Direct Searches for Dark Matter

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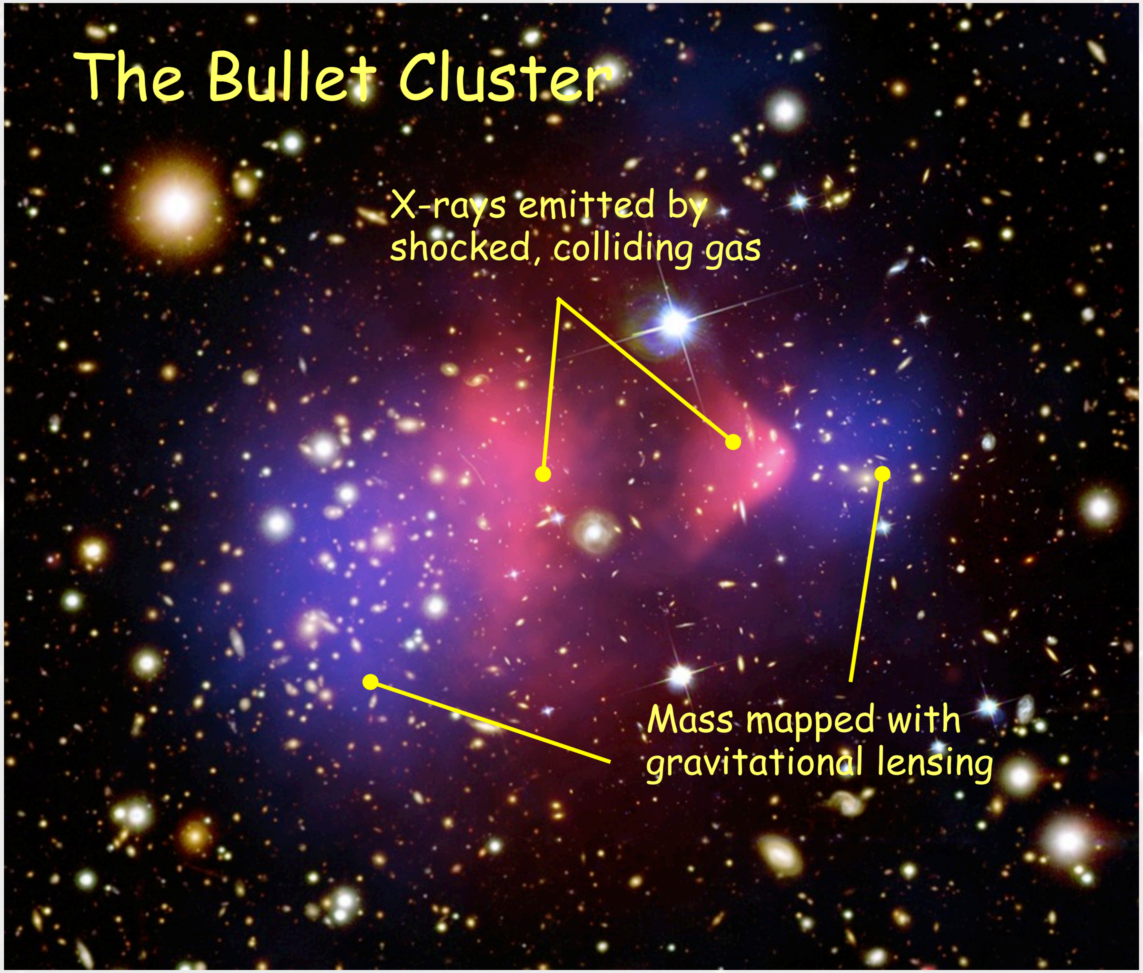
Overview

The Dark Matter Problem



What we know:

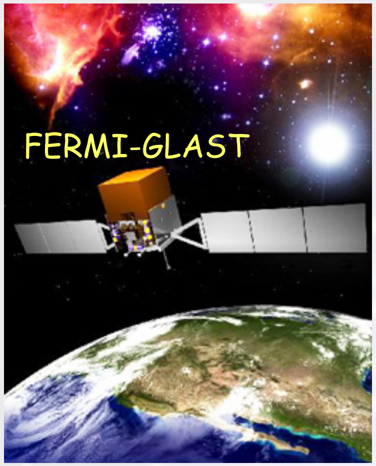
It's stable, cold, gravitationally interacting, non-baryonic, interacts little with itself (or not at all), composes ~85% of matter in the Universe…

But:

No particle in the Standard Model fits !

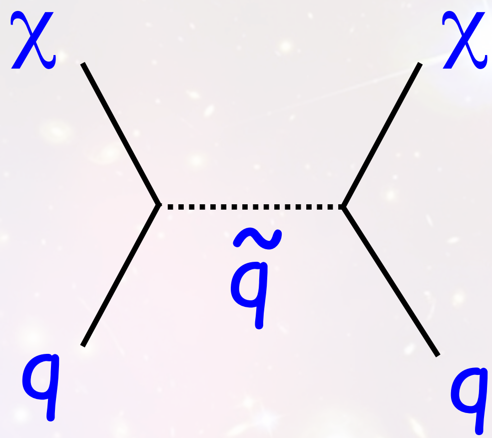
Very weakly interacting GeV-TeV particles do…

How to detect WIMPs



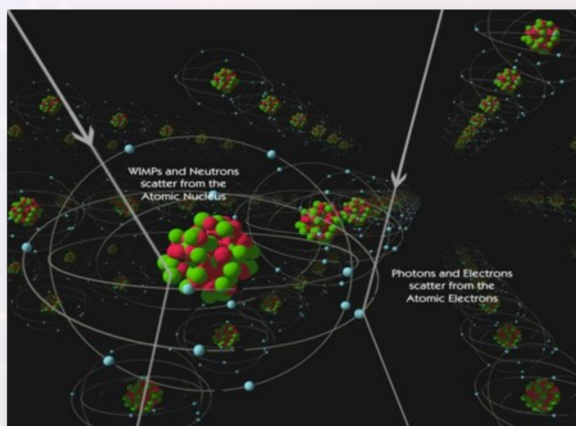
Relic annihilation in the cosmos

INDIRECT DETECTION



man-made COLLIDER production

M. Attisha



Relic WIMP-nucleon elastic scattering

DIRECT DETECTION

WIMP-nucleon scattering 101

$$\sigma_0 = \frac{4\mu^2}{\pi}\left[f_p N_p + f_n N_n\right]^2 + \cancel{\frac{32G_F^2\mu^2}{\pi}\frac{(J+1)}{J}\left[a_p\langle S_p\rangle + a_n\langle S_n\rangle\right]^2}$$

Spin-independent scattering

(f_p and f_n are the coupling to the neutron and proton)

↓

But $f_p \approx f_n$ for most models
so scattering adds coherently with
A^2 enhancement! (A = atomic mass)

↓

EXAMPLE: WIMP-Ge SI cross section is >10^6
larger than WIMP-proton SI cross section

WIMP-nucleon scattering 101

$$\sigma_0 = \cancel{\frac{4\mu^2}{\pi}\left[f_p N_p + f_n N_n\right]^2} + \frac{32 G_F^2 \mu^2}{\pi} \frac{(J+1)}{J} \left[a_p \langle S_p \rangle + a_n \langle S_n \rangle\right]^2$$

Spin-dependent scattering

↓

scales with spin of nucleus (opposite signs can cancel) – NO coherent effect!

WIMP-nucleon scattering 101

$$\sigma_0 = \cancel{\frac{4\mu^2}{\pi}\left[f_p N_p + f_n N_n\right]^2} + \frac{32 G_F^2 \mu^2}{\pi} \frac{(J+1)}{J} \left[a_p \langle S_p \rangle + a_n \langle S_n \rangle\right]^2$$

Nucleus	Z	Odd Nucleon	J	$\langle S_p \rangle$	$\langle S_n \rangle$	C_A^p/C_p	C_A^n/C_n
^{19}F	9	p	1/2	0.477	-0.004	9.10×10^{-1}	6.40×10^{-5}
^{23}Na	11	p	3/2	0.248	0.020	1.37×10^{-1}	8.89×10^{-4}
^{27}Al	13	p	5/2	-0.343	0.030	2.20×10^{-1}	1.68×10^{-3}
^{29}Si	14	n	1/2	-0.002	0.130	1.60×10^{-5}	6.76×10^{-2}
^{35}Cl	17	p	3/2	-0.083	0.004	1.53×10^{-2}	3.56×10^{-5}
^{39}K	19	p	3/2	-0.180	0.050	7.20×10^{-2}	5.56×10^{-3}
^{73}Ge	32	n	9/2	0.030	0.378	1.47×10^{-3}	2.33×10^{-1}
^{93}Nb	41	p	9/2	0.460	0.080	3.45×10^{-1}	1.04×10^{-2}
^{125}Te	52	n	1/2	0.001	0.287	4.00×10^{-6}	3.29×10^{-1}
^{127}I	53	p	5/2	0.309	0.075	1.78×10^{-1}	1.05×10^{-2}
^{129}Xe	54	n	1/2	0.028	0.359	3.14×10^{-3}	5.16×10^{-1}
^{131}Xe	54	n	3/2	-0.009	-0.227	1.80×10^{-4}	1.15×10^{-1}

Tovey et al., PLB488 17 (2000)

