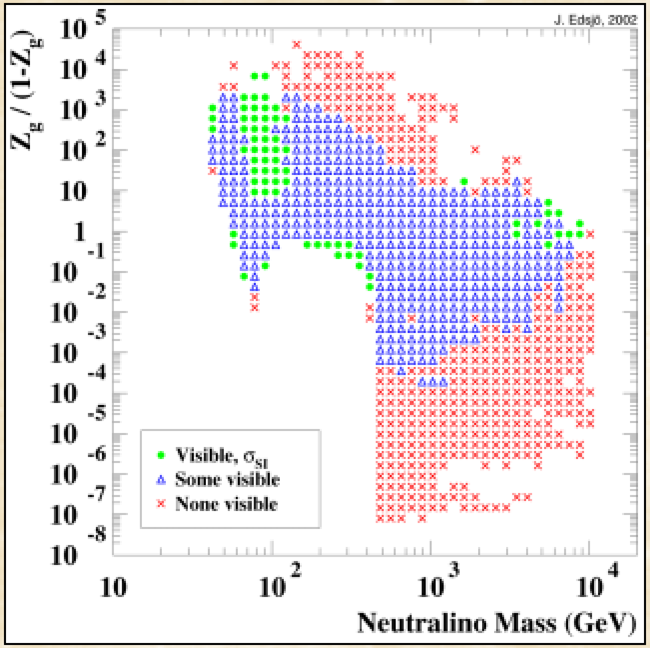
High-energy neutrinos (GeV-TeV) can be measured

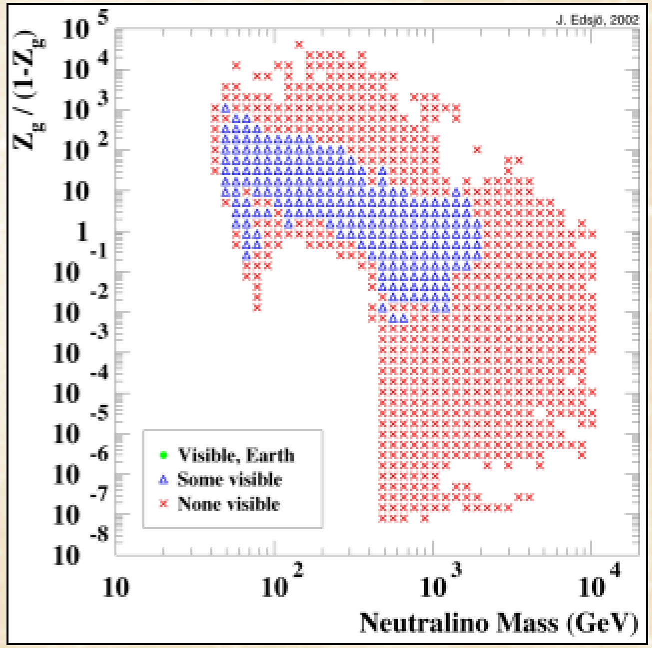
High-Energy Neutrino Telescopes

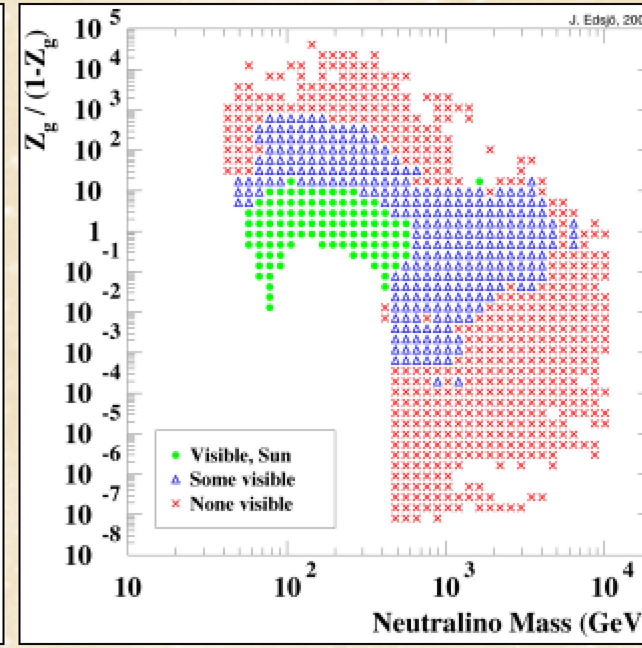


Future WIMP Sensitivities

Direct Detection	Indirect, km^3 Detector	
Genius/CRESST	Earth	Sun







Some Dark Matter Candidates

Supersymmetric particles • Neutralinos • Axinos • Gravitinos Little Higgs models	Gauge hierarchy problem
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 Primordial black holes	Why not?

