The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific
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International Atomic
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SMR.1761- 2

SUMMER SCHOOL IN COSMOLOGY AND ASTROPARTICLE PHYSICS

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Strategies for dark matter detection

Part 2

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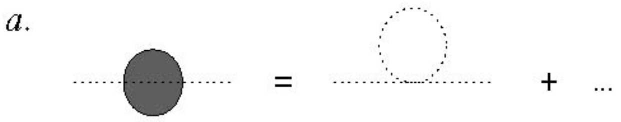
Lecture 2:Thermal Relics

Inputs from Particle Physics
Thermal Relics
Neutrinos
Weakly Interactive Massive Particles

Input from Particle Physics

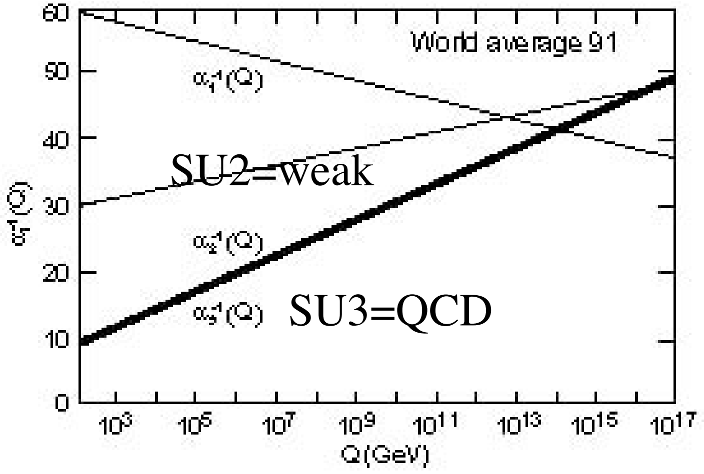
Extremely successful model

QCD
Electroweak symmetry breaking



But incomplete:
Hierarchy problem

mass instability problems
e.g,. What prevents the masses of the Higgs or W to go to the Planck mass



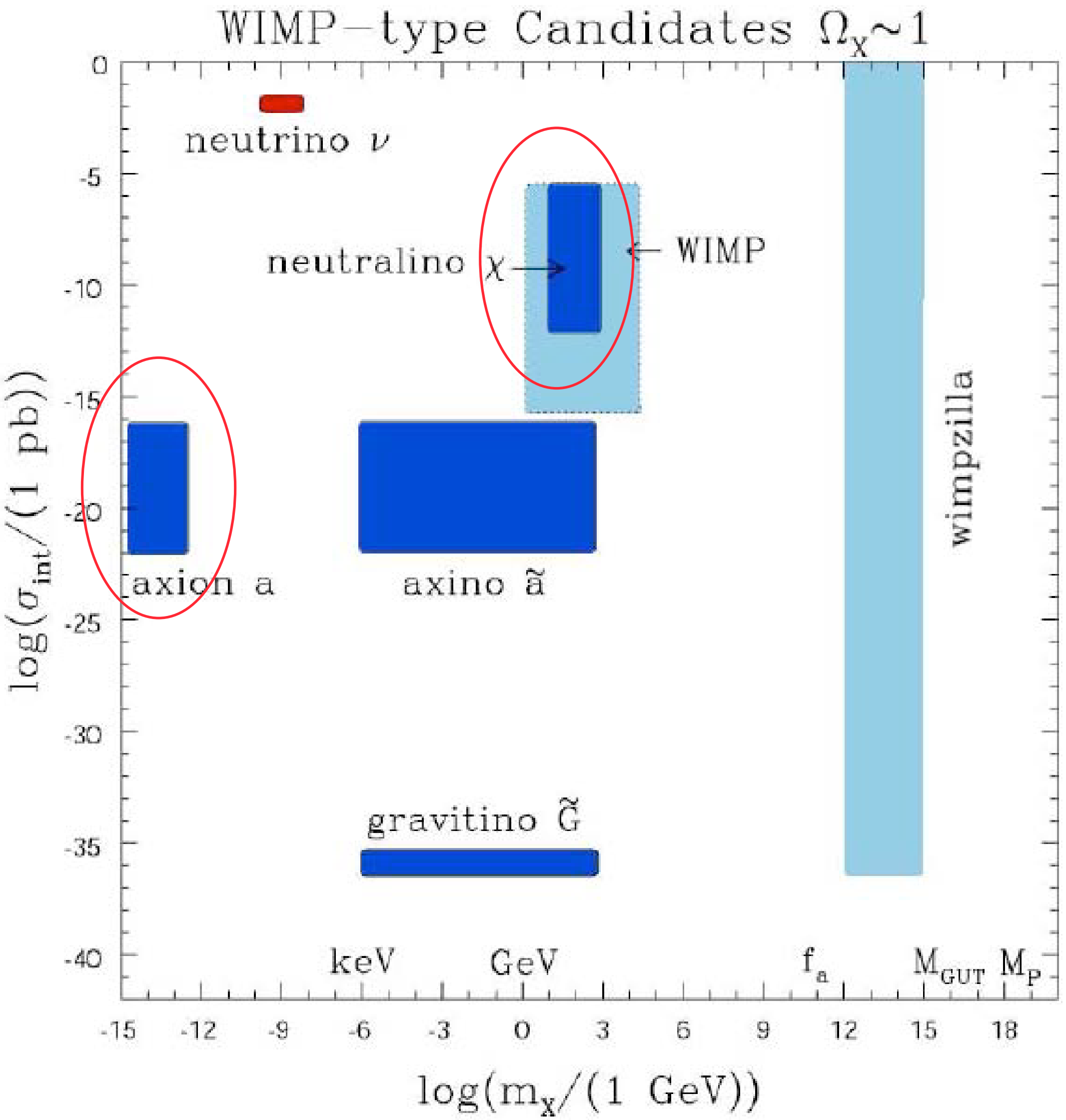
Lack of unification

Does not incorporate gravity

Quantization
Why so weak

1. Input from cosmology
2. Input from gravity
3. **Input from Particle Physics**

Variety of candidates



- neutrino ν – hot DM
- neutralino χ
- “generic” WIMP
- axion a
- axino $\tilde{a}$
- gravitino $\tilde{G}$
- wimpzilla,. . .

L. Roszkowski

Challenges

Electroweak scale: Introduce new physics at 1 TeV

without destroying Standard Model
without induce too high proton decay

Gravity scale

String inspired schemes?

Challenges from cosmology

Dark Matter: Physics beyond the standard model?

