WIMP Direct Detection Searches: Solid State Technologies

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SLAC Summer Institute Lectures
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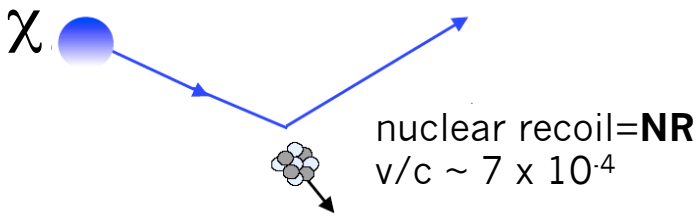
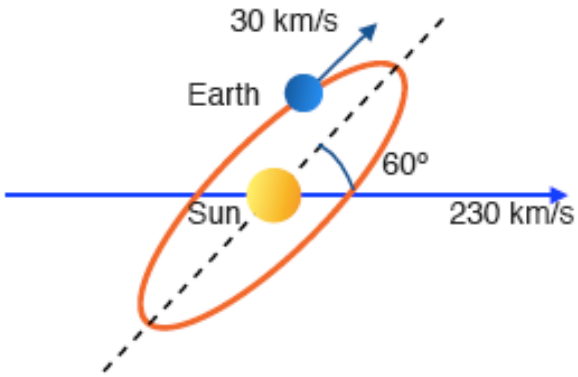
Review Strategies for Direct Detection

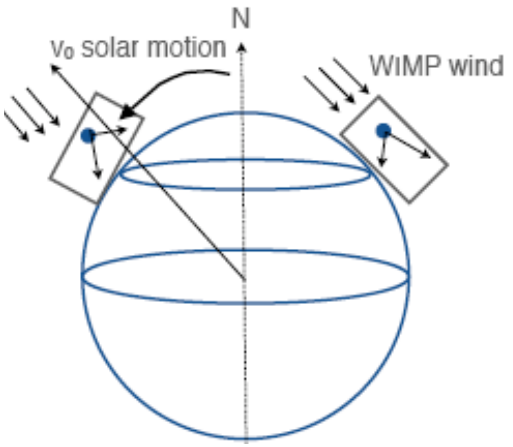
Signal



Count nuclear recoils

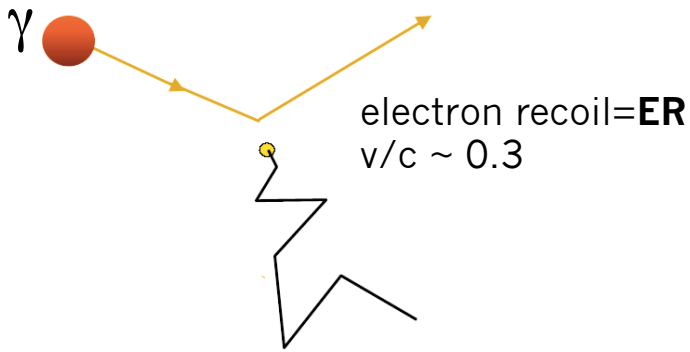


annual flux variation



diurnal directional modulation

Background

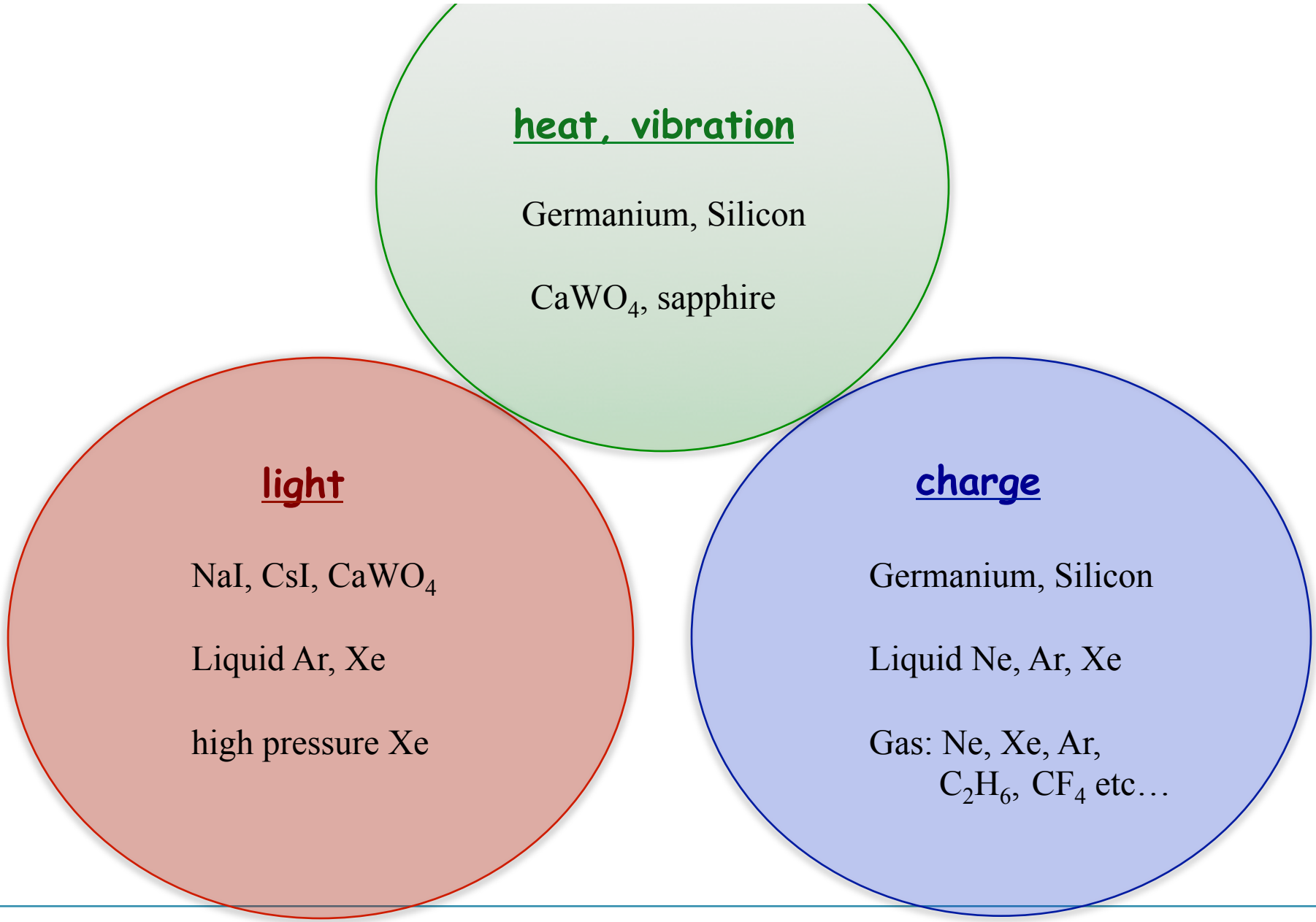


β,γ **discriminate** between ER vs NR
-or- eliminate sensitivity to ER
-or- self-shielding & fiducial cuts

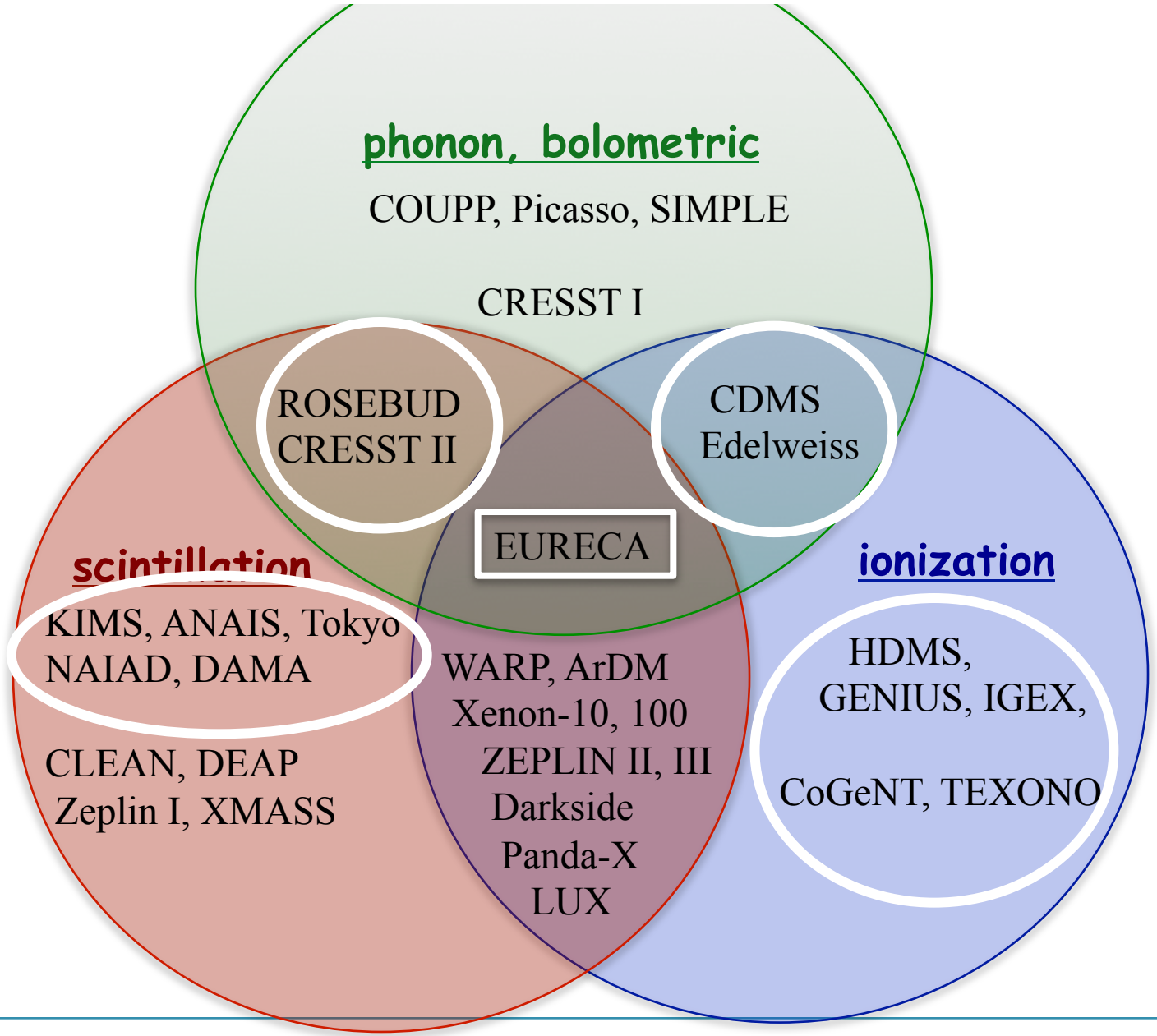
n multiple scatters
σ varies with target
} **avoid** shielding, go deep

α much higher energy deposit. Only a problem for threshold devices, trackers

Counting Nuclear Recoils: Types of Signals



Counting Nuclear Recoils: Experiments



High Purity Germanium Detectors

Impurities as low as 10^{10} atoms/cm^3

N+ Contact: diffused Lithium (thick)

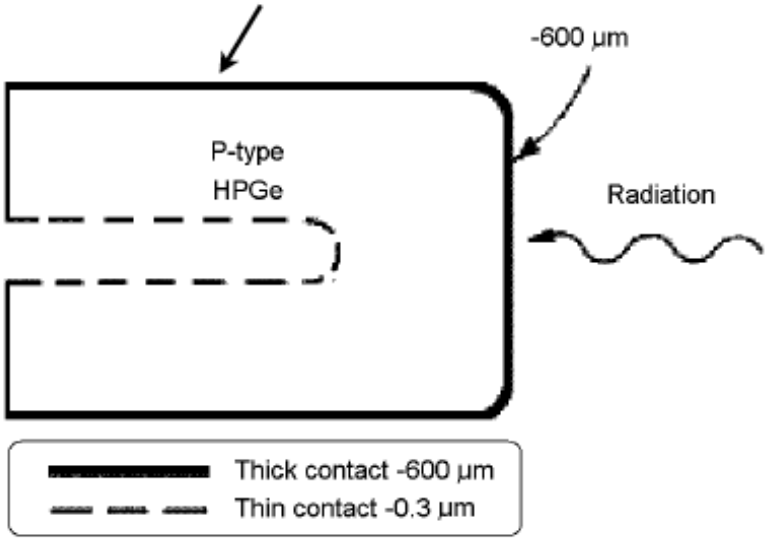


Fig. 1. Closed-end coaxial HPGe detector

P+ Contact: implanted ion (thin)

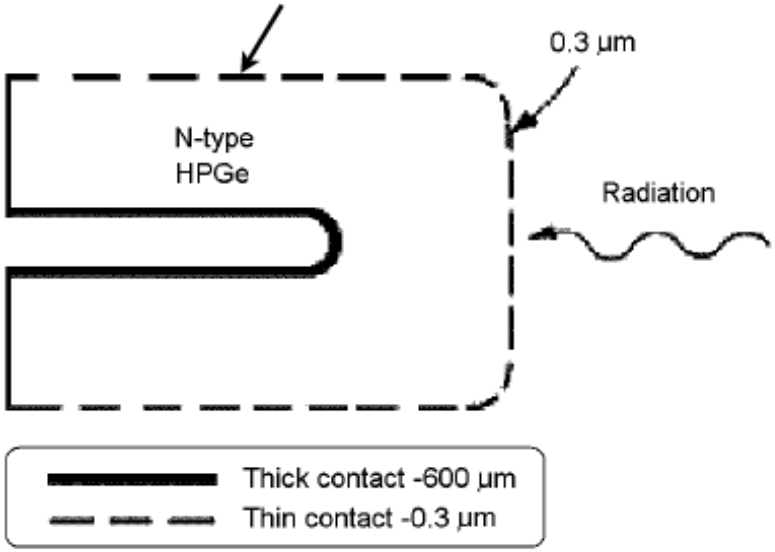


Fig. 2. Reverse electrode coaxial detector

P-type HPGe (GEM):

Most commonly used

Simpler to fabricate/handle/instrument

Larger

N-type HPGe (GMX):

Low gamma threshold (<100 keV)

High Purity Germanium Detectors

- Band gap = 0.7 eV ➔ operate at LN temperatures
- Only ~3 eV to create e-h
- High Z, high density, compact.

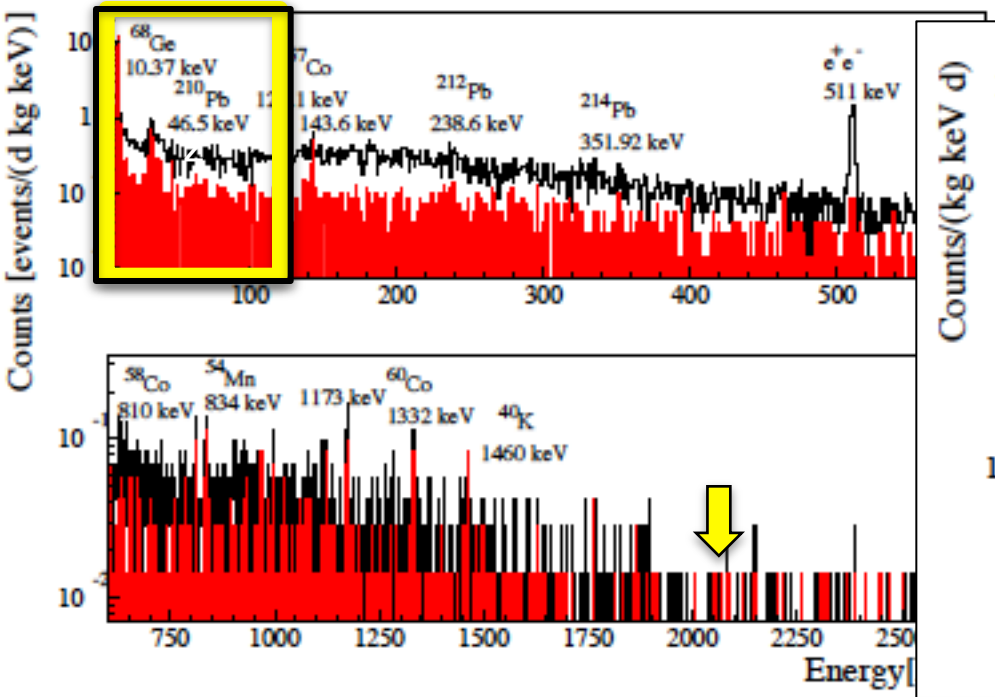
Optimized for neutrinoless double beta decay (Z,A) ➔ (Z+2, A) $+e^- + e^-$

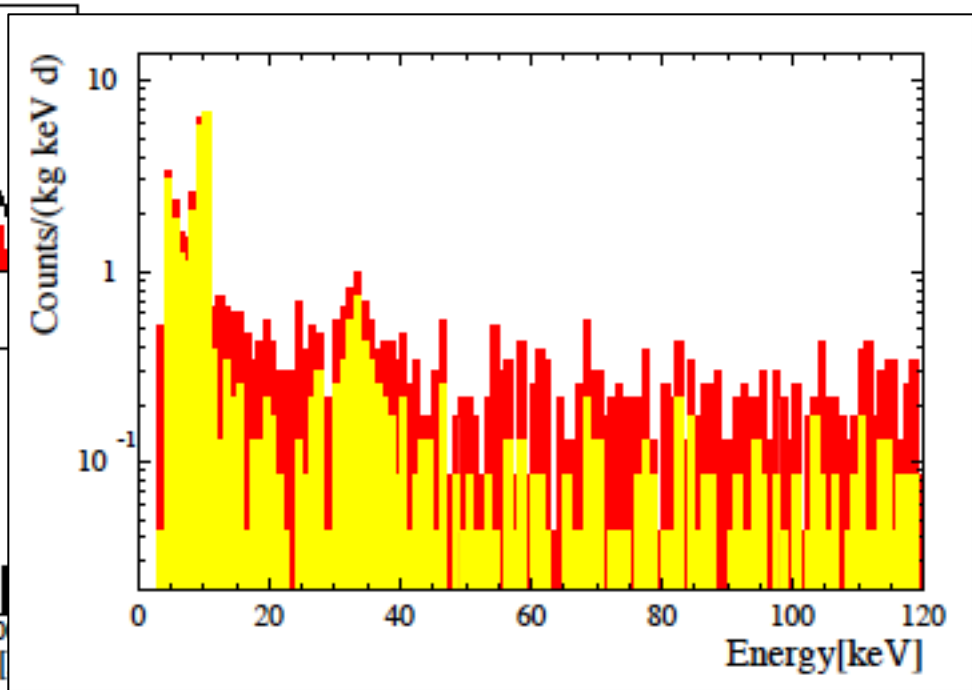
Enriched in ^{76}Ge (even-even nucleus)

Excellent energy resolution: few keV

to distinguish the 2039 keV peak in the background

Energy resolution and low noise is also good for WIMP searches

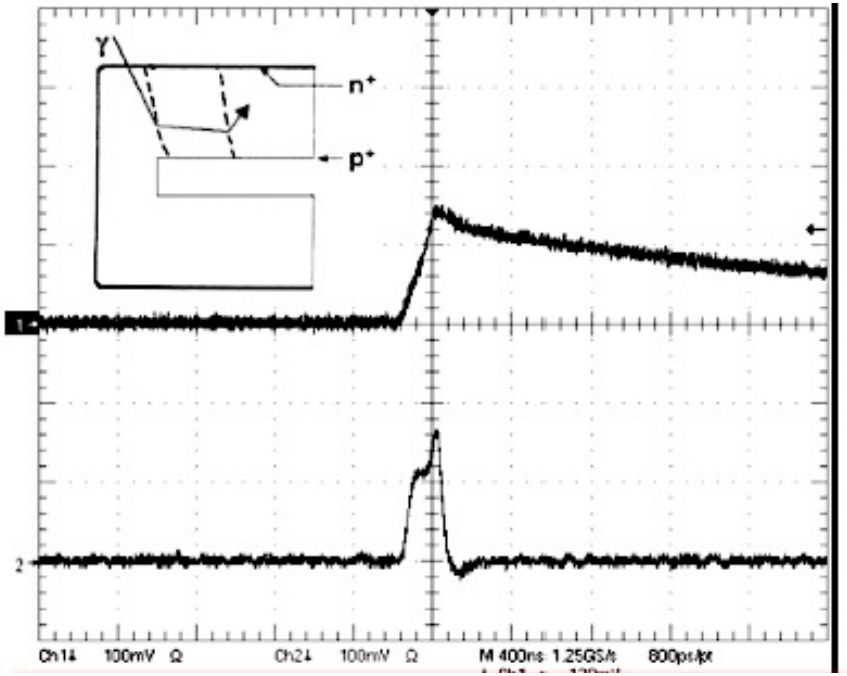


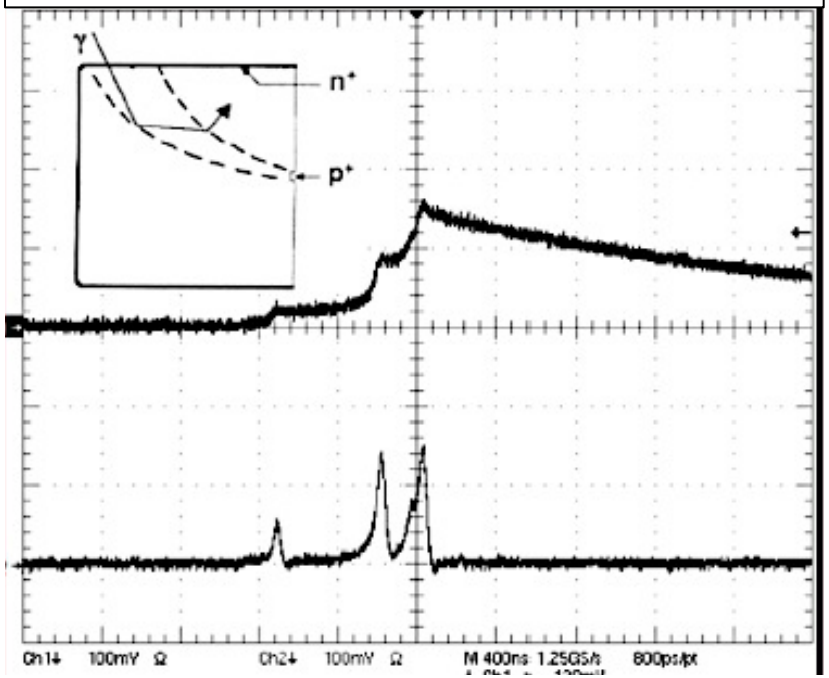


High Purity Germanium: New Advances

Conventional Design
Still used extensively for isotope identification and material screening

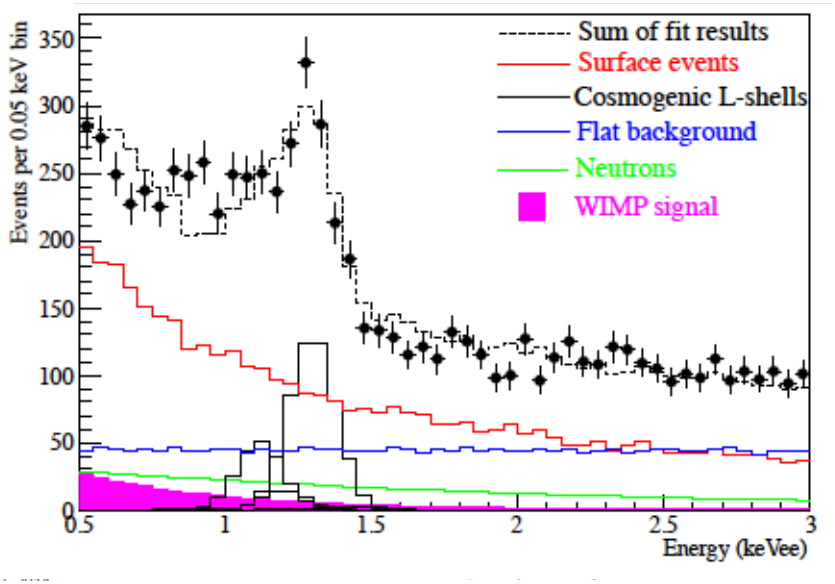
p-type Point Contact
Low capacitance
Sub-keV thresholds
Improved E-Field uniformity
Better E-resolution
Multi-hit rejection

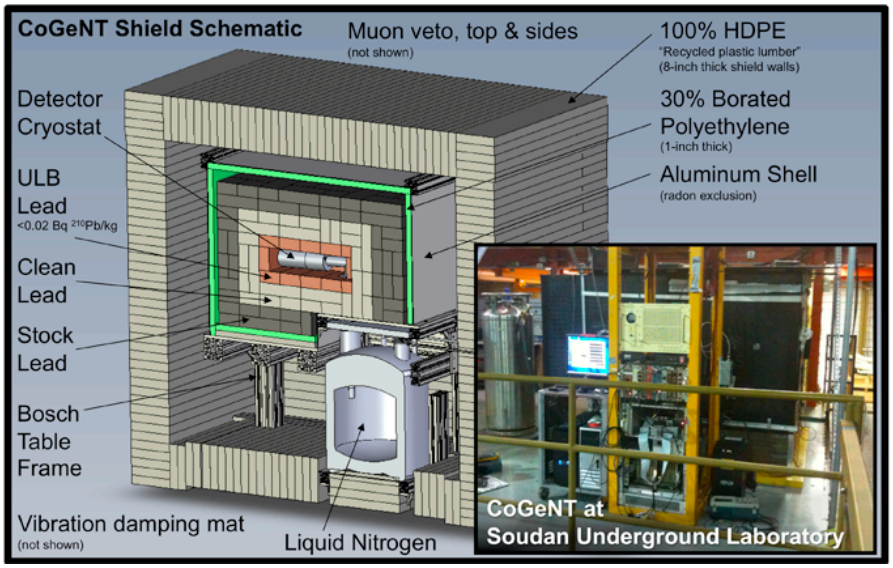




High Purity Germanium: CoGeNT

GoGeNT (440 g) at Soudan Lab
Taking data since Dec 2009



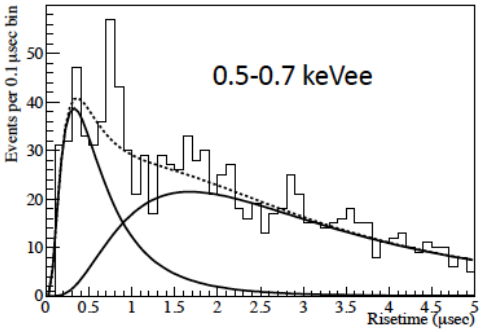


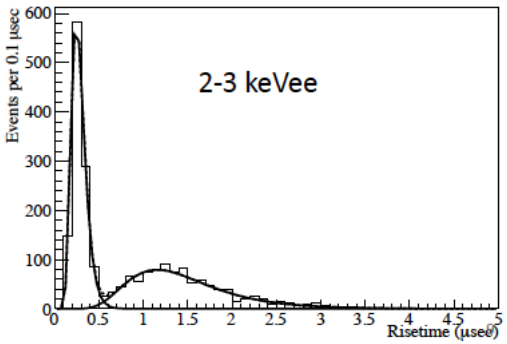
Sees excess at low energy consistent with WIMPs, but Null result only excluded at 1.9 σ

New ann mod is now at 2.2 σ

Implies signal modulation of 35-65% of the WIMPs

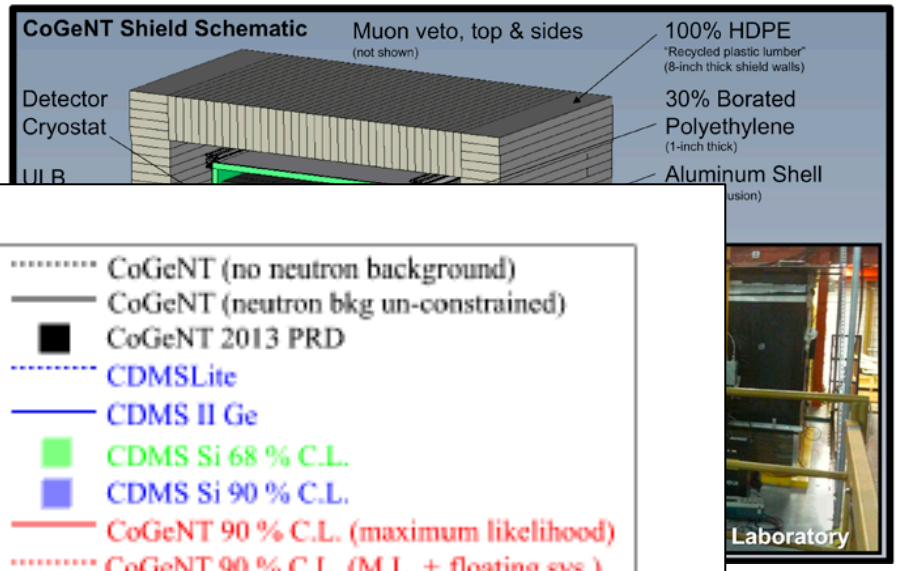
Surface events from dead layer have degraded energy: pileup at low energy.
Surface pulses have slow risetime
Fit and subtract (Sim matches well)

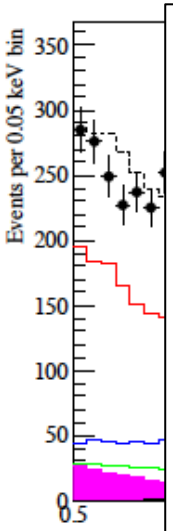


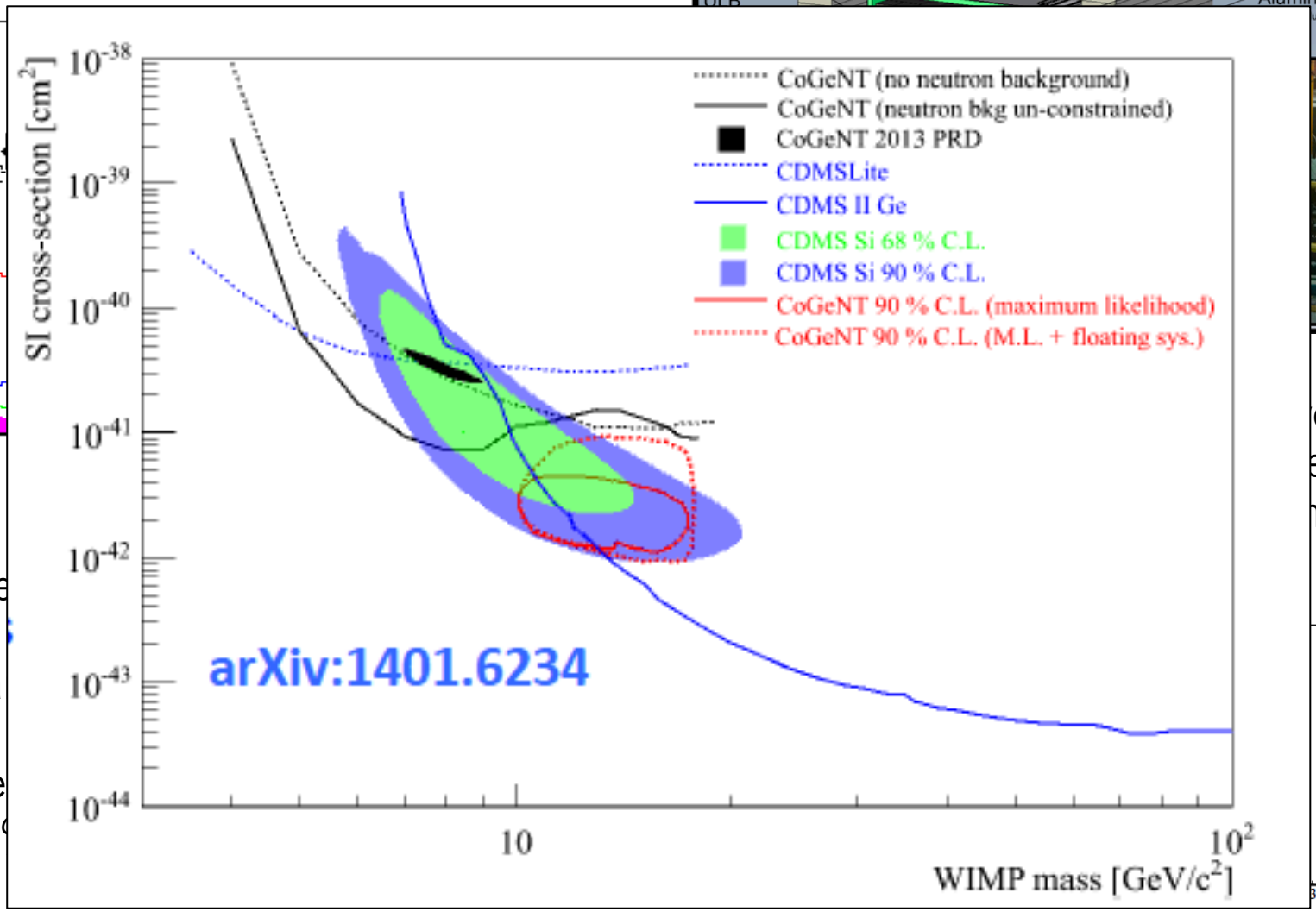


High Purity Germanium: CoGeNT

GoGeNT (100 g) at Soudan Lab
Taking data since Dec 2009







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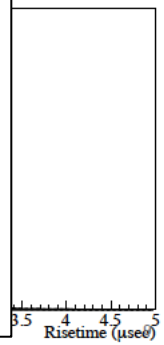
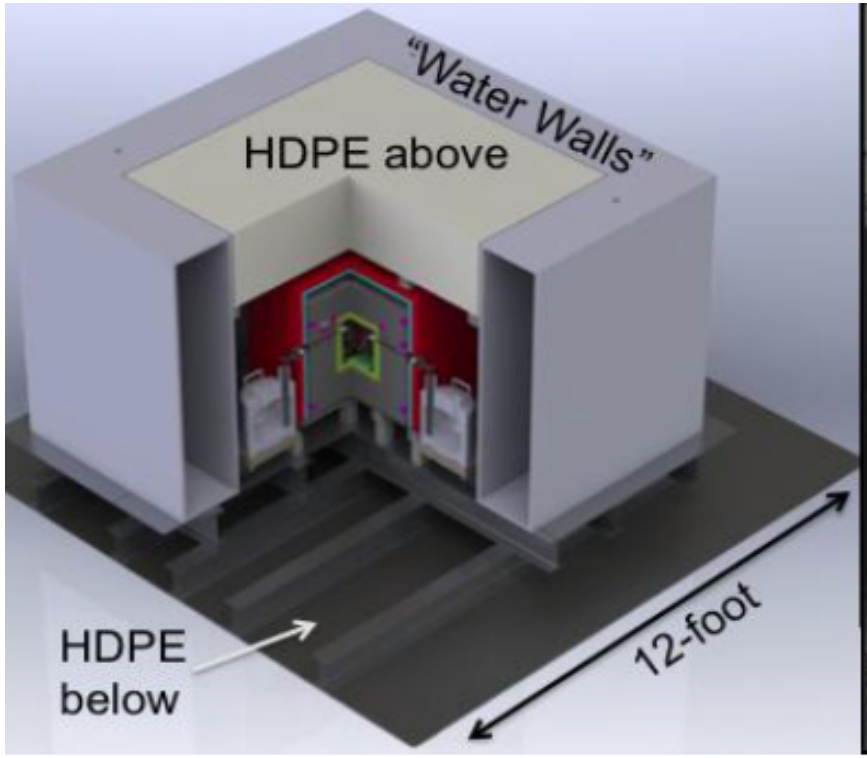
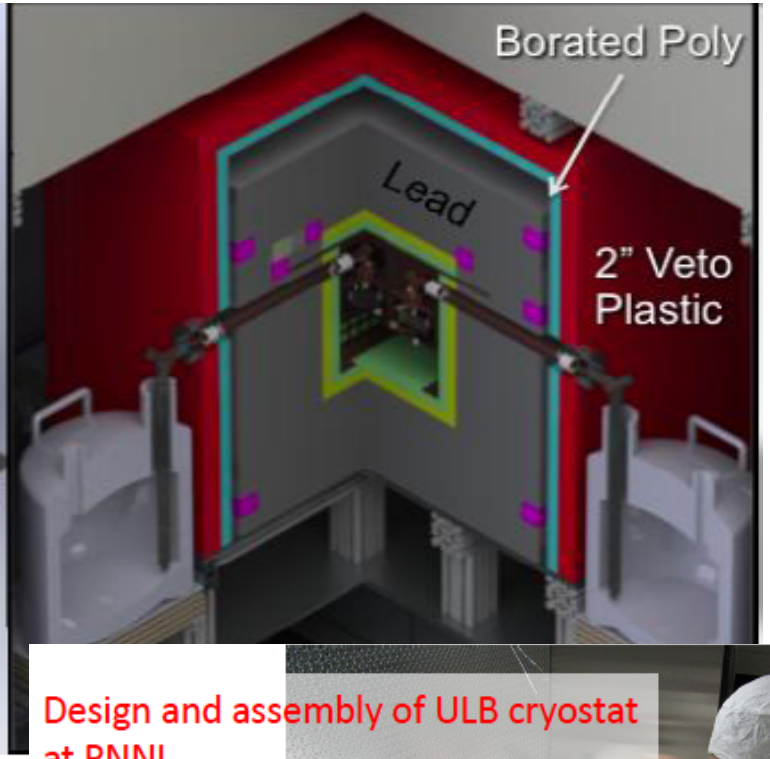
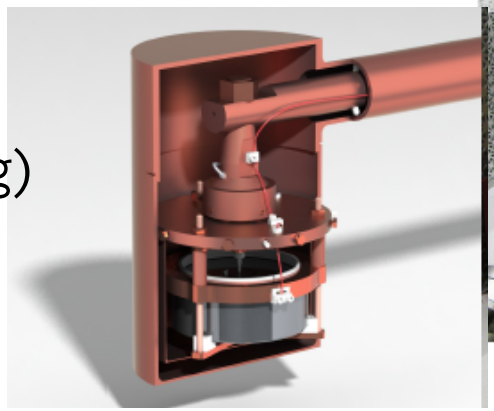


