Direct Detection of Dark Matter

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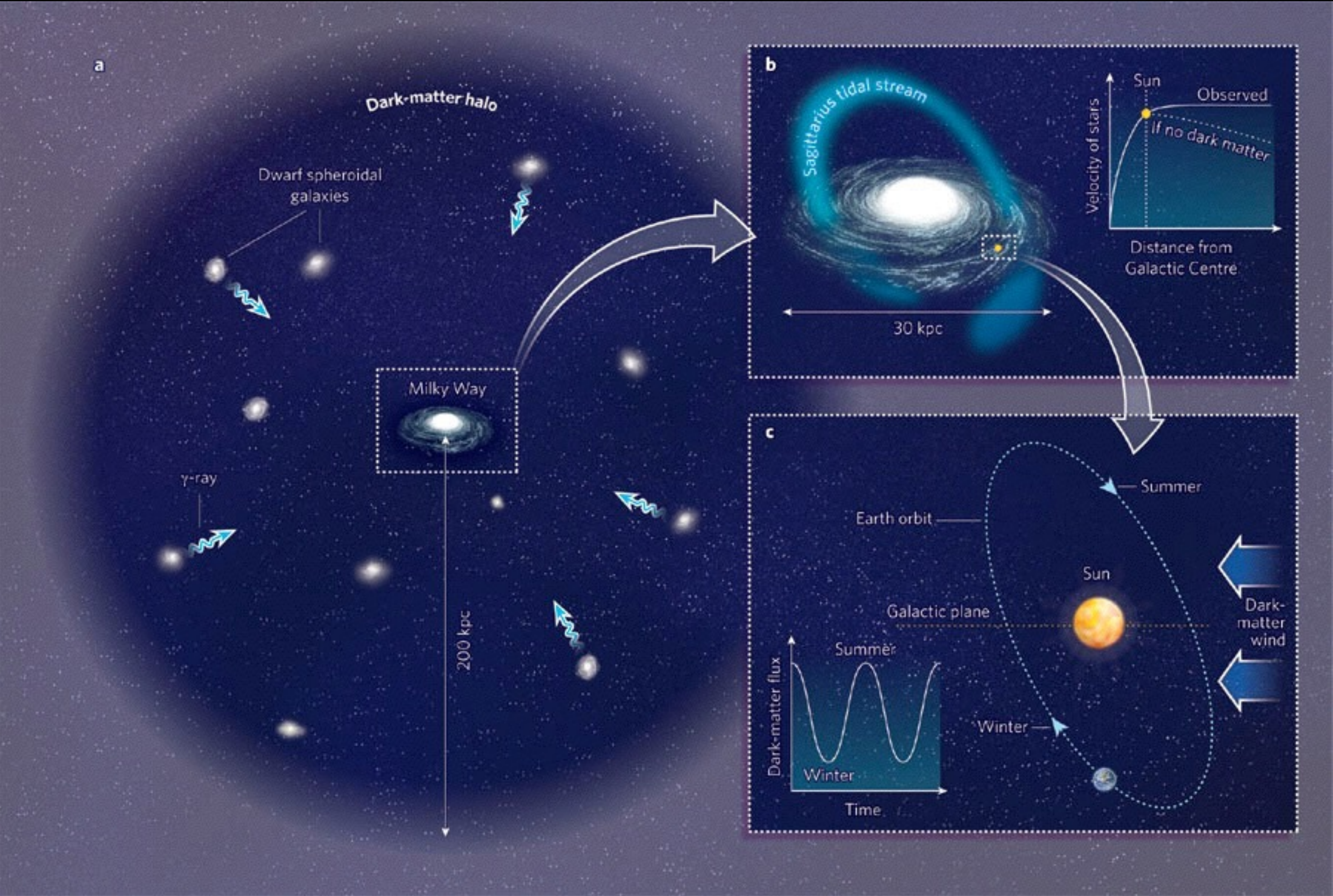
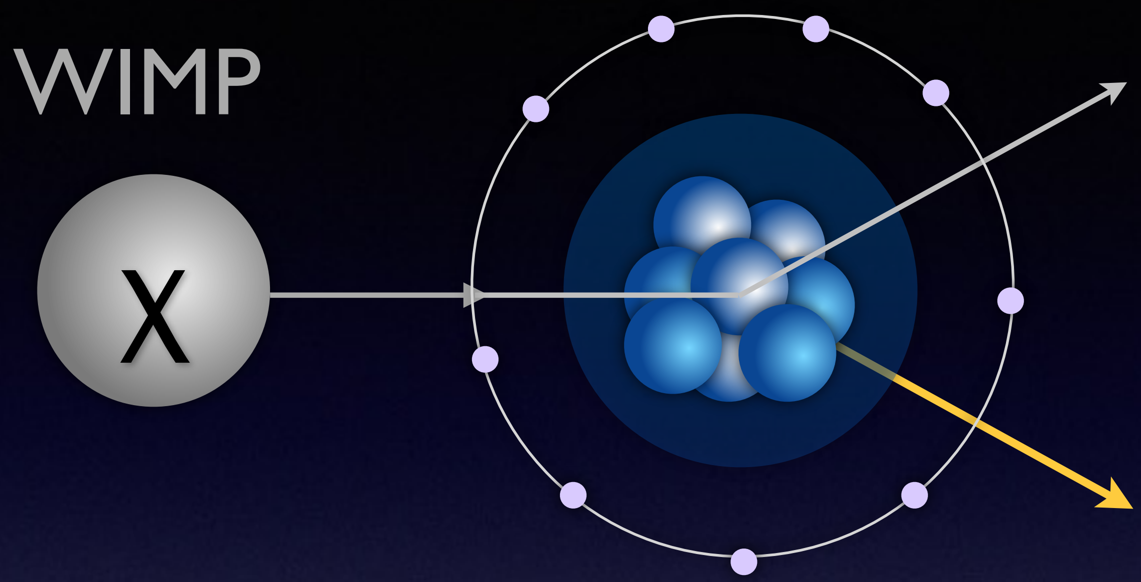


From Cosmology: Dark matter and dark energy
Robert Caldwell & Marc Kamionkowski
Nature 458, 587-589(2 April 2009)
doi:10.1038/458587a

WIMPs galactic wind

WIMP direct detection



$\chi N \rightarrow \chi N$

elastic scattering off nuclei

M. Goodman, E. Witten, PRD 1985

$$E_0 = \frac{1}{2} m_\chi c^2 \beta^2$$

$$r = \frac{4 m_\chi m_N}{\left(m_\chi + m_N\right)^2}$$

$$E_R = E_0 r \frac{\left(1 - \cos\theta\right)}{2}$$

$\beta \approx 10^{-3}$

$m_\chi \approx 1 \div 1000$ GeV

Nucleus recoil energy < 1÷100 keV

Spin Independent:

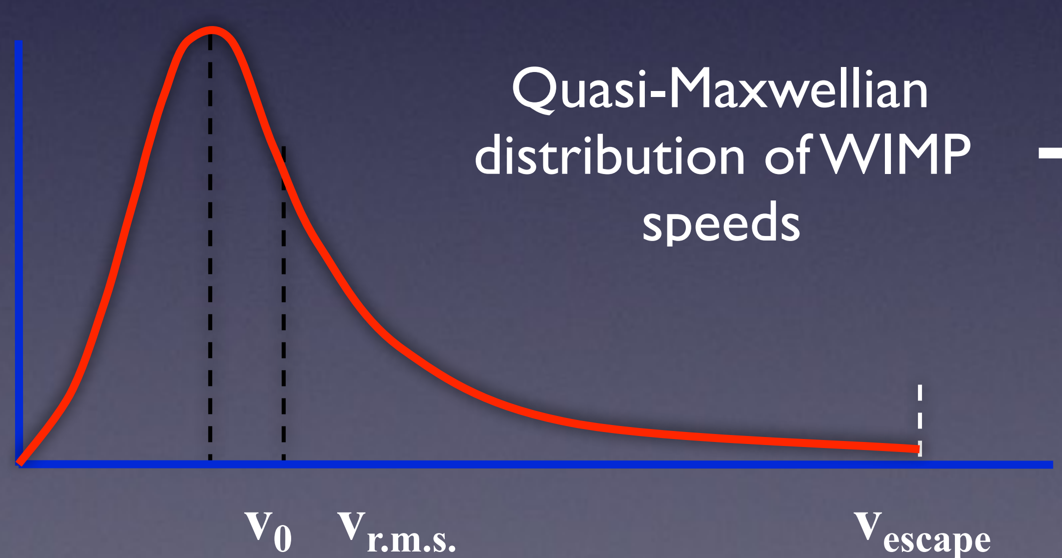
χ scatters coherently off of the entire nucleus A: $\sigma \sim A^2$

Spin Dependent:

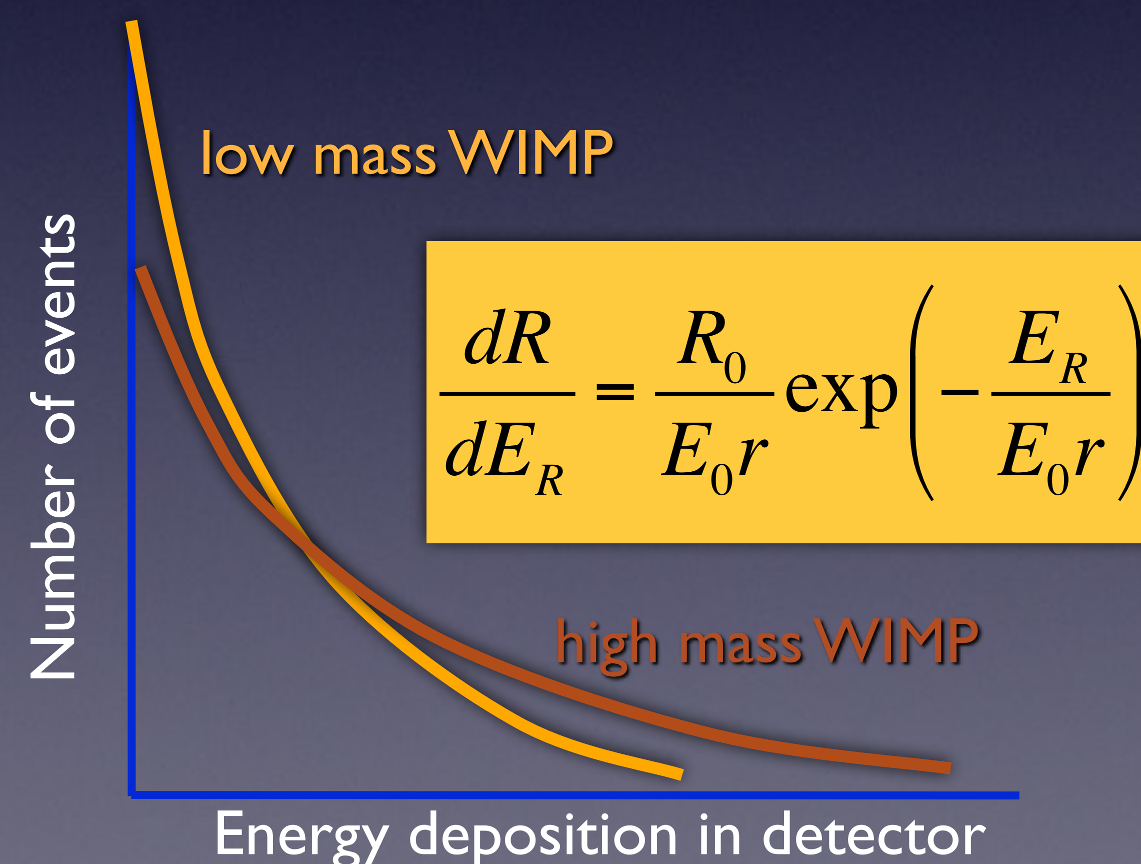
only unpaired nucleons contribute to scattering amplitude: $\sigma \sim J(J+1)$

Expected rate: vanilla model

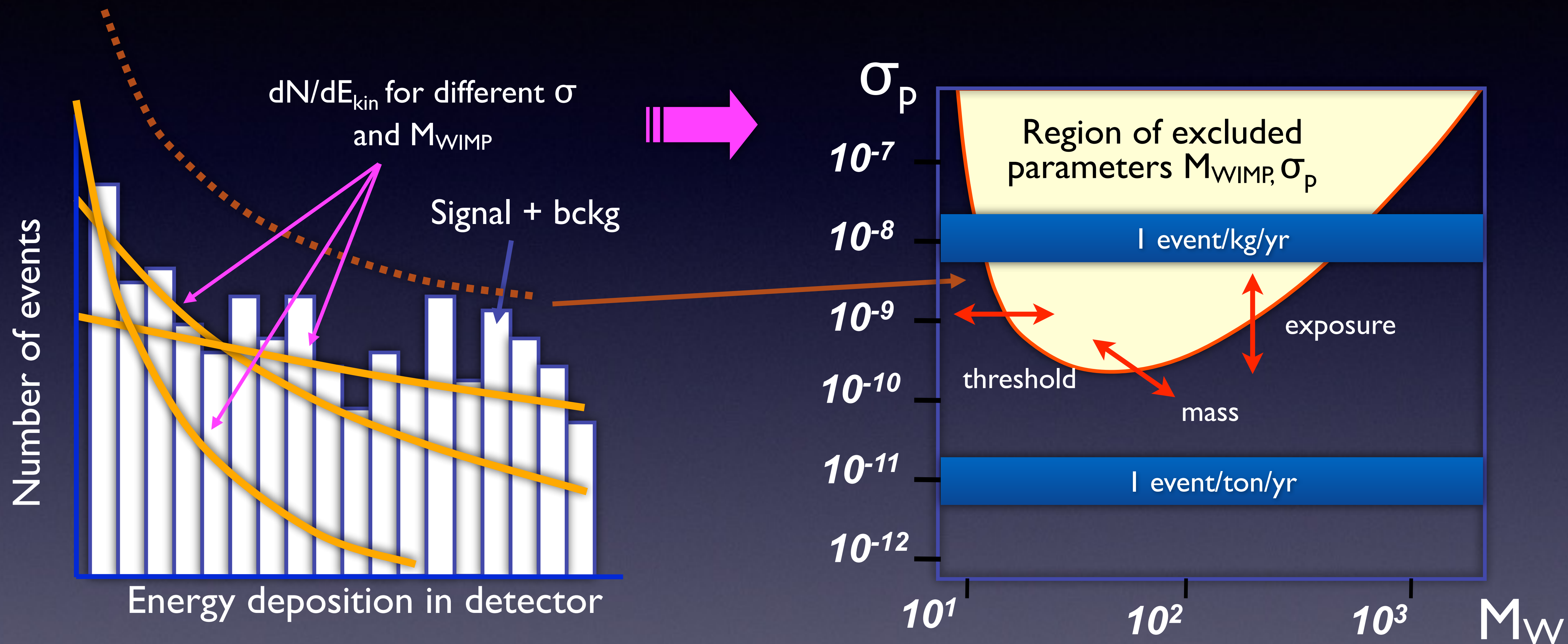
$$\frac{dR}{dE_R} = N_T \frac{\rho_0}{m_W} \int_{\mathrm{v}_{min}}^{\mathrm{v}_{max}} d\mathrm{v}\, f(\mathrm{v})\, \mathrm{v} \frac{d\sigma}{dE_R}$$



Quasi-Maxwellian distribution of WIMP speeds



Vanilla model: exclusion plot

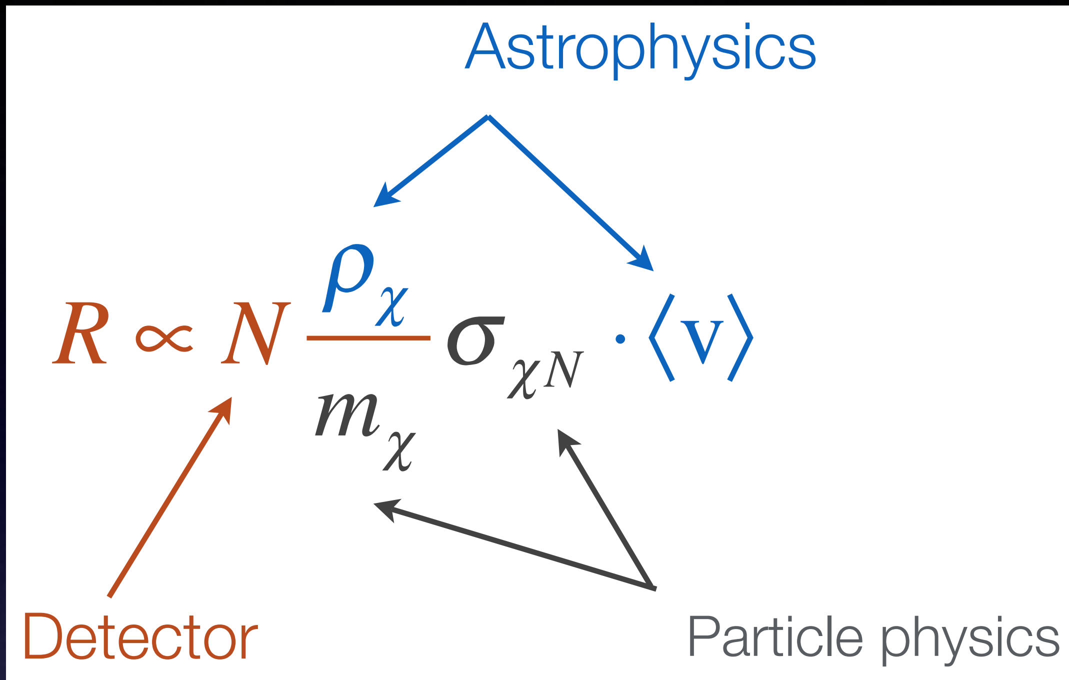


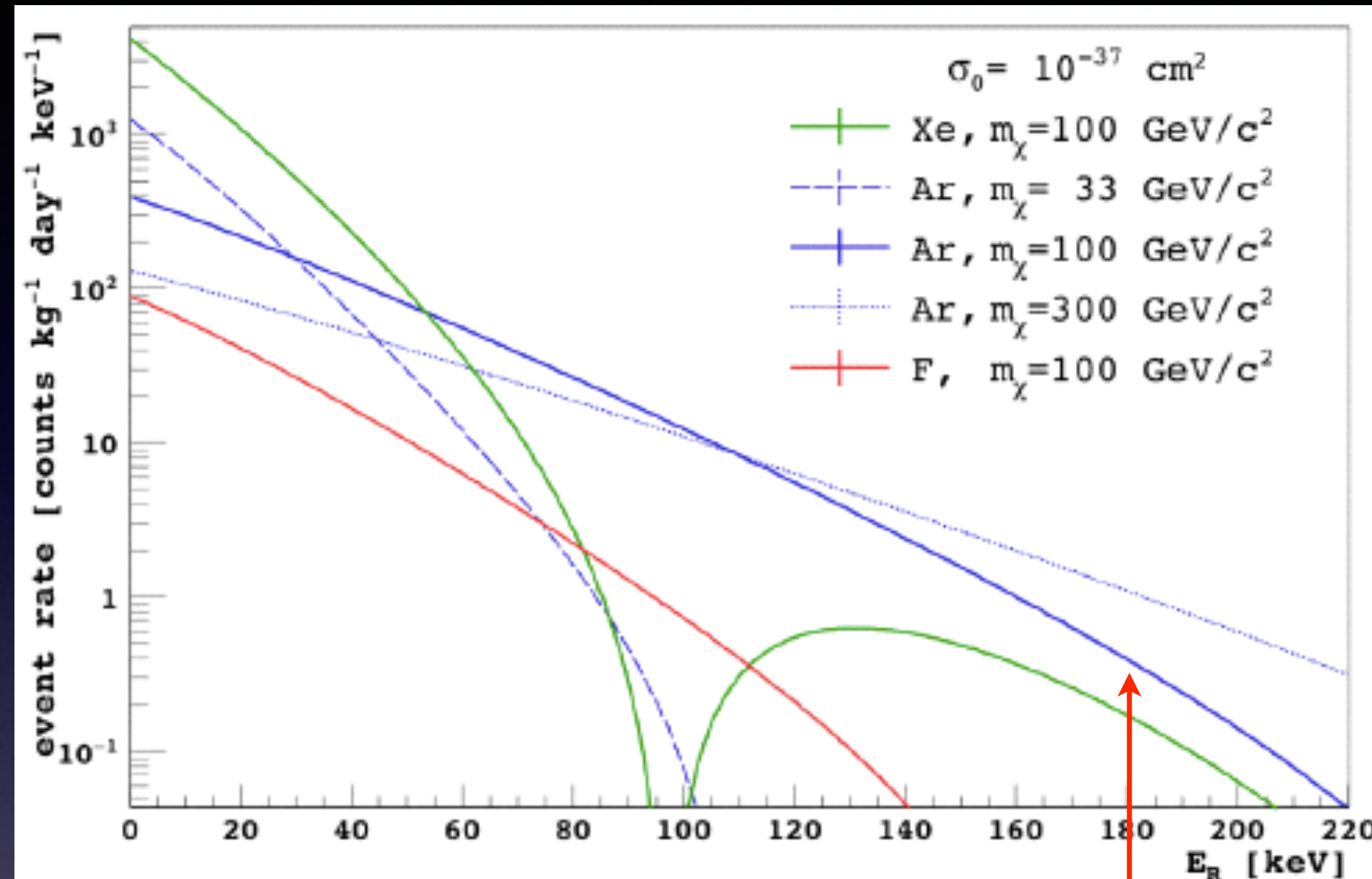
Exponential behavior is very similar to that of bckg of various origins.

Background knowledge/reduction essential

Measurement

Choice of target





Sun's velocity around the galaxy $\langle v \rangle \approx$ 230 km/s
WIMP energy density $\rho_\chi \approx$ 0.3 GeV/cm^3
WIMP cross section $\sigma = 10^{-47}$ cm^2

⇒ R ≈ 1 evt/ton/yr

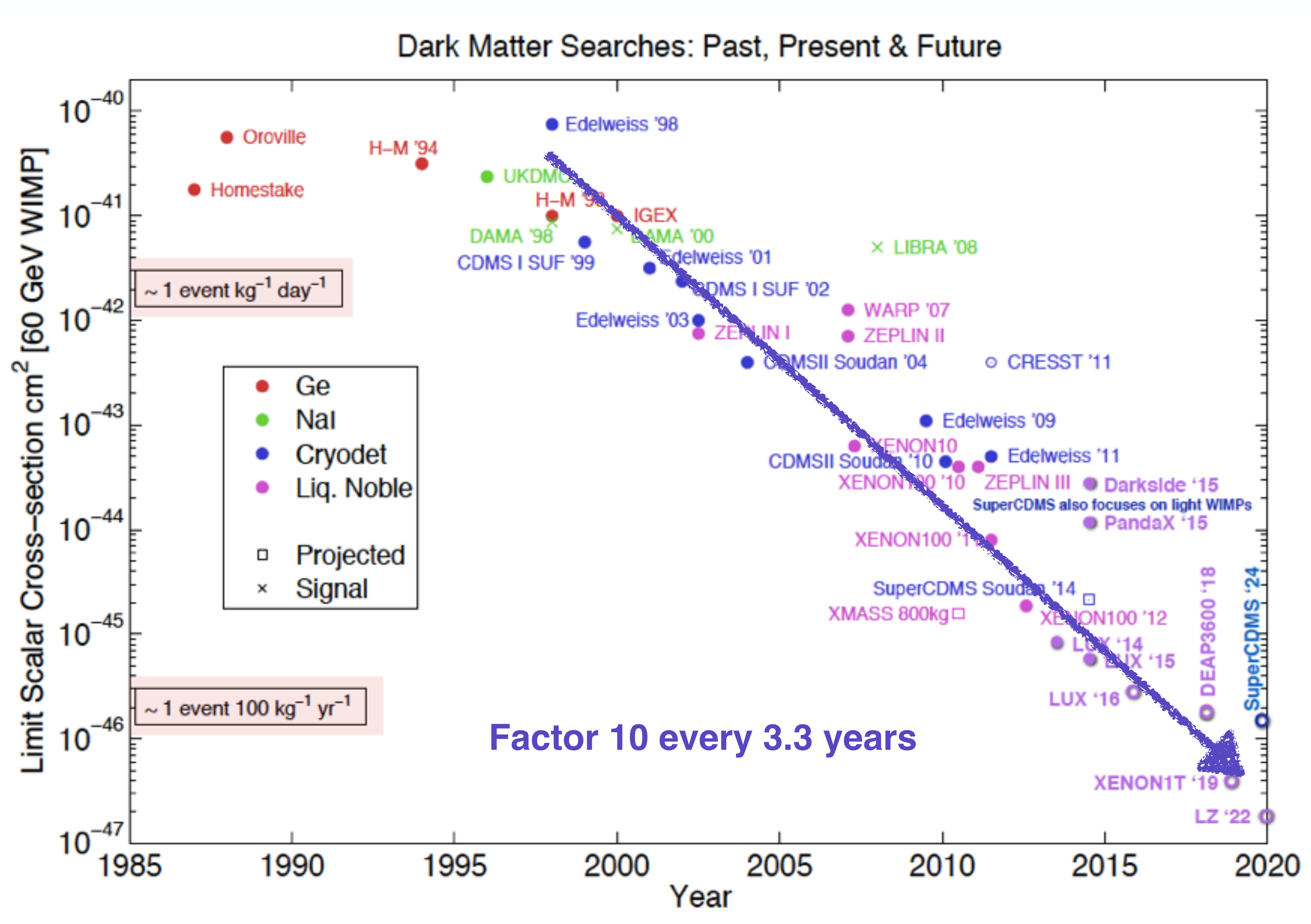
- Large detector mass, long exposure
- Low energy threshold
- Ultra-low radioactive bg
- Good bg discrimination

$$\left.\frac{dR}{dE_R}\right|_{Ideal} = \frac{R_0}{E_0 r} \exp\left(-\frac{E_R}{E_0 r}\right)$$

$$\left.\frac{dR}{dE_R}\right|_{True} = \left.\frac{dR}{dE_R}\right|_{Ideal} \times \left[S(E_R) F^2(q^2) I\right]$$

J.D. Lewin, RF. Smith, Astroparticle Physics 6 (1996) 87-112

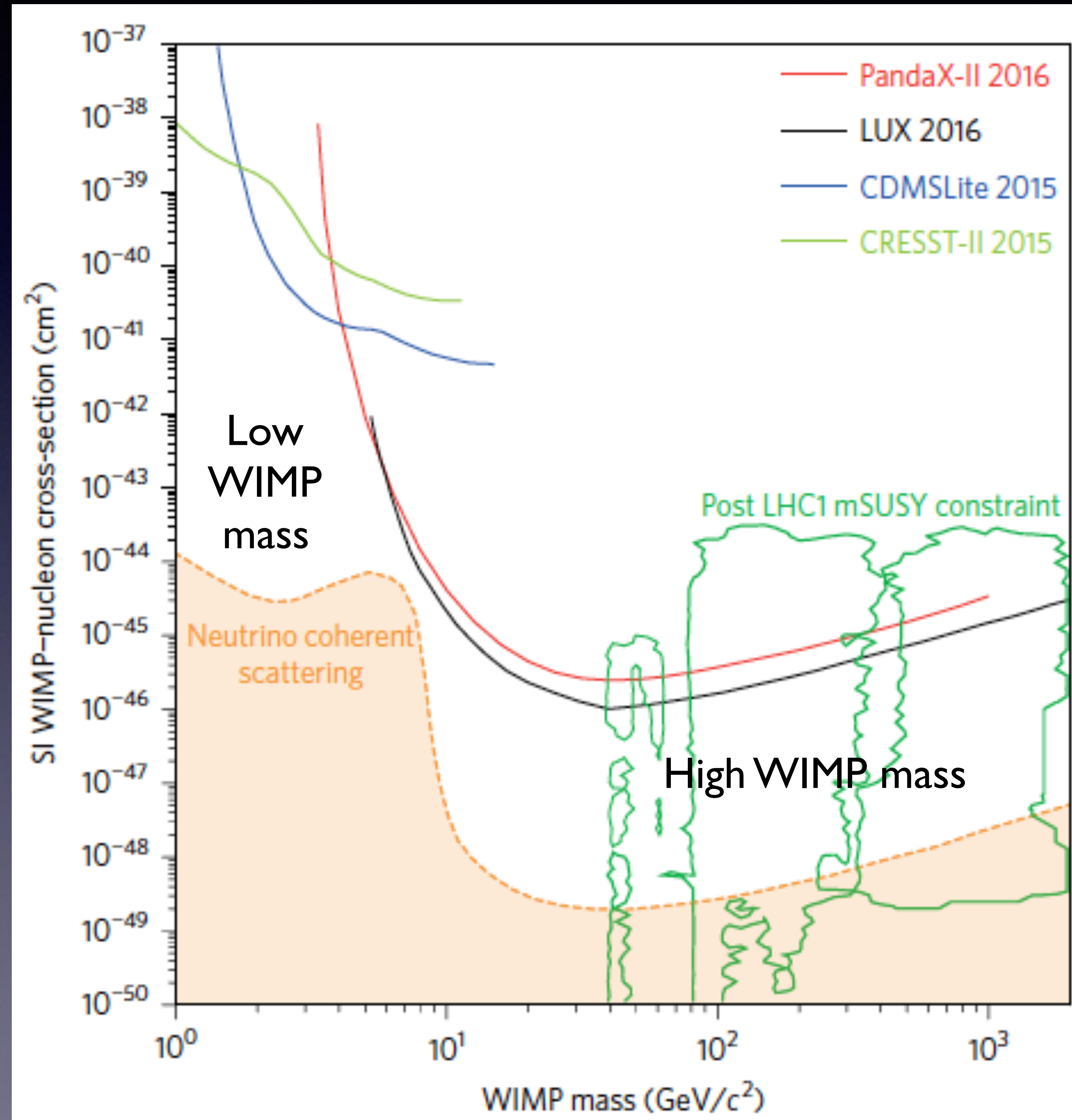
WIMP search sensitivity improvement in time



R. Gaitskell IDM2016

Available parameter space for WIMPs

- High mass
  - no observations so far
- Low mass
  - a number of close contours and exclusion limits



