Bernard Sadoulet
Dept. of Physics /LBNL UC Berkeley
UC Institute for Nuclear and Particle
Astrophysics and Cosmology (INPAC)
UC Dark Matter Initiative

Direct Detection of Galactic Dark Matter

Perspective

- 3 paradigms (Axions, "SUSY" WIMPs, Dark Sector:e.g., asymmetric dark matter)

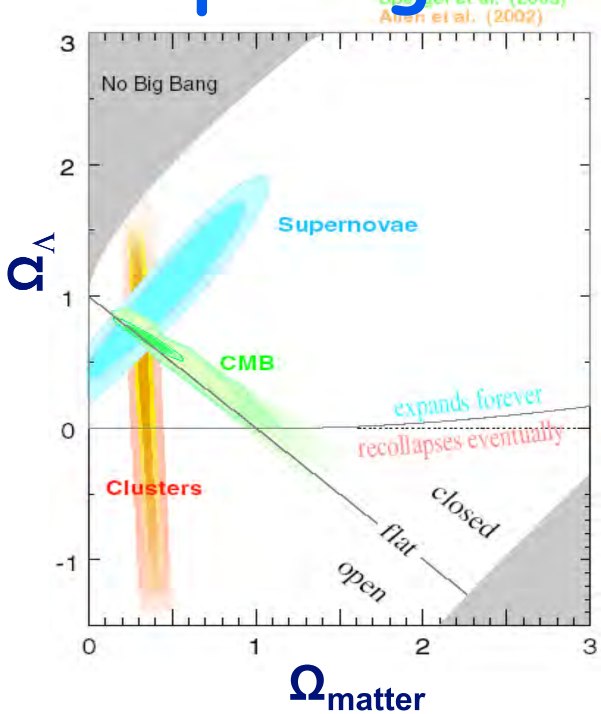
Axions

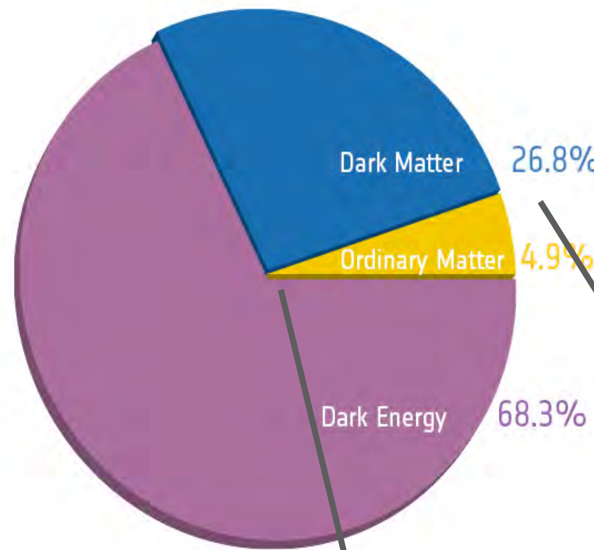
WIMP Direct Detection

- As one of 4 complementary approaches: Cosmological observations, scattering, annihilation and production at accelerators
- Elastic scattering
- Experimental methods
- "Weak Scale" WIMPs
- Low Mass WIMPs
- The future of direct detection
  - Focus both on high mass and low mass
  - Need for at least 2 technologies -> can approach fundamental neutrino limit

Standard Model of Cosmology

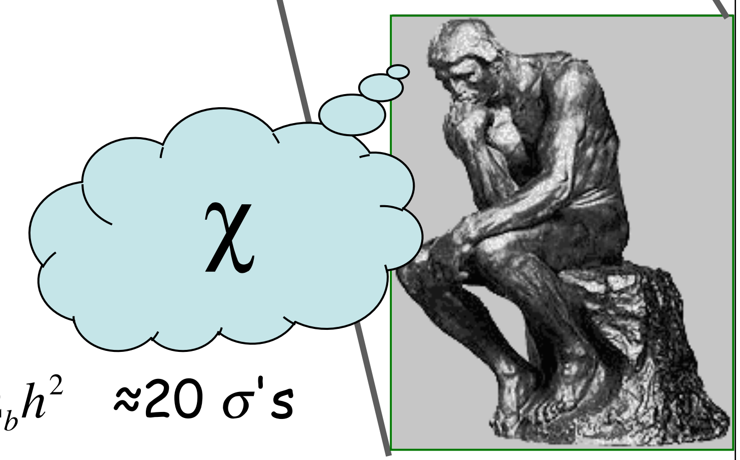
A surprising but consistent picture





Not ordinary matter (Baryons)

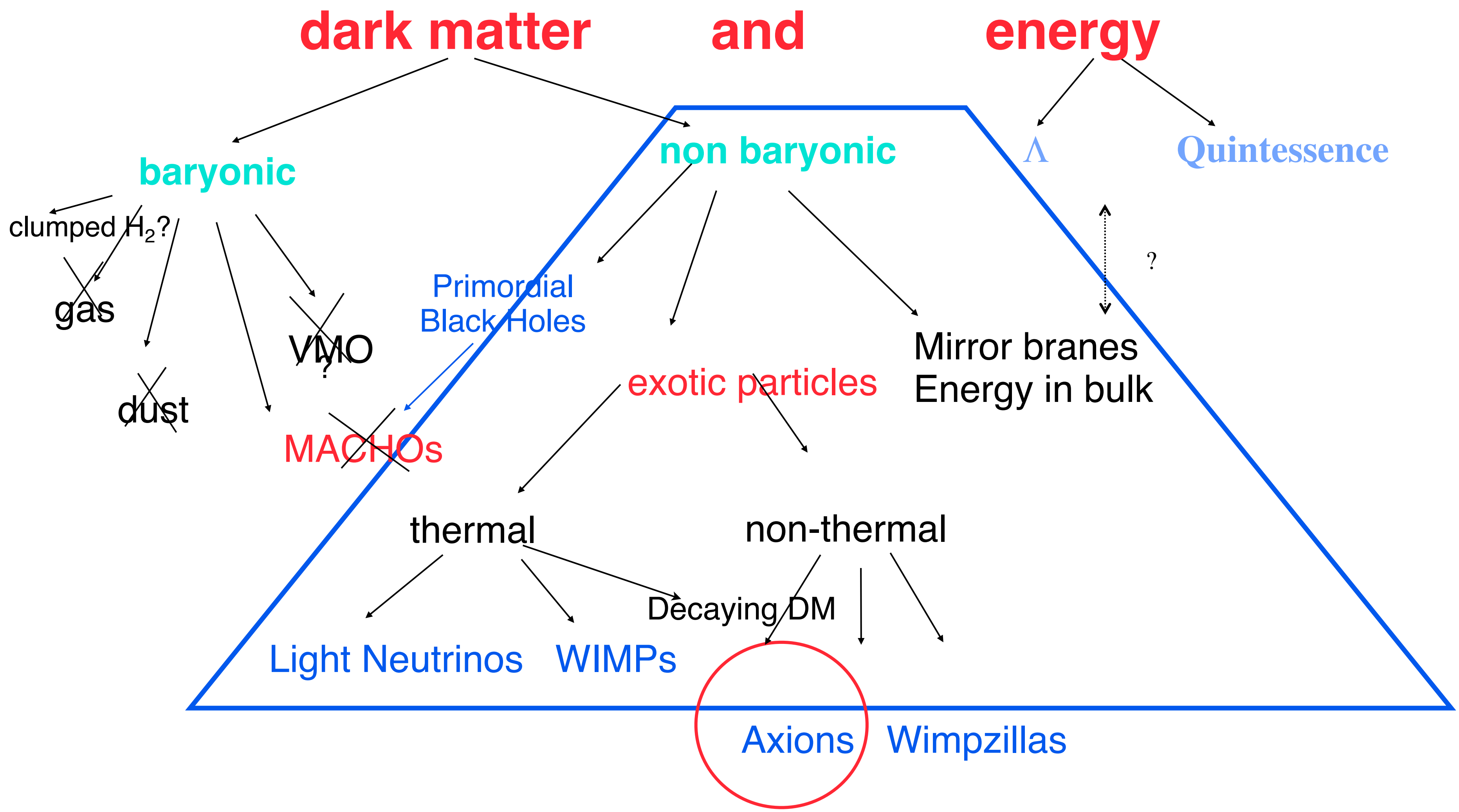
$$\Omega_m >> \Omega_b = 0.049 \pm 0.001 \text{ from} \left| \begin{array}{l} \text{Nucleosynthesis} \\ \text{WMAP/Planck} \end{array} \right.$$