The relic WIMP distribution

Observed energy spectrum & rate depend on WIMP distribution in dark matter halo

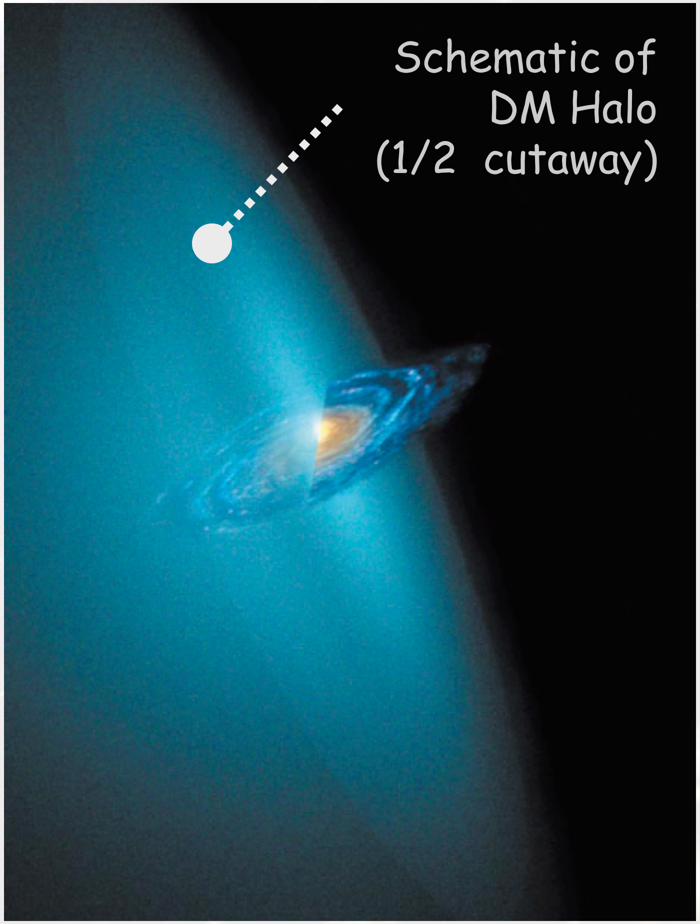
Make the following assumptions:

- **WIMPs distributed in spherical halo**

$$\rho \sim \rho_0 (r/r_s)^{-1} (1+r/r_s)^{-2}$$

- **Assume isothermal Maxwell-Boltzmann velocity distribution (width = 220 km/s)**
- **Ve ~ 245 km/s - WIMP velocity relative to Earth**
- **Local density of WIMPs = 0.3 GeV/cm^3**

If WIMPs are 100 GeV/c^2 particles, then ~10 million pass through your hand each second!



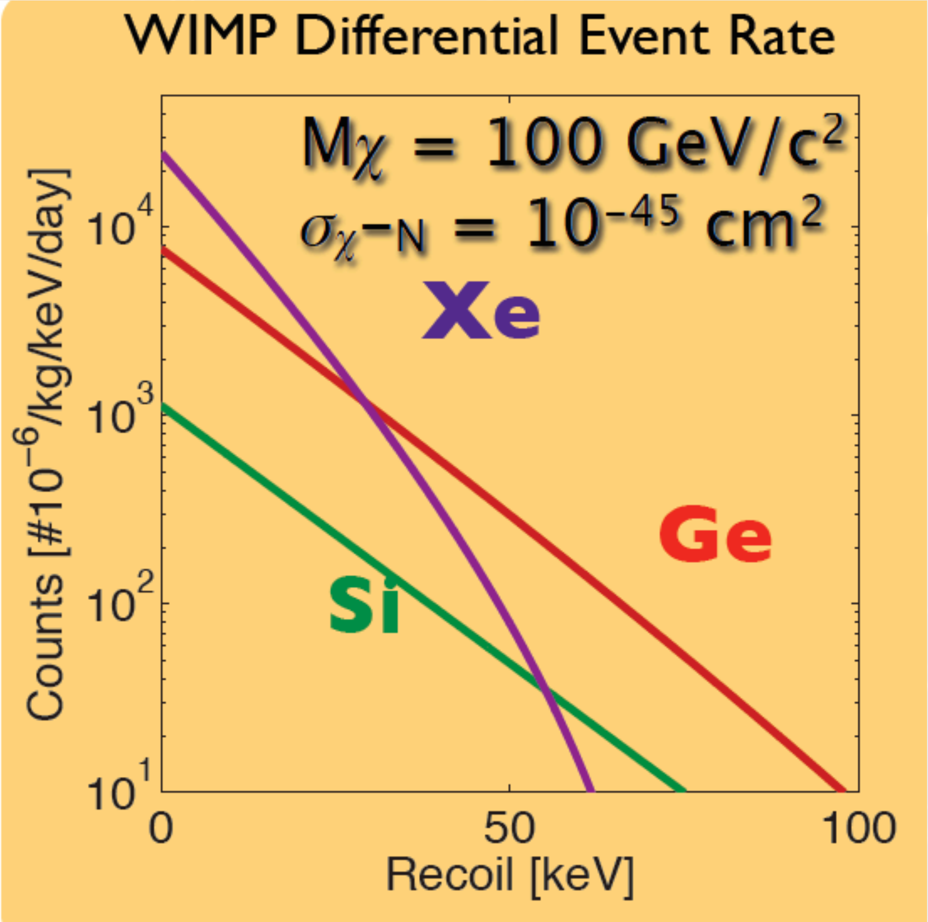
Putting it all together

Expected signal:

- nuclear recoil (from elastic scattering of WIMPs)
- featureless exponential
- rates <<0.1 events /kg/day

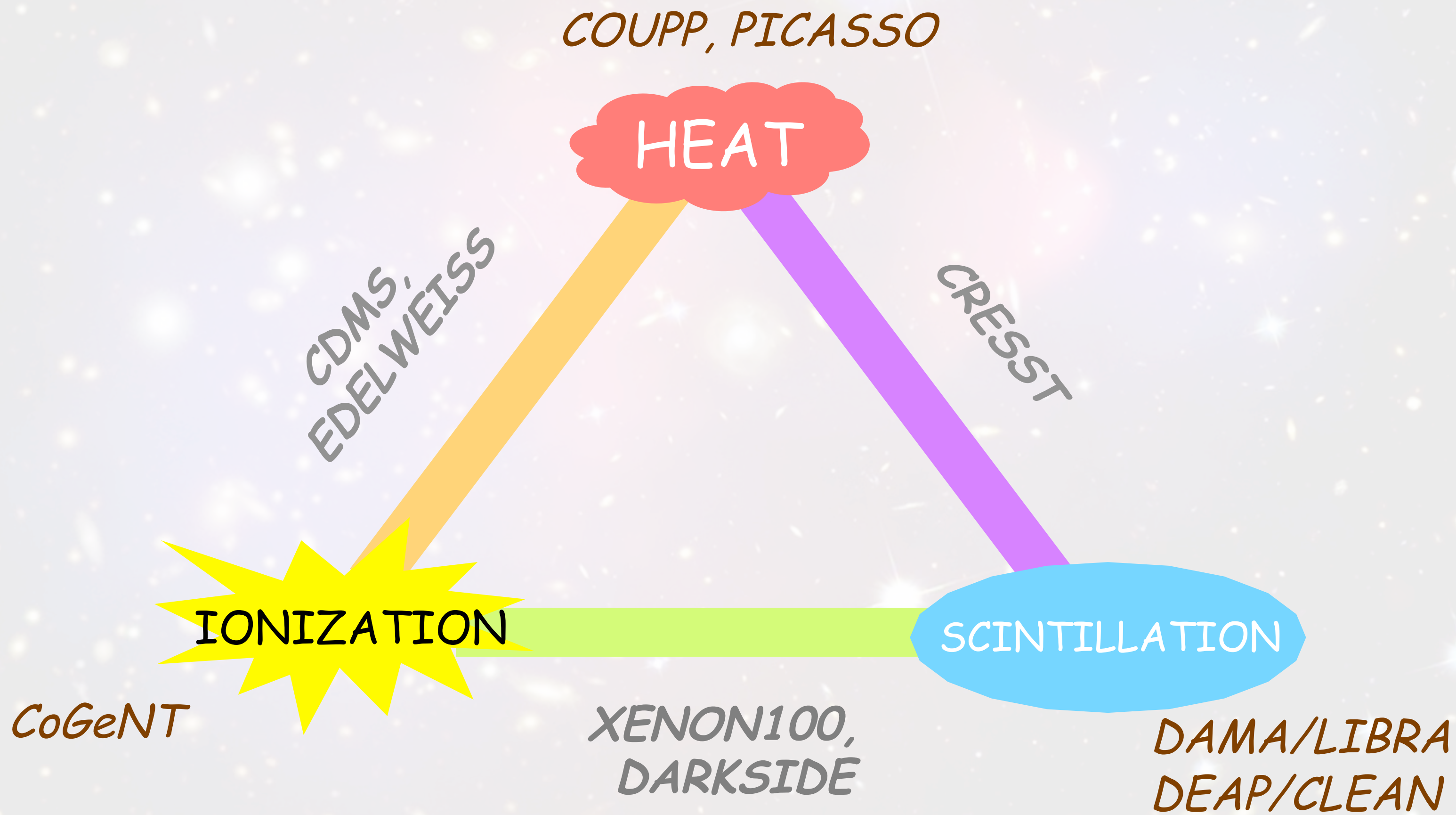
Challenges:

- low energy thresholds (≲10 keV)
- mitigation of natural radioactive background (by factors >10^7)
- long exposures, underground operation

