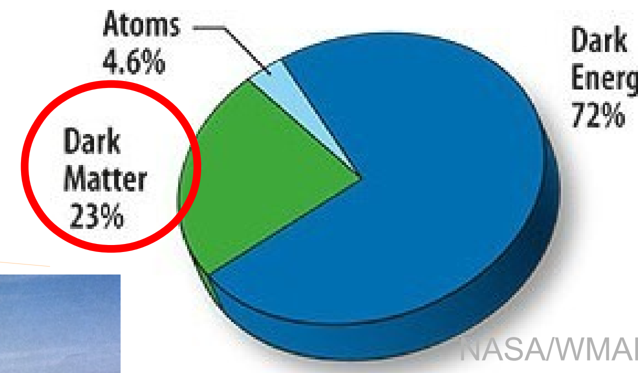
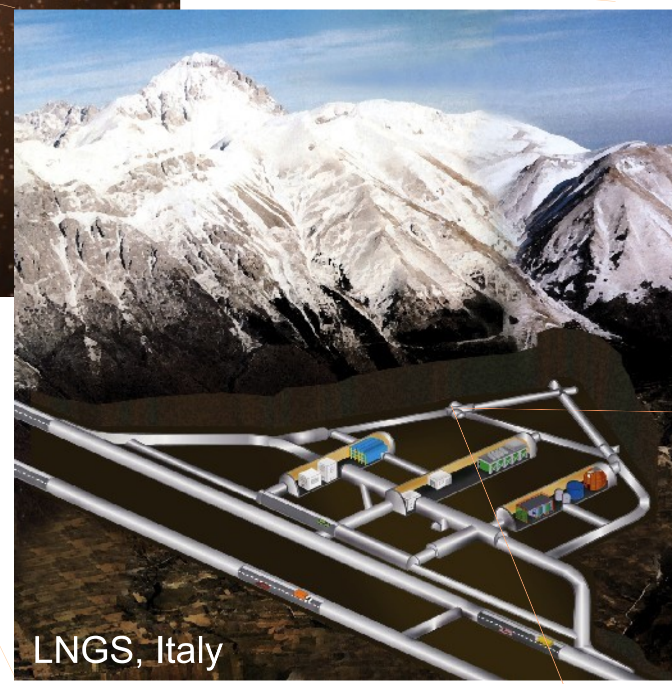
Dark Matter - Direct Searches





Rencontres de Blois 2011

02-May-2011

Uwe Oberlack

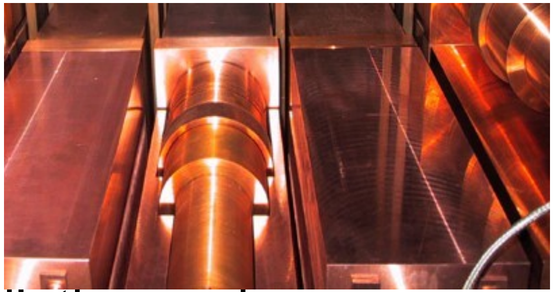
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Outline

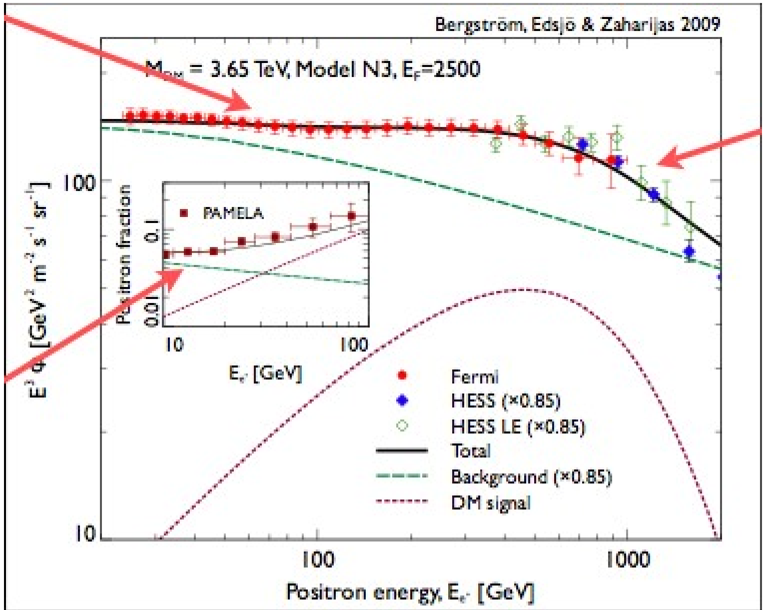
- Dark Matter Evidence & Models
- Direct Detection Technique
- Status of DM Direct Detection
  and discussion of selected experiments
- Future
- Summary

Dark Matter Detection Methods

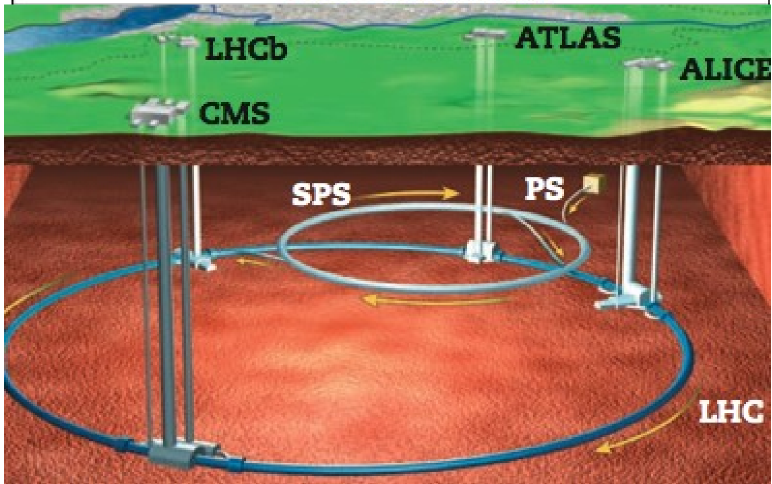
- Astrophysics / Cosmology:
  Measurement of Gravitational Effects.
  - Rotation curves of spiral galaxies
  - Orbital velocities of galaxies in clusters (Zwicky 1933)
  - Colliding clusters (Bullet cluster)
  - Large scale structure, lensing
- **Direct Detection:**
  - **WIMP scattering**
  - Axion searches, ...



- Indirect Detection: from annihilation or decay
  - Cosmic rays
    PAMELA positrons?
    Fermi, ATIC, HESS electrons? Anti-deuterons?
  - Neutrinos
  - Gamma-rays



- Accelerator-based Creation and Measurement:
  - Missing energy / momentum (+ jets + lepton(s))
  - Search for (possibly) DM-related particles
    (SUSY, extra dimensions, dark photon)

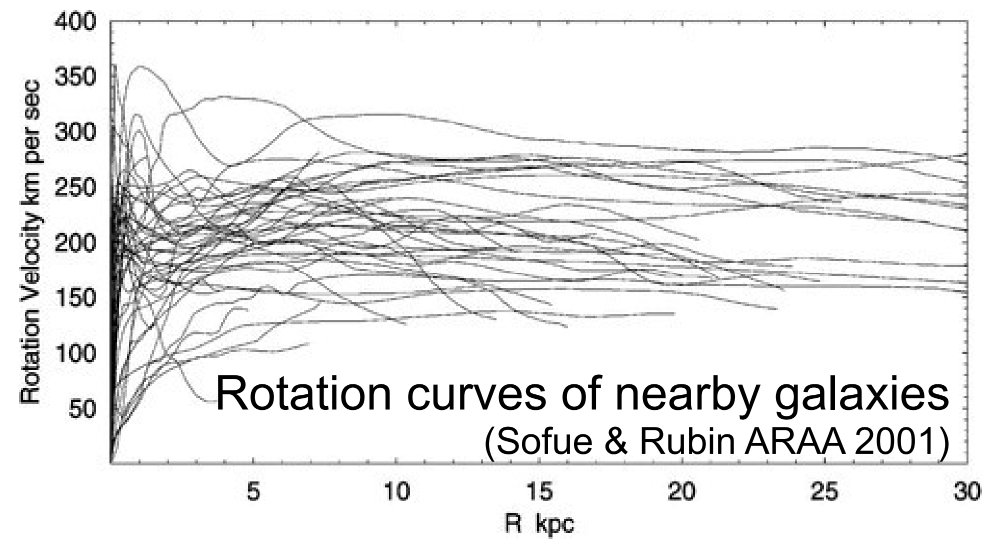


Evidence for Dark Matter
at Different Astrophysics Scales

Spiral Galaxies Scale: ~10^{21} m

Rotation curves remain flat far beyond the edge of the visible disk.

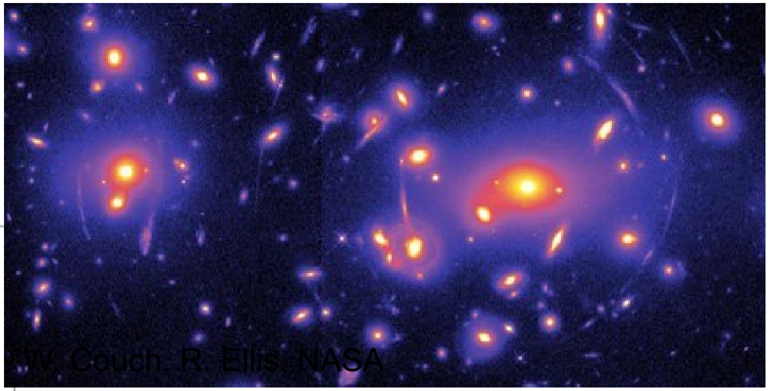
$$\left.\begin{array}{lcl} v(R) & = & \sqrt{GM(R)/R} \\ v(R) & \approx & const \end{array}\right\} \Rightarrow \left\{\begin{array}{lcl} M(R) & \propto & R \\ \rho(R) & \propto & R^{-2} \end{array}\right.$$



Rotation curves of nearby galaxies
(Sofue & Rubin ARAA 2001)

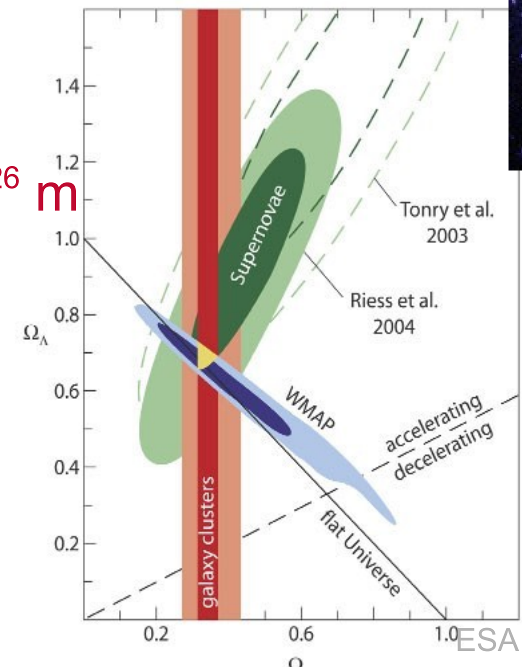
Galaxy Clusters Scale: ~10^{22} m

- Orbital velocities of galaxies (Zwicky's discovery in 1933)
- X-ray gas
- Gravitational lensing

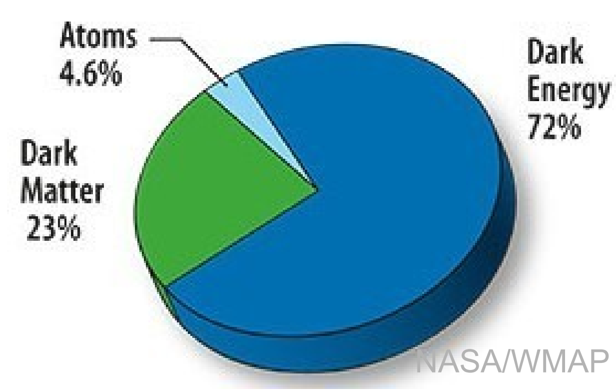

W. Couch, R. Ellis, NASA

The Dark Universe - Scale: ~10^{26} m

- CMB: Ω_{tot}=1.0
- CMB, BBN: Ω_b=0.045
- Galaxy clusters: Ω_m= 0.27
- Supernovae Ia: Ω_m - Ω_Λ
- Structure formation: cold DM



ESA

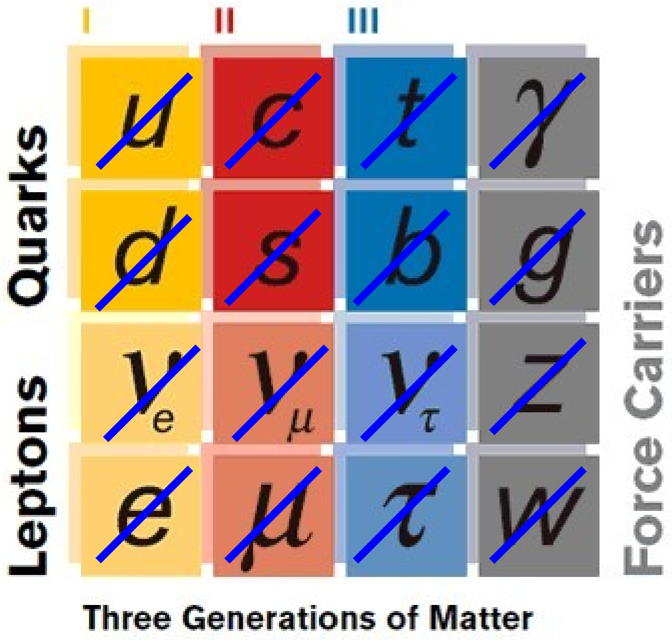


NASA/WMAP

What do we know about Dark Matter?

- Gravitationally interacting
  - How we know about Dark Matter
- Stable or long-lived
  - $\Omega_{DM} = 0.23$
- Cold or warm - not hot (relativistic)
  - Structure formation, CMB
- Non-baryonic
  - CMB, Big Bang nucleosynthesis
- Electrically neutral
  - <u>Dark</u> Matter

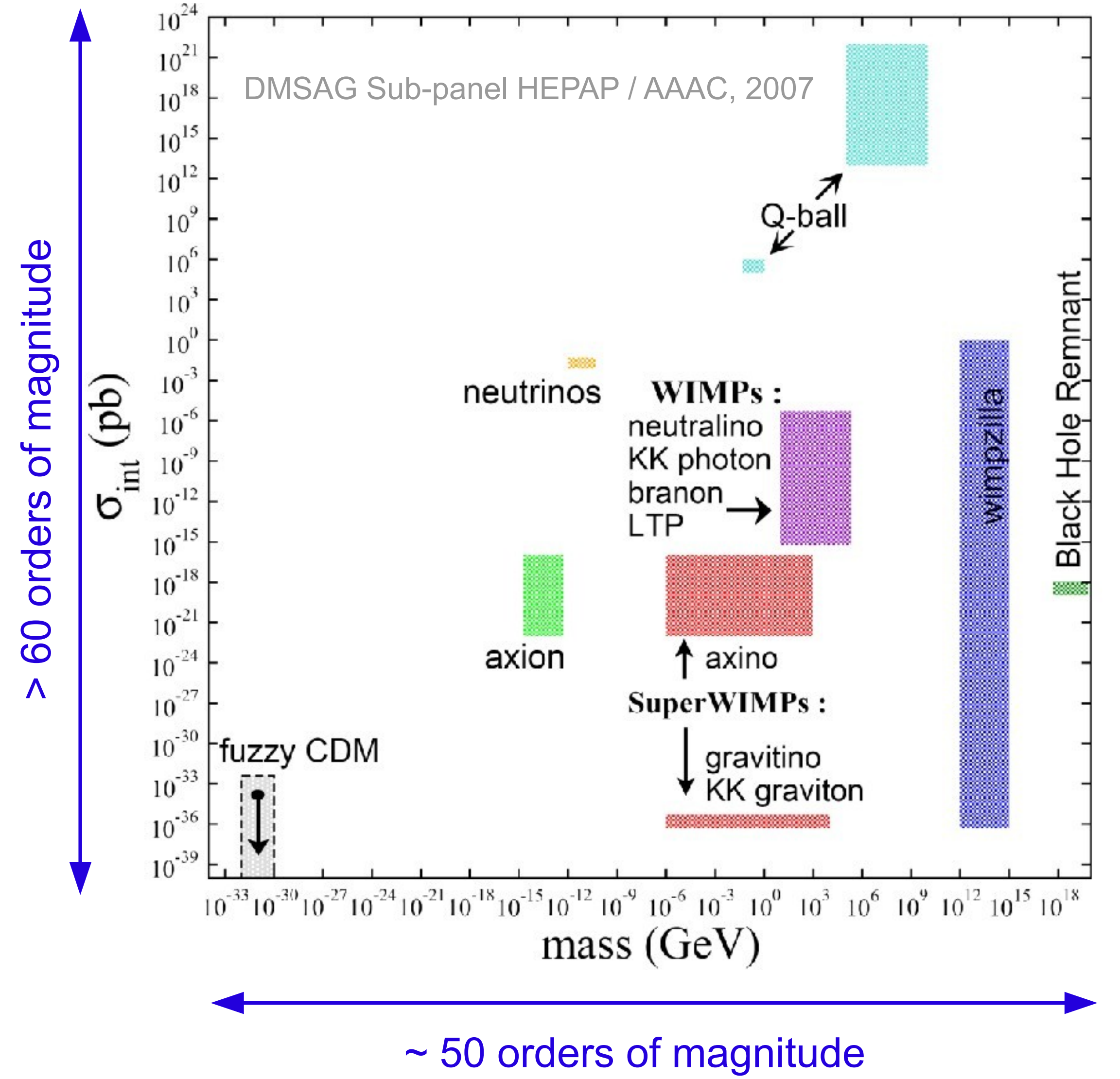
The Standard Model



Dark Matter requires physics beyond the Standard Model.

What do we know about Dark Matter?

