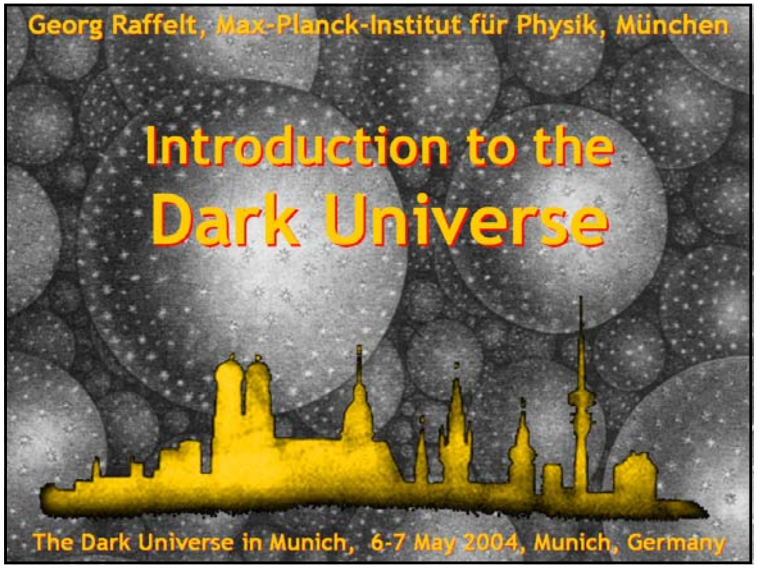
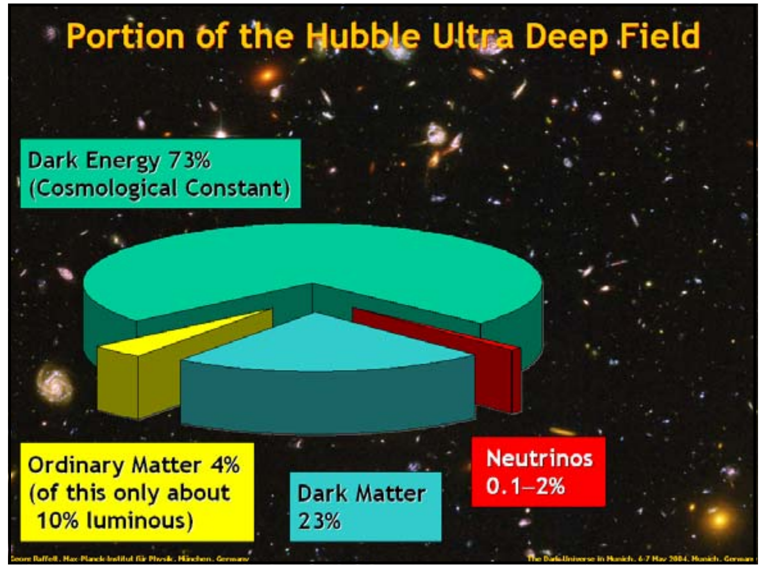
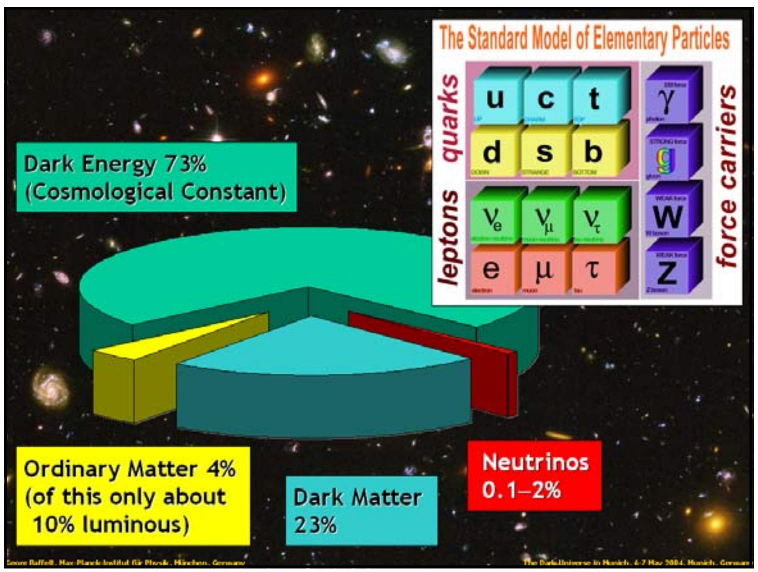



## Baryogenesis in the Early Universe

Andrei Sakharov
1921–1989

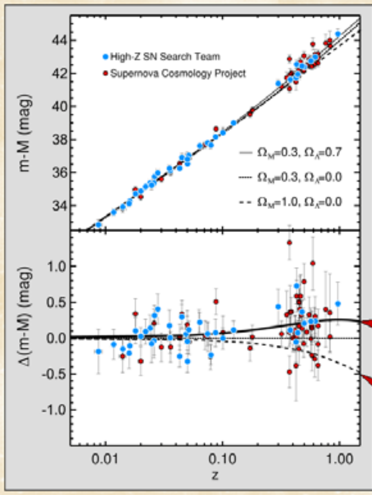
Sakharov conditions for creating the **B**aryon **A**symmetry of the **U**niverse (**BAU**)
- C and CP violation
- Baryon number violation
- Deviation from thermal equilibrium