+ internally to WMAP/Planck $\Omega_m h^2 \neq \Omega_b h^2$ ≈20 σ's

Mostly cold: Not light neutrinos≠ small scale structure

Deciphering the Nature of Dark Matter



Three Paradigms

Axions <= Strong CP problem

Peccei Quinn solution: dynamic restoration of CP

Weak scale WIMPs <= hierarchy problem

Freeze out when annihilation rate ≈ expansion rate

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

coincidence between Cosmology and Particle Physics

Dark Matter Hidden Sector: not necessarily weak scale

e.g., Asymmetric Dark Matter (Zurek) <-> Baryon-Antibarium asymmetry

WIMP-less Dark Matter (Feng)

Dark Photon (Arkani Hamed-Finkbeiner-Weiner), atomic DM, Self Interacting etc..

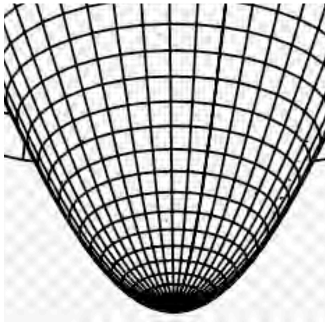
Intriguing but less predictive

Axion Cosmology

Peccei Quinn symmetry

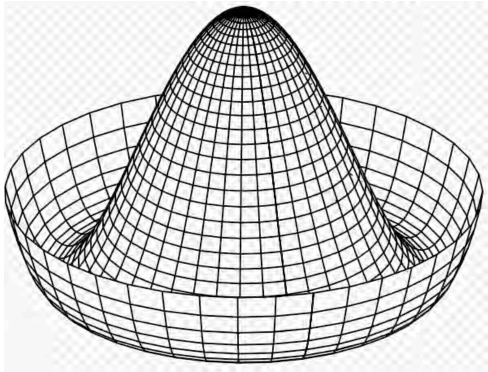
Sikivie ArXiv: astroph 0610440

CP violated by Quantum Chromodynamics
Way out Peccei-Quinn symmetry: dynamic restoration



$$\mathcal{L}_{\mathrm{QCD+a}} = -\frac{1}{4}G^a_{\mu\nu}G^{a\mu\nu} + \frac{1}{2}\partial_\mu a \partial^\mu a + \sum_q \bar{q}(i\gamma^\mu\partial_\mu - m_q)q + \frac{g_s^2}{32\pi^2}(\theta + \frac{a}{f_a})G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

Spontaneously broken Peccei Quinn symmetry -> Goldstone boson

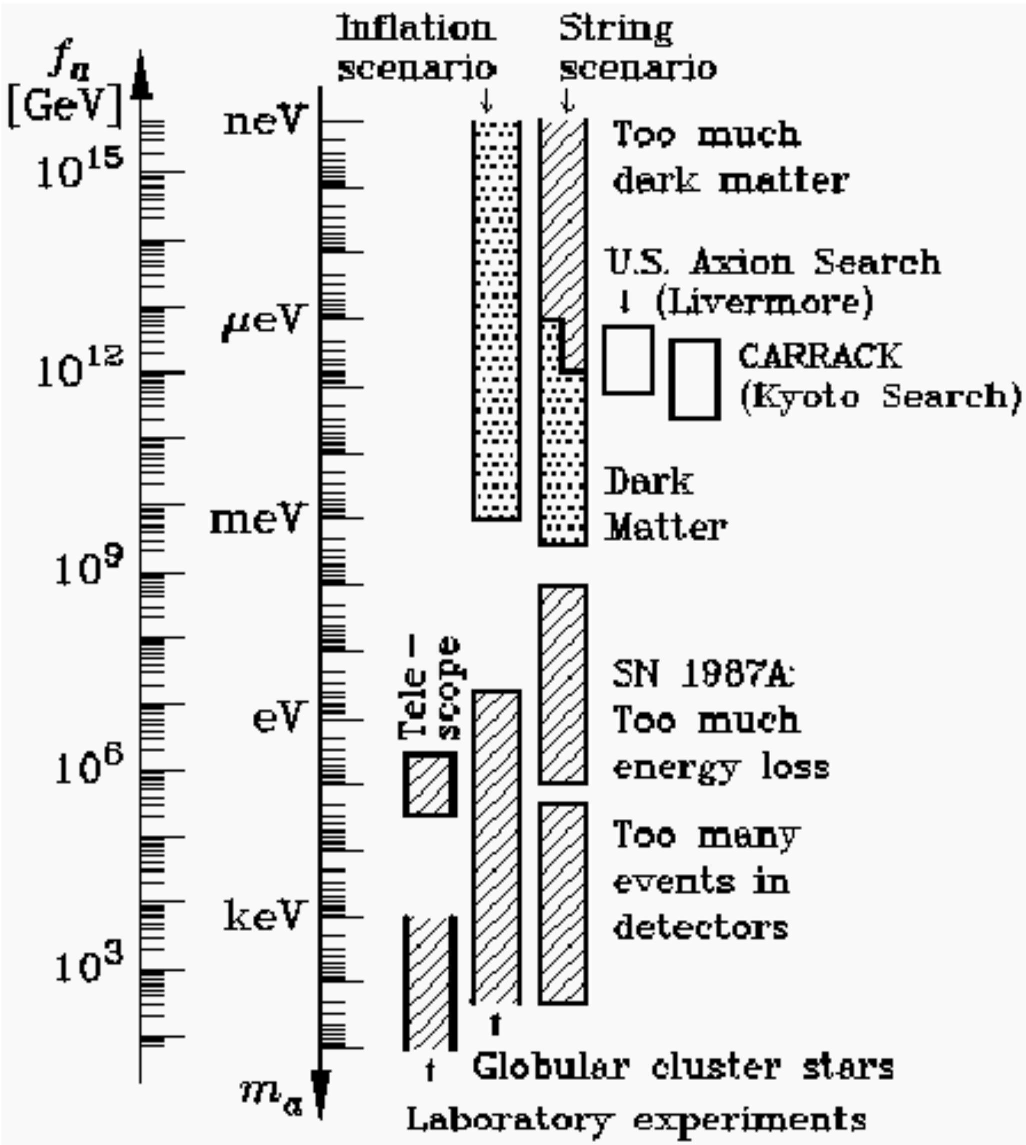


$$m_a \simeq 6\ \mu eV \left(\frac{10^{12}\ \mathrm{GeV}}{f_a}\right)$$

$f_a = v_a/N$. N is an integer characterizing the color

v_a = intermediate scale of physics
N=6 in Peccei-Quinn-Wilczek

Axion limits (Raffelt)



Axion Cosmology 2

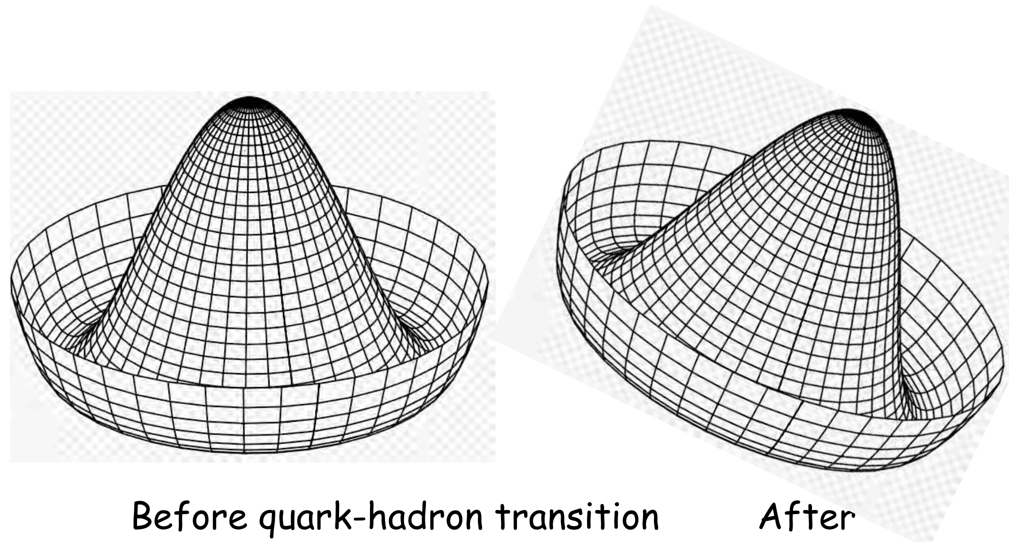
Thermal axions

a possibility

limits coming from same considerations as light neutrinos

Athermal axions

abundance depends on phase angle with respect to quark hadron transition tilting



Before quark-hadron transition After

PQ before inflation

only one angle in our horizon: which value?

