Direct Dark Matter Searches: an Overview

SUSY10
Physikalisches Institut, Bonn

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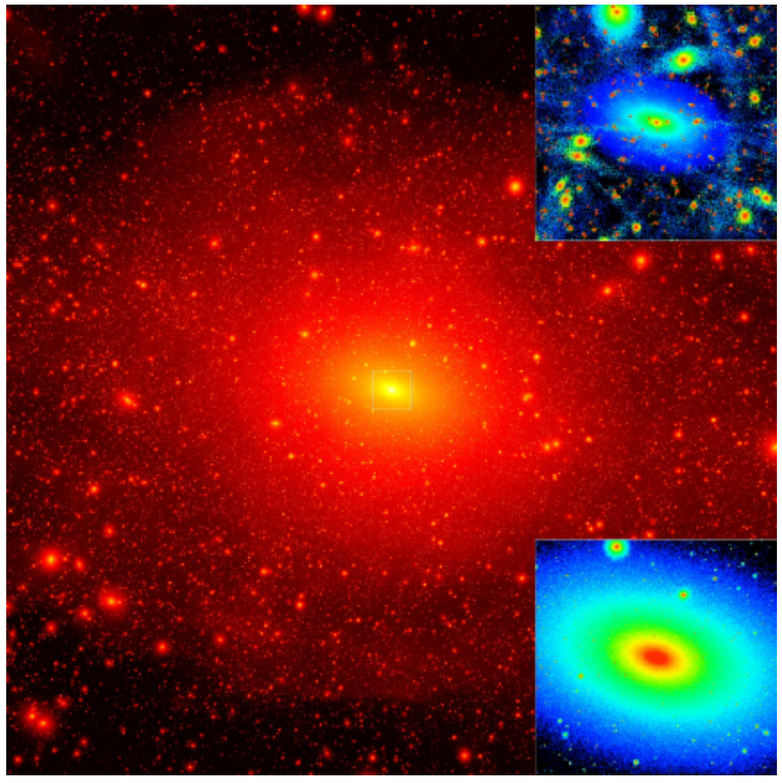
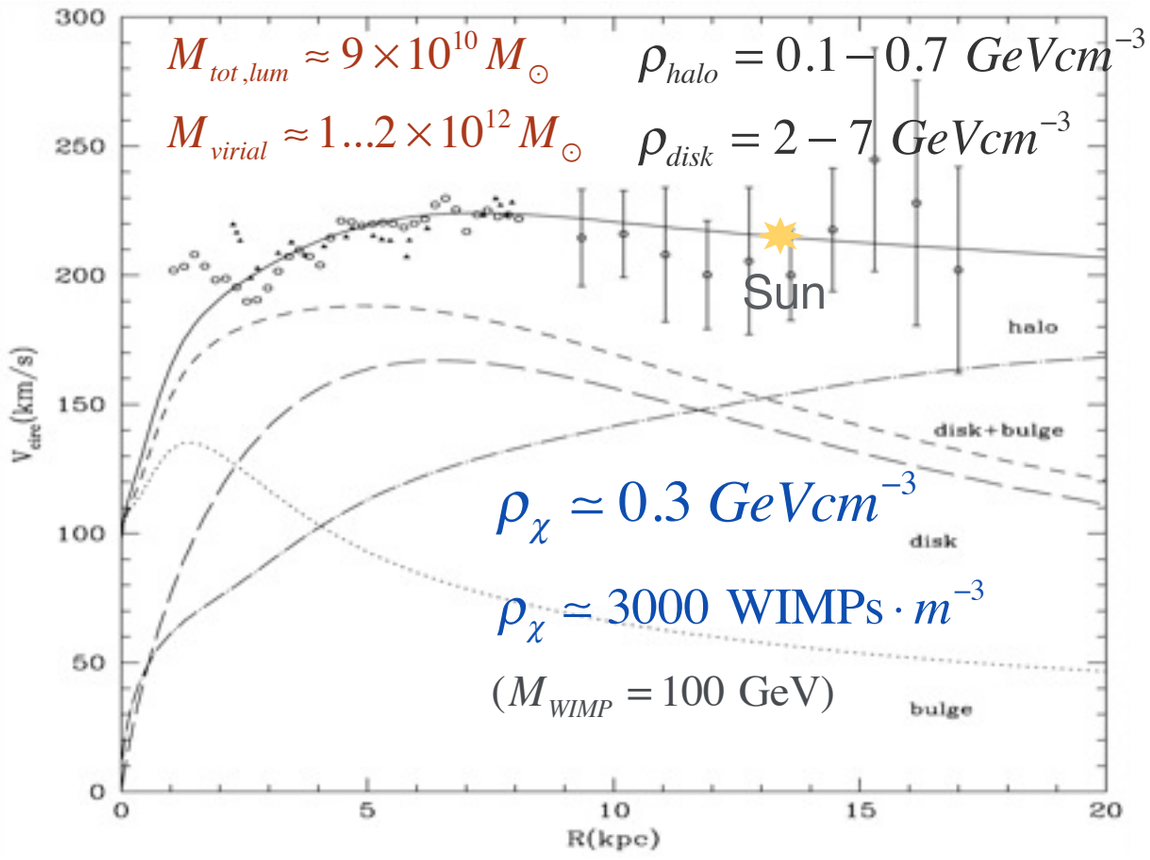
Goal of Direct Detection Experiments

- **Detect new, yet undiscovered particles, which may be responsible for the dark matter in the MW**
- **Here focus on WIMPs** = heavy (few GeV - few TeV), color and electrically neutral particles; in thermal equilibrium with the rest of the particles in the early universe, freeze out when $M_W >> T_F$
- Such particles are predicted by most attempts to understand the *weak mass scale*
- We are interested in the *local* distribution of WIMPs (density and phase-space)



(J. Diemand et all, Nature 454, 2008, 735-738)

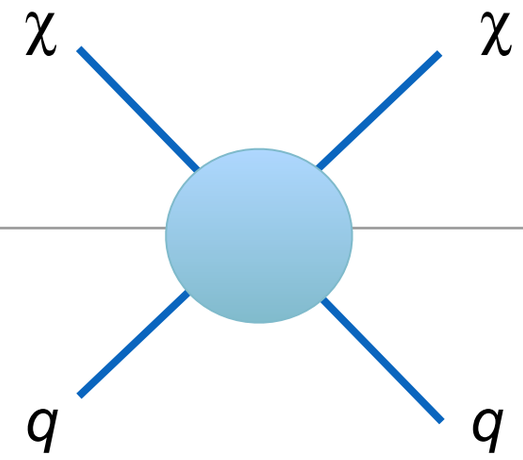


(Klypin, Zhao & Somerville 2002)

WIMP flux on Earth: ~ 10^5 $cm^{-2}s^{-1}$ (100 GeV WIMP)

=> even though WIMPs are weakly interacting, this flux is large enough so that a potentially measurable fraction will elastically scatter off nuclei

Strategy for WIMP Direct Detection



- **Collisions with atomic nuclei**
- Rates depend on: **[m_χ, σ]**, **[f(v), ρ_0]**, **[N, $F^2(E_R)$, E_{th}]** ...

$$\frac{dR}{dE_R} = \frac{\sigma_0 \rho_0}{2 m_\chi \mu^2} F^2(E_R) \int_{v > \sqrt{m_N E_R / 2\mu^2}}^{v_{max}} \frac{f(\vec{v},t)}{v} d^3v$$

- **Recoil spectrum featureless**
- **With WIMP-nucleon cross sections**
  $< 10^{-7}$ pb, the expected rates are

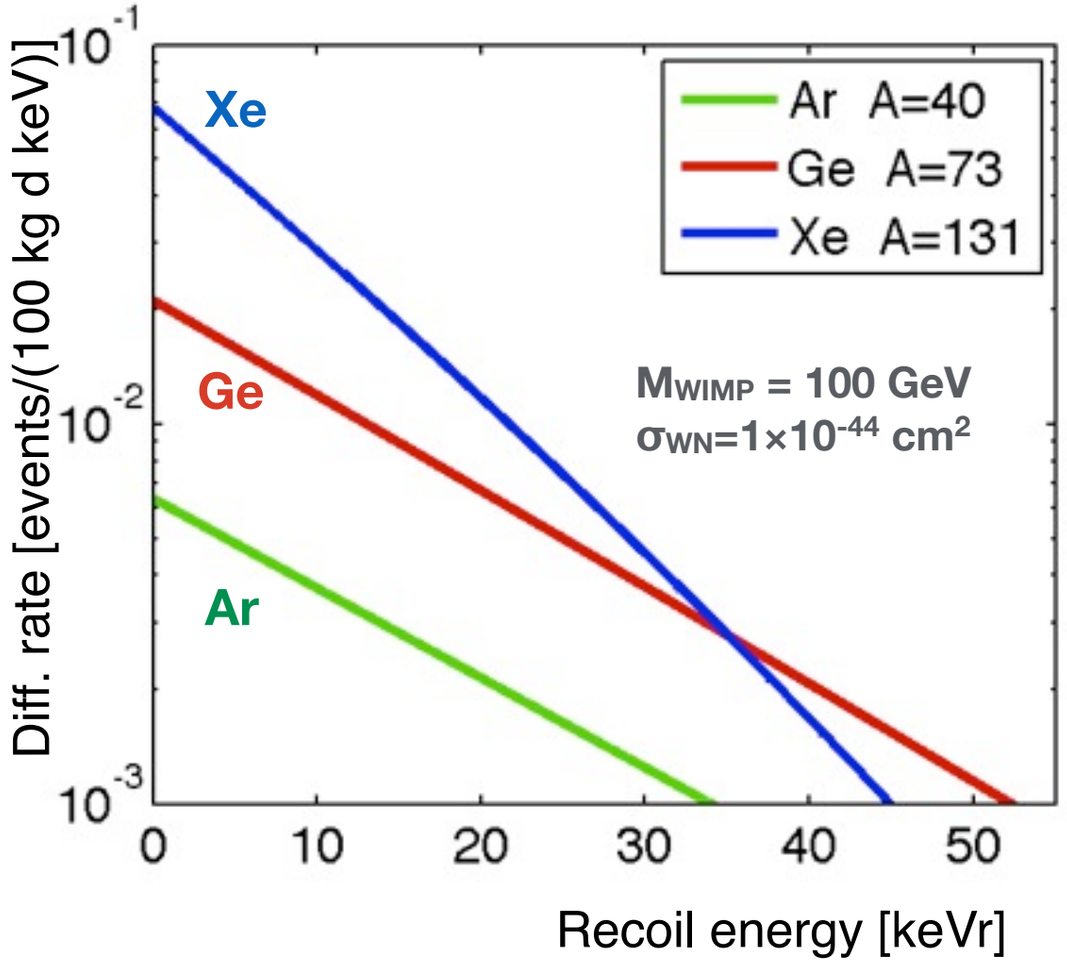
  < 1 event/100kg/day

- **Energy of recoiling nuclei**

$$E_R = \frac{|\vec{q}|^2}{2m_N} = \frac{\mu^2 v^2}{m_N}(1-\cos\theta) \leq 50\ keV$$

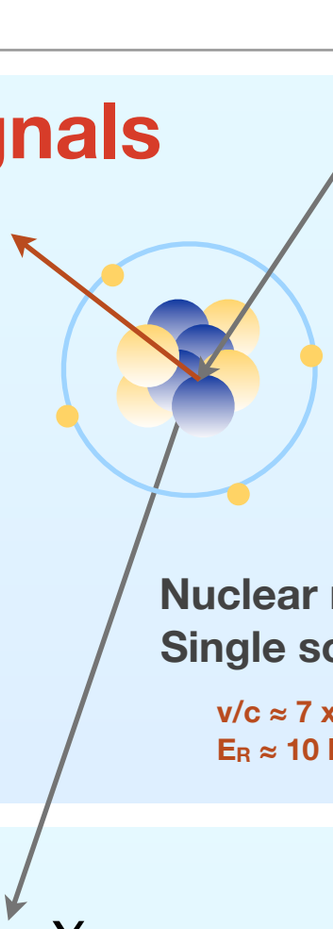
Differential rates (per 100 kg and day) for different targets (Ar, Ge, Xe)

(Standard halo model with ρ= 0.3 GeV/cm³)



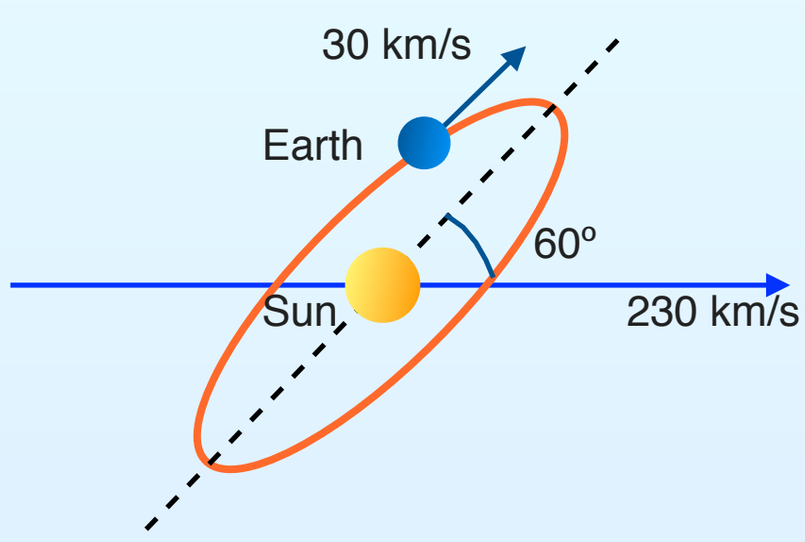
Signals and Backgrounds

Signals

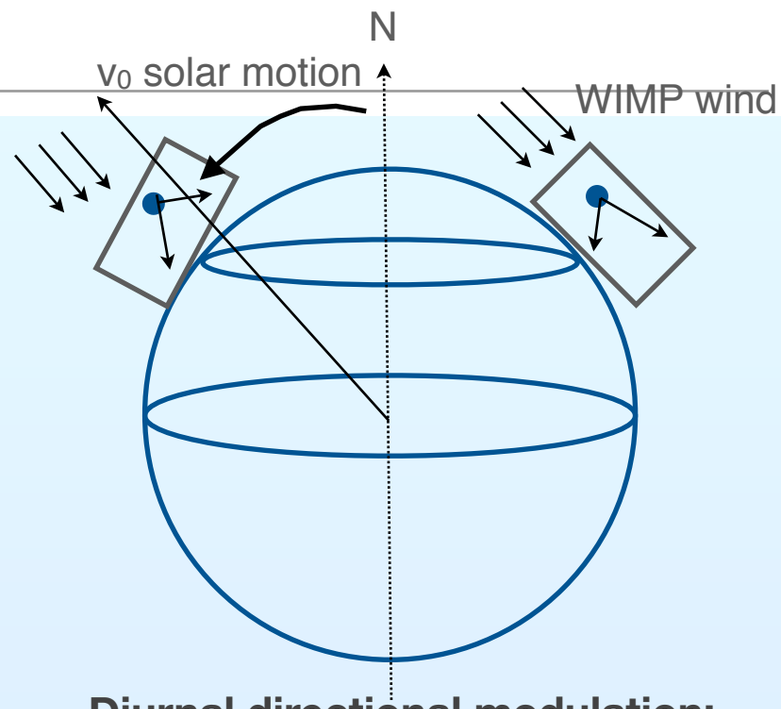


Nuclear recoils
Single scatters

$v/c \approx 7 \times 10^{-4}$
$E_R \approx 10$ keV

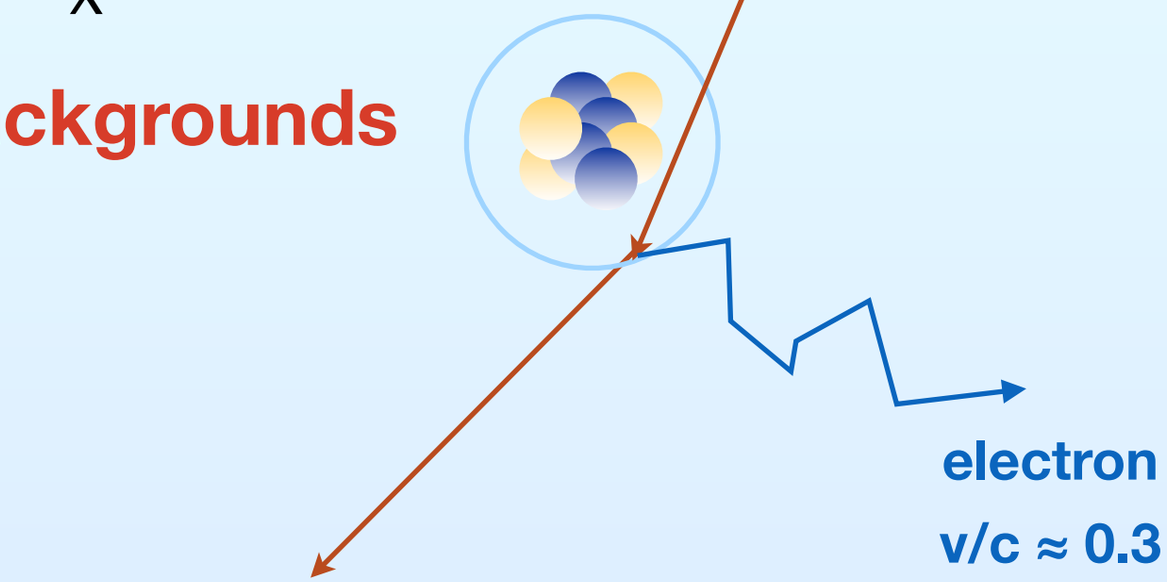


Annual rate variation
~ few % effect



Diurnal directional modulation:
~ 50% effect

Backgrounds



gamma, betas: ER vs NR discrimination and self-shielding

muons: go deep underground, add muon veto

neutrons: NRs, but also capture and multiple scatters

alphas: much higher energy depositions, but recoiling nuclei a problem if **α** energy not seen in active detector volume

The Challenge

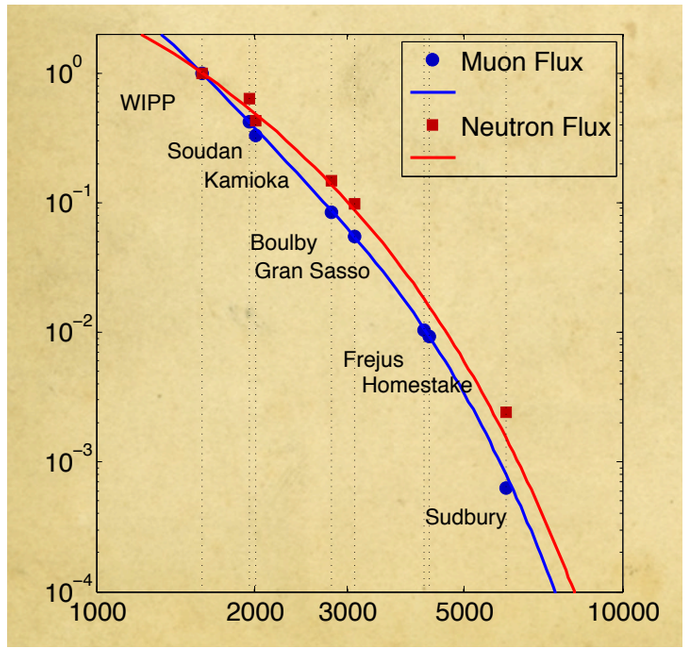
- **To observe a signal which is:**
  - ➡ very small (few keVs)
  - ➡ extremely rare (1 per ton per year?)
  - ➡ embedded in a background which usually is millions of times higher

- **Why is it challenging?**

- Detection of low-energy particles - done!
  - ➡ e.g. microcalorimetry with phonon readout

- Rare event searches with ultra-low backgrounds - done!
  - ➡ e.g SuperK, Borexino, SNO, etc

- **But can we do both?**



Direct Detection Techniques

WIMP

Phonons

Al_2O_3: CRESST-I

Ge, Si: CDMS
Ge: EDELWEISS

$CaWO_4$, Al_2O_3:
CRESST

C, F, I, Br:
PICASSO, COUPP
Ge: Texono, CoGeNT
CS_2,CF_4, ^3He: DRIFT
DMTPC, MIMAC
Ar+C_2H_6: Newage

