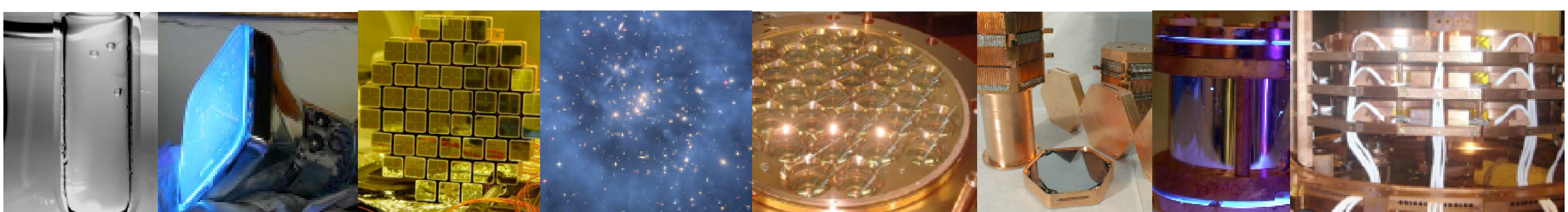
# Direct Dark Matter Searches: an Overview

GGI Conference on Dark Matter

Florence, February 9, 2009

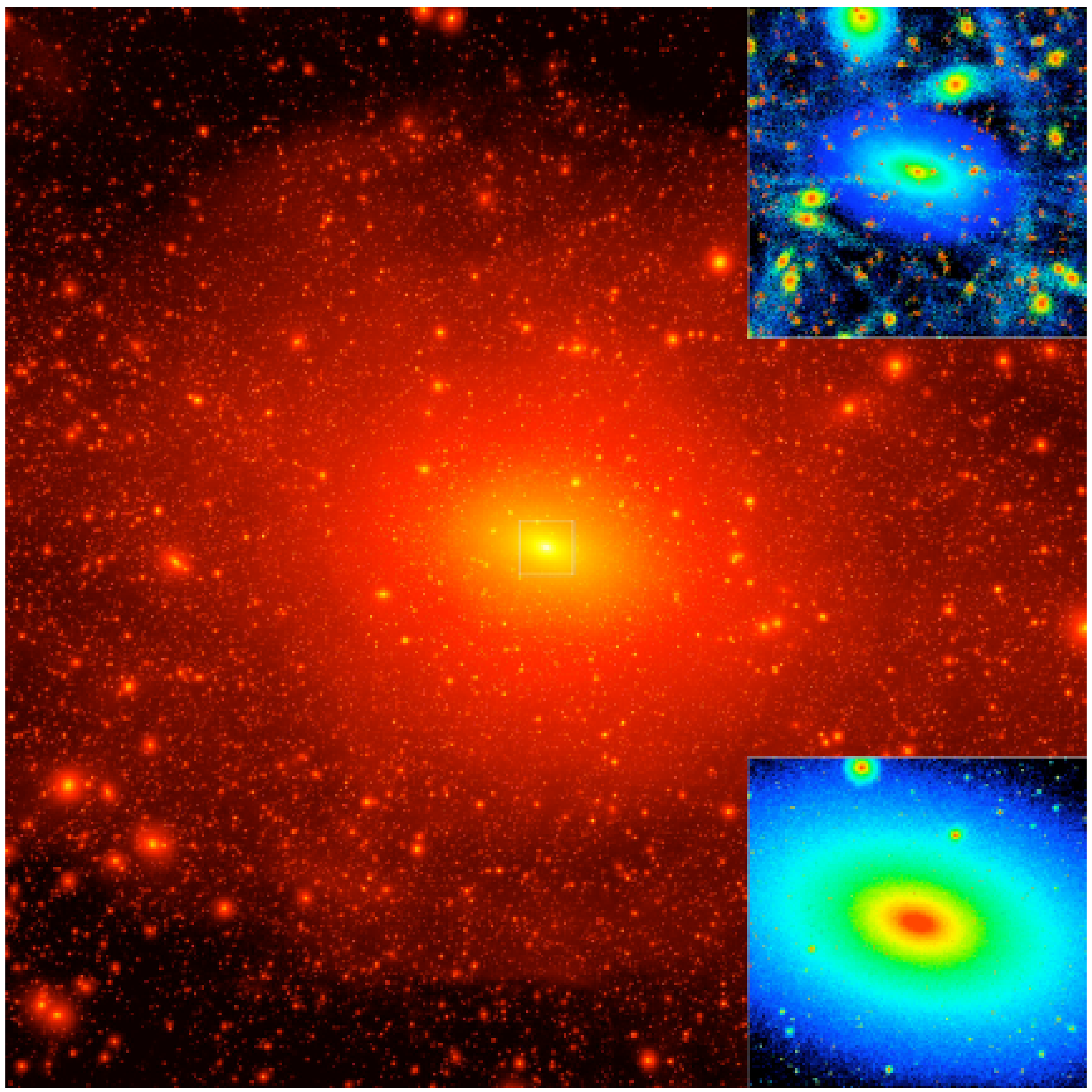
Laura Baudis

University of Zurich

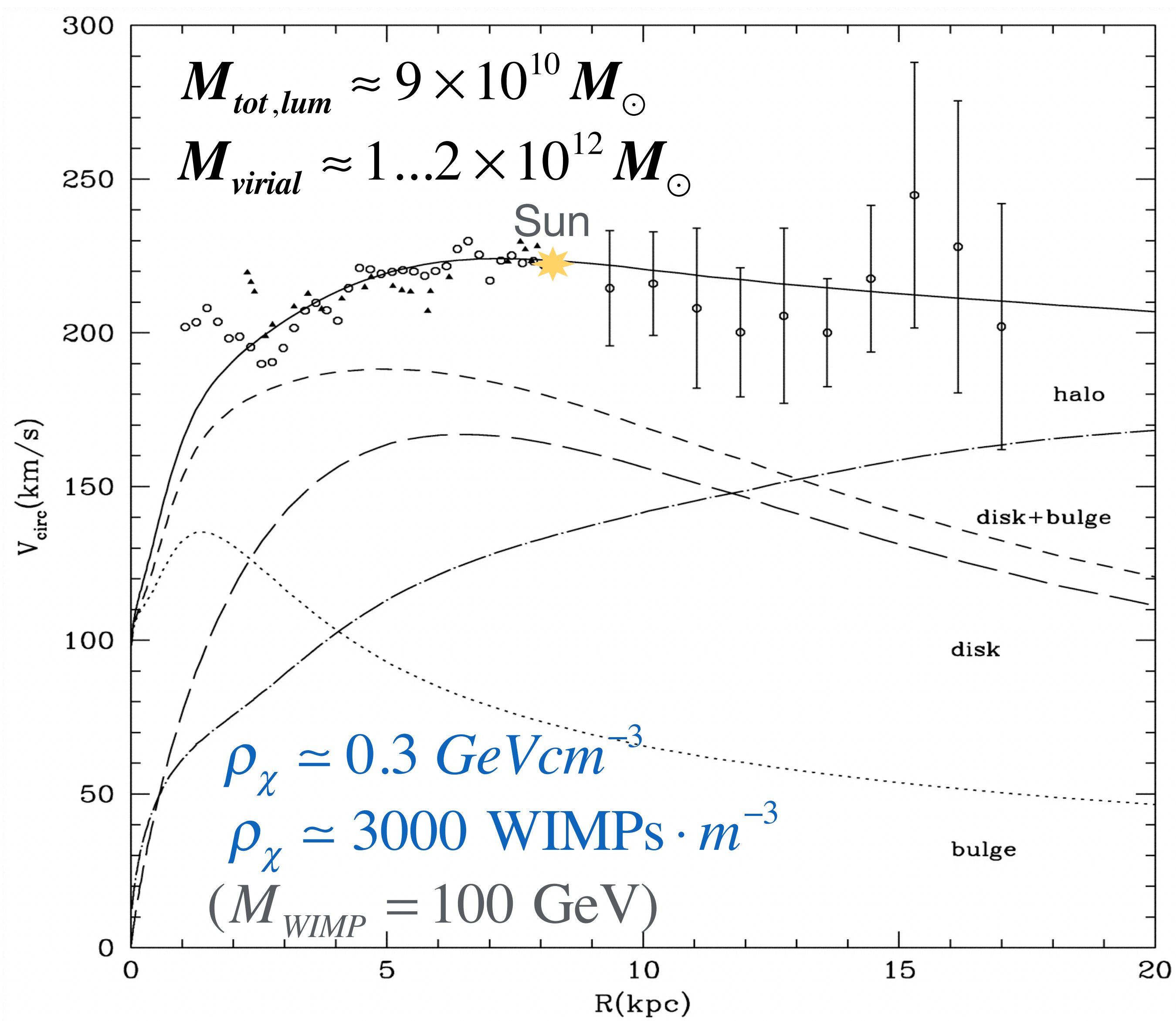


# Goal of Direct Detection Experiments

- Detect new, yet undiscovered particles, which may be responsible for the dark matter in our galaxy. Example: WIMPs = heavy (few GeV - few TeV), color and electrically neutral; in thermal equilibrium with the rest of the particles in the early universe, freeze out when $M_W >> T_F$



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




(Klypin, Zhao & Somerville 2002)

# Strategy for WIMP Direct Detection

- Elastic collisions with atomic nuclei
- Rates depend on: [$m_\chi$, σ], [f(v), $\rho_0$], [N, $E_{th}$] ...

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

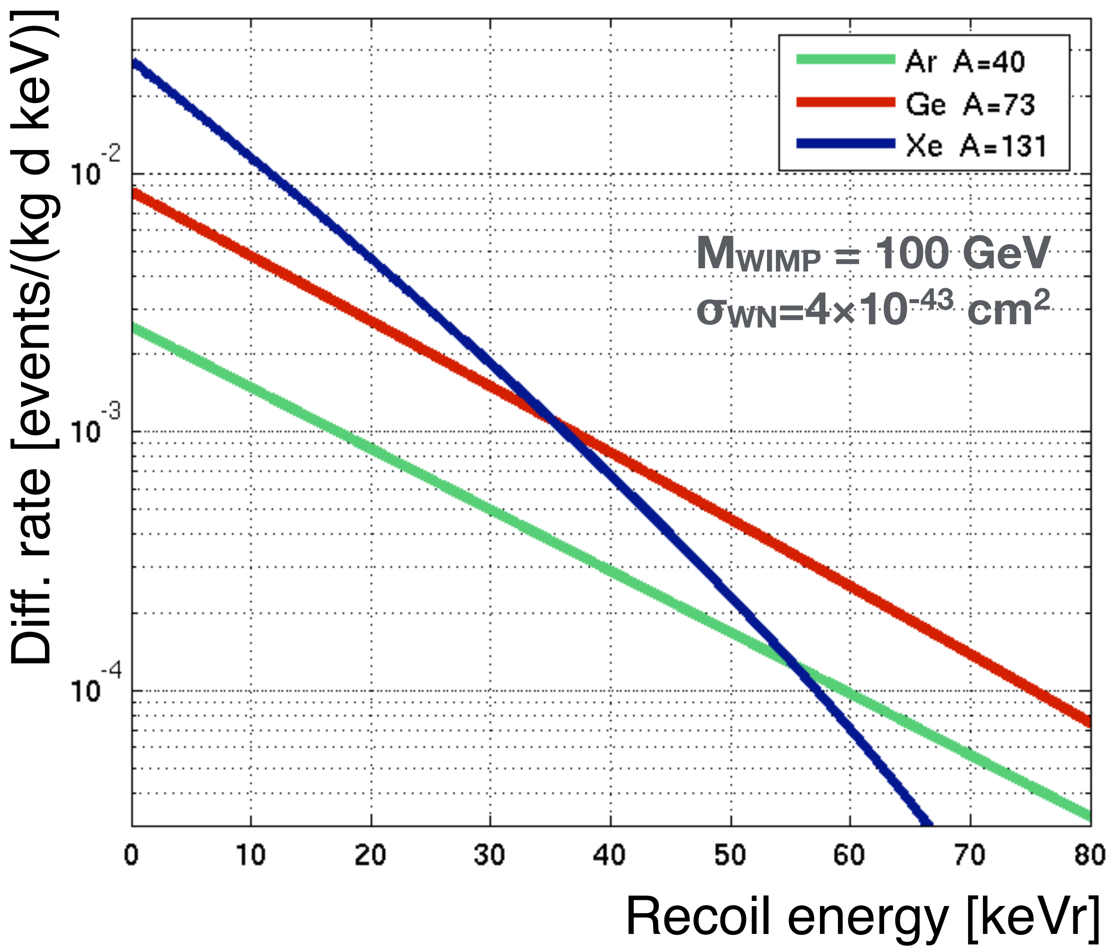
- with WIMP-nucleon cross sections < $10^{-7}$ pb, the expected rates are

**< 1 event/100kg/day**

- Energy of recoiling nuclei

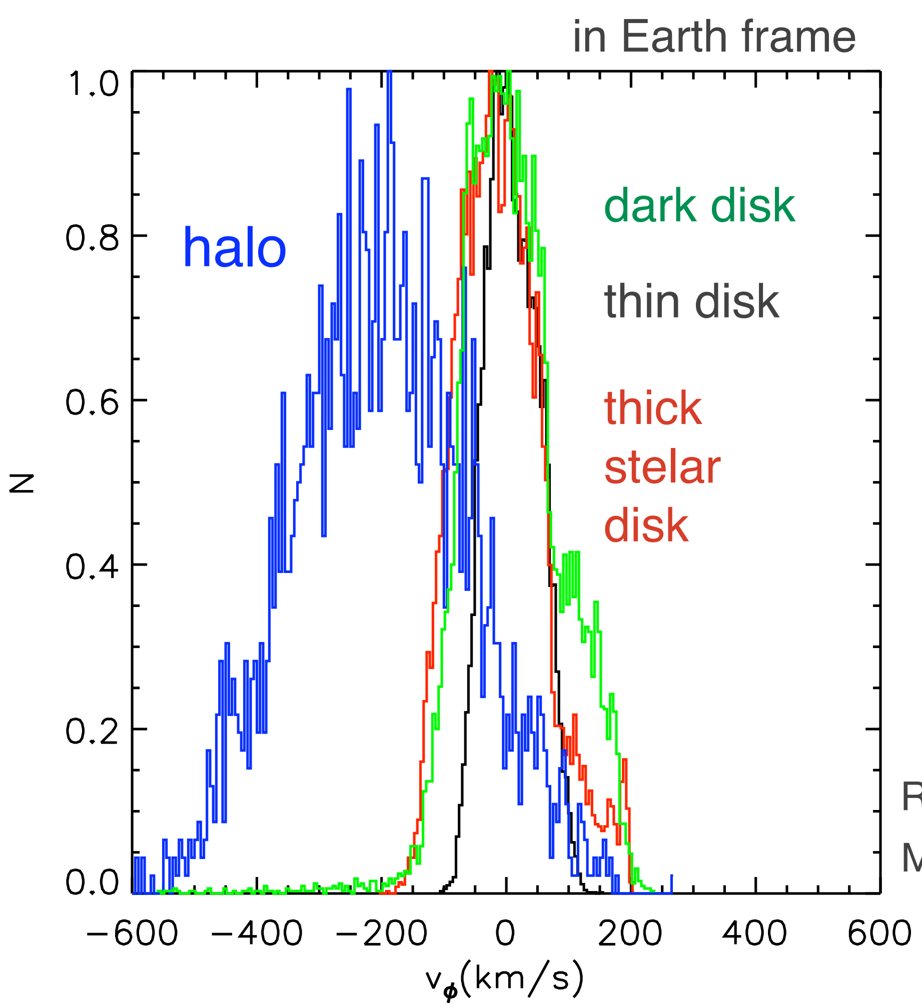
$$E_R = \frac{|\vec{q}|^2}{2m_N} = \frac{\mu^2 v^2}{m_N}(1-\cos\theta) \leq 50\ keV$$

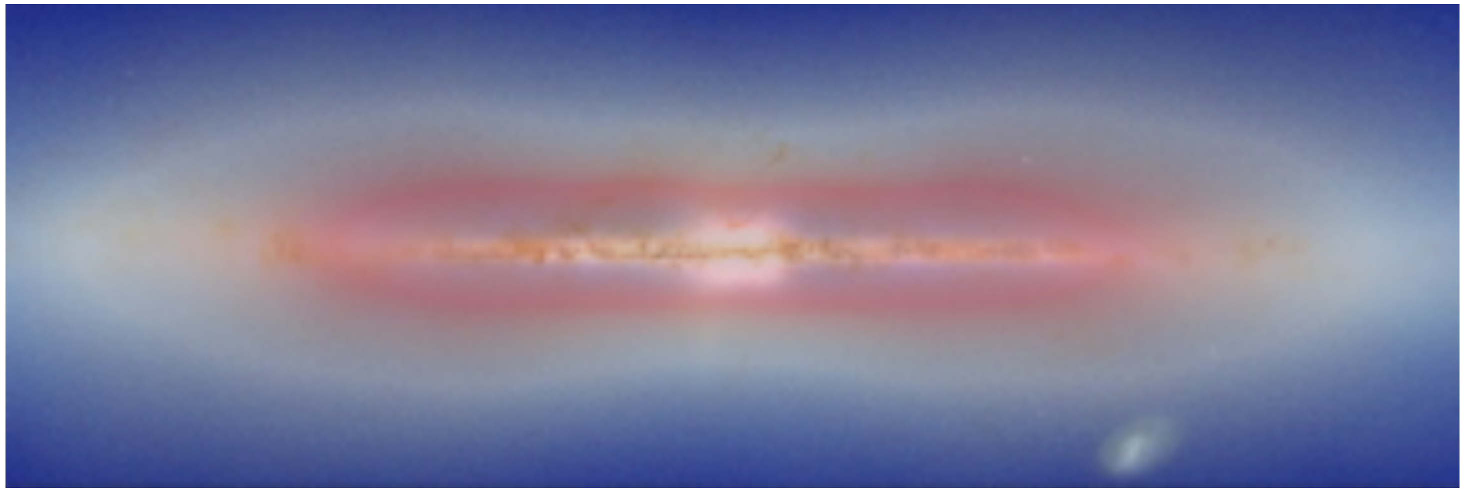
Differential rates for different targets (SHM)



# 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 0.25 - 2 x halo density



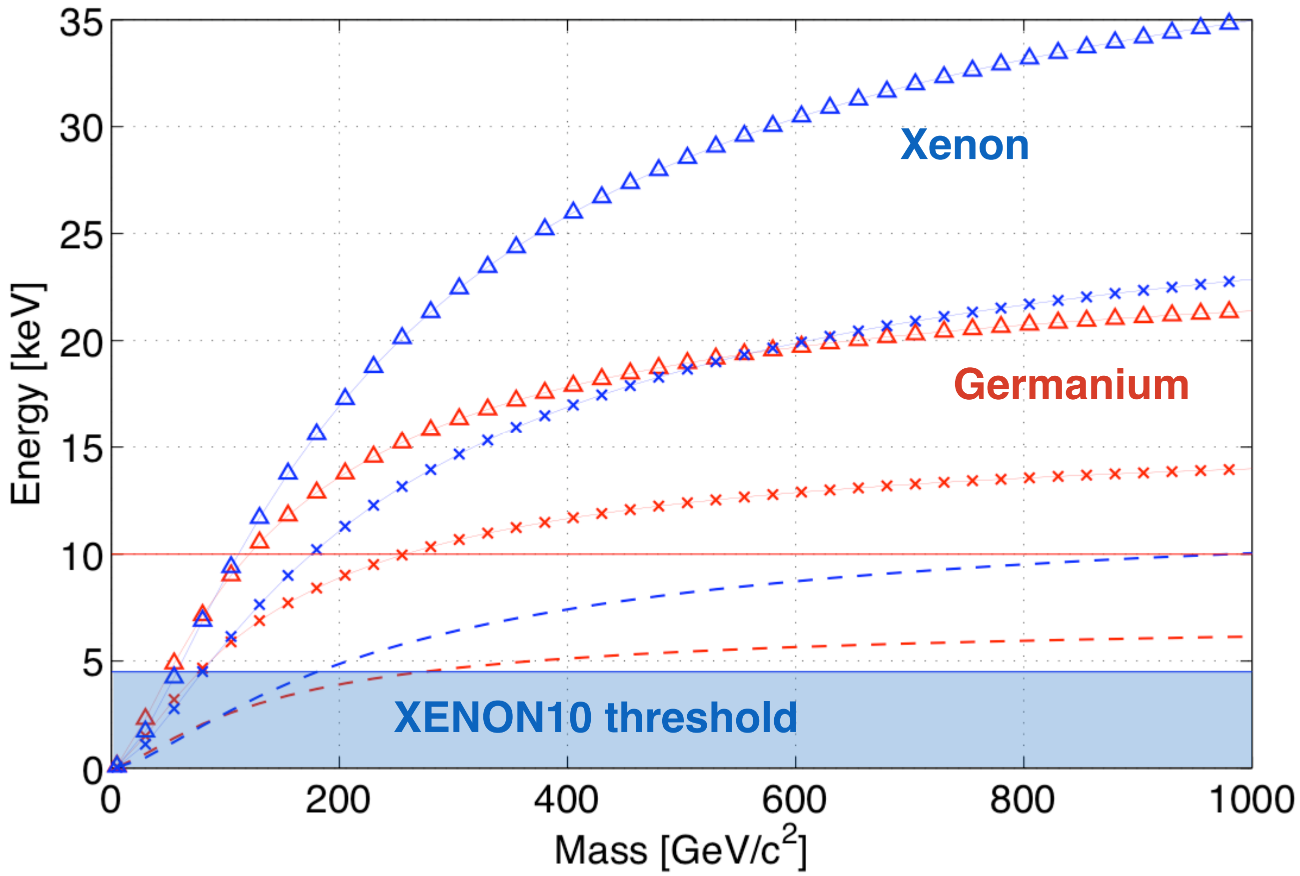



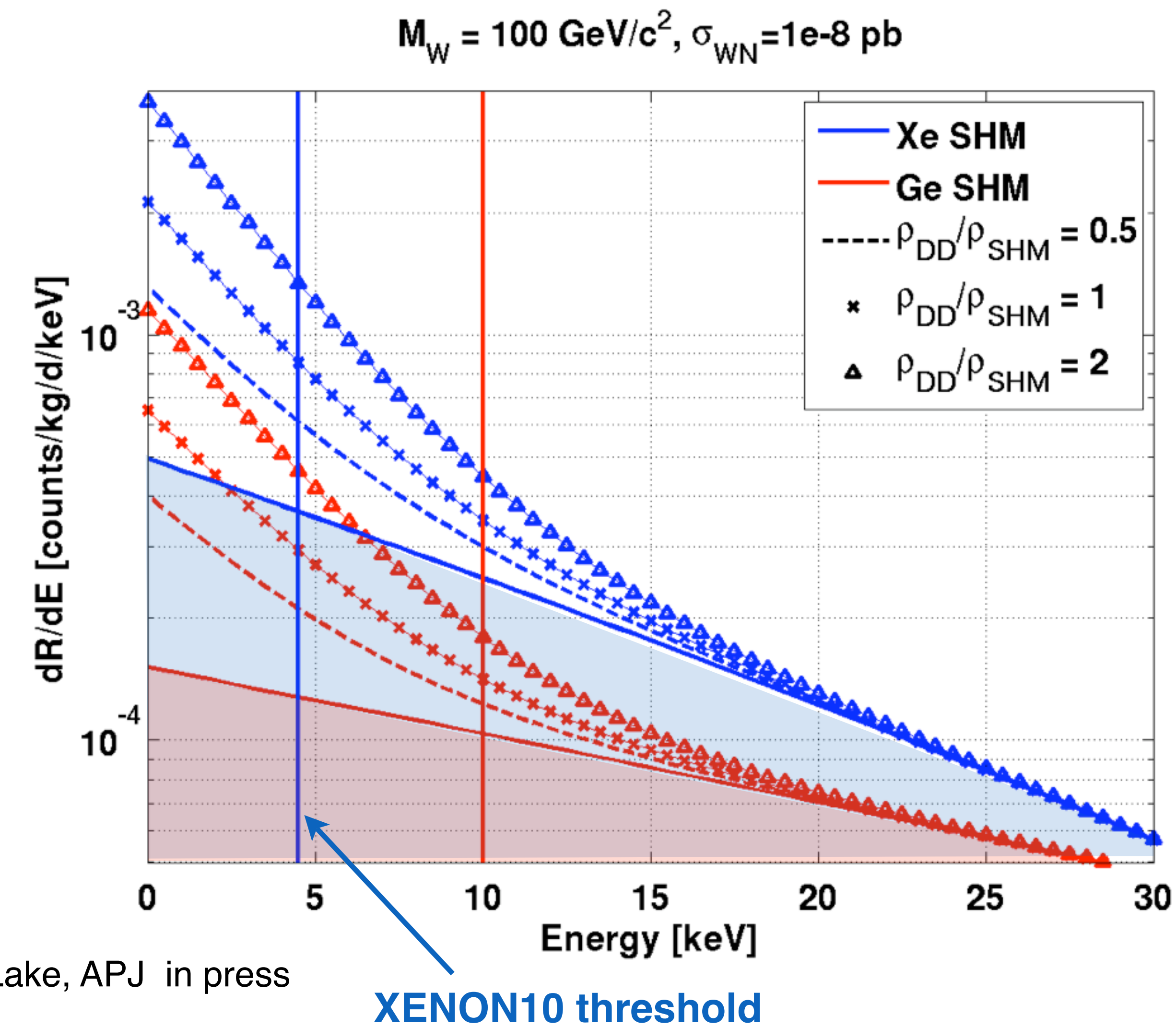
Read, Lake, Agertz, Debattista, MNRAS 389, 1041, 2008