Dark Energy: Fundamental zero point energy fluctuations

$$H = \frac{1}{2}\sum \hbar\omega_k \left(a^+ a + a a^+\right) = \sum \hbar\omega_k a^+ a + \sum_k \frac{1}{2}\hbar\omega_k$$

$$\rho_{vac} = \frac{1}{V}\sum_k \frac{1}{2}\hbar\omega_k \approx \int_0^{M_P} \frac{k^3}{h^3} dk \propto M_P{}^4 \approx \left(10^{28}\,\mathrm{eV}\right)^4 >> \rho_\Lambda \approx \left(2\times 10^{-3} eV\right)^4$$

Even with SUSY (1TeV) $\rho_{vac} \approx \int_0^{1TeV} \frac{k^3}{h^3} dk \approx \left(10^{12}\,\mathrm{eV}\right)^4 >> \rho_\Lambda \approx \left(2\times 10^{-3} eV\right)^4$

Supersymmetry

Bold Assumption

Symmetry between bosons and fermions

Lagrangian invariant when turning bosons into fermions and vice versa

Motivations

1) Solve in an elegant way the mass instability problems (naturalness)

e.g,. Prevent the masses of the Higgs or W to go to the Planck mass

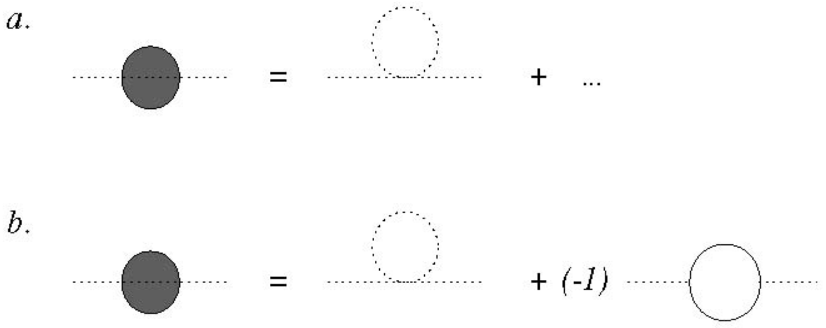


Figure 5. Radiative corrections to the mass of a scalar particle. The dotted curves are scalar propagators, and the solid curves are fermion propagators. (a) Diagrams with no supersymmetry, and (b) Diagrams with supersymmetry.

Every boson loop
is compensated by a fermion
loop equal in magnitude and
opposite.=> only logarithmic
divergence
No need for a unnatural cutoff

Note: another solution is not
to have a scalar Higgs: dynamical
electroweak symmetry breaking
e.g. Technicolor
difficult

2) Provide a first step for the quantization of gravity
In practice, not smooth enough: need supersymmetric strings="Superstring"

3) g-2 of the μ seems to indicate new physics
2-3 σ!

$$\delta a_\mu = \begin{array}{l} 27 \pm 8\ 10^{-10} (e^+e^-) \\ 19 \pm 8\ 10^{-10} (\tau, e^+e^-) \end{array}$$

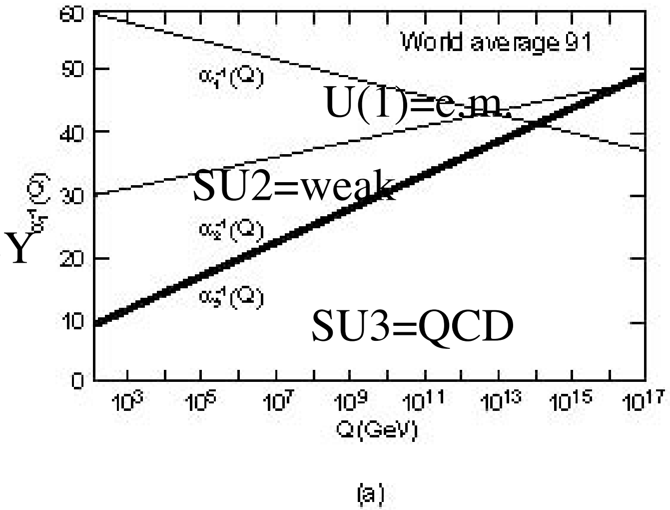
$$-4\ 10^{-10}\ \text{(Melnikov-Vainshtein)}$$

Supersymmetry

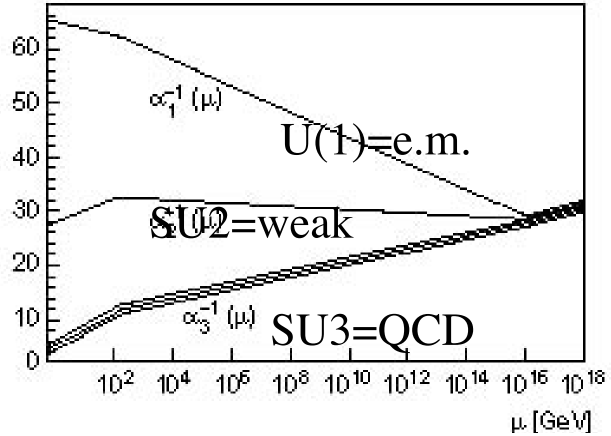
3) Convergence of coupling constants

J. Ellis, S. Kelley and D.V. Nanopoulos, *Phys.Lett.* **260** (1991) 131;
U. Amaldi, W. de Boer and H. Furstenau, *Phys.Lett.* **B260** (1991) 447;

without SUSY



with SUSY



4) Mass of the neutrino

Within see-saw framework

strong indication
for GUT scale

Additional Dimensions

Along idea of Arkani Hamed et al. Phys.Lett. B429 (1998) 263

Gravity is weak because of large additional dimensions

gravitons lives in whole space, other fields on 4D brane

Size ≈ 100μm

Kaluza Klein tower of excitations

Stability of proton => requires lowest one to be stable (new parity)

Usually lightest has spin 1 (≠ neutralino in SUSY spin 1/2) in TeV range

2 Versions

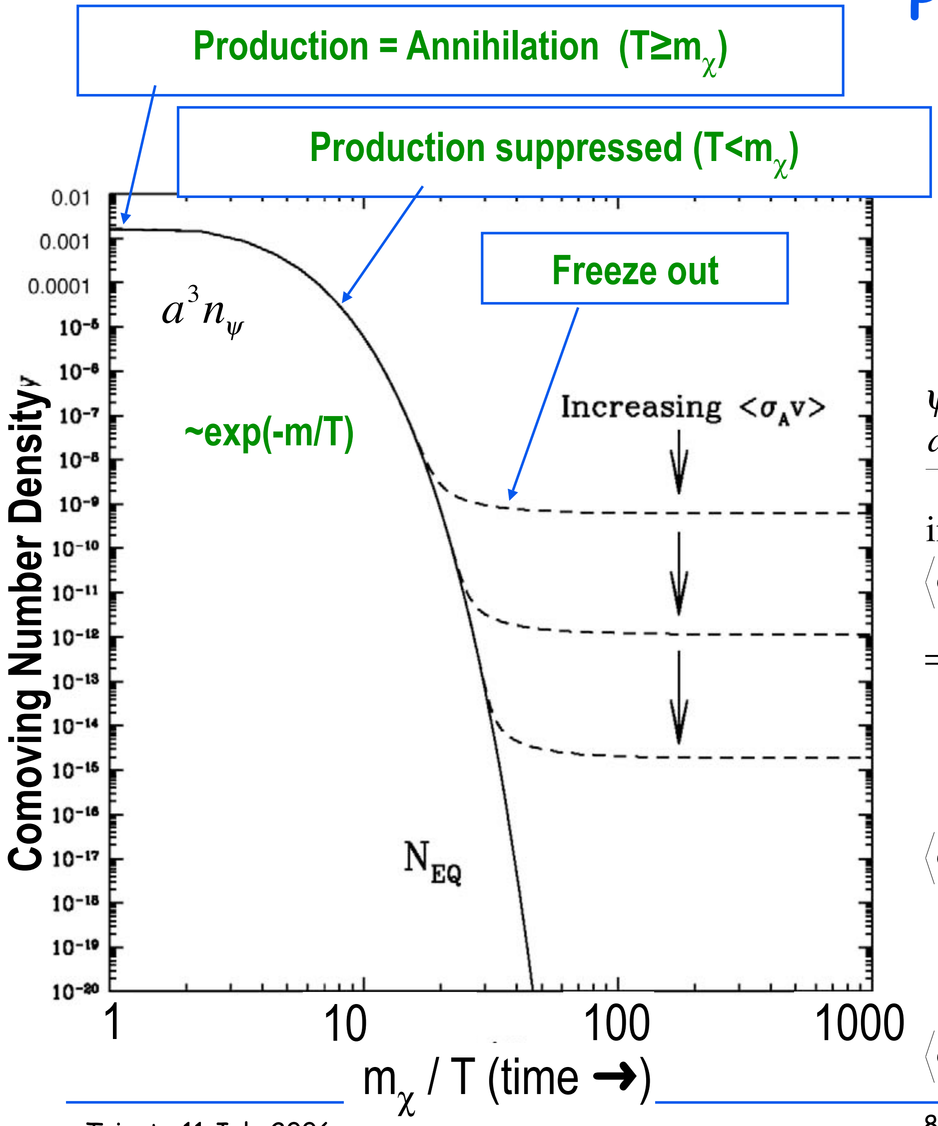
Flat, compact (often chosen to have same R)

H.C. Cheng, J.L. Feng and K.T.Matchev, Phys. Rev. Lett., **89**, 211301 (2002).

