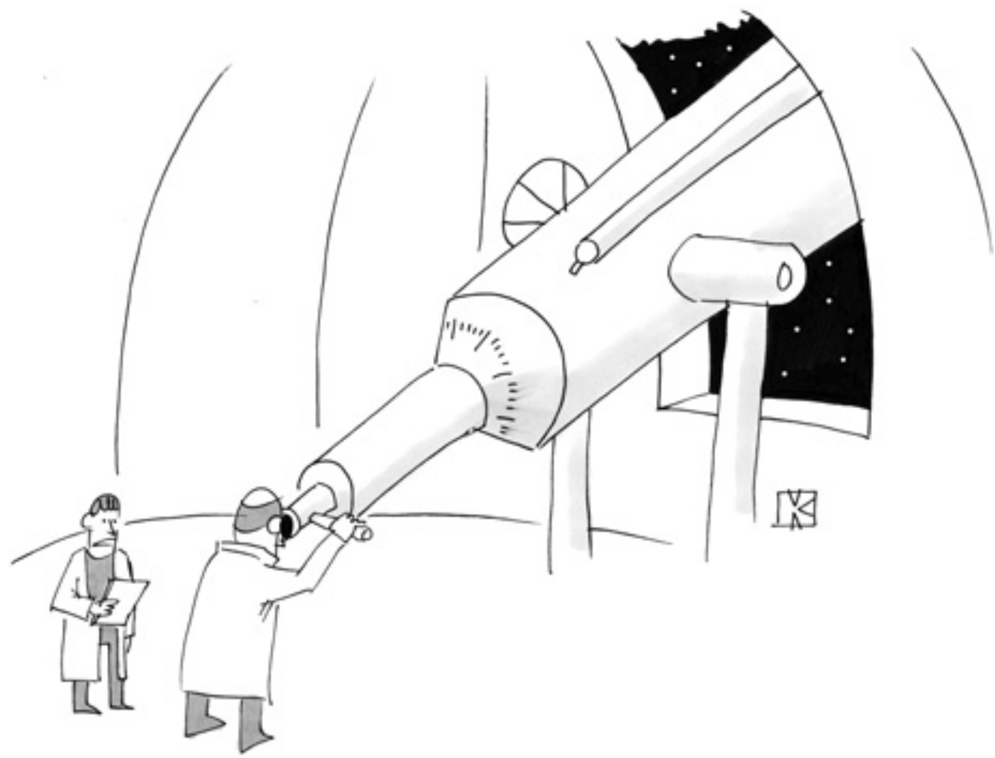
Dark matter: the next great discovery of particle physics?

Lauren Hsu
Fermilab Astrophysics Department
Colloquium, October 31, 2012

The dark matter problem

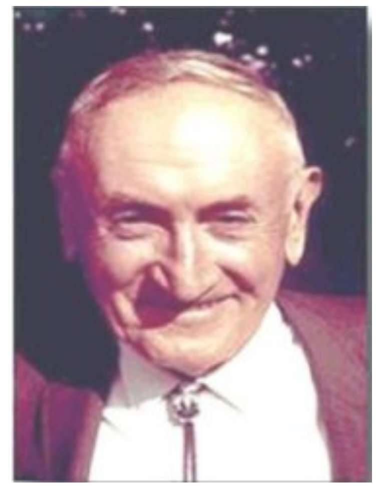


"That isn't dark matter, sir – you just forgot to take off the lens cap."

Zwicky's puzzle

1933:

Fritz Zwicky analyzed velocity dispersion in Coma Cluster



Individual galaxies move too fast for a bound system…

Posited existence of unseen matter in the cluster and named it "dark matter"

Progress stalls for several decades

was Zwicky's observation a brilliant deduction or something else?

Zwicky had a reputation for ideas of questionable merit:

- Artificial meteors
- Solar system relocation
- Reducing air turbulence with firearms

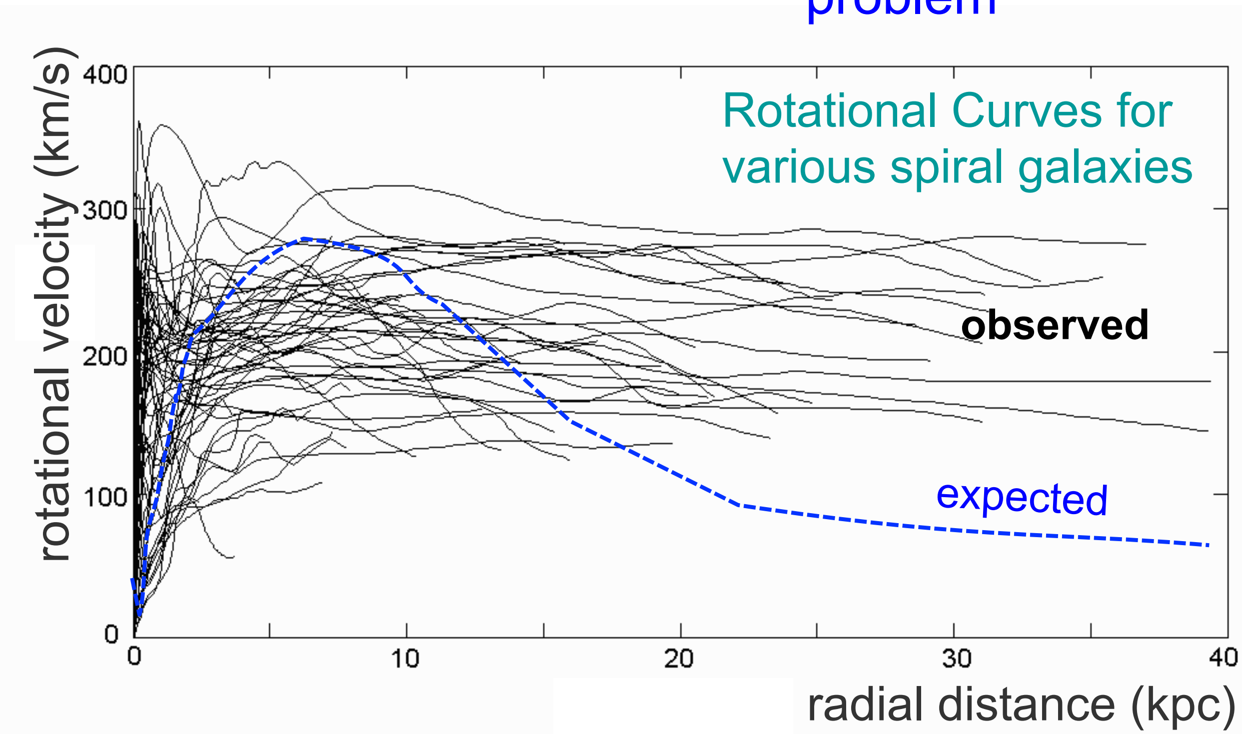
but also for extraordinary insights:

- Supernovae
- Neutron stars
- Gravitational lensing
- Dark matter

Zwicky's contemporaries understandably had trouble seeing the difference !

Galactic Rotation Curves

In the 1970's, flat rotation curves established the missing mass problem



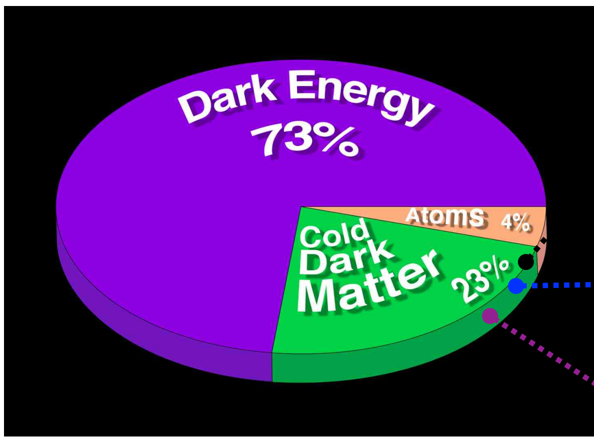
Vera Rubin uses 21 cm hydrogen line to study galactic rotation curves

Instead of falling off, velocities are flat as a function of radius.

Indisputable evidence : Galaxies have massive, unseen halos of matter that extend far outside the region of visible, luminous matter.

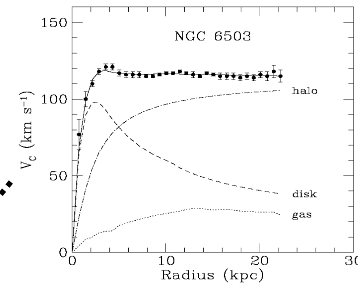
The modern view

We know a lot about dark matter

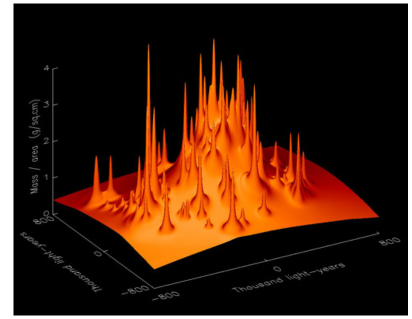


But we still don't know what it is!