Future of CoGeNT is C4





Design and assembly of ULB cryostat at PNNL



First C-4 detector ready
1/3 noise and x3 mass (1.3 kg)
Canberra proprietary mods
Second will be 2 kg
max practical size for PPC

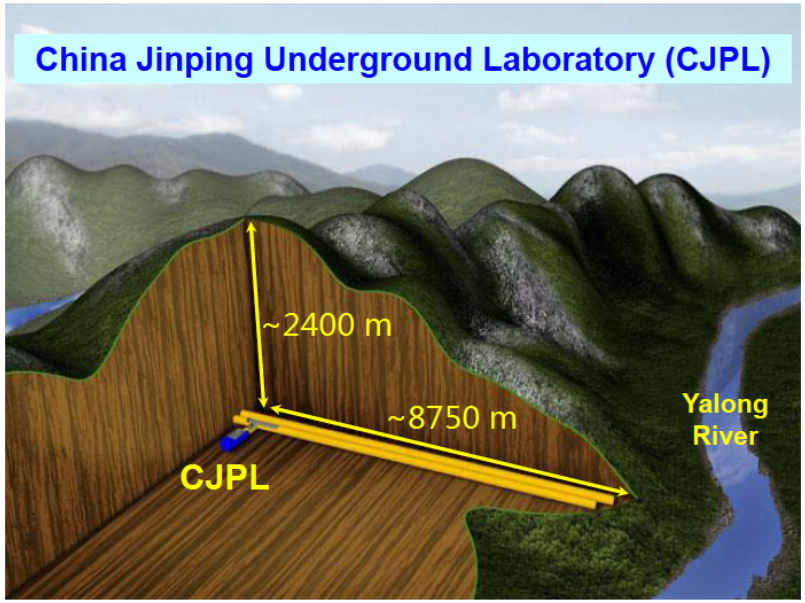
High Purity Germanium: TEXONO/CDEX

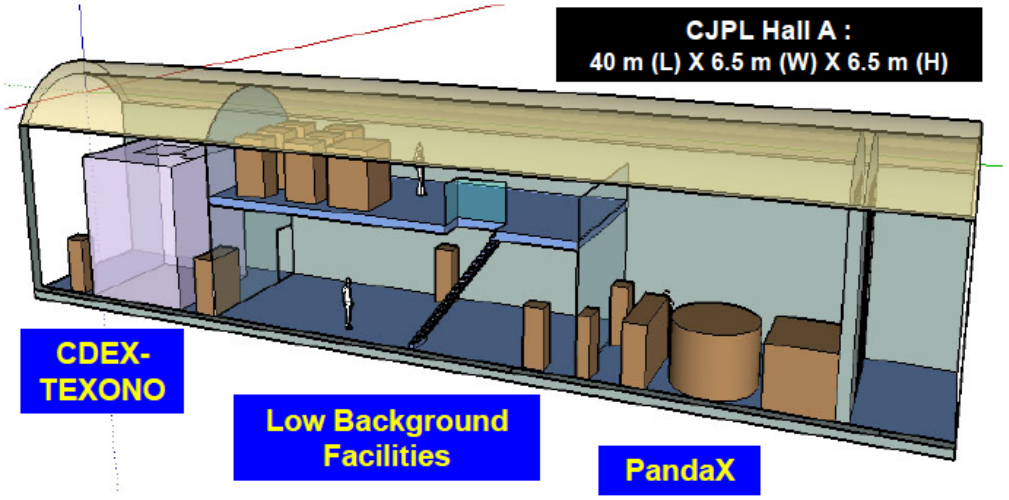
TEXONO (Taiwan EXperiment On neutrinO) at Kuo Sheng Reactor:30mwe

$\sin^2\theta_w$, magnetic moments, ν_e coherent scattering
but also low mass WIMPs

Detectors: ULE-ULB-HPGe (20g)
PCGe (1 kg)
CsI(Tl) (200 kg)

CDEX (**C**hina **D**ark matter **EX**periment) at new Jin-Ping Lab
Move the PCGe deeper (running), PCGe Array (10 kg) under construction

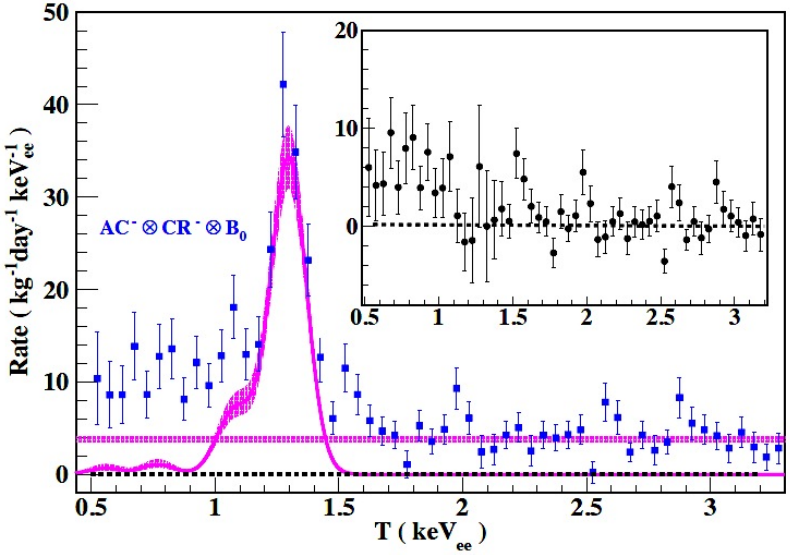


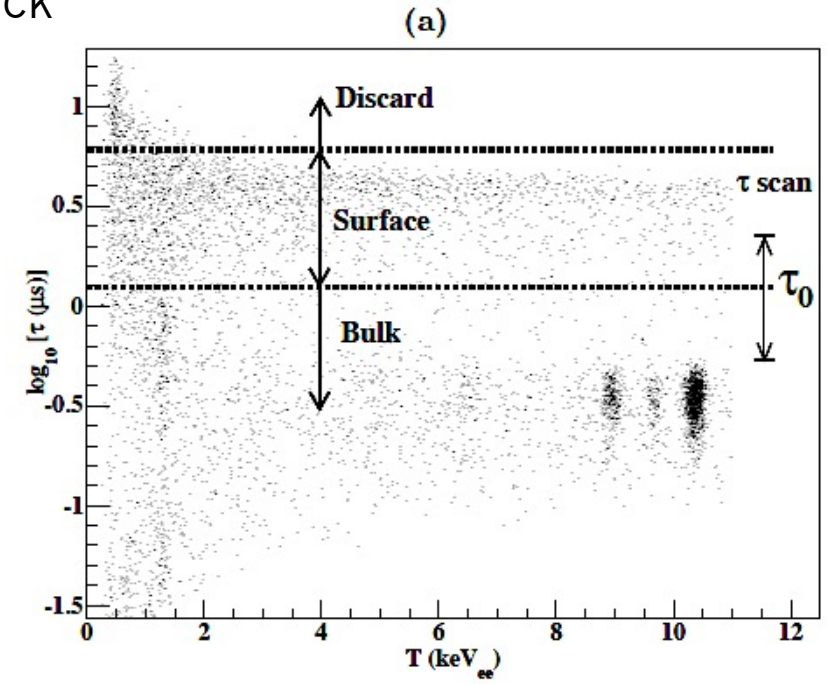


TEXONO

As in CoGeNT, surface events have slower risetime and vary considerably
Lithium diffused n+ contact is 1.2 mm thick

At <2.7 keV, the Bulk and Surface overlap





Tuned pulse shape (surface vs bulk) using new 523g n-type PC
the p+ contact is thin ➔ much fewer surface evts.

Development Effort on n-type PC

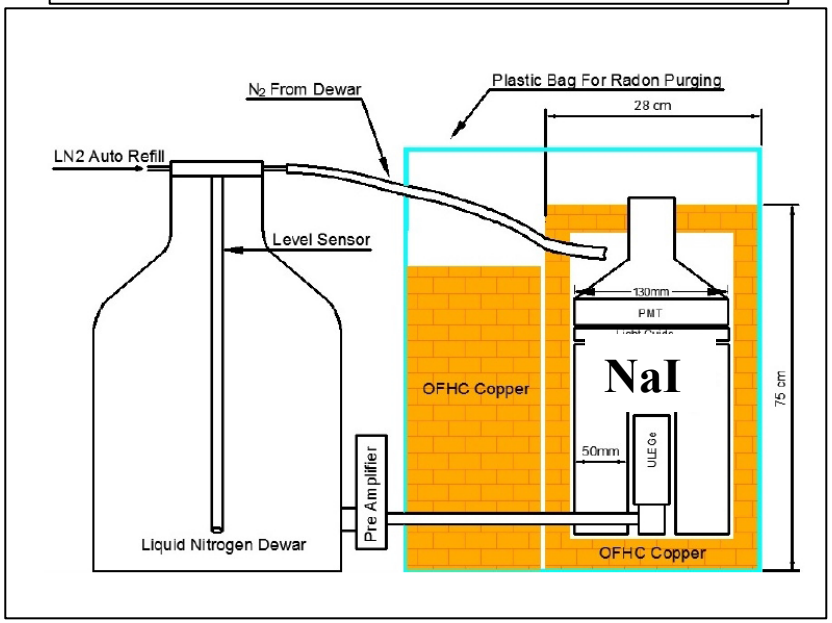
N.B. Luke made n-type but with poor energy resolution due to electron trapping.

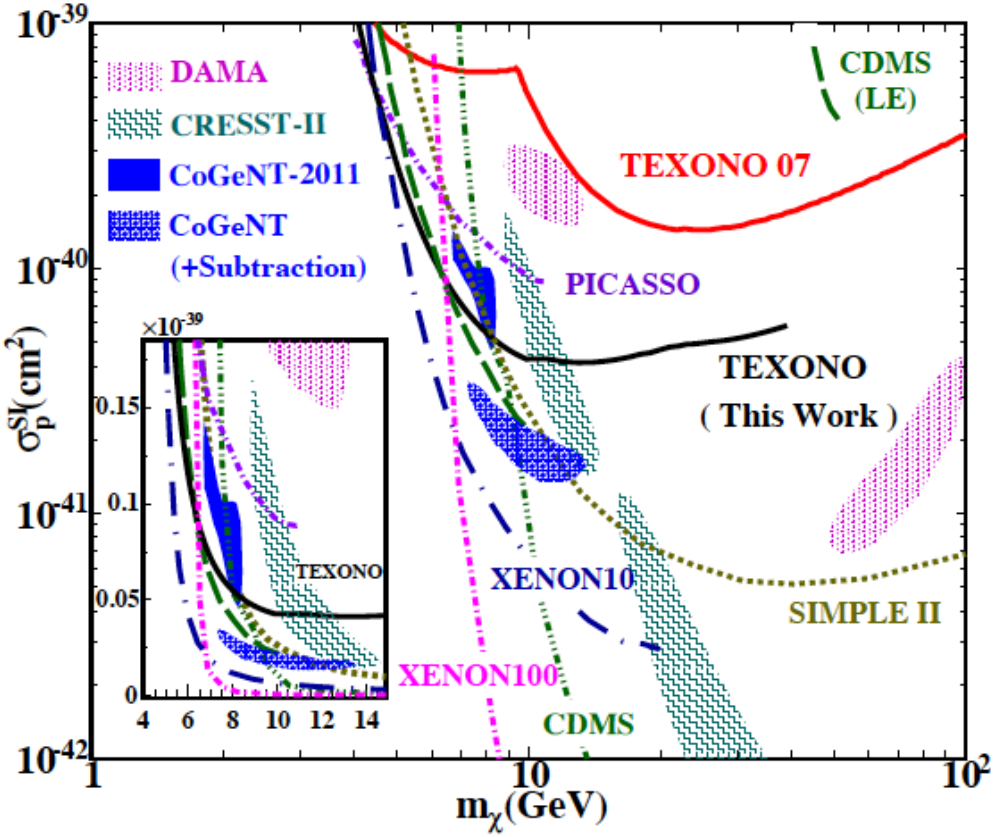
TEXONO Limits

2014 Limit: 53.8 days of 840 g fiducial mass ➔ 39.5 kg-d after cuts

2007 limit was for 4 elements totaling 20 g

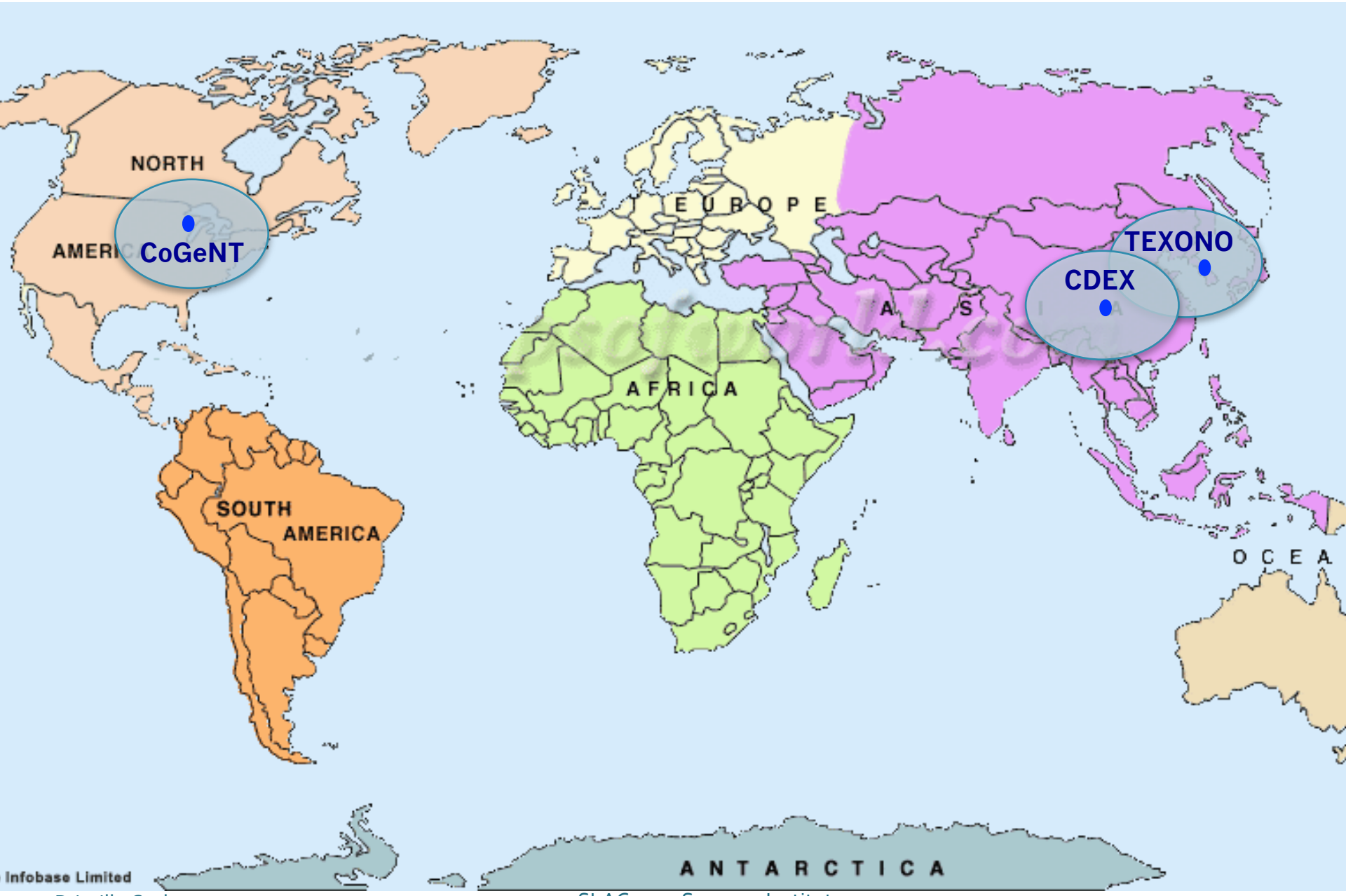
Sodium Iodide Compton Veto





Astroparticle Physics 56, 1 (2014), Phys. Rev. Lett. 110, 261301 (2013)

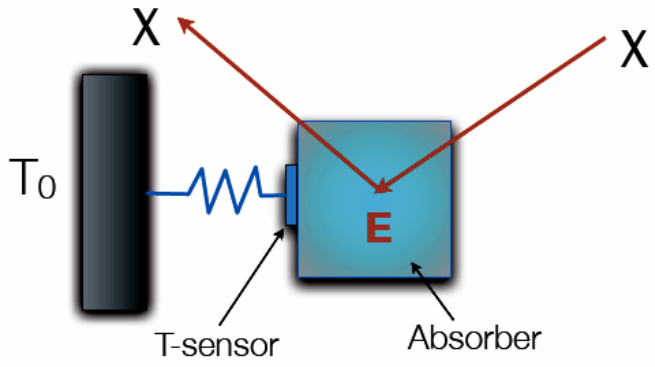
Underground Labs with low threshold HPGe



Very Cryogenic Solid State

Big Advance = Distinguish ER from NR on an event by event basis

Need sensitivity (big ΔT) for small ΔE

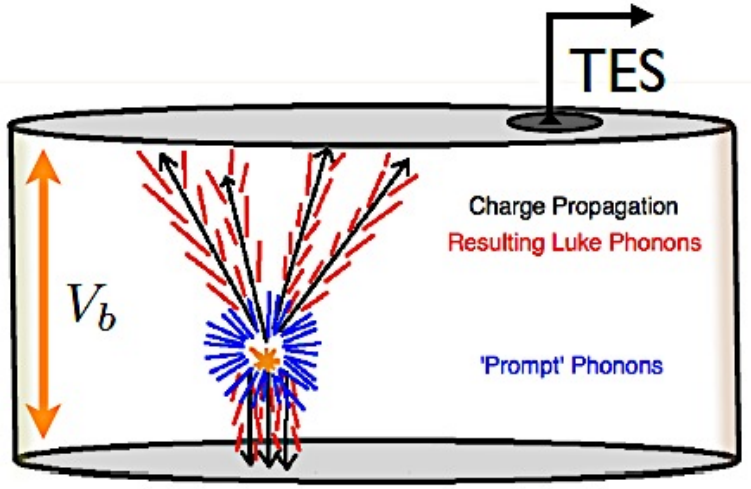


$$C(T) = \frac{\Delta E}{\Delta T} \propto T^3$$

What is different at 50 mK than at 77 K ?

impurity excitation energy is kT < 10 meV
➔ No need for doping – "depleted" already
➔ efficient charge collection at low drift fields

Residual space charge effects are removed by a neutralization process (IR led flashing)



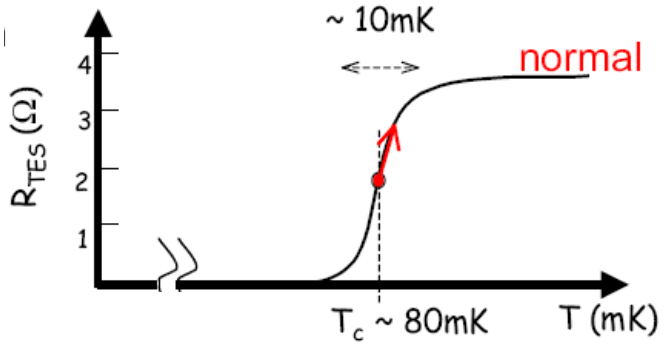
*Neganov and Trofimov, Otkryt. Izobret., **146**, 215 (1985)*
Luke, J. Appl. Phys., 64, 6858 (1988)

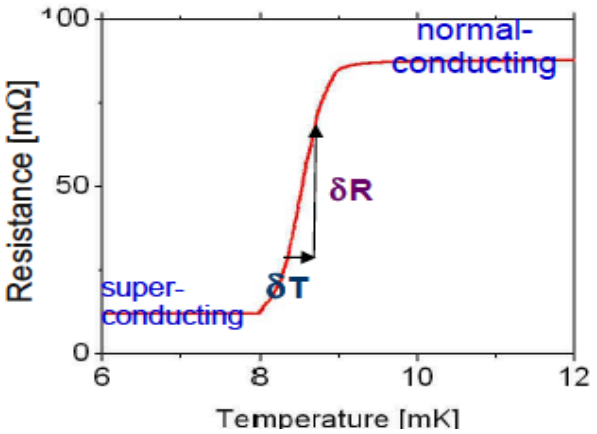
At a few V/cm, e-h holes can propagate without producing more phonons
➔ distinguishing between charge and phonon is not confused.

Very Cryogenic Solid State

The "Heat" Channel

Athermal Phonon Signal: **CRESST, CDMS**
Superconducting Transition Edge Sensors (TES) + SQUID readout





CDMS: thousands of tiny W-TES sensors w/Al fins (photolithography)

CRESST: Evaporated thin W-film with attached heater

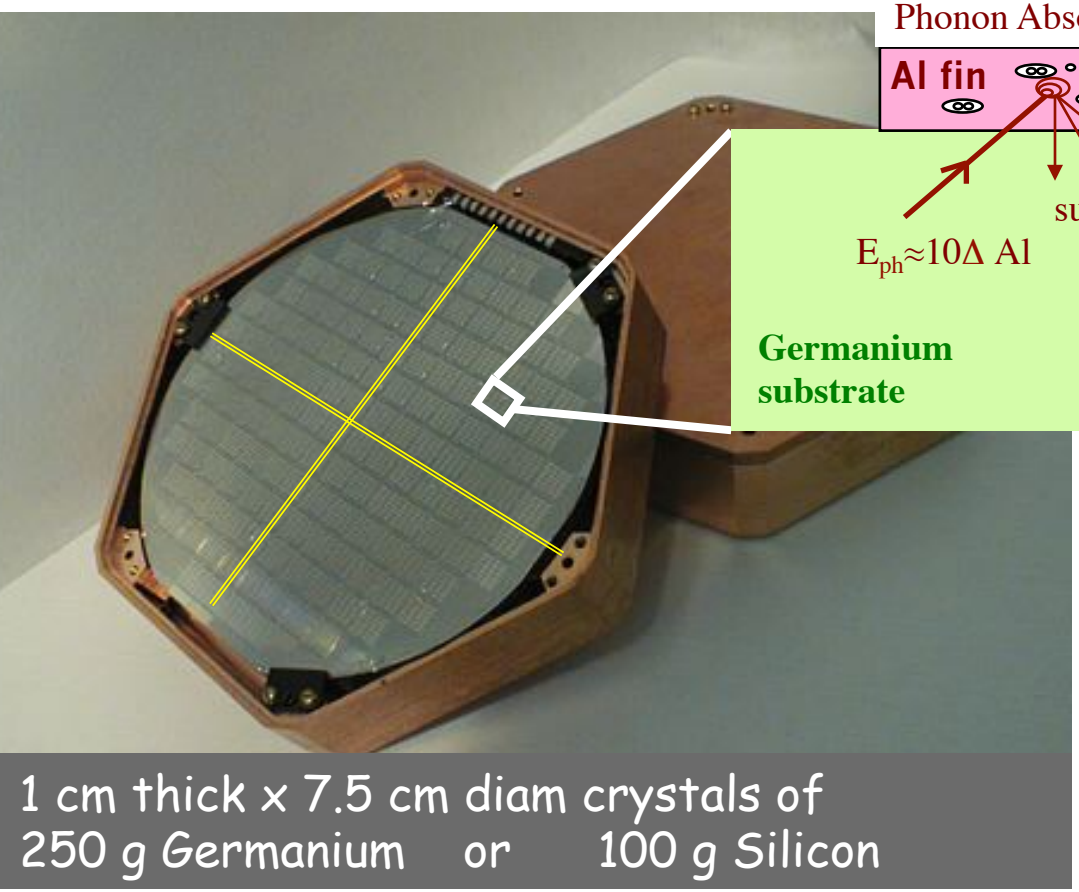
Thermal Phonon (Bolometric): **ROSEBUD, EDELWEISS**
Neutron transmutation-doped Ge (NTD-Ge) sensor +FET

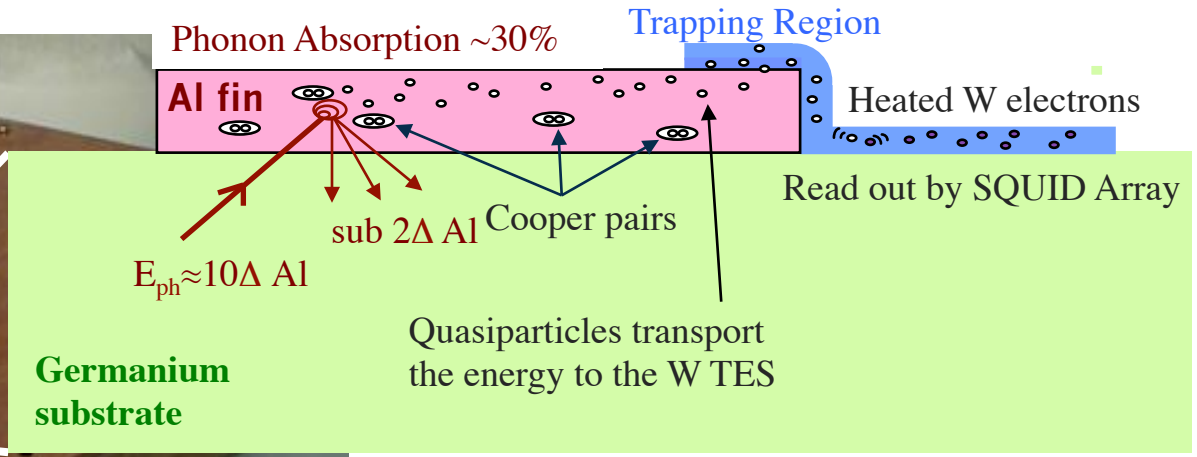
Individual thermistor with very uniform doping ➔ stable dR/dT

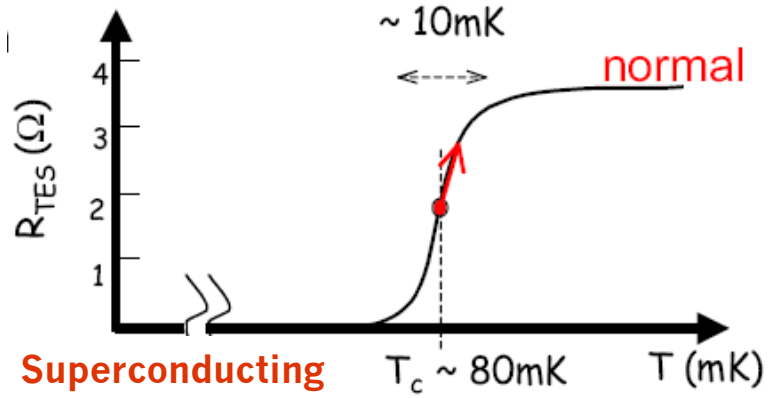
Z I P

CDMS II Detectors (phonon readout)

photolithographic patterning produces 4144 "thermometers"
(quasi-particle-assisted electrothermal-feedback transition-edge sensors)







Very Cryogenic Solid State

The OTHER Channel

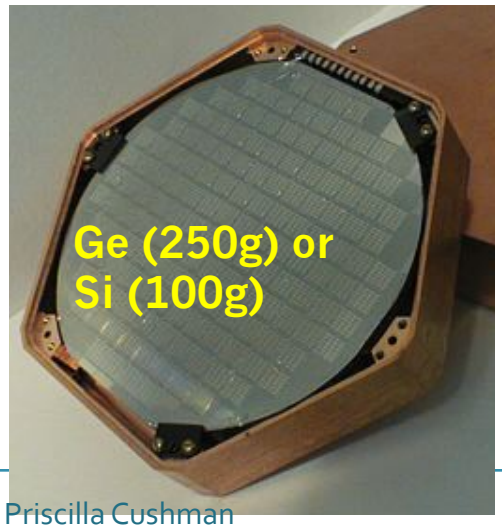
Ionization | *Scintillation*

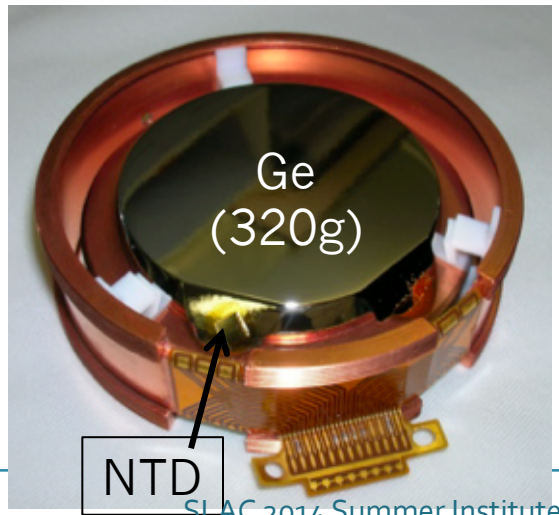
CDMS II (Soudan) | **EDELWEISS (Modane)** | **CRESST II (Gran Sasso)**

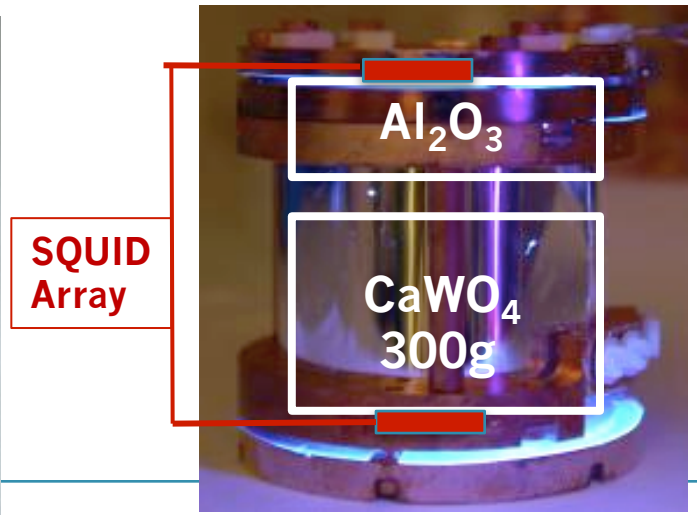
Apply voltage across crystal

Read out drifted charge from FETs

light from $CaWO_4$ via sapphire-silicon sensor W-TES on Al_2O_3+ SQUIDs



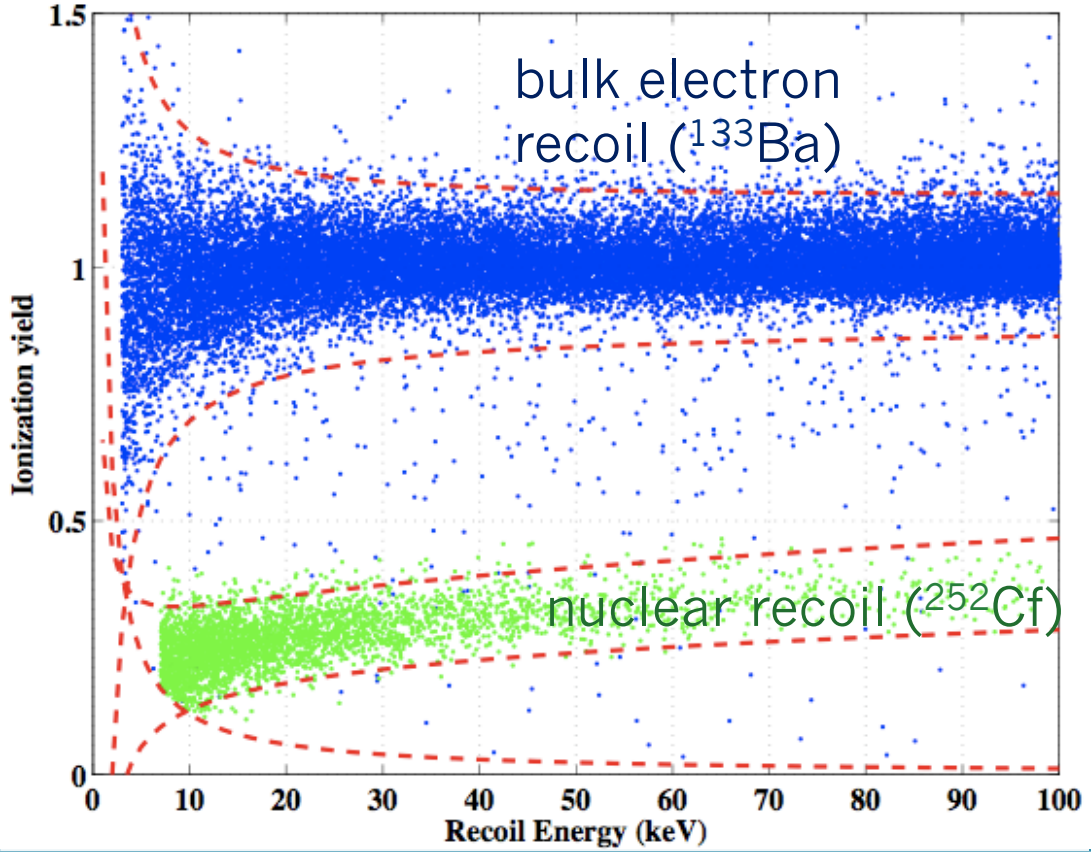


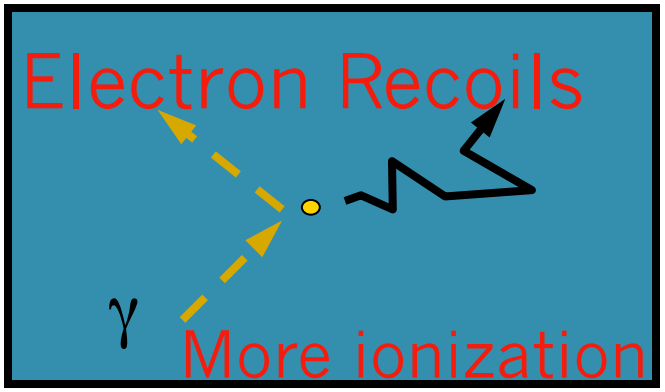


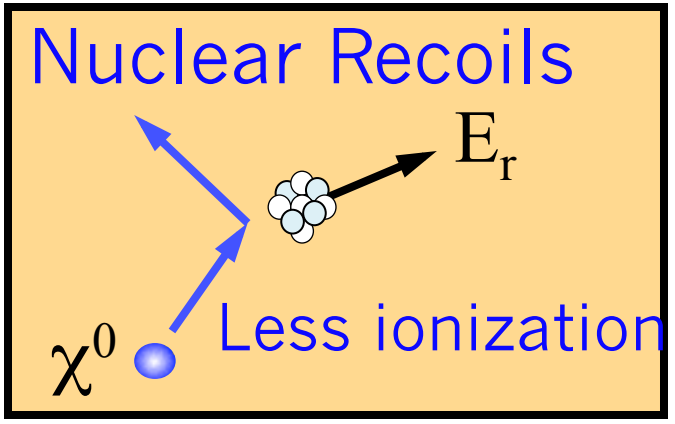
Yield provides ER vs NR discrimination event by event