PQ after inflation

Average over all the angles => well defined

Cosmic strings which radiate

How much density of axions from cosmic strings?

Axions

Invented to save QCD from strong CP violation

Current experimental limits are such that if they exist, they have to be cosmologically significant

Window: 10^{-6}-10^{-3} eV

Produced out of equilibrium

Theoretical discussion if Peccei Quinnn symmetry breaking occurs after inflation

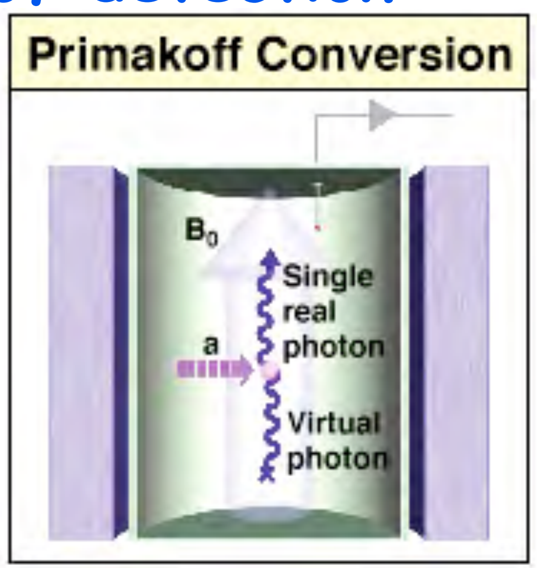
=> global strings which radiate axions. Technically difficult to compute (Shellard≠Sikivie)

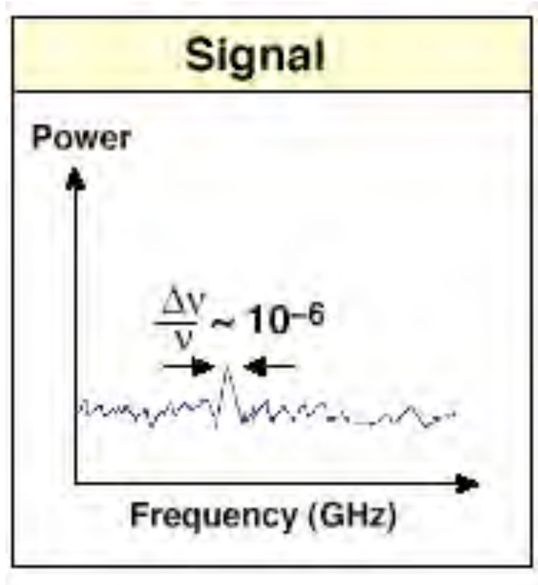
Loss mass region may be not favored

Method of detection

$$m_a = 0.62\text{eV}\left(\frac{10^7\,\text{GeV}}{f_a}\right)$$

$$L_{a\gamma\gamma} = \left(\frac{\alpha_{em}}{2\pi f_a}\right)\vec{E}.\vec{B}\times O(1)$$



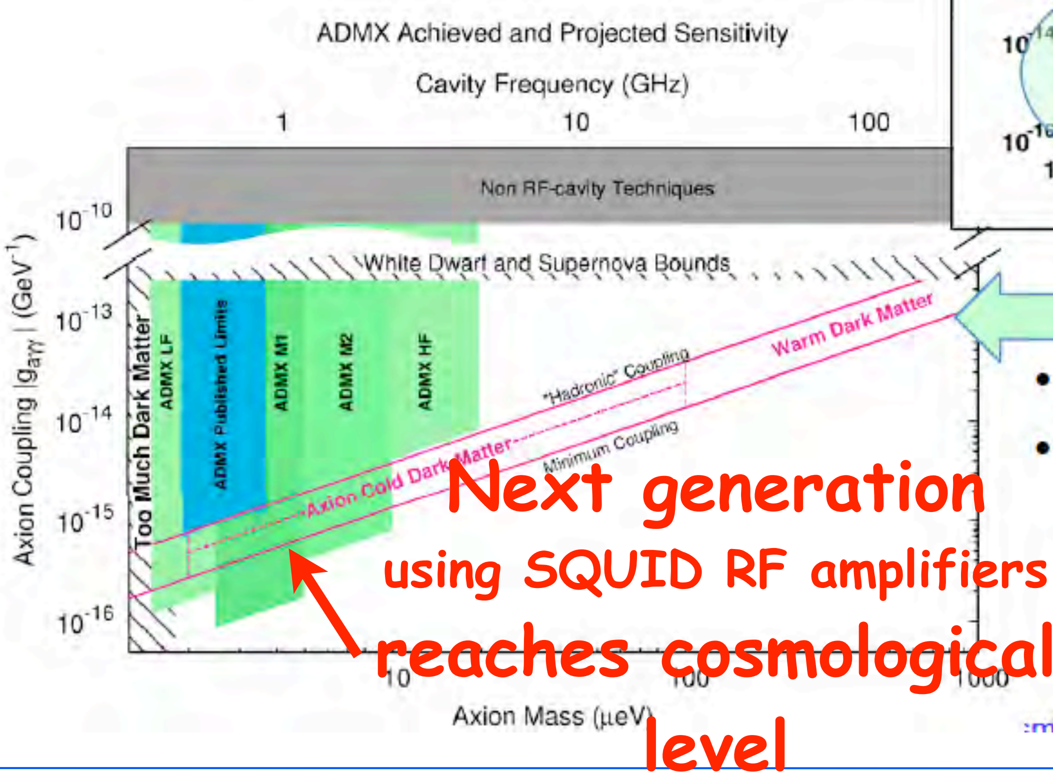


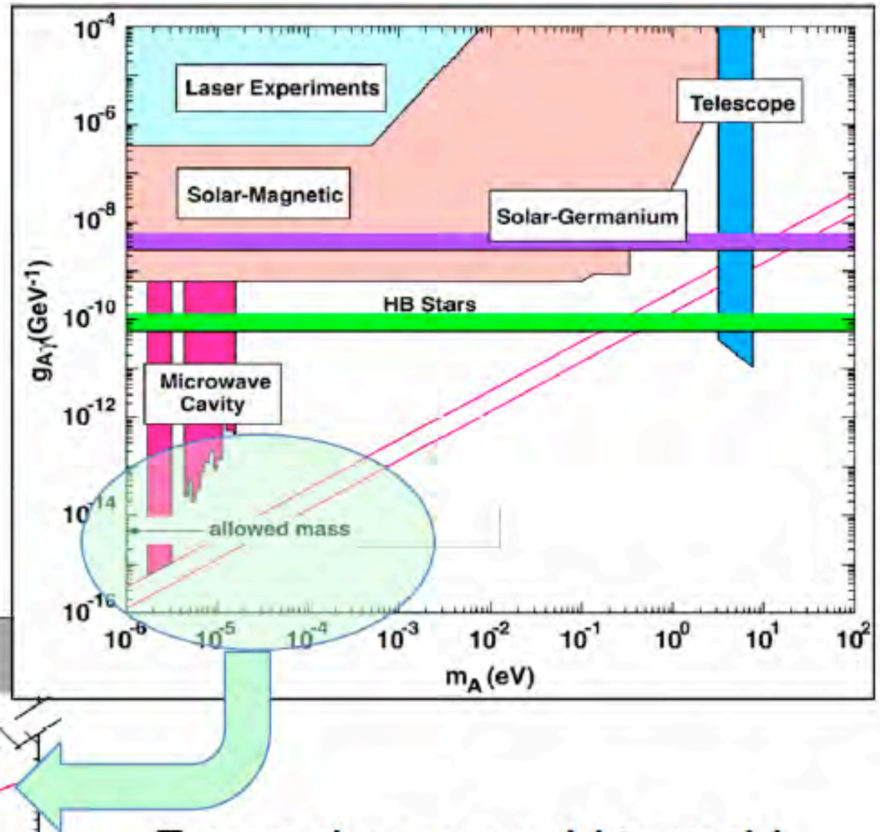
Tunable cavity: Most suitable for low mass region