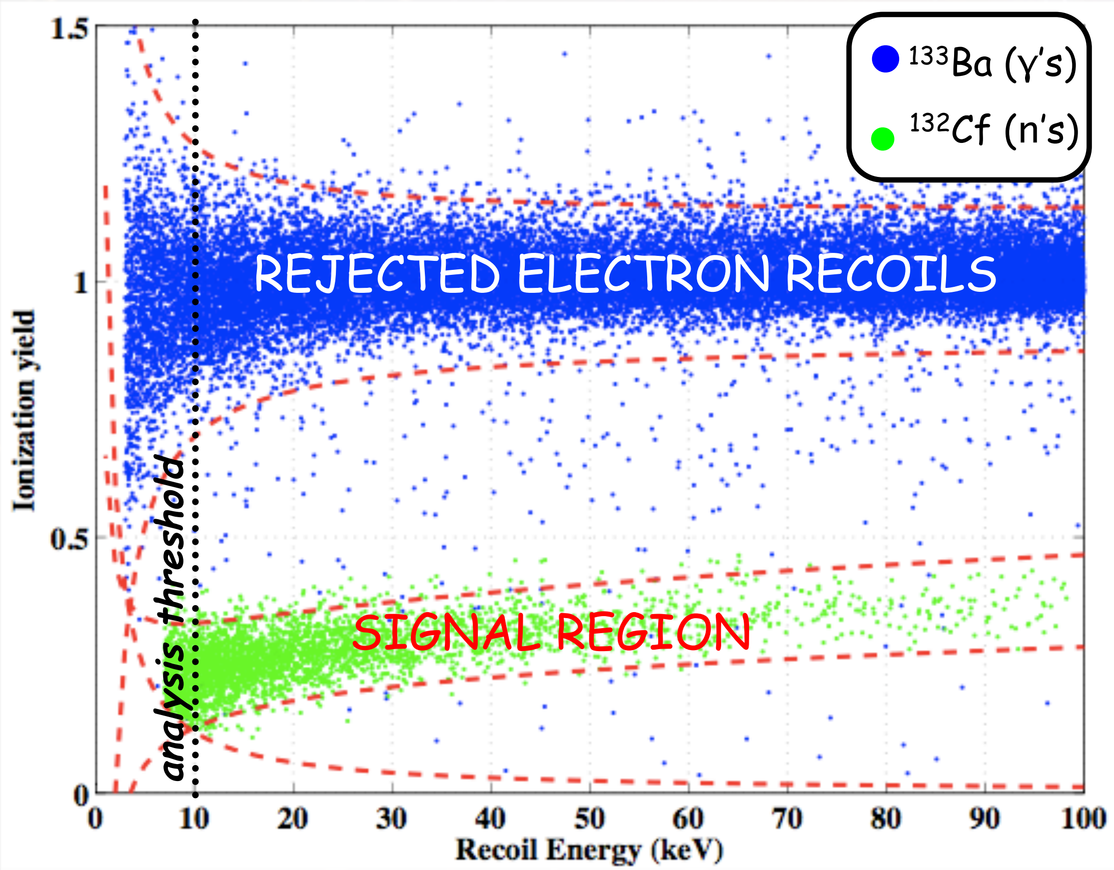


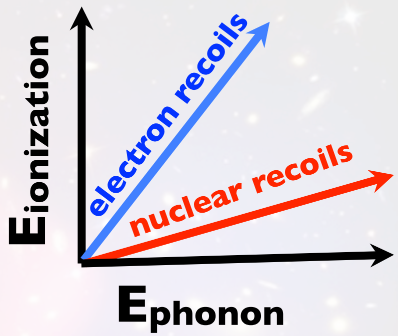
~~WIMP detection~~ techniques

Background rejection



How it works for CDMS



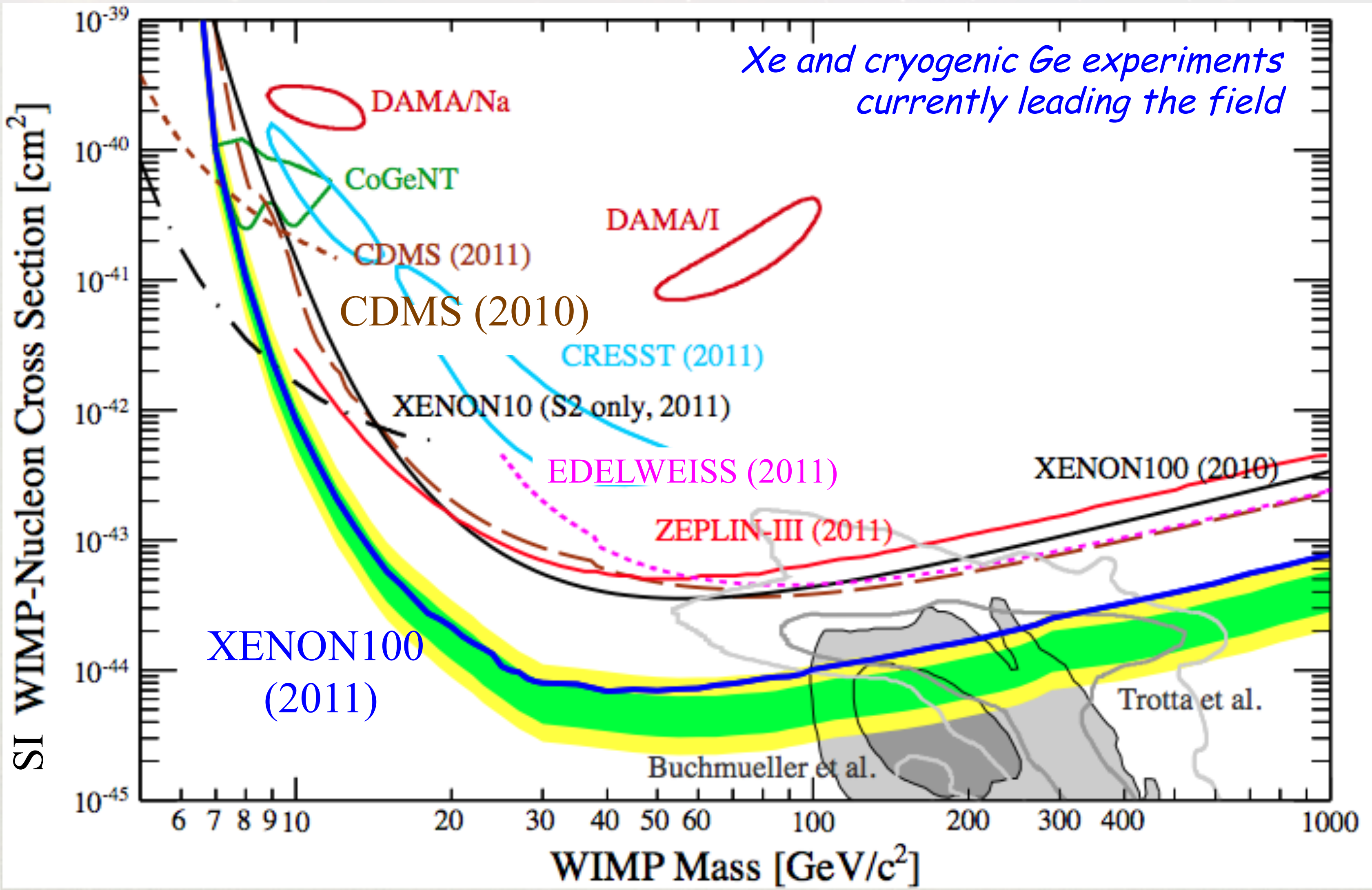


$$\text{ionization yield} = \frac{E_{\text{ionization}}}{E_{\text{phonon}}}$$

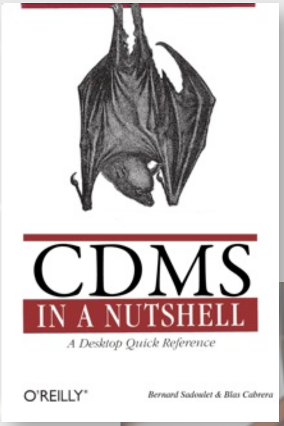
$1{:}10^4$ rejection of gammas based on ionization yield alone

