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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

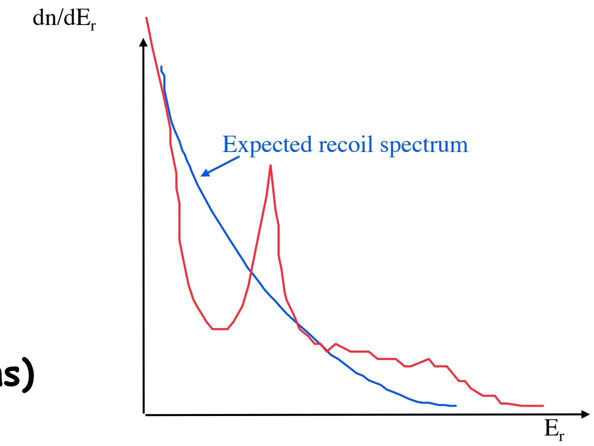
The future of direct detection

- Focus both on high mass and low mass
- Need for at least 2 technologies -> can approach fundamental neutrino limit

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

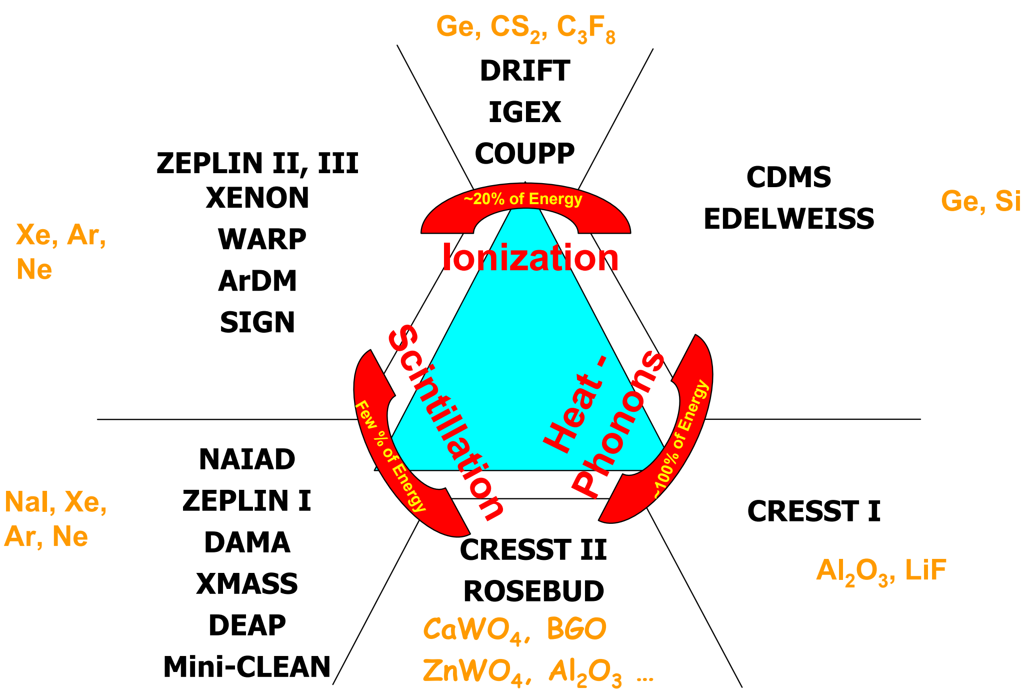
- Nuclear recoil
- Single scatter ≠ neutrons/gammas
- Uniform in detector ≠background from outside

Linked to galaxy

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

Experimental Approaches

Direct Detection Techniques

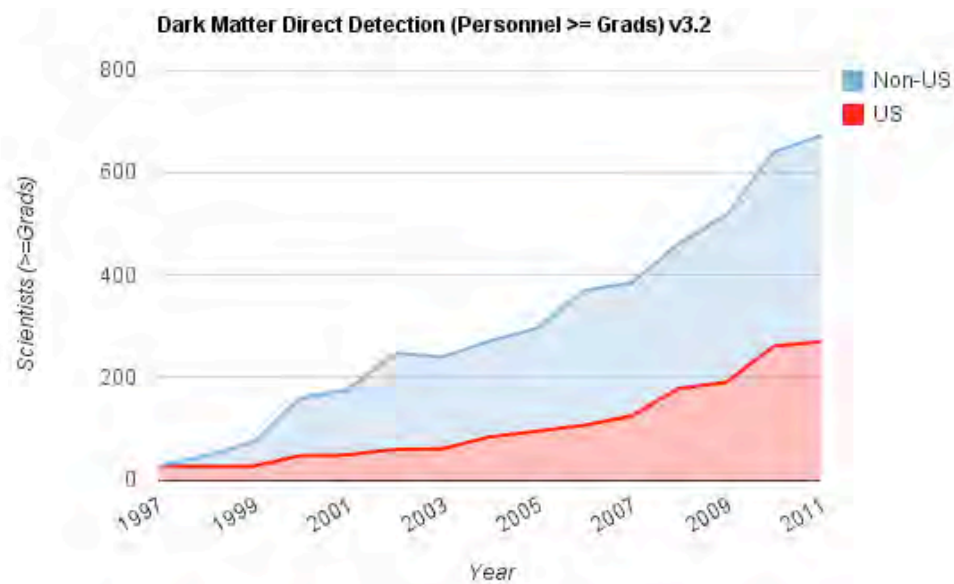


At least two pieces of information in order to
- recognize nuclear recoil
- extract rare events from background (self consistency)
- + fiducial cuts (self shielding, bad regions)

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

An expanding community

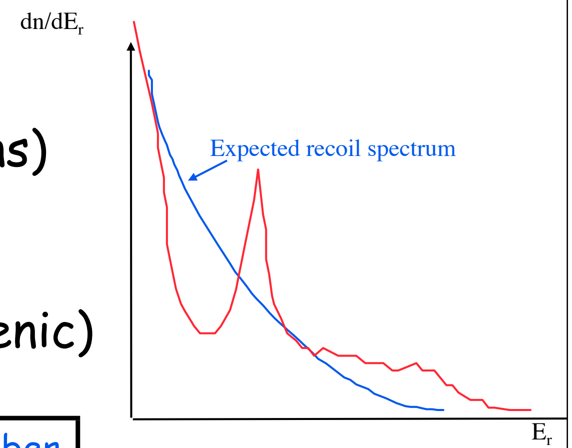
≈ 270 physicists ≈70% FTE
≈ 40% of world



Detection Challenge

A variety of novel and exciting techniques

Exquisite energy sensitivity
3 D reconstruction=>fiducial cuts (self shielding, bad regions)
At least two measurements to distinguish nuclear recoil from electron recoils => as much information as possible
Decrease neutrons to negligible level (radio-purity, cosmogenic)

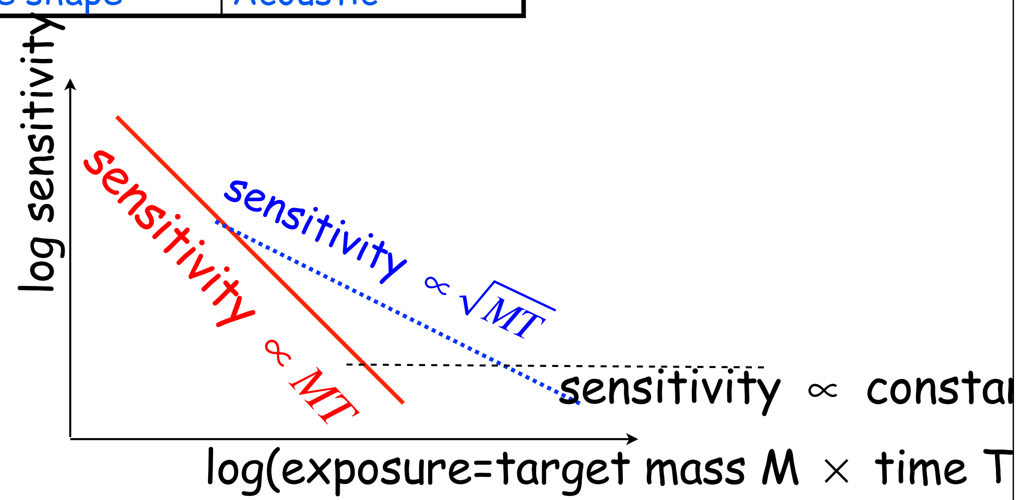


	Liquid Xenon	Liquid Argon	Low temp. Ge	Bubble Chamber
Ionization	√	√	√	high density
Scintillation	√	√		
Phonons			√	
Other		Pulse shape	Pulse shape	Acoustic

+ 77K Ge, NaI

Three Challenges

- Understand/Calibrate detectors
- Be background free
  much more sensitive than background subtraction
  eventually limited by systematics



- Increase mass while staying background free: $10^{-47}cm^2$/nucleon ≈1 evt/ton/year

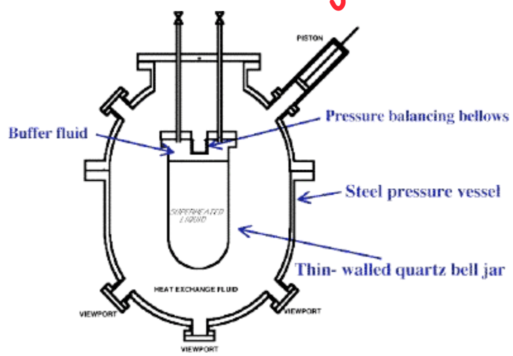
Bubble Chamber

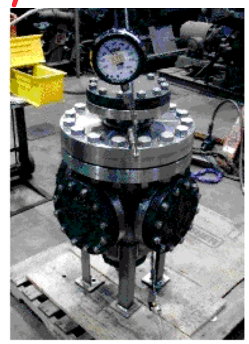
Bubble chamber

Long duration metastable state broken by large ionization events

nuclear recoil or nuclear recoil from alpha (purity level ≈ Borexino)

