Noble Liquid Detectors

SOUP 20|21

Cristiano Galbiati - June 29, 2021

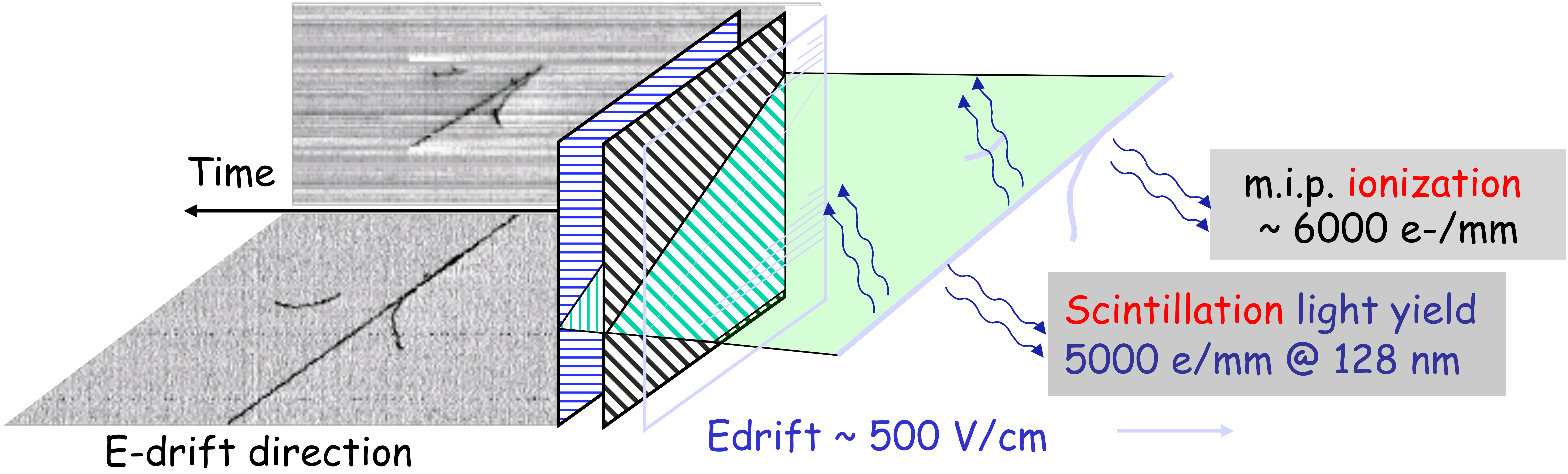
Noble Liquids: the Detection Channels

- Cold
- Can be purified
- Attachment probability for electrons essentially null
    - Can drift charge for very long distances
- Highest scintillation light yields
- Negligible self-absorption
    - Can extract very significant scintillation signal

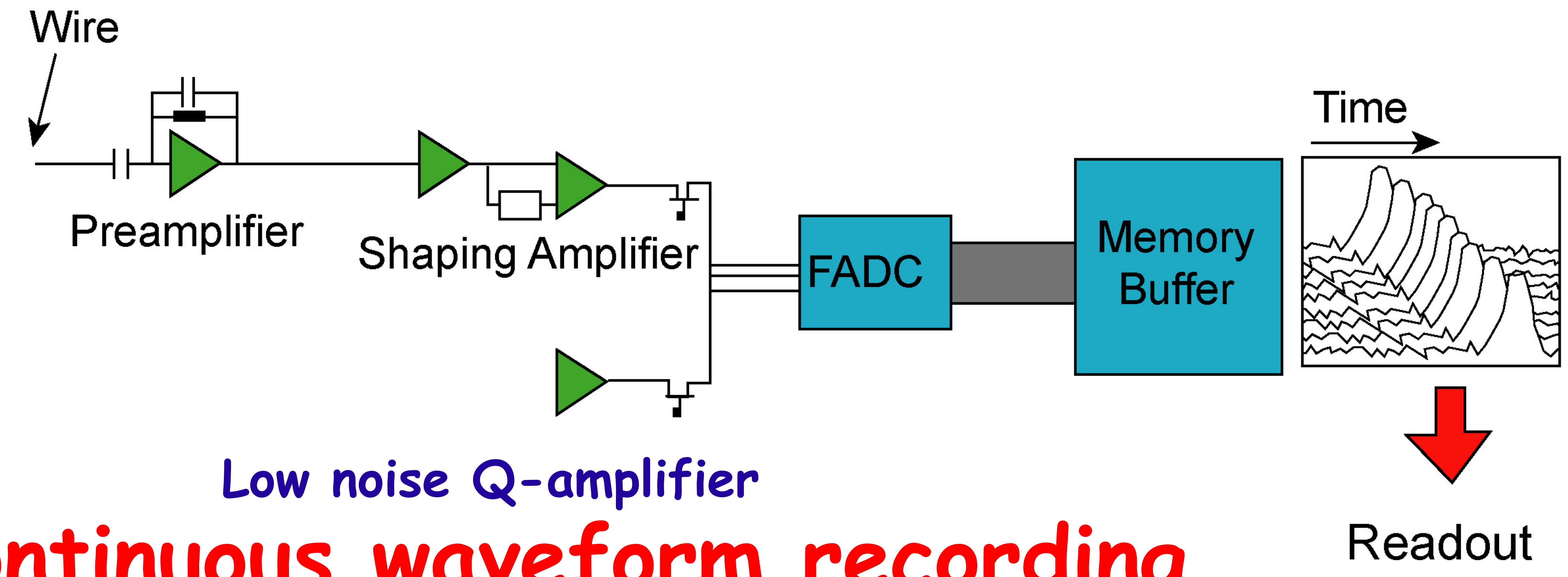
Noble Liquids: Partile Identification

- The two tools:
  - Direct measurement of dE/dx
  - Measurement of scintillation pulse shape which can be strongly influenced by dE/dX

A new, powerful detection technique initiated at CNGS



Drifting electrons are moving to transparent wire arrays oriented in different directions, where signals are recorded.

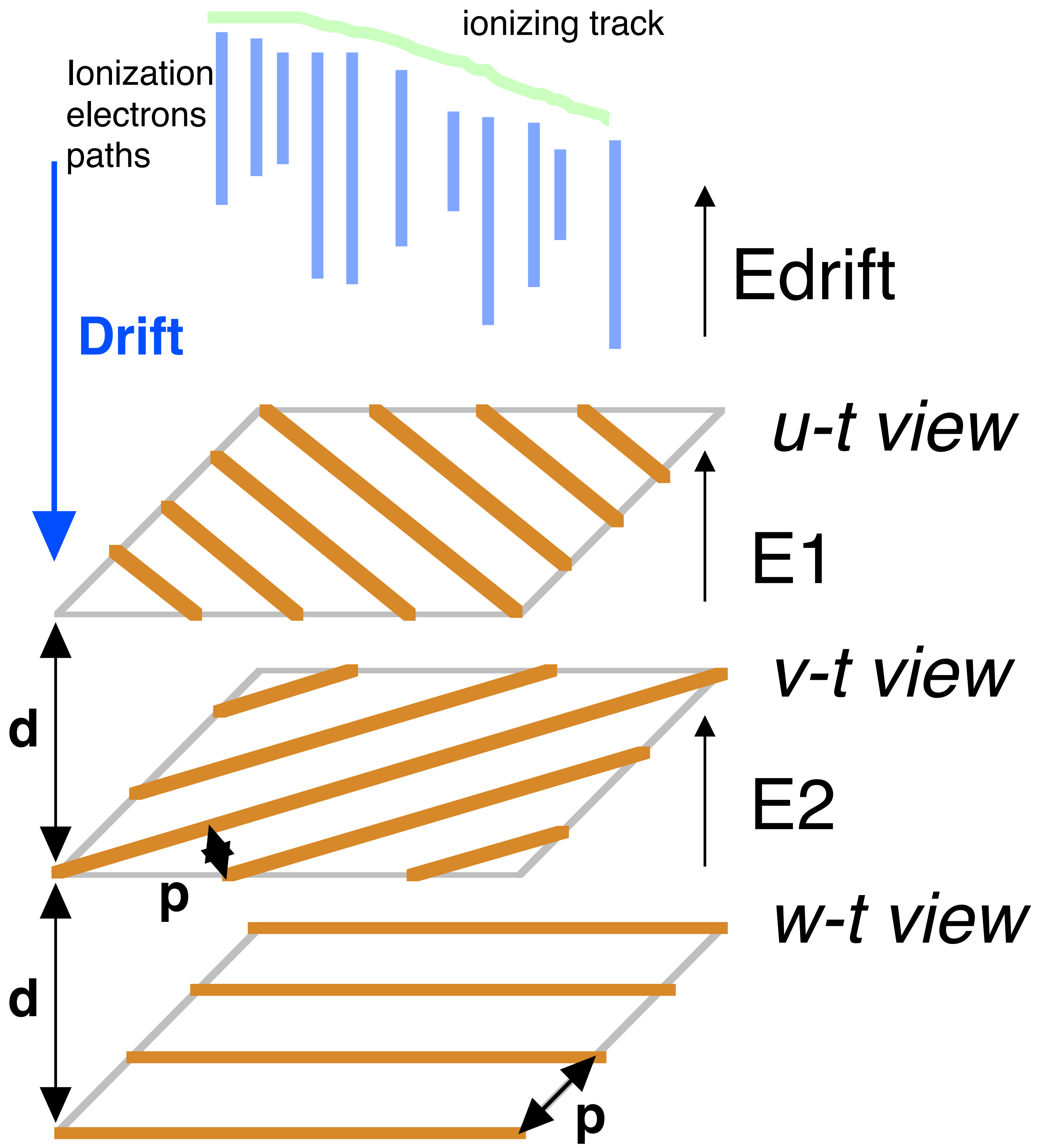


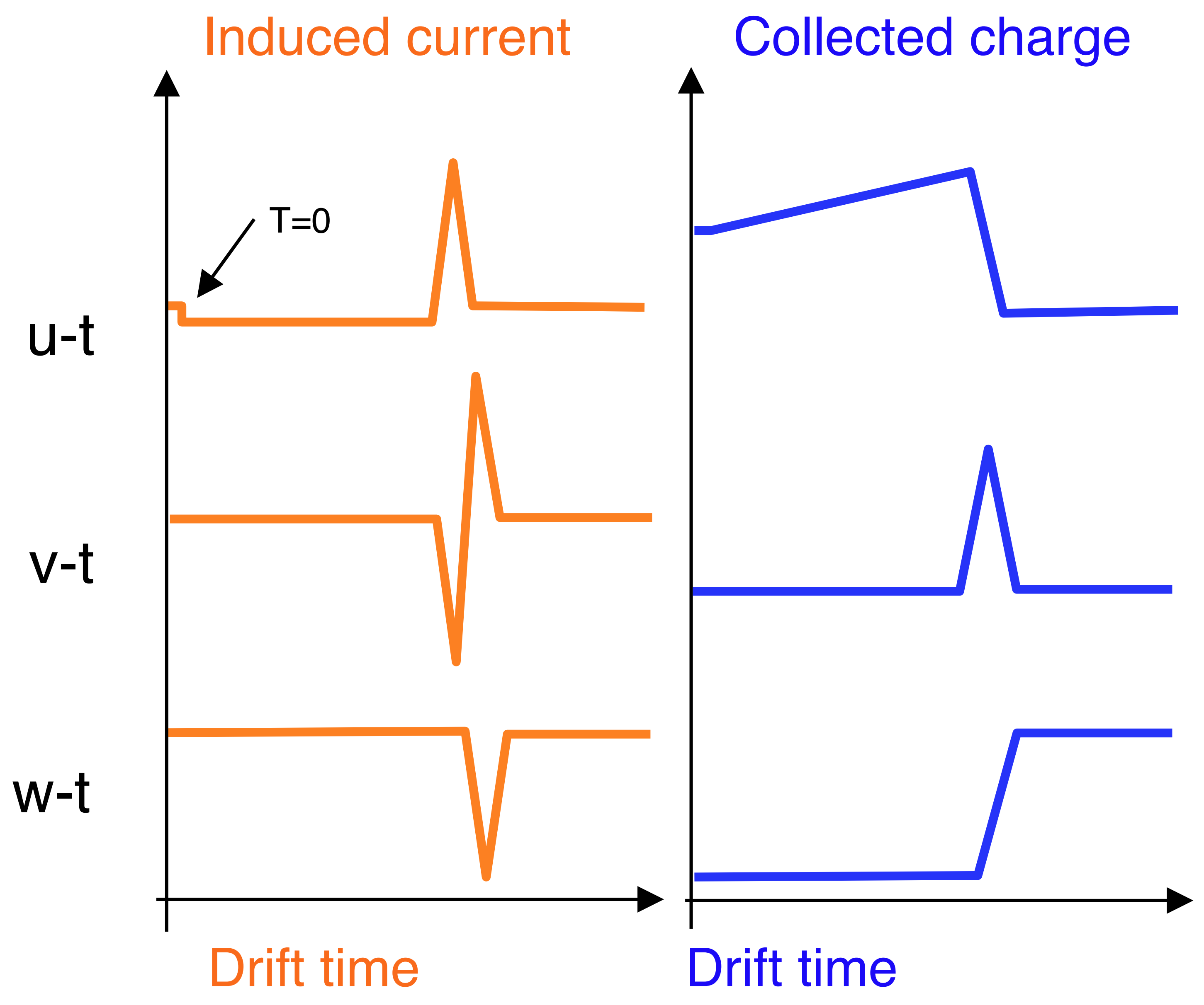
Continuous waveform recording

- High density
- Non-destructive readout
- Continuously sensitive
- Self-triggering
- Very good scintillator: T0

Slide# : 8

Non destructive, multiple charge readout



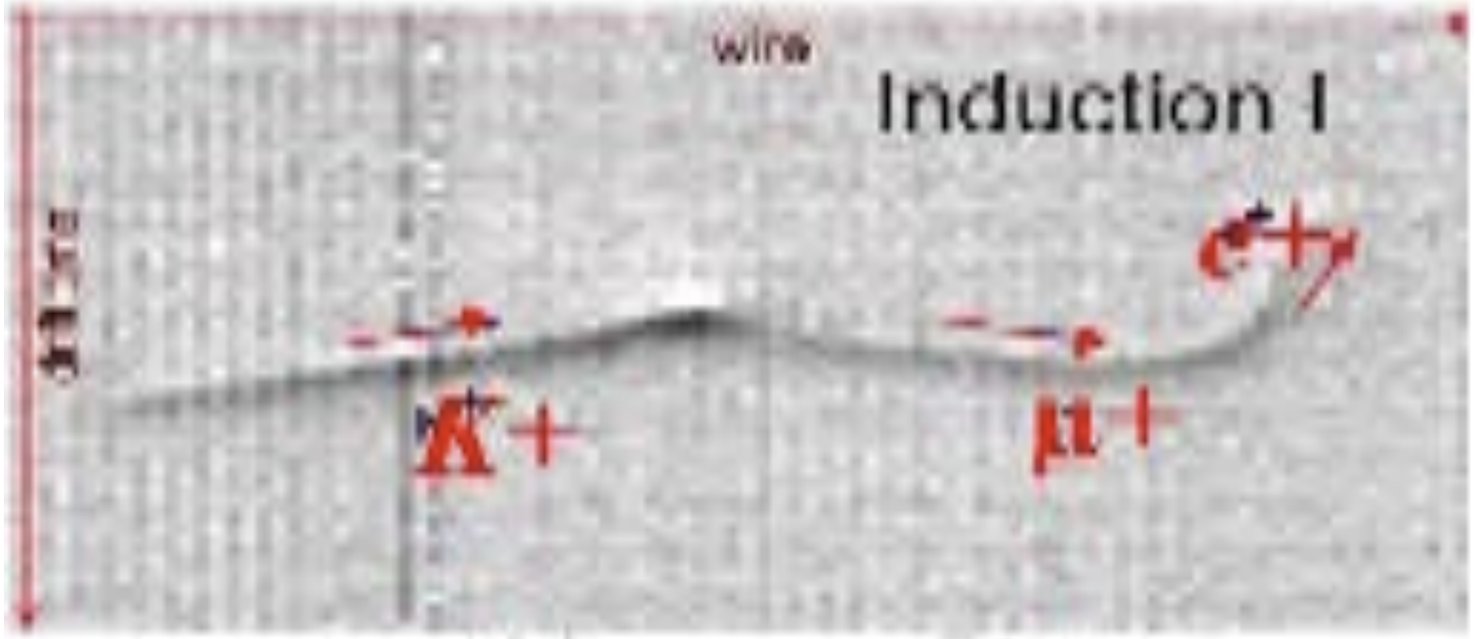


For the ICARUS T600

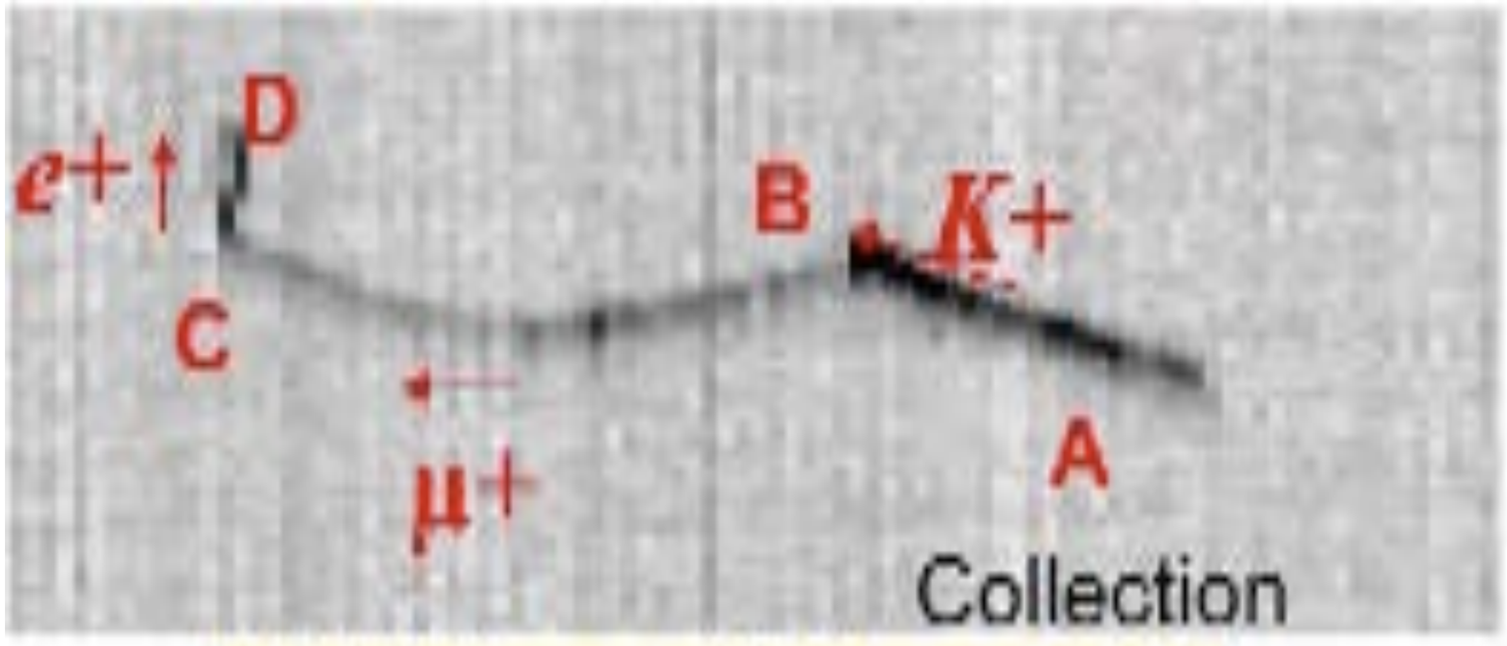
Edrift = 500 V/cm
p = 3 mm
d = 3 mm
r = 0.1mm

