Direct Detection of Dark Matter

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Early indications of Dark Matter

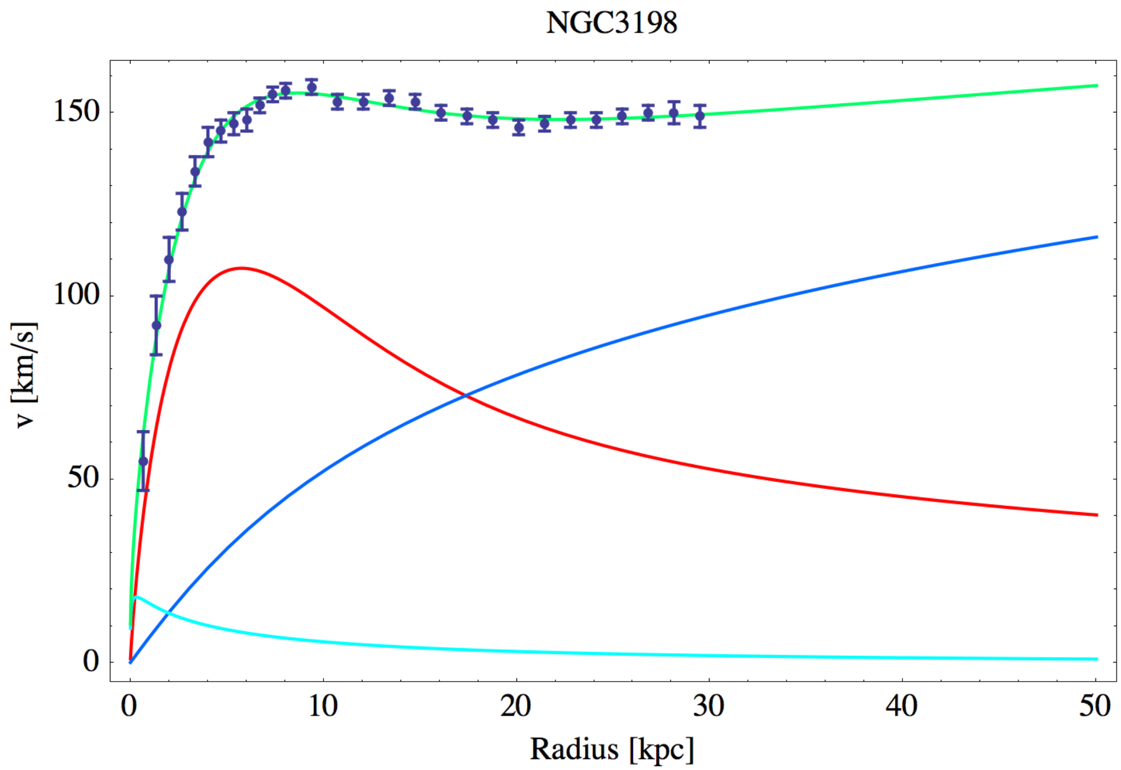
- **1930**: Fritz Zwicky measured the velocity dispersion of galaxies in the Coma Cluster and found that they could not be bound by gravitational attraction of visible matter alone

- **1970**: Vera Rubin measured rotation curves of disk galaxies and found it was flat at large radii

Rotation curve: an example

$$v=\sqrt{\frac{4\pi G}{r}\int_0^r dx\rho(x)x^2}$$

$$v=\sqrt{\frac{GM}{r}}$$



A flat curve implies

M(r) = k r

$\rho \sim 1/r^2$ for a spherically symmetric halo about the center of the galaxy

In brief: evidence of Dark Matter

- Spiral galaxies **rotation curves**: M_{halo} ~ $10M_{stars}$ **(Ω_{matter}>0.1)**
- **Clusters of galaxies** (10^2-10^3 galaxies over 1-2 Mpc): **Ω_{matter}~0.2-0.3** (M/L ~ 100 – 300)
- **CMB anisotropy and BB nucleosynthesis**:

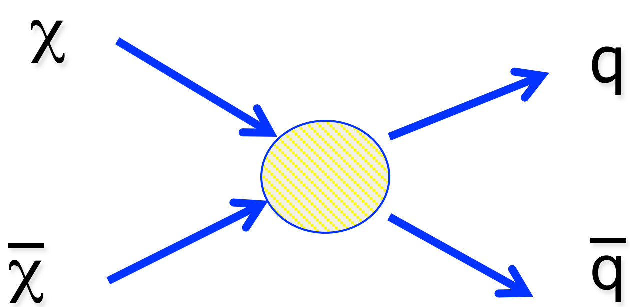
  Ω_{matter}~0.27, $\Omega_{baryons}$~0.04
  - **~85% of mass in the Universe is dark and non-baryonic**
  - **$\langle\rho_{DM}\rangle$ ~ $0.23\rho_{crit}$ ~ 10^{-6} GeV/cm^3**
  - around our Sun: **$\rho_{DM\text{-}Sun}$ ~ 0.3-0.4 GeV/cm^3**
- **Large Scale Structures**:
  - Formation of structures by gravitational clustering support evidence of "cold" (not relativistic) DM

Summary of DM properties

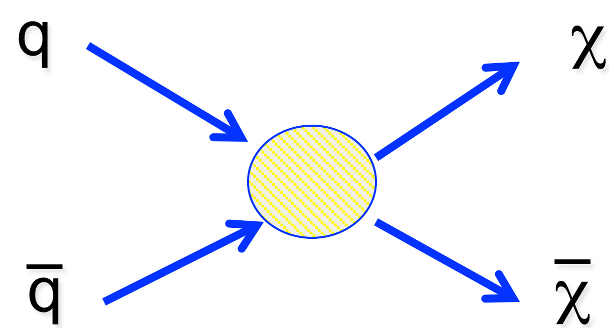
- **DM evidence** based on gravitational interaction
  - This paradigm shows some subtle points
    - Discrepancies between N-body simulations and astrophysical observations
- DM makes up ~**85% of matter** in the Universe
- **DM could be made by unknown** particle(s)
  - WIMPs, axions, …
- These particles are neutral and **gravitationally interacting.** What about:
  - Self interactions ??
  - Dissipative processes ??
- $\mathbf{\Omega_{DM} \sim 5\Omega_b\ (m_p\rho_{DM}/\rho_b \sim 5GeV/c^2)}$
  - Baryon density is asymmetric. What about DM density?
- **Cold** (p/m <<1 at CMB formation)
- **Stable** or very long lived (> 10^{10} years)

The quest for Dark Matter

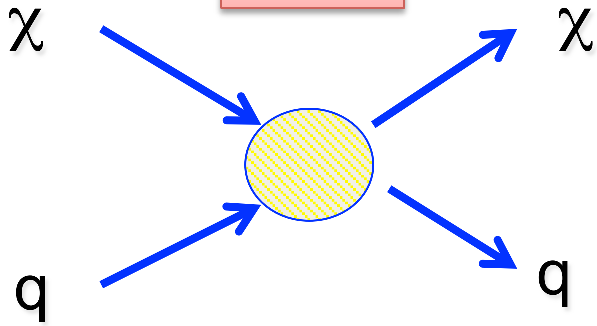
INDIRECT



COLLIDER



DIRECT



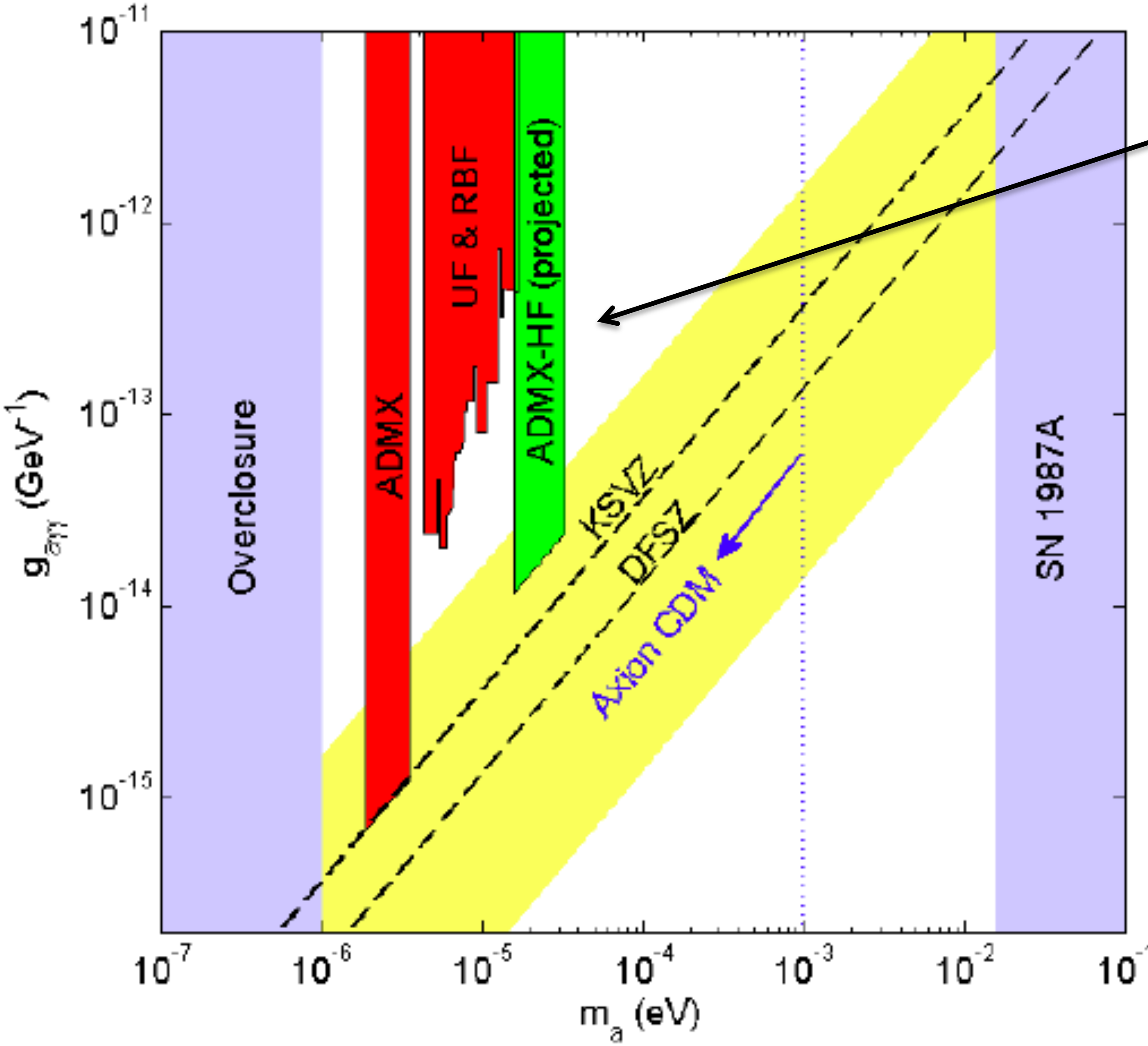
χ = DM particle
q = Standard Model particle

DM particle candidates

- **WIMPs**
  - Weakly Interactive Massive Particles in equilibrium with quarks and leptons in the early universe as a generic class of cold DM candidates

    for the last ~ 20 years the main scenario for DM direct detection
  - Mass ~ 1 – 1000 GeV/c^2
  - $<\sigma_{ann}v>$ ~ 10^{-26} cm^3s^{-1} gives the correct relic density
  - Local number density ~ 10^5 – 10^7 cm^{-3}
  - Flux on Earth for a 100 GeV/c^2 WIMP ~ 10^5 $cm^{-2}s^{-1}$
- **Axions**
  - QCD axions as DM candidates with mass ~ 10 – 100 μeV
  - Local number density ~ 10^{12} – 10^{15} cm^{-3}

Axions as DM candidates



3 years time scale

The quest for axions as DM

- The only experiment in operation at present is **Axion DM eXperiment (ADMX)** a cryogenic microwave cavity in 8T magnetic field sensitive to ~100 MHz
  - improving performances for GHz range sensitivity
- **CAST-CAPP** and **RADES** (UZ and IFIC Valencia)
  - Microwaves cavities in CAST magnet with GHz sensitivity
  - Prototypes installed and tested in 2016

WIMPs

- A general class of weakly interacting massive (1GeV – 10 TeV) particles not from the Standard Model

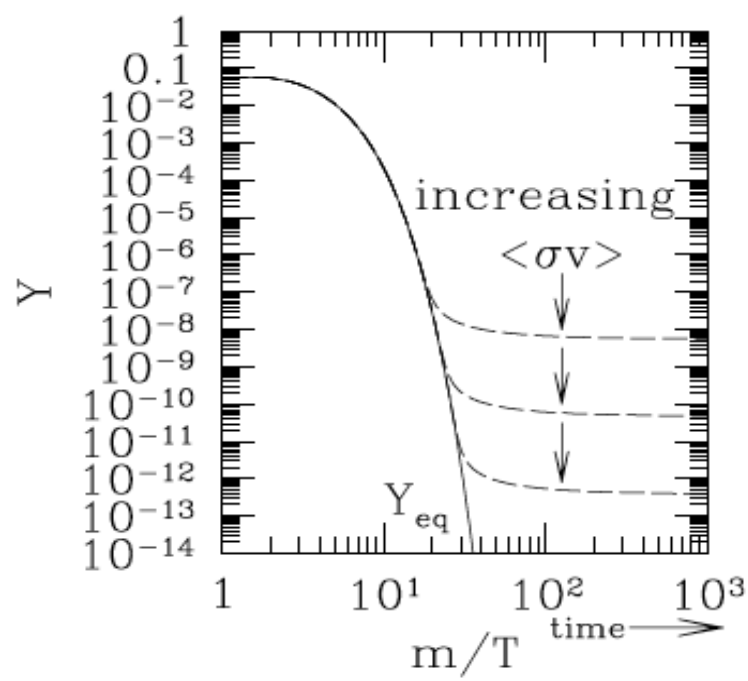
- Assuming thermal equilibrium in the early Universe and non-relativistic decoupling, the energy density for these relic particles is predicted to be:

$$\Omega_\chi h^2 \approx \frac{3\cdot 10^{-27}\ \mathrm{cm}^3 s^{-1}}{\langle \sigma \mathrm{v} \rangle}$$

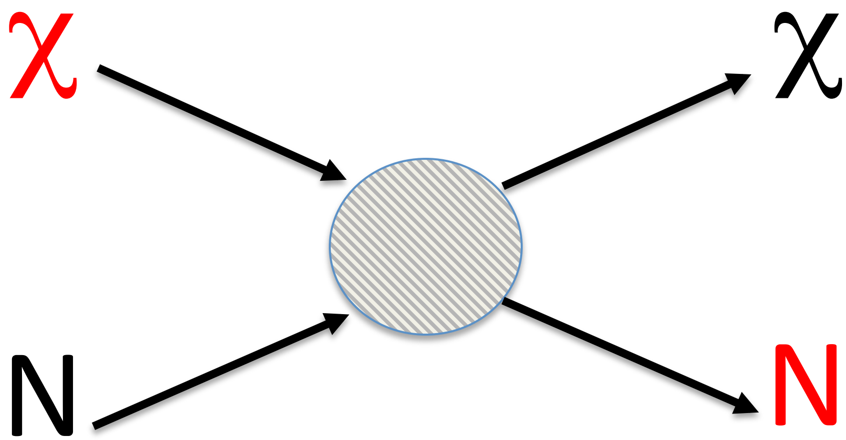
– **$\Omega_\chi \sim 0.2$ for $<\sigma v> \sim 10^{-26}\mathrm{cm}^2$**

– **Electroweak-scale cross section can reproduce correct relic density**

DM number density vs time



Direct Search for WIMPs: nuclear recoil tagging



Goodman and Witten, PRD31, 1985

$$E_{recoil} = \frac{m_N M_\chi^2}{(m_N + M_\chi)^2} v^2 (1 - \cos\theta^*)$$

$v \sim 300$ km/s $\beta \sim 10^{-3}$

$$E_{recoil} \sim 1 - 100 \text{ keV}$$

$$\frac{\lambda}{2\pi} = \frac{h}{p} = \frac{\hbar c}{mc^2 \beta} \approx \frac{197 \cdot 10^{-13} \text{MeVcm}}{100\text{GeV } 10^{-3}} \approx 2 \cdot 10^{-13} cm$$

$$\frac{dR}{dE} = N_t \frac{\rho_\chi}{m_\chi} \frac{m_N}{\mu_n^2} A^2 \sigma_{\chi n} F^2(E) \int_{v \geq v_{\min}(E)} d^3v \frac{f(v)}{v}$$

$$f(v) = \begin{cases} \dfrac{1}{N} e^{-\left(\frac{|v_\chi + v_{sun} + v_{Earth}|}{v_0}\right)^2}, & |v_\chi + v_{sun} + v_{Earth}| < v_{esc} \\ 0, & \text{elsewhere} \end{cases}$$

- 170 km/s < v_0 < 270 km/s
- 450 km/s < v_{esc} < 650 km/s
- ρ_χ ~ 0.3-0.4 Gev/cm^3
- F(E) = nuclear form factor
- f(v) = velocity distribution of WIMPs in the galaxy

Expected rate for WIMPs

$$R = N_t \times \sigma_{\chi A} \times \frac{\rho_\chi}{m_\chi} \times \langle \mathrm{v} \rangle$$

$$R \sim 0.2 \frac{\text{events}}{\text{kg year}} \left(\frac{100}{A} \times \frac{\sigma_{\chi A}}{10^{-38}\,\text{cm}^2} \times \frac{\langle \mathrm{v} \rangle}{250\text{km/s}} \times \frac{\rho_\chi}{0.4\text{GeV/cm}^3} \times \frac{100\text{GeV/c}^2}{m_\chi} \right)$$

Exposure = 1 ton x year

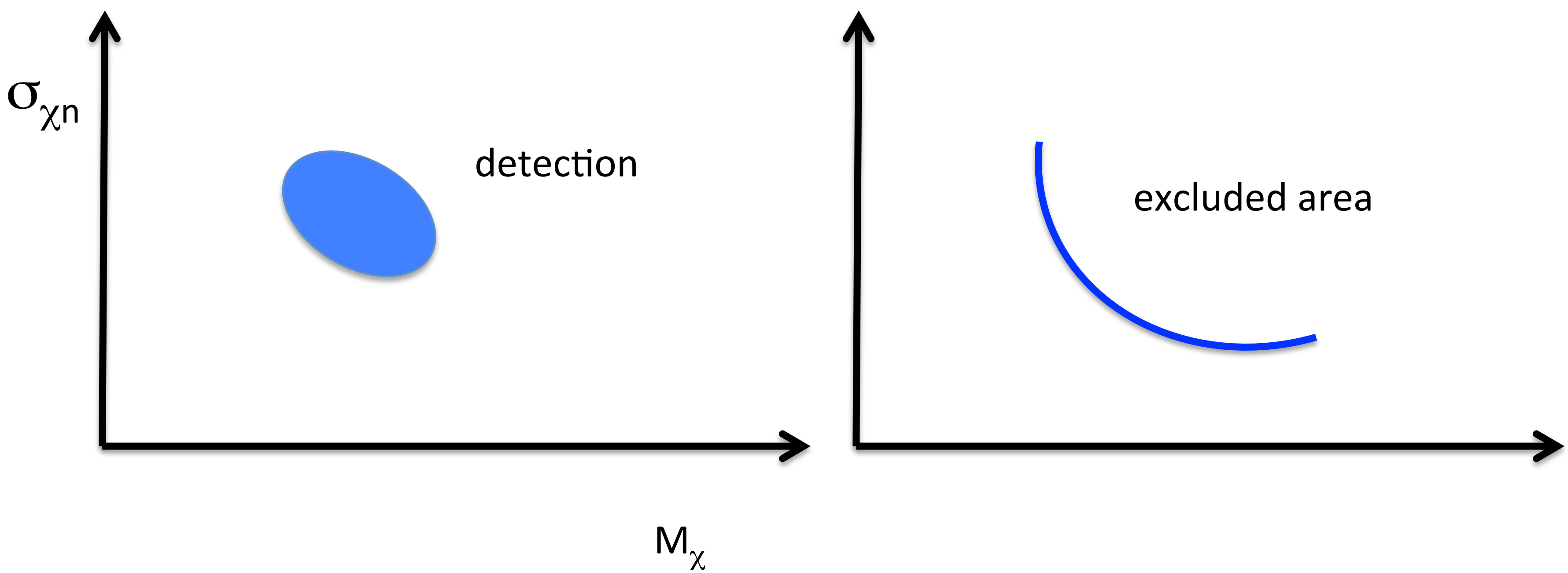
Events ~ 200

1 μBq/kg of radon gives ~ 31500 decays

Need reduction factor > 200 for such a low background level!!!