Axions

Parameter space constrained by

- Supernova cooling
- White dwarf cooling
- Red giant energy transport
- Relic density
- Direct detection constraints

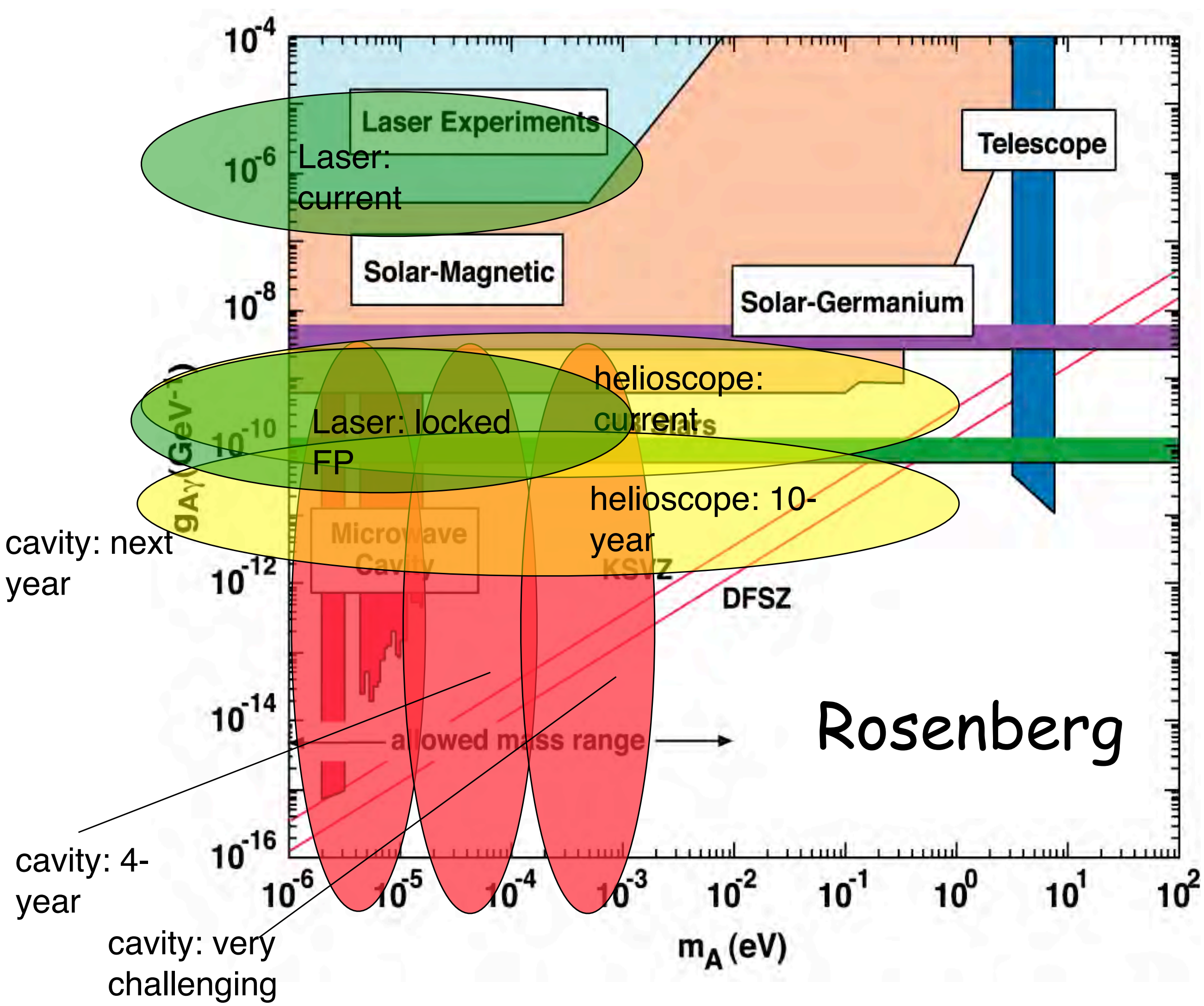




- Favored mass: μeV to meV
- ADMX is projected to cover the first of these three decades in its first year of operations, and the second decade over the following two years

:mic Frontier 25

Axions



3 directions

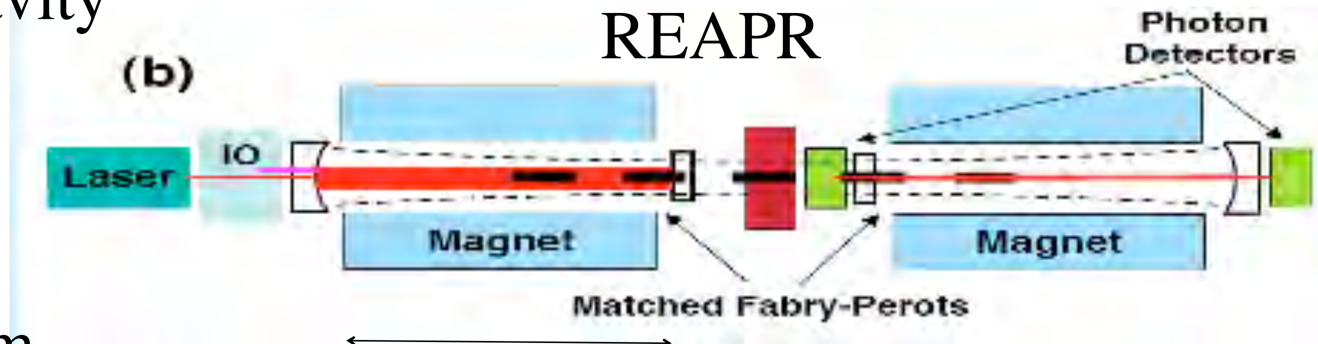
- Cosmological axions with RF cavities
- Solar axions
- Light-through the wall experiments