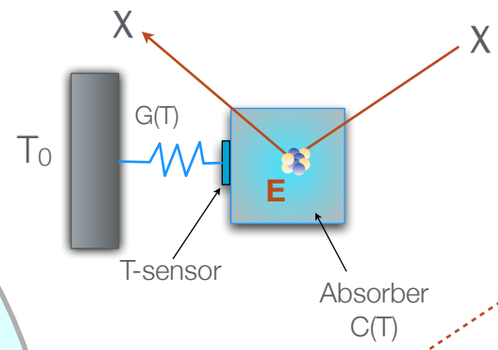
Charge

LXe: XENON
LXe: LUX
LXe: ZEPLIN
LAr: WARP
LAr: ArDM

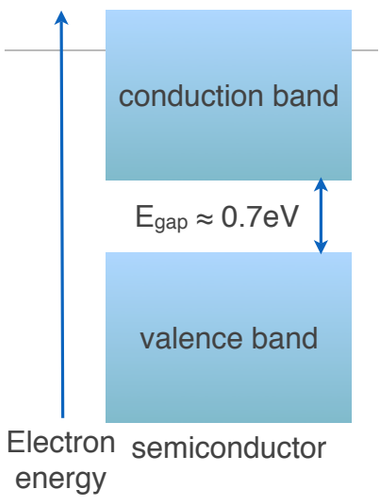
NaI: DAMA/LIBRA
NaI: ANAIS
CsI: KIMS

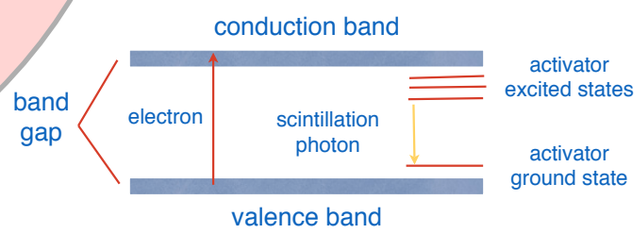
LXe: XMASS
LAr, LNe:
DEAP/CLEAN

Light



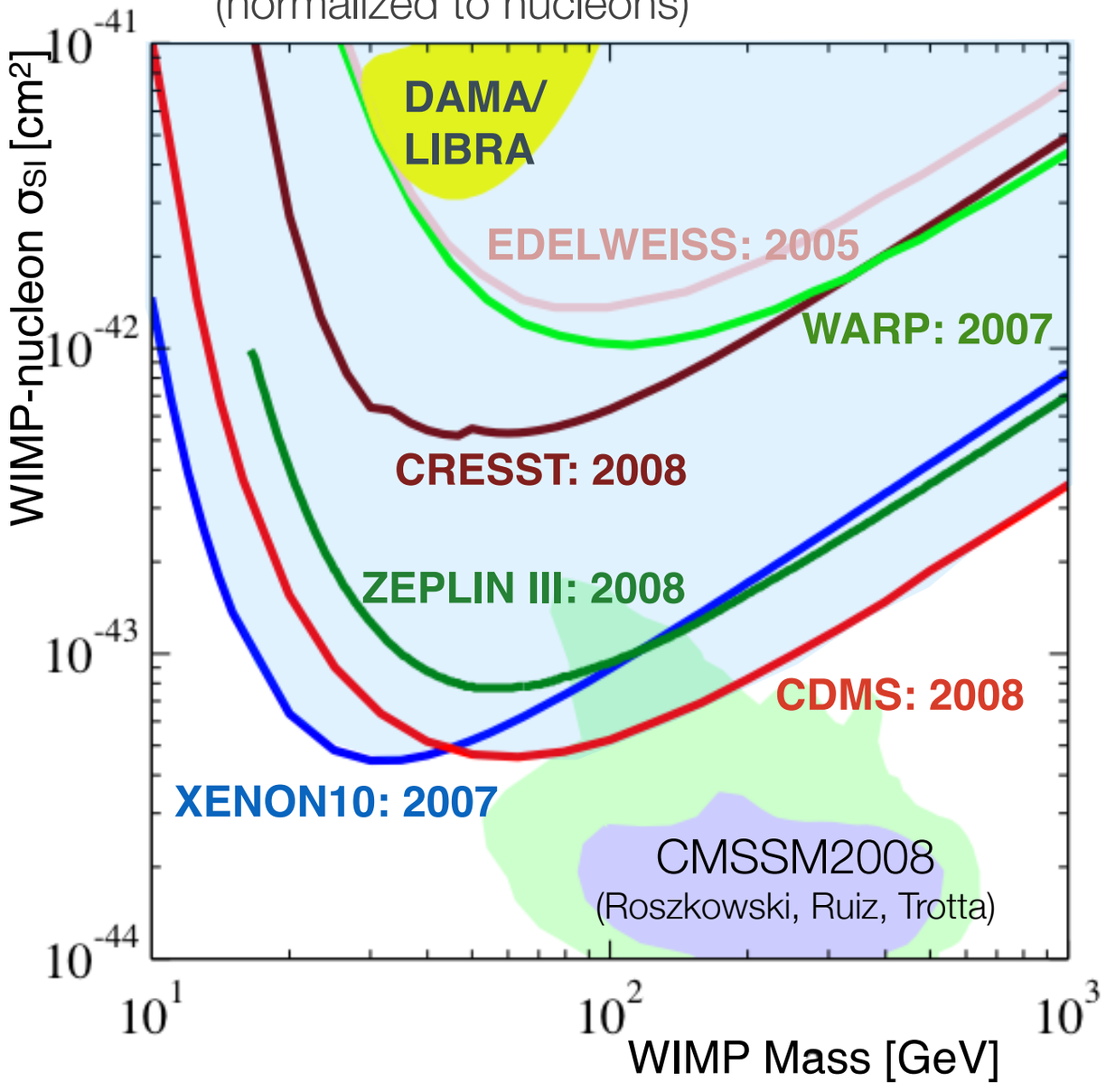
WIMP

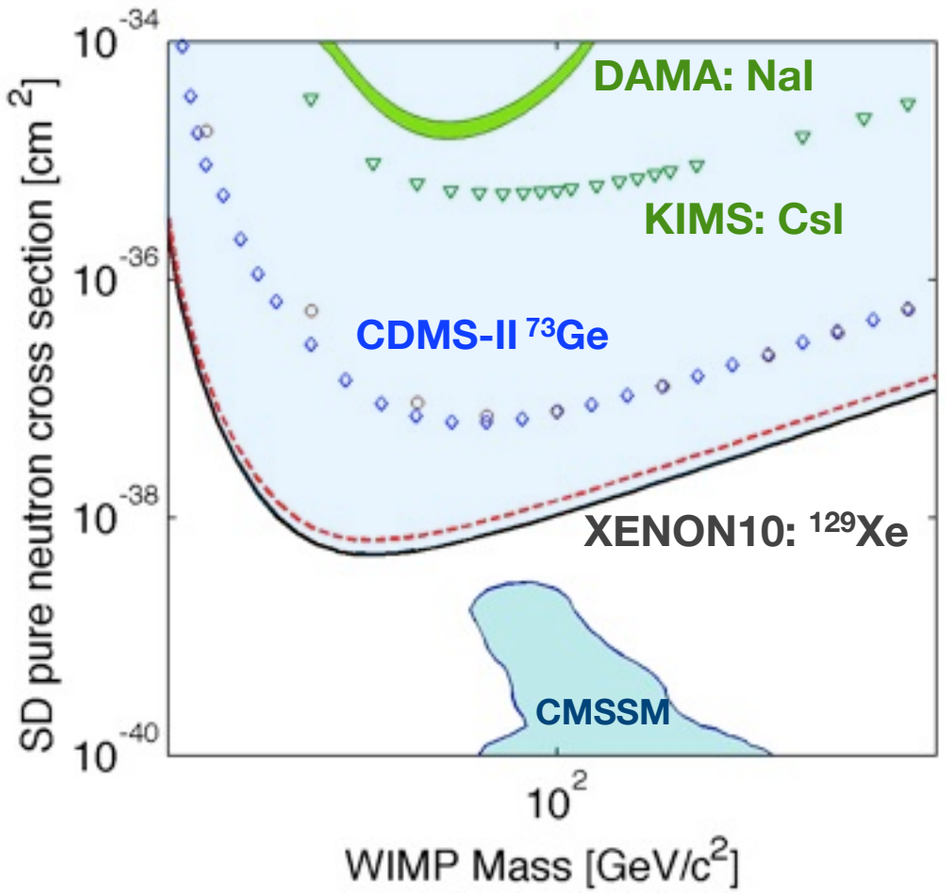


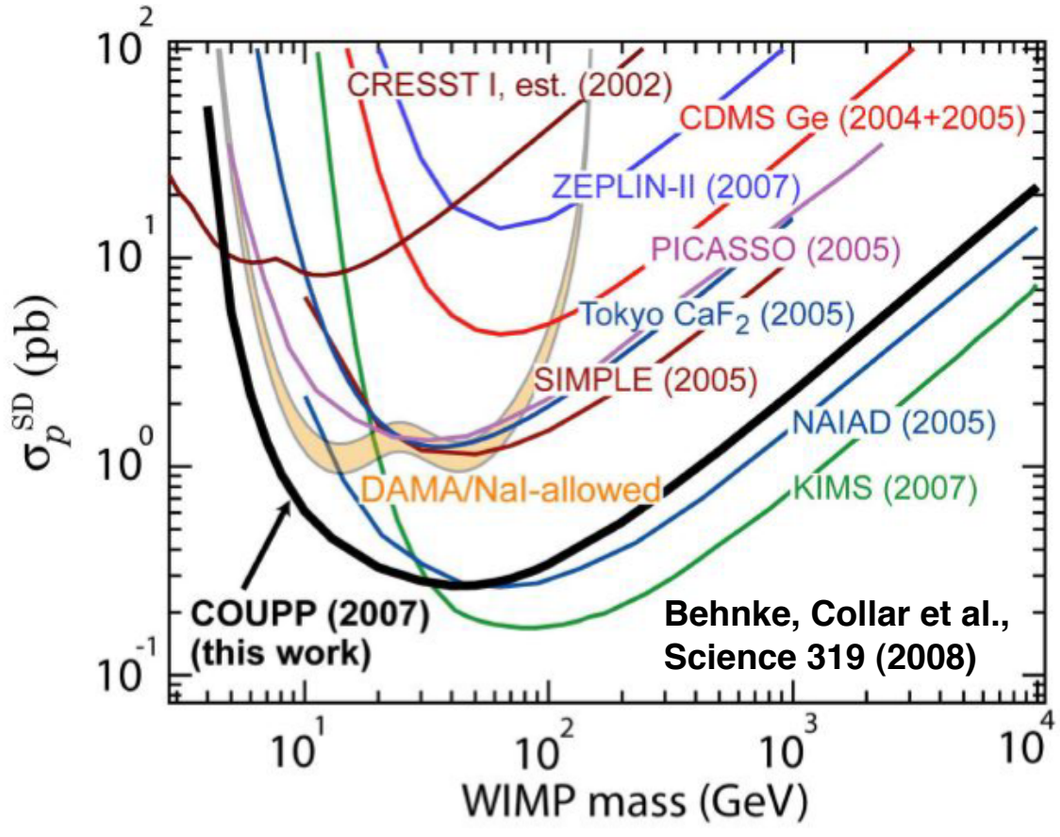


Where did we stand? (by the end of 2009)

Spin-independent cross section
(normalized to nucleons)







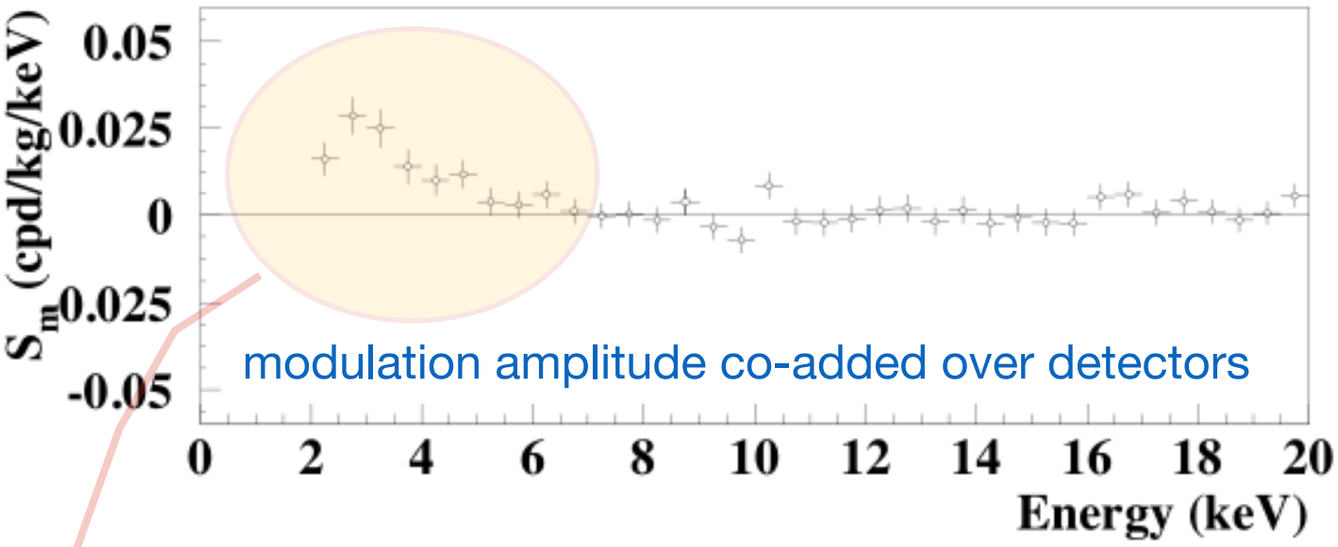
Spin-dependent

This talk: focused on latest results

+ prospects for the future

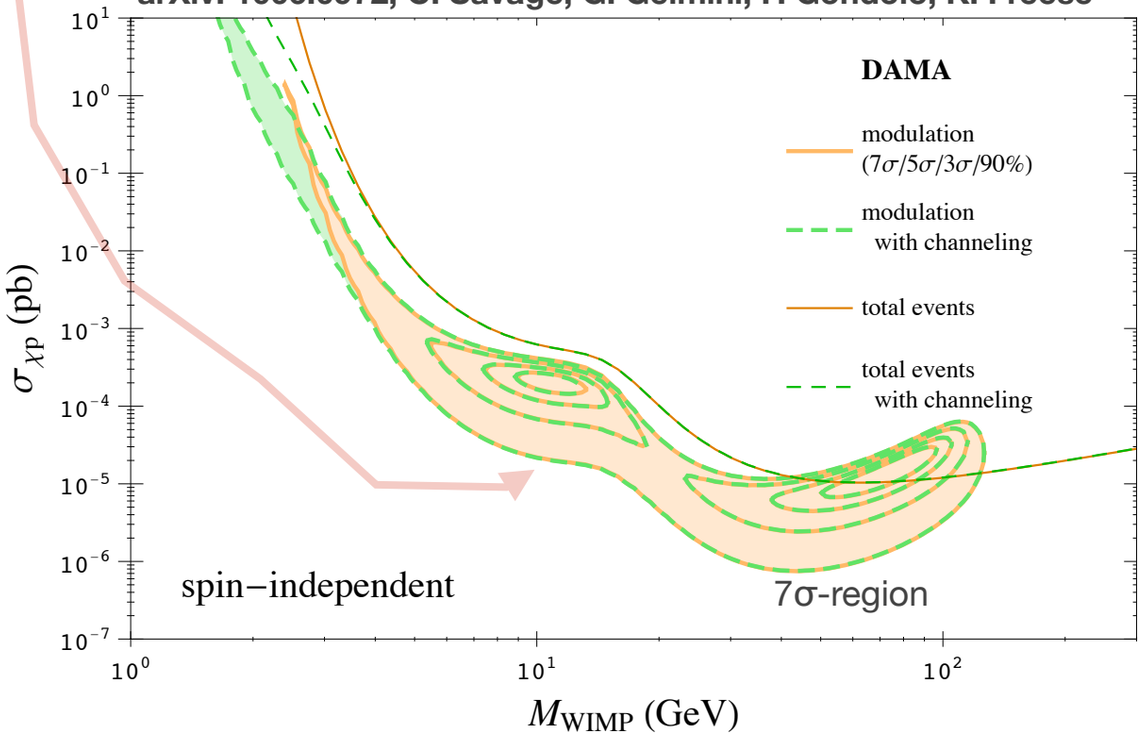
“Evidences” for WIMPs?

DAMA/LIBRA: 1998-2008, 0.82 ton x year

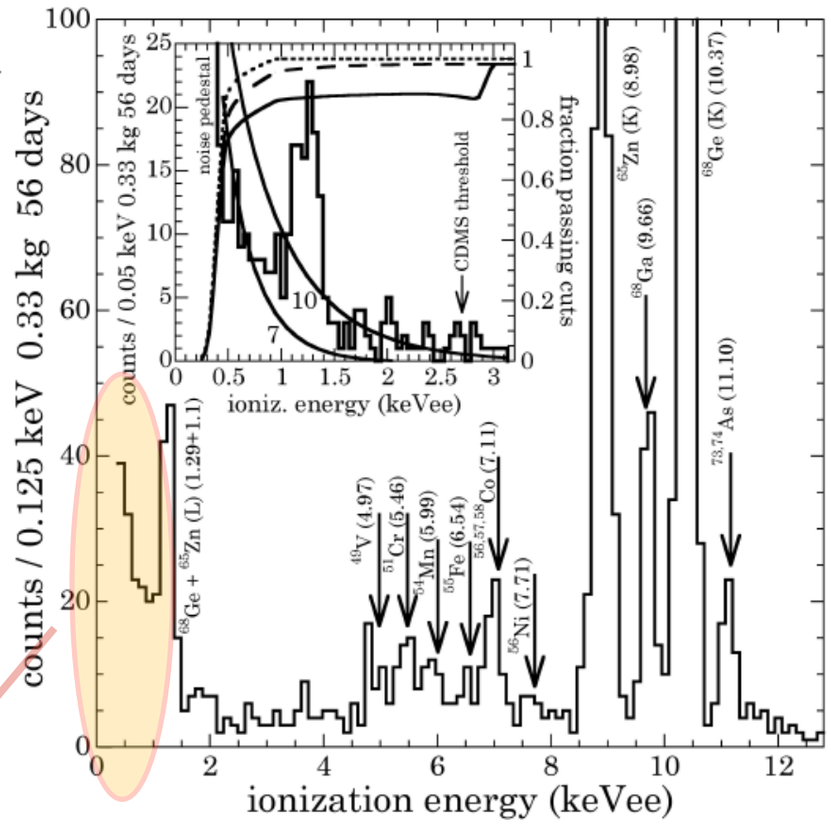


modulation amplitude co-added over detectors

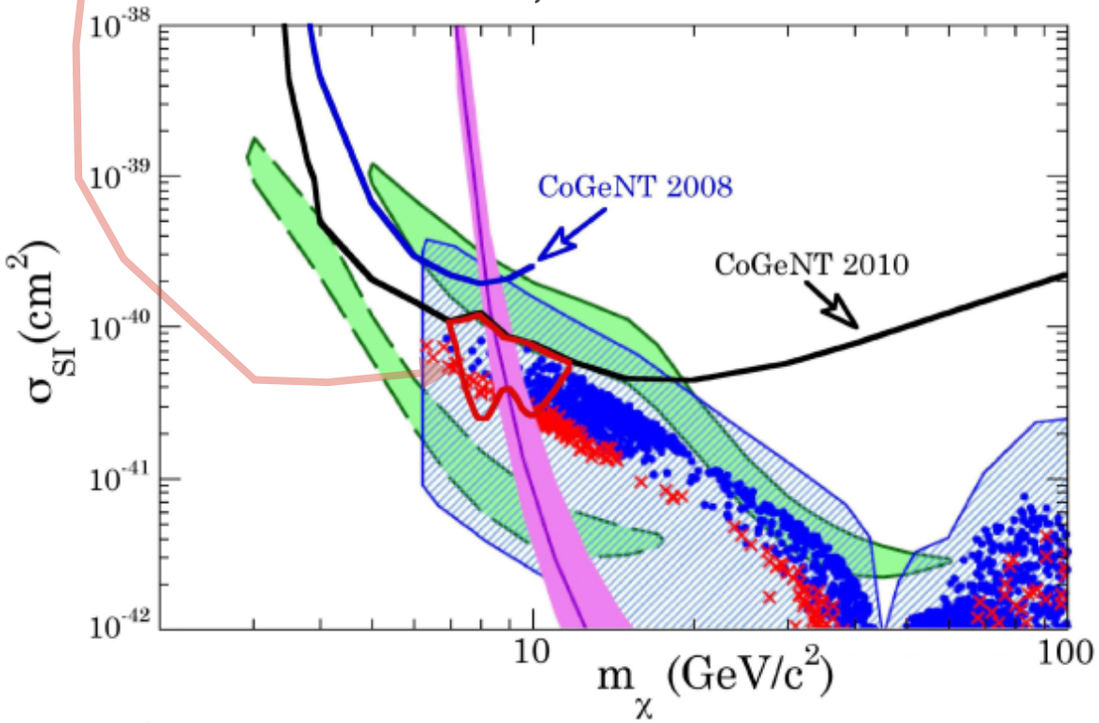
arXiv: 1006.0972; C. Savage, G. Gelmini, P. Gondolo, K. Freese



CoGeNT: 2010; 0.33 kg x 8 weeks

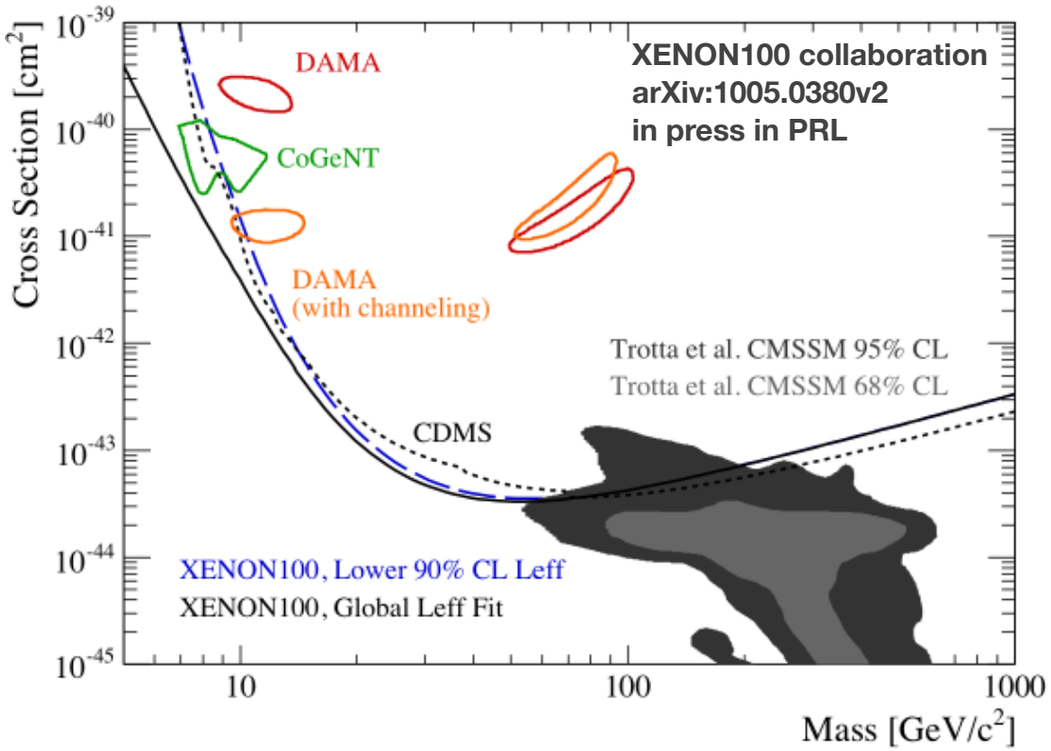


arXiv: 1002.4703; C. E. Aalseth et all

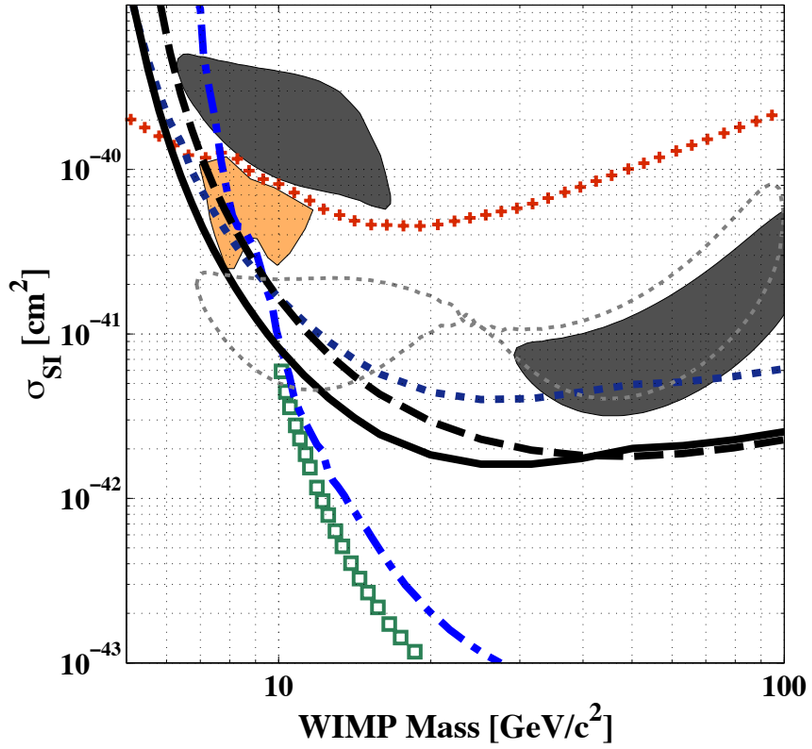


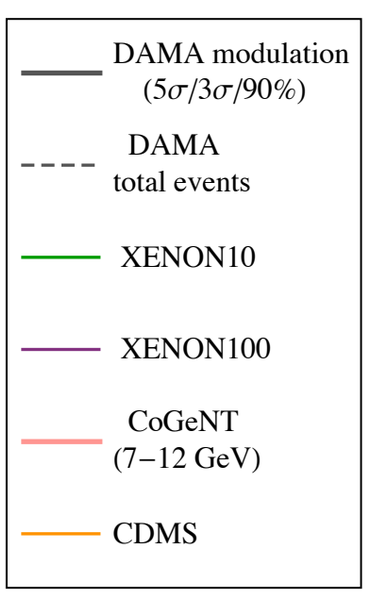
In severe conflict with other experiments!

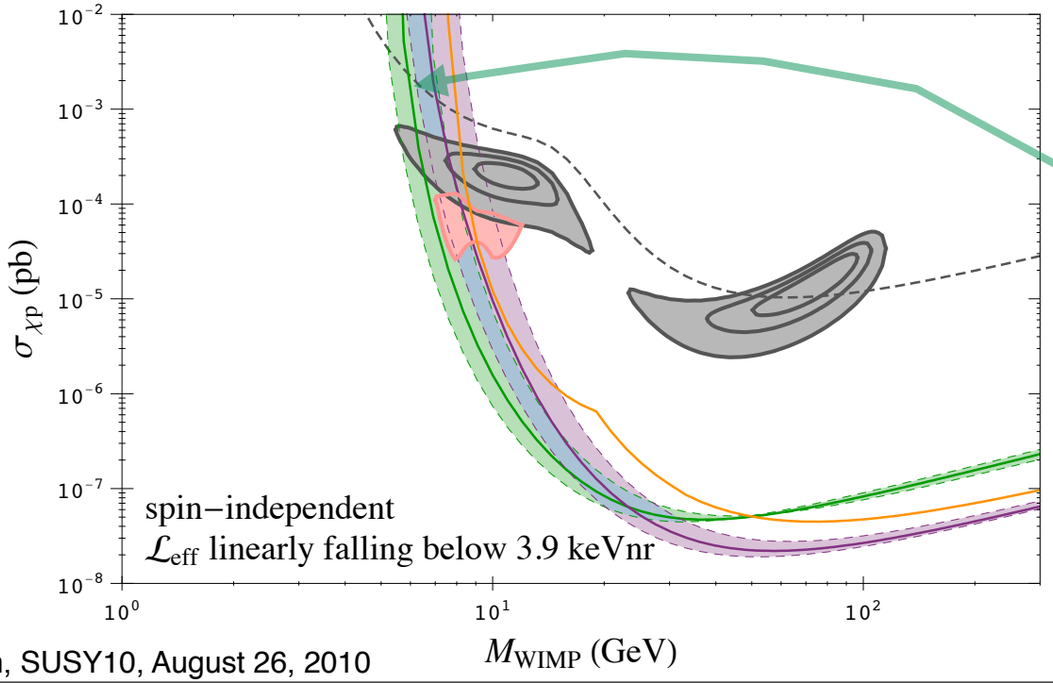
New XENON100 results (more later!)