# 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 by $\delta = \frac{\rho_{Disk}}{\rho_{SHM}} \leq 2$
- 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 provides and modifies the shape of the recoil spectrum, depending on the WIMP mass

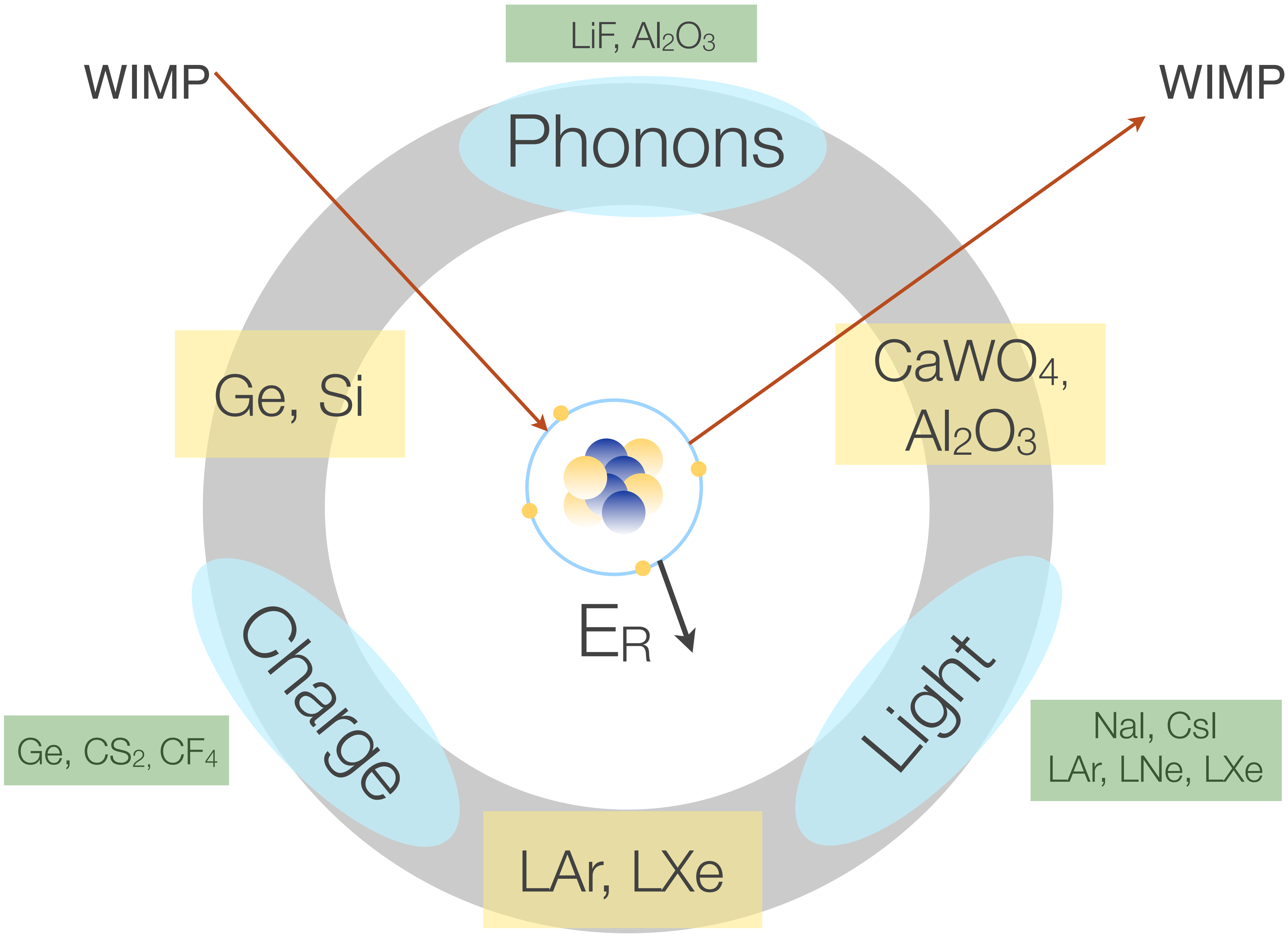
**Recoil energy below which the signal is dominated by the dark disk**



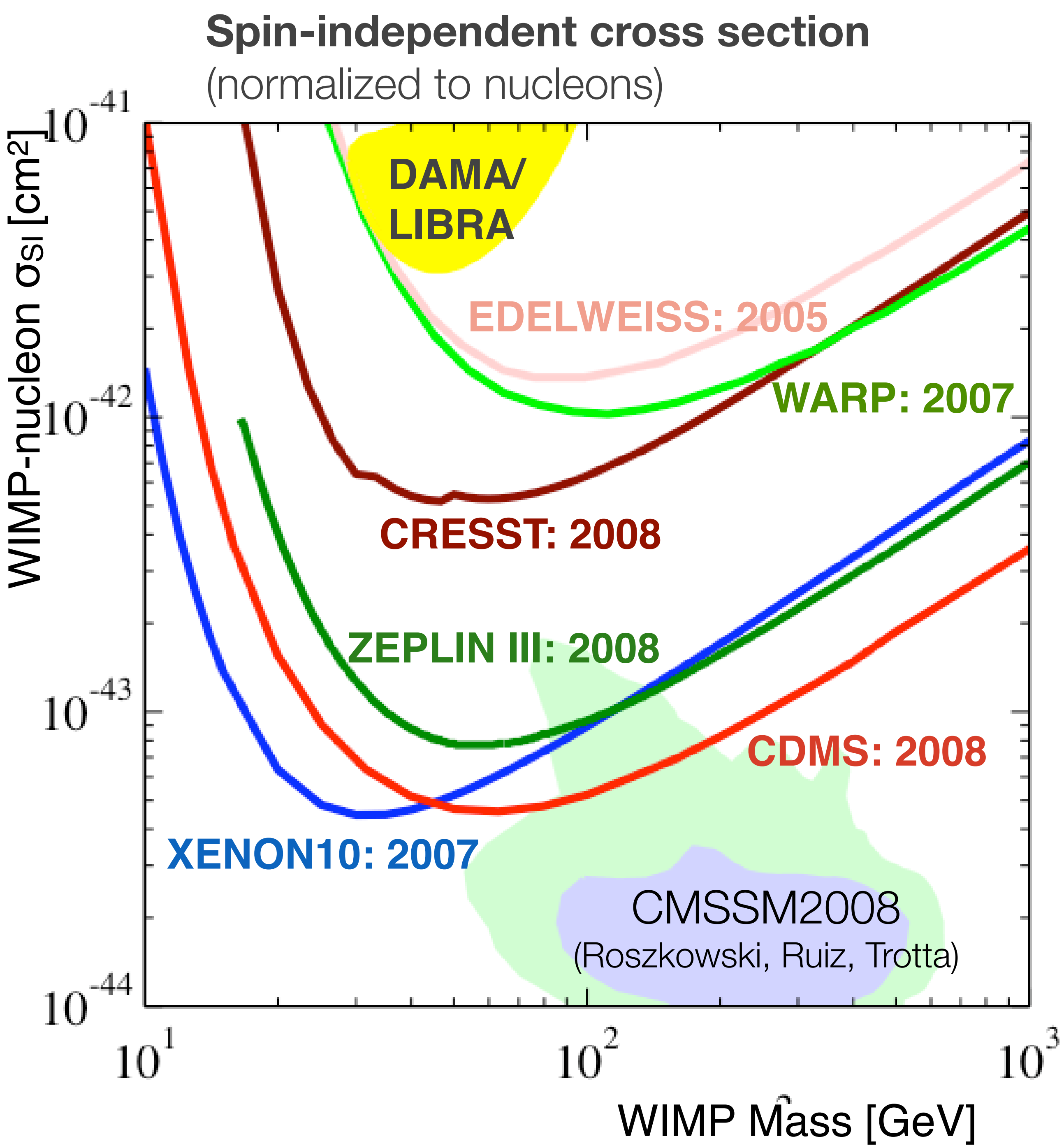

T. Bruch, J. Read, LB, G. Lake, APJ in press

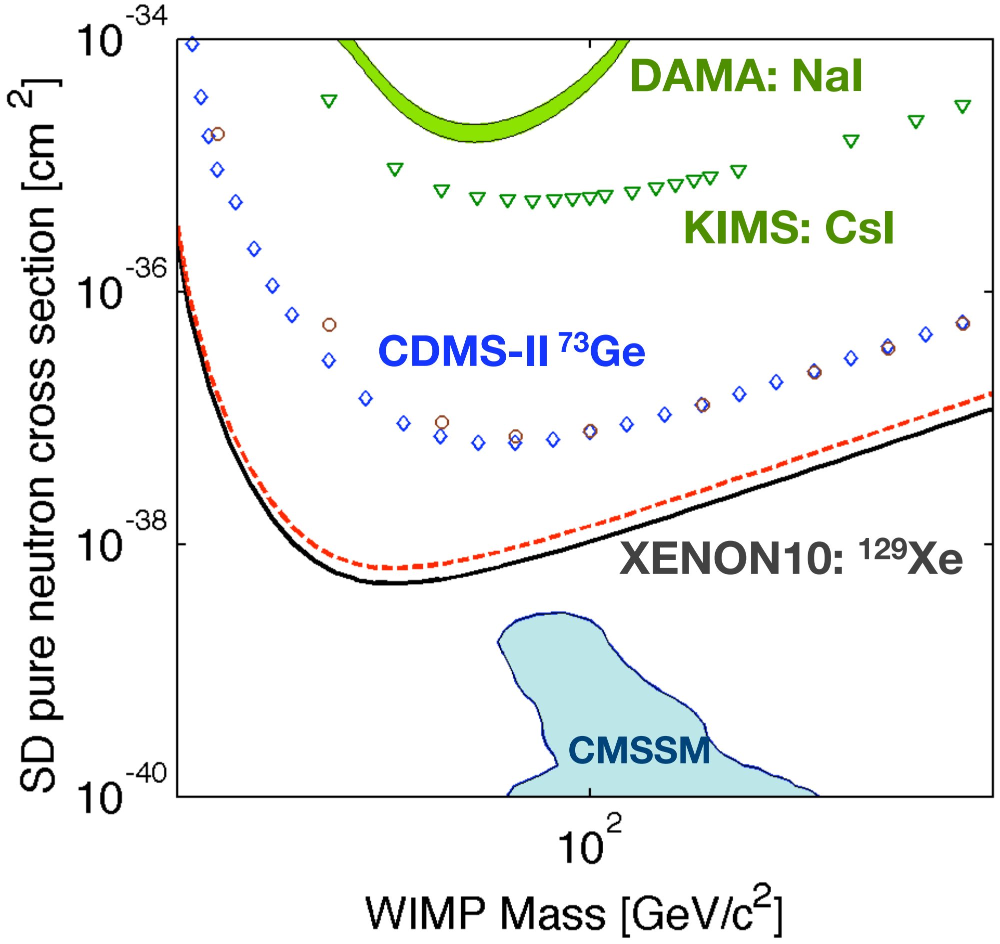
# Direct Detection Techniques

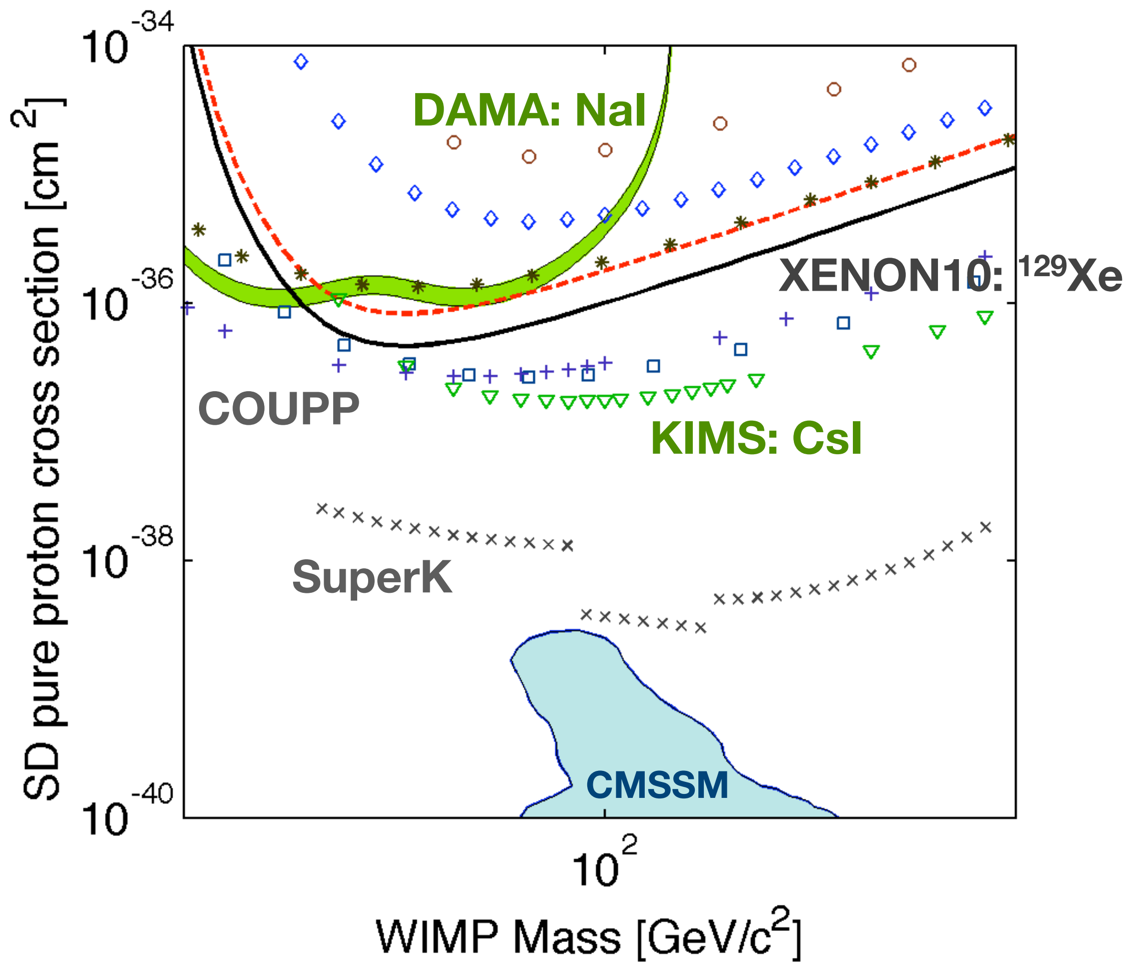



**In this talk: only recent results (2007-2008) and status of near future projects**

# Experimental Results



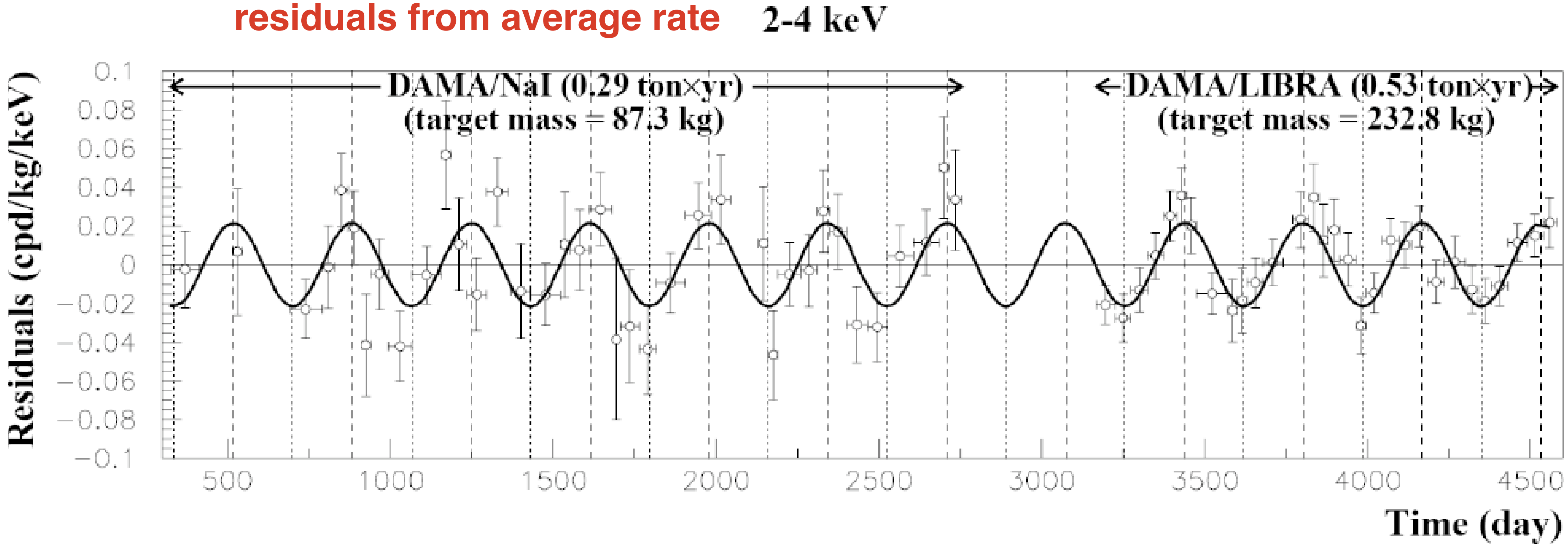




Spin-dependent

# DAMA/LIBRA 2008

- **modulation of 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

residuals from average rate

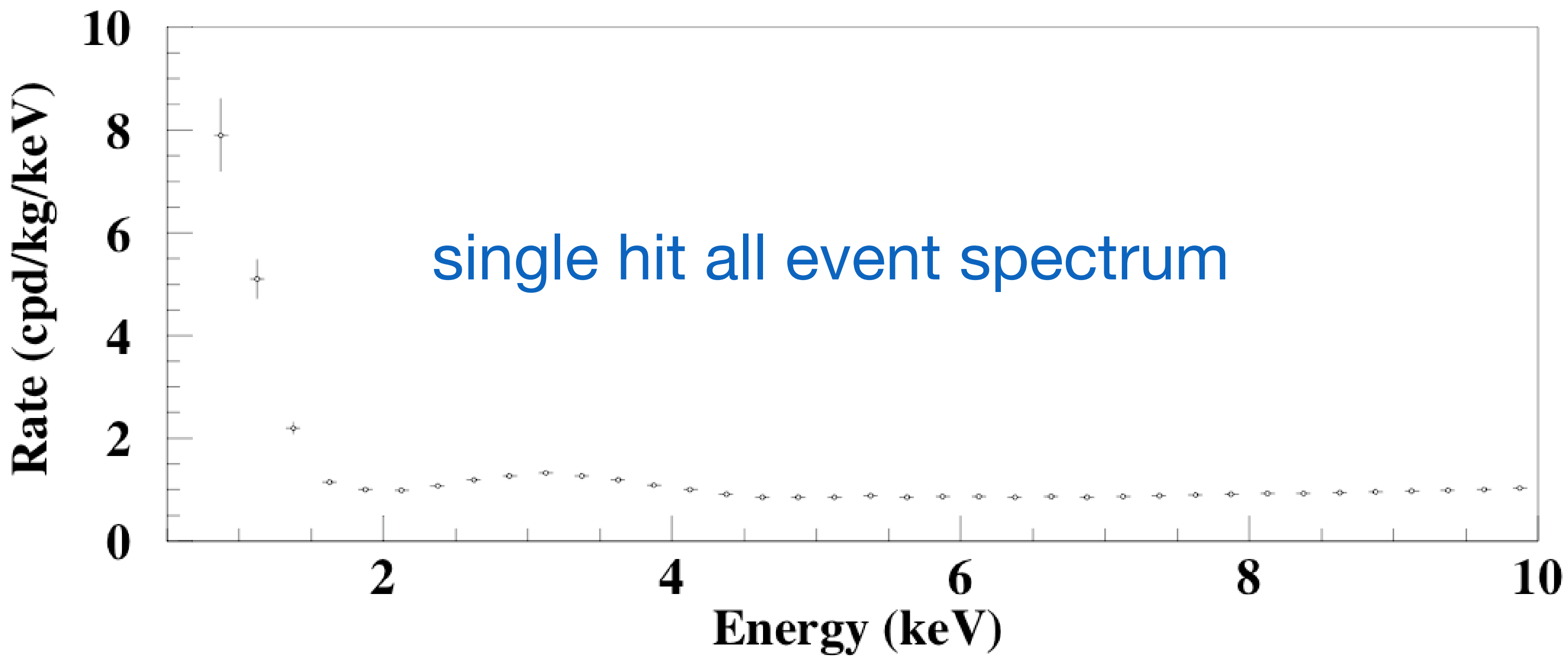


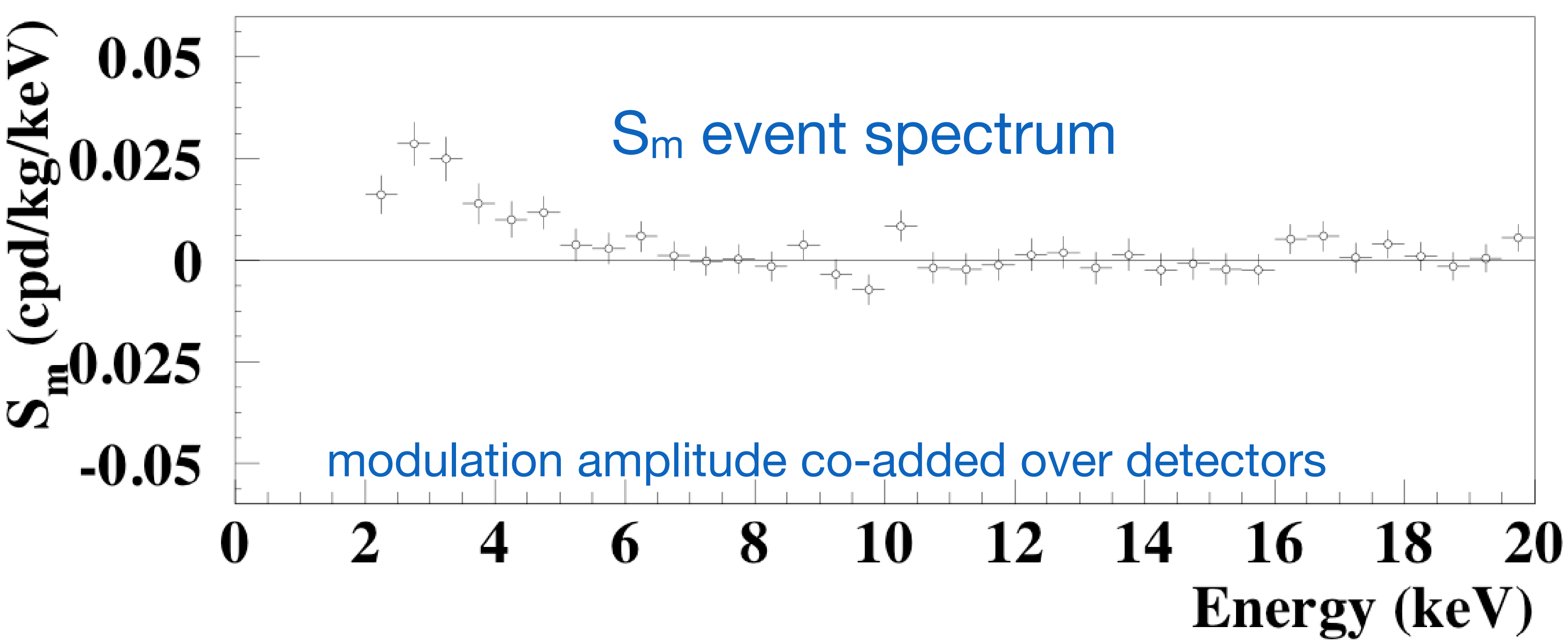

$$\frac{dR}{dE}(E,t) \approx S_0(E) + S_m(E)\cos\omega(t - t_0)$$

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

$t_0$ = 152.5 d
T = 1 year

# DAMA/LIBRA 2008



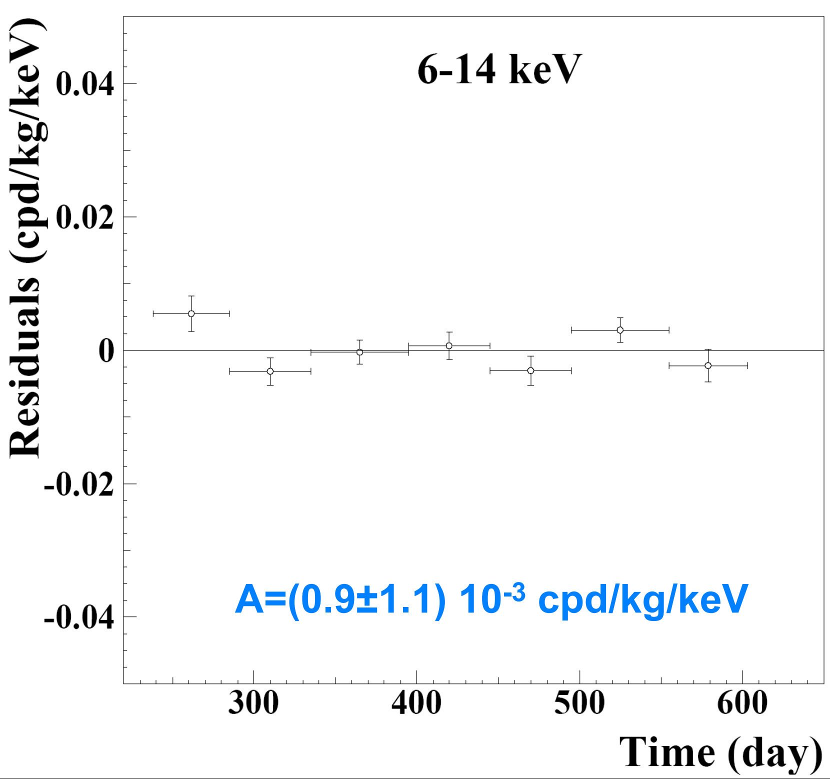




signal in region dominated by PMT noise (does the tail of the noise distribution modulate?)

signal very close to threshold

modulation of a peak around 3 keV?

