



Recent results in Dark Matter direct detection

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LNGS



IFAE 2013 - , CAGLIARI, ITALY
3-5 APRIL 2013

Dark Matter evidence at different scales

The summarizing picture

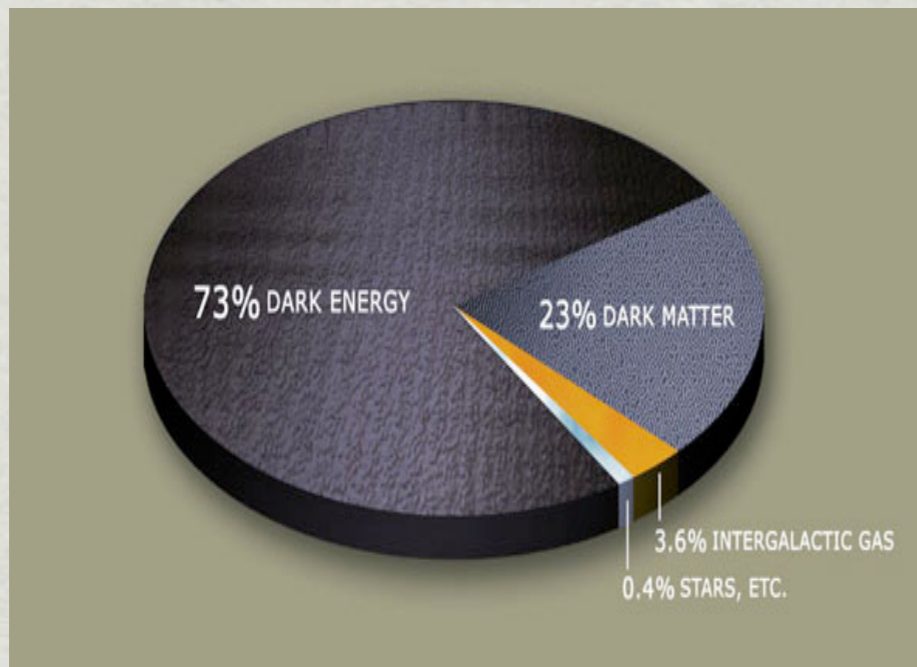
✱ WMAP + galaxy surveys + supernovae + BBN:

- ▶ Total density: $\Omega_{\text{Total}} = 1.02 \pm 0.02$
- ▶ Dark energy: $\Omega_{\Lambda} = 0.73 \pm 0.04$
- ▶ Matter density: $\Omega_{\text{m}} = 0.27 \pm 0.04$
- ▶ Baryon density: $\Omega_{\text{b}} = 0.044 \pm 0.004$
- ▶ Neutrinos (HDM): $\Omega_{\nu} < \sim 0.015$
- ▶ Non-baryonic Cold Dark Matter:

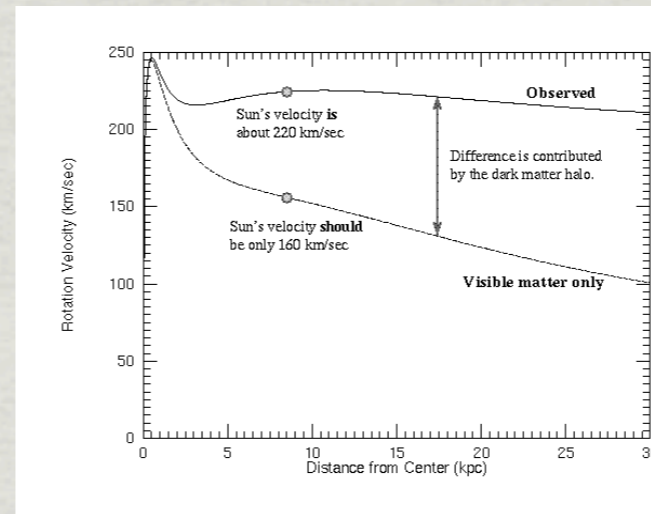
$$\Omega_{\text{d}} = \Omega_{\text{m}} - \Omega_{\text{b}} = 0.22$$

Scale: $\sim 10^{26}$ m
($\sim 10^{10}$ lightyears)

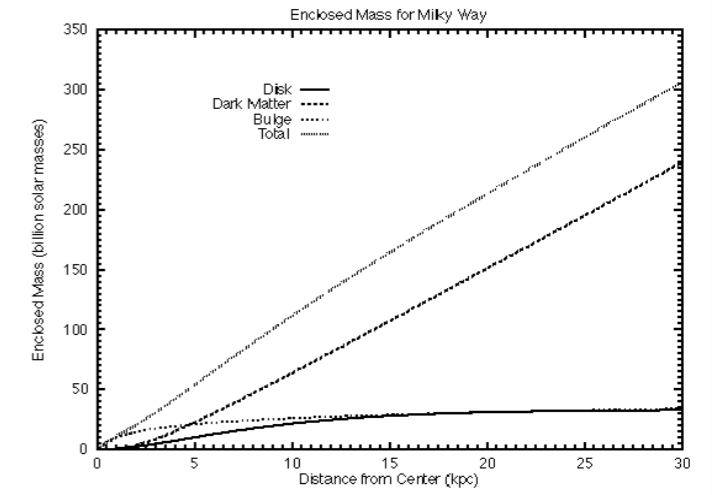
More details on:
[arxiv:0901.0632v2](https://arxiv.org/abs/0901.0632v2)



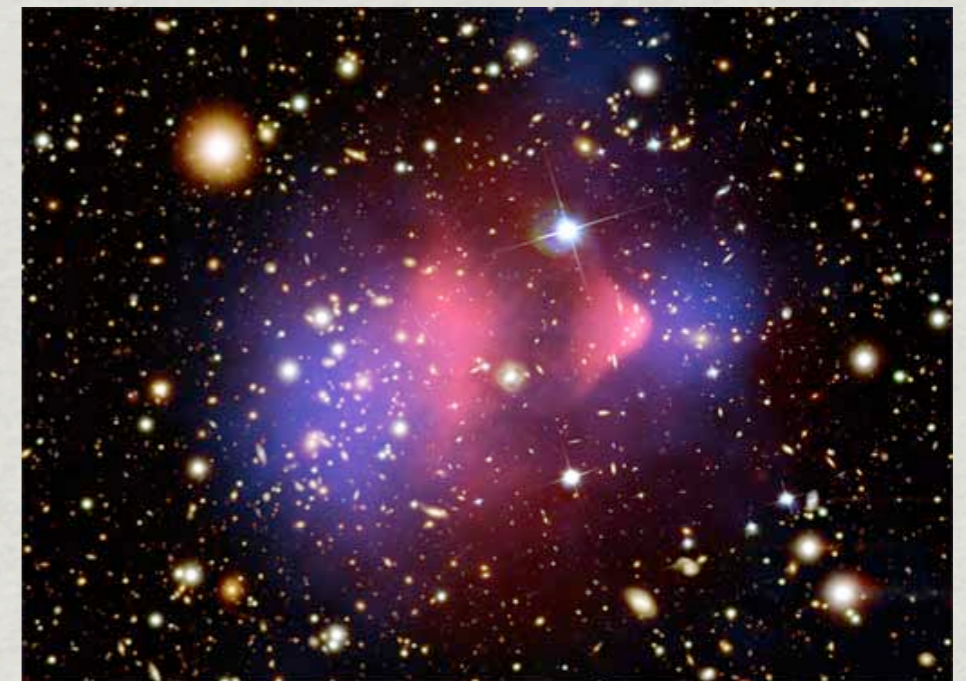
Scale: $\sim 10^{21}$ m
($\sim 10^5$ lightyears)



Rotation curve of the Milky Way



Enclosed mass for the Milky Way

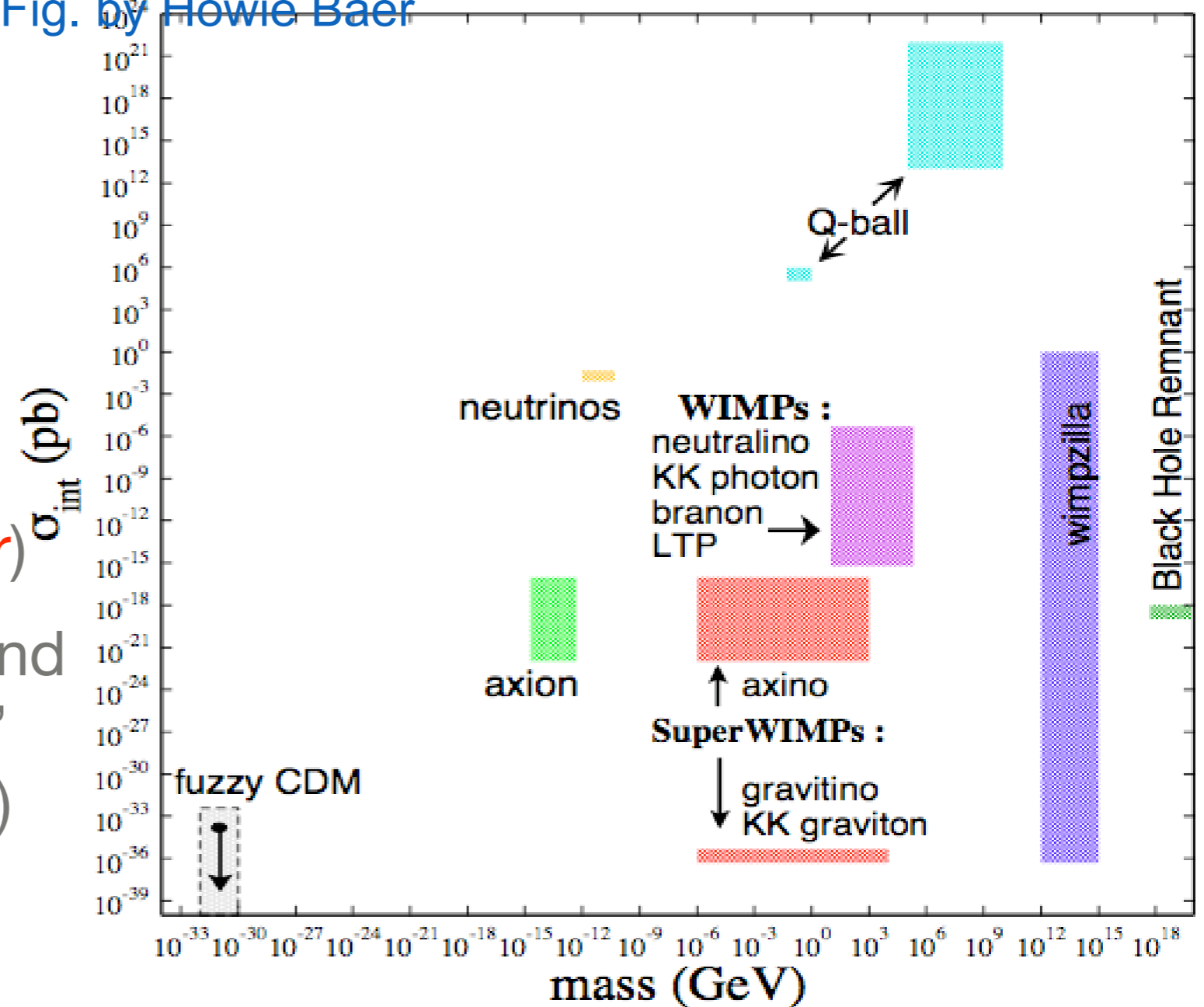


Scale: $\sim 10^{22}$ m
($\sim 10^6$ lightyears)

Dark Matter Particles

- Massive (**gravitation**)
- Long-lived (**Big Bang relic**)
- Electrically neutral (**dark**)
- Non-baryonic (**BBN**)
- Collisionless (**Bullet cluster**)
- Cold, i.e. dissipationless and negligible “free-streaming” effect (**Structure formation**)

Fig. by Howie Baer



Direct WIMP searches

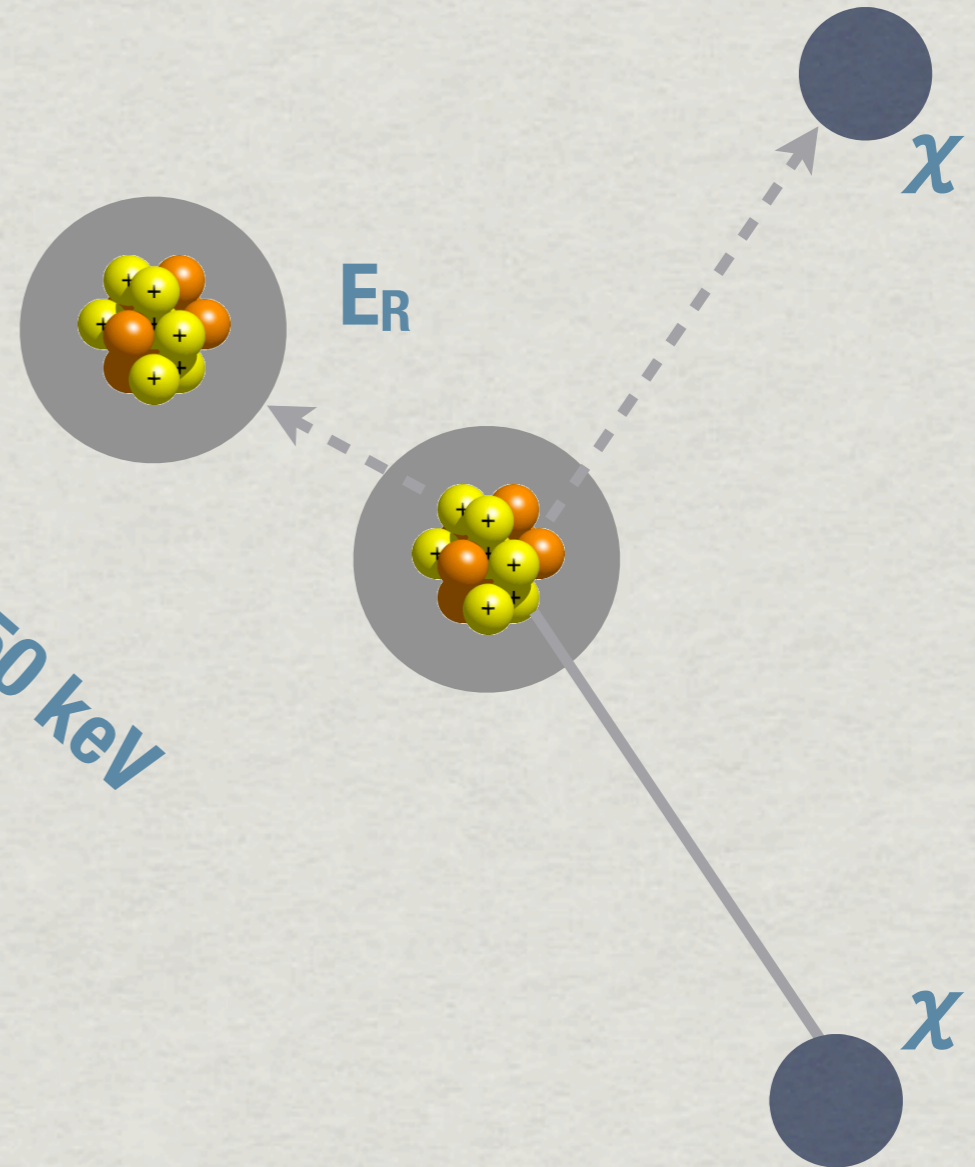
WIMPS INTERACT WITH NUCLEUS!

WIMP may interact with cross sections down to 10^{-47} cm^2

OBSERVABLE QUANTITIES

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

- * q = momentum transfer
- * m_N = target nucleus mass
- * μ = reduced mass $\mu = \frac{m_\chi m_N}{m_\chi + m_N}$
- * v = mean WIMP-velocity on respect to the target
- * θ = scattering angle in the center of mass



Direct WIMP search: rate and signature

MEDIUM RELATED QUANTITY

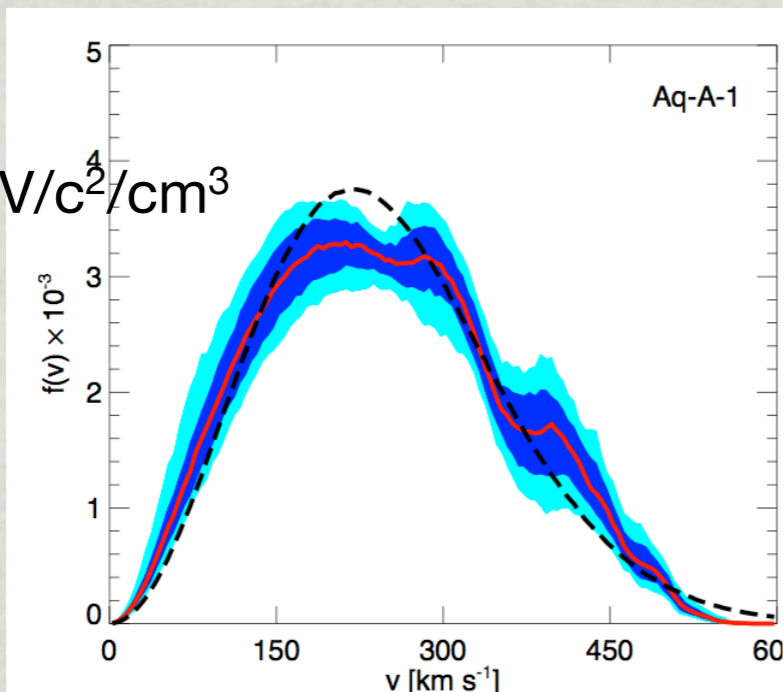
ASTROPHYSICS

$$\frac{dR}{dE_R} \sim \frac{\rho_\chi \sigma_{\chi-N}}{2m_\chi \mu} F^2(E_R) \int_{\nu_{min}}^{\nu_{esc}} \frac{f(\vec{\nu}, t)}{\nu} d^3\nu$$