- At FNAL's shallow depth, the T600 will require two additions:
  - 3 m concrete overburden to mitigate the c. rays background,
  - Particles entering the detector must be removed with a Cosmic Rays Tagging (CRT) around the full LAr volume

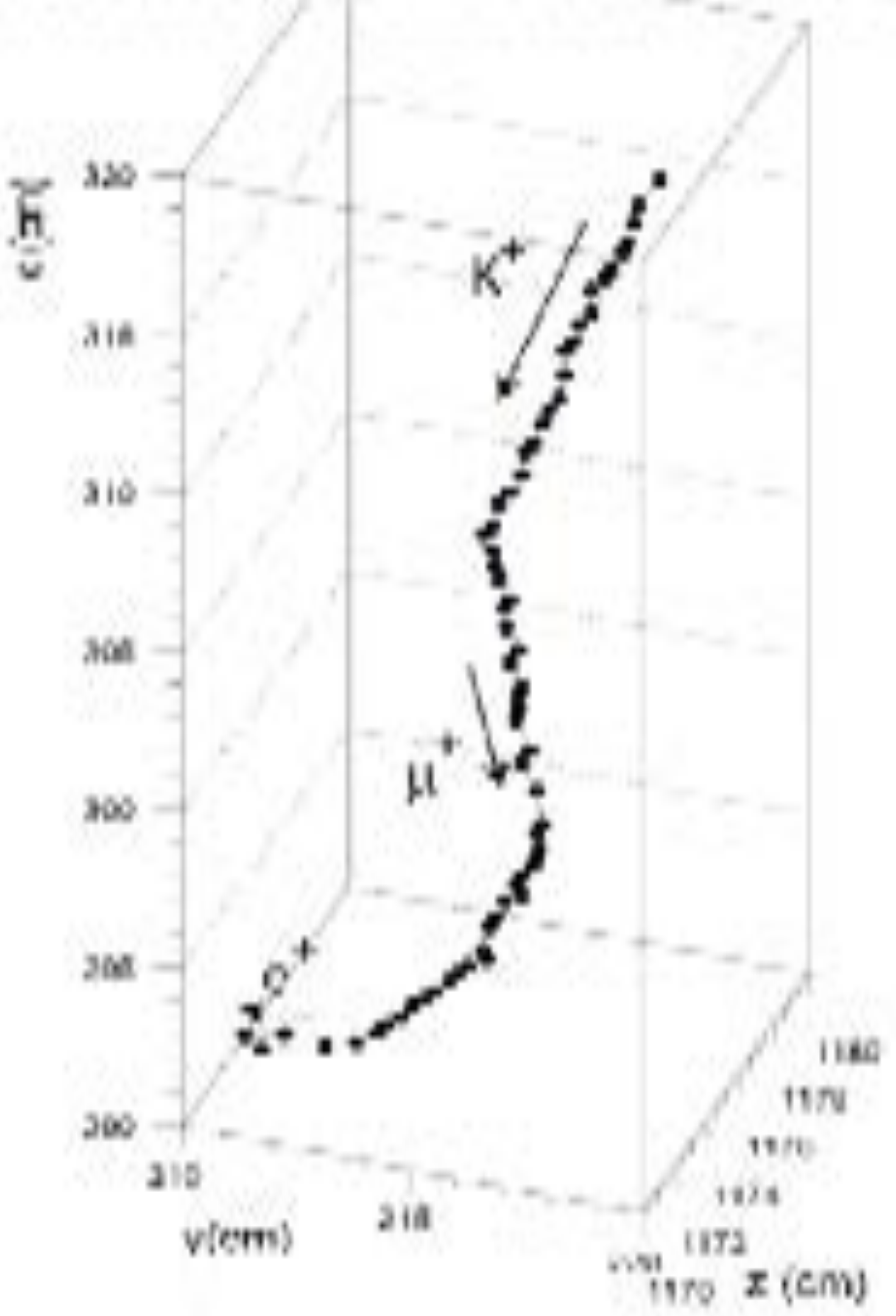
3 D particle Identification ($k^+ \to \mu^+ \to e^+$) at CNGS



ICARUS EVENT

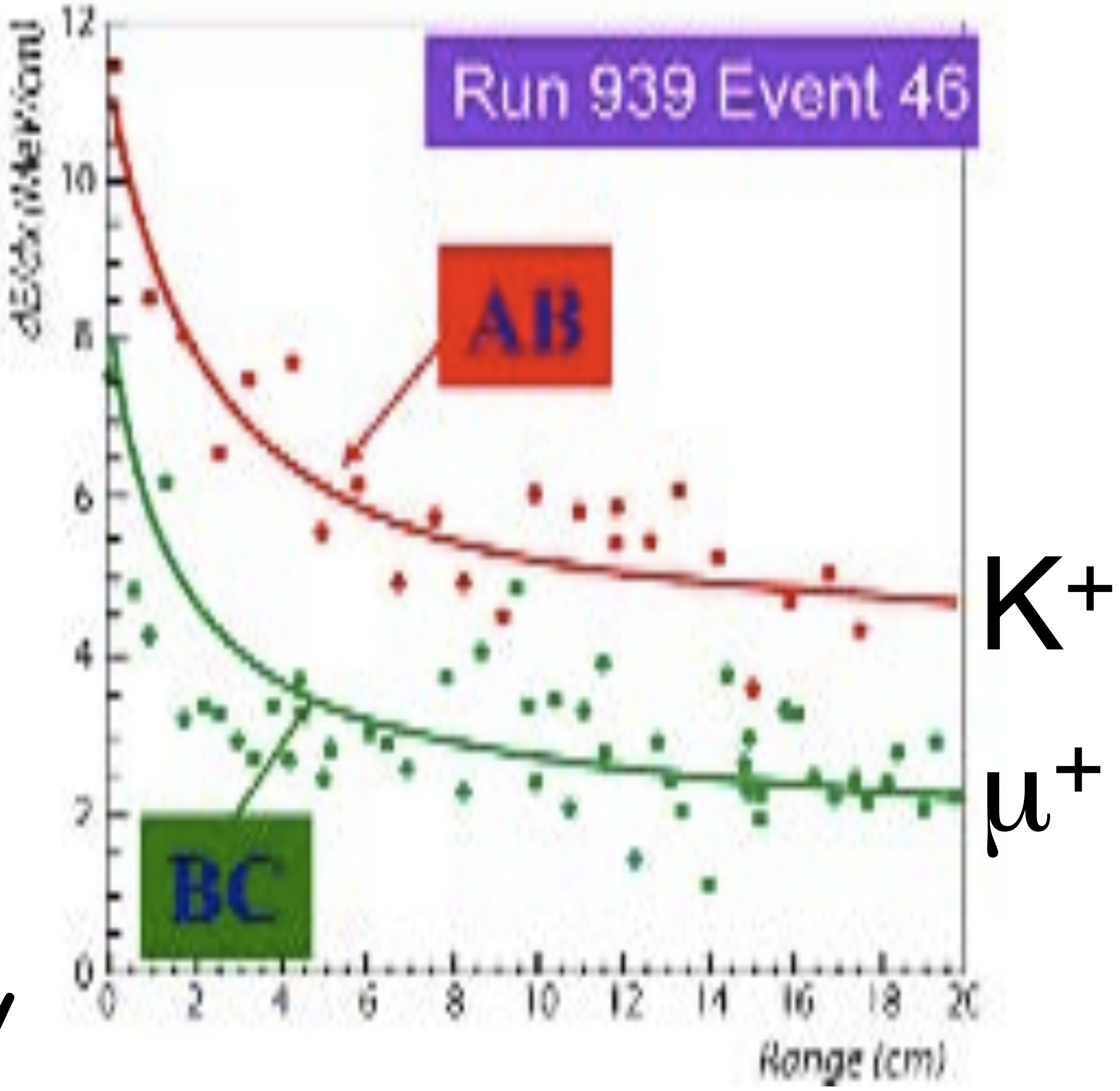


$K^+[AB] \to \mu^+[BC] \to e^+[CD]$



Efficient, low mis-identification, due to precise 3D reconstruction, dE/dx, range measurement

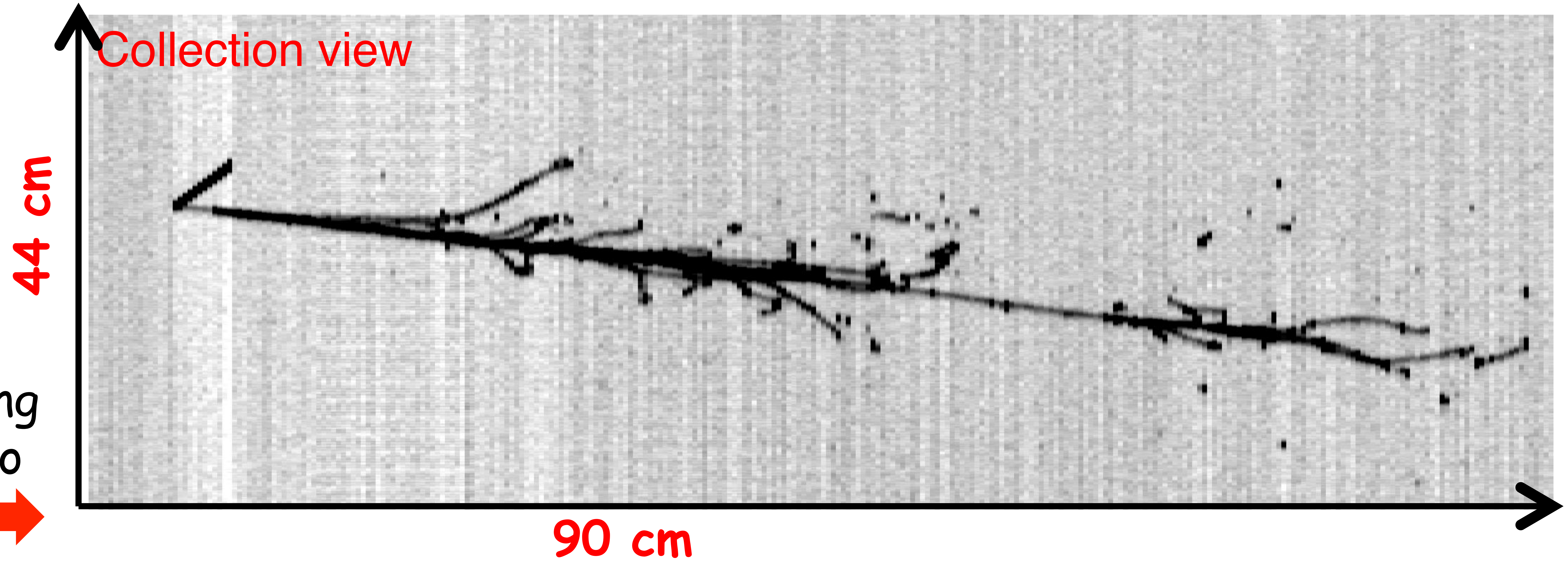
- stopping power
- recognition of secondary particle production after decay interaction



MC event Run 5 SubRun 44 Event 64

- A clear q.e. νe event: p + e.