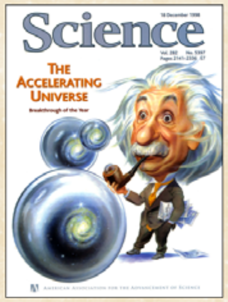
Particle-physics standard model
- Violates C and CP
- Violates B and L by EW instanton effects (B – L conserved)

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

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

## Hubble Diagram




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

Decelerated expansion ($\Omega_M = 1$)



## Einstein's "Greatest Blunder"

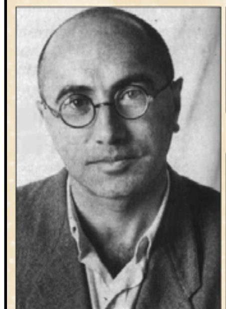
Density of gravitating mass & energy

Newton's constant

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

Friedmann equation for Hubble's expansion rate

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

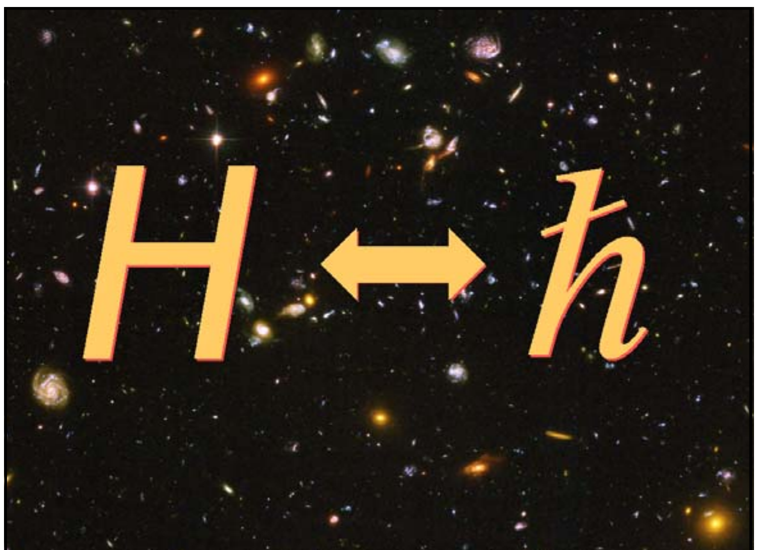


Yakov Borisovich Zeldovich 1914-1987

Cosmological constant $\Lambda$ (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 $\rho_{vac}$ is equivalent to $\Lambda$

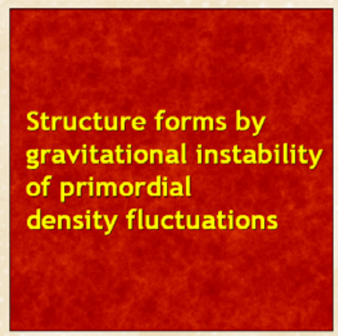


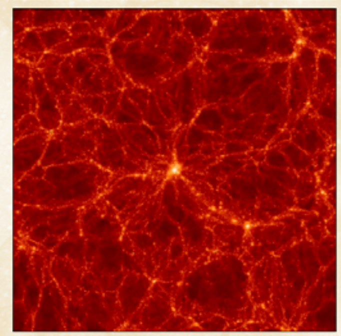




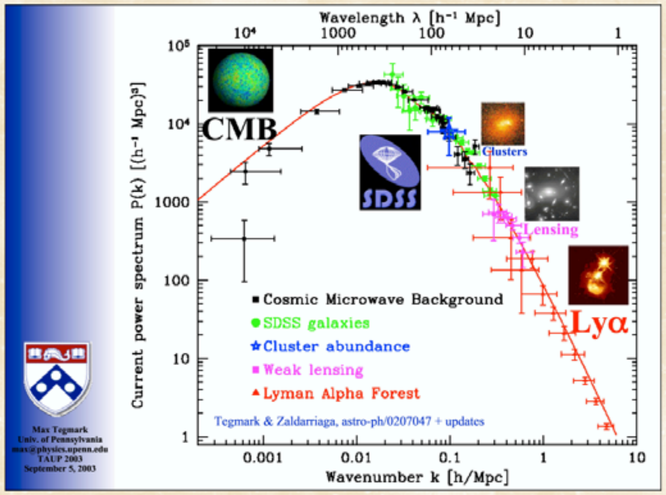

## Formation of Structure

Smooth → Structured



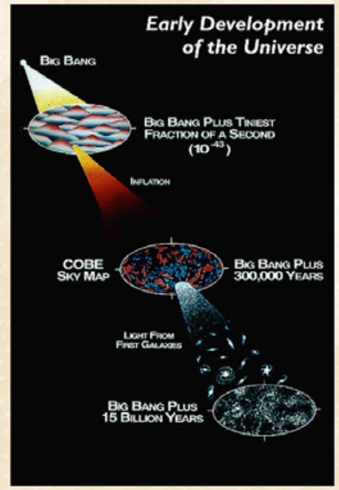



## Power Spectrum of Cosmic Density Fluctuations






## 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



## 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):

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

Here $n_{\nu i}$ = number density of neutrinos of the $i$th kind (notice that in writing this expression we have assumed that both the helicity states are allowed for the neutrinos because of finite rest mass); $E = c(p^2 + m^2c^2)^{1/2}$; $k$ = Boltzmann's constant; $T(z_{eq}) = T_\nu(z_{eq}) = T_e(z_{eq}) = T_\gamma(z_{eq})\cdots$ = 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