- Gravitationally interacting
  - How we know about Dark Matter
- Stable or long-lived
  - $\Omega_{DM} = 0.23$
- Cold or warm - not relativistic
  - Structure formation, CMB
- Non-baryonic
  - CMB, Big bang nucleosynthesis
- Electrically neutral
  - <u>Dark</u> Matter
- Additional constraints from accelerator searches, direct and indirect searches.



This still leaves <u>many</u> options.

Where to start? Look for “well motivated” candidates.

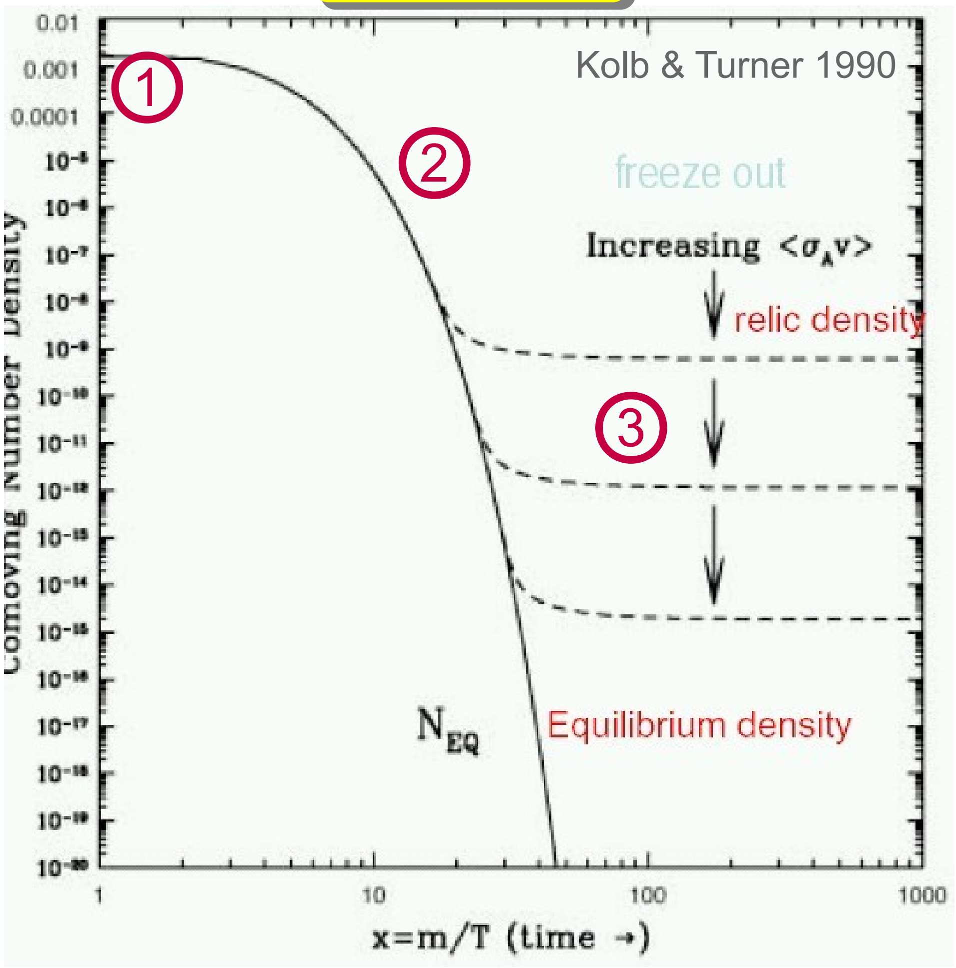
The Appeal of Weakly Interacting Massive Particles (WIMPs): A Thermal Relic at just the Right Density

$$\frac{dn_\chi}{dt} = -3\,H\,n_\chi - \langle \sigma_{\text{eff}}\, v\rangle (n_\chi^2 - n_{\chi,\text{eq}}^2)$$

Decrease due to universe expansion

Boltzmann equation

$$\chi + \chi \leftrightarrow 2\gamma$$
$$\chi + \chi \leftrightarrow f + \bar{f}$$



① $kT >> m_\chi c^2$: equilibrium of WIMP pair creation and annihilation

② $kT < m_\chi c^2$: WIMP creation suppressed by factor $\exp(-kT/m_\chi c^2)$.

③ **Weakly Interacting**: **freeze out** when annihilation rate drops below expansion rate:

$H > \Gamma_{ann} \sim n_\chi \langle\sigma_a v\rangle$

results in **relic density**: $\Omega_\chi h^2 \approx \frac{10^{-27} cm^3 s^{-1}}{\langle \sigma_a v \rangle}$

If m_χ and σ_a related to the electroweak scale

=> $\Omega_\chi h^2 \sim O(0.1)$ ✓

"WIMP miracle"

Massive particles: average WIMP velocity is non-relativistic.

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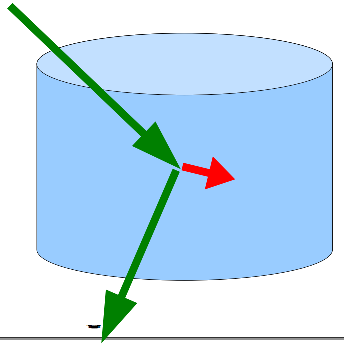
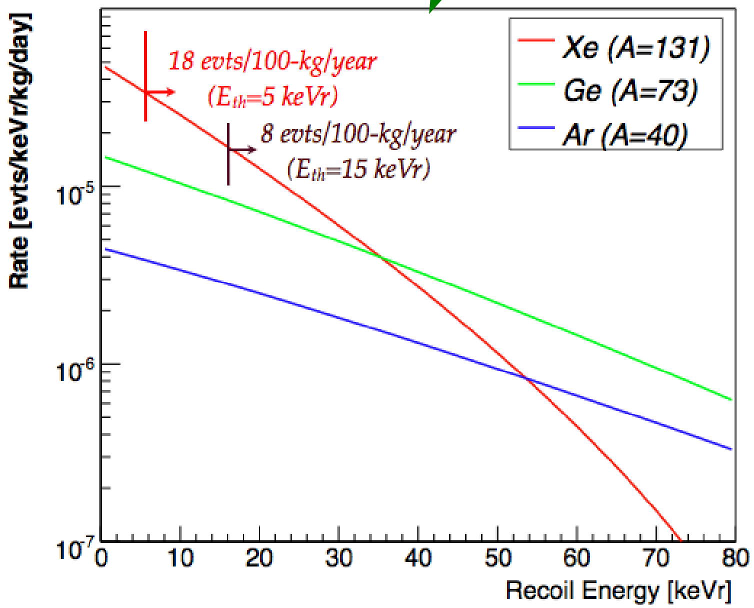
WIMP Dark Matter Direct Detection



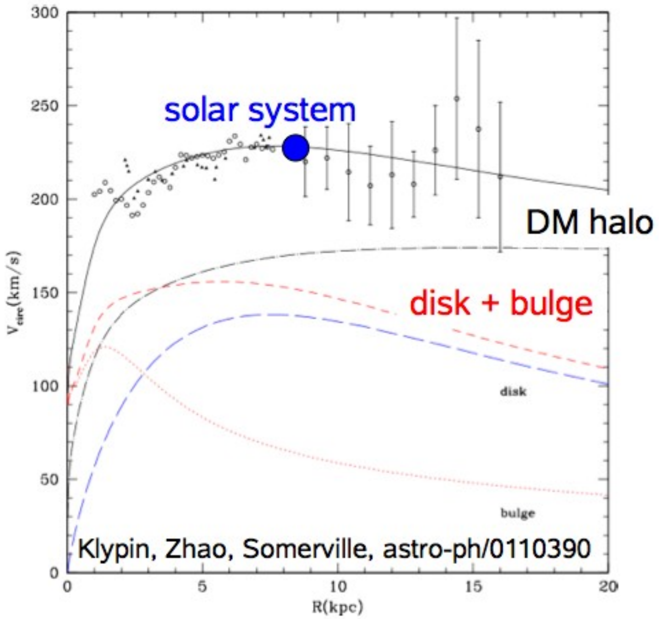
- Scattering of WIMPs χ off of nuclei A.
  - elastic or inelastic?
  - spin-independent (~A^2) or spin-dependent?
- Energy spectrum:

$$\frac{dR}{dE} = \frac{\rho_\chi \sigma_s}{2 m_\chi \mu^2} |F(E)^2| \int_{v_{min}}^{v_{esc}} \frac{f(\mathbf{v}, t)}{v} d^3 v$$

$$f(\mathbf{v}, t) \propto \exp\left(\frac{-(\mathbf{v} + \mathbf{v}_E(t))^2}{2\sigma_v^2}\right)$$



  - m_χ ~ 10 - 10^4 GeV/c^2, $\mu = (m_\chi m_n)/(m_\chi + m_n)$
  - v_χ ~ 230 km/s
  - "Standard" spherical halo: Featureless recoil spectrum <E> ~ O(10 keV)
  - ρ_χ/m_χ: local number density of WIMPs
  - ρ_χ ~ 0.3 GeV/c^2/cm^3, $\rho_\chi/m_\chi \lesssim$ 10 / L
  - σ_s cross section per nucleus.



Typical rate < 10^{-2} events / kg / day

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 very good β and γ background discrimination.
- Shielding: low-activity lead, water, noble liquids (active), liquid N_2, ...

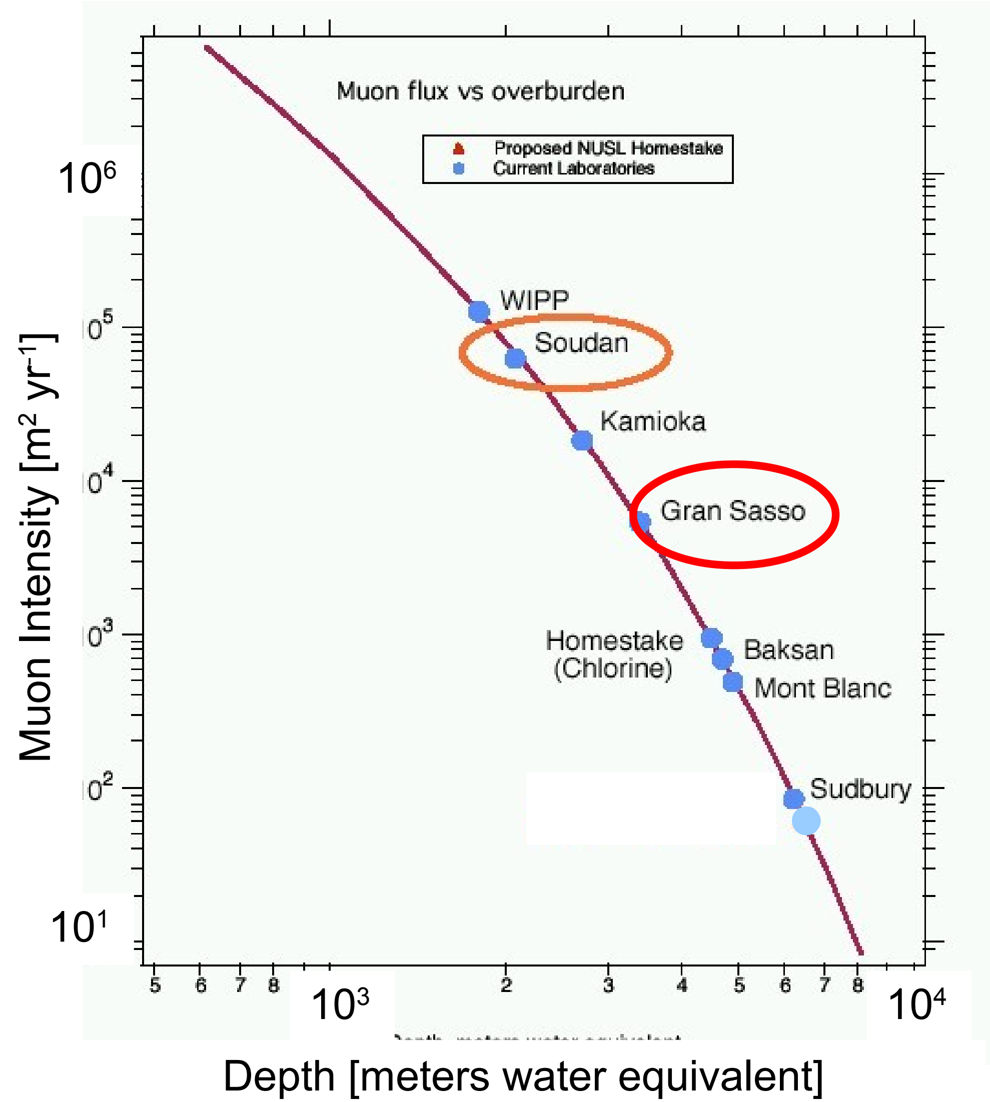
Neutrons from (α, n) and spontaneous fission (concrete, rock, etc.):

- ~ 1 event/kg/day (LNGS)
- Neutron moderator (polyethylene, paraffin, ...)

Neutrons from CR muons:

- Rate depending on depth.
- μ-veto, n-veto, shielding

α decays from Rn daughters, ...



DM Detector Overview
Detection Principles

Bubble Formation
COUPP, PICASSO

Tracking
Drift, DM-TPC, NIT

Ionization
CoGeNT

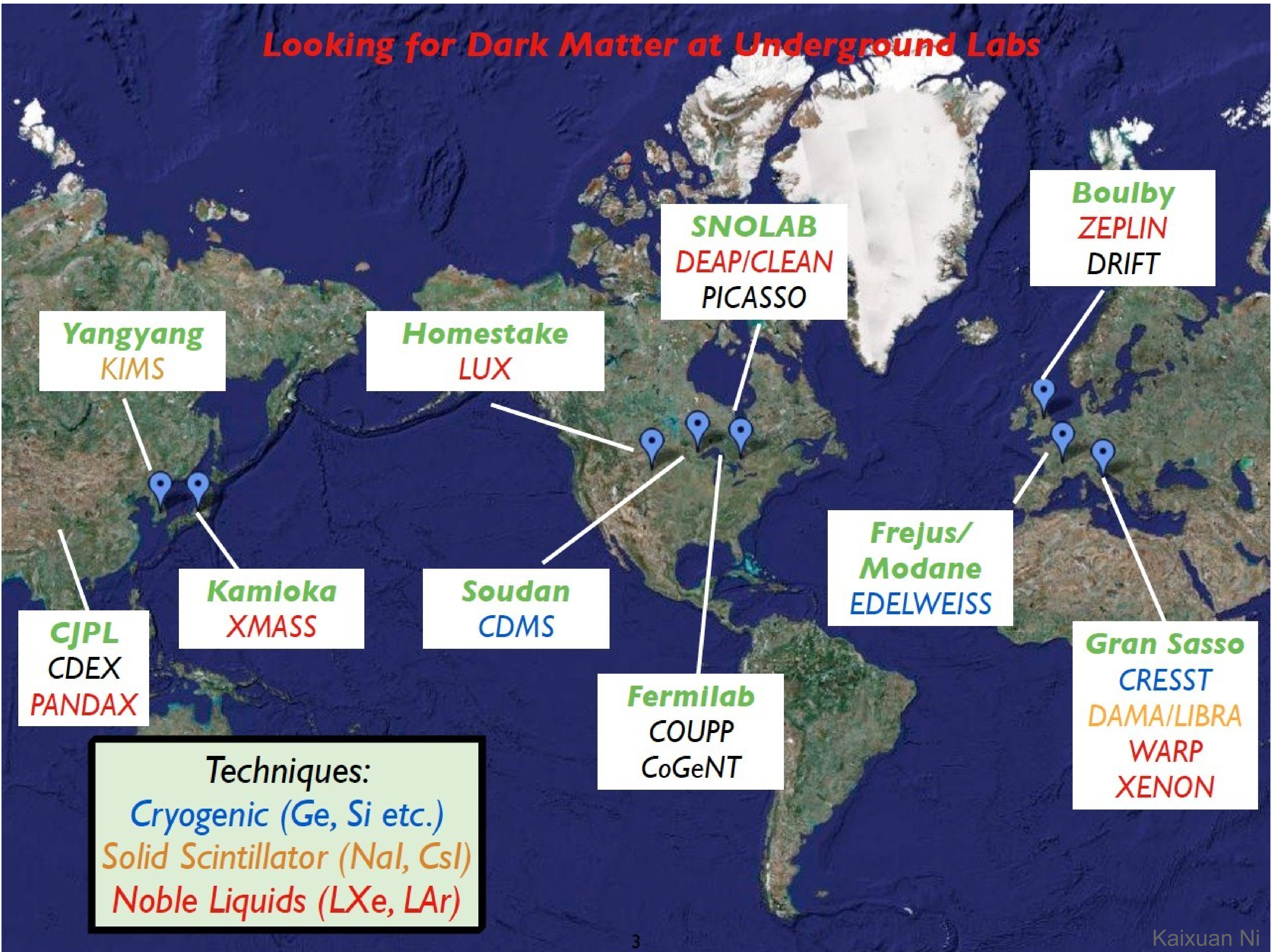
CDMS-II, Super-CDMS
EDELWEISS-II

LAr: WARP, ArDM
LXe: **XENON**, LUX, Zeplin

Phonons

CRESST-II,
ROSEBUD,
EURECA

Scintillation
DAMA/LIBRA
KIMS, XMASS,
DEAP/CLEAN


Looking for Dark Matter at Underground Labs
Boulby
ZEPLIN
DRIFT
SNOLAB
DEAP/CLEAN
PICASSO
Yangyang
KIMS
Homestake
LUX
Frejus/
Modane
EDELWEISS
CJPL
CDEX
PANDAX
Kamioka
XMASS
Soudan
CDMS
Gran Sasso
CRESST
DAMA/LIBRA
WARP
XENON
Fermilab
COUPP
CoGeNT
Techniques:
Cryogenic (Ge, Si etc.)
Solid Scintillator (NaI, CsI)
Noble Liquids (LXe, LAr)
Kaixuan Ni