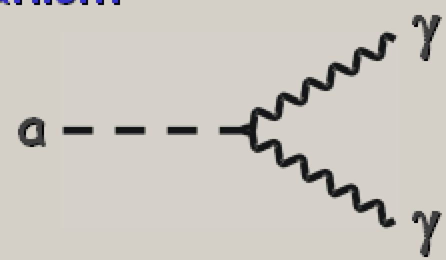
Axion Physics in a Nut Shell

Particle-Physics Motivation

CP conservation in QCD by Peccei-Quinn mechanism

→ Axions $a \sim \pi^0$

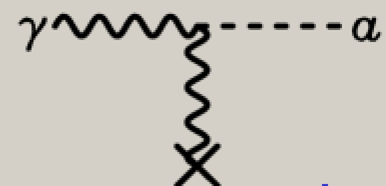
$m_\pi f_\pi \approx m_a f_a$



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

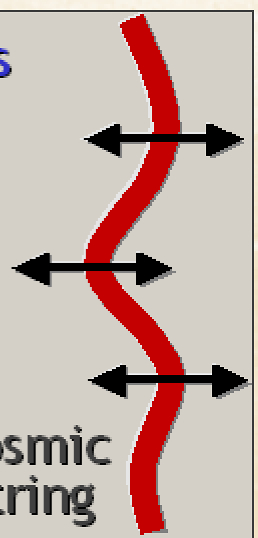


- No excessive energy drain: $m_a < 10$ meV
- Search for solar axions (CAST)

Cosmology

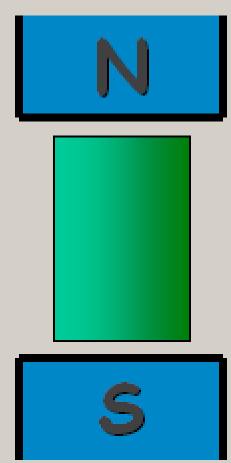
In spite of small mass, axions are born non-relativistically ("non-thermal relics")

