The Direct Search for Dark Matter

with special emphasis on the XENON project

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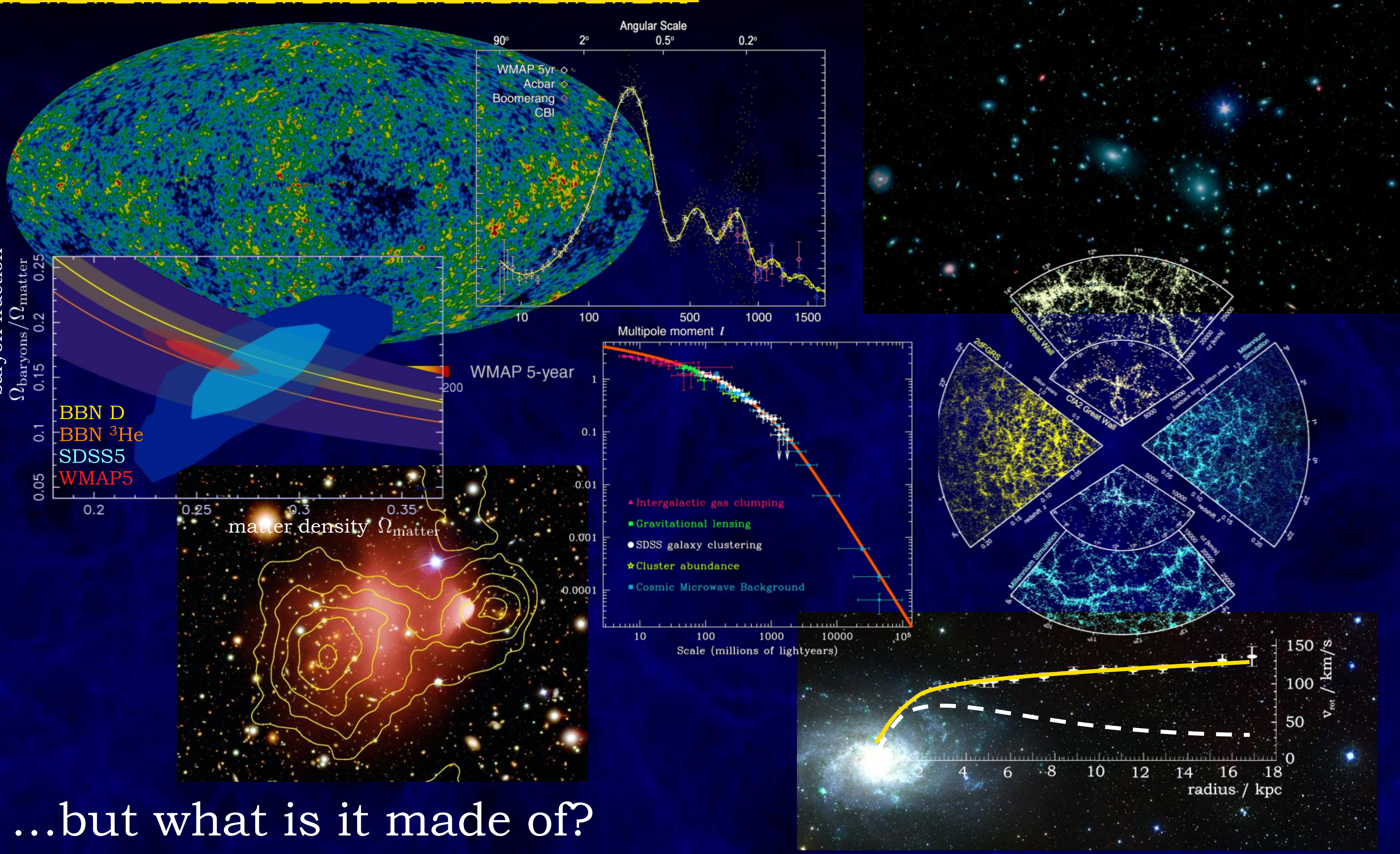
IPMU Tokyo, March 8, 2013

picture: Thomas Tuchan

Dark Matter Exists…



…but what is it made of?

The Direct Search for Dark Matter

- thermal relic hunting basics
- discrimination techniques
- DAMA/LIBRA
- CoGeNT
- CDMS-II and EDELWEISS
- XENON100 and XENON1T

Search for The Invisible

not impossible — a historical perspective:

1844: F. Bessel predicts companion of Sirius
discovered by A. Clark in 1862

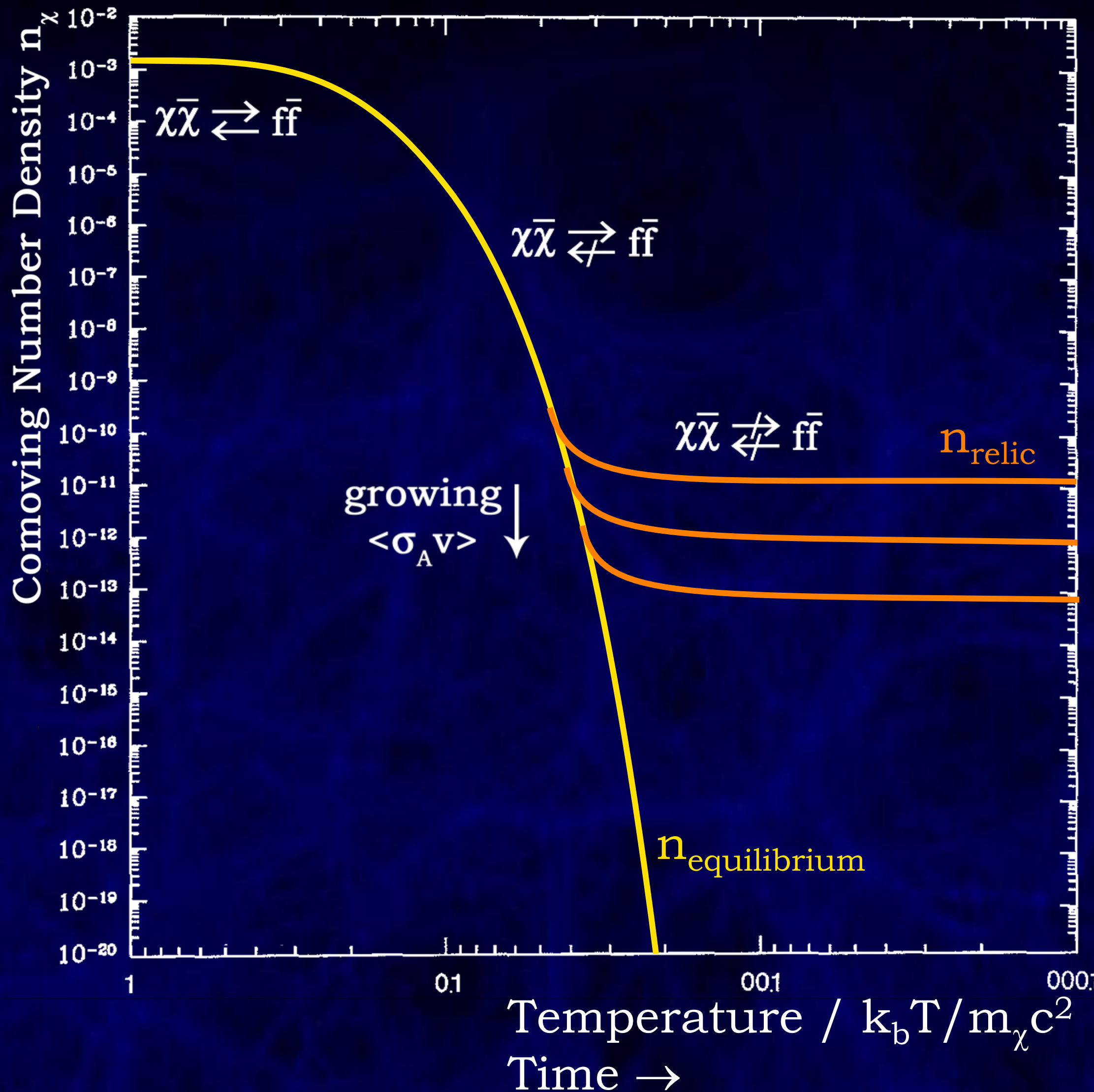
1845: J. Adams, U. Leverrier predict 8th planet
discovered by J. Galle 1846

1930: W. Pauli predicts neutrino
discovered by C. L. Cowan and F. Reines in 1956

and the ~~discovery of ether~~, the black hole at the center of the Milky Way, …

But: Need an idea first!

Idea: It's a Thermal Relic Particle



from cosmology:

$$\Omega_\chi \equiv \frac{n_\chi m_\chi c^2}{\varrho_{\text{critical},0}} \approx \frac{10^5\,\text{pb km/s}}{\langle\sigma_A v\rangle}$$

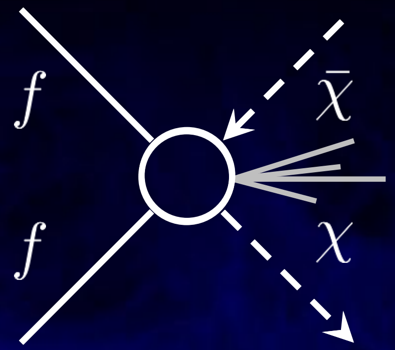
robust scattering prediction:

rate

$$\Gamma \propto \sigma v \varrho_\chi \sim \frac{\sigma v}{\sigma v} = \text{const}$$

How to Search a Thermal Relic

- Production



Collider Searches

- Annihilation

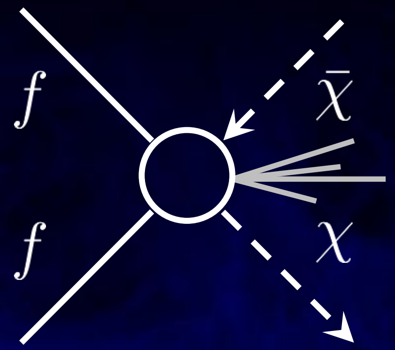
$\bar{\chi}$ f

χ f

Indirect Searches

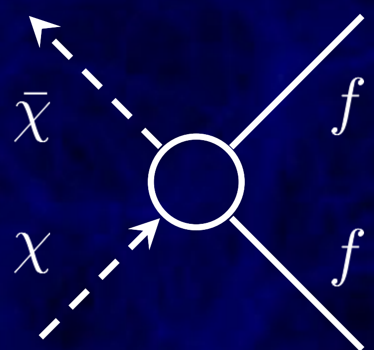
How to Search a Thermal Relic

- Production



Collider Searches

- Annihilation

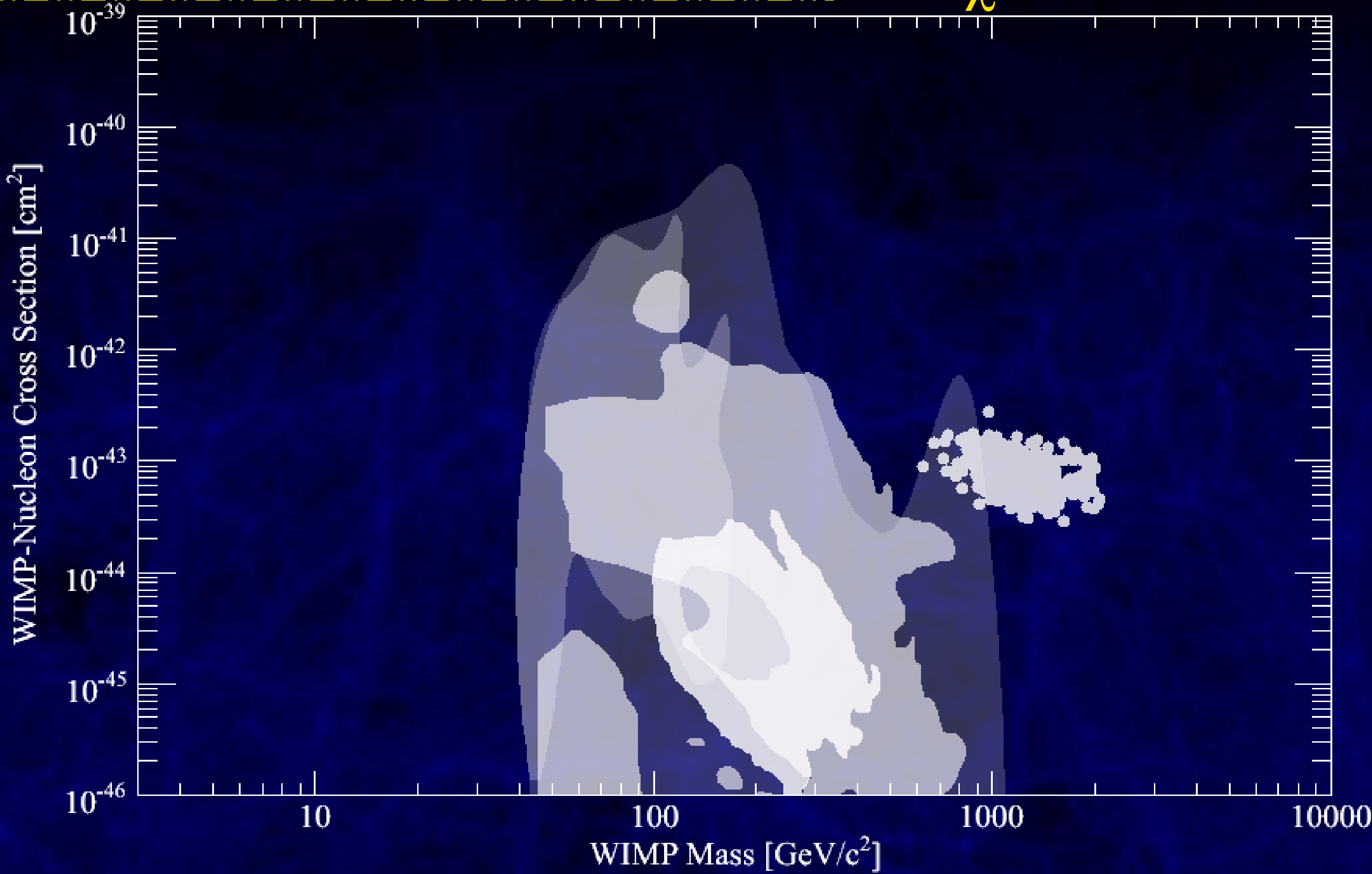


Indirect Searches

- Scattering

Direct Searches

Expectations in σ-m_χ-Space



this is where we would expect the usual new physics (MSSM etc.) to show up

Buchmueller et al. arXiv:1102.4585
Kadastik et al. PRL **104** 201301 (2010)
Roszkowski et al. JHEP**07** 075 (2007)
Baltz&Gondolo PRD **67** 063503 (2003)

Direct Scattering Theory On One Slide

- Rate → large detector, long exposure

$$N = n_{\rm target} \Phi \, \sigma_{\chi,N} \, A^2 \qquad \text{(or } \propto \sigma_{\chi,N} \, J(J+1))$$

- Coherent Scattering → heavy target material

$$\frac{\lambda_{\rm deBroglie}}{2\pi} = \frac{\hbar}{p} = \frac{\hbar c}{mc^2 \, v/c} \sim \frac{197 \text{ MeV fm}}{100 \text{ GeV } 10^{-3}} \approx \text{fm} \approx r_{\rm nucleus}$$

- Maximum Recoil Energy → low energy detector

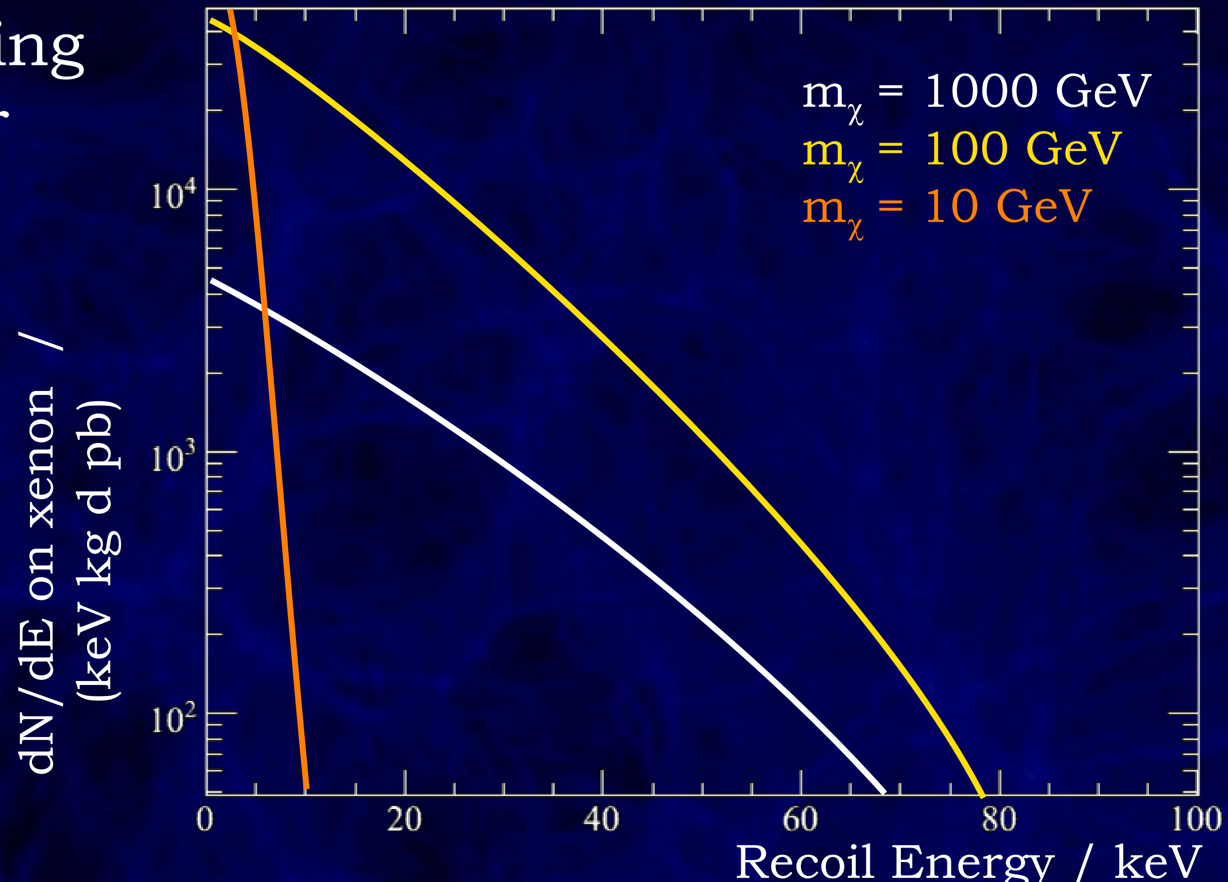
$$E_{\rm r,max} \sim \frac{p_\chi^2}{2m_{\rm N}} \sim \frac{\left(100\,{\rm GeV/c^2} \times 10^{-3}{\rm c}\right)^2}{2 \times 100\,{\rm GeV/c^2}} = 50\,{\rm keV}$$

- Spectrum → shielding, discrimination, multi target

$$\frac{{\rm d}N}{{\rm d}E_r} \propto \Phi \propto \langle v \rangle \propto \int_{v_\chi}^{\infty} \frac{f_{\rm MB}(v)}{v} \, {\rm d}v \propto {\rm e}^{-v_\chi^2} \propto {\rm e}^{-E_r}$$

