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# **Direct Dark Matter Search with Cryogenic Liquids**

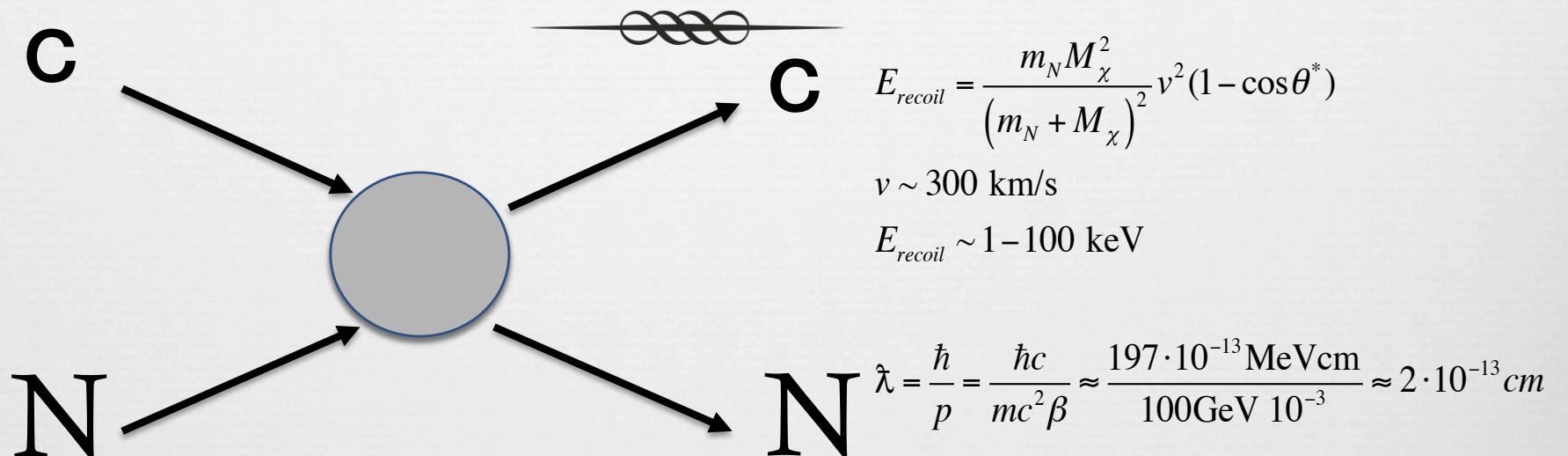
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*5<sup>th</sup> Capri Workshop on  
Theory, Phenomenology and Experiments  
in Flavour Physics*

Capri,  
May 25<sup>th</sup>, 2014

# Direct Search for WIMPs: nuclear recoil tagging

Goodman and Witten, PRD31, 1985

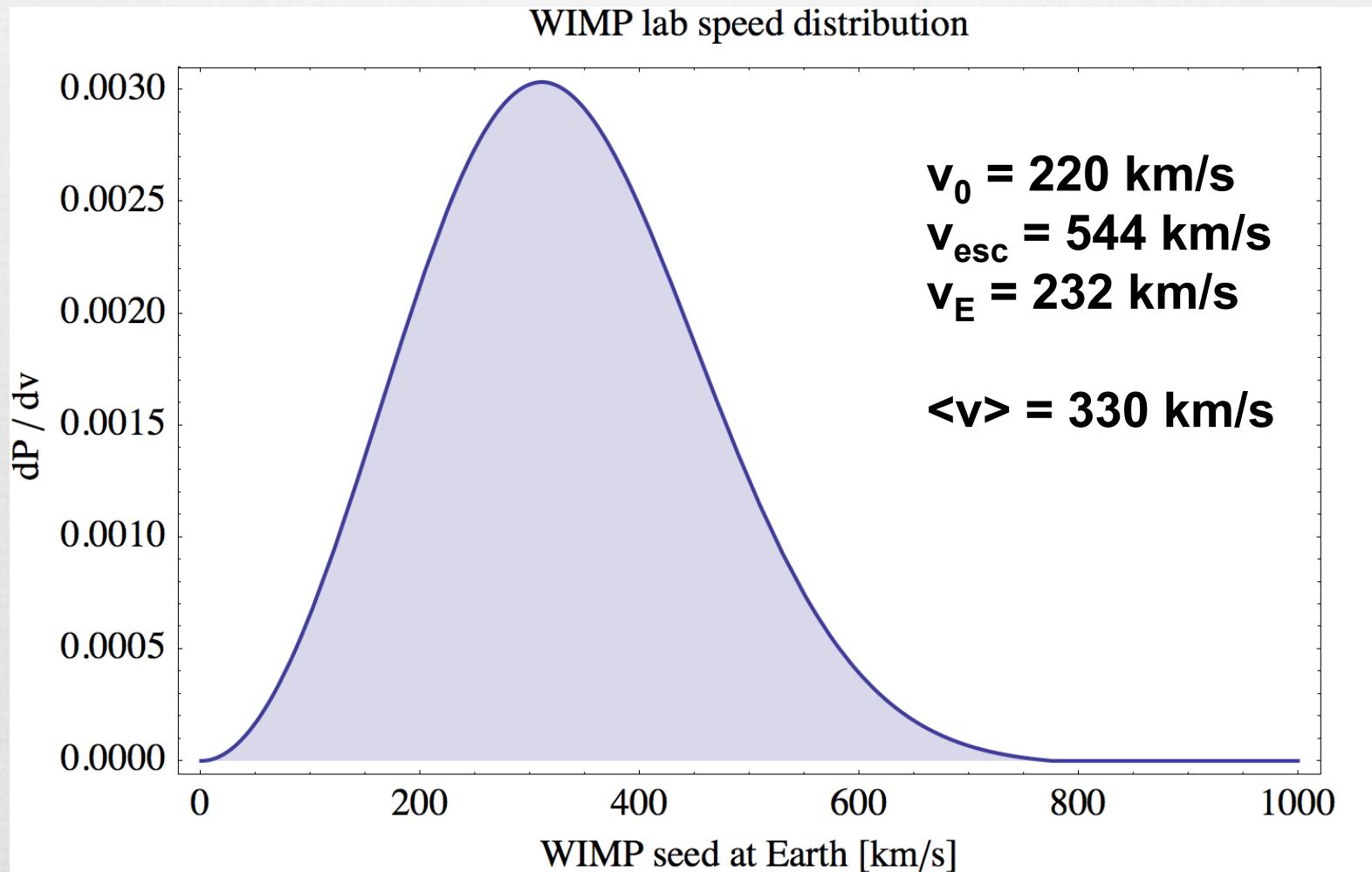


$$\frac{dR}{dE_r} = N_t \frac{\rho_\chi}{m_\chi} \frac{m_N}{\mu_N^2} A^2 \sigma_{\chi n} F^2(E_r) \int_{v \geq v_{\min}(E)}^\infty d^3v \frac{f(v)}{v}$$

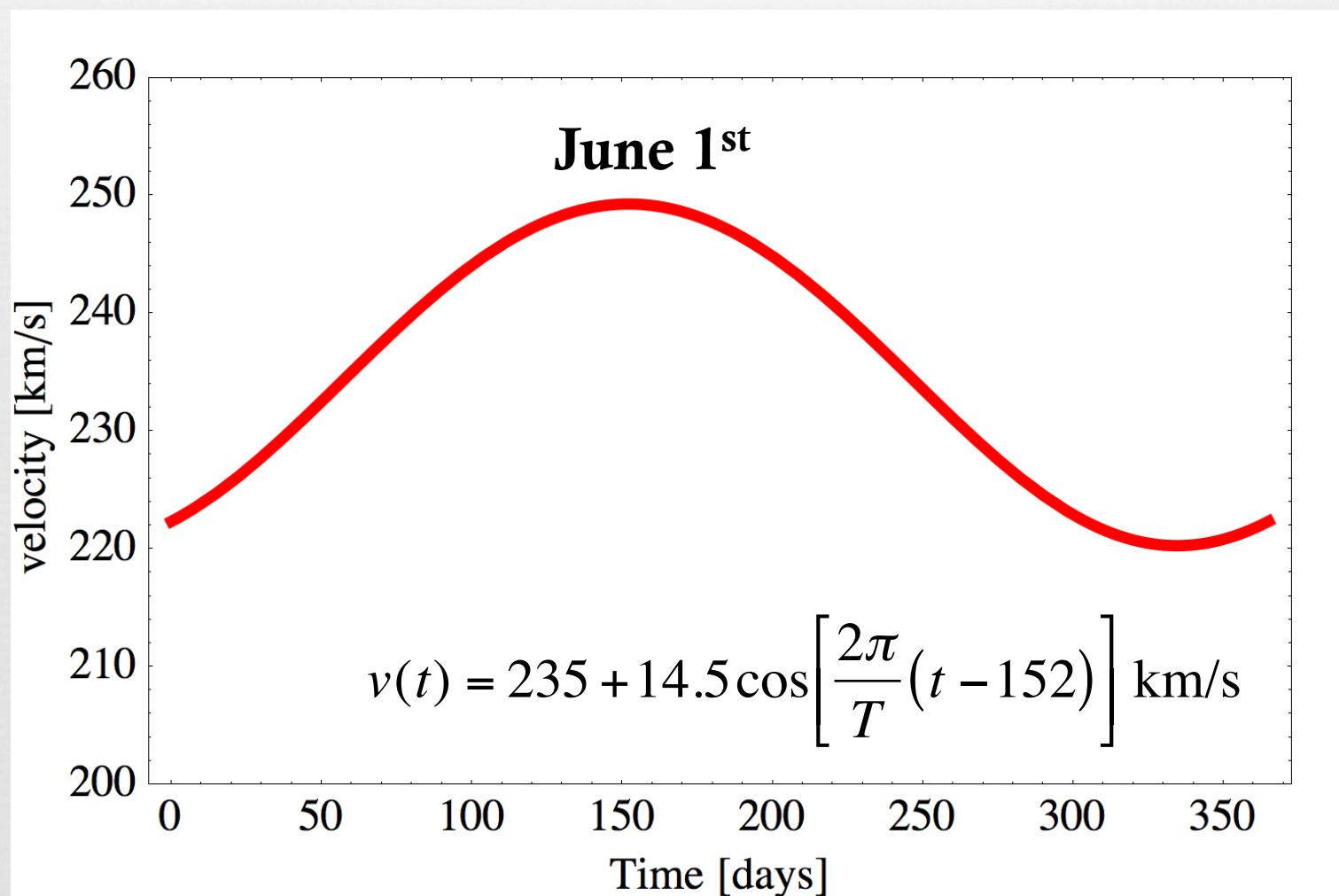
$$f(v) = \begin{cases} \frac{1}{N} e^{-\left(\frac{|v_\chi + v_{\text{sun}} + v_{\text{Earth}}|}{v_0}\right)^2}, & |v_\chi + v_{\text{sun}} + v_{\text{Earth}}| < v_{\text{esc}} \\ 0 & \text{elsewhere}^2 \end{cases}$$

- $170 \text{ km/s} < v_0 < 270 \text{ km/s}$
- $450 \text{ km/s} < v_{\text{esc}} < 650 \text{ km/s}$
- $r_c^{\text{local}} \sim 0.3 \text{ GeV}/(c^2 \text{ cm}^3)$
- $F(E) = \text{nuclear form factor}$
- $f(v) = \text{velocity distribution of WIMPs in the galaxy}$

# Velocity Distribution for WIMPs



# WIMPs Velocity relative to Earth



Flux of 100 GeV/c<sup>2</sup> WIMPs on Earth  $\sim 7 \times 10^4 \text{ cm}^{-2}\text{s}^{-1}$

# “Standard” cross-section

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

So for the “standard”  $f_p = f_n$ ,  $s \sim A^2$

**Spin Dependent** interaction:  $\sigma_p \rightarrow \sigma_p J(J+1)$

Deviations from the “standard” scenario are considered:

Isospin Violating Interactions,  $f_n/f_p \sim -0.7$

Electromagnetic coupling

...

**Important to use different target detectors**

# WIMPs signal and background: general considerations

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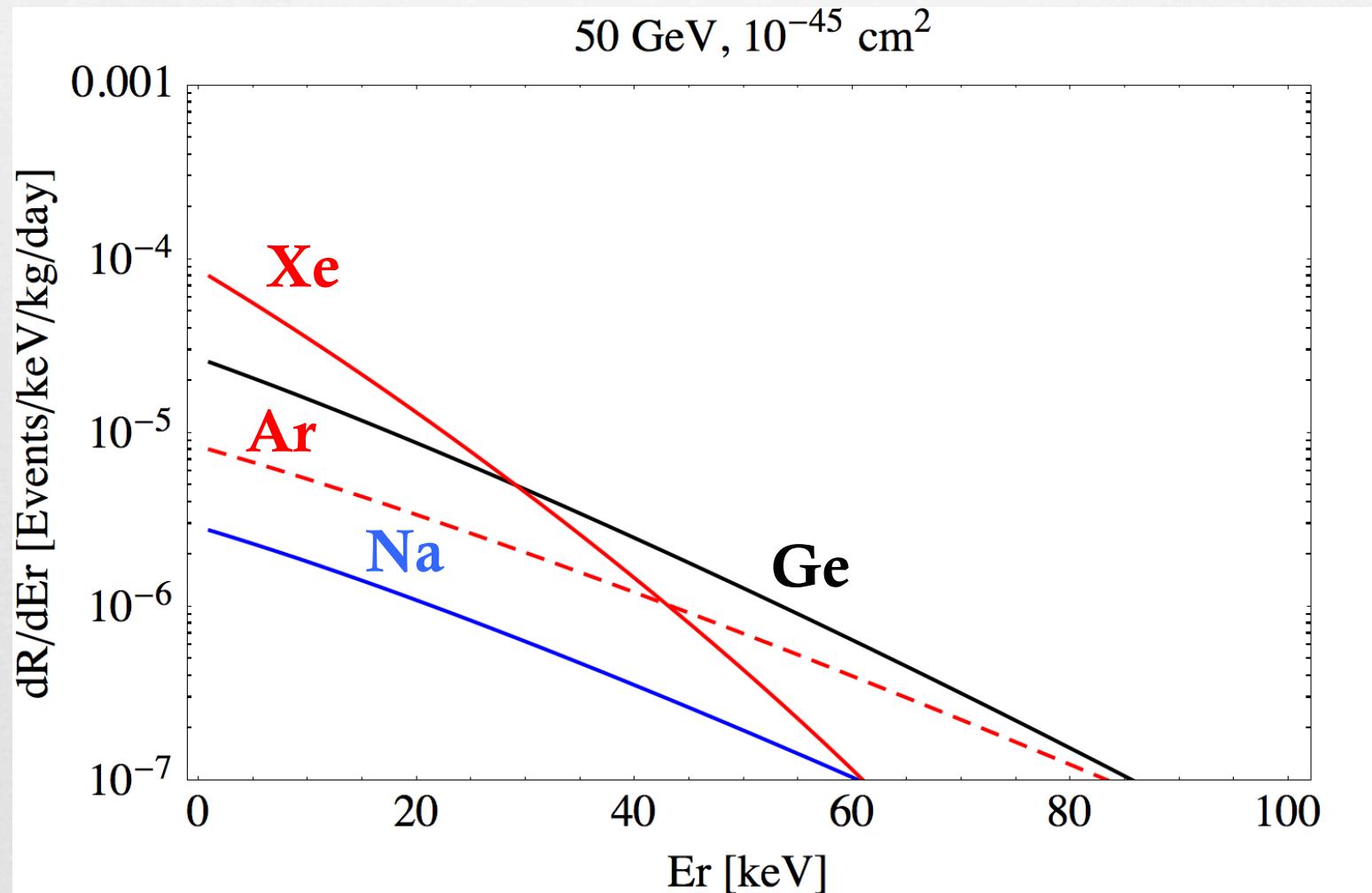
## ➤ Signal:

- Low energy nuclear recoils (1 – 100 keV)
- Low rate ( ~ few counts/year/ton at  $10^{-47} \text{ cm}^2$  )
- No specific features in recoils spectrum

## ➤ Background:

- Electron Recoils (**ER**) from e, g radioactivity rejected by a number of discrimination cuts
- Nuclear Recoils (**NR**) from radiogenic neutrons ask for a “**background free**” detector
- Solar neutrinos:
  - ✓ Elastic Scattering interactions will limit the sensitivity depending on the ER rejection power of the experiment
  - ✓ Neutrino-nucleus coherent interactions sets the limiting sensitivity

# Recoil Spectrum

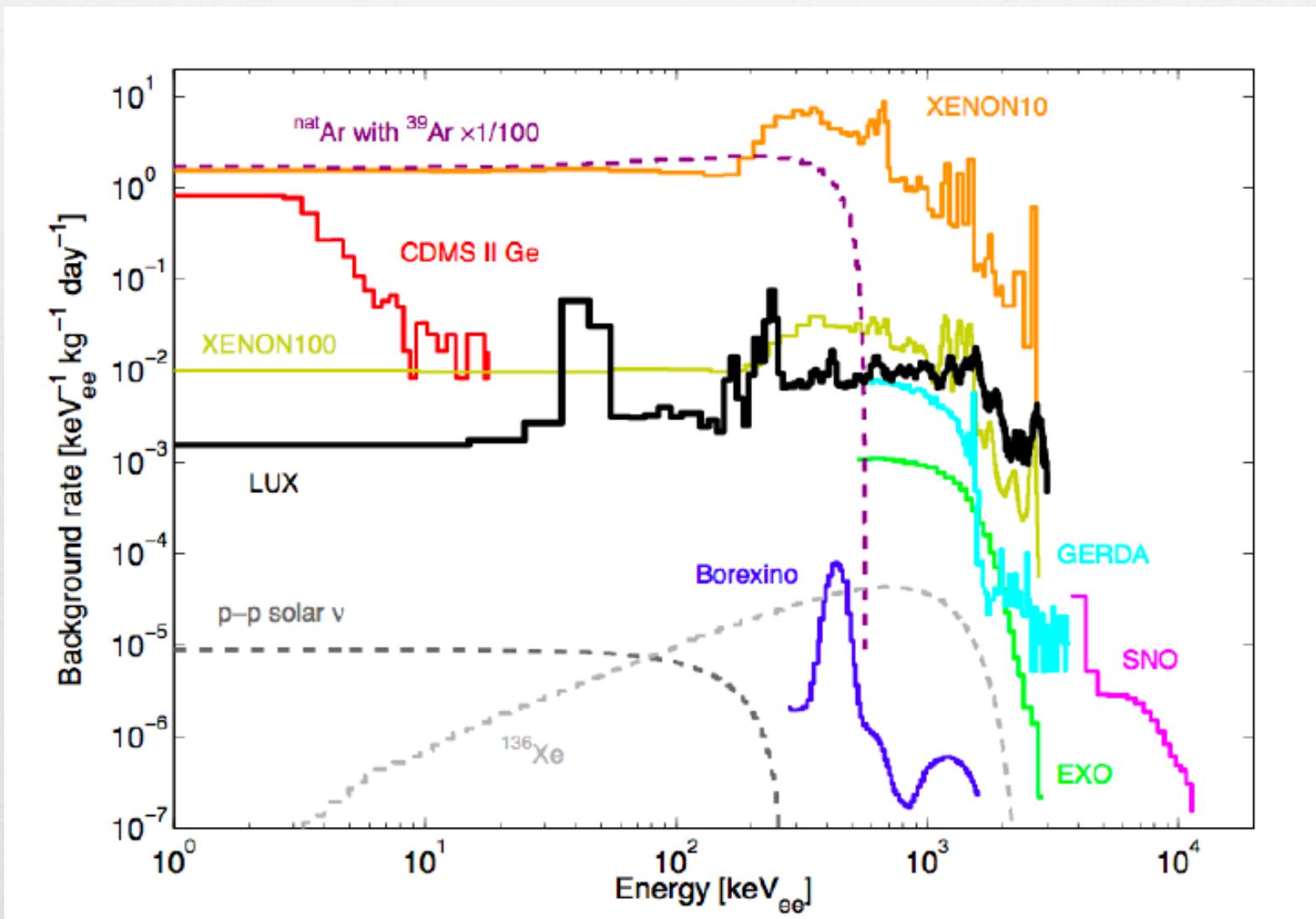


0.3 events/kg/year in Xe for  $10^{-45}$  cm $^2$  and 50 GeV/c $^2$

# Technologies

- ❖ **Cryogenic solid state**
  - ❖ Ionization spectrometer + bolometer operated at < 100mK
  - ❖ CDMS(Si and Ge); CRESST(Ca); EDELWEISS(Ge)
- ❖ **LXe** ([XENON100](#), [LUX](#)) and **LAr** ([DarkSide](#), MiniCLEAN, DEAP, XMASS)
  - ❖ Scintillation + ionization
- ❖ **Superheated liquid**
  - ❖ Nuclear recoil induce bubble nucleation
  - ❖ Mainly with F for SD
- ❖ **Scintillator crystal detectors**
  - ❖ DAMA/LIBRA (NaI), CoGeNT (Ge), KIMS(CsI)
- ❖ **Directional detectors**
  - ❖ Gas TPC

# Background in DM, double beta decay and solar neutrino experiments



Plot by R. Geitskell at DM2014

# Liquified noble gases as WIMPs target

	Ar	Xe	Ne
Atomic number	18	54	10
Mean atomic mass	40	131.3	20.2
Spin	0 (100%)	1/2(26.4%), 3/2(21.2%) 0(52.4%)	0 (99.7%) 1/2(0.3%)
Melting point @ 1atm [K]	83.8	161.4	24.6
Density for liquid [g/cm <sup>3</sup> ]	1.40	2.94	1.21
Volume fraction in atmosphere [ppm]	9340	0.09	18.2
Background isotope	<sup>39</sup> Ar	<sup>136</sup> Xe	
Scintil / Ioniz.	40 ph /keV / 42 e <sup>-</sup> /keV	42 ph /keV / e <sup>-</sup> /keV	
Scintillation em. [nm]	128	178	78
Scint. fast component [ns]	7	3	
Scint. slow component [ns]	1600 <sup>10</sup>	27	

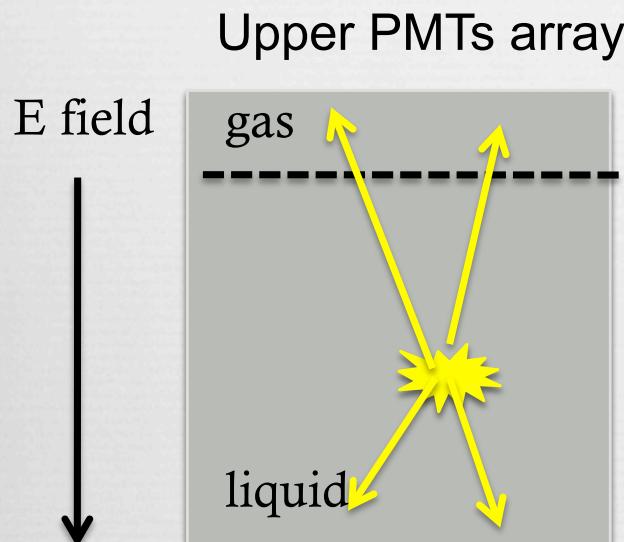
# Single and Dual phase set-up

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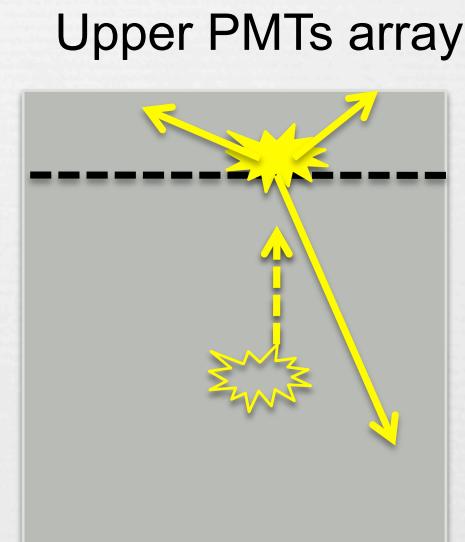


- ❖ **Single phase** detectors
  - Simple design and 4p PMT coverage
  - Position reconstruction ~ cm
  - PSD to select NR vs ER
  
- ❖ **Dual phase** detectors
  - Complex design
  - Electrons drift allow to discriminate ER vs NR
  - PSD to select NR vs ER
  - Position reconstruction ~ mm

# LAr/LXe TPC at Work



**S1** prompt signal  
from LAr



Drift of free  $e^-$   
and delayed  
signal in gas **S2**

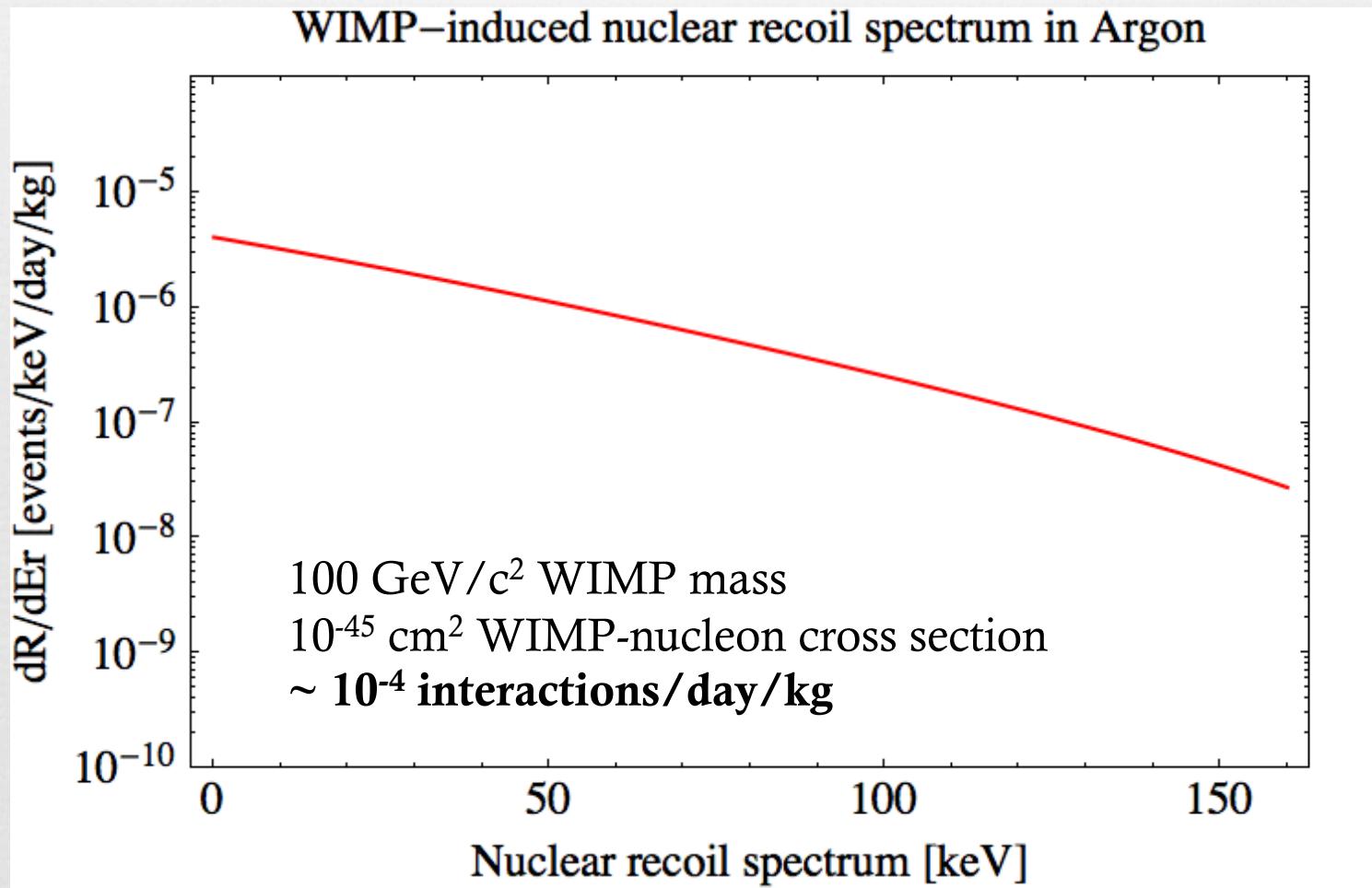
Lower PMTs array

Lower PMTs array

**S1** signal from prompt scintillation: measures energy and time of event

**S2** late signal: measures position of event in LAr and is proportional to fraction of charge that escapes recombination

# Example: Expected WIMPs Signal in LAr



Exposure of 1 ton-year gives about 40 events with these assumptions  
Exposure of 50 kg x 3 years gives about 15 events

