Direct Searches for WIMP Dark Matter

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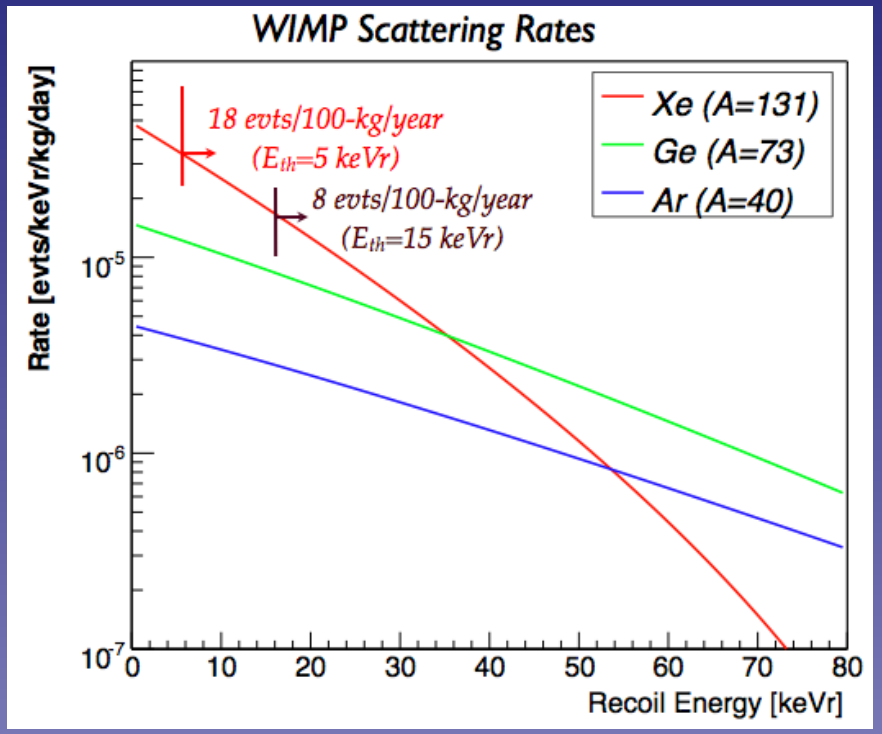
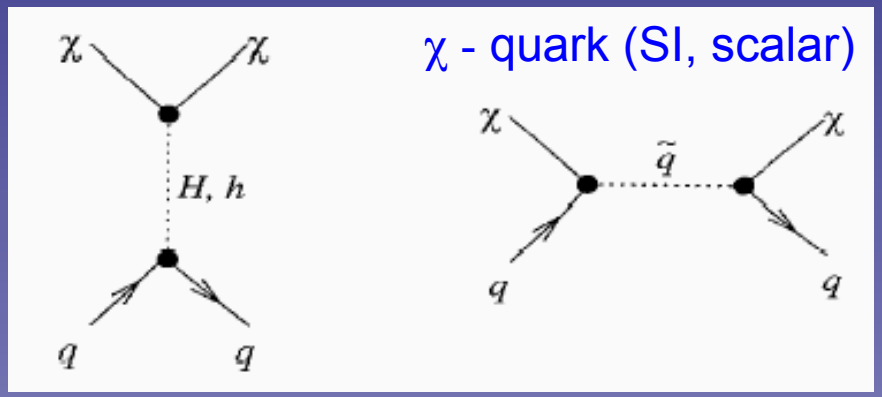
WIMP DM Direct Detection

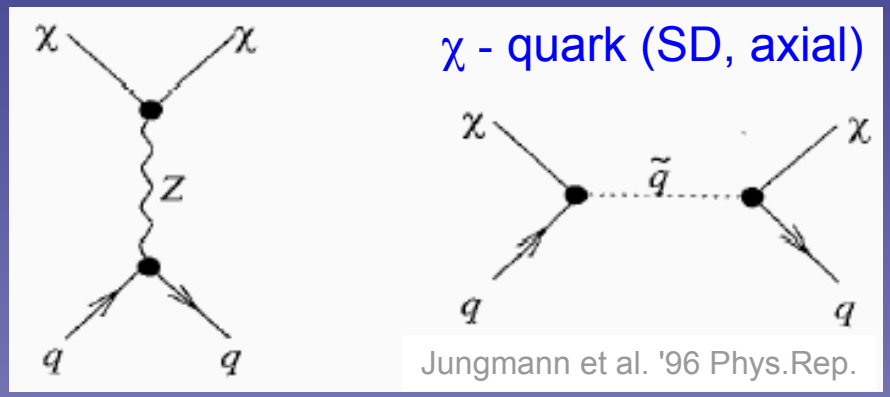
- Elastic scattering of WIMP's χ off of nuclei A.
- Energy spectrum and rate depend on WIMP velocity v_χ and density ρ_χ distribution in DM halo.
  - → Local: $\rho_\chi \sim 0.3$ GeV/cm^3, $(\rho_\chi/m_\chi) \sim 1\text{-}10$ / L
  - → $v_\chi \sim 230$ km/s
- For standard spherical halo: Featureless recoil spectrum with <E> ~ O(10 keV).
- **Scattering rate ~ N $(\rho_\chi/m_\chi) \langle v_\chi\, \sigma_{scat} \rangle$**
  - → N: number of target nuclei in the detector
  - → ρ_χ/m_χ: local number density of WIMPs
  - → σ_{scat} cross section per nucleus. <...>: velocity average
- Rate: 10^{-2} – 10^{-5} events / kg / day



WIMP DM Direct Detection Cross Sections

- Compute cross sections χ – quark and χ – gluon with various SUSY models. Large parameter space, constrained by accelerator and direct search experiments, and cosmology.
  - → spin-independent: coupling to mass of nucleus. Coherence $\Rightarrow$ σA^2
  - → spin-dependent: coupling of spins of nucleus and neutralino interaction with paired nucleons in the same energy state cancel => no A^2 enhancement

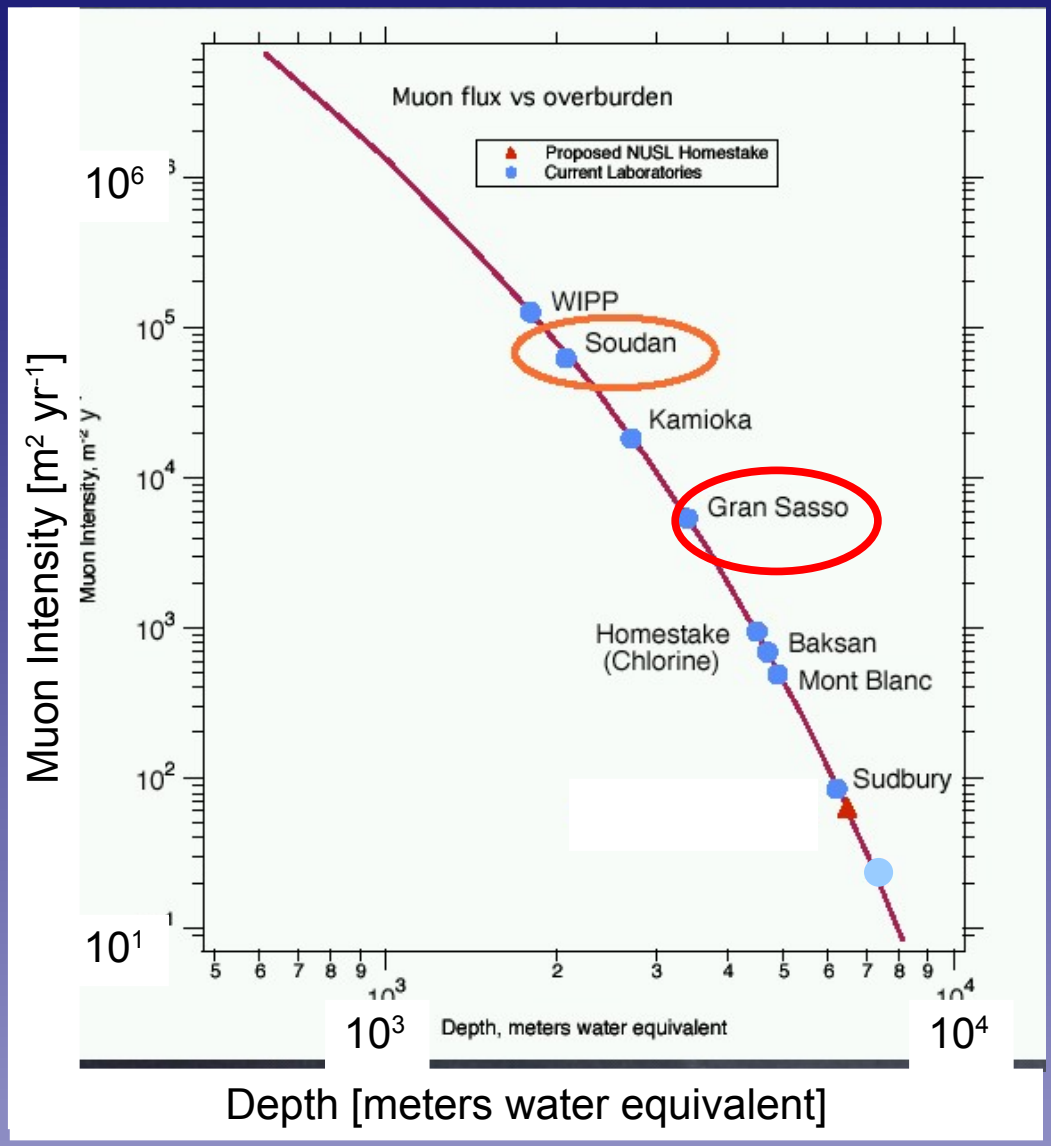




- Distribution of nucleons within nucleus: nuclear form factor.
  - → SI: Large nuclei gain ~A^2 at small momentum transfer, but lose at higher momentum transfer due to coherence loss.

Backgrounds in Direct DM Search

- Cross-sections are *very* small: $<10^{-43}$ cm^2 or 10^{-7} pb (spin-independent)
- Without background, sensitivity $\propto$ (mass × exposure time)$^{-1}$
- With background subtraction $\propto$ (M t)$^{-1/2}$ until limited by systematics.
- Backgrounds:
  - → Gamma-rays & beta decays: ~100 events/kg/day
    - Need efficient β and γ background discrimination.
    - Shielding: low-activity lead, water, noble liquids (active), liquid N_2, ...
  - → Neutrons from (α, n) and spontaneous fission (concrete, rock, etc.): ~ 1 event/kg/day (LNGS)
    - Neutron moderator (polyethylene, paraffin, ...)
  - → Neutrons from CR muons: depends on depth.
    - μ-veto, n-veto, shielding



DM Detector Overview

There are **many** DM detector concepts, with different goals or strengths:

- Sensitivity to spin-independent or spin-dependent interactions (or both).
  - → SD: unpaired protons vs unpaired neutrons.
- Detection principles (1 or 2).
- Energy resolution (threshold detector, low, high).
- Position sensitivity (none, surface/bulk, 3D, tracking).
- Background reduction:
  - → Passive shielding / active veto. (external backgrounds)
  - → Reduction of bulk or surface radioactivities (U, Th, Rn, Kr, etc.)
    - Purification.
    - Material selection / screening.
    - Suppression of α, β, γ, n, as necessary.
    - Level of irreducible intrinsic backgrounds.
- Background discrimination techniques:
  - → 0 or more
  - → Discrimination power
- Stage of fruition.

I will focus on a few examples. For more details, see the conferences DM08 and IDM2008.
http://www.physics.ucla.edu/hep/dm08/
http://agenda.albanova.se/conferenceDisplay.py?confId=355

DM Detector Overview
Detection Principles

Bubble Formation
in superheated
liquids or gels

Tracking
gas TPC
nuclear emulsion

Ionization
Ge

Cryogenic
Ge, Si

LAr, LXe
(dual phase)

Phonons
Al_2O_3

$CaWO_4$, BGO,
Al_2O_3, LiF, ...
with cryogenic
light sensors

Scintillation
NaI, CsI
LAr, LXe
(single phase)

DM Detector Overview
Detection Principles

Bubble Formation
COUPP
PICASSO

Tracking
Drift, DM-TPC, etc.
NIT

Ionization
ConGeNT, GERDA,
MAJORANA

CDMS-II
EDELWEISS

WARP, ArDM
XENON, LUX, Zeplin

Phonons
CRESST

CRESST-II,
ROSEBUD

Scintillation
DAMA/LIBRA
KIMS, XMASS,
DEAP/CLEAN

DM Detector Overview

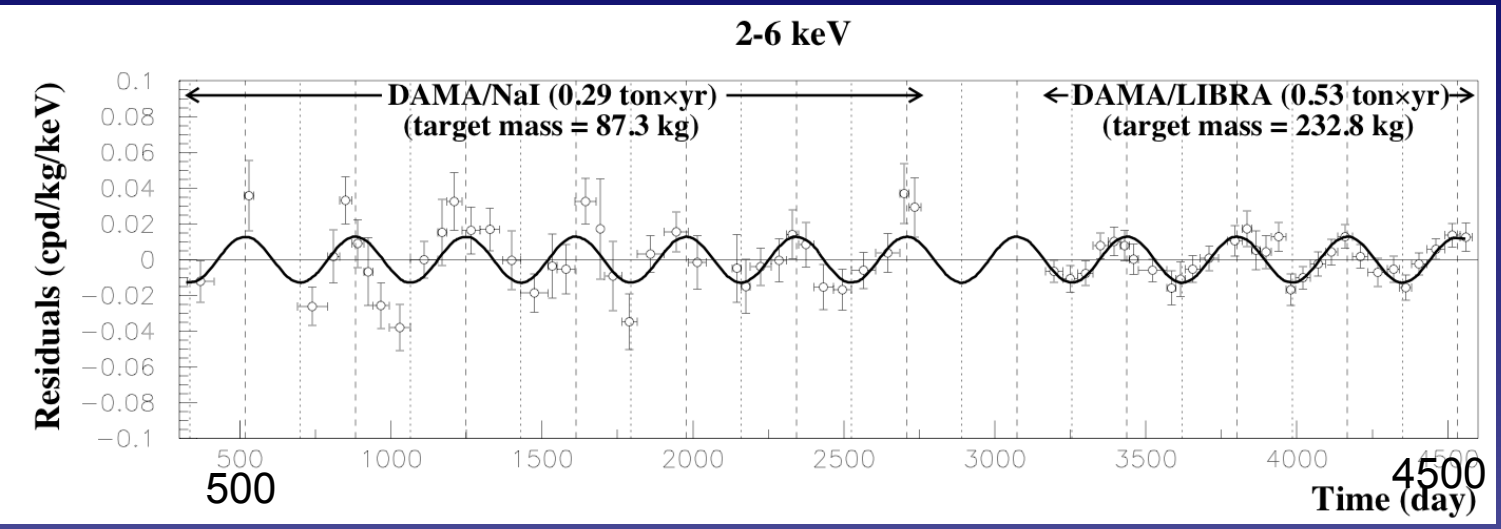
Detector Type	Experiments	Strengths / Caveats	
Ionization	MAJORANA, GERDA	Search for ββ-decay	
Crystal Scintillator	LIBRA/DAMA, NAIAD, KIMS	low threshold, large mass, poor background discrimination	
Cryogenic	CDMS, CRESST, EDELWEISS	good background discrim., smaller mass / high cost	
Liquid Noble Gas	Ar: ArDM, WARP, DEAP/CLEAN	large mass, good backgrnd discrim., position resol. (dual phase)	Ar: intrinsic background
	Xe: XENON, XMASS, ZEPLIN, LUX		Xe: self shielding, odd & even isotopes
Bubble Chamber	COUPP, PICASSO	large mass, good background discrim.	
Gas Detector	DRIFT, DM-TPC	directional information, good background discrim.	