stable, gravitationally interacting

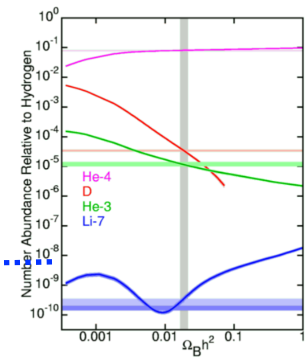


galactic rotation



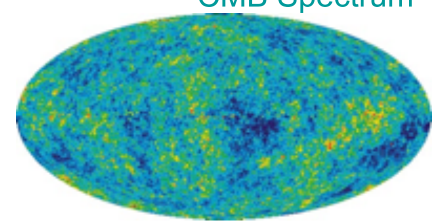
gravitational lensing

non-baryonic

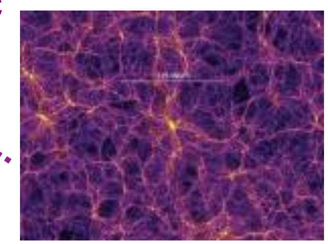


BB nucleosynthesis

CMB Spectrum

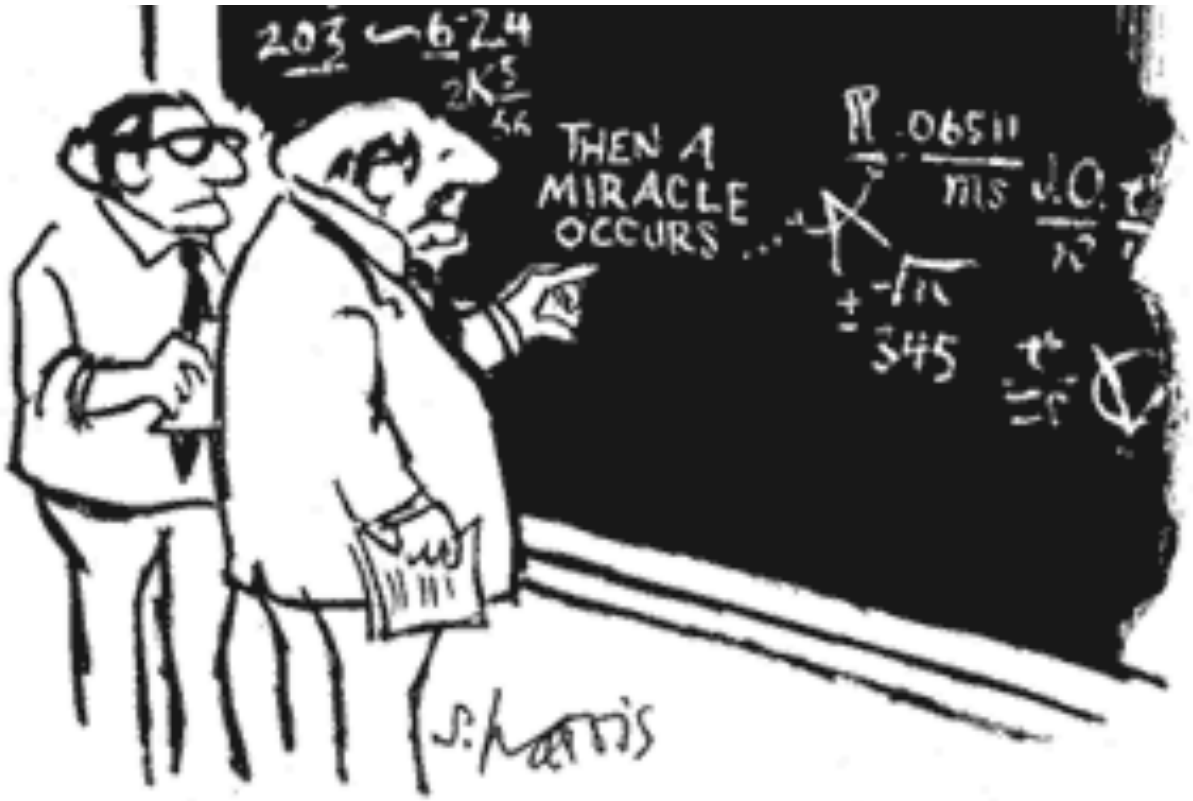


non-relativistic



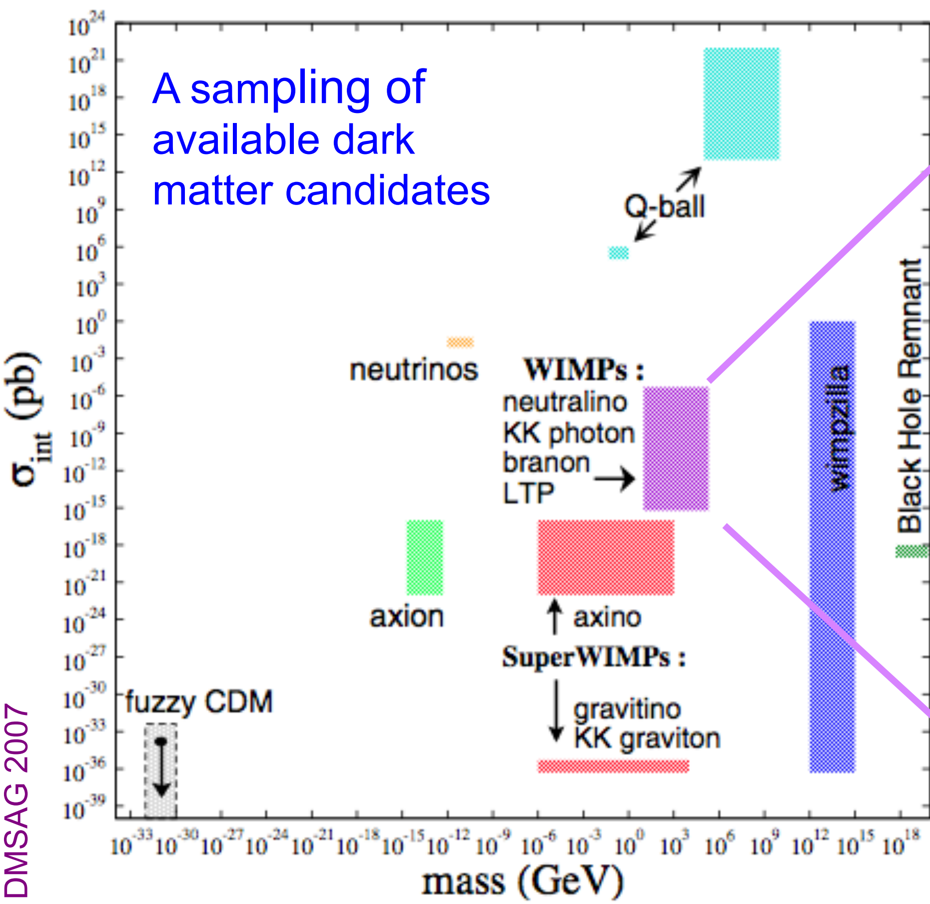
large scale structure formation

WIMP Detection 101



"I THINK YOU SHOULD BE MORE EXPLICIT HERE IN STEP TWO."

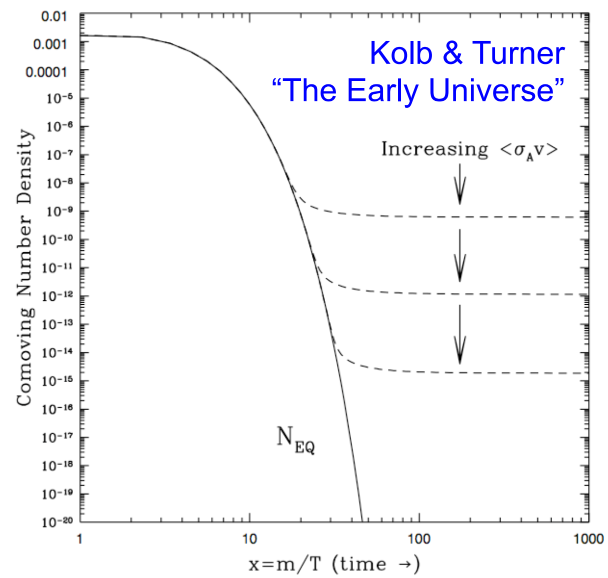
The Weakly Interacting Massive Particle



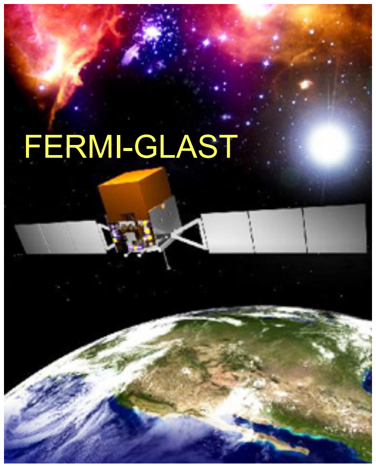
DMSAG 2007

The WIMP "Miracle"

Particles with mass and couplings at the weak scale yield cross sections that correspond to ~correct relic density of CDM

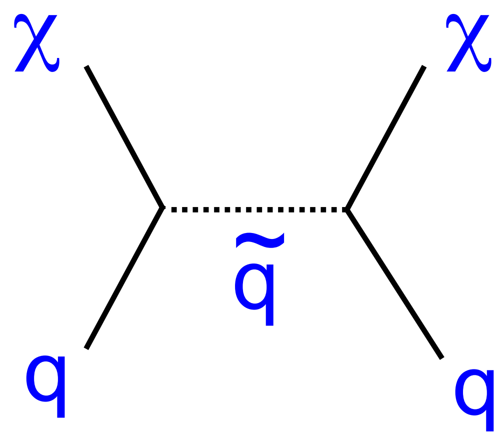


How to detect WIMPs



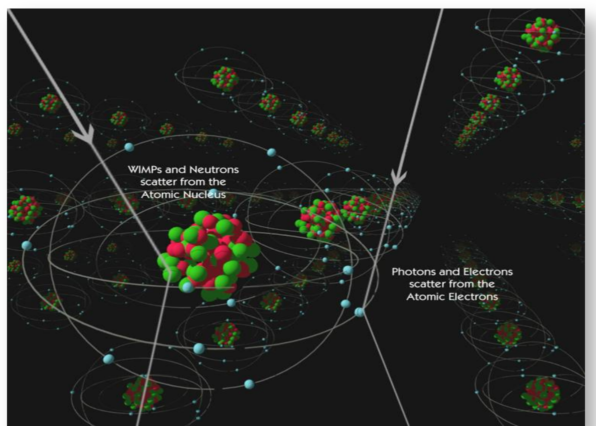
Relic annihilation in the cosmos

INDIRECT DETECTION



man-made COLLIDER production

M. Attisha



Relic WIMP-nucleon elastic scattering

DIRECT DETECTION

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**

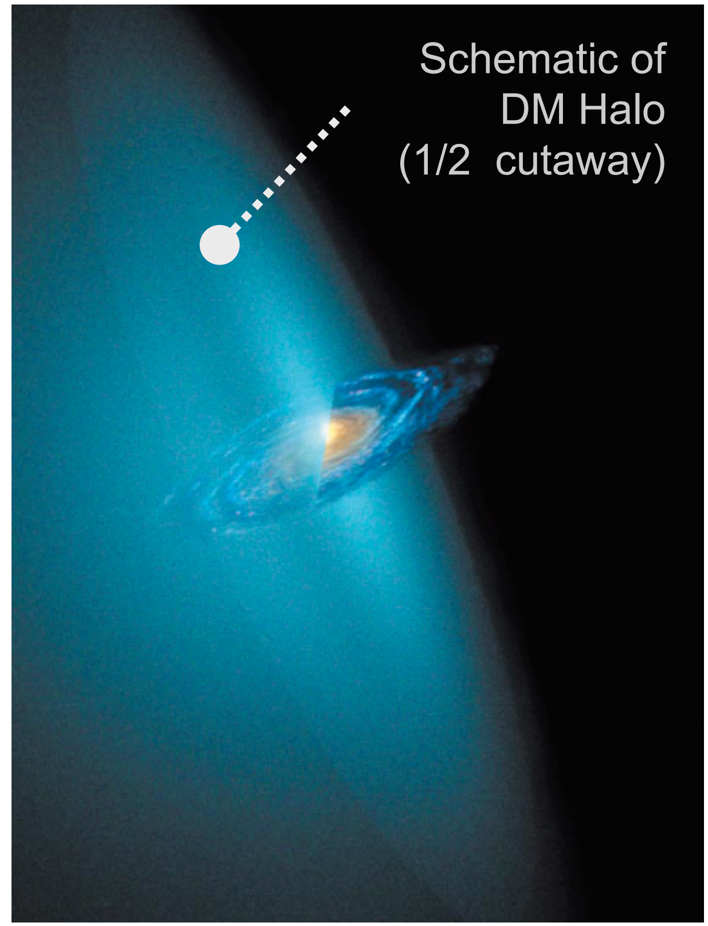
$$\rho \sim \rho_0 (r/r_s)^{-1}(1+r/r_s)^{-2}$$

- **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!



WIMP-nucleon scattering

General WIMP-nucleus elastic scattering cross section (for $q^2 = 0$):

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

WIMP-nucleon scattering

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Spin-independent scattering

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

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Spin-independent scattering

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↓

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

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↓

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

WIMP-nucleon scattering

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

Spin-dependent scattering

WIMP-nucleon scattering

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Spin-dependent scattering

↓

scales with spin of nucleus (opposite signs can cancel) – NO COHERENT EFFECT!

WIMP-nucleon scattering

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

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)

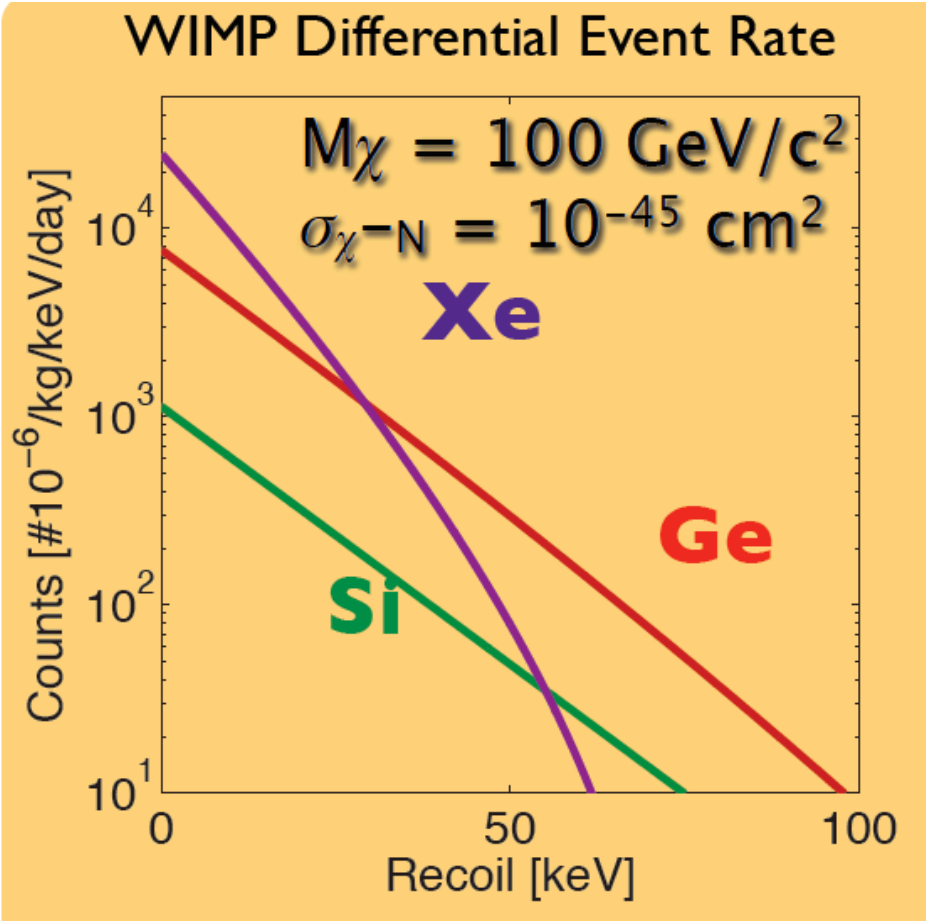
The expected signal

Features:

- nuclear recoil from ES of WIMP
- featureless exponential; few keV to few 10's of keV
- rates <<0.1 events /kg/day