# Example: Pulse Shape Discrimination in LAr

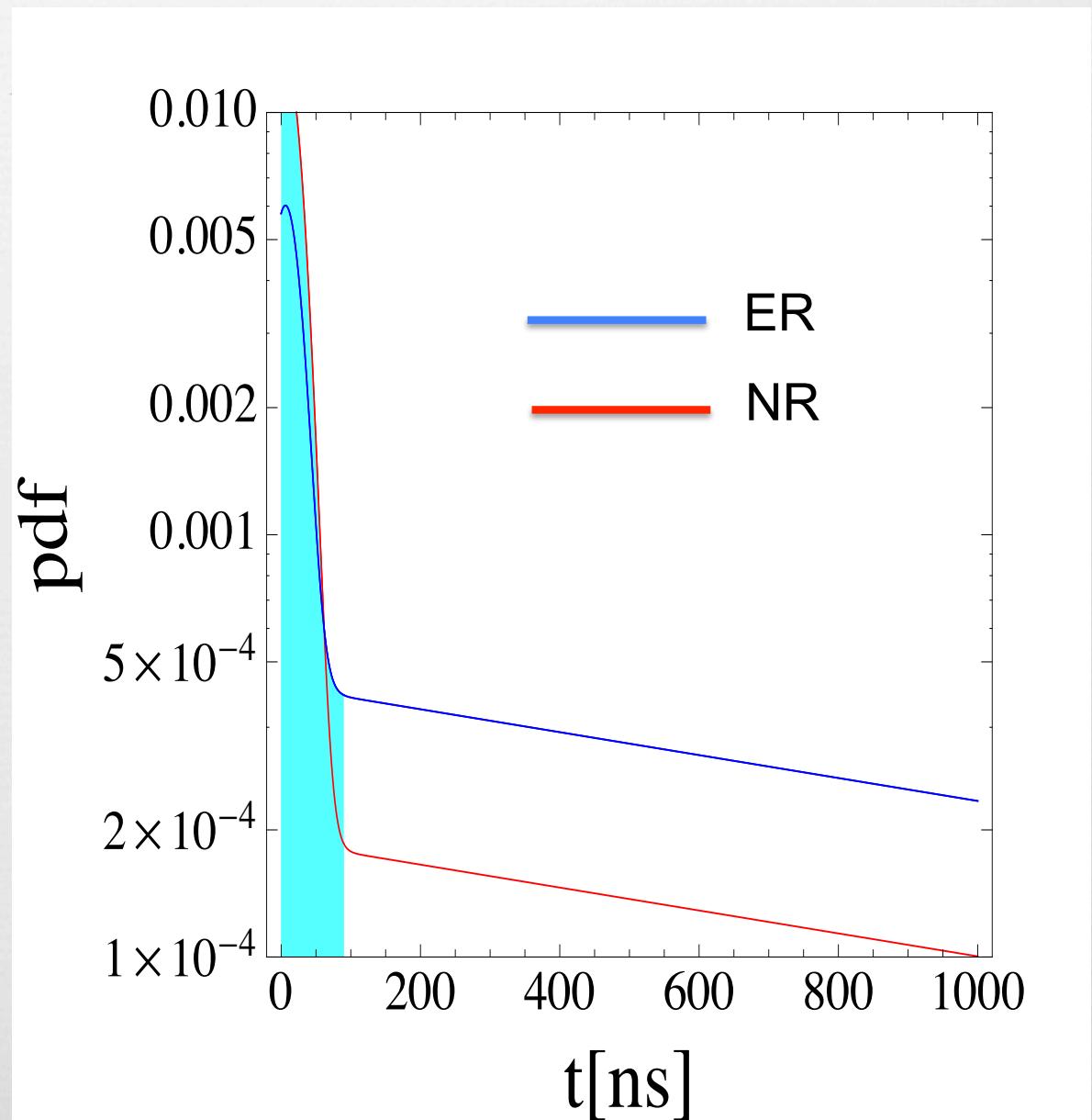
$$f(t) = \left( \frac{q}{\tau_F} e^{-t/\tau_F} + \frac{1-q}{\tau_S} e^{-t/\tau_S} \right)$$

$$\tau_F = 6\text{ns}$$

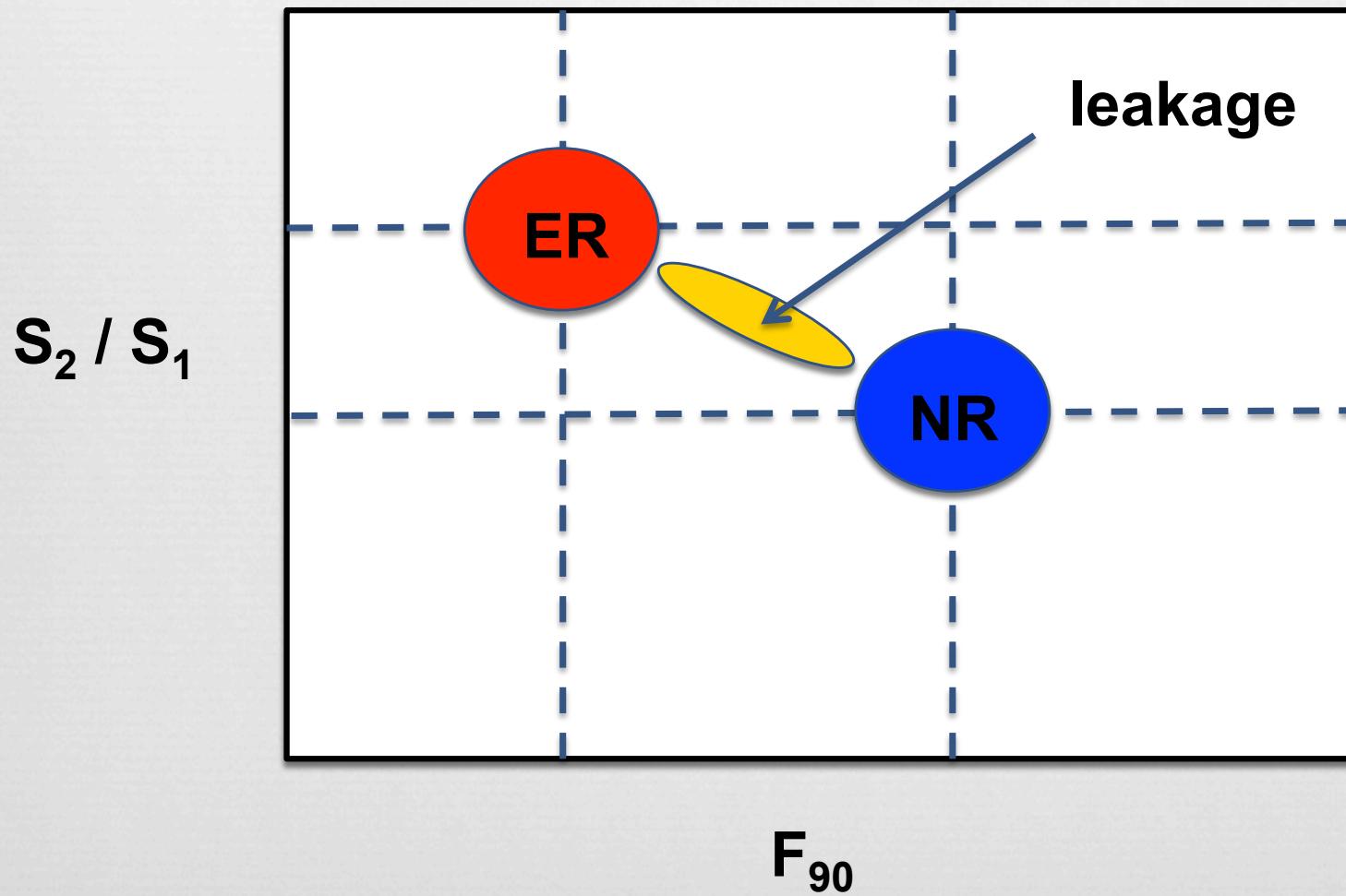
$$\tau_S = 1600\text{ns}$$

$$q = \begin{cases} 0.3 & \text{ER} \\ 0.7 & \text{NR} \end{cases}$$

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

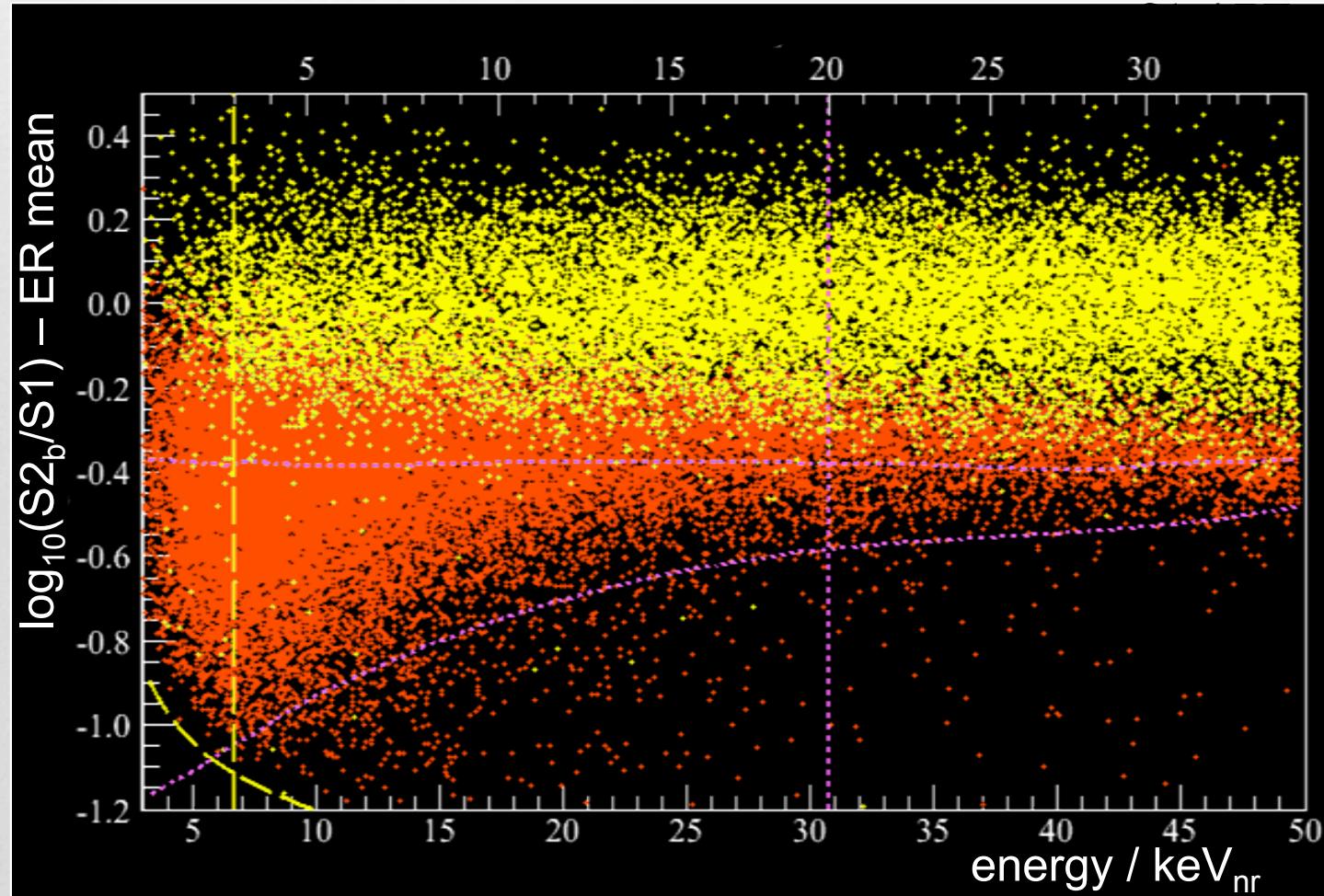


# Scintillation and Ionization Discrimination



# Discrimination using S2/S1 in XENON100

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



electronic recoils  
(background)

nuclear recoils  
(calibration)

~99.5% ER rejection @ 50% NR acceptance

# XENON100 @ LNGS

62 kg of LXe for dual phase TPC with additional 99 kg LXe as active veto

Exposure = 224.6 days x 34 kg

Drift: 530 V/cm Extraction: 12 kV/cm

Detection threshold =

S1 > 3 p.e. S2 > 150 p.e.

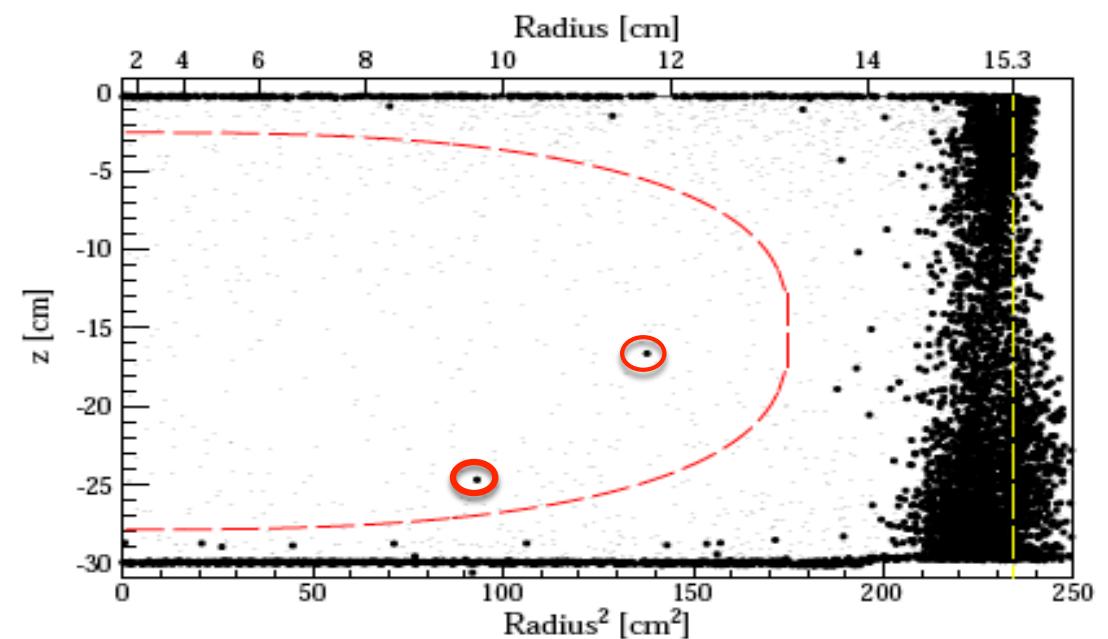
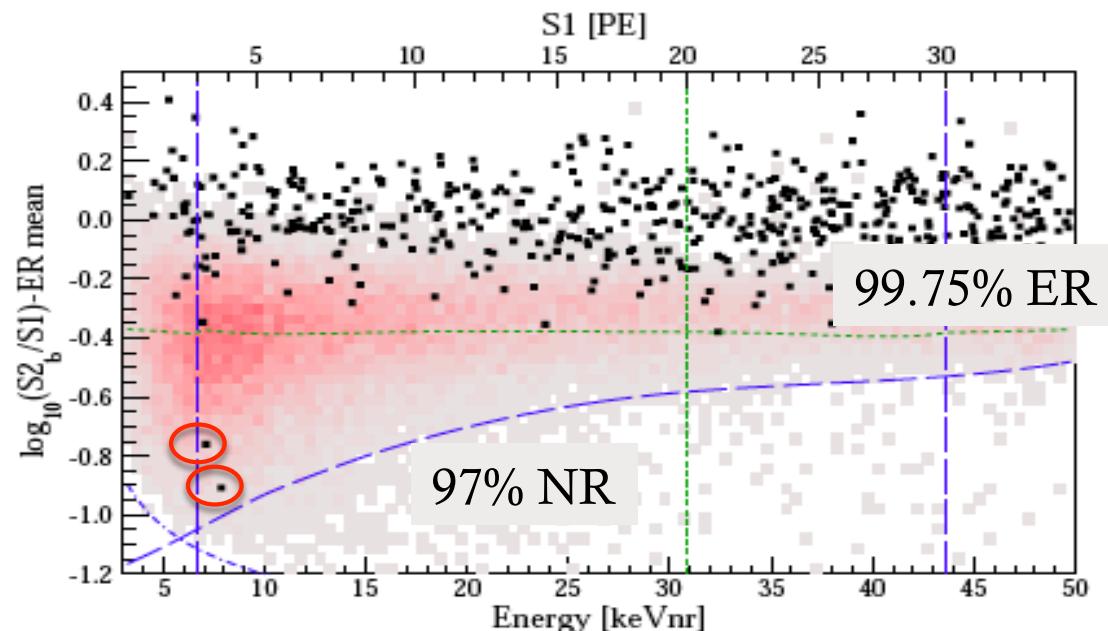
LY =  $2.28 \pm 0.04$  p.e./keVee

