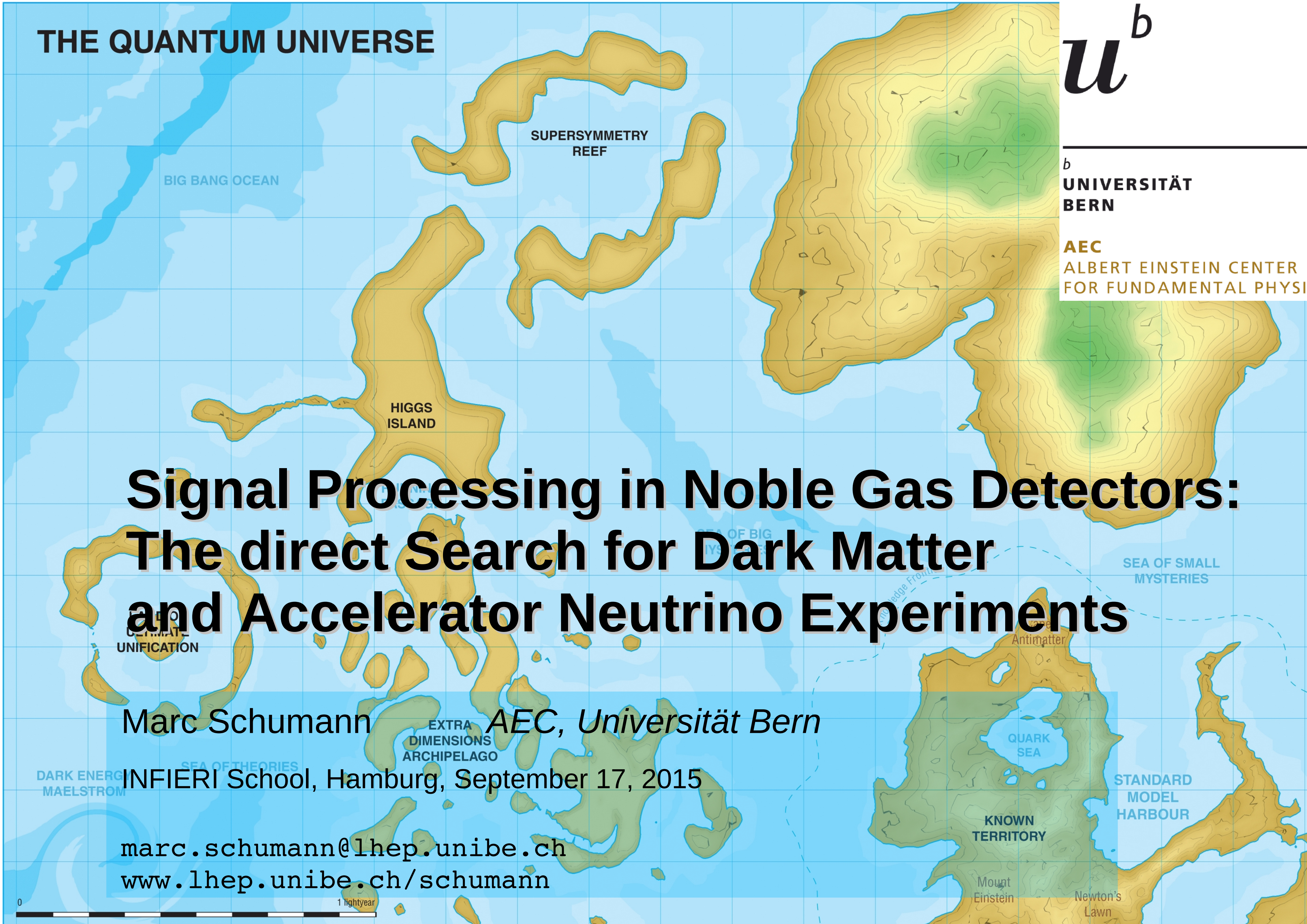

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Signal Processing in Noble Gas Detectors: The direct Search for Dark Matter and Accelerator Neutrino Experiments

Marc Schumann *AEC, Universität Bern*

INFIERI School, Hamburg, September 17, 2015

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`www.lhep.unibe.ch/schumann`

Outline: Signal Processing

wikipedia:

Signal processing is an enabling technology that encompasses the fundamental theory, applications, algorithms, and implementations of processing or transferring information contained in many different physical, symbolic, or abstract formats broadly designated as signals.

It uses mathematical, statistical, computational, heuristic, and linguistic representations, formalisms, and techniques for representation, modelling, analysis, synthesis, discovery, recovery, sensing, acquisition, extraction, learning, security, or forensics.

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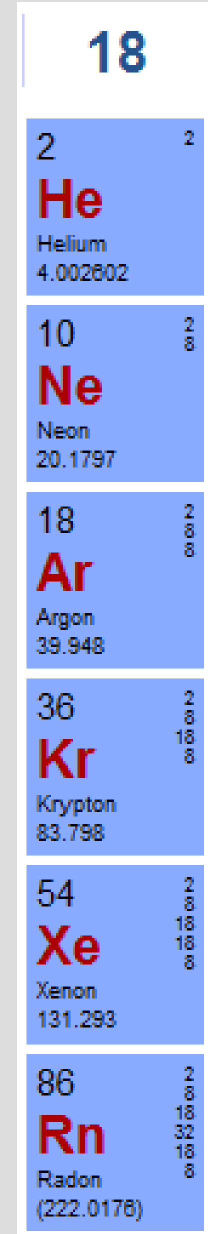
Agenda

1. Noble Liquids as Detectors
2. Dark Matter and Liquid Xenon TPCs → *XENON100*
3. Neutrinos and Liquid Argon TPCs → *MicroBooNE*

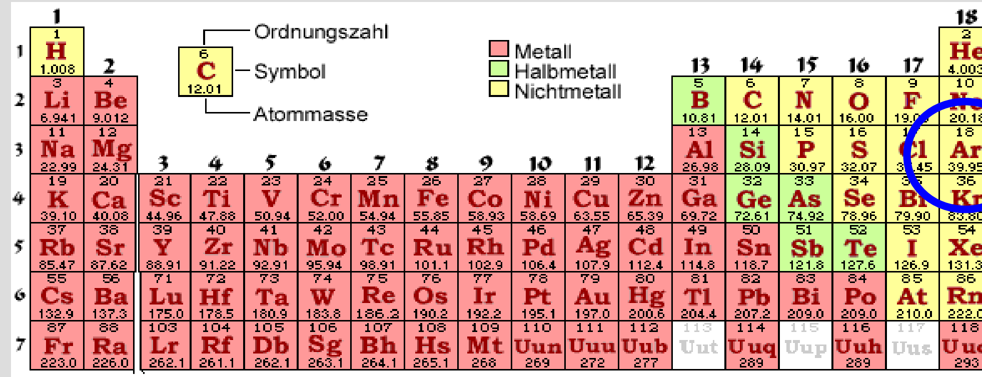
Noble Liquid Targets

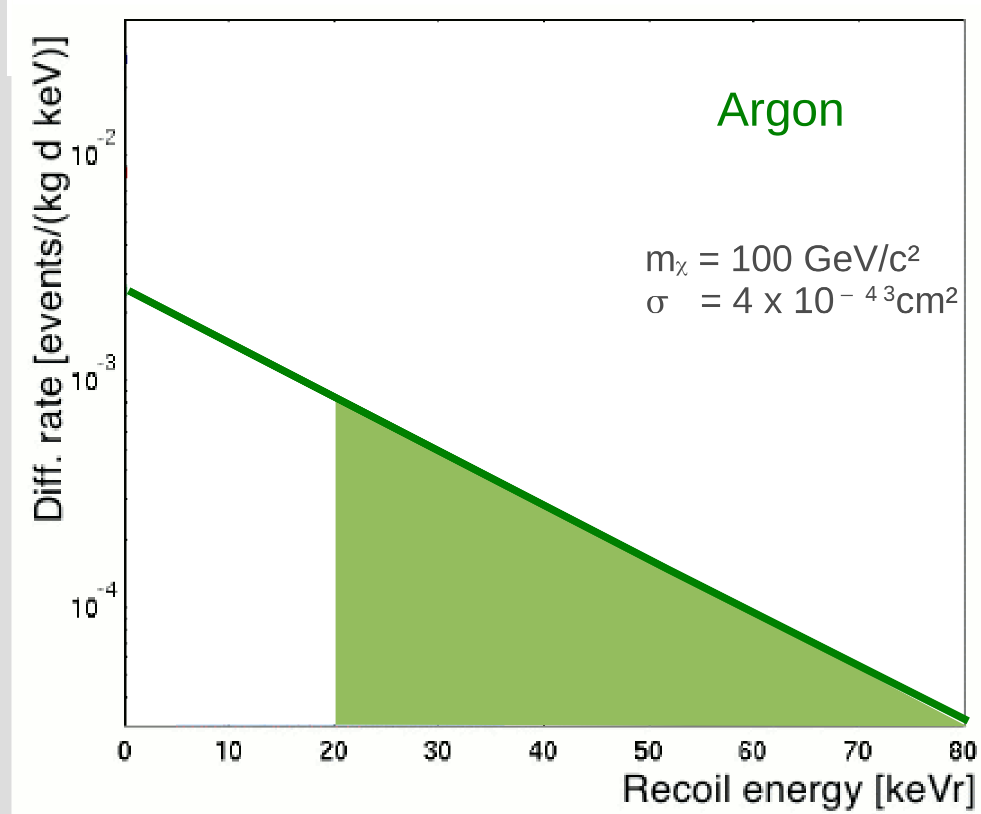
Target	LXe	LAr	LNe
Atomic Number	54	18	10
Atomic mass	131.3	40.0	20.2
Boiling Point T_b [K]	165.0	87.3	27.1
Liq. Density @ T_b [g/cm^3]	2.94	1.40	1.21
Fraction in Atmosphere	0.09	9340	18.2
Price	$$$$	$	$$
Scintillator	✔ 178nm	✔ 128nm	✔ 77nm
Ionizer	✔	✔	✘
W (E to generate e-ion pair) [eV]	15.6	23.6	
W_{ph} (α,β) [eV]	17.9 / 21.6	27.1 / 24.4	
Dark Matter Projects [active collaborations]	~5	~3	½
Neutrino Projects [active collaborations]	✘	~5	✘



Why Argon?

- large abundance
  → modest price
  → can think about gigantic detectors
- relatively compact detectors
  → exploit self shielding
- cryogenics @ –180°C (above LN_2)
- scalability to larger detectors
- excellent background discrimination even when only measuring light
- well established technology





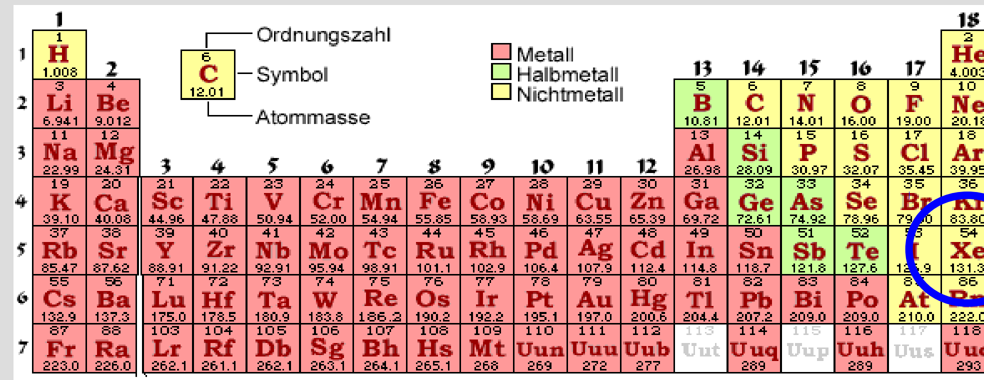
BUT: - low threshold possible???

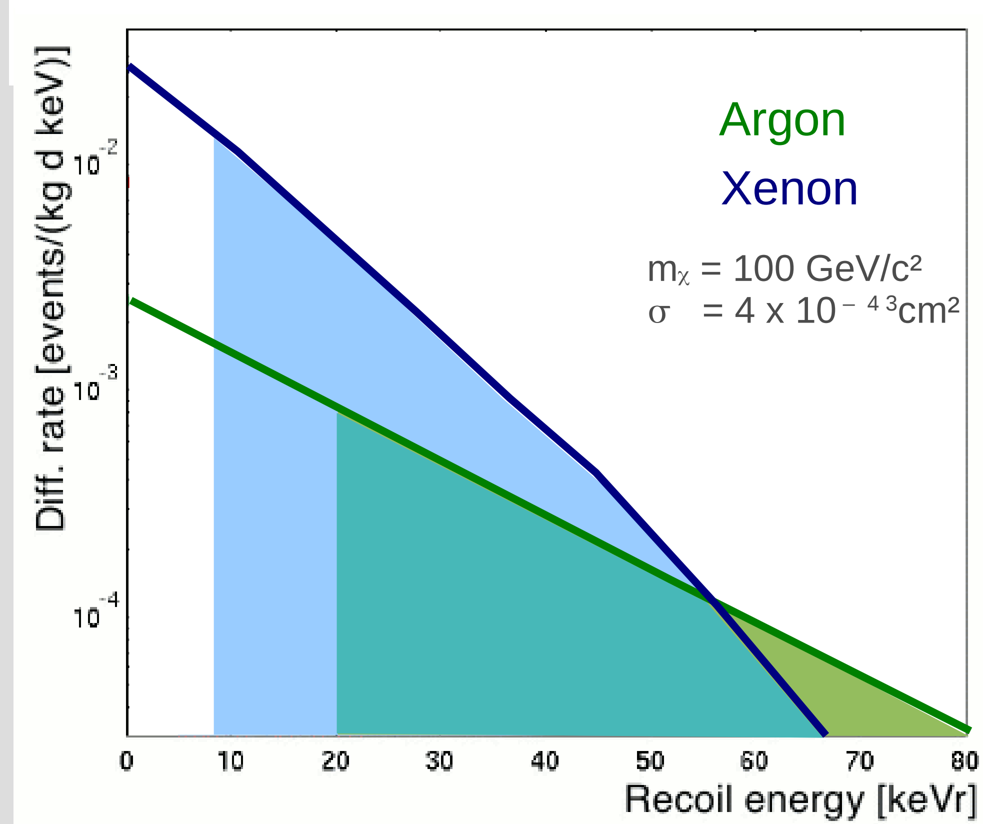
- very high background from Ar39 (~1 Bq/kg)
- need to „shift“ light (128 nm)

Why Xenon?

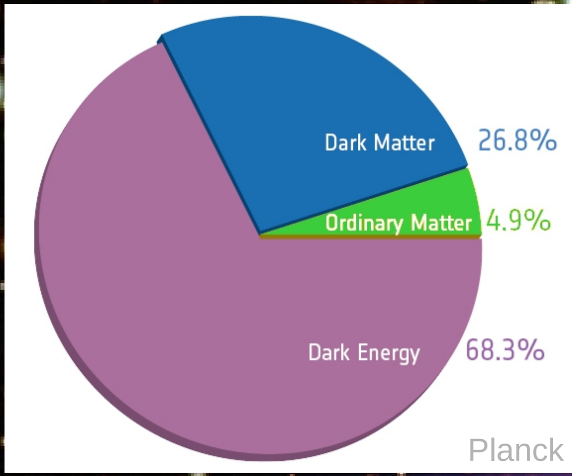
- scintillation light in VUV (178nm)
- high mass number *A*~131
  SI: high WIMP rate @ low theshold
- high *Z*=54, high ρ~3 kg/l:
  self shielding, compact detector
- 50% odd isotopes
- no long lived Xe isotopes
  Kr-85 can be removed to ppt
- "easy" cryogenics @ –100°C
- scalability to larger detectors
- good background discrimination
  when measuring light and charge

BUT: - very expensive
- only fair signal/background
  discrimination compared to Ar

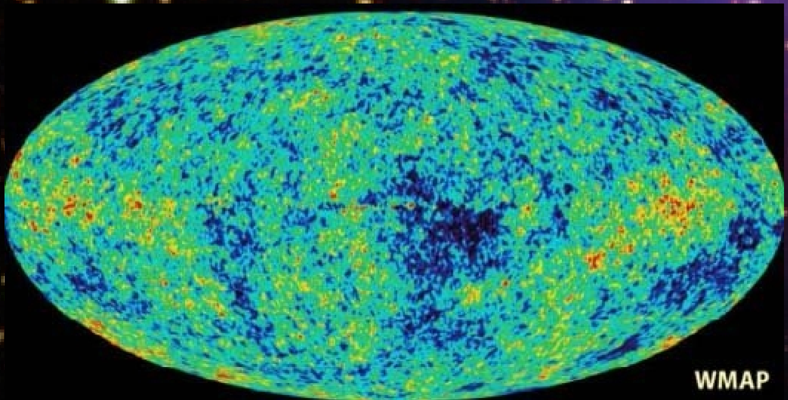


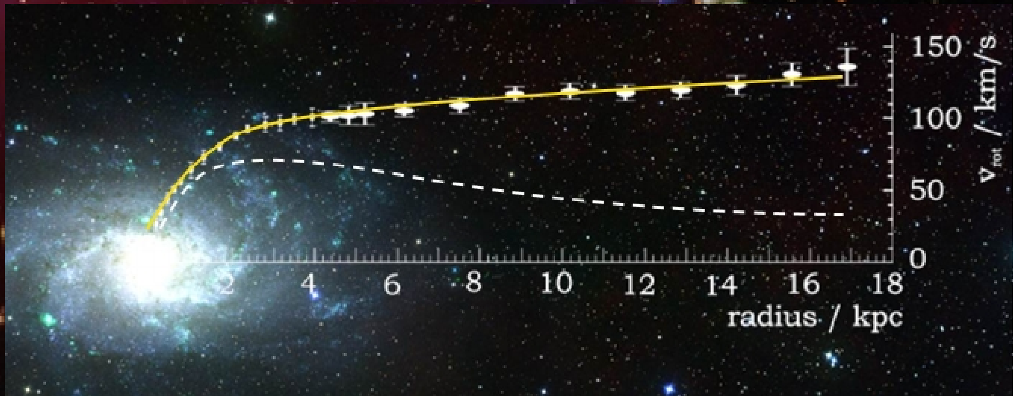


Dark Matter: (indirect) Evidence

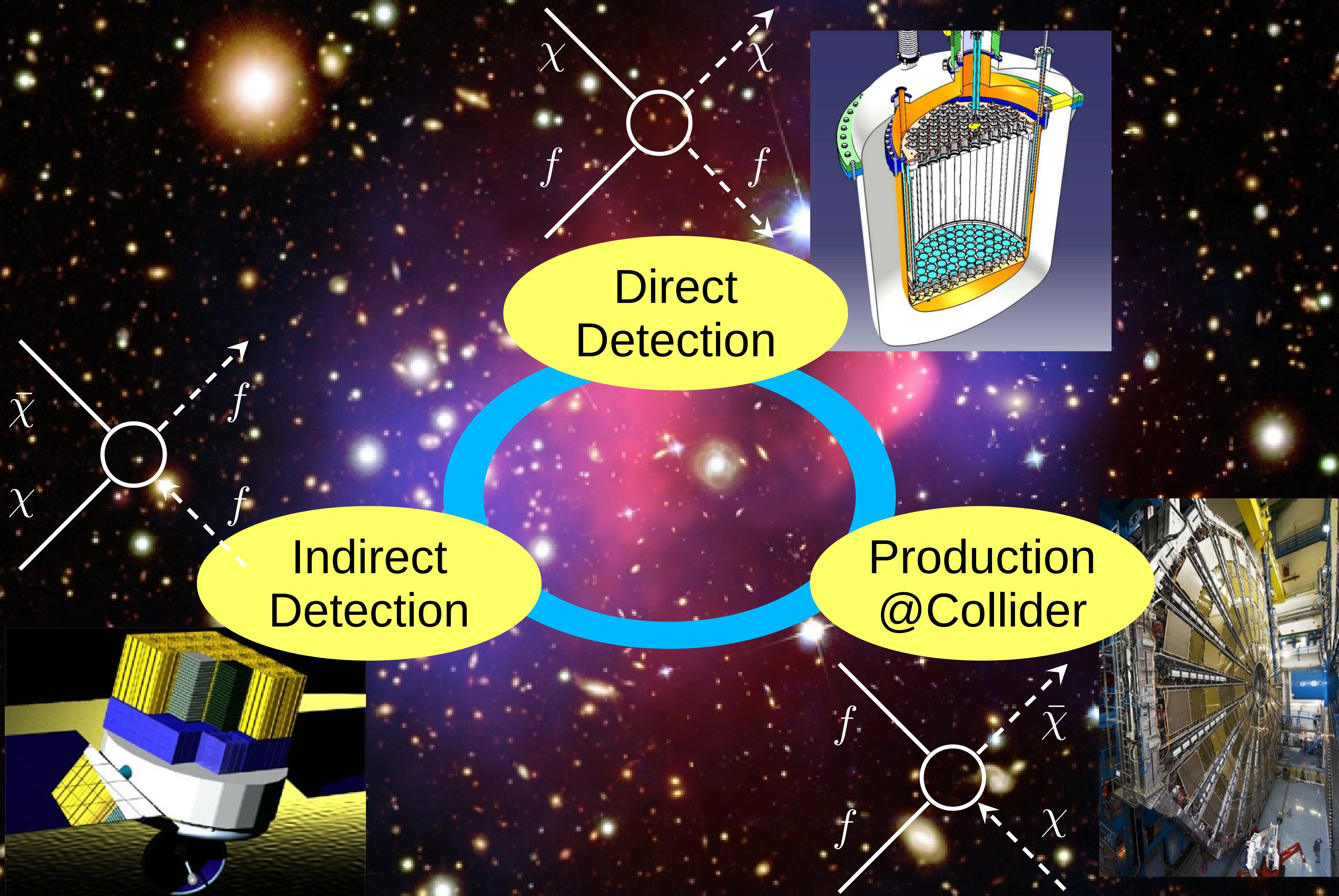


Particle Dark Matter Candidates:
- **WIMP** → *„WIMP miracle“*
- Axion
- SuperWIMPs
- sterile neutrinos
- WIMPless dark matter
- Gravitino
- ...



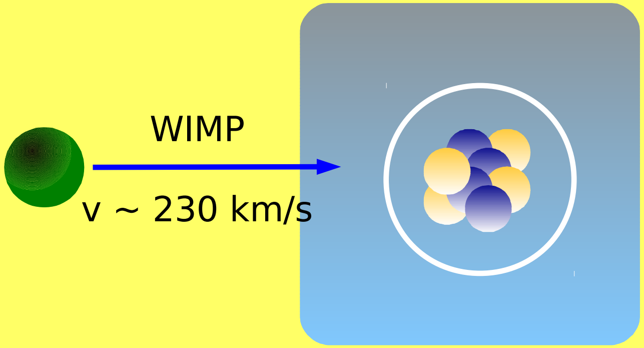


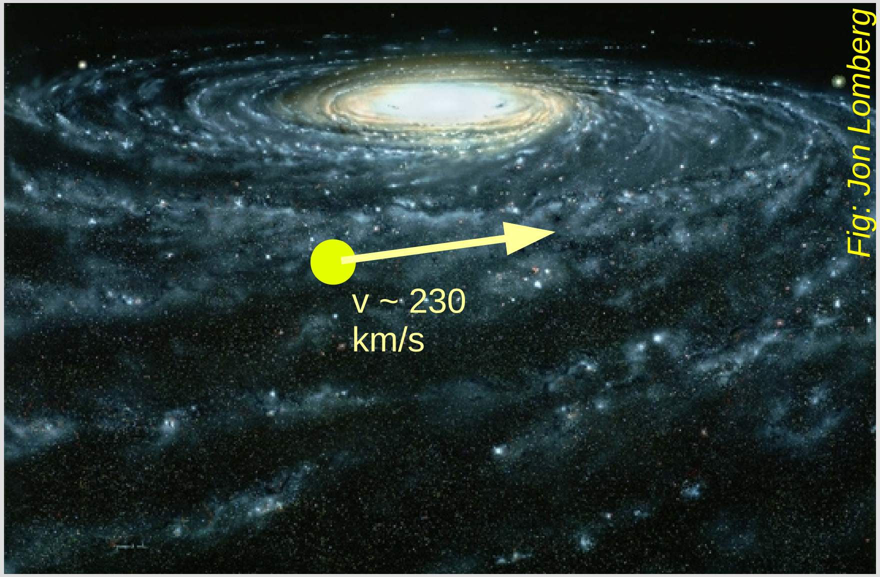
Dark Matter Search



Direct WIMP Search

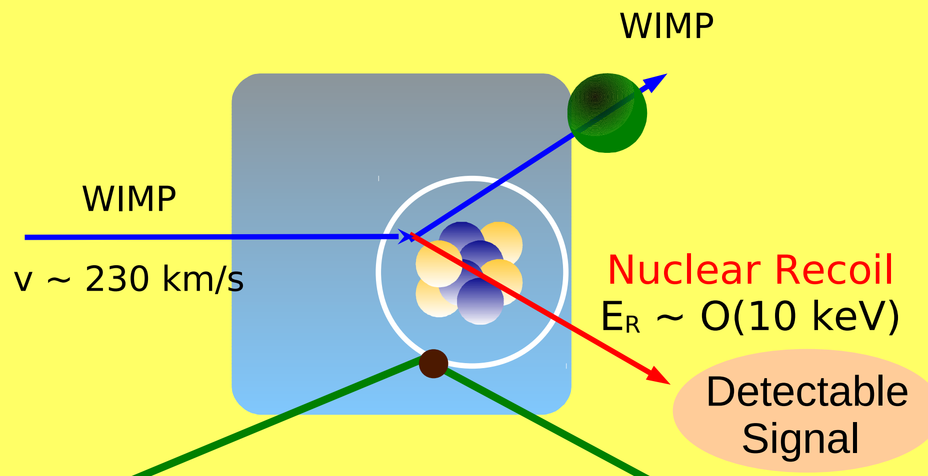
Elastic Scattering of WIMPs off target nuclei





Direct WIMP Search

Elastic Scattering of WIMPs off target nuclei
➡ nuclear recoil



γ- and β-particles (background) interact with the atomic electrons
→ **electronic recoil**

Recoil Energy: $$E_r = \frac{|\vec{q}|^2}{2m_N} = \frac{\mu^2 v^2}{m_N}(1-\cos\theta) \sim \mathcal{O}(10\ \mathrm{keV})$$

Event Rate: $$R \propto N \frac{\rho_\chi}{m_\chi} \langle \sigma_{\chi-N} \rangle$$

Detector

Local DM Density

ρ_χ~0.3 GeV/c²

Physics

N	number of target nuclei
ρ_χ/m_χ	local WIMP number density
$\langle\sigma\rangle$	velocity-averaged scatt. X-section

Direct WIMP Search

Summary: Tiny Rates

$R < 0.01$ evt/kg/day

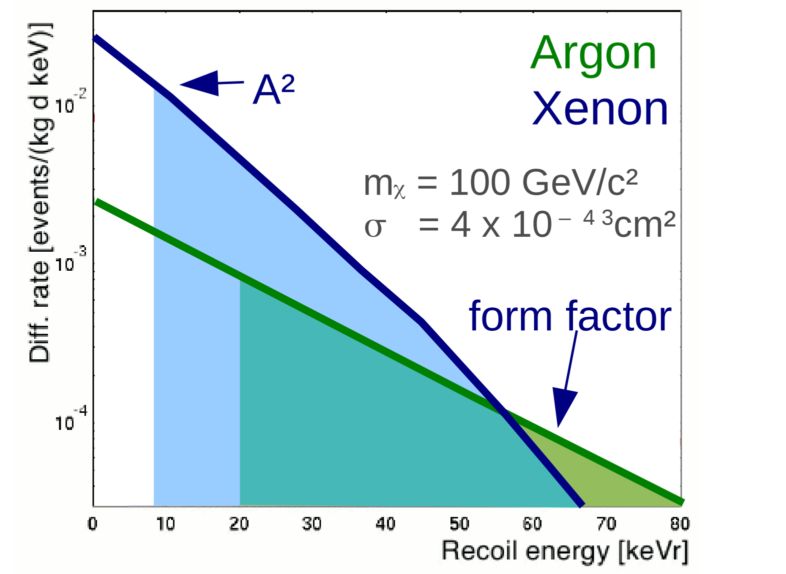
$E_R < 50$ keV

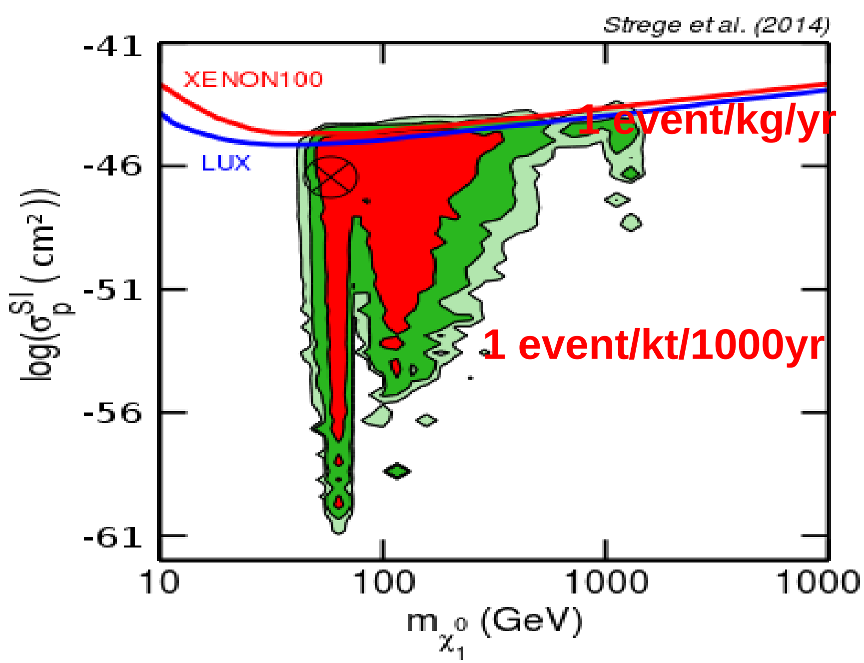
How to build a WIMP detector?