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

As the Universe expands, only the neutrinos (in contrast to all other known particles) survive annihilation because of extremely low cross-sections (deGraff and Tolhoek 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 $(1+z_{eq})/(1+z) = T_\gamma(z_{eq})/T_\gamma(z)$, the number density at the present epoch ($z = 0$) is given by

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

* 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

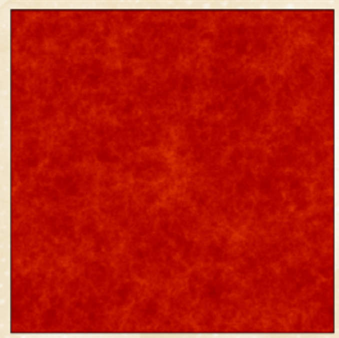
Massive neutrinos are no longer a good candidate (hot dark matter)

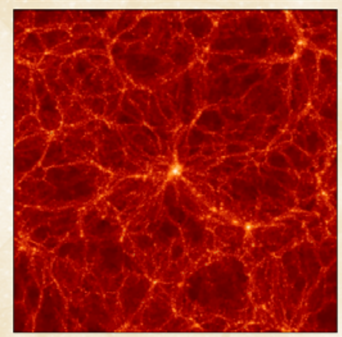
However, the idea of weakly interacting massive particles as dark matter is now standard



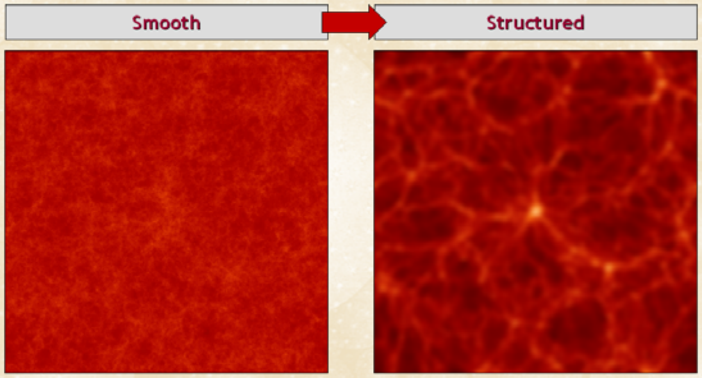
## Formation of Structure

Smooth → Structured





## Formation of Structure




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

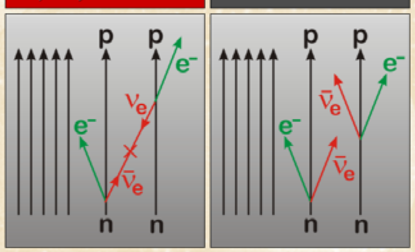
| | |
|---|---|
| $\Sigma m_\nu$ < 2.1 eV | 2dF (Galaxy-galaxy correlation) + WMAP (Cosmic microwaves) |
| $\Sigma m_\nu$ < 1.2 eV | + Small-scale CMBR (breaks degeneracy with bias) |
| $\Sigma m_\nu$ < 1.0 eV | + Priors (1σ) $h = 0.72 \pm 0.08$, $\Omega_M = 0.28 \pm 0.14$ |

Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
The Dark Universe in Munich, 6-7 May 2004, Munich, Germany

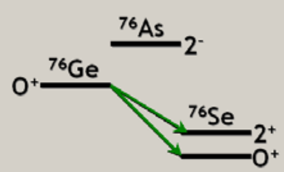
## Neutrinoless ββ Decay

0ν mode, enabled by Majorana mass

Standard 2ν mode



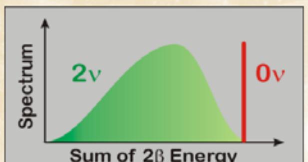

Some nuclei decay only by the ββ mode, e.g.




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 $|m_{ee}| < 0.35$ eV




Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
The Dark Universe in Munich, 6-7 May 2004, Munich, Germany

## 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

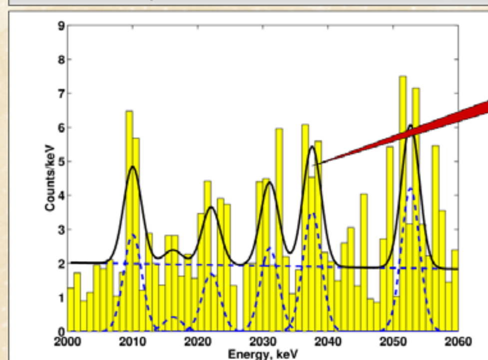



Fig. 31. The single site sum spectrum of the four detectors 2,3,4,5 for the period November 1995 to May 2003 (51.389 kg y), and its fit (see section 3), in the range 2000 - 2060 keV.

