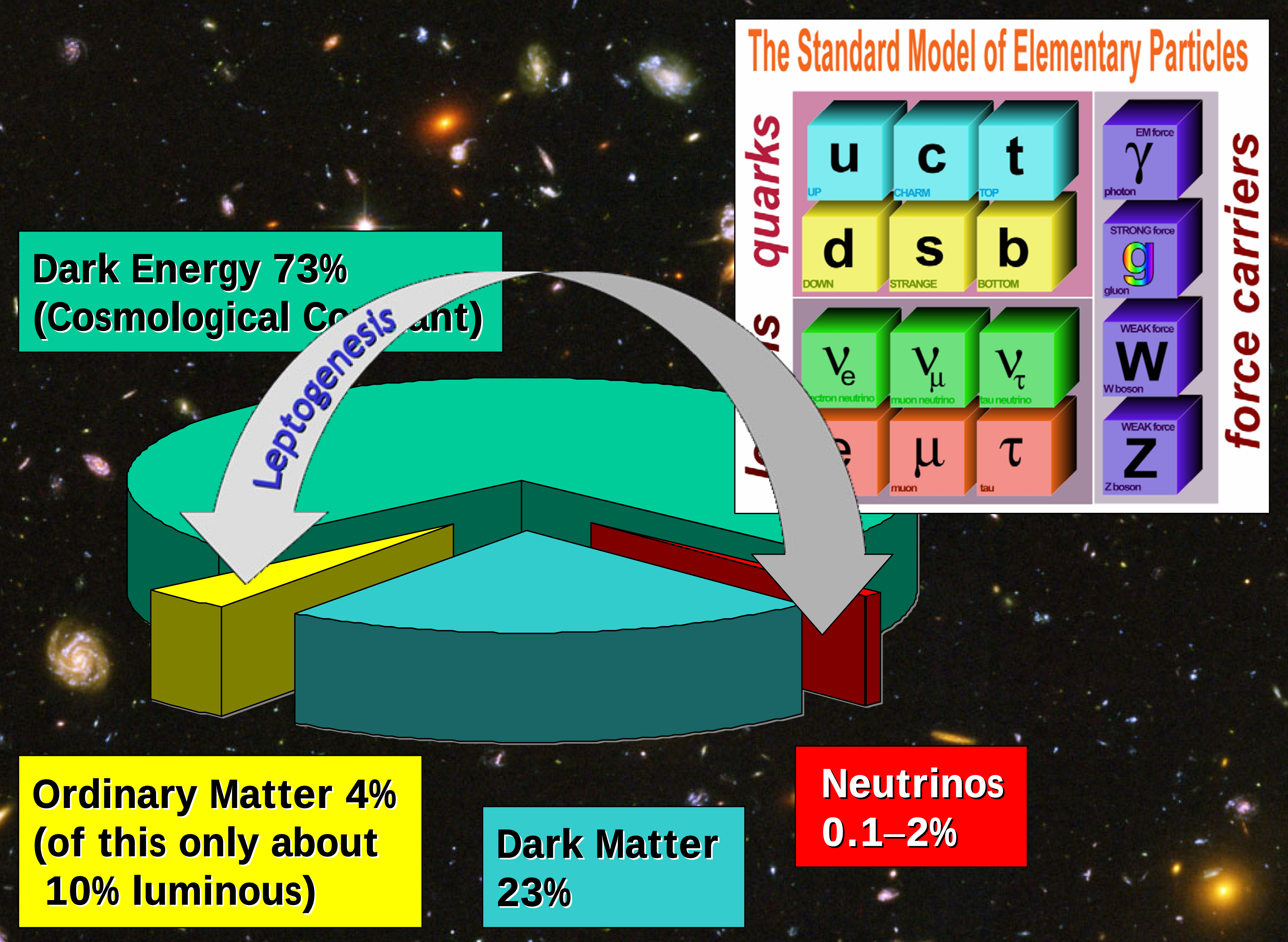
Georg Raffelt, Max-Planck-Institut für Physik, München

Dunkle Materie und Teilchenphysik

Astroteilchenphysik in Deutschland, 4-5 Okt 2005, Zeuthen



Dark Energy 73%
(Cosmological Co... ant)
Leptogenesis
The Standard Model of Elementary Particles
quarks
u UP
c CHARM
t TOP
d DOWN
s STRANGE
b BOTTOM
νe
νμ muon neutrino
ντ tau neutrino
μ muon
τ tau
force carriers
EM force γ photon
STRONG force g gluon
WEAK force W W boson
WEAK force Z Z boson
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

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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):

