Universität Zürich

Direct Dark Matter Searches

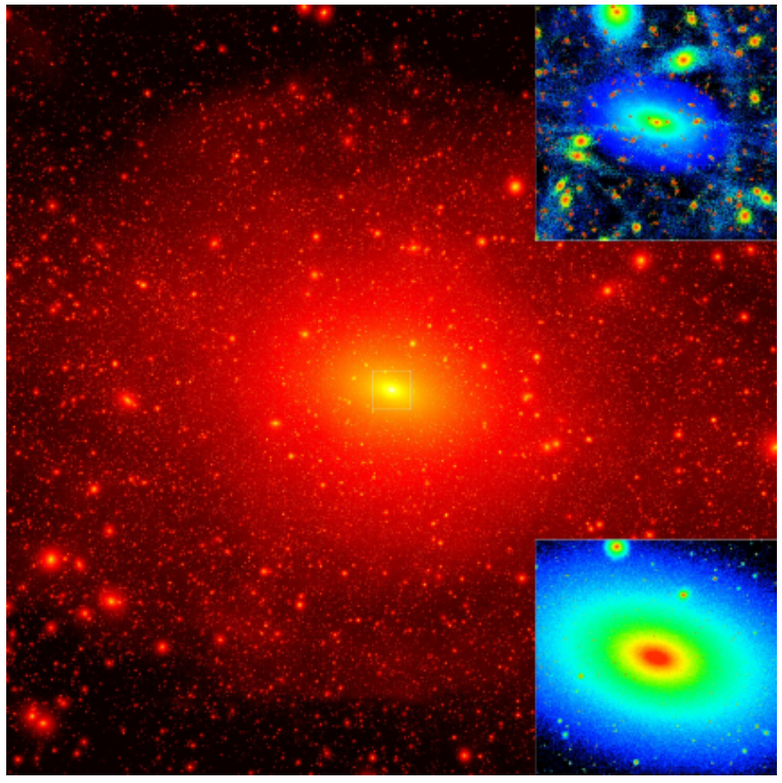
Physics at the LHC
DESY, June 12, 2010

Laura Baudis

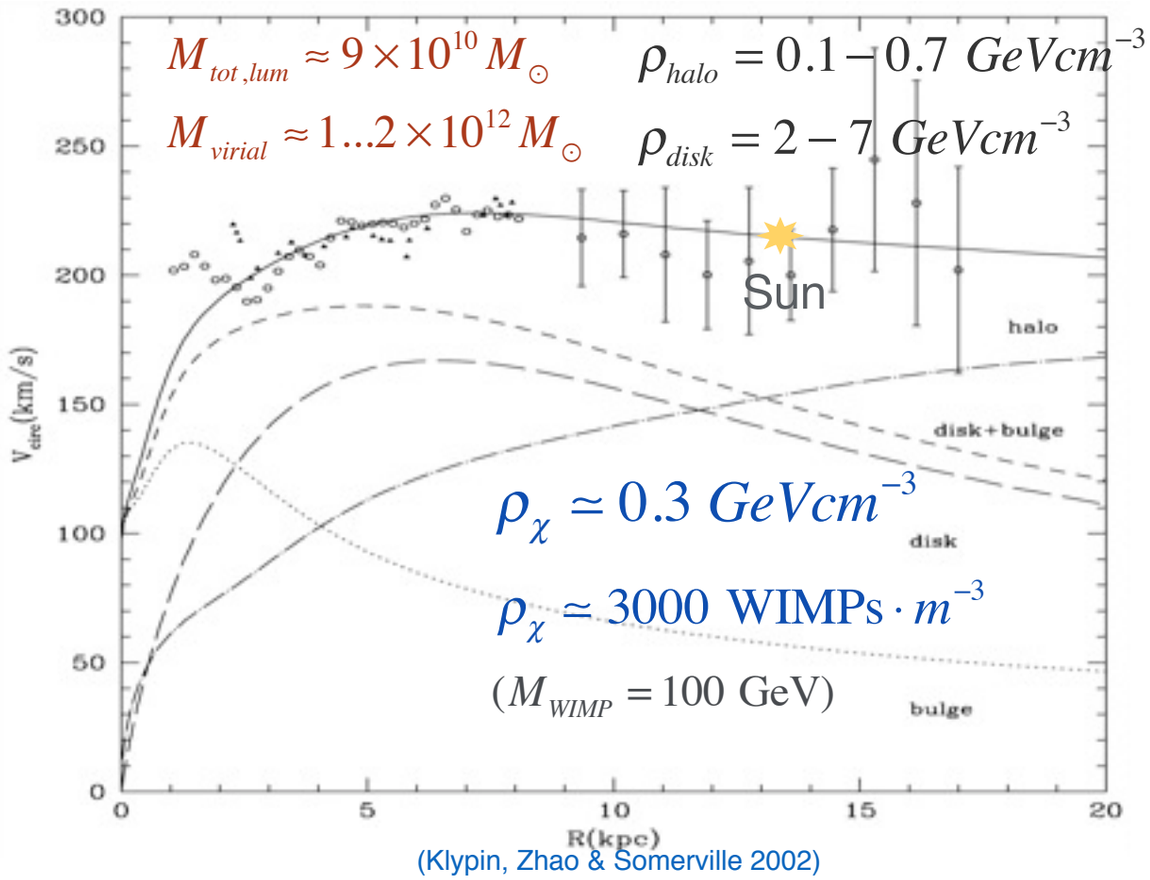
Physik Institut, University of Zurich

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)

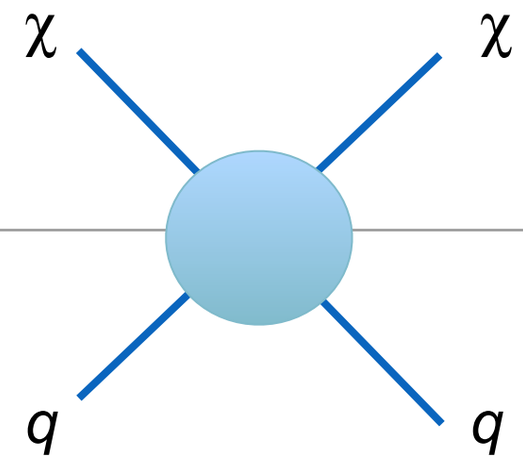


(Klypin, Zhao & Somerville 2002)

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

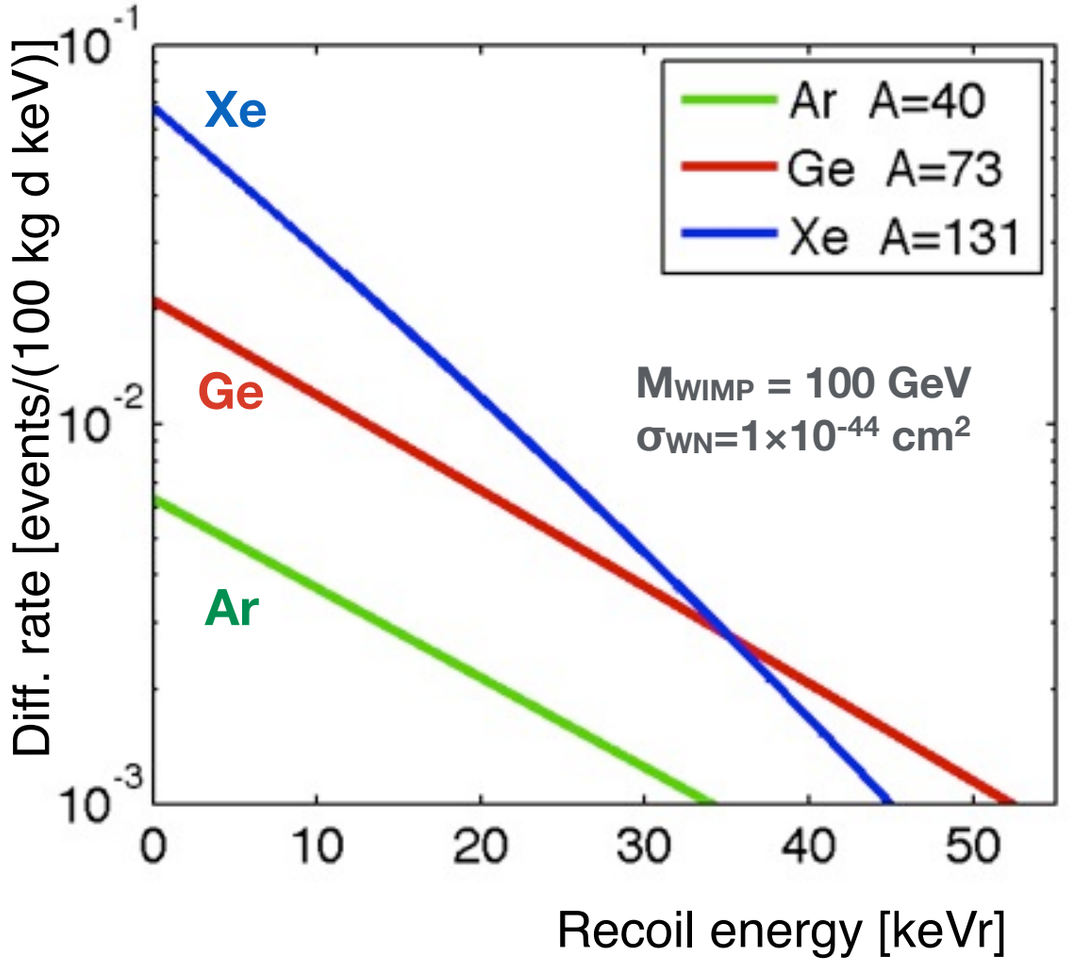
  < 1 event/100kg/day

- **Energy of recoiling nuclei**

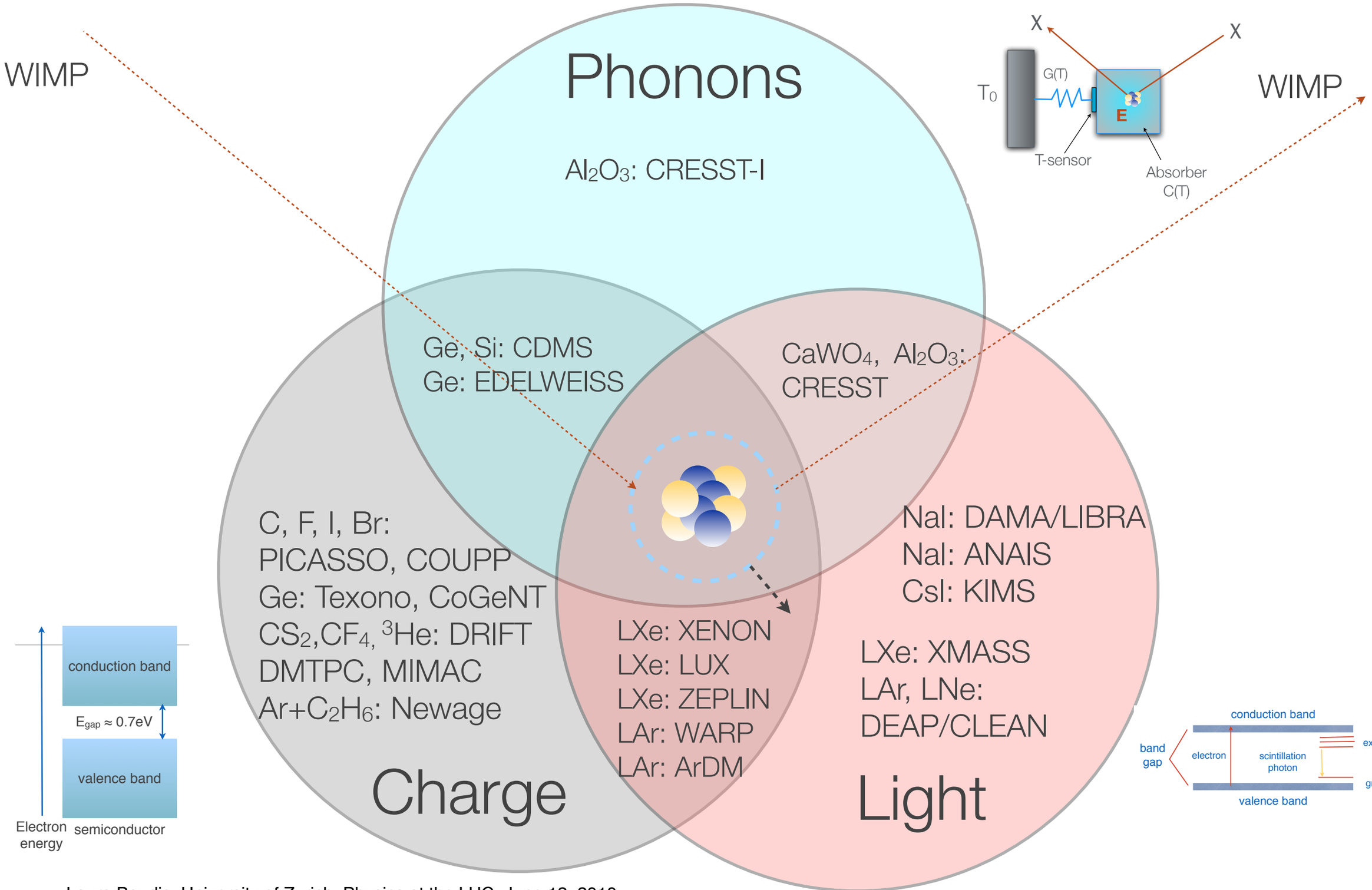
$$E_R = \frac{|\vec{q}|^2}{2m_N} = \frac{\mu^2 v^2}{m_N}(1-\cos\theta) \leq 50\ keV$$

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

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

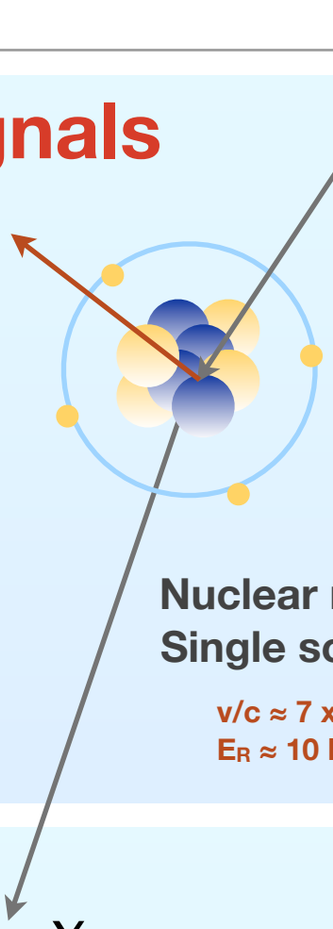


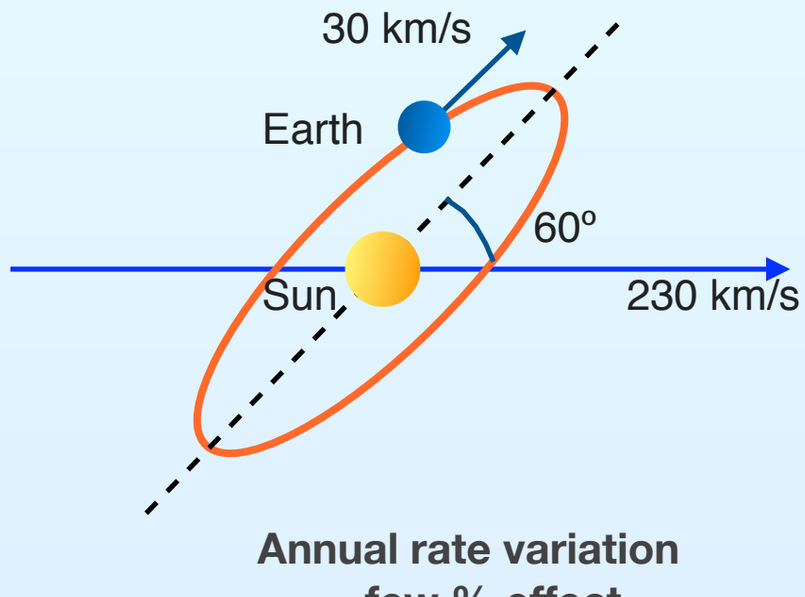
Direct Detection Techniques

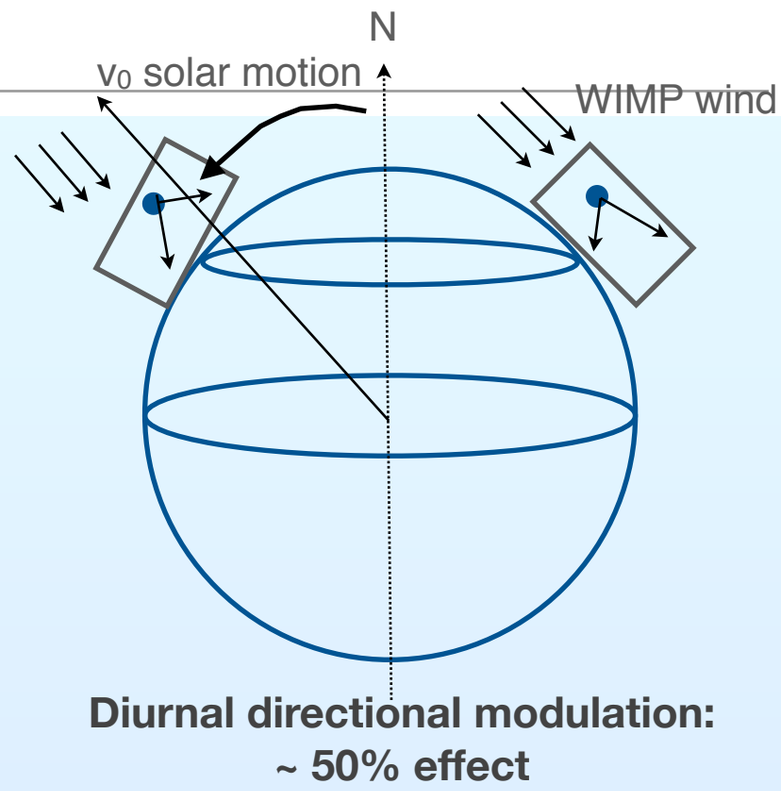


Signals and Backgrounds

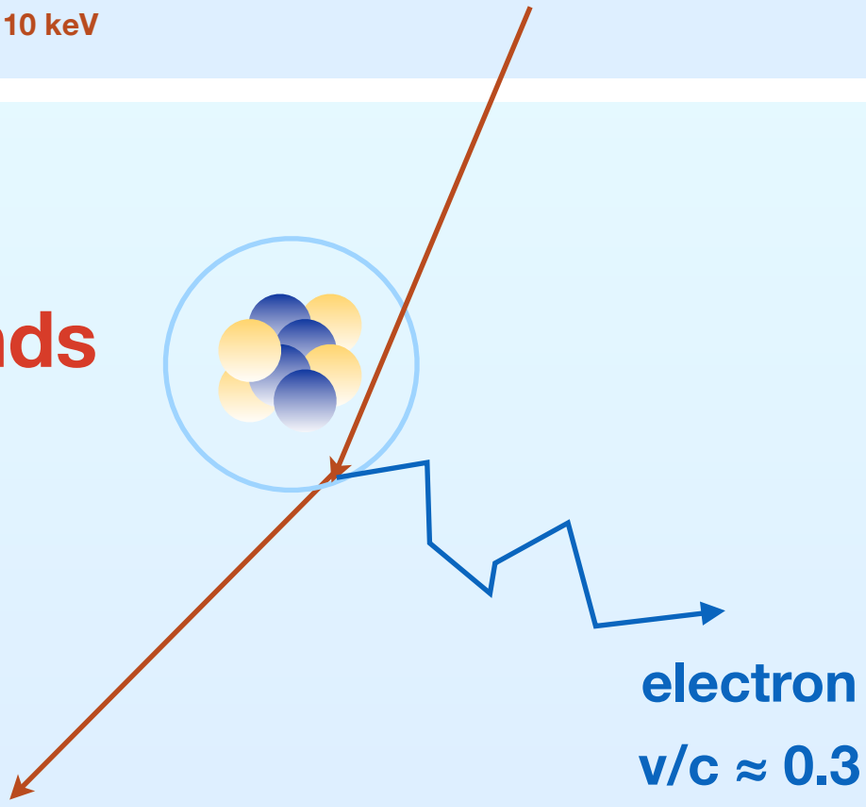
Signals







Backgrounds



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

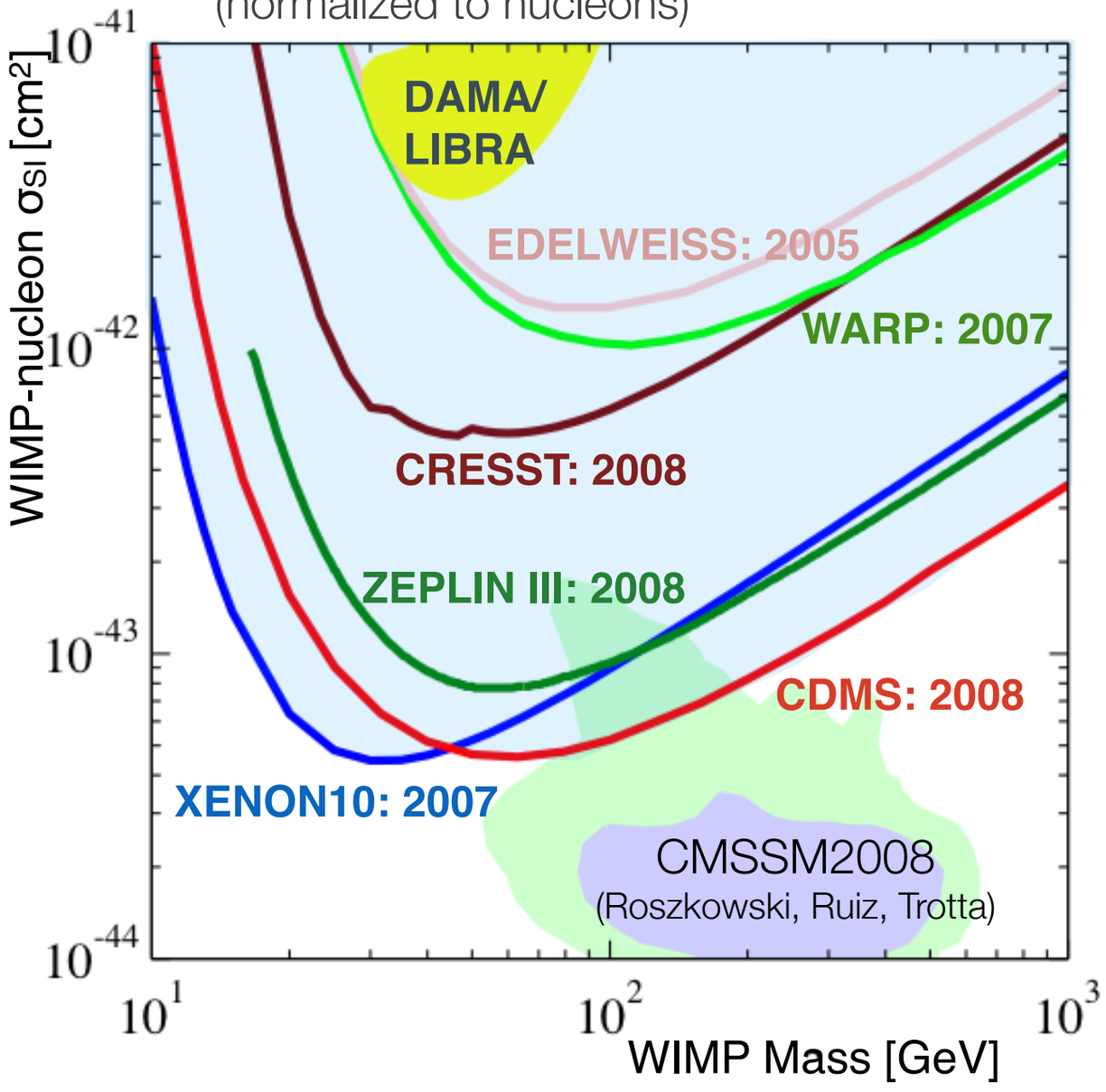
muons: go deep underground, add muon veto

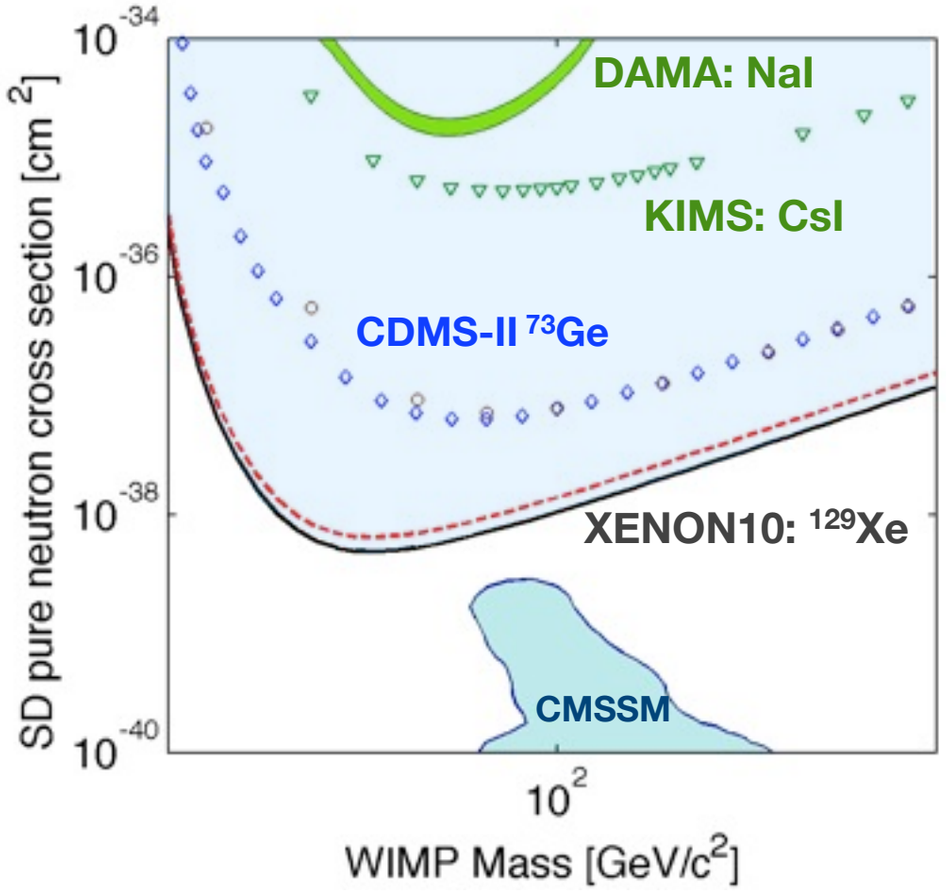
neutrons: NRs, but also capture and multiple scatters