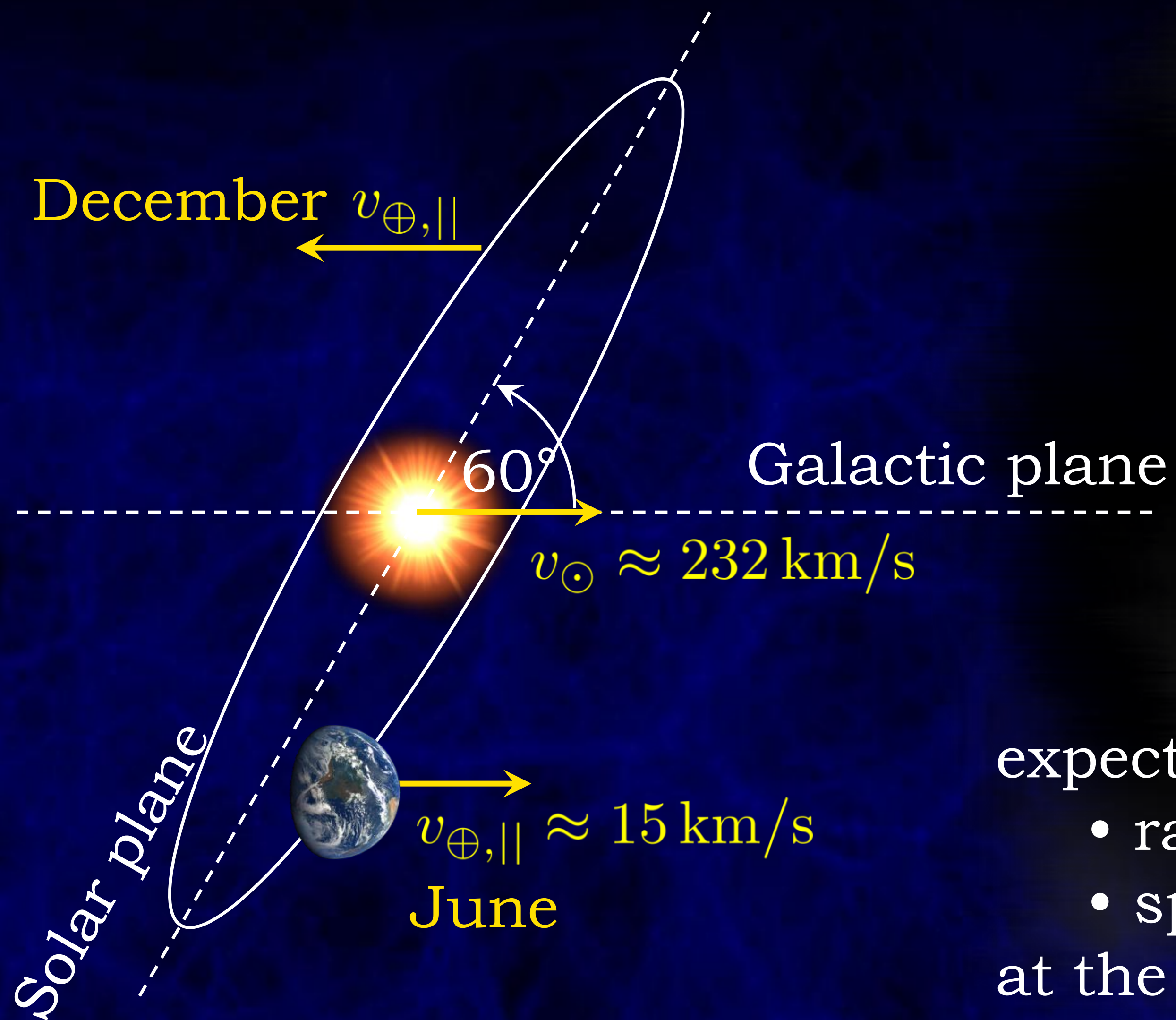
Expected WIMP Spectrum

- isothermal halo
- local density $\varrho_\chi \approx 0.3\,\mathrm{GeV}/c^2/\mathrm{cm}^3$
- $v_\oplus \approx 240\,\mathrm{km/s}$
- coherent scattering
- Helm form factor



challenging signal!

Annual Modulation



expect modulation of

- rate
- spectral shape

at the percent level

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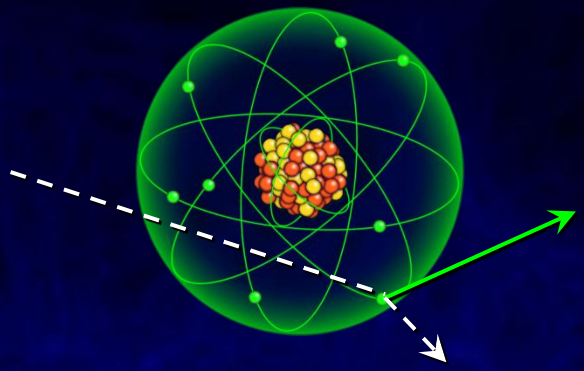
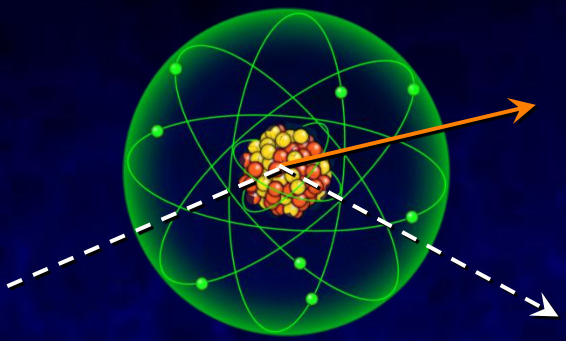
The Power of Discrimination

e$^-$/γ: electronic recoil



α/n/WIMPs: nuclear recoil



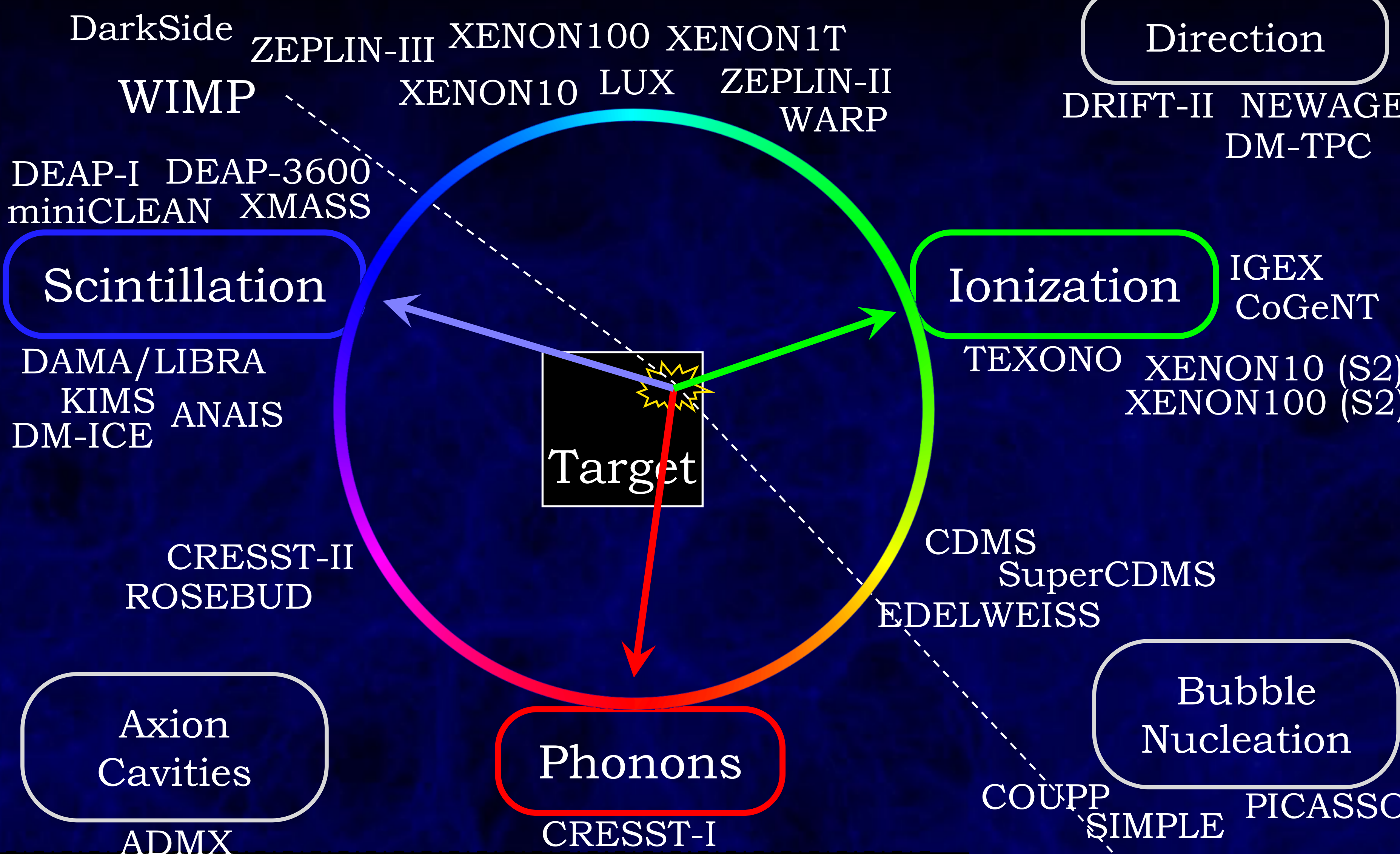
electronic recoils

- are most common background
- scintillate and ionize more (for given energy)

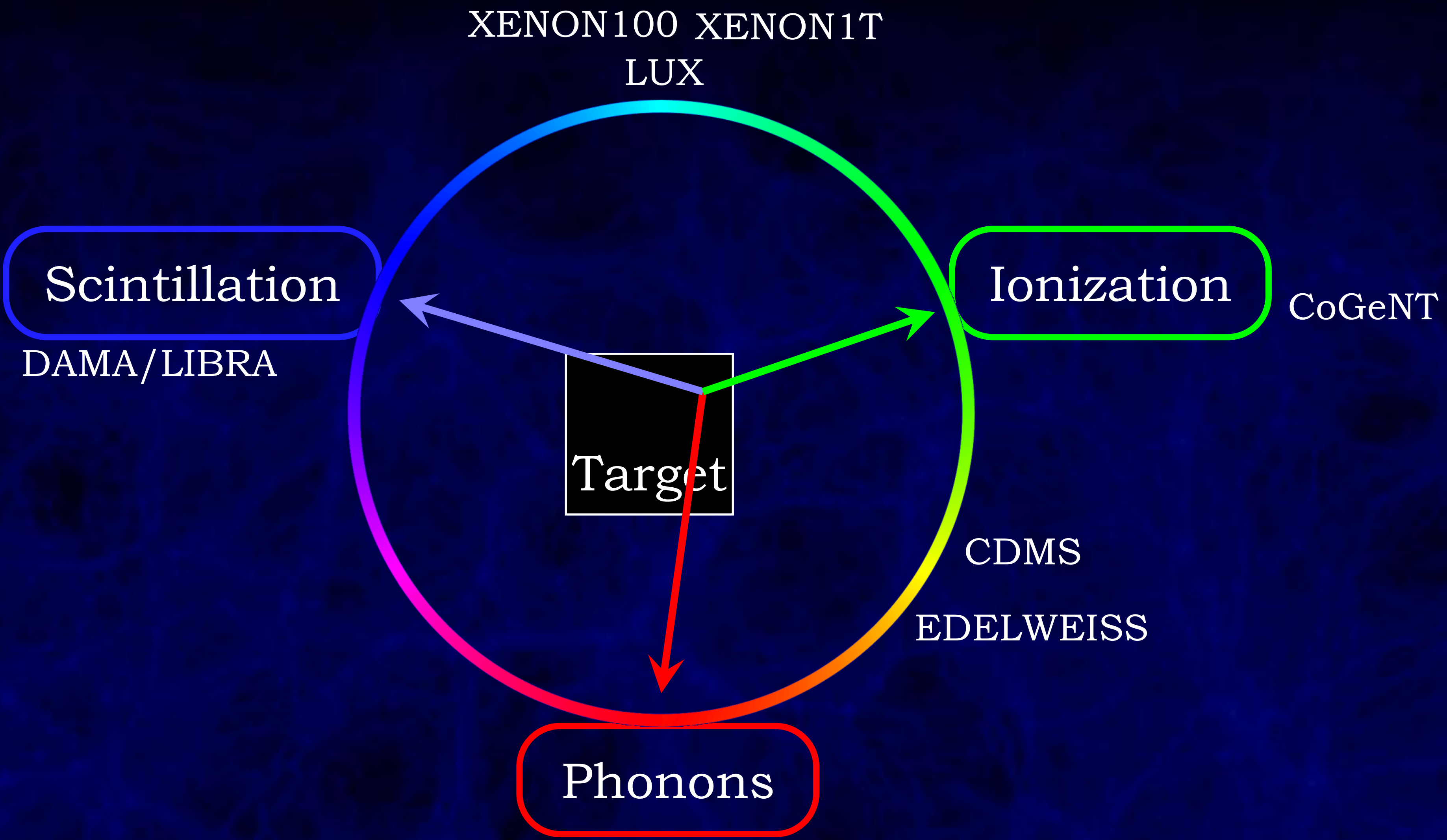
→ discriminate between the two

e.g. measure both energy and some additional parameter (ionization yield, scintillation yield, ratio ionization/scintillation, pulse decay times, acoustic signal)

Particle Detection Channels



Particle Detection Channels



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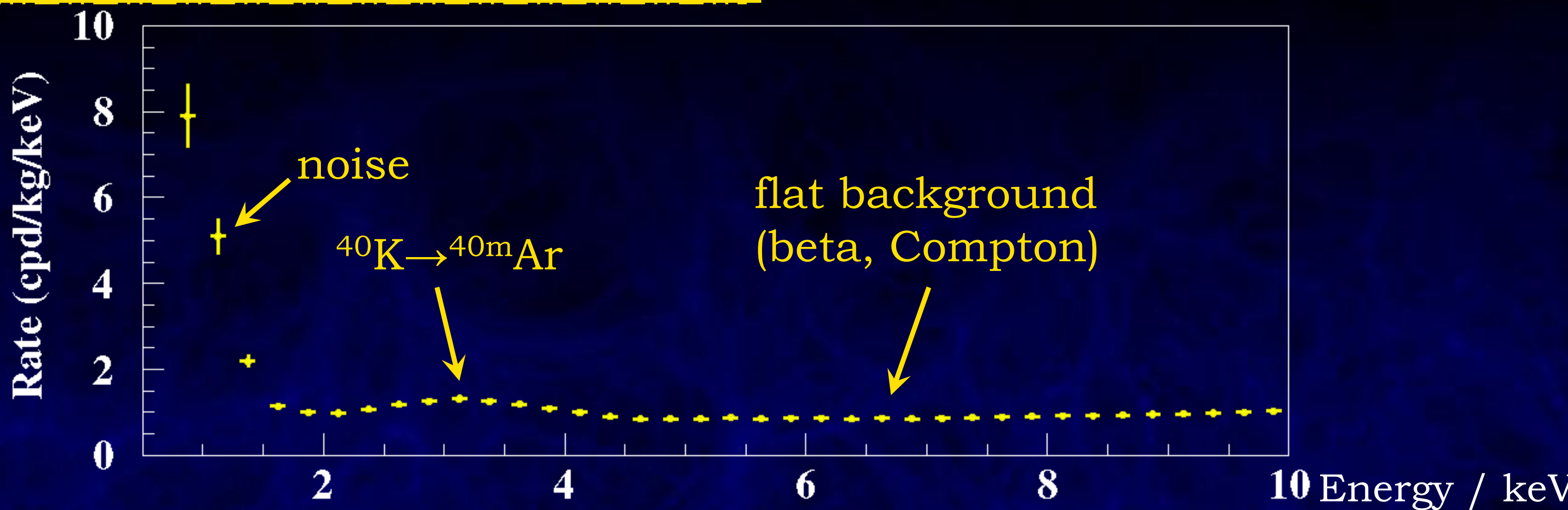
DAMA/LIBRA

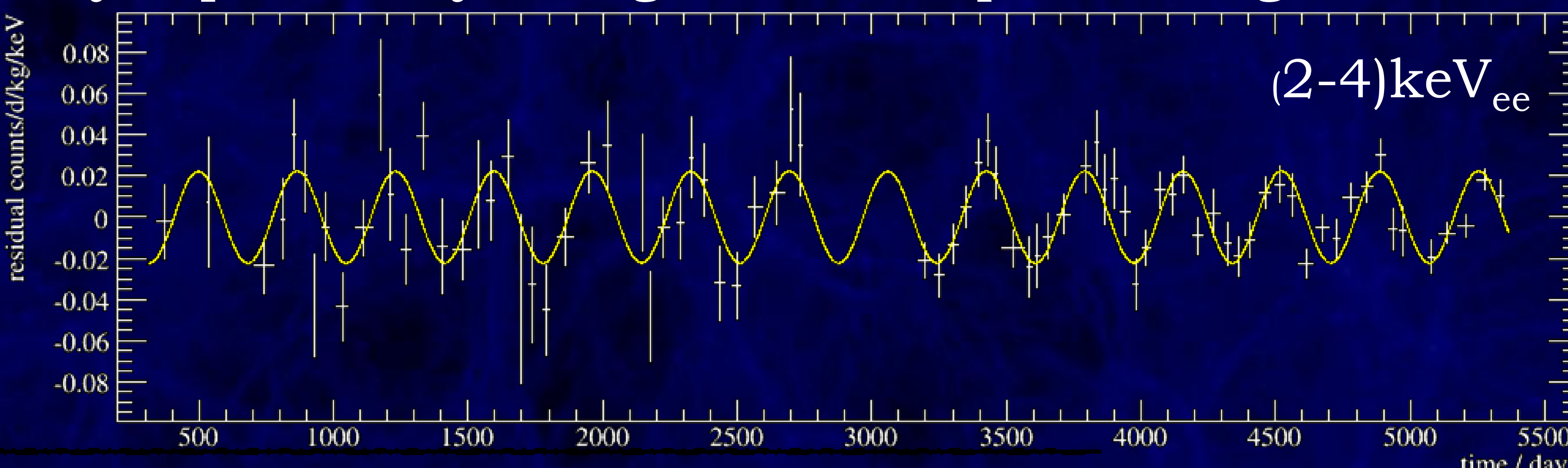
Italy/China: 230kg ultra-pure NaI(Tl) scintillators
by far largest and longest exposure but no discrimination

DAMA/LIBRA Data

arXiv:0804.2741
arXiv:1210.7548

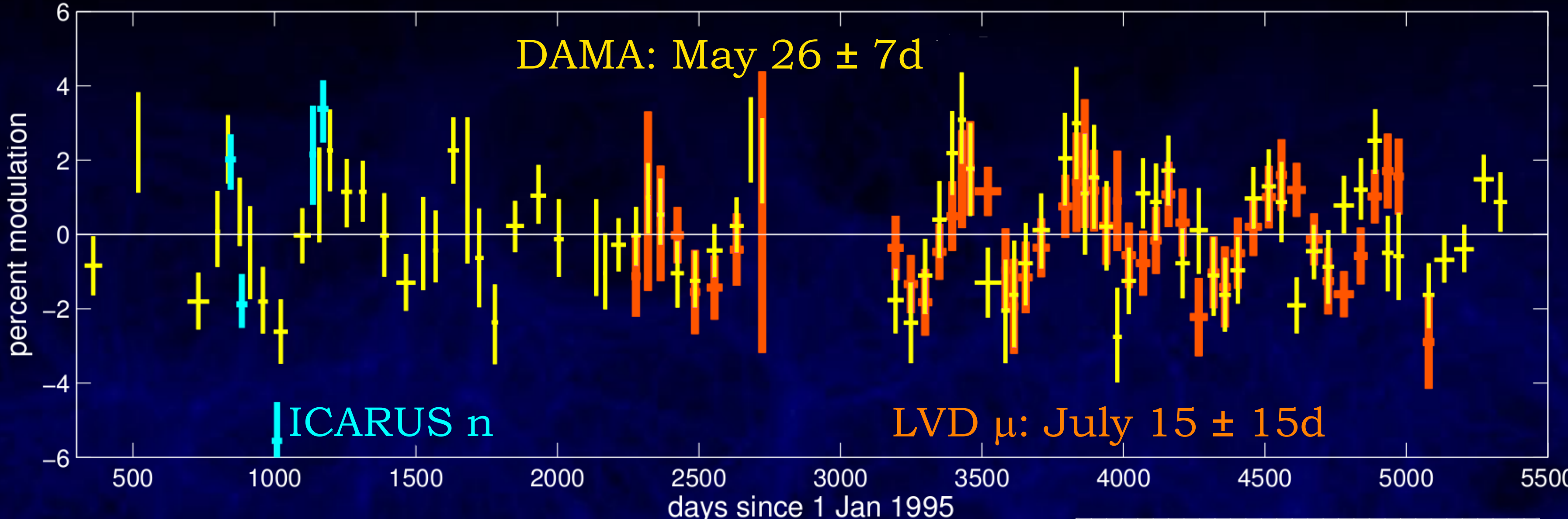


fully explained by background, no space for signal, but:

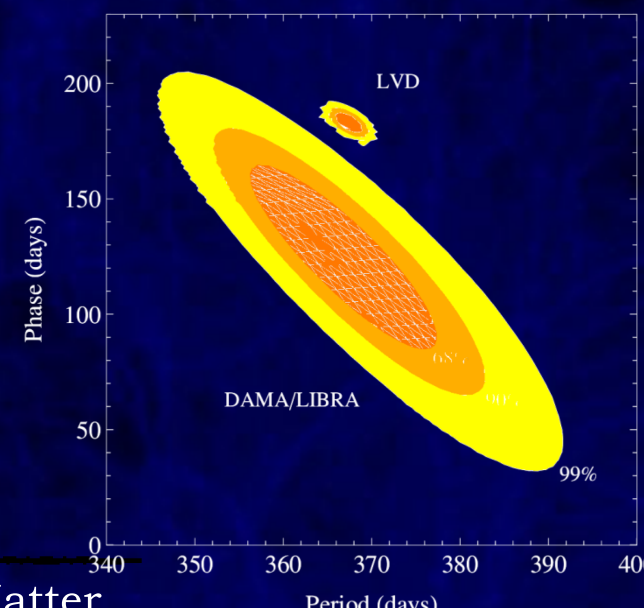


data from arXiv:0804.2741 and arXiv:1002.1028

Muon Flux at Gran Sasso



DAMA and LVD μ phase show striking similarity (amplitude!) but not consistent phase



arXiv:1111.4222

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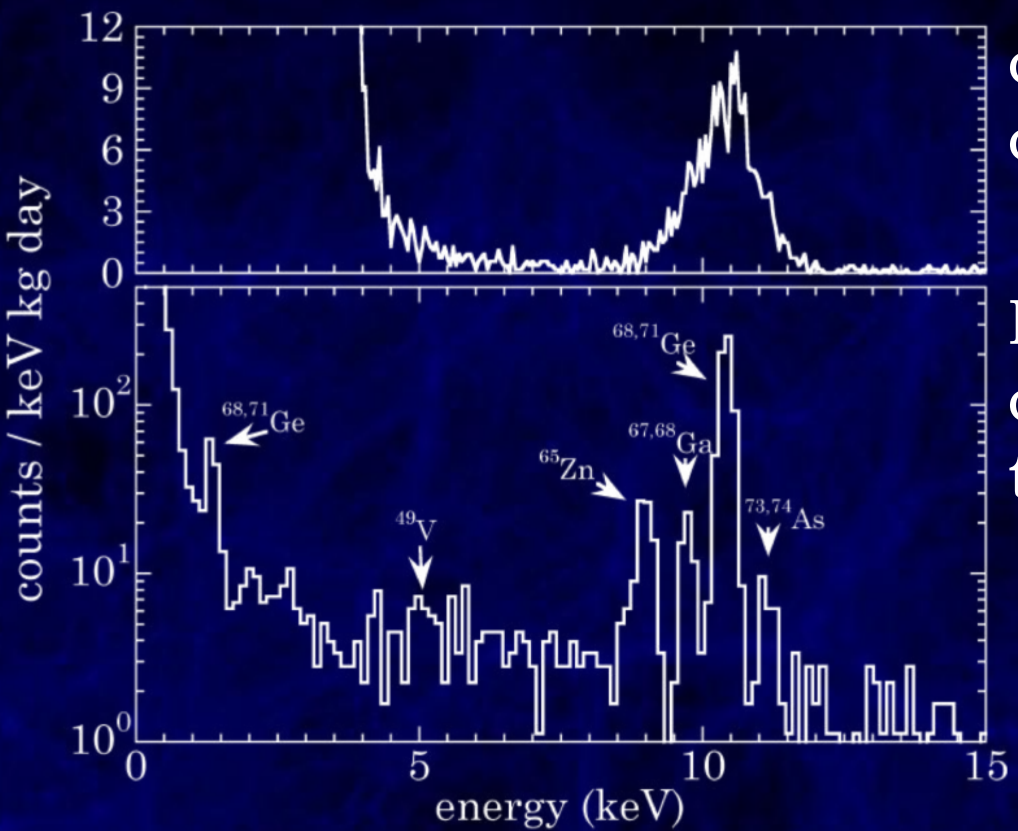
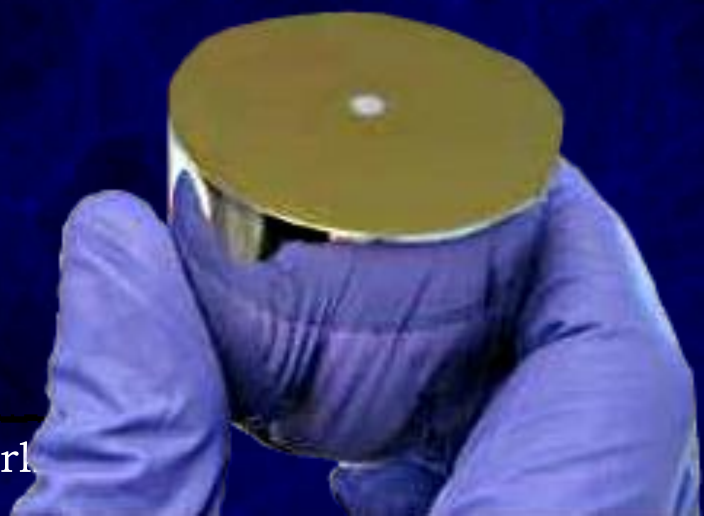
CoGeNT Performance

USA
440g P-type point-contact Ge detector



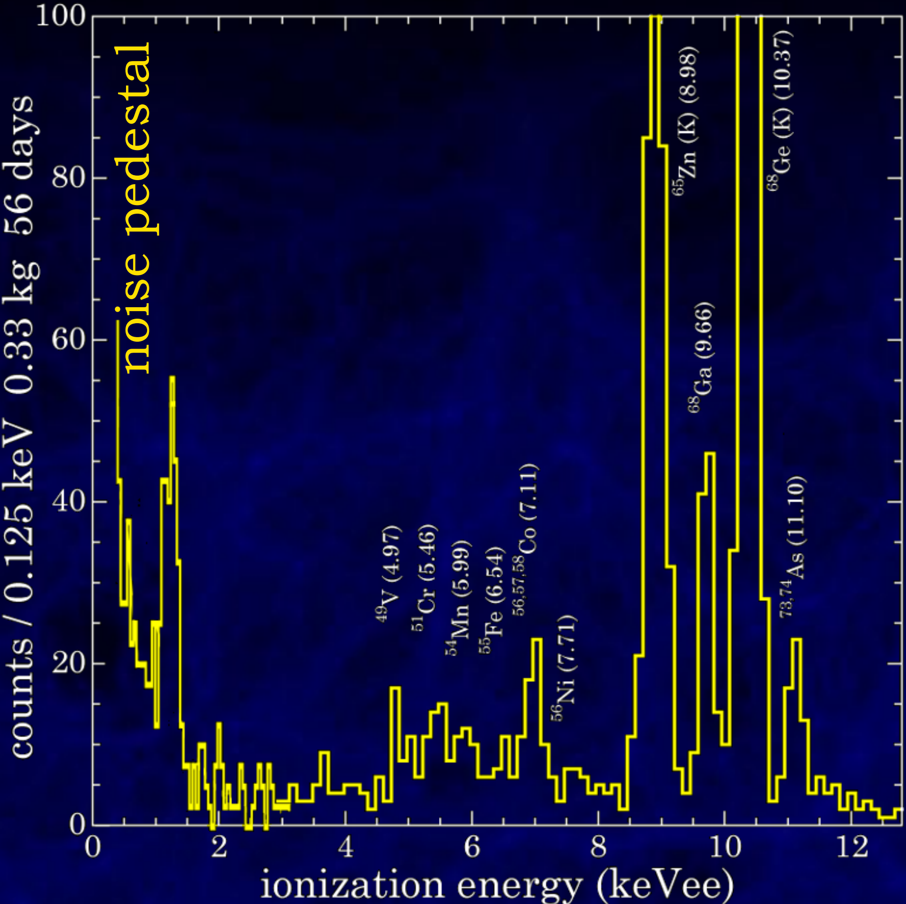
conventional coaxial HPGe

P-type point-contact HPGe threshold 400eV

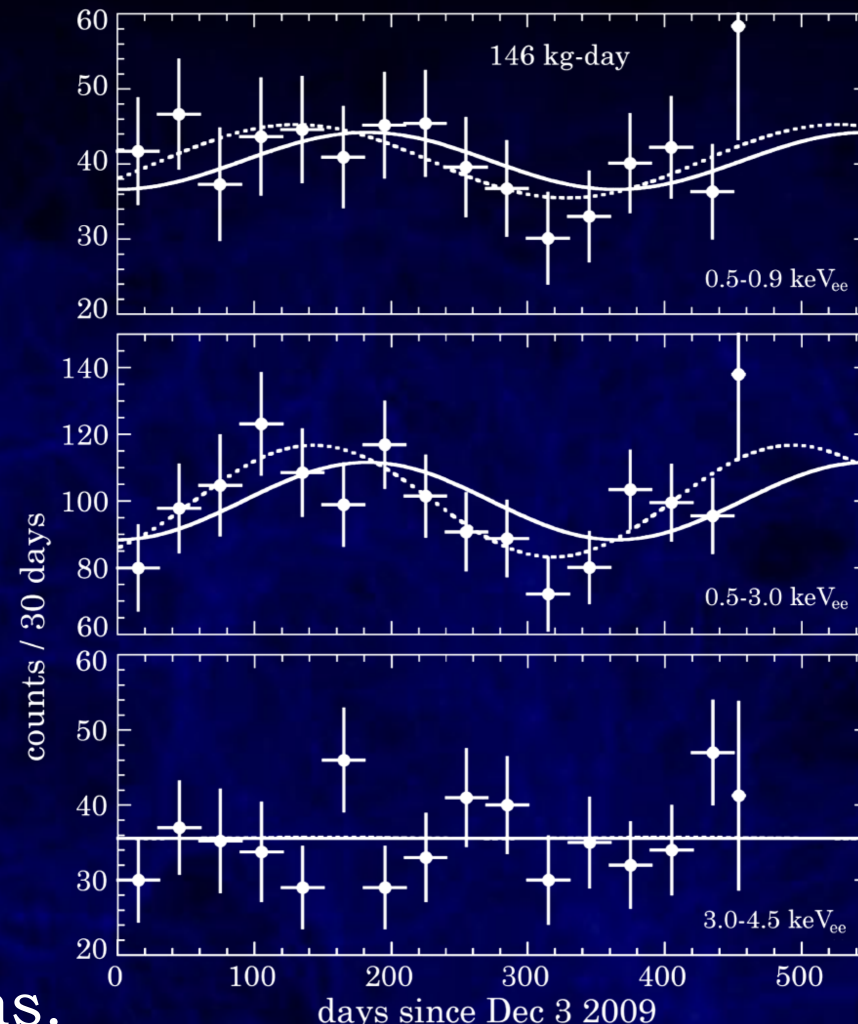


Collar, UC Davis and other talks, 2010

CoGeNT Data



arXiv:1002.4703

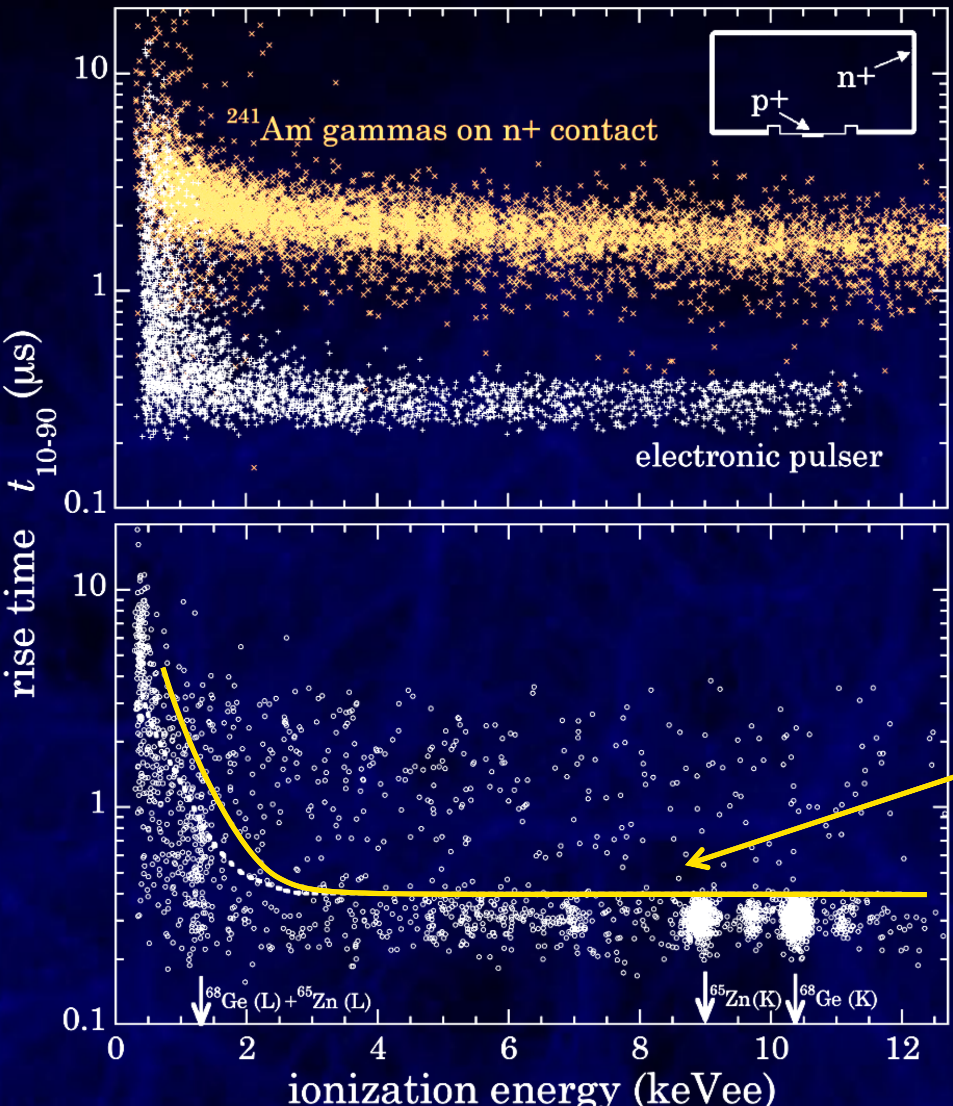


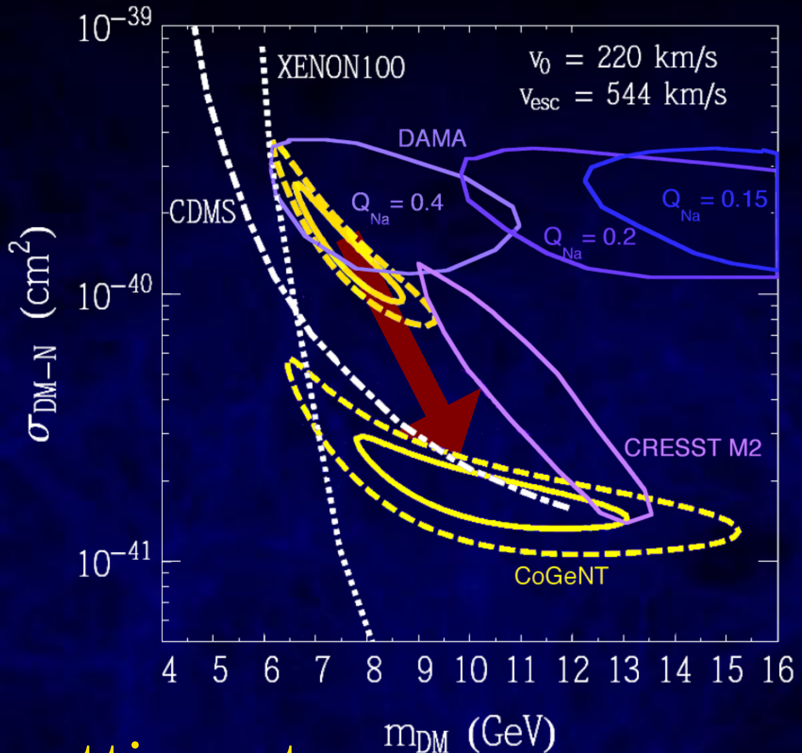
arXiv:1106.0650

~3σ modulation after 15months.
Background rejection?

— expected phase ····· fit

CoGeNT With Background





cutting at constant acceptance

lower limit shifts down by >10σ !
Still different from zero?

J. Collar, Marina del Rey 2012

arxiv:1002.4703

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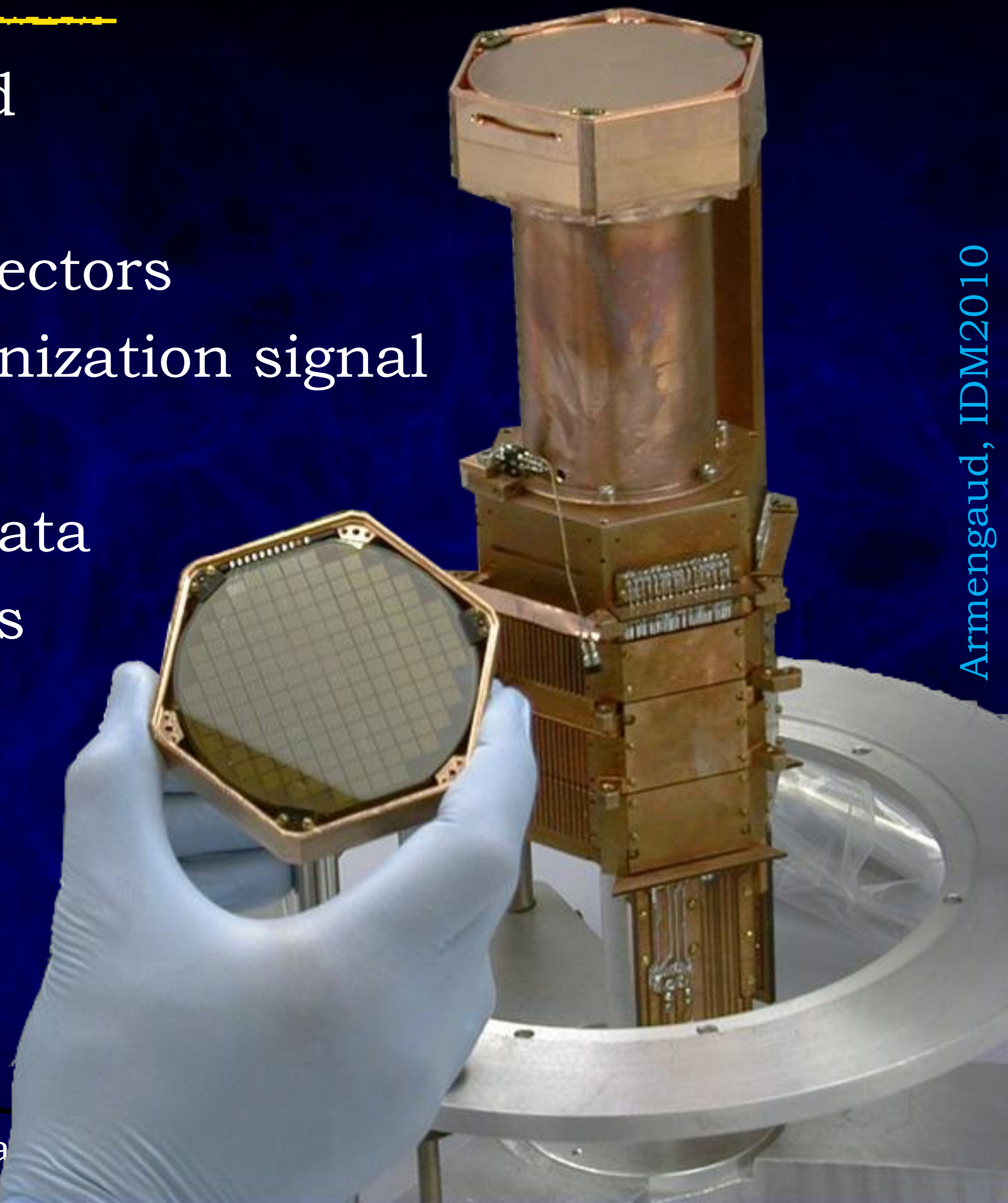
CDMS-II