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

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

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

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

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

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

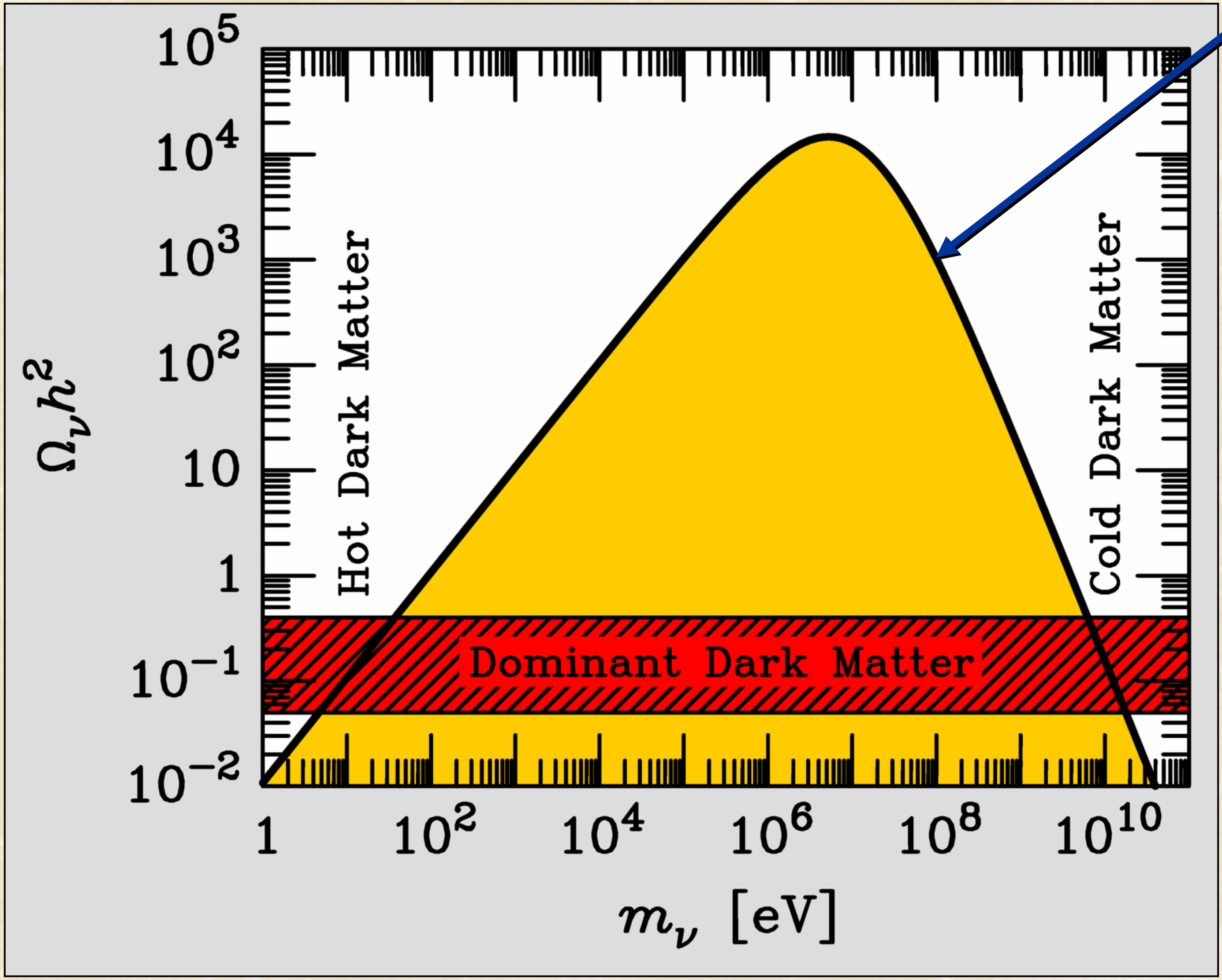
7

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

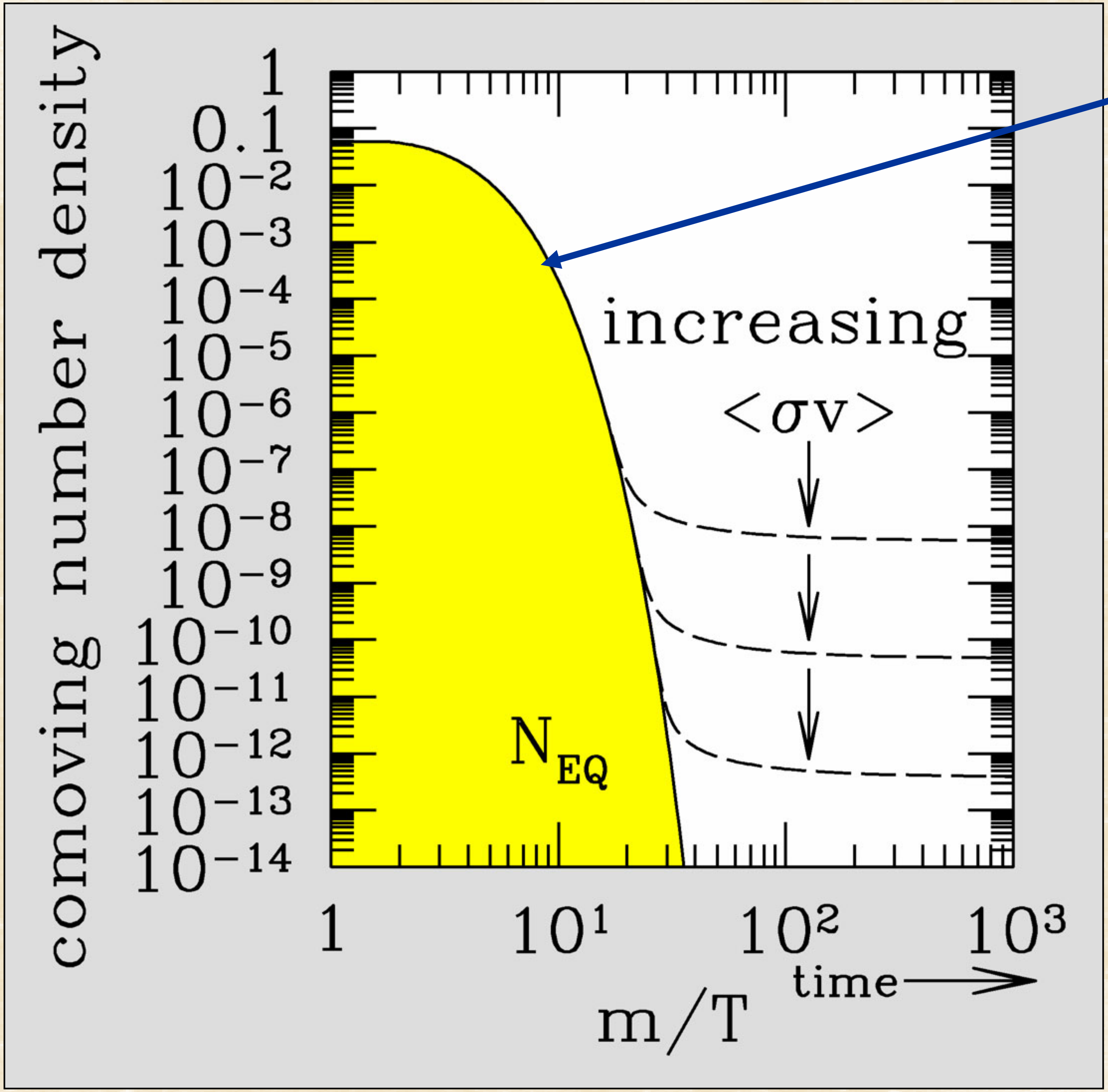
Lee-Weinberg-Curve



- 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

