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Search for Dark Matter

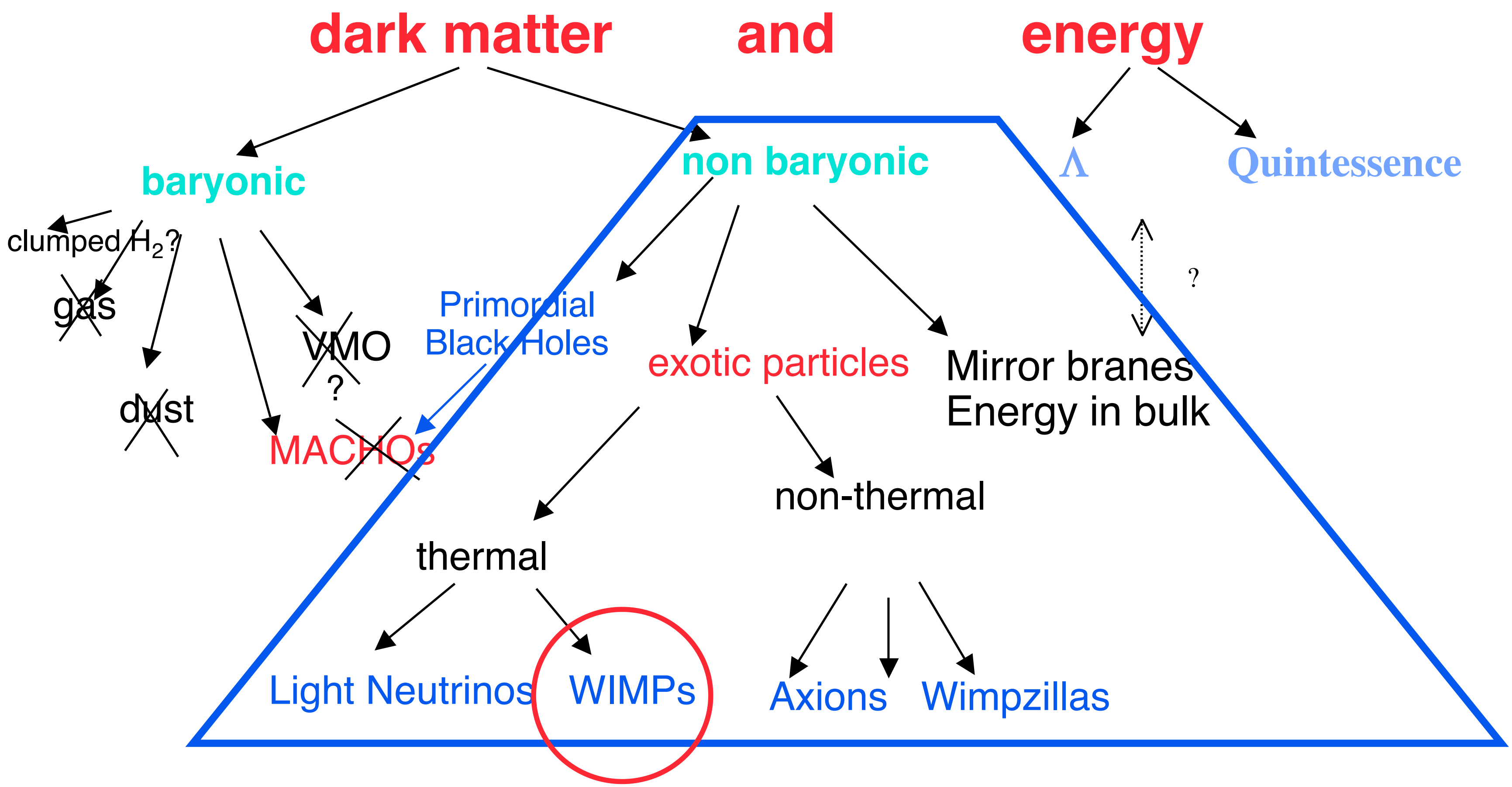
Lecture 3: Weakly Interactive Massive Particles

Supersymmetry

Elastic Scattering

DAMA

Deciphering the Nature of Dark Matter



Weakly Interactive Massive Particles

Particles in thermal equilibrium
+ decoupling when nonrelativistic

Freeze out when annihilation rate $\approx$ expansion rate

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

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

We have to investigate this convergence!

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

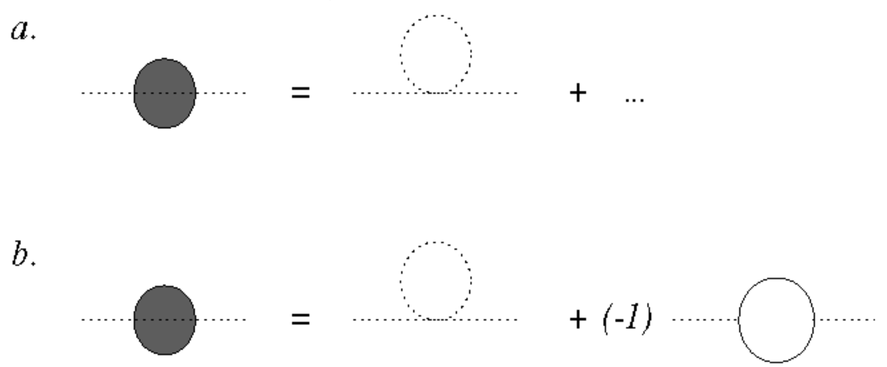


Figure 5. Radiative corrections to the mass of a scalar particle. The dotted curves are scalar propagators, and the solid curves are fermion propagators. (a) Diagrams with no supersymmetry, and (b) Diagrams with supersymmetry.

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!