Other Channel
Heat Channel

Map out yield vs energy using radioactive sources







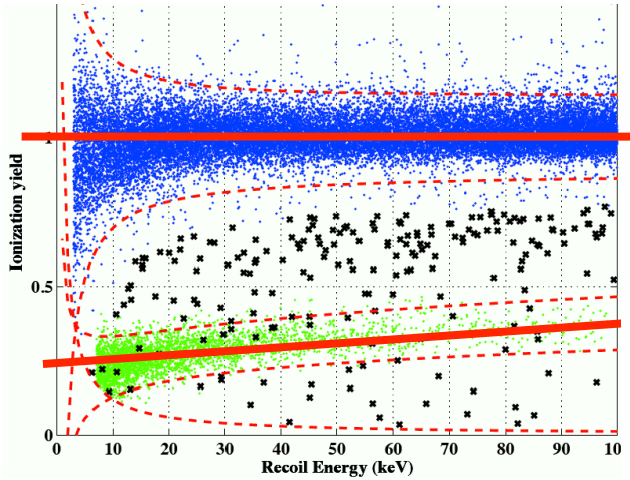
Very Cryogenic Solid State

Ionization *Scintillation*

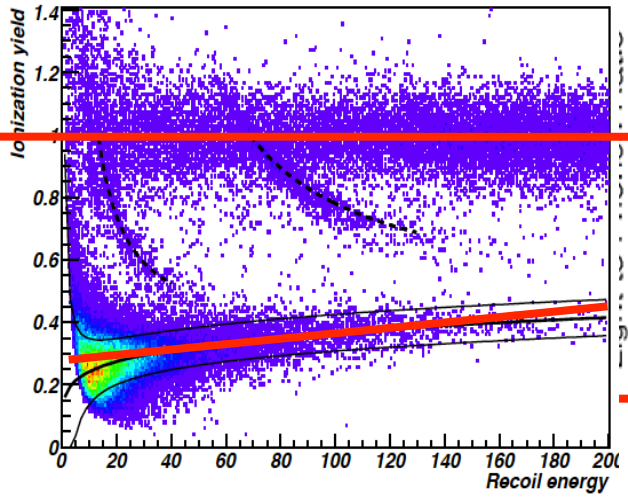
CDMS II (Soudan) | **EDELWEISS** (Modane) | **CRESST II** (Gran Sasso)

Data from radioactive source calibration

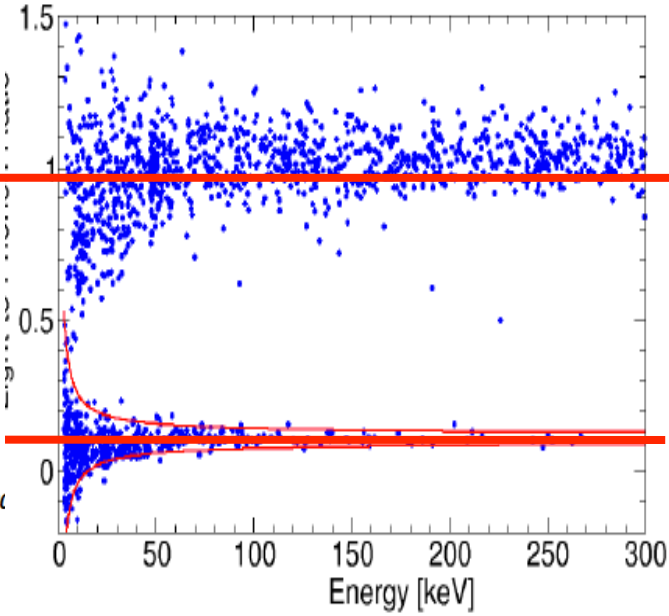
Charge to Phonon ratio



Charge to Heat ratio



Light to Phonon ratio



NR Quenched by factor ~ 3

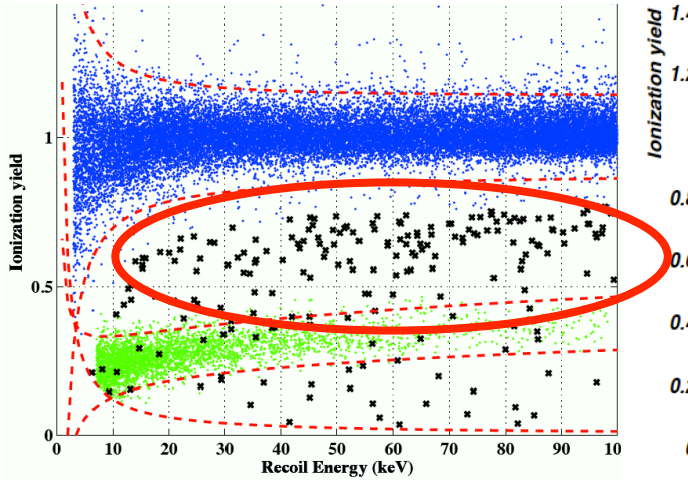
Q(O) ~ 9 ER/NR from CaO
Q(W) ~ 40 ➔ insensitive to n
but big A^2 effect for WIMPs

Very Cryogenic Solid State: Surface Events

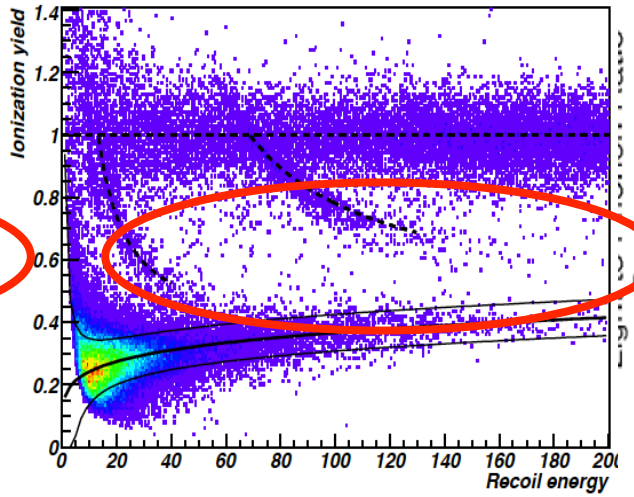
CDMS II (Soudan) | **EDELWEISS** (Modane) | **CRESST II** (Gran Sasso)

Data from radioactive source calibration

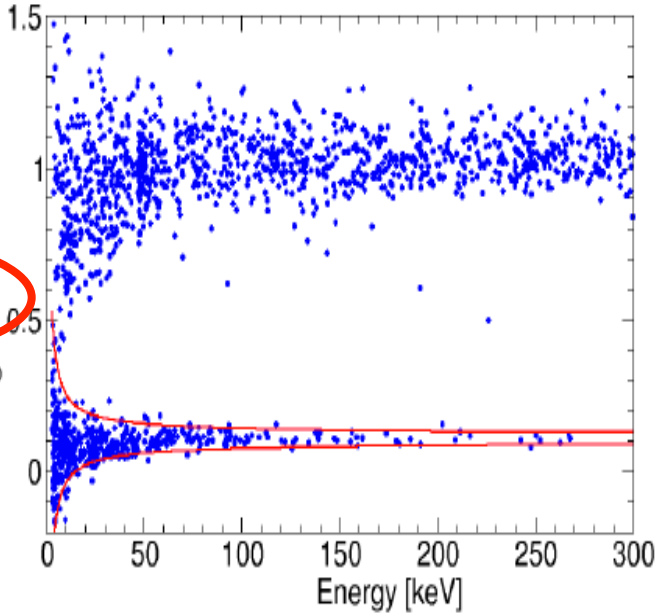
Ionization to Phonon ratio



Ionization to Heat ratio



Light to Phonon ratio

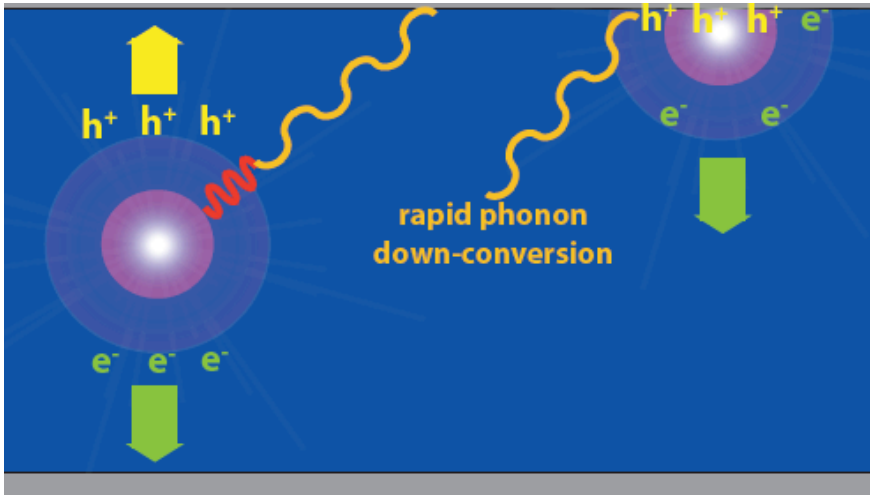


Incomplete charge collection for low energy β
Ionization ratio droops into NR band

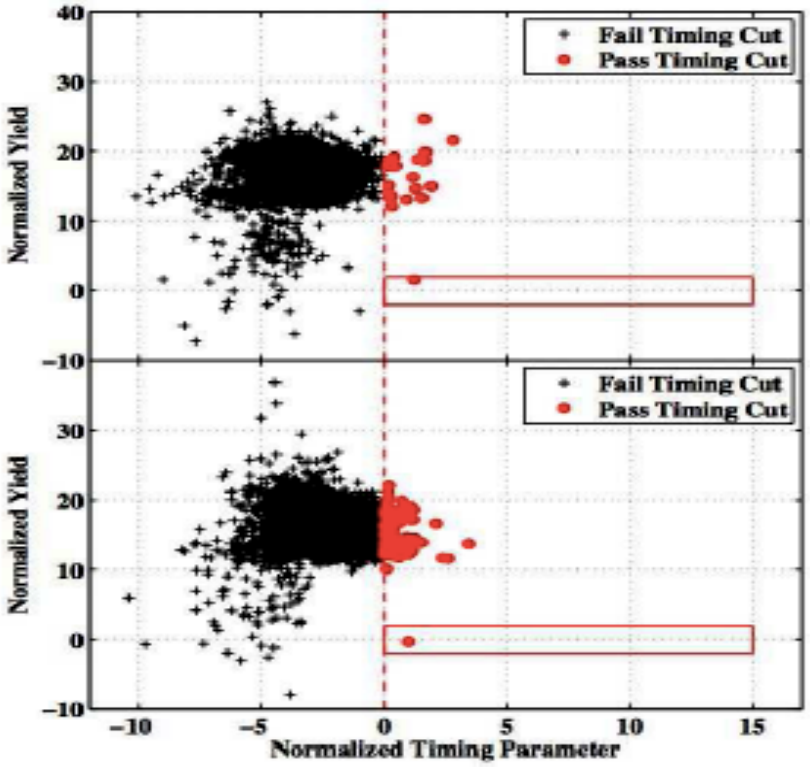
CDMS II Rejected Surface Events with Timing

Data from WIMP Search in 2011
Found 2 candidate events in Ge
But quoted limit

phonon pulse shape gives another handle



Phonons created near surface travel faster through crystal (ballistic)

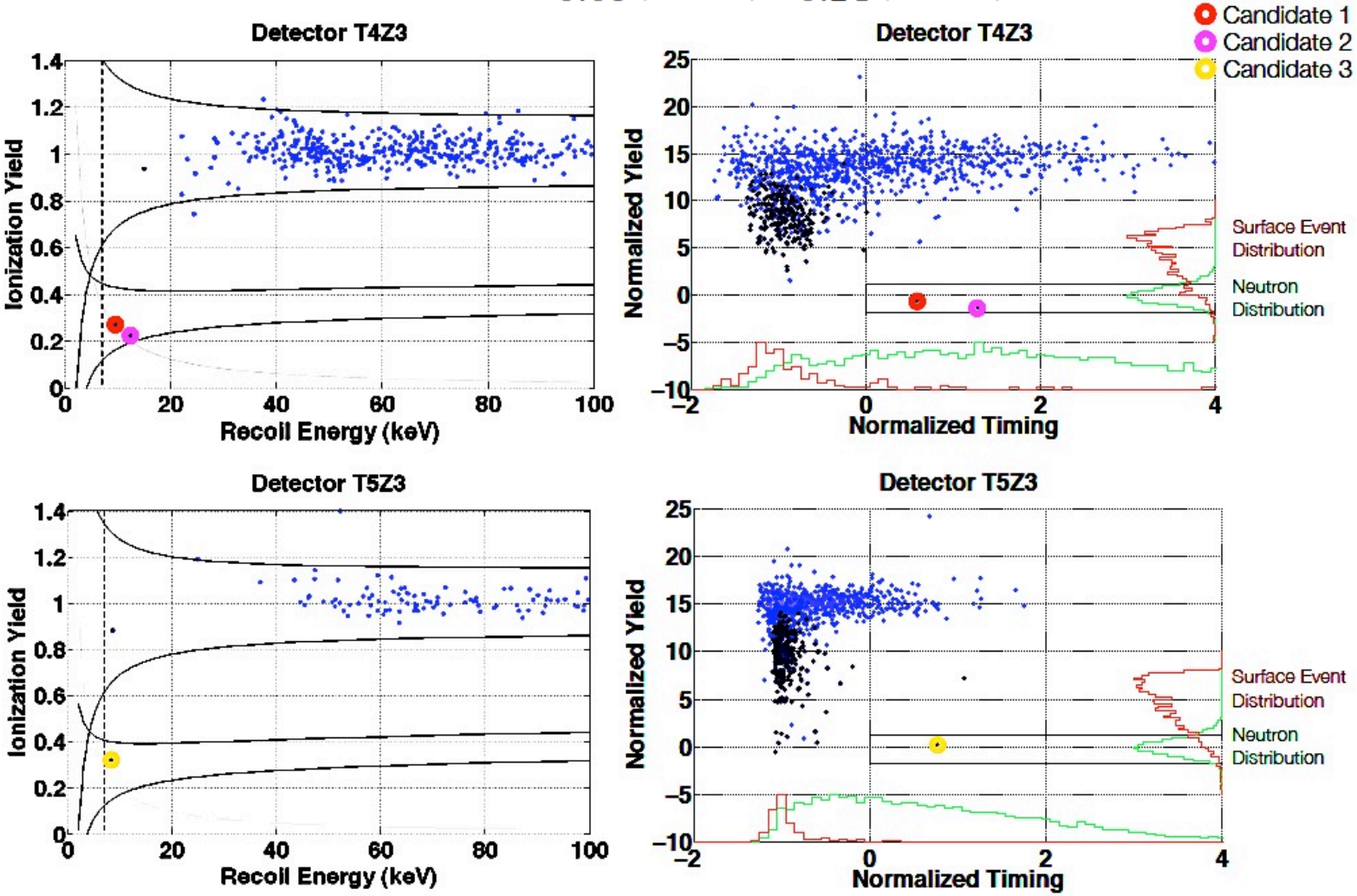


Timing Parameter
linear combination of risetime and delay

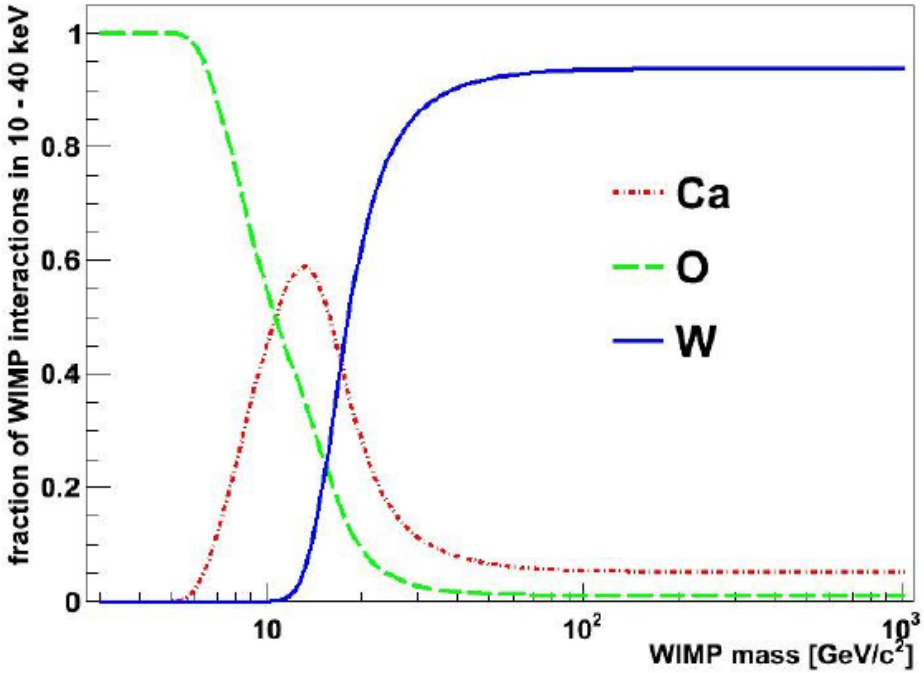
CDMS II Rejected Surface Events with Timing

2013: Using a modified version of the 5D χ^2 phonon timing cut, Silicon reveals 3 events with expected surface leakage of 0.41

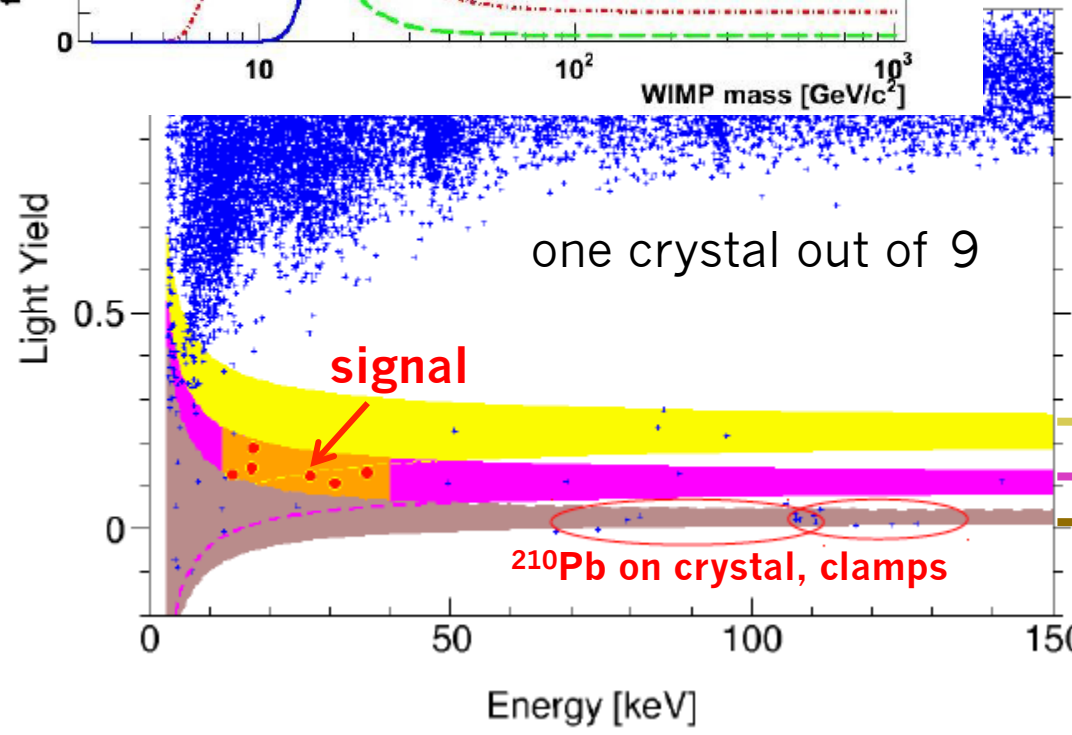
$$0.41^{+0.20}_{-0.08}(stat.)^{+0.28}_{-0.24}(syst.)$$



CRESST II showed an excess of events in 2011



Signal region defined as
10 – 40 keV



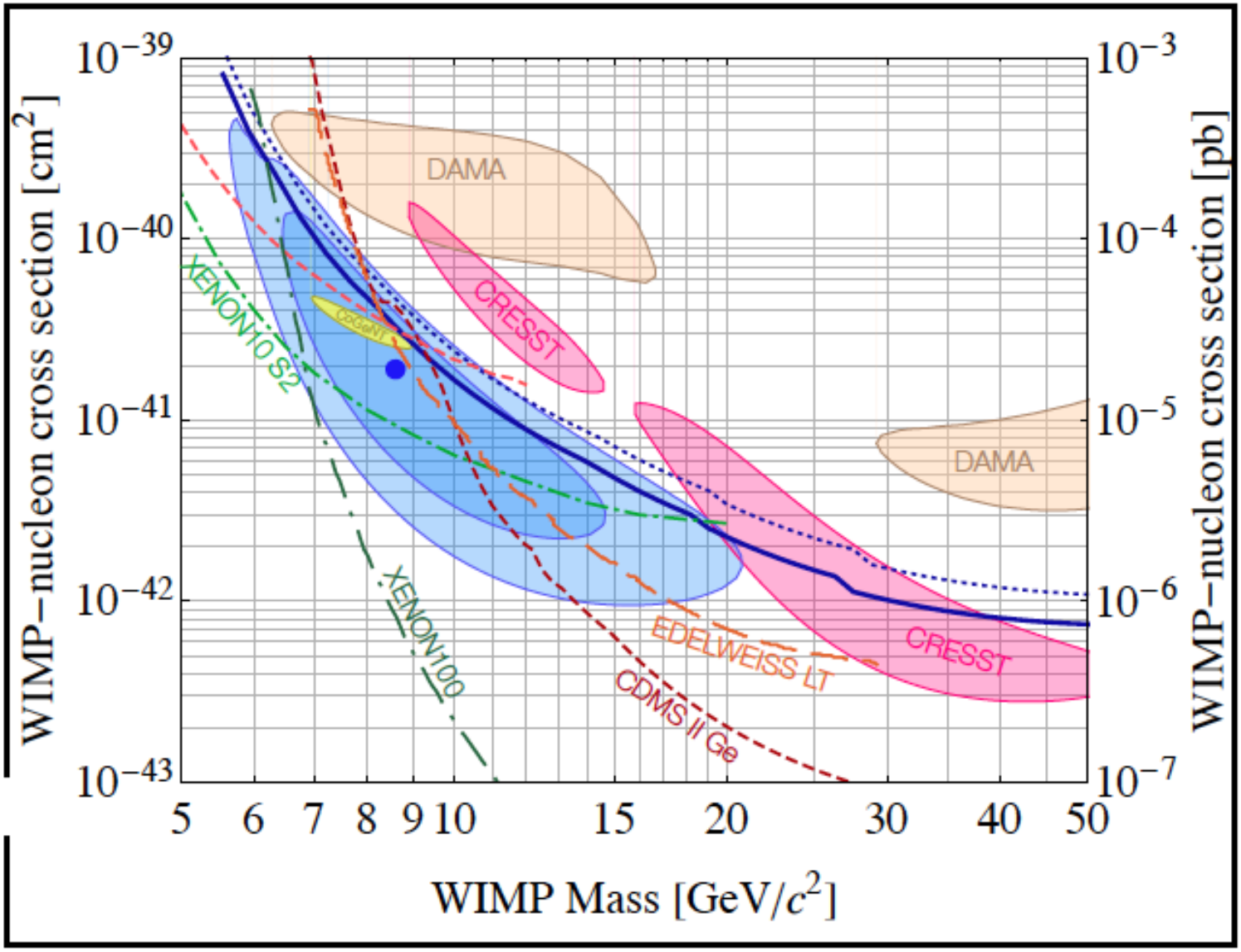
Counts in signal region	**32**
Neutron background	0.8
Alpha background:	6.8
Leakage from gamma band:	1.2
Remaining signal:	**23.2**

$M_W = 12$ GeV/c^2 @ 5.4 σ

564 kg-d from 9 $CaWO_4$ crystals

alpha band
oxygen band
tungsten band

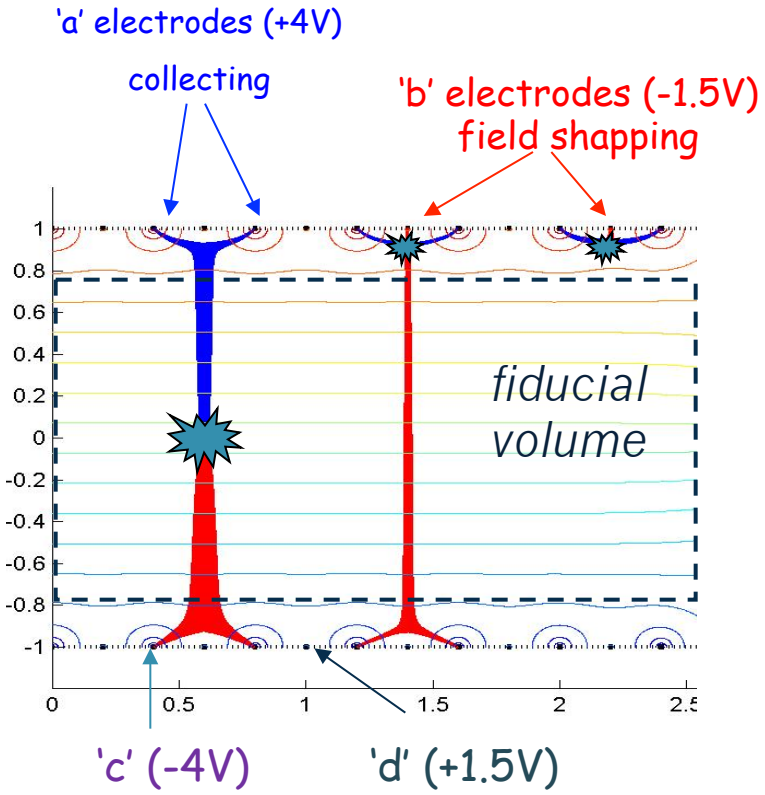
Hints of Low Mass WIMPs



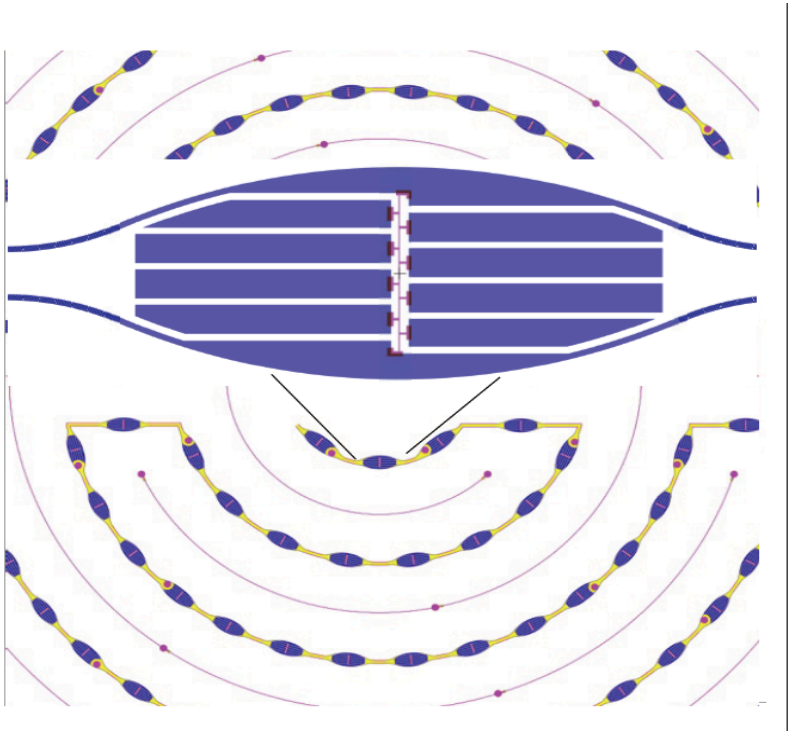
Rejecting Surface Events: Interleaved Electrodes

Charge near surface is collected by electrodes on only one side

EDELWEISS II



SuperCDMS Soudan



Modular Fiducialization

Example: SuperCDMS

Bulk events: charges drift to both sides of crystal

Vertical Fiducialization

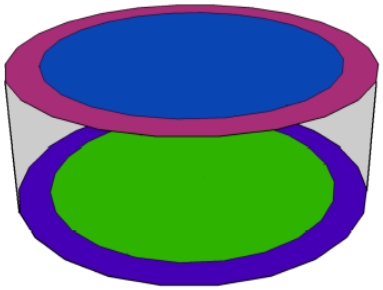
Surface events: charges drift to only one side
Z-partition: charge sharing on both sides

Sidewall Fiducialization

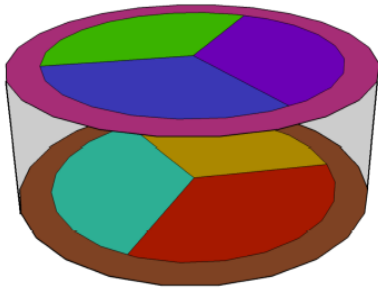
Segmented outer electrode
R-partition: Energy sharing between inner and outer sensors

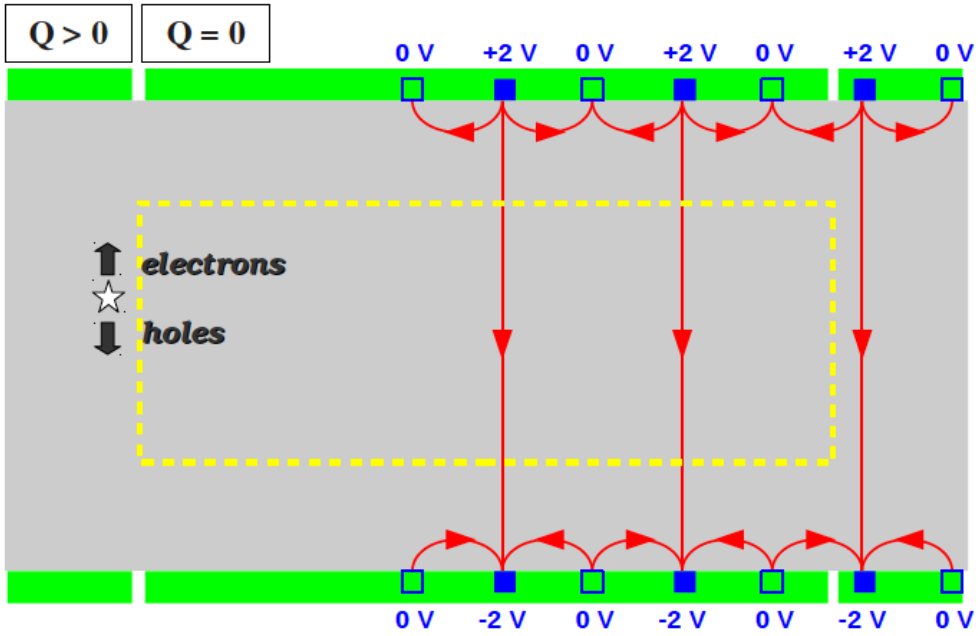
Complementary information from phonon channel partition and risetime