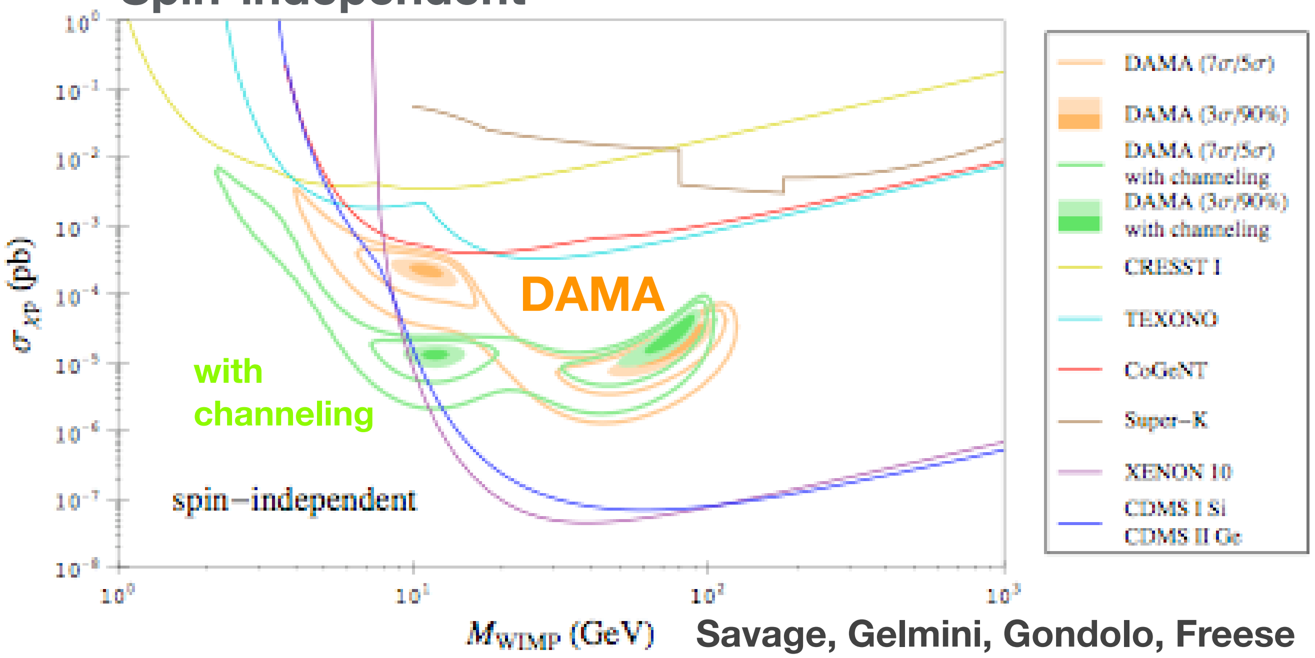
what is the contribution of the $^{40}$K 3 keV X-ray in the singles spectrum?



# DAMA Signal and Existing Experimental Limits at Low WIMP Masses

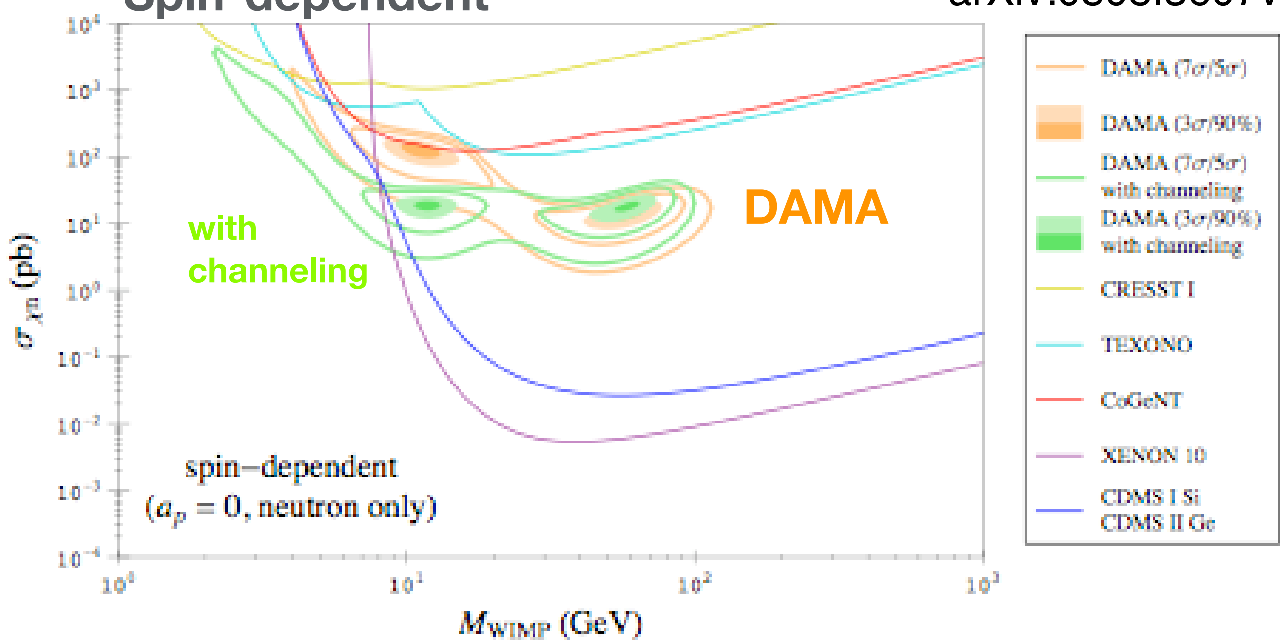
- WIMP hypothesis: severe tension with other experiments!

**Spin-independent**

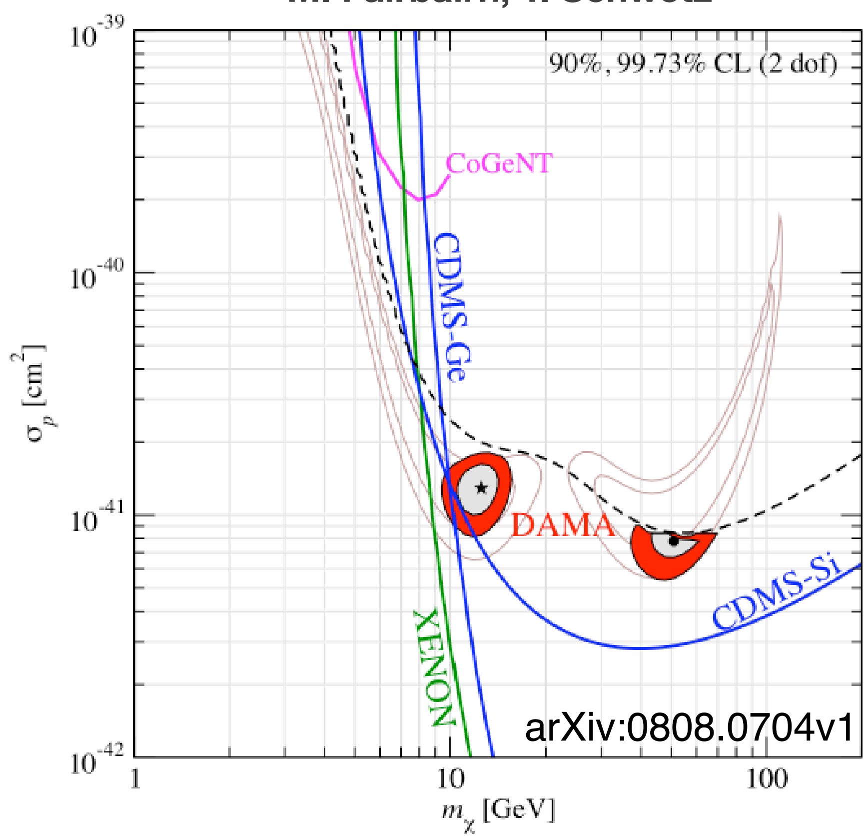



**Savage, Gelmini, Gondolo, Freese**
arXiv:0808.3607v1

**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**

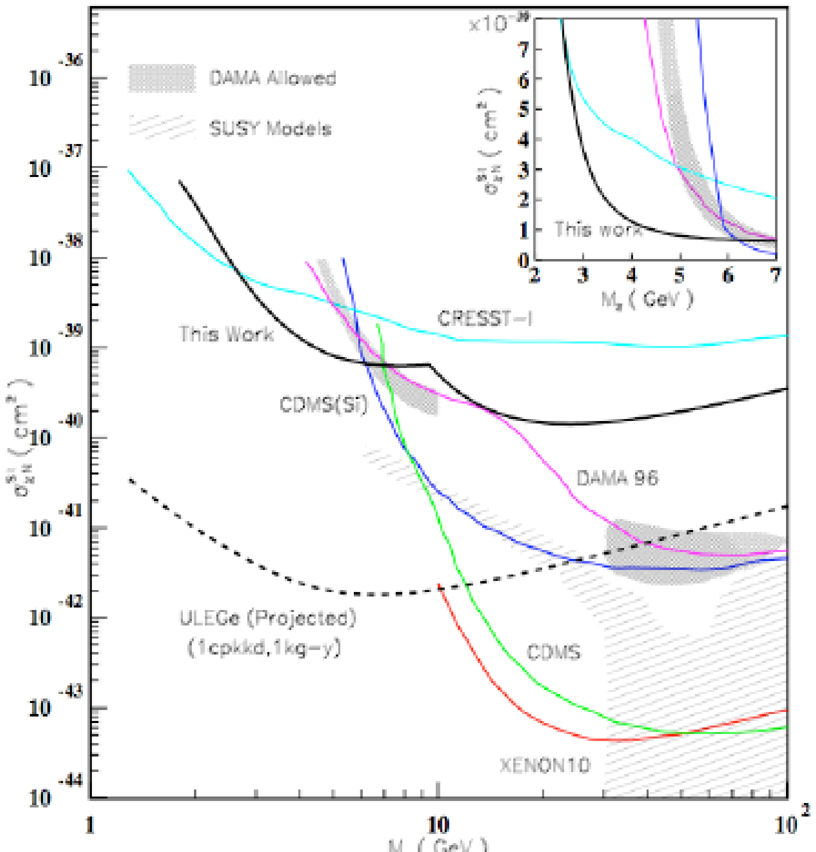
**Channeling: has not yet been demonstrated for nuclear recoils starting from a lattice site, only for incident ion beams; should be tested in dedicated experiment**

**+ many other papers....**

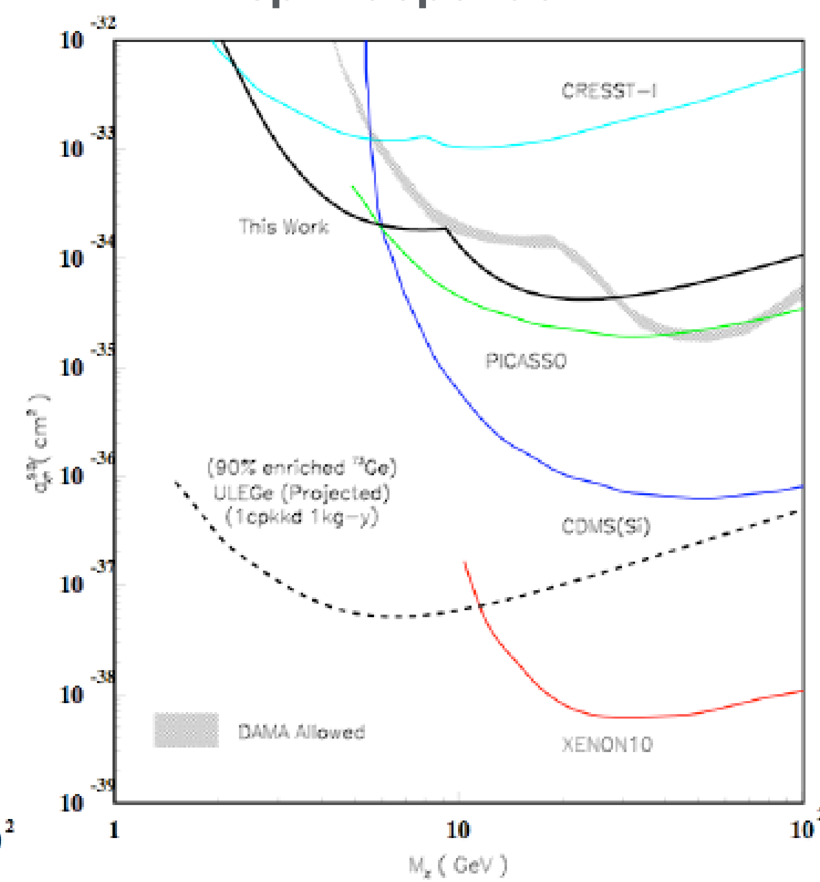
# New Experimental Results at Low WIMP Masses

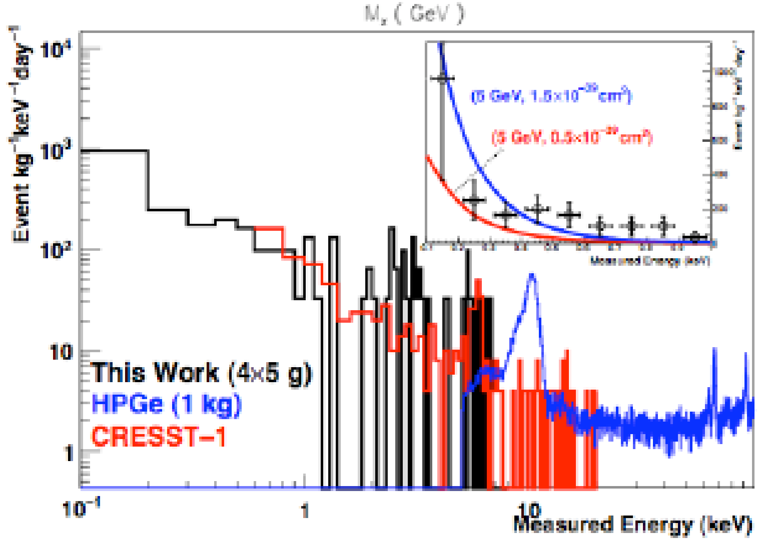
## TEXONO: 4 x 5 g Ge

**spin-independent**




**spin-dependent**



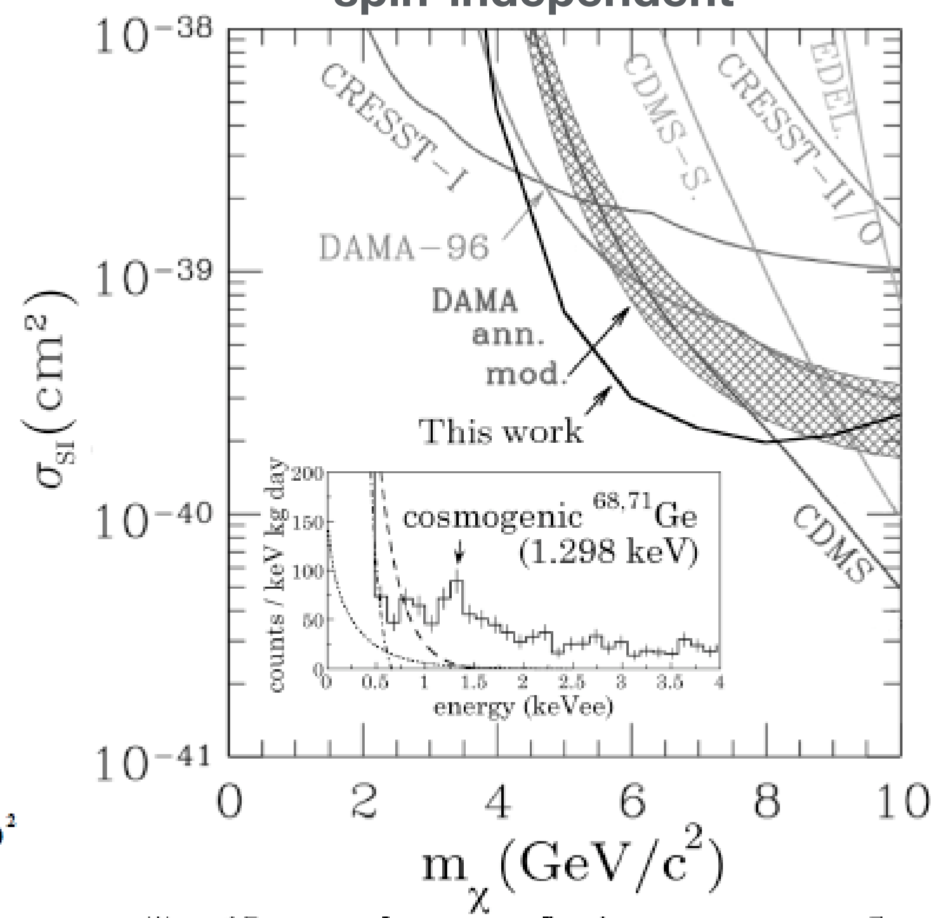



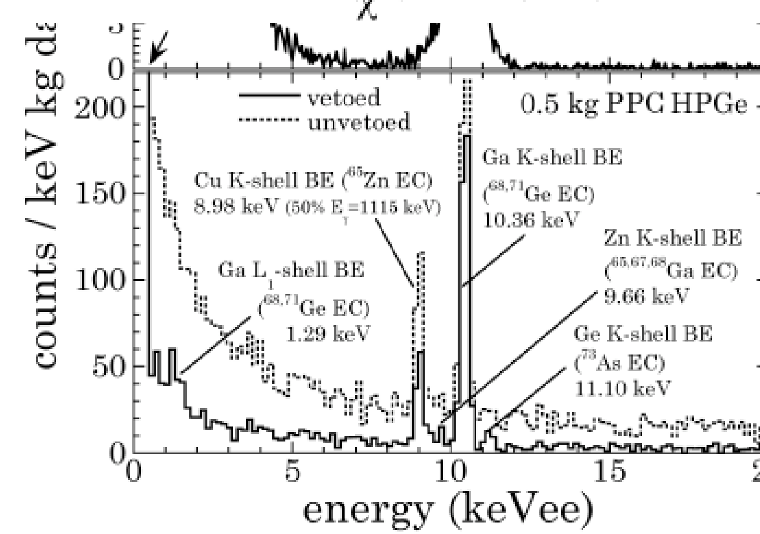

**S.T. Lin et al.**

0712.1645v4

## CoGeNT: 500 g PPC Ge

**spin-independent**



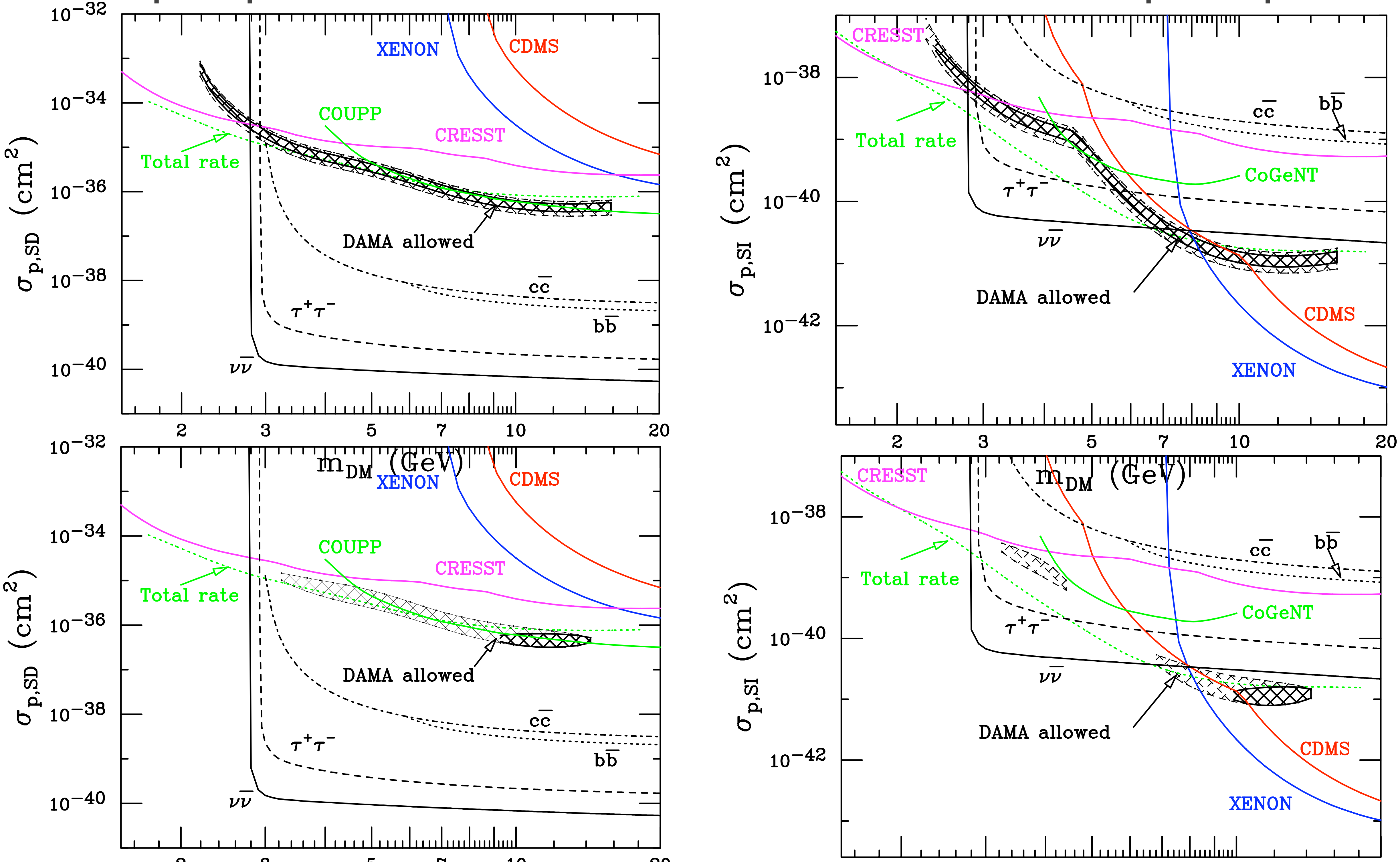




**Aalseth et al.**

PRL 101 (2008)

