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Ditrect Detection of WIMPs

Matt Pyle and I will share the time

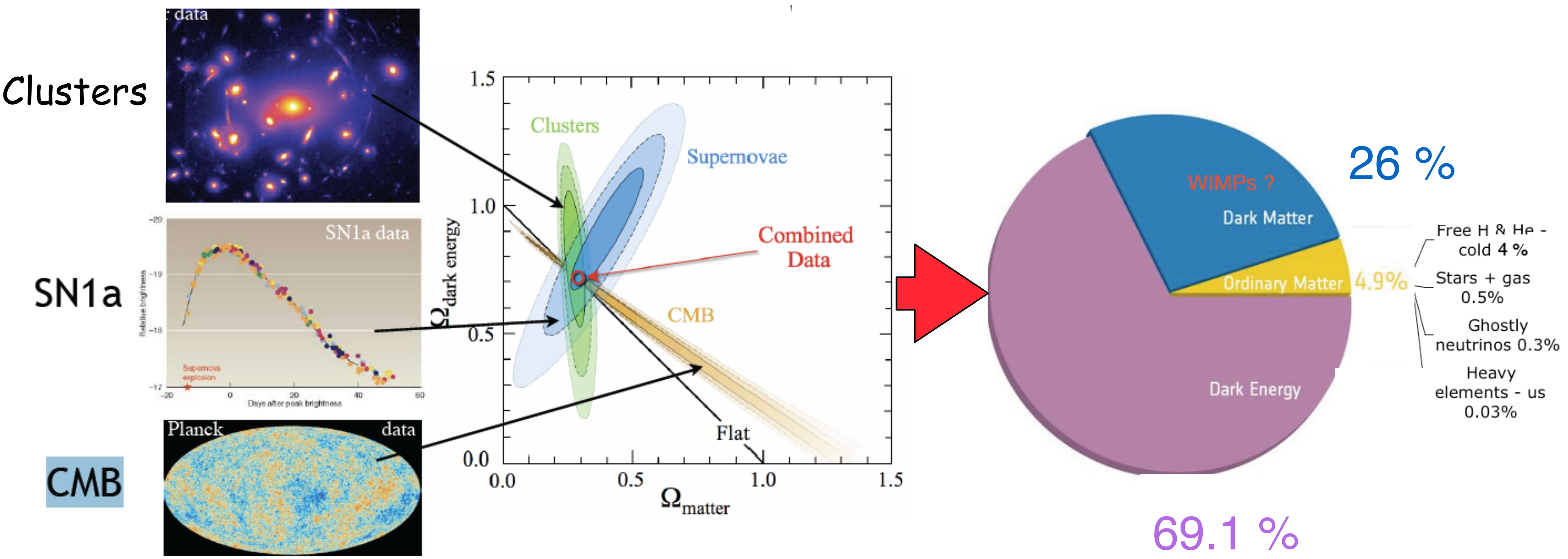
I am in charge of

- General Framework
- Experimental program
- CDMS
- Experimental challenges

Matt: Low Mass (our current mission!)

- Luke Neganov amplification
- Can we recover nuclear recoil discrimination
- Instrumentation challenges

Dark Matter and its Nature



The nature of dark matter is a central problem of cosmology

≠ baryons
≠ light neutrinos

Is it made of particles produced in the early universe?

If yes: evidence for physics beyond standard model!
TeV scale or totally different origin?

What kind of particle?

Particles in thermal equilibrium + decoupling when non-relativistic

Freeze out when annihilation rate ≈ expansion rate

$$\Rightarrow \Omega_{DM} h^2 = \frac{3 \cdot 10^{-27} cm^3/s}{\langle \sigma_A v \rangle} \qquad \Omega_{DM} \approx 25\% \Rightarrow \sigma_A \approx \frac{\alpha^2}{M^2_{EW}}$$

Cosmology points to W&Z scale
Inversely standard particle model requires new physics at this scale
=> significant amount of dark matter

Weakly Interacting Massive Particles
Dark Matter could be due to TeV scale physics

Could detect these by scattering of galactic dark matter on a suitable target in laboratory

A dark sector may be with dark matter—anti dark matter asymmetry

If similar to baryon anti-baryon asymmetry

$$\rho_{DM} \approx 5 \times \rho_{baryon} \Rightarrow M_{DM} \approx 5 \text{ GeV/c}^2$$

Physics could be as complex as our ordinary matter sector:
if light mediator could be at small masses

Athermal production: Result of spontaneous symmetry breaking

Main example Peccei Quinn axions to dynamically restore CP in QCD

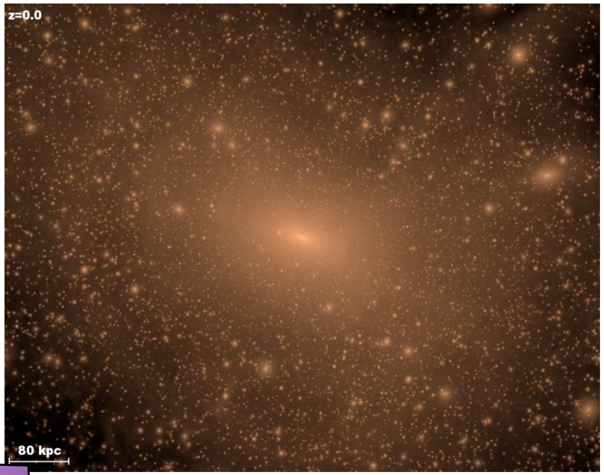
4 Complementary Approaches

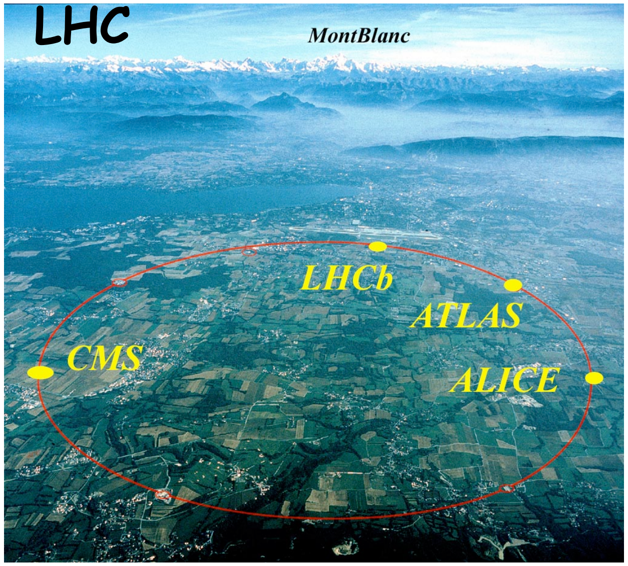
Cosmological Observations

Planck

Keck telescopes

Dark Matter
Galactic Halo (simulation)



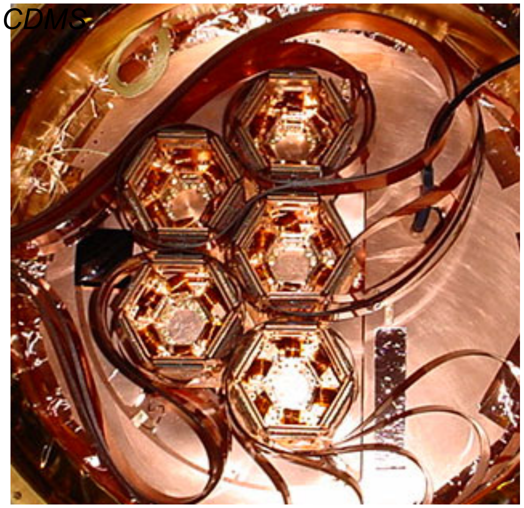


WIMP production on Earth

VERITAS, also HESS, Magic + IceCube (ν)

WIMP annihilation in the cosmos

Fermi/GLAST



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

Energy deposition

Simple non relativistic calculation

J.D. Lewin and P. F. Smith Astroparticle Physics 6 (1996) 87

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

Consider a χ incident with velocity v

$$m_\chi v \rightarrow m_N$$

the velocity of the center of mass V is such that

$$m_\chi (v - V) = m_N V$$

$$V = \frac{m_\chi v}{m_\chi + m_N},\; p^* = \frac{m_\chi m_N v}{m_\chi + m_N} = m_r v$$