ER background:  $(5.3 \pm 0.6) \times 10^{-3}$  events/keVee/kg/day

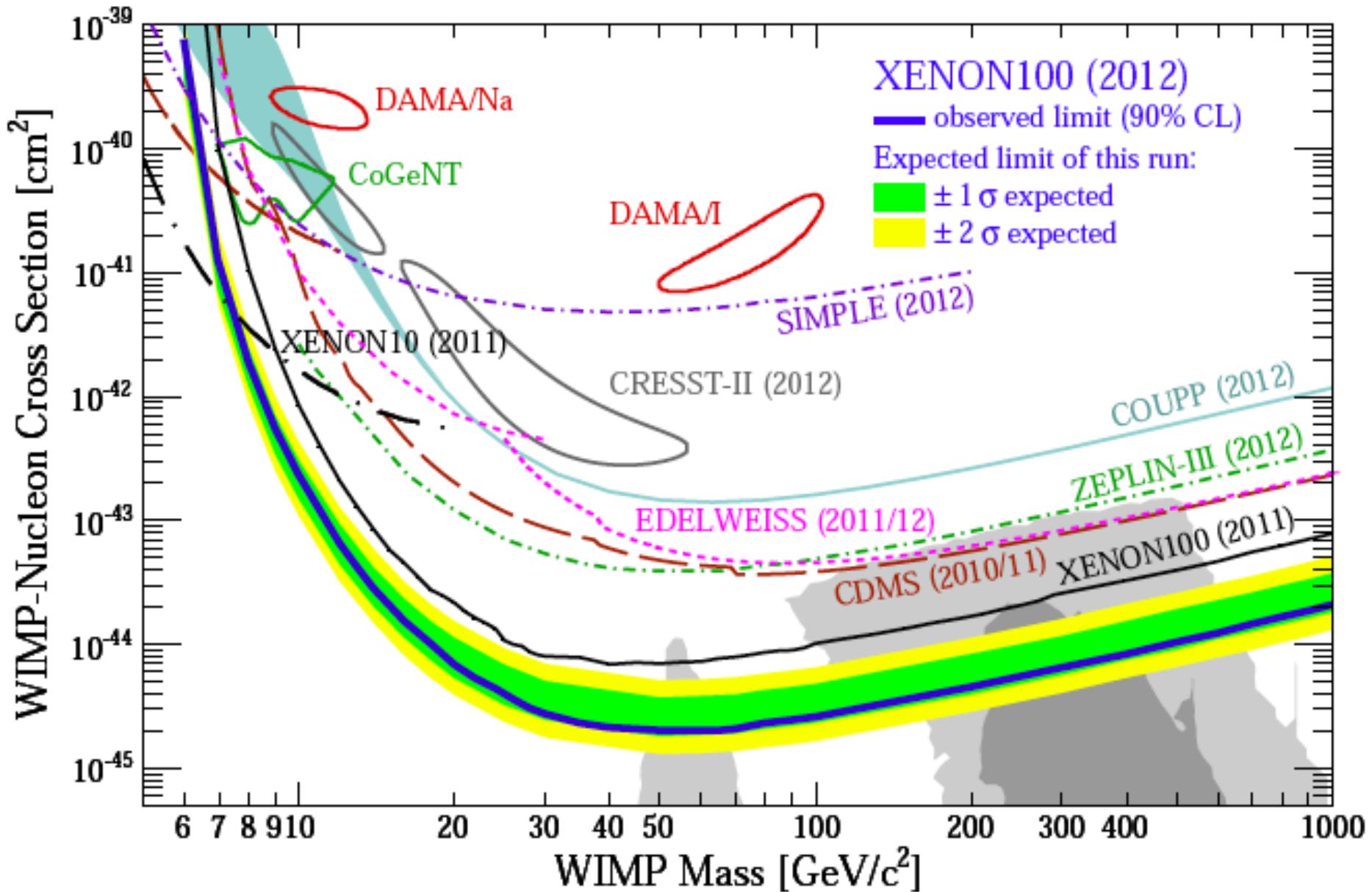
NR 50% acceptance window:  
6.6 – 30.5 keVee

2 observed events and  $1.0 \pm 0.2$  background expected

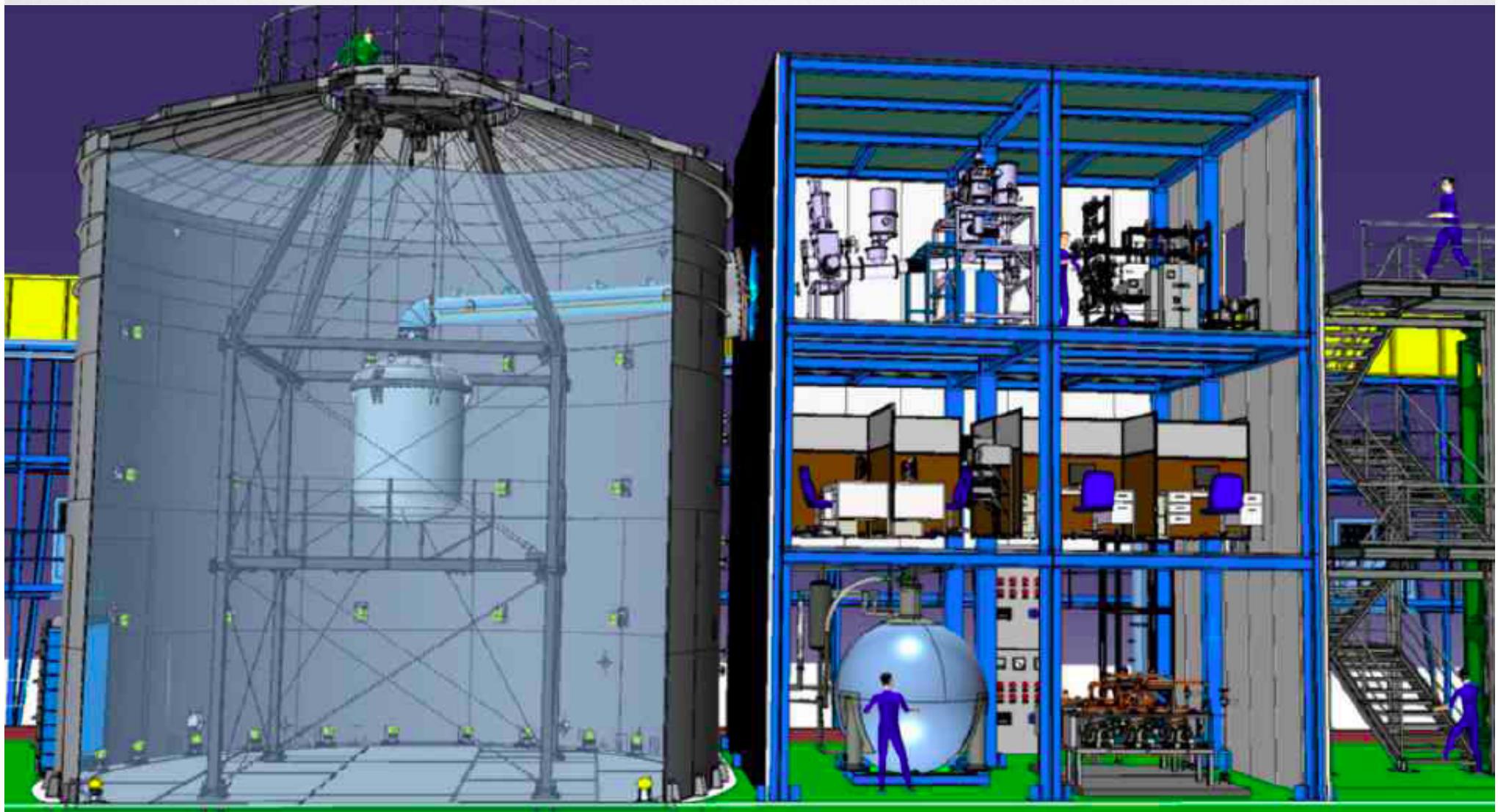
Profile likelihood analysis using ER and NR pdf's



# XENON100 sensitivity



# XENON1t @ LNGS



# LUX detector @ Sanford lab

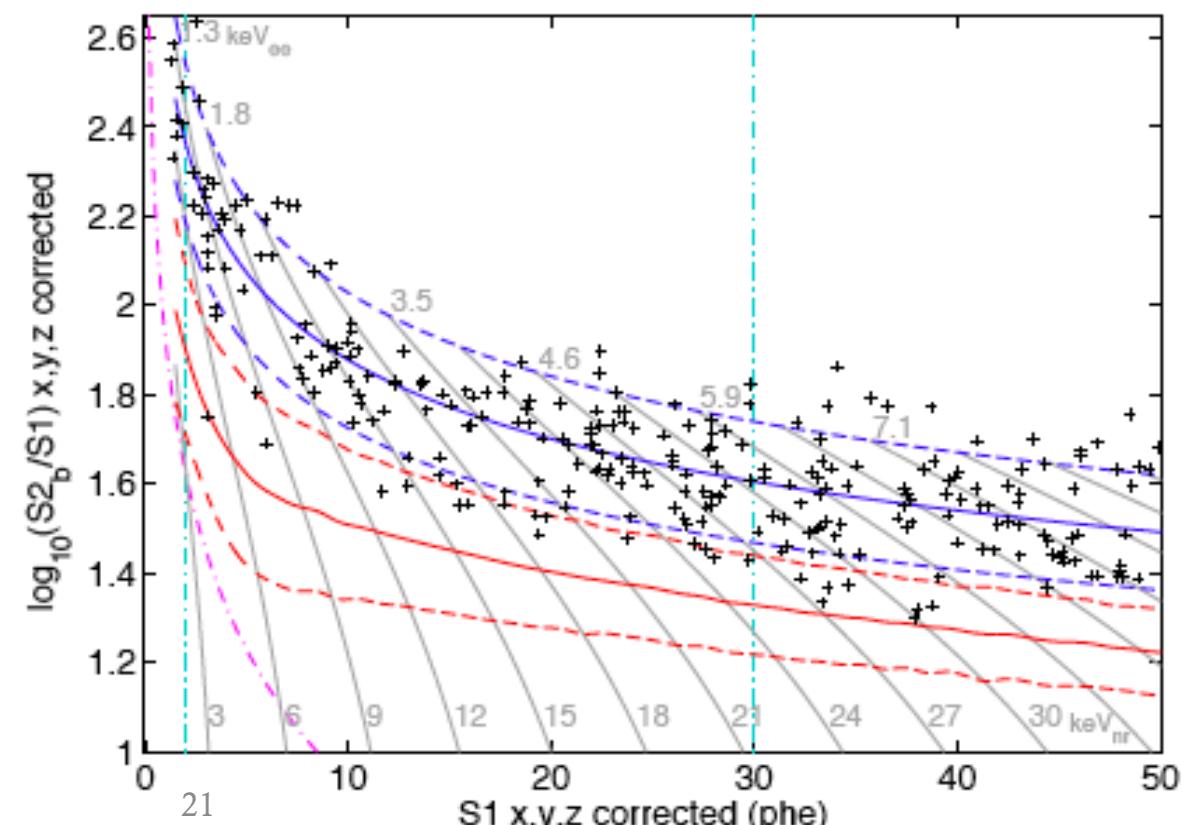


# LUX dual phase LXe TPC



- ❖ 370 kg of LXe with 250 kg in dual phase TPC
- ❖ Drift: 181 V/cm Extraction: 6kV/cm
- ❖ 118 kg and 85.3 days
- ❖ S1 > 3 p.e. S2>200p.e.
- ❖ LY ~ 8.8 p.e./keVee
- ❖ 50% acceptance in [3, 25] keVr
- ❖ Background =  $3.6 \pm 0.3_{\text{stat}}$  events/keVee/kg/day
- ❖ Observed 160 events
- ❖ Background in NR window is  $0.64 \pm 0.16$  from ER leakage

$s > 7.6 \times 10^{-46} \text{ cm}^2$  at  $33 \text{ GeV}/c^2$



# DS-50 @ LNGS

## Rn-free clean room

(10-15 mBq/m<sup>3</sup> in 110 m<sup>3</sup>)