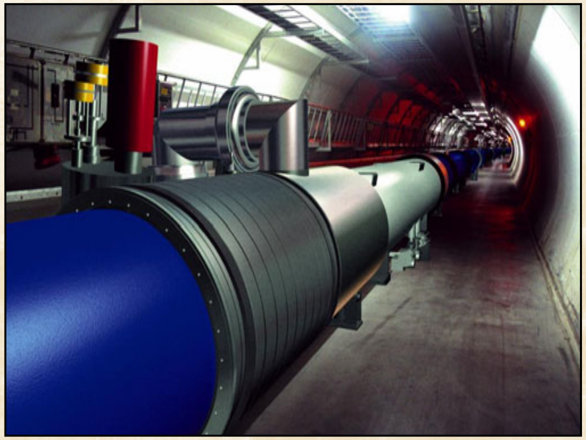
In supersymmetric extensions of the particle-physics standard model, every boson has a fermionic partner and vice versa

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

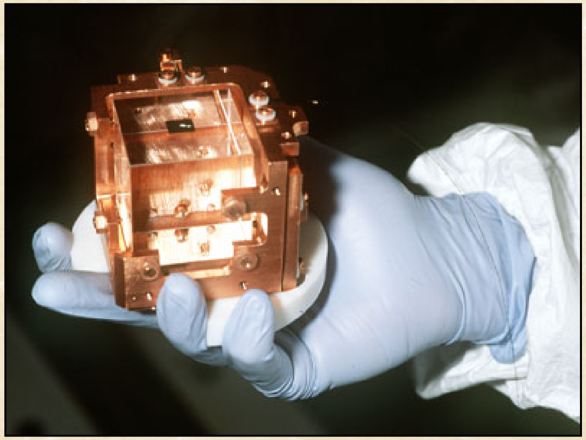
- If R-Parity is conserved, the lightest SUSY-particle (LSP) is stable
- Most plausible candidate for dark matter is the neutralino, similar to a massive Majorana neutrino

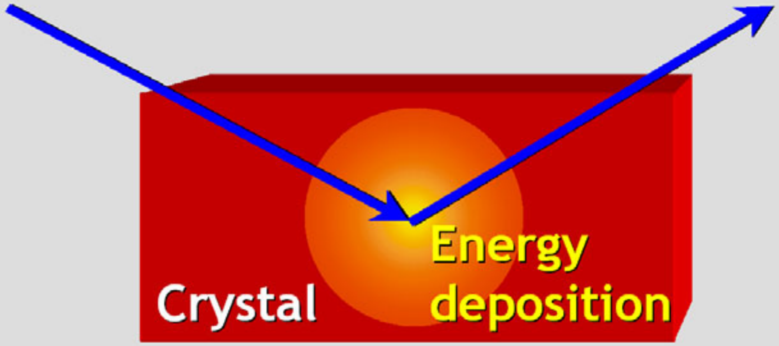
Neutralino = C_1 Photino + C_2 Zino + C_3 Higgsino