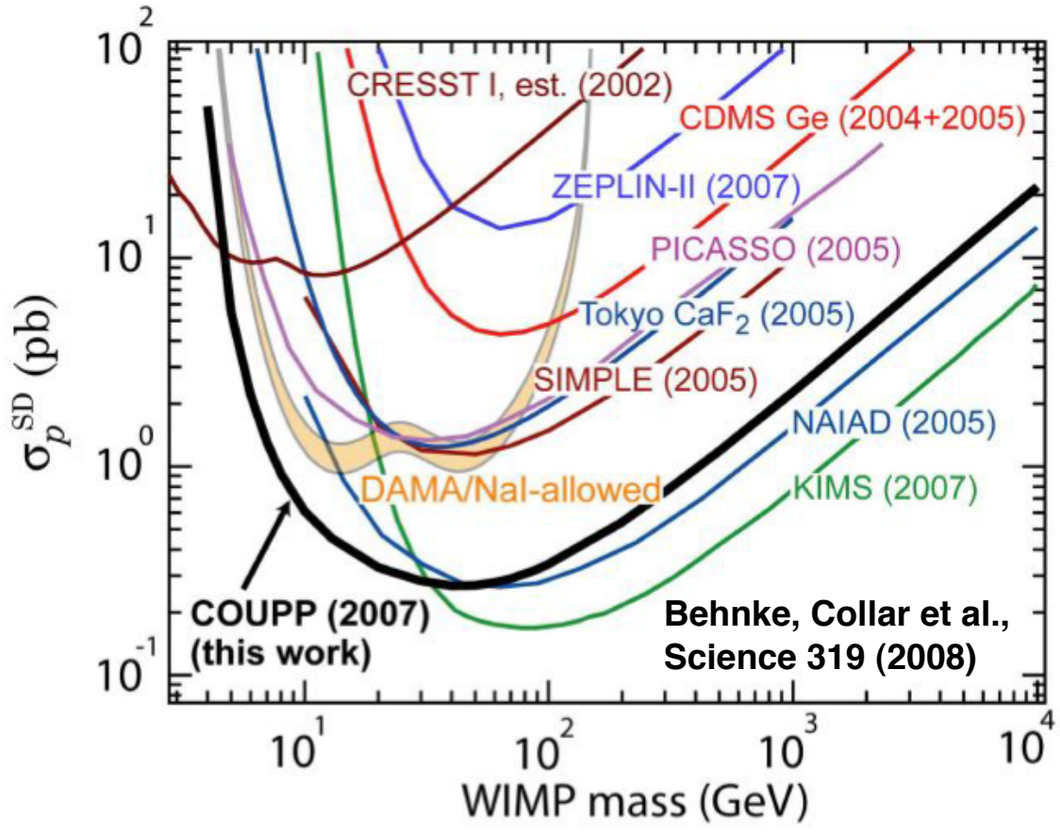
alphas: much higher energy depositions, but recoiling nuclei a problem if **α** energy not seen in active detector volume

Experimental Results by the end of 2009

Spin-independent cross section
(normalized to nucleons)



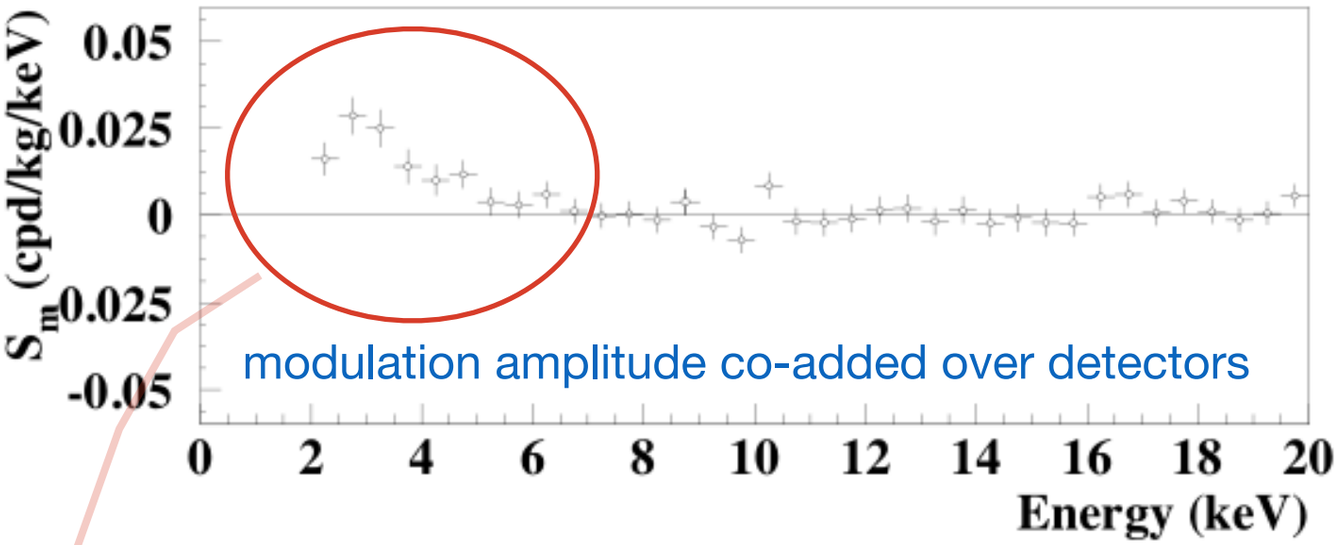




Spin-dependent

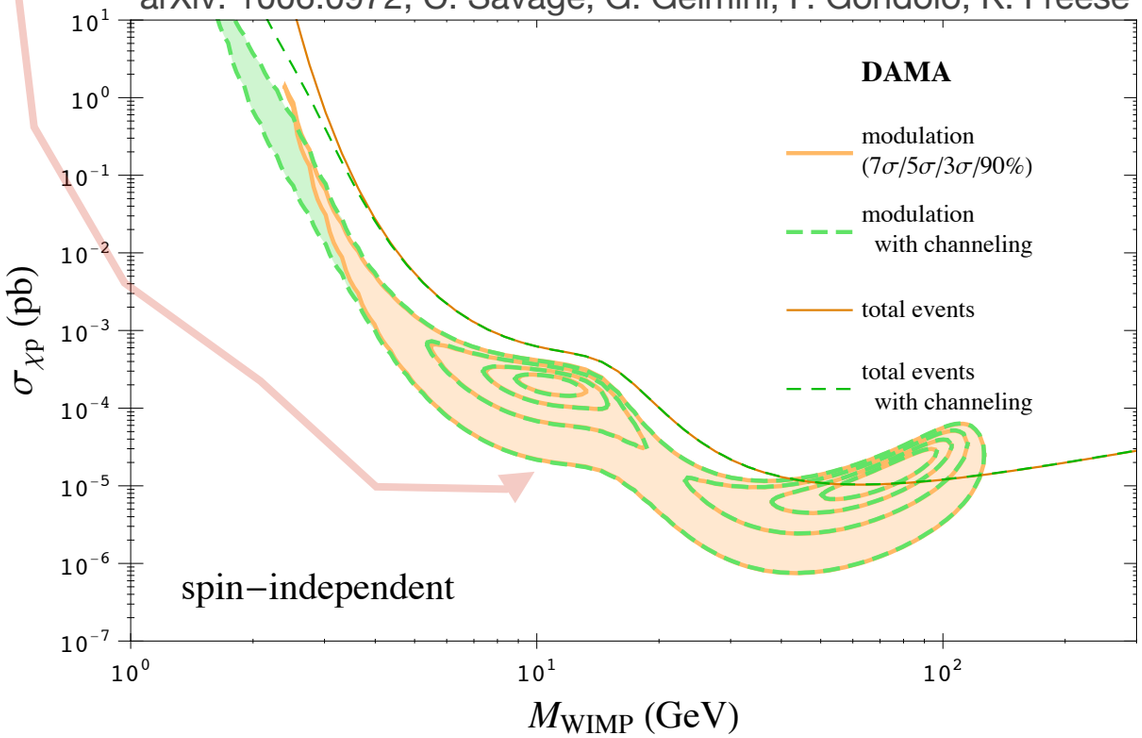
“Evidences” for WIMPs?

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

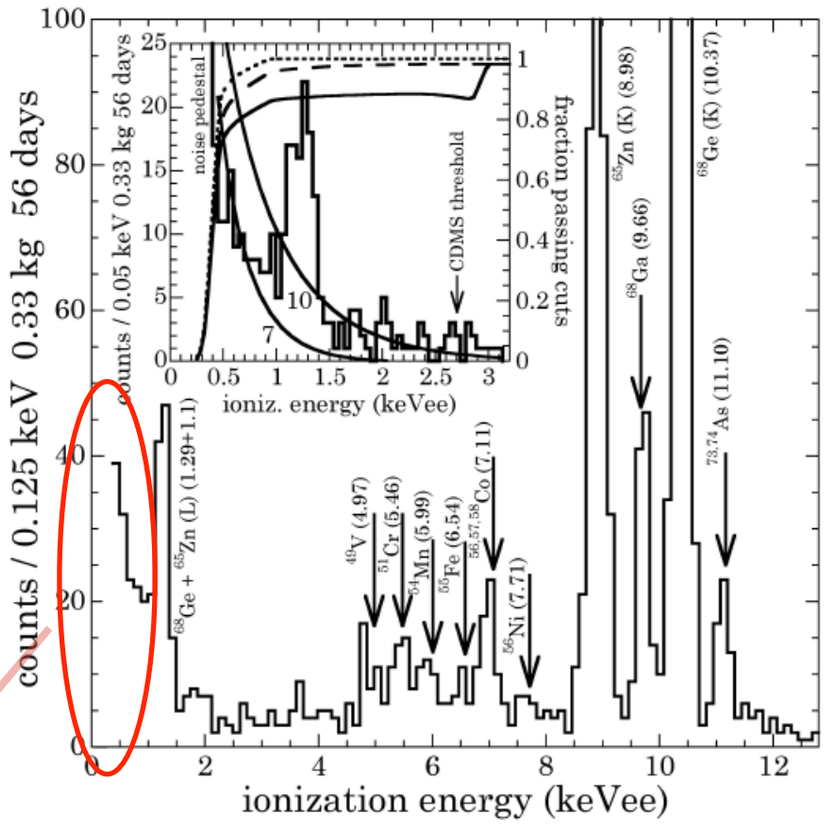


modulation amplitude co-added over detectors

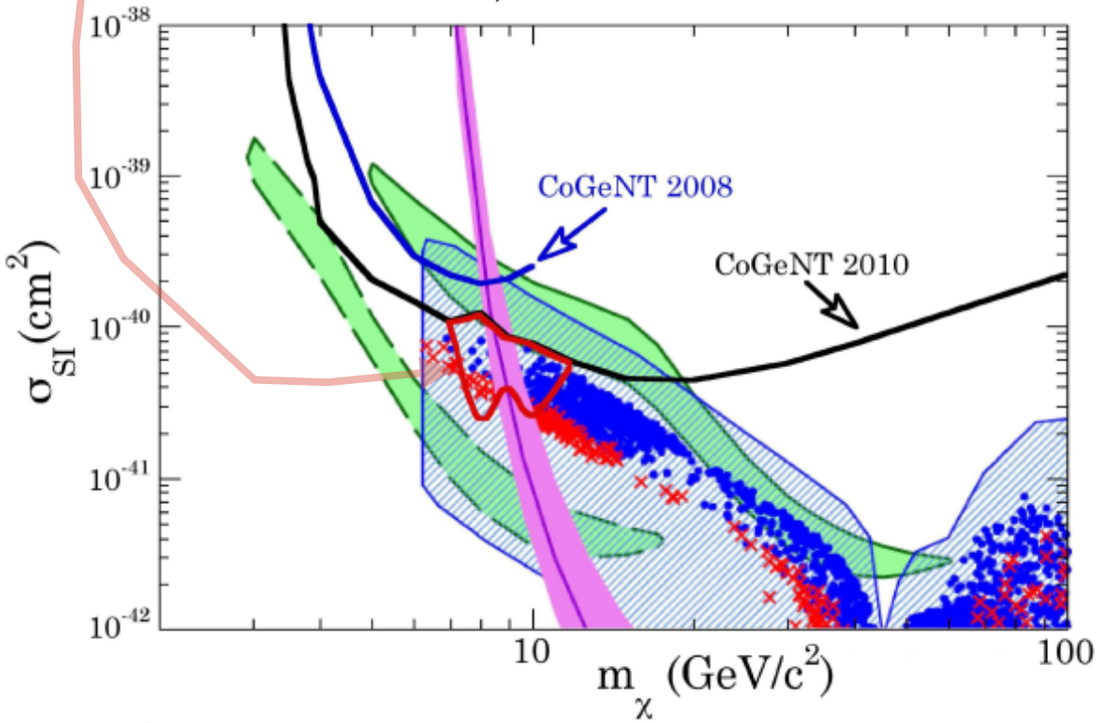
arXiv: 1006.0972; C. Savage, G. Gelmini, P. Gondolo, K. Freese



CoGeNT: 2010; 0.33 kg x 8 weeks

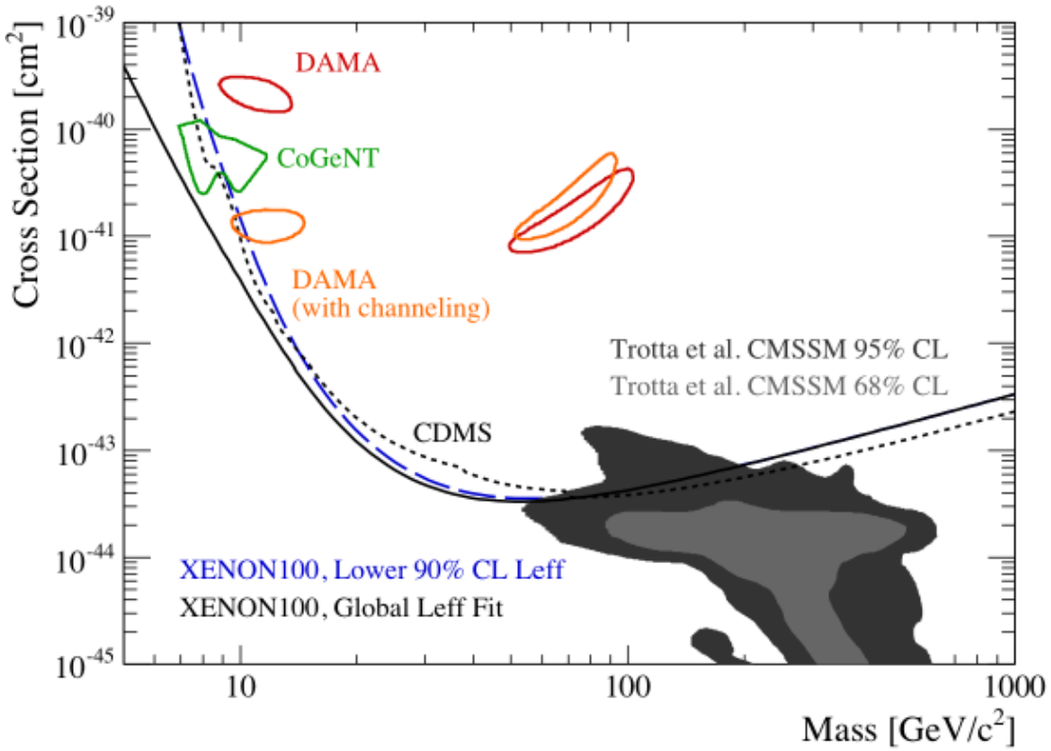


arXiv: 1002.4703; C. E. Aalseth et all

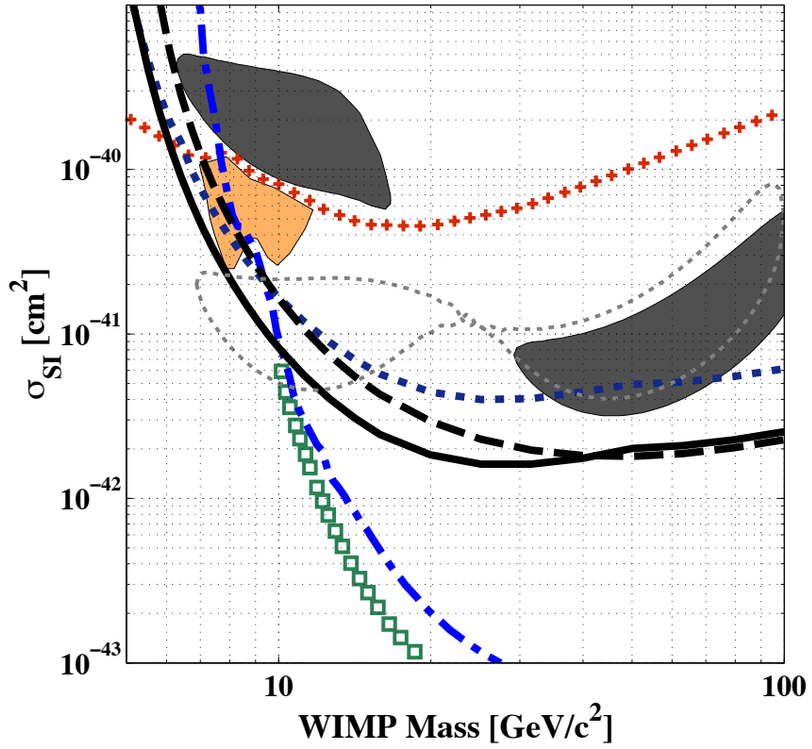


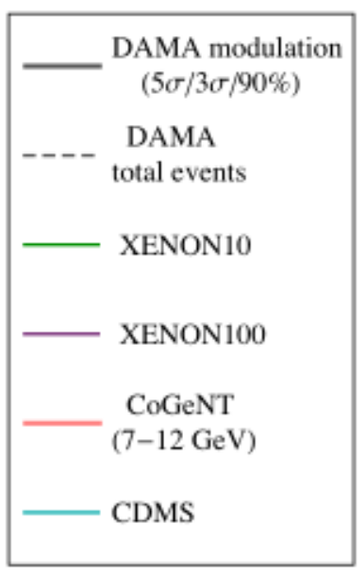
In severe conflict with other experiments!

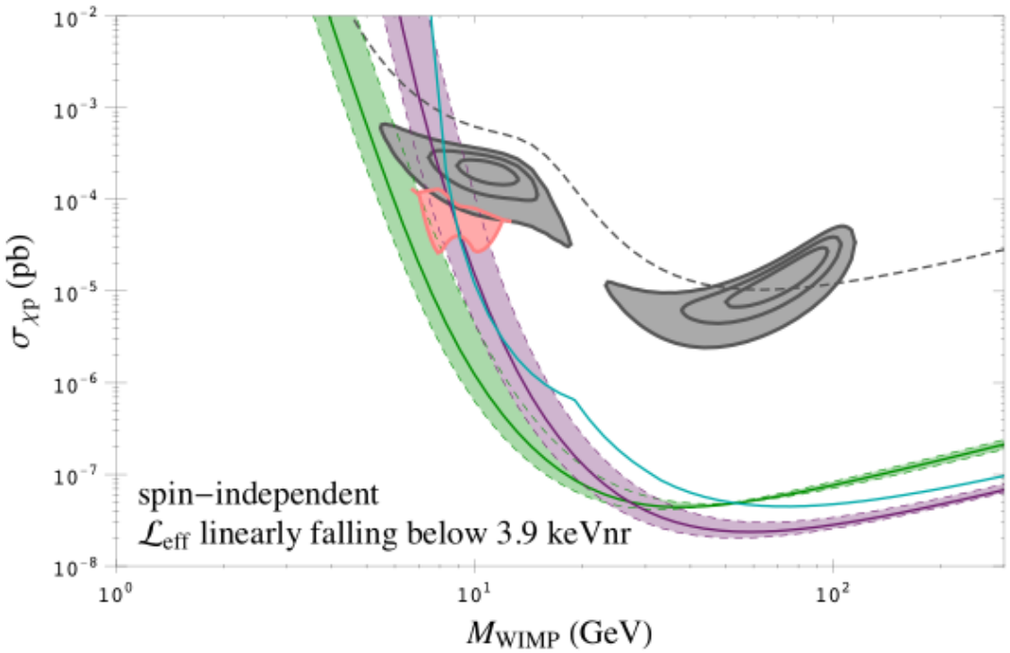
New XENON100 results (more later!)



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







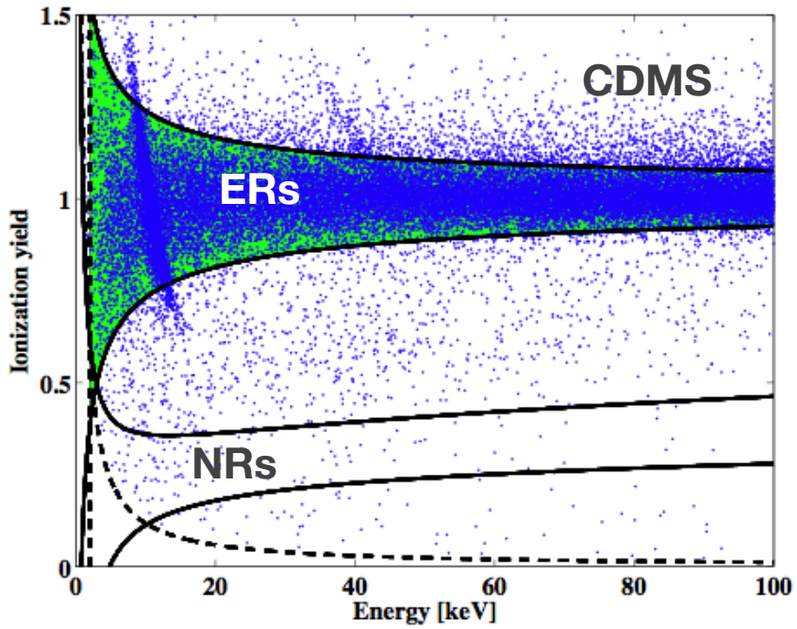
Reanalyzed

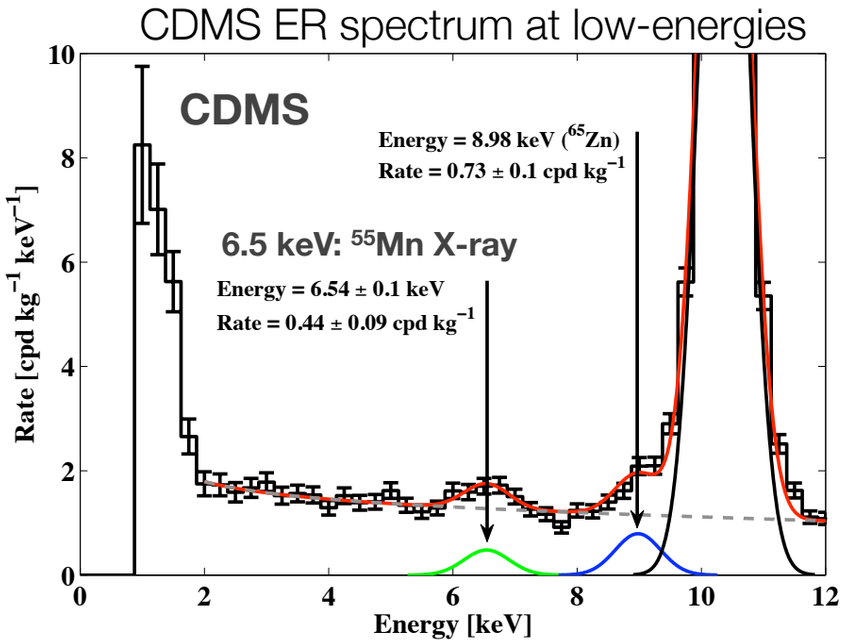
XENON10 results

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

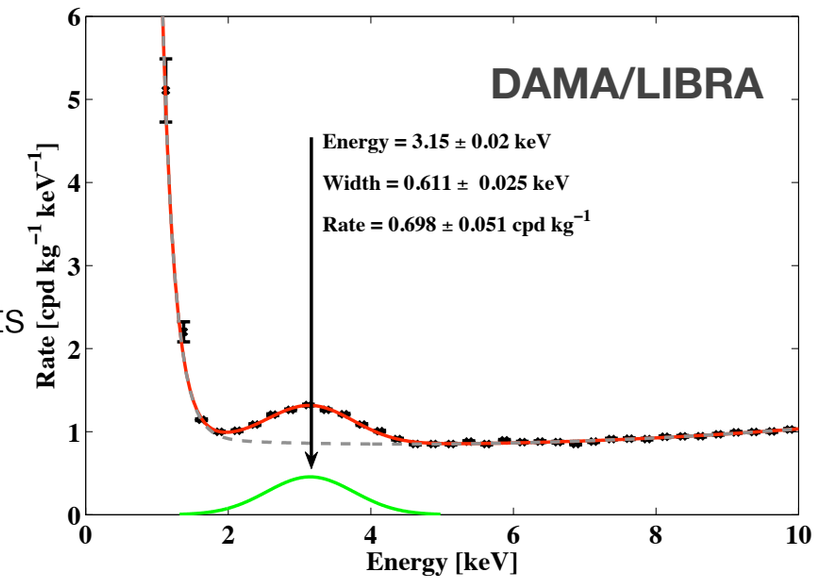
Other interpretations?

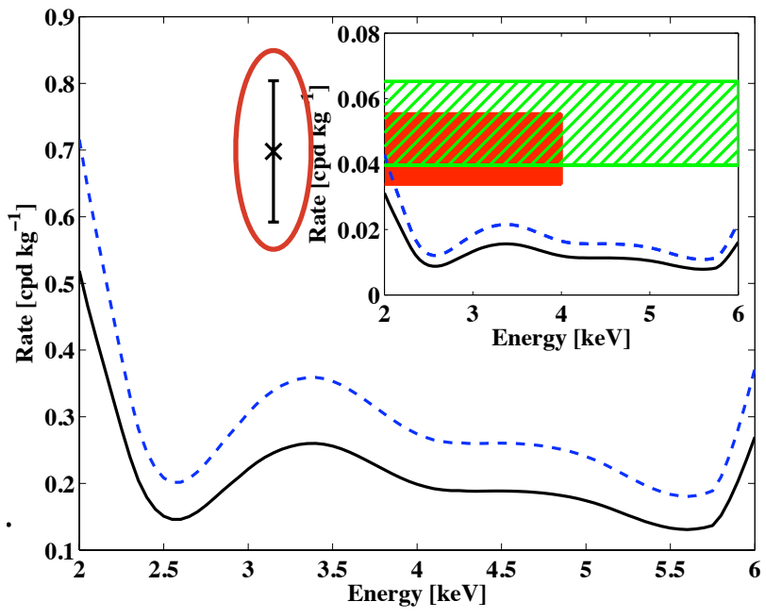
- Particle with EM-interaction (sterile neutrino decaying to light ν + X-ray, something else?)?
- Experiments with particle ID can also analyze their ER spectrum





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)

Other interpretations? iDM...