Warped (à la Randall-Sundrum)

K. Agashe and G.Servant, hep-ph/0403143;
G.Servant and T.M.P.Tait, Nucl. Phys., **B650**, 391 (2003);

Thermal Relics



Production = Annihilation (T≥m$_\chi$)

Production suppressed (T<m$_\chi$)

Freeze out

Particles in thermal equilibrium in early universe

e.g. $\psi\bar{\psi} \leftrightarrow X\bar{X}$

How the density evolve (e.g. Kolb,Turner)

Let us consider a 2 body annihilation channel (can be generalized)

$\psi\bar{\psi} \leftrightarrow X\bar{X}$ where we assume the X to stay in equilibrium

$$\frac{dn_\psi}{dt} + 3\frac{\dot{a}}{a} n_\psi = -\left\langle \sigma_{\psi\bar{\psi}\to X\bar{X}} |v| \right\rangle n_\psi^2 + \left\langle \sigma_{X\bar{X}\to\psi\bar{\psi}} |v| \right\rangle n_{XEQ}^2$$

in equilibrium

$$\left\langle \sigma_{X\bar{X}\to\psi\bar{\psi}} |v| \right\rangle n_{XEQ}^2 = \left\langle \sigma_{\psi\bar{\psi}\to X\bar{X}} |v| \right\rangle n_{\psi EQ}^2$$

$$\Rightarrow \frac{dn_\psi}{dt} + 3\frac{\dot{a}}{a} n_\psi = -\left\langle \sigma_{\psi\bar{\psi}\to X\bar{X}} |v| \right\rangle \left(n_\psi^2 - n_{\psi EQ}^2 \right)$$

Relativistic

Bosons

Fermions

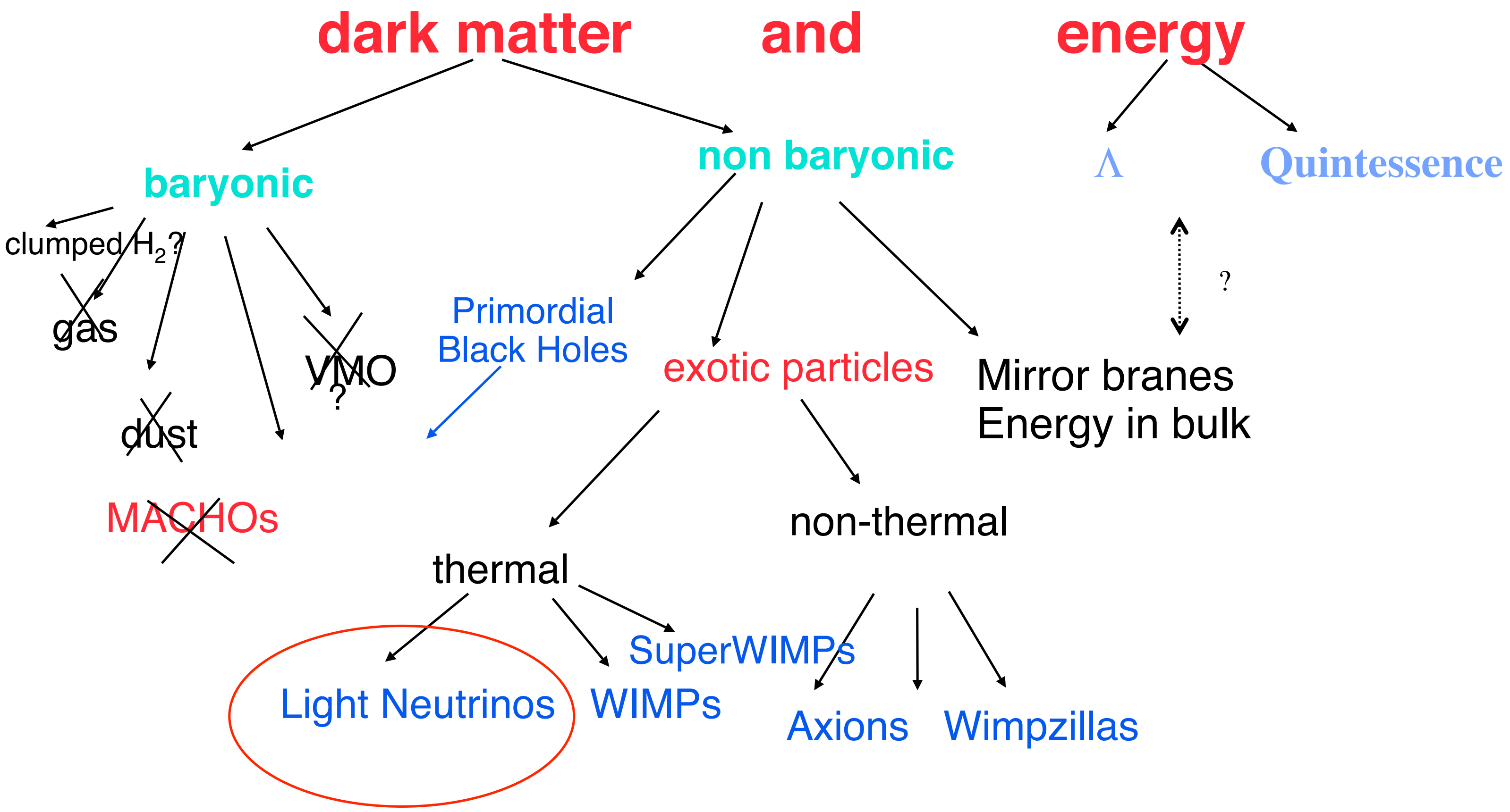
$$\left\langle \sigma_{\psi\bar{\psi}\to X\bar{X}} |v| \right\rangle \text{ large enough } n_\psi = n_{\psi EQ} \propto \begin{cases} \left[\begin{pmatrix} 1 \\ 3/4 \end{pmatrix} g \dfrac{\zeta(3)}{\pi^2 \hbar^3 c^3} (kT)^3 \right] \\ \exp\left(-\dfrac{\varepsilon}{k_B T} \right) \end{cases}$$

Non relativistic

$$\left\langle \sigma_{\psi\bar{\psi}\to X\bar{X}} |v| \right\rangle \text{ too small } \frac{dn_\psi}{dt} + 3\frac{\dot{a}}{a} n_\psi = 0 \quad \Rightarrow n_\psi \propto a^{-3}$$

A map of the territory!

Current candidate explanations: systematic mapping



dark matter and energy

baryonic

clumped H_2?

~~gas~~

~~dust~~

~~MACHOs~~

~~VMO~~ ?