What can we learn from DM Direct Search?

$$\frac{dR}{dE} = N_t \frac{\rho_\chi}{\boxed{m_\chi}} \frac{m_N}{\mu_n^2} A^2 \boxed{\sigma_{\chi n}} F^2(E) \int_{v \geq v_{\min}(E)}^{v_{esc}} d^3v \frac{f(v)}{v}$$



"Standard" cross-section

Spin Independent interaction: $$\sigma^{SI}(E_r) = \sigma_p^{SI}\left[Z + (A-Z)\frac{f_n}{f_p}\right]^2 \left(\frac{\mu}{\mu_p}\right)^2 F_{SI}^2(E_r)$$

with F(0) = 1. So for the "standard" $f_p = f_n$, $\boldsymbol{\sigma^{SI} \sim A^2}$

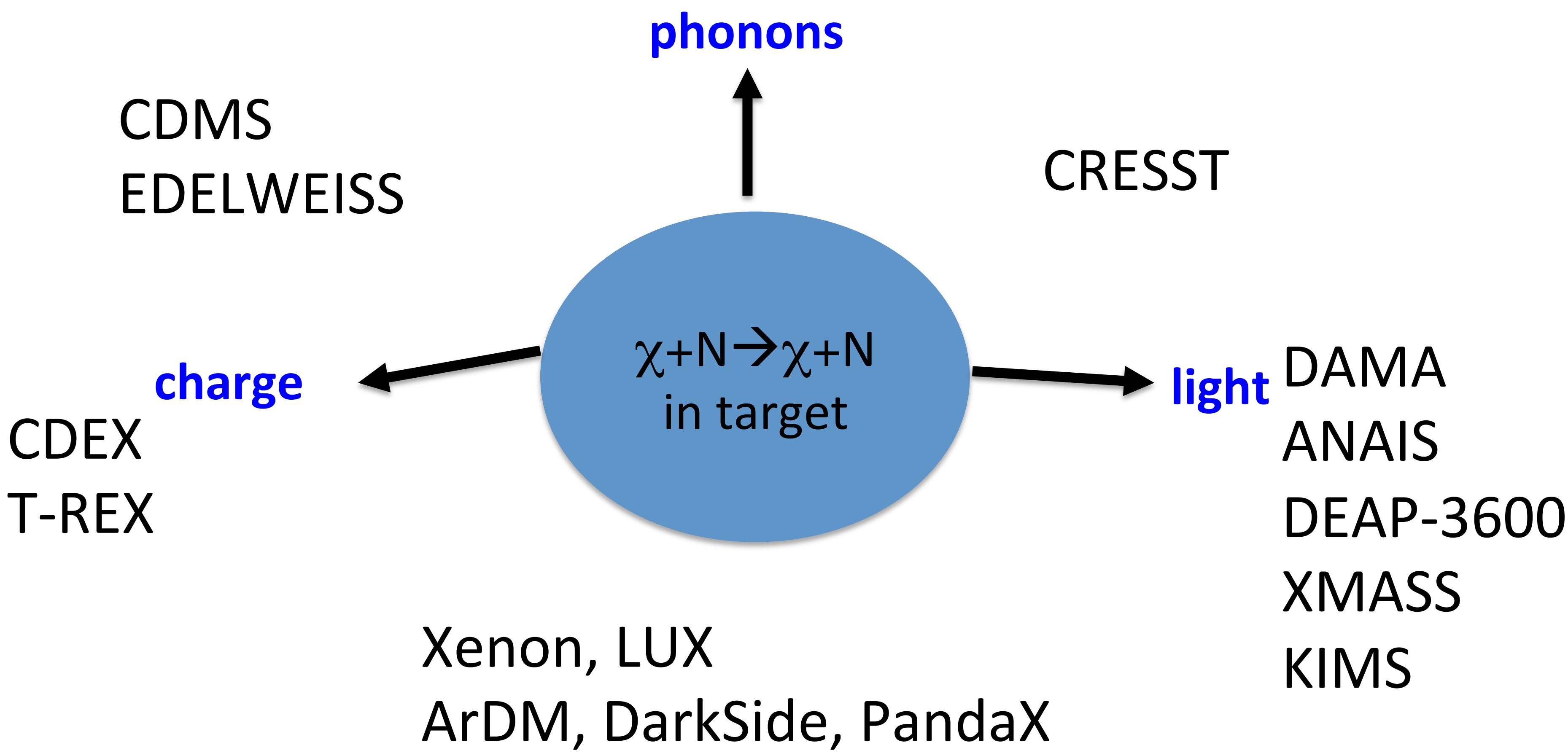
Spin Dependent interaction: $$\sigma^{SD}(E_r) = \sigma_p^{SD}\frac{4}{3}\frac{J+1}{J}\left(\langle S_p\rangle + \langle S_n\rangle\frac{f_n}{f_p}\right)^2 \left(\frac{\mu}{\mu_p}\right)^2 F_{SD}^2(E_r)$$

$\boldsymbol{\sigma^{SI}/\sigma^{SD} \sim A^2}$

Deviations from the "standard" scenario are considered:
- Isospin Violating Interactions, $f_n/f_p \sim -0.7$
  - reduces the coupling with Xe target
- $f_n/f_p \sim -0.8$ reduces the coupling with Ge target
- Electromagnetic coupling
- …

Important to use different target detectors

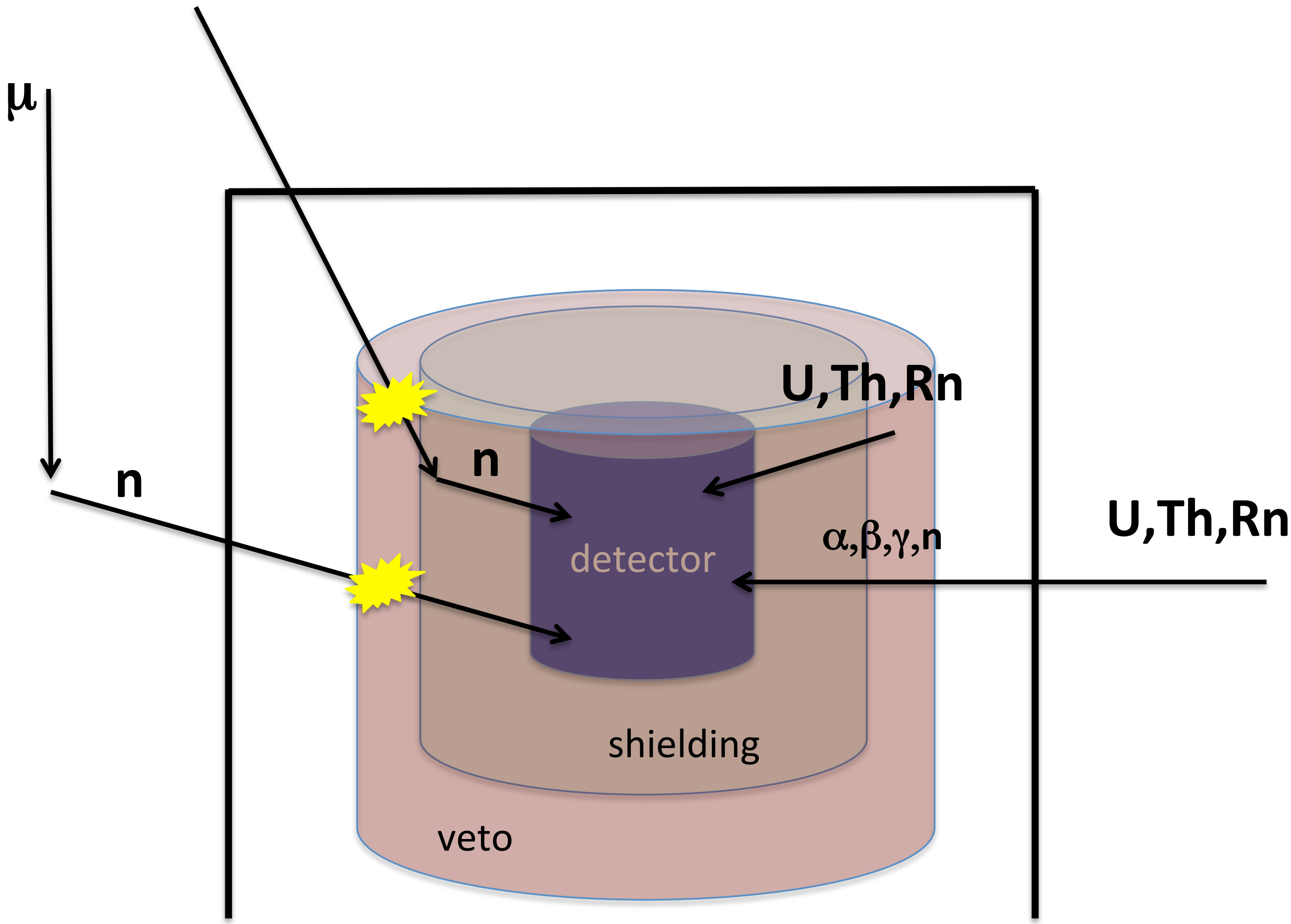
WIMPs Detection Methods



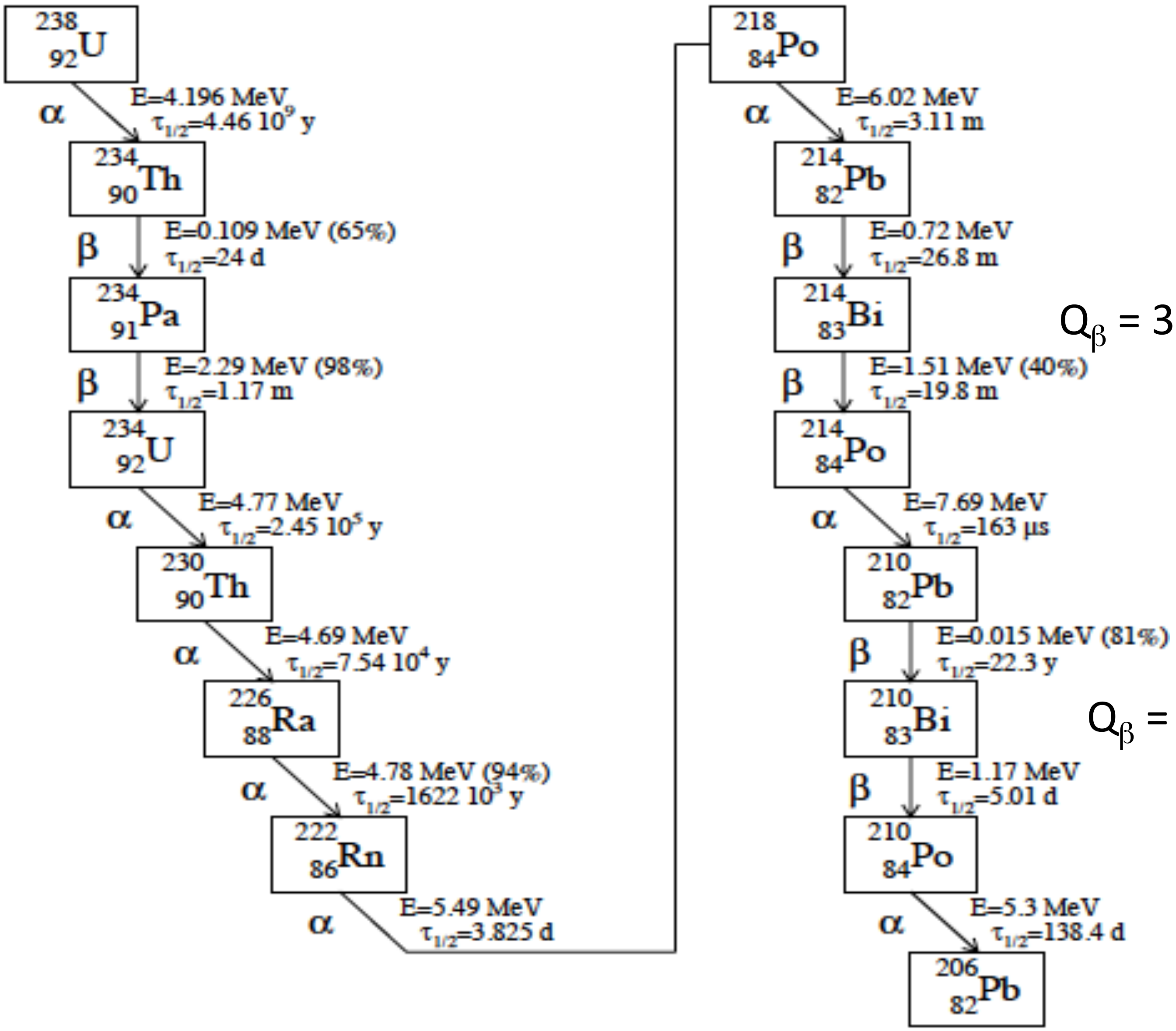
Technologies

- **Cryogenic solid state**
  - Ionization spectrometer + bolometer operated at < 100mK
  - CDMS(Si and Ge); CRESST(Ca); EDELWEISS(Ge)
- **Two-phase TPC with LXe** (XENON100, LUX) **or LAr** (DarkSide, ArDM)
  - Scintillation + ionization
- **Superheated liquid**
  - Nuclear recoil induce bubble nucleation
- **Scintillator crystal detectors**
  - DAMA/LIBRA (NaI), CoGeNT (Ge),CDEX(Ge), KIMS(CsI), XMASS(LXe), DEAP(LAr)
- **Spherical gas TPC**
  - Use H, He, Ne

Background



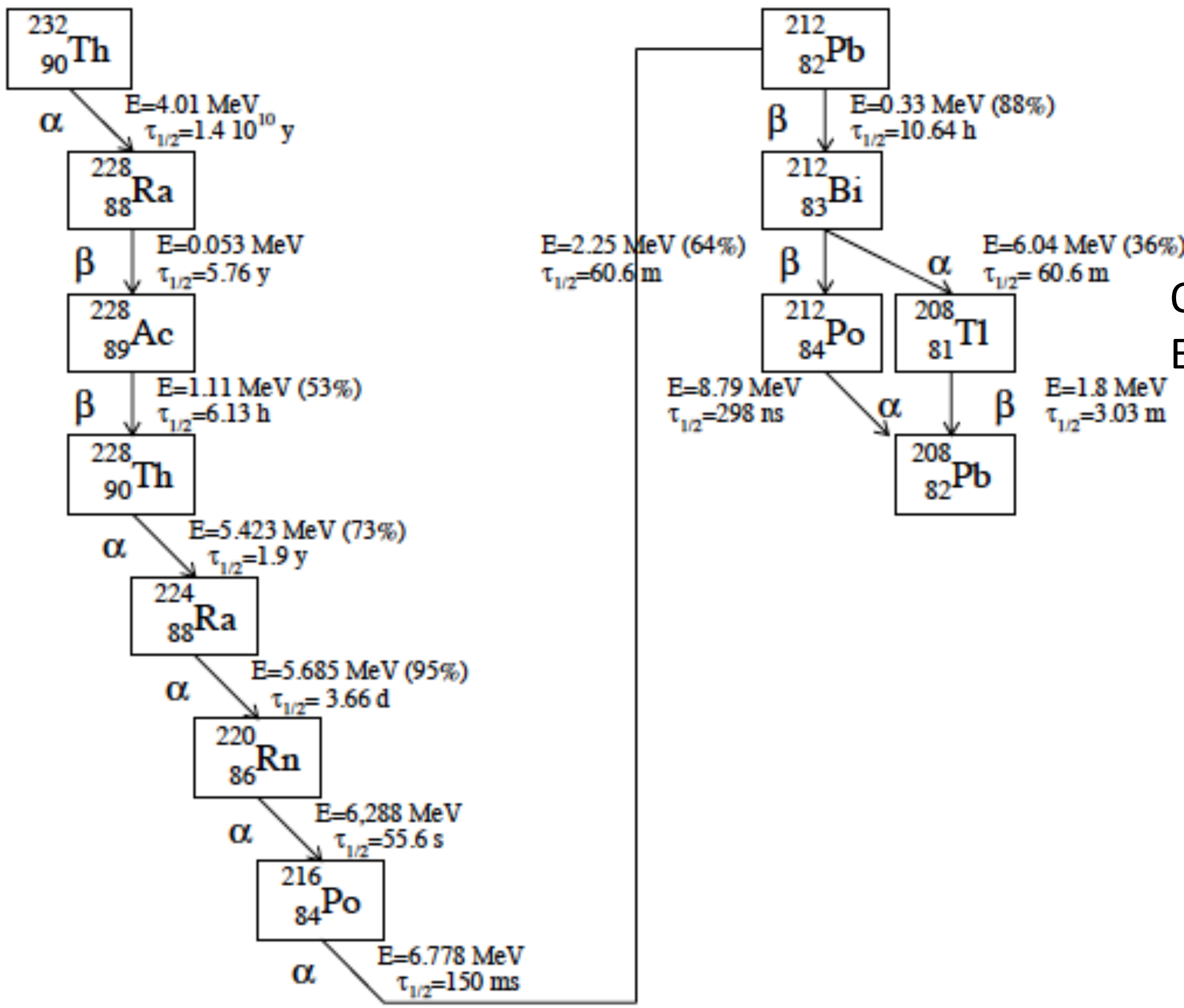
^{238}U chain



Q_{β} = 3.2 MeV

Q_{β} = 1.2 MeV

^{232}Th chain



Q_β = 5.0 MeV

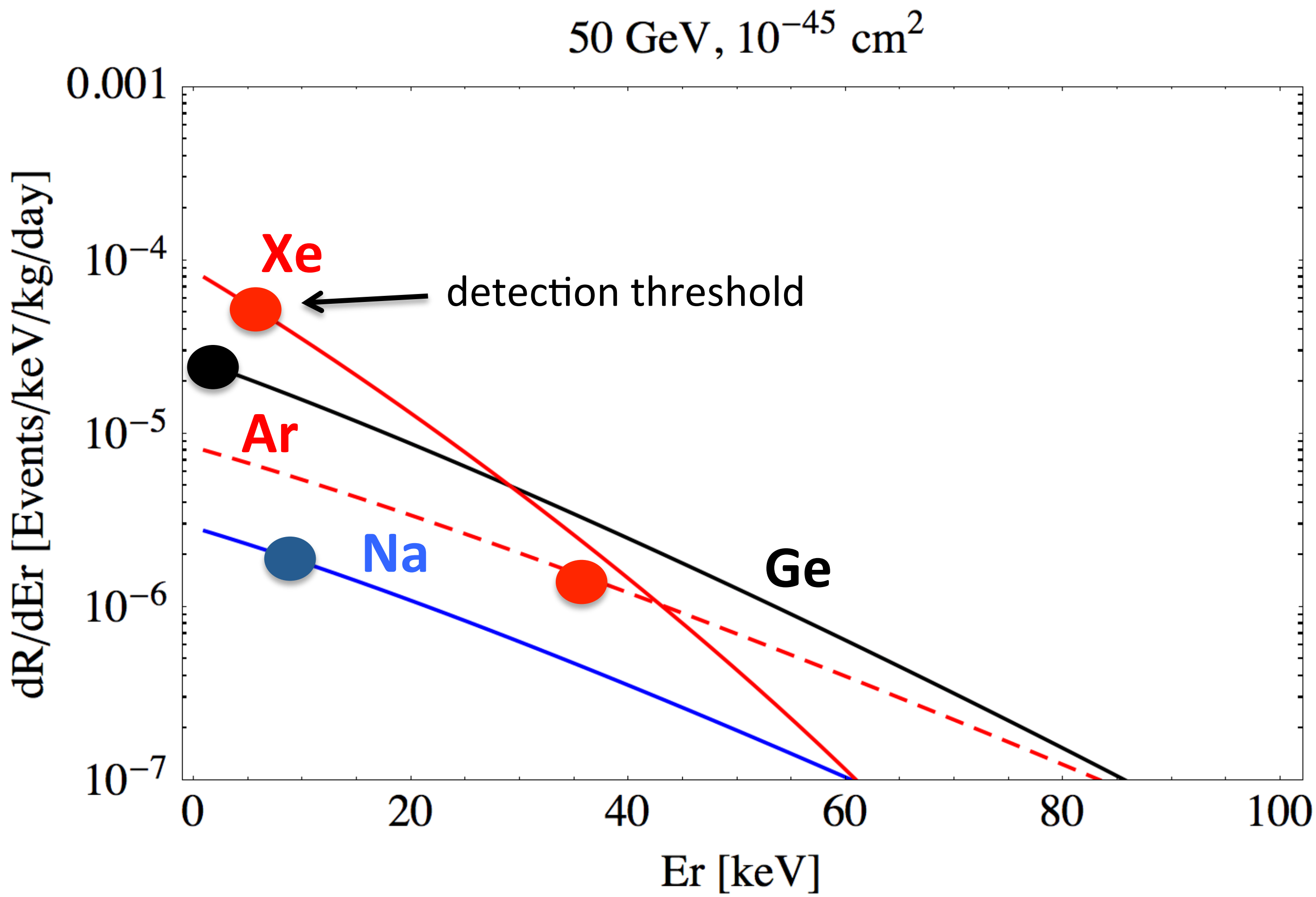
E_γ = 2.6 MeV

WIMPs signal and background

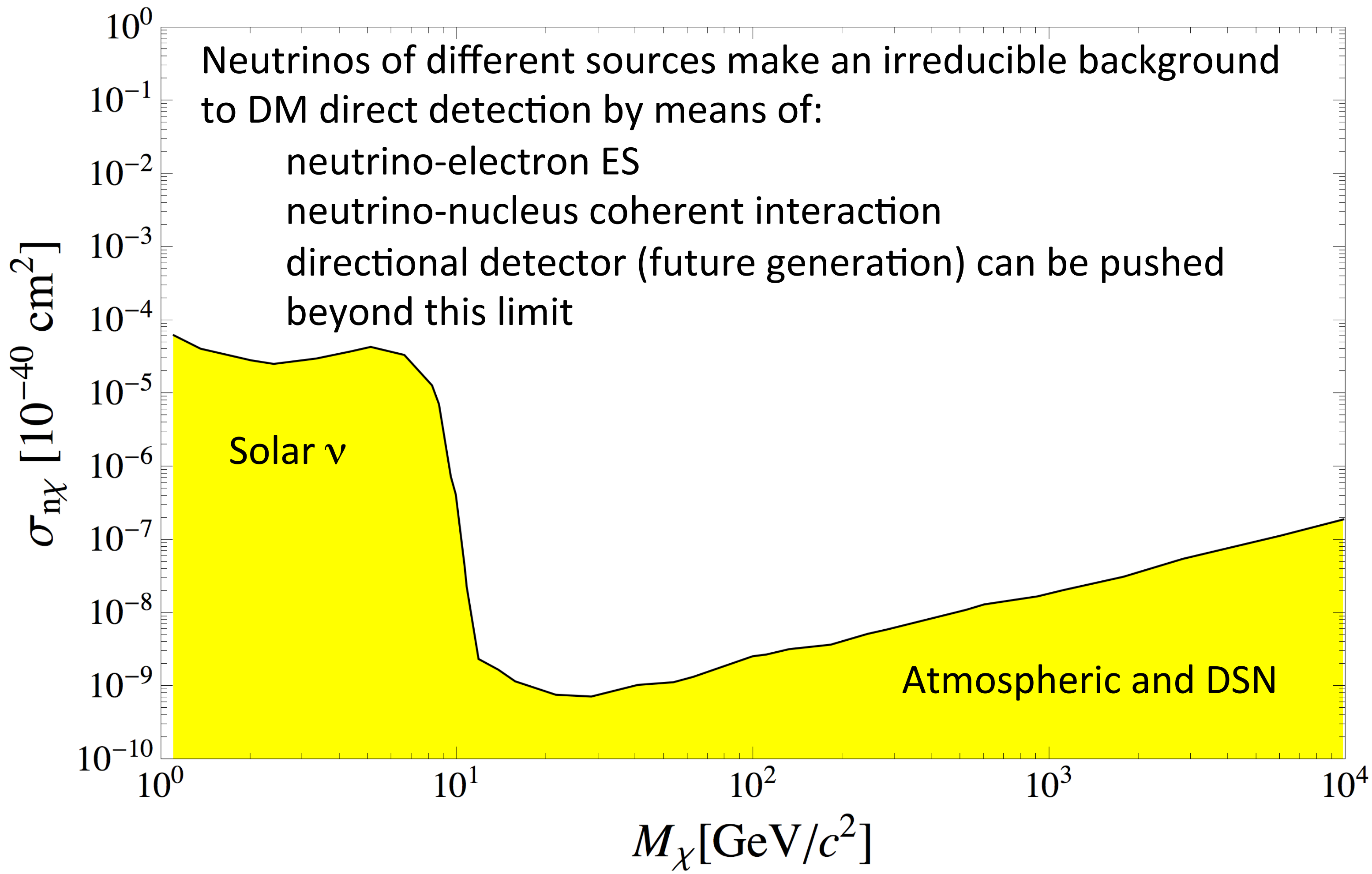
- **Signal**
  - Low energy nuclear recoils (1 – 100 keV)
  - Low rate (~ few counts/year/ton at 10^{-47} cm^2 and 100 GeV/c^2)
  - No specific features in recoils spectrum

