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Direct Detection of Galactic Dark Matter

Why WIMPs?

Experimental situation

- Situation in Summer 2009
  - DAMA
- Recent action Dec 2009-July 2010
  - CDMS II 2 events
  - Xenon 100
  - CoGeNT and DAMA
  - COUPP
  - Ar

The future of direct detection

- Need for at least 2 technologies
- Complementarity with LHC and indirect detection

Dark Matter Could Be Due to New Physics at the TeV Scale!

A remarkable coincidence

Particles in thermal equilibrium + decoupling when nonrelativistic

$$\Rightarrow \Omega_x h^2 = \frac{3 \cdot 10^{-27} cm^3 / s}{\langle \sigma_A v \rangle} \approx 0.12 \quad \Rightarrow \sigma_A \approx \frac{\alpha^2}{M_{EW}^2}$$

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

Weakly Interacting Massive Particles

Large scale structure: ΛCDM amazing first approximation

Rumors of its death may be an exaggeration (25yrs)

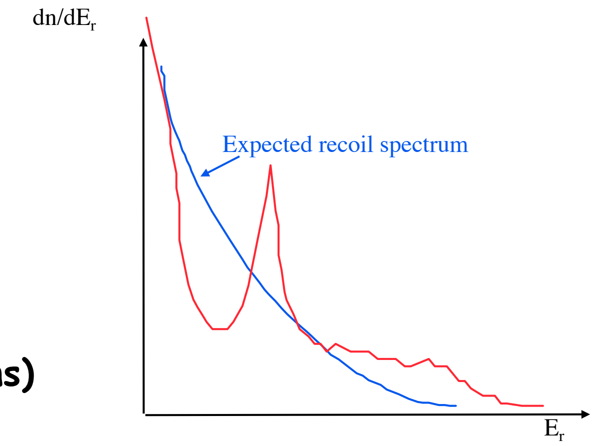
Three detection methods:

- Direct Detection in the Cosmos= Halo WIMP elastic scattering
- Indirect Detection in the Cosmos= Annihilation products $\gamma, e^+, \bar{p}, \nu$
- Production at the large Hadron Collider

Halo WIMP Scattering "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

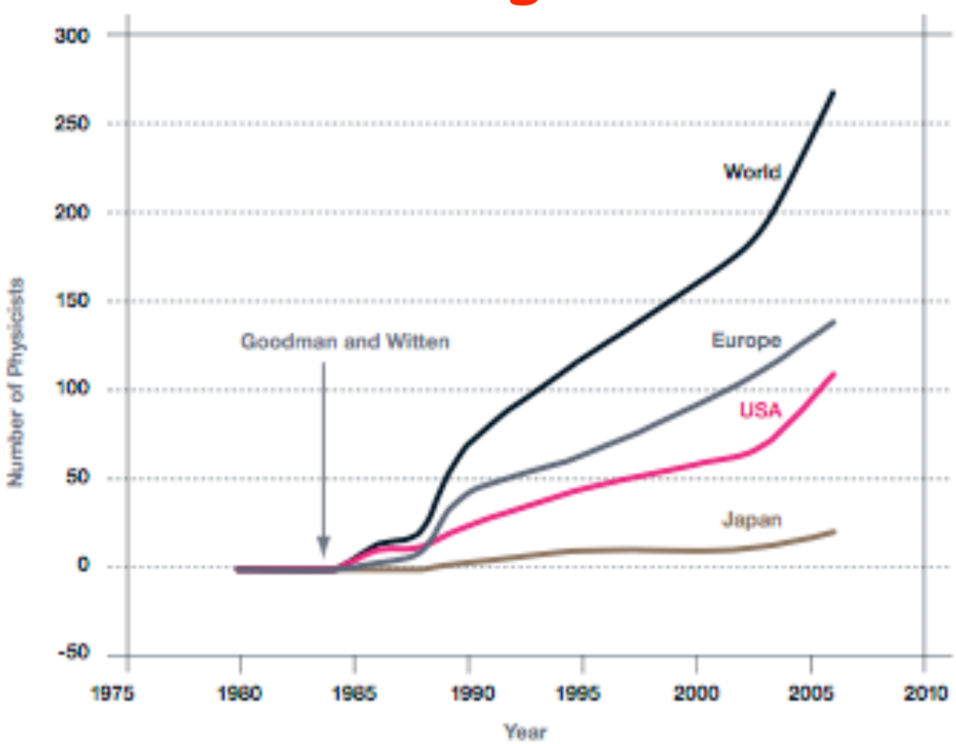
- Nuclear recoil
- Single scatter ≠ neutrons/gammas
- Uniform in detector

Linked to galaxy

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

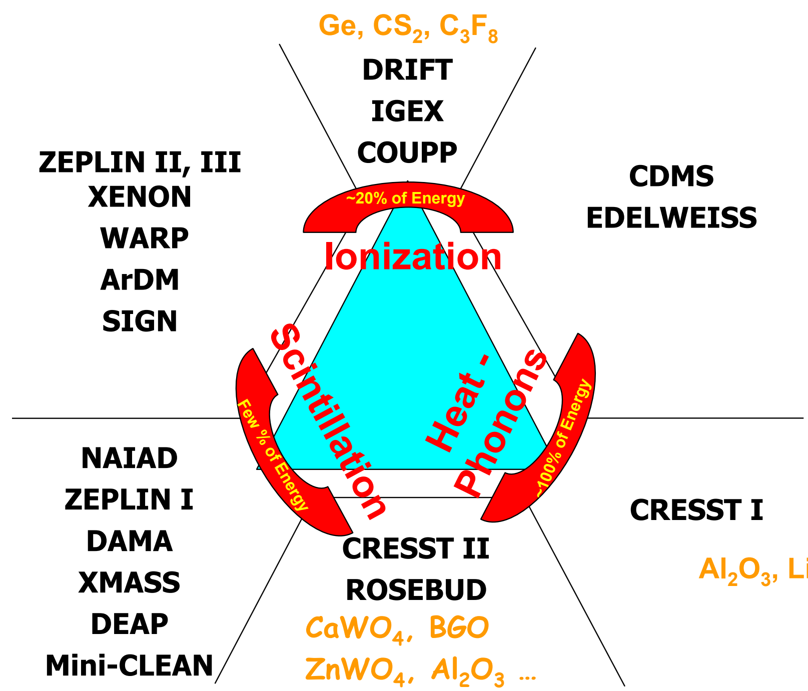
Experimental Approaches

A blooming field



As large an amount of information and a signal to noise ratio as possible

Direct Detection Techniques



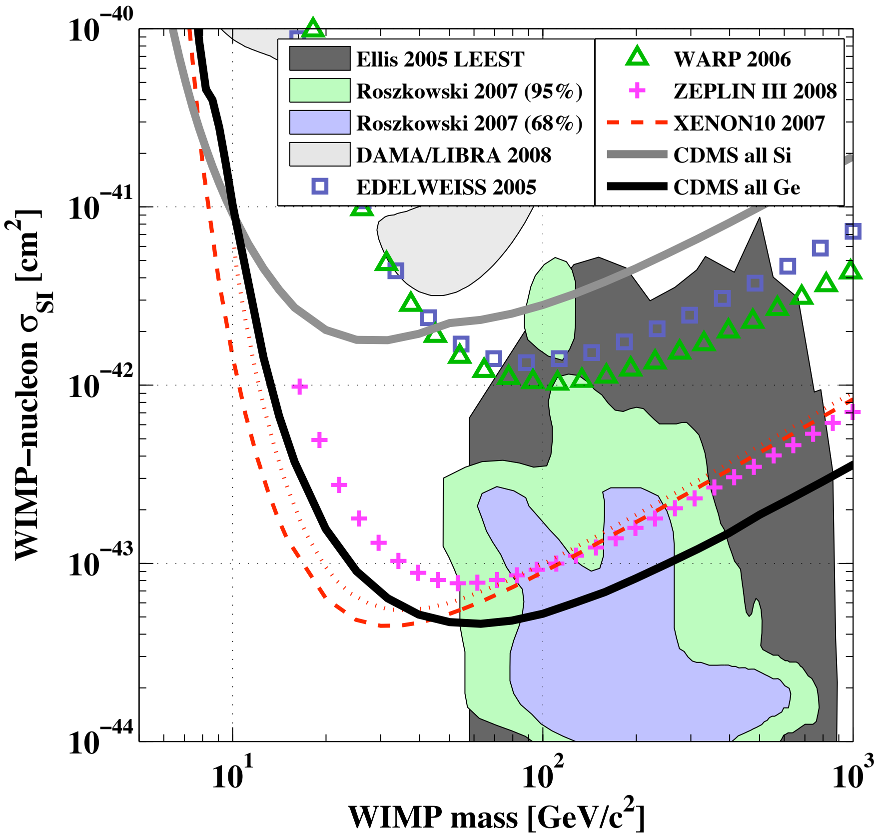
At least two pieces of information in order to
- recognize nuclear recoil
- extract rare events from background (self consistency)
- + fiducial cuts (self shielding, bad regions)

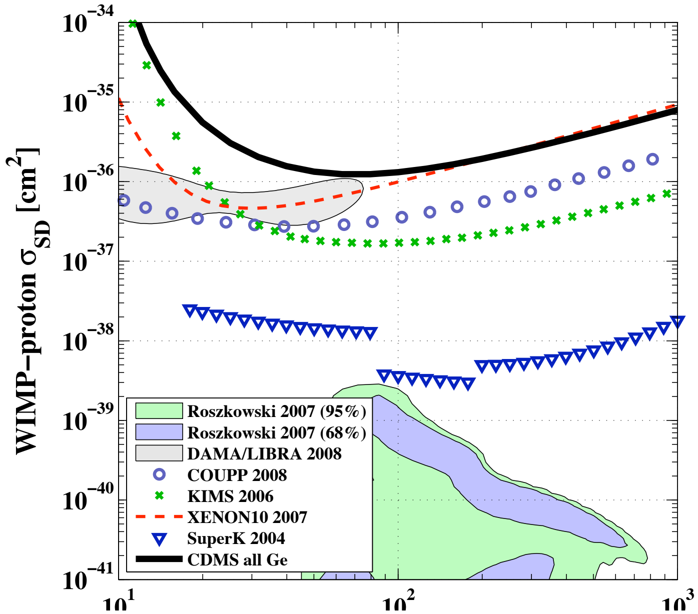
Situation Summer 2009

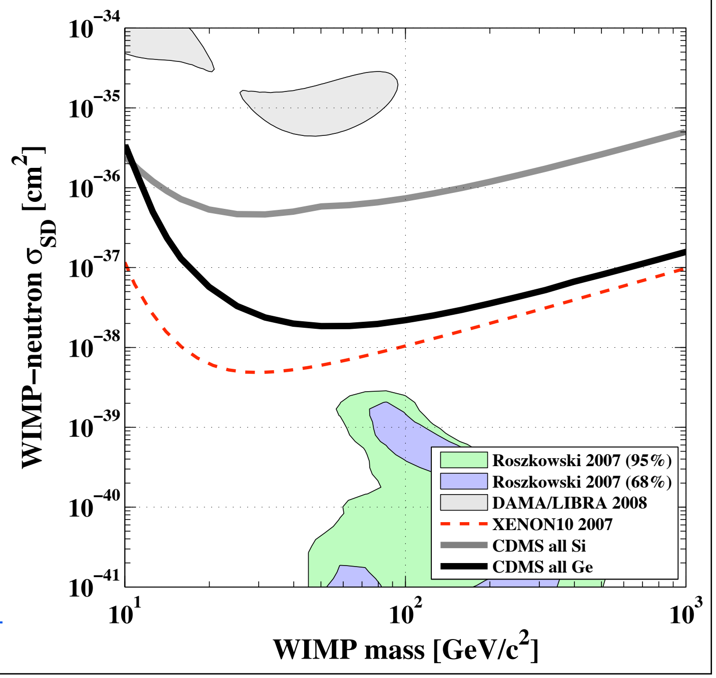
Scalar couplings: Spin independent cross sections

January 2009 compilation by Jeff Filippini

Gray=DAMA 2 regions(Na, I) from Savage et al.



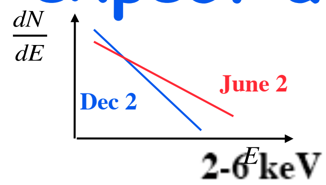


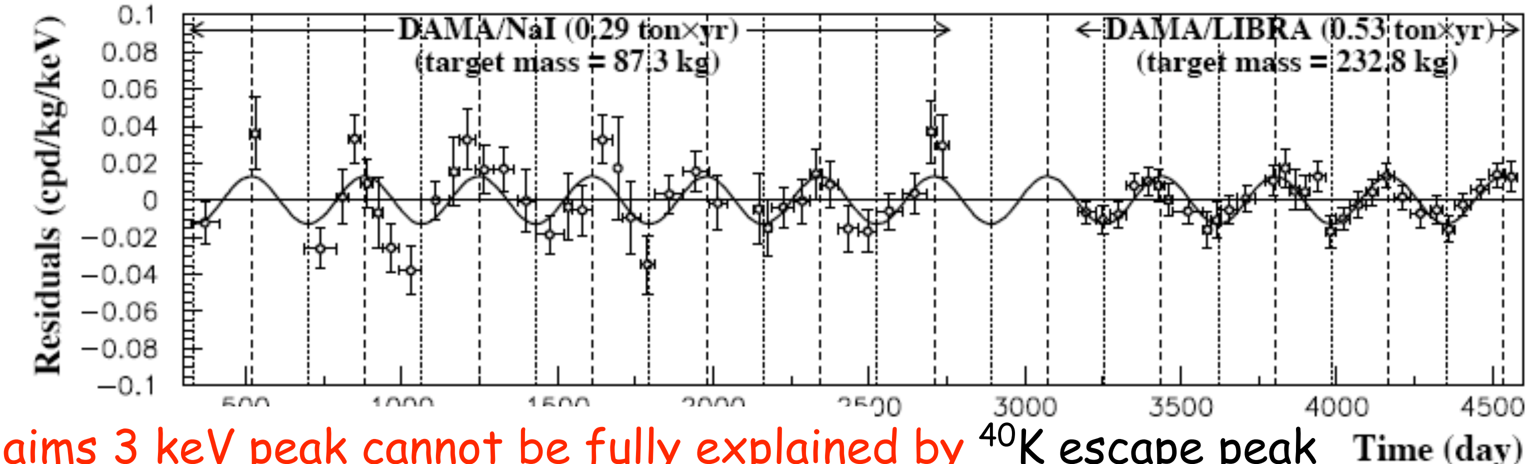


Spin dependent couplings

DAMA Claim April 2008 still stands

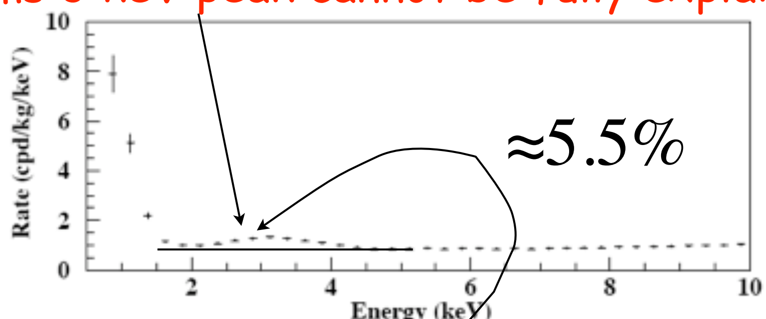
If WIMPs exist, we expect a modulation in event rate





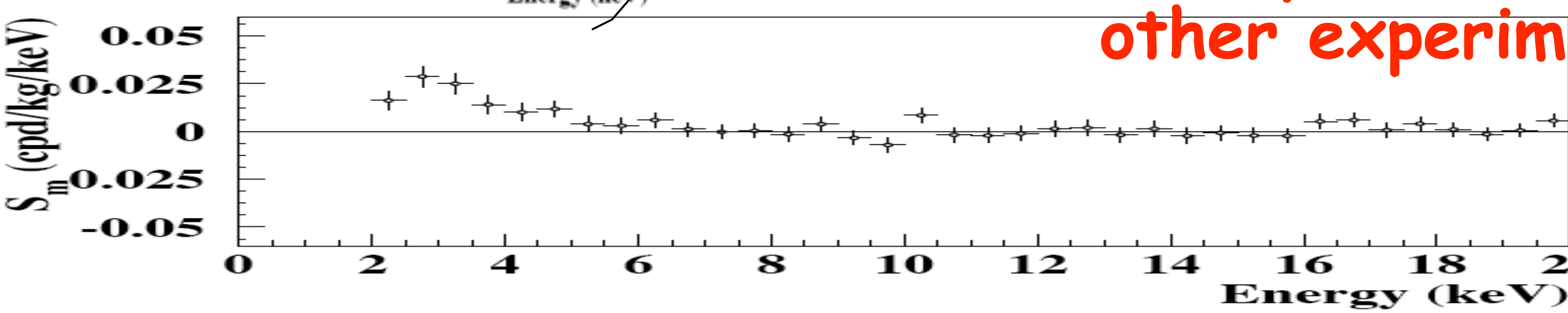
DAMA claims 3 keV peak cannot be fully explained by ^{40}K escape peak

Clearly a modulation



≈5.5%

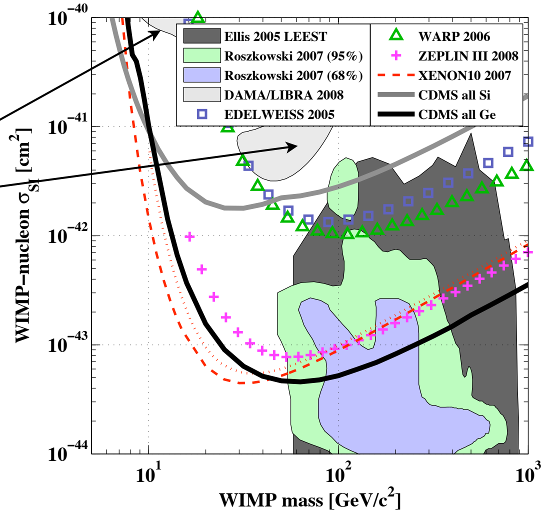
Not a WIMP: incompatible with other experiments



Tension with Other Expts.