rejected by acoustic discrimination

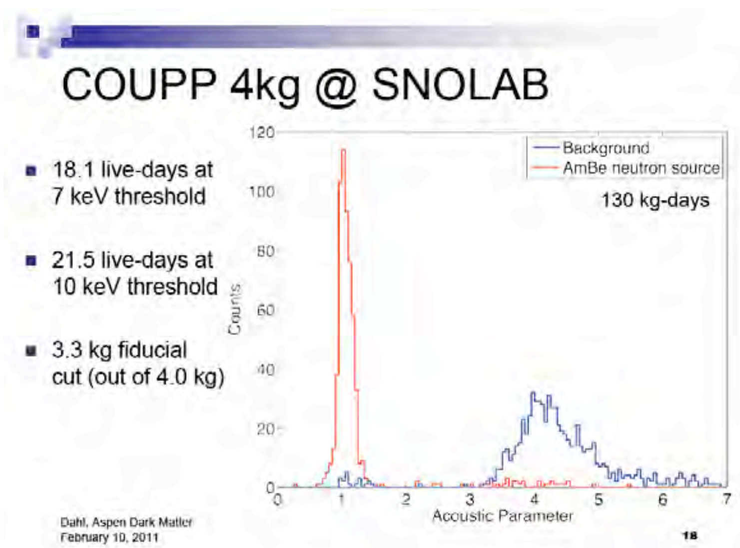




COUPP 4kg at SNOLAB

Acoustic rejection of alphas
but neutrons due to components PZT

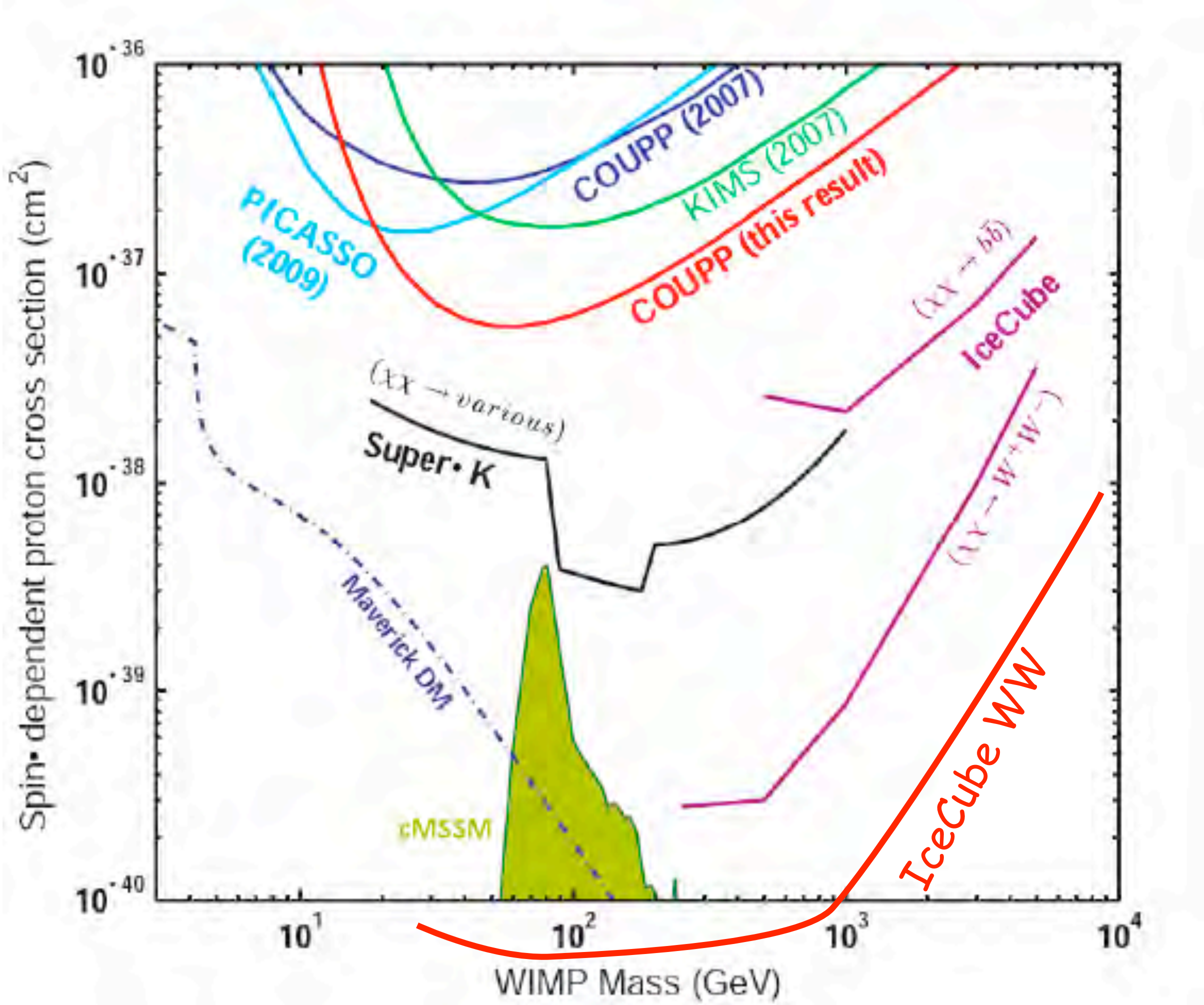
60kg problems with ClF_3 dissociation
solved -> SNOLAB



Likely to be an excellent way to lower upper limit.

Much more difficult to get a convincing positive signal

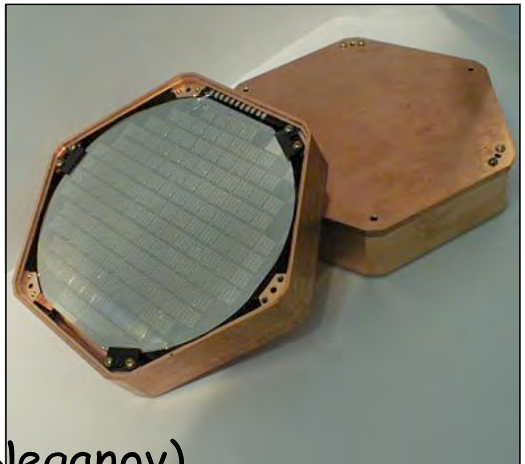
Current results(Spin dependent)

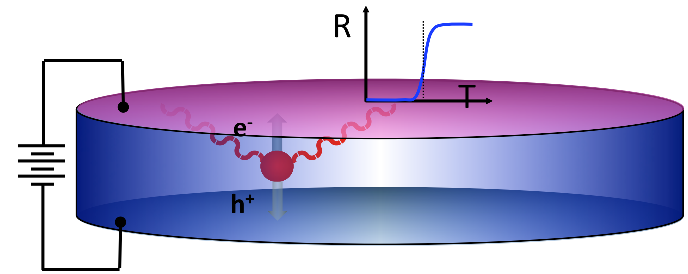


CDMS II->2008

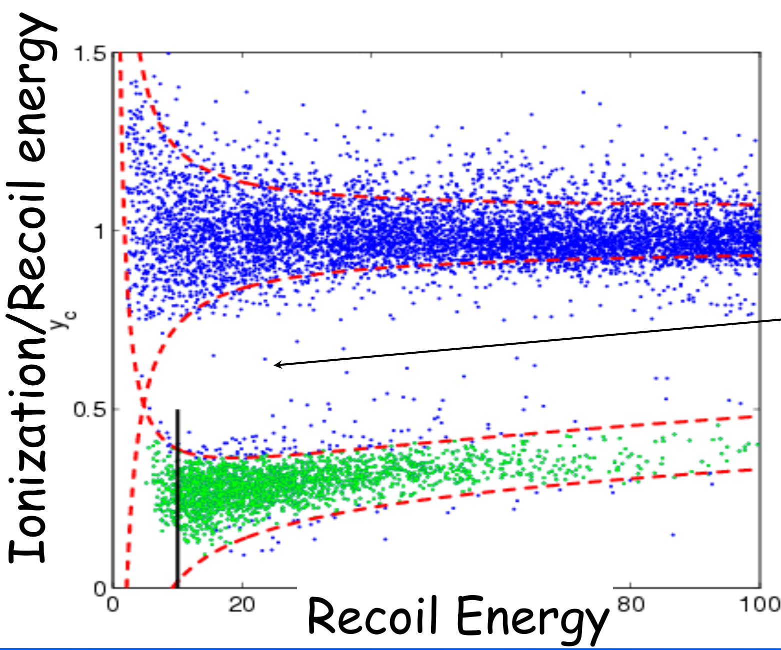
Ionization + Athermal Phonons

7.5 cmØ 1 cm thick ≈250g
4 phonon sensors on 1 face
Transition edge SC
2 ionization channel
Field ≈1V/cm
=> do not create too many phonons (Luke-Neganov)