- **Background**
  - Electron Recoils (**ER**) from e, γ radioactivity
    - ✓ can be rejected by a number of discrimination cuts
  - Nuclear Recoils (**NR**) from **radiogenic and cosmogenic neutrons**
  - **Solar/Atmospheric/Relic Supernova neutrinos**:
    - ✓ Elastic Scattering interactions will limit the sensitivity depending on the ER rejection power of the experiment
    - ✓ Neutrino-nucleus coherent interactions set the limiting sensitivity

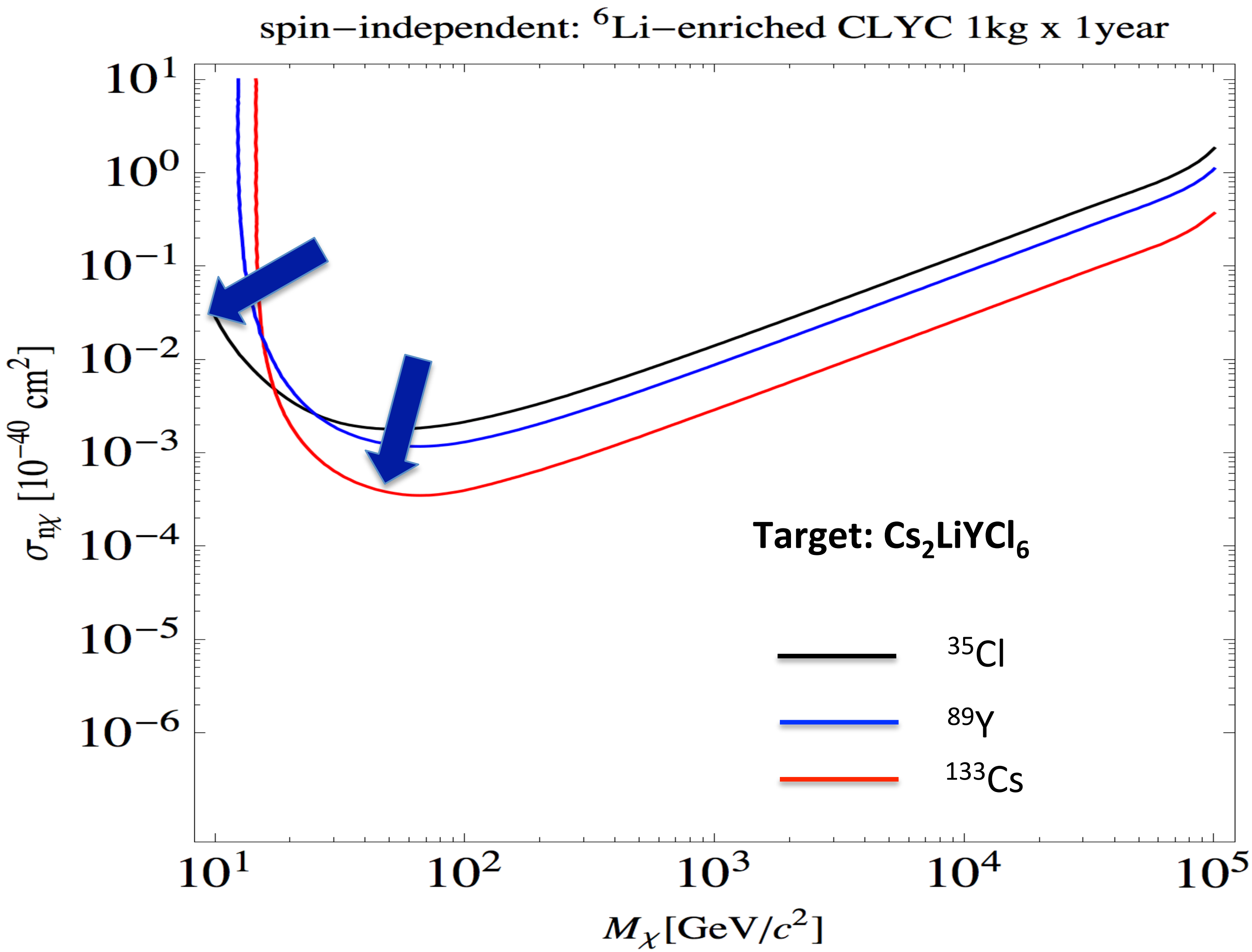
WIMPs Recoil Spectrum



"Neutrino floor" for DM

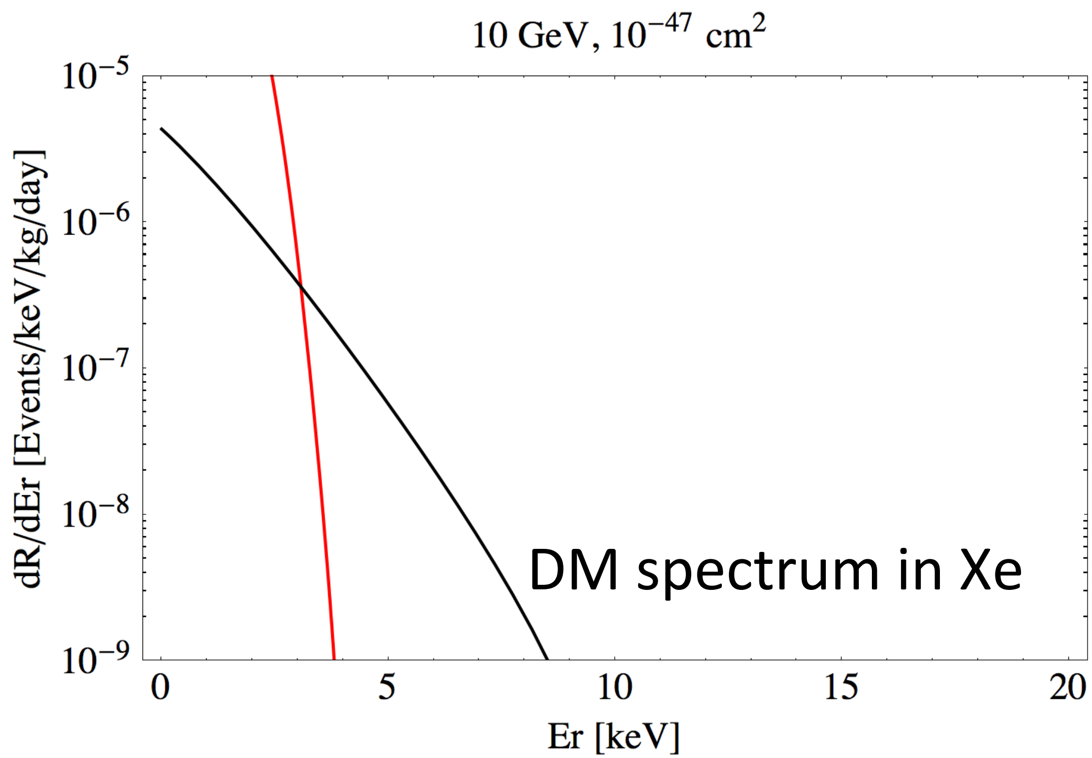


Exclusion plot: example

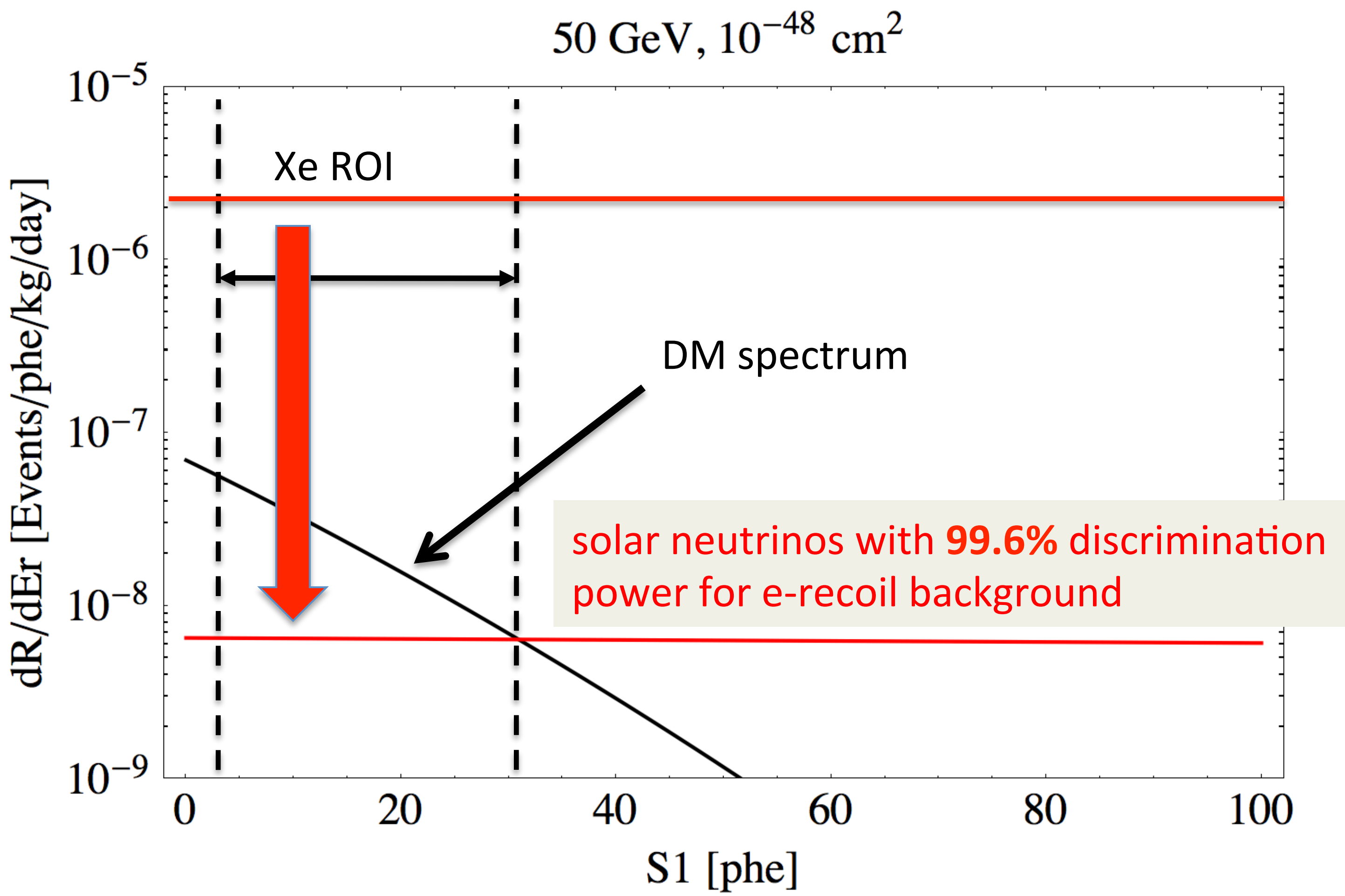


Solar Neutrinos Background in the NR channel

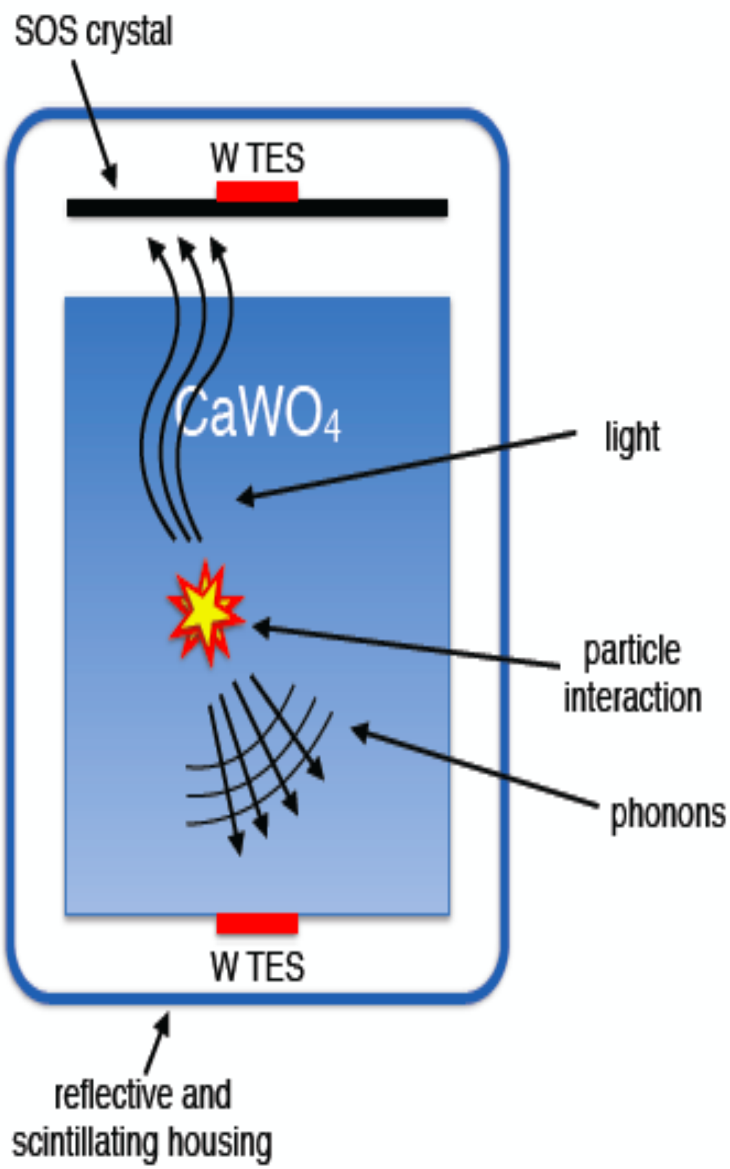
- ν-nucleus coherent scattering
  - Maximum recoil energy for ^8B neutrinos = 4.3 keV
  - Flux of ^8B ~ 6×10^6 $cm^{-2}s^{-1}$