Primordial Black Holes

non baryonic

exotic particles

thermal

Light Neutrinos

WIMPs

SuperWIMPs

non-thermal

Axions

Wimpzillas

Mirror branes
Energy in bulk

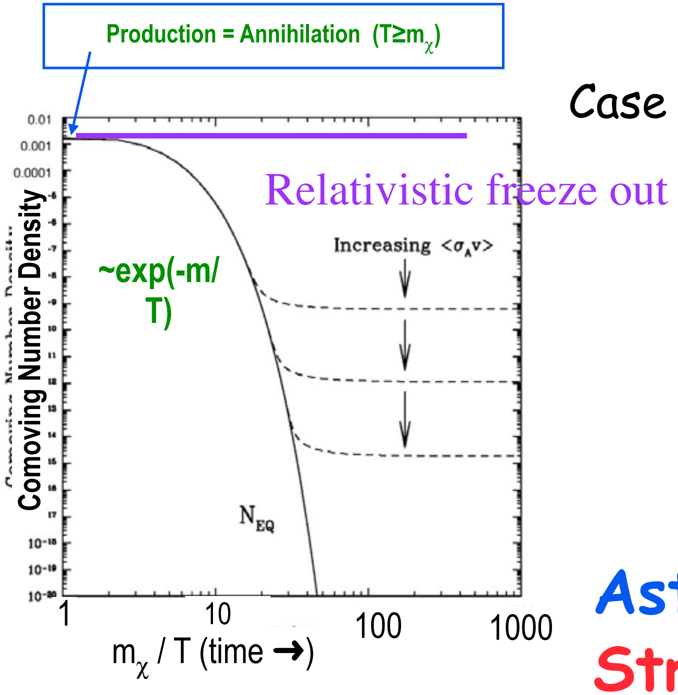
Λ

Quintessence

?

Light Massive Neutrinos

Thermal equilibrium in early universe
+ Decoupling when relativistic



Case of the light week interactions neutrinos

number ≈ number of photons
density <-> mass

$$\Omega_x h^2 = \frac{\sum_i m_{\nu_i}}{94\ \text{eV}}$$

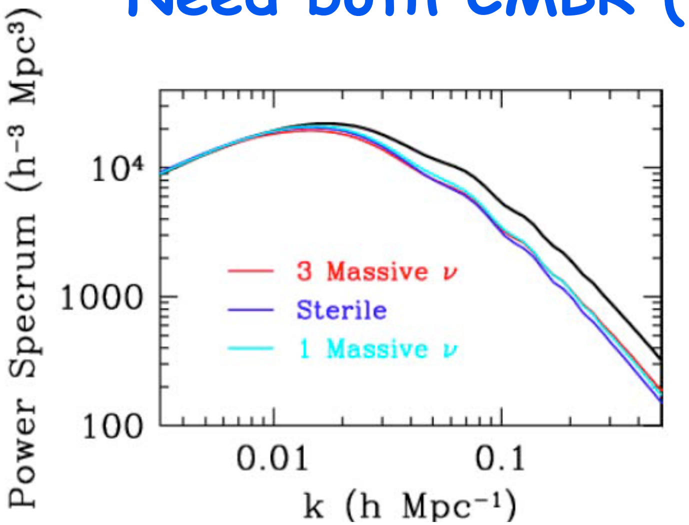
40 eV /c^2 => Ω≈1

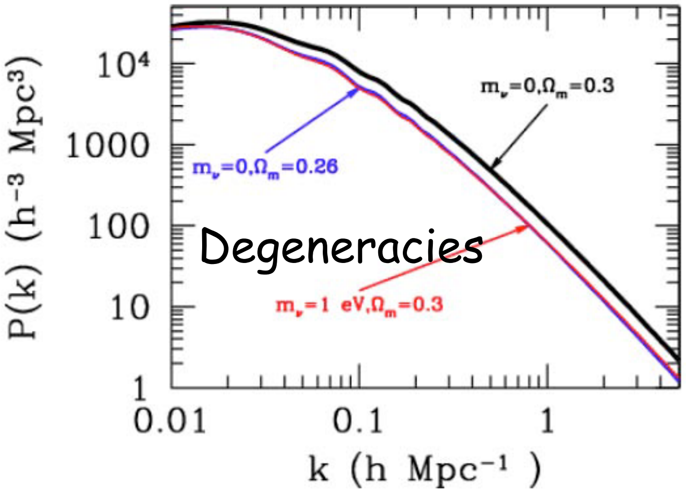
Astrophysics + laboratory =>
Strong evidence for massive neutrinos

Mostly limits on direct mass measurement (Laboratory, Cosmology)