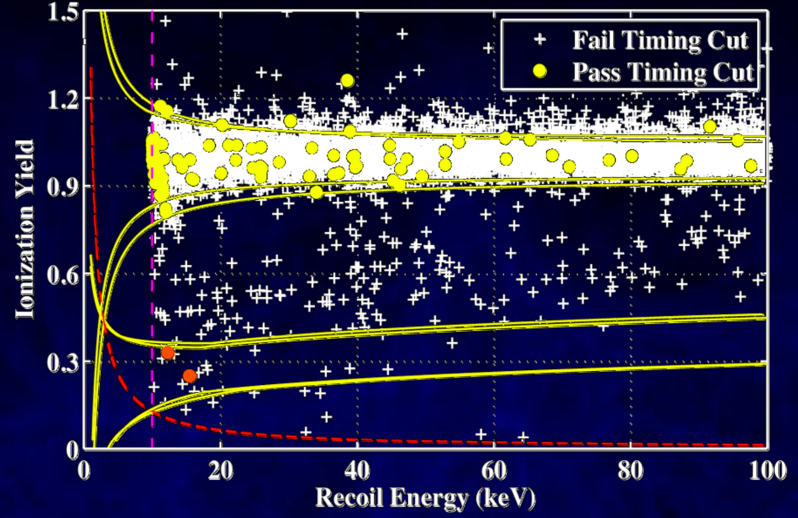
USA/Canada/Switzerland
located at Soudan
19 Ge and 11 Si "ZIP" detectors
with phonon (TES) and ionization signal
data-taking finished
final analysis of 2 years data
from 14 250g Ge detectors

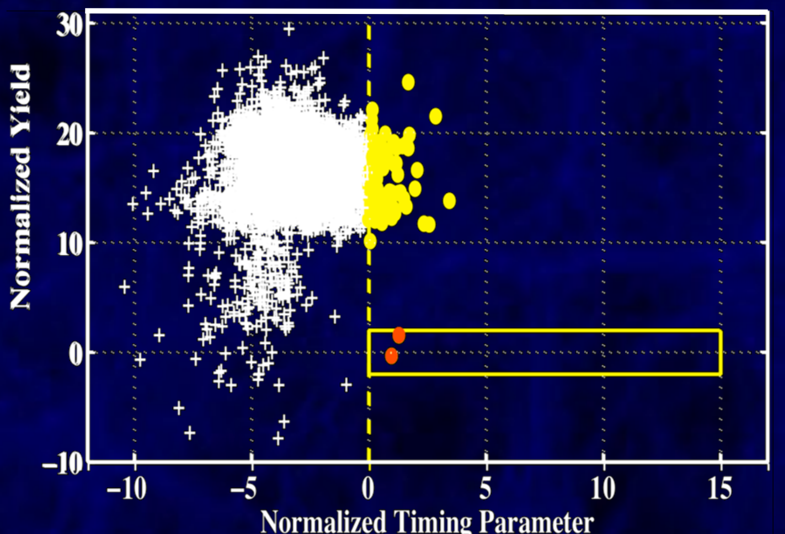
next step: SuperCDMS
with bigger and
interleaved detectors



Armengaud, IDM2010

CDMS-II Results





Ge dark matter search data two detectors with signal candidate events combined:

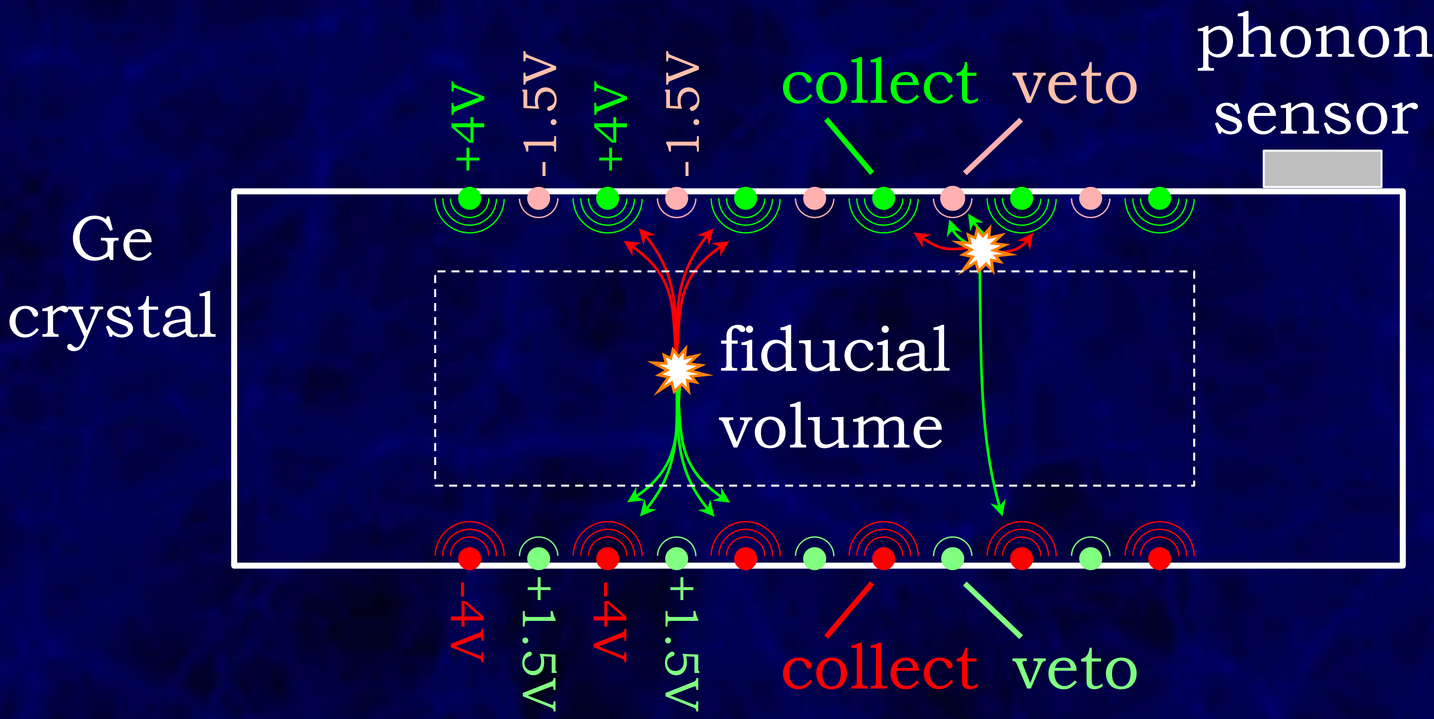
bulk electronic recoils
surface events
bulk nuclear recoils

two events observed, consistent with (revised) background expectation of 0.9 ± 0.2 events.

arXiv:0912.3592 and Saab, IDM2010

EDELWEISS-II (~ SuperCDMS)

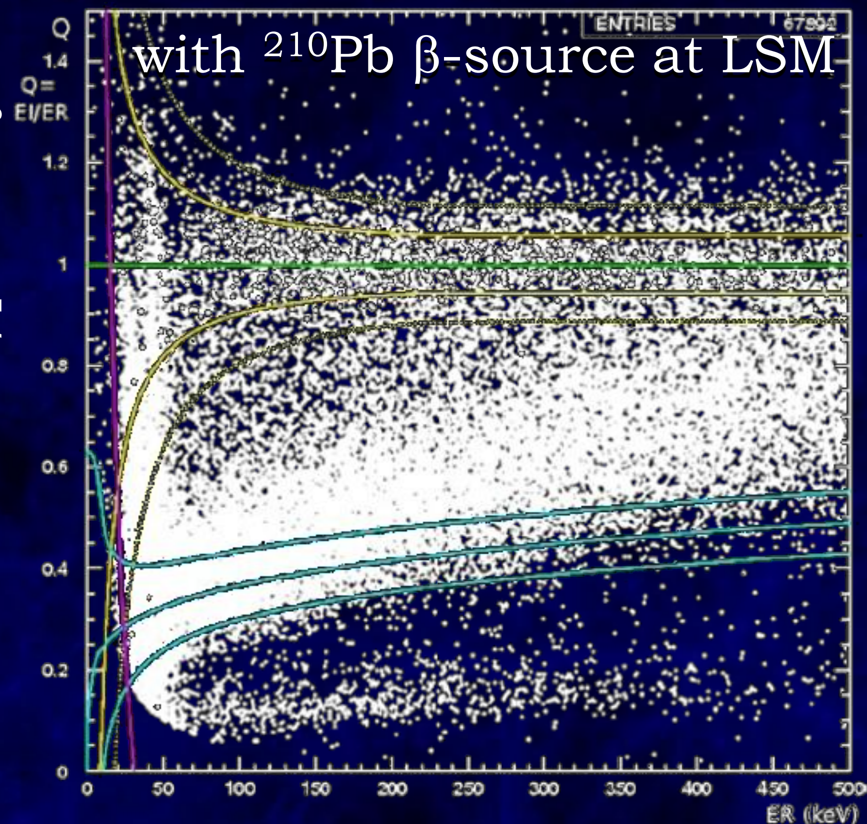
France, Germany, Russia, UK in the Frejus Lab
germanium crystals with phonon/ionization readout
NTD phonon sensors
interleaved electrodes (ionization)



EDELWEISS-II Data

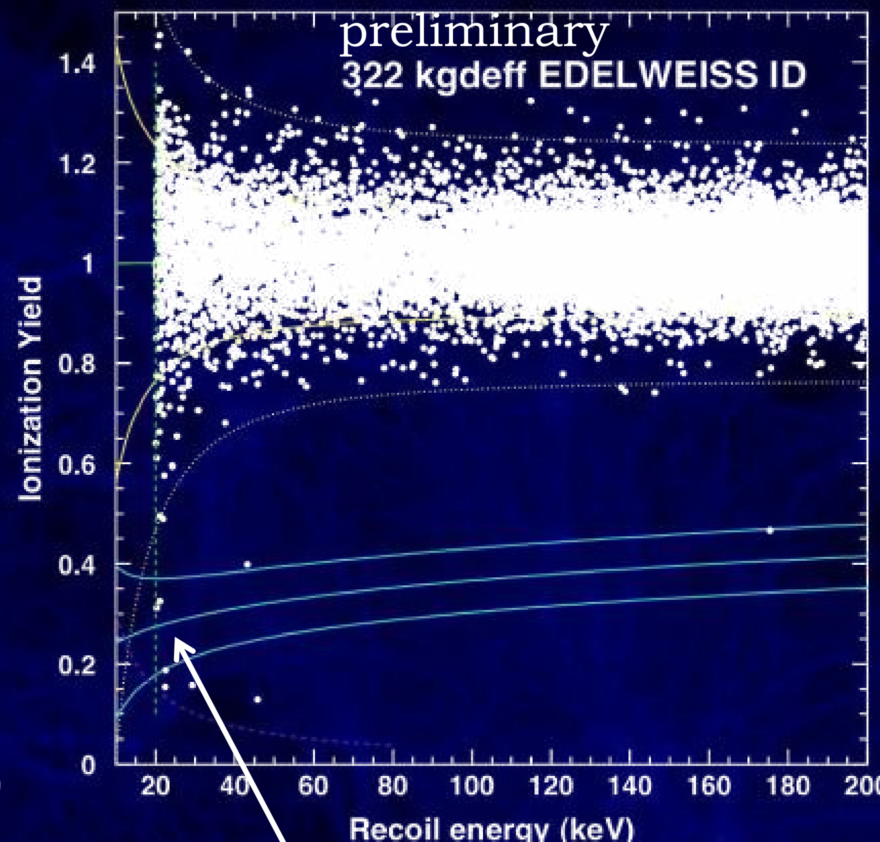
data from 1 year with ten 400g Ge crystals
meanwhile four 800g modules installed

ionization/phonon yield



energy (phonon channel)