NATURE PHYSICS DOI: 10.1038/NPHYS4039

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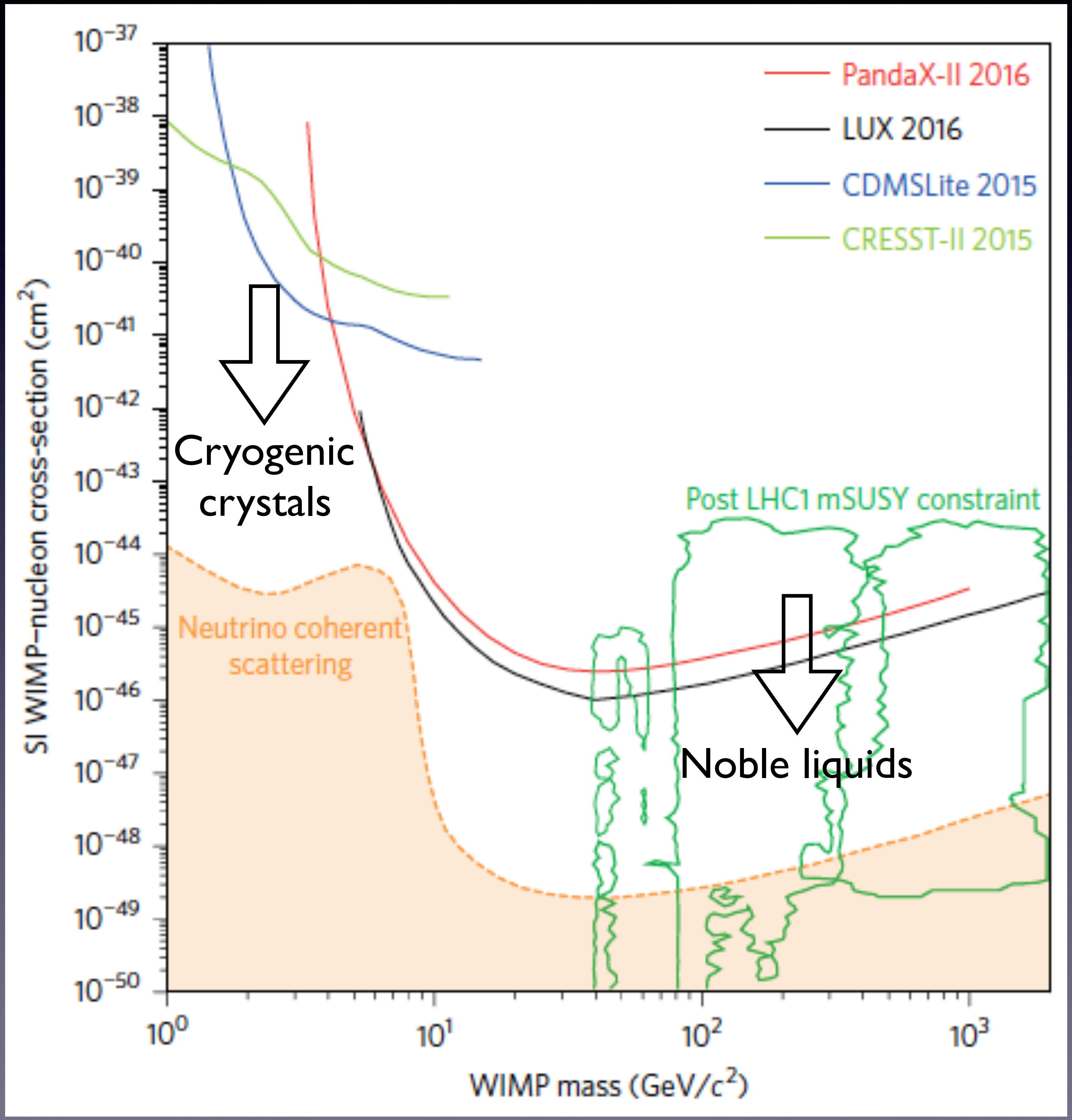


Reaching the Neutrino Floor

irreducible neutrino background (from coherent nuclear recoils) due to several astrophysical sources (Sun, atmosphere, and diffuse Supernovae)

Coherent neutrino scattering on Nucleus (CNS)

$$\nu_x + (A,Z) \rightarrow \nu_x + (A,Z)$$

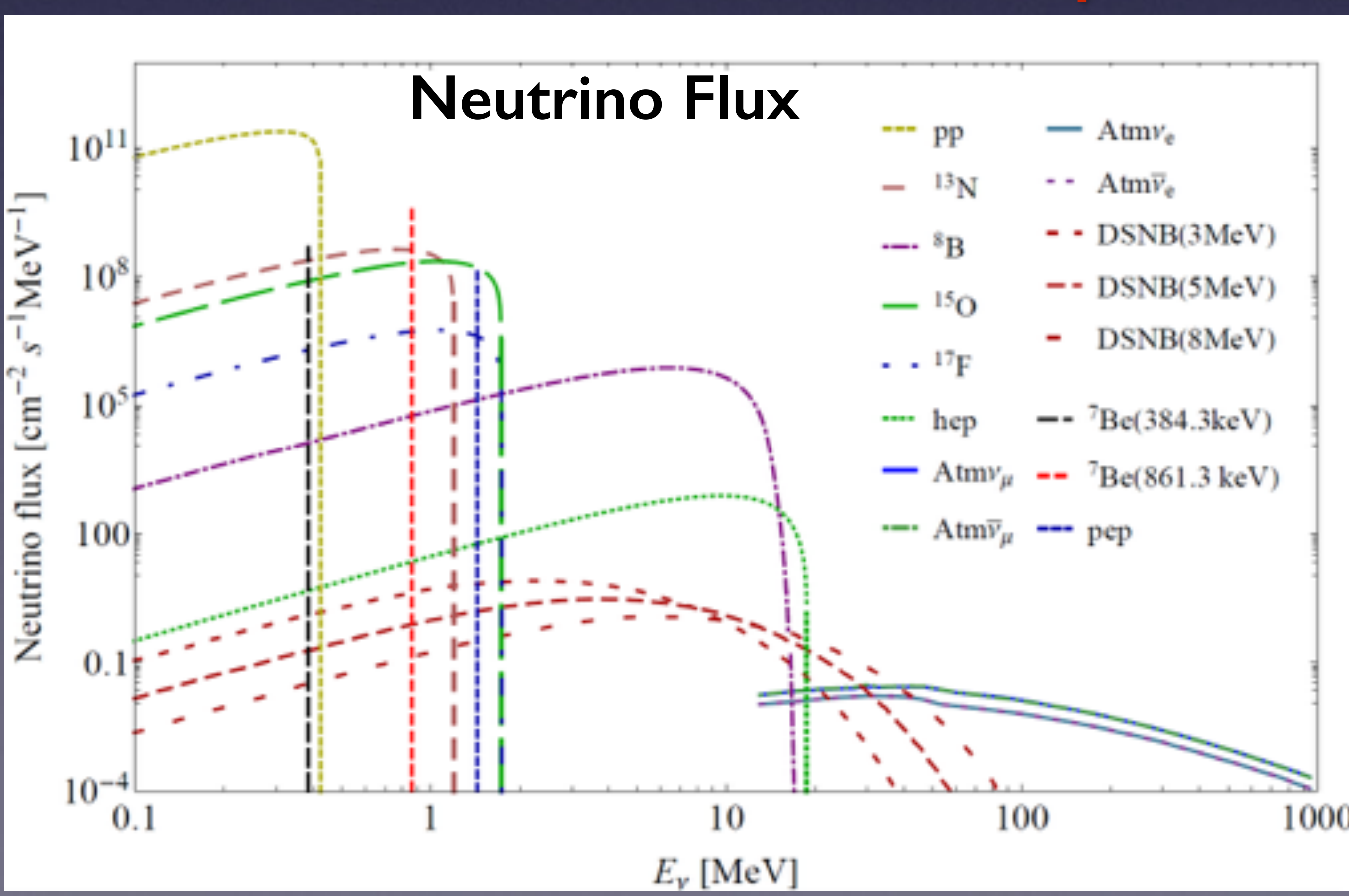
$$\frac{d\sigma^{CNS}(E_\nu, E_r)}{dE_r} = \frac{G_f^2}{4\pi} Q_w^2 m_N \left(1 - \frac{m_N E_r}{2E_\nu^2}\right) F^2(E_r)$$

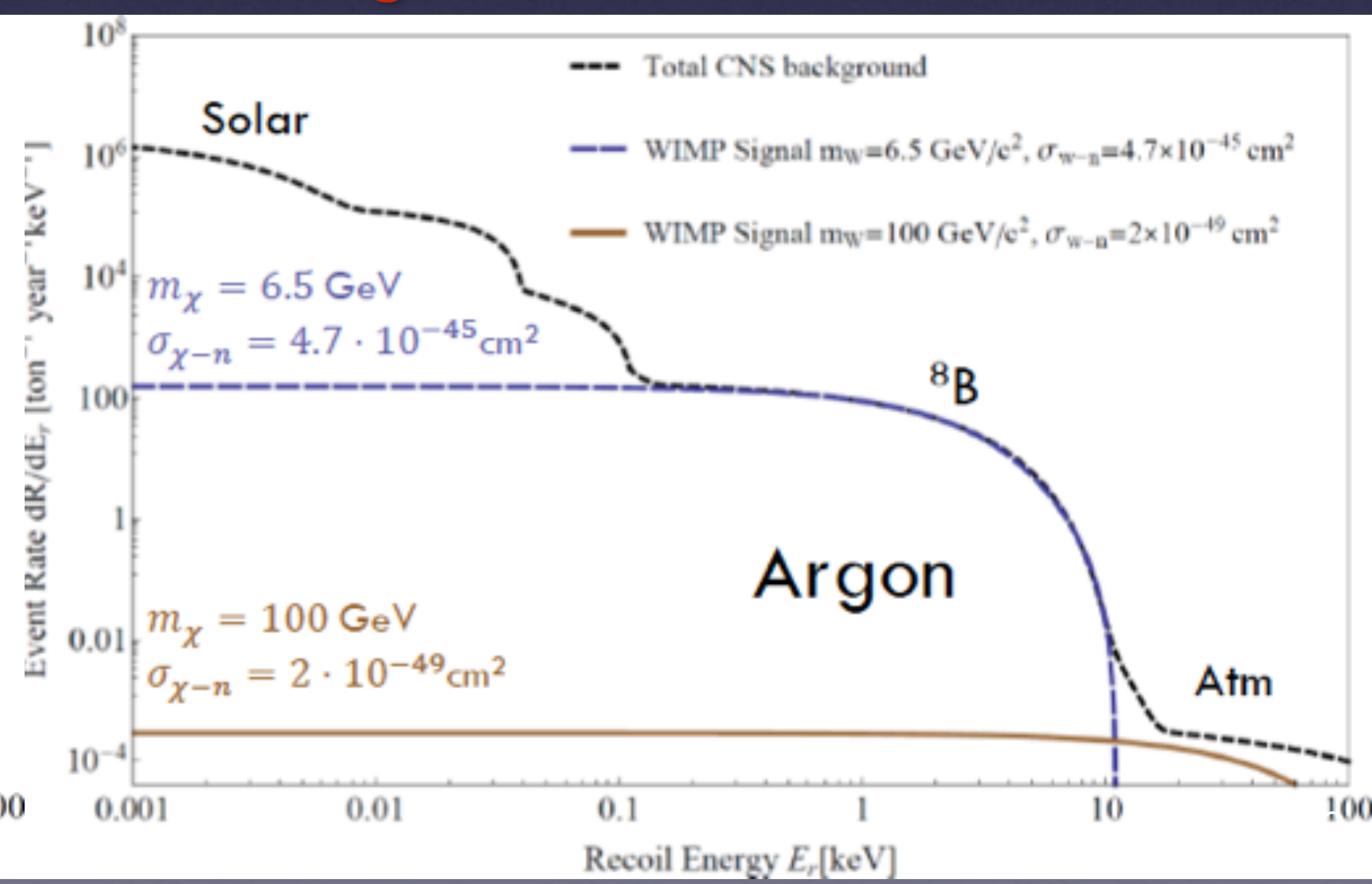
$$E_r^{max} = \frac{2E_\nu^2}{m_N + 2E_\nu}$$

$$Q_w = N - (1 - 4\sin^2\theta_W)Z$$

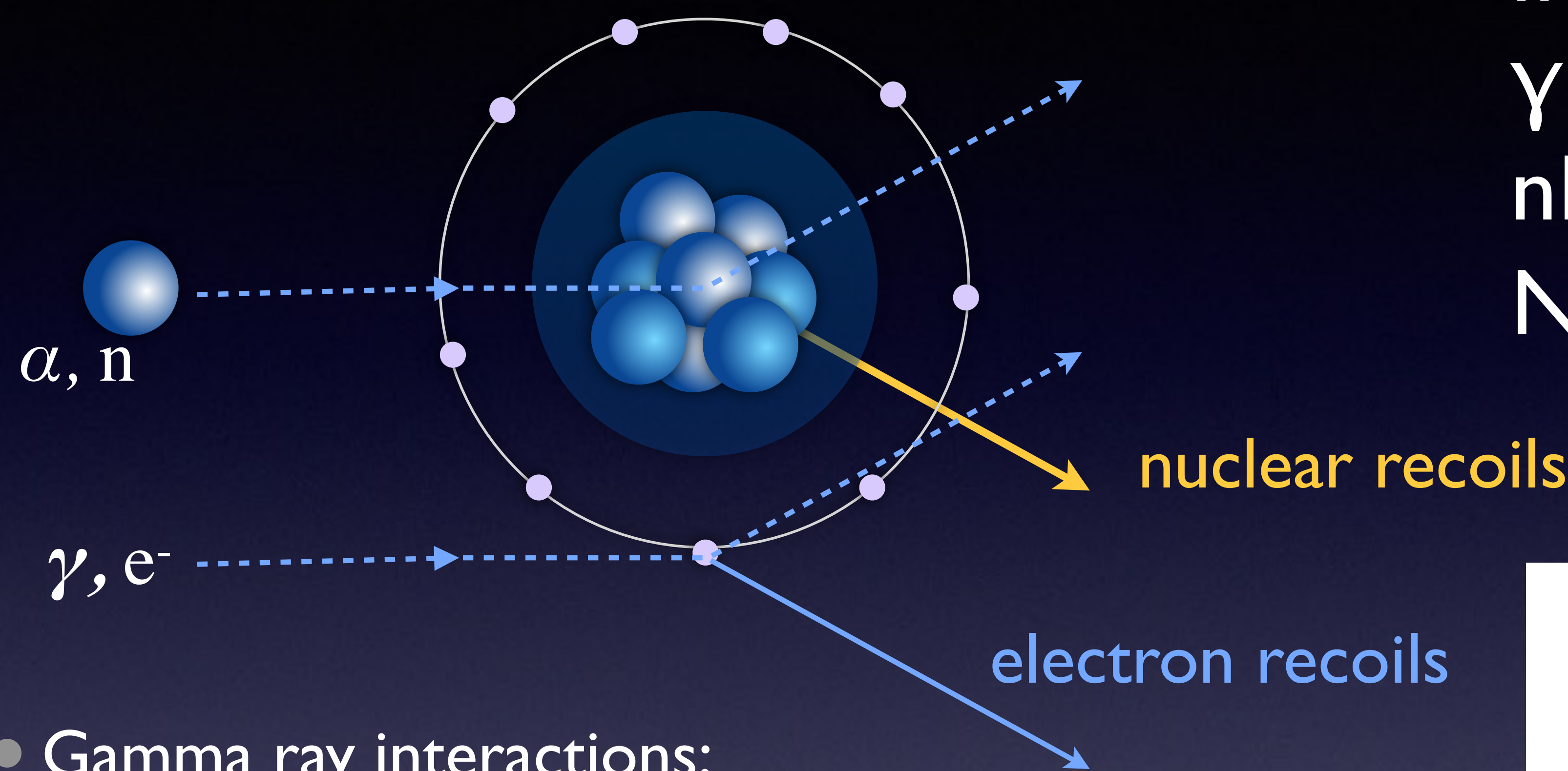
A WIMP signal could almost perfectly be mimicked by solar and atmospheric neutrino backgrounds

M. Cadeddu





Experimental Backgrounds



from natural radioactivity:

γ e⁻ → γ e⁻

nN → nN

N → N' + α, e⁻

- Gamma ray interactions:

  mis-identified electrons mimic nuclear recoil signals

- Neutrons:

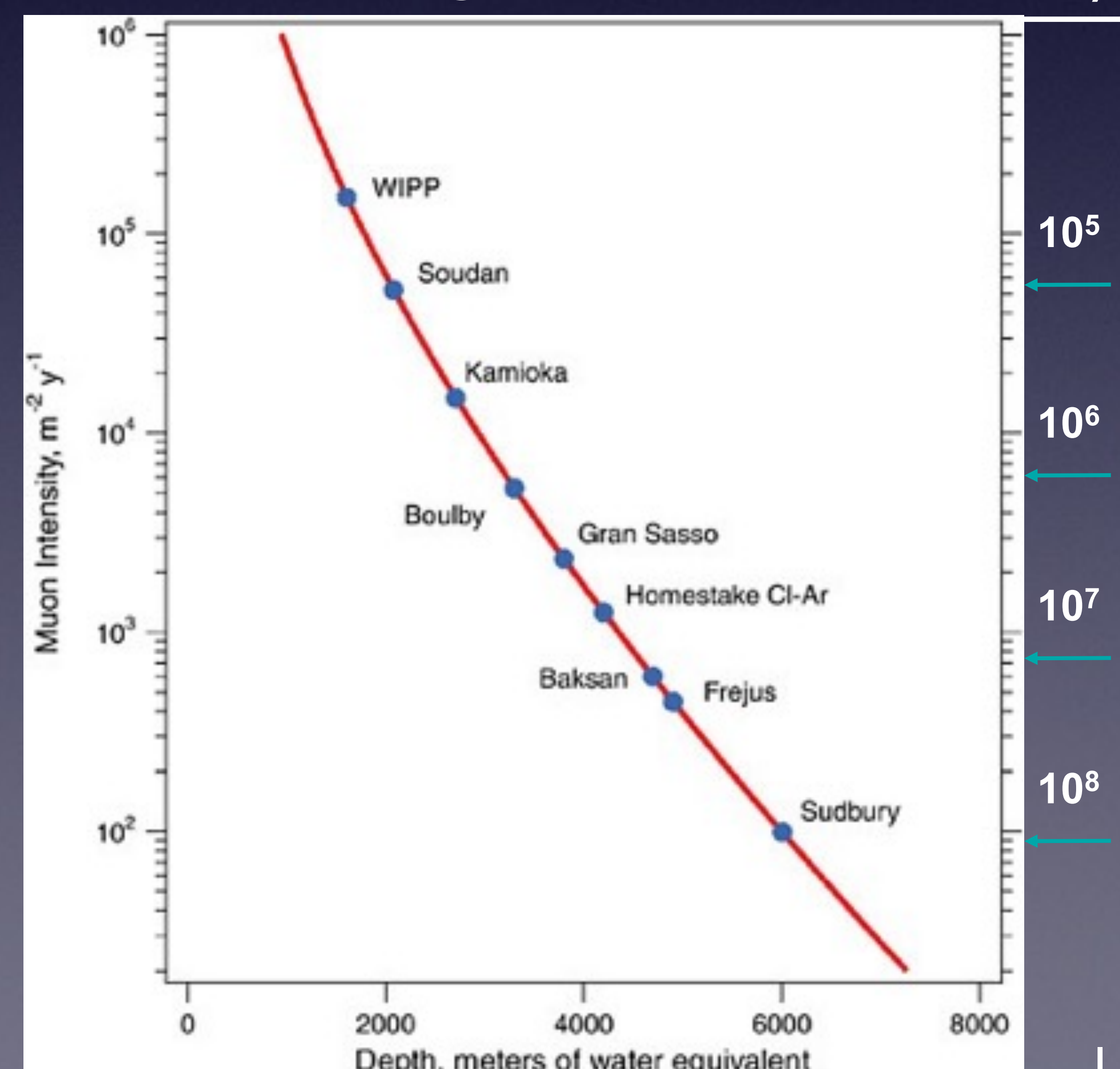
  (α,n), U, Th fission, cosmogenic spallation →

- Contamination:

  ^{238}U and ^{232}Th decays, recoiling progeny mimic nuclear recoils

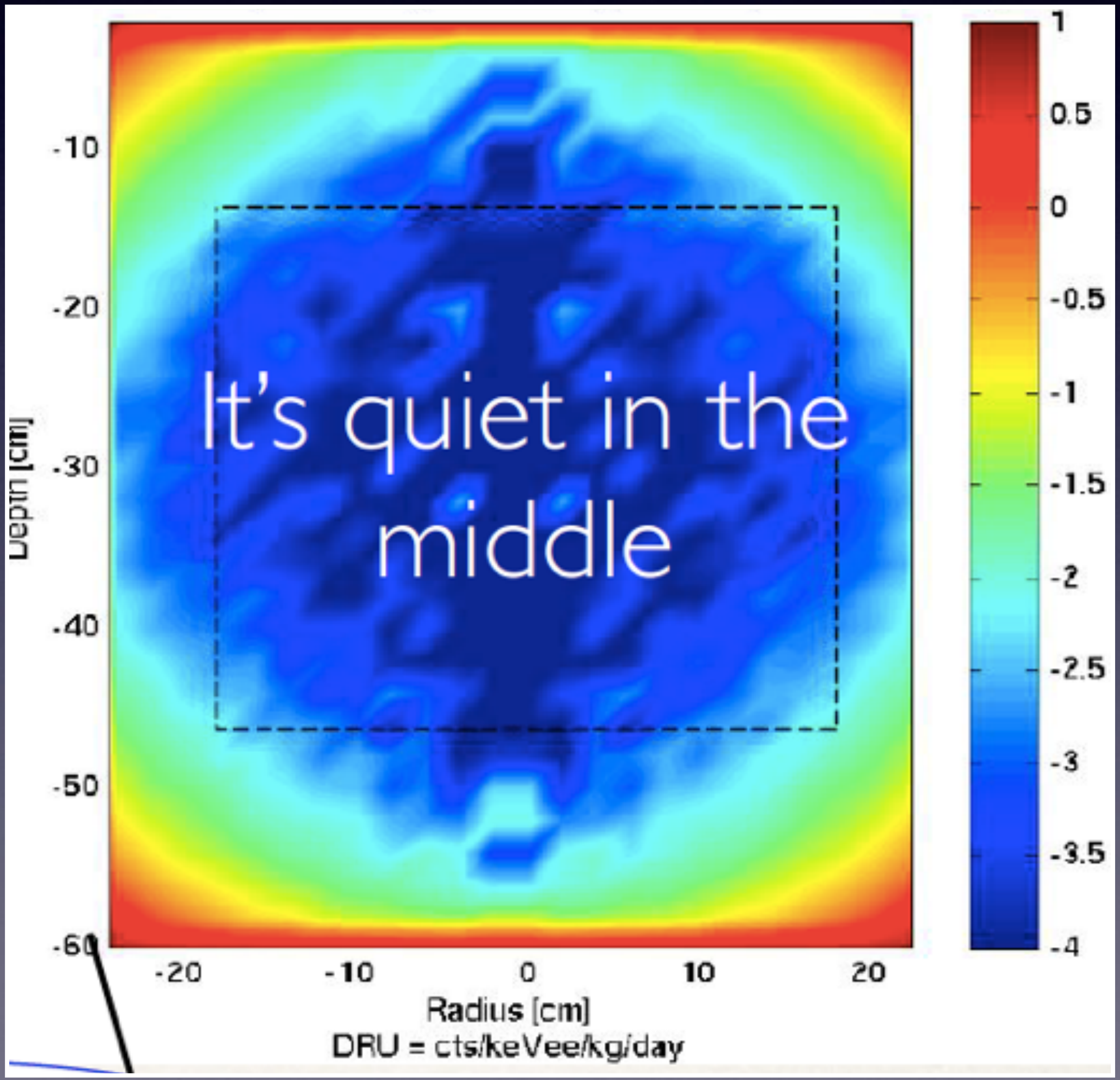
Underground labs

reduction of muon flux by:



How to defeat backgrounds

3-D localization of events can provide self fiducialization
→ background reduction

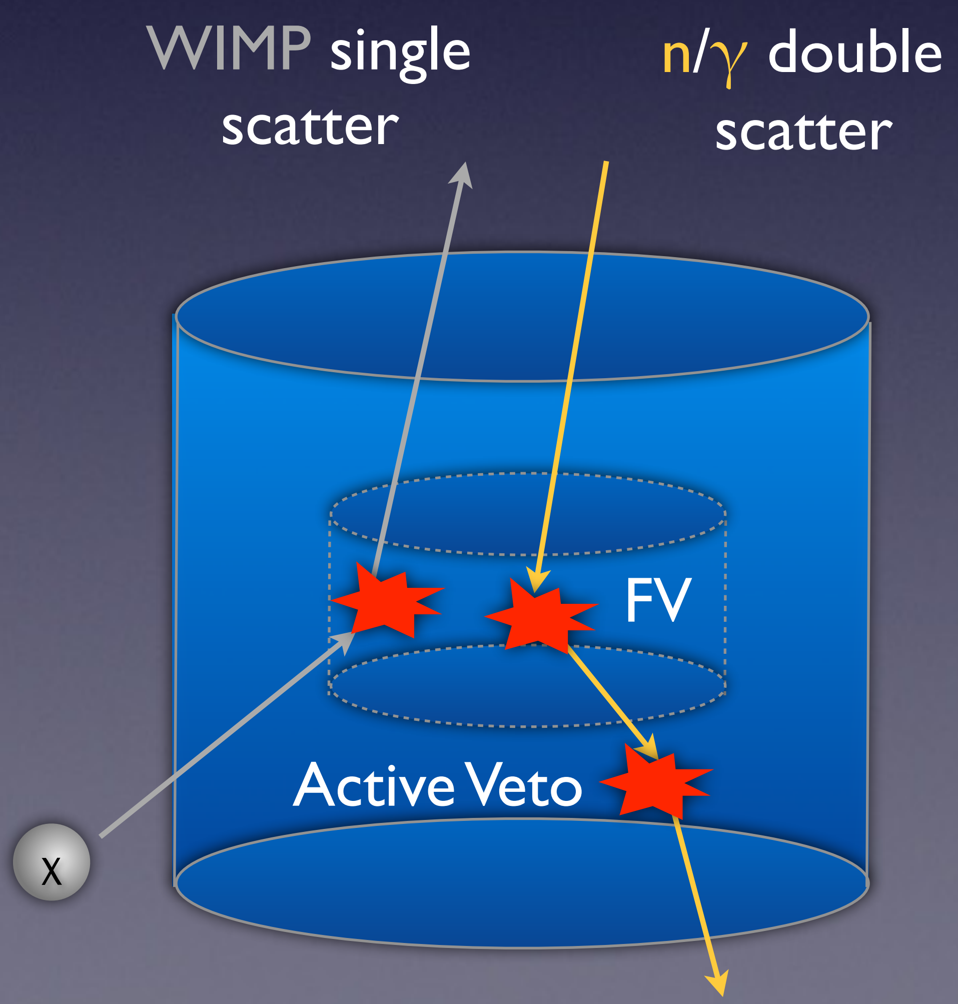


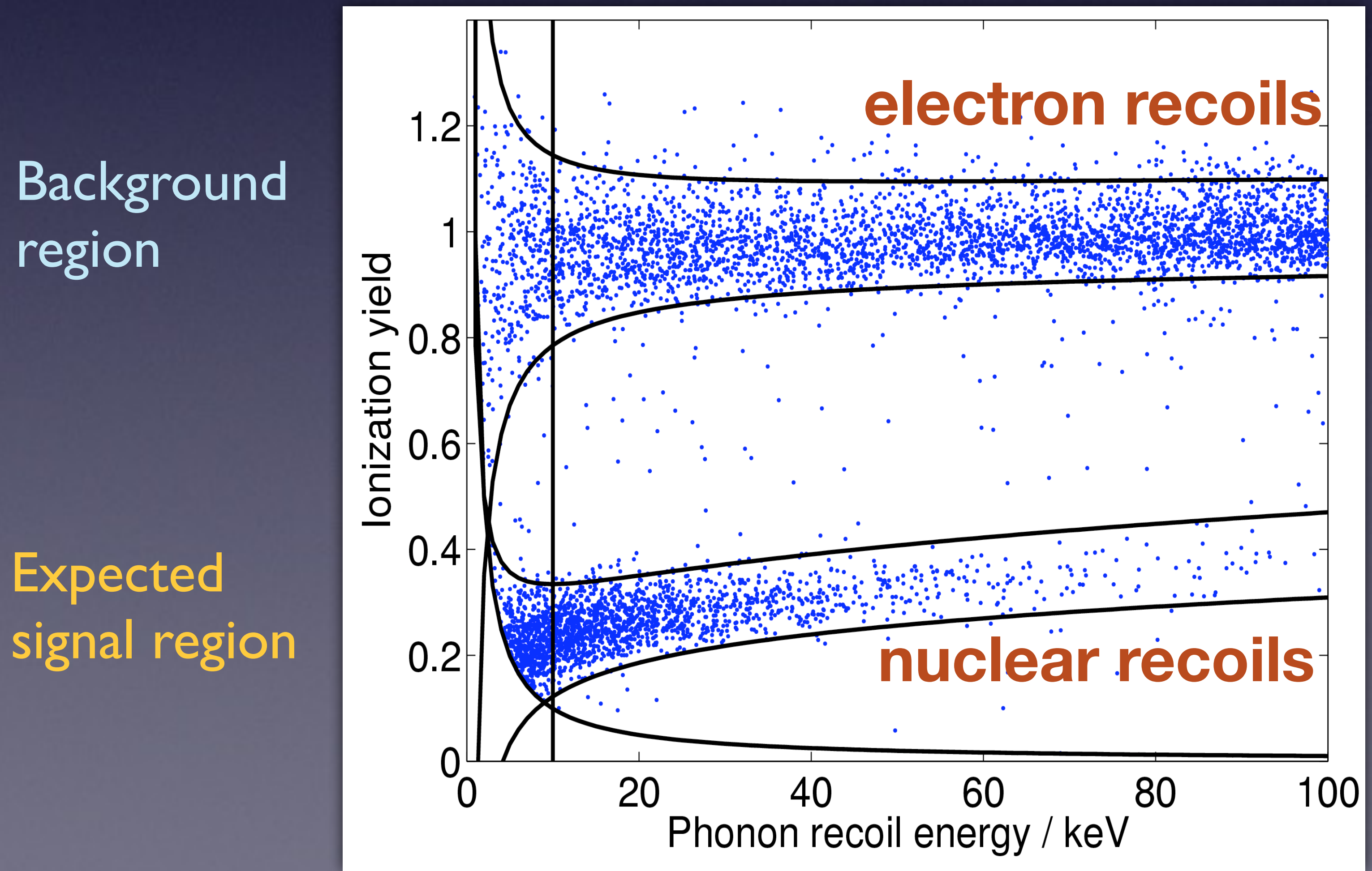
A. Manalaysay, LUX: IDM2016

Discriminating backgrounds

Active veto shield and fiducialization
→ identification of neutron recoils

Signal split in two components which respond differently to NR/ER
→ separation of S and B