Possible evidence for 0ν2β line now ~ 4σ

Georg Raffelt, Max-Planck-Institut für Physik, München, Germany
The Dark Universe in Munich, 6-7 May 2004, Munich, Germany

## 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

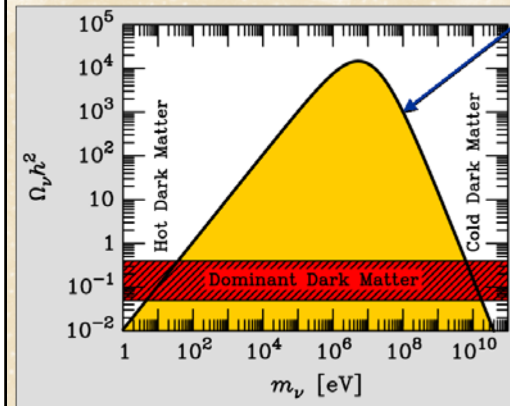
Sufficient deviation from equilibrium distribution of heavy Majorana neutrinos at freeze-out → Limits on Yukawa couplings → Limits on masses of ordinary neutrinos

**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 ($e$, $\nu_e$, ...)<br>Quarks ($u$, $d$, ...) | Sleptons ($\tilde{e}$, $\tilde{\nu}_e$, ...)<br>Squarks ($\tilde{u}$, $\tilde{d}$, ...) | 0 |
| 1 | Gluons<br>$W^\pm$<br>$Z^0$<br>Photon ($\gamma$) | Gluinos<br>Wino<br>Zino<br>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)

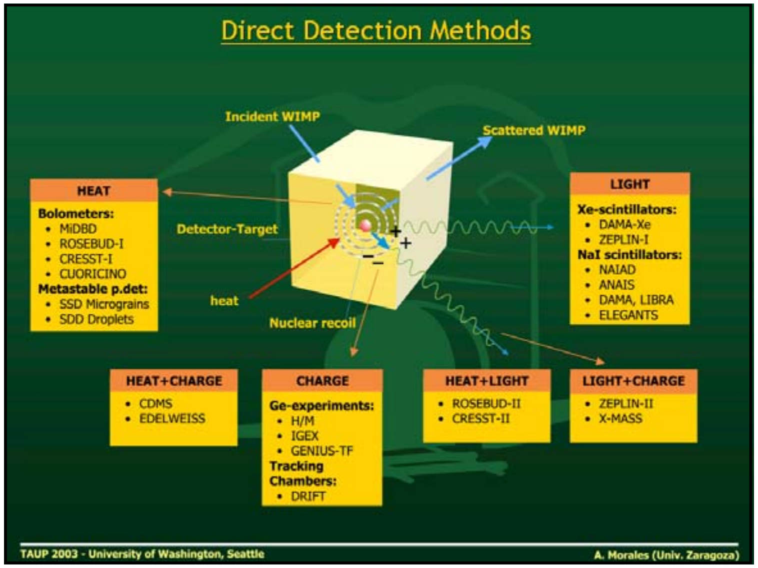

Recoil energy (few keV) is measured by
- Ionisation
- Scintillation
- Cryogenic

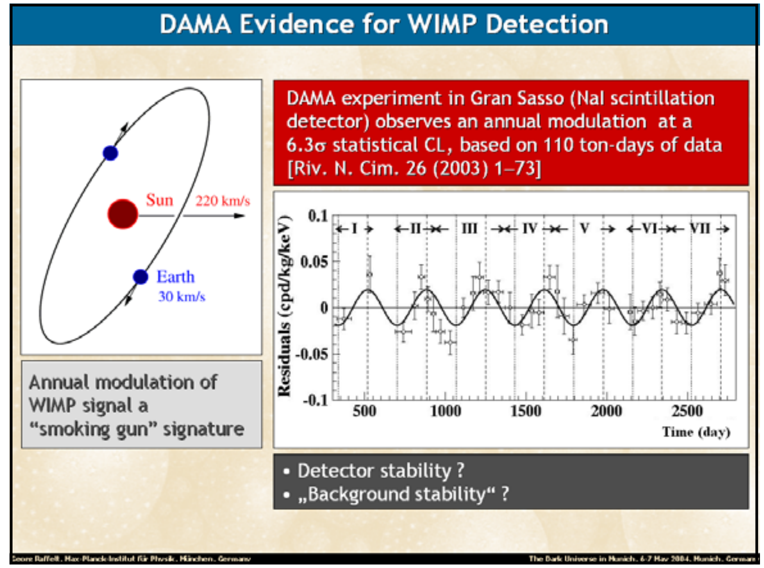
PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