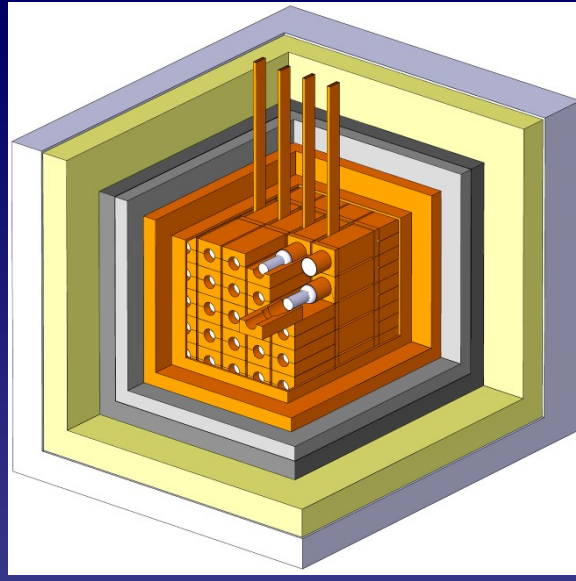
Background Discrimination Techniques:

- none (low bgd)
- pulse shape
- charge/phonon
- light/phonon
- light/charge
- super-heated bubbles/droplets
- ionization track
- plus: 3D position

DAMA/LIBRA Annual Modulation

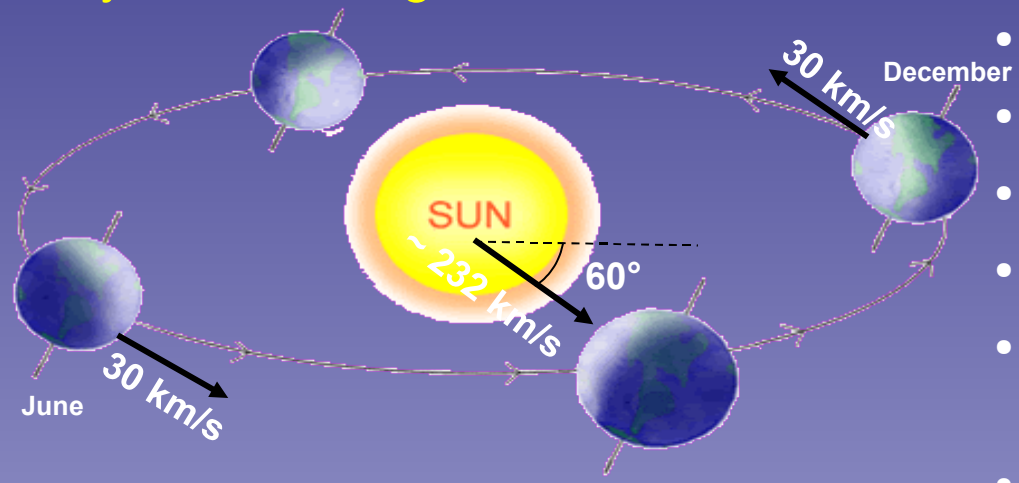
(R. Bernabei et al. arXiv:0804.2741)





~250 kg of NaI counters (24 operational)

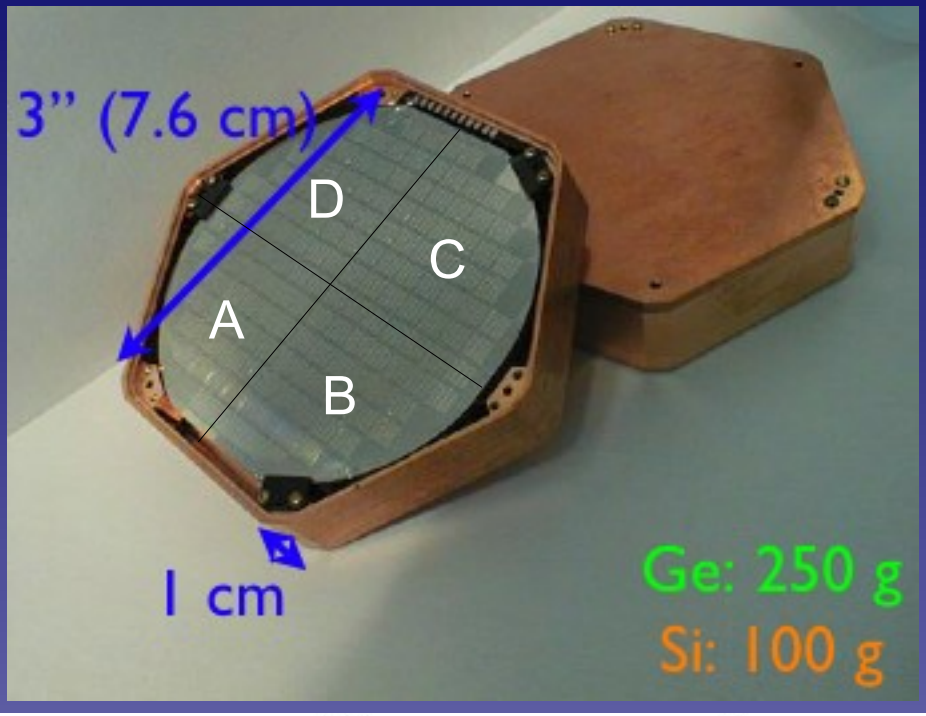
→ plenary talk Friday 11am by Chris Savage



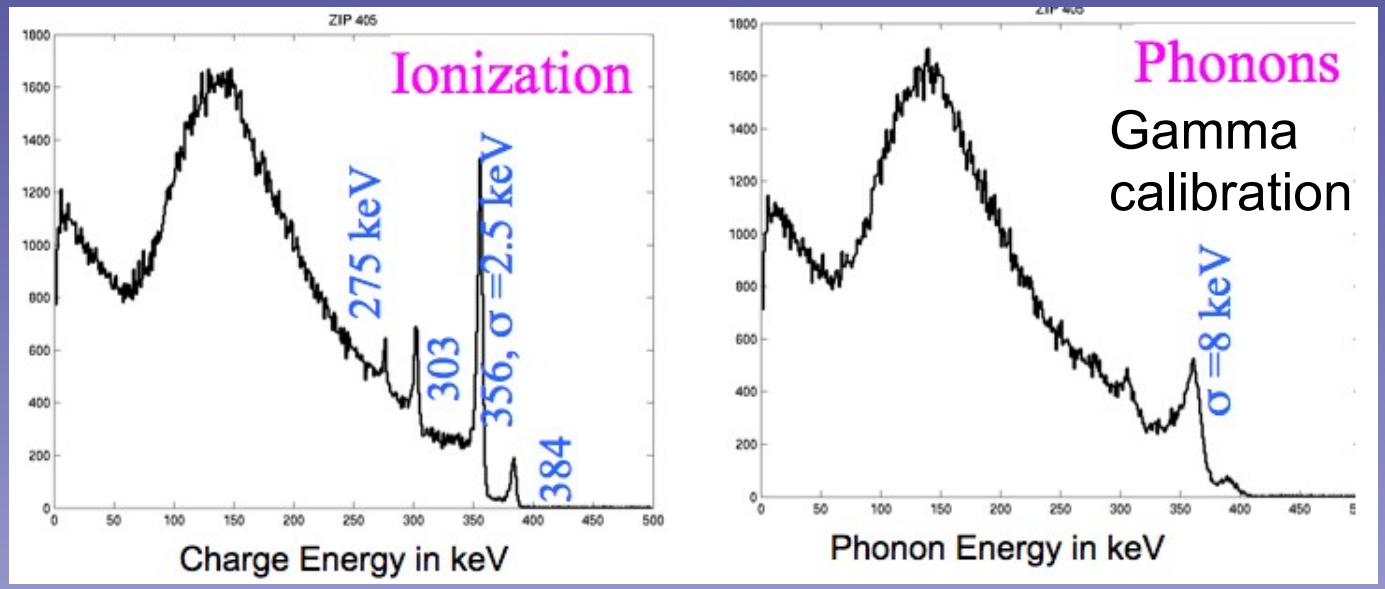
Drukier, Freese, Spergel PRD86
Freese et al. PRD88

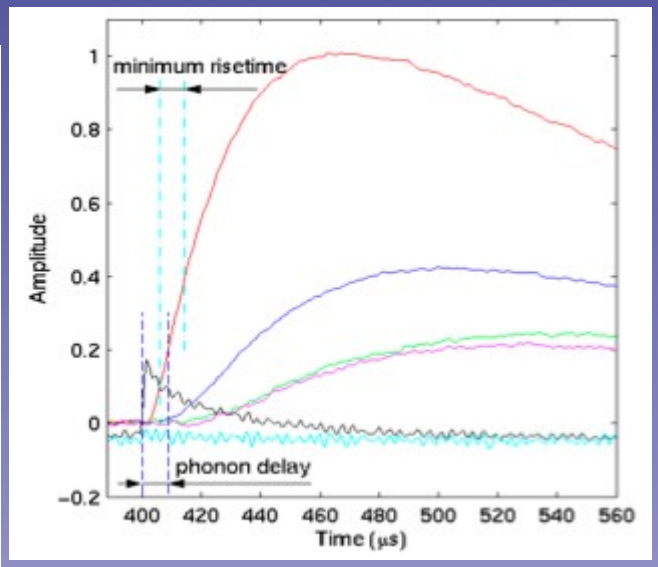
- Modulation in 2-6 keV single hits: 8.2 σ
- Mostly in 2-4 keV, ~0.02 cts/d/kg/keV
- Total single rate ~1 cts/d/kg/keV
- Standard DM distribution: ~5% modulation
- Period & phase about right for DM.
- No annual modulation in 6-14 keV.
- No annual modulation in multiple hits. (Statistics?)
- Claim of DM detection.
- Conflict with other experiments in standard scenarios.

CDMS II: Z-sensitive Ionization and Phonon Detectors (Ge,Si)



- Phonon Side: 4 quadrants of phonon sensors (Transition Edge Sensors)
  → Energy & Position (Timing)
- Charge Side: 2 concentric electrodes
  → Energy (Background discrimination) & Veto

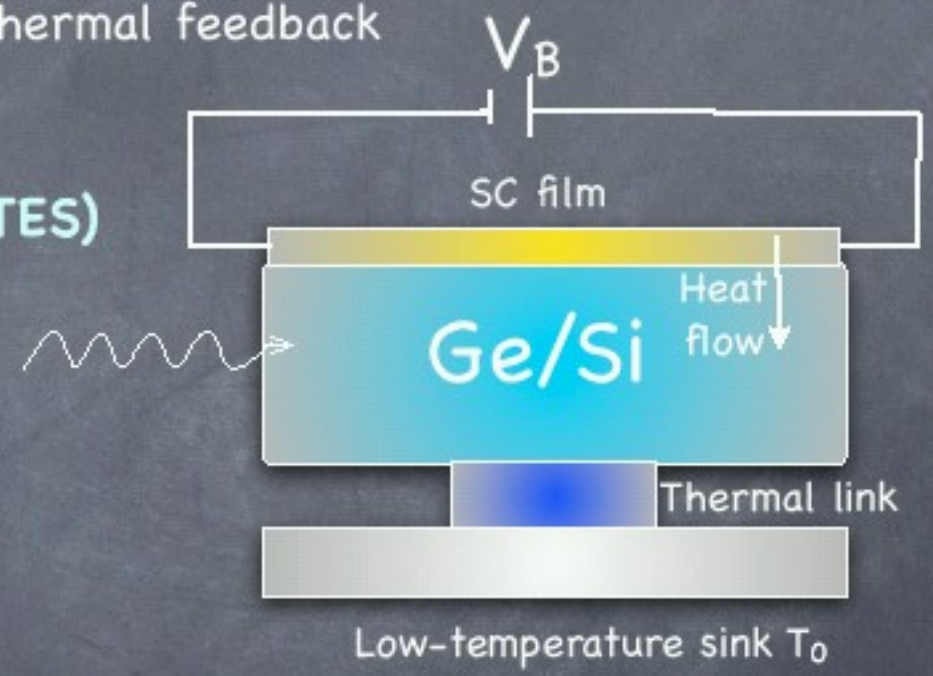




CDMS II: Transition Edge Sensors with Electrothermal Feedback for Fast Phonons

Detect **fast phonons,** after a WIMP interacts in a Ge/Si absorber using transition edge sensors with electrothermal feedback