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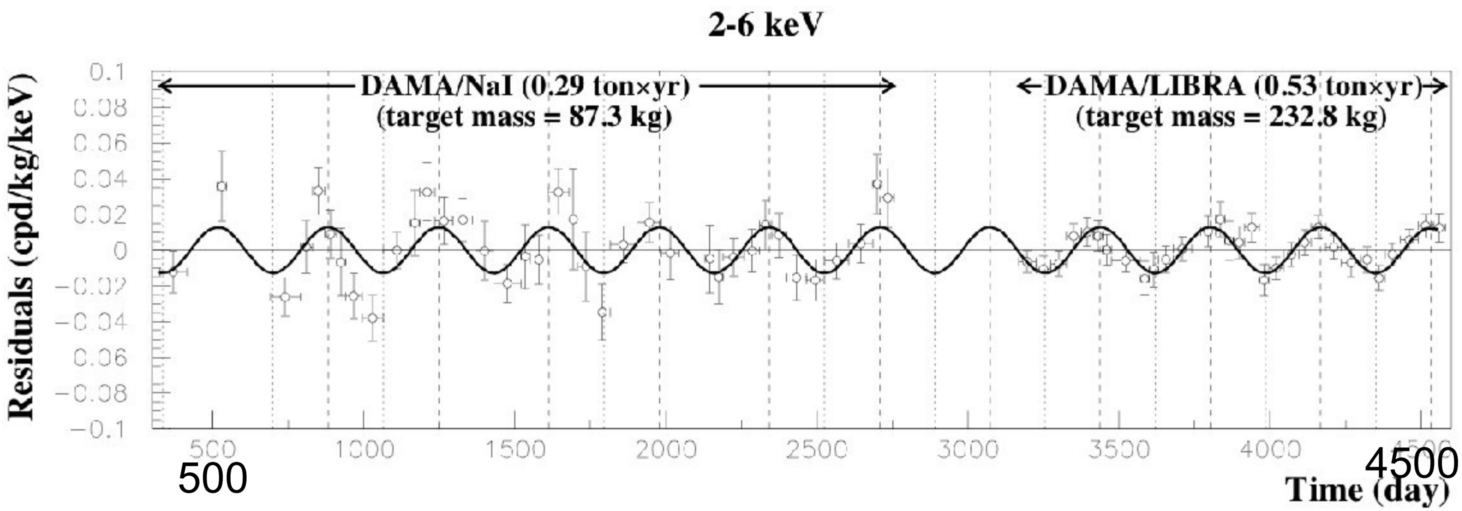
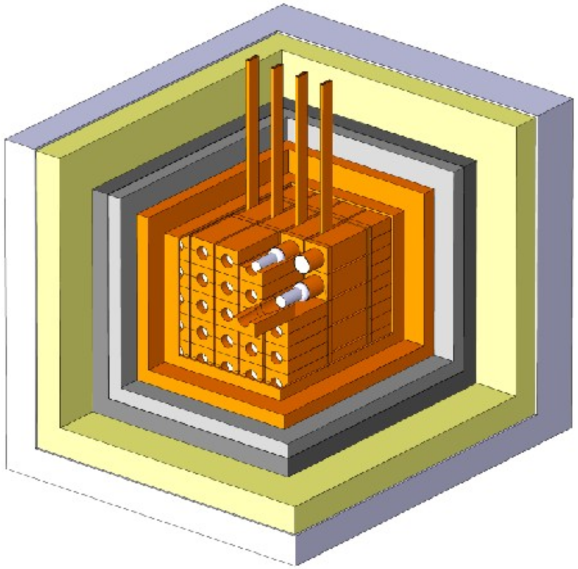
Part 1: Signals ?

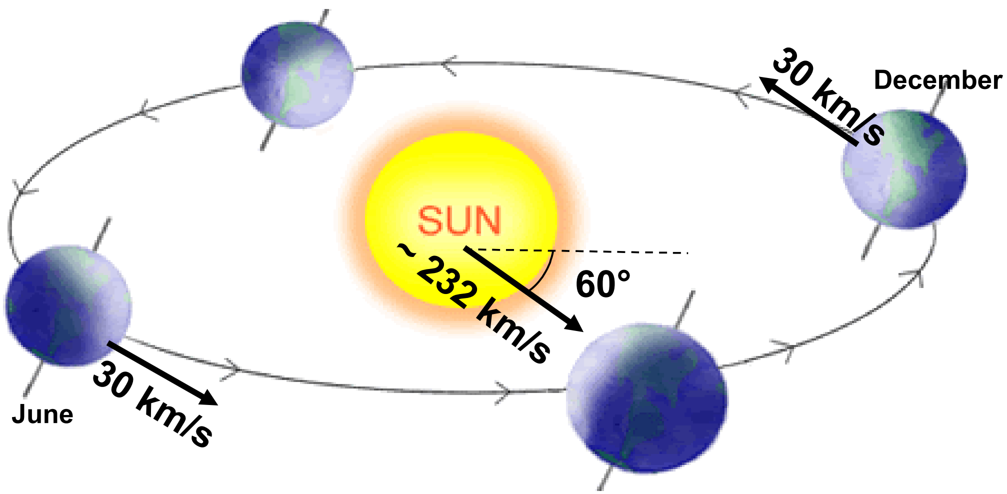
DAMA/LIBRA Annual Modulation

R. Bernabei et al. arxiv:0804.2741, arxiv:1002.1028





- ~250 kg of NaI counters
- 1.17 ton-year exposure (2010)



Drukier, Freese, Spergel PRD 86
Freese et al. PRD 88

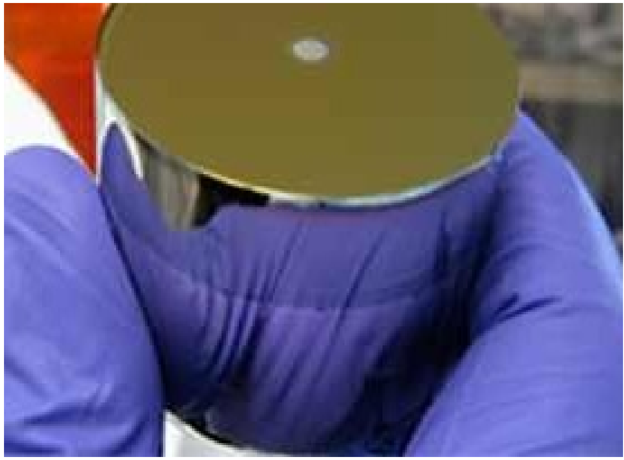
- Modulation in 2-6 keV single hits: 8.9 σ
- Mostly in 2-4 keV, ~0.02 cts/d/kg/keV
- Total single rate ~1 cts/d/kg/keV
- Standard DM distribution: ~5% modulation
- Period & phase about right for DM.
- No annual modulation in 6-14 keV.
- No annual modulation in multiple hits. (statistics?)
- **DM detection?**
- Conflict with other experiments in standard scenarios that test the larger steady state effect!

Low Mass WIMPs?
Inelastic Dark Matter?
Luminous DM?

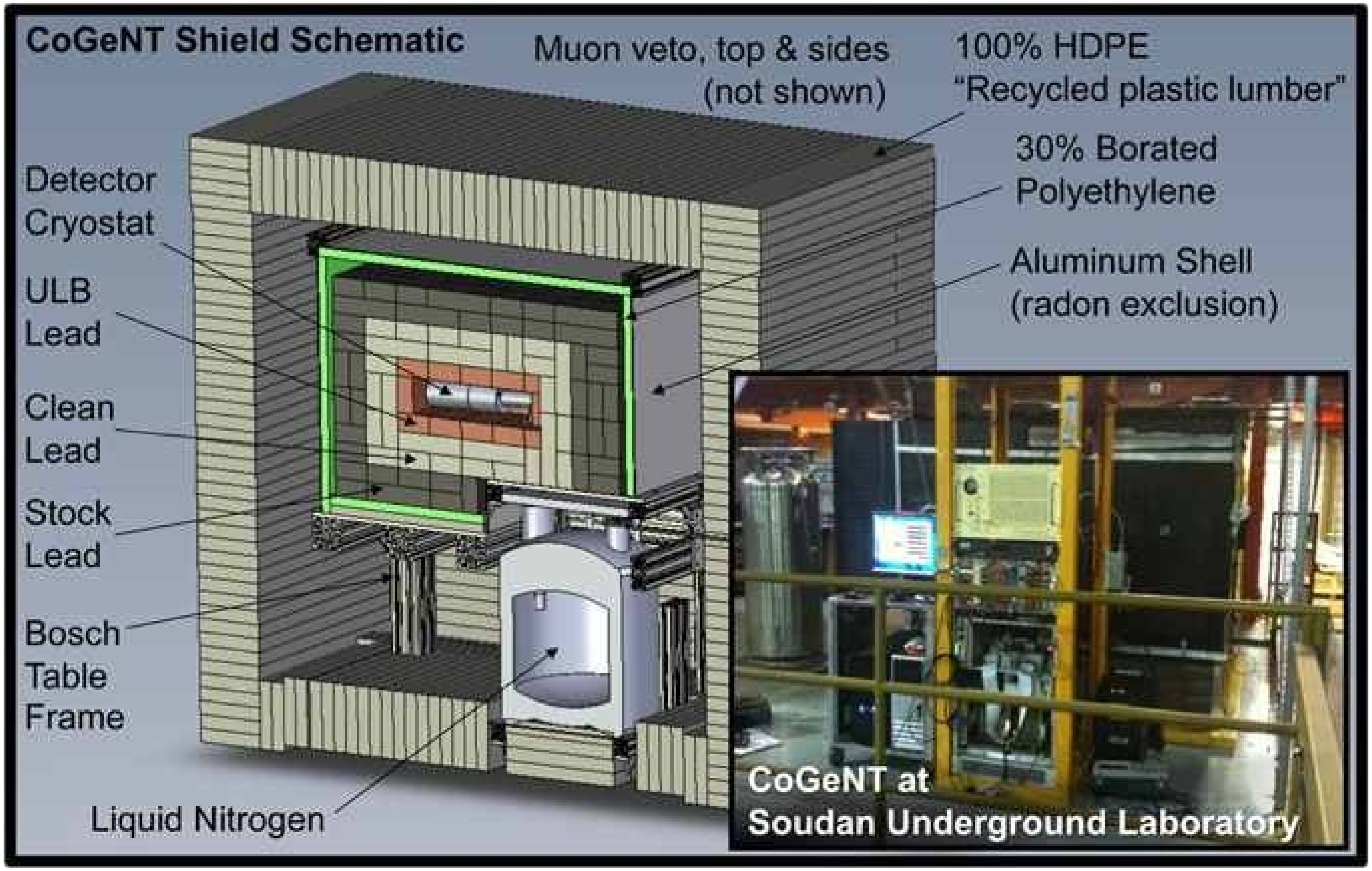
…

… or some yet to be understood detector or background effect?

CoGeNT: What are these excess events?

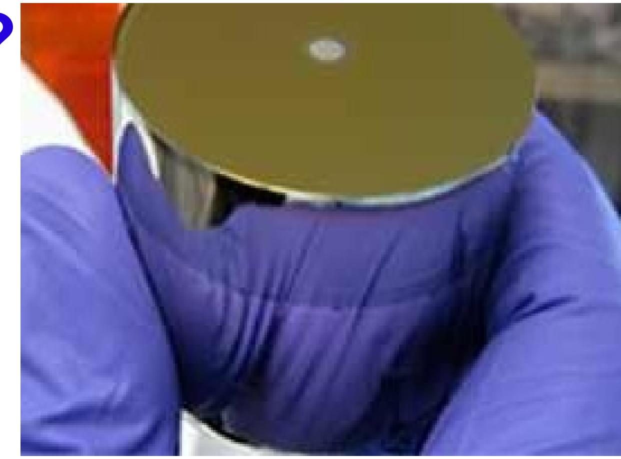


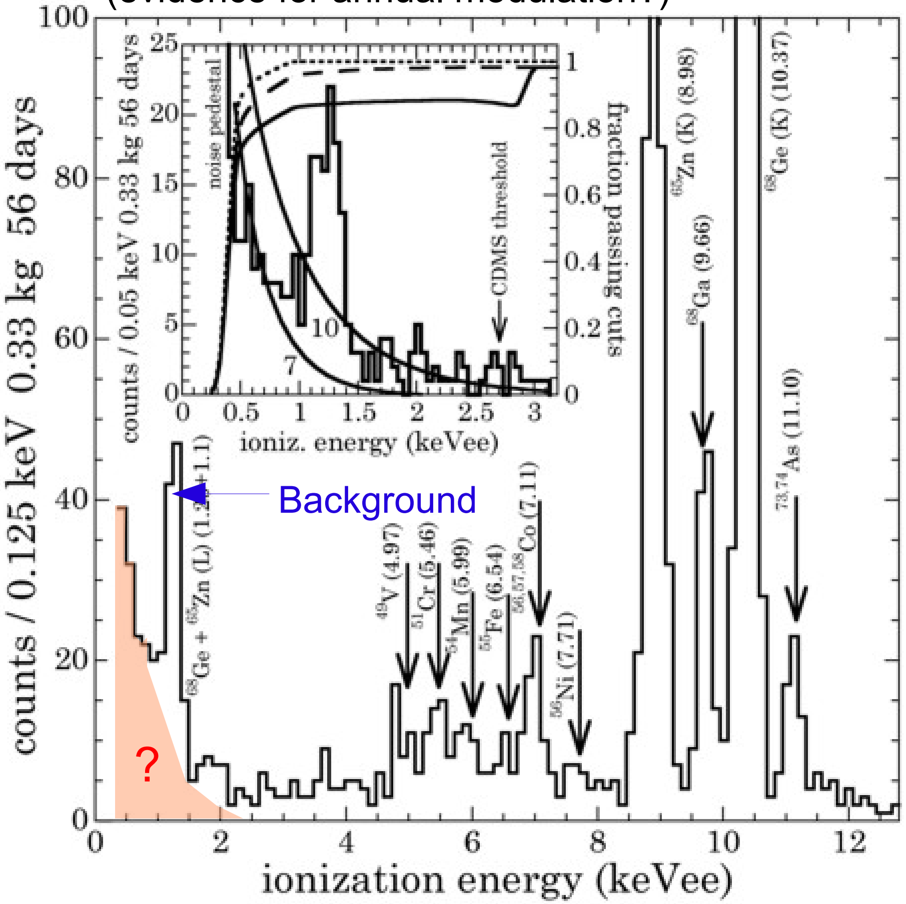
- Single P-type point contact (PPC) Germanium detector:
  - 440 g mass, 330 g fiducial (CDMS: 250 g per detector)
  - Low electronic noise, hence low threshold (0.4 keVee)
- Located in Soudan mine (2100 mwe)
- Passive shield + Muon veto

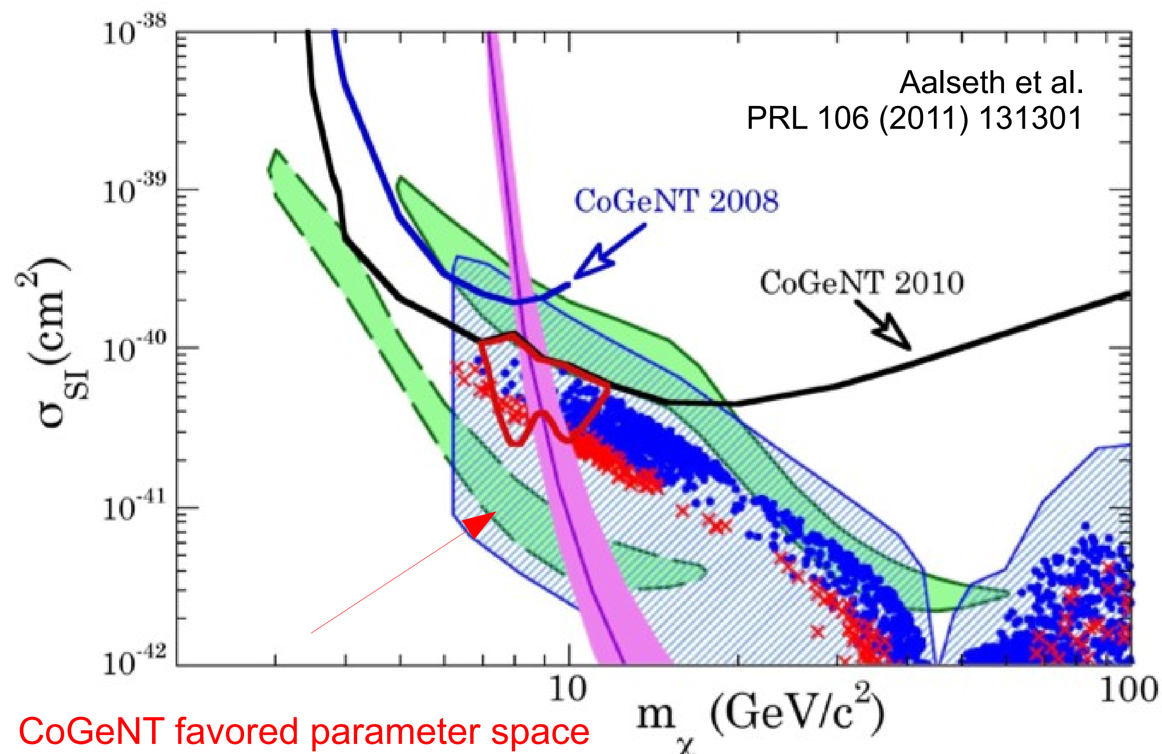


CoGeNT: What are these excess events?

- Single P-type point contact (PPC) Germanium detector:
  - 440 g mass, 330 g fiducial (CDMS: 250 g per detector)
  - Low electronic noise, hence low threshold (0.4 keVee)
- Located in Soudan mine (2100 mwe)
- Passive shield + Muon veto
- Exposure: 18.5 kg d
  - Data meanwhile available: 145 kg d
    (evidence for annual modulation?)







CoGeNT favored parameter space
if excess is interpreted as SI WIMP
scattering

Low Mass WIMPs?