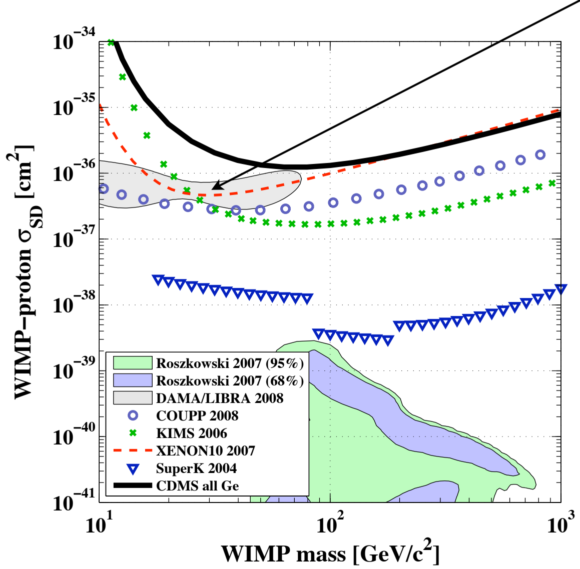
Spin independent interactions

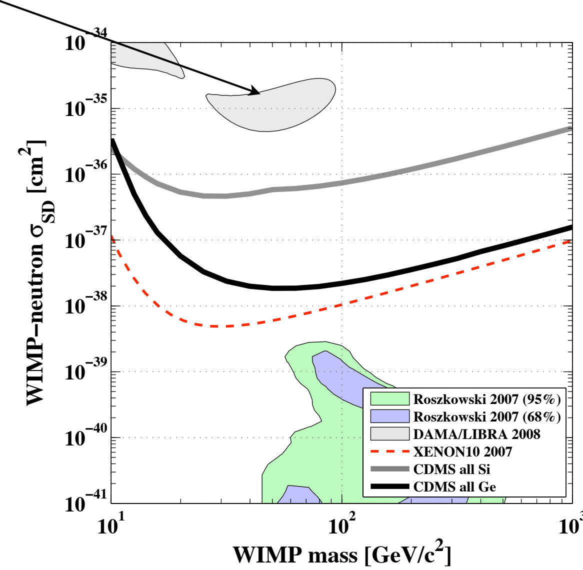
DAMA



Spin dependent

DAMA





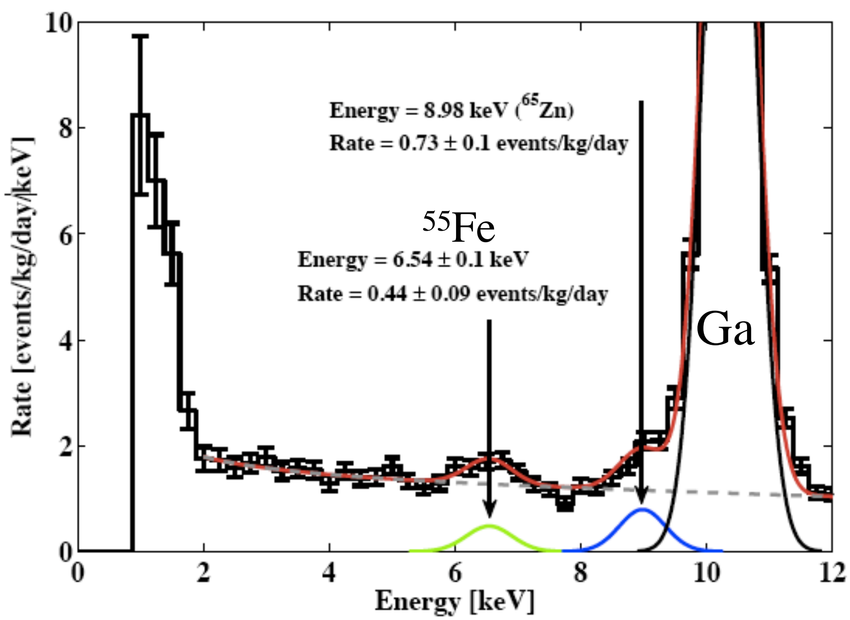
What could it be: Physics?

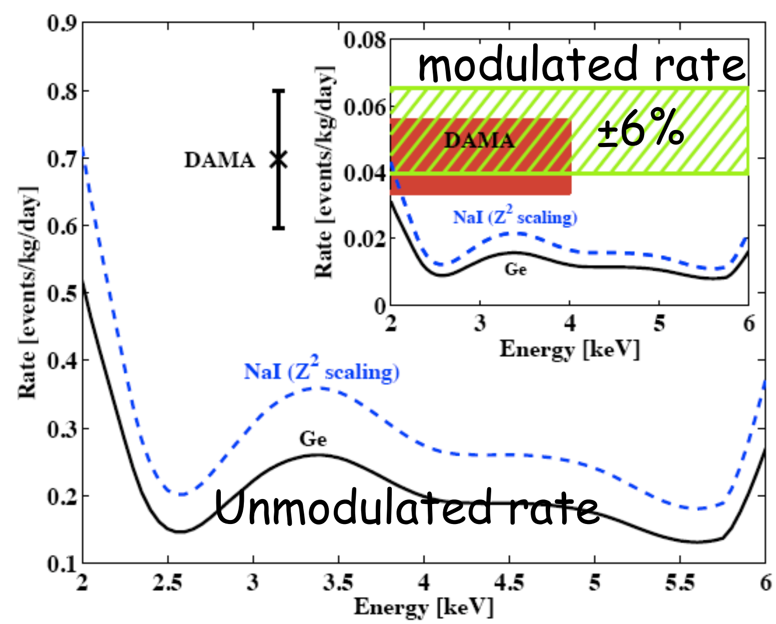
An axionic type particle of 3 keV converting its mass into electromagnetic energy in detector

- Modulation by flux Electron recoil line at 3 keV
- Checked by other detectors: CoGeNT, CDMS!

3 keV peak excluded cf. CDMS arXiv:0907.1438

- 3 keV peak in DAMA single rate is not physical (if Z^2 scaling)
  - Probably ^{40}K escape (1.46MeV missed)
- Excludes as modulation signal as big as DAMA (even in optimistic case of ±6%)
  - Note that cross sections of exothermic radiations tend to be inversely proportional to velocity => modulation very much suppressed (Pospelov et al. 2008)





What could it be?

Most likely very subtle detector problem

- Modulation is basically summer-winter
- Example of the cosmic muon rate which is modulated with the same phase (decay path of the pions change with temperature)
- Many things change: temperature, water in mountain, humidity, electric voltage

What seems excluded

- Neutron from muons
- Direct effect of muons on detector

Examples of effects which have not been excluded convincingly

- Modulation of the efficiency
  - e.g. of the PM noise rejection algorithm
- Modulation of the ^{40}K 1.46 MeV gamma detection efficiency
  - (e.g. varying humidity in purge gas=> modulation of dead layer=> 3 keV escape

Not blind analysis!

Sociological problem:

Nobody finds the result plausible enough to repeat the experiment!

However, as a field we need to cross check the only claim.

A different team has to redo the experiment!

in Southern Hemisphere?

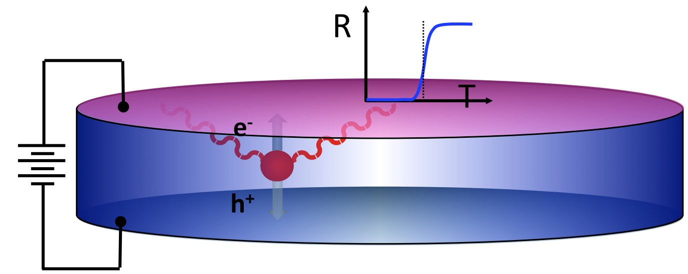
e.g. NaI detectors in a hole in Antarctic Ice (Stubbs, Fisher, IceCube, B.S.)

in Borexino?