G3 plans

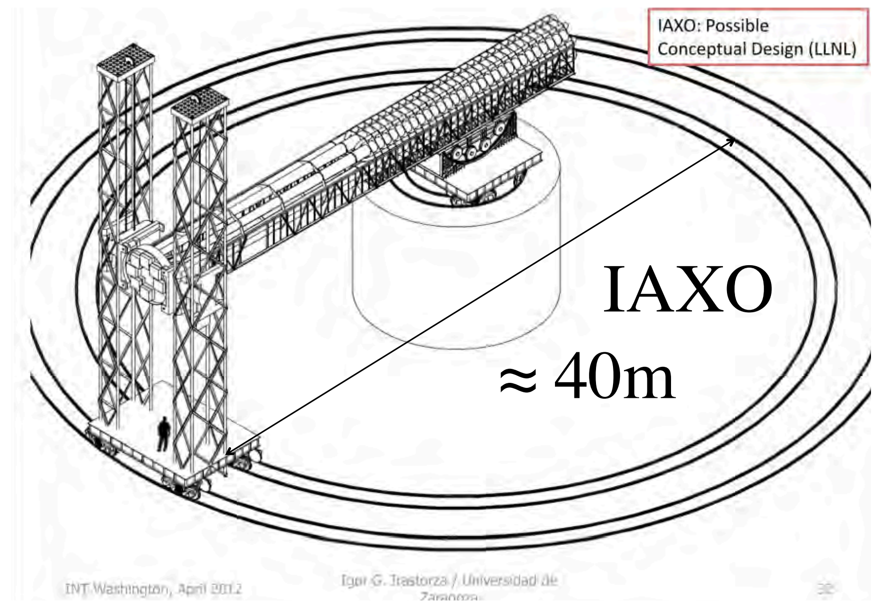
ADMX G3 HF cavity

≈2m

REAPR



≈ 10m

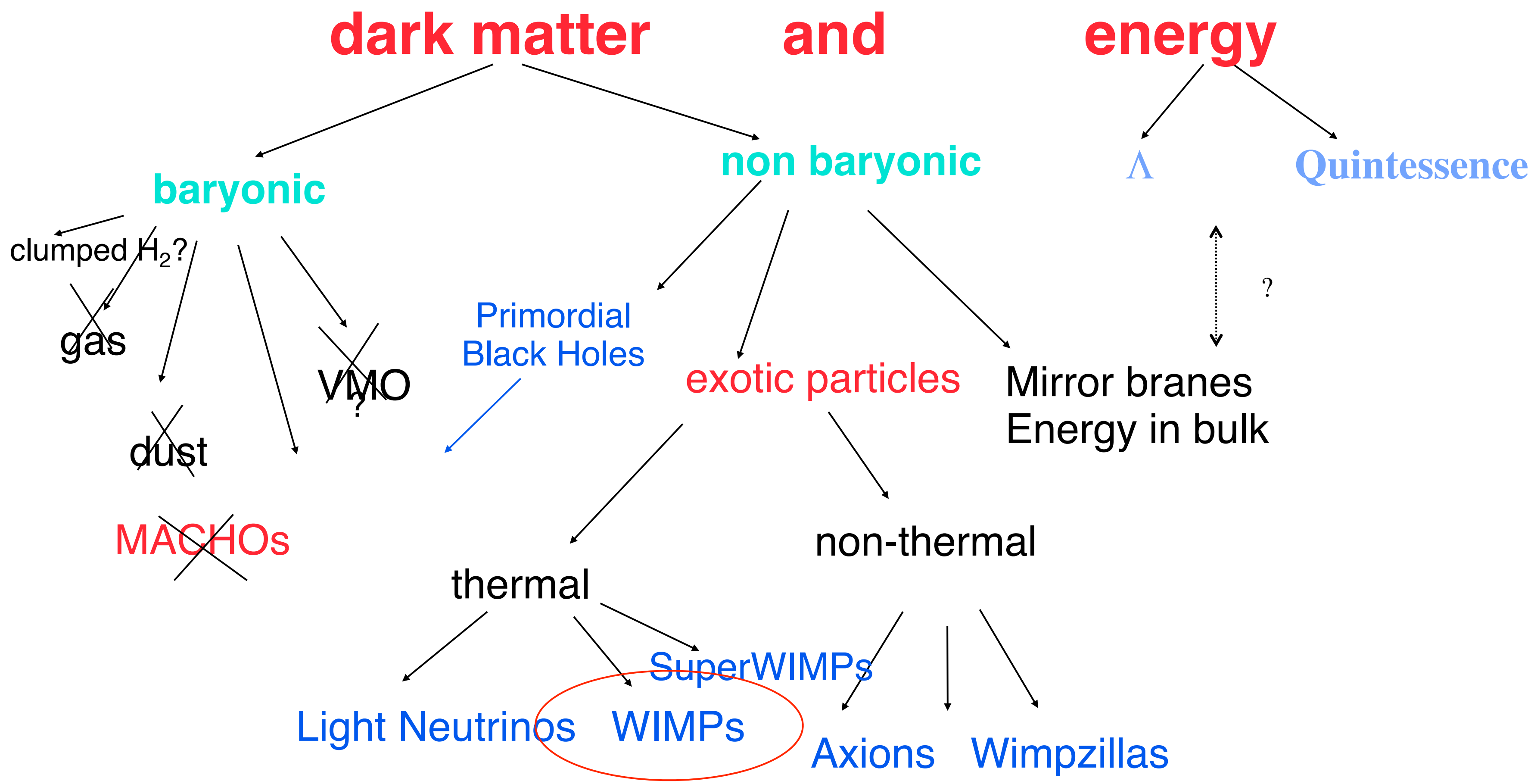


IAXO magnet may be > $100M

But, according to Rosenberg,

" realistically, the G3 axion program will come in below $100M"

A map of the territory!



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Intriguing but less predictive

Weak scale WIMP: How It All Started!

My subjective impression of key steps

Dark Matter

B Lee and S. Weinberg 1977 annihilation rate-> density

Article of Silk and Srednicki, 1984 annihilation in gamma rays

Low temperature detectors -> neutrinos

Drukier and Stodolsky Dec 1984

Cabrera, Krauss, Wilzcek, Dec 1984

Goodman and Witten Jan 1985

Direct detection is possible!

Ionization and Nuclear recoil recognition

Nuclear recoils will ionize! (Marv Cohen-> Lindhardt) ≈1986

Germanium (Avignone, Caldwell) 1987-88

excluded Z0

Importance of nuclear recoil (CDMS) 1989

Low pressure TPC (Tao, ≈1990)

DAMA (Bernabei) 1990-2000

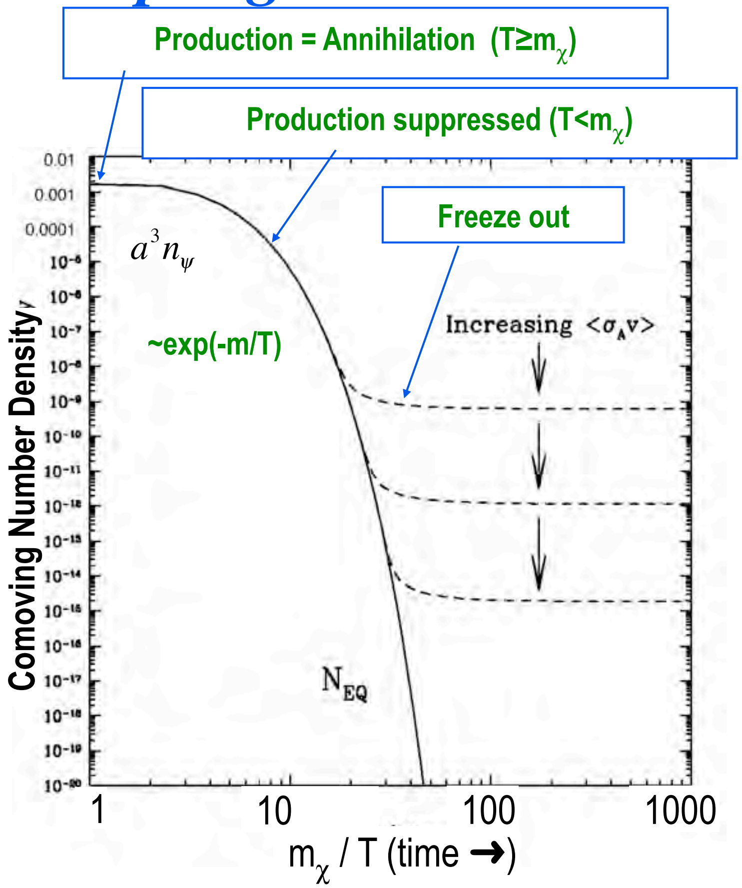
Liquid Xenon (Elena Aprile)1998-2002

Weakly Interactive Massive Particles

Particles in thermal equilibrium

+ decoupling when nonrelativistic

Density ~ 1/(interaction rate)
$\Omega \approx 1 \Rightarrow \sigma v \approx 10^{-26}\ cm^3/s$
Generic Class



