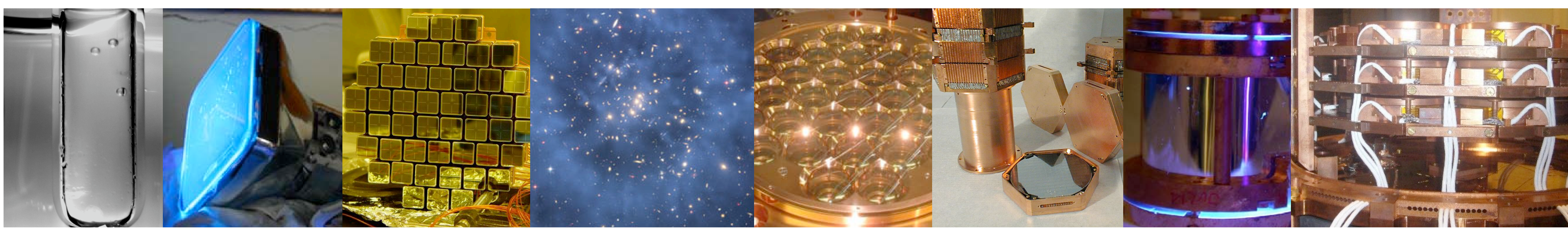
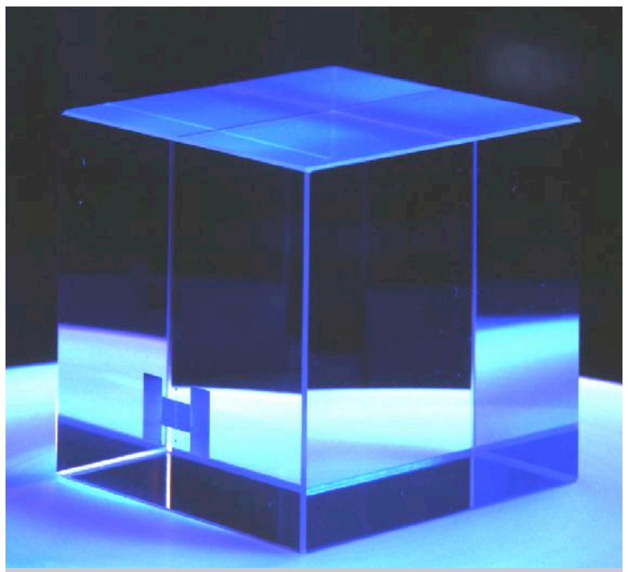
Direct Detection of Dark Matter

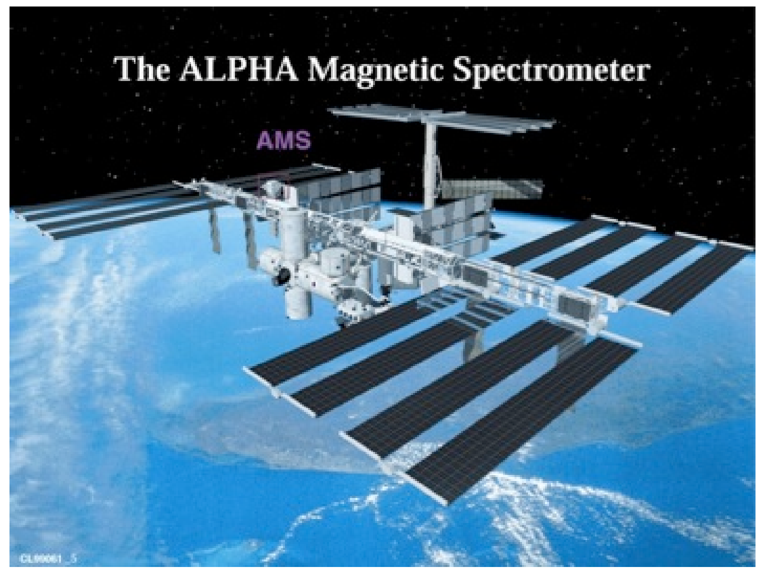
Laura Baudis, RTWH Aachen University/University of Zurich

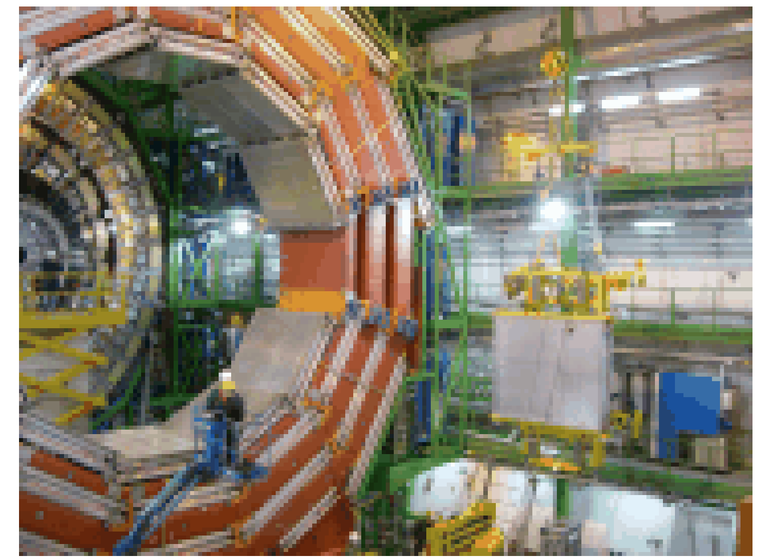
SUSY 2007, Universität Karlsruhe
August 1st, 2007

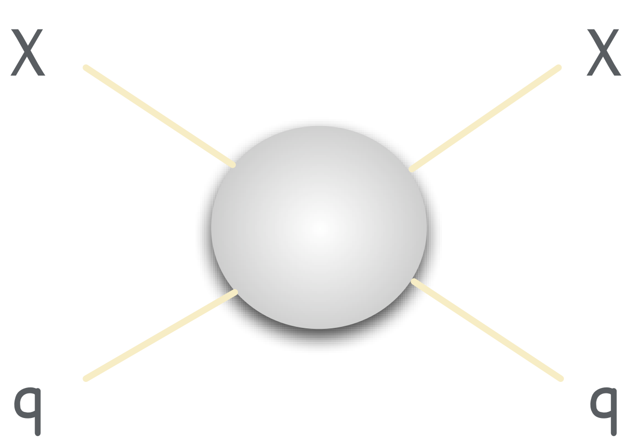


Approaches to (WIMP) Dark Matter Detection

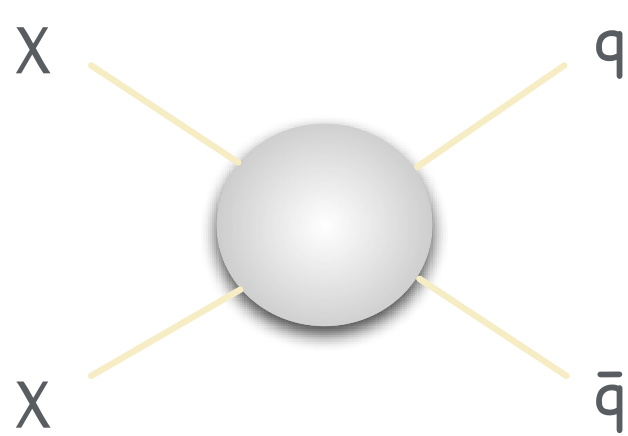




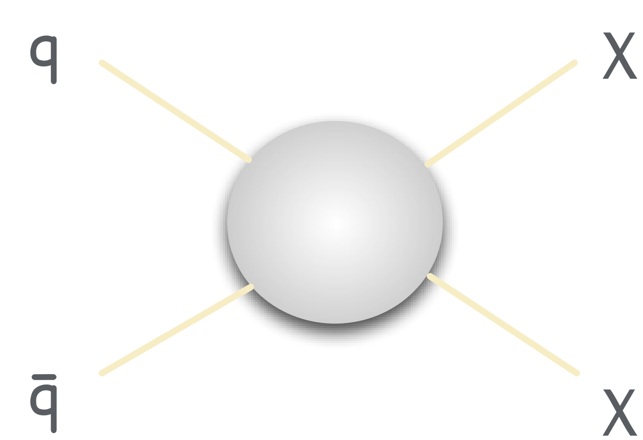




Direct



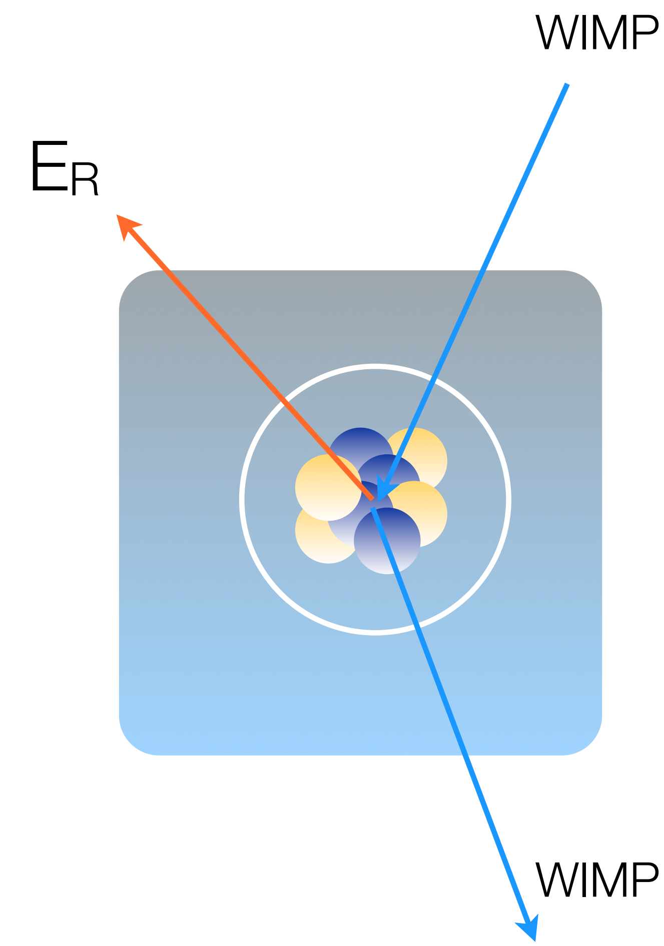
Indirect

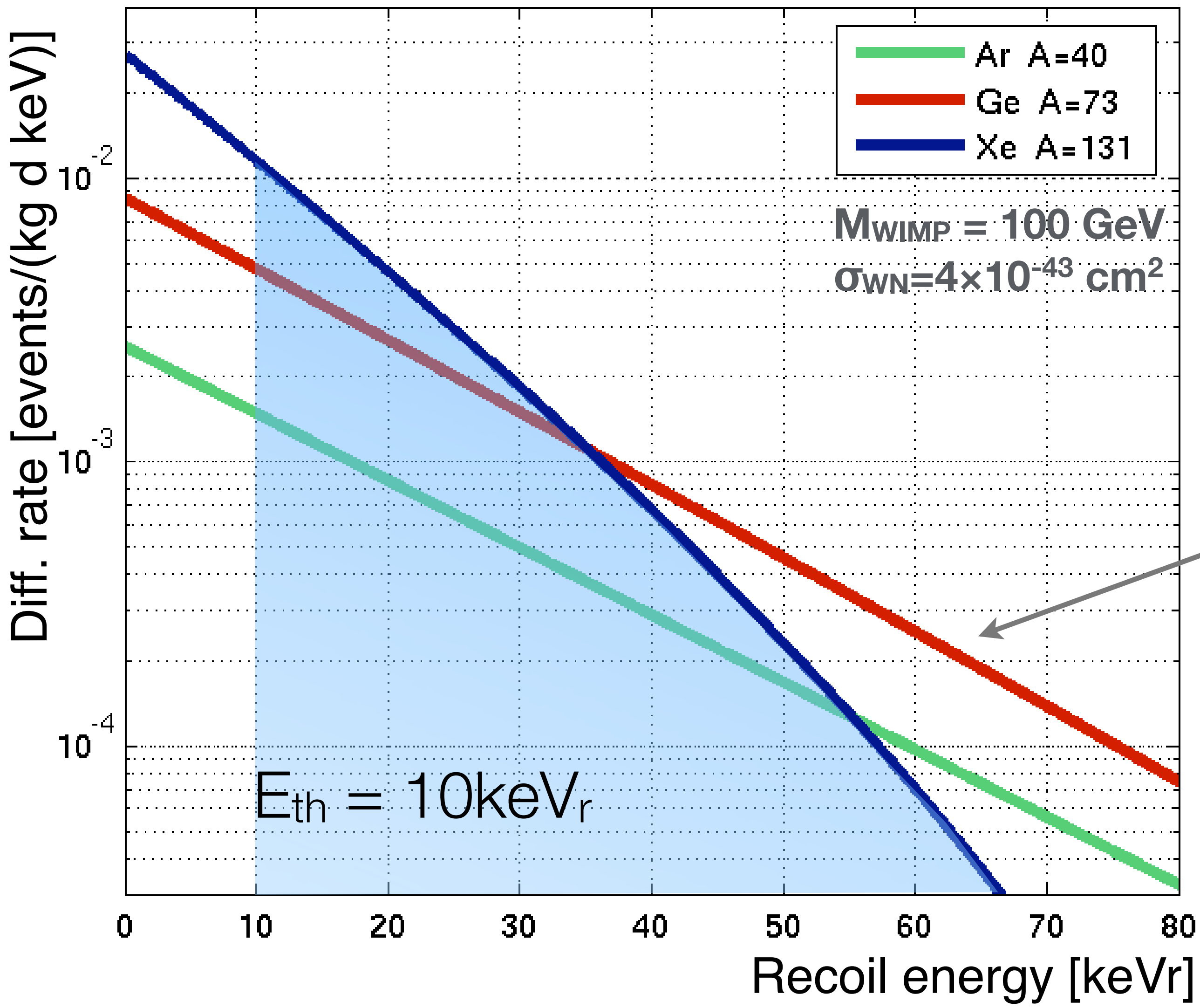


Colliders

Near Term Goals of Direct Detection Experiments

- Detect galactic WIMPs by their **elastic collision with nuclei**:
  - ➡Achieve low (< 5 keVr) nuclear recoil energy thresholds
  - ➡Achieve WIMP-nucleon σ sensitivity of ~ 1×10^{-9} pb in 2009



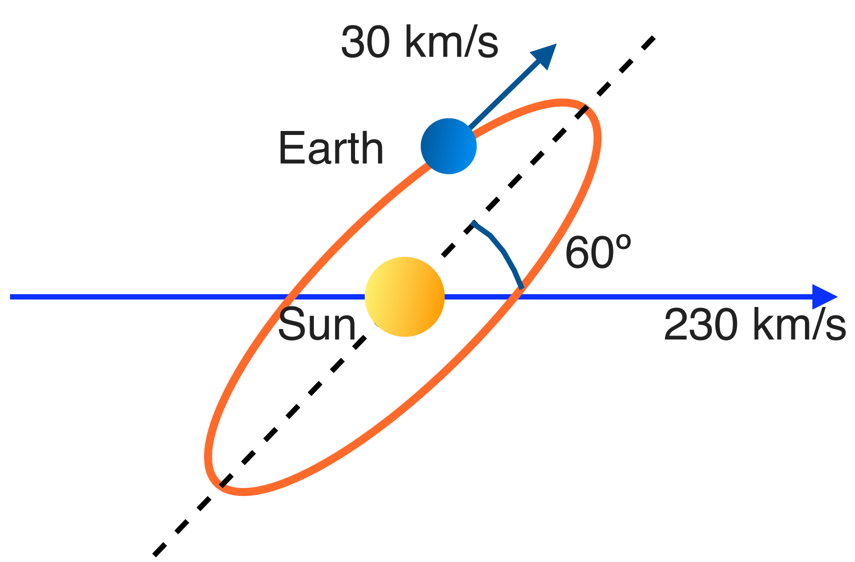


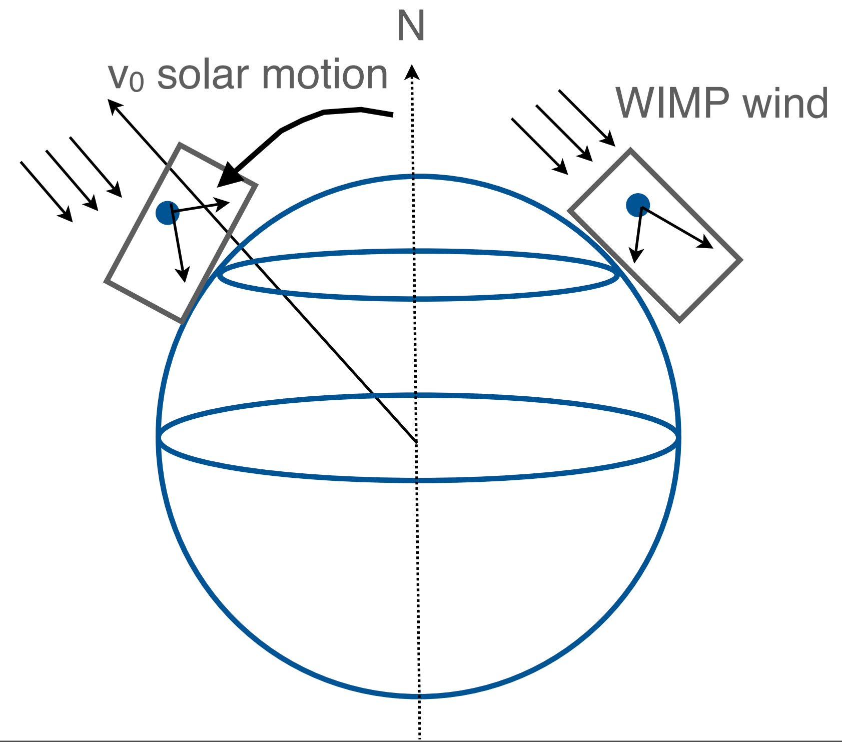
$$\frac{dR}{dQ} = \frac{\sigma_0 \rho_0}{\sqrt{\pi} v_0 m_\chi \mu^2} \exp\left(-\frac{Q m_N}{2\mu^2 v_0^2} \right) F^2(Q)$$

$$F^2(Q) = \left[\frac{3 j_1(qR_1)}{qR_1} \right]^2 \mathrm{e}^{-(qs)^2}$$

WIMP Signatures

- **WIMP interactions in detector should be:**
  - nuclear recoils
  - single scatters, uniform throughout detector volume
- **Spectral shape** (exponential, however similar to background)
- **Dependance on material** (A^2, $F^2(Q)$, test consistency between different targets)
- **Annual flux modulation** (~ 3% effect, most events close to threshold)
- **Diurnal direction modulation** (larger effect, requires low-pressure gas target)



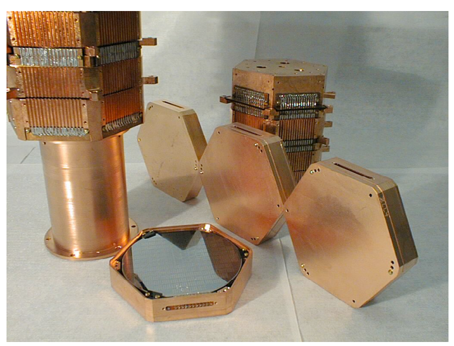


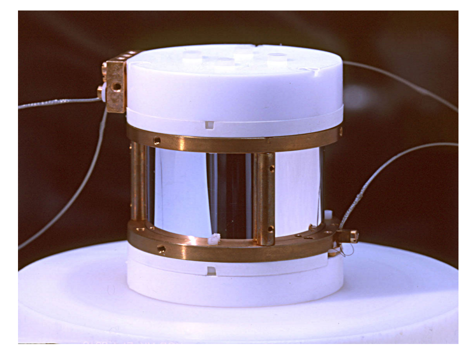
Direct WIMP Detection Experiments

COUPP,
PICASSO

Phonons

CDMS
EDELWEISS





CRESST
ROSEBUD

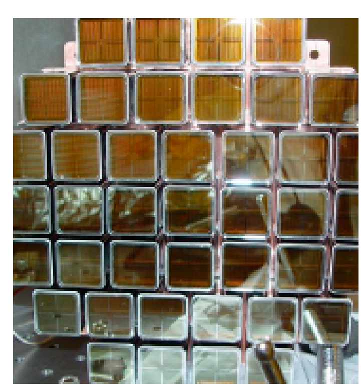
E_R

Charge

Light

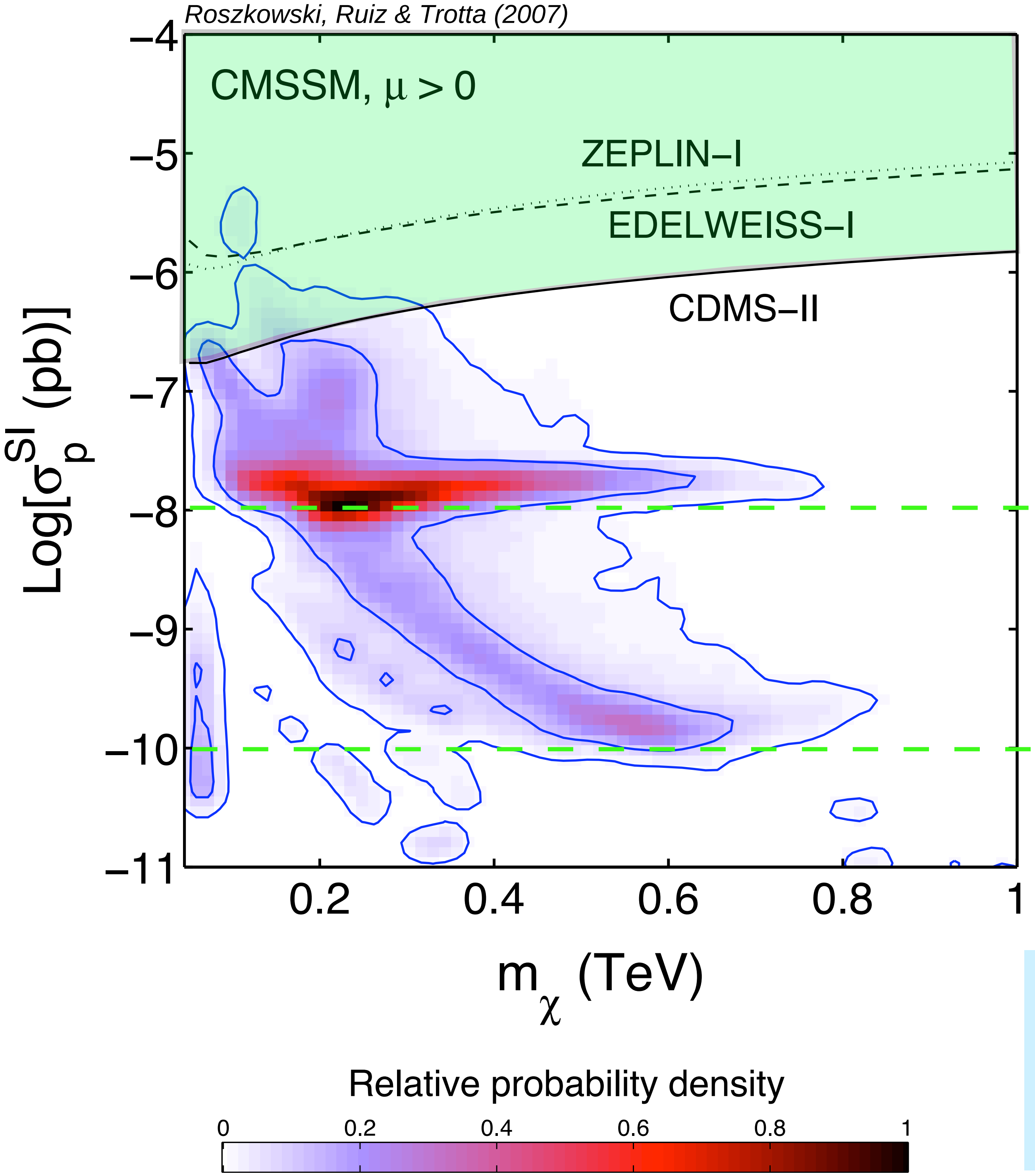
DAMA, LIBRA,
XMASS, CLEAN,
ANAIS, KIMS

HDMS, DRIFT,
GERDA, MAJORANA



ZEPLIN, XENON,
WARP, ArDM

Experiments and SUSY Predictions



excluded by CDMS-II
(situation before 2007)

1 event/kg/yr

CDMS-II, XENON10+, COUPP,
CRESST-II, EDELWEISS-II, ZEPLIN-III,...

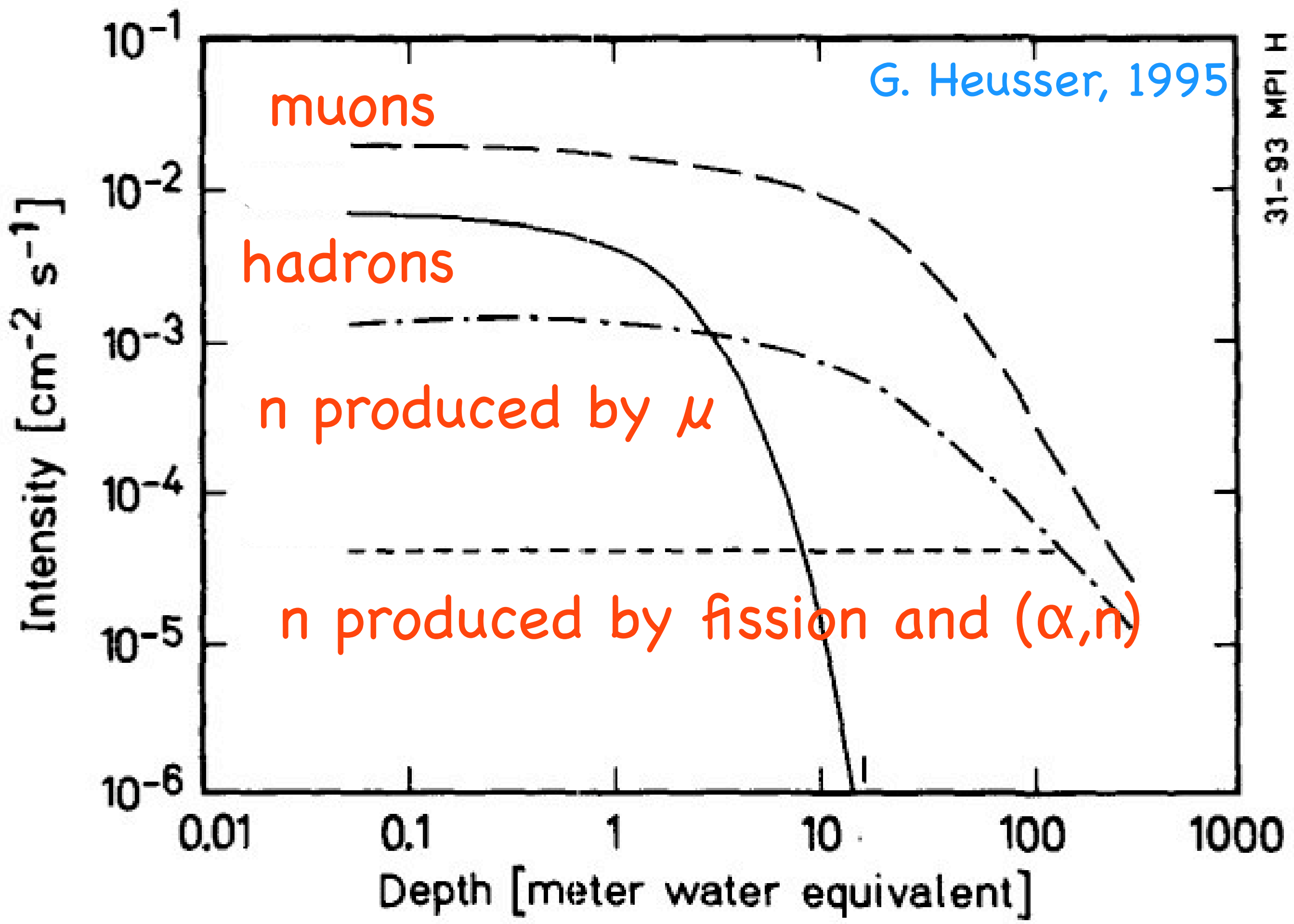
1 event/t/yr

SuperCDMS1t, WARP1t, ArDM
XENON1t, EURECA, ELIXIR, XMASS, ...

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

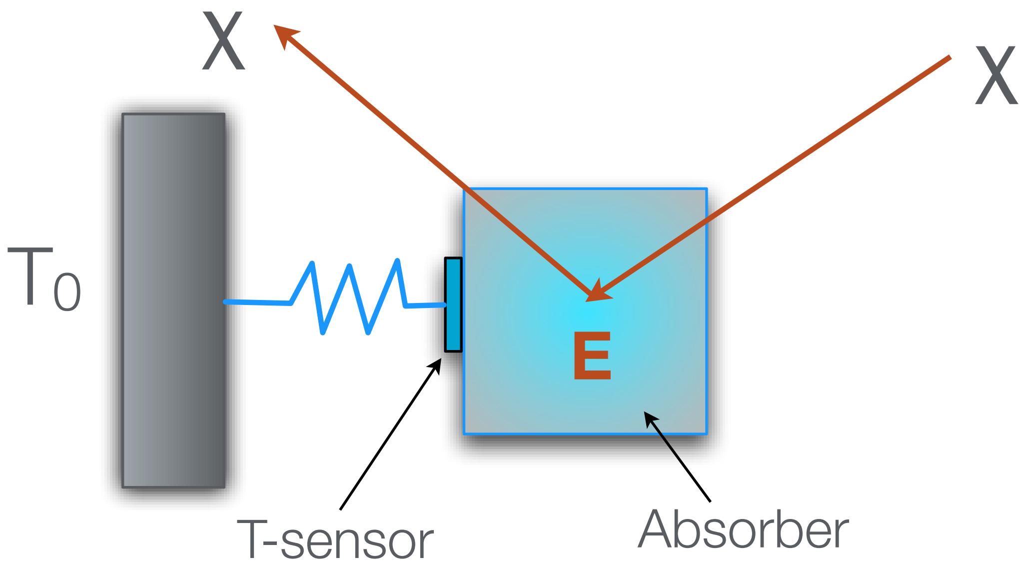
Challenges of Direct Detection Experiments

- **Low event rates** ⇒ ton-scale detectors
- **Small deposited energies** ⇒ low (~ few keV) energy thresholds
- **Low backgrounds**
  - shield against cosmic rays (deep underground laboratories → μ-spallation reactions)
  - low intrinsic radio-activity (ultra-pure materials → (α,n)-reactions)
  - shield radio-activity from surroundings (Pb, PE, H_2O, etc)
- **Good background rejection**
  - Particle identification
    - nuclear vs. electron recoils
  - Identification of surface events
  - Position sensitivity/fiducialisation
  - Self-shielding



Cryogenic Experiments at mK Temperatures

- **Principle:** a deposited energy E produces a temperature rise ΔT

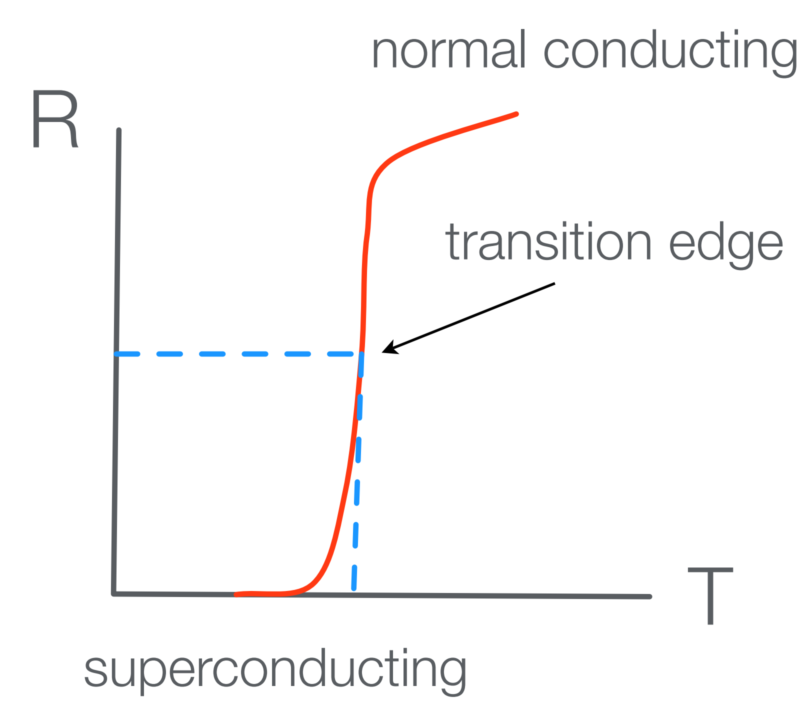


$$\Delta T \propto \frac{E}{C(T)}$$

$$T \ll T_c \Rightarrow C(T) \propto T^3$$

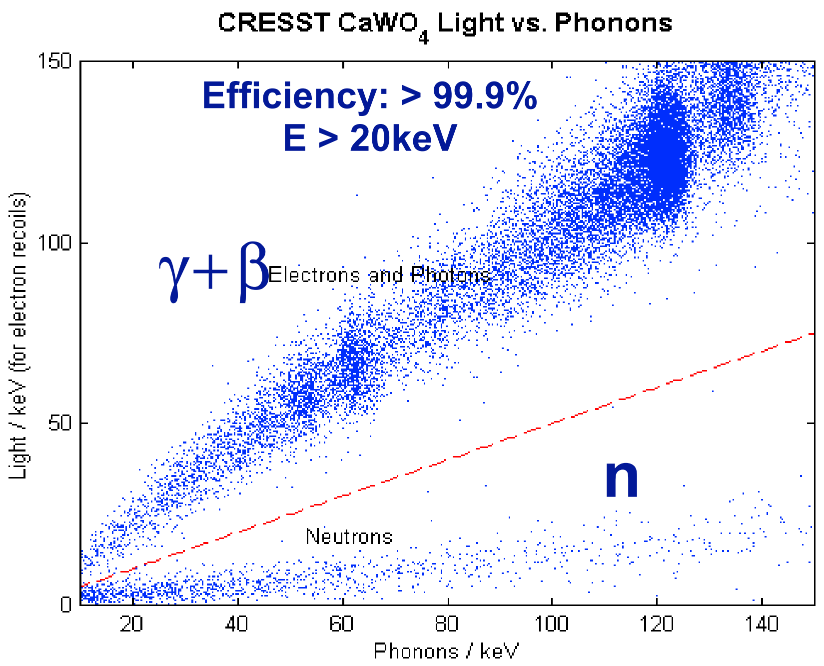
=> the lower T, the larger ΔT per unit of absorbed energy

- **T-sensors:**
  - **superconductor thermistors**
    (highly doped superconductor): NTD Ge → EDELWEISS
  - **superconduction transition sensors**
    (thin films of SC biased near middle of normal/SC transition):
    TES→CDMS, SPT→CRESST

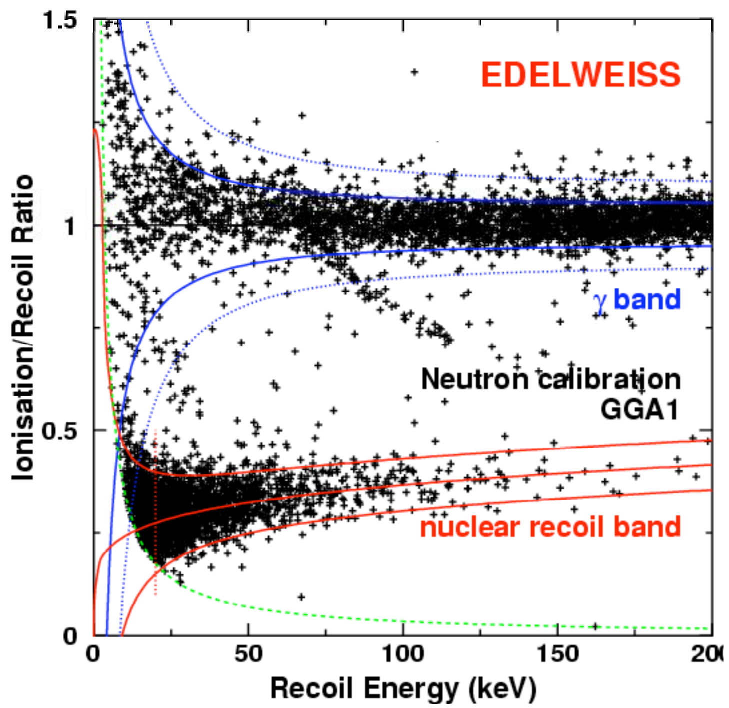


Cryogenic Experiments at mK Temperatures

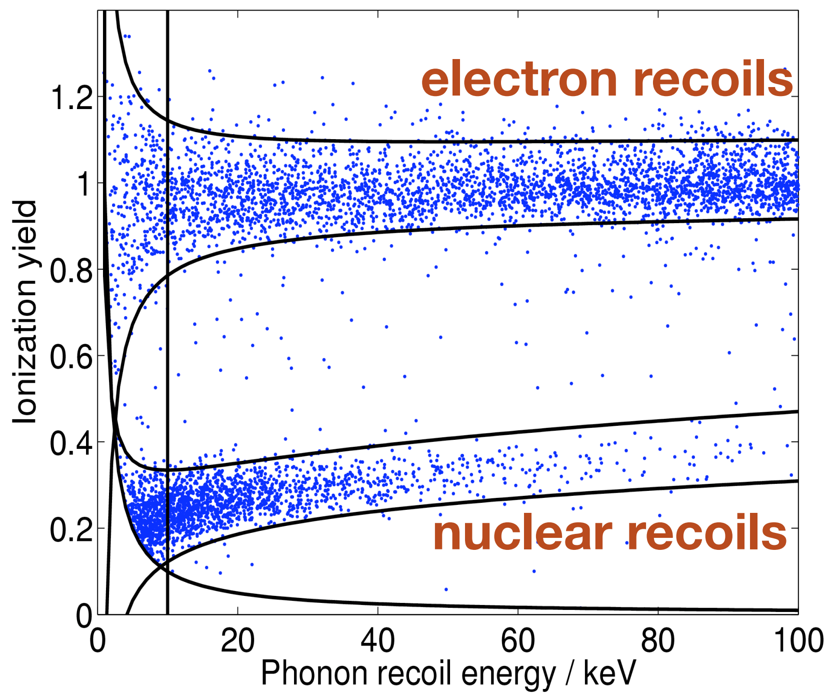
- **Advantages: high sensitivity to nuclear recoils**
  - measuring the full nuclear recoil energy in the phonon channel
  - low energy threshold (keV to sub-keV), good energy resolution
  - light/phonon and charge/phonon: **nuclear vs. electron recoil discrimination**