K.D.Irwin et al., Rev. Sci. Instr. 66 (1995)



$T_0 \ll T_C$; V_B is placed across the film (TES)

=> equilibrium: when ohmic heating balanced by heat flow into the absorber

When an excitation reaches the TES

=> R ↗ => I ↘ by ΔI => P ↘

=> feedback signal = change in Joule power heating the film ($P=IV_B=V_B^2/R$)

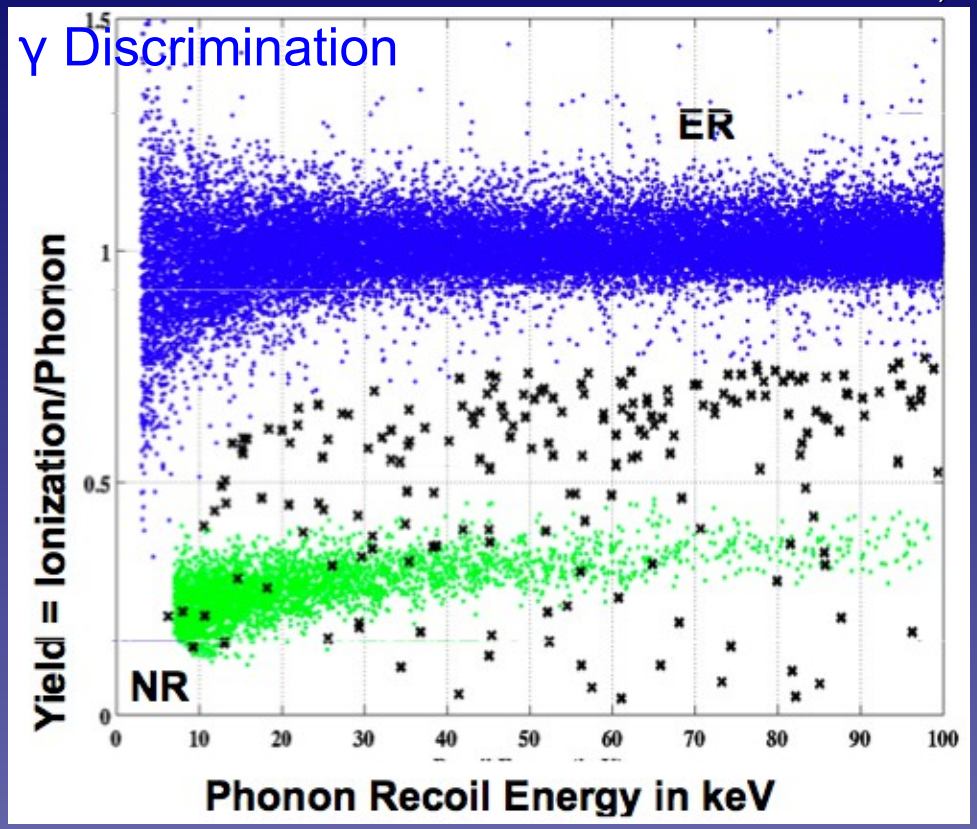
The deposited energy:

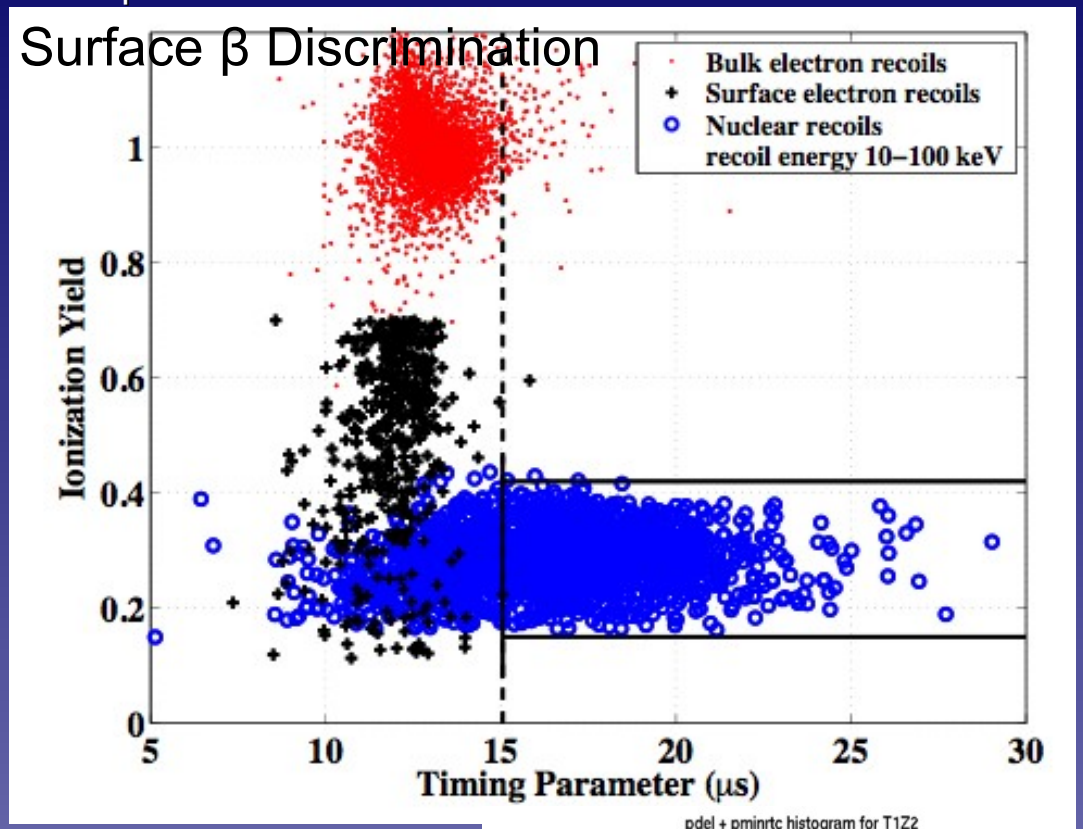
$$E = -V_B \int \Delta I(t)\,\mathrm{d}t$$

L. Baudis

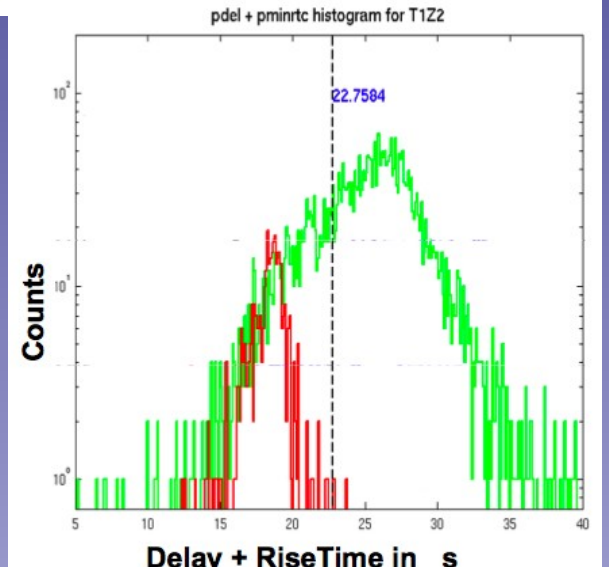
CDMS II Background Discrimination

arXiv:08020350, R. Mahapatra PPC2008



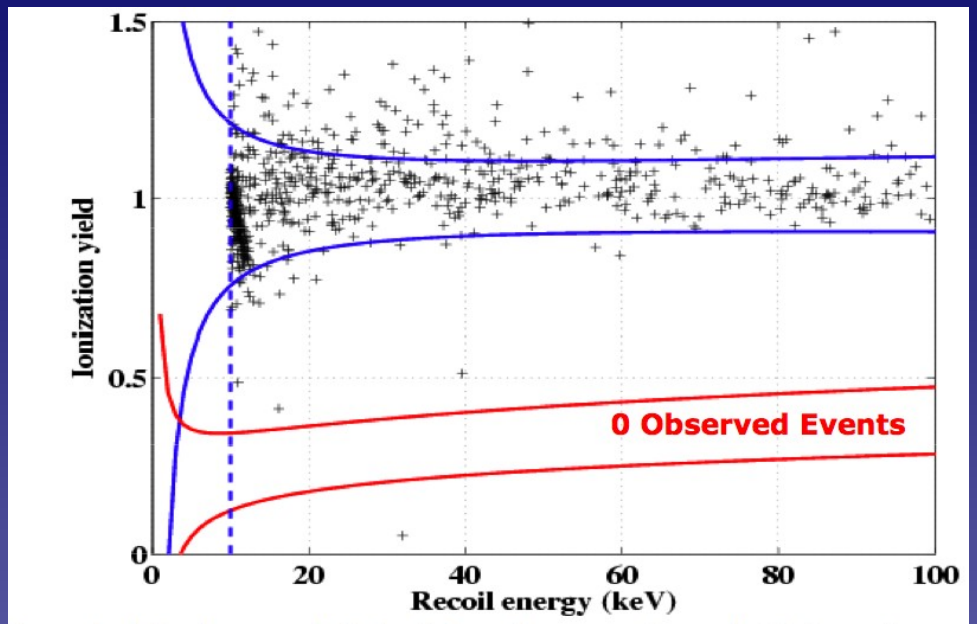


- 5 towers of detectors (previously 2)
- Fix cuts blind with calibration data.
- Choose cuts aiming at background level ~0.5 events, i.e., efficiency goes down with time.
- So far losses offset by analysis and detector improvements.