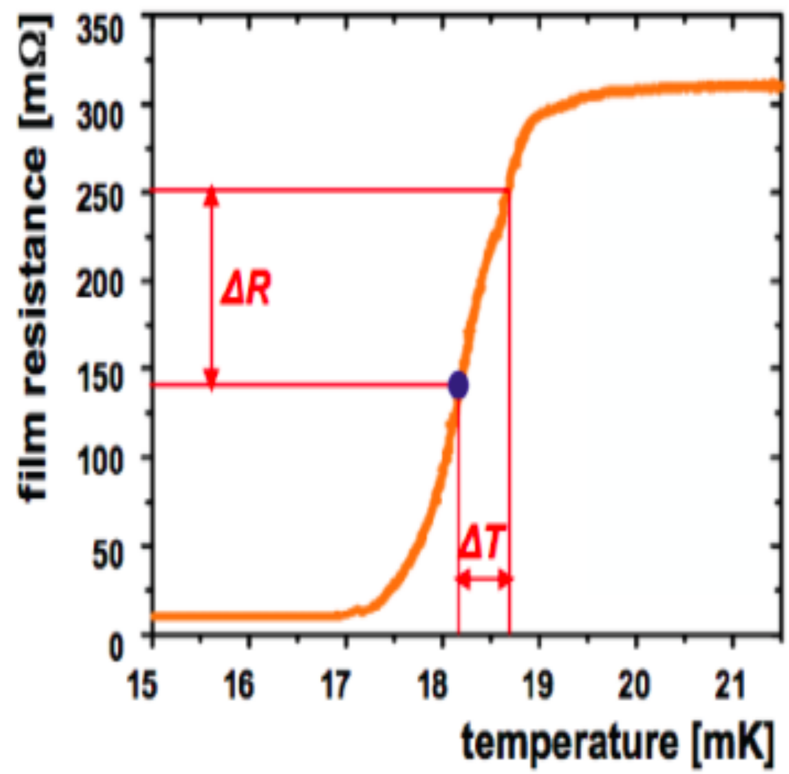


Solar Neutrinos as Background in ER channel

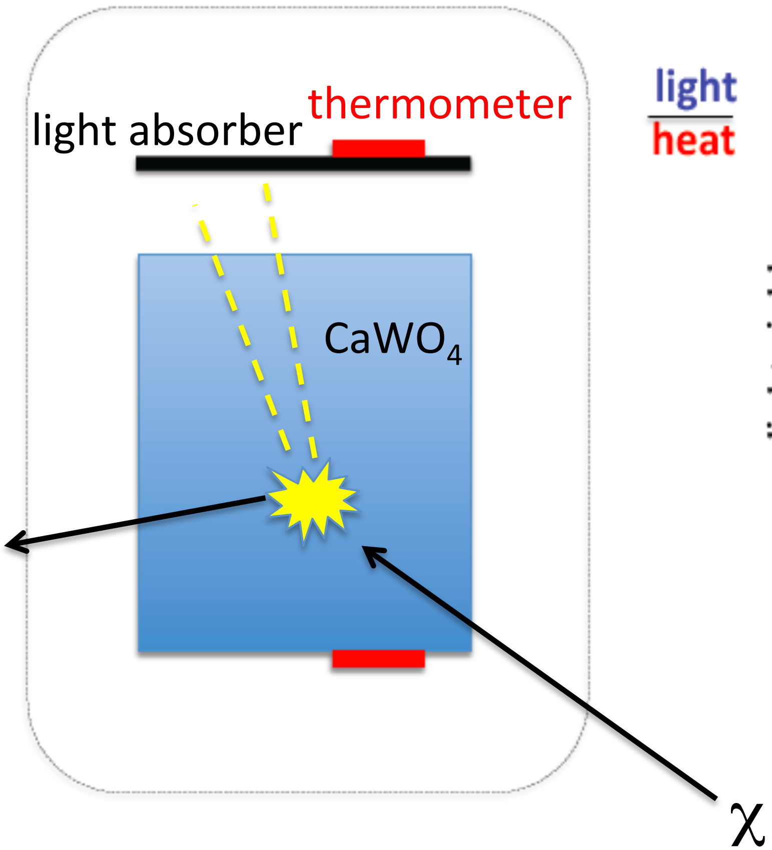


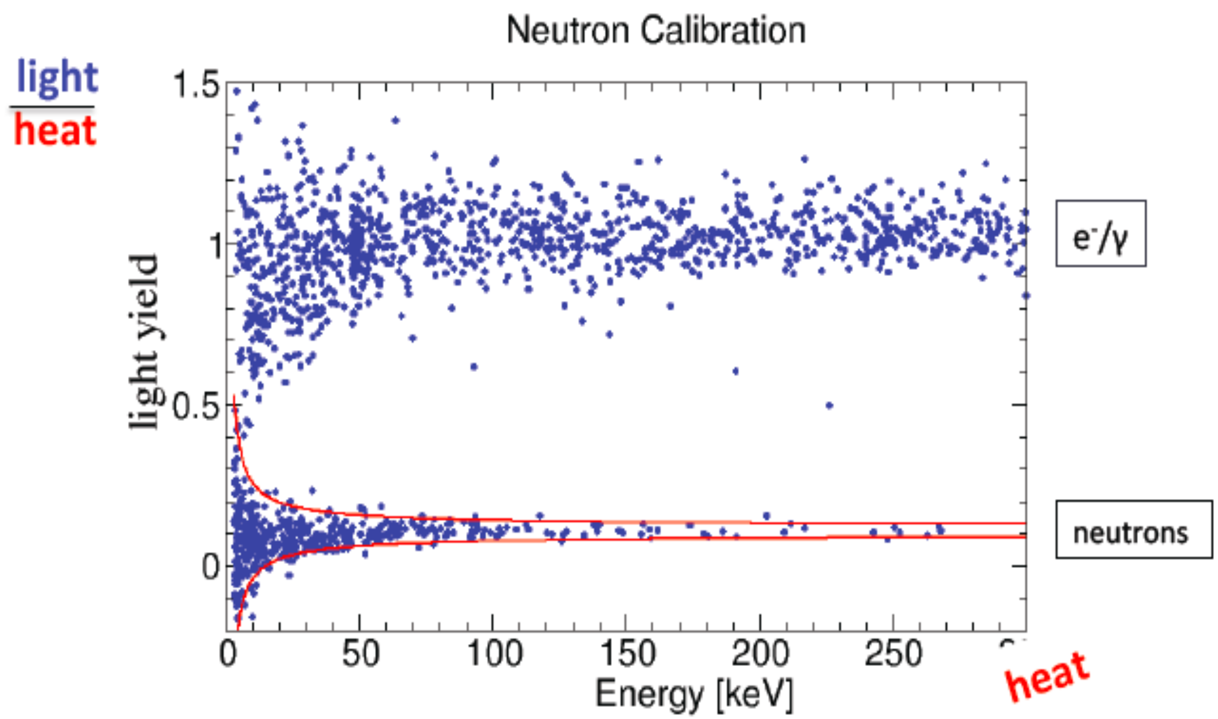
CRESST Detectors





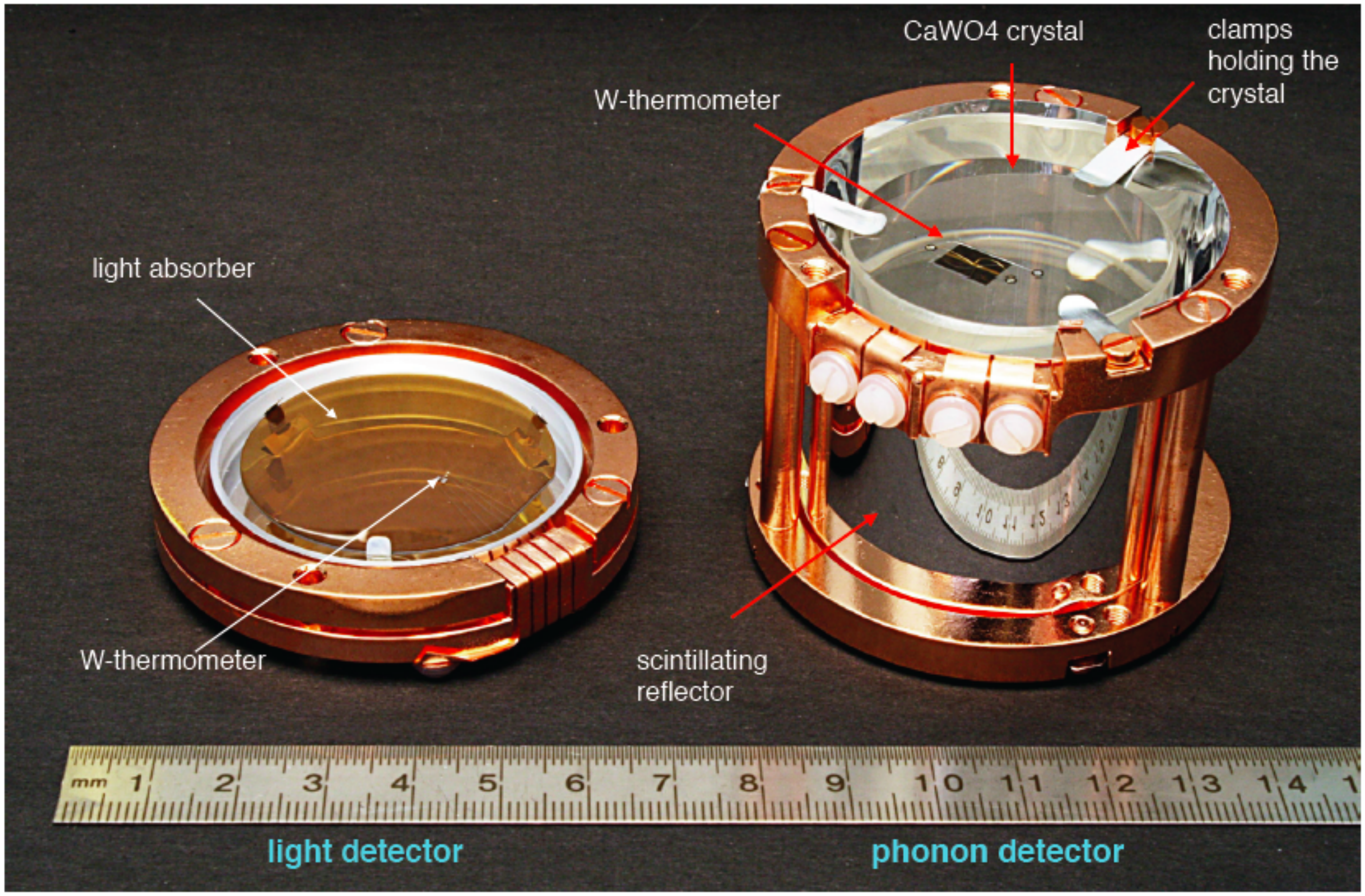
Background rejection: an example from CRESST





CRESST Crystal

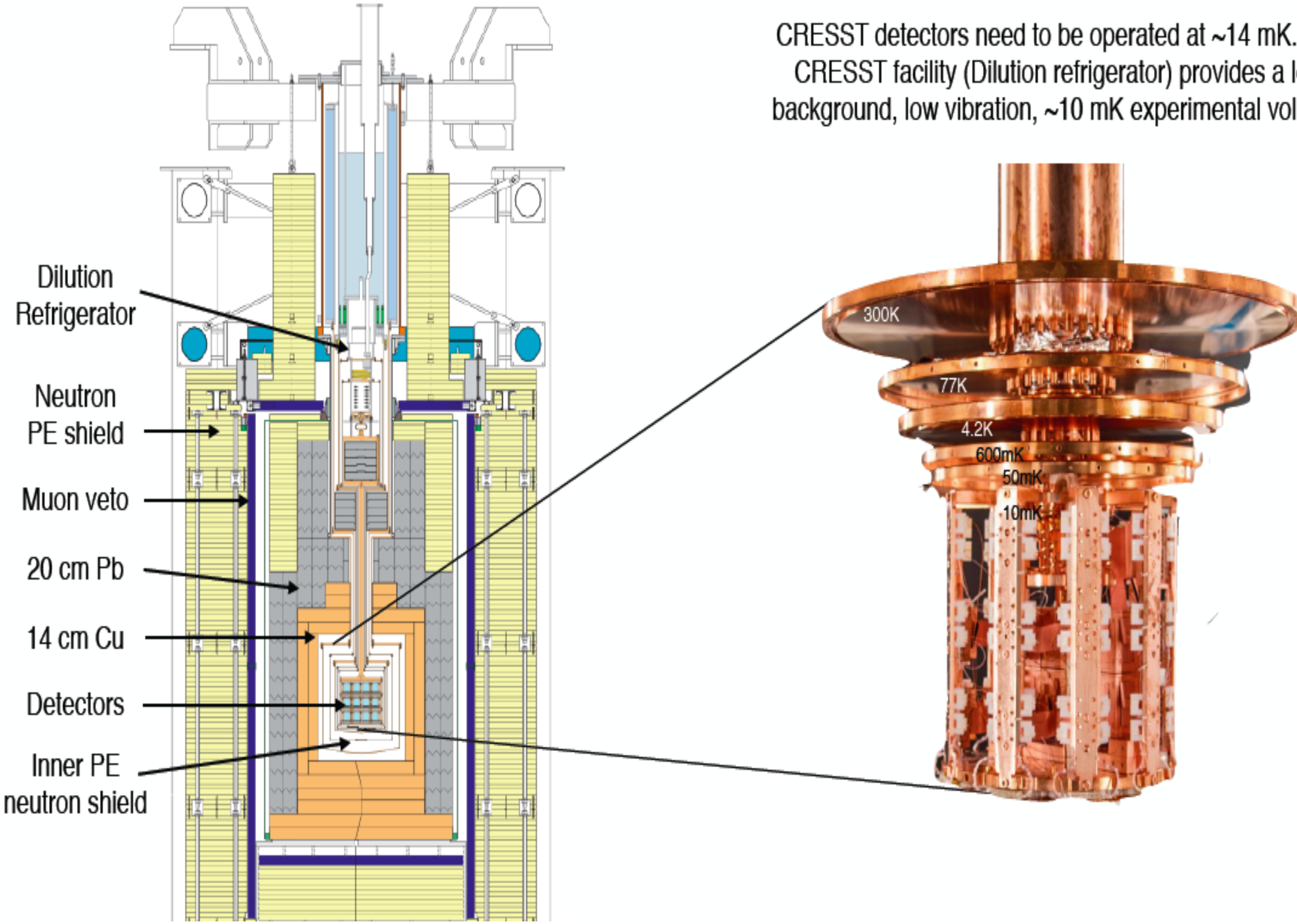
300 g Detector Module



The CRESST Experiment

Cryogenic Rare Event Search with Superconducting Thermometers

CRESST detectors need to be operated at ~14 mK. The CRESST facility (Dilution refrigerator) provides a low background, low vibration, ~10 mK experimental volume.



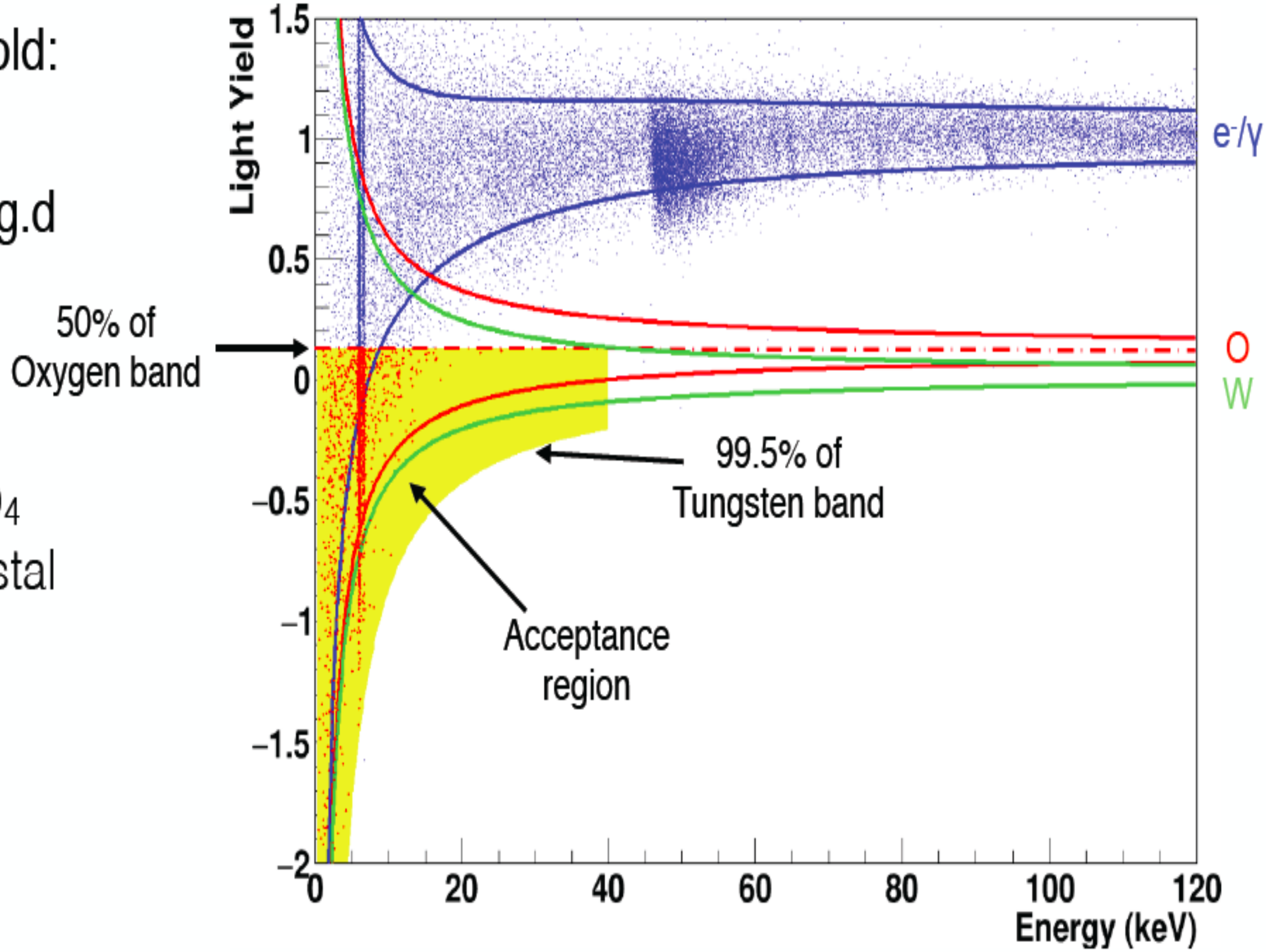
Results from CRESST-II Phase 2: the Lise module

Energy threshold:
307 eV

Exposure 52 kg.d

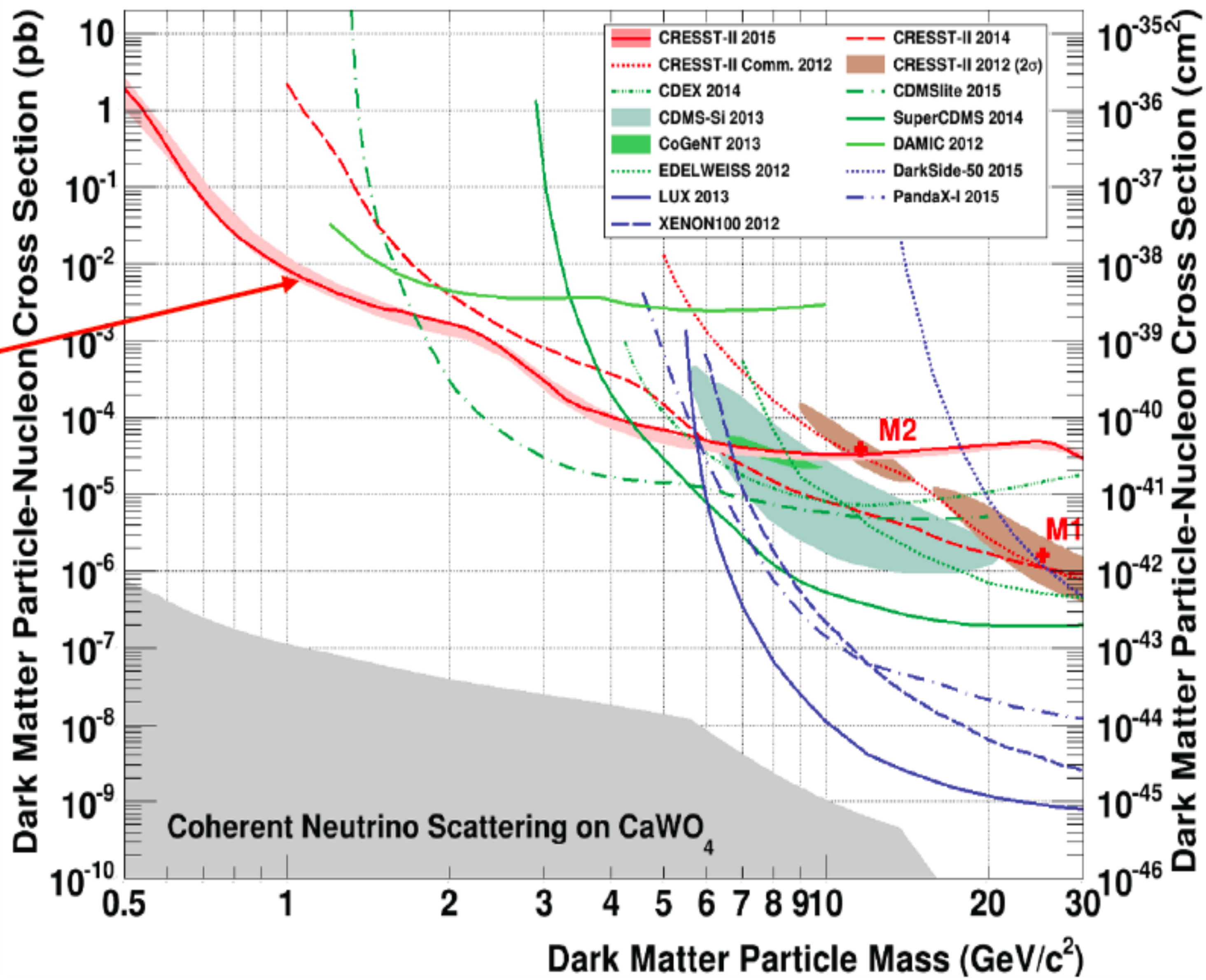
300 g $CaWO_4$
cylindrical crystal

Eur.Phys.J.
C76 (2016)25

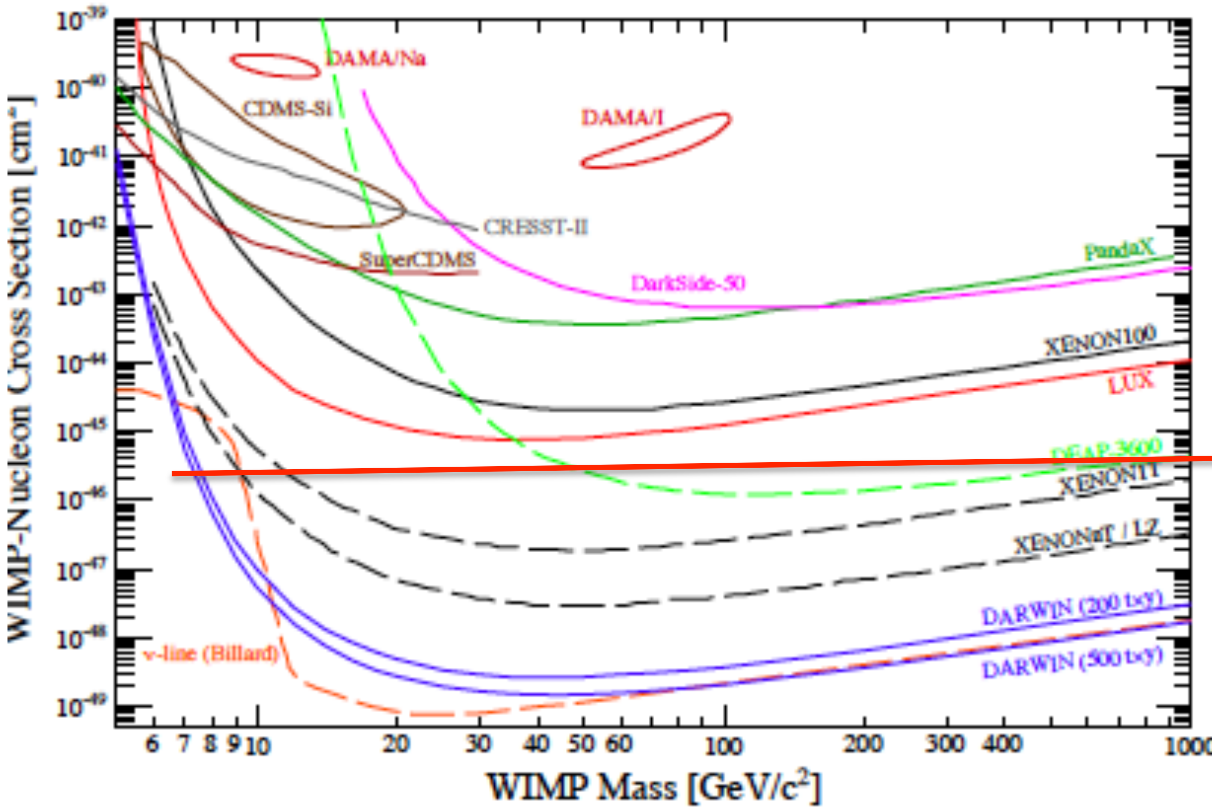


Results from CRESST-II Phase 2: the Lise module

CRESST-II
Phase 2
Eur.Phys.J.
C76 (2016) 25



Spin-independent WIMP-nucleon results and predictions



best limit at present

from LUX and PandaX

Plot by L. Baudis, Ann. Phys. (Berlin), 1-10 (2015)

Direct Dark Matter search with liquid Xe and Ar in a two-phase TPC

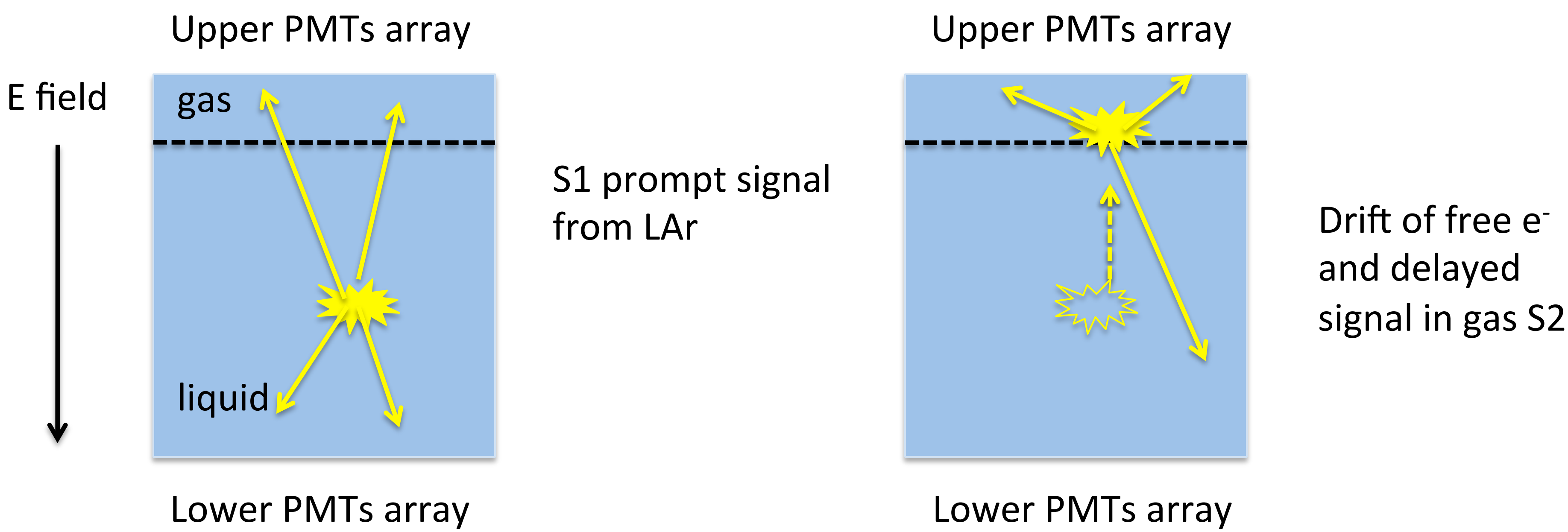
Features of LAr and LXe

- High scintillation yield (> 40000 photons/MeV)
- High intrinsic purity
- Unique capability to produce scintillation and drifting the ionization charge to > 1m length
- Possibility to extract the charge into gas phase and produce secondary scintillation or avalanche

Liquified noble gases as WIMPs target

	Ar	**Xe**
Atomic number	18	54
Mean atomic mass	40	131.3
Boiling point @ 1atm [K]	87.3	165.0
Density for liquid [g/cm^3]	1.40	2.94
Volume fraction in atmosphere [ppm]	9340	0.09
Scintillation λ [nm]	128	178
Scint. fast component [ns]	7	3
Scint. Slow component [ns]	1600	27

Two-phase TPC at Work: basic



S1 measures energy and time of event
S2 measures position of event in LAr and is proportional to the fraction of charge that escapes recombination (this fraction depends on the drift field)
S2/S1 = f(dE/dx) important for ER vs NR discrimination
Drift time allows to measure z-coordinate at < mm level
S2 allows to measure x-y coordinates at mm level