CRESST



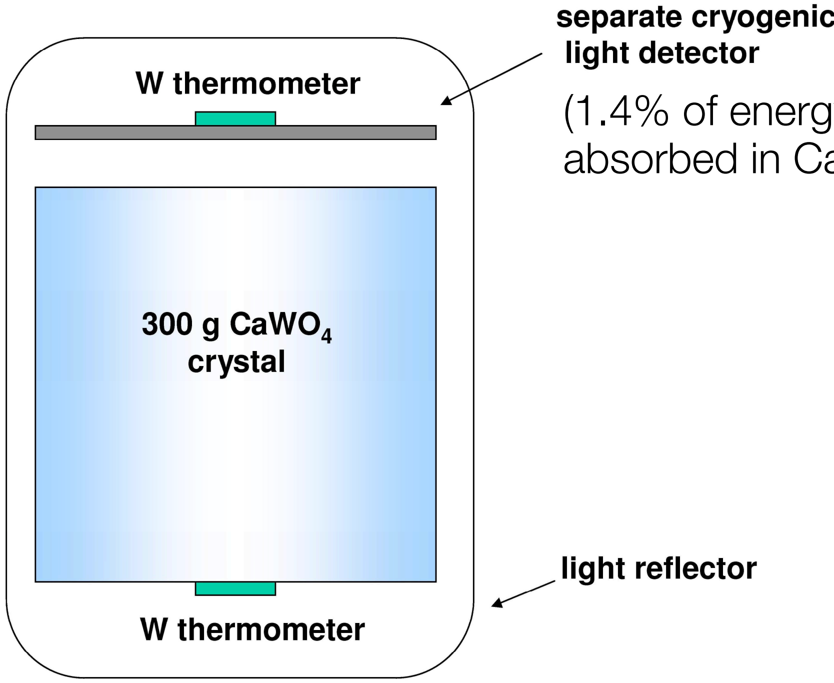
EDELWEISS



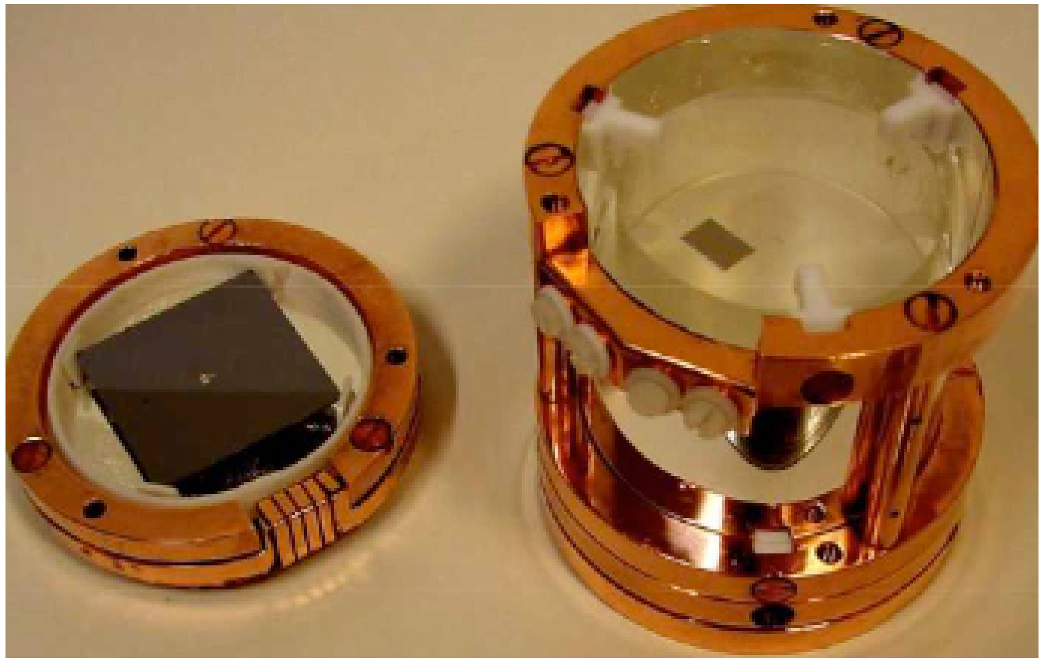
CDMS

Light/phonons: the CRESST Experiment at LNGS

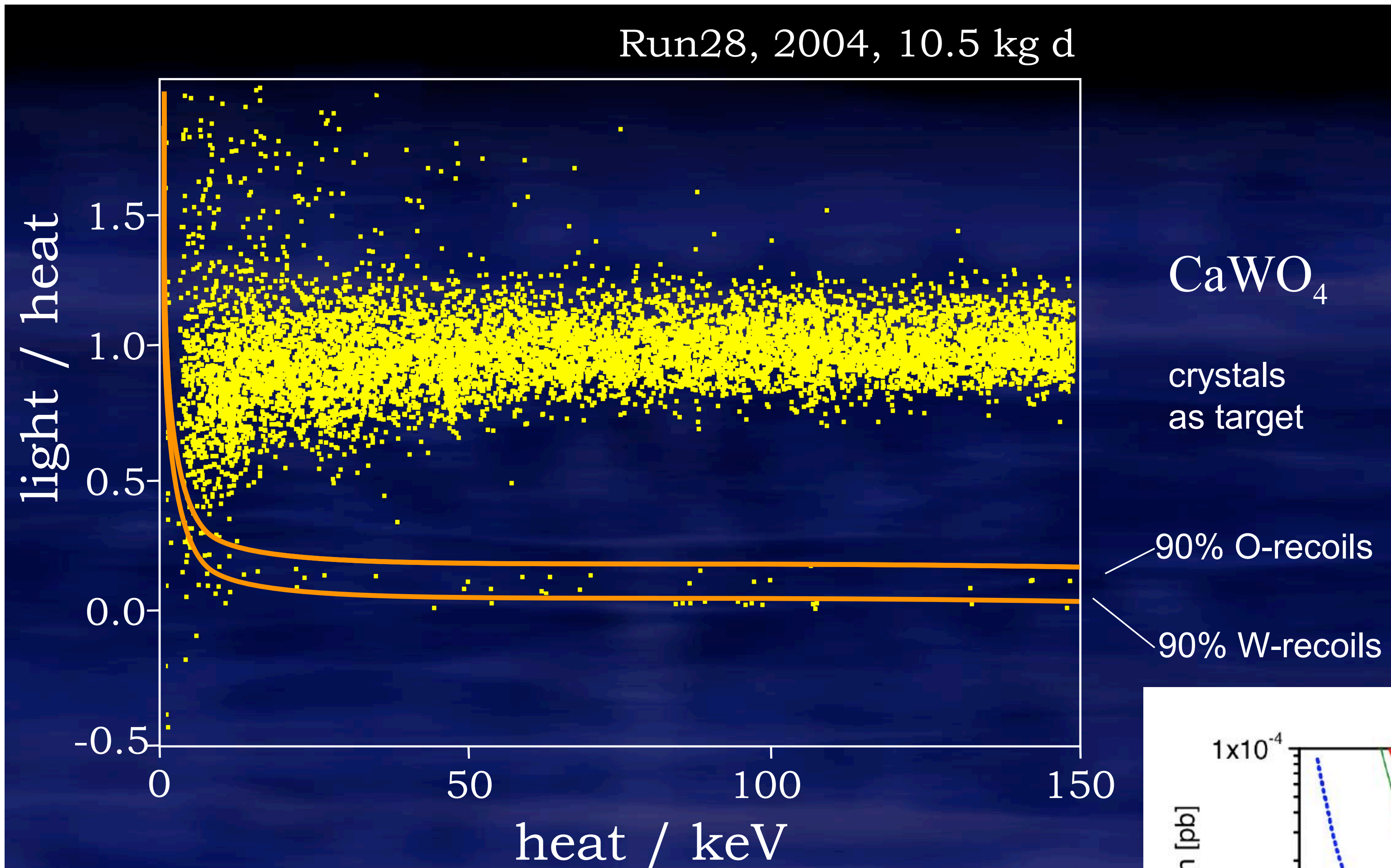
- **Phonons and scintillation**
  in $CaWO_4$ targets (300g) at ~ 10 mK
- **Phonon detector:**
  W-SPT thermometers (T_c at 15 mK)
- **Light detector:**
  Si wafer read out by W-SPT
  (E_{thr} → few optical γ, ~ 20eV)
- **No dead layer effects**

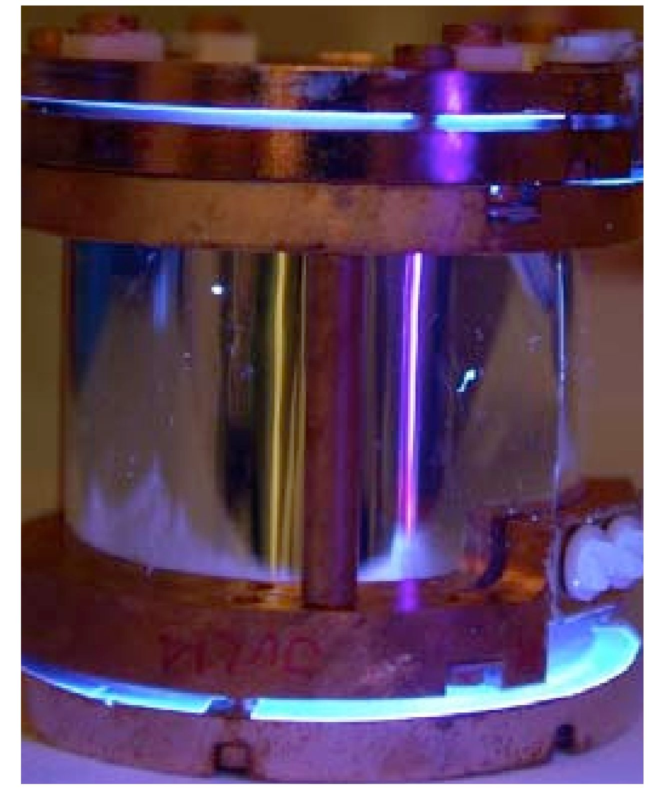


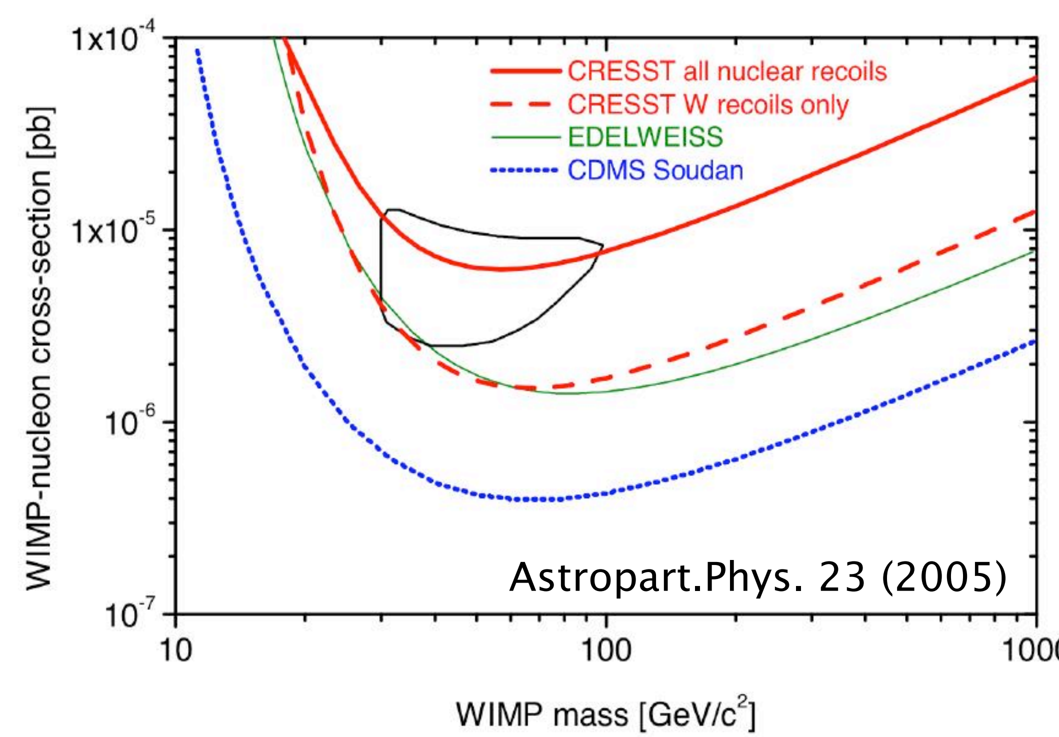
(1.4% of energy absorbed in $CaWO_4$ crystal)



CRESST-II Results (2005)





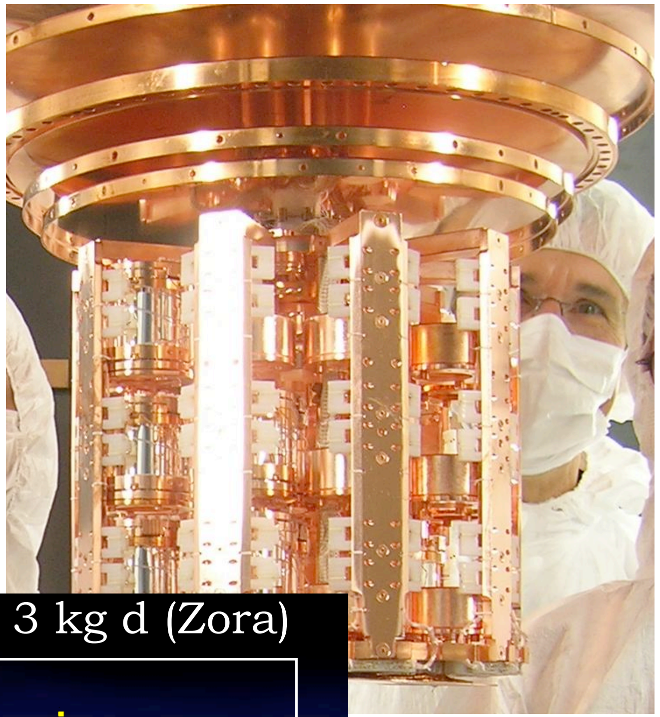


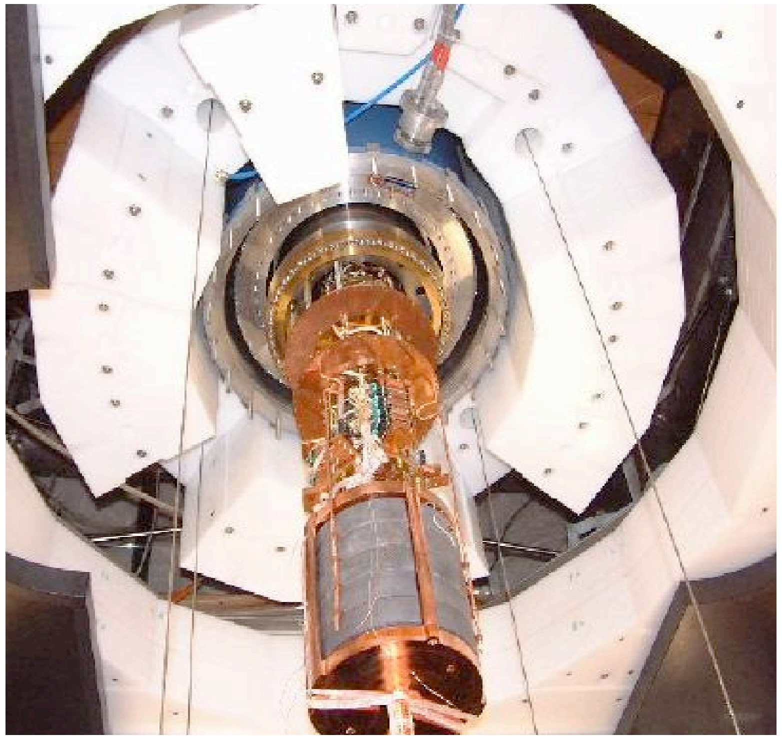
→ Gamma background (light/heat ≈ 1)
→ Neutron background:
oxygen recoils, no tungsten recoils
between 12-40 keV

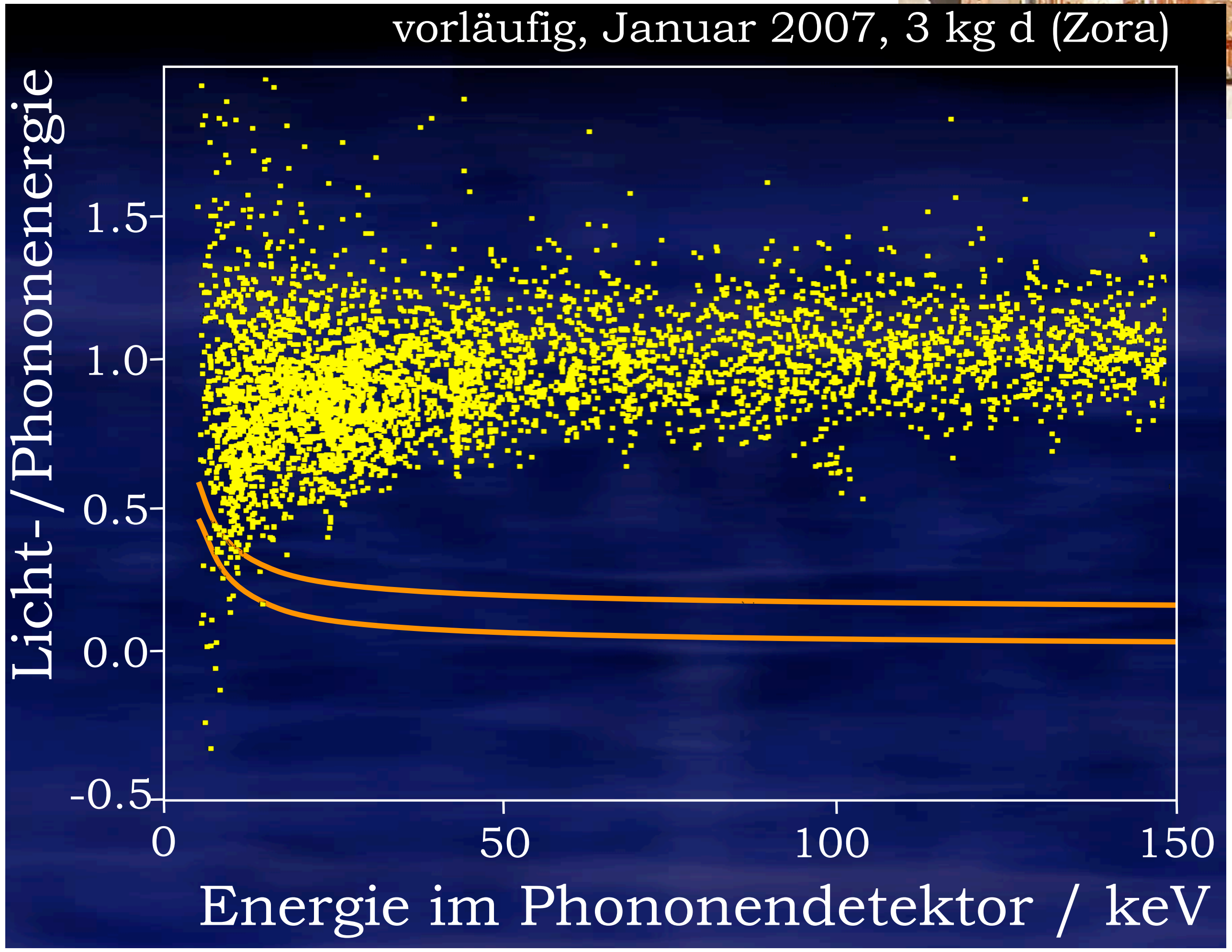
No n-shield; results limited by n-flux at LNGS

CRESST Upgrade: more channels + n-shield

- 2004: installation of PE neutron moderator (50 cm)
- 2004/05: upgrade to 66 channel SQUID array
- 2005: added muon veto
- **2007**: started installation of 10kg target mass (33 modules)
- 2 detectors running in WIMP search mode since spring 2007
- **expect new results soon!**



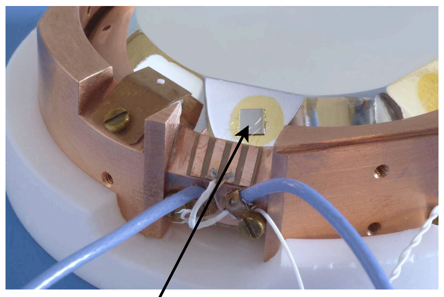




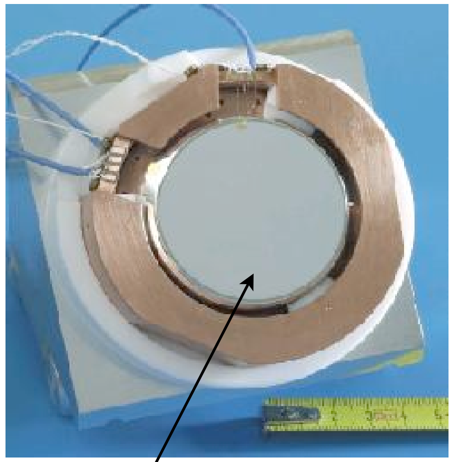
J. Jochum, Heidelberg, March 2007

Charge/phonons: EDELWEISS at LSM (Frejus Lab)

- **EDELWEISS-I**: Ge NTD heat and ionization detectors (3 x 320 g at 17 mK)
- Data taking period: Fall 2000 - March 2003; 62 kg day final exposure

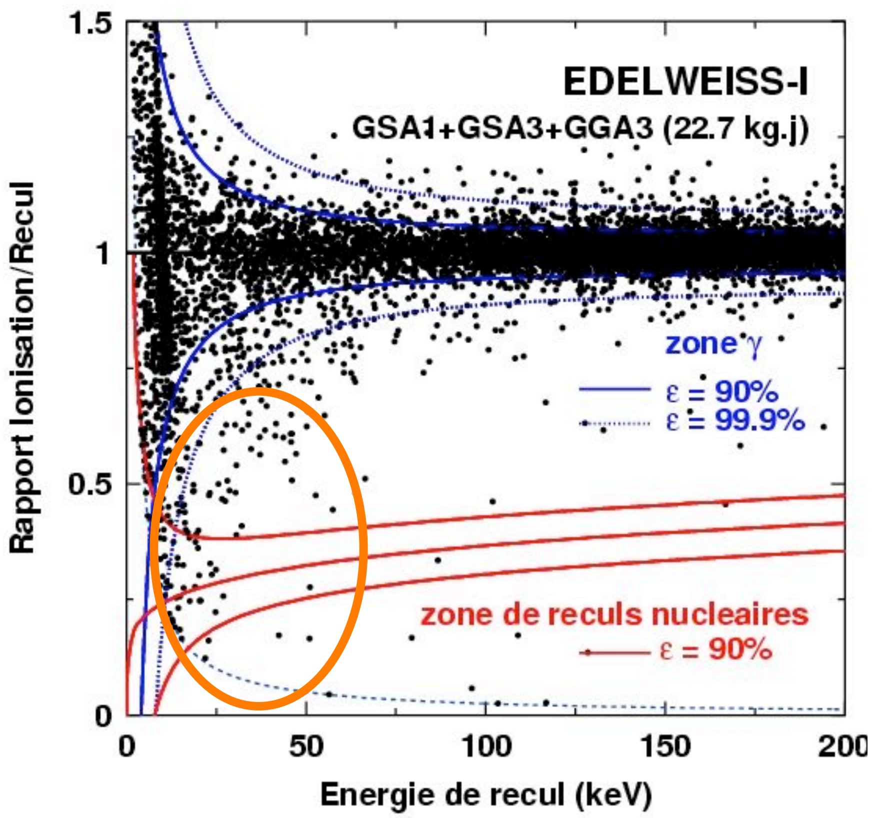


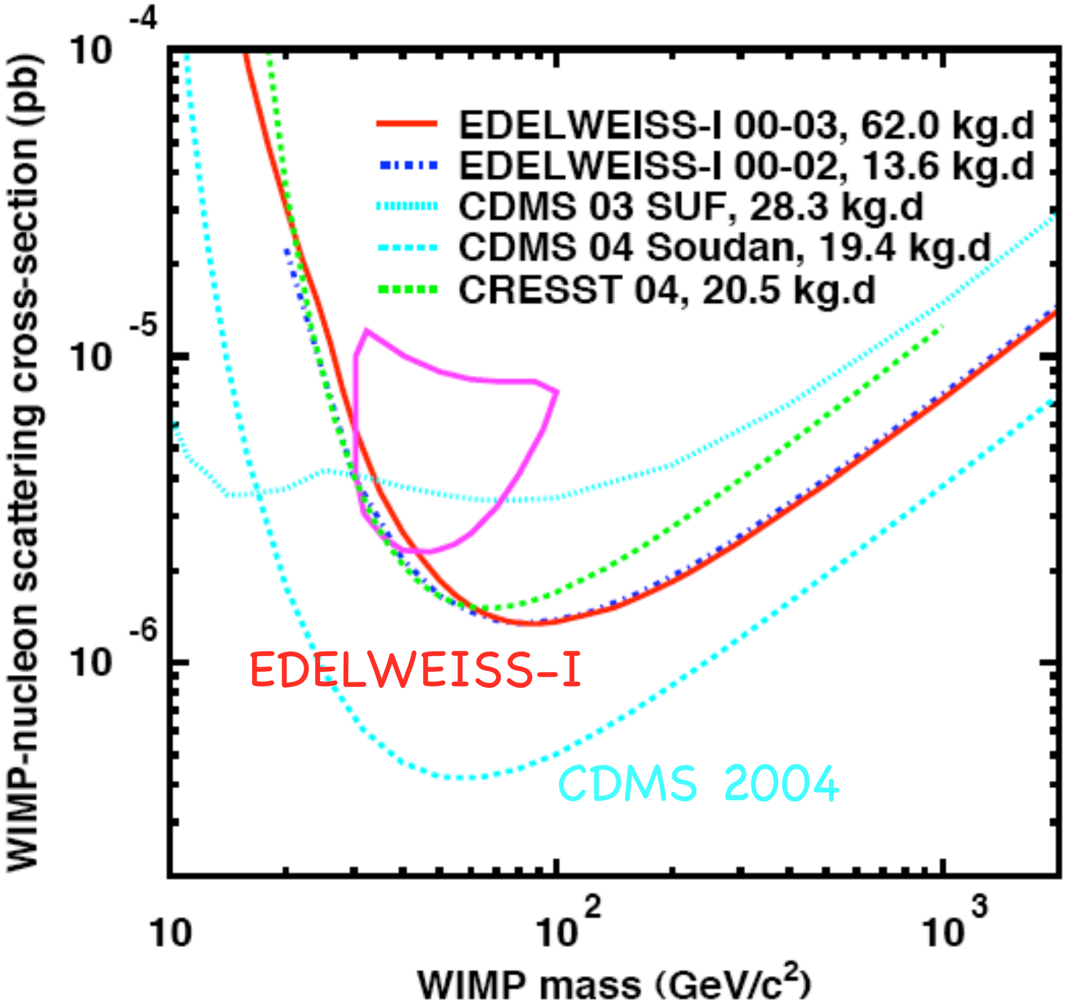
NTD heat sensor



Al sputtered electrodes

Talk by Astrid Chantelauze in Cosmology session





Backgrounds from:

→ neutrons

→ surface electron recoils (bad charge collection): ^{210}Pb, ^{14}C (?)

→ Radon (α-rate ≈ 5/kg d)

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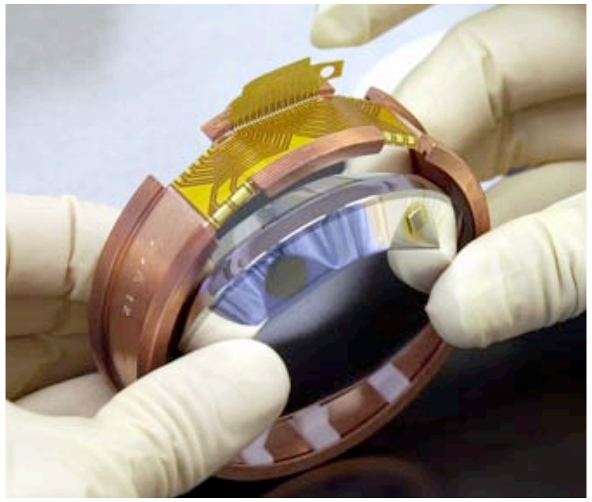
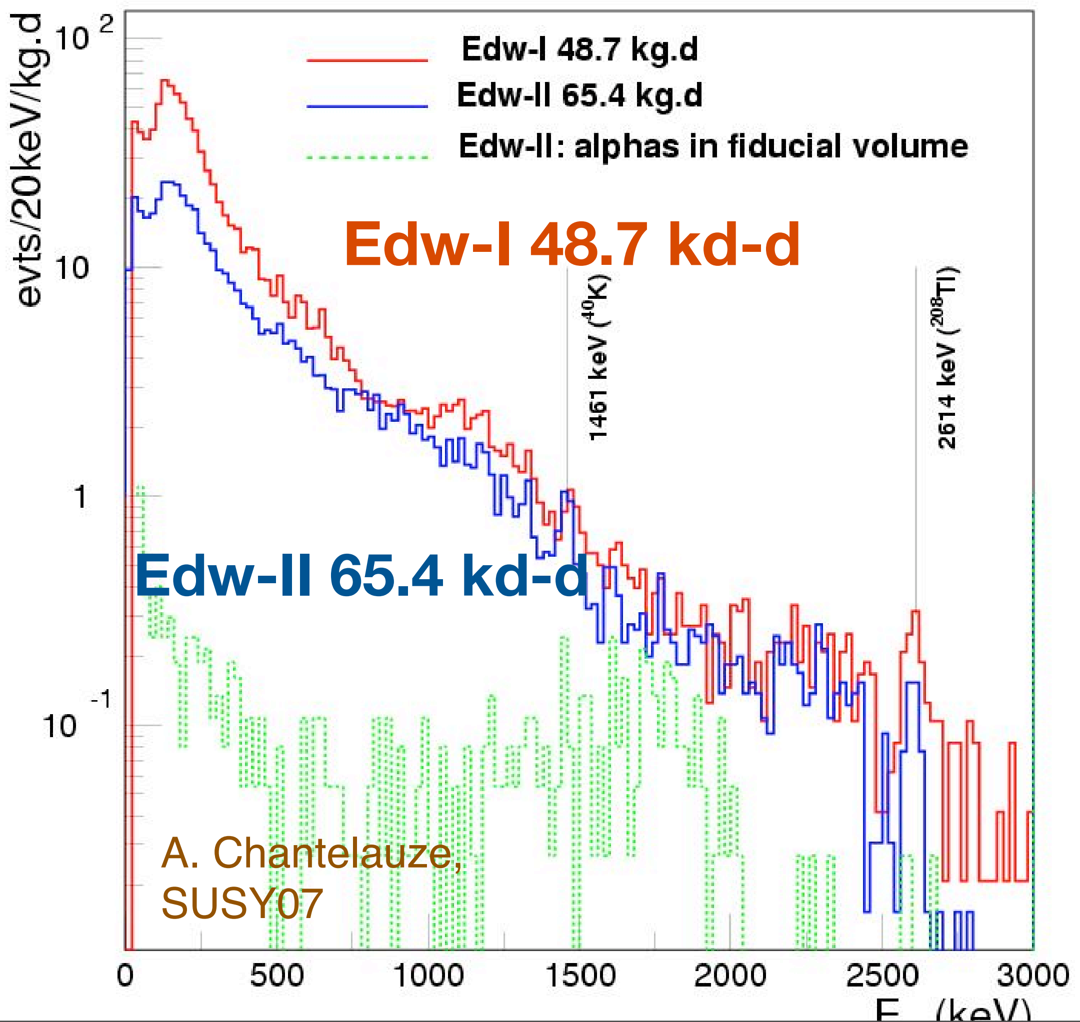
EDELWEISS-II

- **Goal:** total of 30 kg (100 detectors) with the first phase at 10 kg (30 detectors)
- Current (2007): 22 x 320 g NTG Ge, 5 Ge/NbSi , 1x70 g ^{73}Ge NTD, 1 scint/phonon detectors installed in new (nitrogen free) cryostat (50 l), commissioning run
- NbSi thin films thermometer for active surface event rejection
- **Dark matter run: summer 2007**



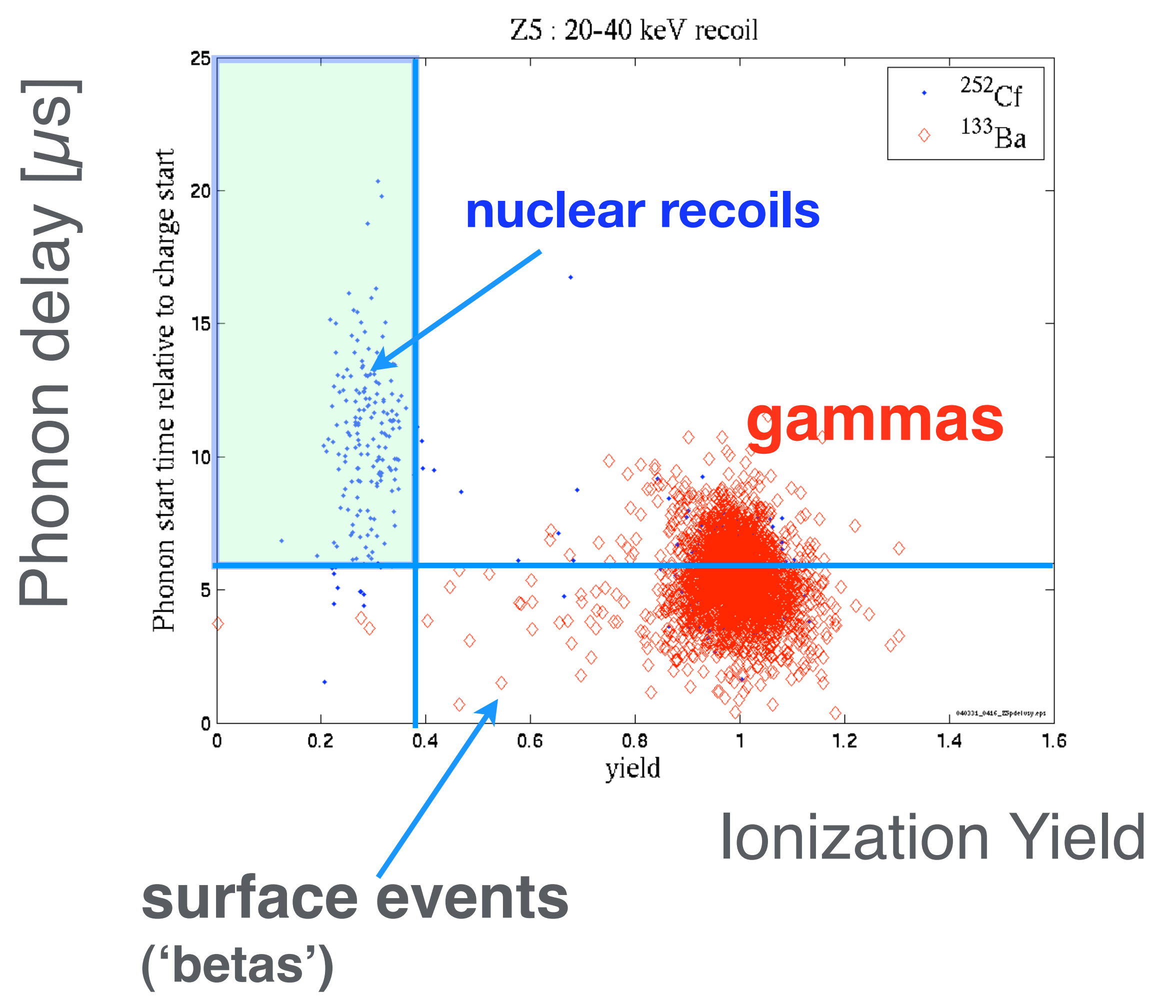
Background spectrum

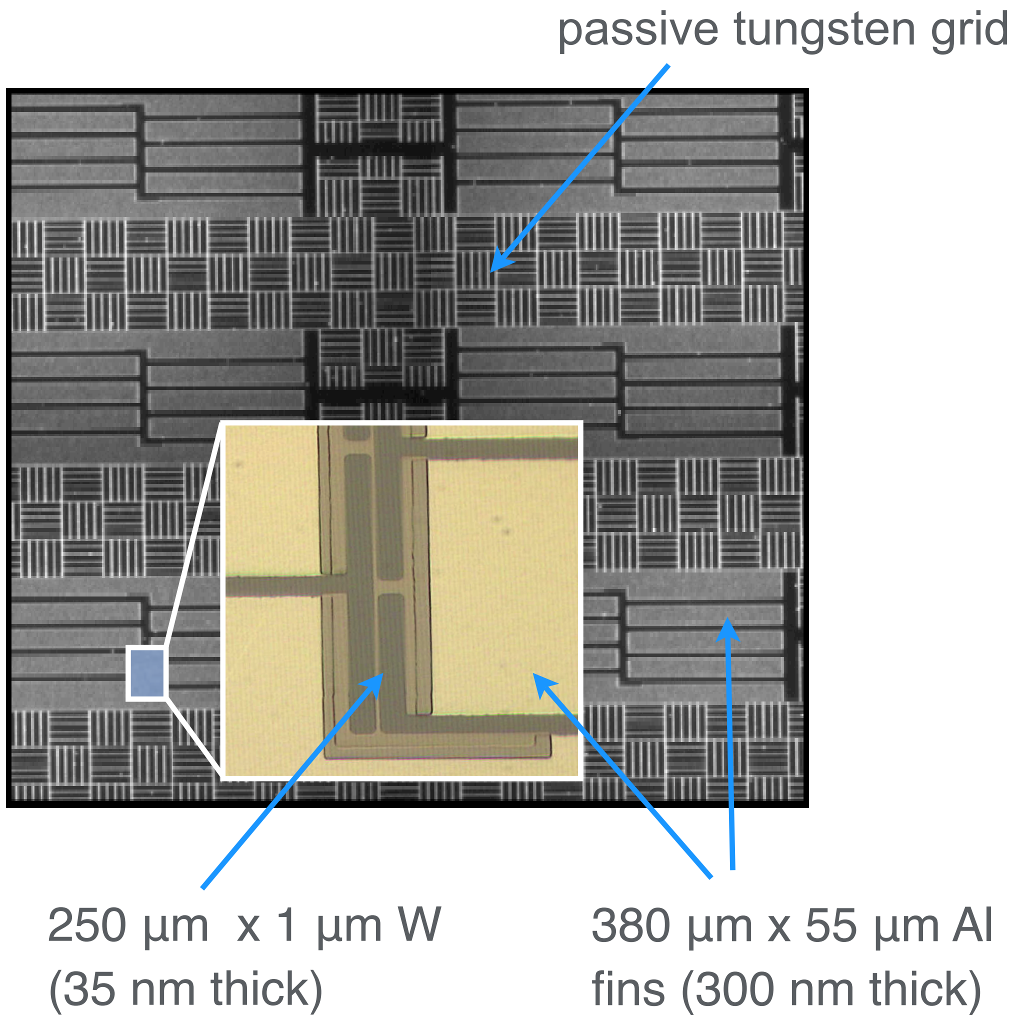
Edelweiss-II, May 07, 65.4 kg.d total volume