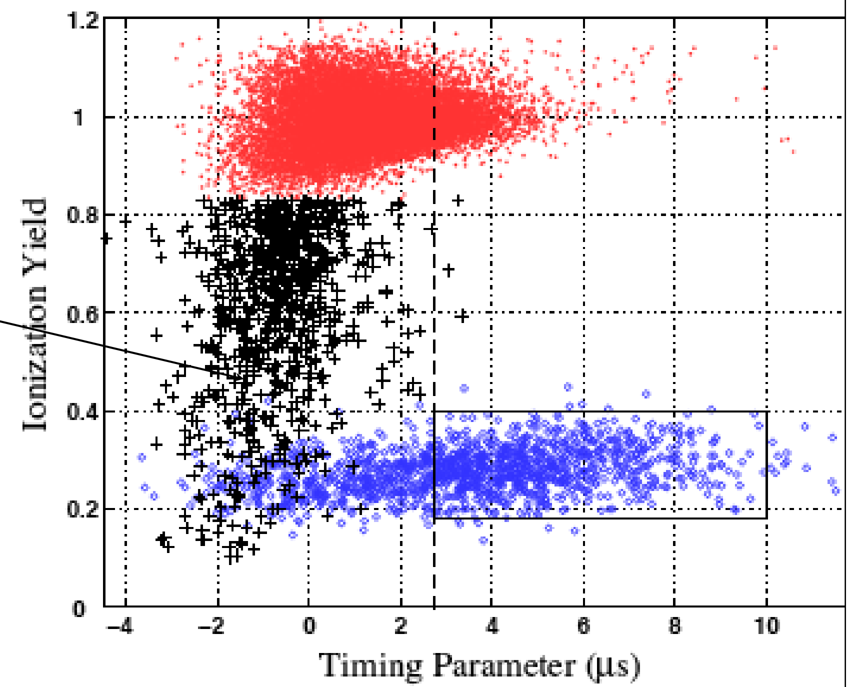




Ionization yield

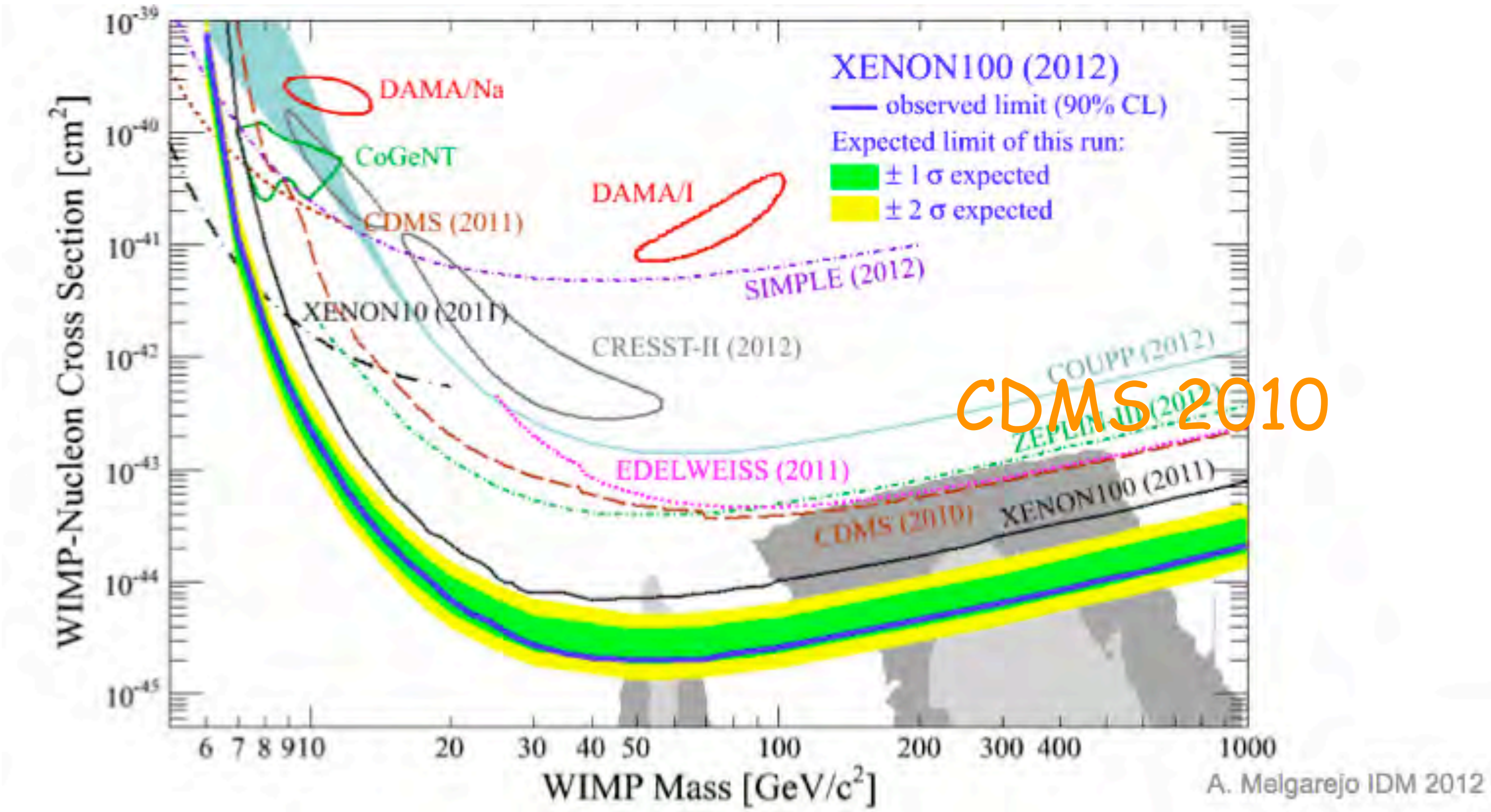


Timing -> surface discrimination



Surface Electrons

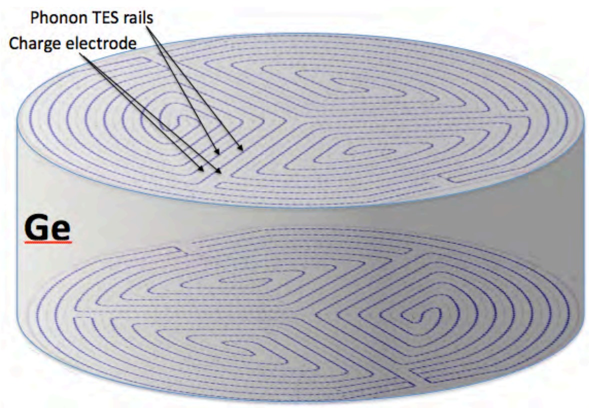
CDMS: Best limits ->2010

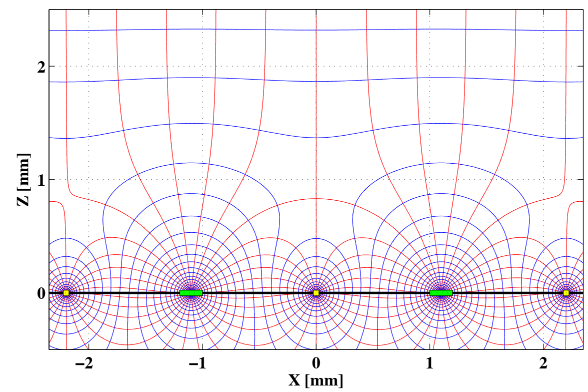


Edelweiss came close

Combination of CDMS and Edelweiss data

SuperCDMS:Getting rid of the surfaces





Interleaved electrodes

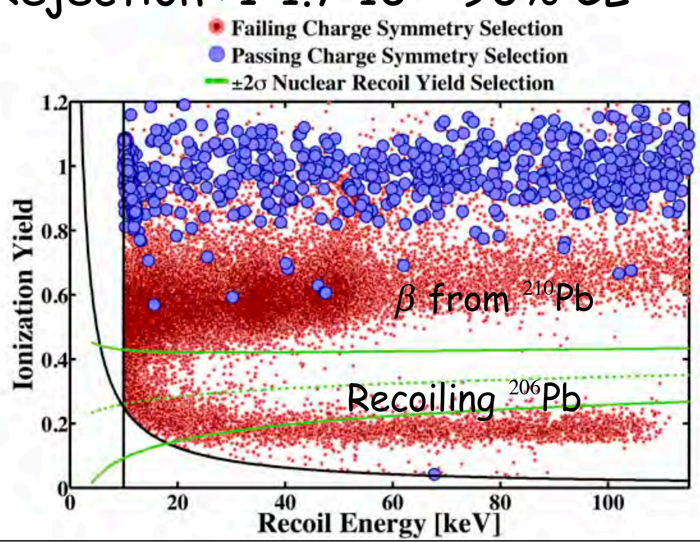
Reviving an idea of P. Luke (also used by EDELWEISS)

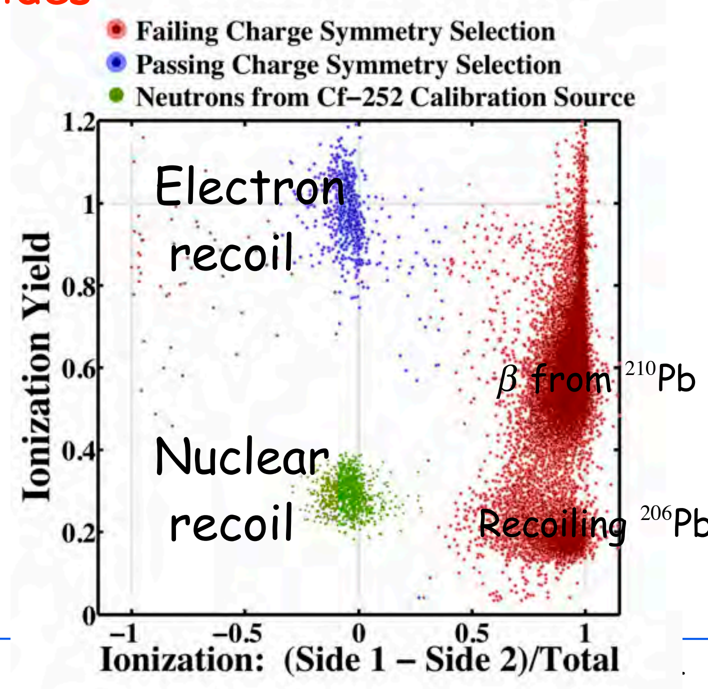
Events close to the surface seen on one side

≠Events in the bulk seen on both sides

Test underground with Pb 210

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

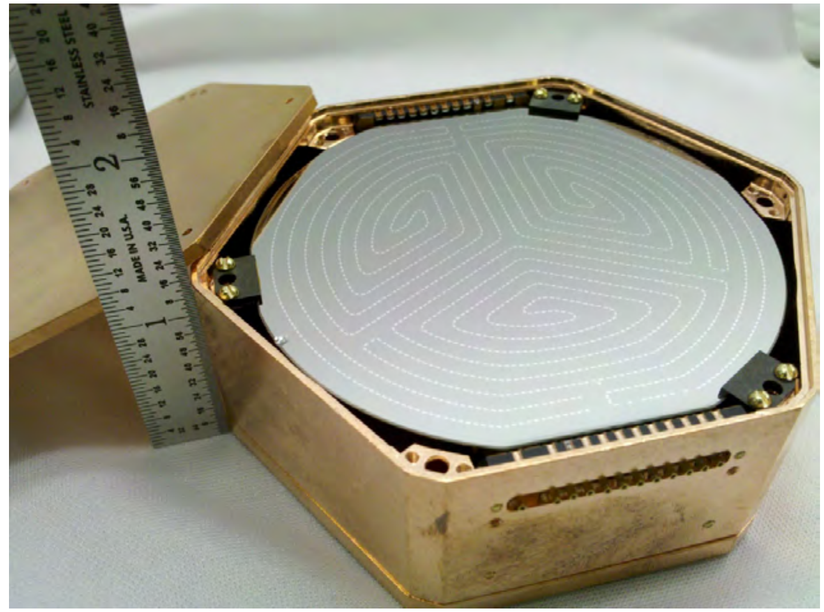


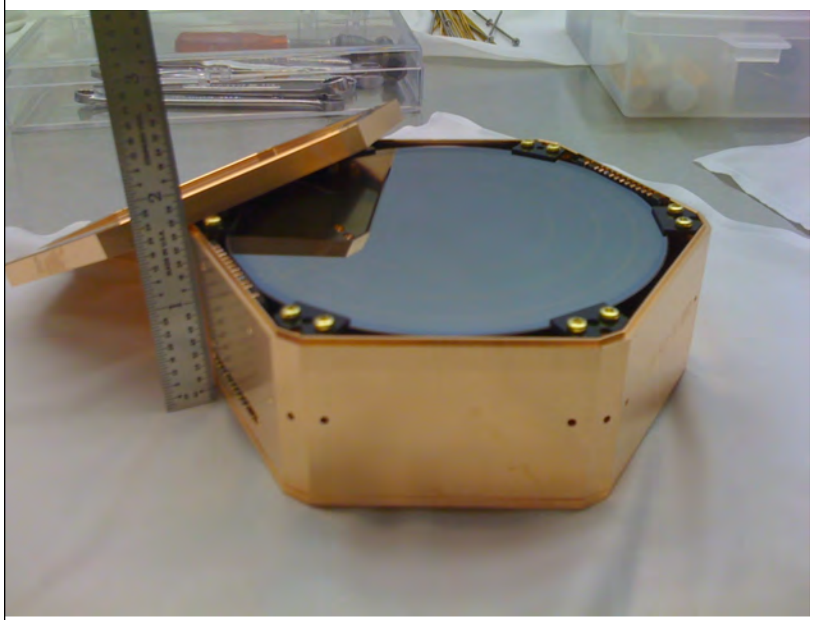


Ge: Towards Larger detectors

Currently in Soudan Mine

76mmx25mm (630g) -> 9kg





Rejection good enough for 0.3 ton year (<0.6 evt)

SNOLAB 100mmx33mm (1.6kg) ->200 kg

Excellent S/N, surface rejection, background control

Drawback of technology: getting to large target mass

Noble liquids (Single Phase)

A way to get large mass relatively cheaply!

Simplest idea: single phase detectors

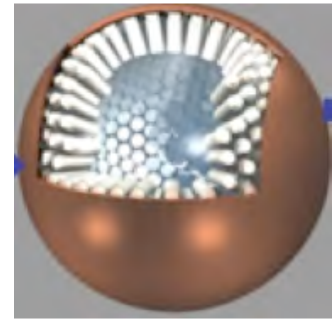
Single phase detectors Xe

Xenon: Rely on self shielding + position reconstruction:

XMASS 800kg

Danger: misreconstruction <= surface radioactivity

Indeed what happened! => Redesign



Liquid Argon (or Neon)

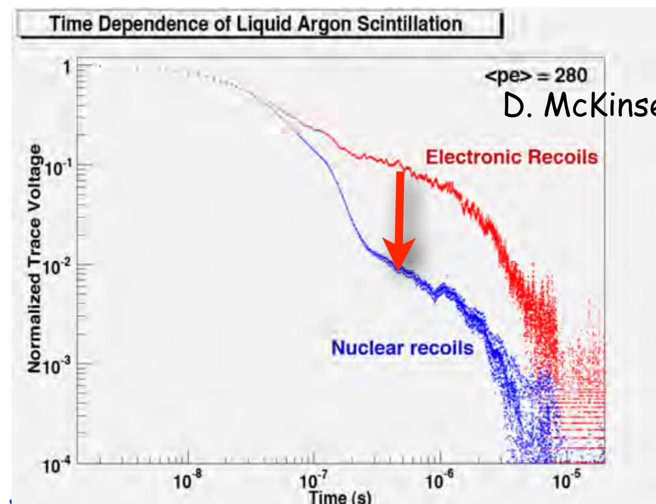
For light liquids, one additional handle : rise time

Triplet (long decay time) killed by nuclear recoil

Far UV scintillation => wave shifter

Need enough photo electrons

=> Higher thresholds



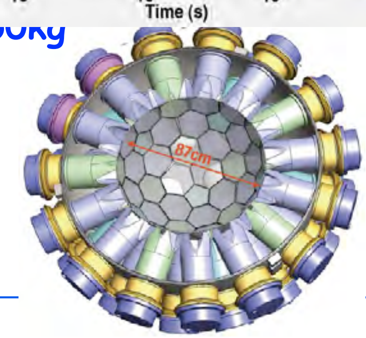
D. McKinsey

Pulse shape discrimination

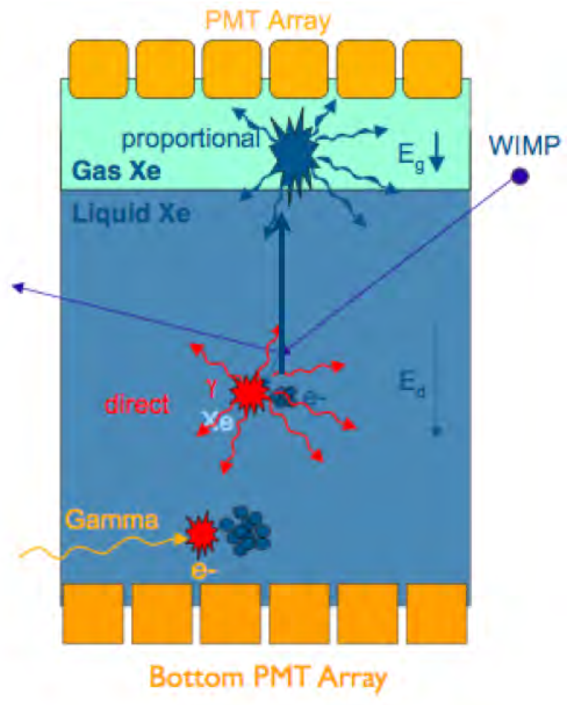
Argon: Rely on pulse shape discrimination:

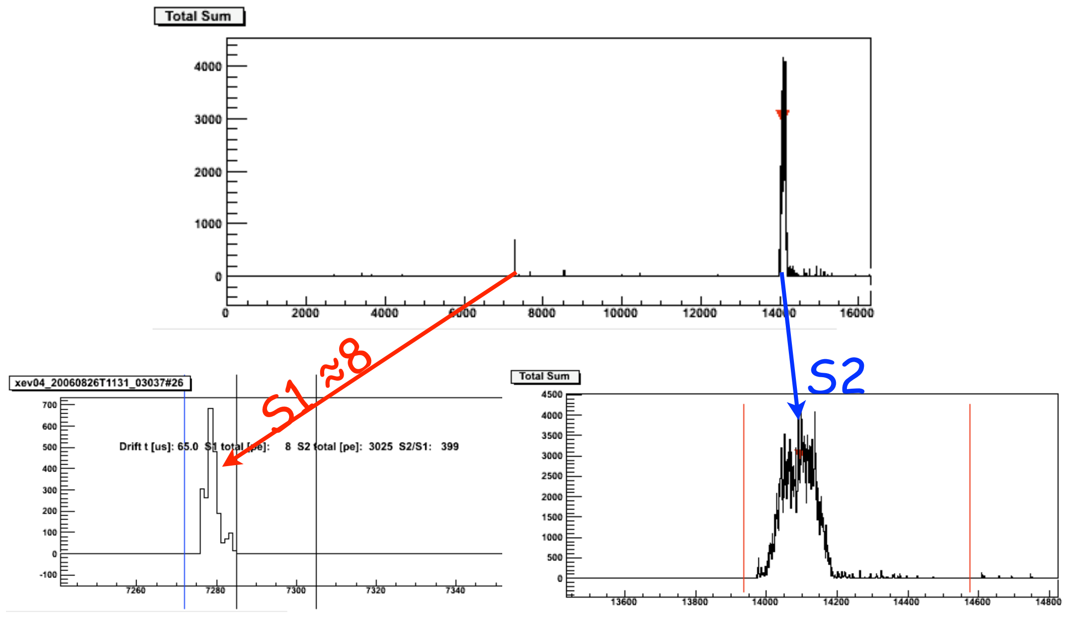
Mini Clean 150kg fiducial Ar 2013 6-7 pe/keV

DEAP-3600 1000kg fiducial 2014



Dual phase Xe and Ar





Liquid Xenon or Argon: Scintillation + ionization

two photon pulses => depth

Lux 300kg

Xenon 100kg

Dual phase Xenon

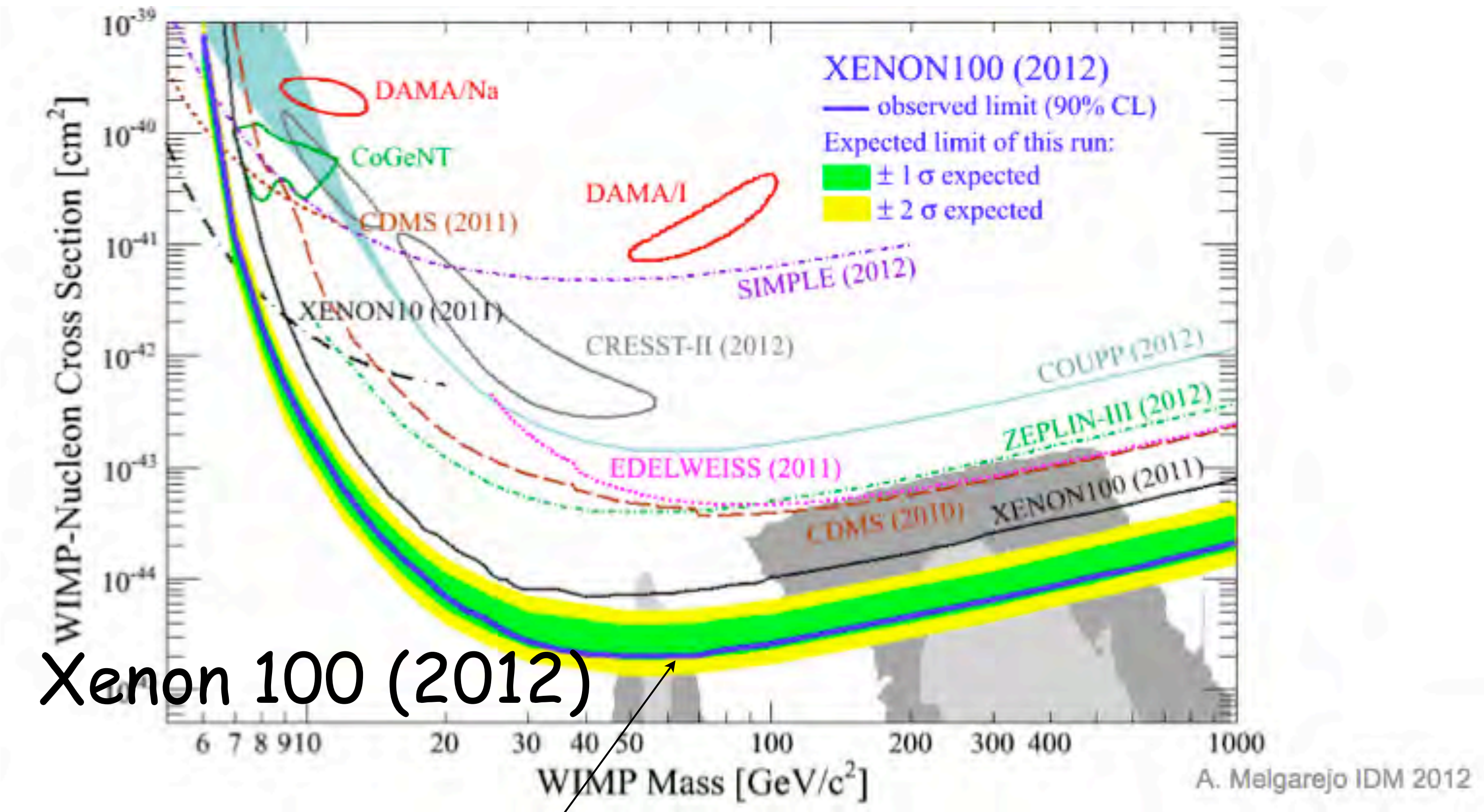
Xenon 100 : Assembled in Gran Sasso. Furst results 2011- 2012

LUX 300kg -> 100kg fid : SUSEL (Homestake)

Surface: Fall 2011

4850 ft: Summer 2012-> Fall 2013

Current results (Spin independent)

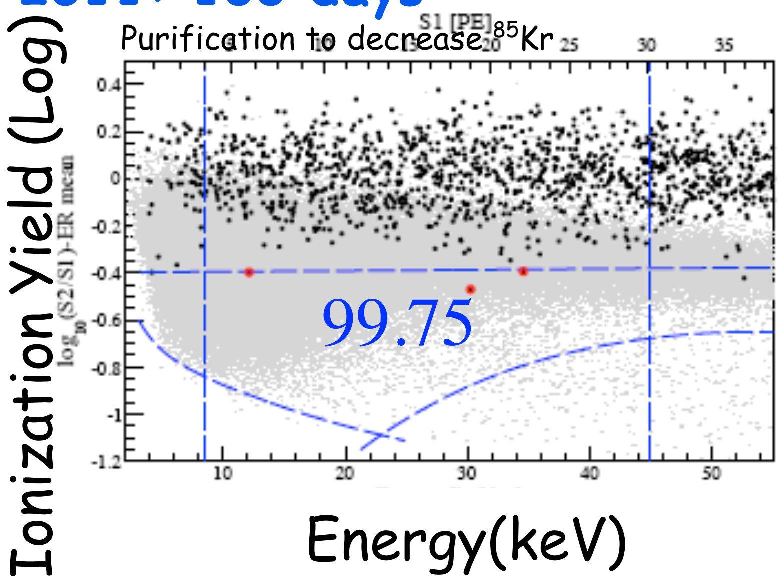


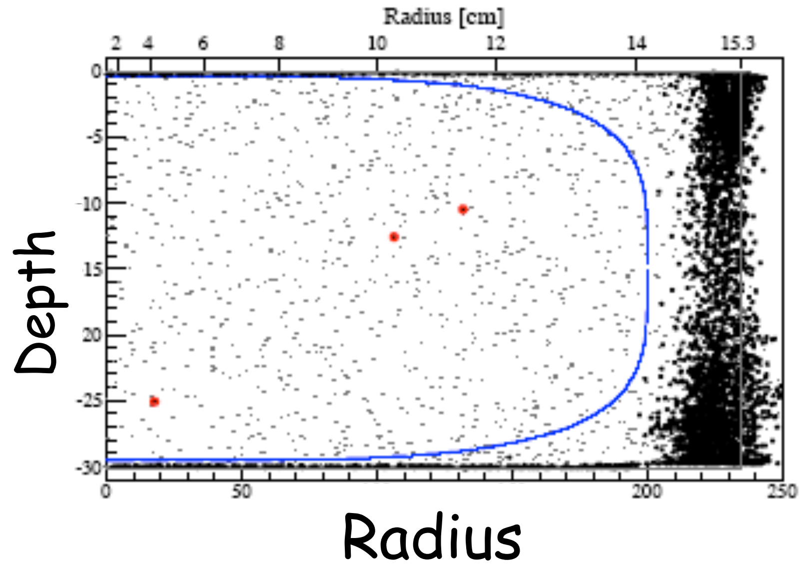
1 evt/kg/ 160 days

Progress from 100 days to 200 days

2011: 100 days

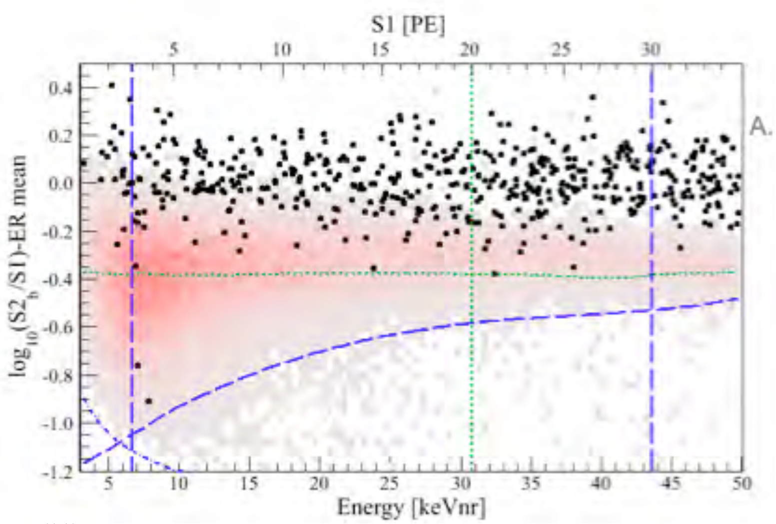
Purification to decrease ^{85}Kr

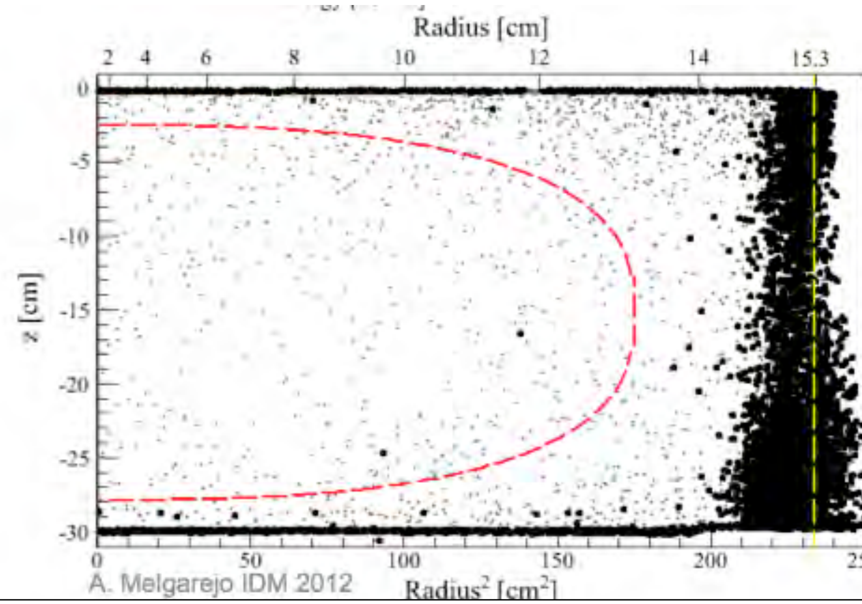




2012 200days:Much improvement on ^{85}Kr background

but still problem with purity of liquid (bad collection uniformity, evolving electron life time)





Xenon Outlook

Xenon 100kg: 34kg fiducial, 225 days 2 events

Abnormal S1/S2?