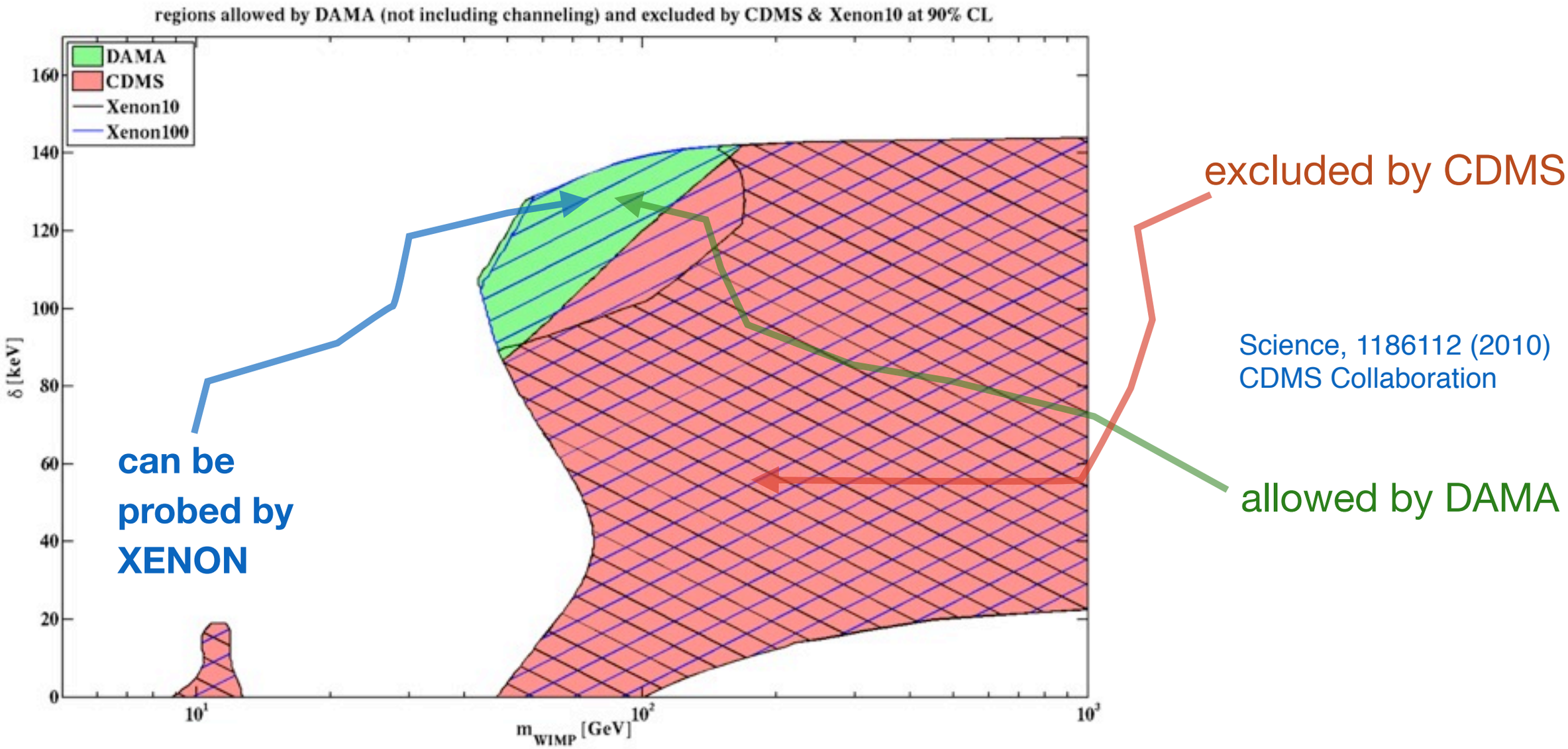
- **Inelastic dark matter:** 2 states with a mass splitting around 100 keV: by "coincidence" equal to the kinetic energy of WIMPs in the halo

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

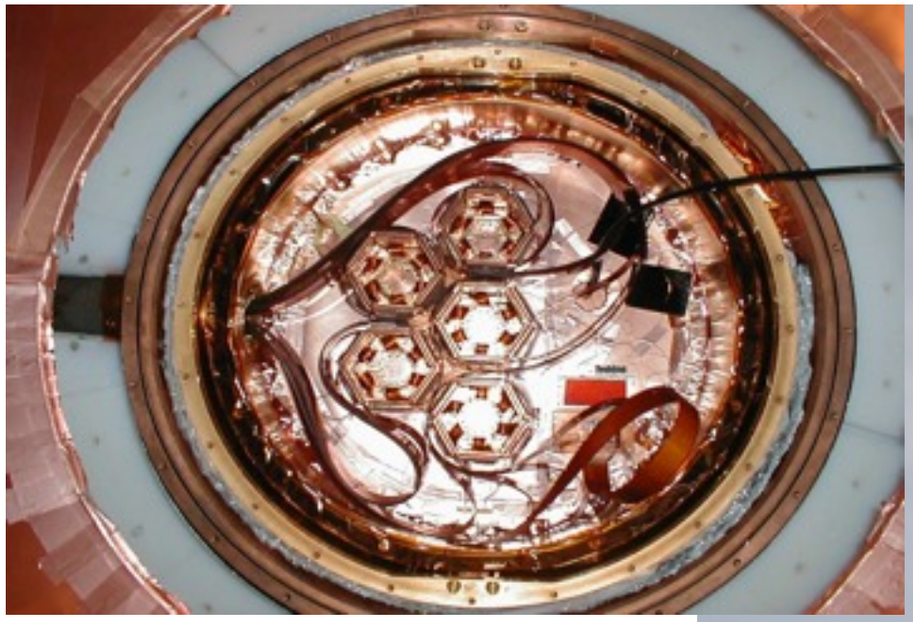
S. Chang et al., Phys.Rev.D79:043513,2009

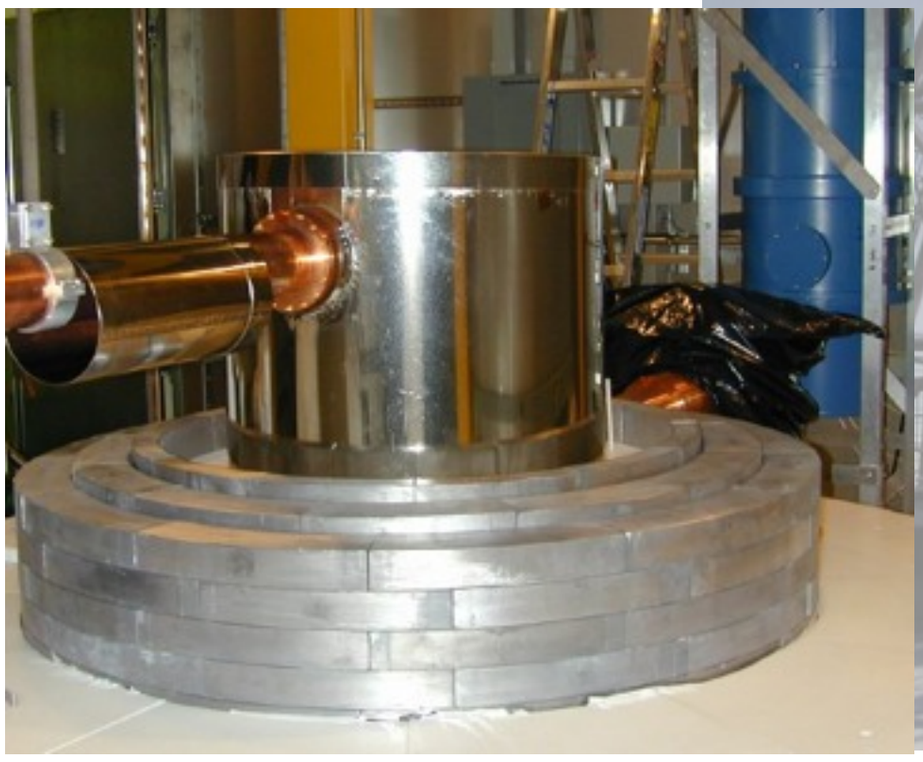
➡ WIMP-nucleus scattering occurs through a transition to a WIMP excited state

➡ probes high end of the WIMP velocity distribution

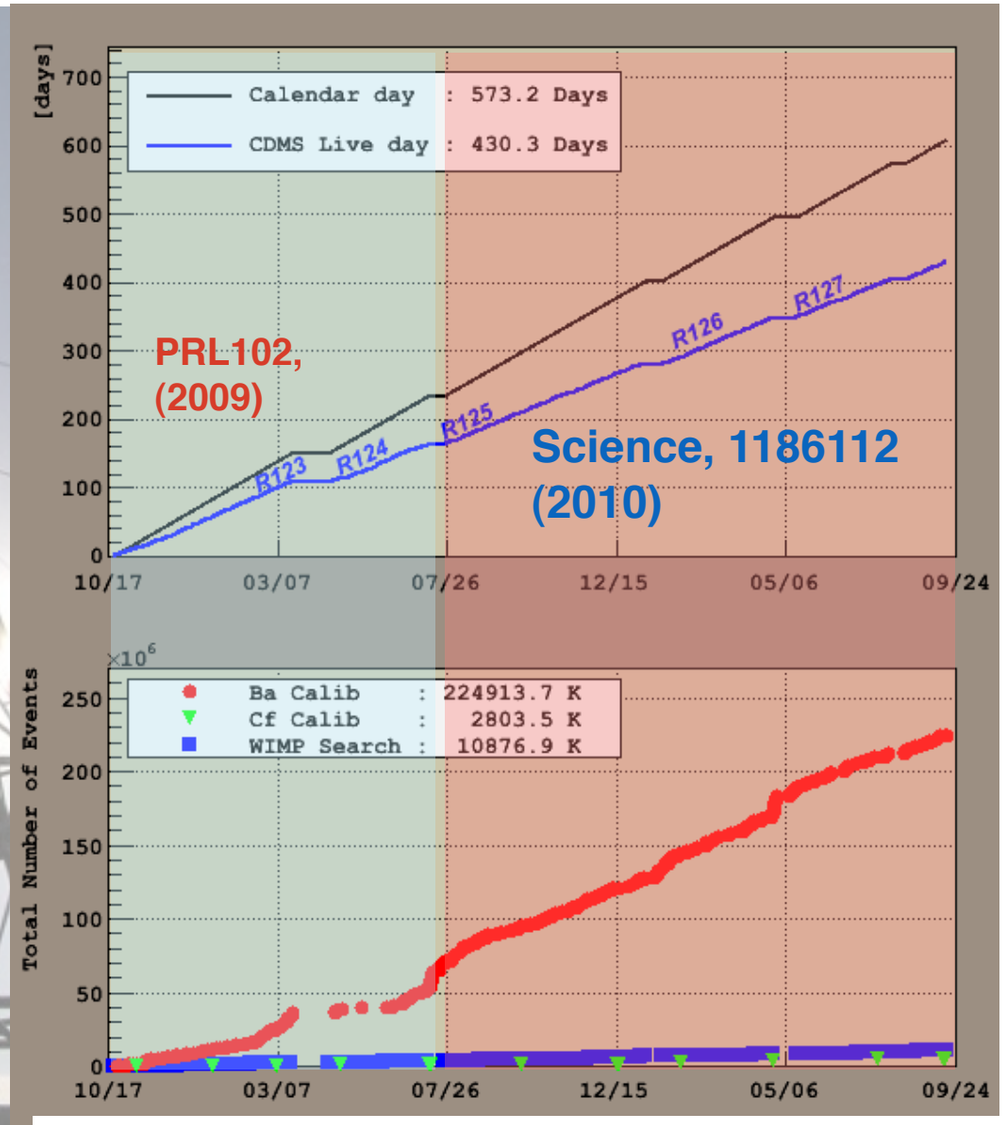


The CDMS Experiment at the Soudan Mine





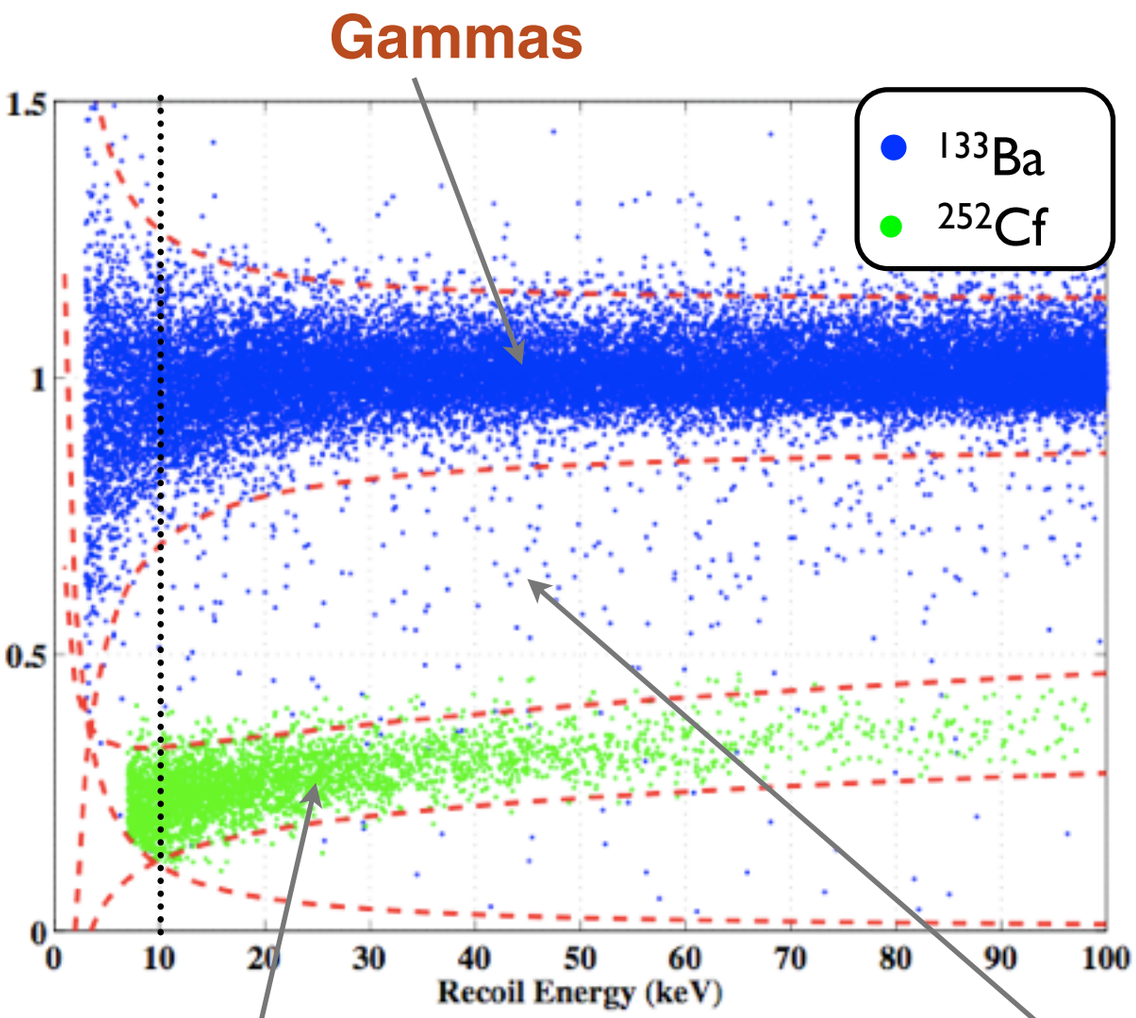
5 towers:
30 Ge
and Si
detectors
at
2000 mwe

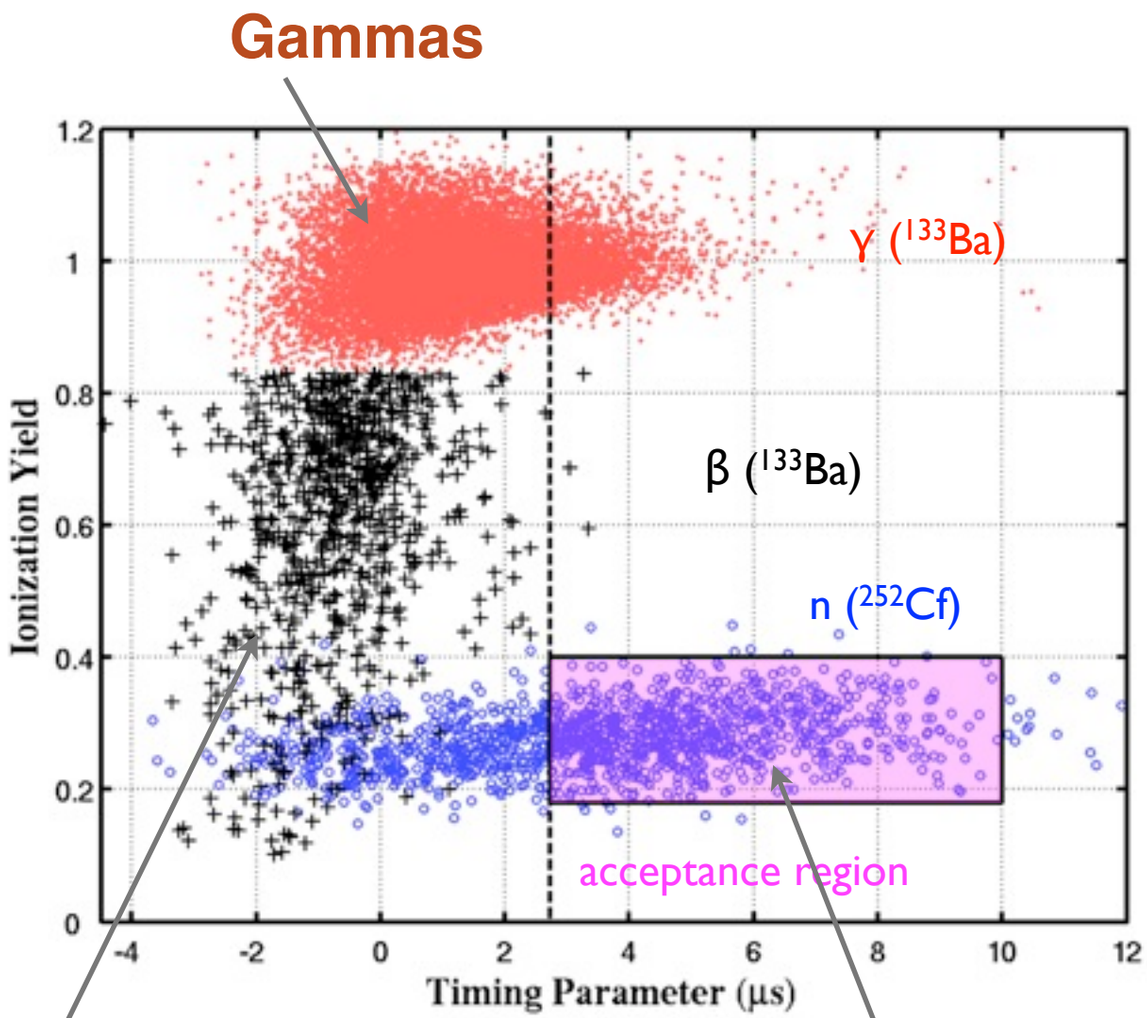


	T1	T2	T3	T4	T5
Z1	G6	S14	S17	S12	G7
Z2	G11	S28	G25	G37	G36
Z3	G8	G13	S30	S10	S29
Z4	S3	S25	G33	G35	G26
Z5	G9	G31	G32	G34	G39
Z6	S1	S26	G29	G38	G24

CDMS: Signal versus Background

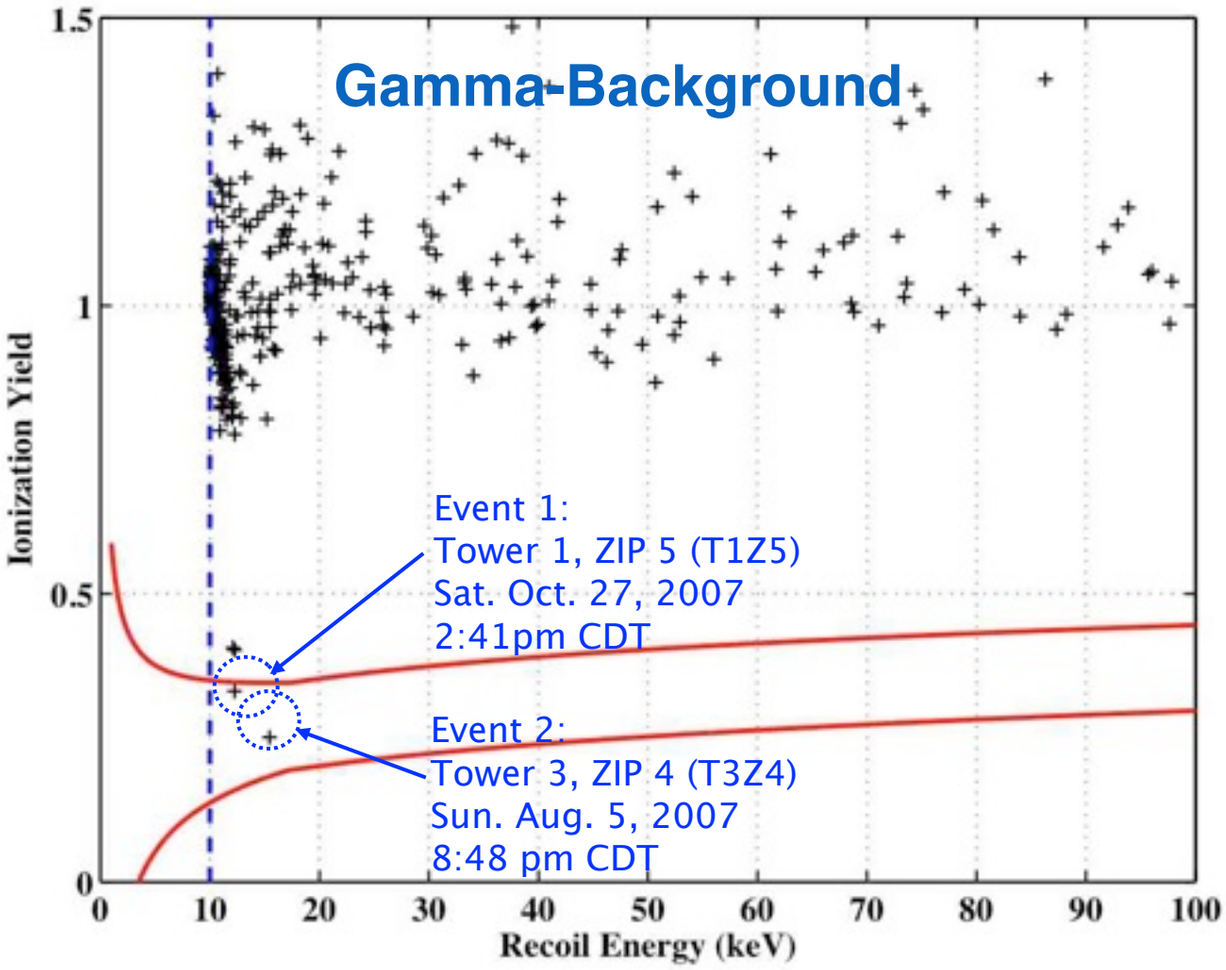
- Ratio of the charge/phonon-signal and time difference between charge and phonon signals => distinguish signal (WIMPs) from background of electromagnetic origin