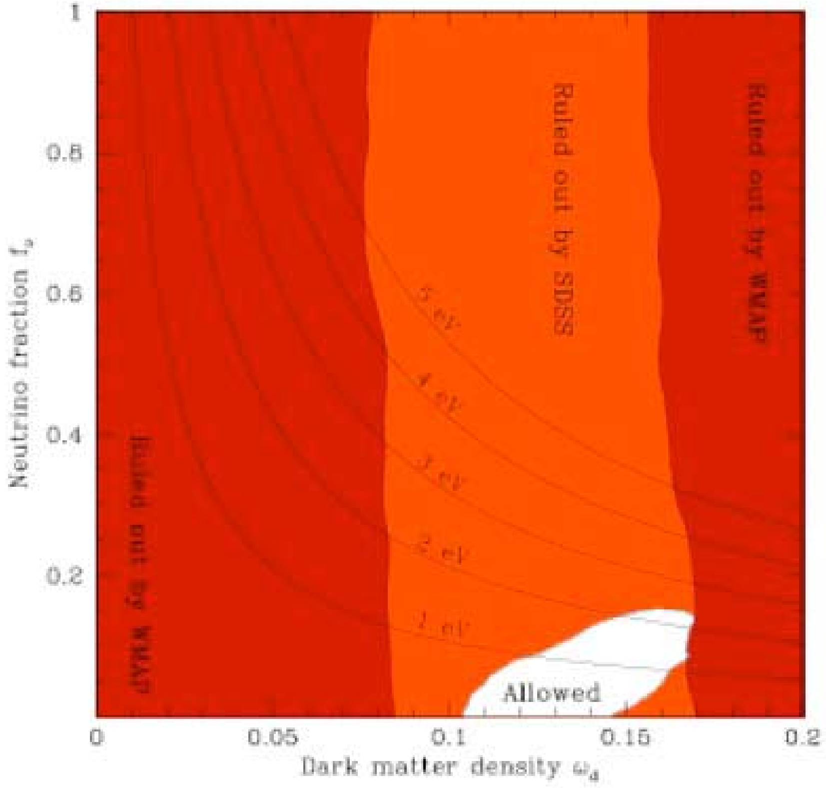
Fluctuations at small scales

Need both CMBR (to fix amplitude) and LSS





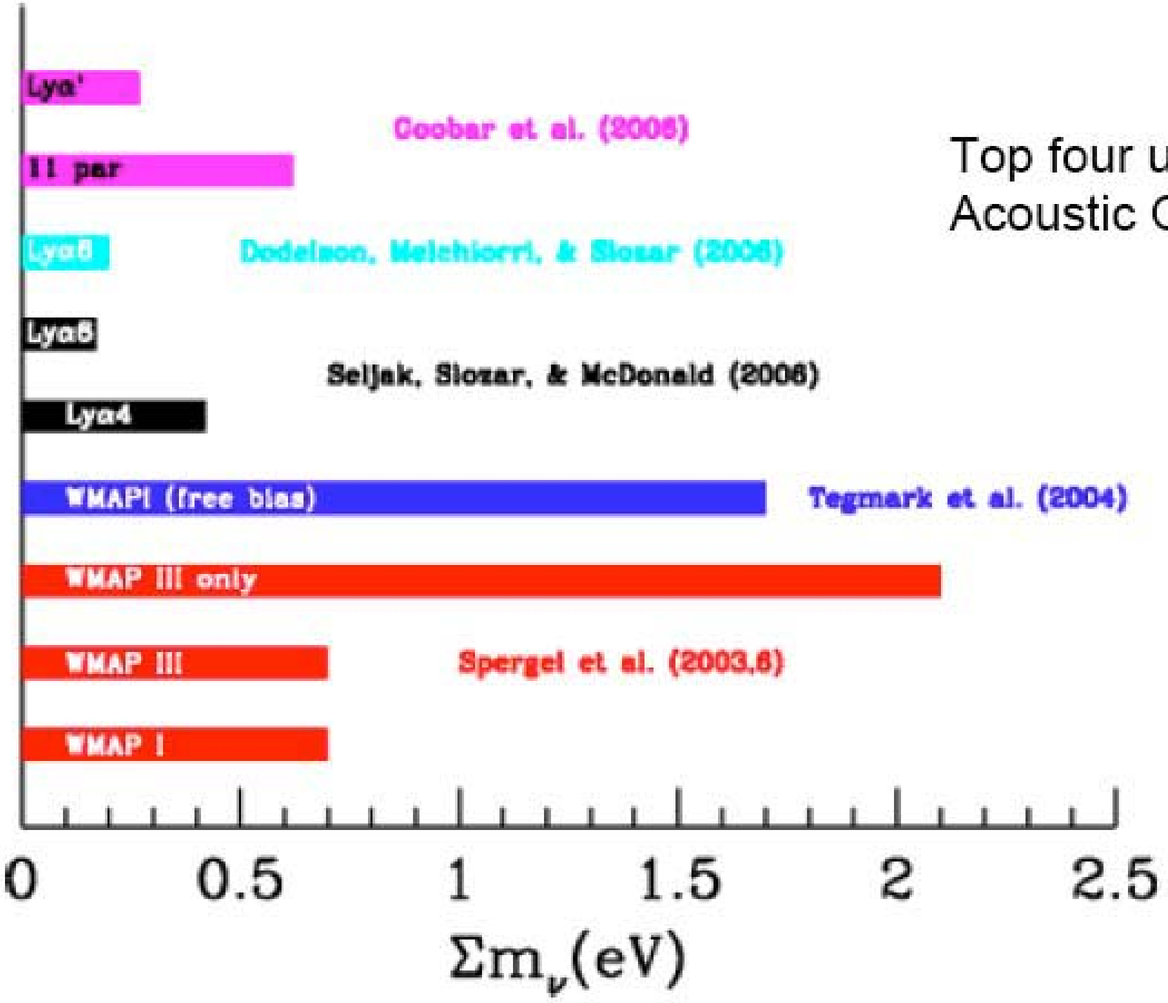
Degeneracies



Tegmark, et al. 2004

Cosmological Constraints

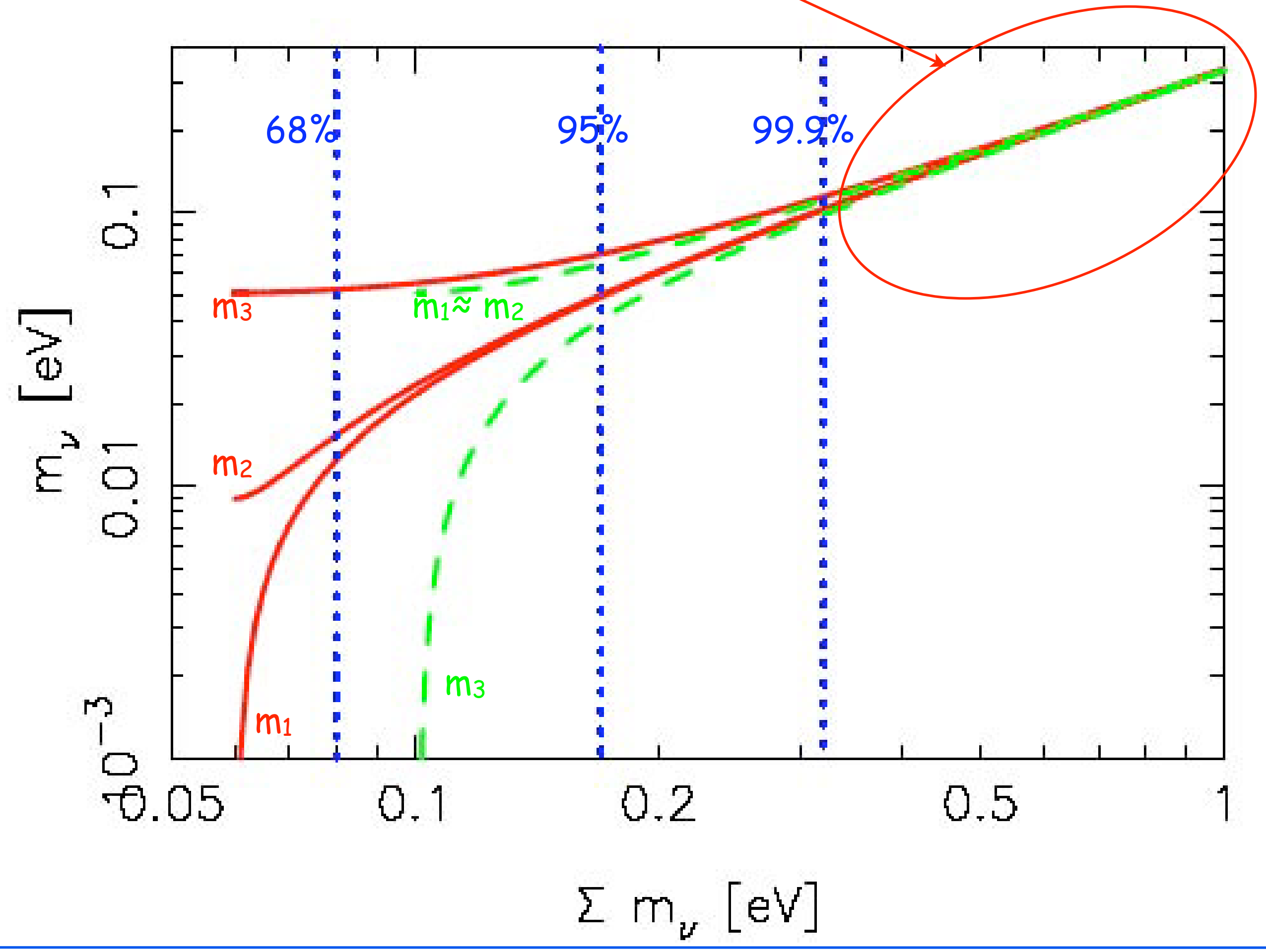
Dodelson Neutrino 06 Santa Fe



Top four use Baryon Acoustic Oscillations

Degenerate Scenario Disfavored

Seljak, Slozar, McDonald astro-ph/0604335



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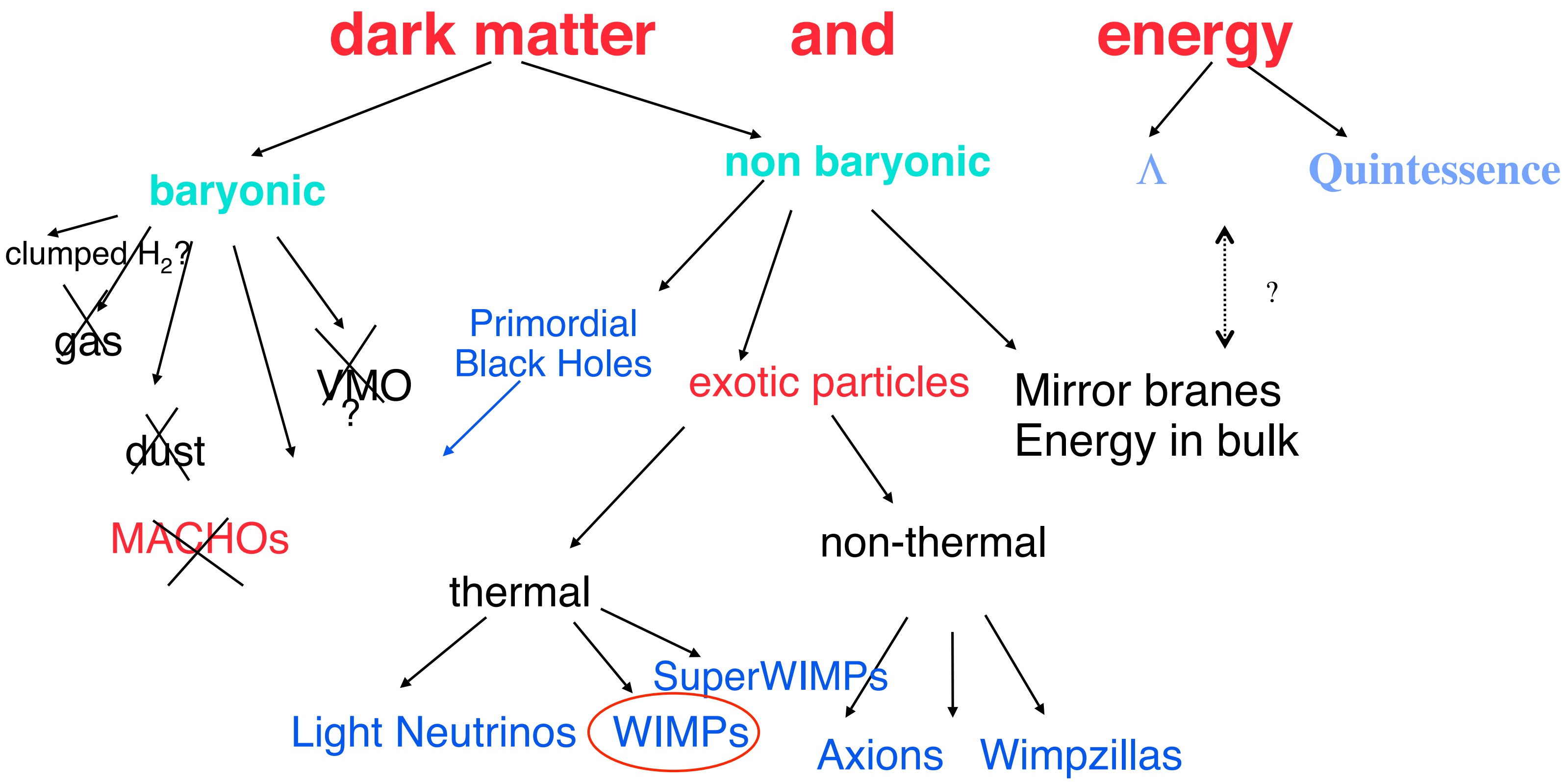

dark matter and energy

baryonic

clumped H_2?

~~gas~~

~~dust~~

~~MACHOs~~

~~VMO~~ ?

non baryonic

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exotic particles

thermal

Light Neutrinos

WIMPs

SuperWIMPs

non-thermal

Axions

Wimpzillas

Mirror branes
Energy in bulk

Λ