Cosmology points to W&Z scale
Inversely standard particle model requires new physics at this scale
(e.g. supersymmetry) => significant amount of dark matter

Weakly Interactive Massive Particles

Calculation

Lee and Weinberg Phys. Rev. Lett. 39, 165 (1977)
cf. Supersymmetric Dark Matter G. Jungman, M. Kamionkowski, K. Griest Phys.Rept. 267 (1996) 195-373. See also Kolb and Turner 119-130

Assuming $\sigma_A v = a + bv^2$
the solution of the Boltzmann equation is approximatively given by

$$\Omega_x h^2 \propto \frac{x_f}{\sqrt{g^*_{T_{freeze}}}\left\{a + 3\frac{(b - 1/4a)}{x_f}\right\}}$$

$$m_{Planck} = \sqrt{\frac{\hbar c}{G_N}} = 1.22 \cdot 10^{19}\,\mathrm{GeV}/c^2$$

with $x_f = \frac{k_b T_{freeze}}{m_\chi}$ given by the solution of $x_f \approx \ln \frac{0.1\, m_{Planck} m_\chi (a + 6b/x_f)}{(\hbar c)^2 \left(g^*_{T_{freeze}} x_f\right)}$

Typically $x_f \approx 0.05$ with a logarithmic dependence on m_χ

and $\Omega_x h^2 = \frac{3 \cdot 10^{-27}\, cm^3/s}{\langle \sigma_A v \rangle}$ This implies a $\langle \sigma_A v \rangle$ of the order of the Weak Scale

WIMPs 2

Intuitive argument

If cross section is too large: will annihilate before decoupling

Not the dark matter today

If cross section is too small: will be diluted away by the expansion

Would over-close the universe

Delicate balance

Note involves both the Hubble constant and cross section.
The "fine tuning" can be in the Hubble constant

Ways to turn argument:

- Initial asymmetry

Suppose that $\chi \neq \overline{\chi}$

Cross section may be very large (e.g. heavy Dirac neutrino)

we are left with only small excess

Attractive to explain why same order of magnitude as protons

- Dilution by entropy production after freeze out

e.g. QCD or electroweak (if low enough) in case they are strongly first order
Unlikely

Notes:

The higher the cross section the lower the density!

Formula in previous slide not valid near pole, threshold or coannihilation

$$\chi\overline{\chi} \underbrace{\leftrightarrow}_{\text{strong interactions}} \chi'\overline{\chi}' \text{ with } \chi' \text{ slightly heavier:}$$

governed by the largest annihilation cross section

Model independent upper limit

K.Griest and M. Kamionkowski Phys Rev. Lett 64 (1990) 615

Starting from $\sigma_A v = a + bv^2$,
partial wave unitarity limits from above a (s wave) and b (p wave)

$$\Rightarrow \Omega_x h^2 > \left(\frac{m_\chi}{300 \text{ TeV/c}^2 \alpha} \right)^2$$ where α is the square of the coupling constant

If the couplings of the order of $\alpha \approx 10^{-2}$ (cf. SUSY)

$$\Omega_x h^2 > \left(\frac{m_\chi}{3 \text{ TeV/c}^2} \right)^2 \Rightarrow m_\chi \leq \text{few TeV} / c^2$$

Essentially model independent!

Detection methods

Annihilation rate provides a normalization

Directly fixes annihilation rate in halo

However we are sensitive only to specific channels

e.g. $\chi\bar{\chi} \to \gamma\gamma$ while $\sigma_A v = \sum_{\text{all final states}} \chi\bar{\chi} \to \cdots$

Dependent on n_χ^2

- e.g. presence of a cusp in the galactic center e.g. due to black hole or low entropy WIMP
- + survival probability in halo if charged particles (pbar and e^+)

Elastic scattering : Direct detection

$$\chi q \to \chi q = \text{crossed channel of } \chi\bar{\chi} \to q\bar{q}$$

Usually crossing operation gives factor of the order of unity

Still dependent on ratio between the cross sections (usually few %)

$$\chi\bar{\chi} \to q\bar{q} \quad \text{and} \quad \sum_{\text{all final states}} \chi\bar{\chi} \to \cdots$$

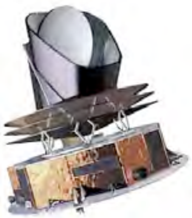
Annihilation in center of the sun or the earth -> high energy neutrinos

Combination of elastic scattering to get trapped and annihilation in the center of the object

Production at accelerators

4 Complementary Approaches

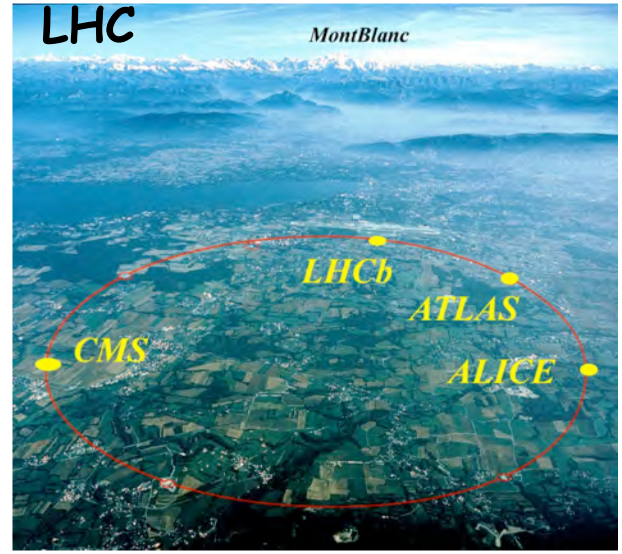
Cosmological Observations



Planck

Keck telescopes

Dark Matter
Galactic Halo (simulation)

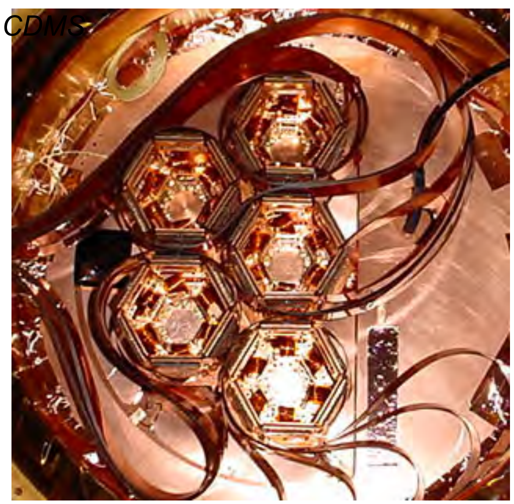


WIMP production on Earth

VERITAS, also HESS, Magic + IceCube (ν)

WIMP annihilation in the cosmos

Fermi/GLAST



WIMP scattering on Earth:e.g. CDMS, Xenon 100,etc.

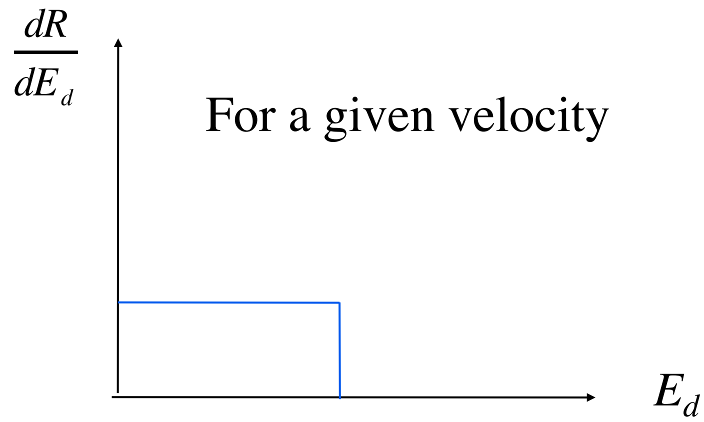
Differential Cross Section

Energy Deposition:

Simple non relativistic calculation

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

minimum velocity for given energy



Convolve with Halo velocity distribution

First let us make simplifying assumptions

- Interaction with the full nucleus (no form factor)
- Maxwellian distribution of velocity in the halo
- No Earth/Sun velocity
- No escape velocity

$$f(v)d^3v = \frac{1}{v_o^3\pi^{3/2}}\exp\left(-\frac{v^2}{v_o^2}\right)v^2 dv\, d\cos\theta\, d\varphi$$

Note: $\int_0^\infty f(v)d^3v = 1$

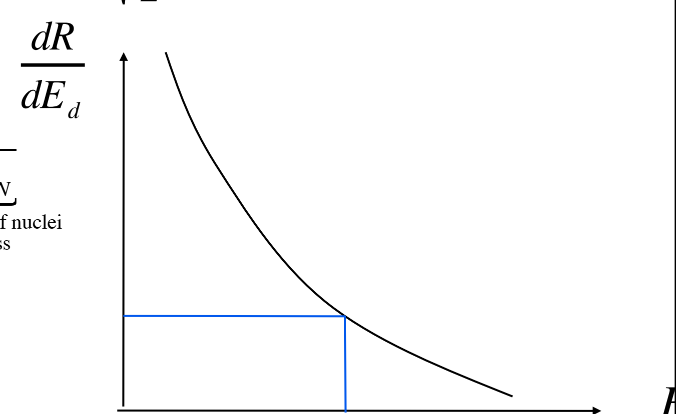
$$\mathrm{v}_{\mathrm{rms}} = \sqrt{\frac{3}{2}}v_o \approx 270 \text{ km/s}$$

The rate per unit target mass is

$$\underbrace{\frac{dR}{dE_d}}_{\text{Differential rate by unit mass}} = \int_{v_{\min}(E_d)}^{\infty} \frac{1}{v_o^3\pi^{3/2}}\exp\left(-\frac{v^2}{v_o^2}\right)v^2\, dv\, d\cos\theta\, d\varphi \; \underbrace{\frac{d\sigma}{d\cos\theta^*}}_{\text{differential cross section}} \left|\frac{d\cos\theta^*}{dE_d}\right| \underbrace{\frac{\rho_0}{m_\chi}v}_{\text{WIMP flux}} \underbrace{\frac{1}{m_N}}_{\text{number of nuclei / unit mass}}$$

where ρ_0 is the local mass density of the halo $\approx 0.3\ \mathrm{GeV/c^2/cm^3}$

$$\Rightarrow \boxed{\frac{dR}{dE_d} = \frac{1}{\pi^{1/2}}\frac{\sigma_0\rho_0}{m_r^2 m_\chi v_0}\exp\left(-\frac{m_N E_d}{2m_r^2 v_o^2}\right)} \equiv \text{Equation 8.6 of Jungman, Griest and Kamionkowski}$$



Complication 1: Coherence!

Momentum transfer are small =>coherence over nucleus.

Oversimplification:

Quarks->nucleons->nucleus

Effective matrix elements: traditionally focus only on 2...

Spin independent= additive quantum number is mass

But not necessarily true, could be isospin dependent

Spin dependent= additive quantum number is spin

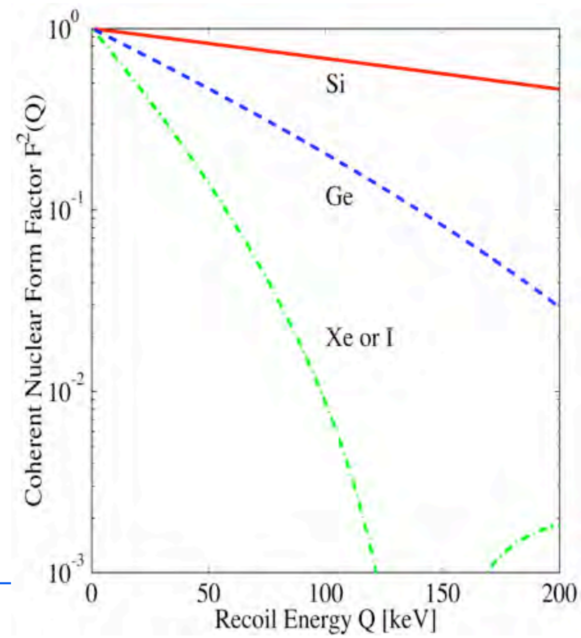
<= e.g., axial vector coupling (for Majorana particle vector coupling is zero)

Because axial vector is so small, usually spin independent dominates

As momentum transfer increased, loss of coherence => Form factors

Difference between spin independent and spin dependent

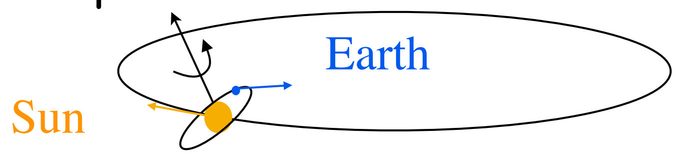
See for instance G. Jungman, M. Kamionkowski, K. Griest Phys.Rept. 267 (1996) 195-373



Complication 2: Earth velocity

Sun travels at 220km/s in galaxy ≈ 300km/s rms velocity of the WIMPs:
WIMPs are coming one way.

The earth travels at 30km/s around the sun (not in the same plane ≈ 60°)
+ rotate around polar axis



Convolution with velocity distribution in the halo

Can be done in the same way but now

$\vec{v} = \vec{v}_g + \vec{v}_e(t)$ where the Earth velocity $\vec{v}_e$ depends on the time of the year

If Maxwellian in galaxy rest frame $f(v_g)d^3v_g = \frac{1}{v_o^3\pi^{3/2}}\exp\left(-\frac{v_g^2}{v_o^2}\right)d^3v_g$

differential rate per unit mass

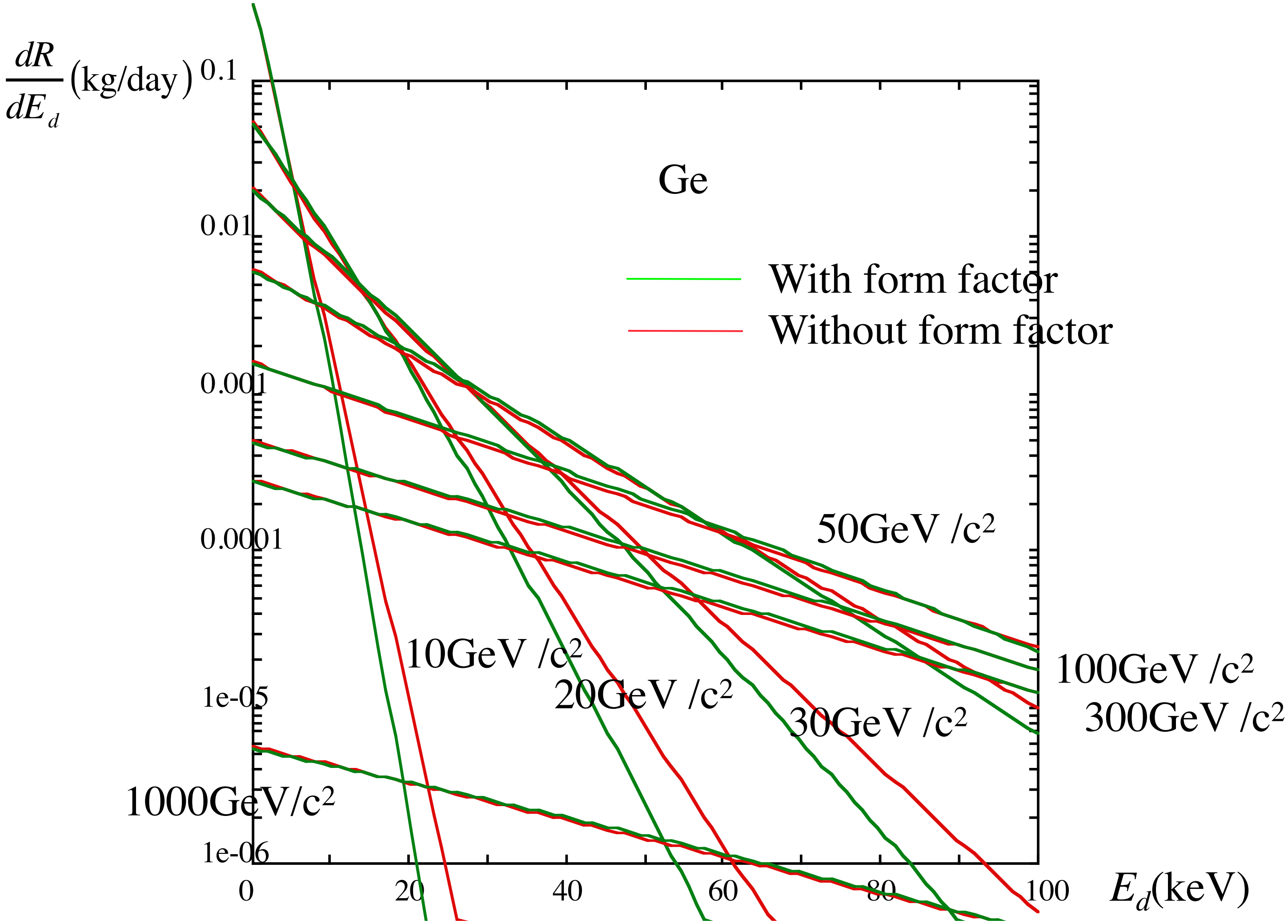
$$\frac{dR}{dE_d} = \frac{\sigma_o\rho_o}{4v_e m_\chi m_r^2}F^2(q)\left[\mathrm{erf}\left(\frac{v_{\min}+v_e}{v_o}\right)-\mathrm{erf}\left(\frac{v_{\min}-v_e}{v_o}\right)\right]$$