Ionization read-out channels



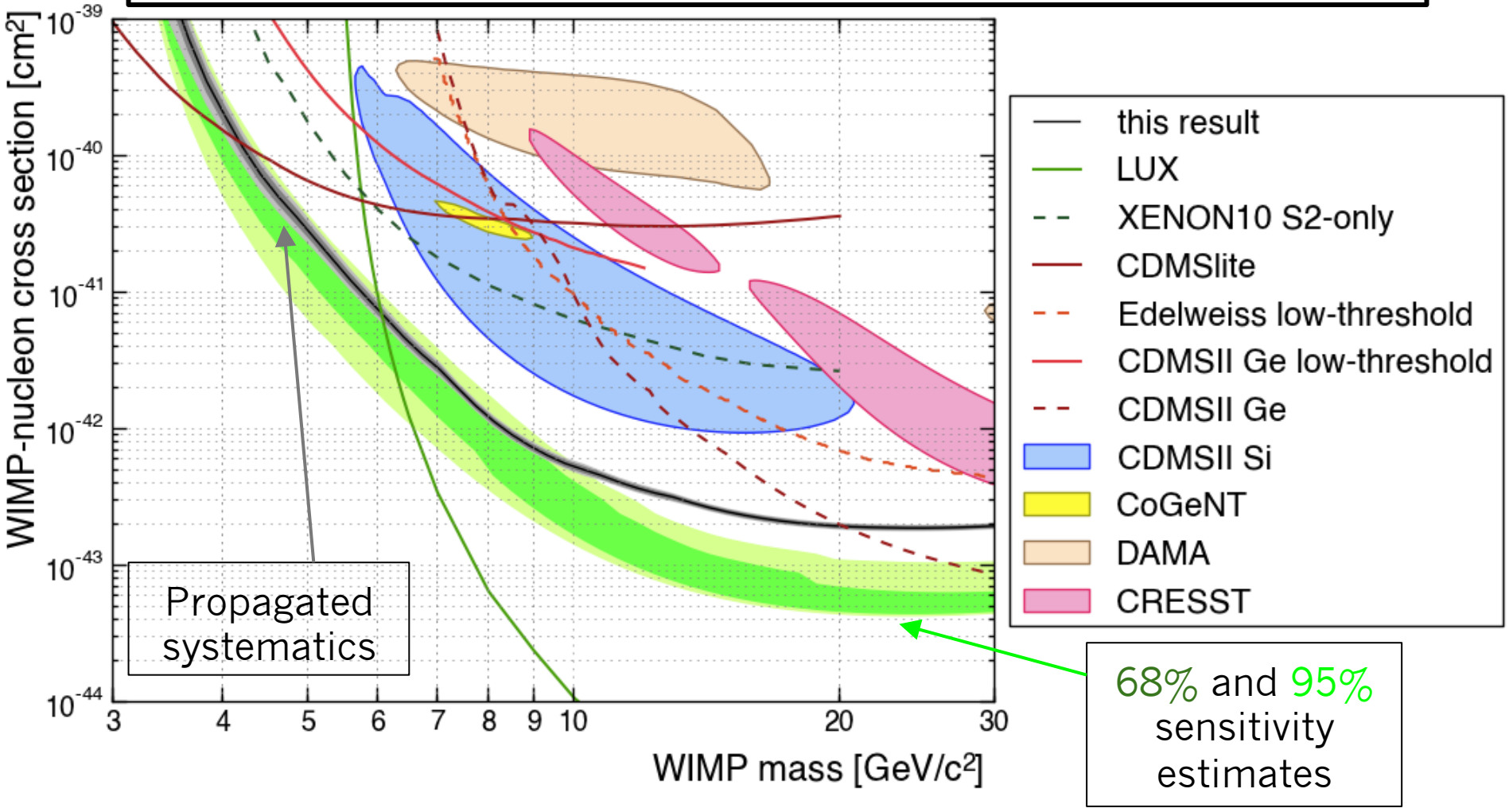
Phonon read-out channels





New Limits from SuperCDMS Ge iZIPs

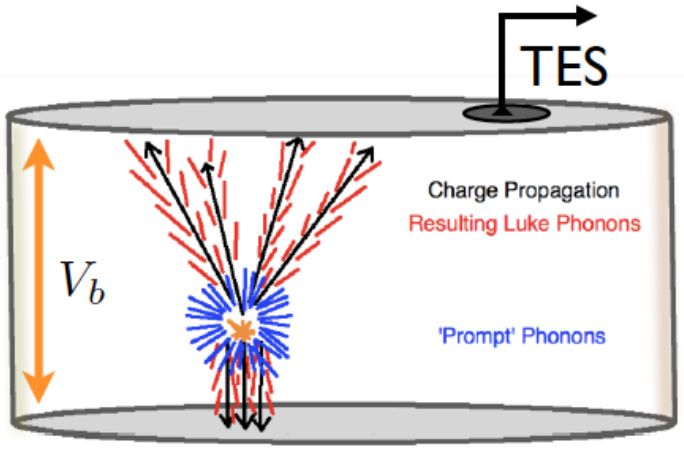
Seven iZIPs analyzed down to trigger thresholds (1.6 keV_{nr});
577 kg-days total exposure yields 90% upper CL on WIMP-nucleon cross-section of $\sigma = 1.2 \times 10^{-42}$ cm^2
11 candidates seen on expectation of 6.04 [+1.14 -0.82]



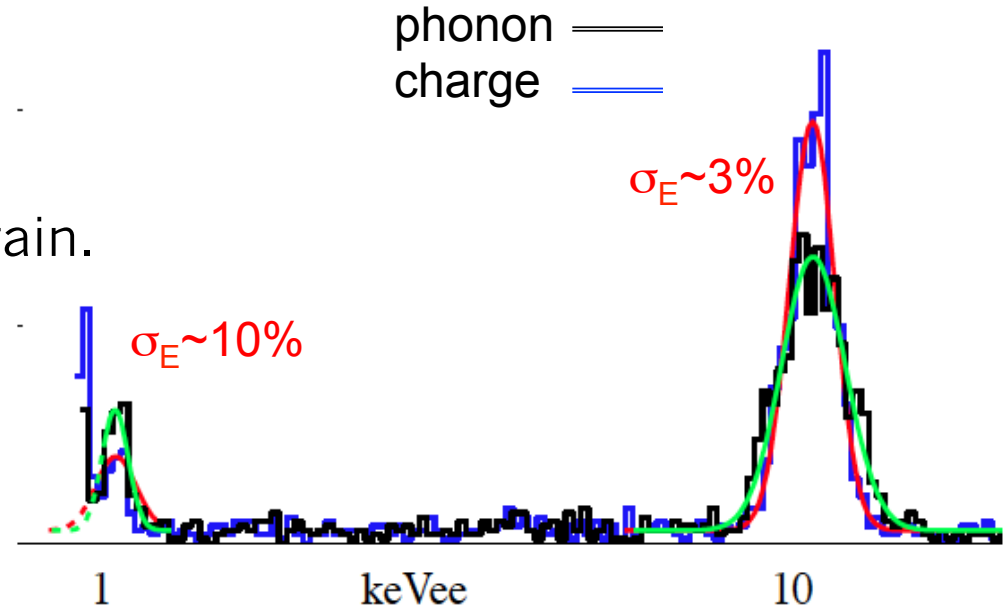
CDMSLite: Low Ionization Threshold Experiment

$$E(\text{phonon}) = E(\text{recoil}) + \frac{eV_b}{\varepsilon} E(\text{charge})$$

Luke Phonons interfere with timing cut and complicate yield discrimination
So CDMS runs with V_b <10 (Luke Gain ~ 2) to minimize effect



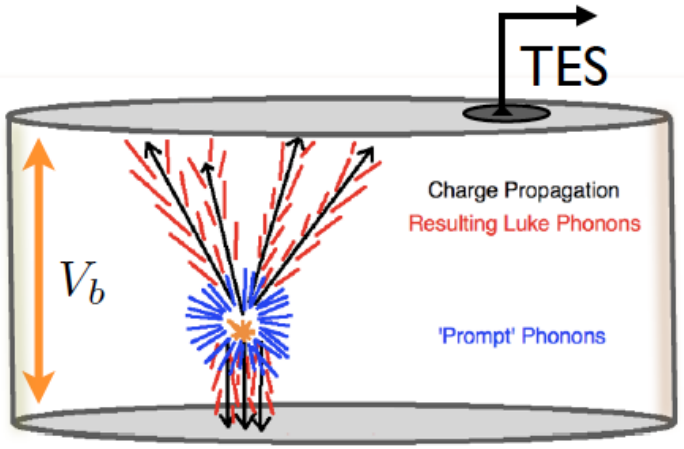
To lower threshold, crank up the gain.
Use ionization readout to measure phonons.



Neutron activation lines at 1.3 keV, 10.4 keV

CDMSLite: Low Ionization Threshold Experiment

$$E(\text{phonon}) = E(\text{recoil}) + \frac{eV_b}{\varepsilon} E(\text{charge})$$

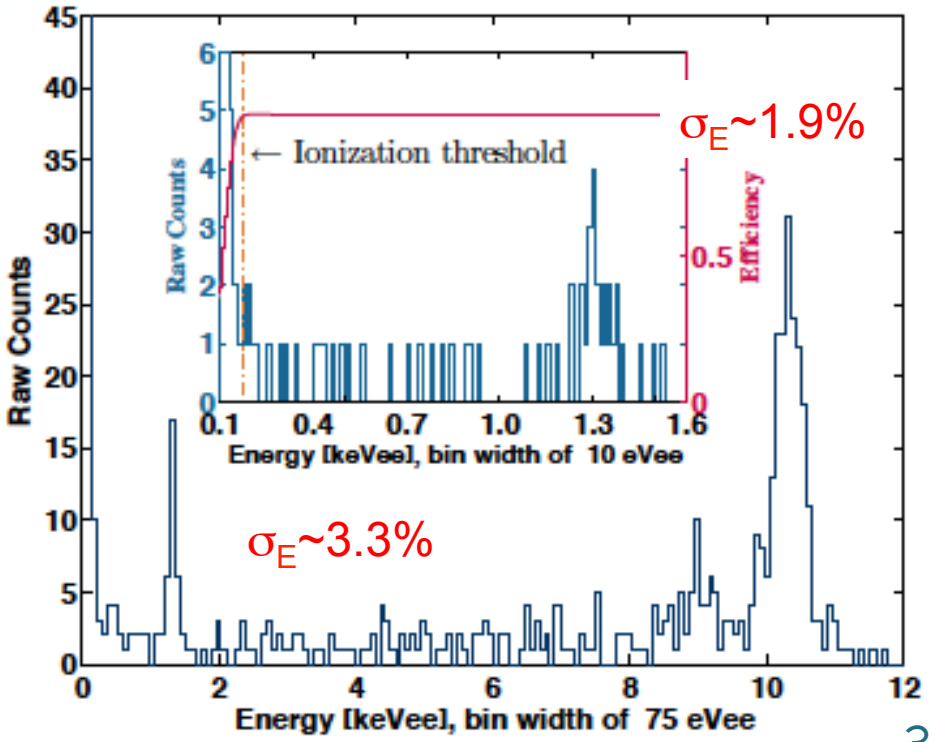


Luke Phonons interfere with timing cut and complicate yield discrimination
So CDMS runs with V_b <10 (Luke Gain ~ 2) to minimize effect

Improves resolution to 14 eVee

So you can look *below* the 1.3 keV line

For V_b ~ 70 v , the Luke Gain ~ 24

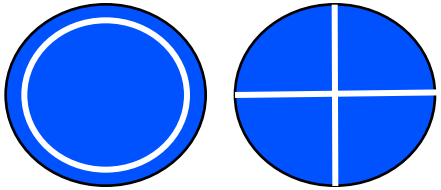


An Evolving Detector

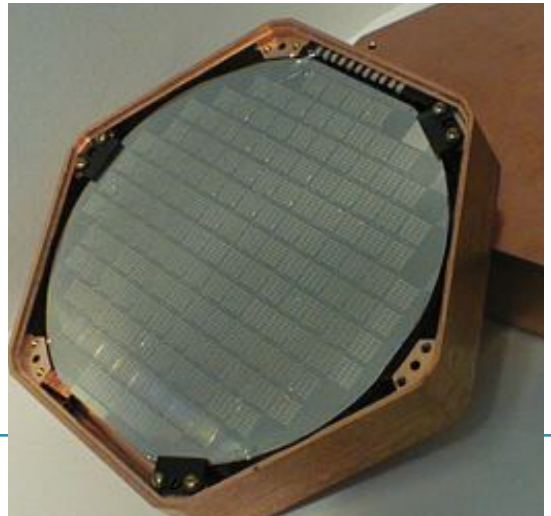
CDMS II

Single-sided
1 cm thick
3”diameter
250 g Ge

2 charge + 4 phonon



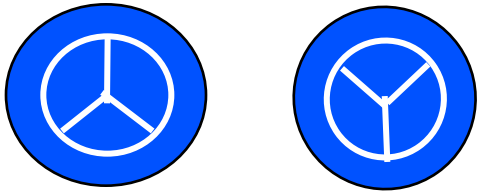
5 towers of 6 det each



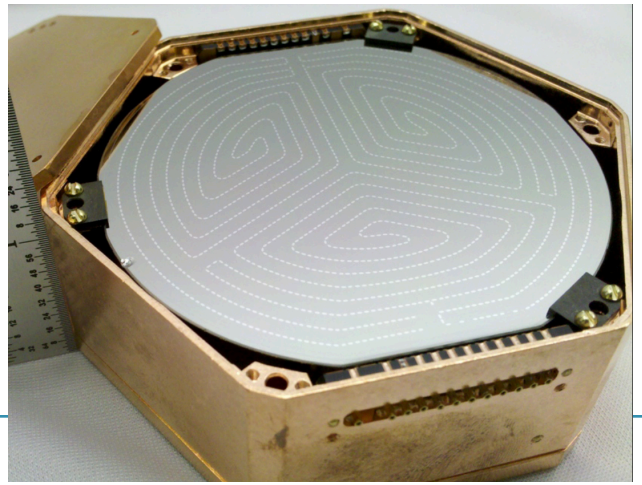
SuperCDMS Soudan

Double-sided
2.5 cm thick
3”diameter
620 g Ge

2 charge + 2 charge
4 phonon + 4 phonon



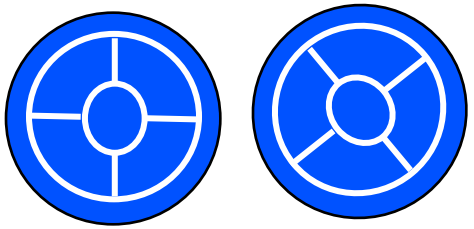
5 towers of 3 det each



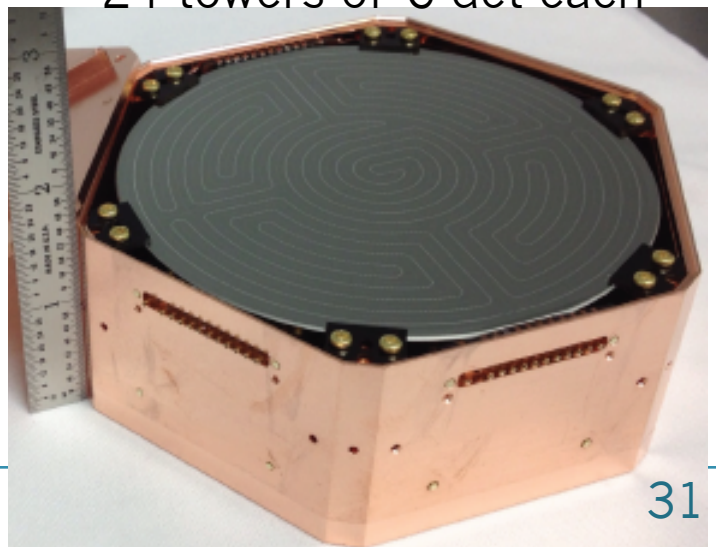
SuperCDMS SNOLAB

Double-sided
3.3 cm thick
4”diameter
1.38 kg Ge

2 charge + 2 charge
6 phonon + 6 phonon

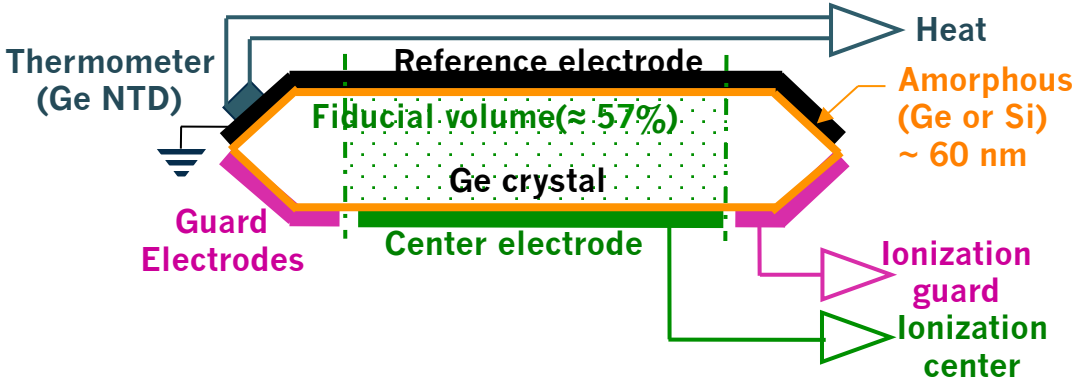


24 towers of 6 det each

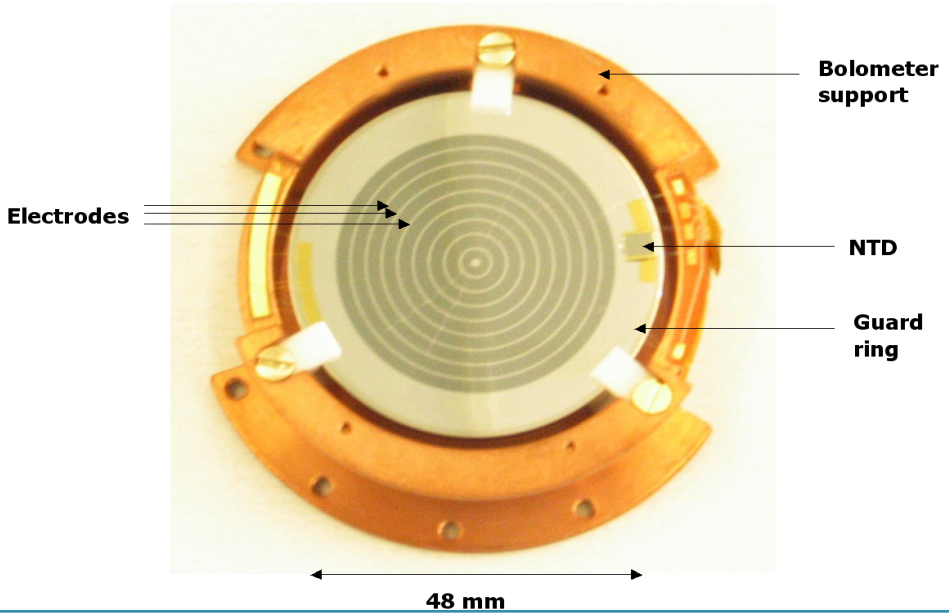


We are all evolving!

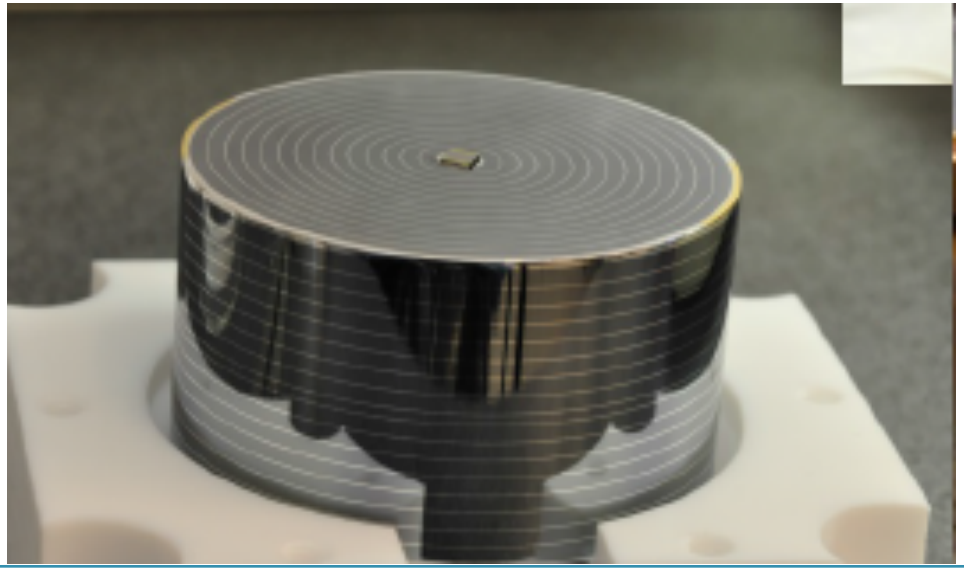
EDELWEISS



EDELWEISS-II

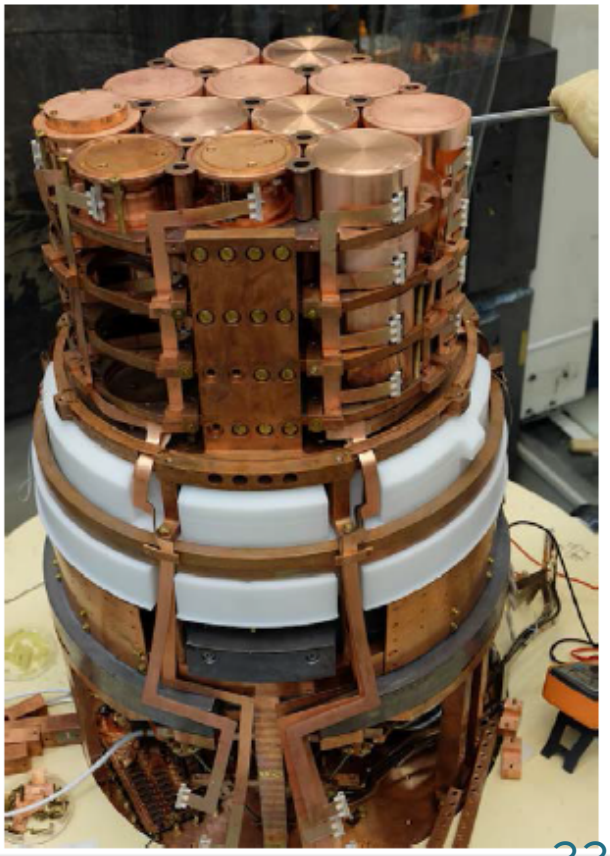


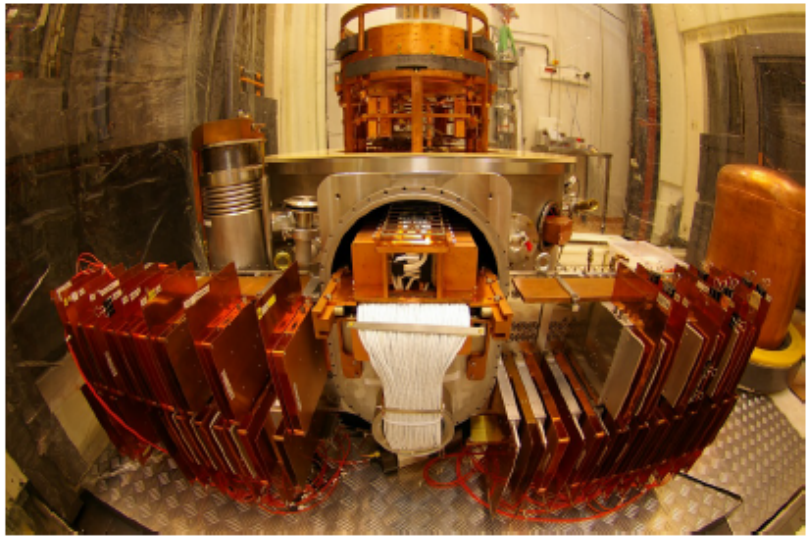
EDELWEISS-III



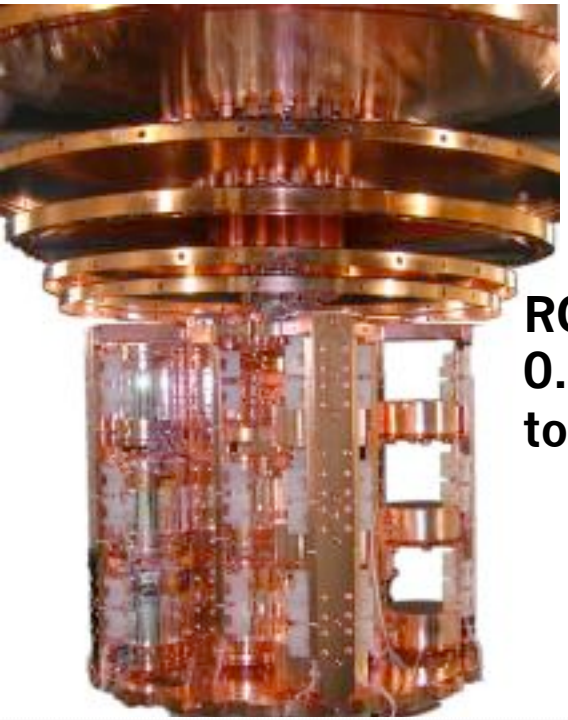
EDELWEISS-III as of March 2014

- upgraded cryogenics
- upgraded readout electronics (FIC)
- new Kapton cables
- inner PE shield + new Cu screens
- 36 FID 800g detectors installed
- 3 $ZnMoO_4$ detectors installed ($0\nu\beta\beta$ search)
- T(mixing chamber) = 25mK
- **EDELWEISS-III with 3000 kg.d by end 2014**



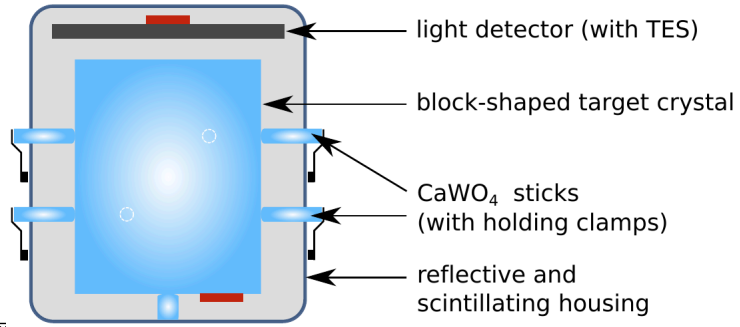


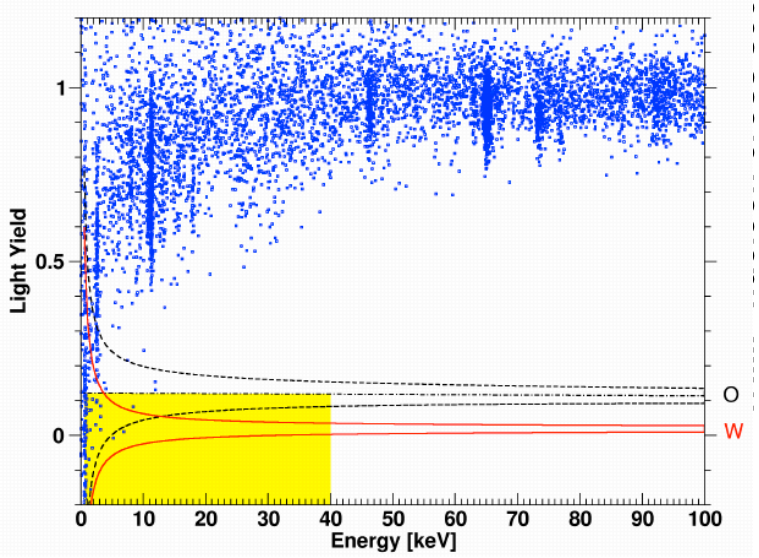
CRESST II Improvements

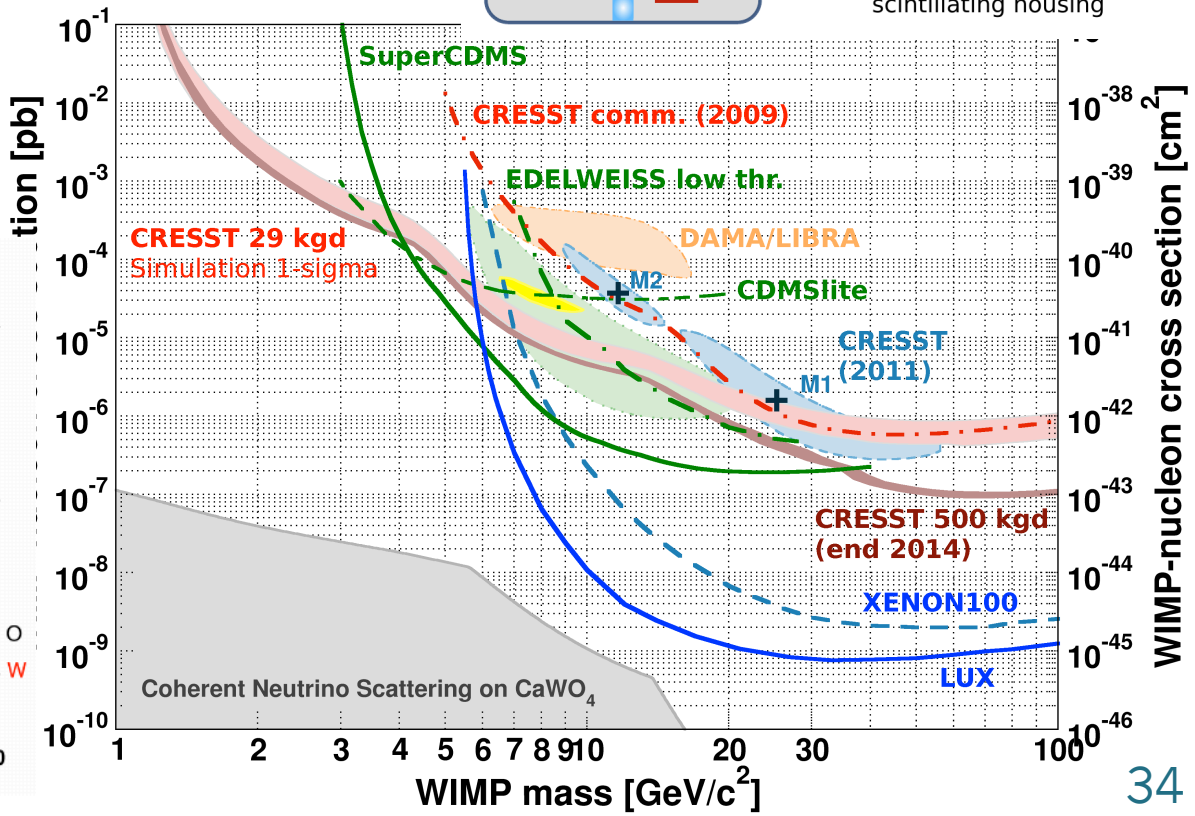


18 modules running since July 2013
Composite detector design (simplified TES)
Improve clamps

ROI:
0.6 keV (50% trigger eff)
to 40 keV

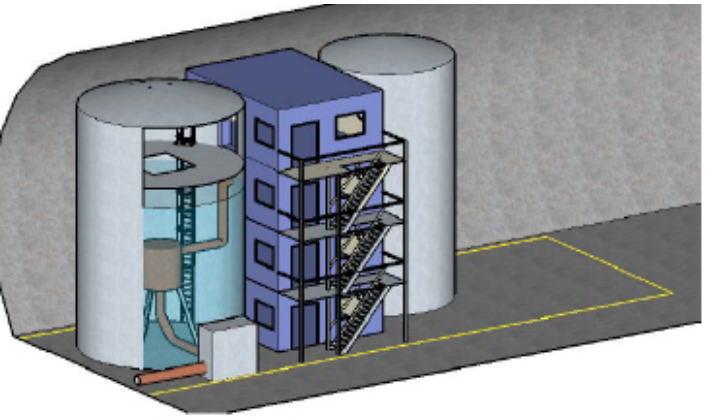


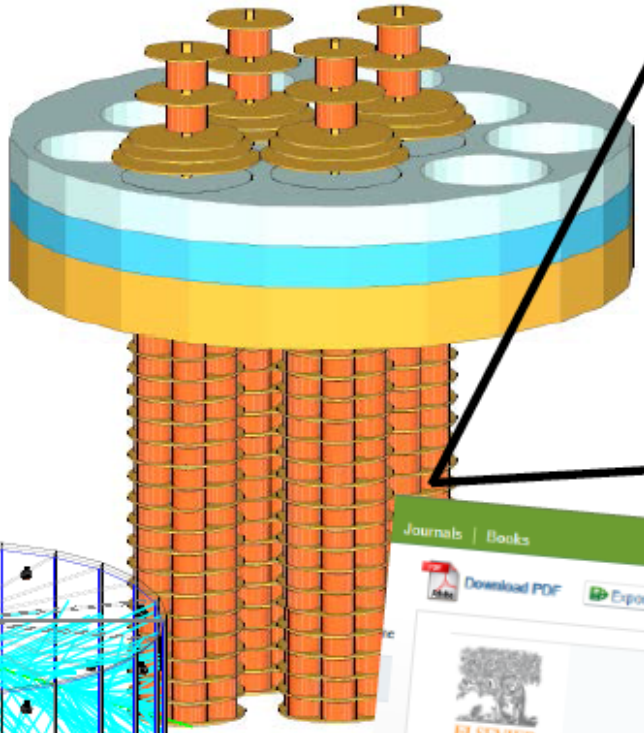


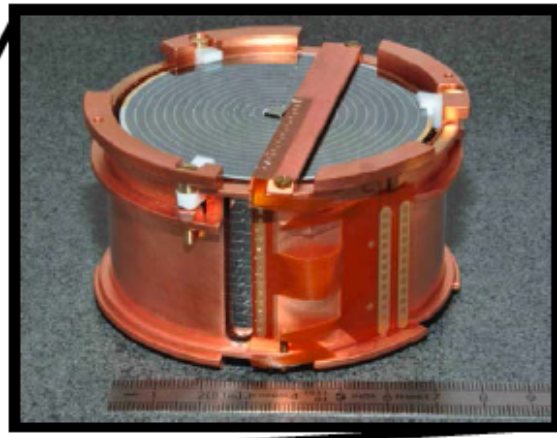


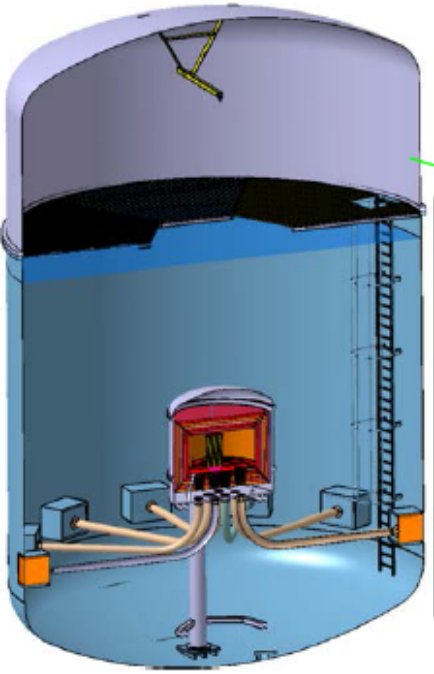
EURECA: The ton scale follow-on to **EDELWEISS + CRESST**

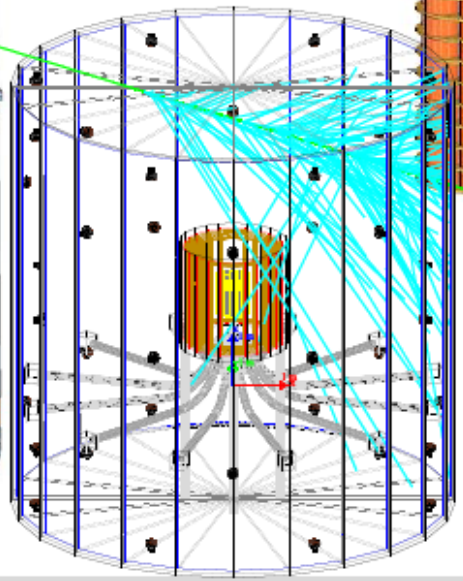
Located in an extension of Modane:











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Physics of the Dark Universe

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EURECA Conceptual Design Report The EURECA Collaboration

G. Angloher, E. Armengaud, C. Augier, A. Benoit, T. Bergmann, J. Blümer, A. Broniatowski, V. Brudanin, P. Camus, A. Cazes, M. Chapellier, N. Coron, G.A. Cox, C. Cuesta, F.A. Danevich, M. De Jésus, L. Dumoulin, K. Eitel, A. Erb, A. Ertl, F. von Feilitzsch, D. Filosofov, N. Fourches, E. Garcia, J. Gascon, G. Gerbier, C. Ginestra, J. Gironnet, A. Giuliani, M. Gros, A. Gütlein, D. Hauff, S. Henry, O. Heuermann, J. Jochum, S. Joklisch, A. Juillard, C. Kister, M. Kleifges, H. Kluck, E.V. Korolkova, V.Y. Kozlov, H. Kraus, V.A. Kudryavtsev, J.-C. Lanfranchi, P. Loaiza, J. Loebell, I. Machulin, S. Marnieros, M. Martínez,