CDMS Si results; J. Filippini, PhD thesis, UCB







Reanalyzed

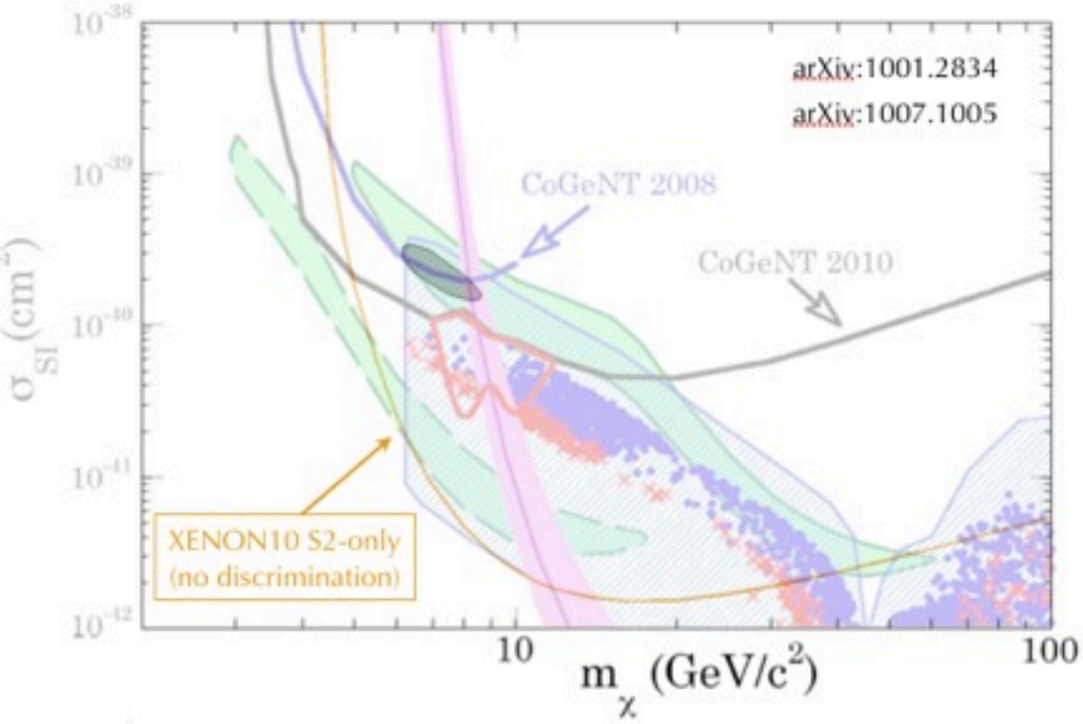
XENON10 results

arXiv: 1006.0972v2
C. Savage, G. Gelmini, P. Gondolo, K. Freese

Low mass WIMPs: excluded?

Preliminary!

P. Sorensen, IDM2010

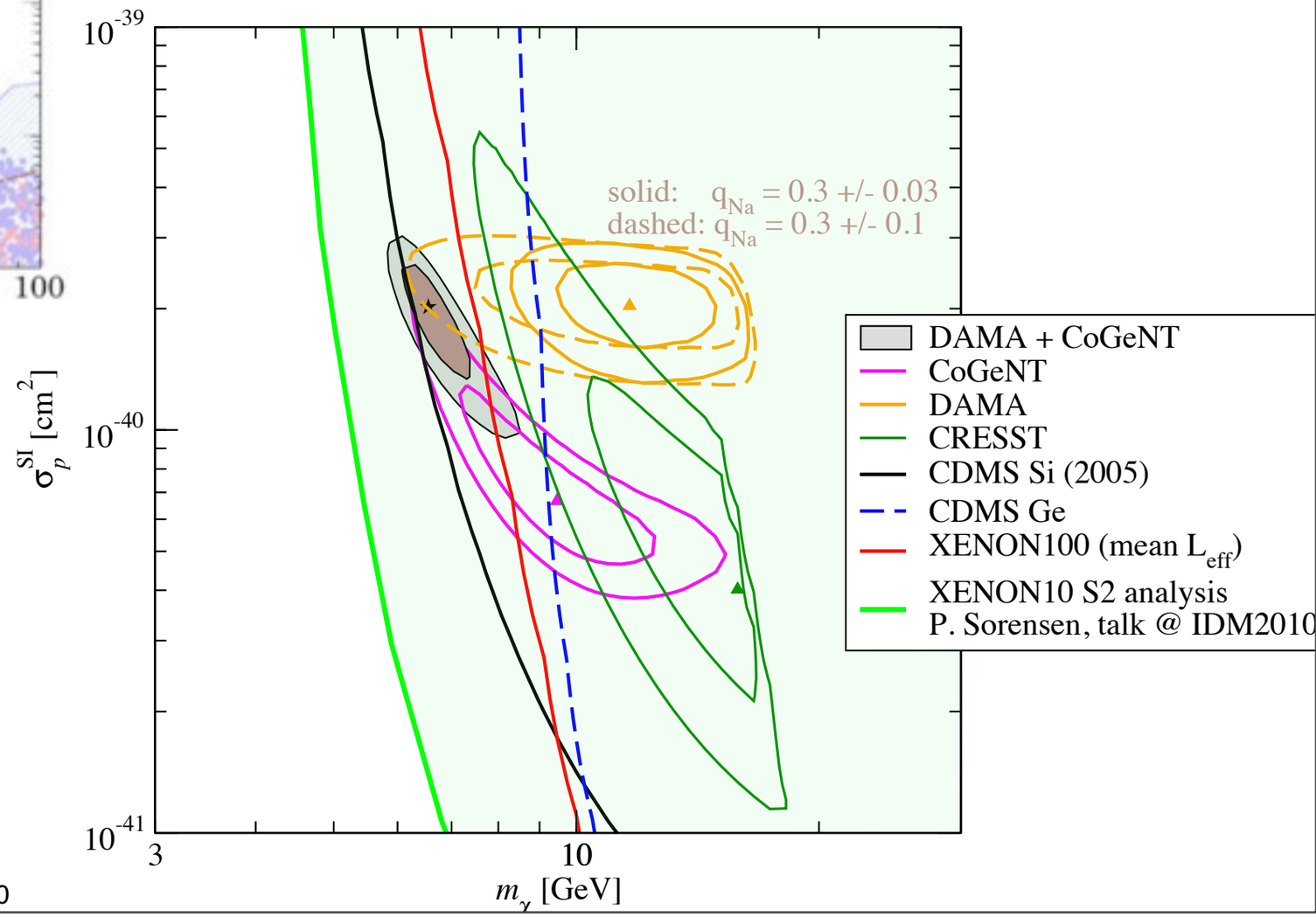


- Reanalysis of XENON10 data using S2 (charge) only and a 1.2 kg target
- z-cut based on S2-width
- Energy threshold: 1.6 keVr

- Max Gap 90% C.L. upper limit between 1.6 keVr and 3.8 keVr
- 12.5 live days
- 1.2 kg target
- conservative -1σ Q_y energy calibration
- no account of resolution (this would improve limits)

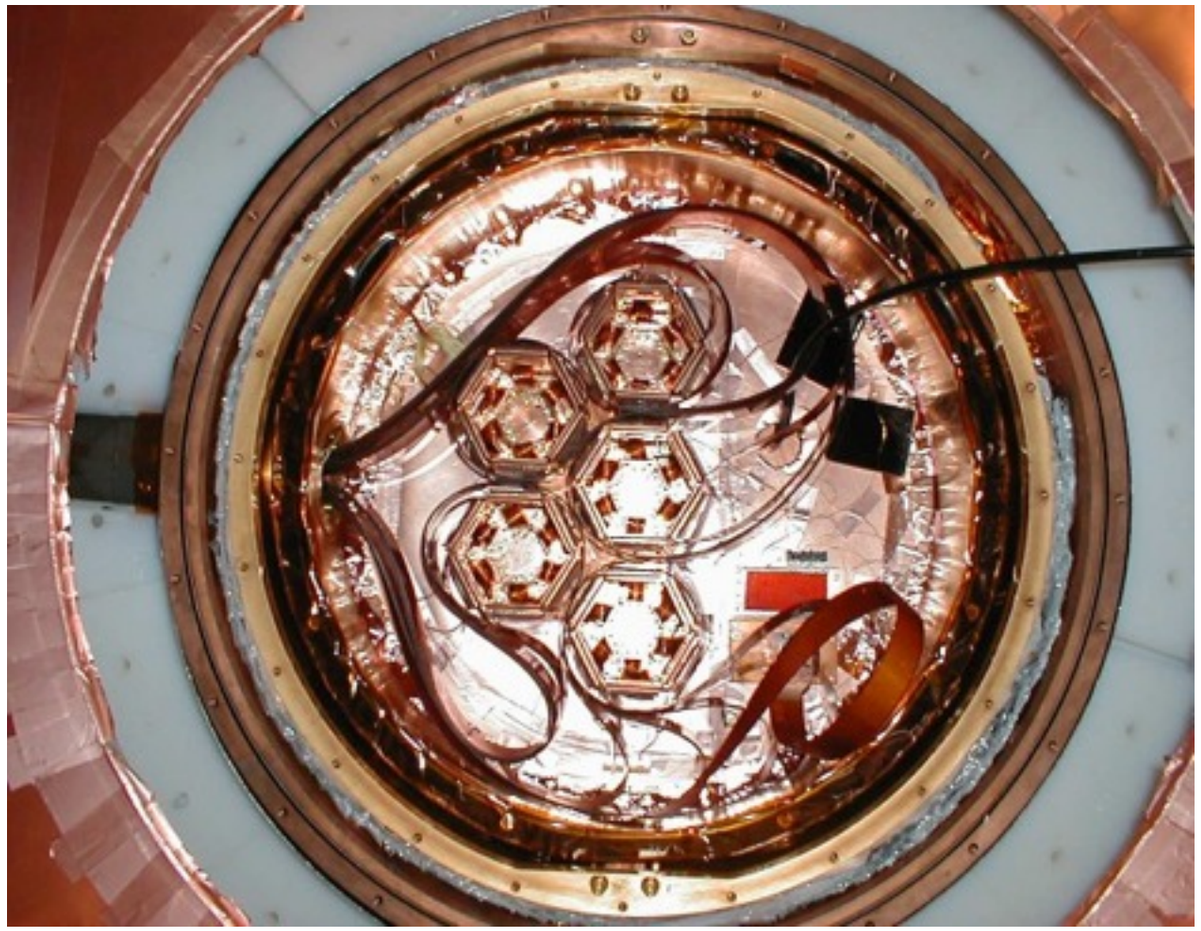
Summary by

T. Schwetz, IDM2010



The CDMS-II Experiment

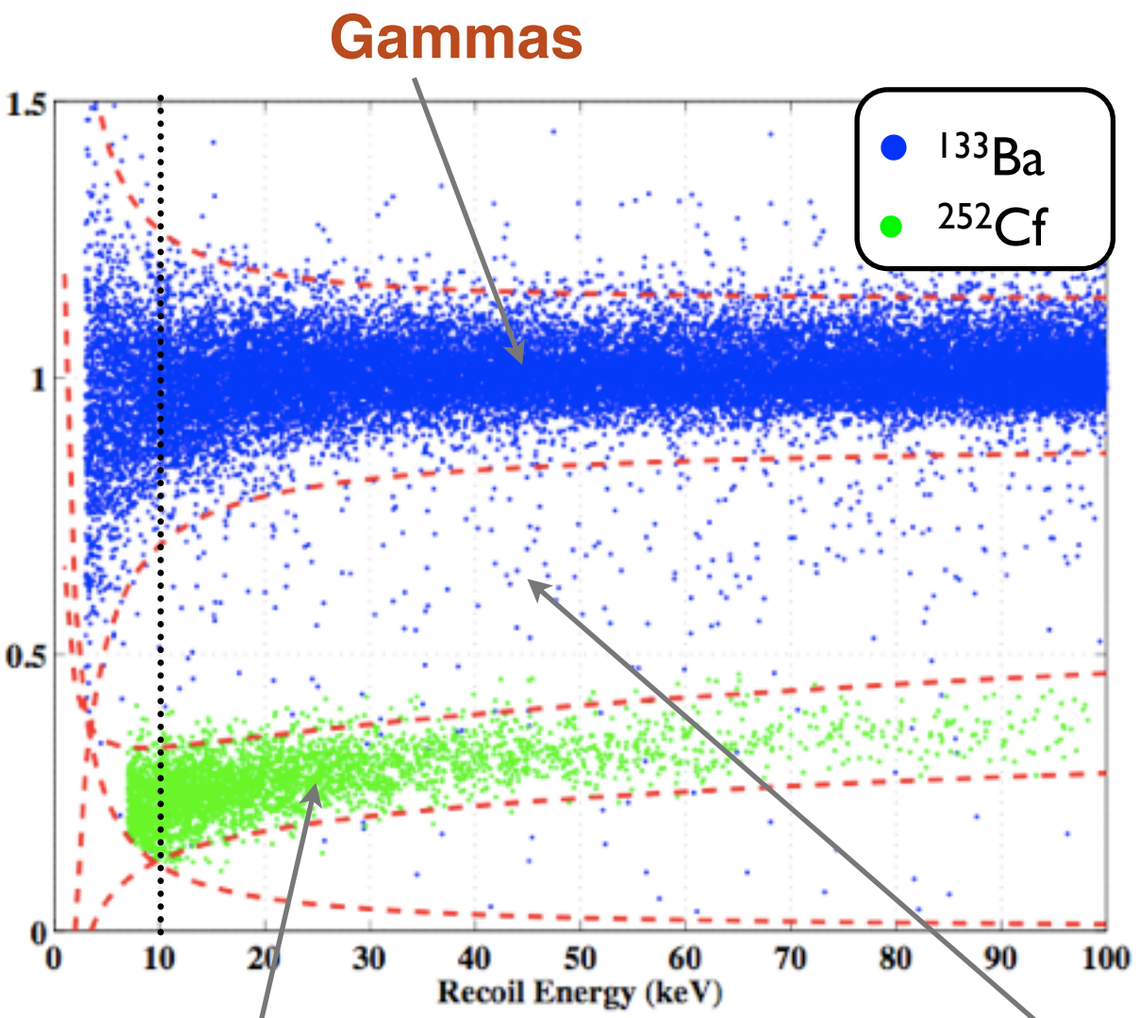
- 30 Ge (4.75 kg) and Si (1.1 kg) phonon and ionization detectors below 40 mK in 5 towers
- At Soudan since 2003
- **Latest CDMS-II analysis:** 191 kg days (Ge) of exposure

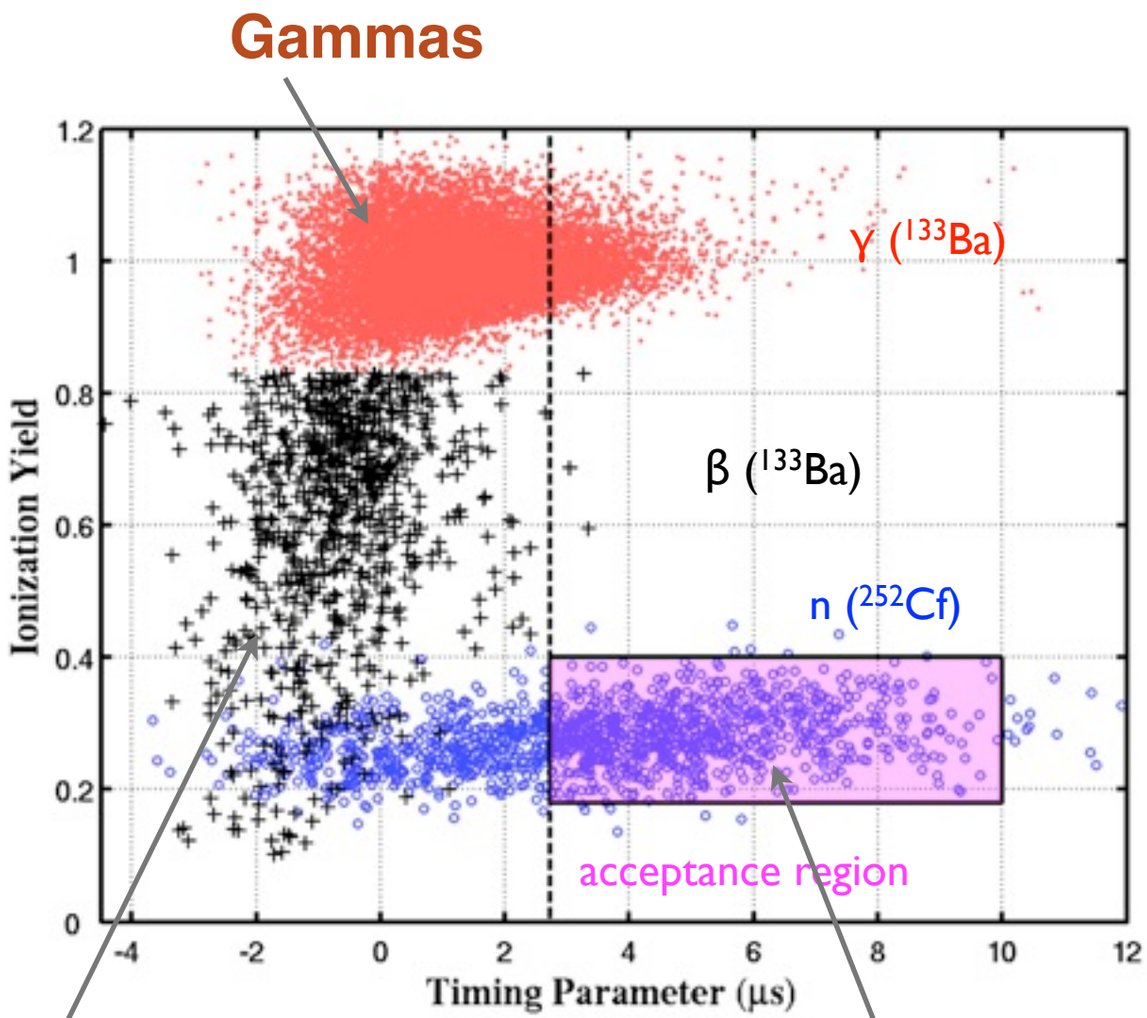


Entrance to the Soudan mine

CDMS: Signal versus Background

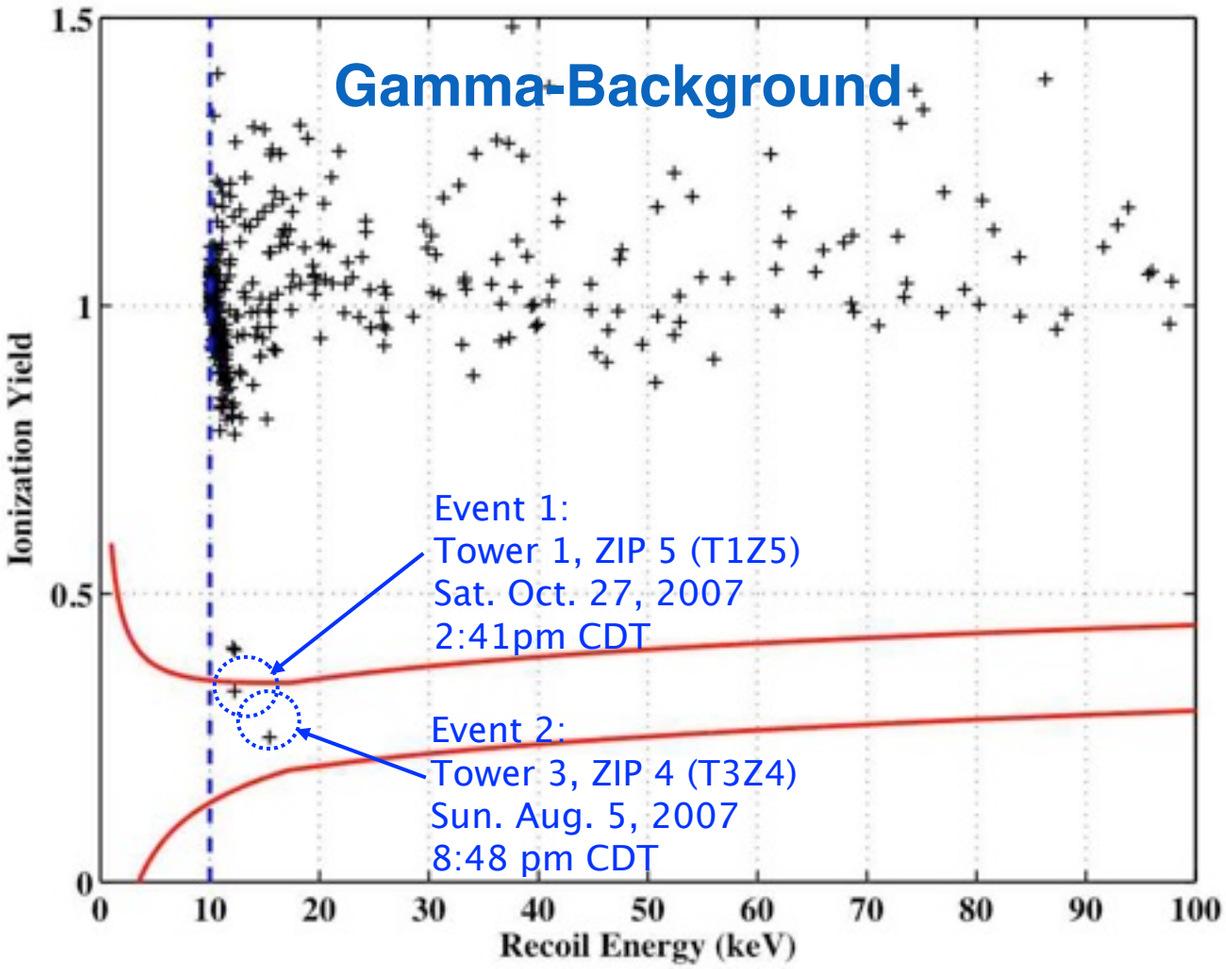
- Ratio of the charge/phonon-signal and time difference between charge and phonon signals => distinguish signal (WIMPs) from background of electromagnetic origin