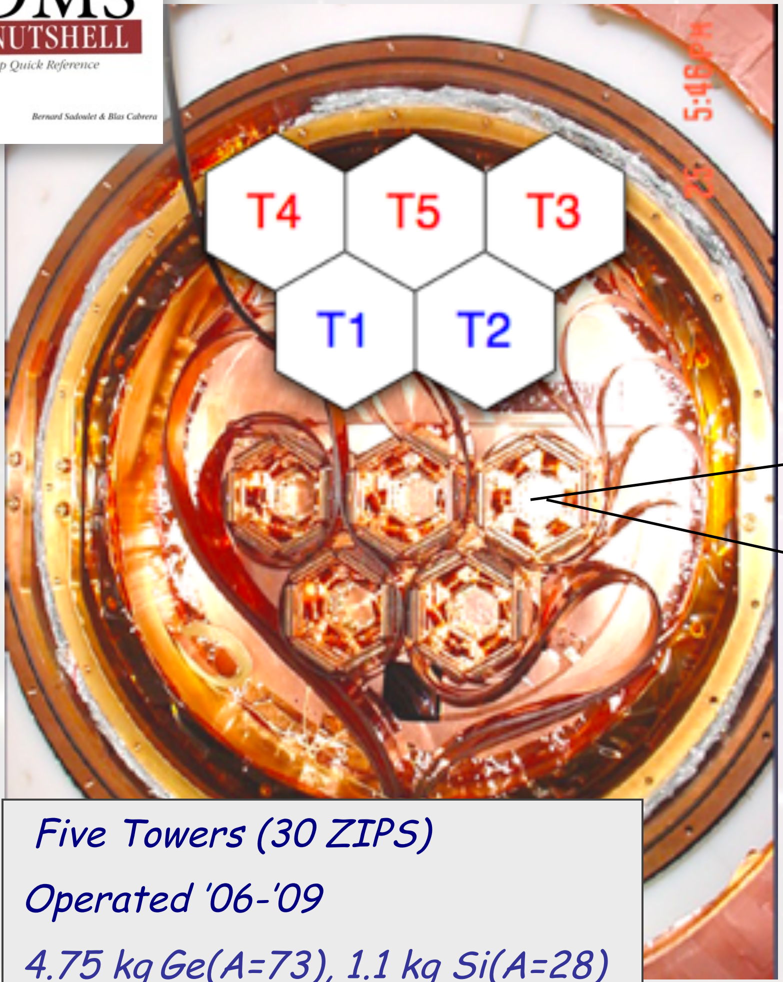
Status of Running Experiments

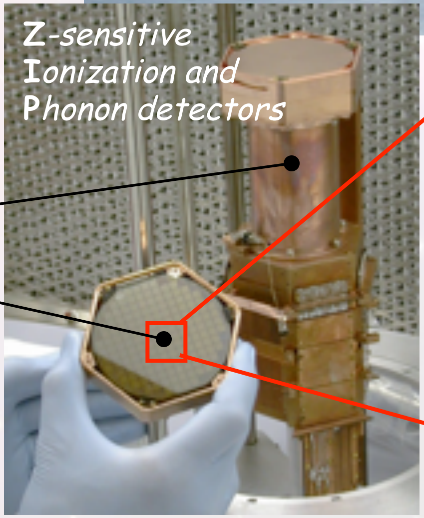
Spin-Independent Landscape

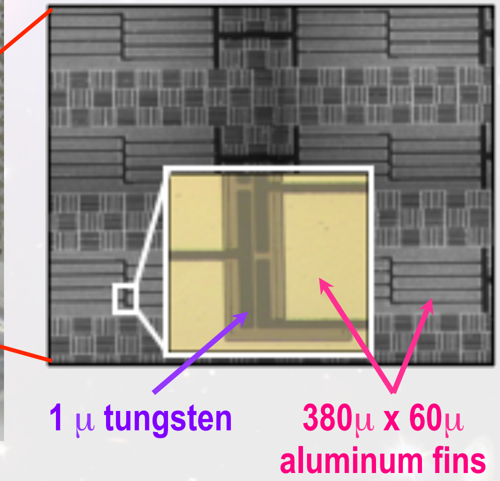


Cryogenic Dark Matter Search







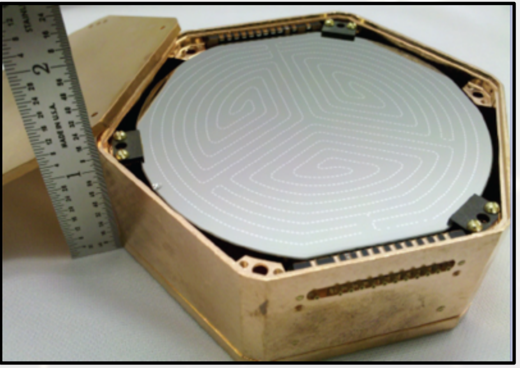


Five Towers (30 ZIPS)

Operated '06-'09

4.75 kg Ge(A=73), 1.1 kg Si(A=28)

Longtime leader in SI sensitivity due to superior background rejection (ER:NR is $>10^6$:1)

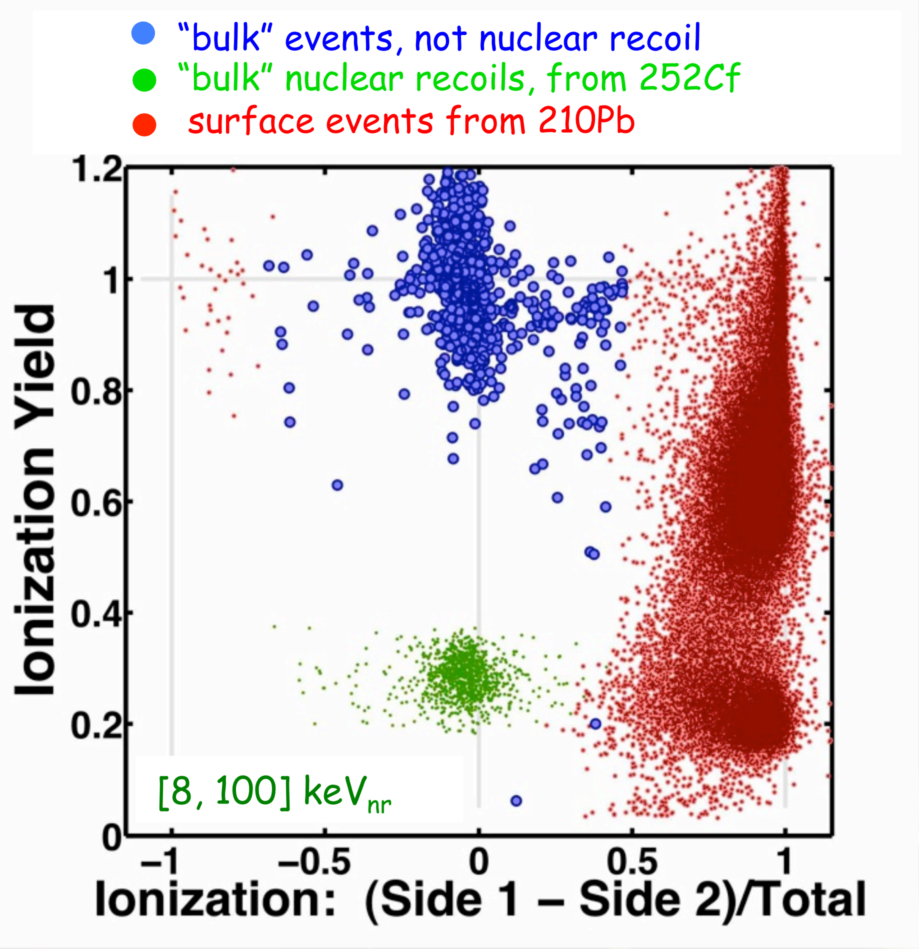


SuperCDMS Soudan

Taking data since March 2012

- 9 kg of Ge arranged in 5 towers at Soudan
- Sensitivity 5-7X better than CDMSII (limited by neutrons)
- New iZIP design gives > 100X better rejection of surface events

iZIP operation at Soudan proves design good enough for ≥200 kg experiment



See parallel session talk by L.Hsu in track 11

XENON100

Leading the field in SI sensitivity (and SD coupling to neutrons)

- Dual phase, TPC measures:
  - S1 – Primary scintillation
  - S2 – Electroluminescence from drifted electrons
- S1/S2 gives O(100):1 separation between ER and NR
- 3-D position information (mm precision) enables self-shielding

Schematic of a liquid noble TPC

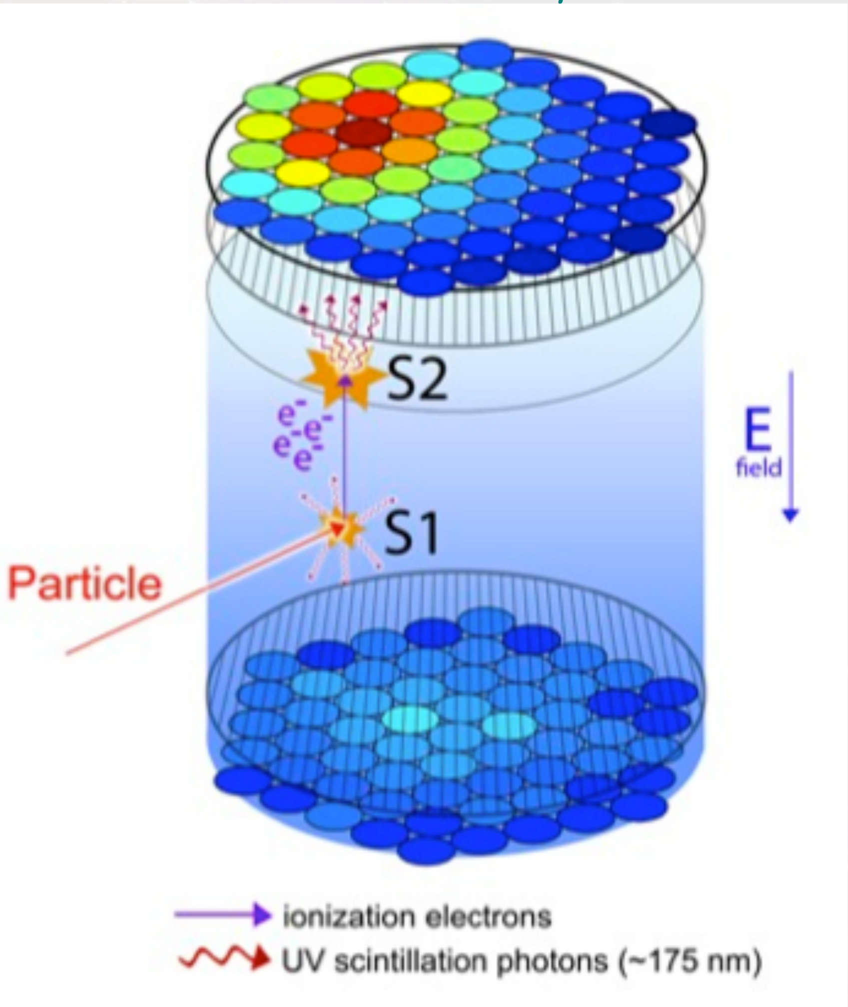
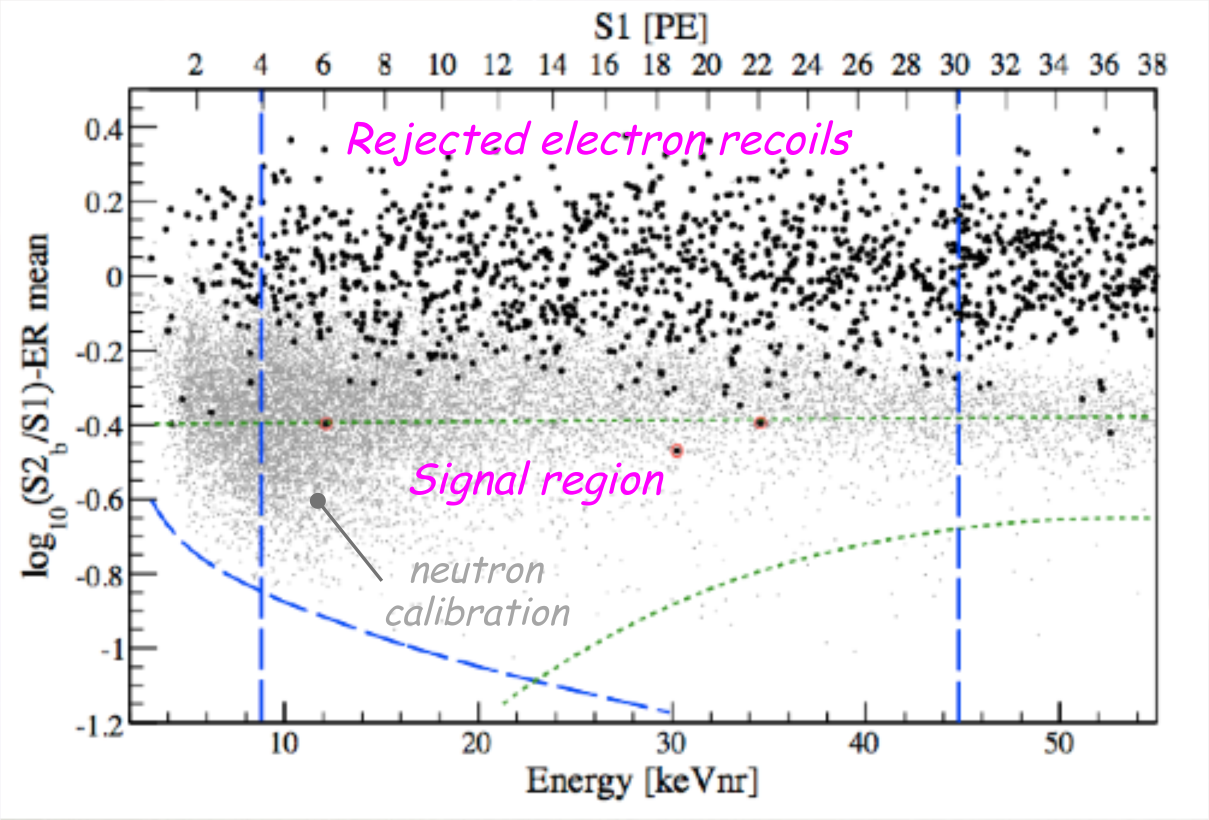