Eν = 1.34 GeV   Edep = 1.29 GeV



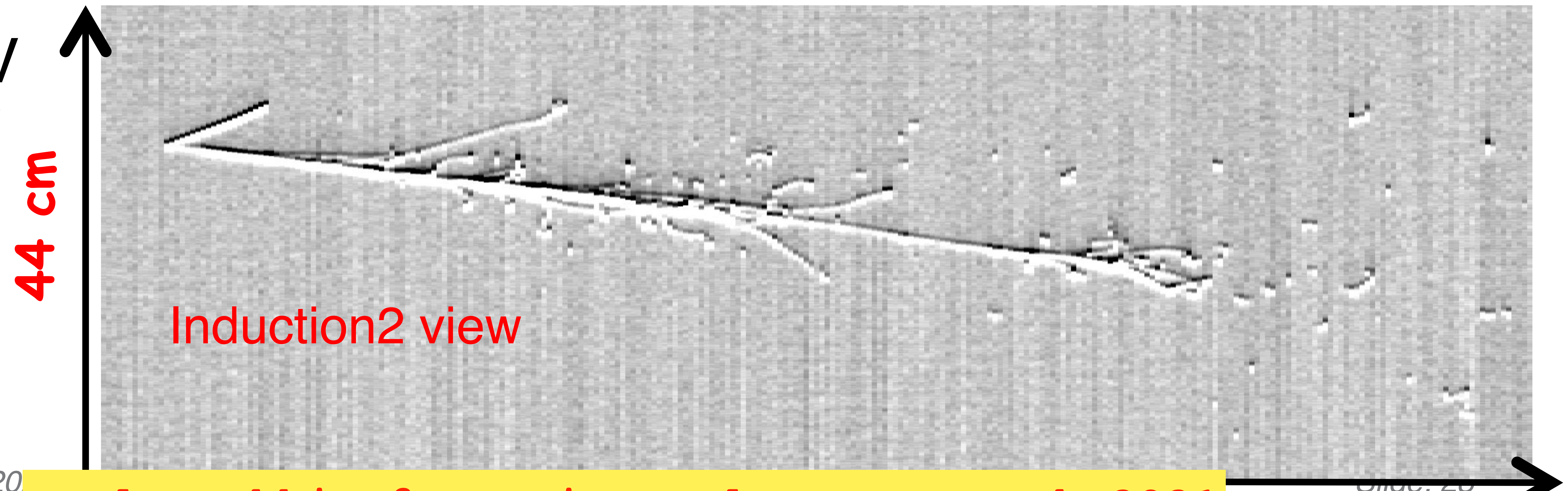
Incoming neutrino

E_e = 1.21GeV

T_p = 93 MeV

R_p = 7cm

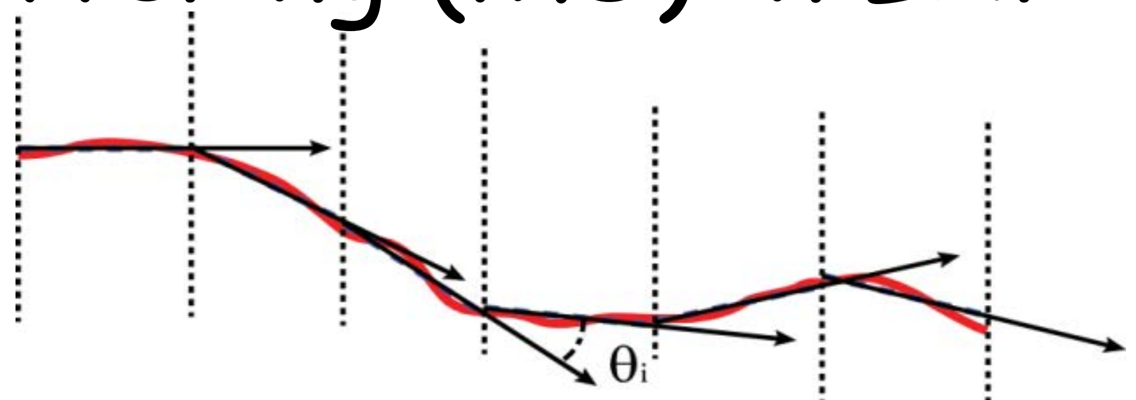
T_p/R_p = 13.2 MeV/cm



Measurement of muon momentum via multiple scattering

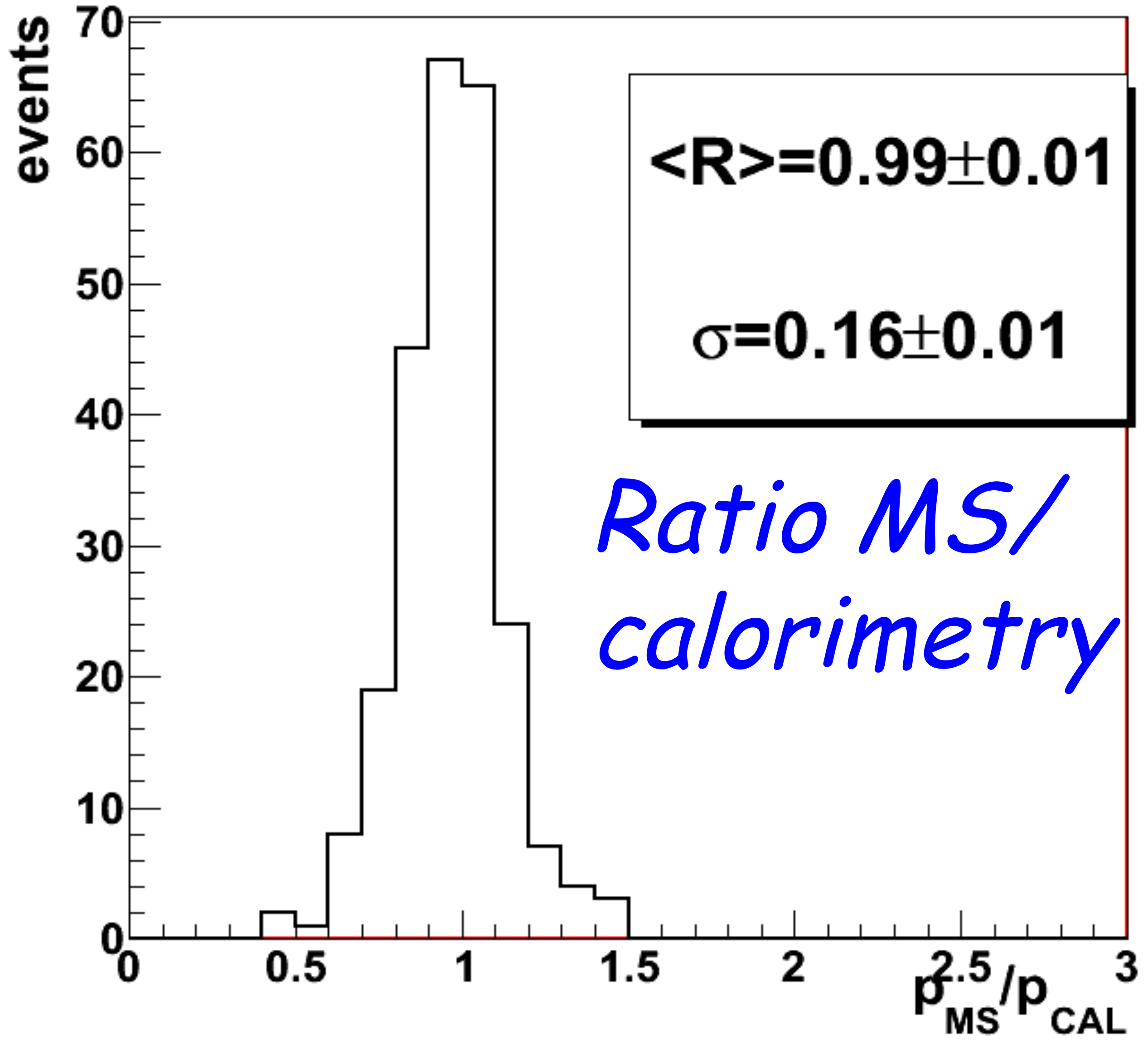
In absence of a magnetic field, the initial m momentum may be determinec through the reconstruction of multiple Coulomb Scattering (MS) in LAr

RMS of θ deflection of μ depends on p, spatial resolution σ and track segmentation

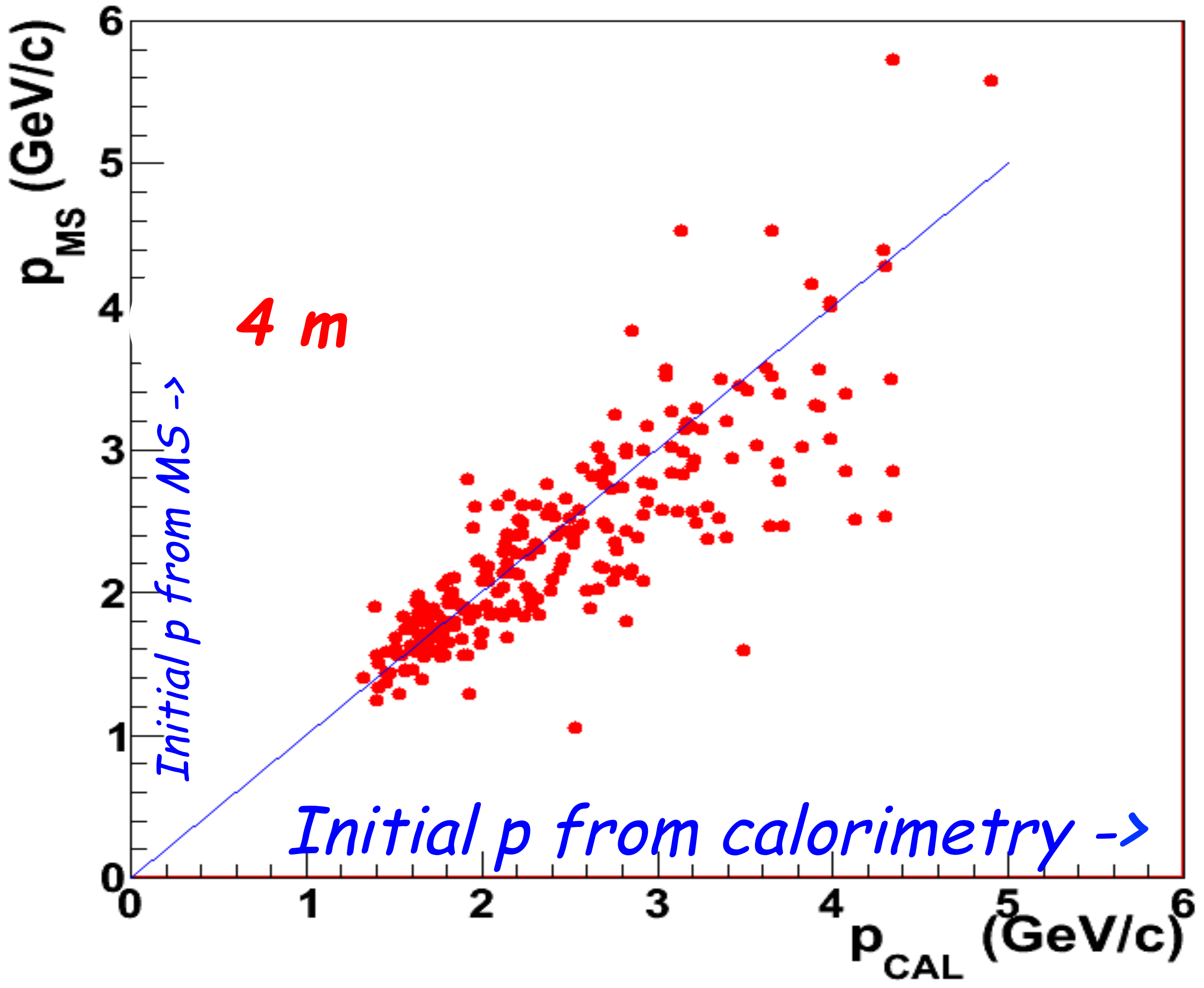


$$\theta_{RMS} \div \frac{13.6MeV}{p}\sqrt{\frac{l}{X_0}} \oplus \frac{\sigma}{l^{3/2}}$$

Method tested on ~103 stopping μ's from CNGS ν interactions in upstream rock, comparing PMS measured by MS with the corresponding calorimetric PCAL



μ track length: > 5m
Used length: 4m



~16% resolution has been obtained in the 0.4-4 GeV /c momentum range of interest for the future short/long base-line experiments

Neutrino related anomalies ?

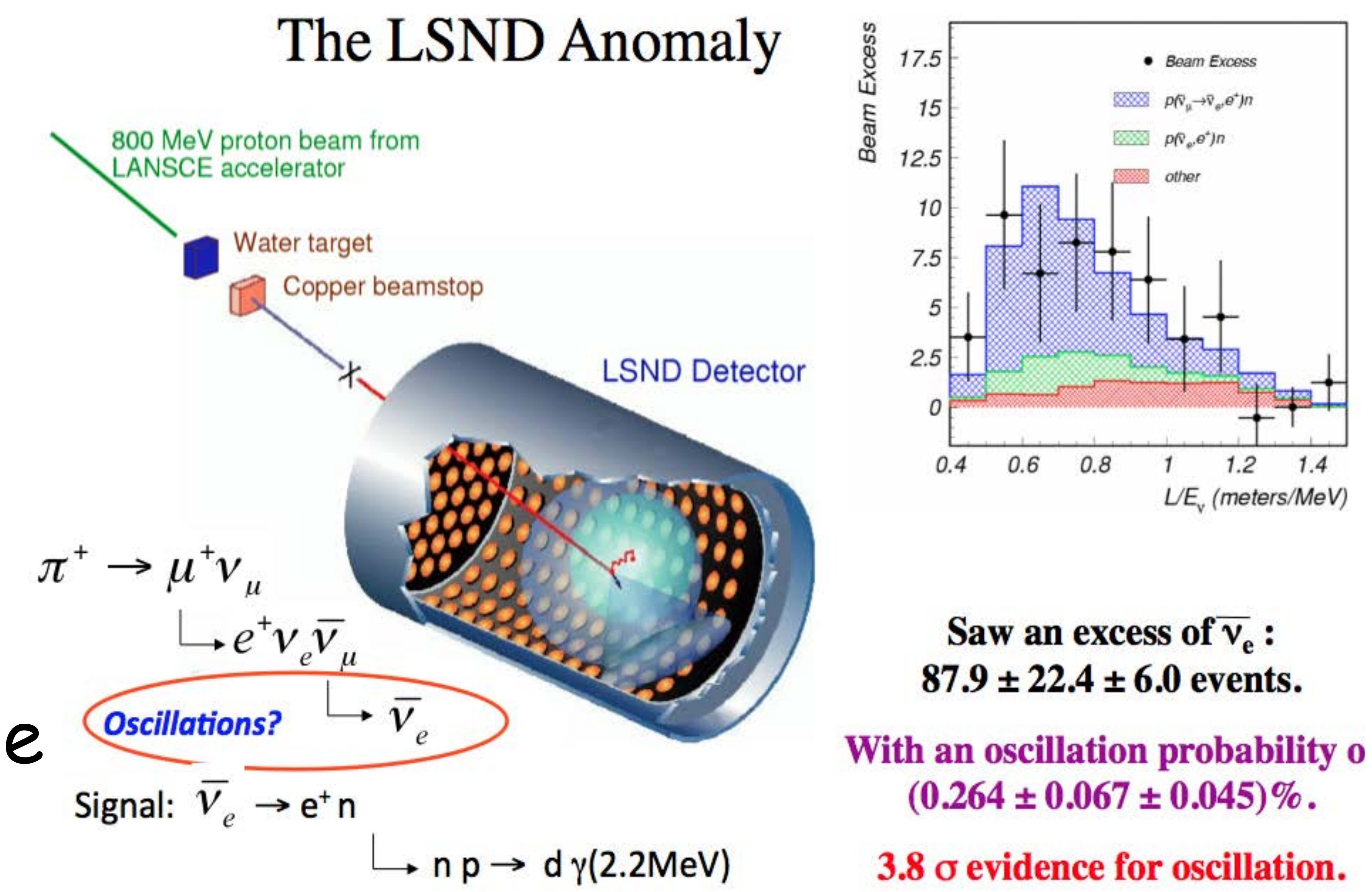
- Several anomalies have been collected for two decades in the neutrino sector suggesting the existence of some additional new related states beyond an ordinary 3-flavour mixing picture

➢ anti−νe appearance in the accelerator LSND experiment; Reaction is anti ν-e to e++n with n captured by a p; n + p into d + γ.

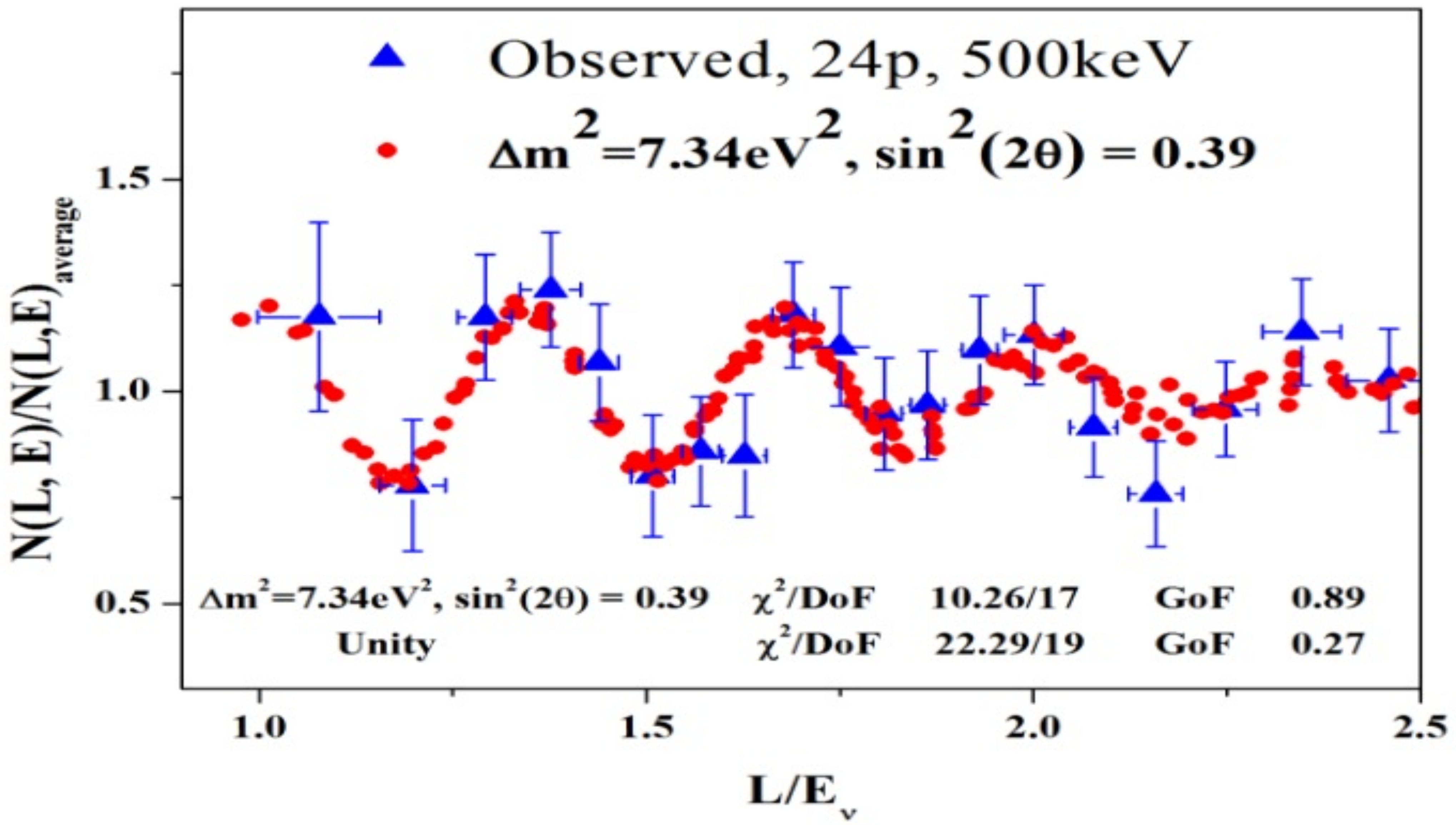
➢ νe disappearance: SAGE, GALLEX experiments with Mega-Curie sources and observed/predicted rate R = 0.84±0.05;

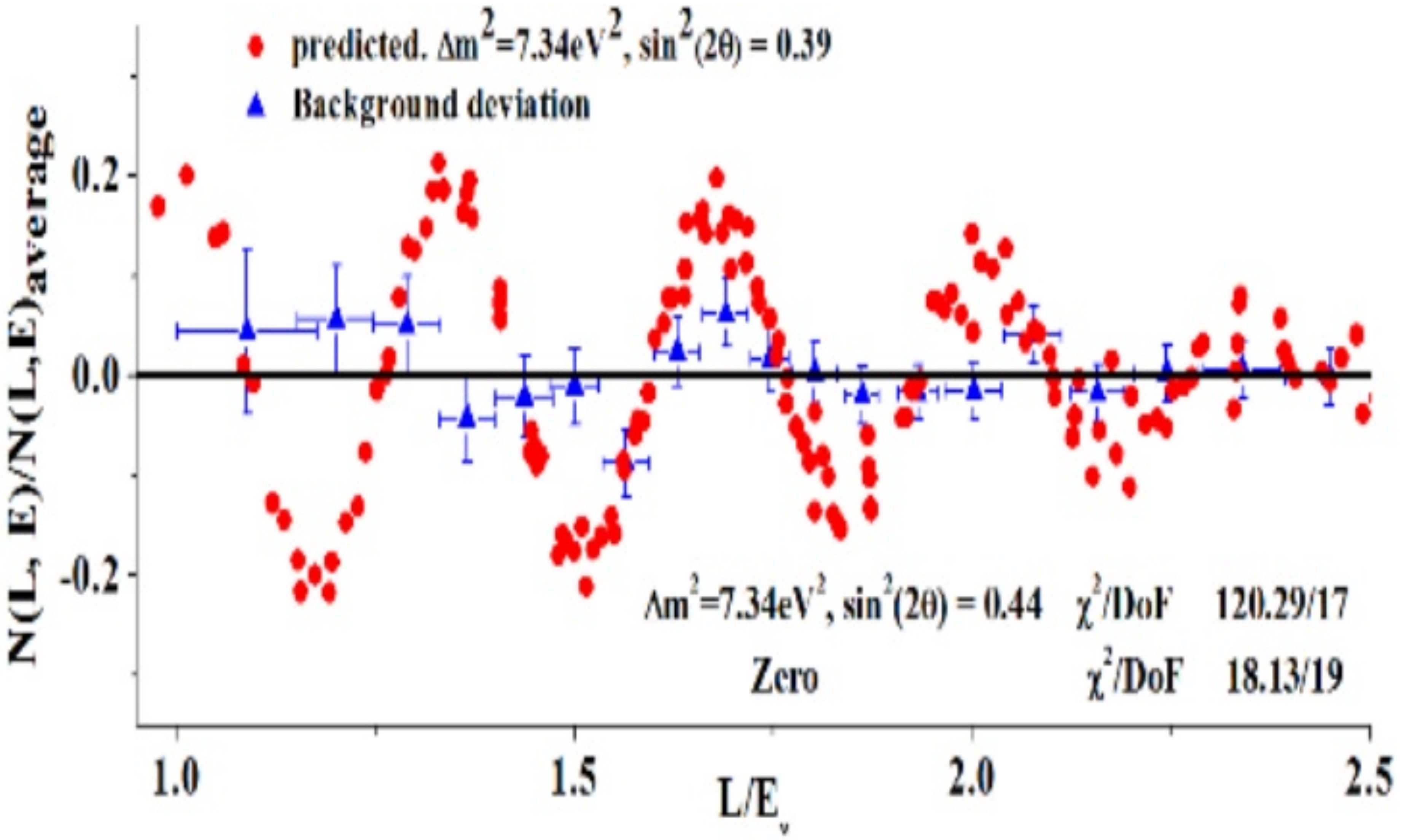
➢ anti-νe disappearance of near-by nuclear Reactor experiments and rate R = 0.934±0.024