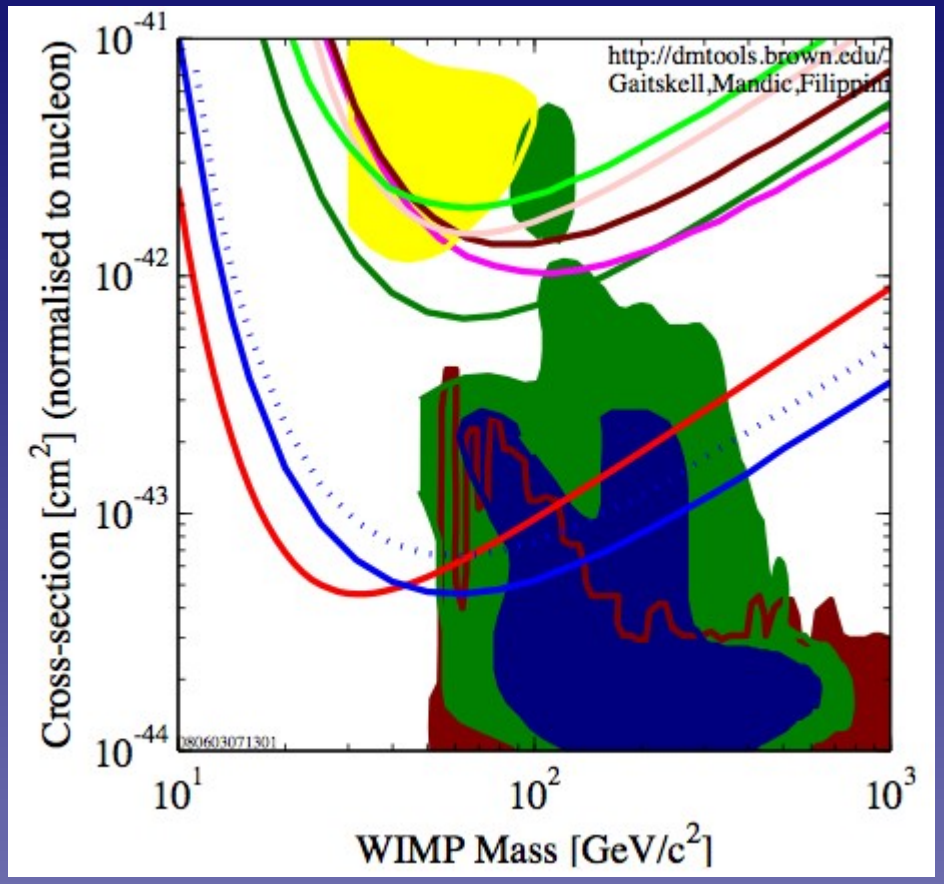


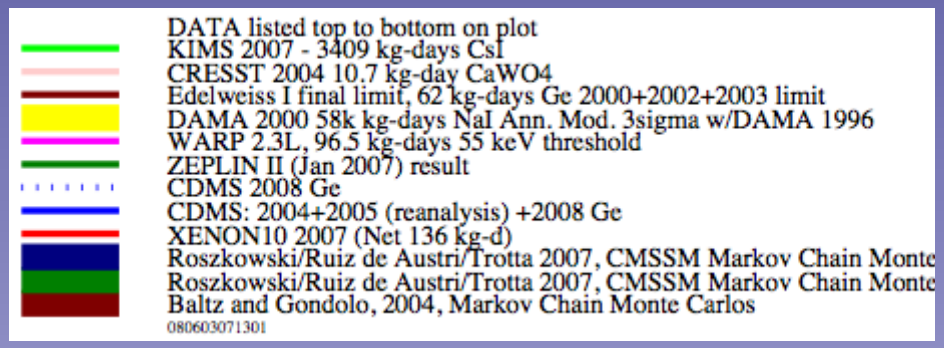
CDMS II – 2008 Result

arXiv:08020350



Expected Background: 0.6 ± 0.5 surface events and < 0.2 neutrons

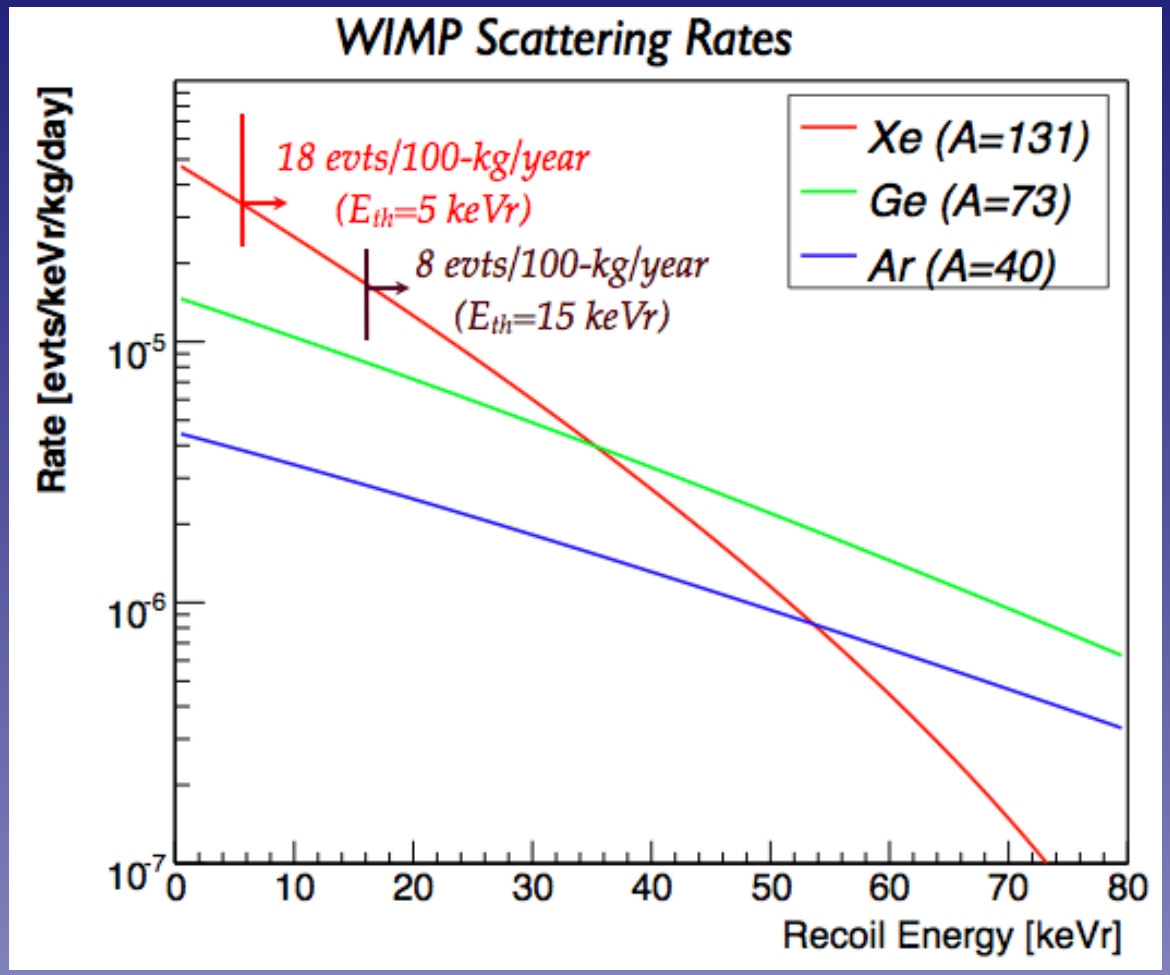




- 5 towers of detectors (previously 2)
- Fix cuts blind with calibration data, aiming at γ background ~0.5 events, i.e., efficiency goes down with time.
- So far losses offset by analysis and detector improvements.
  Exposure: 121.3 kg days
- Expect ~0.2 events neutron background.

Liquid Xenon for Dark Matter Search

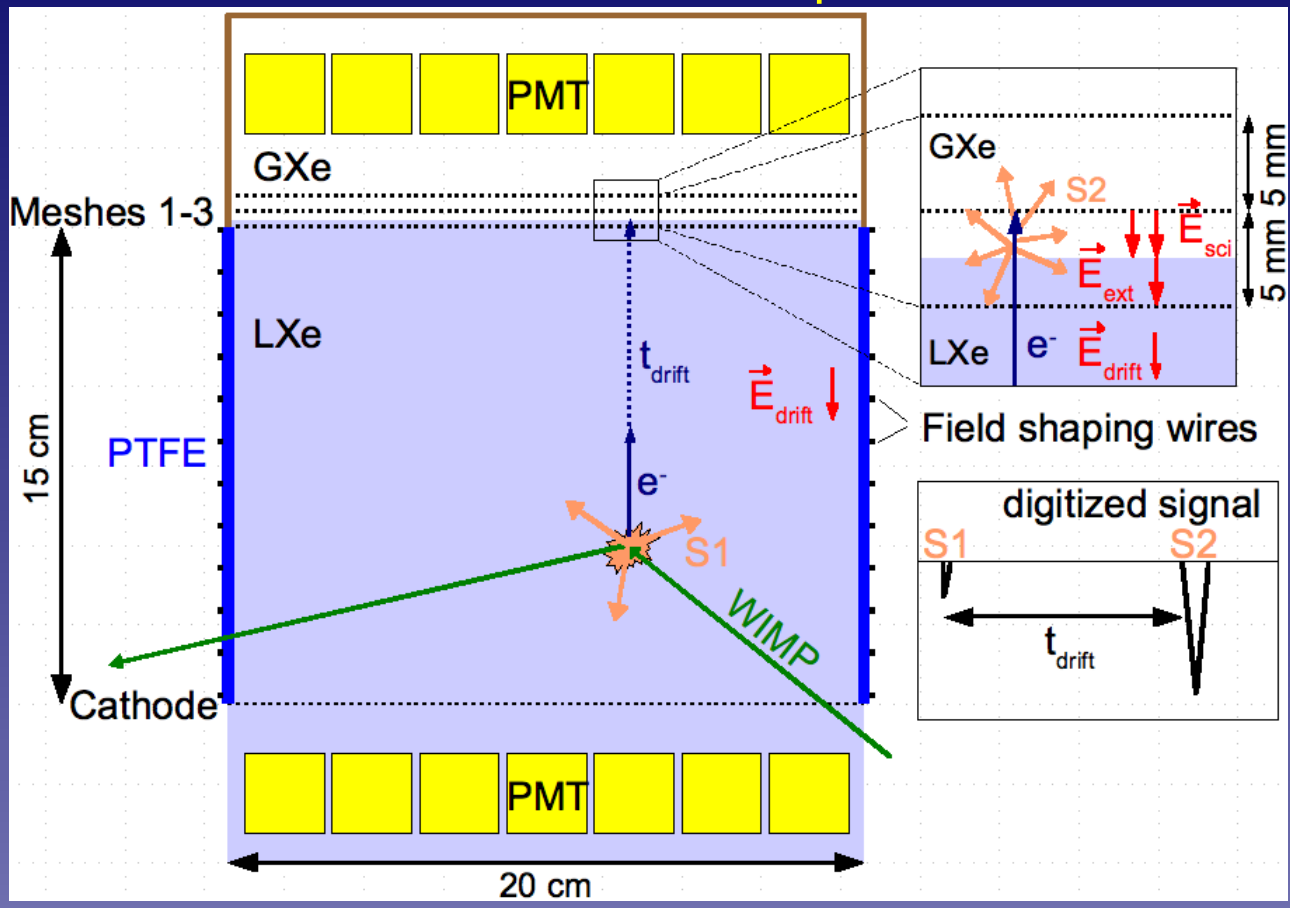
- Large atomic number A~131 best for SI interactions ($\sigma \sim A^2$) if low threshold
- ~50% odd isotopes: very good for SD interactions
- No long-lived isotopes. Kr-85 reduction to ppt proven.
- High Z (54) and density:
  → compact & self-shielding
- Scalability to large mass for $\sigma \sim 10^{-47}$ cm^2 ~ 1evt/1ton/yr
  → cost
  → "easy" cryogenics (-100°C)
- Efficient scintillator
- Background discrimination
  → Ionization/Scintillation
  → 3D imaging of TPC



Liquid Xenon Dual Phase TPC *

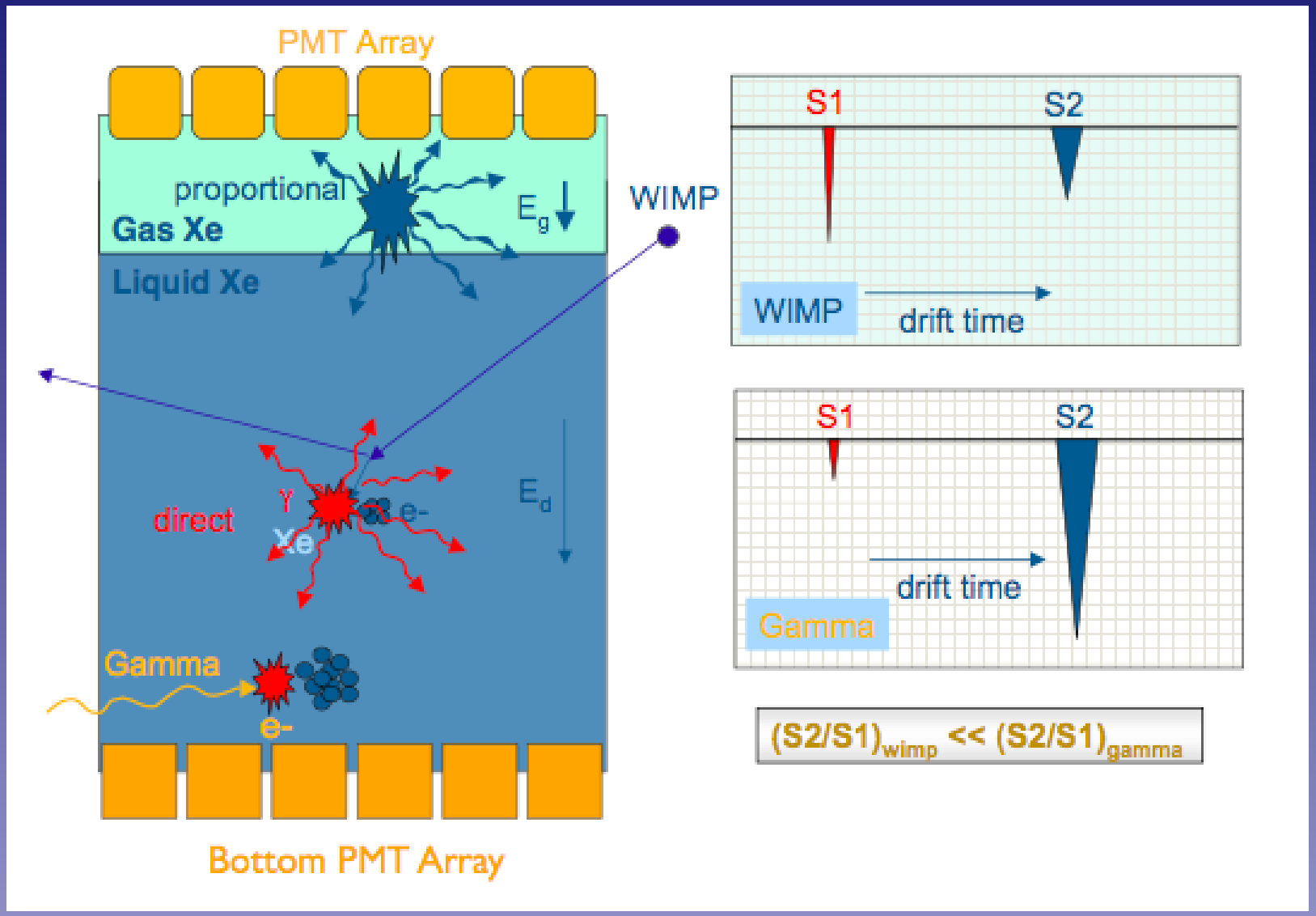
* LAr dual phase TPC similar

- Dual phase liquid/gas xenon TPC at ~ -94˚C / 2 bar
- Wimp recoil on Xe nucleus in dense liquid (2.85 g/cm^3) → Ionization + UV Scintillation
- Detection of primary scintillation light (S1) with PMTs on top and bottom
- PTFE cylinder for reflectivity
- Charge drift towards liquid/gas interface at field of 0.73 kV/cm (XENON10)
- Charge extraction liquid/gas at high field (5 kV/cm) between meshes 1 (liquid) and 2 (gas)
- Charge produces proportional scintillation signal (S2) in the gas phase (10 kV/cm)