Used for assembling TPC  
and deployment

## Water Cherenkov muon veto:

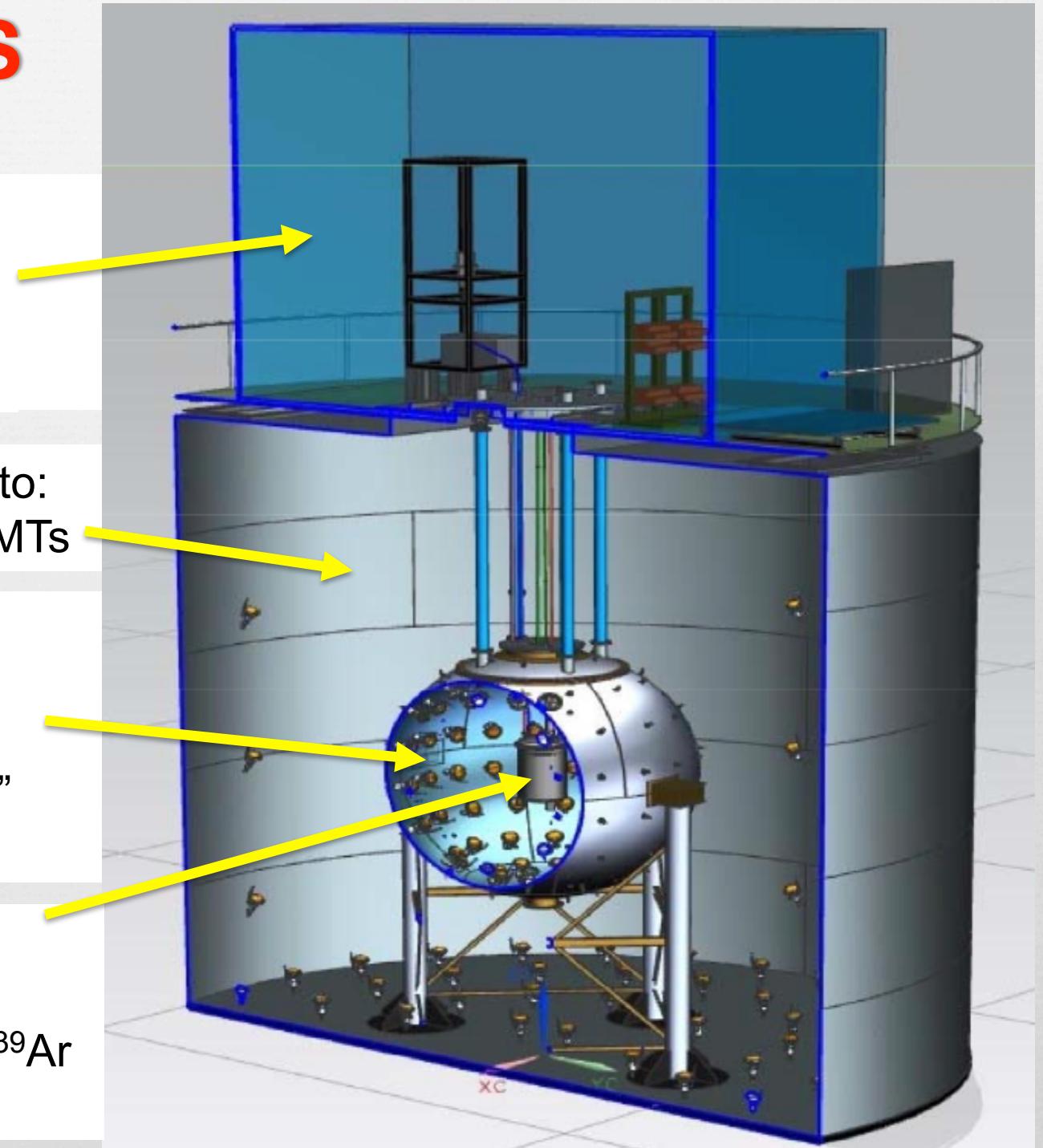
10<sup>3</sup> m<sup>3</sup> H<sub>2</sub>O with 76/80 8" PMTs

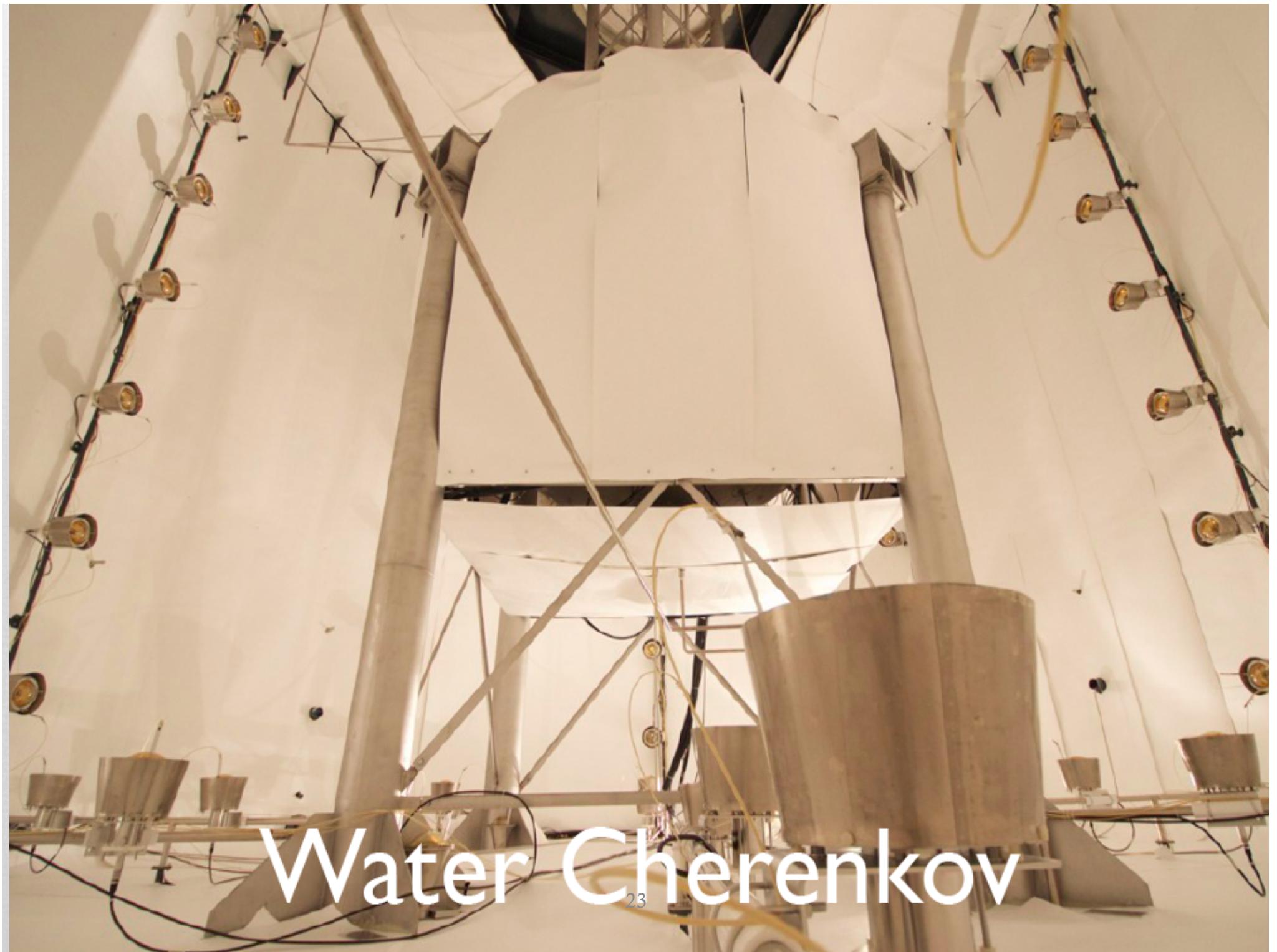
## Boron-loaded liquid scintillator

(50% TMB + 50% PC) as  
neutron veto with 108/110 8"  
PMTs

## 150kg LAr TPC with 2 x 19 3" PMTs

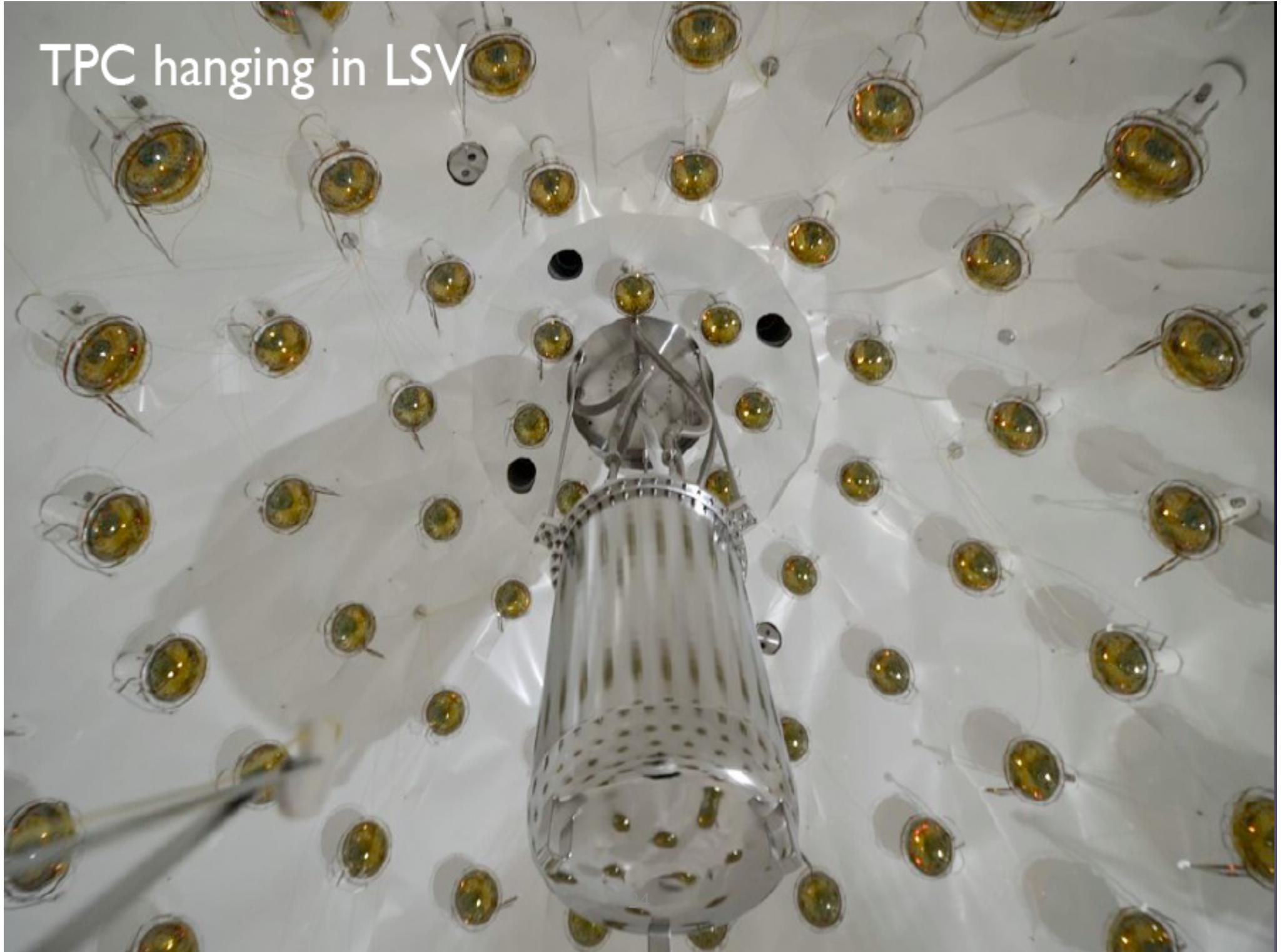
AAr at present with 1Bq/kg <sup>39</sup>Ar  
UAr with < 6.5 mBq/kg <sup>39</sup>Ar





Water Cherenkov

TPC hanging in LSV





# The problem of $^{39}\text{Ar}$

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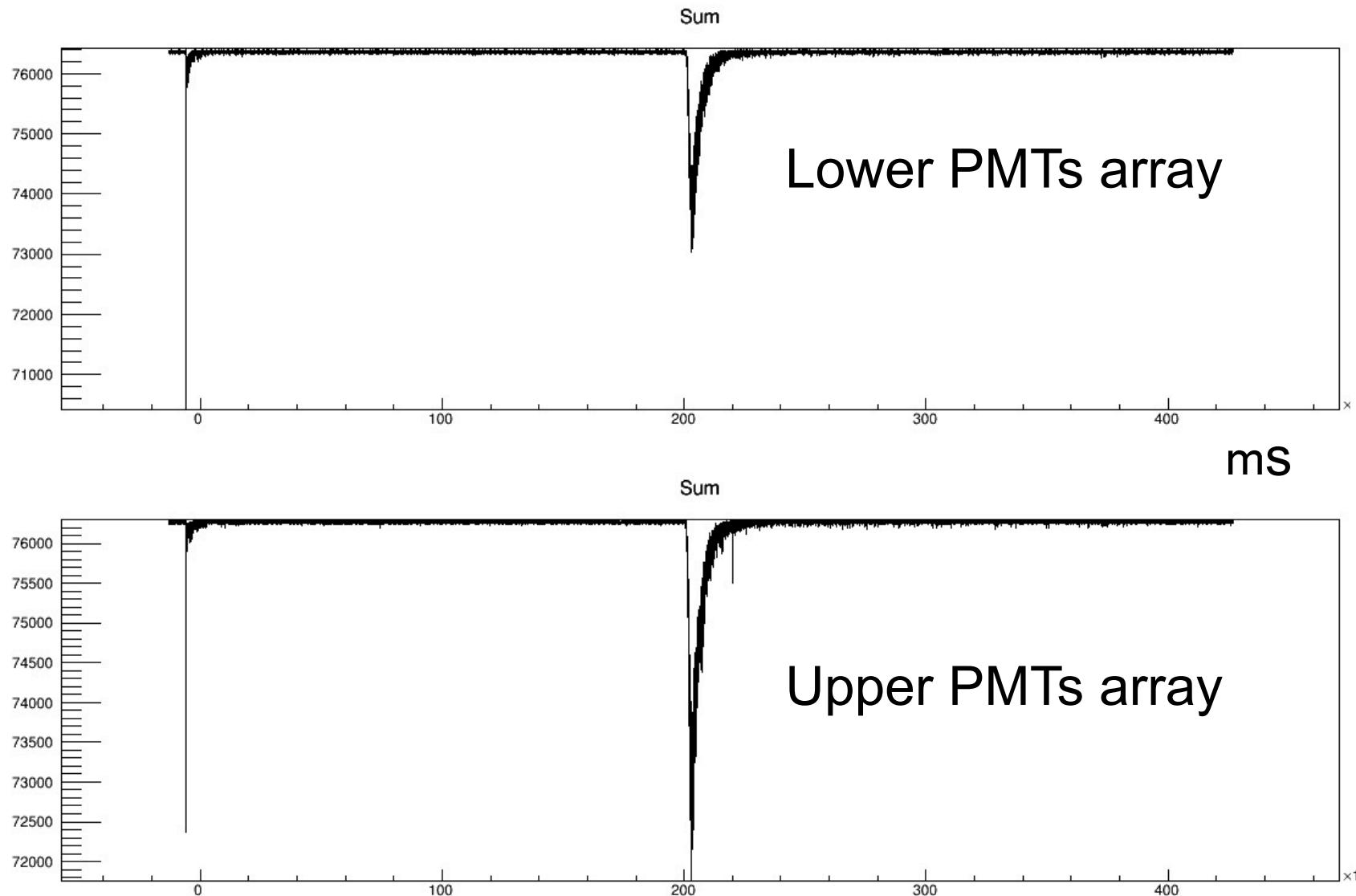
- ◆ Ar Naturally present in the atmosphere at 1% level
- ◆  $^{39}\text{Ar}$  formed by cosmic muon interactions
  - $^{40}\text{K}(\text{n},2\text{n})^{39}\text{Ar}$
- ◆  $^{39}\text{Ar}$  is a b emitter with  $Q_b=565 \text{ keV}$  and  $T_{1/2}=269 \text{ years}$
- ◆ In Ar from the atmosphere,  $^{39}\text{Ar}$  is at the level of 1 Bq/kg
  - $\sim 9 \times 10^4$  decays/kg/day
  - WIMPs(100GeV,  $10^{-45} \text{ cm}^2$ )  $\sim 10^{-4}$  events/kg/day
  - $^{39}\text{Ar}$  is a b emitter with  $Q_b=565 \text{ keV}$  and  $T_{1/2}=269 \text{ years}$
- ◆ **Underground Ar (UAr):** It is possible to obtain Ar depleted in  $^{39}\text{Ar}$  from underground  $\text{CO}_2$ . Present limit on  $^{39}\text{Ar}$ : < 6.5 mBq/kg