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

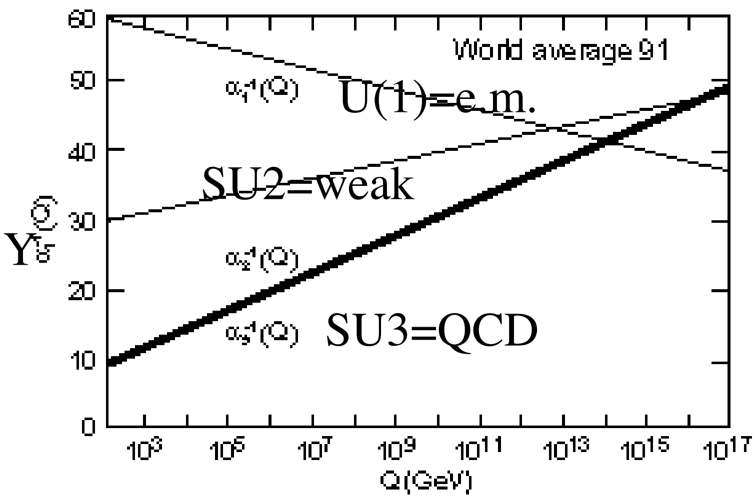
$$-4\ 10^{-10}\ \text{(Melnikov-Vainshtein)}$$

Supersymmetry

3) Convergence of coupling constants

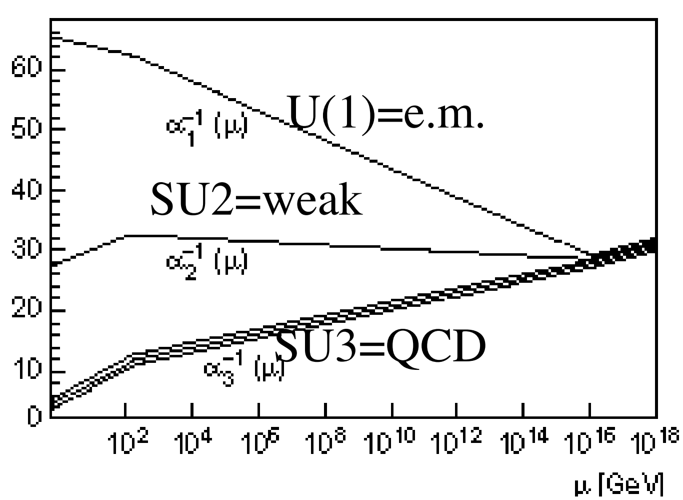
J. Ellis, S. Kelley and D.V. Nanopoulos, *Phys.Lett.* **260** (1991) 131;
U. Amaldi, W. de Boer and H. Furstenau, *Phys.Lett.* **B260** (1991) 447;

without SUSY



(a)

with SUSY



4) Mass of the neutrino
Strong indication
for GUT scale

Minimum Supersymmetry

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

R parity

$$R = (-1)^{3(B-L)+2S}$$

If conserved, stay in supersymmetric
Sector: produced in pair
Lightest=stable

Super-potential

$$W = -\mu \hat{H}_1 \hat{H}_2 + \hat{H}_1 h_e^{ij} \hat{L}_{Li} \hat{e}_{R_j} + \hat{H}_1 h_d^{ij} \hat{Q}_{Li} \hat{d}_{R_j} - \hat{H}_2 h_d^{ij} \hat{Q}_{Li} \hat{u}_{R_j}$$

$i, j =$ flavor

19 parameters

Gauge couplings

$$-\frac{1}{4} F_{\mu\nu}^a F_a^{\mu\nu} - g V_\mu^a \overline{\psi} \gamma^\mu \psi$$

$$-ig V_\mu^a \tilde{\psi}^+ T_a \overleftrightarrow{\partial}_\mu \tilde{\psi} \quad (T_a = \text{ gauge generator})$$

$$-\sqrt{2} g \left(\overline{\tilde{V}}_\mu^a \psi T_a \tilde{\psi} + \overline{\psi} \tilde{V}_\mu^a T_a \tilde{\psi} \right)$$

$+ \ldots$

SUSY breaking terms

Another 44 phenomenological parameters: masses and trilinear coupling

Superfield	Component Fields		Quantum Numbers	Name
	Matter Fields		(SU(3),SU(2),U(1))	
$\hat{Q}_L$	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$	Q_L	$(3, 2, \frac{1}{3})$	Left-handed
	$\begin{pmatrix} \tilde{u}_L \\ \tilde{d}_L \end{pmatrix}$	$\tilde{Q}_L$		quark doublet
$\hat{u}_R$	u_L^c		$(3^*, 1, \frac{4}{3})$	Right-handed
	$\tilde{u}_L^c$			up-quark singlet
$\hat{d}_R$	d_L^c		$(3^*, 1, +\frac{2}{3})$	Right-handed
	$\tilde{d}_L^c$			down-quark singlet
$\hat{L}_L$	$\begin{pmatrix} \nu_L \\ e_L^- \end{pmatrix}$		$(1, 2, 1)$	Left-handed
	$\begin{pmatrix} \tilde{\nu}_L \\ \tilde{e}_L \end{pmatrix}$			lepton doublet
$\hat{e}_R$	e_L^c		$(1, 1, +2)$	Right-handed
	$\tilde{e}_L^c$			lepton singlet
	Gauge Fields			
$\hat{W}$	$\begin{pmatrix} W^\pm \\ W^3 \end{pmatrix}$		$(1, 0, 3)$	$SU(2)_L$
	$\begin{pmatrix} \tilde{W}^\pm \\ \tilde{W}^3 \end{pmatrix}$			gauge fields
$\hat{B}$	B		$(1, 1, +2)$	$U(1)$
	$\tilde{B}$			gauge field
	Higgs fields			
$\hat{H}_2$	$\begin{pmatrix} \phi_u^+ \\ \phi_u^0 \end{pmatrix}$		$(1, 2, +1)$	up type
	$\begin{pmatrix} \tilde{\phi}_u^+ \\ \tilde{\phi}_u^0 \end{pmatrix}$			higgs doublet
$\hat{H}_1$	$\begin{pmatrix} \phi_d^+ \\ \phi_d^0 \end{pmatrix}$		$(1, 2, 1)$	down-type
	$\begin{pmatrix} \tilde{\phi}_d^+ \\ \tilde{\phi}_d^0 \end{pmatrix}$			higgs doublet

Mass Spectrum

Higgs

Initial 8 degrees of freedom: 3 absorbed by $W^{\pm}$, Z longitudinal polarization => 5 Higgs left: h,H (both CP even),$H^{\pm}$,A (CP odd)

Mass are related

$$m_{h,H}^2 = \frac{1}{2}\left(m_A^2 + m_Z^2 \pm \sqrt{\left(m_A^2 + m_Z^2\right)^2 - 4 m_A^2 m_Z^2 \cos^2 2\beta} \right) \text{ with } \tan\beta = \frac{\langle \tilde{H}_u \rangle}{\langle \tilde{H}_d \rangle}$$

+ strong radiation corrections ($m_t \approx 175 \mathrm{GeV}/c^2$)

Neutralino

4 states with the same quantum number $\tilde{B}, \tilde{W}_3, \tilde{H}_1, \tilde{H}_2$

=> mix!