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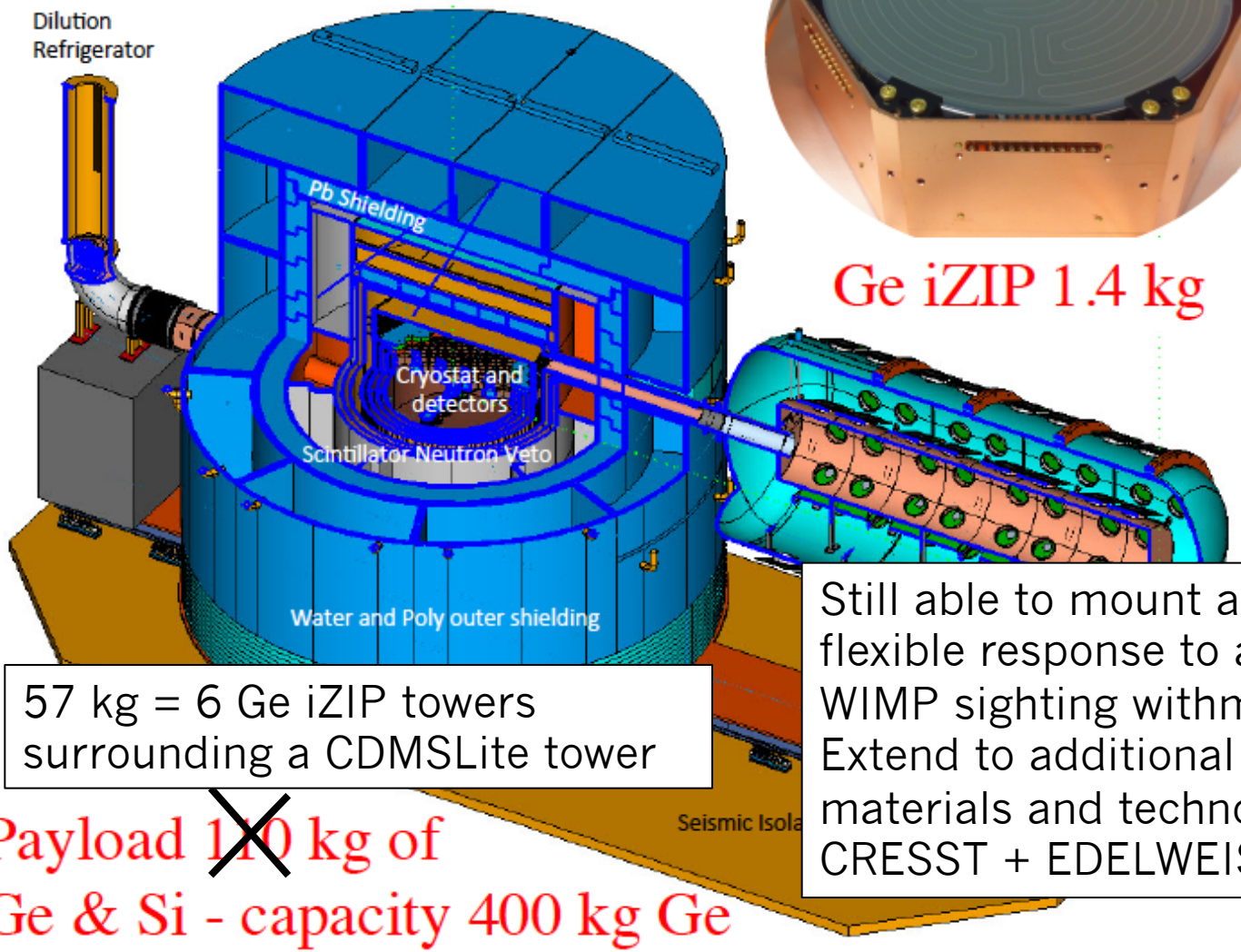
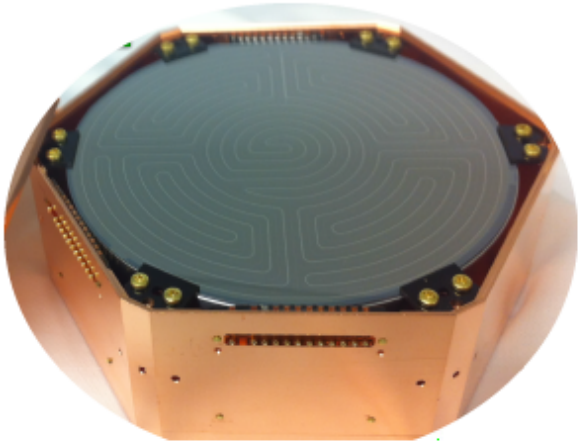
http://dx.doi.org/10.1016/j.dark.2014.03.004

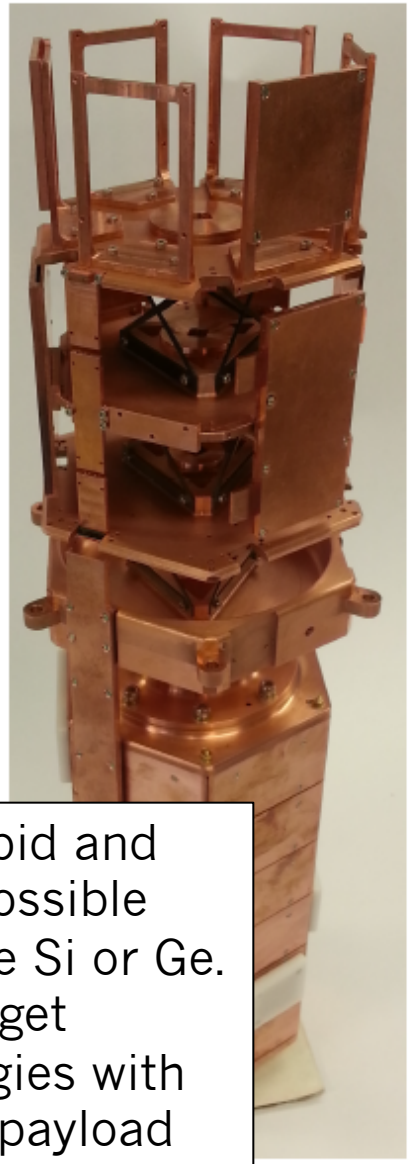
SuperCDMS SNOLAB Experiment

- SNOLAB 6010 mwe





Ge iZIP 1.4 kg



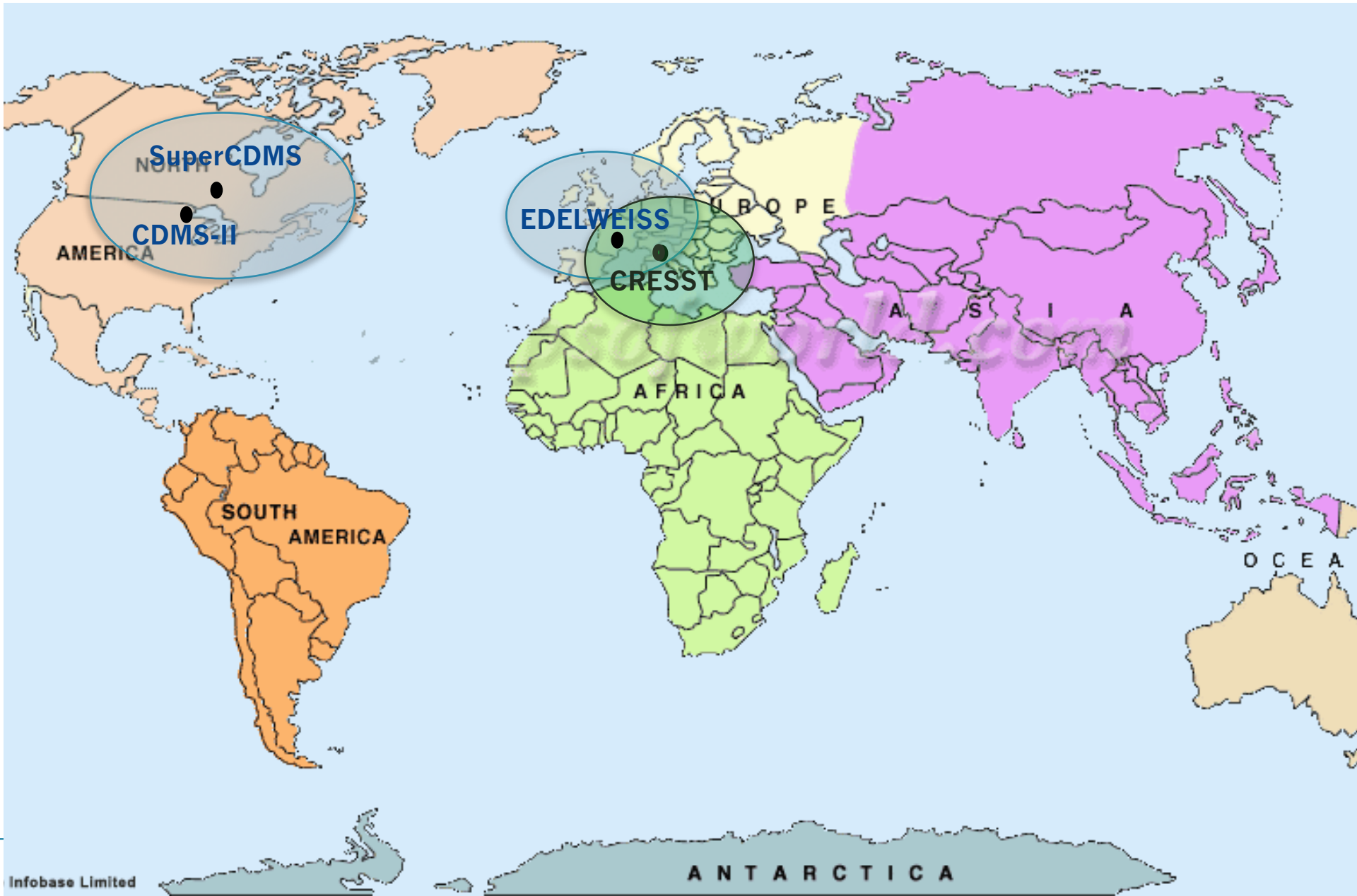
Ge Tower 8.4 kg

57 kg = 6 Ge iZIP towers surrounding a CDMSLite tower

Payload ~~1~~10 kg of Ge & Si - capacity 400 kg Ge

Still able to mount a rapid and flexible response to a possible WIMP sighting withmore Si or Ge. Extend to additional target materials and technologies with CRESST + EDELWEISS payload

Underground Labs with Cryogenic Solid State



Purified Inorganic Crystals: NaI(*Tl*) and CsI(*Tl*)

Experiments: KIMS and DAMA

	CsI(Tl)	NaI(Tl)
Photons/MeV	~60,000	~40,000
Density(g/cm3)	4.53	3.67
Decay Time(ns)	~1050	~230
Peak emission(nm)	550	415

- Modular, room temperature scintillators,
  read out with lowrad PMT at each end for coincidence.

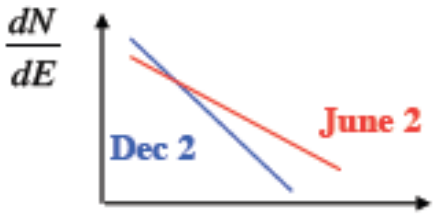
- Stability ➔ exploit annual modulation: DAMA with NaI
- ER vs NR discrimination possible via PSD: KIMS with CsI

- High light yield (~ 6 pe/keV)

- Targets (mass): Na (23), I (127), Cs (133) and even 10^{-3} of Tl (204)

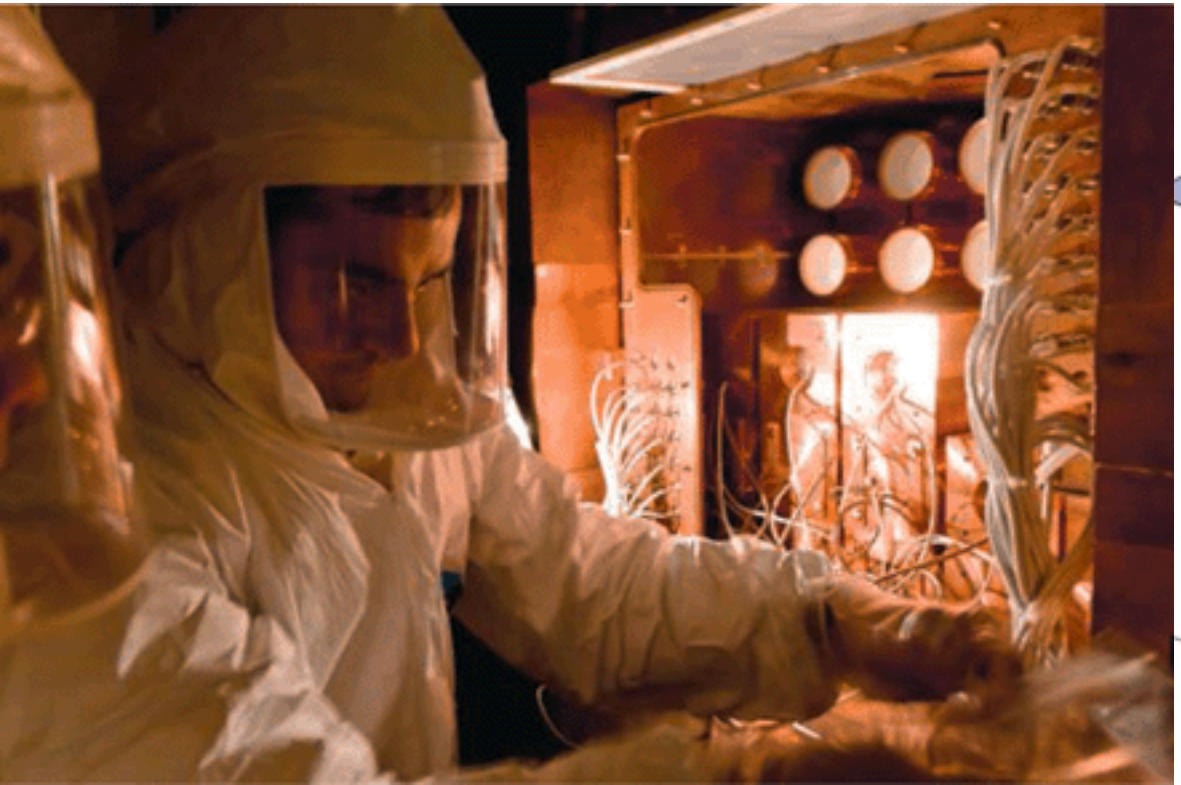
- Spin-dependent sensitivity in both

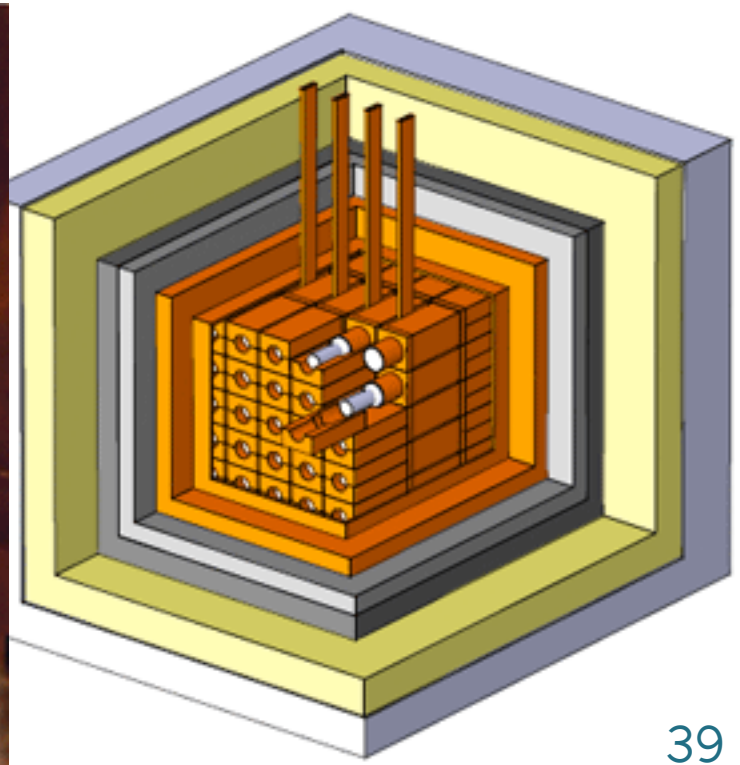
DAMA Annual Flux Variation



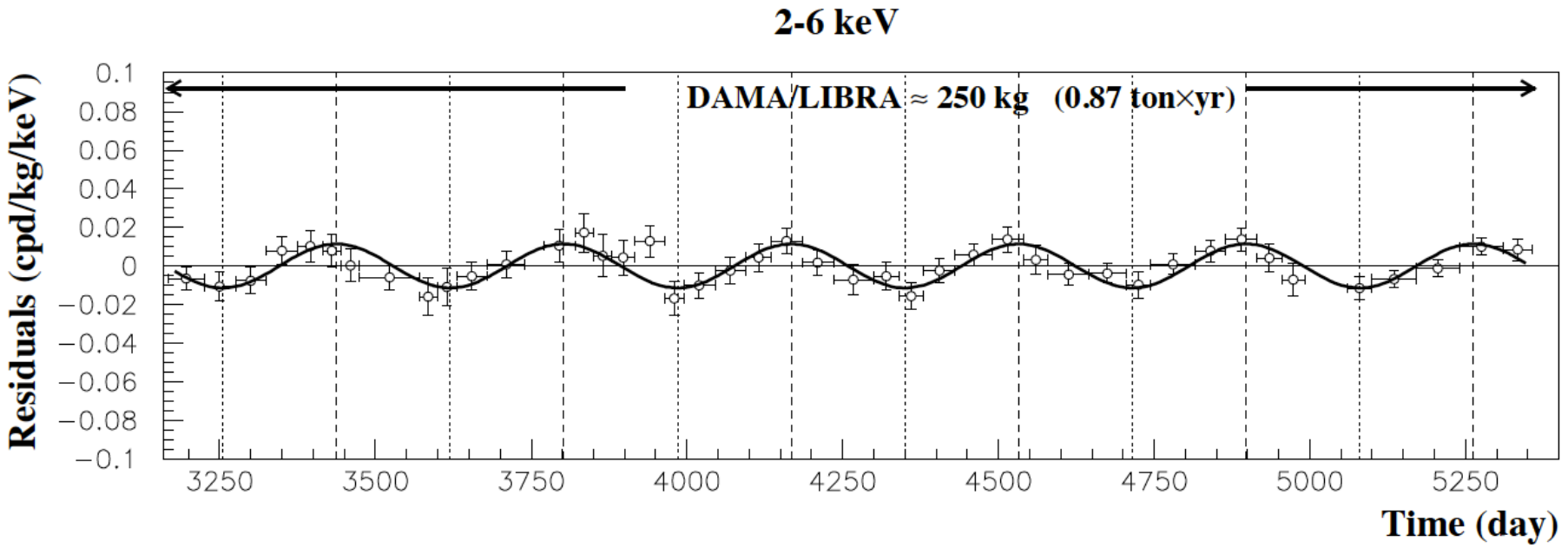
DAMA/LIBRA exposure = 1.33 ton·years of NaI(Tl) at LNGS
25 crystals, each 9.5 kg, running for 6 y in LIBRA (13 yrs total)

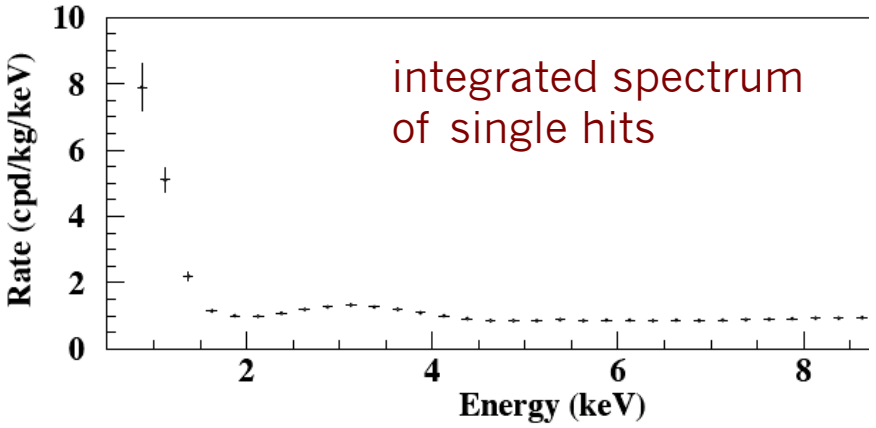
Amplitude of a few percent **Phase Max on June 2** **Significance of 9.3 σ**

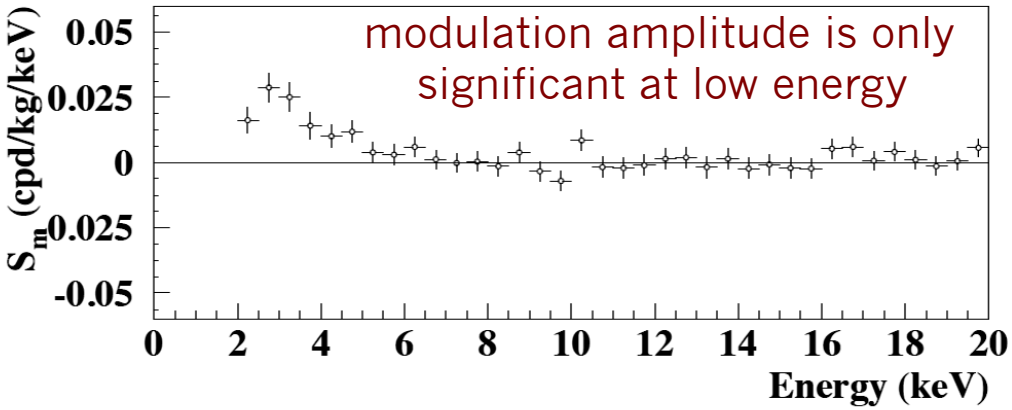




DAMA Annual Flux Variation







Finally, a worldwide effort to check DAMA

Borexino (Gran Sasso)
NaI crystals surrounded
by ultra-clean LS
Same Lab
Study backgrounds

ANAIS (Canfranc)
250 kg NaI inside
lead/poly shield
DAMA-size array in
Different Lab

Requires crystals purities < 1 ct/keV/day
St Gobain has exclusive contract with DAMA
New R&D on NaI purity w/ St Gobain

DM-Ice (South Pole)
250 kg NaI
Different Systematics
and environ.

If DAMA signal is astrophysical➔ a 5-sigma measurement in 2 years with 250 kg and comparable background to DAMA.

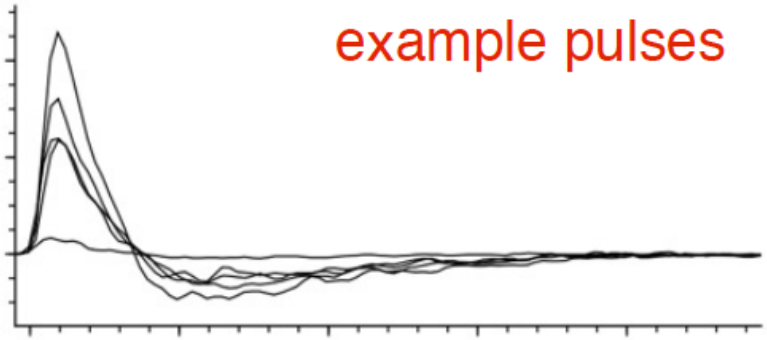
DM-Ice

Ann Mod: Same phase if WIMPs,
Opposite phase for most
seasonal backgrounds
No radon or water table fluctuations

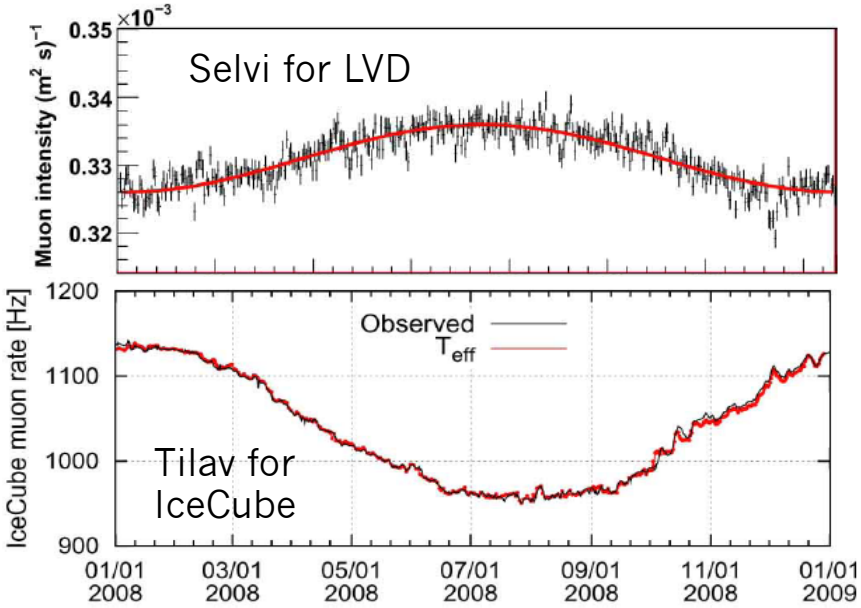
At 2450 m depth, constant T= −20° C
(warmer than a Minnesota winter)

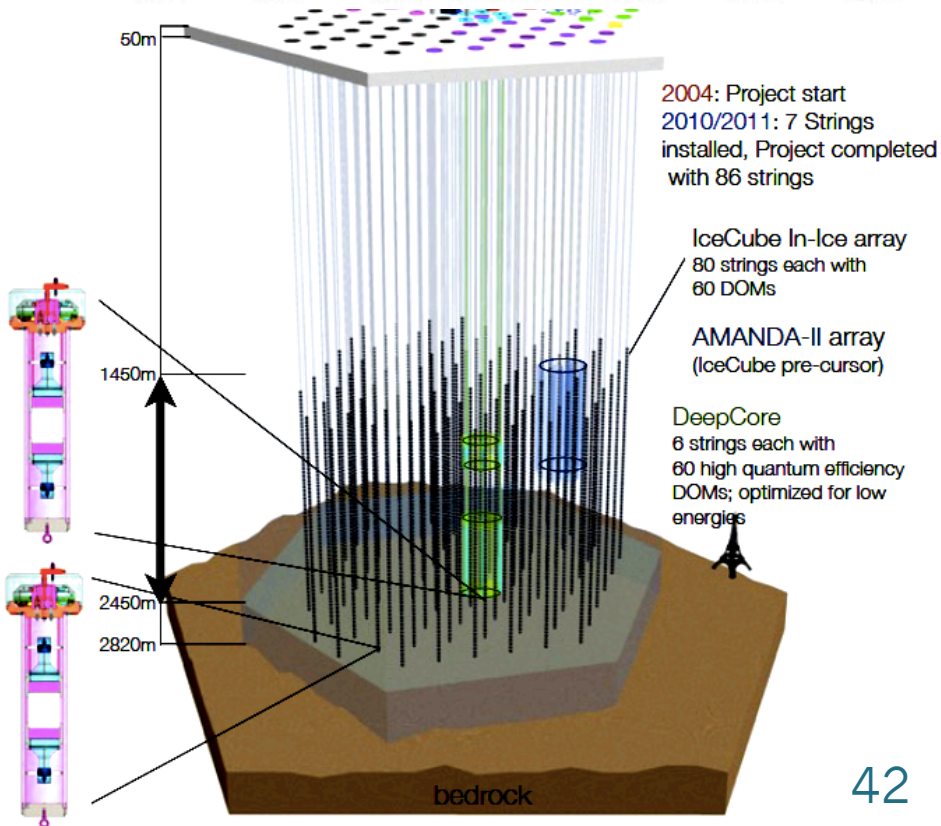
IceCube provides a muon veto,
radiopure shielding
lab infrastructure

Prototype: 8.5 kg NAIAD crystals
(~8 cts/keV/d) at the bottom
of two IceCube strings (Dec 2010)



example pulses





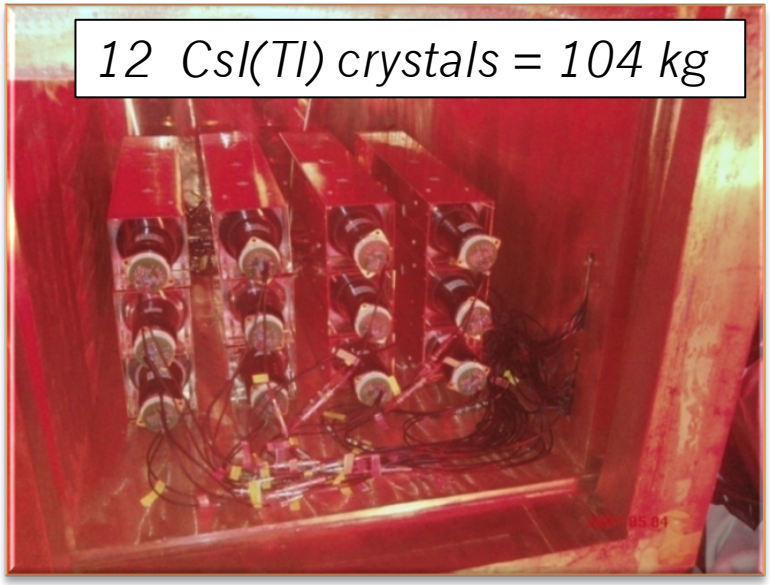
Counting Recoils: KIMS

KIMS (Yangyang Lab, Korea - 2400 mwe)

H.S. Lee,[1,*] H. Bhang,[2] J.H. Choi,[2] S. Choi,[2] I.S. Hahn,[3] E.J. Jeon,[4] H.W. Joo,[2] W.G. Kang,[4]
B.H. Kim,[2] G.B. Kim,[2] H.J. Kim,[5] J.H. Kim,[3] K.W. Kim,[2] S.C. Kim,[2] S.K. Kim,[2]
Y.D. Kim,[4,6] Y.H. Kim,[4,7] J.H. Lee,[2] J.K. Lee,[2] S.J. Lee,[2] D.S. Leonard,[8] J. Li,[4] J. Li,[9]
Y.J. Li,[9] X.R. Li,[10] S.S. Myung,[2] S.L. Olsen,[2] J.W. Park,[2] I.S. Seong,[2] J.H. So,[4] and Q. Yue[9]

CsI vs NaI

- **Better PSD than NaI(Tl)**
- **Less Hygroscopic**
- **High cesium radioisotopes**
  - *Reduce ^{137}Cs in processing (water)*
  - *^{134}Cs ($\tau_{1/2}$ = 2 y) cosmogenic activation*
  - *Reduce ^{87}Rb (in Cs ore)*
    - *via repeated recrystallization*

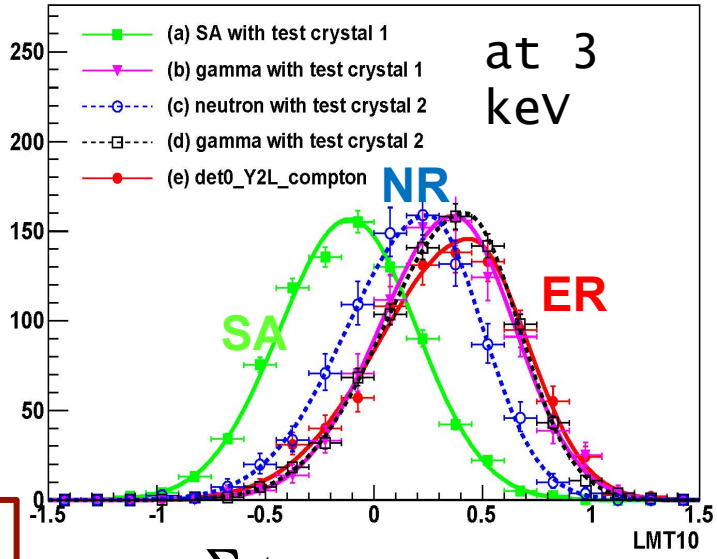


Bkd achieved: **2~3 cpd/kg/keV**

Counting Recoils: KIMS

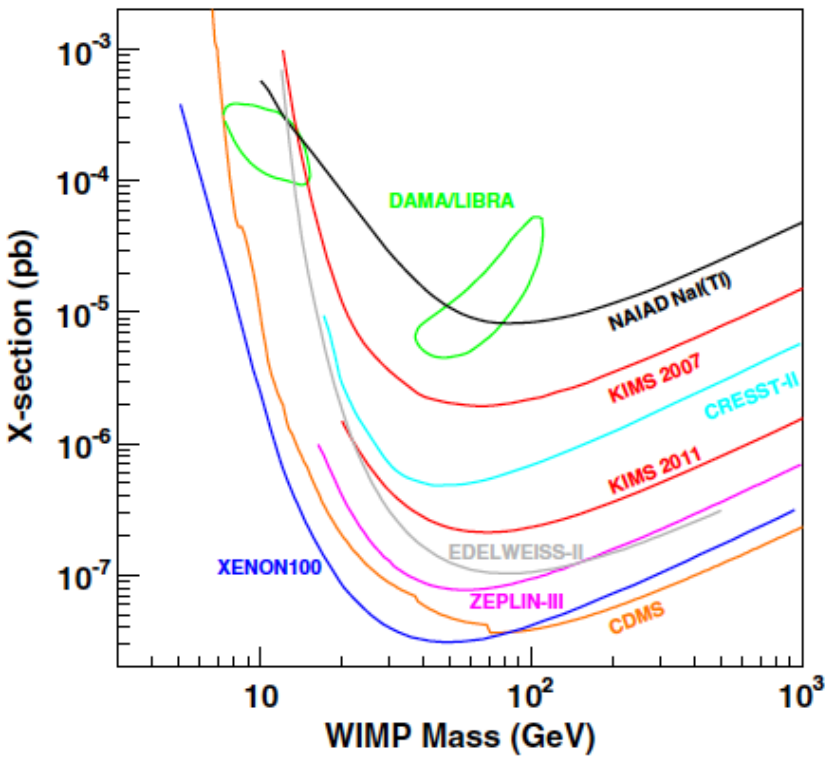
Data taking 2009-2012 corresponding to 67 kg-y
Results from 67 kg-y (2009-2010)