# DarkSide program @ LNGS

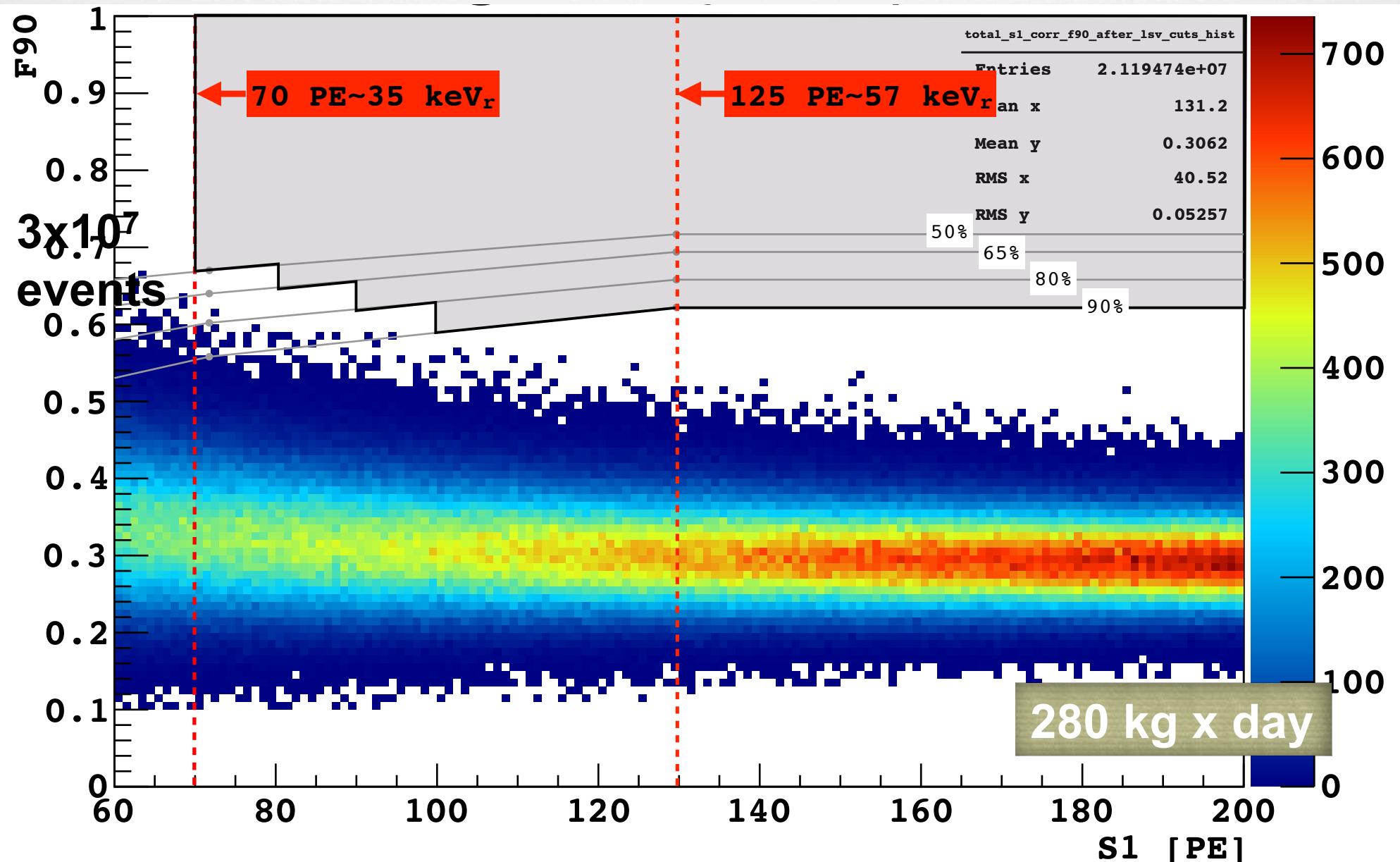
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- ◆ Scalable technology for a two-phase TPC in LAr
  - ✓ **DarkSide-10** (DS-10)
    - 10 kg active mass
    - Operated in 2012 @ LNGS
    - Technical prototype for larger TPC
  - ✓ **DarkSide-50** (DS-50)
    - 50 kg active mass
    - Built inside Borexino CTF Water Tank with active neutron veto
    - Launch technology for next generation detectors (ton scale FM)
    - In operation since Nov 2013
    - Expected WIMP sensitivity  $10^{-45}$  cm $^2$  with UAr
  - ✓ **DarkSide-G2**
    - 3600 kg fiducial mass
    - Can be built inside present DS-50 neutron veto
    - Expected sensitivity  $10^{-47}$  cm $^2$