Diagonalize

$$\begin{pmatrix} M_1 & 0 & -m_z s_{\theta W} c_\beta & m_z s_{\theta W} s_\beta \\ 0 & M_2 & m_z c_{\theta W} c_\beta & -m_z c_{\theta W} s_\beta \\ -m_z c_{\theta W} c_\beta & m_z c_{\theta W} c_\beta & 0 & -\mu \\ m_z s_{\theta W} s_\beta & -m_z c_{\theta W} s_\beta & -\mu & 0 \end{pmatrix}$$

$$\Rightarrow \text{Lightest : } \chi_1^{\,o} = z_1 \tilde{B} + z_2 \tilde{W}_3 + z_3 \tilde{H}_1 + z_4 \tilde{H}_2$$

The Game

Choose favorite parametrization

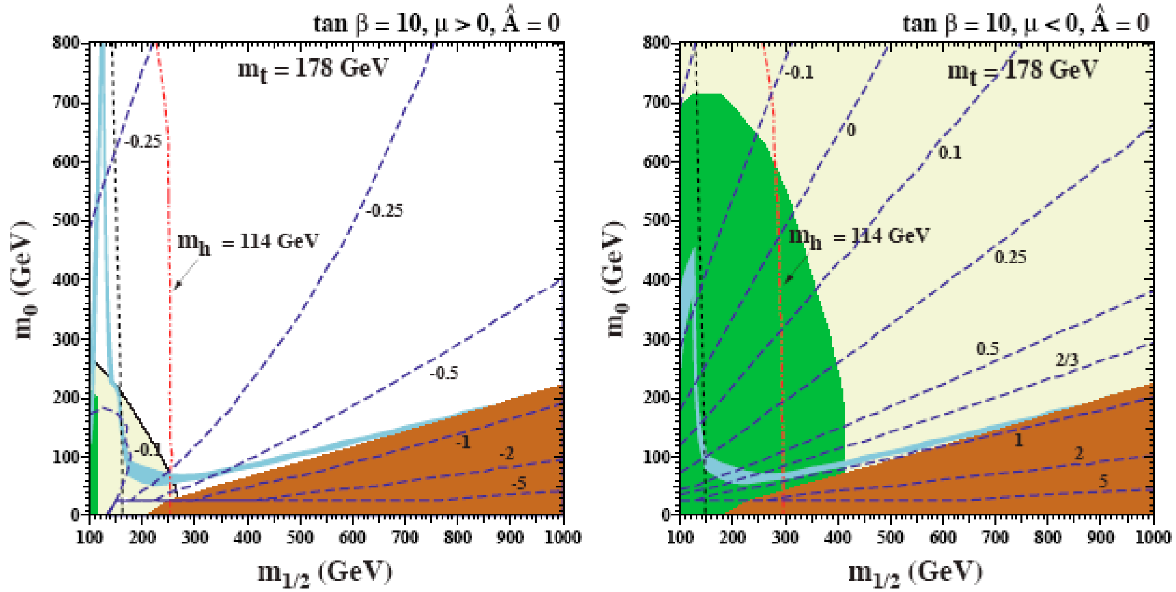
- 63 parameters are too much! => simplifying assumptions (e.g. unification)
- In some cases could be too restrictive

Sample parameter space:

- e.g. uniformly in log in "natural" region
- Impose constraints from accelerators (+g-2?)

Compute annihilation cross section

- Further restriction on parameters to have reasonable $\Omega_m h^2$ WMAP

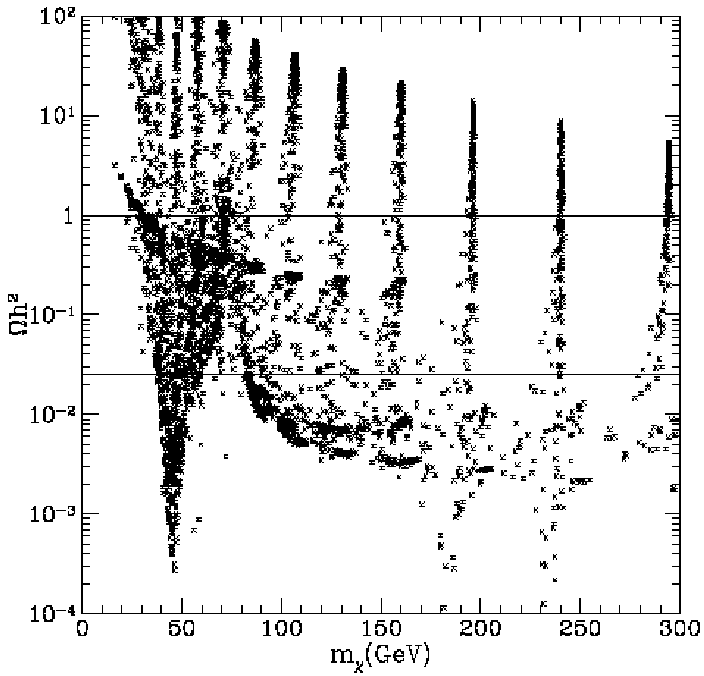


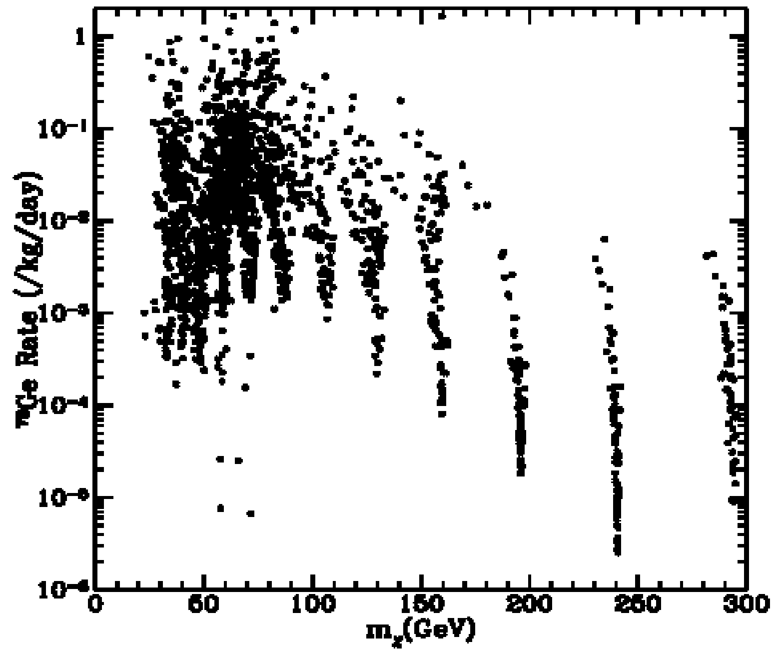
Compute rates of interest

Examples

G. Jungman, M. Kamionkowski, K. Griest

Phys.Rept. 267 (1996) 195-373





Notes:

Lowest cross section-> higher Ωh^2

No real lower limits (some in restricted parametrization if you believe in g-2)

MSSM: 2 philosphies

Try to minimize number of parameters

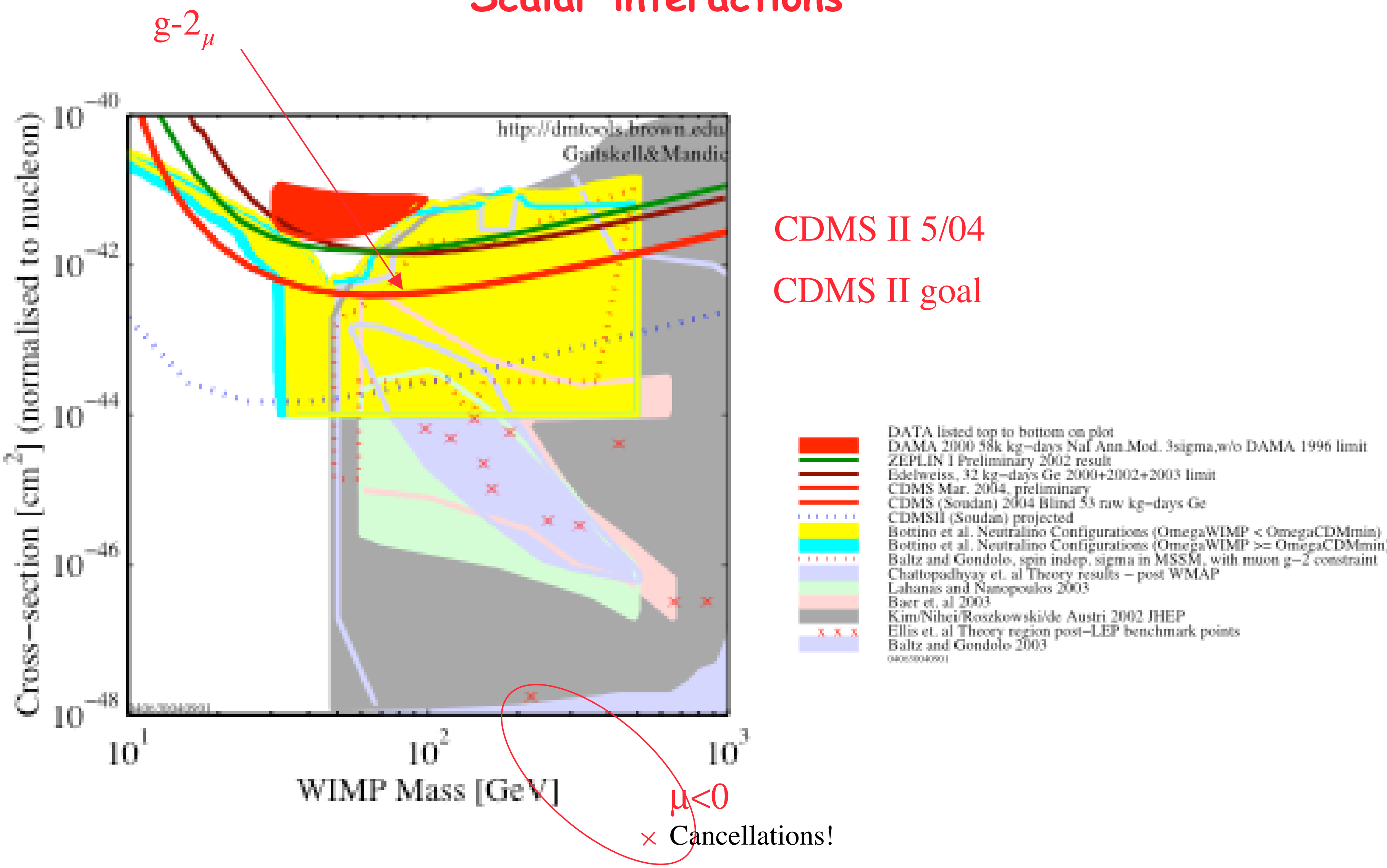
- Through "reasonable" assumptions
- Ellis, Olive et al. Constrained Minimum Super Symmetry Model CMSSM
  - GUT relationships
  - Scalar unification at unification scale
  - Some parameters at
- Recently very constrained
  - Amazing that still parameter space

Maximum flexibility

- No strong theoretical justifications for any constraints
- Trying to accommodate DAMA (Bottino et al.)
- Have to be somewhat careful: some regions unacceptable theoretically
  - (e.g. Tachyons, unstable vacuum)

Examples (Elastic Scattering)

Scalar interactions



A loop hole: Gravitinos

Can be the Lightest Supersymmetric Particle (LSP)

Unfortunately no good method for detection
(purely gravitational interaction)

Regain of interest because of leptogenesis

- e.g. W. Buchmuller et al hep-ph/040614
- High reheating=> overproduction of gravitinos, whose decays inject too much entropy
- Ways out: make it very heavy >50TeV/c^2 or make it the LSP!

Constraints in SSM parameters

- Decay of next to lightest supersymmetric particle (NSP) occurs after Big Bang Nucleosynthesis and injects entropy: too much would destroy agreement between CMBR and BBN synthesis results

$$\eta_{CMB} = \frac{n_B}{n_\gamma} = 6.1^{+0.3}_{-0.2}\ 10^{-10} \qquad \eta_{BBN} = \frac{n_B}{n_\gamma} = 5.9 \pm 10^{-10}$$

- Possible if

$$\Omega_{NSP} \leq 10^{-2}\Omega_b h^2 \approx 10^{-4}$$

- Same exercise and indeed regions of parameter space are allowed (Ellis et al., hep-ph 0312262)!