Hunting WIMPs

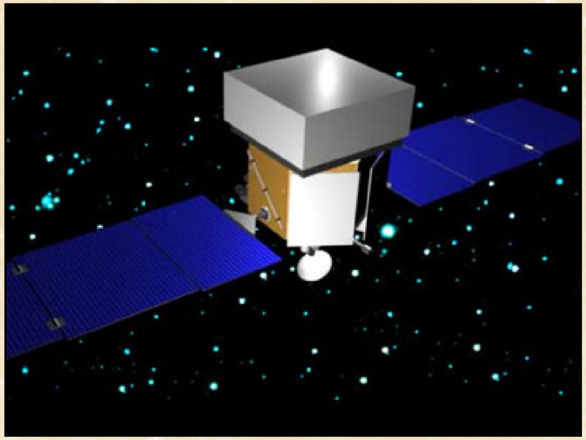


Search for new particles at accelerators, notably the Large Hadron Collider (LHC) at CERN (> 2007)





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

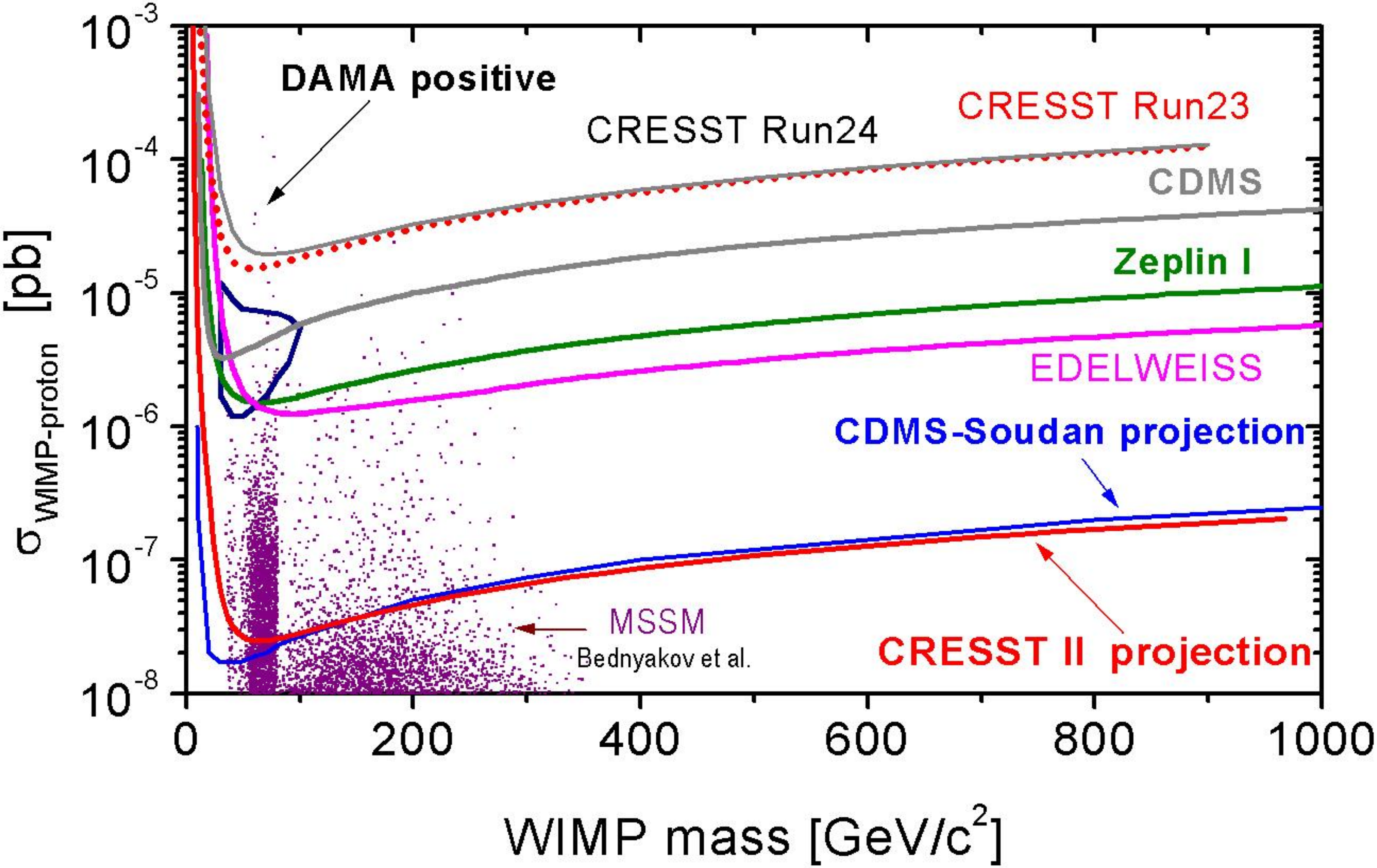


Search for WIMP annihilation products in the form of
- Gamma rays (e.g. EGRET, HESS, MAGIC, GLAST)
- Anti-protons (AMS)
- Positrons
- High-energy neutrinos from the Sun or Earth (e.g. Super-K, Amanda/IceCube, Antares, …)