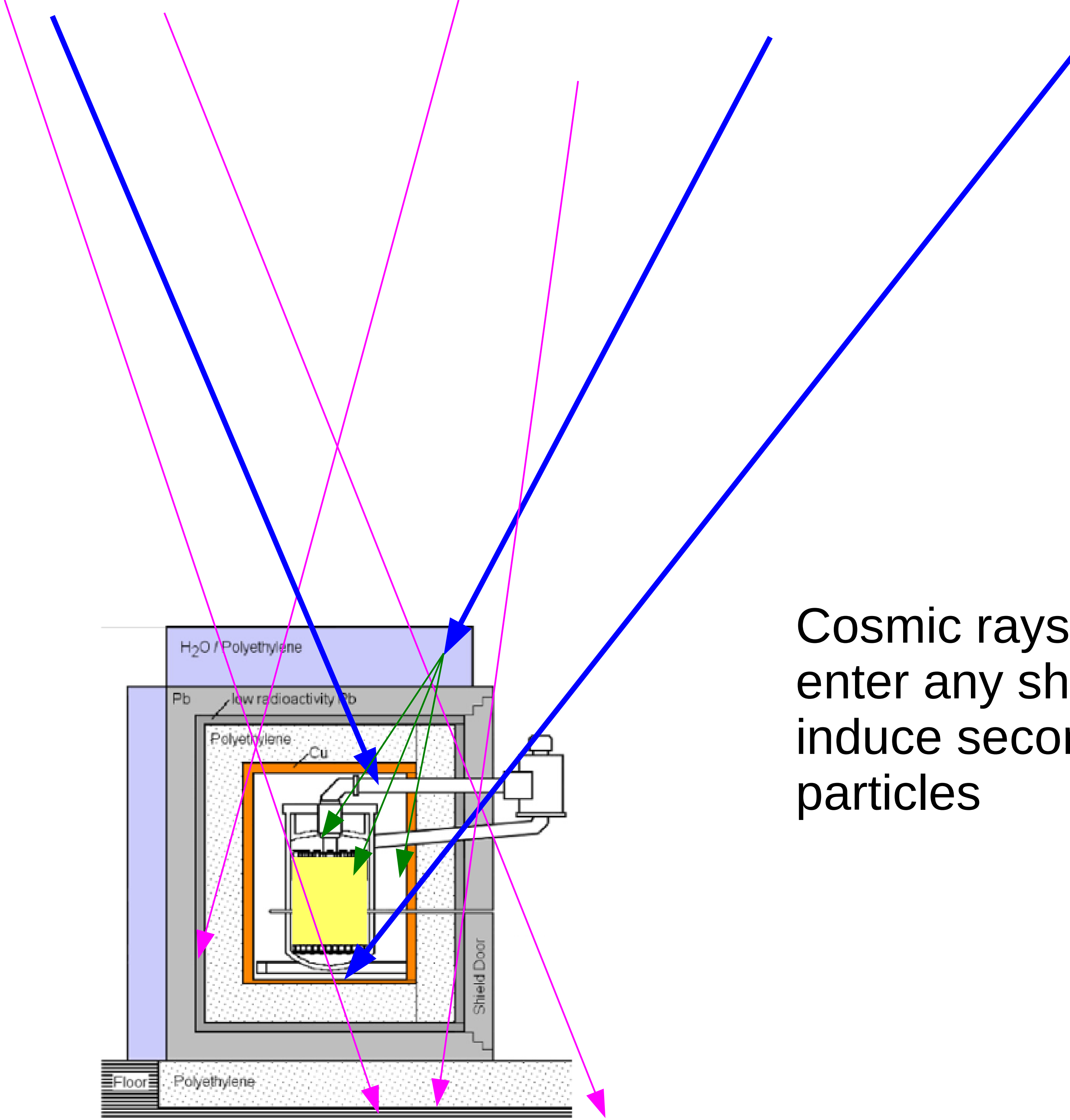
- large total mass, high A
- low energy threshold
- ultra low background
- good background discrimination

We are dealing with

- extremely **low rates** (1 – 1000 Hz)
- Only a **few channels** (~250)
- extremely **low thresholds** (2 keV)
- extremely **low radioactive** backgrounds





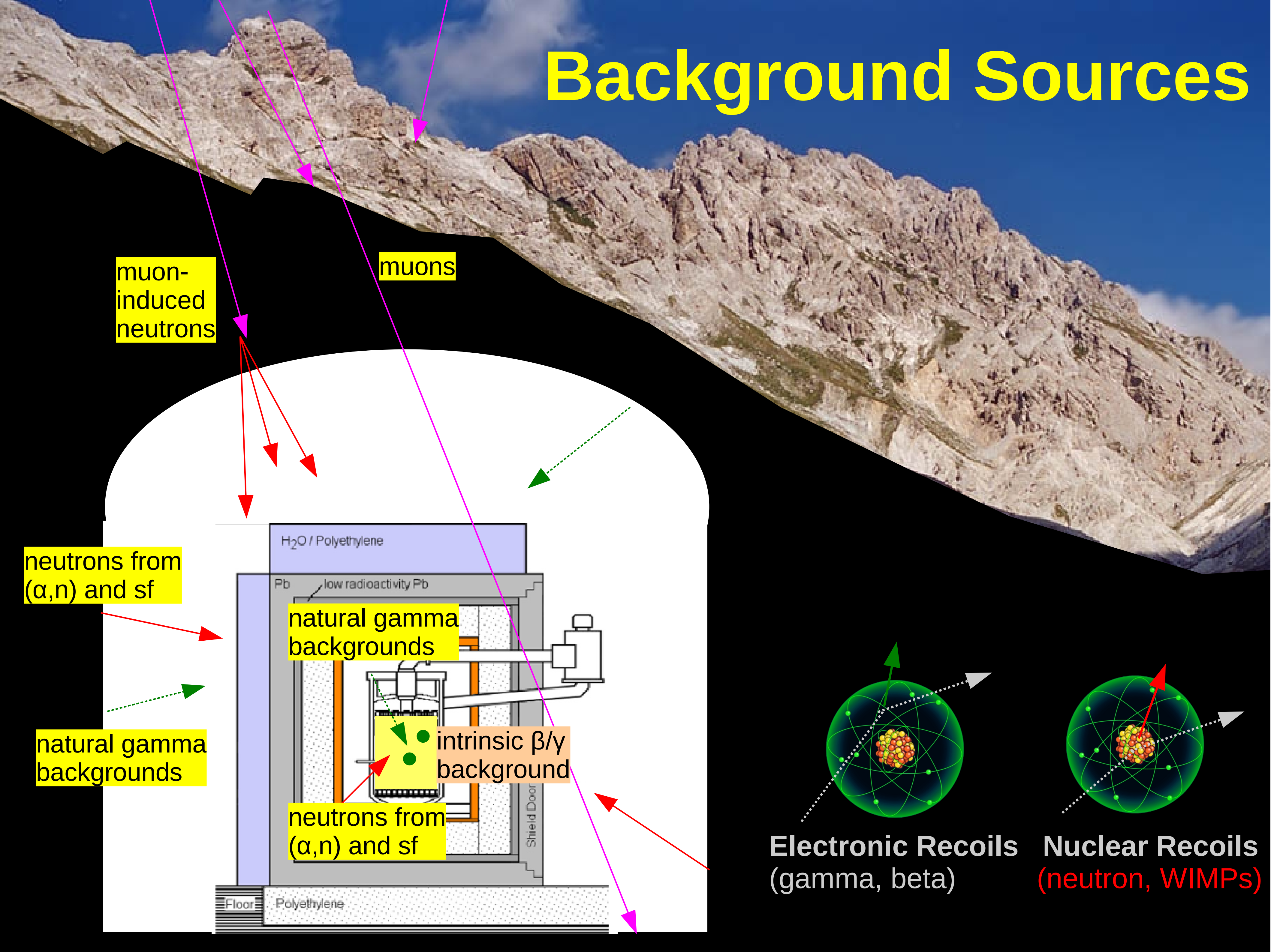


Cosmic rays (p, n, μ) enter any shielding or induce secondary particles

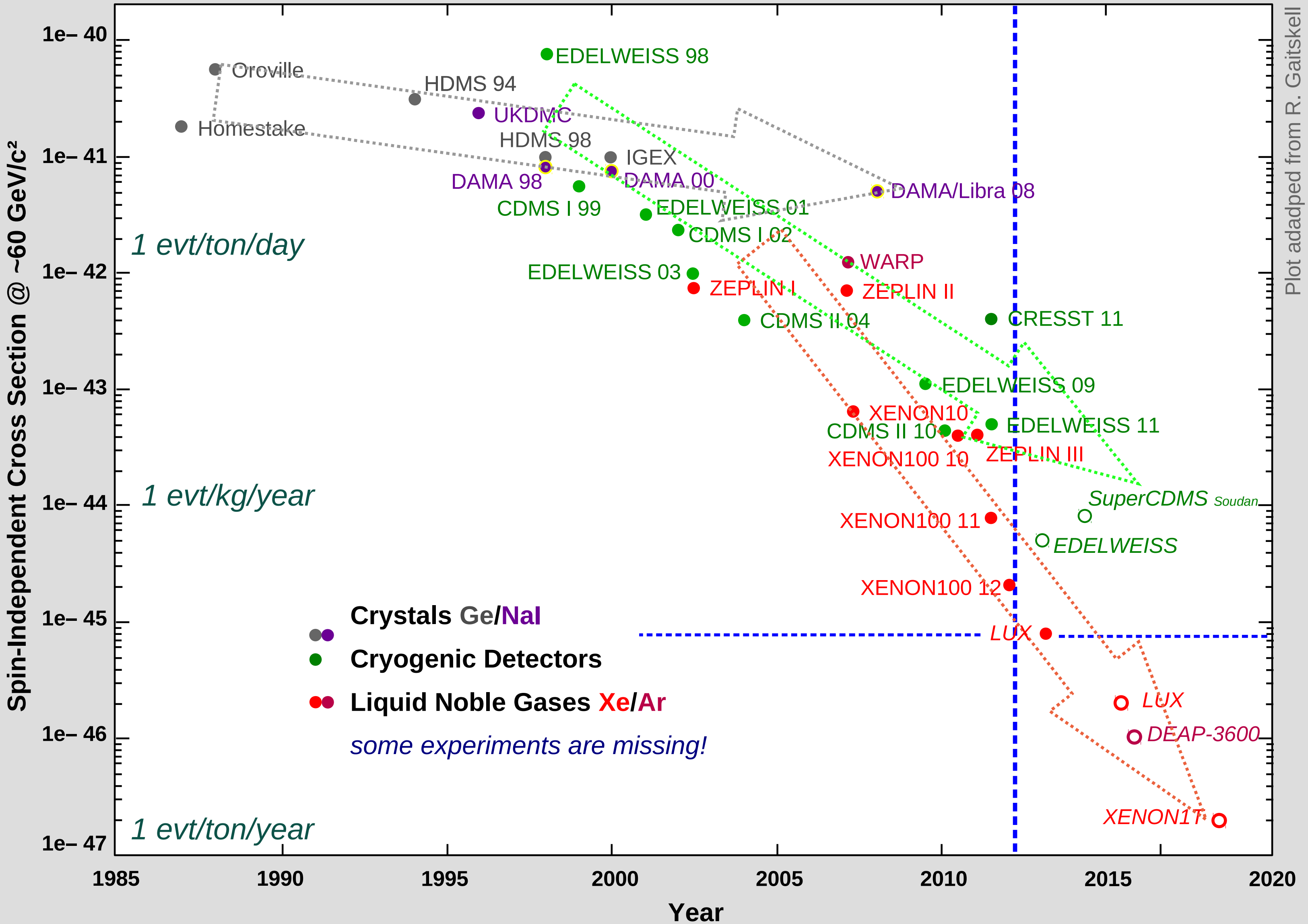

ALARM
OSSIGENO OXYGEN
LUD ZONE

Laboratori Nazionali del Gran Sasso

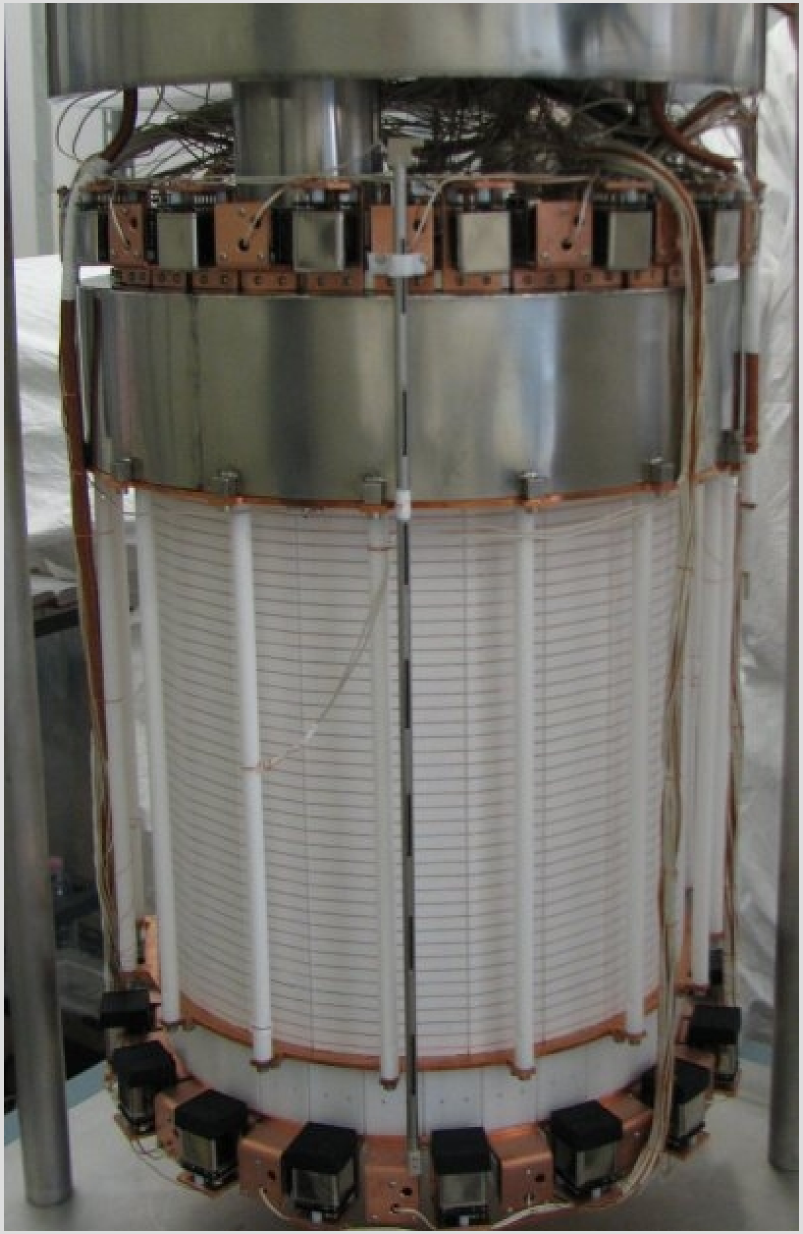
Background Sources

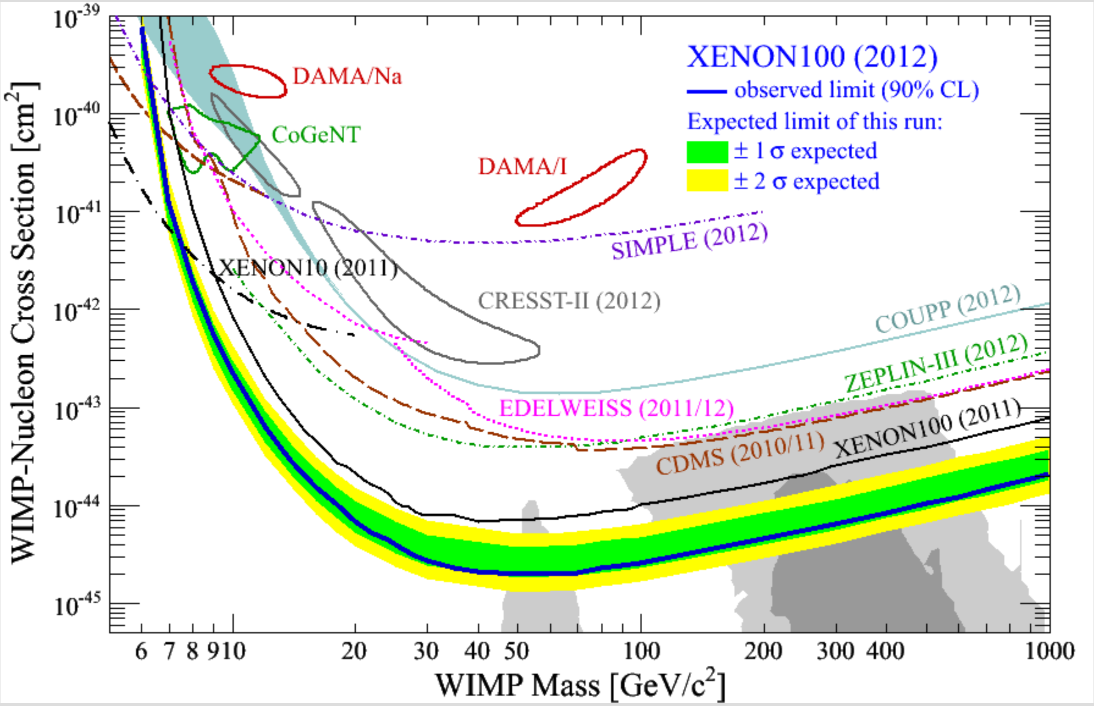


WIMP Seaches and Noble Liquids

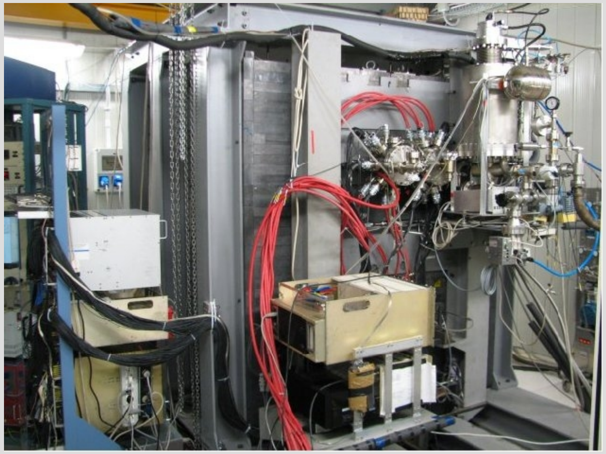


Example: XENON100

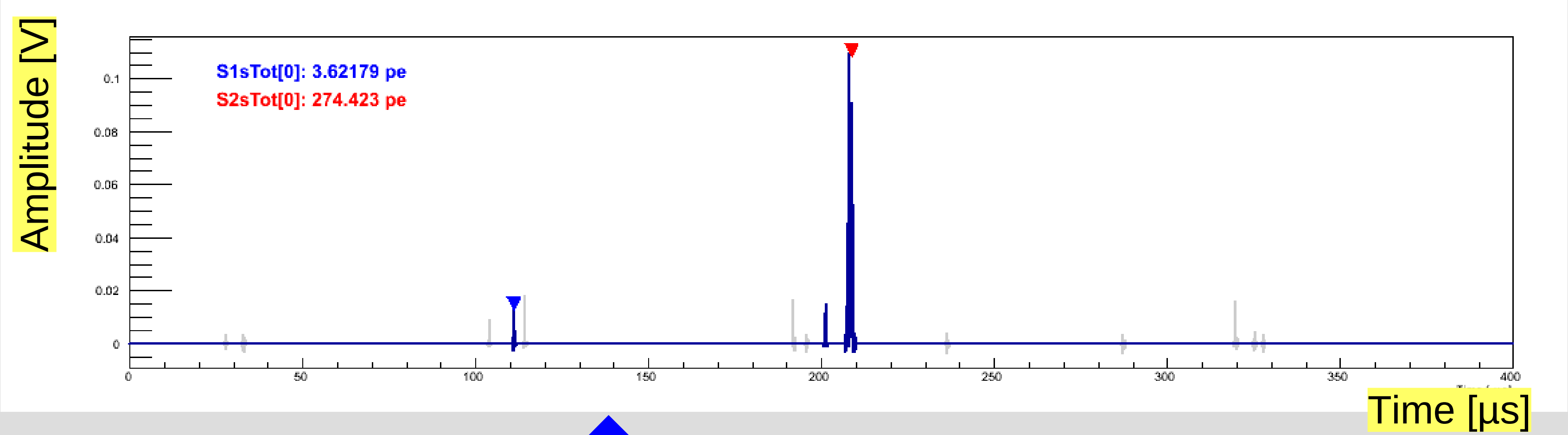




arXiv:1207.5988, PRL 109, 131801 (2012)



Signals in a LXe TPC



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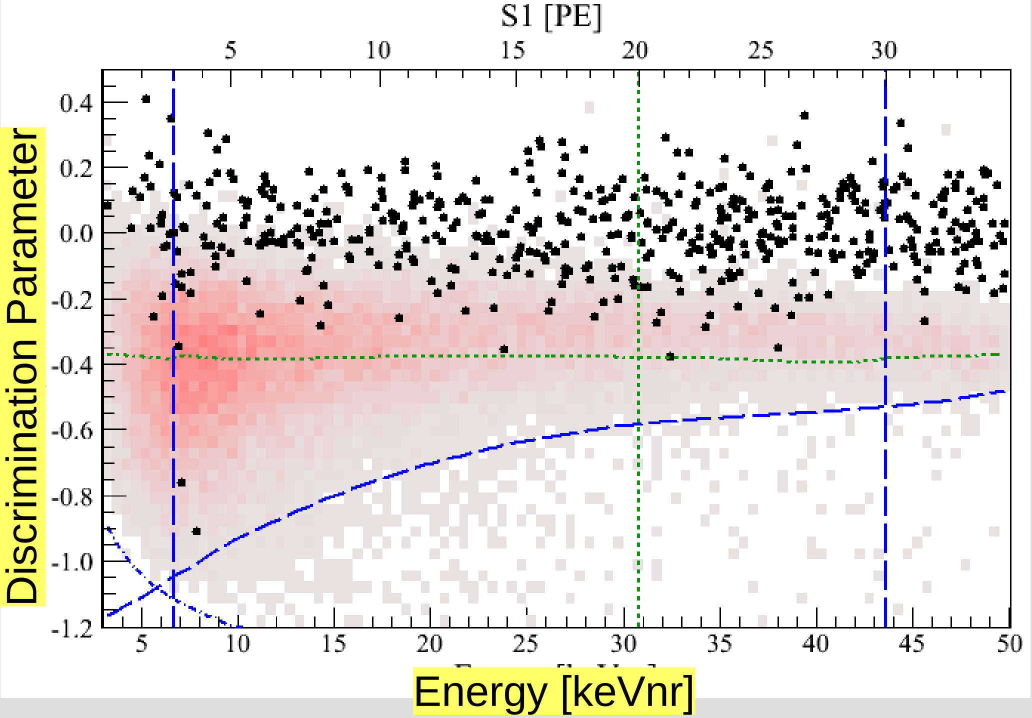


How does XENON100 work?

How to get signals to analyze?

How to get correct signals?

How to get the interesting signals?

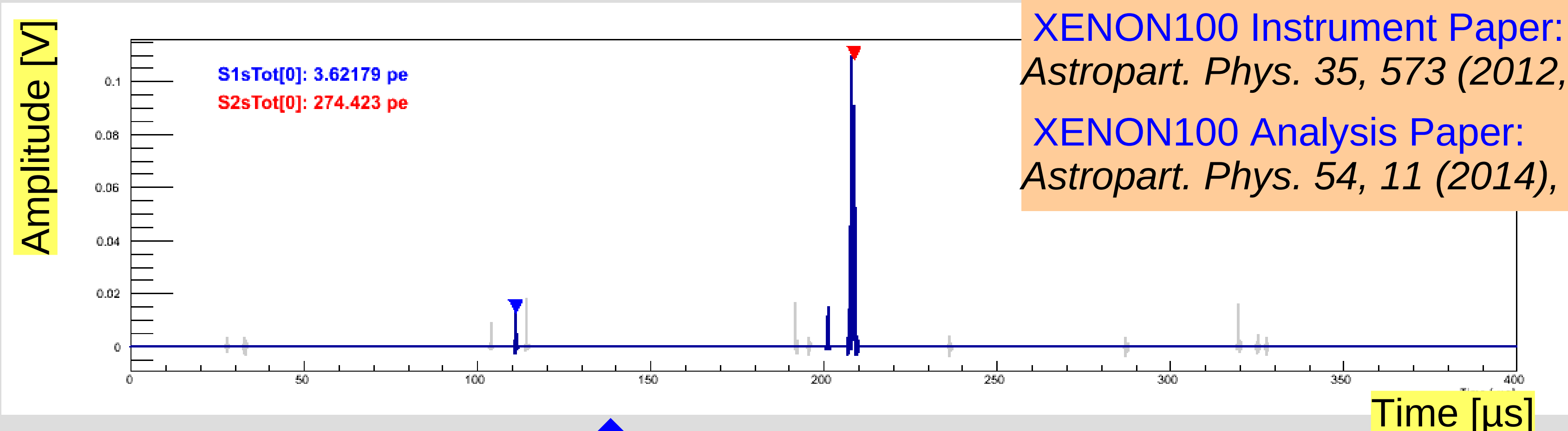
How do we get an energy scale?

Signals in a LXe TPC

mainly based on

XENON100 Instrument Paper:
Astropart. Phys. 35, 573 (2012, arXiv:1107.2155

XENON100 Analysis Paper:
Astropart. Phys. 54, 11 (2014), arXiv: 1207.3458



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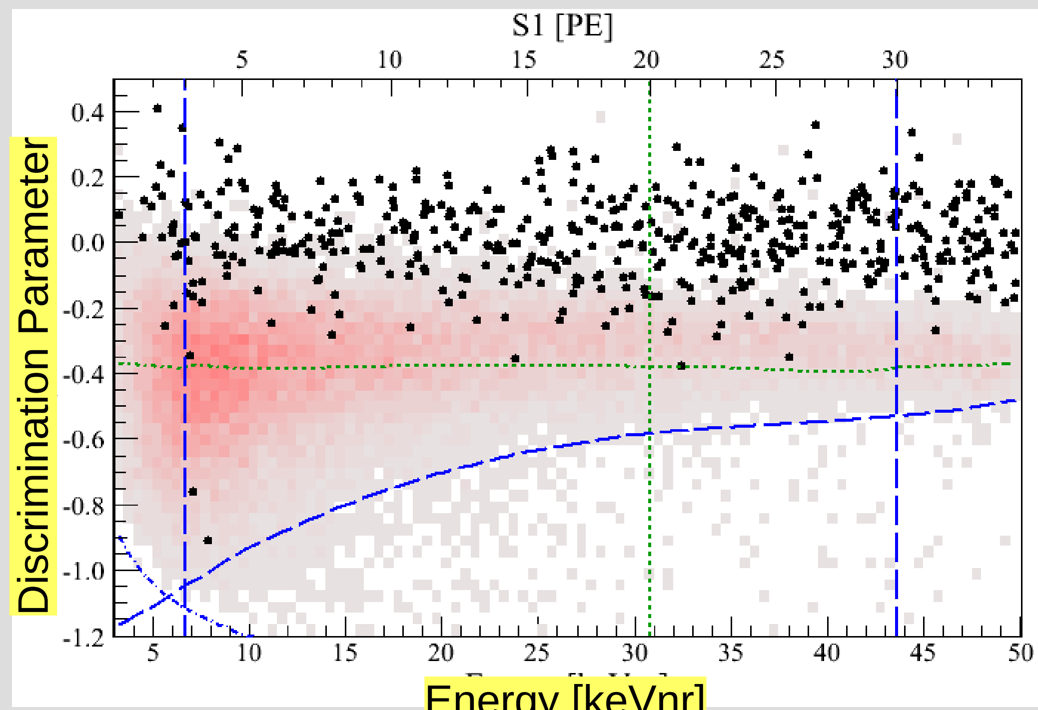


How does XENON100 work?

How to get signals to analyze?

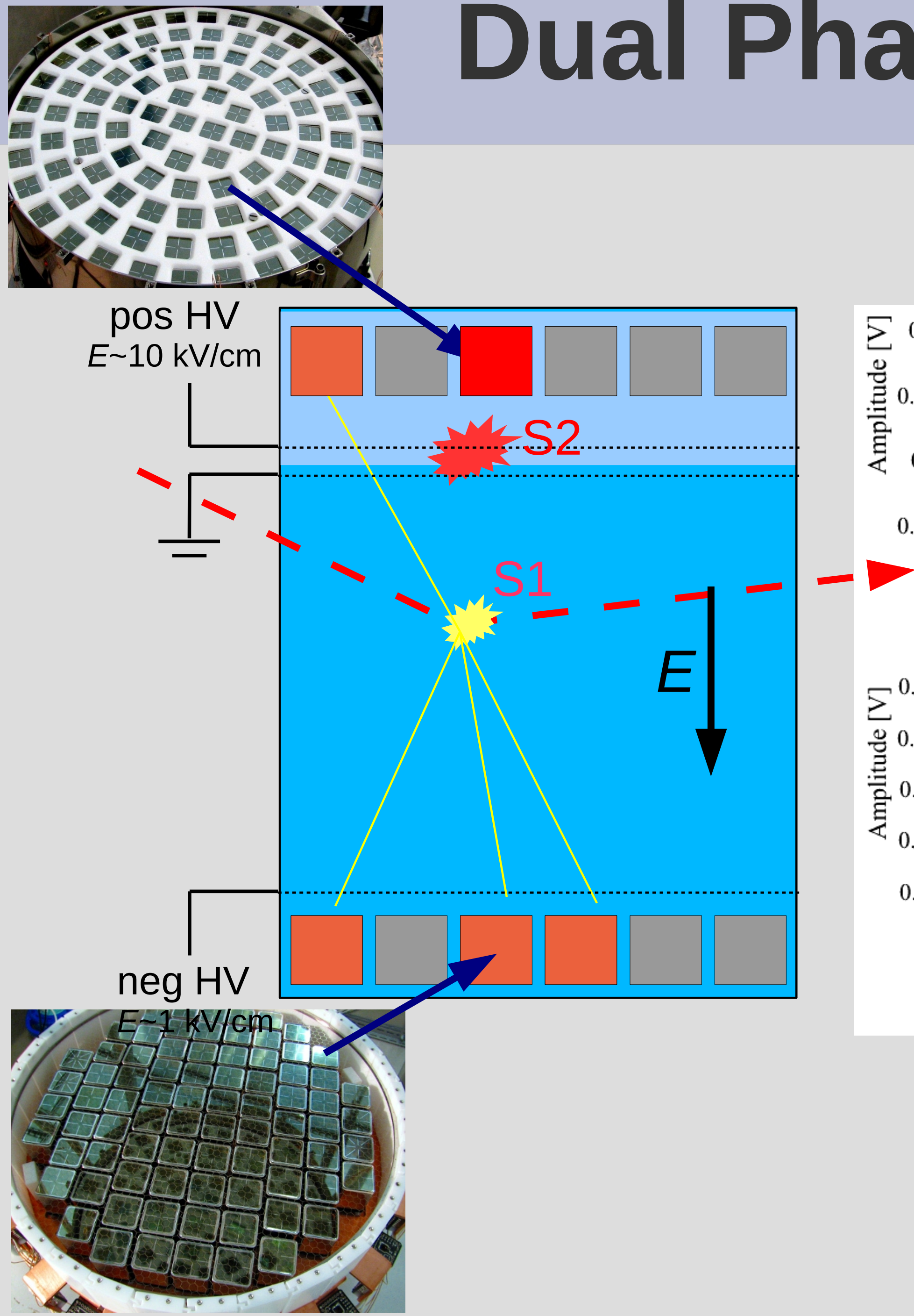
How to get correct signals?