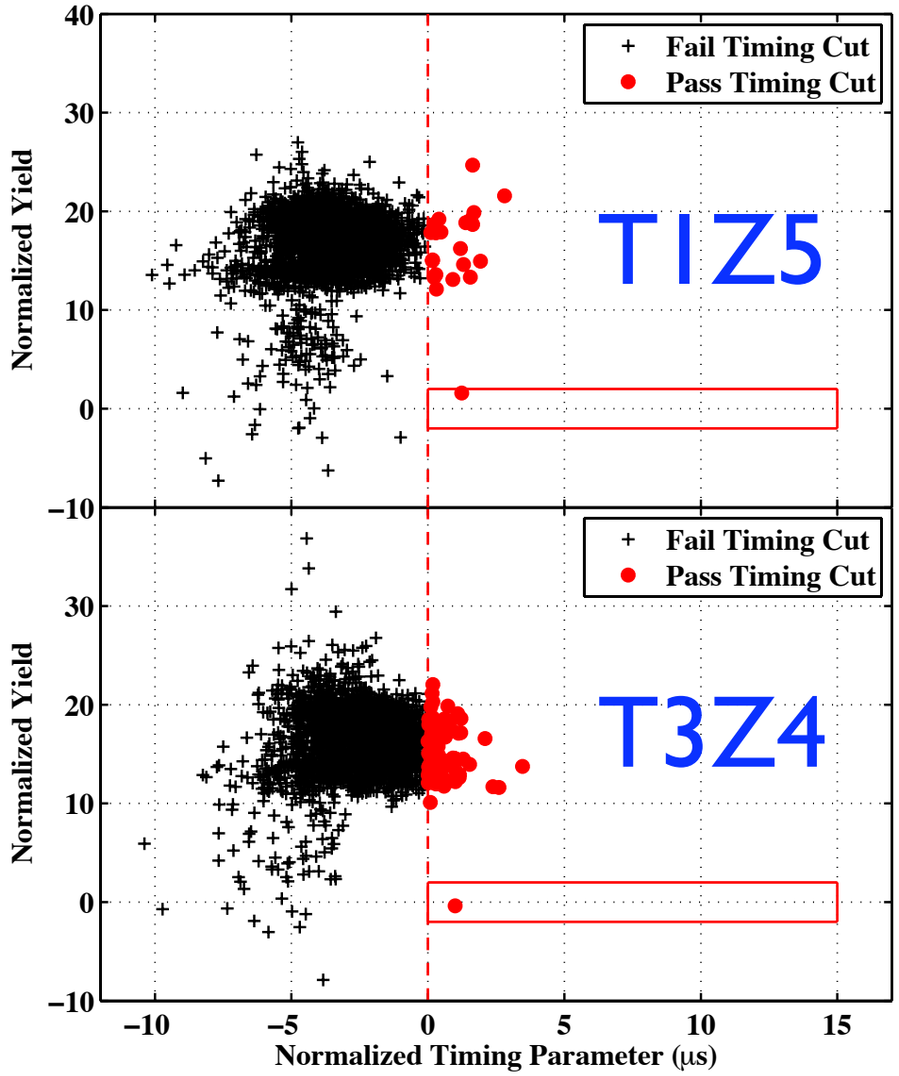




Surface events

Final CDMS WIMP Search Runs: 191 kg days



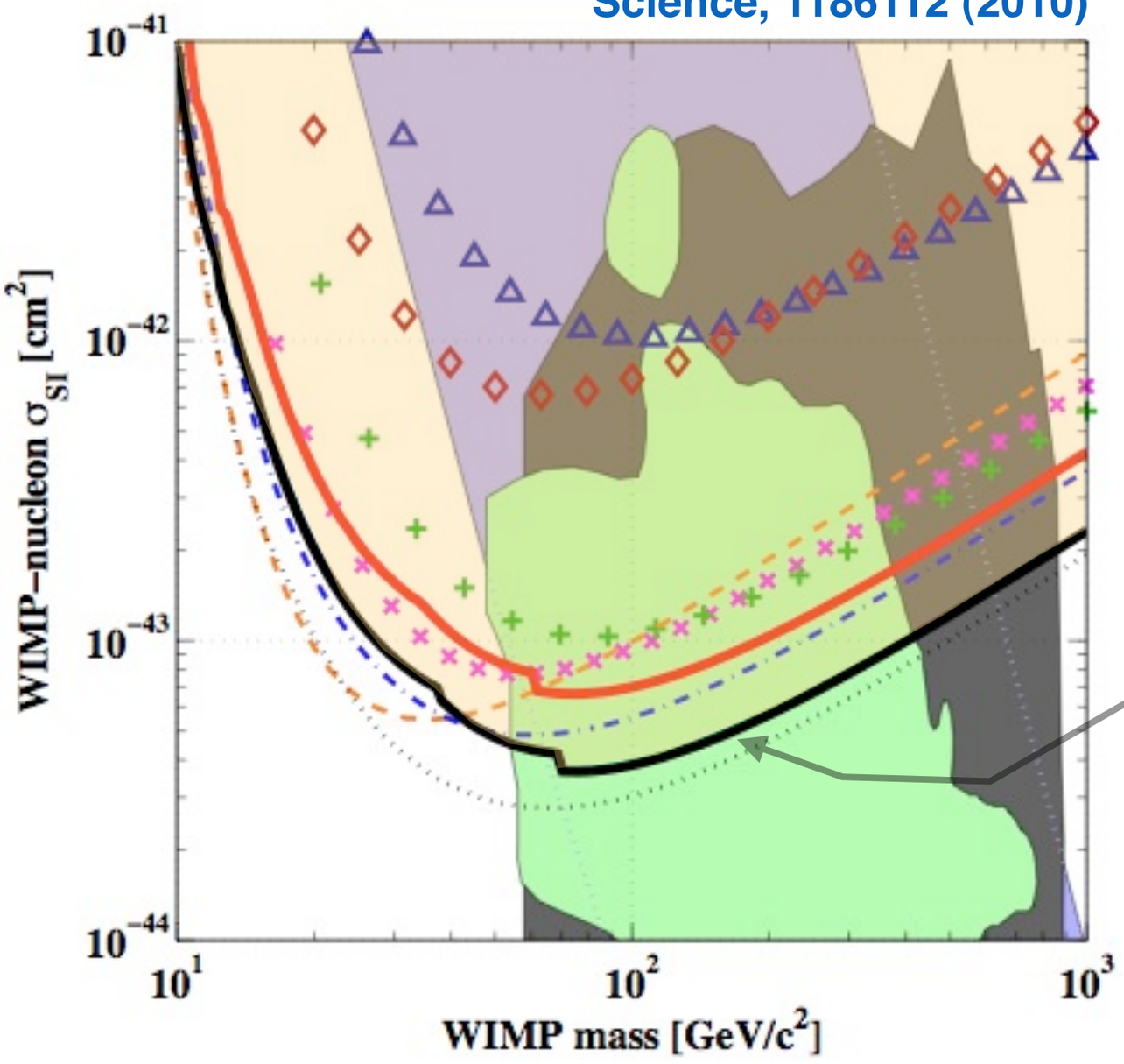


Two events passing all cuts

(which were set based on calibration and background data outside the WS region)

The CDMS 90% Confidence Upper Limit

Science, 1186112 (2010)



- **CDMS combined Soudan data:**
  - ➡ at a WIMP mass of 70 GeV, the limit on the spin-independent WIMP-nucleon cross section is: 3.8×10^{-44} cm^2 (90% C.L.)

- **Background estimate:**
- 0.8±0.1(stat.)±0.2(sys.) surface events

$0.04^{+0.04}_{-0.03}$ cosmogenic neutrons

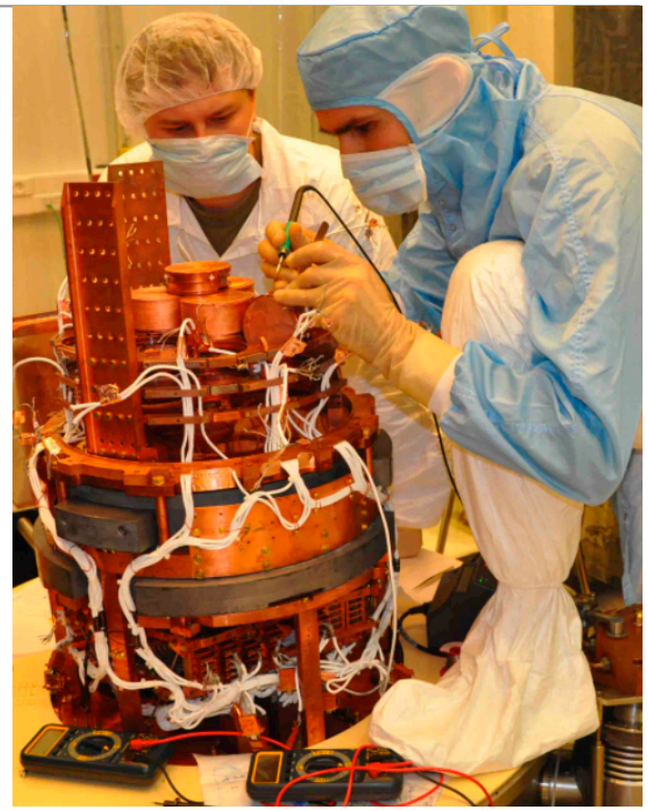
0.04 – 0.06 radiogenic neutrons

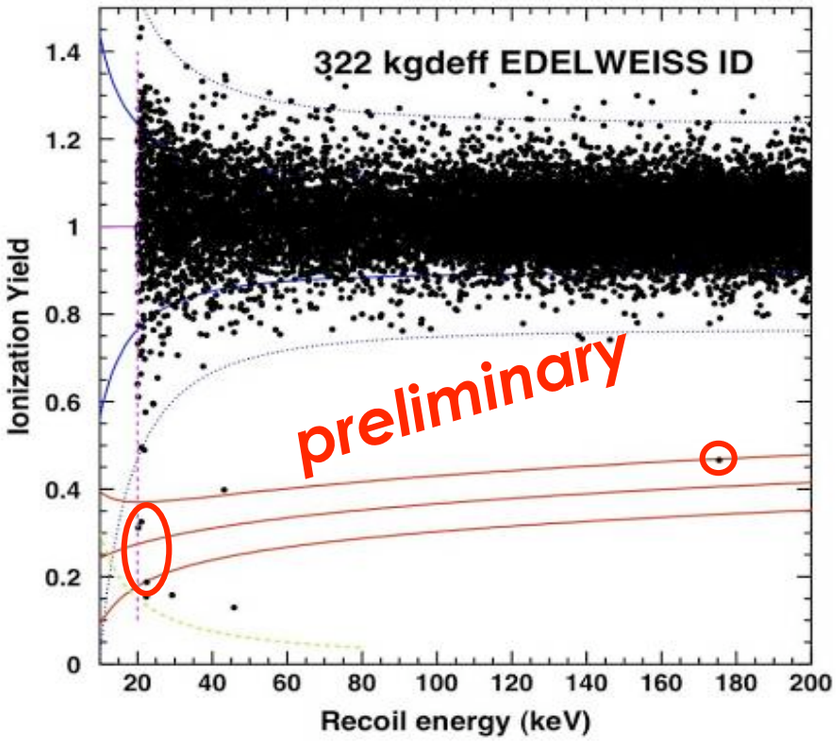
Probability to observe 2 or more background events is 23%

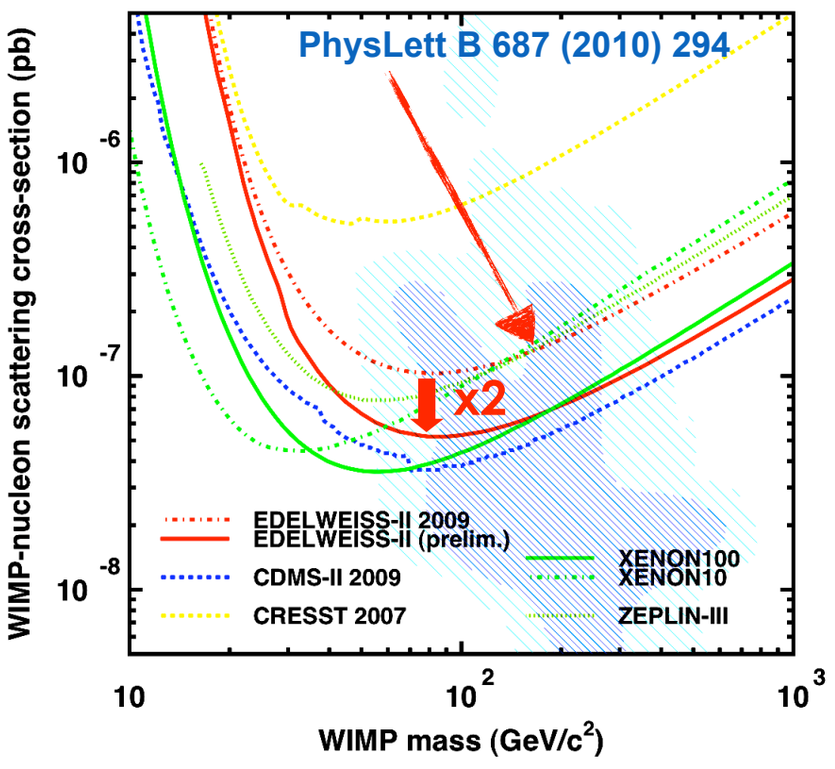
New results: EDELWEISS

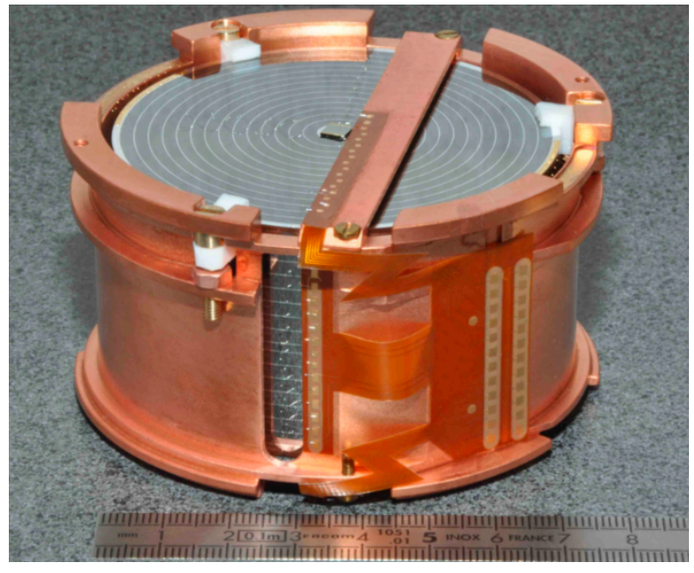
See talk by Klaus Eitel, Friday afternoon

- Bolometric detectors (Ge) at 18 mK at LSM, France
- Latest analysis: **322 kg days** of exposure
  - ➡ 3 events near threshold, 2 outliers (background?)
  - ➡ background estimate < 1.6 events for the run
- New run with 4 x 800 g detectors started on July 3rd
  - ➡ Goal: 40 detectors, 3000 kg days in 2012



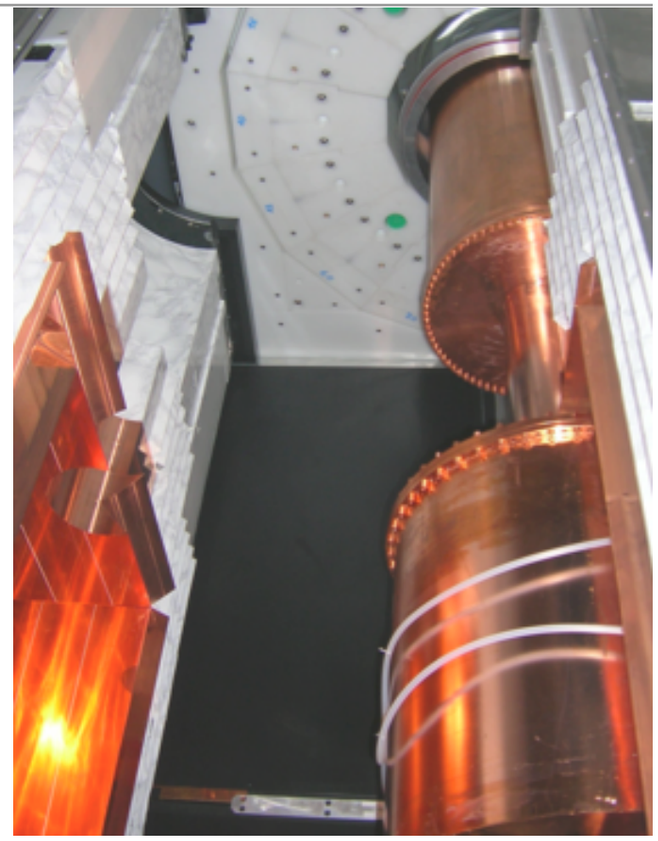


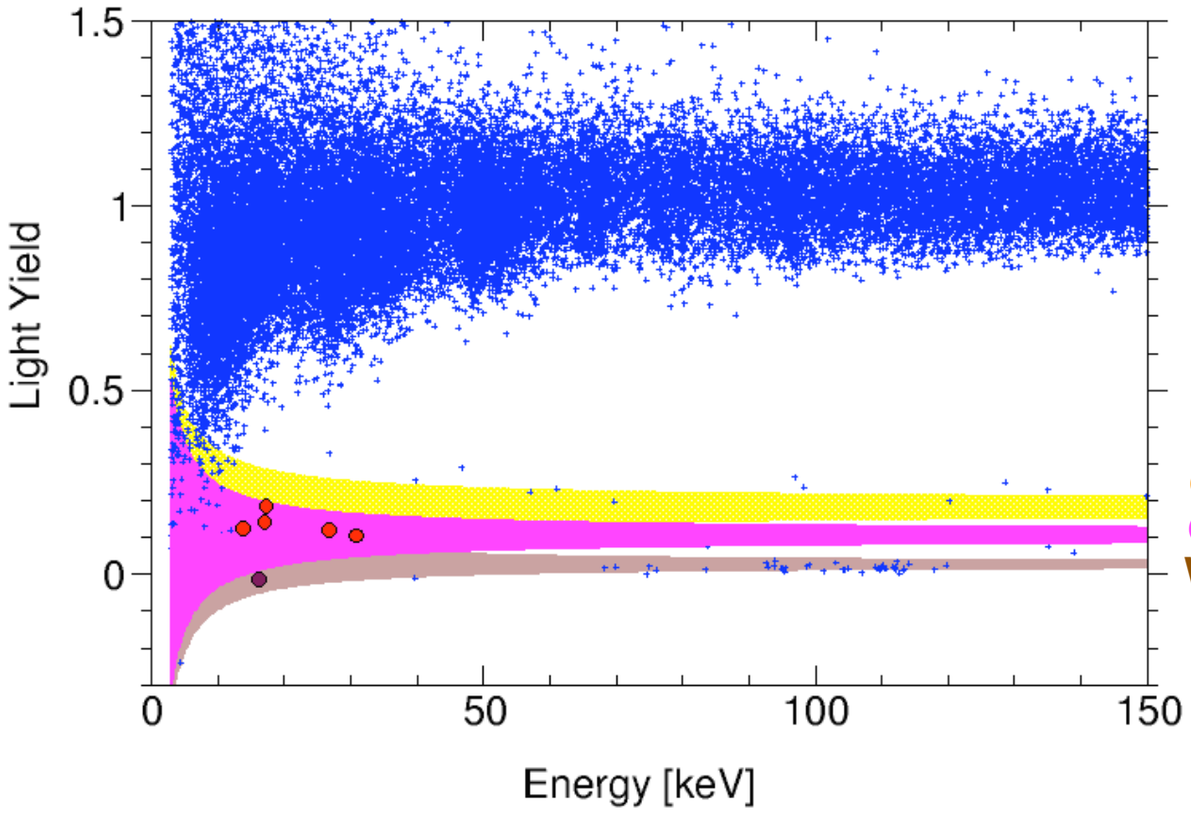




New results: CRESST

- Bolometric detectors ($CaWO_4$) at 20 mK at LNGS, Italy
- Latest analysis: ~ **400 kg days** of exposure
  - ➡ 32 events observed
  - ➡ background estimate 8.7 ± 1.4 events for the run
- Next step: new run with strongly reduced α background
- Goal: 40 detectors, 3000 kg days in 2012



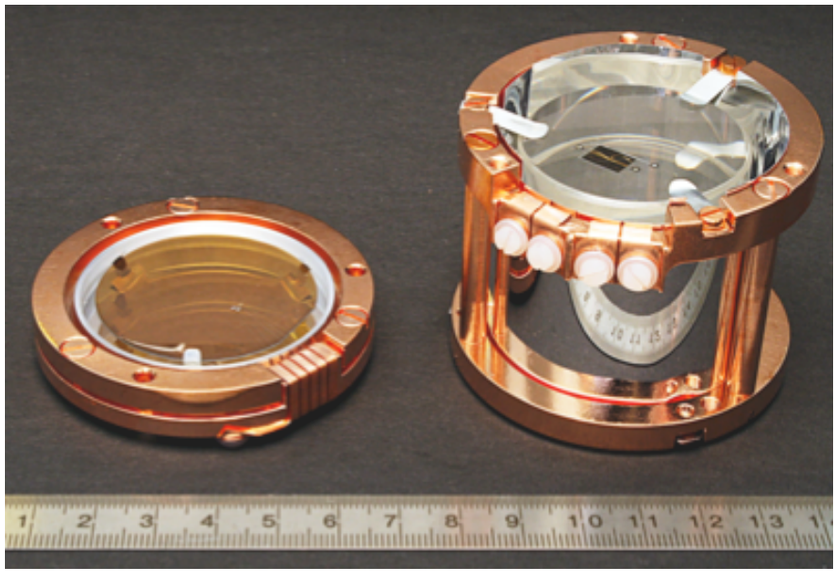


γ + β band

α band (Pb-recoils)

O-recoil band

W-recoil band



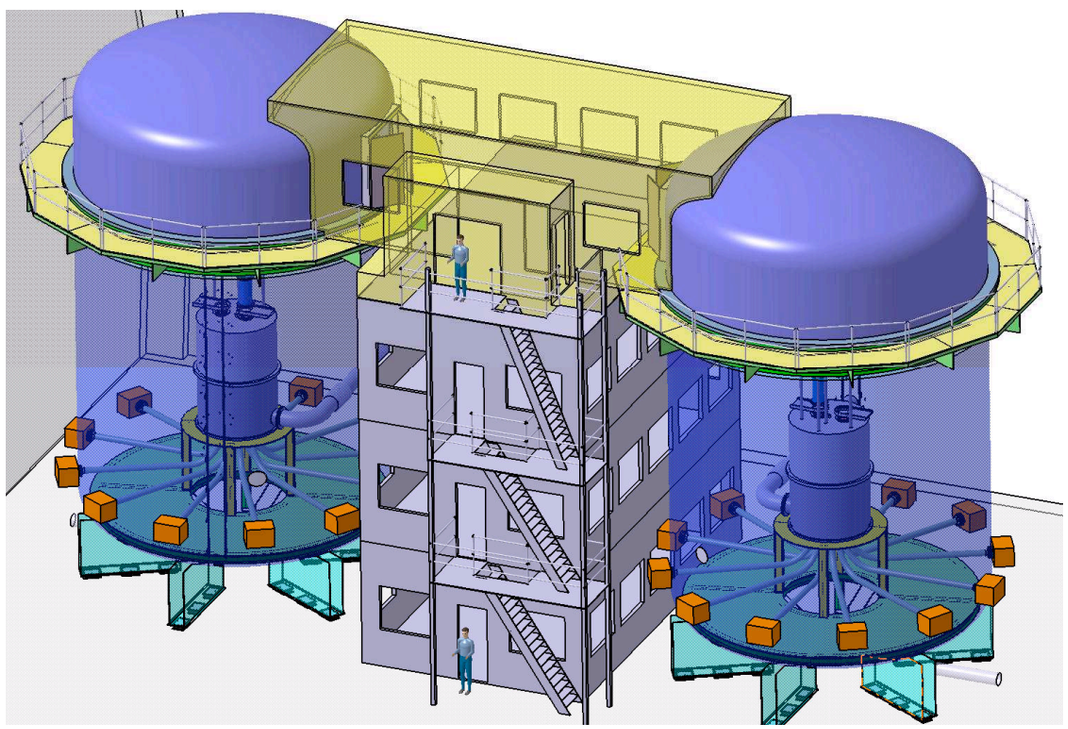
Cryogenic mK Experiments: Near Future

EURECA at ULISSE Lab (LSM extension)

Joint effort for 100 kg -1t experiment in Europe
Cresst, Edelweiss, Rosebud + others
Multi-target approach

Design study (2009-2012) :
approved by ASPERA first call

Operation:
by 2015 (150 kg version)
2018 (1 ton version)