Unexpected background

Evidence for low mass WIMP ≠ efficiencies

Needs additional purification or for 1 tonne scale

Xenon 1ton approved, under construction

LUX (300kg) results this Fall

will also be important to judge potential of the technology:

larger number of photoelectrons/ keV

Impressive

Drawback of technology:

Relative small rejection of electron recoils 99.??%=> rely on self shielding

Purity of liquid has to improve proportionally to sensitivity goals

+ try to improve rejection by working at low field (important against

Dual Phase Argon

ArDM: 500kg commissioning at CERN

Going soon to Camfranc

WARP is dead

ArDM

Dark Side

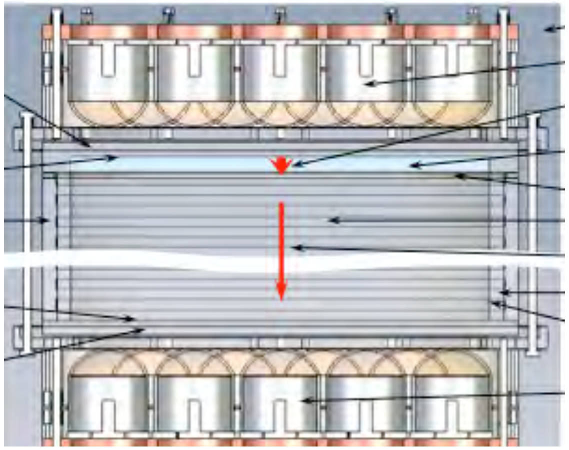
in Borexino CTF

50 kg

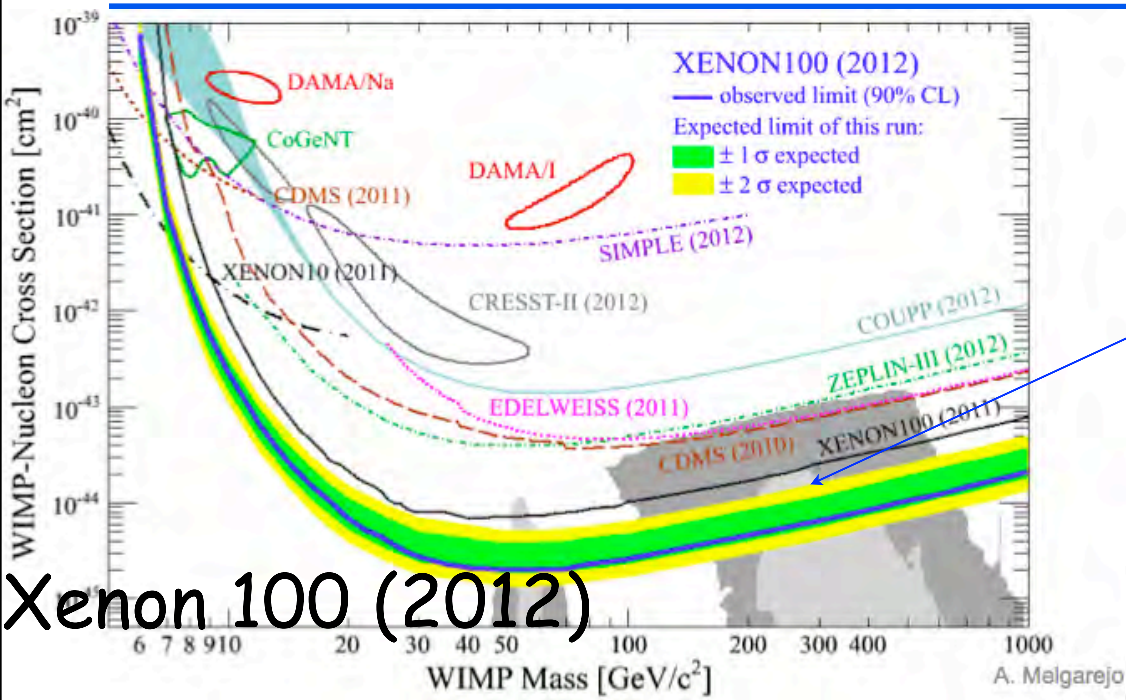
Depleted ^{39}Ar

(underground argon)

Dark Side:



Direct Detection Status Sept. 2013



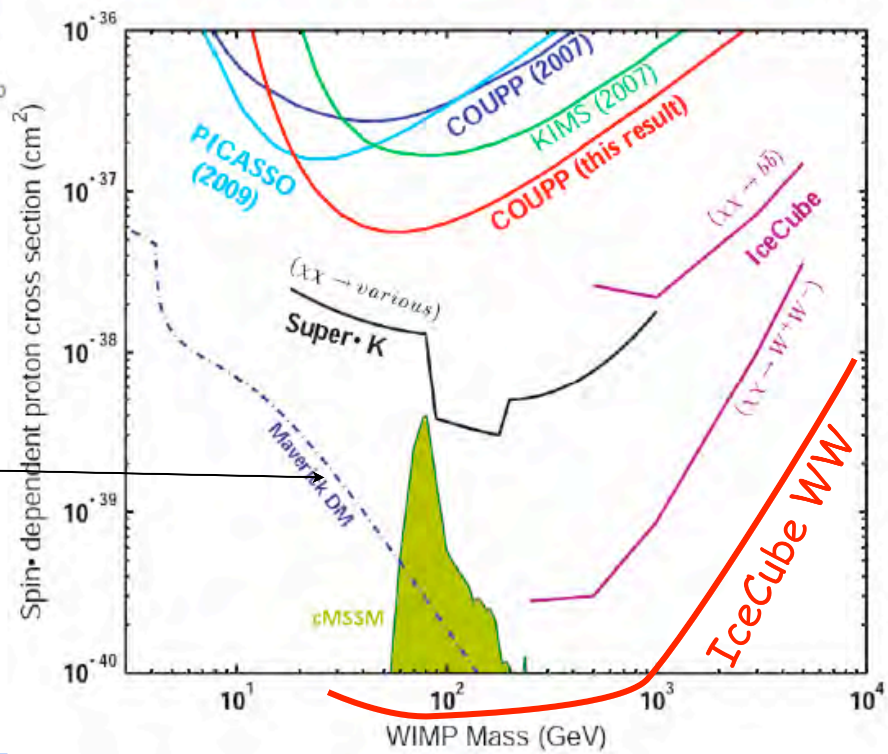
Xenon 100 (2012)

CMSSM≈mSUGRA Focal point region
(old Buchmueller 2011)

No threshold for Direct Detection

LHC Monojets

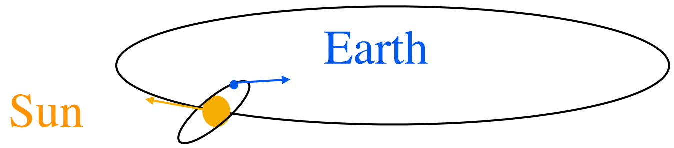
$$\left(\bar{\chi}\gamma_\mu\gamma_5\chi\right)\left(\bar{q}\gamma_\mu\gamma_5 q\right)$$



B.Sadoulet

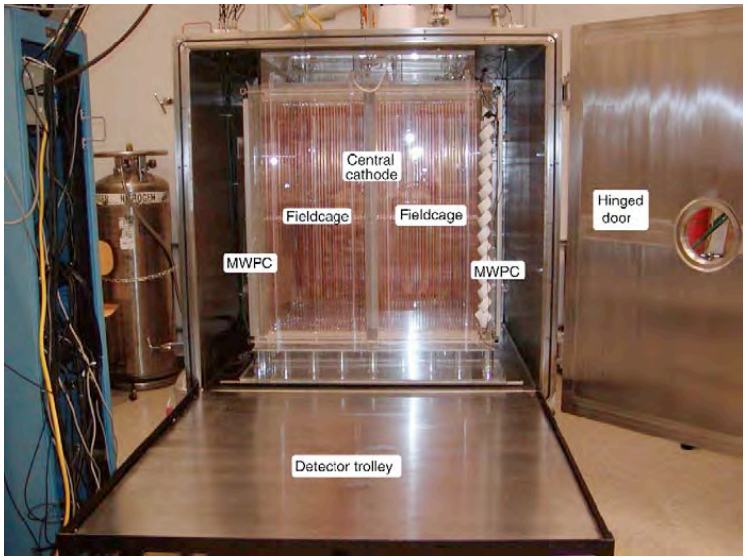
Directionality

How to get access to diurnal rotation of recoil direction?



Tracking

But in a solid ≈100Å
=> Low density gas:
Prototypes DRIFT, DMTPC,MIMAC ≈1 m^3
Challenge: 100g/m^3 =>
10000 m^3/ton with 10^{22} mm^3 pixels
New idea: DNA labeling of Au balls



Anisotropy of detector medium

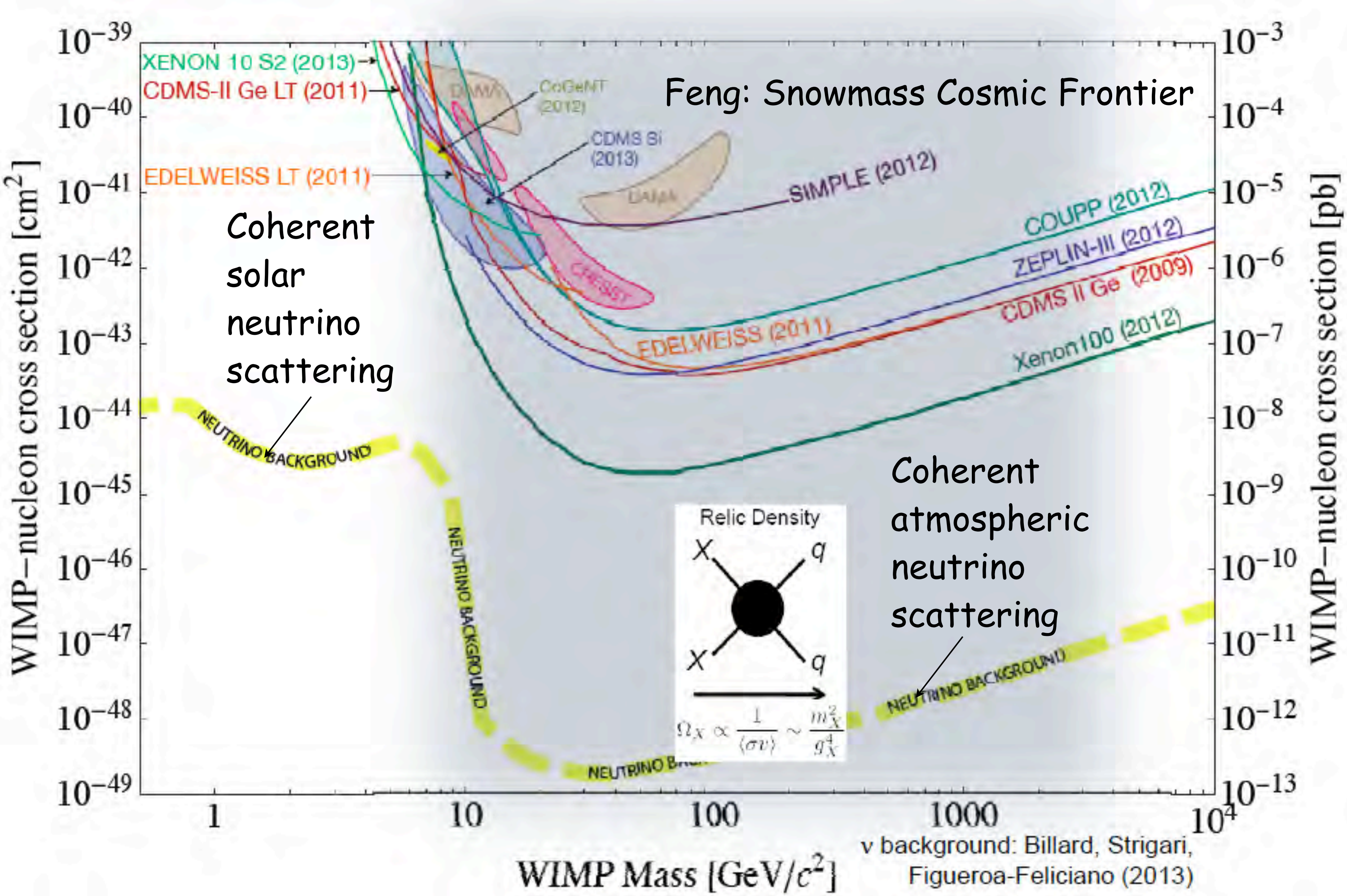
Scintillator (but need to measure independently energy)
Germanium

Columnar recombination

David Nygren
Recombination-> Scintillation
(enhance with TMA)
Compare with Ionization

Weak Scale WIMPs

High Mass WIMP Parameter Space



No evidence yet for Weak Scale WIMPs

No direct indication of weak scale by cosmology

Nothing in Direct Detection

Best limit: Xenon 100

No smoking gun in Indirect Detection

Positron excess can be pulsars

Fermi: not yet sensitive enough for high mass (unless unphysical boosting factors)

135 GeV line? Not WIMP-like (no continuum=> dark sector or sterile ν)

No sign yet for SUSY at LHC

mSUGRA≈CMSSM too simple: excluded except focus point (high $m_0, m_{1/2}$)