Image by CH Faham

100 Live Days of XENON

- 62(48) kg active(fiducial)
- 3 events, consistent w/ bg
- Limited by ^{85}Kr contamination
- Since then, repurified xenon. Kr problem solved. Other backgrounds remain?

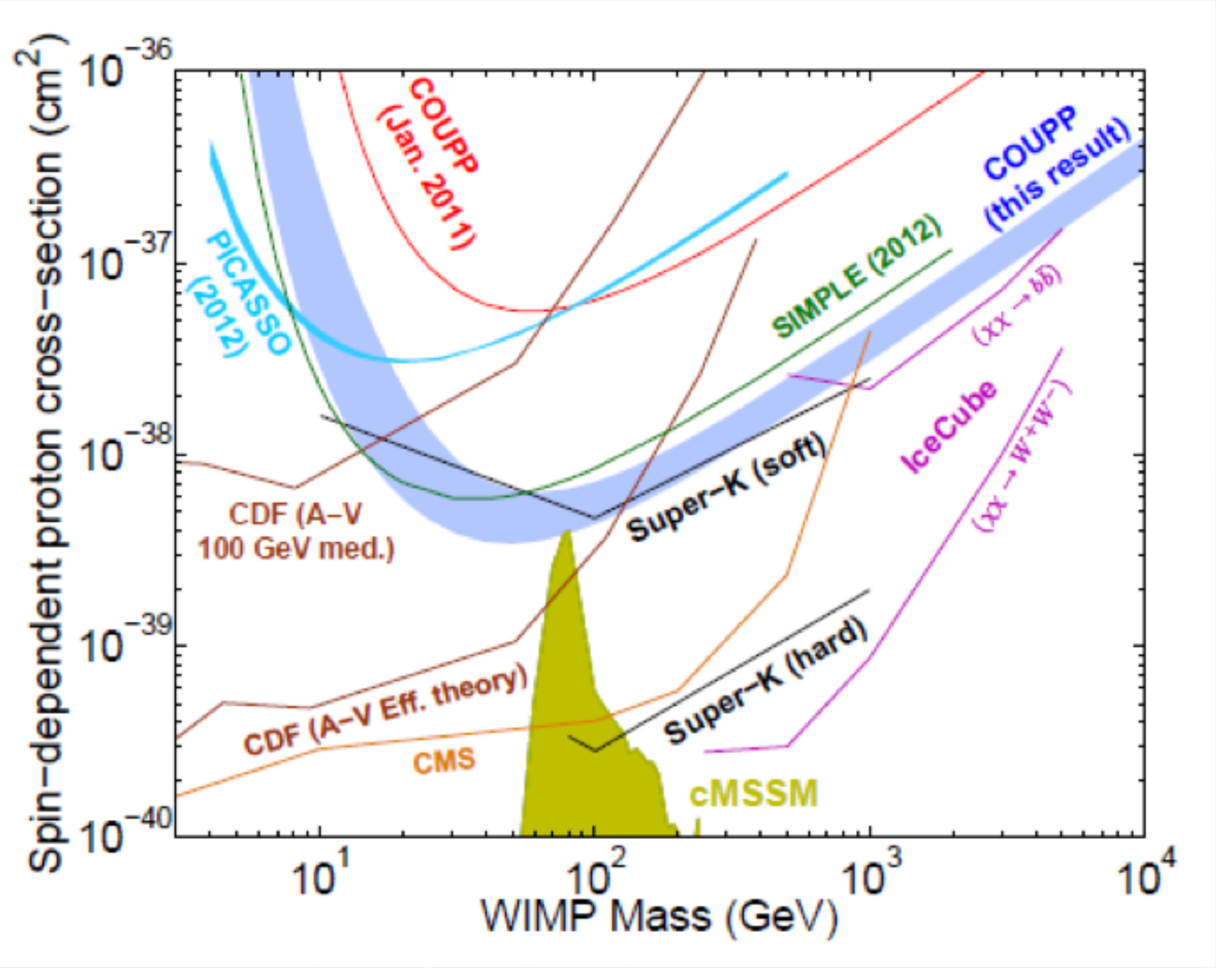
Phys.Rev.Lett. 107 (2011) 131302



New result with 2-3X better sensitivity expected any day now….

Spin-Dependent Landscape

Limit below is only for proton coupling (neutron coupling led by XENON100)



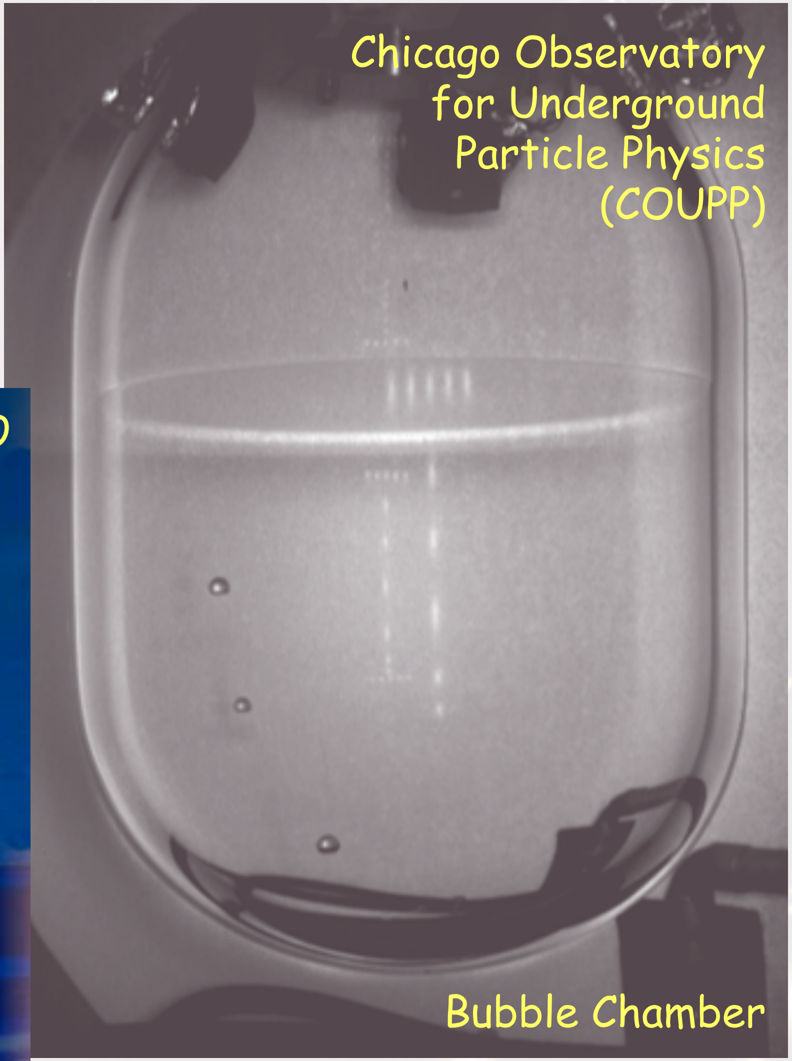
See parallel session talks by R. Neilson and Y. Kim in track 11 for recent SD limits