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

LABORATORY	EXPERIMENT	TECHNIQUE
Bern (Switzerland)	ORPHEUS	(SSD) Tin Superconducting Superheated Detector
Boulby (UK)	NAIAD ZEPLIN I ZEPLIN II DRIFT	NaI scintillators (46-65 Kg) Liquid Xe scintillator (4 Kg) Liquid-Gas Xe (scintillation/ionization) (30 Kg) (R+D) Low pressure Xe TPC $1 m^3$ (R+D)
Canfranc (Spain)	IGEX GEDEON ANAIS ROSEBUD	Ge ionization detector (2.1 Kg) Set of Ge ionization detector (in project) (4x7x2 Kg) NaI scintillators (110 kg) $CaWO_4$ and BGO scintillating bolometers (50-200 g)
Frejus/Modane (France)	EDELWEISS	Sets of Ge thermal+ionization detectors (n x 320 g)
Gran Sasso (Italy)	H/M HDMS GENIUS-TF DAMA LIBRA Liquid-Xe CaF_2 CRESST CUORICINO CUORE	Ge ionization detector (2.7 Kg) Ge ionization in Ge well Set of Ge crystals in LN_2 (40 Kg) NaI scintillators (~100 Kg) NaI scintillators 250 kg (starting) Liquid Xe scintillator (6 Kg) Scintillator Set of $CaWO_4$ scintillating bolometers (n x 300 g) Set of TeO_2 thermal detector (41 Kg) 1000x760 g TeO_2 (in project)
KAMIOKA (Japan)	XMASS	Large mass Xe scintillators (R+D)
Rustrel (France)	SIMPLE	(SDD) Superheated Droplets Detectors (Freon)
Soudan (USA)	CDMS	Sets of Ge and Si thermal + ionization detectors
SNO (Canada)	PICASSO	(SDD) Superheated Droplets Detectors (Freon)
OTO (Japan)	ELEGANTS V ELEGANTS VI	Large set of massive NaI scintillators (670 kg) CaF_2 scintillators

Projected WIMP Sensitivities



DarkSUSY Home Page

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

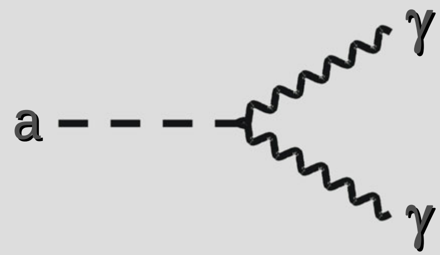
Axion Physics in a Nut Shell

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

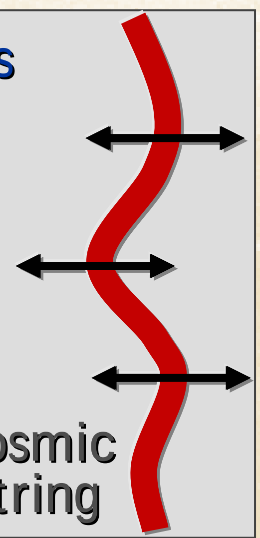
Axions thermally produced in stars, e.g. by Primakoff production

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

Cosmology

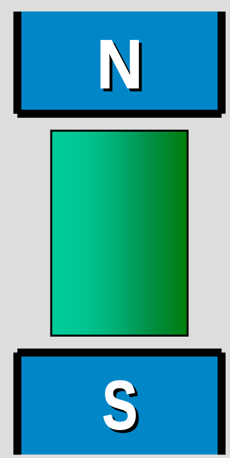
In spite of small mass, axions are born non-relativistically ("non-thermal relics")

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

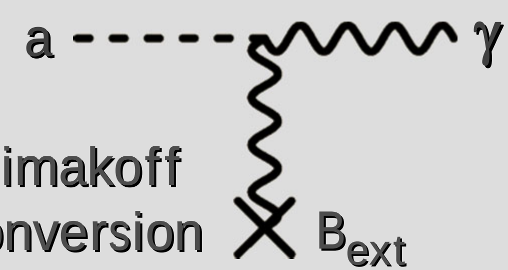


Cosmic String

Search for Axion Dark Matter



Microwave resonator (1 GHz = 4 μeV)