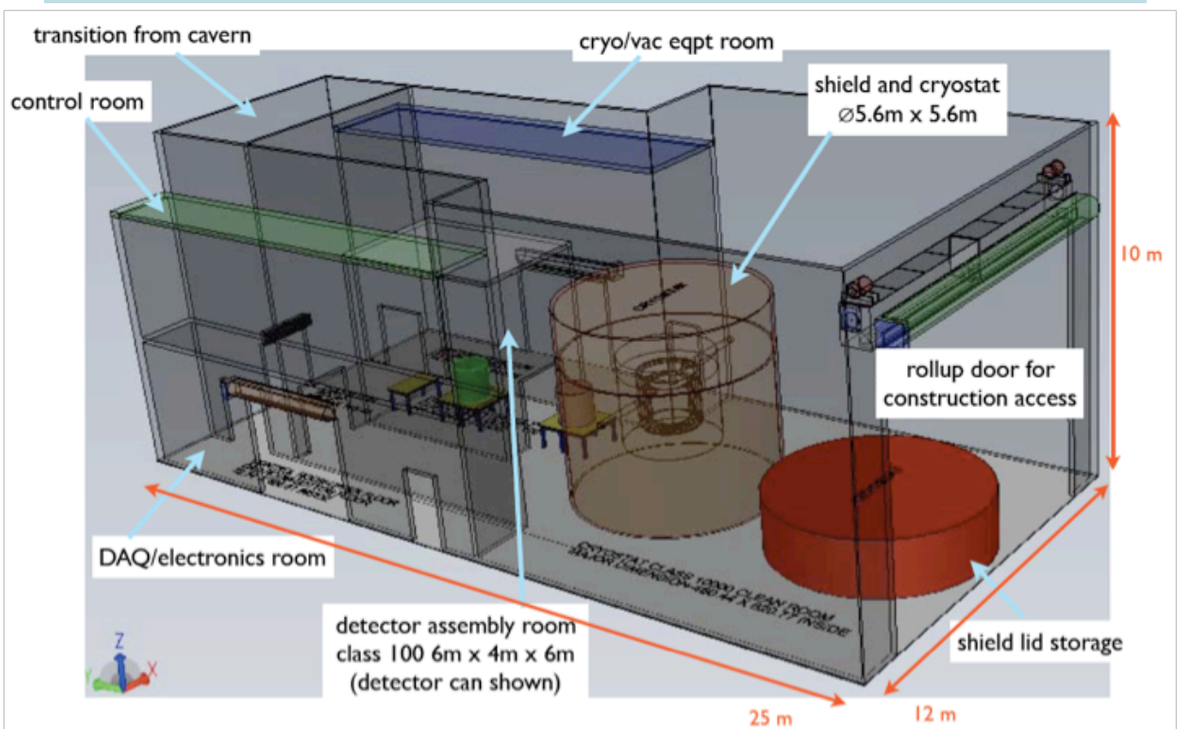
SuperCDMS/GEODM at Soudan/SNOLAB/DUSEL

US/Canada program for 15 kg - 1.5 t Ge experiment

15 kg at Soudan, approved
(detectors: 1" thick ZIPs, each 650 g of Ge; first SuperTower run has been completed)

100 kg at SNOLAB

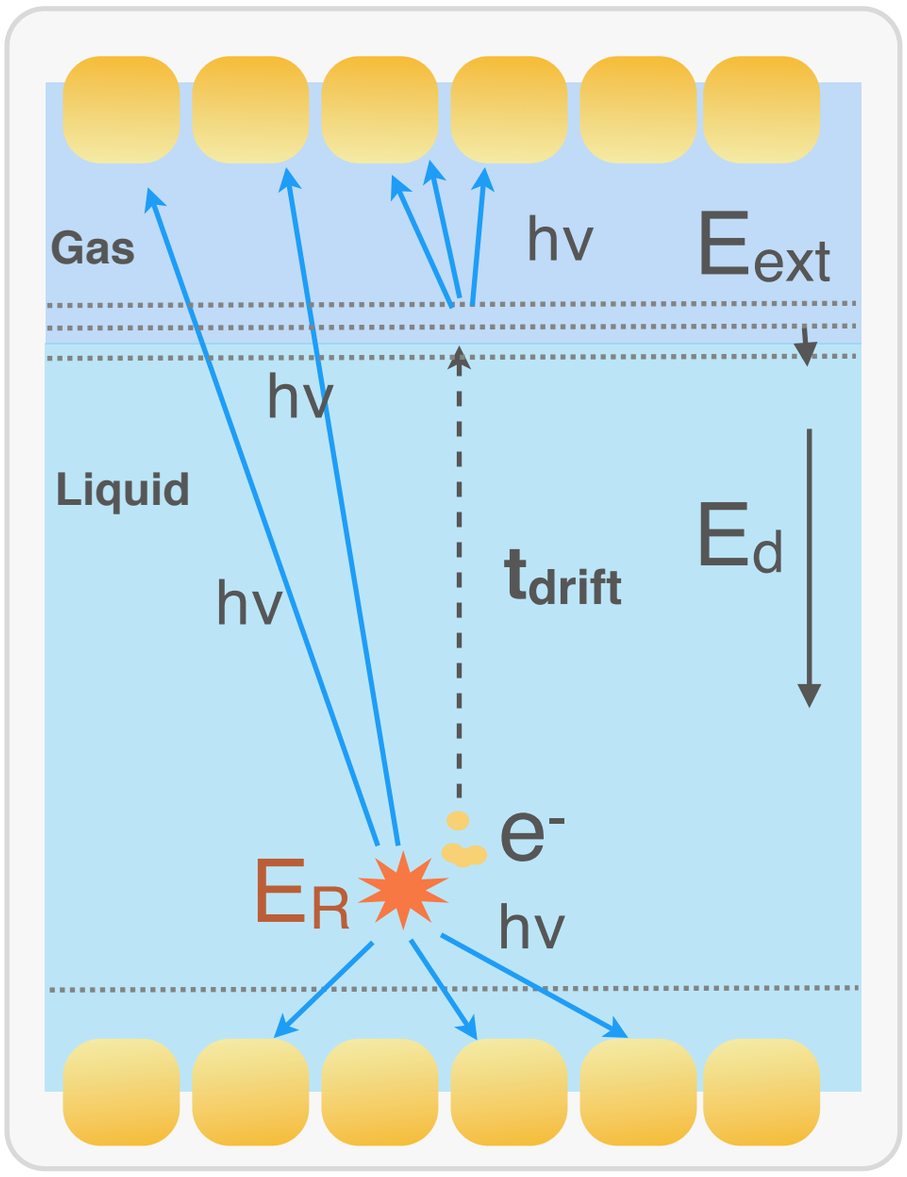
1.5 tons at DUSEL



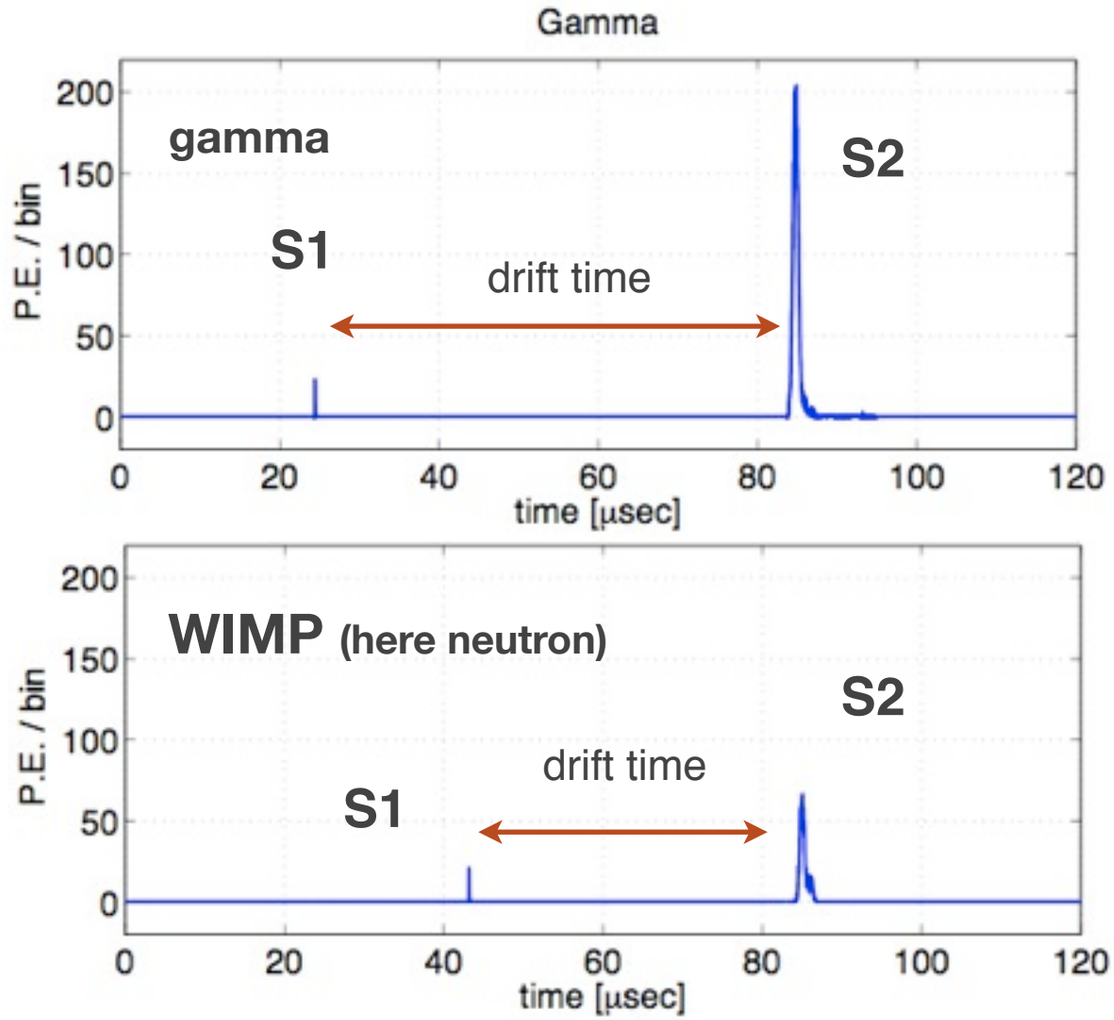
Noble Liquids Time Projection Chambers

Ar (A = 40); λ = 128 nm
Xe (A=131); λ = 175 nm

- **Dense, homogeneous targets/detectors; high light and charge yields**
- **Prompt (S1) light signal** after interaction in active volume; charge is drifted, extracted into the gas phase and detected as **proportional light (S2**)

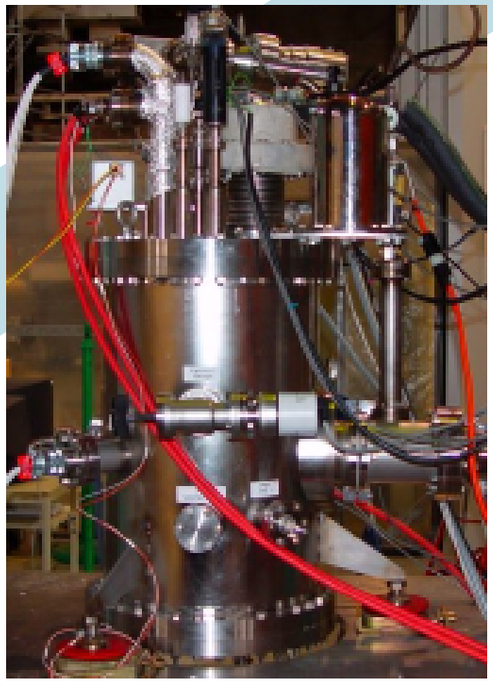


- S2/S1 depends on dE/dx
- good 3D position resolution } **=> particle identification**



The XENON Program

XENON10

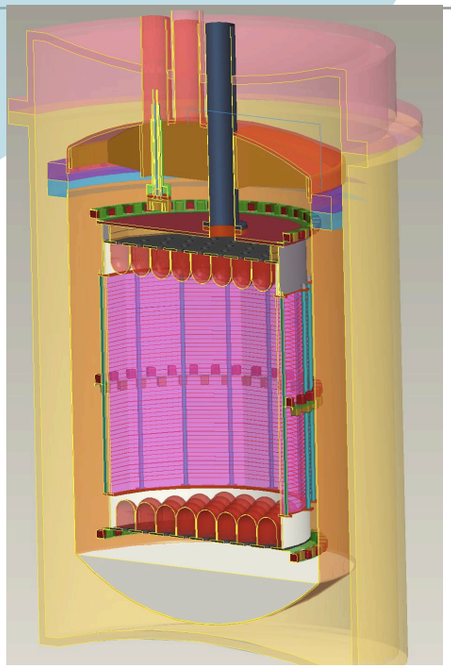


2005-2007

XENON100

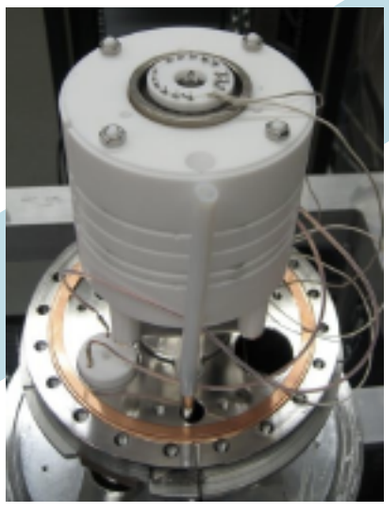
2008-2011
taking science data

XENON1t



2011-2015
studies in progress
technical proposal
submitted to LNGS
end of April, 2010

XENON R&D

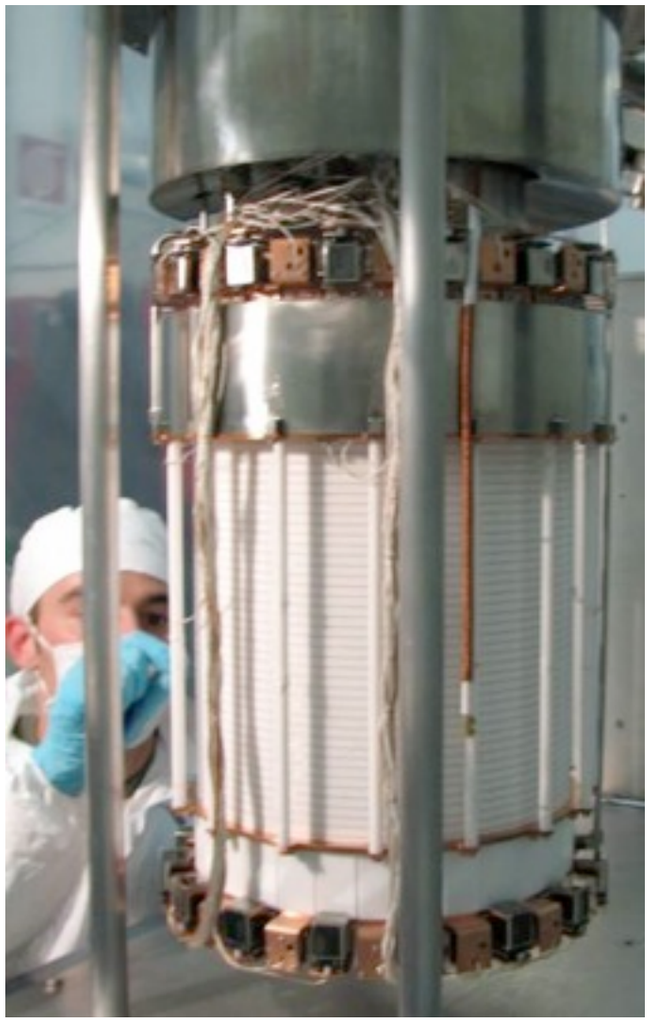


ongoing

Columbia, Zürich, Coimbra, Rice (Mainz), LNGS, Münster, MPIK, Subatech, SJTU, UCLA, Bologna, Torino, Nikhef

The XENON100 Experiment at LNGS

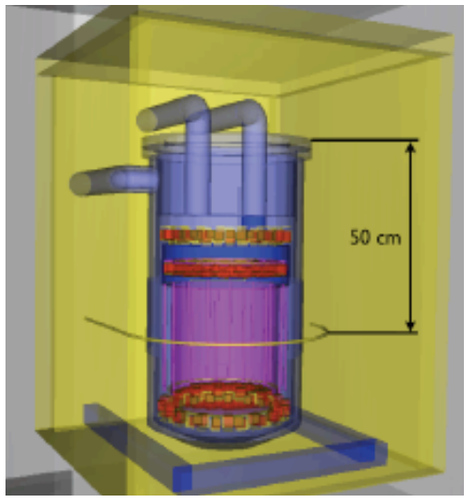
- 161 kg ultra-pure LXe: 62 kg in the active target surrounded by 99 kg LXe as scintillator veto
- 30 cm drift gap TPC with two PMT arrays to detect both charge and light signals
- 242 1-inch square PMTs with < 1 mBq/PMT in $^{238}U/^{232}Th$ and high QE (25-33%) at 178 nm
- 3D event localization with few mm x-y-z resolution

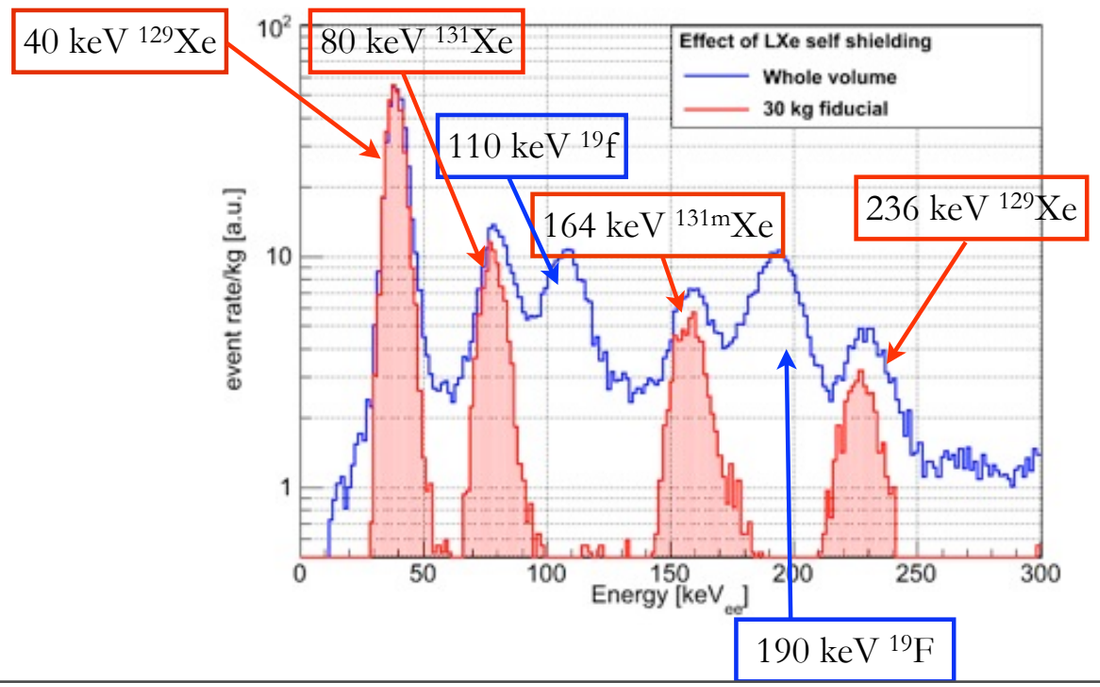


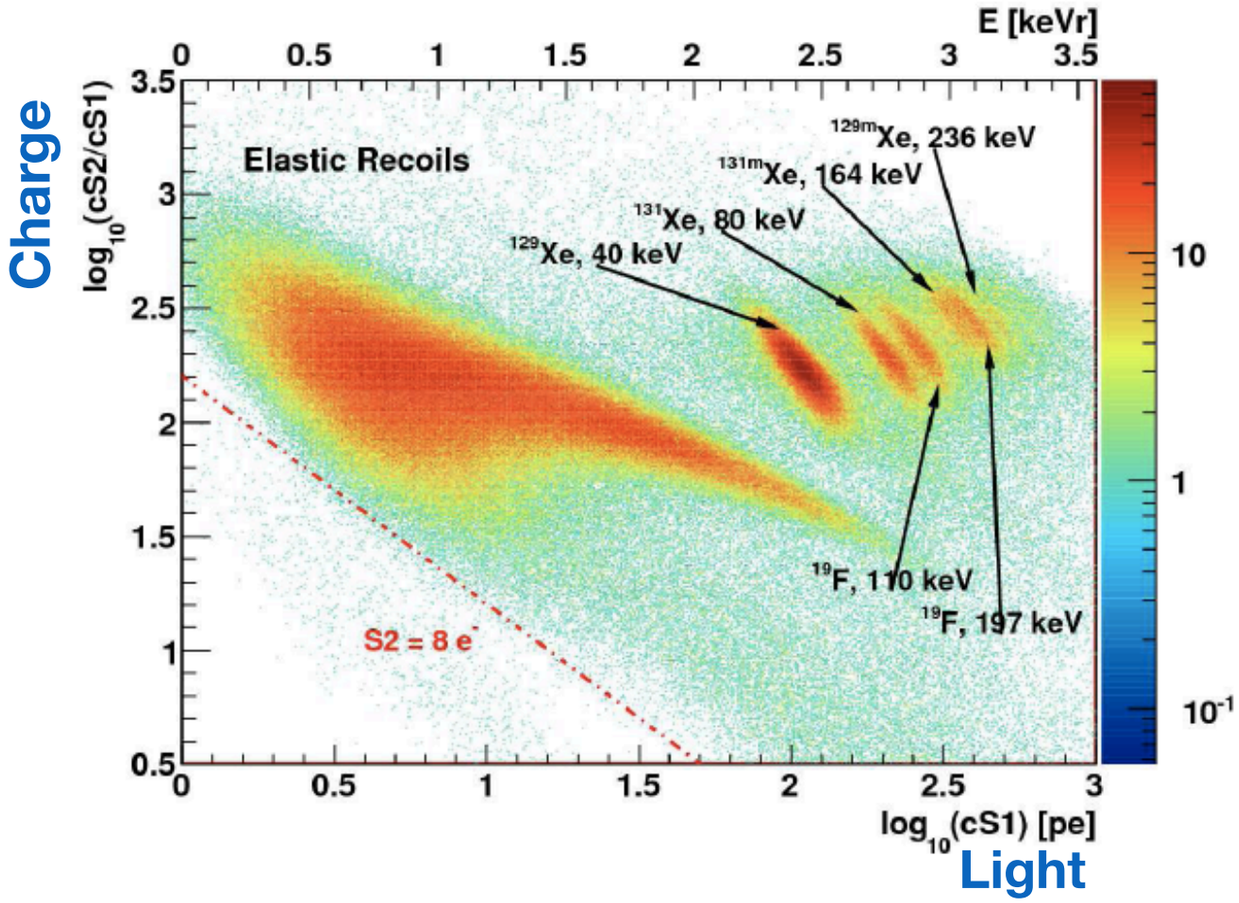
The XENON100 detector in its low-background shield at LNGS

XENON100 Neutron Calibrations

- AmBe (~ MeV neutrons) data to map the nuclear recoil band, 220 n/s
- Inelastic n-scattering on Xe: $^{129,131}Xe + n \rightarrow {}^{129,131}Xe + n + \gamma$ (40 keV, 80 keV)







Gammas from inelastic scatters used to check/correct signal dependency with position

XENON100 Backgrounds: Data and Predictions

- Preliminary: **data** and **MC** (no MC tuning; before the active LXe veto cut)
- More detailed studies are in progress (include cosmogenics)
- The background meets the design specifications:

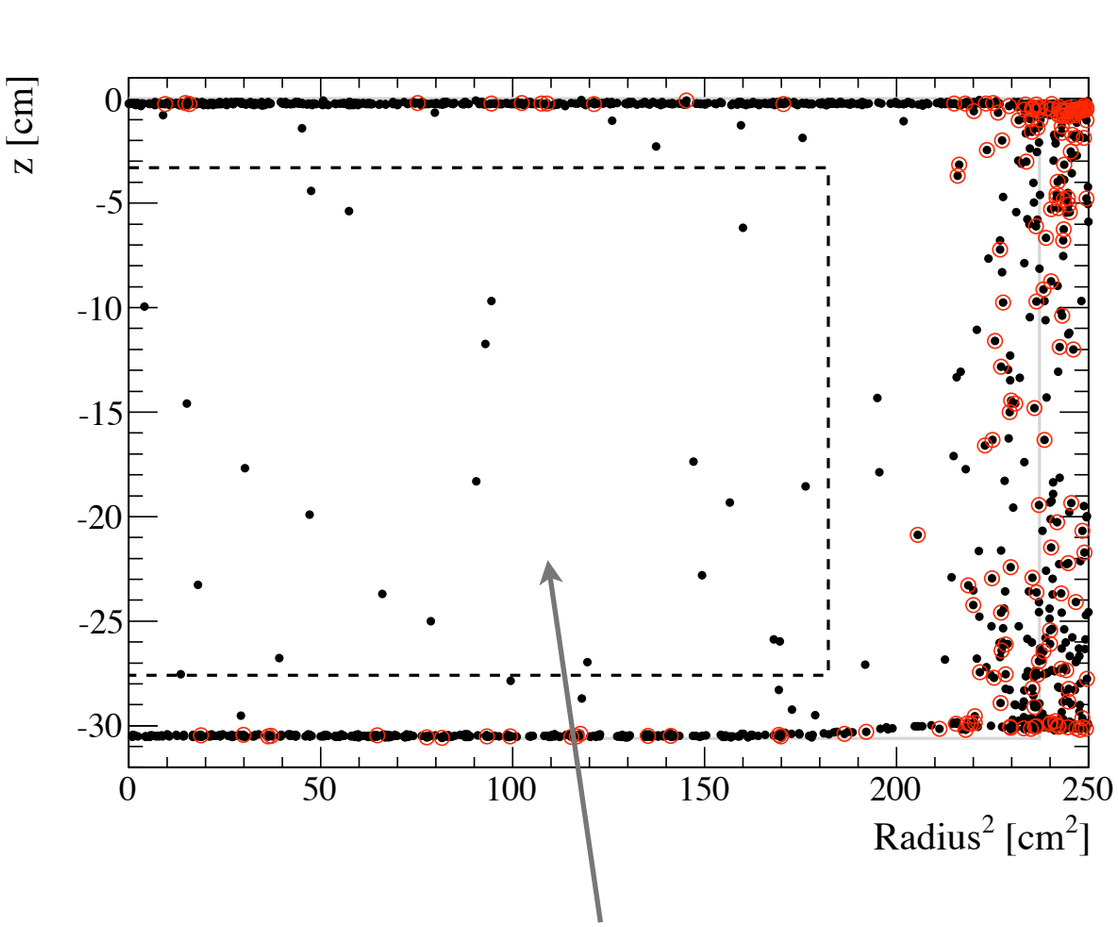
  ➡ **100 times lower than in XENON10** (and than in any other direct dark matter detection experiment)