After the scattering with angle θ^* the momentum of thenucleon is

$$p'^*_{N\parallel} = m_r v \cos\theta^*,\; p'^*_{N\perp} = m_r v \sin\theta^*$$

Back in the lab frame, the momentum of the nucleon is

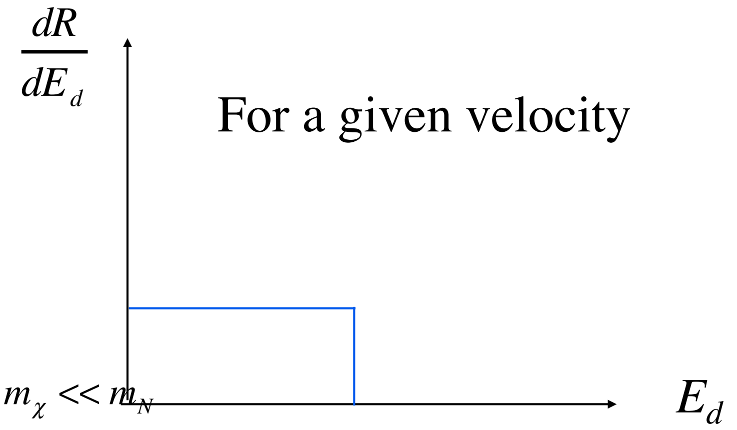
$$p'_{N\parallel} = m_r v \cos\theta^* - m_r v,\; p'_{N\perp} = m_r v \sin\theta^*$$

The square of the momentum transfer is

$$|\vec{q}|^2 = {p'_{N\parallel}}^2 + {p'_{N\perp}}^2 = 2 m_r^2 v^2 \left(1 - \cos\theta^*\right)$$

and the energy deposition

$$\boxed{E_d = \frac{|\vec{q}|^2}{2m_N} = \frac{m_r^2}{m_N} v^2 \left(1 - \cos\theta^*\right) = \frac{m_\chi^2 m_N}{\left(m_\chi + m_N\right)^2} v^2 \left(1 - \cos\theta^*\right)} \propto \left| \begin{array}{l} m_\chi^2 v^2 \left(1 - \cos\theta^*\right) \text{ if } m_\chi << m_N \\ m_N v^2 \left(1 - \cos\theta^*\right) \text{ if } m_\chi >> m_N \end{array} \right.$$



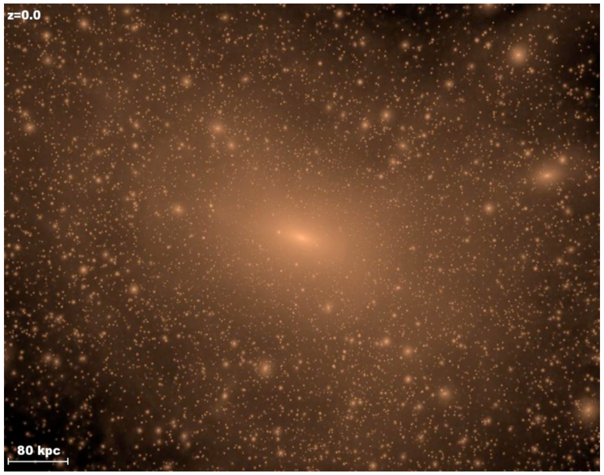
Notes

This is for elastic scattering. Inelastic has threshold effect!

For a given energy deposition E_d is a minimum velocity $v_{\min} = \sqrt{\frac{E_d m_N}{2m_r^2}} = \sqrt{\frac{|\vec{q}|^2}{4m_r^2}}$

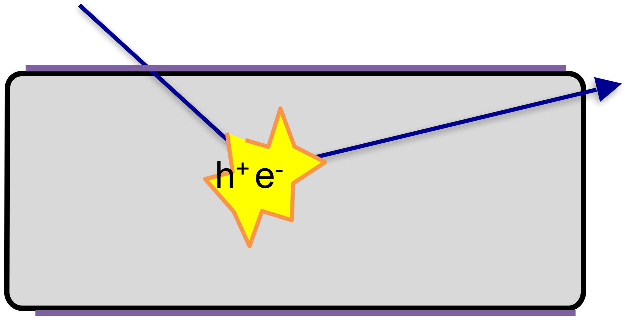
S wave scattering -> flat in $\cos\theta^*$

Direct Detection



Our lab is in the halo of the galaxy

Looking for (mostly) inelastic scattering

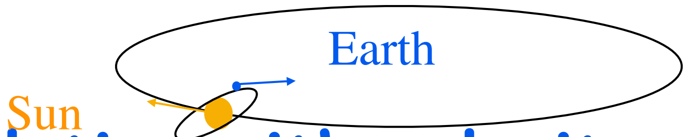


WIMP velocity≈ 300km/s

Taking into account 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°)



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

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

where

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

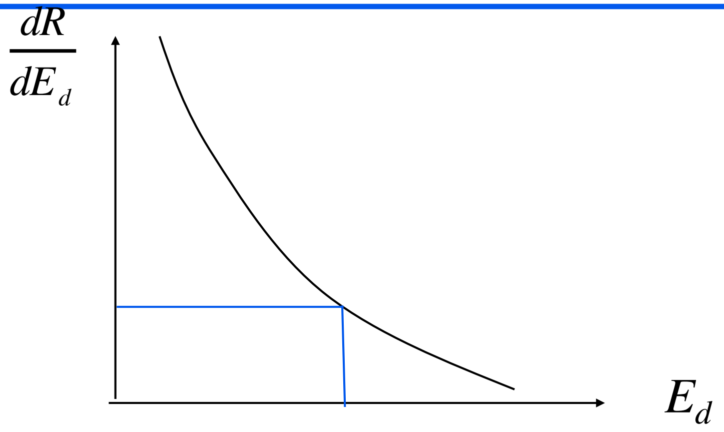
$$\rho_o = \text{local density of halo}$$

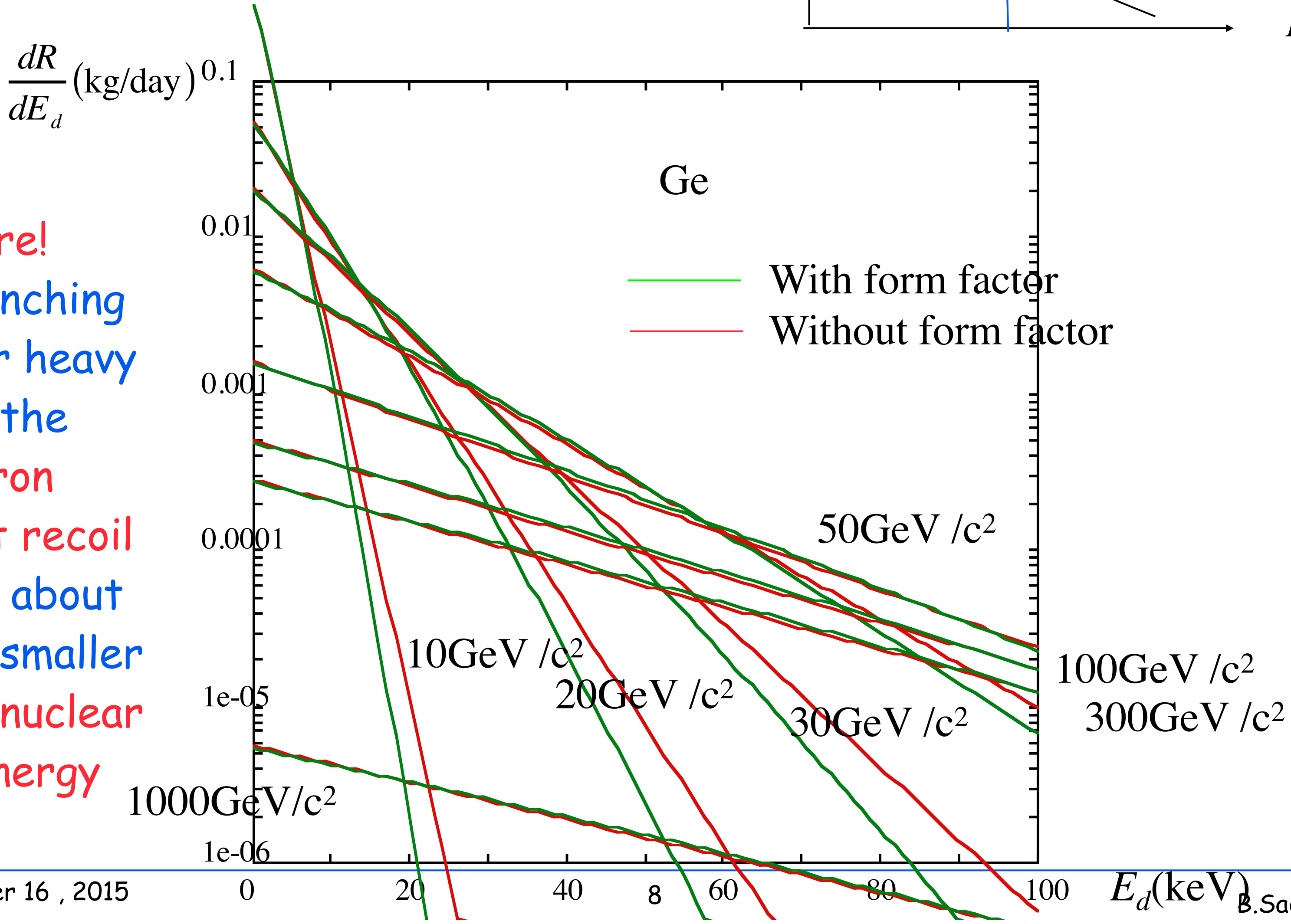
$$v_{\min} = \left(\frac{E_d m_N}{2m_r^2}\right)^{1/2}$$

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

Elastic Scattering Rates 2

Unfortunately featureless!