➢ recent observation of sterile neutrino oscillations by the NEUTRINO-4 experiment



NEUTRINO-4 reactor signal

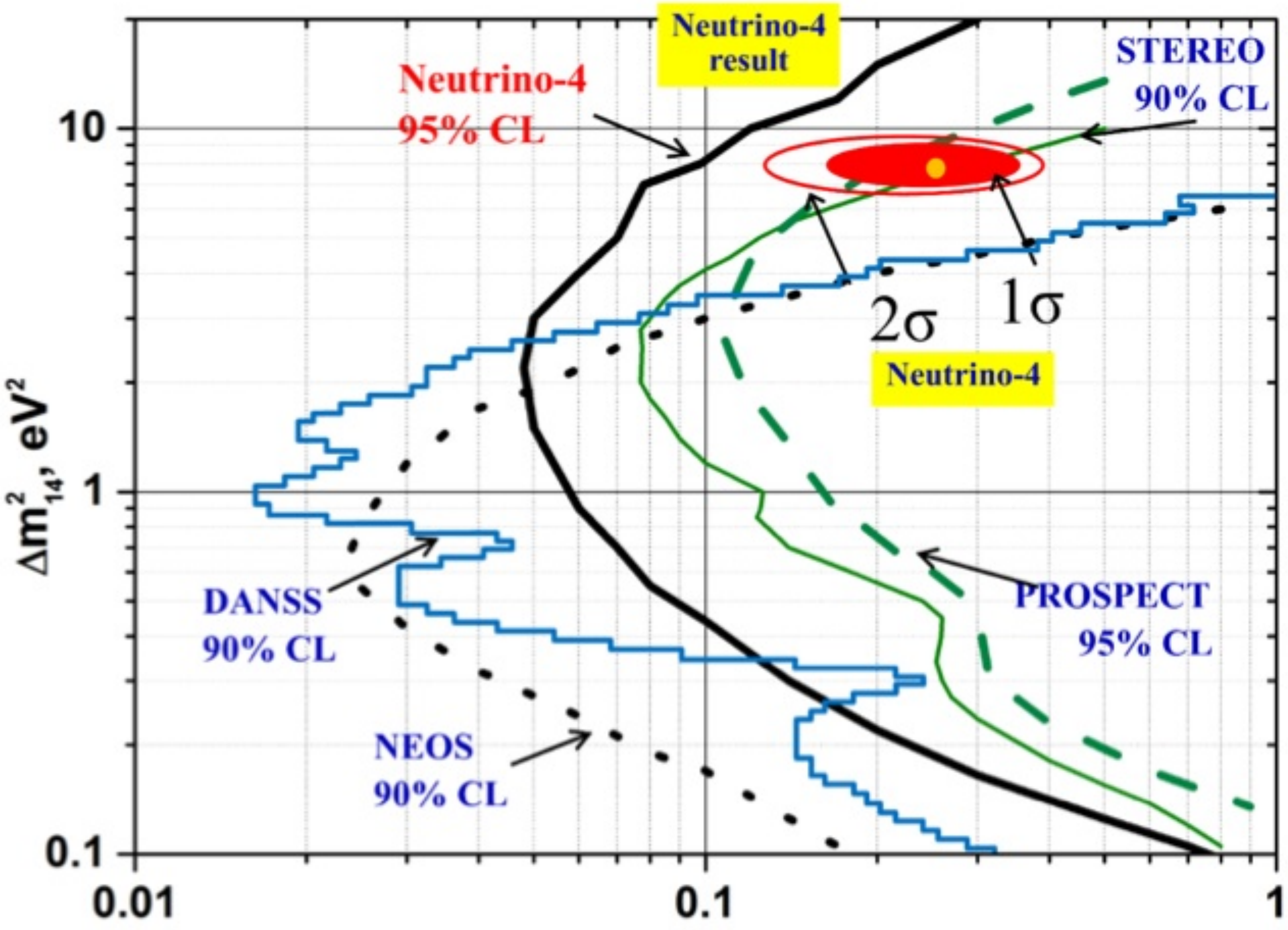




- Data has been collected for 3 years until June 2019, followed by background measurements until January 2020: 720 days reactor "on" and 417 days reactor "off", with 87 reactor cycles.
- The difference ON-OFF is 223 events per day in the range from 6.5 to 9 meters. The signal/background ratio is 0.54.
- The obtained value of the difference between the masses of the electron and sterile neutrinos is Δm_{14}^2 = 7.26 ± 0.13 stat ± 1.08 syst => 7.25 ± 1.09 eV^2 and the angle θ_{14} parameter $\sin^2(2\theta_{14})$ = 0.26 ± 0.08 stat ± 0.05 syst => 0.26 ± 0.09. Lower probability satellite peaks are also observed at other masses.

Summary

- Comparison of results of the NEUTRINO-4 and experiments STEREO and PROSPECT



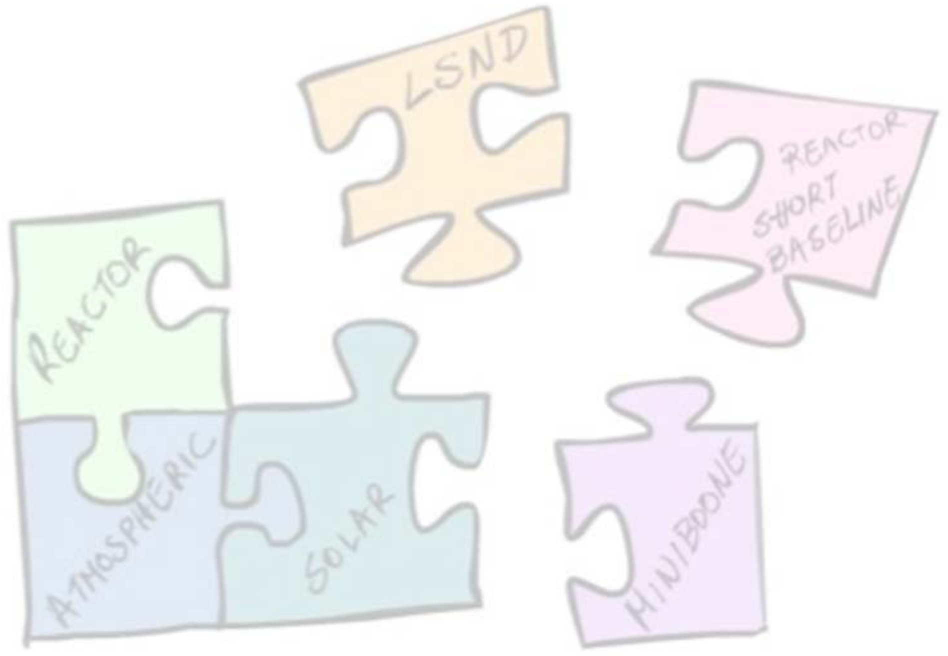
Carlo Rubbia @Neutrino Telescopes, Feb 2021

The puzzling picture of short baseline ν oscillations

Three independent classes of anomalous experimental results in the last 20 years, not fitting into the “standard” landscape of 3-flavour ν mixing:

- disappearance of anti-ν_e detected from near-by nuclear reactors;
- disappearance of ν_e from intense calibration sources in solar ν experiments;
- appearance of $\nu_e/\bar{\nu}_e$ in $\nu_\mu/\bar{\nu}_\mu$ beams at particle accelerators.

Experiment	Type	Channel	Significance
LSND	DAR accelerator	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	3.8 σ
MiniBooNE	SBL accelerator	$\nu_\mu \rightarrow \nu_e$	4.5 σ
		$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	2.8 σ
GALLEX/SAGE	Source – e capture	ν_e disappearance	2.8 σ
Reactors	β decay	$\bar{\nu}_e$ disappearance	3.0 σ

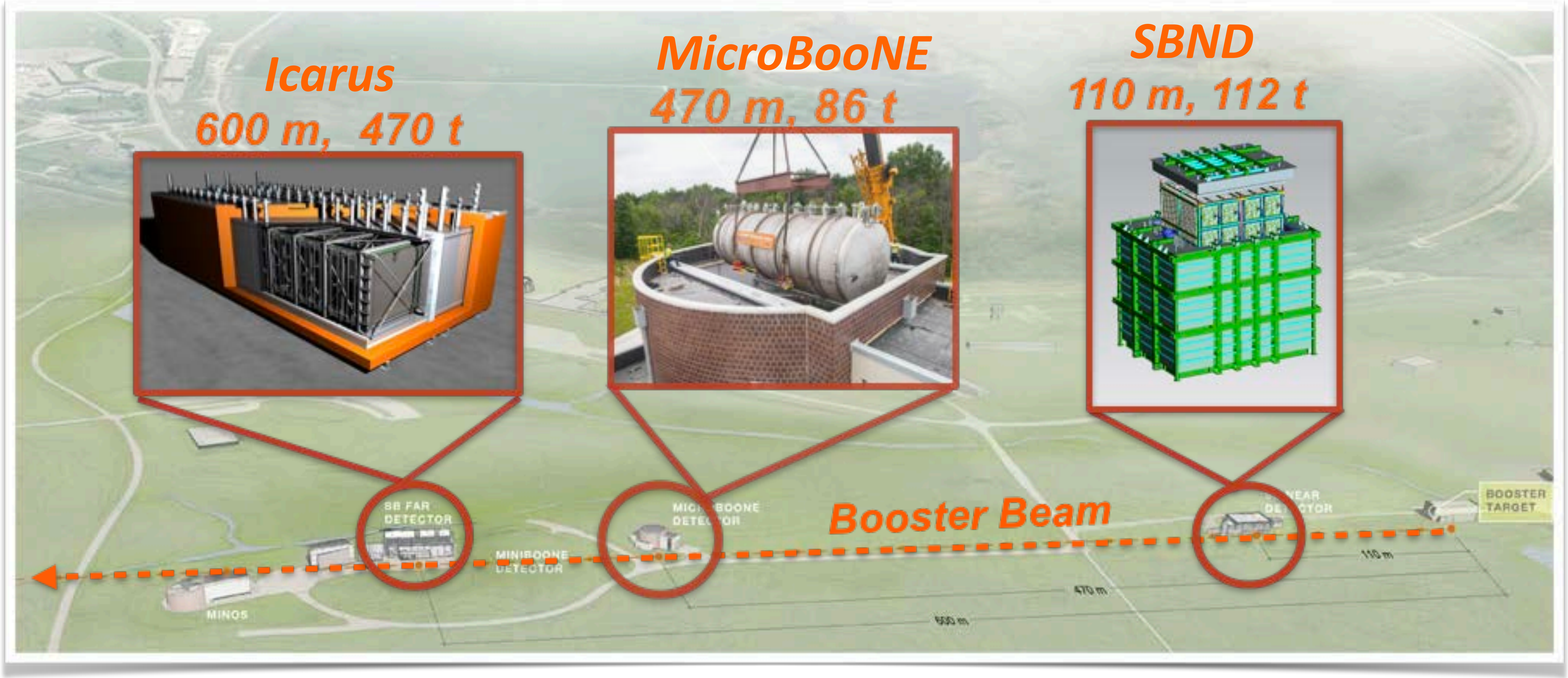


Each possibly explained by nonstandard “sterile” neutrino state(s) driving oscillations at $\Delta m^2_{new} \approx 1$ eV^2 and relatively small $\sin^2(2\vartheta_{new})$, but no model so far successful in fitting all experimental results at once.

Short Baseline Neutrino Program at Fermilab

Program aimed at definitely solving the "sterile neutrino puzzle" by exploiting:

- the well characterized FNAL Booster ν beamline;
- three detectors based on the same liquid argon TPC technique.

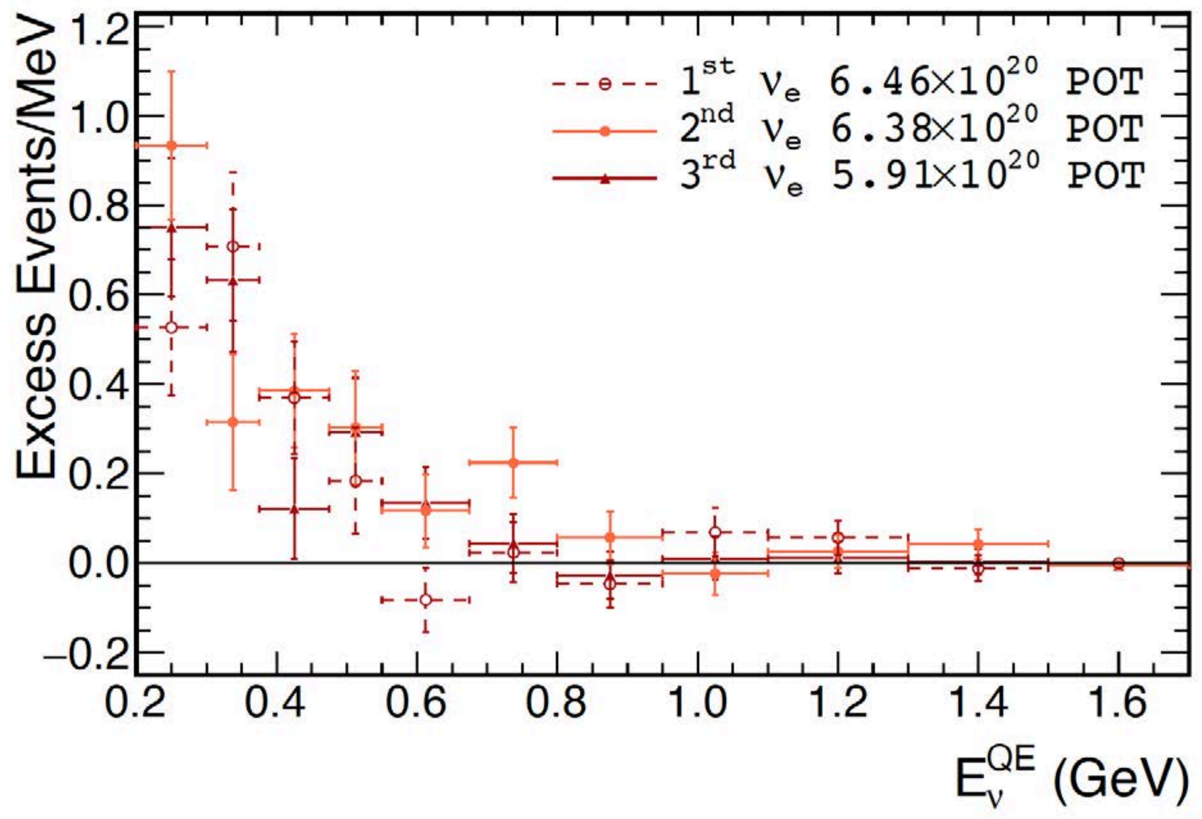


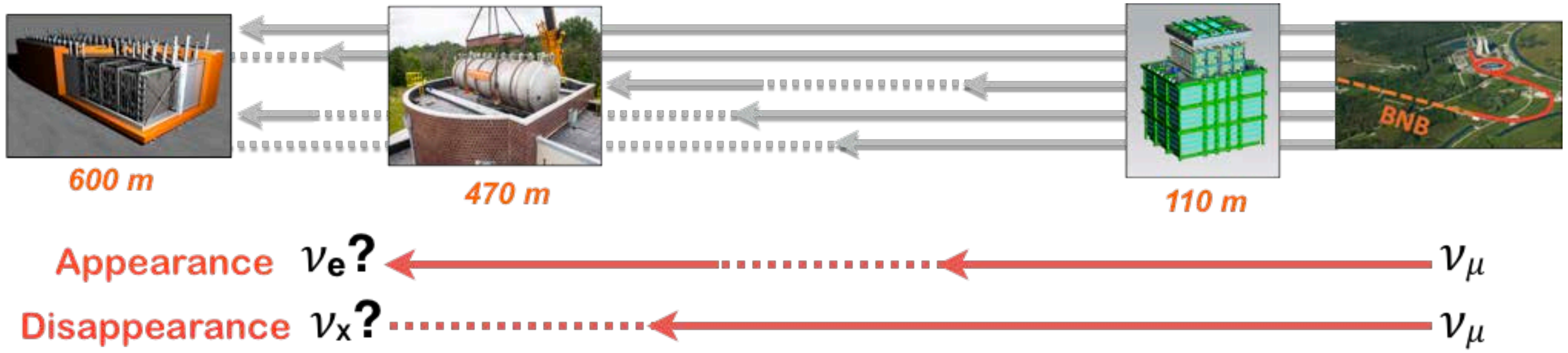
SBN goals

- **MicroBooNE**
  Understand the nature of the MiniBooNE "low energy" excess anomaly, using the same beam.