CDMS II December 2009

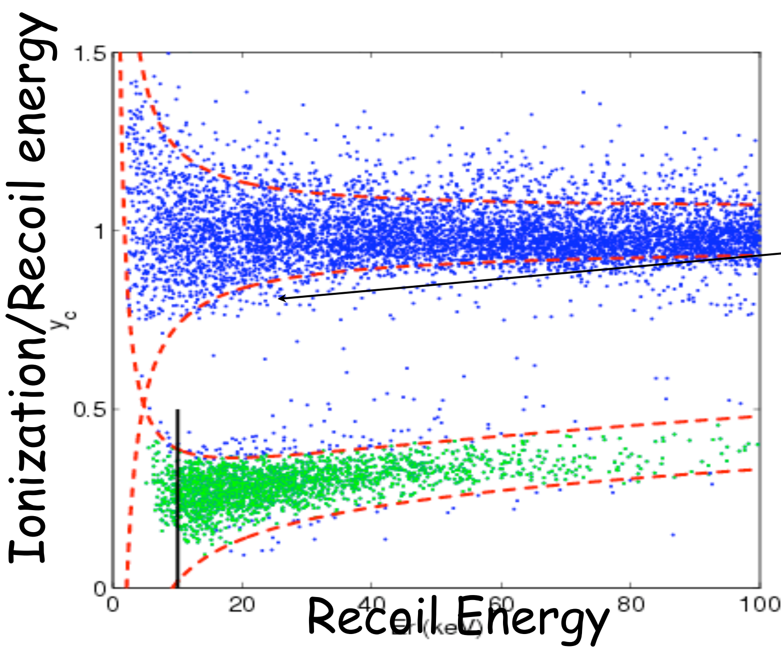
Ionization + Athermal Phonons

7.5 cmØ 1 cm thick ≈250g
4 phonon sensors on 1 face
2 ionization channel

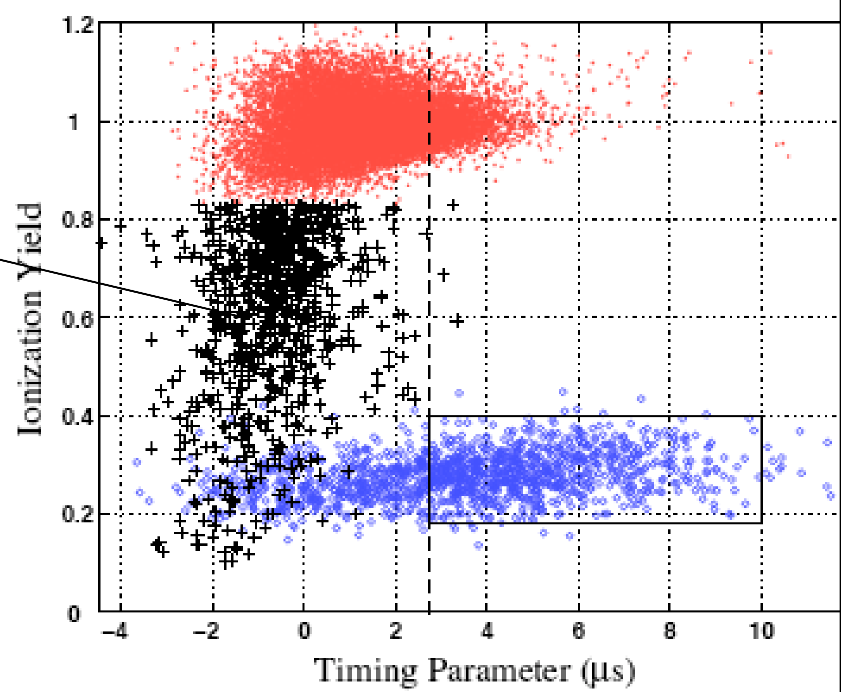


Ionization yield

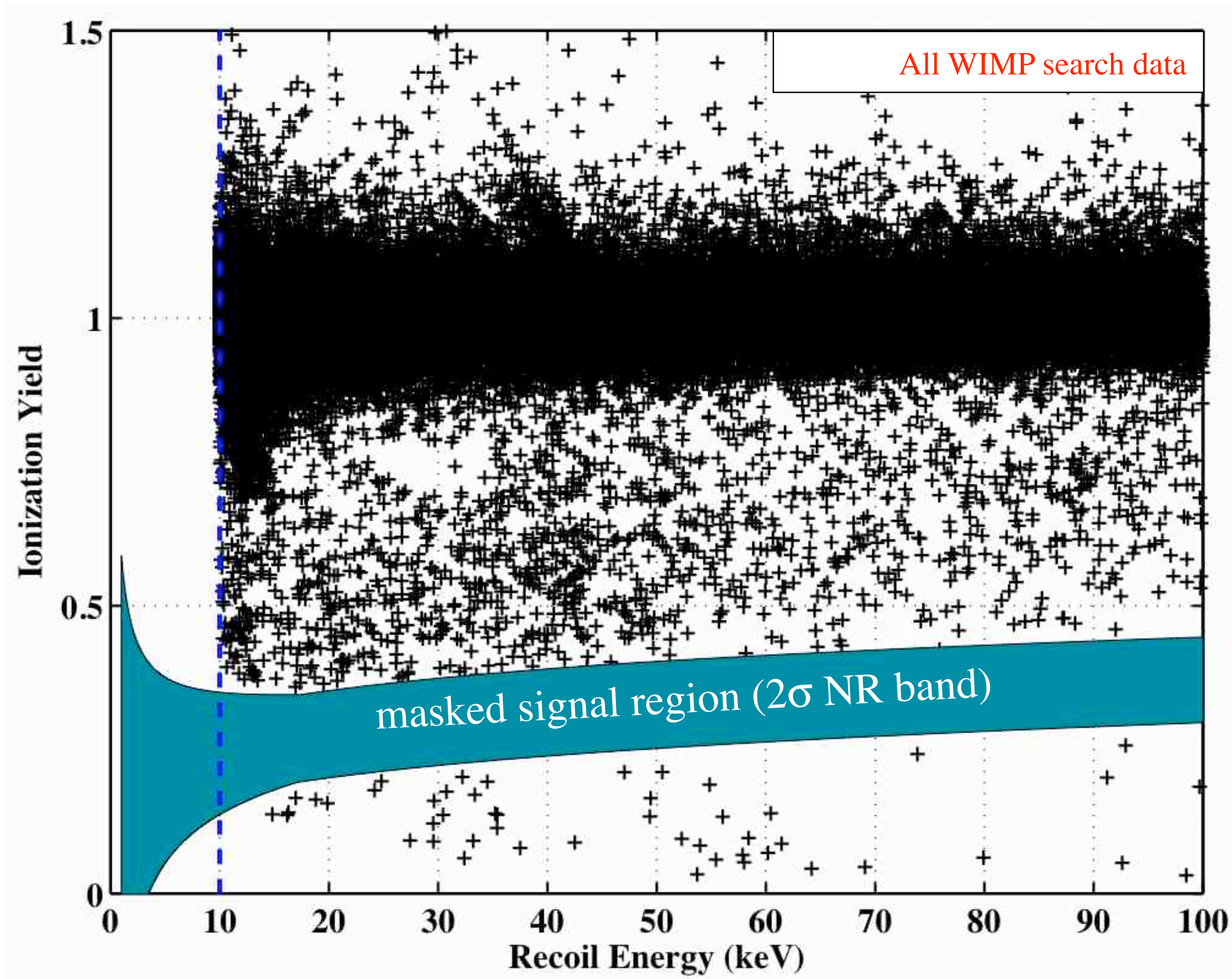
Timing -> surface discrimination



Surface Electrons

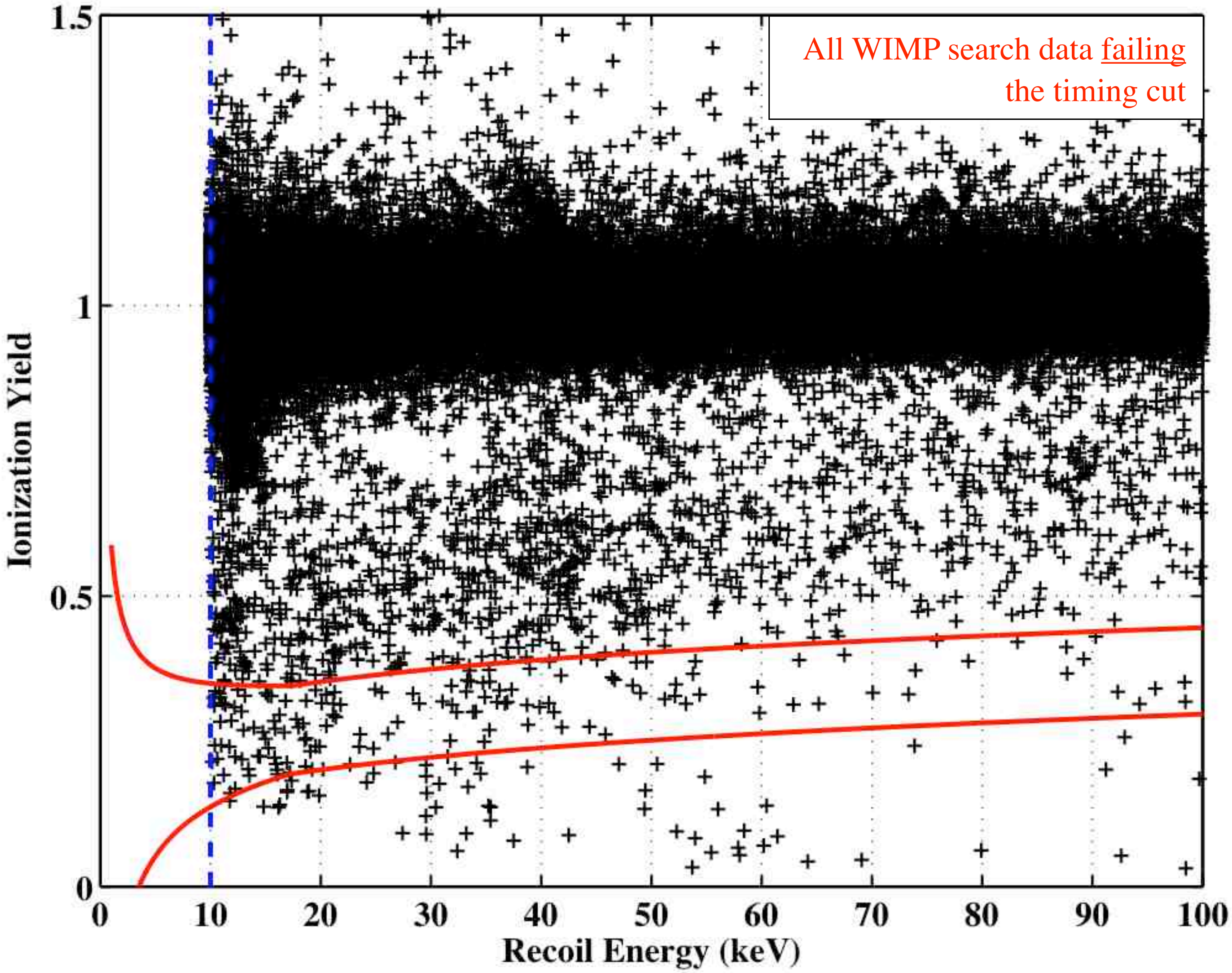


CDMS Blind Analysis



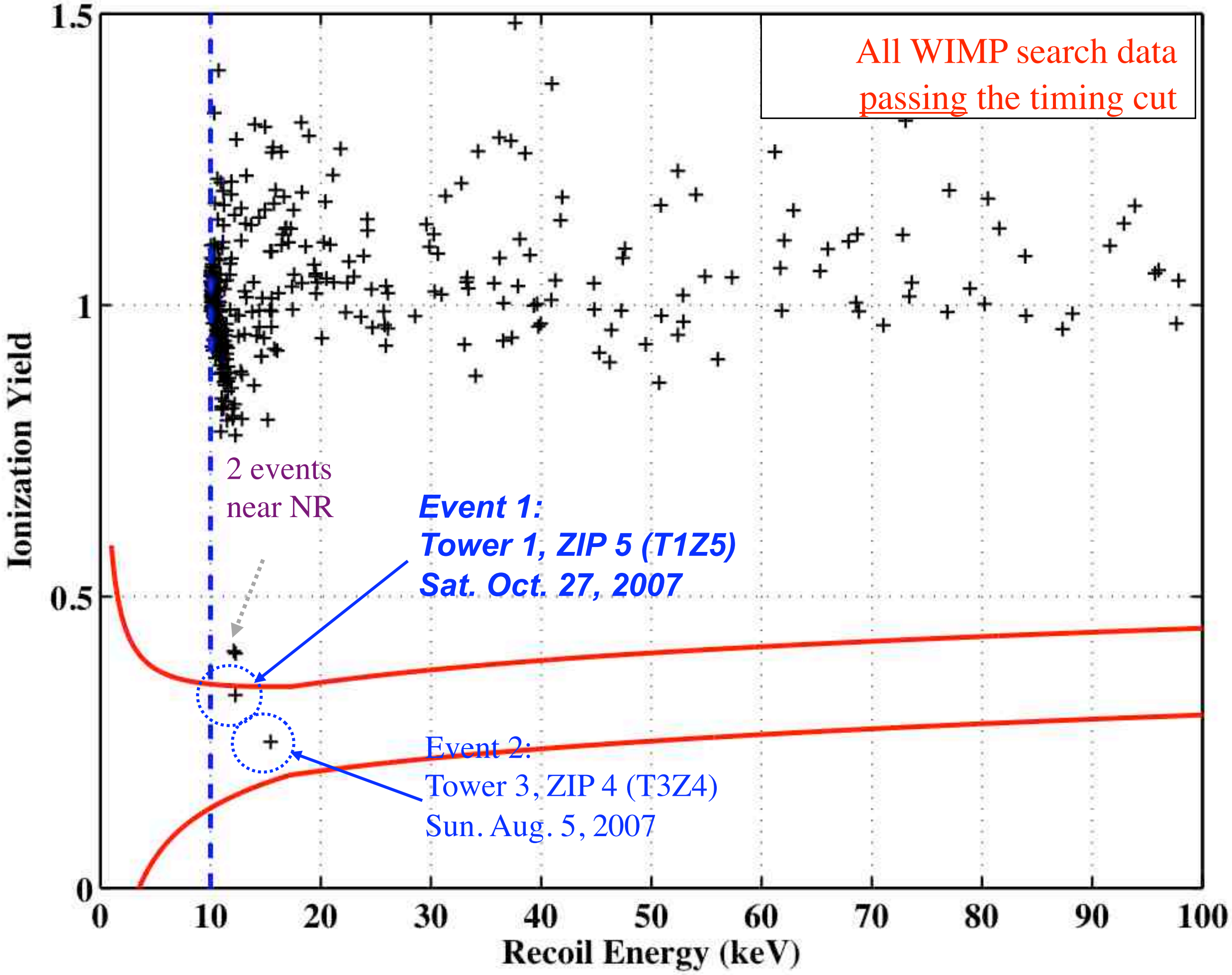
We unblinded the signal region November 5, 2009

Unblind Events Failing Timing Cut



150 events in the NR band fail the timing cut, consistency checks deemed ok

Unblind Events Passing Timing Cut



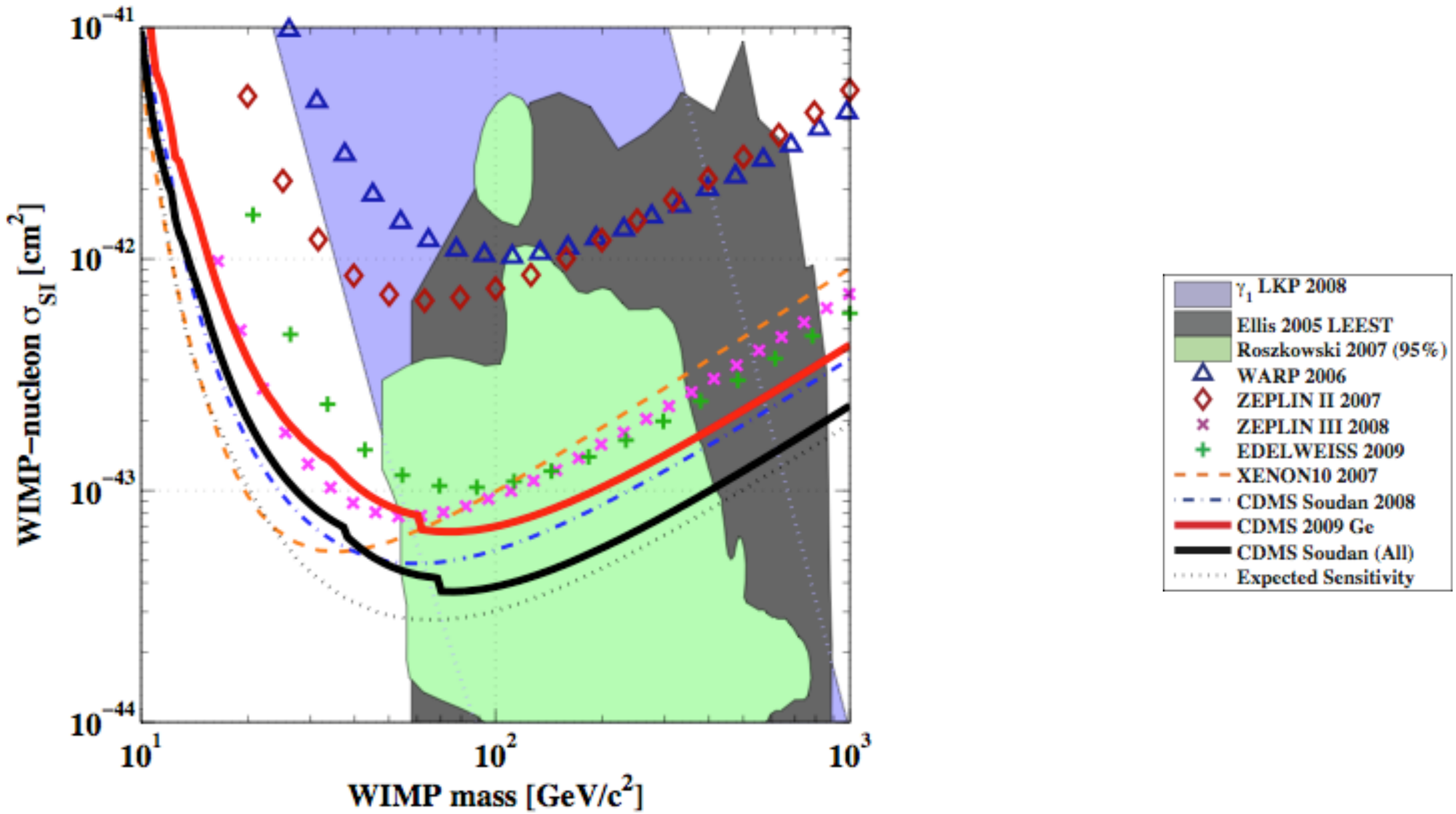
2 events in the NR band pass the timing cut!

Background 0.8 ± 0.1 (stat) ± 0.2 (syst) surface events

+ 0.1 ± 0.05 (syst) neutron => 23% Probability

90% C.L. Spin-Independent Limit

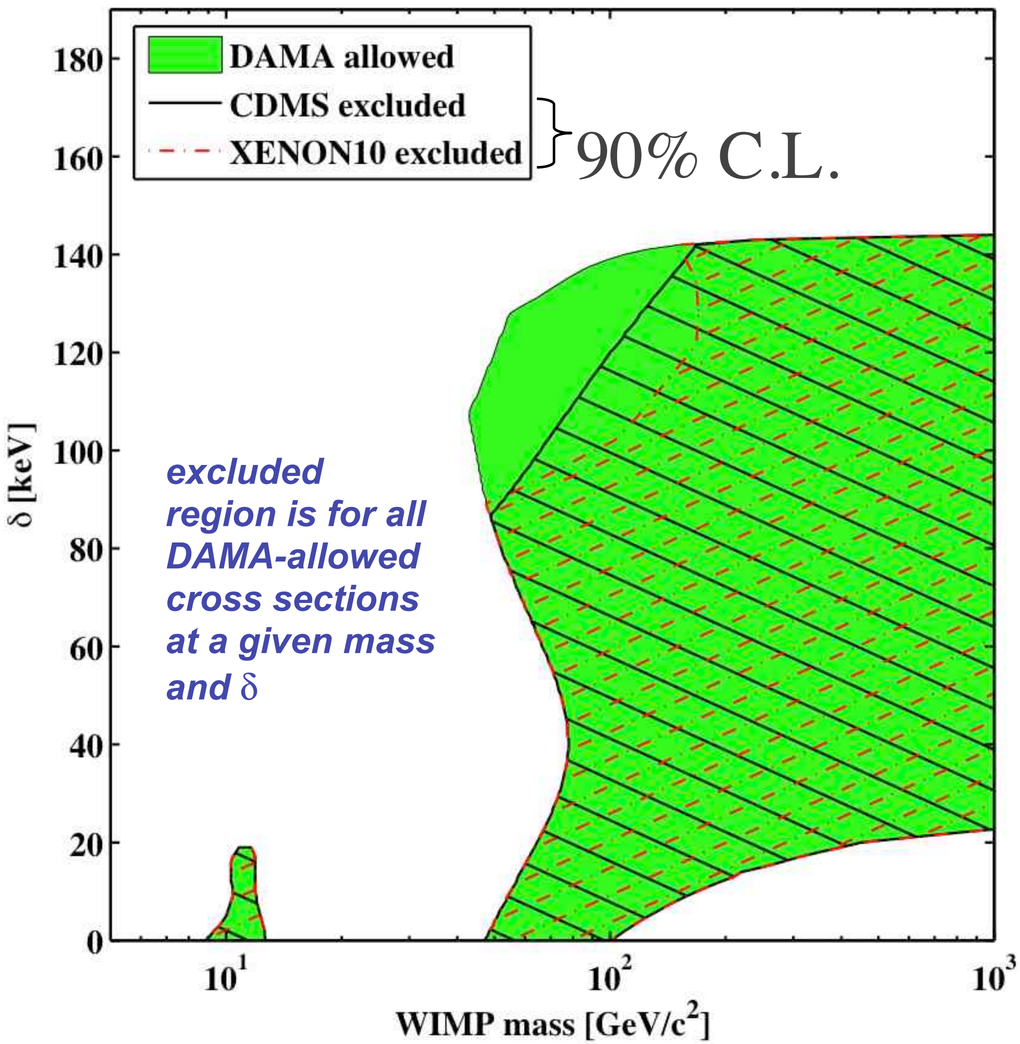
Science 12 February 2010



Upper limit at the 90% C.L. on the WIMP-nucleon cross section :