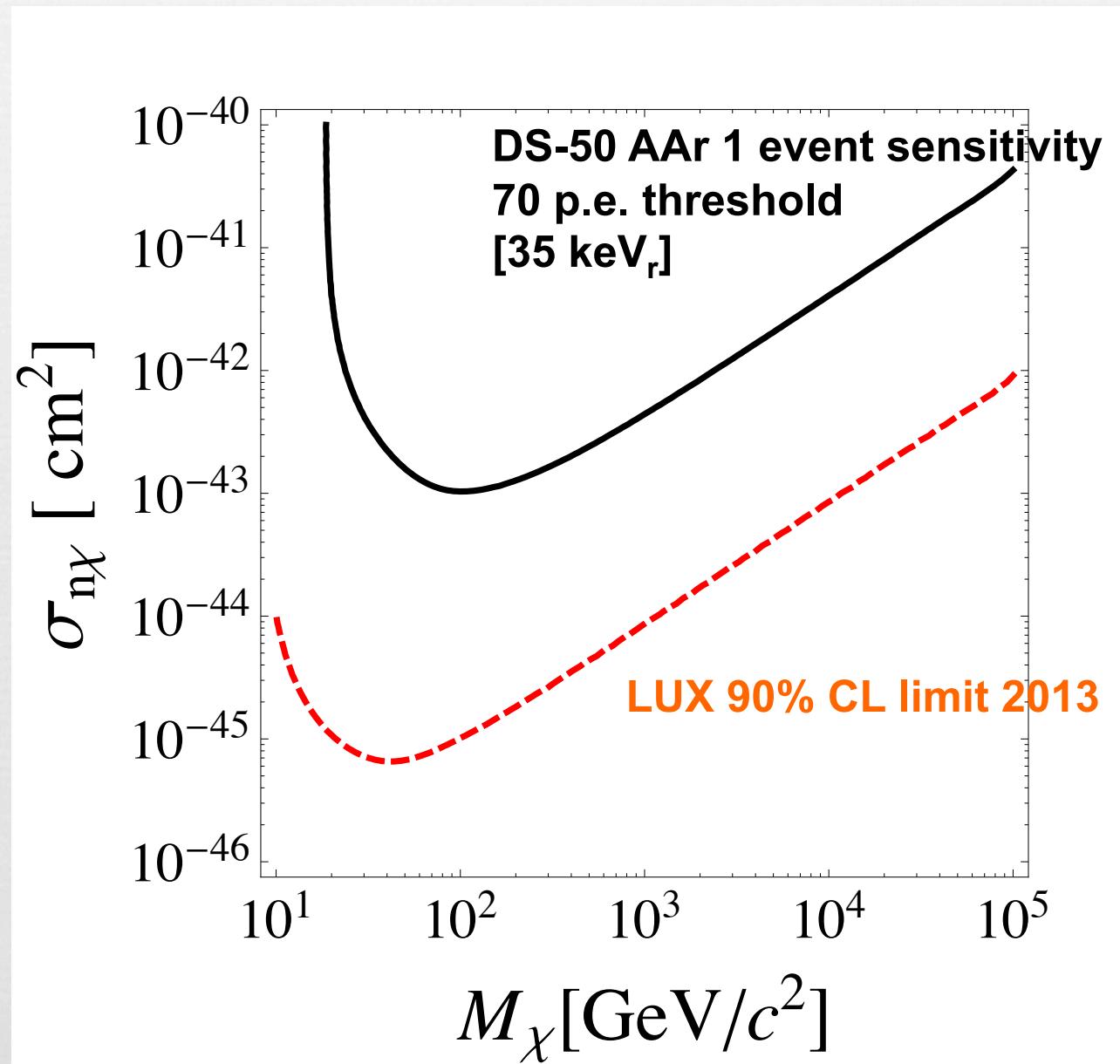
# S1 and S2 signals



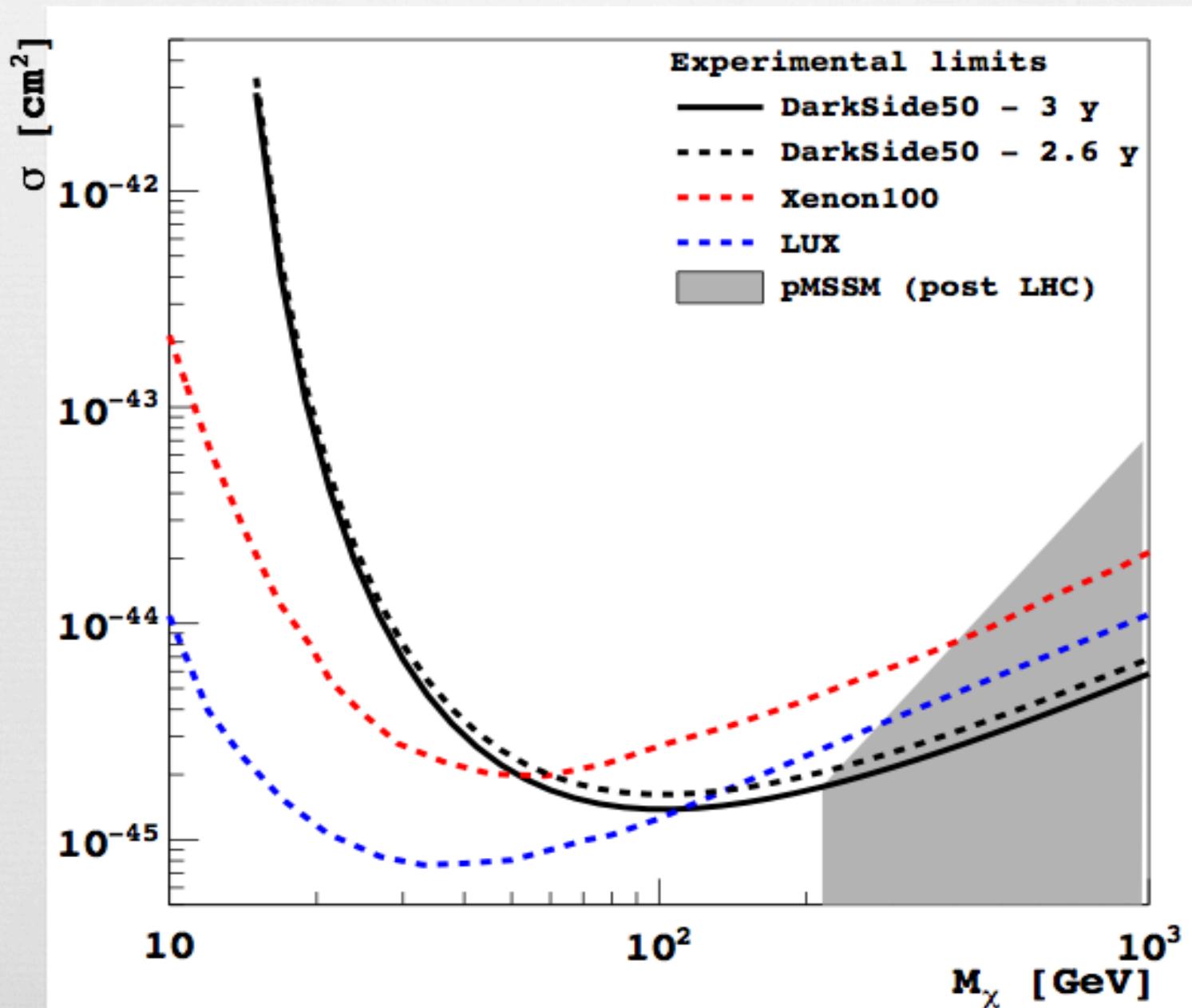
# Pulse Shape $F_{90}$



# DS-50 sensitivity with 280 kg x day

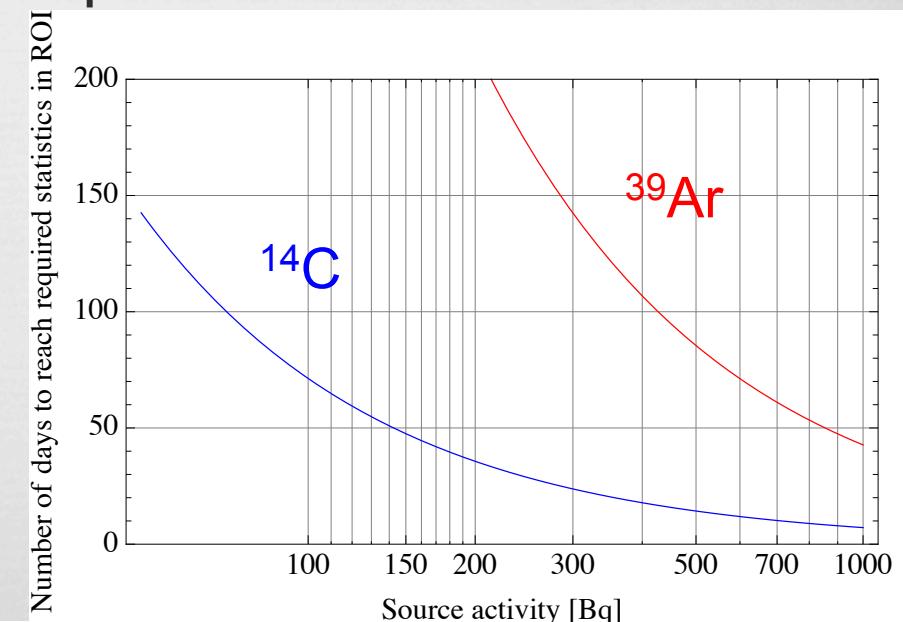


# DS-50 expected sensitivity with UAr



# **$^{39}\text{Ar}$ spike to probe DS-G2 PSD**

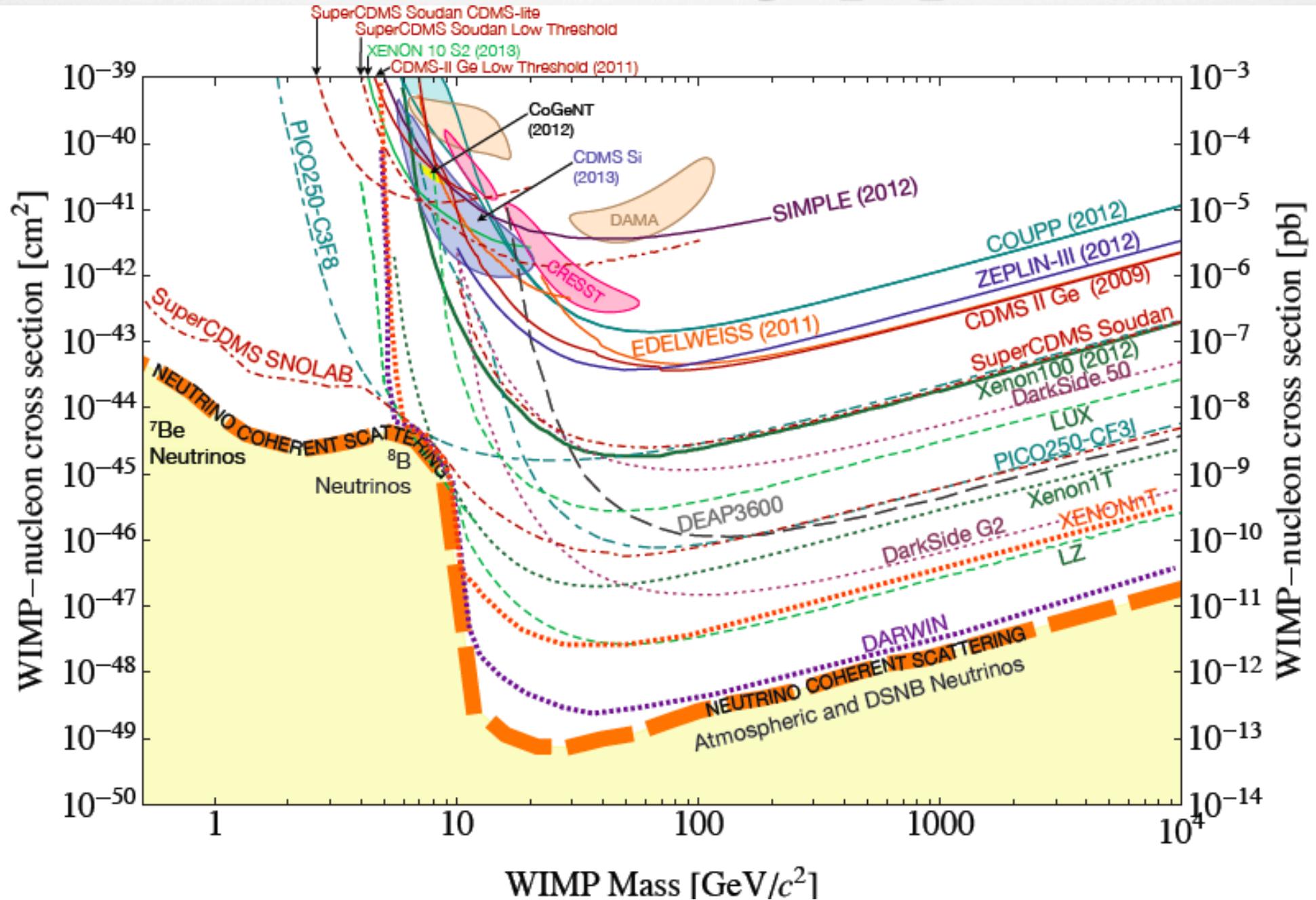
- ❖ DS-G2 will have 3.6 ton fiducial mass and could take data for 5 years (18 ton-year)
- ❖ At  $55 \text{ keV}_r \sim 17 \text{ keV}_{ee} \sim 120 \text{ p.e.}$  the expected  $^{39}\text{Ar}$  events in ROI (1 keV above threshold) is  $7.4 \times 10^6$
- ❖ Generate this number of events to probe PSD by means of b sources



# Summary [1]

- ❖ At present XENON100, LUX and DarkSide-50 at work with LXe and LAr
- ❖ Best sensitivity from LUX set at  $7.6 \times 10^{-46} \text{ cm}^2$  for 33 GeV/c<sup>2</sup>
- ❖ Next generation detectors aim to “zero background” design
- ❖ XENON100 turn to XENON1t (> 2016)
- ❖ LUX will turn to LZ which includes an active Gd-loaded liquid scintillator and 5600 kg FM (> 2016 if funded)
- ❖ DarkSide-50, already operates with a B-loaded liquid scintillator, will turn to DarkSide-G2 with 3600kg FM (> 2017 if funded)
- ❖ Robust case supported by multiple detectors / multiple techniques
- ❖ Ideas to build very massive detectors in LXe and/or LAr to reach ultimate sensitivity
- ❖ Development of low background could allow sensitivity to annual modulation

# Summary [2]



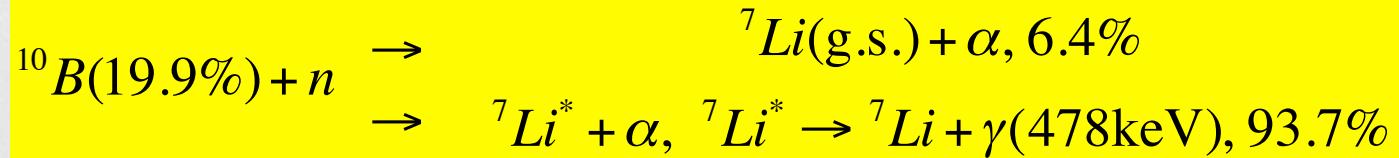
# Spare



# Neutron veto in DarkSide



- ꝝ 30 tons of boron-loaded liquid scintillator
- ꝝ 50% TMB [  $B(OCH_3)_3$  ] + 50% PC + 3 g/l PPO



- ꝝ 108 8" PMTs
- ꝝ High reflectivity of inner surface of containment vessel
- ꝝ n-veto expected performance: < 1 event in 3 years after n-veto rejection and TPC cuts

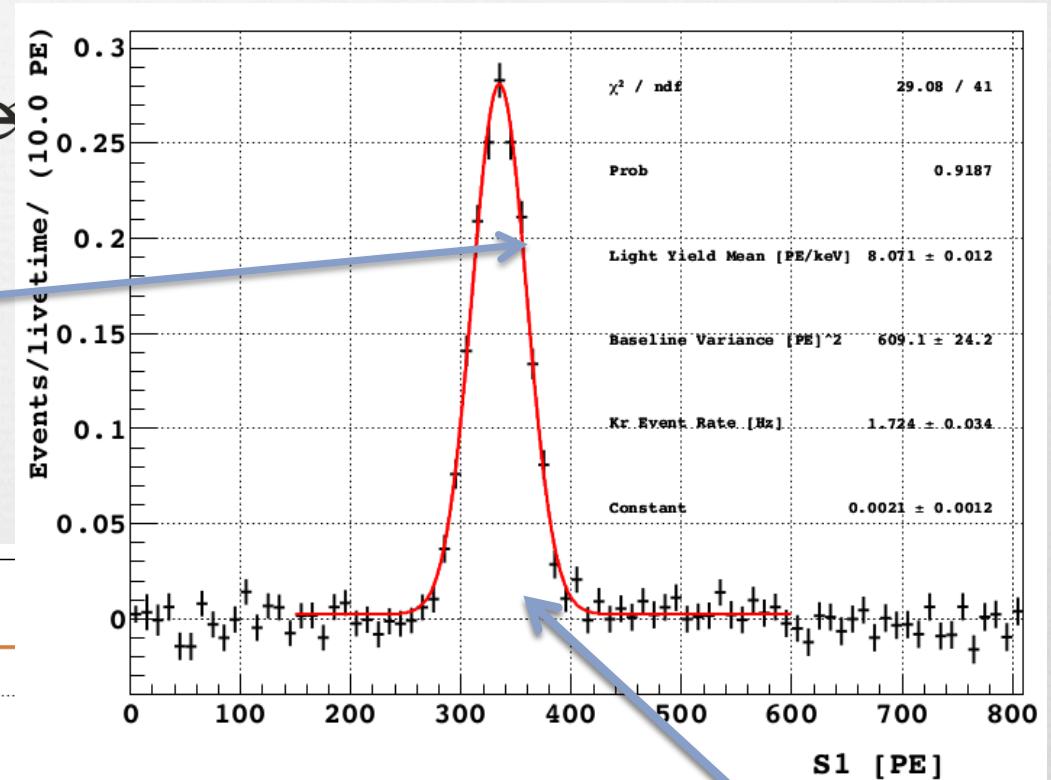
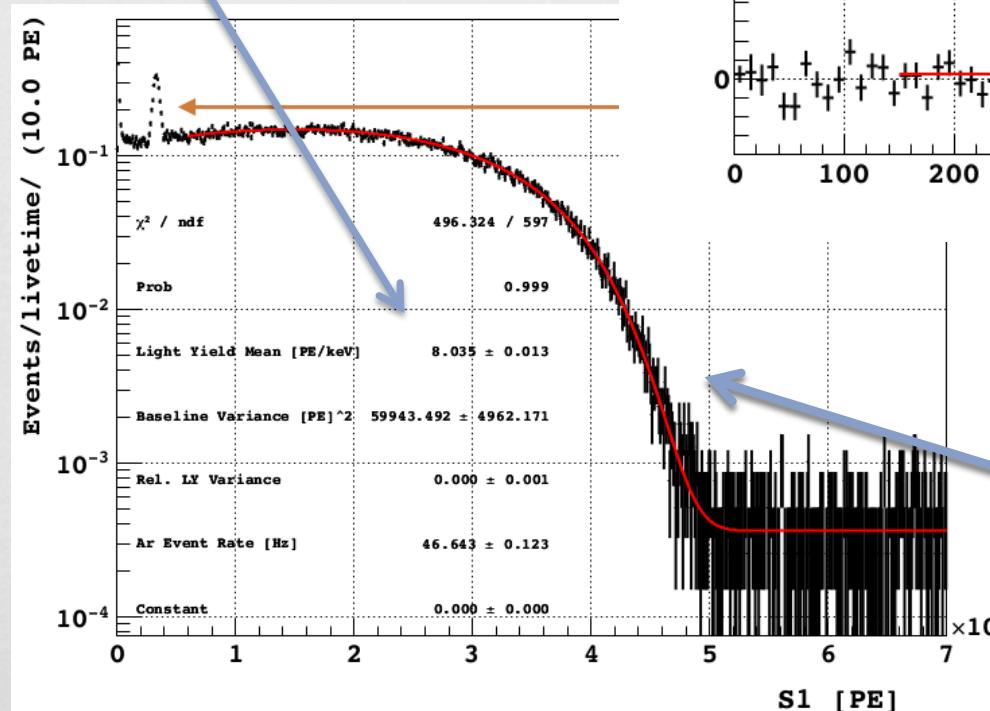
# DarkSide-50 LAr TPC



- ❖ In operation S1/S2 mode with 50 kg AAr
- ❖ Expected 1-2 neutron/month (mainly from measured activity of PMTs) w/o veto cut with R11065 PMTs.
  - ❖ Veto rejection factor = 100:
  - ❖ TPC cuts rejection factor = 30  
need a n-veto
- ❖ In operation with 38 3" R11065 PMTs
  - Gain stability 1-2%
  - HV:  $E_{\text{drift}} = 200 \text{ V/cm}$ ,  $E_{\text{extraction}} = 2.8 \text{ kV/cm}$
  - Light yield  $\sim 8 \text{ p.e./keVee}$
  - Electron lifetime  $\sim 5\text{ms}$ 
    - To compare with max drift time of  $\sim 400 \text{ ms}$
  - $^{83\text{m}}\text{Kr}$  internal calibration (two times) 41.5 keVee sum line

# DS-50 Light yield @ null field

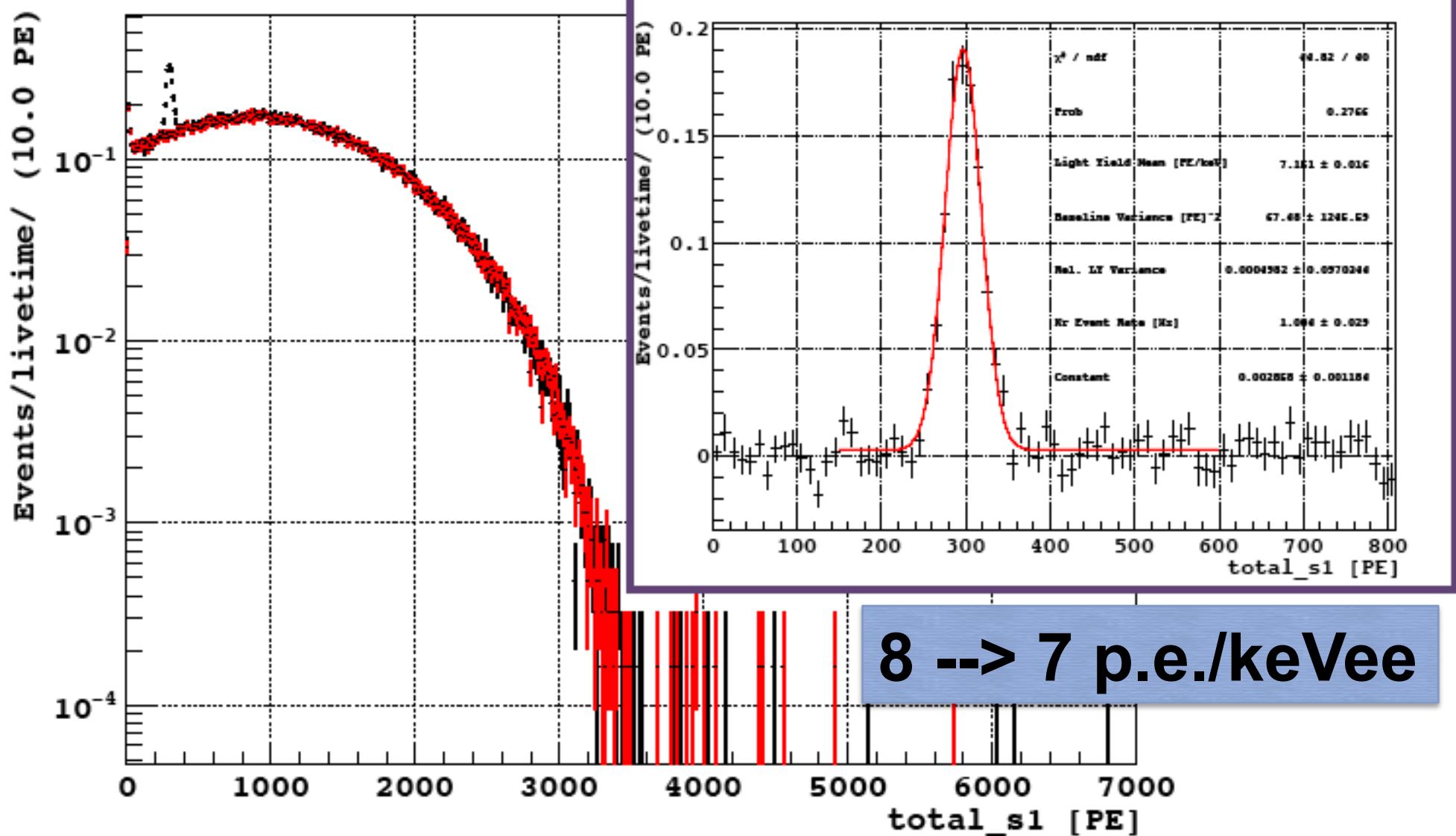
Light Yield  $\sim 8$  pe/keV<sub>ee</sub>  
at null field