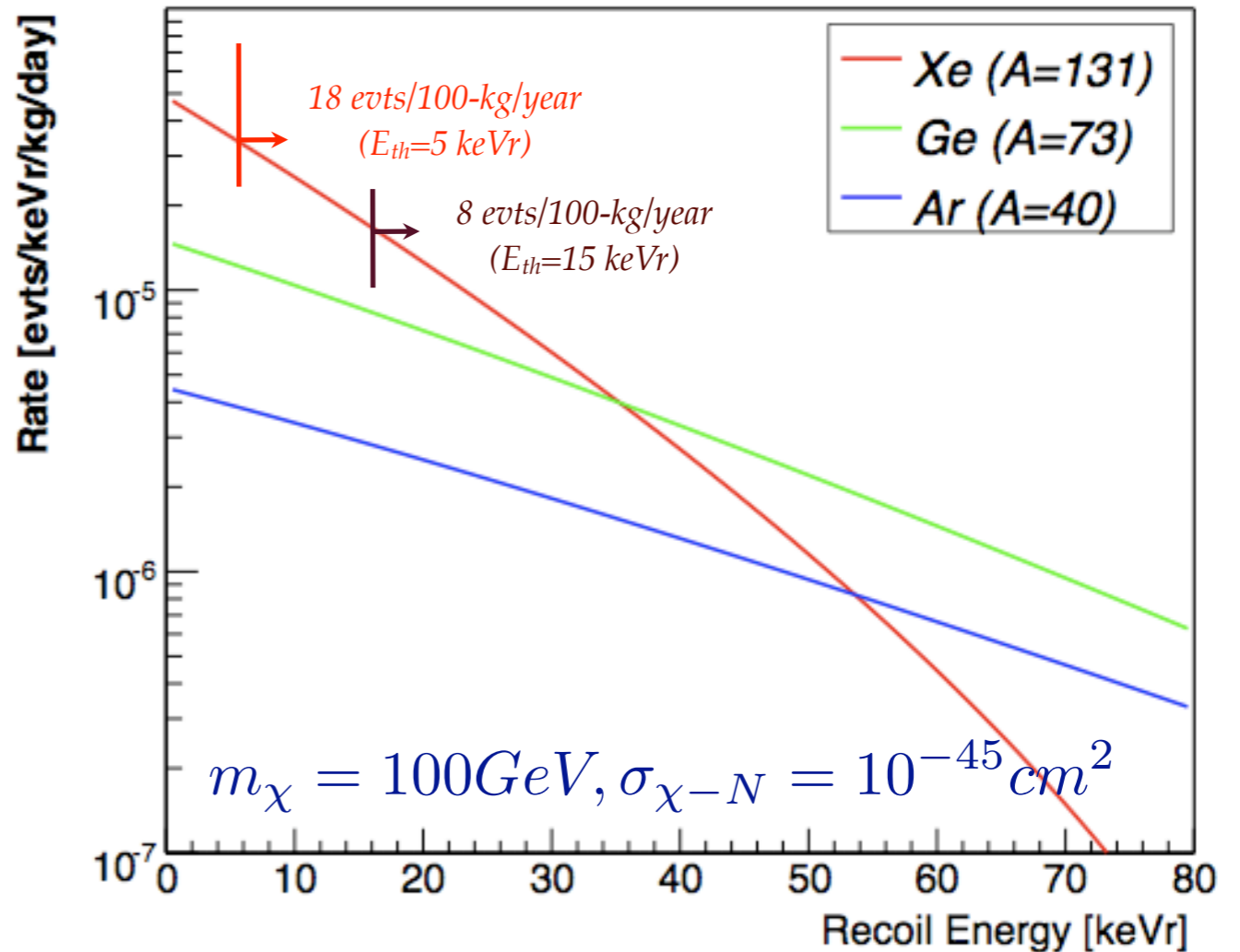
PARAMETERS UNDER MEASURE

Integrate over WIMP velocity distribution; in general assumed to be of Maxwell-Boltzmann type, which so far is a pretty good approximation

$$\rho_\chi \sim 0.3 \text{ GeV}/c^2/\text{cm}^3$$



WIMP Scattering Rates



Direct WIMP search: the cross sections

- General WIMP candidate: fermion (Dirac or Majorana), boson or scalar
- 4 types of interaction (S, P, V, A)
- In the limit relevant for galactic WIMPs ($v_{\text{WIMP}} \sim 10^{-3} c$), the interaction becomes:
- **scalar interaction** (scalar and vector parts of L, spin independent)

$$\sigma_{SI} = \frac{m_N^2}{4\pi(m_\chi + m_N)^2} [Z f_p + (A - Z) f_n]^2$$

- **scalar interaction** (axial part of L, spin dependent)

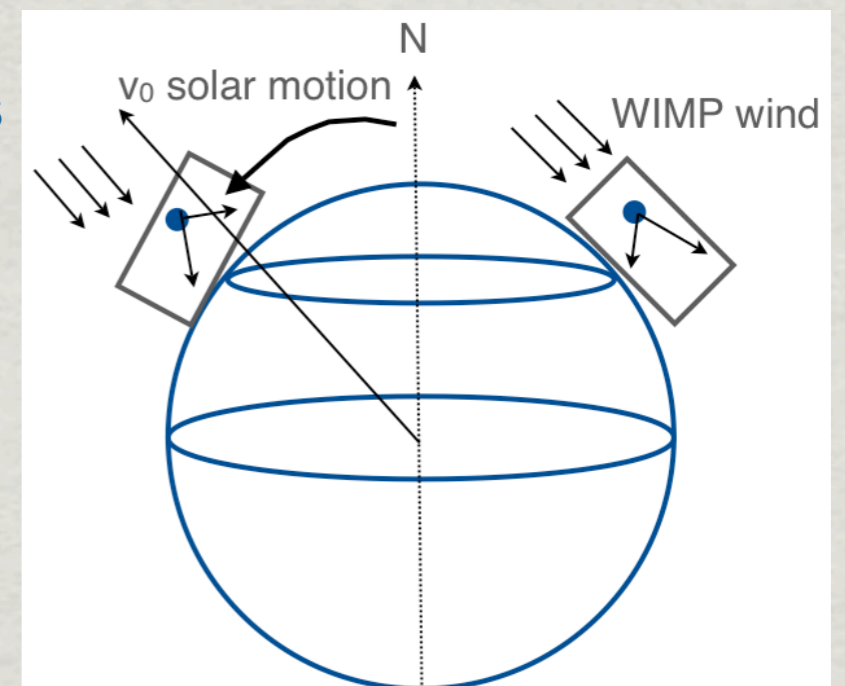
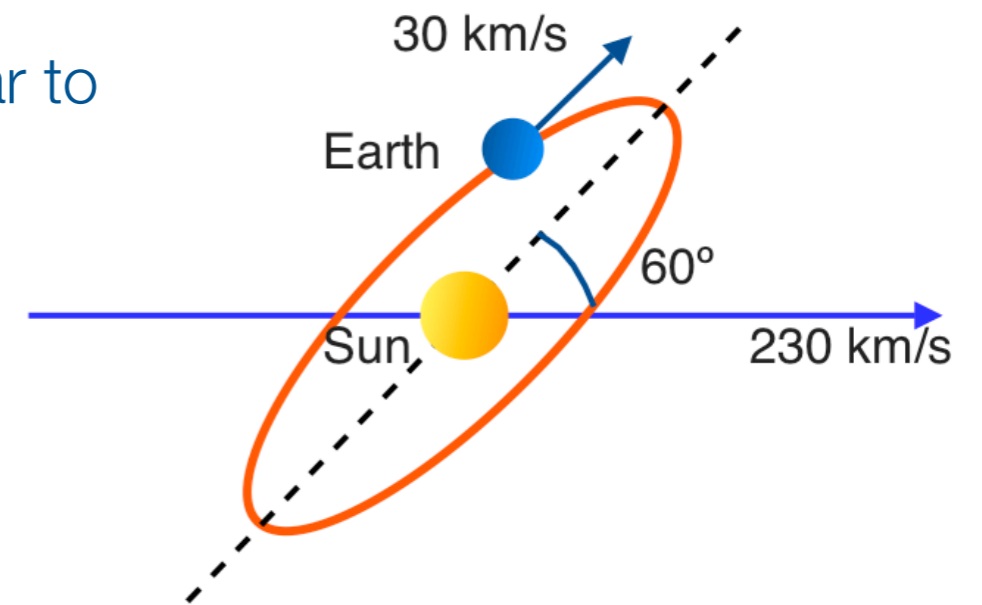
$$\sigma_{SD} = \frac{32}{\pi} G_F^2 \frac{m_\chi^2 m_N^2}{(m_\chi + m_N)^2} \frac{J_N + 1}{J_N} (a_p \langle S_p \rangle + a_n \langle S_n \rangle)^2$$

- Interaction is coherent over nucleus, since de Broglie wavelength of WIMP is of nuclear dimensions:

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

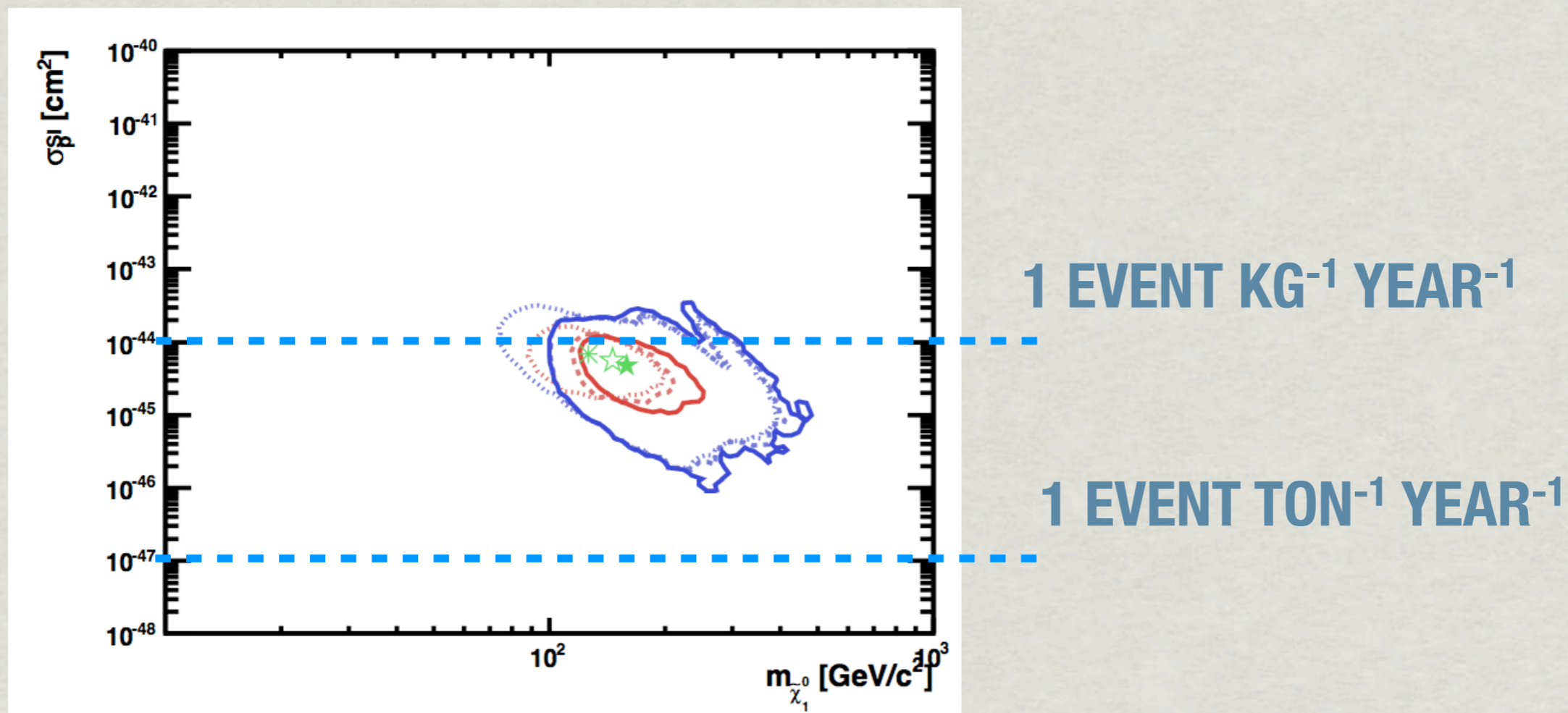
Direct WIMP search: on the Earth

- WIMP interactions in detector should be:
 - nuclear recoils
 - single scatters, uniform throughout detector volume
- Spectral shape (exponential, however featureless, similar to background)
- Dependence on detection medium (A^2 , $F^2(Q)$, test consistency between different targets)
- Our galaxy is immersed in a WIMP halo
- WIMPs in such halo have a certain velocity distribution
- The Sun moves at a speed of 232 km/s
- The Earth moves around the Sun with a speed of 30 km/s
- Annual flux modulation ($\sim 3\%$ effect, most events close to threshold)
- Diurnal direction modulation (larger effect, requires low-pressure gas target)



Direct WIMP search: the parameter space

Example from the recent supersymmetry predictions:
cross section down to $\sim 10^{-47} \text{ cm}^2$



Direct WIMP search: the backgrounds

- cross-sections ($<10^{-44}$ cm²)
- without background
Sensitivity $\approx M \times t$
- with background
Sensitivity $\approx (M \times t)^{1/2}$
until limited by systematics

NATURE:

α , β , γ , n, μ

SOURCES:

Artificially produced radionuclides
(⁸⁵Kr, ¹³⁷Cs) - **Gamma**

Cosmogenic radionuclides
(⁶⁰Co) - **Gamma**

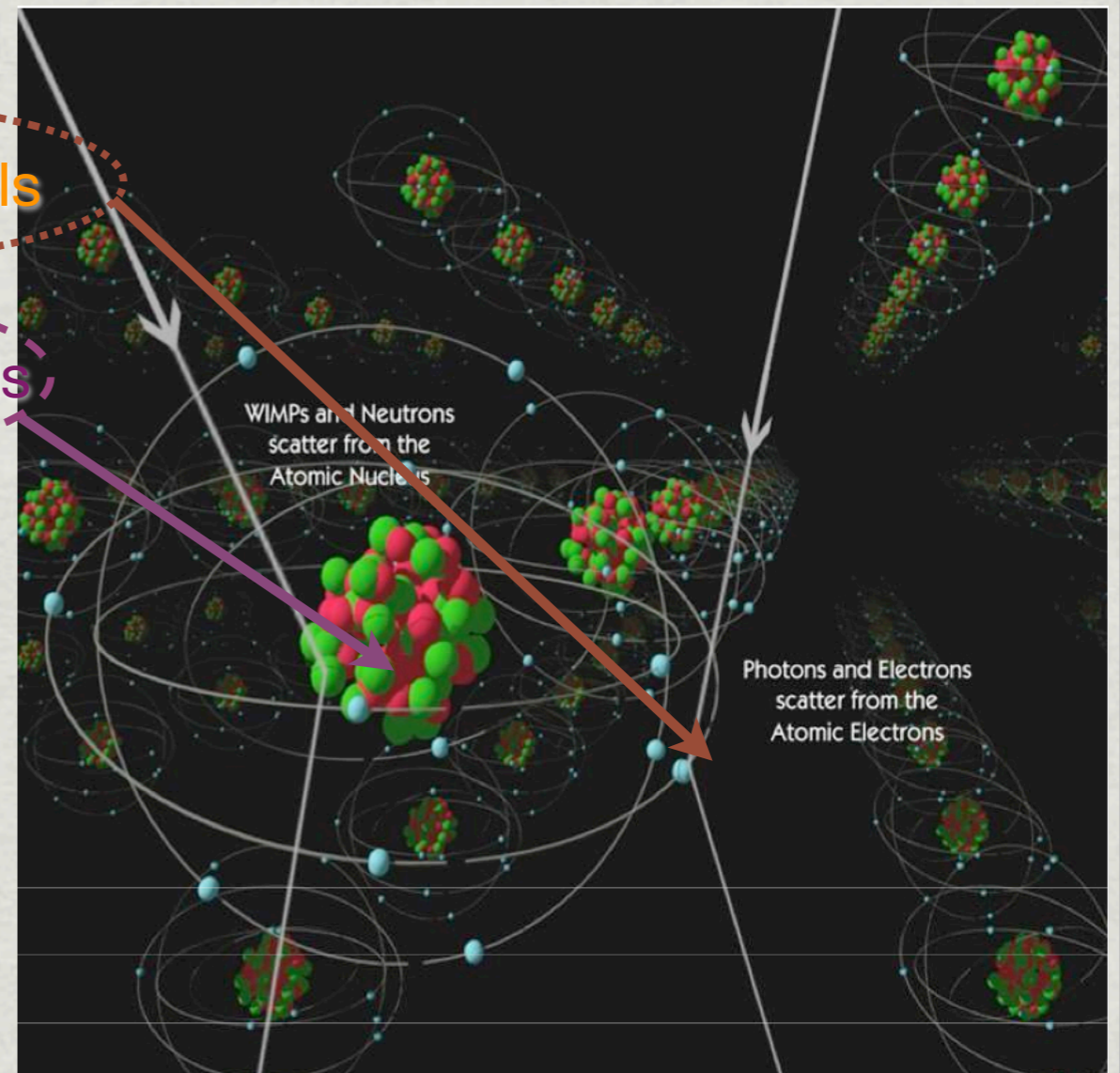
Natural primordial radionuclides
(²³⁸U, ²³²Th, ⁴⁰K) - **Gamma** and **Neutrons**

Cosmic muons - **Neutrons**

SIGNALS:

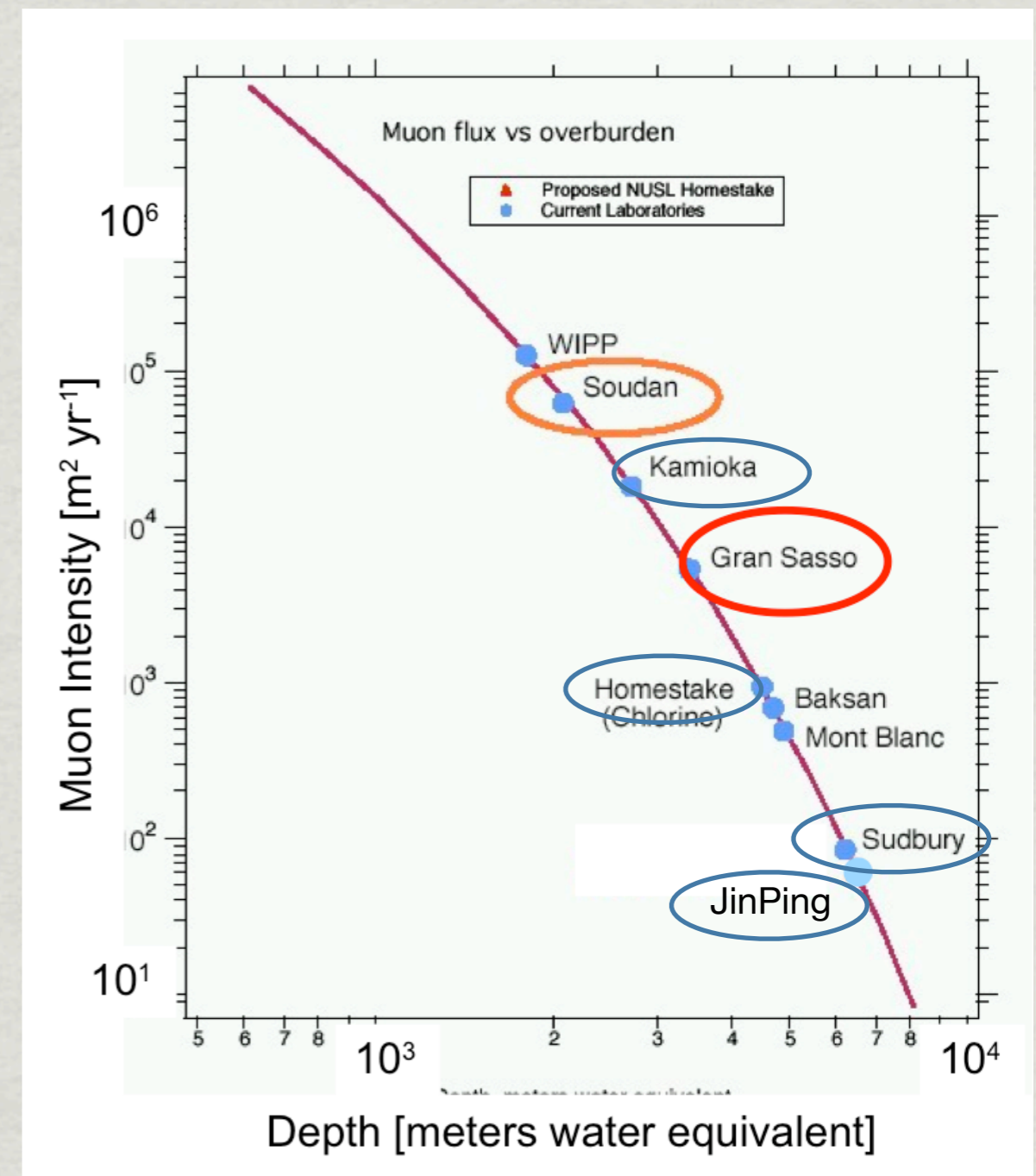
Electronic recoils

Nuclear recoils



Direct WIMP search: how to fight backgrounds

- * Move detector underground (reduce μ)
- * Shield (actively and/or passively) detector from environmental radioactivity (reduce $\alpha, \beta, \gamma, n, \mu$)
- * Select detector construction materials
- * Big detector with multiple scattering identification allow further background reduction
- * Use event positioning (if possible) for sensitive medium self shielding and/or surface events rejection
- * Use other methods to reject the main background, i.e. β and γ from real signal