Charge/phonons: CDMS-II at Soudan

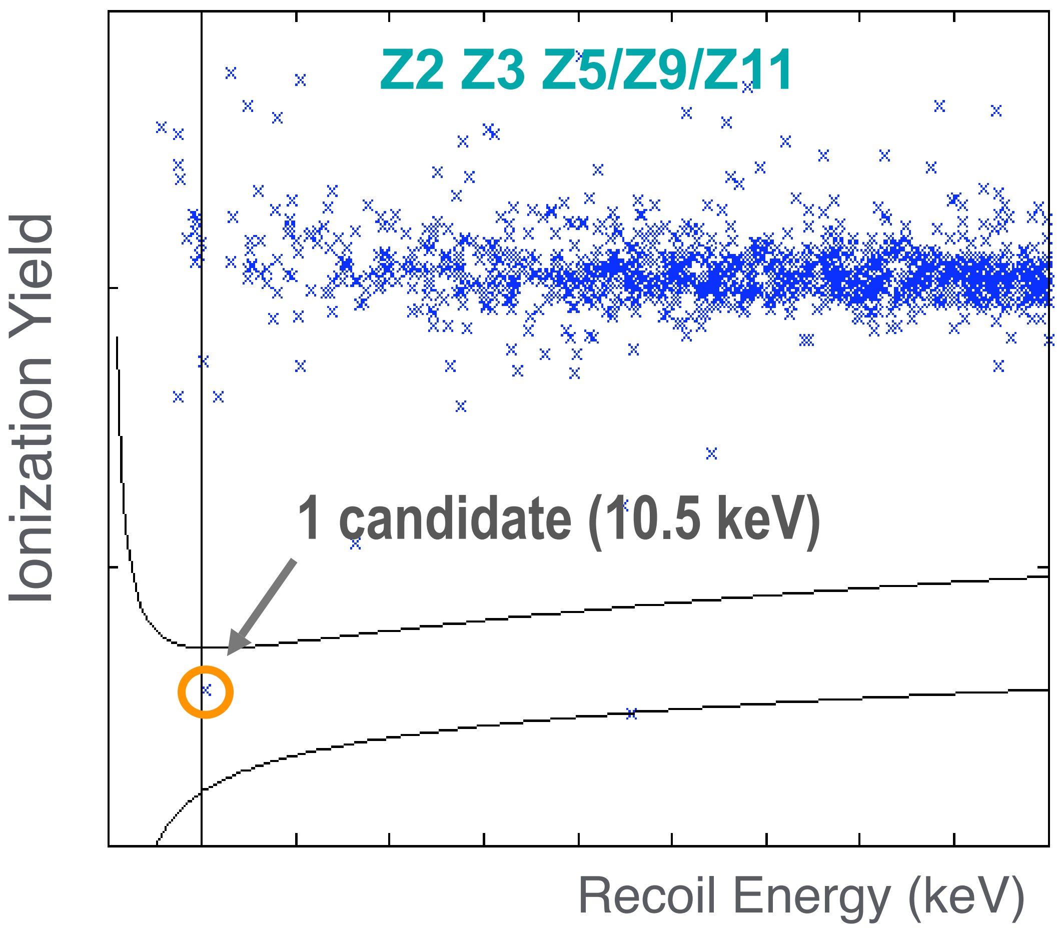
- **5 towers a 6 Ge/Si detectors at 20 mK in Soudan cryostat**
- 250 g Ge, 100 g Si crystals with Al+W TES collecting athermal phonons
- **Phonon sensors:** 4 quadrants, each 1036 TES in parallel => x-y position of events
- **Charge electrodes:** inner, disk shaped, outer, ring-like; e^--h drift in E-field (3V/cm)
- **Surface event rejection based on phonon timing** (2 x 10^{-3} misidentified events)



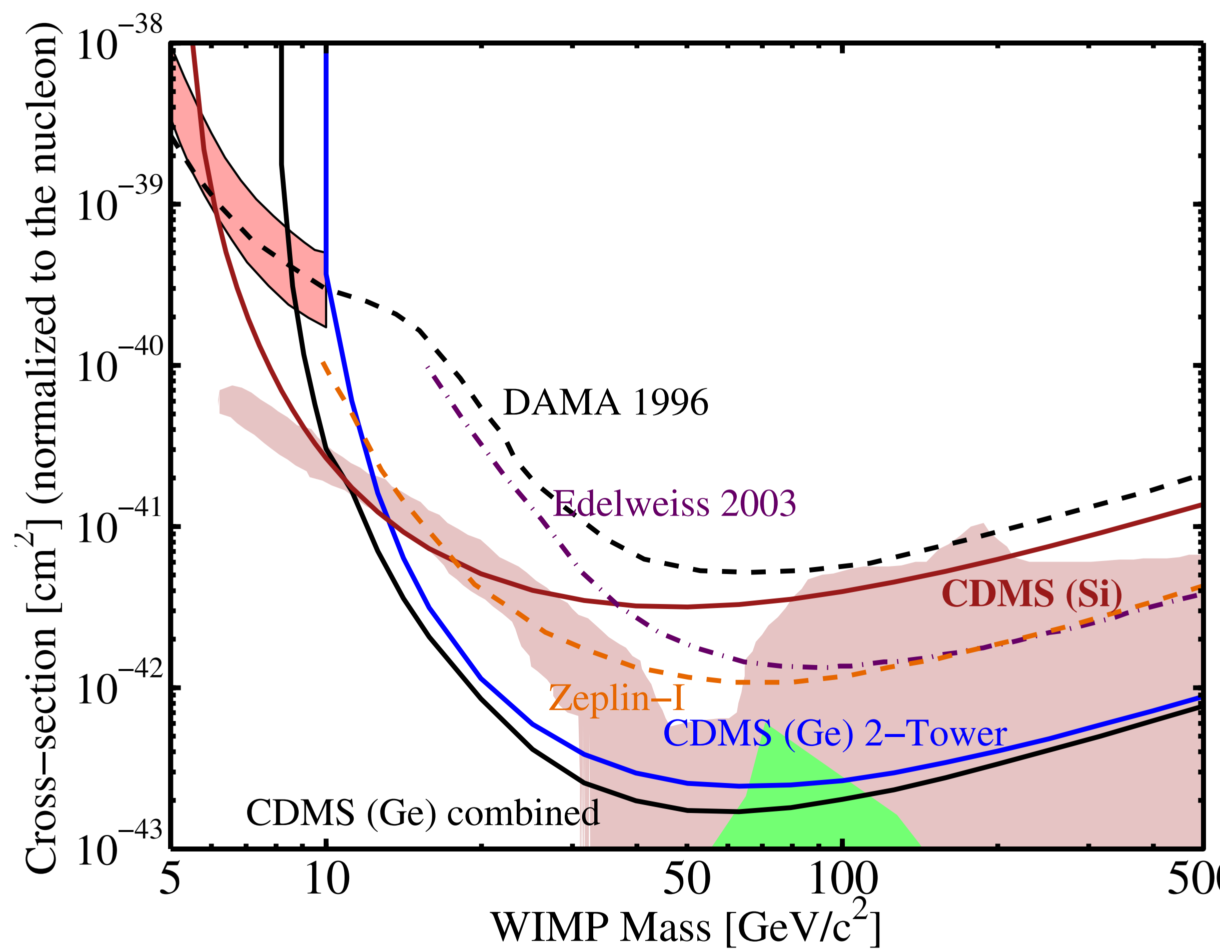


CDMS-II at Soudan

- **2003-2004 first 2 runs at Soudan with one, and two towers**
- 2-tower run (6 Ge, 6 Si); raw exposure 97 kg d (Ge), 34 kg d (Ge) after cuts
- 1 candidate event compatible with expected BG; limits published
- Current: combined analysis of both runs with improved surface event rejection



candidate consistent with expected BG from surface events



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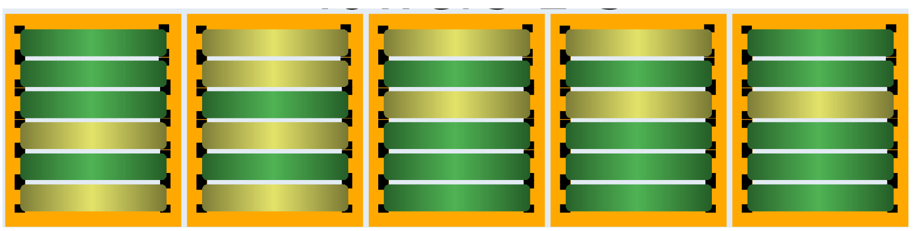
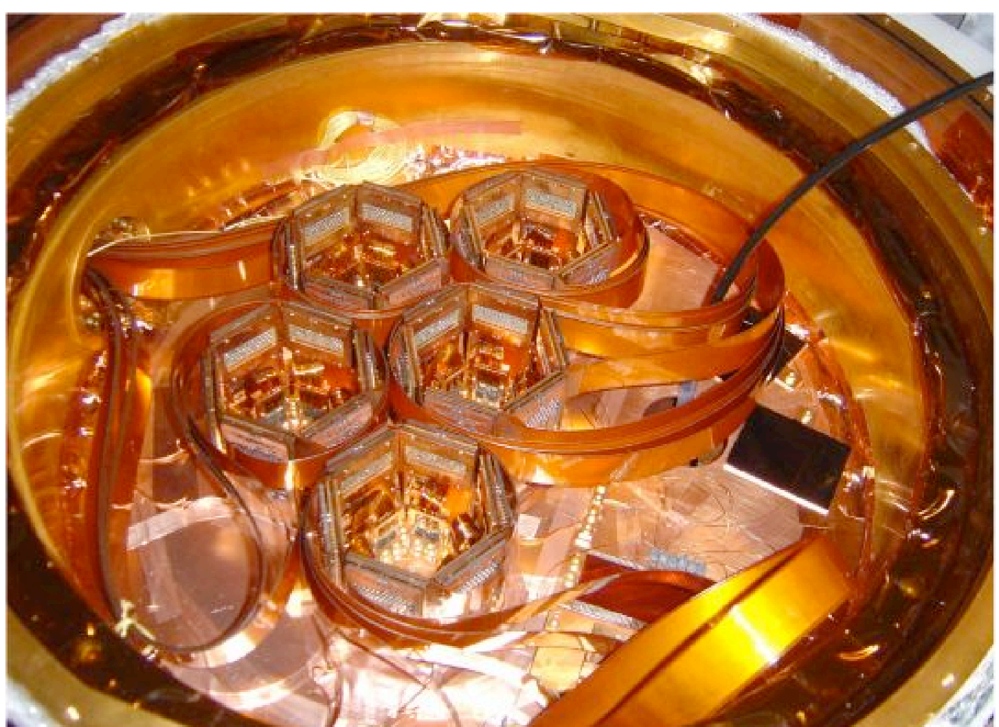
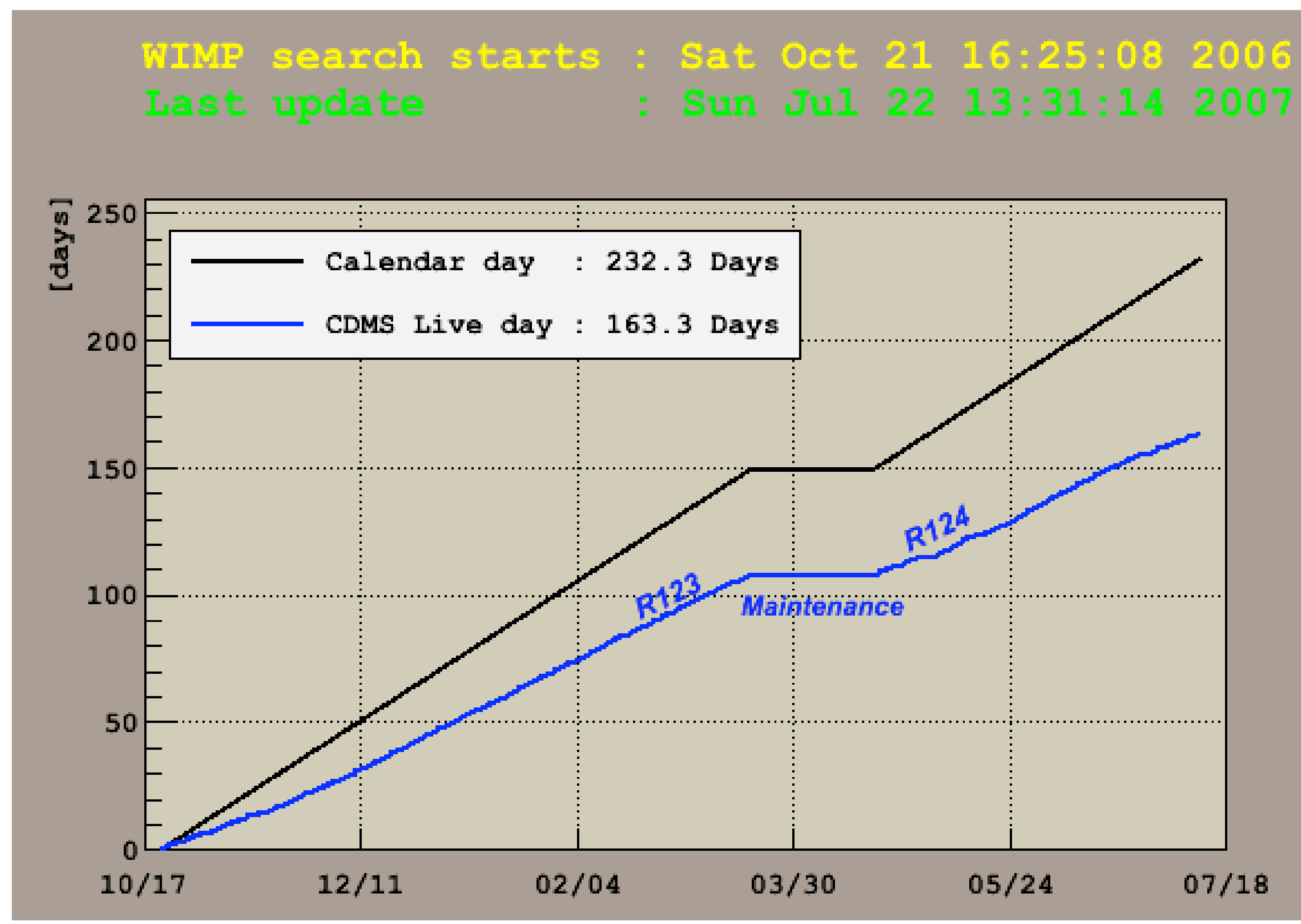
CDMS-II 5 tower run

- **Dark matter run** with 30 detectors since October 21, 2006
- **Run 123** (until March 20, 07): 430 kg d raw data (Ge); analysis is ongoing
- **Run 124**: started, expected exposure > 840 kg-d raw (Ge) in spring 2008
- **Expected sensitivity with 1300 kg · d raw Ge exposure: 2 x 10^{-8} pb**

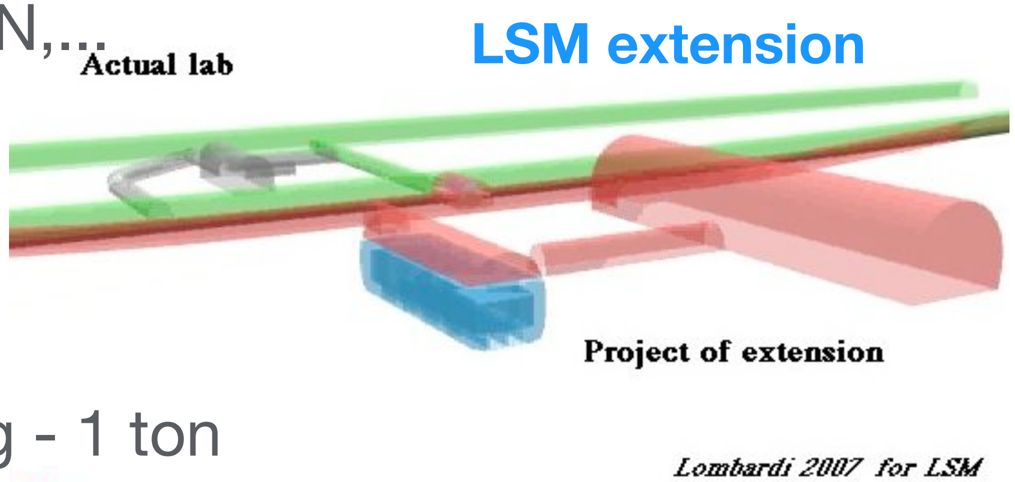






Future mK Cryogenic Dark Matter Experiments

- **EURECA (European Underground Rare Event Calorimeter Array)**
- Joint effort: CRESST, EDELWEISS, ROSEBUD, CERN,...
- Mass: 100 kg - 1 ton, multi-target approach
- FP7 proposal for design study submitted



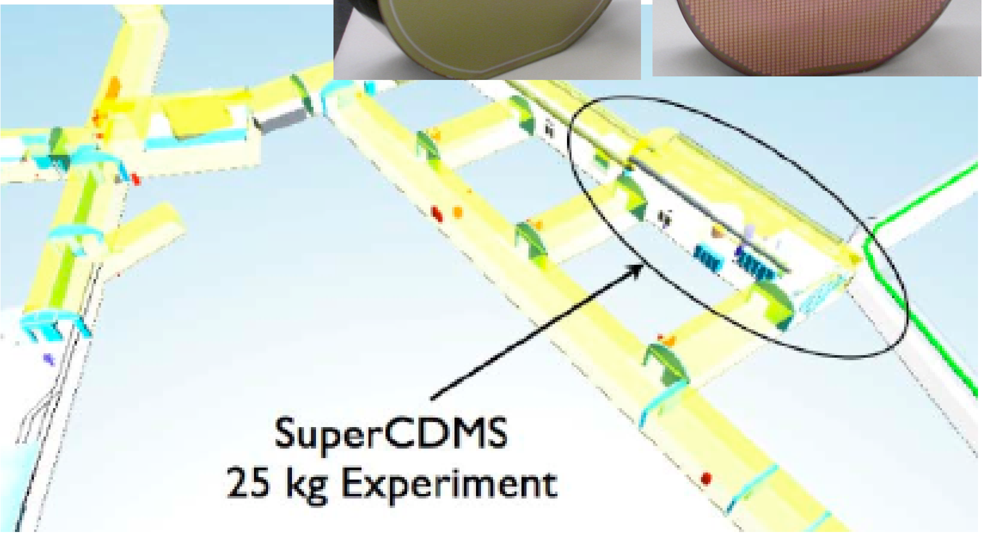
- **SuperCDMS (US/Canada):** 3 phases 25 kg - 150 kg - 1 ton
- 640 g Ge detectors with improved phonon sensors
- 4 prototype detectors built and tested

R&D for SuperCDMS:

1” thick **SuperZIPs** (0.64 kg)

2 SuperTowers at Soudan

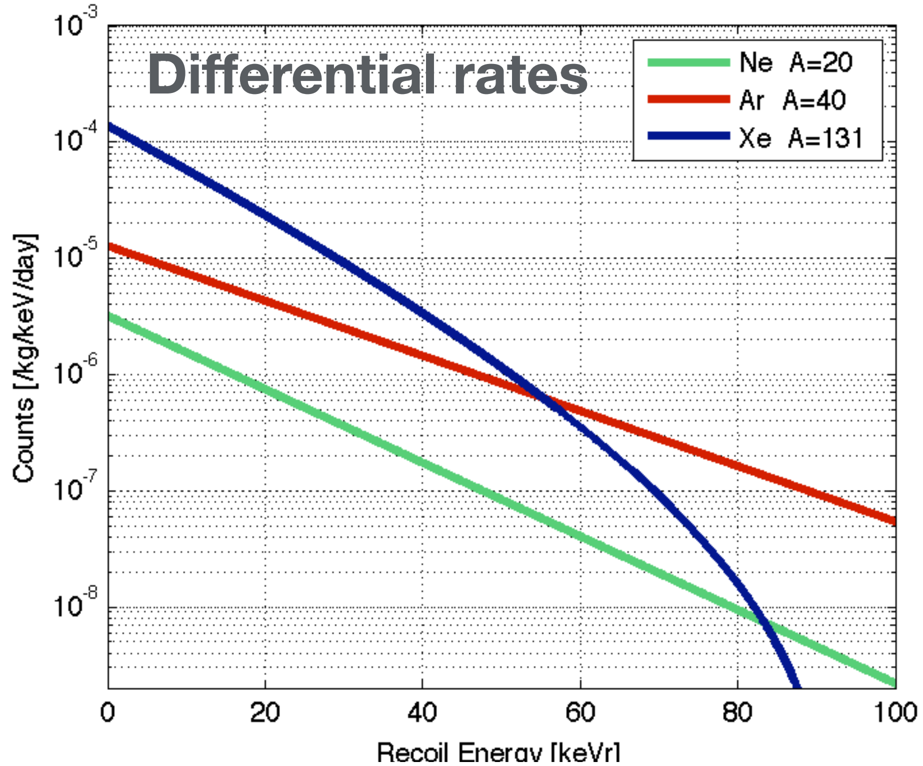
7 SuperTowers at SNOLAB

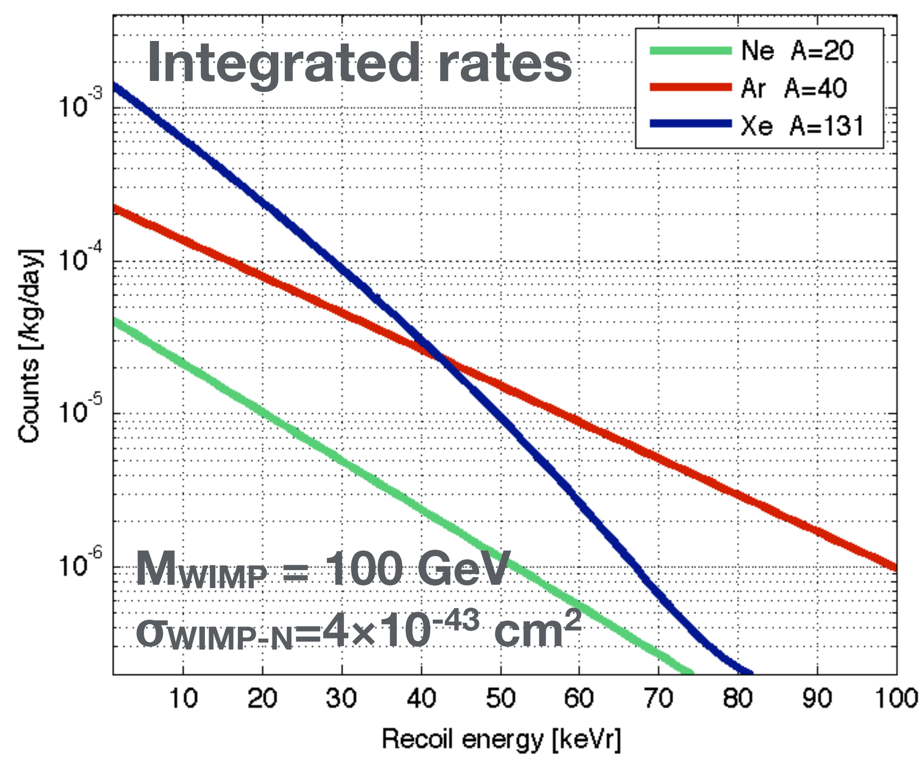


Noble Liquids as Dark Matter Detectors

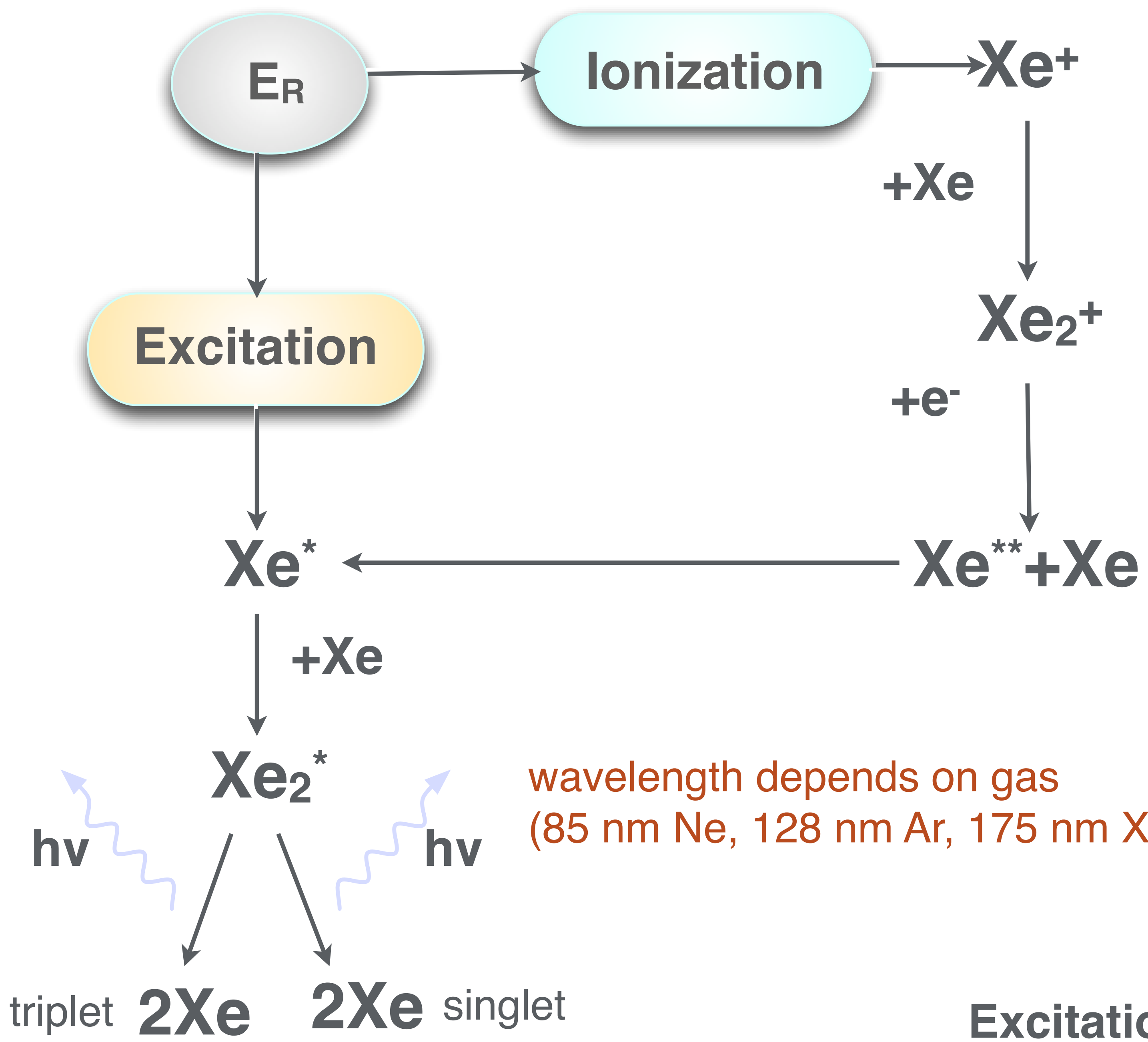
Dense, homogeneous targets/detectors
High scintillation/ionization yields
Commercially easy to obtain and purify

	Scintillation Light	**Intrinsic Backgrounds**
Ne (A=20) \$60/kg 100% even-even nucleus	**85 nm** requires wavelength shifter	Low BP (20 K), all impurities frozen out No radioactive isotopes
Ar (A=40) \$2/kg 100% even-even nucleus	**128 nm** requires wavelength shifter	Natural Ar contains ^{39}Ar at 1Bq/kg, corresp. to ~150 ev/kg/day/keV at low energies
Xe (A=131) \$800/kg 50% odd nuclei (^{129}Xe, ^{131}Xe)	**175 nm** UV quartz PMT window	No long lived isotopes ^{85}Kr can be removed by active charcoal filter or distillation





Charge and Light in Noble Liquids



wavelength depends on gas
(85 nm Ne, 128 nm Ar, 175 nm Xe)

time constants depend on gas
(few ns/15.4µs Ne, 10ns/1.5µs Ar, 3/27 ns Xe)

$$Xe^* + Xe \rightarrow Xe_2^*$$
$$Xe_2^* \rightarrow 2Xe + h\nu$$

$$Xe^+ + Xe \rightarrow Xe_2^+$$
$$Xe_2^+ + e^- \rightarrow Xe^{**} + Xe$$
$$Xe^{**} \rightarrow Xe^* + heat$$
$$Xe^* + Xe \rightarrow Xe_2^*$$
$$Xe_2^* \rightarrow 2Xe + h\nu$$

Excitation/Ionization depends on dE/dx!
=> discrimination of signal (**WIMPs=>NR**)
and (most of the) background (**gammas=>ER**)!

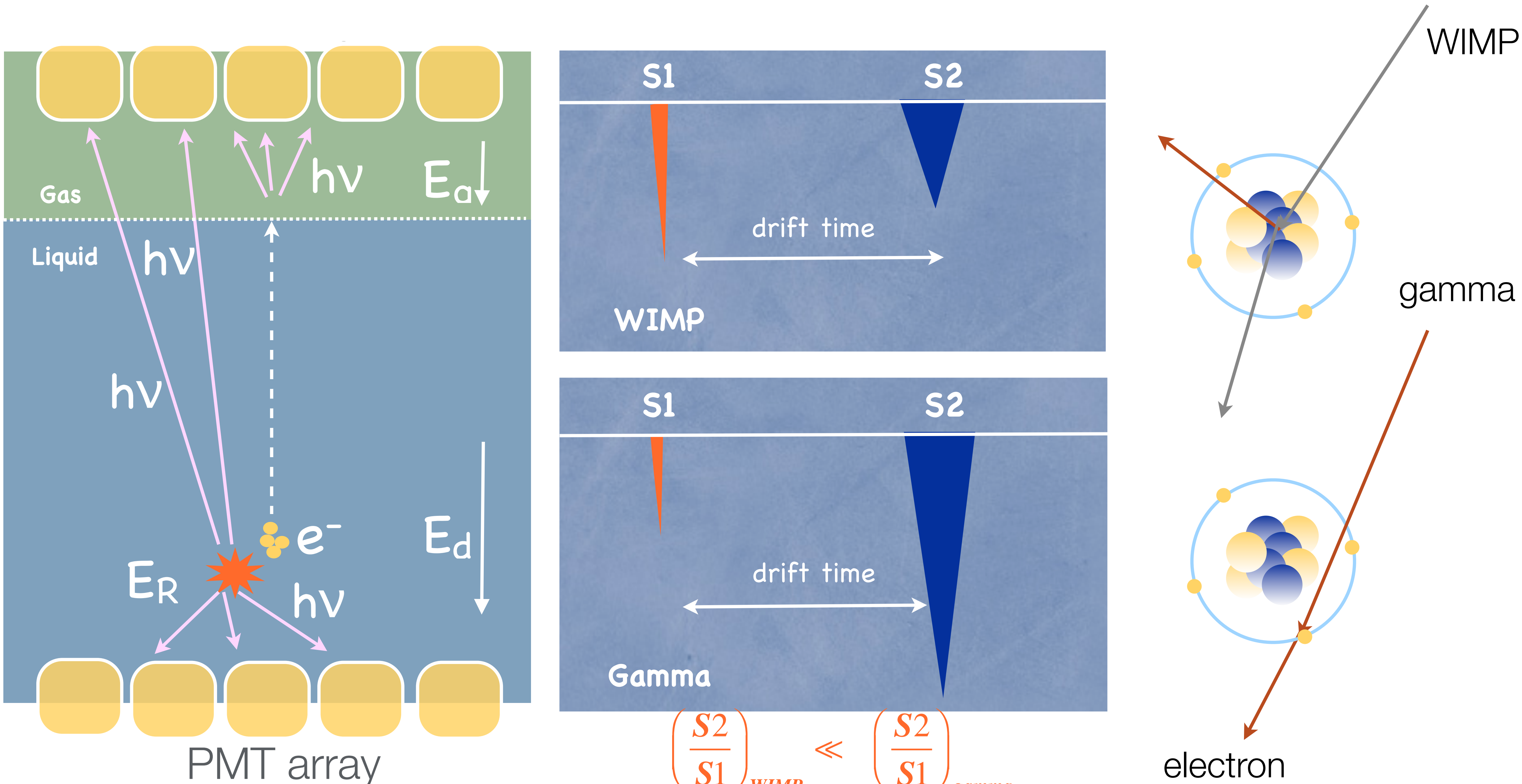
Noble Liquid Detectors: Existing Experiments and Proposed Projects

	Single Phase (liquid only) PSD	**Double Phase (liquid and gas) PSD and Charge/Light**
Neon (A=20)	miniCLEAN (100 kg) CLEAN (10-100 t)	SIGN (high P Ne gas)
Argon (A=40)	DEAP-I (7 kg) miniCLEAN (100 kg) CLEAN (10-100 t)	ArDM (1 ton) WARP (3.2 kg) WARP (140 kg)
Xenon (A=131)	ZEPLIN I XMASS (100 kg) XMASS (800 kg) XMASS (23 t)	ZEPLIN II + III (31 kg, 8 kg) XENON10, XENON10+ LUX (300 kg), ELIXIR (1t)

- **Single phase:** e^--ion recombination occurs; singlet/triplet ratio is 10/1 for NR/ER
- **Double phase:** ionization and scintillation; electrons are drifted in ~ 1kV/cm E-field

Two-Phase (Liquid/Gas) Detection Principle

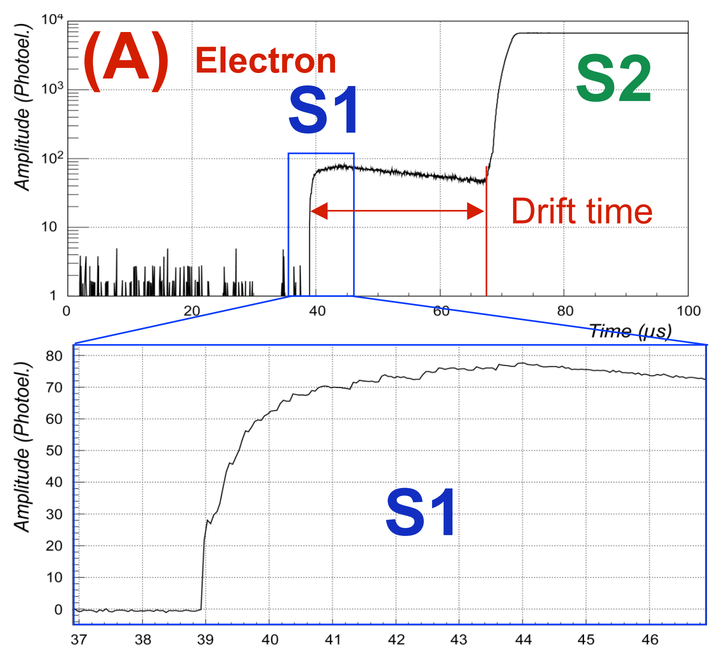
- **Prompt (S1) light signal** after interaction in active volume; charge is drifted, extracted into the gas phase and detected **directly**, or as **proportional light (S2)**
- **Challenge:** ultra-pure liquid + high drift field; efficient extraction + detection of e^-

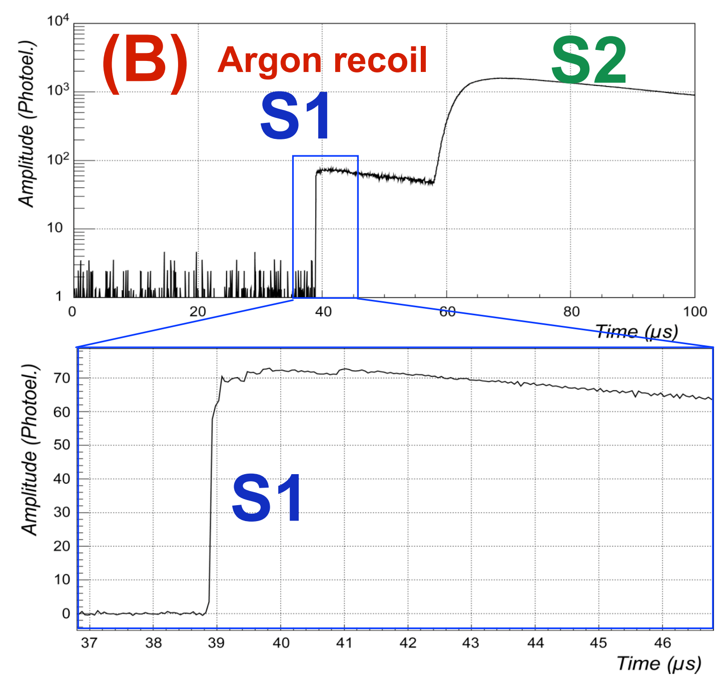


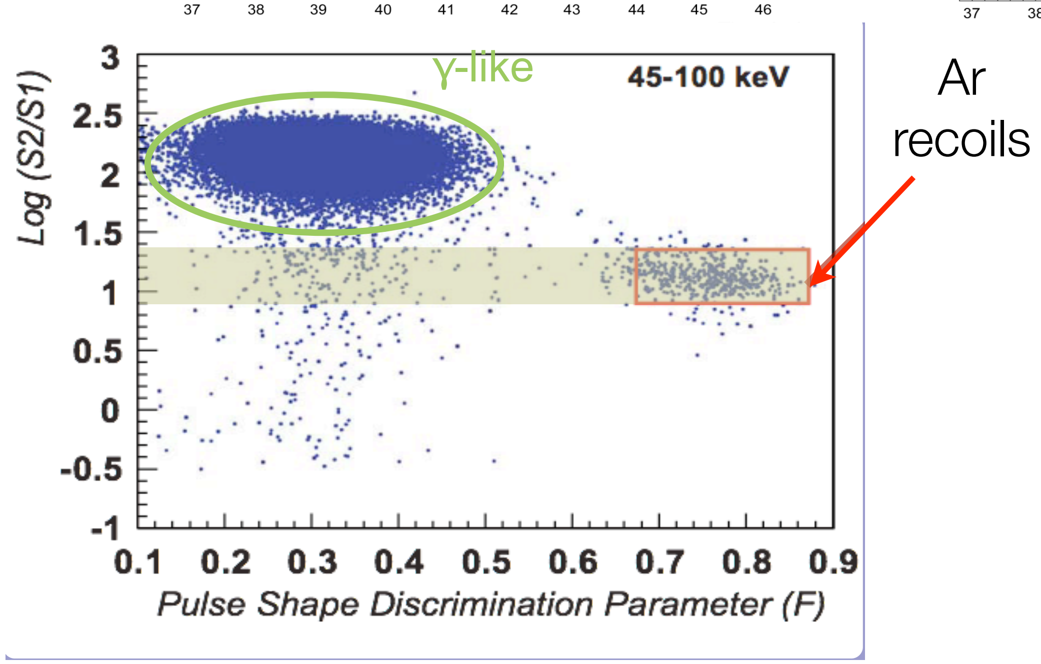
$$\left(\frac{S2}{S1}\right)_{WIMP} \ll \left(\frac{S2}{S1}\right)_{gamma}$$