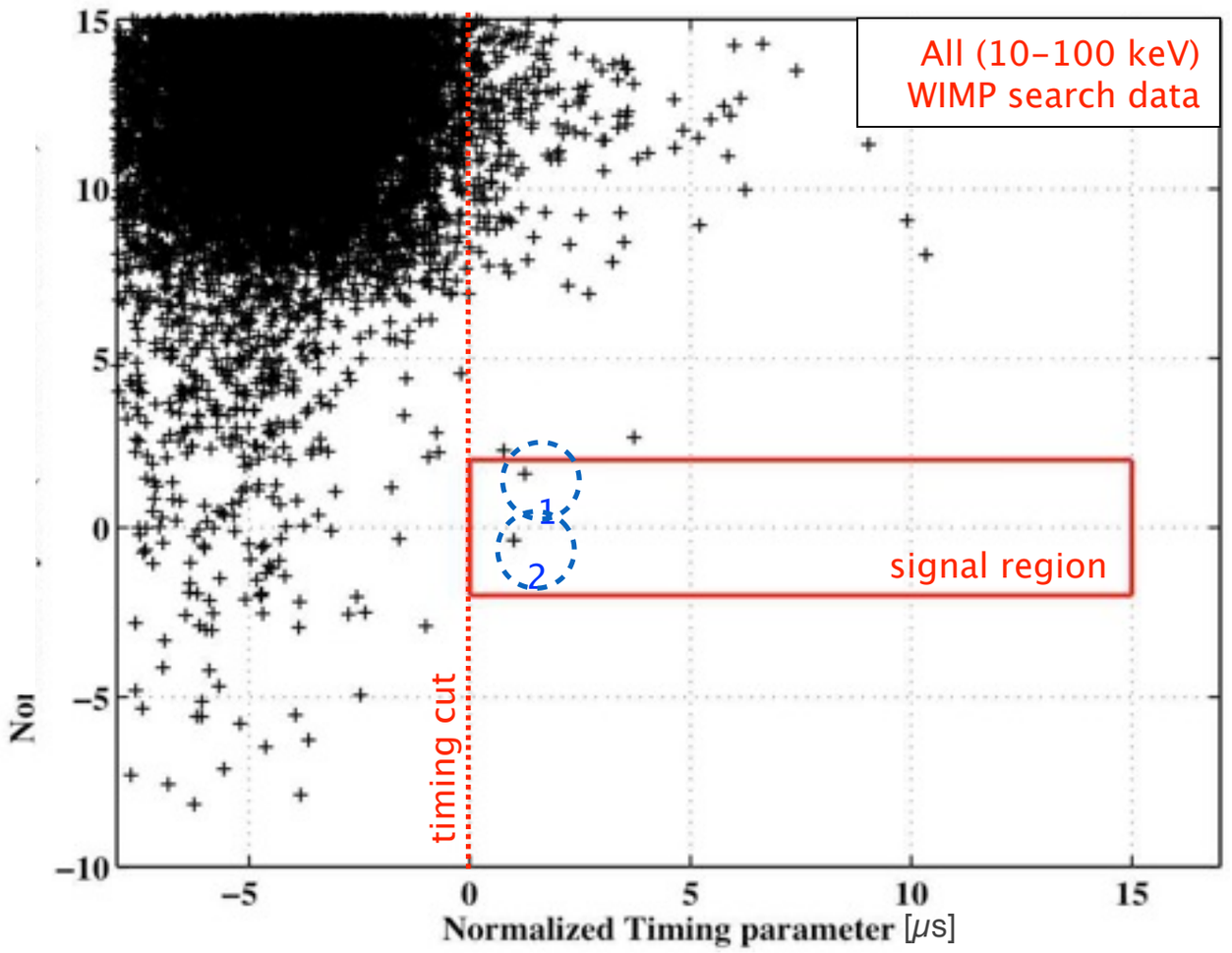




Surface events

Final CDMS WIMP Search Runs: 191 kg days



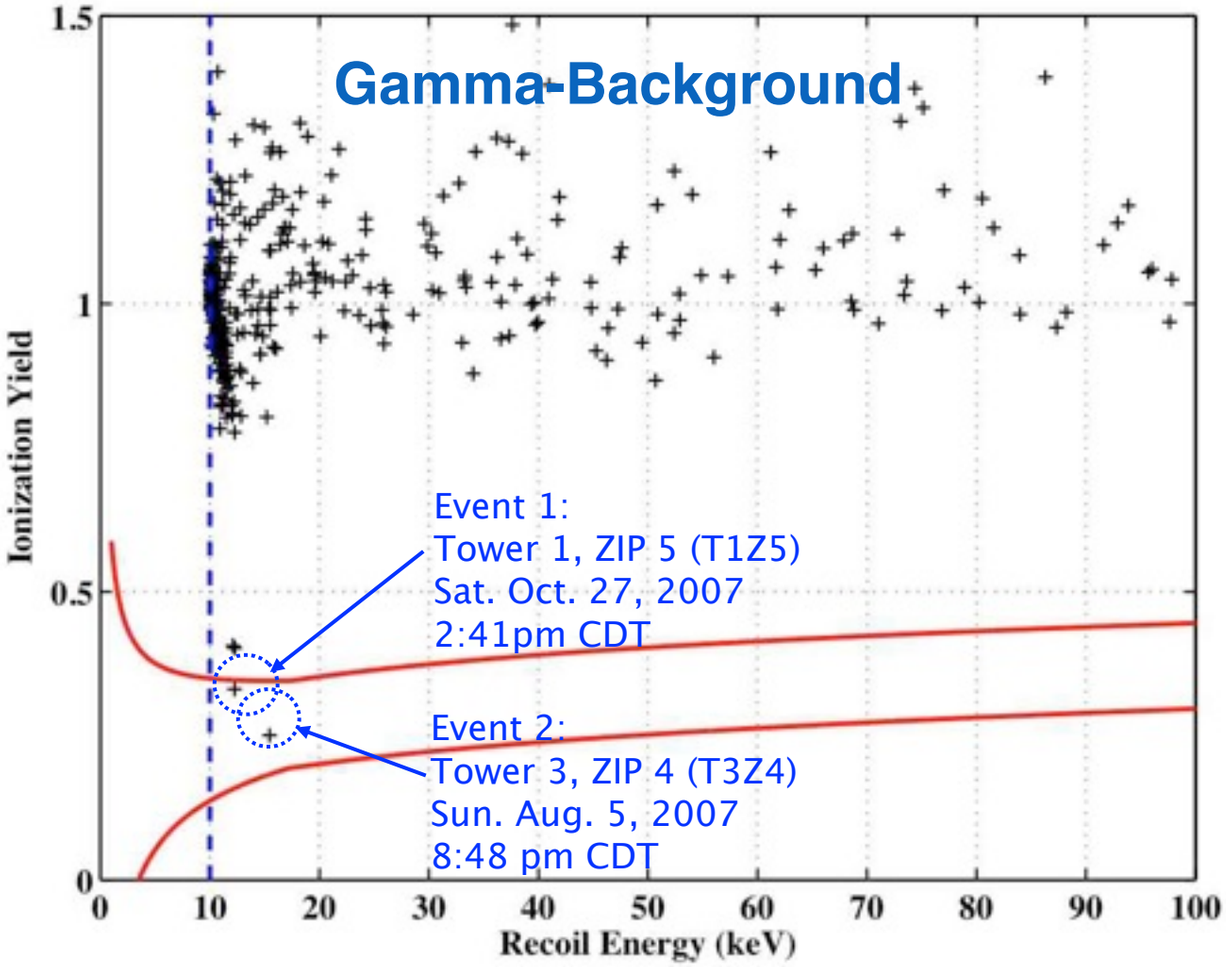


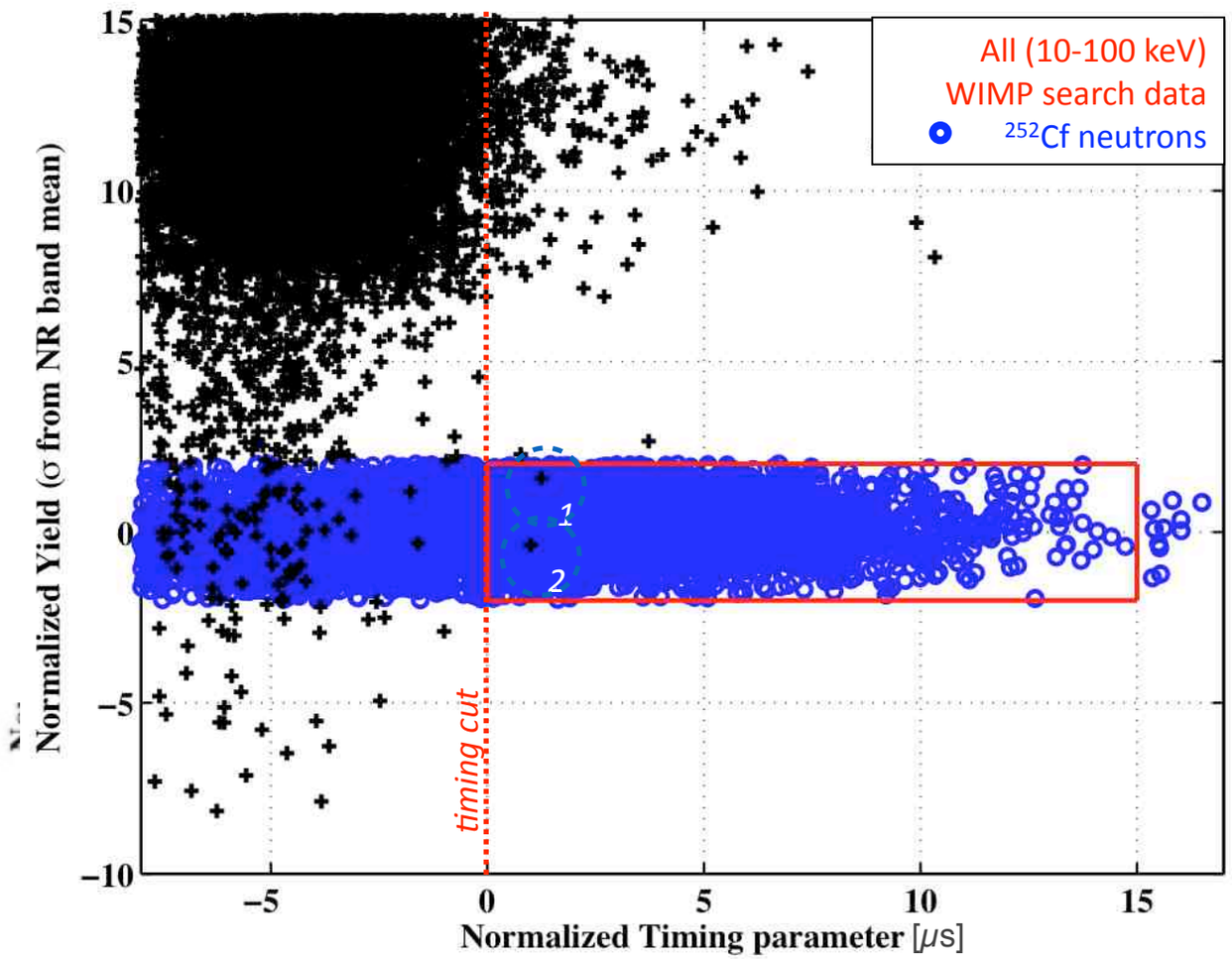
Two events passing all cuts (which were set based on calibration and background data outside the WS region)

Background estimate: 0.8 ± 0.1 (stat) ± 0.2 (syst)

Probability to observe 2 or more background events is 23%

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)

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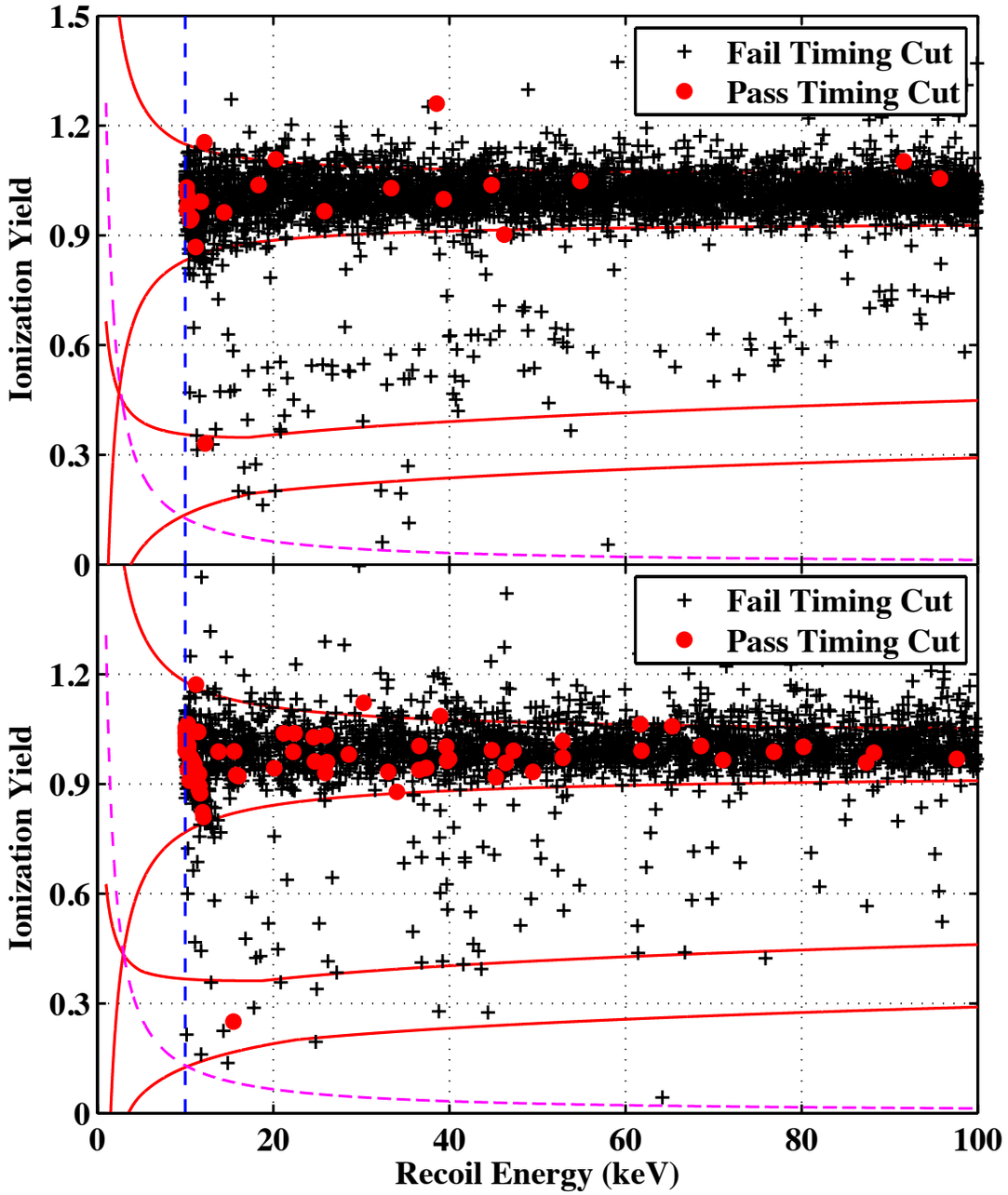
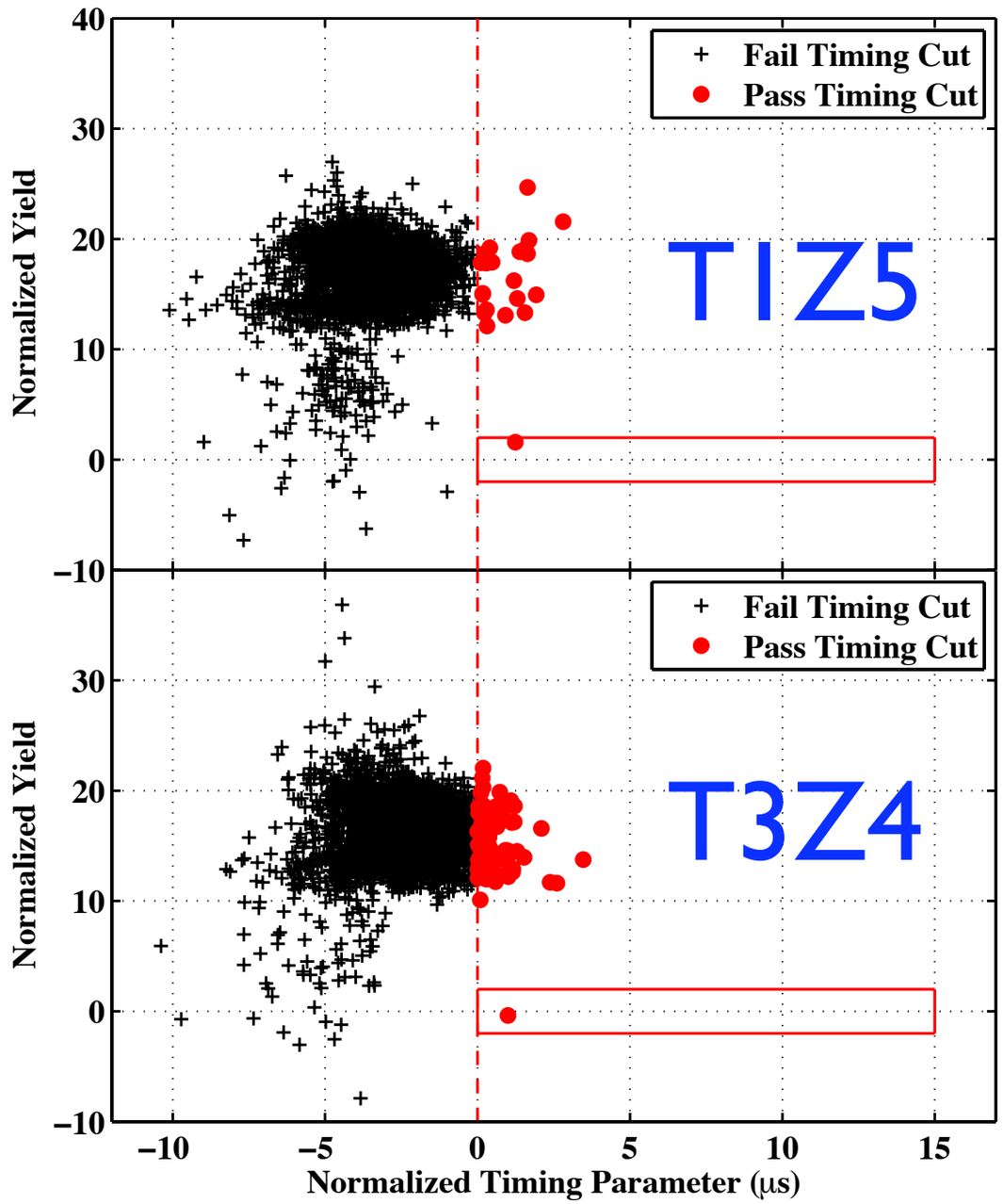
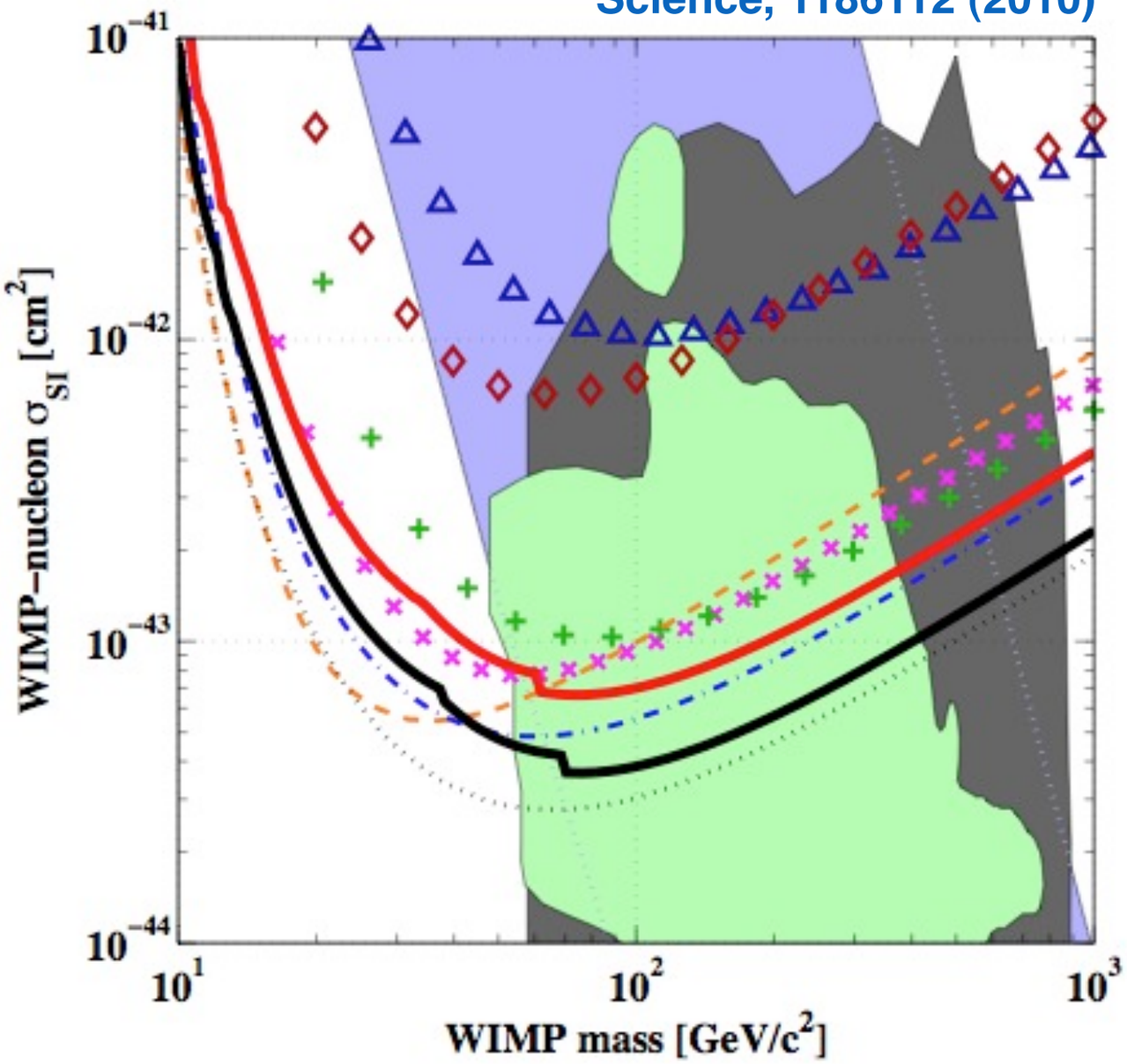
The Two CDMS Candidate Events





The CDMS 90% Confidence Upper Limit

Science, 1186112 (2010)



- **30 Ge (4.75 kg) and Si (1.1 kg) detectors below 40 mK in 5 towers**

- For 2 events (no background subtraction)
- **CDMS combined Soudan data:**
  - ➡ at a WIMP mass of 70 GeV, the limit on the spin-independent WIMP-nucleon cross section is: 3.8 x 10^{-44} cm^2 (90% C.L.)
- **Background estimate:**
- 0.8±0.1(stat.)±0.2(sys.) surface events

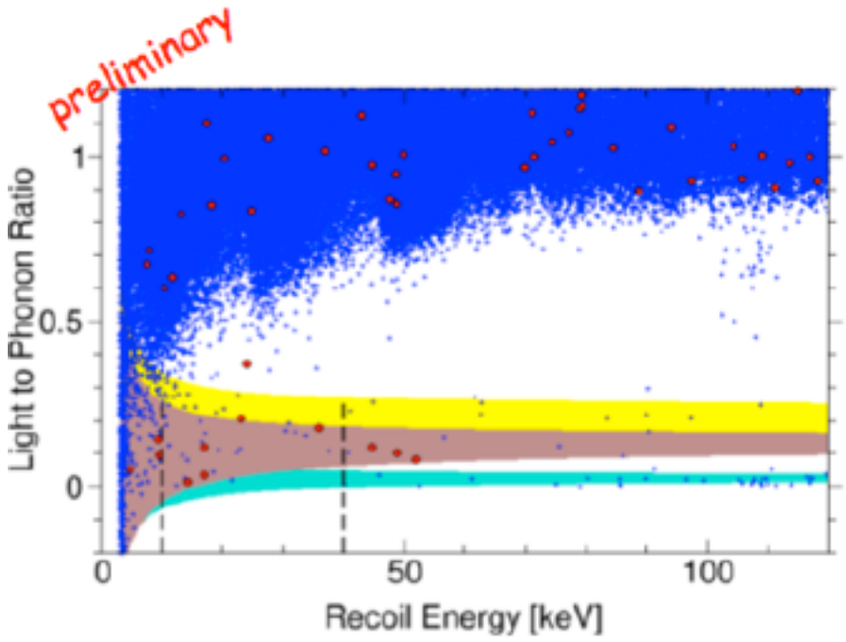
$0.04\ ^{+\ 0.04}_{-\ 0.03}$ cosmogenic neutrons

0.04 – 0.06 radiogenic neutrons

Cryogenic mK Experiments: Near Future

CRESST at LNGS

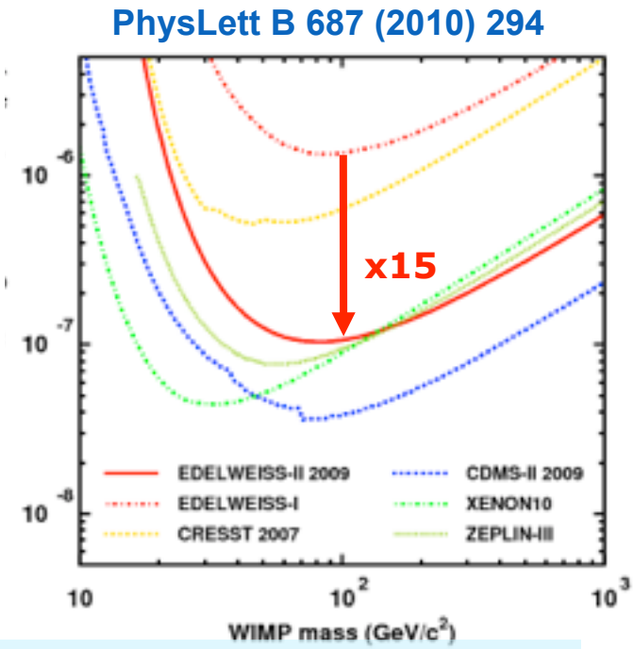
Goal: 10 kg array of 33 $CaWO_4$ detectors
- new 66 SQUID channel array
- new run in progress at LNGS, with 10 detector modules



EDELWEISS at LSM

New results in 2010
Run with detectors with new charge electrodes (removed surface event problem)
- 300 kg d under analysis
- data taking in progress

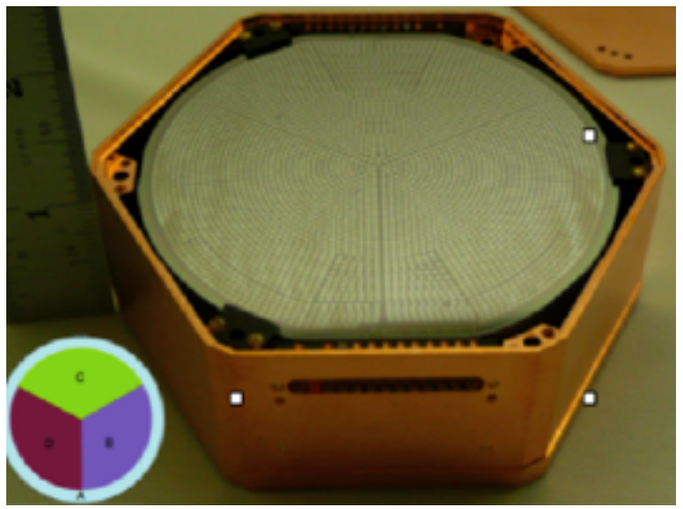
PhysLett B 687 (2010) 294



CDMS/SuperCDMS at Soudan

Detectors: 1" thick ZIPs, each 650 g of Ge
First SuperTower run at Soudan has been completed
Data is now being analyzed for surface background characterization

First goal: 5 x 10^{-45} cm^2 with 15 kg Ge at the Soudan Underground Laboratory



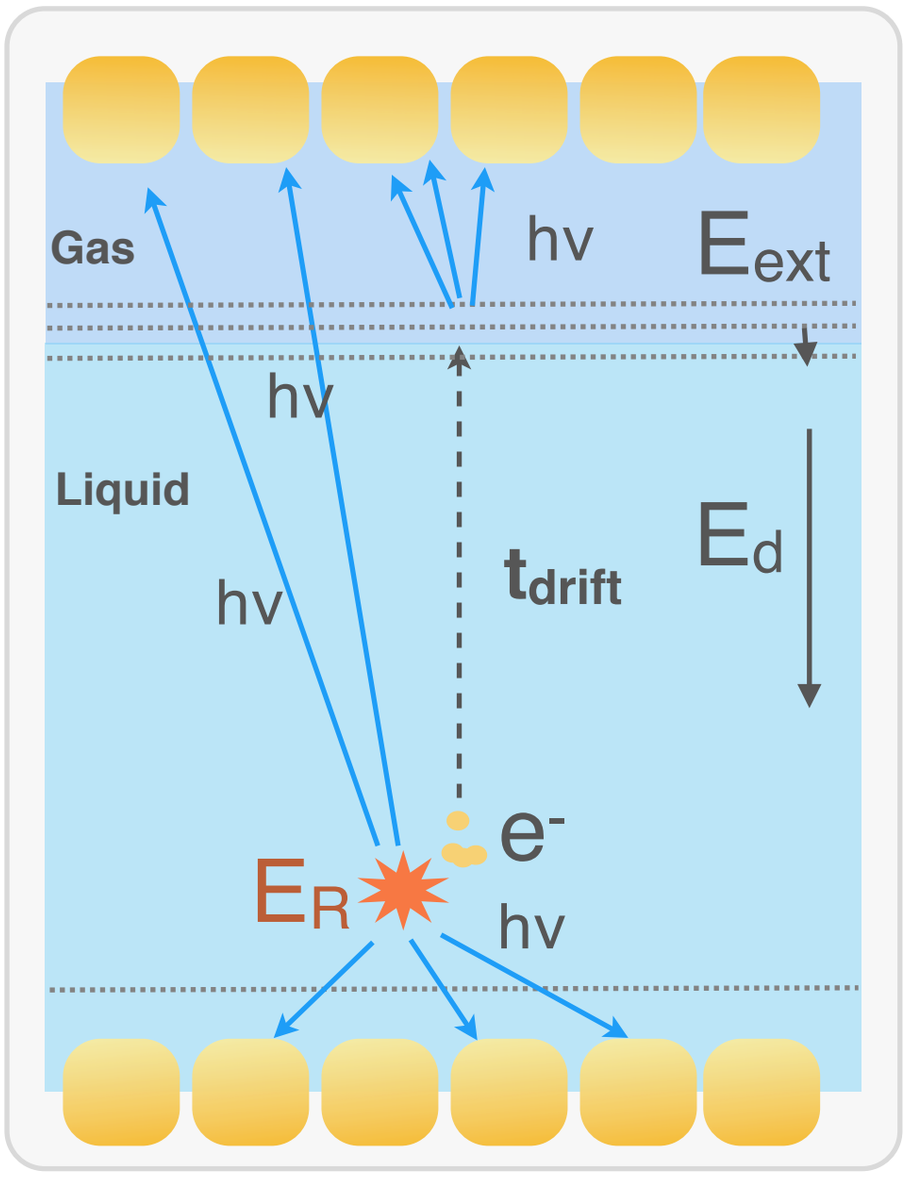
EURECA: joint effort for 100 kg -1t experiment in Europe
(ULISSE laboratory = Modane extension)
Operation: by 2015 (150 kg version) 2017 (1 ton version)

Goal: 100 kg Ge at SNOLAB
1.t tons of Ge at DUSEL
(MoU signed with EURECA)