3.8×10^{-44} cm^2 for a WIMP of mass 70 GeV/c^2

Inelastic Dark Matter



No channeling

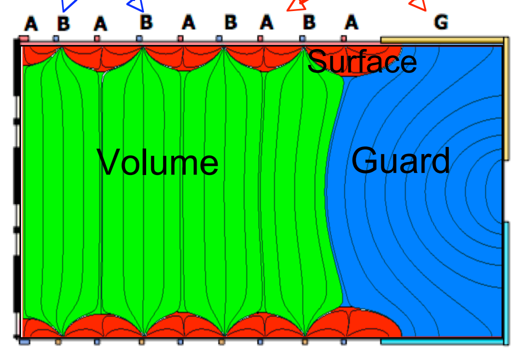
Has been invoked by Weiner et al. to explain DAMA/LIBRA data, among other things.
[Phys. Rev. D 64, 043502 (2001)]

- Scattering occurs via transition of WIMP to excited state (with mass splitting δ)

- spectrum peaks at higher recoil energies

- DAMA, allowed regions (at 90% C.L.) computed from χ^2 goodness-of-fit and standard truncated halo-model
[JCAP 04 (2009) 010]

The future of Ge



Breakthrough: Interdigitated detectors

Positive and ground electrodes on top side
Negative and ground on negative
=> separate surface (asymmetric) from bulk (symmetric)
CDMS + EDELWEISSS

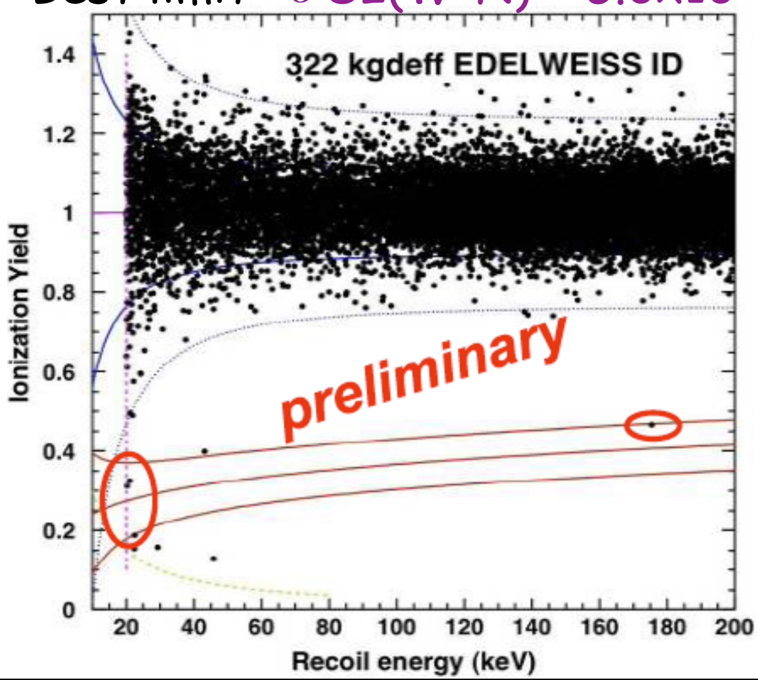
The surfaces are gone!

Rejection should be good enough-> ton scale

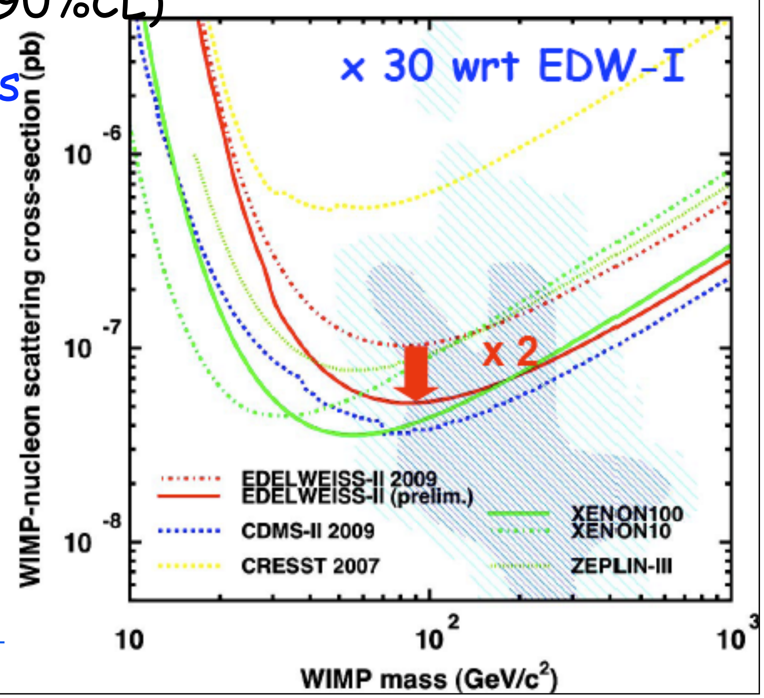
Is this true? EDELWEISS results presented Sunday 7/18

3 evts near threshold + 1 evt at 175 keV in the nuclear recoil region (1.6 evt expected)

Best limit: σ SI(W-N) = 5.0×10^{-44} cm^2 at M_W= 80 GeV(90%CL)



→background starts to appear?
Gammas?



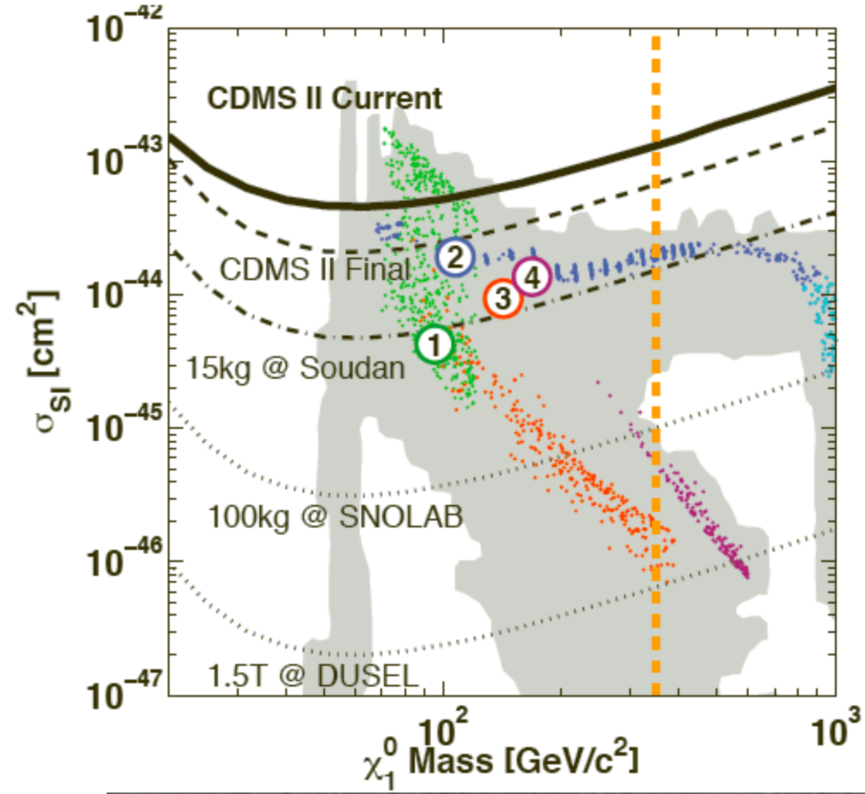
The future of Ge 2

SCDMS Soudan 15kg
2011-2012: 5 10^{-45} cm^2

SCDMS SNOLAB 100kg
2014-2017 3 10^{-46} cm^2

GEODM DUSEL 1.5 tonne
2017-2021 2 10^{-47} cm^2

Challenge is to produce detector at low enough cost ($50M)



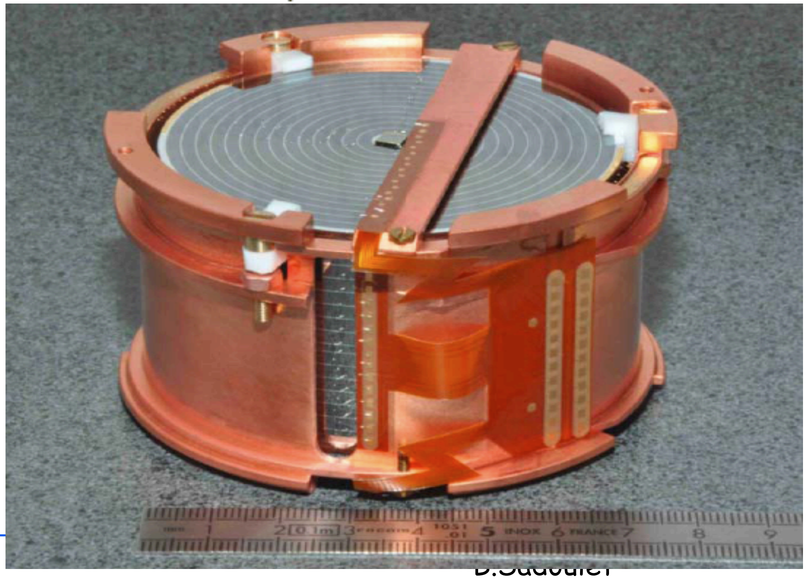
EDELWEISS
2012: 5 10^{-45} cm^2

40 detectors 800g + improvement background, electronics

EURECA 100kg
2013-2016

few 10^{-46} cm^2

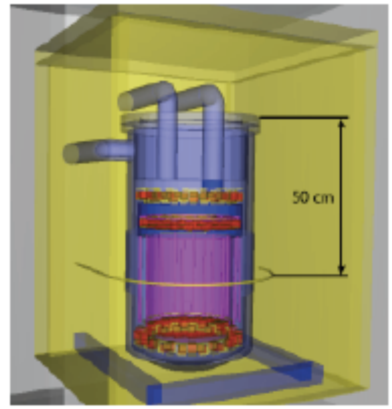
-> tonne



New results of Xenon 100 May 2010

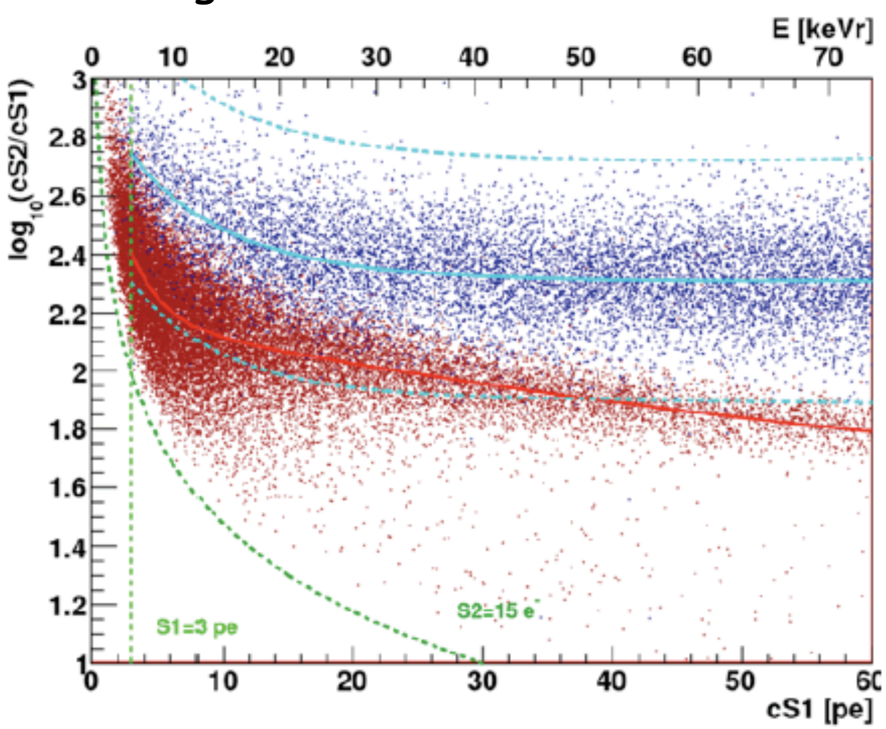
Liquid Xenon

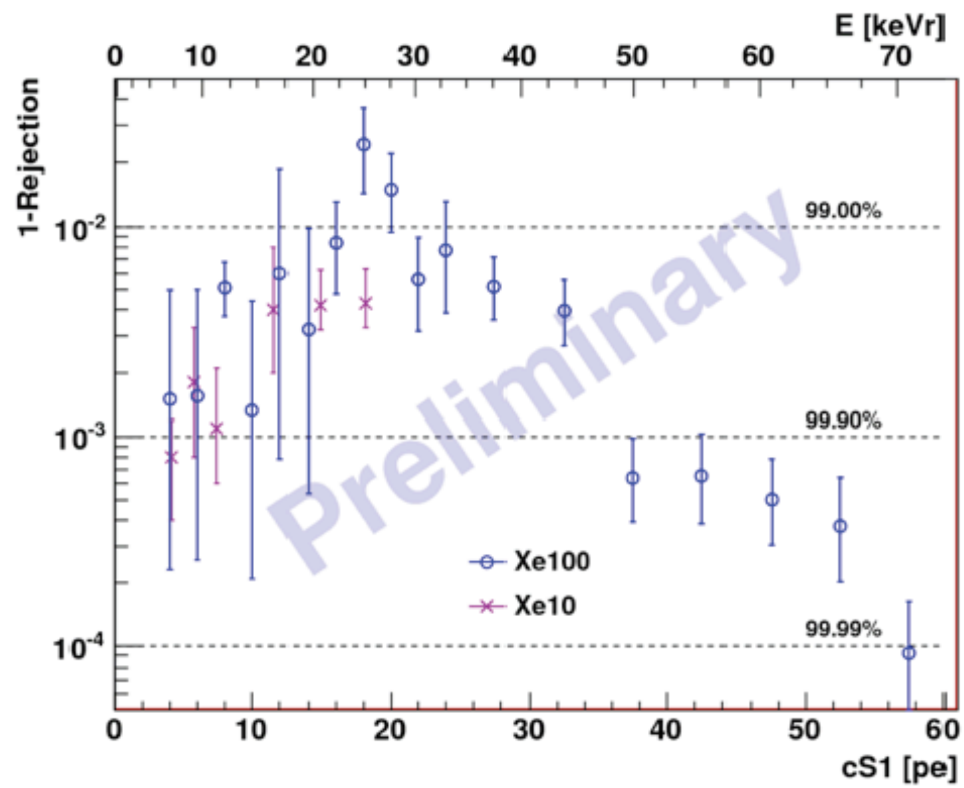
161kg Xe
40kg active volume



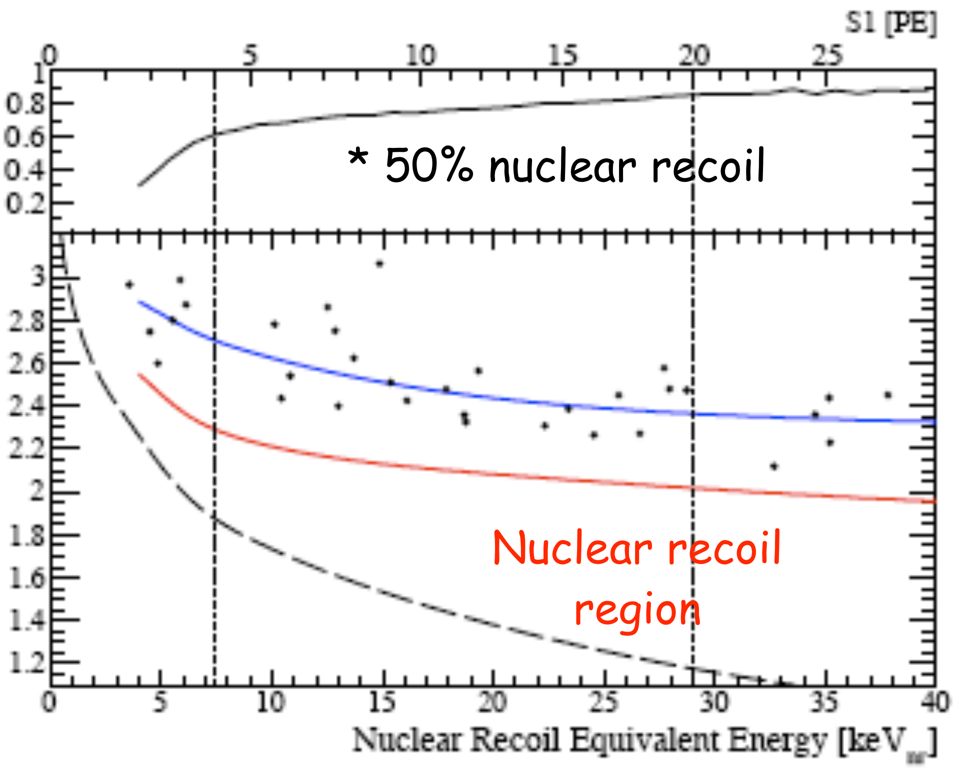
Scintillation (S1) + Ionization (S2)

