Dark Matter Experiment

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and Consequences in Accelerators and Cosmology
University of Sussex
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Outline

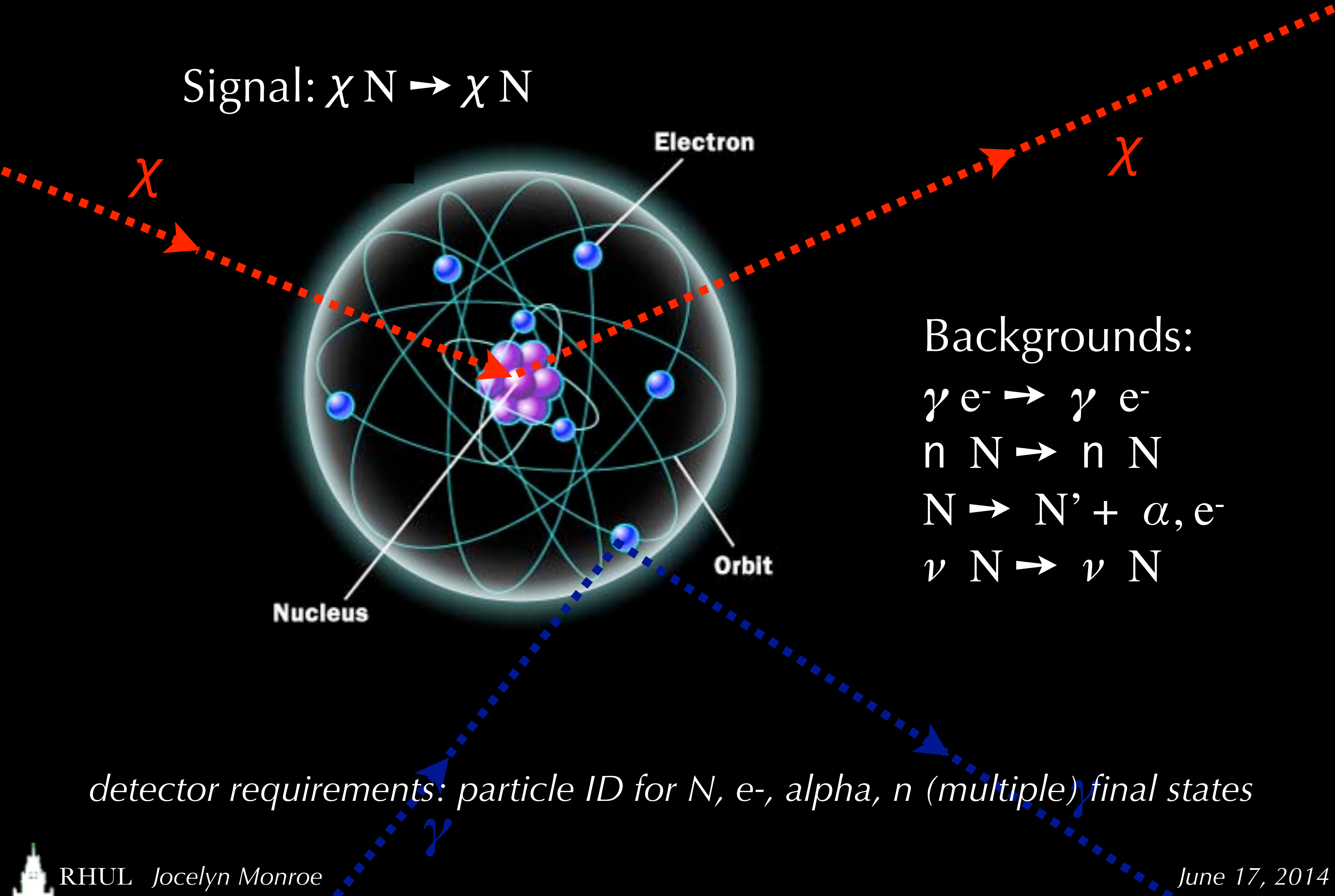
Experimental Considerations

Status and Prospects of Direct Detection Searches

Future Directions

Dark Matter Direct Detection

Signal: χ N → χ N



Backgrounds:

$\gamma\ e^- \rightarrow \gamma\ e^-$

n N → n N

N → N' + α, e^-

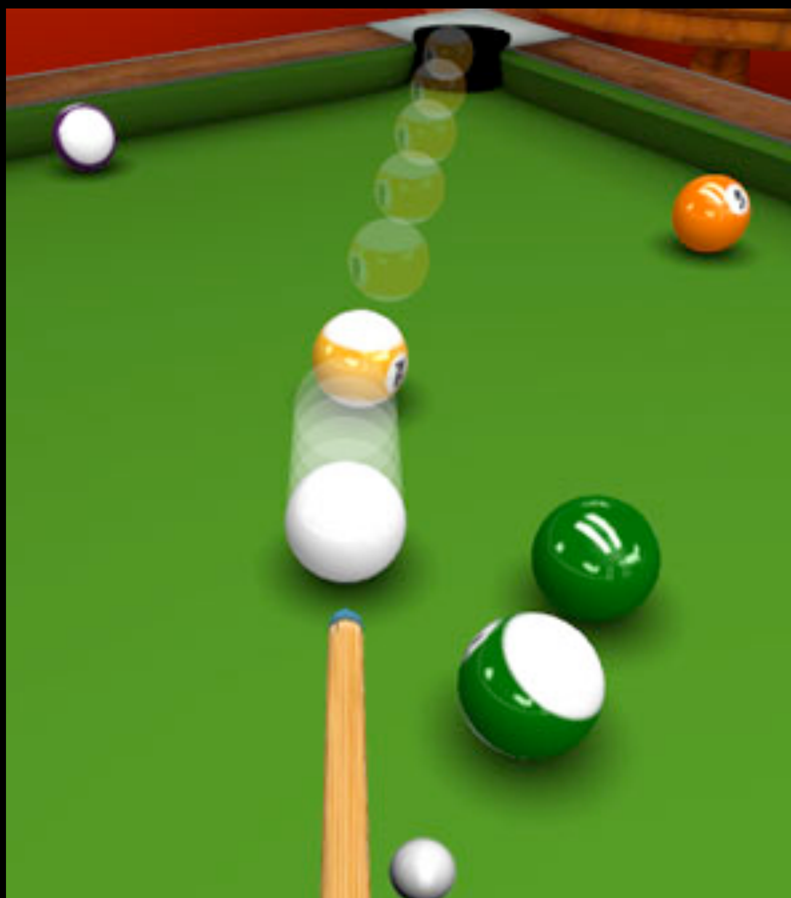
ν N → ν N

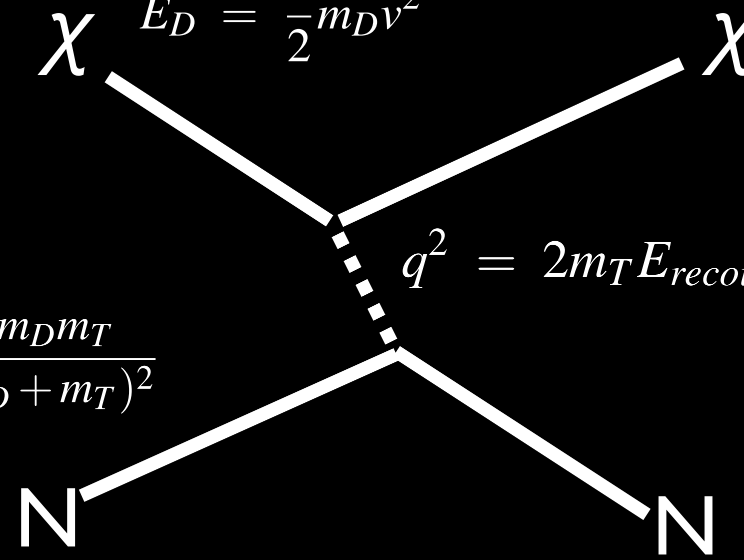
detector requirements: particle ID for N, e-, alpha, n (multiple) final states

WIMP Scattering

kinematics: *v/c ~ 8E-4!*

recoil angle strongly correlated with incoming WIMP direction





$$E_D = \frac{1}{2} m_D v^2$$

$$q^2 = 2 m_T E_{recoil}$$

$$r = \frac{4 m_D m_T}{(m_D + m_T)^2}$$

$$E_{recoil} = E_D r \frac{(1 - cos\theta)}{2}$$

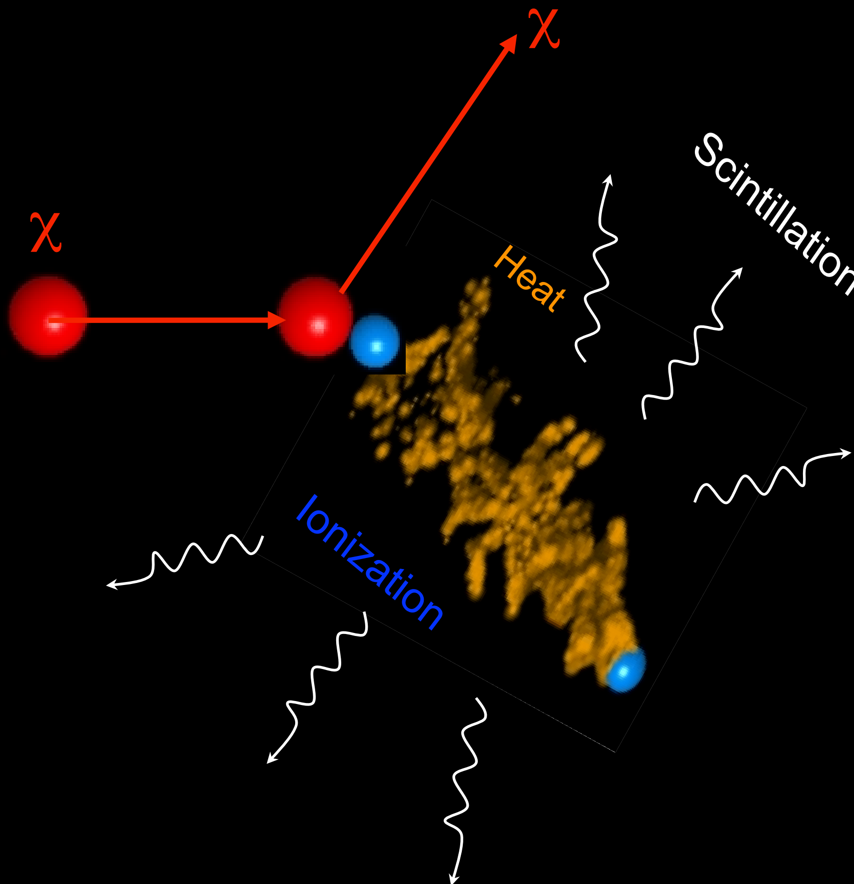
<u>Spin Independent:</u>
χ scatters coherently off of the entire nucleus A: $\sigma \sim A^2$

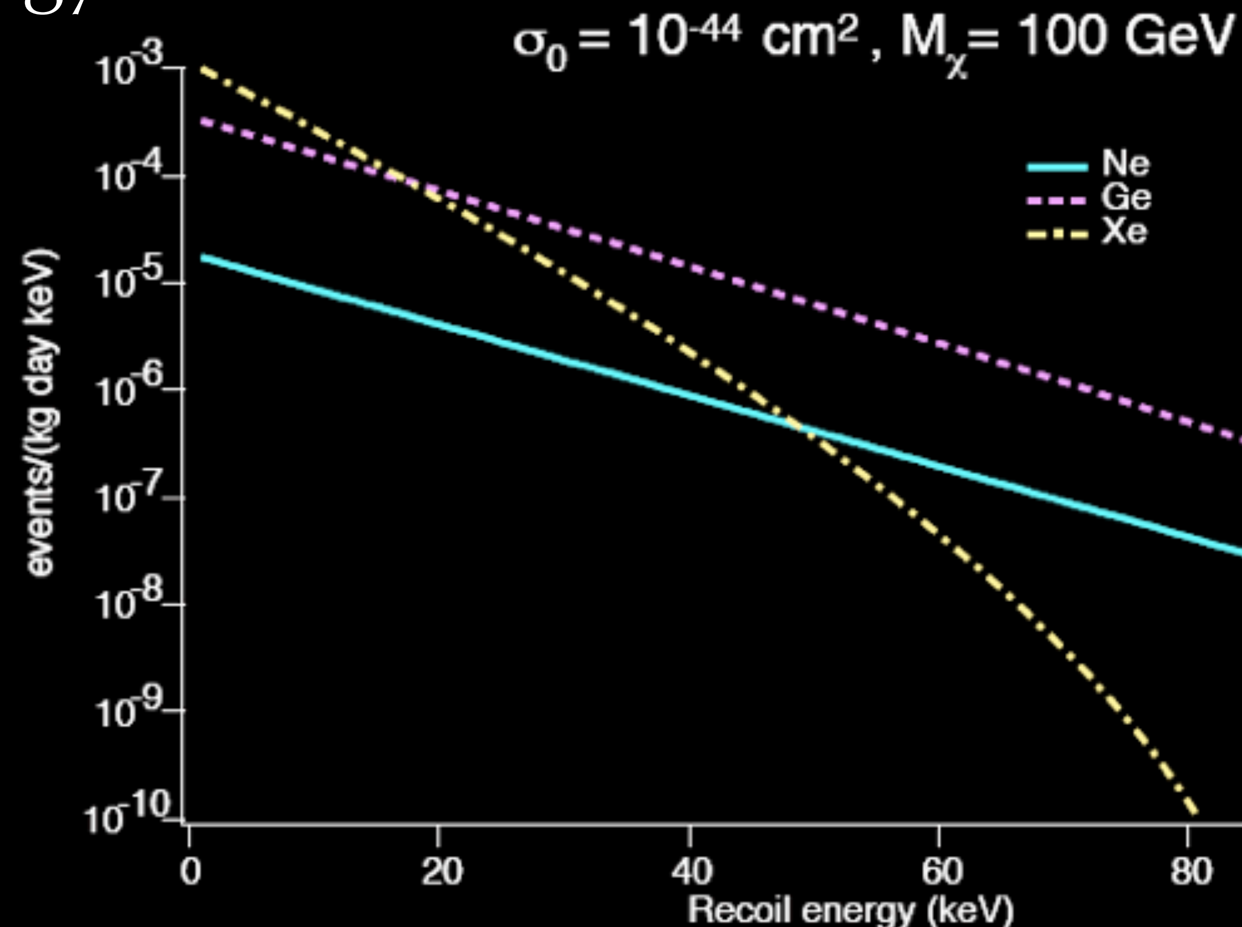
D. Z. Freedman, PRD 9, 1389 (1974)

<u>Spin Dependent:</u>
mainly unpaired nucleons contribute to scattering amplitude: $\sigma \sim J(J+1)$

detector requirements: measure recoil energy, and ideally angle as well

Observable: Recoil Energy





Scattering rate

Sun's velocity around the galaxy

WIMP velocity distribution

$$dR/dQ \sim (\sigma_0 \rho_0 / \sqrt{\pi}\, v_0 m_\chi m_r^2)\, F^2(Q)\, T(Q)$$

WIMP energy density, 0.3 GeV/cm^3

Form factor

detector requirements: ~1-10s of keV energy threshold, very low backgrounds

Detection Medium

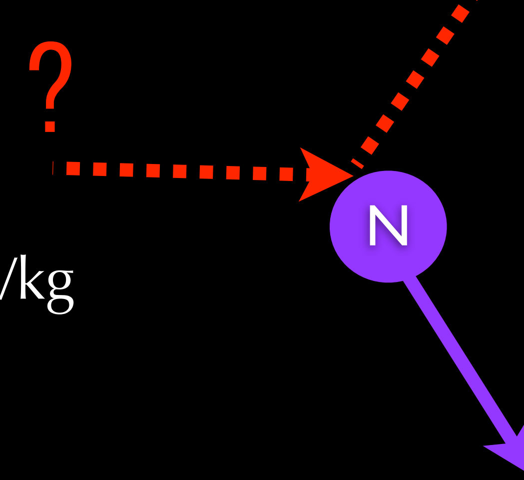
PICO
Xenon100
IGEX
COUPP
Picasso
Newage
DRIFT
ArDM
ZeplinIII
DarcSide
CDMS
Edelweiss
LUX
CoGeNT
DMTPC

ANaIS
XMASS
DEAP/CLEAN
CRESST
KIMS
CRESSTII
Dama/LIBRA
ROSEBUD

existing detectors: many targets (Xe, Ge, Ar, NaI, CsI, CaWO, ...)