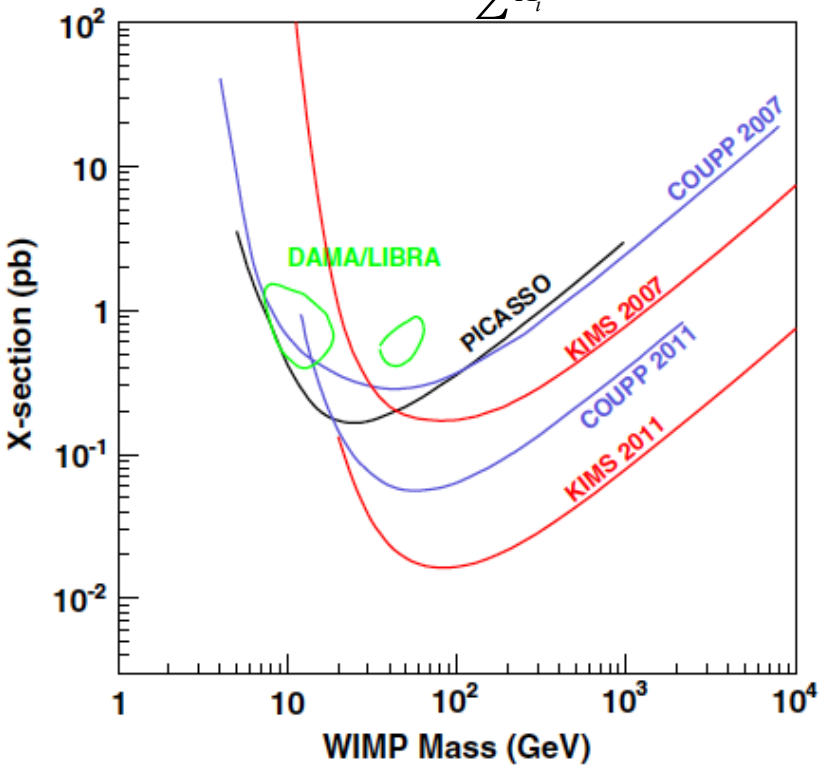
now upgrading PMTs for better light output
➔ *lower threshold*



using PSD ➔ 3 keV$_{ee}$ thresh.
PRL 108, 181301 (2012)

$$\langle t \rangle = \frac{\sum A_i t_i}{\sum A_i}, \quad \text{LMT10} = \log_e(\langle t \rangle)$$





Counting Recoils: KIMS

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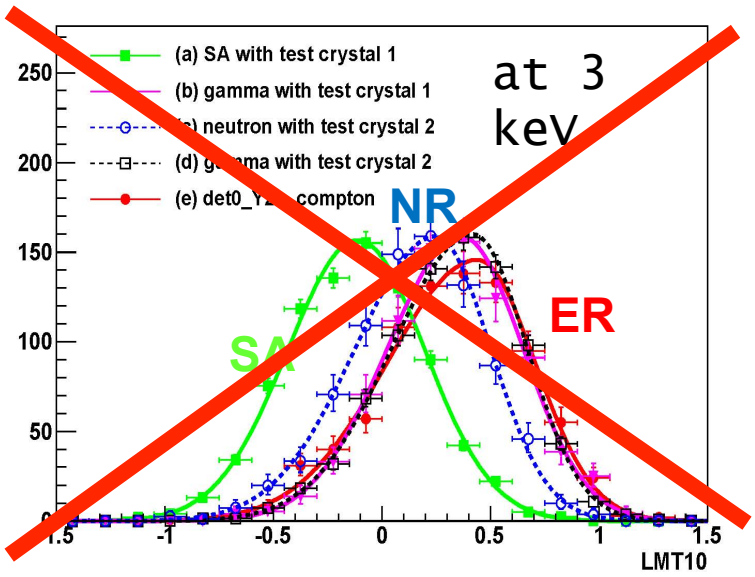
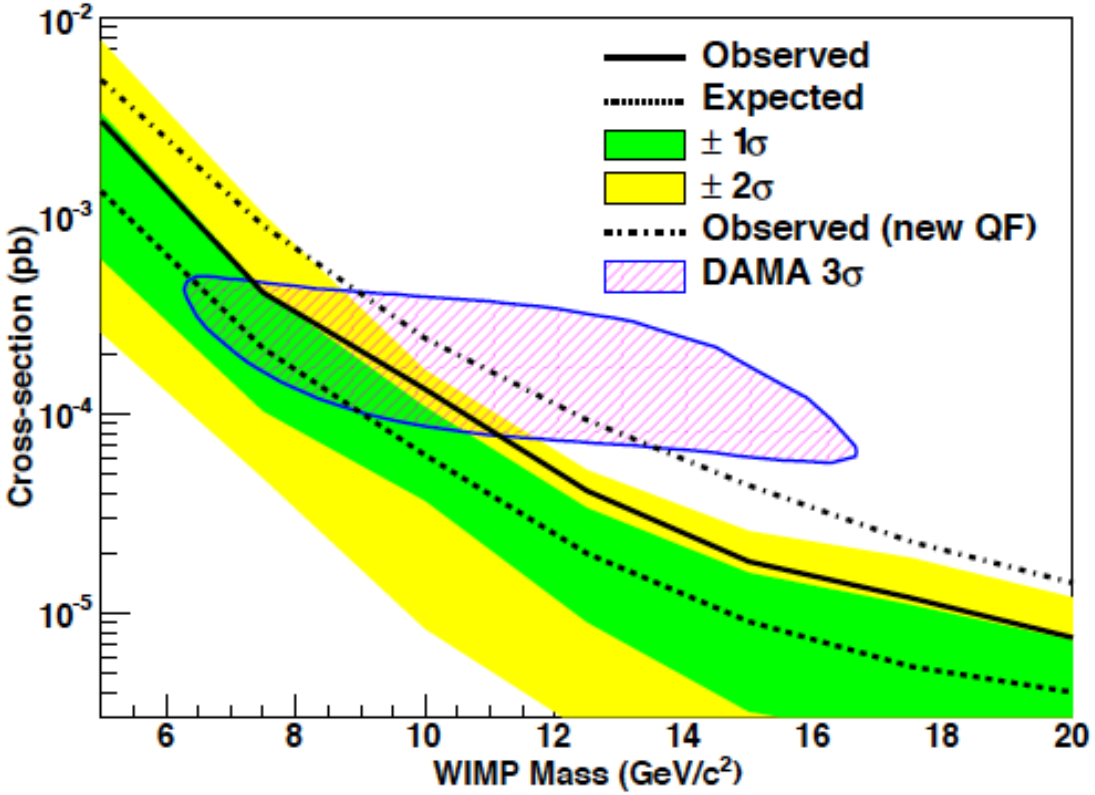
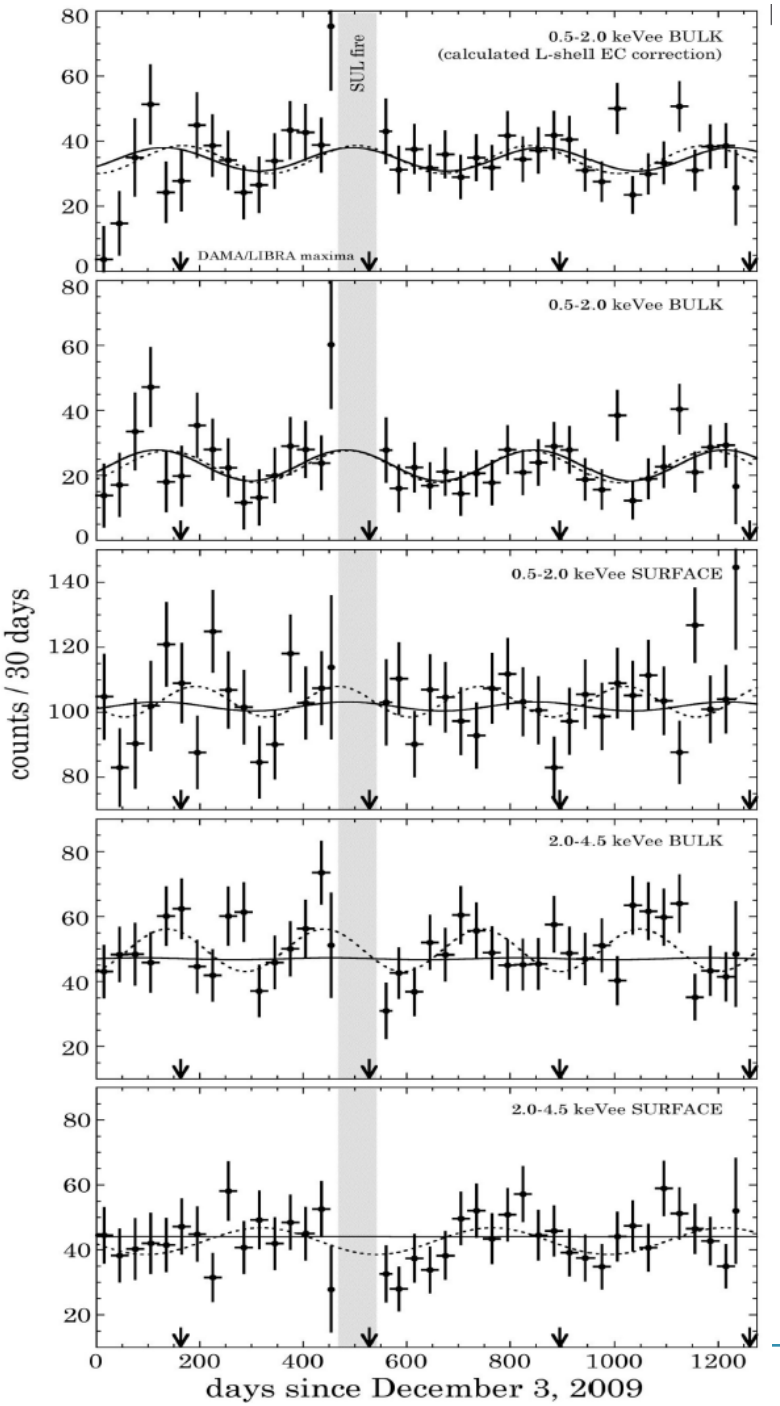




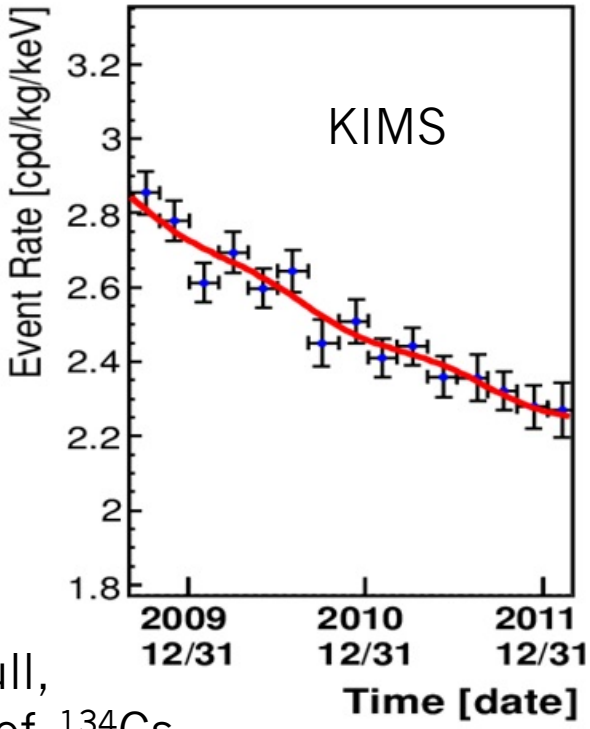
without PSD (>2 keV$_{ee}$)
arXiv:1404.3443v2

Annual Modulation in other experiments

requires a low threshold for DAMA check



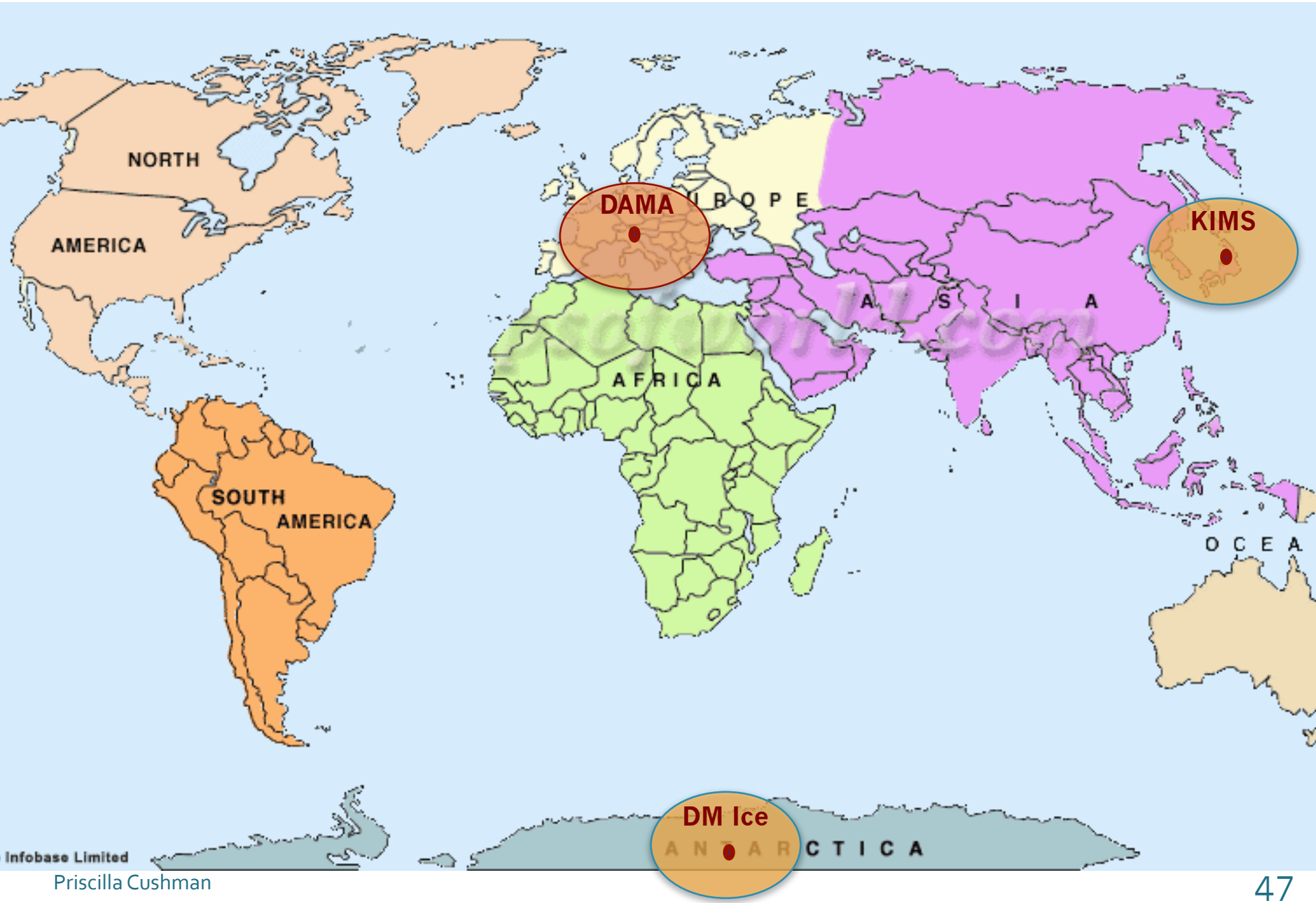
CoGeNT sees a 2.2 σ effect



KIMS Ann Mod amp is consistent with null, incl. the exp. decay of ^{134}Cs.

The 90% upper limit of KIMS amplitude is comparable to DAMA's ann mod (0.0189 cpd/kg/keV)

Underground Labs with Inorganic Crystals



Spin Dependent Cross Sections

Couples to net nuclear spin J_N

$$\sigma_{SD} = \frac{32}{\pi} G_F^2 \frac{m_\chi^2 m_N^2}{(m_\chi + m_N)^2} \frac{J_N + 1}{J_N} \left(a_p \langle S_p \rangle + a_n \langle S_n \rangle \right)^2$$

Very dependent on material. Need multiple experiments to explore parameters
WIMP capture rate in sun (proton scattering) gives good indirect limits

neutron coupling

CDMS, EDELWEISS

^{73}Ge (7.73%) *odd n with J = 9/2*
or **90%** *for enriched (***CDEX/TEXONO***)*
^{29}Si (4.68%) *odd n with J = 1/2*

Xenon100,XMASS, etc.

^{129}Xe (26%) $\langle S_n \rangle = .359$ $J=1/2$
^{131}Xe (21%) $\langle S_n \rangle = -.227$ $J=3/2$

proton coupling

CRESST phonon (Al_2O_3)

^{27}Al $\langle S_p \rangle = .343$ $J= 5/2$

DAMA/LIBRA, NAIAD, ANAIS (NaI)
KIMS (CsI)

^{127}I $\langle S_p \rangle = .309$ $J=5/2$
^{23}Na $\langle S_p \rangle = .248$ $J=3/2$
^{133}Cs $\langle S_p \rangle = -.370$ $J=7/2$

proton & neutron coupling

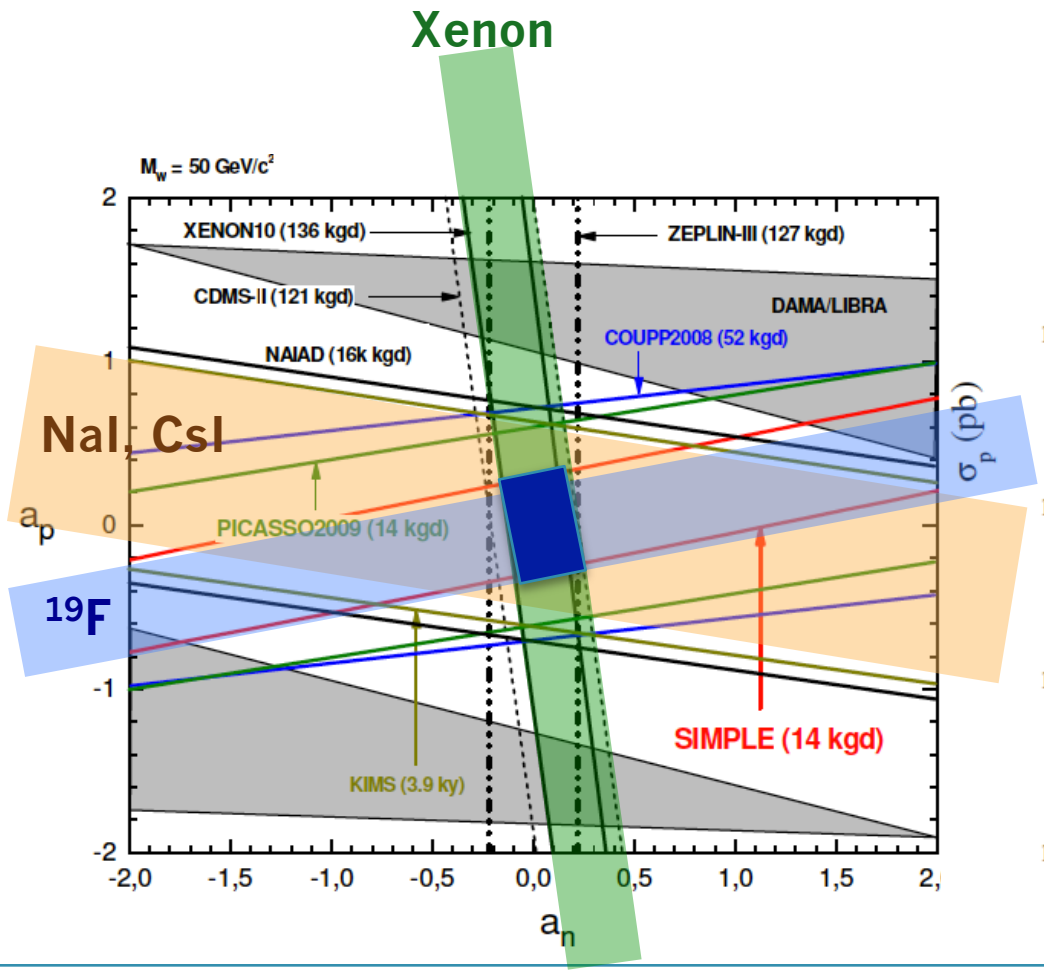
Tokyo $CaF_2(Eu)$ **PICASSO** C_4F_{10} **SIMPLE** $C_2Cl F_5$ **COUPP** CF_3I

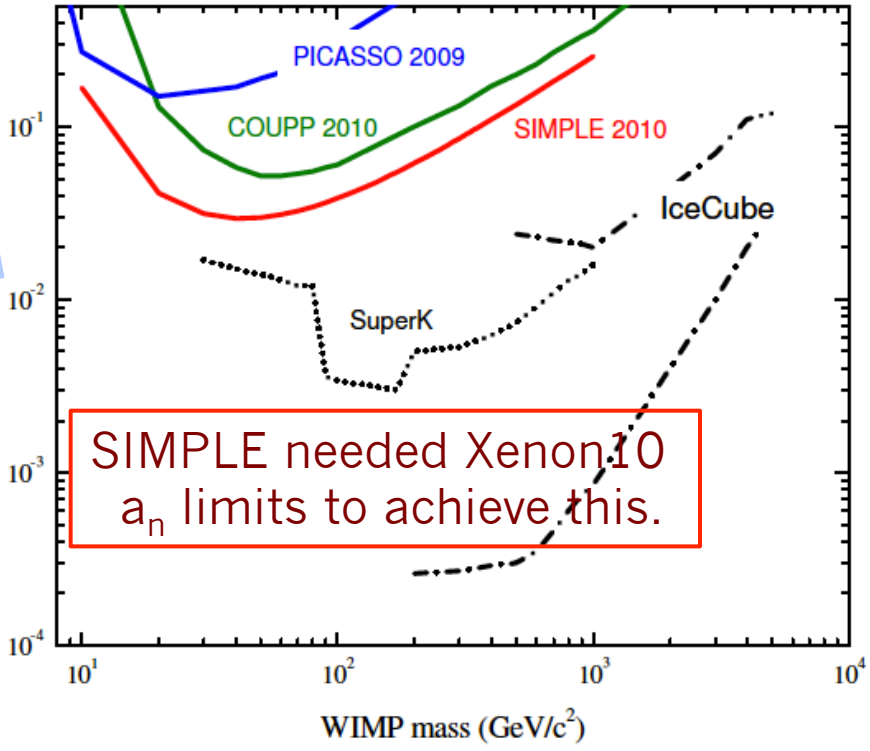
^{19}F (% depends on fluorocarbon mixture used)
$\langle S_n \rangle = -.109$ $\langle S_p \rangle = .441$ $J=1/2$

Example: SD Limits depend on other targets

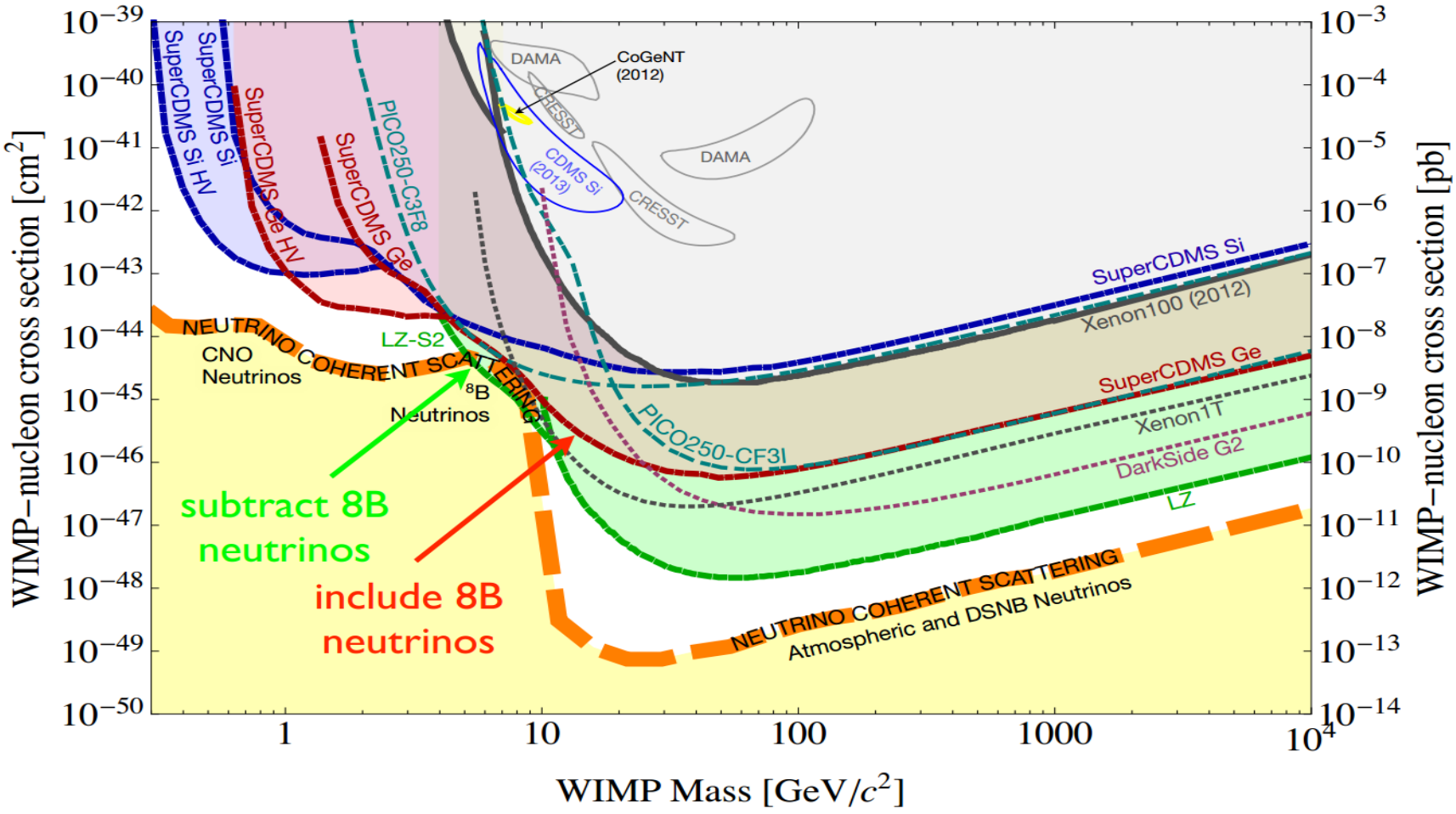
SD limits for SIMPLE ($C_2Cl F_5$) superheated droplets

$|a_p| < 0.32, |a_n| < 0.17$ *for 50 GeV/c² WIMP*

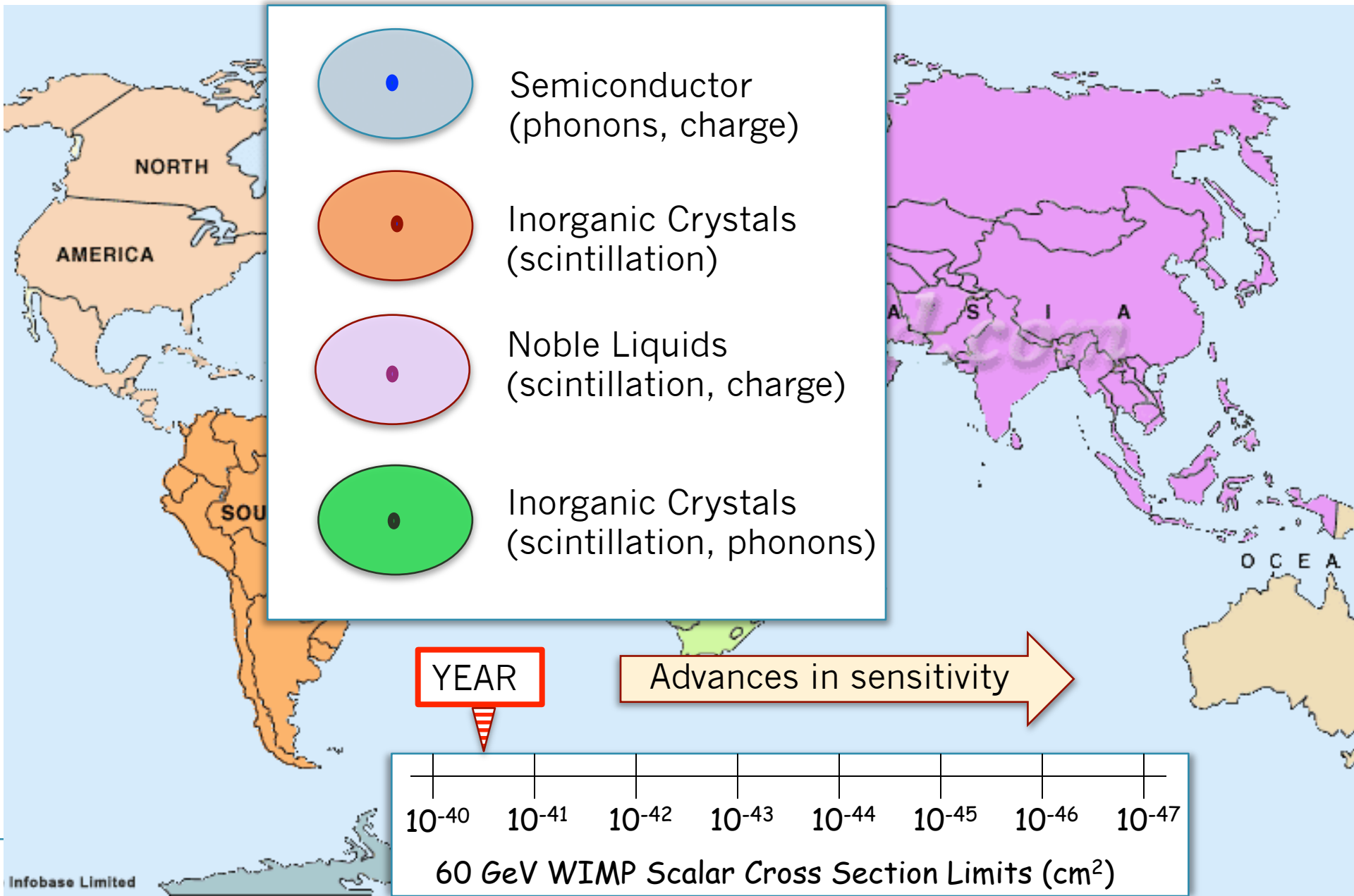




The G2 downselect landscape tries to cover the entire parameter space



A Brief History of Direct DM Searches



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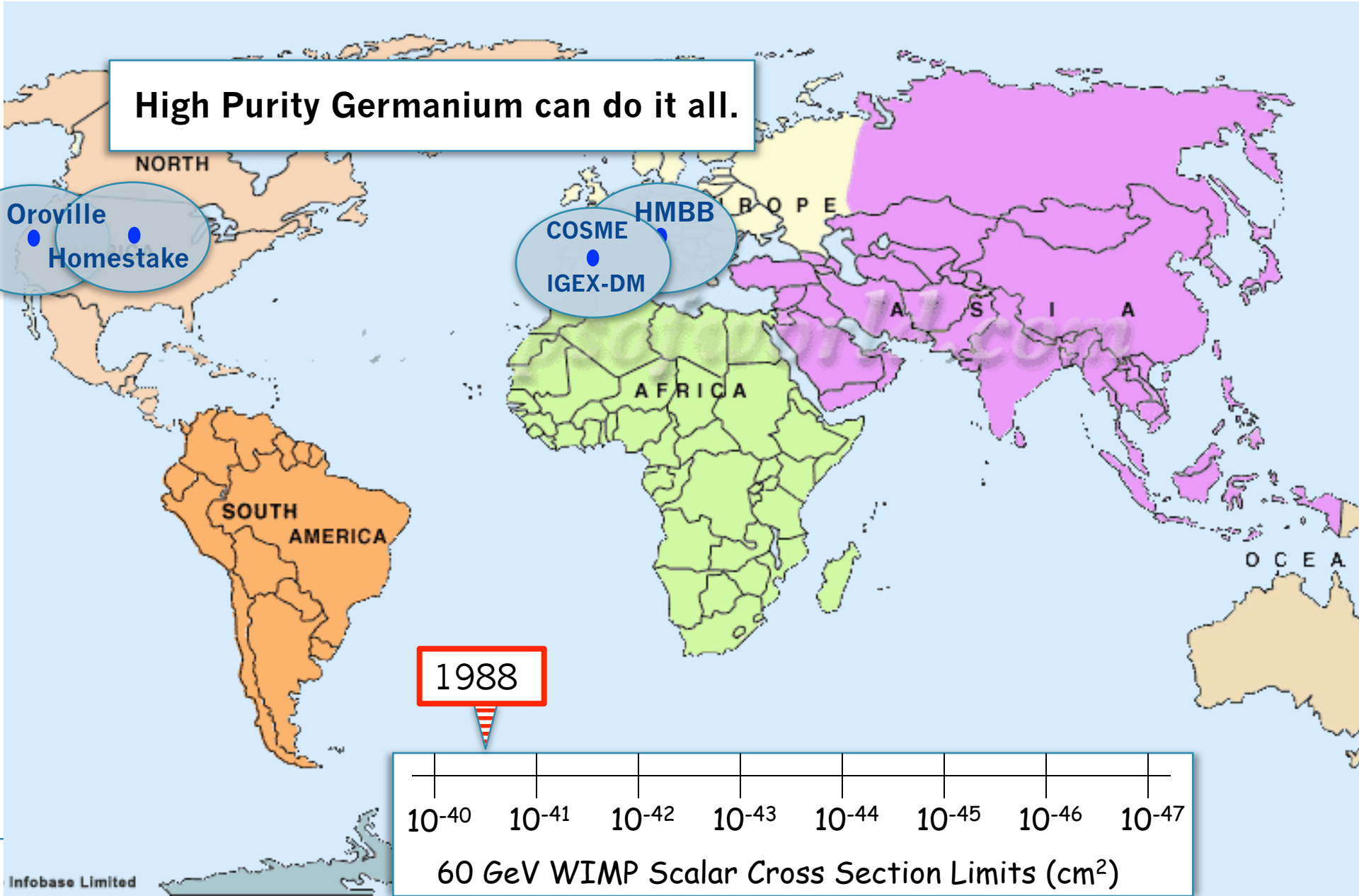
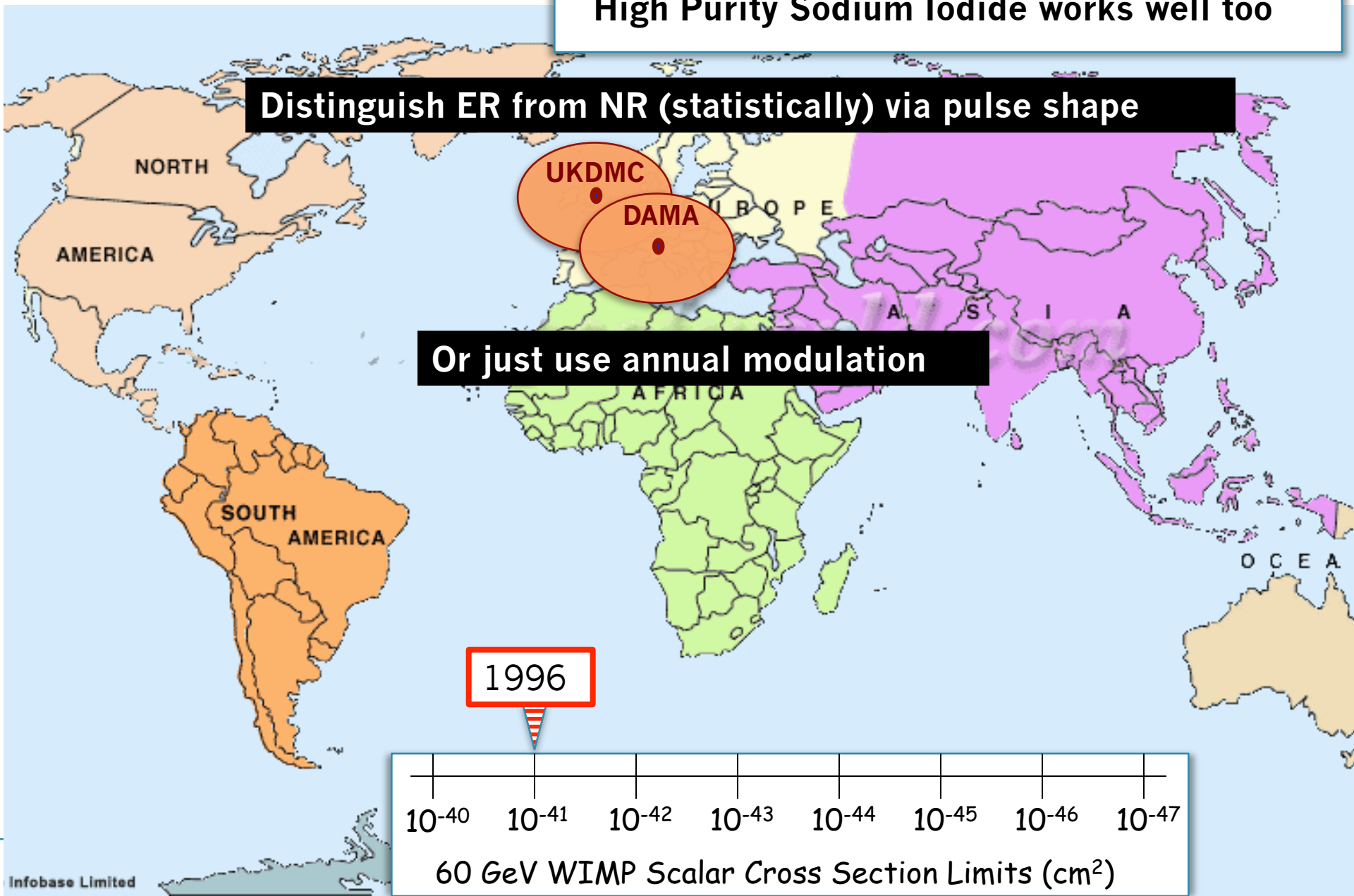