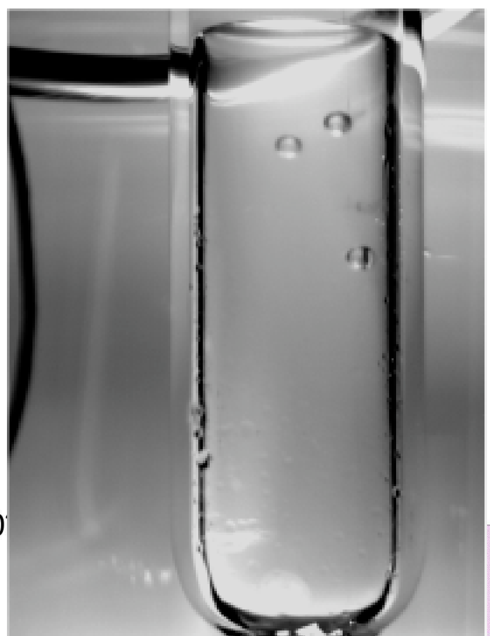
# Limits from indirect detection of ν's (SuperK)

**Spin-dependent** Hooper, Petriello, Zurek, Kamionkowski, arXiv:0808.246v4 **Spin-independent**



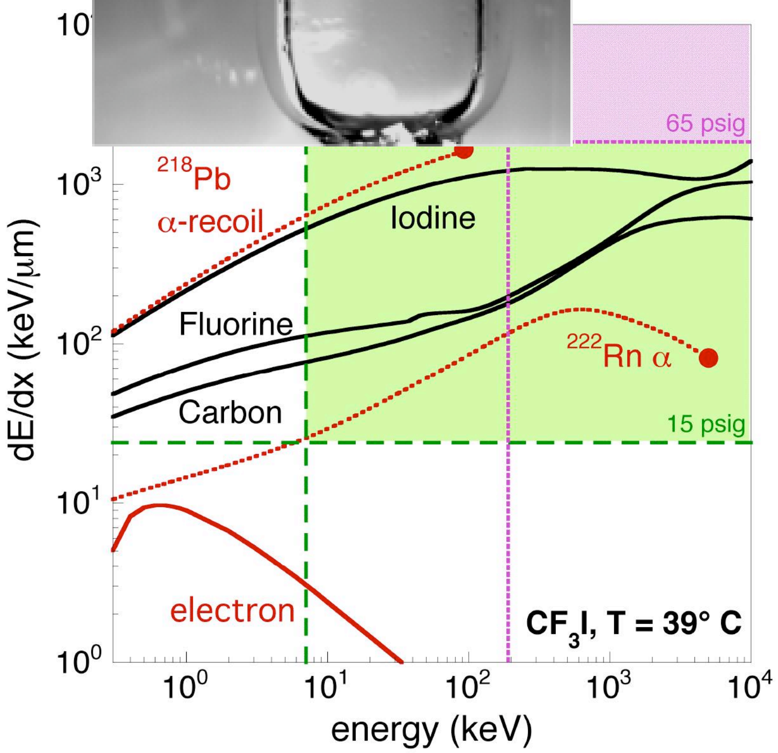
# The COUPP Experiment

- superheated liquid -> detects single bubbles induced by high dE/dx nuclear recoils; **advantage:** large masses, low costs, SD, SI (I, Br, F, C), high spatial granularity, 'rejection' of ERs $10^{10}$ at 10keV$_r$; **challenge:** reduce alpha background

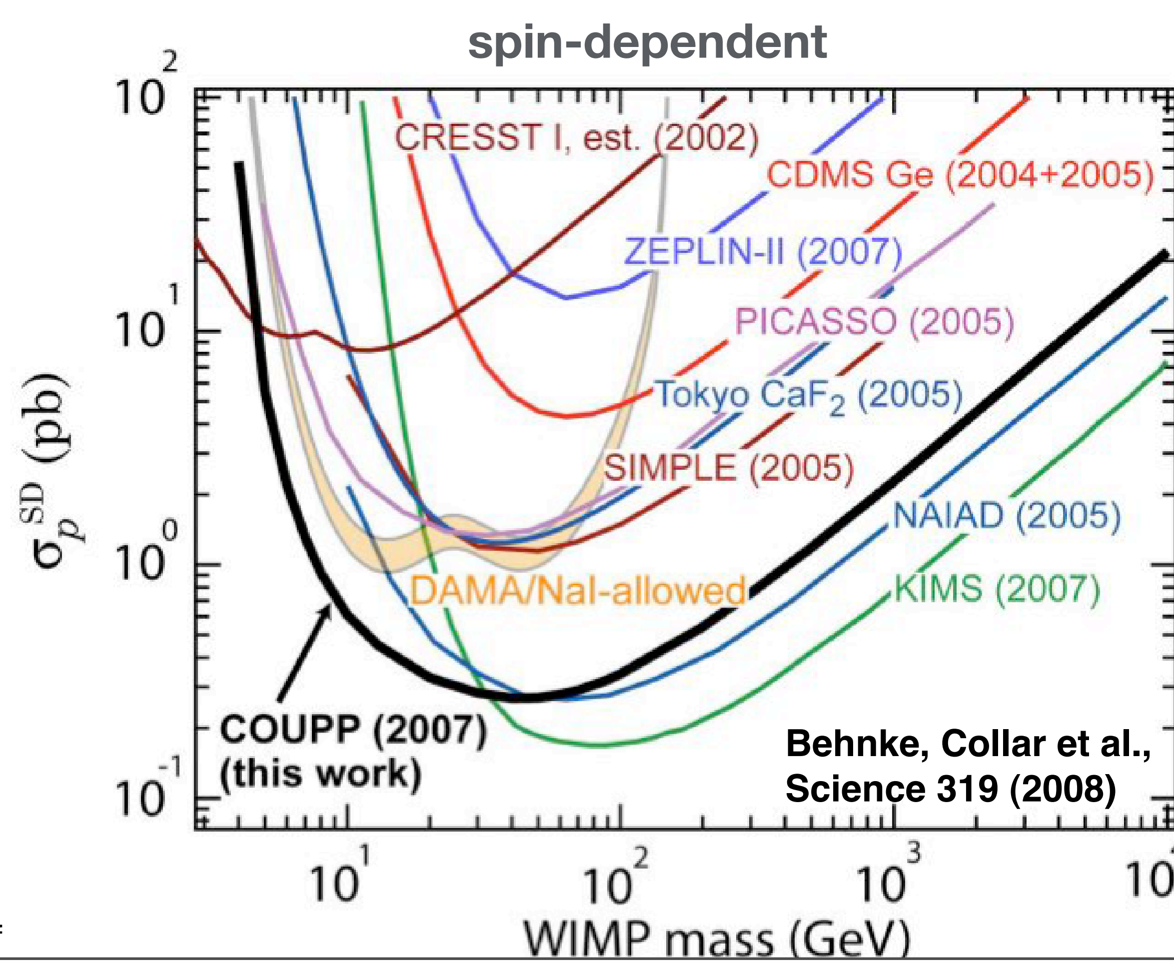
- 

n-induced event (multiple scatter)

WIMP: single scatter

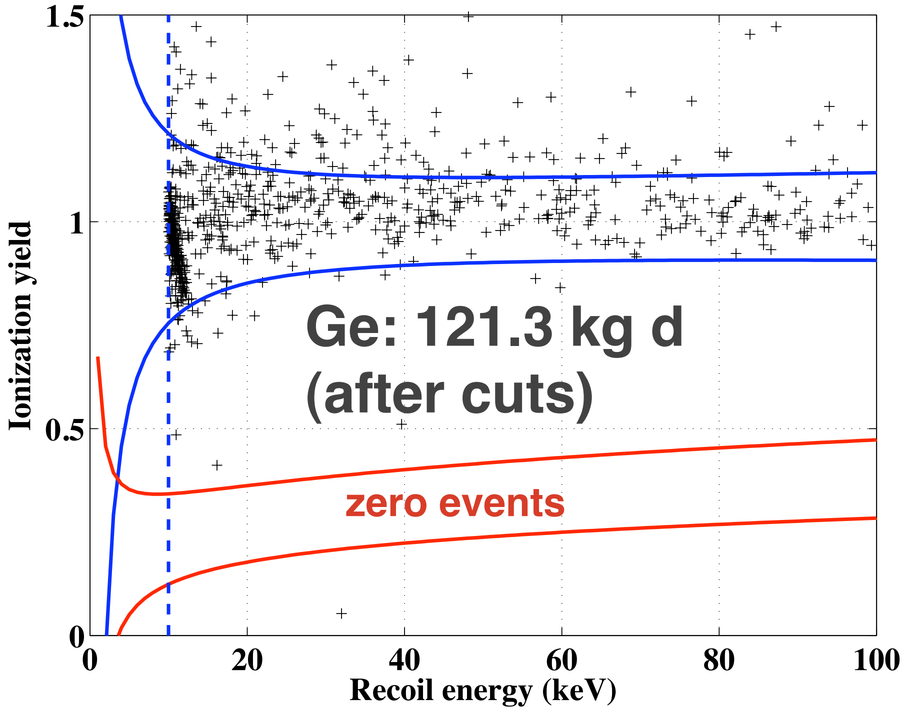


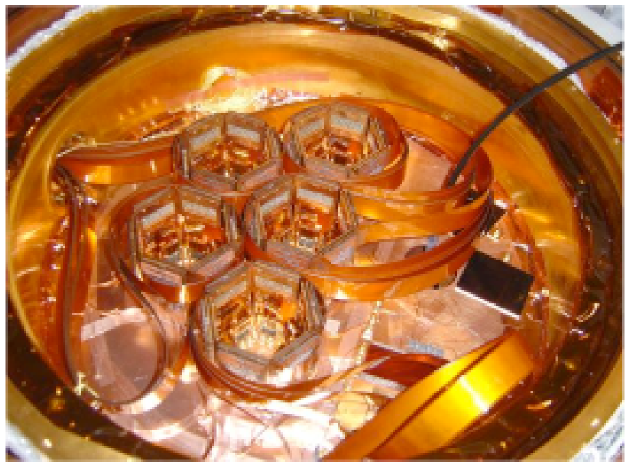

2 kg detector at 300 mwe in 2006: α BG from walls
$^{222}$Rn decays -> $^{210}$Pb plate-out + $^{222}$Rn emanation
**run with 2 kg in 2007/2008 (reduced backgrounds)**
**60 kg module under construction at FNAL -> 3 x $10^{-8}$pb**

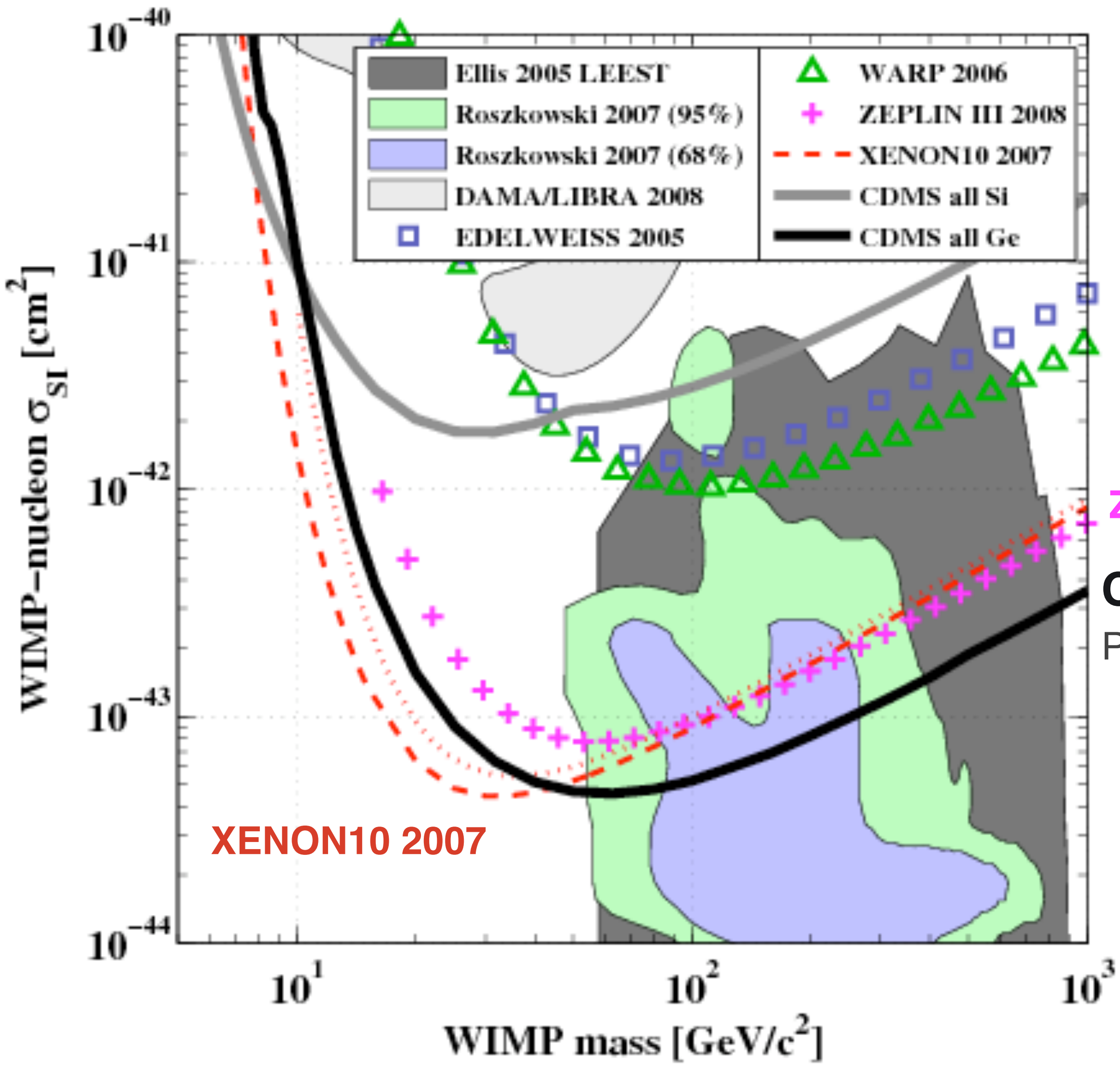



# CDMS Results from the Soudan Mine

- **30 Ge (4.75 kg) and Si (1.1 kg) detectors at ~ 20 mK in 5 towers**
- **Run 123+124:** 163 live days, results published in PRL102 (2009) 011301
- **Run 125-128:** 240 live days under analysis, first results in summer 09 (sensitivity reach ~ $1 \times 10^{-44}$ $cm^2$)






ZEPLIN III 2008

**CDMS 2009**

PRL102 (2009) 011301

# Cryogenic mK Experiments: Near Future

**CRESST at LNGS**

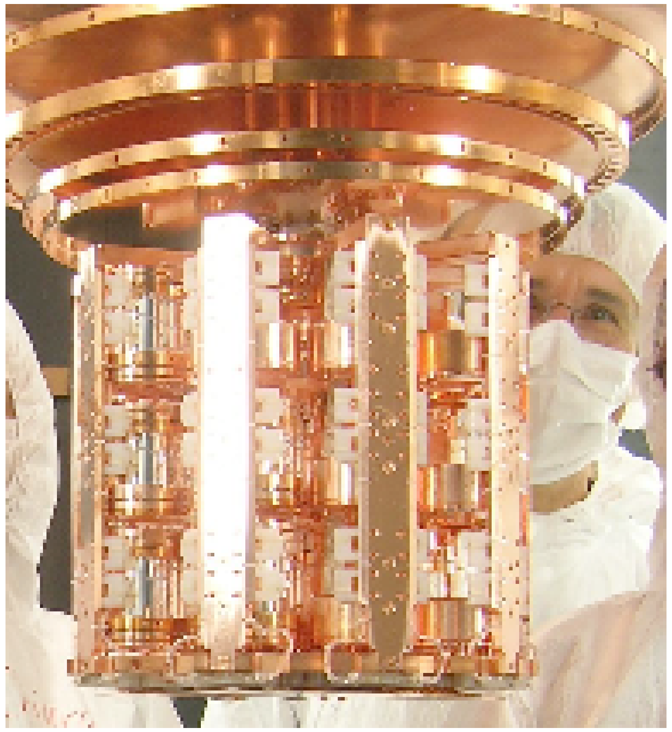
10 kg array of 33 $CaWO_4$ detectors
new 66 SQUID channel array
- **new limit from operating 2 detectors (48 kg d) published in 2008,** arXiv:0809.1829v1
- new run in progress

**EDELWEISS at LSM**

10 kg (30 modules) of NTD and NbSi Ge detectors in new cryostat
- new charge electrodes
- 100 kg d under analysis
- **data taking in progress**

**CDMS/SuperCDMS at Soudan**

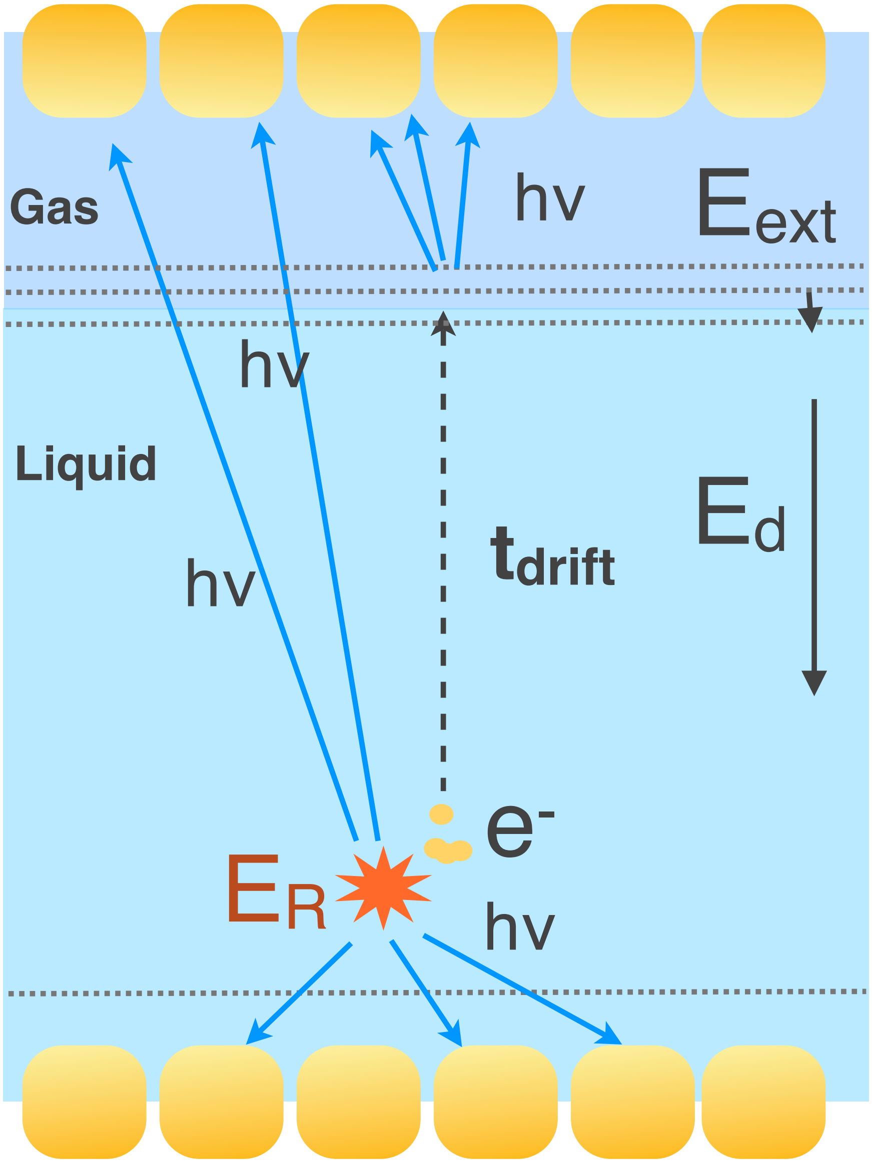
CDMS-II run 129 in progress
SuperCDMS detectors (1'' thick ZIPs, each 650 g of Ge) have been tested
Installation of first SuperTower at Soudan in spring 2009
**Goal: $5 \times 10^{-45}$ cm$^2$ with 16 kg Ge**