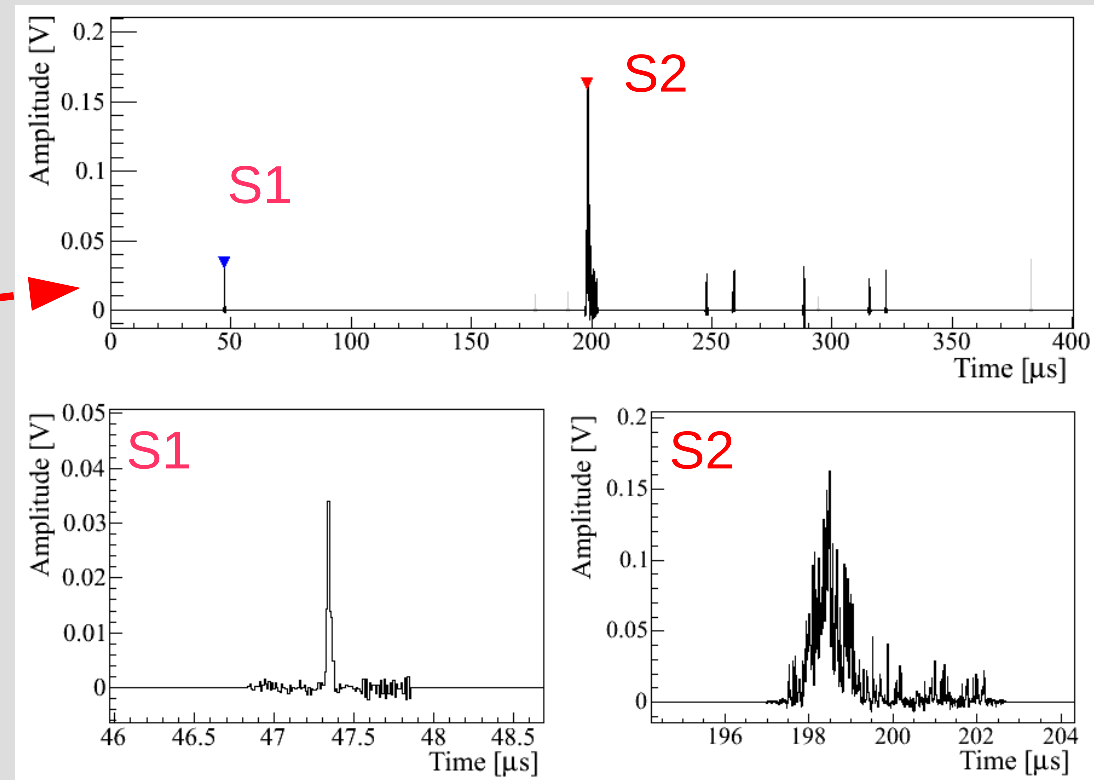
How to get the interesting signals?

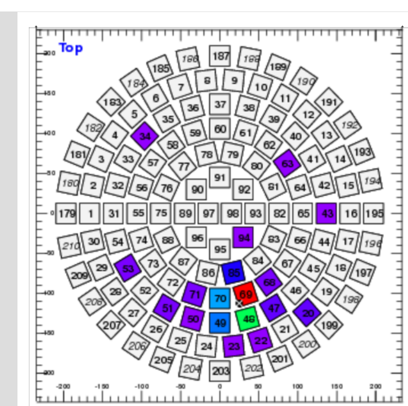
How do we get an energy scale?

Dual Phase TPC

TPC = time projection chamber



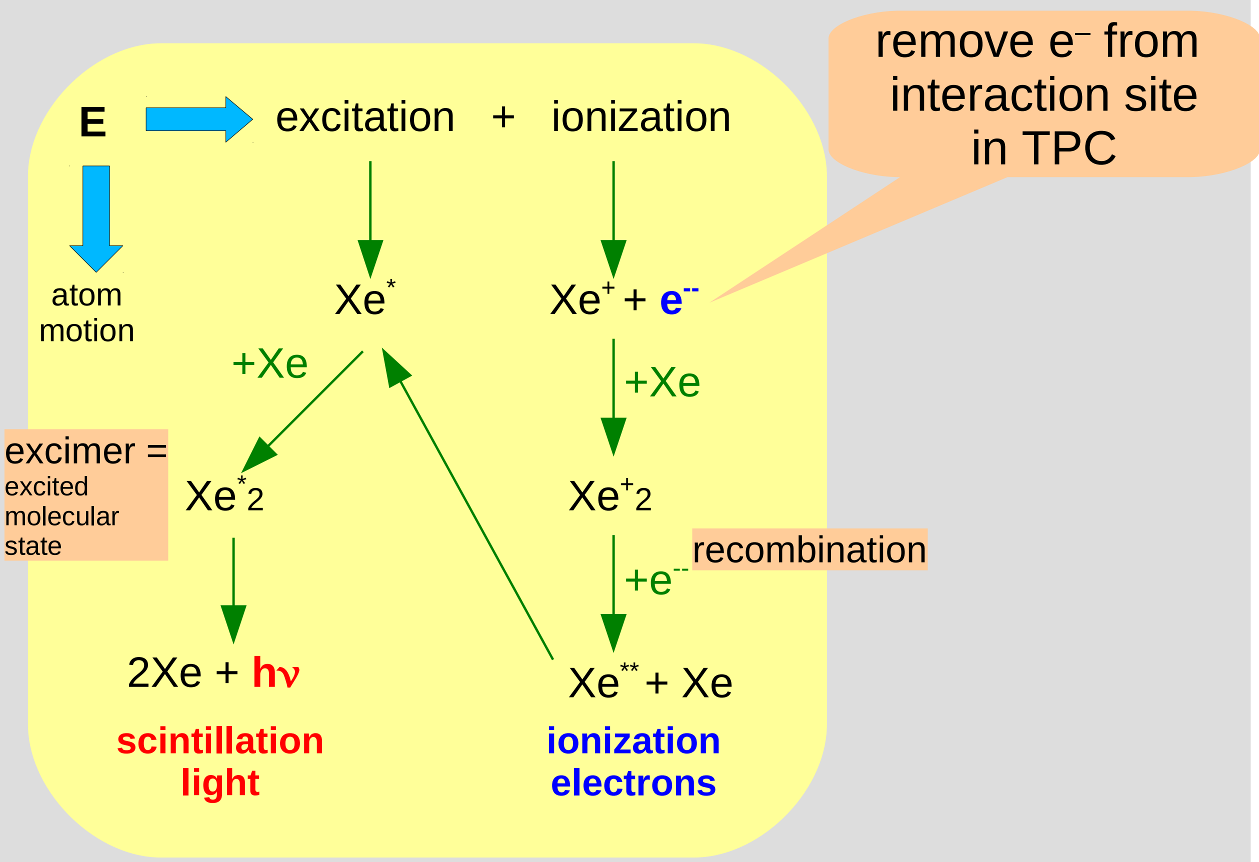


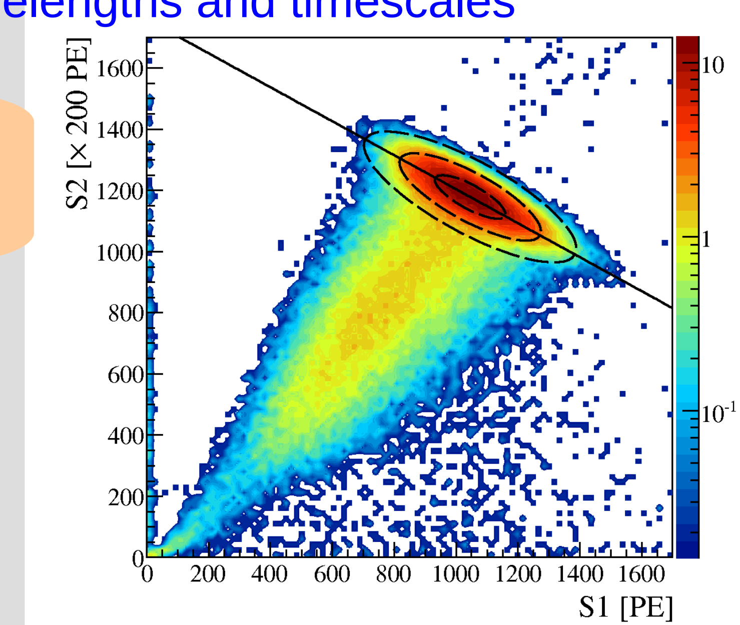


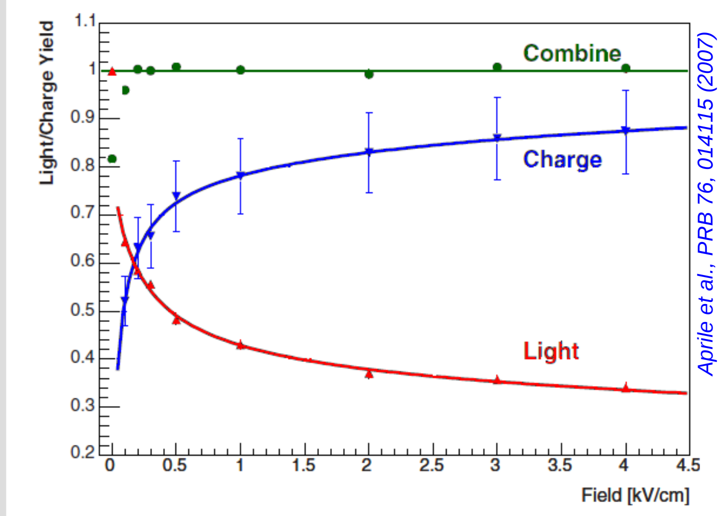
How to get signals to analyze?

Xenon: Light and Charge

→ Argon identical scheme, just different wavelengths and timescales



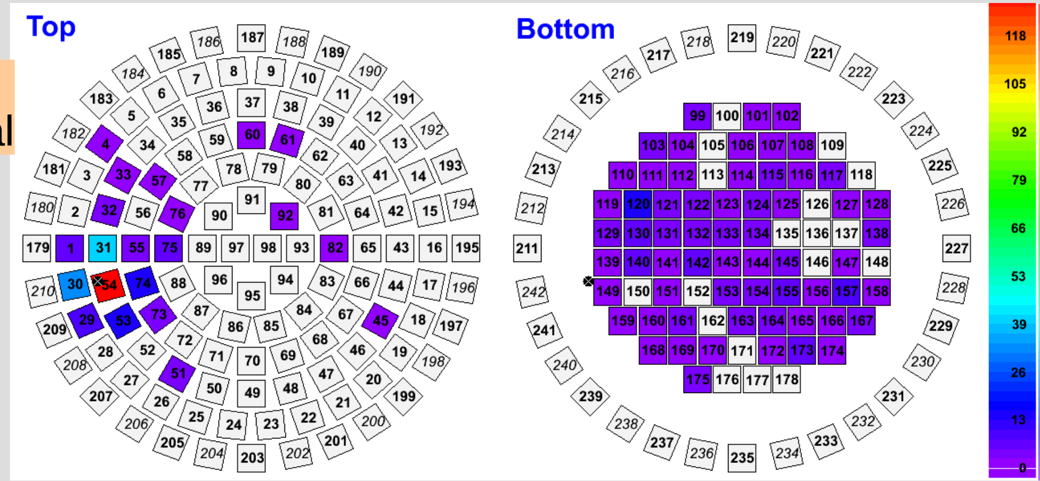


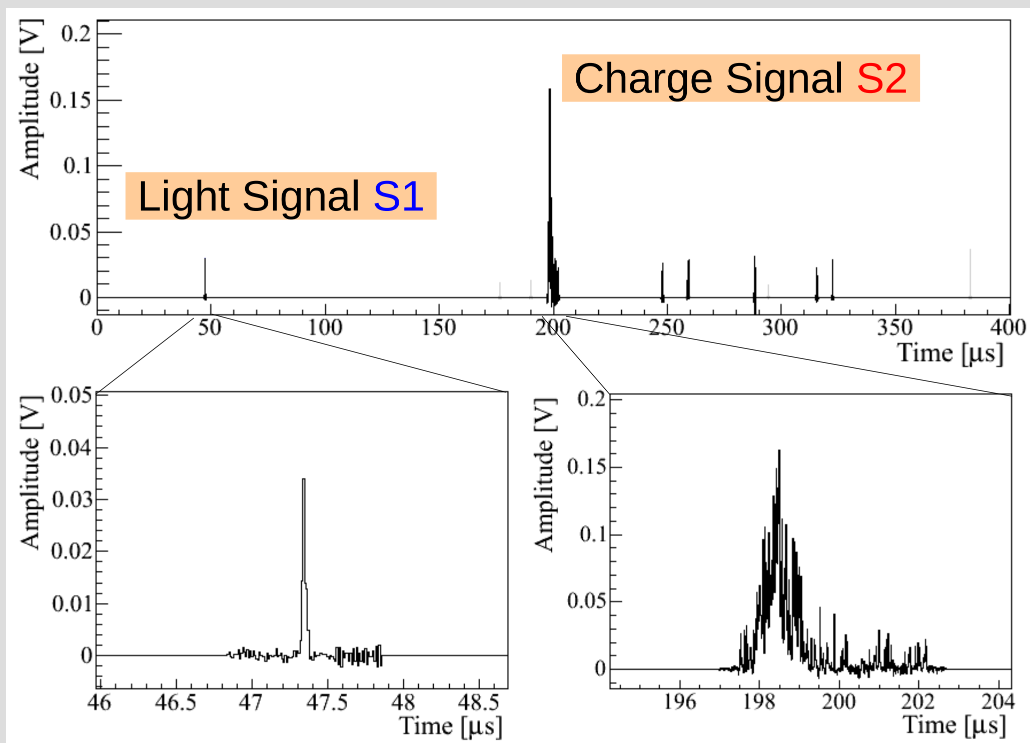


LXe is transparent to its scintillation light
→ can be used as target and detector!

What do we measure?

PMT Hitpattern of the S2 Signal

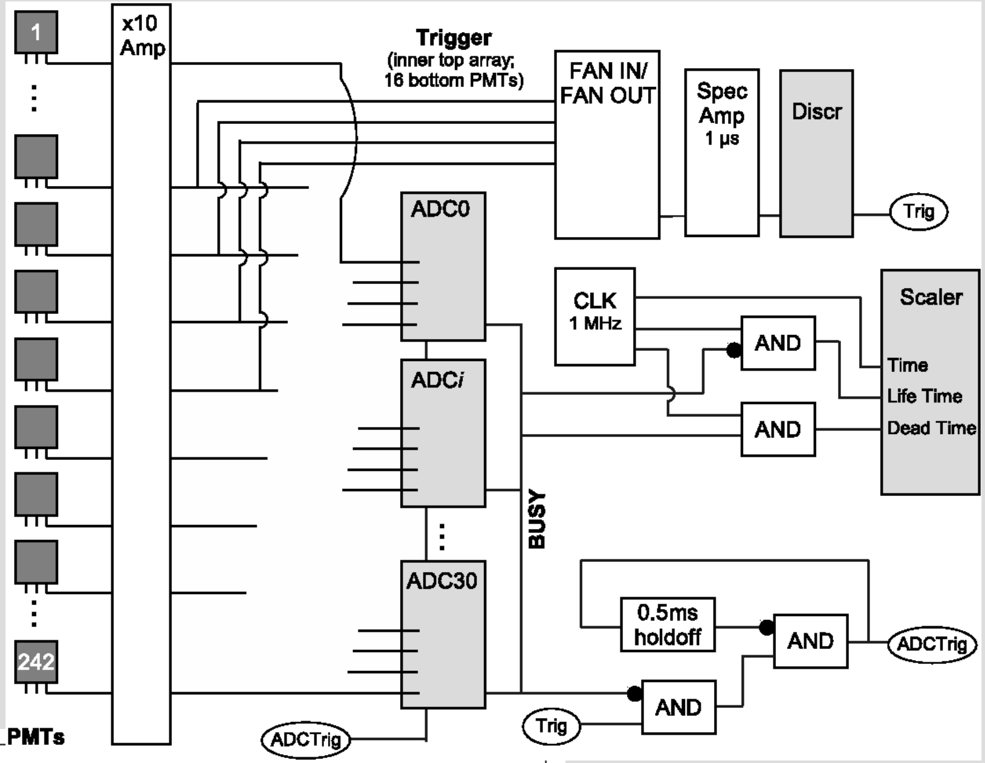


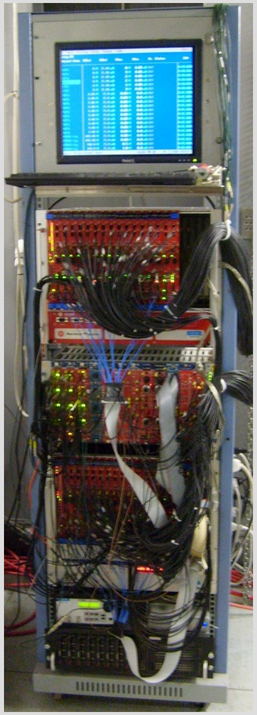


This is everything you get for a nice dark matter candidate!

Data Acquisition

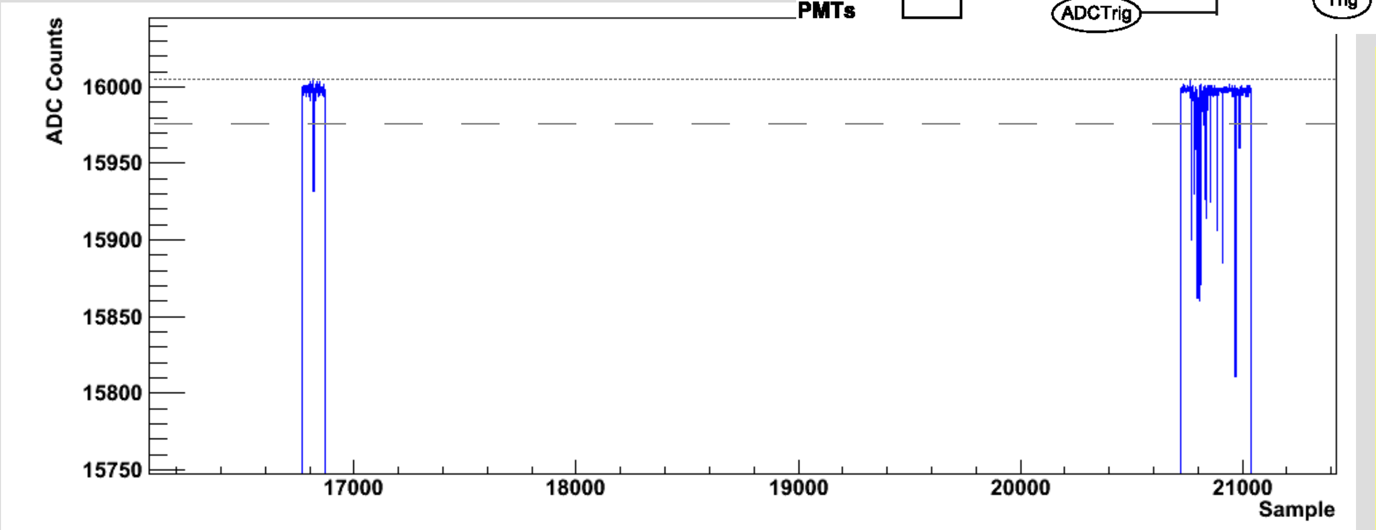
Design requirements:
– lowest possible threshold
– high data throughout (calibration)
– no deadtime
– veto possiblity: high *E*, high *r* (calibration)





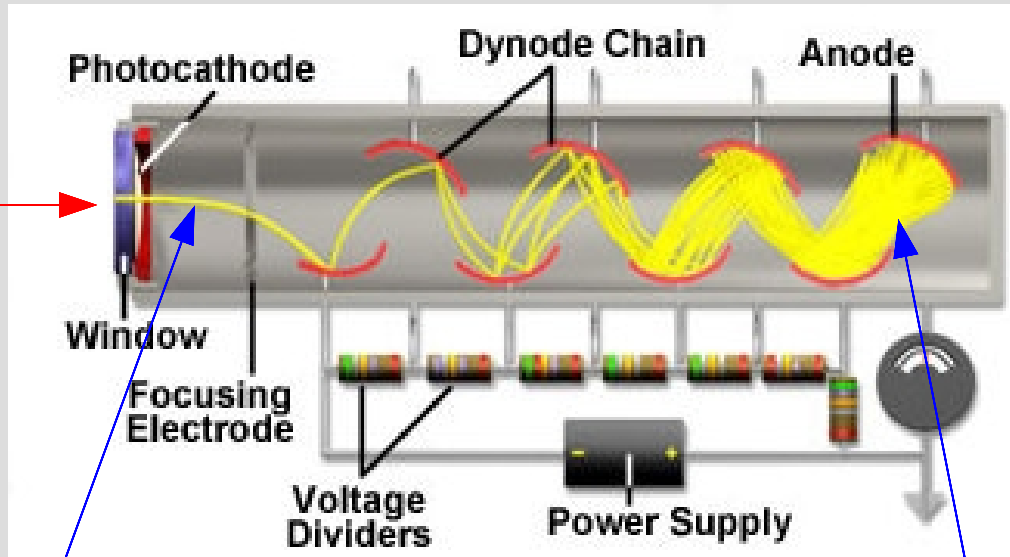
Based on CAEN waveform digitizers:

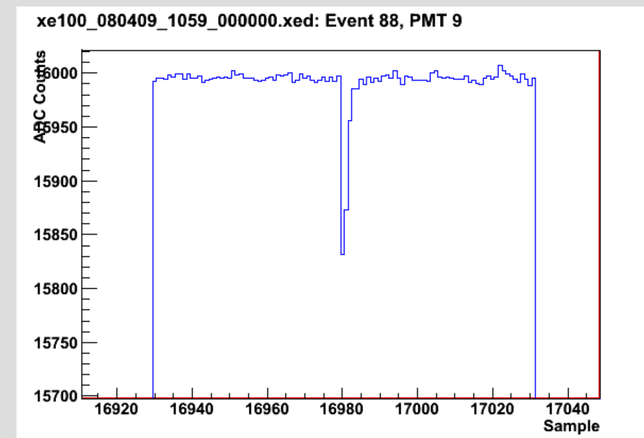
- 100 MHz sampling frequency
- 40 MHz input bandwidth
- 2.25V max. input signal
- 14bit resolution
- continuous buffer
  → deadtime-less measurement
- zero-length encoding
- high energy veto
- on-line deadtime measurement



new: **XENON1T**
- continuous, asynchronous readout of 256 PMTs
- zero-suppression
- no common trigger: events reconstruction on PC farm
- parallel readout
- acquisition monitor
- sophisticated veto

Photoelectrons – the basic unit





γ

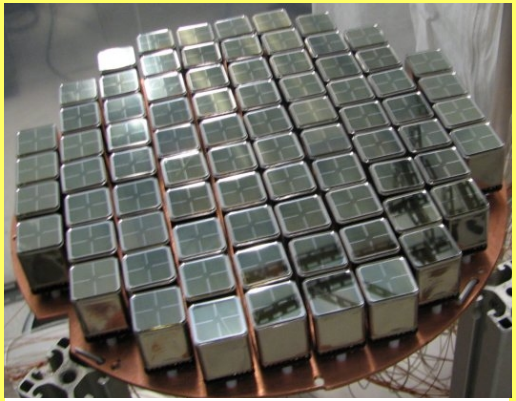
one photoelectron

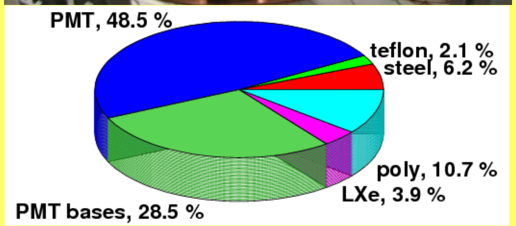
many electron signal
→ measure current

gain

alternatives to PMTs: APDs, SiPMs, new detectors (R&D ongoing)

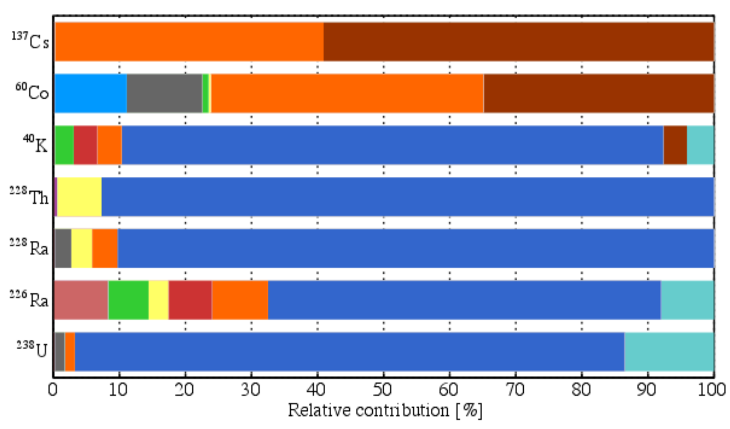
PMTs for 178 nm

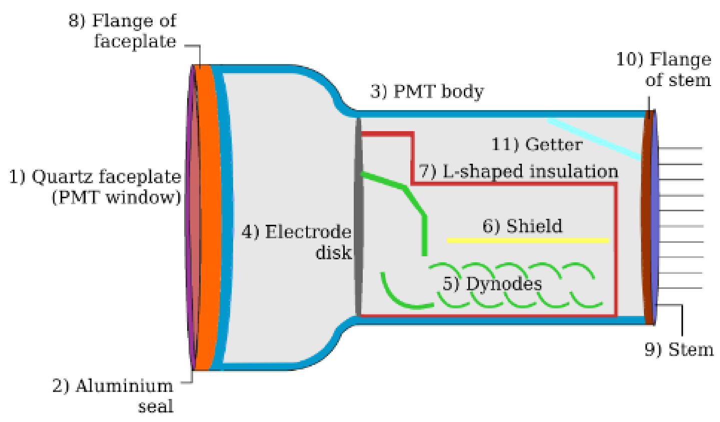




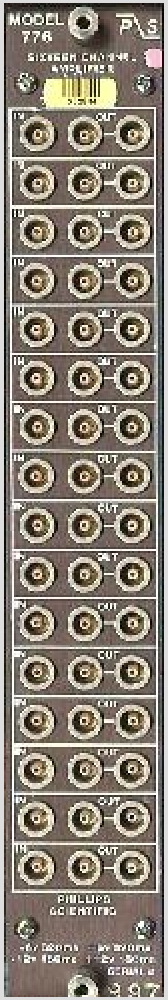
Hamamatsu R8520
- 1“ cube mesh PMT
- low background; but dominating Xe100 background
- high QE (24% @ 178nm; the bottom tubes 32%)
- moderate CE (~70%) due to box shape

Hamamatsu R11410-21
- 3“ diameter
- very low background; developed in collaboration with Hamamatsu *arXiv:1503.07698*
- high QE (36% @ 178nm)
- extensive testing in cryogenic environments *JINST 8, P04026 (2013)*



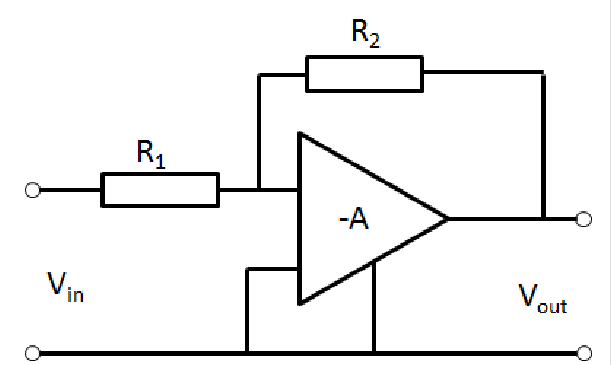


PMT Amplifiers



Phillips 776 – PMT Amplifier → „old school but surprisingly good“

General	16 channels, 1 input, 2 outputs
Gain	**10** +2%, non-inverting
Stability	+/-5.0 uVolt/°C, referred to the input.
Linearity	+/-0.1% to -3 Volts, DC to 100 MHz
Bandwidth	DC to 275 MHz minimum, 3 db point.
Risetime:	Less than 1.3 nsec.
Crosstalk	Greater than 60 db, DC to 100 MHz.
Output Delay	Typically 3.0 nsec.