before / after fiducialization

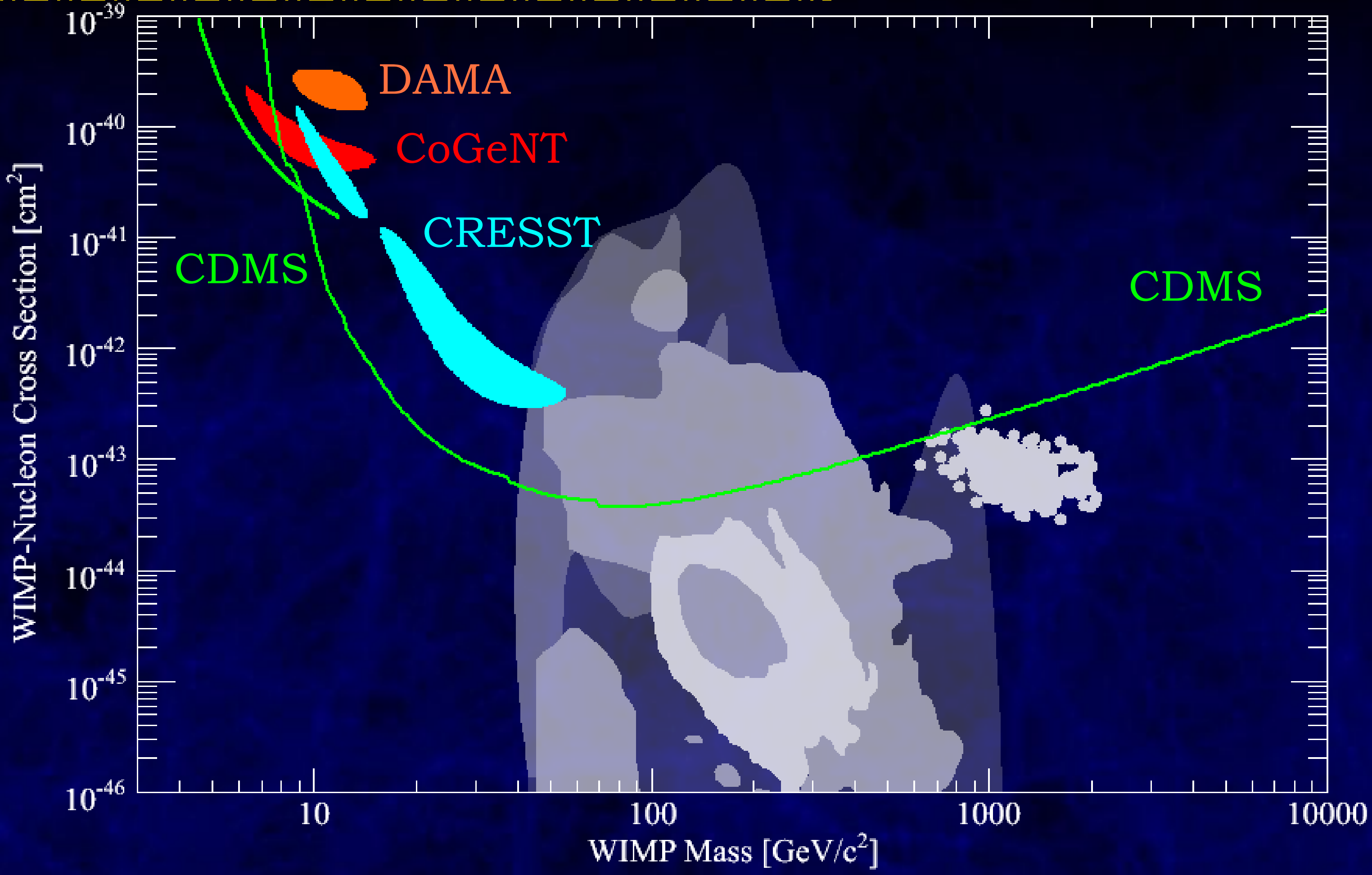


3 events near threshold

Kraus, IDM2010

Armengaud, IDM2010

CDMS Limits

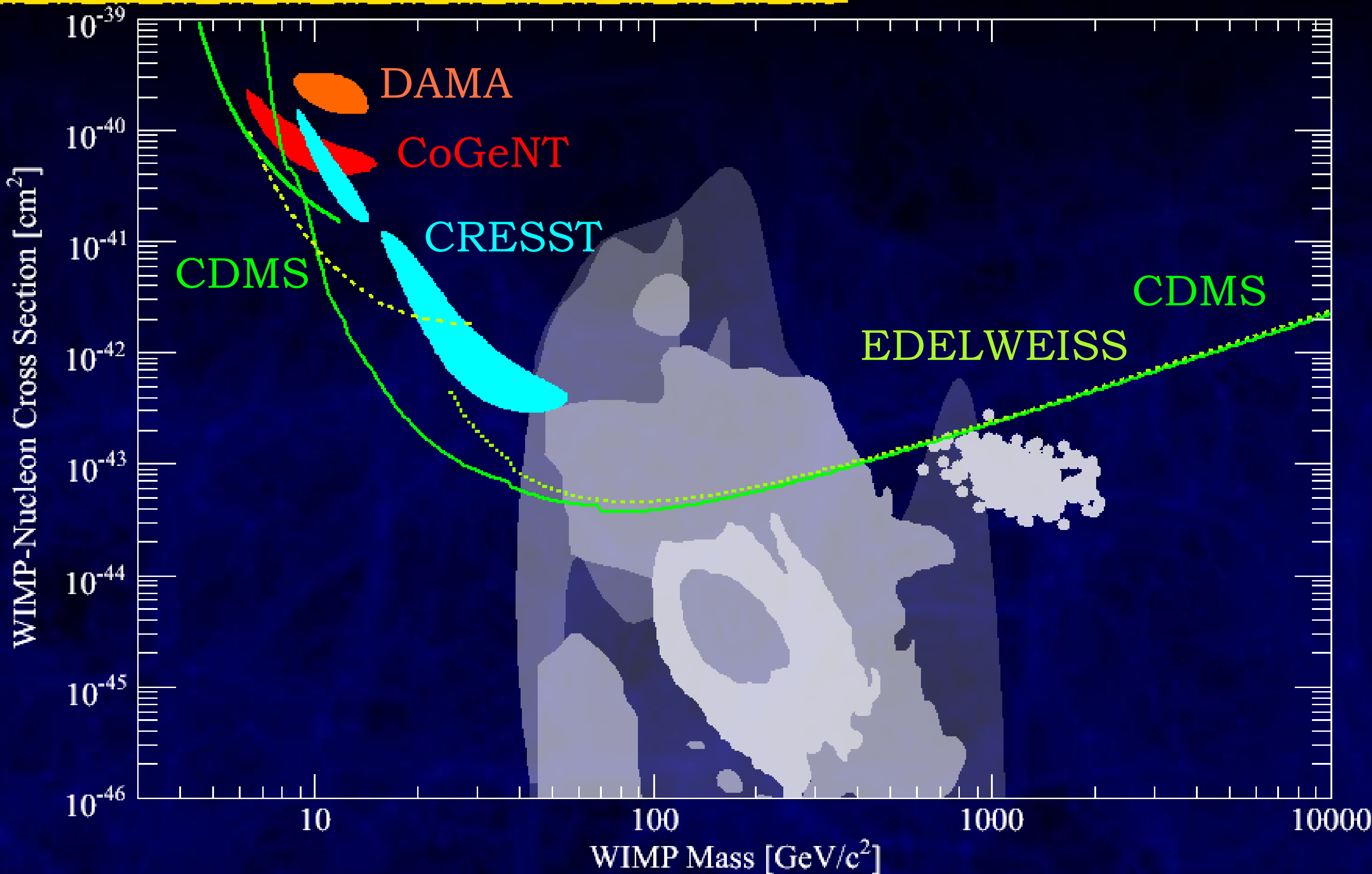


strong limit

dedicated analysis constrains CoGeNT interpretation

arXiv:0912.3592
arXiv:1011.2482

EDELWEISS Limit



Armengaud IDM2010

interleaved detectors ready for the next step in sensitivity

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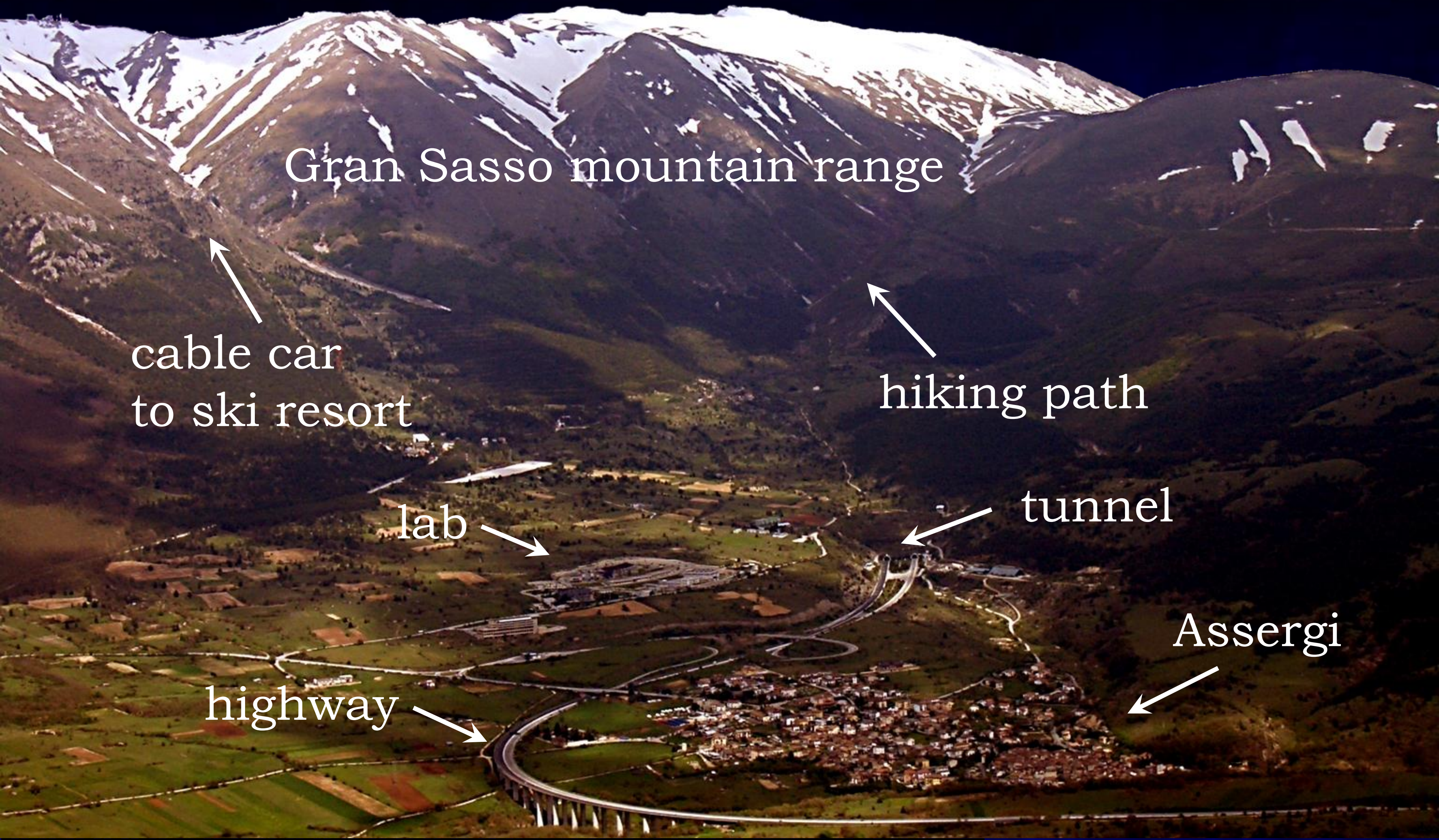
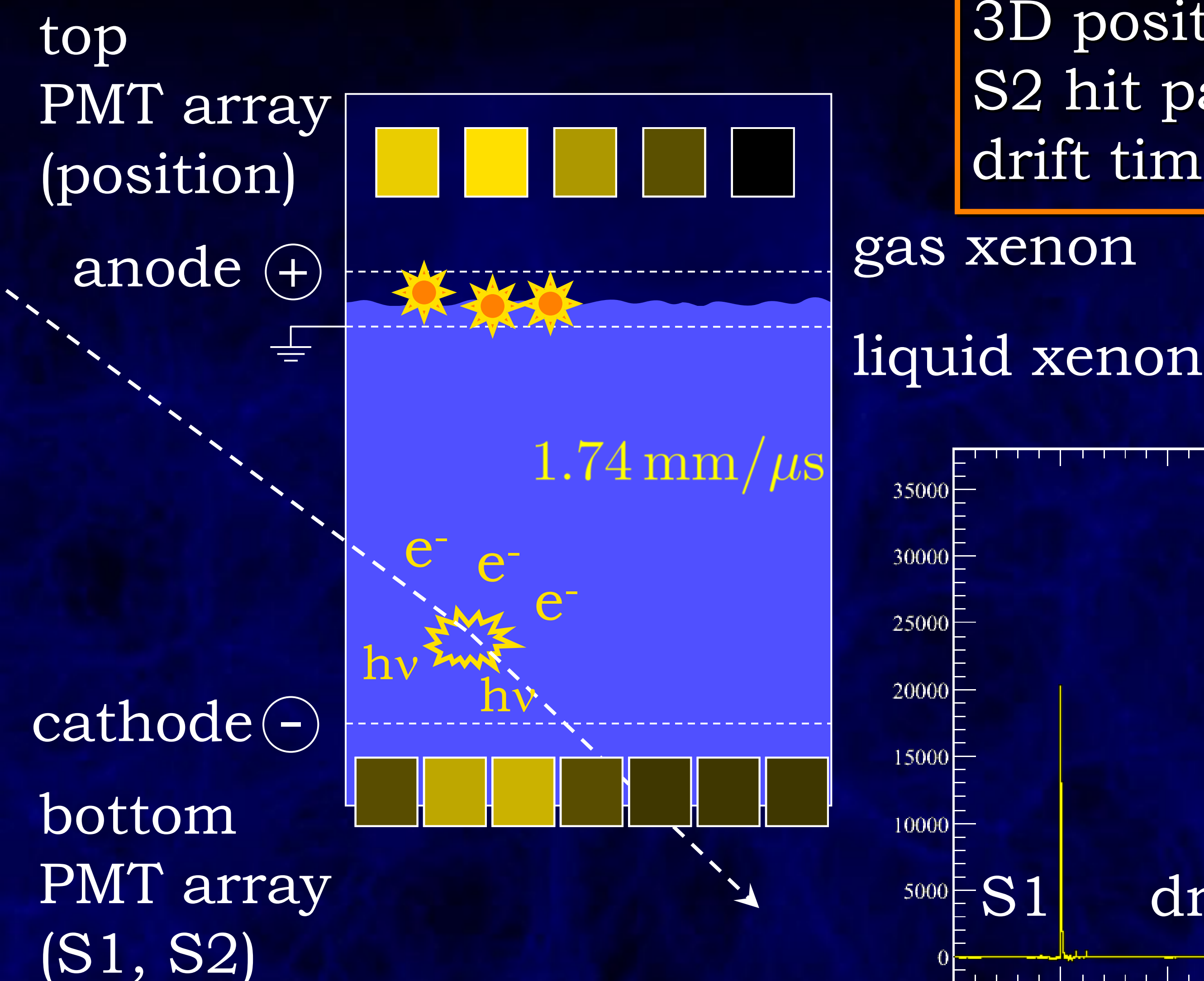
  cleanest solid-state technology
- XENON100 and XENON1T

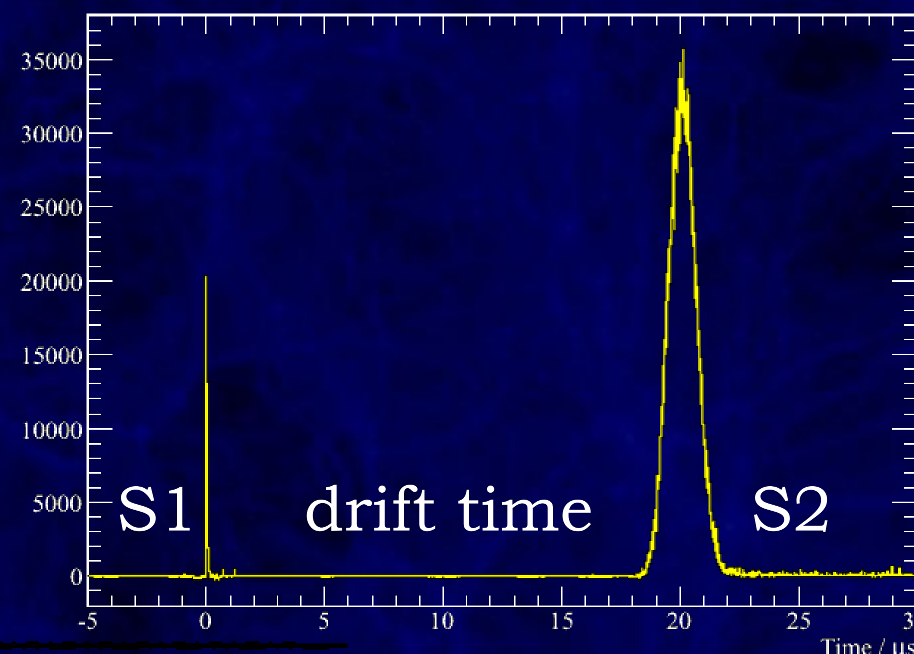
Gran Sasso Underground Lab



Dual-Phase Xenon TPC

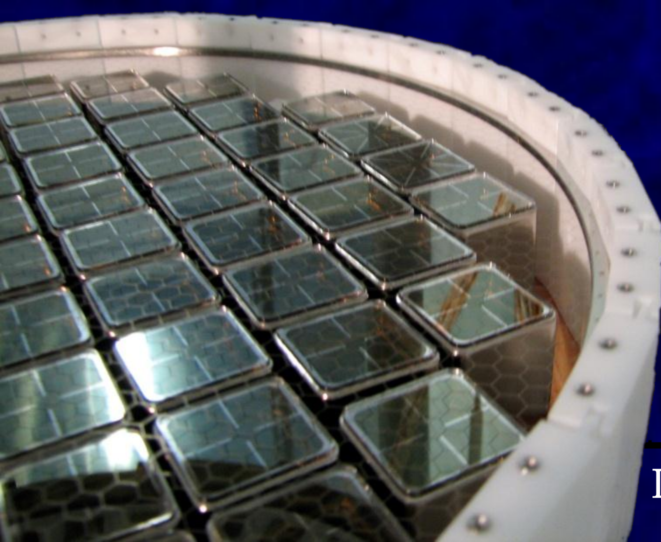
3D position information
S2 hit pattern: $\delta r < 3\,\mathrm{mm}$
drift time: $\delta z < 300\,\mu\mathrm{m}$