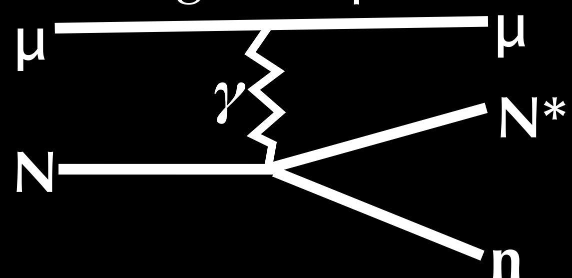
Around the World

Backgrounds

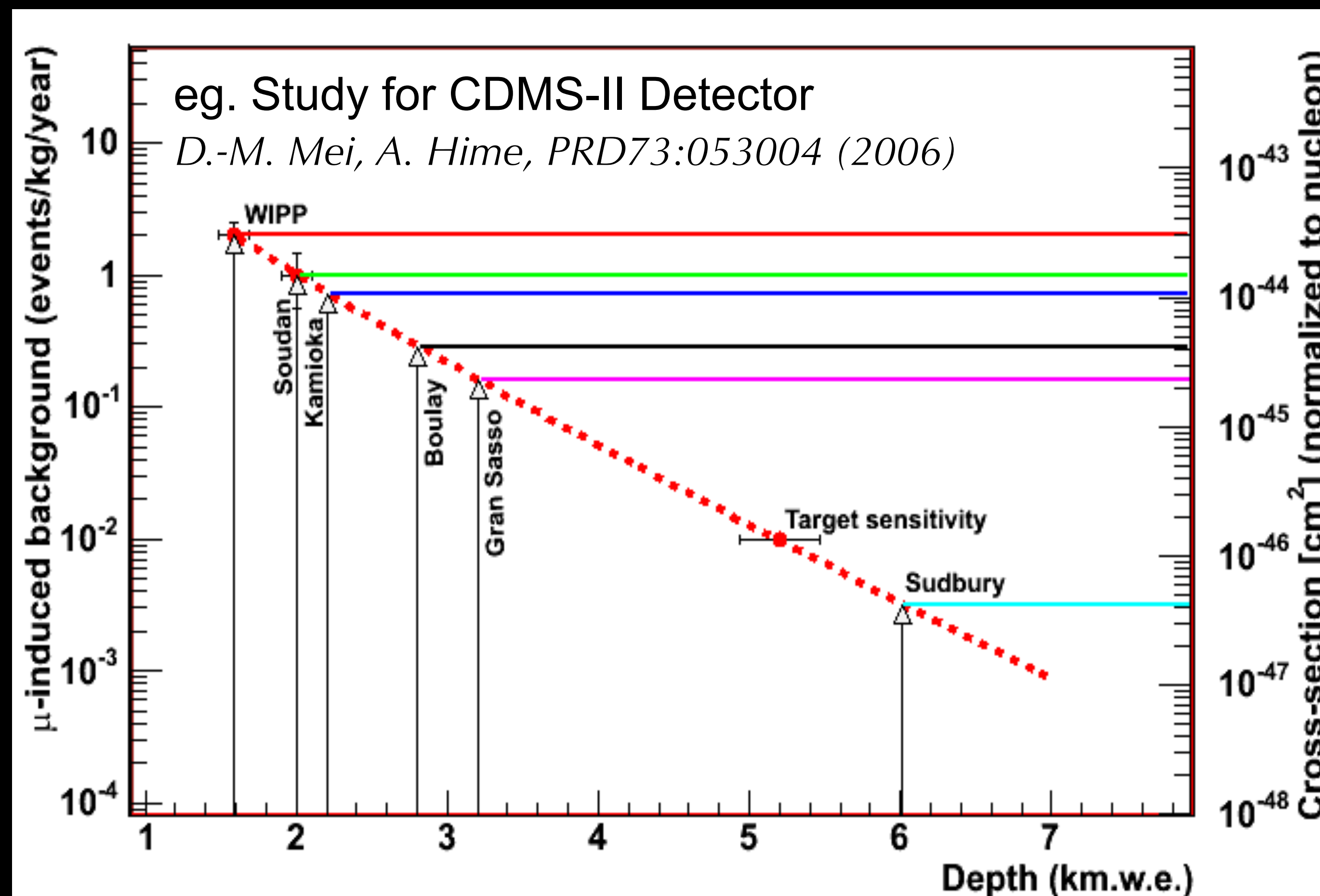


Gamma ray interactions:
rate ~ N_e x (gamma flux), typically 10 million events/day/kg
mis-identified electrons mimic nuclear recoil signals

Neutrons:
(alpha,n), U, Th fission,
cosmogenic spallation



nuclear recoil final state

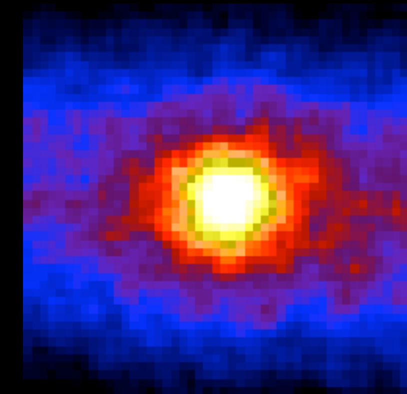


Contamination:
^{238}U and ^{232}Th decays,
recoiling progeny and
mis-identified alphas
mimic nuclear recoils

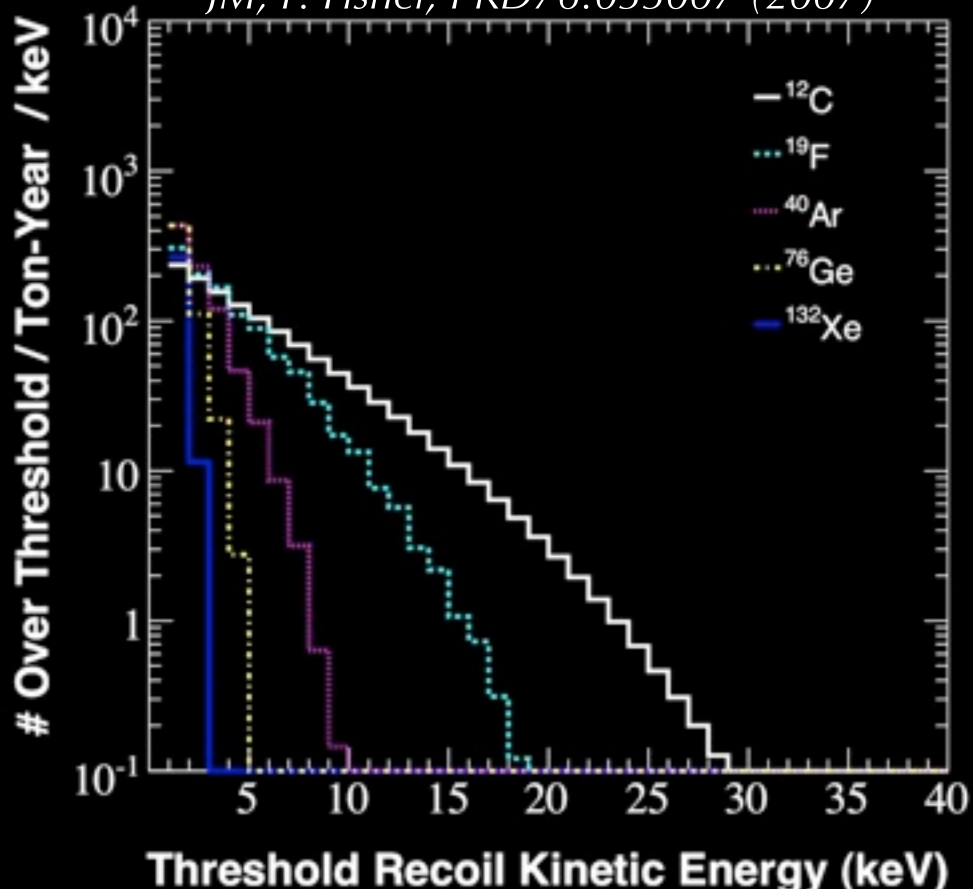
Irreducible Backgrounds

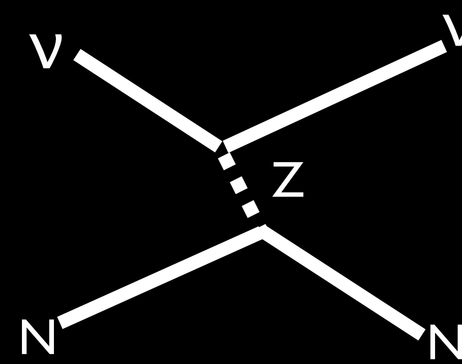
impossible to shield a detector from coherent neutrino scattering!

$\Phi_{(\text{solar } B^8)} = 5.86 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$



JM, P. Fisher, PRD76:033007 (2007)





nuclear recoil final state
1 event/ton-year = 10^{-46}-10^{-48} cm^2 limit
with current recoil energy thresholds
in zero-background paradigm

unless you measure the direction!

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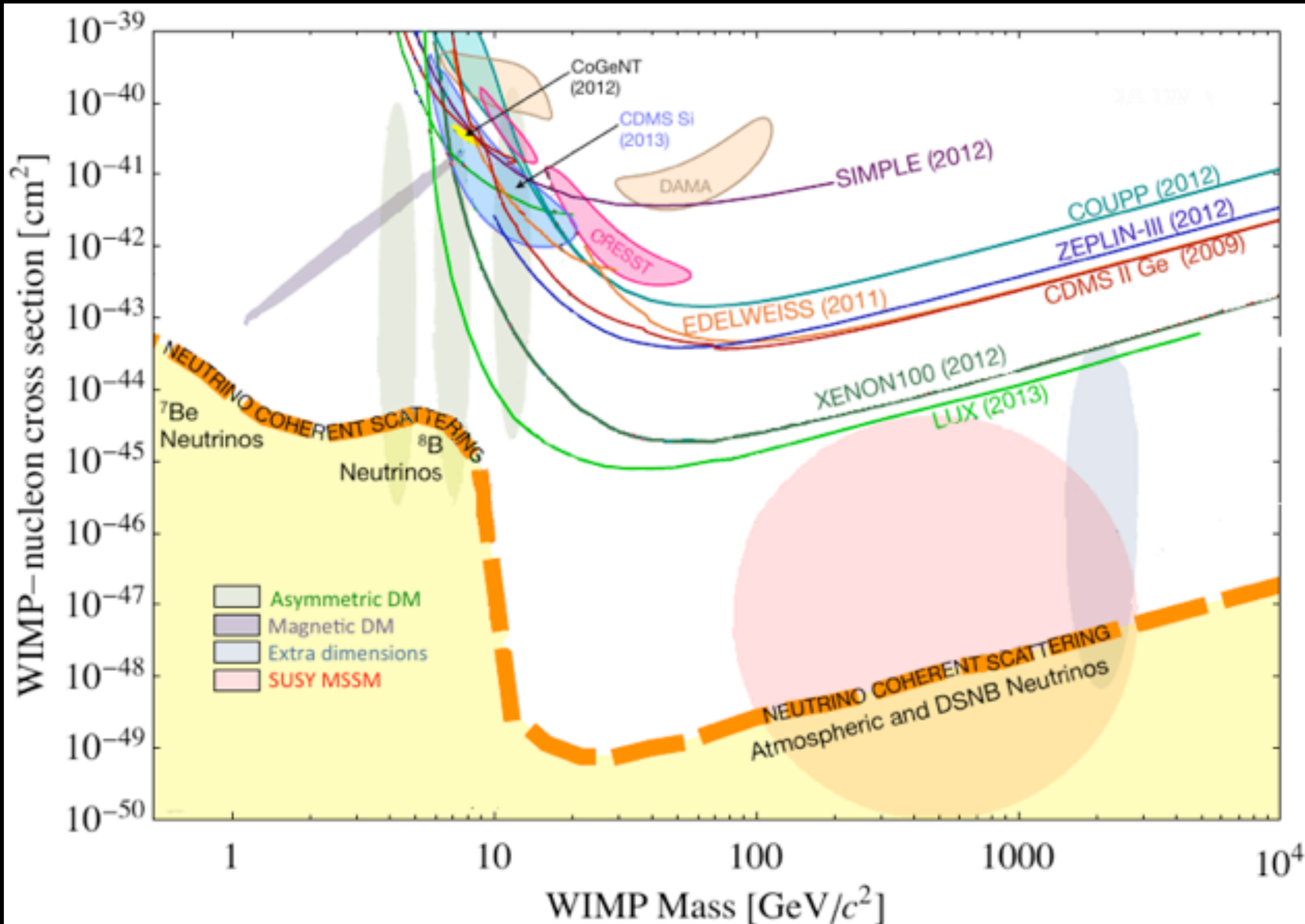
The Low-Background Frontier: Status of SI Searches



← 1 event/ kg/day

← 1 event/ 100kg/day

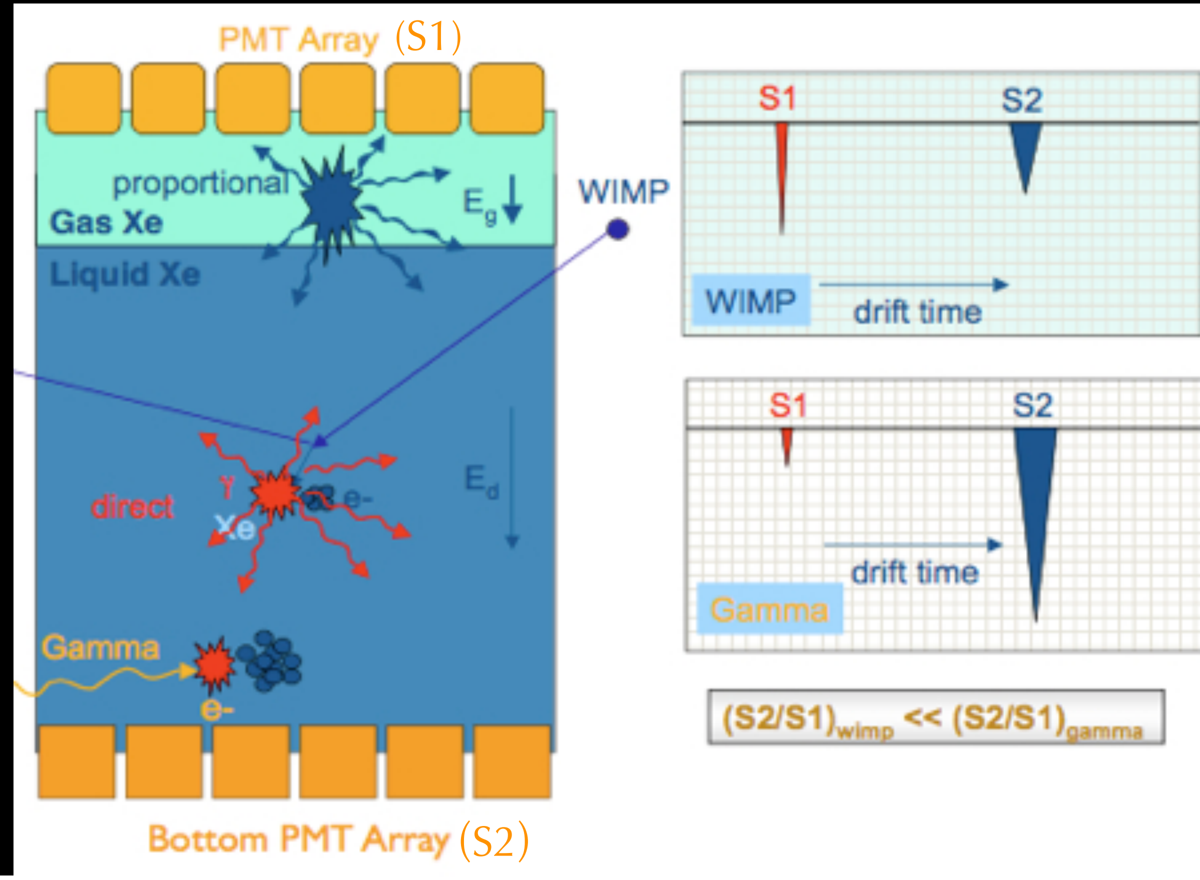
← 1 event/ 100 kg/ 100 days

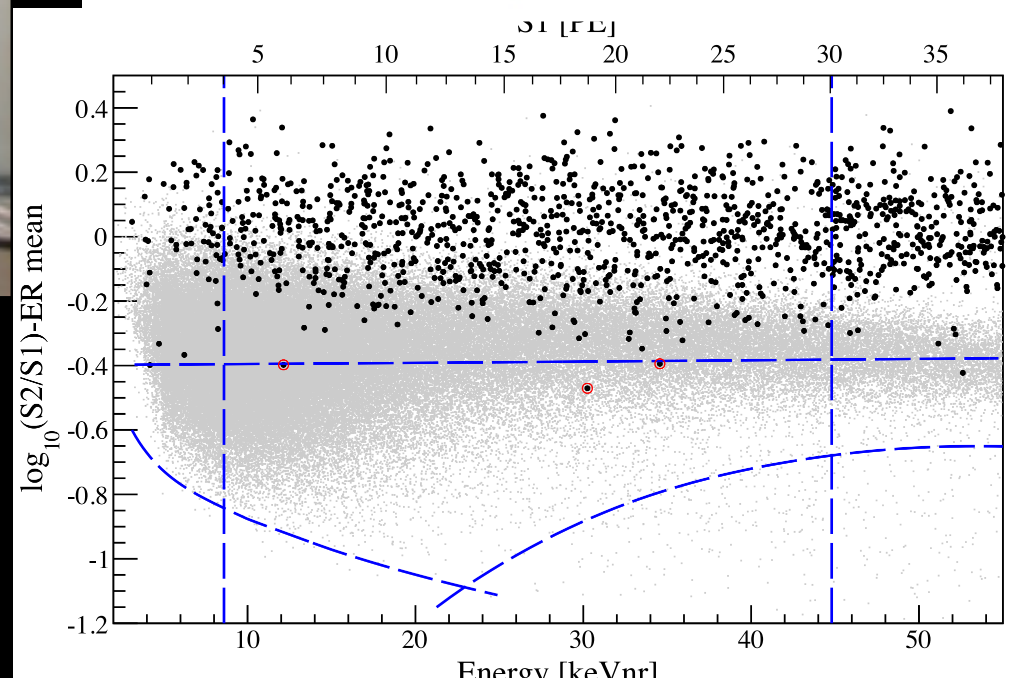
so far: ~3 years / order of magnitude

Two-Phase LXe TPCs

Xenon 10, 100, 1T, nT (LNGS)

LUX (SURF)





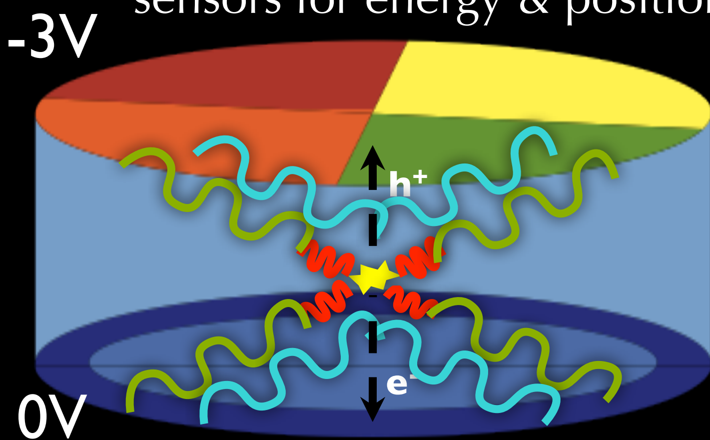
E. Aprile et al., PRL 107 (2011) 131302

"S2": primary scintillation
"S1": amplified, drifted ionization signal
both read out with PMTs

Bolometers: EDELWEISS (LSM) and CDMS (Soudan)