Voltage pre-amplifier

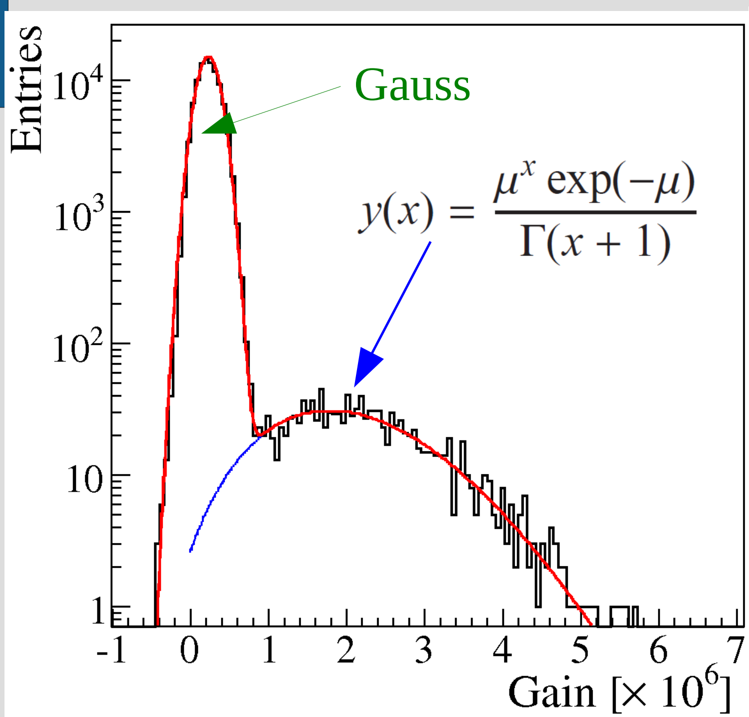
$$V_{out} \cong -\frac{R_2}{R_1} V_{in}$$

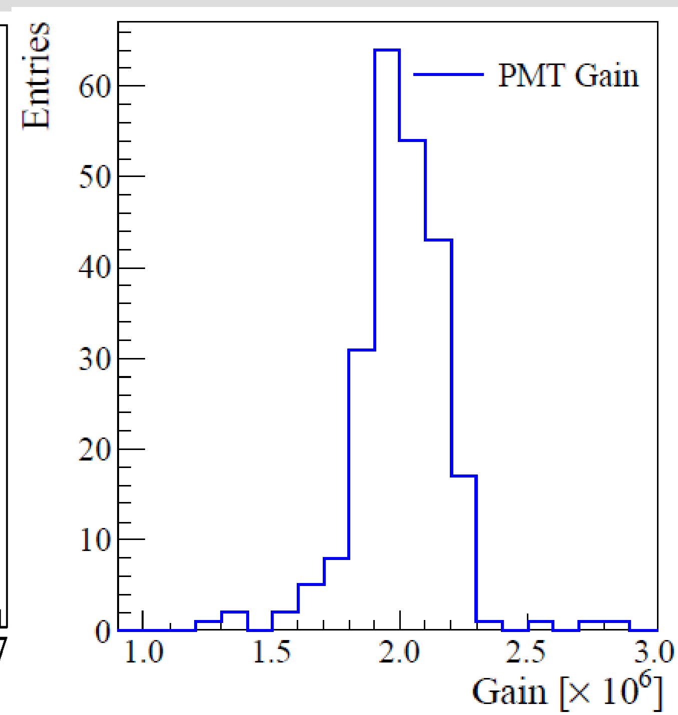
If $\frac{R_2}{R_1} \ll A$

Typically, one wants the pre-amplifiers as close to the PMTs as possible.
Problem here: radioactivity → move further away
Exploit: triggering on (already amplified) S2 signal

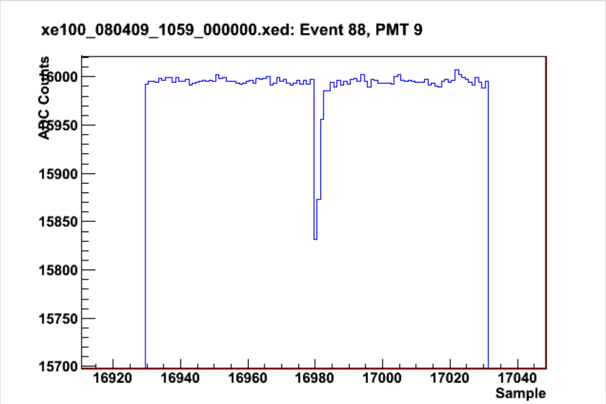
PMT Gain Calibration

Principle: stimulation of the emission of single photoelectrons from the photocathode by very low intensity blue LED light
→ trigger on LED pulser
→ 3-5% of events contain a photoelectron
→ the others contain only noise





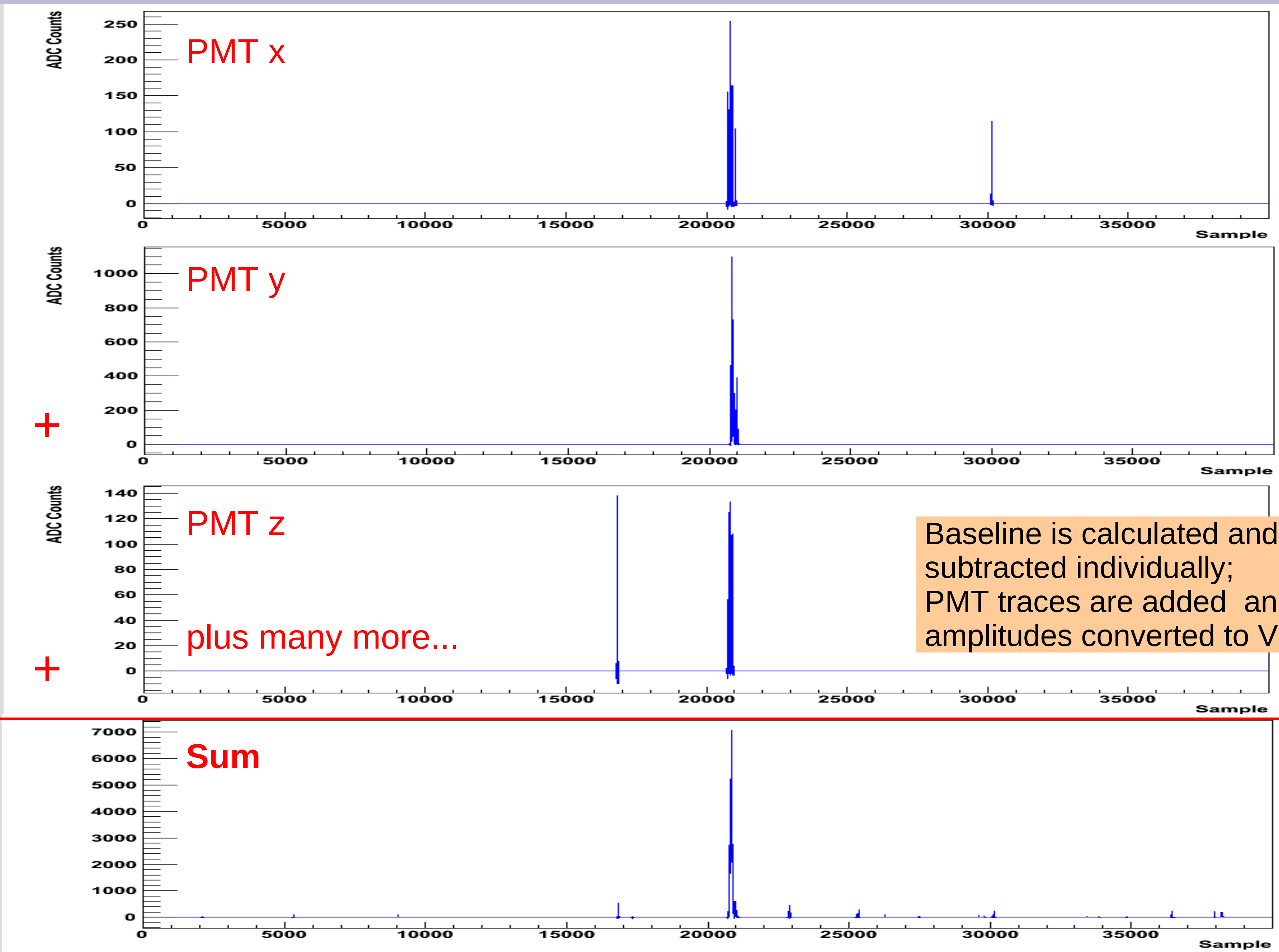
gains of all 242 PMTs are equalized to 2×10^6



$$\begin{aligned}\text{Peak Area} = V \times T &= R \times I \times T \\ &= R \times \frac{Q}{T} \times T \\ &= R \times Q \\ &= R \times n_e \times q_e \\ \Rightarrow n_e &= \frac{V \times T}{R \times q_e}\end{aligned}$$

convert peak area into number of detected electrons
→ one PE is amplified to n_e electrons
→ definition of the gain

Waveform Reconstruction



Baseline is calculated and subtracted individually;
PMT traces are added and amplitudes converted to Voltage

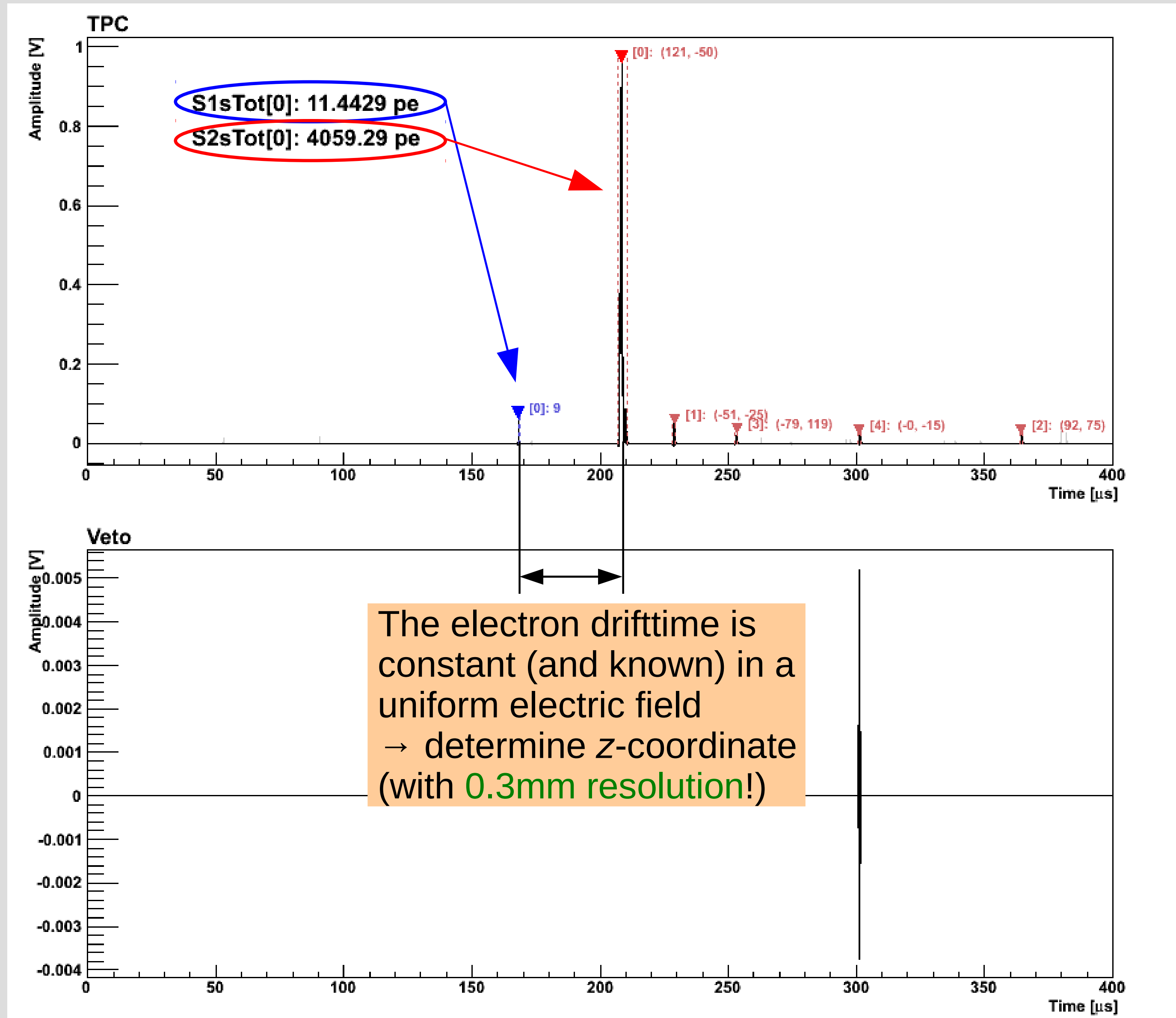
Peak Processing

The peak processor gets physical quantities from the waveforms:

1. Search for S2s
apply a digital low-pass filter to smoothen trace
→ search for S2 candidates (>0.6 µs wide peaks)

2. Search for S2s
use unfiltered waveform; do not search after the first larger S2

For each candidate obtain
- area (PE)
- height (V)
- width (ns)
- contributing PMTs
- ...



The electron drifttime is constant (and known) in a uniform electric field
→ determine *z*-coordinate (with 0.3mm resolution!)

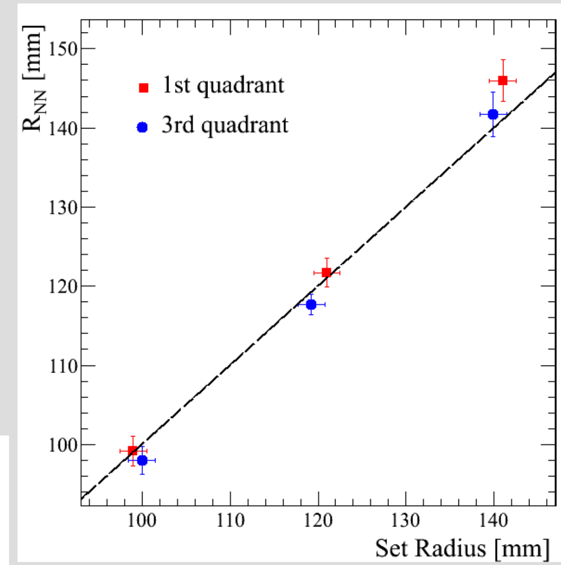
xy-Position Reconstruction

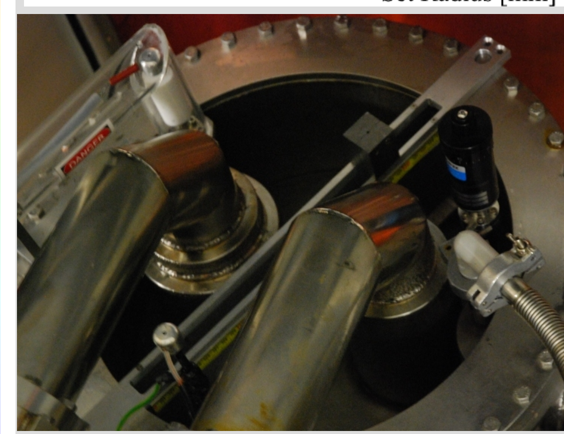
Goal: obtain xy-position from comparison of the observed top S2 pattern to a MC generated one
- χ^2 algorithm
- support vector machine (SVM)
- neural network (NN)

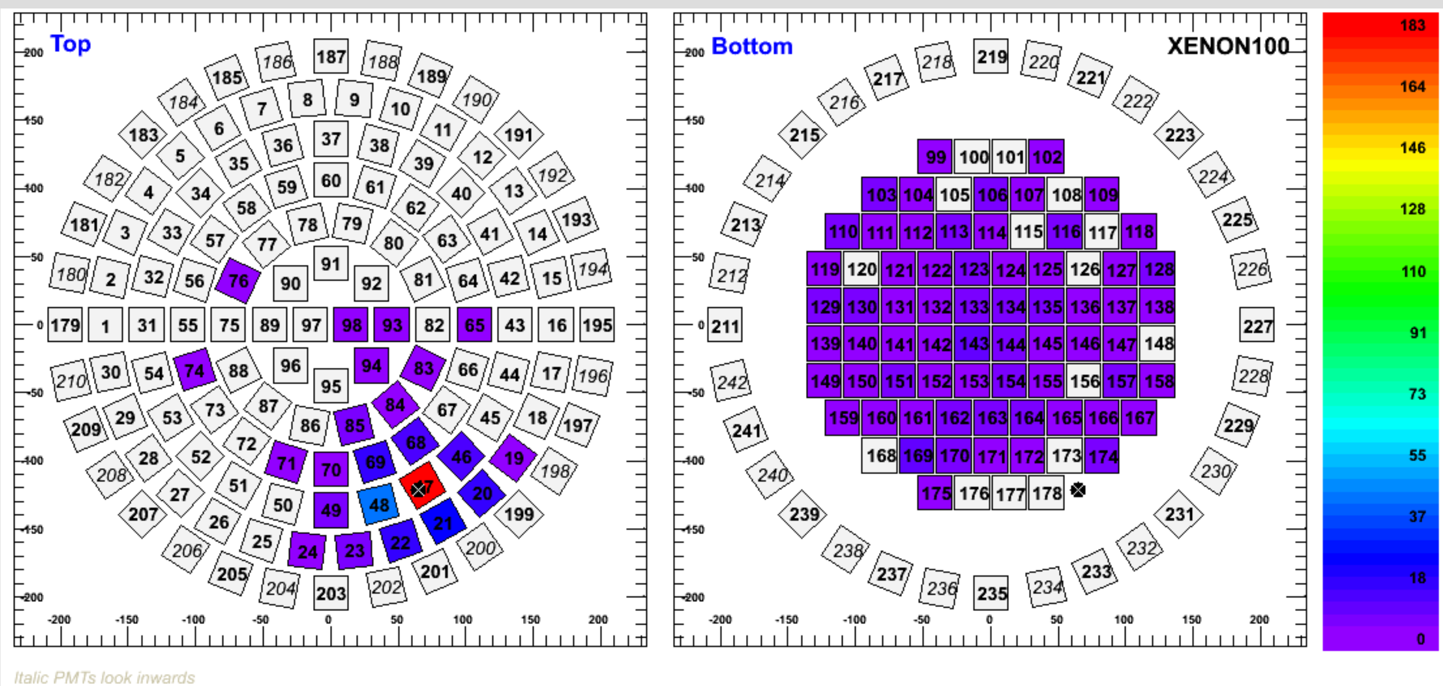
all algorithms give consistent results for R<142mm

measured position resolution: <3mm (1σ)

Neural Network:

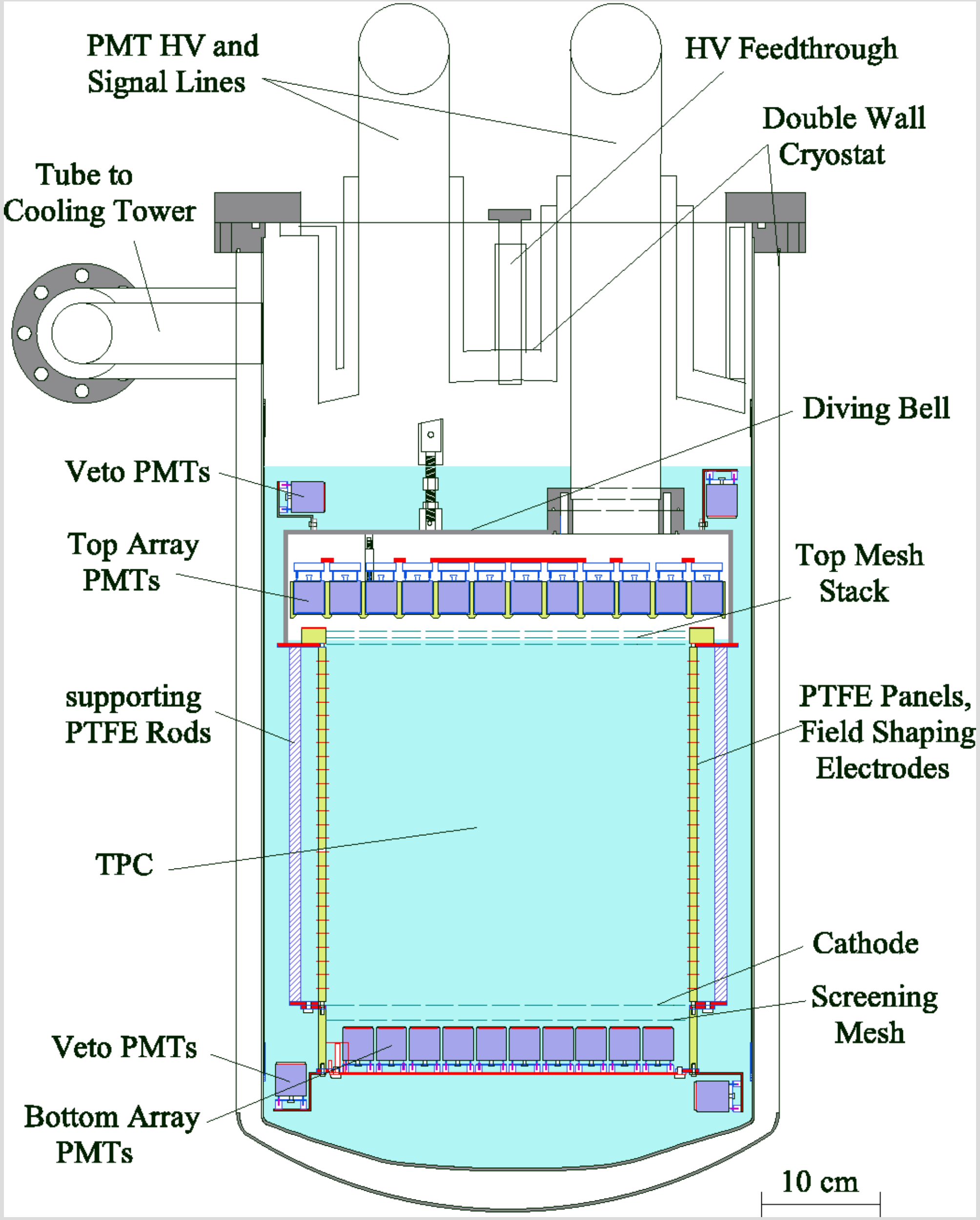


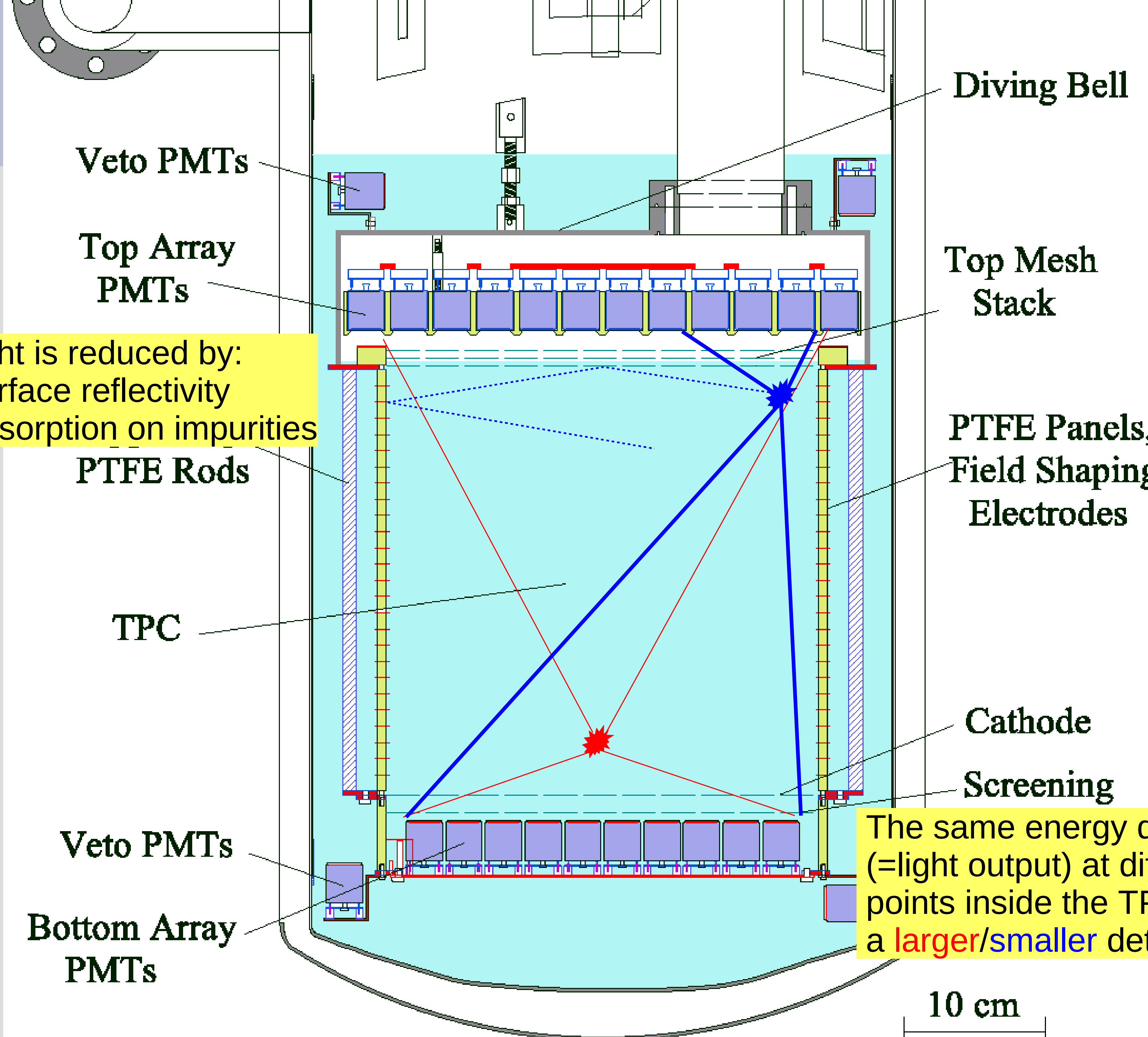




How to get correct signals?

Spatial Signal Dependencies

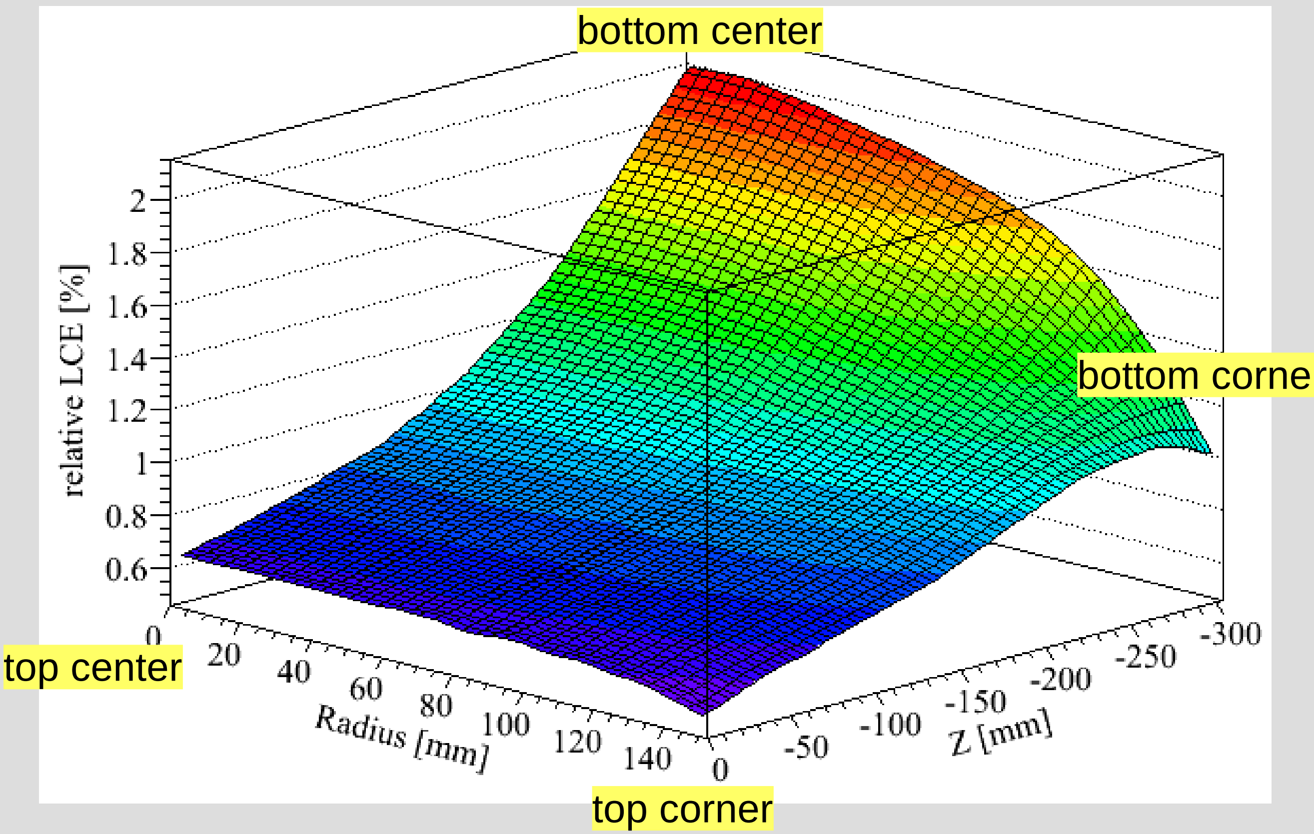




Light is reduced by:
- surface reflectivity
- absorption on impurities

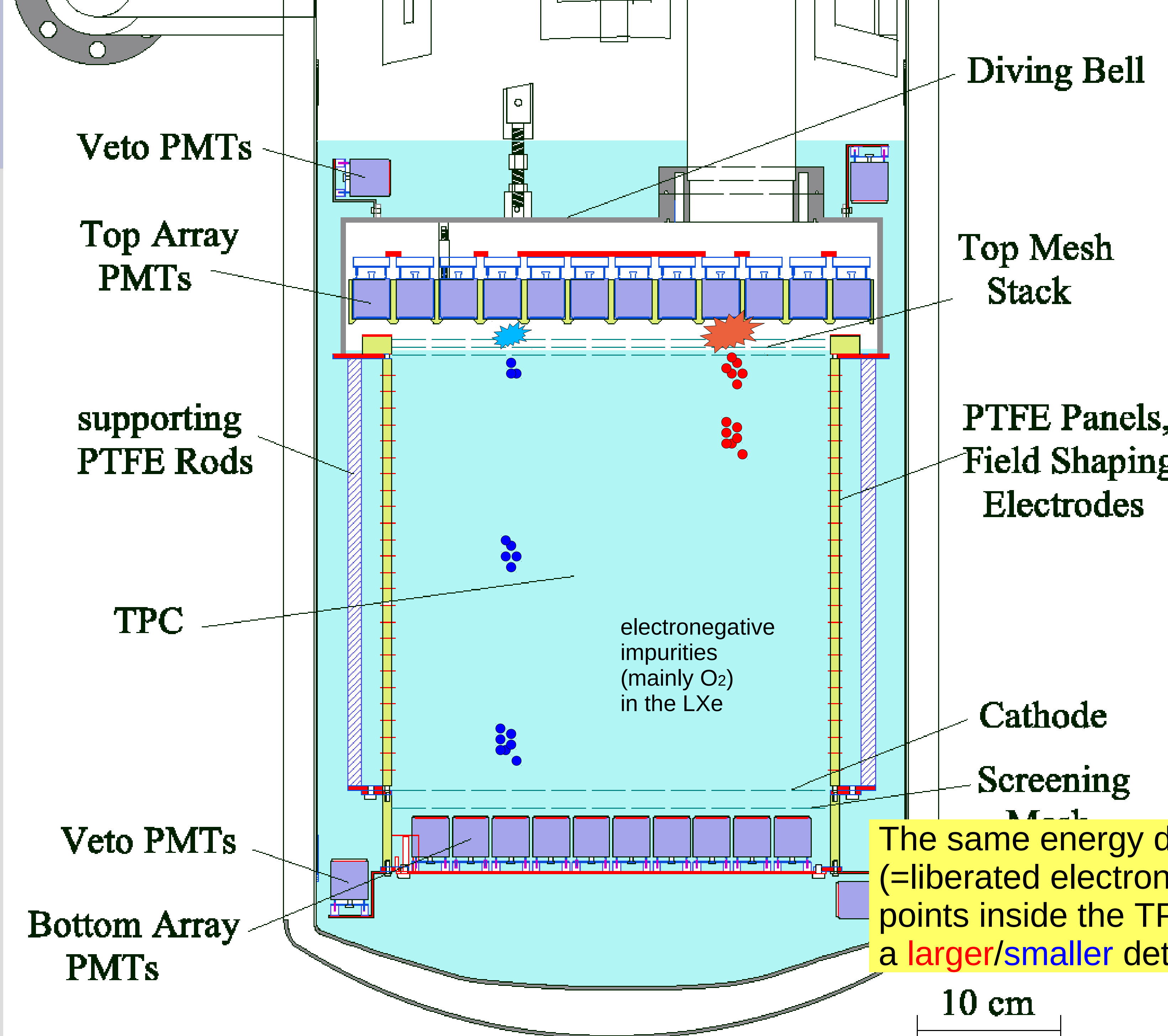
The same energy deposition (=light output) at different points inside the TPC yields a larger/smaller detected signal

Light Collection Efficiency



1. Map out light response in small detector volumes
2. Determine the volume-averaged response
3. Define a correction map which tells us how much the observed amount of light deviates from the average

This is the largest correction in XENON100!