…

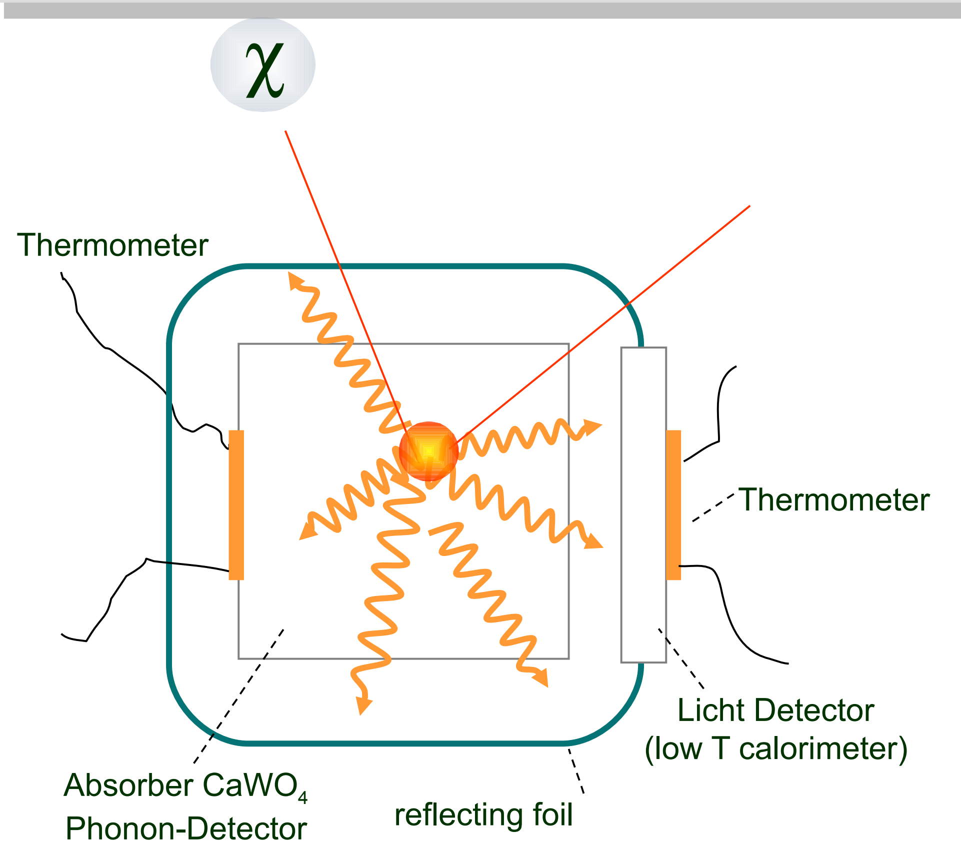
… or some yet to be understood detector or background effect?

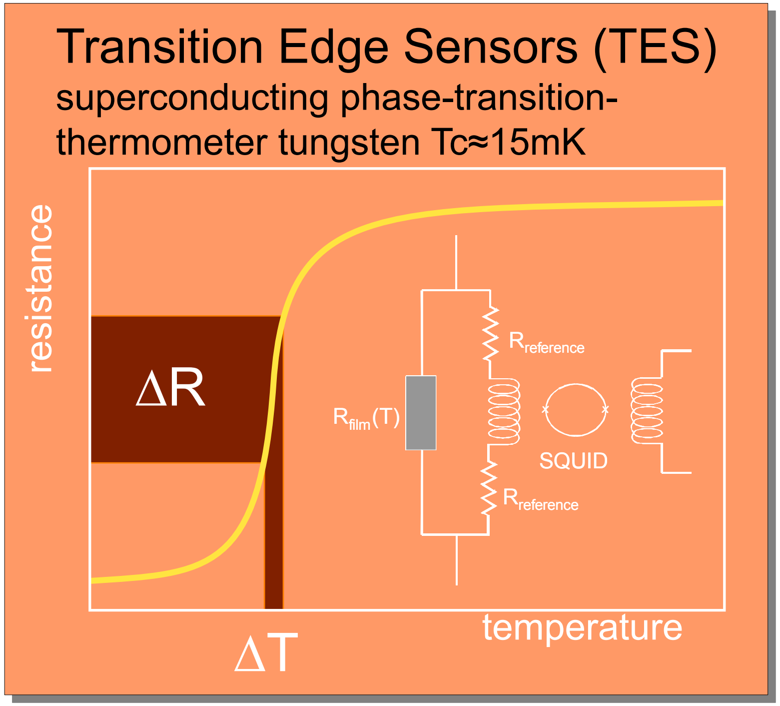
CRESST II: Phonons + Scintillation

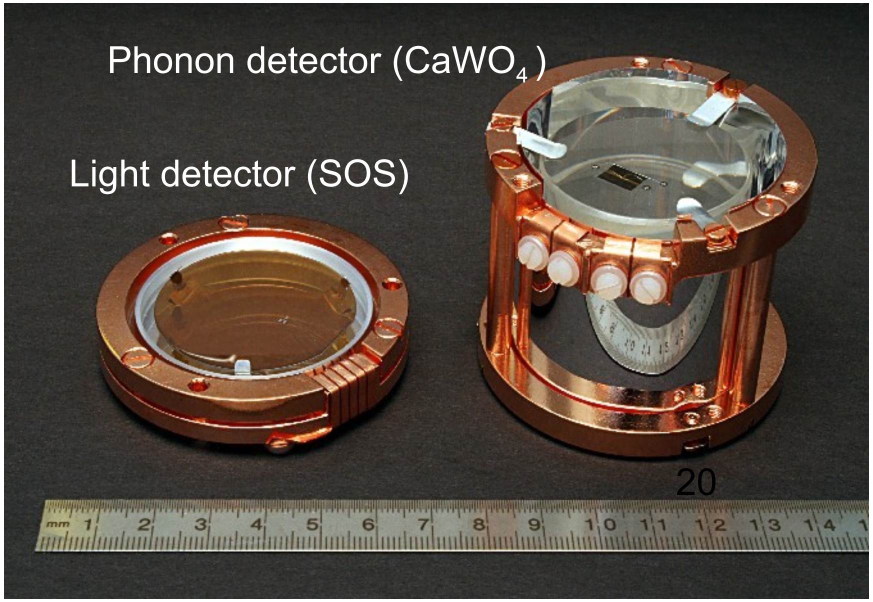
CRESST
Cryogenic Rare Event Search with Superconducting Thermometers

light + phonons (scintillating crystals)

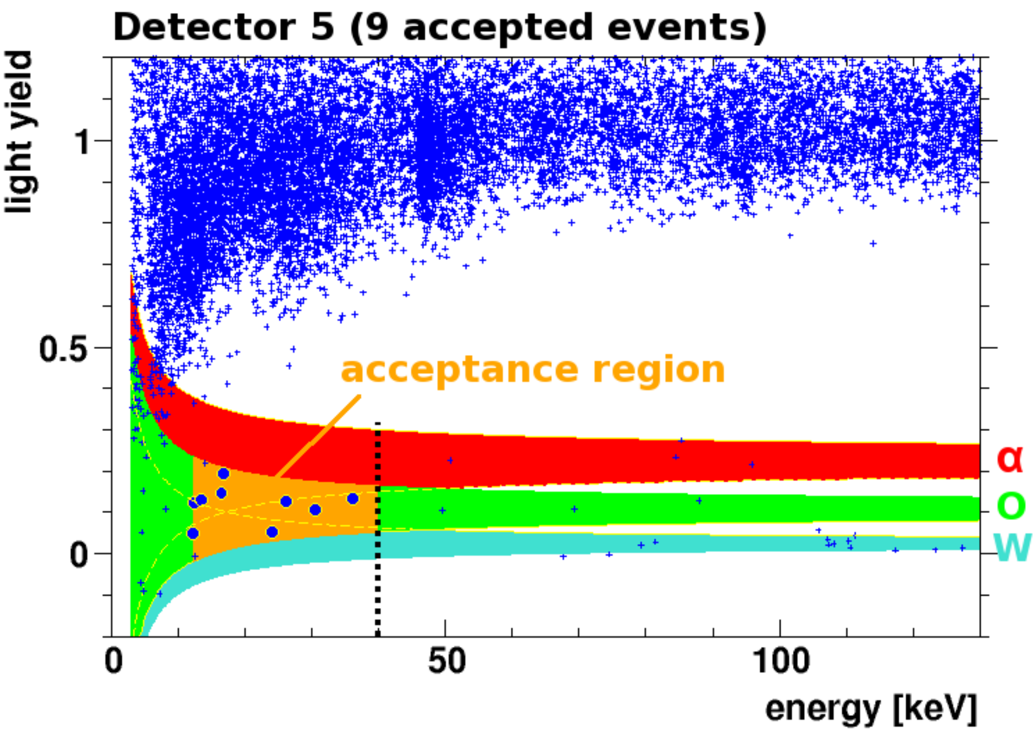
Max-Planck-Institut München, TU München
Universität Tübingen, Oxford University, Gran Sasso

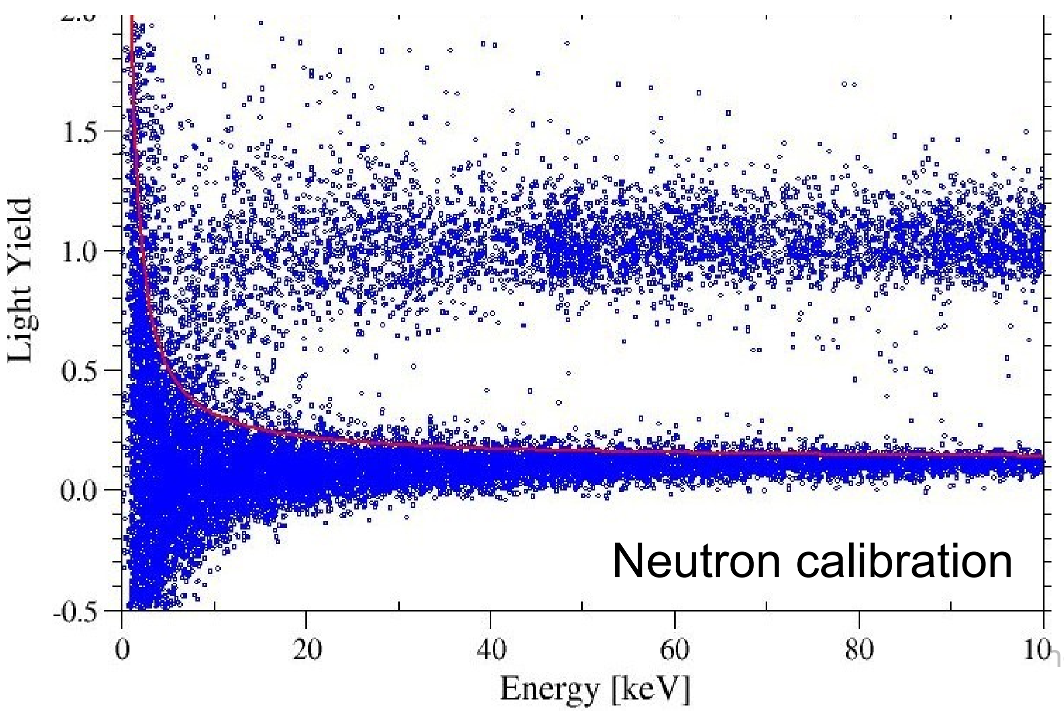






CRESST II: What are these excess counts?



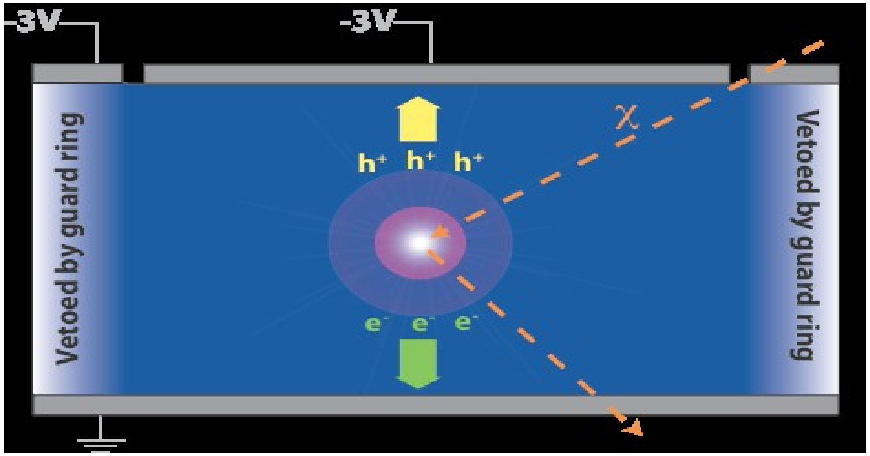


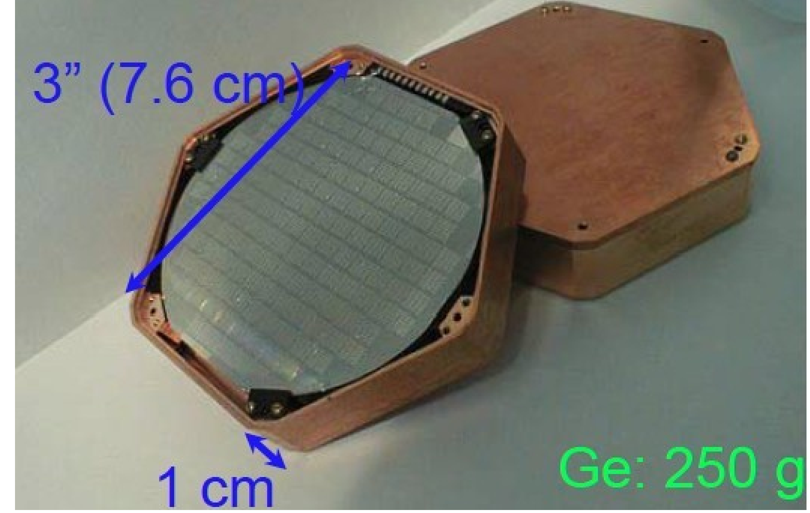
- Data from 9 $CaWO_4$ detectors
- Exposure: 730 kg d
- 57 events observed in O-band (in allen Detektoren)
- Acceptance region (detector specific): O-band in ~10-40 keV

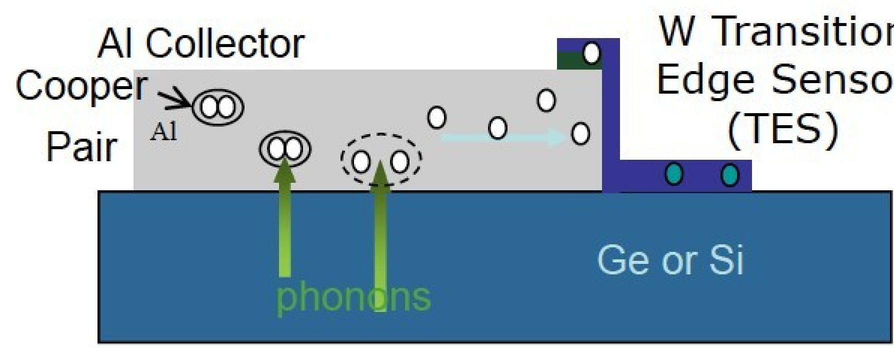
- Background estimated from sidebands:
  - α-events: 9.3
  - neutrons (generate mostly O-recoils): 17.3
  - e/γ leakage: 9.0
- Excess events not explained by modeled background: 4.6 σ (?)
- Hint of low-mass WIMPs?
  - best fit: $M_\chi \sim 13$ GeV/c^2, $\sigma \sim 3\times10^{-5}$ pb $= 3\times10^{-41}$ cm^2
  - confidence region?
- Systematic background uncertainty?
- Further background reduction planned.