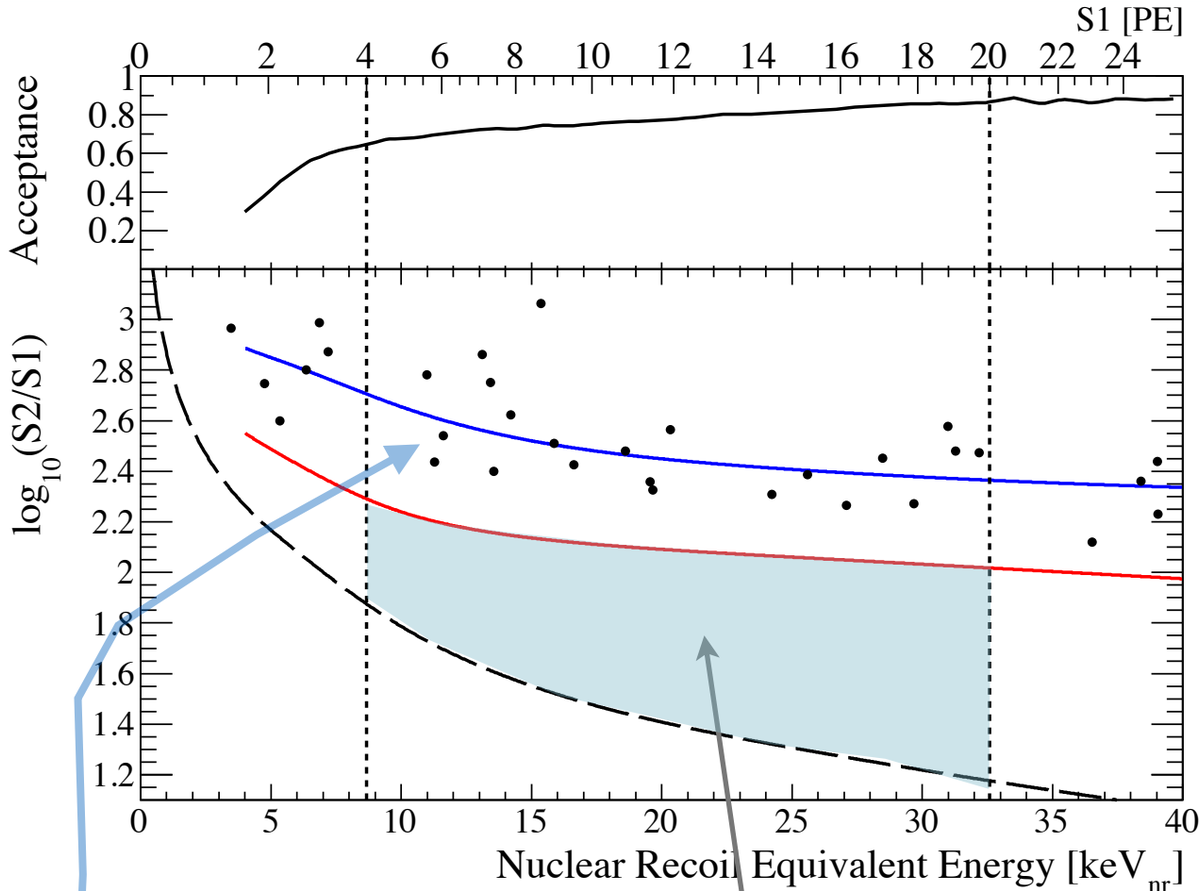
Overall XENON100 background spectrum

Zoom into the low energy region

Analysis of XENON100 “non-blinded” data

Exposure ≈ 170 kg days = 11.2 live days × 40 kg × 0.76 (ε) × 0.50 (50% NR acceptance)
(data taken between Oct - Nov 2009)

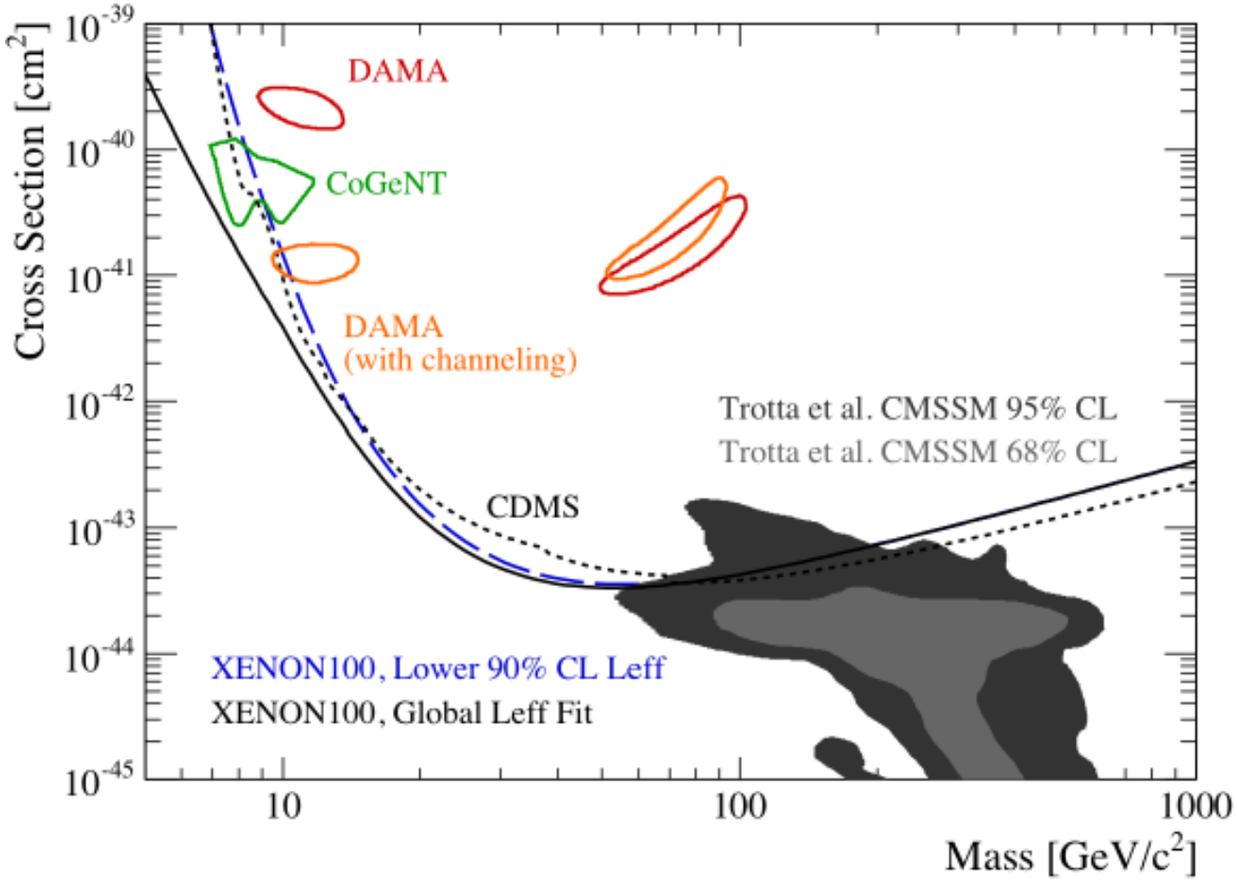


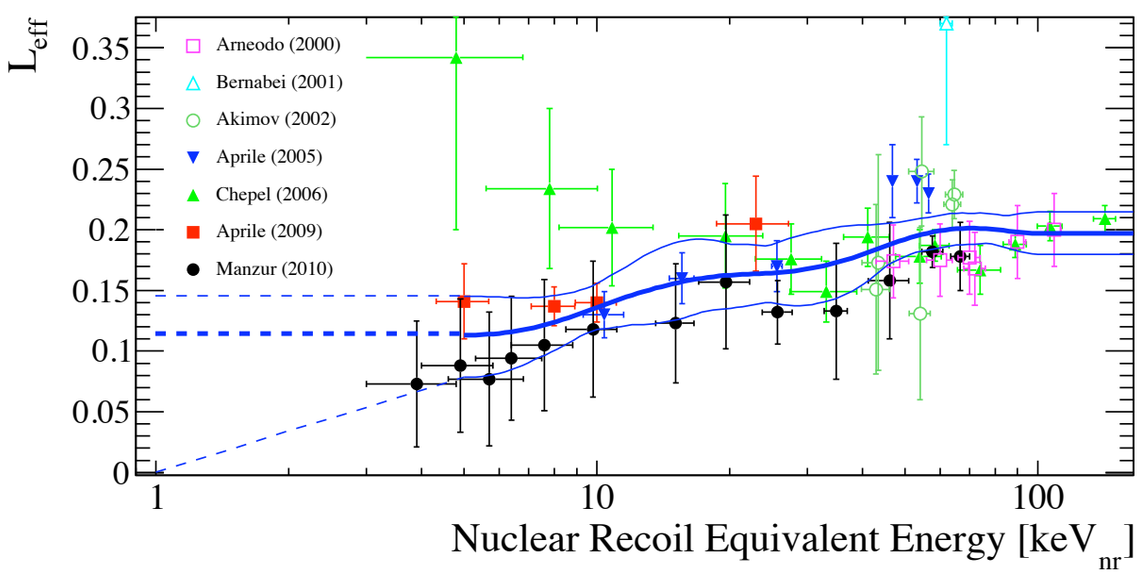


Fiducial mass region:
40 kg of liquid xenon
22 events (all ER background)

Signal region:
no events are observed in
the given exposure

XENON100: First Spin-Independent Results



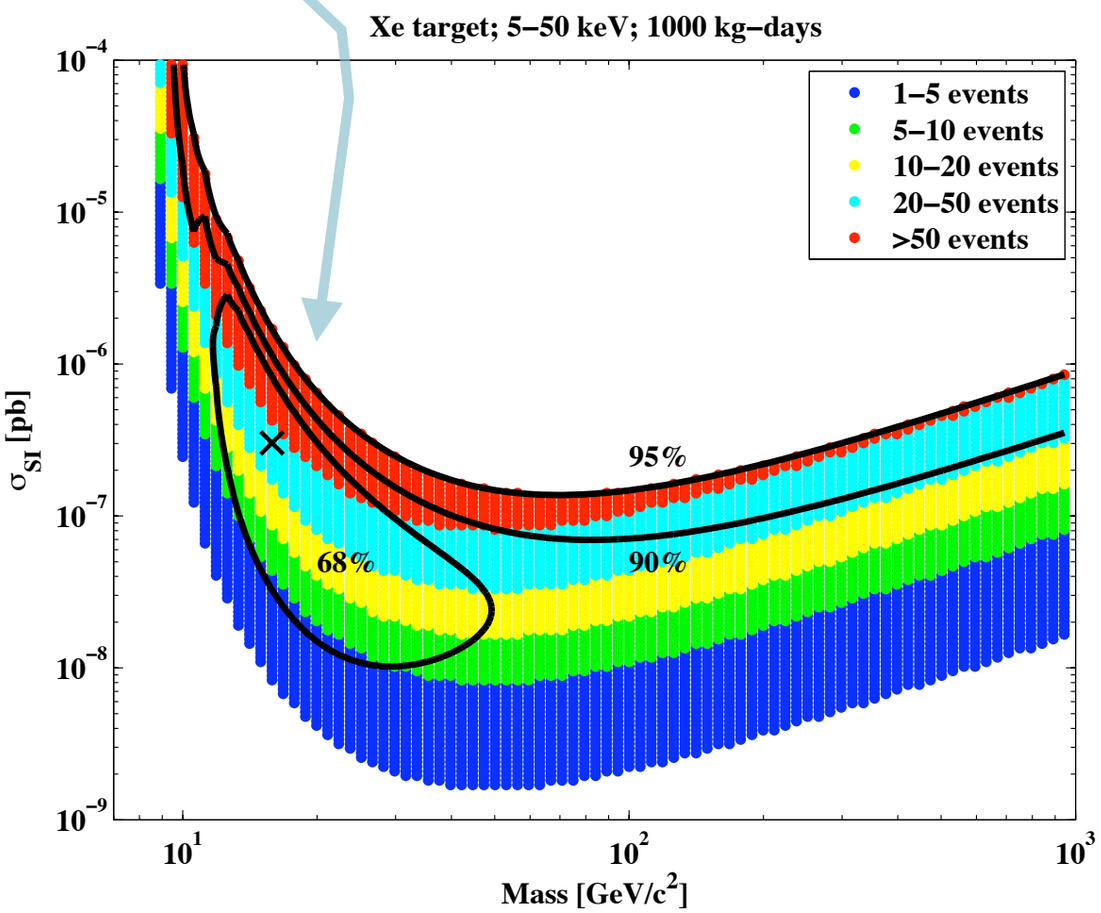


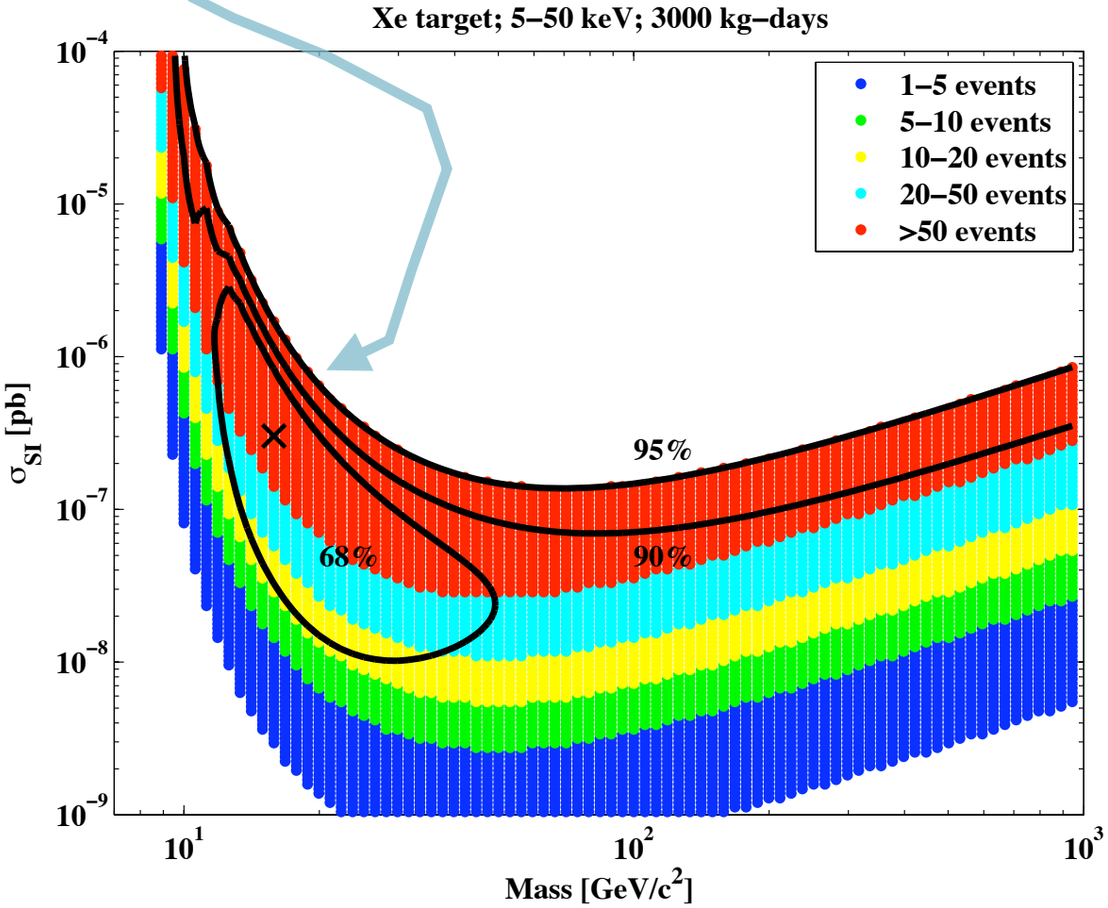
XENON100 collaboration
arXiv:1005.0380v2
PRL 2010, in press

- **New upper limit:** based on zero events in the pre-defined signal region
  - ➡ at a WIMP mass of 55 GeV, the limit on the spin-independent WIMP-nucleon cross section is: 3.4 x 10^{-44} cm^2 (90% C.L.)
- **WIMP search run started on January 13, 2010**
  - ➡ science data throughout 2010
  - ➡ annual modulation analysis
  - ➡ analysis of the ER spectrum
  - ➡ analysis of the large (masked) data set

Let's dream for a moment...

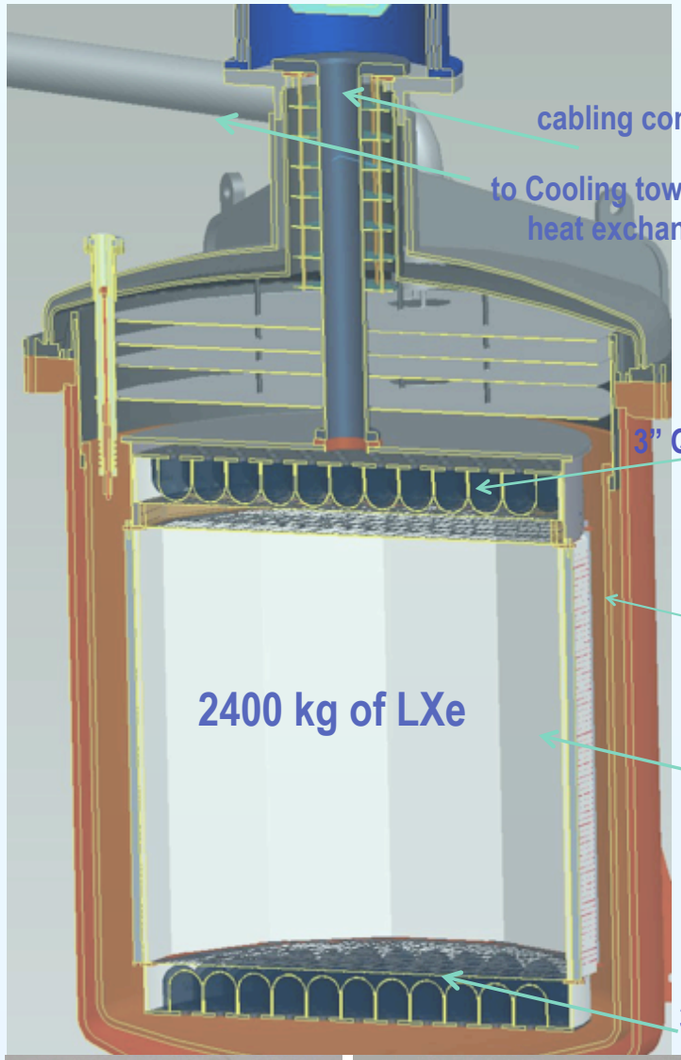
- What if the two CDMS events are WIMPs?... *What would XENON100 see?*
- Assumptions:
  - ➡ 50 kg x 40 days x 50% signal acceptance = **1000 kg days exposure**
  - ➡ 30 kg x 200 days x 50% signal acceptance = **3000 kg days exposure** (lower background)





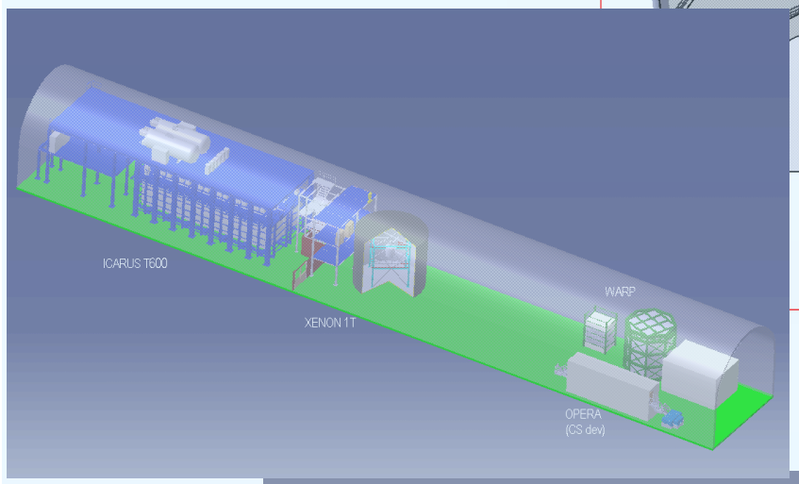
Next Step: XENON1T

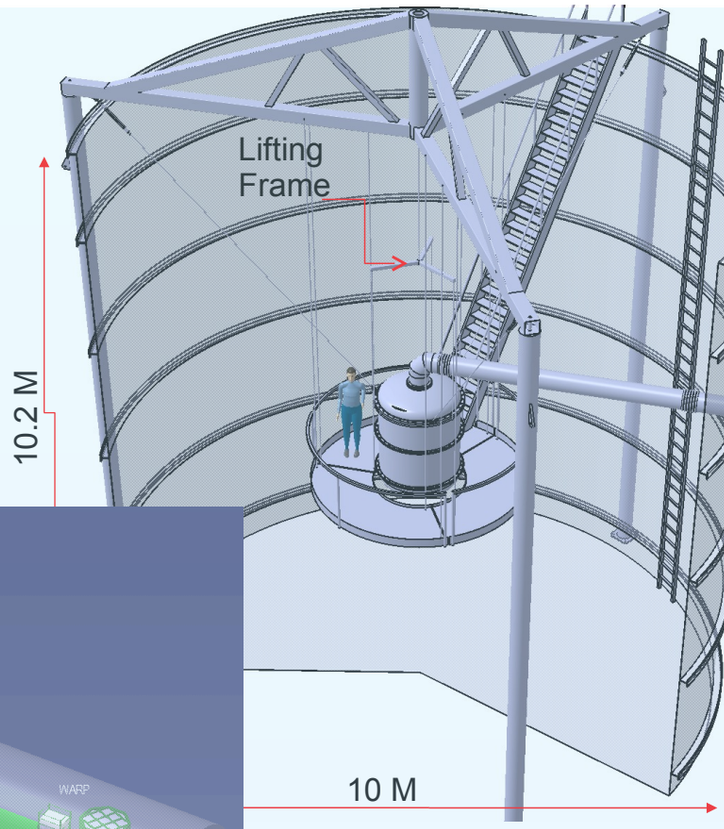
Construction starting in 2011
Dark matter run in 2013