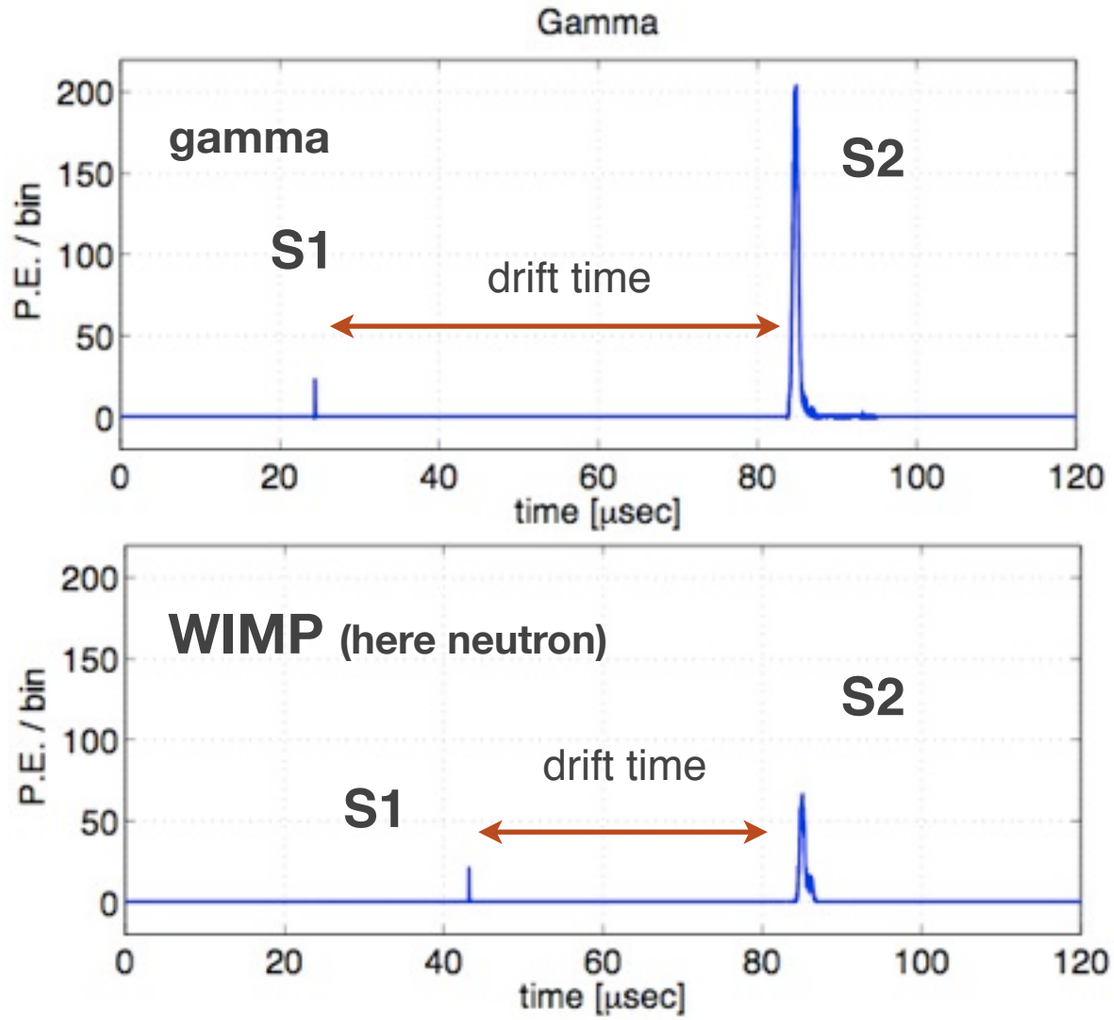
Noble Liquids Time Projection Chambers

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**)

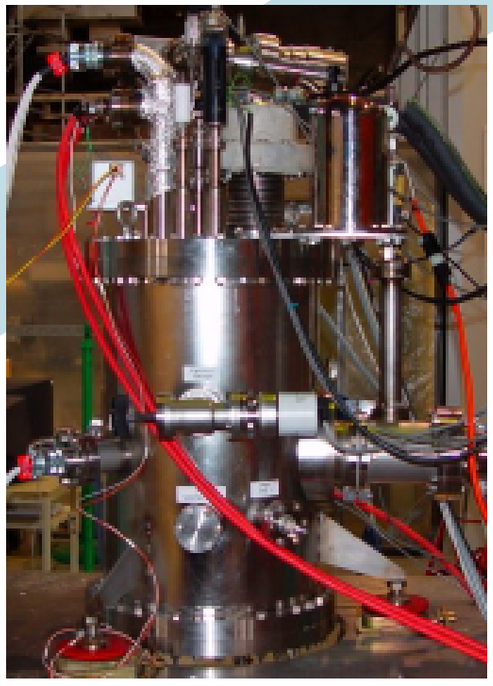


- S2/S1 depends on dE/dx
- good 3D position resolution } **=> particle identification**



The XENON Program

XENON10

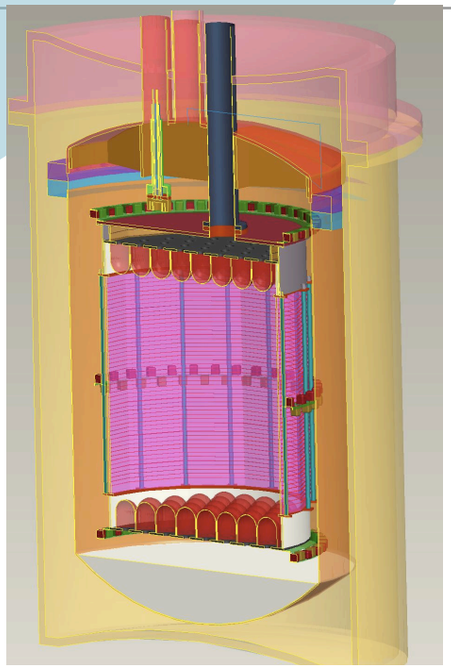


2005-2007

XENON100

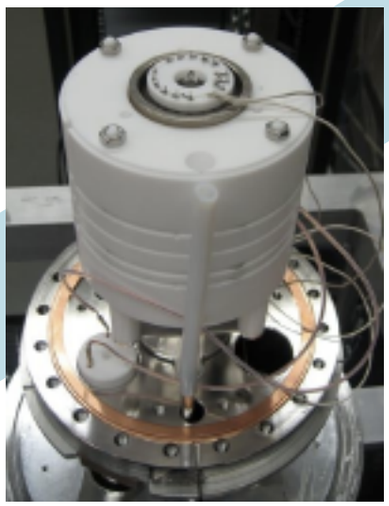
2008-2010
taking science data

XENON1t



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

XENON R&D

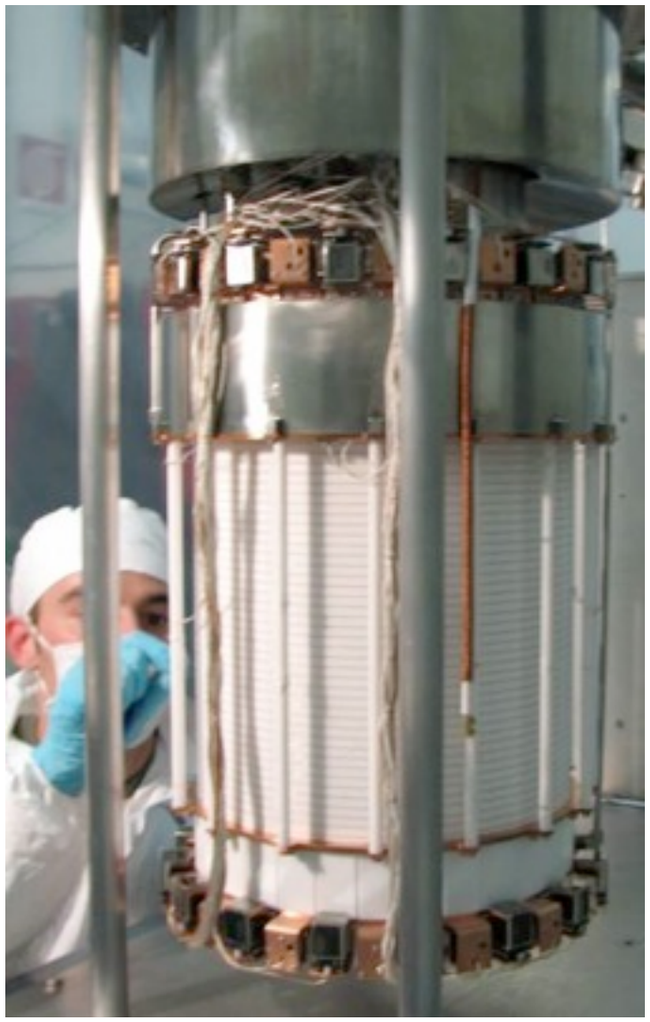


ongoing

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

The XENON100 Experiment at LNGS

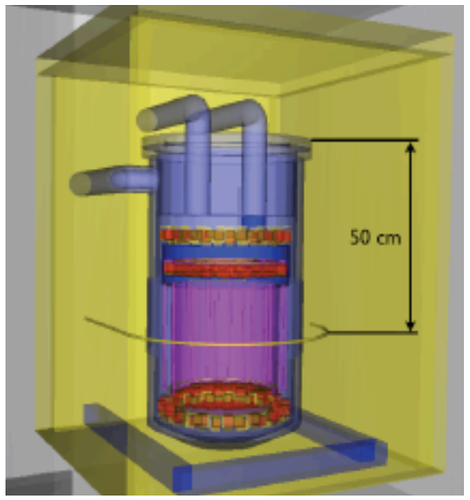
- 161 kg ultra-pure LXe: 62 kg in the active target surrounded by 99 kg LXe as scintillator veto
- 30 cm drift gap TPC with two PMT arrays to detect both charge and light signals
- 242 1-inch square PMTs with < 1 mBq/PMT in $^{238}U/^{232}Th$ and high QE (25-33%) at 178 nm
- 3D event localization with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

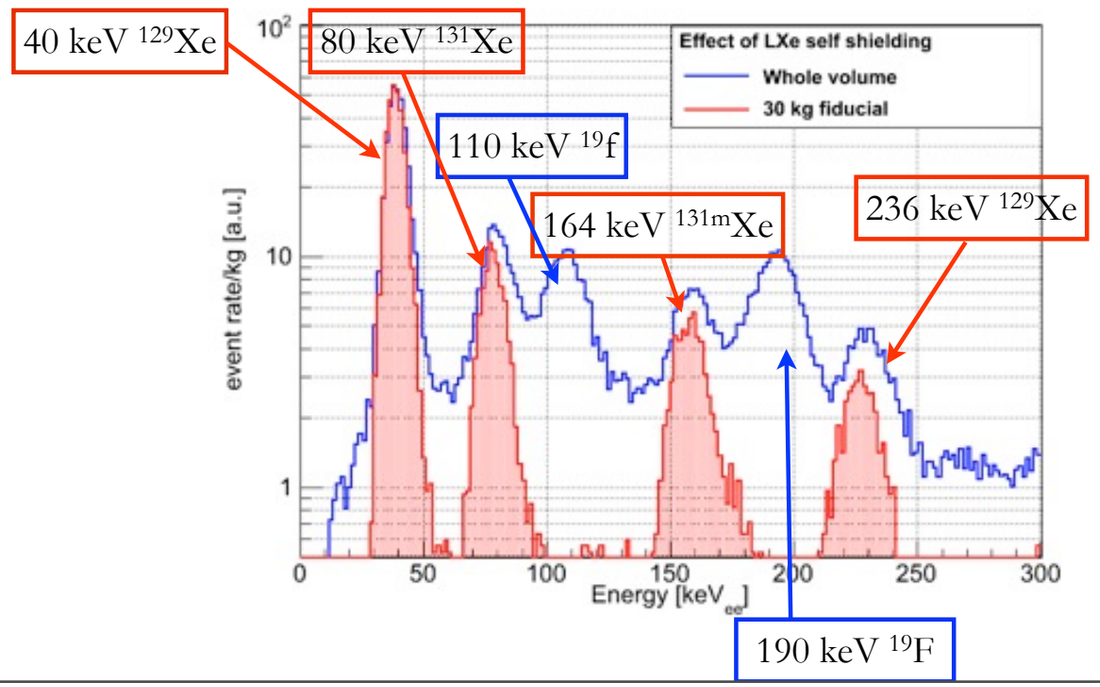


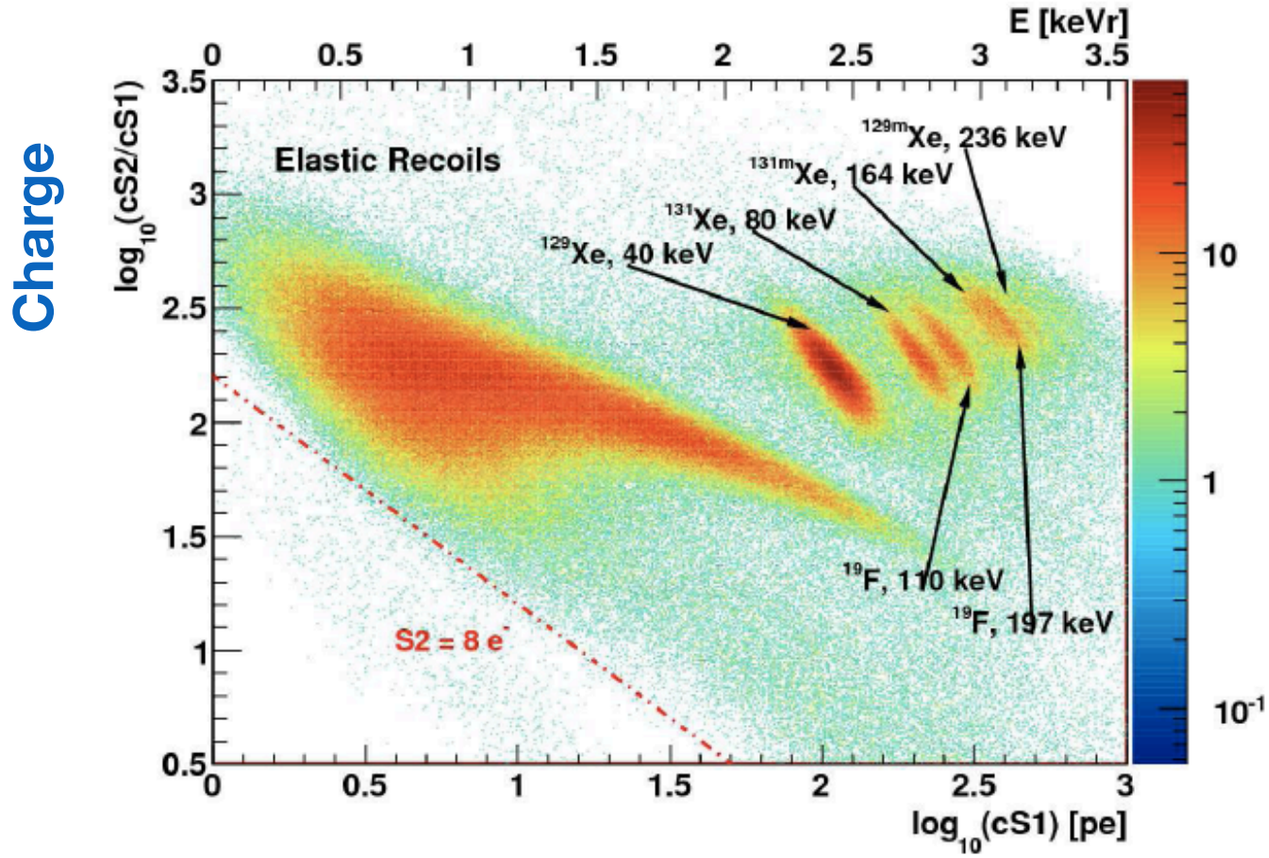
The XENON100 detector in its low-background shield at LNGS

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)





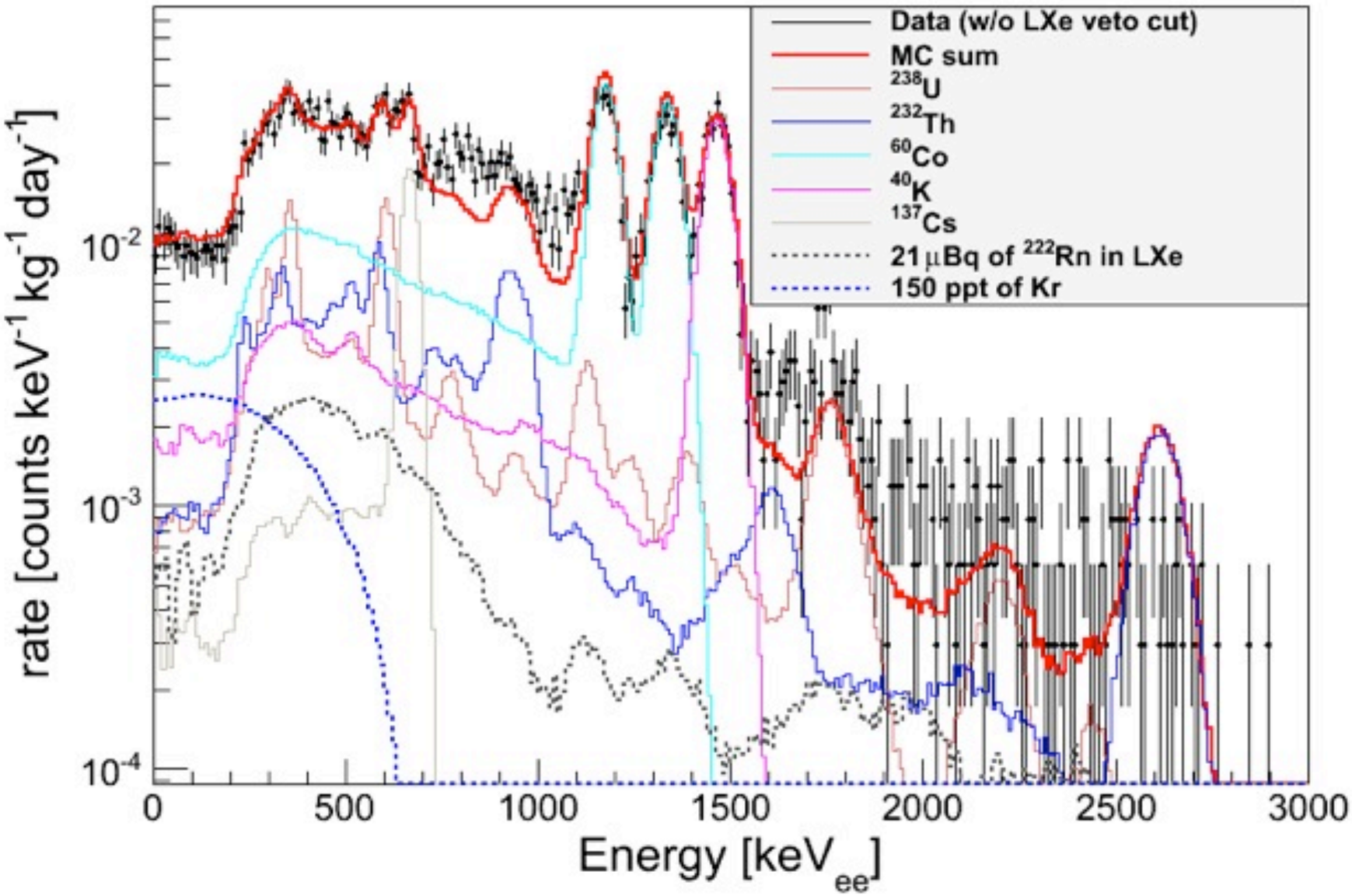


Light

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

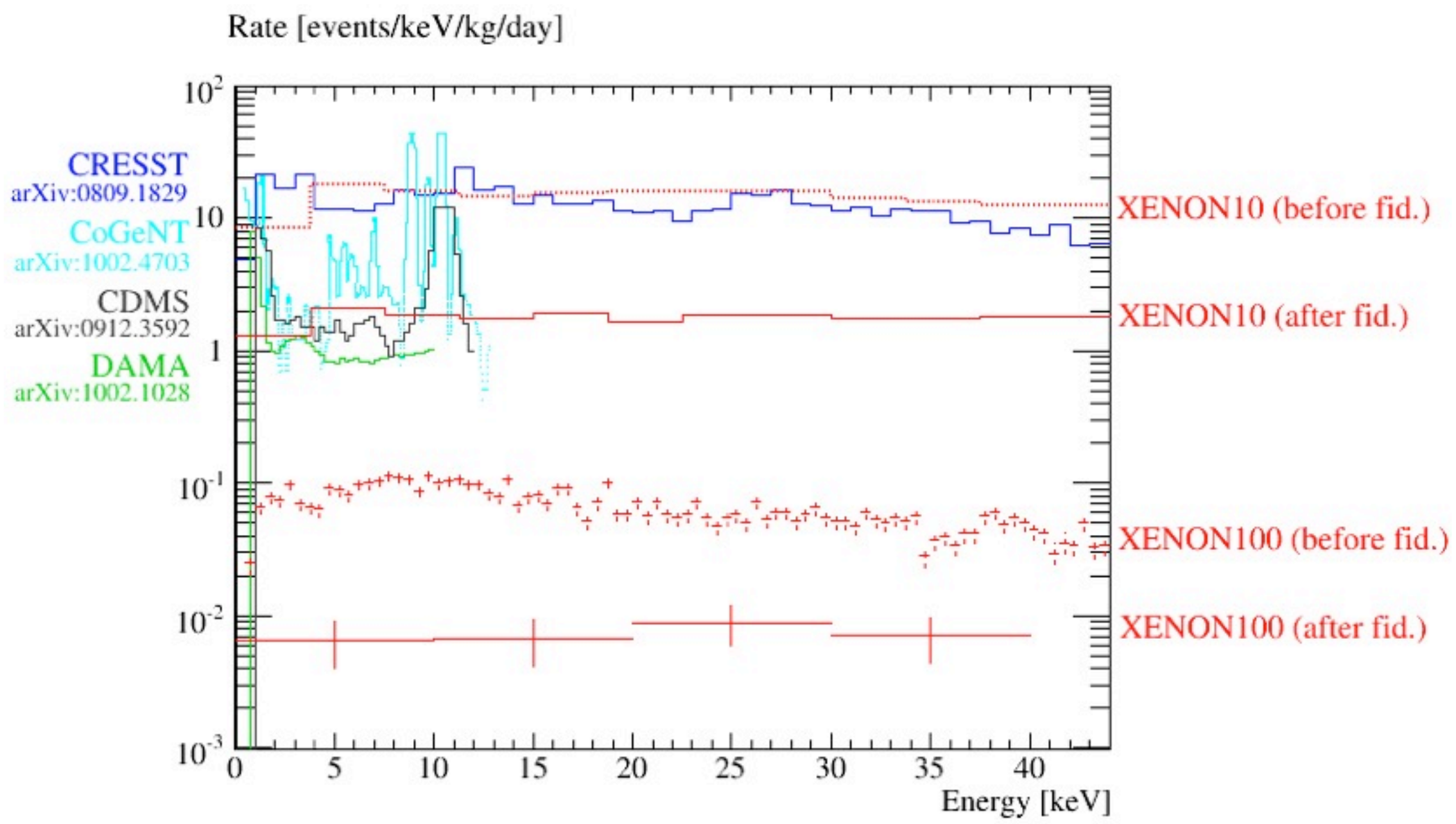
XENON100 Backgrounds: Data and Predictions

- Preliminary: data and MC (no MC tuning) - before the active LXe veto cut!
- More detailed studies are in progress (include cosmogenics)



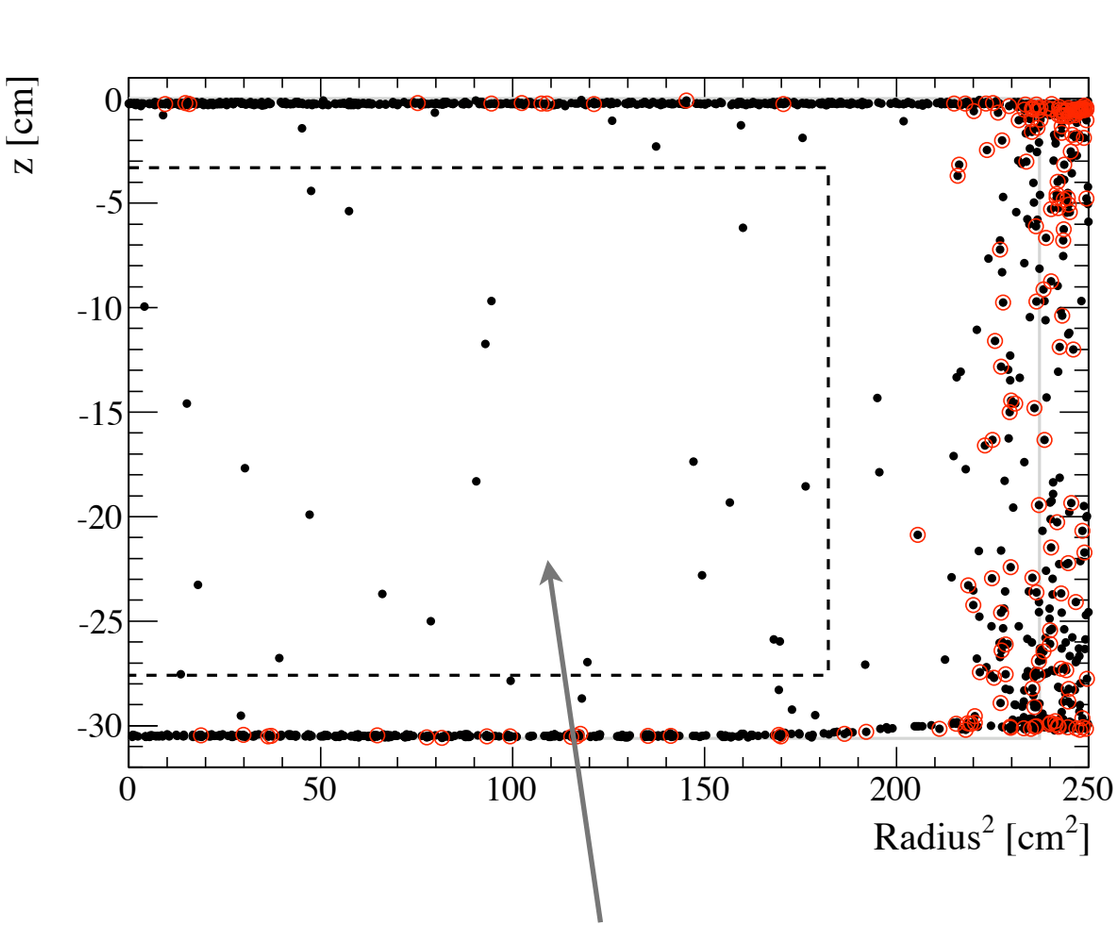
XENON100 Backgrounds: Low-Energy Region

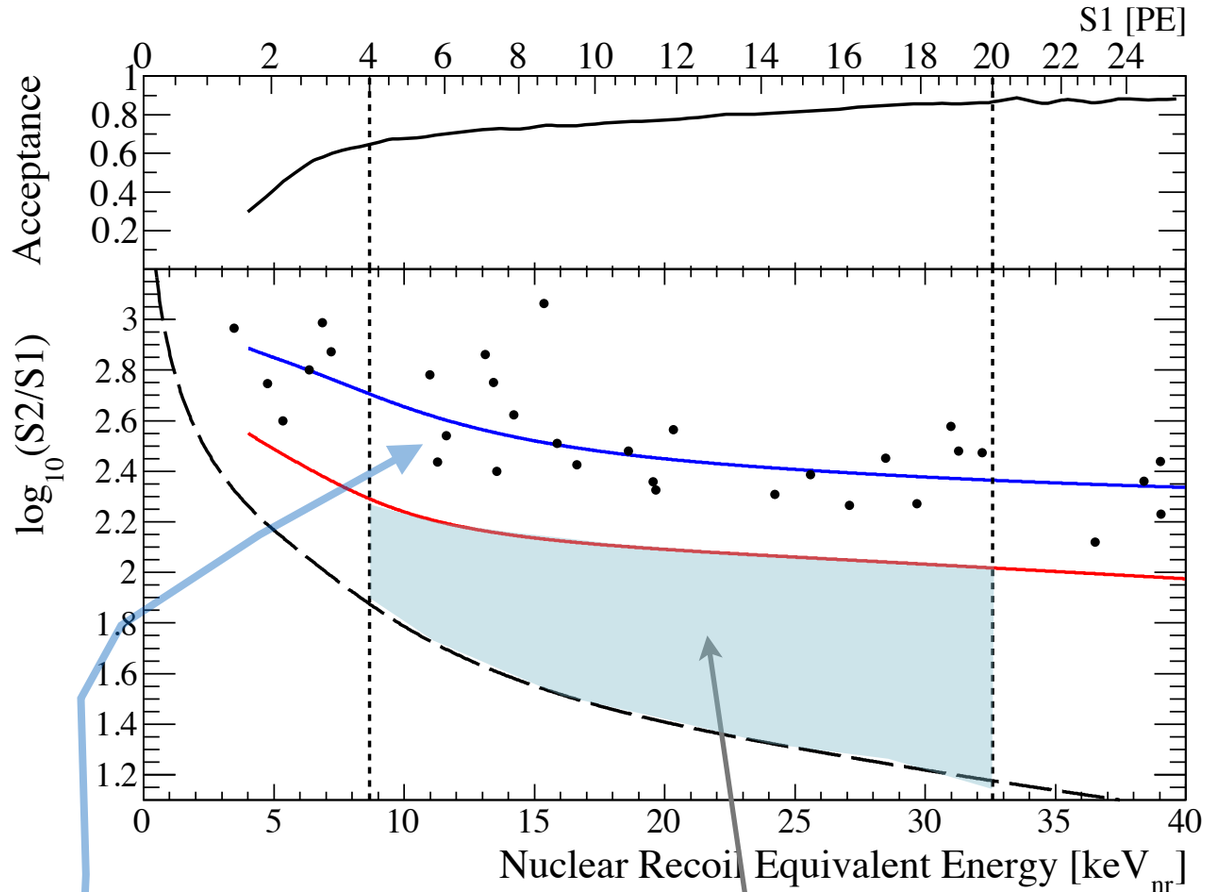
- The background meets the design specifications: 100 times lower than in XENON10 (and than in any other direct dark matter detection experiment)