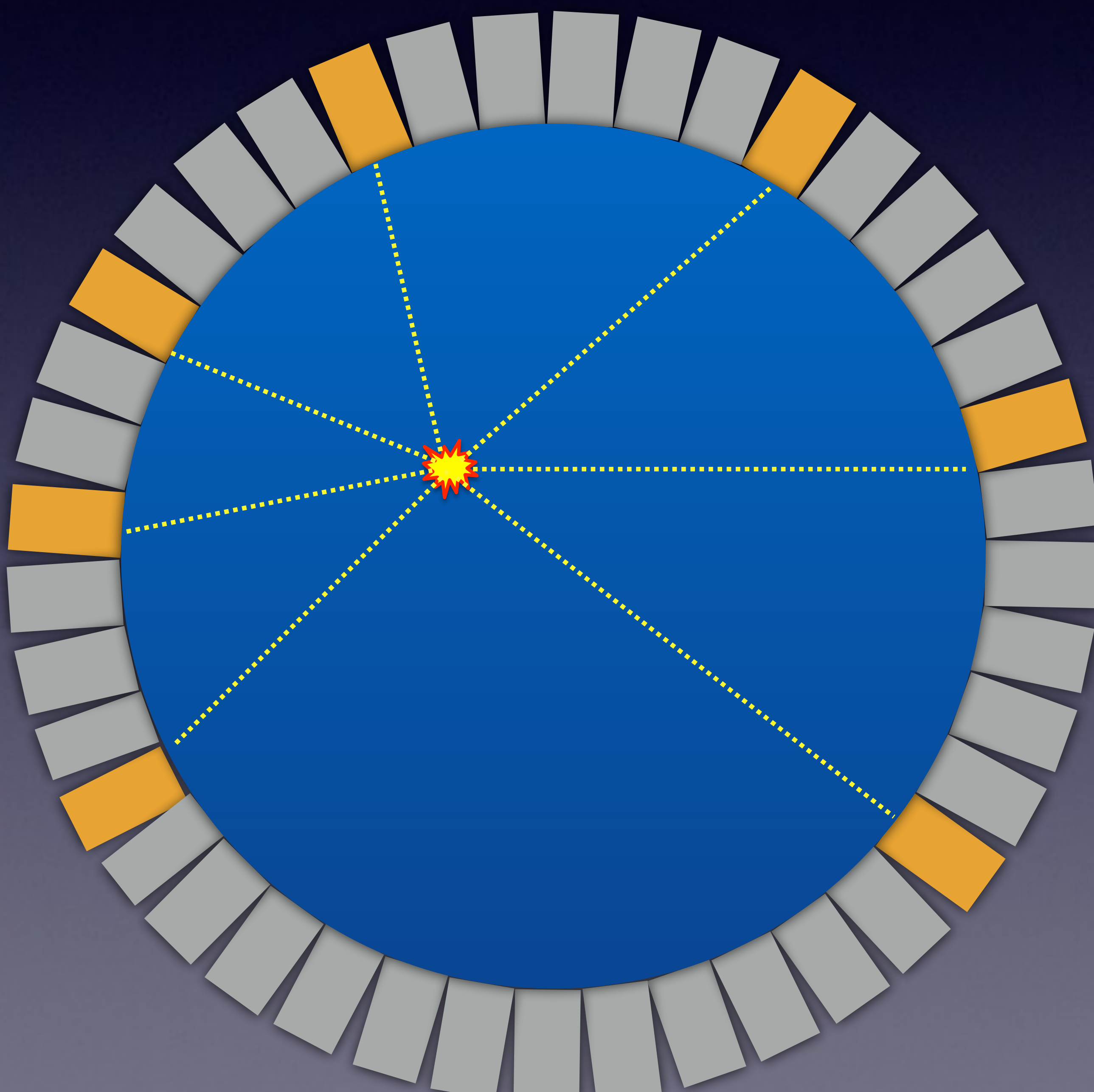
High mass WIMPs: noble liquids

Light & Charge:	Xenon
	LUX/LZ
	Panda-X
Light:	XMASS

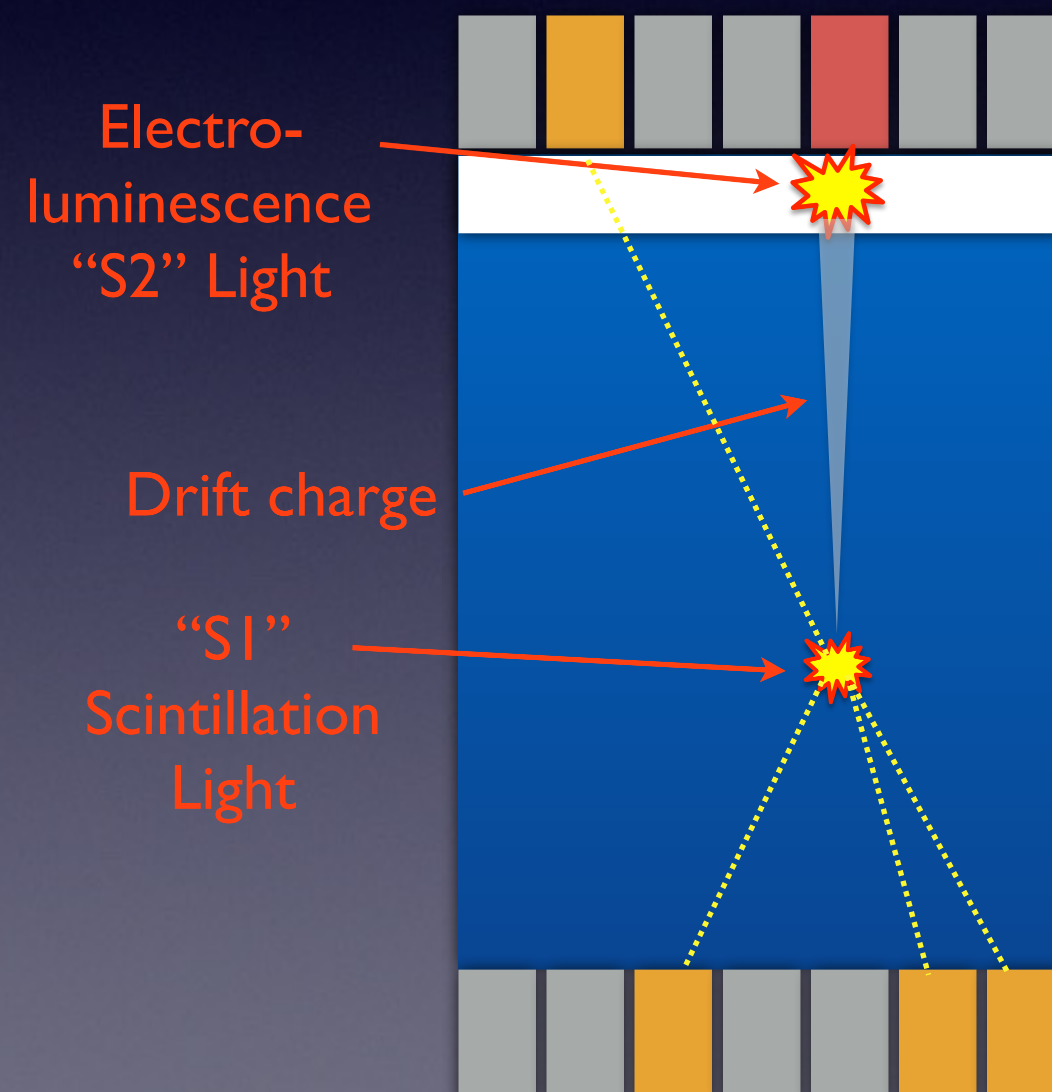
Light & Charge:	DarkSide
	ArDM
Light:	MiniCLEAN
	DEAP-3600

Detector concepts

Single phase 4π scintillation
Light



Dual phase TPC
Light & Charge

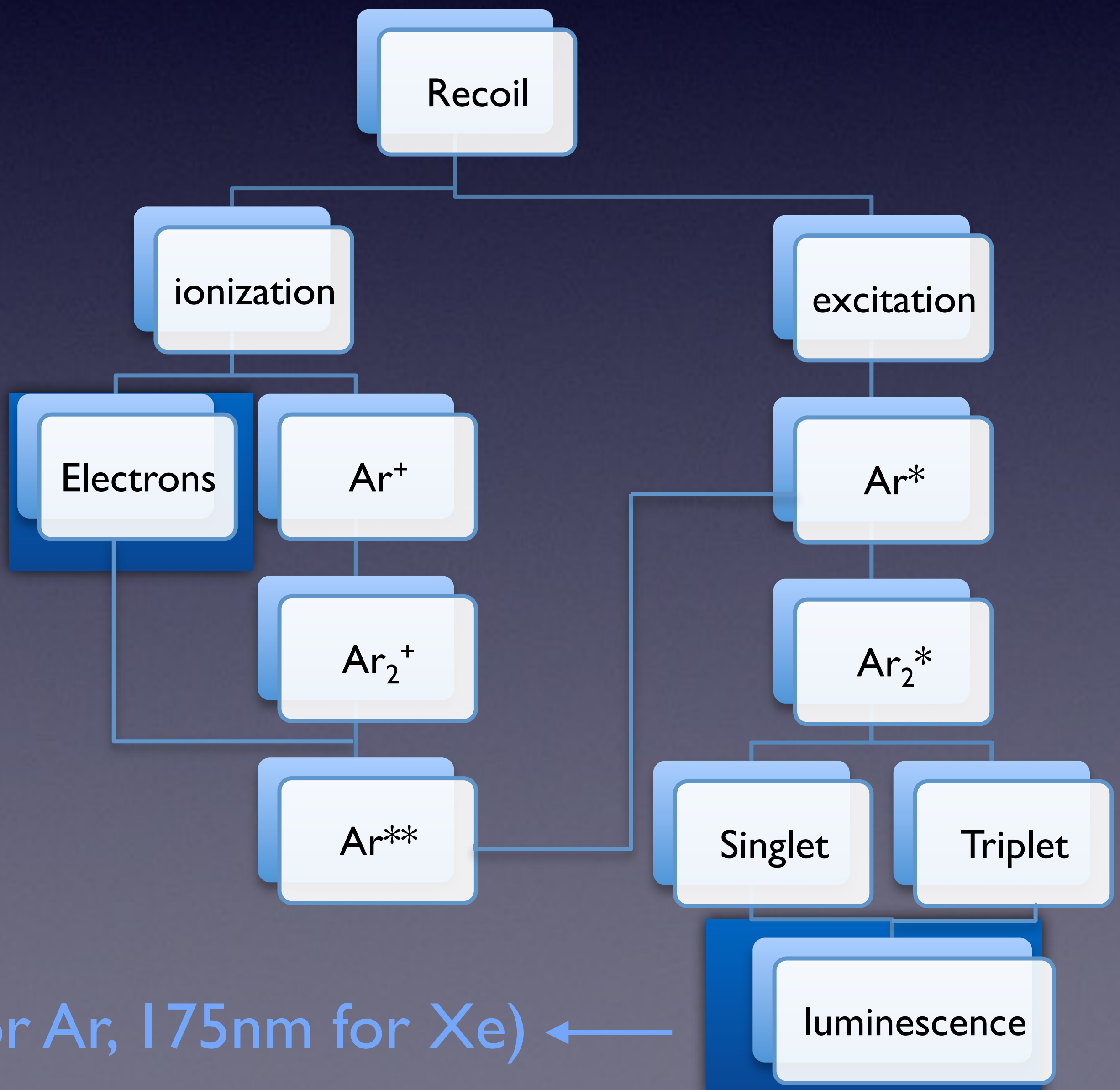


Why noble liquids

- Large mass detectors → scalability, fiducialization
- Multiple targets available: Xe, Ar
- Bright scintillators: Light Yield ~ 40 γ/keV → low threshold

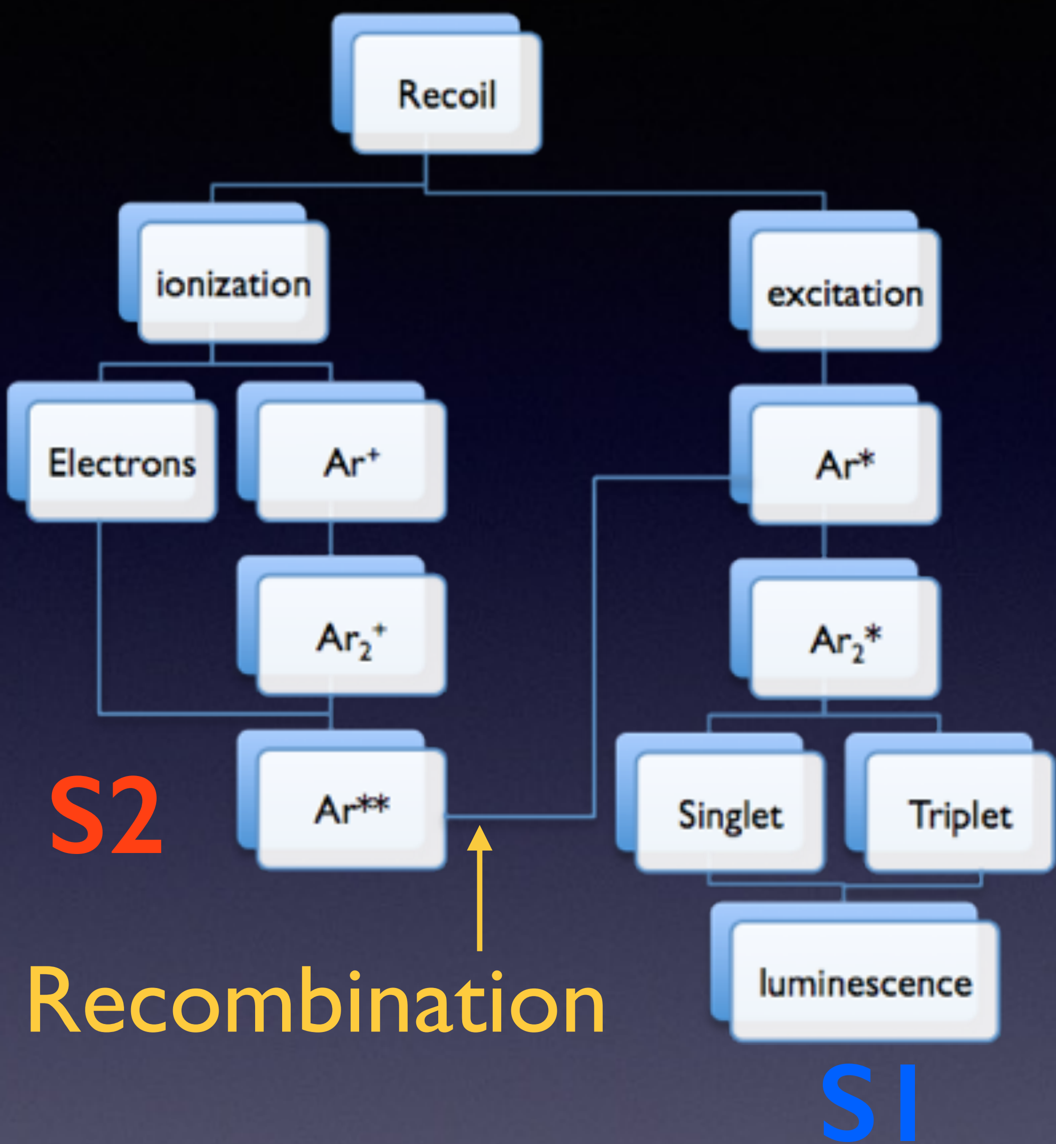
Two detection channels:
ionization charge (S2)
scintillation light (S1)

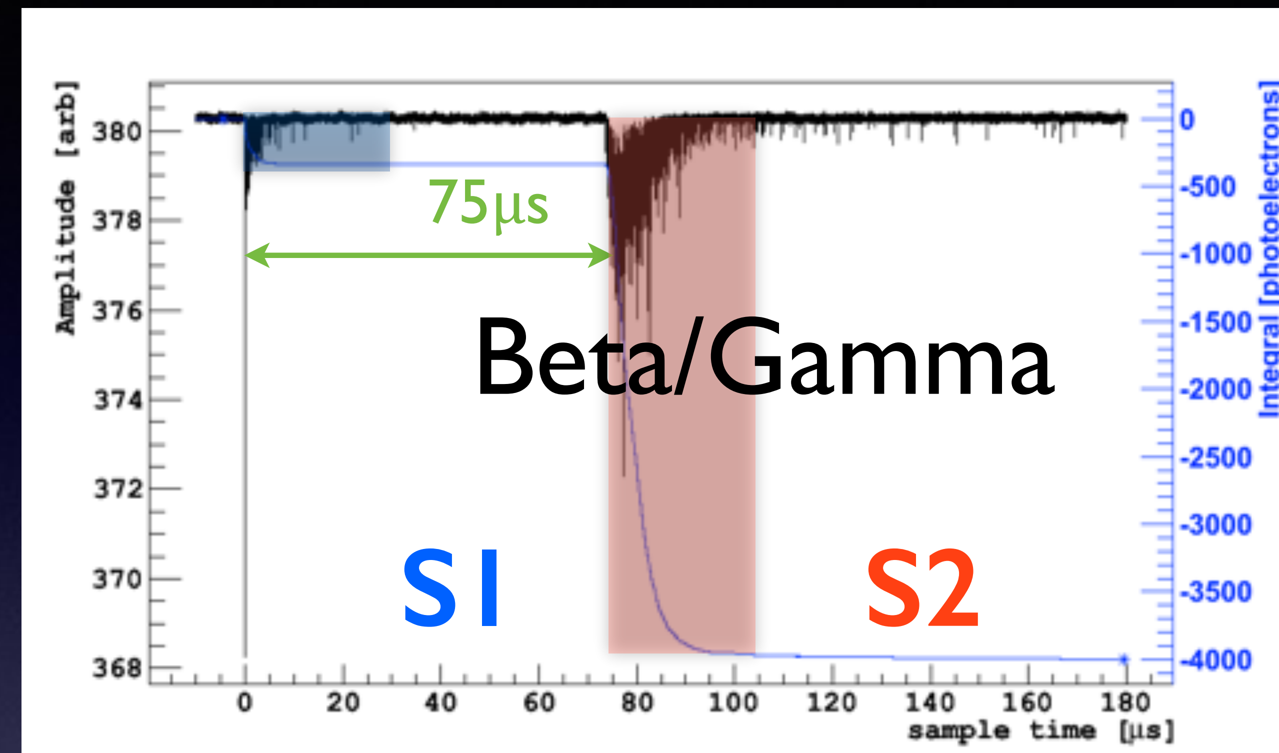
different dE/dx from nuclear and electron recoils
→ background discrimination

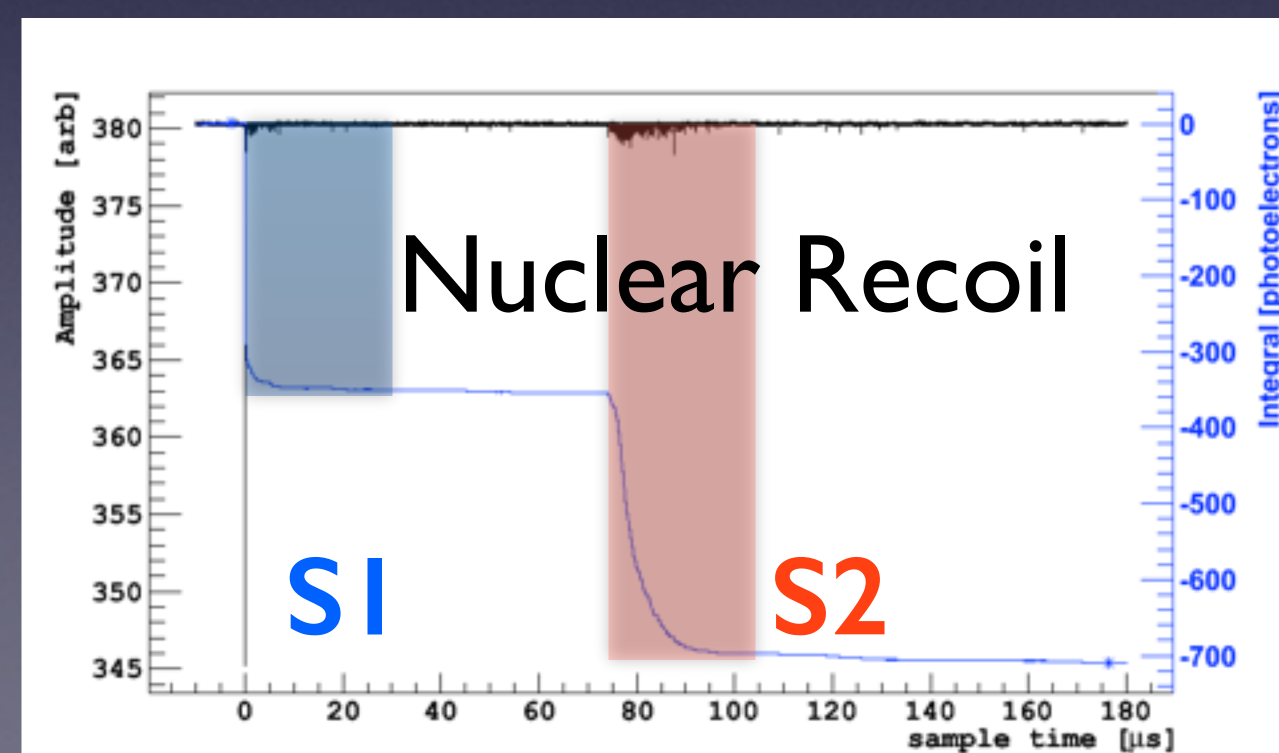


VUV light (128nm for Ar, 175nm for Xe) ←

Ionization/Scintillation

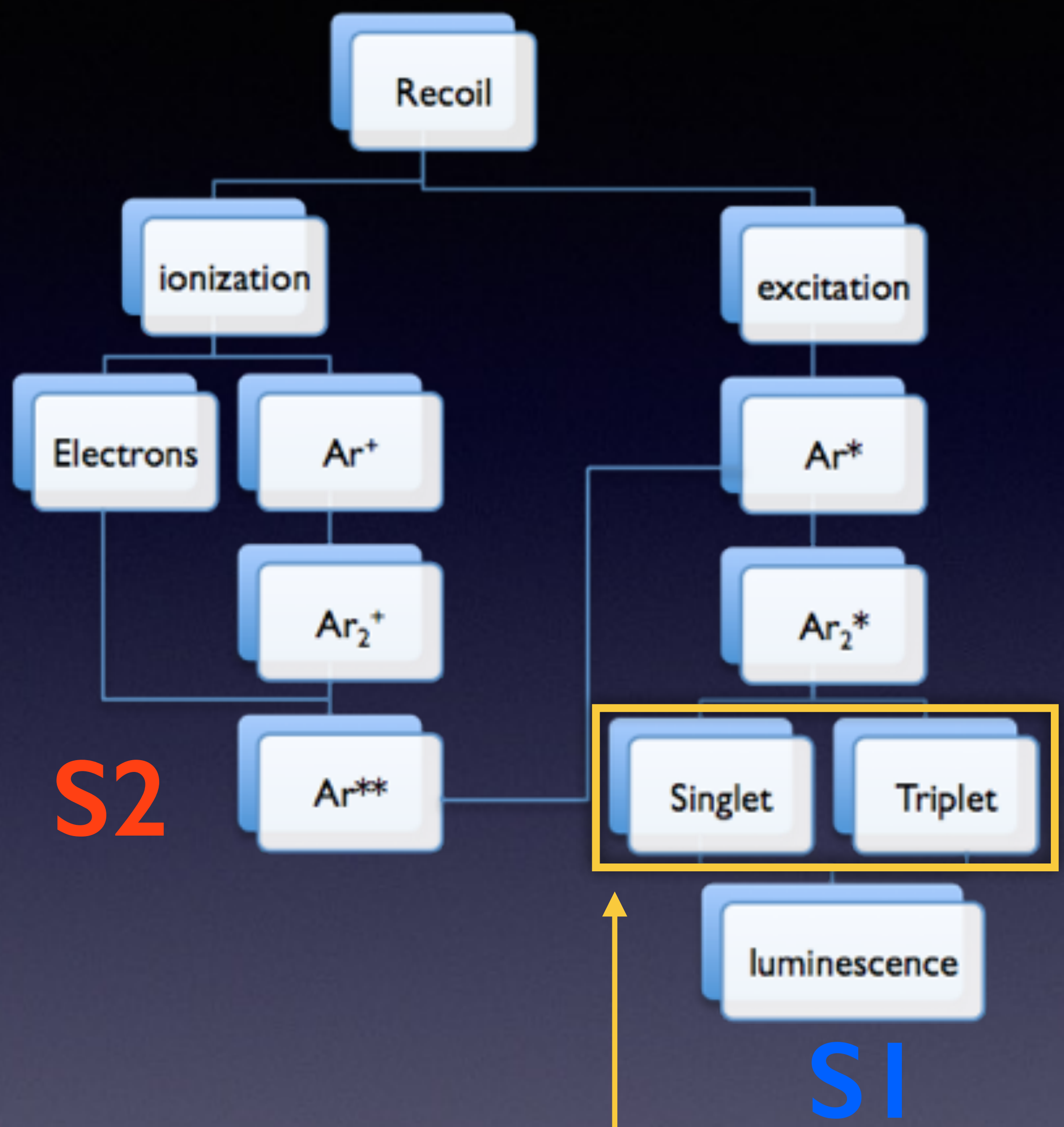


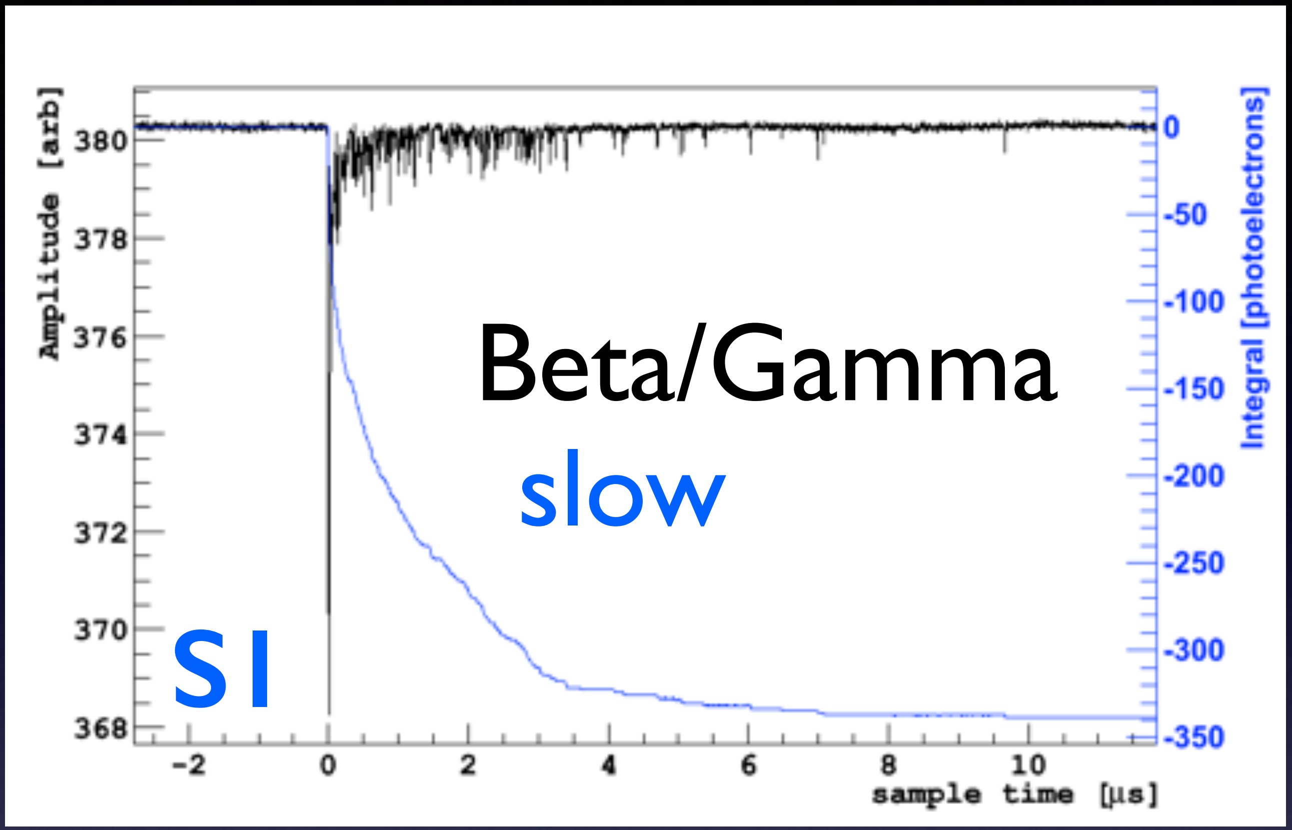


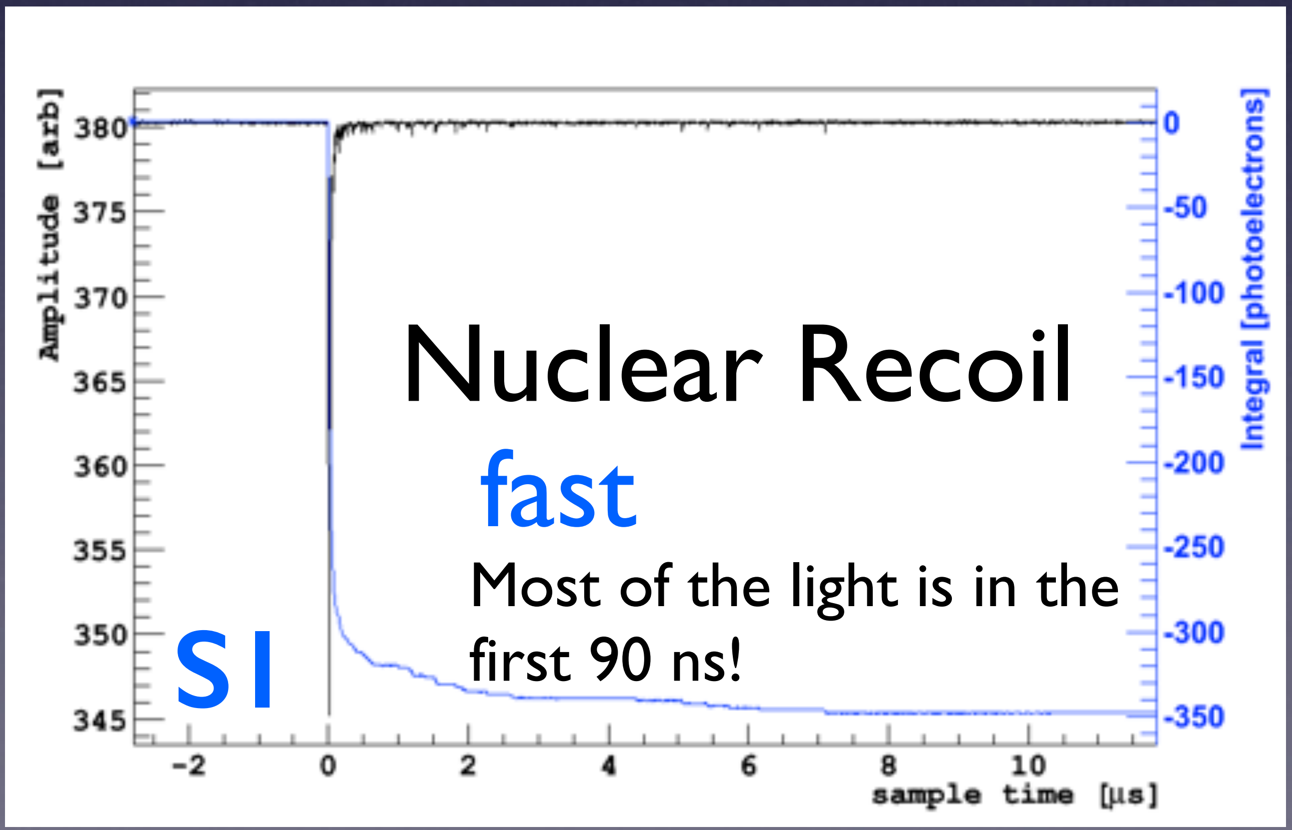


The ratio of S2 to S1 depends on ionization density

Pulse Shape Discrimination





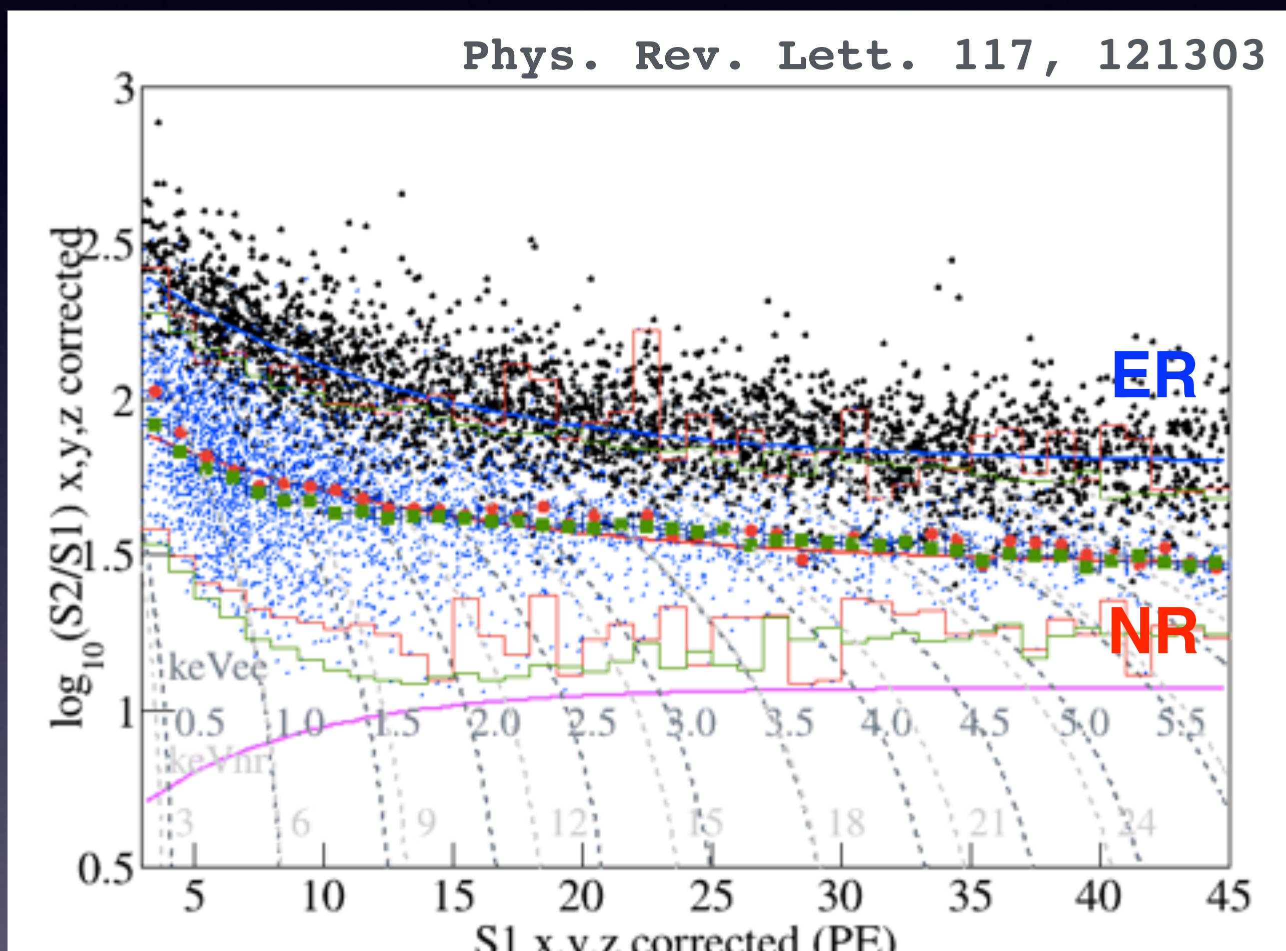


The ratio of light from singlet and triplet depends on ionization density

Ar	$t_{singlet} = 7$ ns	$t_{triplet} = 1600$ ns
Xe	$t_{singlet} = 3$ ns	$t_{triplet} = 27$ ns