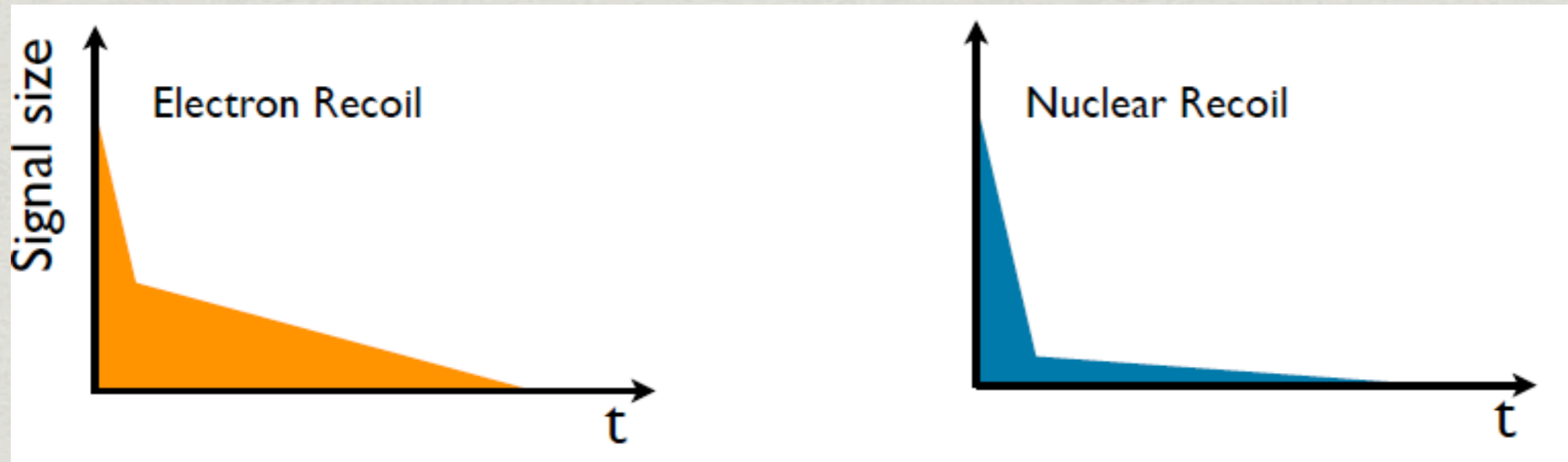


Direct WIMP search: the world wide race

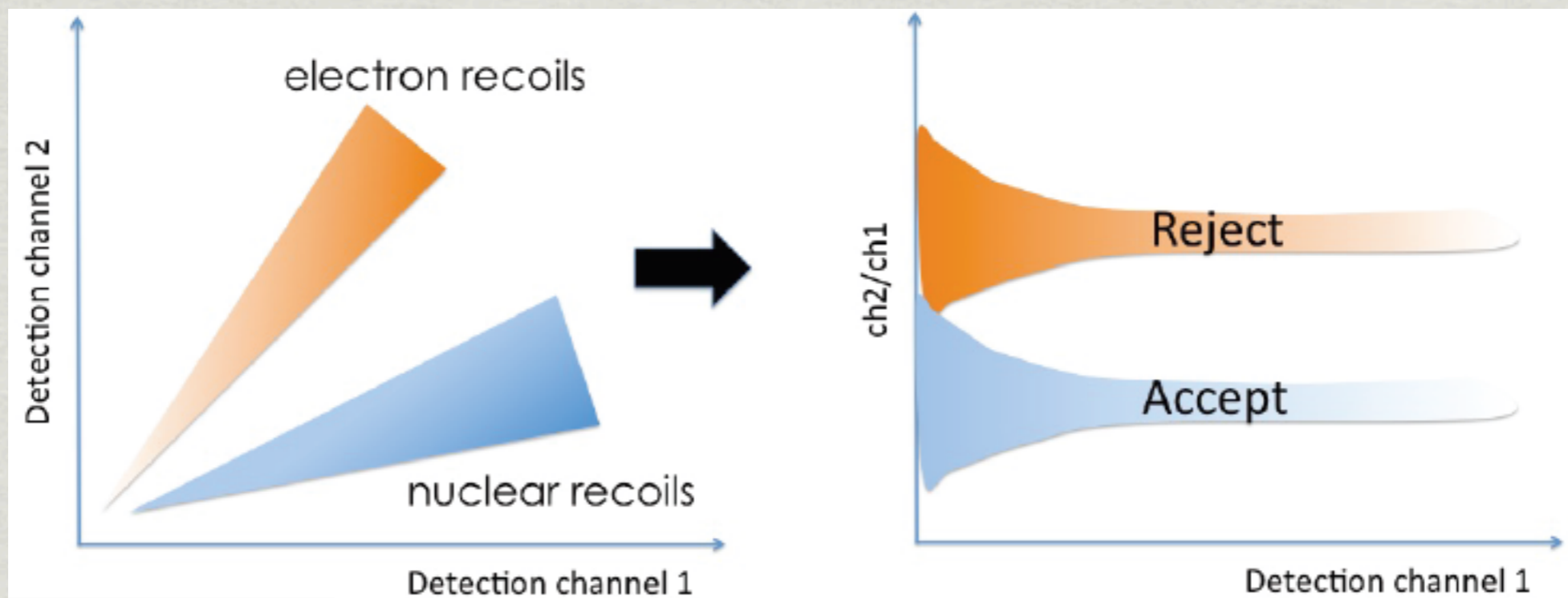


Direct WIMP search: background reduction techniques

LOOK AT SCINTILLATION LIGHT



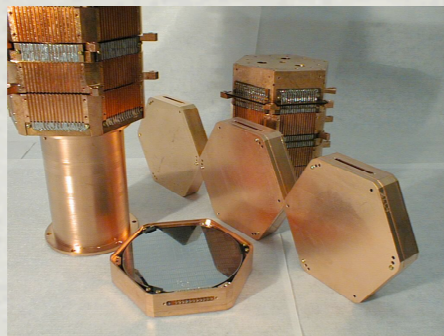
LOOK AT PARTICLE PROPERTIES



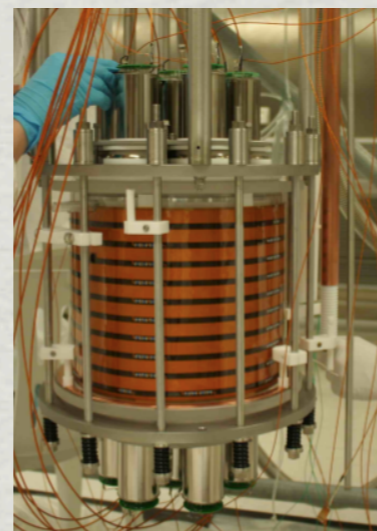
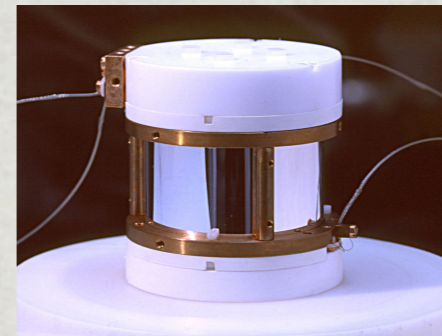
Direct WIMP search: the approaches

COUPP, PICASSO, SIMPLE

CDMS
EDELWEISS



CRESST
ROSEBUD



DAMA/LIBRA
XMASS
DEAP
CLEAN
KIMS
DM-Ice

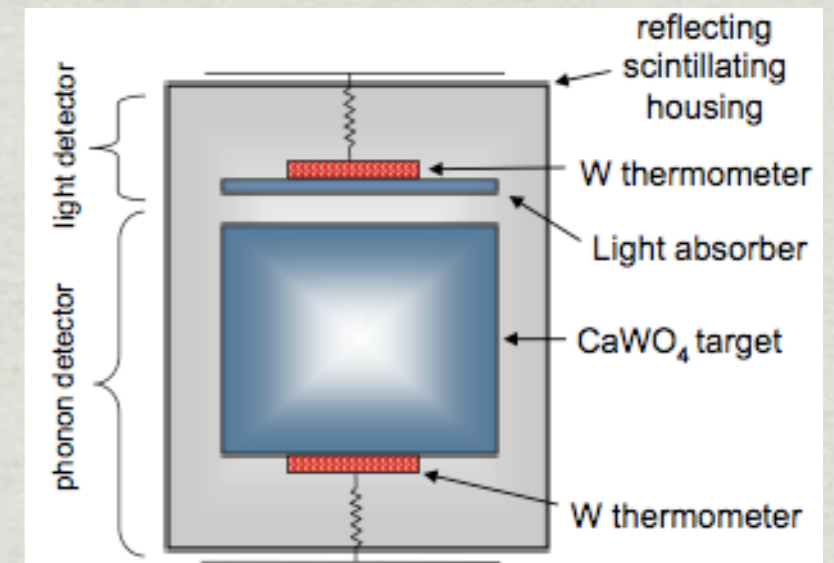
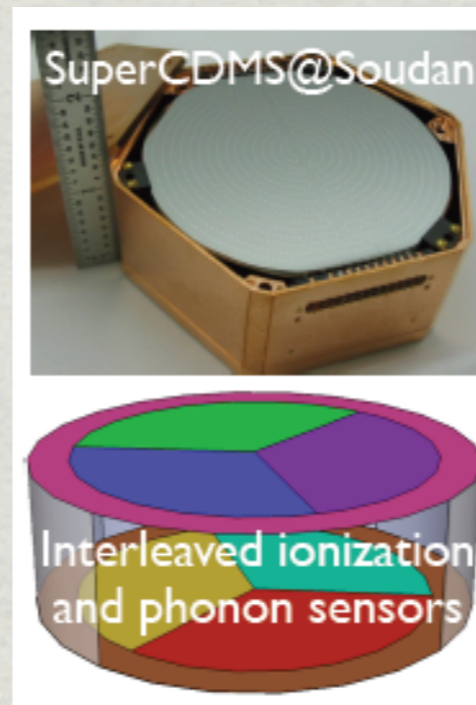
CoGeNT
Texono
CDEX
DMTPC
DRIFT
MIMAC
Newage

ZEPLIN, LUX, XENON,
WARP, ArDM, DarkSide, Panda-X

Direct WIMP search: Solid state cryogenic detectors

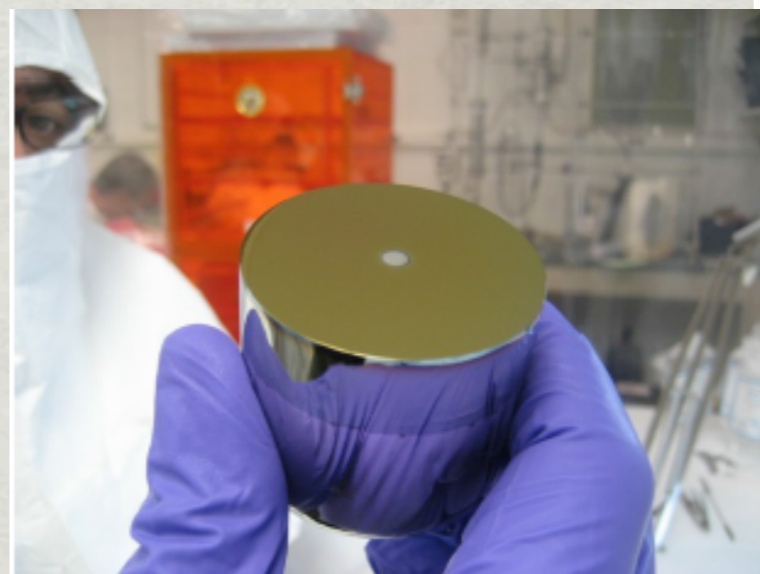
BOLOMETERS

- * Sub-K temperatures
- * < 10 keV energy threshold
- * Excellent energy resolution
- * Phonon signal combination with light (CRESST) or charge (EDELWEISS and CDMS) for background rejection

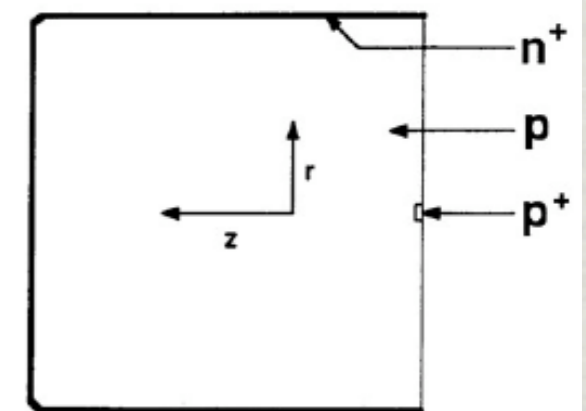


TRADITIONAL HPGE

- * Sub-keV energy threshold
- * No background rejection
- * Position sensitivity for surface events rejection
- * CoGeNT, TEXONO

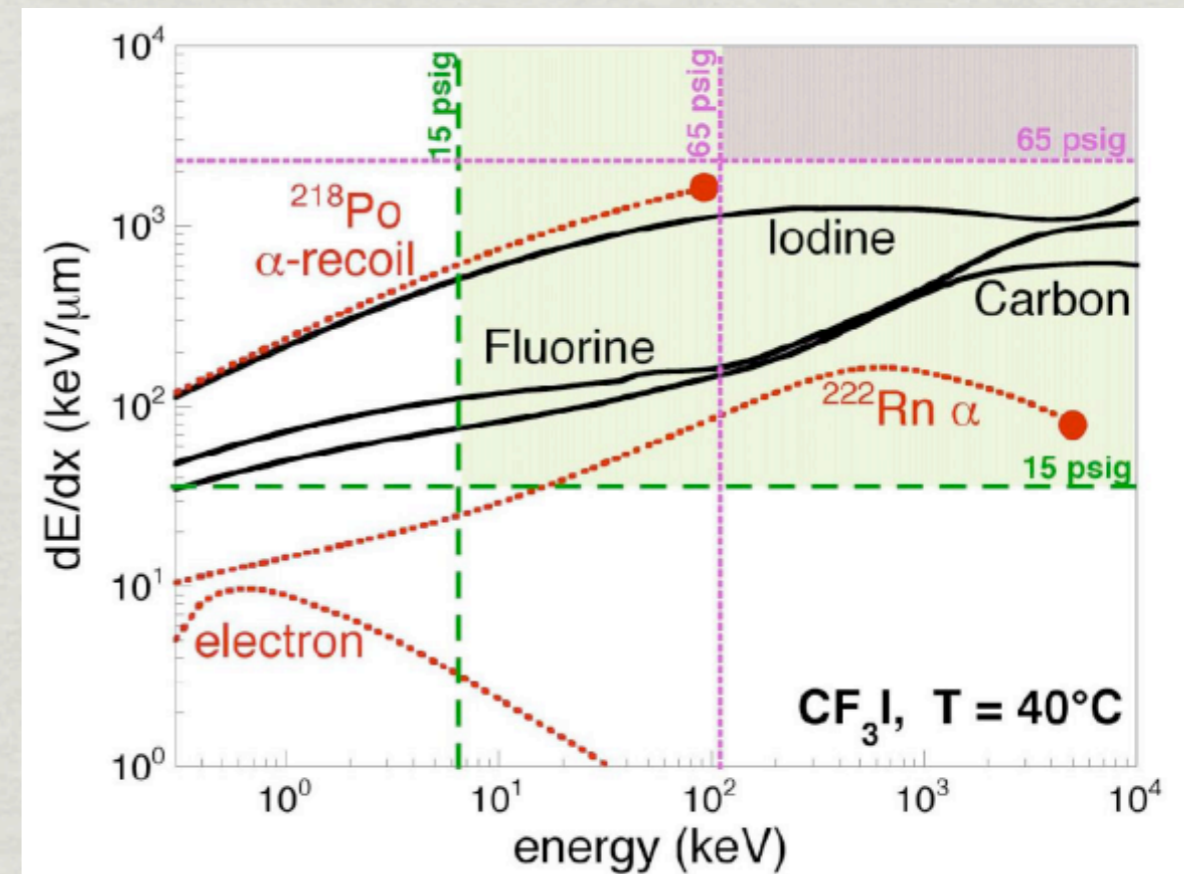
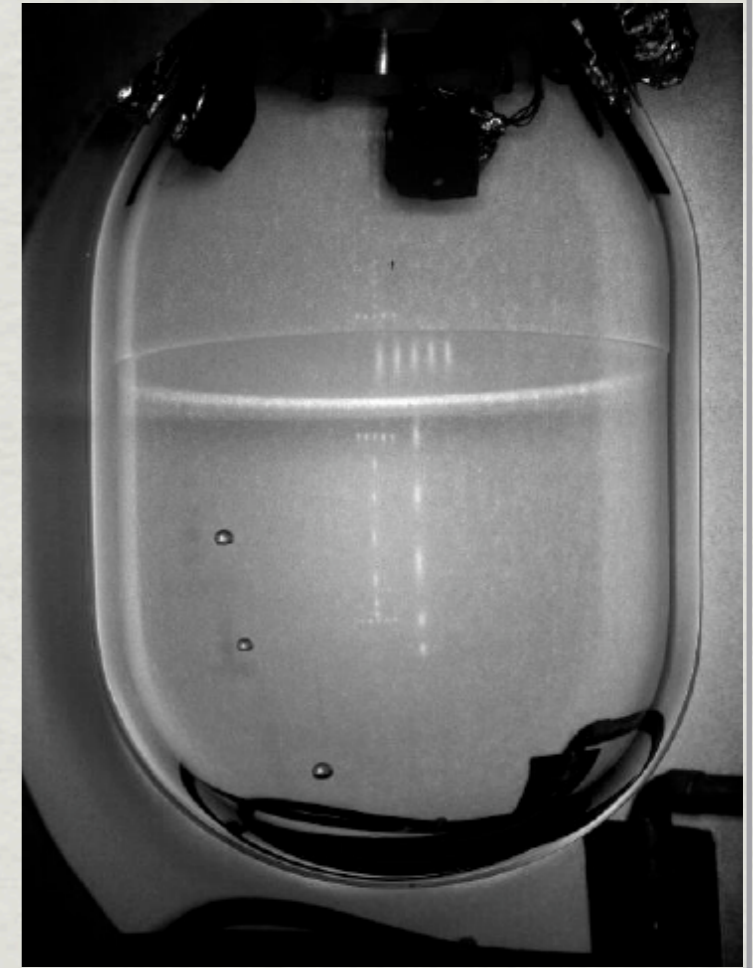