Beware!

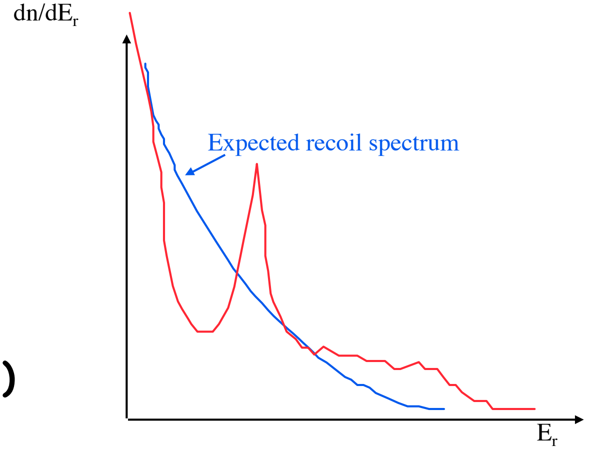
From quenching factor for heavy nuclei the electron equivalent recoil energy is about ten times smaller than true nuclear recoil energy

Halo WIMP Scattering "Direct Detection"

Mostly 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)**



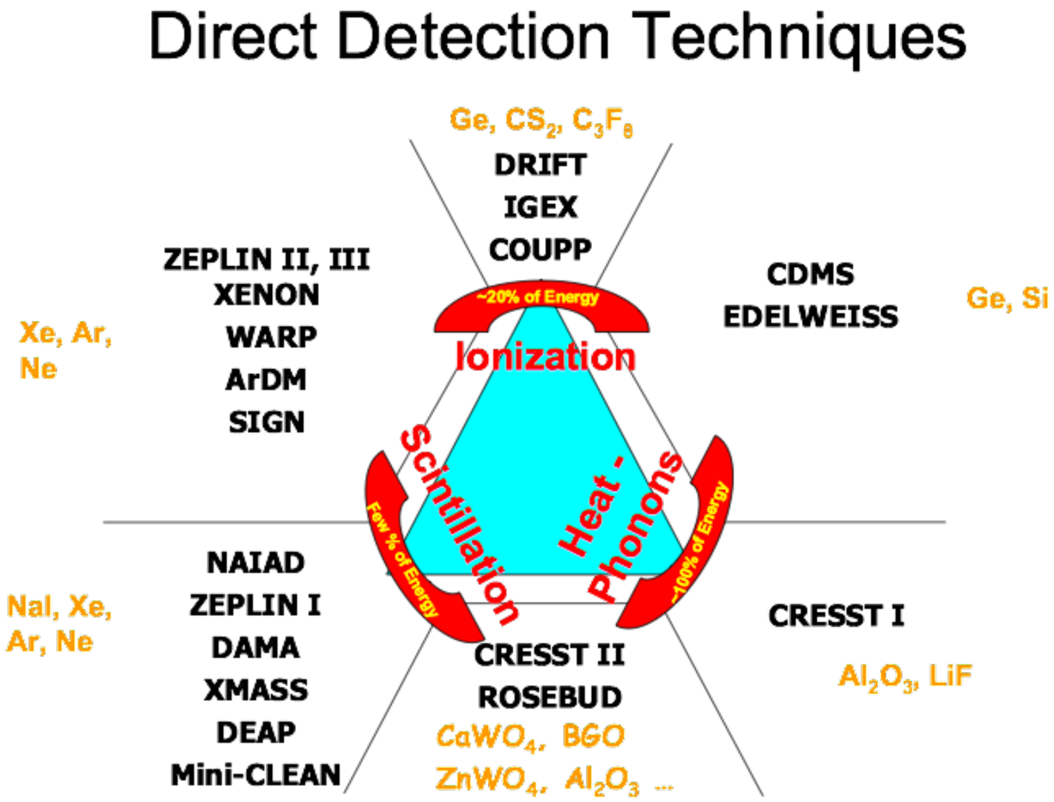
Signatures

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

Linked to galaxy

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

Many approaches



Direct Detection Techniques

Ge, CS$_2$, C$_3$F$_8$
DRIFT
IGEX
COUPP

~20% of Energy
Ionization

Xe, Ar, Ne
ZEPLIN II, III
XENON
WARP
ArDM
SIGN

CDMS
EDELWEISS
Ge, Si

Scintillation
Few % of Energy

Heat - Phonons
~100% of Energy

NaI, Xe, Ar, Ne
NAIAD
ZEPLIN I
DAMA
XMASS
DEAP
Mini-CLEAN

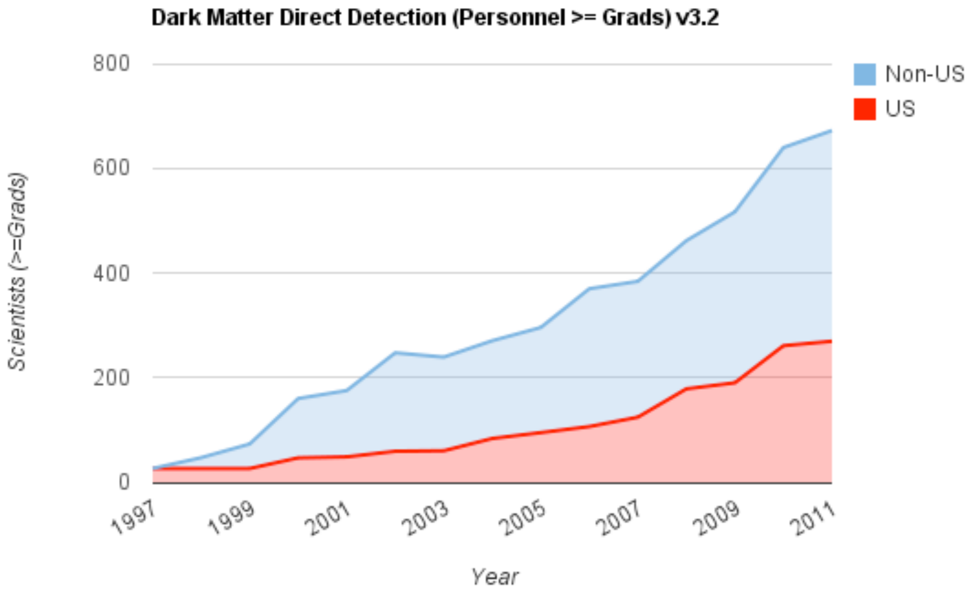
CRESST II
ROSEBUD
CaWO$_4$, BGO
ZnWO$_4$, Al$_2$O$_3$ ...