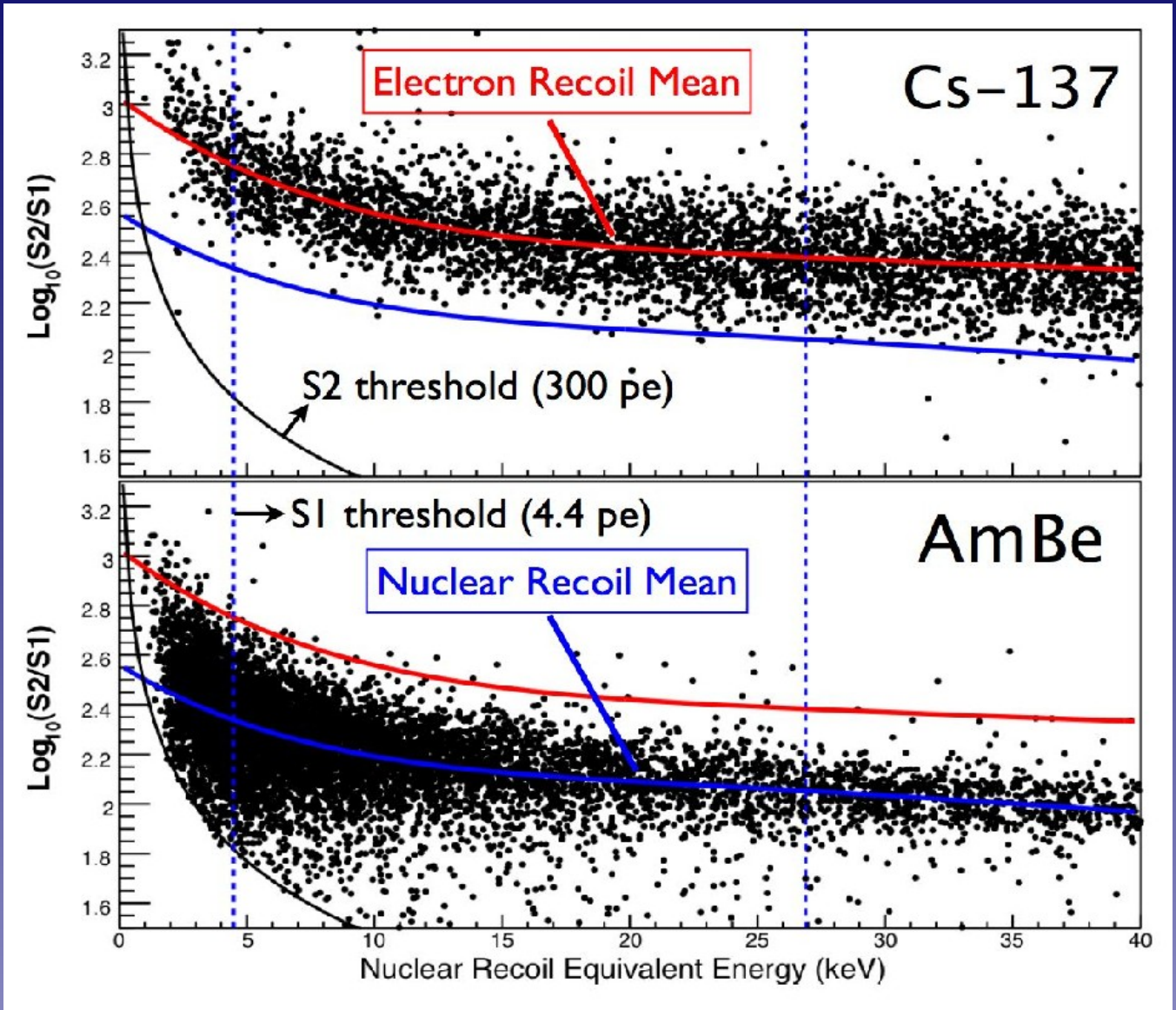


- 3D position measurement:
  - → X/Y: from S2 signal, resolution few mm due to small PMT size (1”).
  - → Z: from electron drift time (~1 mm).

Background Discrimination based on Ionization/Scintillation Ratio in Dual Phase LXe/LAr TPC's



XENON10 Background Rejection: S2/S1



Gamma Calibration (ER band)

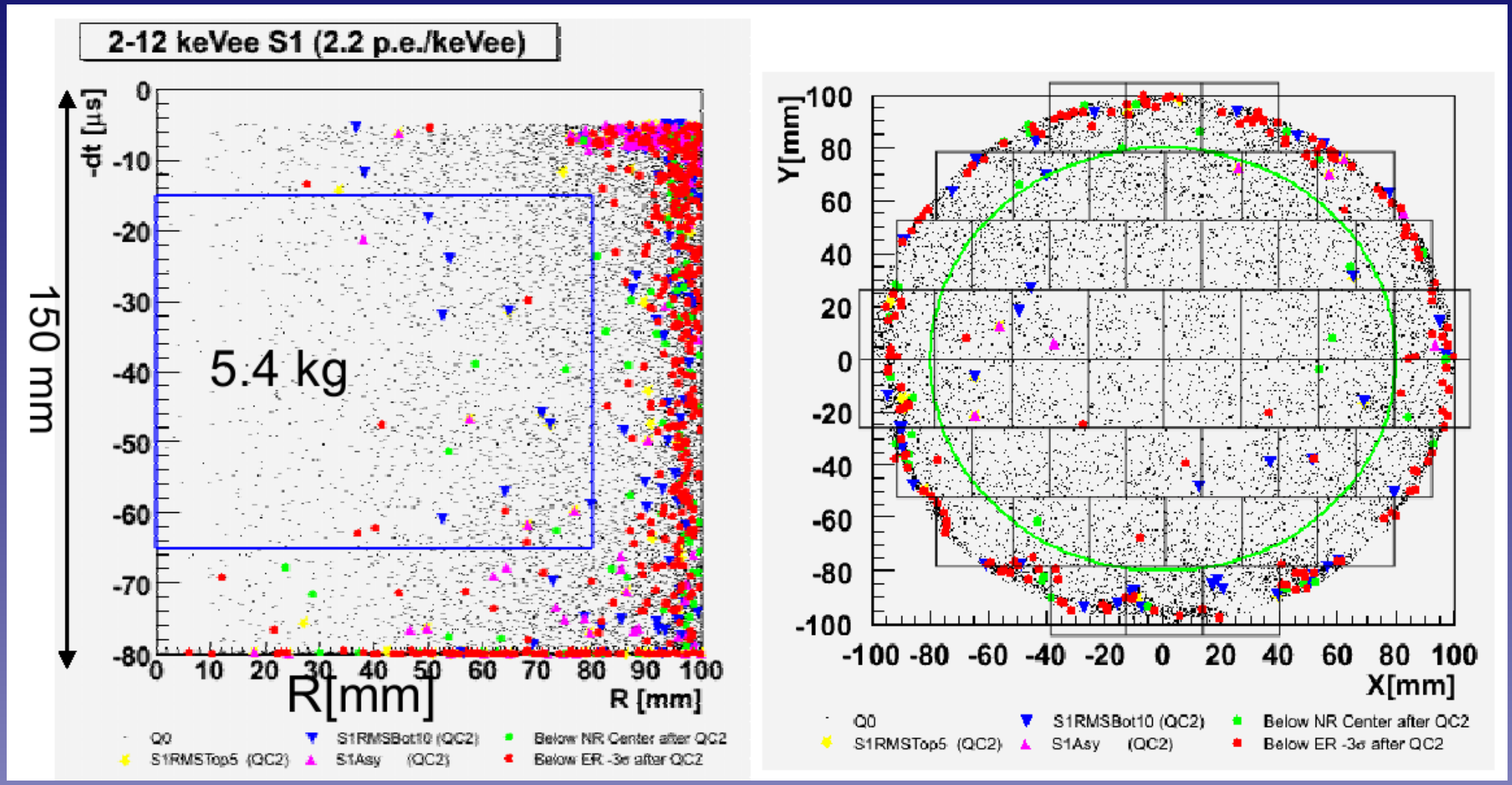
- Weekly
- Cs-137 source (1 kBq) in shield

Neutron Calibration (NR Band)

- Dec 1, 2006 (12 h)
- AmBe source (3.7 MBq) in shield
- Single interactions

99.5% background rejection (99.9% at low E) at 50% acceptance.

XENON10 Background Rejection: Spatial

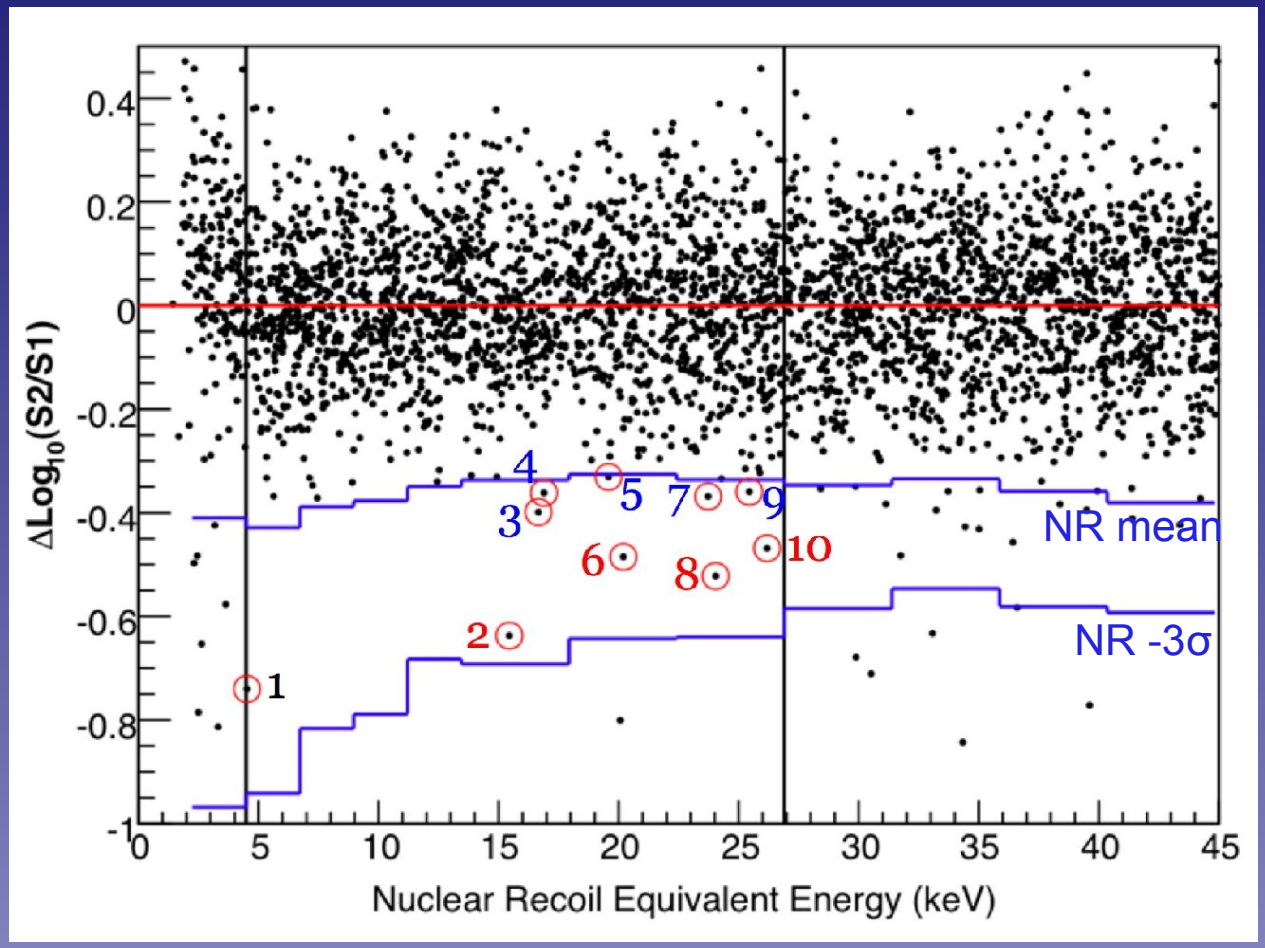


13 events inside fiducial volume removed by final quality cut.

XENON10 WIMP Search with Blind Cuts

Oct 6, 2006 – Feb 14, 2007: 136 kg days exposure

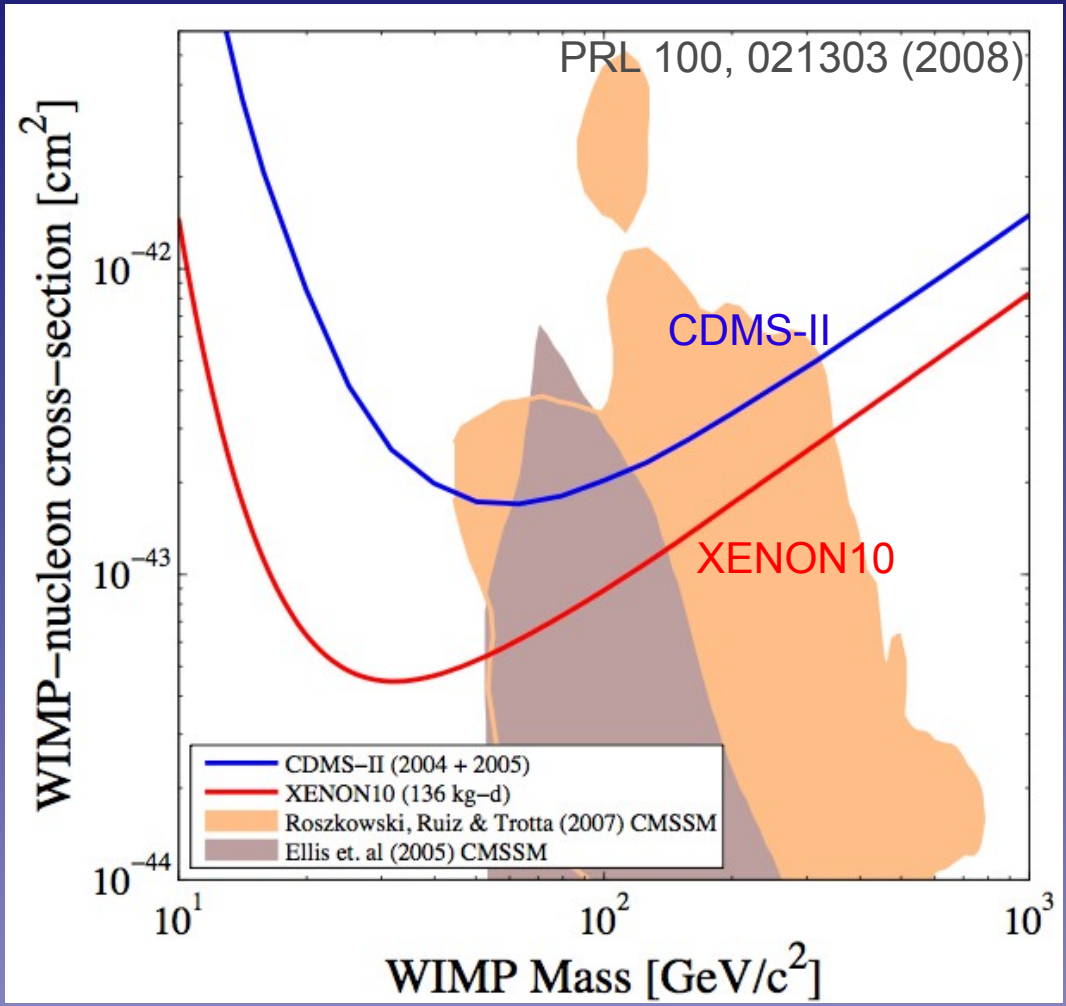
(58.6 live days × 5.4 kg × 0.86 cut efficiencies × 0.50 NR acceptance)



- WIMP search box defined by 50% NR acceptance region (blue lines) and E_r in 4.5-27 keV (black lines).
- Search box optimized with calibration data and additional 40 live days of unmasked data.
- 10 events in the box from "blind" data after cuts.
- Energy spectrum <u>not</u> as expected from WIMPs.
- ~7 events expected from gamma-ray leakage.
- NR energy scale based on 19% constant "quenching factor" at low energies.