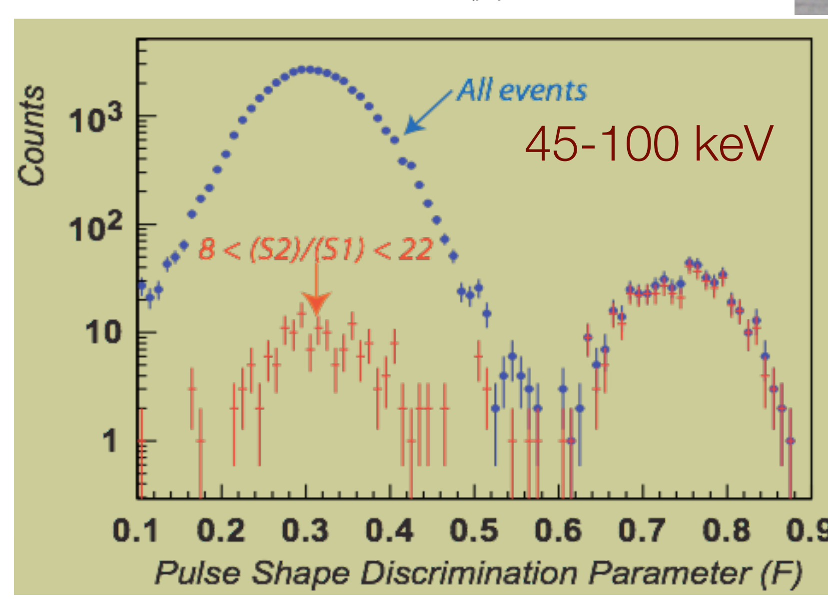
Two-Phase Argon: WARP

- 3.2 kg detector is running at LNGS (first installation in 2004)
- WARP discrimination: PSD and S2/S1









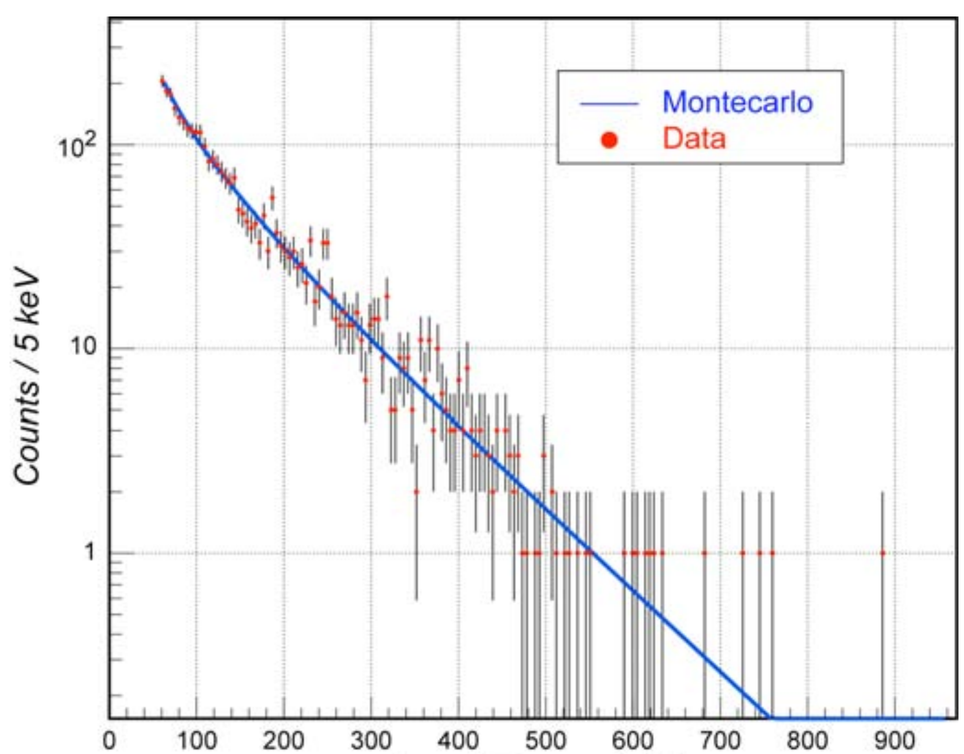
n-calibration data

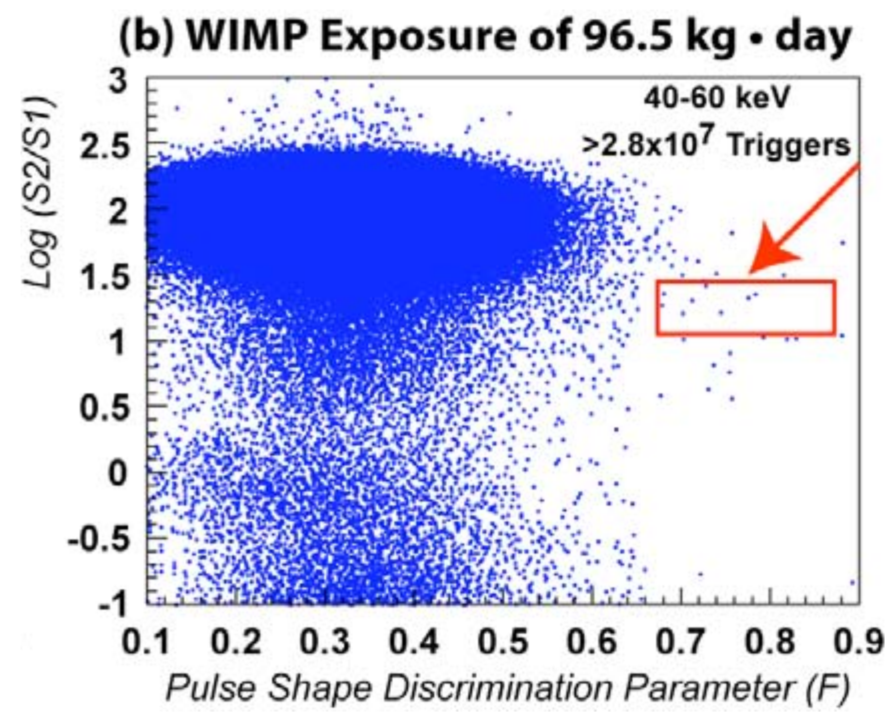
effect of S2/S1 ratio cut

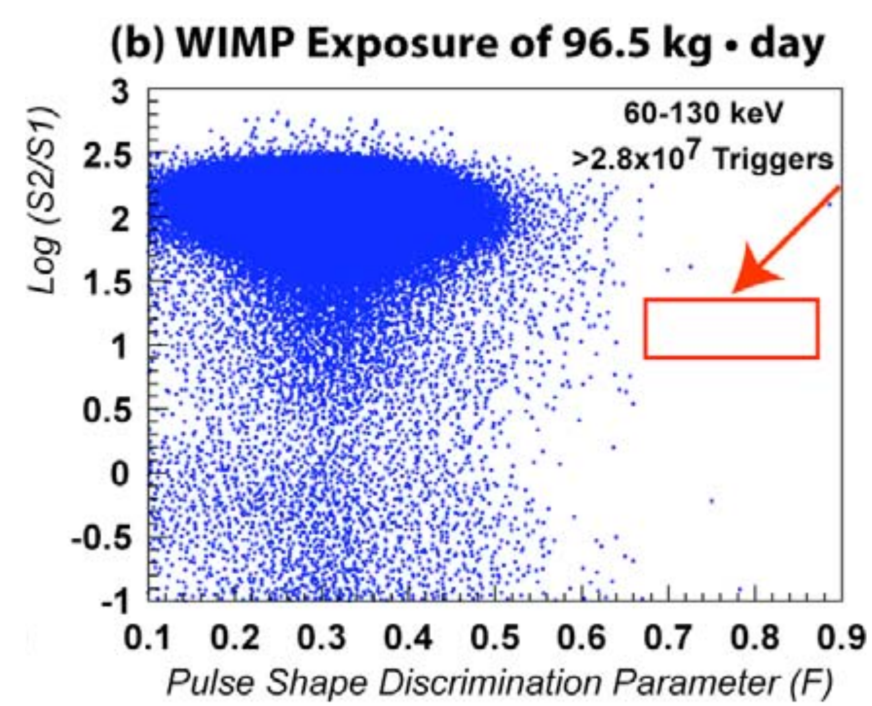
=> depletes the gamma-like population (F < 0.6)

WARP Recent Results

- WARP reported results from ~ **3 months of WIMP search data at LNGS**
- Analysis based on **zero events > 55 keV**
- The reported limit is ~ **5 times above CDMS result**
- New data (50 kg days) in hand, improved electronics
  - ➡**Results soon; 140 kg detector in preparation**
- WARP energy calibration: n-calibration
  - ➡fitted with MC over the range 60 - 700 keVr



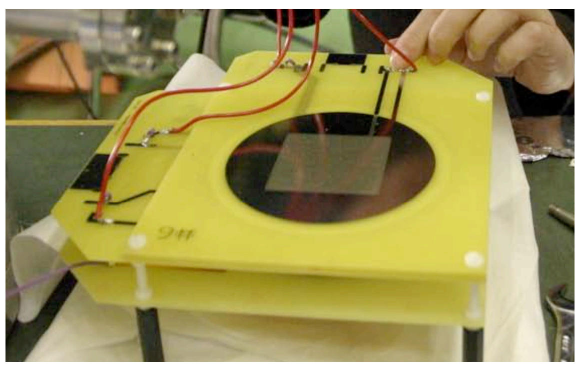
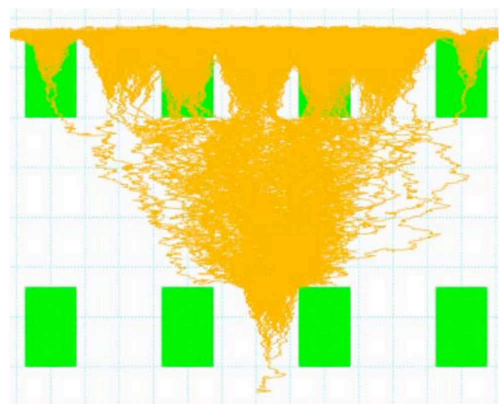
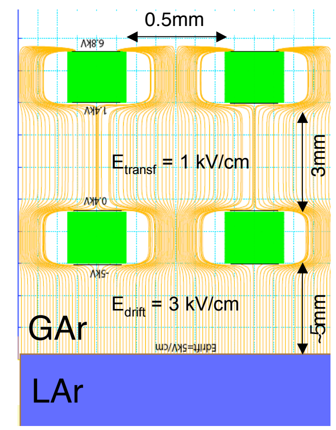




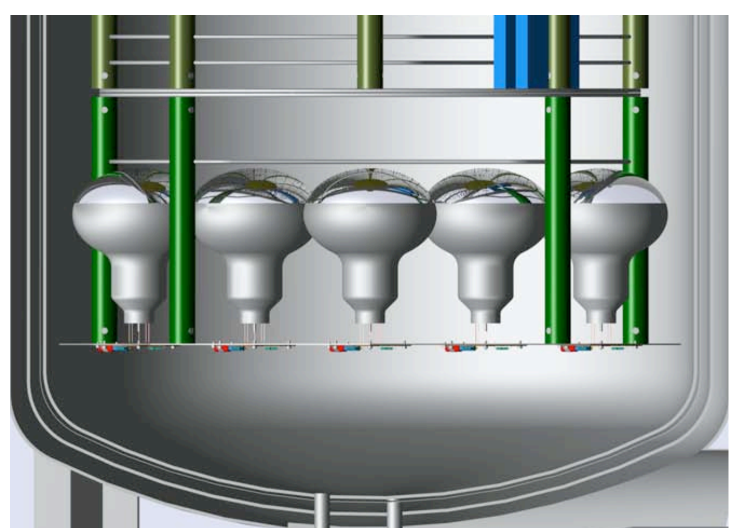
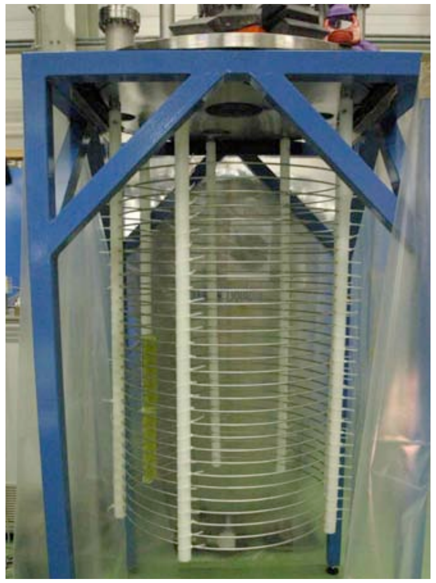
P. Benetti et al.,
astro-ph/0701286

Two-Phase Argon: ArDM

- **1 ton prototype under construction at CERN**
- Direct charge readout with 2 stage, thick LEM (macroscopic GEM, gain up to 10^4)

- Photon readout: 85 tetra-phenyl-butadiene coated PMTs: shift λ 128 nm -> 430 nm (20%QE)

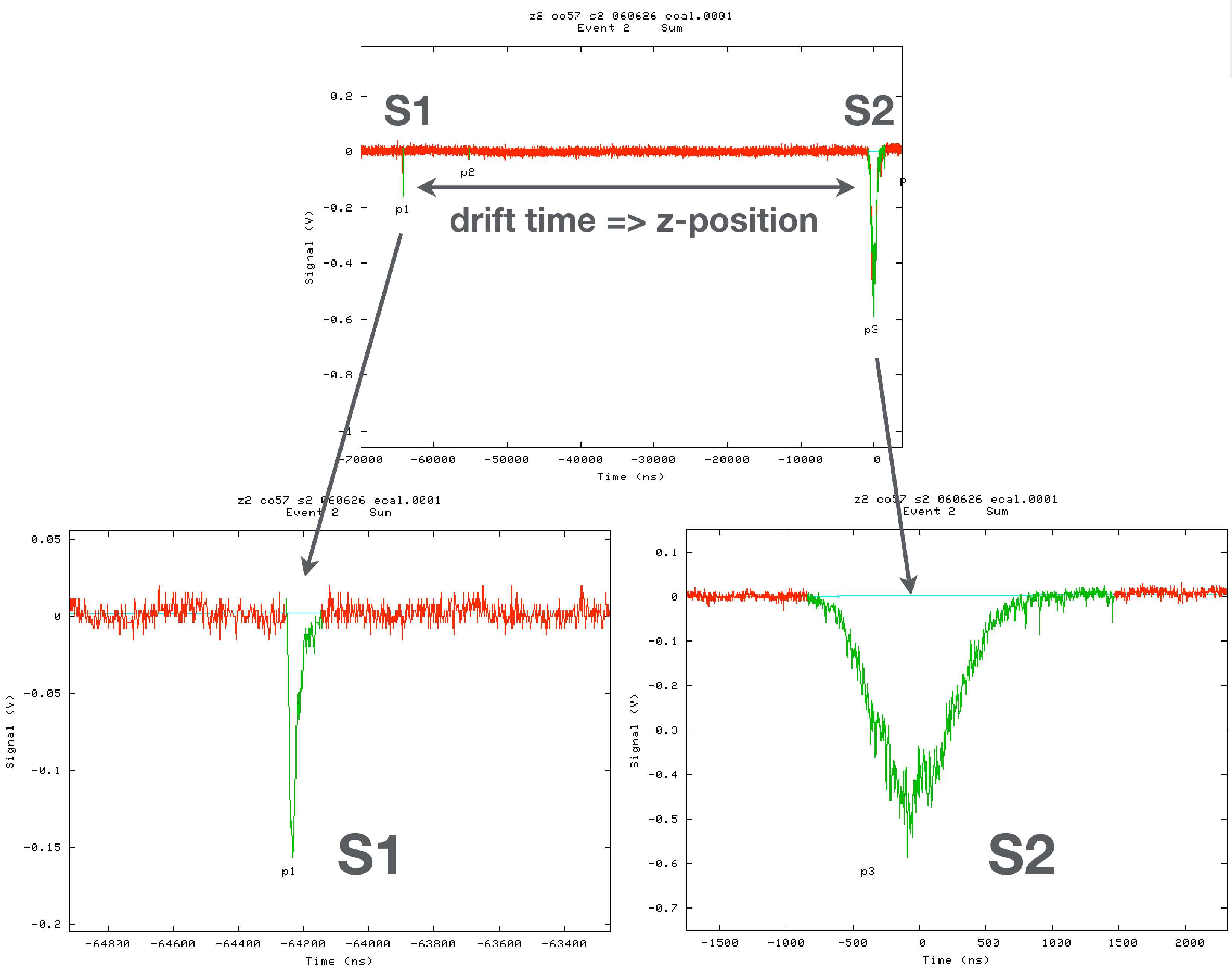




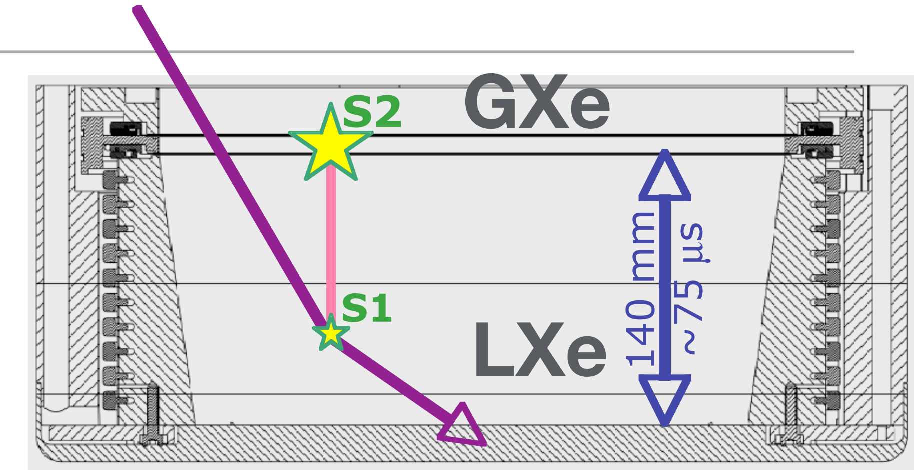

- Field: Greinacher Chain + field shapers
- Goal: test at CERN (2007), then move to Canfranc (07-08)
- Expect: **1 event/ton/day for $\sigma=10^{-8}$ pb (E_{th}=30keVr)**

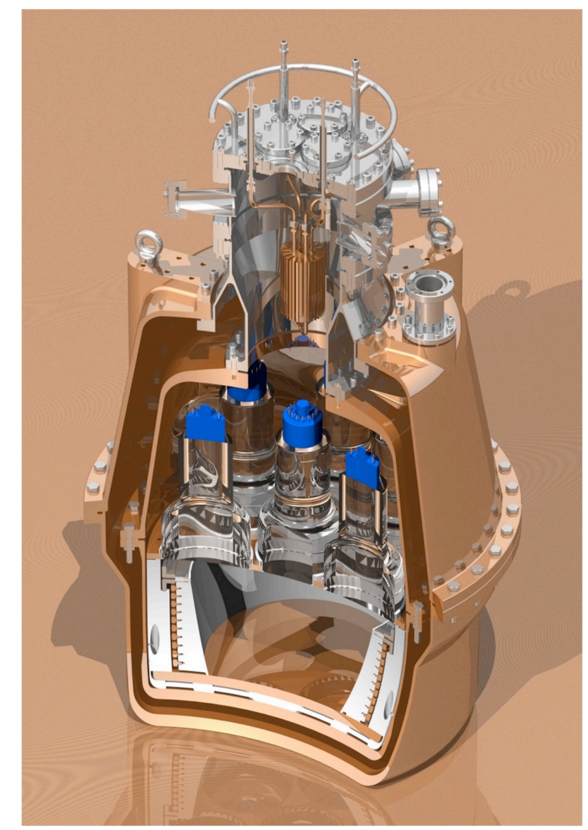
M. Laffranchi et al., astro-ph/0702080

Two-Phase Xenon: ZEPLIN-II

- 5 months continuous operation at the Boulby Lab
- **1.0 t *day raw Wimp Search data**



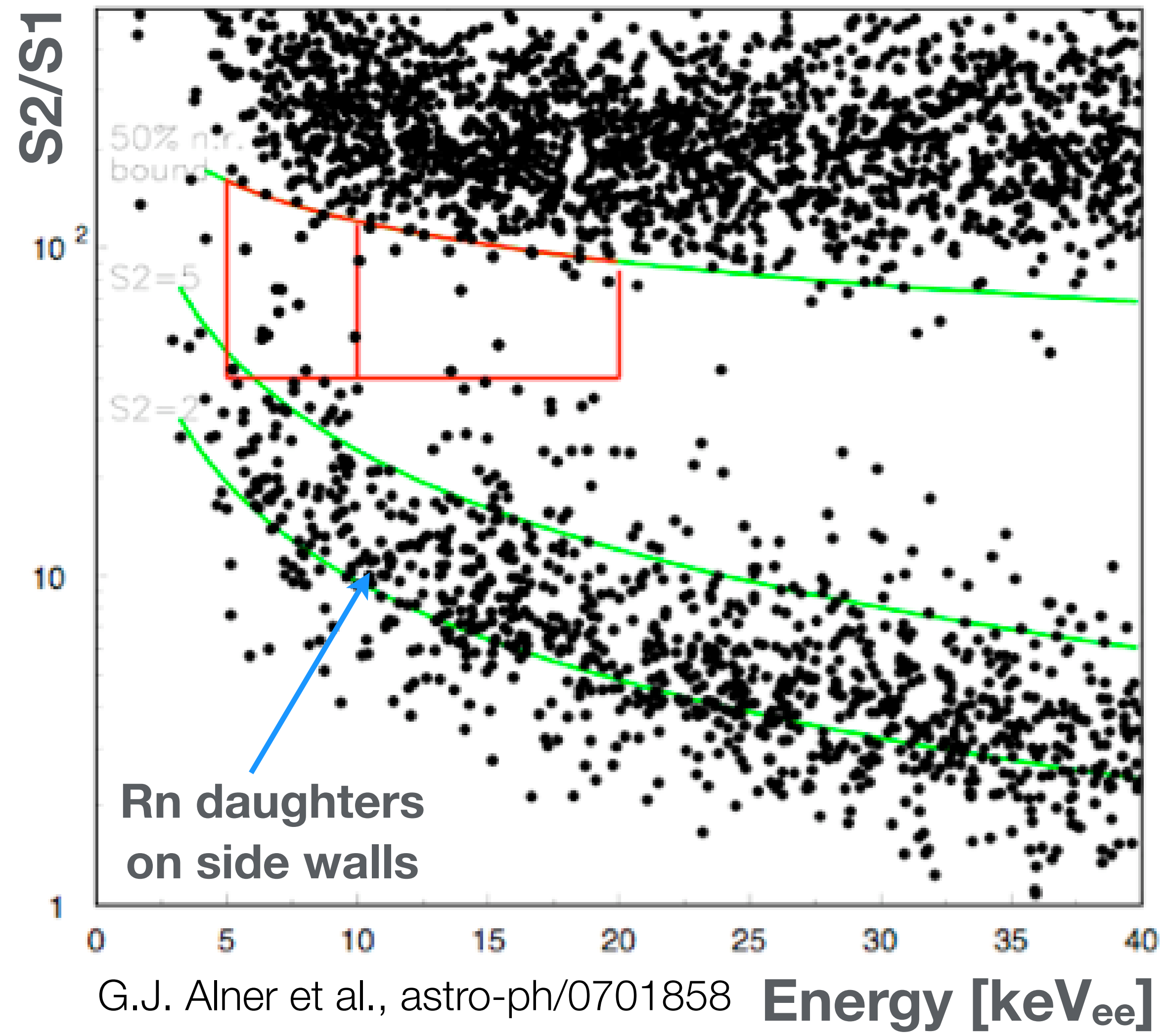




31 kg LXe (7.2 kg fiducial)
7 x 13 cm ø ETL-PMTs
1 cm spatial resolution
0.55 pe/keV$_{ee}$ (^{57}Co, w. field)

ZEPLIN-II Wimp Search Data and Results

- **31 live days running, 225 kg d exposure**
  - ➡**Red box: 5-20 keVee, 50% NR acceptance** based on neutron calibration
  - ➡**29 candidate events seen**
  - ➡50% from ER leakage from upper band
  - ➡50% from lower band (Rn daughter recoils on PTFE side walls)



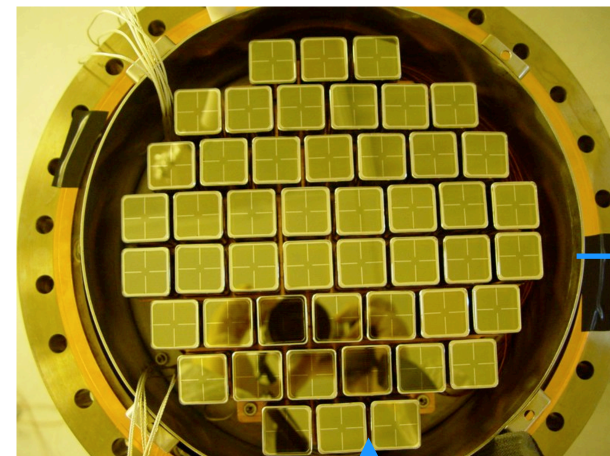
G.J. Alner et al., astro-ph/0701858

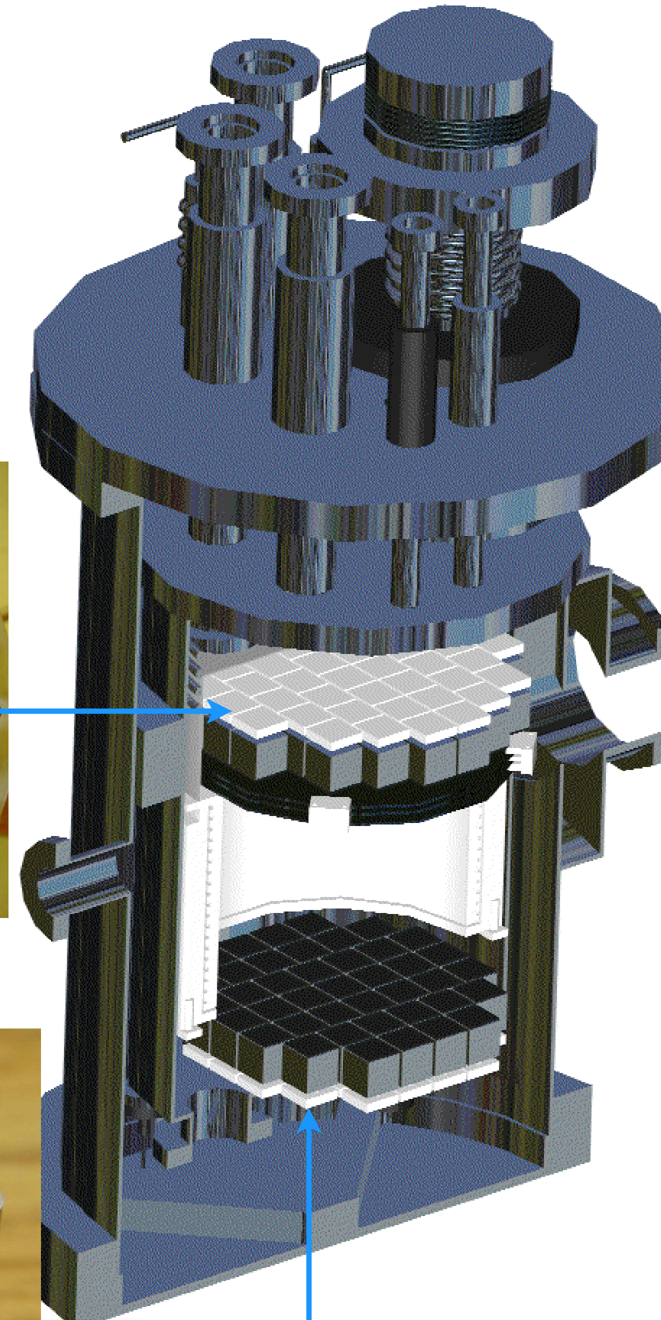
- **Both populations have been modeled and background subtraction performed**
- With **29 events observed**, and **28.6±4.3 predicted**, the final results is < 10.4 events (90% CL) => translates to a min. upper limit ~ **6.6 x 10^{-7} pb at 65 GeV WIMP mass**
- New run with low Rn-levels (high T getter) in preparation; **ZEPLIN-III** (kg fiducial mass, 31 low-background PMTs in liquid, 3.5 cm drift) being deployed at Boulby

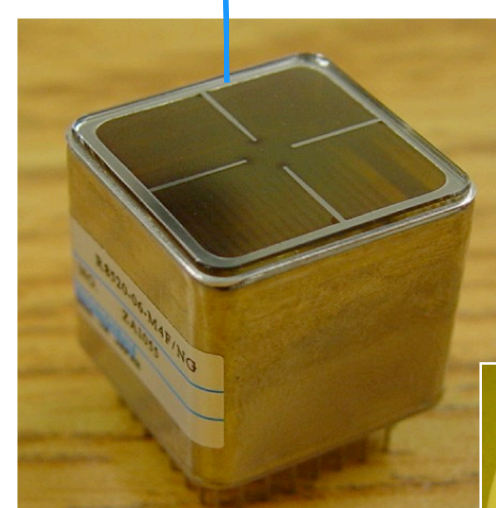
Two-Phase Xenon: XENON10 at the Gran Sasso Lab

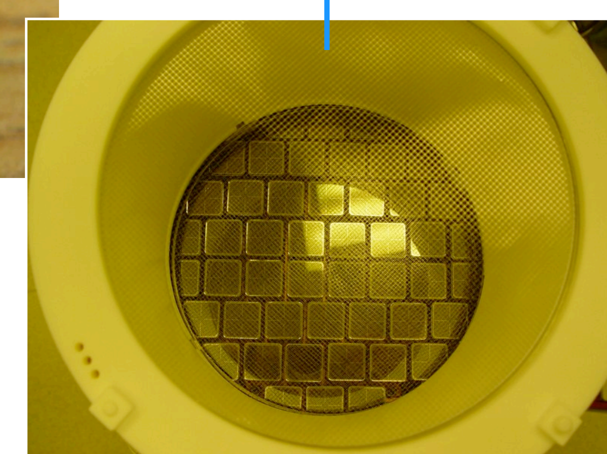
The XENON10 Detector

- **22 kg of liquid xenon**
  - ➡15 kg active volume
  - ➡20 cm diameter, 15 cm drift
- **Hamamatsu R8520 1”×3.5 cm PMTs**
  bialkali-photocathode Rb-Cs-Sb,
  Quartz window; ok at -100°C and 5 bar
  Quantum efficiency > 20% @ 178 nm
- **48 PMTs top, 41 PMTs bottom array**
  - ➡x-y position from PMT hit pattern; $\sigma_{x\text{-}y} \approx$ 1 mm
  - ➡z-position from Δt_{drift} ($v_{d,e-} \approx$ 2mm/μs), $\sigma_Z \approx$0.3 mm
- **Cooling: Pulse Tube Refrigerator (PTR),**
  90W, coupled via cold finger (LN_2 for emergency)





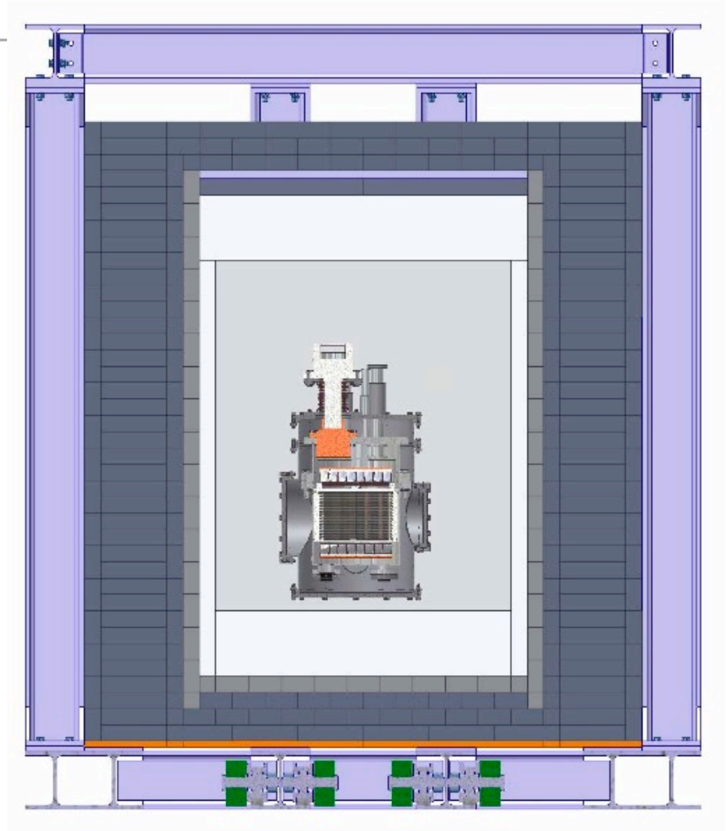


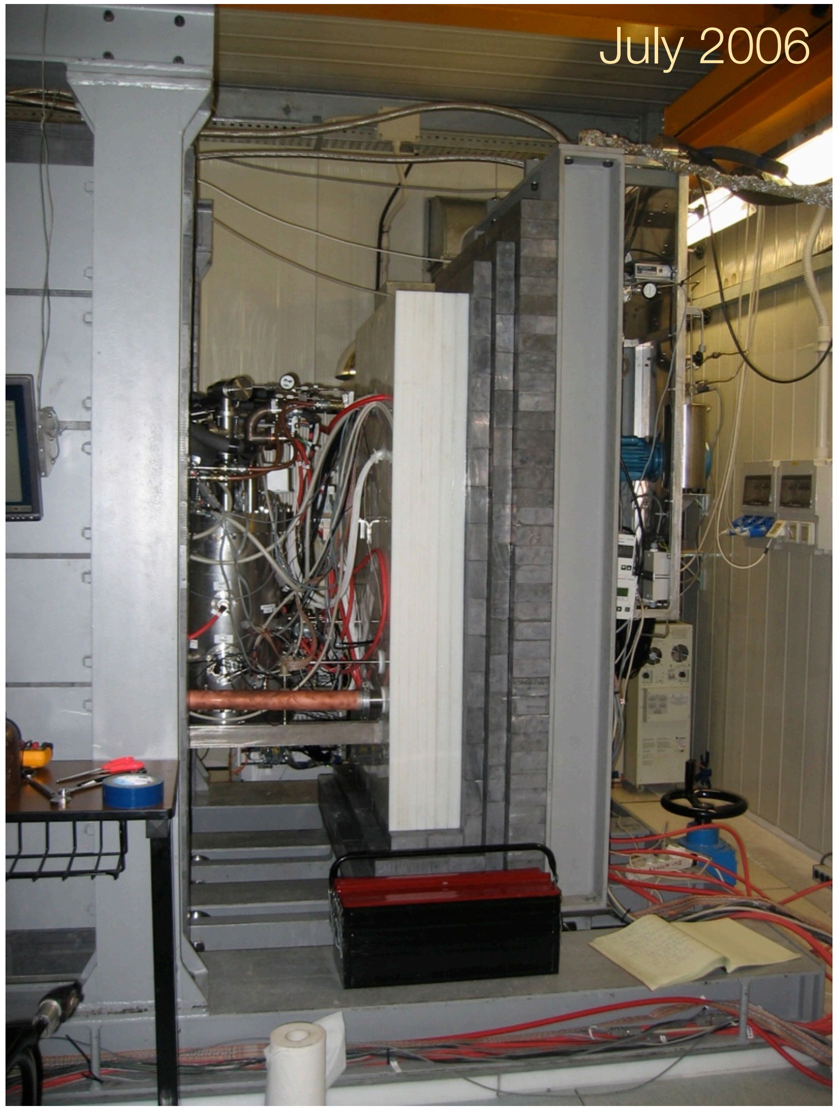


Talk by Dan McKinsey in Cosmology session

XENON10 at the Gran Sasso Laboratory

- **March 06:** detector first installed/tested outside the shield
- **July 06:** inserted into shield (20 cm Pb, 20 cm PE, Rn purge)
- **August 24, 06: start WIMP search run**