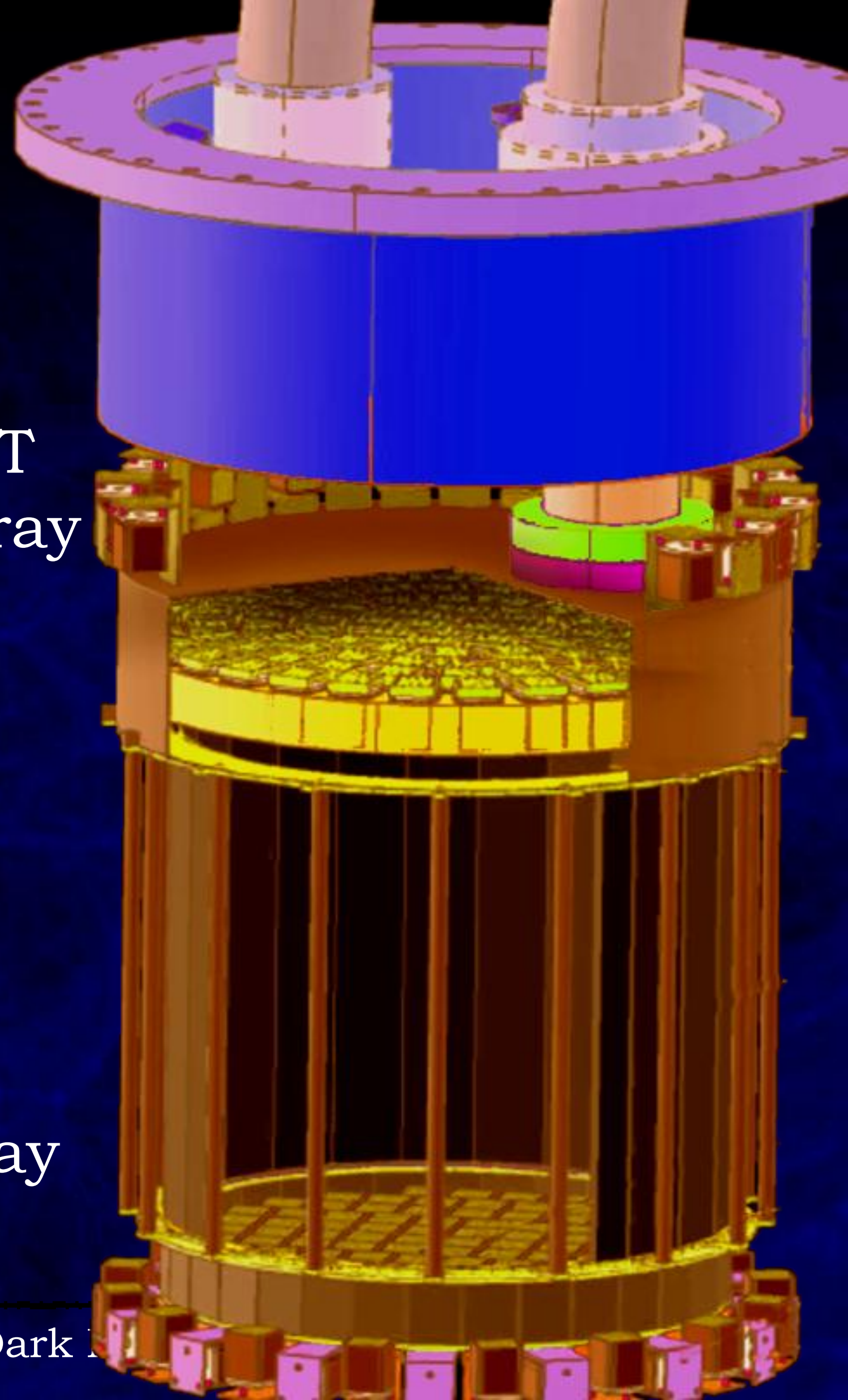


XENON100

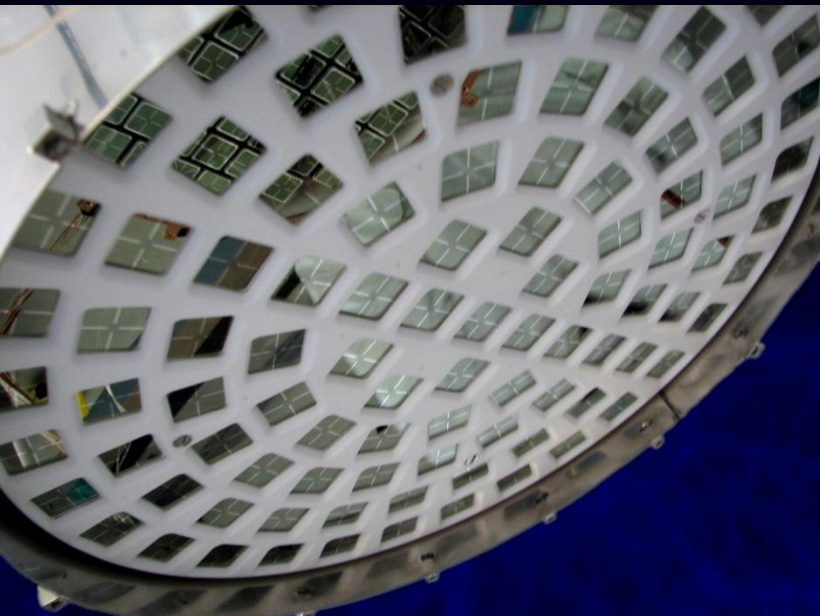
98 PMT
top array



80 PMT
bottom array



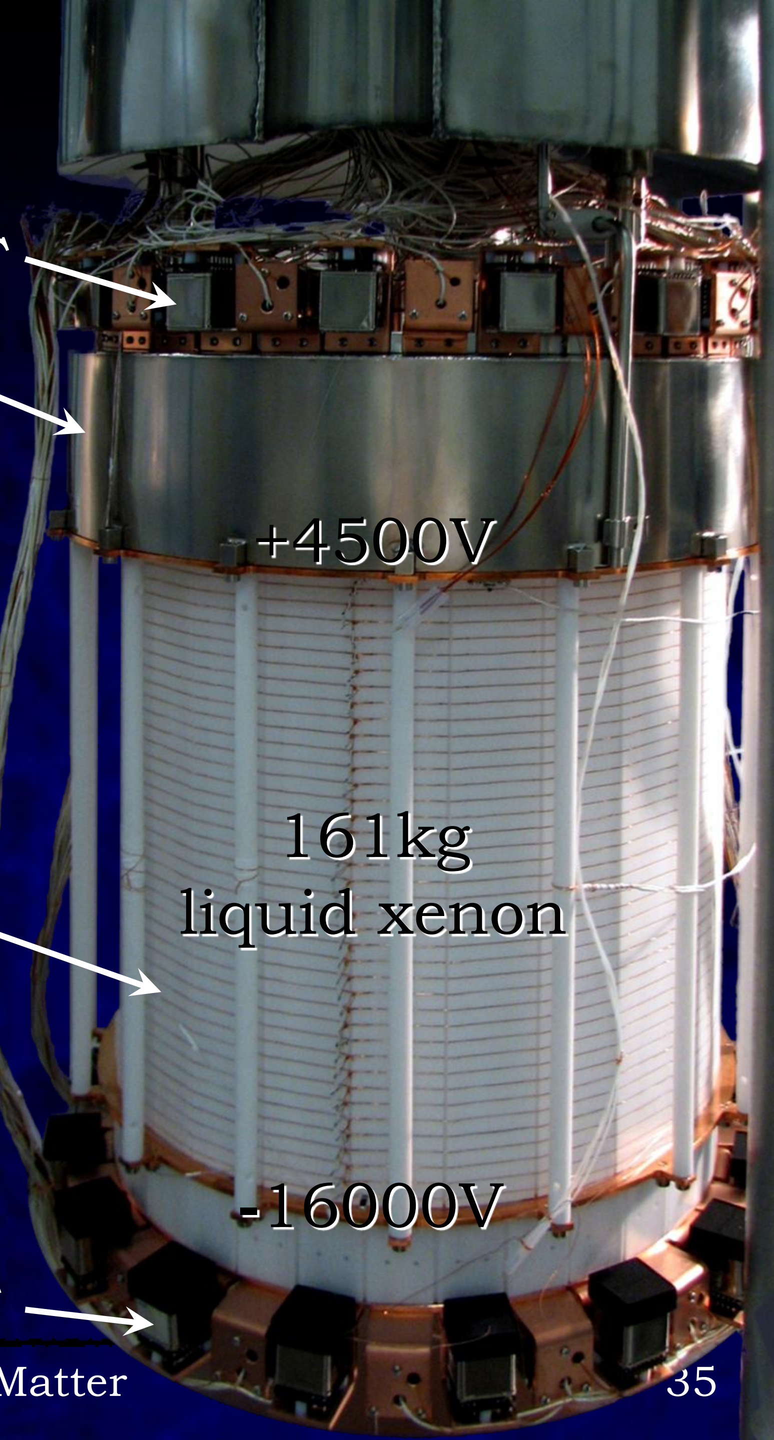
XENON100



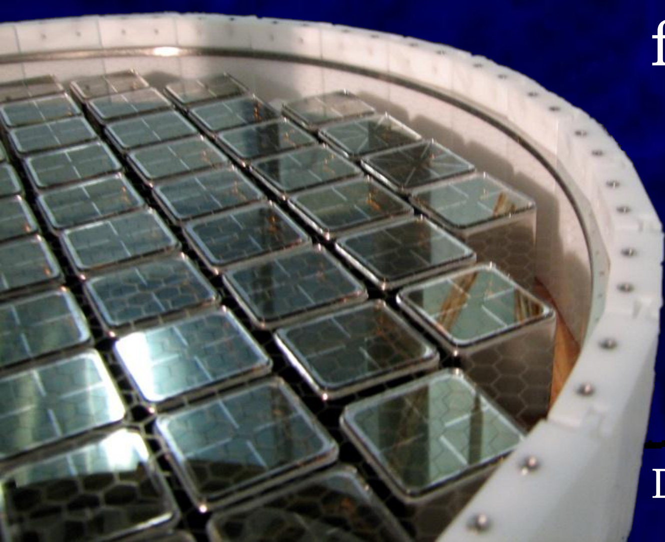
veto PMT

bell

98 PMT
top array



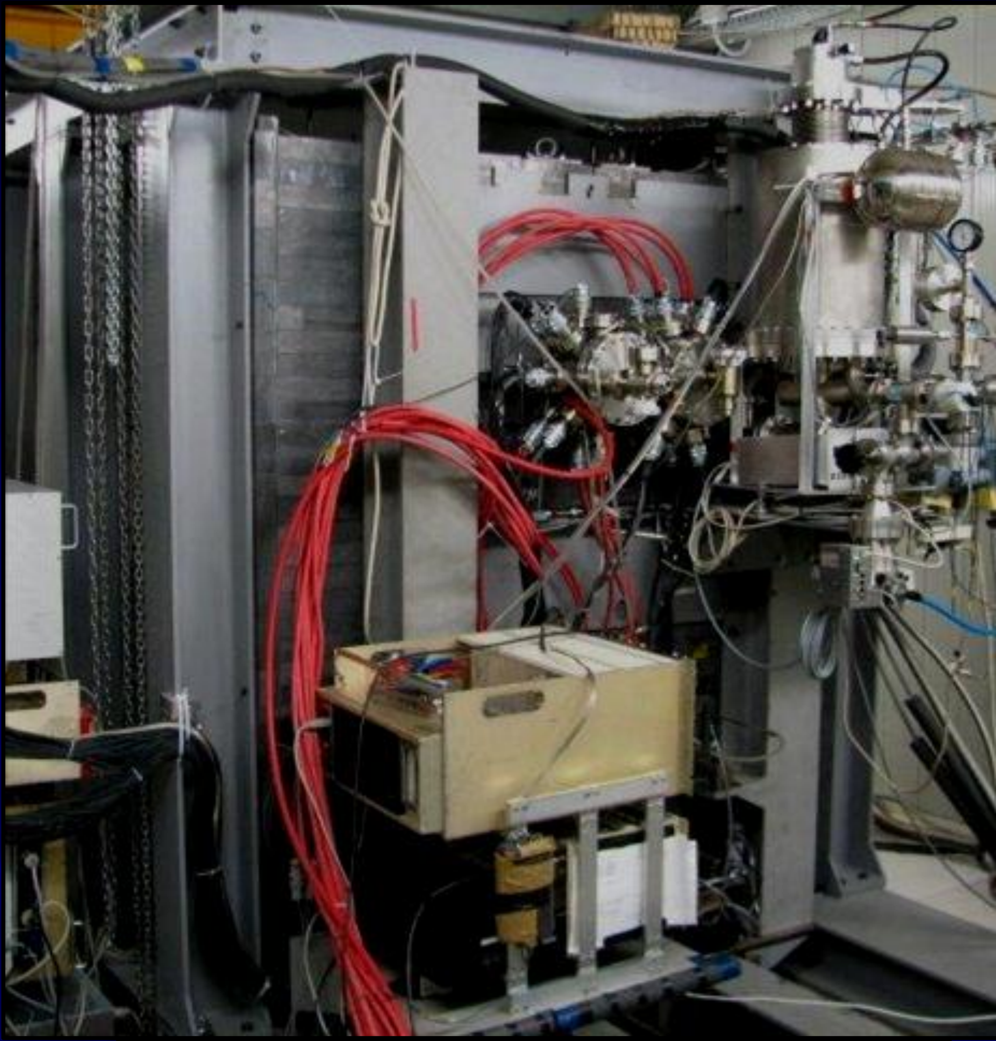
PTFE TPC,
field shaping



80 PMT
bottom array

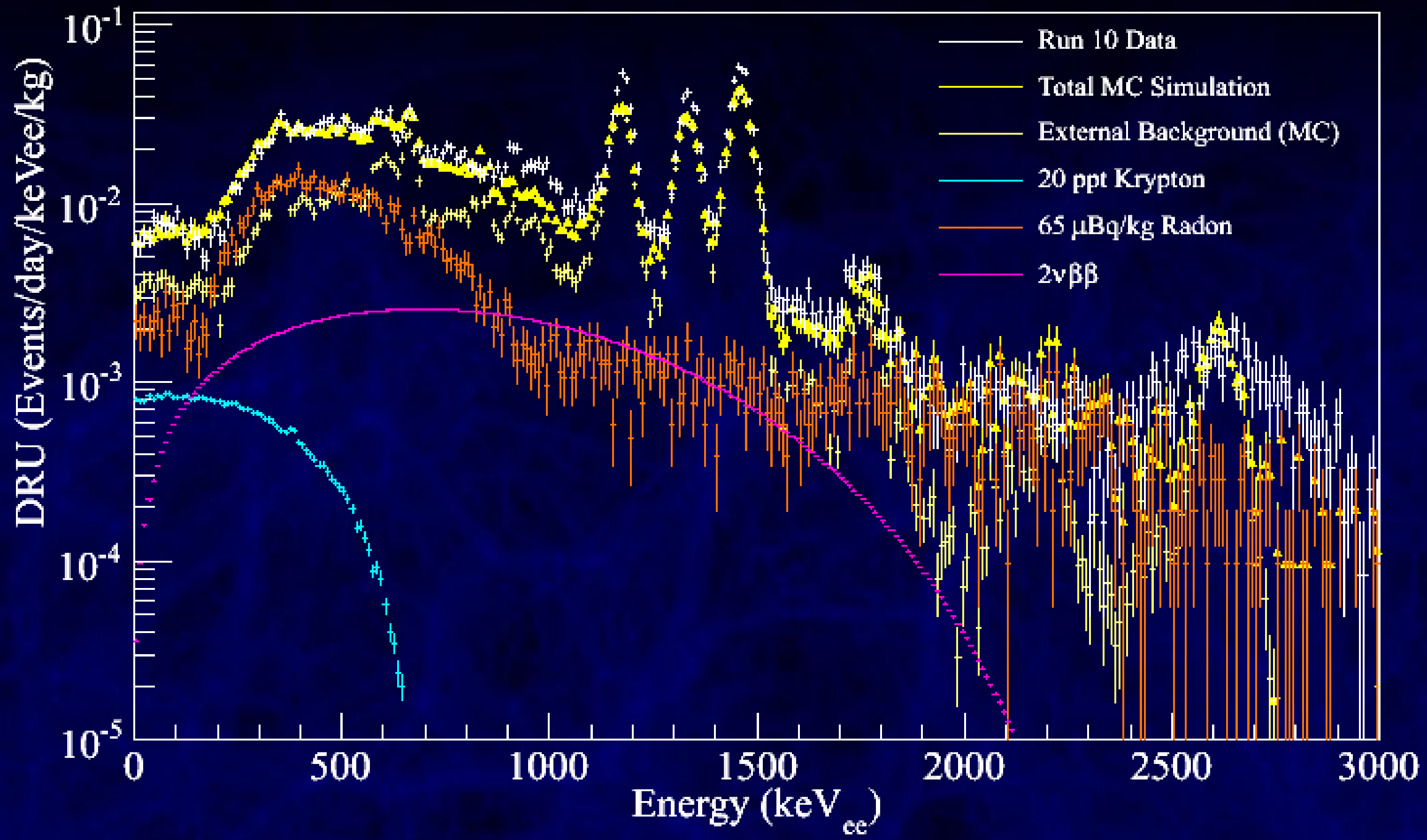
veto PMT

XENON100 Shield



20cm H_2O, 15cm Pb, 5cm French Pb, 20cm PE, 5cm Cu

Background Spectrum Understood



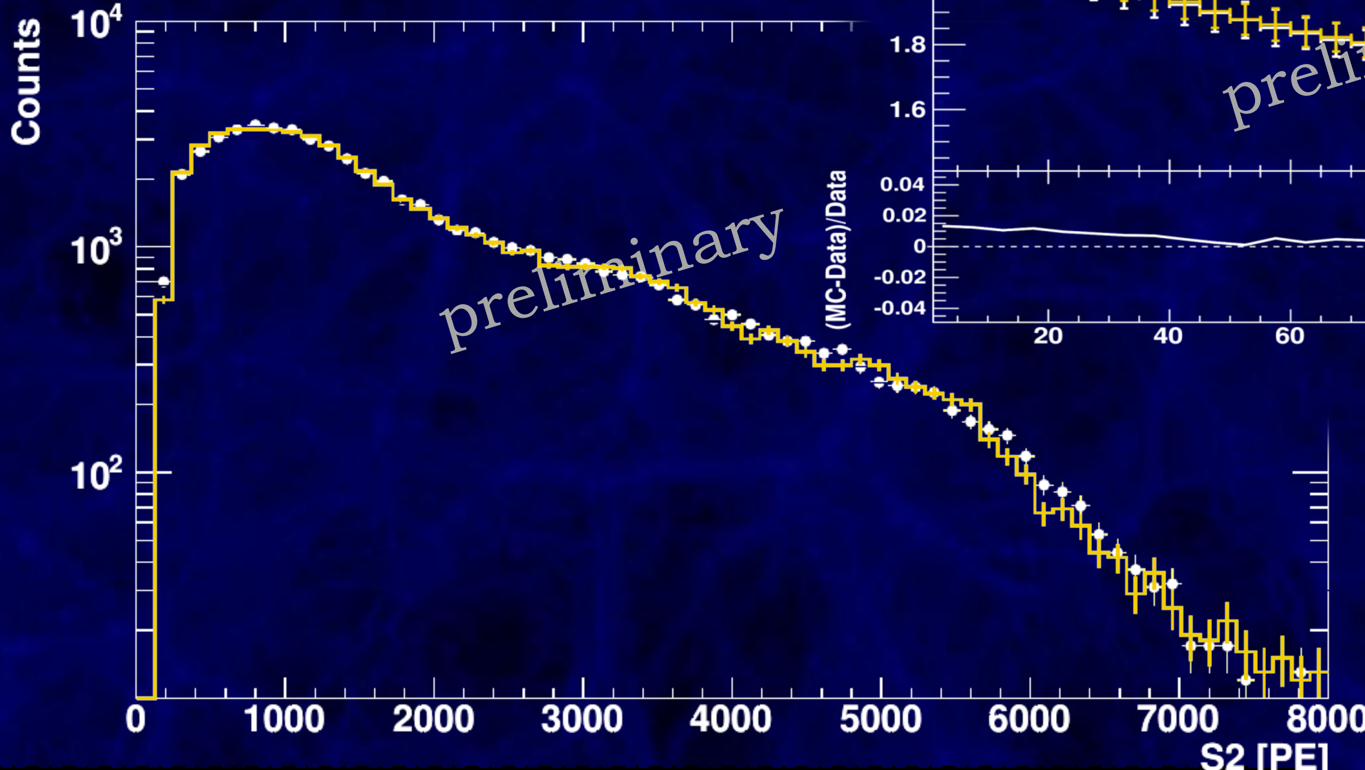
low-energy background before discrimination

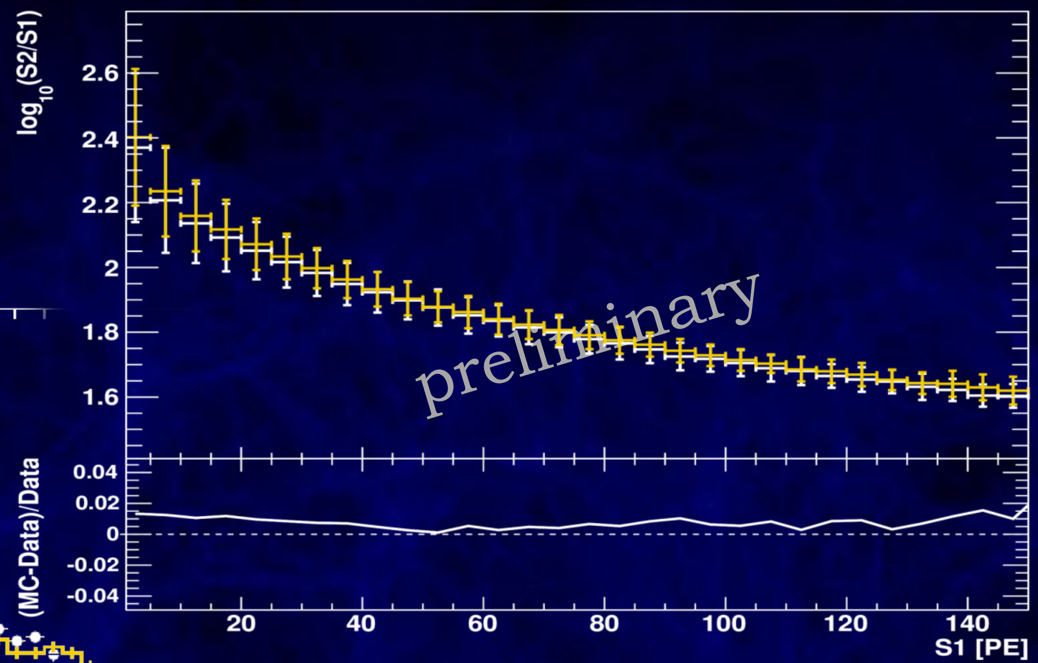
$(5.3 \pm 0.6) \times 10^{-3}$ events/keV_{ee}/kg/day

2 orders of magnitude below other Dark Matter searches

Absolute (!) Rate Matching

XENON100 AmBe calibration: understanding at %-level

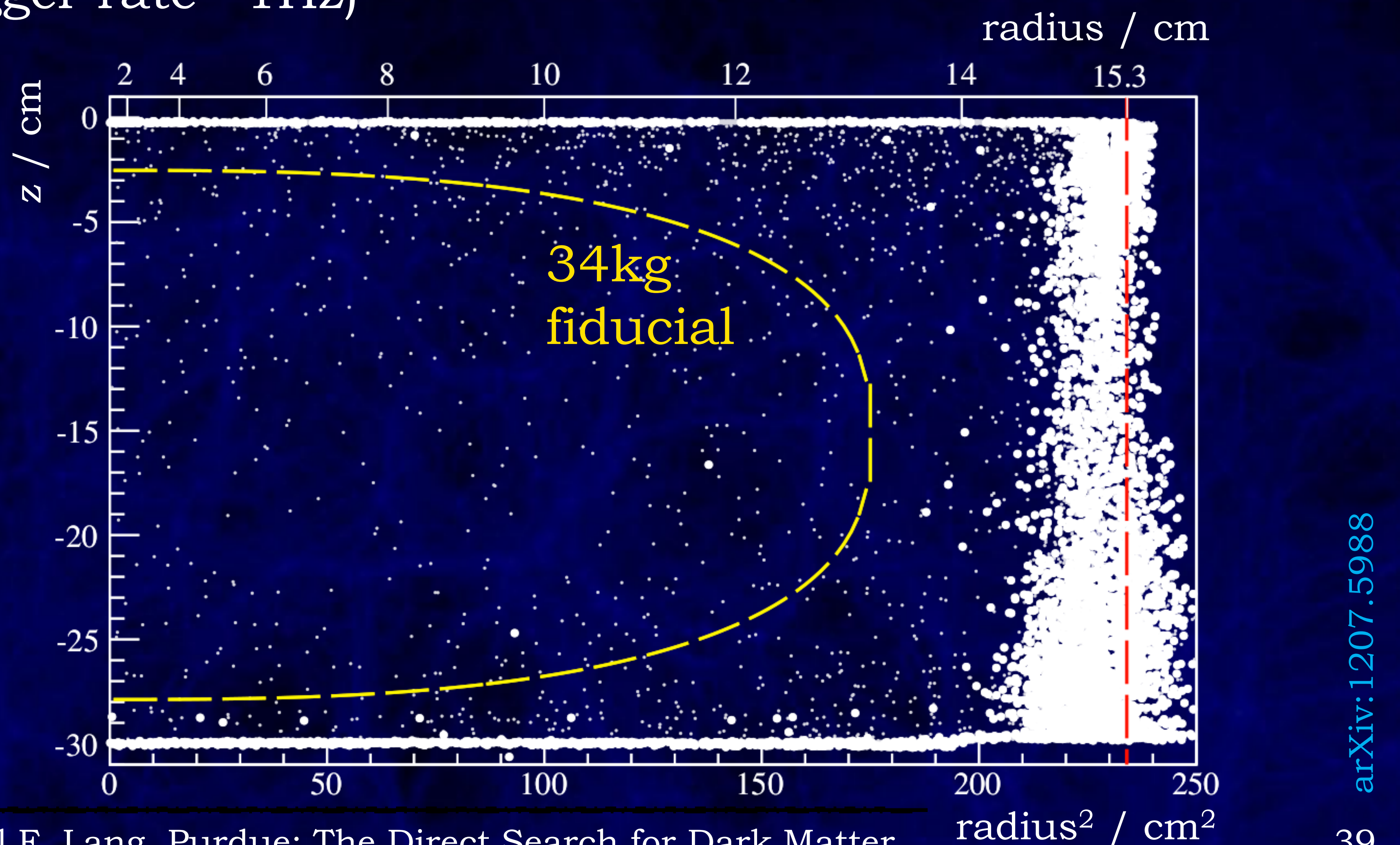




in preparation

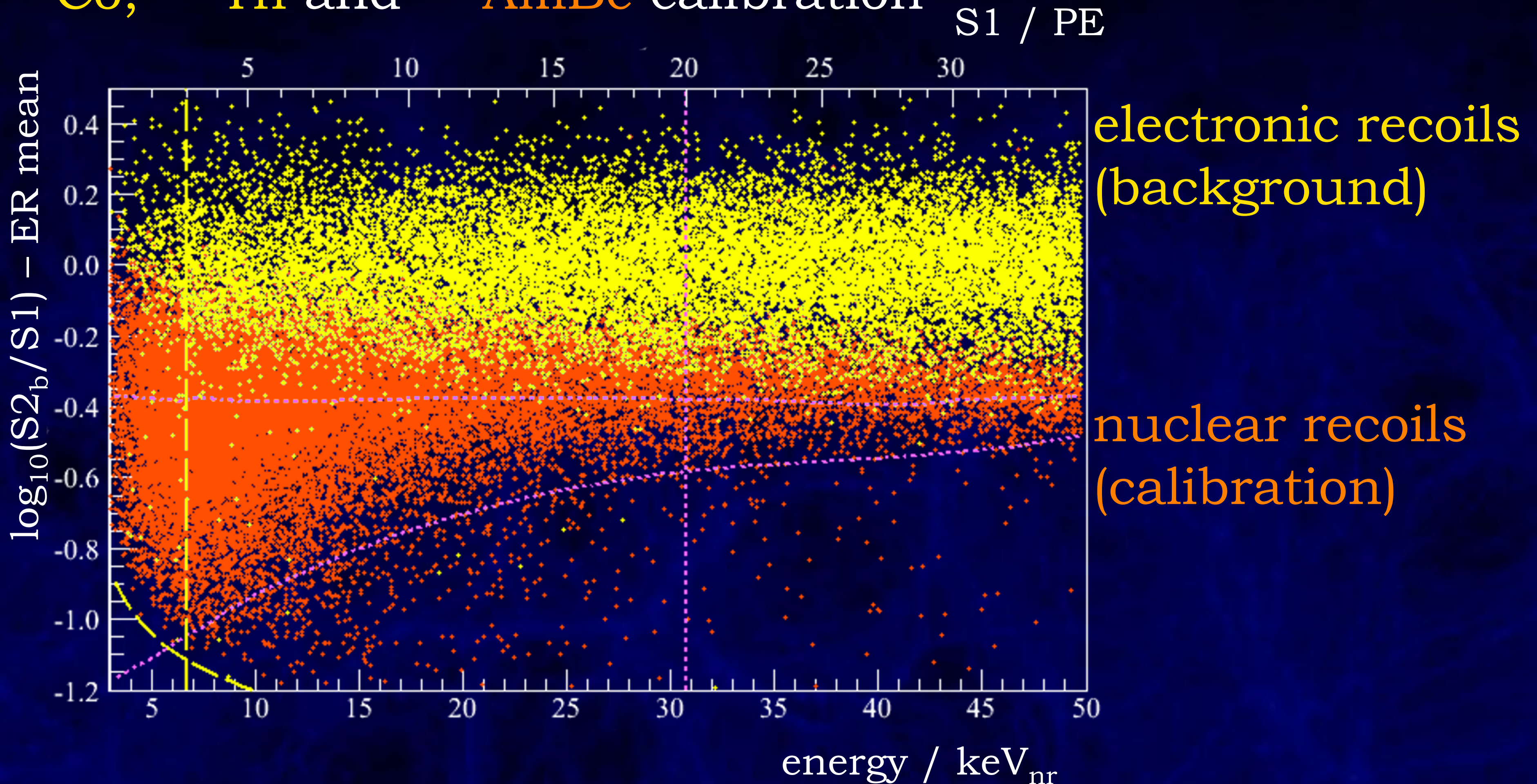
The Power of Fiducialization

events after 225 live days of data taking 2011/2012:
(trigger rate ~1Hz)