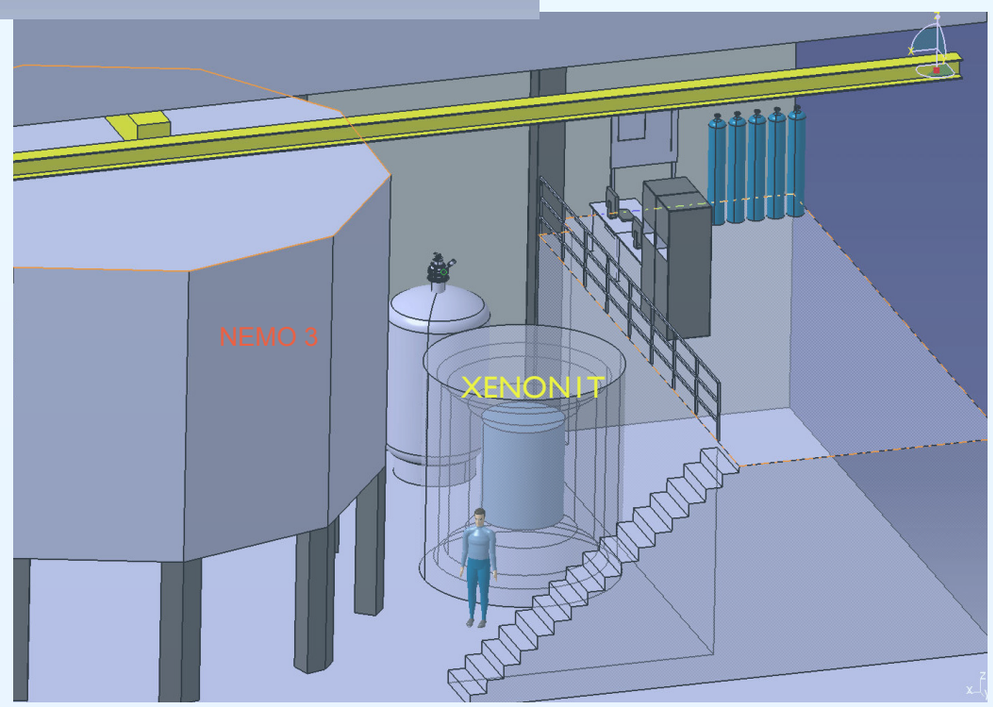


Hybrid photo-sensors

LNGS option (Hall B)







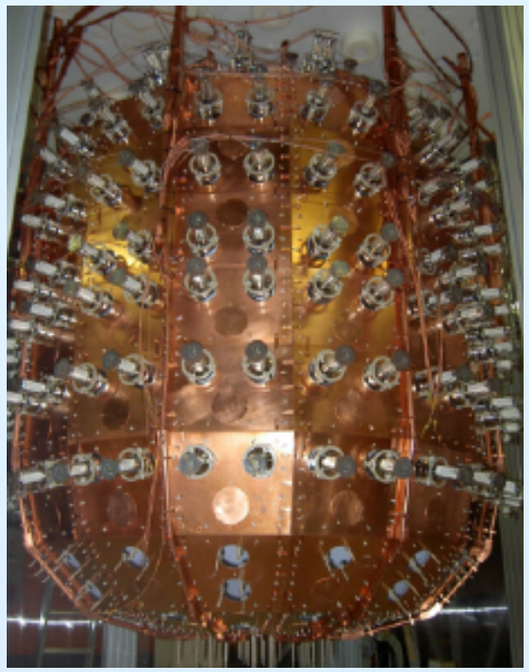
LSM option

Two-phase Argon Detectors

WARP at LNGS

WIMP target: 140 kg LAr
- S1 and S2 read-out with 41 x 3'' PMTs
- active LAr shield: ~ 8t, viewed by 300 PMTs

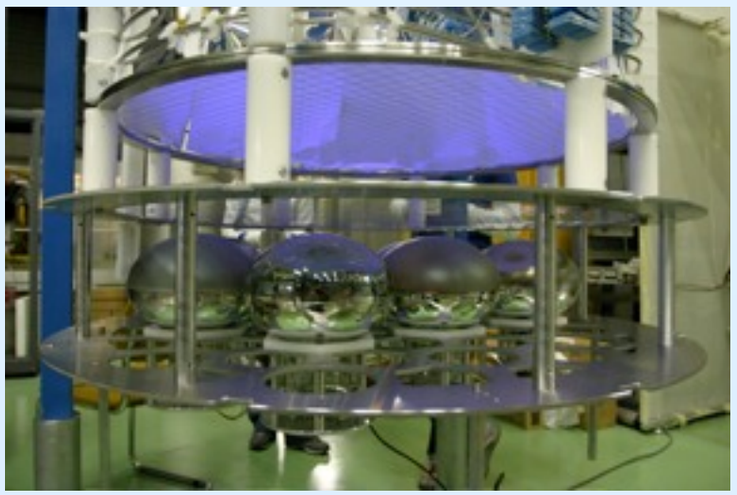
Detector had been installed in December 08
Some technical problems with HV
Now again under commissioning at LNGS

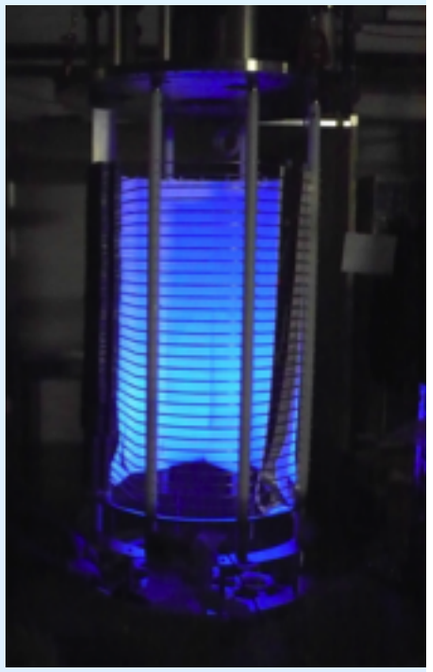


ArDM at CERN

WIMP target: ~1 ton LAr
- S1 read-out with 14 x 8'' PMTs
- direct electron readout via LEMs
  (thick macroscopic GEM)

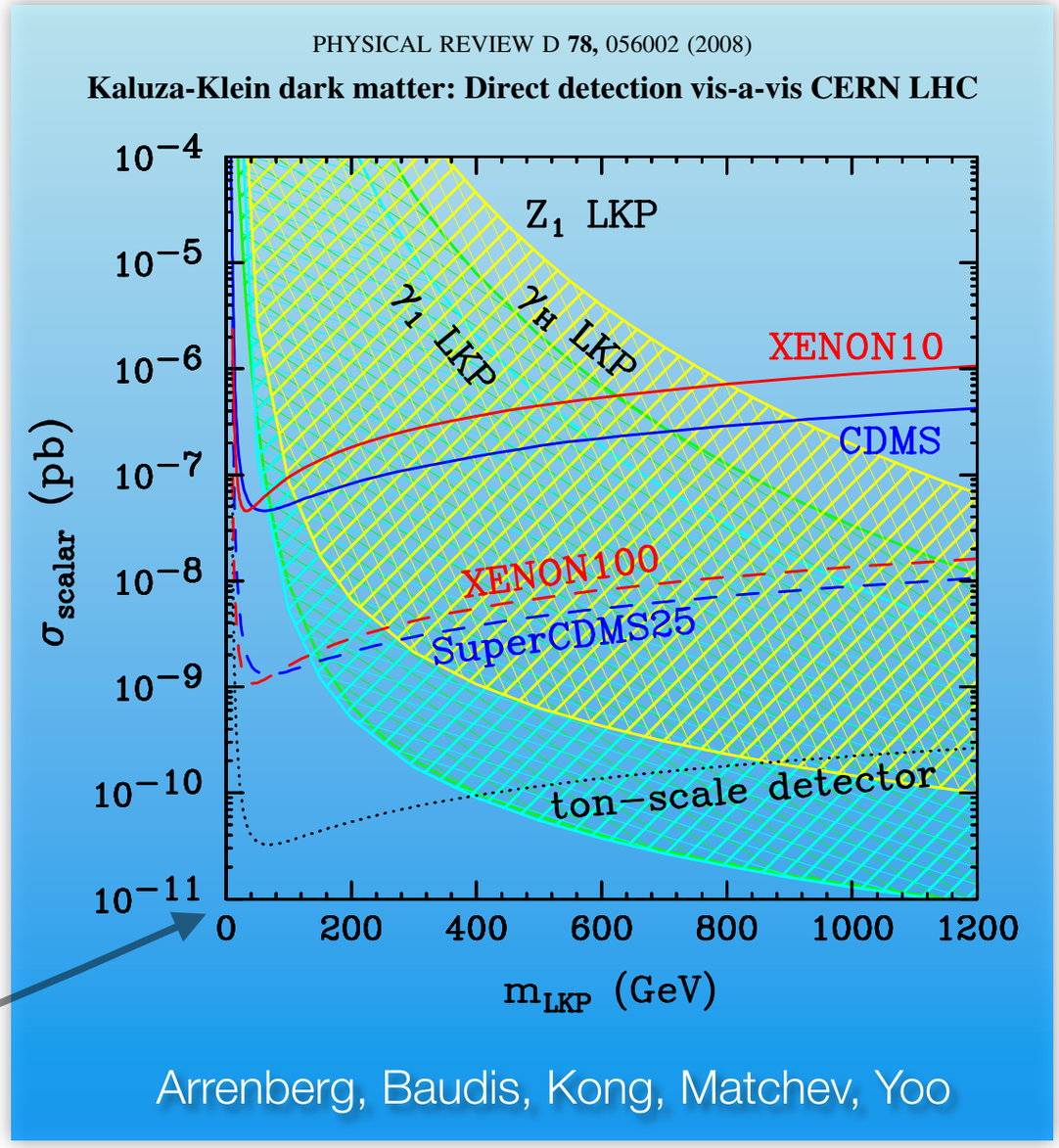
Detector is being commissioned at CERN
Underground operation: LS Canfranc in 2011





DARWIN
(DARk matter WImp search with Noble liquids)

- R&D and design study for **next-generation noble liquid facility in Europe**
- Approved by ASPERA (AStroParticle ERAnet) in late 2009
- **Focus:** coordinate existing European activities in liquid argon and xenon towards the construction of a multi ton dark matter facility
- **Possible locations**: LNGS (Italy) or ULISSE (Modane extension, France)
- **Physics goal**: probe WIMP-nucleon SI cross sections well below 10^{-47} cm^2



DARWIN

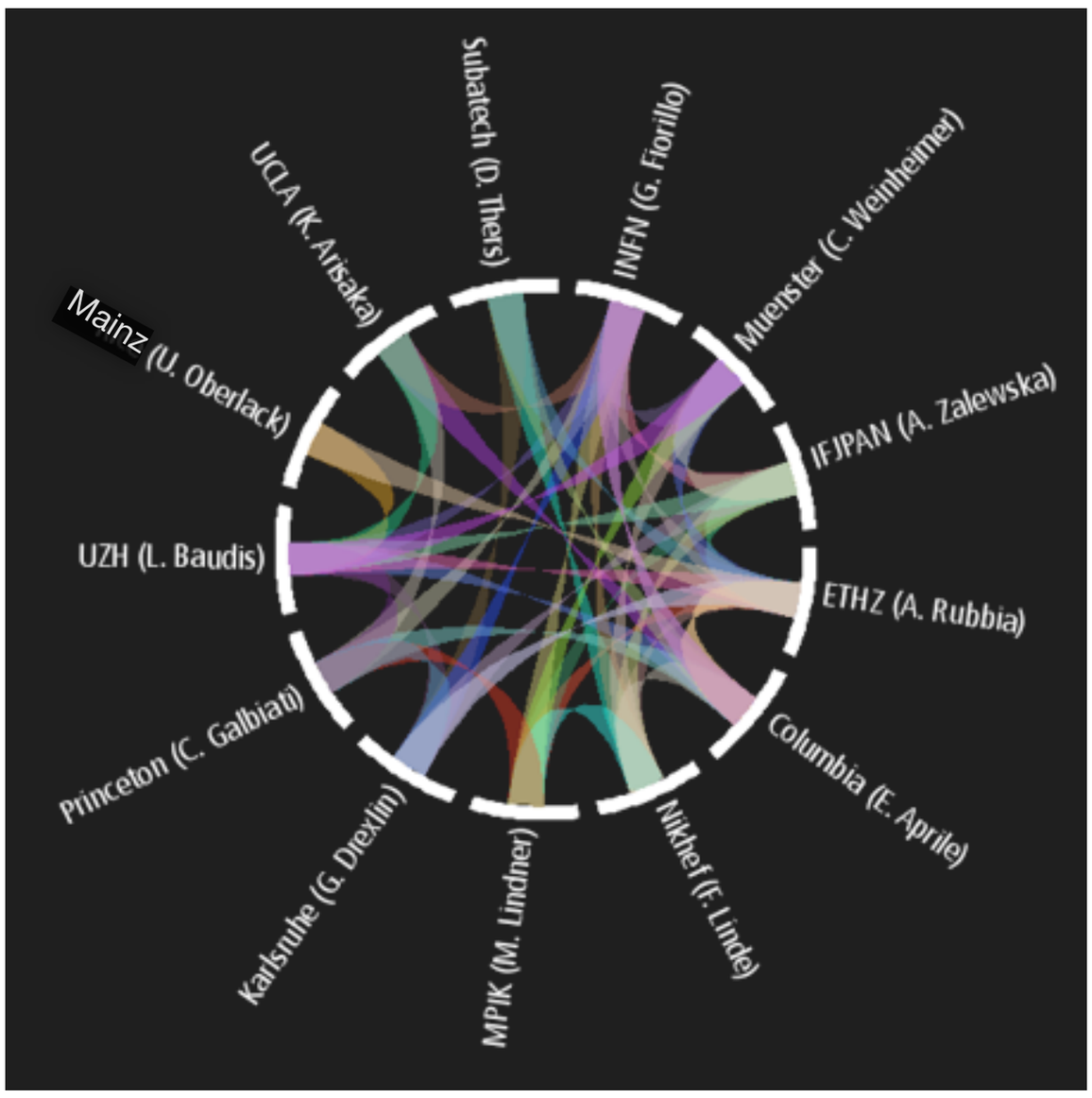
Institutions and Connections

A total of 22 groups from:

ArDM and WARP for LAr
XENON for LXe

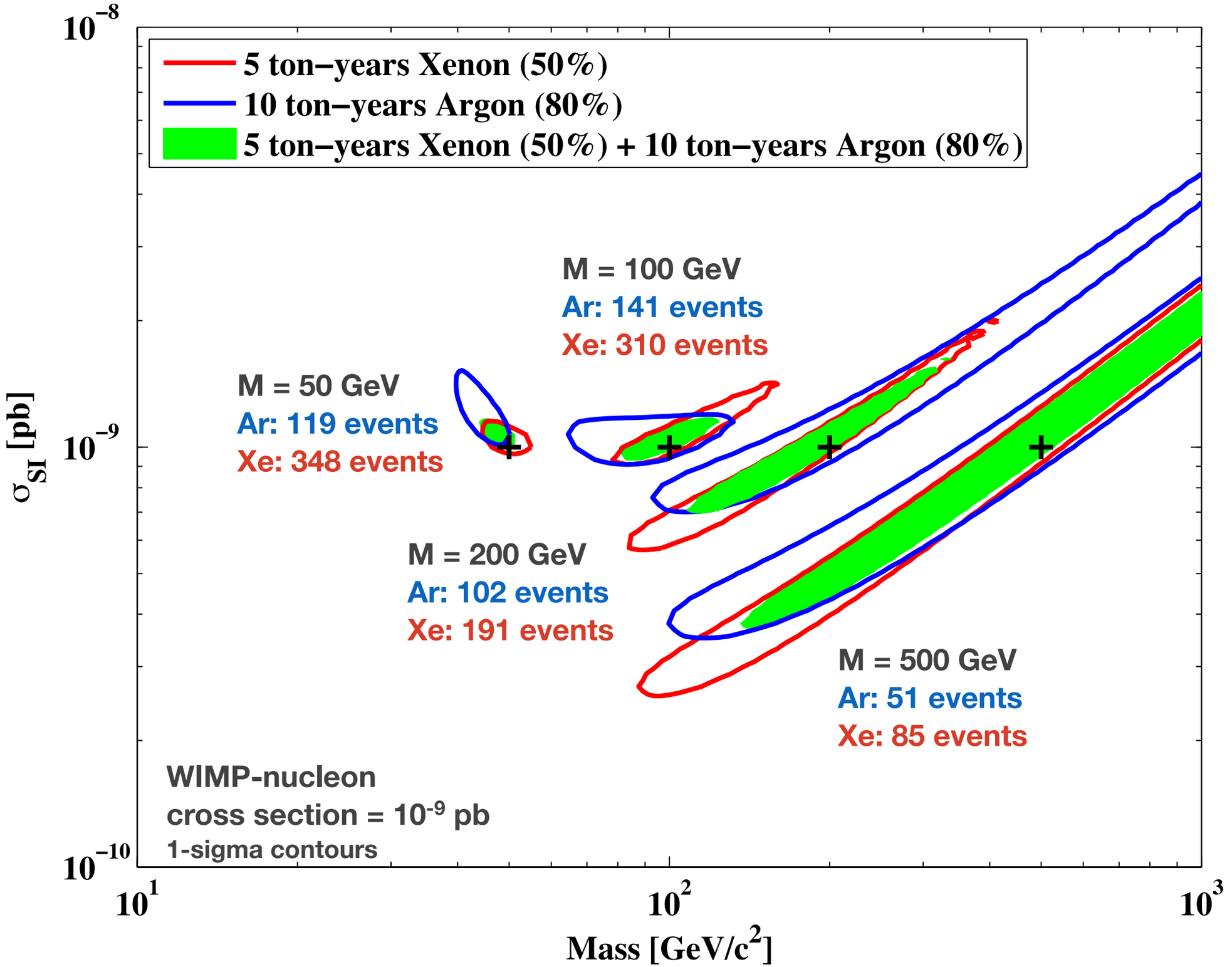
Europe: UZH, INFN, ETHZ, Subatech, Mainz, MPIK, Münster, Nikhef, KIT, IFJPAN

USA: Columbia, Princeton, UCLA



Complementarity between LAr and LXe

DARWIN

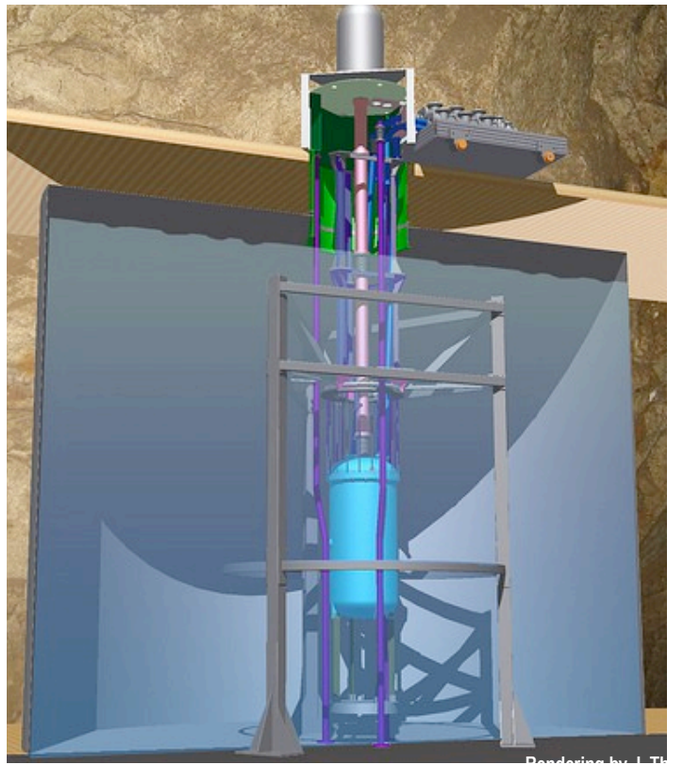


International Competition (I)

- **To XENON100:**

- **LUX in the US**
  - ➡ 350 kg LXe TPC, 100 kg fiducial
  - ➡ to be operated above ground at Homestake in 2010
- **XMASS in Japan**
  - ➡ 800 kg single phase detector (642 PMTs), 100 kg fiducial, 10x10 m water shield
  - ➡ under construction at Kamioka
  - ➡ to start science run in summer 2010
- **Mini-CLEAN in Canada**
  - ➡ 500 kg LAr (150 kg fiducial)
  - ➡ under construction at SNOLAB

LUX at Homestake

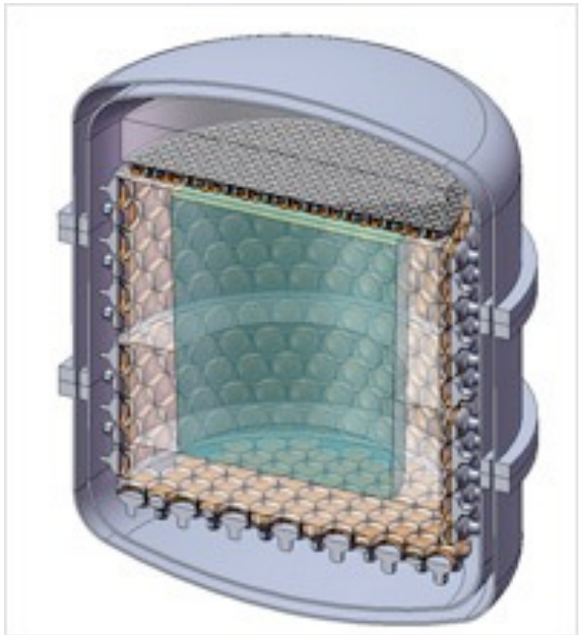


XMASS at Kamioka

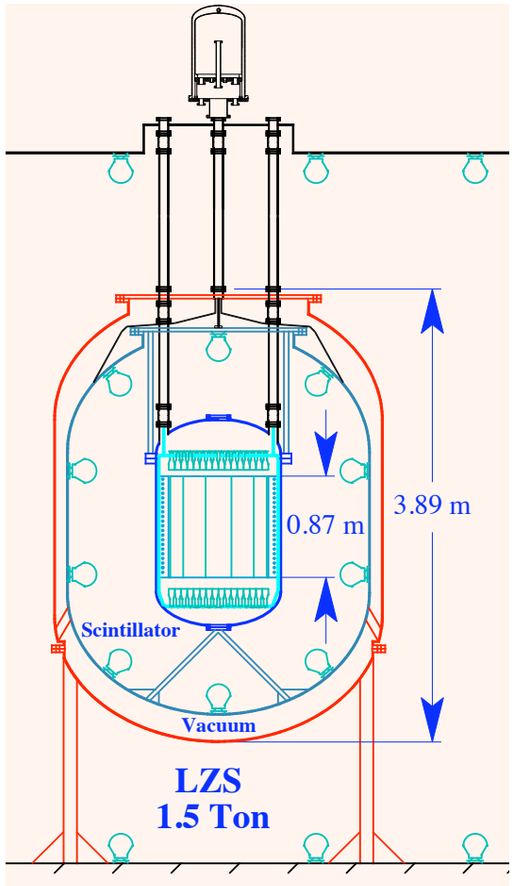
Mini-CLEAN at SNOLAB

International Competition (II)