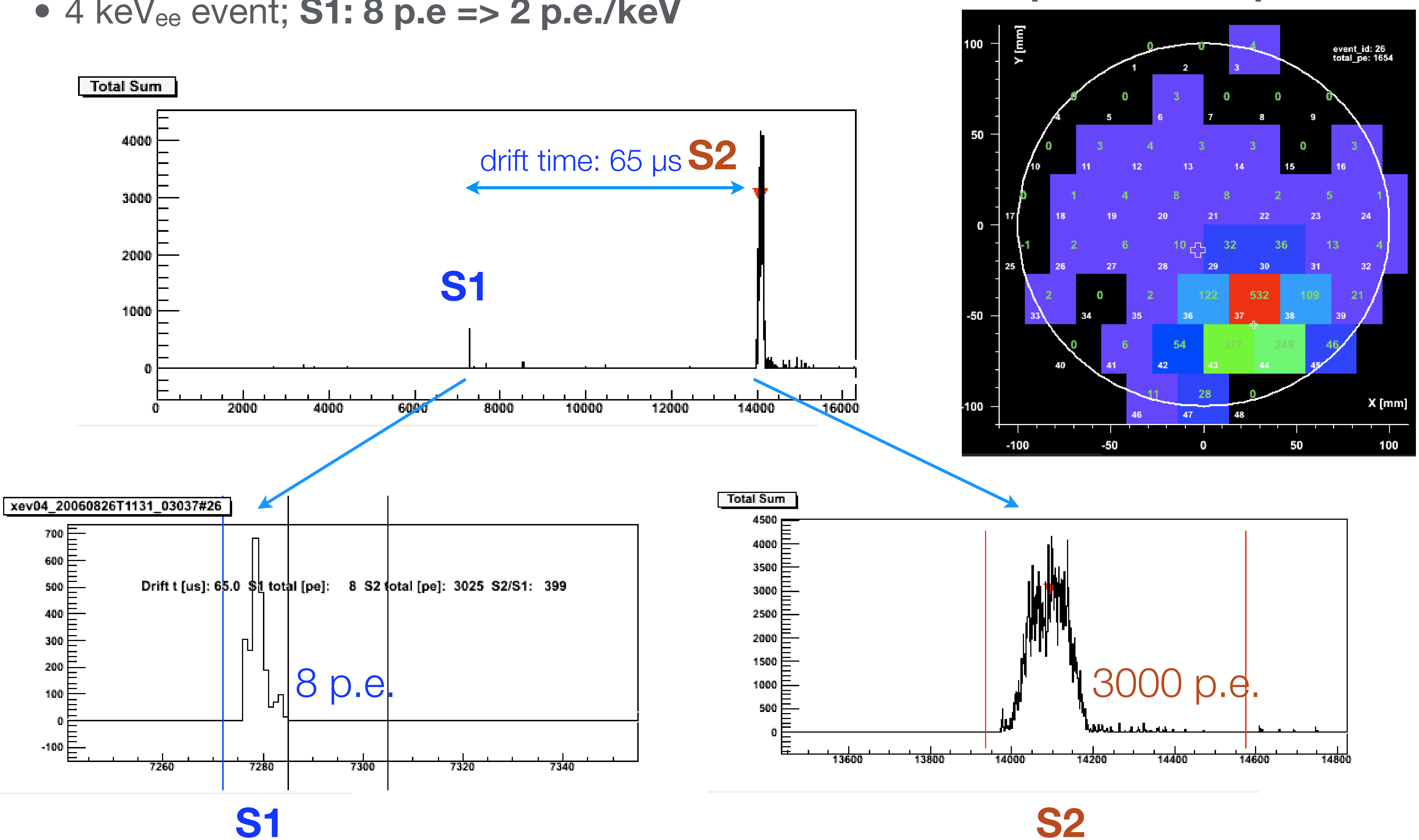




Typical XENON10 Low-Energy Event

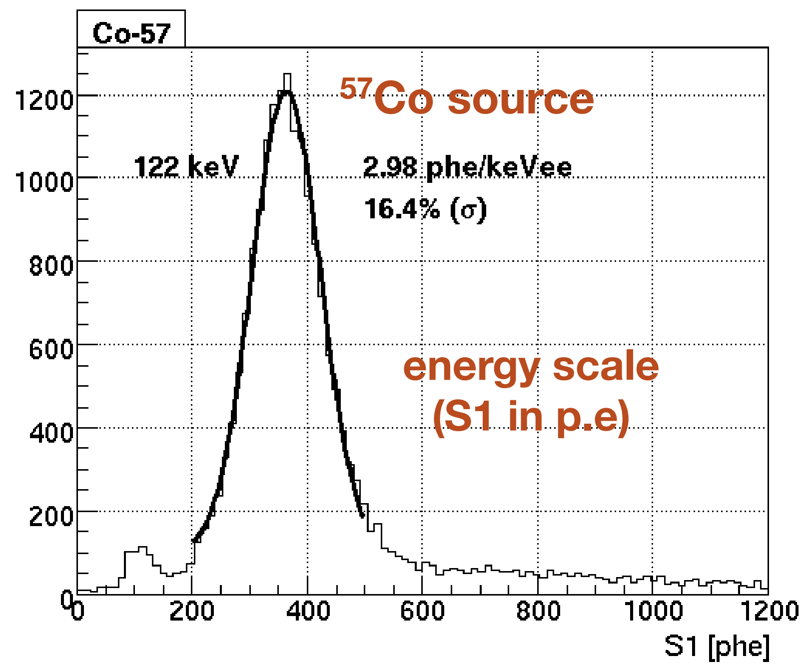
- 4 keV_{ee} event; **S1: 8 p.e => 2 p.e./keV**

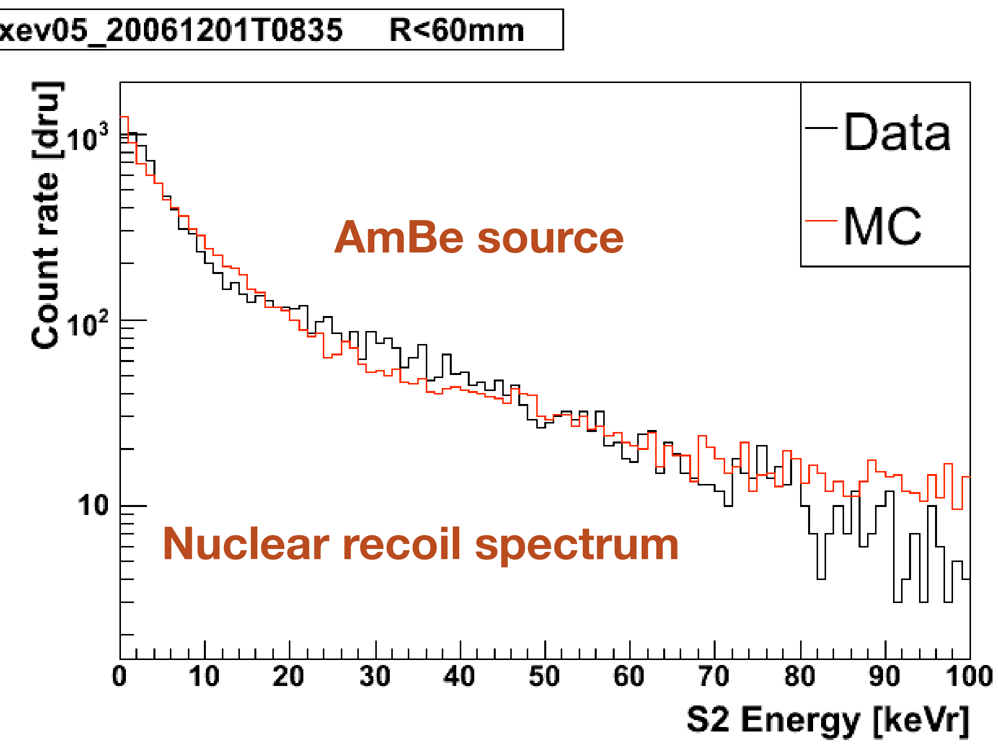
Hit pattern of top PMTs

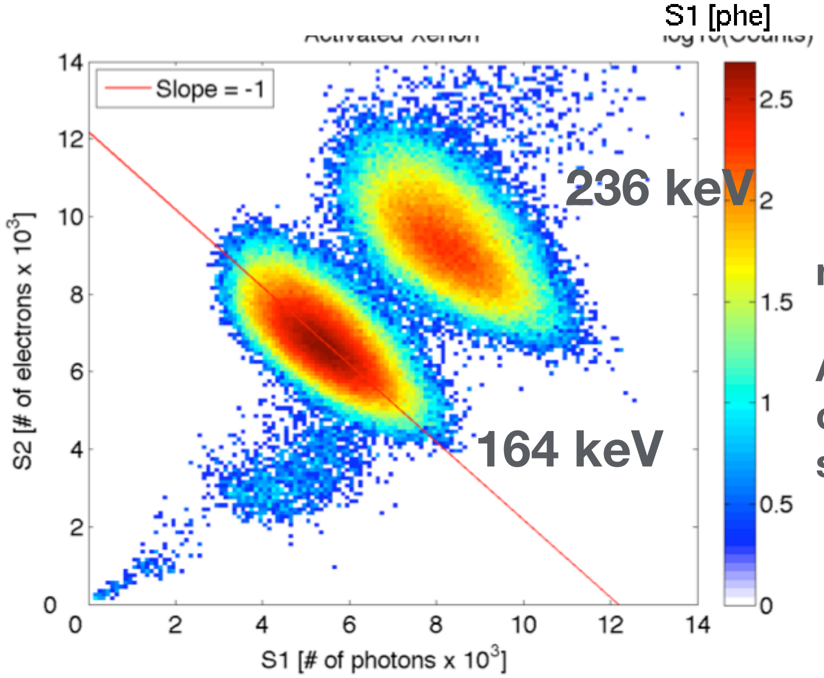


XENON10 Calibrations: Gammas and Neutrons

- **Sources**: ^{57}Co, ^{137}Cs, AmBe, n-activated Xe -> determine energy scale and resolution; position reconstruction; uniformity of detector response, positions of ER and NR band, electron lifetime: (1.8±0.4) ms => << 1ppb (O_2 equiv.) purity

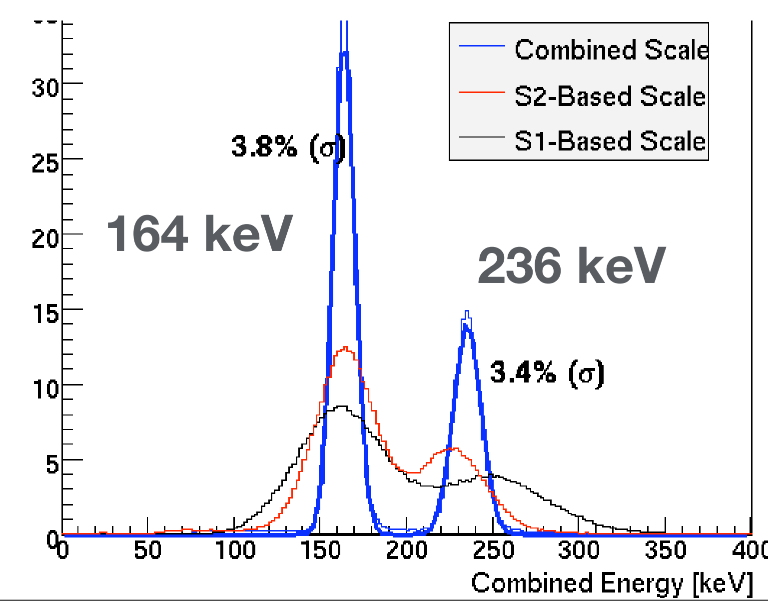






n-activated Xe:

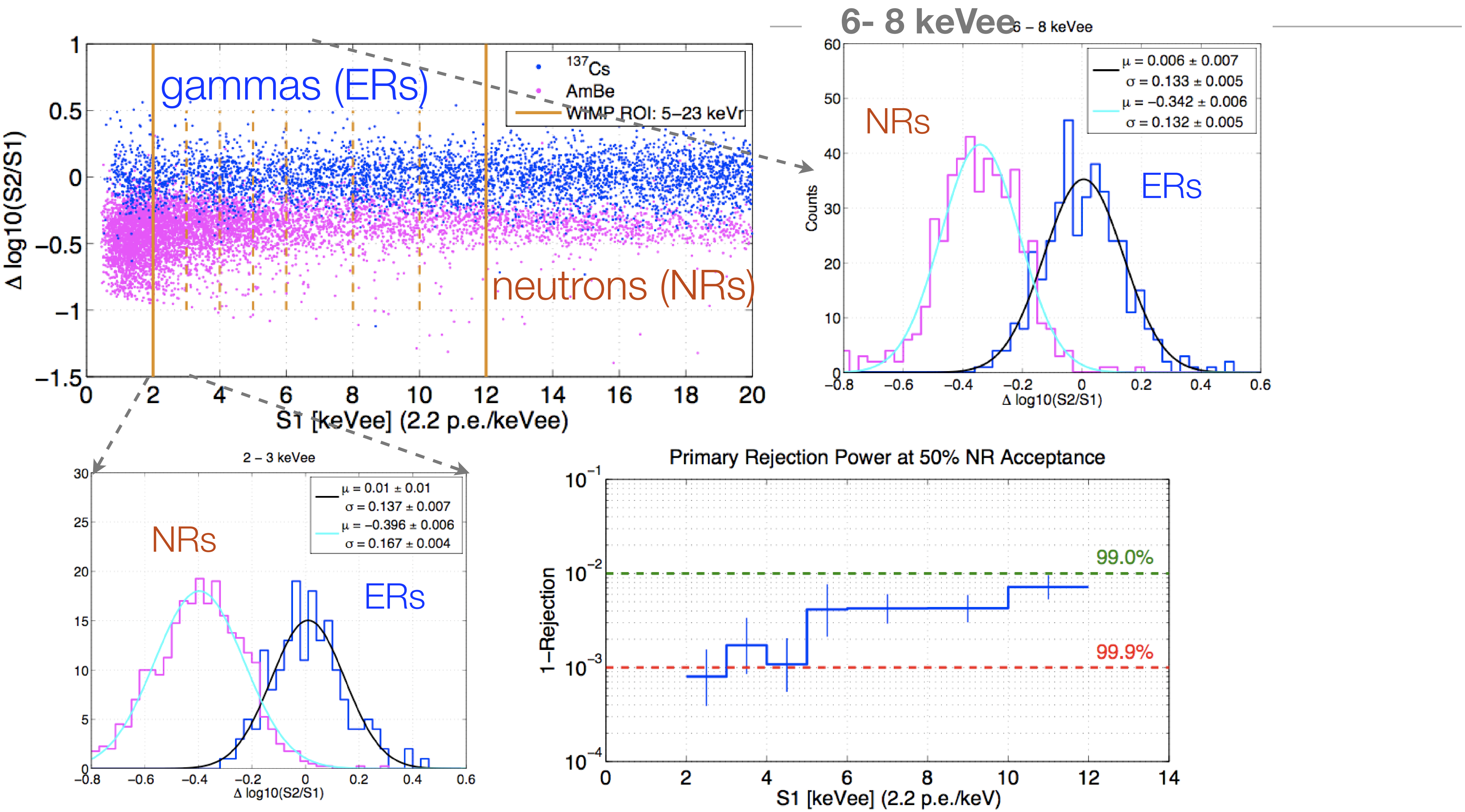
Anti-correlation of charge/light signals



n-activated Xe:

Combined energy spectrum

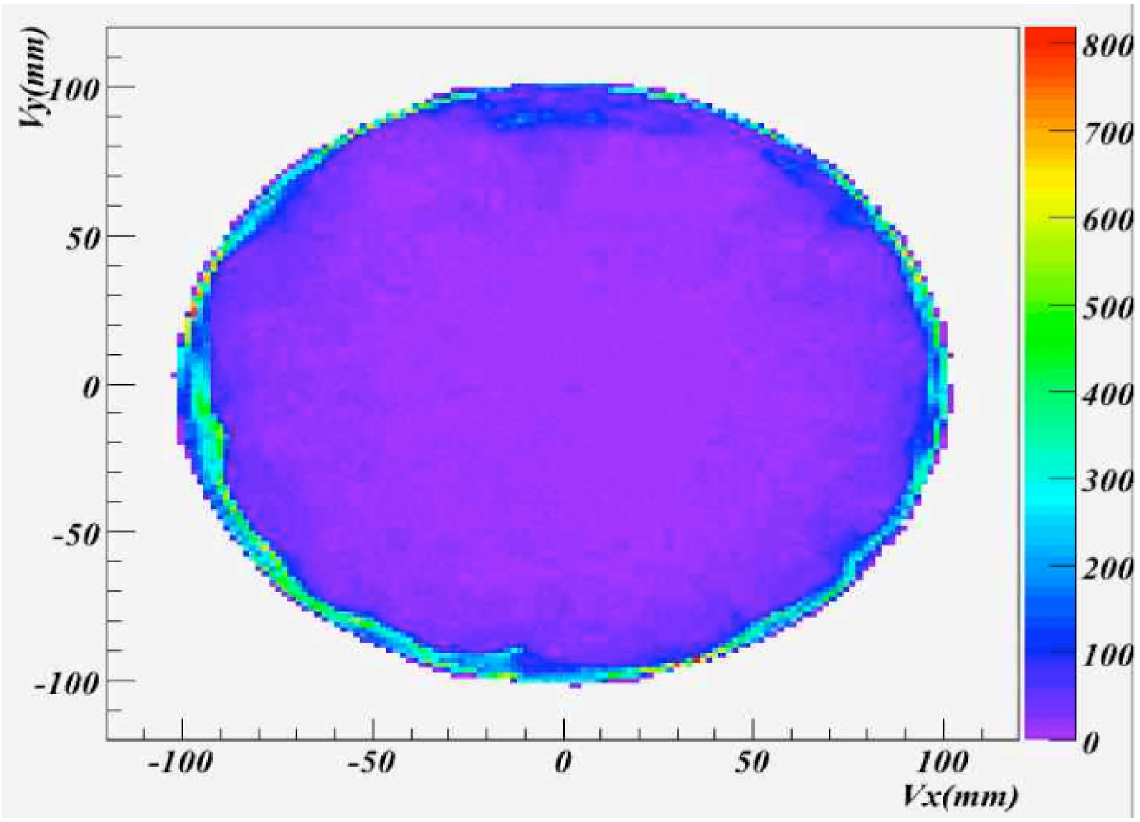
XENON10 Discrimination

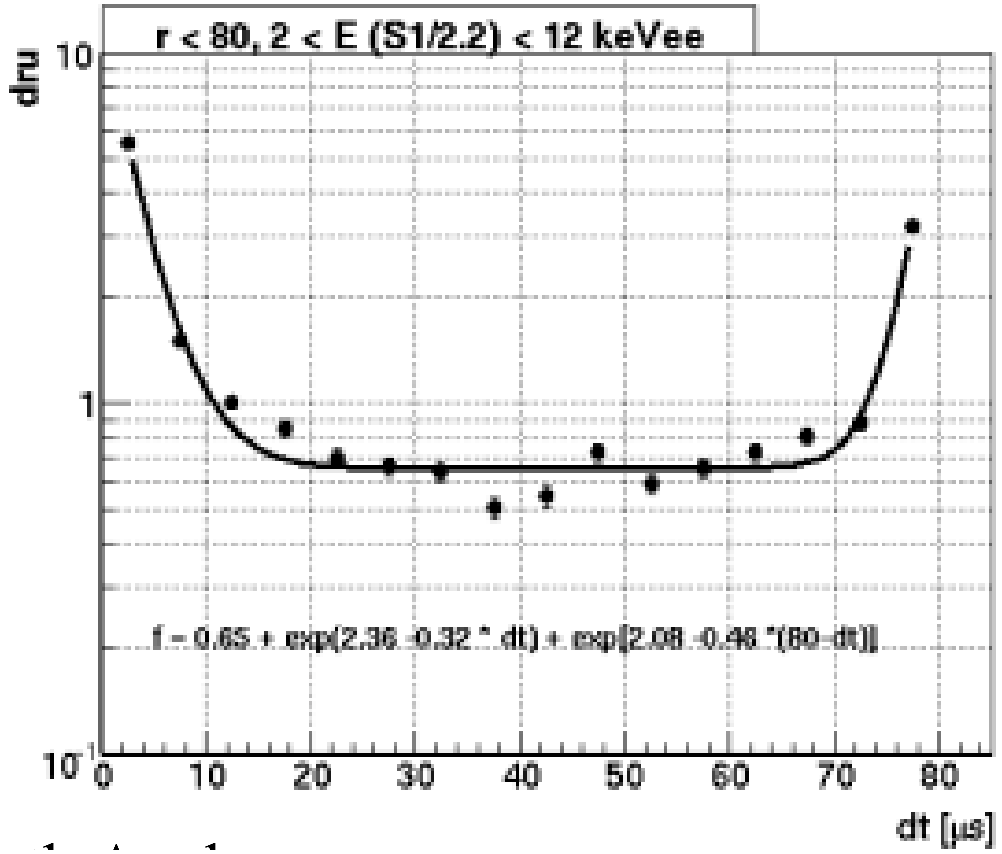


- **Rejection is > 99.6% for 50% Nuclear Recoil acceptance**
  - ➡ **Cuts:** fiducial volume (remove events at teflon edge where poor charge collection)
  - ➡ Multiple scatters (more than one S2 pulse)

XENON10 Blind WIMP Analysis Cuts

- Energy window: 2 - 12 keVee -> based on 2.2 p.e./keVee
  - ➡Basic Quality Cuts (QC0): remove noisy and uninteresting (no S1, multiples, etc) events
  - ➡Fiducial Volume Cuts (QC1): capitalize on LXe self-shielding
  - ➡High Level Cuts (QC2): remove anomalous events (S1 light pattern)

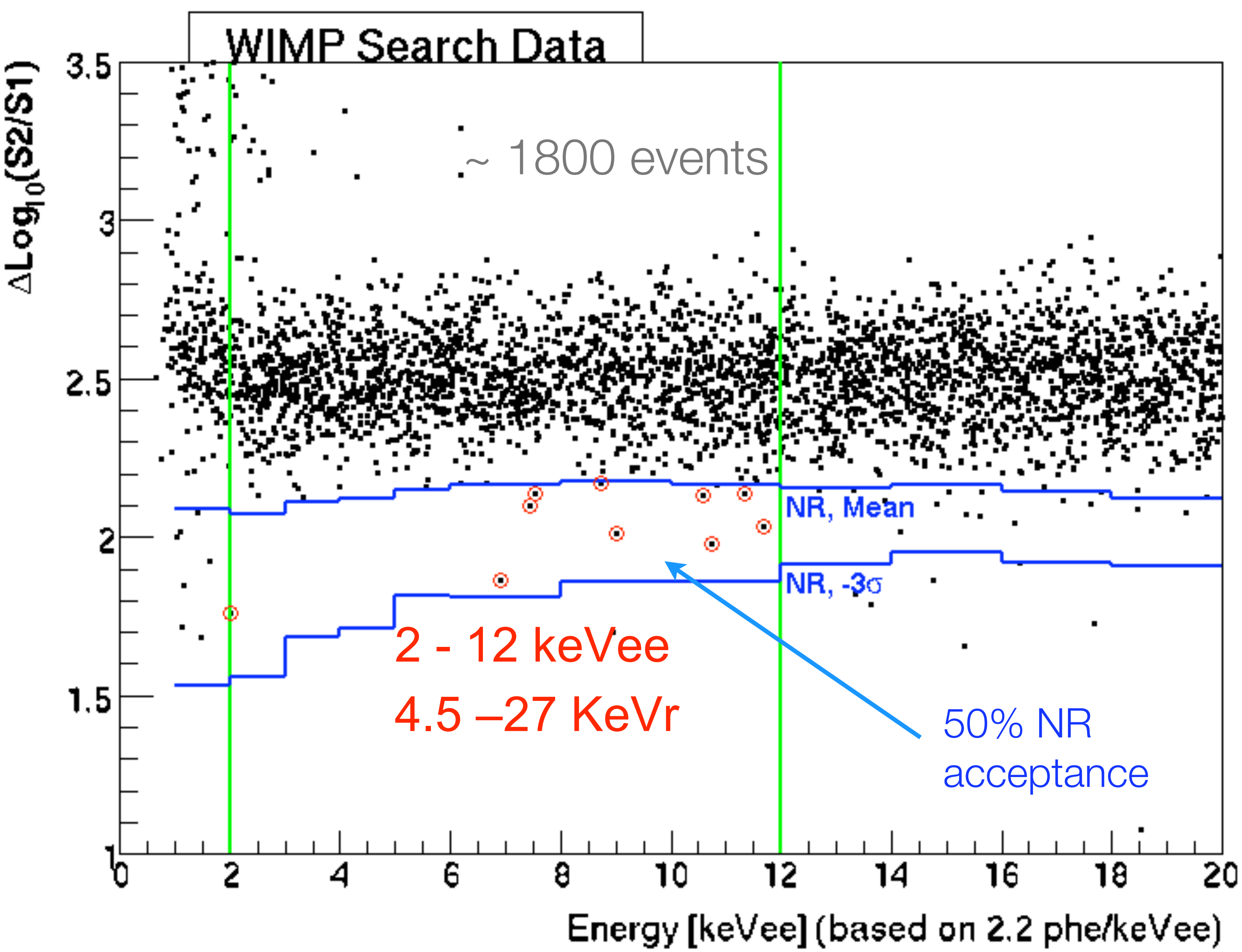




- **Fiducial Volume Cut**: 15 μs < dt < 65 μs, r < 80 mm => fiducial mass = 5.4 kg
- **Overall Background** in Fiducial Volume: ~ **0.6 events/(kg · day · keVee)**

XENON10 WIMP Search Data

- WIMP search run Aug. 24. 2006 - February 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)



4.5 keVr **27 keVr**

WIMP 'Box' defined at

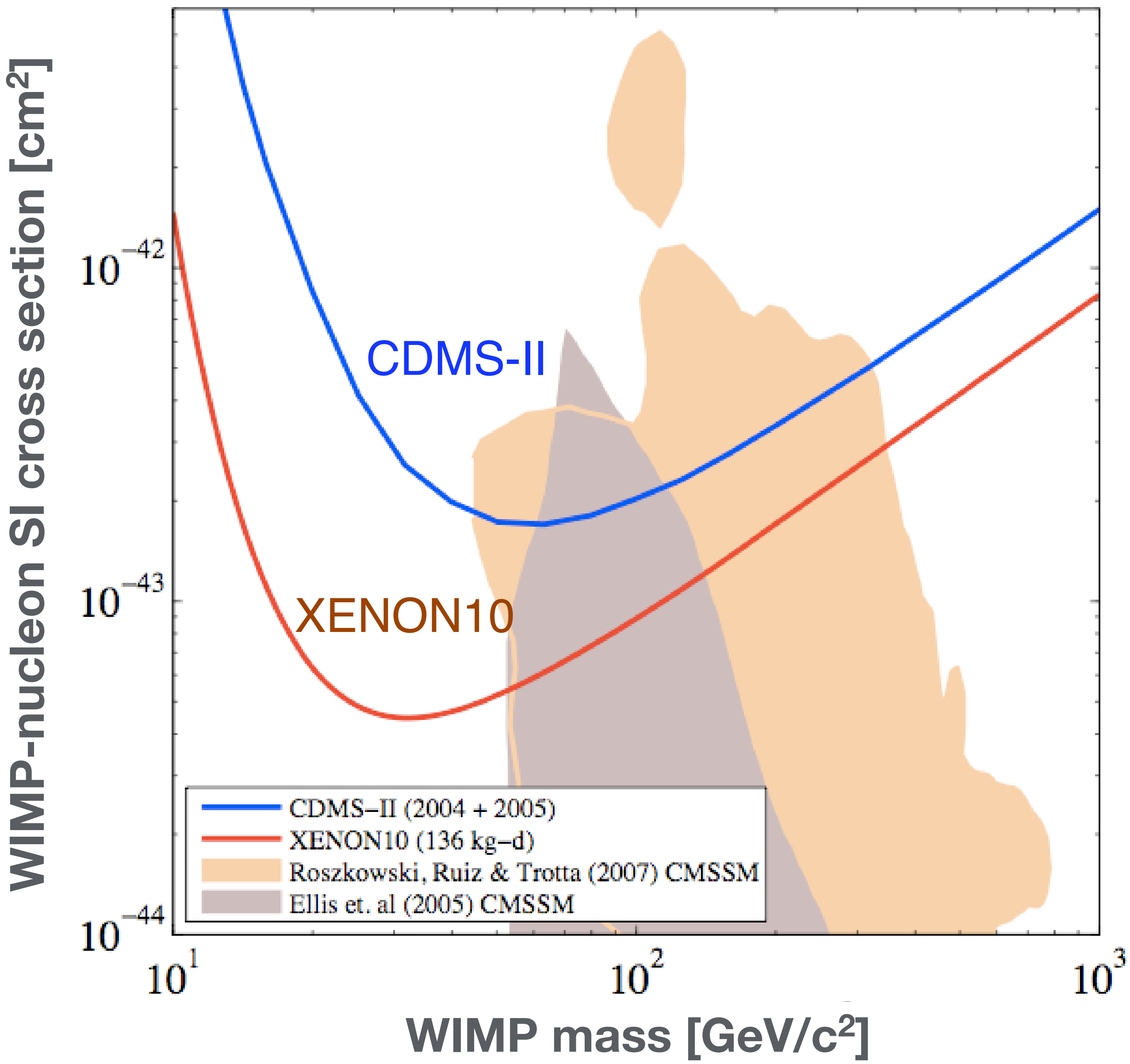
50% acceptance of NRs (blue lines): [Mean,-3σ]

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 Interactions

- To set limits: all 10 events considered, thus no background subtraction performed
- Probe the elastic, SI WIMP-nucleon σ down to ≈ **4×10^{-44} cm^2** (at M_{WIMP} = 30 GeV)



Upper limits in WIMP-nucleon cross section derived with Yellin Maximal Gap Method [PRD 66 (2002)]

At 100 GeV WIMP mass

9.0×10^{-44} cm^2 (no background subtraction, red curve)

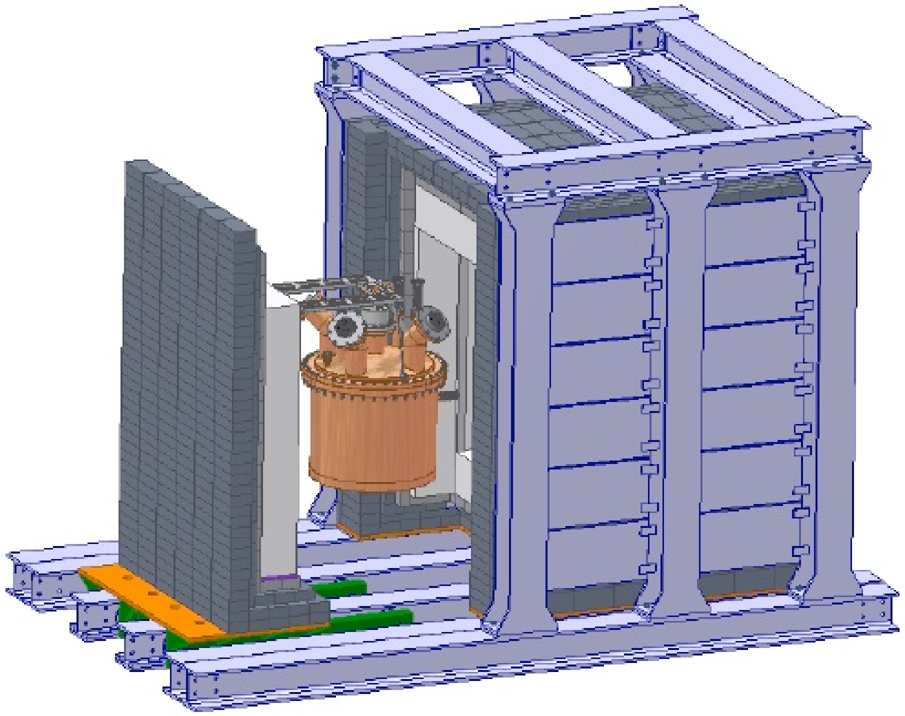
5.5×10^{-44} cm^2 (known background subtracted, not shown)

Factor 6 below previous best limit

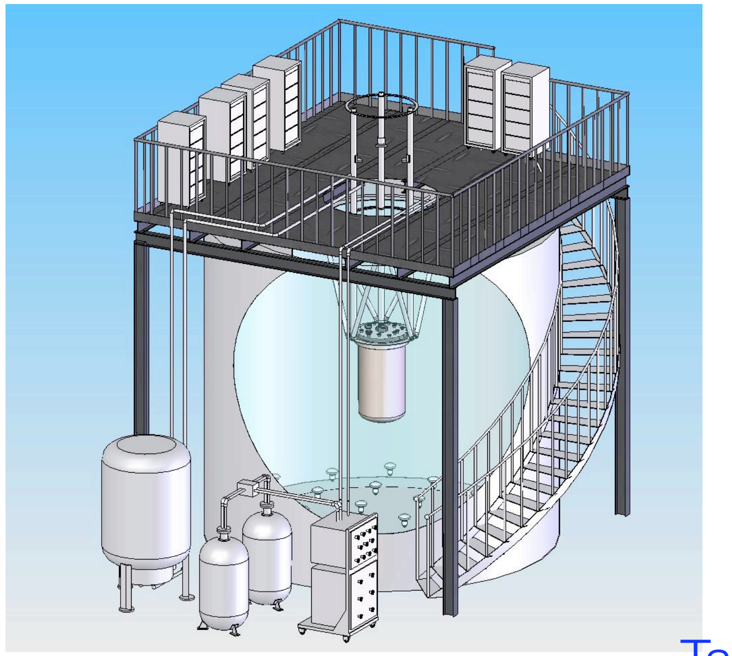
Results submitted to PRL
arXiv:0706.0039 (XENON collaboration)

Dual-Phase Xenon: Future Projects

- **XENON10+:** US/EU Collaboration to build ~ 60kg (fiducial) LXe detector in (conventional: Pb, PE) XENON10 shield at LNGS (NSF/SNF/FCT proposal)
- **LUX** (Large Underground LXe detector): US Collaboration to build a 100 kg (fiducial) LXe detector at DUSEL in large (6 m ø water shield) (NSF/DoE proposal)
- **ELIXIR** (European Liquid Xenon Identifier of Recoils): Large European design study for **ton-scale LXe detector**; Construction after completion of ZEPLIN-III, XENON10 + (FP7 proposal for design study submitted)



XENON100 experiment

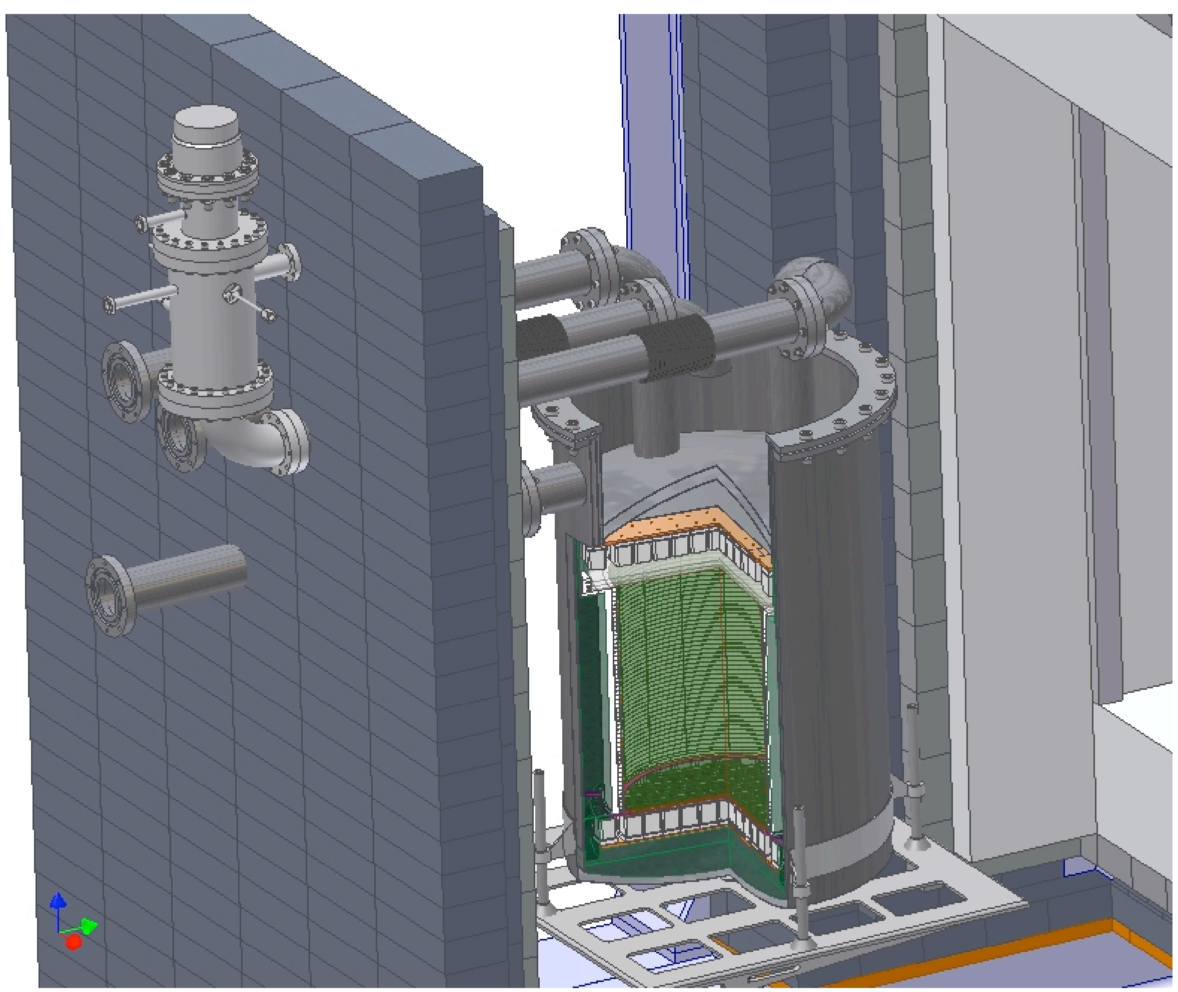


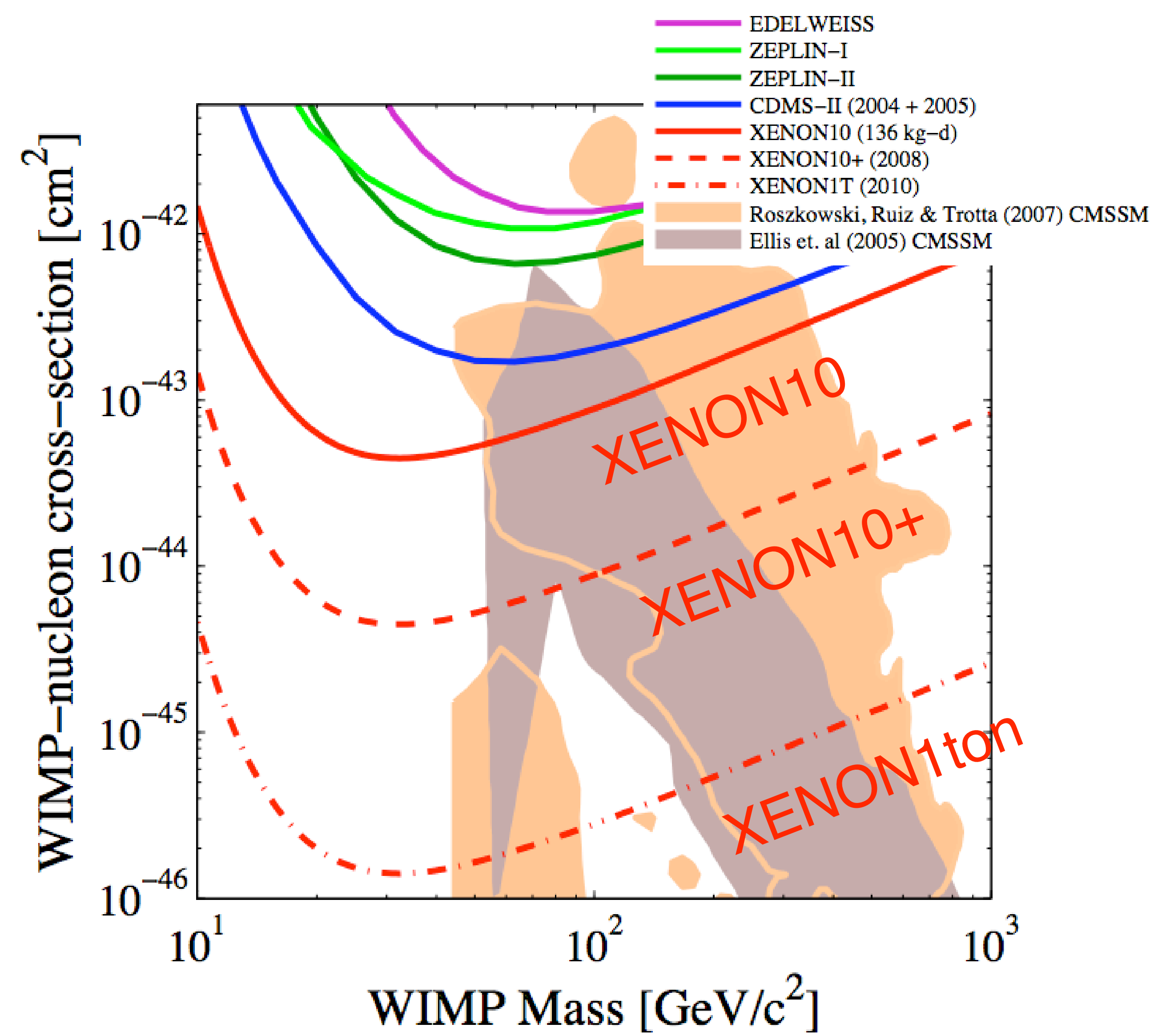
LUX experiment

Talk by Mani Tripathi
in Cosmology session

The XENON10+ Experiment at Gran Sasso

- Xenon10+: ‘de-scoped’ version of Xenon100, approved by NSF in US
- low-background (steel) cryostat; cryogenics and FTs outside passive shield
- larger number of PMTs, larger target mass, active LXe veto
- design/MCs in progress; results expected by end 2008 (aim factor 10 in sensitivity)