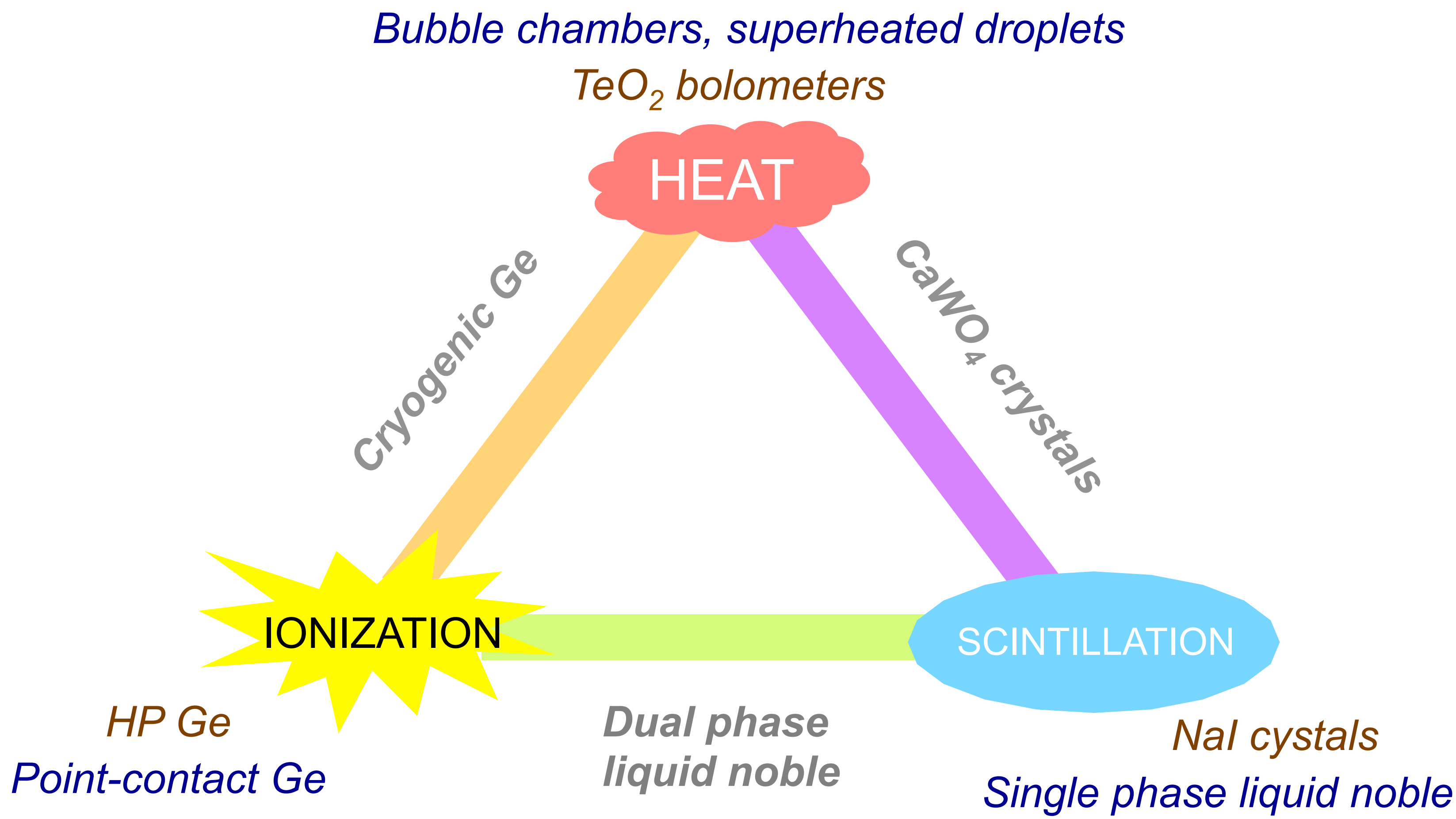
Challenges:

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



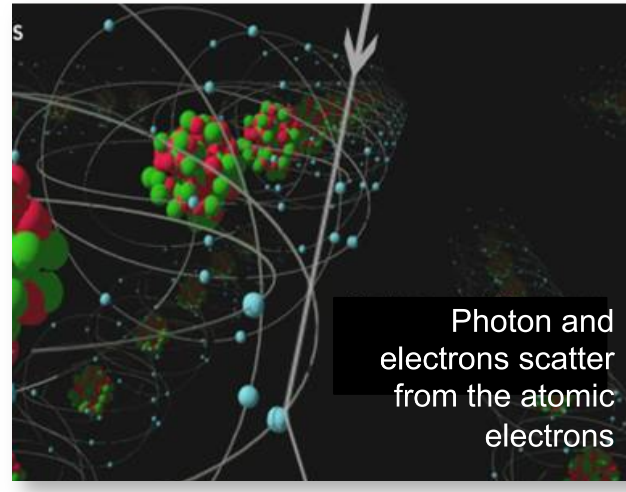
~~WIMP detection~~ techniques

Background rejection



Its all about backgrounds

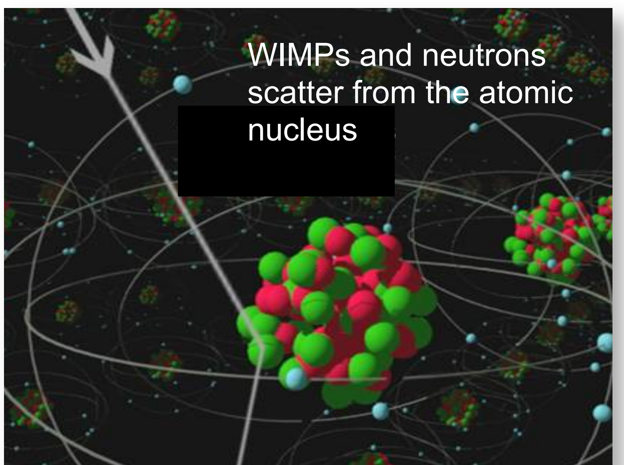
ELECTRON RECOILS



Gamma: MOST PREVALENT BACKGROUND

Beta: "surface events"

NUCLEAR RECOILS

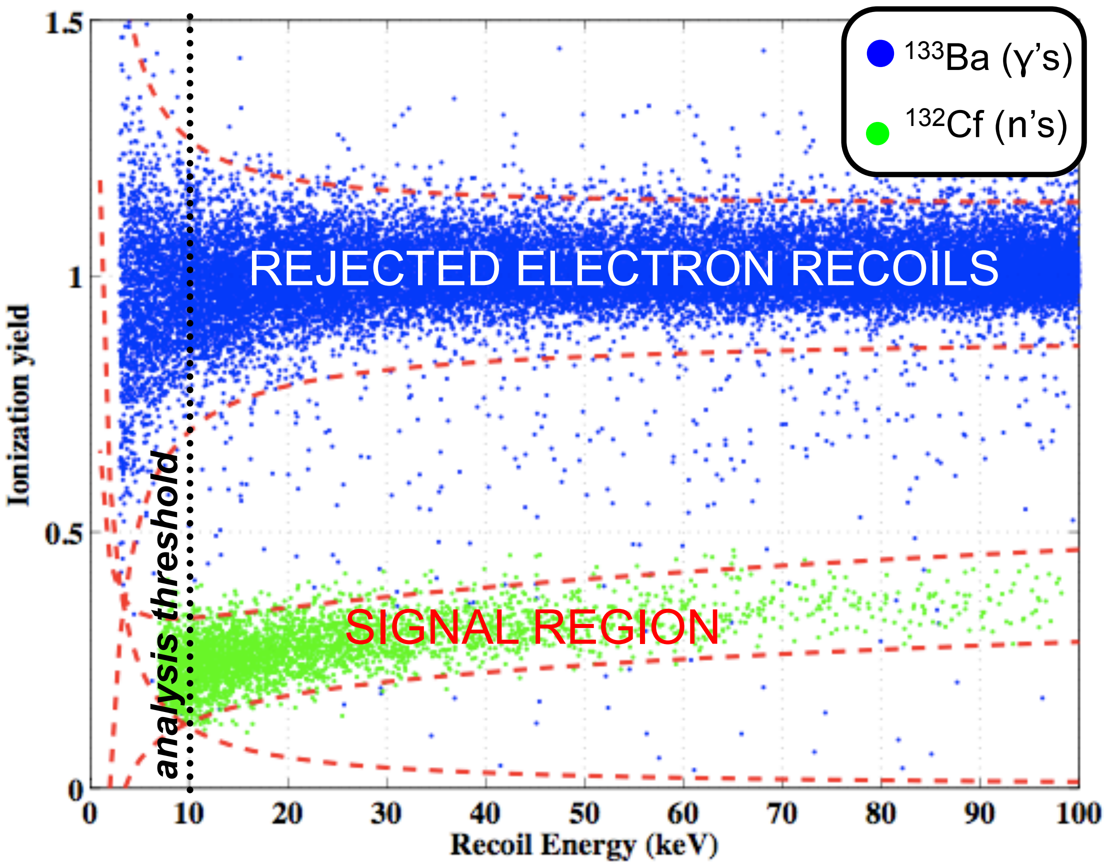


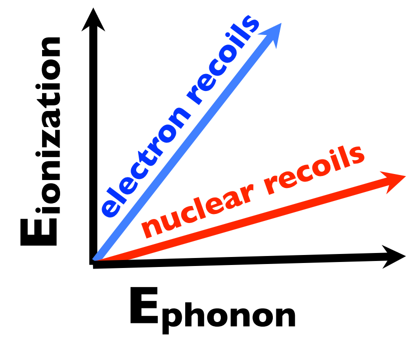
Neutron: rare but NOT distinguishable from WIMP signal

Alphas: another class of surface event

Recoiling parent nucleus: yet another surface event

Textbook example w/ CDMS





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

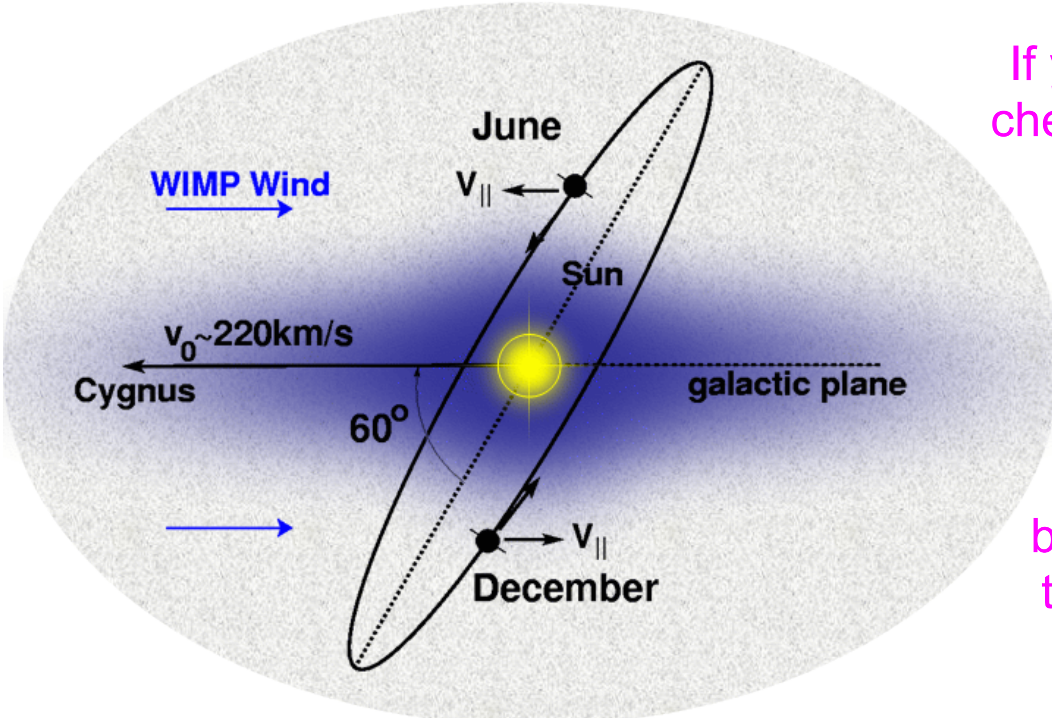
1:10^4 rejection of gammas based on ionization yield alone

Surface events are a near-universal problem in direct detection (!)

Annual modulation effect

Earth's motion about the Sun produces small changes in velocity relative to the dark halo

➔ Modulates expected rate of dark matter interactions detected on Earth



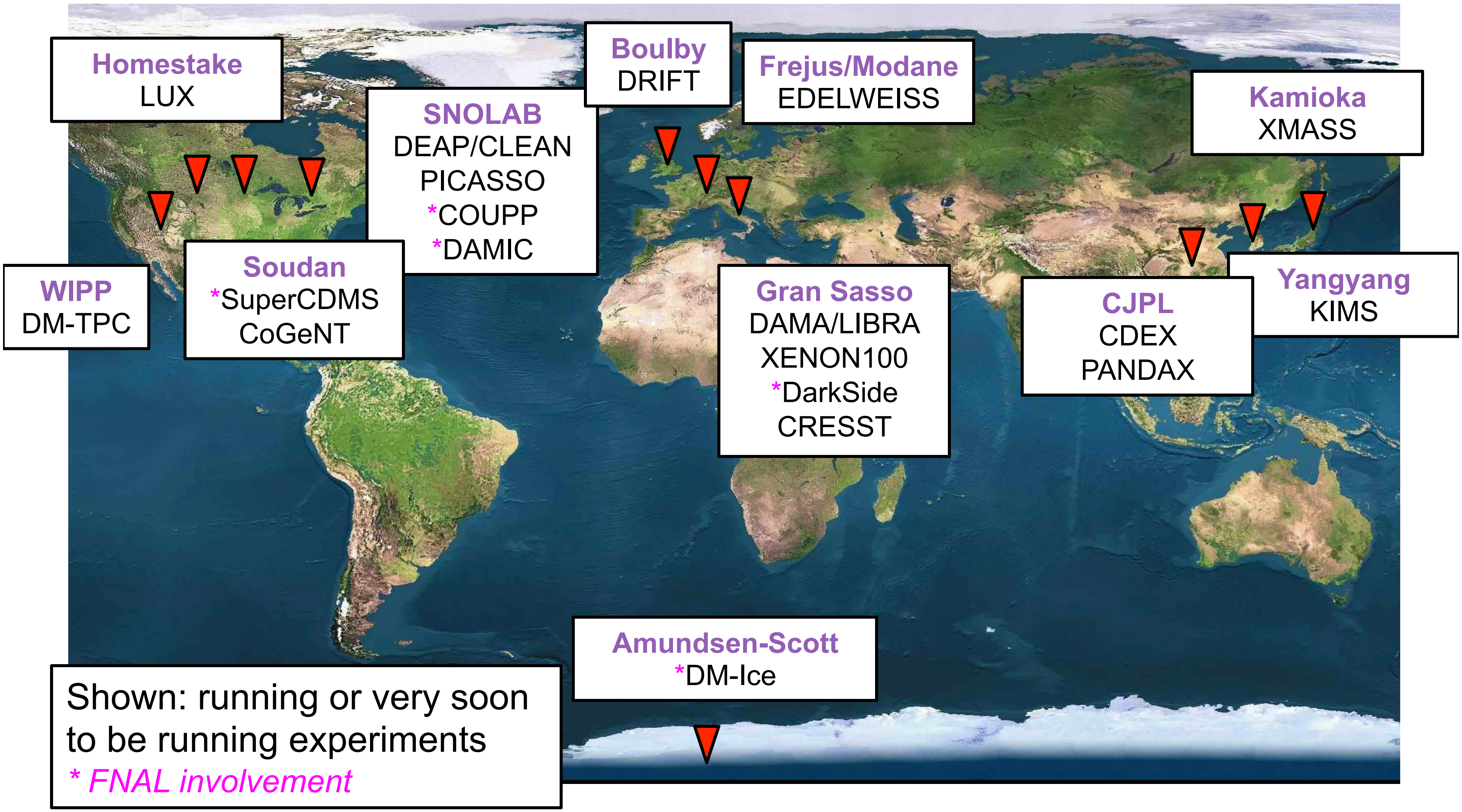
If you see a signal, check for an annual modulation