Superheated Liquid Detectors

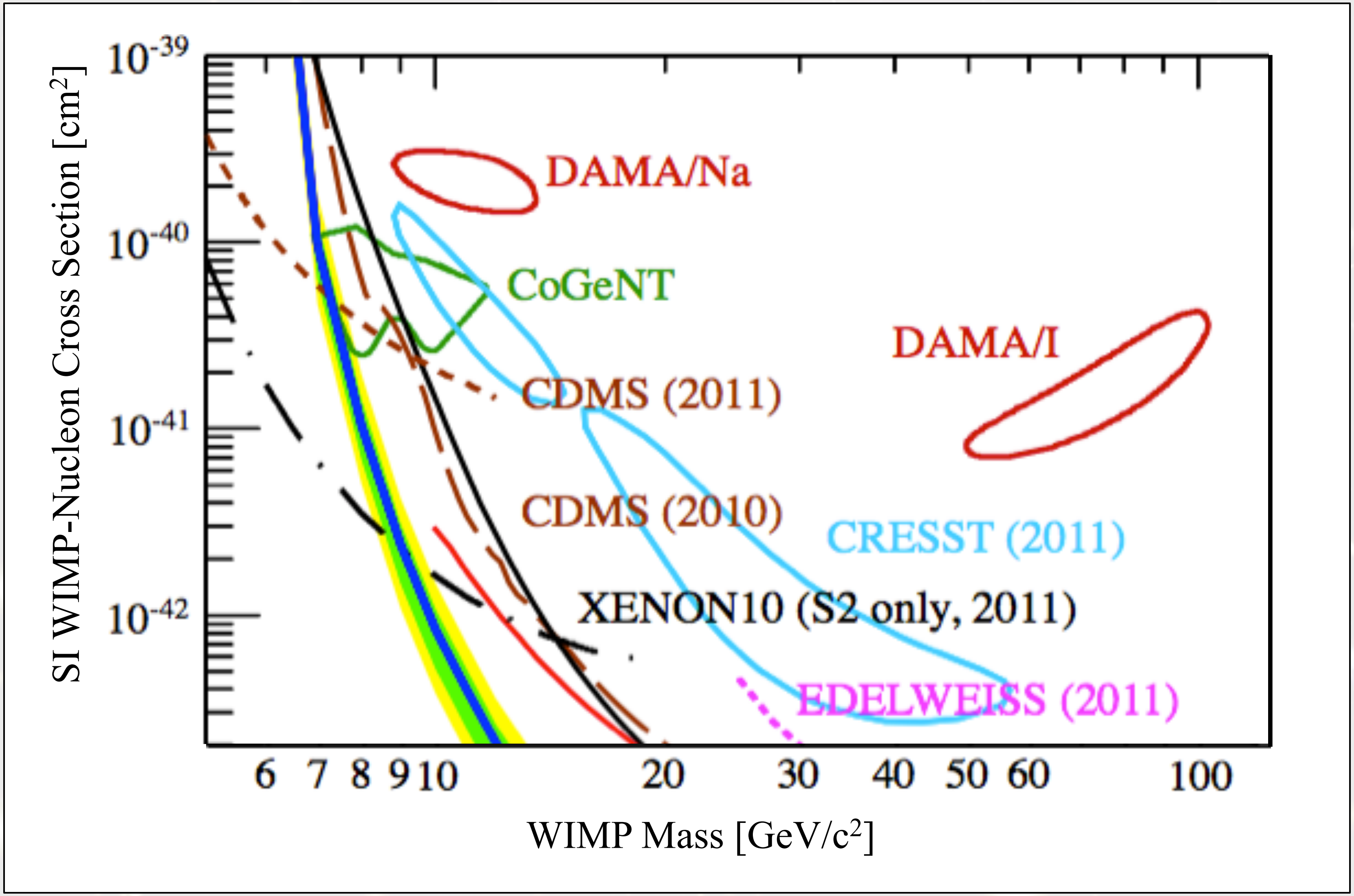
At low degrees of superheat, bubbles nucleated only by nuclear recoils

So far, competitive only in SD measurements

Better control of backgrounds could make them future competitors in SI arena....



Low Mass Landscape: WIMPs or Background?



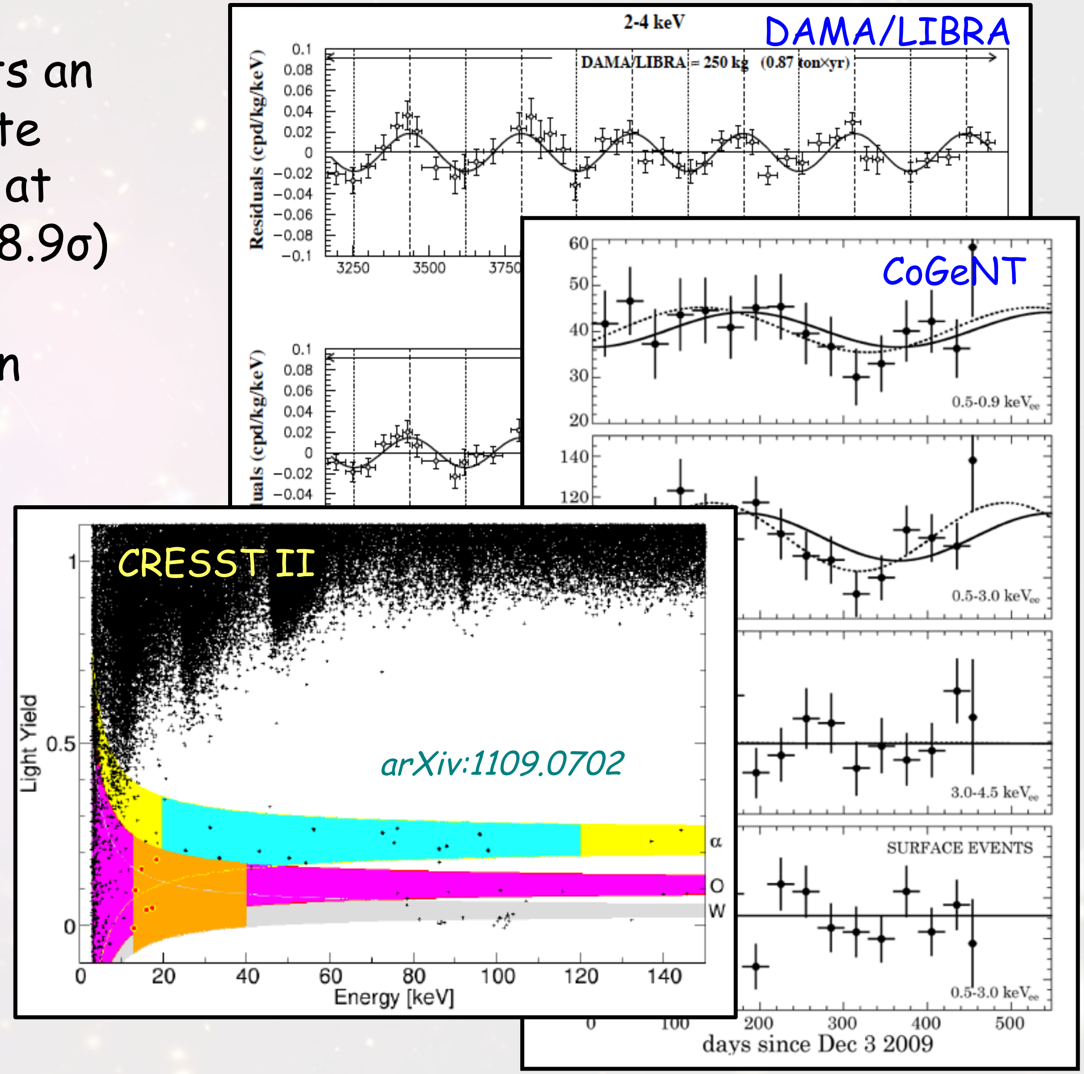
Unexplained Events

2008: DAMA/LIBRA reports an annual modulation in event rate consistent with dark matter, at high statistical significance (8.9σ)

2010/11: CoGeNT reports an overall excess of low-energy events, and an annual modulation – albeit with only ~2σ significance

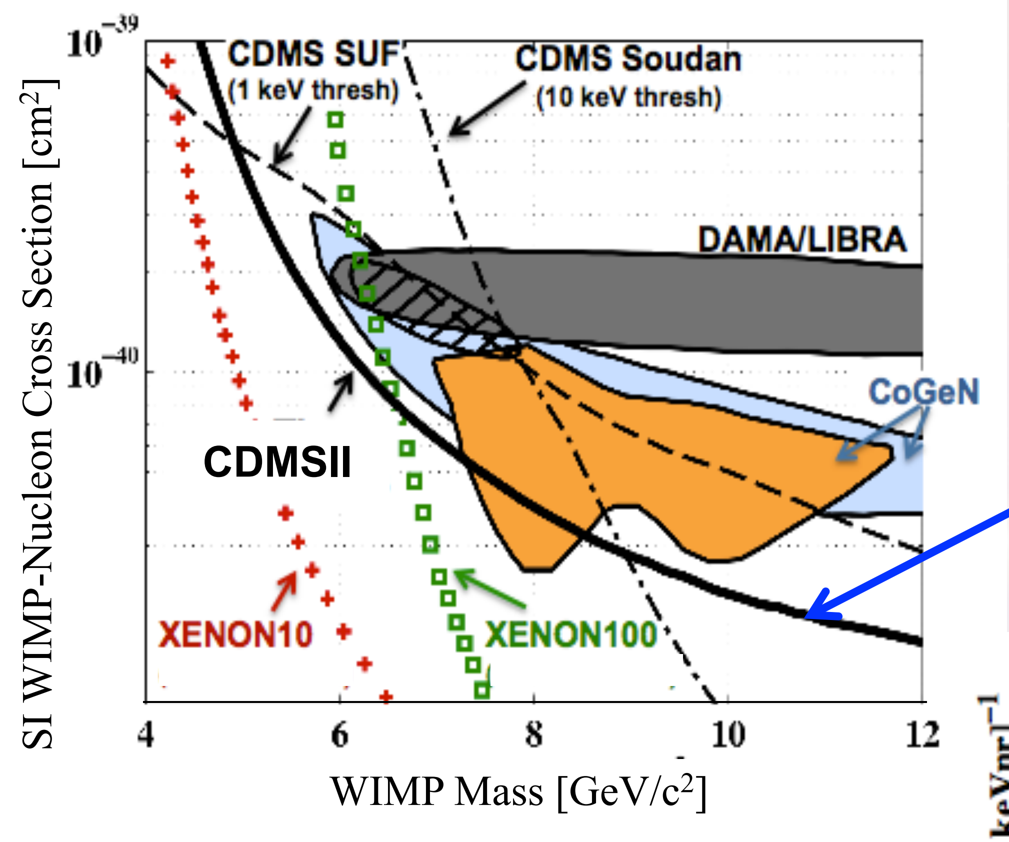
2012: CRESST-II reports a 4.2σ excess of low-energy events

Bernabei et al., Eur Phys J C56 (2008)



Phys. Rev. Lett. 107 (2011) 141301

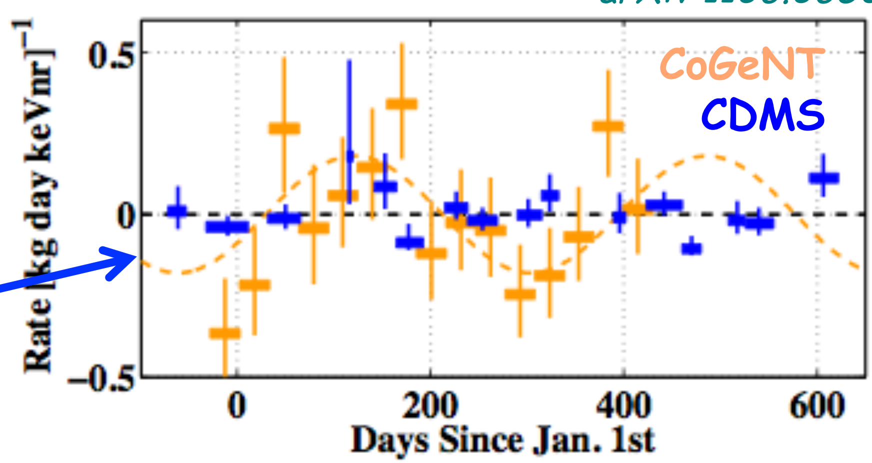
Null Observations



2011: CDMS (and XENON) extend analysis to lower thresholds by allowing more background.