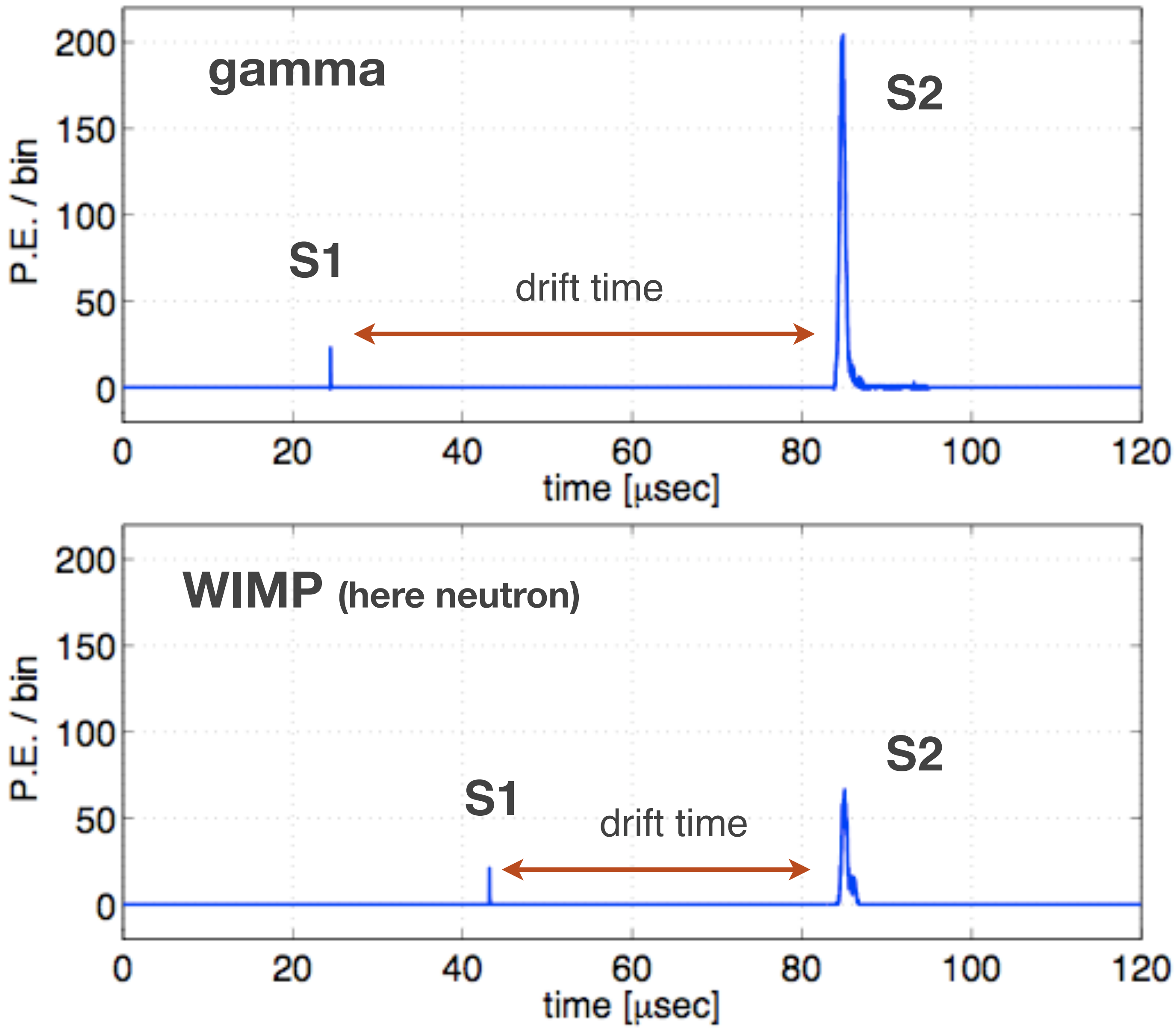


# Noble Liquids Time Projection Chambers

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

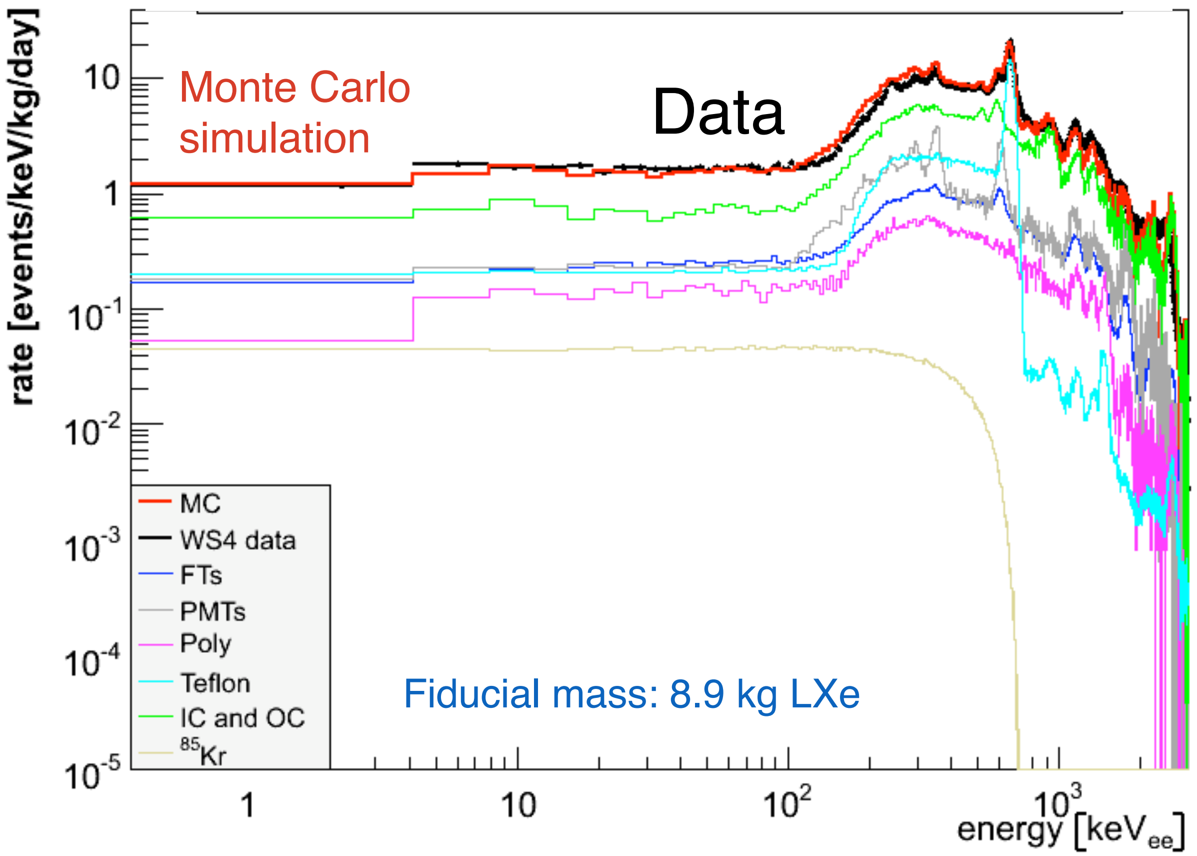
- **Dense, homogeneous targets/detectors; high light and charge yields**
- **Prompt (S1) light signal** after interaction in active volume; charge is drifted, extracted into the gas phase and detected as **proportional light (S2)**

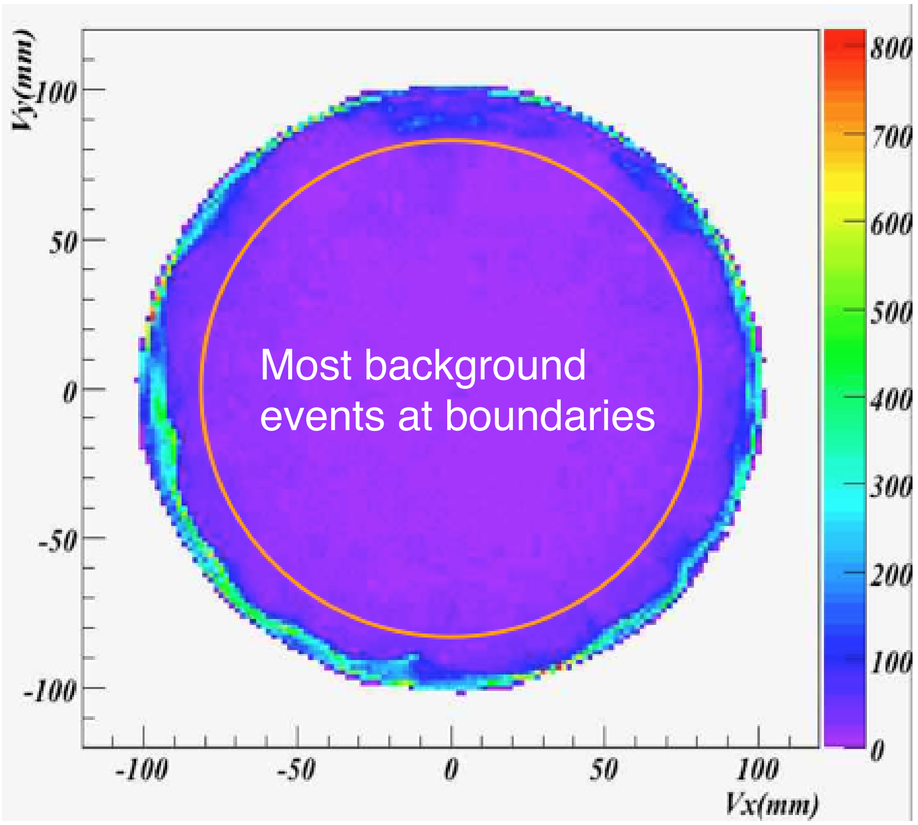


# The XENON10 Experiment at LNGS

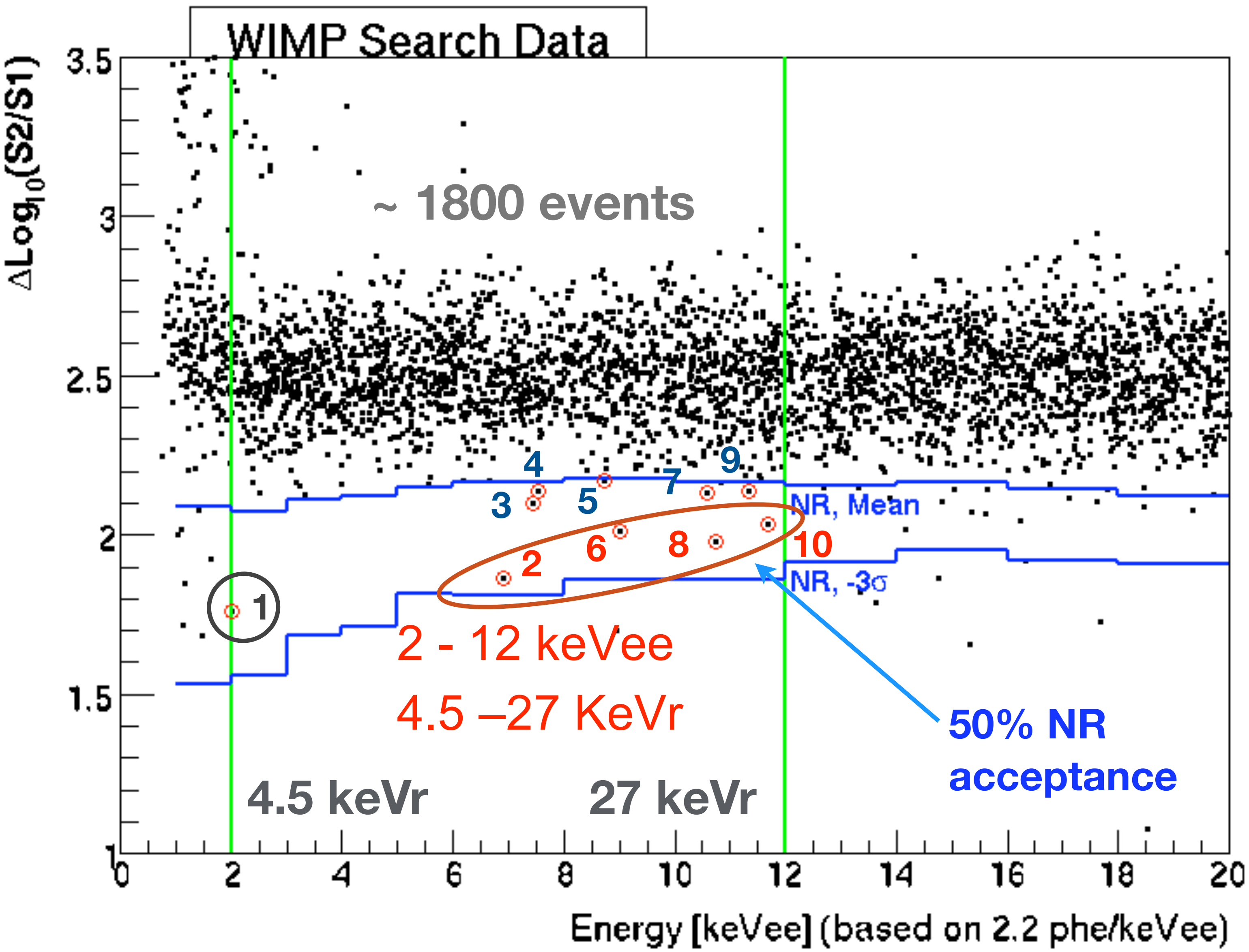
- 22 kg LXe (15 kg in active volume)
- 89 1”x 3.5cm R8520 PMTs, in 2 arrays
  - ➡ x-y position from PMT hit pattern; $\sigma_{x\text{-}y} \approx 1$ mm
  - ➡ z-position from $\Delta t_{drift}$ ($v_{d,e-} \approx 2$mm/µs), $\sigma_Z \approx 0.3$ mm
- backgrounds: dominated by detector materials, well understood



# XENON10 WIMP Search Data

- WIMP search run  Aug. 24. 2006 - Feb. 14, 2007: ~ **60 (blind) live days**
- **136 kg-days exposure** = 58.6 live days × 5.4 kg × 0.86 (ε) × 0.50 (50% NR acceptance)




**WIMP 'Box' defined at**

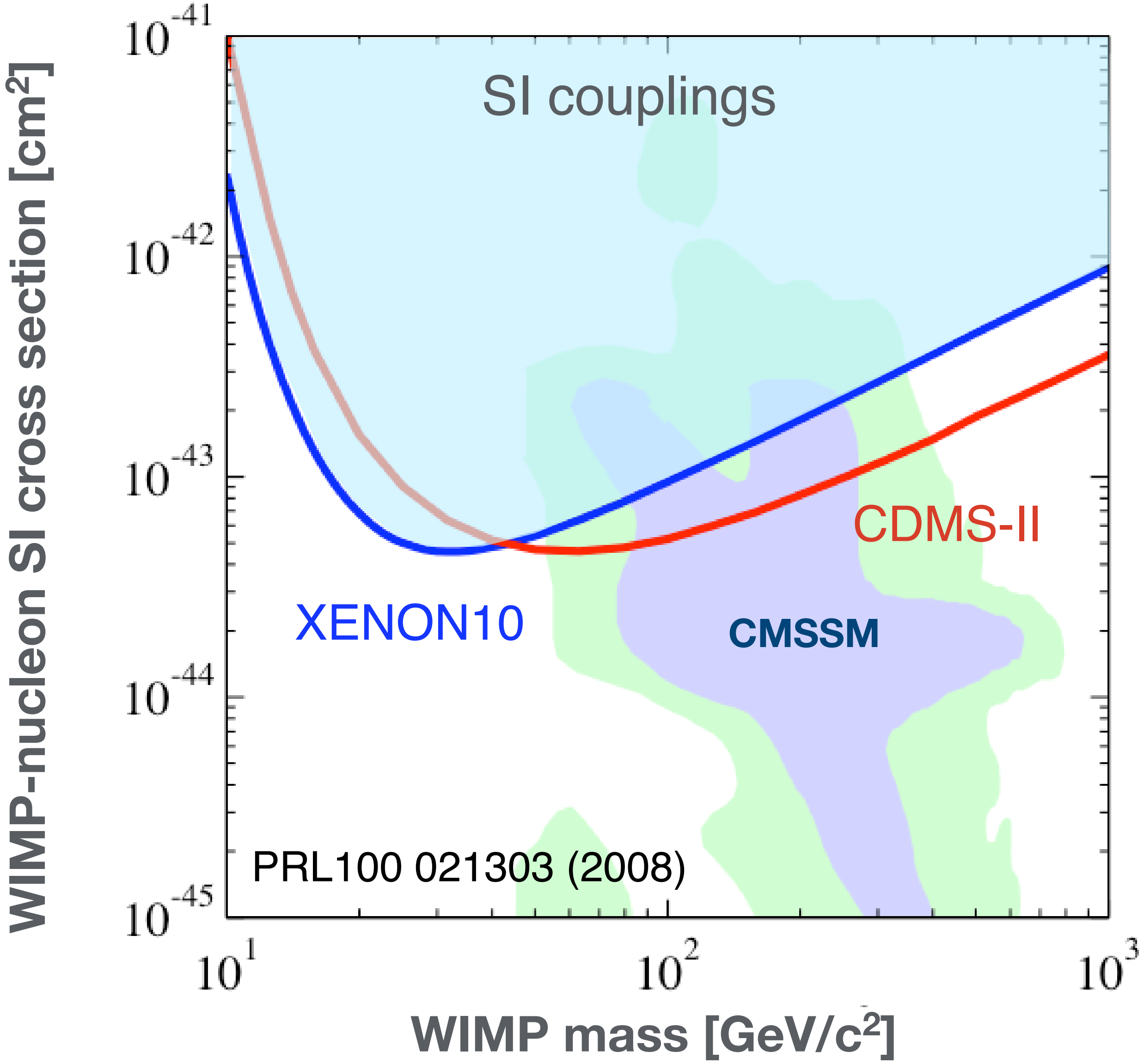
50% acceptance of NRs (blue lines): [Mean,-3σ]

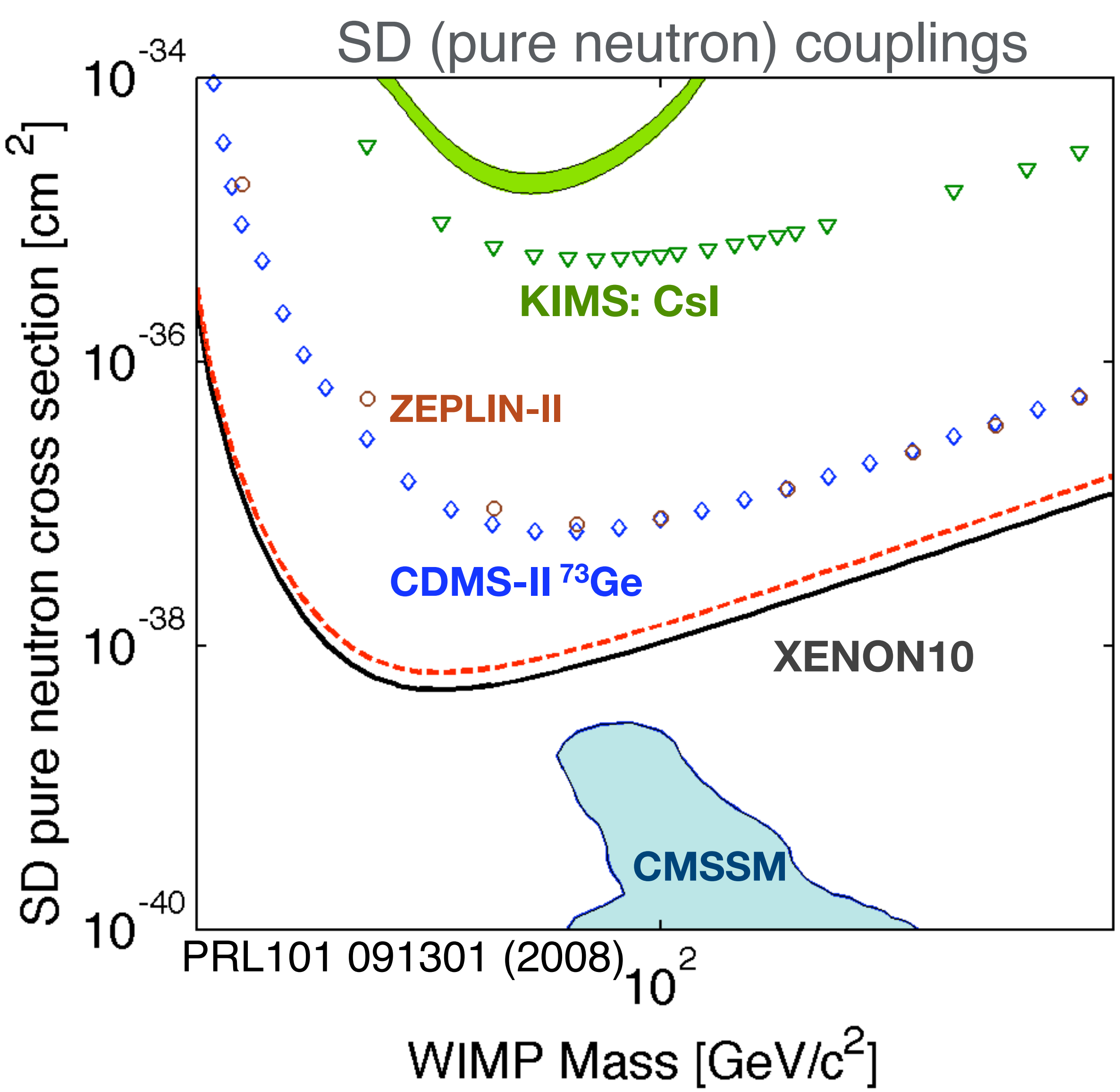
**10 events in 'box' after all cuts**
7.0 ($^{+1.4}_{-1.0}$) statistical leakage expected from the gamma (ER) band

NR energy scale based on constant 19% QF

# XENON10 WIMP Search Results for SI and SD Interactions

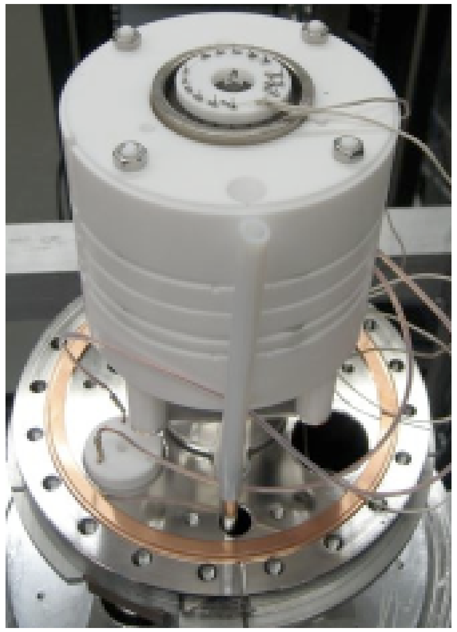
- To set limits: all 10 events considered, thus no background subtraction performed
  - ➡ probed the elastic, SI WIMP-nucleon σ down to **≈ 4 × $10^{-44}$ cm²** (at $M_{WIMP}$ = 30 GeV)
- natural Xe: $^{129}$Xe, 26.4 %, spin 1/2, $^{131}$Xe, 21.2%, spin 3/2
- use shell-model calculations by Ressel and Dean [PRC 56, 1997] for <$S_n$>, <$S_p$>