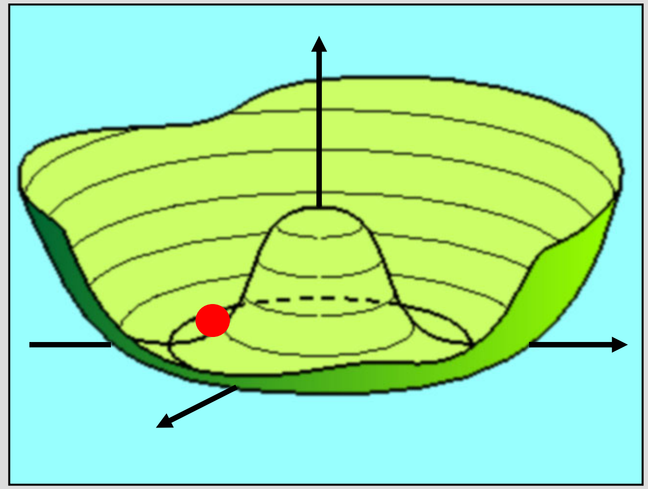


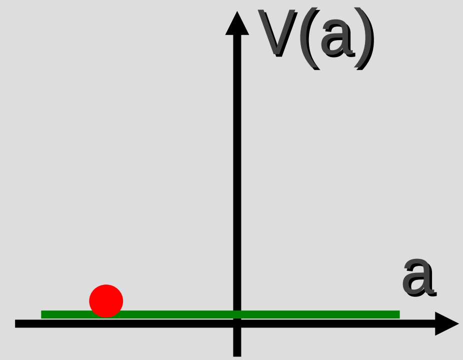
Primakoff conversion

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

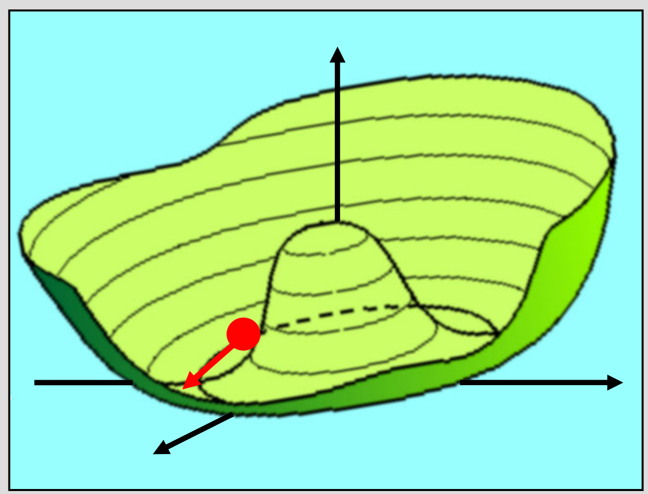
$E \approx f_a$

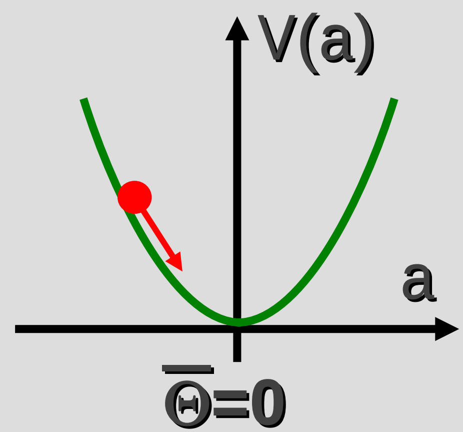




- $U_{PQ}(1)$ spontaneously broken
- Higgs field settles in "Mexican hat"