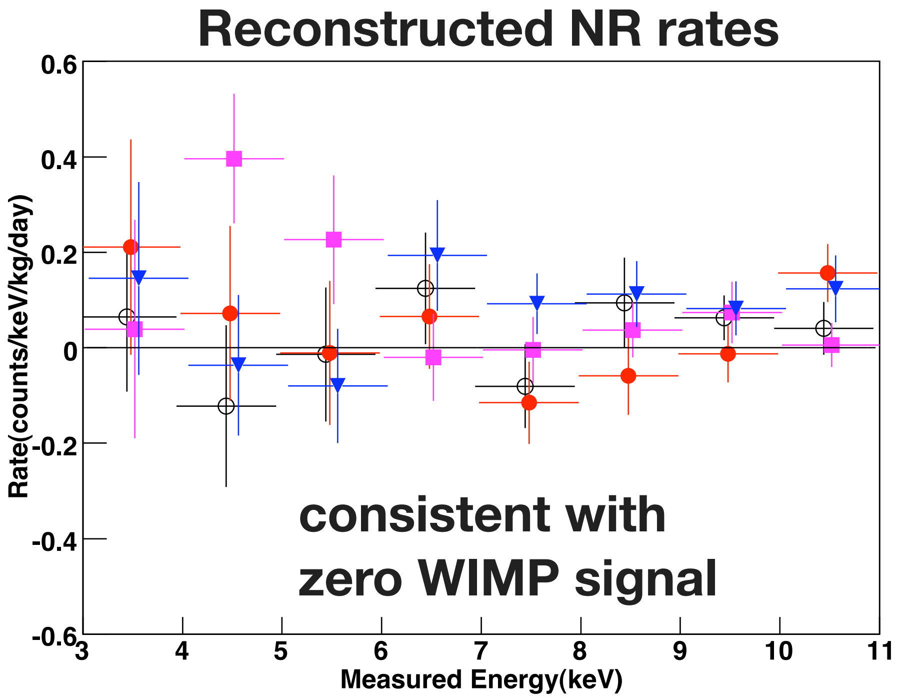
The KIMS Experiment

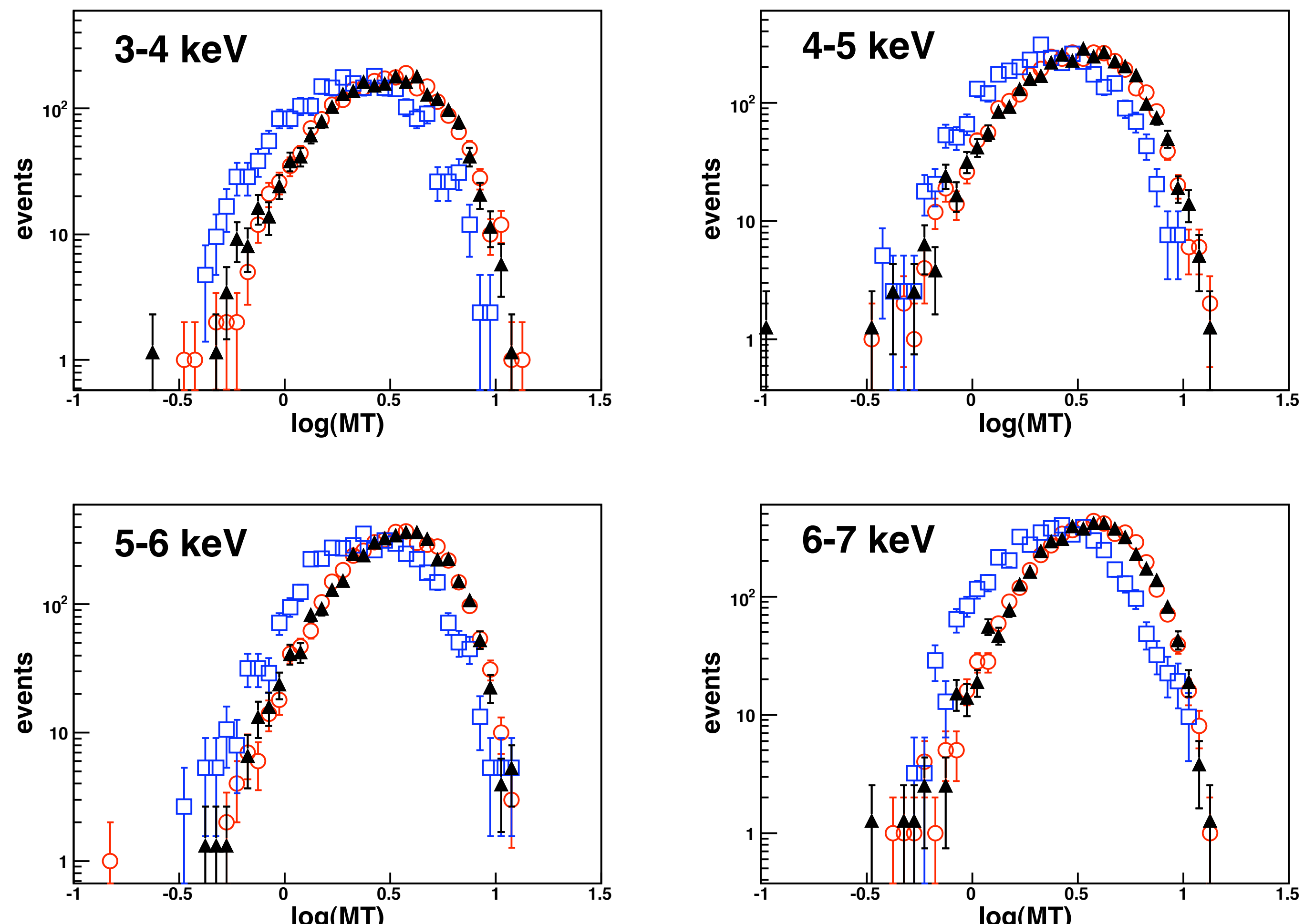
- 4×CsI (Tl) crystals (34.8 kg) at the Yangyang Laboratory in Korea (2000 m.w.e.) at 0ºC
- Background reduction by Pulse Shape Discrimination
- **3407 kg · days of WIMP Search data**

	CsI(Tl)	NaI(Tl)
Density(g/cm3)	4.53	3.67
Decay Time(ns)	~1050	~230
Peak emission(nm)	550	415
Hygroscopicity	slight	strong

H.S. Lee et al., arXiv:0704.0423

blue: nuclear recoils (calib n-source)
red: electron recoils (calib γ-source)
black: WIMP search data

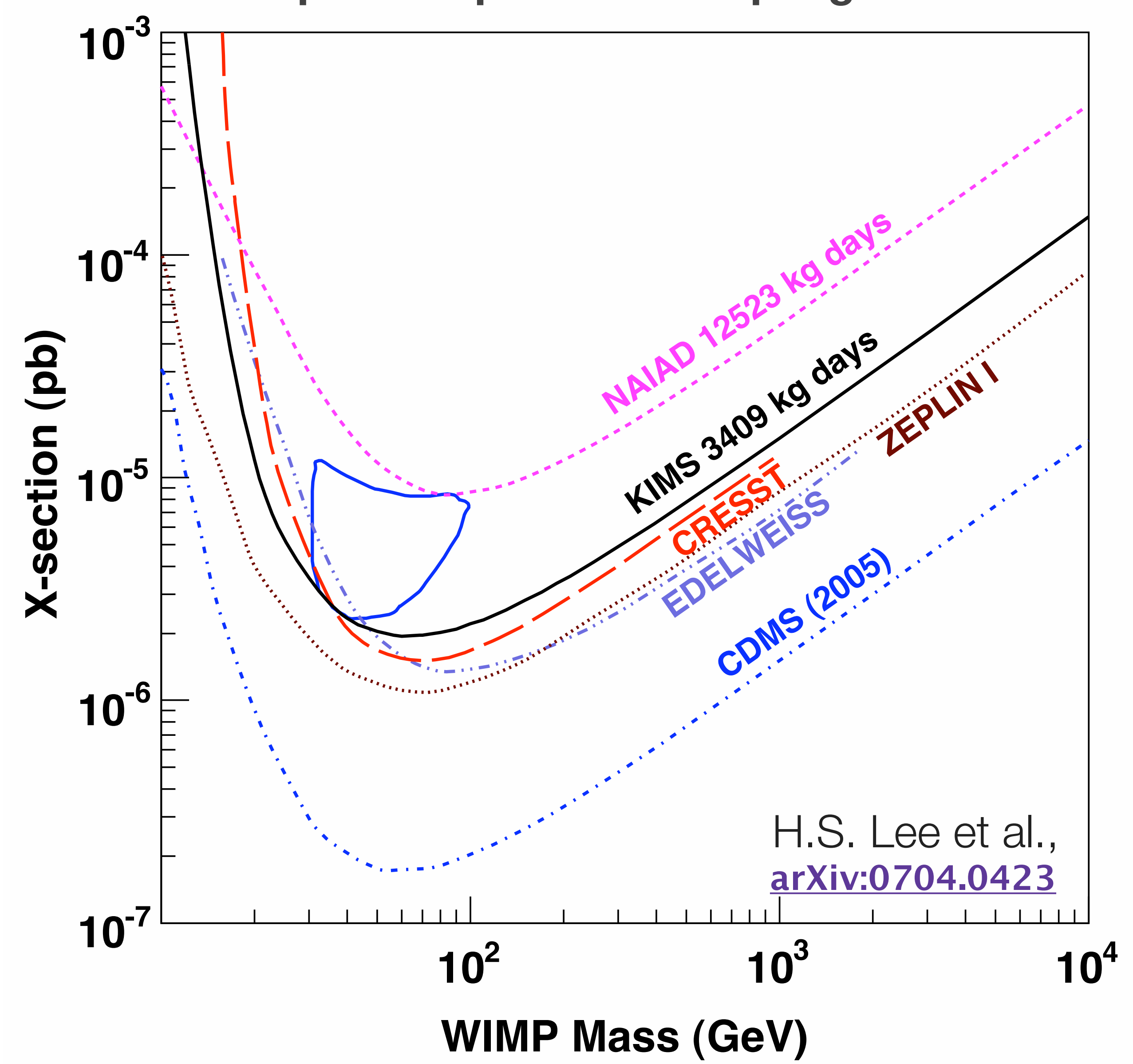




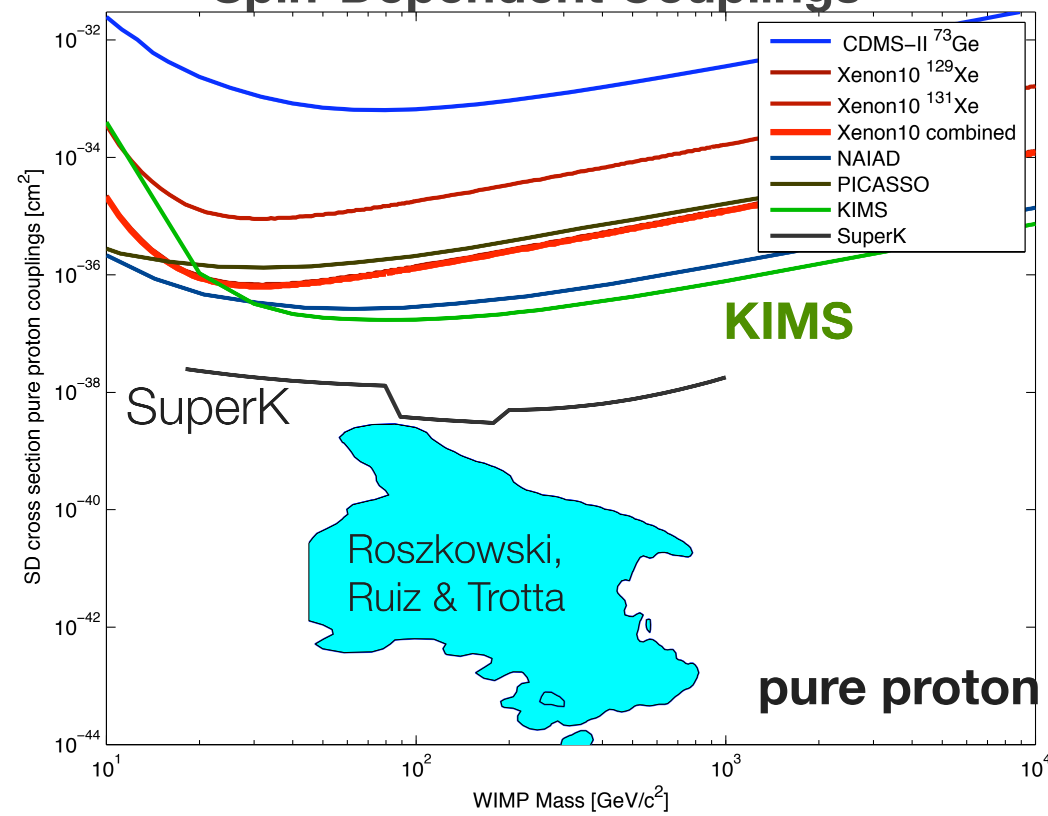
(**MT**: mean time of event)

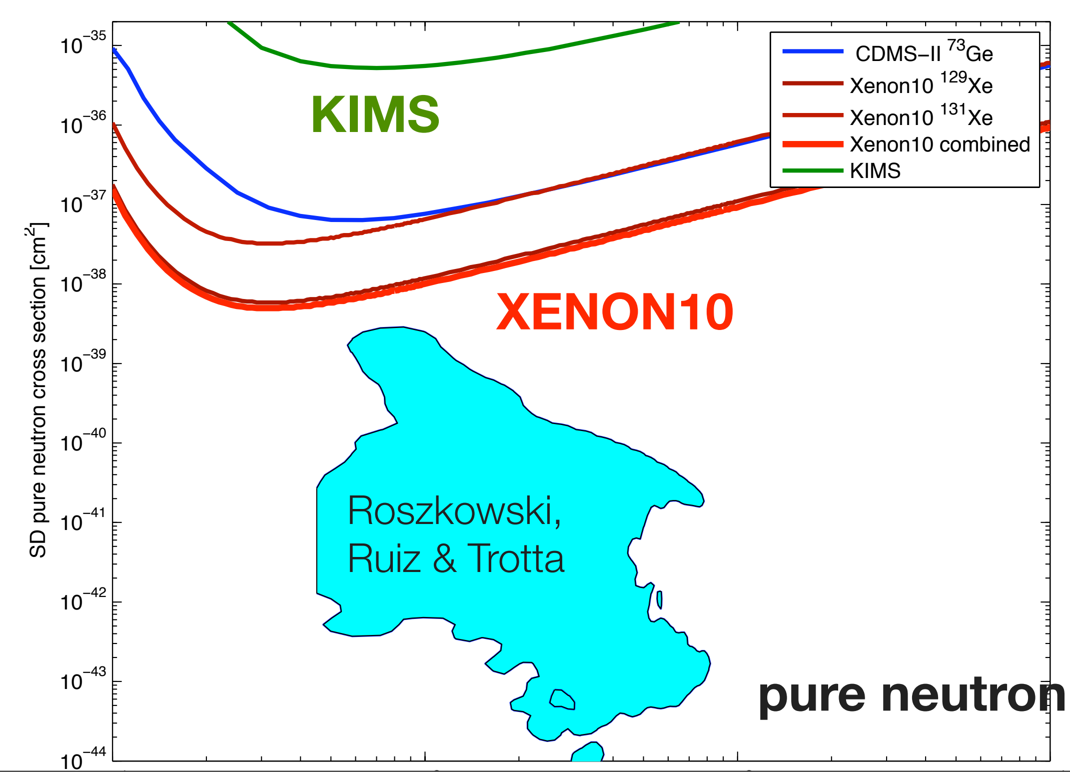
KIMS Results on WIMP Searches

Spin-Independent Couplings



Spin-Dependent Couplings

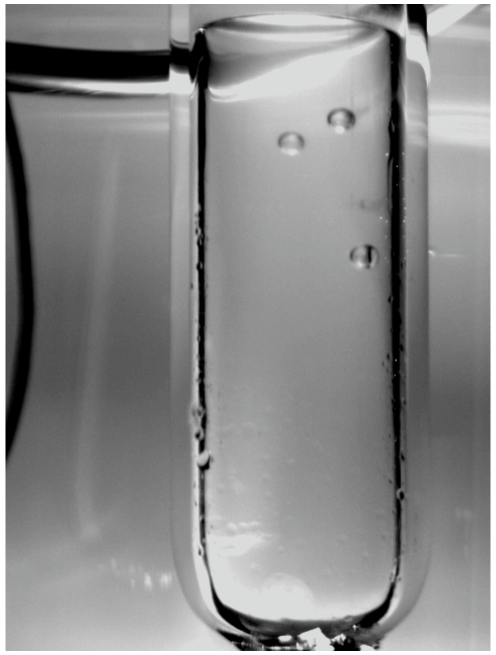




Excludes DAMA for SI and SD couplings
(with CsI scintillating crystals!, M_W>20GeV/c^2)
Best limit for SD pure p-couplings

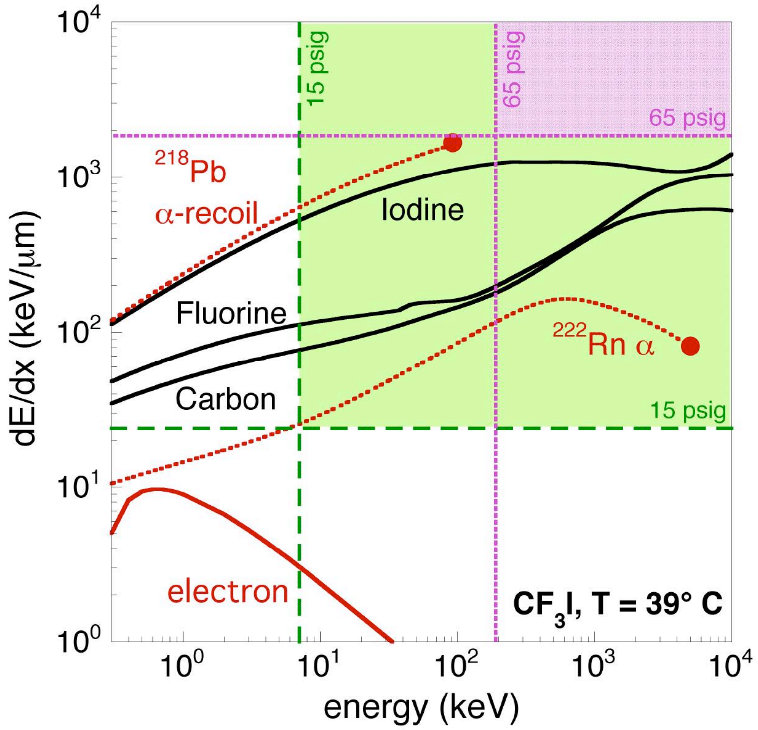
Bubble Chambers as WIMP Detectors

- **COUPP**: 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

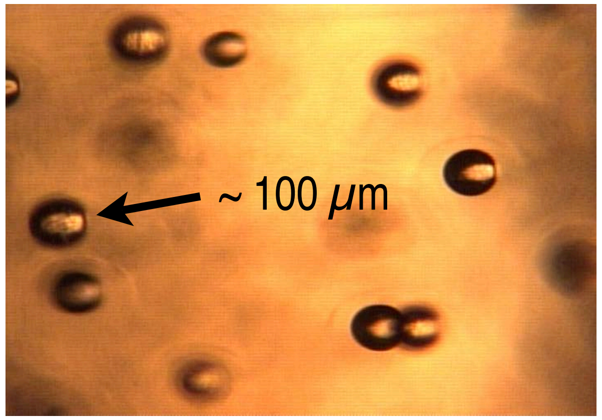


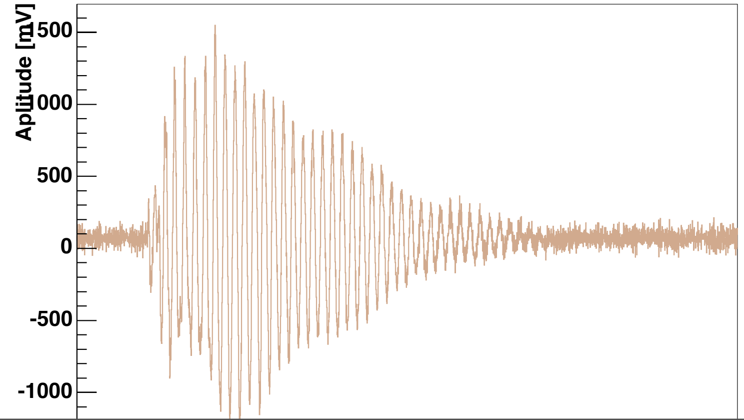
2 kg detector at 300 mwe in 2006: alpha BG from walls ^{222}Rn decays -> ^{210}Pb plate-out + ^{222}Rn emanation from materials

new run with 2 kg in 2007 (reduced backgrounds)

80 kg module approved by FNAL ready by end of 2007 -> 3 x 10^{-8}pb

- **PICASSO**: bubbles of liquid C_4F_{10} in matched density CsCl gel; acoustic read-out, 10^7 rejections of ERs



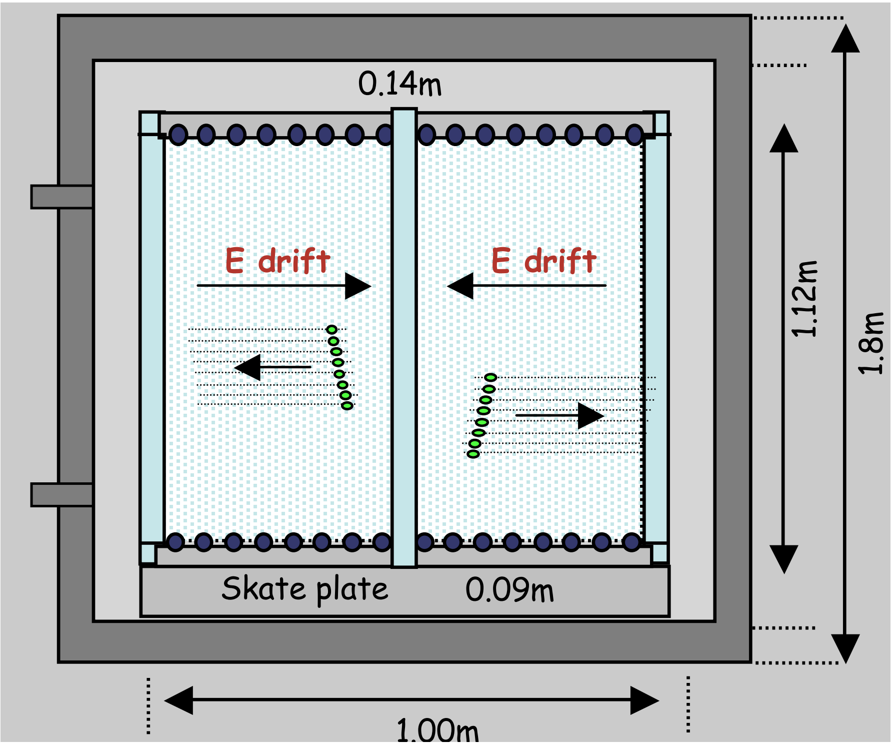


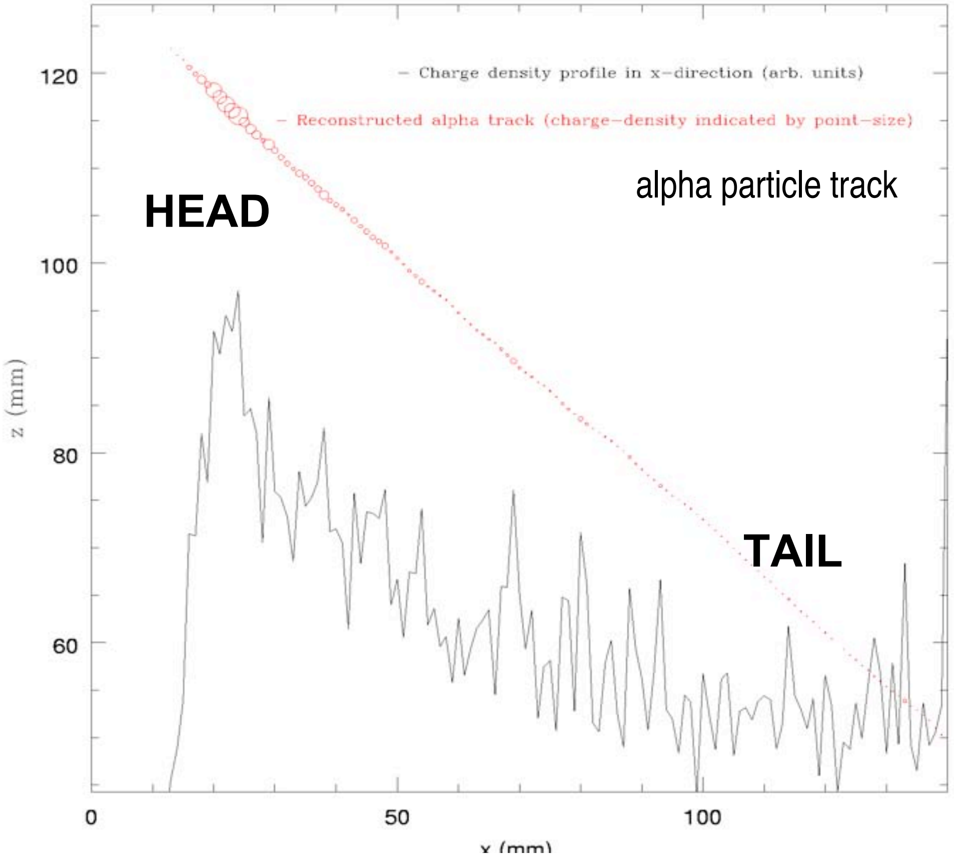
2 kg-d in 2004; alpha BG from CsCl competitive proton SD limits (1 pb)

installing 34 x 4.5 l detectors = 2.6 kg improved backgrounds
4 already running => new results soon!

Directional Detectors: DRIFT

- **Negative ion (CS_2) TPC**: 1 m^3 40 Torr CS_2 gas (0.17 kg); 2 mm pitch anode + crossed MWPC grid->2D
- NR discrimination via track morphology in gas (gamma misidentification probability < 5 x 10^{-6})
- **3D track reconstruction** for recoil direction: find head-tail of recoil based on dE/dx; so far demonstrated for alphas with 100 mm long tracks
- DRIFT IIa operated at Boulby in 2005: background from Rn emanation of detector components (recoiling nuclei from alpha-decays on cathode wires); 6 kd-d of data being analyzed
- **DRIFT IIb: installed in 2006, run in summer 2007 with strongly reduced Rn backgrounds**



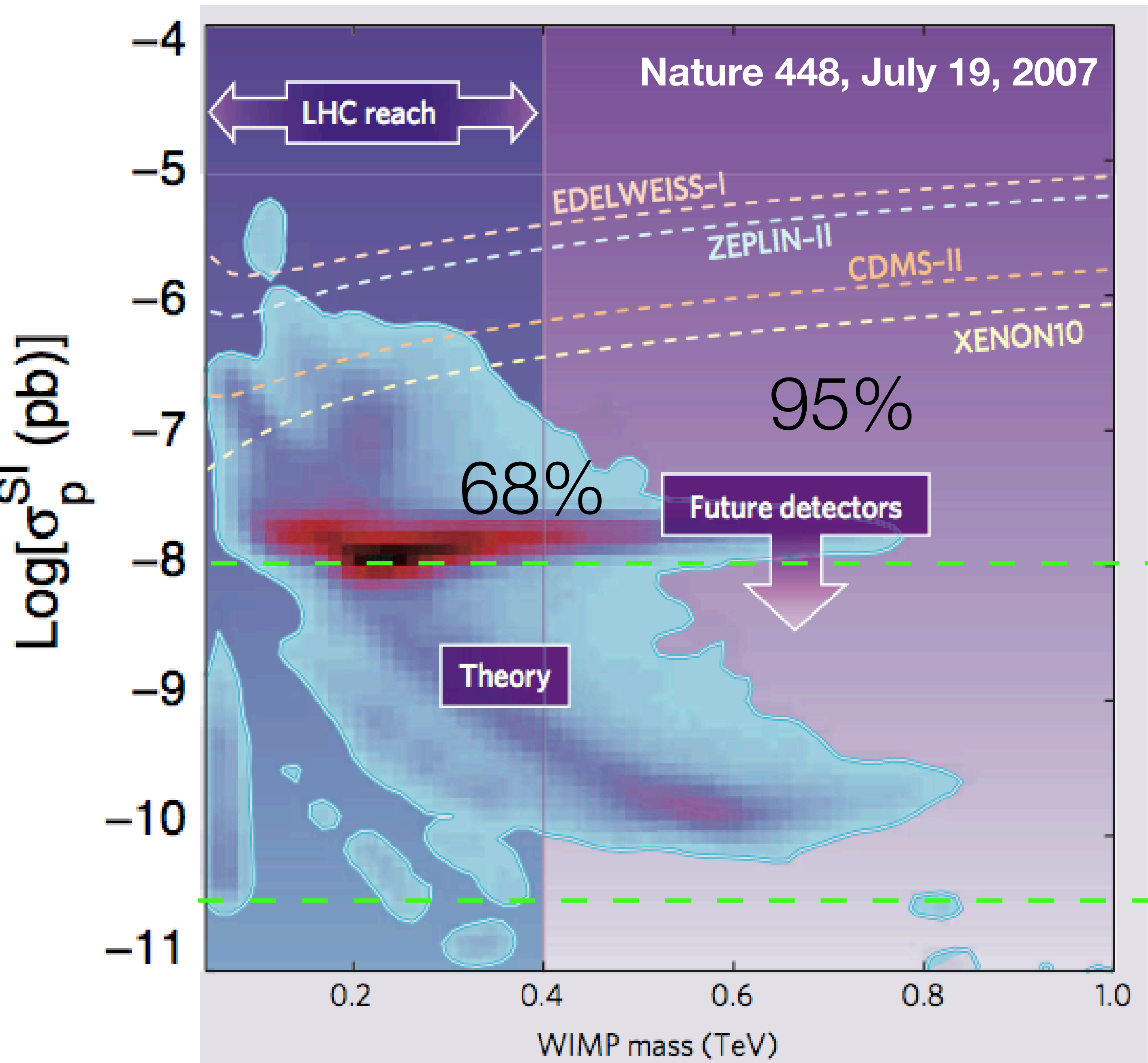


Summary

Many different techniques/targets are being employed to search for dark matter particles

Sensitivities are now approaching the theoretically interesting regions!

Next generation projects: should reach the $\lesssim 10^{-10}$ pb level => WIMP (astro)-physics



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

1 event/kg/yr

CDMS-II, XENON10+, COUPP, CRESST-II, EDELWEISS-II, ZEPLIN-III,...

1 event/t/yr

SuperCDMS1t, WARP1t, ArDM XENON1t, EURECA, ELIXIR, XMASS, ...