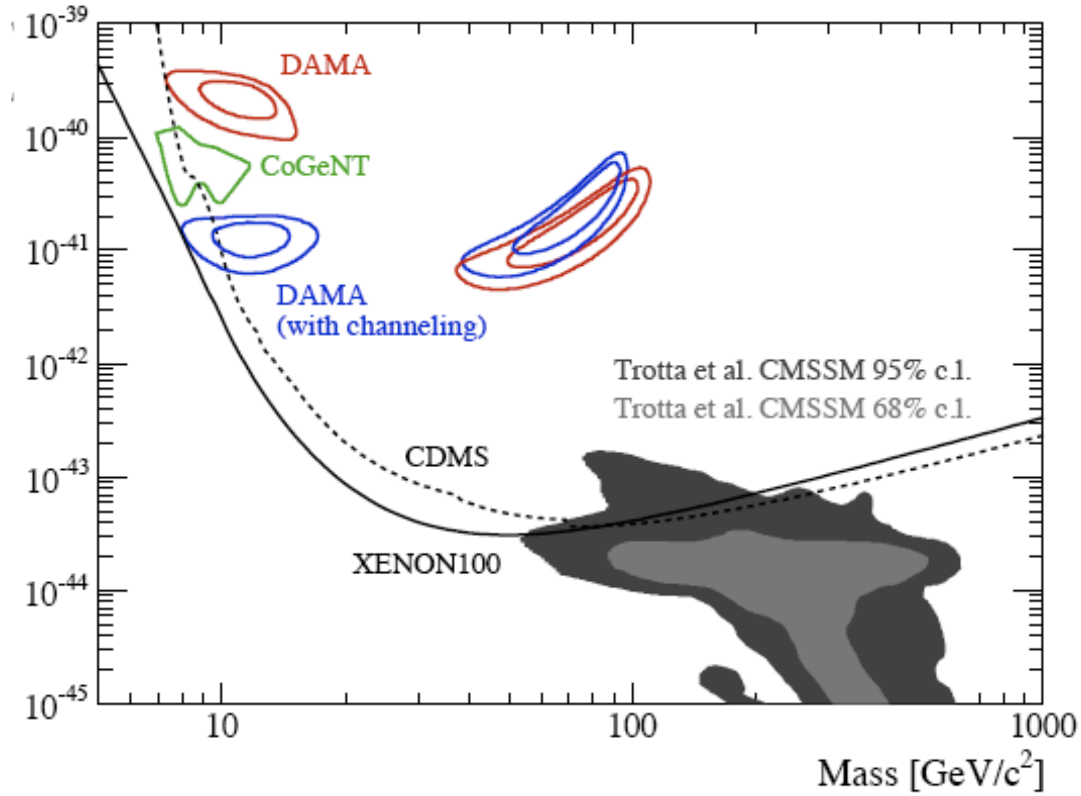
Log scale





Exclusion limit





11 days preliminary run (not blind)

Very few events in fiducial region

Sensitivity ≈ CDMS

- Increasing tension with DAMA
- Do not see evidence for low mass seen by CoGeNT

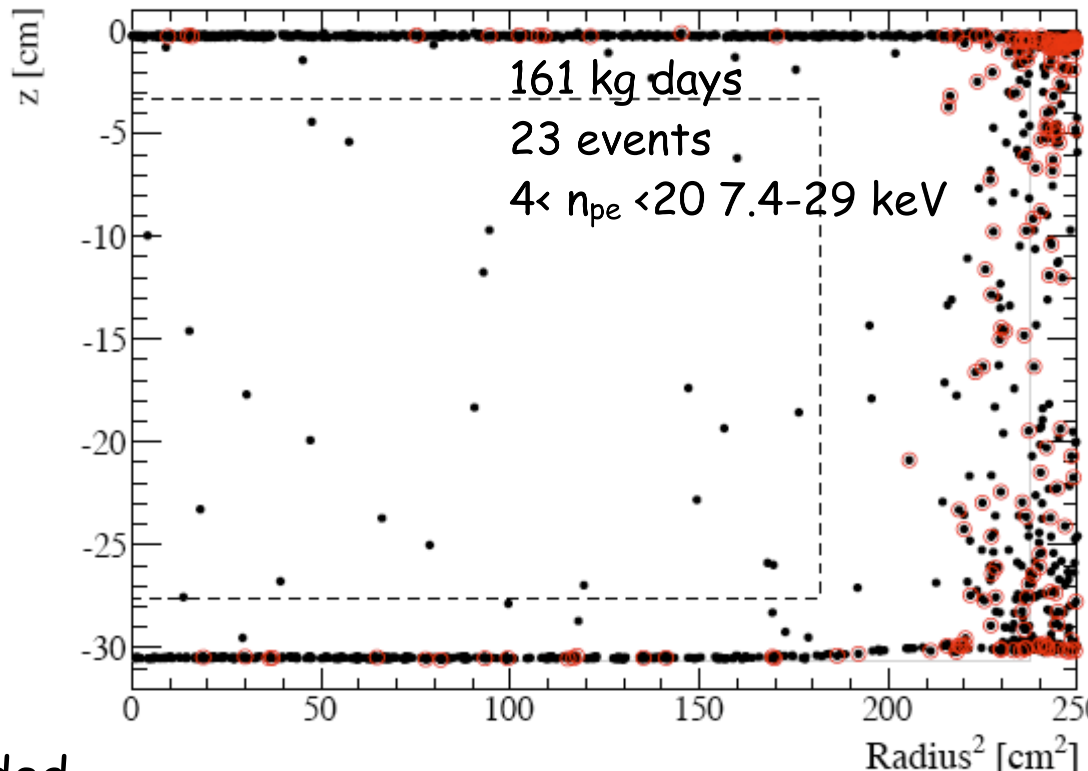
The future of Xenon

3 experiments

XMASS (single phase)
Xenon 100-> 1t
LUX 350kg-> few tons

Exciting

Currently running
With rejection of ≈7 10^{-3}
could improve by factor 5
≈ 5 10^{-45} cm^2/nucleon



But clearly see volume contamination

Will have to understand

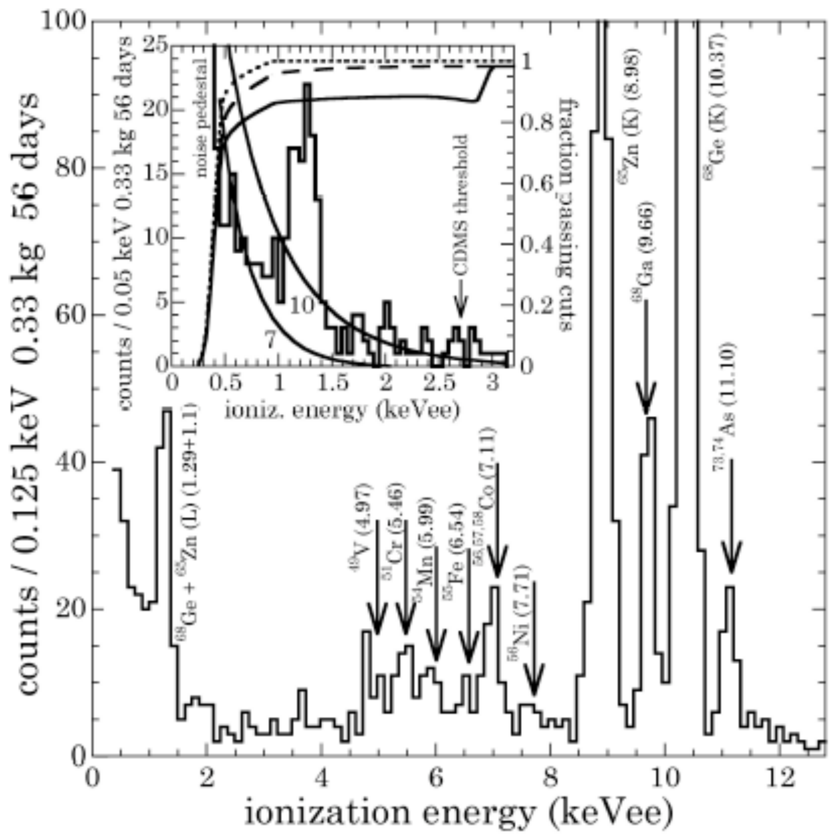
Still far from performance needed
for 10^{-47} cm^2/nucleon (Generation 3 experiment goal!)

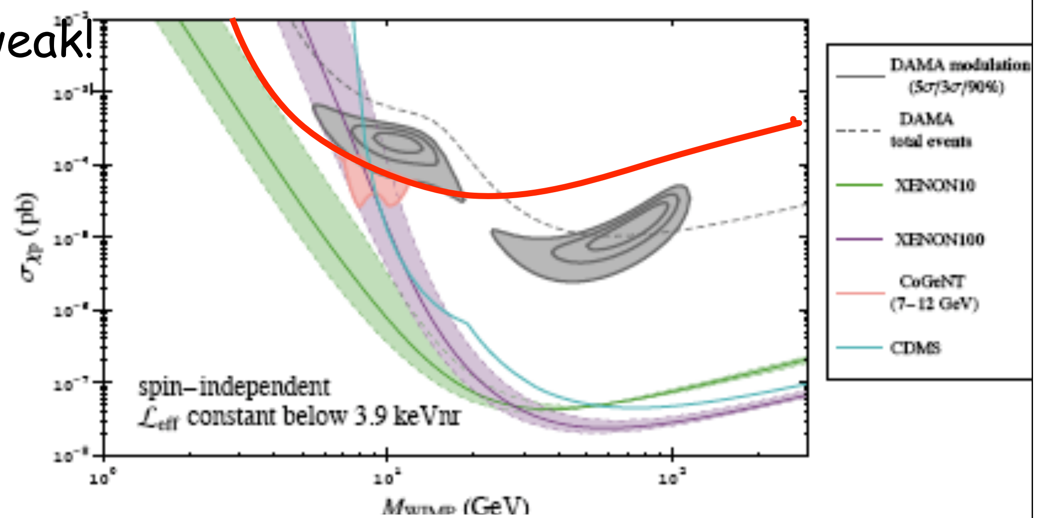
CoGeNT Feb 2010

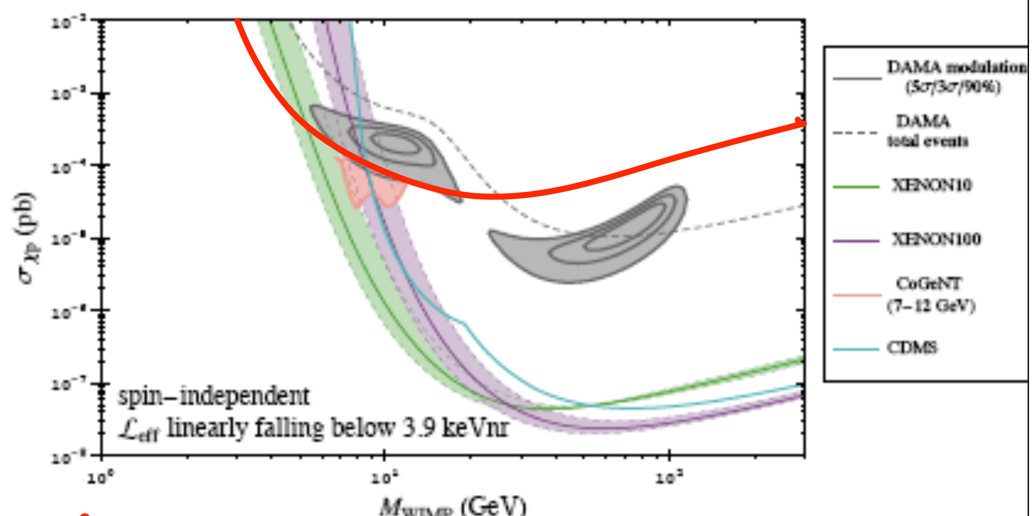
Small Ge liquid N_2 high resolution

Evidence for a signal ?

Detailed shape of the background: very weak!