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

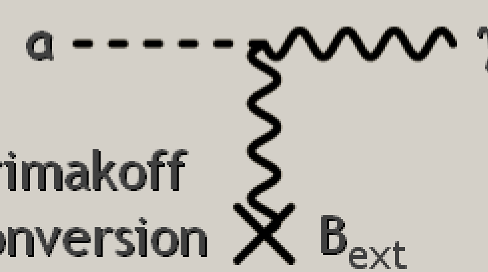


Cosmic String

Search for Axion Dark Matter

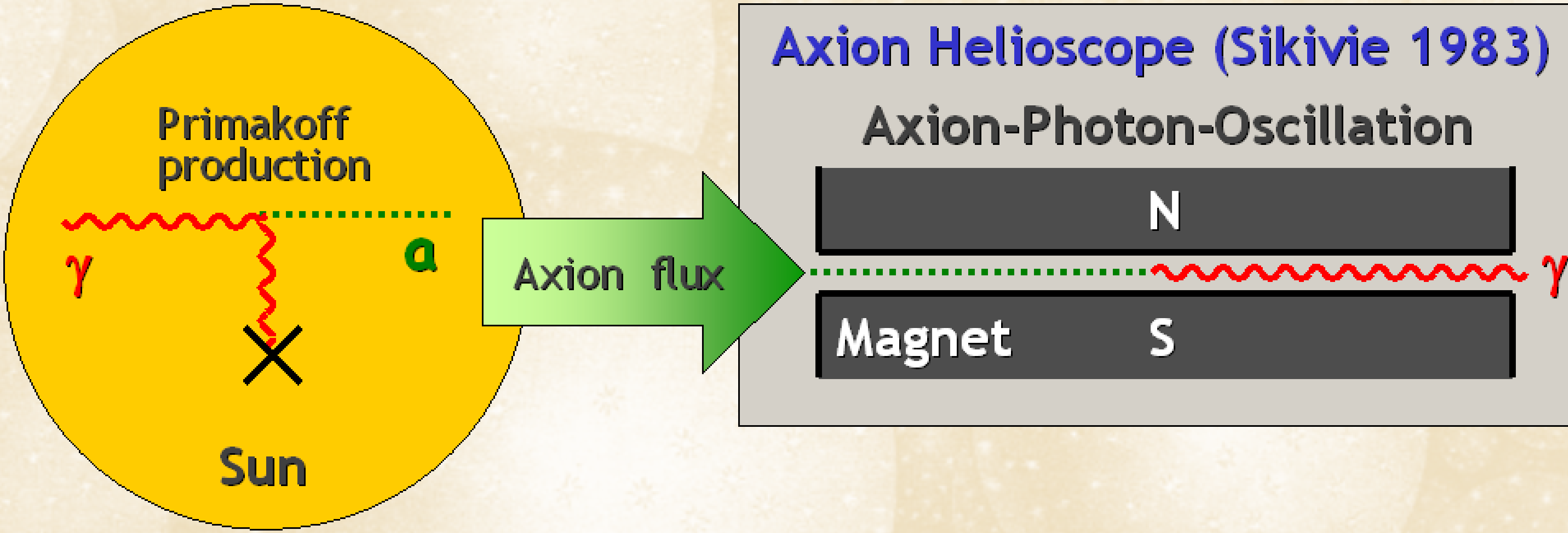


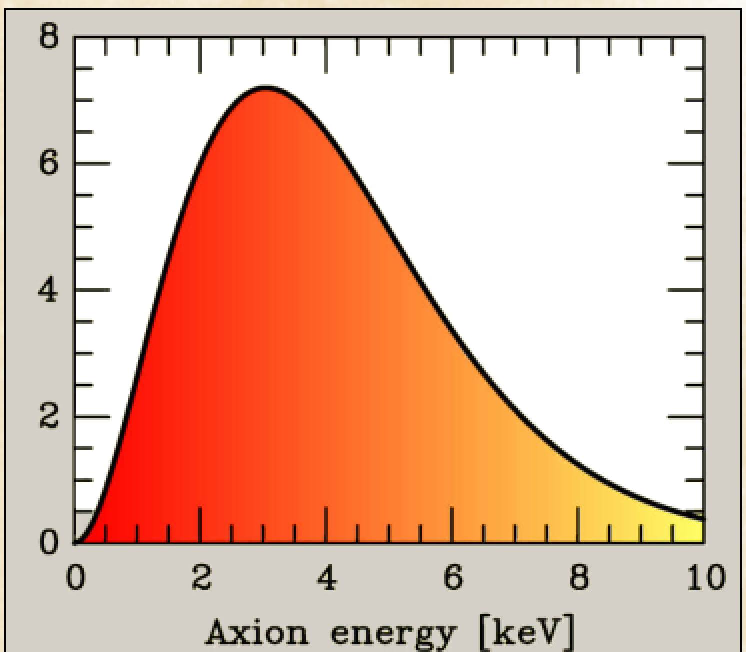
Microwave resonator (1 GHz = 4 μeV)



Primakoff conversion

Search for Solar Axions





- → Tokyo Axion Helioscope (Results since 1998)
- → CERN Axion Solar Telescope (CAST) (in preparation)

Alternative Technique:
Bragg conversion in crystal
Experimental limits on solar axion flux from dark-matter experiments (SOLAX, COSME, DAMA, ...)

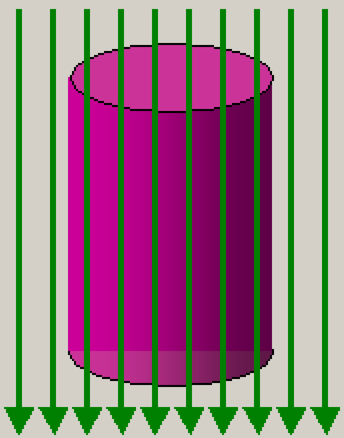
Recent Picture of CAST (12 August 2002)

Experimental Search for Galactic Axions

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

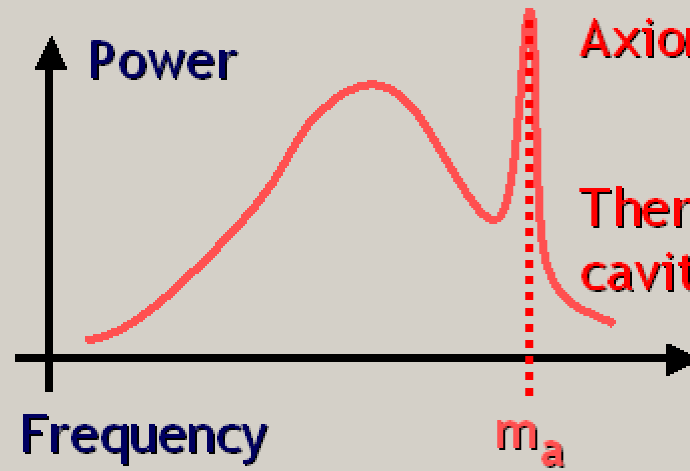
Microwave Energies (1 GHz ≈ 4 μeV)

Axion Haloscope (Sikivie 1983)