Quintessence

?

Weakly Interactive Massive Particles

Generic Class

Particles in thermal equilibrium + decoupling when nonrelativistic

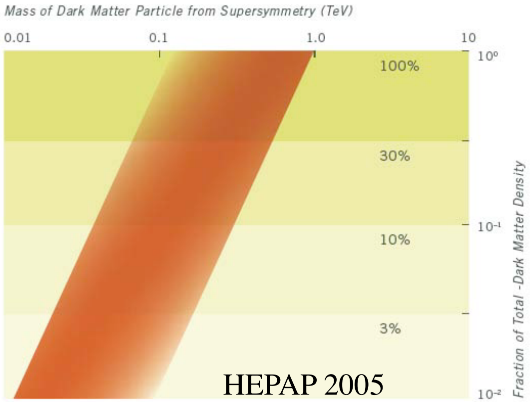
Freeze out when annihilation rate ≈ expansion rate

$$\Rightarrow \Omega_x h^2 = \frac{3\cdot 10^{-27}\,cm^3/s}{\langle \sigma_A v \rangle} \Rightarrow \sigma_A \approx k\frac{\alpha^2}{M^2_{EW}}$$

By crossing $\sigma_{\chi q \to \chi q} = k'\frac{\alpha^2}{M^2_{EW}}$

Cosmology points to W&Z scale

Inversely standard particle model requires new physics at this scale (e.g. supersymmetry) => significant amount of dark matter



HEPAP 2005

Note: not only supersymmetry

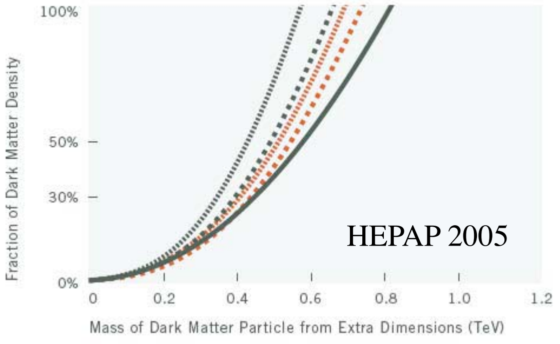
Ex. Additional dimensions

WIMP could be stable Kaluza Klein excitation in additional dimensions (compact or warped)