MAX at DUSEL



LZS at DUSEL

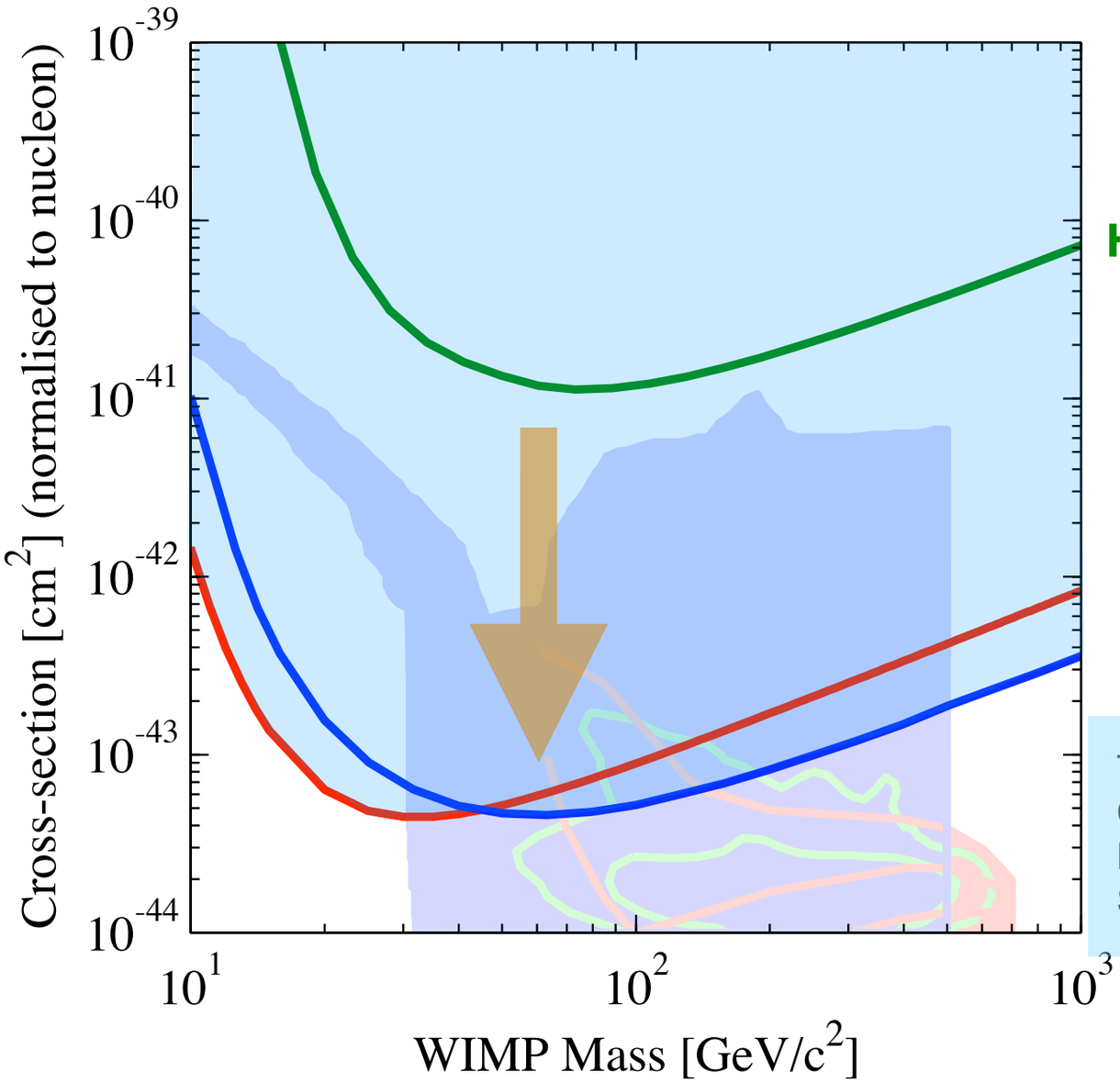


DEAP-3600 cavern at SNOLAB

- **To XENON1t and DARWIN:**
- **MAX in the US**
  - ➡ engineering study for 5t LAr and 2.4t LXe TPCs at DUSEL (ISE)
  - ➡ DarkSide + XENON + new groups
- **LZS in the US**
  - ➡ engineering study for 1.5 ton LXe experiment for the ISE at DUSEL
  - ➡ LUX+ZEPLIN-III+ new groups
- **DEAP-3600**
  - ➡ 3.6 t of LAr (1 ton fiducial)
  - ➡ under construction at SNOLAB
  - ➡ first dark matter run planned for 2012

Summary/Outlook (I)

- Direct search for dark matter particles: a very active field!
- Steady progress in the last ~ 10 years: **> factor 100 increase in sensitivity!**



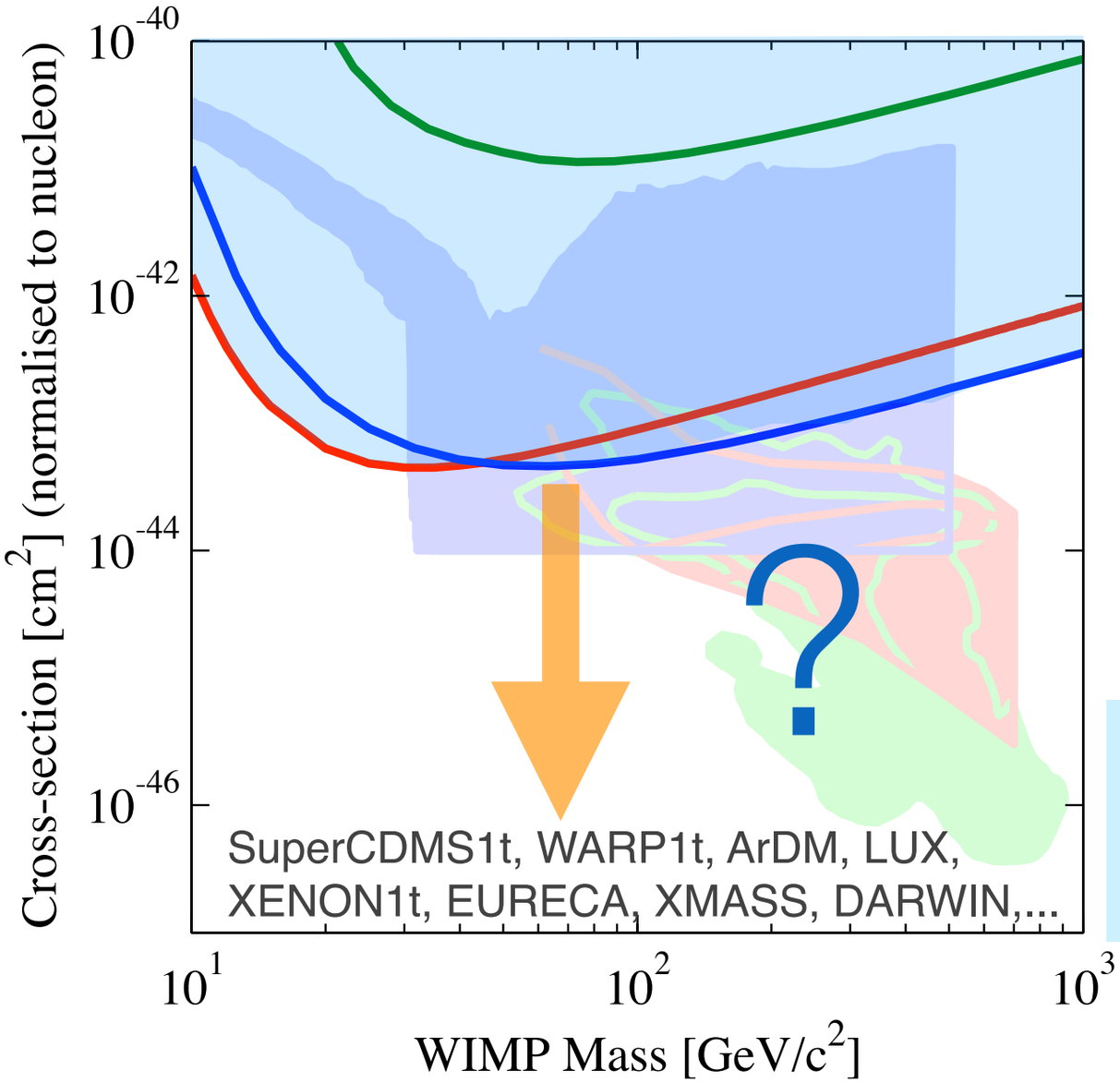
Heidelberg -Moscow 1998

Best current limits

Theory (SUSY): Balz, Baer, Bednyakov, Bottino, Cirelli, Chattopadhyay, Ellis, Fornengo, Giudice, Gondolo, Massiero, Olive, Profumo, Roszkowski, Ruiz, Santoso, Spanos, Strumia, Tata, Trotta ...+ many others

Summary/Outlook (II)

- **Good news:** experiments are probing some of the theory regions
- Next generation projects should reach the ≲ 10^{-10} pb level
- What will they see? *(nobody has been there before!)*



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End

Nuclear Recoil Equivalent Energy Scale

Energy of nuclear recoils (NRs)

Measured signal in nr. of p.e.

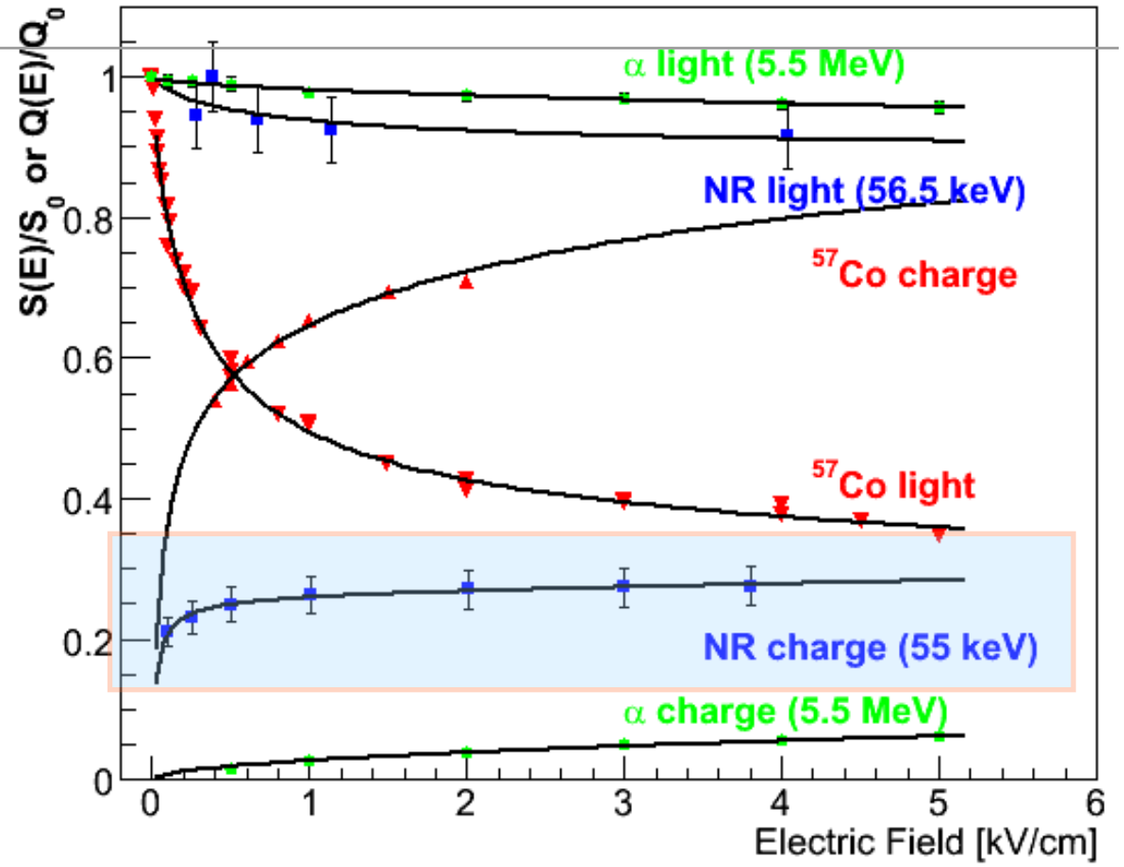
Quenching of scintillation yield for 122 keV γ's due to field (0.58 at ~ 0.5 kV/cm)

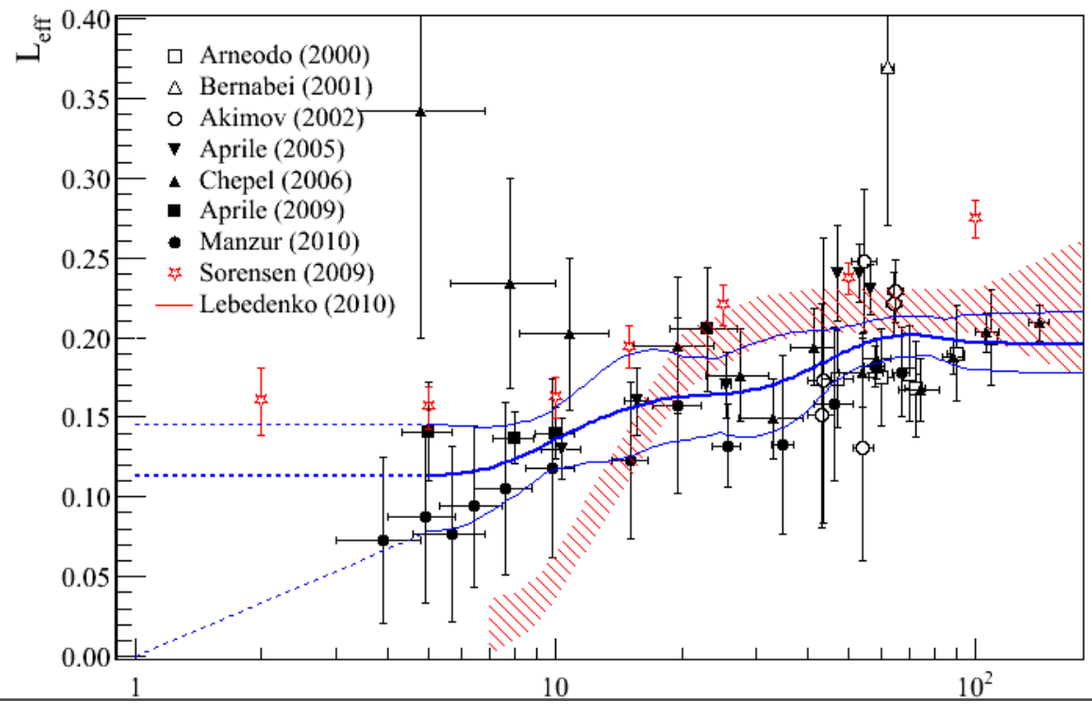
$$E_{nr} = \frac{S1}{L_y \cdot \mathcal{L}_{eff}} \times \frac{S_{er}}{S_{nr}}$$

Light yield for 122 keV γ in p.e. (~ 2.00 p.e./keV)

Relative scintillation efficiency of NRs to 122 keV γ's at zero field

Quenching of scintillation yield for NRs due to field (0.95 at ~0.5 kV/cm)





Other interpretations? iDM...

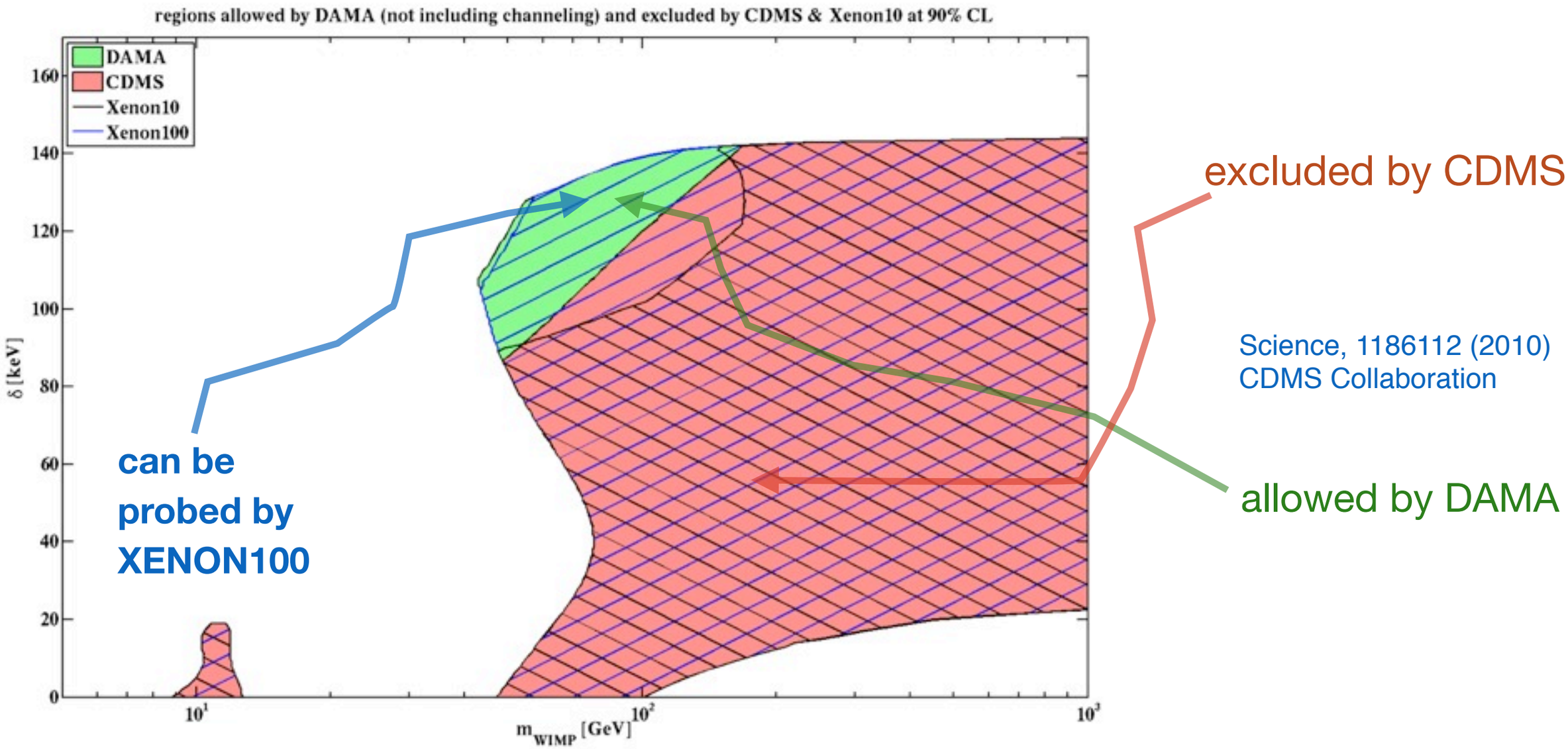
- **Inelastic dark matter:** 2 states with a mass splitting around 100 keV: by "coincidence" equal to the kinetic energy of WIMPs in the halo

$$\delta = m_{\chi^*} - m_\chi \sim \beta^2 m_\chi \sim 100 \text{ keV}$$

S. Chang et al., Phys.Rev.D79:043513,2009

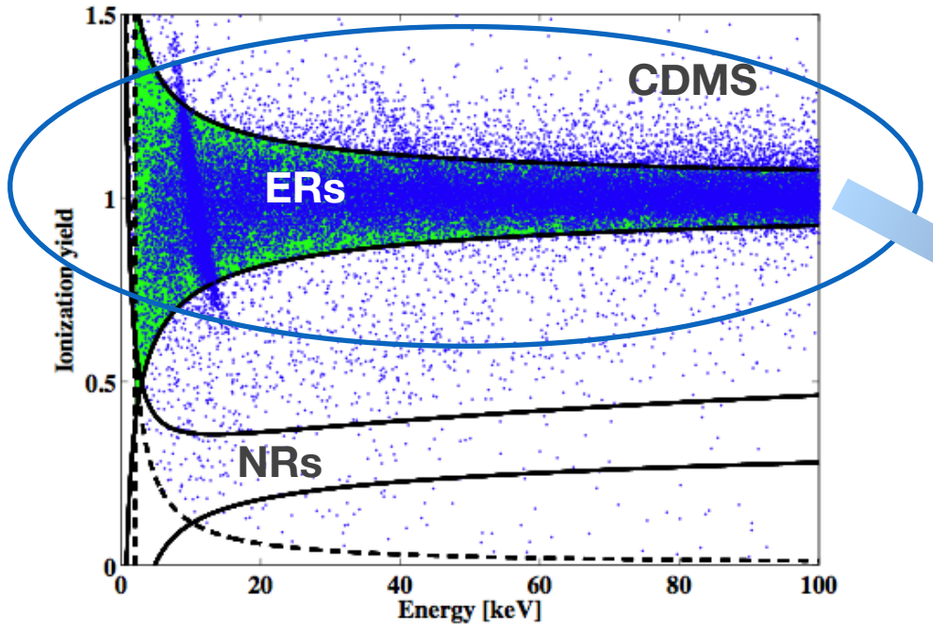
➡ WIMP-nucleus scattering occurs through a transition to a WIMP excited state

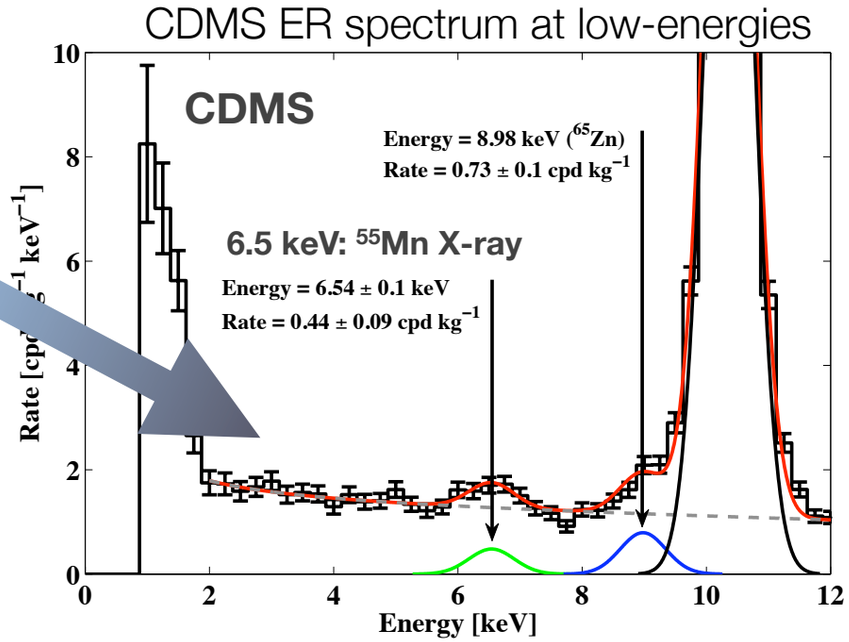
➡ probes high end of the WIMP velocity distribution



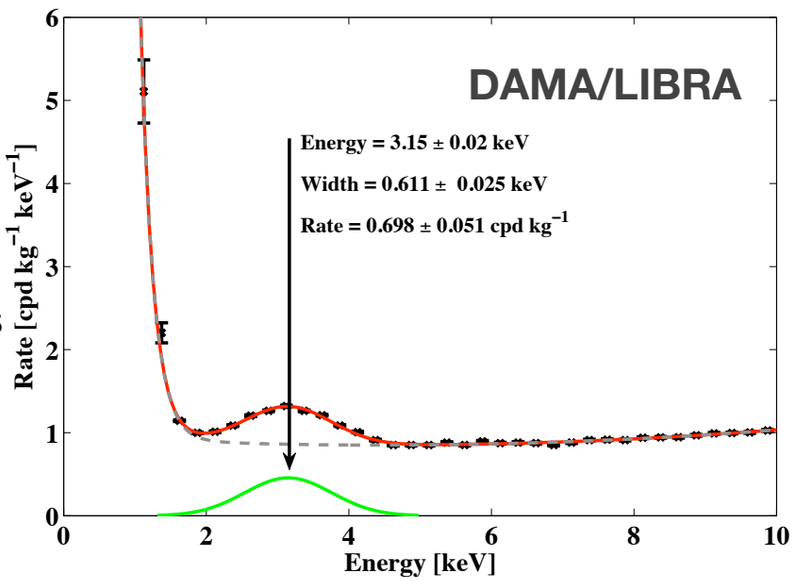
Other interpretations?

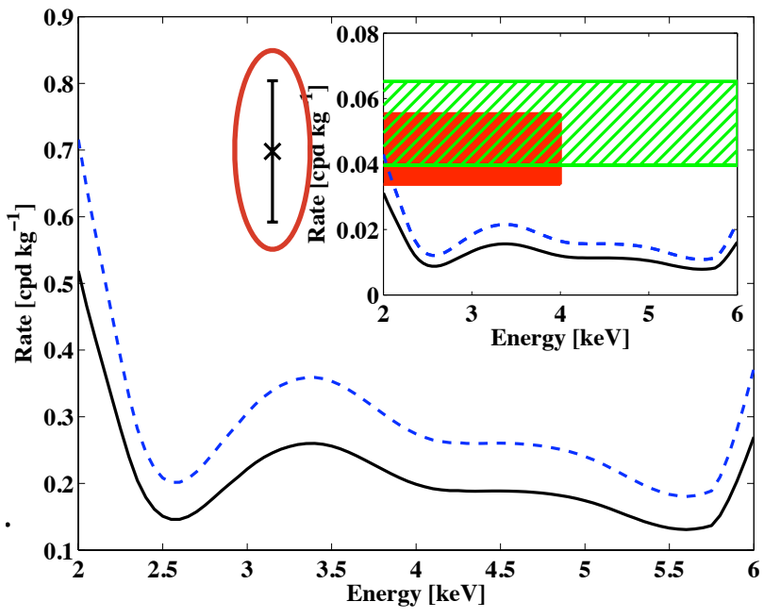
- Particle with EM-interaction (sterile neutrino decaying to light ν + X-ray, something else?)?
- Experiments with particle ID can also analyze their ER spectrum





DAMA: modulation at 2-4 keV and excess of events at 3.15 keV





CDMS Collaboration
PRD 81, 042002 (2010)

Upper limit on the total counting rate in Ge
- direct (solid)
- Z2-scaling (dashed)