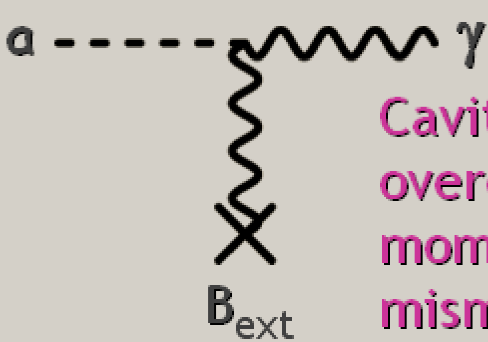


$B_{ext} \approx 8$ Tesla

Microwave Resonator $Q \approx 10^5$



Primakoff Conversion

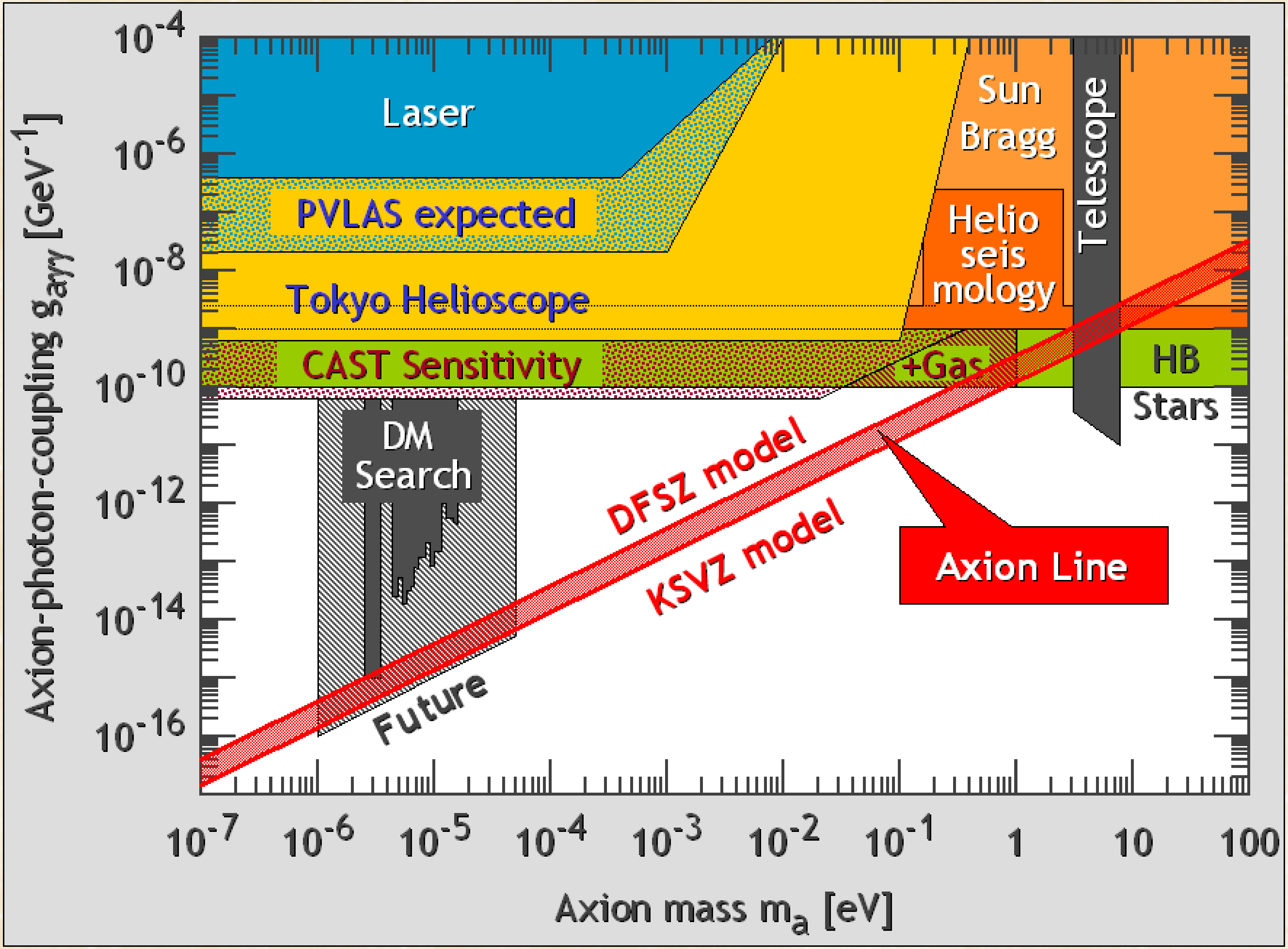


Cavity overcomes momentum mismatch

2 Experiments in Operation

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

Limits on Axion-Photon-Coupling



Overcoming Obstacles

Ringberg Castle, Tegernsee