P-type Point Contact (PPC)



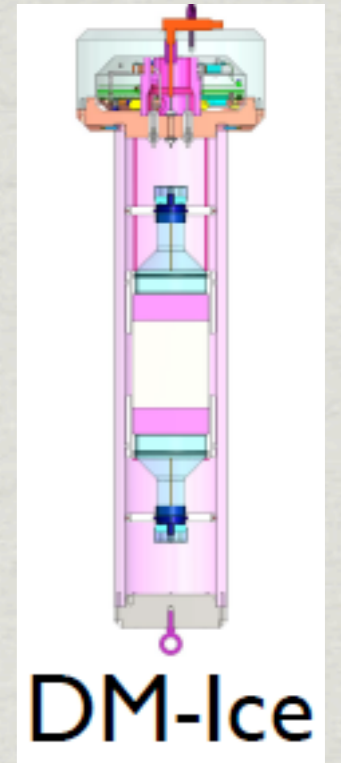
Direct WIMP search: Superheated liquid detectors

- * Superheat detector in a metastable state
- * An energy deposit can destroy a metastable state and generate bubbles
- * Tune P and T to be sensitive only to nuclear recoils
- * α -particles can be acoustically discriminated
- * All experiments use Fluorine, containing ^{19}F that has a good sensitivity to SD interactions
- * COUPP (CF_3I), PICASSO (C_4F_{10}), SIMPLE (C_2CIF_5)



Direct WIMP search: Scintillating crystals

- * Good light yield and energy resolution
- * ~ keV energy threshold
- * DAMA/LIBRA [NaI(Tl)], KIMS [CsI(Tl)], ANAIS [NaI(Tl)], DM-Ice [NaI(Tl)]

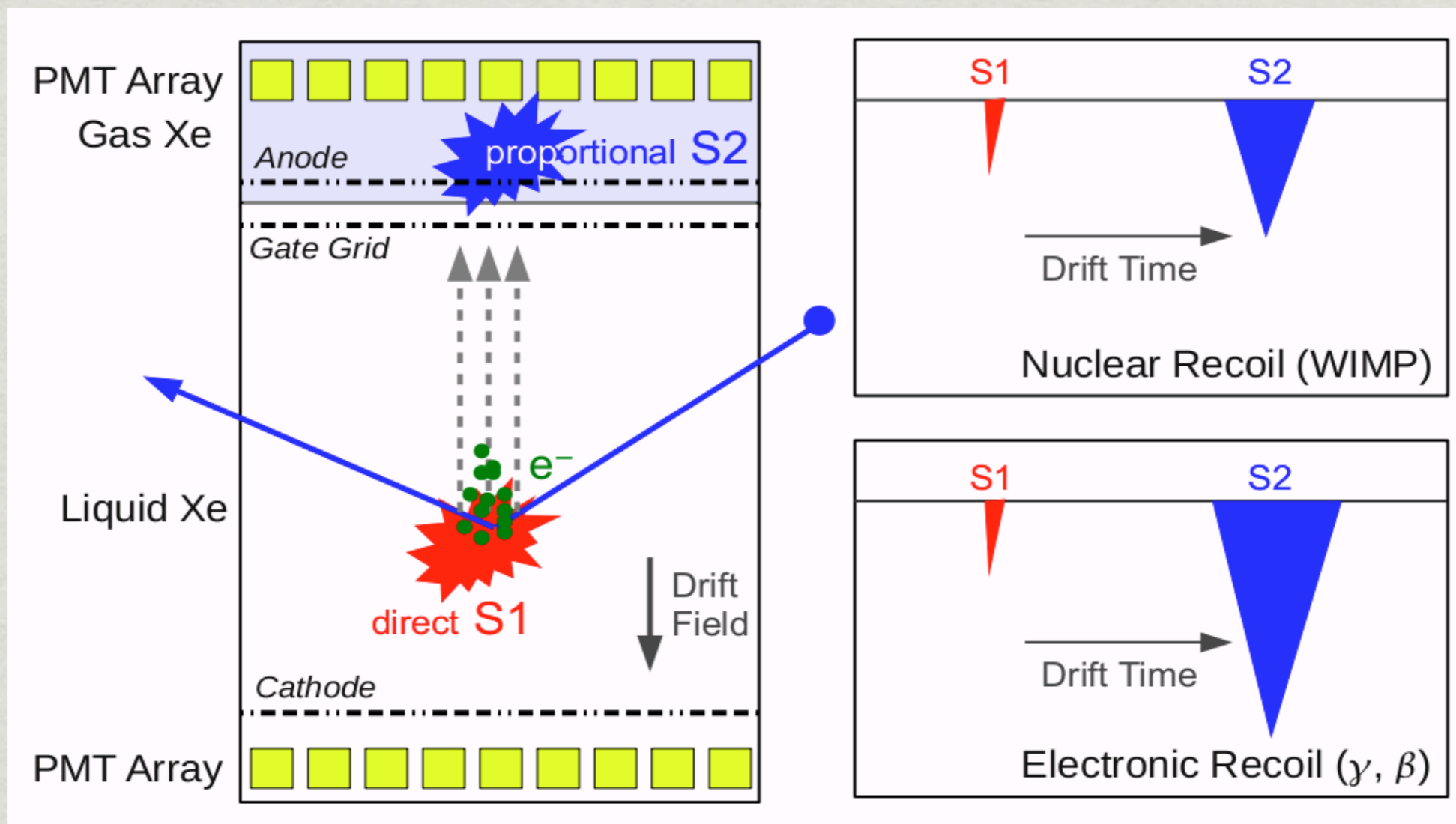


Direct WIMP search: Directional detectors

- * Simultaneous measurement of E_r and recoil track direction
- * Use gas mixture at ~ 100 mBar
- * Detect day-night directional modulation
- * DRIFT, DM-TPC, MIMAC
- * Recently a proposal to use nuclear emulsions

Direct WIMP search: Noble liquid detectors

- * Good self-shielding, homogeneous
- * Easily scalable to large masse
- * Good scintillators
- * If used in 2-phase TPC mode:
 - * both ionization and scintillation can be used for discrimination
 - * 3D positioning for fiducialization

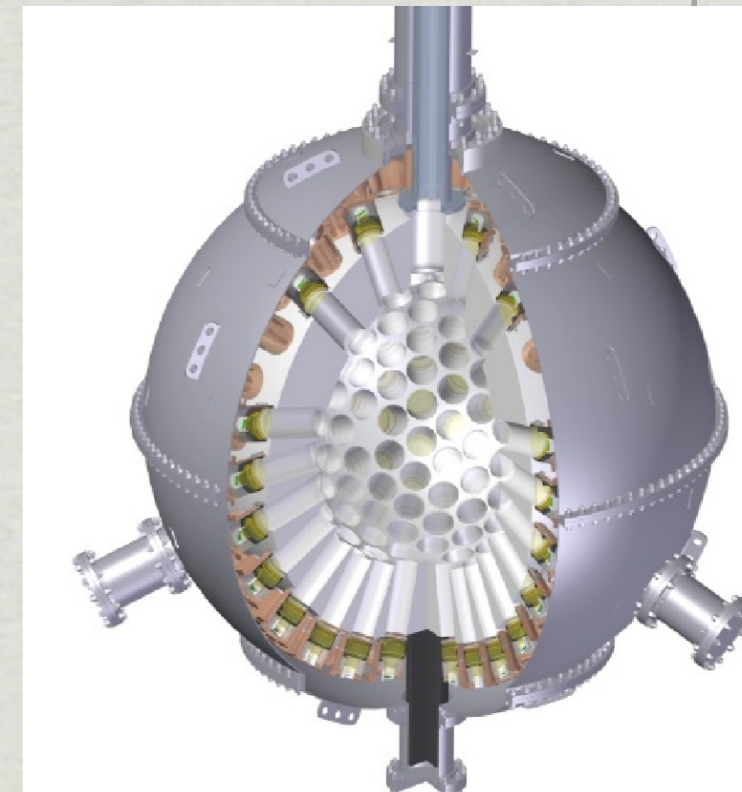
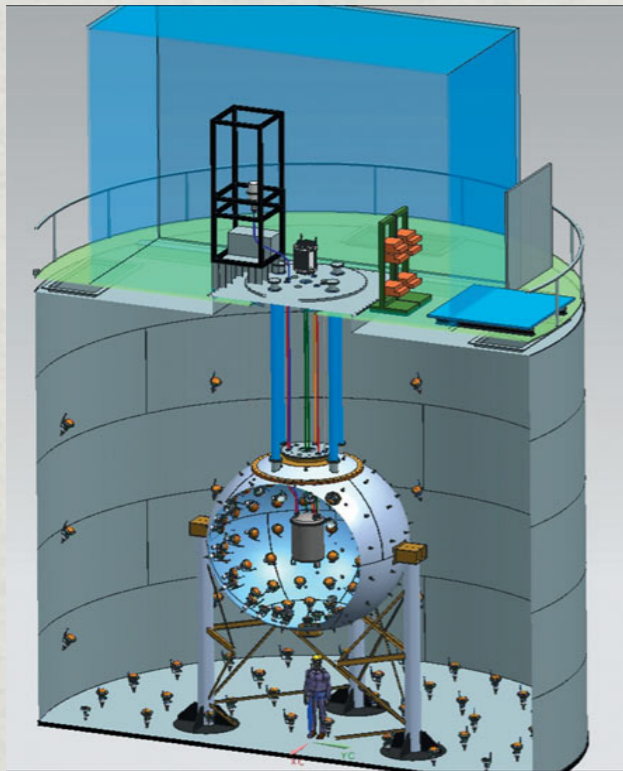


Noble liquid detectors: LAr

**DARK SIDE @GRAN
SASSO:
10 L PROTOTYPE
RUNNING
50 L DETECTOR IN
PREPARATION
USE OF DEPLETED AR**

**ARDM@CANFRANC:
850 KG TARGET
JUST INSTALLED IN
CANFRANC
OPERATIONS TO BE
STARTED IN 2013**

**DEAP/CLEAN @SNOLAB
3600KG LAR
SINGLE PHASE**



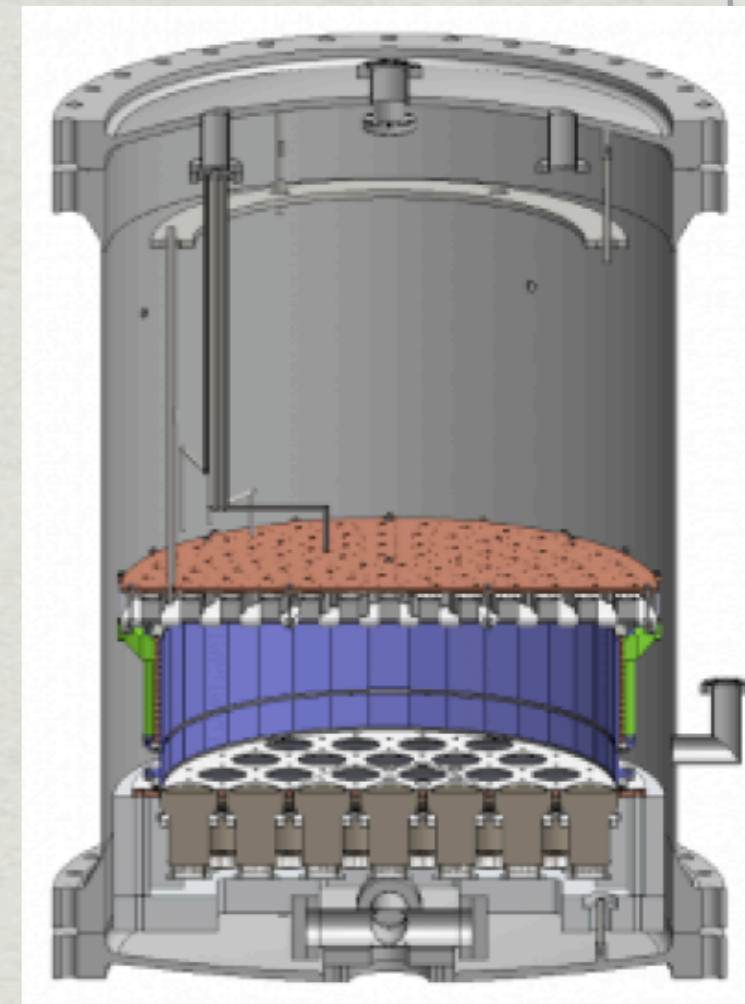
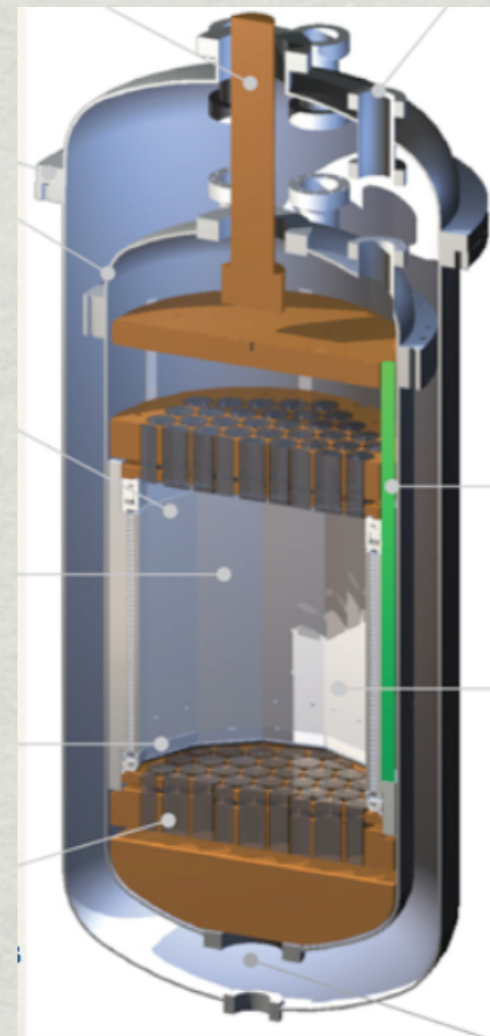
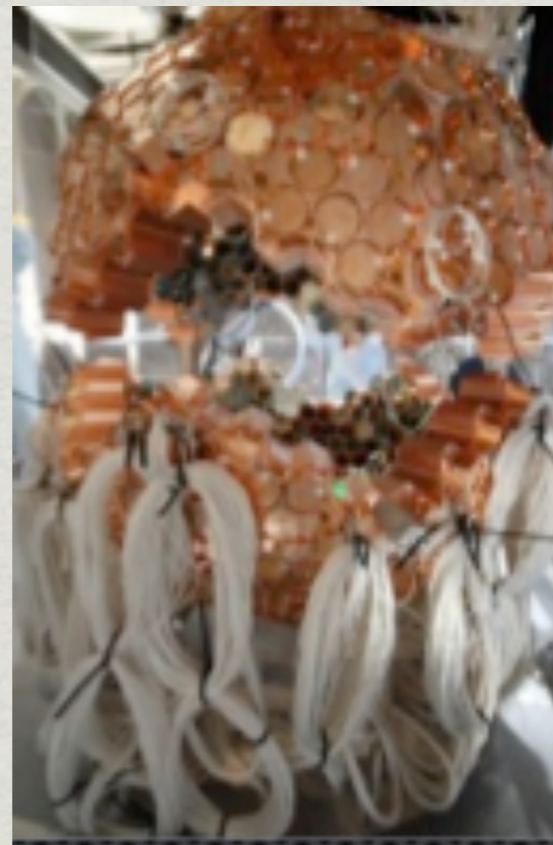
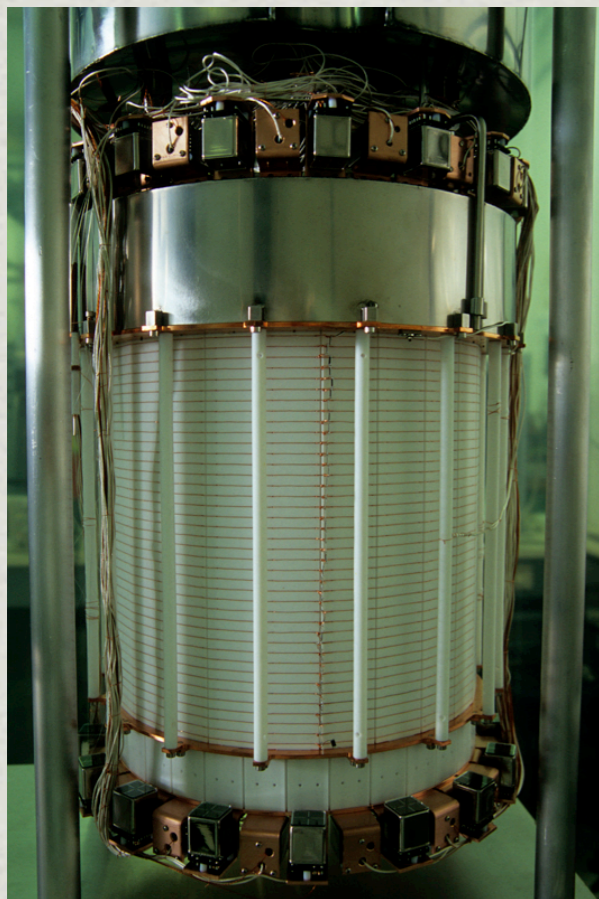
Noble liquid detectors: LXe

XENON @ GRAN SASSO
62 KG IN FIDUCIAL VOLUME
BEST LIMITS ON SI
ONE TONNE MODULE IN PREPARATION

XMASS @ KAMIOKA
835KG LXe, SINGLE PHASE; WATER SHIELDING;
642 PMTS

LUX @ HOMESTAKE
100KG FIDUCIAL
MOVED UNDERGROUND IN JULY 2012

PANDA-X @ JIN-PING: SCALABLE DESIGN
25 KG FIDUCIAL (PHASE 1A)
300 KG (PHASE 1B)



Direct WIMP search: Signals?