CRESST I
Al$_2$O$_3$, LiF

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

An expanding community

≈ 270 physicists ≈70% FTE
≈ 40% of world



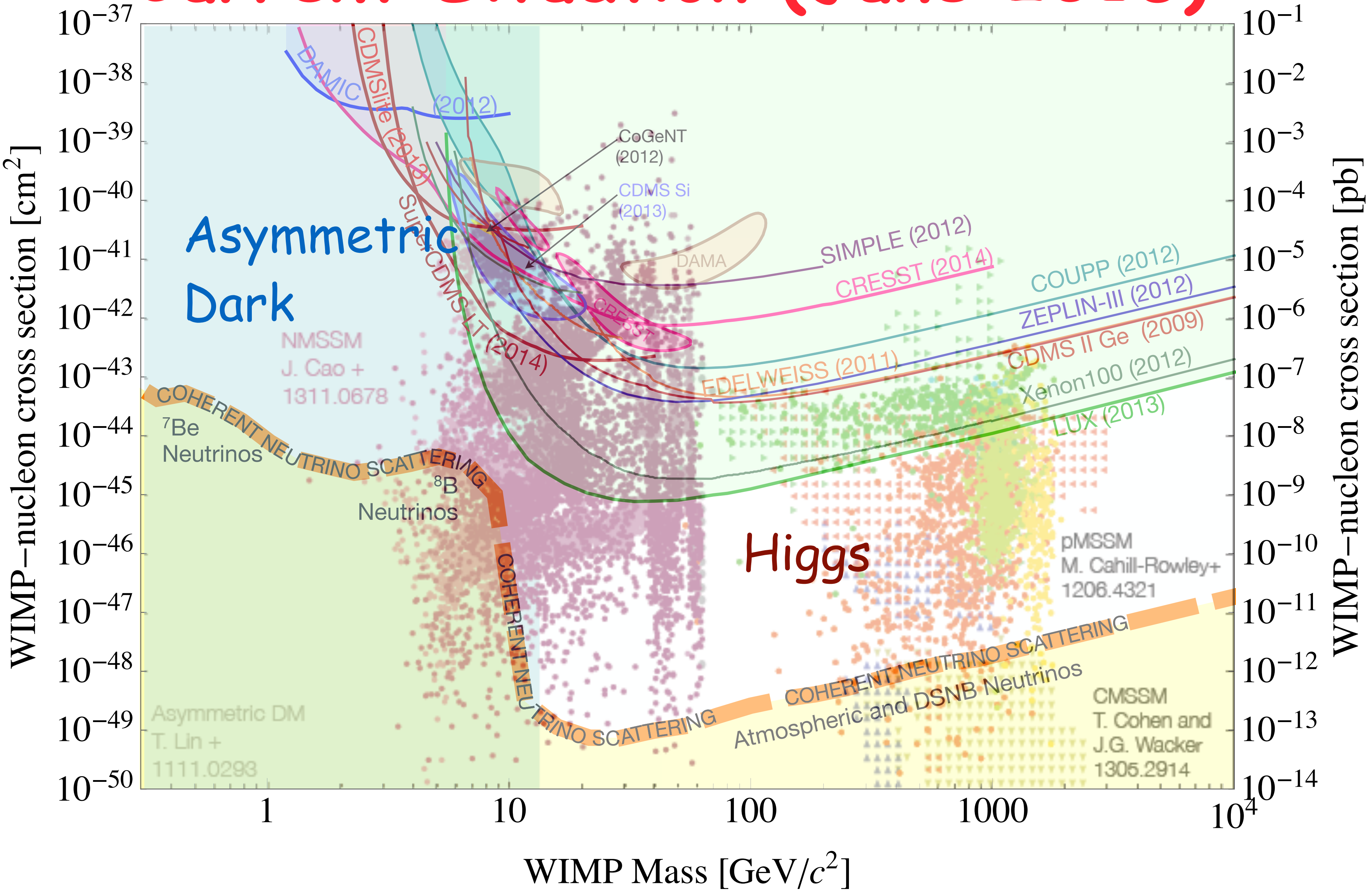
A number of other brilliant detector ideas

Low pressure gas as directional detecto
C. Tao, D. Snowden Ifft, J. Martoff
Ultra stable bubble chambers
J. Collar, A. Sonnenschein

etc...

Direct Detection

Current Situation (June 2015)



Remarkable Progress

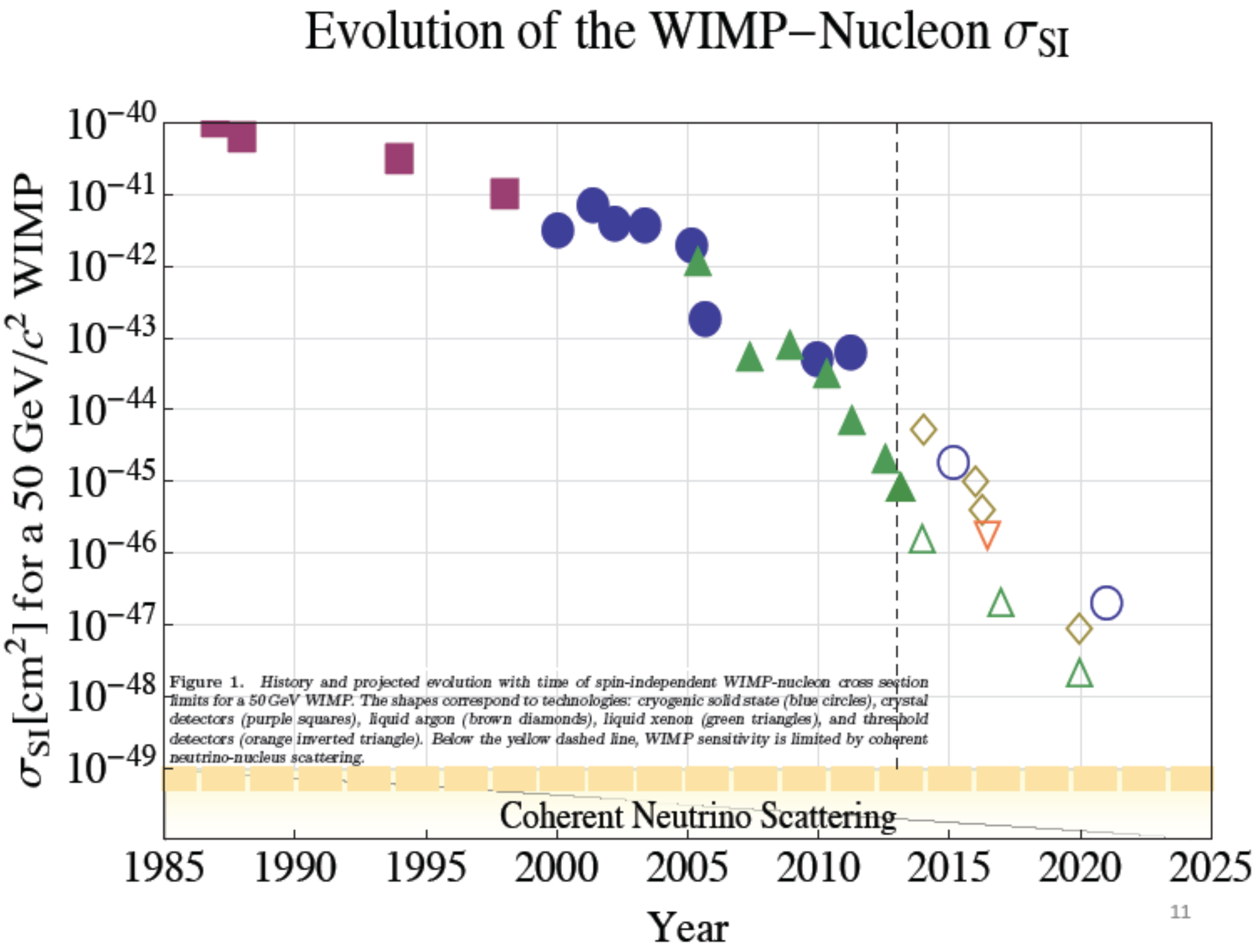


Figure 1. *History and projected evolution with time of spin-independent WIMP-nucleon cross section limits for a 50 GeV WIMP. The shapes correspond to technologies: cryogenic solid state (blue circles), crystal detectors (purple squares), liquid argon (brown diamonds), liquid xenon (green triangles), and threshold detectors (orange inverted triangle). Below the yellow dashed line, WIMP sensitivity is limited by coherent neutrino-nucleus scattering.*