OR

If you have irreducible backgrounds, use the modulation to pick out a signal

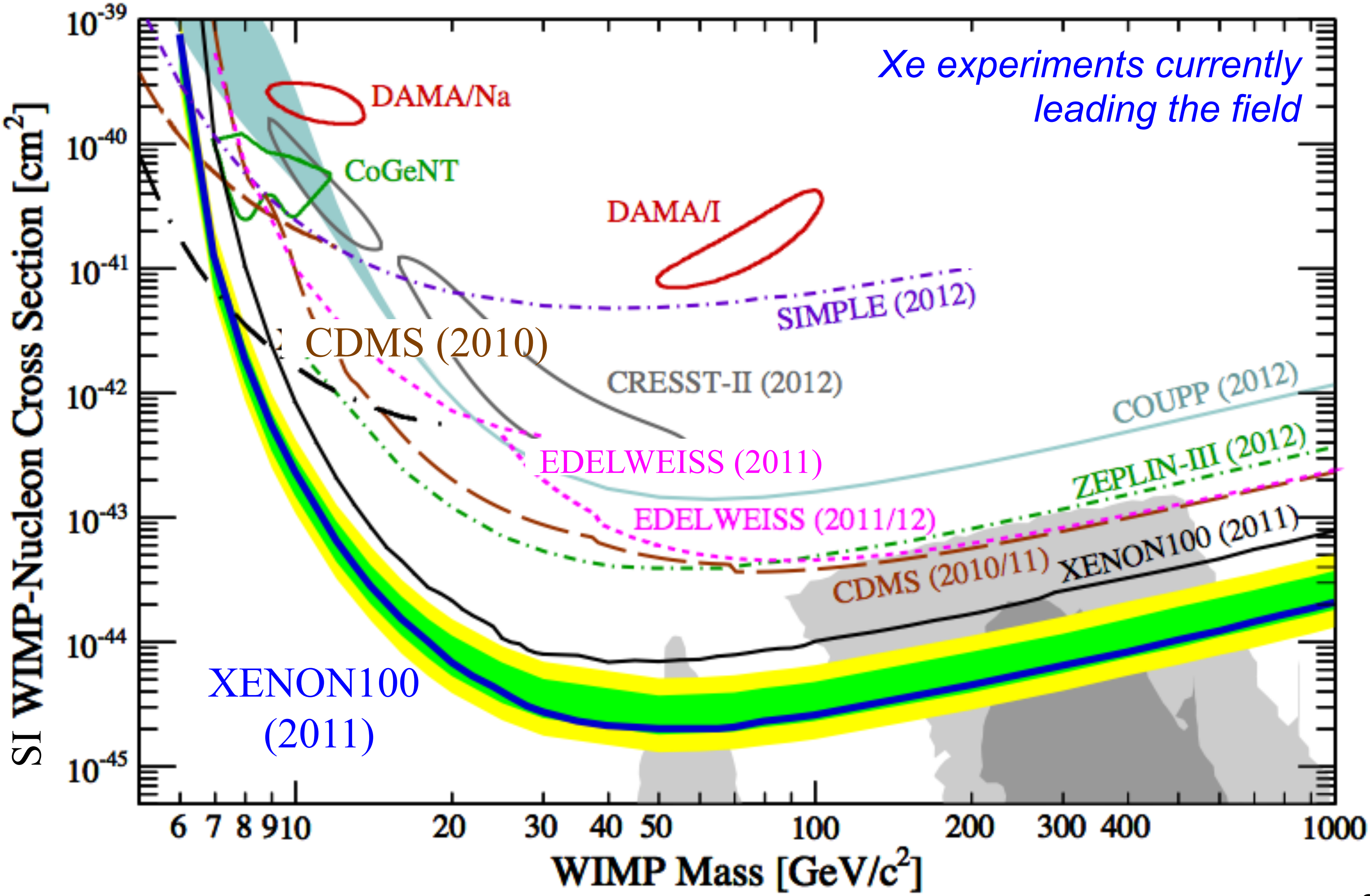
A dark-matter-induced modulation will have extrema in June and December (whether it's max or min depends on target and threshold)

World-wide search



Status of running experiments

Spin-Independent Landscape



XENON100

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

- Dual phase, TPC measures:
  - S1 – Primary scintillation
  - S2 – Electroluminescence from drifted electrons (ionization)
- 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

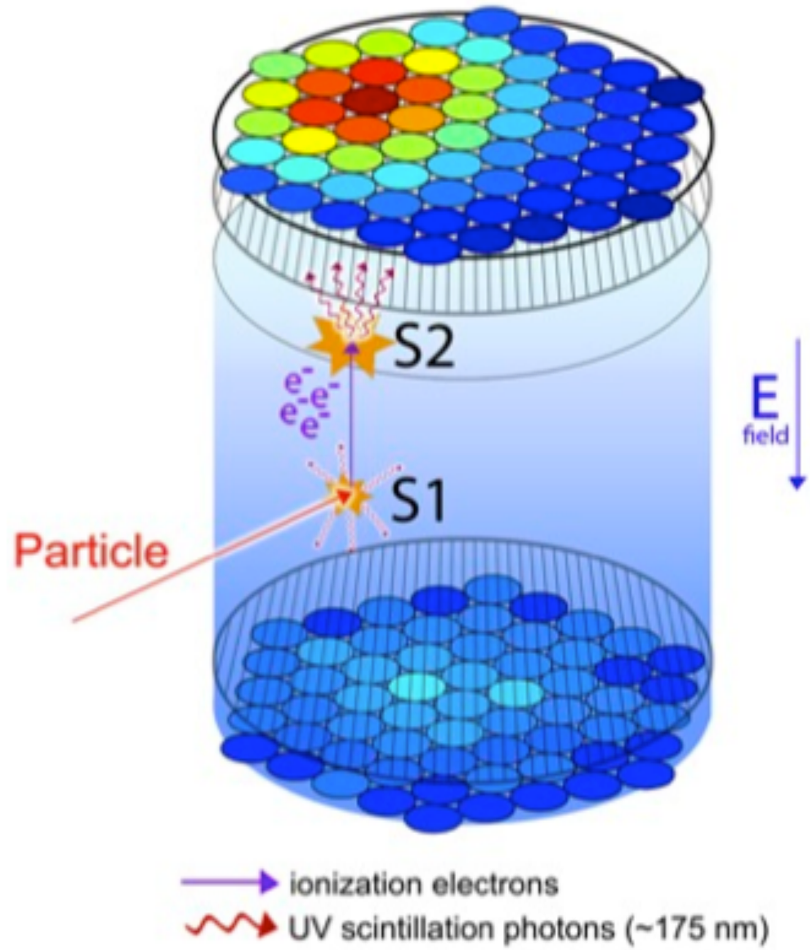
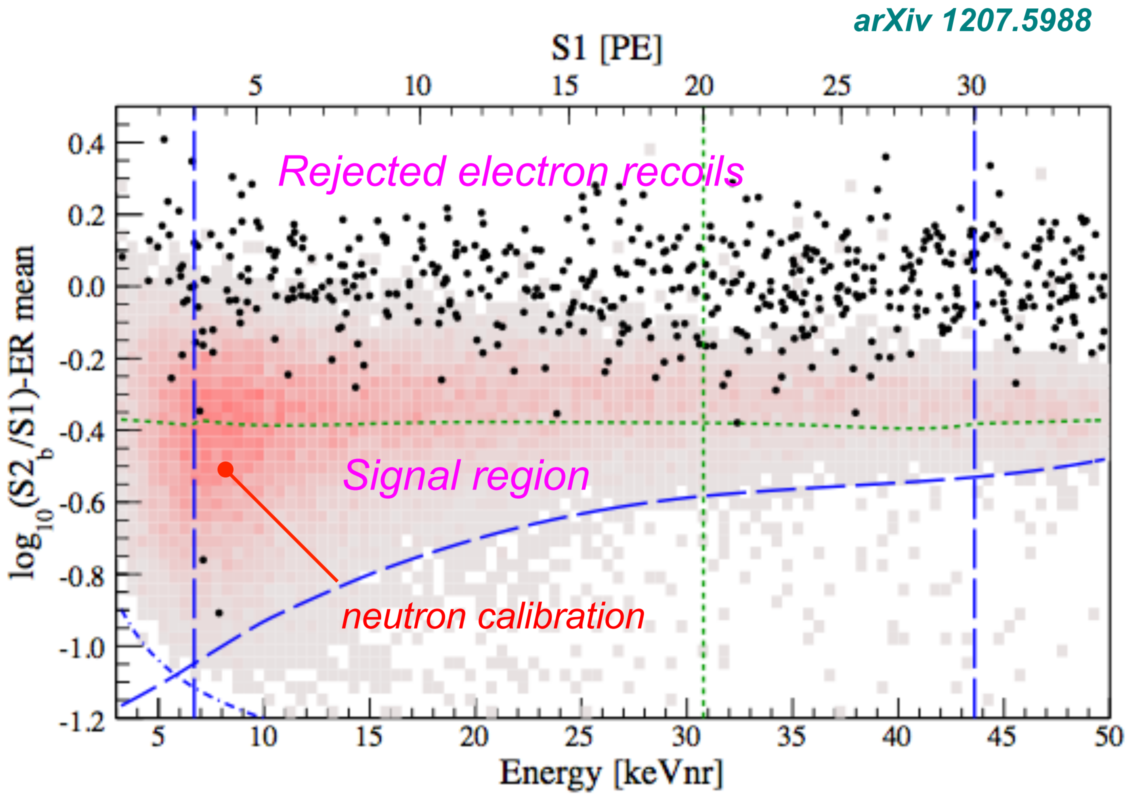


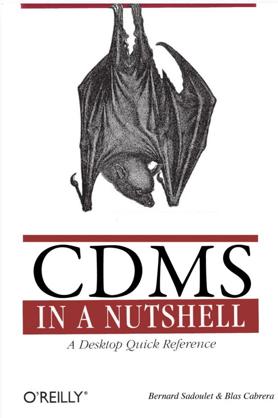
Image by CH Faham

225 Live Days of XENON

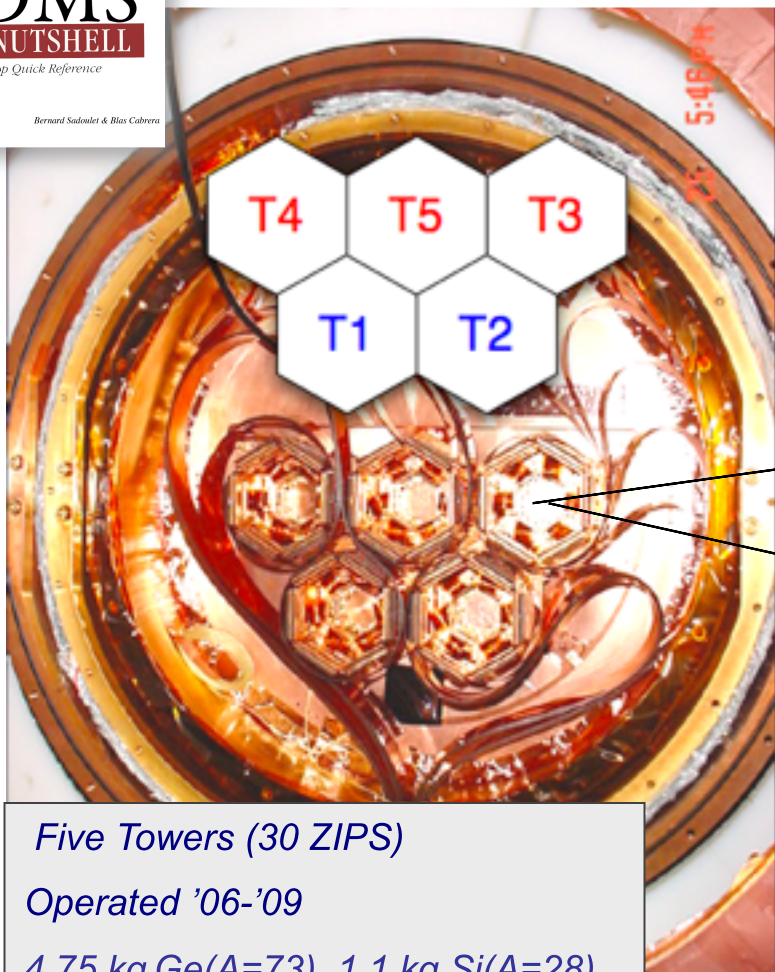
- 62(34) kg Xe active (fiducial) target
- 2 events, consistent w/ background estimate, but not consistent with background distributions
- ^{85}Kr significantly reduced, S2 trigger threshold reduced