Note: we loose the naturalness of the cross section

Except maybe in specific gauge coupling models (W. Buchmuller et al Phys. Lett B 574 (2003) 156)

$$\Omega_{3/2} h^2 \approx 0.05 - 0.2$$

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

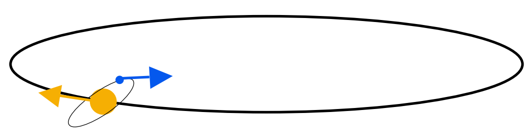
Convolution with velocity distribution in the halo

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

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



Annual modulation
±4.5%

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

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

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

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

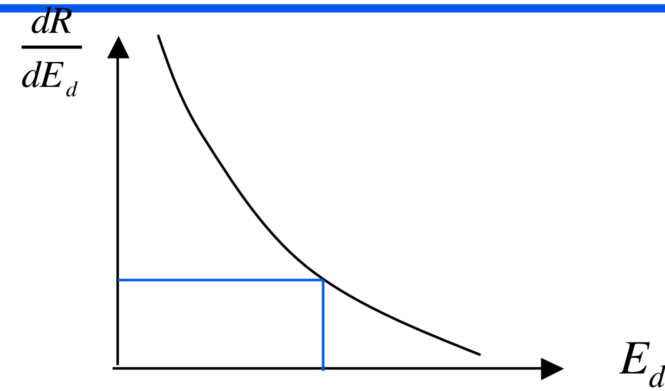
Spin is never very large: usually <2nd order

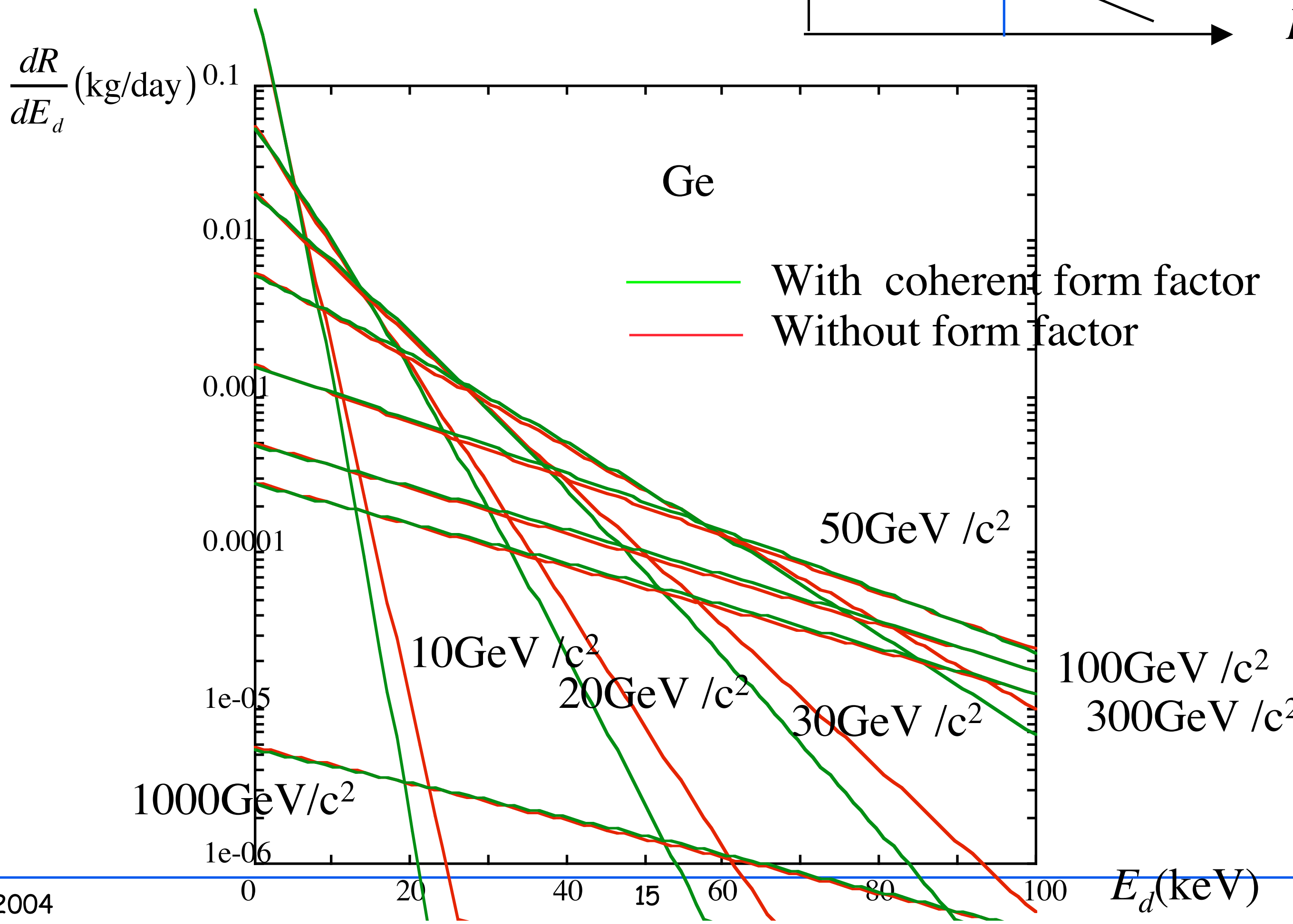
Uncertainties on spin content of nucleon

"Peripheral" form factor

Elastic Scattering Rates 2

Unfortunately featureless!





Direct Detection

Elastic scattering

Expected event rates are low

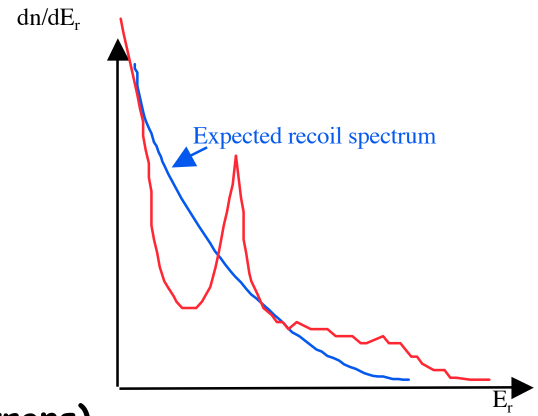
(<< radioactive background)

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)

Detection methods

A variety (next slide)