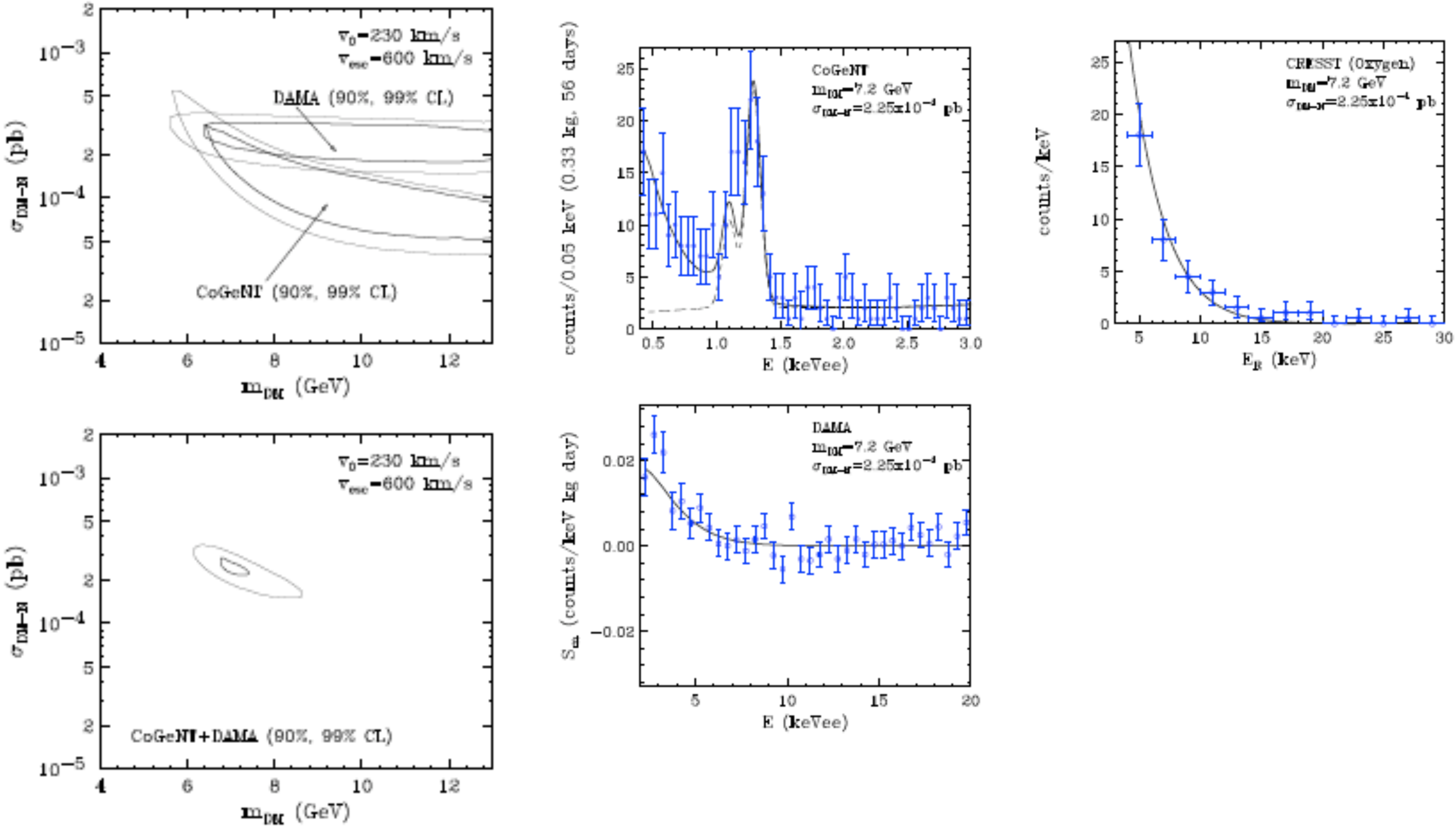
Excluded by Xenon 10-100?

it all depends on Leff calibration

Savage et al ArXiV 1006.0972

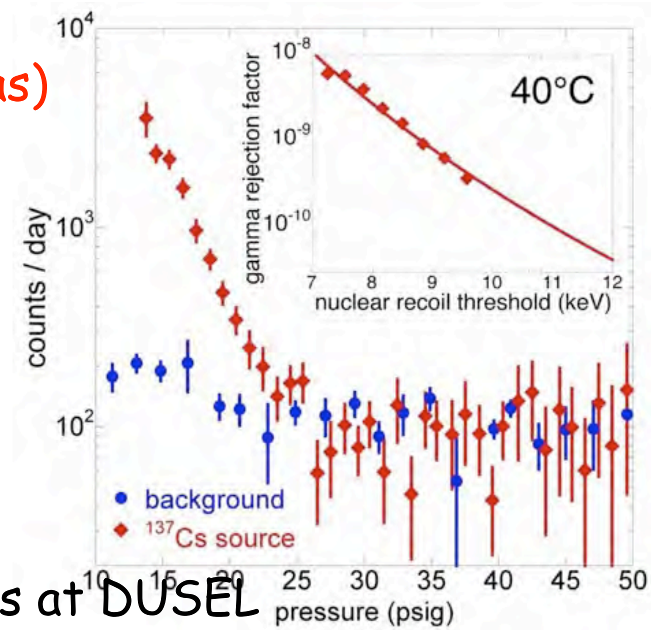
Compatibility between CoGeNT and DAMA?

Hooper, Collar, Hall, McKinsey arXiv 1007.1005



Metastable Detectors

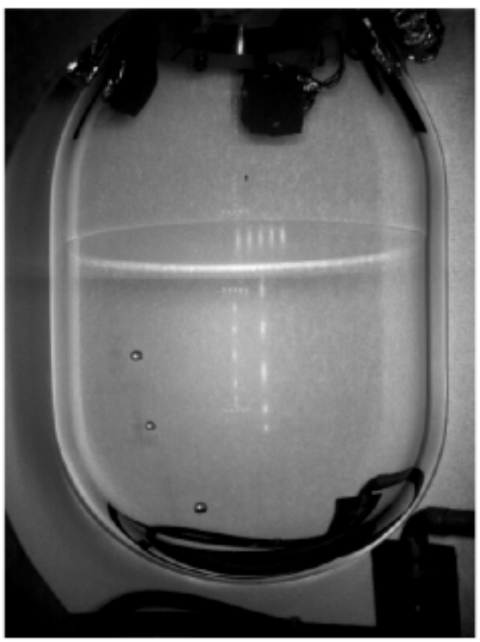
Only triggered by large deposited- energy density
Insensitive to electron recoils (but sensitive to alphas)
Cheap, Scalable
But do not measure energy . Need to scan!



PICASSO Granules

COUPP Bubble chambers

4kg in 2009, 60kg in progress, 500kg then 16 tons at DUSEL

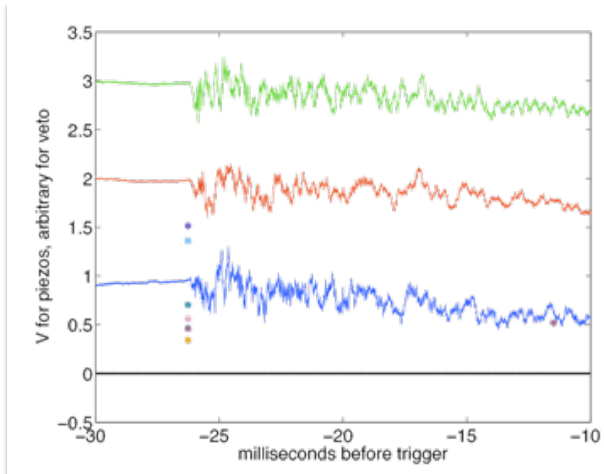


New: Alpha discrimination!

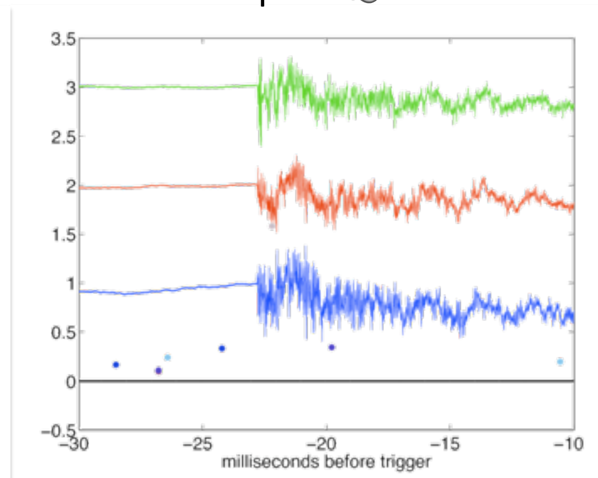
Alpha are louder, higher frequency

More proto-bubbles!

Neutron

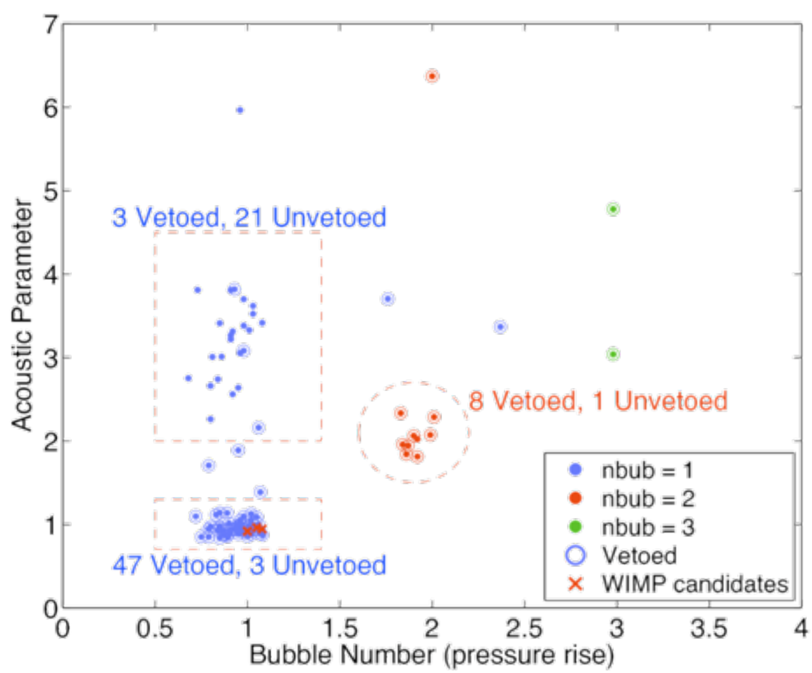


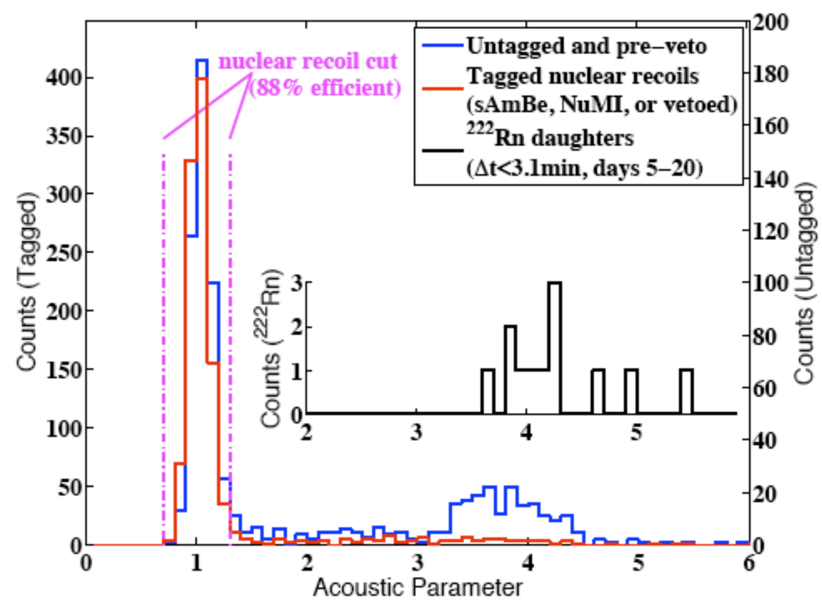
Alpha



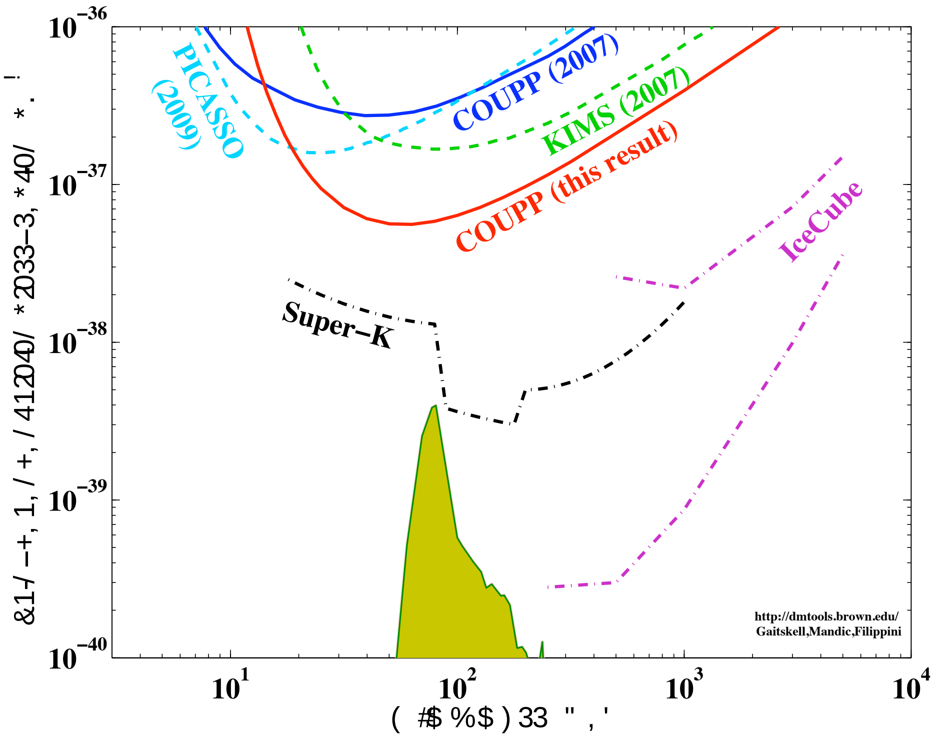
=> Discrimination

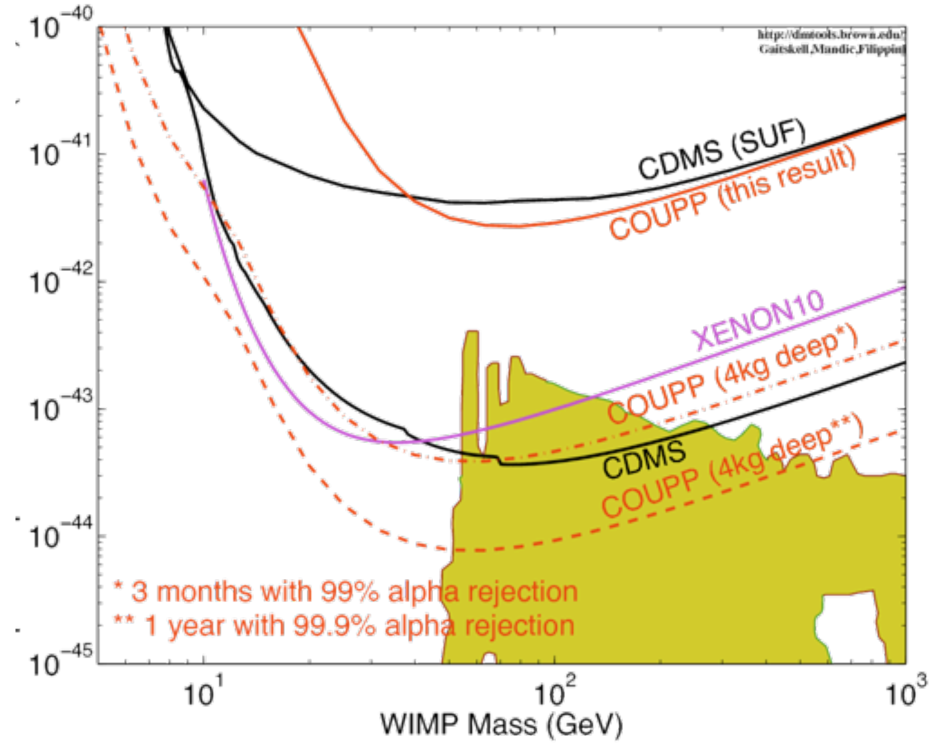
More proto-bubbles!





Preliminary Results May 2010





Is there enough information?

Energy scanning penalty

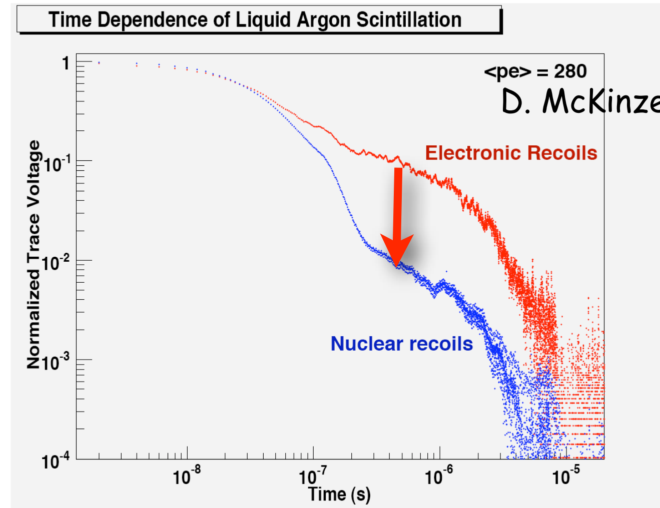
Upper limit machines?