Low Mass Region

Optimistic

Accumulation of claims in that region

The exclusion by some experiments is based on unreliable calibration

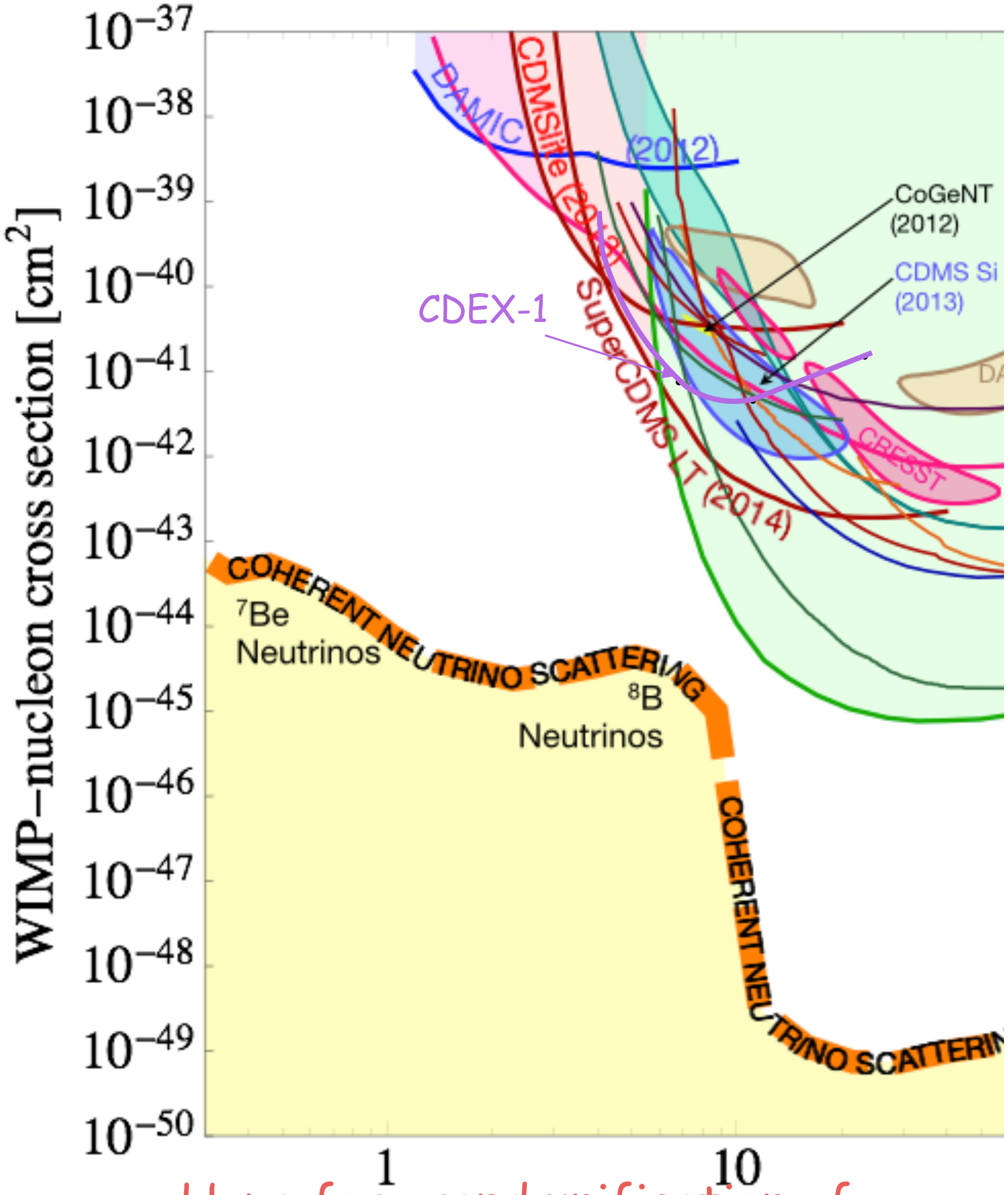
Just the region expected for asymmetric dark matter

Pessimistic

Not compelling evidence

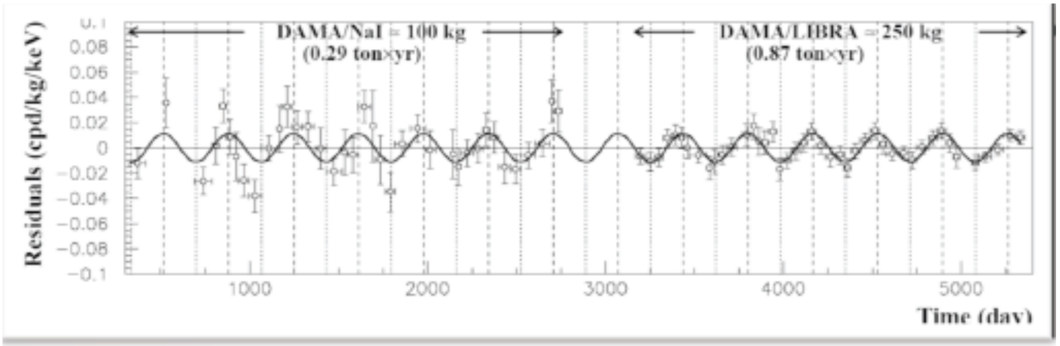
Close to threshold: Outliers ?

Excluded by
XENON100
LUX
SuperCDMS Soudan



Hope for grand unification of claims was clearly premature!

DAMA



Clearly modulation

although not blind

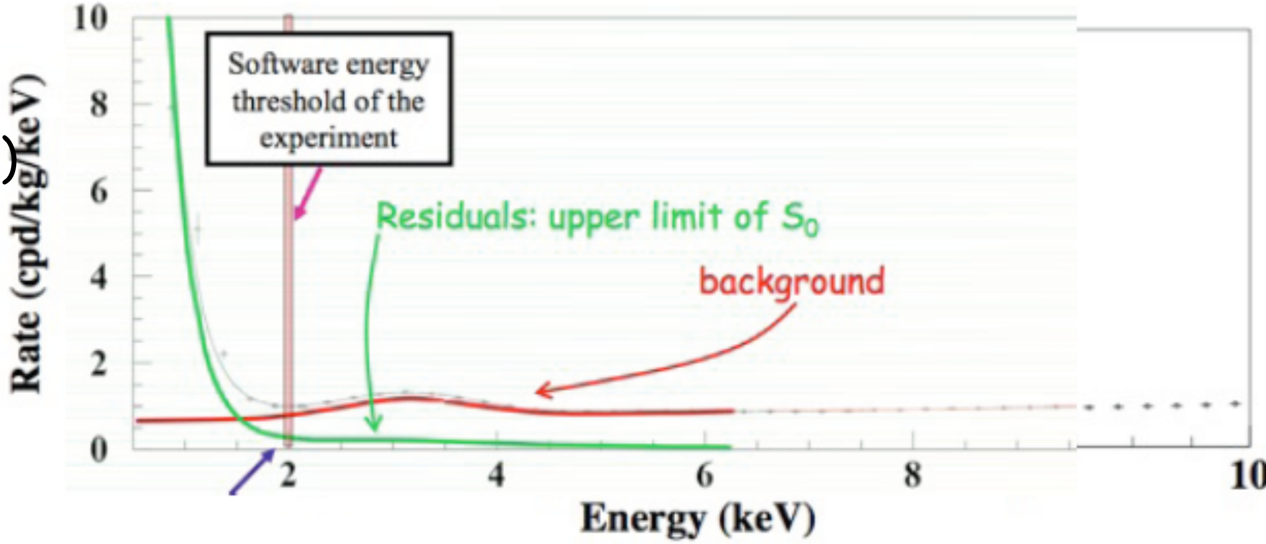
Is it a signal?

incompatible with other
experiments (New: KIMs)

Saturates single rate

=>Unphysically

large modulation



Software energy threshold of the experiment

Residuals: upper limit of S_0

background

If true important!

Can it be instrumental?

Unstability in threshold: modulation appears smaller in LIBRA than in DAMA?

Delayed pulses from muons (not neutrons, but defects): problems single rate +phase

Awkward to the community: What to do?

Lower threshold: LIBRA has changed Phototubes to high QE + background model

Experiment by other groups: DM-Ice,ANAIS,KIMS, Princeton

What Next? 2015

Some closed contours: discovery?