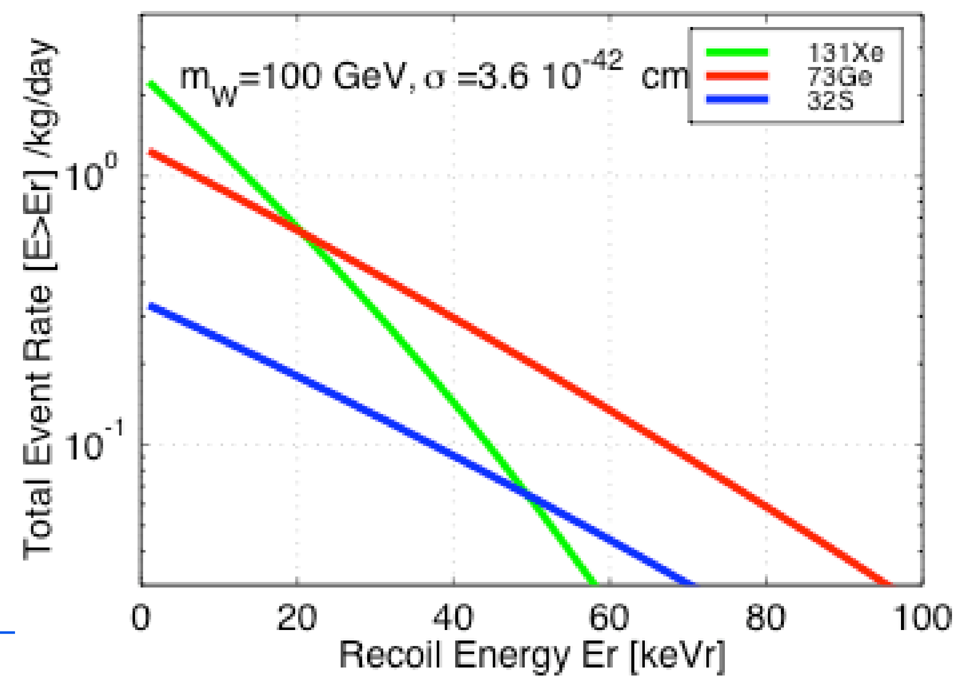
Usually less sensitive for nuclear recoils (" quenching")

- lower excitation of electrons => less ionization/scintillation
- higher deposited-energy density => recombination, difference of pulse shape

Important note: Most group quote the electron equivalent recoil energy ≈10x smaller than true nuclear recoil energy

Important in particular for Xe

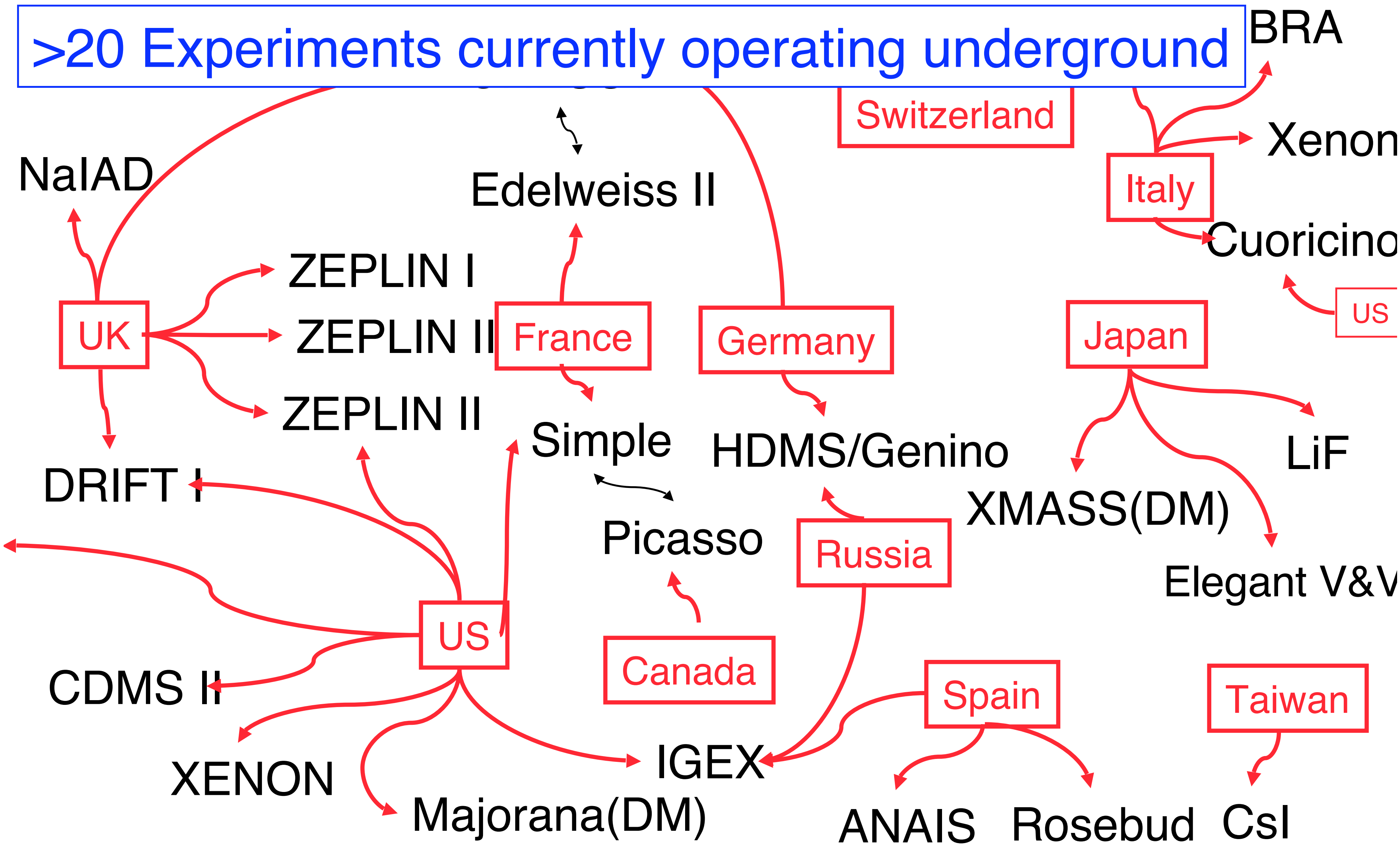
Zero of form factor



Detection Techniques

Method	Detection	Electron recoil	Nuclear recoil	Discrimination	Example of 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 Genino
Gas Ionization	electrons	20eV/electron	60eV/electron	Yes at low pressure	DRIFT
Liquid Xe					
Scintillation	Light	200eV	1600eV	Pulse shape or combined with ionization	Rome, ZEPLINI
Ionization	electrons	30eV/electron	90eV/electron	Yes combined with scintillation	ZEPLIN II Columbia
Phononon mediated	phonons	100μeV/phonon	100μeV/phonon	Combined with ionization or scintillation	Cuerocino (2β) CRESST I
Ionization @ low temperature: e.g. Ge,Si	Electrons + holes	3eV/carrier	9eV/carrier	Combined with phonons	CDMS Edelweiss
Scintillation e.g. CaWO4	Light	100eV/ photoelectron	O?: 900eV/ photoelectron	Combined with phonons	CRESST II
Superheated Droplets	Sound	not sensitive	10keV-100keV tunable	by construction	Simple Picasso