Liquid Argon

Liquid Argon (or Neon)

For light liquids, **one additional handle : rise time**

Triplet (long decay time) killed by nuclear recoil

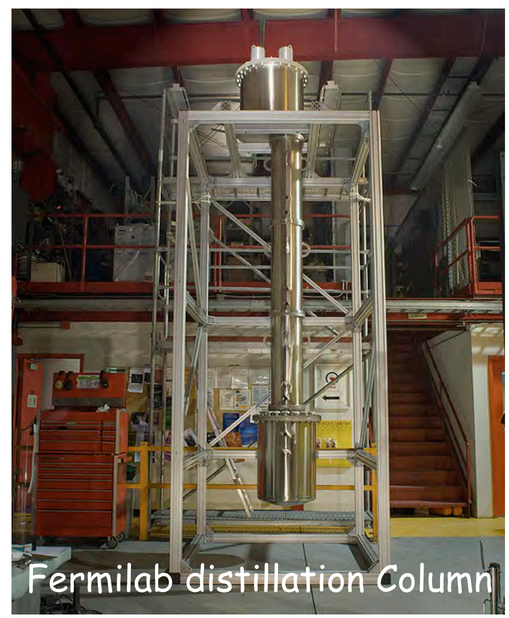


However

Far UV scintillation => wave shifter

Need enough photo electrons => Higher thresholds

^{39}Ar: 1 count/s/kg   Need to deplete (underground Ar)
seems to work! >1/20



Fermilab distillation Column

Liquid Argon: A lot of action!

Single Phase

Mini CLEAN 280kg 2010
DEAP 3600 2012

Dual phase Argon

WARP 140kg: Technical run at Gran Sasso
ArDM: Being assembled

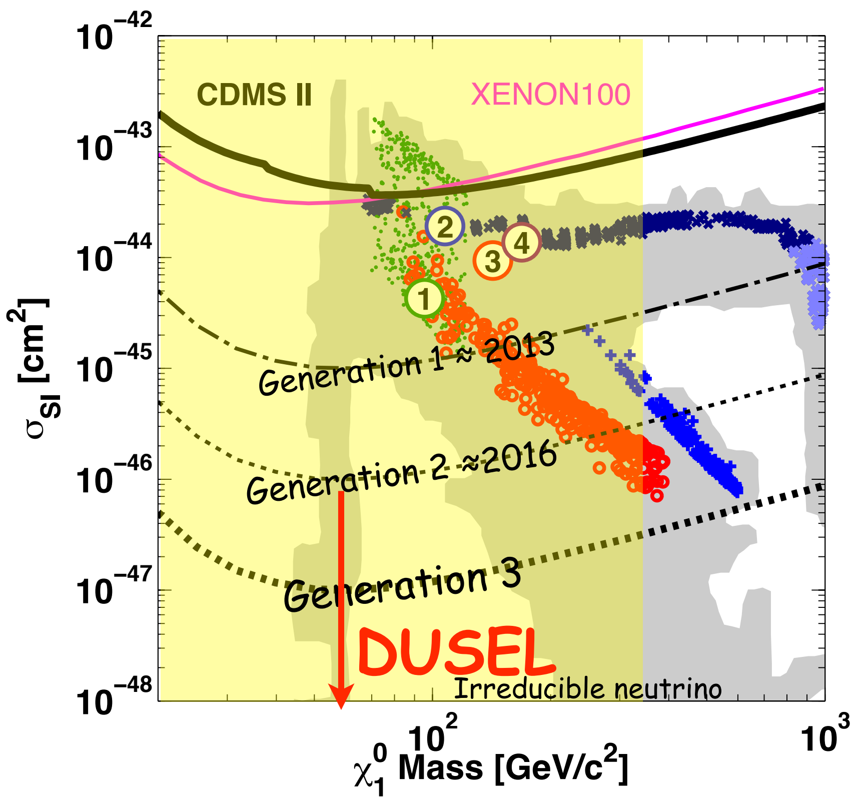
Depleted dual phase Argon

Dark side
50kg 2011 in CTF (Borexino test facility)
->1tonne 2014 -> 20tonne DUSEL

The future of Direct Detection

Technologies are rapidly reaching the needed level of sensitivity/background rejection

- Ge
- Xe
- Bubble Chamber
- Ar



We need several technologies

Several targets to check A dependence

spin

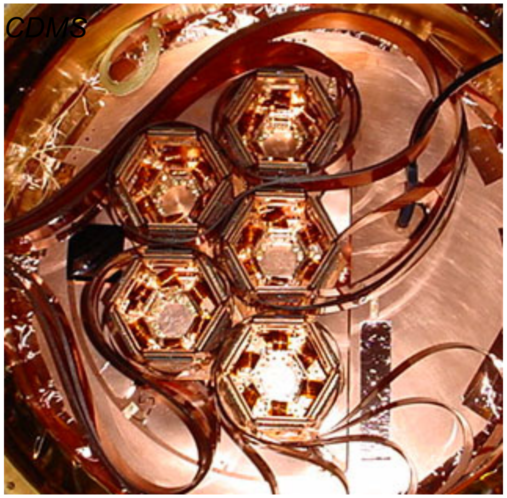
threshold effects (e.g. light dark matter)

Need several technologies with different systematics

cross checks

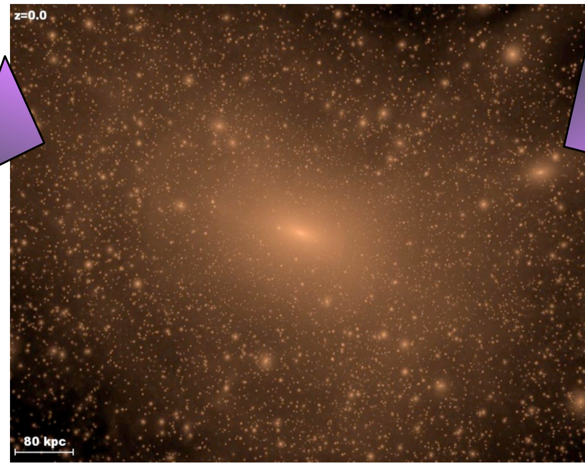
insurance against failure (e.g. unknown background)

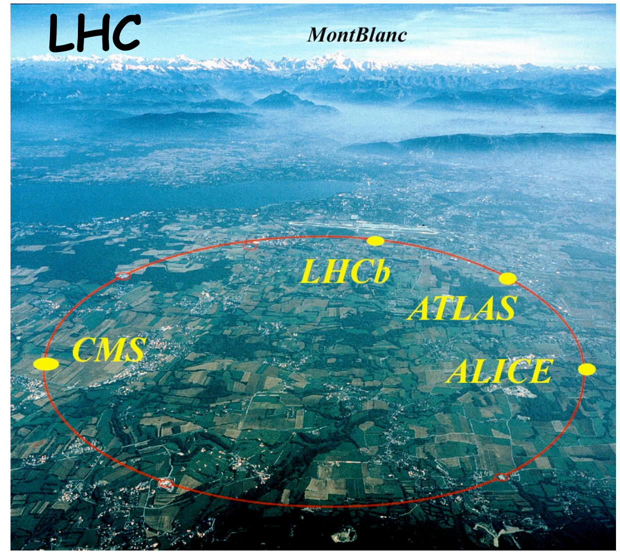
3 Complementary Approaches



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

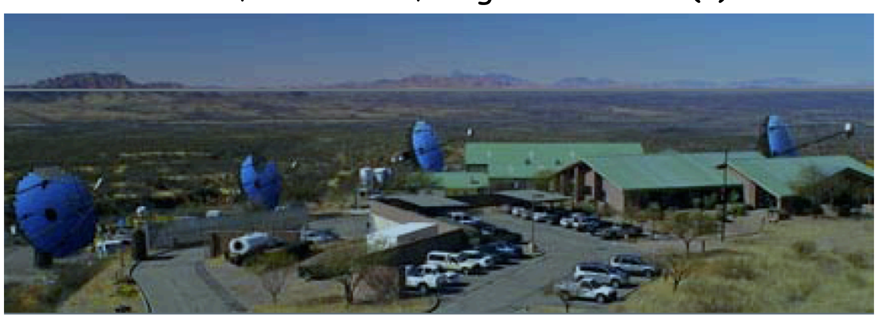
Dark Matter
Galactic Halo (simulation)





WIMP production on Earth

VERITAS, also HESS, Magic + IceCube (ν)



Fermi/GLAST

WIMP annihilation in the cosmos

We Need All Three Approaches

LHC

Could see quite rapidly some missing energy: New Physics!
But cannot prove that the new particles are stable and form the Dark Matter
e.g., χ -> gravitino +… ("Super-WIMP")

Need to detect those particles in the cosmos

Elastic scattering of halo WIMPs in the laboratory

Very clean + would prove that these particles are stable
But can only measure approximately a cross section and a mass:

Little input on the fundamental physics

Annihilation products in the galactic halo

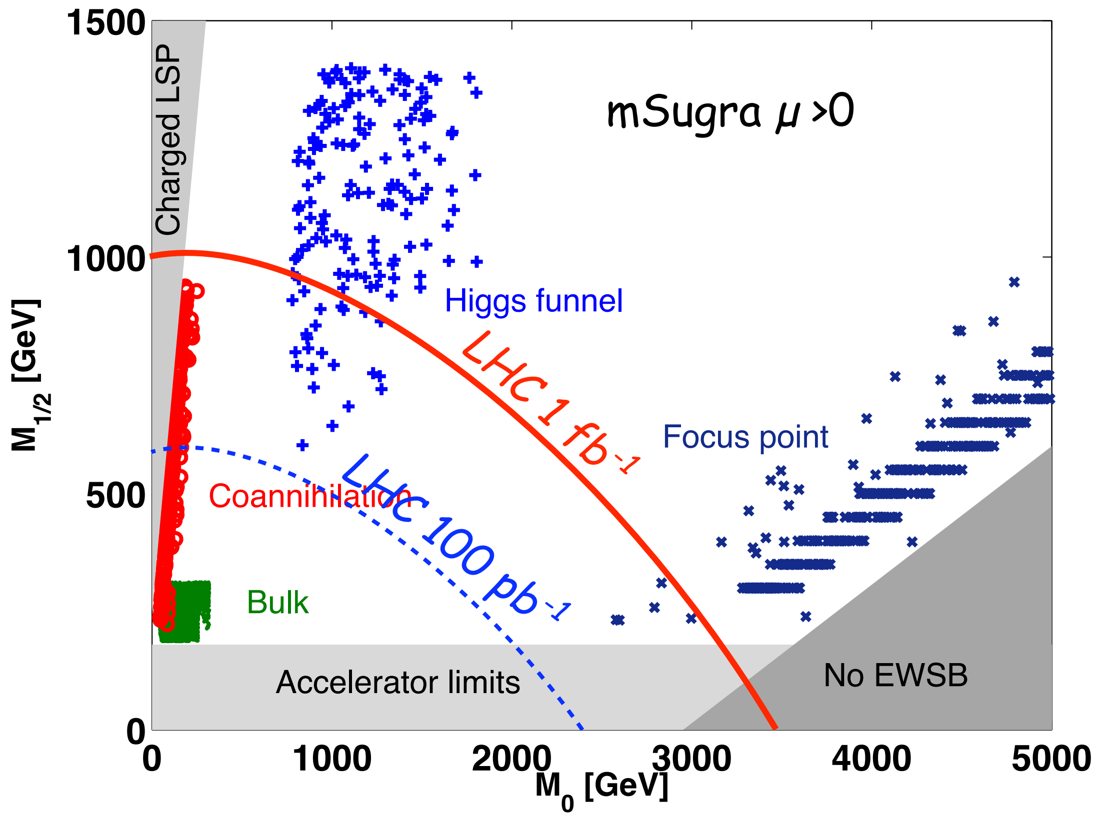
Most evidence will be ambiguous <- variety of astrophysics phenomena

Would need confirmation

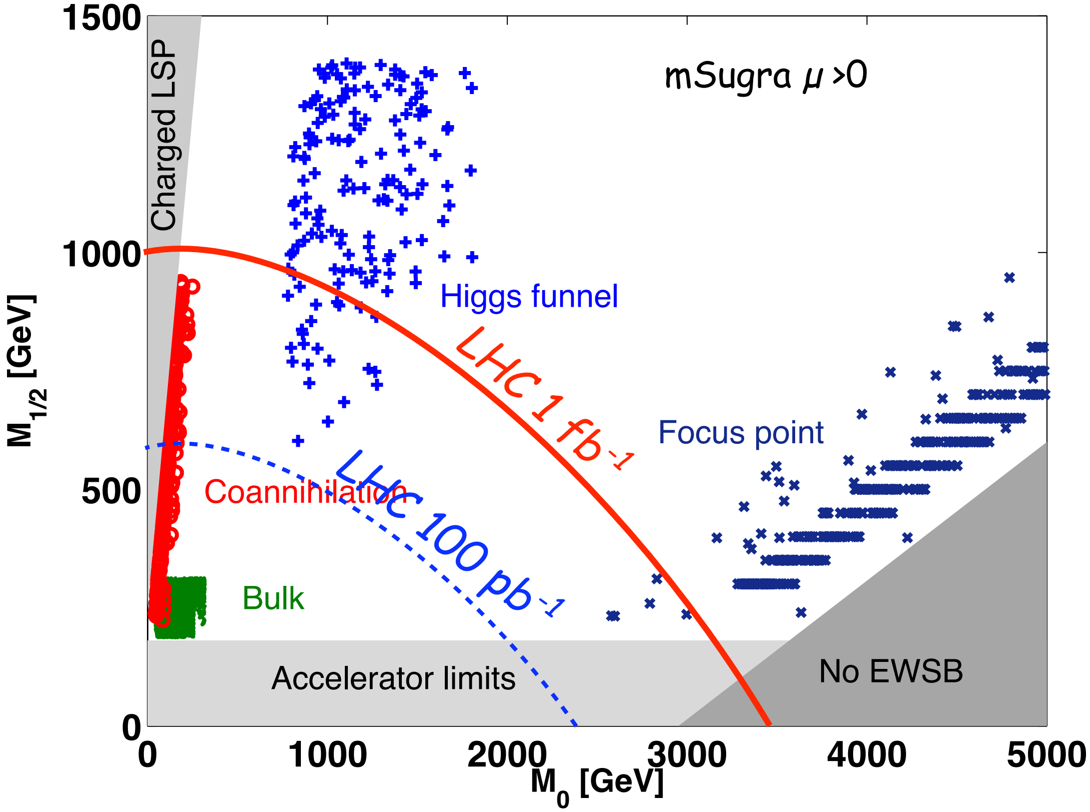
Complementary region of sensitivities

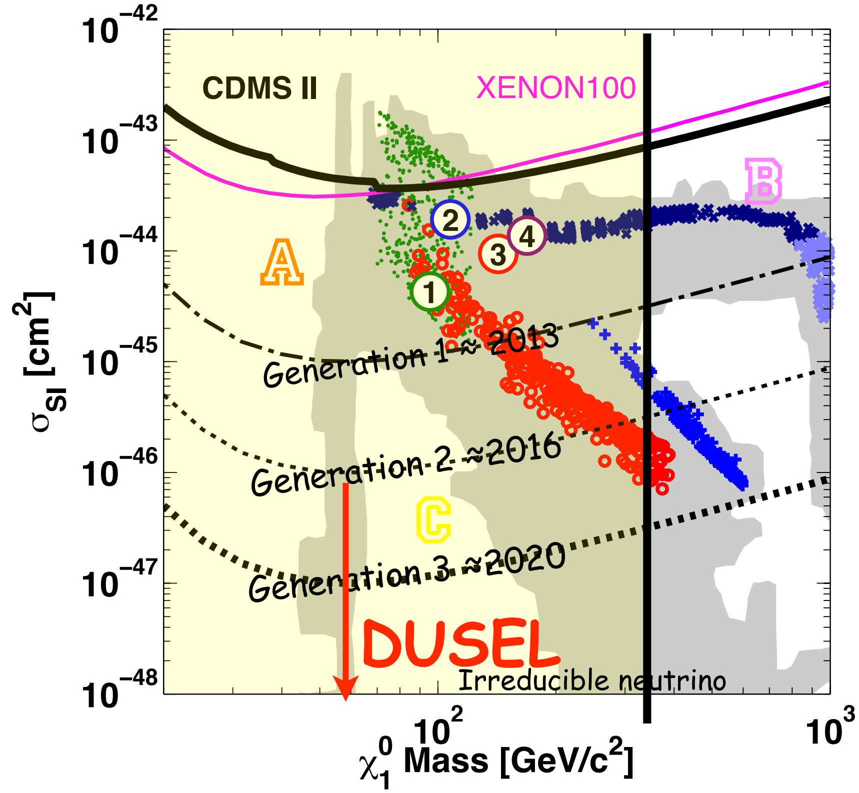
Take as an example mSUGRA

(Over) Simplification of Supersymmetry through GUT assumptions
-> 4 parameters + sign
4 regions where the relic density is compatible with our measurements