DAMA/LIBRA

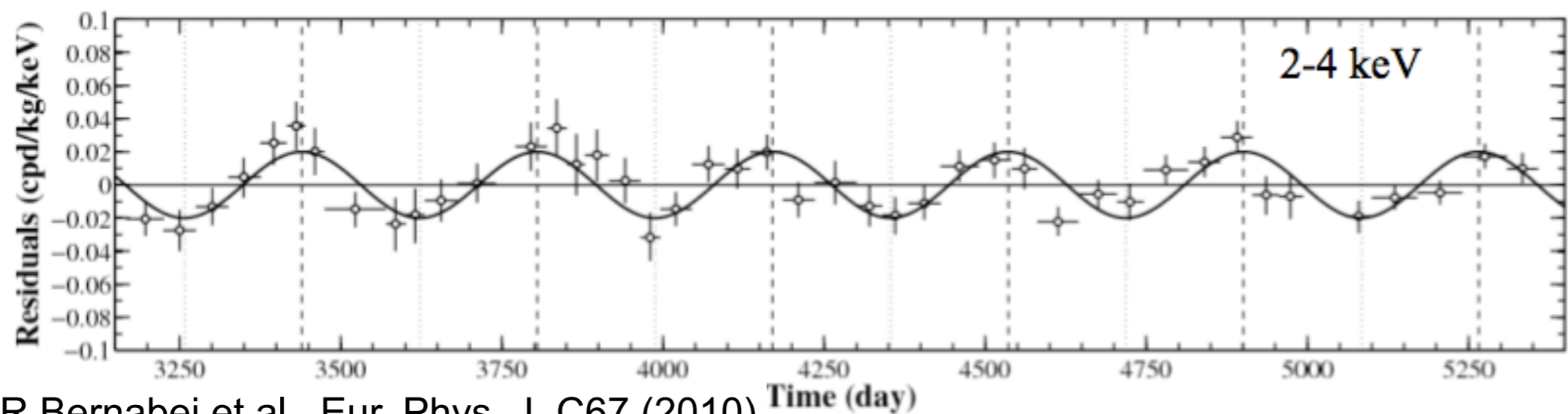
- * Installed at LNGS, uses NaI(Tl)
- * Only scintillation is detected with specially developed Hamamatsu PMTs
- * No background discrimination is applied
- * Started with DAMA/NaI in 1996 and upgraded the detector several times.
- * > 13 years of live-time
- * > 1 ton x year of exposure



Direct WIMP search: Signals?

DAMA/LIBRA

- Observes a time modulation of the signal event rate with a $T=1$ year and $\Phi = \text{June } 2 \pm 7 \text{ days}$
- Amplitude of the modulation $0.018 \text{ counts day}^{-1} \text{ kg}^{-1} \text{ keV}^{-1}$
- Signal significance: 8.9σ
- Modulation signal in the lowest energy bins: 2-6 keV bin, most evident 2-4 keV
- Signal in conflict with other experiment

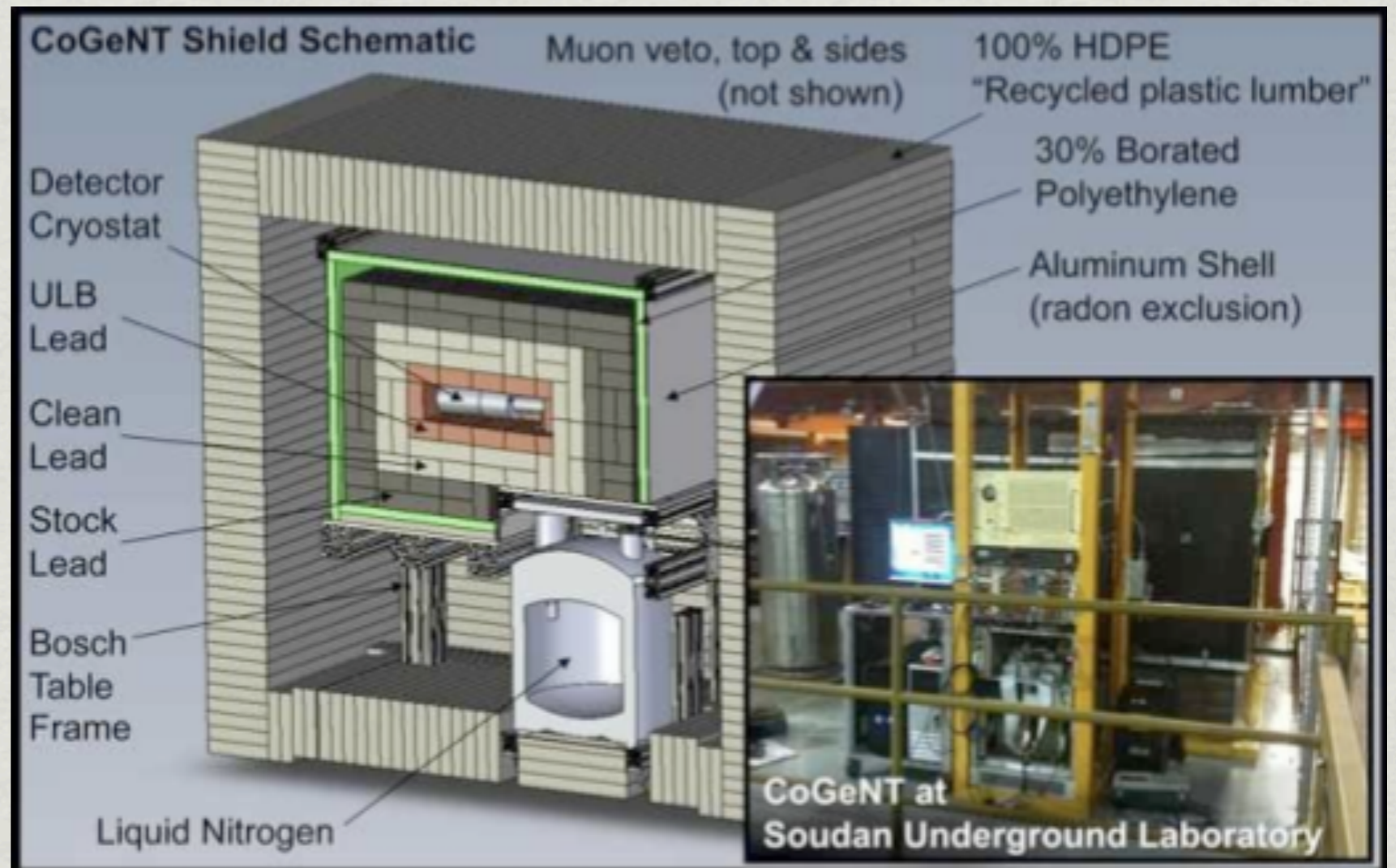


R. Bernabei et al., Eur. Phys. J. C67 (2010)

Direct WIMP search: Signals?

CoGeNT

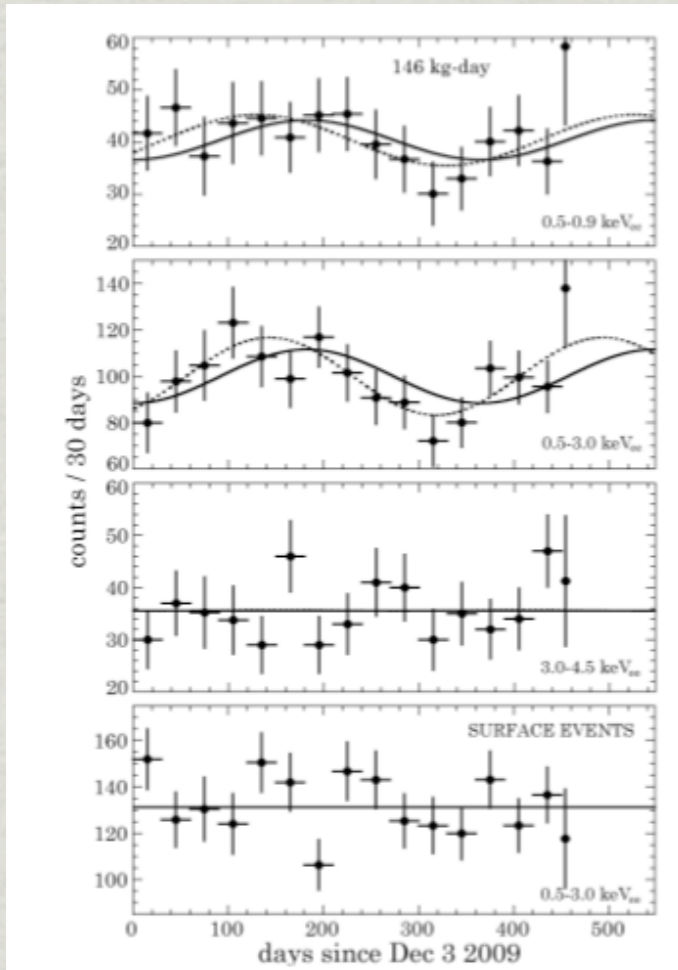
- * Located in Soudan mine (2100 mwe)
- * Single P-type point contact (PPC) Germanium detector:
 - * 440 g mass, 330 g fiducial
 - * Low electronic noise, i.e. low threshold (0.4 keVee)
- * Passive shield + Muon veto
- * No background rejection



Direct WIMP search: Signals?

CoGeNT

- Observed an exponential excess of events in the very low energy region < 2 keV
- Claim also annual modulation at 2.8σ level in the $[0.5, 3.0]$ keVee bin, ~ 450 live-days

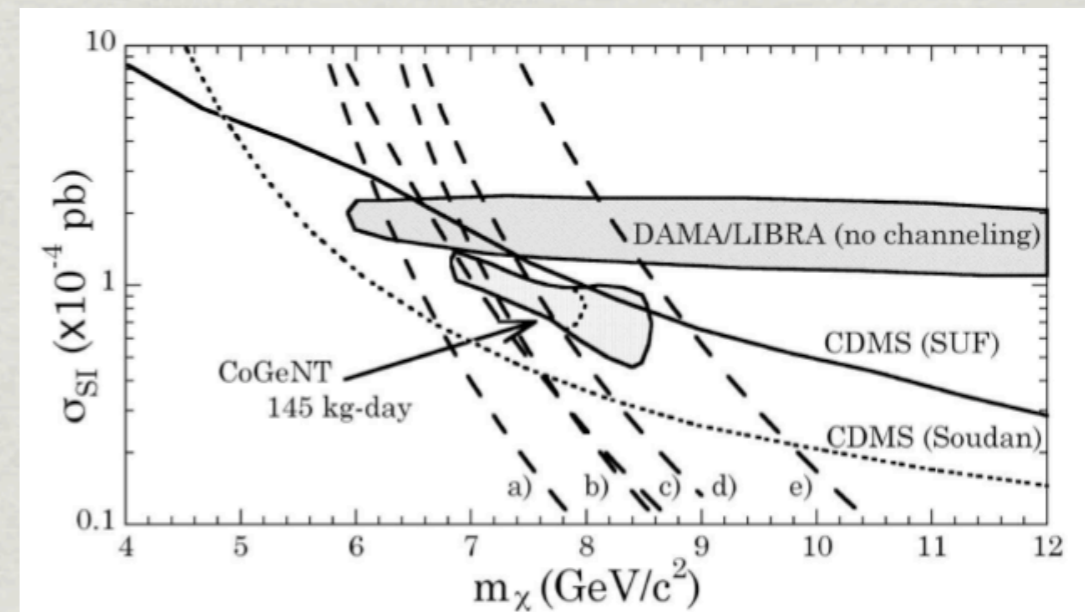
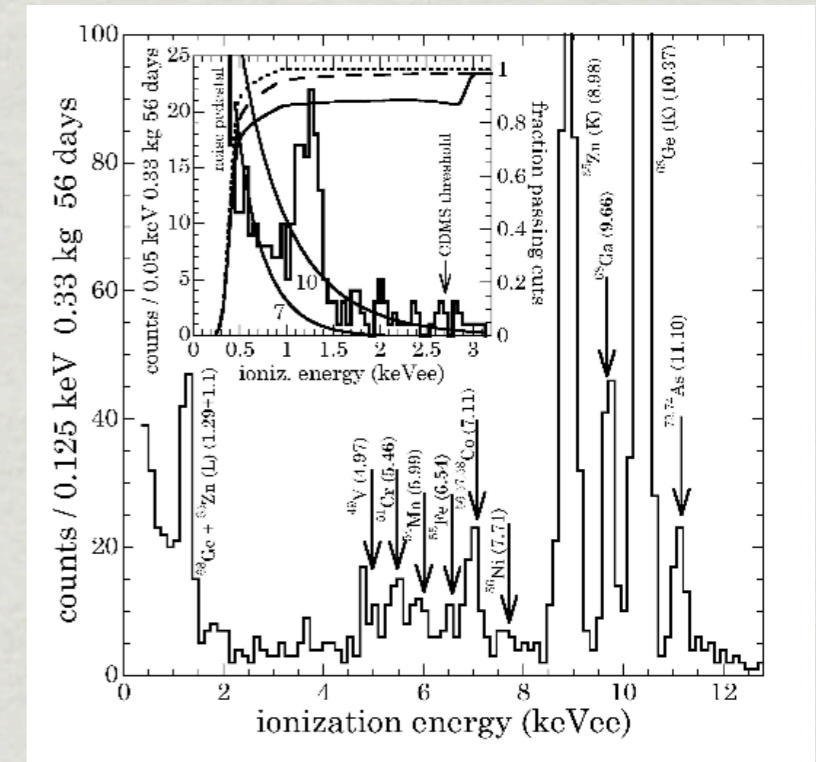


0.5 - 0.9 keV

0.5 - 3.0 keV

3.0 - 4.5 keV

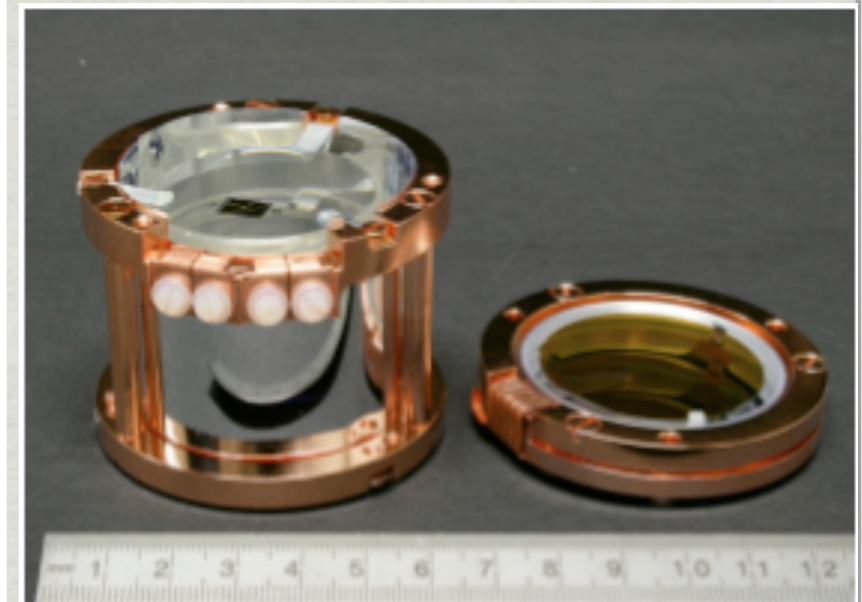
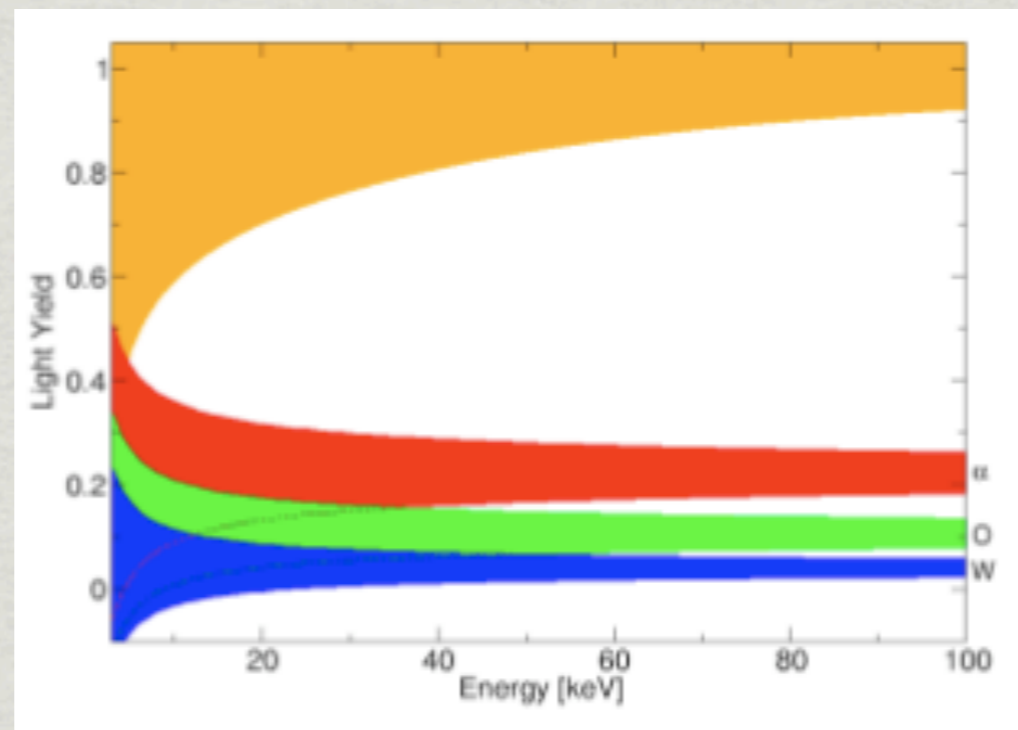
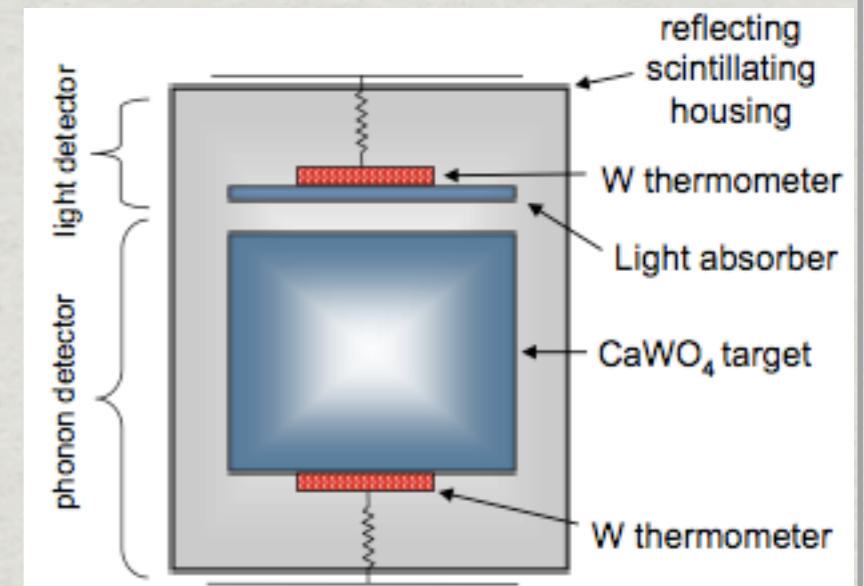
surface events



Direct WIMP search: Signals?