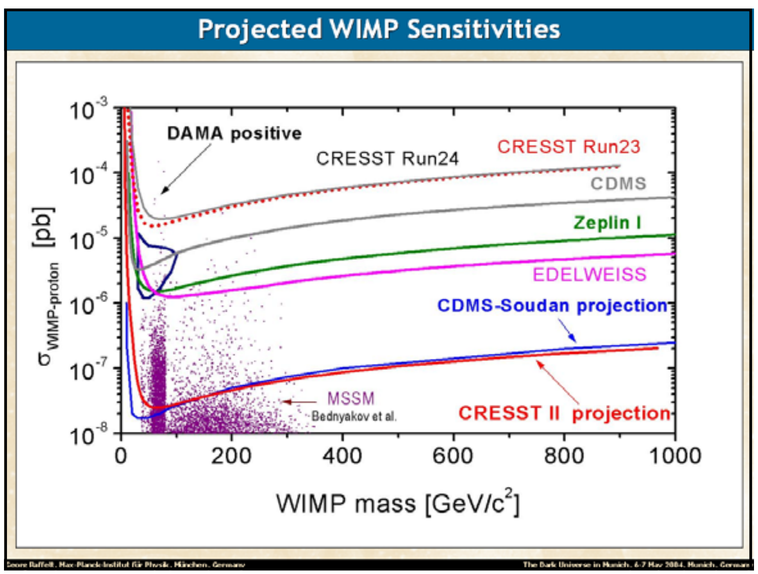
### Detectability of certain dark-matter candidates

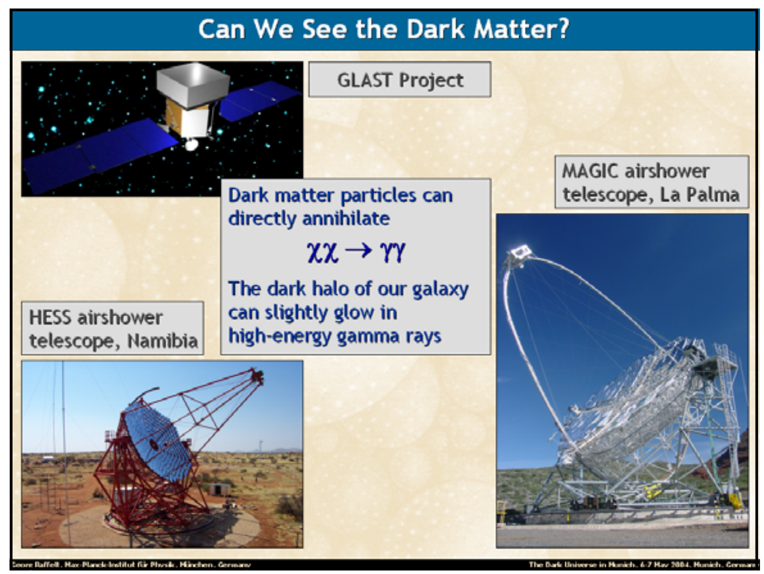
Mark W. Goodman and Edward Witten
*Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544*
(Received 7 January 1985)

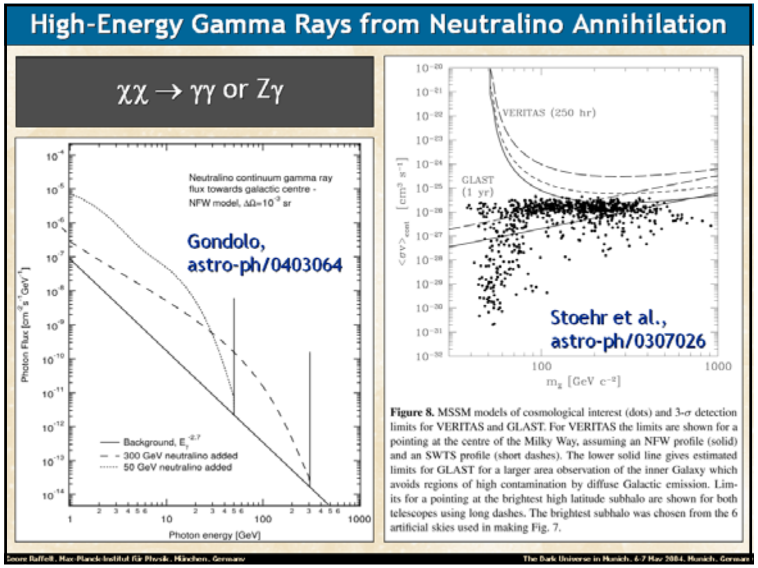
We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and 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.