Axions

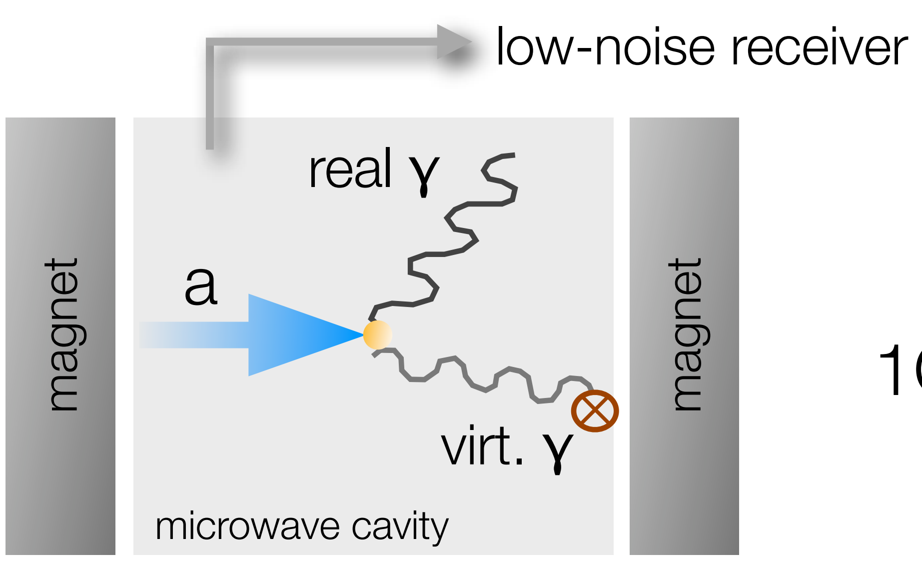
- postulated to explain the absence of CP violation in the strong interaction
- **axion**: zero spin, zero charge, negative intrinsic parity, two-photon coupling ($\tau \approx 10^{50}$ s)
- **axion mass:** not a priori known, any mass can solve the 'strong CP problem'; constraints from nuclear and HE physics, stellar evolution and cosmology

$$10^{-6}\ \mathrm{eV} \lesssim m_a \lesssim 3 \cdot 10^{-3}\ \mathrm{eV}$$

- **axion detection**: by stimulating their conversion into microwave photons in an electromagnetic cavity permeated by a strong magnetic field (Sikivie, 1983); the condition for resonant conversion is:

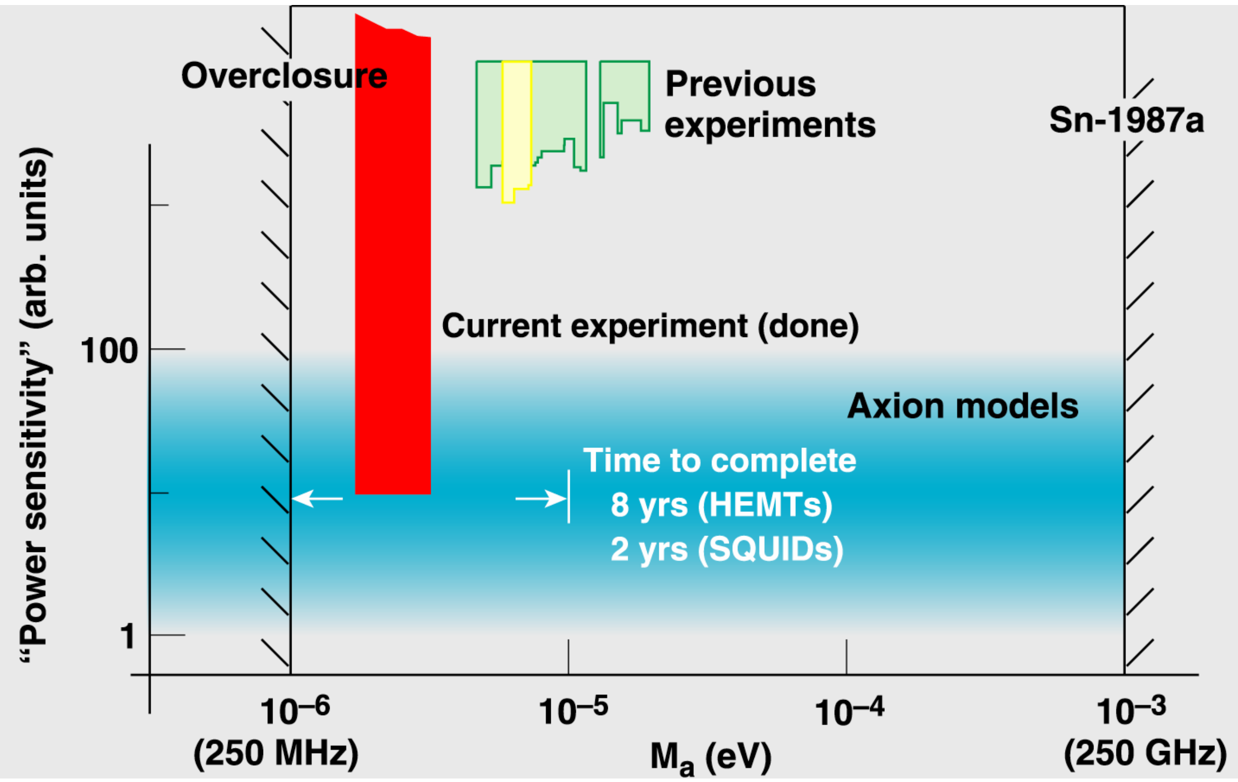
$$h\nu \cong m_a \cdot c^2$$

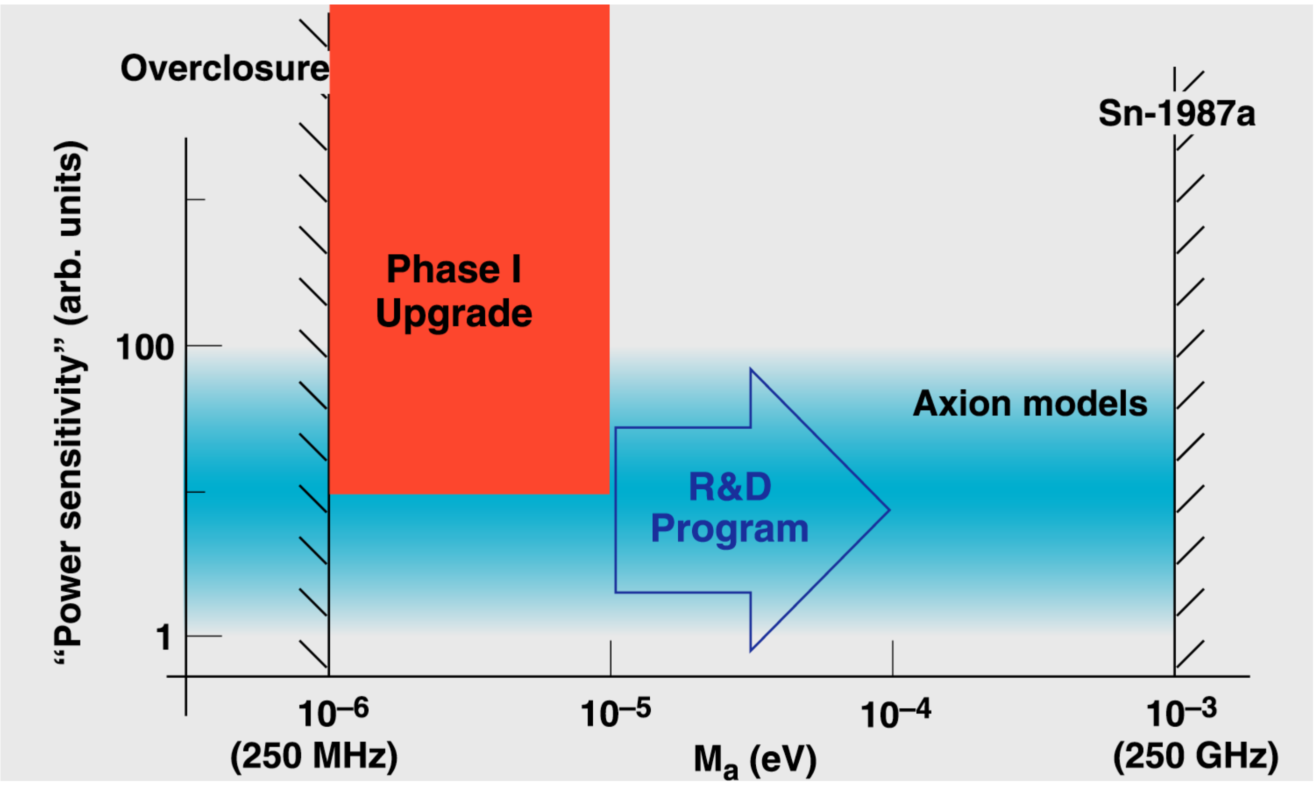
- **experiments:** AXDM (US), CARRACK (Japan), CAST (solar axions, international collaboration, at CERN)

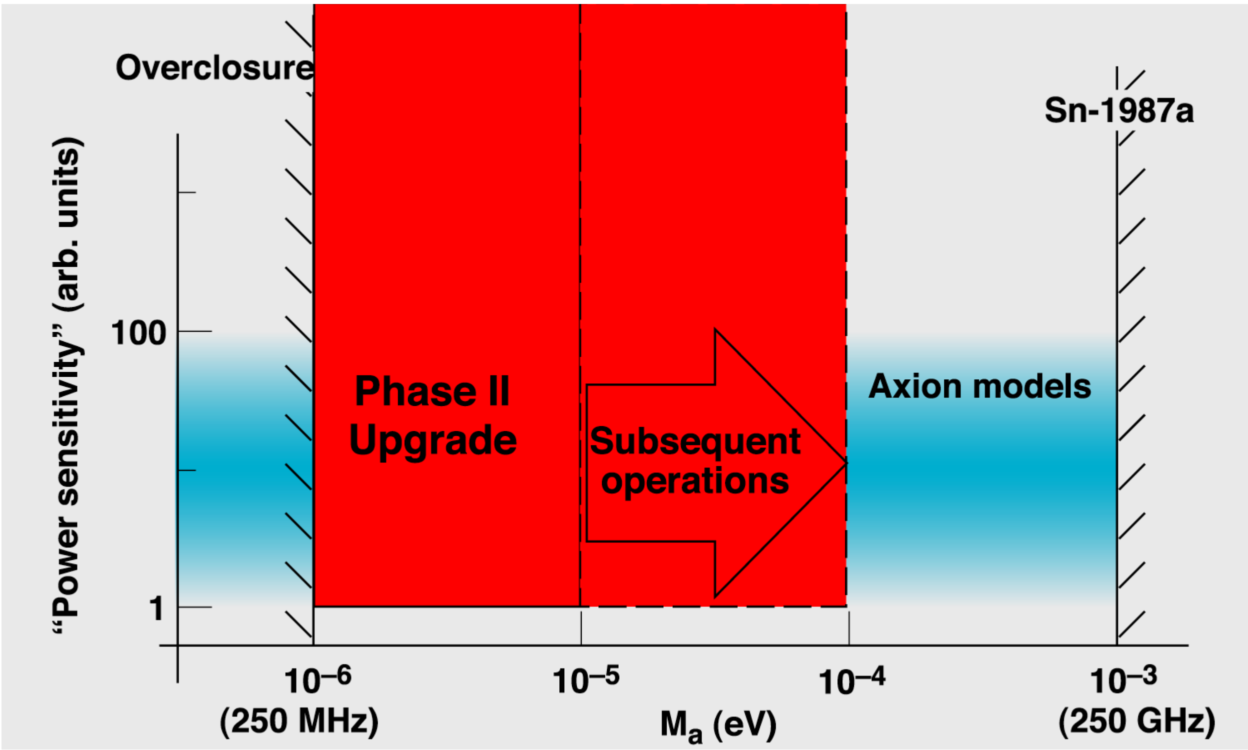


1GHz = 4μeV

Parameter space for axions as DM candidates







S. Asztalos, Patras, June 2007

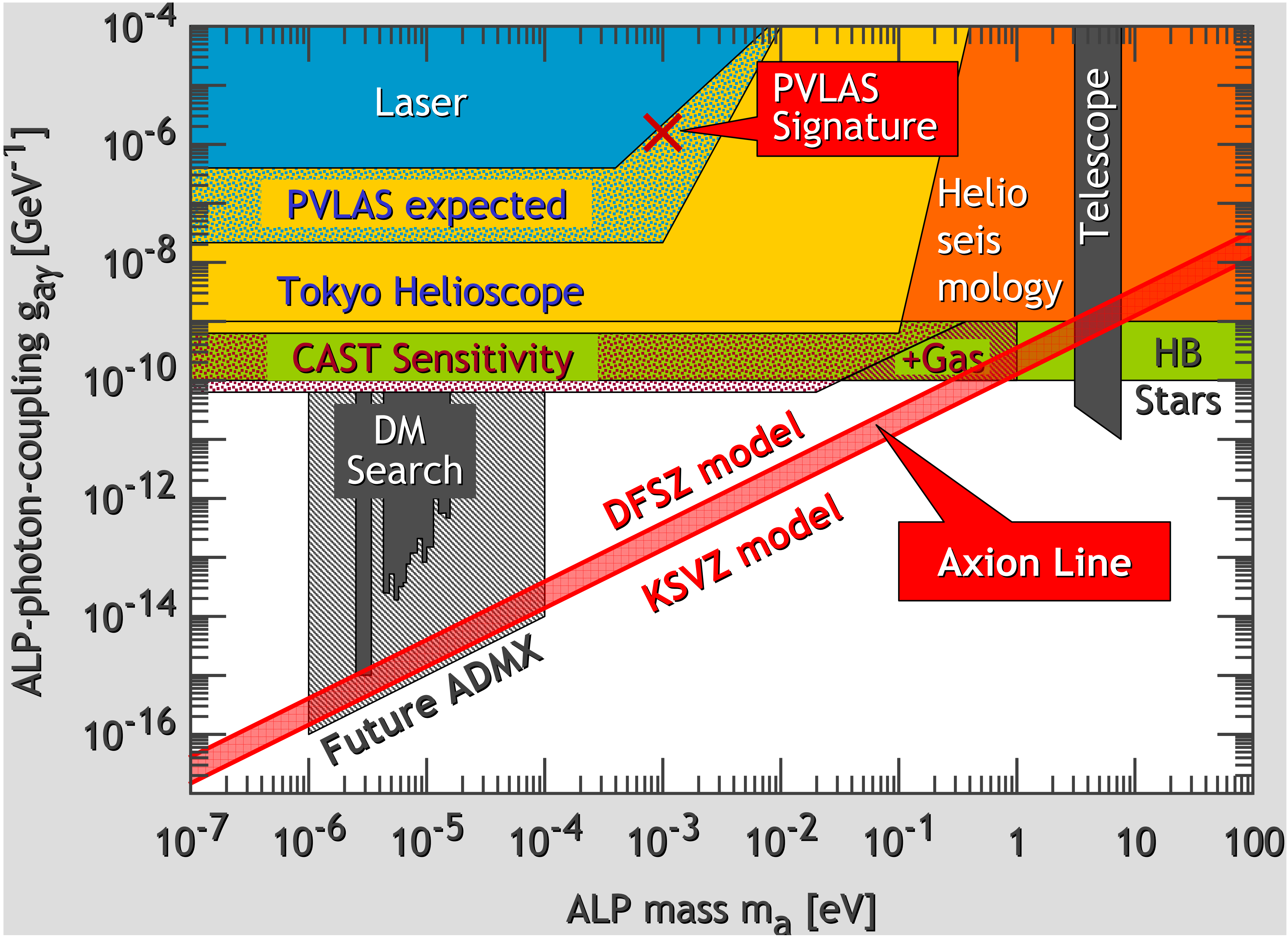
Current ADMX experiment:
- cooling: pumped LHe, conventional readout (HFETs)
- physical T = 1.3 K, system noise T_S = 3 K

Phase I Upgrade:
- SQUID readout
- physical T = 1.3 K, system noise T_S = 1.3 K
- upgrade is ongoing; run ~ mid 2007

Phase II Upgrade:
- dilution refrigerator: T ~ 100 mK, $T_S \leq$ 200 mK
- upgrade is planned

+ R&D: could cover 2/3 of predicted axion models

Constraints on the ALP Parameter Space



G. Raffelt, May 2007

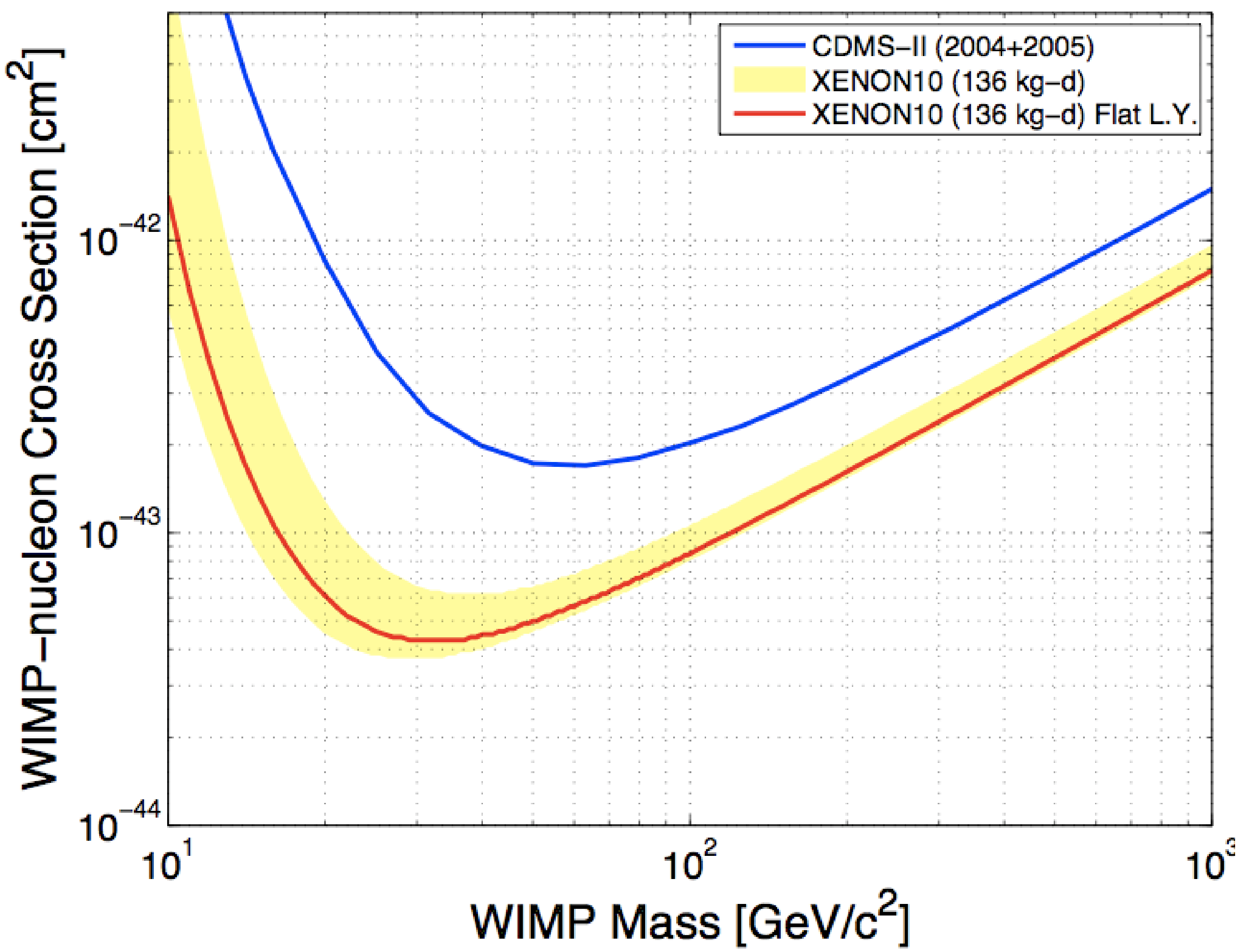
more slides

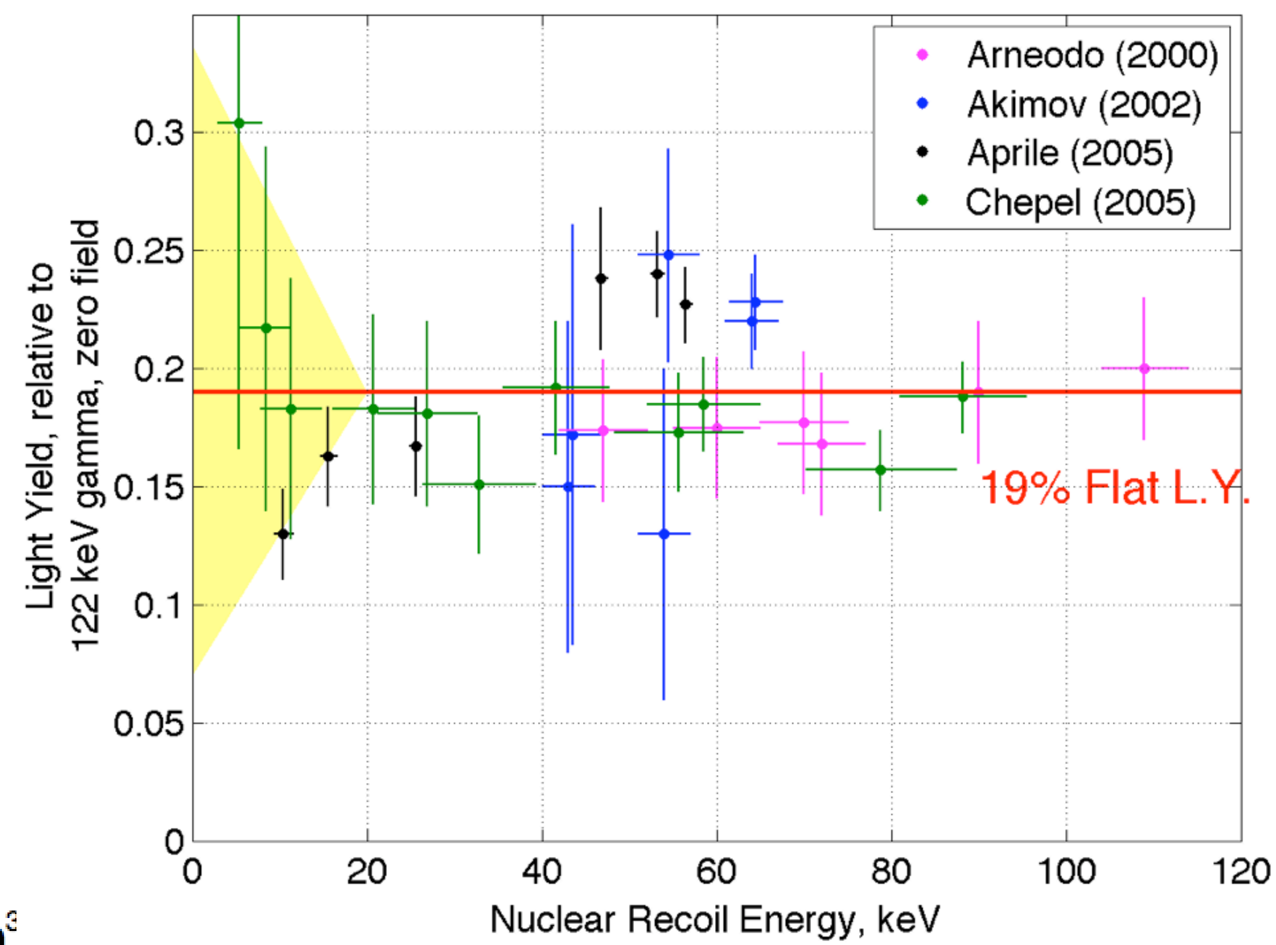
Noble Liquids as Detector Media

	Z (A)	BP (T_b) at 1 atm [K]	liquid density at T_b [g/cc]	ionization [e-/keV]	scintillation [photon/keV]
He	2 (4)	4.2	0.13	39	15
Ne	10 (20)	27.1	1.21	46	7
Ar	18 (40)	87.3	1.40	42	40
Kr	36 (84)	119.8	2.41	49	25
Xe	54 (131)	165.0	3.06	64	46

- Liquid noble gases yield both charge and light
- Scintillation is decreased (~ factor 2) when drift field to extract charge is applied

XENON10 Results: Effect of Light Yield Uncertainty





XENON10 Neutron Calibration

Energy of nuclear recoils (NRs)

Measured signal in nr. of p.e.

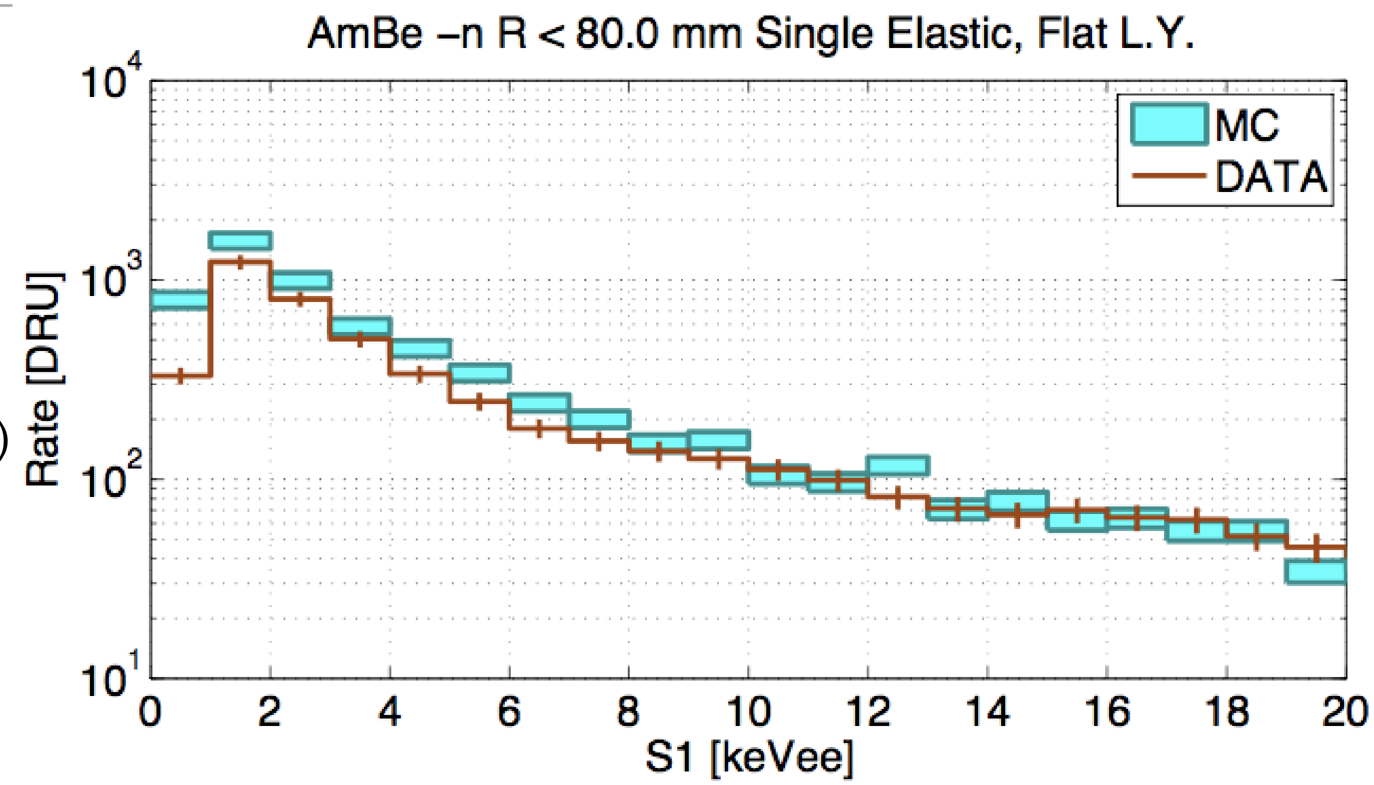
Quenching of scintillation yield for 122 keV γ's due to field (0.54 at 0.73 kV/cm)

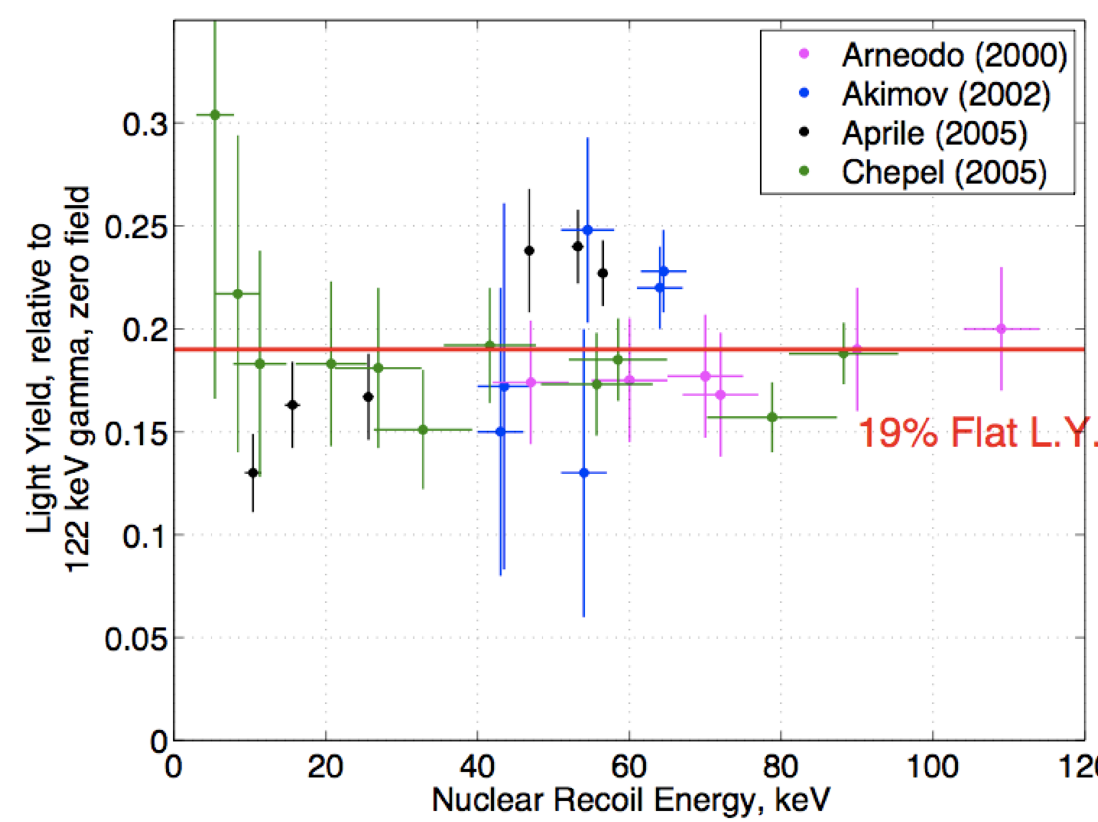
$$E_{nr} = \frac{S1}{L_y \cdot \mathcal{L}_{eff}} \times \frac{S_{er}}{S_{nr}}$$

Light yield for 122 keV γ in p.e. (3.00 p.e./keV)

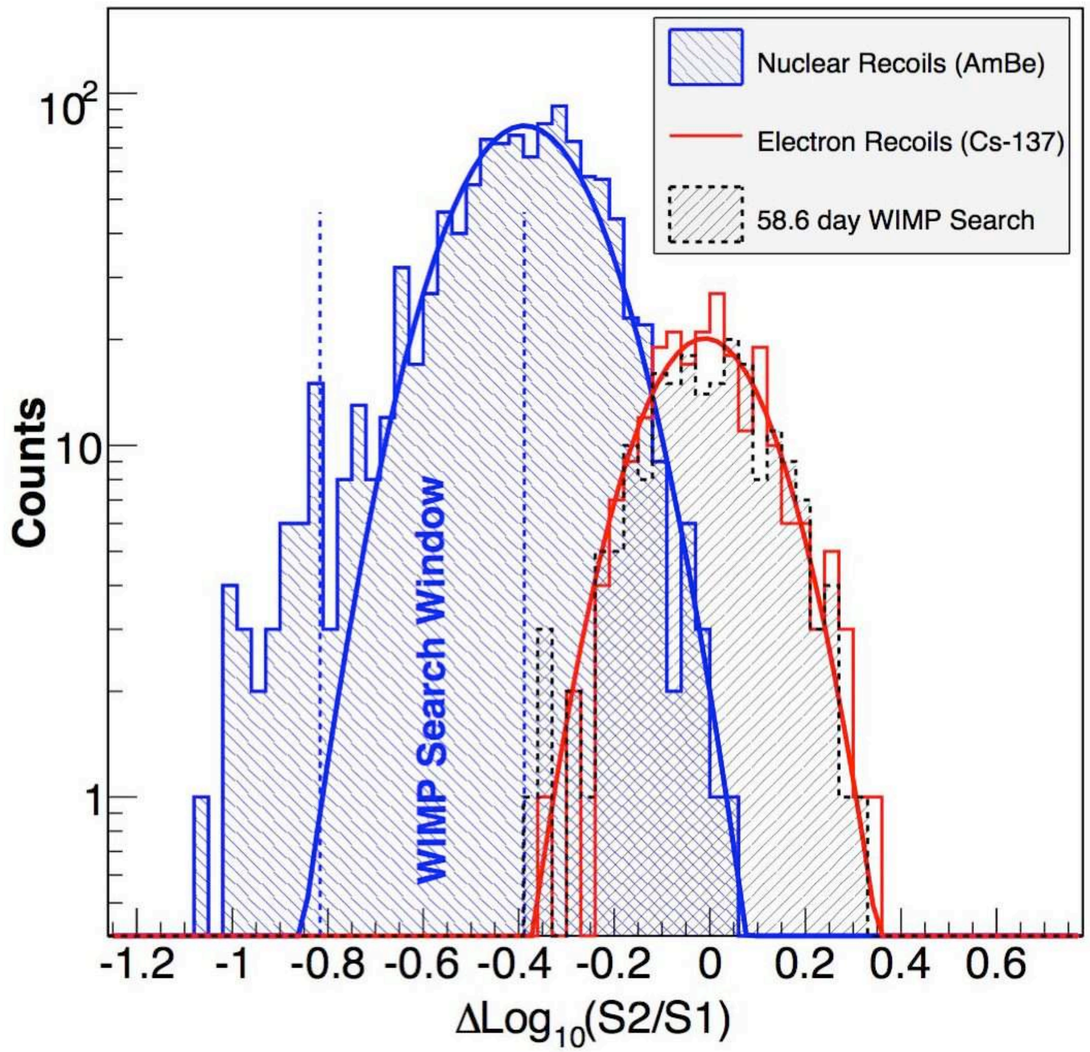
Relative scintillation efficiency of NRs to 122 keV γ's at zero field (flat value: 0.19)

Quenching of scintillation yield for NRs due to field (0.93 at 0.73 kV/cm)





XENON10: Event Distribution and Predicted Leakage



$\Delta Log_{10}(S2/S1)$ distribution in the 6.7-9.0 keVr energy bin

The distribution for ERs is fit by a Gaussian
-> the parameters are used to predict the number of stat. leakage events

Total cut efficiency on NRs

Acceptance of NRs

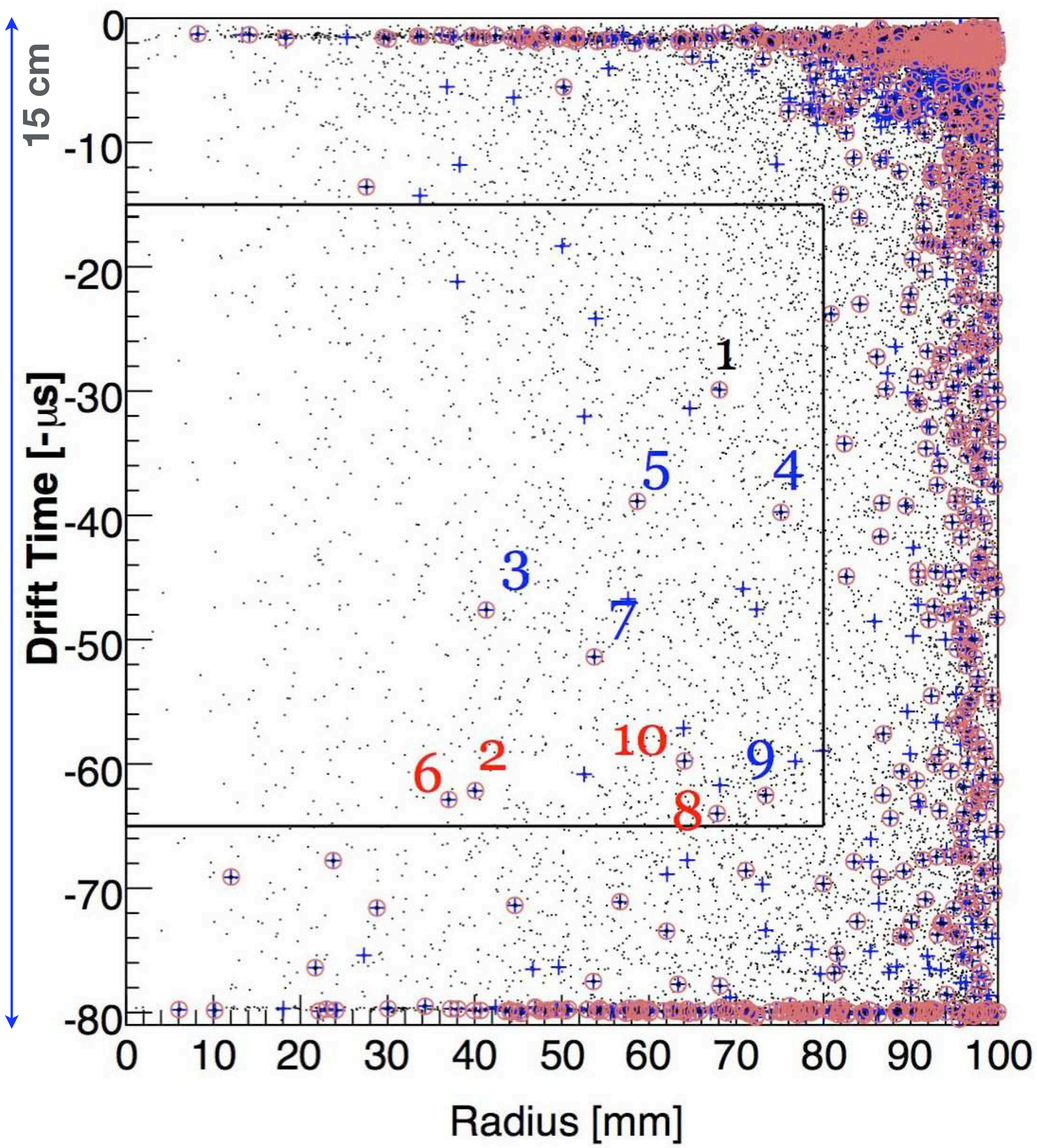
1 - ER rejection efficiency

E_{nr} (keV)	ε_c	A_{nr}	1 - R_{er} (10^{-3})	N_{evt}	N_{leak}
4.5 - 6.7	0.943	0.446	$0.8^{+0.7}_{-0.4}$	213	$0.2^{+0.2}_{-0.1}$
6.7 - 9.0	0.902	0.458	$1.7^{+1.6}_{-0.9}$	195	$0.3^{+0.3}_{-0.2}$
9.0 - 11.2	0.894	0.457	$1.1^{+0.9}_{-0.5}$	183	$0.2^{+0.2}_{-0.1}$
11.2 - 13.4	0.854	0.442	$4.1^{+3.6}_{-2.0}$	190	$0.8^{+0.7}_{-0.4}$
13.4 - 17.9	0.827	0.493	$4.2^{+1.8}_{-1.3}$	332	$1.4^{+0.6}_{-0.4}$
17.9 - 22.4	0.797	0.466	$4.3^{+1.7}_{-1.2}$	328	$1.4^{+0.5}_{-0.4}$
22.4 - 26.9	0.766	0.446	$7.2^{+2.4}_{-1.9}$	374	$2.7^{+0.9}_{-0.7}$
Total				1815	$7.0^{+1.4}_{-1.0}$

Predicted nr. of stat. leakage

Total nr. of events in 4.5-26.9 keVe

XENON10: Spatial Distribution of Events



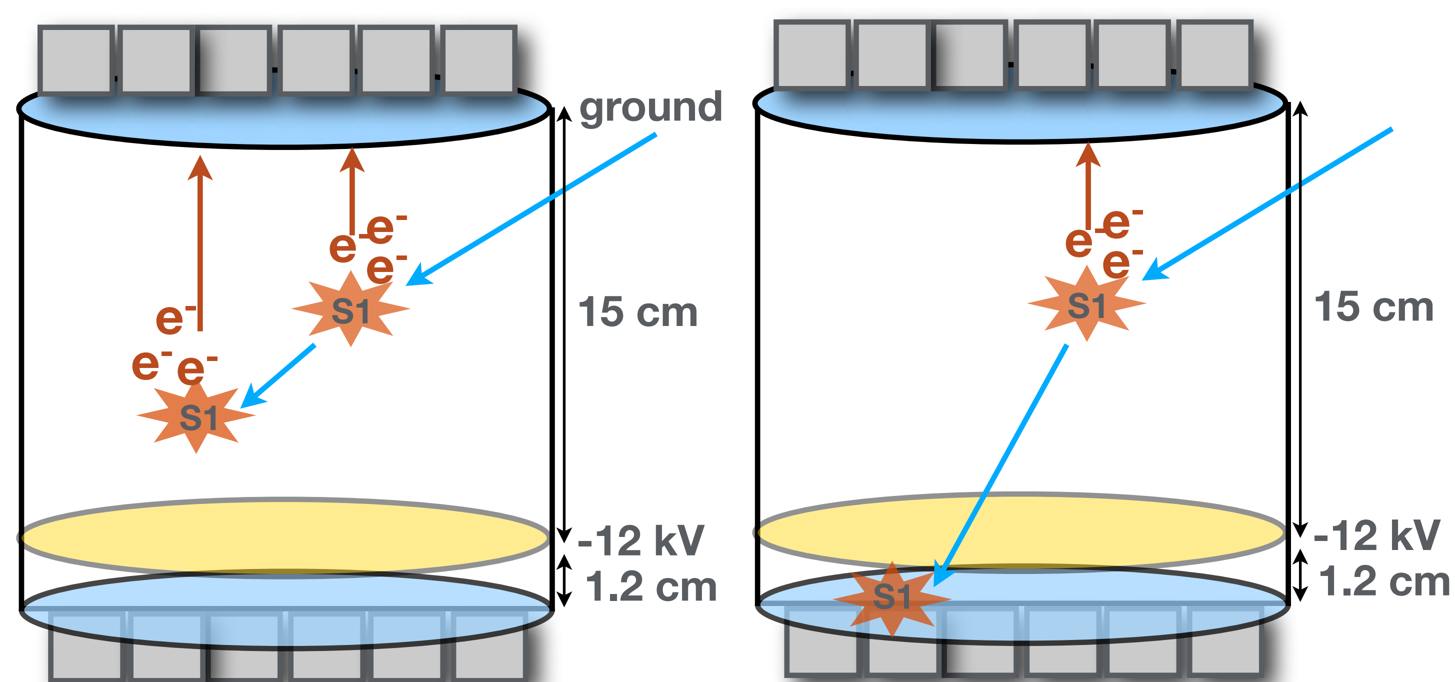
‘Gaussian events’: nr. 3, 4, 5, 7,9

‘Non-Gaussian events’: nr: 1, 2, 6, 8, 10

Ev. nr. 1: S1 due to noise glitch (a posteriori)

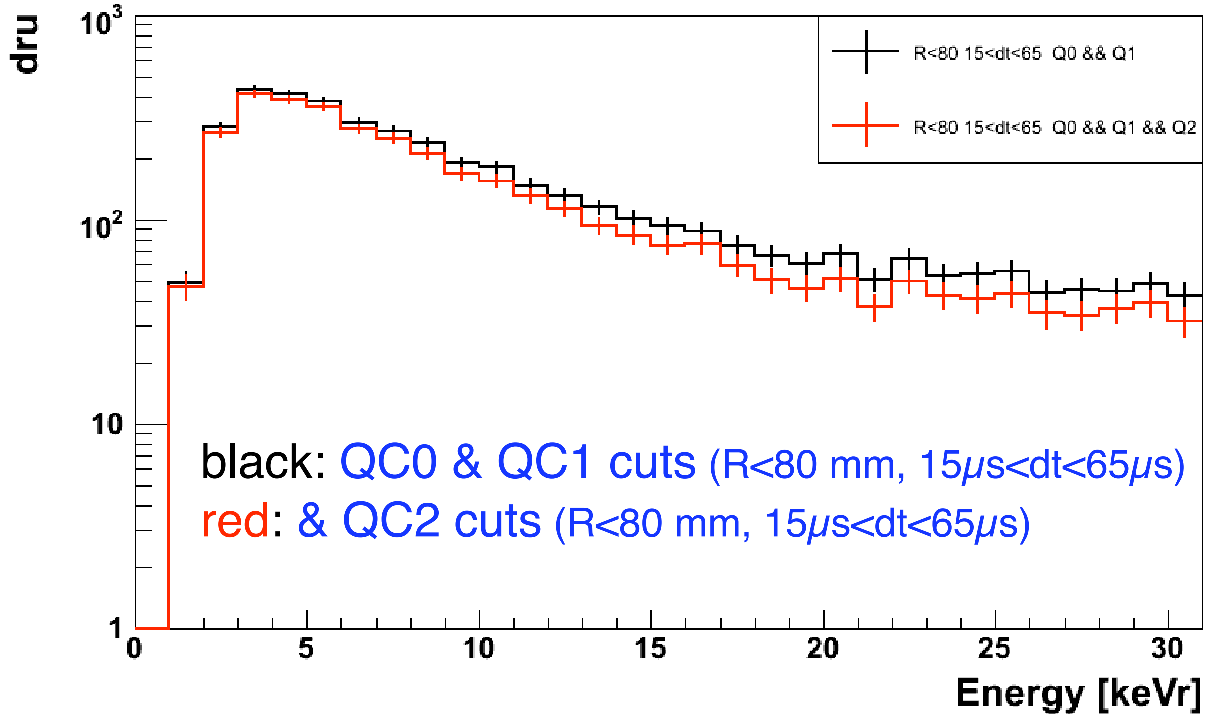
Ev. 2, 6, 8, 9 -> not WIMPs!