Scintillation and charge in LAr and LXe

- Energy deposited in LXe or LAr will excite some atoms and ionize others
- The excited atoms produce scintillation
- Stopping power, dE/dx, for NR is higher than for ER, the density of charge will be higher leading to quenching for ER
- The fraction of ionization vs excitation depends on the electric field applied
- The fraction of collected electron, which escapes recombination, is smaller for larger ionization density

Calibration of the NR scale

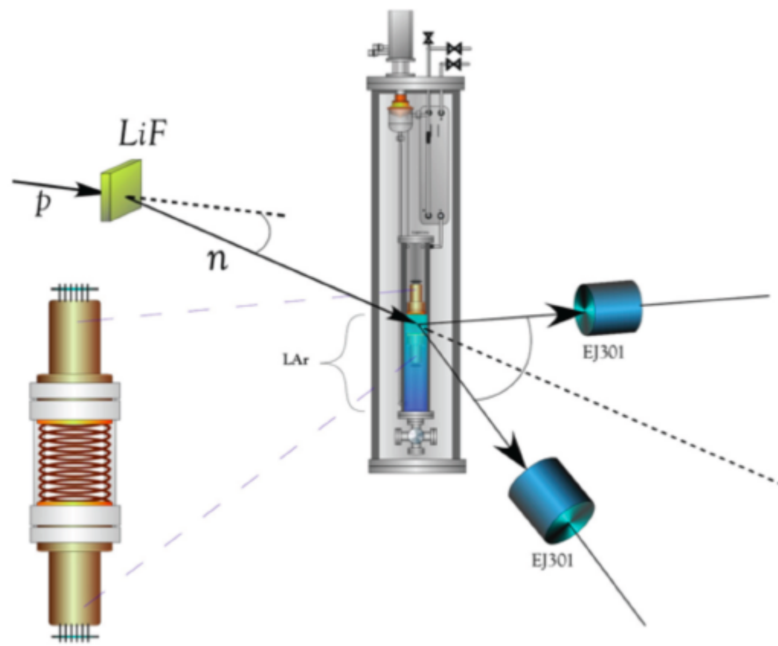
$$E_{ER} = w(n_\gamma + n_e)$$

$$E_{NR} = w(n_\gamma + n_e)\frac{1}{Q}$$ Q=quenching factor

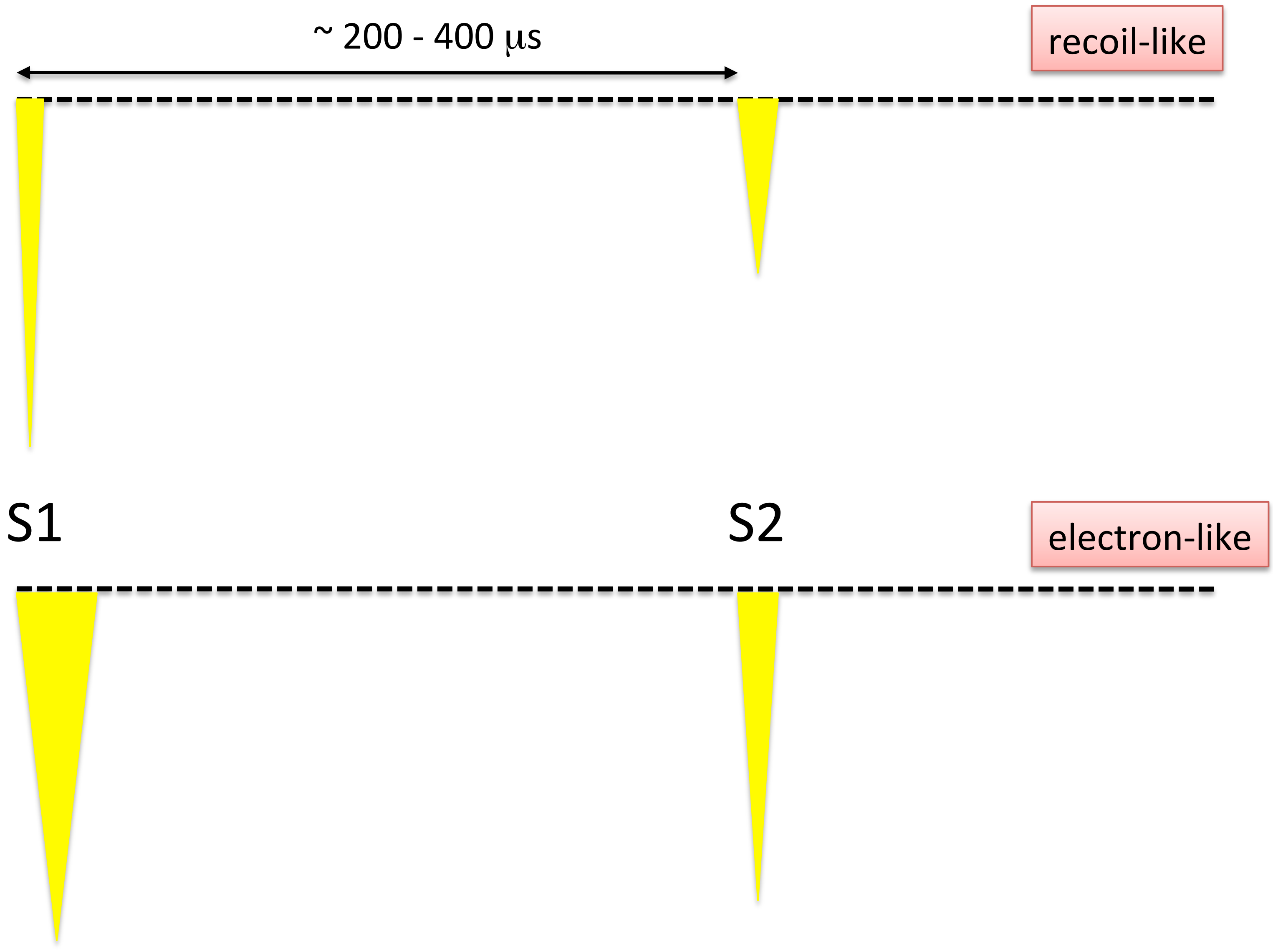
$w_{Xe} \sim 14\text{keV}$ $w_{Ar} \sim 24\text{keV}$

$$S_1(LAr) = L_Y \cdot E_{ER} = L_Y \cdot \boxed{Q(E_{NR})} \cdot E_{NR}$$

$$4E_{ER} \approx E_{NR}$$



LAr two-phase TPC at Work: signals

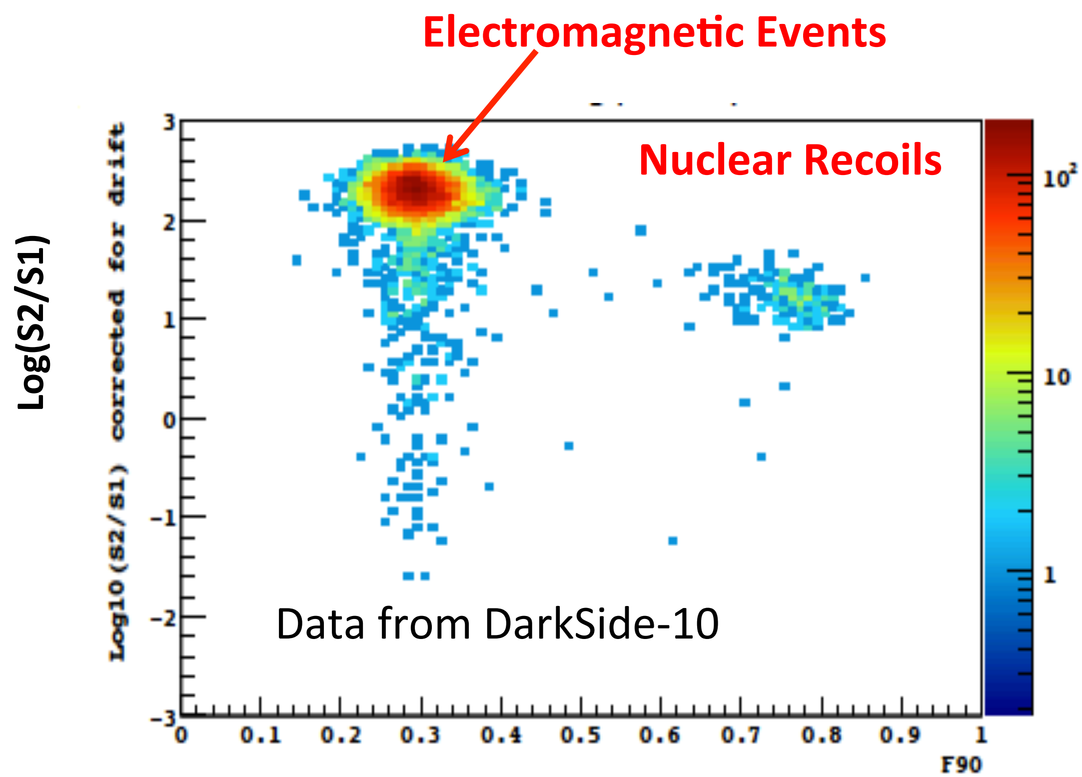


Two-phase TPC at Work: figure-of-merit for background discrimination

Background reduction performed by exploiting

a) Pulse shape of S1 through a parameter which measures the fraction of fast to slow component in scintillation.

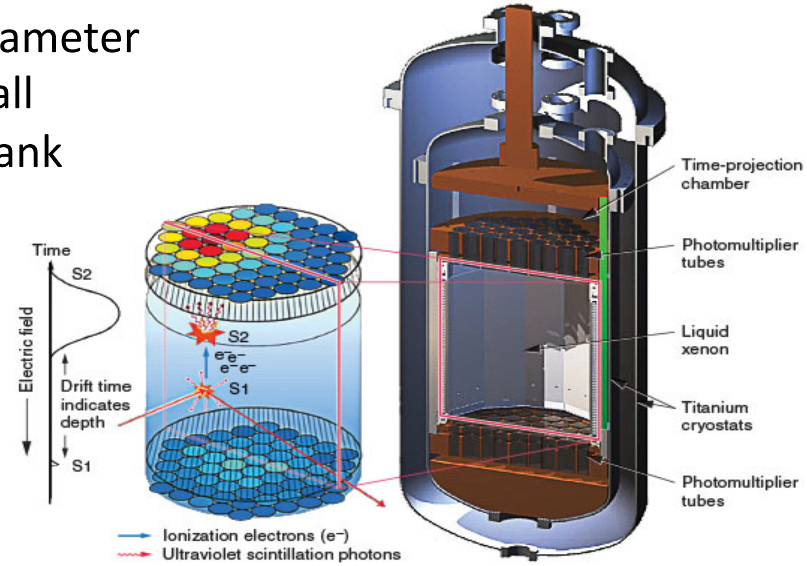
$$F_{90} = \frac{\int_0^{90ns} f_{S_1}(t)\,dt}{\int_0^{\infty} f_{S_1}(t)\,dt}$$

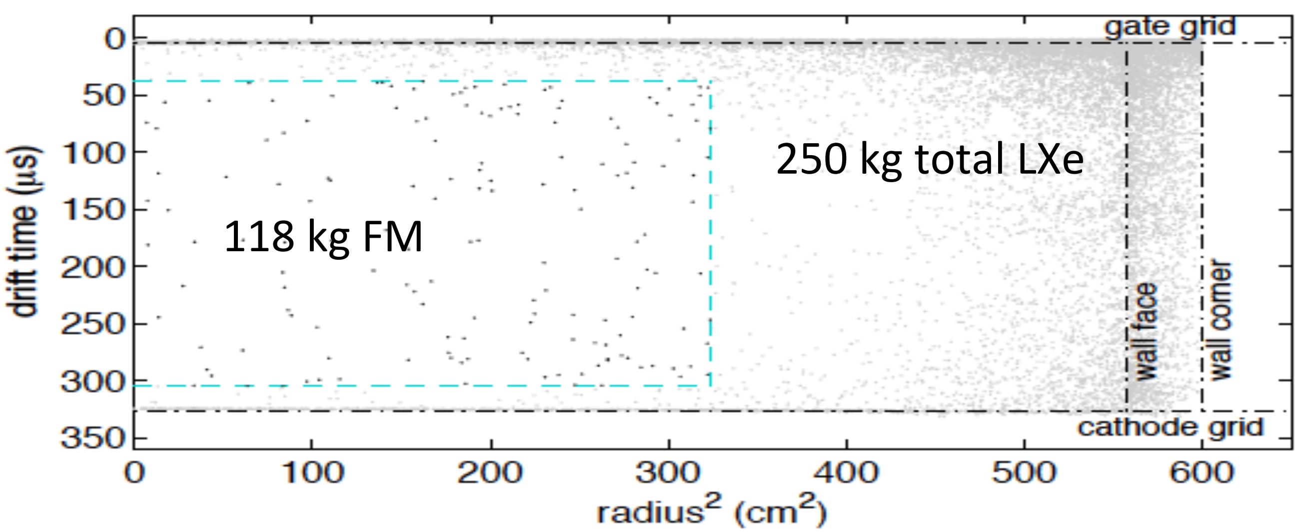


b) S2/S1: larger for e-like

Fiducial Volume Selection in LUX

7.6m diameter
6.1 m tall
water tank



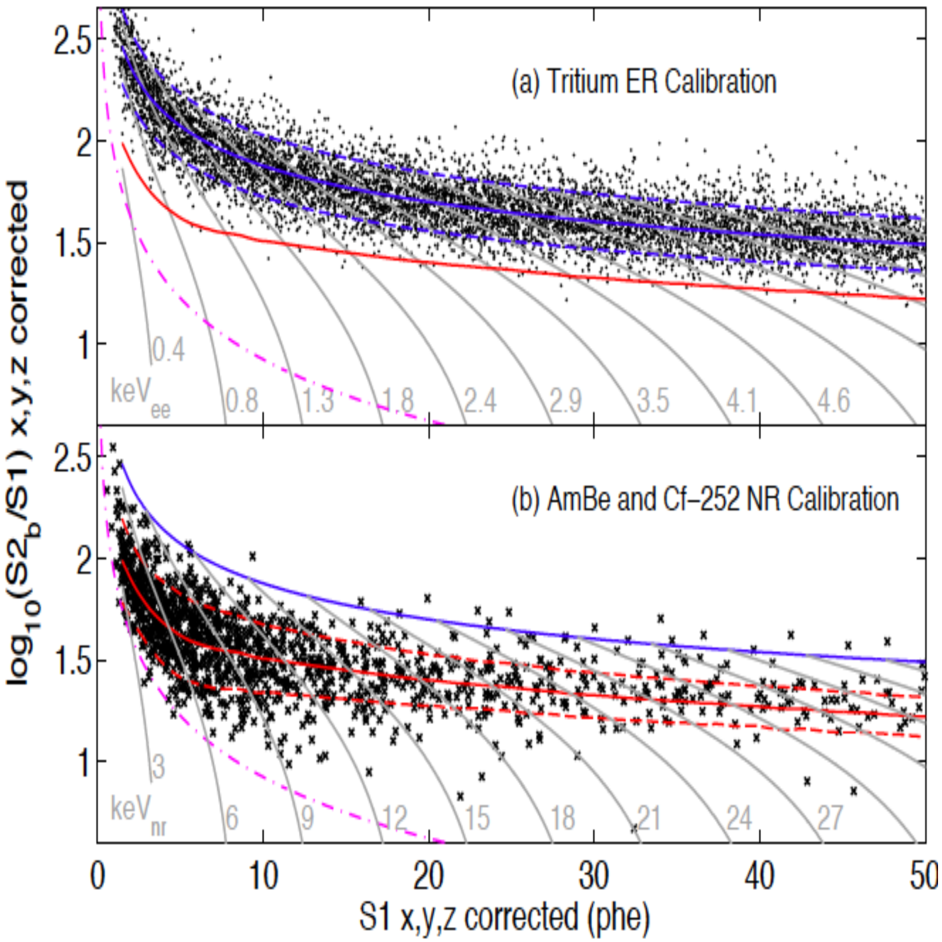


LUX coll., Rev. Lett. 112, 091303 (2014)

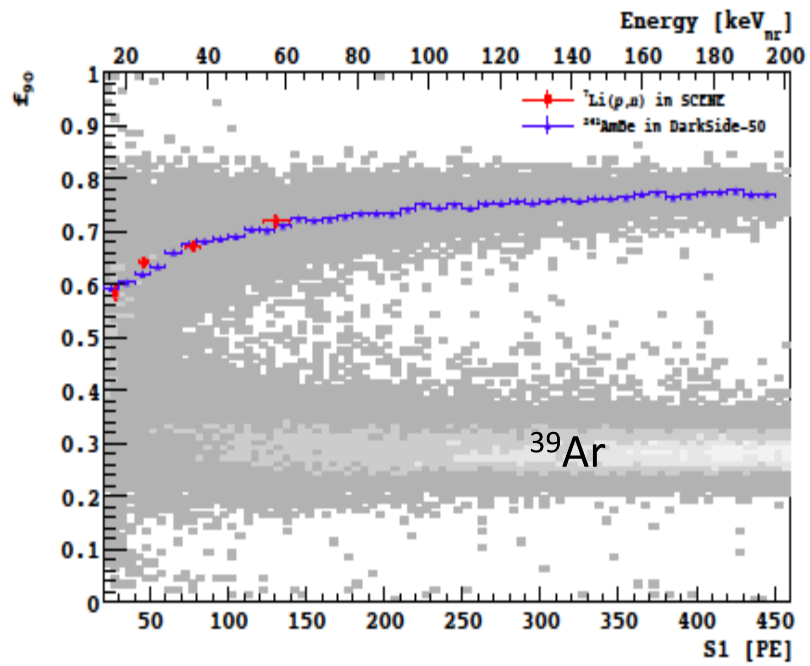
Calibrations for ER and NR response

- ^{83m}**Kr**: 1.8h half-life monoenergetic, injected and uniformly distributed in FM
  - 31.5keV + 9.4keV = 41.5keV line
- **CH_3T** (tritiated methane): injected and spatially uniform, Q_β = 18.6 keV
- **Deuterium-Deuterium neutron generator**: 2.45 MeV monoenergetic
- **AmBe** neutron source
  - $^{241}Am \rightarrow \alpha + ^{9}Be \rightarrow ^{12}C + n + 5.71MeV$
- **External gamma-ray sources**

Calibration of PSD parameters



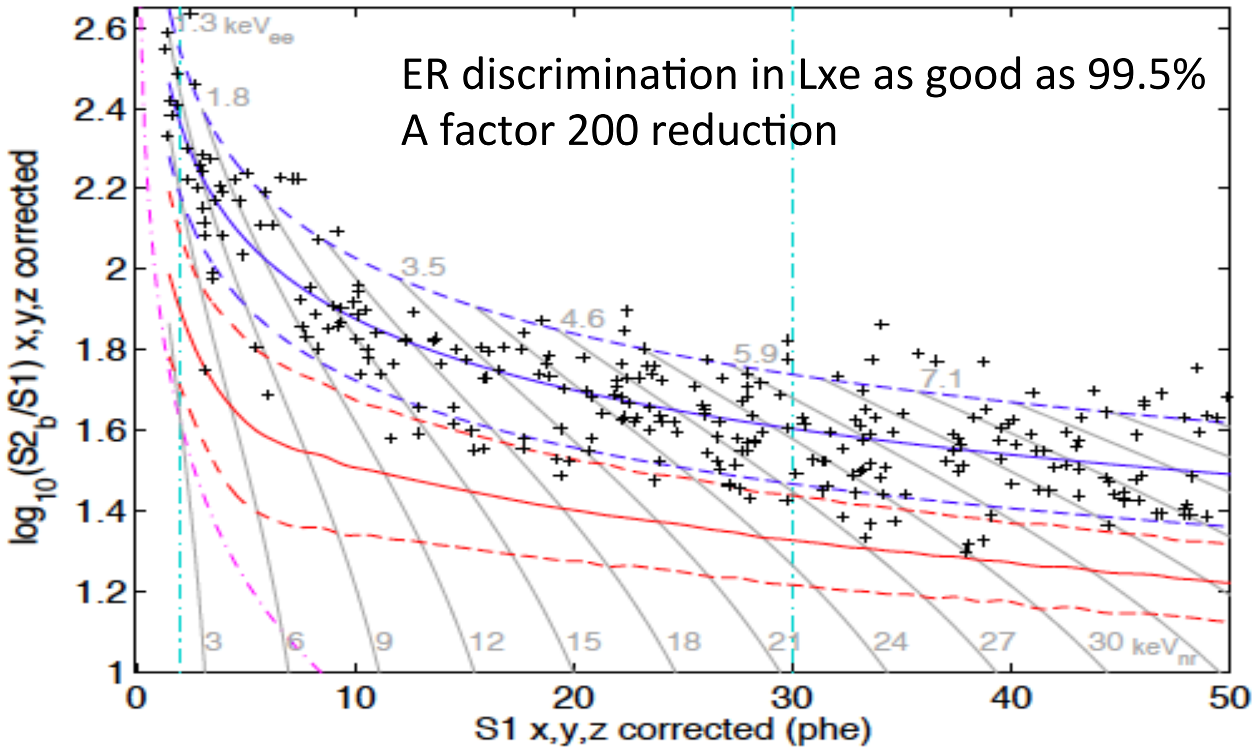
LUX coll., Rev. Lett. 112, 091303 (2014)



DS-50 coll., Phys. Rev. D 93, 081101 (2016)

LUX 2013 results

LUX data
85.3 live-days
118 kg
160 events in
[2,30]phe
0.64 ER leakage
with 50% NR
acceptance