CRESST-II

- * Located at LNGS
- * Target: 9 CaWO_4 + 1 ZnWO_4 scintillating crystals of CaWO_4
- * Crystals are operated as cryogenic calorimeters (~ 10 mK)
- * Fast phonon read-out with Tungsten Transition-edge sensors (TES)
- * Light read-out
- * e.m. background suppression via phonon-to-light ratio

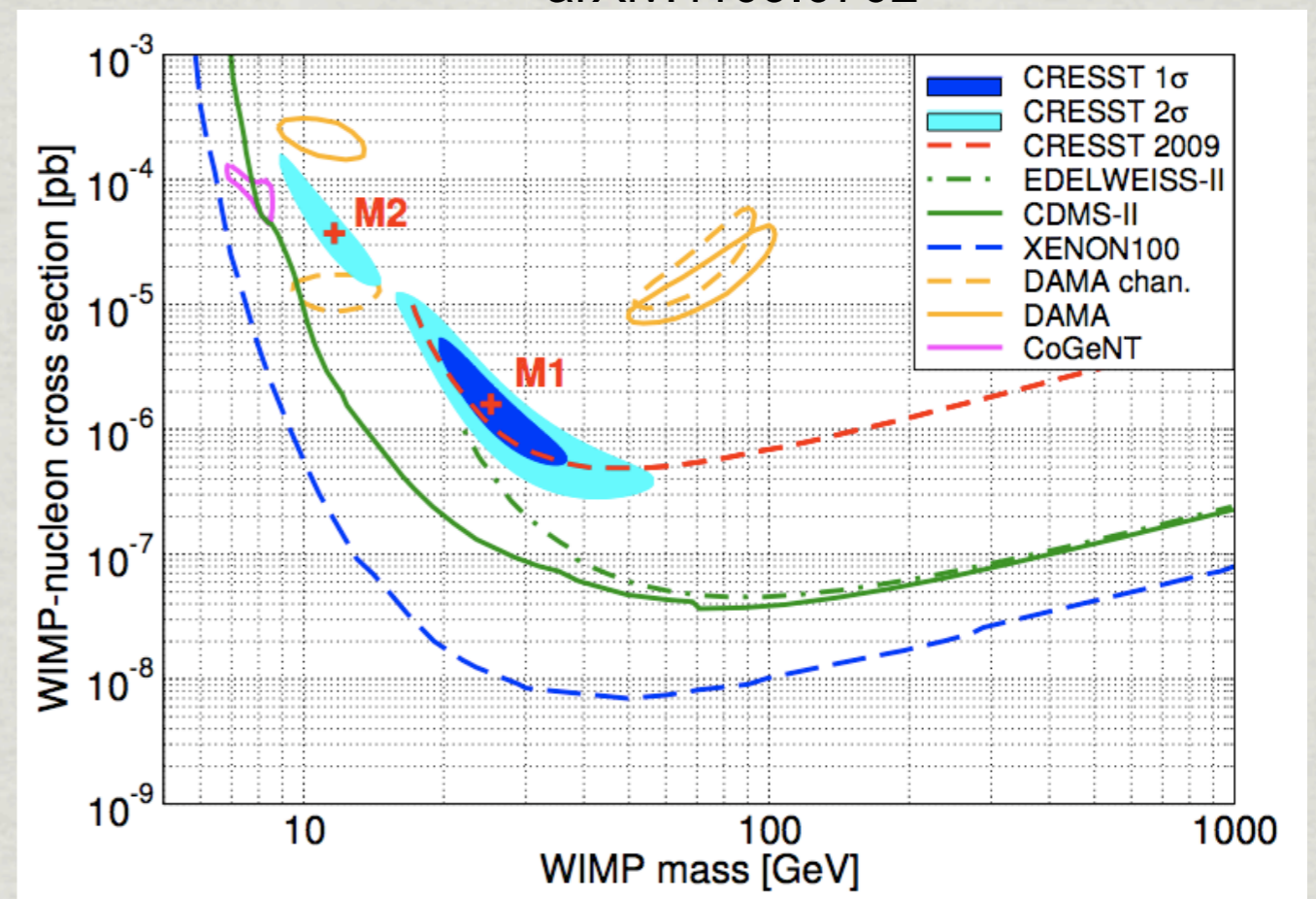


Direct WIMP search: Signals?

CRESST-II

- * With an exposure of 730 kg x day
- * After applying the basic cuts they are left with 67 events
- * Possible background that could affect this number are taken into account
- * With a likelihood ratio test they find that, at a significance $> 4\sigma$, the backgrounds are not enough to explain so many events
- * They derive the confidence level region in the WIMP parameter space that is compatible with the CRESST-II results
- * Further background reduction is planned in order to reproduce these results

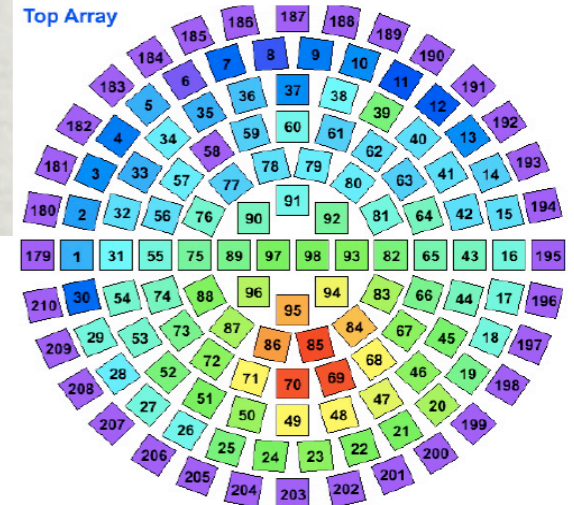
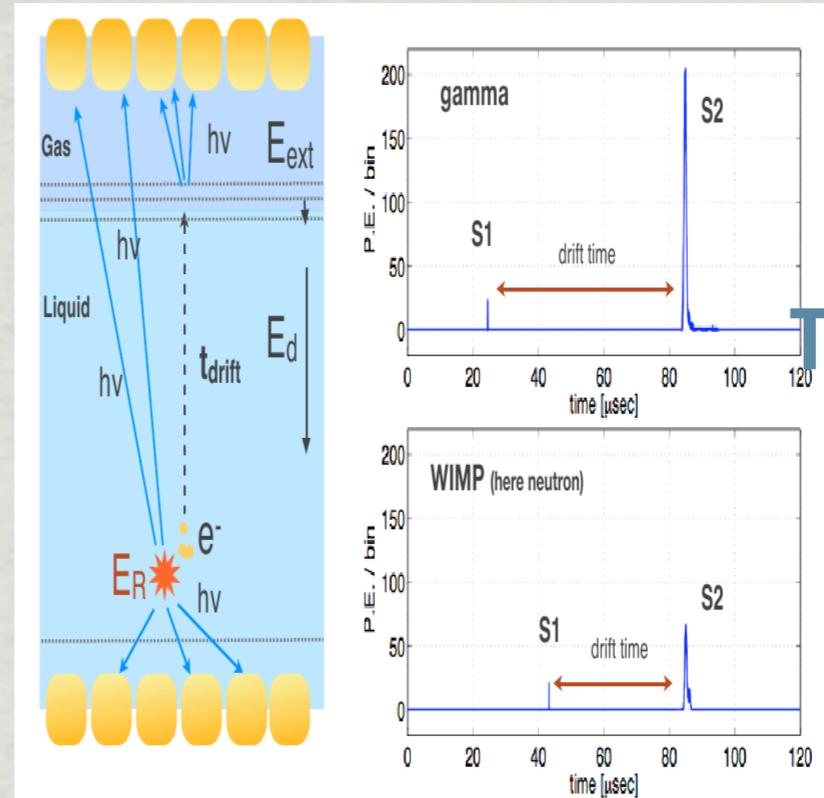
arXiv:1109.0702



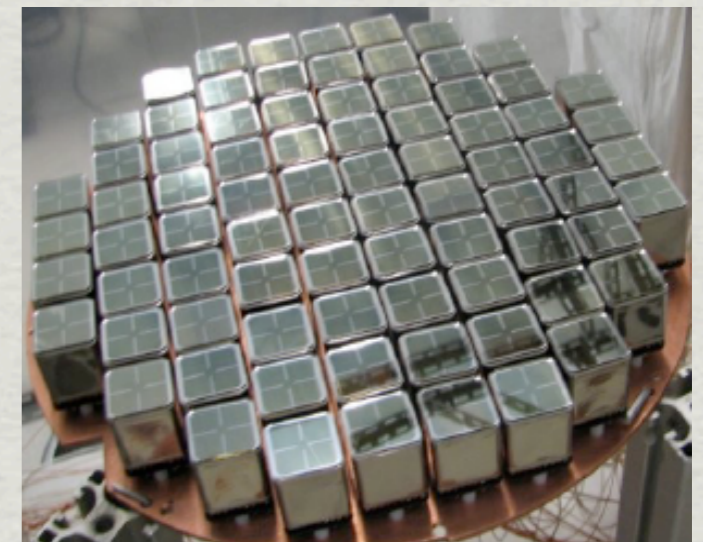
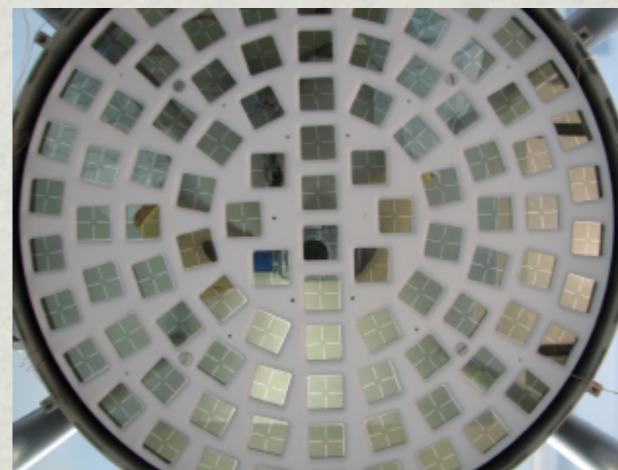
Direct WIMP search: Limits

- Installed at LNGS
- Dual phase LXe TPC
- 3D position sensitivity (~ 3 mm resolution in z)
- Extensive material screening and selection campaign
- The volume surrounding the TPC is
- filled with ~ 100 kg of liquid xenon
- This liquid xenon acts as a radiation
- shield thanks to the high Z and density ($2.82 \text{ kg/cm}^3 @ 2.3 \text{ Atm}$)
- The volume is instrumented with 64 PMTs facing the top, bottom and sides of the TPC to reject interactions with one deposition inside the TPC and one in outside

XENON100



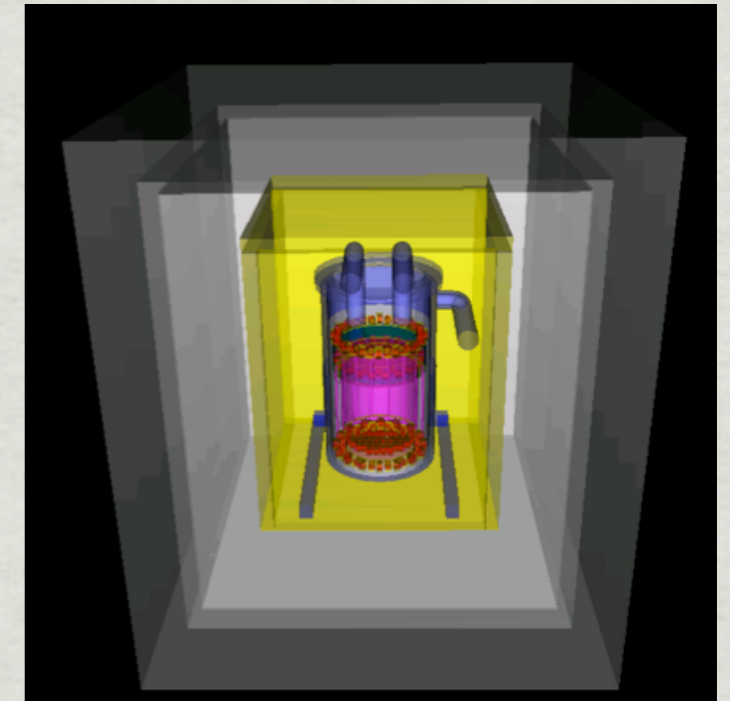
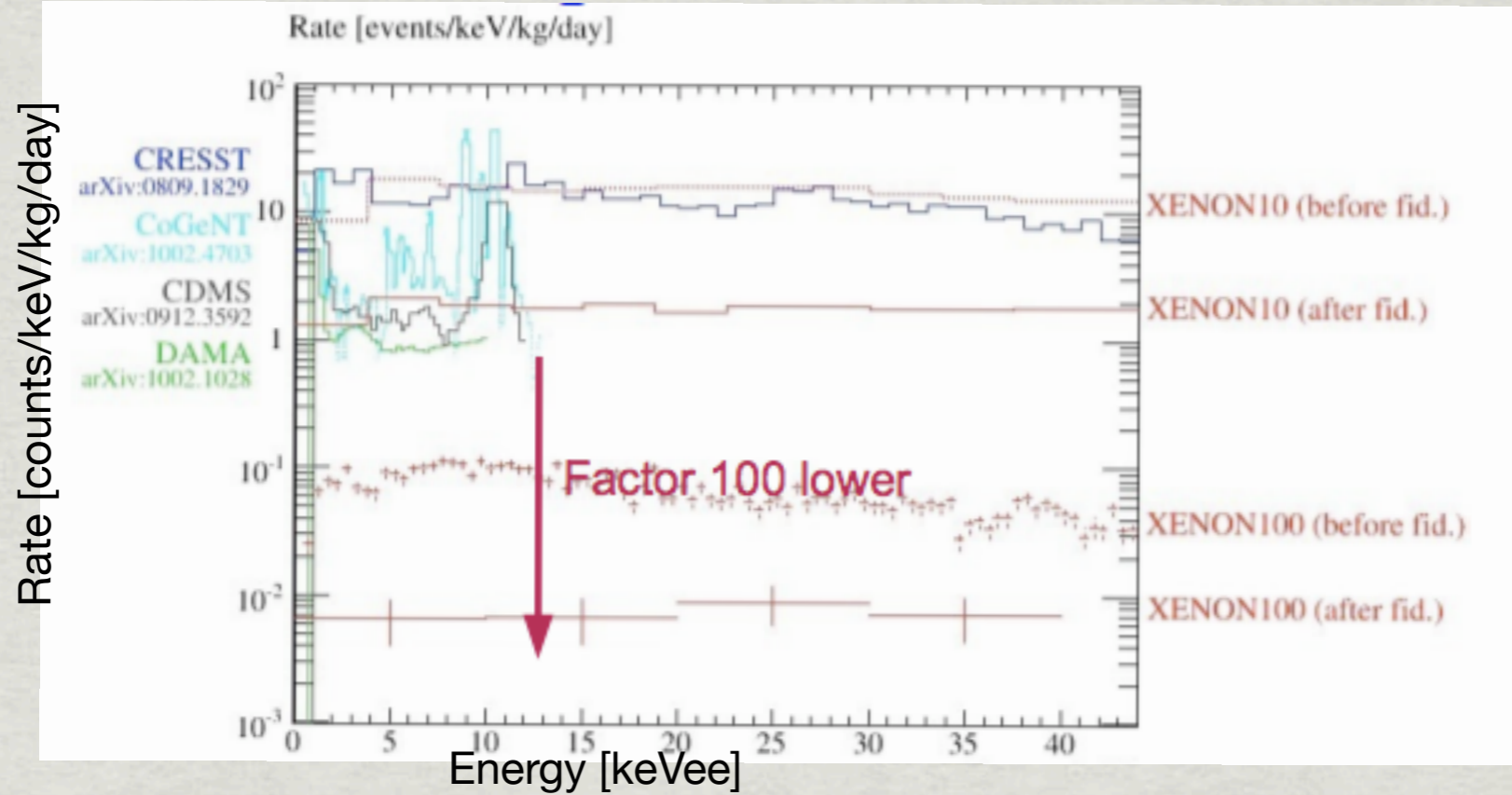
TOP S2 HIT PATTERN