ER/NR discrimination

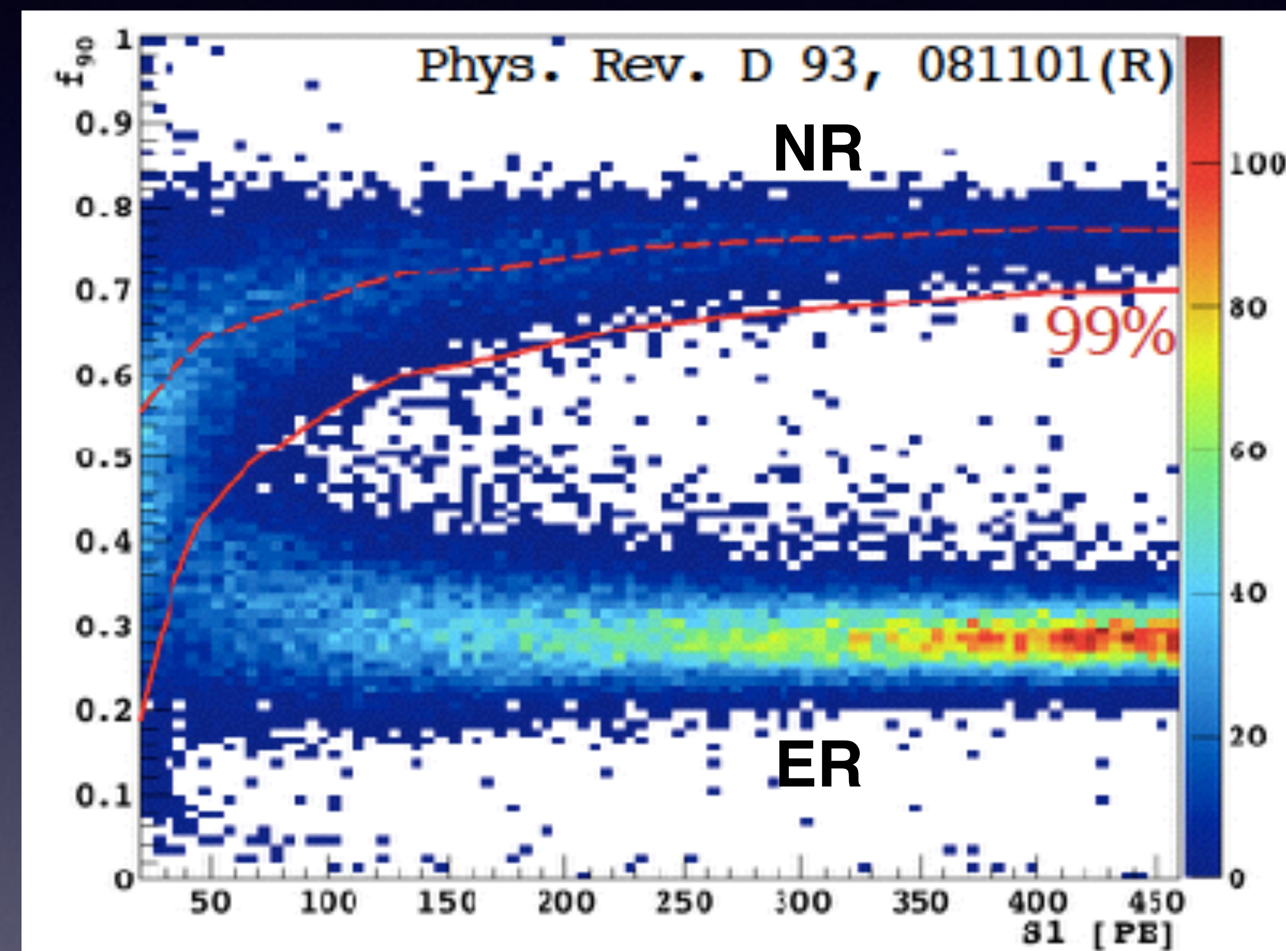
Ratio of charge to light in LXe



Tritium and AmBe calibrations in PandaX

Discrimination power ~ 10^3 (PandaX)

Pulse shape discrimination in LAr



NR band from the AmBe calibration and lower ER band from β-γ backgrounds

Exceptional discrimination > 10^8 (DarkSide)

Argon as target for DM detection

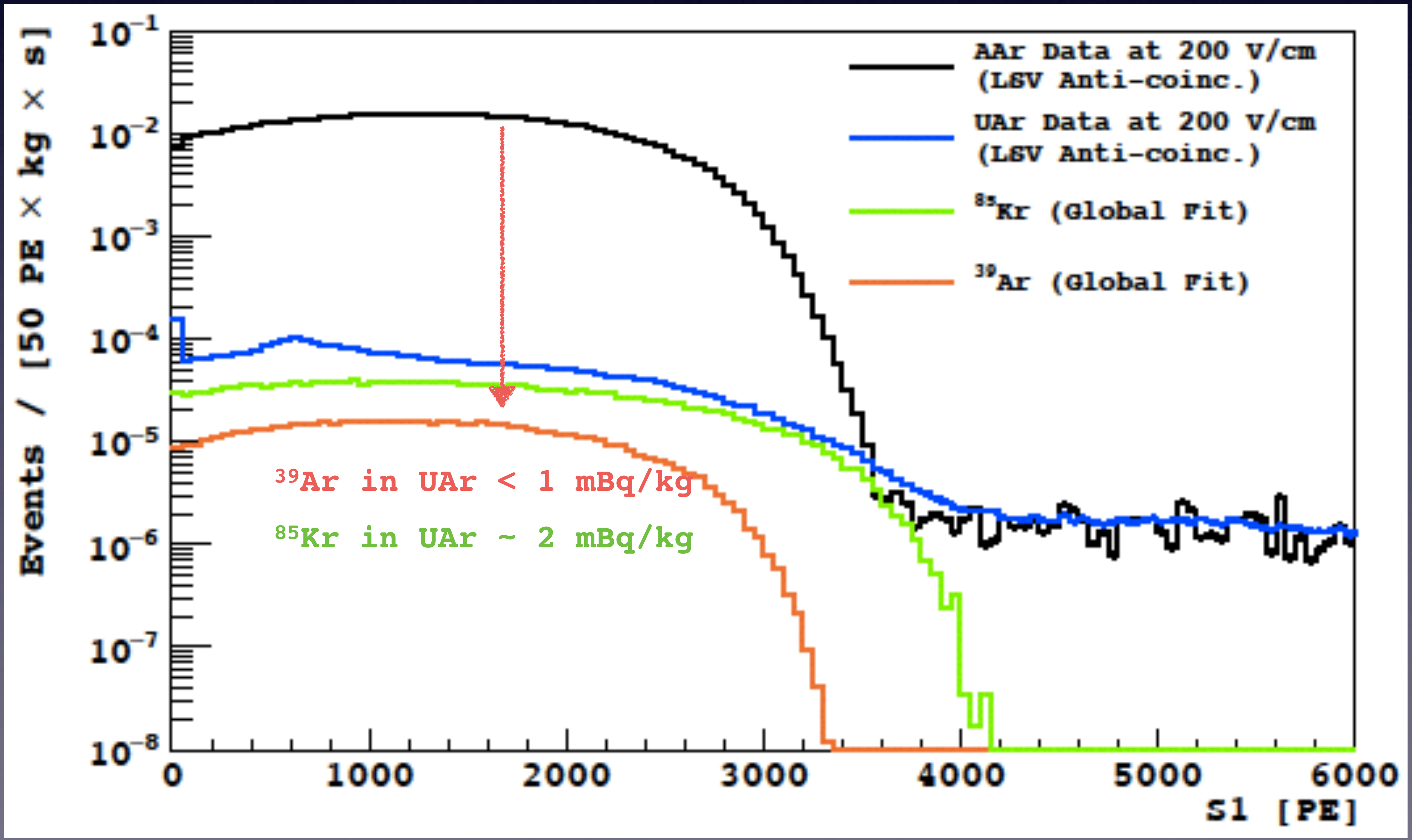
^{39}Ar beta decays with 565 keV endpoint, with half-life 269 years

^{39}Ar production supported by cosmogenic activation via ^{40}Ar(n,2n)^{39}Ar

^{39}Ar activity in atmospheric argon ~1 Bq/kg

Underground argon (UAr): 150 kg successfully extracted from a CO2 well in Colorado

➡ ^{39}Ar depletion factor >1400



PRD, 93 (2016): 081101(R)

Noble liquid dual phase TPC

LUX @ SURF LXe

- 48cm×48cm, 250 kg target
- in-situ NR calibration studies
  arXiv:1608.05381

New result August 2016

Phys. Rev. Lett. 118, 021303 (2017)

- 3.4 10^4 kg d = 0.1 t yr
- no signal excess
- 2.2 10^{-46} cm^2 @ 50 GeV

PandaX-II @ CJPL LXe

- 60cm×60cm, 500 kg target
- 2nd largest running LXe TPC

New result July 2016

Phys. Rev. Lett. 117, 121303 (2016)

- 3.3 10^4 kg d = 0.1 t yr
- no signal excess

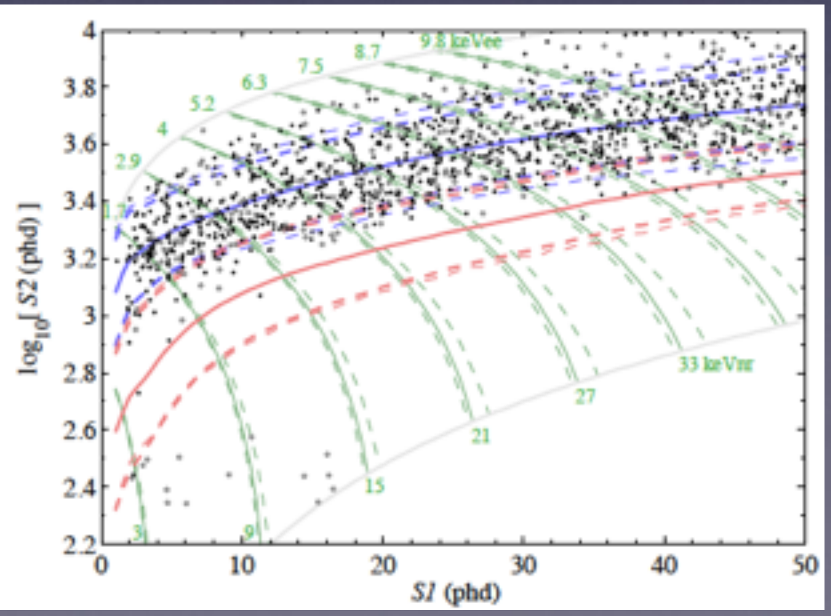
DarkSide-50 @ LNGS UAr

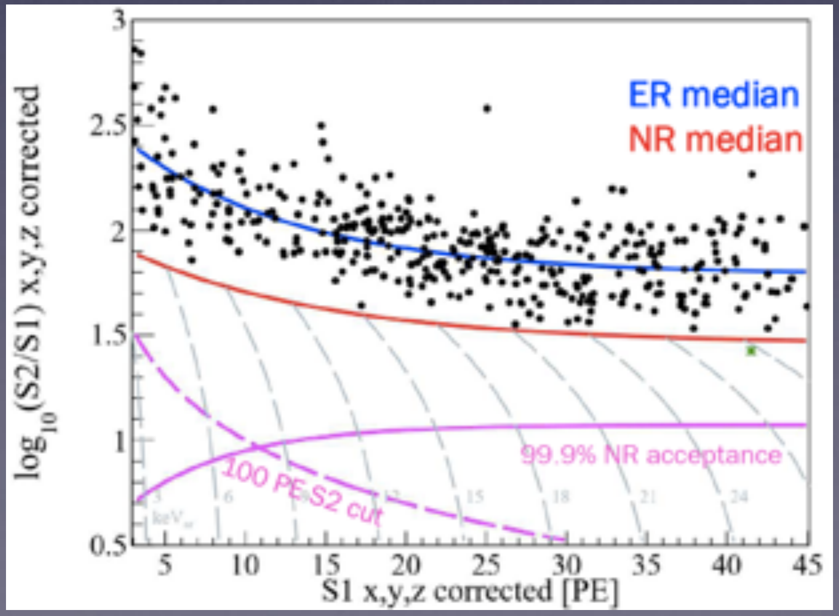
- 36cm×36cm, 46 kg active target
- inside a LSci 30 t neutron veto and a 1 kt Water Cerrenkov muon veto

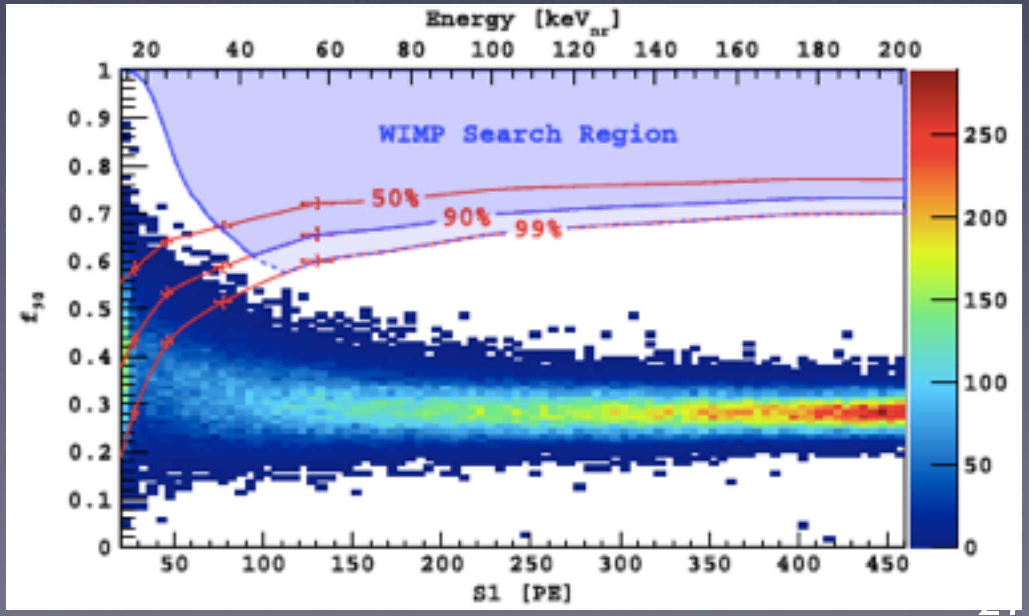
Latest result October 2015

Phys. Rev. D 93, 081101(R)

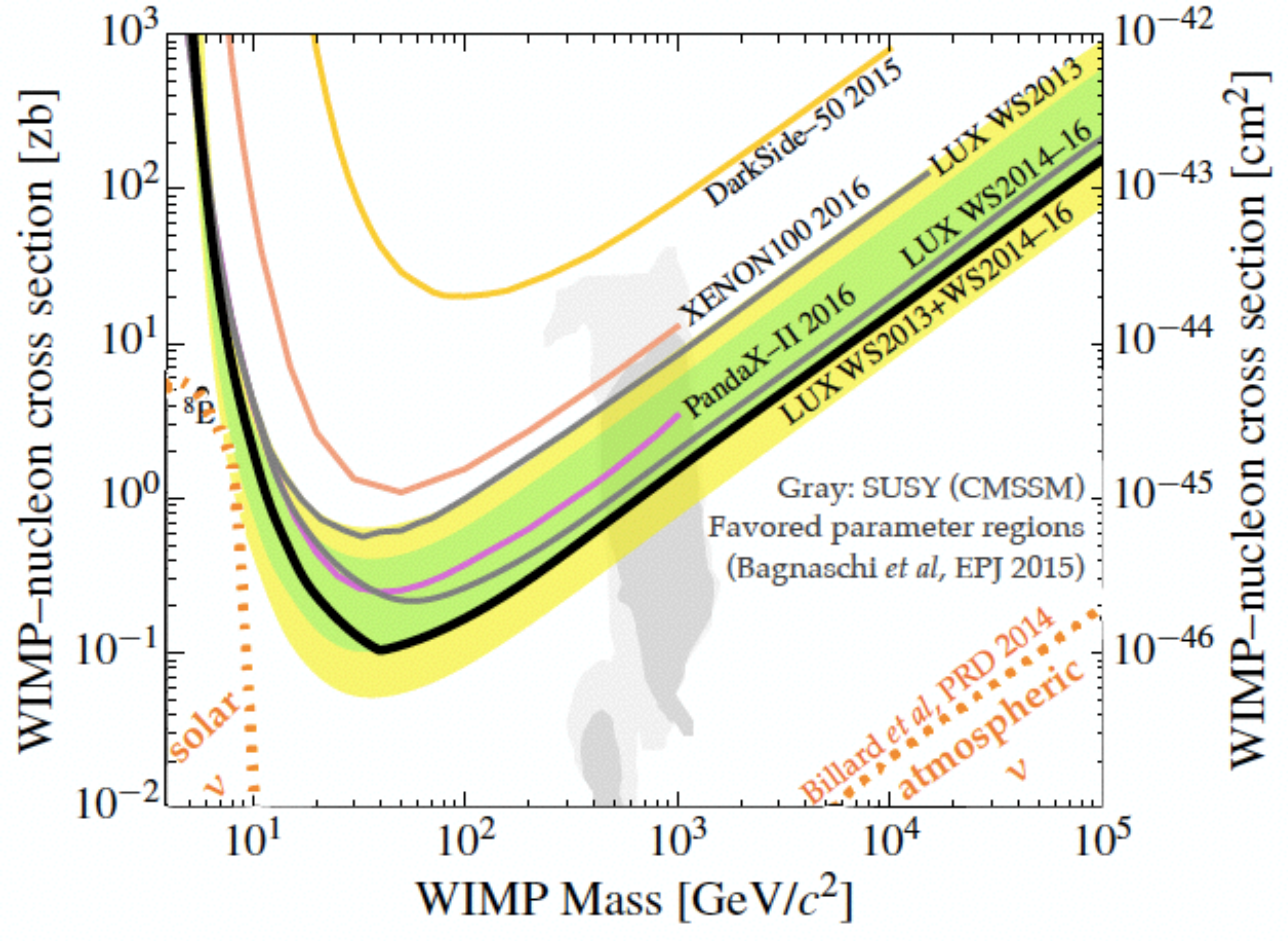
- 2616 kg d exposure
- no signal excess
- 2.0 10^{-44} cm^2 @ 100 GeV







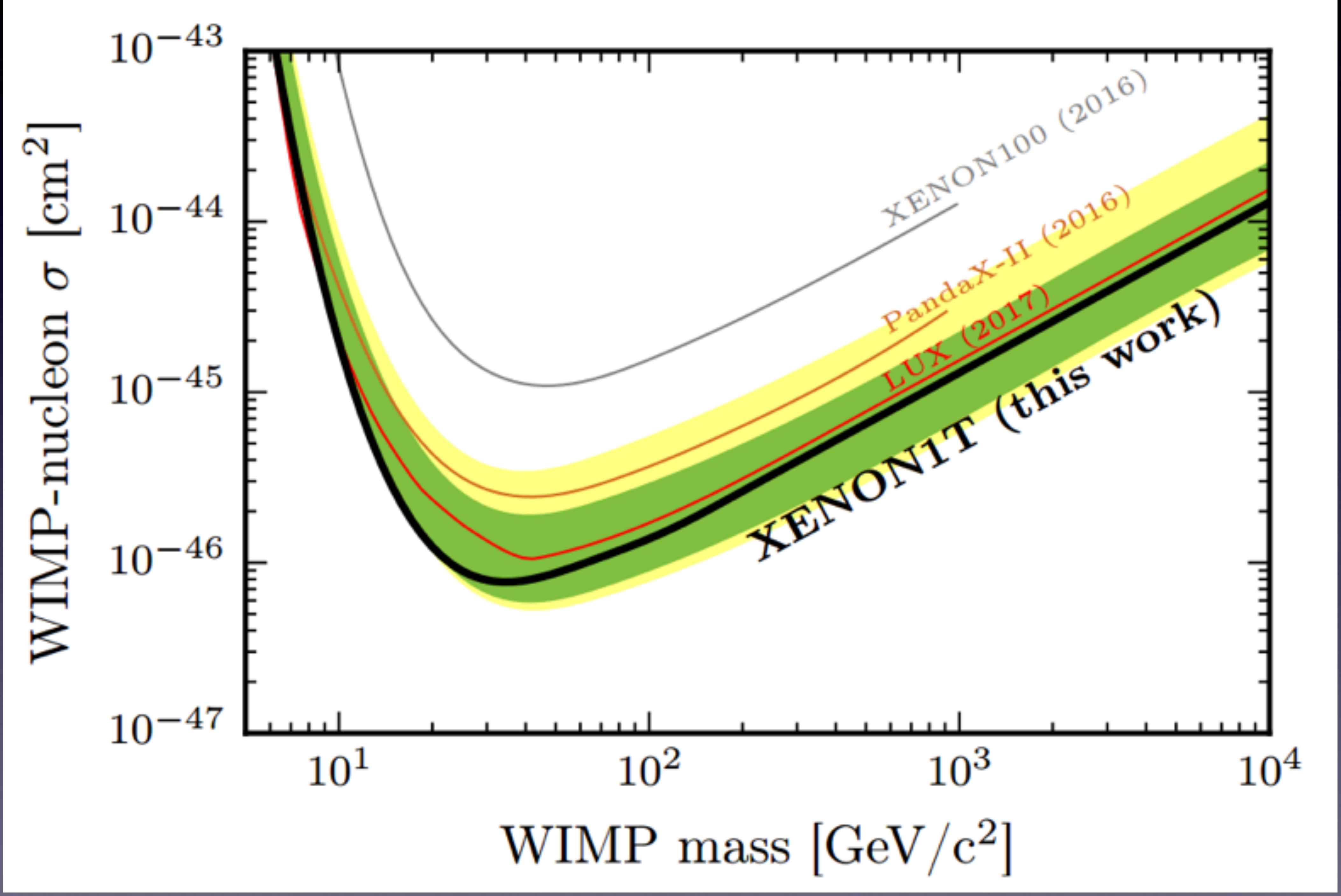
Noble liquid dual phase TPC



E. Pease, Berkeley December 2016

LUX results combined 1.1 10^{-46} cm^2 at 50 GeV

Noble liquid dual phase TPC



arXiv:1705.06655v1

XENON1T results released on May 18, 2017

XENON1T/XENONnT @ LNGS

Target/Detector:

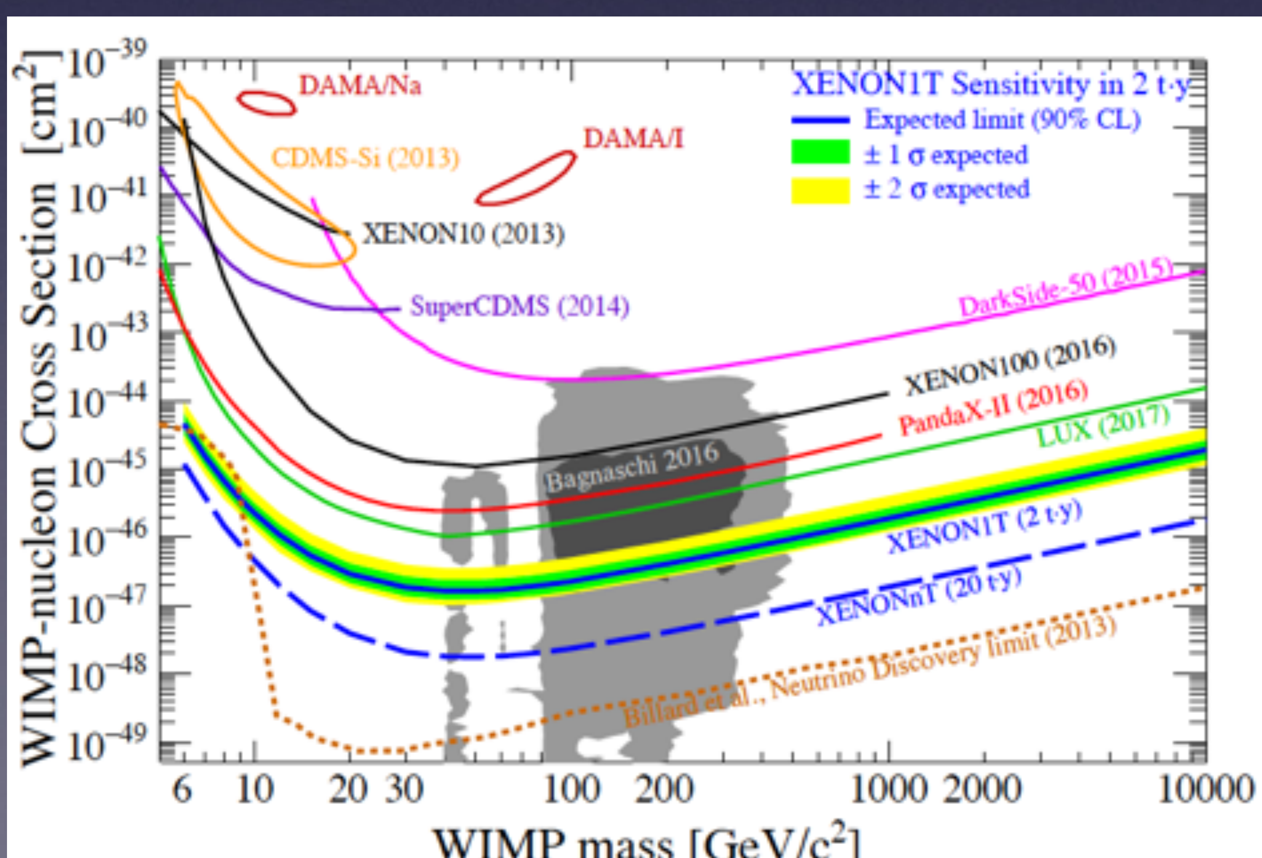
- 3.5 (8) ton XeTPC **in** water Cherenkov muon veto.