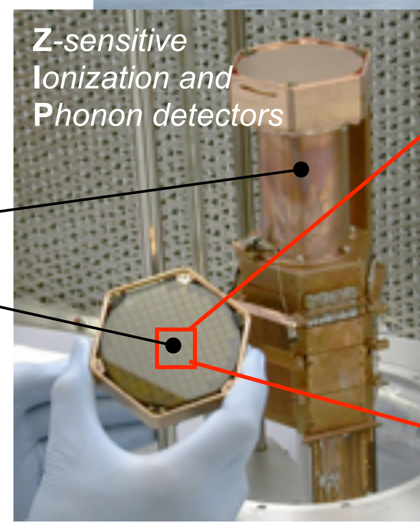


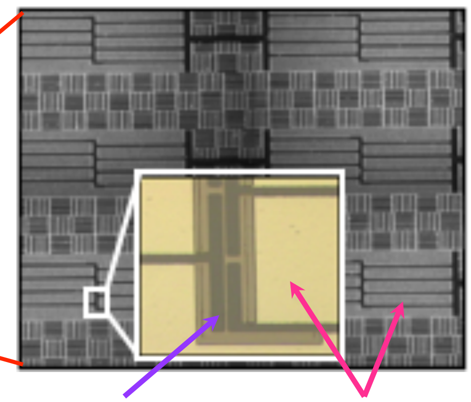
XENON100 will continue to run but collaboration now focusing on building 1T detector



Cryogenic Dark Matter Search







Five Towers (30 ZIPS)

Operated '06-'09

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

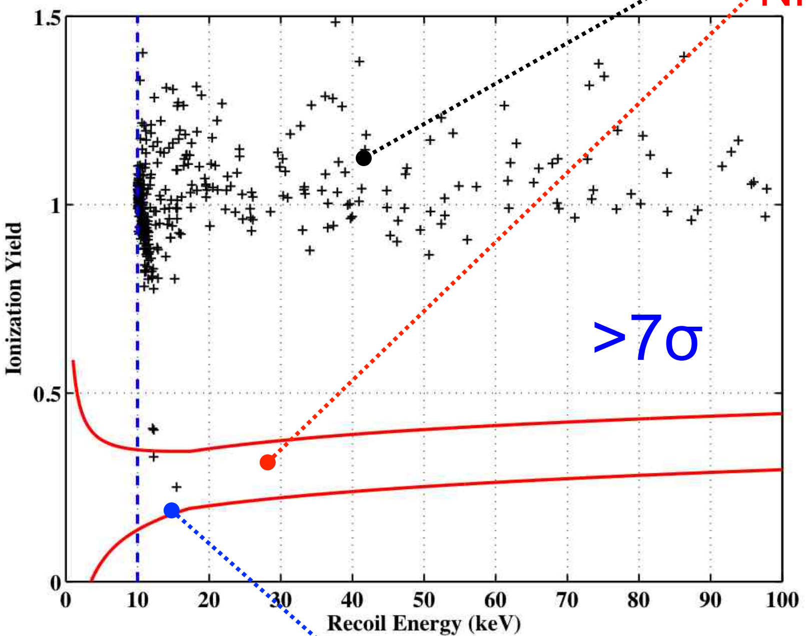
Longtime leader in SI sensitivity due to superior background rejection
(ER:NR is $>10^6$:1)

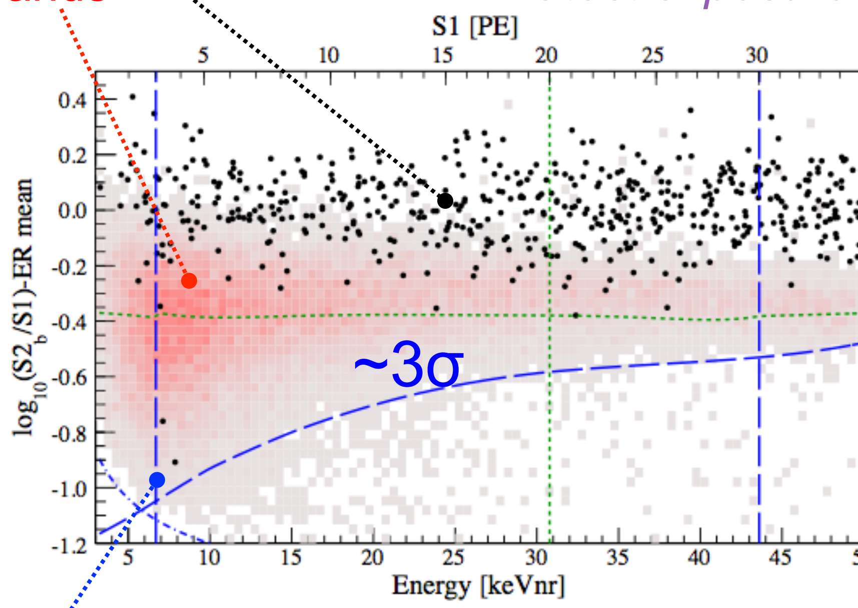
ER/NR Separation: Compare the leading brand to its competition

CDMS II
final exposure

ER bands
NR bands

XENON 100
latest exposure

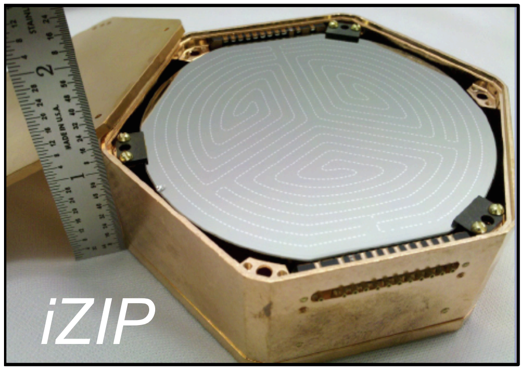




Surface events

Two events consistent w/ background

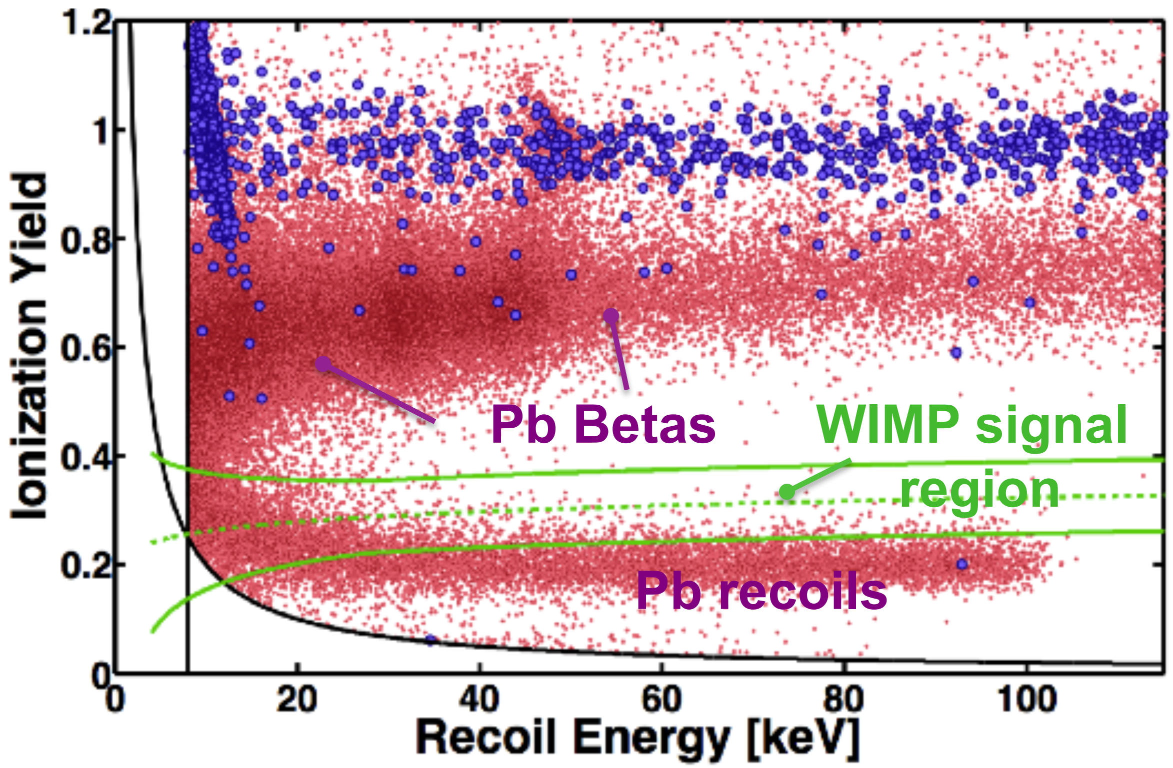
Unknown? background



SuperCDMS Soudan

Will compete with XENON and explore low mass WIMPs in 2013

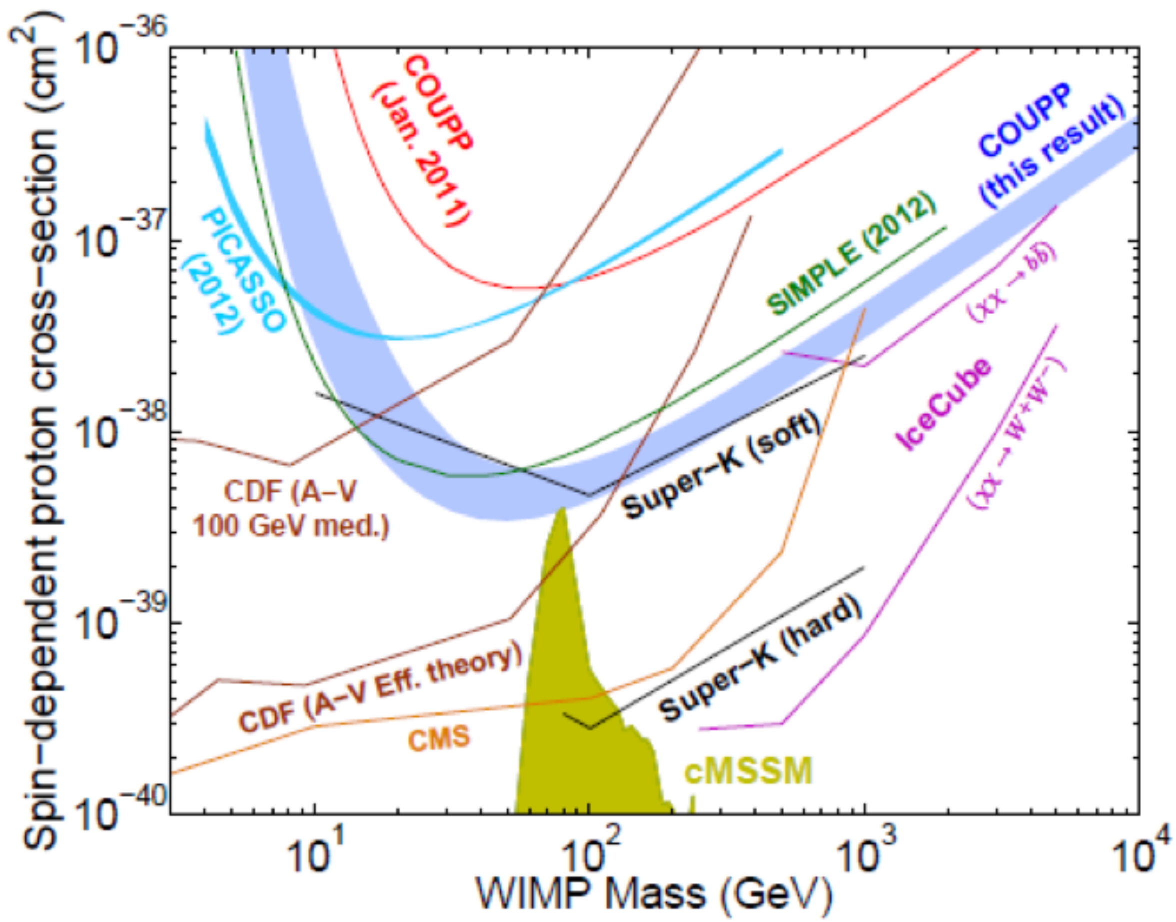
- 80,000 surface events from ^{210}Pb source, ZERO observed in signal region
- New iZIP design gives > 100X better rejection of surface events over CDMS II
- 9 kg of Ge arranged in 5 towers at Soudan