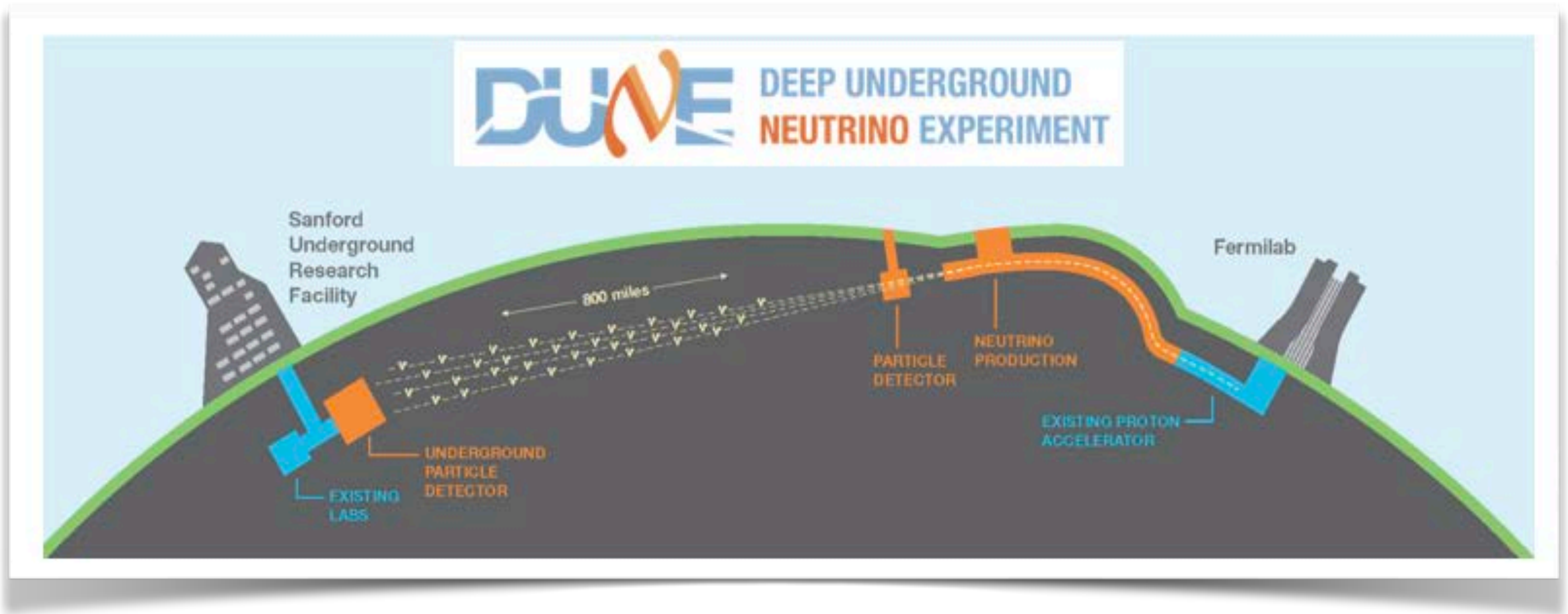
- **SBND + ICARUS**
  Search for short baseline oscillations both in appearance and disappearance channels.

arXiv: 2006.16883

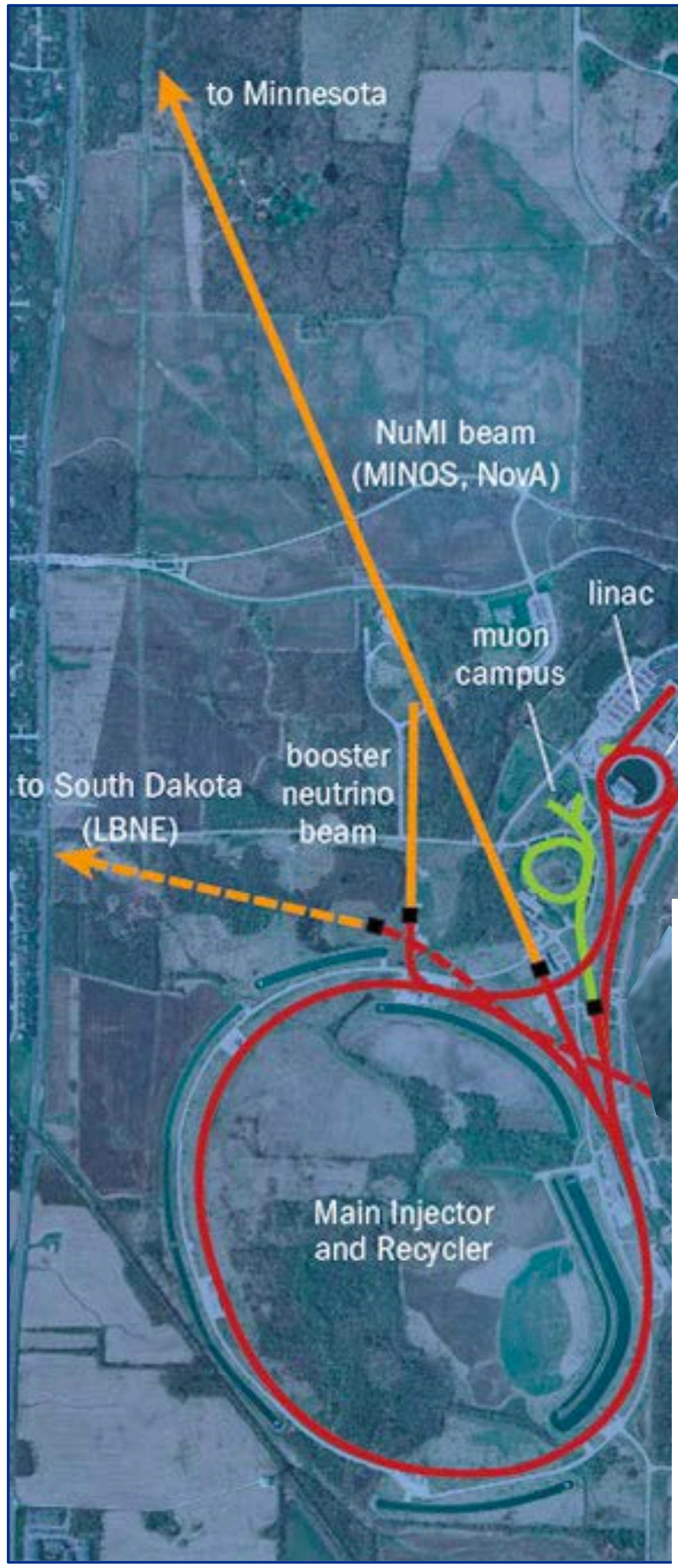


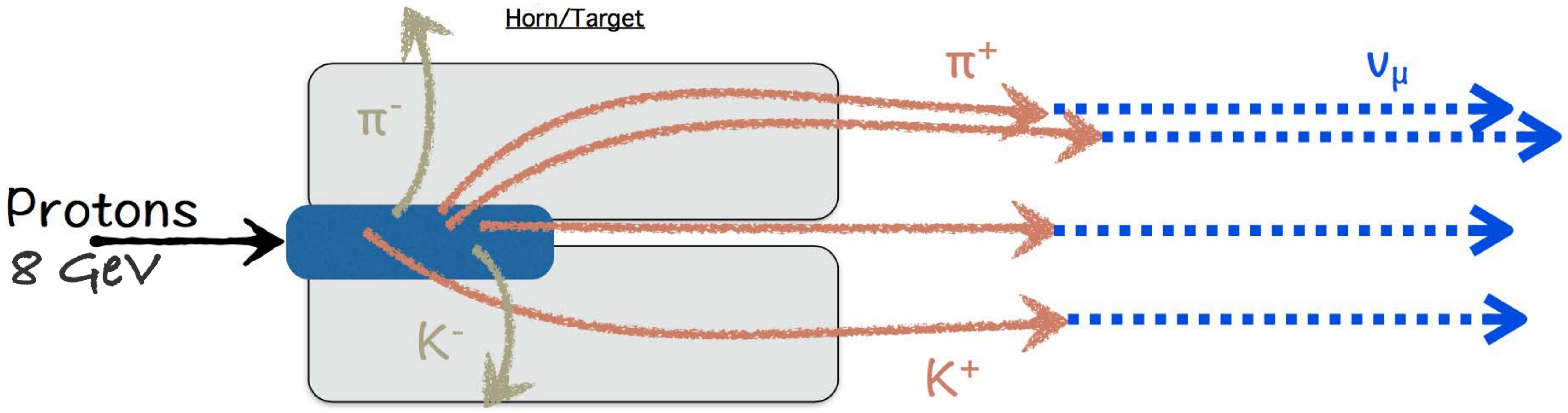


- Lay the ground for future long baseline program
  - Further develop LAr-TPC detector technology & software
  - Measure ν-Ar cross sections at energies relevant to DUNE



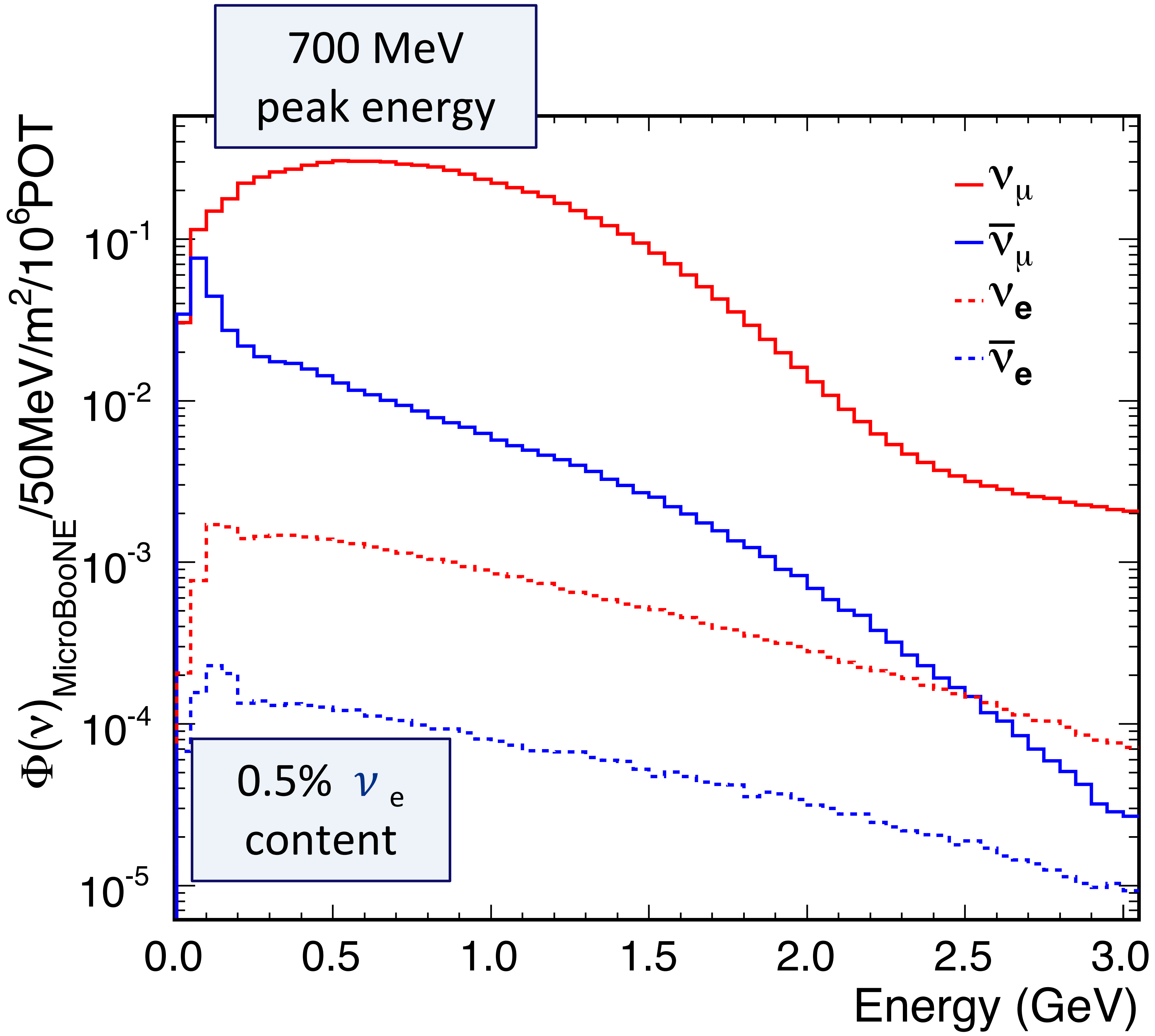
The Booster Neutrino Beam





@ SBND:
- BNB: 0.25 Hz ν, 0.03 Hz cosmic

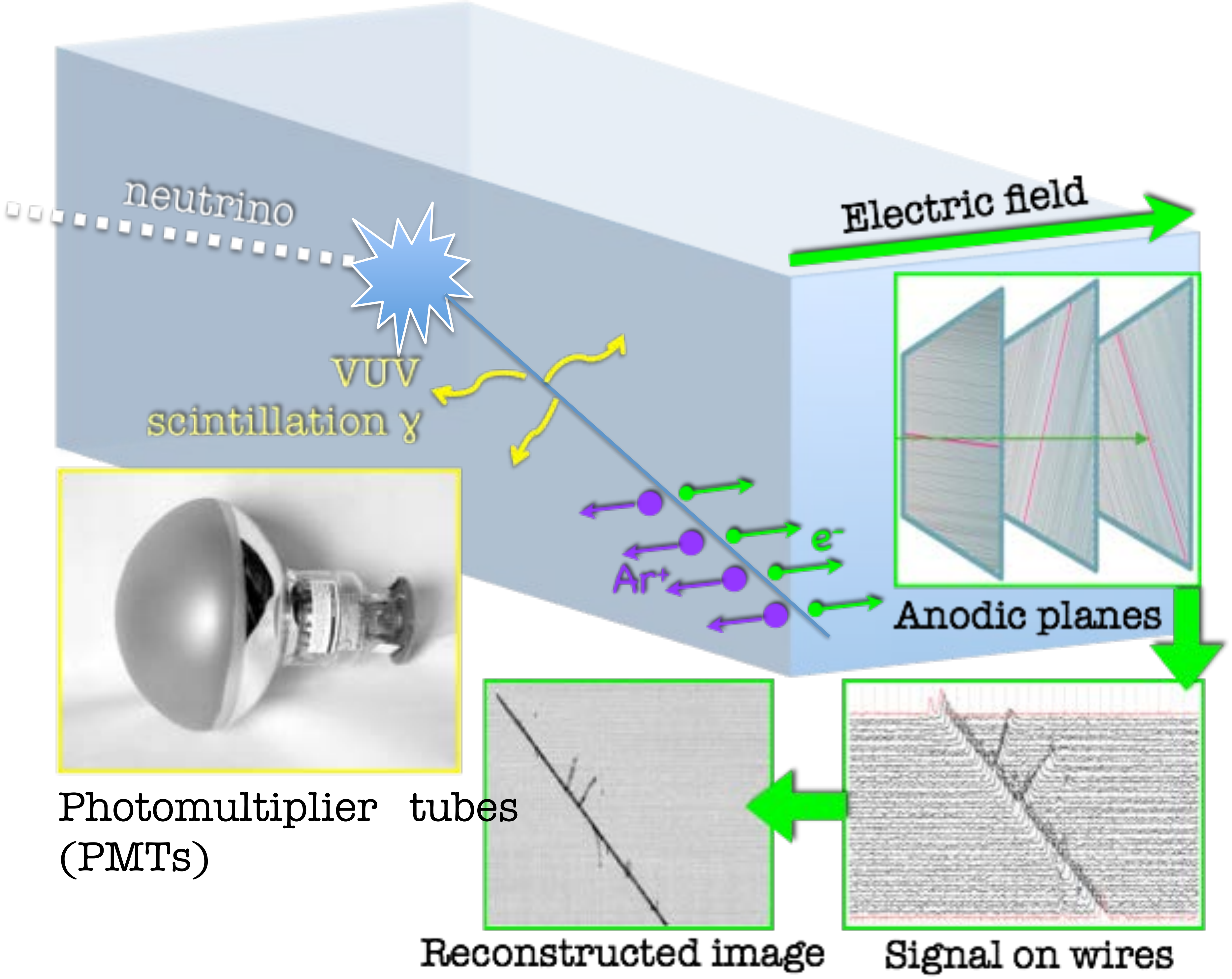
@ ICARUS:
- BNB 0.03 Hz ν, 0.14 Hz cosmic
- NuMI: 0.014 Hz ν, 0.08 Hz cosmic



Liquid Argon TPC detection technique

Very well suited for the experimental study of Neutrino Physics, pioneered by Icarus Collaboration.

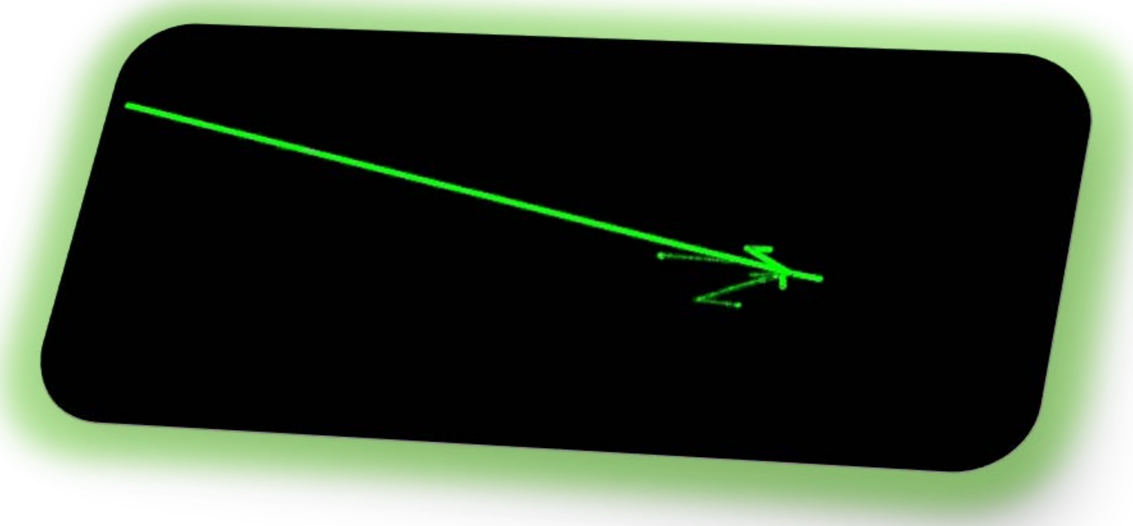
Massive yet homogeneous target, excellent tracking & calorimetric capabilities.