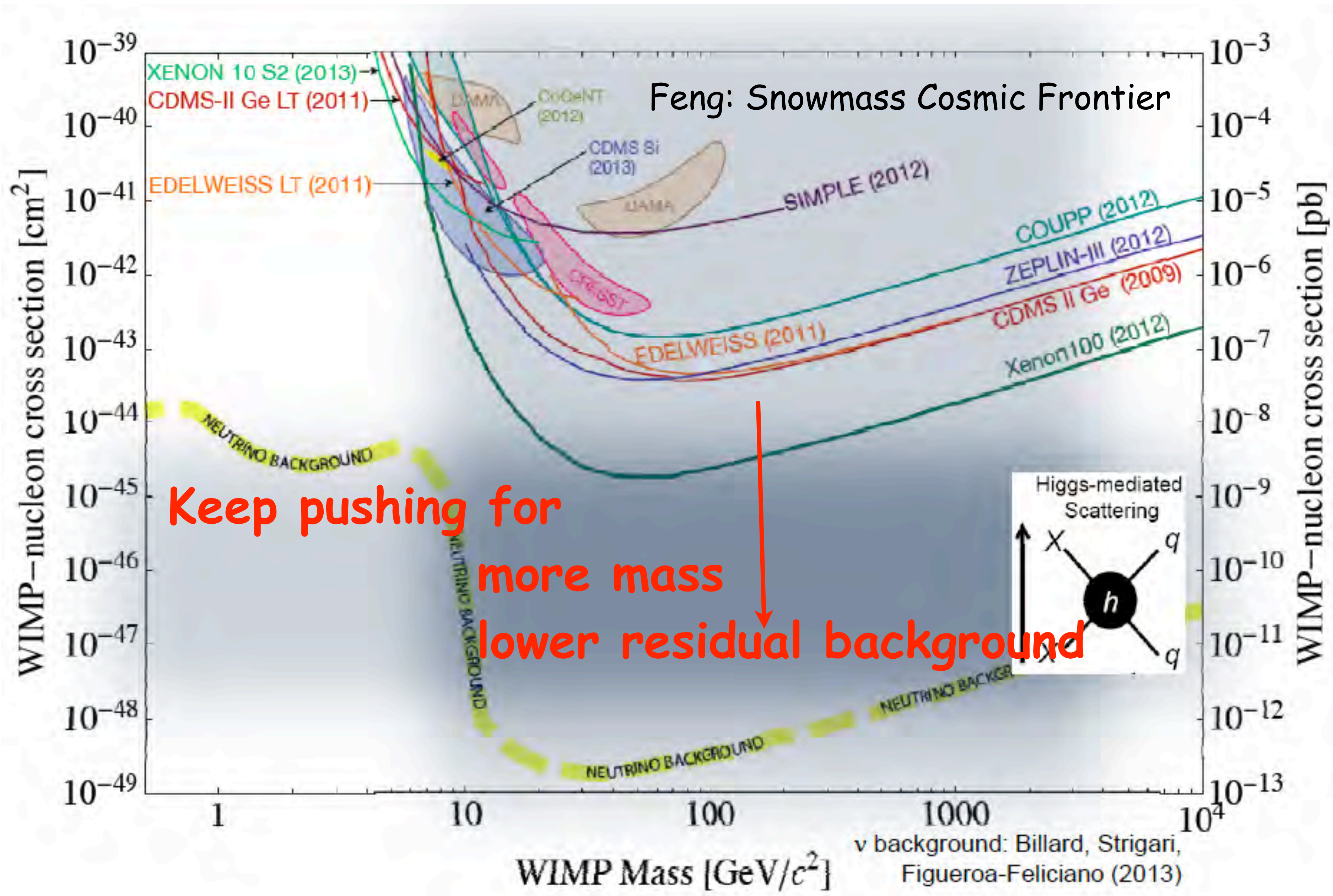
Natural, Simplified models M >600 GeV/c^2

Models with more parameters (pMSSM) have no problem but fine tuning...

"Only new fact": Higgs at 126 GeV/c^2

-> scale of interaction

Higgs Exchange



Low Mass WIMPs

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)

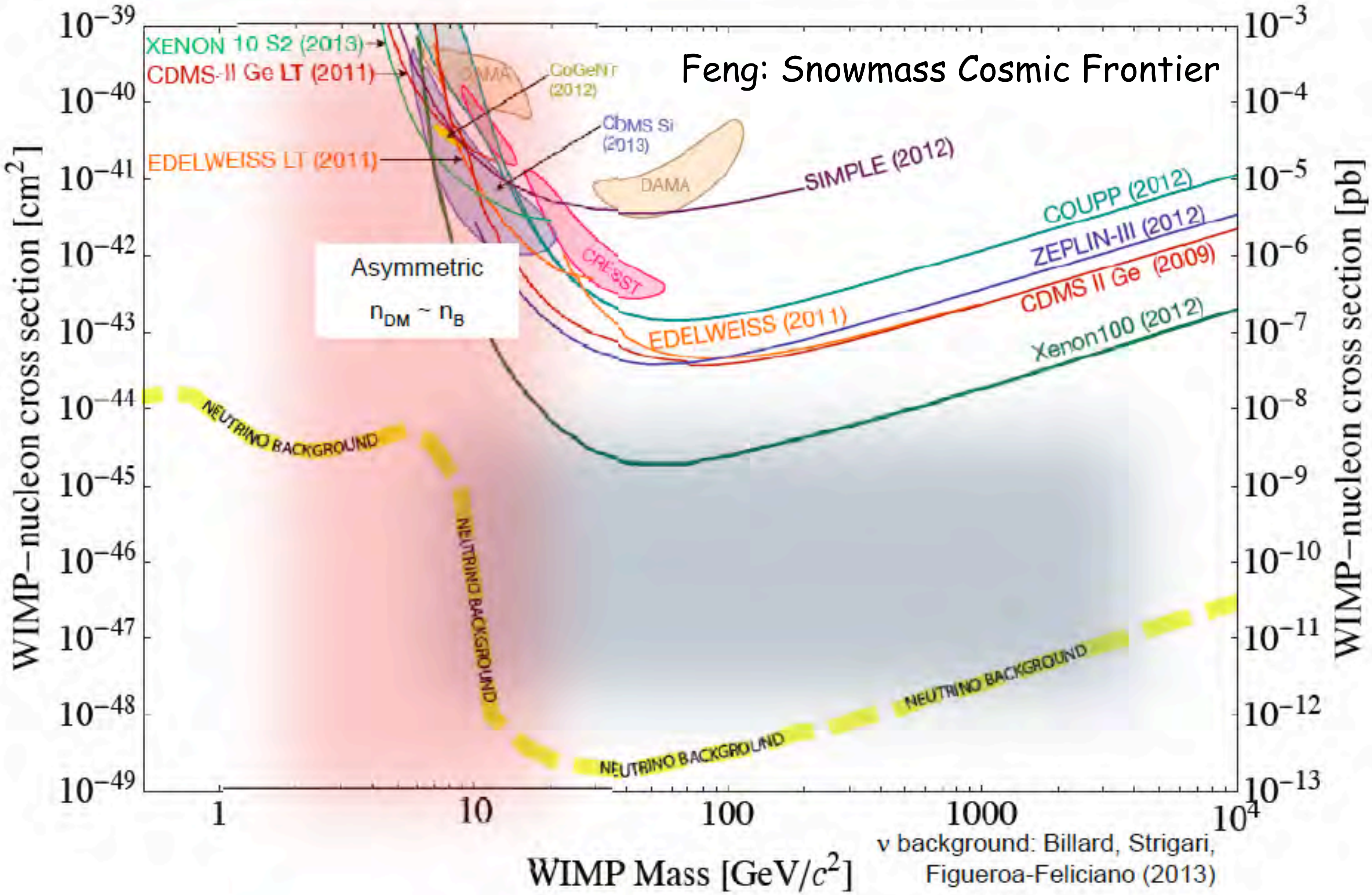
Dark Photon (Arkani Hamed-Finkbeiner-Weiner)

=> atomic DM, Self Interacting etc..

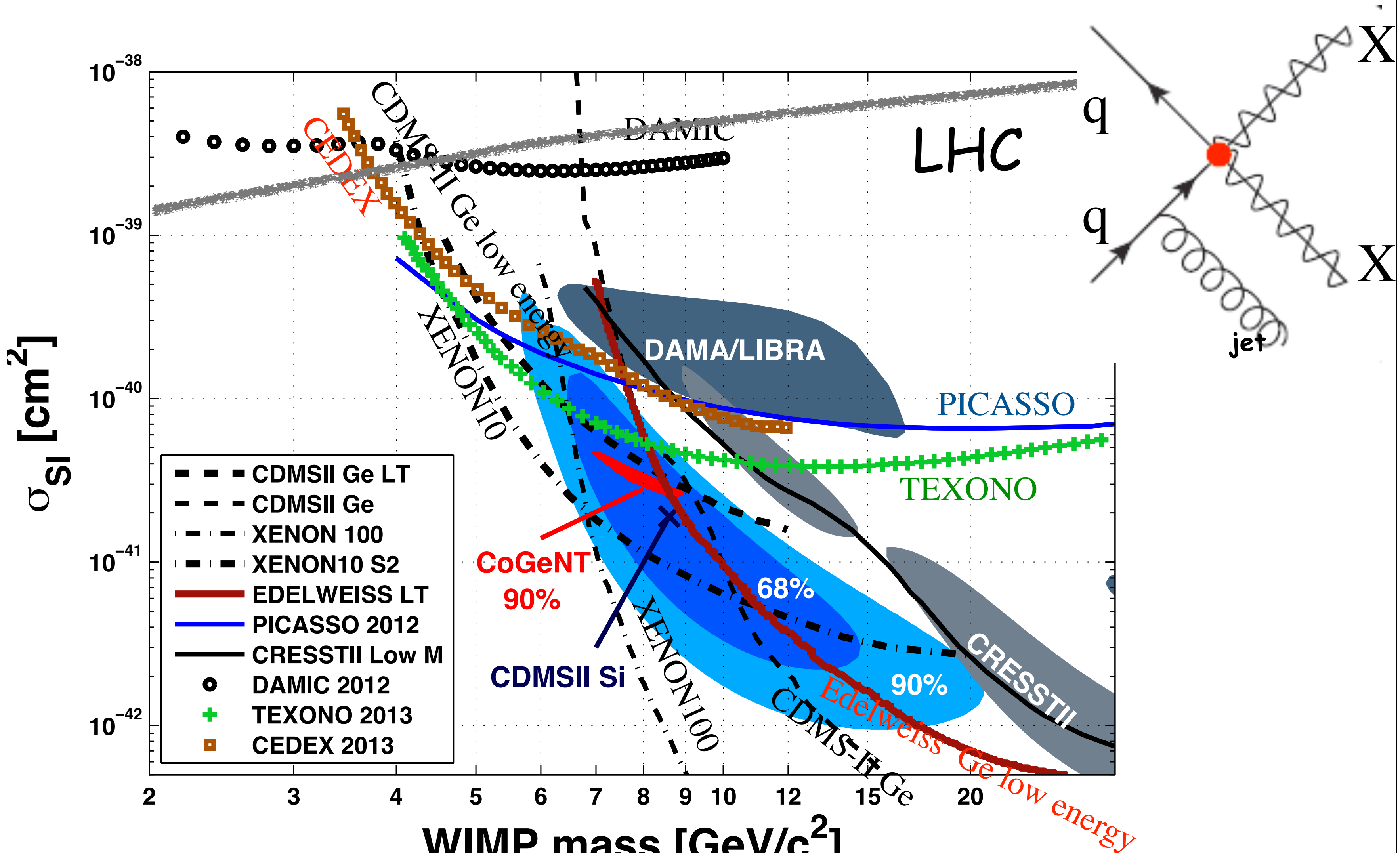
Intriguing but less predictive

Note that if cores in dwarf galaxies + deficit of large satellites are confirmed, and if astrophysics processes (baryon ejection) are not powerful enough, we may need strongly self interacting dark matter => Dark sector

Low Mass WIMP Parameter Space



An expanded view



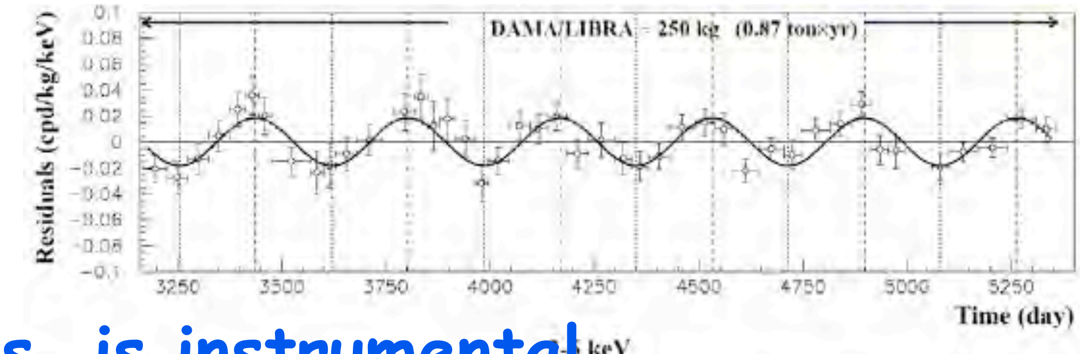
Compatible with LHC monojet limits

unless DM couples to gluons (D11 matrix ≈10^{-45} cm^2/nucleon)

Making sense of a confusing situation

DAMA

clear summer-winter modulation



Wide suspicion that this is instrumental

but no convincing explanation so far! Subtle problem!