Infrastructure and Cryogenic Plants:

- designed for ***XENON1T and its upgrade*** to ***XENONnT***

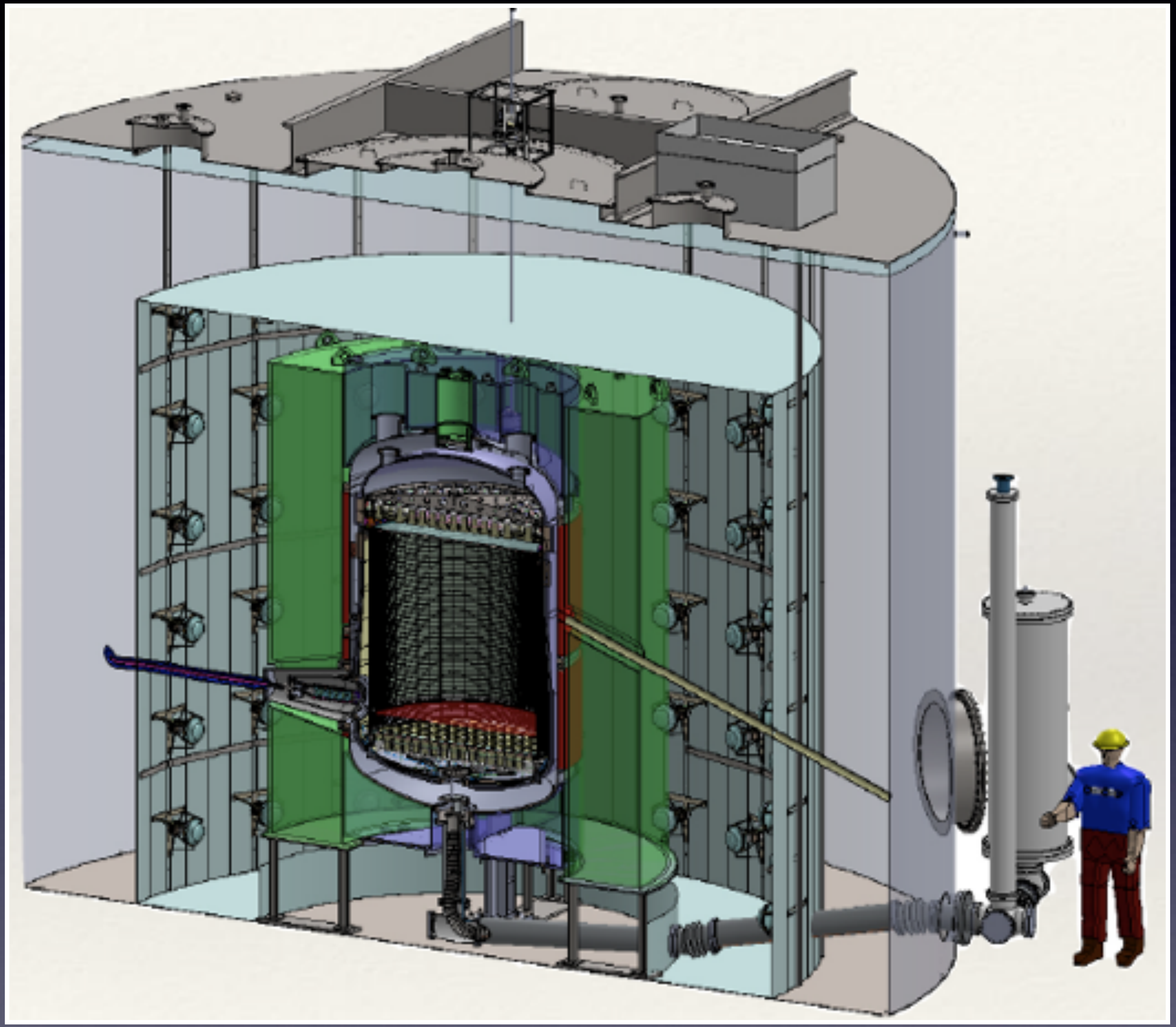
Status:

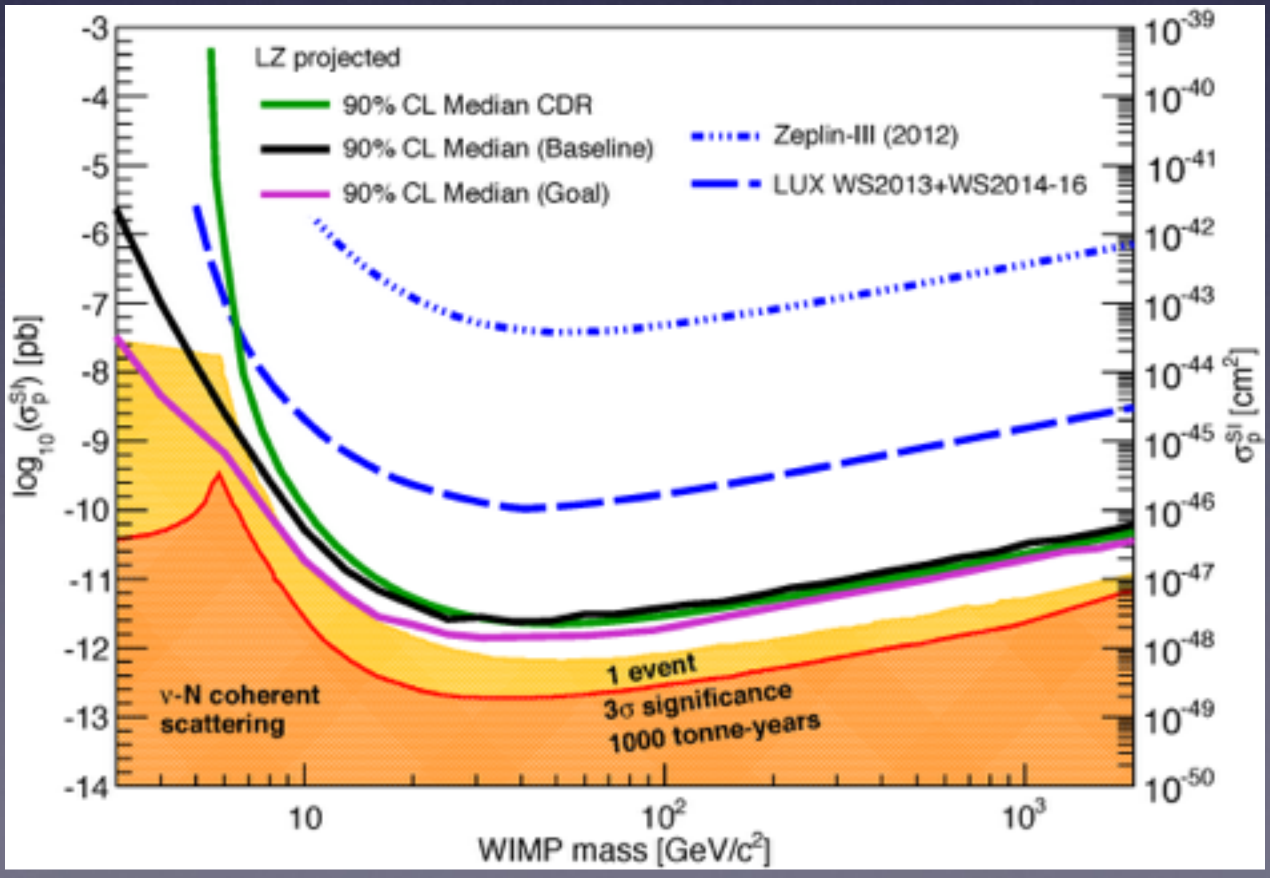
- **XENON1T first result with 1 month exposure just released.** Resources in place for XENONnT phase to start in Spring 2019



Next future: LZ @ SURF

- 50 × larger than LUX
- 10t total LXe mass, 7t active target, 5.6t fiducial target
- Gadolinium loaded liquid scintillator veto in acrylic tanks

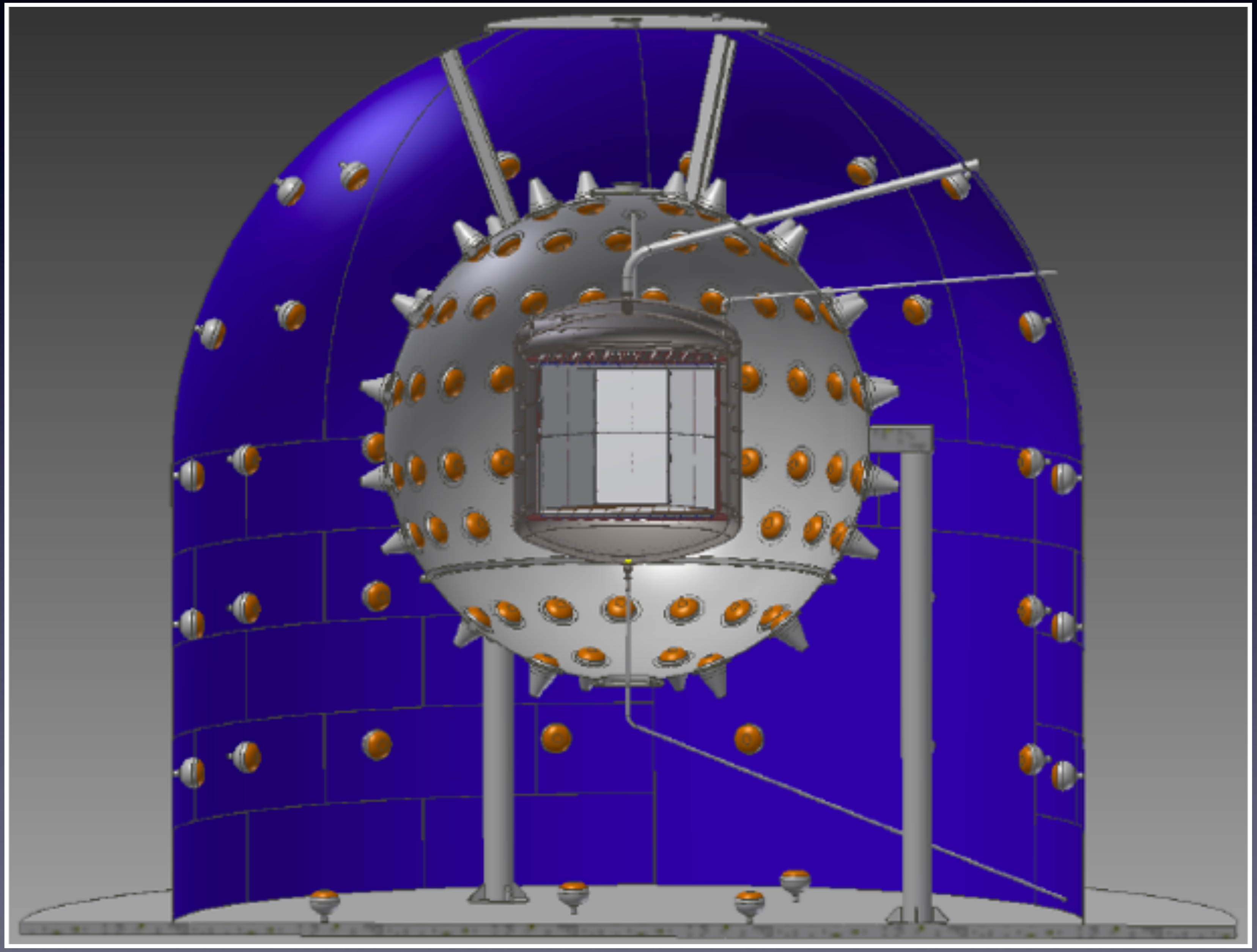




- Received final approval from the DOE in February, 2017
- Start of operation in 2020 (pushing to advance to 2019)

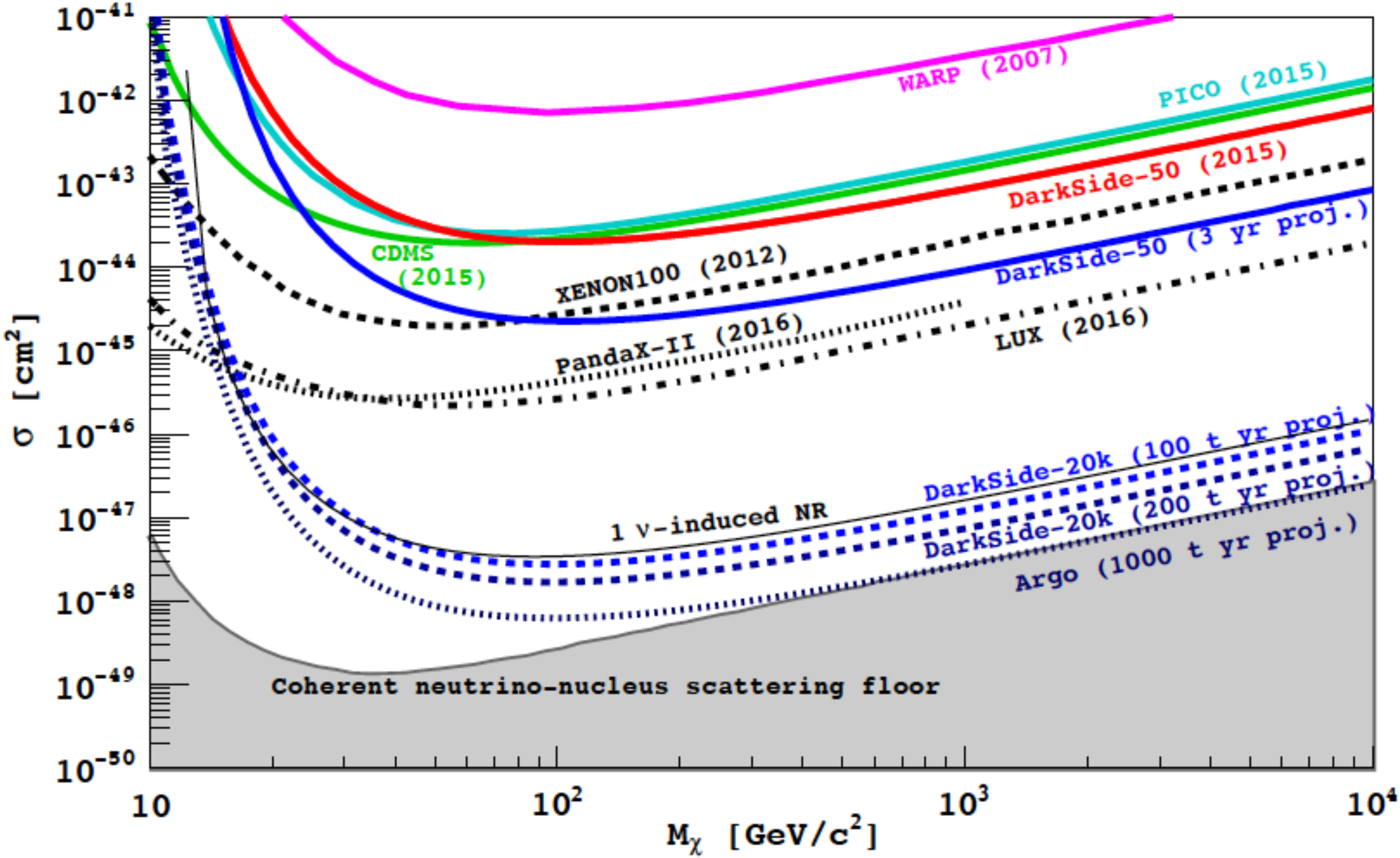
DarkSide-20k @ LNGS

- 30 ton total, 20 ton fiducial, argon from underground wells, depleted in radioactive ^{39}Ar
- inside a 8m diameter SS sphere filled with boron-loaded liquid scintillator, serving as active neutron veto
- inside a 15m diameter 16m tall water tank, as active muon veto
- radiopure construction
- 15m^2 SiPM sensors (low radioactivity, increased LY)
- Scalable design for application to larger scale detector



Start of operation in 2021

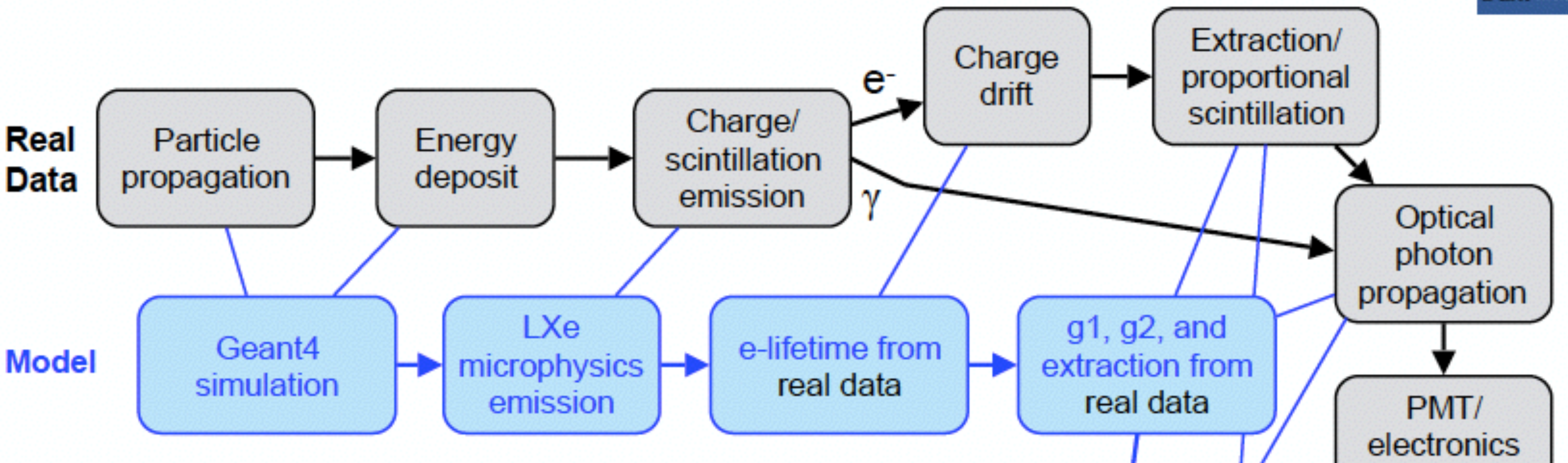
DarkSide-20k sensitivity

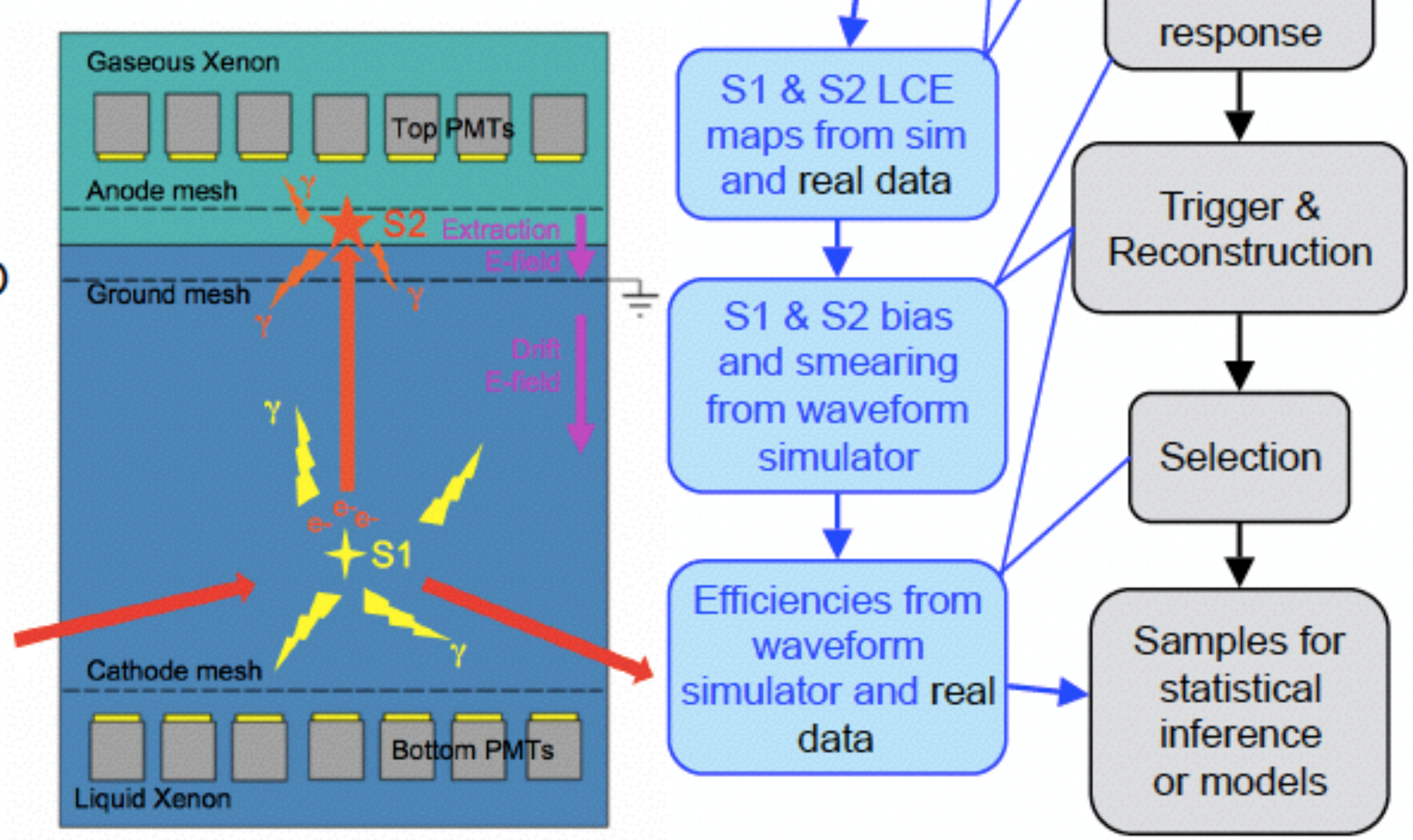


Modelling a noble liquid TPC

detector geometry
detector response
liquid target microphysics: ionization, scintillation and electron-ion recombination

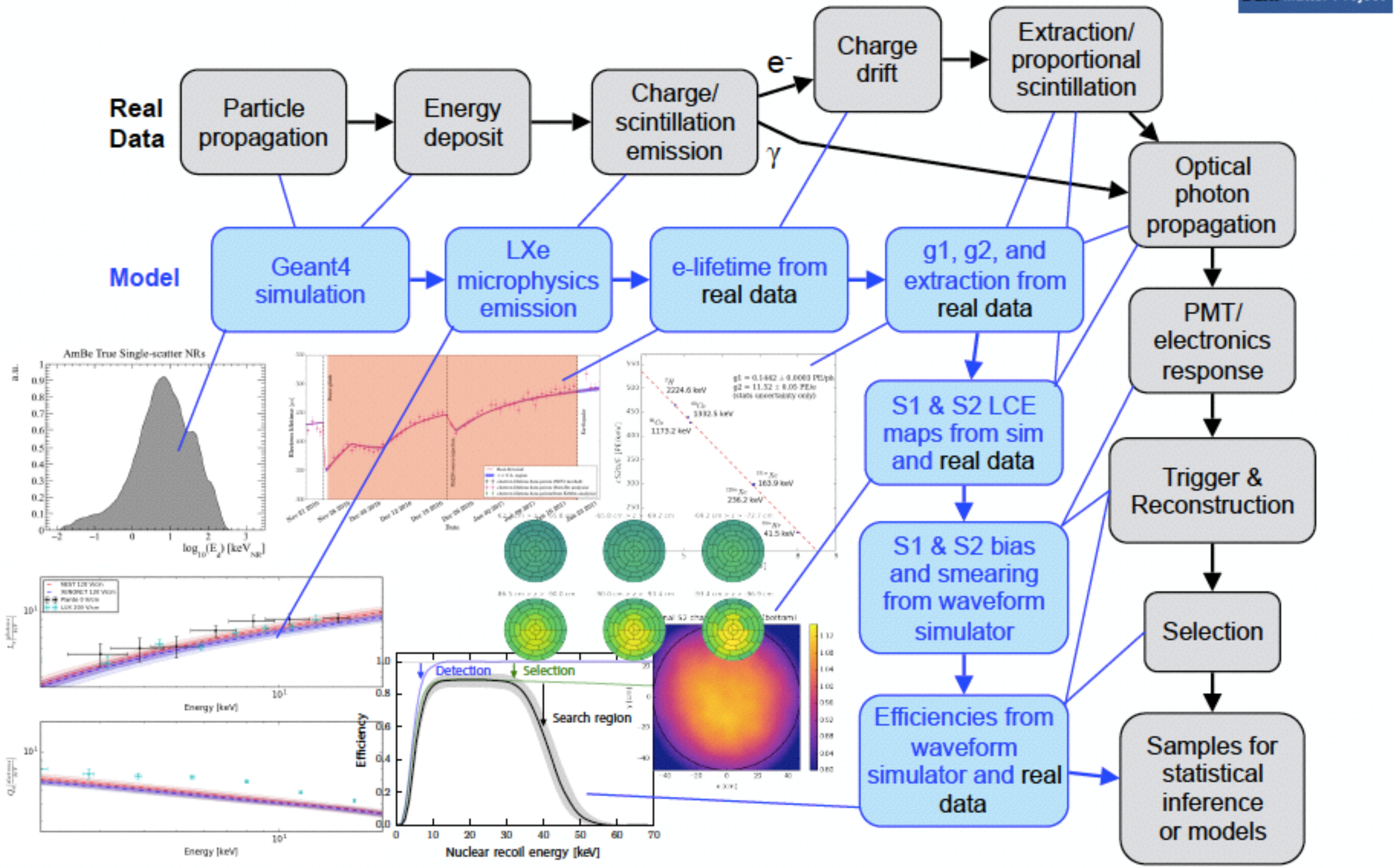
The ER and NR Models





- Simulate LXe microphysics & detector response to fit Rn220 and AmBe calibration data
- Background and signal predictions from tuned models

The ER and NR Models



G4DS, the DarkSide Simulation

Geant-4 based simulation of detectors geometry, TPC response

Tuning of the **optics** (no energy assumption) at the %level

Calibration of the **energy scale (S1 and S2)**

Effective parameterization of recombination probability of ions (E)

Pulse Shape Discrimination

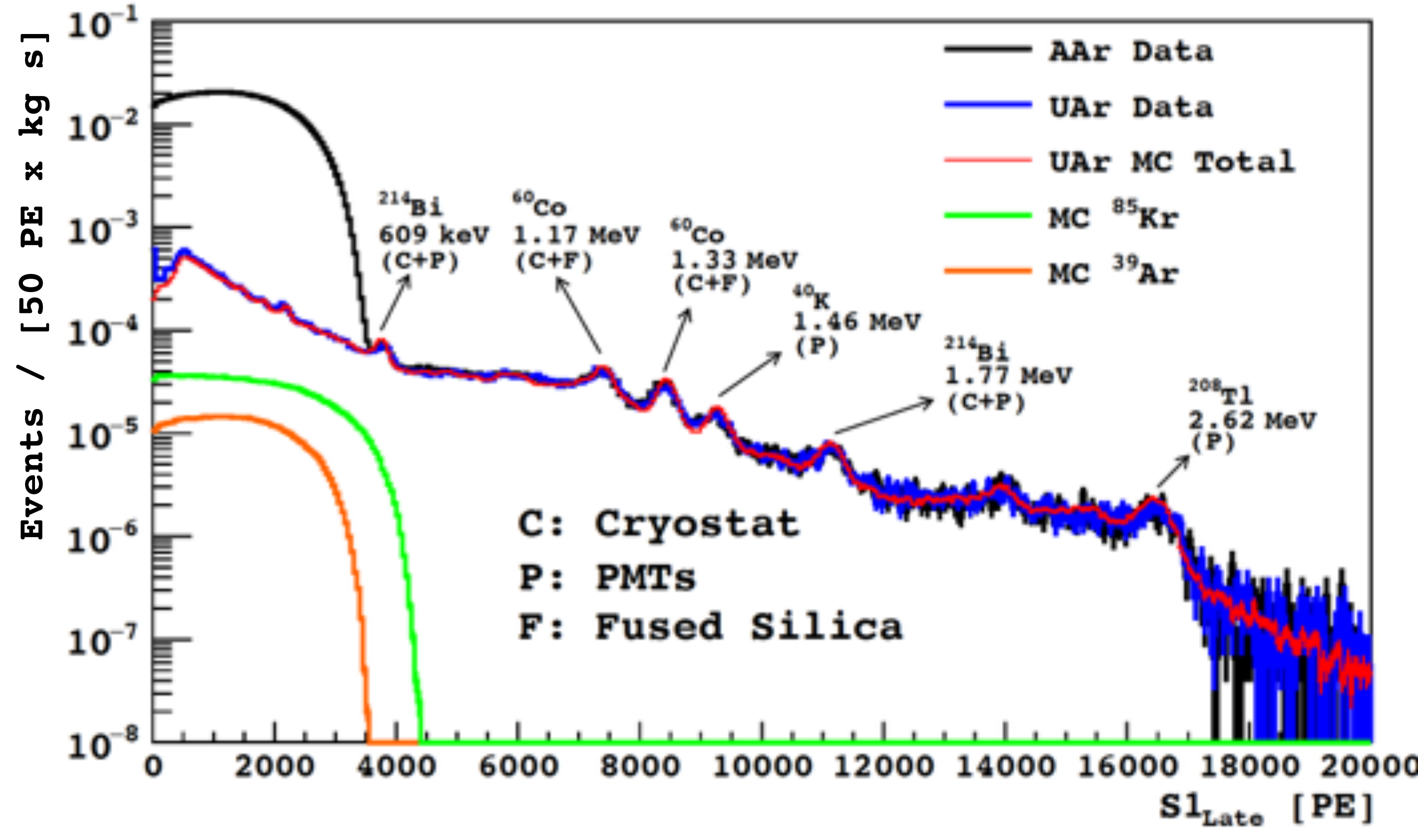
Simulation of the **vetoes**

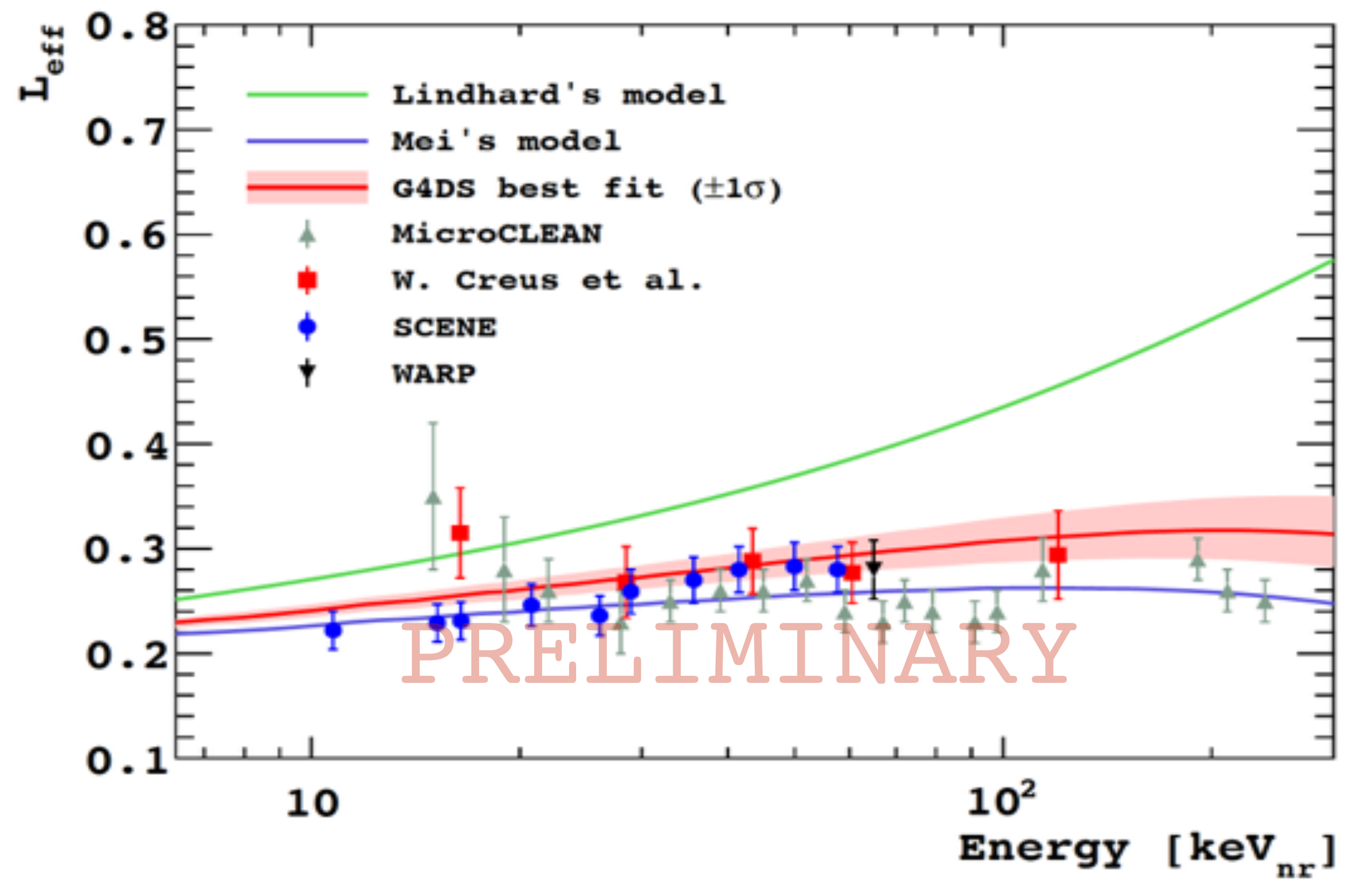
Some results:

Depletion factor (1400±200) and discovery of **^{85}Kr contamination** with spectral fit

Quenching factor for NR with AmBe

Paper in preparation, soon ready!