Set conservative upper limits w/o bg subtraction....

arXiv 1106.0650



2012: CDMS looked for an annual modulation of low energy recoils and didn't see any

Controversy?

in 2010 Hooper et al. open possibility that uncertainty in energy scale brings various discrepancies into agreement. Meanwhile, many theories propose dark matter that evades CDMS/XENON while being seen in DAMA/LIBRA

However, CDMS and CoGeNT were particularly difficult to reconcile b/c they are both Ge experiments

CoGeNT's annual modulation never reported as a statistically significant signal. If true, constitutes a very large modulation and hence requires unusual dark matter velocity profile

Last year, CoGeNT revised their analysis and is now reporting a smaller excess (just out of reach of CDMS bounds).

Meanwhile CRESST is making modifications to reduce backgrounds. DAMA/LIBRA's claim remains unresolved…

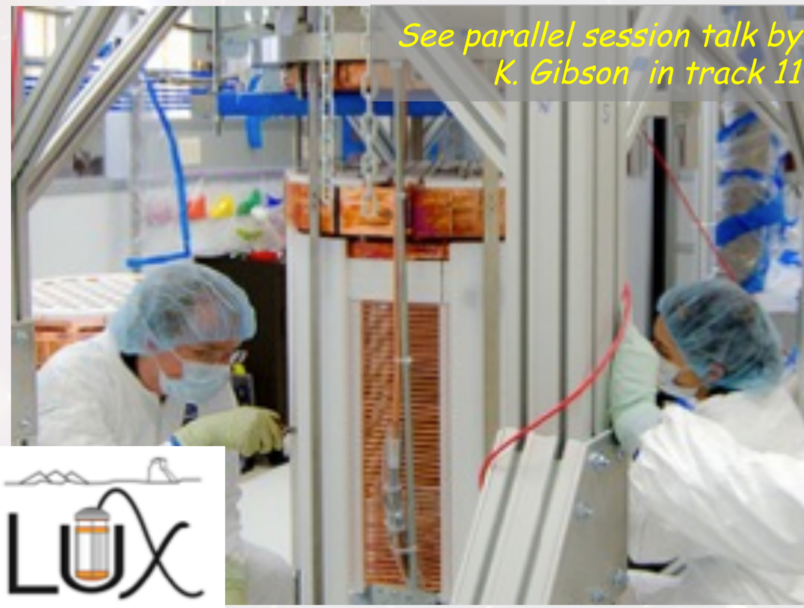
Future Prospects

Liquid Xenon

With XENON100 in the lead and LUX possibly to follow, arguably the most promising technology in the immediate future of direct detection

O(100) kg, results in the next 1-2 yrs?: LUX, XMASS, PANDAX(?)
(XMASS is currently running, but bg is unexpectedly high, requires hardware changes)

O(1000)kg, detector commissioning ≥ 3 yr from now: XENON1T, LZ, PANDAX (?)



Pros: Large A^2 enhancement, low intrinsic contamination, self-shielding, SD and SI sensitivity, deployment of large masses feasible

Cons: Poor ER/NR rejection (only factor of few hundred or none at all) compared to other technologies ➔ *vulnerable to contamination (e.g. Kr), material screening is critical*

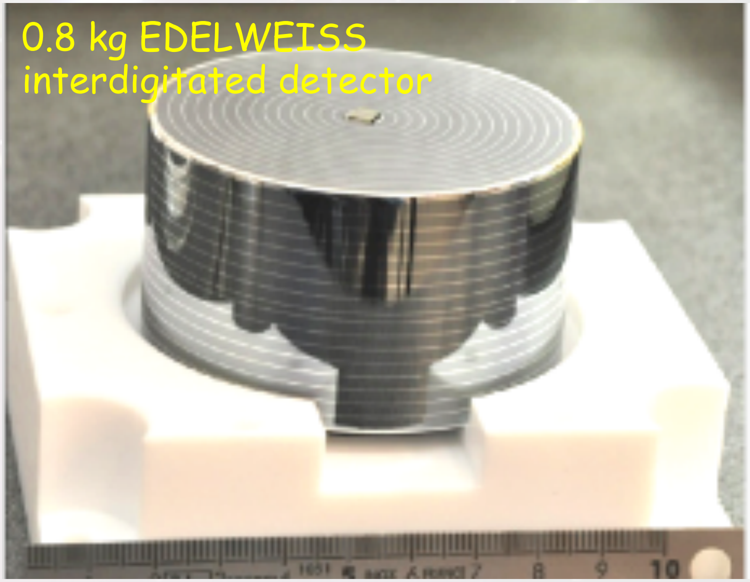
Cryogenic Germanium

Ge experiments have shaped direct detection for ~2 decades, will they continue to lead the field?

EDELWEISS III: ~40 kg, deployment in 2013, sensitivity ~few x 1e-45 cm^2

SuperCDMS SNOLAB: ~200 kg with sensitivity < 1e-46 cm^2 construction start 2014(?)

Eureca: mixed O(1000) kg payload after 2015 (Ge, $CaWO_4$, …)



Pros: Superb ER/NR separation, no intrinsic contamination, excellent energy resolution, low energy thresholds, "sweet spot" of A^2 enhancement, phased deployment is natural and minimizes background uncertainty – *maximal information available per event*

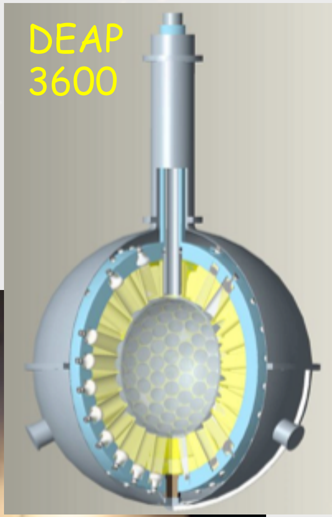
Cons: scaling to larger masses makes this the most expensive technology (main focus of current R&D efforts), detector fabrication takes time

Liquid Argon

Darkside 50 and DEAP3600 are under construction now…

DARKSIDE 50: dual phase TPC, 50 kg liquid Ar (depleted of ^{39}Ar), sensitivity at ~1e-45 by ~2015

DEAP3600: single phase (scintillation only), 3600 kg of liquid Ar, sensitivity at ~1e-46 by ~2015



Pros: Extraordinary ER/NR separation using pulse shape, deployment of large masses feasible

Cons: light nucleus (less A^2 enhancement), sensitivity to < ~10 GeV/c^2 WIMPs is poor due to high recoil thresholds, ^{39}Ar must be removed for multi-ton scale, no SD sensitivity

Directional Detectors

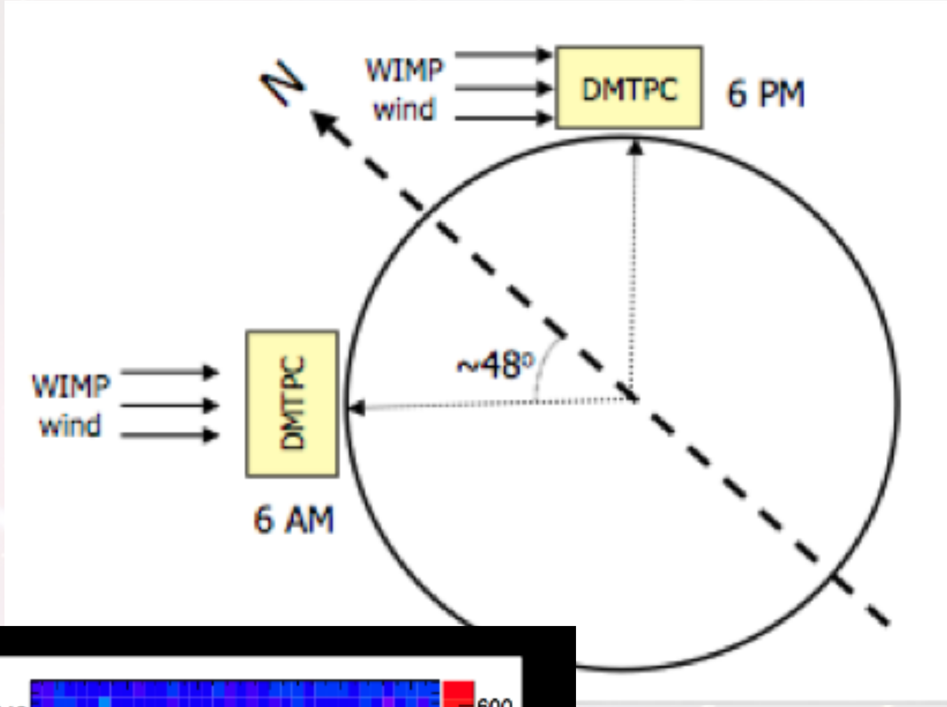
Sun's motion through the dark matter halo can be perceived as a "WIMP wind"