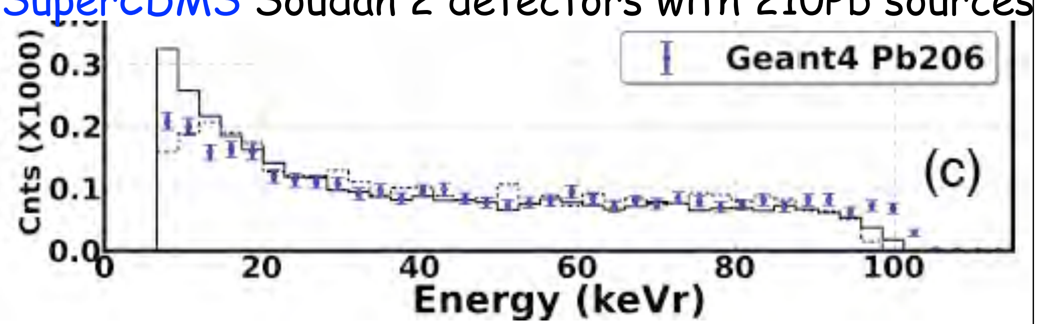
Repeat the experiment

South Pole: DMIce
Princeton
KIMS (100kg CsI, 3 keVee, next NaI, cf Hongjoo Kim's talk)

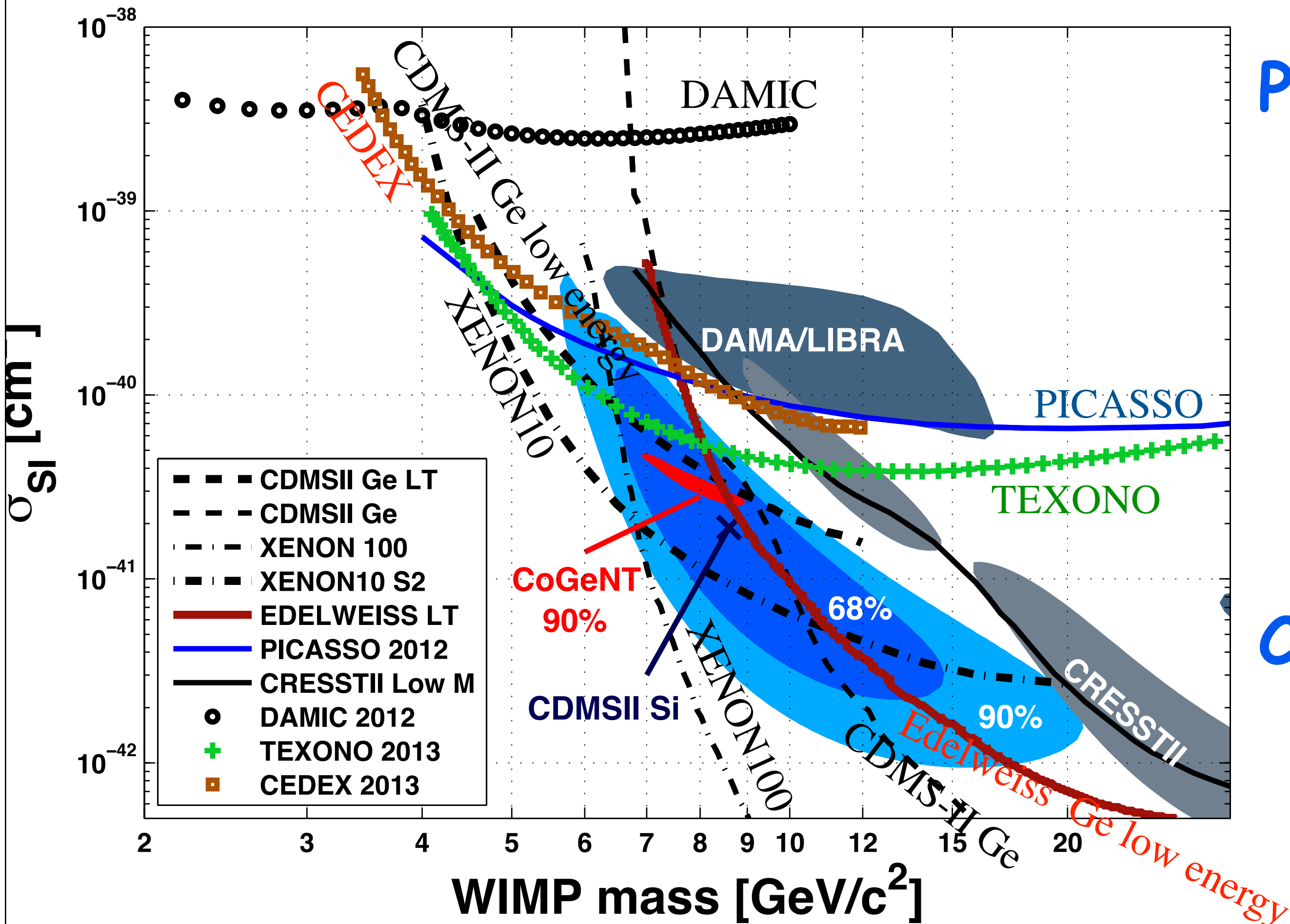
CRESST

High background
Likely ^{206}Pb
New run with reduced background

SuperCDMS Soudan 2 detectors with 210Pb sources



Ge/Si Detectors



Point contact detectors

- CoGeNT evolving: 75% are surface events
  <= contact simulations
- But Malbeck "We cannot establish a clear separation" => upper limit, cf. CEDEX and TEXONO

CDMS II

- Ge: Collar and Fields claim
- But needs detailed understanding of zero charge events.
- Clearly incorrect (signal in multiples!)
- Si: 3σ effect
- But blind analysis
- Need to extend to lower energy (cf.parallel session)

new results soon!

Tension with Xenon

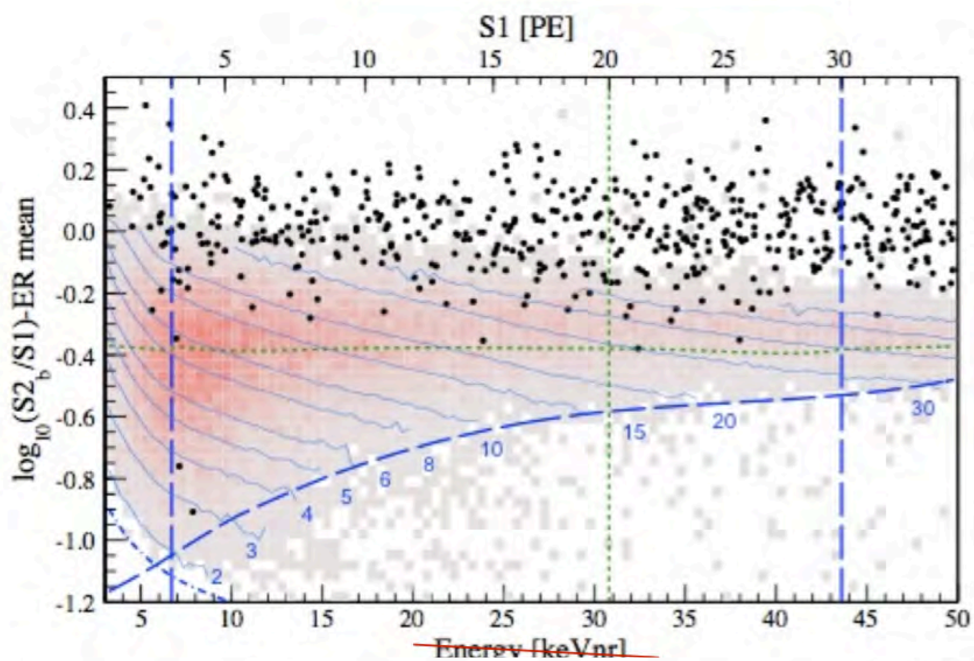
- Xenon 10 erratum: no big problem
- Xenon 100: Are the two events seen compatible (Hooper)?
  + uncertainty in calibration
- Sensitivity to halo velocity

What about XENON100?

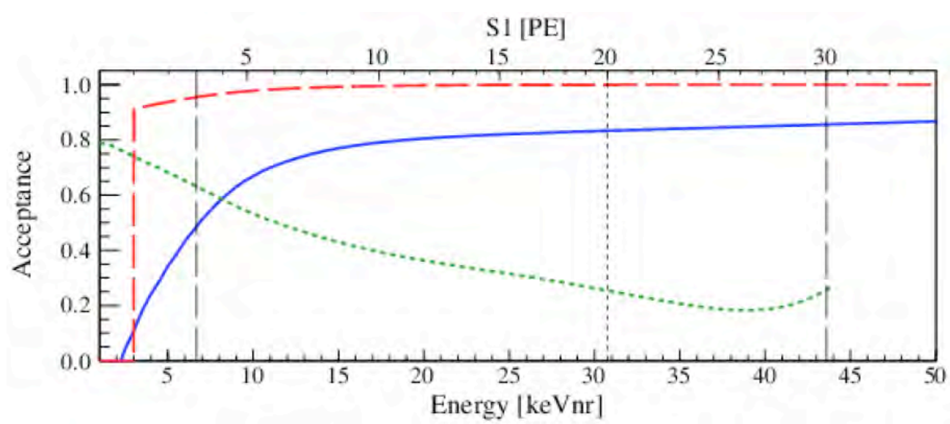
Sorensen, Phys. Rev. D **86** 101301(R) (2012)

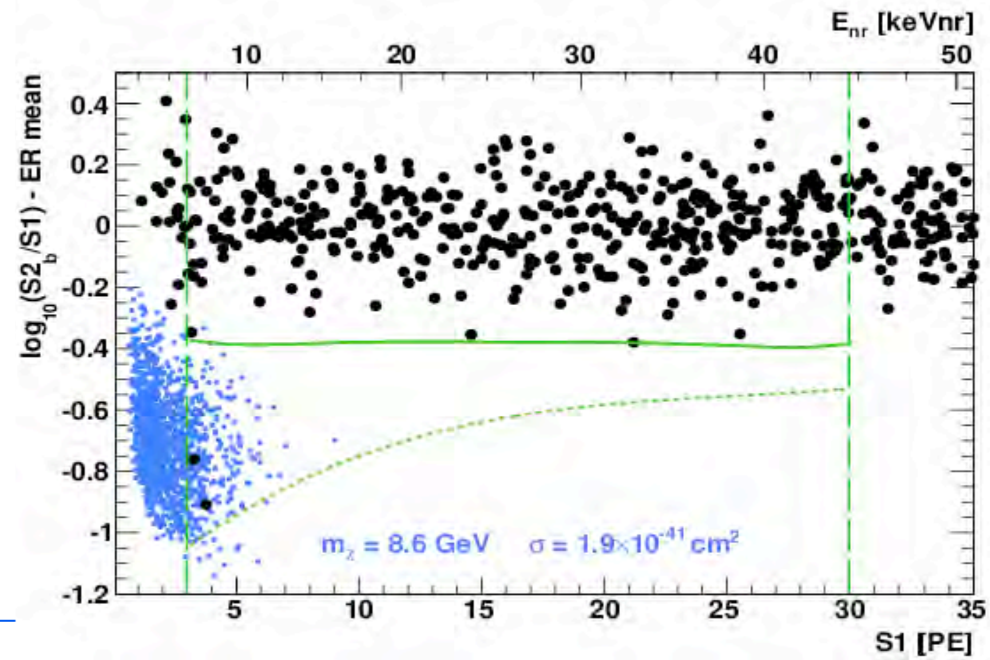
XENON100's exposure = 34 kg * 224 days = 7636 kg-day!

They see two events… could this be compatible?