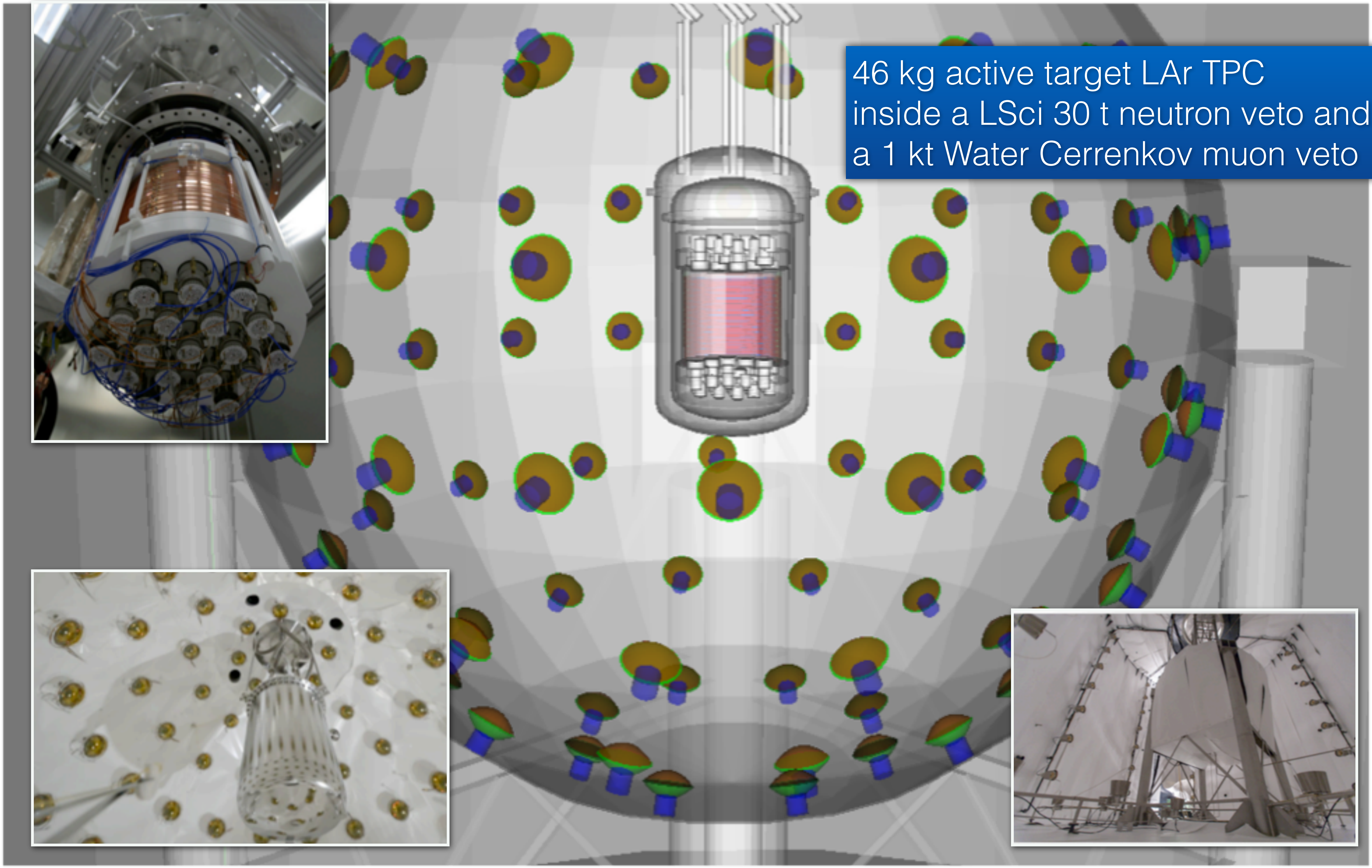




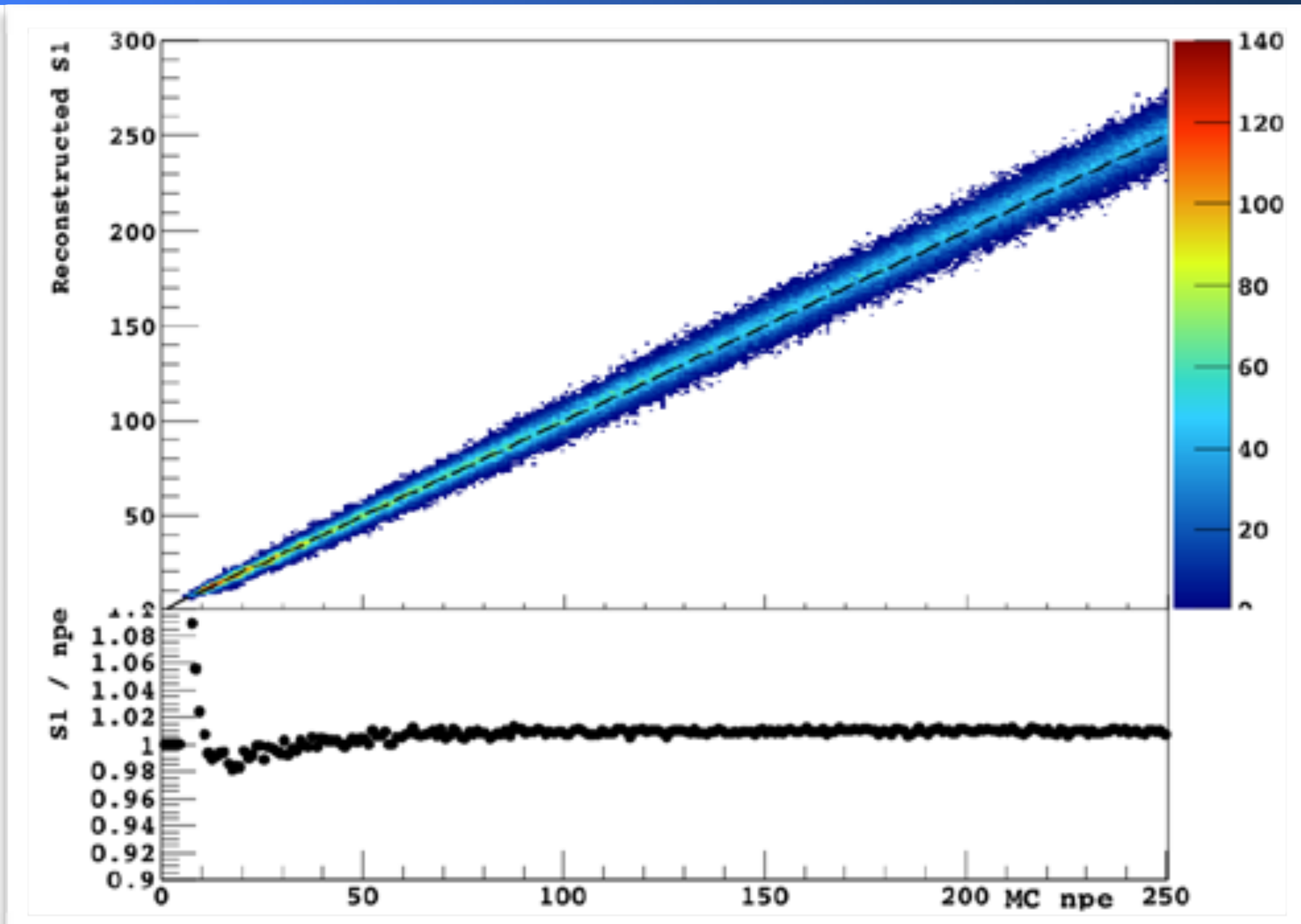
G4DS: the DarkSide simulation

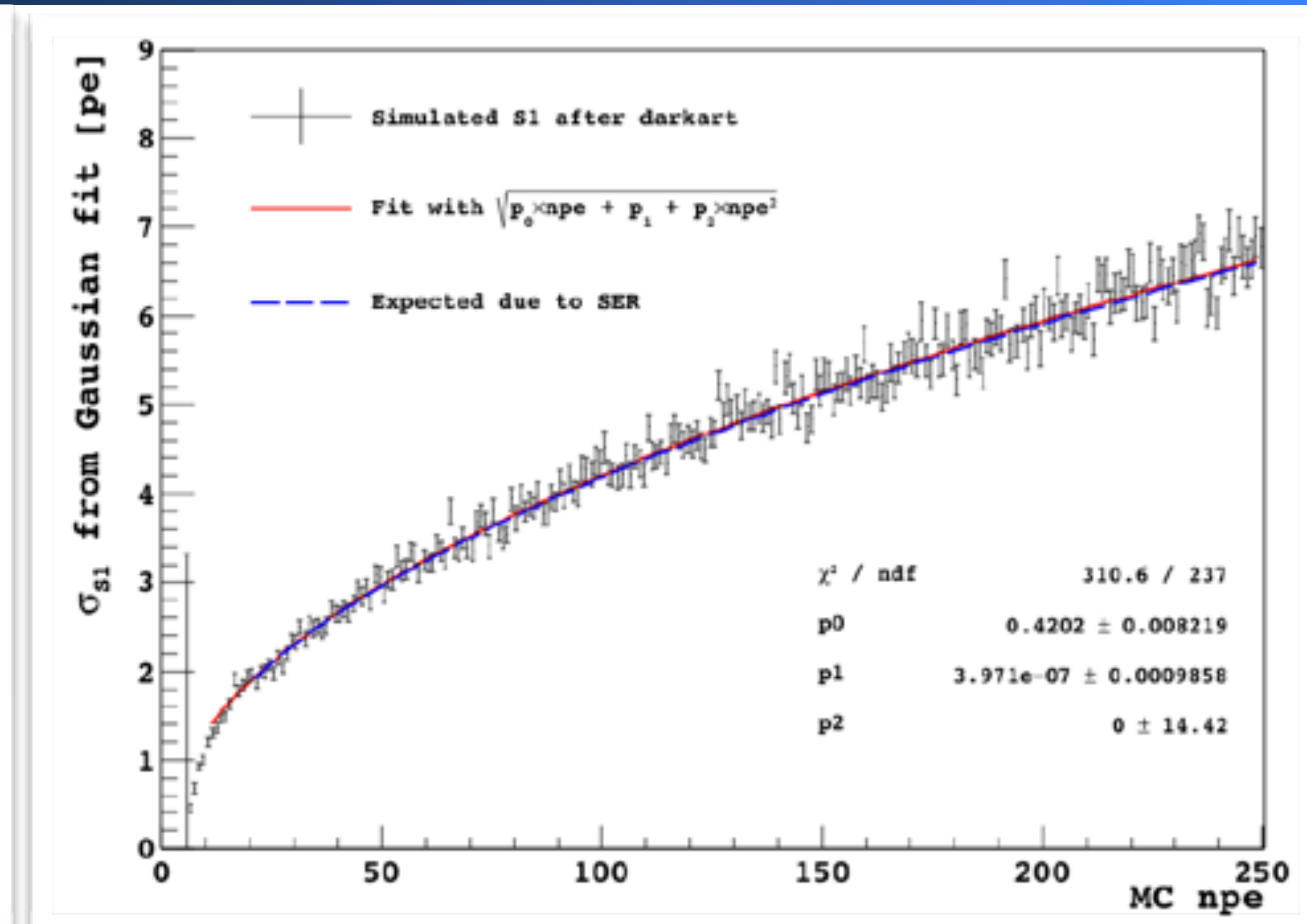
- modular architecture → full description of all the detectors belonging to the DarkSide program
- event generators for 39Ar and 85Kr beta decays, radioactive decays, cosmic muon and neutron fluxes as measured at LNGS, and AmBe and AmC neutron sources
- full optical propagation of photons up to photosensors; conversion of photoelectrons into charge signal handled by electronic simulation → S1, S2
- tuning of the optical properties based on data (PMT channel occupancies and top-bottom asymmetries)
- ionisation and scintillation response modelled in custom made G4 module Precision Argon Response Ionisation and Scintillation (PARIS)

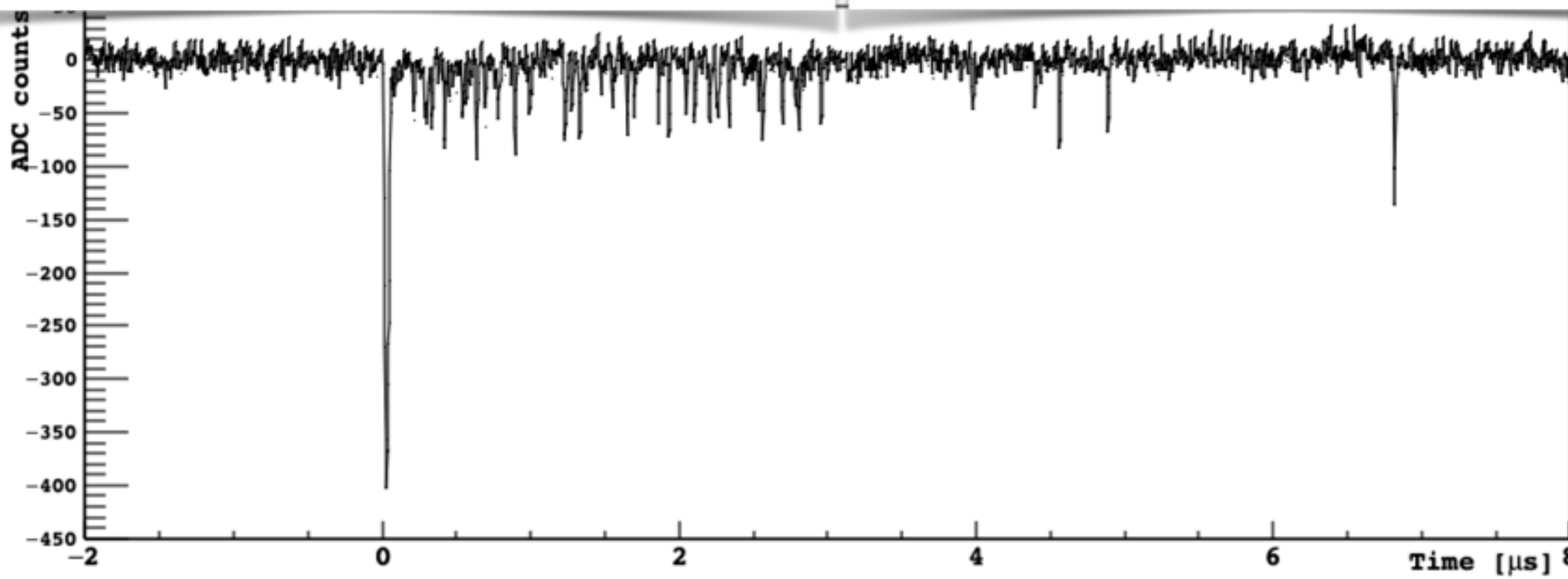
DarkSide-50 Geometry



Simulation of the Electronics







G4DS - Optical Tuning

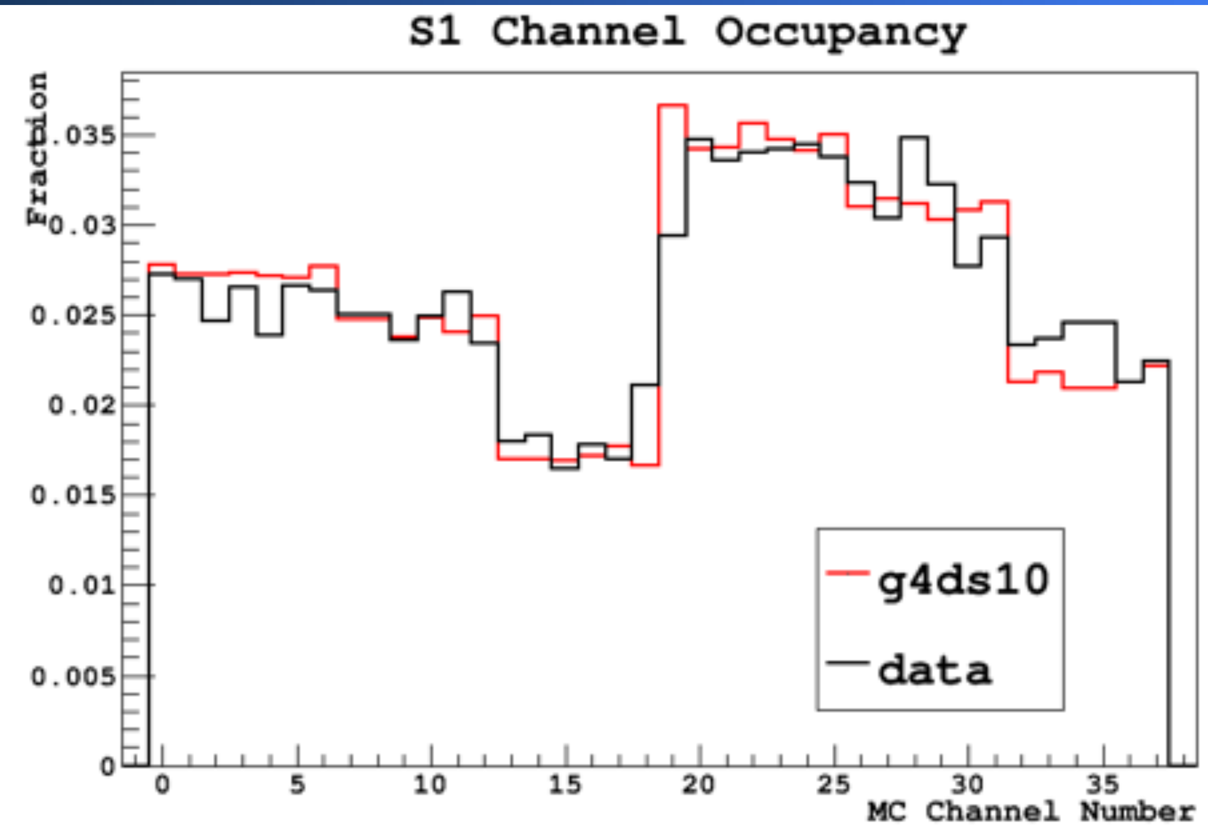
38 PMTs (3 inches), two arrays (top and bottom)

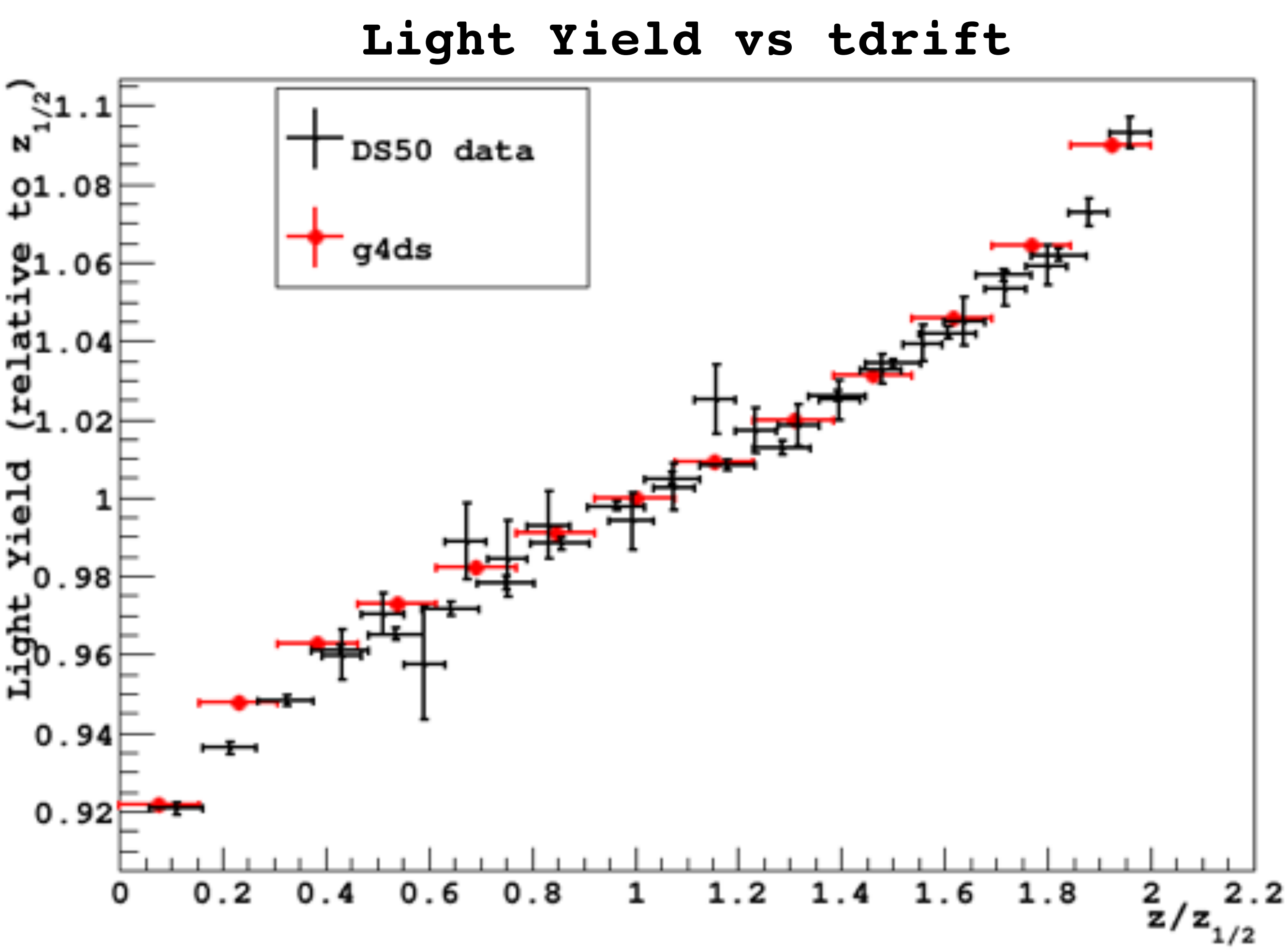
1. Relative quantities: no assumption on energy

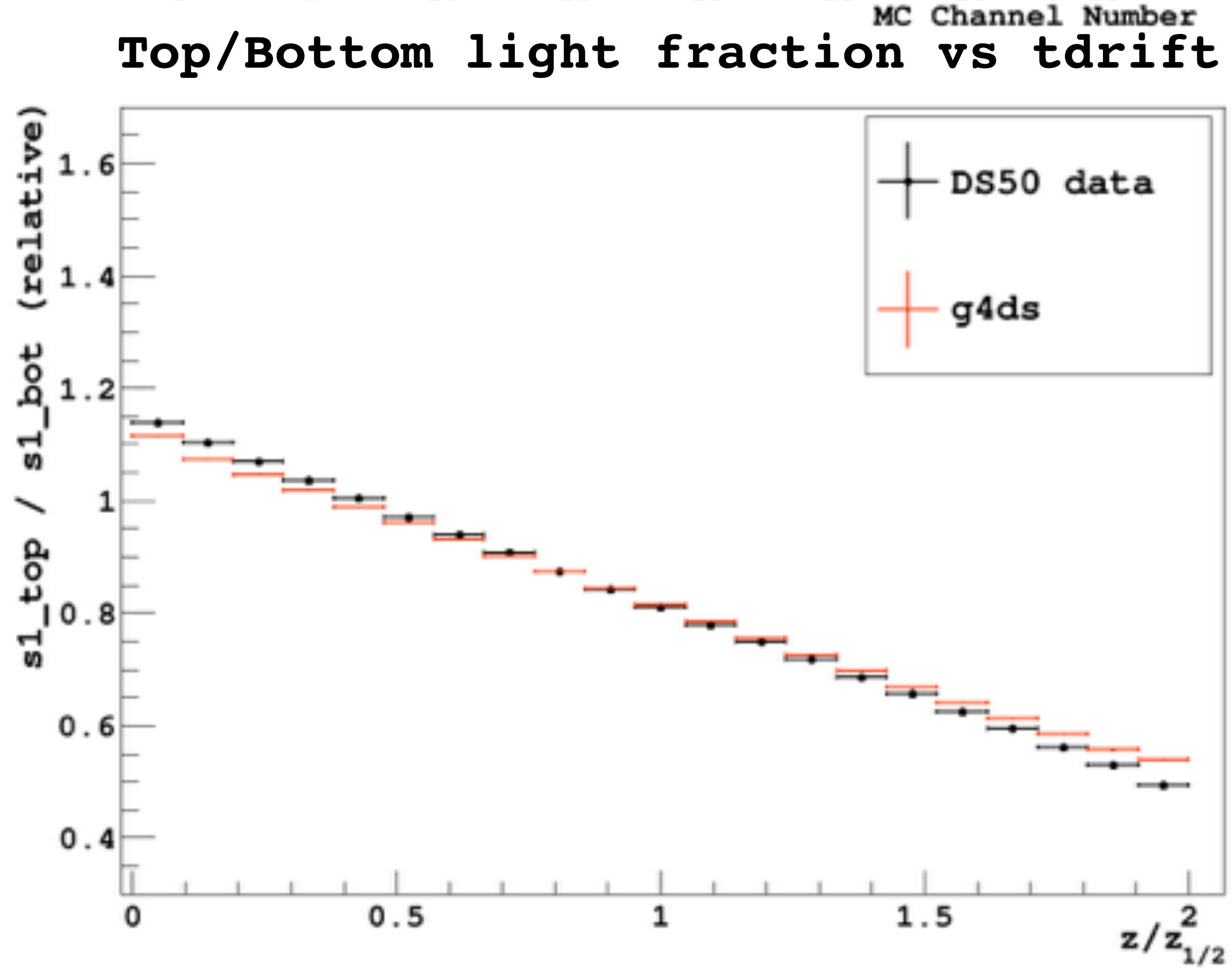
2. Tuning of optical parameters

(refractive indexes, absorption lengths, WLS…)

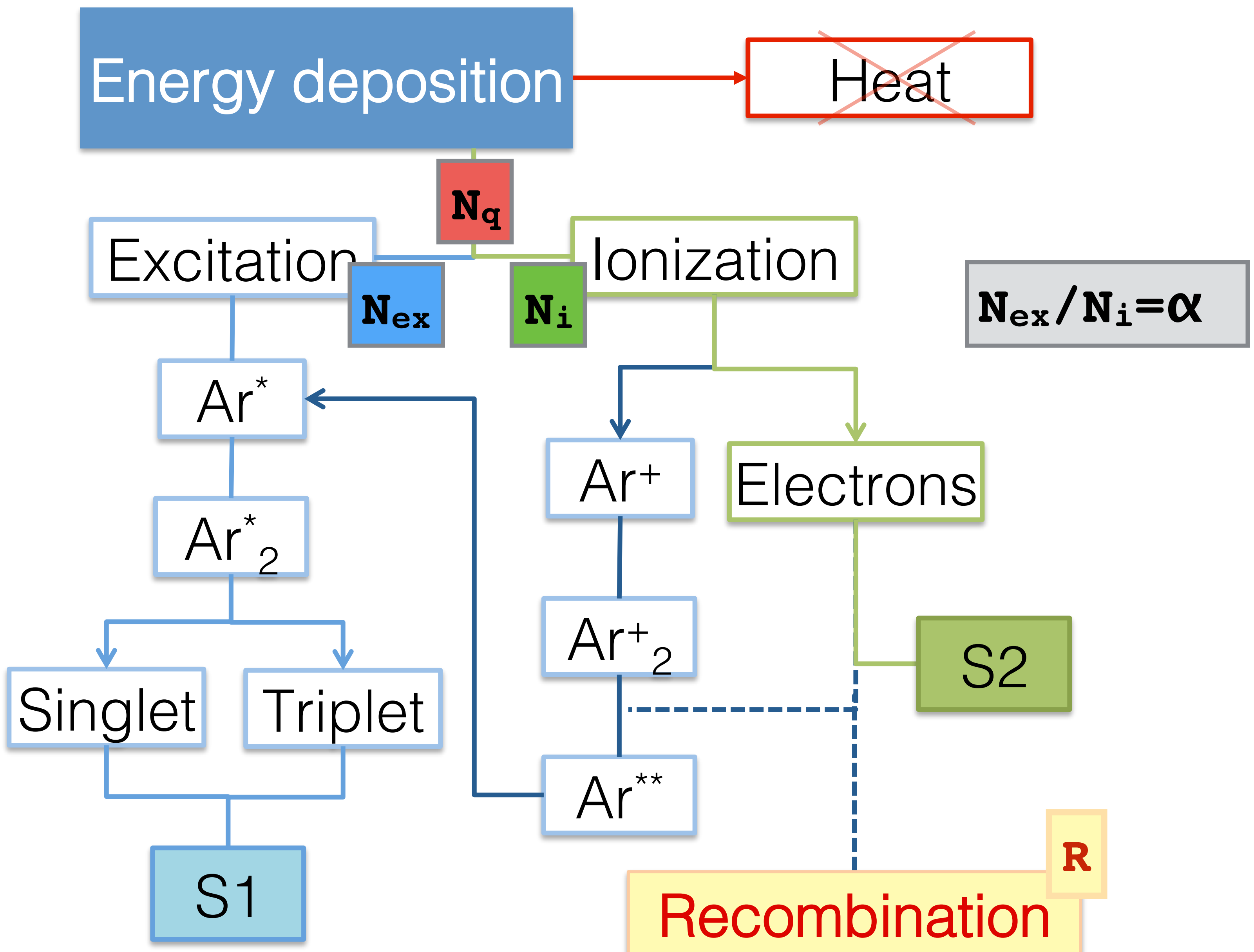
+ condensed Ar layer found/WLS defects







The PARIS Model



$N_q = E / W$

$N_i = N_q / (1+\alpha)$

$N_{ex} = N_q - N_i$

$N_{g1} = Y_{S1} (N_{ex} + RN_i)$

$N_{g2} = Y_{S2} \; N_i (1 - R)$

fluctuations

$S1 = g_1 N_{g1}$

$S2 = g_2 N_{g2}$

Assumptions:

$W = 19.5$ [eV]

$\alpha = 0.21$ (ER)

$\alpha = 1.00$ (NR)

Constant Y_{S1} (~1) and Y_{S2} (~270) (independent on E, field)

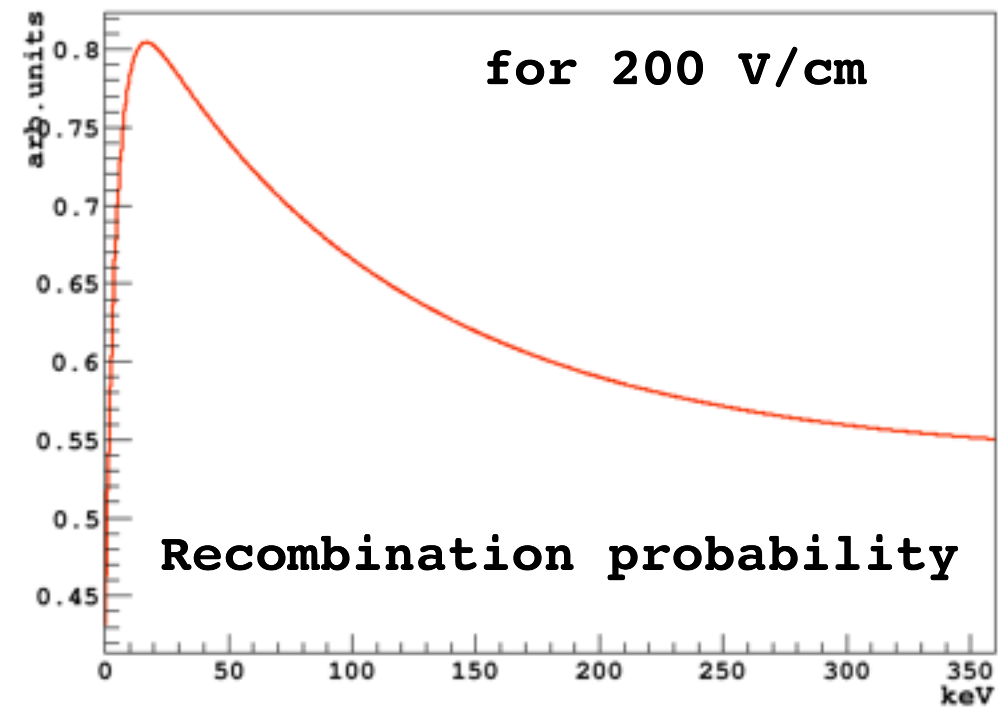
The goal is to model **R**
(the recombination probability)
as a function of the **recoil energy** and **drift field**

Recombination models

- Columnar Recombination
  - Jaffé, Phys. Rev., 58:968–976, 1940
- Box Model short tracks
  - Thomas and Imel, Phys. Rev. A, 36:614–616, 1987
- Doke - Birks Model long tracks
  - Doke et al., NIM A, 269:291–296, 1988
- NEST Model Geant4 simulation code, constrained by Xe data
  - Szydagis et al., JINST, 6(10):P10002, 2011

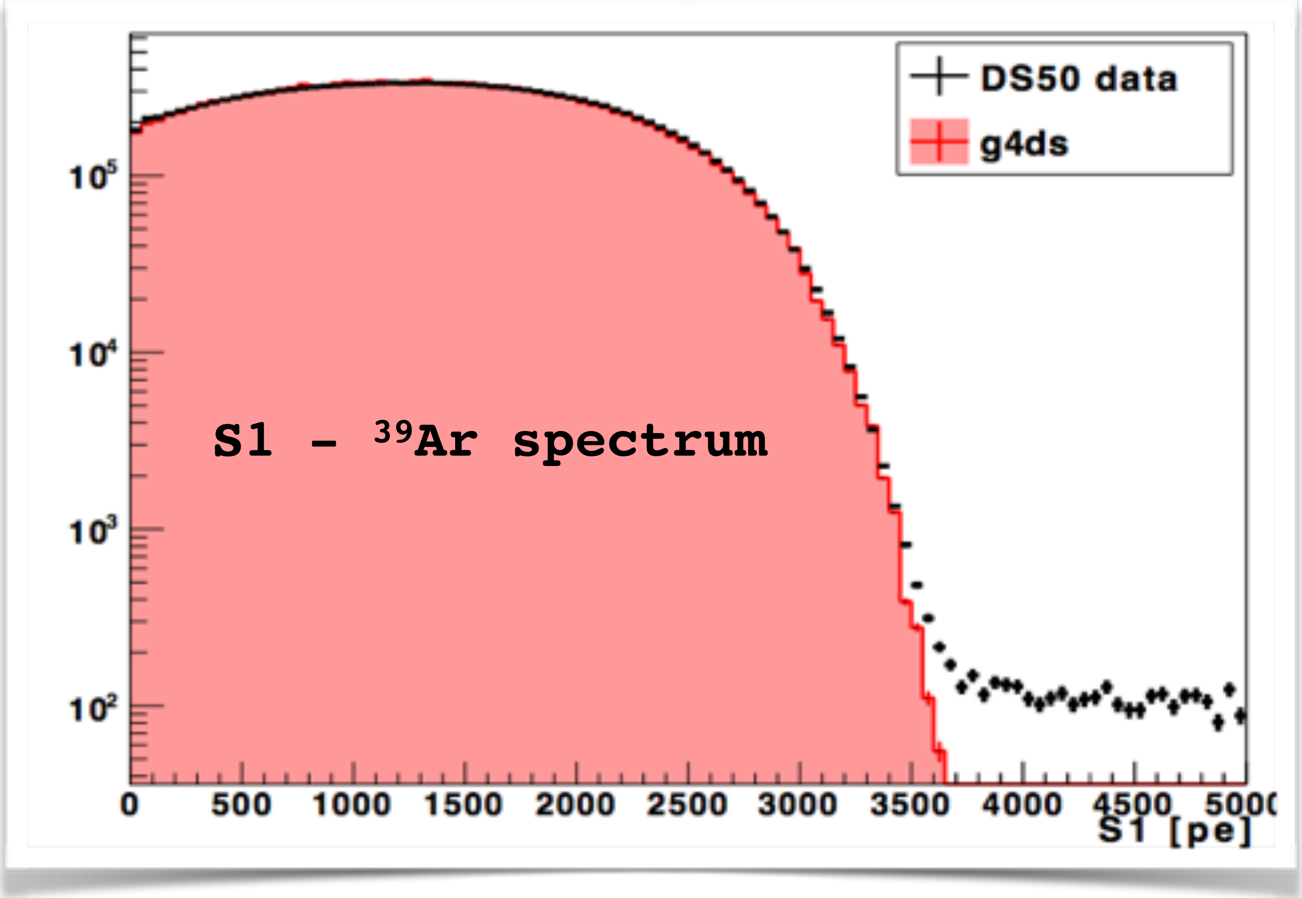
The Recombination Probability

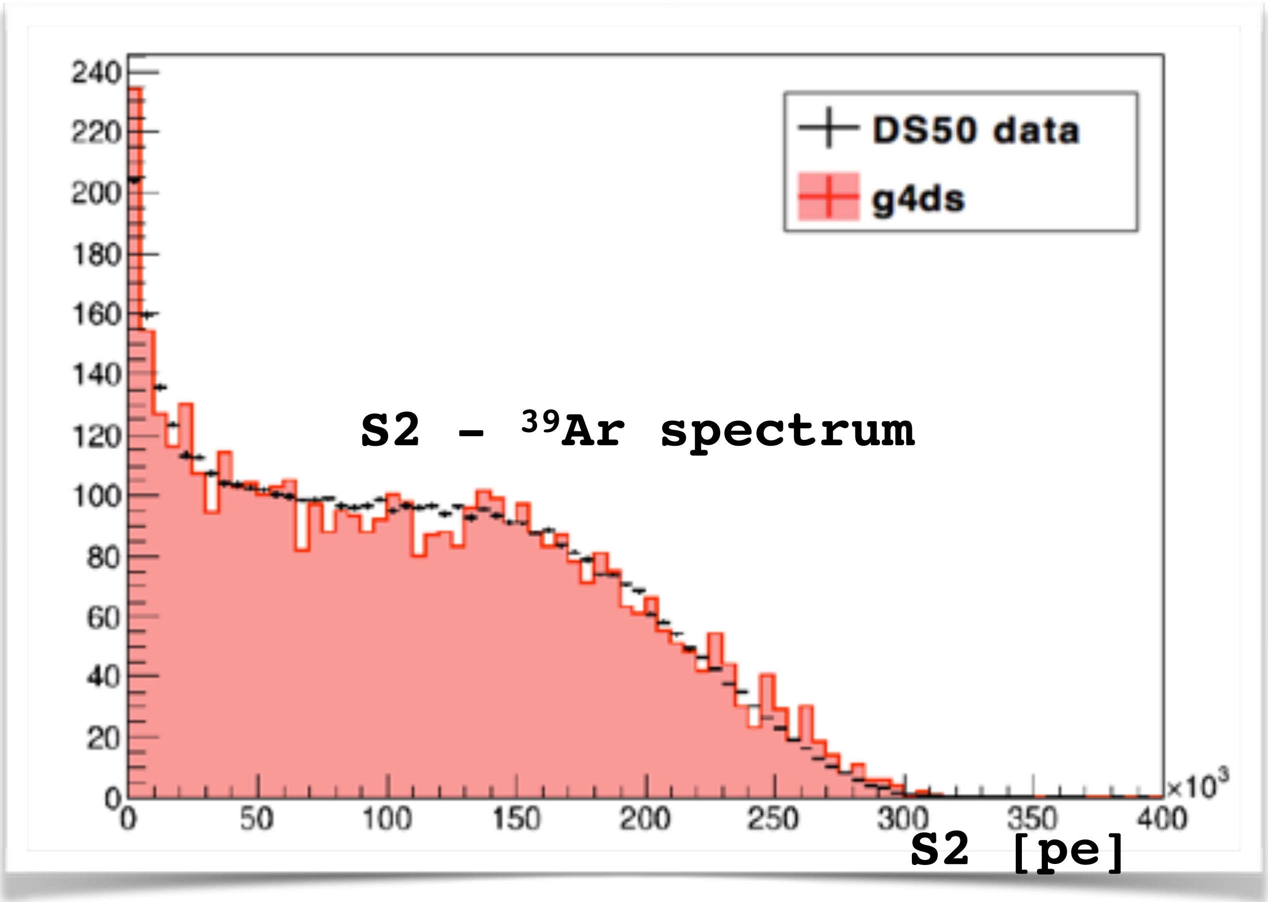
Extraction of the recombination probability from DS50 data



An **effective parameterisation** (4 parameters)

Fit of the
- endpoint of ^{39}**Ar** spectrum (565 keV),
- ^{83m}**Kr** (9.4 keV + 32.1 keV) peak
- ^{37}**Ar** peak (2.7 keV) peak



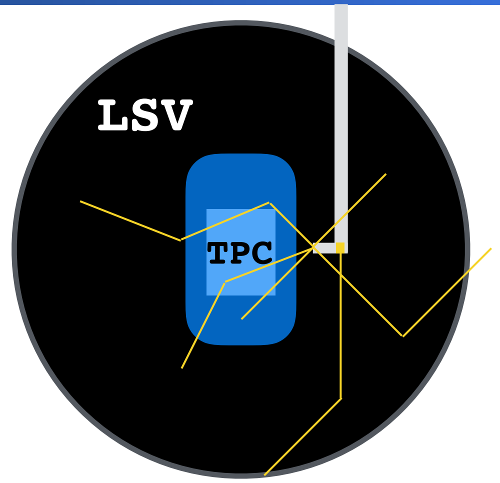


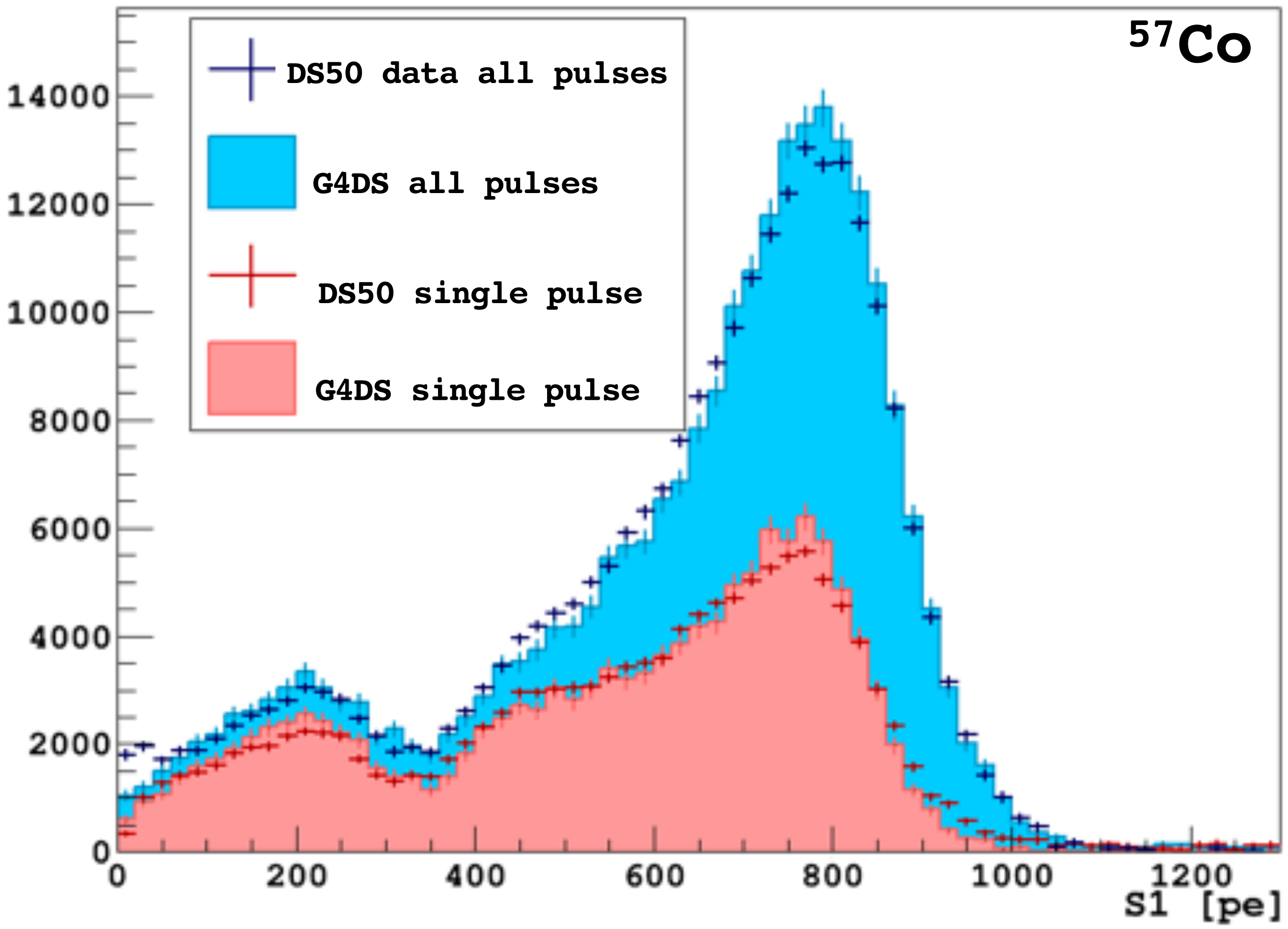
Electronic Recoils: Cross Check

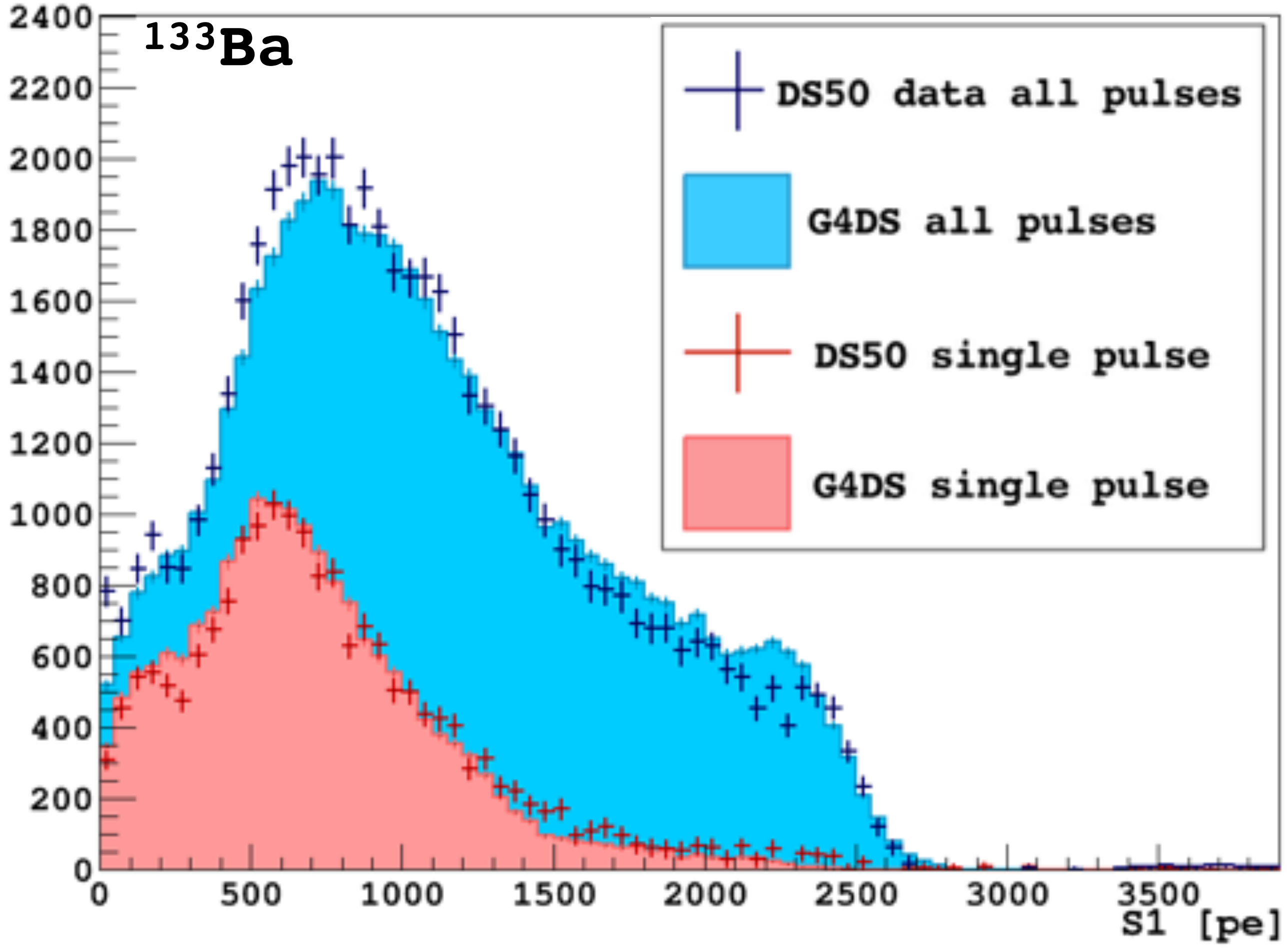
Cross check with **external calibration sources** (^{57}Co and ^{133}Ba)

CALIS (calibration insertion system)

S1 after statistical background (^{39}Ar) subtraction:







Same agreement for number of pulses, tdrift vs x-y distribution…

No additional smearing required!

Nuclear recoil quenching

Mei et al., Astropart. Phys. Vol 30-1(2008)

Lindhard theory + Birks' saturation law.

One free parameter: **k_B**.

$$L_{eff}^{M} = L_{eff}^{L} \times \frac{1}{1 + k_B \frac{dE}{dx}}$$

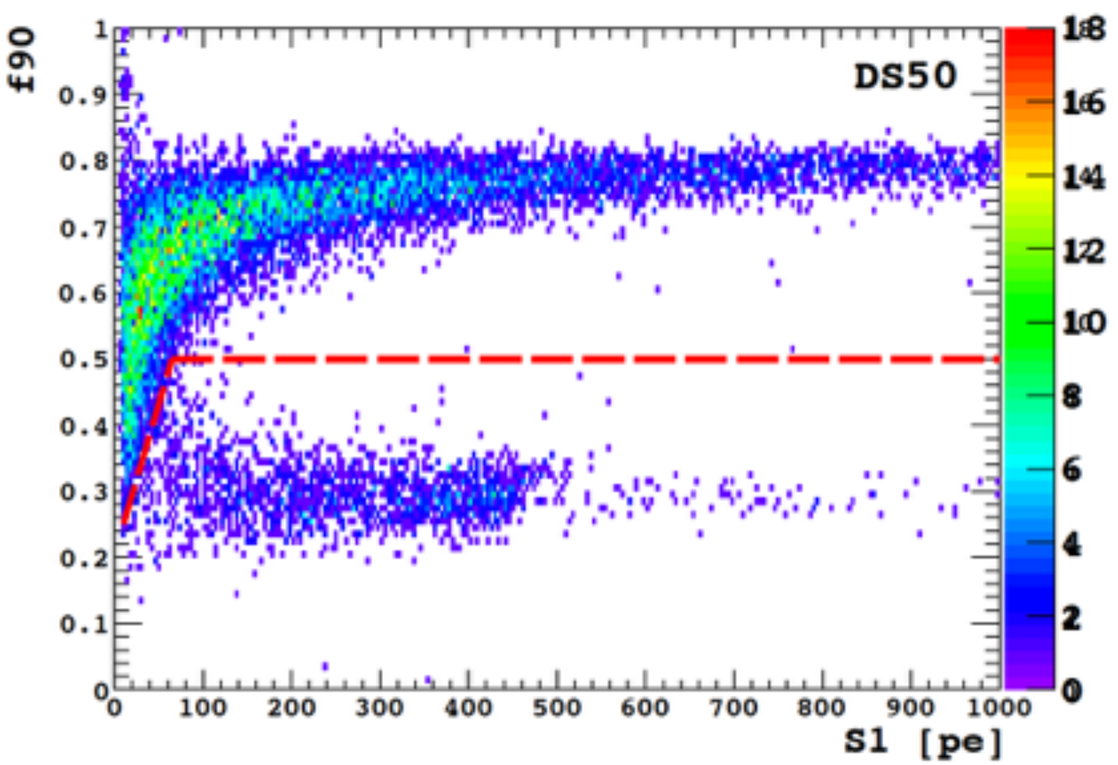
Mei suggested 7.4 E-4

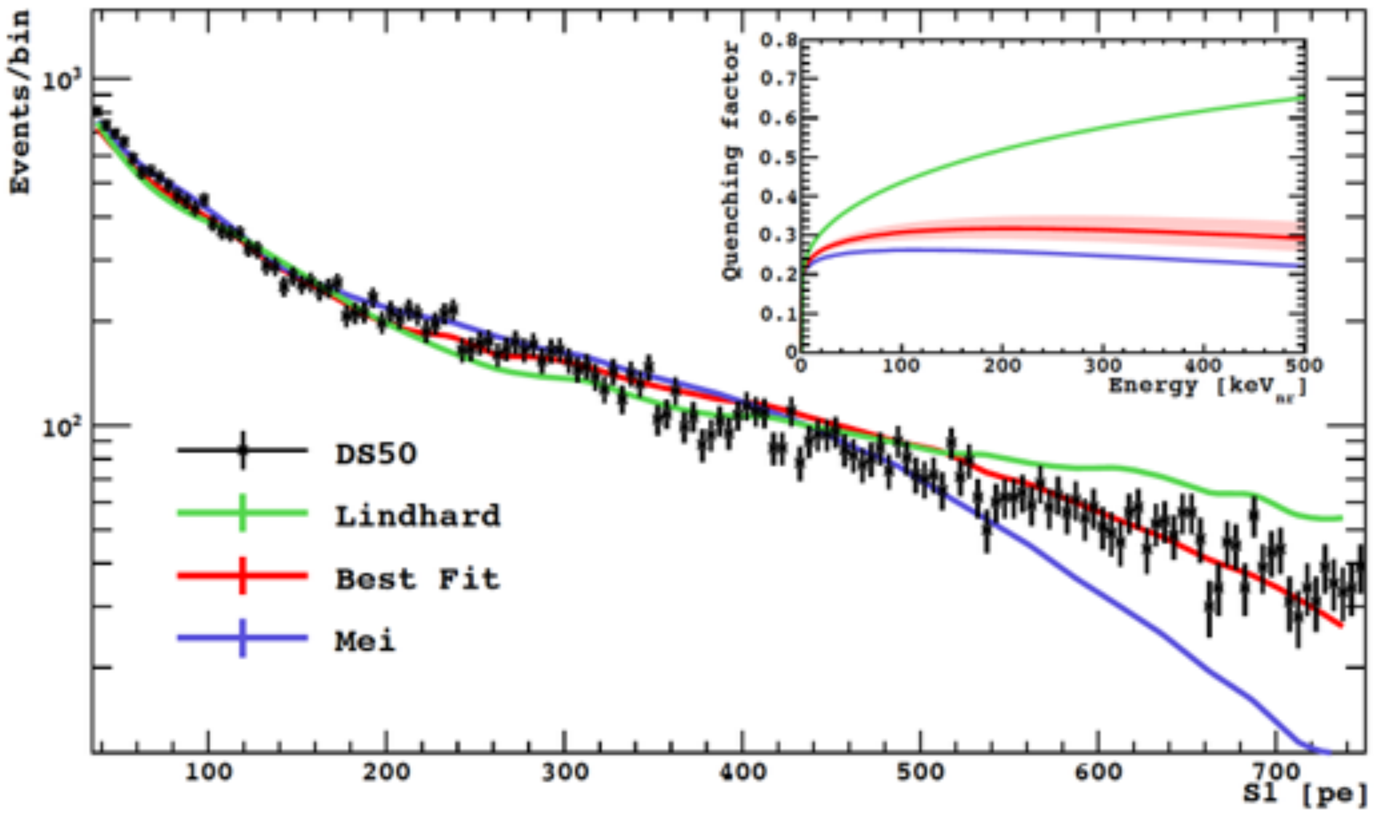
DS50 data **4.5 E-4** (E ON) and 5.75 (E Off)

MC fit to clean neutron sample in AmBe data

$$4.66^{+0.86}_{-0.94} \times 10^{-4}\ \mathrm{MeV}^{-1}\ \mathrm{g\ cm}^{-2}.$$

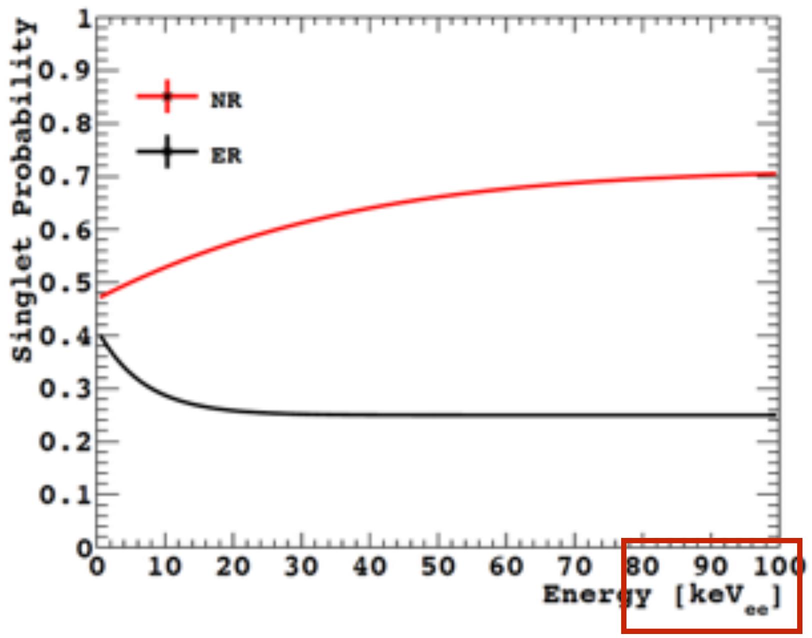
Data/MC S1 projections

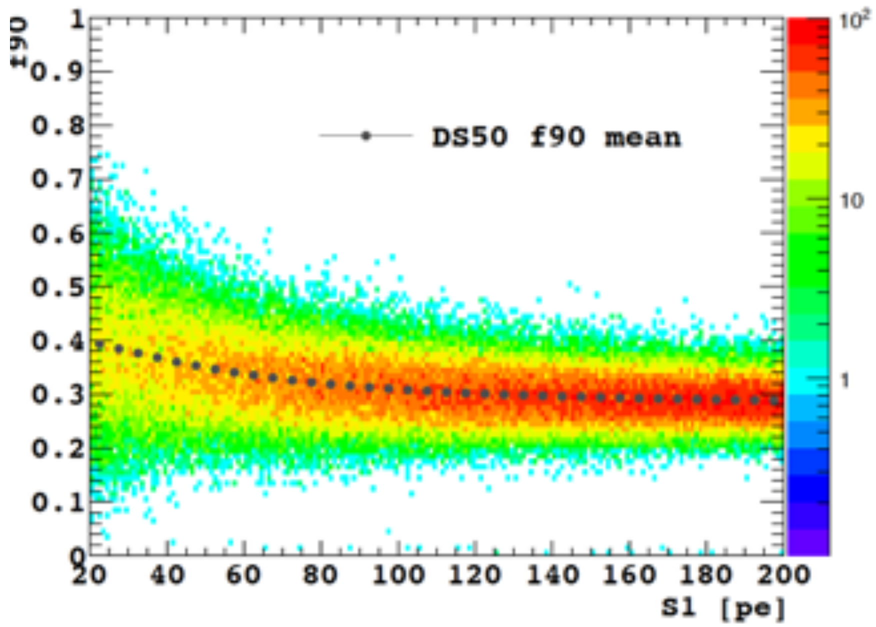




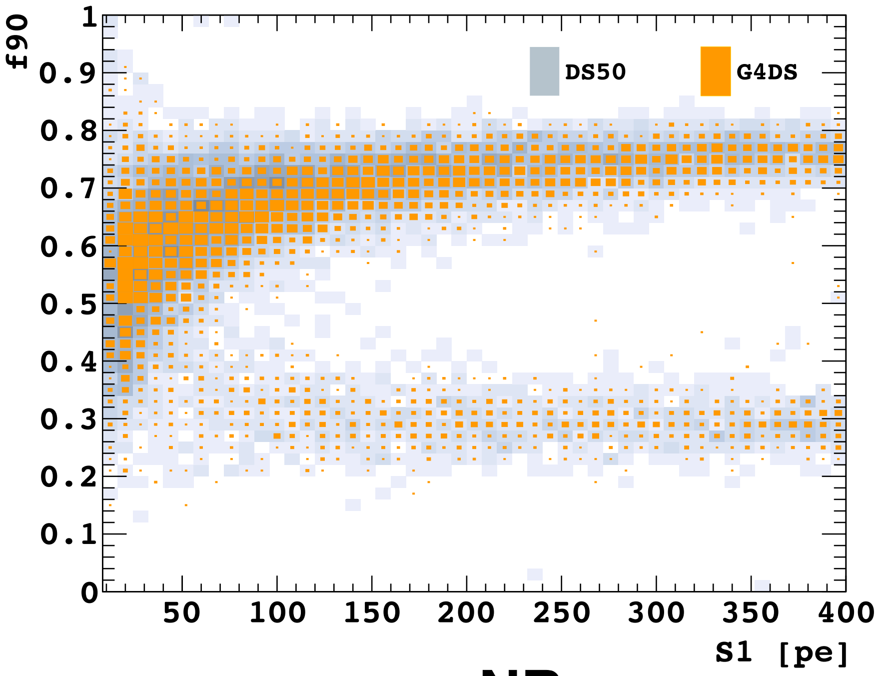
f90

Input parameters (fit of data with Hinkley model). Tested up to 10x the statistics as AAr.