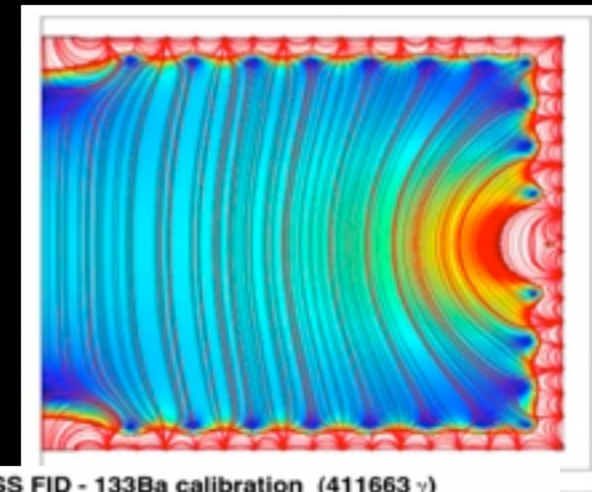
Transition Edge Sensors, operated at ~40 mK on Ge and Si crystals

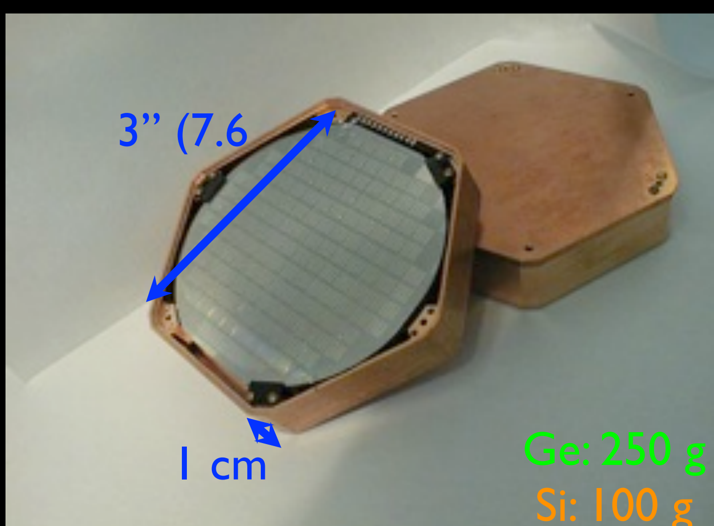
Phonon side: 4 quadrants of phonon sensors for energy & position (timing)

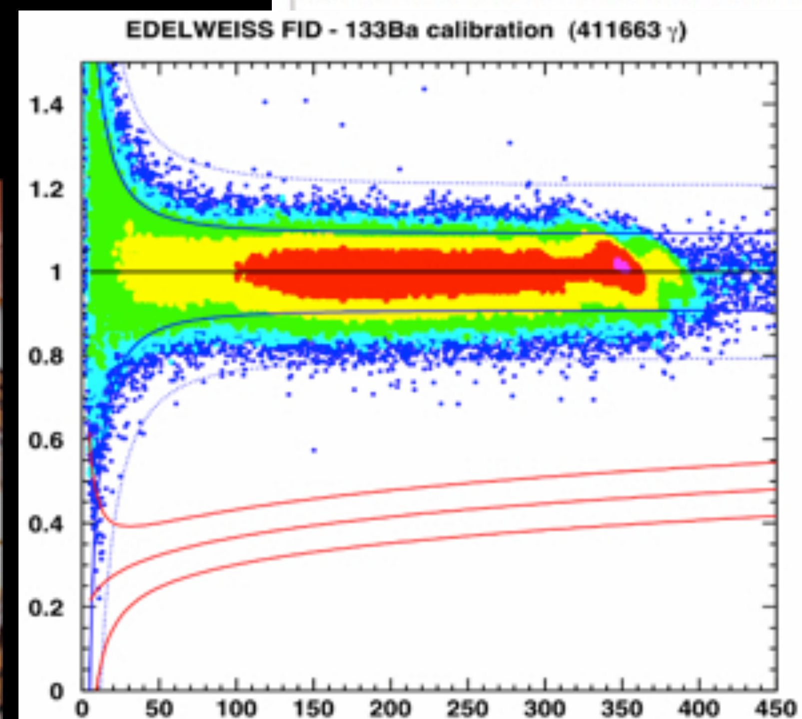


Charge side: 2 concentric electrodes (inner & outer) energy (& veto)

CDMS re-design a la EDELWEISS to reduce surface backgrounds x10^4

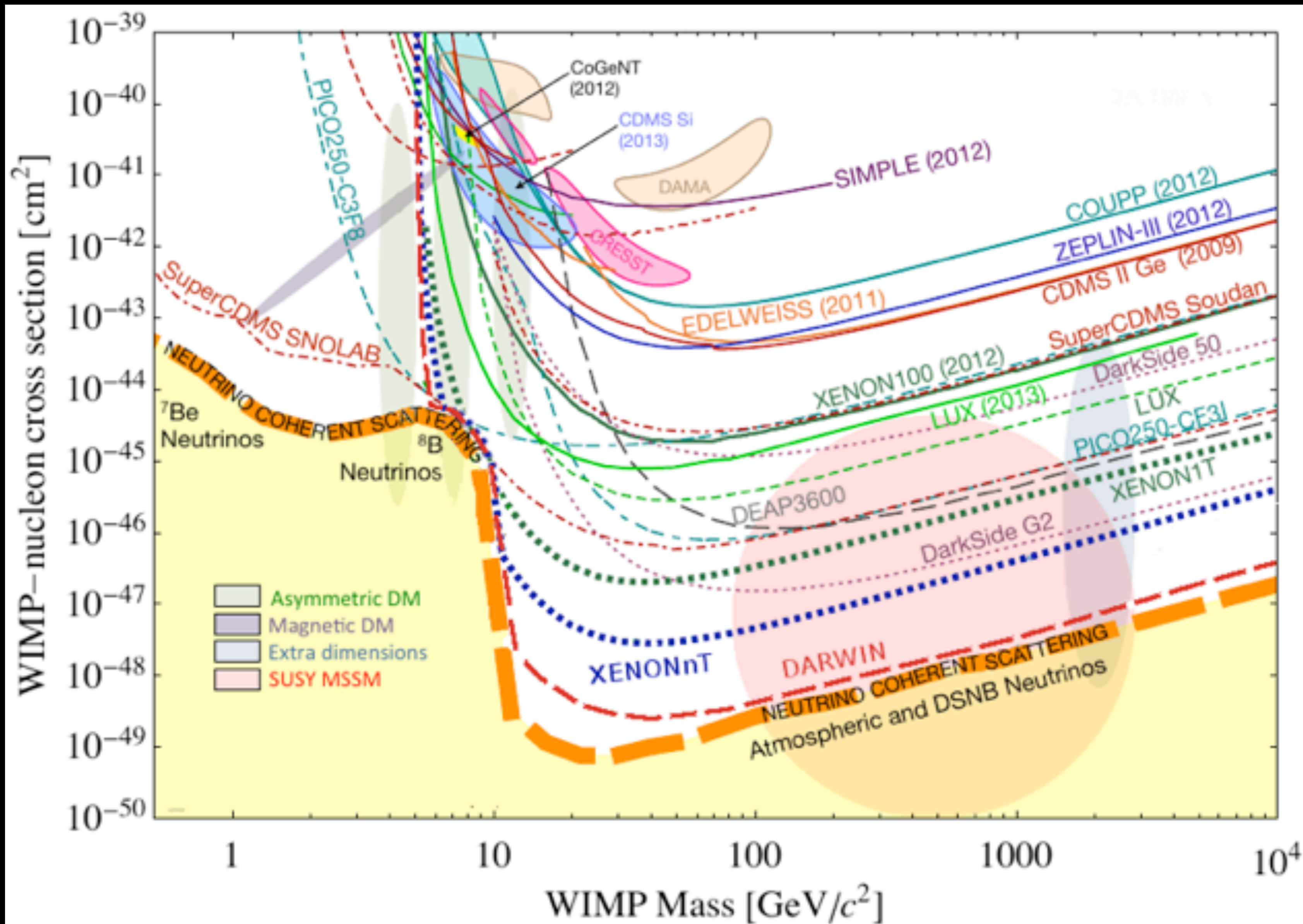






Ionization/Phonon yield vs. E_{recoil} (keV)

The Low-Background Frontier: Prospects



← 1 event/ kg/day

← 1 event/ 100kg/day

← 1 event/ 100 kg/ 100 days

so far: ~3 years / order of magnitude

Argon Experiments

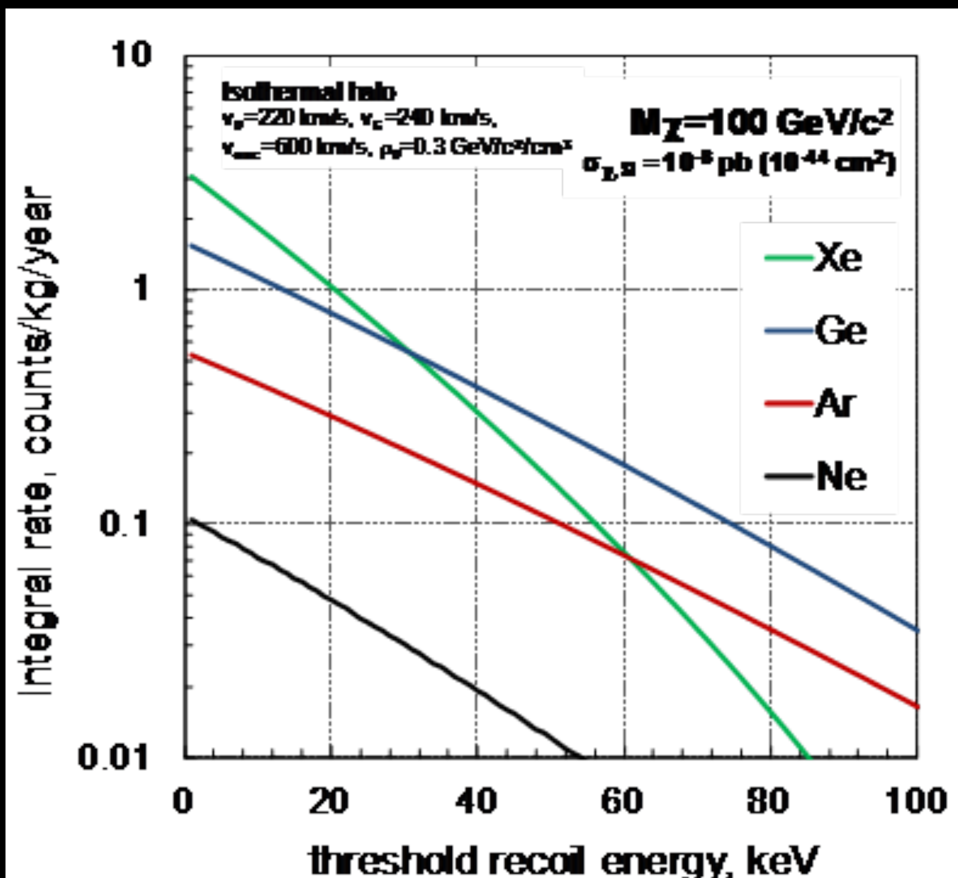
DarkSide (LNGS), DEAP (SNOLAB)

<u>advantages</u>: x250 difference between singlet and triplet lifetimes: 10^{10} electron rejection, kills solar pp nu-e- scattering background

Table 3: Scintillation parameters for liquid neon, argon, and xenon.

Parameter	Ne	Ar	Xe
Yield ($\times 10^4$ photons/MeV)	1.5	4.0	4.2
prompt time constant τ_1 (ns)	2.2	6	2.2
late time constant τ_3	15 μs	1.59 μs	21 ns
I_1/I_3 for electrons	0.12	0.3	0.3
I_1/I_3 for nuclear recoils	0.56	3	1.6
λ(peak) (nm)	77	128	174
Rayleigh scattering length (cm)	60	90	30

favorable form-factor: higher energy threshold ok, enhanced sensitivity to heavy DM



<u>practicalities</u>:
relatively low cost O(1$/kg),
very large detectors possible

excellent light yield / $$

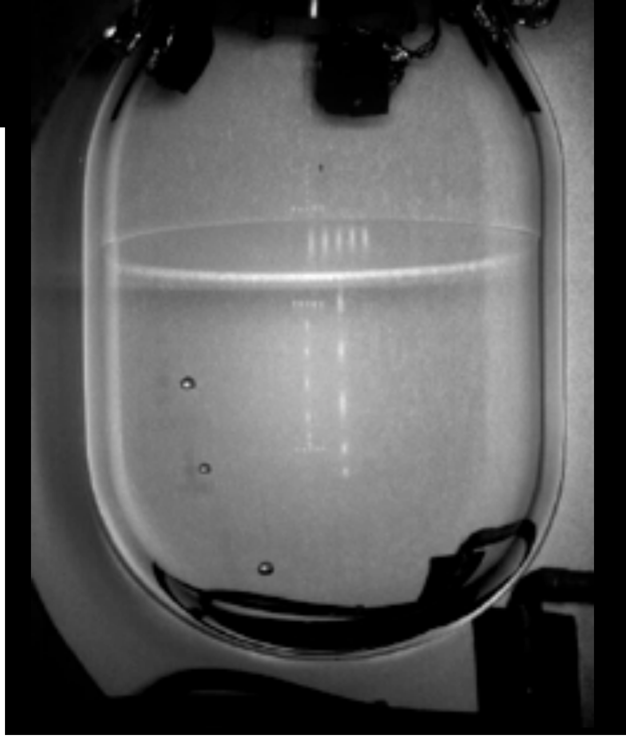
straightforward to purify

<u>drawbacks</u>:
smaller interaction cross section (A^2)

Ar-39, trade-off between background rejection and threshold

low-background Ar sources reduce Ar-39 by a factor of >50 *Xu et al, arXiv:1204.6011*

Bubble Chambers



COUPP-60

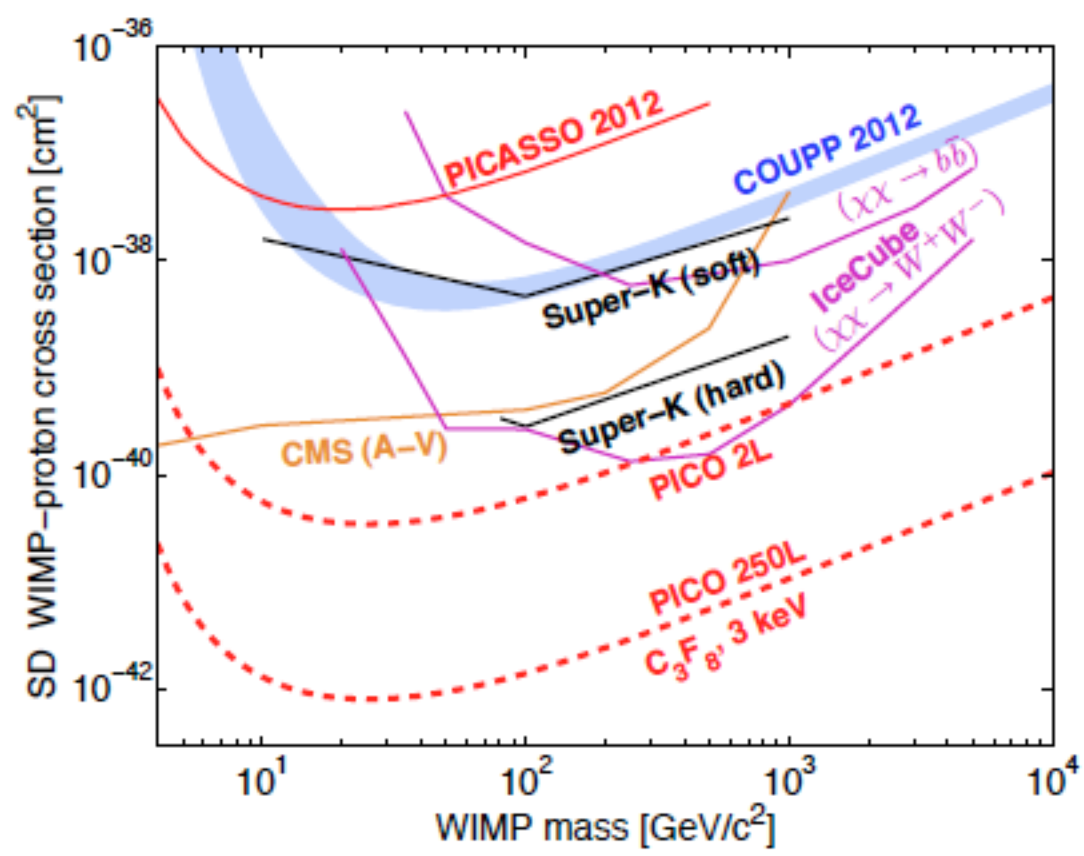
- Filled with 37 kg of CF_3I on April 26, 2013
- First bubble May 1, 2013 (radon decay)
- Installation completed May 31, 2013
- Started first physics run in late June
- Increase target mass to 75 kg in fall/winter
- Ultimate goal of 3 year run (50000 kg-days exposure)

PICO-lite

- Joint effort between COUPP & PICASSO
- C_3F_8 chamber (2L) in existing COUPP-4 infrastructure at SNOLAB
- 3 keV threshold
- Excellent low-mass WIMP and SD coupling sensitivity
- CDMS-Si result gives 1 event/day in COUPP-4lite
- Deploy September 2013

PICO-250

- 250L bubble chamber design effort
- Well developed Conceptual Design
- Straightforward scale-up from COUPP-4 and COUPP-60
- Begin construction in 2014-2015



Superheated CF_3I bubble chambers, in SNOLAB.