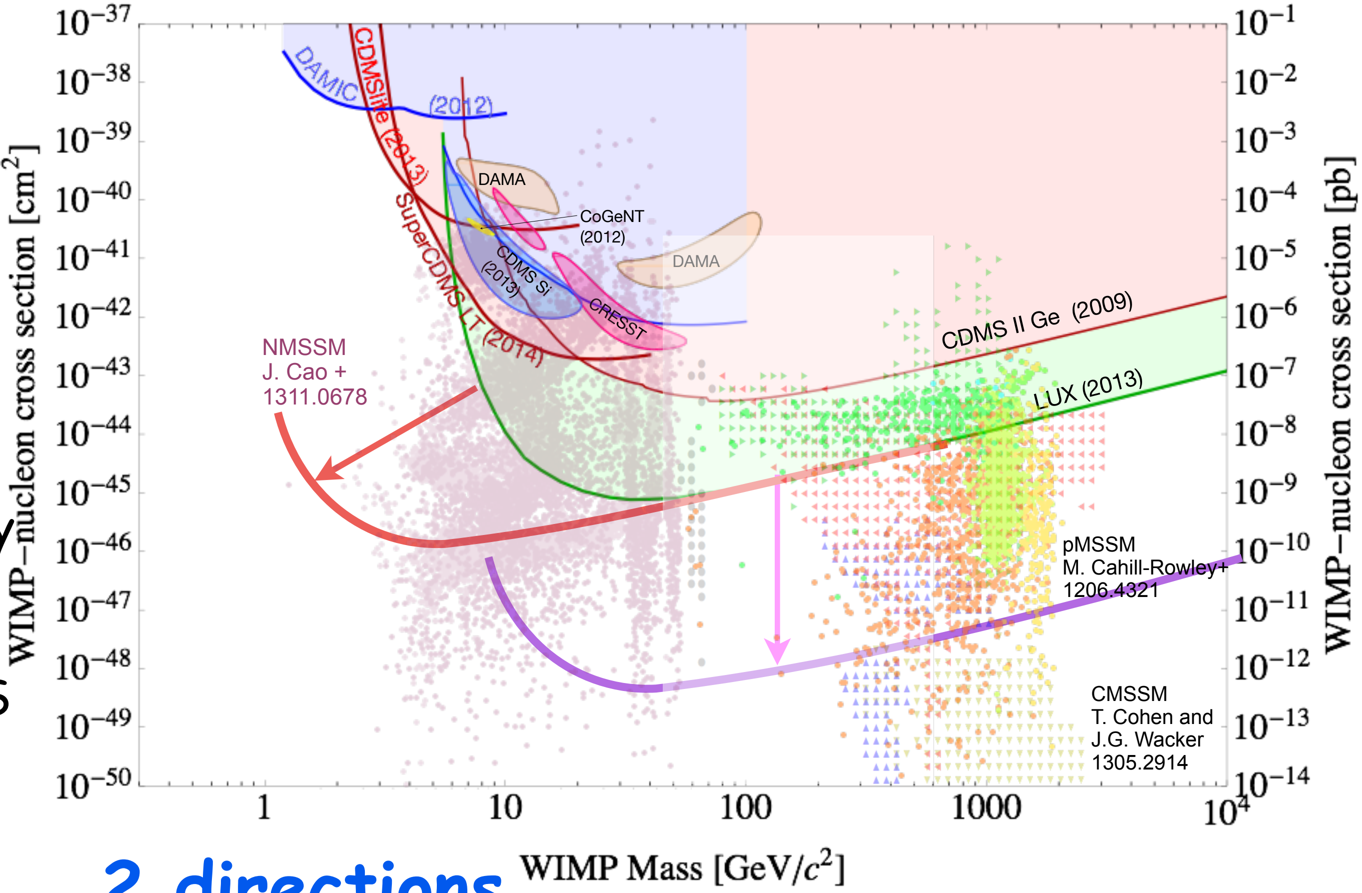
More likely misunderstood backgrounds

No discovery at LHC

Mass of supersymmetry pushed to higher energy: Unnatural?

or more complex NMSS

or dark sector



2 directions

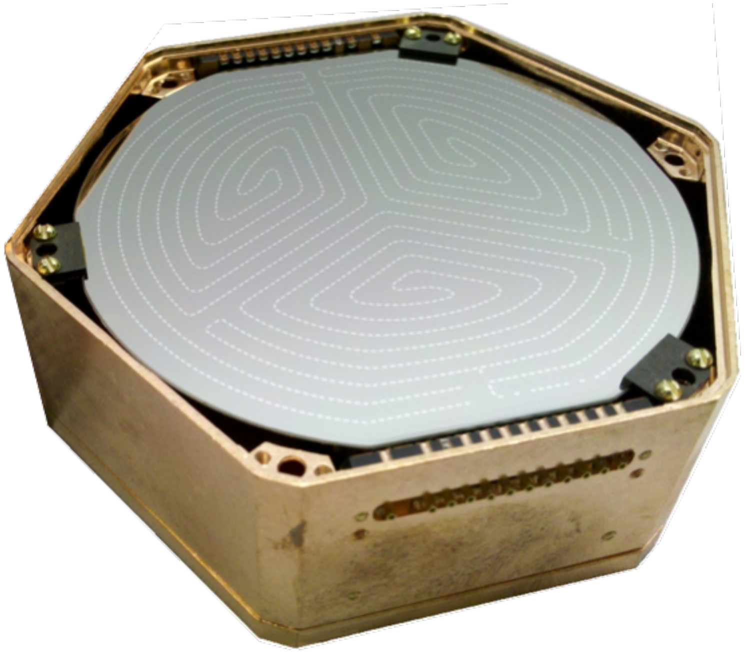
1. Improve sensitivity at large mass

2. Improve sensitivity at small mass

Generation 2 Dark Matter Program (DOE+NSF)

SuperCDMS ≈$33M

30mK Large Mass Calorimeters
Phonons & Ionization (High Mass)
Phonons (Low Mass)



LZ ≈$75M (+XENON)

Xenon 2 Phase TPC
Scintillation & Ionization (High Mass)
Ionization (Low Mass)

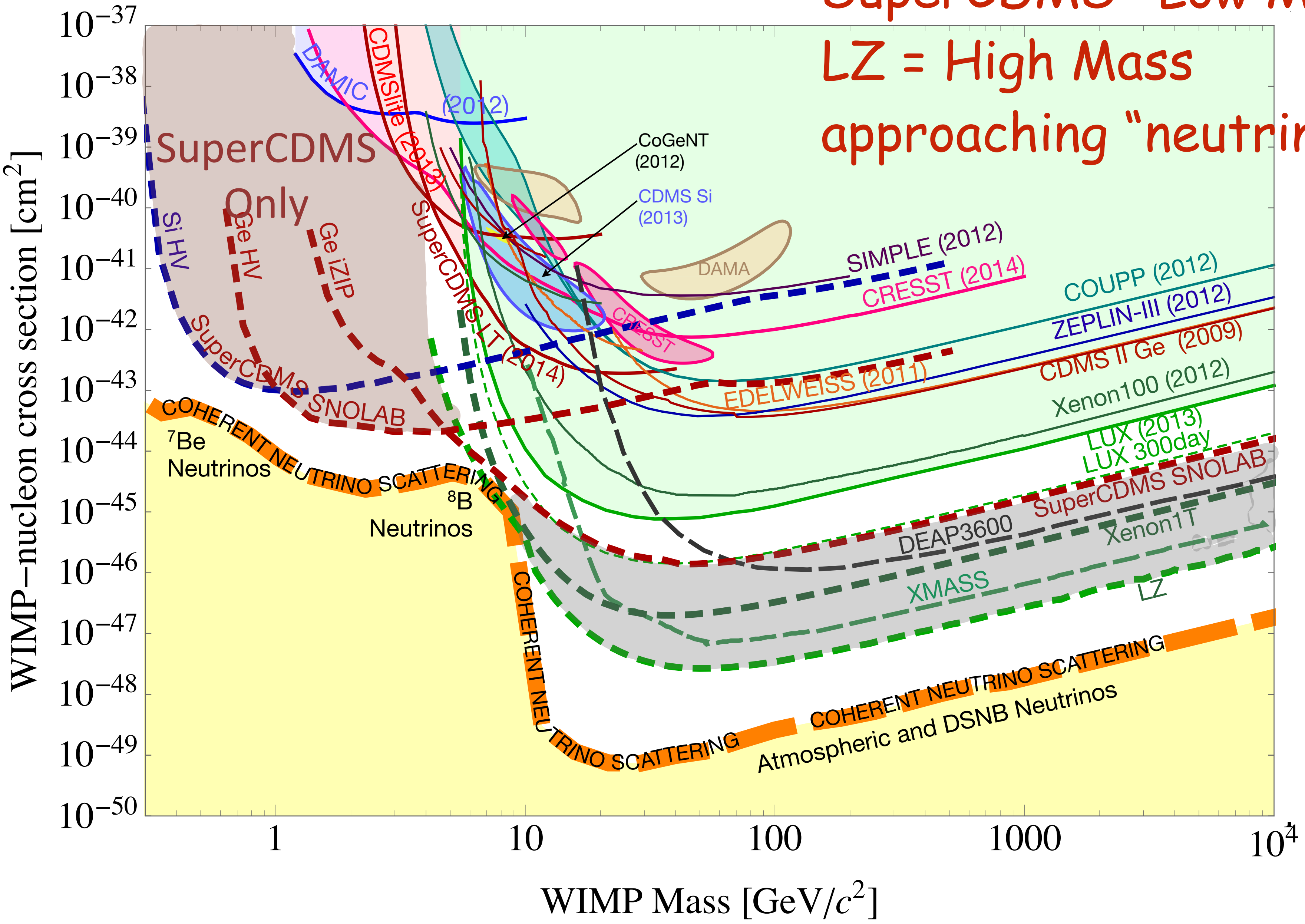
+ Axion: ADMX

G2 WIMP Sensitivity

SuperCDMS= Low Mass

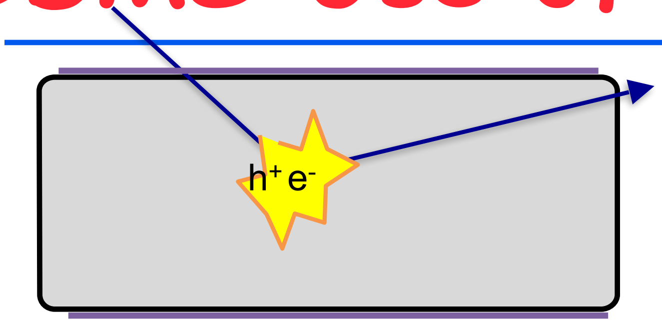
LZ = High Mass

approaching "neutrino floor"