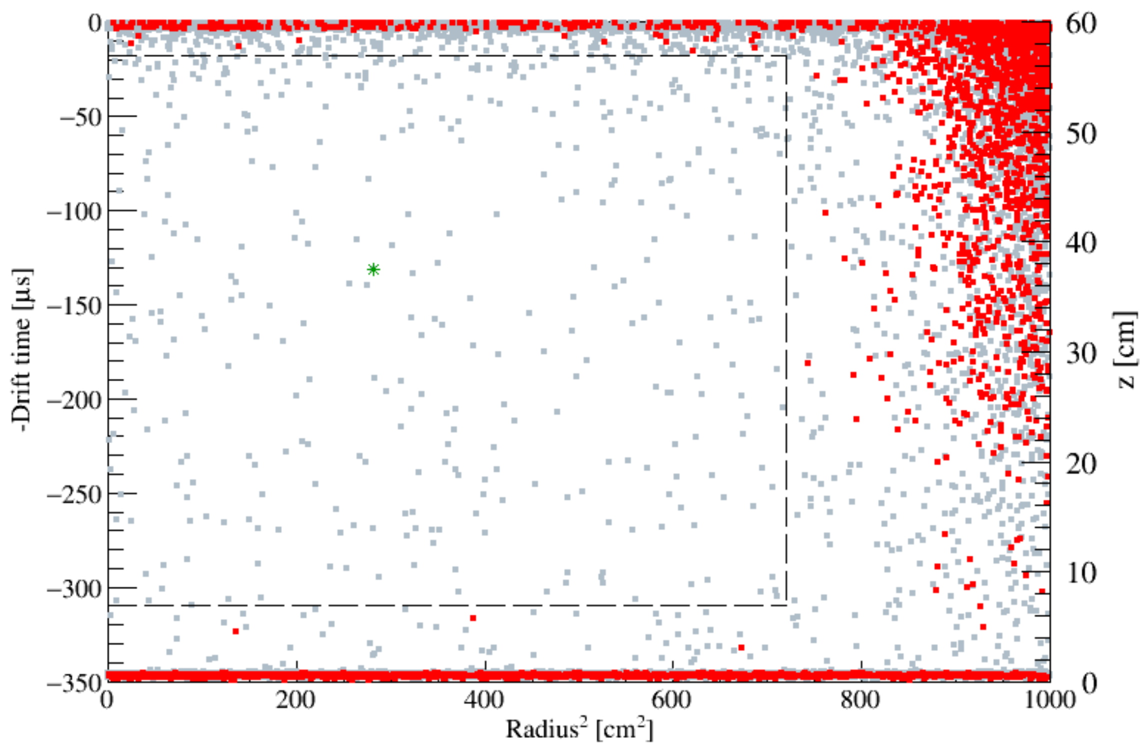


1DRU =
1 count/keV/kg/day

Source	Background rate [mDRU]
γ−rays	1.8±0.4
^{127}Xe	0.5±0.1
^{214}Pb	0.11-0.22 (90% C.L.)
^{85}Kr	0.13±0.07
Total predicted	2.6±0.4
Total observed	3.6±0.3

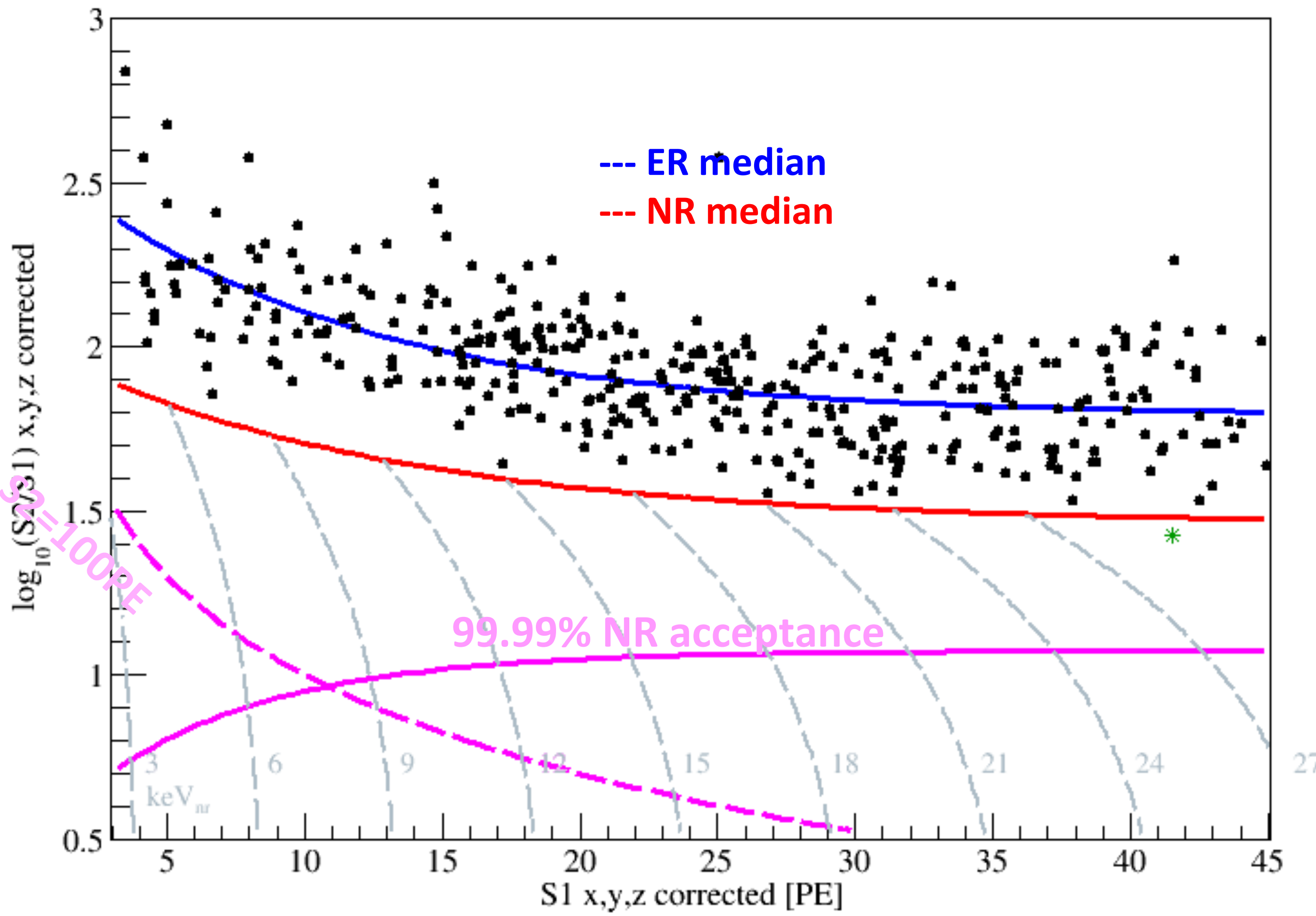
PandaX-II Run-9 final candidates

Gray: all
Red: below NR median
Green: below NR median and in FV

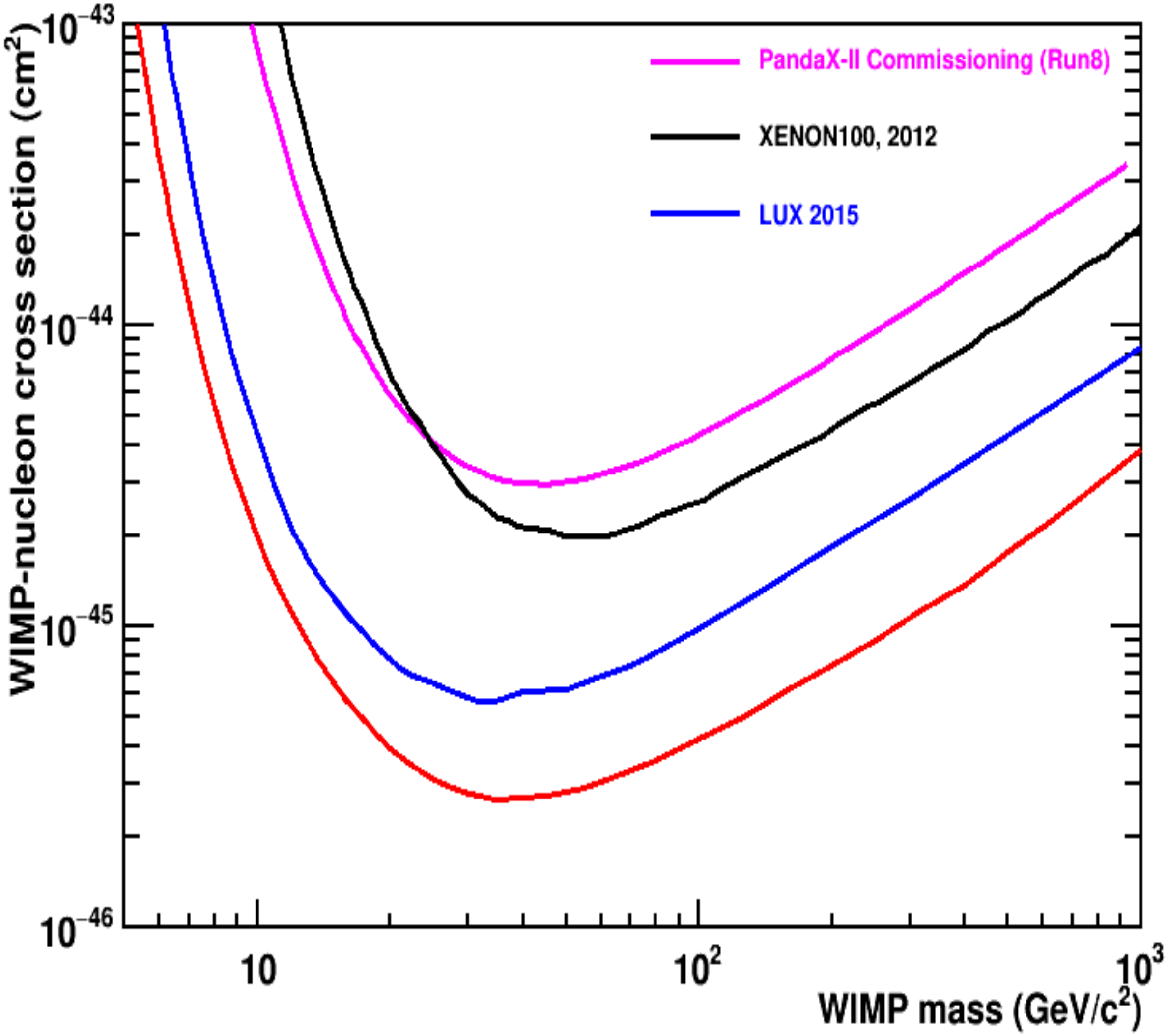


- 380 total candidates found in the FV
- **1** below NR median
- Outside FV, edge events more likely to lose electrons, leading to S2 suppression

PandaX-II Run-9 Final candidates

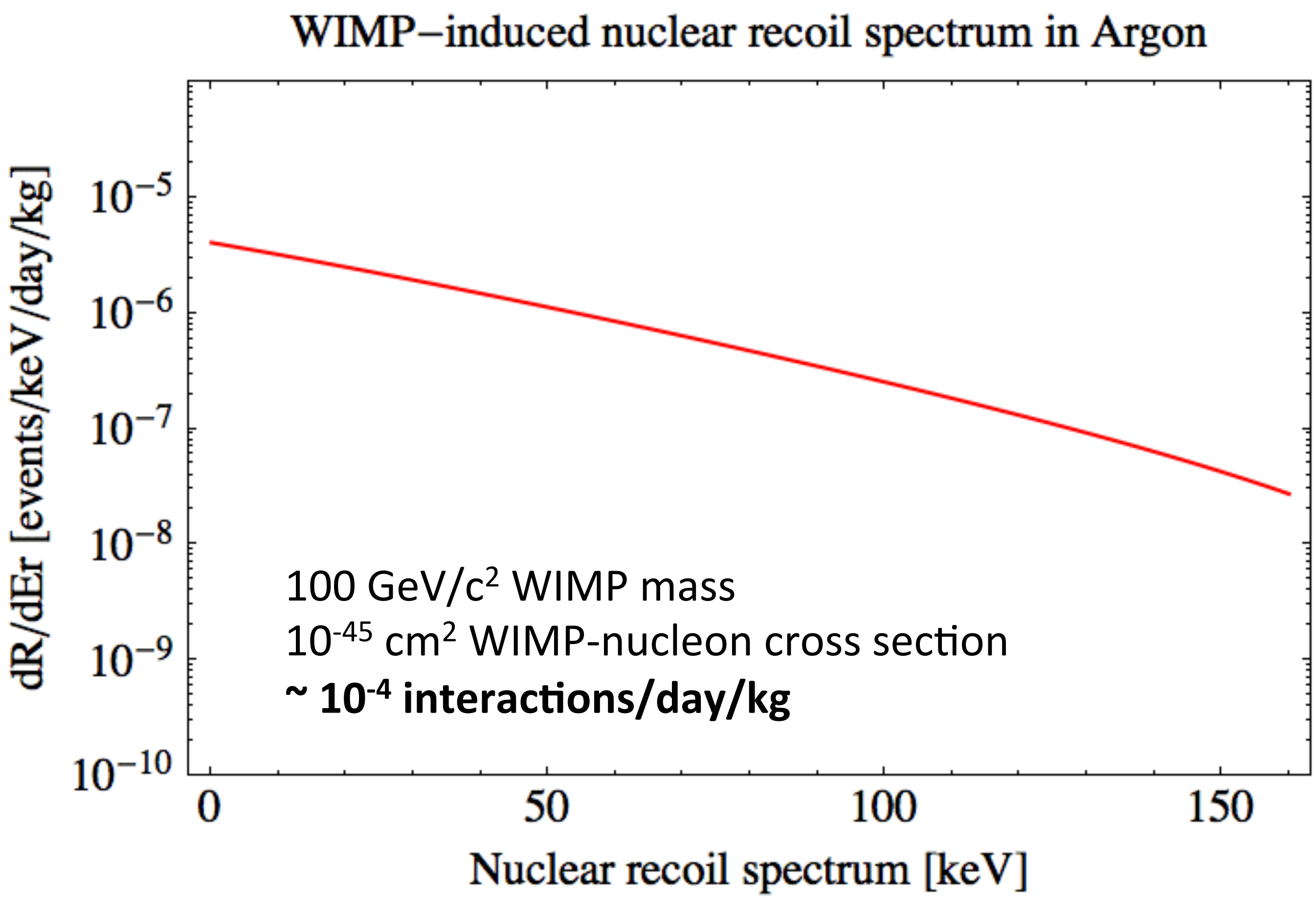


PandaX-II preliminary results



Minimum upper limit for isoscalar SI elastic cross section at 2.7×10^{-46} cm^2, more than a factor of 2 improvement compared to the LUX 2015 results

Expected WIMPs Signal in LAr



Exposure of 1 ton-year gives about 40 events with these assumptions

Laboratorio Subterráneo de Canfranc

The problem of ^{39}Ar

- ✓ Ar naturally present in the atmosphere at 1% level
- ✓ ^{39}Ar formed by cosmic muons interactions
  - $^{40}K(n,2n)^{39}Ar$
- ✓ ^{39}Ar is a β emitter with Q_{β}=565 keV and $T_{1/2}$=269 years
- ✓ In Ar from the atmosphere, ^{39}Ar is at the level of 1 Bq/kg
  - **~ 9×10^4 decays/kg/day**
  - WIMPs(100GeV, 10^{-45} cm^2) ~ **10^{-4} events/kg/day**

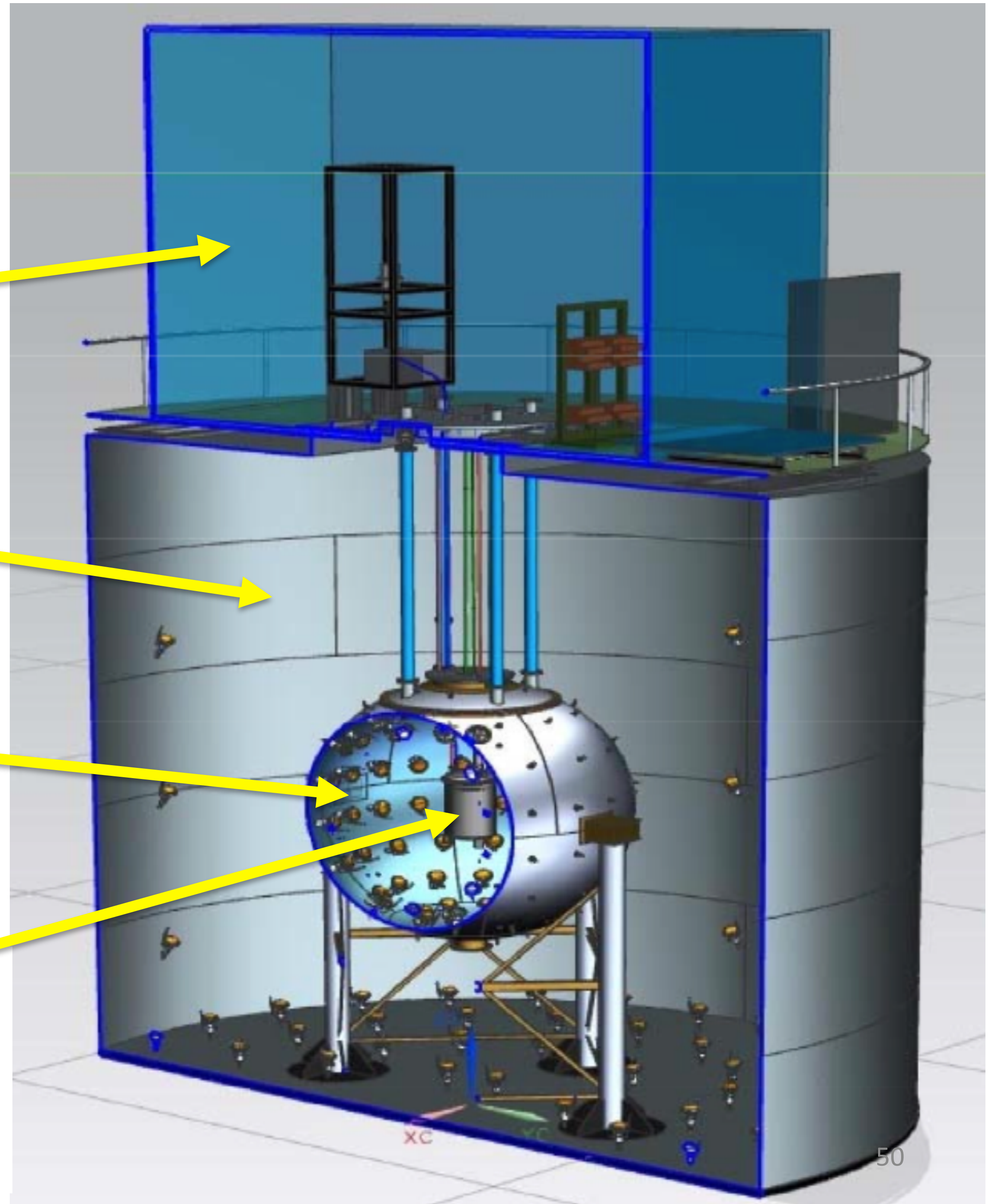
DS-50 @ LNGS

Rn-free clean room
(1-10 mBq/m^3 in 110 m^3)
Used for assembling TPC
and deployment

Water Cherenkov muon veto:
10^3 m^3 H_2O with 76/80 8” PMTs

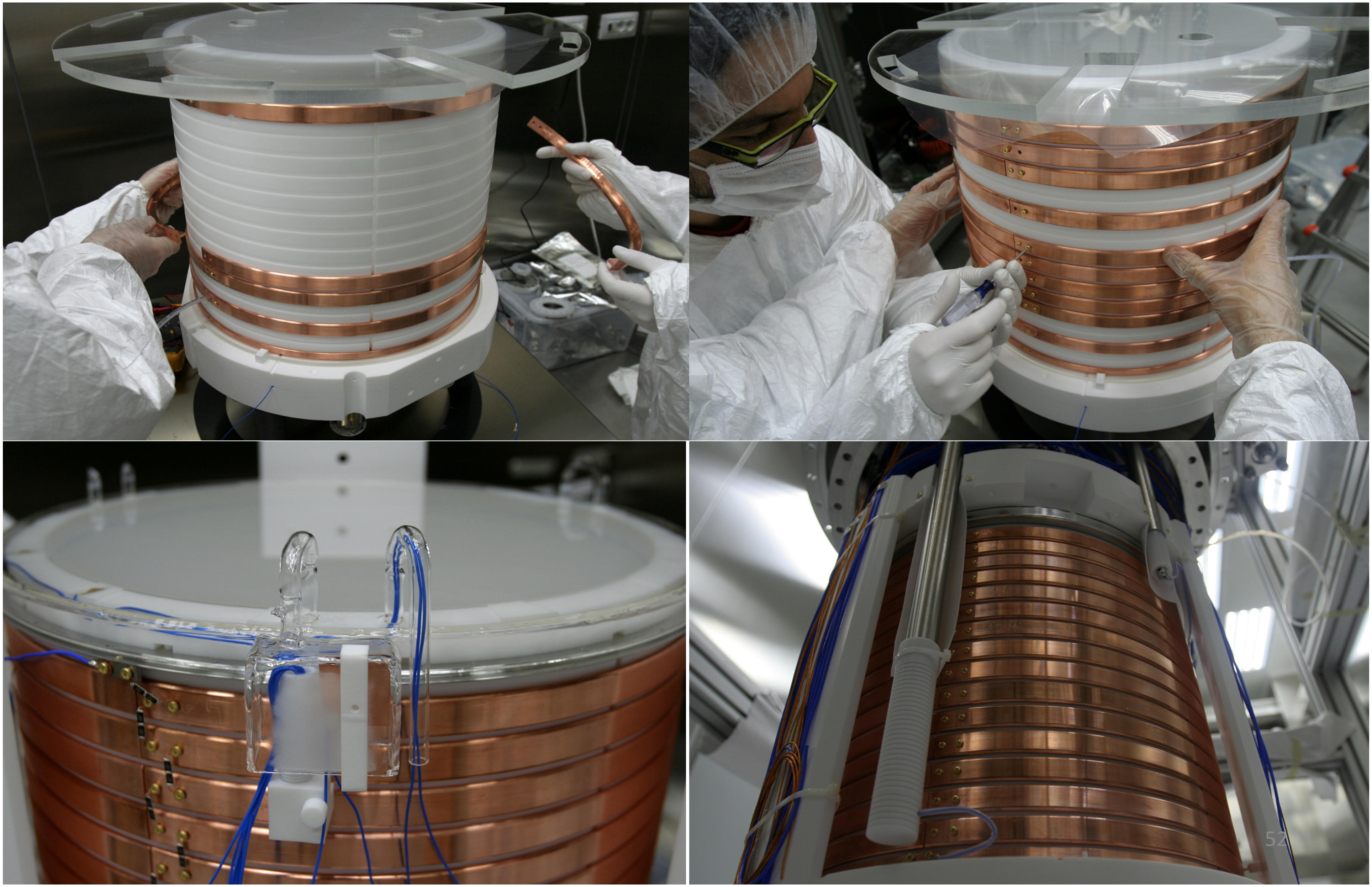
Boron-loaded liquid scintillator
(5% TMB + 95% PC) as
neutron veto with 108/110 8”
PMTs + 1.4 g/l PPO

150kg LAr TPC with 2 x 19
3” PMTs
AAr with 1Bq/kg ^{39}Ar
UAr with < 0.7 mBq/kg ^{39}Ar




Water Cherenkov

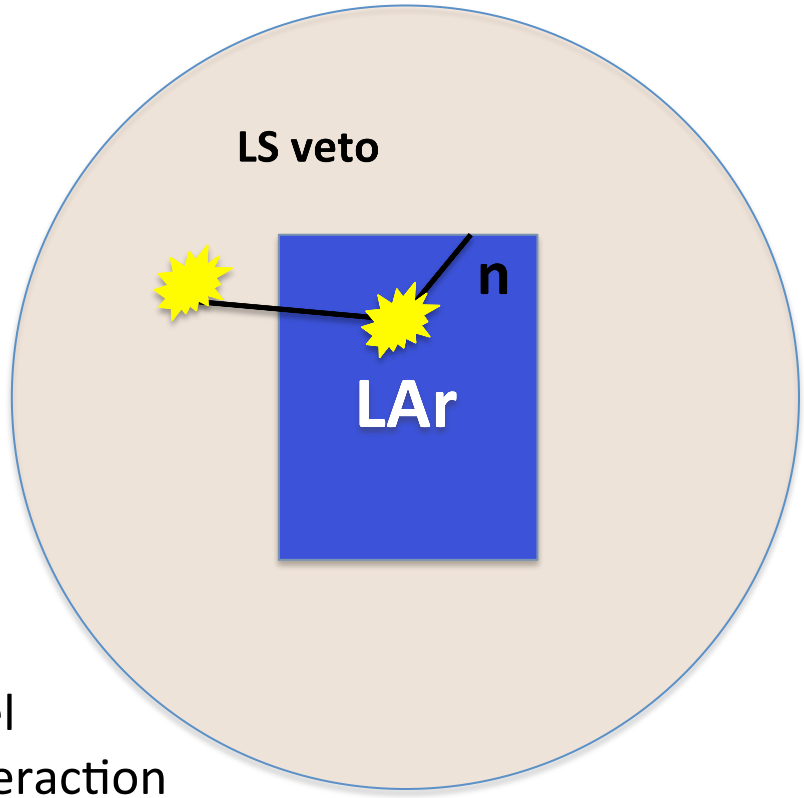
DS-50 TPC



TPC hanging in LSV

Total inventory of the devices
110 new PMTs for the neutron veto
80 old PMT from CTF for the muon veto
plus a few spares

The Neutron Veto: general idea



A radiogenic neutron
from the cryostat steel
or PMTs makes an interaction
in LAr (WIMP-like) and later
is captured in the LS veto.
This type of event is rejected.