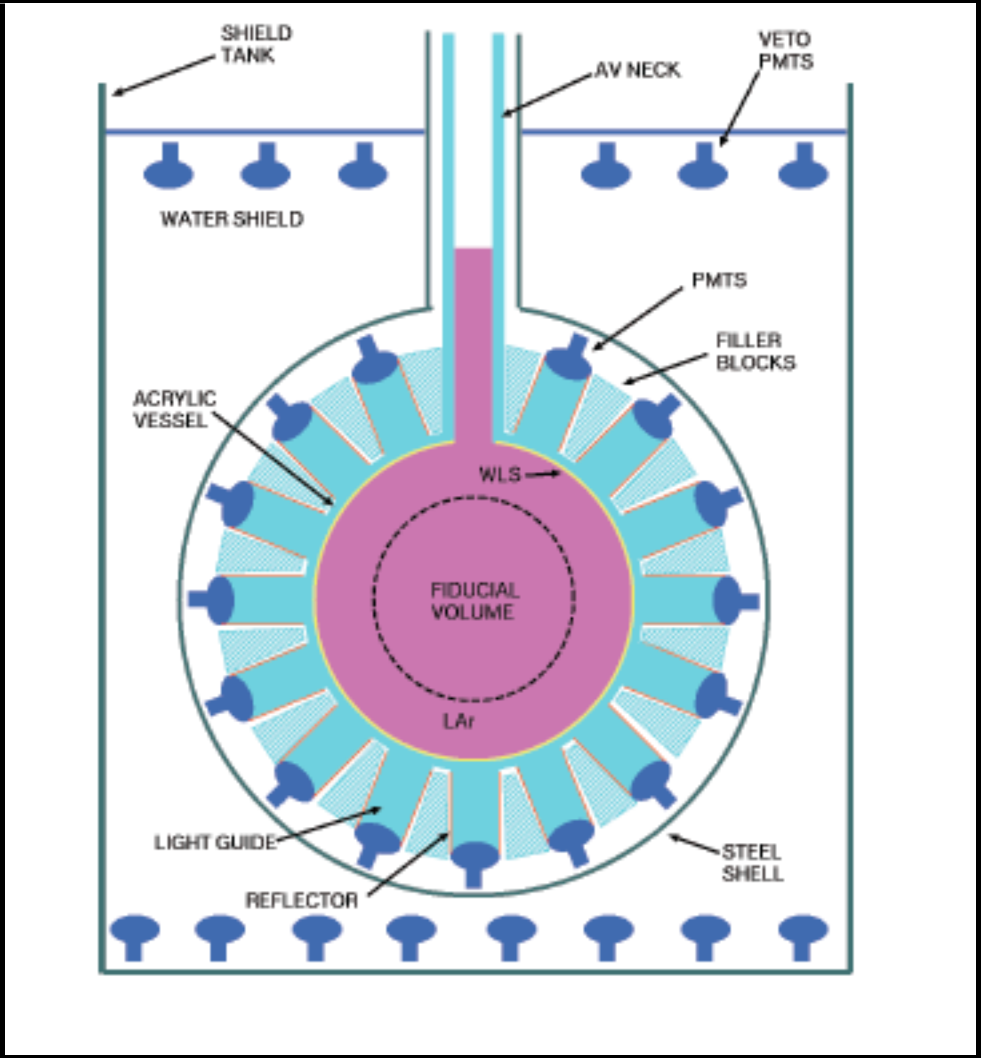
-readout with cameras and piezos

-threshold detectors: measure integral counts for particles with dE/dx > threshold to nucleate bubble

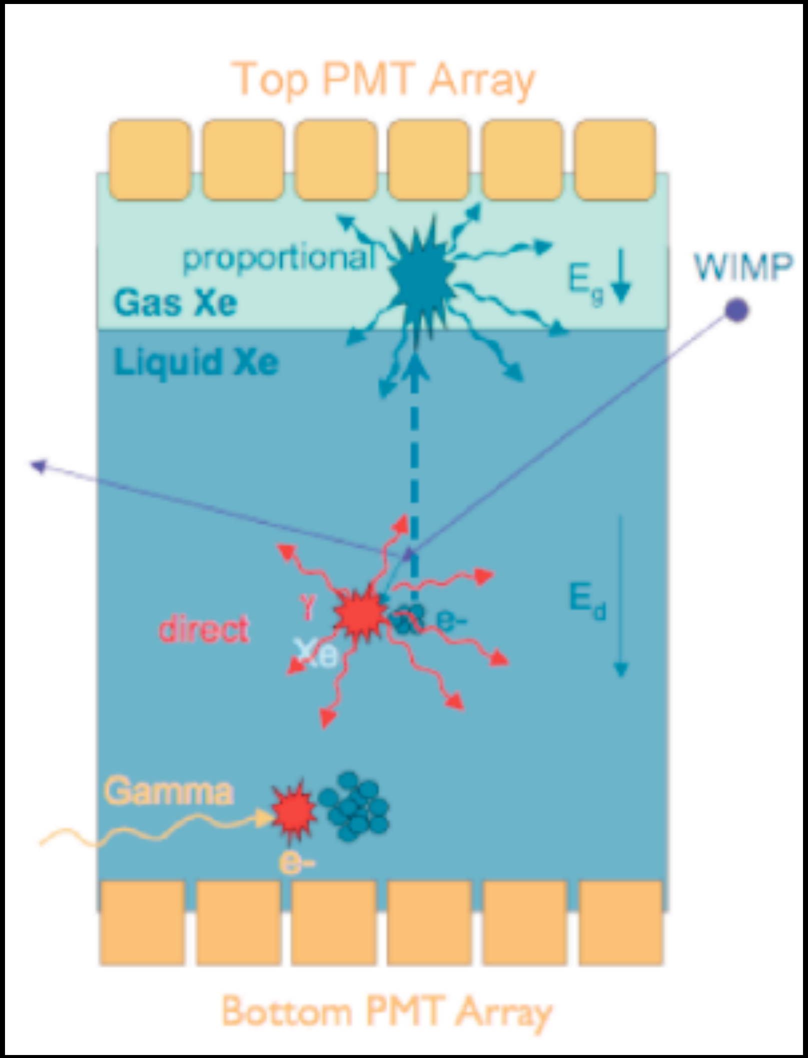
-gammas below threshold to nucleate

Single Phase a la Neutrinos

high light yield *and self-shielding* of target



background discrimination from prompt scintillation timing...



no electric fields = straightforward scalability
1) no pile-up from ms-scale electron drift in E
2) no recombination in E (high photons/keVee)
but no charge background discrimination either!

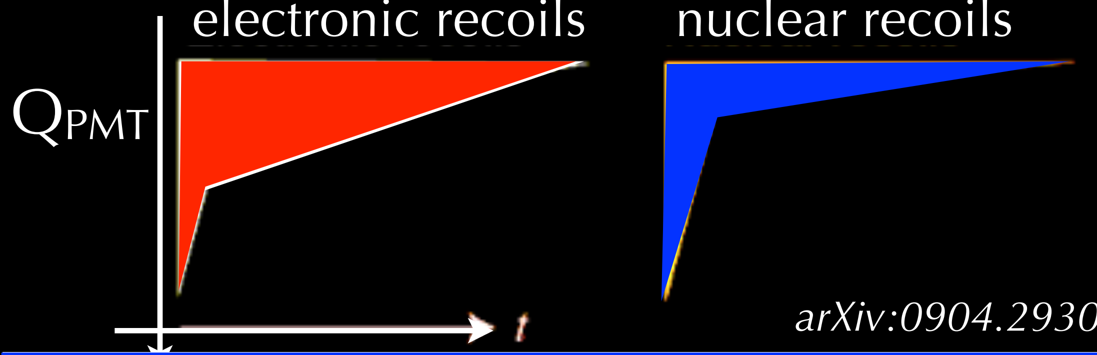
cf. Two Phase Detector: *and* charge (proportional scintillation)

DEAP3600

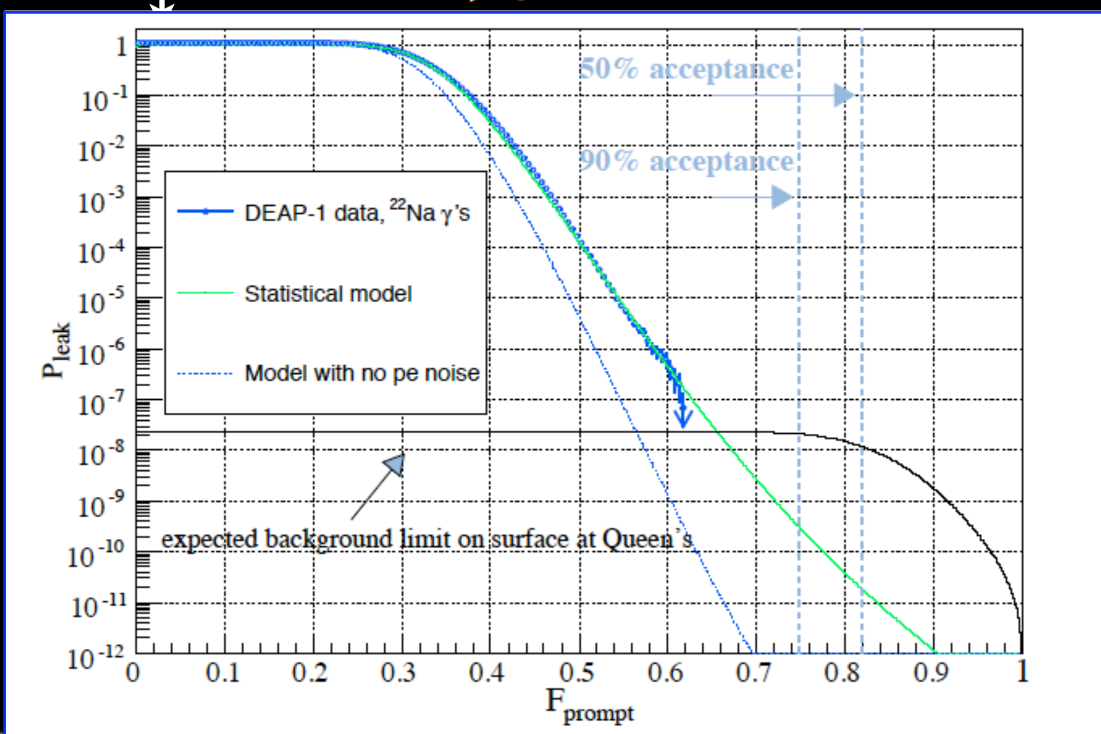
single-phase LAr detector at SNOLAB, prototype for kT-scale detector...

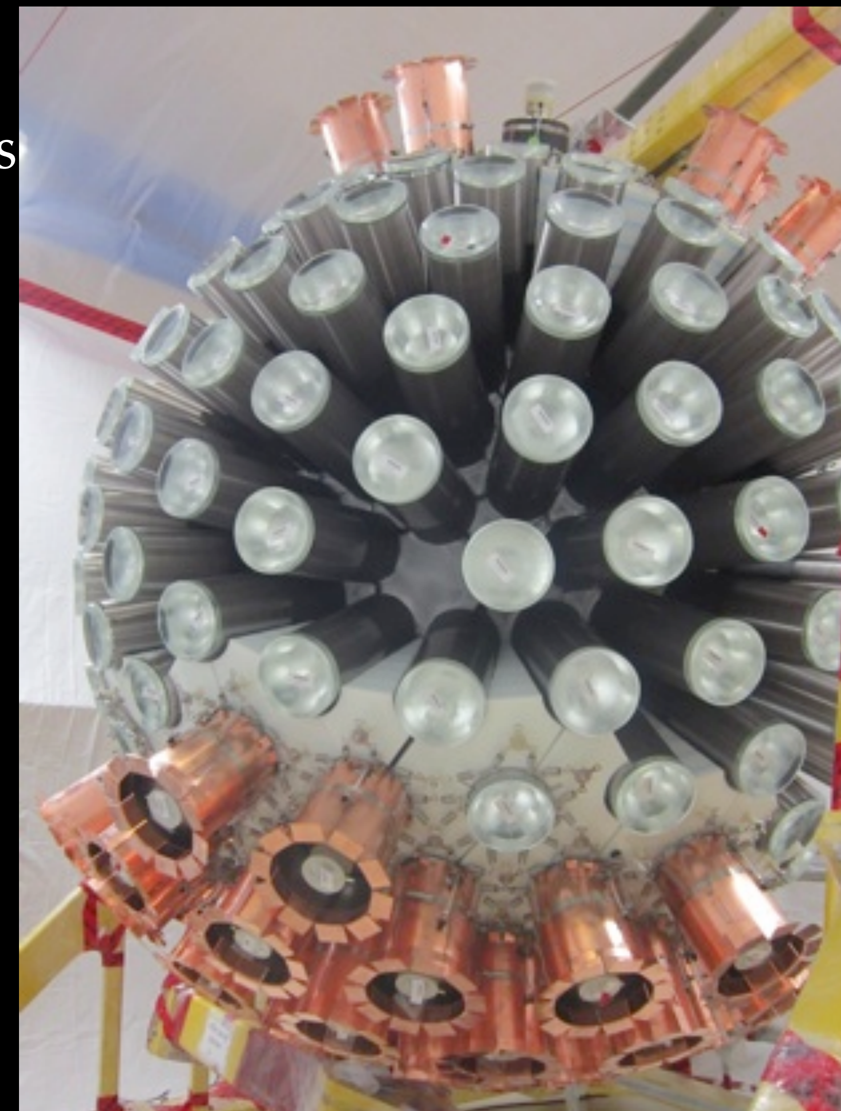
3.6 tonnes of which 1 tonne fiducialized by event position reconstruction *arXiv:1211.0909*

Ar-39 background rejection at 1:1E10 from scintillation time constants: 6±1 ns, 1600±100 ns



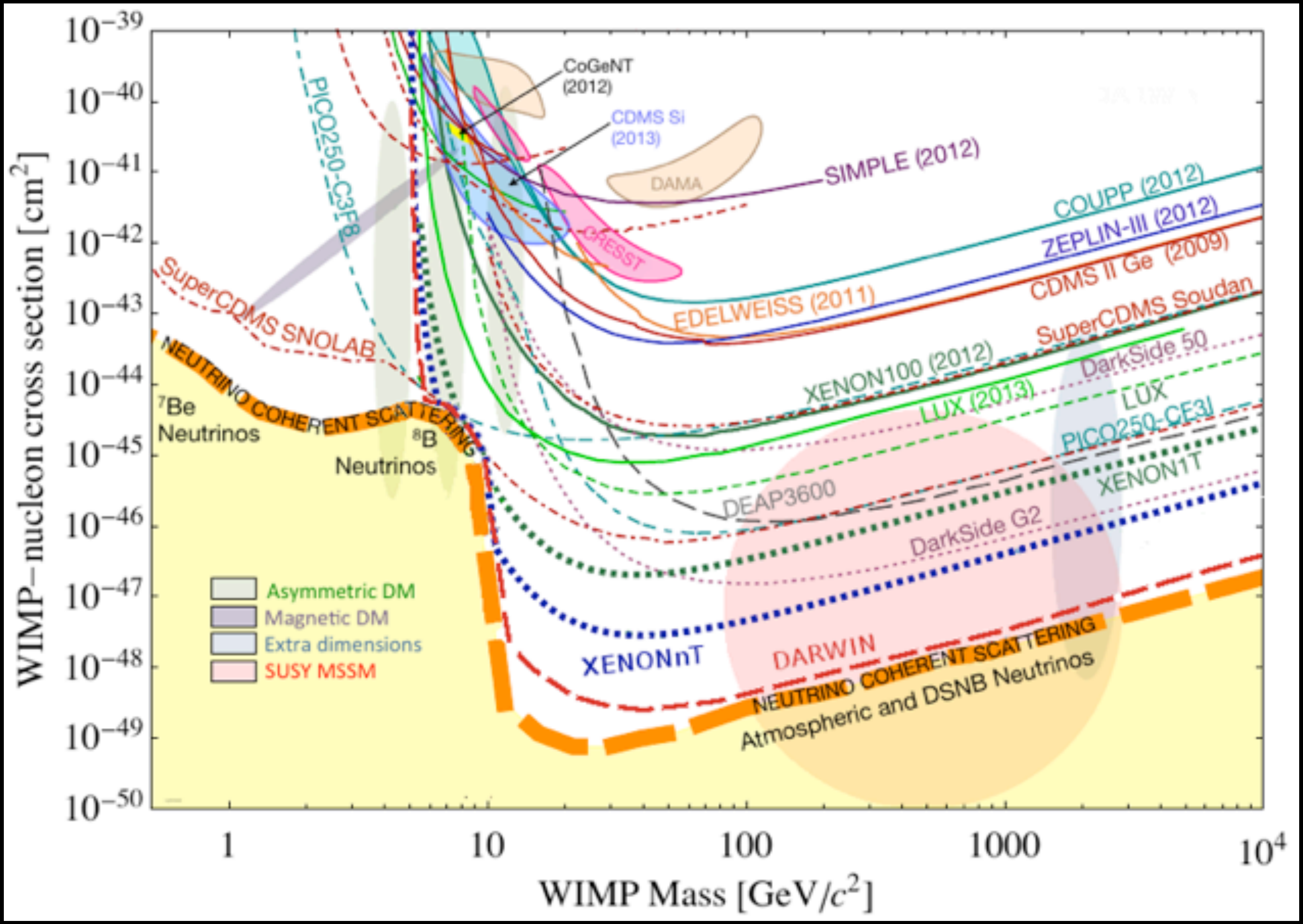
arXiv:0904.2930





commissioning starts Summer 2014

The Low-Background Frontier: Signals



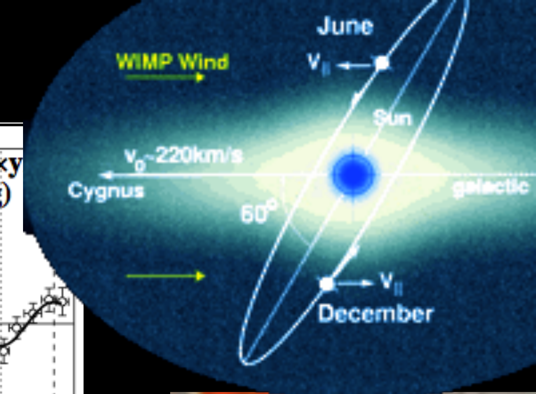
← 1 event/ kg/day

← 1 event/ 100kg/day

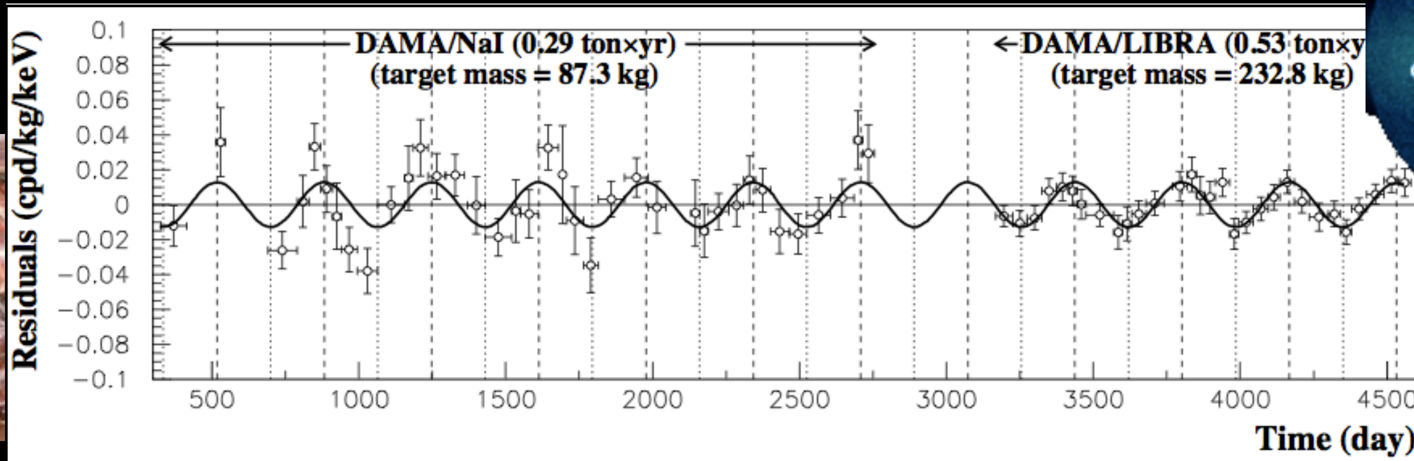
← 1 event/ 100 kg/ 100 days

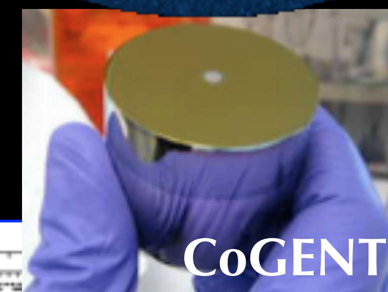
How do we know when we have discovered dark matter?