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)

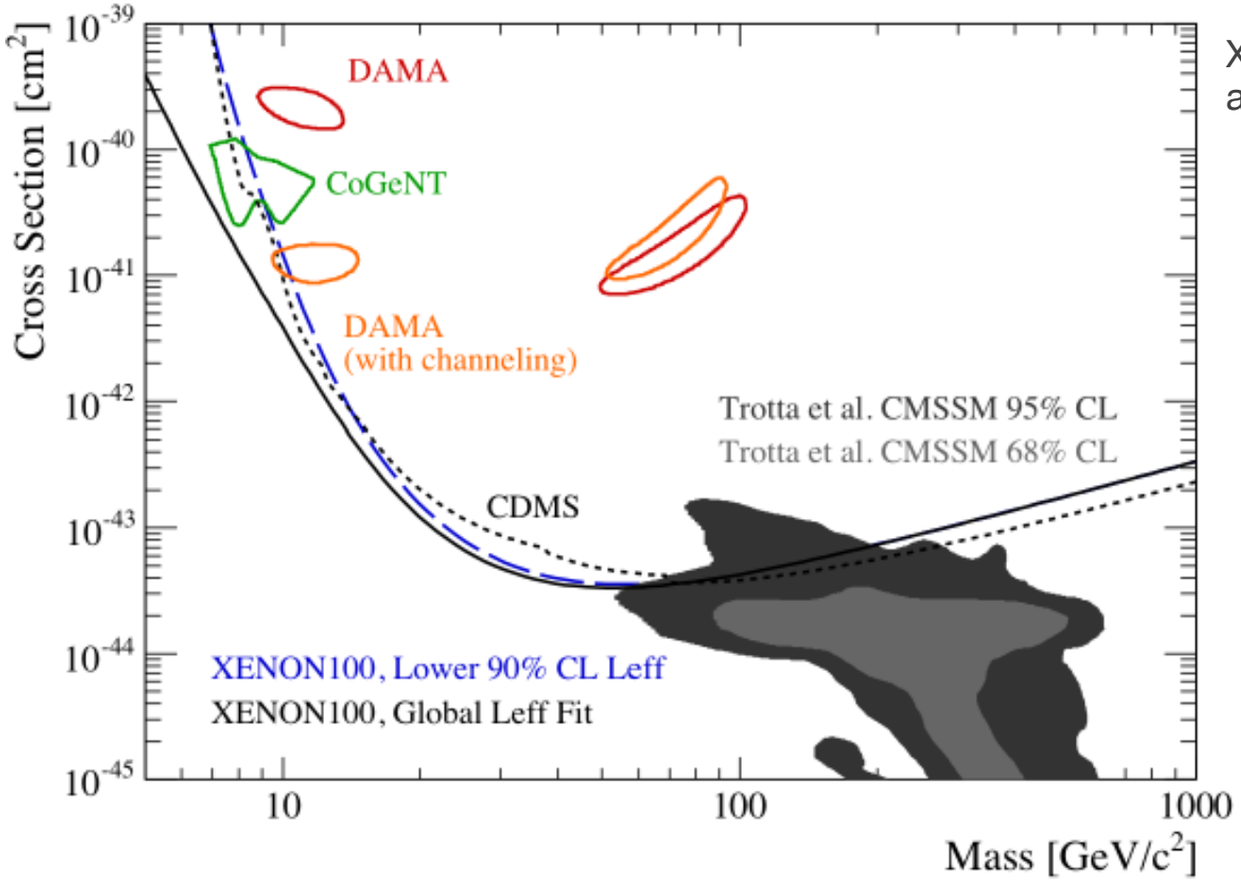




Fiducial mass region:
40 kg of liquid xenon
22 events (all gamma background)

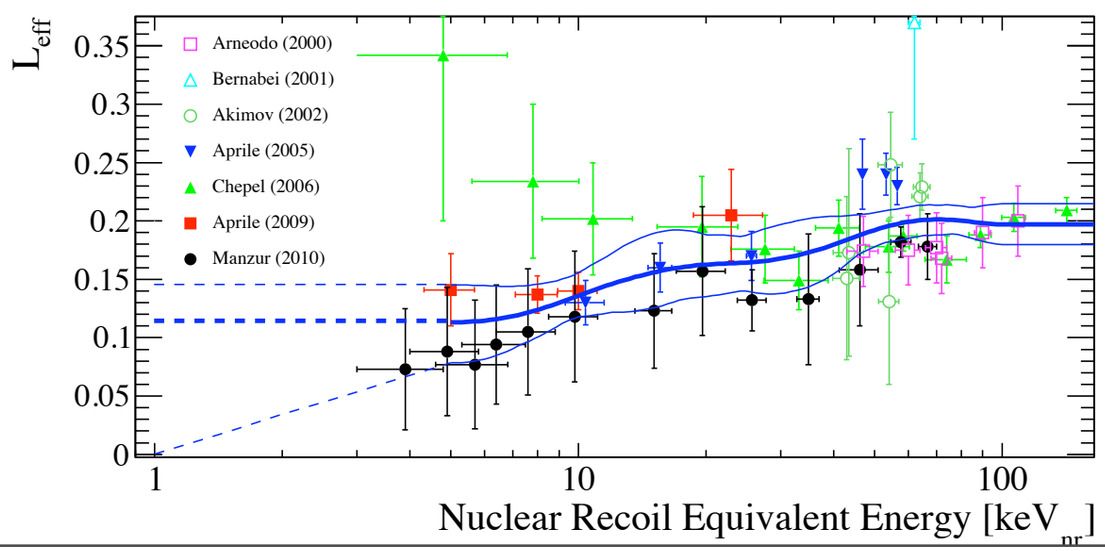
Signal region:
no events are observed in
the given exposure

XENON100: First Spin-Independent Results



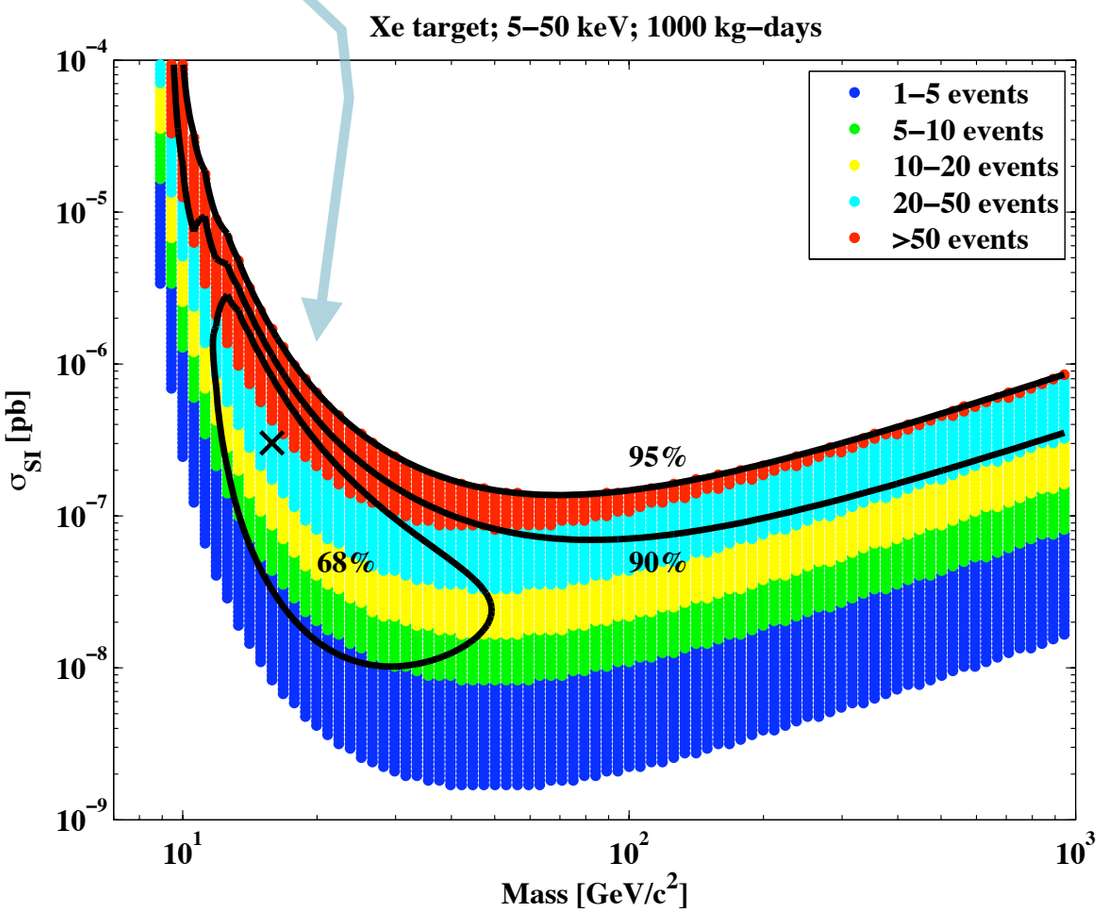
XENON100 collaboration
arXiv:1005.0380v2

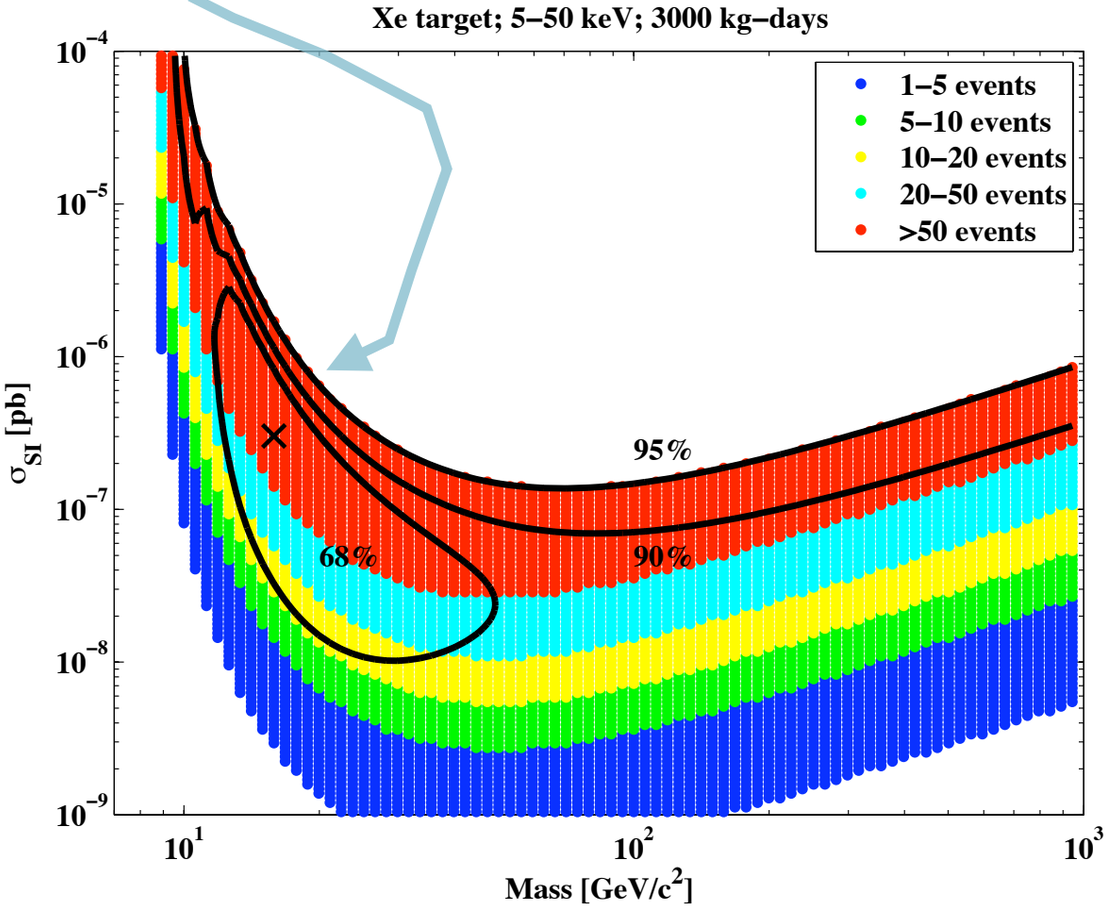
- **New upper limit:** based on zero events in the pre-defined signal region
  - ➡ at a WIMP mass of 55 GeV, the limit on the spin-independent WIMP-nucleon cross section is: 3.4 x 10^{-44} cm^2 (90% C.L.)
- **WIMP search run started on January 13, 2010**
  - ➡ science data throughout 2010
  - ➡ annual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



Let's dream for a moment...

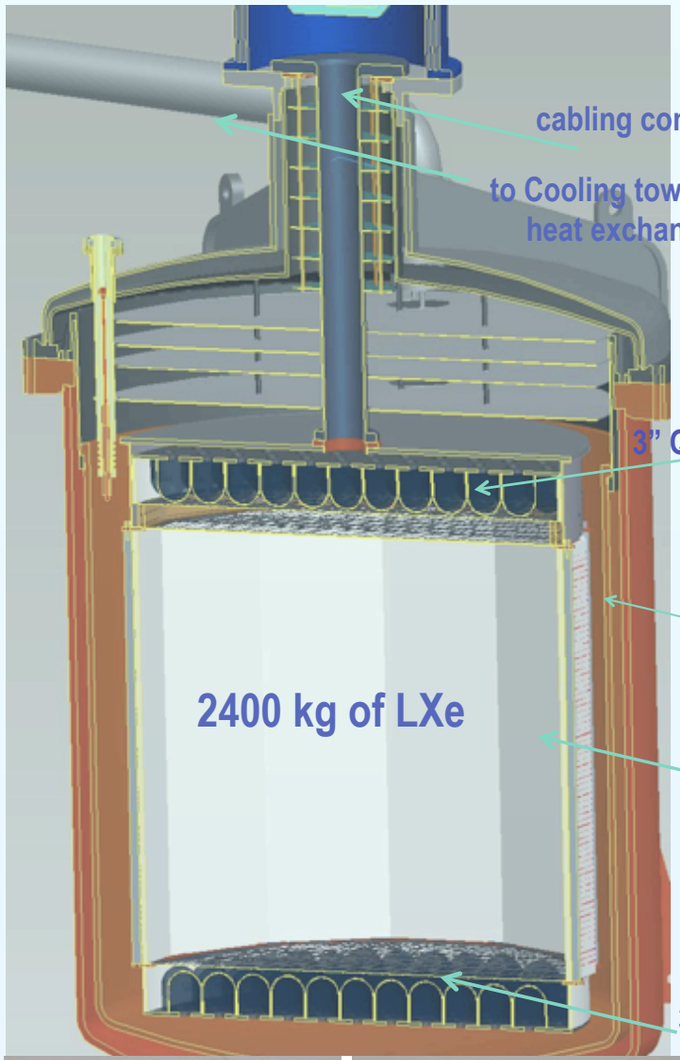
- What if the two CDMS events are WIMPs?... *What would XENON100 see?*
- Assumptions:
  - ➡ 50 kg x 40 days x 50% signal acceptance = **1000 kg days exposure**
  - ➡ 30 kg x 200 days x 50% signal acceptance = **3000 kg days exposure** (lower background)



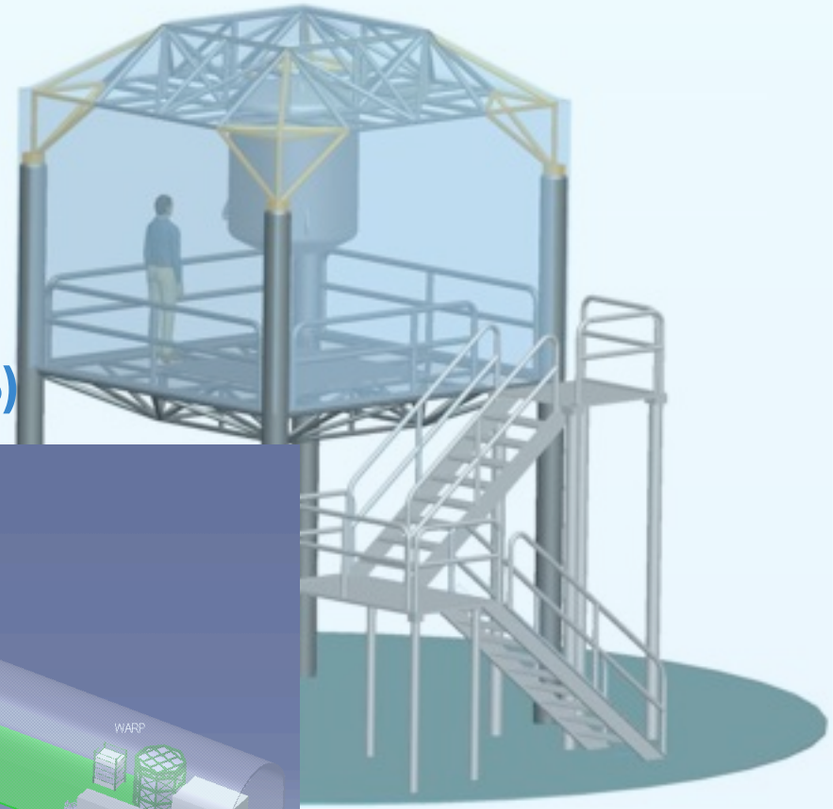


Next Step: XENON1T

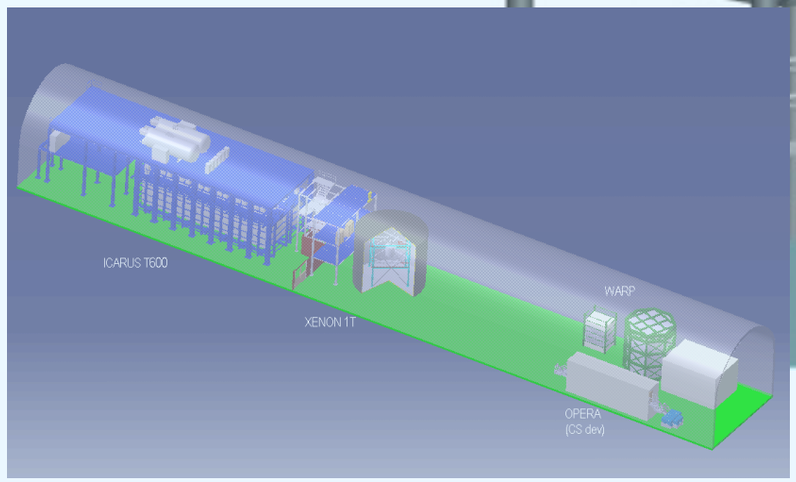
Construction starting in 2011
Dark matter run in 2013

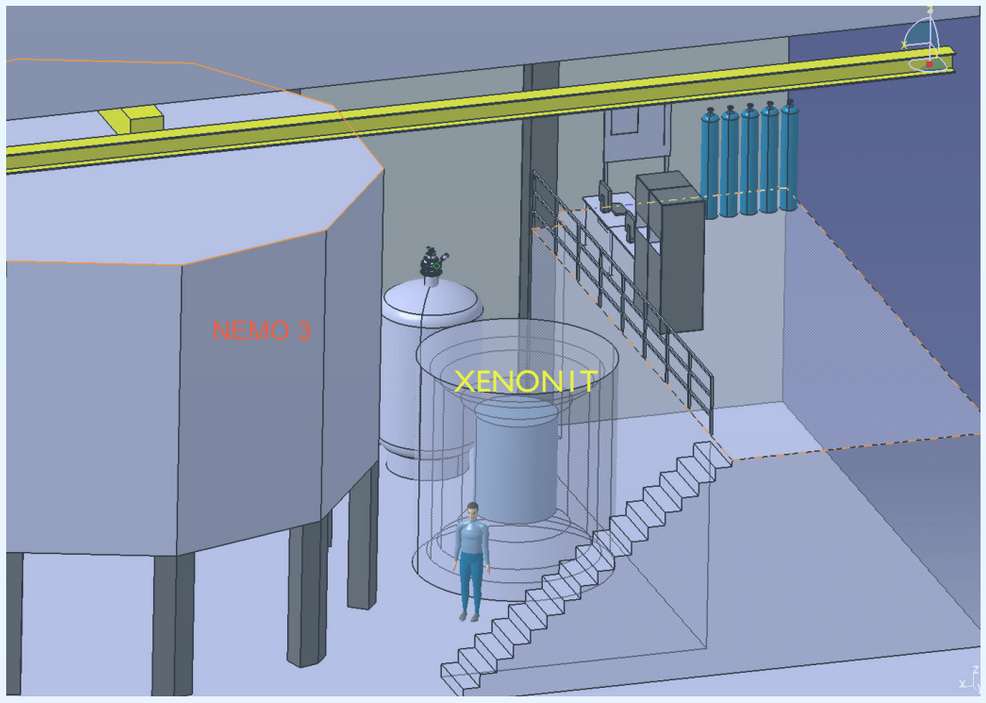


Hybrid photo-sensors



LNGS option (Hall B)





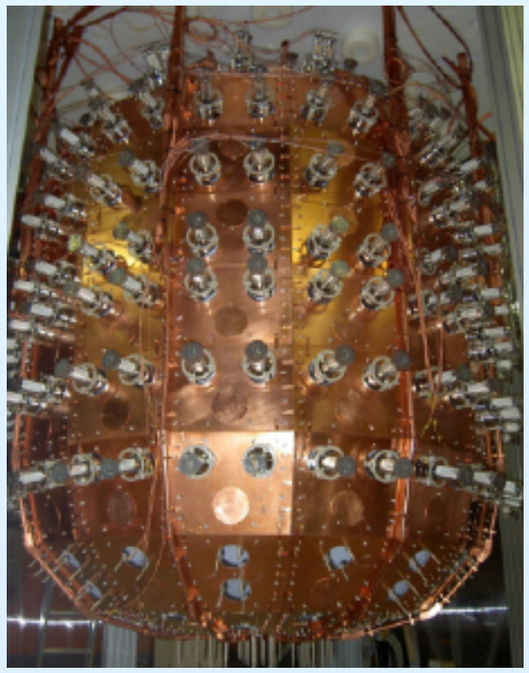
LSM option

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

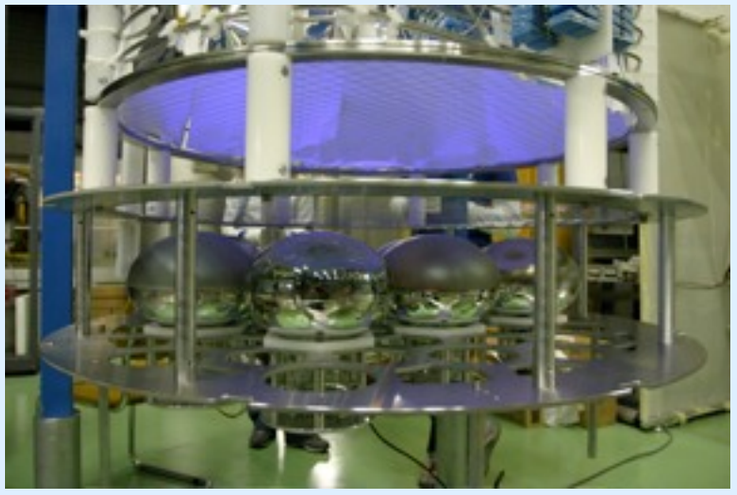
Detector had been installed in December 08
Some technical problems with HV
Now again under commissioning at LNGS

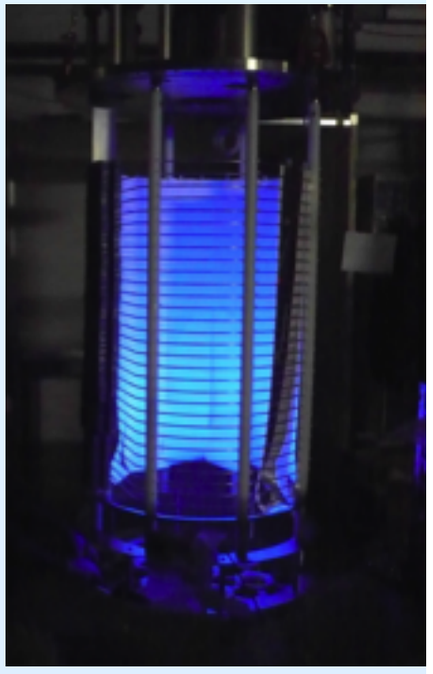


ArDM at CERN

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: LSC or SunLab





DARWIN
(DARk matter WImp search with Noble liquids)

- Design study for **next-generation noble liquid facility in Europe**
- Approved by ASPERA (AStroParticle ERAnet) in late 2009

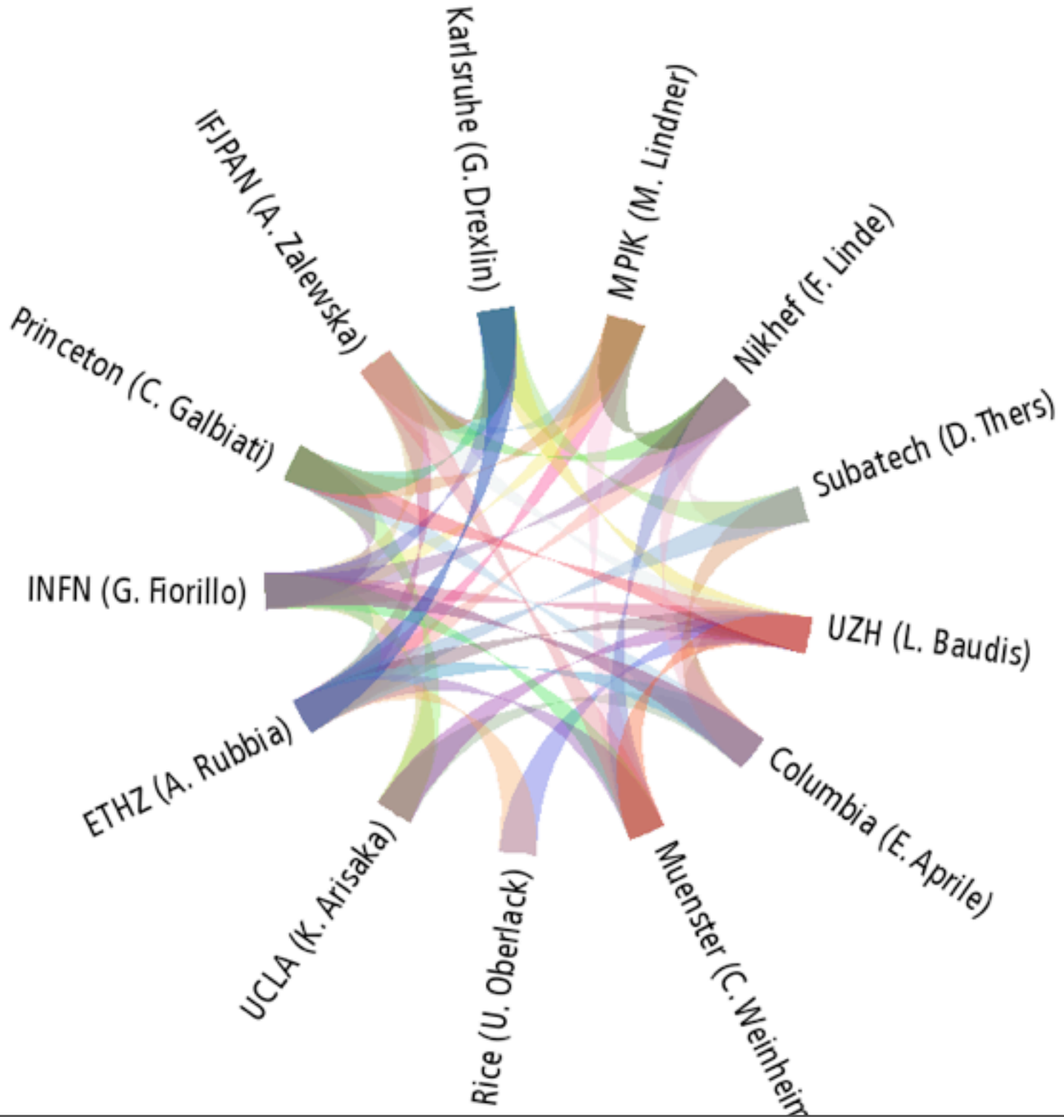
- **Goals:**
  - ➡ unify and coordinate extensive existing expertise in Europe (XENON, WARP, ArDM plus new groups, including US groups from XENON and WARP)
  - ➡ study both argon and xenon as WIMP target media and provide recommendation for facility (full technical design report) in 2-3 years from now
  - ➡ submit full proposal in response to second ASPERA call

- **Possible locations**: LNGS (Italy) or ULISSE (Modane extension, France)

- **The outcome of the collaborative work will be:**

  - ➡ *a technical design report for the construction of a ton-scale LXe and multi-ton scale LAr experiment* (the DARWIN facility), with the goal of reaching below 10^{-47}cm^2 in sensitivity for the WIMP-nucleon cross section, which is three orders of magnitude below the current best results.