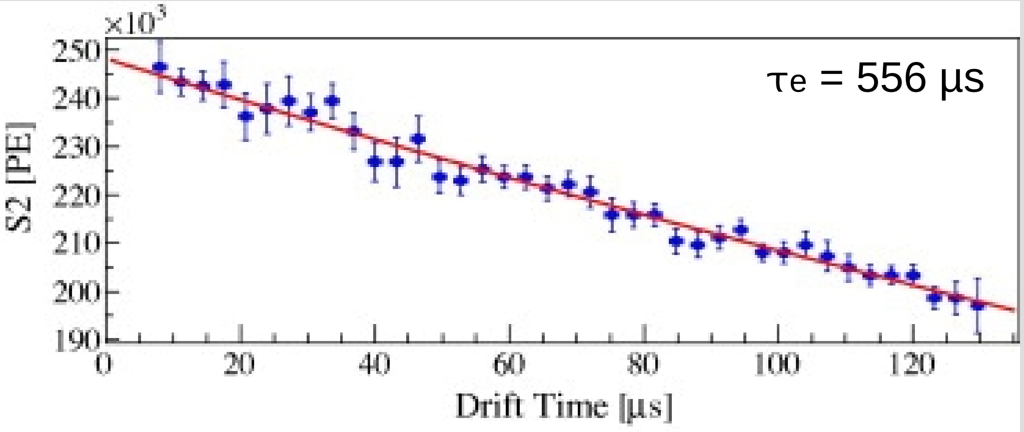
The same energy deposition (=liberated electrons) at different points inside the TPC yields a larger/smaller detected signal

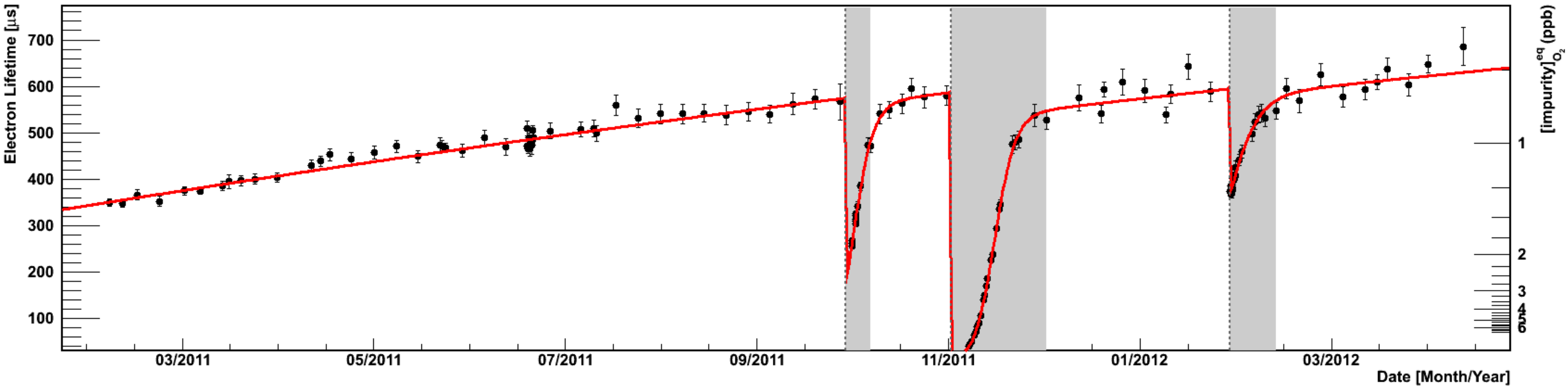
Electron Lifetime Correction

1. Measure the S2 signal of a gamma peak vs dt
2. The observed trend can be described by an exponential

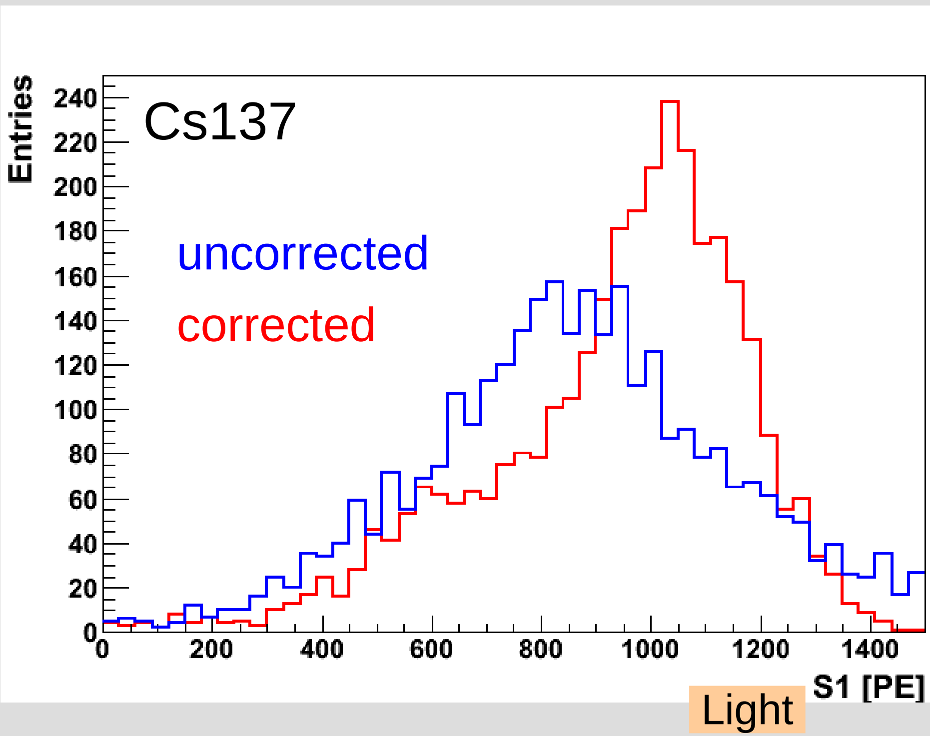
$$S2(E) = S2_0(E)\ \exp\left(-\frac{\Delta t}{\tau_e}\right)$$

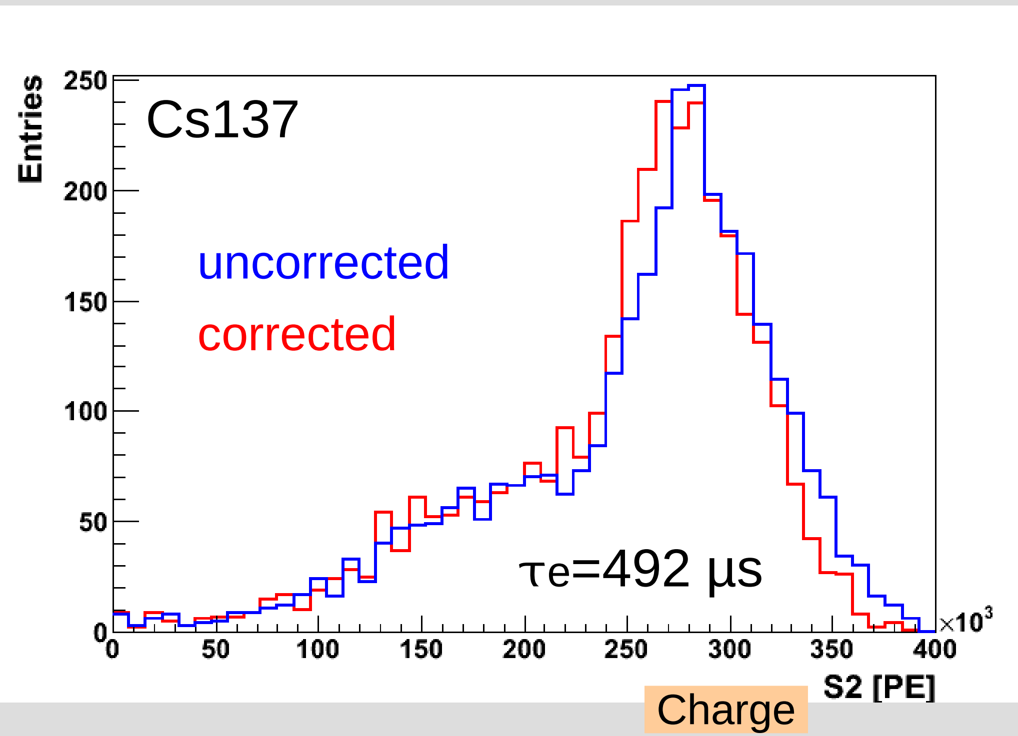
If τ_e is too small, the TPC is blind to signals close to the bottom, maximum Δt = 175 µs





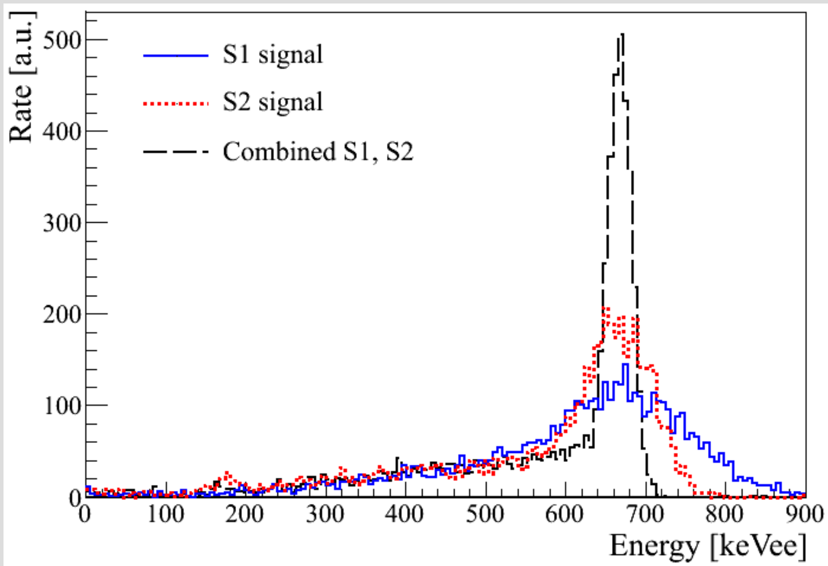
Impact of Corrections

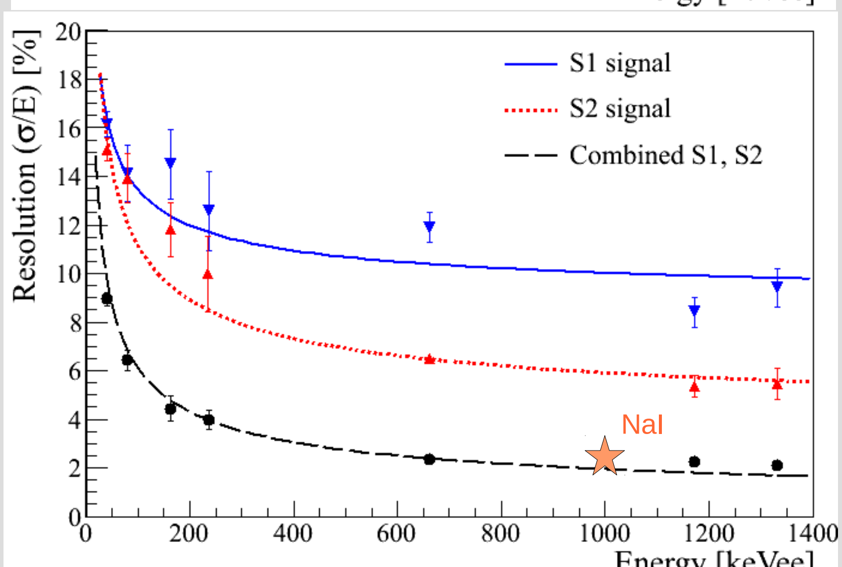


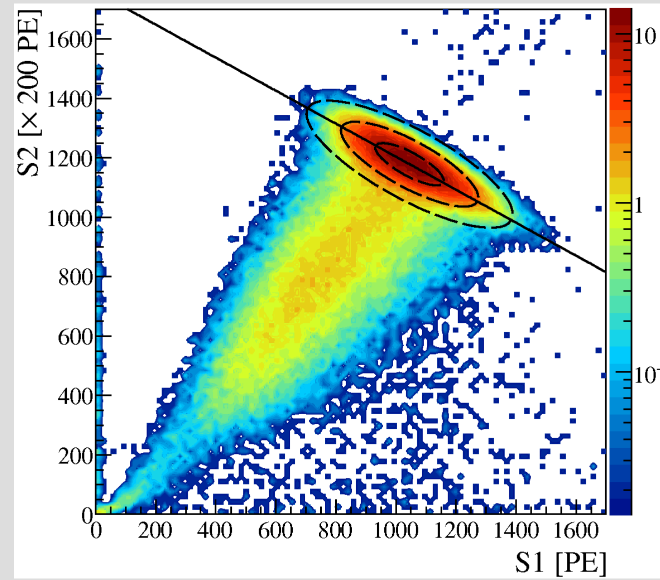


→ S1 light collection correction dominates over S2 corrections (electron lifetime+LCE)

Resolution and Anti-Correlation







Exploiting the anti-correlation between light and charge leads to an energy resolution around 2% (σ/E) at 1 MeV

→ comparable to NaI crystals

BUT: rather poor resolution in
WIMP search energy region

How to get the interesting signals?

Background Suppression

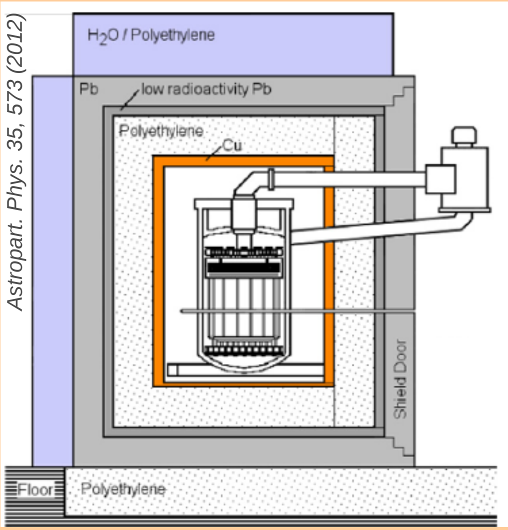
A Avoid Backgrounds

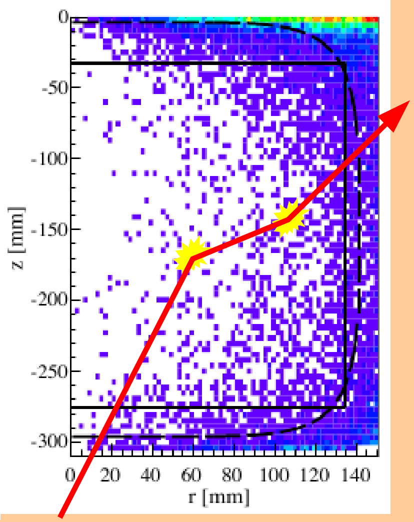
Use of radiopure materials

Shielding

deep underground location
large shield (Pb, water, poly)
active veto (μ, γ coincidence)

self Shielding → fiducialization





B Use knowledge about expected WIMP signal

WIMPs interact only once

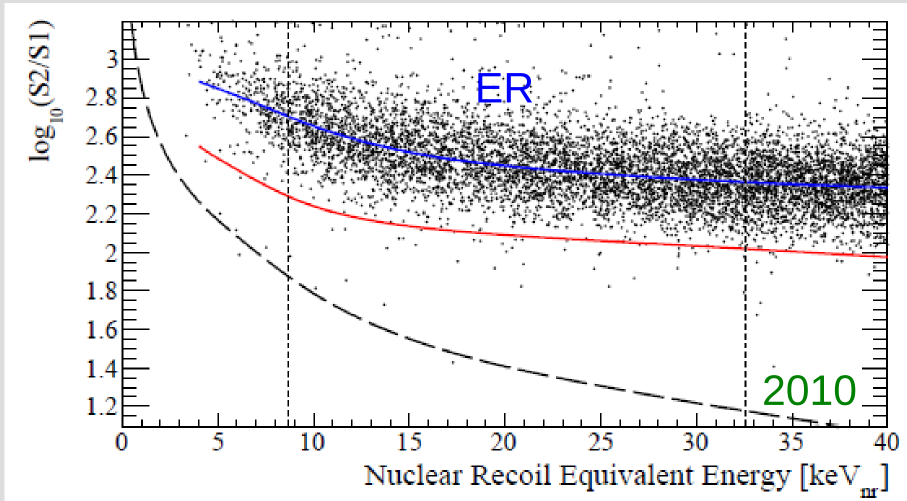
→ single scatter selection
require position resolution

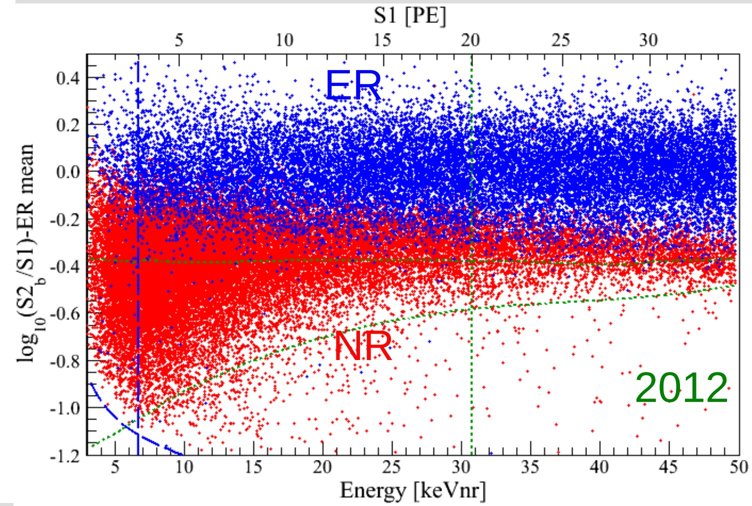
WIMPs interact with target nuclei

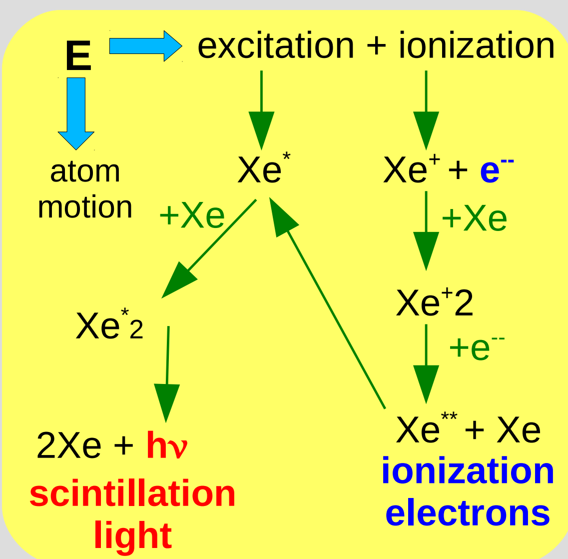
→ nuclear recoils
exploit different dE/dx from
signal and background

Charge/Light Ratio

S2/S1 Discrimination



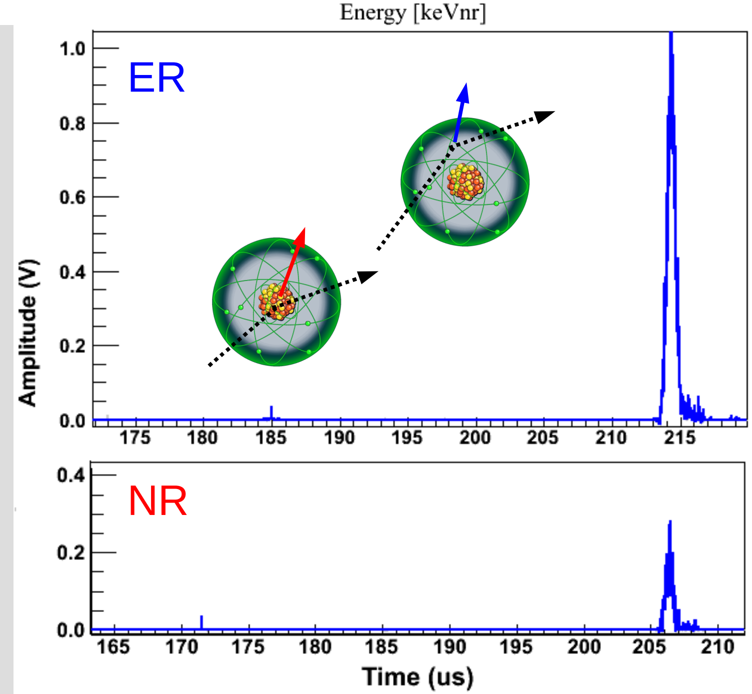




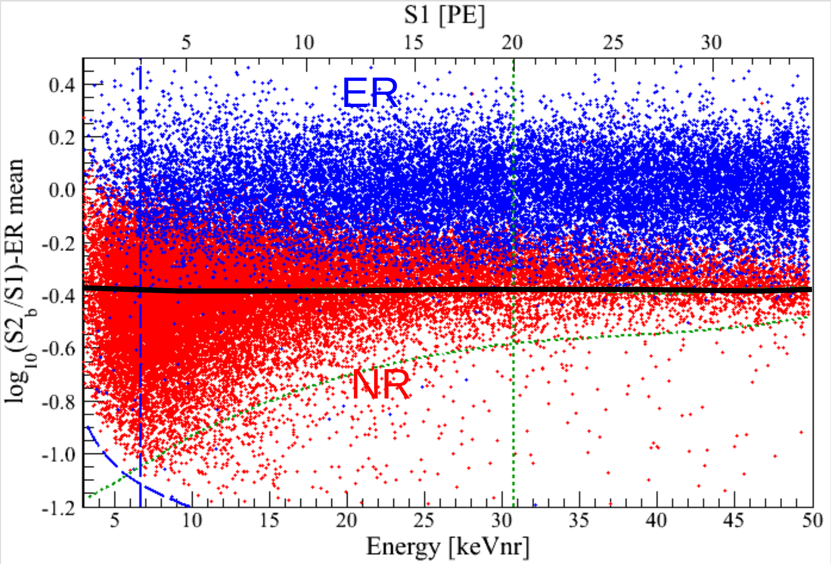
Ratio of excitation and ionization depends on dE/dx and the type of interaction

→ exploit to discriminate between signal (NR) and background (ER)

>99.5% rejection @ 50% NR acceptance



Cuts: Acceptance and Rejection



Acceptance:
the fraction of good events which pass a certain cut
→ you want to have it as high as possible

Rejection:
the fraction of bad events which get removed by a cut
→ you want to have it as high as possible

this example: ~99.5% ER rejection
50% NR acceptance

note: all other cuts have a much higher acceptance!

main difficulty: ideally, one needs a clean data sample of signals (=WIMPs) to determine the acceptance.
Of course, this does not exist for WIMPs! Use single scatter neutrons.

our approach: evaluate acceptance loss as fraction of calibration events (usually AmBe) failing this cut only. This works as invalid events (=not WIMP like) are most likely rejected by several events.

Cuts are treated simultaneously if they are found to be not independent.

Data Analysis Cuts

Basic Data Quality Cuts

- reject non useable waveforms (muons, micro-discharges, ...) 98%
- S1 coincidence 60-99%
- S1 noise cut 99.9%
- S2 asymmetry 99.6% (wrong depth if wrong S1 is chosen)

Energy Cuts

- low E region (S1>3 PE) n/a stay at reasonable acceptance
- S2 software threshold 80-100% stay at 100% trigger efficiency

Single Scatter Selection

(WIMPs interact only once!)

- only one S2 peak >95%
- only one S1 peak 98.8%
- active veto cut 99.6%

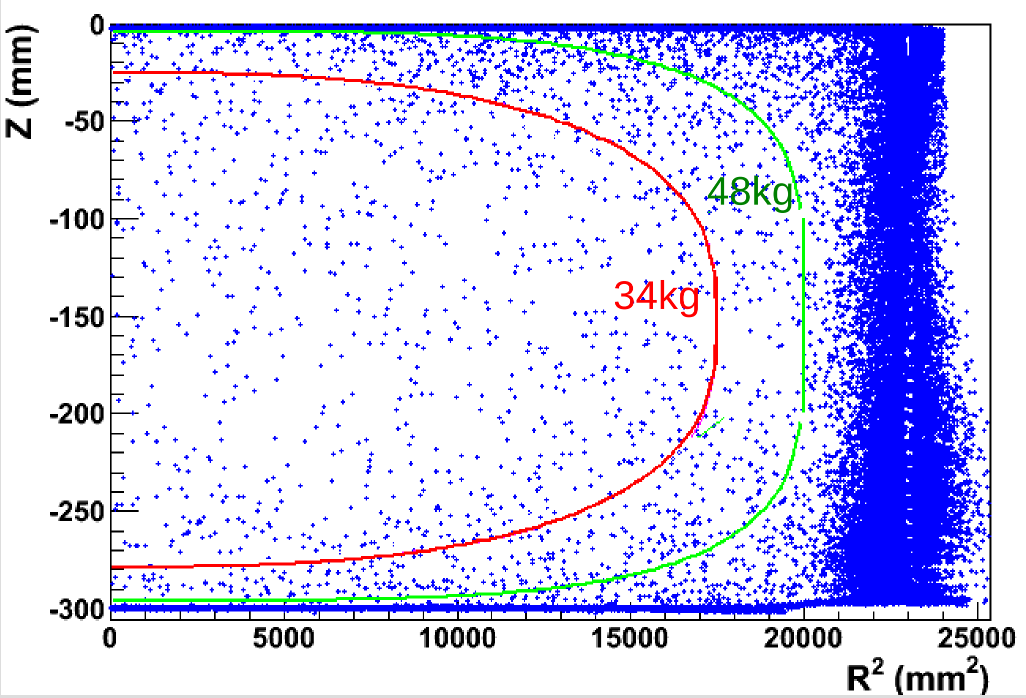
Consistency Cuts

- S2 width cut 93% (drift time ok? gas events)
- position reconstruction 99.6%

Fiducial Volume

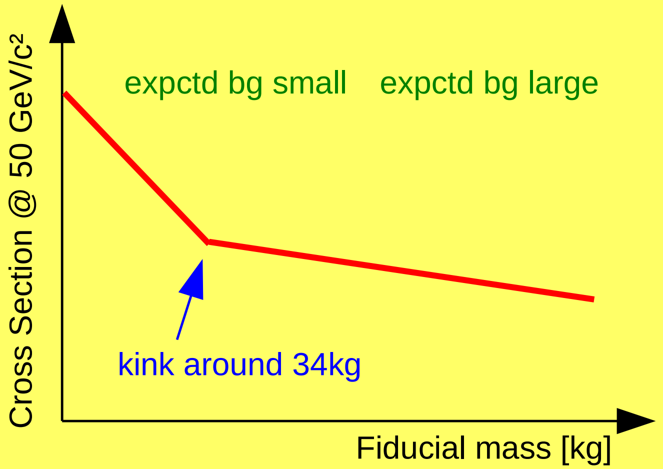
The high density of LXe (ρ~3 g/cm³) efficiently blocks gamma background from the outside.