Part 2: Limits

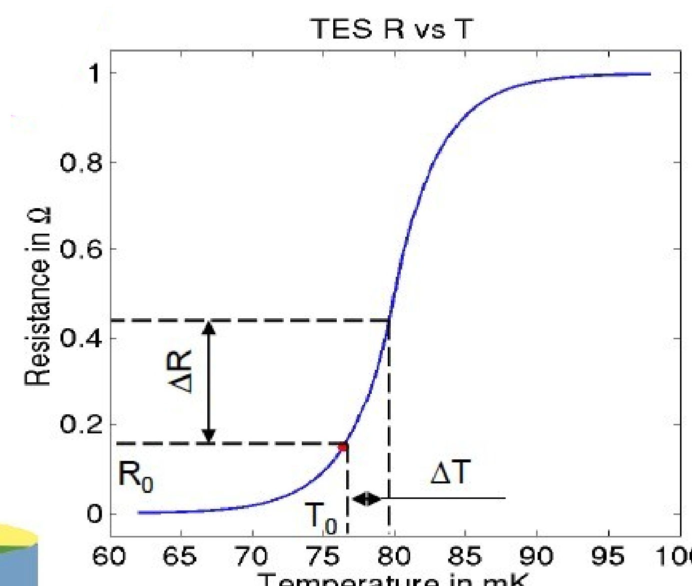
CDMS-II: Phonons + Charge
(Cryogenic Germanium)





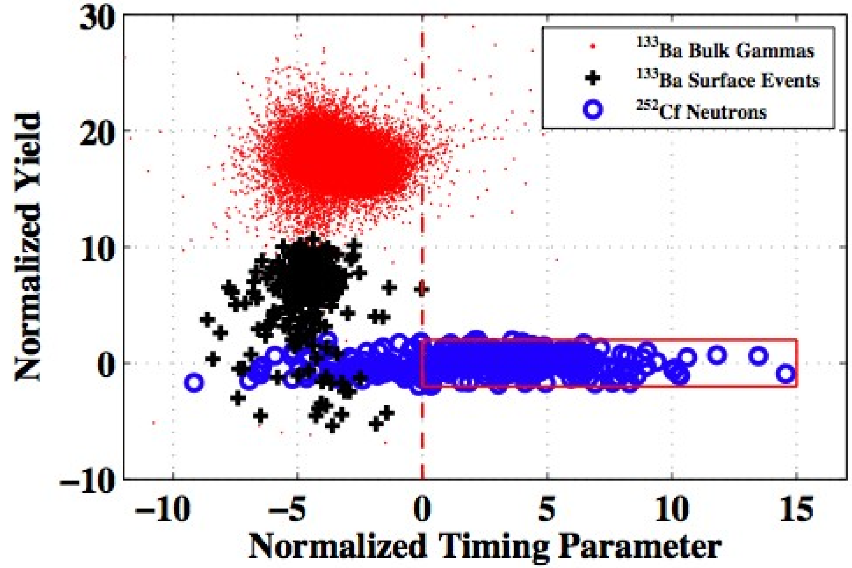


- Located at Soudan mine (Minnesota)
- Ge crystals operated at ~40 mK
- Fast phonon read-out with Tungsten Transition-edge sensors (TES)
  - direct measurement of nuclear recoil energy
  - SQUID Readout
- Low-voltage drift for charge read-out
  - e.m. background suppression with charge / phonon ratio
- Suppression of surface events with phonon timing signal

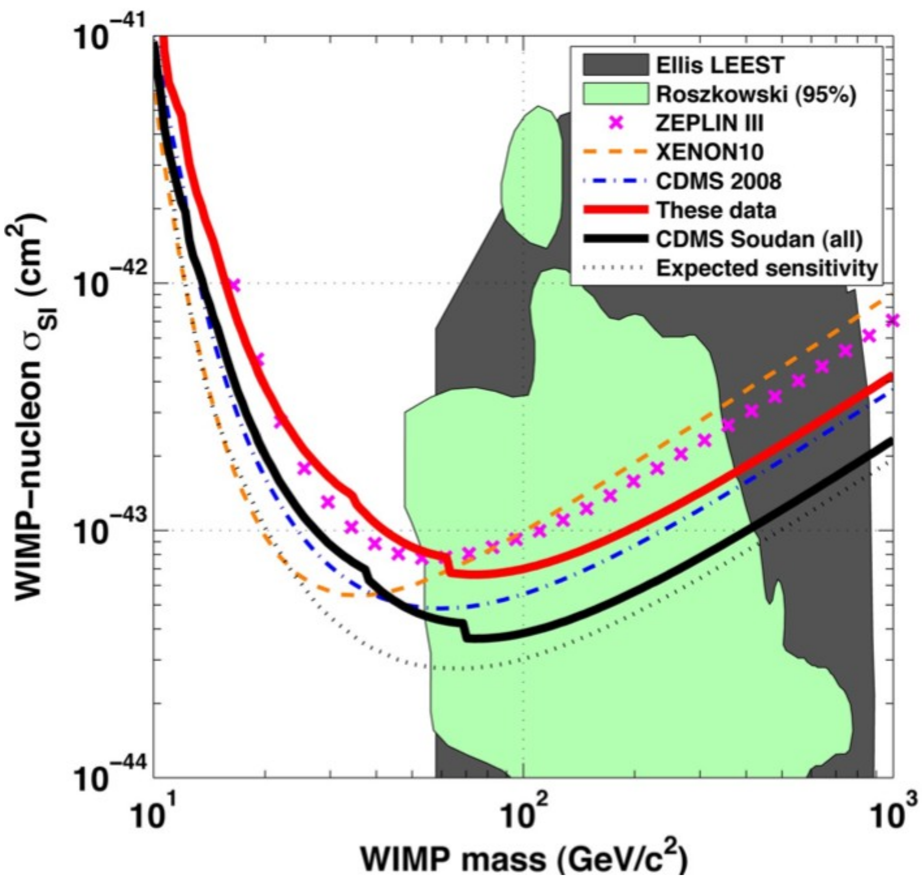


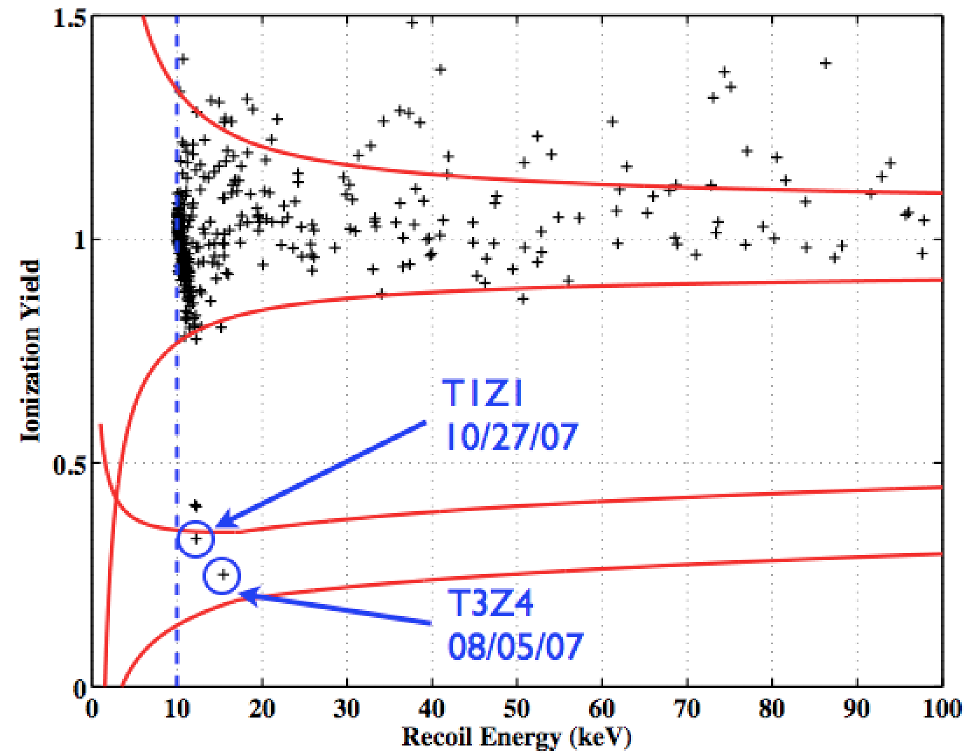
CDMS-II
Spin-Independent Limit

- 2 events observed after all cuts.
- Pre-opening background estimate: 0.6 events
- Revised estimate: 0.8 +/- 0.1 events
- 23% chance for background.
- CDMS-II completed.
- Next phase: Super-CDMS (15 kg) at Soudan mine construction and first operation in parallel



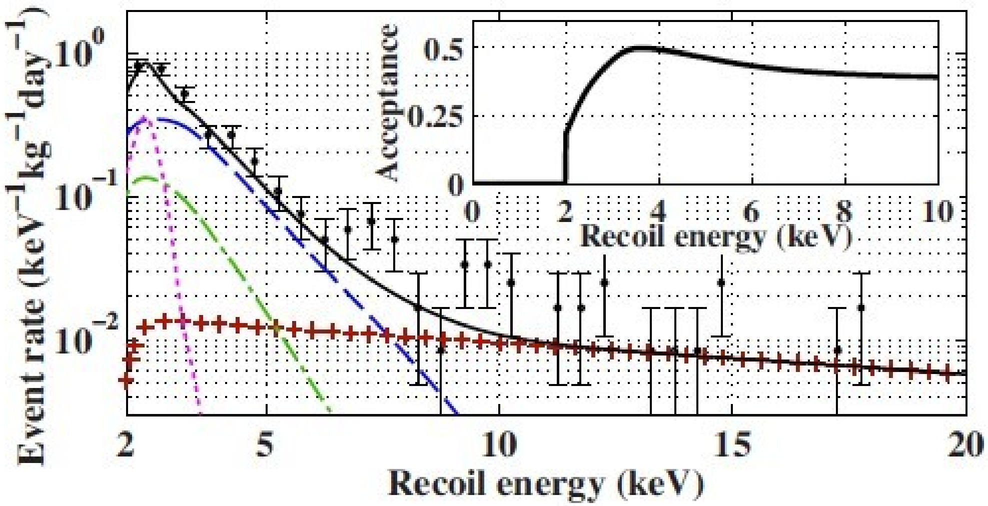
Science 327, Issue 5973, 1619 (2010)

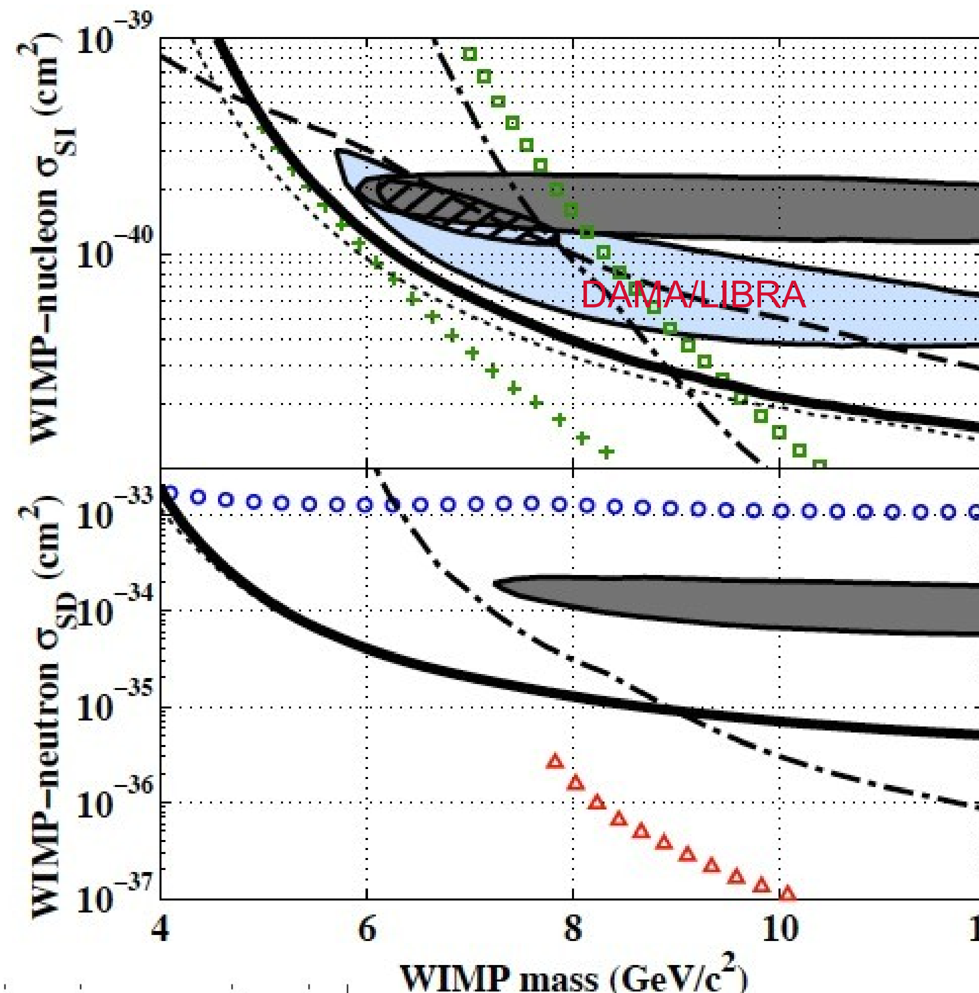




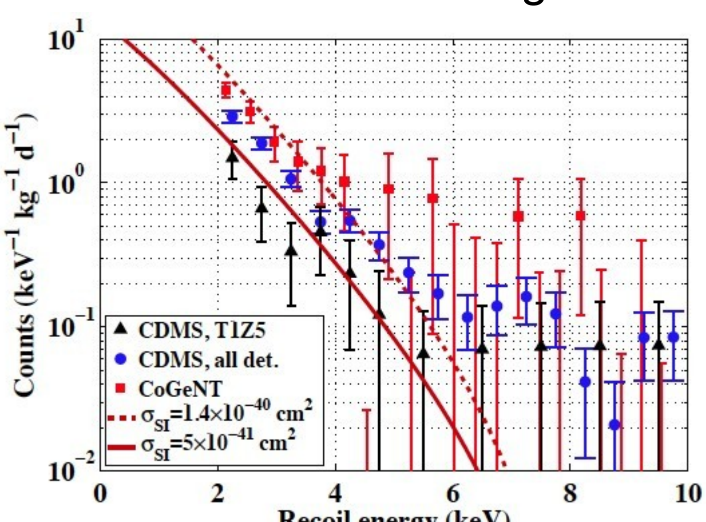
CDMS Low Threshold Limit

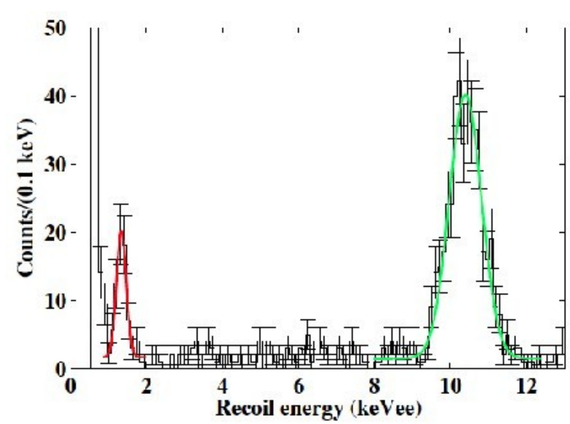
PRL 106, 131302 (2011), arXiv:1011.2482





- Strong tension with low mass WIMP interpretation of CoGeNT & DAMA/LIBRA results
- Discussion about background subtraction



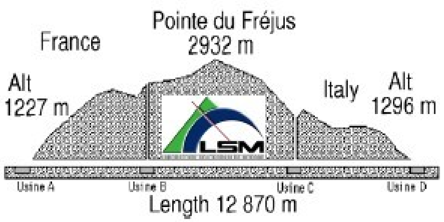


Edelweiss-2

(Phonons + Charge: Cryogenic Ge)

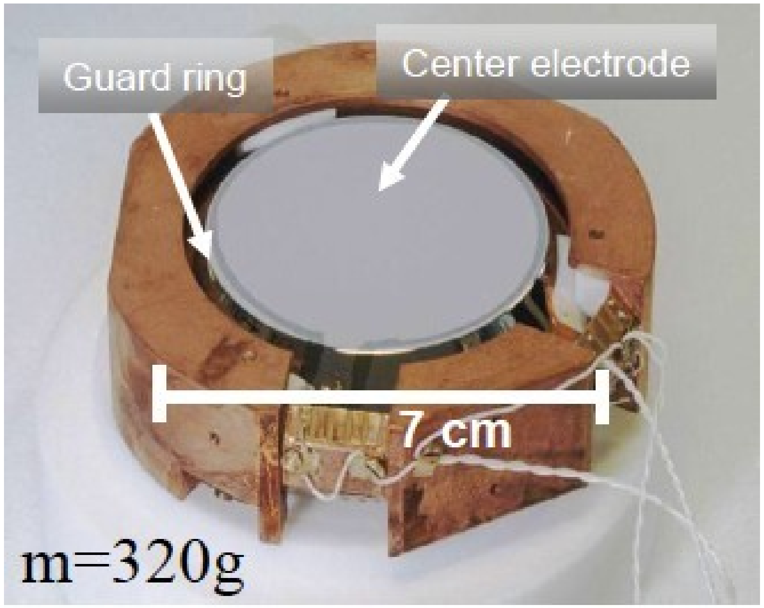
EDELWEISS
Experience pour DEtecter Les Wimps En Site Souterrain
CEA, CNRS, Oxford, Dubna, Sheffield, Karlsruhe

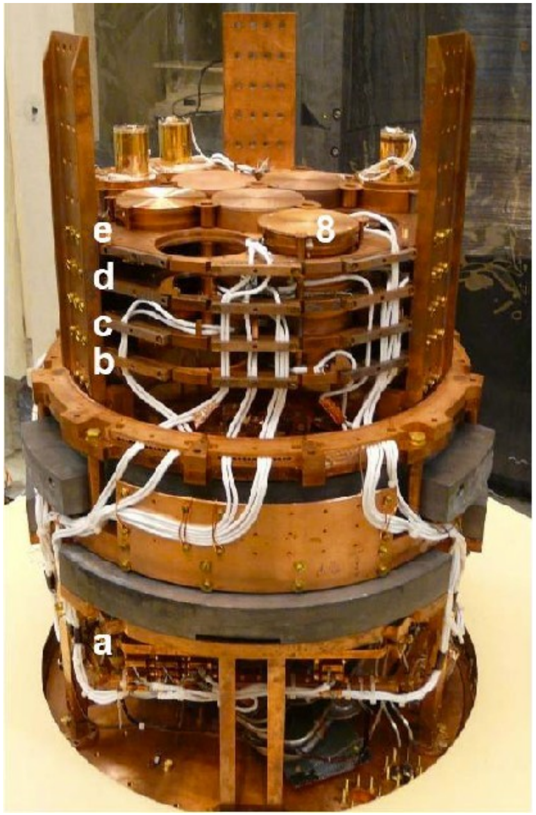
- Simultaneous measurement
  - Heat @ 18 mK
    with Ge/NTD (neutron transmutation doped) thermometer
  - Ionization @ few V/cm
    with Al electrodes
- Event by event identification of recoil type by ratio Ionization / E_{recoil}