DARWIN Institutions and Connections



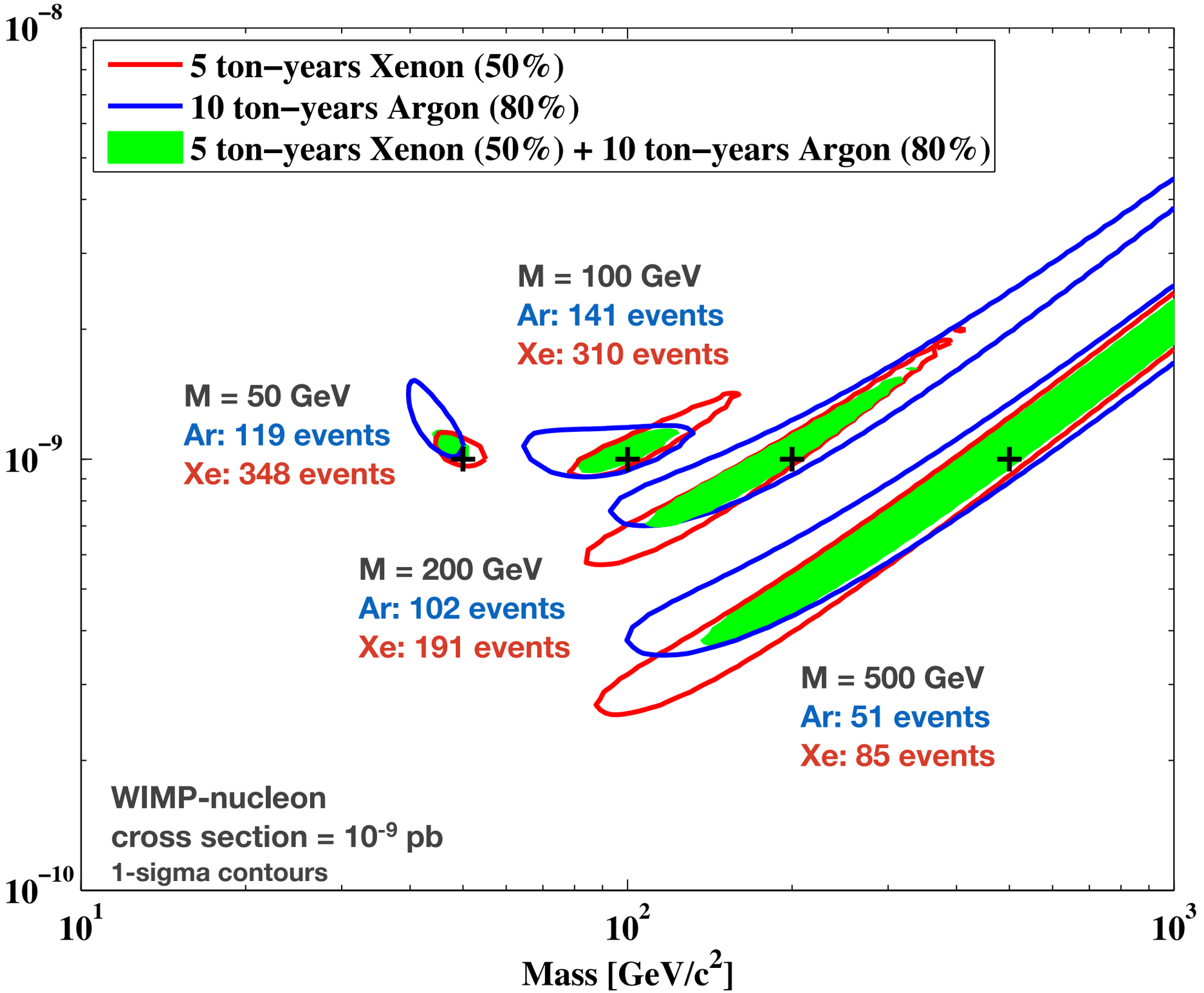
Groups from:

ArDM and WARP for LAr
XENON for LXe

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

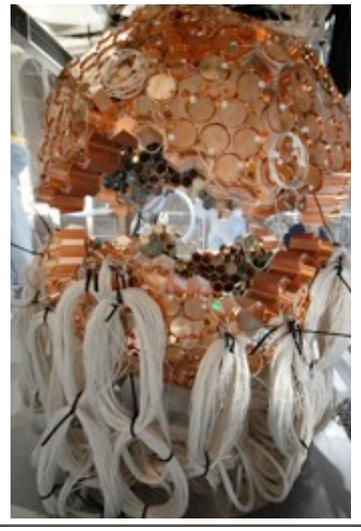
USA: Columbia, Princeton, Rice (-> Mainz), UCLA

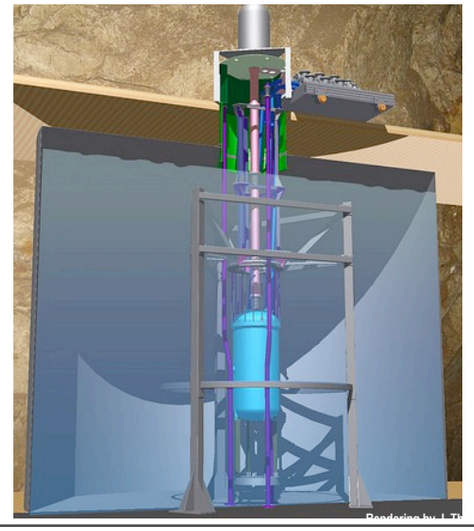
Complementarity between LAr and LXe

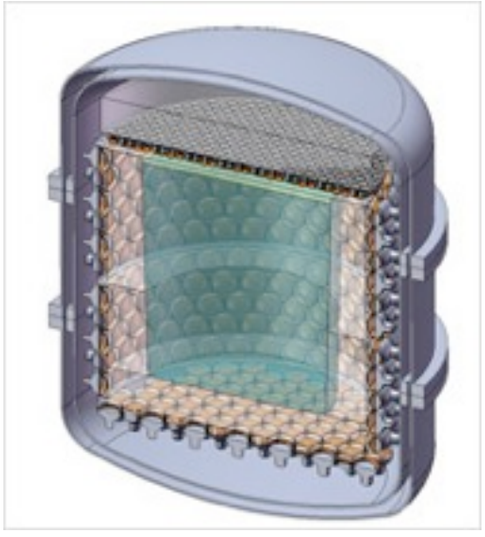


International Competition

- **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
- **To XENON1t and DARWIN:**
- **MAX in the US**
  - ➡ engineering study for 5t LAr and 2.4t LXe TPCs at DUSEL (ISE); 3.5 Mio US $
  - ➡ DarkSide + XENON + new groups
- **LZS in the US**
  - ➡ engineering study for 1.5 ton LXe experiment for the ISE at DUSEL; 3.5 Mio US $
  - ➡ LUX+ZEPLIN-III+ new groups

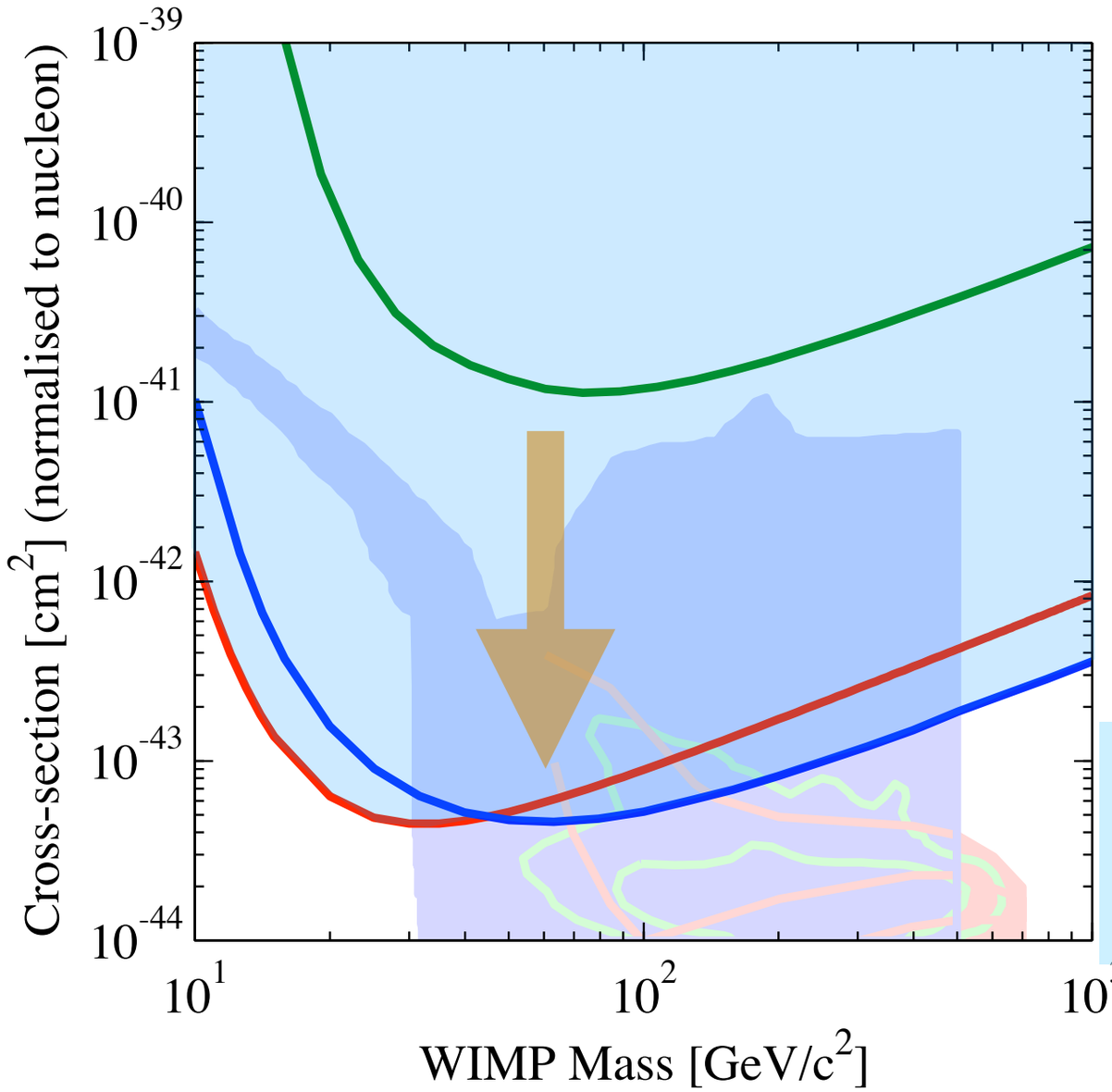






Summary/Outlook (I)

- A variety of techniques/targets are being employed to search for dark matter particles
- Steady progress in the last ~ 10 years: **> factor 100 increase in sensitivity!**



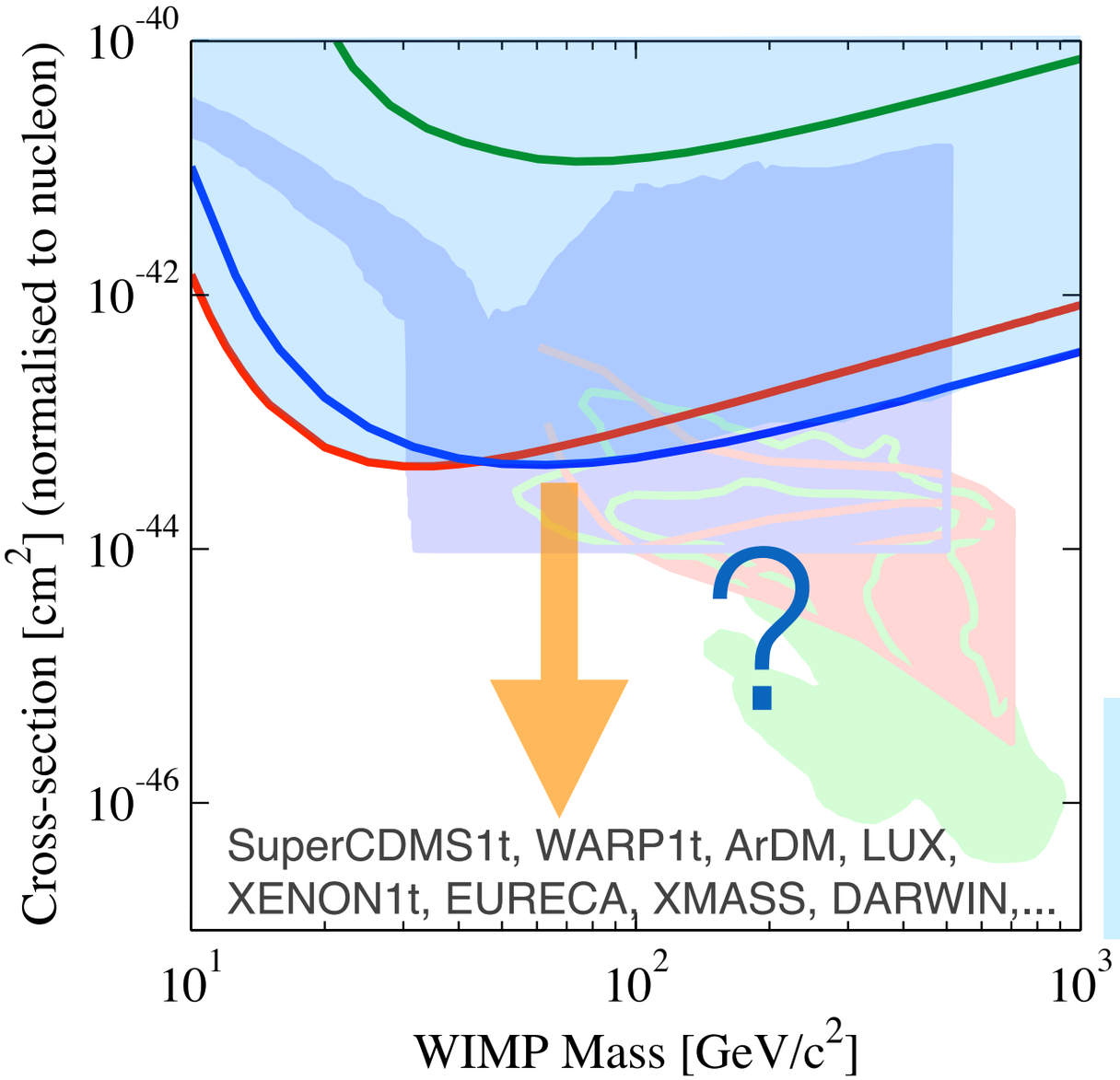
Heidelberg -Moscow 1998

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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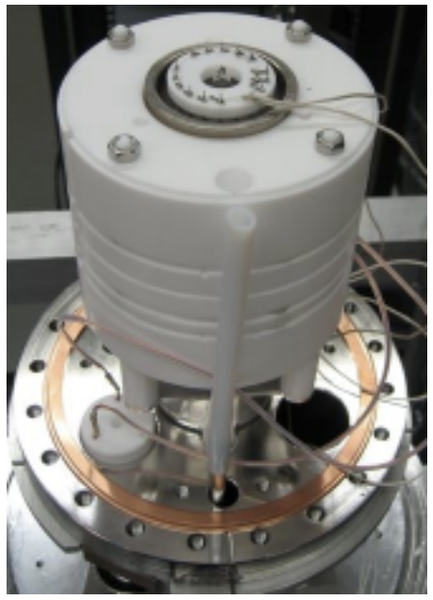
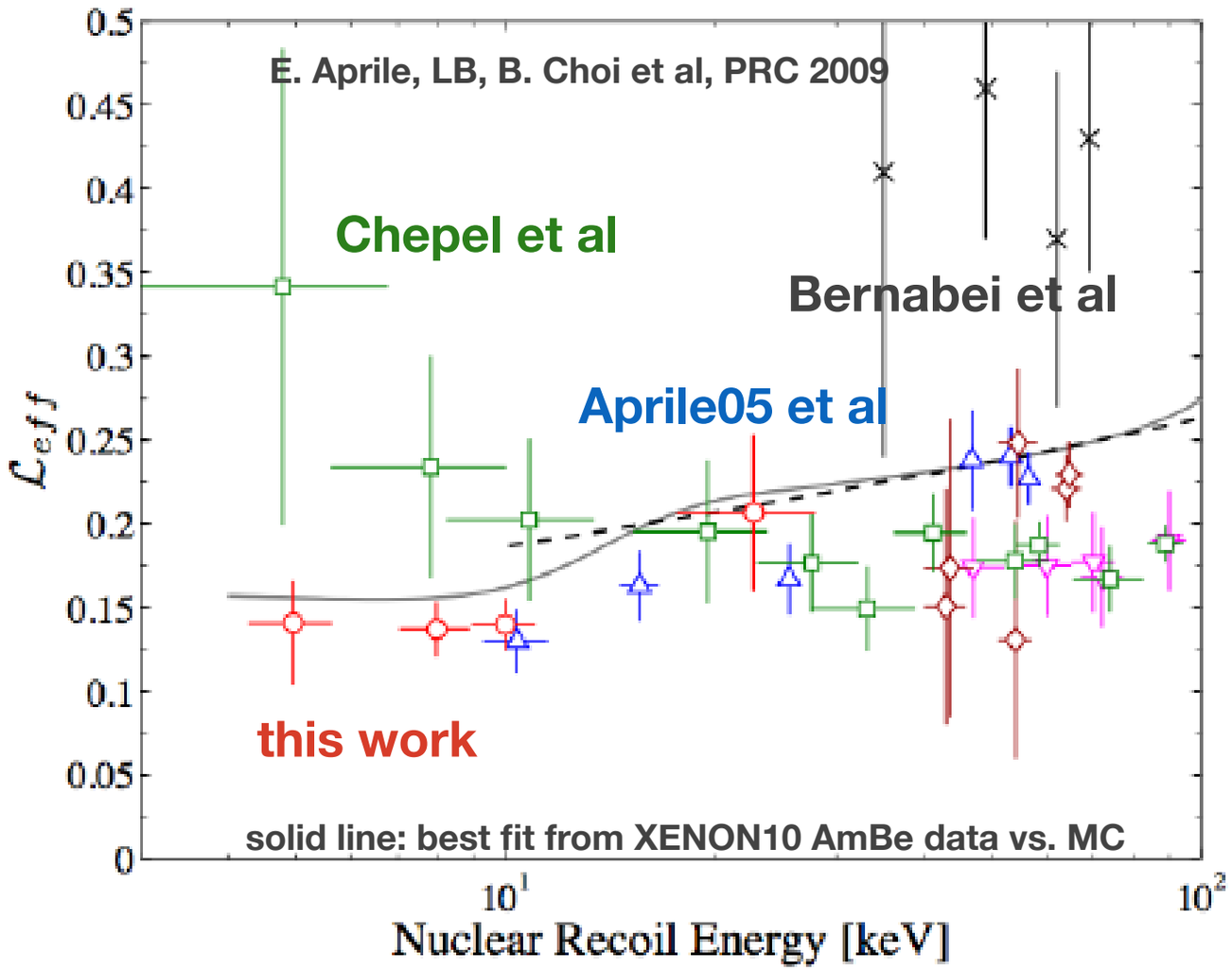
6th Patras Workshop on Axions, WIMPs and WISPs: University of Zurich, axion-wimp.desy.de

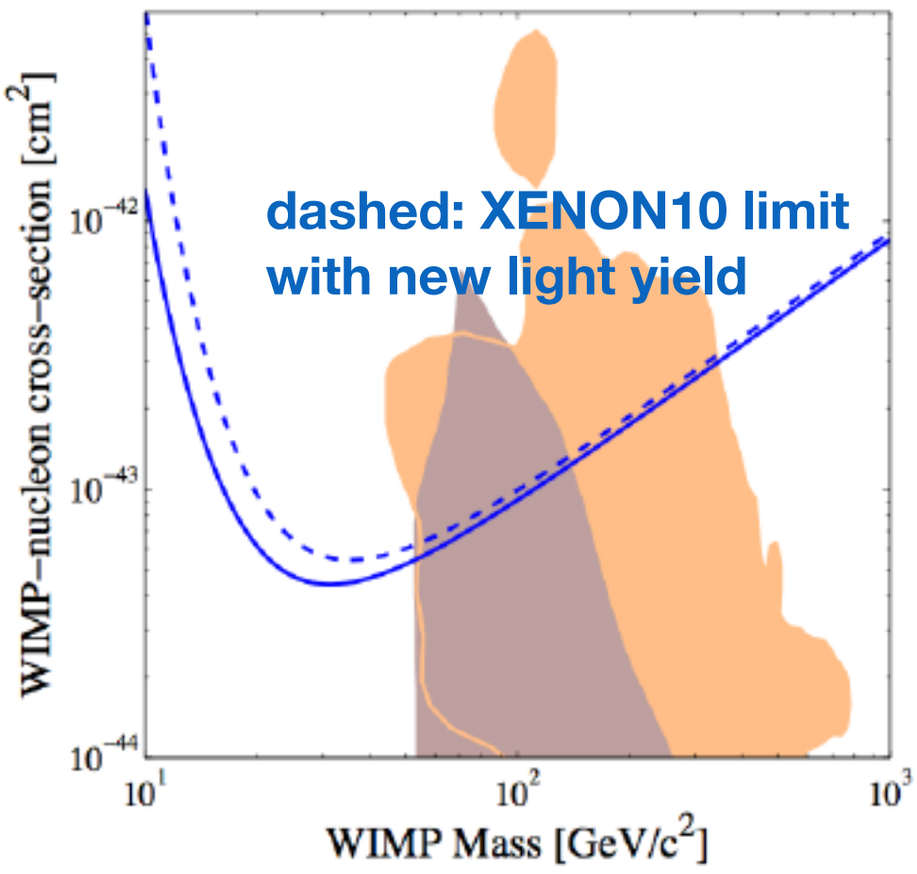
End

New measurements of the Light Yield in LXe

- Columbia + Zurich: at RaRAF (Nevis Labs), 1 MeV n-beam
- Detector: XeCube, 6 R8520 PMTs, 2.5 cm^3 LXe, zero field
- New experiment for charge/light yield under preparation at UZH (using D-D neutron generator) and at Columbia

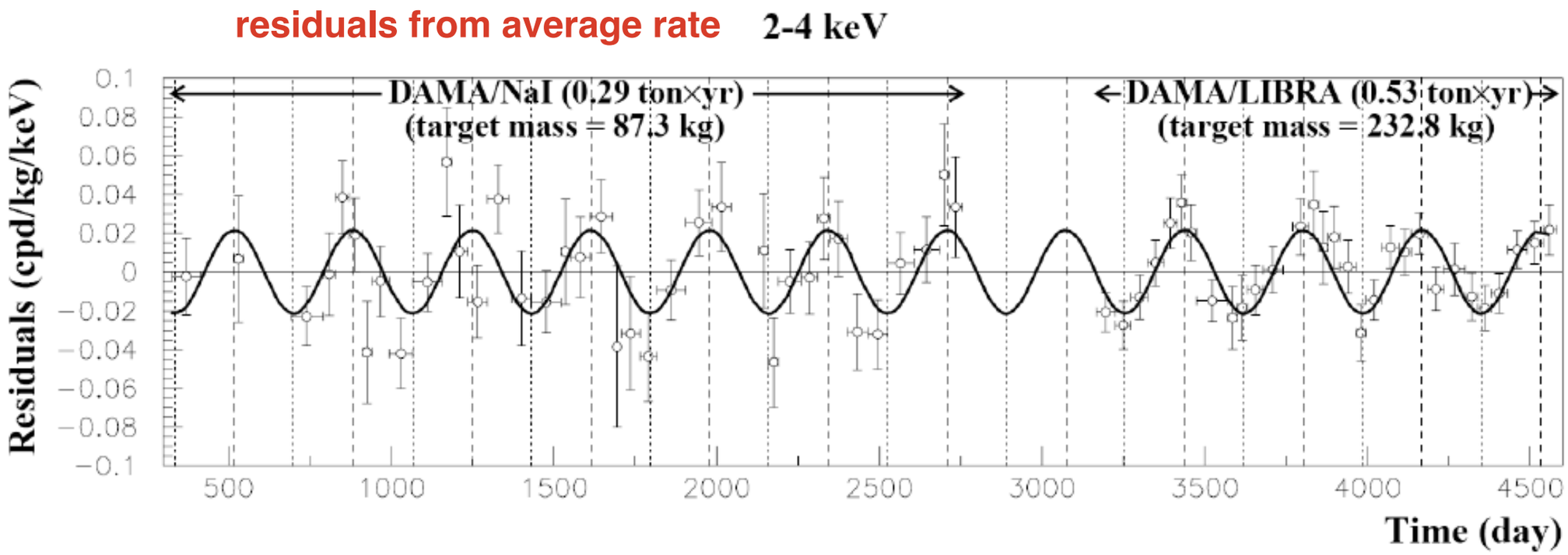






DAMA/LIBRA 2008

- **Modulation of observed event rate confirmed in 2008**
- 25 NaI detectors a 9.7 kg; each viewed by 2 PMTs (5.5-7.5 p.e./keVee)
- 4 years of data taking: 192 x 10^3 kg days



$$\frac{dR}{dE}(E,t) \approx S_0(E) + S_m(E)\cos\omega(t - t_0)$$

S_m = (0.0215 ± 0.0026) counts/(day kg keV)

t_0 = 144 ± 8 days

T = 0.998±0.003 year

Other interpretations?