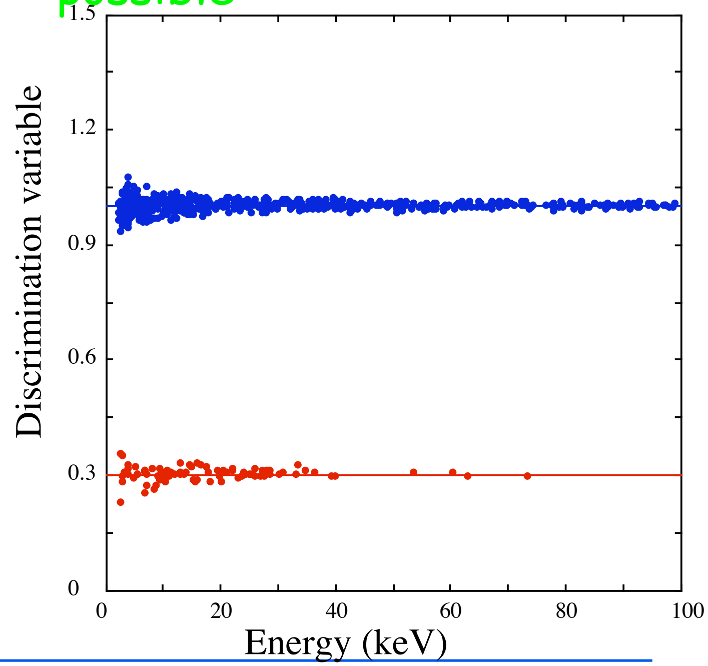
Dark Matter Experiments *(Running/Active Collaborations)*



Background Limited!

3 fundamental strategies

Aggressively tackle the background	Statistical method	Actively reject the background
State of the art: Heidelberg Moscow Extreme proposal: GENIUS 12m Ø liq. N_2 tank 10^4 improvement on current level	• Multiple scattering • Pulse shape discrim. • Annual modulation Large mass => simple detectors e.g. NaI	Active rejection with the best possible discrimination <= Best technology signal to noise no dead region/tails As much information as possible



Direct Detection: Summer 1998

Initially no discrimination

- Ge diodes (1989: USC/PNL, UCSB/LBNL)

-> Heidelberg/Moscow = most reliable limit at large mass

- Large NaI counters (100 kg -> 250kg installed in Gran Sasso!)

Spin Independent (Scalar)

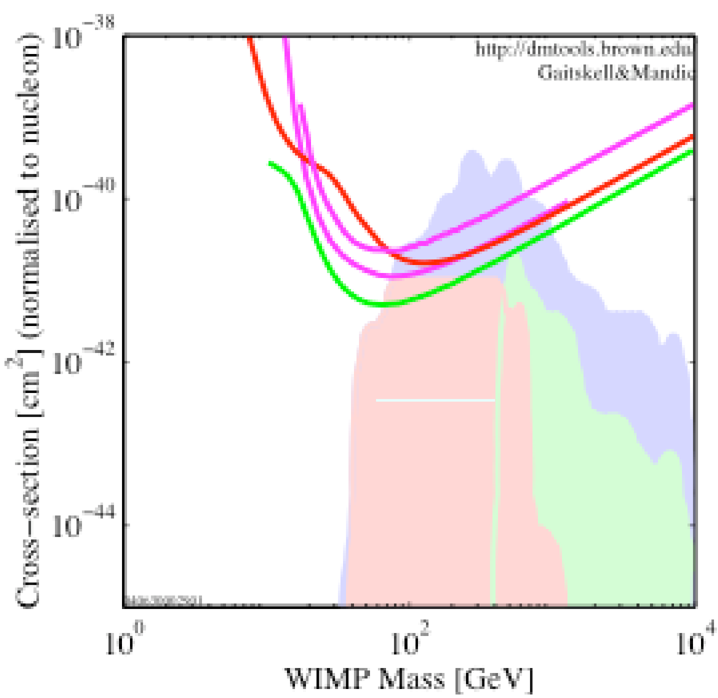
Background limited

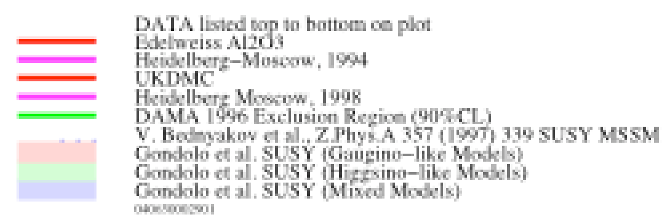
=>Effective mass is small

mass of background-less detector giving same

2.5 evt./kg/day

$(MT)_{eff}$=1kg.day

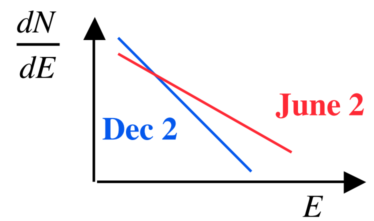




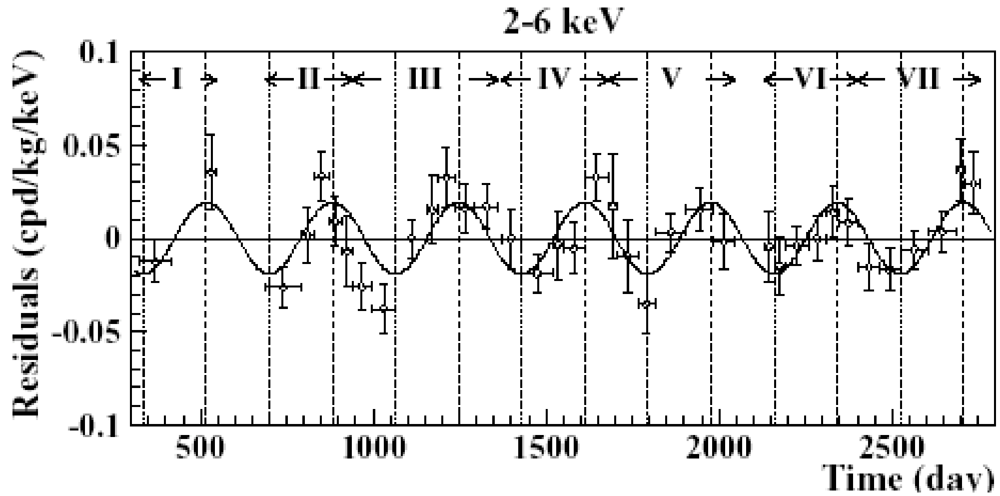
DAMA

If WIMPs exist, we should observe a modulation in event rate: cf. bicycling in the rain