Fiducialization reduces the background, but also reduces the exposure (= mass x time), hence reduces the sensitivity

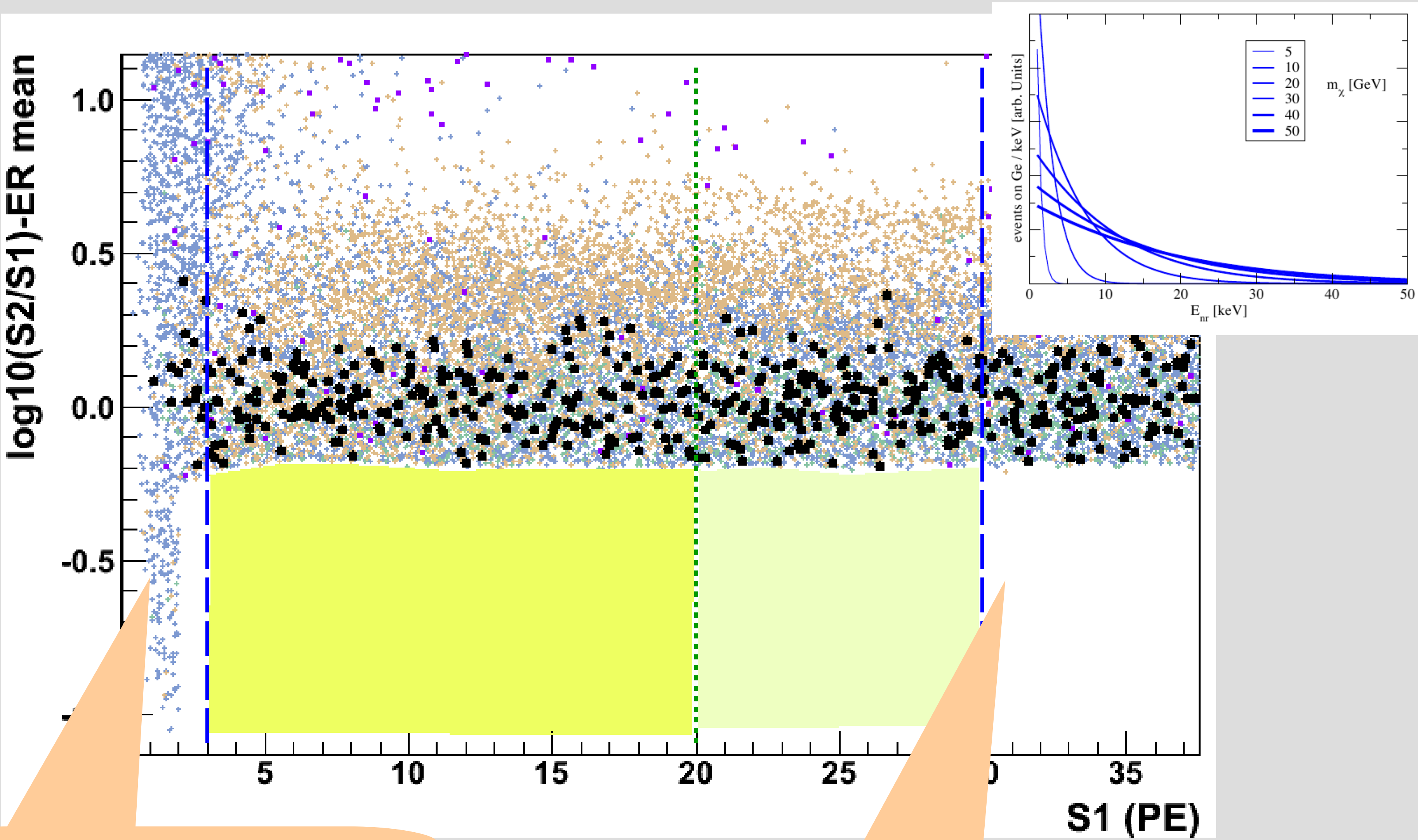


Optimize shape taking into account various inputs:
- spatial distribution of background
- type of background
- known detector response

Optimize fiducial mass by finding the best compromise between sensitivity (with a given background) and the possibility for a detection:



Select Energy Range



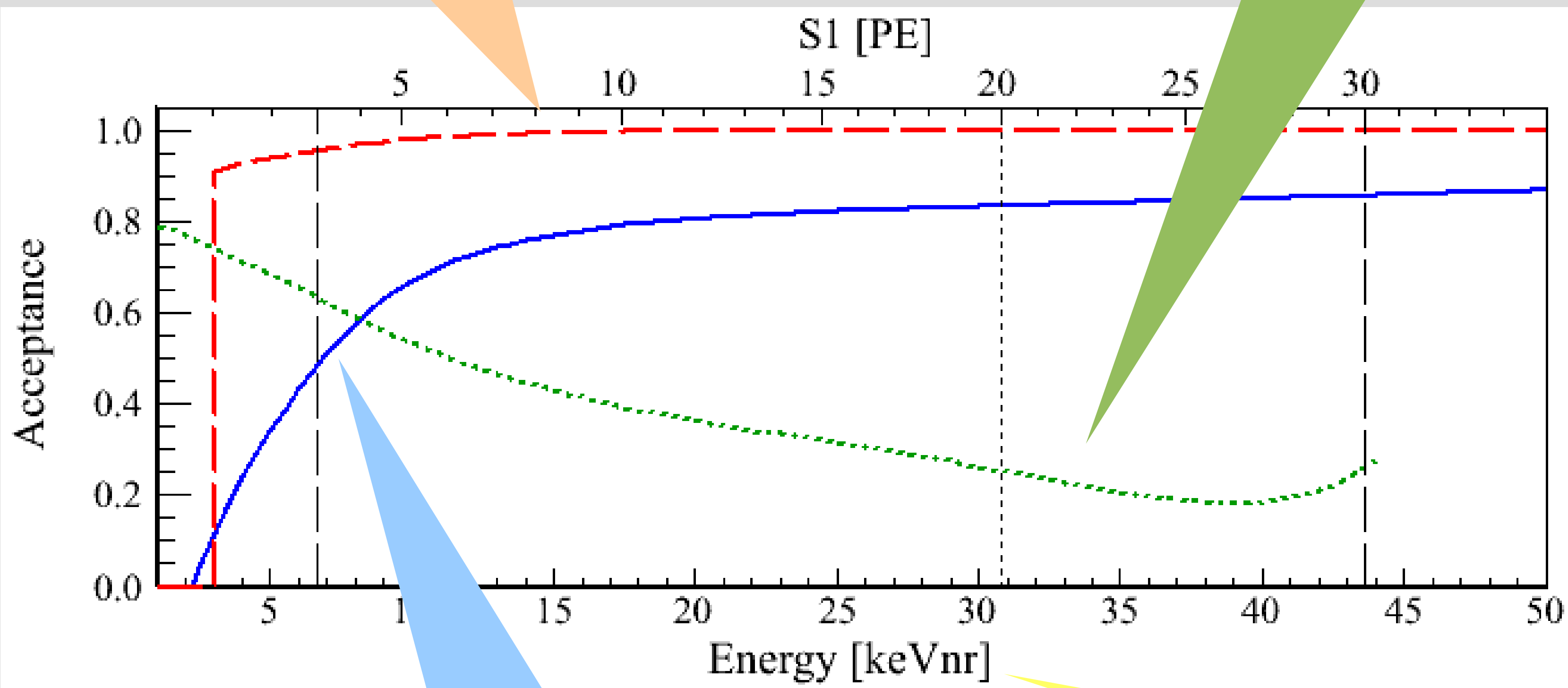
stay at reasonable acceptance,
„not too small“ signals

no expected WIMP signal,
use region for backgrond tests
(high energy sideband)

Cuts and Acceptance

S2 Threshold acceptance
(to be applied before S1 smearing)

NR acceptance
(benchmark region only, need to define a ER rejection level)



Cuts Acceptance

NR equivalent energy scale
→ signal quenching!

Signal Quenching

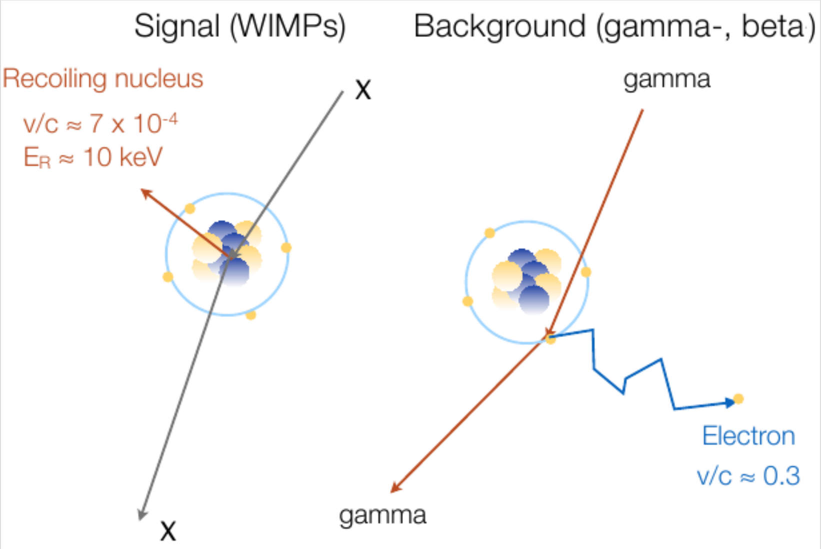
WIMPs (and neutrons) scatter off nuclei
→ nuclear recoils
γ and β backgrounds scatter off electrons
→ electronic recoils

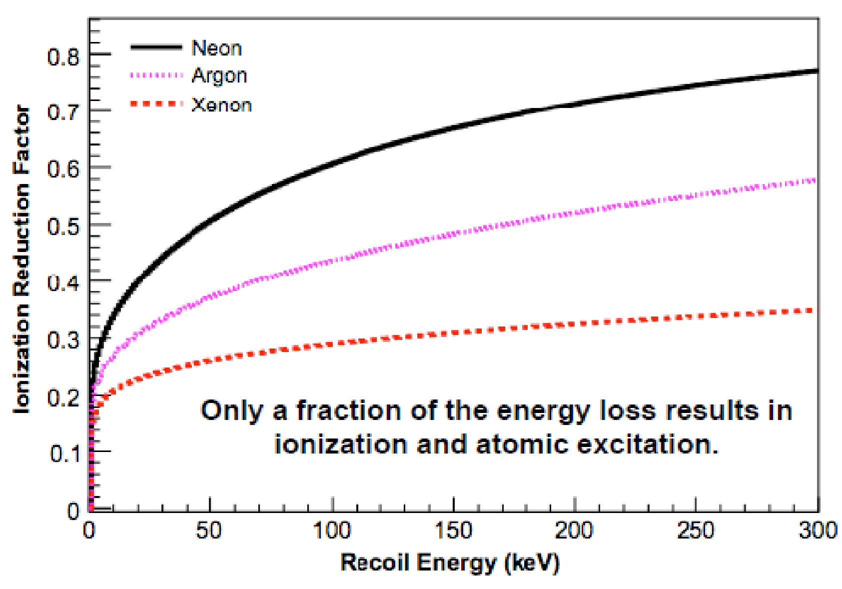
Detectors respond differently to both types of recoils since the energy loss mechanisms are weighted differently:

$$\left(\frac{dE}{dx}\right)_{tot} = \underbrace{\left(\frac{dE}{dx}\right)_{elec}}_{\text{ionization, excitation}} + \underbrace{\left(\frac{dE}{dx}\right)_{nucl}}_{\text{heat}}$$

In the regime of low nuclear E_r, the nuclear stopping power plays a significant role
→ less ionization and excitation of target atoms
→ less observed signal in ionization/scintillation detectors
→ Signal Quenching („Lindhard theory")

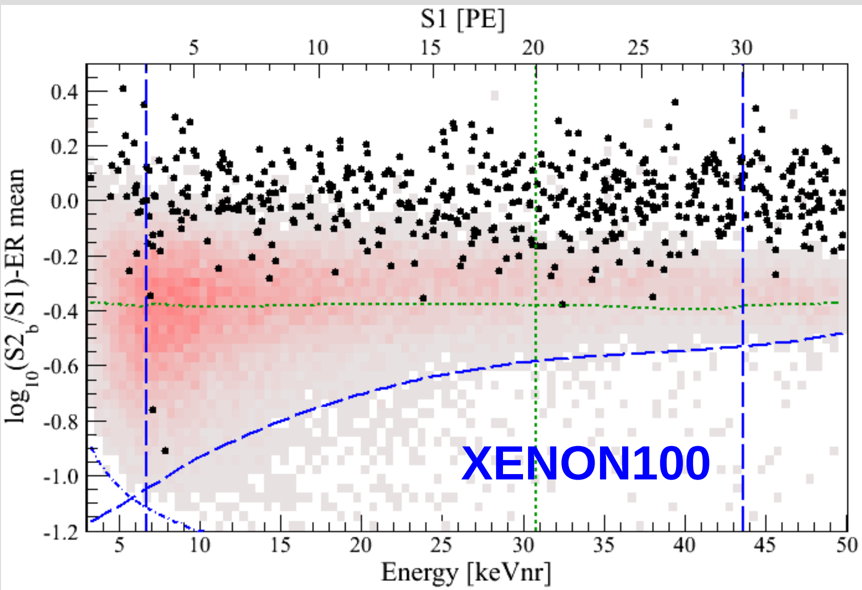
In addition to this, there might be other effects which lead to quenching, e.g. bi-excitonic quenching in LXe
(higher ionization density from NRs impacts the generation of scintillation light)



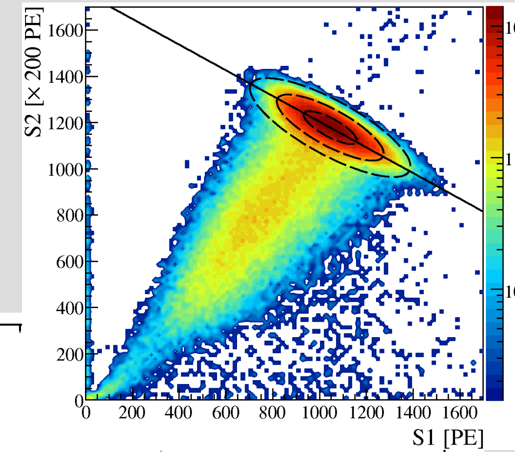


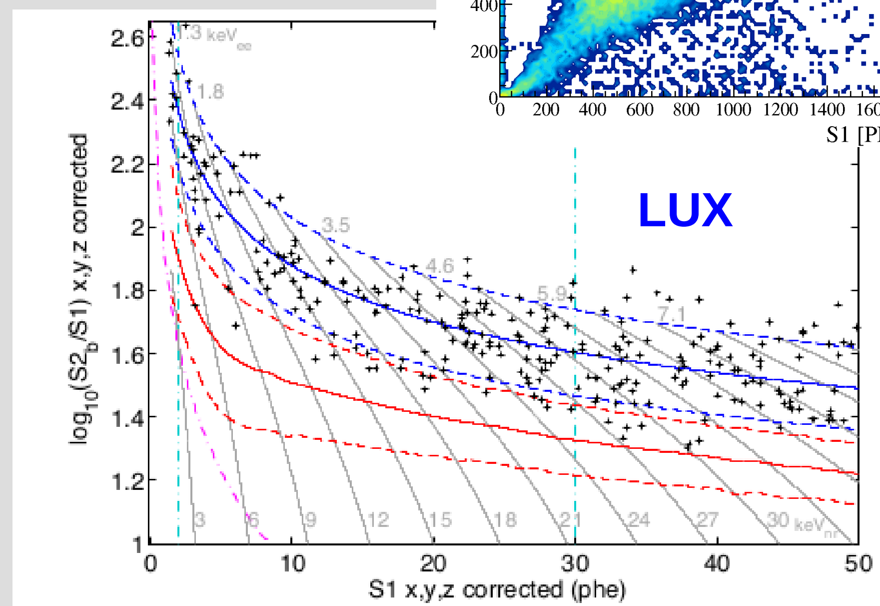
S1 and combined S1+S2 Scale

$$E_{\mathrm{nr}} = \frac{\mathrm{S1}}{\mathrm{LY}} \frac{1}{\mathscr{L}_{\mathrm{eff}}(E_{\mathrm{nr}})} \frac{S_{\mathrm{ee}}}{S_{\mathrm{nr}}}$$



Example:
3 PE → 6.6 keVnr
4 PE → 8.2 keVnr
10 PE → 17.2 keVnr
20 PE → 30.5 keVnr
30 PE → 43.3 keVnr



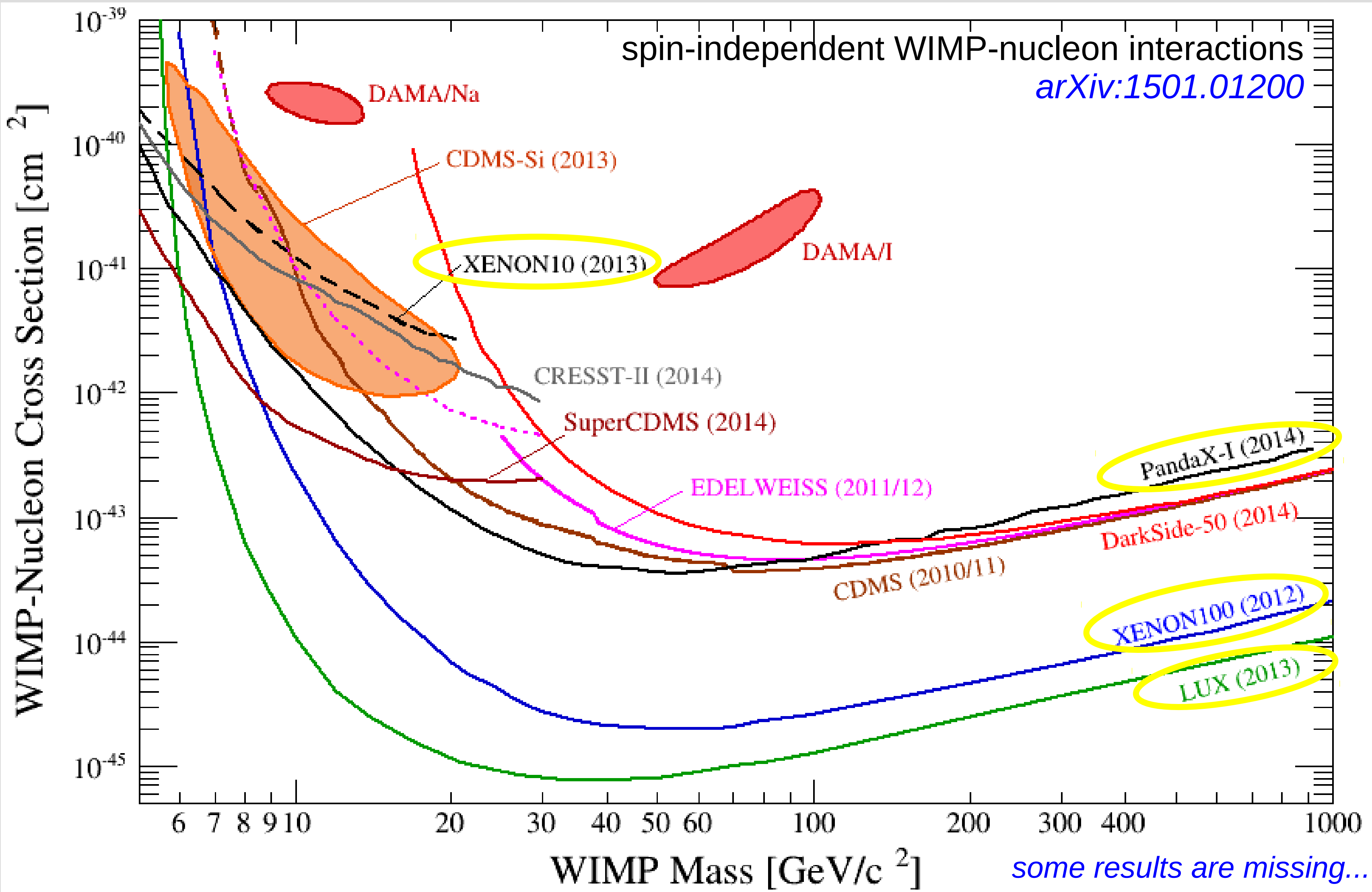


Use a combination of S1 and S2 signal to get a better energy estimator

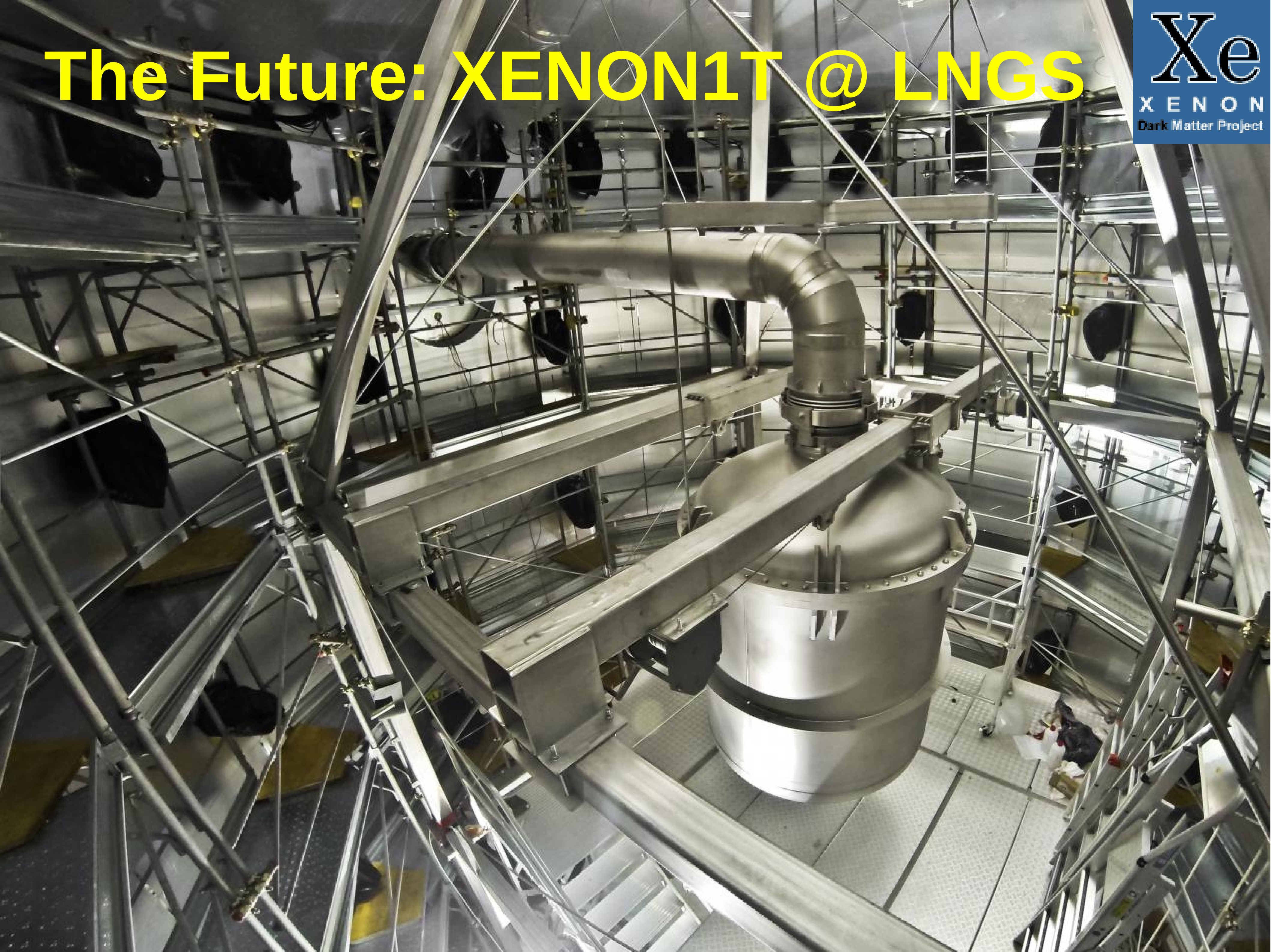
→ next step: combine signal and background distributions plus nuisance parameters in Likelihood analysis → WIMP detection or upper limit

The current WIMP landscape

→ dominated by liquid xenon TPCs



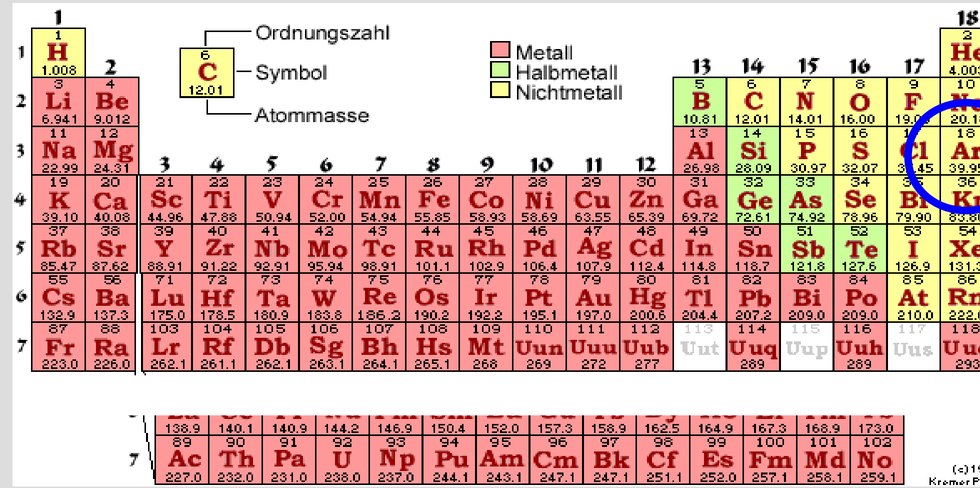
The Future: XENON1T @ LNGS



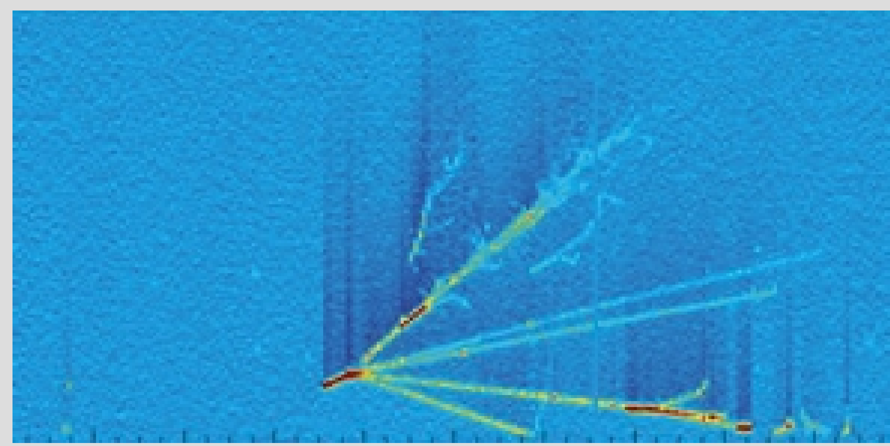
Now, let's switch to Argon...

Why Argon? – Neutrinos!

- large abundance
  → modest price
  → can think about gigantic detectors
- relatively compact detectors
  → exploit self shielding
- cryogenics @ –186°C (above LN_2)
- scalability to larger detectors
- excellent background discrimination even when only measuring light
- well established technology

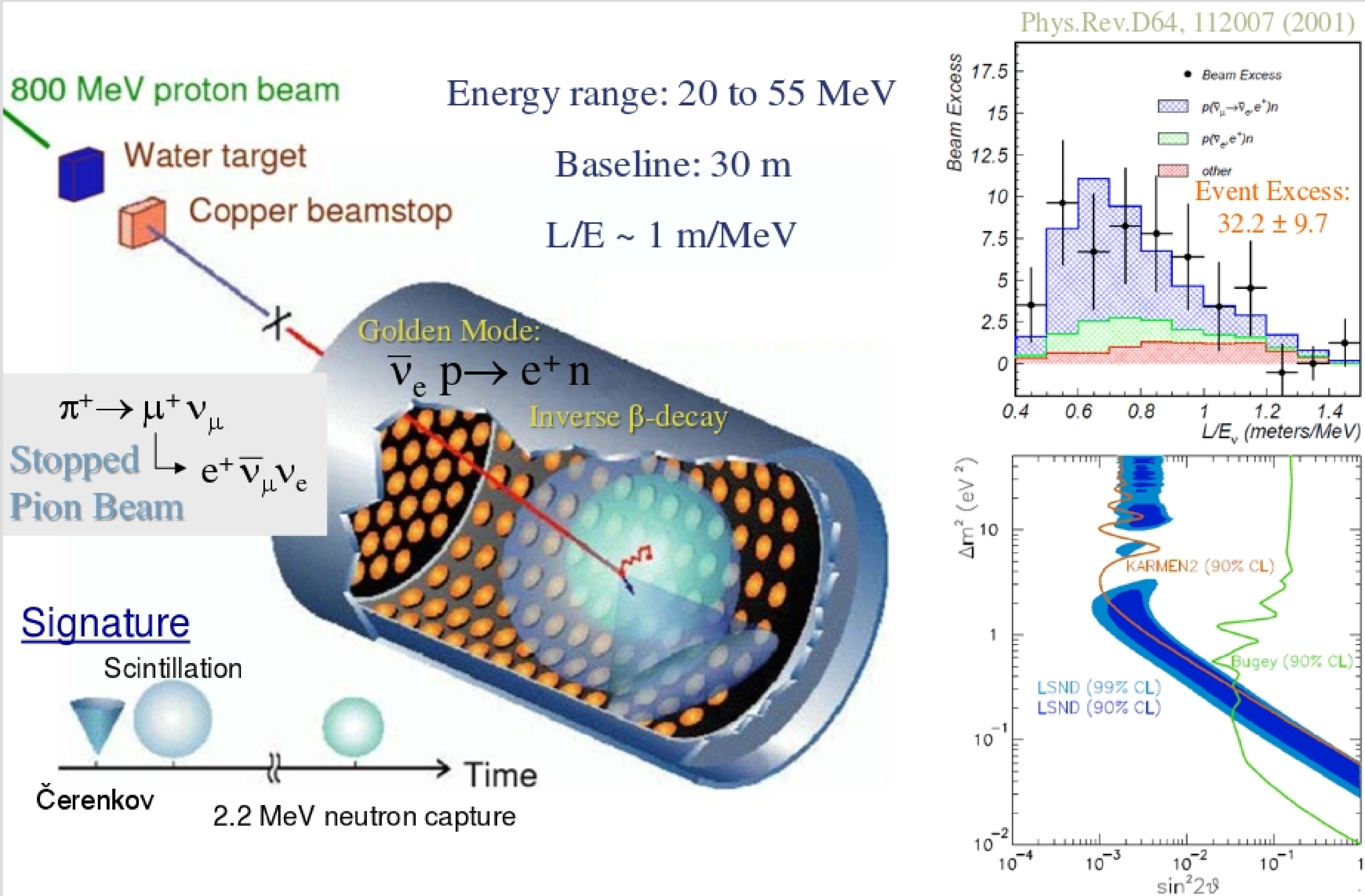


- neutrinos interact with energies well above natural radioactivity (~1 GeV)
- use LAr to measure charge tracks
  → very good particle ID
- More efficient than water Cerenkov detectors



ArDM

LSND: Excess in $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ Appearance



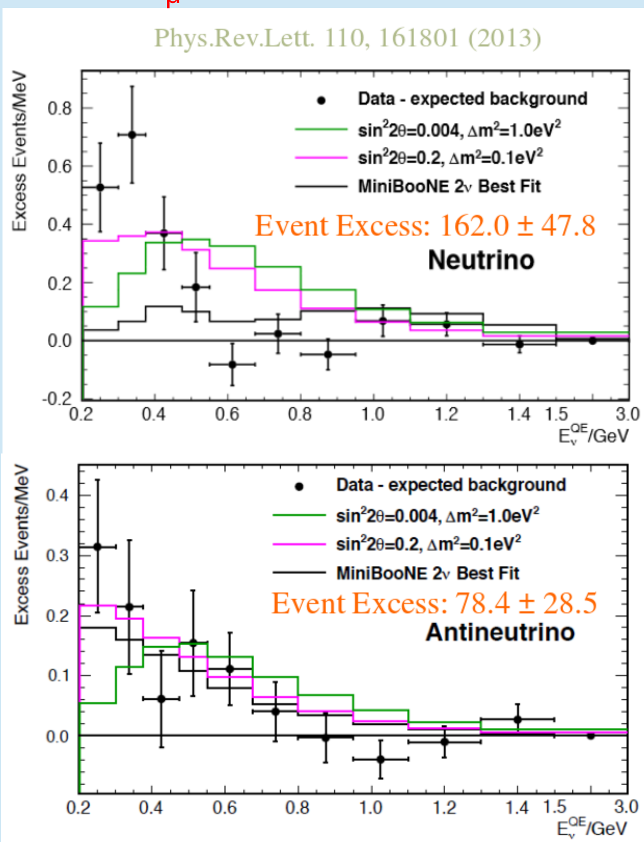
Interesting experimental Situation

MiniBooNE: low enerhy event excess in

$\nu_\mu \rightarrow \nu_e$ appearance

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance

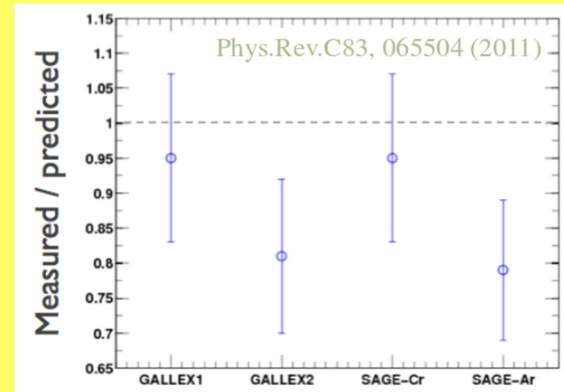
but NO ν_μ disappearance



No global fit with LSND possible!