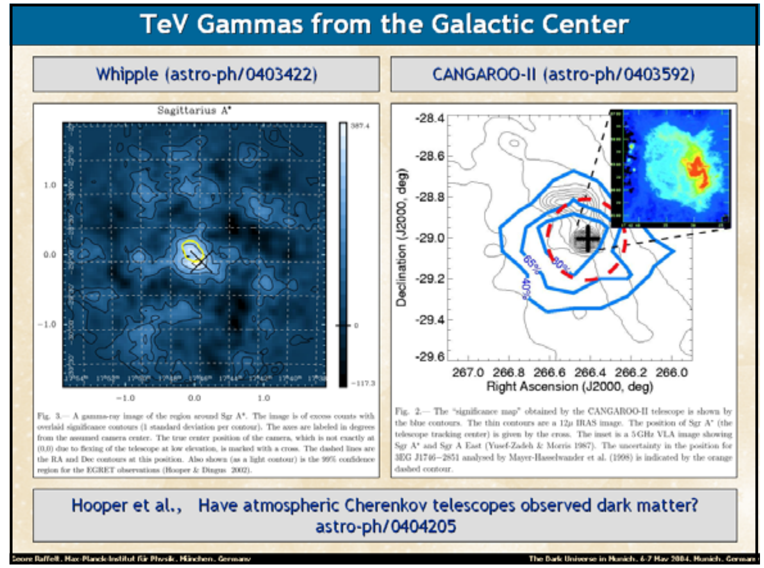

Direct Detection Methods
Incident WIMP
Scattered WIMP
Detector-Target
heat
Nuclear recoil
HEAT
Bolometers:
• MiDBD
• ROSEBUD-I
• CRESST-I
• CUORICINO
Metastable p.det:
• SSD Micrograins
• SDD Droplets
LIGHT
Xe-scintillators:
• DAMA-Xe
• ZEPLIN-I
NaI scintillators:
• NAIAD
• ANAIS
• DAMA, LIBRA
• ELEGANTS
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
TAUP 2003 - University of Washington, Seattle
A. Morales (Univ. Zaragoza)

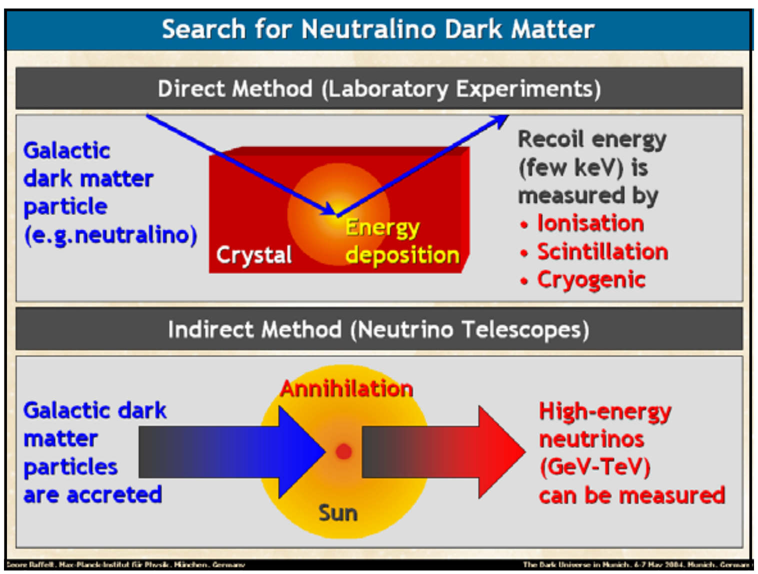

DAMA Evidence for WIMP Detection
Sun
220 km/s
Earth
30 km/s
DAMA experiment in Gran Sasso (NaI scintillation detector) observes an annual modulation at a 6.3σ statistical CL, based on 110 ton-days of data [Riv. N. Cim. 26 (2003) 1–73]
Residuals (cpd/kg/keV)
Time (day)
Annual modulation of WIMP signal a "smoking gun" signature
• Detector stability ?
• „Background stability" ?

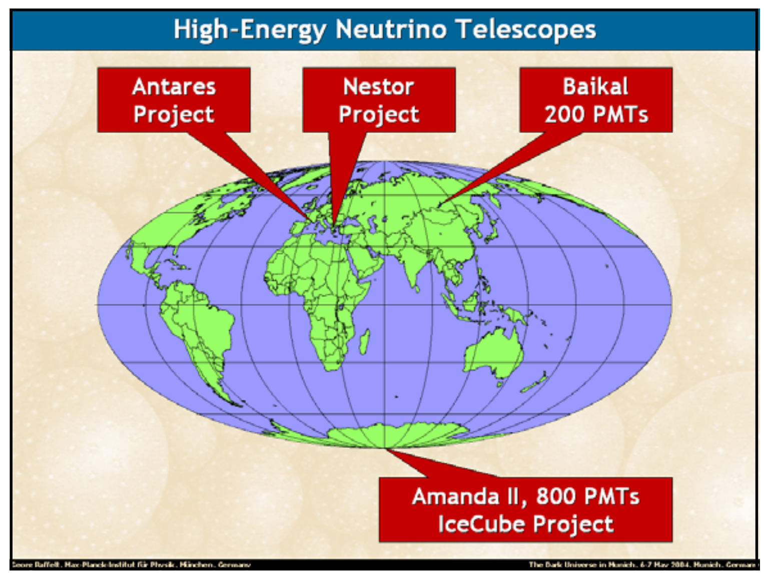

Projected WIMP Sensitivities
DAMA positive
CRESST Run24
CRESST Run23
CDMS
Zeplin I
EDELWEISS
CDMS-Soudan projection
MSSM
Bednyakov et al.
CRESST II projection
σ WIMP-proton [pb]
WIMP mass [GeV/c²]


Can We See the Dark Matter?
GLAST Project
Dark matter particles can directly annihilate
χχ → γγ
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 $Z\gamma$
Neutralino continuum gamma ray flux towards galactic centre - NFW model, $\Delta\Omega = 10^{-3}$ sr
Gondolo, astro-ph/0403064
Background, $E_\gamma^{-2.7}$
300 GeV neutralino added
50 GeV neutralino added
Photon energy [GeV]
Photon Flux [cm$^{-2}$ s$^{-1}$ GeV$^{-1}$]
VERITAS (250 hr)
GLAST (1 yr)
Stoehr et al., astro-ph/0307026
$m_\chi$ [GeV c$^{-2}$]
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.