XENON10 WIMP Search Result for Spin-Independent Interactions

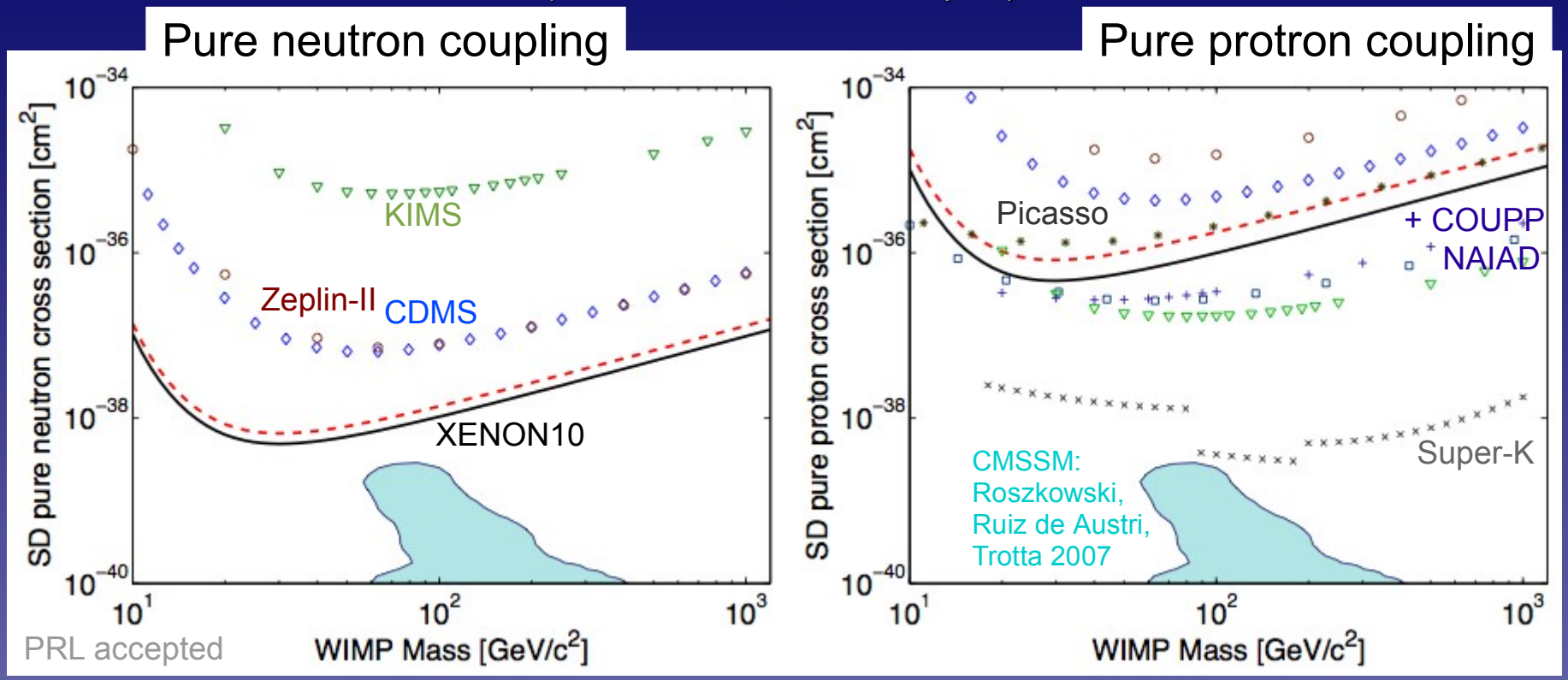
Status 2007



- 90% CL upper limit on WIMP-nucleon cross section derived with Maximal Gap Method [Yellin, PRD 66 (2002)]
- At 100 GeV/c^2 WIMP mass 8.8×10^{-44} cm^2 (no background subtraction)
- Uncertainty in scintillation efficiency: conservative $< 1.0 \times 10^{-43}$ cm^2

XENON10 Spin-Dependent Limits

(arXiv:0805.2939, PRL accepted)



$$\frac{d\sigma}{d|\mathbf{q}|^2} = \frac{C_{spin}}{v^2} G_F^2 \frac{S(|\mathbf{q}|)}{S(0)}$$

$$C_{spin} = \frac{8}{\pi}[a_p\langle S_p\rangle + a_n\langle S_n\rangle]^2 \frac{J+1}{J}$$

S(|**q**|): Spin structure function at momentum transfer q.

G_F: Fermi constant.

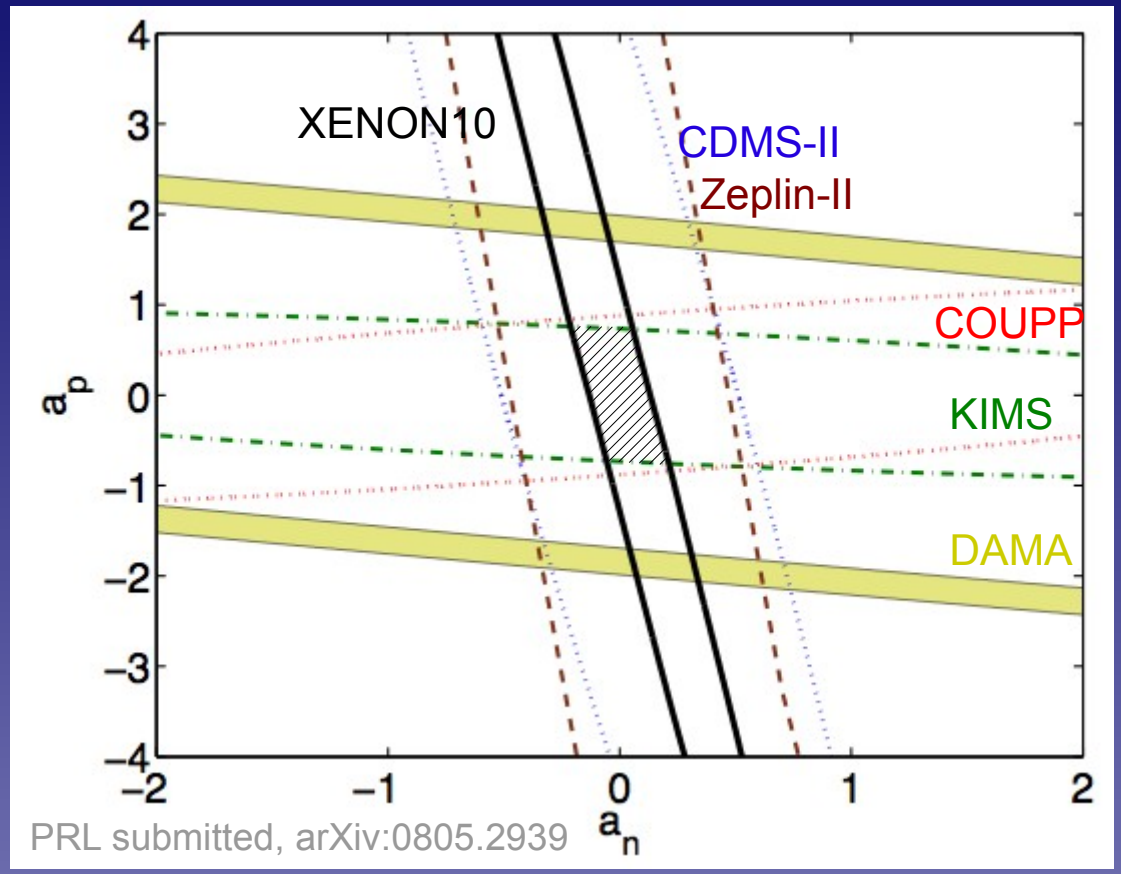
C_{spin}: spin enhancement factor

$\langle S_{p,n}\rangle$: expectation value of spin content of proton/neutron groups within nucleus.

J: total nuclear spin.

Pure neutron cross section: world best limit. At 30 GeV/c²: $\sigma < 5\times10^{-39}$ cm²

XENON10 Spin-Dependent Limits



- Plot for WIMP mass of 50 GeV/c^2
- Elliptical contours: expected events $N_{evt} = A\, a_p^2 + B\, a_p\, a_n + C\, a_n^2$
- New regions excluded in a_p-a_n plane.

The Next Generation: XENON100 at LNGS

- Use of XENON10 shield + inner Cu layer
- Goal: 50-100 times lower background
- Material screening
- 10 times larger target mass:
  50 kg fiducial, 170 kg total LXe
- Active LXe Veto
- New PMTs with low activity and high QE
- Improved grids, electronics, ...
- Cryocooler/Feedthroughs outside shield
- DM search in 2008

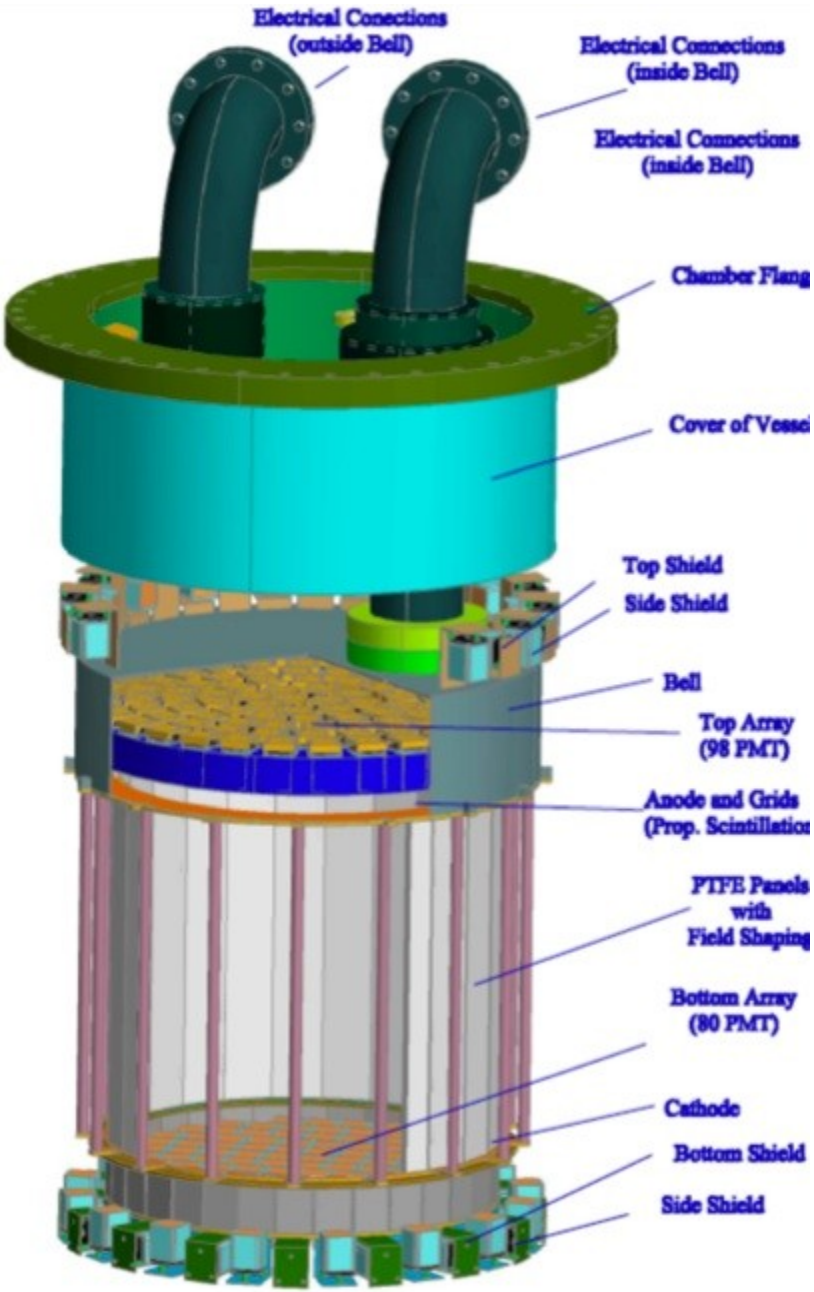
Status:
- Shield modification completed Jan 08
- Detector underground mounted in shield Feb 08
- LXe purification/circulation tested Mar'08
- Modifications May'08, starting filling.