Experiments with Candidate Signals

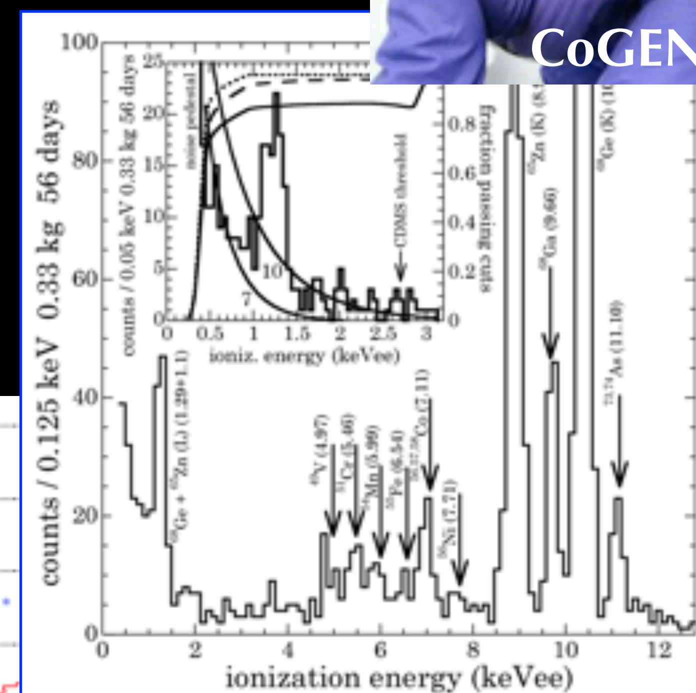


DAMA/ Libra

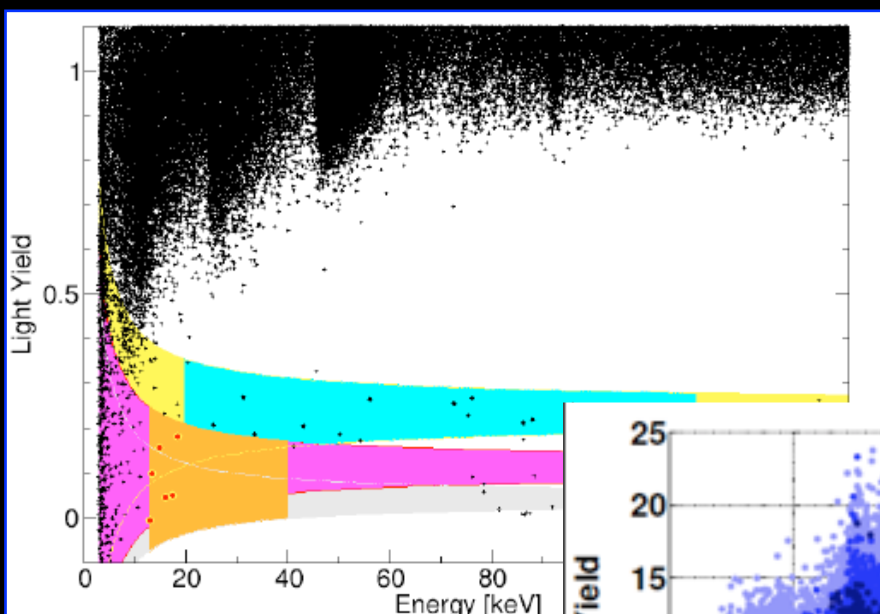




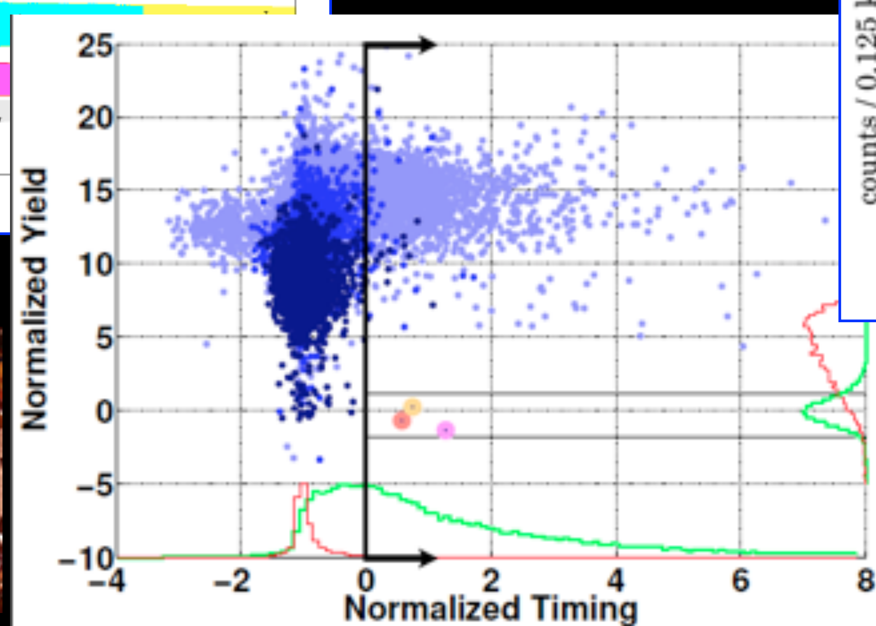
CoGENT



CRESST-II



CDMS



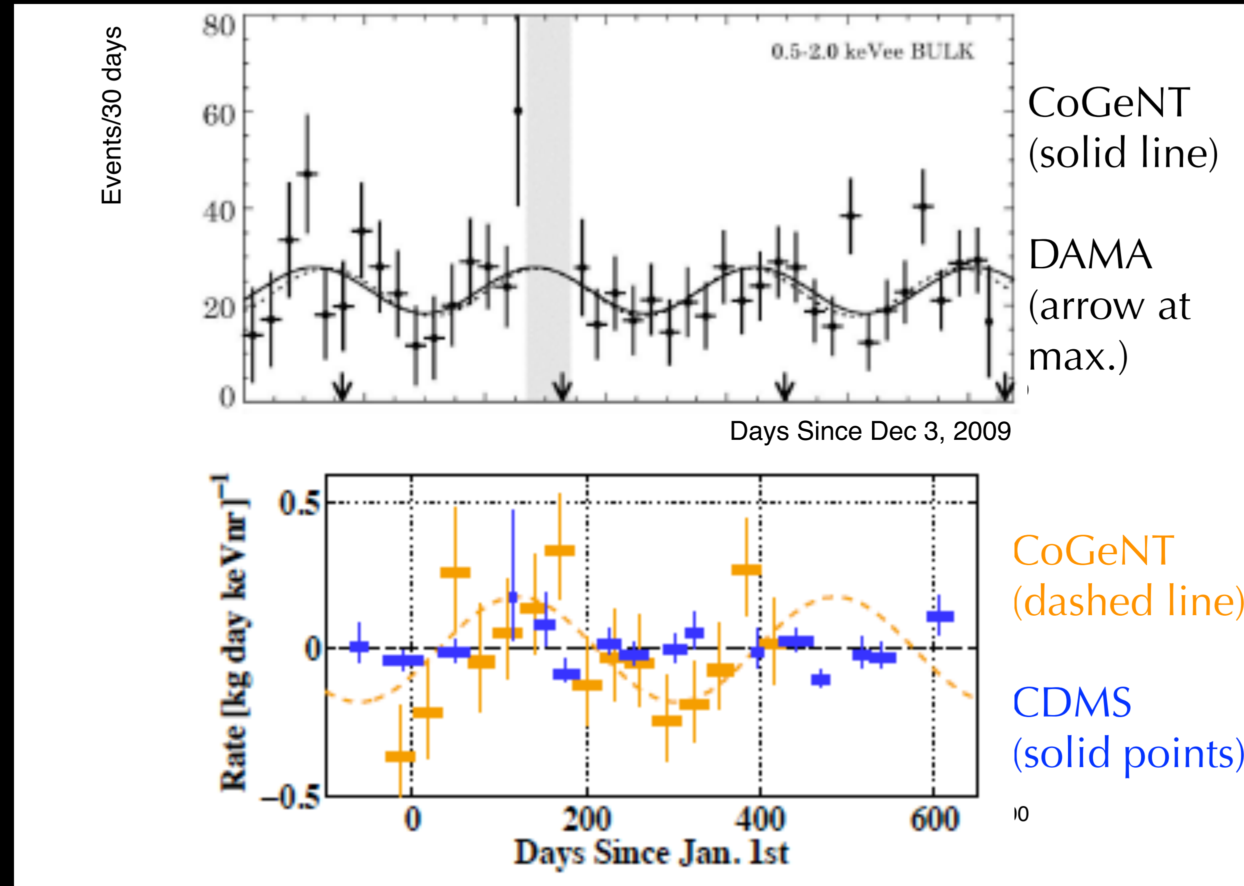
dark matter?
backgrounds?

Annual Modulation Tests

Ge: *COGENT(~consistent with DAMA/LIBRA)*
CDMS (not consistent)
MALBEK (not consistent)
arXiv:1401.3295, arXiv:1203.1309
J. Wilkerson, UCLADM'14

CsI: *KIMS (not consistent)*
J.Phys.Conf.Ser. 384 (2012) 012020

NaI: many efforts underway, all <25 kg active mass, scale up depends on crystal radiopurity



Northern Hemisphere	Gran Sasso **DAMA/Libra** 250kg running	Gran Sasso **Princeton-NaI** R&D	Canfranc **ANAIS** ~100kg starting in 2014?	**PICO-LON** **KIMS** etc...
Southern Hemisphere	South Pole **DM-Ice** 17 kg running R&D for 250 kg	**ANDES** Lab (proposed) expected start 2018		

ice **rock**

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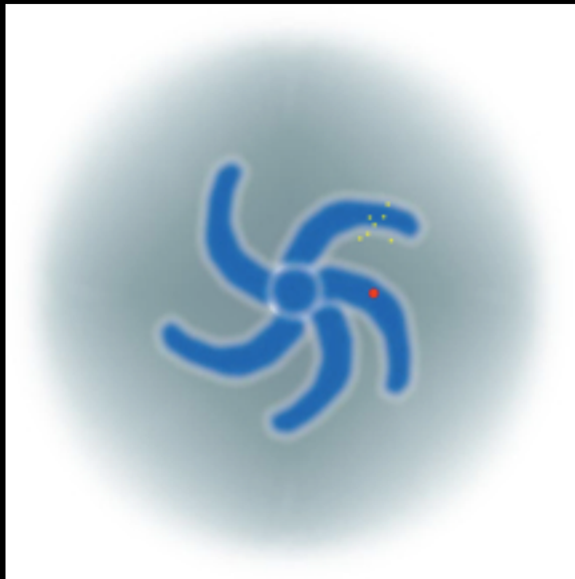
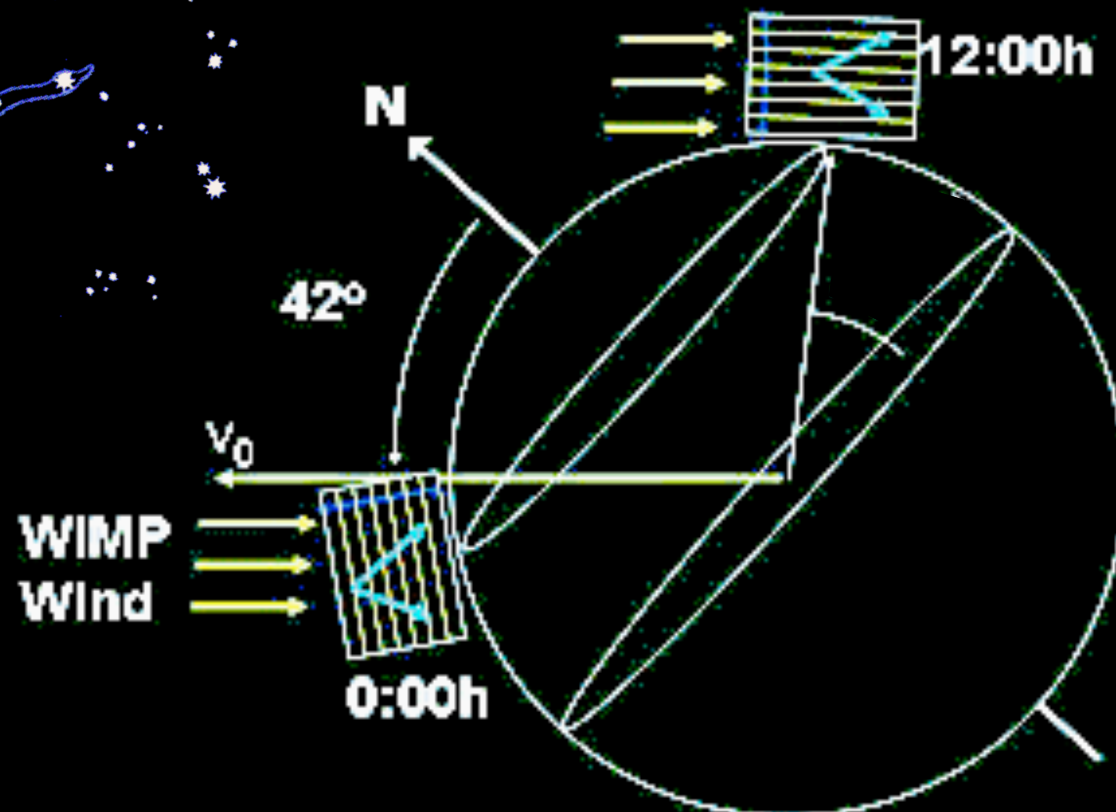


The Dark Matter Wind apparently “blows” from Cygnus

directional detection:
search for a dark matter source



Daily direction modulation:
asymmetry ~ 20-100%
in forward-backward
event rate.

Spergel, Phys. Rev. D36:1353 (1988)

definitive test of the astrophysical origin of a candidate dark matter signal

Optimization

how many events to detect the dark matter wind?