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

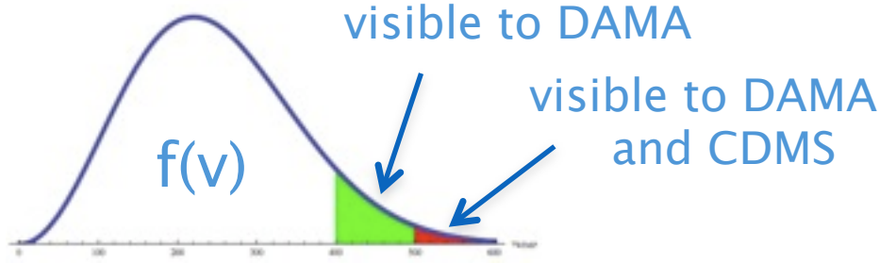
$$\delta = m_{\chi^*} - m_\chi \sim \beta^2 m_\chi \sim 100 \text{ keV}$$

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

➡ (elastic scattering $\chi + N \rightarrow \chi + N$ is forbidden, inelastic scattering $\chi + N \rightarrow \chi^* + N$ is allowed)

➡ only WIMPs with sufficient kinetic energy to up-scatter into the heavier state will scatter off nuclei

$$\beta_{\min} = \sqrt{\frac{1}{2 m_N E_R}} \left(\frac{m_N E_R}{\mu} + \delta \right)$$



Neil Weiner, IDM08

- Consequences for experiments:

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

➡ suppression of signals on lighter vs heavier target

➡ enhancement of the modulated vs unmodulated signal (20-30%)

➡ elimination of low energy events; signal peaks at ≈ 70 keV for Ge, 35 keV for I/Xe, 25 keV for W

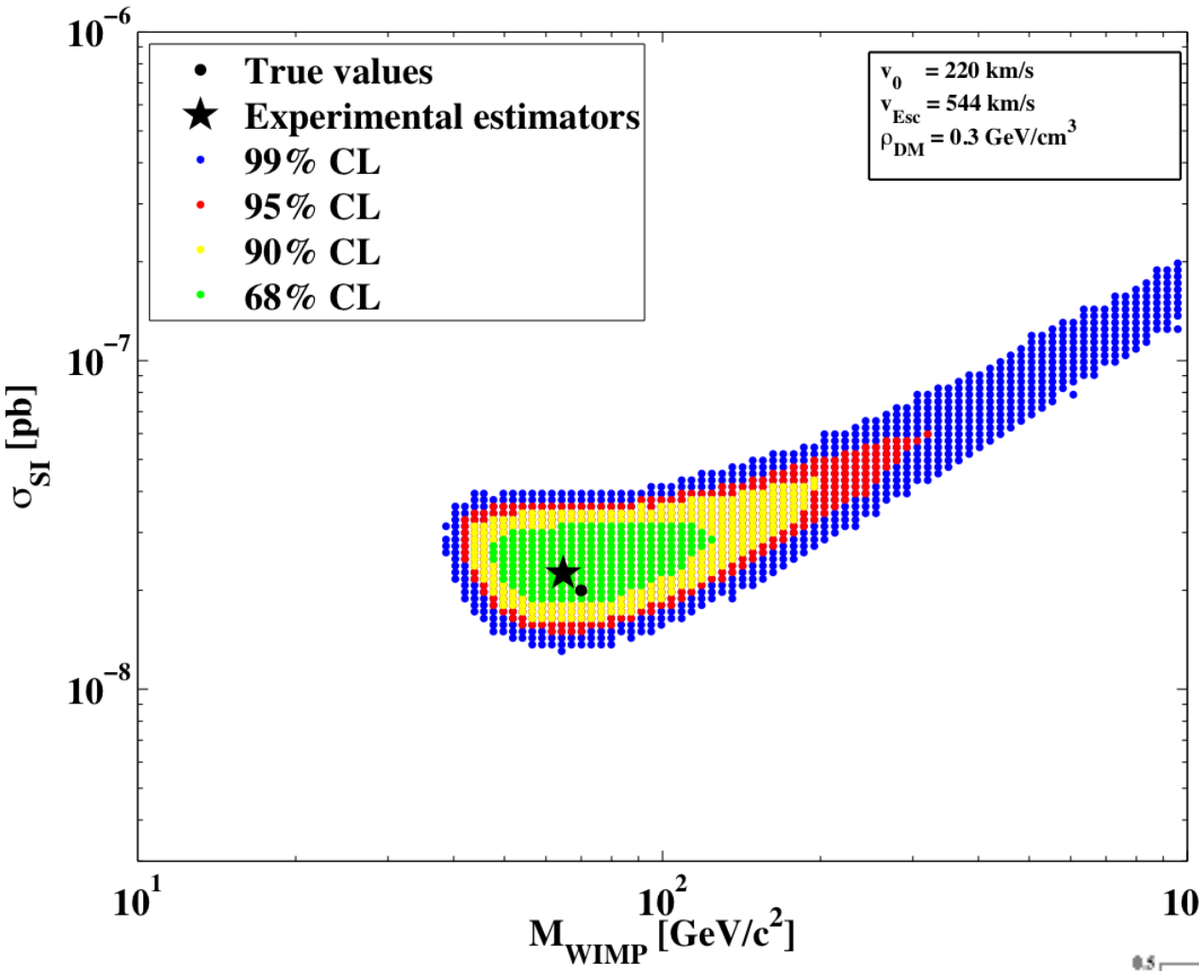
Model still in agreement with current results

Upcoming data from Ge, Xe, I and W should test this explanation for the DAMA signal very soon

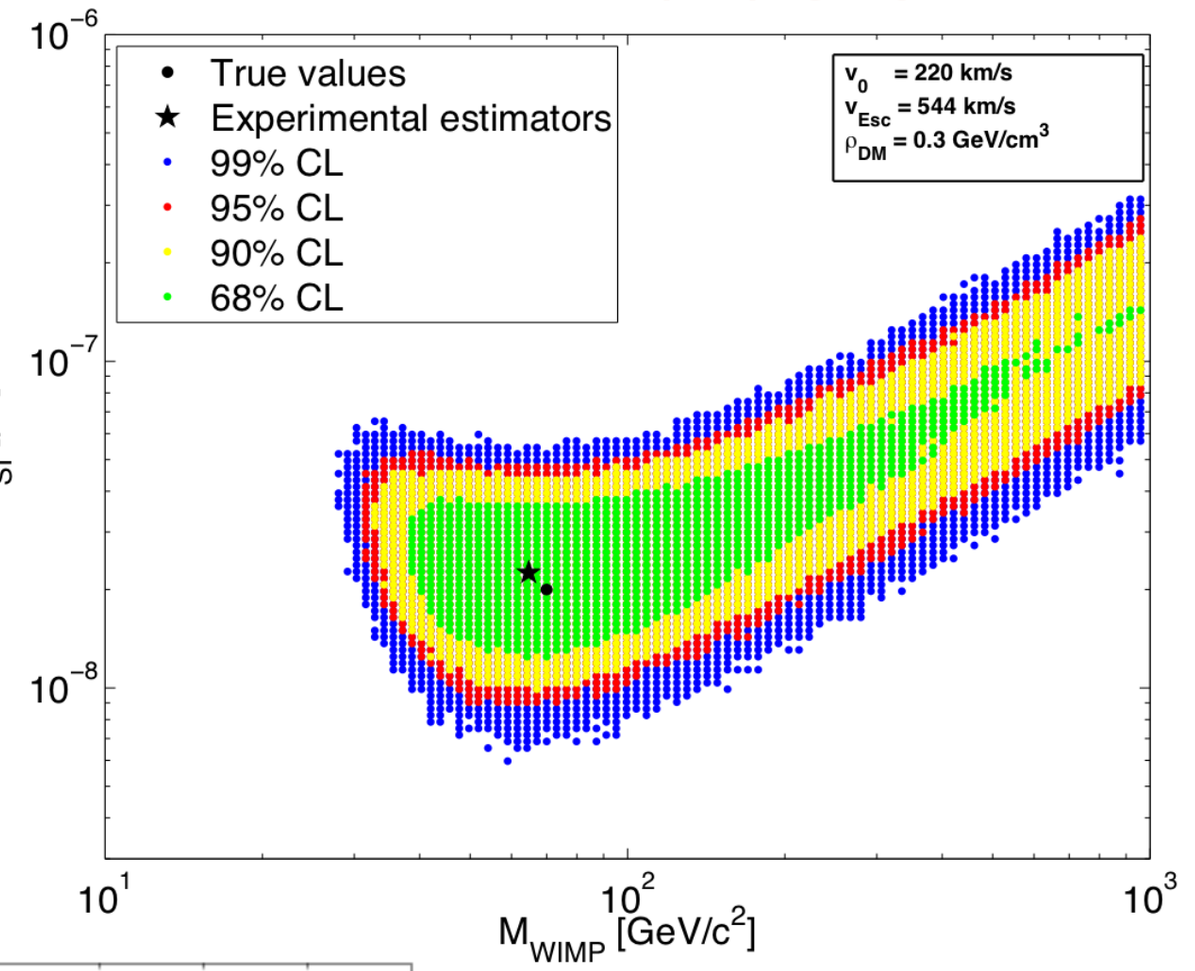
Laura Baudis, University of Zurich, Physics at the LHC, June 12, 2010

How well would we determine the WIMP mass?

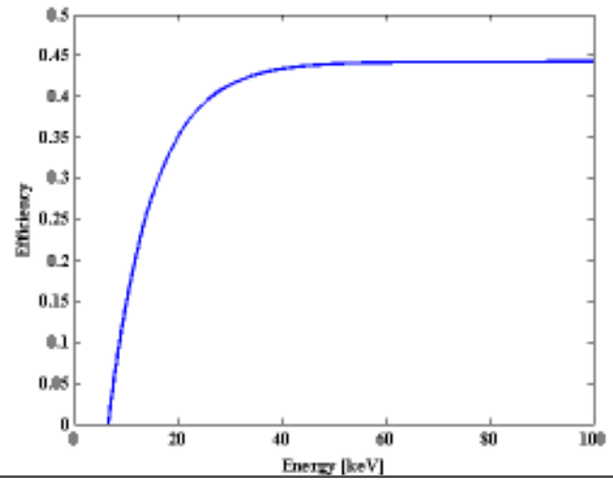
30 events in 12'250 (raw) kg days



8 events in 3'500 (raw) kg days



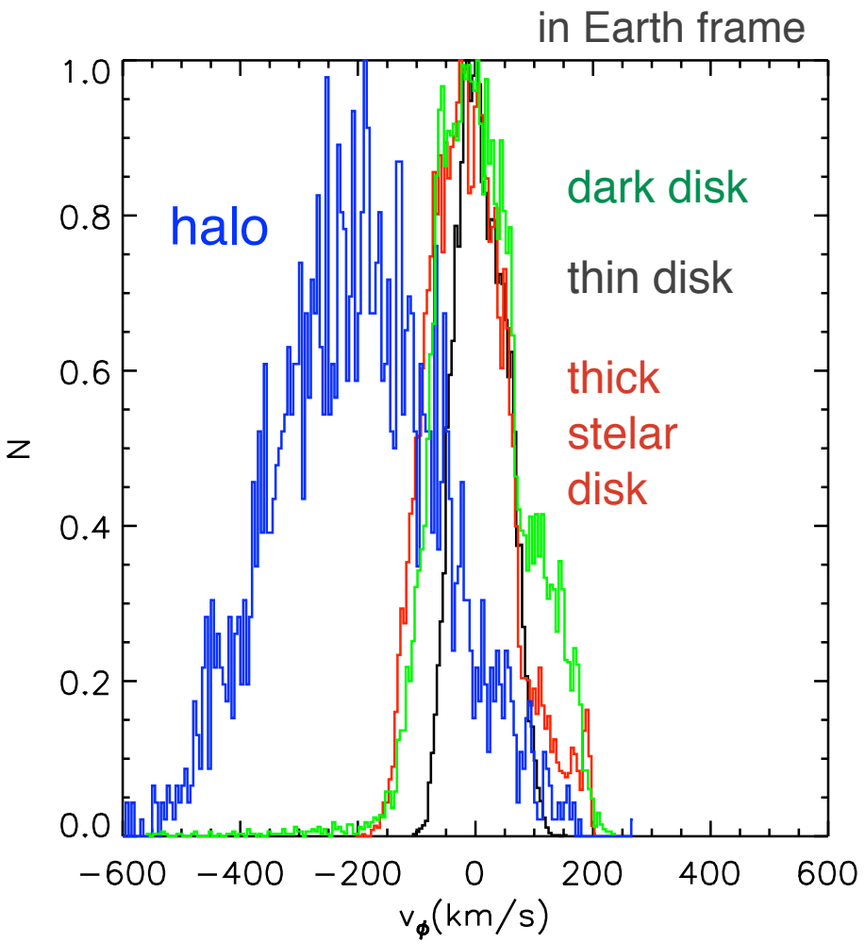
Preliminary study:
Tobias Bruch, Zurich

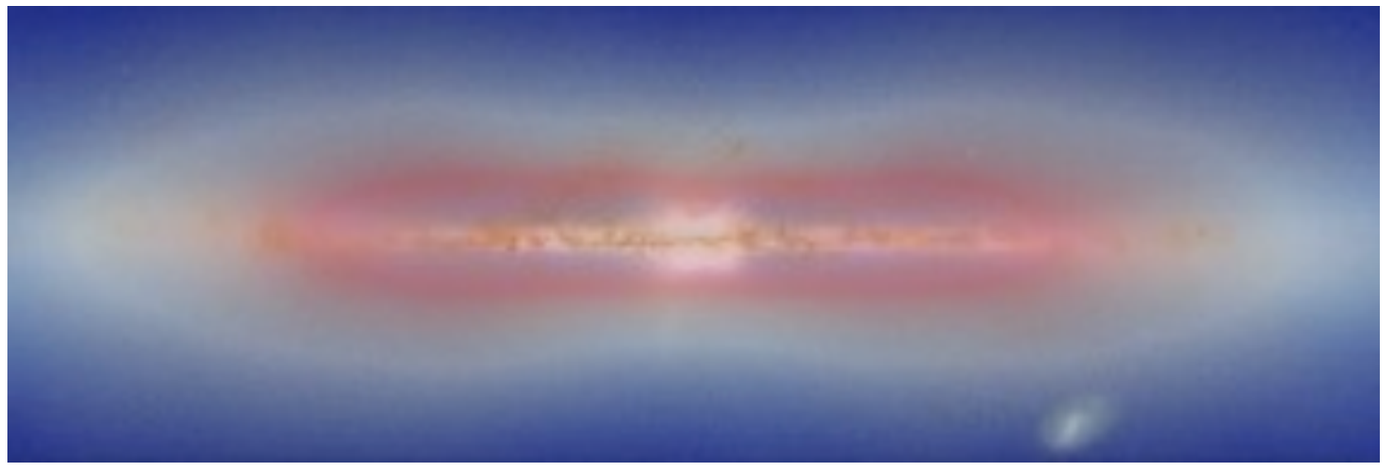


assumed detection efficiency

A Dark Matter Disk in The Milky Way

- **From ΛCDM numerical simulations which include the influence of baryons on the dark matter**
  [J. I. Read, G. Lake, O. Agertz, V. P. Debattista, MNRAS 389, 1041, 2008]
- **The stars and gas significantly alter the local phase space density of dark matter**
  - ➡ stars and gas settle onto the disk early on (z=1), affecting how smaller dark matter halos are accreted
  - ➡ the largest satellites are preferentially dragged towards the disk by dynamical friction, then torn apart
  - ➡ **the material from the satellites settles into a thick disk of stars, and dark matter**
  - ➡ the dark matter density in the disk is constrained to about **(0.20 - 2.00) x halo density**





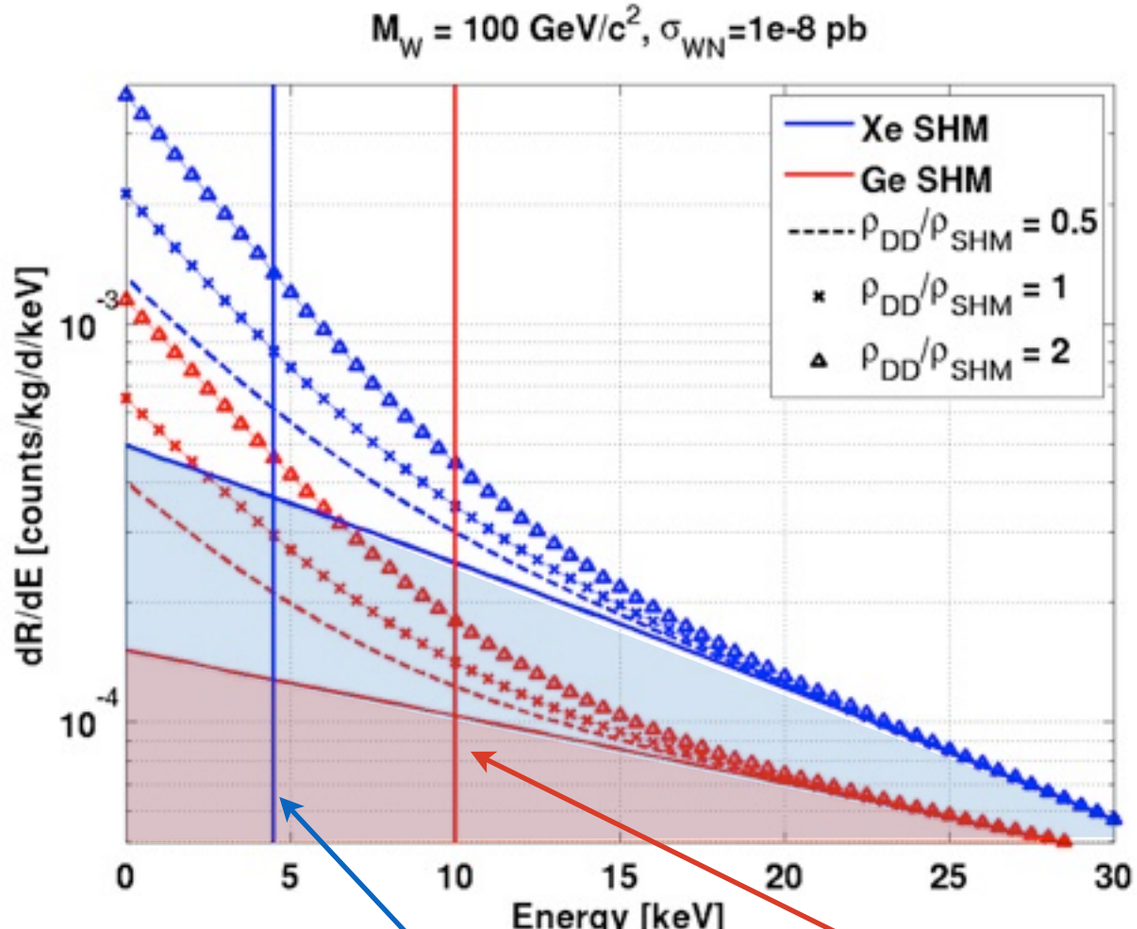
Read, Lake, Agertz, Debattista,
MNRAS 389, 1041, 2008

A Dark Matter Disk in The Milky Way

- **The solar system is embedded into the macroscopic structure of the dark disk**
- the local density is constrained to $\delta = \frac{\rho_{Disk}}{\rho_{SHM}} \leq 2$
- the velocities and dispersions are taken as $v_{disk} = [0,50,0]\ km \cdot s^{-1}$; $\sigma_{disk} = 50\ km \cdot s^{-1}$

➡ **the dark disk increases the rates at low recoil energies and modifies the shape of the recoil spectrum, depending on the WIMP mass**

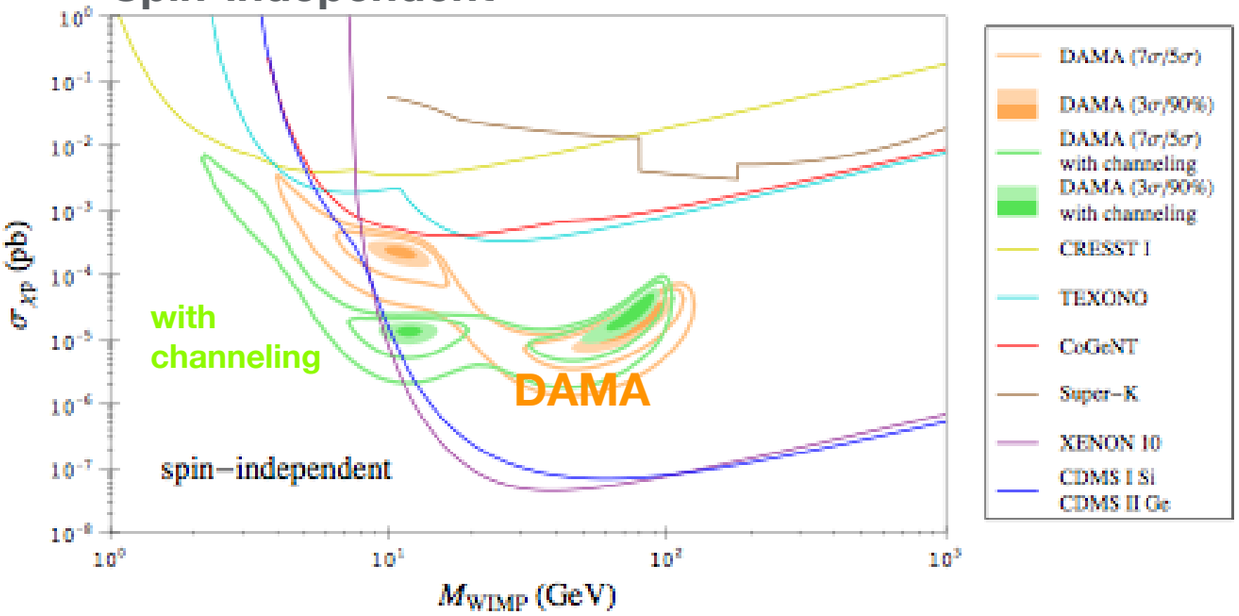
Recoil energy below which the signal is dominated by the dark disk



T. Bruch, J. Read, LB, G. Lake, APJ 696 (2009)

WIMP hypothesis: severe tension with other experiments

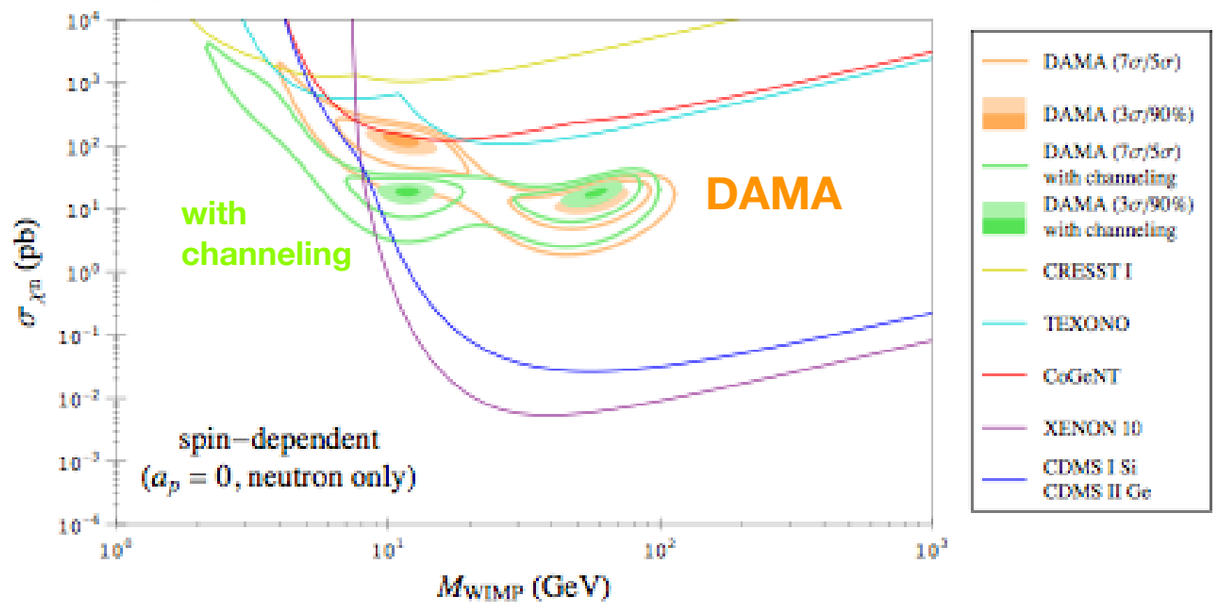
Spin-independent



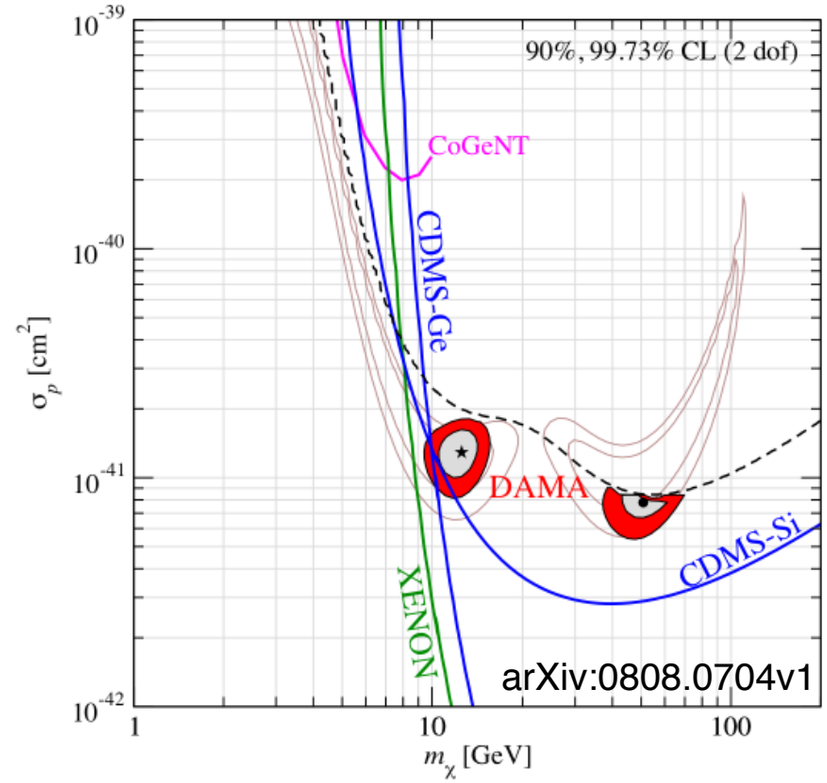
Savage, Gelmini, Gondolo, Freese

arXiv:0808.3607v1

Spin-dependent



M. Fairbairn, T. Schwetz



Ion channeling effect: scattered ion parallel to crystal axis will undergo small-angle scattering which will channel it along the gaps in the lattice; such an ion has lower dE/dx, yielding increased light , effectively reducing the energy threshold for low-energy nuclear recoils

Channeling: has not yet been demonstrated for low-energy nuclear recoils starting from a lattice site, only for incident ion beams; should be tested in dedicated experiment!

+ many other papers....