Gallium anomaly (ν_e disappearance)

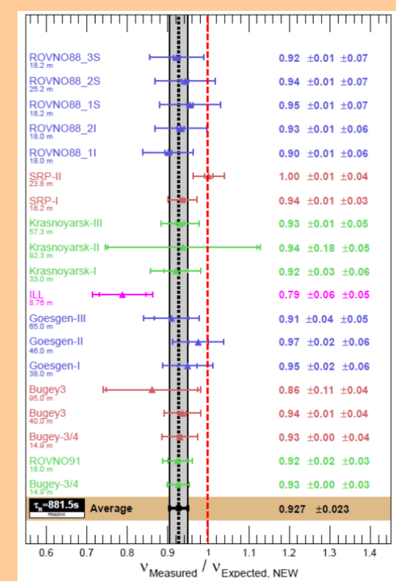
→ new analysis suggests that radiochemical experiments Gallex/SAGE saw too few calibration events



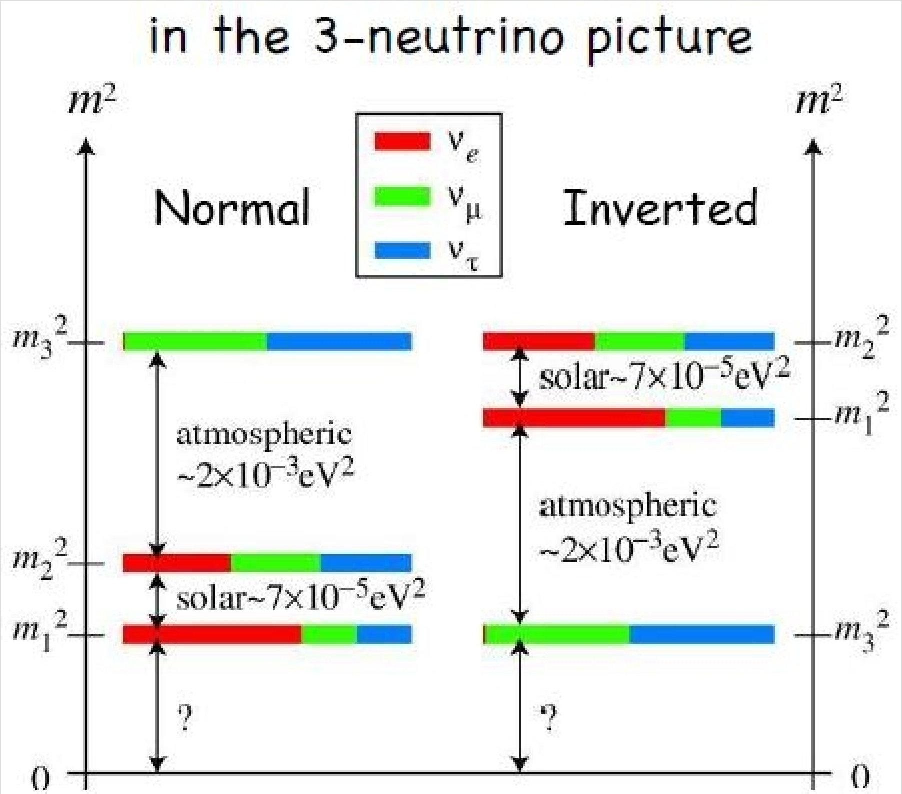
Reactor anomaly

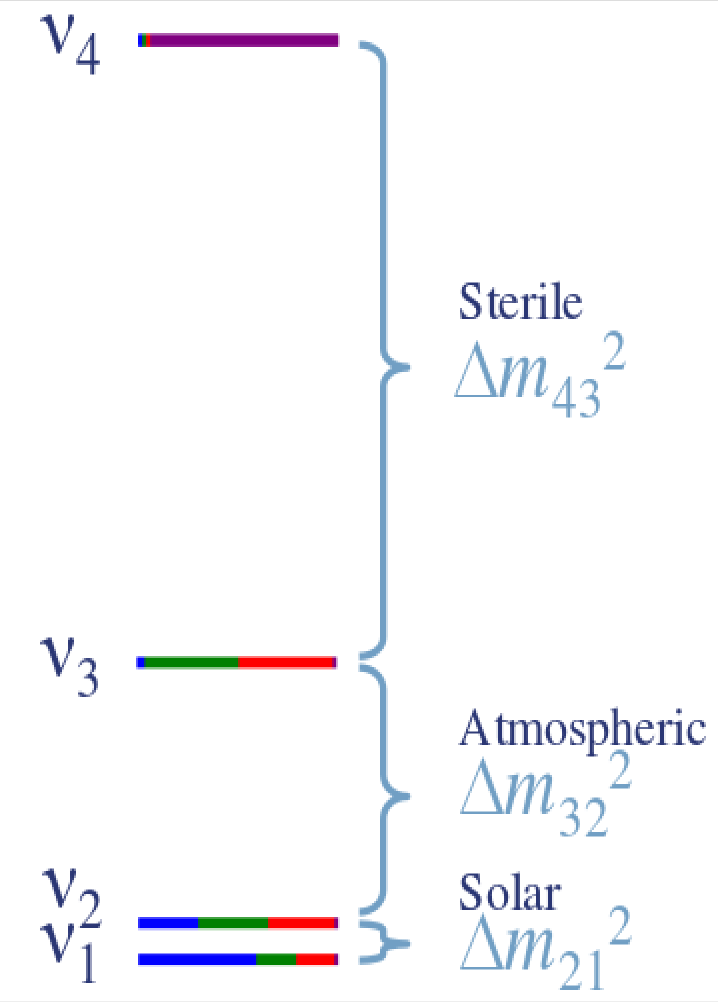
($\bar{\nu}_e$ disappearance)

→ new calculations indicate that measured neutrino fluxes are ~3.5% too low



Sterile Neutrinos?

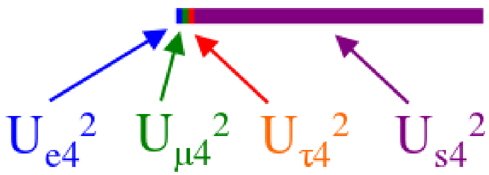


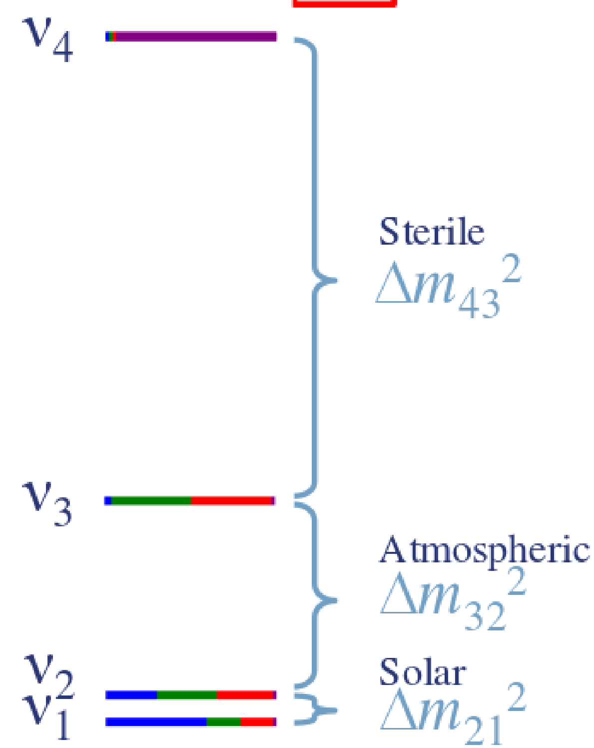


4-Neutrino Mixing

With a single sterile neutrino we get a 4×4 PMNS mixing matrix and 3 independent Δm^2s.

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_s\end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4}\\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4}\\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4}\\ U_{s1} & U_{s2} & U_{s3} & U_{s4}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\\ \nu_4\end{pmatrix}$$





The appearance probability:

observed? $P_{\mu e} = 4U_{e4}^2\, U_{\mu4}^2 \sin^2(1.27\Delta m_3^2 L/E)$

The ν_e disappearance probability:

observed? $P_{ee} \approx P_{es} = 4U_{e4}^2\, U_{s4}^2 \sin^2(1.27\Delta m_3^2 L/E)$

The ν_μ disappearance probability:

not observed! $P_{\mu\mu} \approx 4U_{\mu4}^2\, U_{s4}^2 \sin^2(1.27\Delta m_3^2 L/E)$

© J. Link

→ test in neutrino beam experiments
→ generate mono-type ν-beam and detect ν-disappearence or ν-appearance of other flavors

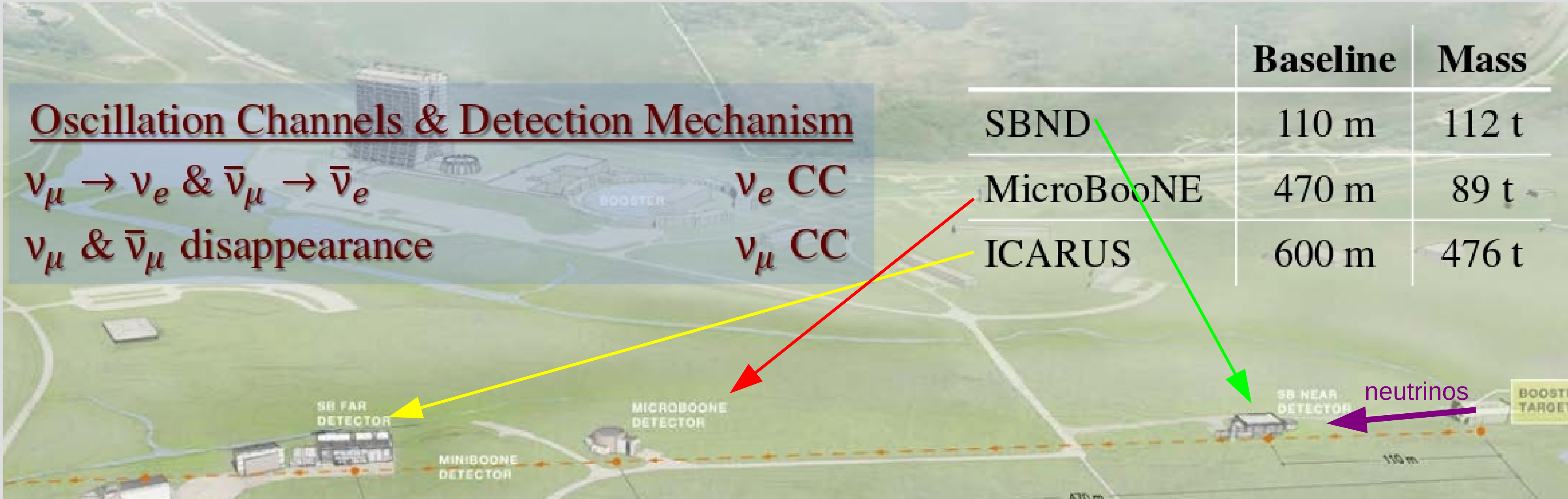
Liquid Argon Detectors for Accelerator-based Neutrino Physics

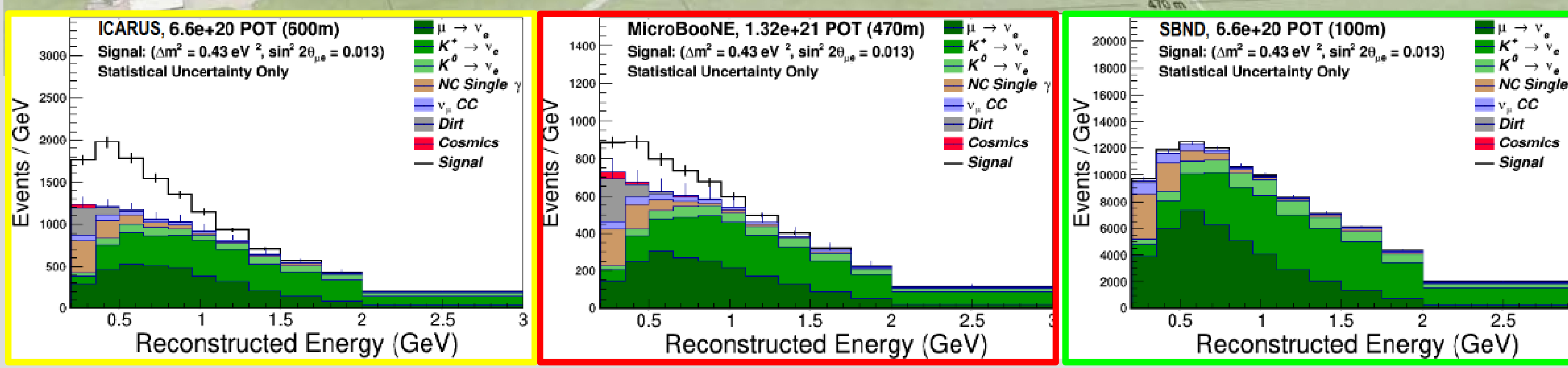
Fermilab Short-Baseline Program

Oscillation Channels & Detection Mechanism

$\nu_\mu \rightarrow \nu_e$ & $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	ν_e CC
ν_μ & $\bar{\nu}_\mu$ disappearance	ν_μ CC

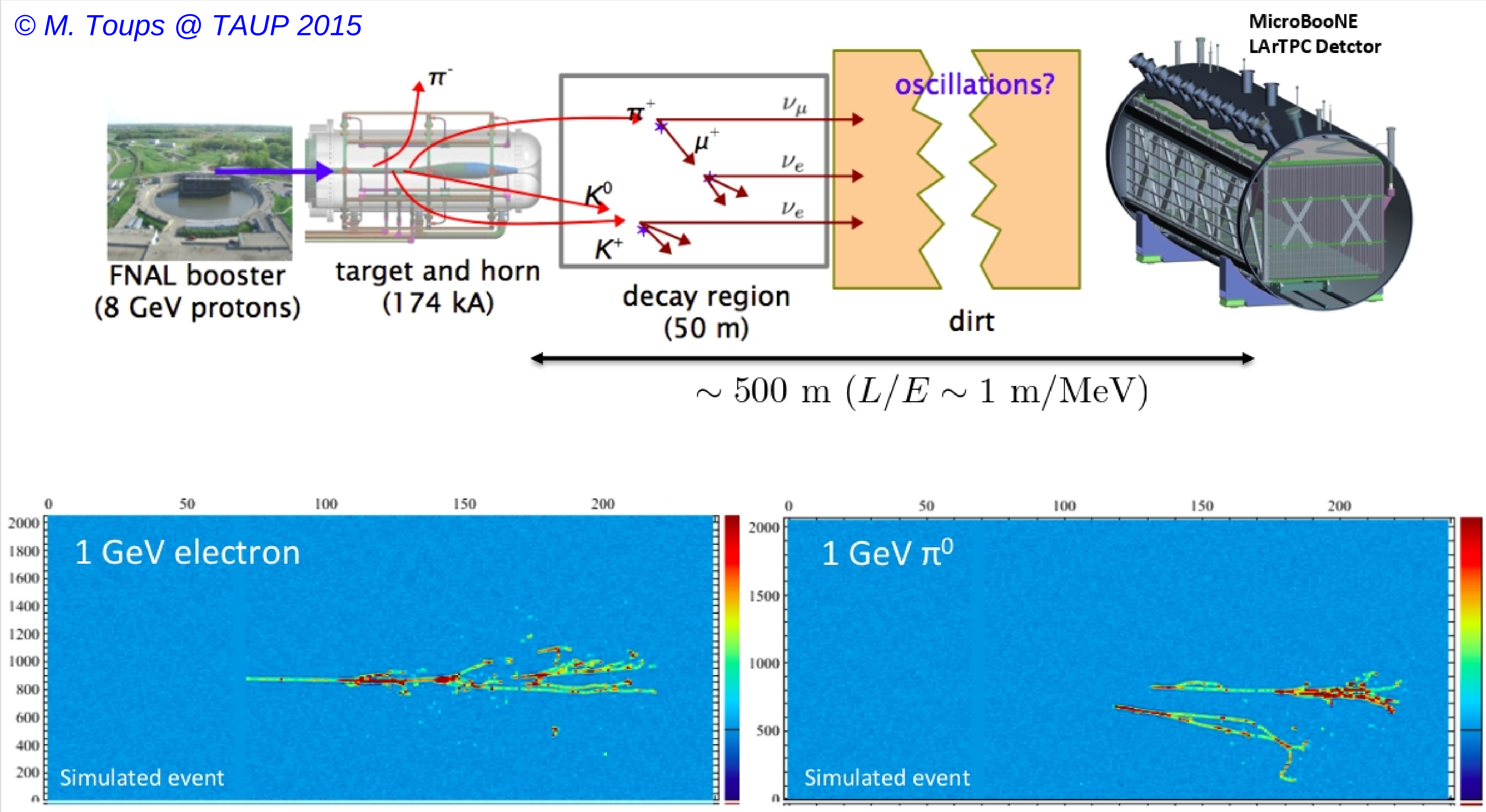
	Baseline	Mass
SBND	110 m	112 t
MicroBooNE	470 m	89 t
ICARUS	600 m	476 t





– 3 LAr detectors: very good particle ID to reduce background misidentification
– near detecotor (SBND): measure inclusive beam and misidentified backgrounds
– cover different L/E values; large ICARUS increases statistics

MicroBooNE



Goals: – what is the MiniBooNE excess at low energies?
– measure ν cross sections
– R&D for future LarTPCs (e.g. long drift, cold electronics, no evacuation before LAr filling)

M. Mezzeto
@ TAUP 2015

LBNF-DUNE: 1.2 MW beam from FNAL, 40 kt Lar TPC at SURF, 1st 10kt installation in 2021, CD-1 refresh out in June, CD2a-CD3a (cavern) this autumn

★ **Three main pillars**

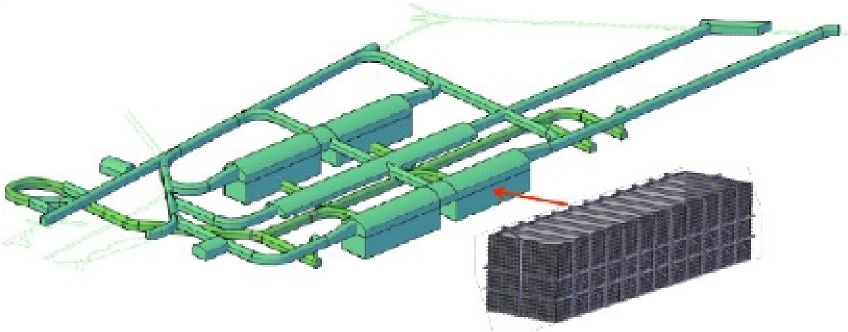
1) **LBL Neutrino Physics**
   - CPV in the leptonic sector
   - Mass Hierarchy
   - Precision oscillation physics (θ_{23} octant, …)
   - Testing 3-flavour paradigm

2) **Nucleon Decay**
   - Targetting SUSY-favoured modes, e.g. $p \rightarrow K^{+}\nu$

3) **Astro-particle Physics**
   - Core collapse super-nova, sensitivity to ν_e

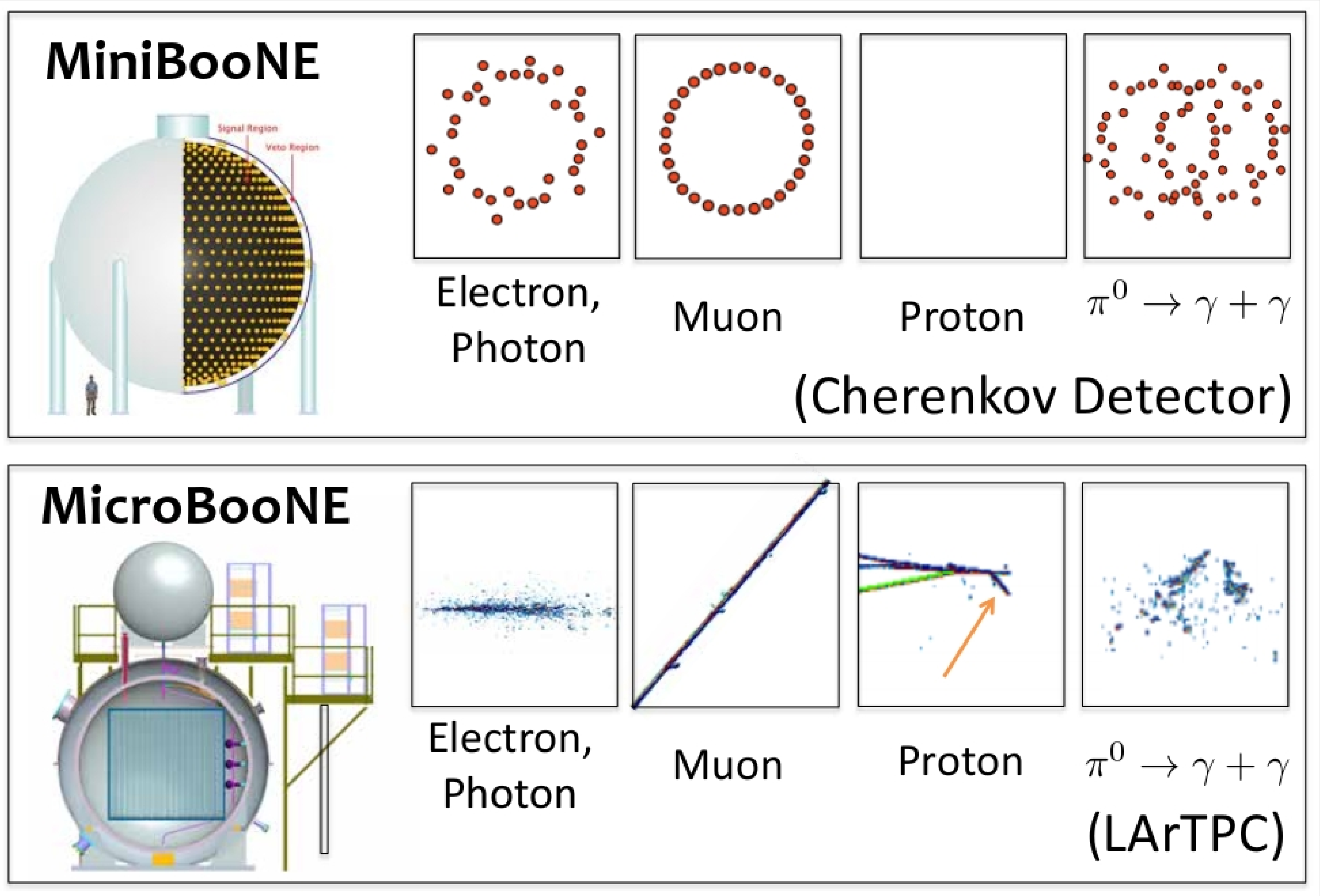
\+ **Precision neutrino physics in the near neutrino detector**

★ **LBNF will provide "homes" for the DUNE FD modules**
   - Four caverns + four cryostats for four 10 kt FD LAr-TPCs



★ **Modular design provides flexibility w.r.t. FD design and funding**

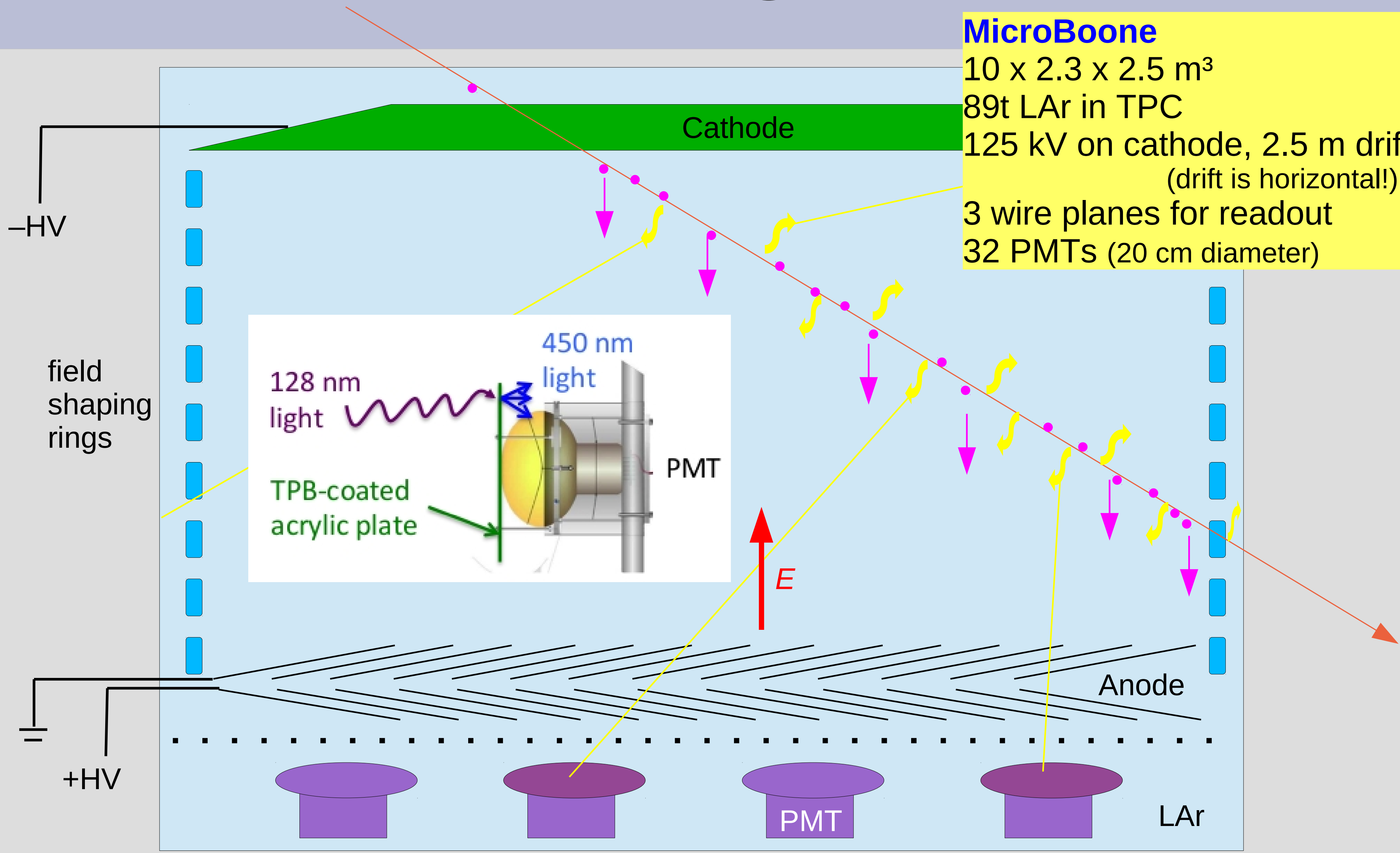
MiniBooNE vs MicroBooNE



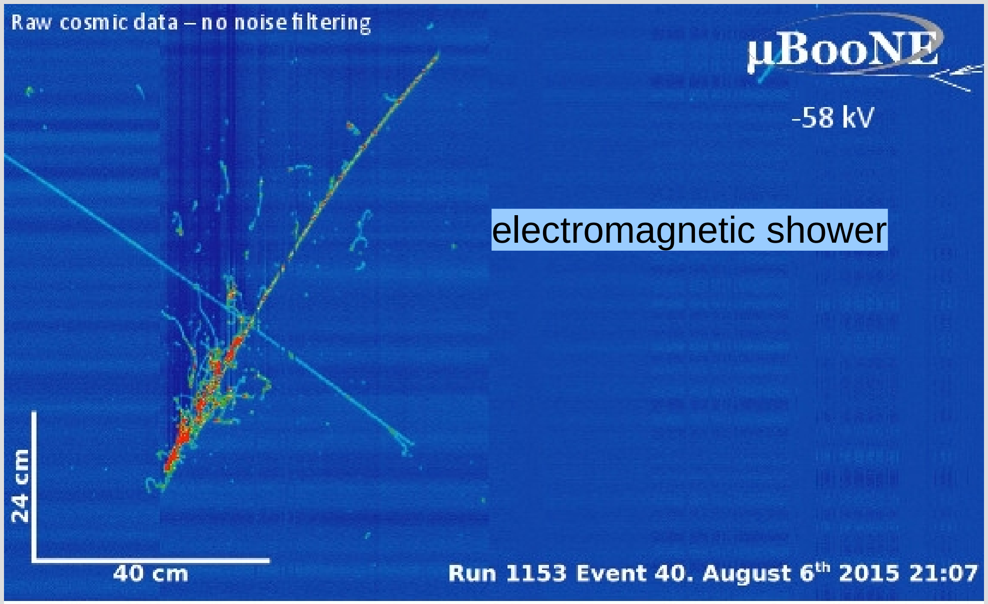
→ excellent particle ID capabilities, using dE/dx and event topology
→ tracks can be reconstructed in 3D