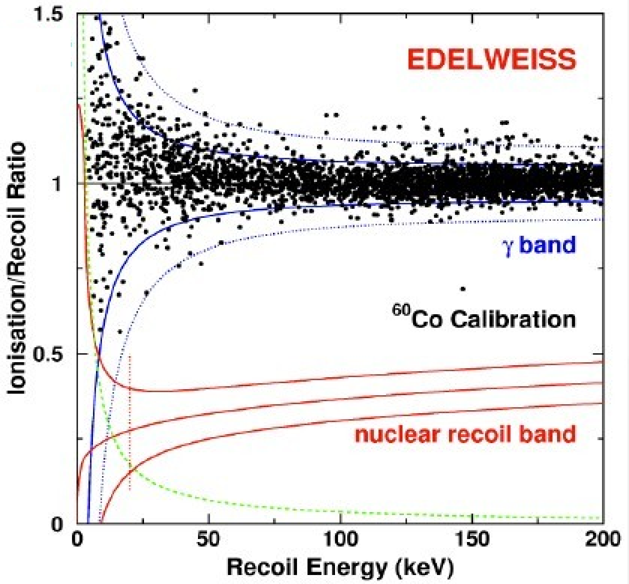


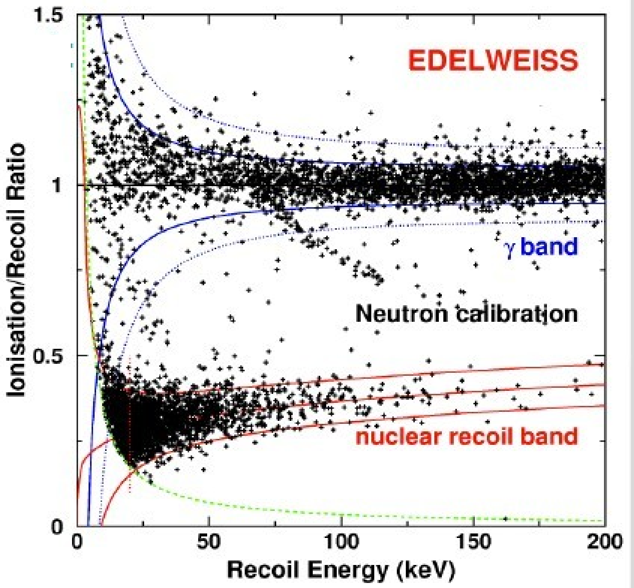
Shielding: ~ 4800 mwe

μ-flux: ~ 5 / m² / day



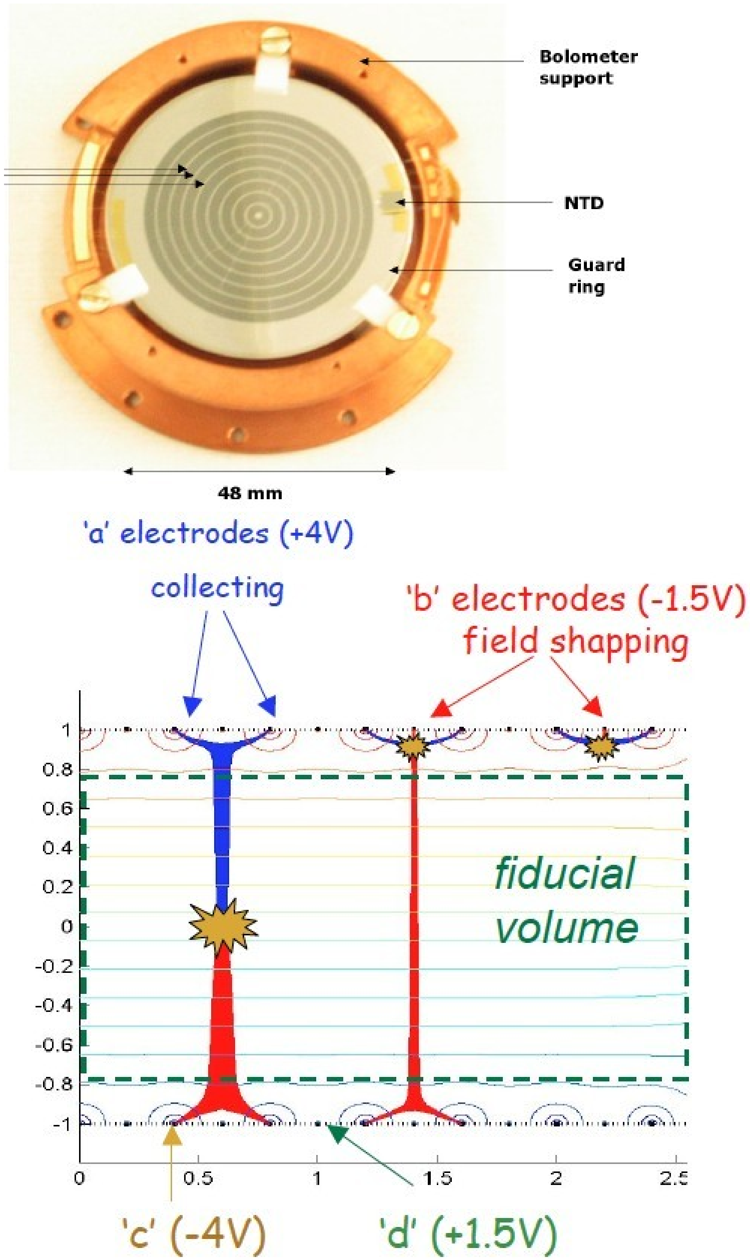


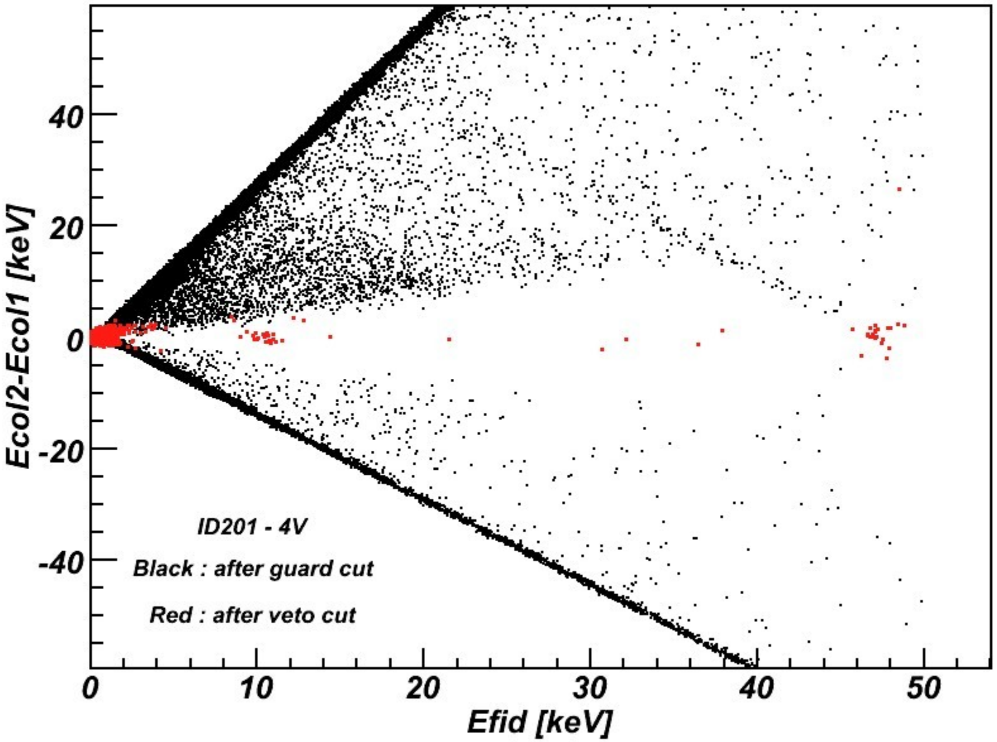




Edelweiss-2 – Interleaved Electrodes

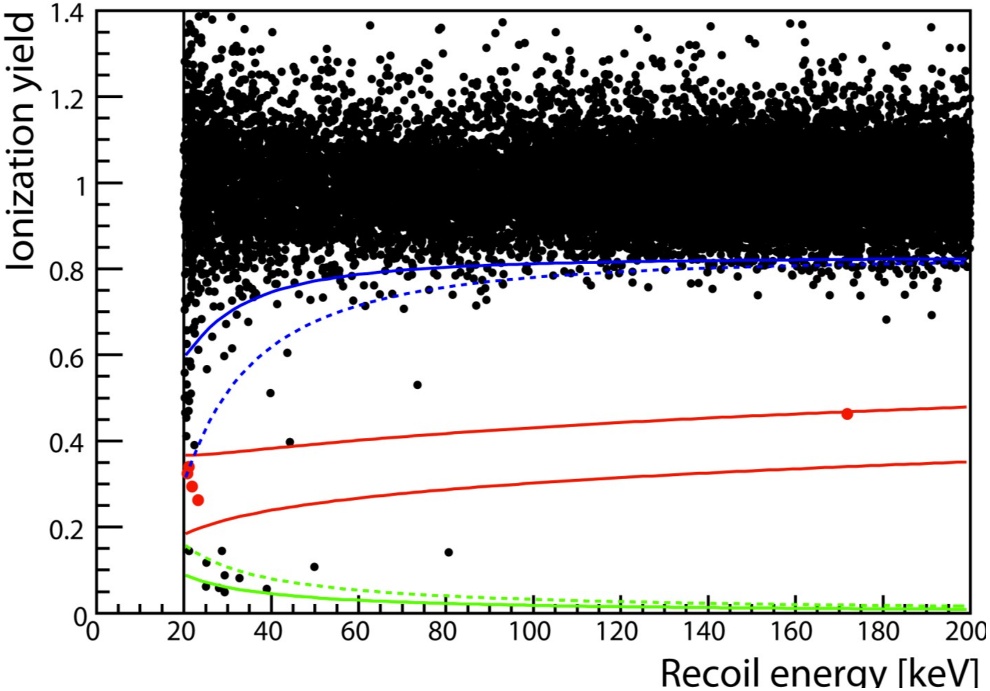
PLB 681 (2009) 305-309
[arXiv:0905.0753]

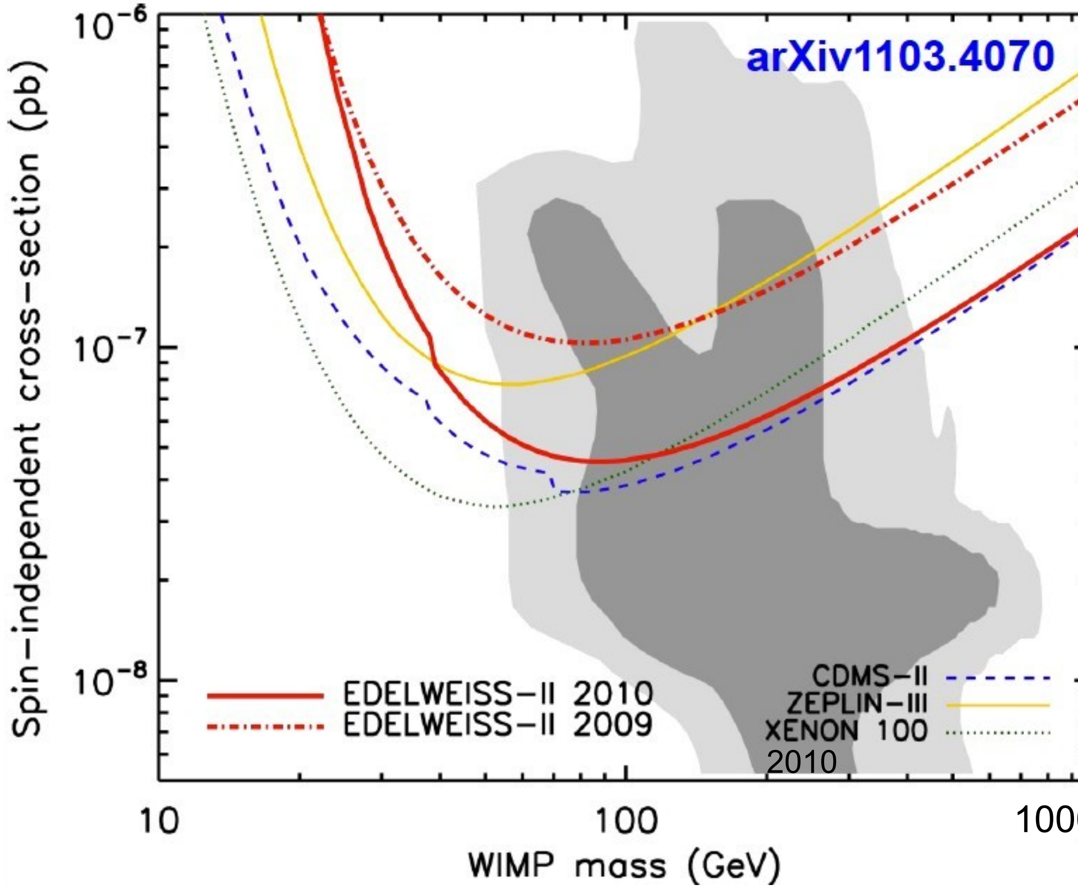




- Modification of E field near the surfaces with interleaved electrodes
- Use 'b' and 'd' signals as vetos against surface events
- Separation of surface and volume events.
- Beta rejection ~ 10^{-5}
- Substantial improvement over discrimination based on phonon timing (CDMS)

Edelweiss-2 WIMP Search
Result 2009-2010 data



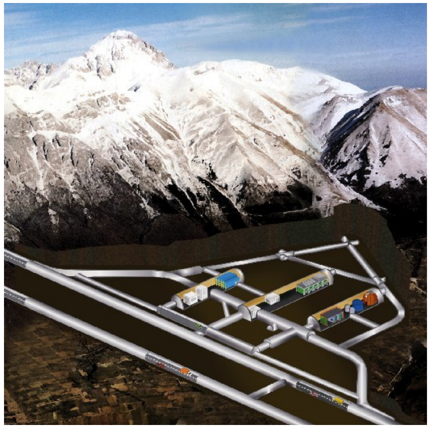


- total exposure of 427 kg.d
  - 384kg.d in 90% NR band (WIMP RoI)
- 5 events observed
  - 4 with E<22.5keV
  - 1 with E=172keV
- Expected background: ~ 3 events

$\sigma_{SI} < 4.4 \times 10^{-8}$ pb (90% CL) for $M_\chi = 85$ GeV/c^2

The XENON Program

Collaboration: US (3)+ Switzerland (1) + Italy (2) + Portugal (1) + Germany (3) + France (1) + Netherlands (1) + Israel (1) + China (1)



GOAL: Explore WIMP Dark Matter with a sensitivity of σ_{SI}~10^{-47} cm^2.

- Requires ton-scale fiducial volume with extremely low background.

CONCEPT:

- Target LXe: excellent for DM WIMPs scattering.
  - Sensitive to both axial and scalar coupling.
- Detector: two-phase XeTPC: 3D position sensitive, self-shielding.
- Background discrimination: simultaneous charge & light detection (>99.5%).
- PMT readout with >3 pe/keV. Low energy threshold for nuclear recoils (~5 keV).

PHASES:

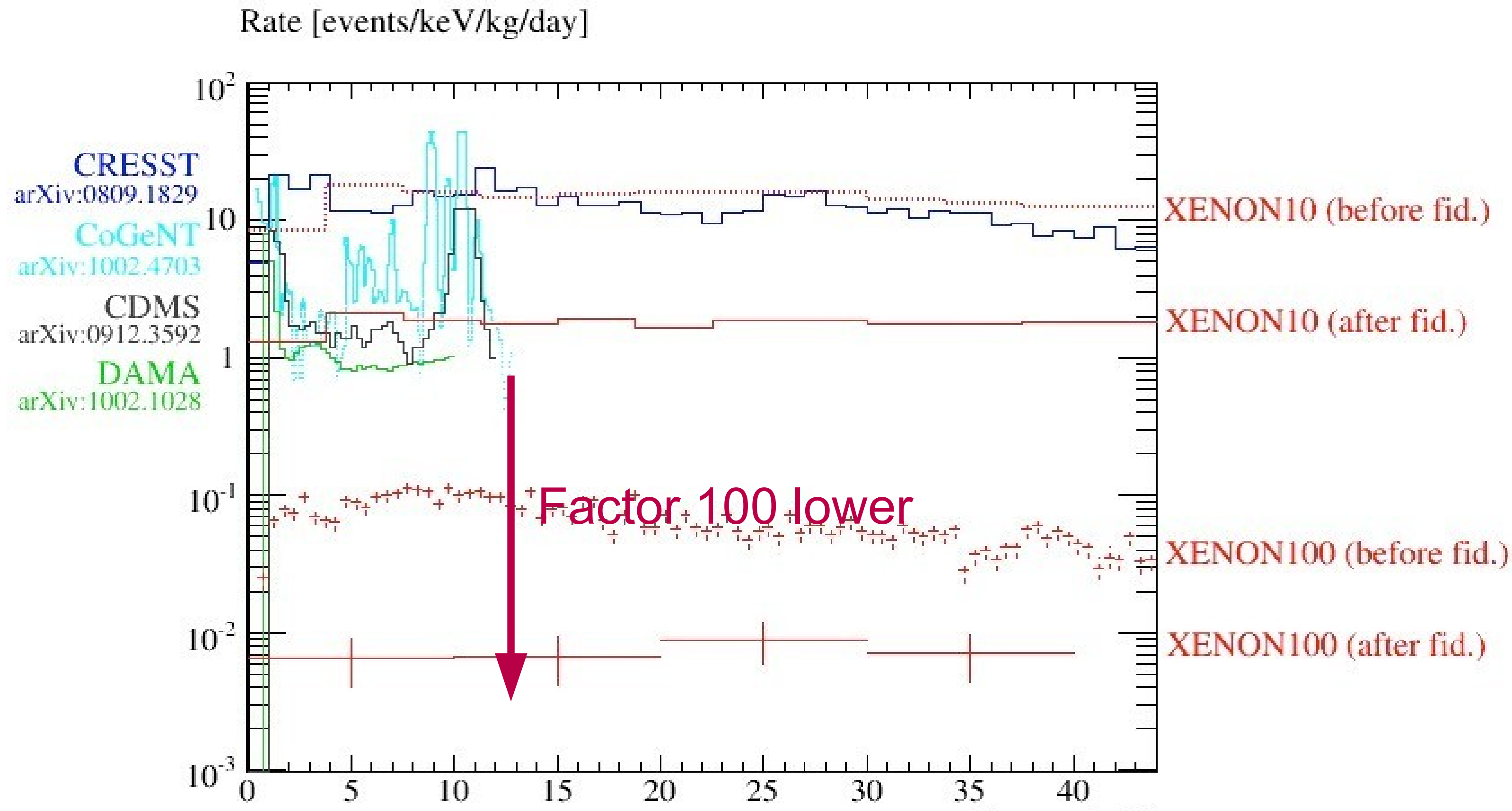
R&D Start: 2002	**XENON10** 2005-2007	**XENON100** 2008-2011+	**XENON1T** 2011-2015
	Proof of concept. Total mass: 14 kg 15 cm drift. Best limit in '07: σ_{SI}~10^{-43} cm^2	Dark Matter run ongoing. Total mass: 170 kg 30 cm drift. 2011: σ_{SI}~ 7 x 10^{-45} cm^2 Goal: σ_{SI}~ 2 x 10^{-45} cm^2	Technical design studies. Total mass: ~2.5 t 90 cm drift. Goal: σ_{SI} ~ 3 x 10^{-47} cm^2