where

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

$$v_{\min} = \left(\frac{E_d m_N}{2m_r^2}\right)^{1/2} \quad v_e = v_o\left[1.05 + 0.07\cos\left(\frac{2\pi(t-\text{2ndJune})}{1\text{yr}}\right)\right]$$

Elastic Scattering Rates(average)



Still roughly exponential!

2 consequences

Directionality of the recoil

Spergel D. Phys. Rev. D 37:1353 (1988)

$$\frac{dR}{dE_d\, d\cos\gamma} = \frac{\sigma_o \rho_o}{2\sqrt{\pi} v_0 m_\chi m_r^2} F^2(q) \exp\left(-\frac{(v_e \cos\gamma - v_{\min})^2}{v_0^2} \right)$$

where γ is the angle between the recoil and the velocity of the earth in the galaxy frame

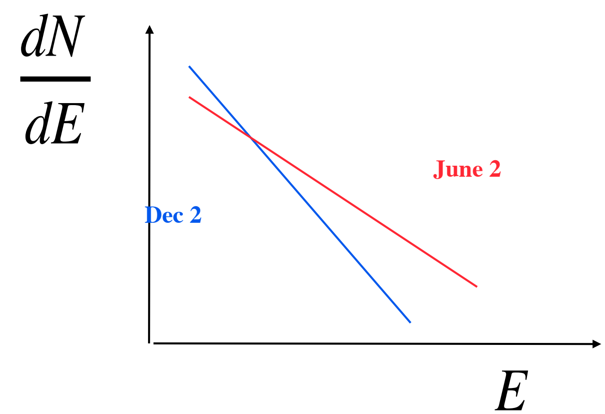
Very large asymmetry especially if you can detect head and tail of the recoil: factor 4 forward to backward ratio (zero energy threshold)

Low pressure Time projection Chamber

Annual modulation

both due to change of flux
and mean energy

Annual modulation
±4.5%



A.K. Drukier, K. Freese and D.N. Spergel, Phys. Rev. D 33 (1986) 3495.

At the basis of the claim by DAMA

Realistic velocity distribution

Not Maxwell!

Cut off at escape velocity

Not as sharp than often assumed ≈540km/s

Exact velocity shape

Streams: delta function in evlocity (but rare in simulations at our radius)
"Debris" from earlier mergers: tendency to have large velocity
See M.Kuhlen, M. Lisanti, D.N. Sergel arXiv:1202.0007

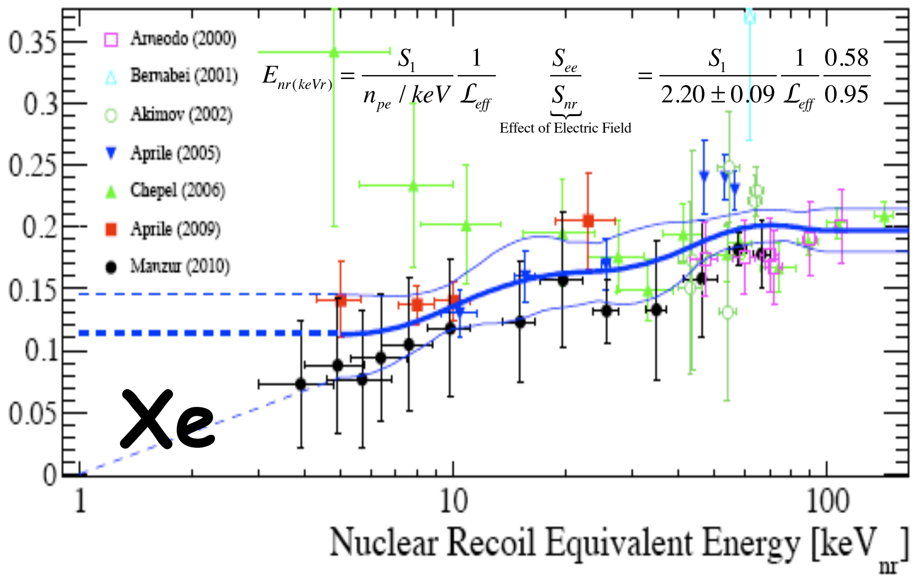
Could be important when comparing different target mass

e.g., Si and Xe for M≈8 GeV with existing threshold are sensitive to very different parts of the distribution
Model independent approach: Fox, Liu, Weiner arXiv:1011.1915

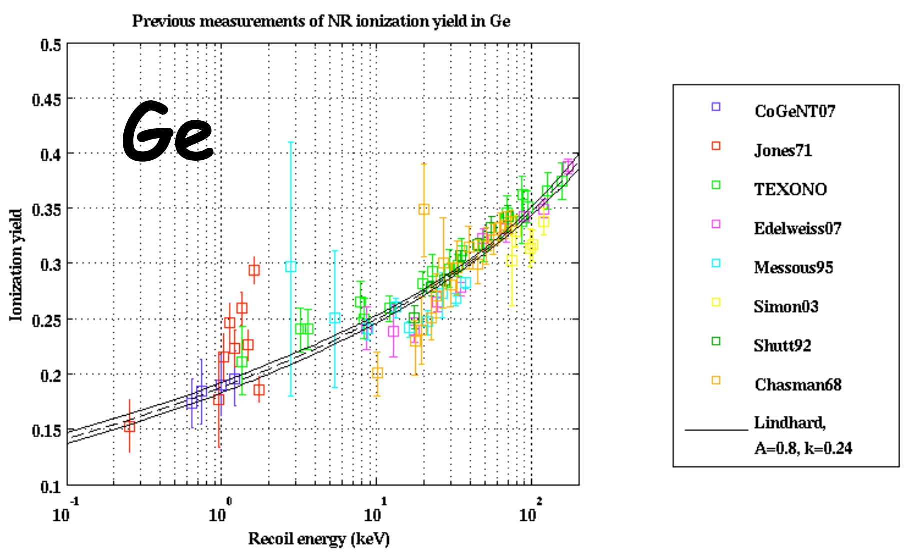
Complication 3: Yields for nuclear recoils

Sometimes called quenching factors

Scintillation yield (compared to 122KeV)



ionization yield



Need to be measured

all components

e.g., scintillation +ionization (Xe)

phonons+ionization (G)

including dependence on field!

large in Xe (recombination)

=> energy calibration

efficiency (energy)