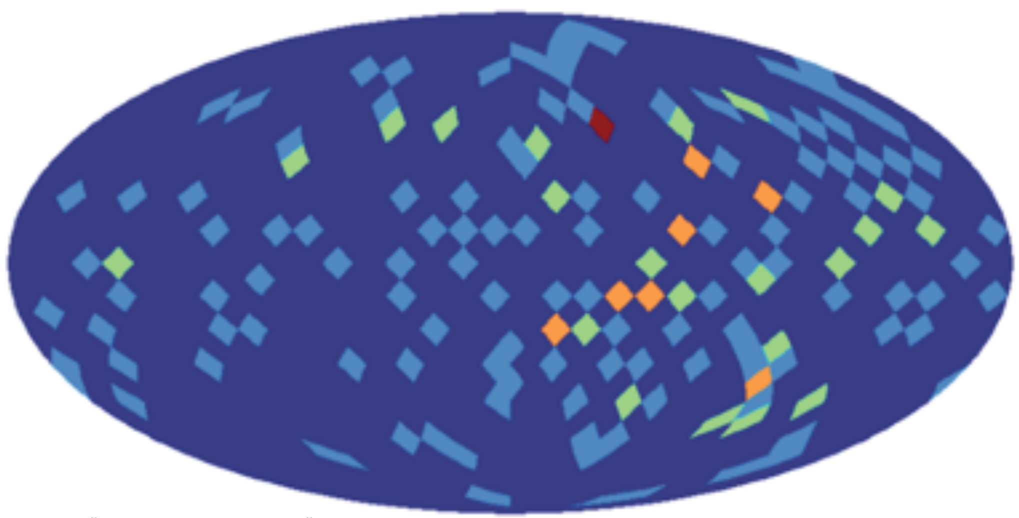
<u>Detector Properties:</u>

detector resolution
energy threshold
background
reconstruction
(2D vs. 3D)
vector or axial
reconstruction

No background, 3-d vector read-out, $E_T = 20$ keV	5
$E_T = 50$ keV	5
$E_T = 100$ keV	3
$S/N = 10$	8
$S/N = 1$	17
$S/N = 0.1$	99
3-d axial read-out	81
2-d vector read-out in optimal plane, reduced angles	12
2-d axial read-out in optimal plane, reduced angles	190

A. M. Green, B. Morgan, Astropart.Phys.27:142-149,2007

J. Billard, F. Mayet, D. Santos, arXiv:1009.5568



simulation with
100 signal, 100 background

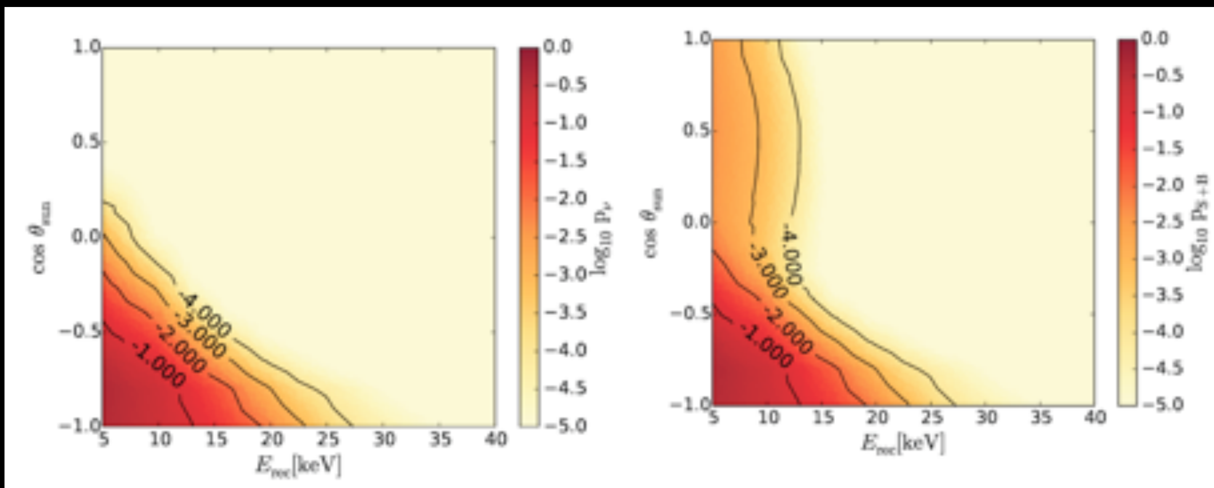
Billard et al. 2010

do not need "zero background" for directional detectors

Beyond the Neutrino Bound

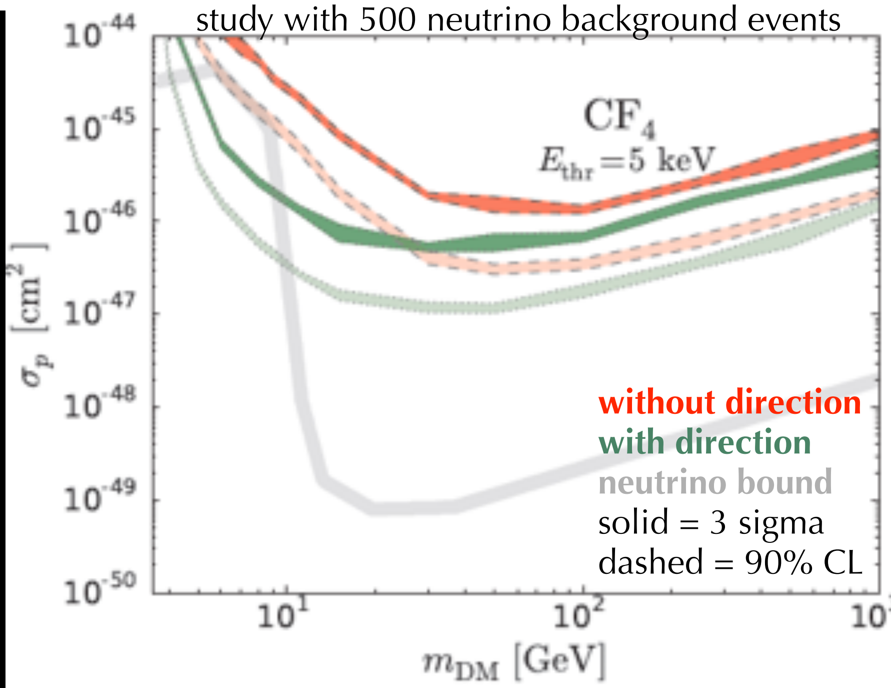
Grothaus, Fairbairn, JM, Fisher
in preparation

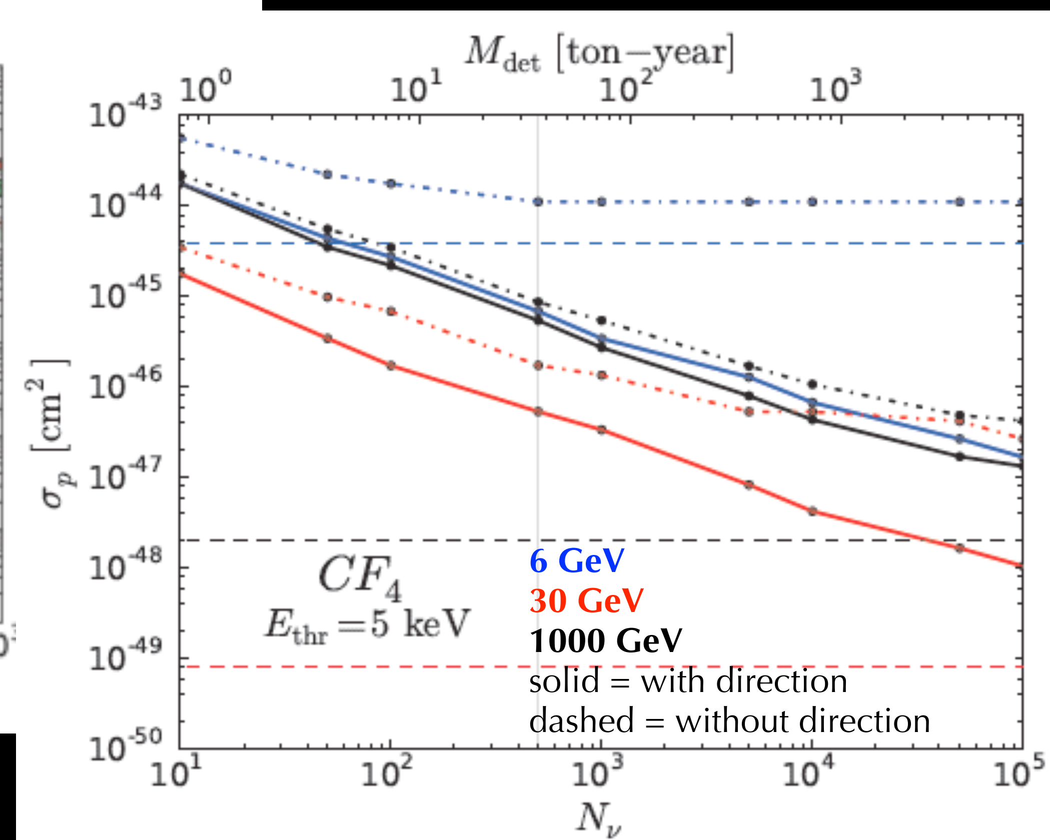
PDFs in (energy, angle, time) of event for coherent solar nu background vs. background+signal show significant differences:



statistical test (CLs) shows
1) directionality gains 10x in sensitivity in presence of background
2) no neutrino bound for directional detectors!

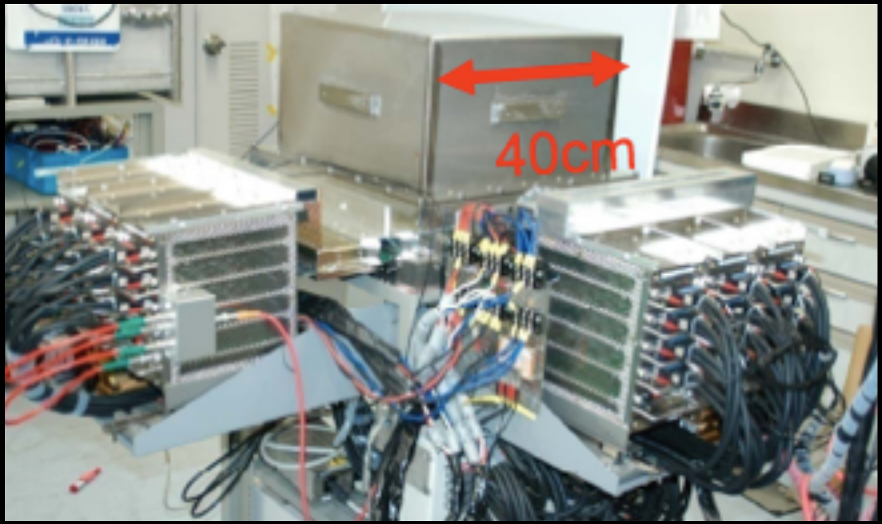
study with 500 neutrino background events





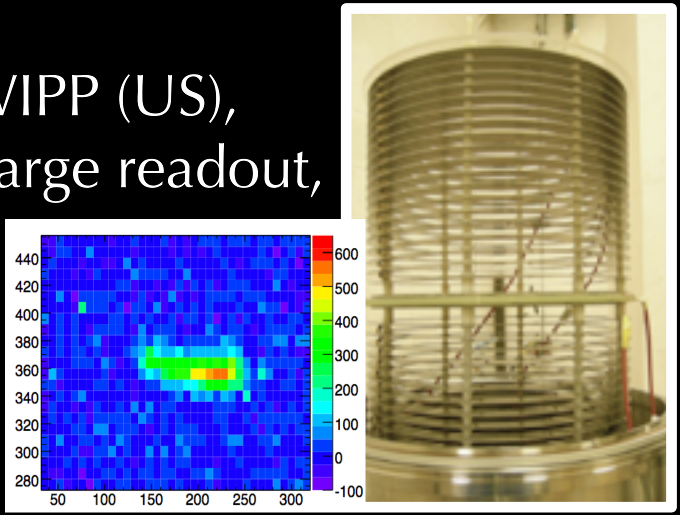
Directionality R&D Around the World

DRIFT: in Boulby (UK),
first directional experiment

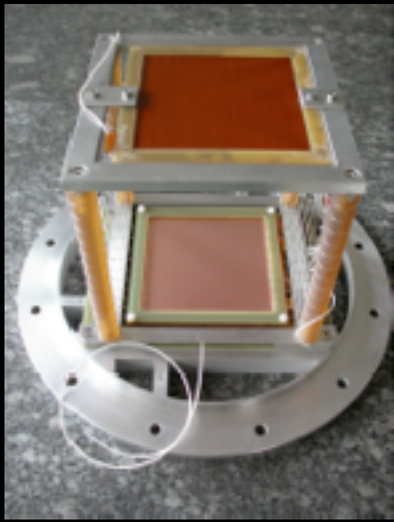


NEWAGE: in Kamioka (Japan),
first directional dark matter limit!

DMTPC: in WIPP (US),
optical and charge readout,
demonstrated
40° resolution



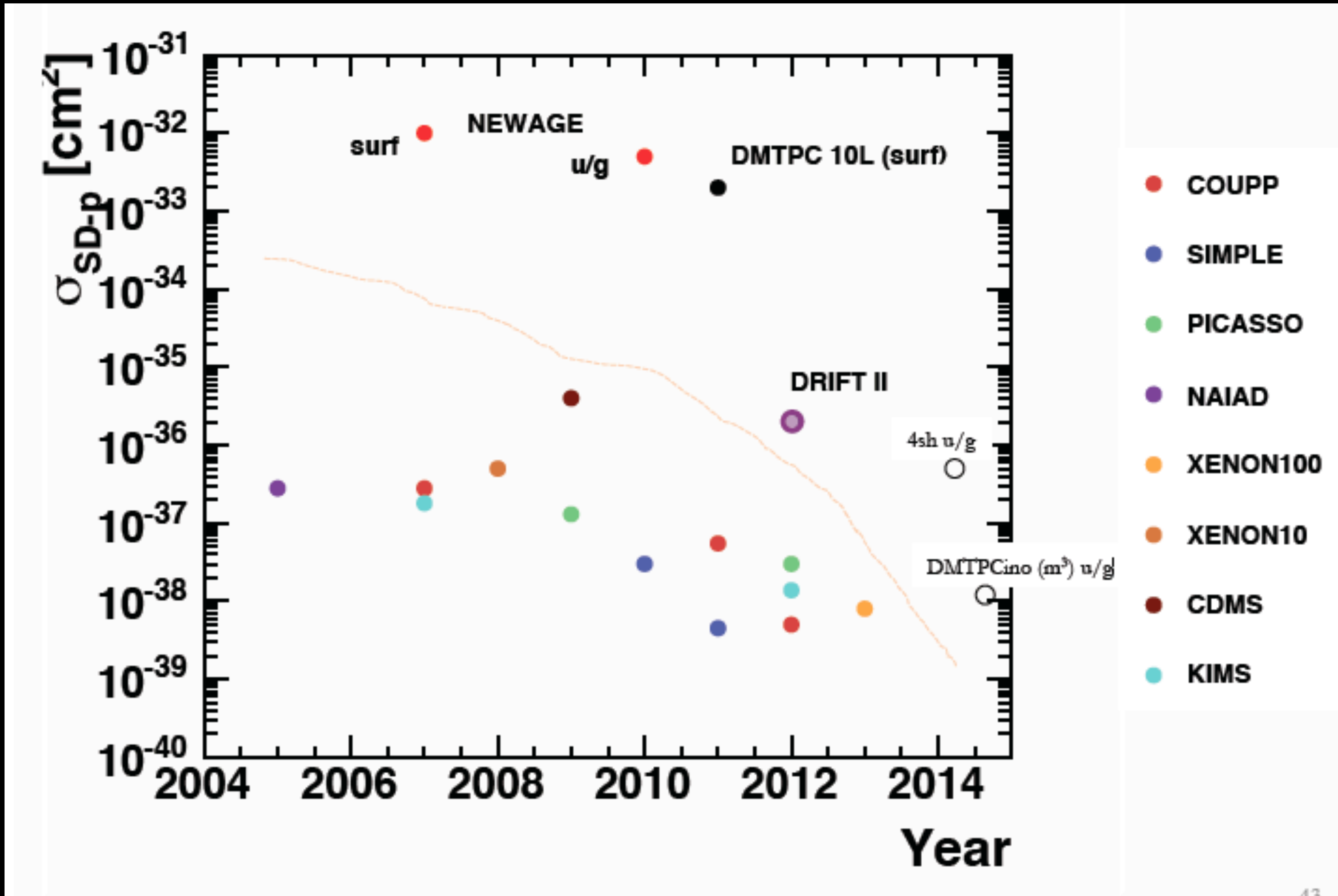
MiMAC-He3: ILL,
in Modane (France)
micromegas readout,
A-dependence



CYGNUS: coordinated effort of all

All in R&D stage towards detector requirements:
~30° resolution, ~50 keV threshold, low background, good efficiency, scalable

Directional Detection: Progress



O(1m^3) detector to be competitive with current non-directional SD searches

directionality is starting to catch up....

Directional Detection Future

Eventually: large detector, 10^{-46} cm^2 sensitivity, how big is it?

MiniBooNE: 6 x 6 x 6 m^3

Directional Detection Observatory (10^{-46} cm^2) 16 x 16 x 16 m^3

1 ton of CF_4 @50Torr

MINOS: 15 x 13 x 30 m^3

SNO: 21 x 21 x 34 m^3

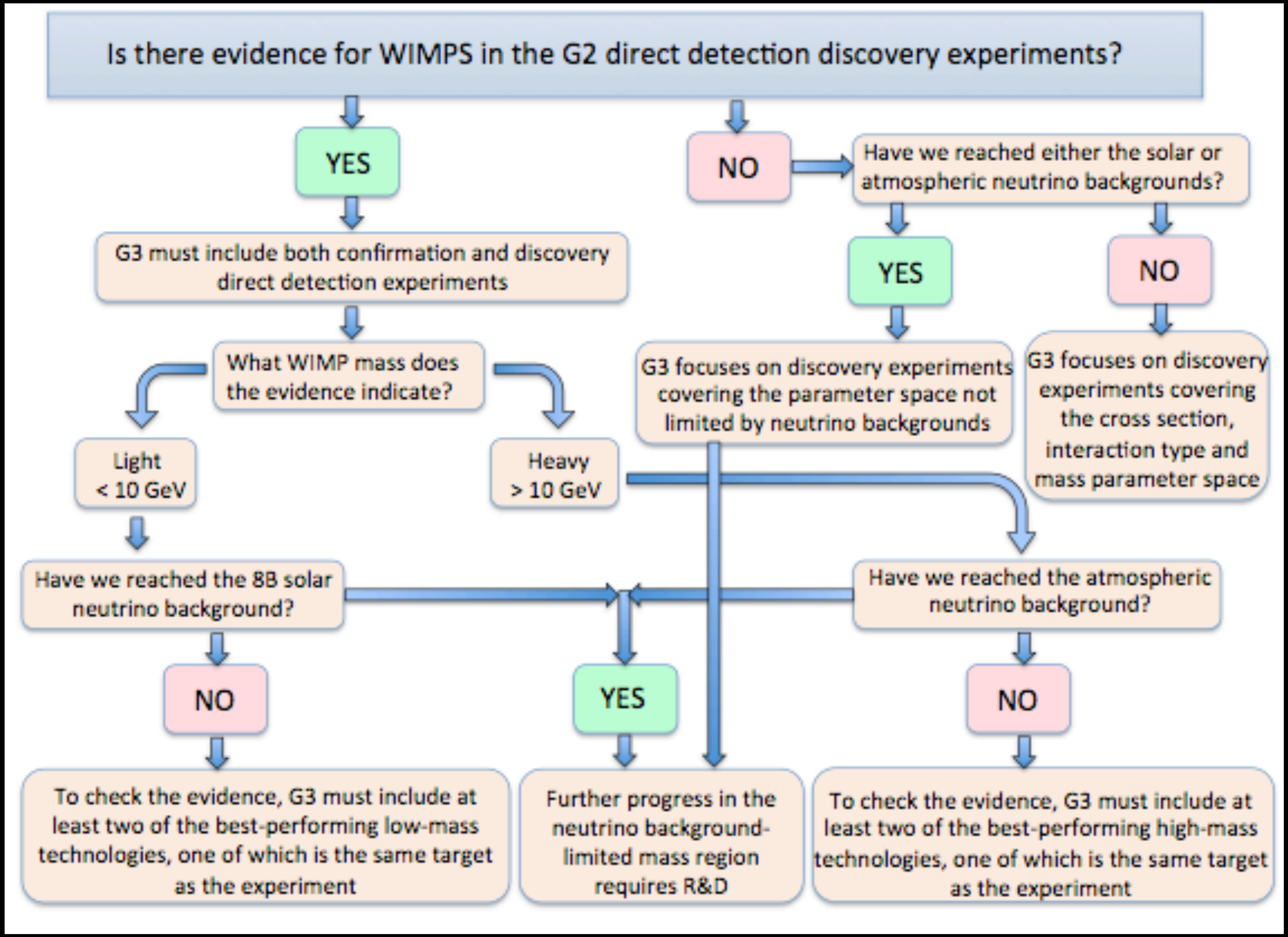
SuperK: 40 x 40 x 40 m^3

detector size for 10^{-44} cm^2 SI sensitivity

Summary & Outlook

Direct detection experiments will test SI WIMP parameter space down to 10^{-46} cm^2 in next few years, and ~to neutrino bound in next decade