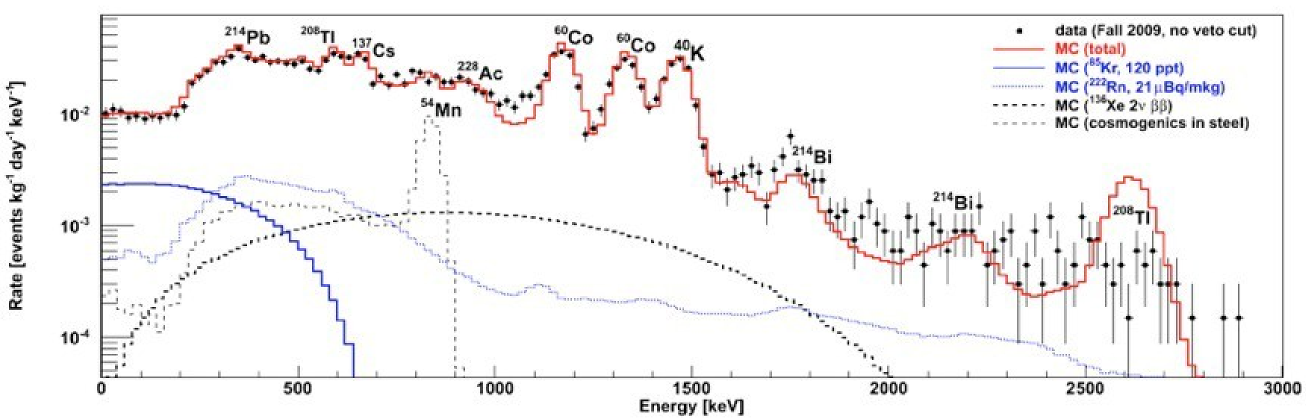
XENON100 (2008-2011+)

- 100 times lower background than XENON10
  - Material screening
  - Active LXe Veto
  - Upgrade of XENON10 shield (Cu, water)
  - Cryocooler/Feedthroughs outside shield
  - Low activity stainless steel
  - LXe self-shielding
- ~7 times larger target mass
  - 62 kg in target volume, 165 kg total LXe
- New PMTs with lower activity and high QE
- Improved electronics, grids, ...
- Gamma & neutron calibrations.
- DM search Jan – June 2010.
  Next run started ~2 months ago.

New results!

XENON100:
The Lowest Background Dark Matter Detector

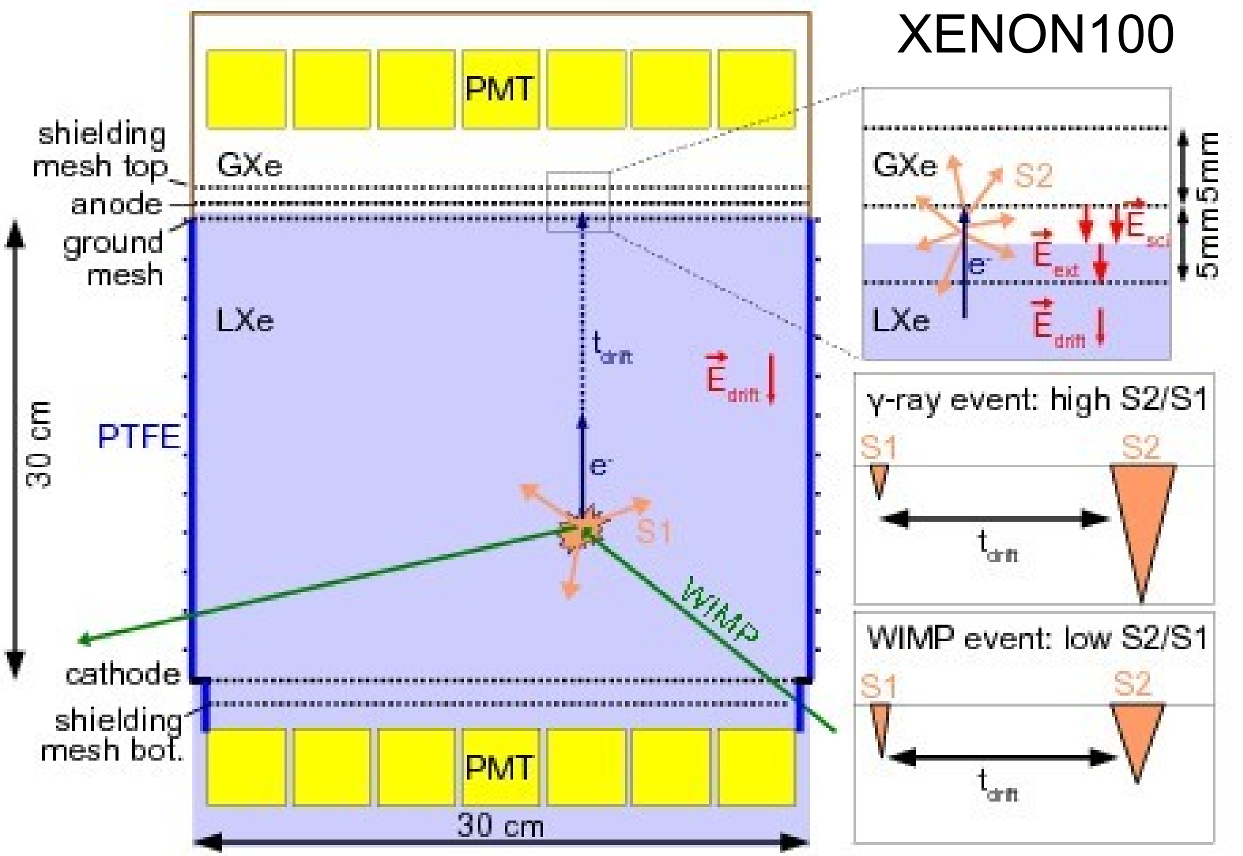




Phys. Rev. D 83, 082001 (2011)

The Liquid Xenon Dual Phase TPC
Ionization + Scintillation

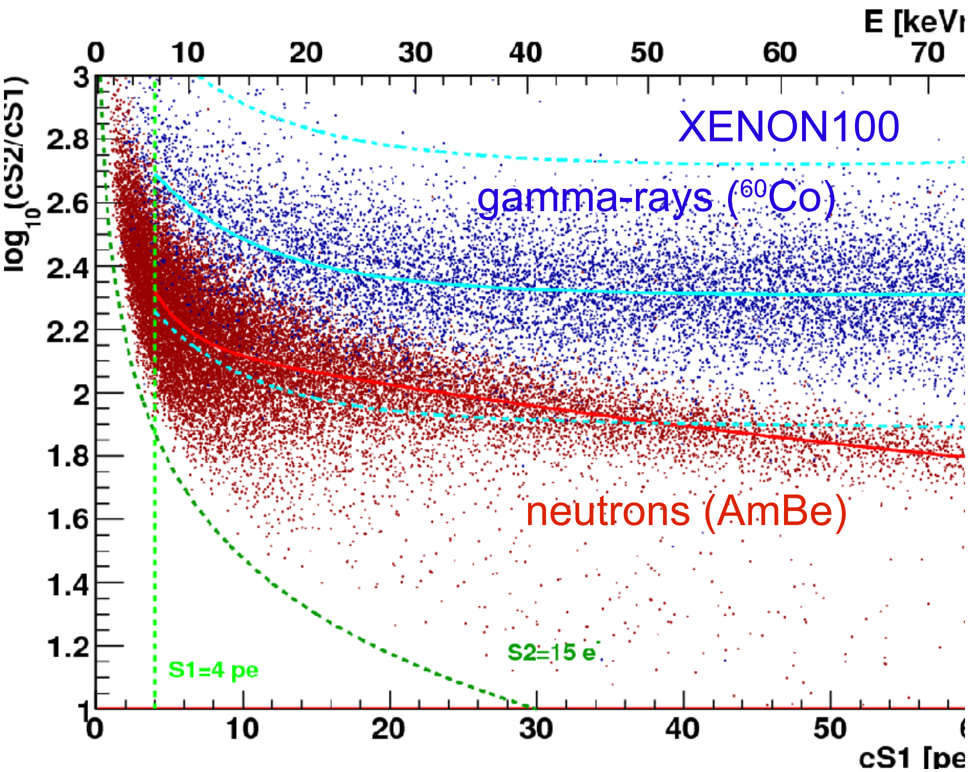
- Wimp recoil on Xe nucleus in dense liquid (2.9 g/cm^3)
  → Ionization + UV Scintillation
- Detection of primary scintillation light (S1) with PMTs.
- Charge drift towards liquid/gas interface.
- Charge extraction liquid/gas at high field between ground mesh (liquid) and anode (gas)
- Charge produces proportional scintillation signal (S2) in the gas phase (10 kV/cm)



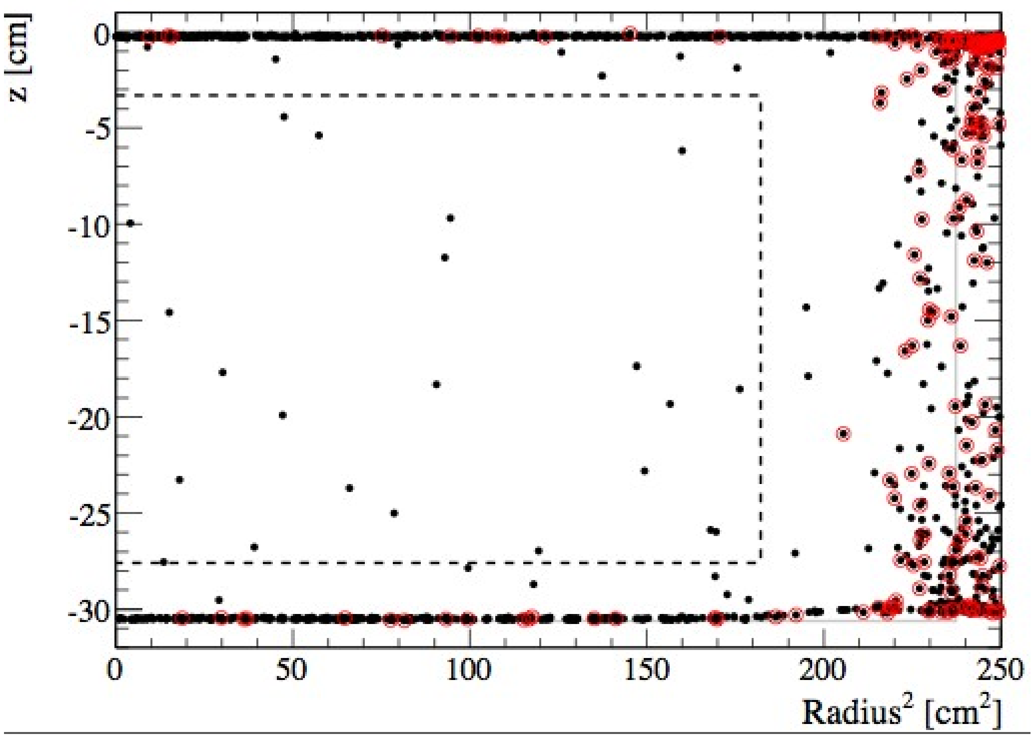
- 3D position measurement:
  - X/Y from S2 signal. Resolution few mm.
  - Z from electron drift time (~1 mm).

Background Discrimination in Dual Phase Liquid Xenon TPC's

Ionization/Scintillation Ratio S2/S1



3D Position Resolution: fiducial cut, singles/multiples

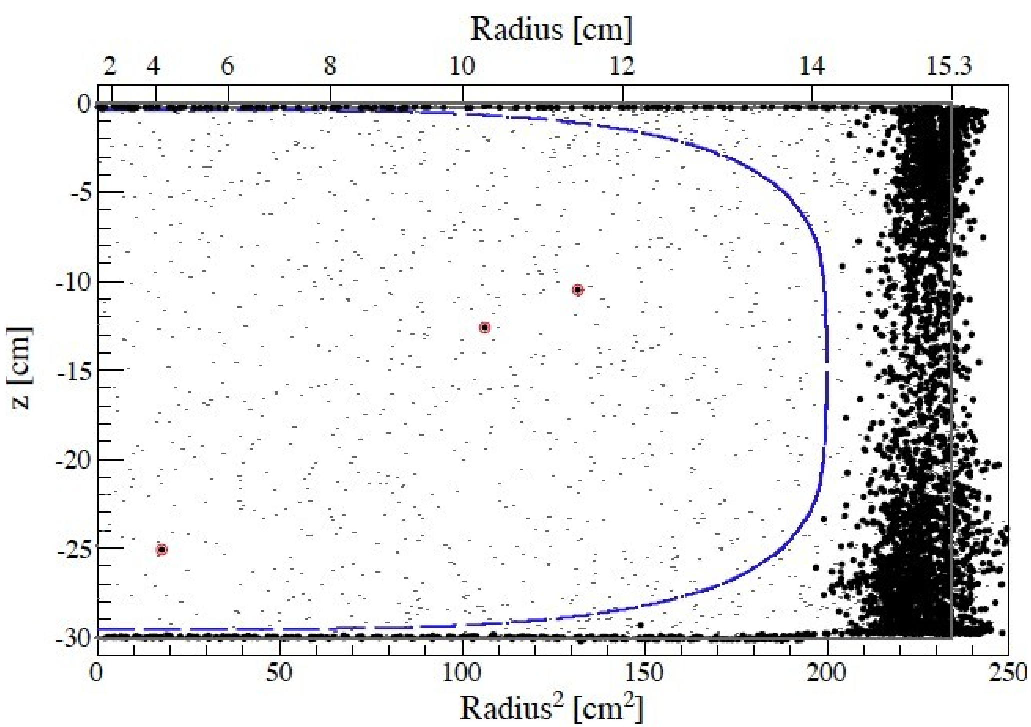


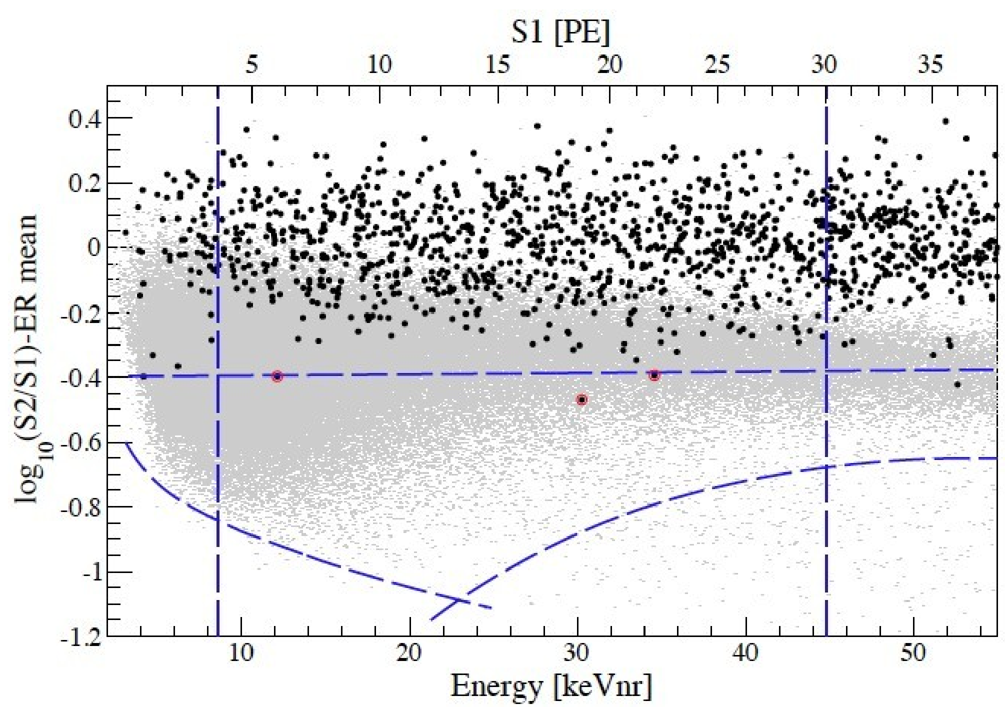
XENON100 – 2010 Run

New Result!

arXiv:1104.2549

- 100.9 live days, exposure: **1471 kg×d**
- Energy window: 4 – 30 PE S1 / 8.4 – 44.6 keVnr
- Observed after all cuts: 3 events. Expected background: (1.8 ± 0.6) events (25% probability)
- Profile Likelihood limit based on side-bands from calibration