CDMS

CDMS:Use of Phonons and Cooper Pairs



<1meV quanta

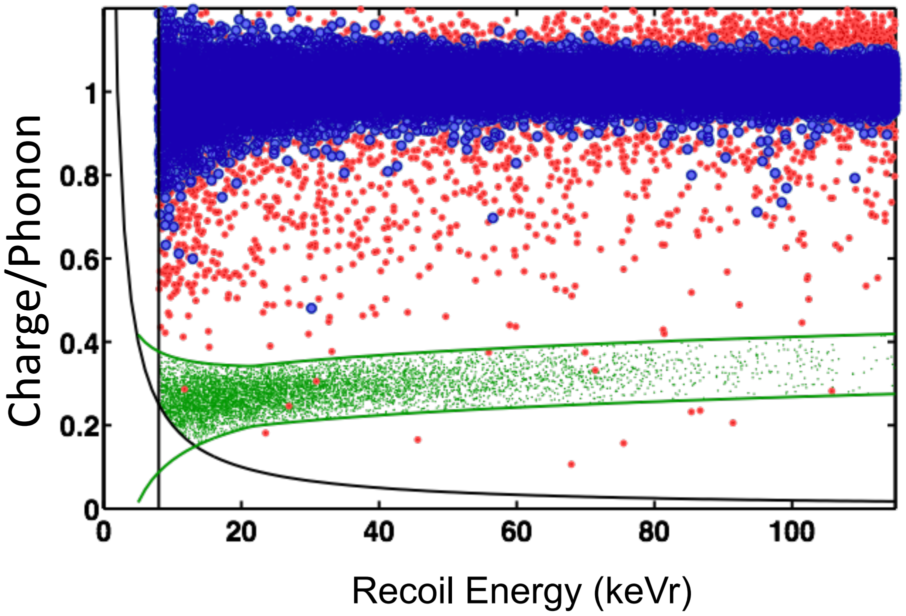
=> sensitivity but ≈30mK

detailed information about the event

Recognition of nuclear recoils

Nuclear Recoils
- 8% e^-/h^+
- 92% phonons

Electron Recoils
- 25% e^-/h^+
- 75% phonons



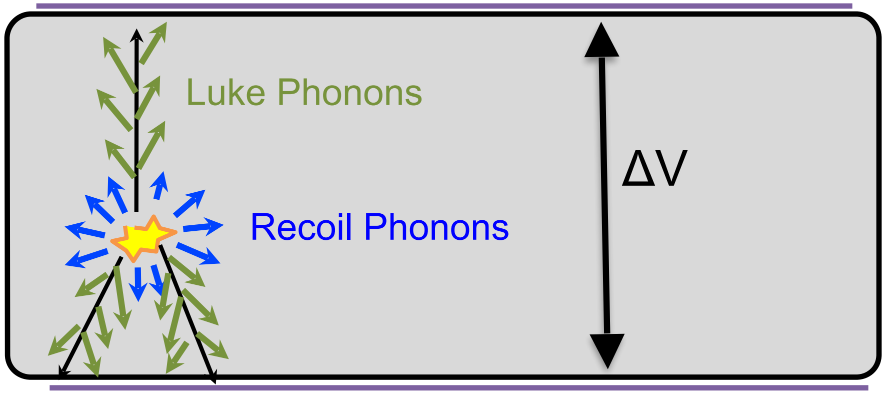
Fiducialization

We can efficiently get rid of surfaces

Amplification of ionization

CDMS-HV: give up nuclear recoil ID

$$E_{\text{total}} = E_{\text{initial phonons}} + Nq\Delta V$$



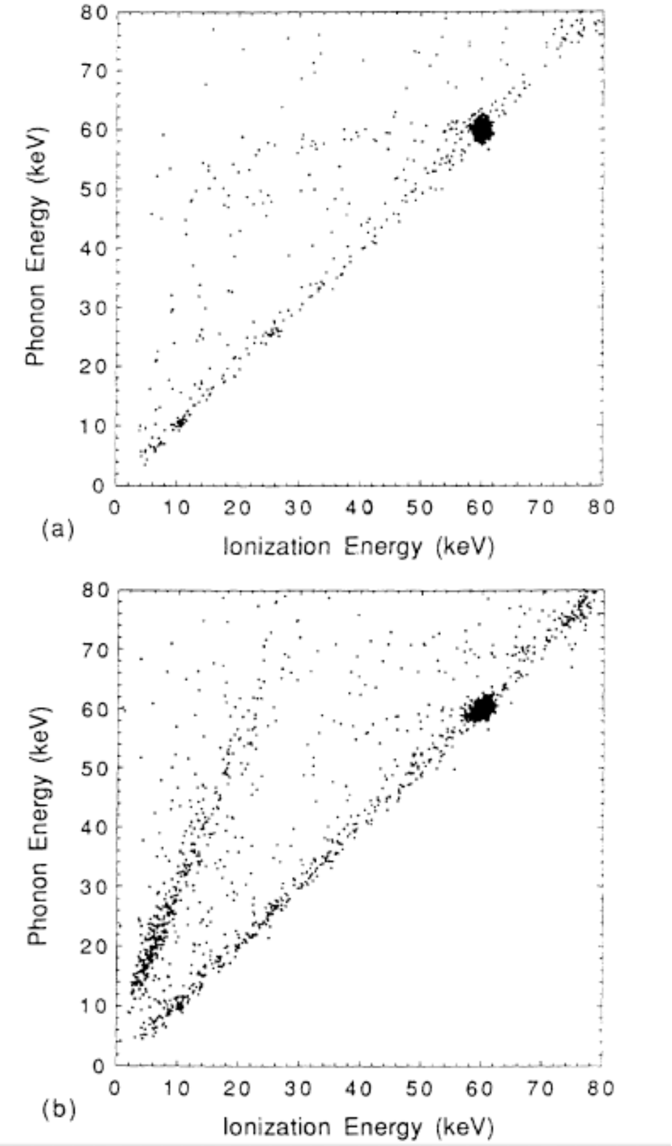
Ge: A Serendipitous Discovery

An accidental discovery

Summer 1989 Mis-wiring of sensor -> 2 types of pulses

=> collection of ionization

=> We could recognize nuclear recoils!



=> Experimental verification

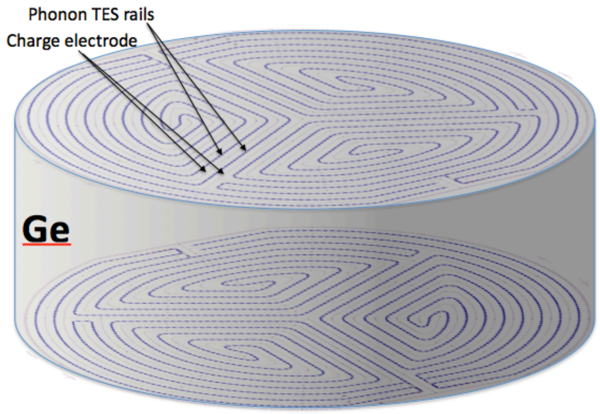
-> 60g detector => Shutt et al PRL 1992

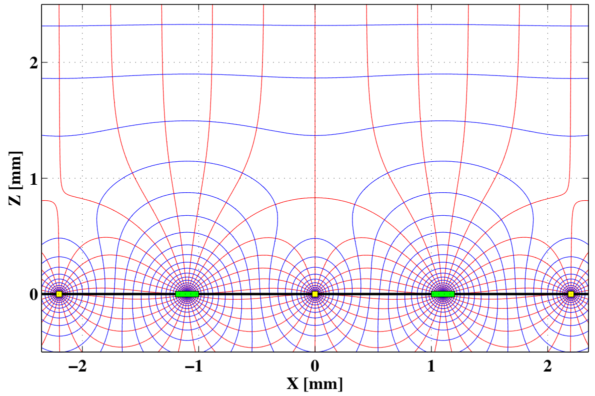
Unconventional use of Ge:

not depleted (≠ 77K) but filled traps (stay ≈filled below 4K)

lesser requirement in term of purity

SuperCDMS:Getting rid of the surfaces





Interleaved electrodes

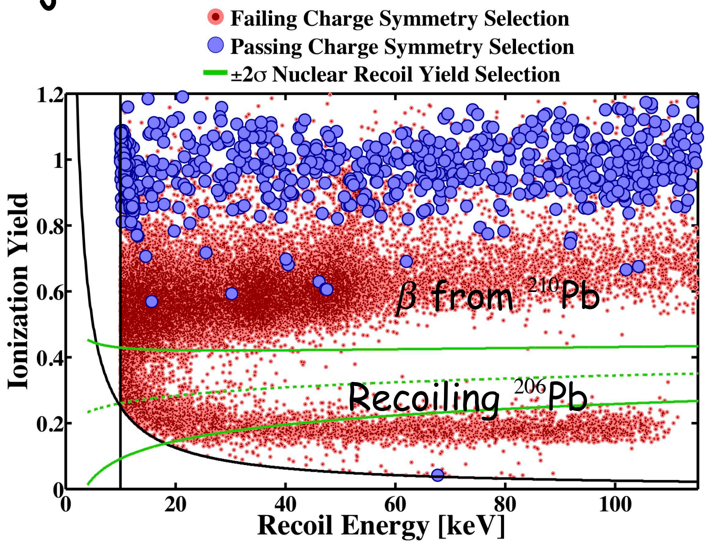
Reviving an idea of P. Luke (also used by EDELWEISS)