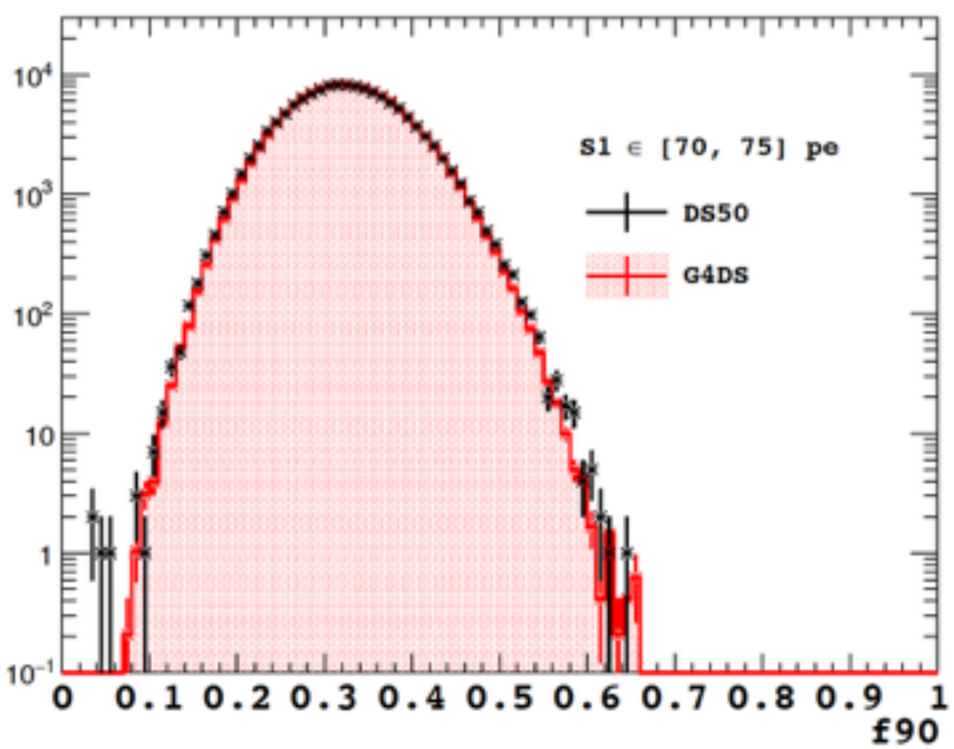


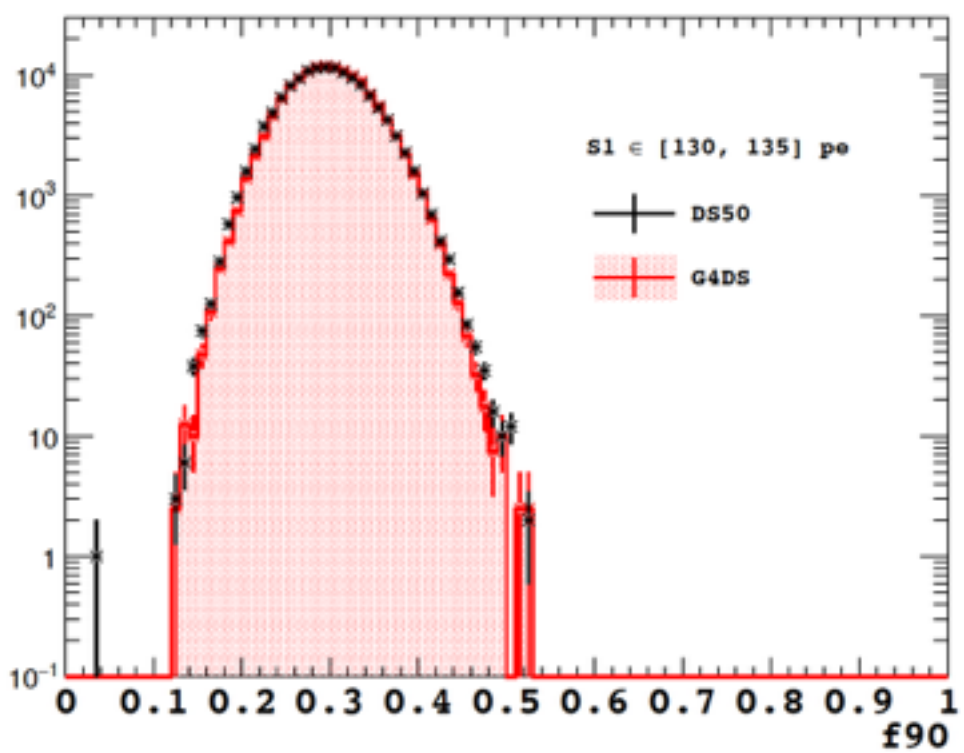


ER



NR





^{39}Ar events

- spectral shape
- full optics + SPE
- S1 in [70,75]
- S1 in [130,135]

DarkSide-20k

Photodetectors and Simulation

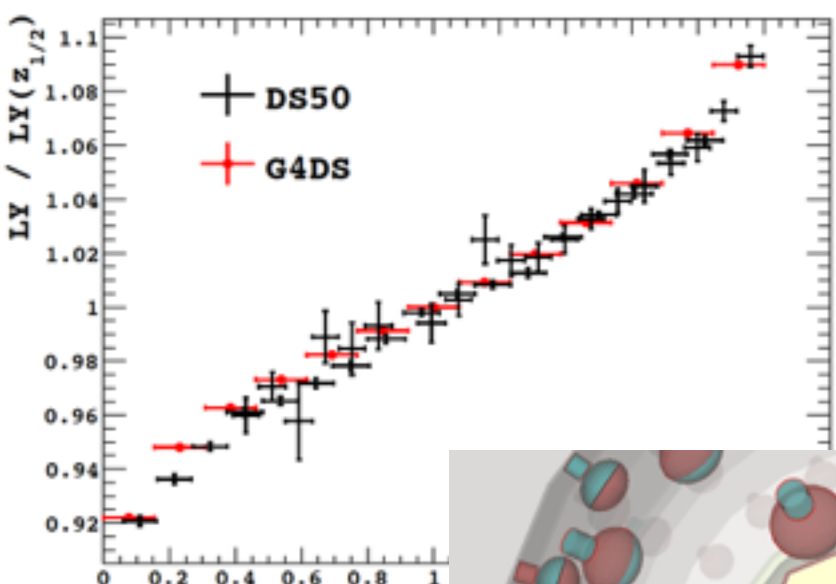
Proposed layout in DS20k

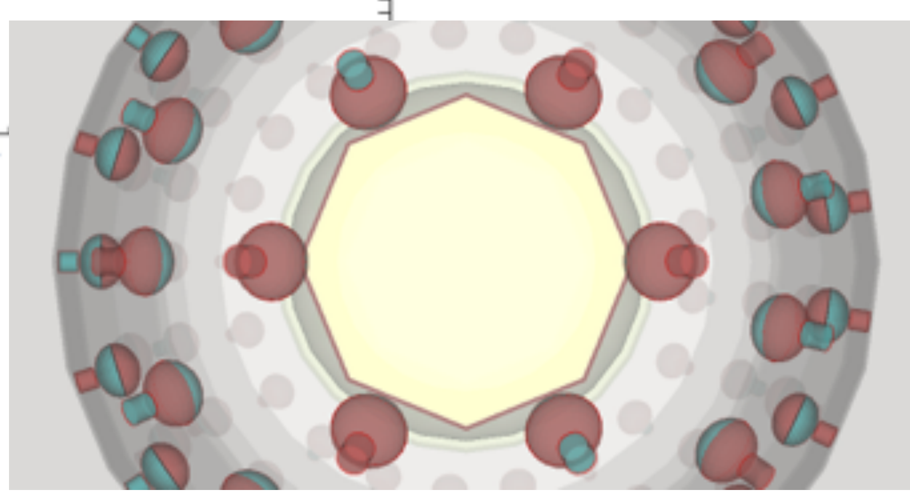
- grouped in 5x5 cm² tiles (~5k channels)
- readout currently being optimized:
  - single pe regime for S1 (timing)
  - full charge integration for S2 (energy)

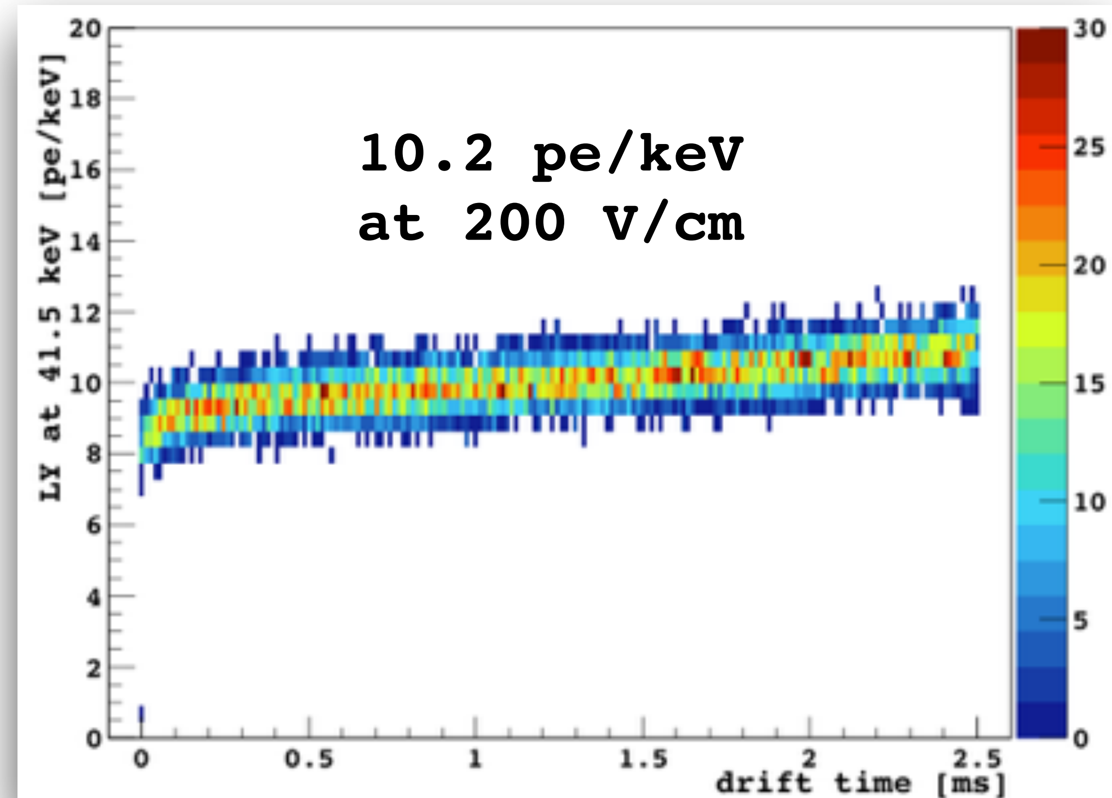
Requirements:
Low DCR (10^{-1} Hz/mm²)
40% PDE (QE x Fill Factor)
Dynamic Range > 50 pe
Time resolution < 10 ns
Power < 250 mW /tile

G4DS is tuned to reproduce **DS50 TPC response**

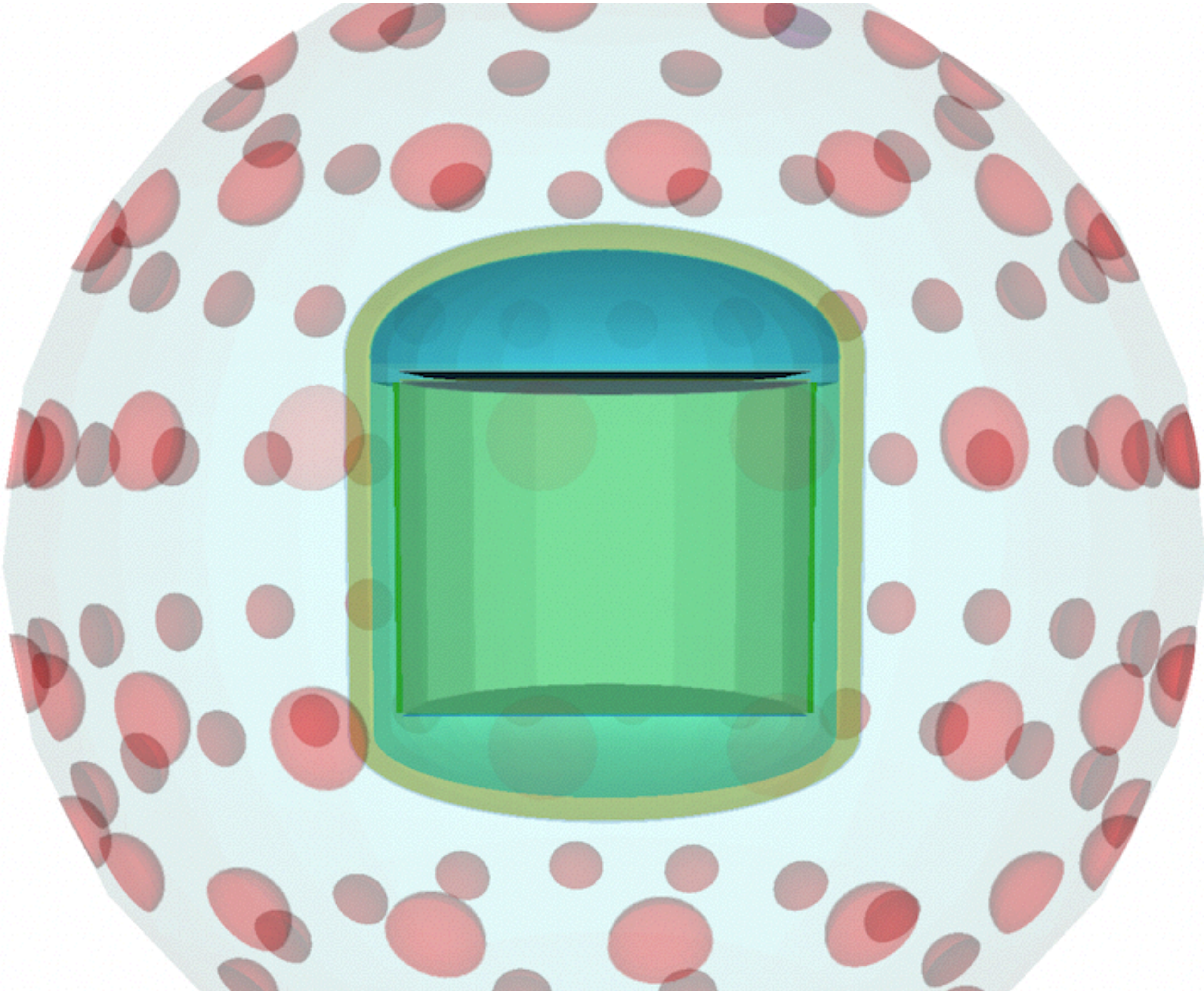
- \+ DS20k geometry
- \+ SiPM readout



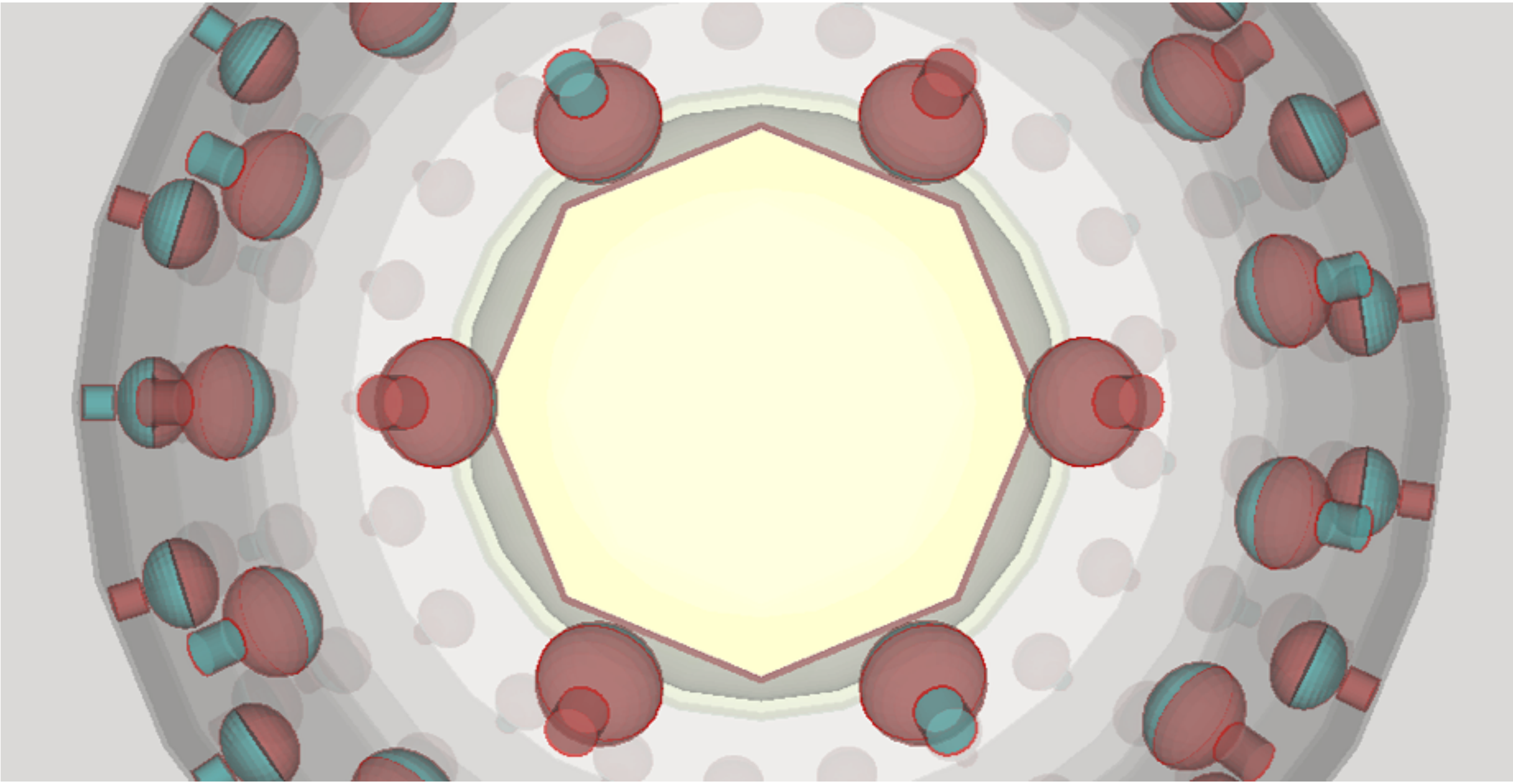




Geometry



Geometry



DarkSide-20k Projected Sensitivity

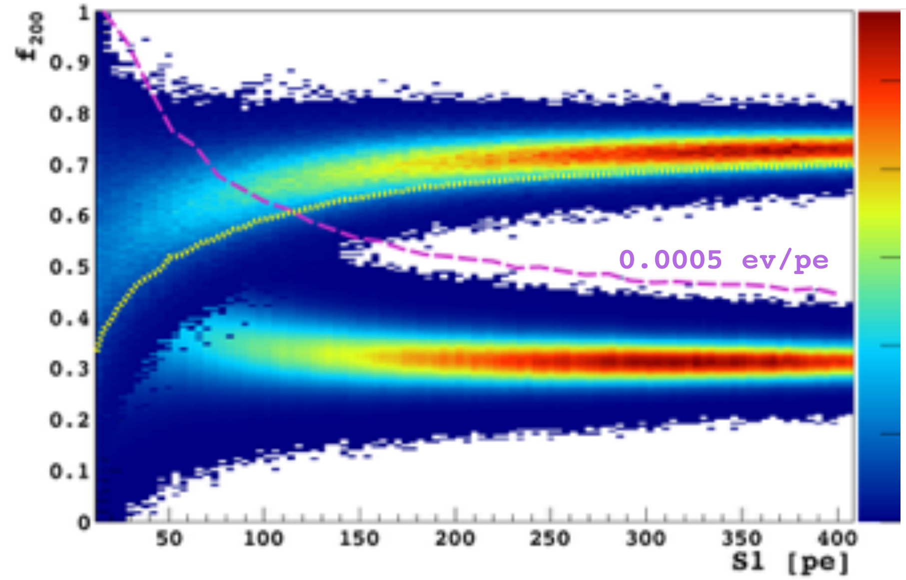
Simulation of several millions of events (ER and NR) to determine **the acceptance to WIMPs,** assuming NR + ER background < 0.1 events.

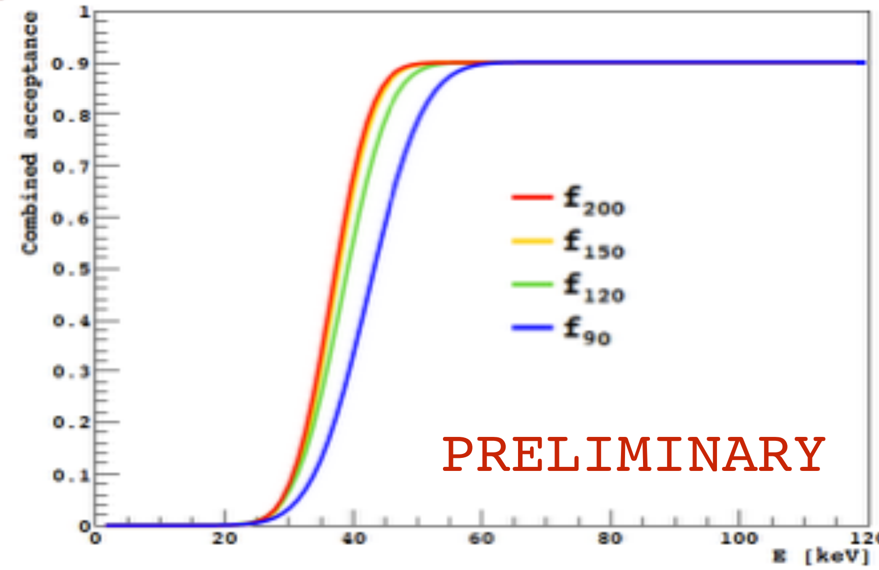
+ Nuclear recoil quenching from DS50

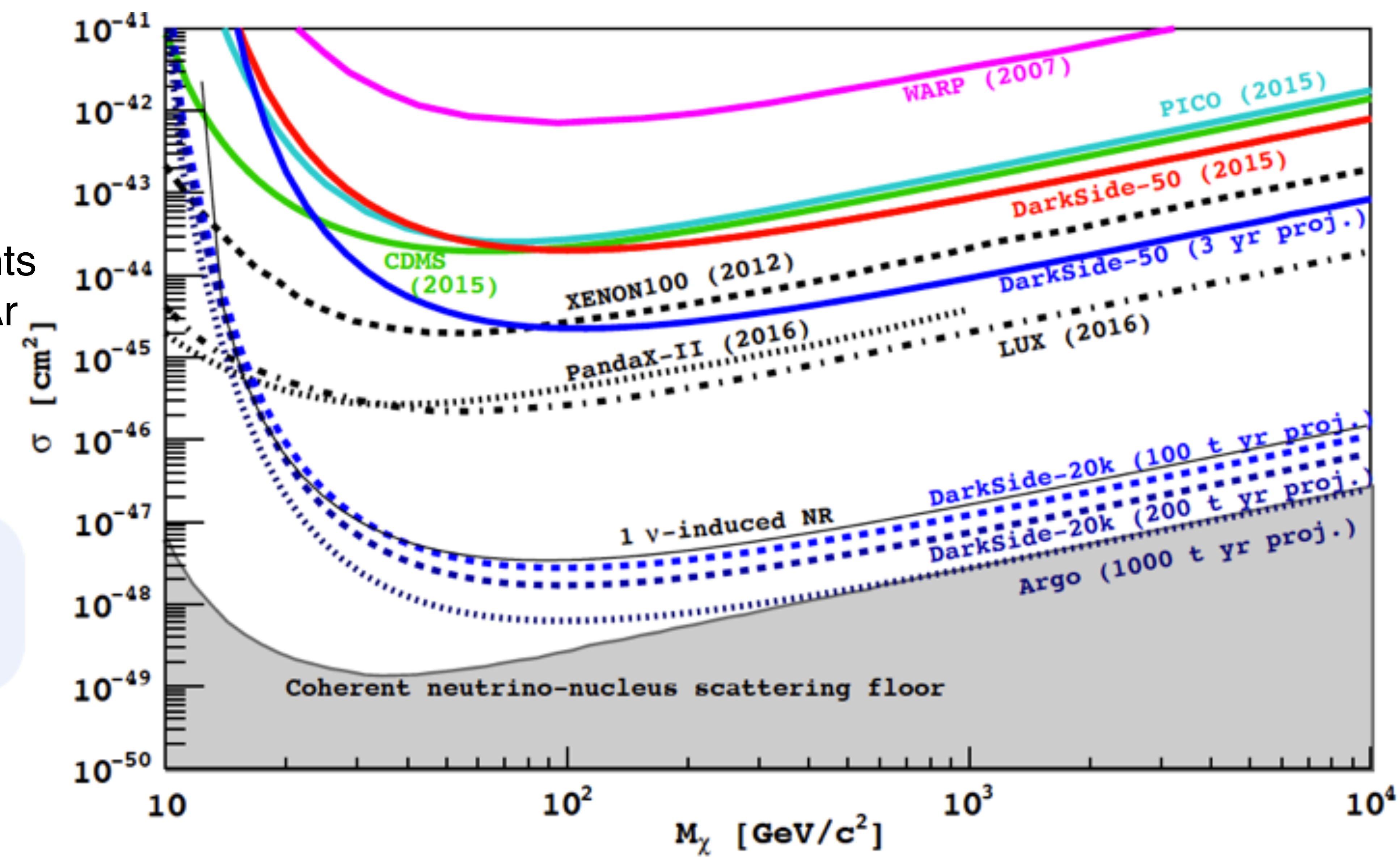
Optimization of PSD parameter for the best sensitivity.

Expected **>200x10⁶** events (1400 depletion) from ³⁹Ar only in [0,50] keV.
A simulation of the **full statistics** is ongoing.

1.6 CNNS events expected, likelihood approach in progress.



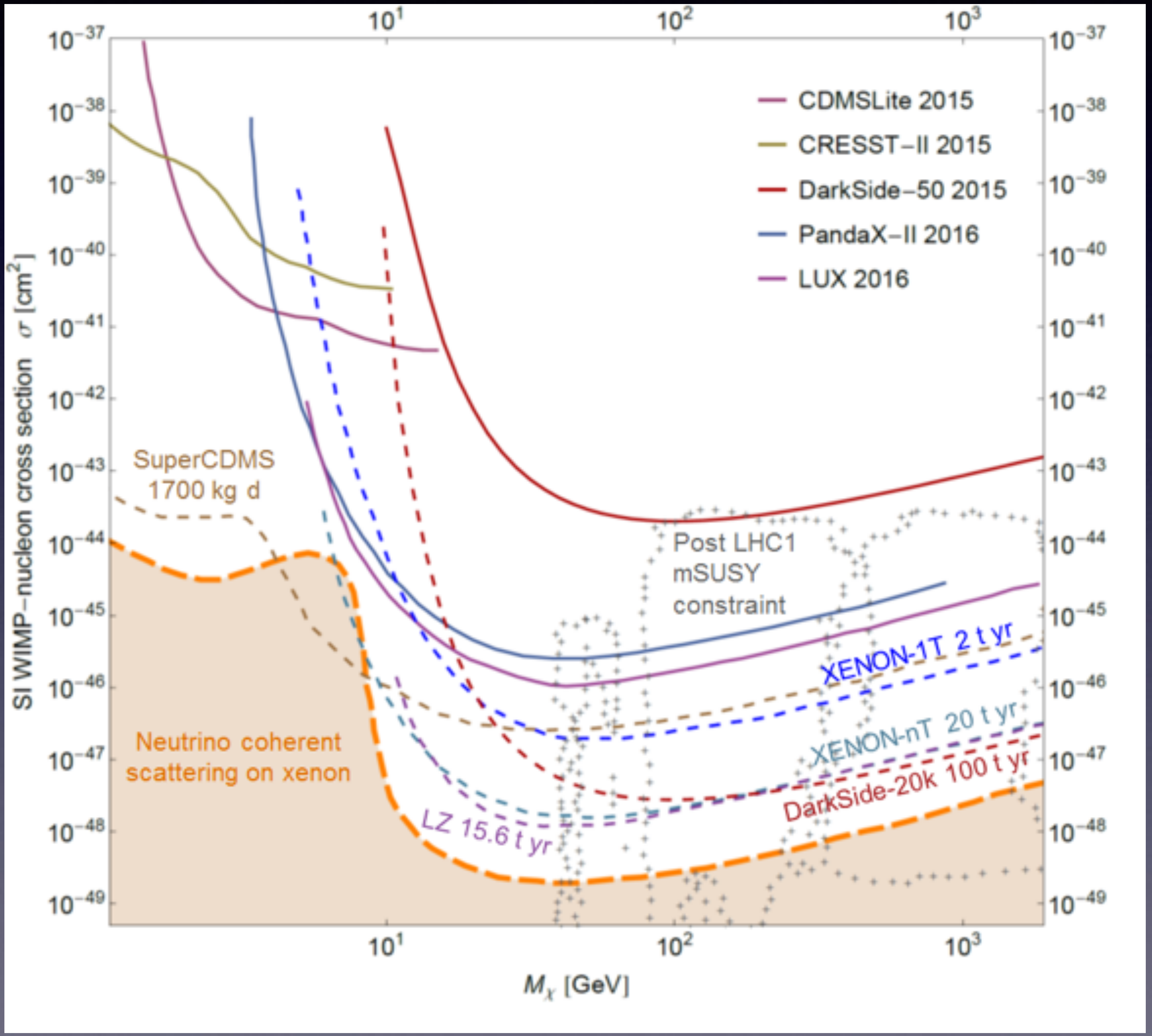




High mass WIMPS: future perspective

- Ar complimentary to Xe – only other target allowing such large exposure
- DS-20K competitive with LZ and XENONnT – start operation 2021
- LAr 1000-tonne years (future detector) reaches down to neutrino floor
- b/γ discrimination: solar pp neutrino ES background not a concern – in X1T, LZ expected dominant bkg at 0.5 event per tonne-year after recoil discrimination
- Through the neutrino floor
  - directional measurements?

by M. Cadeddu (adapted from **NATURE PHYSICS** DOI: 10.1038/NPHYS4039)



Thank you