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

Spin-Dependent Landscape

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

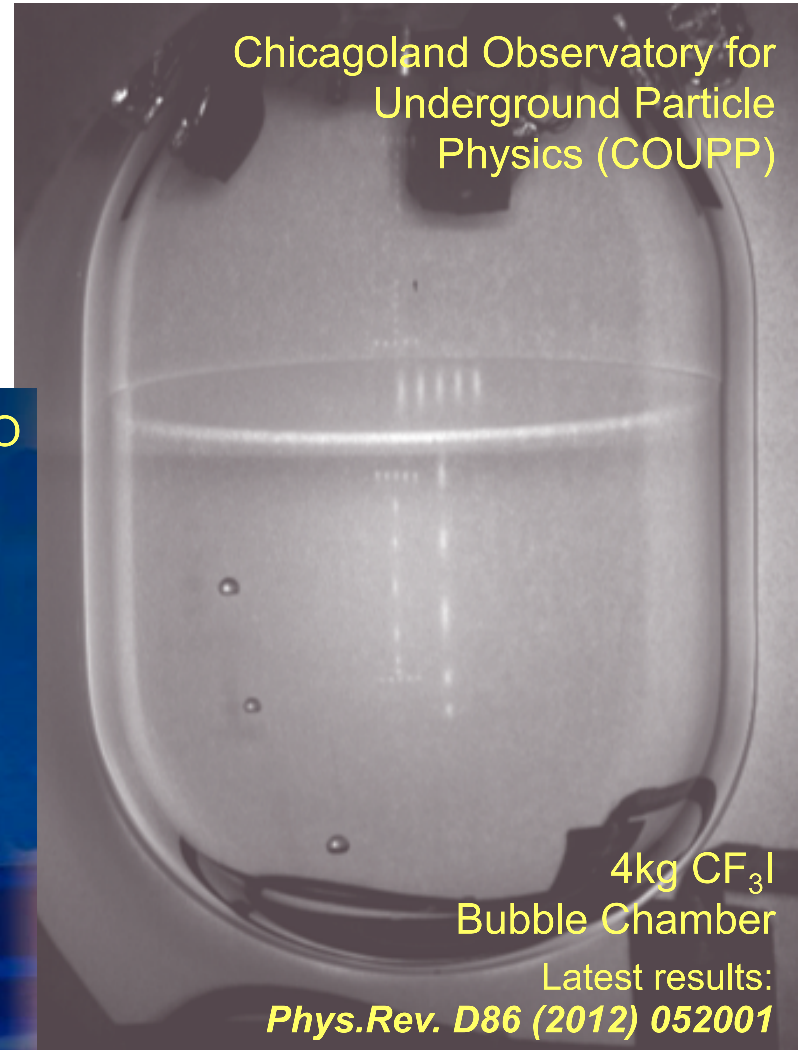


Superheated Liquid Detectors

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

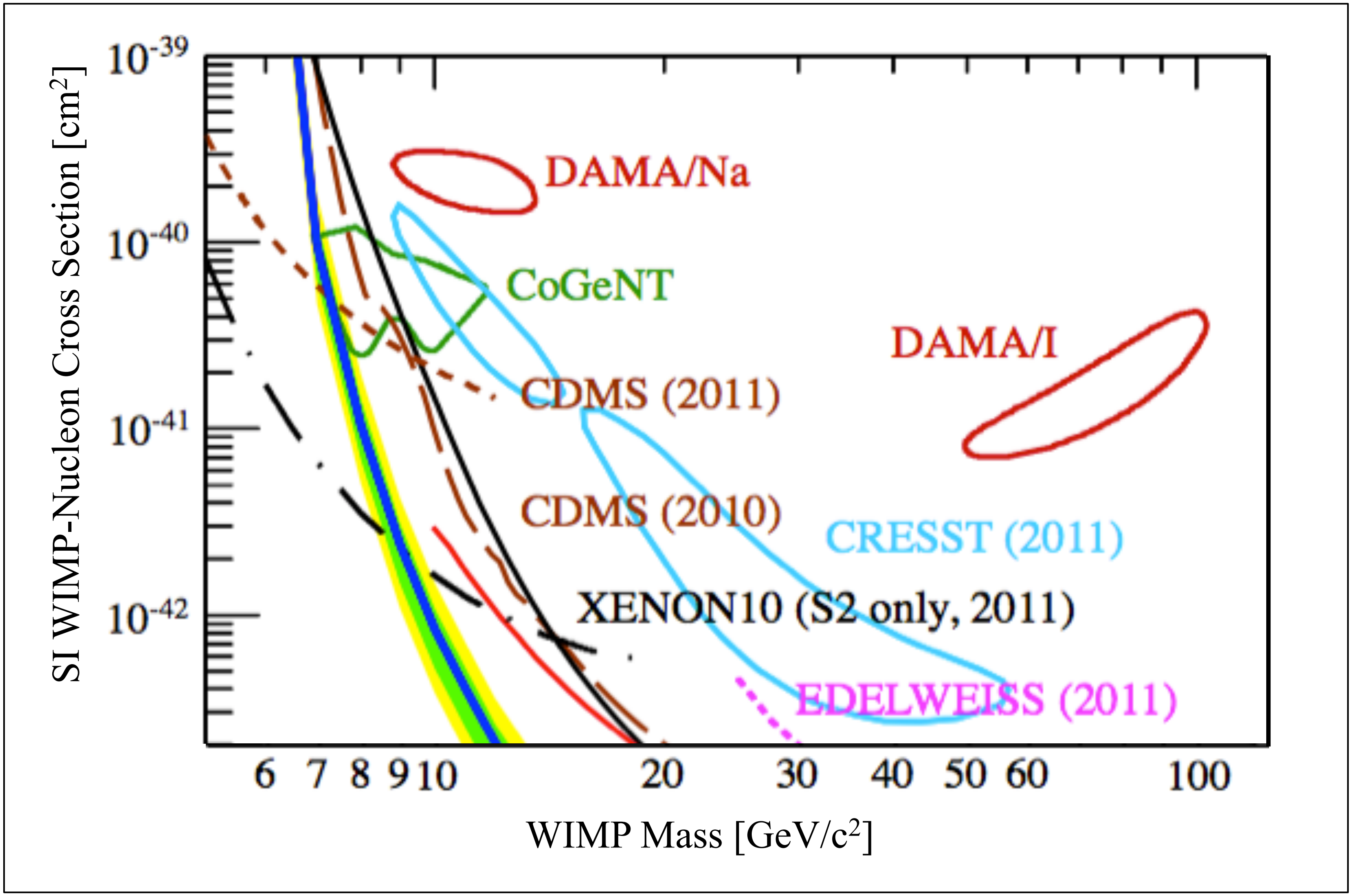
Most competitive in SD measurements

Better control of backgrounds could make them competitors in SI arena, relatively soon….



Low mass WIMPs

Low Mass Landscape: WIMPs or Background?



Unexplained Events

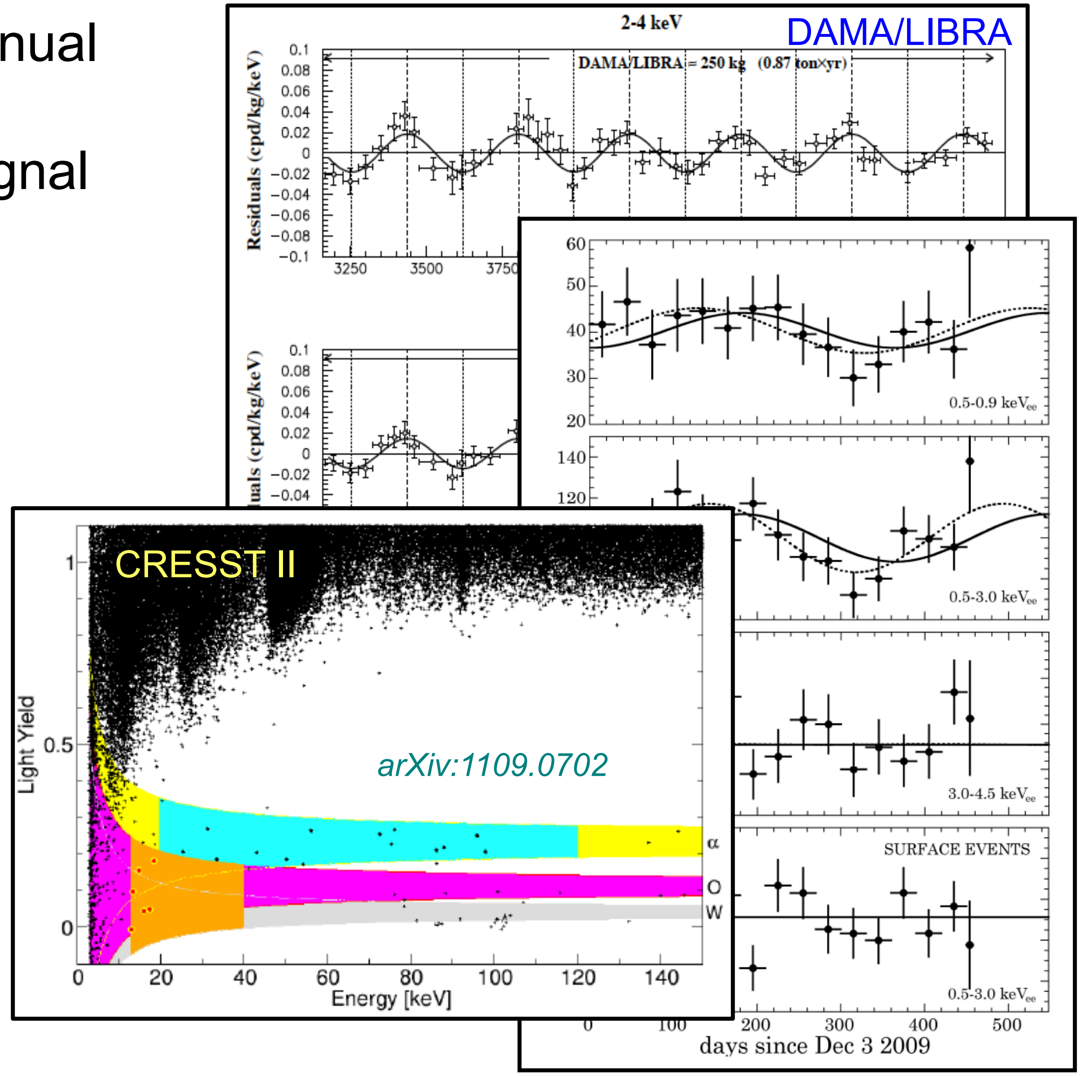
1998: DAMA/NaI reports annual modulation in event rate consistent w/ dark matter signal

2008: DAMA/LIBRA confirms annual modulation with 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

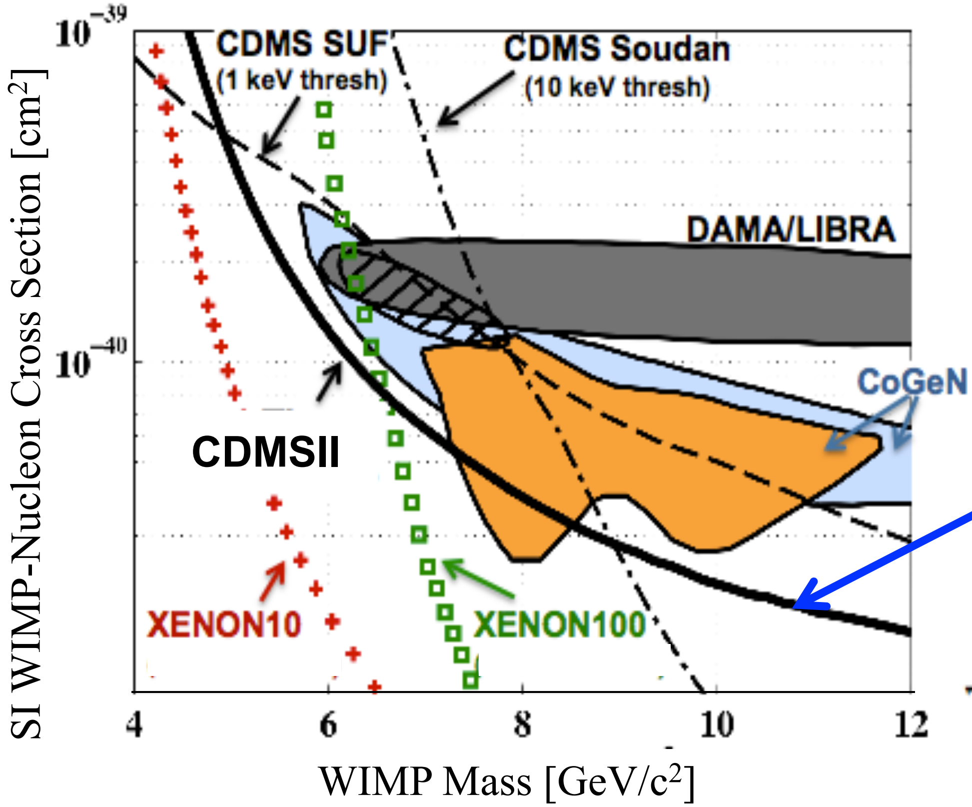
2012: CRESST-II reports a 4.2σ excess of low-energy events