arXiv:1310.8327

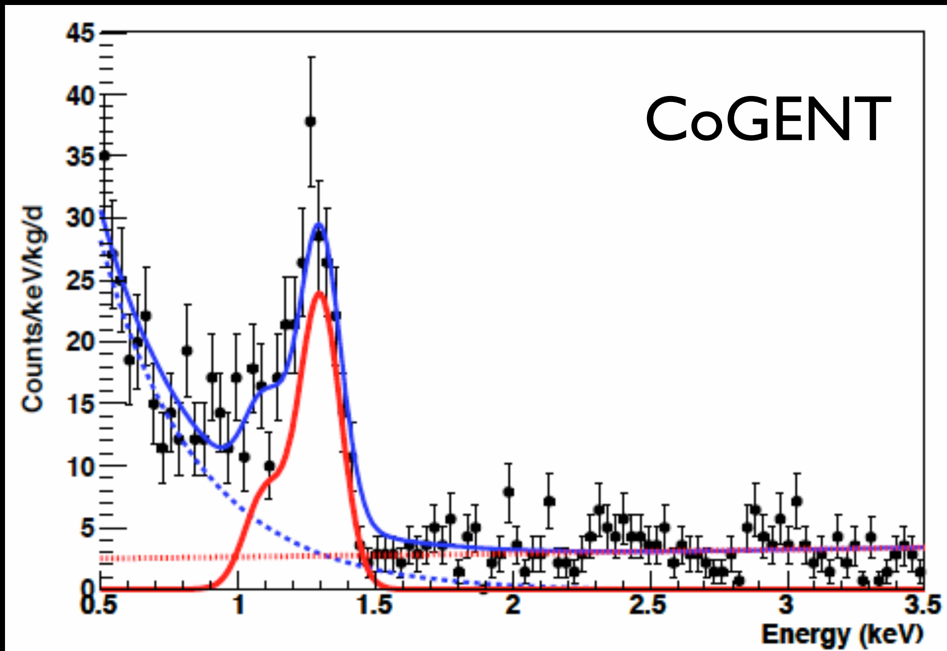


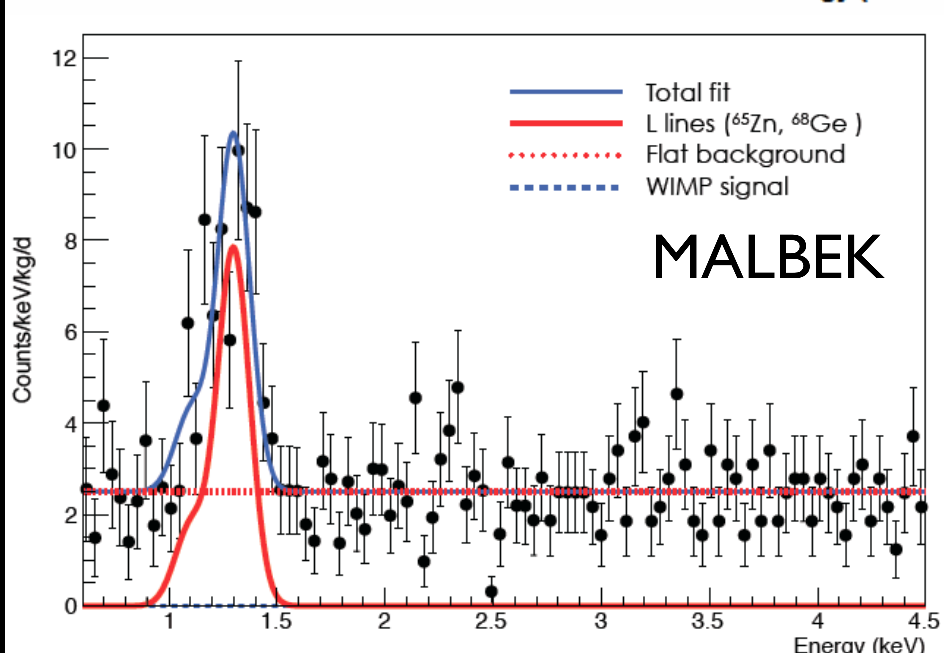
Directional detectors needed to go beyond...

Extra Slides

CoGENT and MALBEK

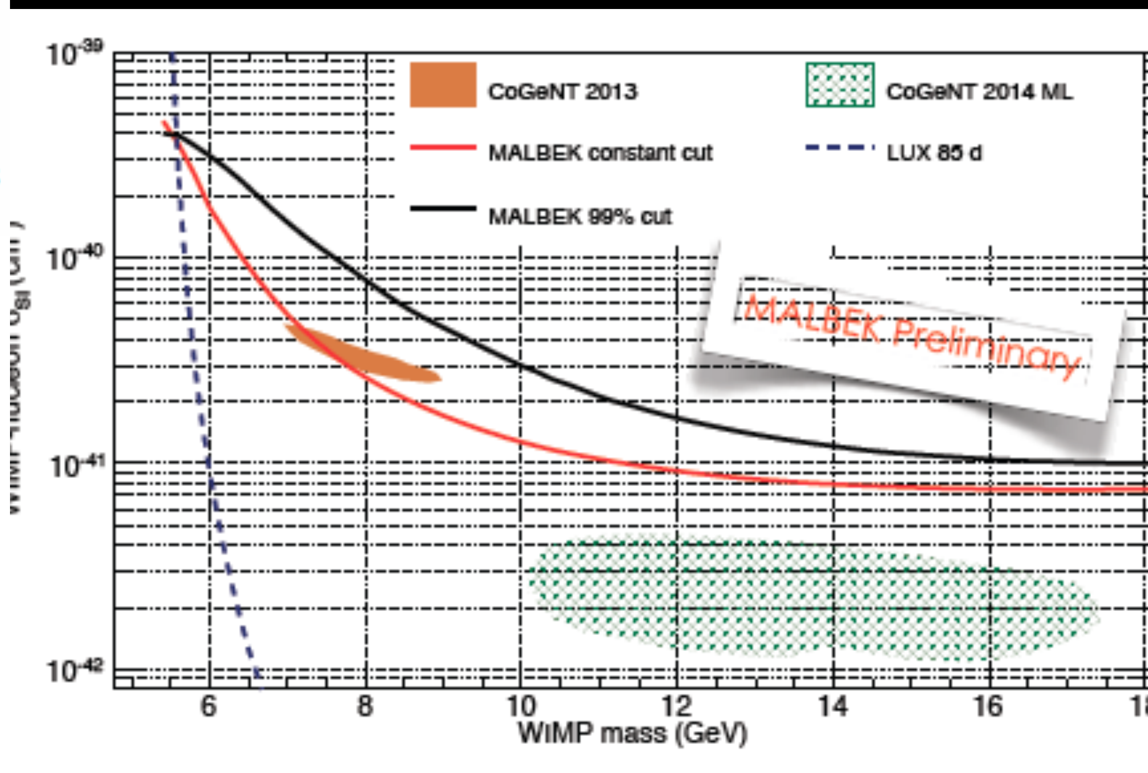
J. Wilkerson, UCLA DM '14





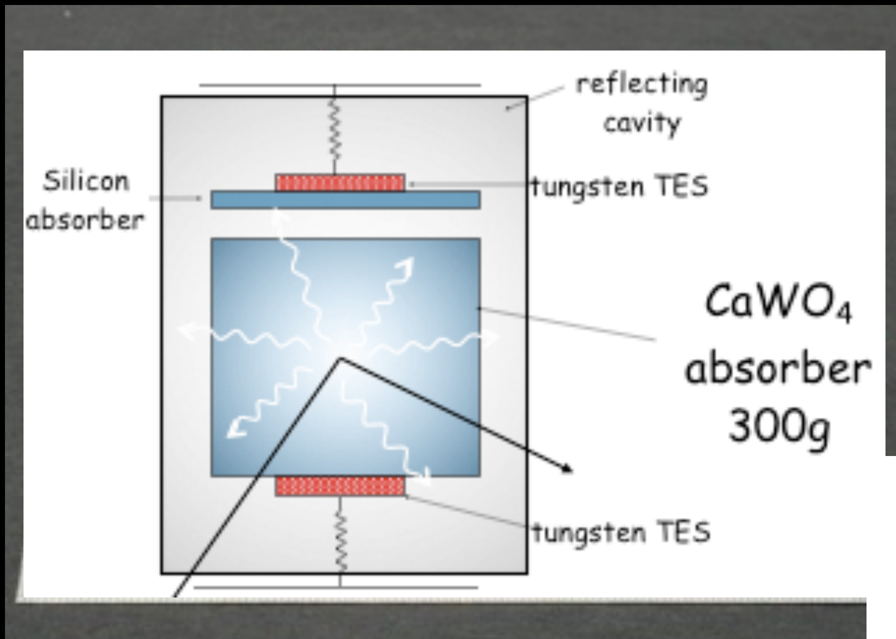
0.44 kg Ge detector, point contact

- 0.5 keV energy threshold
- COGENT: excess fit by 8 GeV WIMP
- MALBEK: similar detector, assayed detector components, found Pb-210 background from clamps, reran without them, best fit: no DM



- CoGENT 2013 allowed region excluded, CoGENT 2014 region allowed

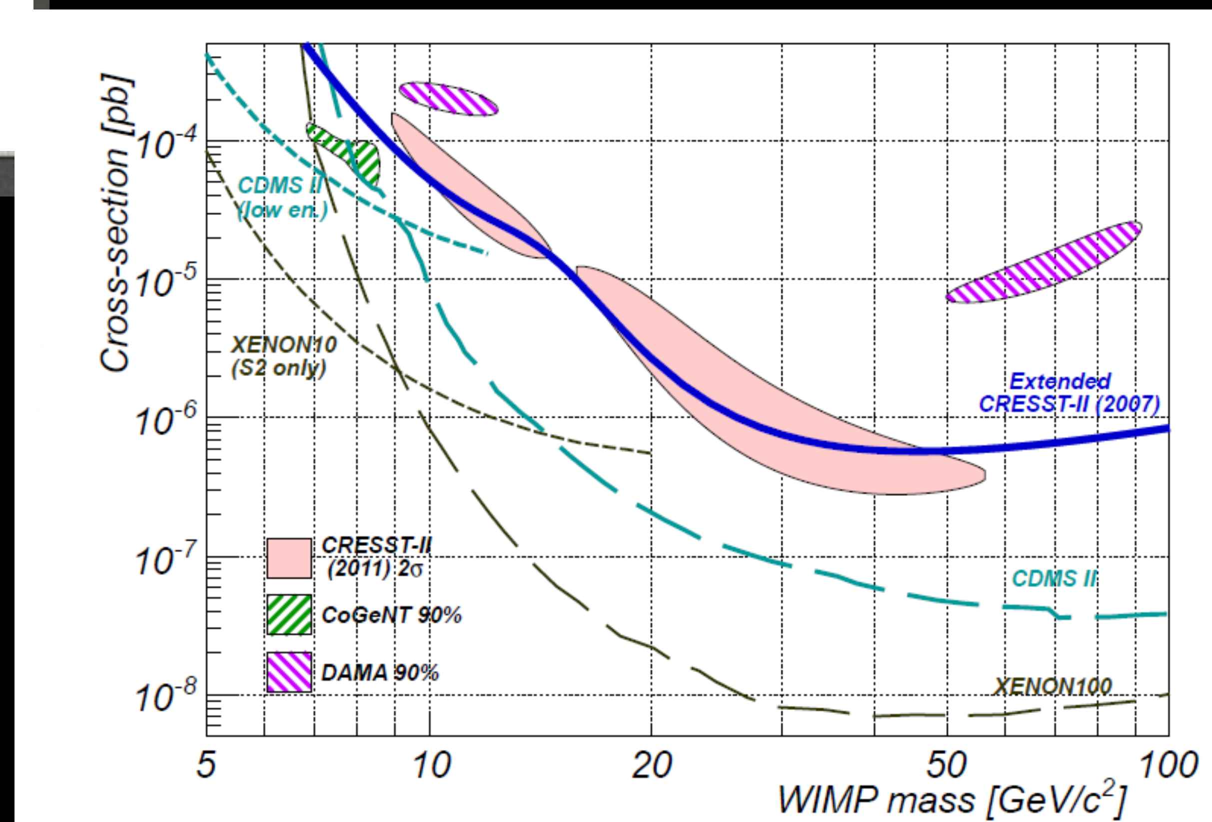
CRESST-II



Scintillation and Phonon detectors on $CaWO_4$ absorbers, TES readout, operating in Gran Sasso

- 730 kg-day science run sees excess of events
- difficult to explain with backgrounds so far

arXiv:1109.0702



CRESST likelihood contours from arXiv:1109.0702 (and other results)

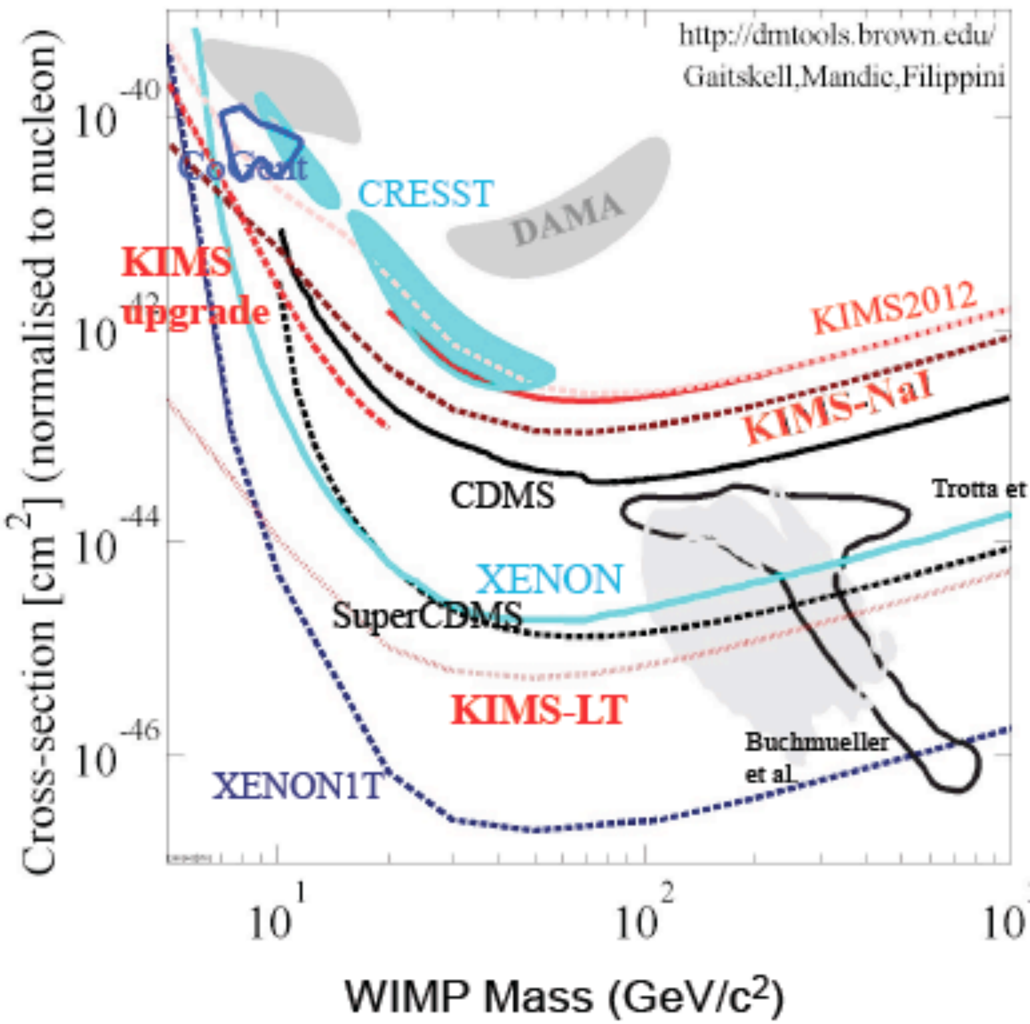
in tension with

CRESST commissioning data, extended analysis by *Brown, et al. PRD 85 (2012) 021301(R) (also: arXiv:1109.2589)*

Run started with new clamps, more detectors, improved shielding in July 2013.