As radius of additional dimension fixed by electro-weak scale or relic density

cross sections also in the same region

Typically spin 1 instead of 1/2

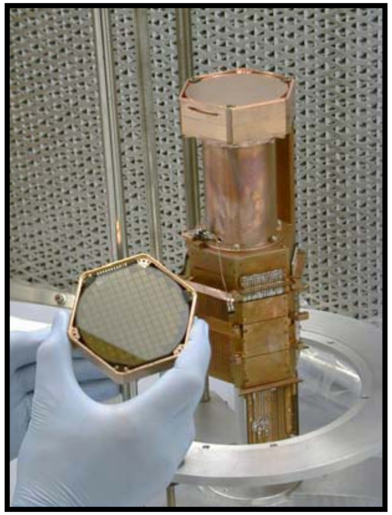


HEPAP 2005

Detection Schemes

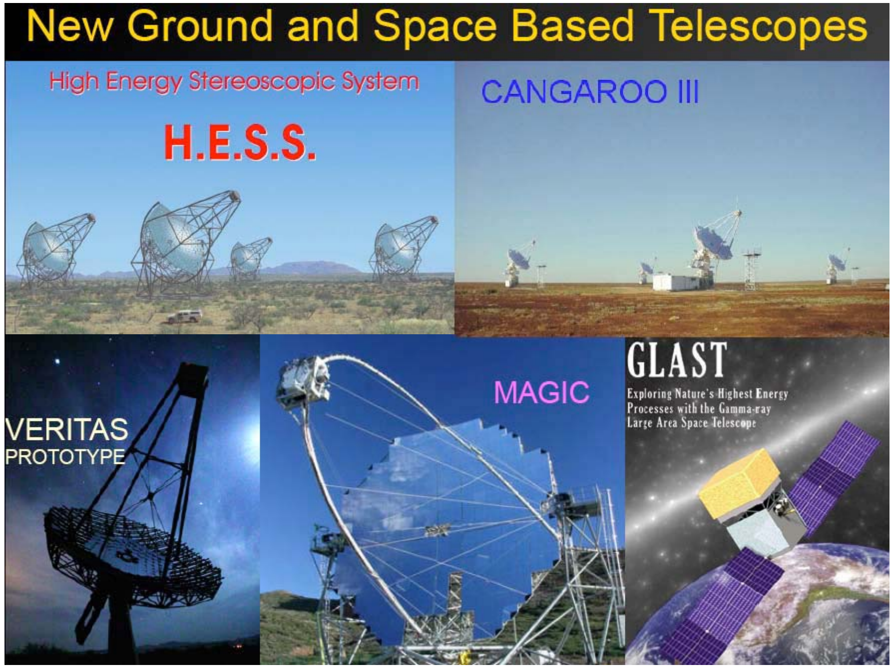
Elastic scattering: “Direct Detection”

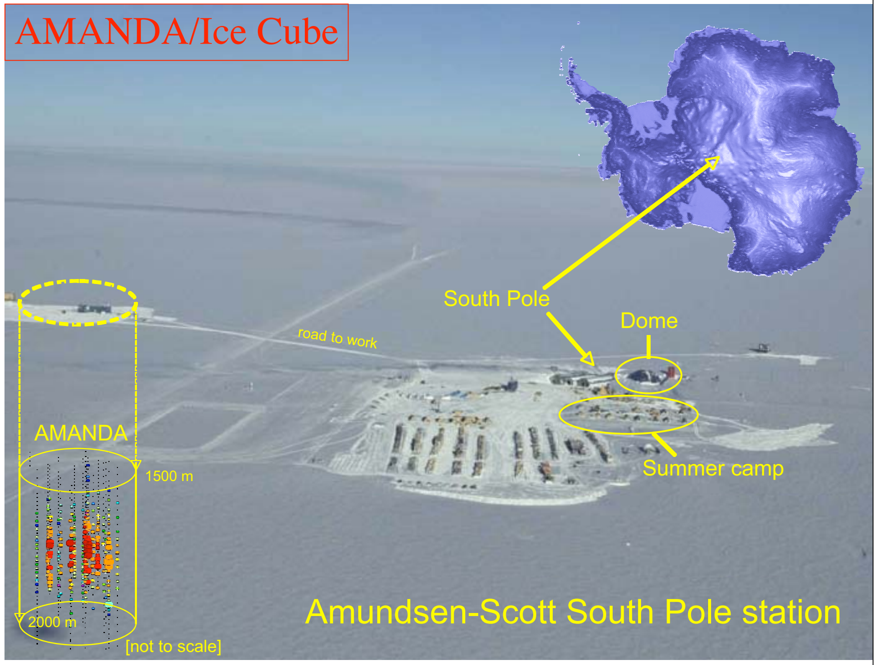
halo is full of WIMPs , which can scatter on a suitable target



Annihilations in halo: “Indirect Detection”

Capture in sun
+ annihilation into ν





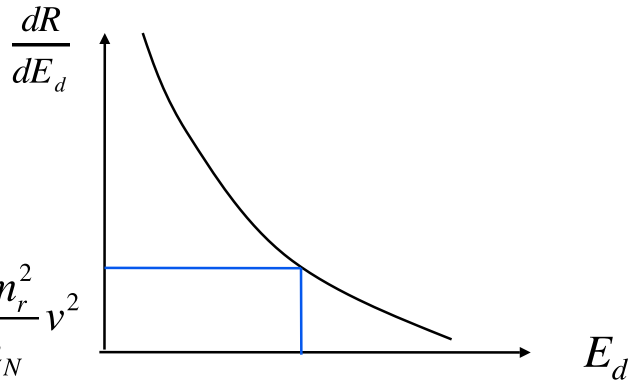
Elastic Scattering Rates

Energy deposition

cf J.D Lewin and P.F. Smith AstroPart. Phys. 6(1996) 87

Simple non relativistic calculation

$$E_d = \frac{q^2}{2m_N} = \frac{m_\chi^2 m_N}{\left(m_\chi + m_N\right)^2} v^2 \left(1-\cos\theta^*\right) = \frac{m_r^2}{m_N} v^2 \left(1-\cos\theta^*\right)$$



s-wave scattering:

for given velocity v, flat between 0 and $E_{d\max} = \frac{2m_r^2}{m_N} v^2$

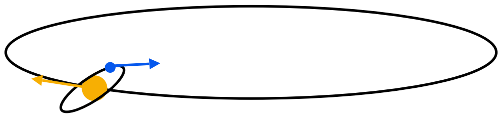
Convolution with velocity distribution in the halo

If Maxwellian in galaxy rest frame

$$f(v')d^3v' = \frac{1}{v_o^3 \pi^{3/2}} \exp\left(-\frac{v'^2}{v_o^2}\right) d^3v'$$

differential rate per unit mass

$$\boxed{\frac{dR}{dE_d} = \frac{\sigma_o \rho_o}{4 v_e m_\chi m_r^2} F^2(q) \left[\mathrm{erf}\left(\frac{v_{\min} + v_e}{v_o}\right) - \mathrm{erf}\left(\frac{v_{\min} - v_e}{v_o}\right) \right]}$$



where

$$\sigma_o = \int_0^{4m_r^2 v^2} \frac{d\sigma(q=0)}{d\left(|\vec{q}|^2\right)} d\left(|\vec{q}|^2\right) = \text{independent of v}$$

ρ_o = local density of halo

$$v_{\min} = \left(\frac{E_d m_N}{2m_r^2}\right)^2$$

Annual modulation ±4.5%

$$v_e = v_o \left[1.05 + 0.07 \cos\left(\frac{2\pi(t - \text{2ndJune})}{\text{1yr}}\right)\right]$$

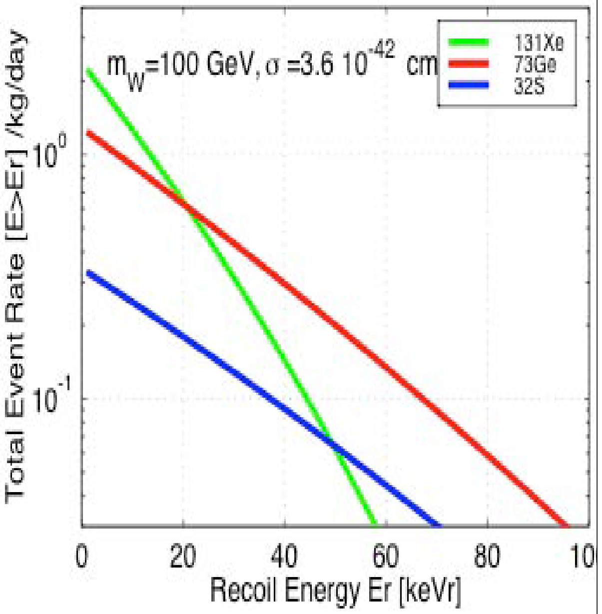
Coherent Scattering

The energy transfer is small compared to inverse size of nucleus

Conventionally

- "Spin independent" : additive quantum number is mass, number of protons or neutrons!