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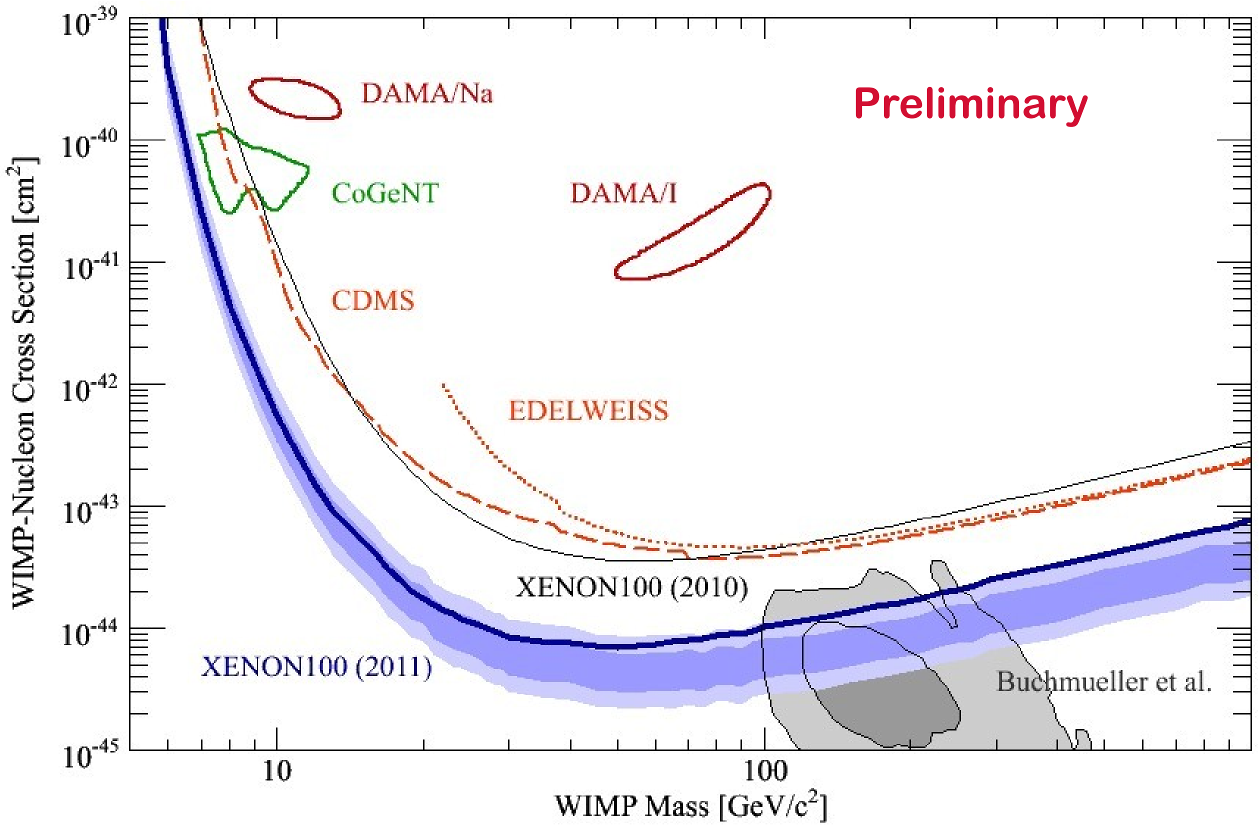
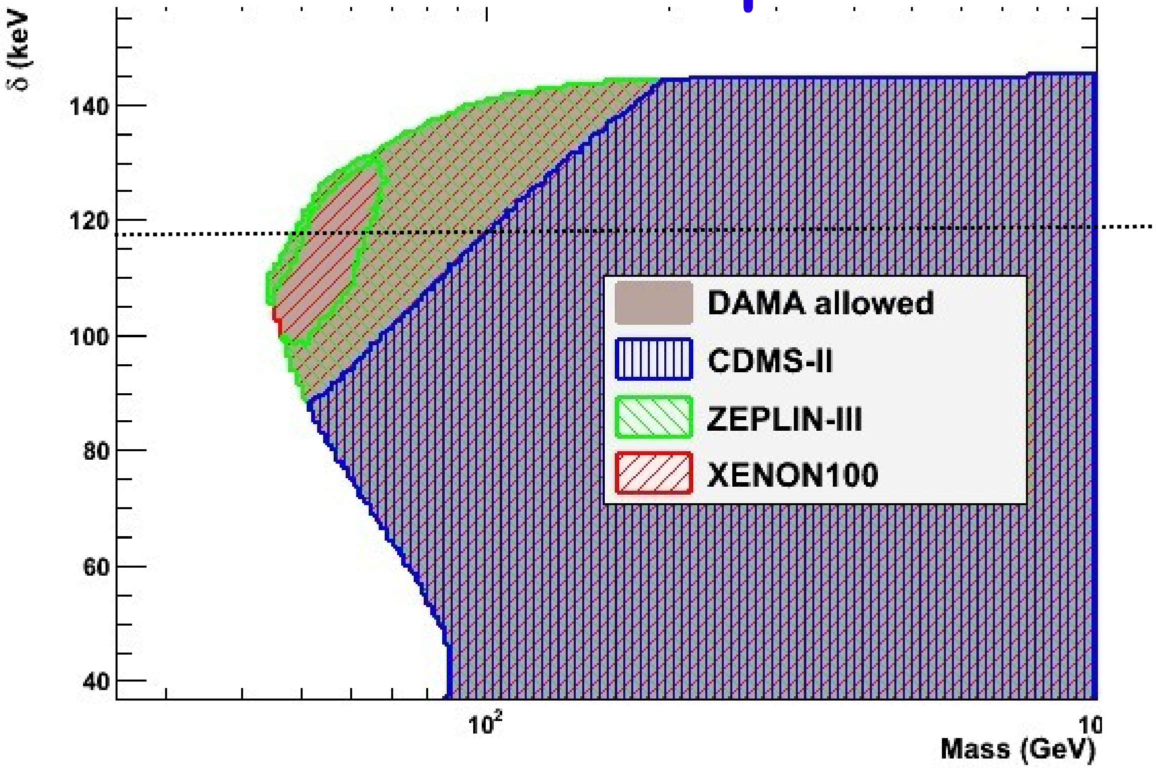
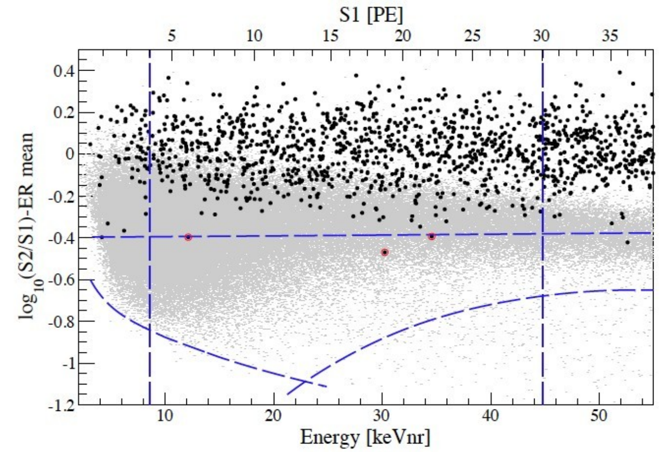
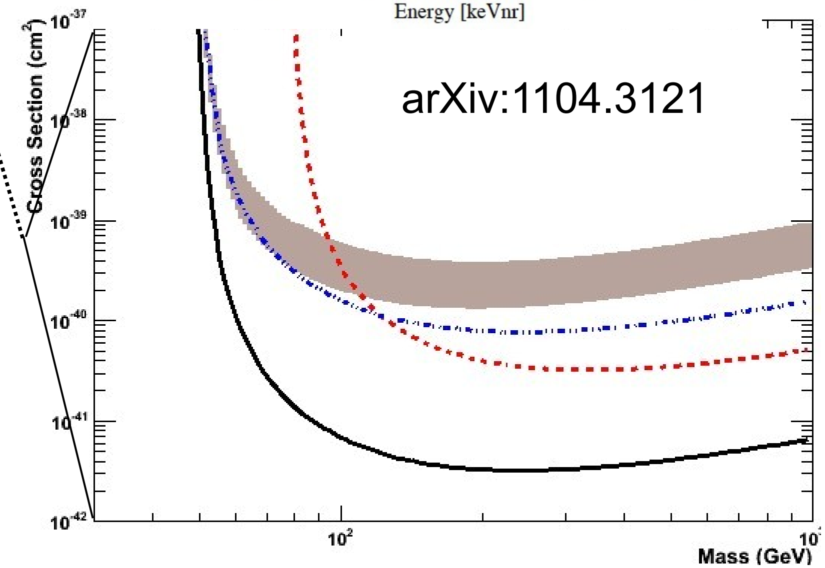
- Energy window: 4 – 30 PE S1 / 8.4 – 44.6 keVnr
- Observed after all cuts: 3 events. Expected background: (1.8 ± 0.6) events (25% probability)
- Profile Likelihood limit based on side-bands from calibration
- Best SI limit. Minimum $\sigma_S = 7.0\times10^{-45}$ cm^2 @ 50 GeV/c^2
- SUSY (CMSSM) parameter space further constrained in updated models incl. LHC limits.
- Strong tension with low mass WIMP interpretation for DAMA, CoGeNT, CRESST
- Inelastic DM as explanation for DAMA annual modulation ~ ruled out.



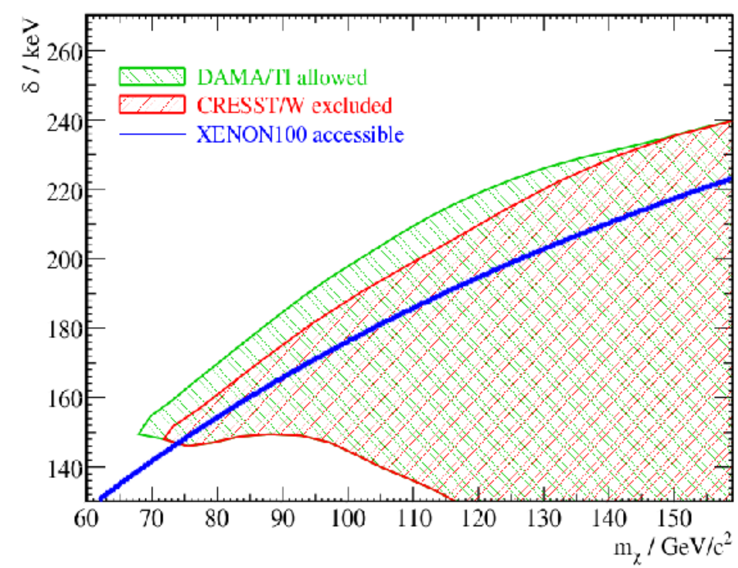
Inelastic Dark Matter – dead for DAMA interpretation?







- Model: Elastic scattering is suppressed.
  DM scatters preferentially in a low-lying excited state.
- Motivation: make DAMA/LIBRA annual modulation compatible with SI limits at energy splitting ~90 – 140 keV and WIMP masses 50 – 140 GeV/c².
- XENON100 rules this scenario out (for Na, I).
- Caveat: WIMP scattering off heavy Tl (A=204) 10^{-3} abundance in NaI(Tl) – fine-tuned parameters survive for Xe target. Use W in CRESST?



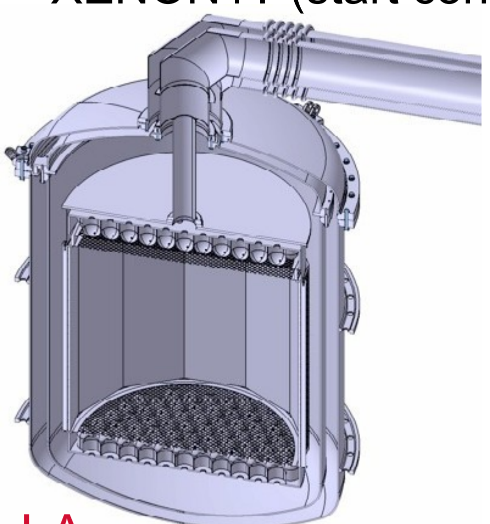
Outline

- Dark Matter Evidence & Models
- Direct Detection Technique
- Status of DM Direct Detection:
  - with discussion of selected experiments
- Future
- Summary

Future Developments

Noble Liquids

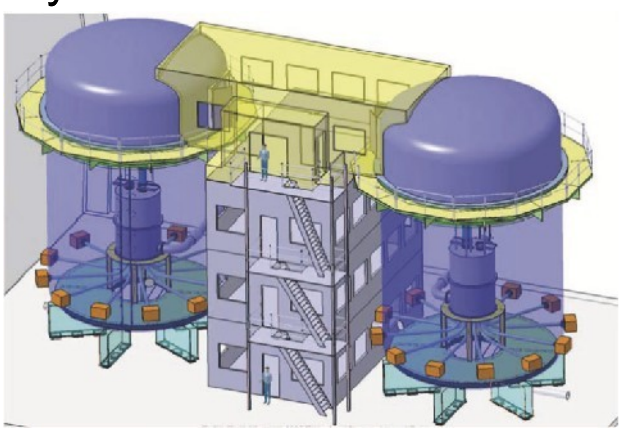
- LXe:
  - XENON100 (taking data)
  - XMASS (LXe scint., construction completed)
  - LUX (LXe, under construction)
  - XENON1T (start construction 2011)



- LAr:
  - WARP (commissioning phase)
  - ArDM (moving underground)
  - Mini-Clean (scint., under construction)
  - DEAP-3600 (under construction)

Cryogenic Germanium

- USA:
  - Super-CDMS (under construction)
  - GeoDM (R&D)
- Europe:
  - Edelweiss-3 (under construction)
  - EURECA (R&D)
    possible combination of cryogenic crystals and Ge



Superheated liquids

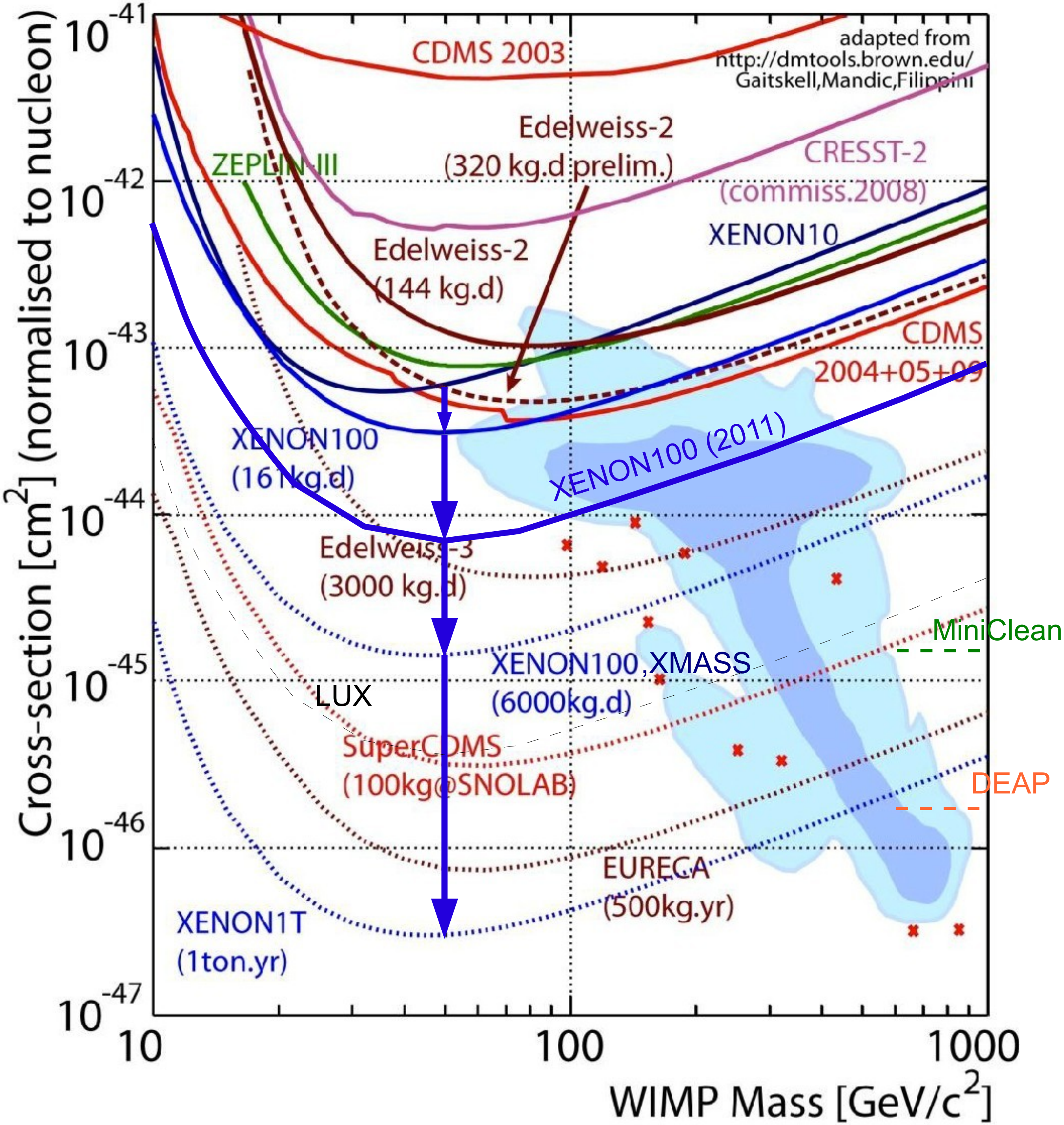
- COUPP (60 kg under construction)
- PICASSO

The Future of Direct Dark Matter Searches
(next ~5 years)

Spin-independent sensitivity

measured: solid
expectations: dashed

COUPP may enter the picture if acoustic background suppression works very well



Summary & Outlook

- **Progress in Dark Matter direct searches:**
  - Sensitivity advanced by 2-3 orders of magnitude in the last decade, increasing pace.
  - Noble liquid detectors are starting to set the pace in sensitivity.
- **Exciting new results in the last year**:
  - CoGeNT, CRESST excess events & DAMA/LIBRA annual modulation:
    Low mass WIMPs with $\sigma_S \sim 10^{-40}$ cm^2 @ ~7 GeV/c^2? Or poorly understood backgrounds?
- **New XENON100 result April 2011**:
  - Upper limit on (spin-independent) WIMP-nucleon cross-section
    $\sigma_s = 7.0\times10^{-45}$ cm^2 @ 50 GeV/c^2
    ~ Factor 5 improvement over previous limits.
  - XENON100 challenges the low mass WIMP interpretation. (+ low threshold CDMS)
  - Inelastic DM (nearly) ruled out as explanation for annual modulation in DAMA/LIBRA.
- **The future looks exciting:**
  - Rapid progress at the LHC:
    Limits on new physics improving fast. Will we see SUSY soon?
  - New results in indirect searches:
    but fundamental problems of background subtraction remain (so far).
  - Direct + indirect searches + LHC:
    We will know much more about DM within the next 5 years.
    If DM consists of WIMPs we will likely have found signs of them.

Thank you for your attention!