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

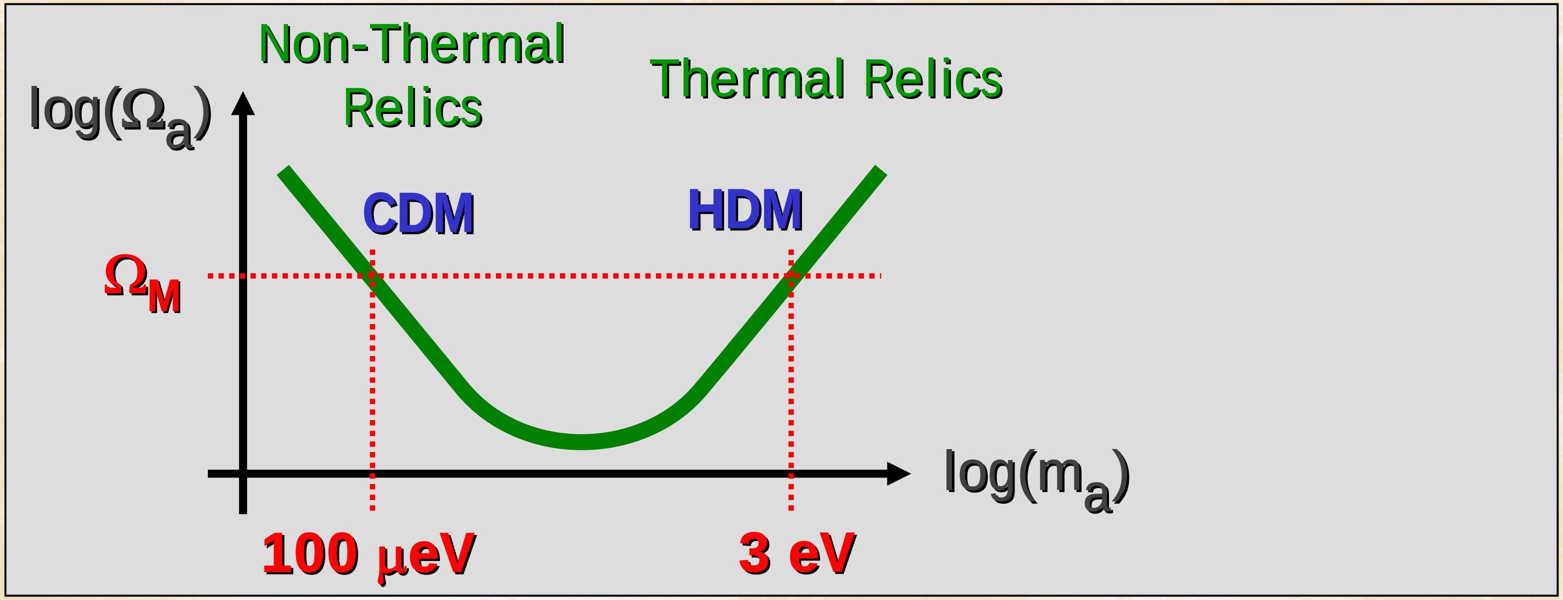




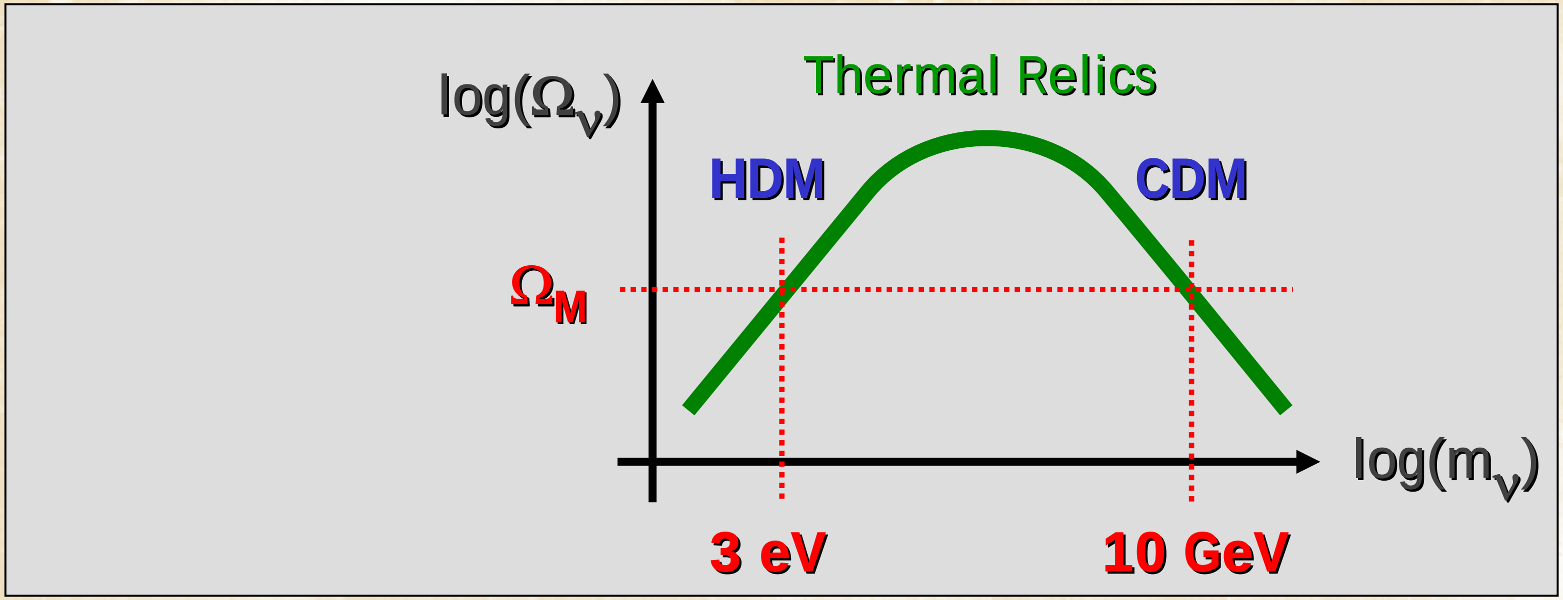
- $U_{PQ}(1)$ explicitly broken by instanton effects
- Mexican hat tilts
- Axions acquire a mass

Lee-Weinberg Curve for Neutrinos and Axions

Axions



Neutrinos

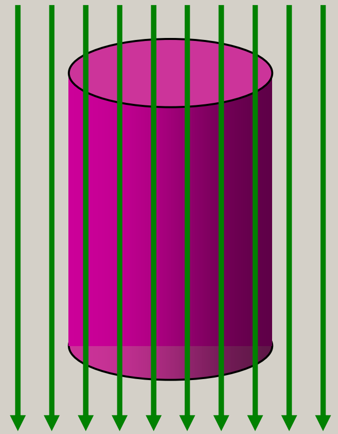


Experimental Search for Galactic Axions

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

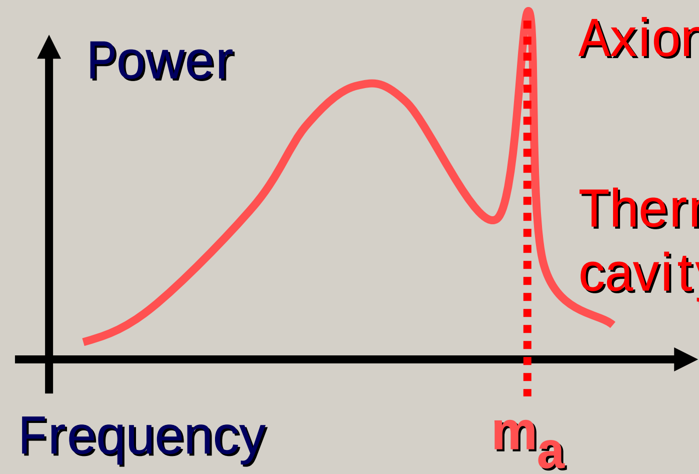
Microwave Energies
(1 GHz ≈ 4 μeV)