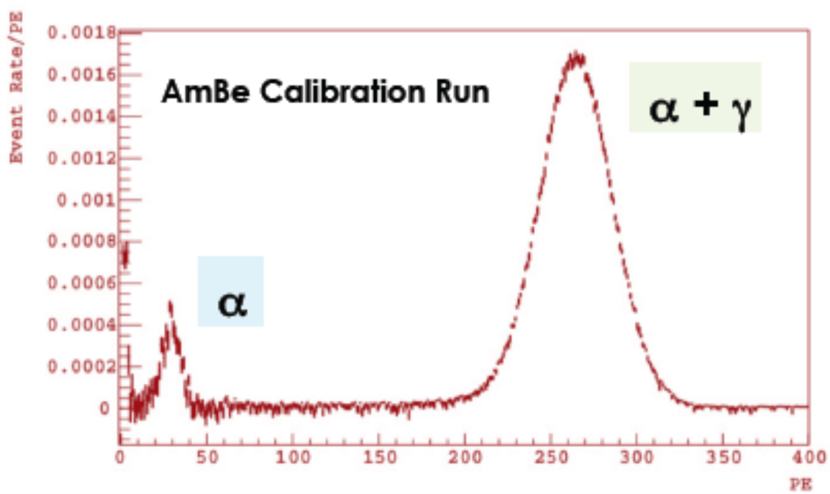
The Neutron Veto in DarkSide50

$n + {}^{10}B \rightarrow {}^{7}Li\ (1015\ keV) + \alpha\ (1775\ keV)$ (6.4%)

$n + {}^{10}B \rightarrow {}^{7}Li^{*}\ (839\ keV) + \alpha\ (1471\ keV)$ (93.7%)

$\downarrow$

${}^{7}Li + \gamma\ (478\ keV)$



Neutron Veto Efficiency

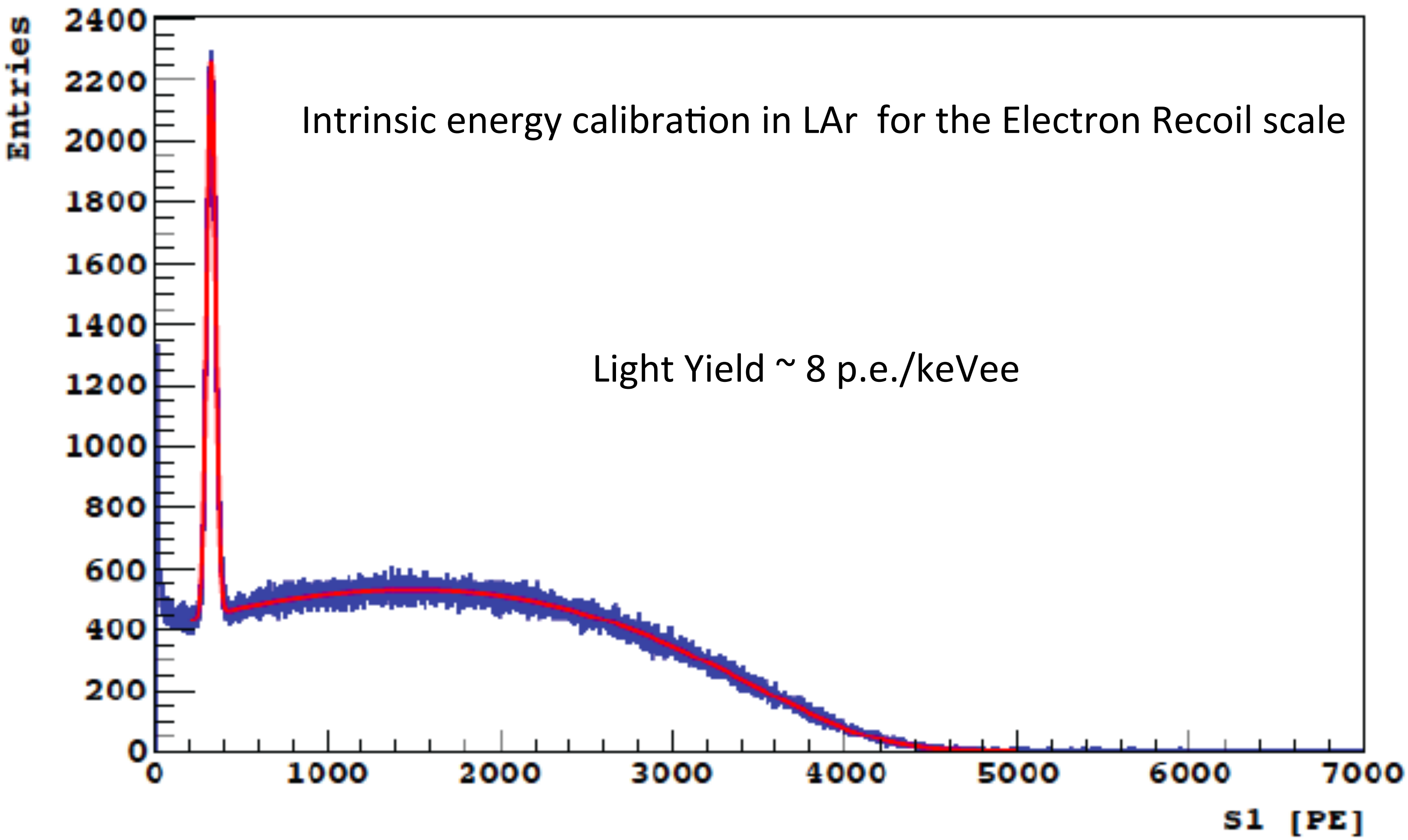
Efficiency from capture signal alone at > 99%
(from calibrations and simulations)

- ~0.6% of lost neutrons because of escaping proton capture gamma
- ~0.05% of neutrons leave no signal in LSV at all

Larger total efficiency due to thermalization signal

Cut at 1 PE threshold: ~0.9% acceptance loss

^{39}Ar + ^{83m}Kr energy calibration in DarkSide-50



Pulse Shape Discrimination in LAr

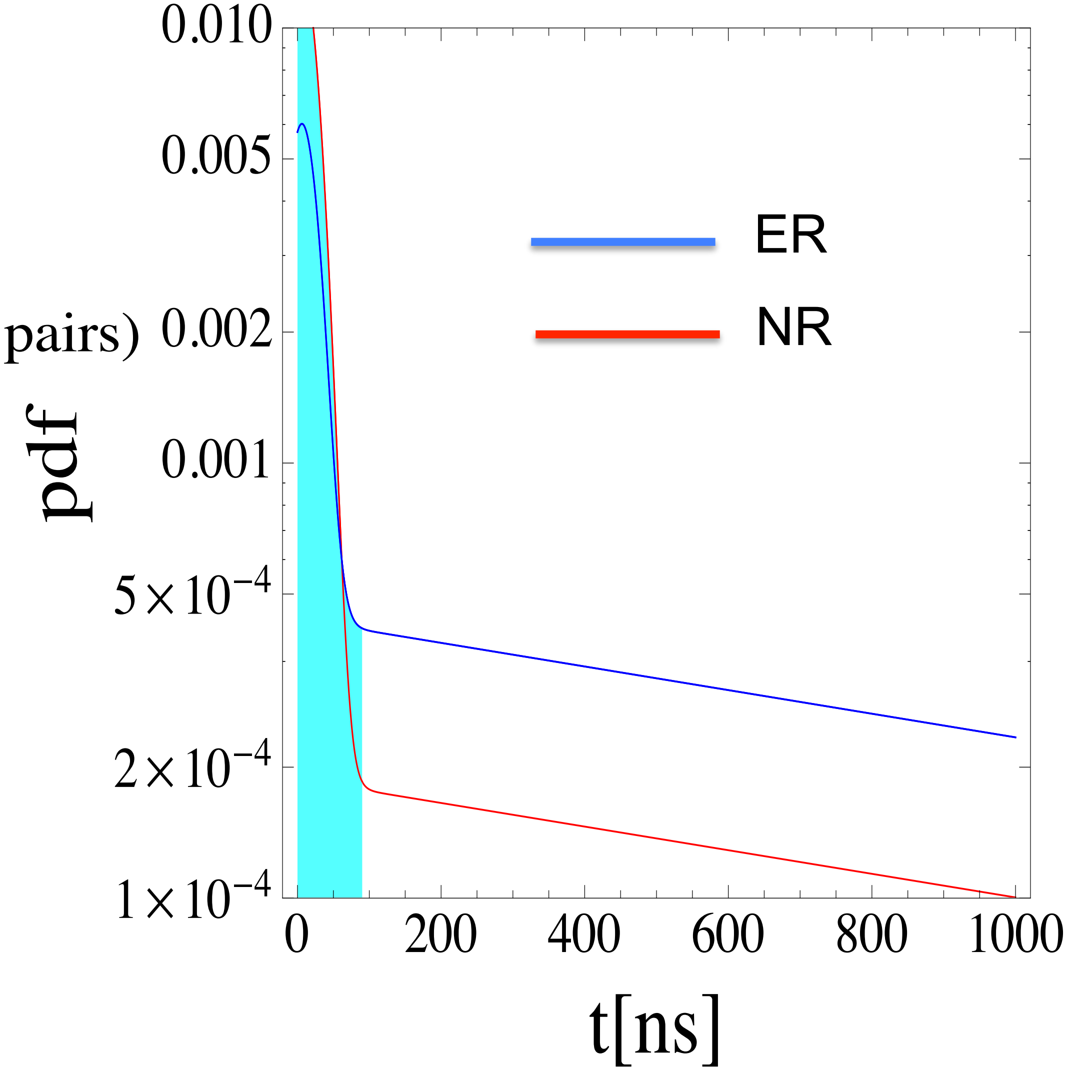
$$f(t) = \left(\frac{q}{\tau_F} e^{-t/\tau_F} + \frac{1-q}{\tau_S} e^{-t/\tau_S} \right)$$

$$\tau_F = 6ns$$

$$\tau_S = 1600ns$$

$$q = \begin{cases} 0.3 \text{ ER (low density e-ion pairs)} \\ 0.7 \text{ NR} \end{cases}$$

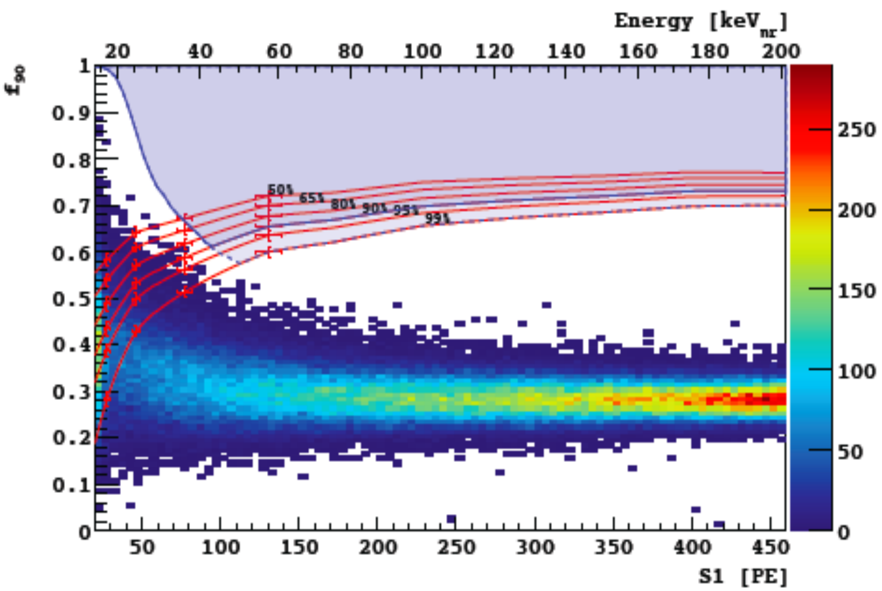
$$F_{90} = \frac{\int_0^{90ns} dt\, f(t)}{\int_0^{\infty} dt\, f(t)} = \begin{cases} 0.3 \text{ ER} \\ 0.7 \text{ NR} \end{cases}$$



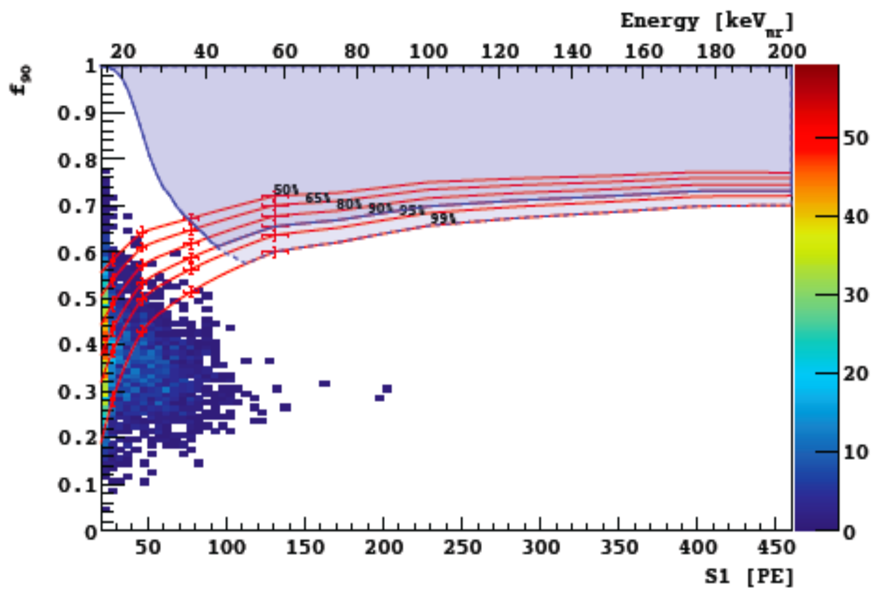
DarkSide-50 results

150 kg of LAr in cryostat with a 50 kg two-phase TPC

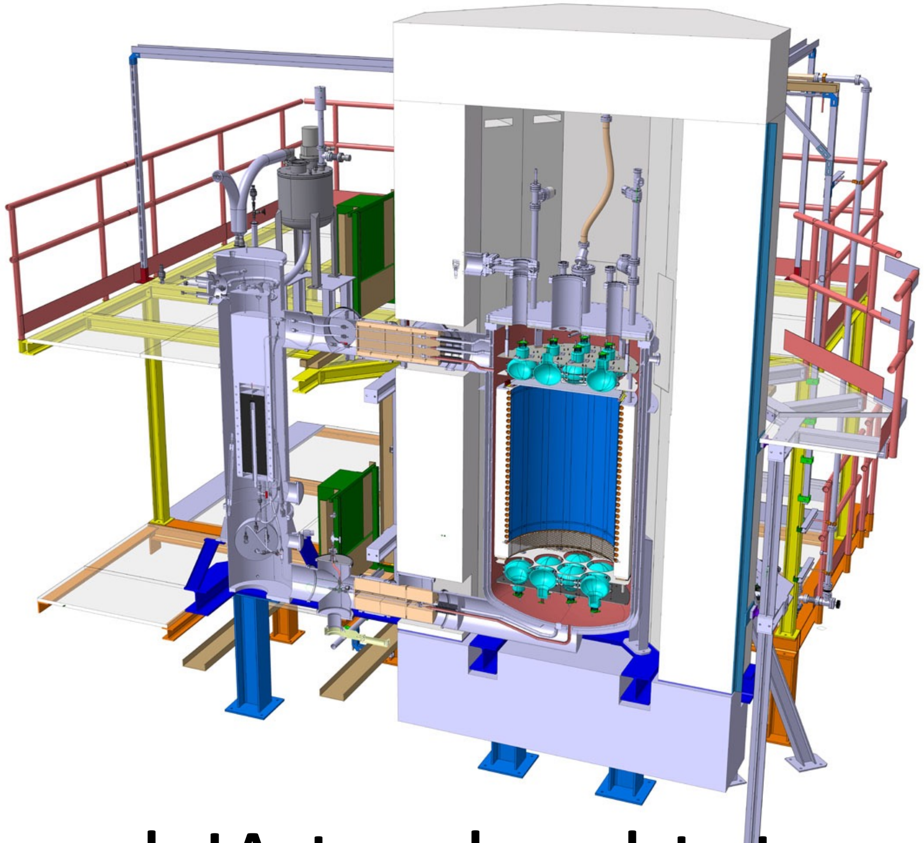
With Atmospheric Argon
1422 kg-day
PSD > 1.5×10^7

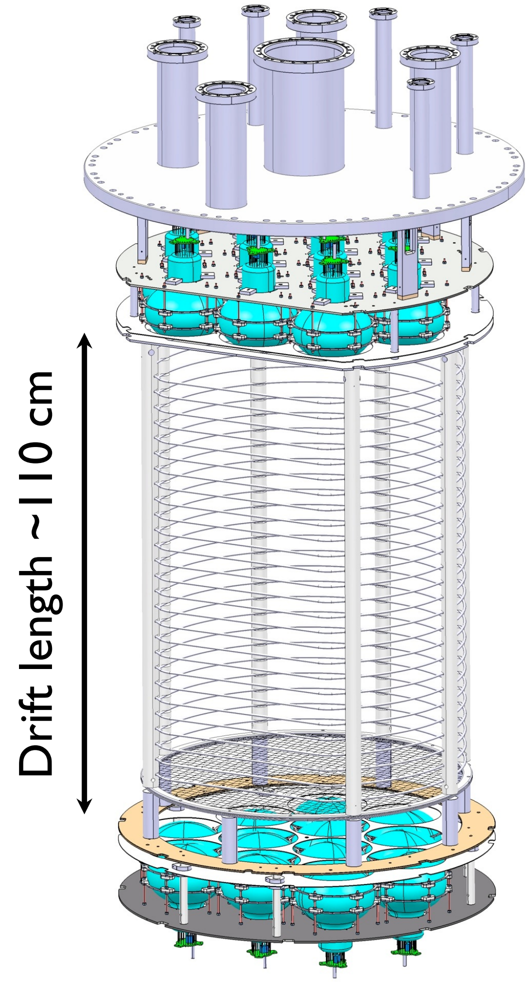


With Underground Argon
2616 kg-day
Depletion factor > 1400



ArDM at LSC: largest 2-phase LAr DM detector





Ton scale LAr two-phase detector

2 ton LAr with 850 kg active mass

8” PMTs in 12 (anode) + 12(chatode)

passive external shielding with 20 ton of polyethylene

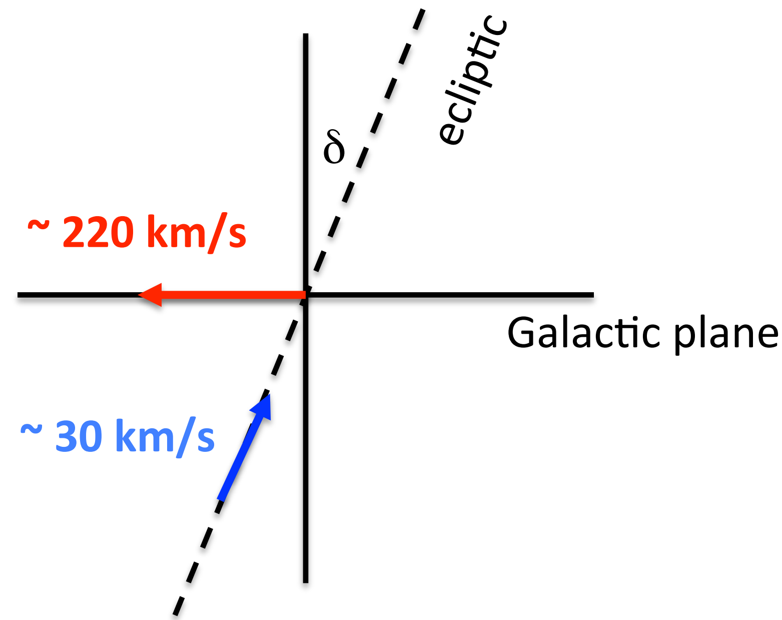
10^5 reduction factor for neutrons

Installed at LSC in 2014; running in single phase in 2015

Direct Dark Matter search with NaI(Tl)