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



Phys. Rev. Lett. 107 (2011) 141301

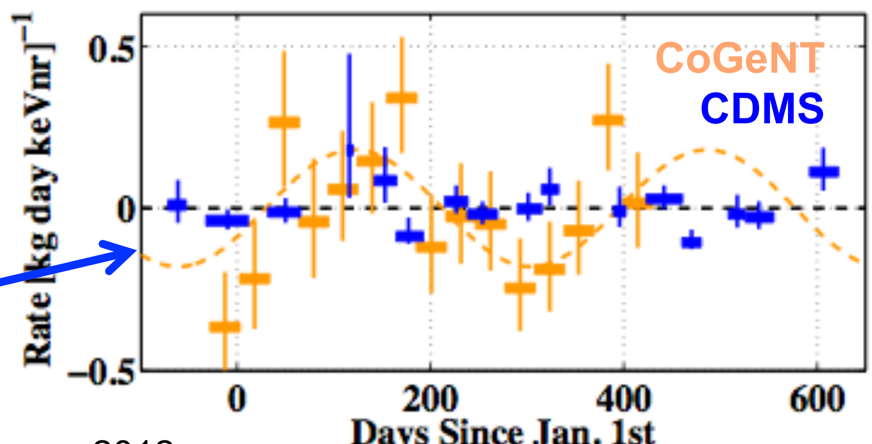
Null Observations



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 Recap

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

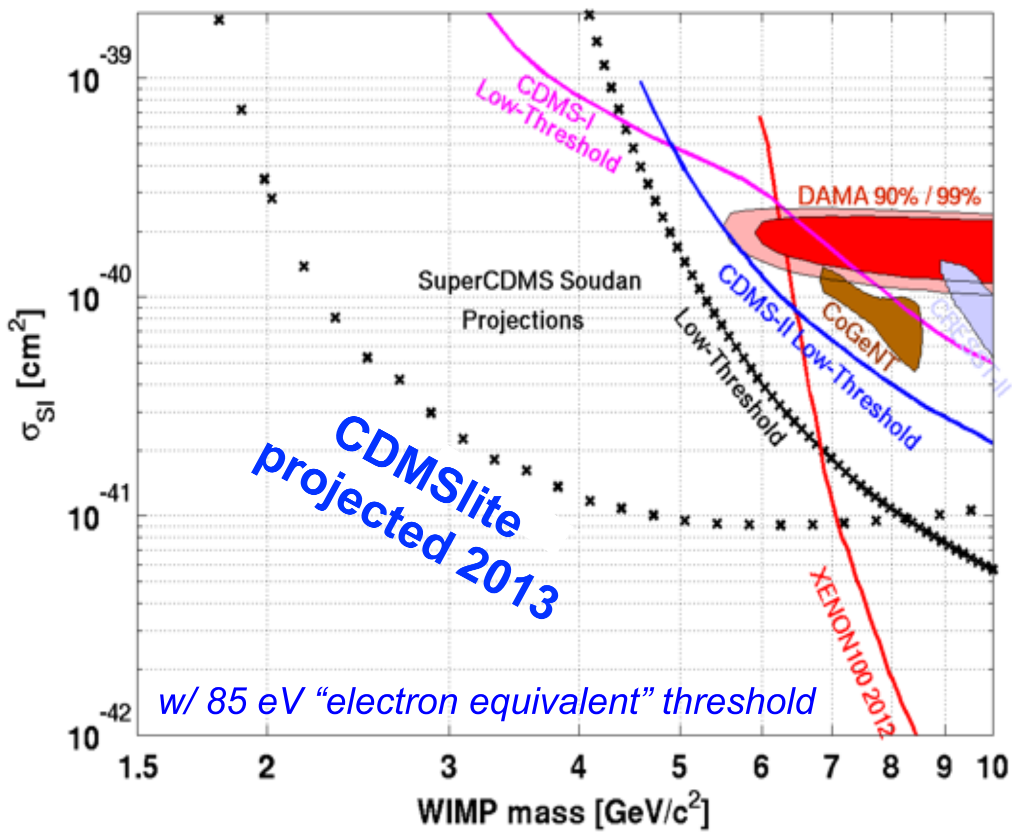
CoGeNT's annual modulation never reported as a statistically significant signal. If true, constitutes a very large modulation and hence requires unusual dark matter velocity profile

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

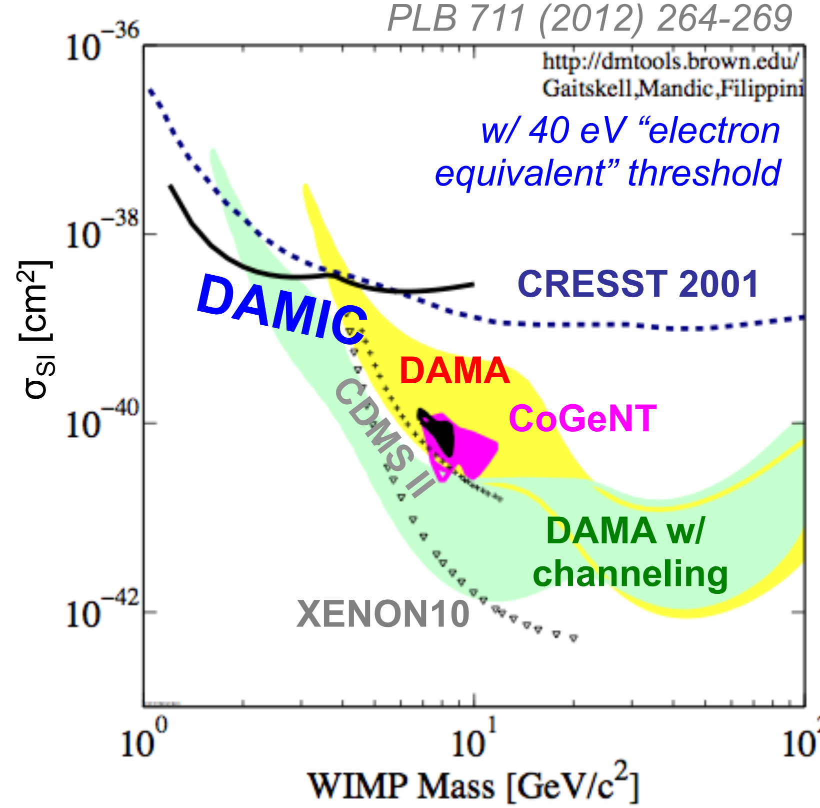
Meanwhile CRESST is making modifications to reduce backgrounds. DAMA/LIBRA's claim remains unresolved.

A path towards resolution?

Avoid systematics near the energy threshold by designing an experiment where recoils of interest are well above the threshold



PLB 711 (2012) 264-269

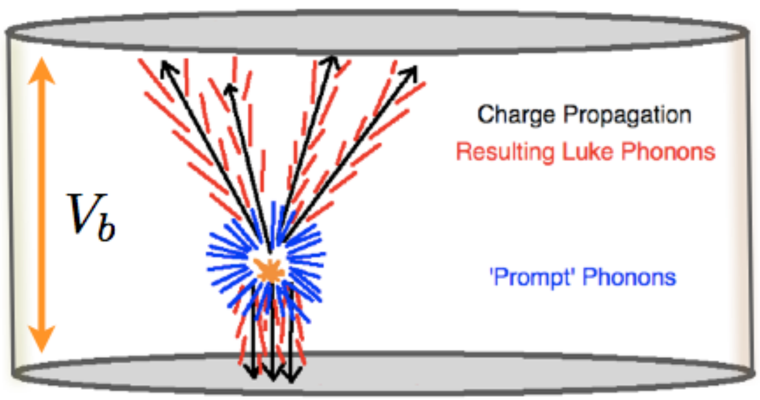


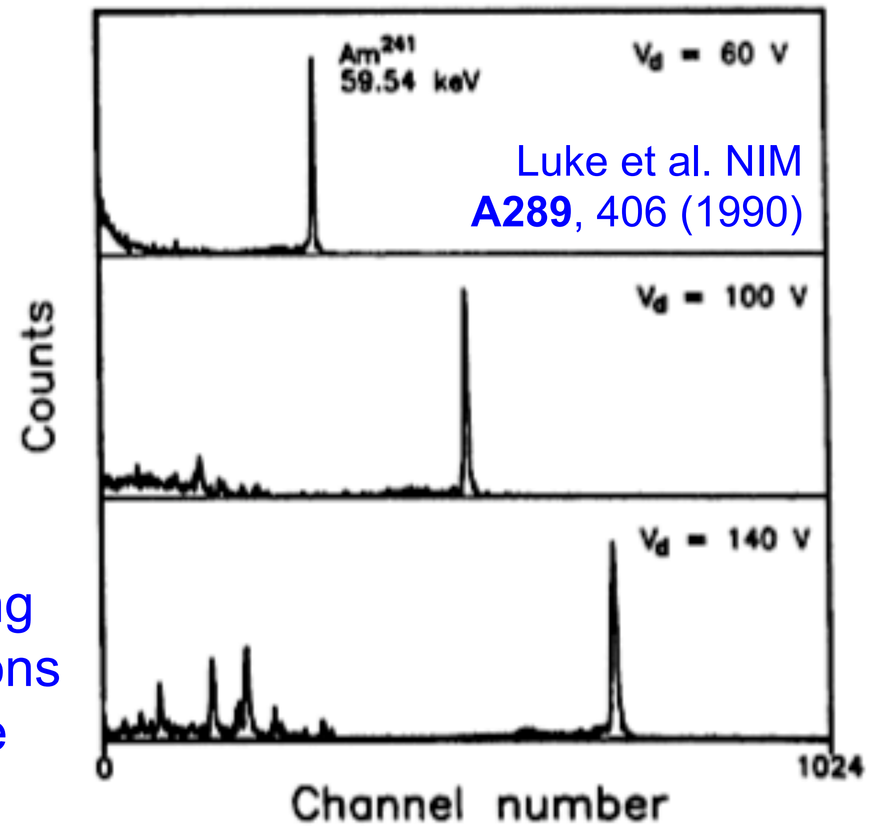
Both efforts led by FNAL groups

(Ultra) Low Ionization Threshold Experiment: CDMSlite

Neganov-Luke amplification of phonon response allows operation at very low energy thresholds

How does it work?





Luke et al. NIM **A289**, 406 (1990)

Aside from "prompt" phonons, resulting electrons and holes will radiate phonons proportional to V_{bias} as they drift to the electrodes.

➔ Apply large V_{bias} to amplify ionization signal

Future prospects

zeptobarn = 10^{-45} *cm*

Liquid Xenon

Arguably the most promising in the near term; LUX is the experiment to watch

O(100) kg, results in the next 1-2 yrs?: LUX, XMASS *(single phase)*, PANDAX(?). *LUX will be commissioning before end of 2012*

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 and target purification are critical*

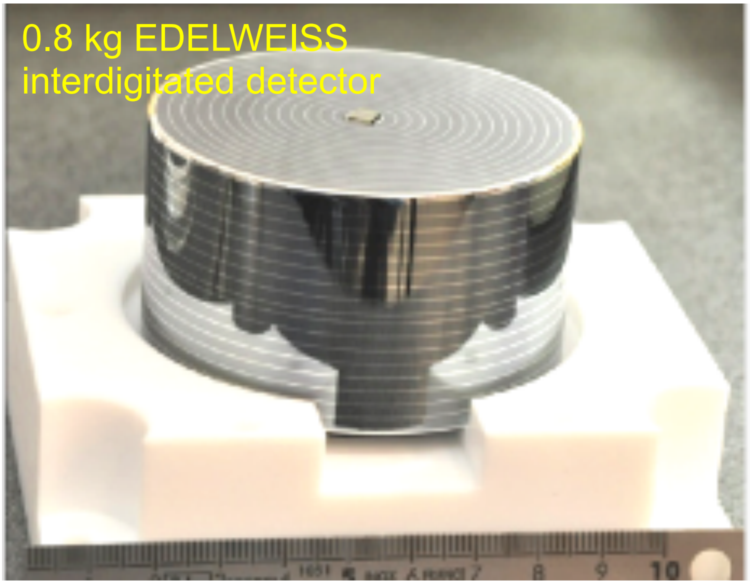
Cryogenic Germanium

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

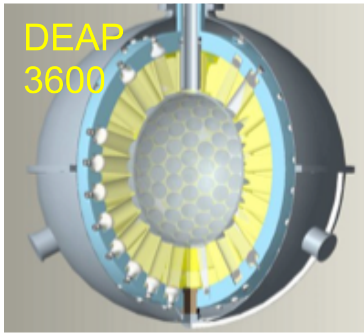
SuperCDMS SNOLAB: ~200 kg with sensitivity < 1e-46 cm^2
construction start 2014(?)

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



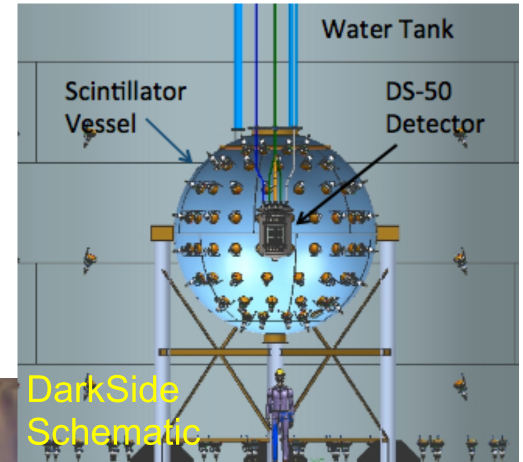
Pros: Superb ER/NR separation, no intrinsic contamination, excellent energy resolution, low energy thresholds, “sweet spot” of A^2 enhancement, phased deployment is natural and minimizes background uncertainty

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 will begin operation in 2013



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

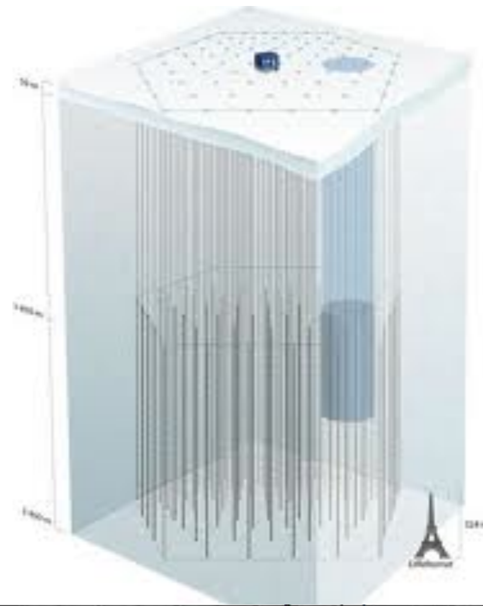
DEAP-3600: single phase (scintillation only), 3600 kg of liquid Ar, sensitivity at ~1e-46 by ~2015

Pros: Exquisite ER/NR separation using pulse shape, deployment of large masses feasible, natural argon is relatively cheap and abundant

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

Annual Modulation Searches

Resolving the DAMA annual modulation puzzle remains a high scientific priority !