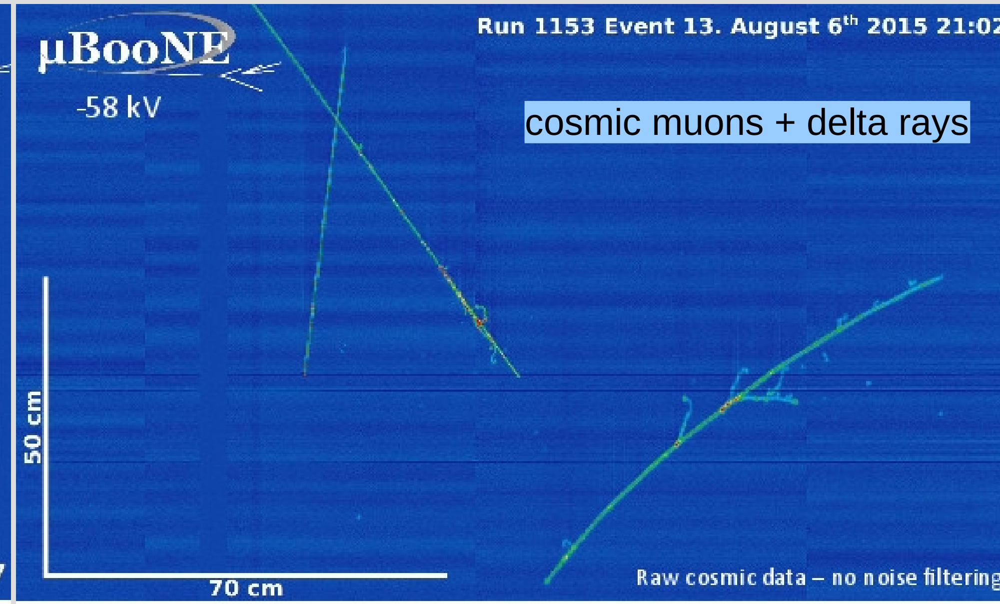
LArTPC

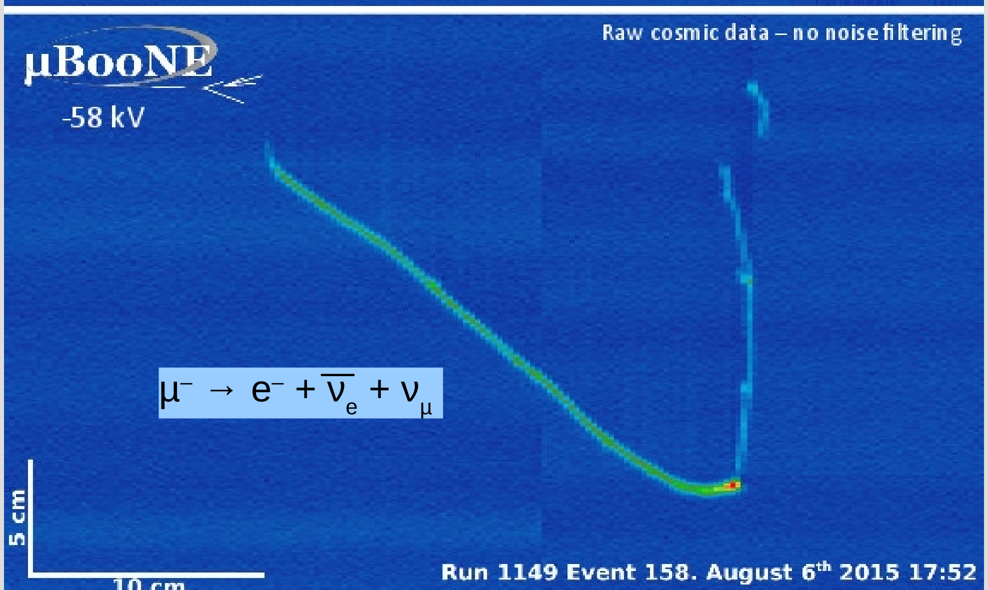
MicroBoone
10 x 2.3 x 2.5 m³
89t LAr in TPC
125 kV on cathode, 2.5 m drift
(drift is horizontal!)
3 wire planes for readout
32 PMTs (20 cm diameter)

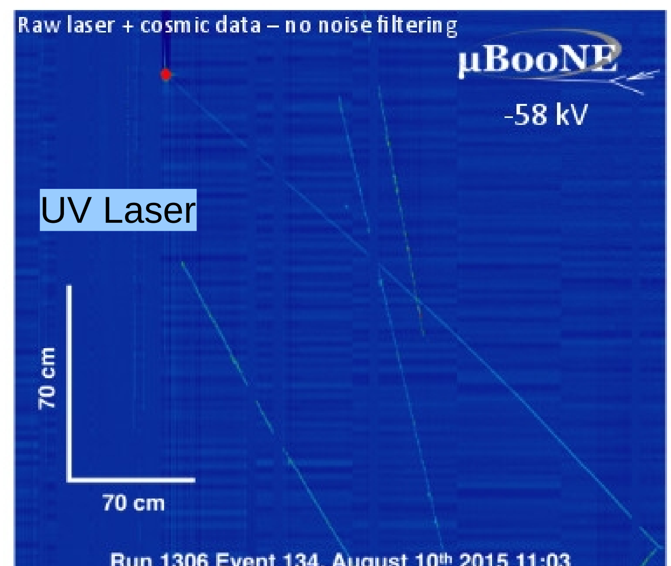


MicroBooNE Tracks



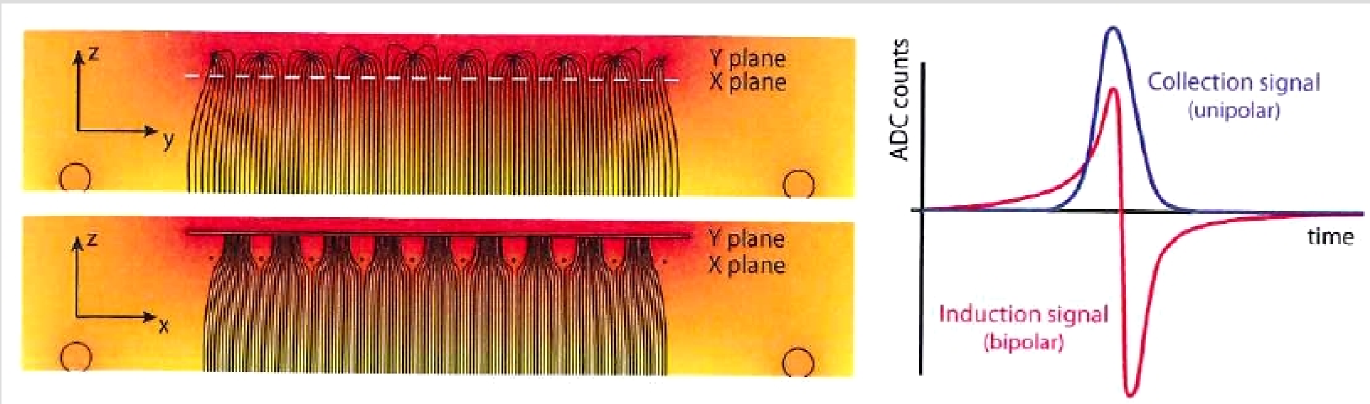






From Energy Deposition to Tracks

Charge Readout: Wire Planes



Transparency condition

$$|\vec{E}_i| > \frac{1+\rho}{1-\rho}|\vec{E}_j|$$

$$\rho = 2\pi r/d$$

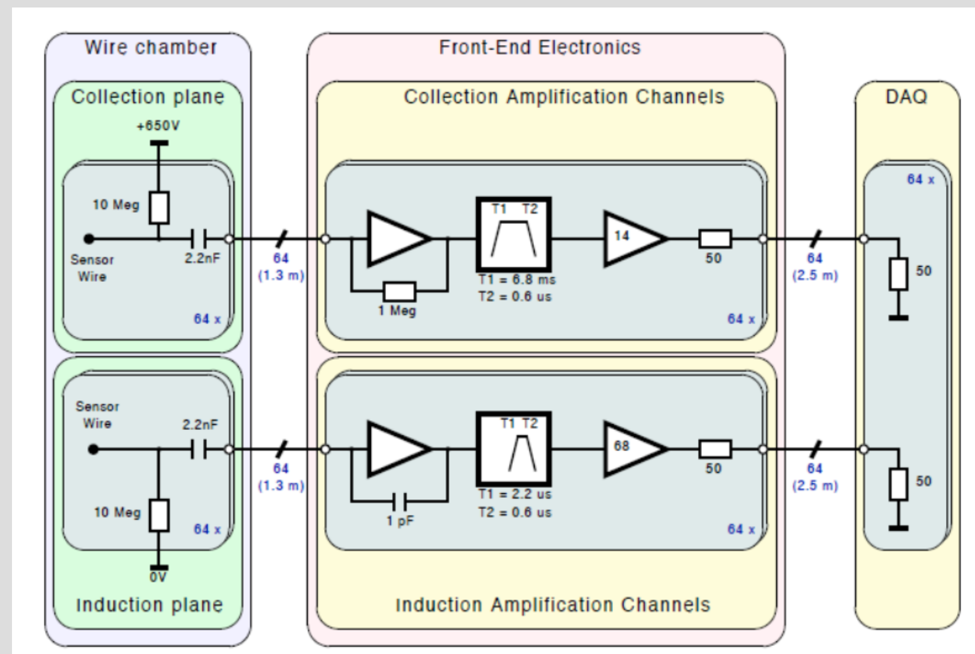
field between wires

drift field

wire radius

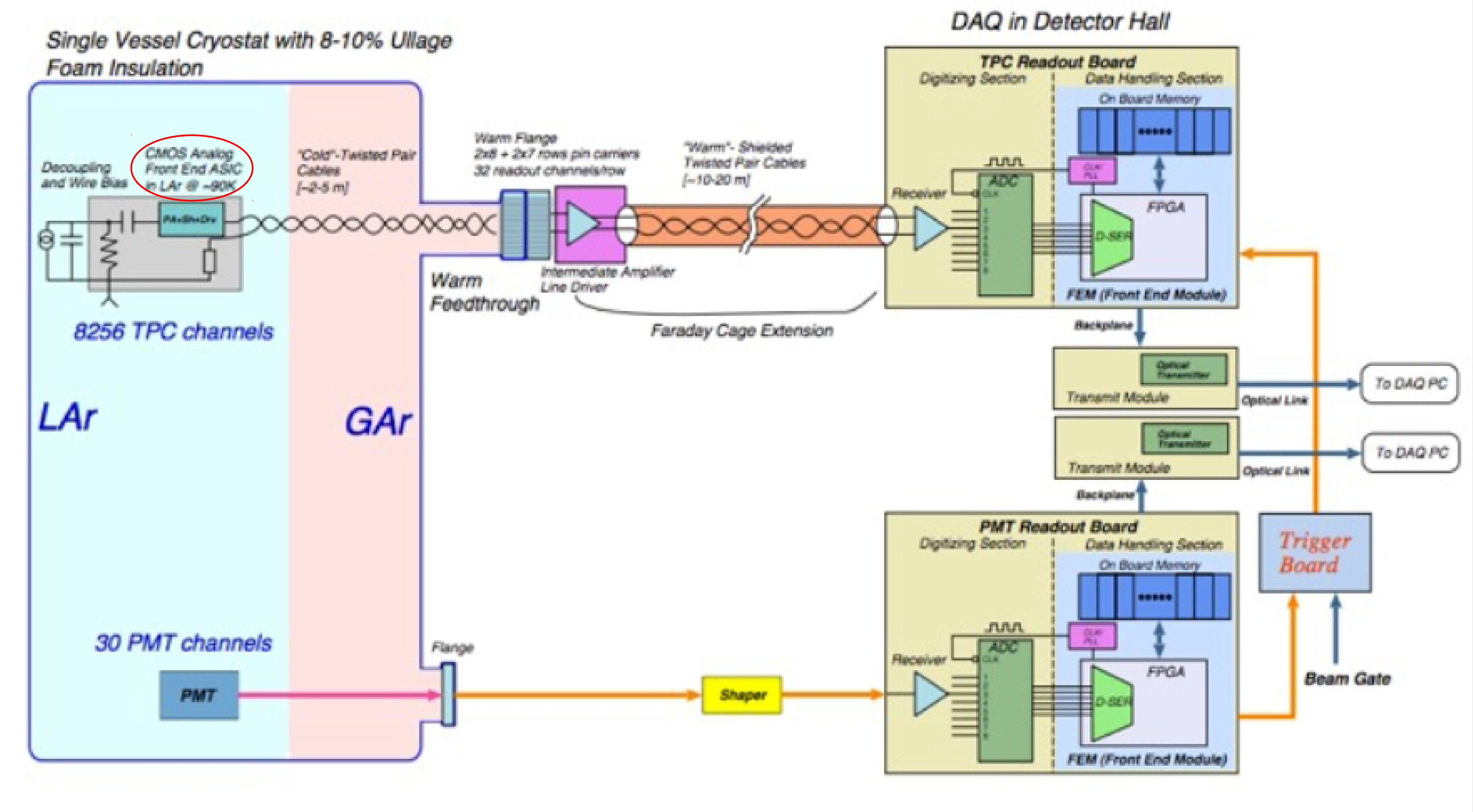
wire spacing

- 2 (or more) planes of parallel wires (2-4mm pitch) arranged with a gap of ~5mm in between
- inner wire plane (induction plane) is on ground
- prevent that the electrons are collected on the wires by positively biasing the outer wire plane
  → electrons pass the induction plane, inducing a bipolar current pulse (non-destructive readout)
  → 2nd signal on collection plane (unipolar signal, destructive readout)
- get 3D position in TPC from 2 parallel wires and time difference to trigger signal (scintillation light)
- typical signal for MIP: O(5000) e^{-}/wire ~O(1) fC
  → need sensitive pre-amplifier



R&D on alternative readout schemes ongoing (pads, LEMs, TGEMs)

MicroBooNE DAQ



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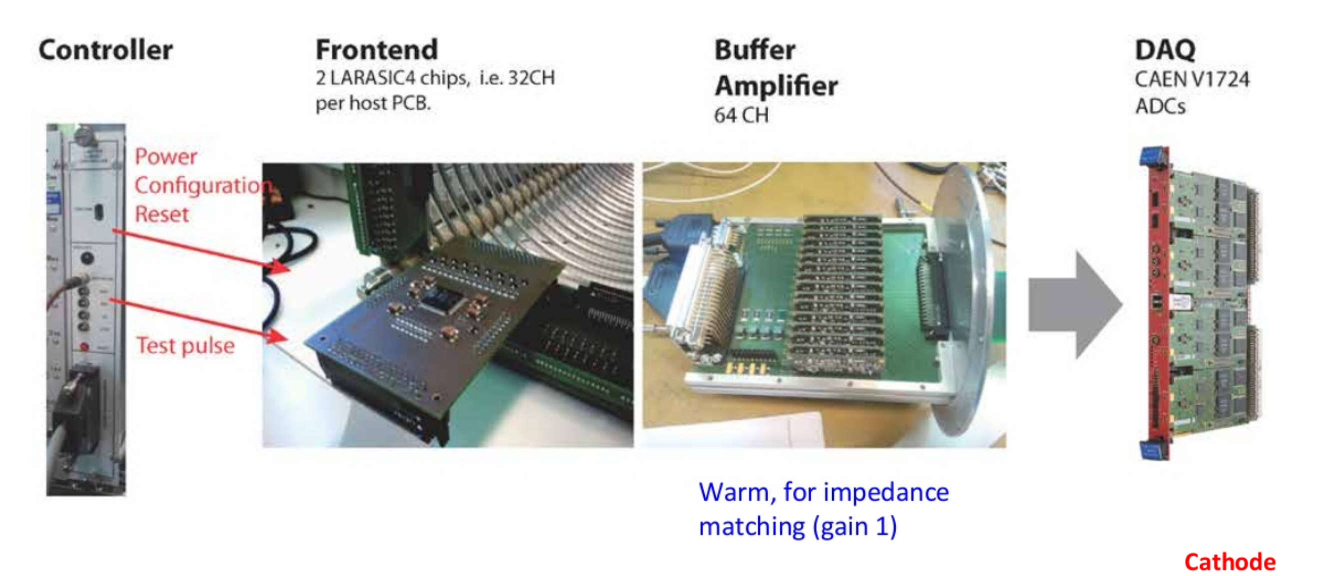
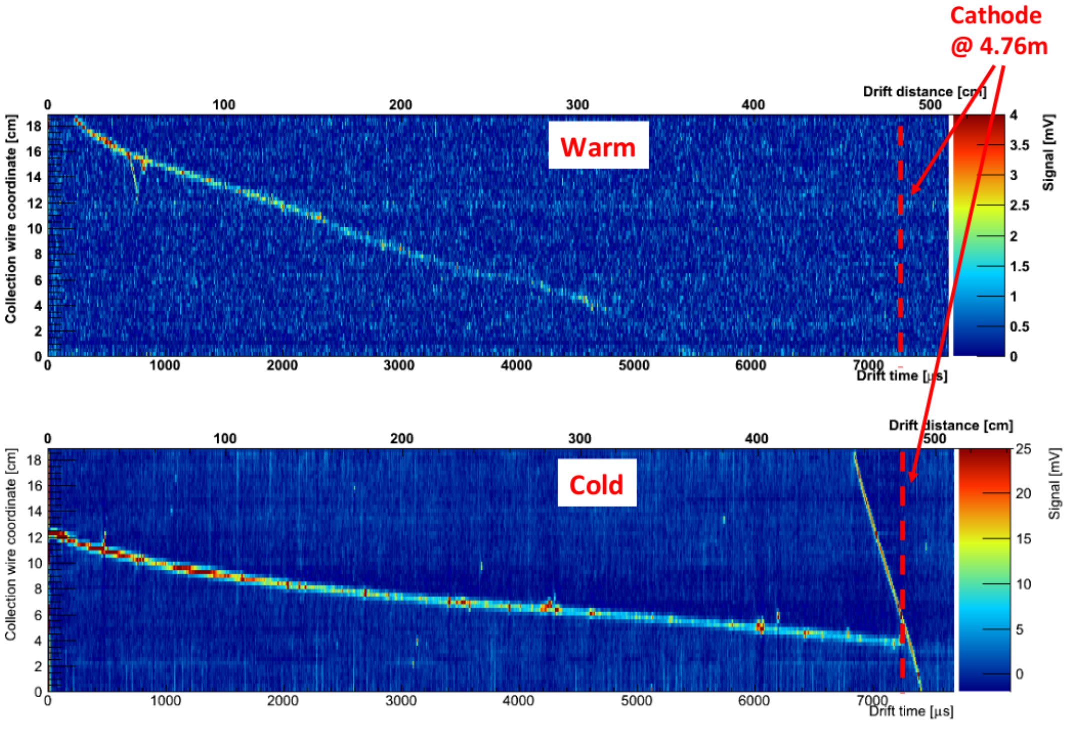
DAQ Test @ ARGONTUBE

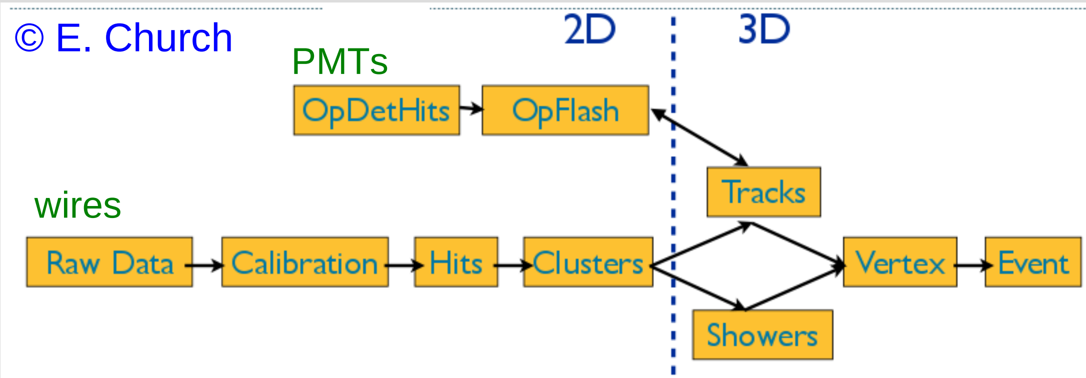
„The world's longest TPC"



Cold frontend electronics
LARASIC by BNL
→ cold at 87K,
→ configurable settings
J. Phys.: Conf. Ser. 308 012021
→ directly on wire planes
→ reduce thermal noise, capacitive noise and pickup



From 2D Images to 3D Tracks

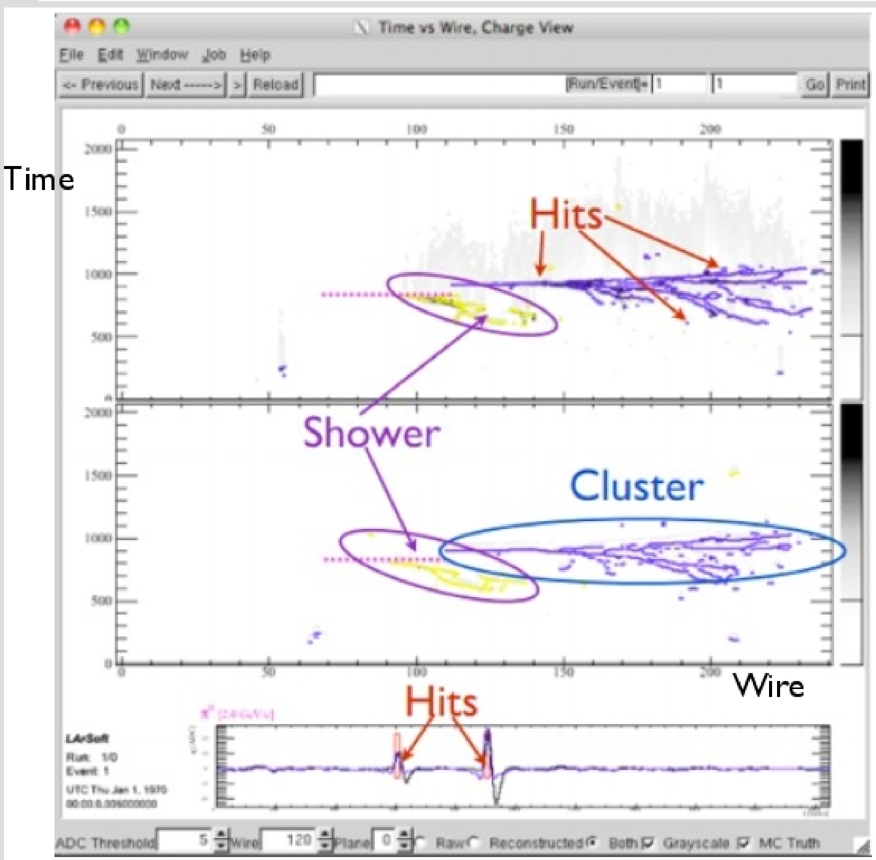


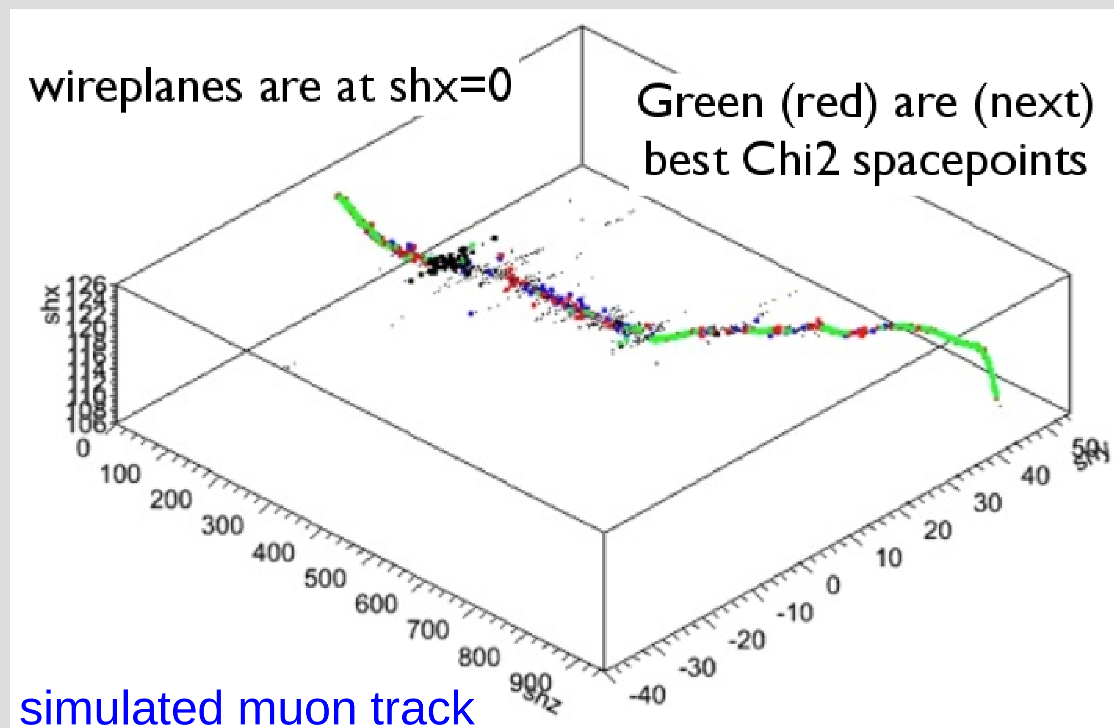
For track ID:

– HEP techniques such as Kalman Filters or Hough Transforms

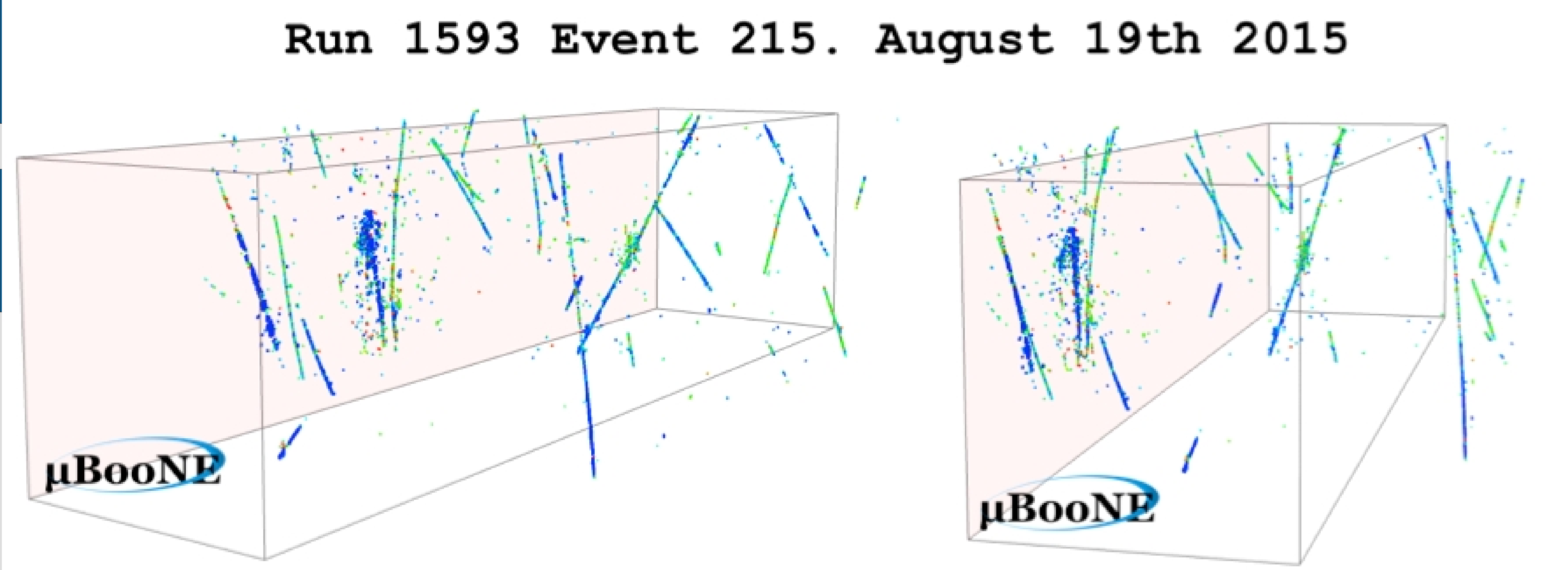
– also use „non traditional“ image processing techniques

→ use patter recognition algorithms (SVM, NN, etc.) to classify track topologies





MicroBooNE 3D tracks



Still work to do until LAr tracks can be reconstructed fast, reliably and automatically.

Main challenges:
– distorted tracks, missing pieces (at low E)
– overlapping events (pile-up, cosmics!)
– noise
– ...

The End

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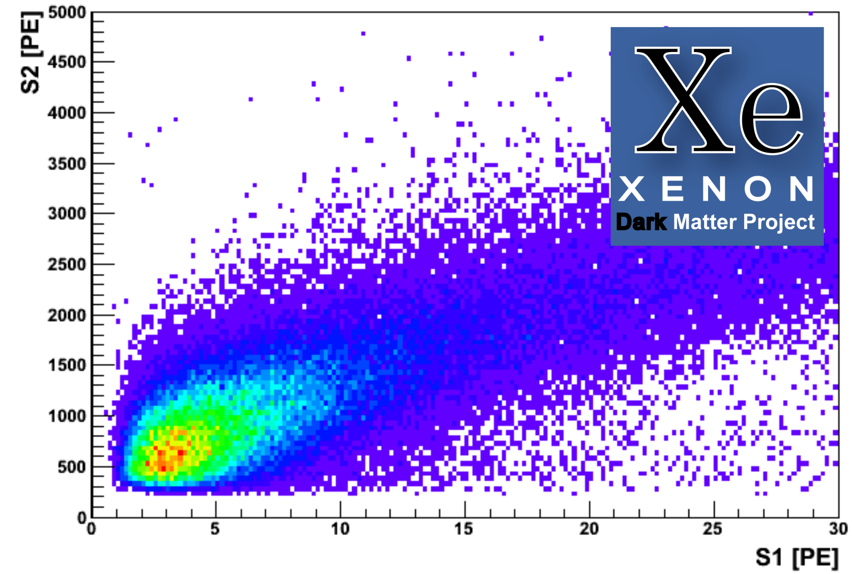
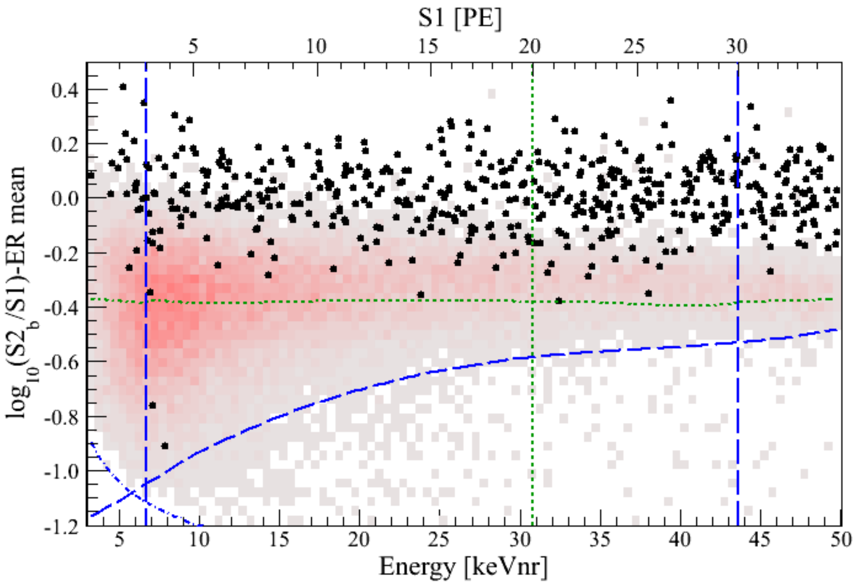
Liquid Xenon TPC: **Dark Matter**





Liquid Argon TPC: **Sterile Neutrinos**