Mass Complementarity





WIMP elastic scattering sensitive to bulk (Generic)

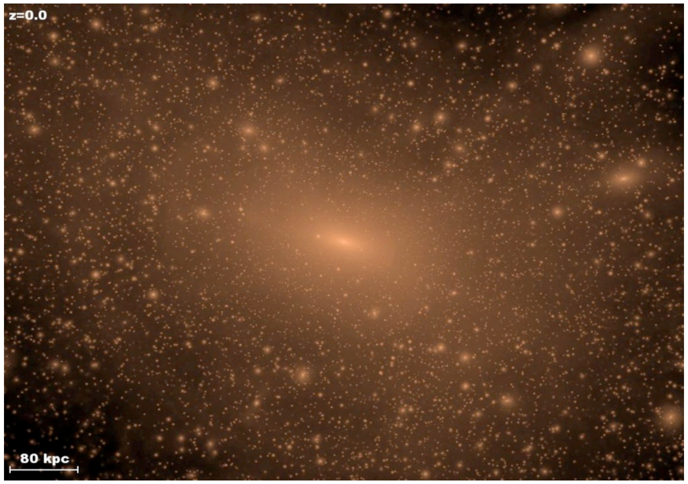
and focus point region regions A+B

Significant Higgsino component => high cross sections in spite of large masses

LHC limited to low mass <350GeV/c^2 regions A+C

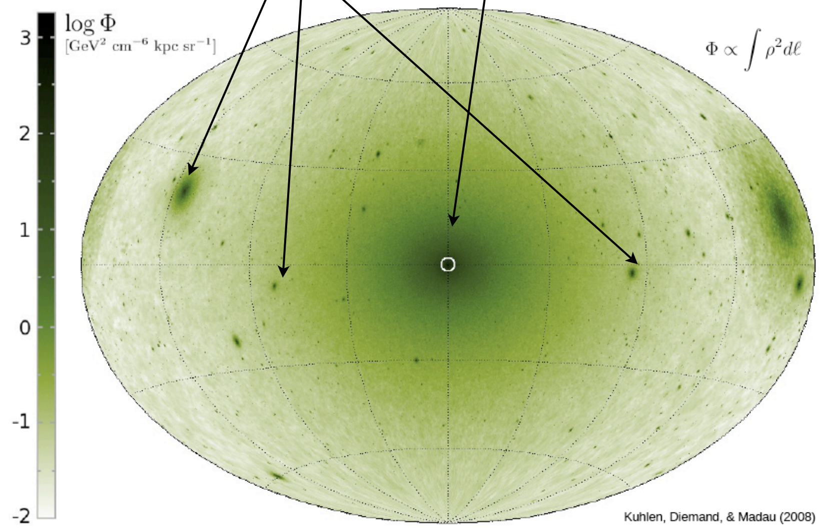
Direct detection experiments do not have an upper mass cut-off: B

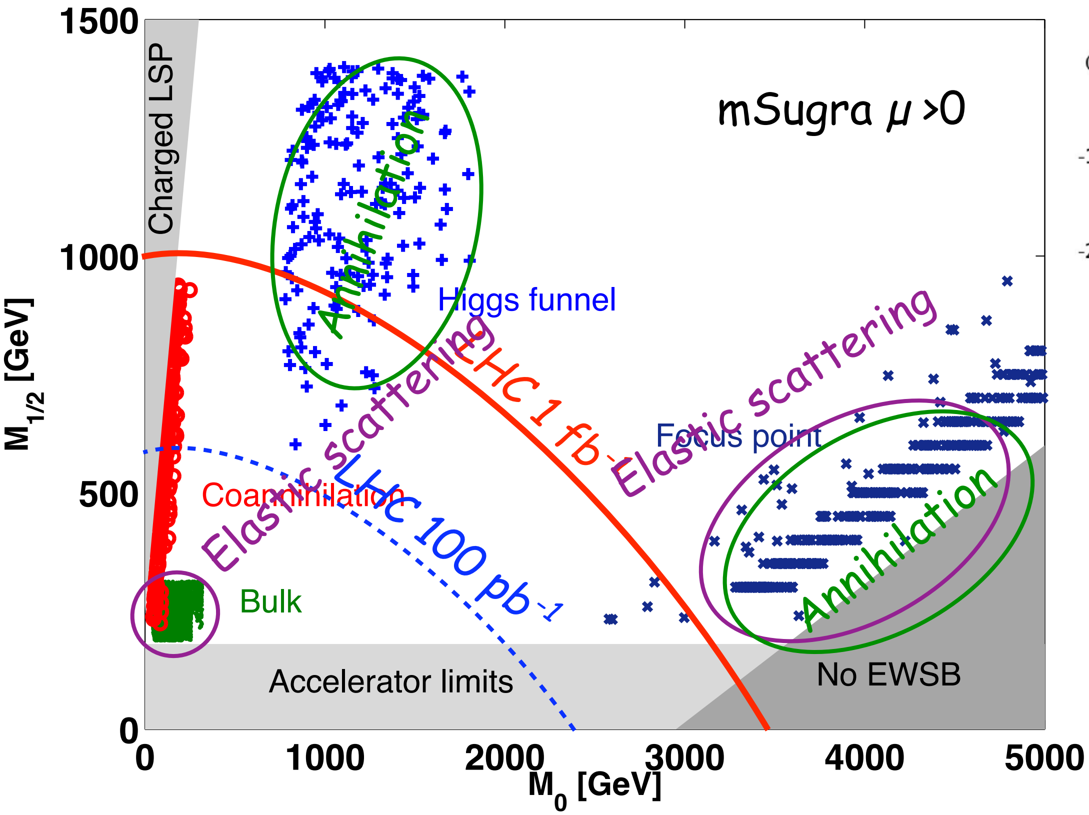
WIMPs Annihilation into Gamma Rays

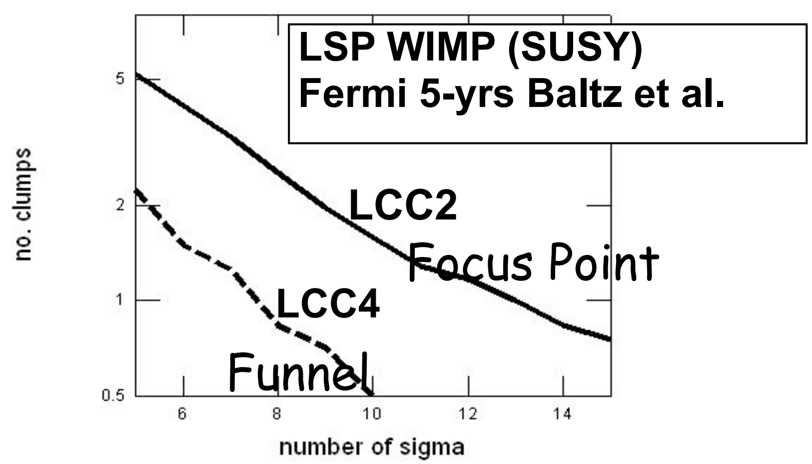


Broad peak towards the galactic center

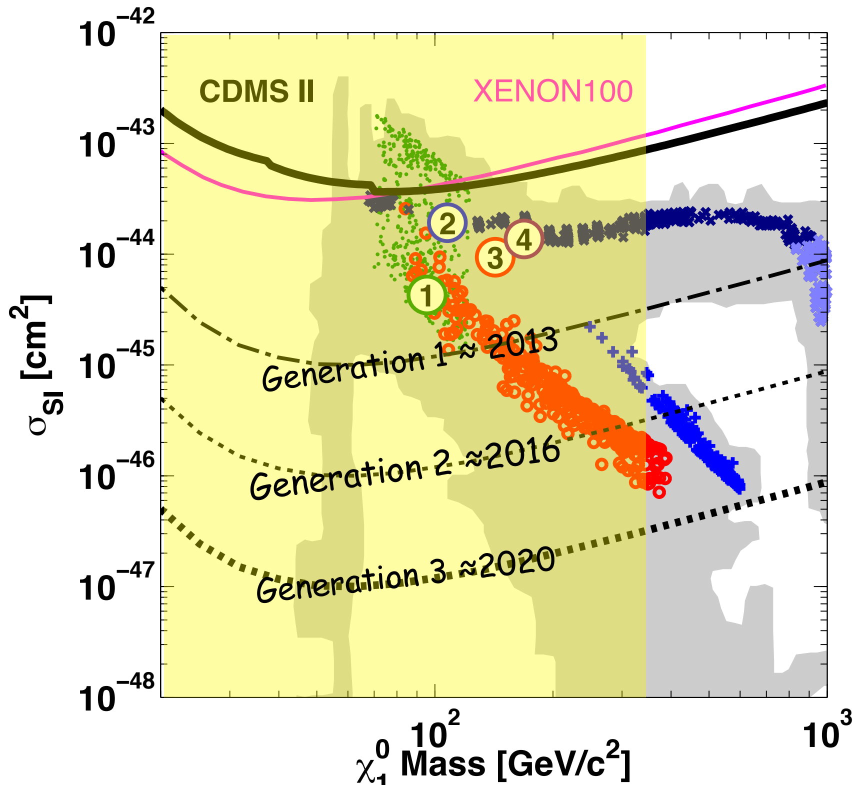
Dwarf galaxies

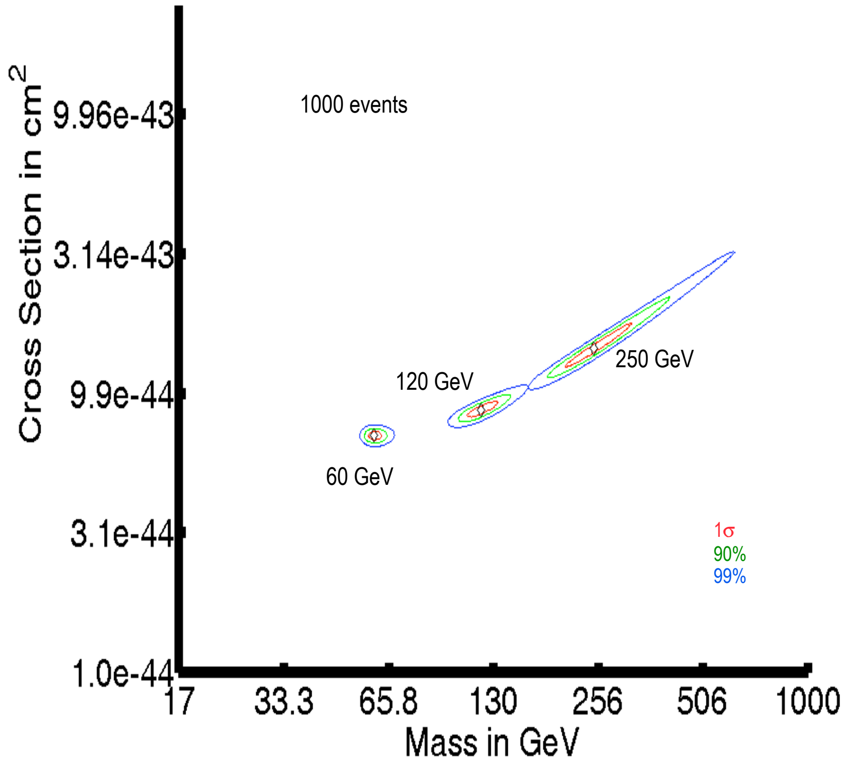






Rich Physics in Overlap Regions

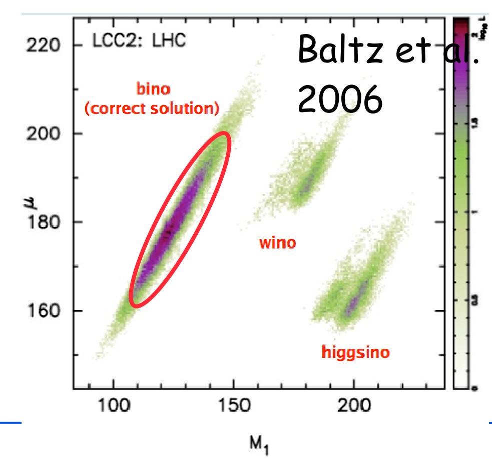




e.g. in region A where both LHC and elastic scattering

Help of the WIMP direct detection
in unravelling complex structure
+ check that we have the same mass

In some case LHC may not have access
to the full spectrum of particles:
elastic scattering can break ambiguities
and check that we get the right relic density



Conclusions

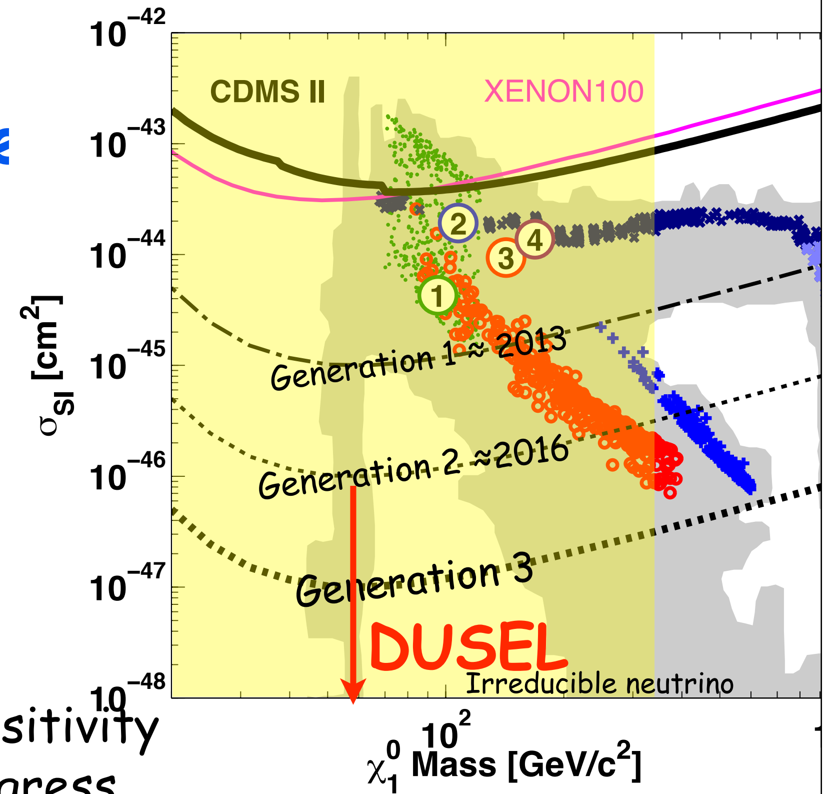
The nature of Dark Matter: Very fundamental question!

Weakly Interactive Massive Particle

Dark Matter could be due to TeV Scale

Next five years will be very important

Direct Detection: A lot of action



Ge and Xe are reaching interesting level of sensitivity
Bubble chamber and Ar are making a lot of progress
Indirect detection: Fermi is a powerful instrument
+ IceCube
LHC is starting to run
Complement region of sensitivities
In overlap region rich physics!