Discrimination using S2/S1

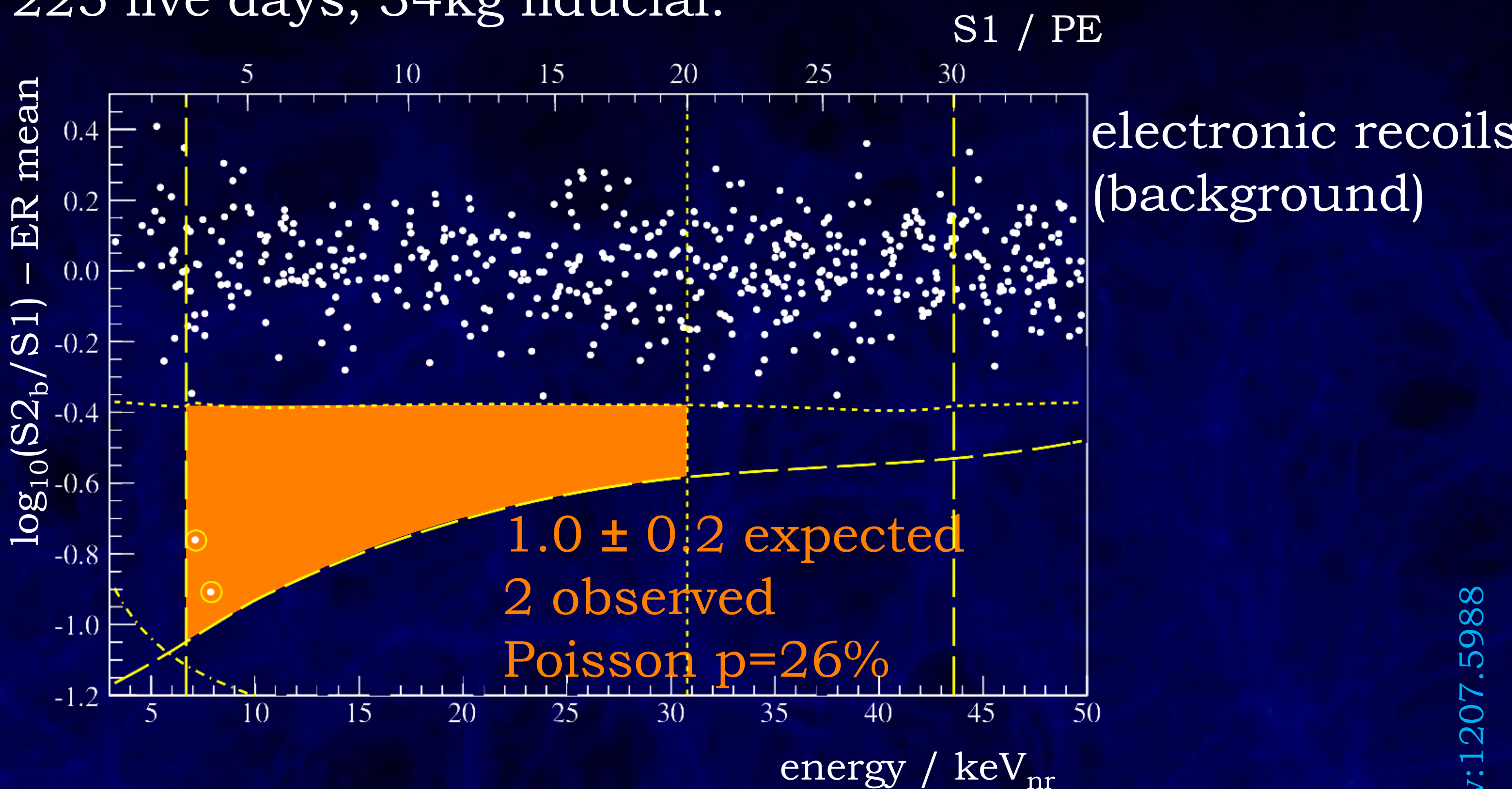
^{60}Co, ^{232}Th and $^{241}AmBe$ calibration



~99.5% ER rejection @ 50% NR acceptance

No Signal Observed

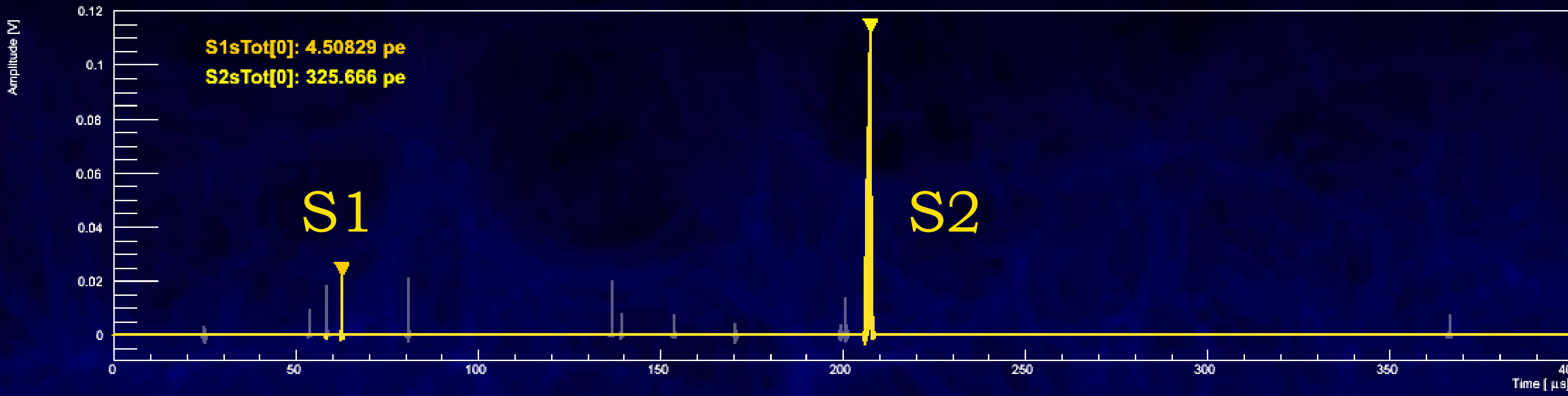
225 live days, 34kg fiducial:

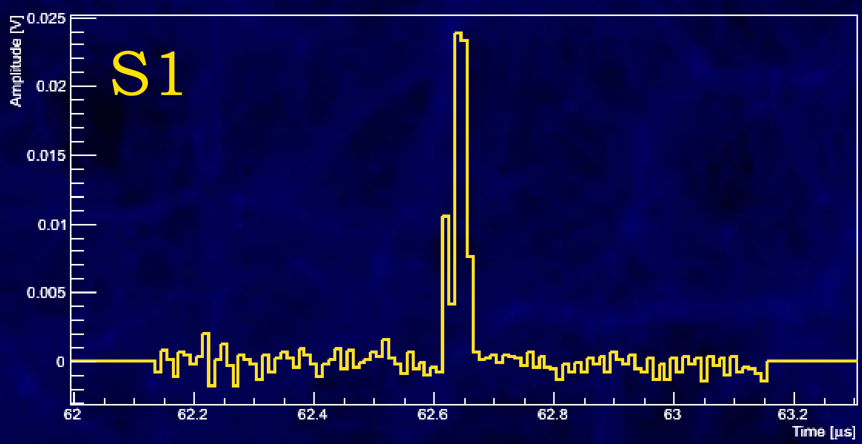


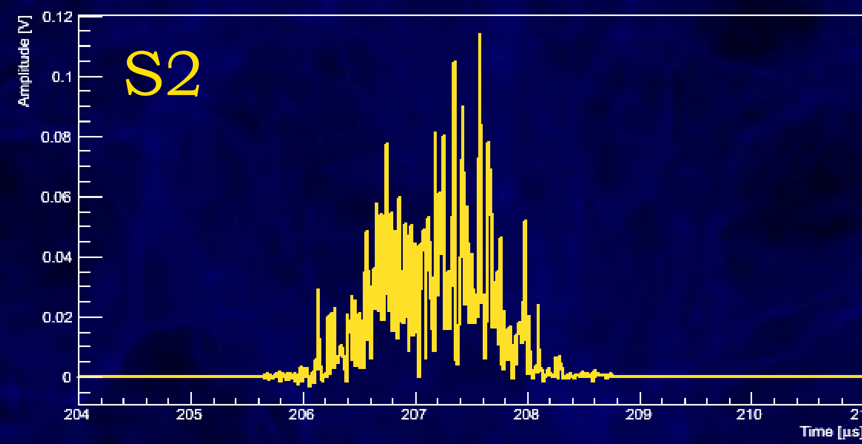
arXiv:1207.5988

likelihood analysis: background-only p-value $> 5\% \; \forall m_\chi$

Candidate Event: Waveform



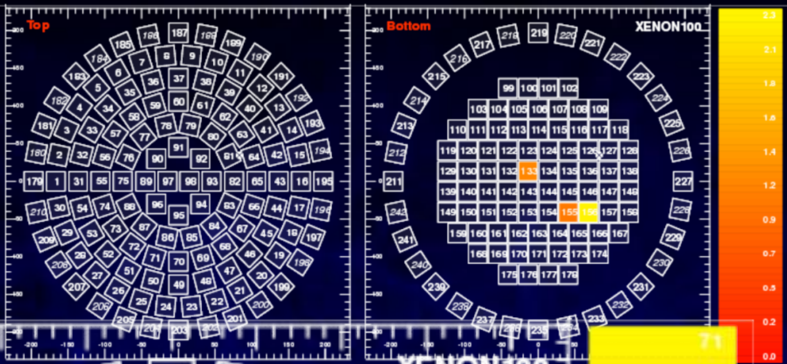




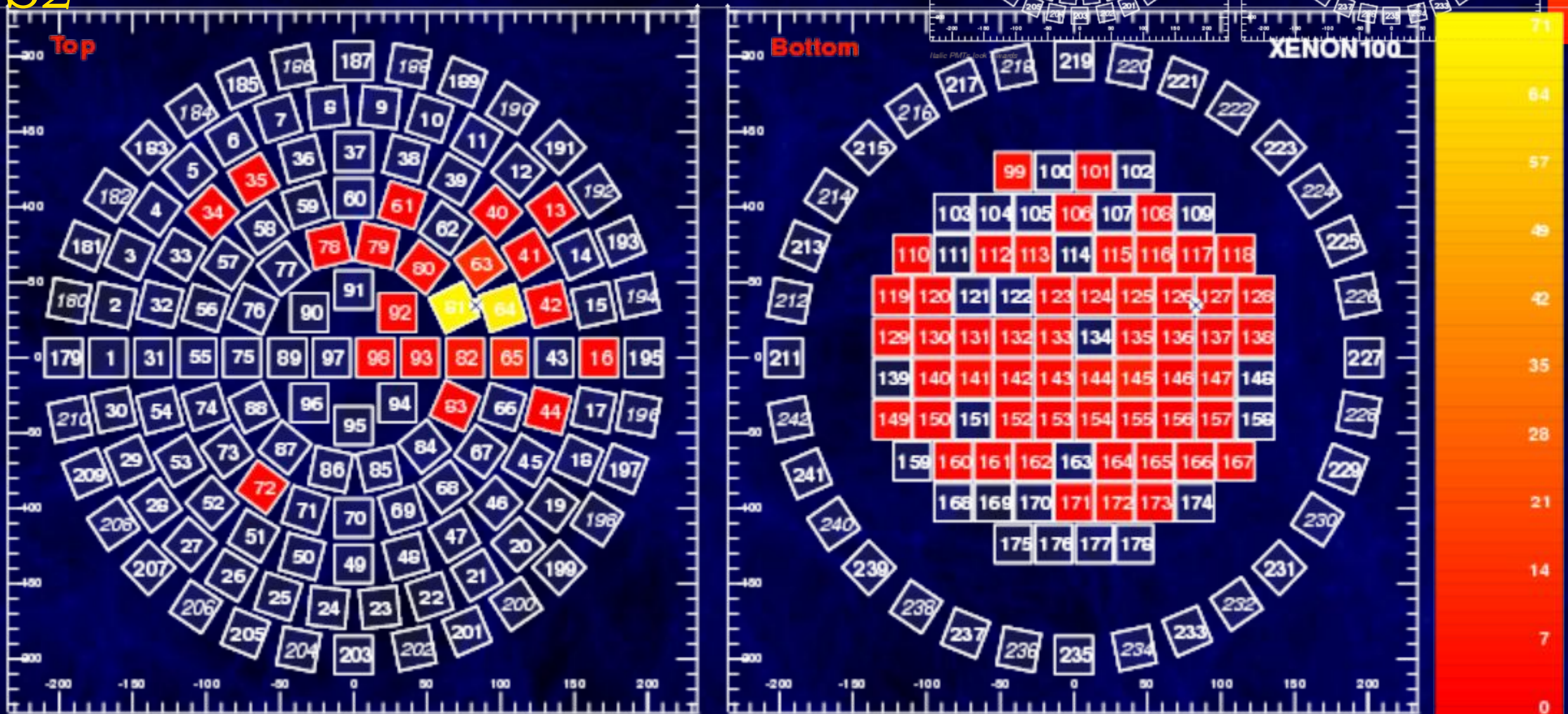
Candidate Event: PMT Pattern

excellent positioning
$(\delta r < 3\,\mathrm{mm})$
even near threshold

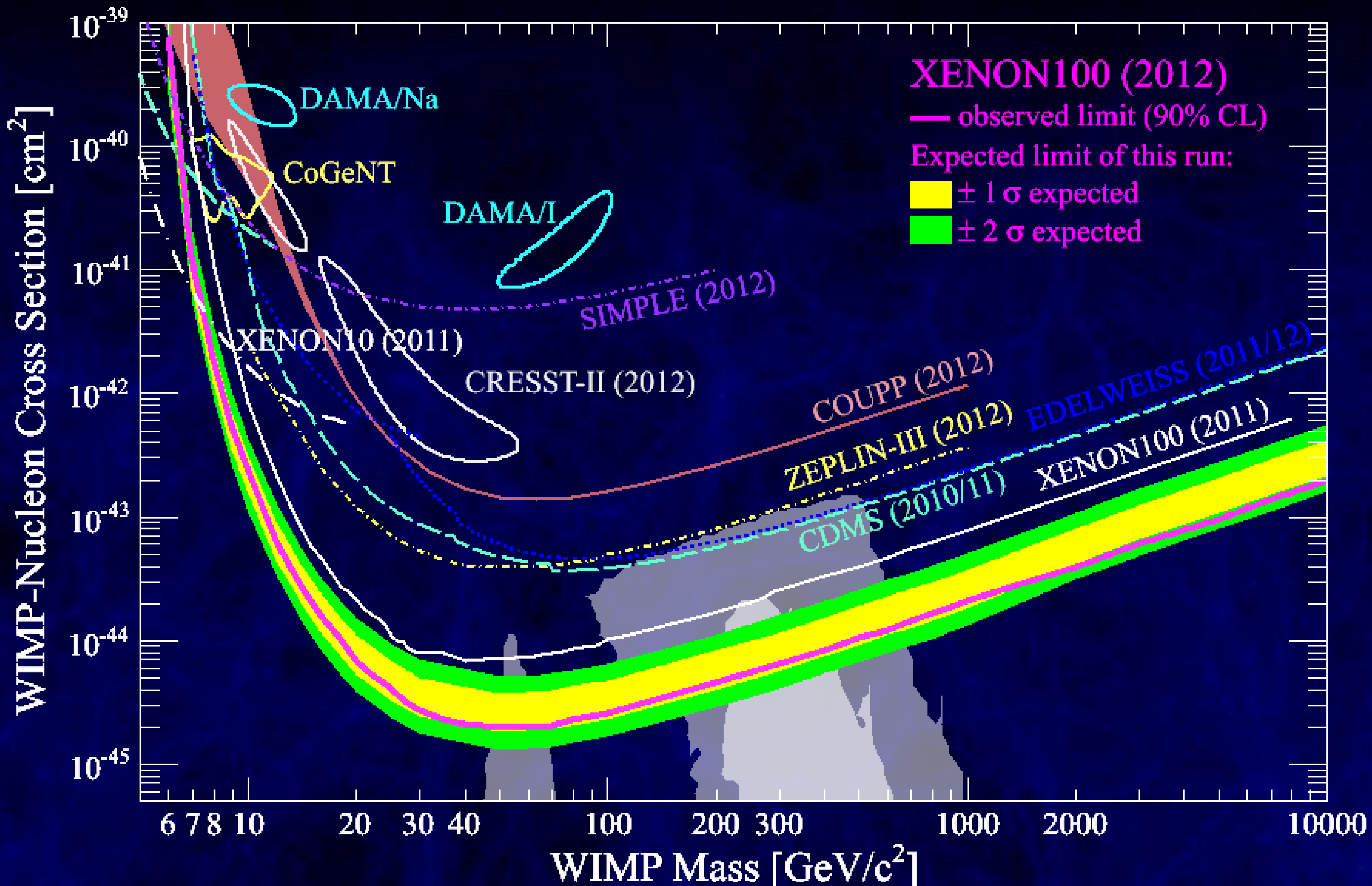
S1



S2



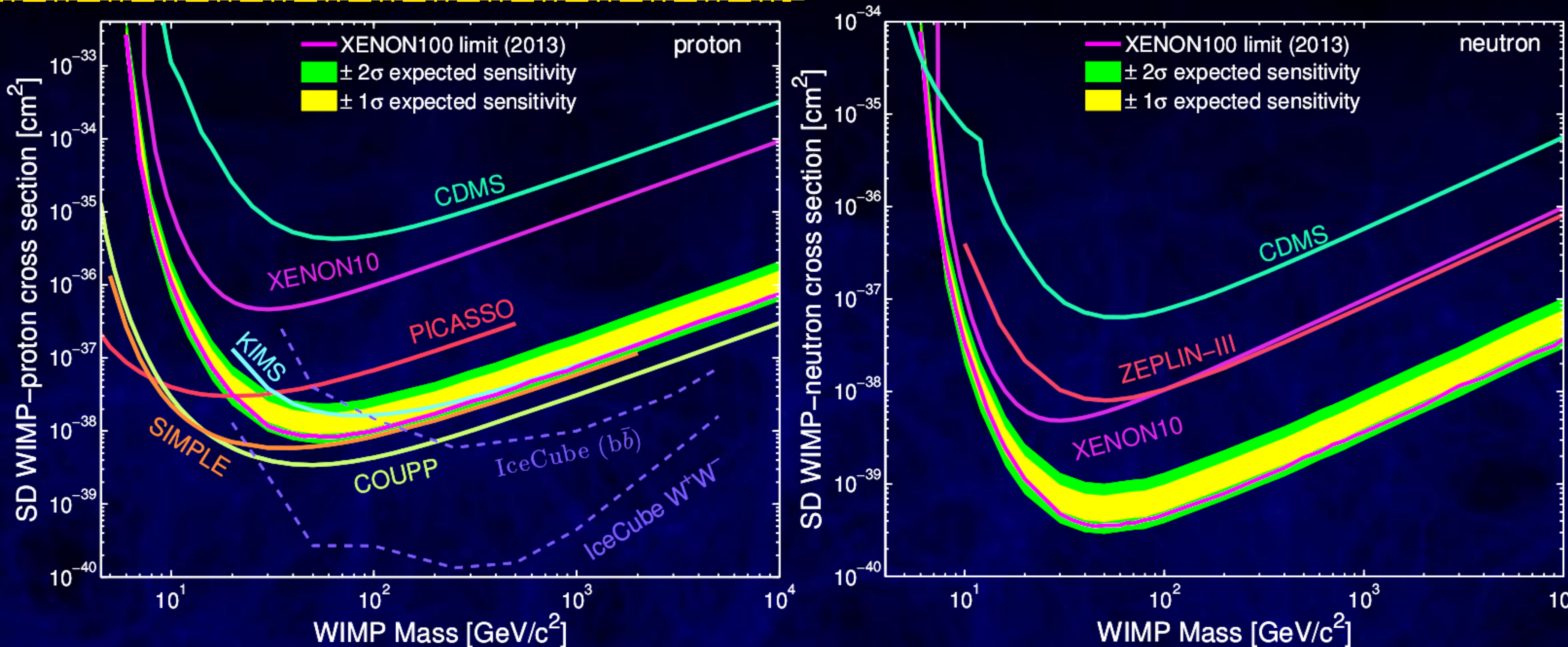
XENON100 SI Limit 2012



XENON100 yields strongest limit to date

arXiv:1207.5988

XENON100 SD Limits



~50% of xenon has spin

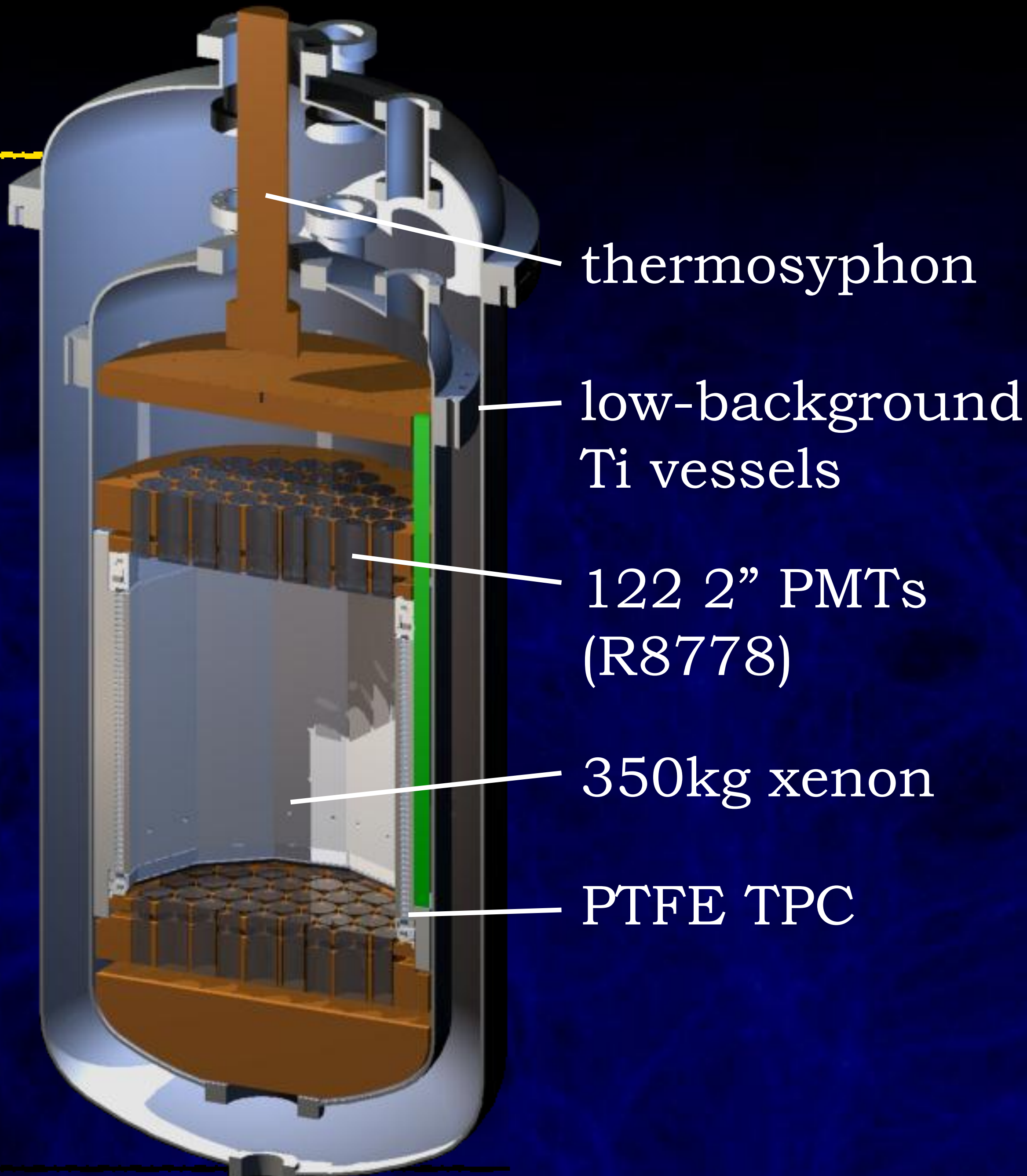
- competitive proton-only limits
- leading neutron-only limits

arXiv:1301.6620

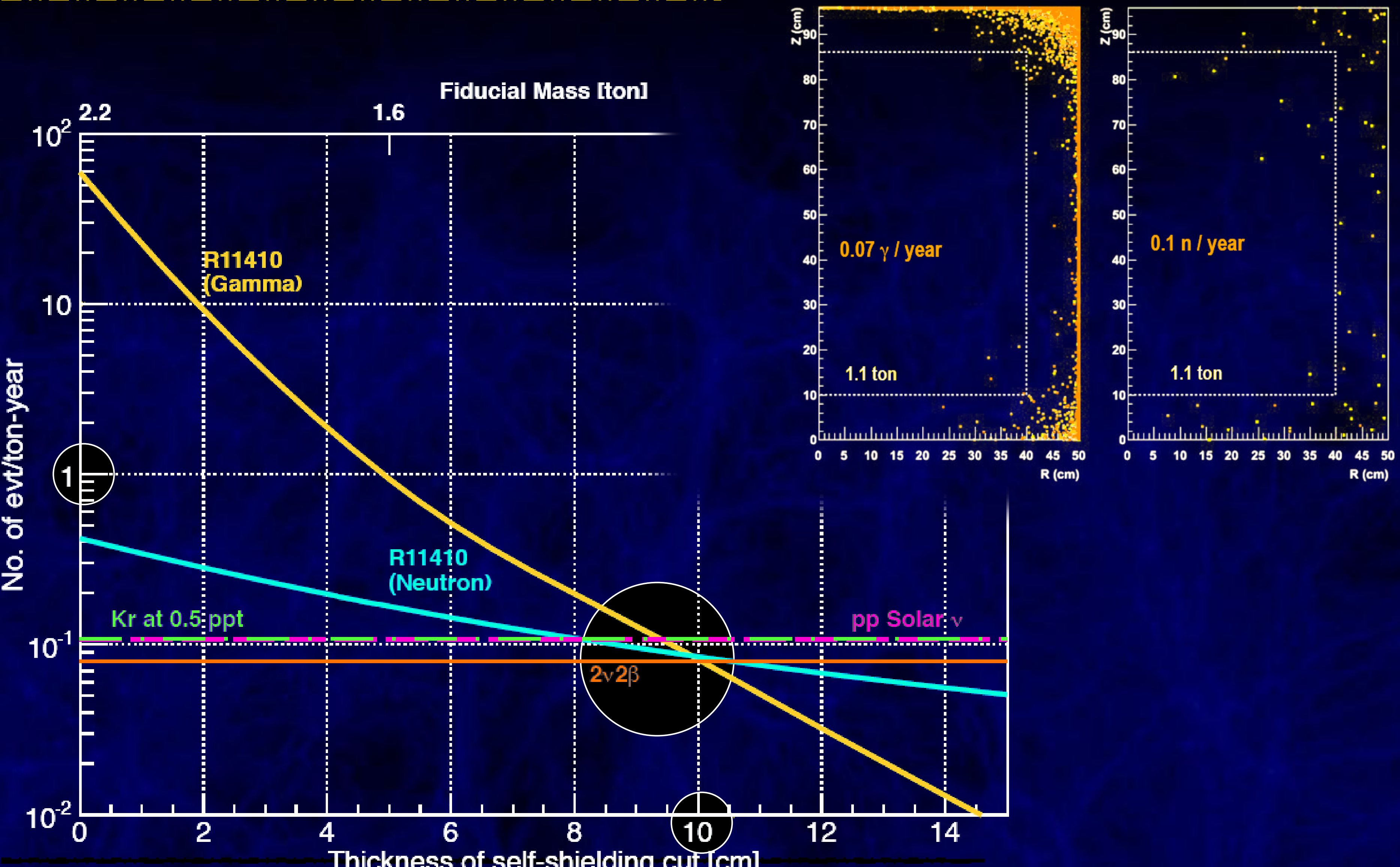
Larger: LUX

US collaboration two-phase liquid xenon target

now being commissioned underground



Even Larger: XENON1T

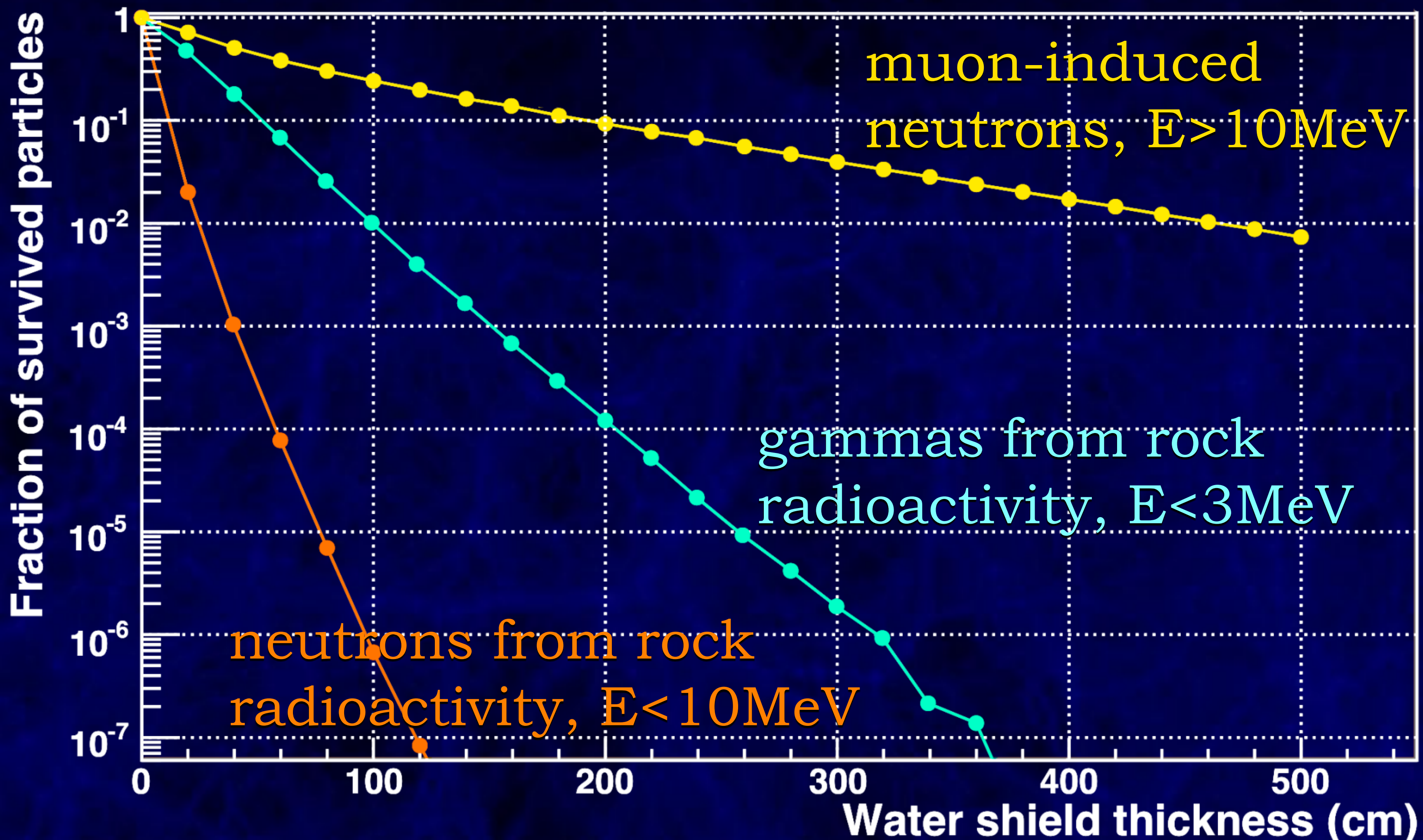


Key Challenges

	XENON100	XENON1T
• liquid xenon	161 kg	~3500 kg
• background	$5 \cdot 10^{-3}$ dru	$5 \cdot 10^{-5}$ dru
• krypton/xenon	(19±4) ppt	<0.5 ppt
• radon/xenon	~65 μBq/kg	~1 μBq/kg
• electron drift	30 cm	1 m
• cathode	-16 kV	-100 kV
• filling-to-search	several months	2 months

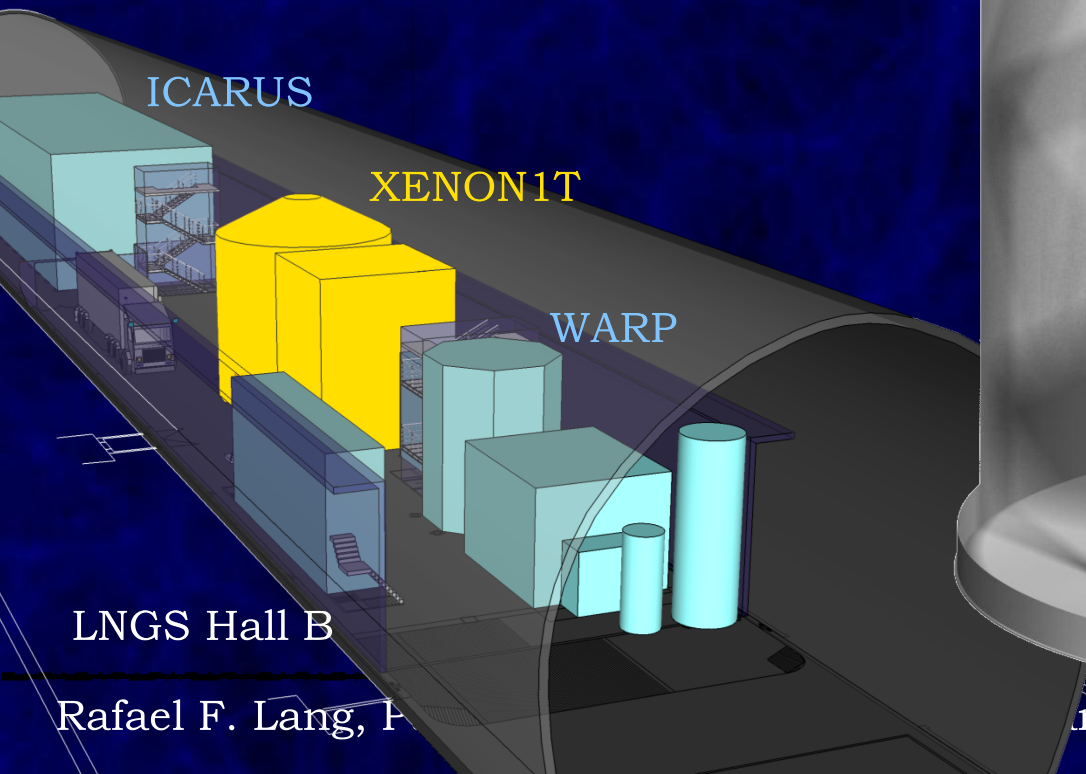
The Need for a Muon Veto

shielding of high-energy n insufficient: requires veto

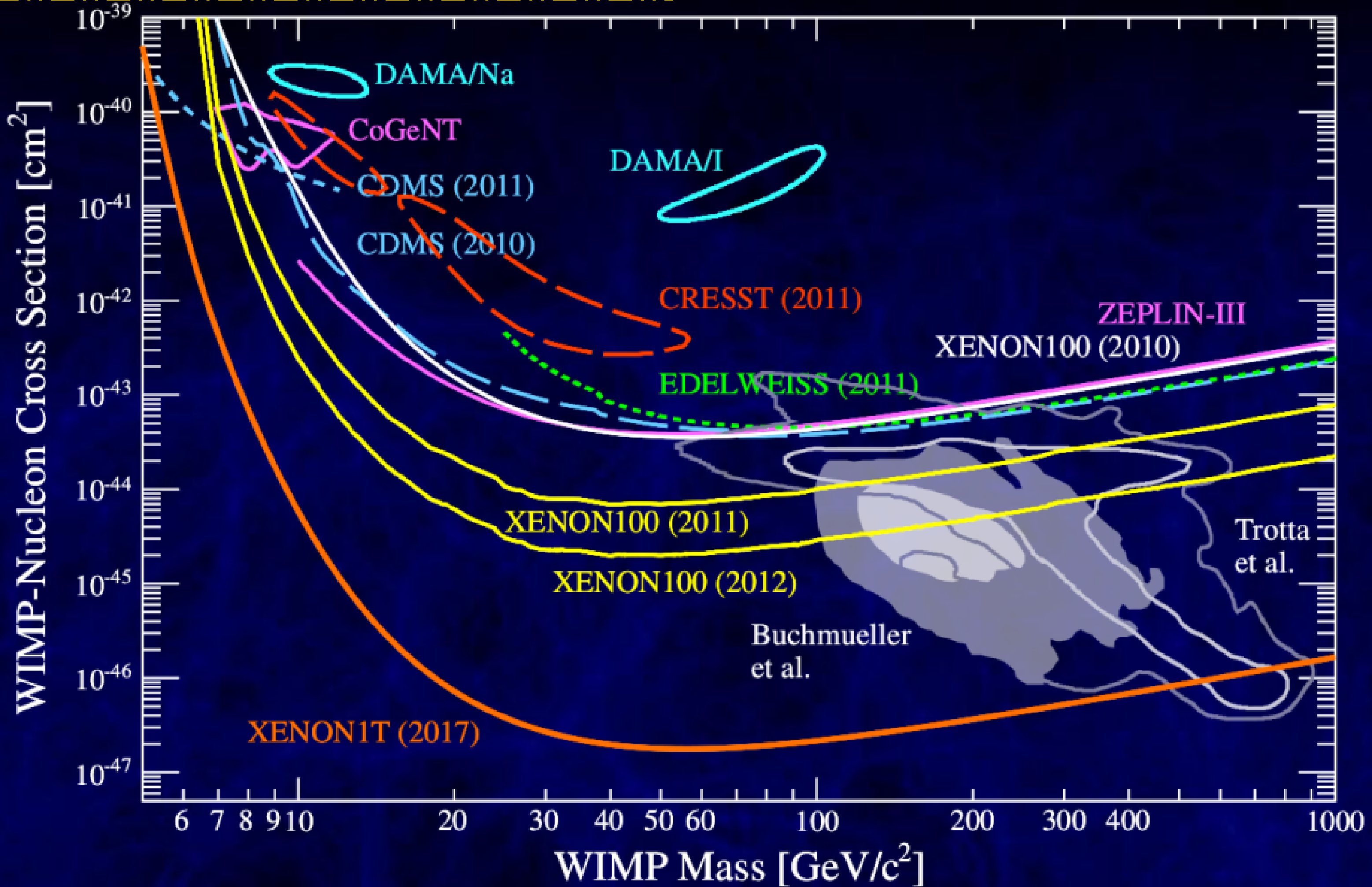


XENON1T

- fully funded
- construction started
- 10m high, Ø9.6m tank
- at Gran Sasso
- commissioning next year!



A Bustling Field of Research



improve by 2 orders of magnitude within 5 years