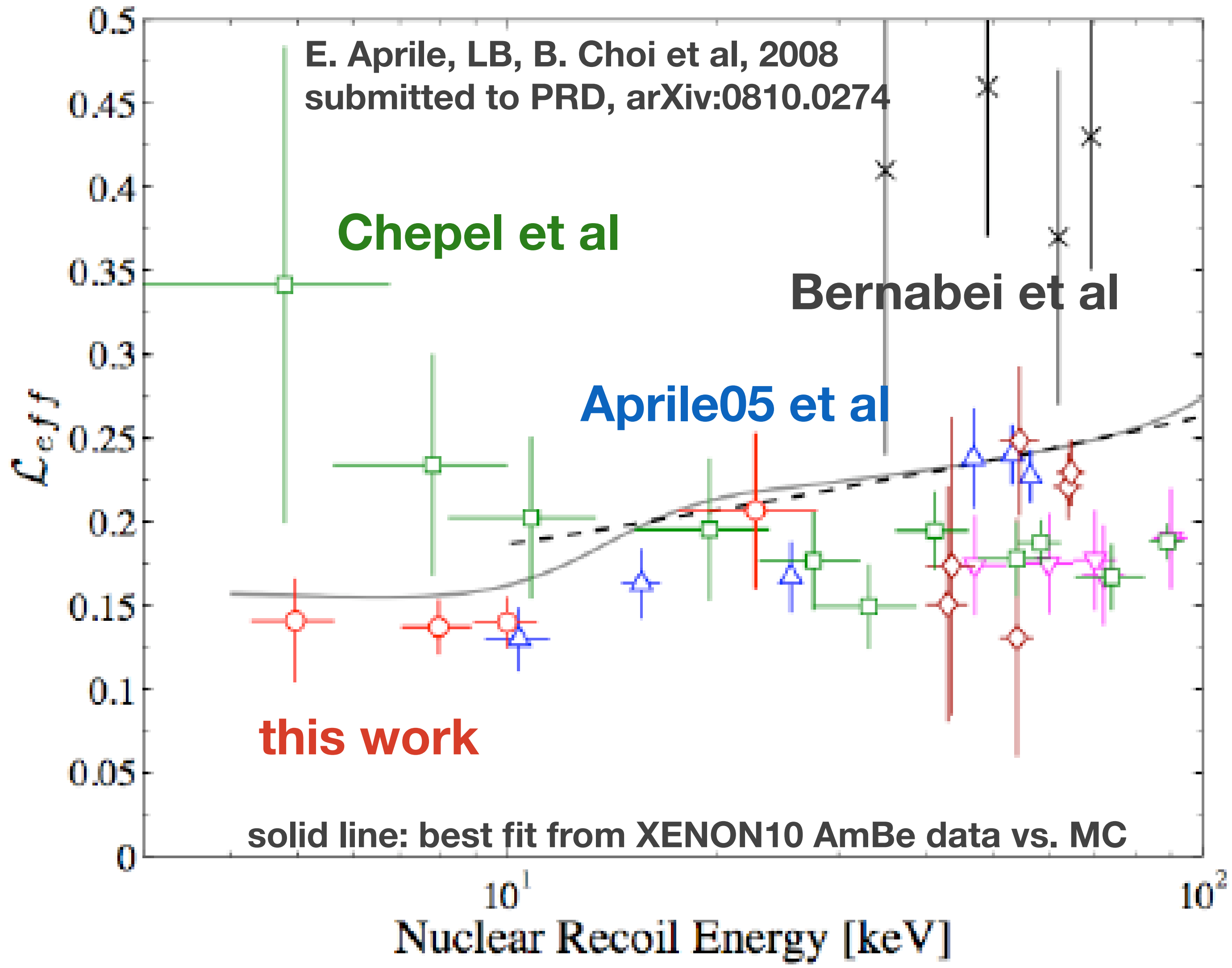


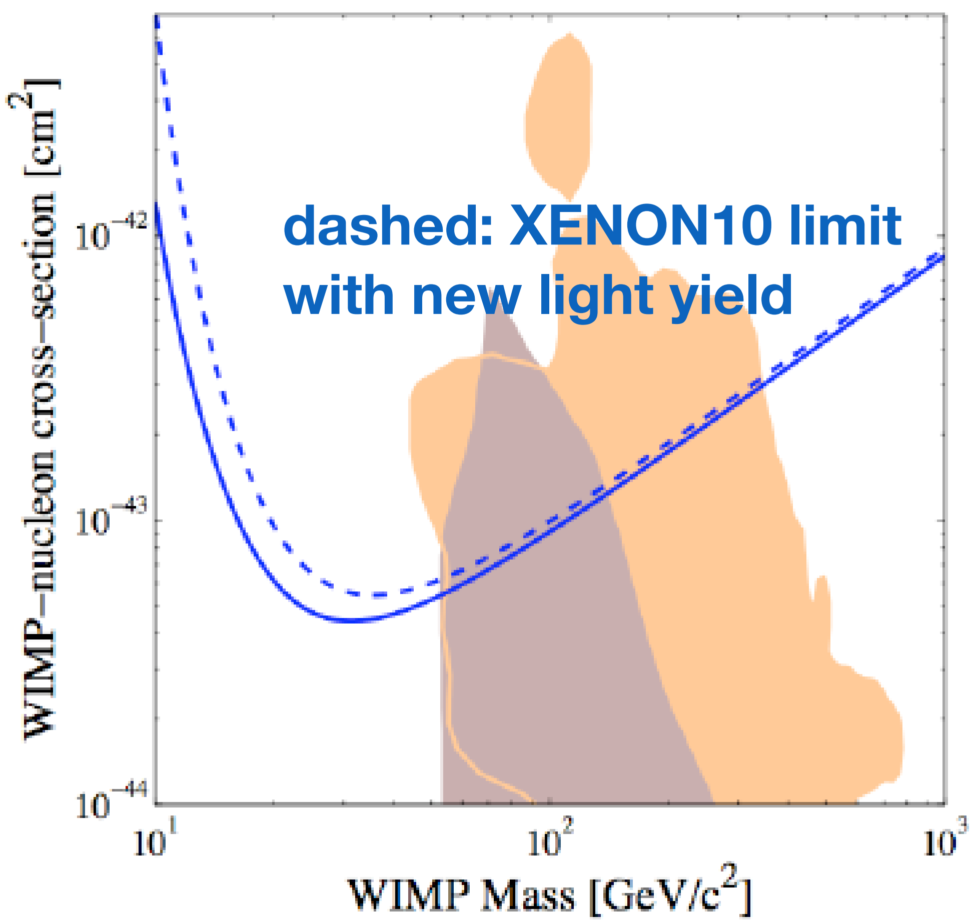



# New measurements of the Light Yield in LXe

- Columbia + Zurich: at RaRAF (Nevis Labs), 1 MeV n-beam
- Detector: XeCube, 6 R8520 PMTs, 2.5 cm³ LXe, zero field
- New experiment for charge/light yield under preparation at UZH (using D-D neutron generator)

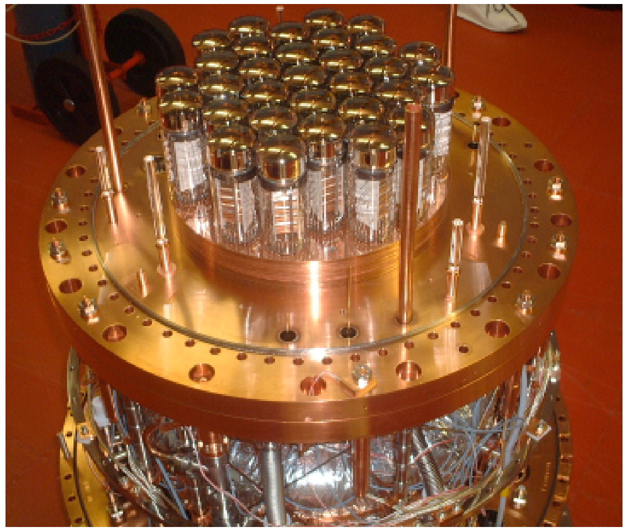


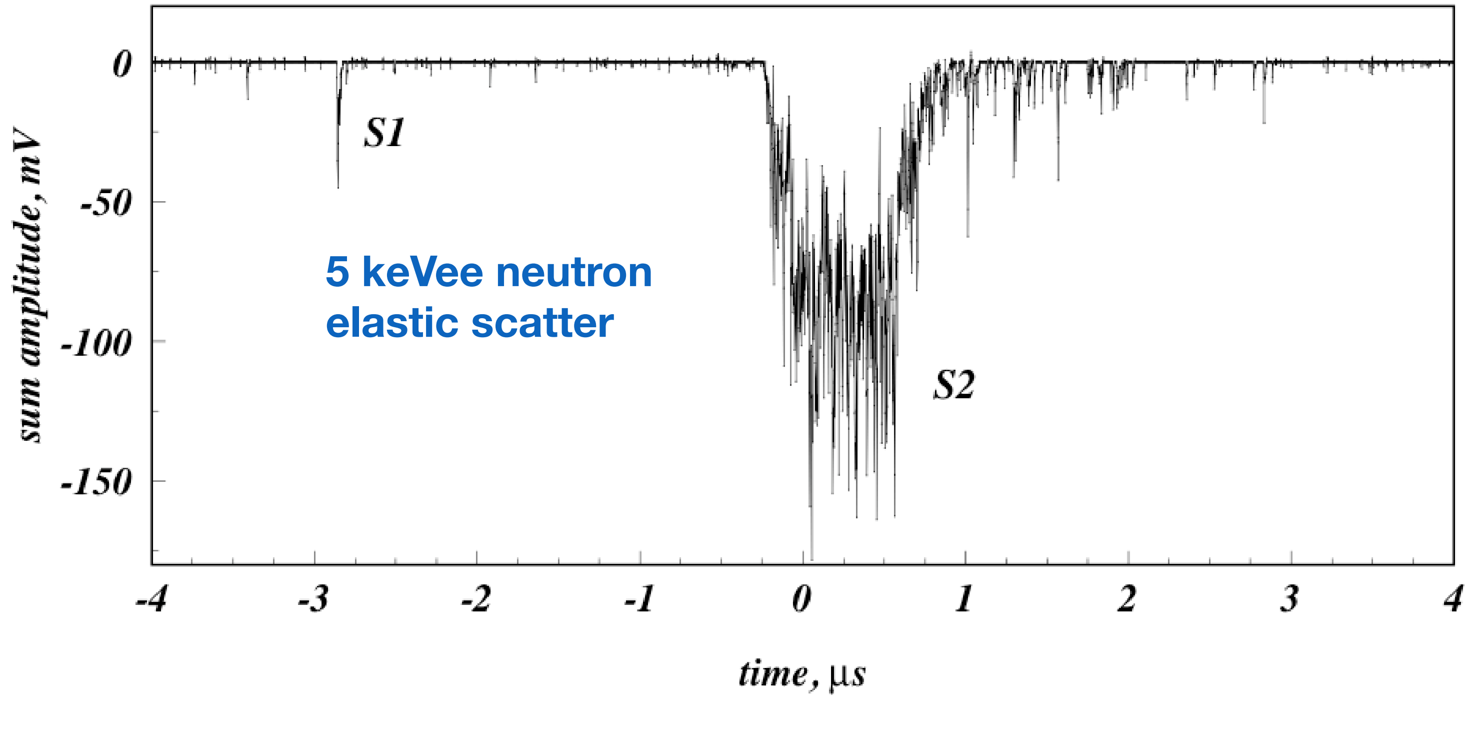



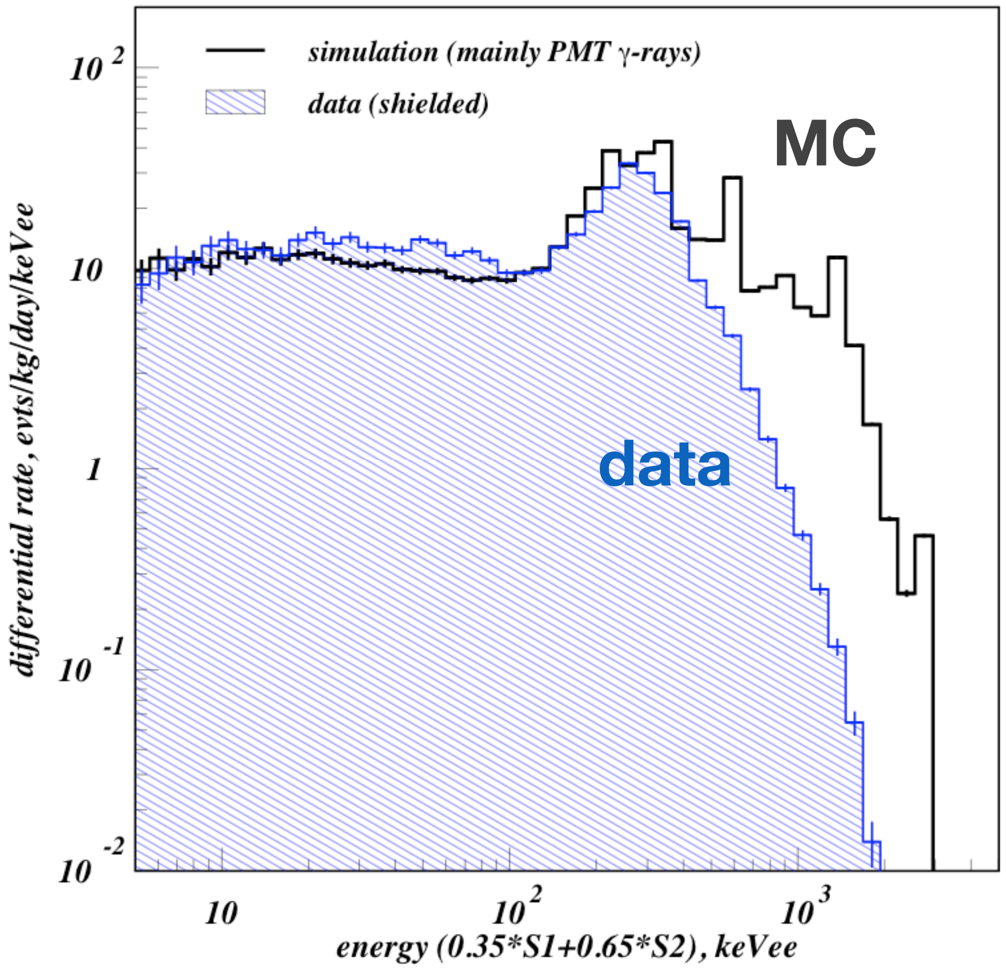



# The ZEPLIN-III Experiment at the Boulby Mine

- Two-phase xenon TPC: 12 kg of LXe in active volume
- 31 x 2" PMTs detect both primary and proportional light signal
- field: 3.9 kV/cm in liquid, 7.8 kV/cm in gas
- backgrounds (about 10× higher than in XENON10):
  - ➡ dominated by radioactivity of PMTs



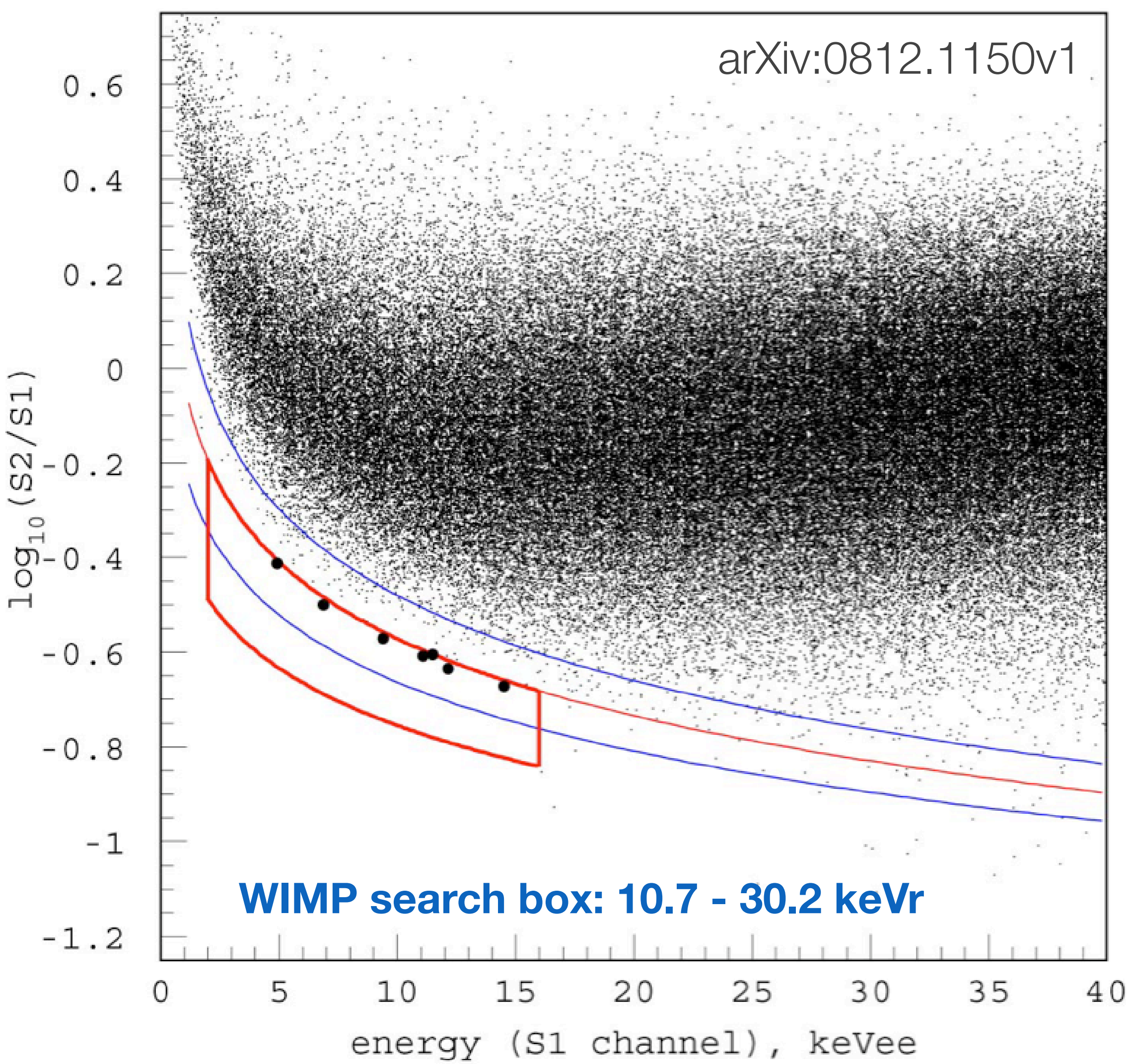


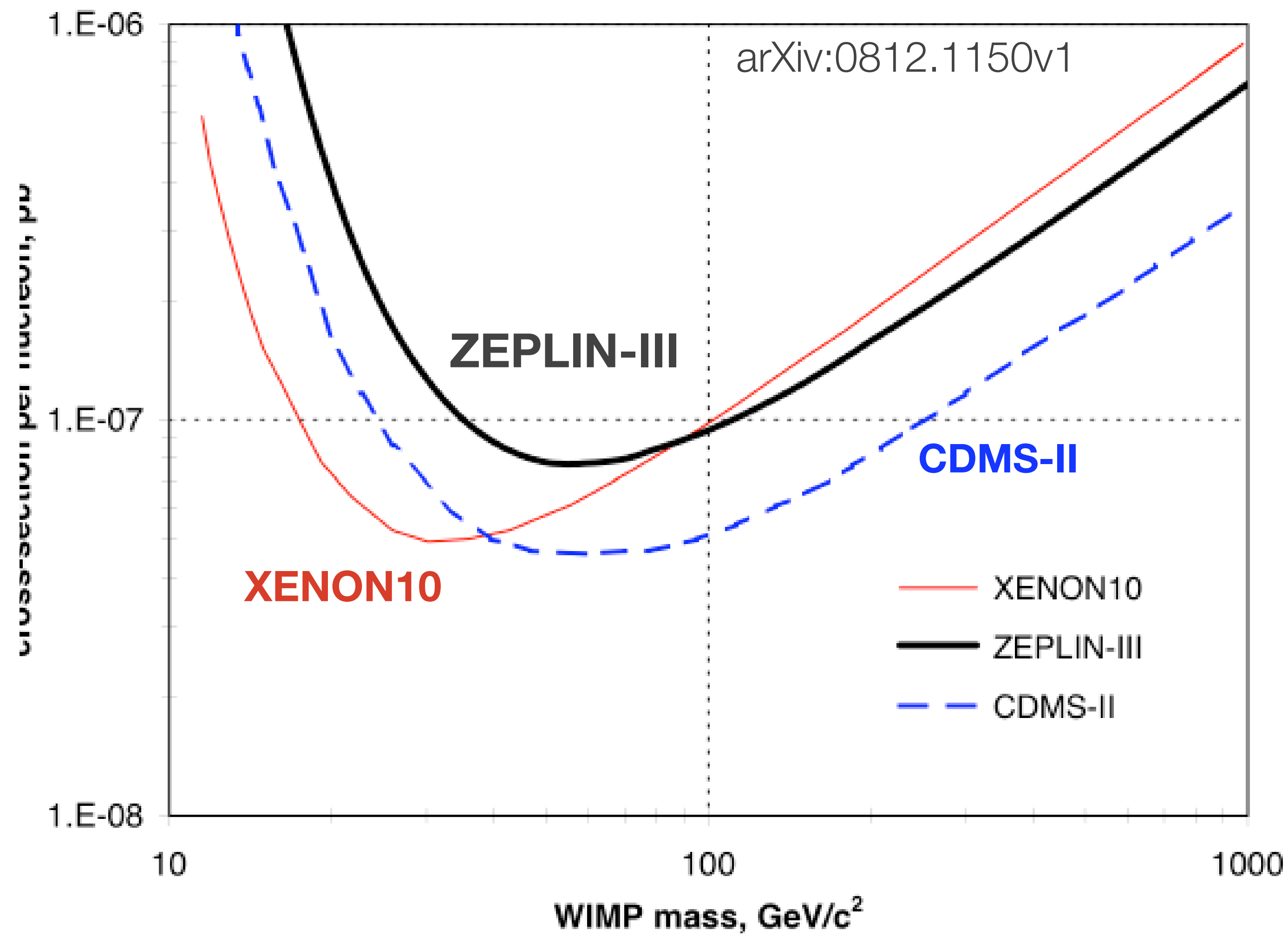




- new run, with low-BG PMTs is planned

# ZEPLIN-III WIMP Search Data and Results

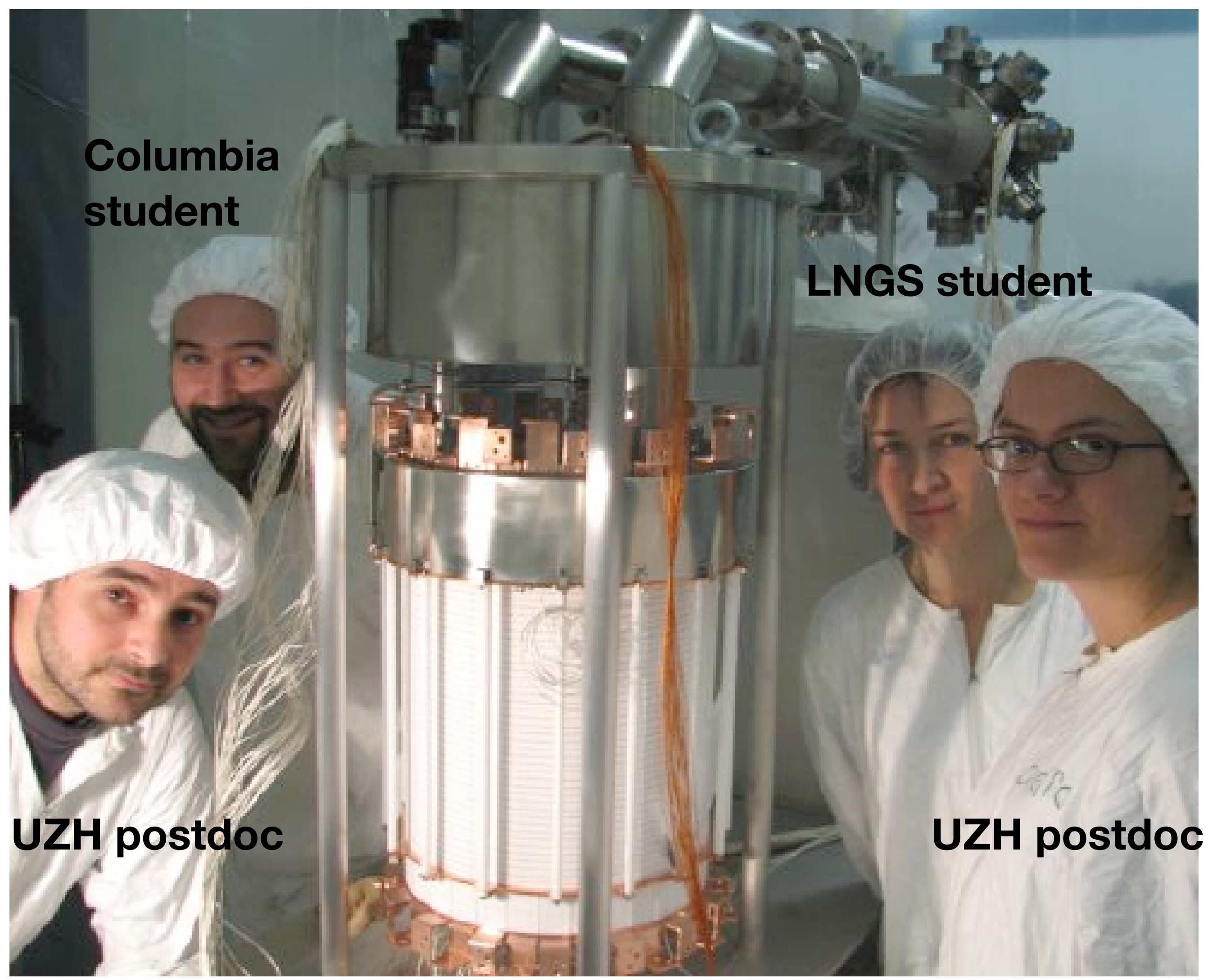
- **WIMP search data: 127 kg days (after cuts) in 6.7 kg fiducial**
- 7 events observed in the 'WIMP box', 11.6 ± 3.0 events expected (from non-blind WS data)
- Consistent with zero signal, 90% upper signal limit of 2.9 events