The XENON100 / XENON1T Collaboration

Elena Aprile	Uwe Oberlack	Katsushi Arisaka	Laura Baudis	Jose Matias Lopes	Francesco Arneodo
Columbia Univ.	Rice University	UCLA	Univ. of Zurich	Univ. of Coimbra	LNGS

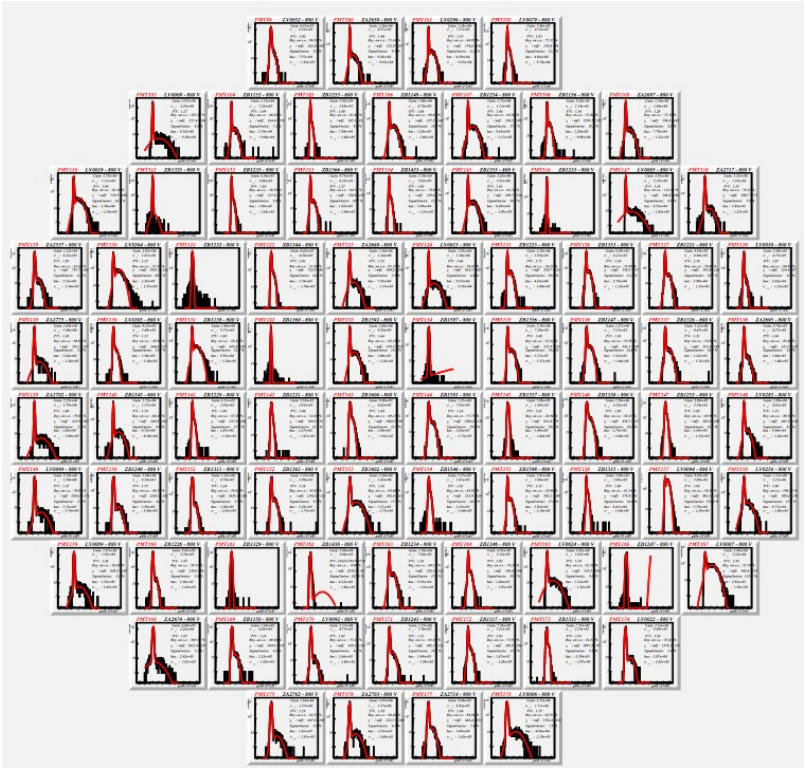
8 faculty - 3 research scientists - 7 postdocs- 12 Ph.D. students ~ 30

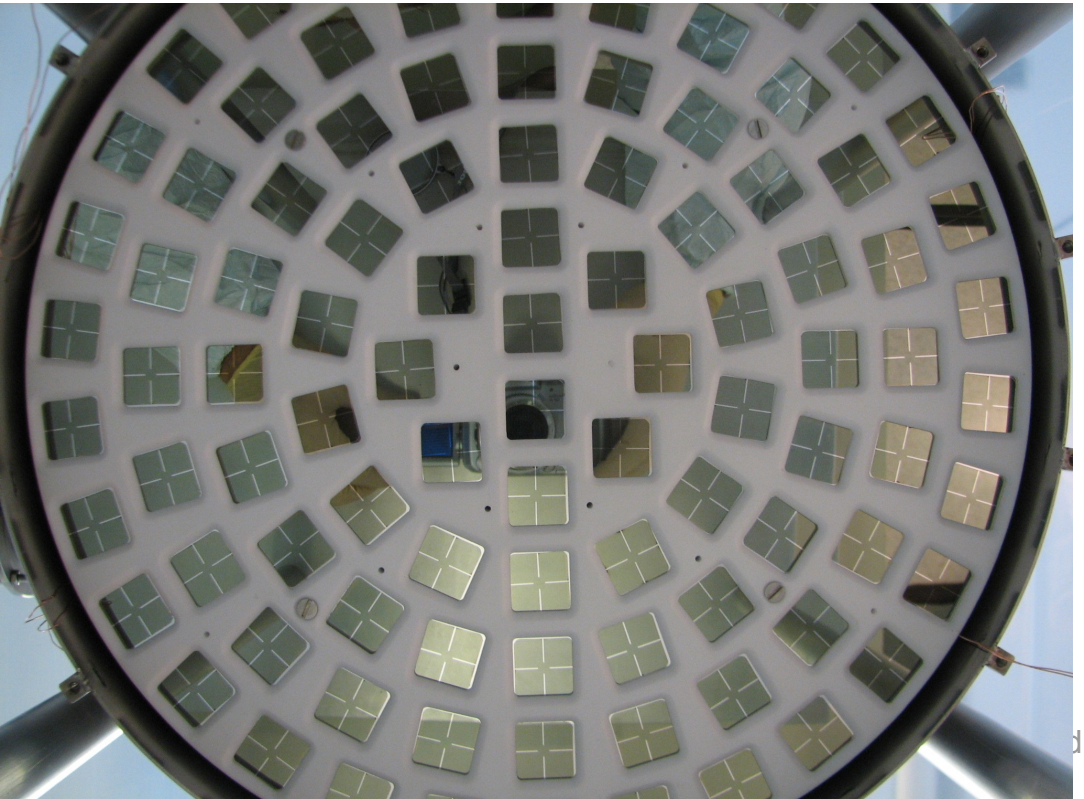
XENON100 TPC

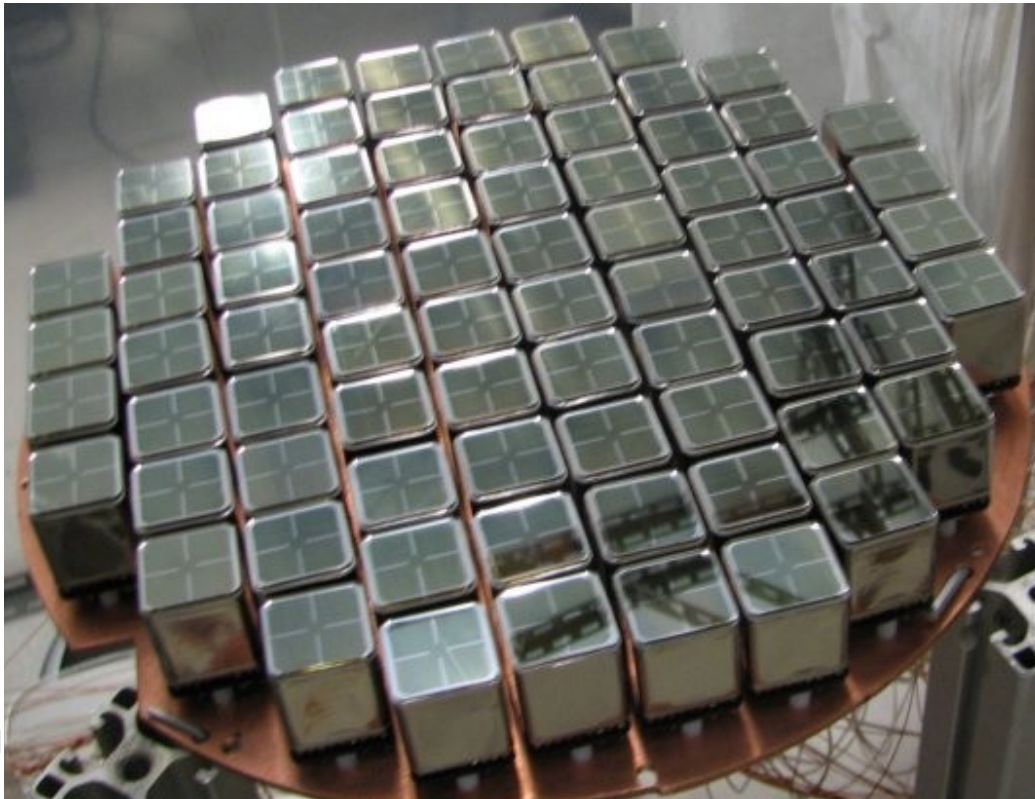


Status of XENON100 PMTs

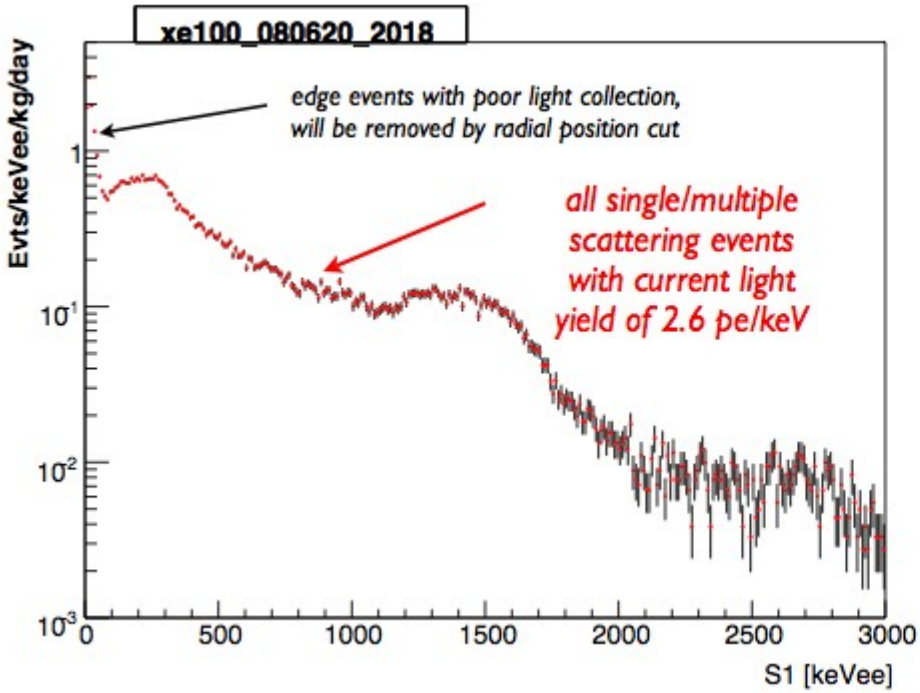
- Photomultipliers: Hamamatsu R8520-06-Al
- 98 on top - 80 on bottom - 64 in active LXe shield
- QE~23% for top array; QE~33% for bottom array
- XENON10 PMTs for LXe shield
- Calibrated with external LED's & quartz fibers
- S1 source calibrations with gamma sources