  Usually scalar interaction dominates Cross sections≈A^2 + "filled sphere" form factor



- "Spin dependent" : additive quantum number is spin

  First order interaction of Majorana spin 1/2 particle is axial vector -> spin at low energy

  depends on spin content of the nucleus (Most nuclei spinless)

  Spin is never very large: usually <2nd order

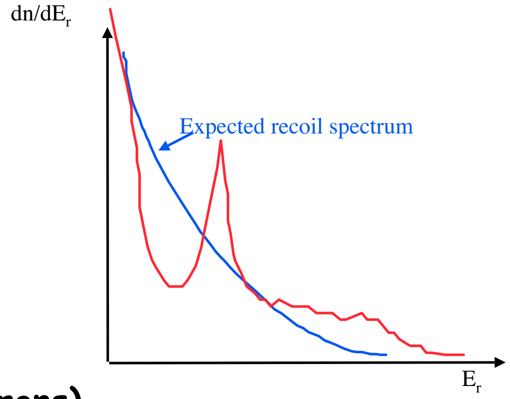
  Uncertainties on spin content of nucleon + "Peripheral" form factor

Direct Detection

Elastic scattering

Expected event rates are low
(<< radioactive background)
Small energy deposition (≈ few keV)
<< typical in particle physics

Signal = nuclear recoil (electrons too low in energy)
≠ Background = electron recoil **(if no neutrons)**



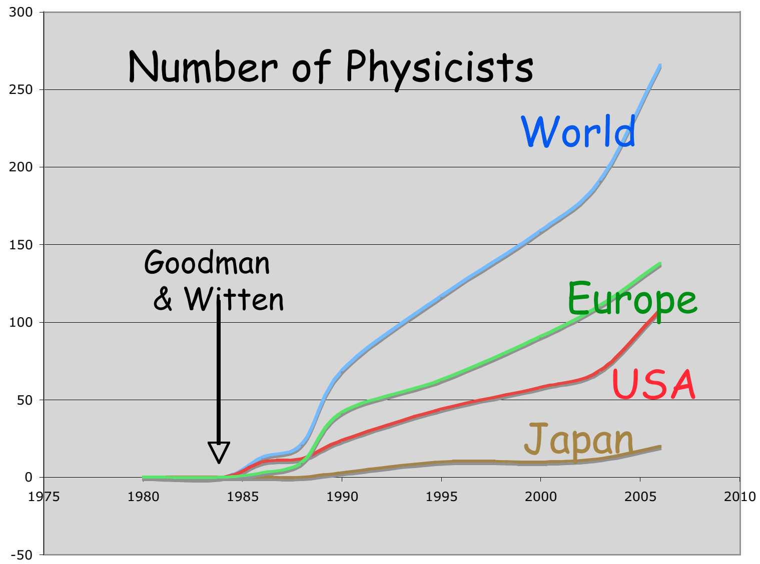
Signatures

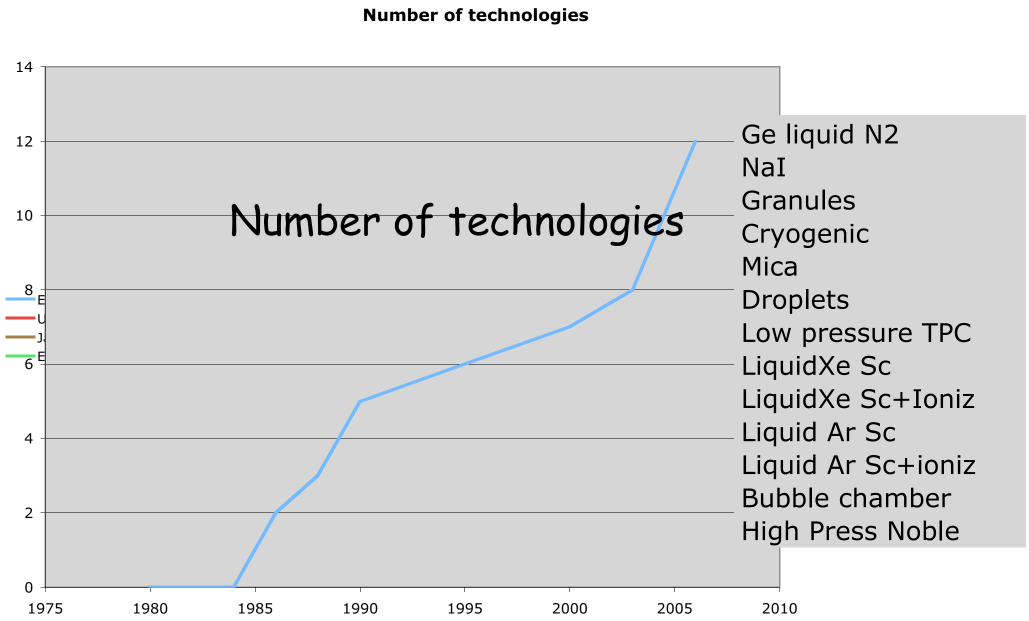
- Nuclear recoil
- Single scatter ≠ neutrons/gammas
- Uniform in detector

Linked to galaxy

- Annual modulation (but need several thousand events)
- Directionality (diurnal rotation in laboratory but 100 Å in solids)

Fast Expanding Community





Ge liquid N2
NaI
Granules
Cryogenic
Mica
Droplets
Low pressure TPC
LiquidXe Sc
LiquidXe Sc+Ioniz
Liquid Ar Sc
Liquid Ar Sc+ioniz
Bubble chamber
High Press Noble

Detection Techniques

Method	Detection	Electron recoil	Nuclear recoil	Discrimination	Groups
Scintillation e.g. NaI	Light	≈200eV/ photoelectron	I: ≈1600eV/ photoelectron	Pulse shape	DAMA, UK NaI, Elegant
Germanium @liquid nitrogen	Electrons + holes	3eV/carrier	9eV/carrier	No	Heidelberg-Moscow
Gas Ionization	electrons	20eV/electron	60eV/electron	Track Length	DRIFT
High pressure gas	electrons+light	20eV/electron	60eV/electron	Ionization +Scintillation	UCLA/Texas
Liquid Xe Scintillation	Light	≈200eV/photo electron	≈1600eV/photo electron	Pulse shape 4ns/22ns	Rome, ZEPLIN I, XMASS
Liquid Xe Ionization + Scintillation	electrons	15eV/electron ≈200eV/p.e.	45eV/electron ≈1600eV/p.e.	Ionization Yield Pulse shape	ZEPLIN II-II-IV XENON
Liquid Ar Scintillation	Light	500eV/p.e.	600-2000 eV/p.e ?	Pulse shape 6ns/1.6μs	MiniClean
Liquid Ar Ionization + Scintillation	electrons	20eV/electron 500eV/p.e.	60eV/electron 600-2000 eV/p.e ?	Ionization Yield Pulse shape	WArp ARP
Phonon mediated	phonons	100μeV/phonon	100μeV/phonon	No	Cuerocino (2β) CRESST I
Ionization/phonons @ low temperature	Electrons + holes Phonons	3eV/carrier 100μeV/phonon	9eV/carrier 100μeV/phonon	Ionization yield Phonon timing/ shape	CDMS,SCDMS Edelweiss
Scintillation/phonons @ low temperature	Light Phonons	100eV/ photoelectron	on O 900eV/ photoelectron	Scintillation yield at least on O	CRESST II
Superheated Droplets	Sound	not sensitive	10keV-100keV tunable	energy density sensitive to alphas	Simple Picasso
Bubble chamber	CCD camera	not sensitive	10keV-100keV tunable	energy density sensitive to alphas	COUPP