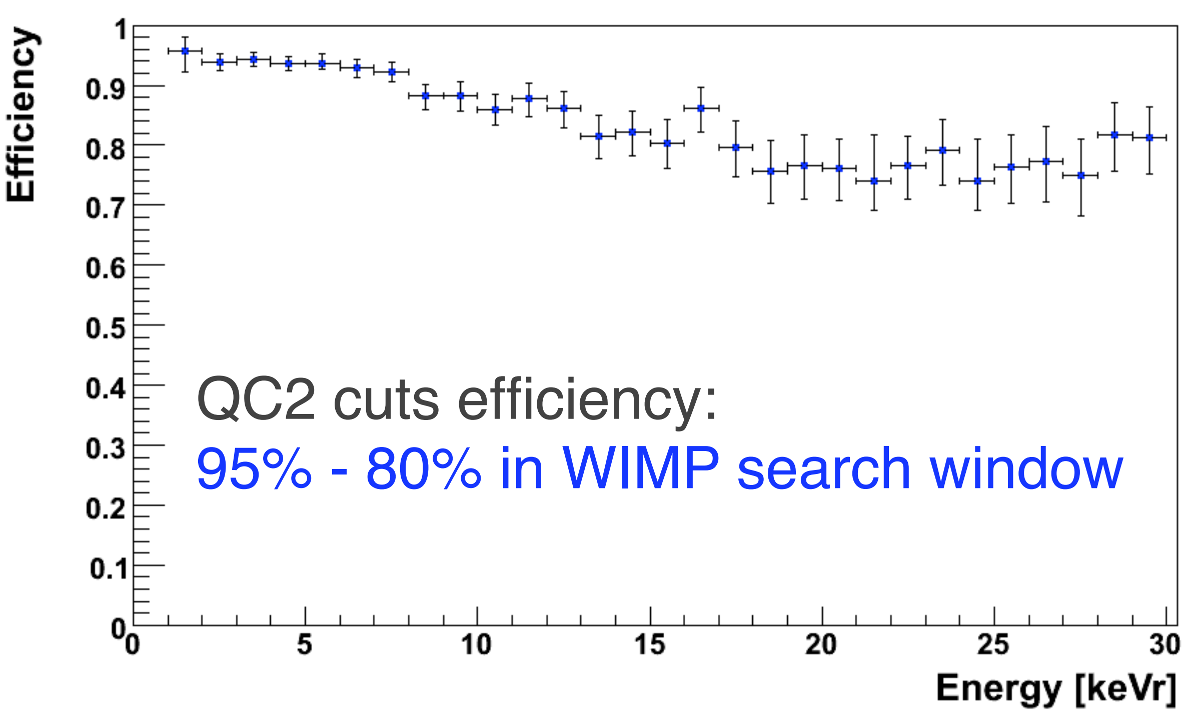
Likely explanation: reduced S2/S1-events due to double scatters with one scatter in a ‘dead’ LXe region => no S2 for 2nd scatter



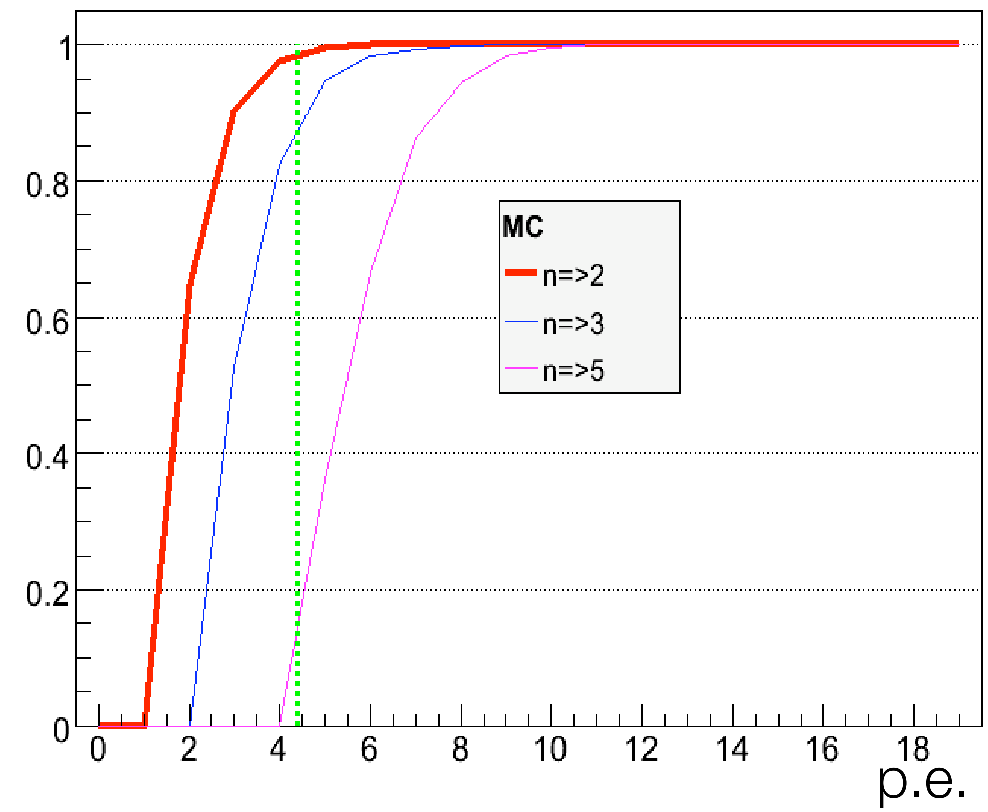
XENON10: Analysis Cut Efficiencies

neutron data





S1 efficiency

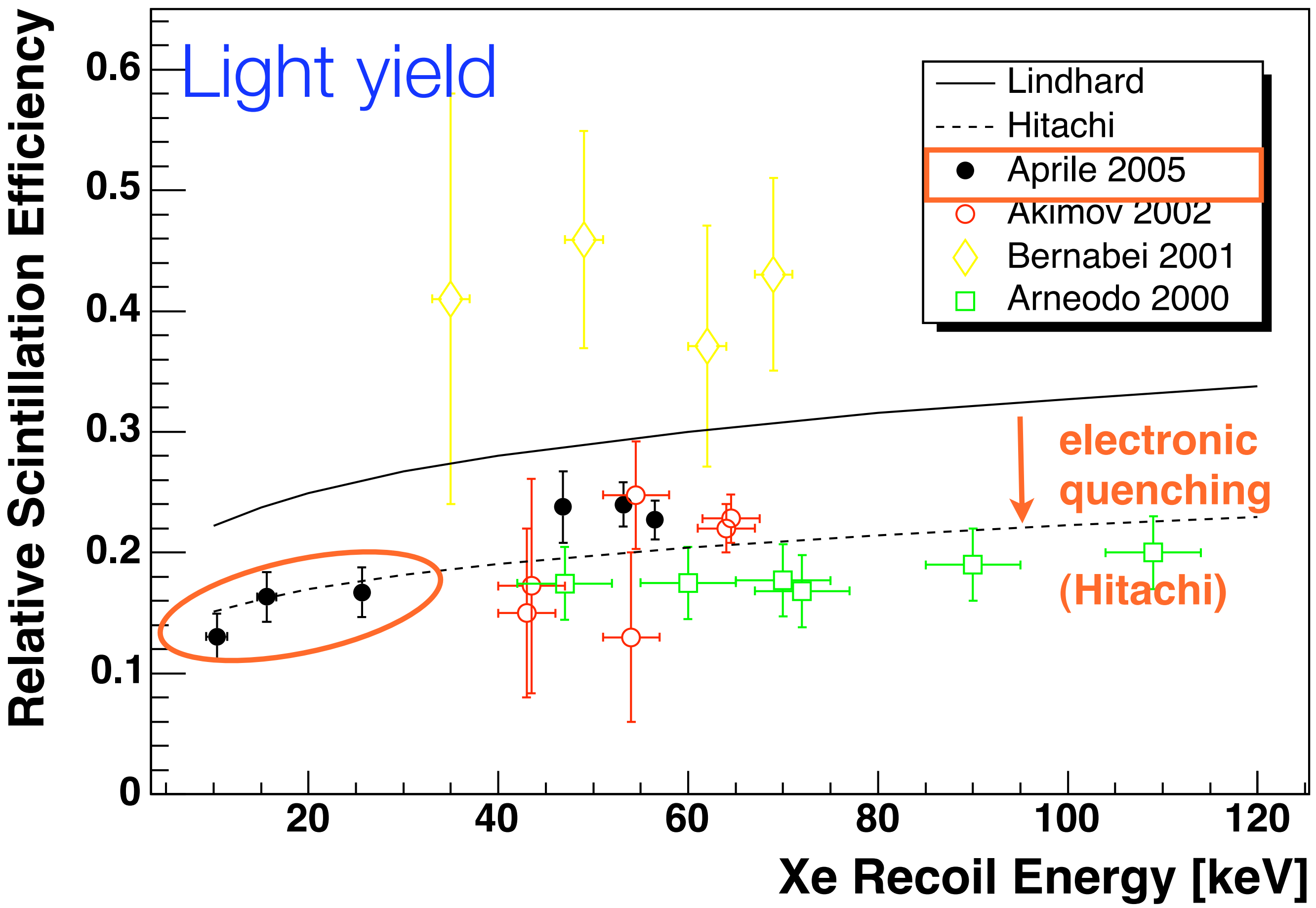


Trigger: S2 sum signal from top PMTs
S2 threshold: 300 p.e. (~ 20 e^-)
(gas gain of a few 100s allows 100% S2 trigger efficiency)

S1 signal associated with S2: searched for in offline analysis -> coincidence of 2 PMT hits
S1 energy threshold is set to 4.4 p.e. (efficiency is 100% at 2 keVee)

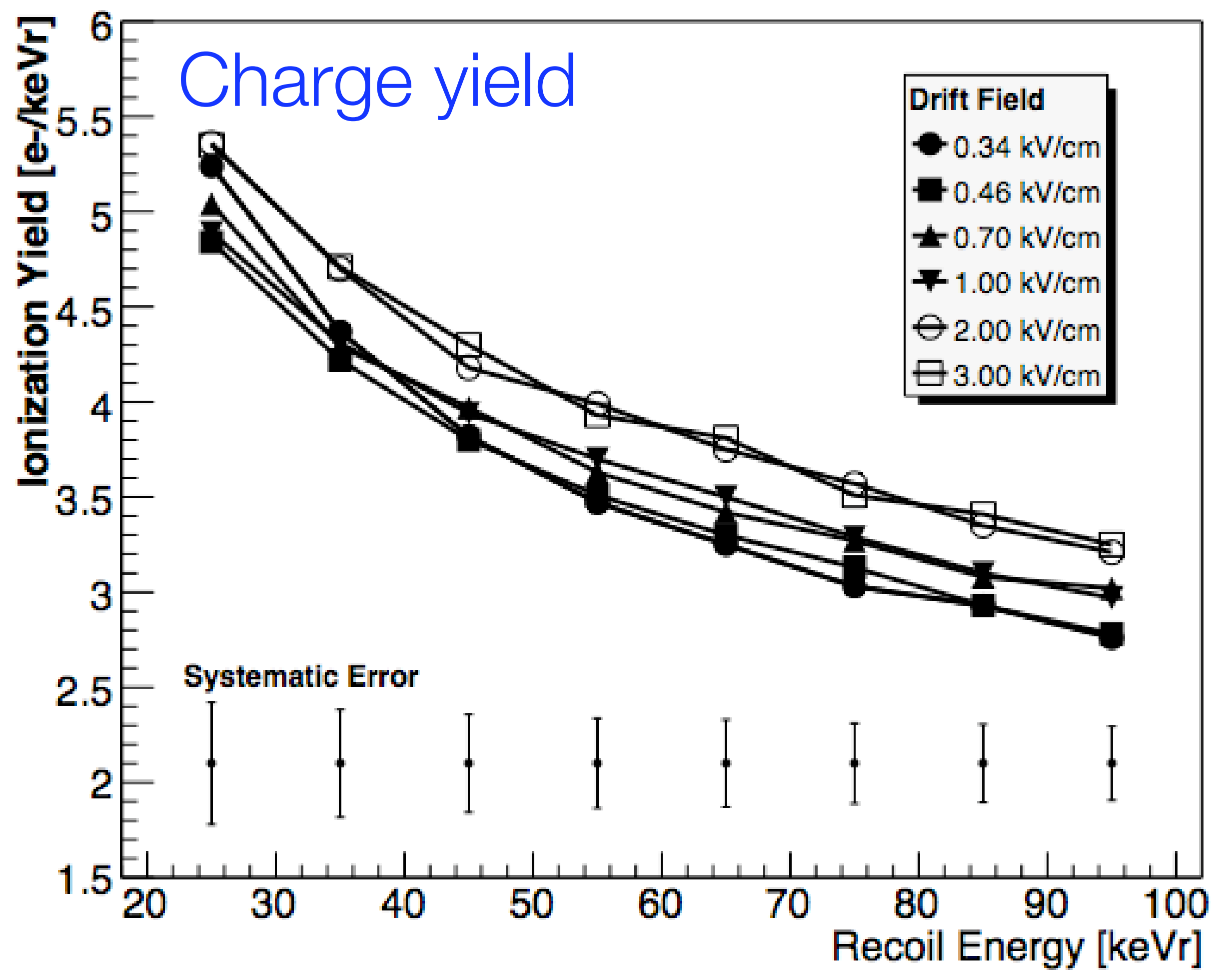
Liquid Xenon for Dark Matter Searches

- light and charge yield measured at **low nuclear recoil energies** for the first time



Data down to 10 keVr; yield: 13% - 20% from 10 keVr to 60 keVr. Good agreement with prediction by Hitachi (Astrop. Phys. 24, 2005) at low recoil energies

Aprile et al., Phys. Rev. D. 72 (2005)

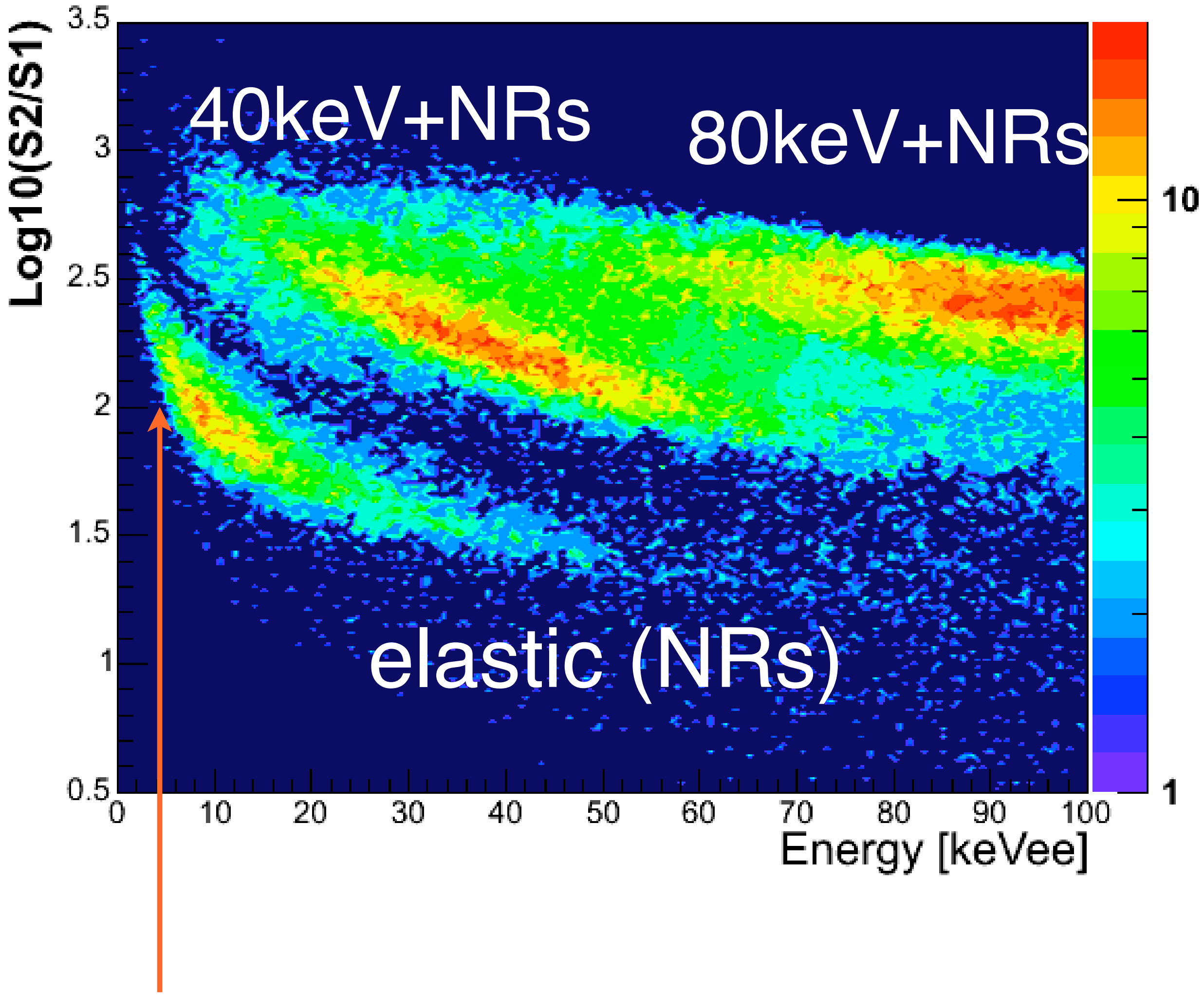


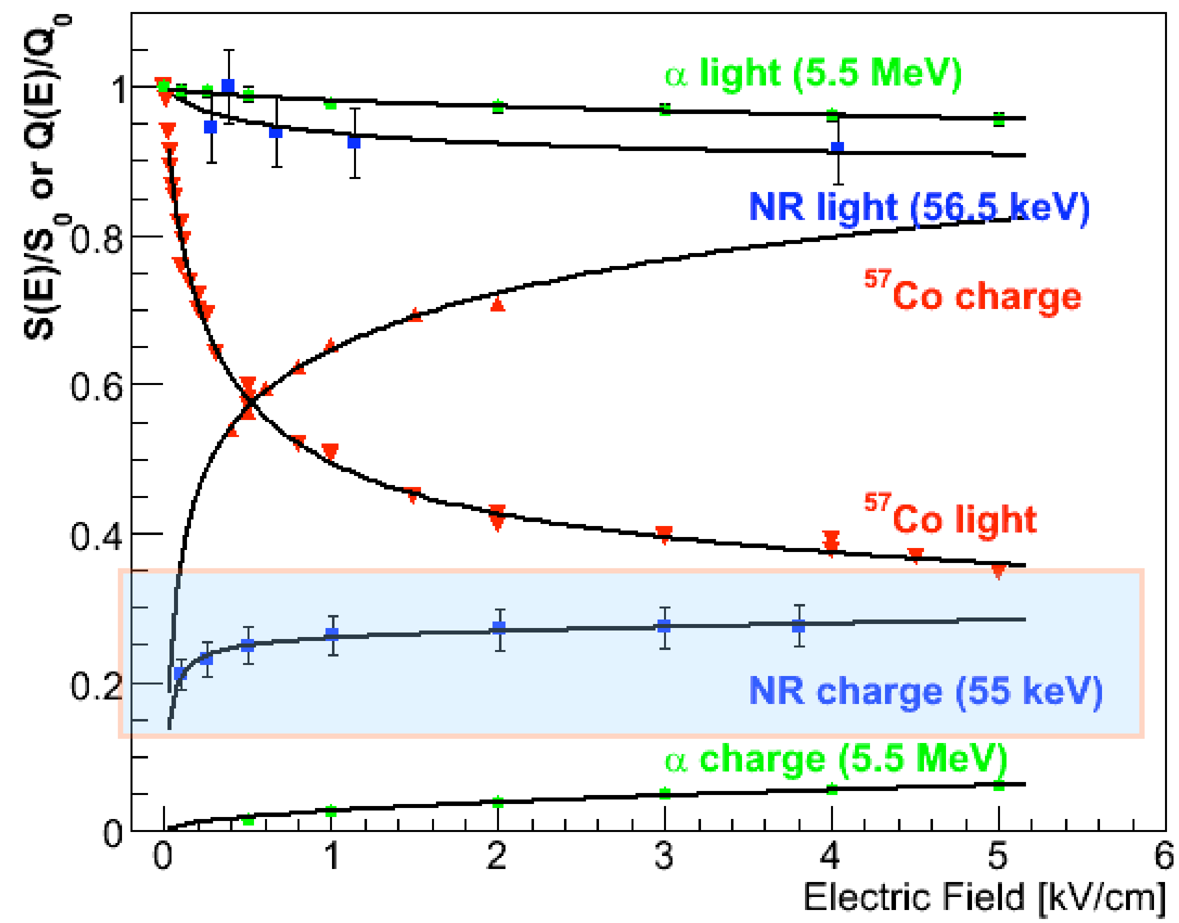
Weak dependence on electric field
Yield increases at low recoil energies

Aprile et al., Phys. Rev. Lett. 97 (2006)

Ionization Yield and Discrimination in Liquid Xenon

AmBe n-source





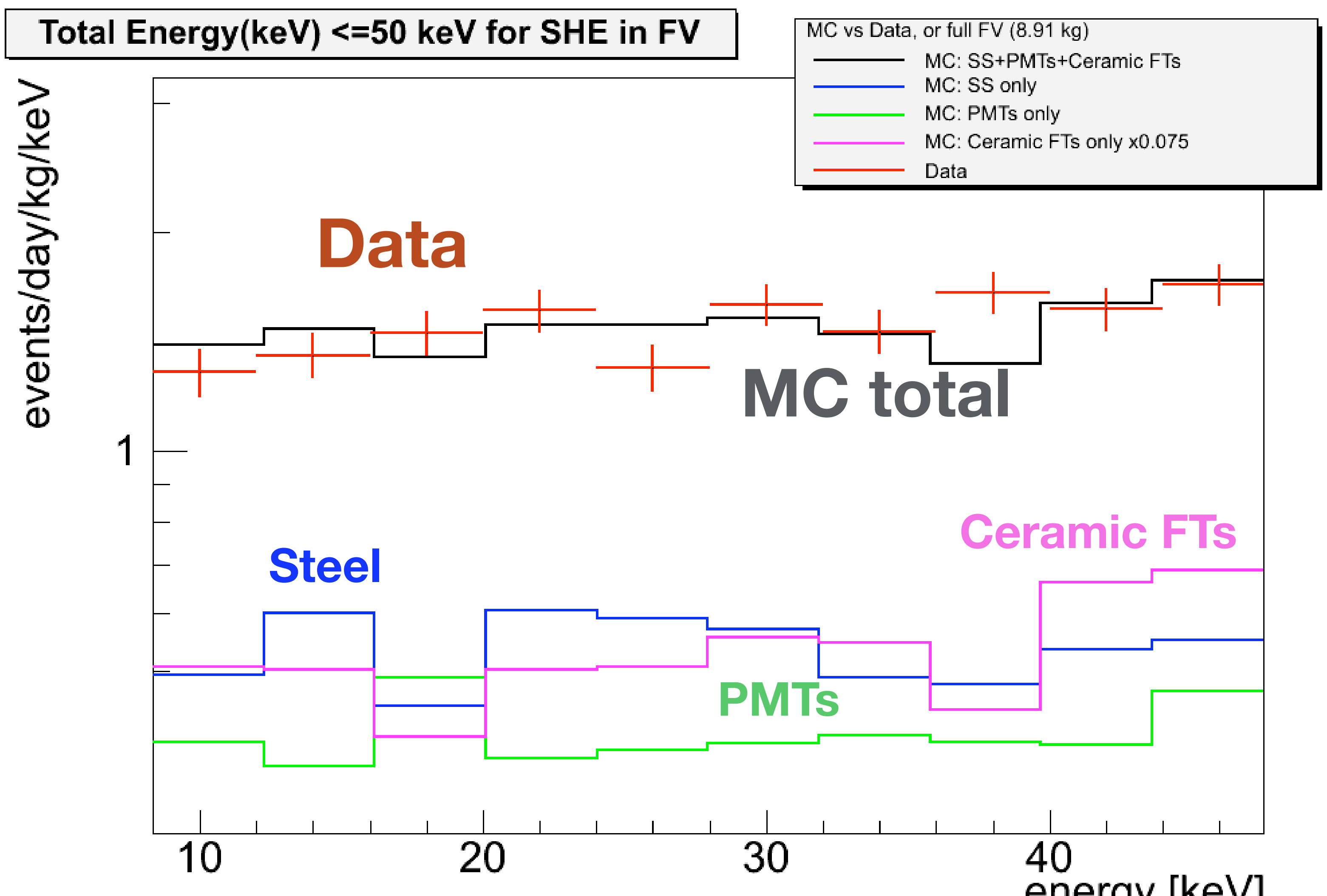
Electric Field [kV/cm]

5 keVee energy threshold = 10 keVr
good discrimination (>99%) between NR und ER

Aprile et al., Phys. Rev. Lett. 97 (2006)

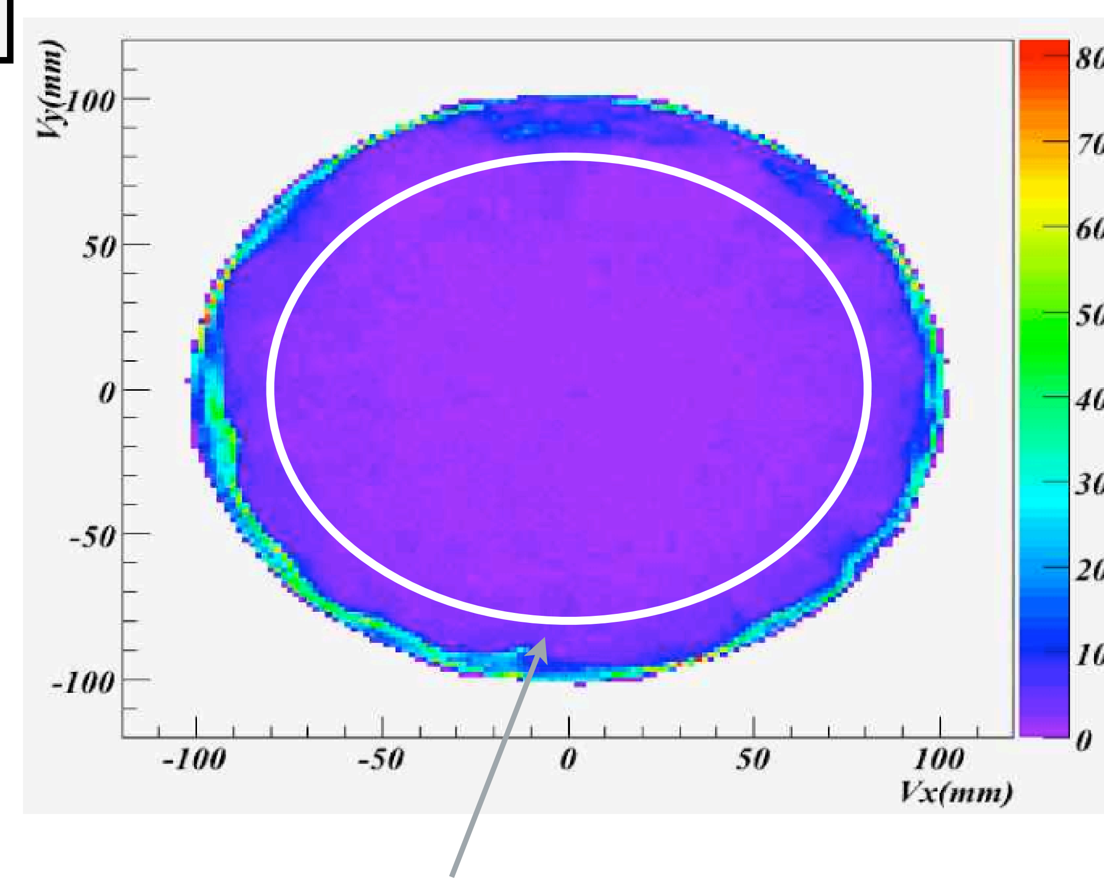
XENON10 Backgrounds

- **Red crosses**: data; **Black curve**: sum of background contributions from MC
  - ➡ < 1event/(kg d keV) (< 1 dru) (for r < 8 cm fiducial volume cut)



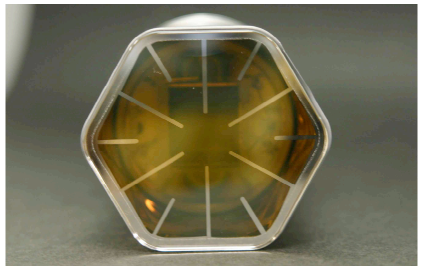
Single hits in fiducial mass (8.9 kg)

x-y position of WS data



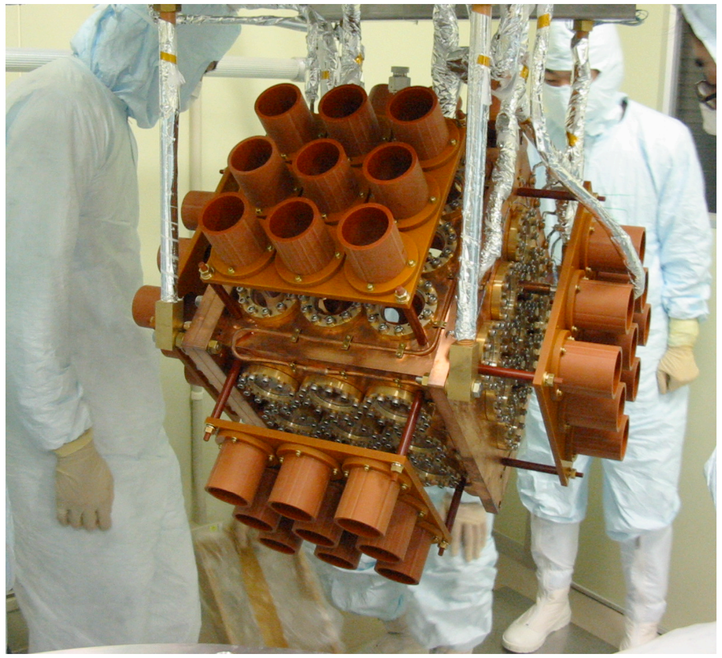
r < 8 cm fiducial volume cut

XMASS

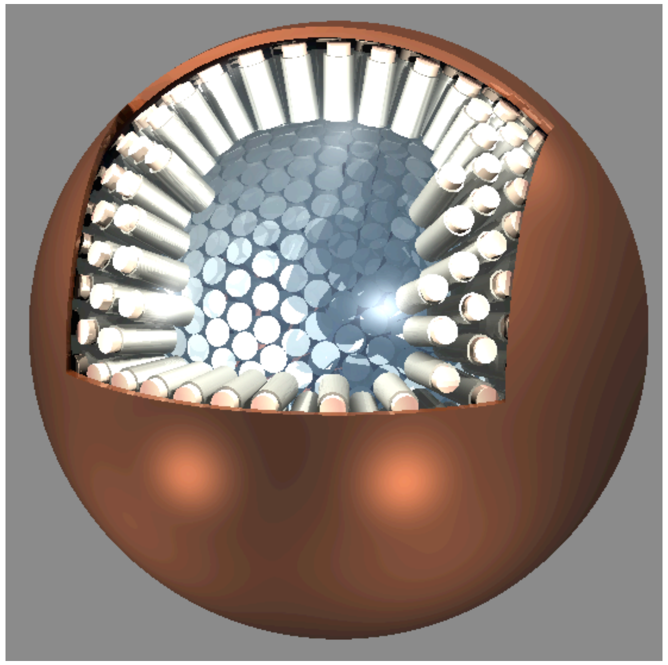


- 100 kg (3 kg fiducial mass) prototype operated (52 2” Hamamatsu R8778 PMTs)
  - the PMT coverage was limited, thus also the position reconstruction of edge events
- next step: 800 kg with 812 PMTs (67% photo coverage)
  - basic performance confirmed with prototype
  - vertex reconstruction, self-shielding, BG level studied with MCs
- detector is being designed, excavations will start soon

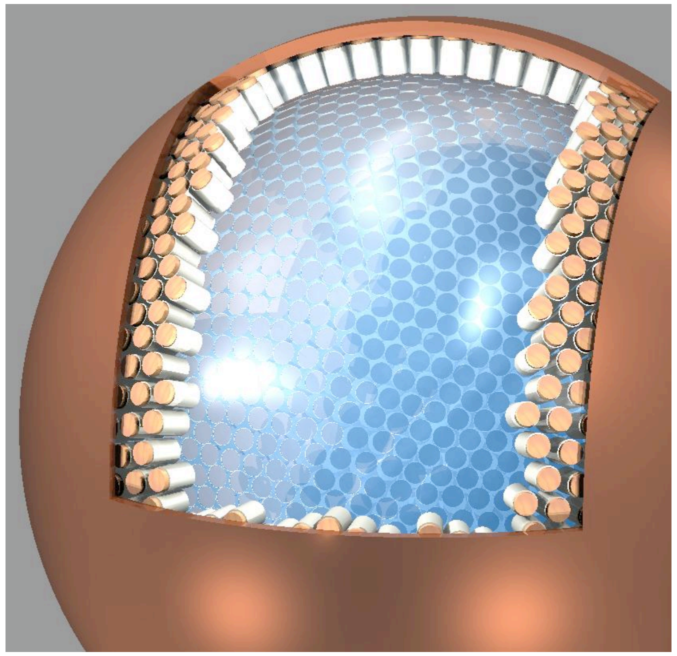
S. Moriyama, KEKPH07, March 07



100 kg (3 kg fiducial)



800 kg (100 kg fiducial)



23 t (10 t fiducial)

CMSSM

- a new exploration of the CMSSM parameter space with 8D Markov Chain MC technique + bayesian analysis including:
  - CMSSM parameters ($m_{1/2}$, m_0, A, $\tan\beta$)
  - SM parameters: m_b, M_t, $\alpha_{em}(M_Z)$, $\alpha_s(M_Z)$
  - collider observables
  - cosmological abundance of CDM (WMAP)

CMSSM parameters θ	
"2 TeV range"	"4 TeV range"
$50 < m_0 < 2$ TeV $50 < m_{1/2} < 2$ TeV $\|A_0\| < 5$ TeV	$50 < m_0 < 4$ TeV $50 < m_{1/2} < 4$ TeV $\|A_0\| < 7$ TeV
$2 < \tan\beta < 62$	
SM (nuisance) parameters ψ	
$160 < M_t < 190$ GeV $4 < m_b(m_b)^{\overline{MS}} < 5$ GeV $127.5 < 1/\alpha_{\rm em}(M_Z)^{\overline{MS}} < 128.5$ $0.10 < \alpha_s(M_Z)^{\overline{MS}} < 0.13$	

- **=> probability distributions**
- **=> look for high P regions of CMSSM parameter space**

Ruiz, Trotta, Roskowski