<u>λ = 128 nm scintillation light</u>:
40000 γ/MeV wo electric field.
Response time ~ 6 ns ÷ 1.6 μs.

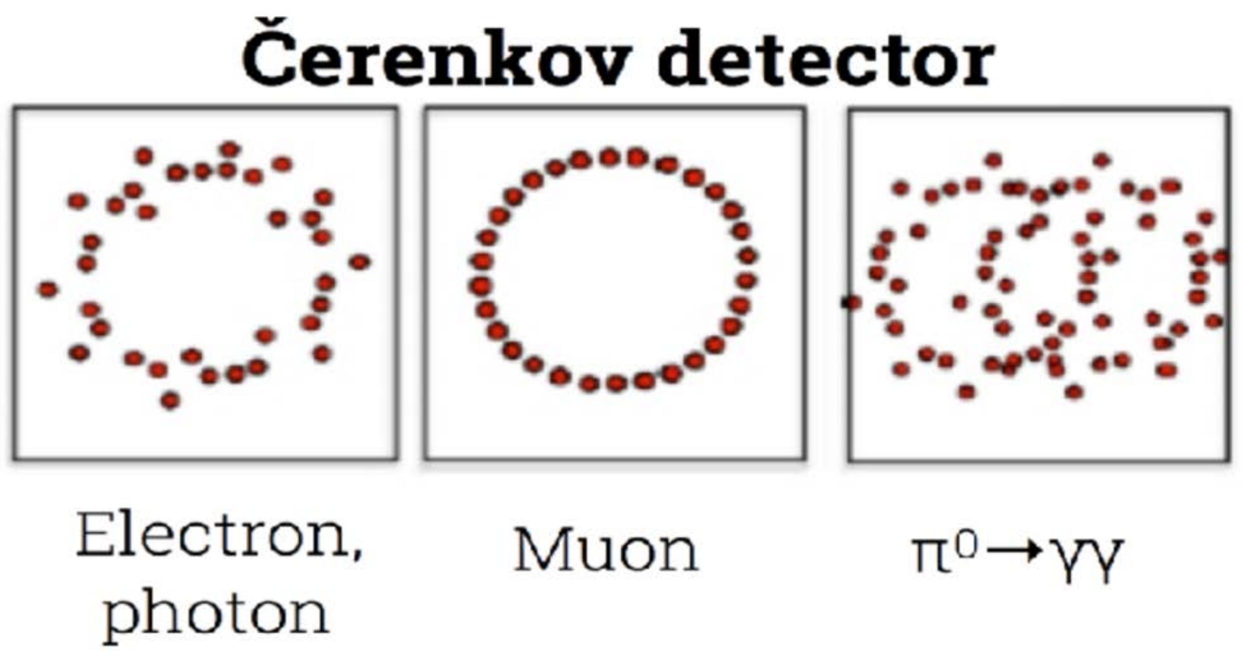
<u>Ionisation electrons</u>:
42000 e^-/MeV.
Drifted (E) toward planes of wires on which they induce a signal.
Response time = drift time (~ ms).

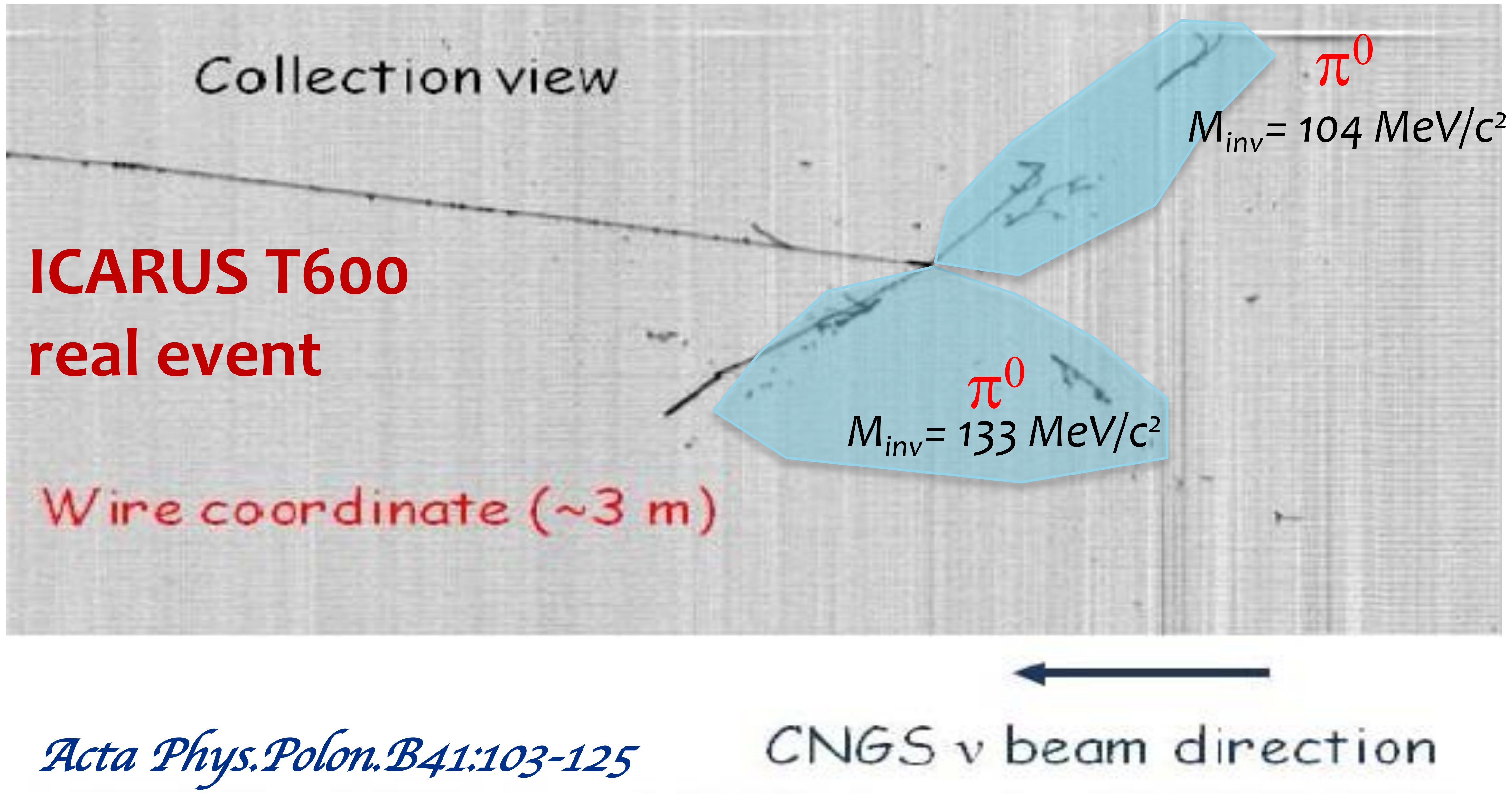
3D image reconstruction by combining coordinates on different wire planes at the same drift time.



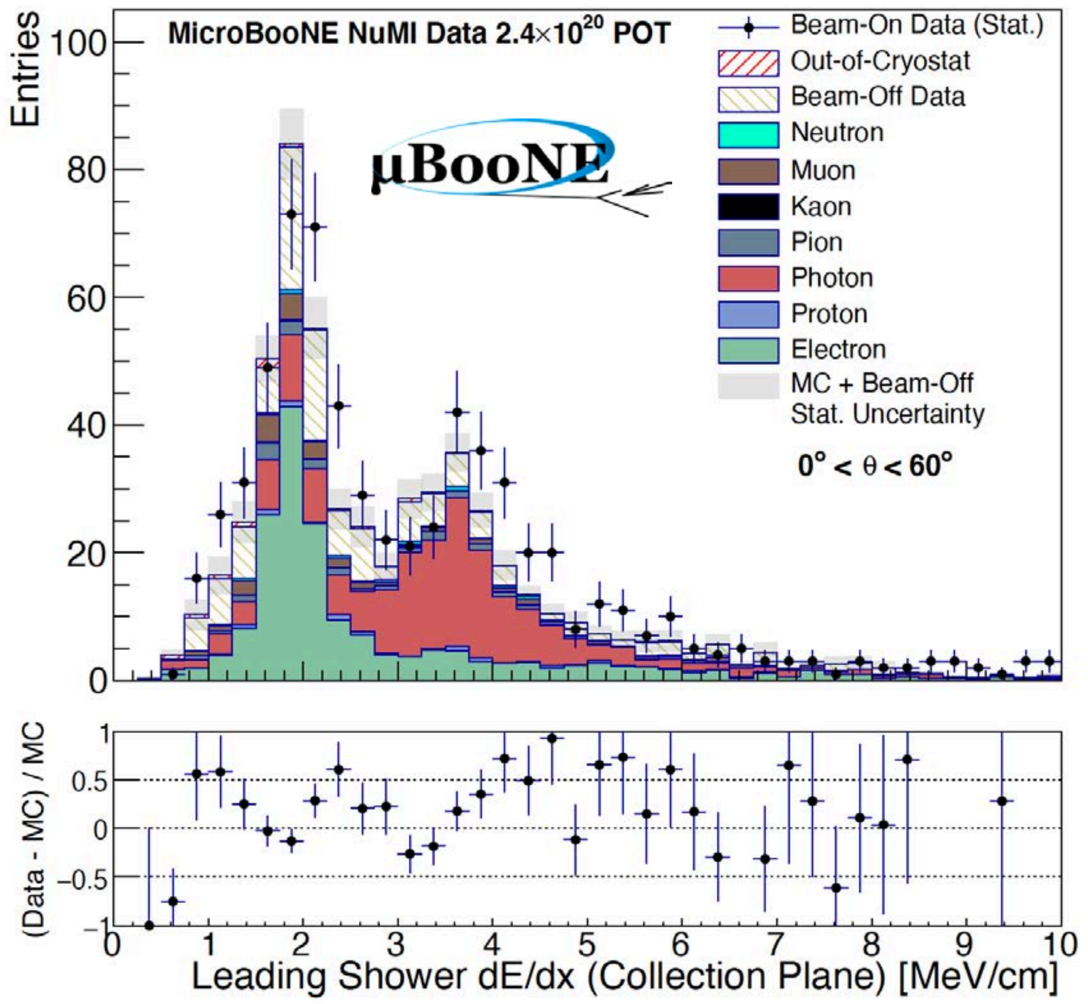
Electron neutrinos in LAr-TPC

Fine tracking & calorimetry essential for e/γ separation and π^0 reconstruction

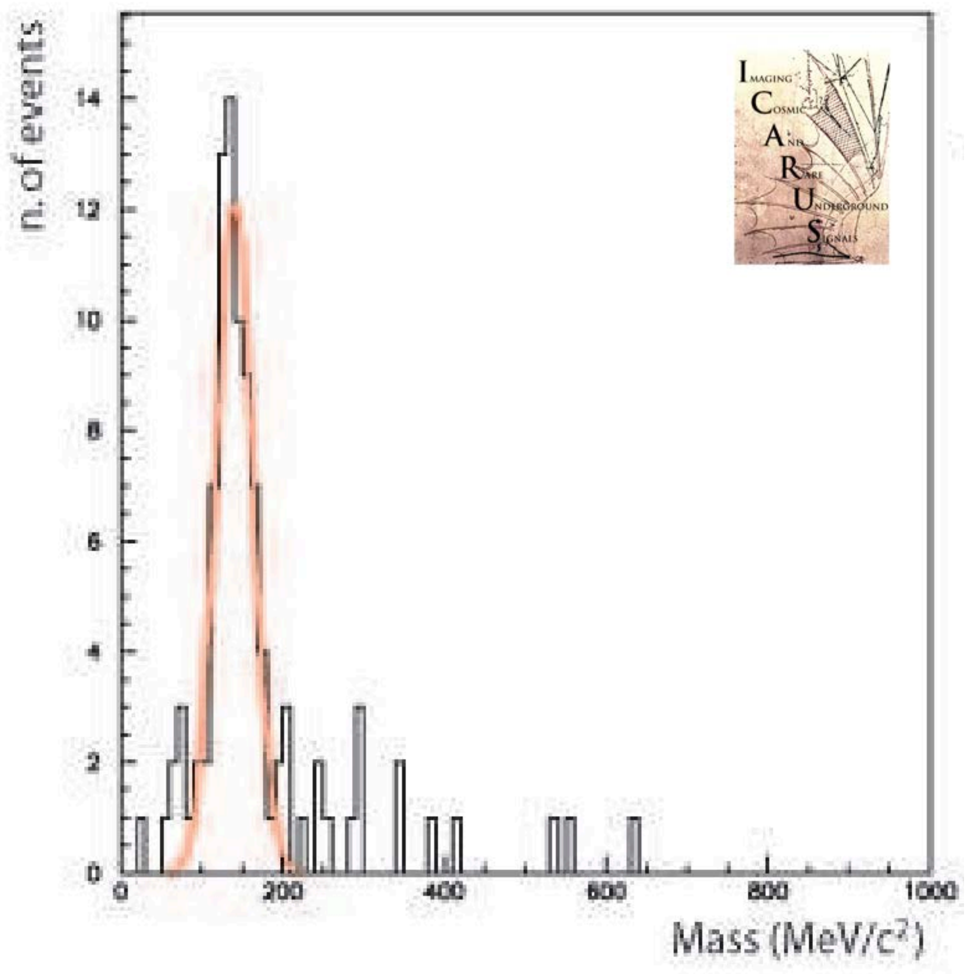




arXiv: 2101.04228



Acta Phys.Polon.B41:103-125

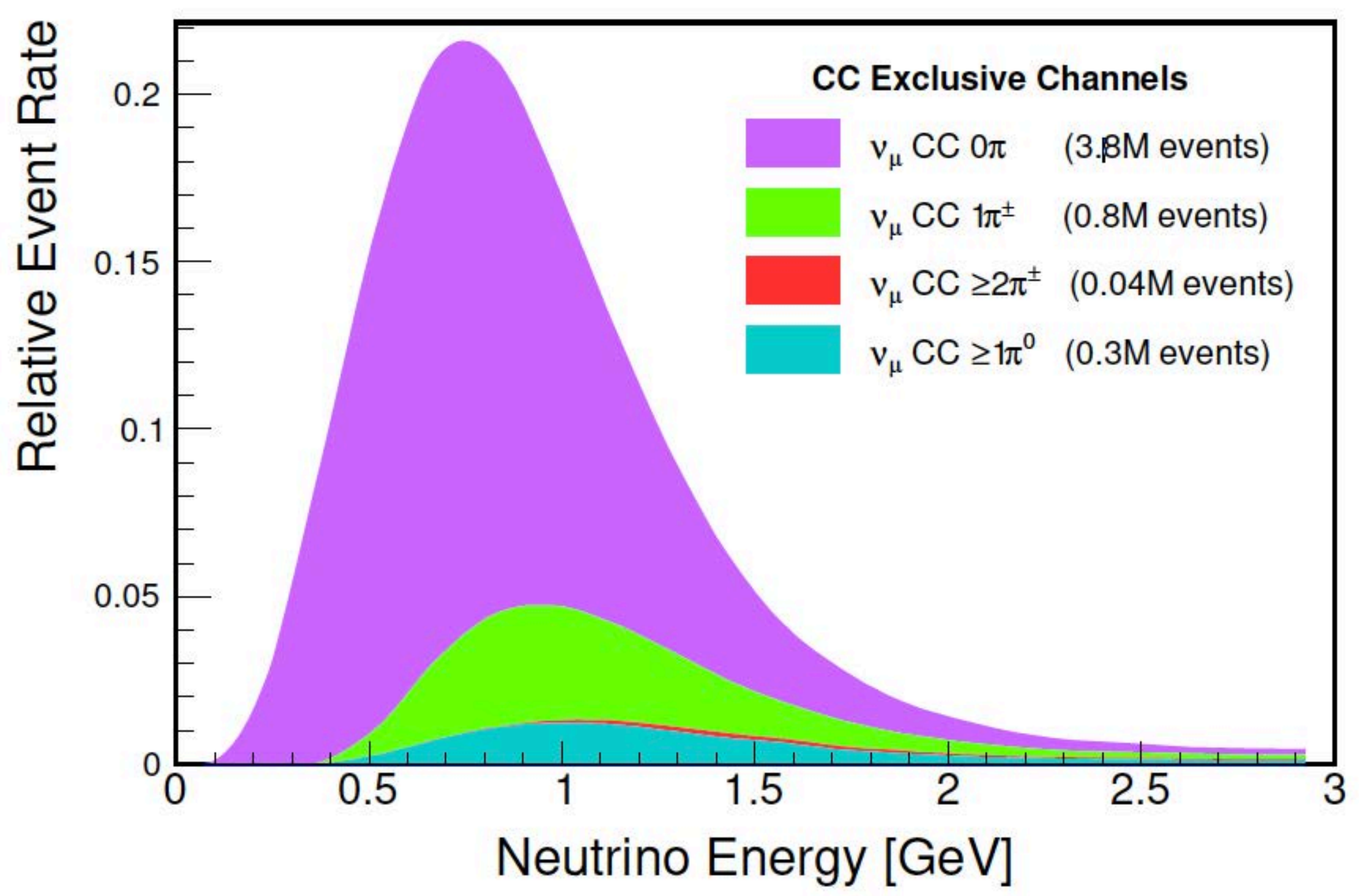


- Gap between vertex and shower.
- Ionization in the first segment of showers (1 mip or 2 mips).
- π^0 invariant mass.