Earth adds or subtract 15km/s to the velocity of the sun going through the halo => ±4.5% modulation in rate and energy



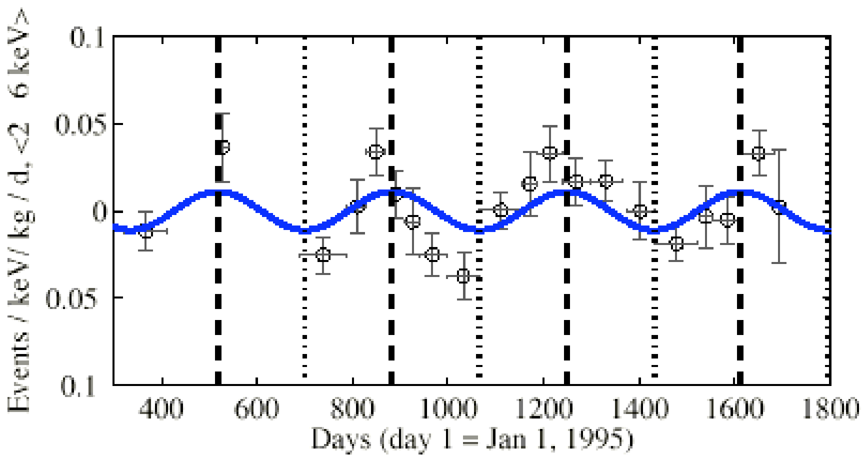
7 years data with 100kg NaI impressive modulation

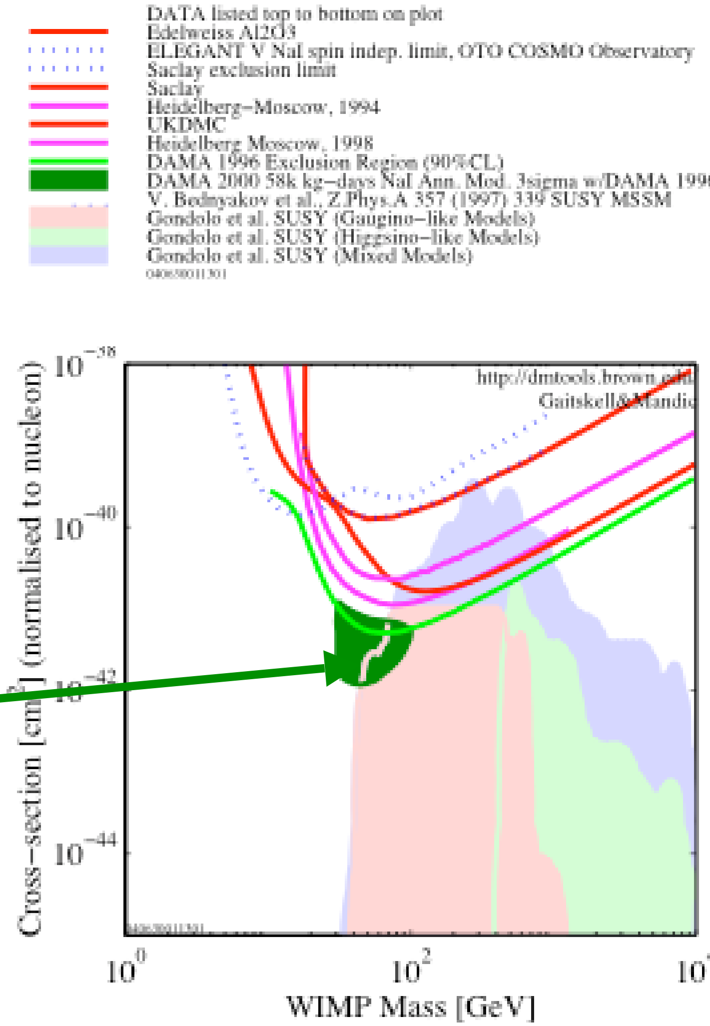


Source DAMA
Astro-ph/0307403

DAMA claim

If we interpret the modulation as evidence for WIMPs





In conventional halo model
+ scalar scaling of matrix element

Note: ≈ Incompatible with rate

- Heart shape + best fit close to top
- Half of the modulation fitted

Technical Questions about DAMA

Efficiency?

The signal is a a region of sharply increasing efficiency

Method of determining and monitoring efficiency

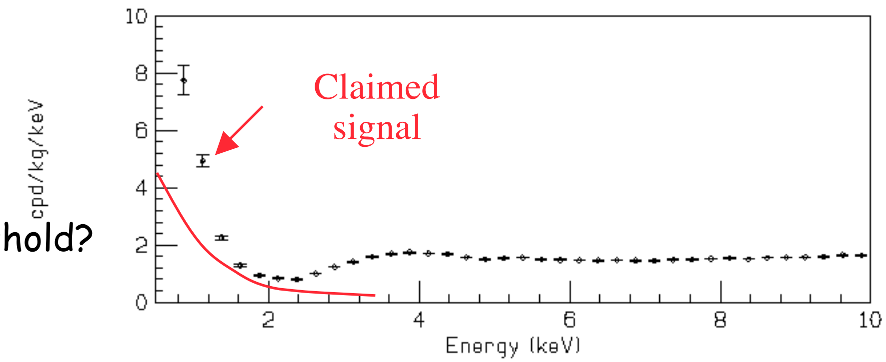
- Local source
- Spectrum of gammas

Shape of the spectrum?

Spectrum before cut?

Detailed explanation of shape:

e.g. why does it decrease at threshold?



Stability?

Is threshold stability sufficient? (<1%)

DAMA: No modulation of multiples

Monitoring of other quantities (noise etc...)

Have They Discovered the WIMPs?

Unfortunately ambiguous

Many things vary between the summer and the winter

DAMA: "We have not found any cause for our modulation"

They may just not have found the culprit yet

A number of technical questions are still unanswered

Internal consistency

Determination and stability of their efficiency in signal region

Incompatible with new generation of WIMPs searches

At least in conventional scaling on target atomic number
and standard halo model

If DAMA is right, something unexpected!

Other groups are gearing up to check their result