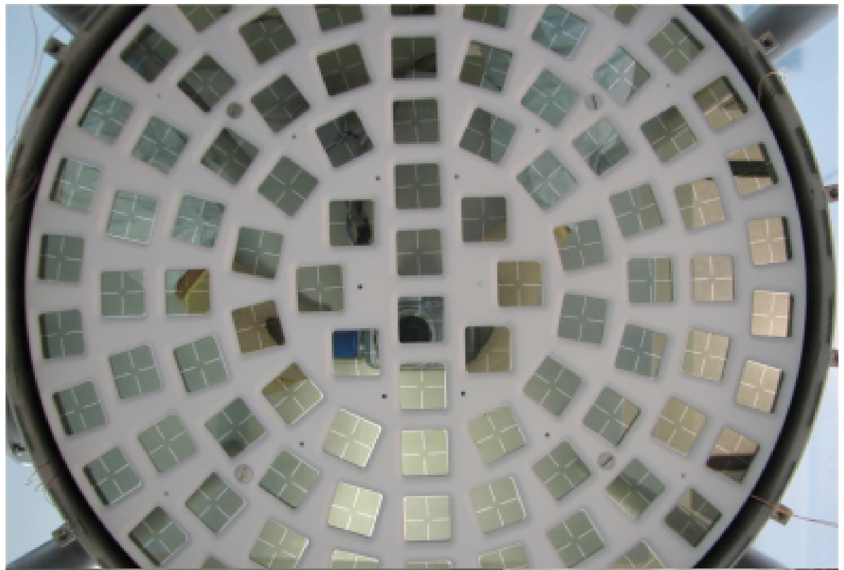
# LXe TPCs: near future

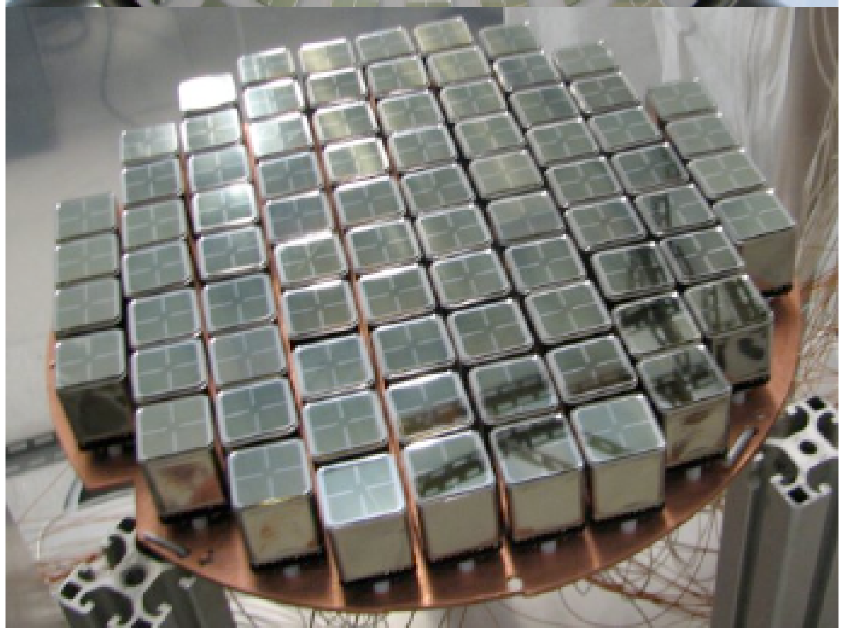
- **XENON100:** under commissioning at LNGS, expected to start WS run in spring 2009
- 170 kg (100 kg in active veto) LXe, viewed by 242 PMTs, 30 cm ⌀, 30 cm drift
- **Goal: factor 100 lower background, factor 10 higher mass than XENON10**

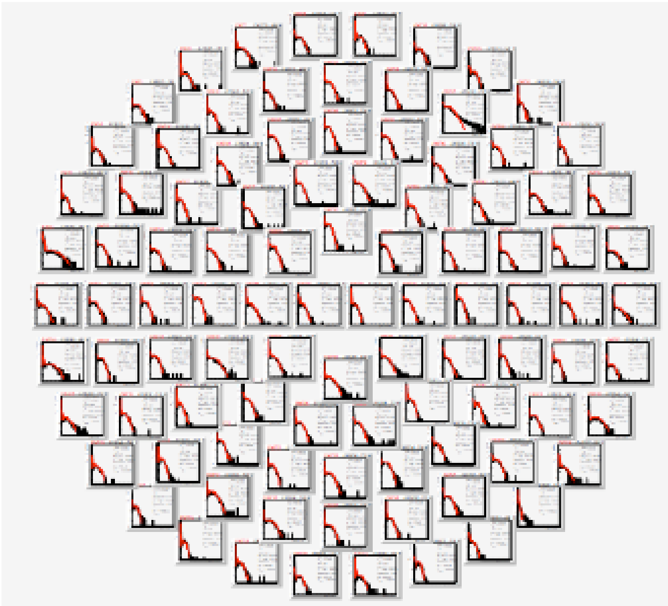



# XENON100 Light Detectors

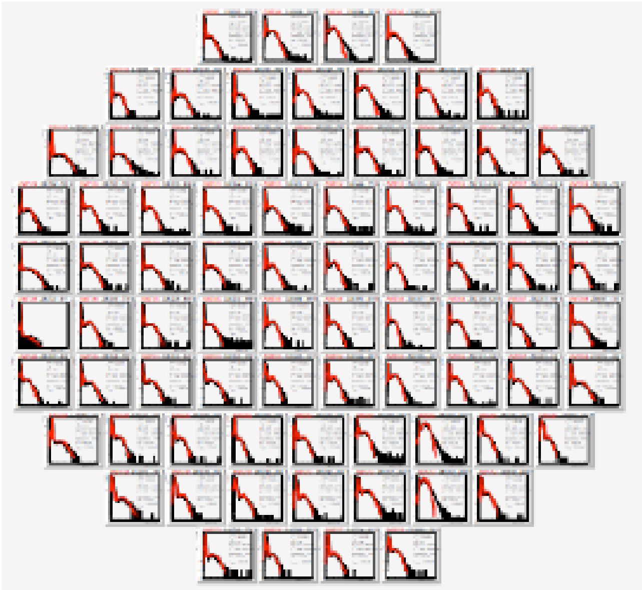
- **242 (Hamamatsu R8520) 1”x1”, low radioactivity PMTs; 80 with high QE of 33%**
  - ➡ 98 top: for good fiducial volume cut efficiency
  - ➡ 80 bottom: for optimal S1 collection efficiency (thus low threshold); 64 in active LXe shield
- PMT gain calibration with blue LEDs; the SPE response is measured







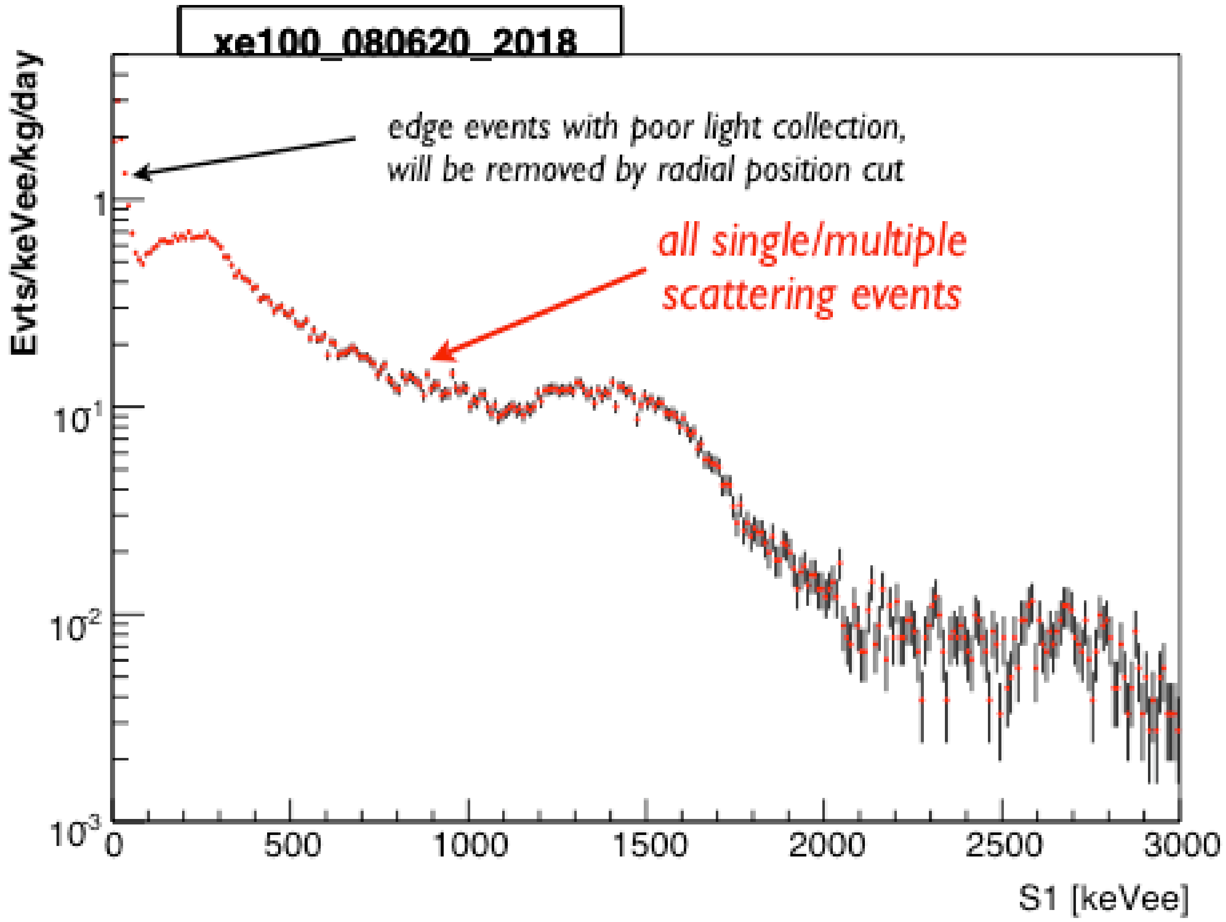
**top PMT array**
**(gain equalized to $2x10^6$)**



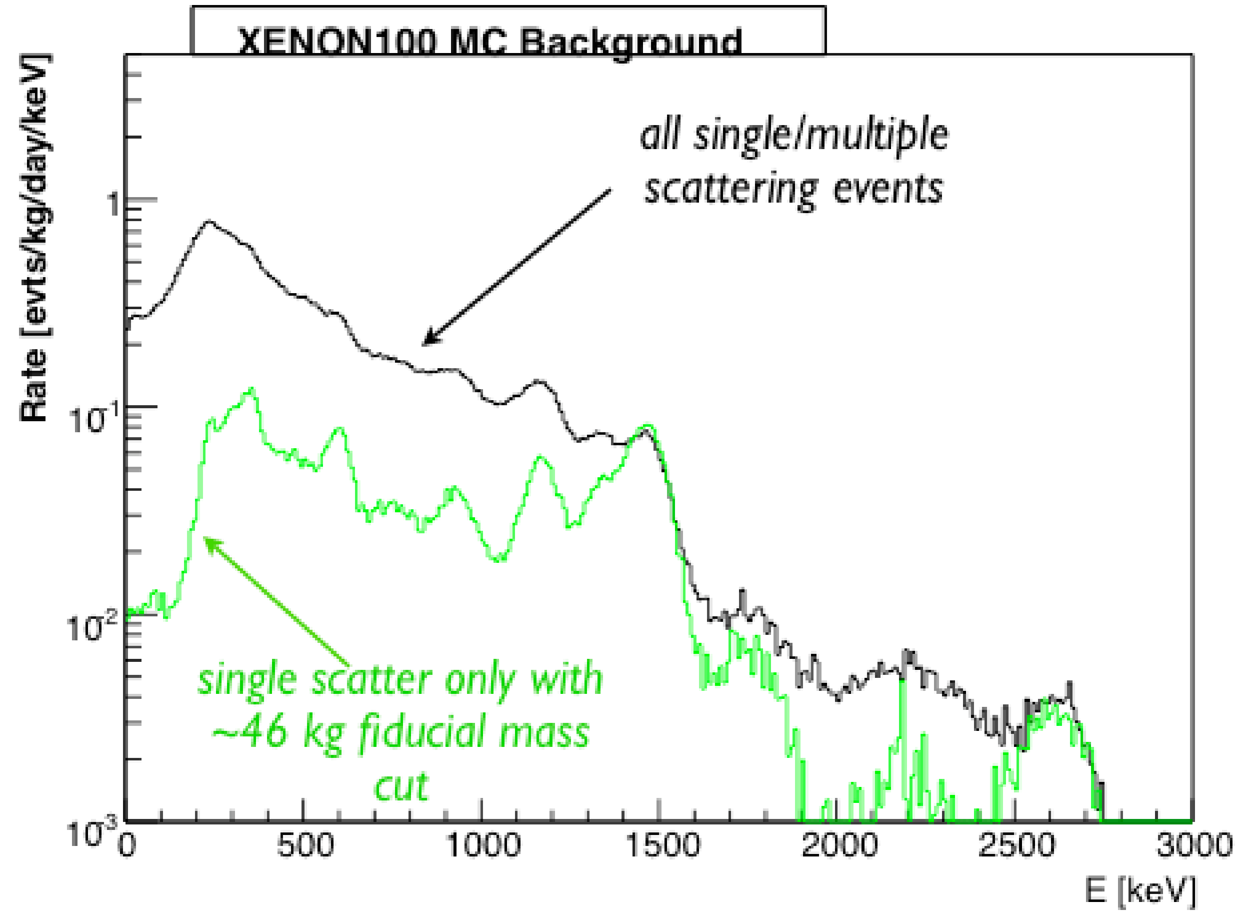
**bottom PMT array**
**(gain equalized to $2x10^6$)**

# Preliminary Background from XENON100 Data

**data (S1 only)**



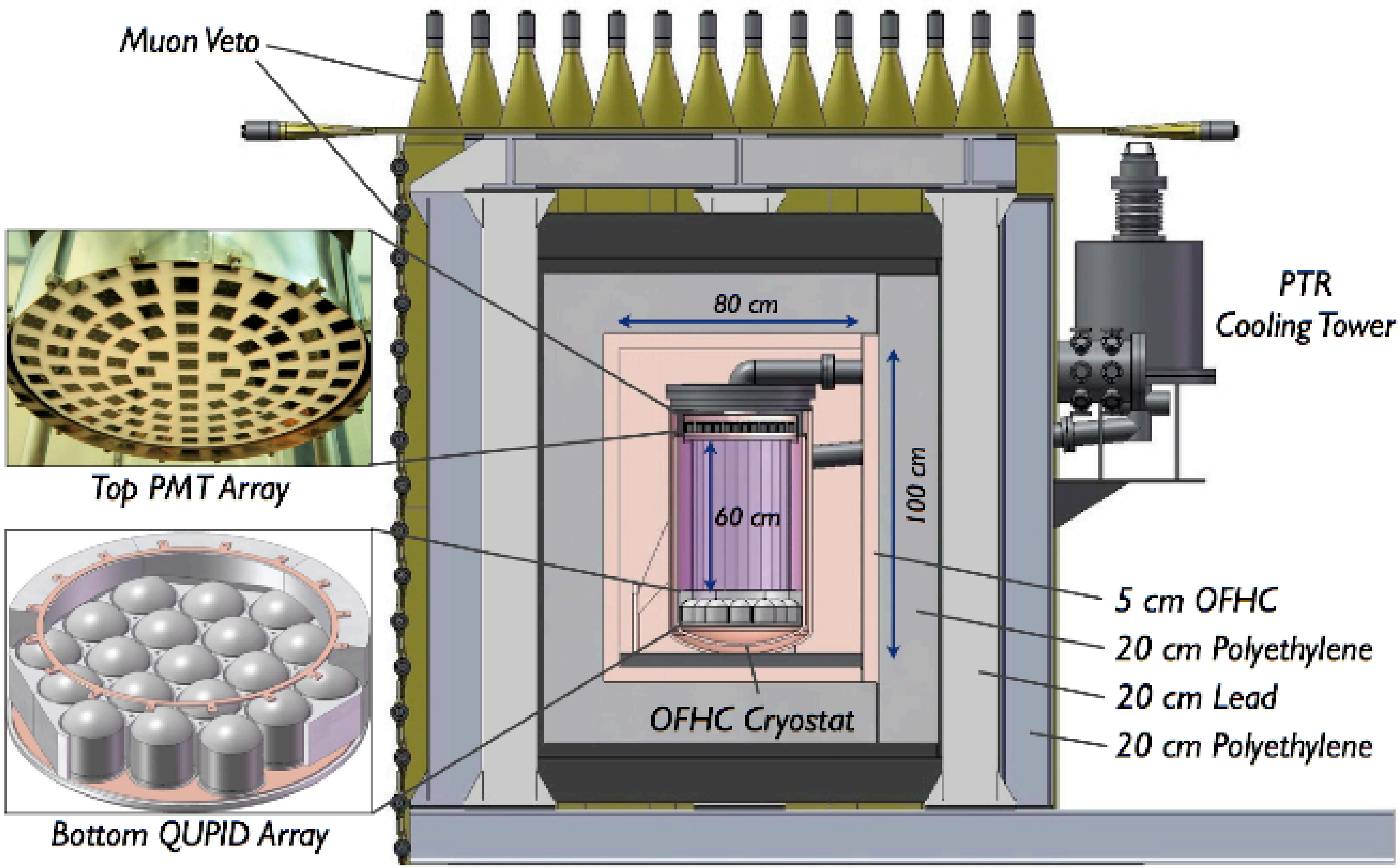

**Monte Carlo simulations**

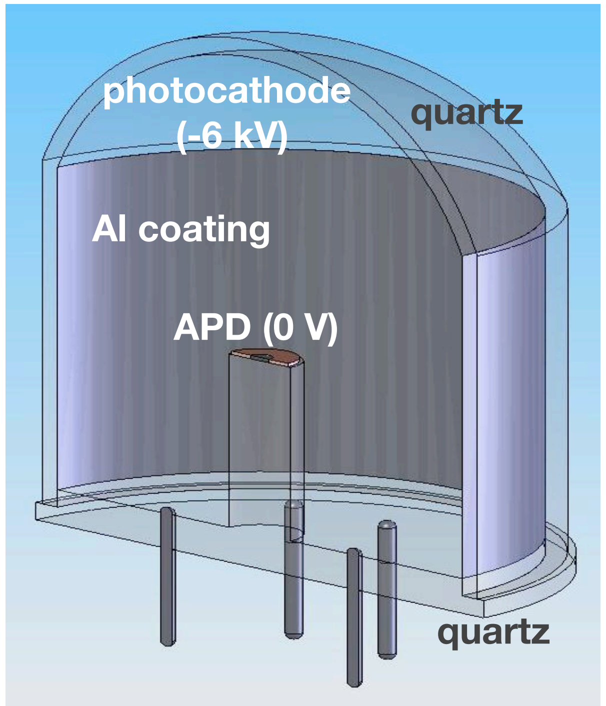



**Data and Monte Carlo predictions are in good agreement for overall rate**

# Next Step: The Xenon100 Upgrade

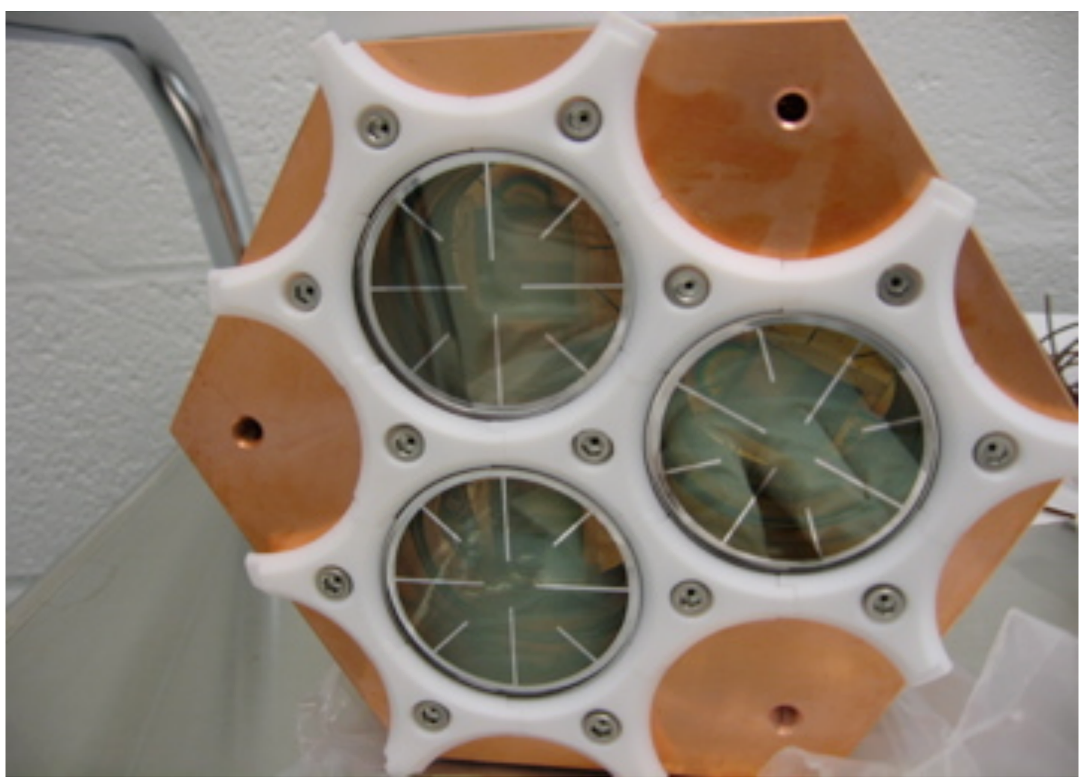
- **100 kg fiducial mass (total of 260 kg LXe), background $5 \times 10^{-4}$ events/(kg day keV)**
- new photon detectors, QUPIDs; ultra-low BG Cu cryostat, new shield, including muon veto
- **construction 2010; WIMP search 2011-2012**




# The LUX Experiment

- **300 kg dual phase LXe TPC (100 kg fiducial), with 122 PMTs in large water shield with muon veto**
- 50 kg LXe prototype with 4 R8778 PMTs being assembled and tested at CWRU
- full detector to be installed at Homestake Davis Cavern, 4850 ft in fall 2009 (in 8 m ∅ water tank)
- **WIMP sensitivity goal: 7 × $10^{-10}$ pb after 10 months**