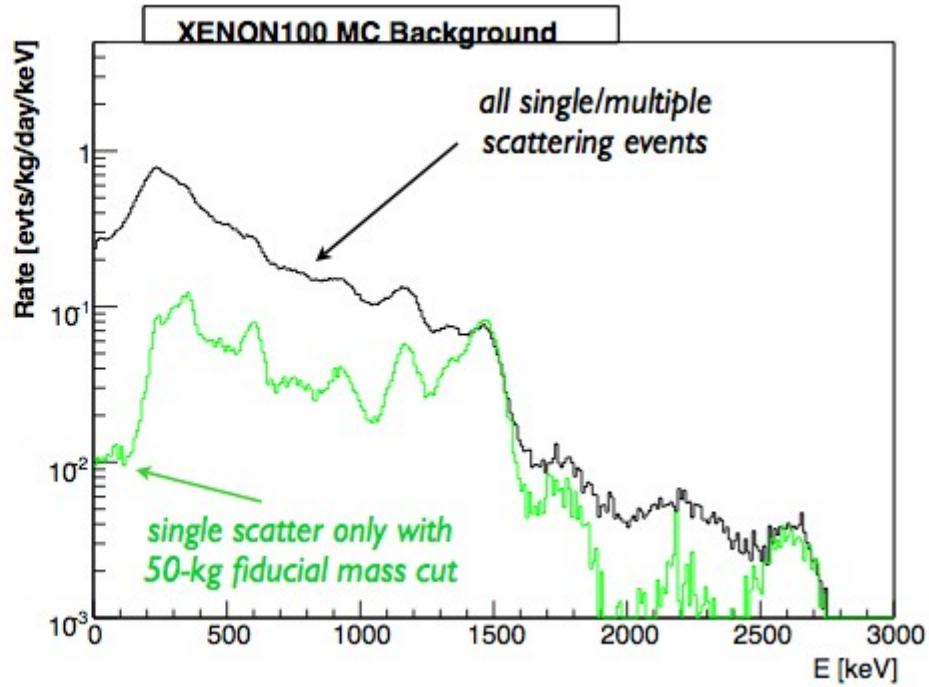




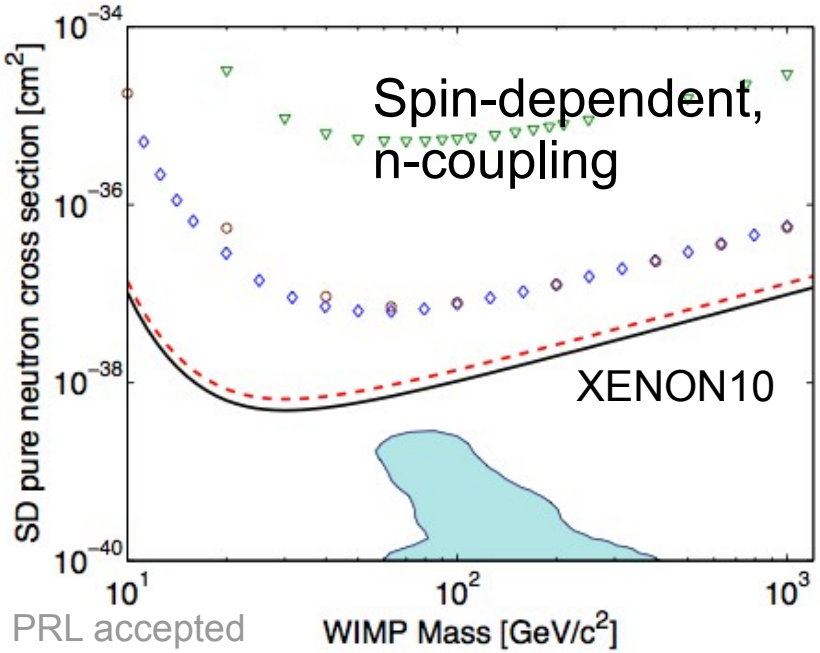


Status of XENON100 – Background



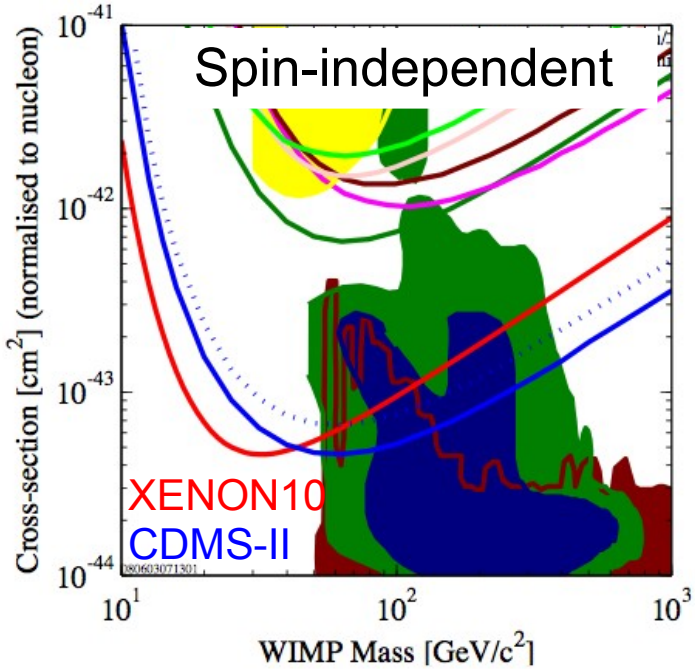


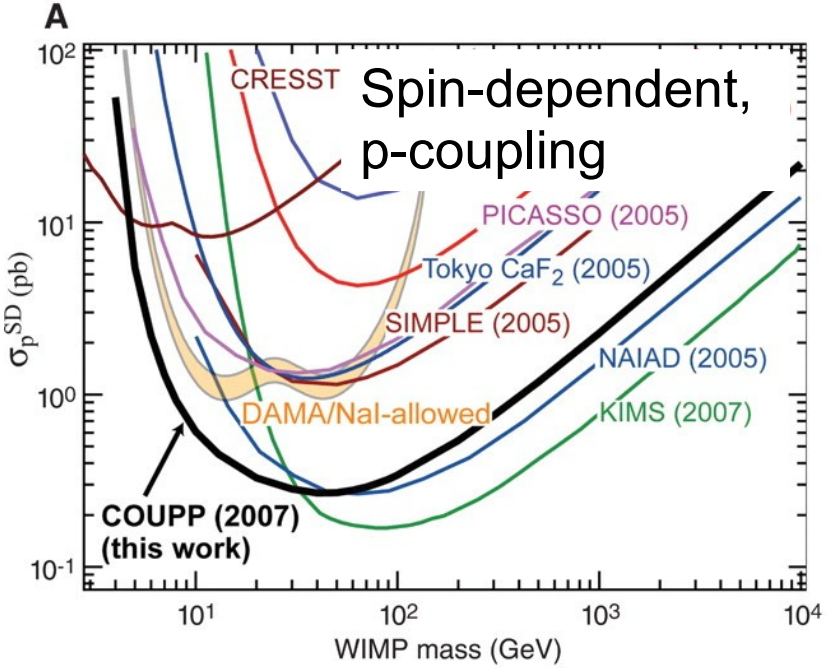
Current Status in WIMP DM Sensitivities

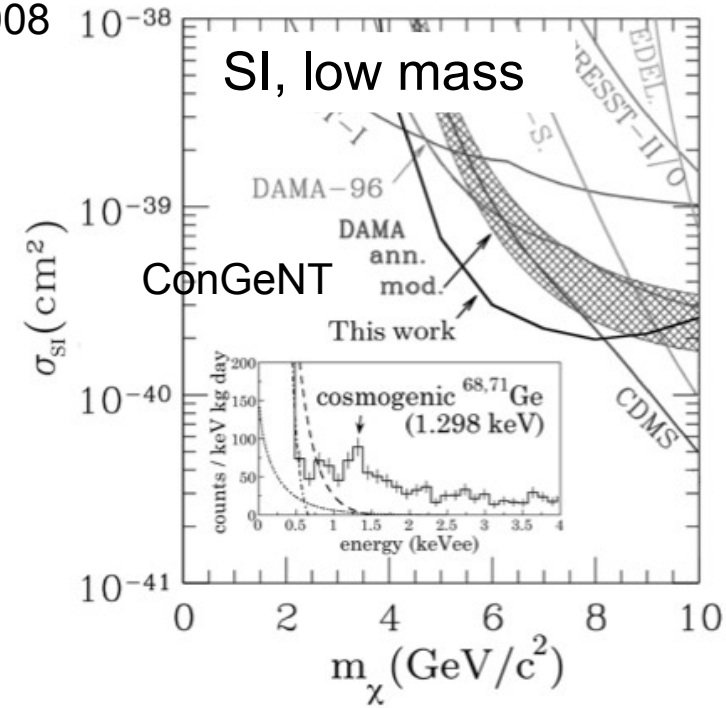


PRL accepted

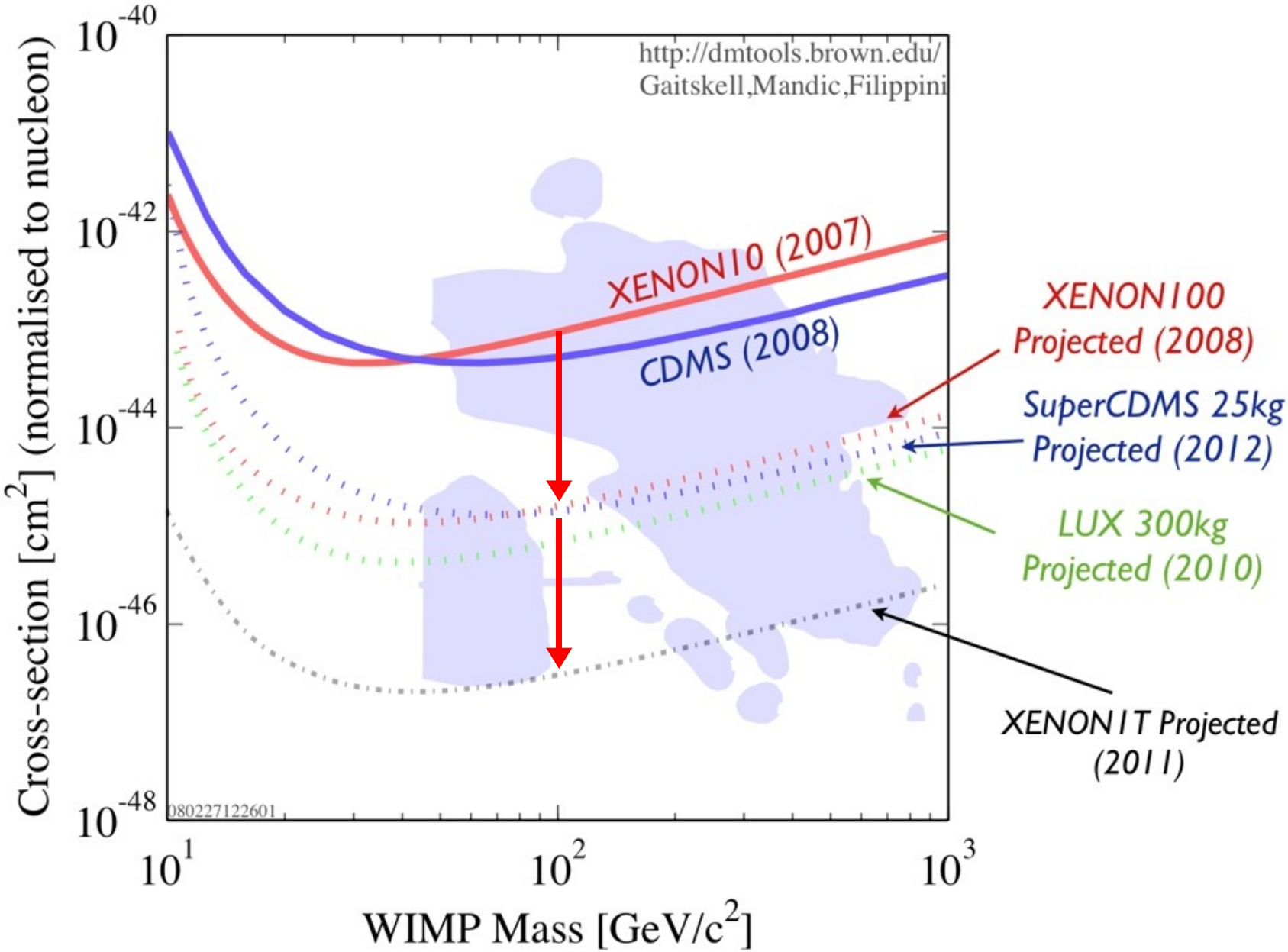
- J. Angle et al., arxiv:0805.2939v1 (XENON10 SD)
- J. Angle et al., 2008 PRL 100 (2) 021303 (XENON10 SI)
- Z. Ahmed et al., arxiv:0802.353v1 (CDMS-II SI)
- C.E. Aalseth et al. arxiv:0807.0879v1 (ConGeNT SI)
- E. Behnke et al., 2008 Science 319, 933 (COUPP SD)



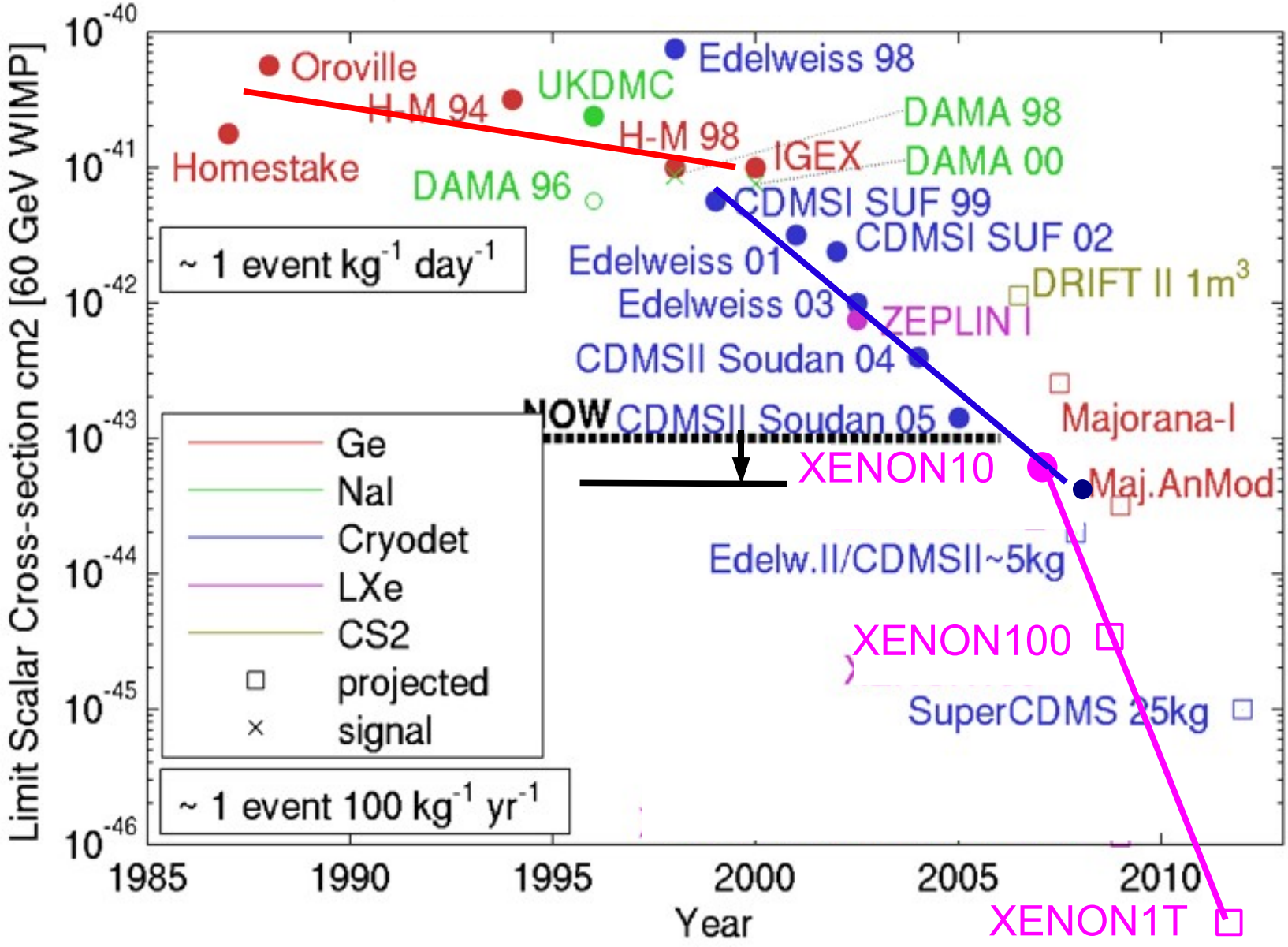




Projected DM Sensitivities 2008-2012



DM Direct Searches: Progress Over Time



Plot updated from DM Review: R. Gaitskell, Ann. Rev. Nucl. Part. Sci. 54 (2004) 315-359

Summary & Outlook

- Cryogenic Ge (CDMS) has been the driver over the last ~8 years. Will expand to 5 towers. Scalability improved with lower grade Ge?
- Various new detector technologies are maturing. Liquid noble gas concepts have made rapid progress (XENON, WARP) and are starting to set the pace.
- XENON10 provided the best spin-independent DM limits in 2007. Currently neck and neck with CDMS.
- Next step XENON100 currently in progress (2008).
- LUX: ~2× mass of XENON100, arriving later. Single & double phase LAr, ...
- Scalability of liquid noble detectors promises ton-scale detectors by ~2011, multi-ton for DUSEL (~2015?).
- Progress for SD limits as well (COUPP, XENON10).
- Timeline for new DM direct search detectors is compatible with LHC (2008) and indirect searches by GLAST (launched in June)
- DAMA/LIBRA annual modulation: new physics or nasty old physics? DM? Large detector, huge exposure, but little information on events compared to recent concepts.
  Look for more signatures with current and upcoming experiments.
- *This is a very exciting period in WIMP DM search – stay tuned!*