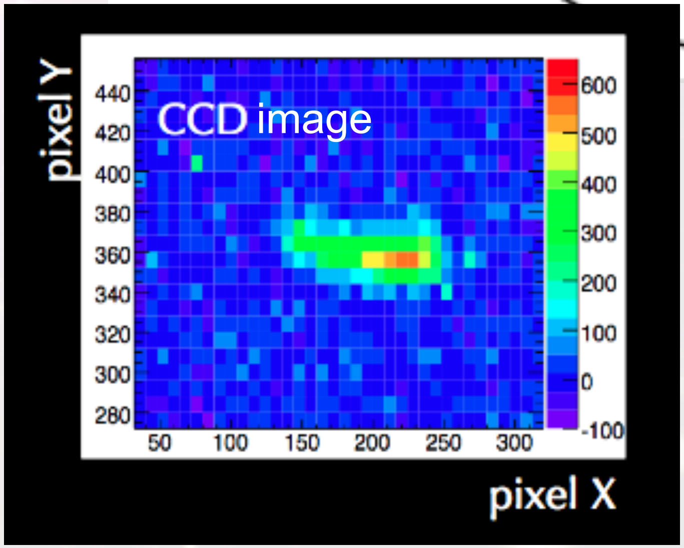
Low pressure TPC's preserve dE/dx profile such that "head to tail" measurement can be made

Recently: first limits from directional detectors:

- *Drift: arXiv:1110.0222*
- *DMTPC: PLB 695 (2011)*

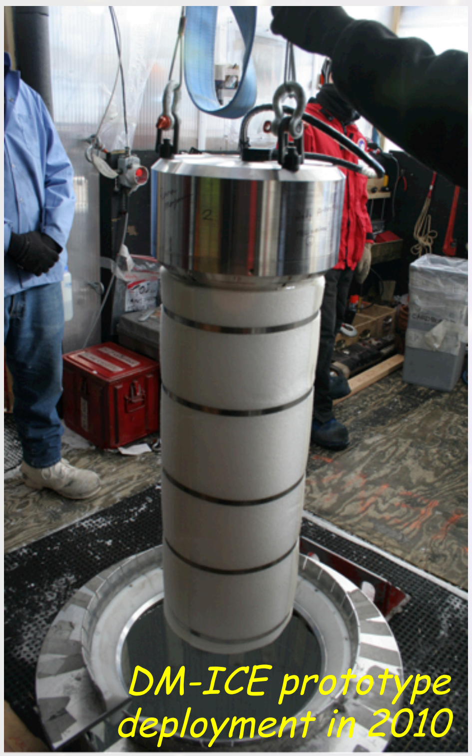
Sensitivity to zeptobarn cross sections requires scaleup to very large volumes (R&D underway)





Annual Modulation Searches

Resolving the DAMA annual modulation puzzle remains a high scientific priority

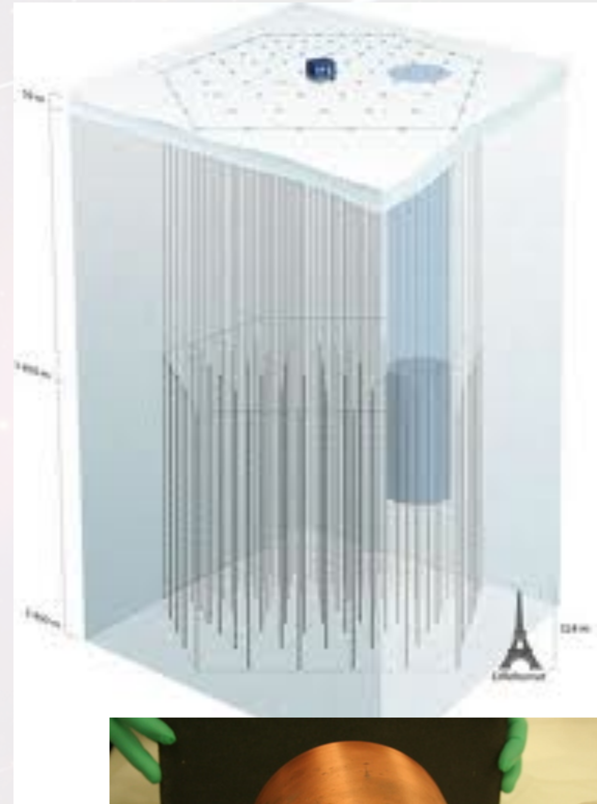


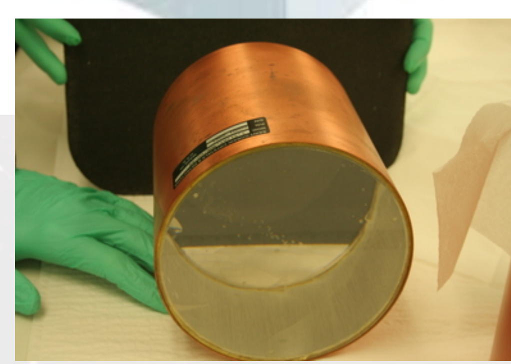
DM-ICE prototype deployment in 2010

DM-ICE

A new effort to deploy ~200 kg of NaI crystals on ICECUBE strings, within the ICECUBE detector

Backgrounds tied to seasonal effects will modulate with a different phase in the Southern Hemisphere





Backgrounds and sensitivity described in: Astropart. Physics 35 (2012), 749-754

Complementarity

Do we really need so many experiments?

Well, probably not *all* of them, but short answer is YES we do want multiple direct detection experiments ! Its important to have several different technologies and several different target nuclei

Theoretical argument

Scattering off different targets can be used to extract dark matter properties and determine what type of particle it is

Experimental argument

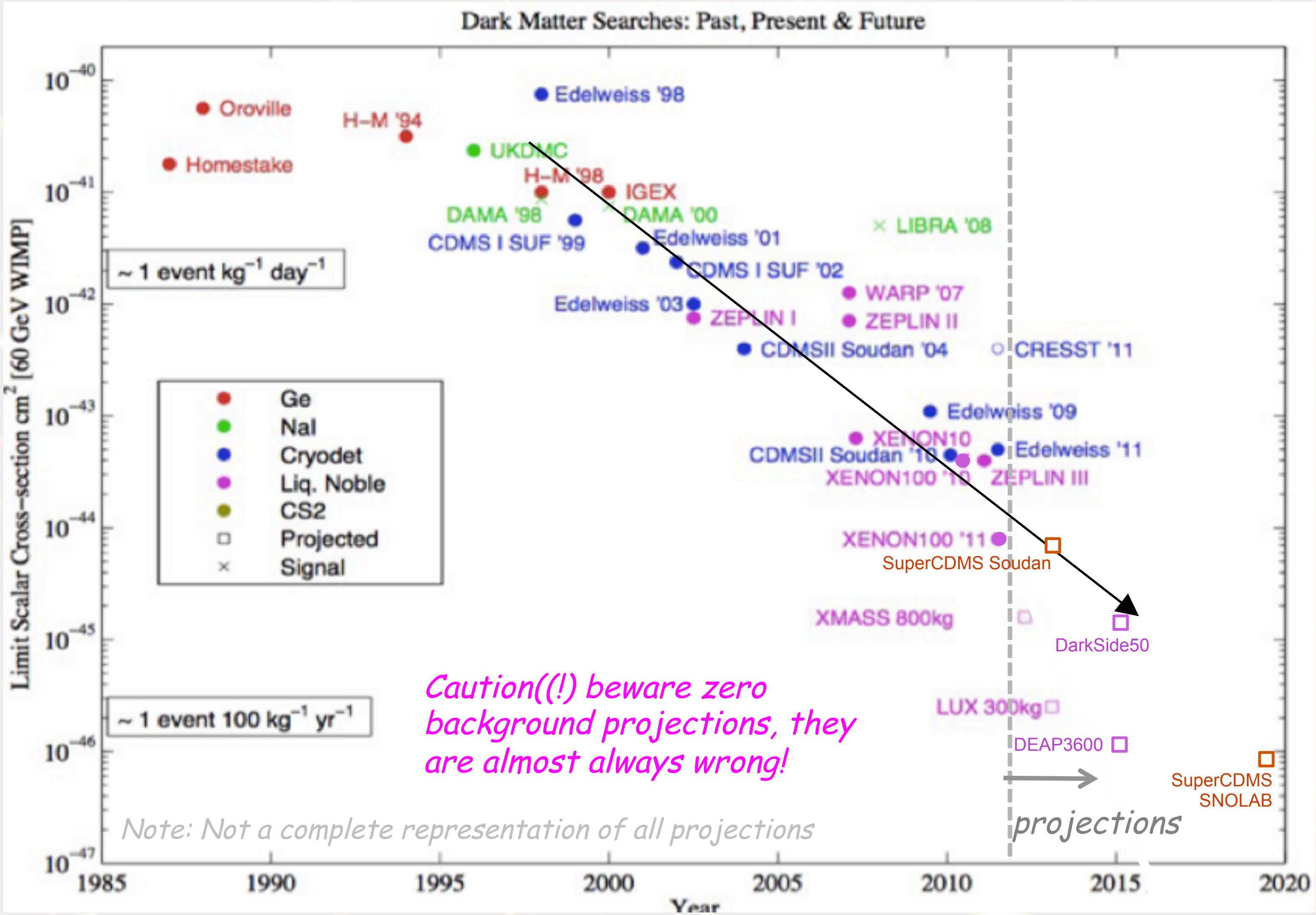
Picking out a true WIMP signal from vast backgrounds is tricky. Different technologies are susceptible to different backgrounds so having cross checks is important. Take the low mass WIMP discussion as an example

Practical argument

Direct detection experiments are inexpensive on the scale of HEP, science output per dollar is high!

Moore’s Law for Direct Detection

Sensitivity roughly doubled every ~20 months for the past decade (!)



Summary

Direct detection is complementary to indirect and collider searches for dark matter

Novel detector designs and fierce competition drive the fast and exciting progress in this field

Running experiments and those soon to be commissioned are about to explore one of the most interesting theoretical regions

Now that we think we've found the Higgs, will dark matter be the next great discovery of particle physics?

Too many endeavors, too little time (!) – I apologize if I left your favorite experiment out of the discussion