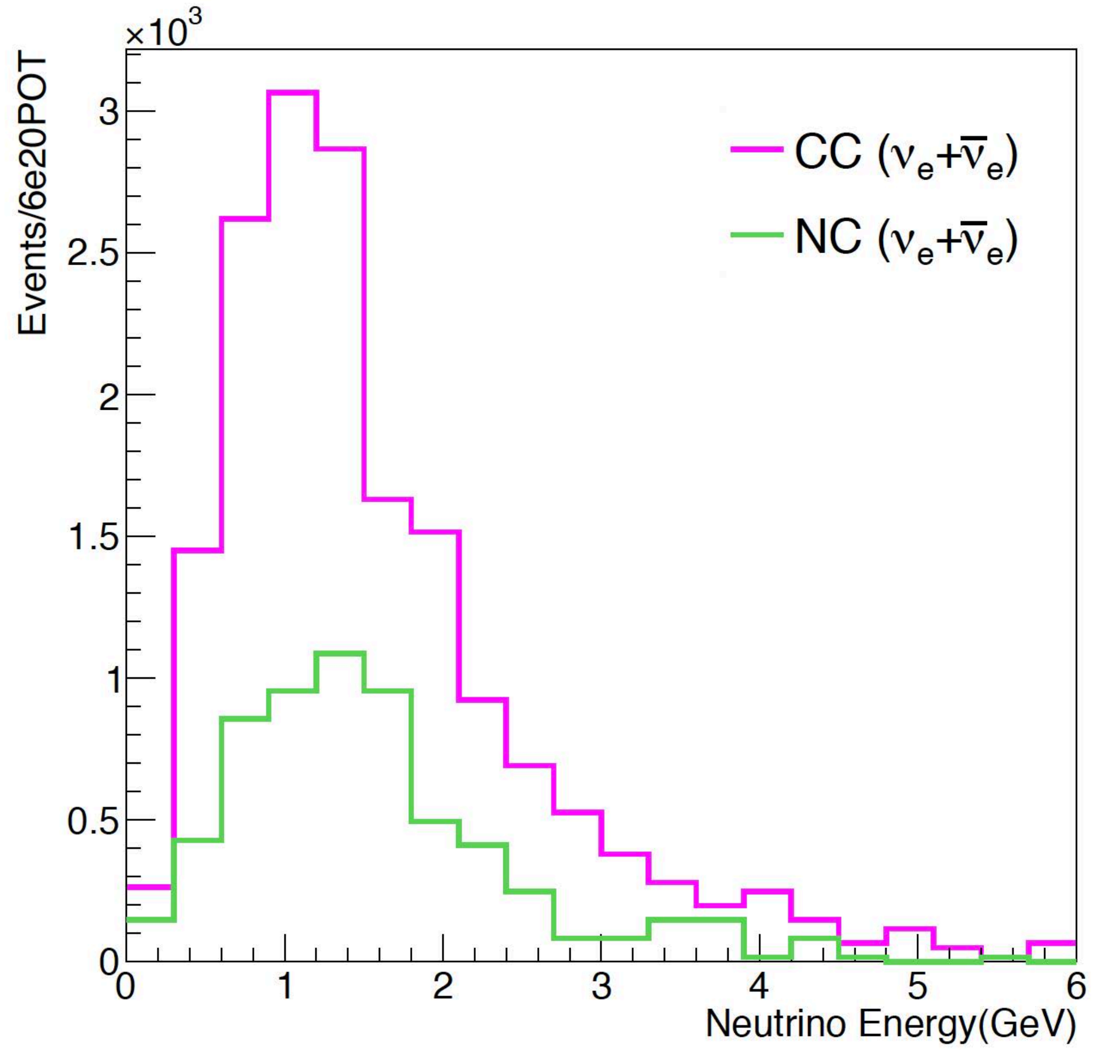
Neutrino interactions at SBN

- High statistics precision measurements of neutrino argon cross sections in the DUNE energy range.
  - SBND: word's highest statistics cross section measurements on argon, ~ 7 million ν_μ and ~ 50,000 ν_e in 3 years
  - ICARUS: high statistics electron neutrino cross section measurement using the NuMI off axis, ~ 10^5 events/year
  - MicroBooNE is now delivering the first results on cross section measurements

ν_μ from the Booster at SBND



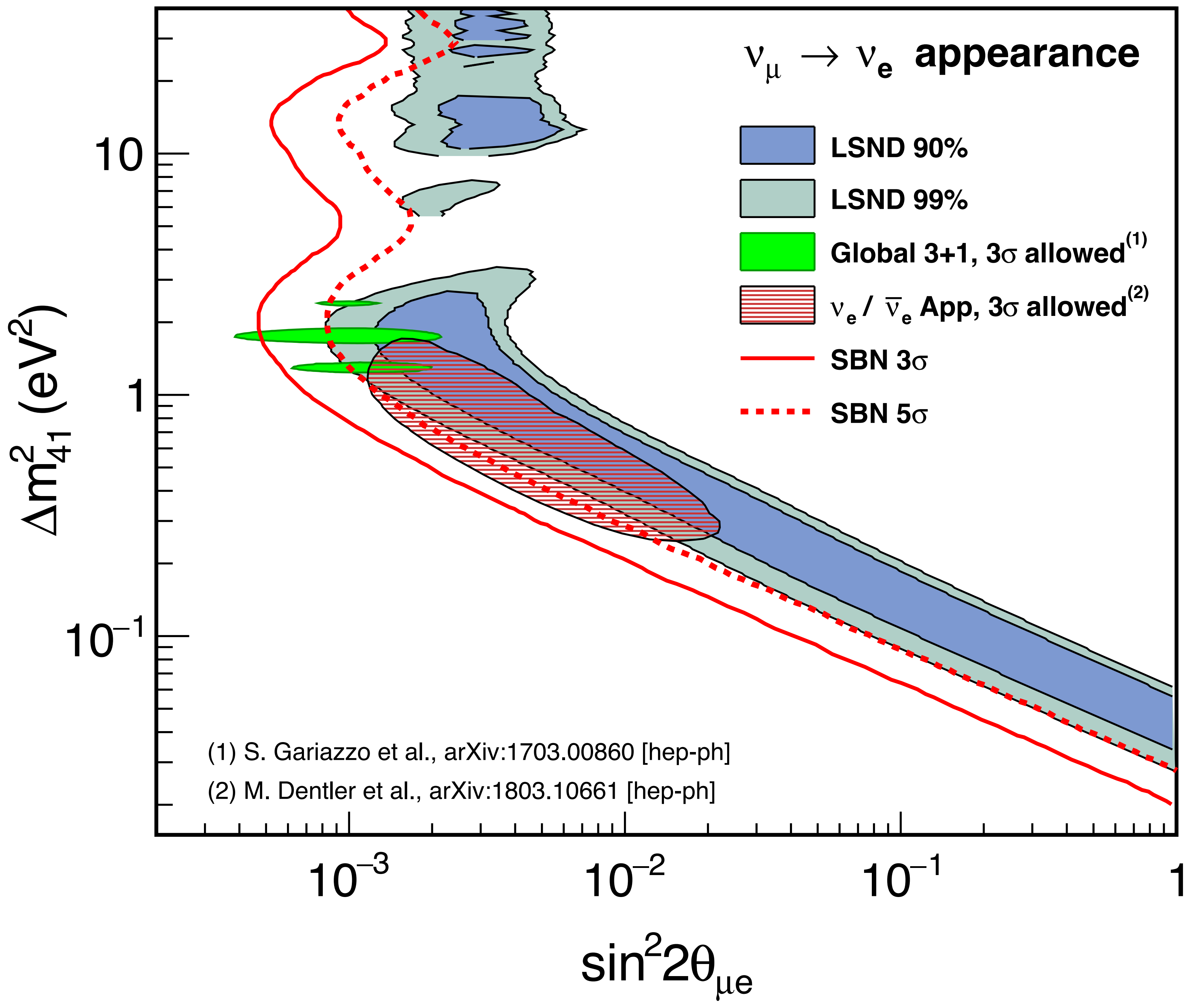
ν_e from the NuMI off axis at ICARUS

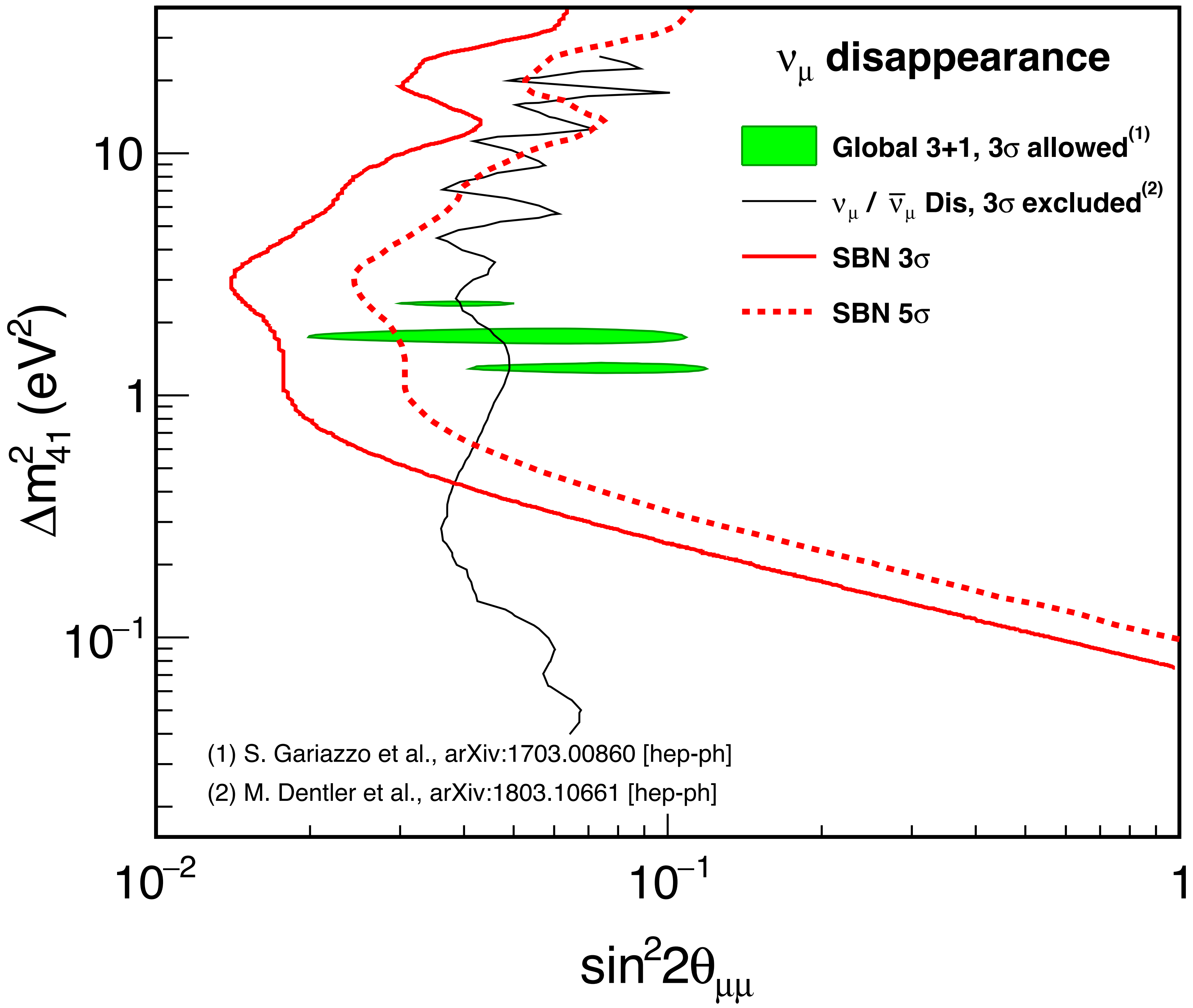


- Rich BSM searches: neutrino tridents, dark matter, millicharged particles… EX: MicroBooNE heavy neutral lepton search *Phys. Rev. D 101, 052001 (2020)*

Sterile neutrino sensitivity

Annual Rev. Nucl. Part. Sci. 2019.69:363-387





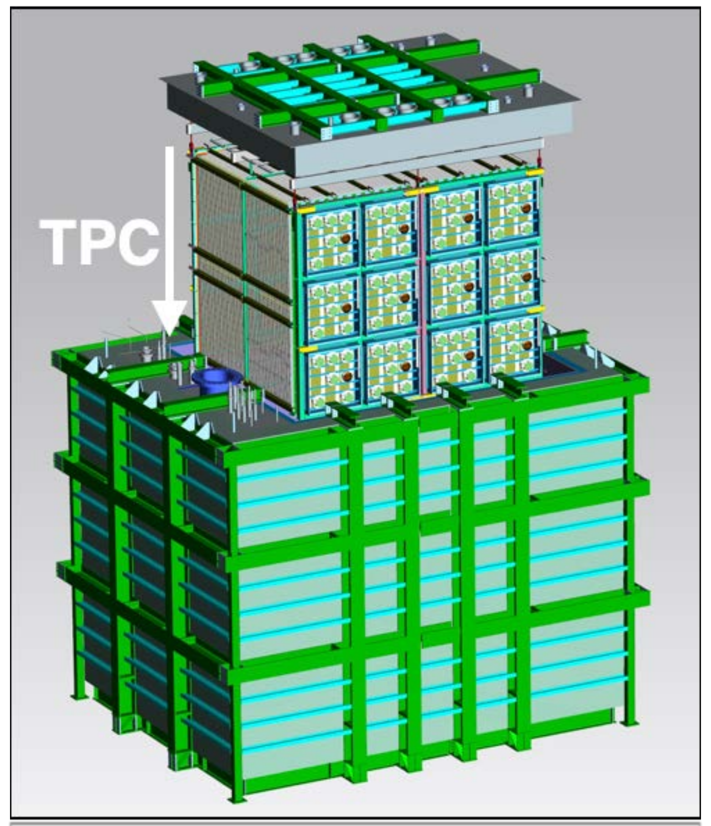
5σ coverage of the parameter area relevant to the LSND/MiniBooNE anomaly in 3 years (6.6 x 10^{20} pot).

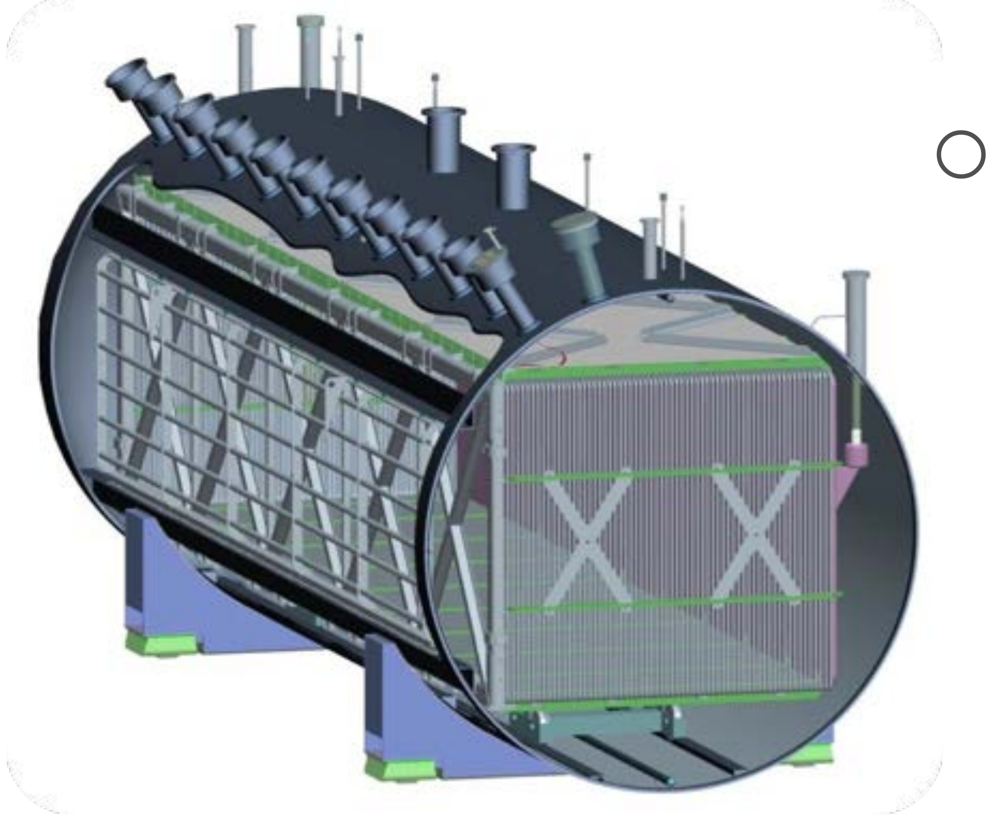
1 order of magnitude beyond SciBooNE + MiniBooNE limits in 3 years (6.6 x 10^{20} pot). Probing the parameter area relevant to reactor and gallium anomalies.