Axion Haloscope (Sikivie 1983)



$B_{ext} \approx$ 8 Tesla

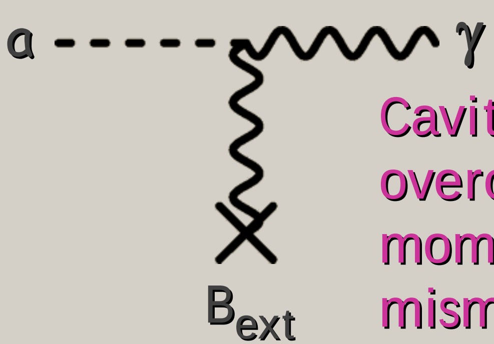
Microwave Resonator
$Q \approx 10^5$



Axion Signal

Thermal noise of cavity & detector

Primakoff Conversion



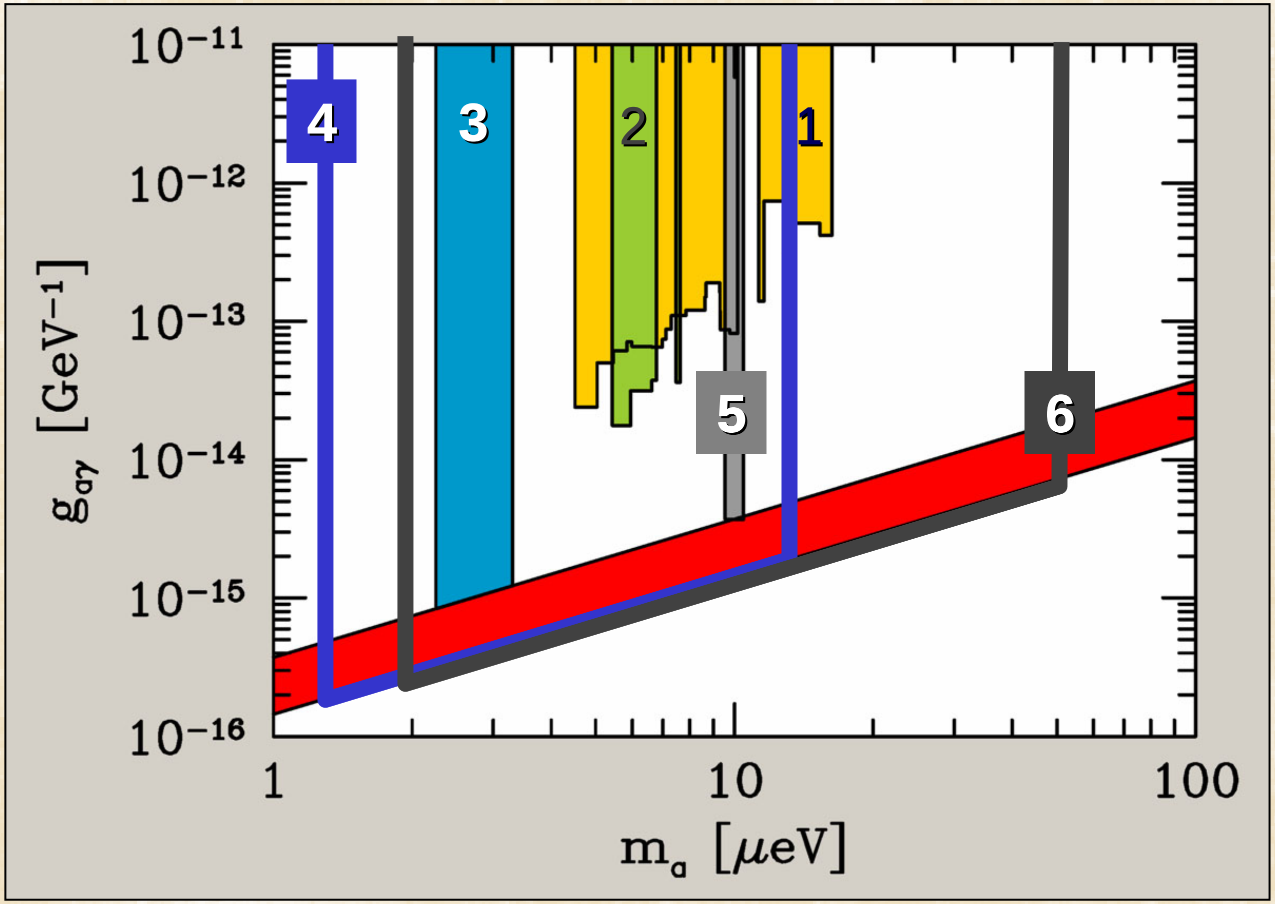
Cavity overcomes momentum mismatch

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
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3. US Axion Search (Livermore)
   ApJL 571 (2002) L27
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   Phys Repts 325 (2000) 1
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   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	

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  Rev. Mod. Phys. 75 (2003) 777


DENNIS the MENACE
4-24
"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)