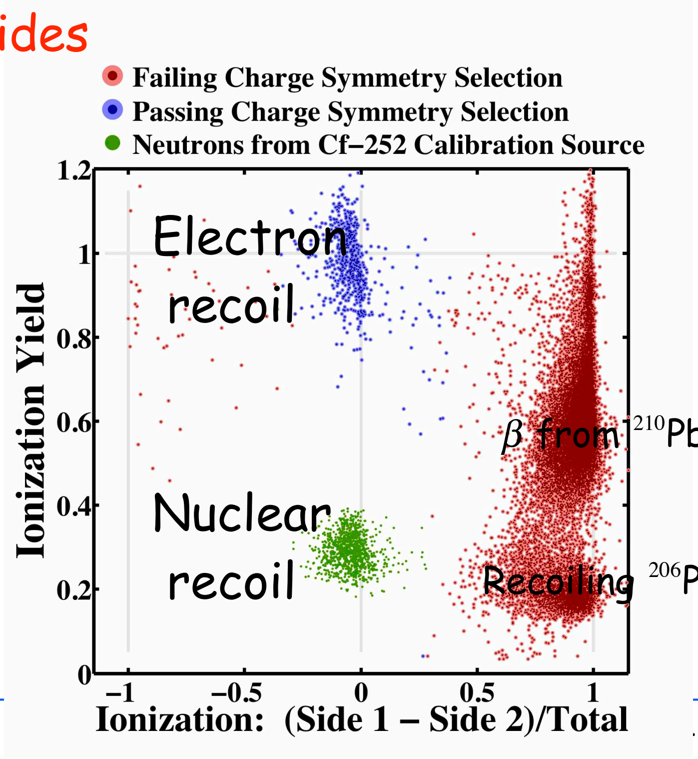
Events close to the surface seen on one side

≠Events in the bulk seen on both sides

Test underground with Pb 210

Rejection >1-1.7 10^{-5} 90% CL





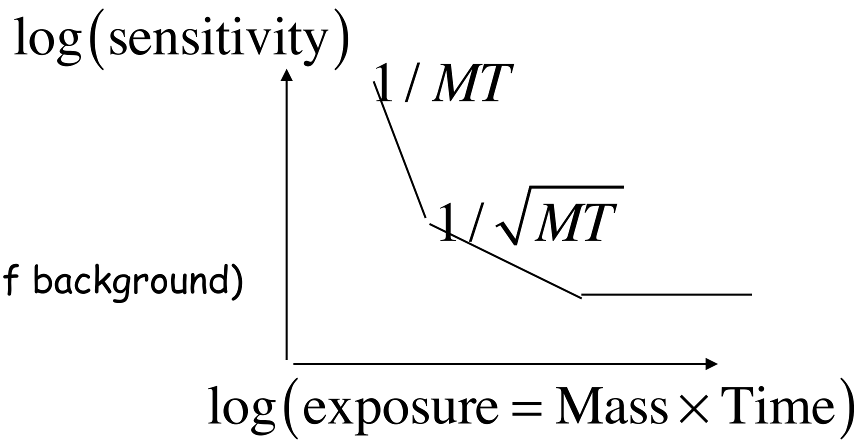
Experimental Challenges

Detector sensitivity

By definition discrimination disappears close to threshold

Not an accident that all claims are at low mass/energy

Trying to get background free



3 statistics methods

- Maximum interval
- Maximum likelihood (but need analytical form of background)
  - Feldman Cousins
- Boosted Decision Tree (but need training set)

Need to be blind

≠ Bias

Problem of outliers

Multidimensionality (outside manifold)

Check on events which cannot be signal (e.g., multiple, outside nuclear recoil etc..)

Conclusions

Lessons learnt in the last few years

Difficulty to get unambiguous results!

Phenomenology may be more complex than for the "vanilla" WIMP scenarios.

Unambiguous results

The goal should be negligible background!

We should not abandon blind analyses:

- only unbiased way

Use likelihood methods to get confirmation of a signal

- But extremely sensitive to background model. What about the unknown unknowns?

Use knowledge acquired about leaking backgrounds to design better detectors

Complementarity of experiments

Real proof requires 2 experiments, which are as different as possible

We should pursue both the low and high mass regions (different paradigms)

We need a variety of targets to elucidate couplings and protect against cancellation

Where is this going?

Importance of the 13 TeV LHC run (starting now)

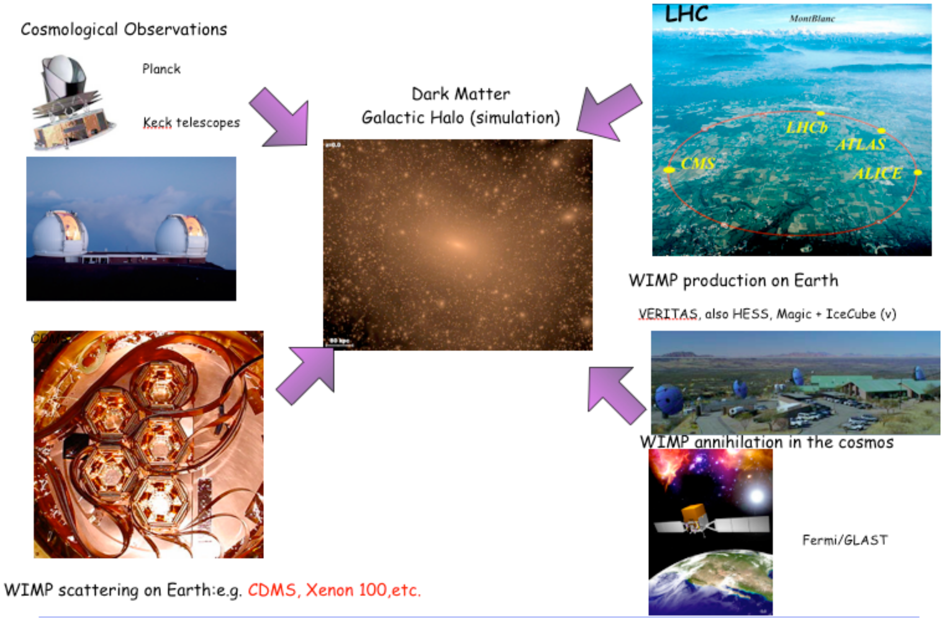
- Discovery of supersymmetry
  - Why so high scale?
  - Is this responsible for Dark Mattter: detect in Cosmos
- No supersymmetry
  - End of the naturalness concept?
  - Even larger importance of direct detection -> Dark Sector (low mass)
  - High mass inaccessible to LHC + indirect detection

Fascinating time

4 prong approach=>

complementary coverage

constrain theory speculations



Additional Slides

How can we provide unambiguous evidence?

Discussion using CDMS and the low mass region as an example.

Powerful detector designs

Massive => large number of events
Reduction of the background /self shileding (
Active background rejection/signal identification <= multi dimensional
high signal to noise
Good energy calibration for various kinds of recoils
Identification backgrounds and good understanding of detector response

Feedback
on new
designs

Unbiased analysis methods

Blind cut analysis essential, but blunt instrument
How to decide whether passing events are signal
known or unknown background?
=> Likelihood methods, but highly dependent of your background model

Feedback
on new
designs

Complementary experiments

Cross check each others
Understand dependence on target nucleus

Athermal Phonon Sensors

Collect and Concentrate Phonon Energy into tungsten Transition Edge Sensor