KIMS Plans

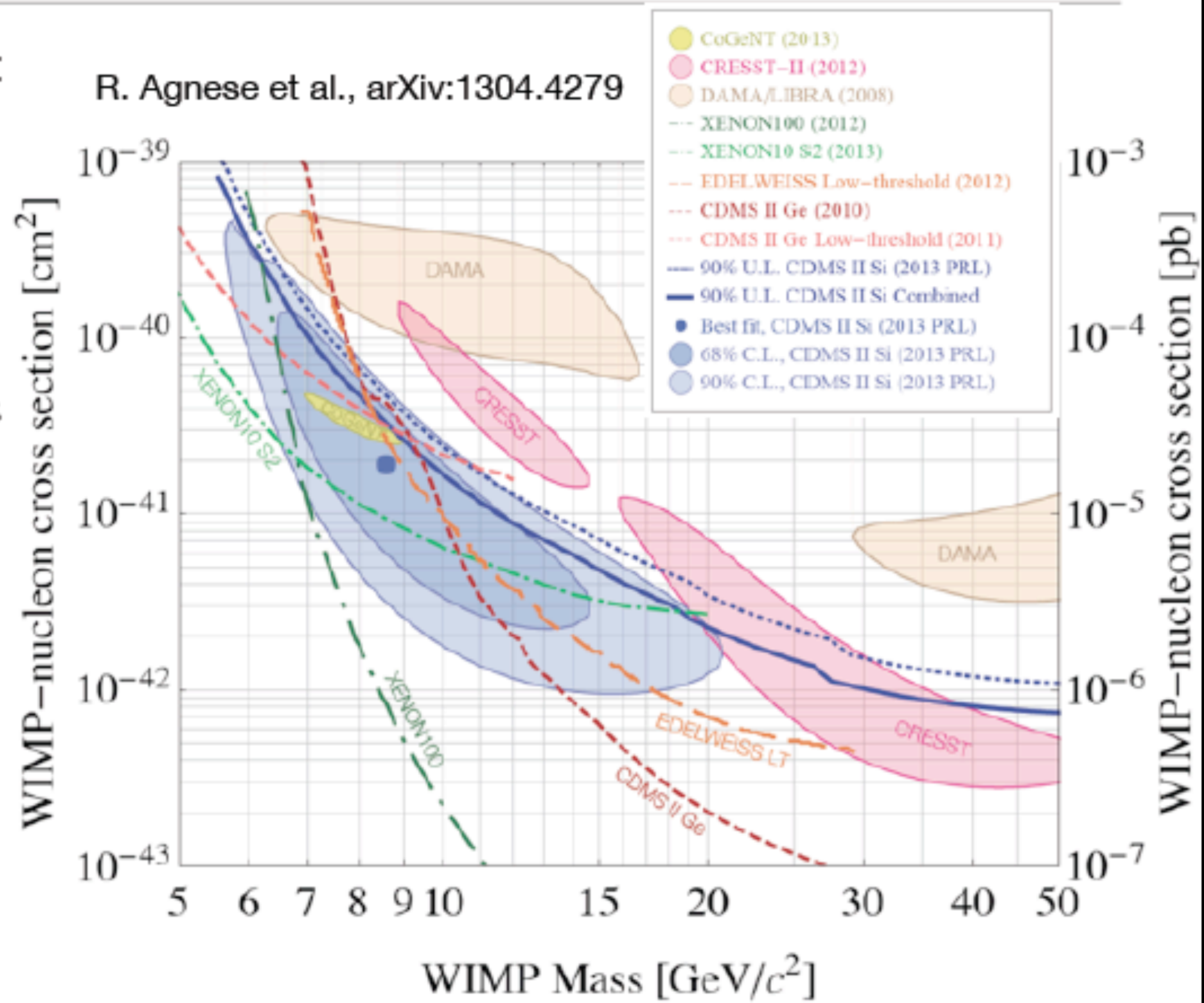
- **KIMS-CsI:** Upgrade of CsI(Tl) crystal detector
  - Lower threshold ~ 1.5keV, < 1dru, counts/(keV kg day).
- **KIMS-NaI:** new NaI(Tl) detector
  - Duplicate DAMA experiment with ultra-low background NaI(Tl) crystals.
  - 200kg run in 2015-2016



- **KIMS-LT**
  - Use scintillating bolometer such as $^{nat}Ca^{nat}MoO_4$ crystals ~ 200 kg year.
  - High sensitivity to low mass WIMP.
  - Operations in 2019-2022

Profile Likelihood analysis

- The maximum likelihood occurs at a WIMP mass of 8.6 GeV/c^2 and WIMP-nucleon cross section of 1.9×10^{-41} cm^2
- Probability of observing 3 or more events from background fluctuations is equal to 5.4%
- Goodness of fit of the WIMP +Background model is 68.6%
- A profile likelihood ratio test statistic favors the WIMP +Background hypothesis over the background only at 99.81% C.L.



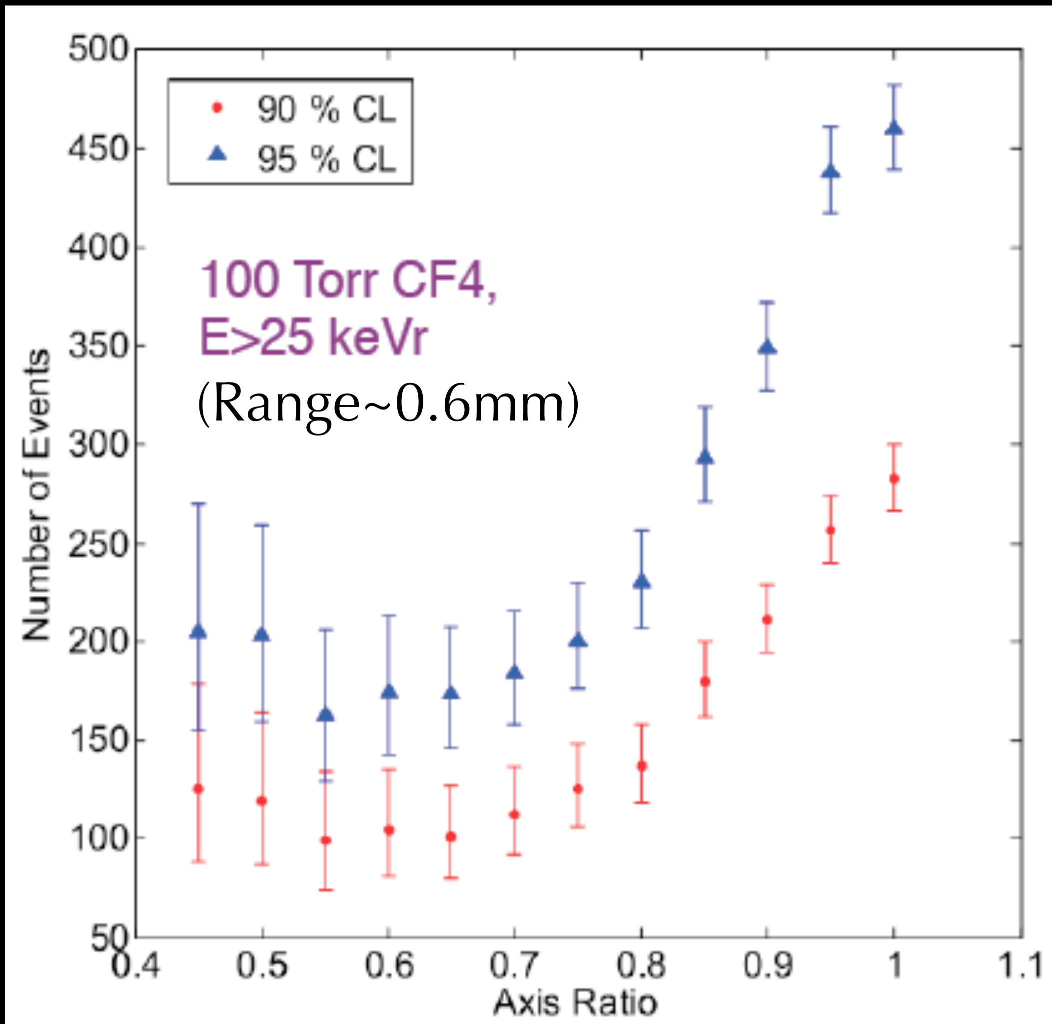
We do not believe this result rises to the level of a discovery, but does call for further investigation.

Now: some SuperCDMS detectors are Si, and working on phonon-only analysis.

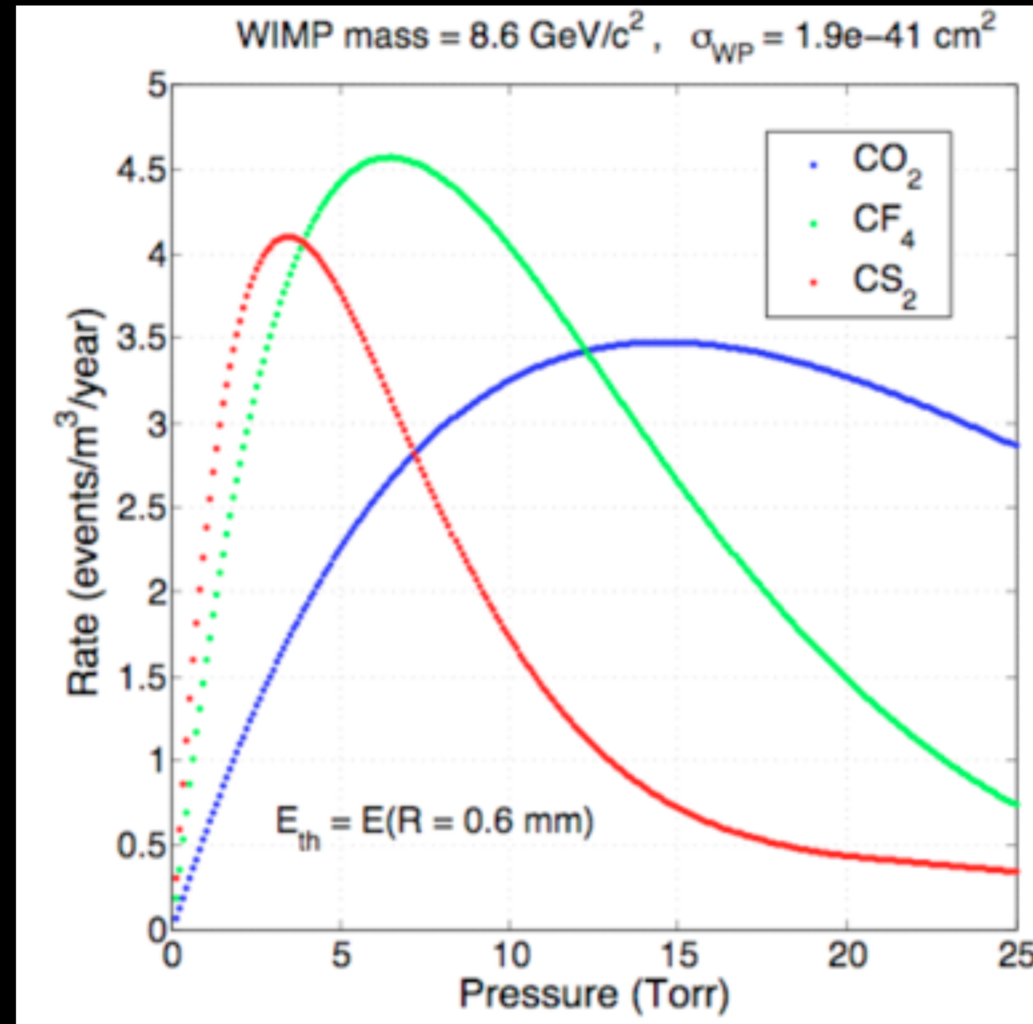
Directionality and Low Mass Dark Matter

(D. Loomba, Cygnus'13)

1) Number of events to reject isotropy as a function of track 'ellipticity:'



2) Require $E_{threshold}$ for R>=0.6mm, find gas pressure to maximize rate



Bottom line: directional detection of low-mass dark matter possible with low gas pressures and low energy thresholds (need large volume, high S:N)

Directionality without Tracking

(D. Nygren, Cygnus'13)

Ratio of recombination to ionization yield in gas target is sensitive to track direction relative to TPC drift field.

- Columnar Recombination (CR) occurs when:
  - A drift electric field ***E*** exists;
  - Tracks are highly ionizing;
  - Tracks display an approximately linear character;
  - The angle α between ***E*** and track is small:
  - **Recombination** ≈ dot-product of vectors E and "track"

Photons from R vs. I separated in arrival time at TPC readout plane.
Measure event energy vs. time of day (direction to cygnus), in HPXe TPC.
No tracking needed for directional dark matter detection!

Impact of Dark Disk

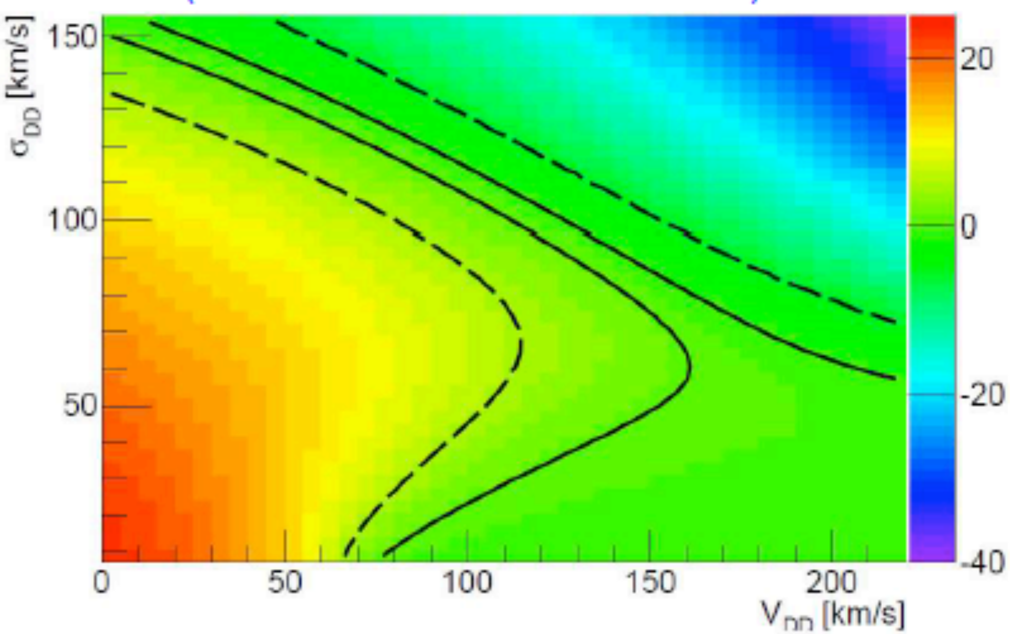
Discovery : beyond the standard halo

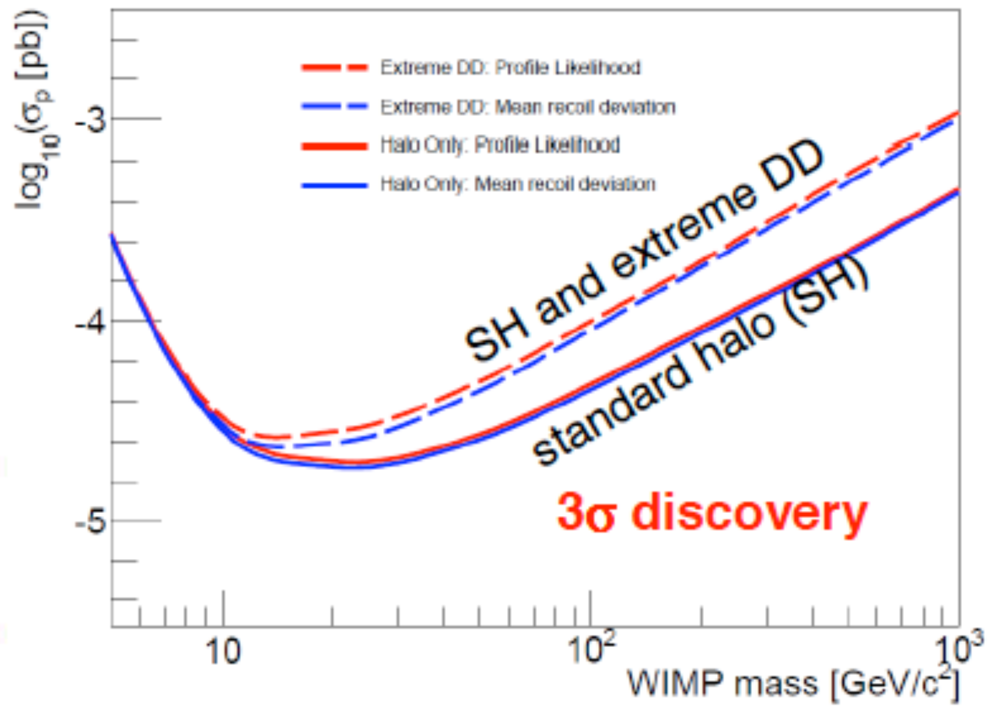
J. Billard *et al.*, PLB 2013

N-body simulations favor a co-rotating Dark Disk (10%-50% of local DM density)

→for a nul lag velocity, Dark Disk Wimps have an isotropic velocity distribution

Relative Asymmetry
(in the mean recoil deviation)





→only extreme Dark Disk parameters may affect the directional signal

→not a threat for directional detection

What to do with Directional Data?

1. Exclusion

- Maximum Patch Method, *S. Henderson, JM and P. Fisher, PRD 2008*
- Directional Likelihood Method, *J. Billard, F. Mayet and D. Santos, PRD 2010*

bottom line: 2 variables (angle + energy) can be better or worse than 1 (energy)

2. Hypothesis Test: is a candidate signal compatible with background?

- *C. J. Copi & L. M. Krauss, PLB 1999; C. J. Copi & L. M. Krauss, PRD 2001; B. Morgan & A. M. Green, PRD 2005; B. Morgan, A. M. Green and N. J. C. Spooner, PRD 2005; A. M. Green & B. Morgan, PRD 2008; O. Host & S. H. Hansen, JCAP 2007; J. D. Vergados & A. Faessler, PRD 2007; M. S. Alenazi & P. Gondolo, PRD 2008*

bottom line: require few 10s of events to reject isotropy

3. Discovery: search for a signal from the direction of Cygnus

- Median Recoil DIrection Test: *A. M. Green & B. Morgan, PRD 2010*
- Blind Likelihood Test: *J. Billard et al., PLB 2010*

bottom line: high significance discovery with relatively small exposure (~10 kg-yr)

4. Study Dark Matter Properties: halo, mass, cross section

- *Lee and Peter, arXiv:1202.5035; Borzognia, Gelmini, Gondolo, arXiv:1111.6361; Billard, Mayet and Santos, PRD 2011; Copi et al., PRD 2007; Green and Morgan, Astropart. Phys. 2007; ...*
- Dark Matter Model Discrimination: *D. Finkbeiner, T. Lin, N. Weiner, PRD80 (2009)*
- Community White Paper: *S. Ahlen et al., Int.J.Mod.Phys.A25:1-51,2010*
- And beat the neutrino background limit! *M. Fairbairn et al. IOP2014, in preparation*

bottom line: need large numbers of events O(1000+) to measure halo parameters