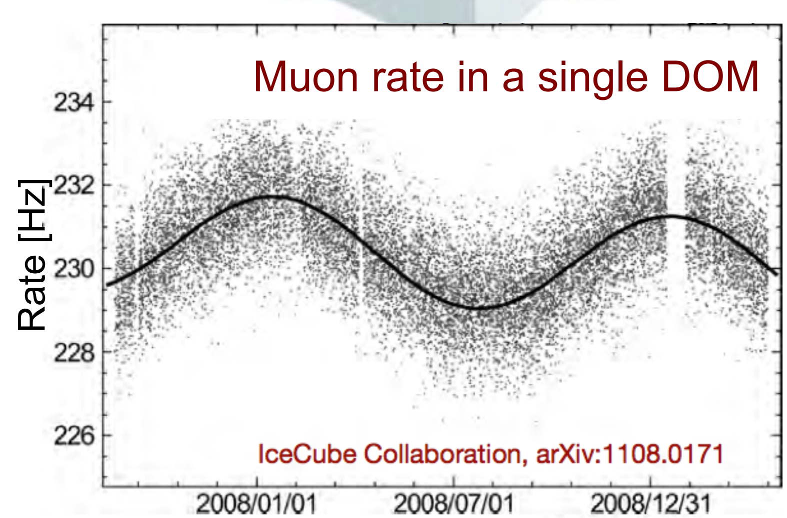


DM-Ice:

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



Additional independent efforts to develop radiopure NaI for dark matter:

Anais, KIMS, R&D at Princeton

DM-Ice-17: First Step

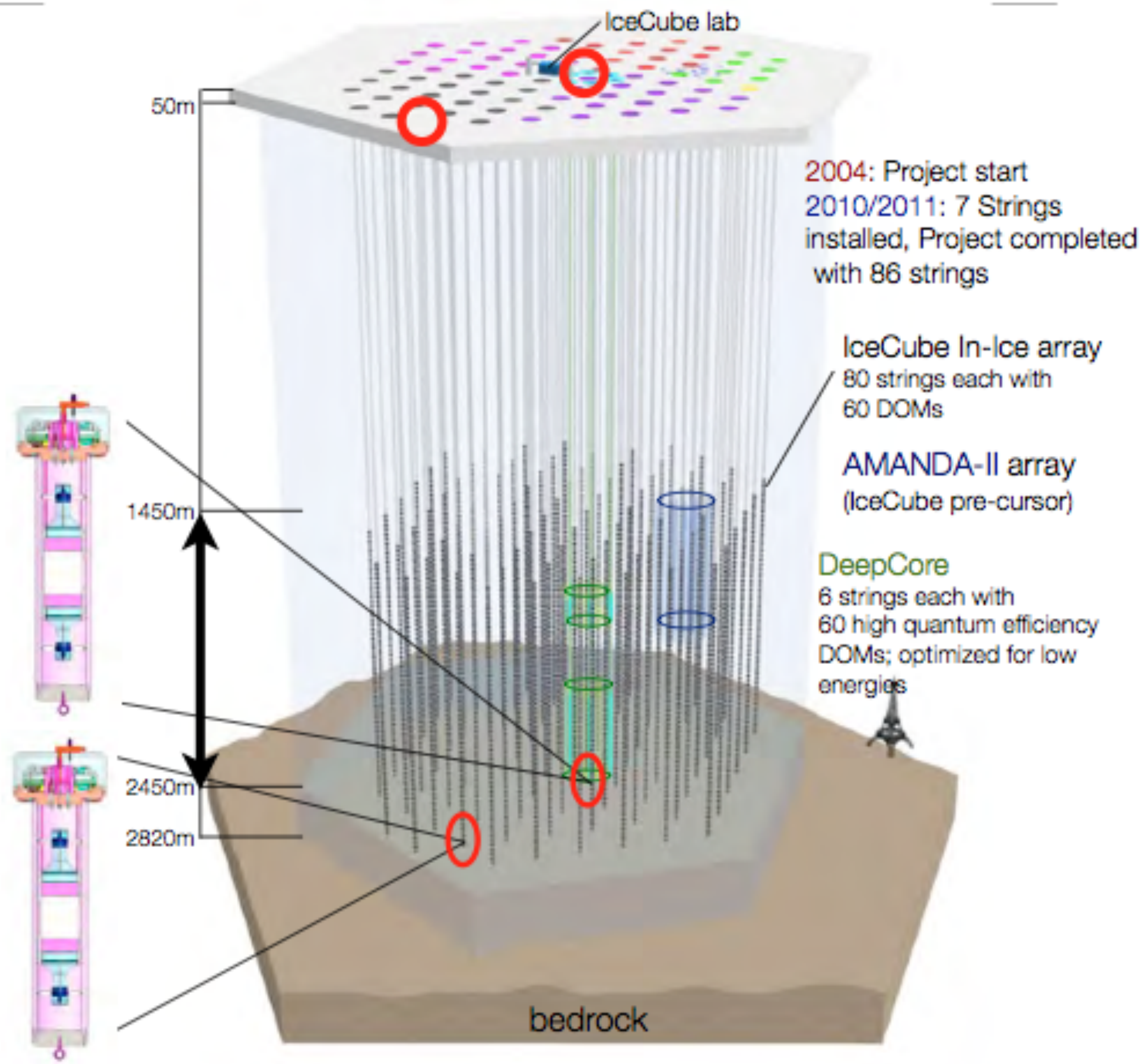
Detectors:

- Two 8.5 kg NaI detectors from NAIAD (17 kg total)

Goals:

- Assess the feasibility of deploying NaI(Tl) crystals in the Antarctic Ice for a dark matter detector
- Establish the radiopurity of the antarctic ice / hole ice
- Explore the capability of IceCube to veto muons

Installed Dec. 2010



stolen from ⇧

Directional Detectors

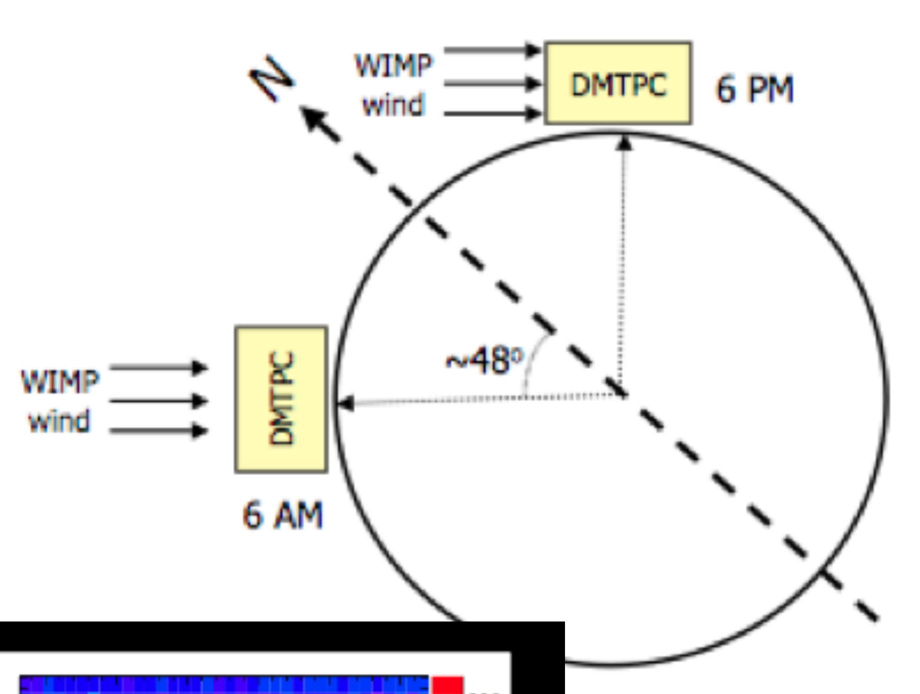
Sun's motion through the dark matter halo can be perceived as a "WIMP wind"

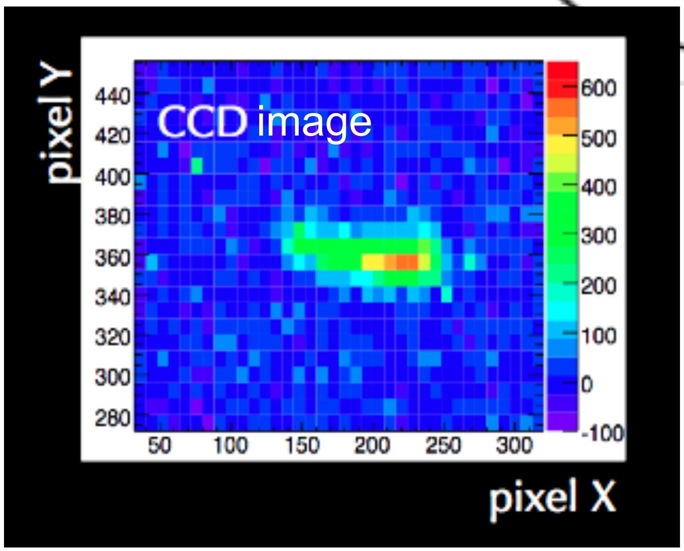
Low pressure TPC's preserve dE/dx profile such that "head to tail" measurement can be made

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)





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

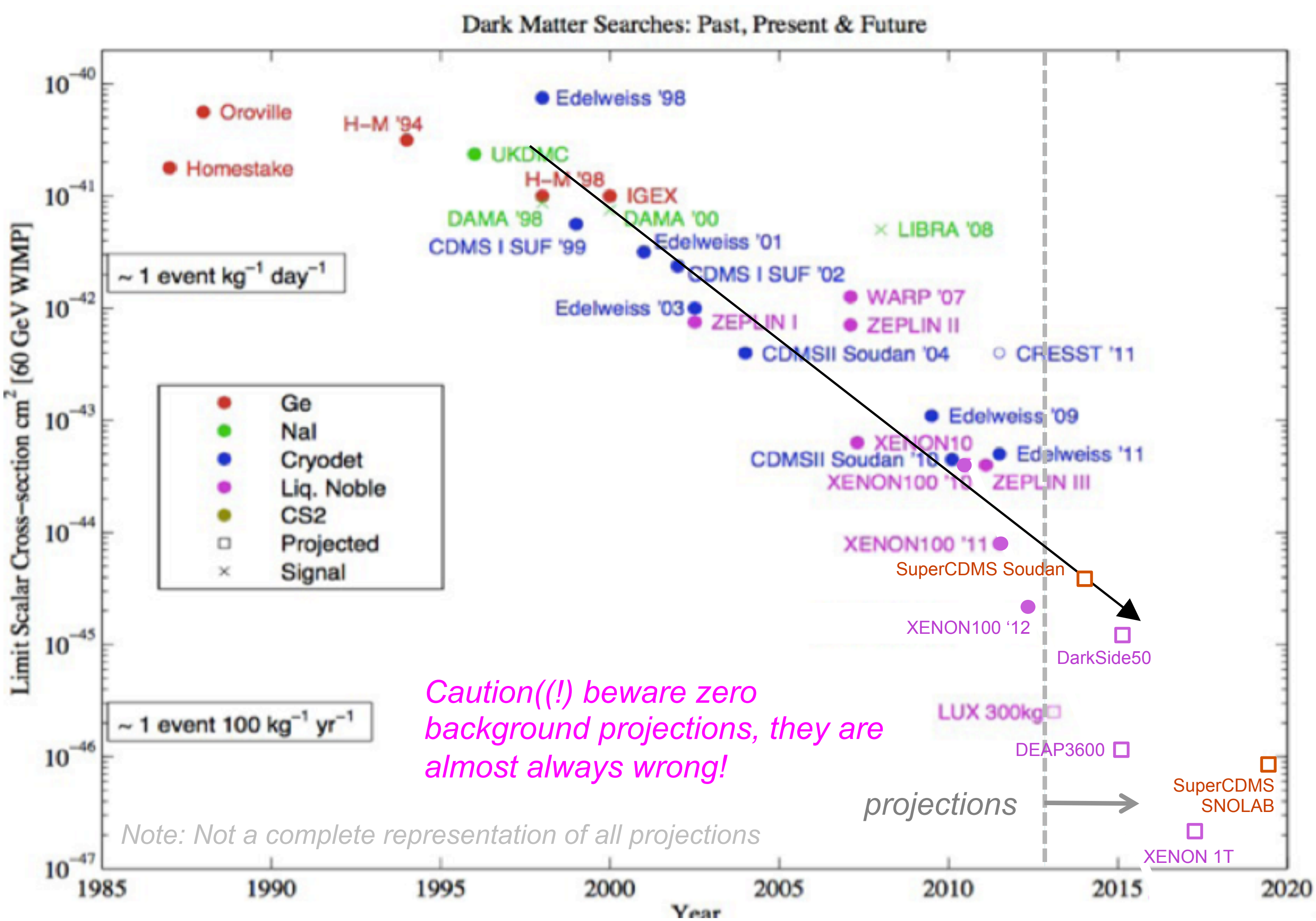
Picking out a true WIMP signal from vast backgrounds is tricky. Different technologies are susceptible to different backgrounds so having cross checks is important. Take the low mass WIMP discussion as an example

Practical argument

Science output per dollar is high!

Moore’s Law for Direct Detection

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



Summary

Understanding the nature of dark matter is one of the highest scientific priorities for HEP

Novel detector designs and fierce competition drive the fast, diverse 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

Thank you