A Brief History of Direct DM Searches

High Purity Sodium Iodide works well too

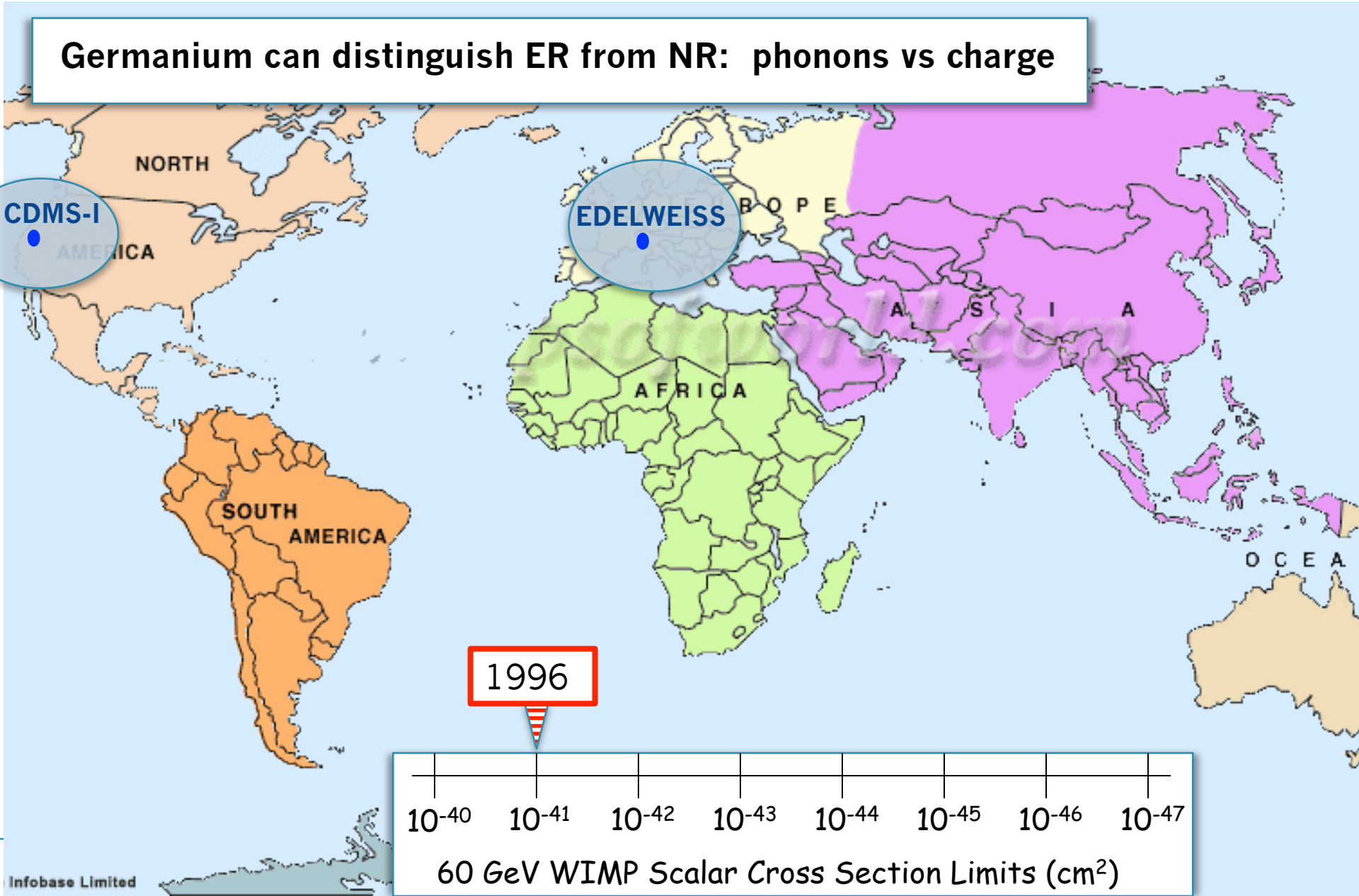
Distinguish ER from NR (statistically) via pulse shape

Or just use annual modulation



A Brief History of Direct DM Searches

Germanium can distinguish ER from NR: phonons vs charge



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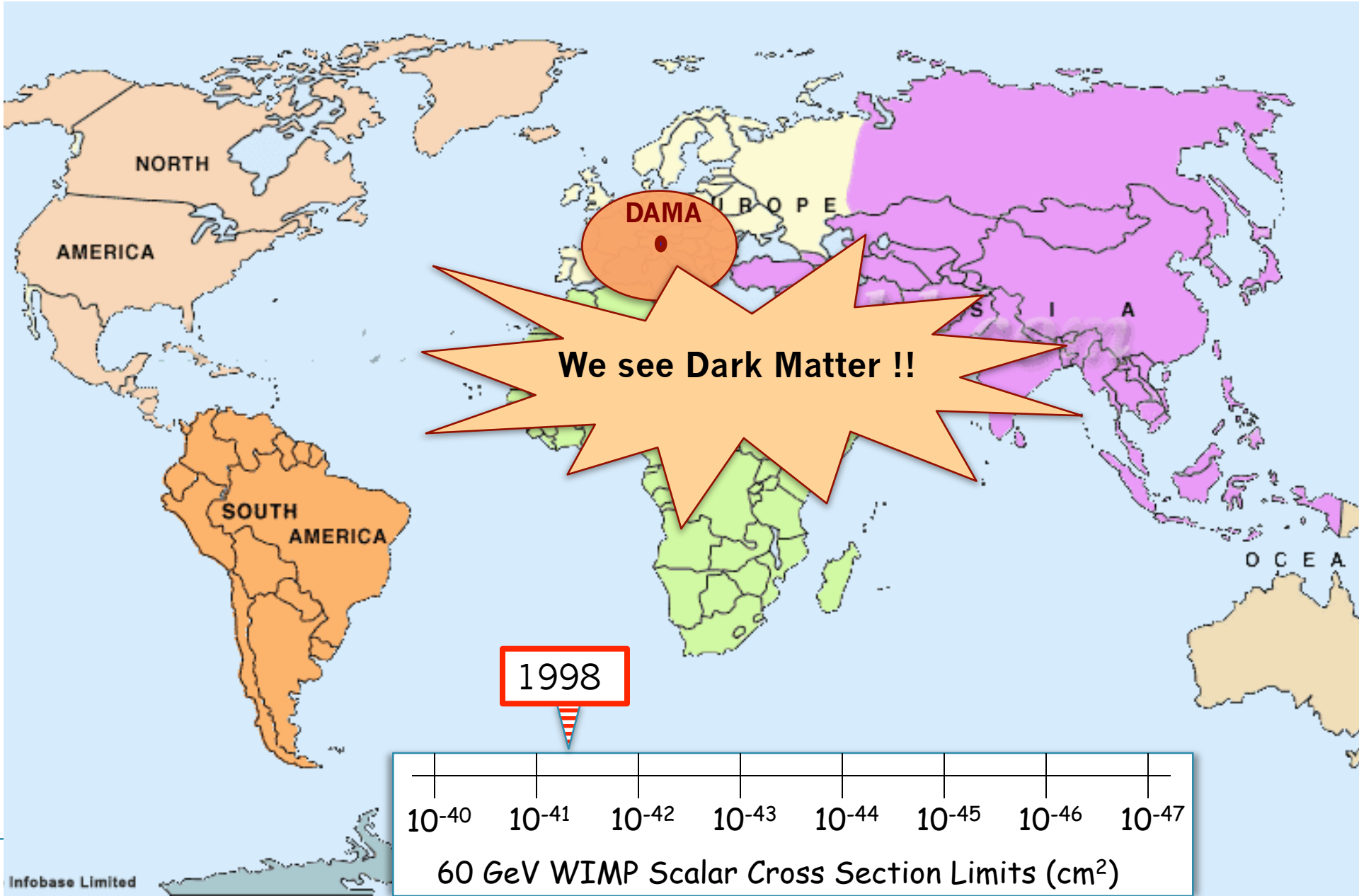

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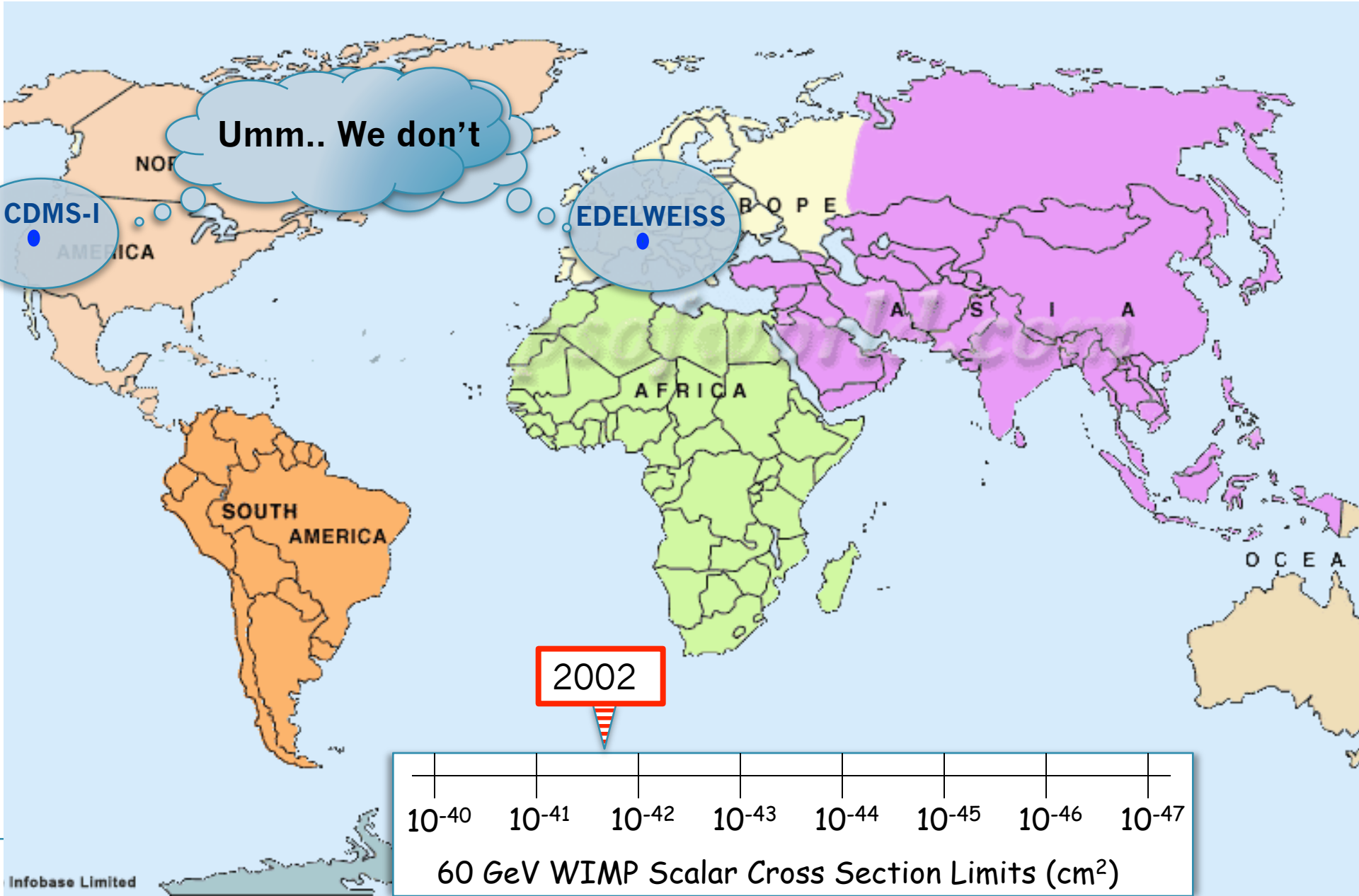

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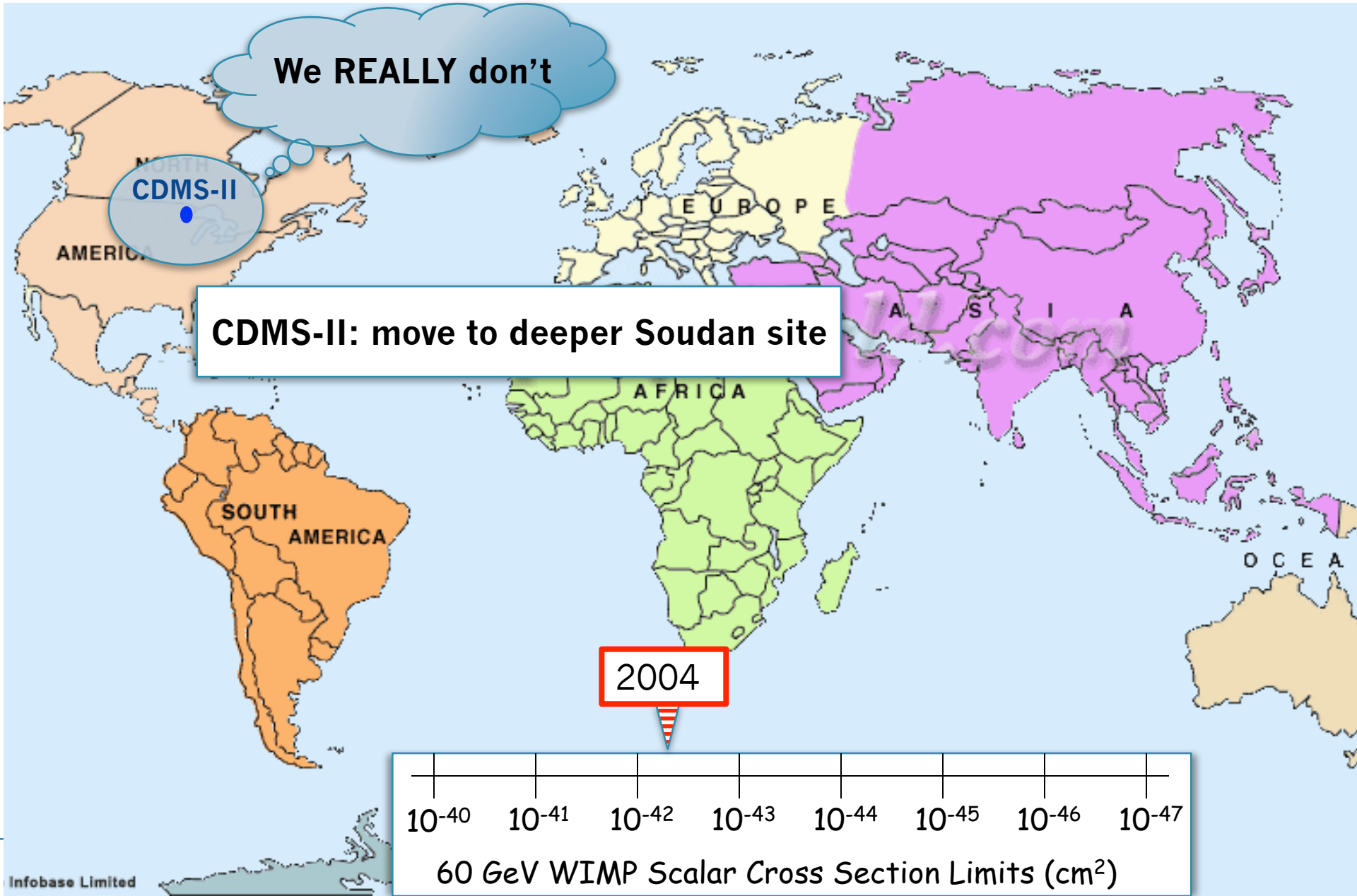

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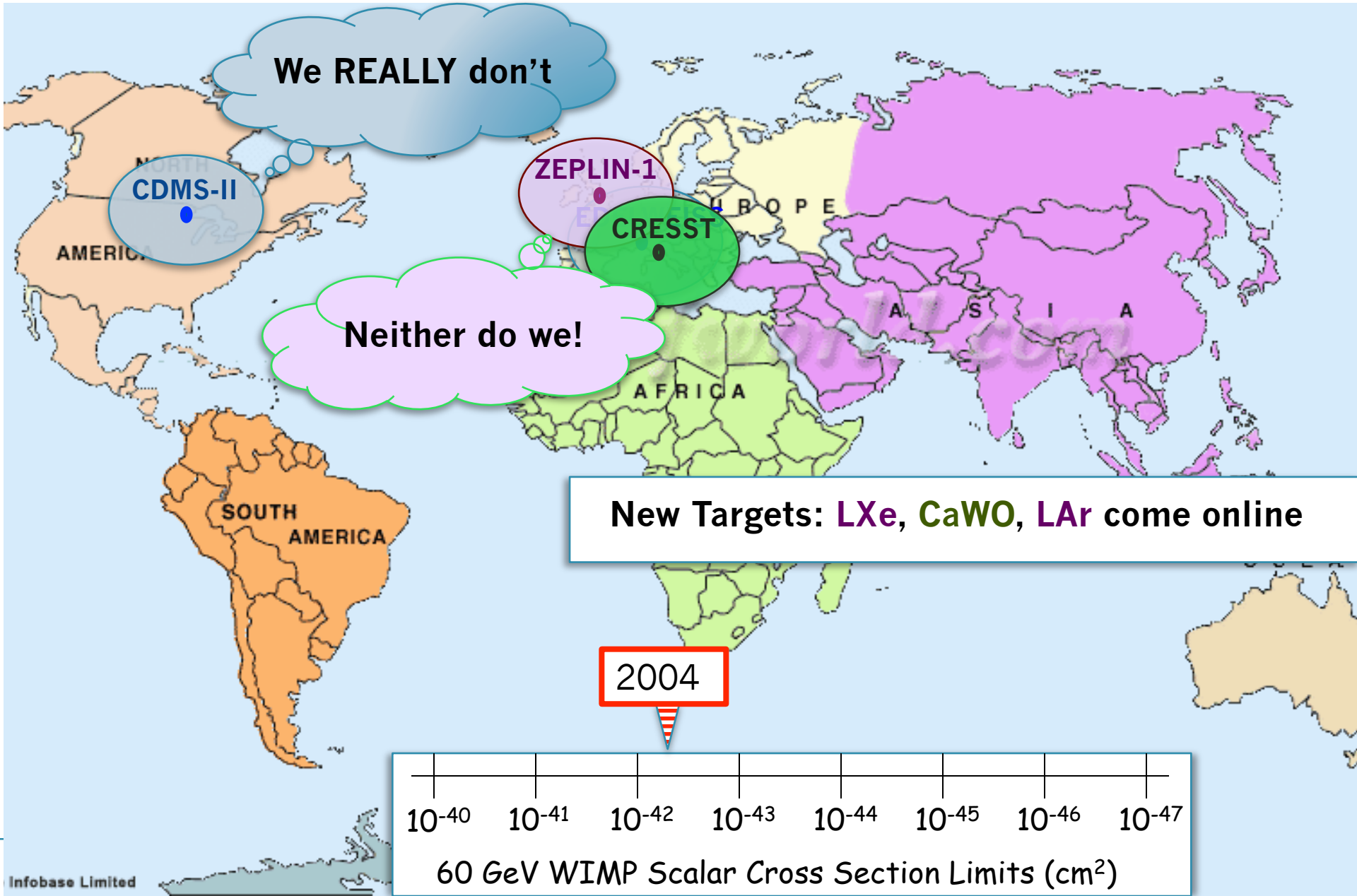

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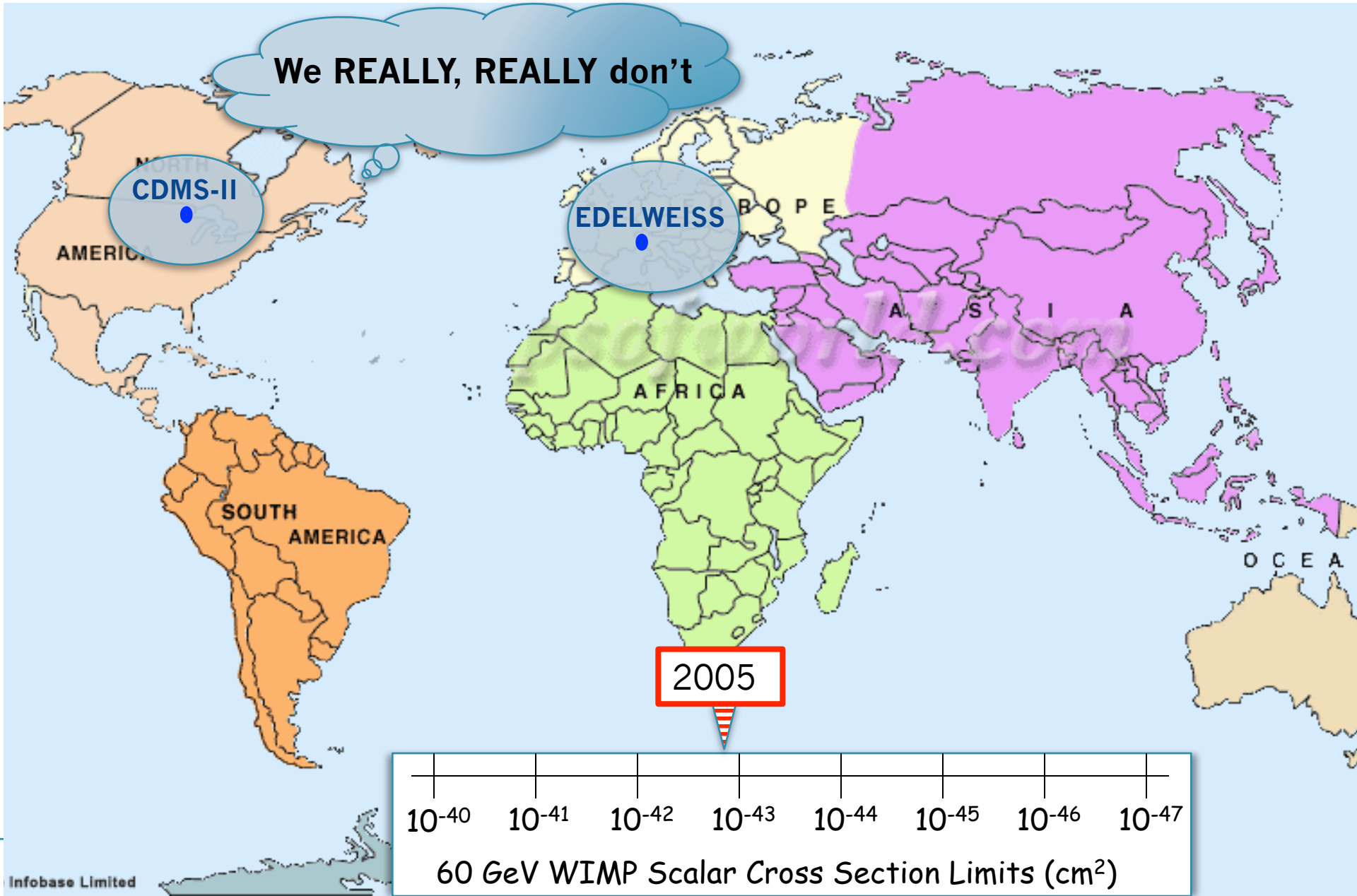

A Brief History of Direct DM Searches

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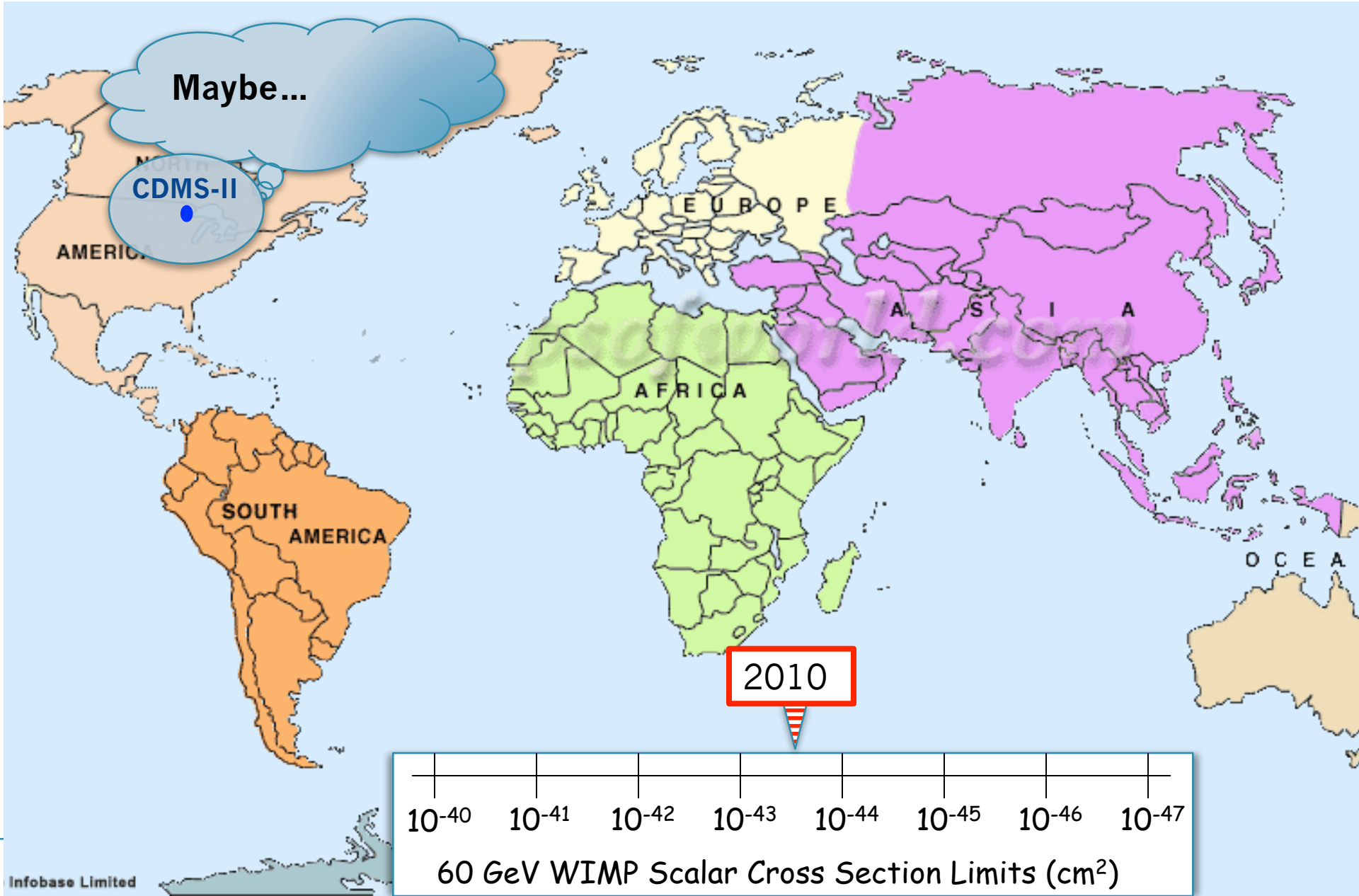

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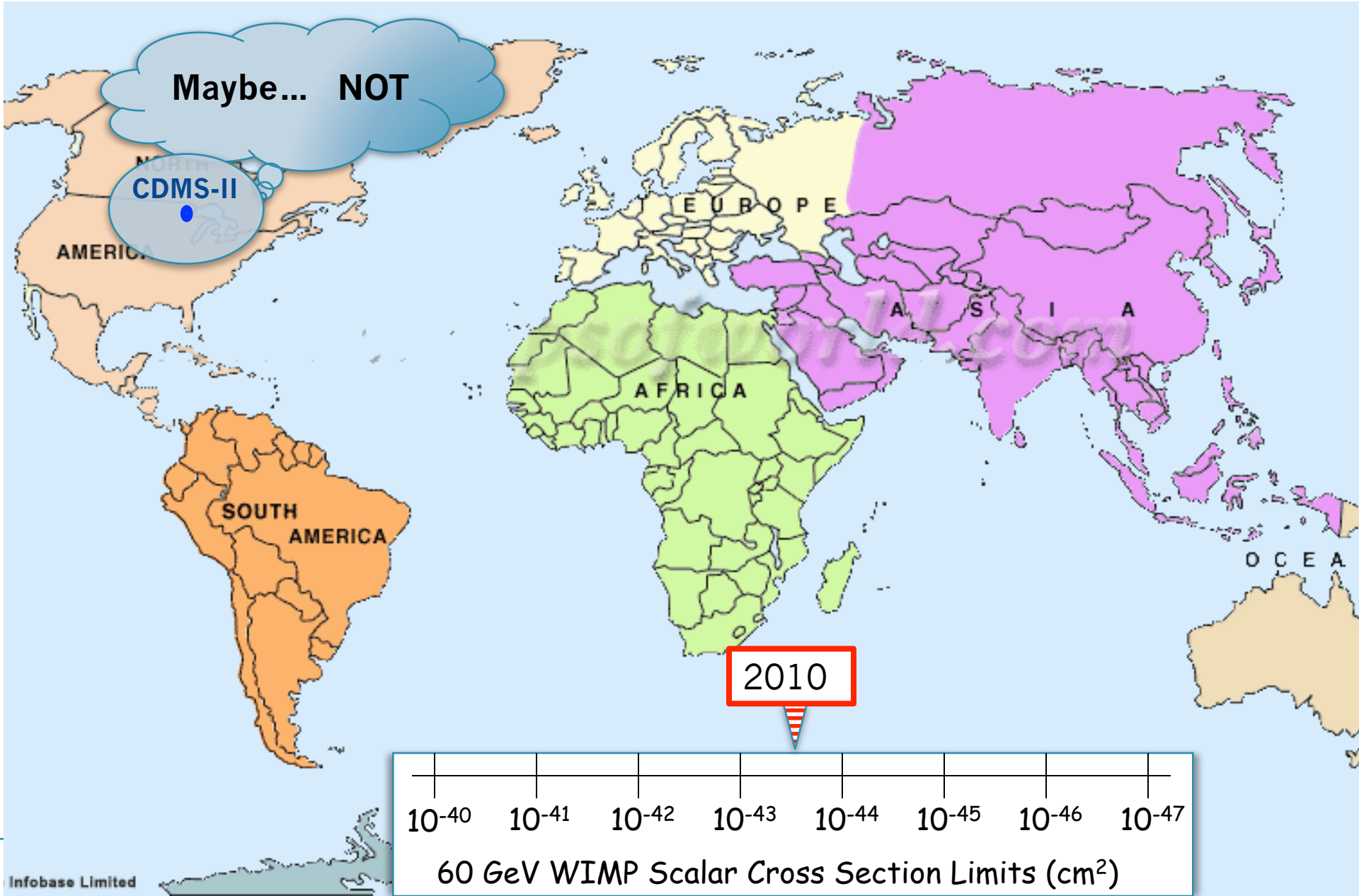

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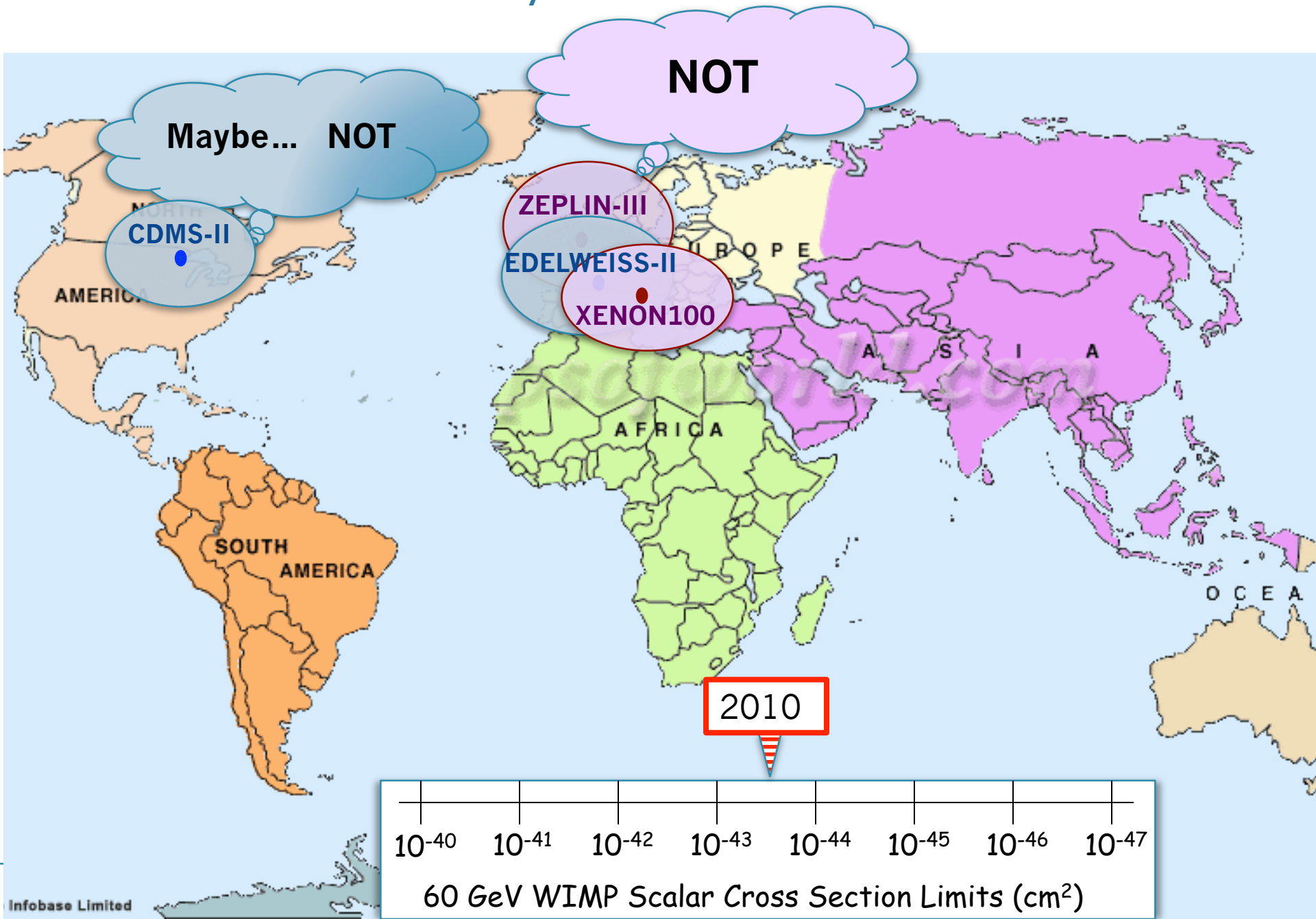