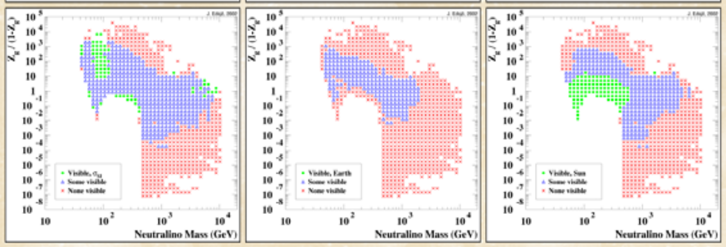

TeV Gammas from the Galactic Center
Whipple (astro-ph/0403422)
CANGAROO-II (astro-ph/0403592)
Sagittarius A*
Declination (J2000, deg)
Right Ascension (J2000, deg)
Hooper et al., Have atmospheric Cherenkov telescopes observed dark matter? astro-ph/0404205


Search for Neutralino Dark Matter
Direct Method (Laboratory Experiments)
Galactic dark matter particle (e.g.neutralino)
Crystal
Energy deposition
Recoil energy (few keV) is measured by
• Ionisation
• Scintillation
• Cryogenic
Indirect Method (Neutrino Telescopes)
Galactic dark matter particles are accreted
Annihilation
Sun
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

## Future WIMP Sensitivities

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






## Some Dark Matter Candidates

| | |
|---|---|
| Supersymmetric particles<br>• Neutralinos<br>• Axinos<br>• 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 | |



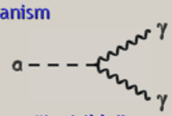
## Axion Physics in a Nut Shell

### Particle-Physics Motivation

CP conservation in QCD by Peccei-Quinn mechanism

→ Axions $a \sim \pi^0$

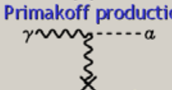
$m_\pi f_\pi \approx m_a f_a$




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



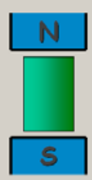

• No excessive energy drain: $m_a$ < 10 meV
• Search for solar axions (CAST)

### Cosmology

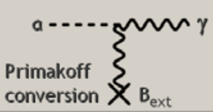
In spite of small mass, axions are born non-relativistically ("non-thermal relics")

→ "Cold dark matter" candidate
$m_a$ ~ 1-1000 μeV


### Search for Axion Dark Matter

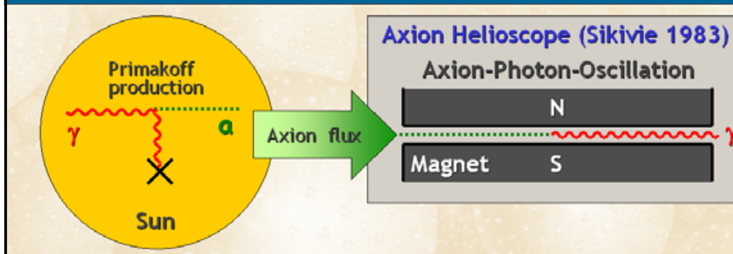


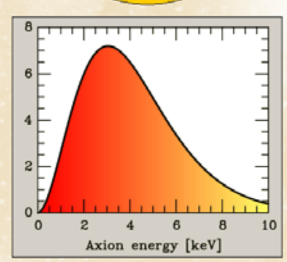

Microwave resonator (1 GHz = 4 μeV)