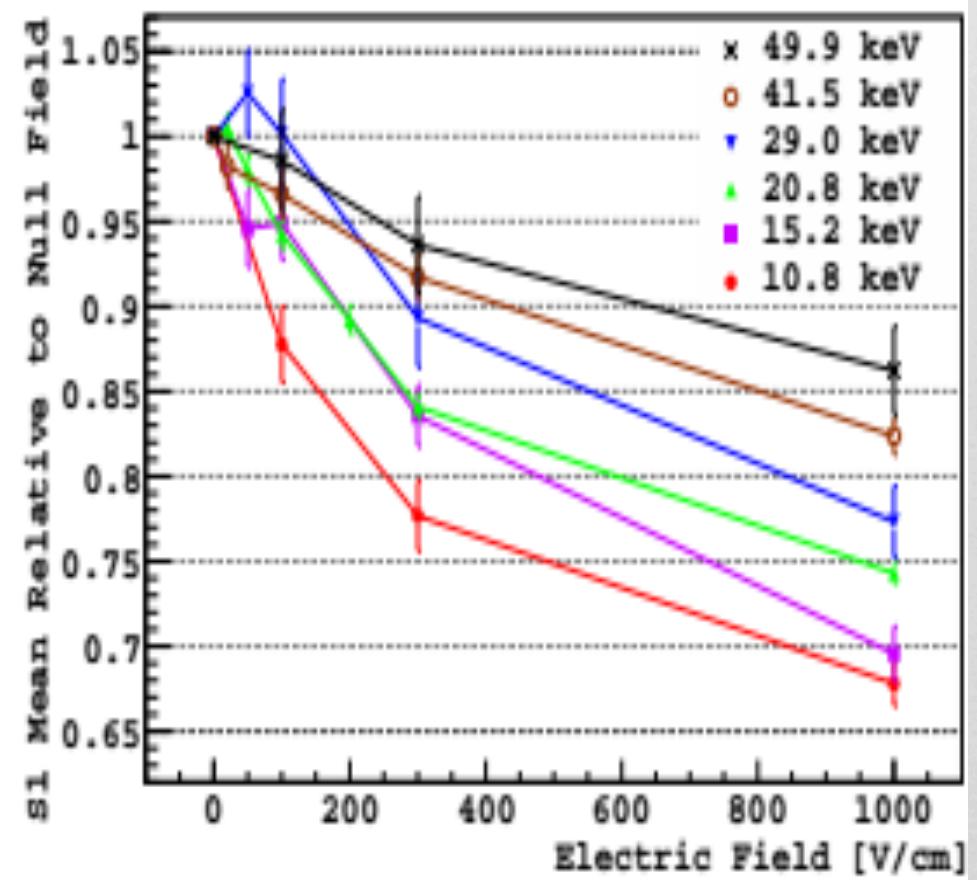
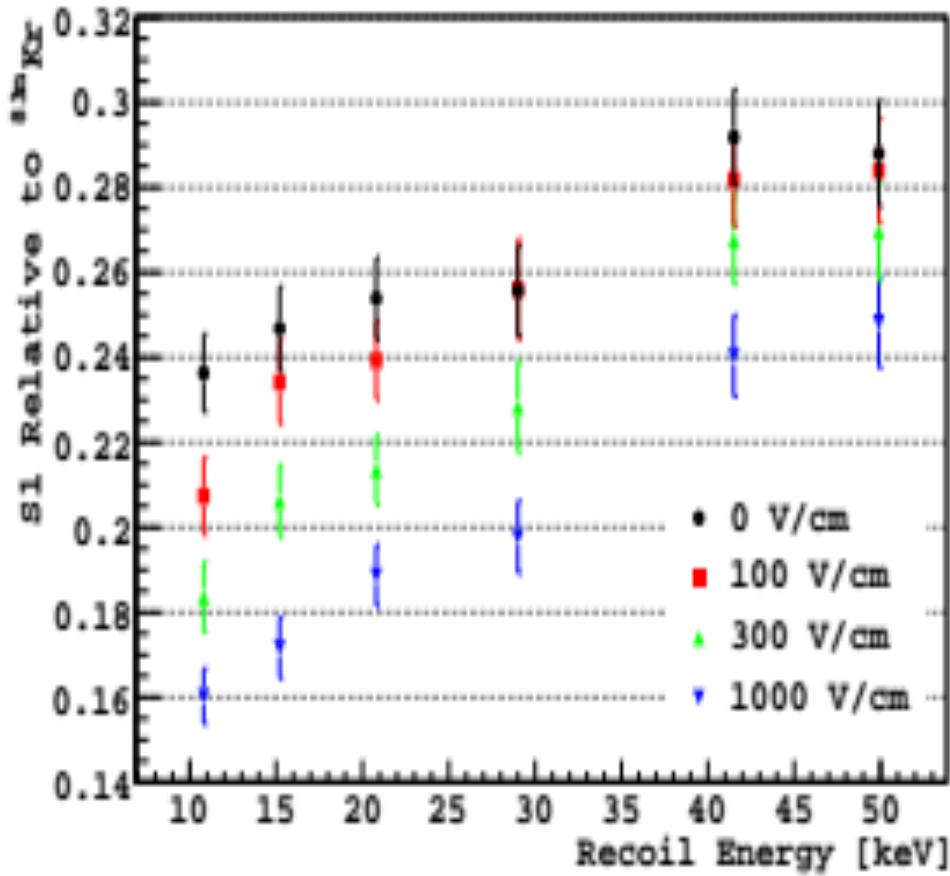
$^{83m}\text{Kr}$  peak  
41.5 keV,  $T_{1/2} = 1.83\text{h}$

$^{39}\text{Ar}$  spectrum  
565 keV

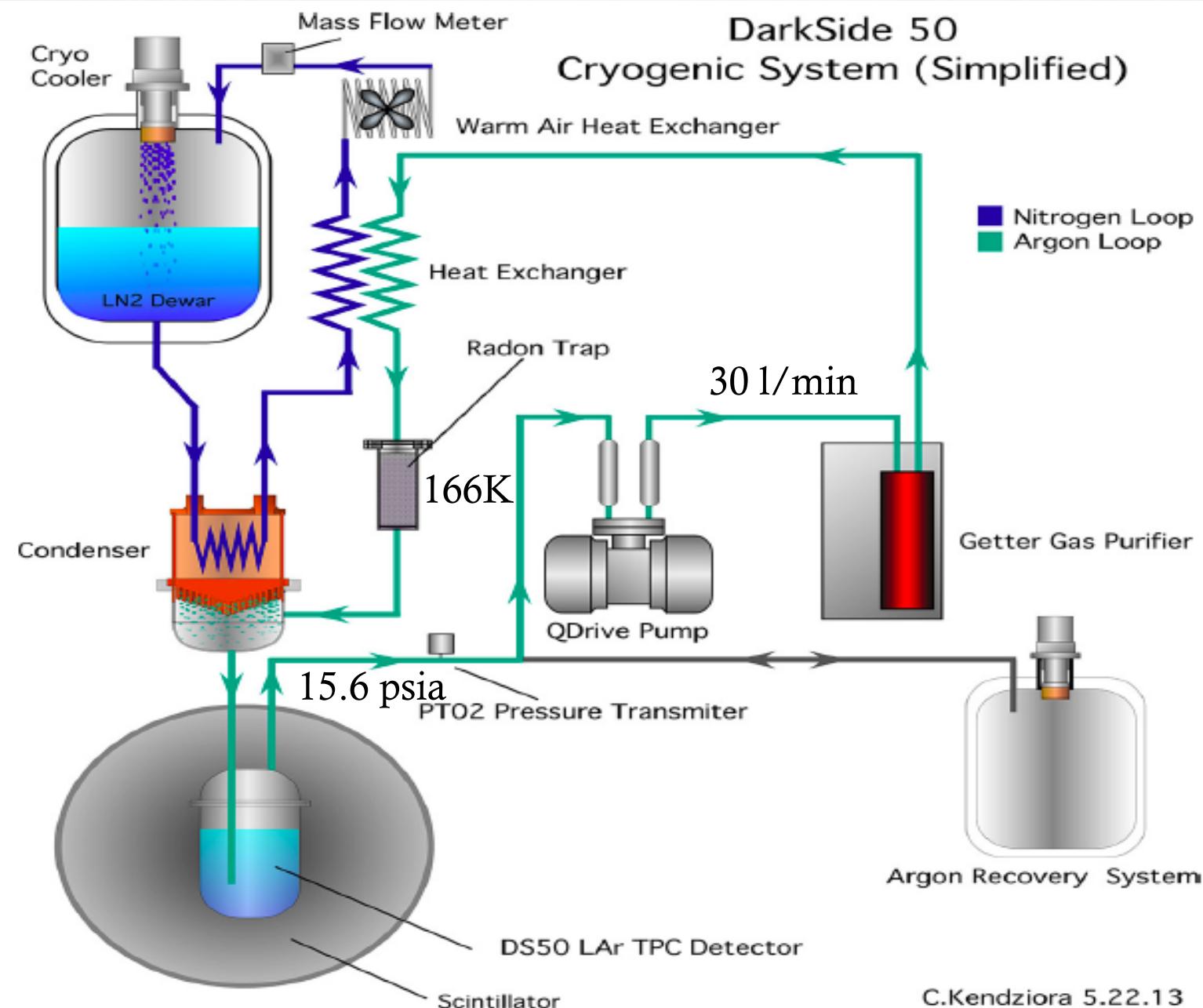
# DS-50 Light Yield @ 200V/cm



# Scene: set-up to study recoil energy scale in LAr



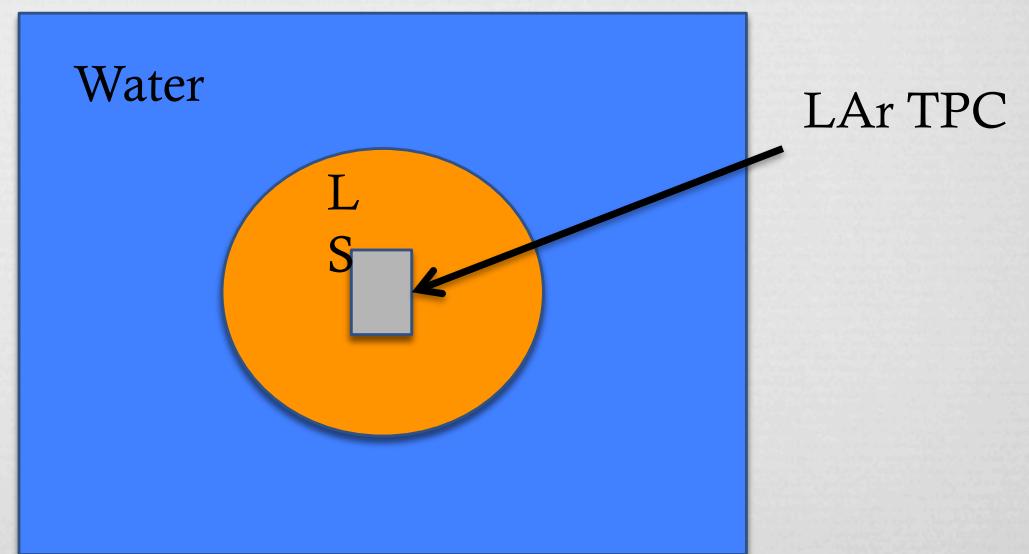
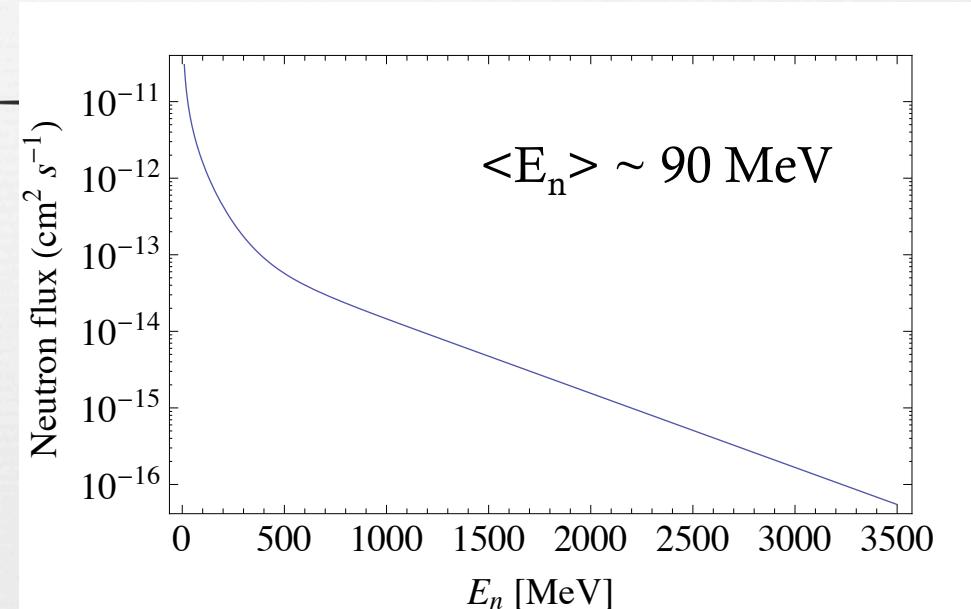
# Cryogenic for DS-50 TPC



# Cosmogenic Neutrons

- Flux at Gran Sasso lab:
  - ✓  $2.4 \text{ m}^{-2} \text{ day}^{-1}$
  - ✓  $0.7 \text{ m}^{-2} \text{ day}^{-1}$  for  $> 10 \text{ MeV}$
- Expected rate  $\sim 3 \times 10^{-33} / \text{s/atom}$
- WIMPS rate  $\sim 10^{-34} / \text{s/atom}$
- Neutrons from surrounding rocks reduced by shielding
  - ✓ In DS-50 3m of water  $\sim 10^{-3}$  and 0.04 from 1.5m of liquid scintillator:  $\sim 4 \times 10^{-5}$

m-induced neutron →  
→  
→



# Underground Argon

$^{39}\text{Ar}$  depletion factor  $>10$   
from direct counting,  $>50$  from  
spectral fit with surface detector

In progress study with counting  
detector underground at KURF  
(1400 m.w.e.) Virginia, USA