Annual Modulation of WIMP interaction rate

The WIMPs interaction rate is oscillating during one year due to the relative motion of the Sun with respect to the halo reference frame



$$\mathrm{v}_\chi(t) = \mathrm{v}_{\mathrm{sun}} + \mathrm{v}_{\mathrm{earth}} \sin\delta \cos\left[\frac{2\pi}{T}(t - t_0)\right]$$

$$\mathrm{v}_\chi(t) \sim 220 + 15\cos\left[\frac{2\pi}{365}(t - 153)\right] \ \mathrm{km/s}$$

$$\boxed{\mathrm{R}(\mathrm{E}_r, t) = R_0(E_r) + R_1(E_r)\cos\left[\frac{2\pi}{365}(t - 153)\right]}$$

Expected modulation (at **% level**) of

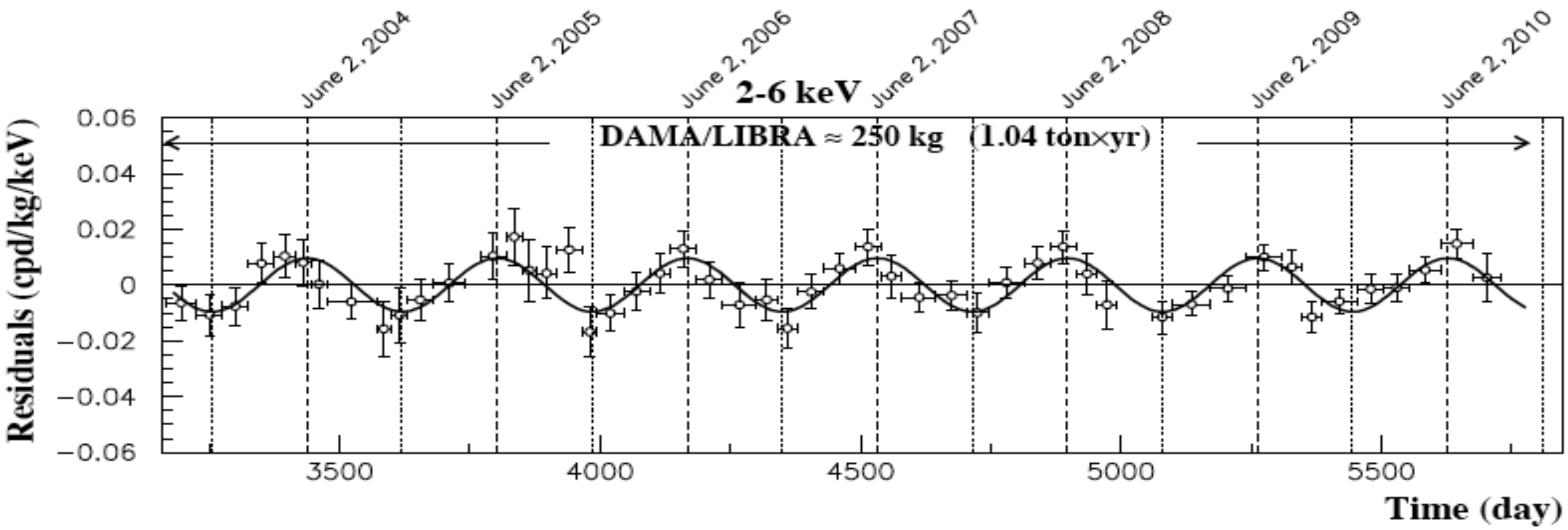
1. rate
2. spectral shape

This is a **model independent signature**

DAMA/LIBRA @ LNGS

- **DAMA**
  - Low radioactivity 100 kg NaI array operated from 1996 to 2002 at Gran Sasso
  - Measures scintillation in crystal
  - No discrimination between ER and NR
  - 0.29 ton-year
  - Positive signal for annual modulation
- **LIBRA**
  - 250 kg NaI array operated since 2003
  - > 1 ton-year exposure achieved
  - Positive signal for annual modulation
  - **Expected new results in 2017**

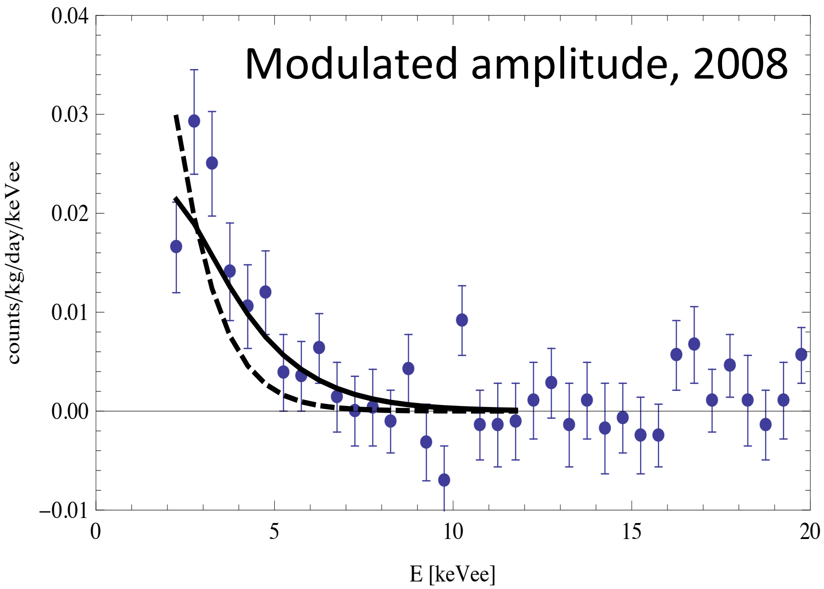
DAMA/LIBRA: results

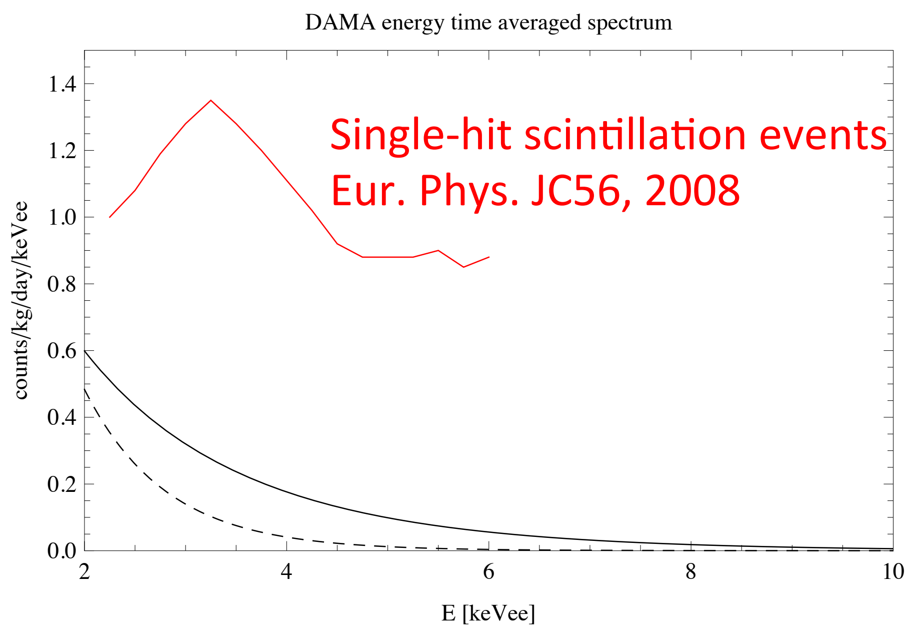


- Modulation observed over 14 cycles
- Cumulative exposure = 1.33 ton-year (for published data)
- Significance of modulation signal is 9.3σ
- Modulation amplitude in [2,6]keV = 0.0112±0.0012 cpd/kg/keV
- Phase = 144±7 days
- Period = 0.998 ± 0.002 year

DAMA/LIBRA: WIMPs fit

Target	LY [pe/keV]	Threshold ER [pe/keV]	Threshold NR [keVr]	σ/E
NaI	5.5-7.5	2	6.7(Na) 22(I)	~7% at 60keV

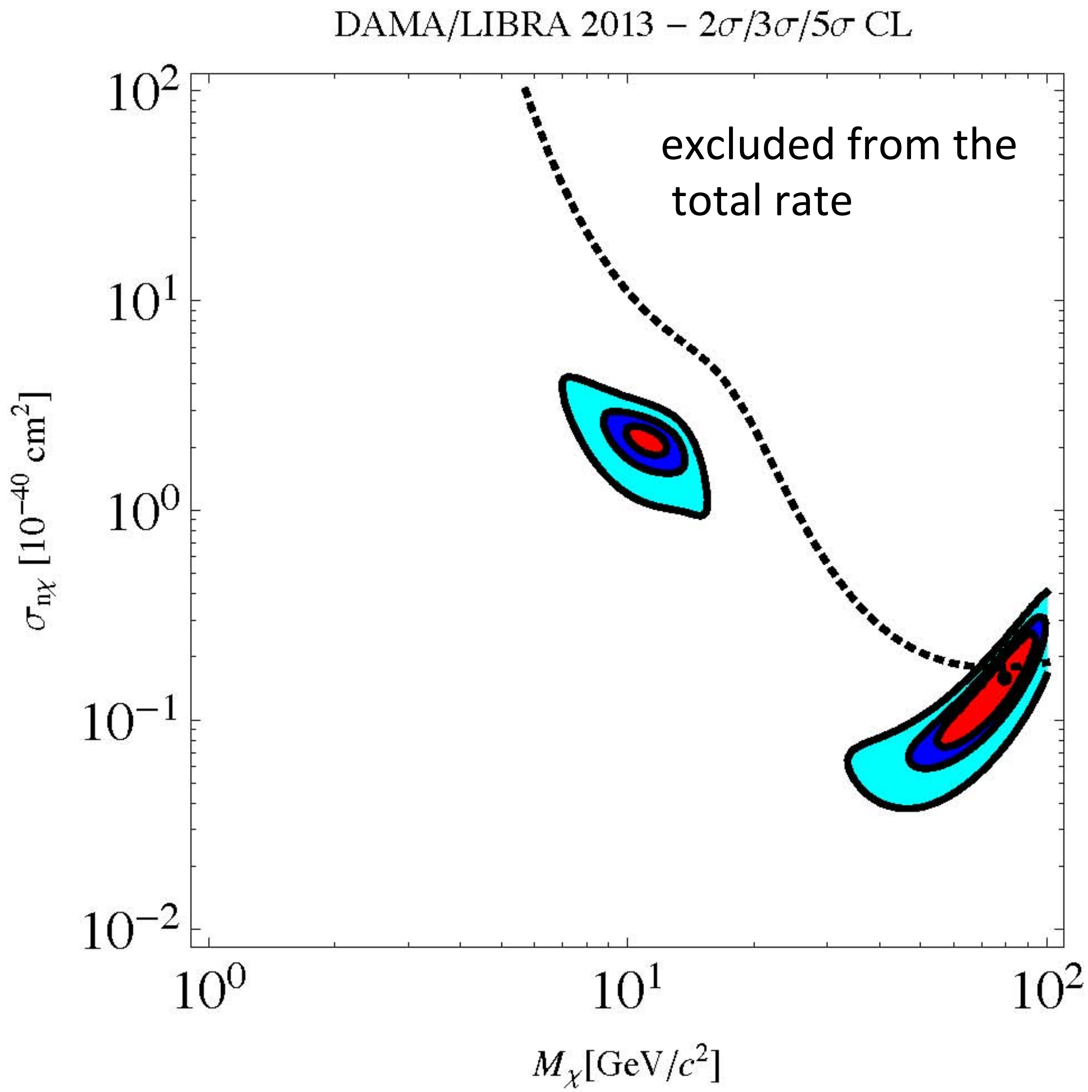




———— M_χ = 12 GeV/c^2 $\sigma_{\chi p}$ = 1.5×10^{-41} cm^2 χ^2/Ndof = 1.02

- - - - M_χ = 8.6 GeV/c^2 $\sigma_{\chi p}$ = 1.9×10^{-41} cm^2 χ^2/Ndof = 1.69

DAMA/LIBRA fit for "standard" SI WIMPs



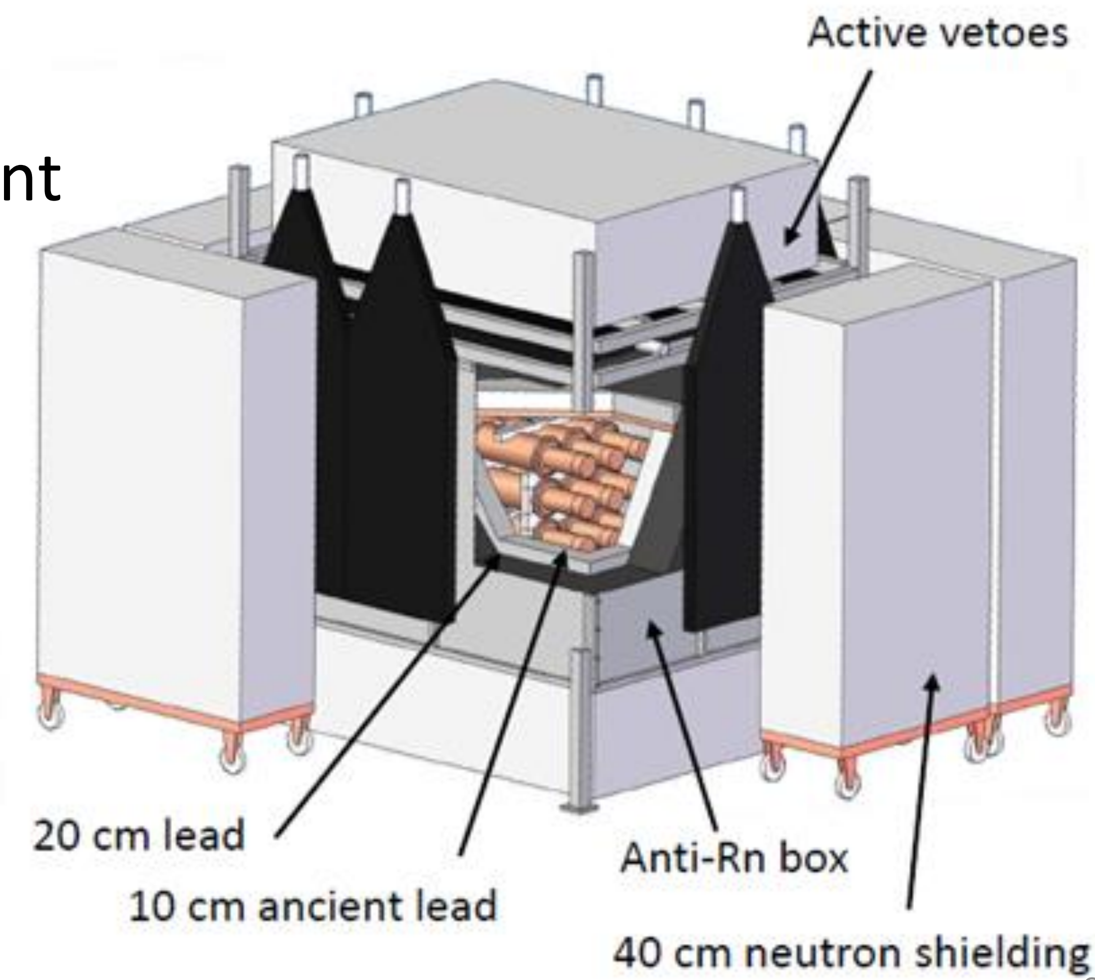
NaI(Tl) detectors for DM search

- **DAMA/LIBRA** in operation
  - Total rate in ROI ~ 1 cpd/kg/keV (1 DRU)
- **ANAIS** at Canfranc
  - 112 kg of NaI(Tl) in 2016
- **SABRE** at LNGS and Stawell (Australia)
  - ~60 kg NaI(Tl) + Liquid Scintillator active veto
  - 2016 crystal characterization (might have 0.1 DRU in ROI)
- **KIMS-NaI**
  - 200 kg x 3 years in Yangyang (Korea)
  - Liquid Scintillator active veto
  - 2016 crystal characterization
- **PICO-LON** in Kamioka
  - 200 kg NaI(Tl) target mass
  - 2016 crystal characterization/run
- **ALL efforts have**
  - **> 10 p.e./keV yield**
  - **Issues with intrinsic radiopurity from ^{40}K, ^{210}Pb, …**
  - **Cosmogenic background will delay physics run by 1-2 years since crystal production t_0**
    - **No real test of DAMA/LIBRA before 2019-2020**

Annual modulation with NAI Scintillators (ANAIS)

Goal: confirmation
of DAMA/LIBRA in
a different environment
with 112.5 kg NaI(Tl)
crystals array

3x3 array of 12.5 kg
high purity crystals



Detectors made at Alpha Spectra, Inc, CO, US

12.5 kg mass each
LY ~ 15 pe/keV
Cylindrical in shape

Hamamatsu PMTs R12669SEL2

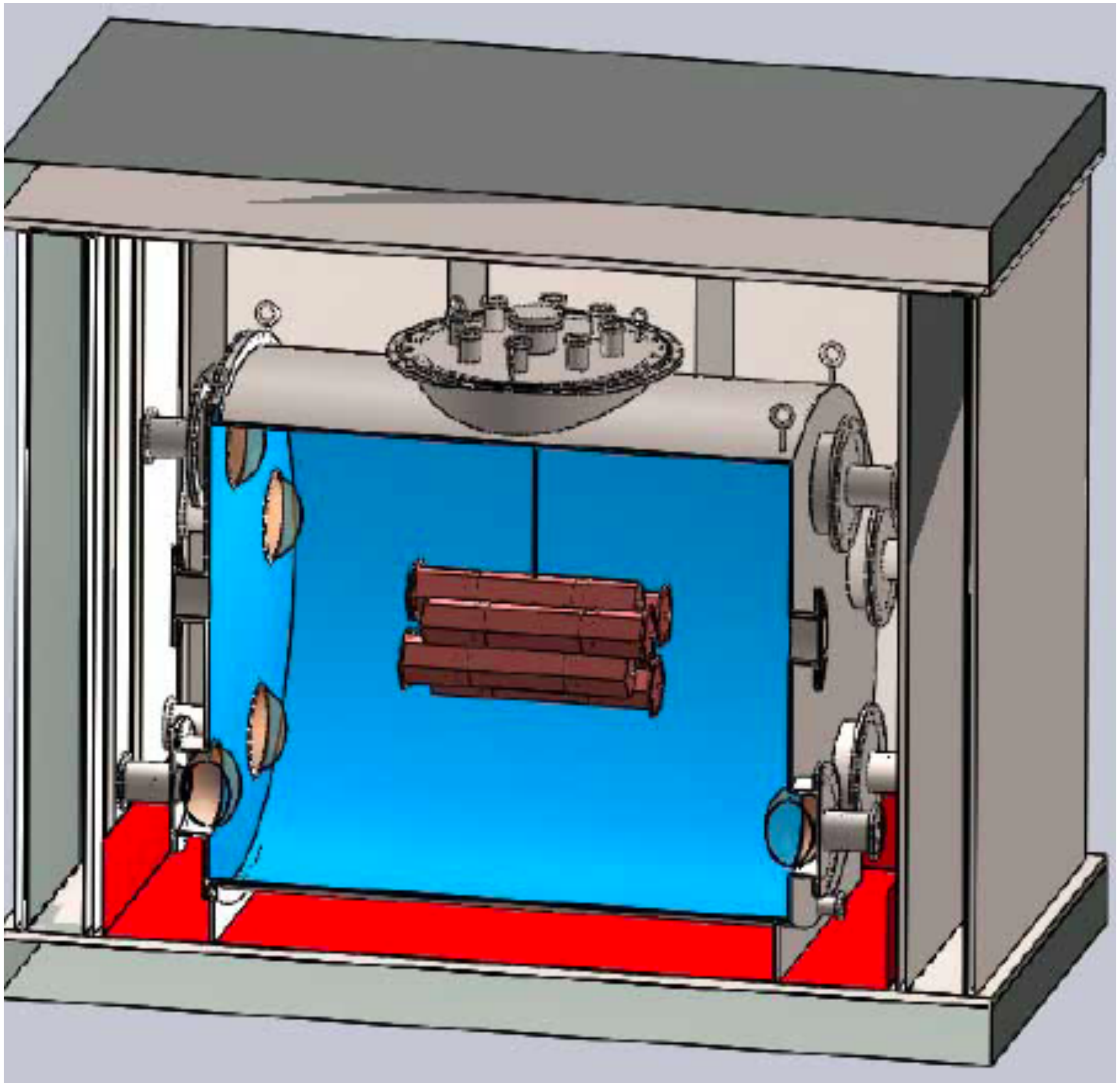
Low – background + High Quantum Efficiency

PMTs housing made at LSC by electro-forming copper stored underground since 2006

SABRE

SABRE has proposed:

1) NaI(Tl) crystals inside an active veto made of high purity liquid scintillator to improve background rejection at 90%
2) Make two twin detectors one at Gran Sasso and one in Stawell, Australia



Conclusions

- WIMPs search with LXe has reached ~2×10^{-46} cm^2 at ~50 GeV/c^2 for spin-independent interaction
  - Strong tension with DAMA/LIBRA
- Expected sensitivity with upcoming LXe and LAr detector at 10^{-47} cm^2
  - Complementarity
  - LXe (Xenon1t and LZ could probe ^{8}B solar neutrinos)
- Long term WIMPs search program aims to reach the ultimate sensitivity of 10^{-47}-10^{-48} cm^2 > 10 GeV/c^2
- In 2017 expected new DAMA/LIBRA results with 1keV threshold
  - a number of new efforts are underway to test DAMA/LIBRA (but not before 2020)
- New efforts in the search for QCD axions but not as much as for WIMPs (new results not before 2020)