## Search for Solar Axions

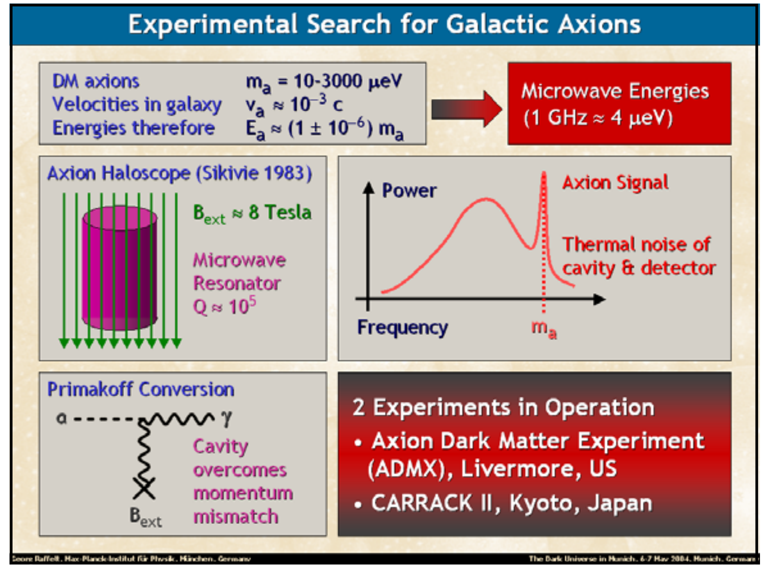


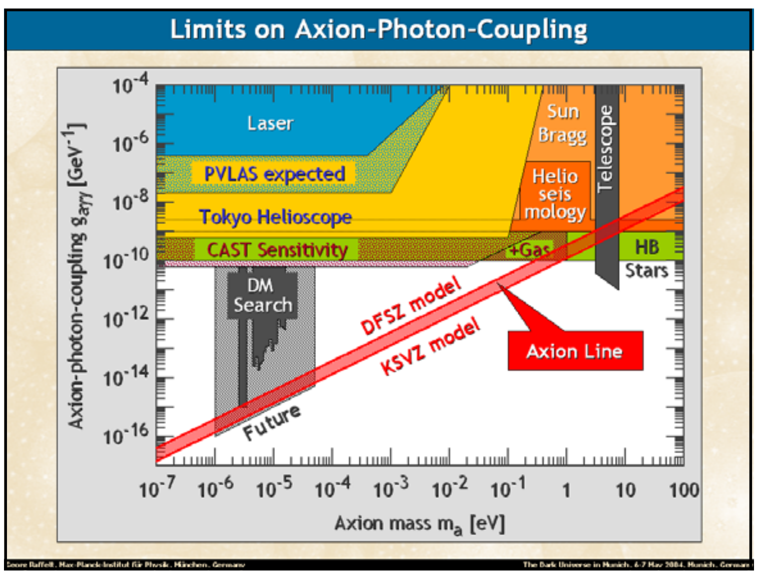



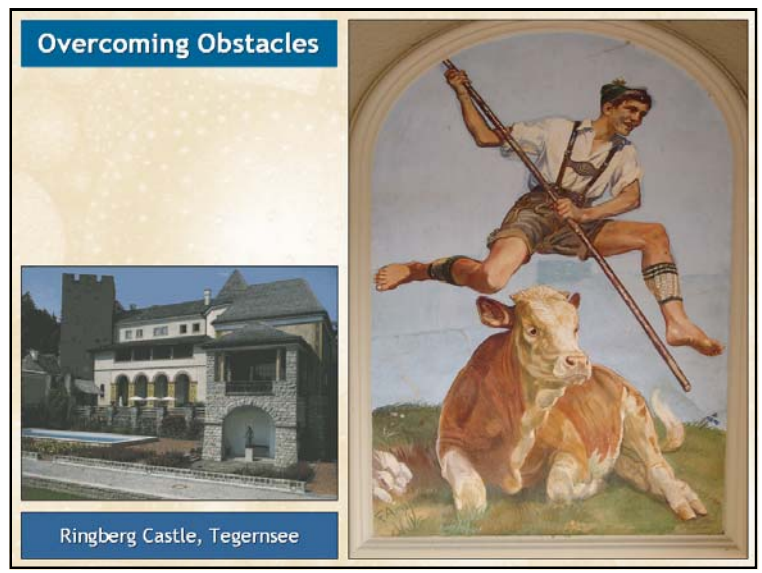

➔ Tokyo Axion Helioscope (Results since 1998)
➔ CERN Axion Solar Telescope (CAST) (in preparation)

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)
CAST


Experimental Search for Galactic Axions
DM axions
Velocities in galaxy
Energies therefore
$m_a$ = 10-3000 μeV
$v_a \approx 10^{-3}$ c
$E_a \approx (1 \pm 10^{-6})\, m_a$
Microwave Energies
(1 GHz ≈ 4 μeV)
Axion Haloscope (Sikivie 1983)
$B_{ext} \approx$ 8 Tesla
Microwave
Resonator
$Q \approx 10^5$
Power
Axion Signal
Thermal noise of
cavity & detector
Frequency
$m_a$
Primakoff Conversion
a
γ
Cavity
overcomes
momentum
mismatch
$B_{ext}$
2 Experiments in Operation
• Axion Dark Matter Experiment (ADMX), Livermore, US
• CARRACK II, Kyoto, Japan


Limits on Axion-Photon-Coupling
Laser
PVLAS expected
Tokyo Helioscope
CAST Sensitivity
Sun
Bragg
Helio
seis
mology
Telescope
+Gas
HB
Stars
DM
Search
DFSZ model
KSVZ model
Axion Line
Future
$10^{-4}$
$10^{-6}$
$10^{-8}$
$10^{-10}$
$10^{-12}$
$10^{-14}$
$10^{-16}$
Axion-photon-coupling $g_{a\gamma\gamma}$ [$GeV^{-1}$]
$10^{-7}$ $10^{-6}$ $10^{-5}$ $10^{-4}$ $10^{-3}$ $10^{-2}$ $10^{-1}$ 1 10 100
Axion mass $m_a$ [eV]


Overcoming Obstacles
Ringberg Castle, Tegernsee