Direct WIMP search: Limits

XENON100

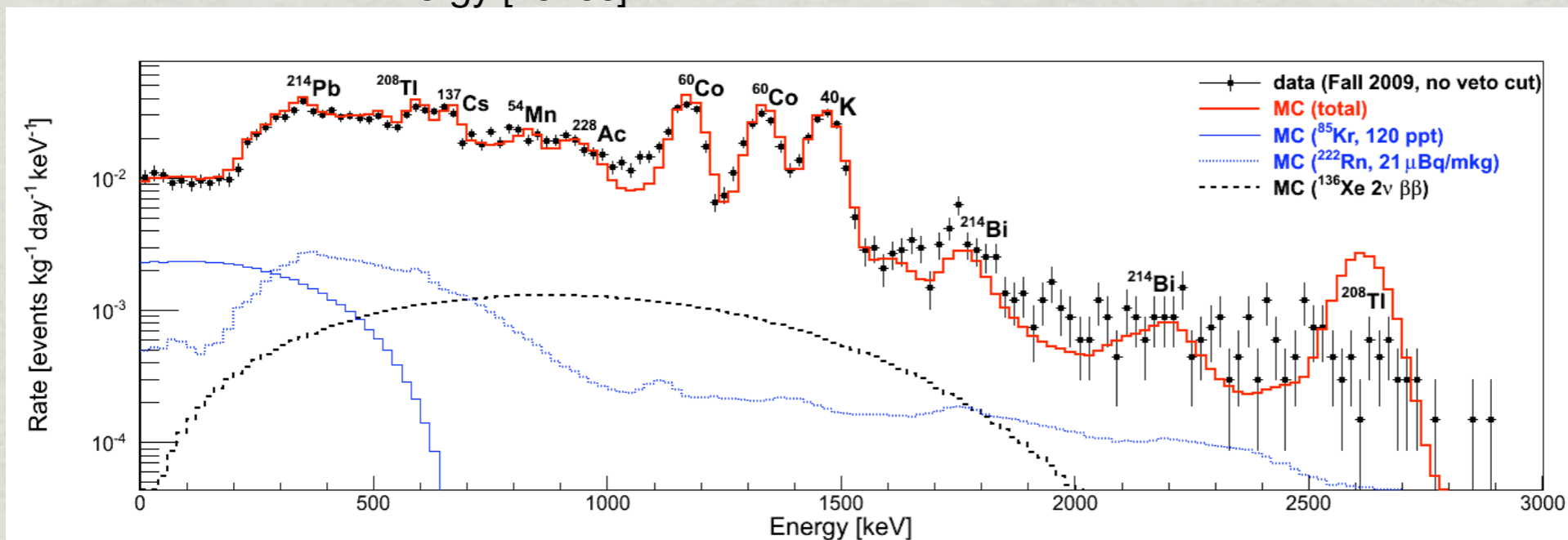
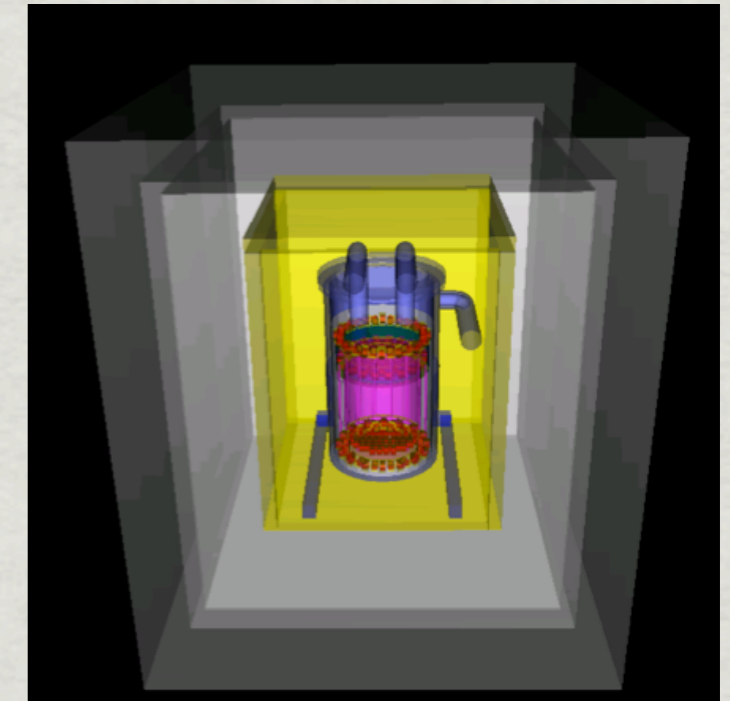
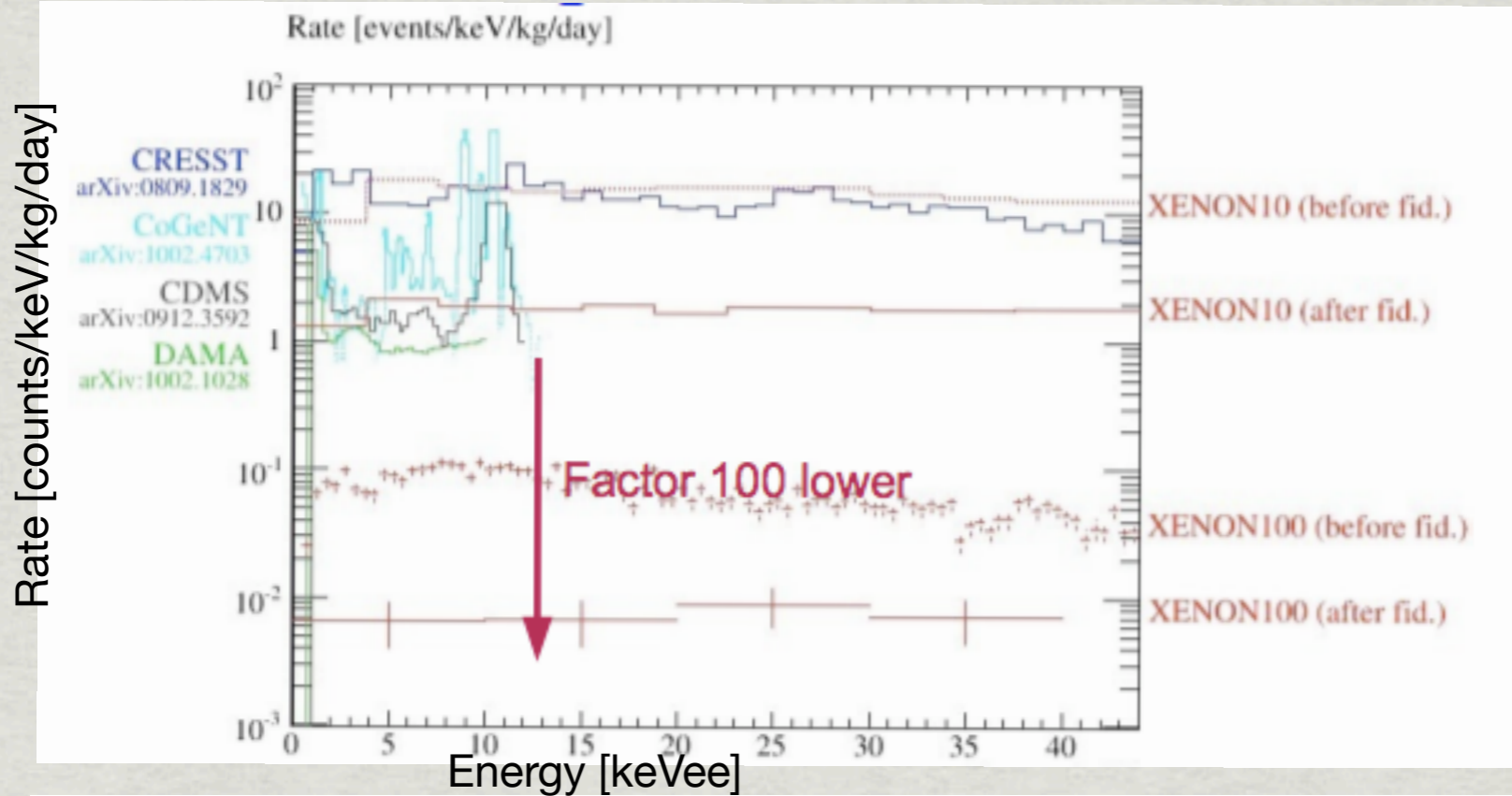
LOWEST BACKGROUND DARK MATTER DETECTOR



Direct WIMP search: Limits

XENON100

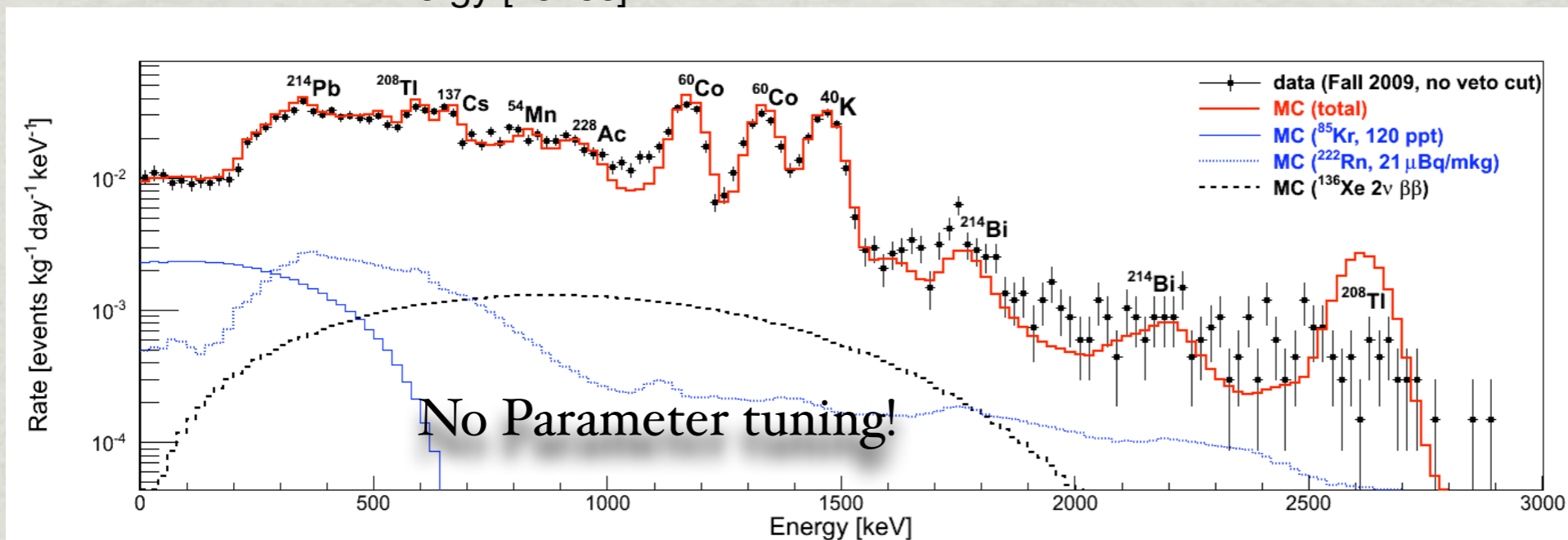
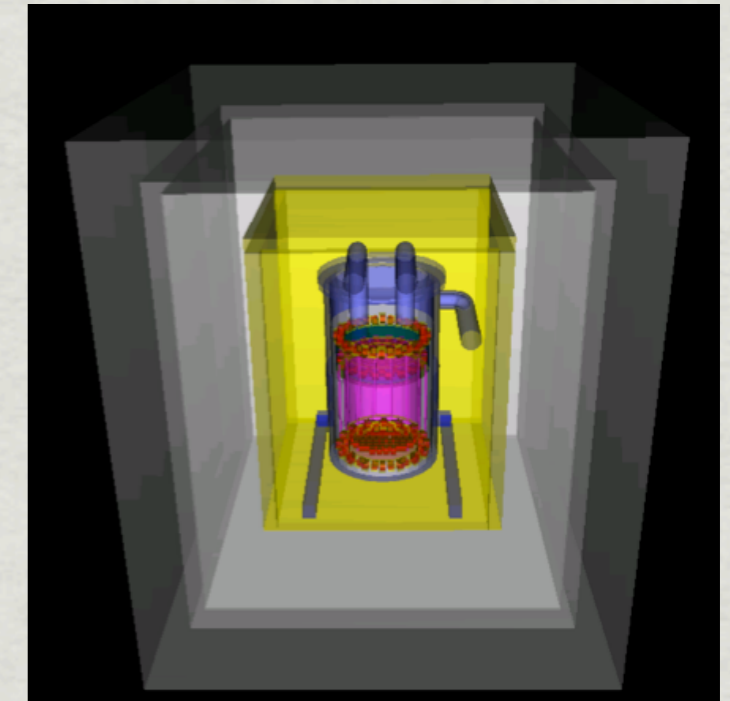
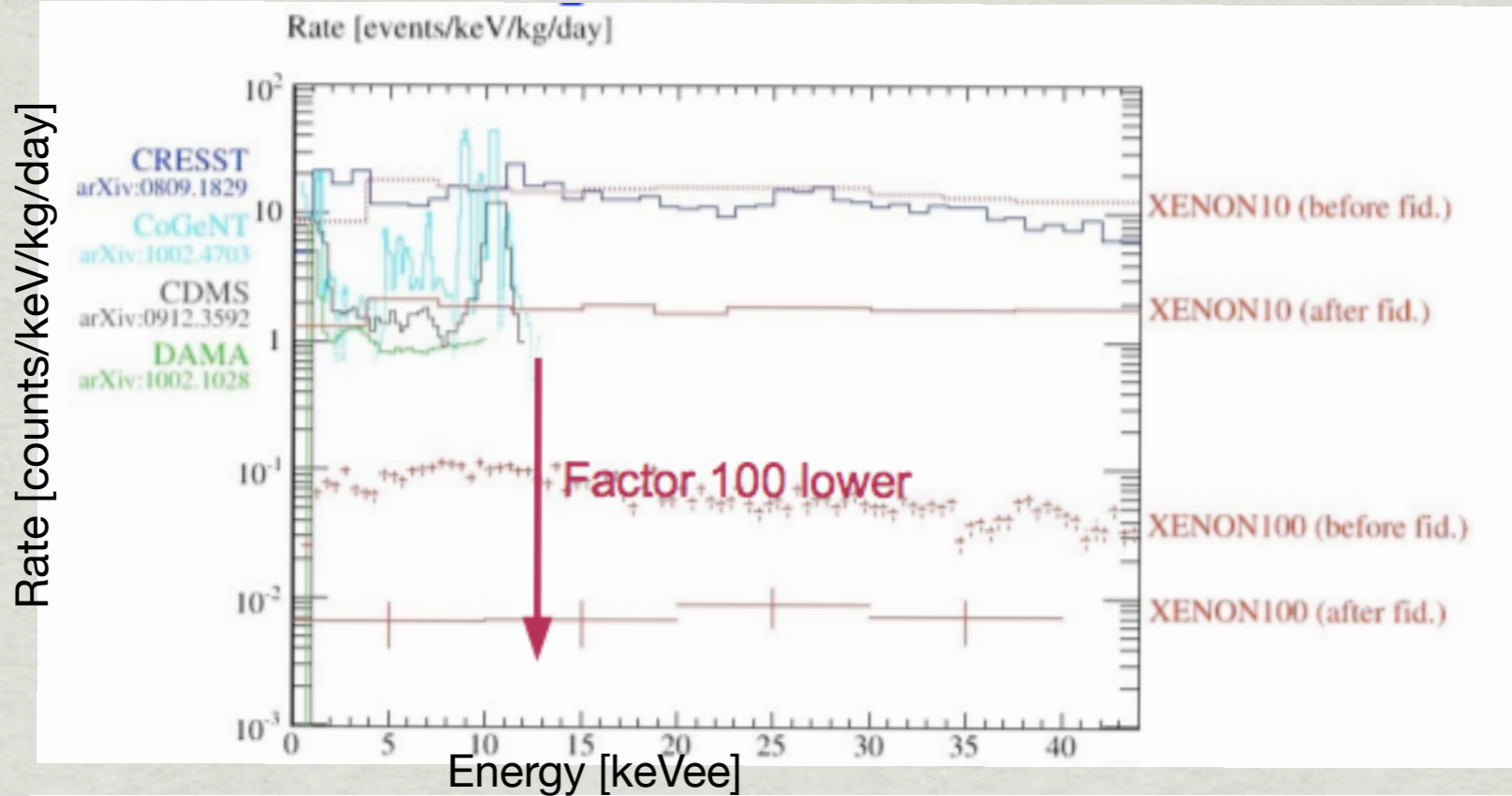
LOWEST BACKGROUND DARK MATTER DETECTOR



Direct WIMP search: Limits

XENON100

LOWEST BACKGROUND DARK MATTER DETECTOR



Direct WIMP search: Limits

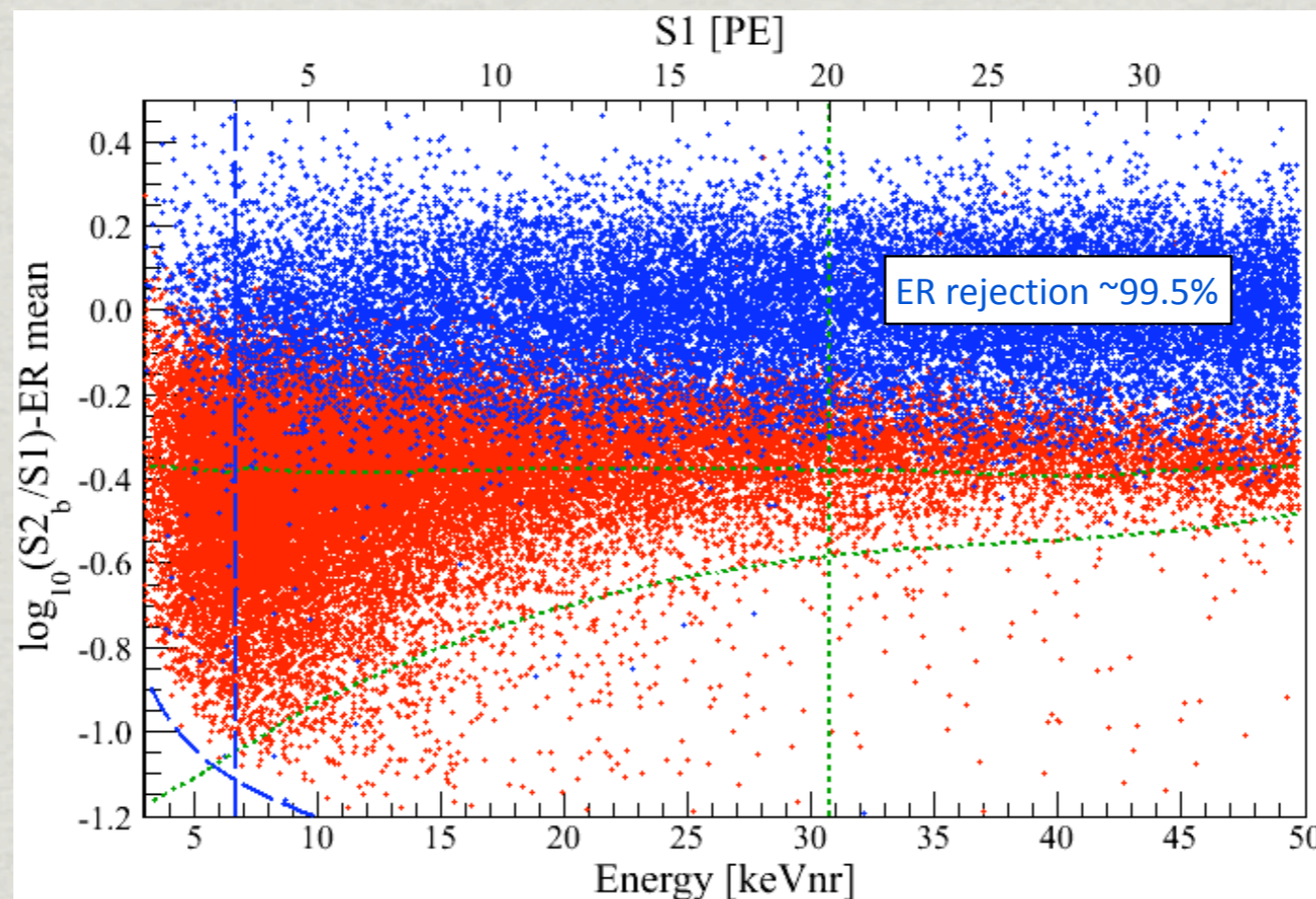
XENON100

It is possible to distinguish between nuclear recoils and electronic recoils due to their different charge-to-light ratio

The rejection efficiency is $\sim 99.5\%$ in the range 4 - 20 pe

3D Position sensitivity:

- Fiducial cut
- single/multiple discrimination

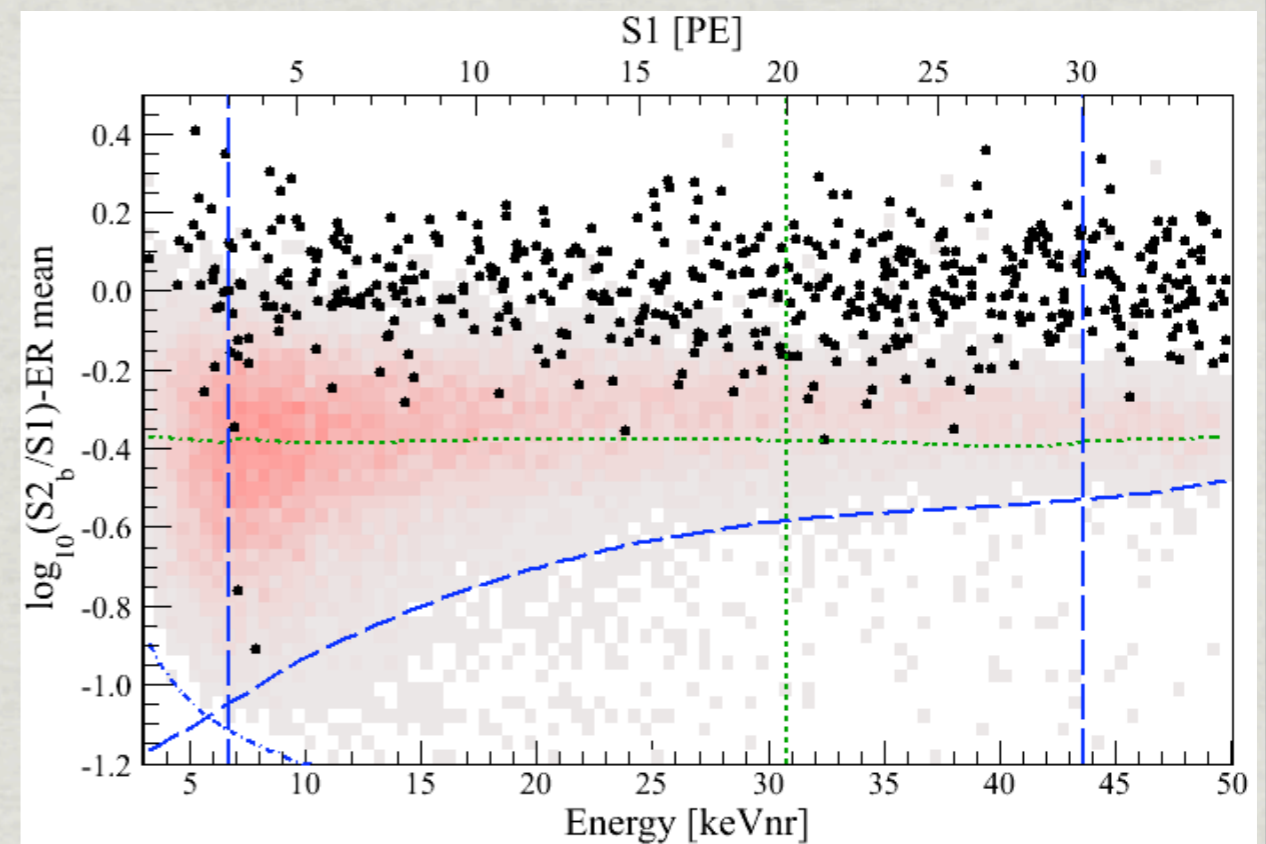


Direct WIMP search: Limits

XENON100

Result

Predicted 1.0 ± 0.2 background events
Observed 3 vents



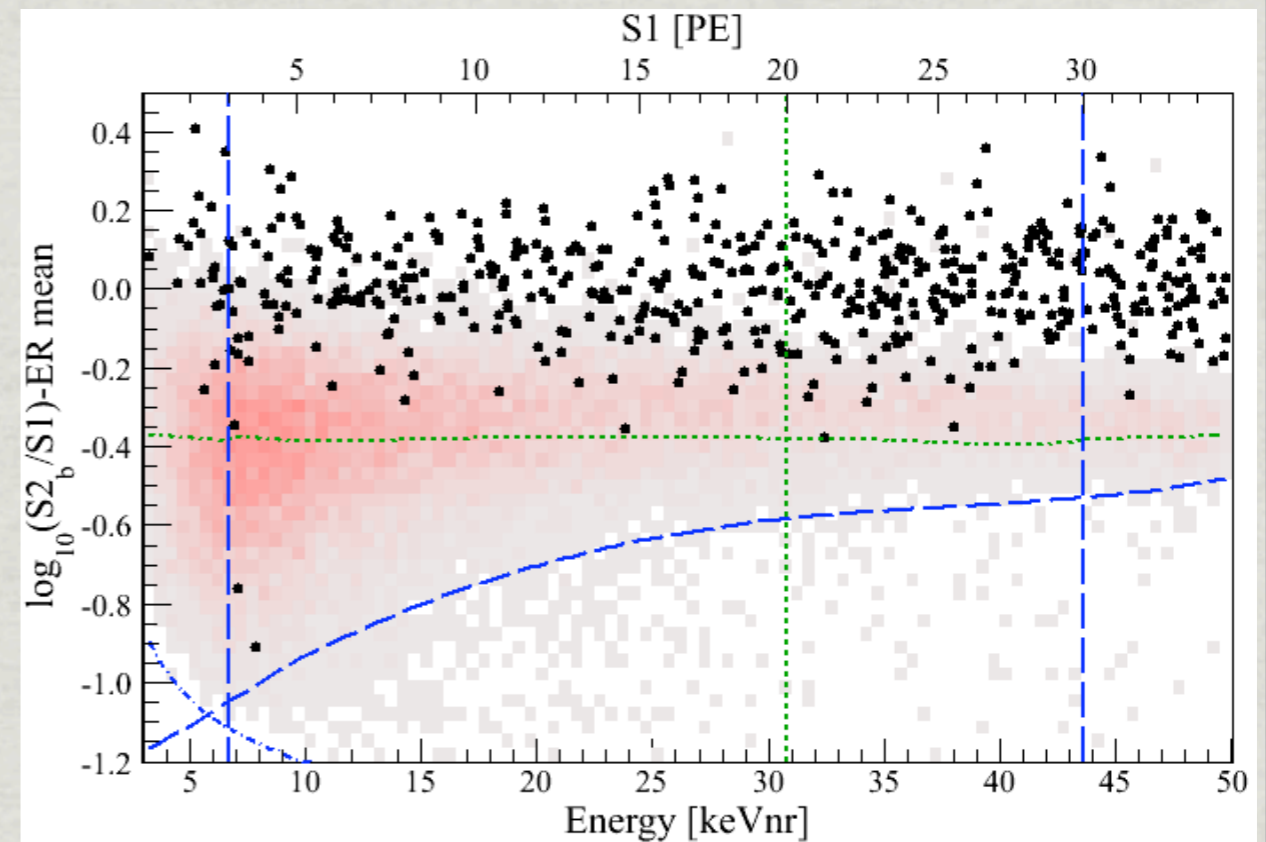
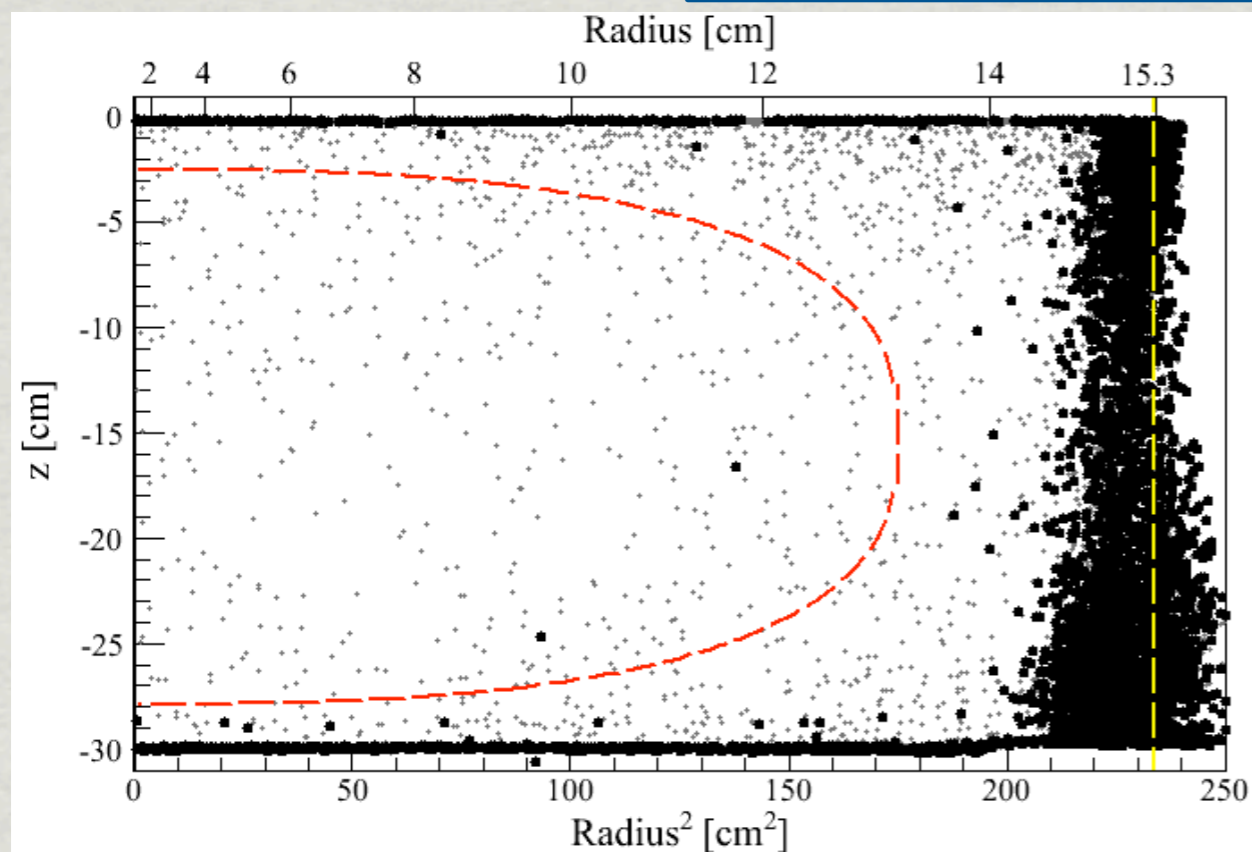
Super-elliptical 48 kg fiducial volume cut

Direct WIMP search: Limits

XENON100

Result

Predicted 1.0 ± 0.2 background events
Observed 3 vents



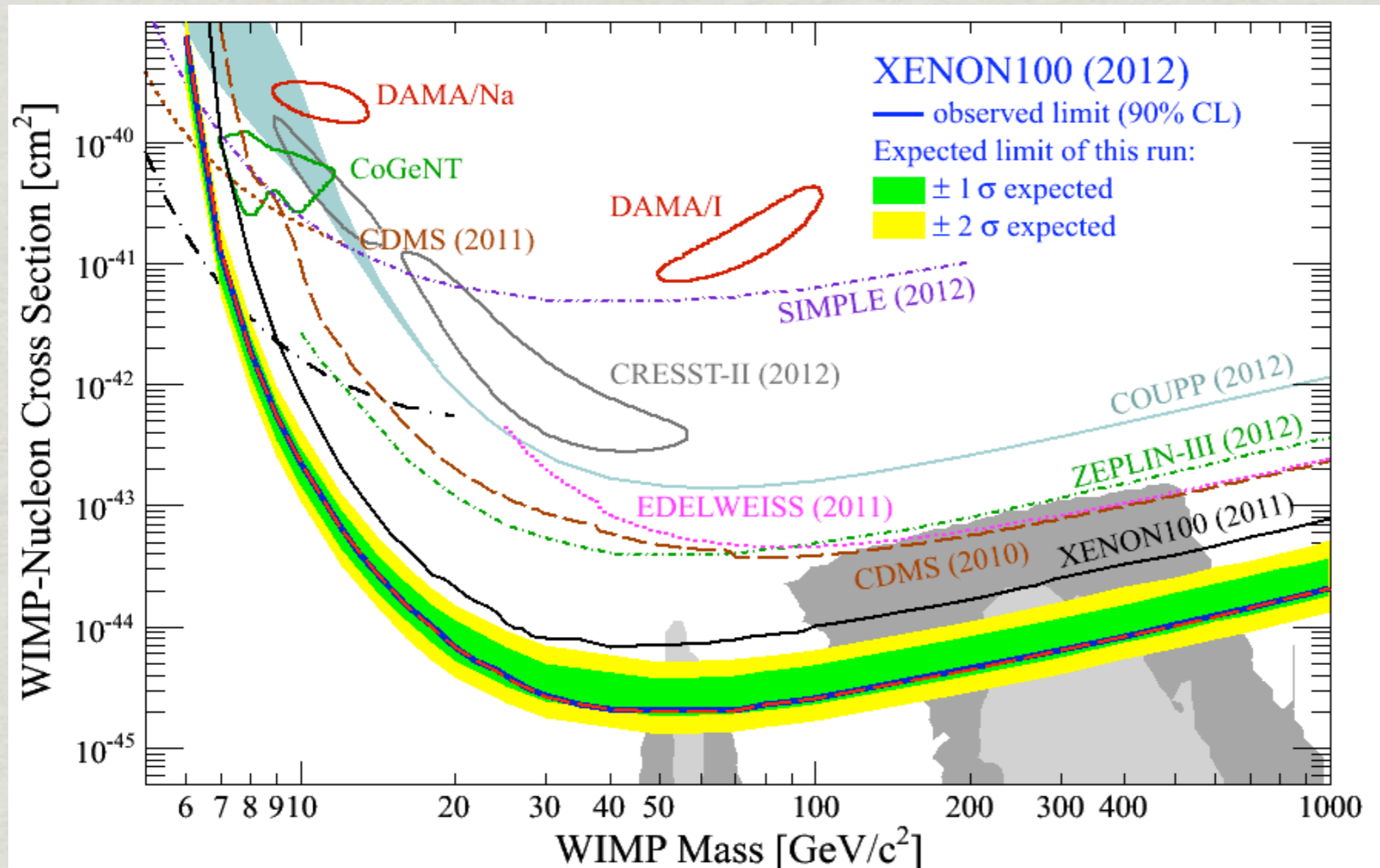
Super-elliptical 48 kg fiducial volume cut

Direct WIMP search: Limits

XENON100

**MOST STRINGENT LIMIT
TO DATE**

E. Aprile et al., Phys. Rev. Lett. 109 (2012) 181301

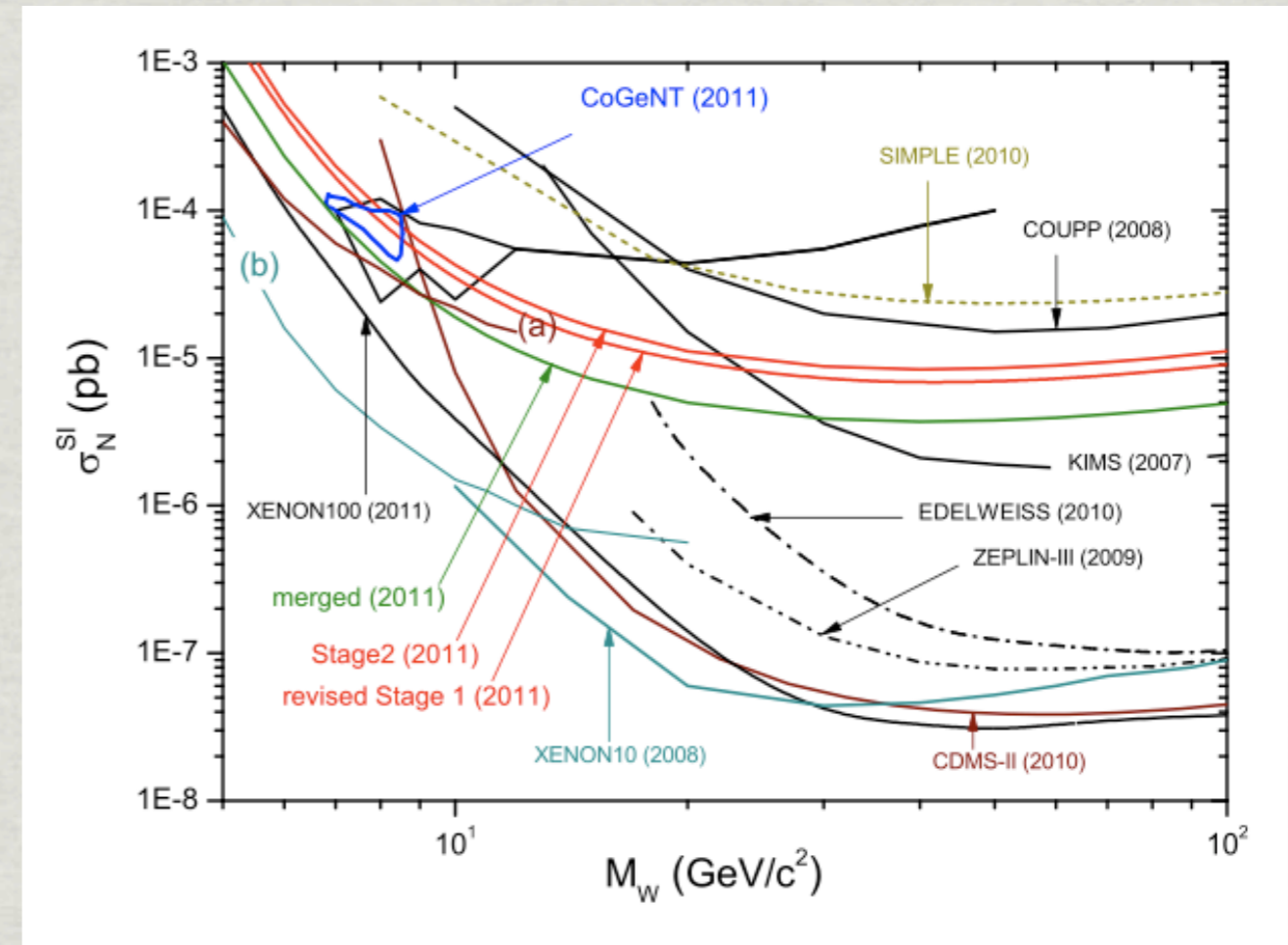


Direct WIMP search: what's next?

Analyzing	Installation/Construction/R&D	@ LNGS
Zepelin-III	CoGeNT-4	
	CRESST-II upgrade	
	SuperCDMS	
Data taking	LUX350	
DAMA/LIBRA	ArDM	
Xenon100	DM-Ice-250	
COUPP-4kg	PICASSO	
DM-Ice-17	DarkSide50	
DarkSide-10	Xenon1t	
	MiniCLEAN	
	DEAP-3600	
	EDELWEISS-II	
Commissioning	Panda-X 1a/1b	
XMASS	CDEX-10kg	
COUPP-60	All directional TPC	
CDEX-1kg	...	
		Future
		EURECA
		DARWIN
		DarkSide5T
		Panda-X 2
		MAX
		COUPP-500

Direct WIMP search: Summary

- * Dark matter was first predicted 80 years ago
- * Direct detection experiments are approaching the theory predicted WIMP region
- * The WIMP parameter space diagram is now quite crowded but new curves to be appeared soon
- * More than one experiment has claimed hints of low mass WIMPS
- * However, other experiments have found results incompatible with these claims
- * New data are needed and will be available soon that will further clarify the situation



Direct WIMP search: Perspectives

- ➔ Sensitivity advanced by 2-3 orders of magnitude in the last decade, and keeps increasing.
- ➔ Noble liquid detectors are starting to set the pace in sensitivity.
- ➔ Promising Future:
 - ✓ LHC is close to SUSY
 - ✓ New results from indirect searches are coming soon.
 - ✓ Direct+indirect+LHC:
We will know much more about DM (WIMPs or not) within the next 5 years

STAY TUNED!