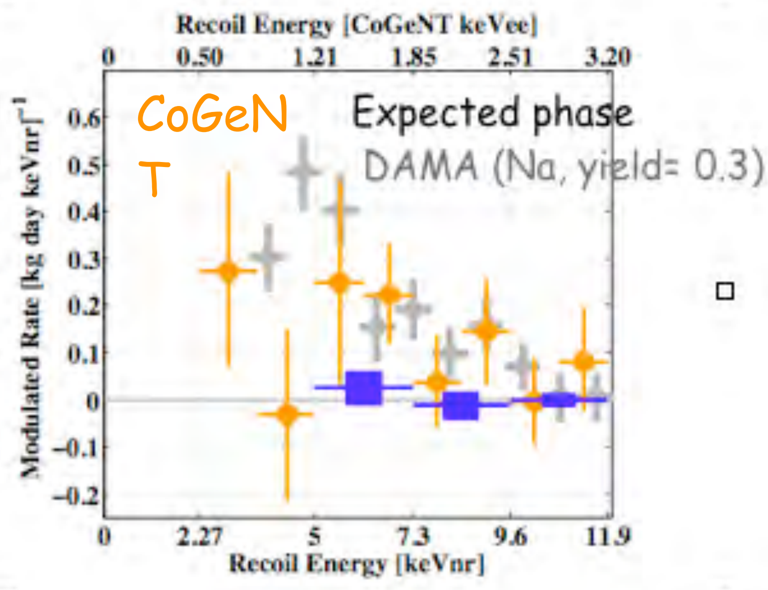


Depends strongly on the nuclear energy scale, the efficiency, and threshold…





Low mass WIMPs?



Claims for very large modulations

Statistical significance of CoGeNT marginal (2.8 sigma) => more statistics.

Malbeck (≈same) does not see any modulation

CDMS does not see modulation (but needs to go below 5 keV: about to publish)

KIMS (CsI) no modulation 2 σ discrepancy with DAMA

Indirect Detection

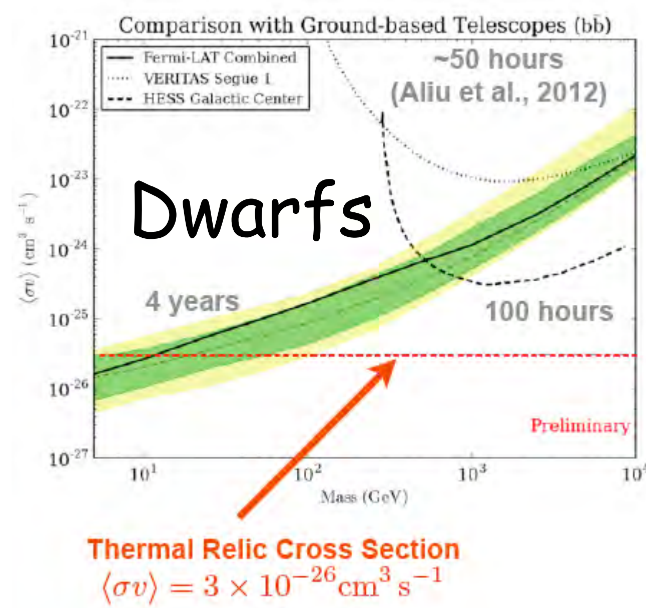
Fermi Dwarf limit:

apparent exclusion comes from 100% BR assumption e.g. in bbar

Disappears in realistic BR models

Galactic Center low energy excess: Hooper

Fermi team: not statistically significant when taking the "look elsewhere" effect



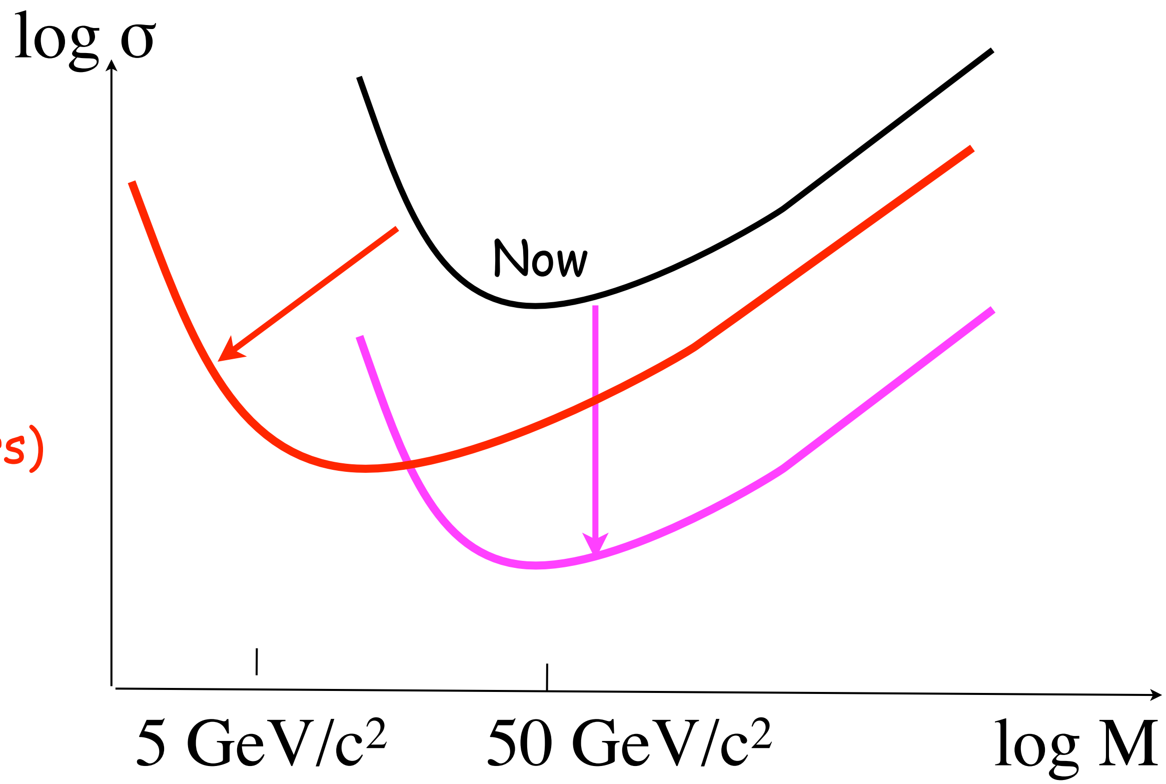
Experimental Strategy

Experimental Strategy

2 directions

1. Improve sensitivity at large mass (e.g., liquid noble)

2. Improve sensitivity at small mass
(low temperature detectors)



Lessons learnt in the last few years

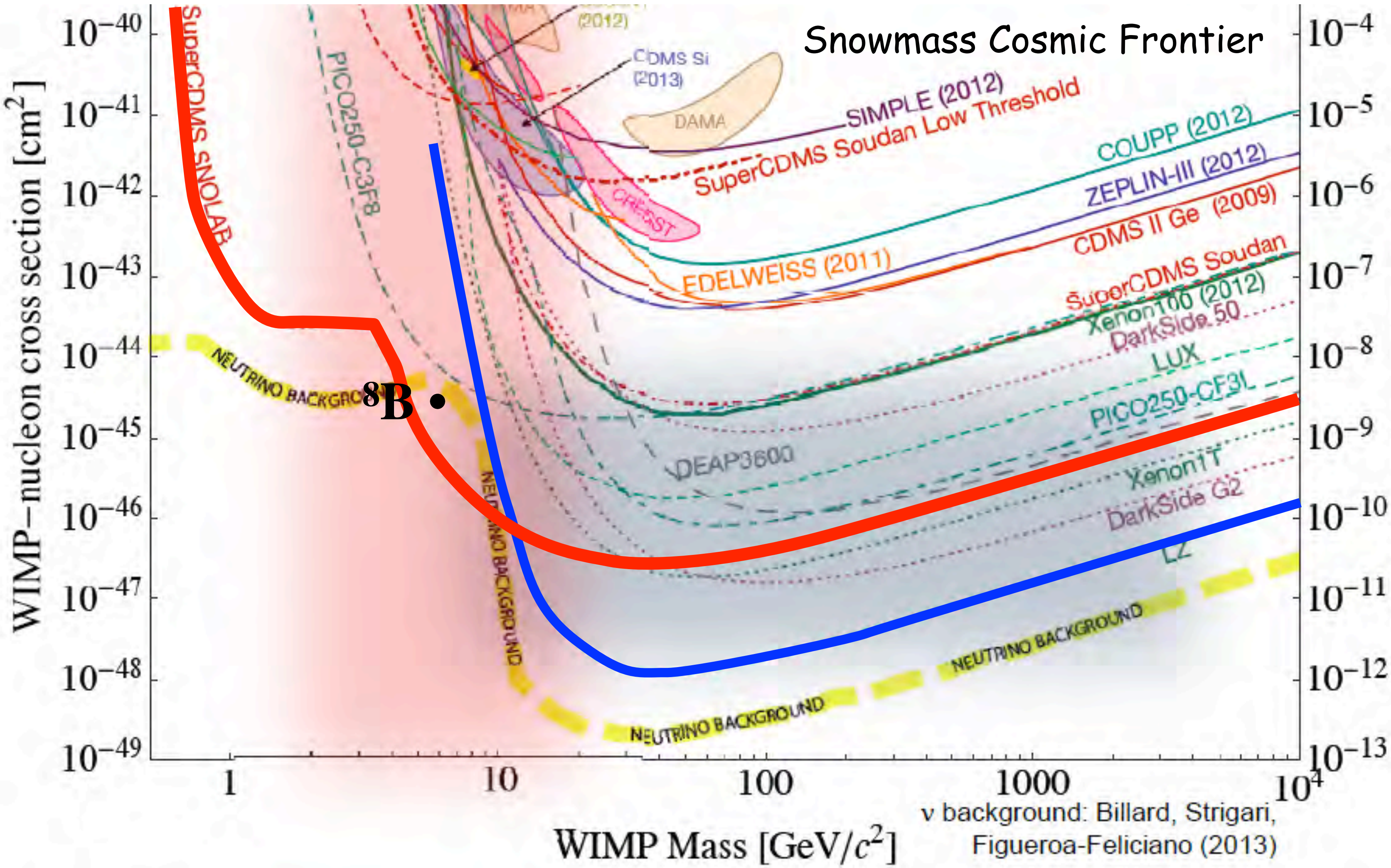
Phenomenology may be more complex than for the "vanilla" WIMP scenarios.
Difficulty to get unambiguous results

Significantly more than 2 detectors worldwide

Several technologies with complementary capabilities
- Different susceptibility to background.
- Enough sensitivity overlap to have at least a second experiment able to cross-check any claim.

Generation 2

Combination of liquid Xe/Ar + low temperature detectors can approach fundamental neutrino limit +^{8}B detection



Conclusions

Axions: we can reach the cosmological limit (at low mass)

WIMPs: ≥Two paradigms

- Weak scale
- Dark Sector

Phenomenology (e.g., dependence on the target nucleus) may be more complex than for the “vanilla” WIMP scenarios.

Fascinating time

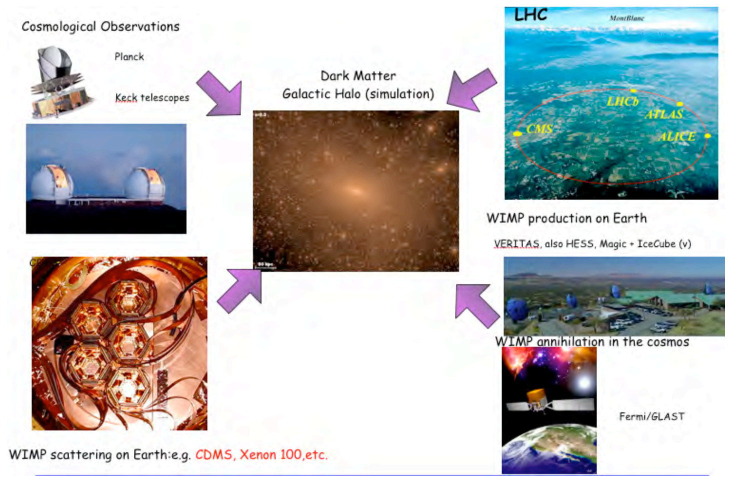
4 prong approach=>

complementary coverage

constrain theory speculations

No convincing result so far

But both paradigms still in good shape



Strategy for WIMP Direct Detection

Several technologies with complementary capabilities

2 frontiers:

- high WIMP mass natural region of noble liquids (background control)
- low WIMP mass: S/N of low temperature (target mass cost)

Good chance that we can reach the neutrino background

An Exciting Time

Credit: Joerg Jaeckel