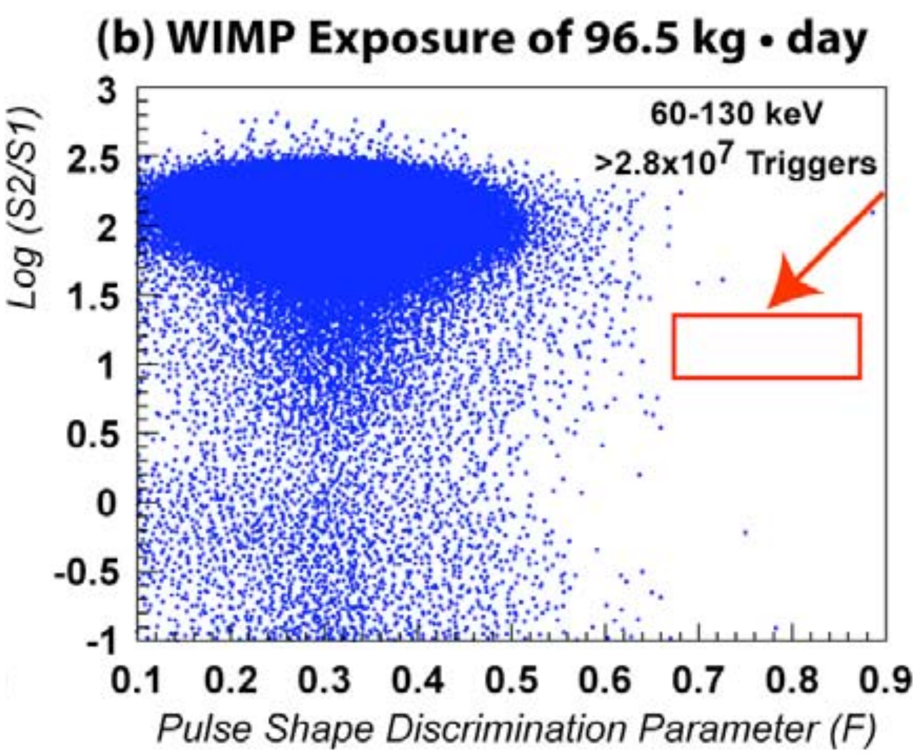


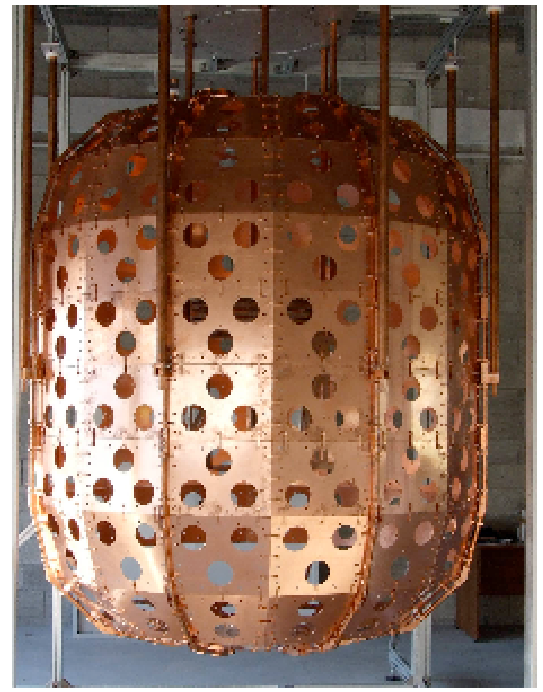
R. Gaitskell, IDM08, Stockholm

# Two-phase Argon Detectors

**WARP at LNGS**

3.2 kg LAr operated at LNGS; results from zero events > 55 keVr

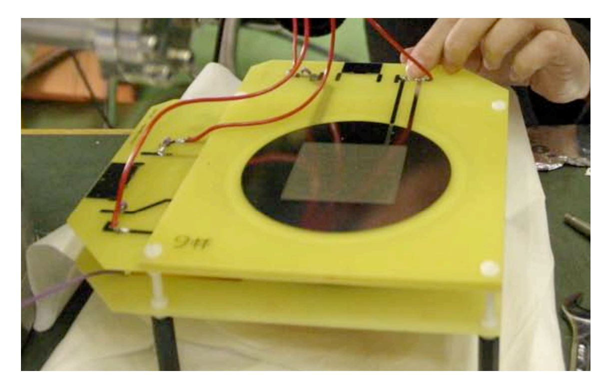


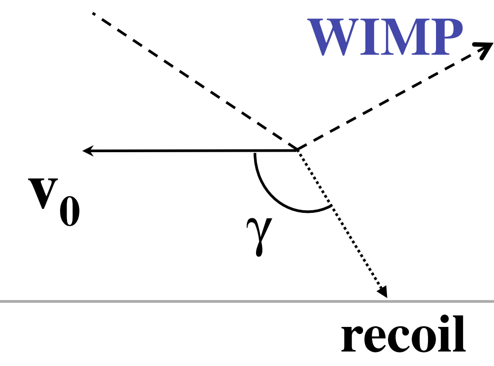
140 kg LAr, 41 3” PMTs under construction
active LAr shield: ~ 8t, viewed by 300 PMTs

**ArDM at CERN**

1 t LAr prototype under construction
direct electron readout via LEMs (thick macroscopic GEM)
S1 with 14 x 8” PMTs



# Directional Detectors: gas TPCs

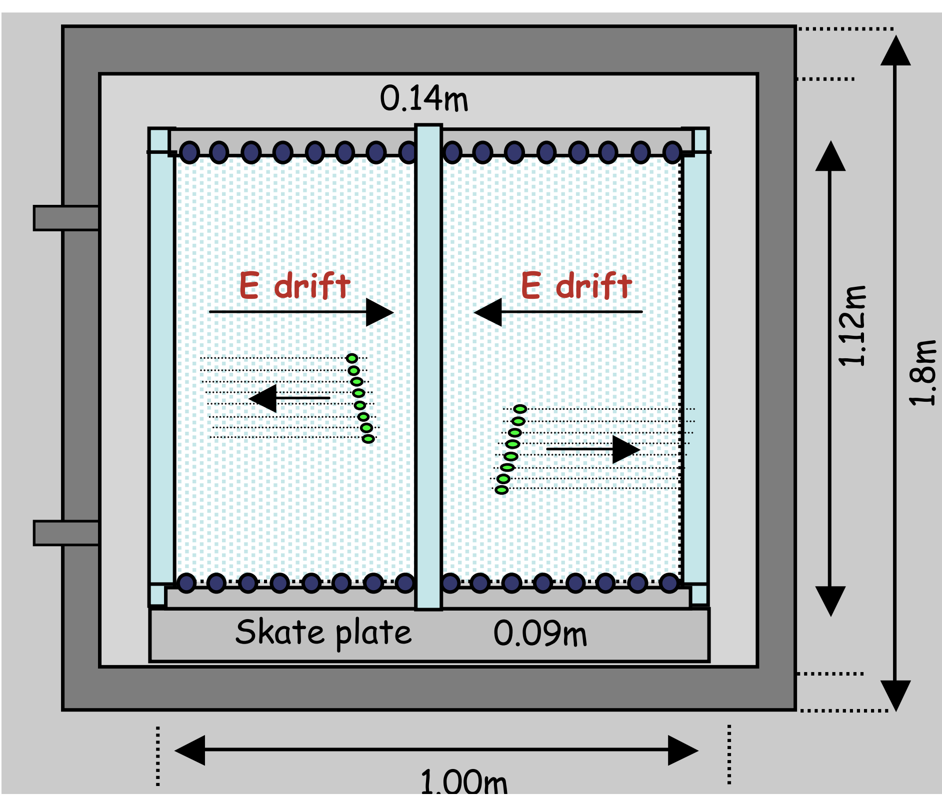


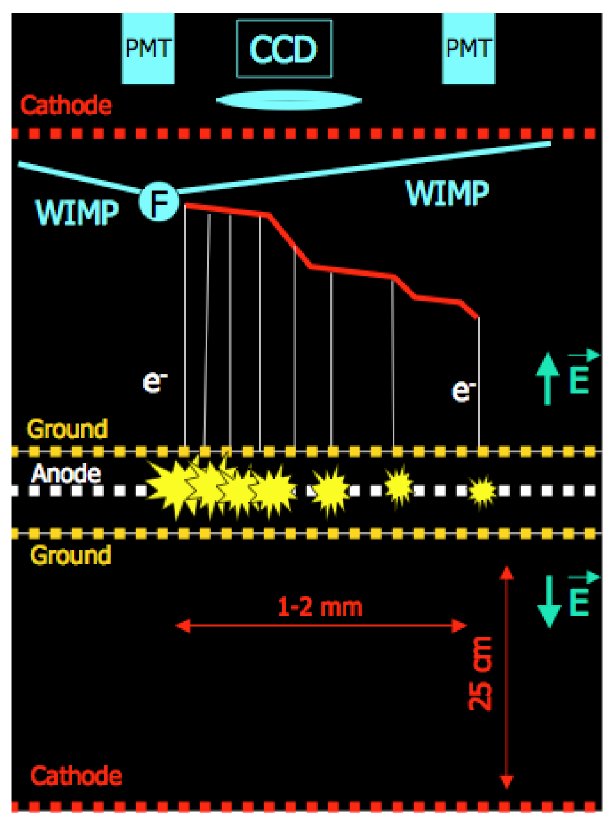

## DRIFT at Boulby

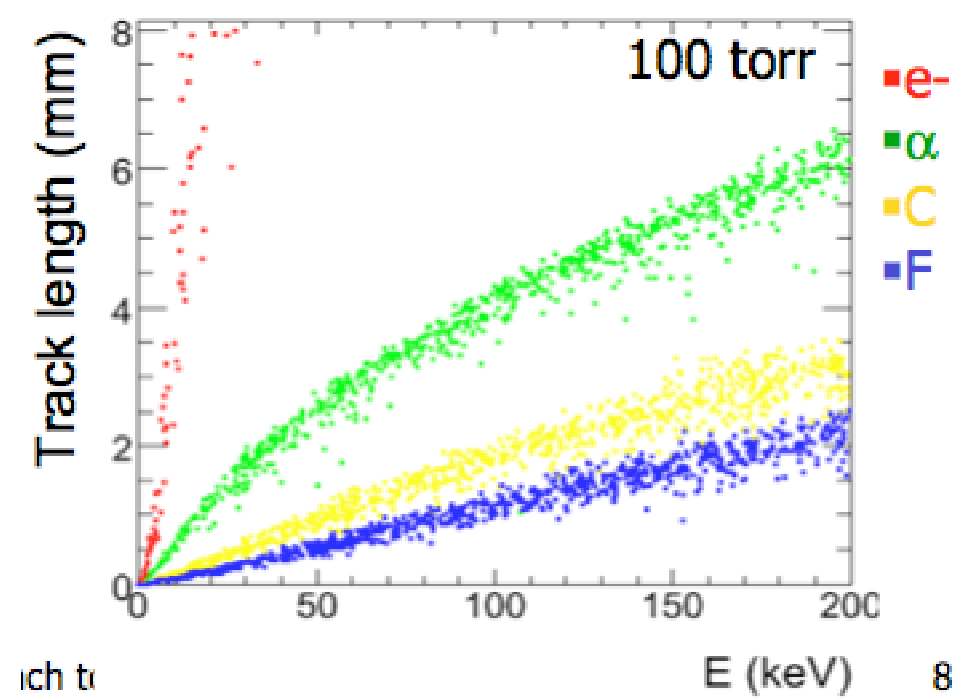
negative ion ($CS_2$) TPC: 1 $m^3$ 40 Torr $CS_2$ gas (0.17 kg); 2 mm pitch anode + crossed MWPC
- NR discrimination via track morphology
- 3D track reconstruction for recoil direction: find head-tail of recoil based on dE/dx
- new run in 2007/08 at Boulby with strongly reduced Rn backgrounds

## DM-TPC

low-pressure $CF_4$ gas TPC: 50 Torr
- 40 keV recoil ~ 1-2 mm track
- PMTs for trigger => z - information
- CCD images avalanche region => E and x-y
- head-tail of recoil based on dE/dx
- 2 x $10^{-2}$ $m^3$ modules under commissioning at MIT and ready for operation at WIPP in 2009
- 1 $m^3$ detector being designed (0.25 - 0.5 kg/$m^3$)

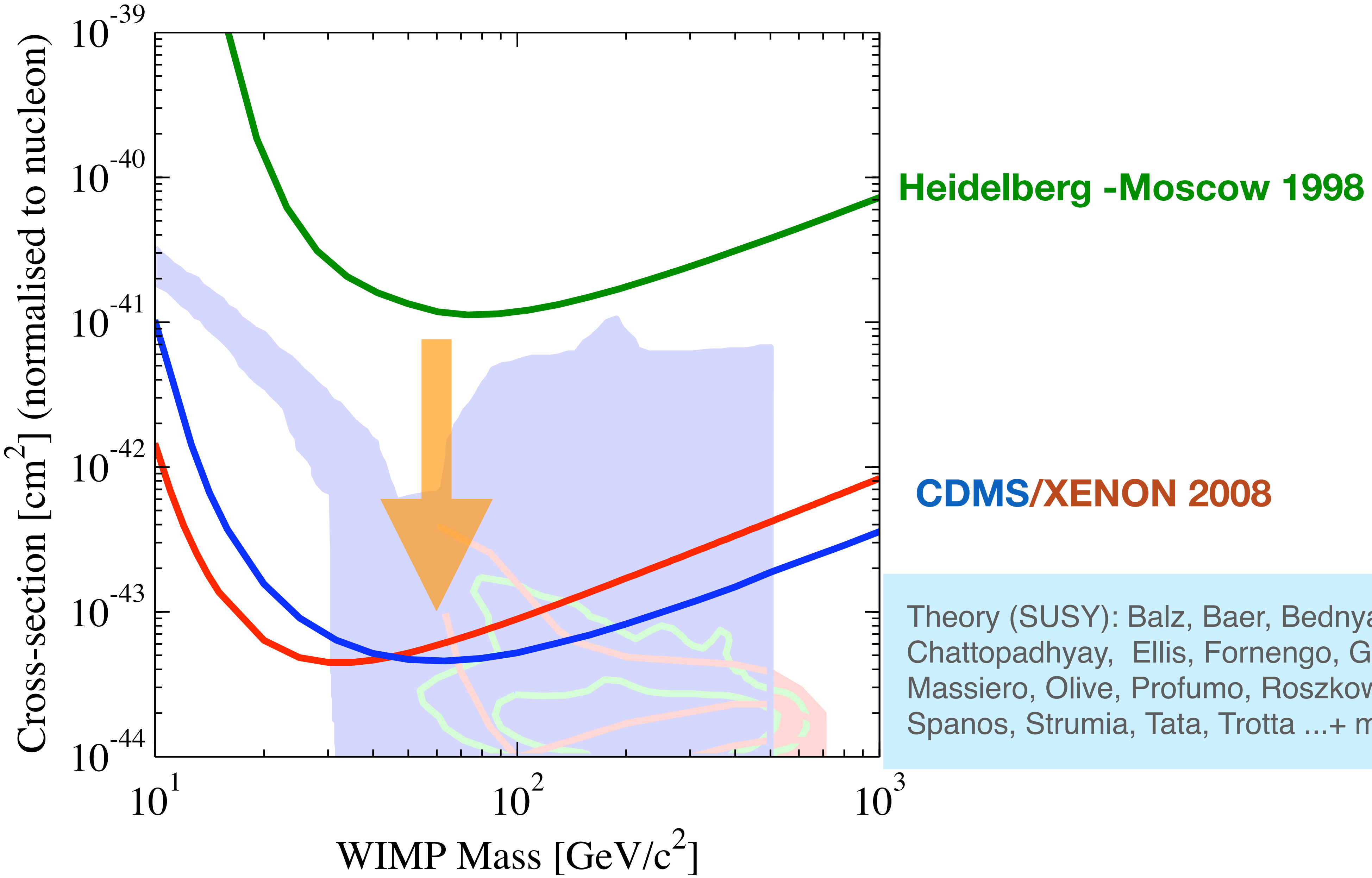


# Summary/Outlook

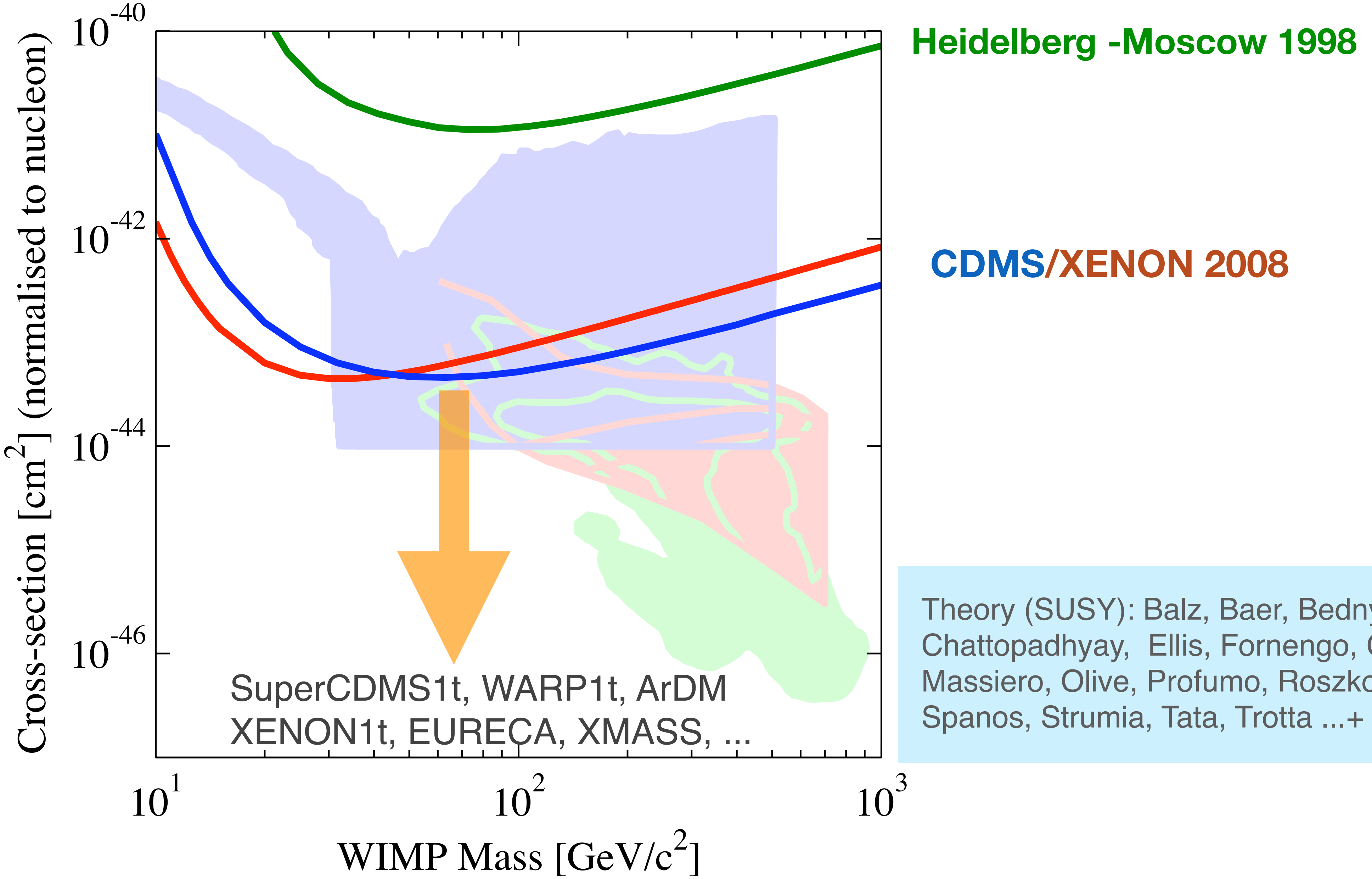
- Many different techniques/targets are being employed to search for dark matter particles
- Steady progress in the last ~ 10 years: **> factor 100 increase in sensitivity!**




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

- Experiments are probing some of the theory regions for WIMP candidates
- Next generation projects: should reach the ≲ $10^{-10}$ pb level => WIMP (astro)-physics

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# End

# Inelastic Dark Matter: an explanation for DAMA/ LIBRA signal?

- **possible explanation for DAMA signal and null results for other experiments by:**
  - ➡ suppressing signals on lighter vs heavier target
  - ➡ enhancing the modulated vs unmodulated signal (20-30%), because the model is sensitive to the high velocity component of the halo
  - ➡ eliminating low energy events; signal peaks at higher energies (70 keV for Ge, 35 keV for I/Xe, 25 keV for W)

- **needed:**
  - ➡ 2 dark matter states with a mass splitting of about 100 keV (by "coincidence" equal to $m_\chi v^2$)
  - ➡ WIMP-nucleus scattering occurs through a transition to an WIMP excited state
  - ➡ elastic scattering ($\chi N \rightarrow \chi N$) must be forbidden, or highly suppressed
  - ➡ inelastic scattering ($\chi N \rightarrow \chi^* N$) is allowed

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

$$\frac{v^2 \mu_{\chi N}}{2} > \delta$$

Tucker-Smith, Weiner, 2001
Neil Weiner, IDM08, Stockholm

# Inelastic Dark Matter: an explanation for DAMA/LIBRA signal?

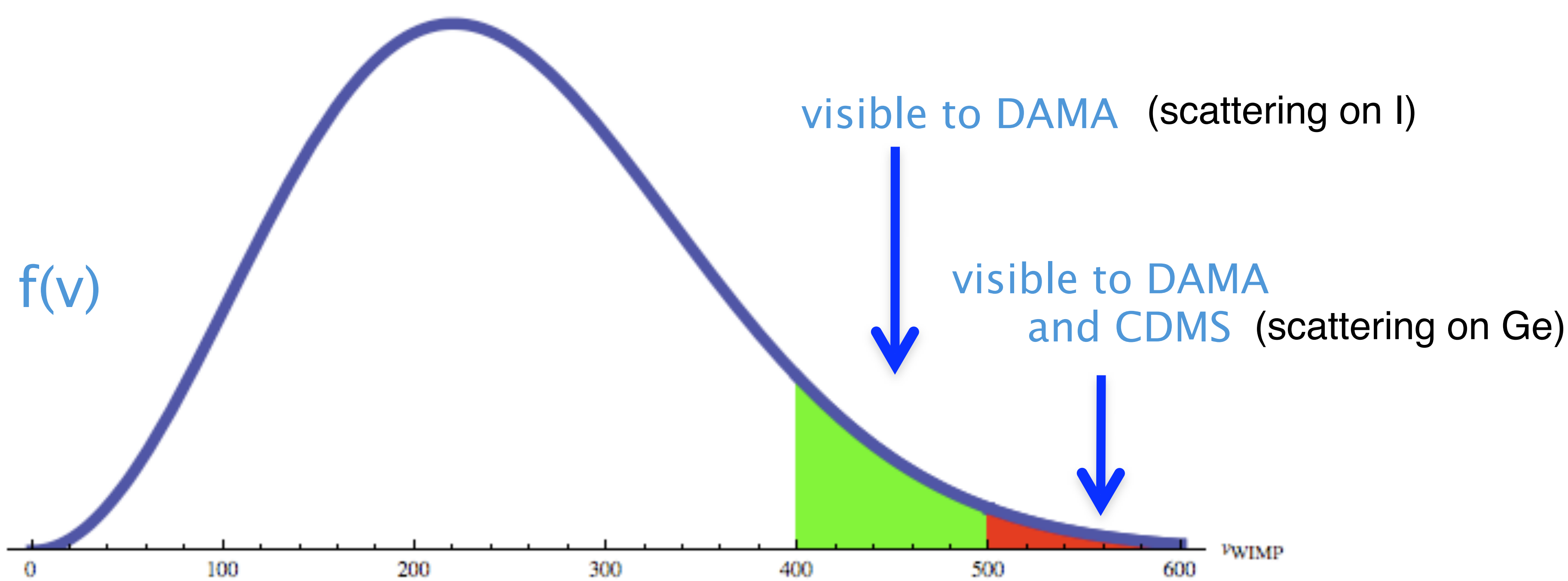
- The mass splitting is comparable to the kinetic energy of a WIMP in the halo
- Only WIMPs with sufficient kinetic energy to up-scatter into the heavier state will scatter off nuclei in a detector:

$$\frac{v^2 \mu_{\chi N}}{2} > \delta$$

➡ Minimum velocity requirement: experiments will probe the higher velocity region of the WIMP halo distribution

➡ Heavier targets will be favored over light targets

Neil Weiner, IDM08



# Inelastic Dark Matter: an explanation for DAMA/ LIBRA signal?

- Some benchmark points:

| # | $m_\chi$ (GeV) | $\sigma_n$ ($10^{-40}$ cm$^2$) | $\delta$ (keV) | DAMA 2-6 keVee ($10^{-2}$ dru) | XENON 4.5-45 keV (counts) | CDMS 10-100 keV (counts) | ZEPLIN 5-20 keVee (counts) | KIMS 3-8 keVee ($10^{-2}$ dru) | CRESST 12-60 keV (counts) |
|---|---|---|---|---|---|---|---|---|---|
| expt | | | | $1.31 \pm 0.16$ | 24 (31.6) | 2 (5.3) | 29 (37.2) | $5.65 \pm 3.27$ | 6 (10.5) |
| 1 | 70 | 11.85 | 119 | 0.93 | 1.39 | 0 | 8.81 | 0.77 | 8.92 |
| 2 | 90 | 5.75 | 123 | 1.25 | 5.52 | 0 | 14.87 | 1.62 | 9.38 |
| 3 | 120 | 3.63 | 125 | 1.24 | 9.06 | 0.26 | 18.61 | 2.27 | 9.64 |
| 4 | 150 | 2.92 | 126 | 1.21 | 11.17 | 1.19 | 20.55 | 2.63 | 9.82 |
| 5 | 180 | 2.67 | 126 | 1.18 | 12.46 | 2.22 | 21.69 | 2.85 | 9.93 |
| 6 | 250 | 2.62 | 127 | 1.14 | 14.01 | 3.95 | 23.03 | 3.12 | 10.02 |

obs. # events

pred. # events

- Upcoming results from Ge (peak at ~70 keV), Xe (35 keV), I (35 keV) and W (25 keV) should test this explanation for the DAMA signal!