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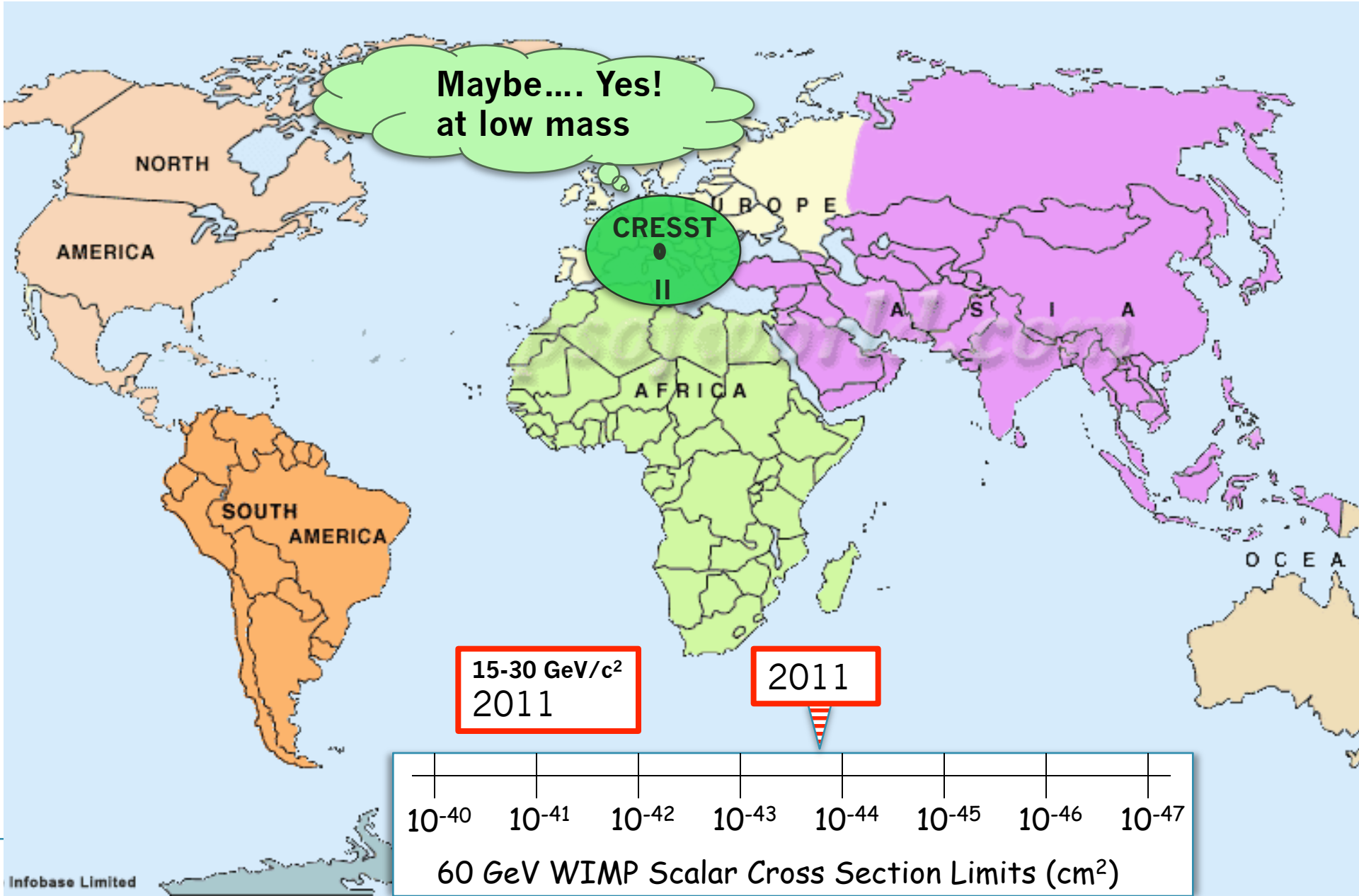

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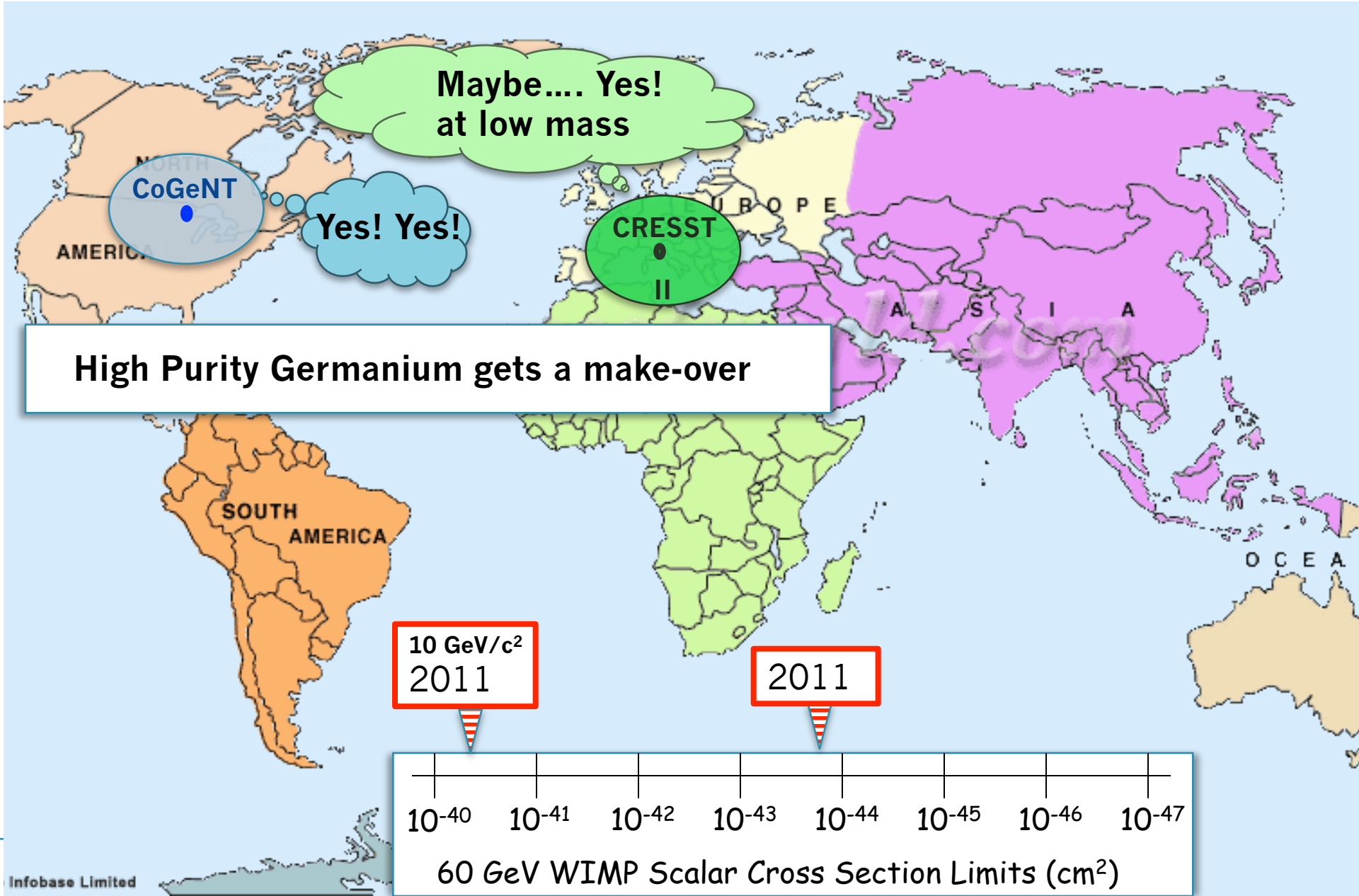

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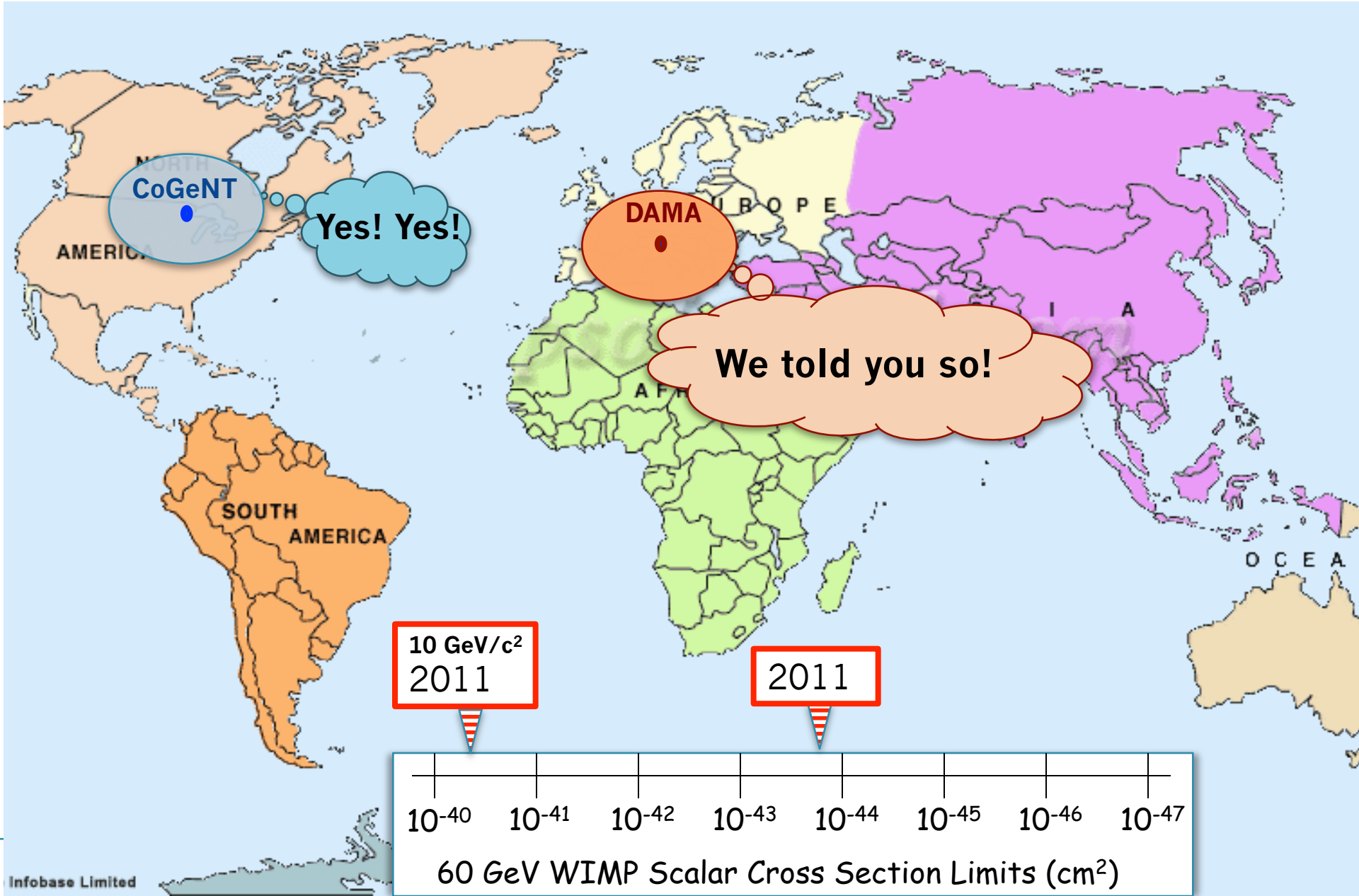

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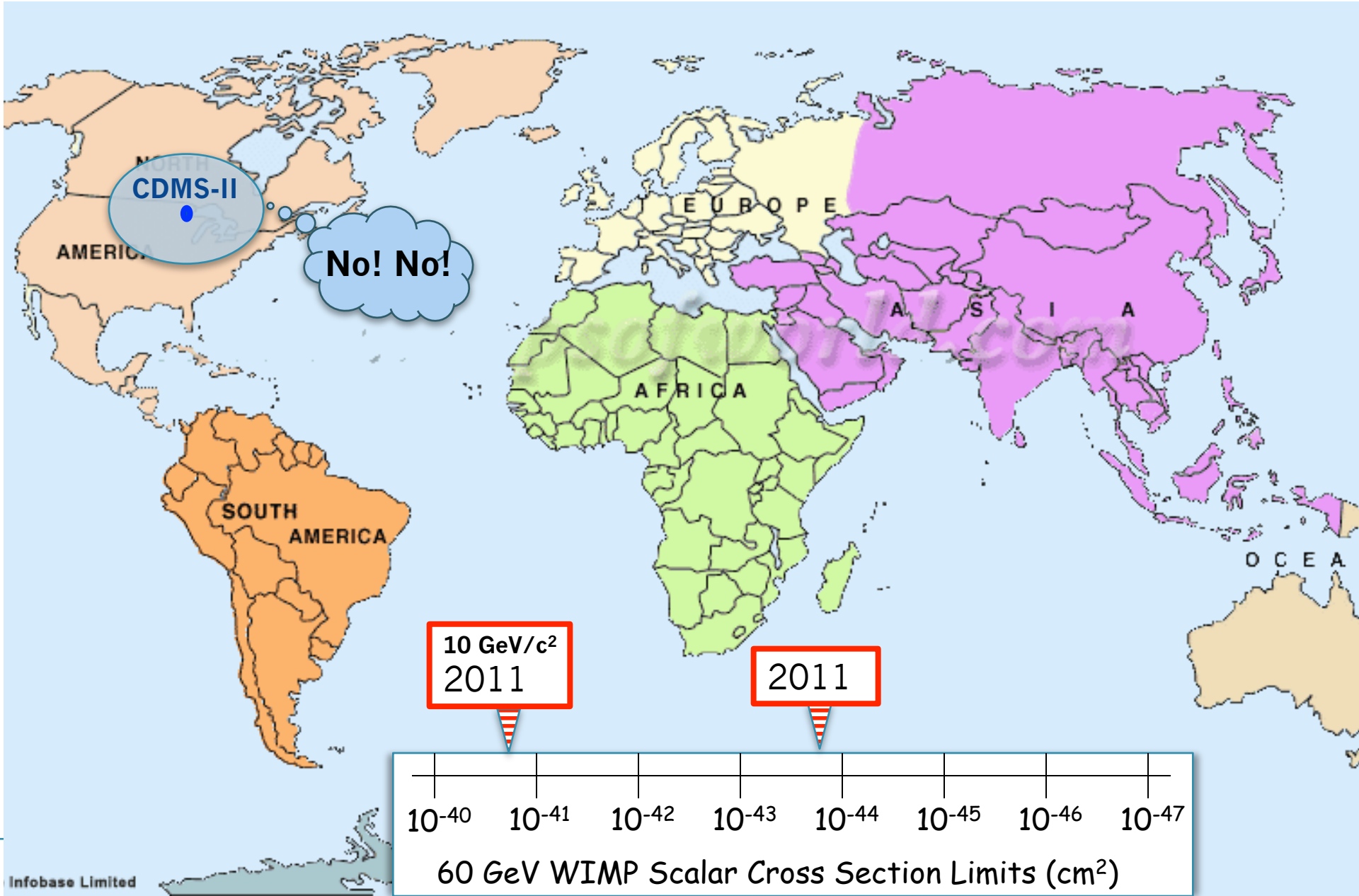

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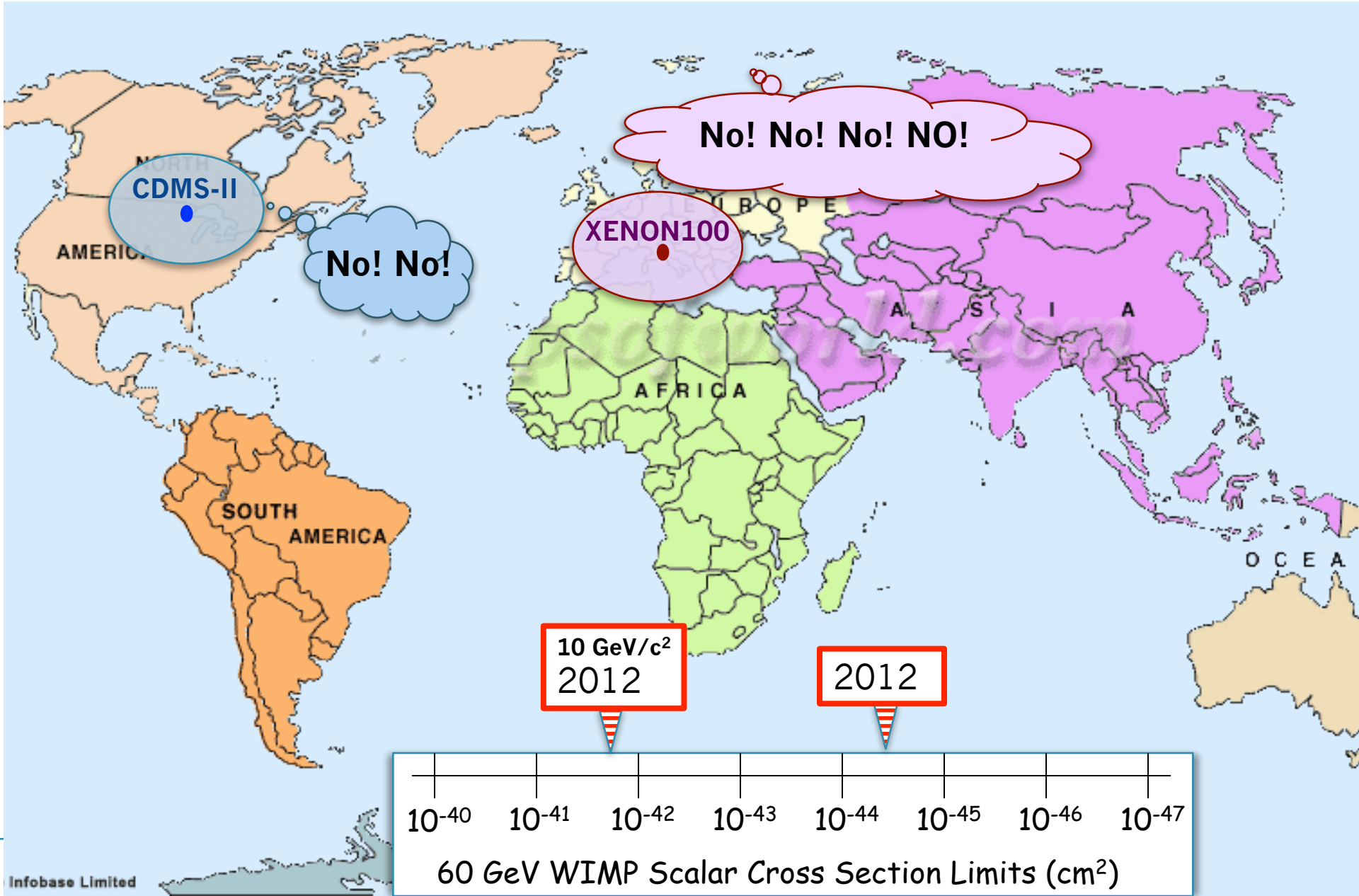

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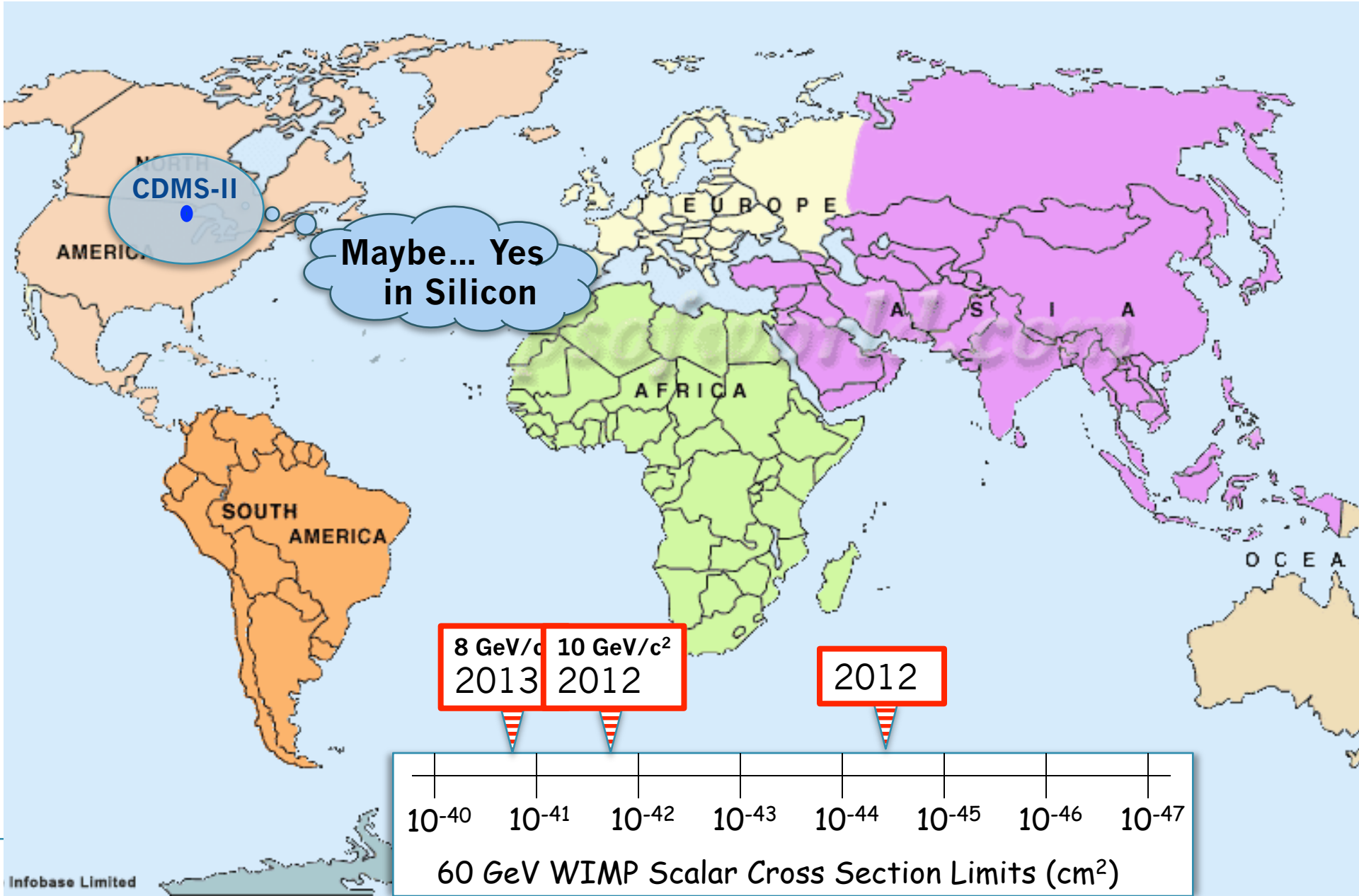

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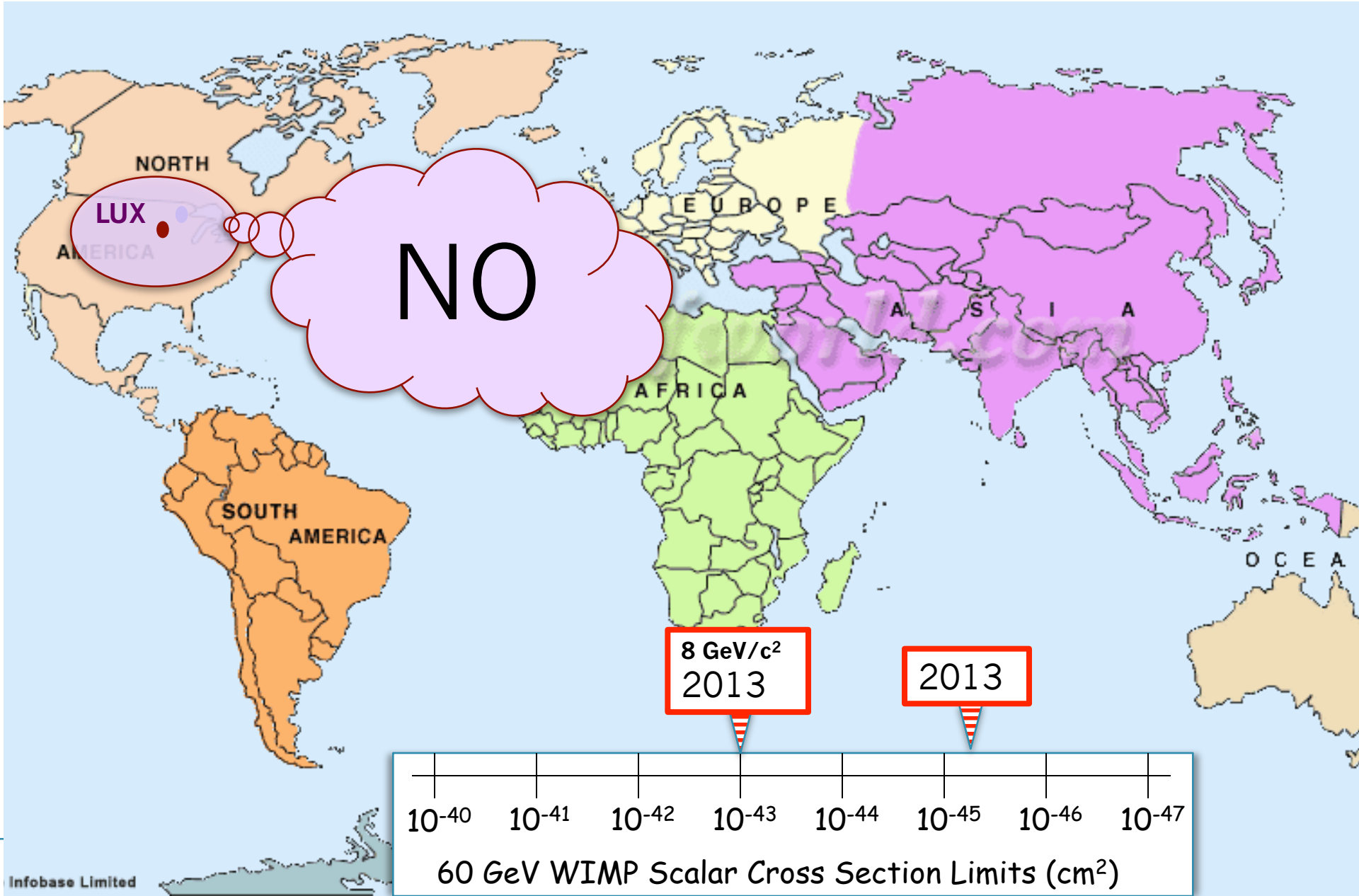

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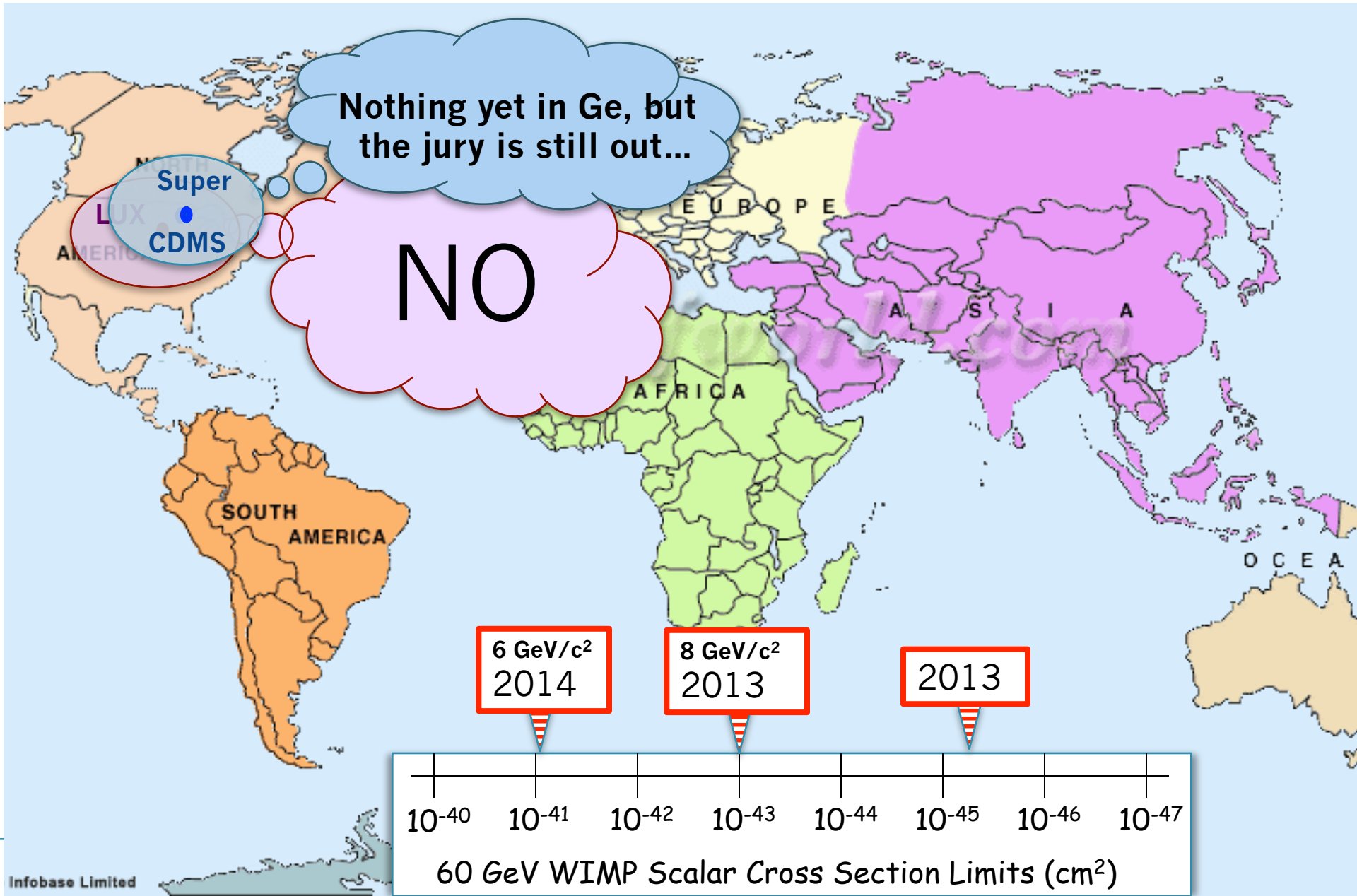
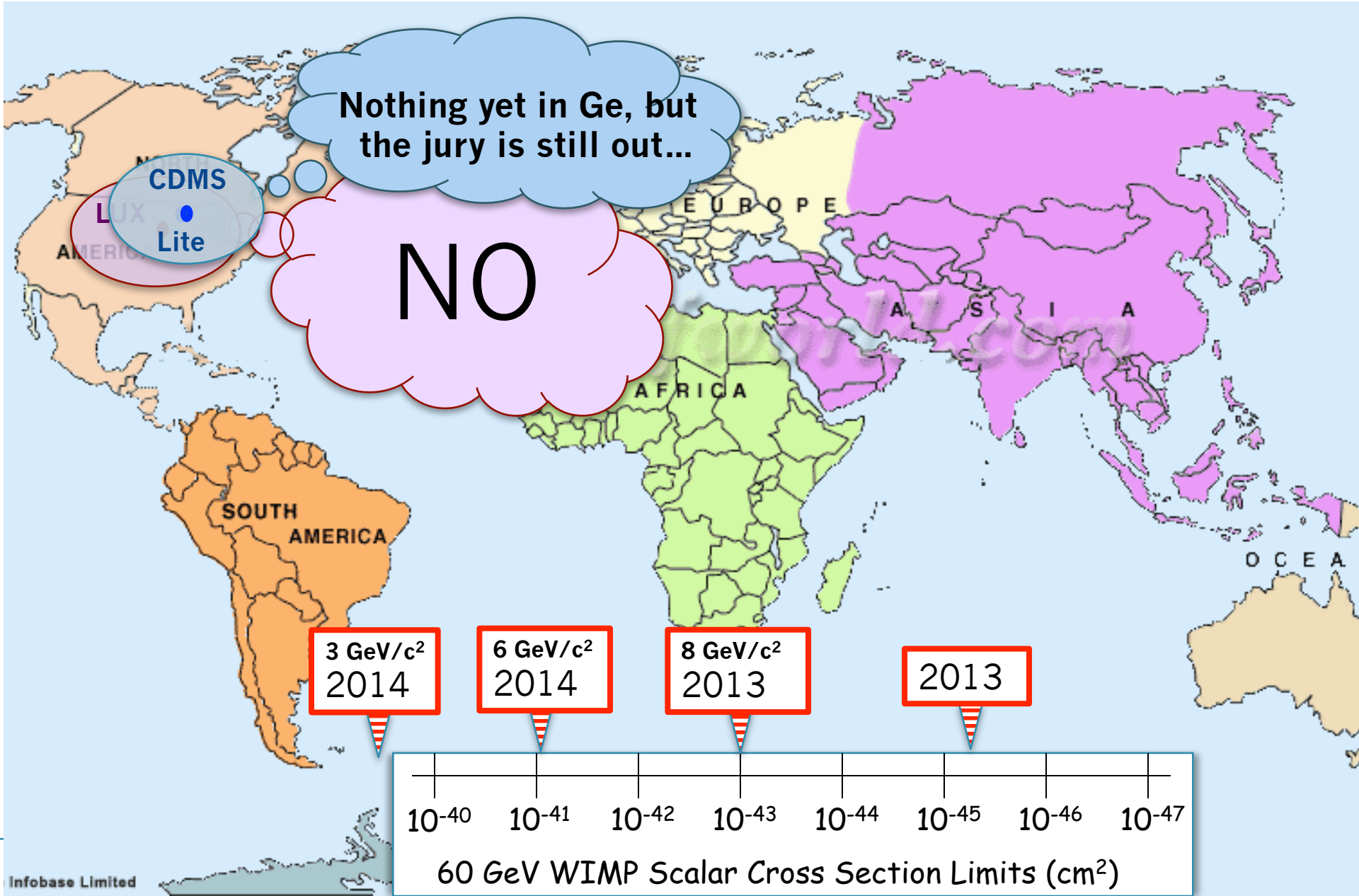
A Brief History of Direct DM Searches