Unique capability to study appearance and disappearance channels simultaneously

The SBN detectors

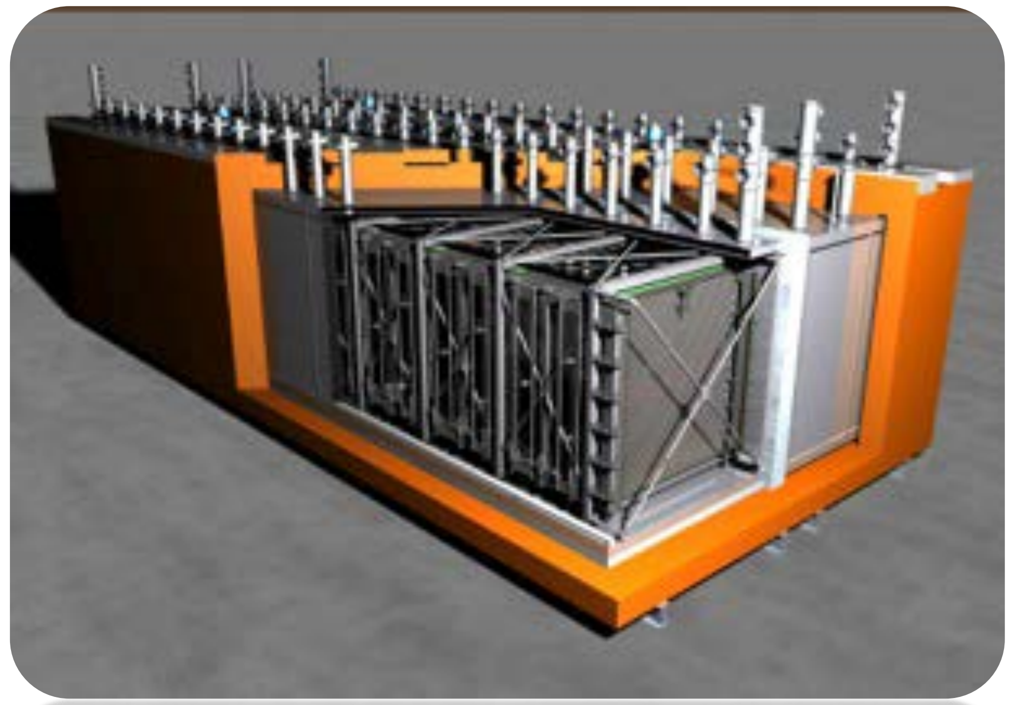
- **SBND** _ construction/installation
  - 260 t of LAr (112 t active), 110 m from target.
  - 2 TPCs with 2 m drift
  - 120 8” PMTs (96 coated with TPB), 192 X-ARAPUCA modules, TPB coated reflector foils on the cathode.
  - 4π CRT (cosmic ray tagger) coverage



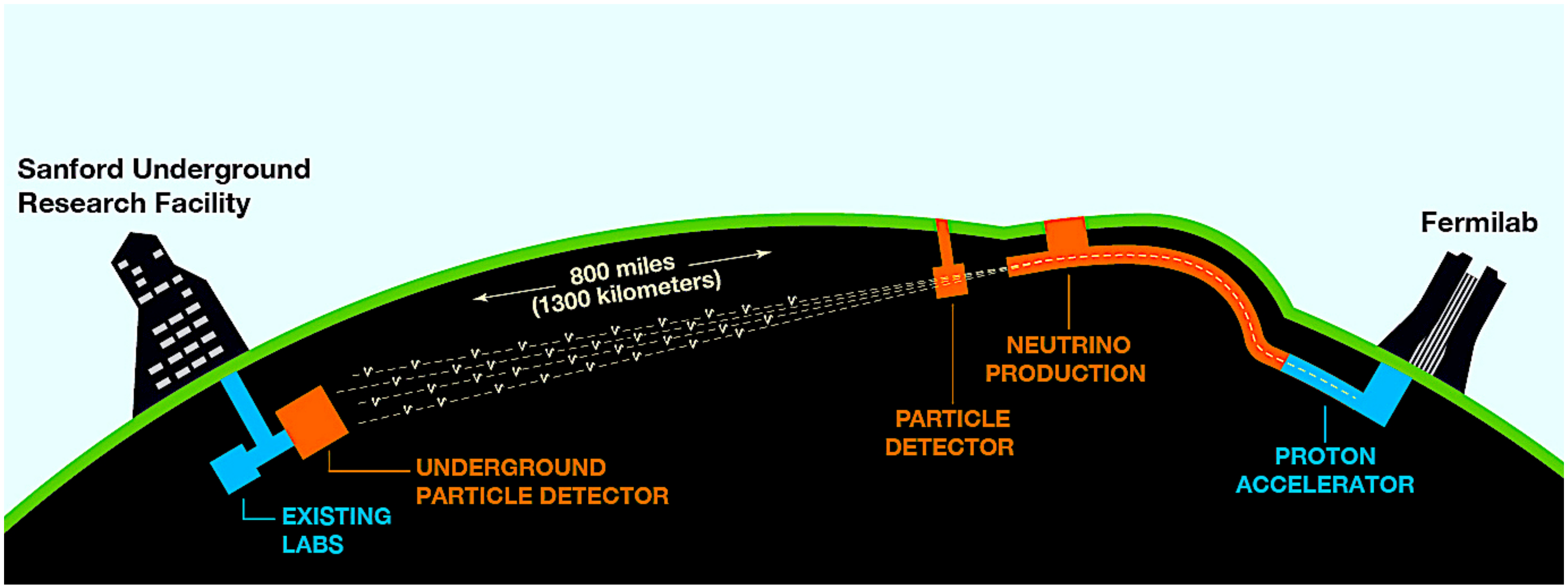


- **MicroBooNE** _ physics run completed
  - 170 t of LAr (87 t active), 470 m from target.
  - 1 TPC with 2.5 m drift.
  - 32 8” PMTs on acrylic support coated with TPB.
  - Top and side CRT.

- **ICARUS** _ commissioning
  - 760 t of LAr (476 t active), 600 m from target.
  - 4 TPCs with 1.5 m drift.
  - 360 8” PMTs coated with TPB.
  - Almost full CRT coverage.



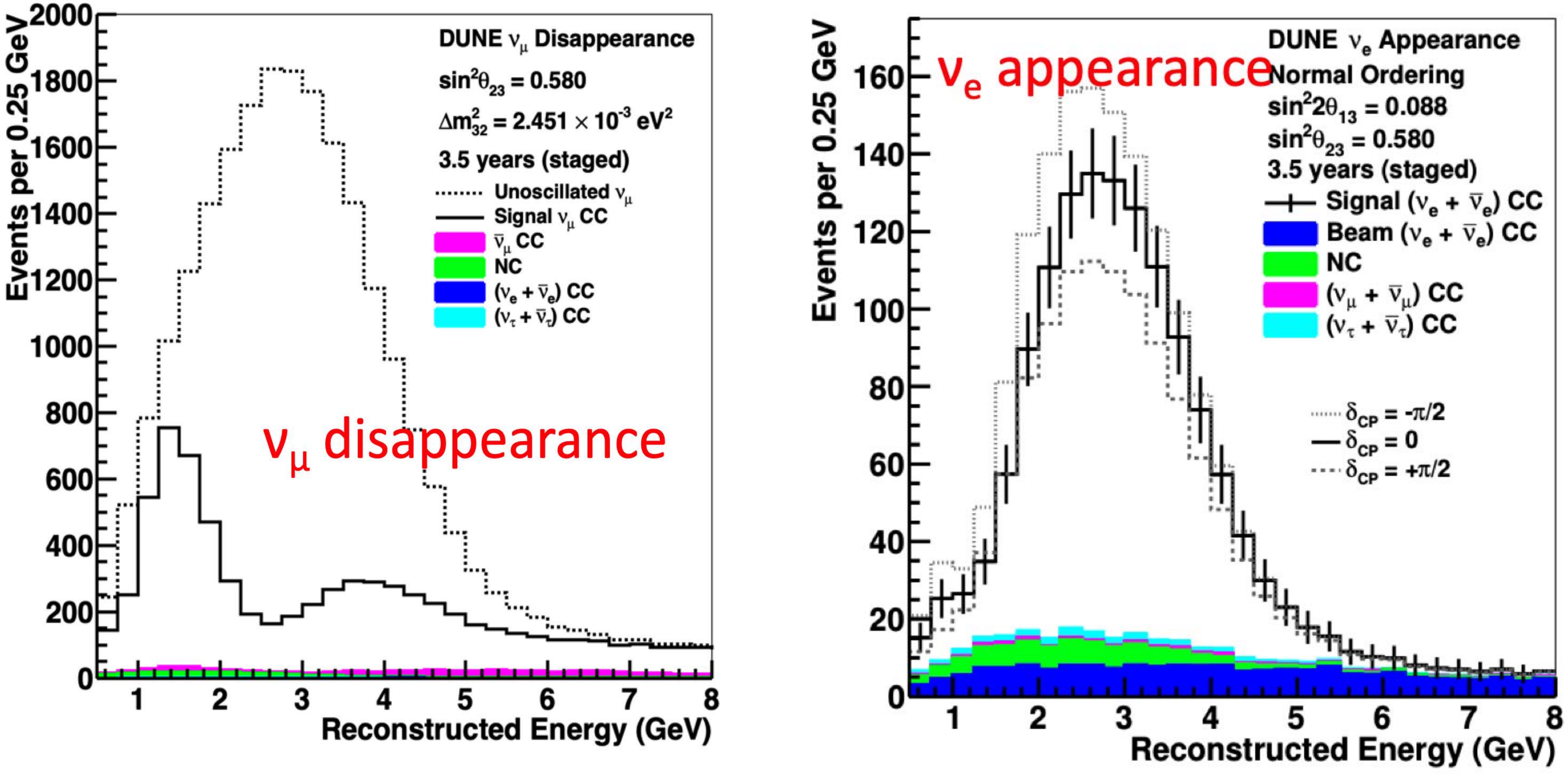
Deep Underground Neutrino Experiment, a Long-baseline Neutrino Experiment



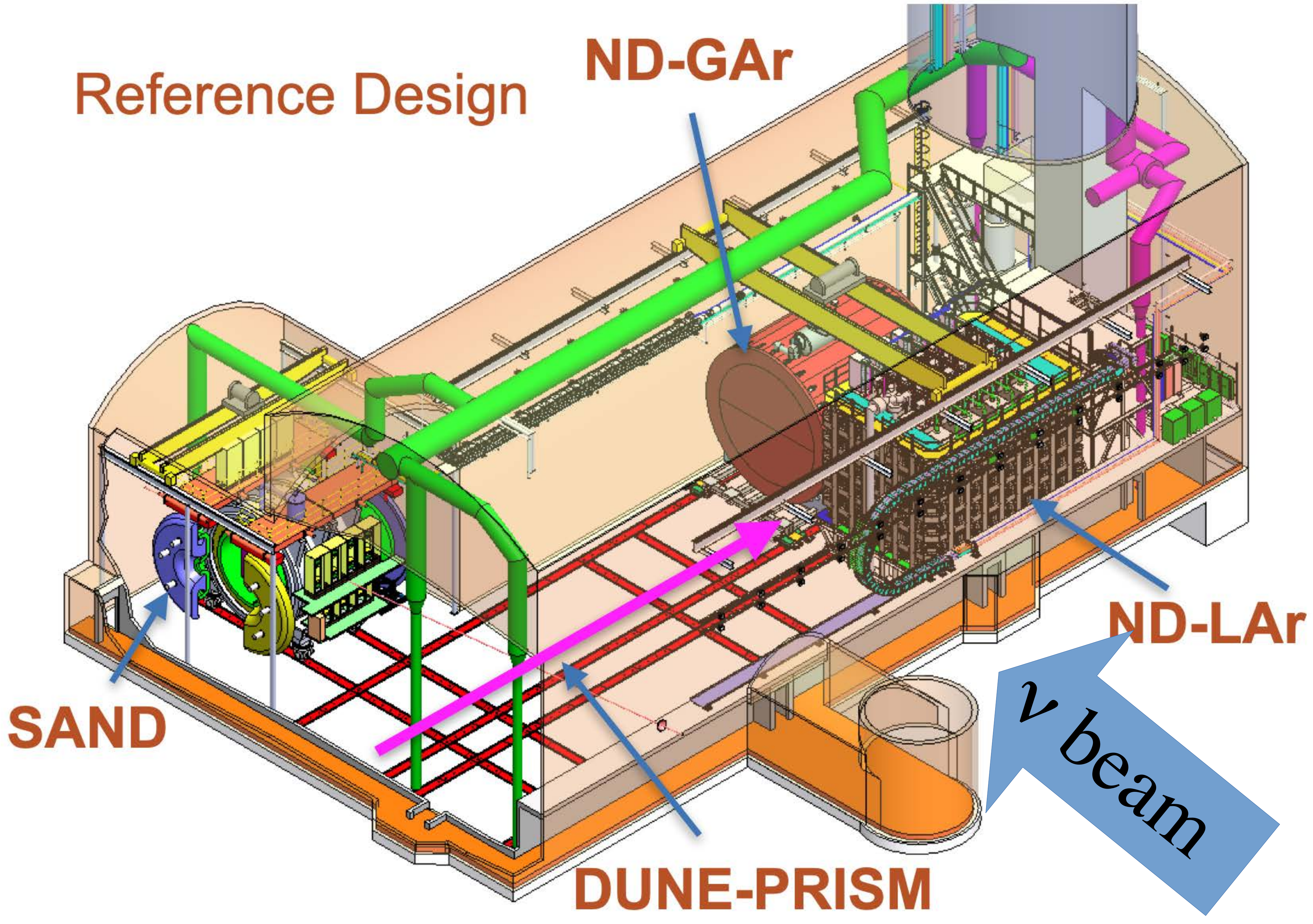
- 1.2 MW, upgradable to 2.4 MW high-intensity, wide-band neutrino beam
  - Produced at Fermilab and sent to Sanford Underground Research Facility, 1300 km away
- 40 kT liquid Argon time projection chamber far detector
- Highly capable near detector complex:
  - Precise neutrino cross-section measurements and characterization of the spectrum and flavor composition of the beam

DUNE's Rich Physics Program

- Oscillation physics program:
  - Measurement of the leptonic CP violation
  - Determining the neutrino mass hierarchy
  - Precise measurement of PMNS parameters



DUNE Near Detector Complex



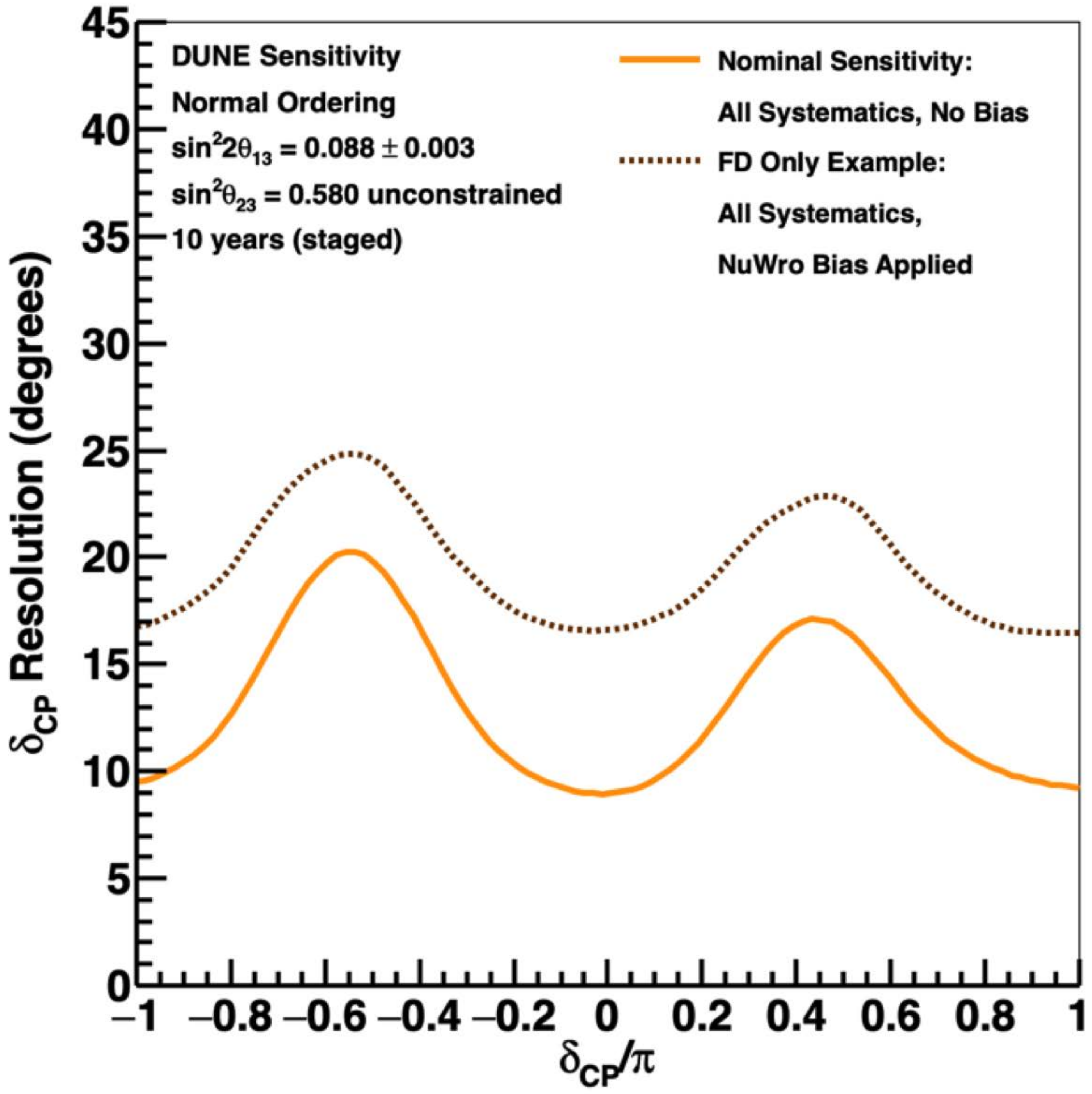
- Near detector hall houses various near detector components and enables the DUNE PRISM program:
  - ND-LAr ArgonCube, Liquid Argon time projection chamber
  - ND-GAr, magnetized gaseous Argon time projection chamber surrounded by ECAL calorimeter
  - SAND, system for on-axis neutrino detection

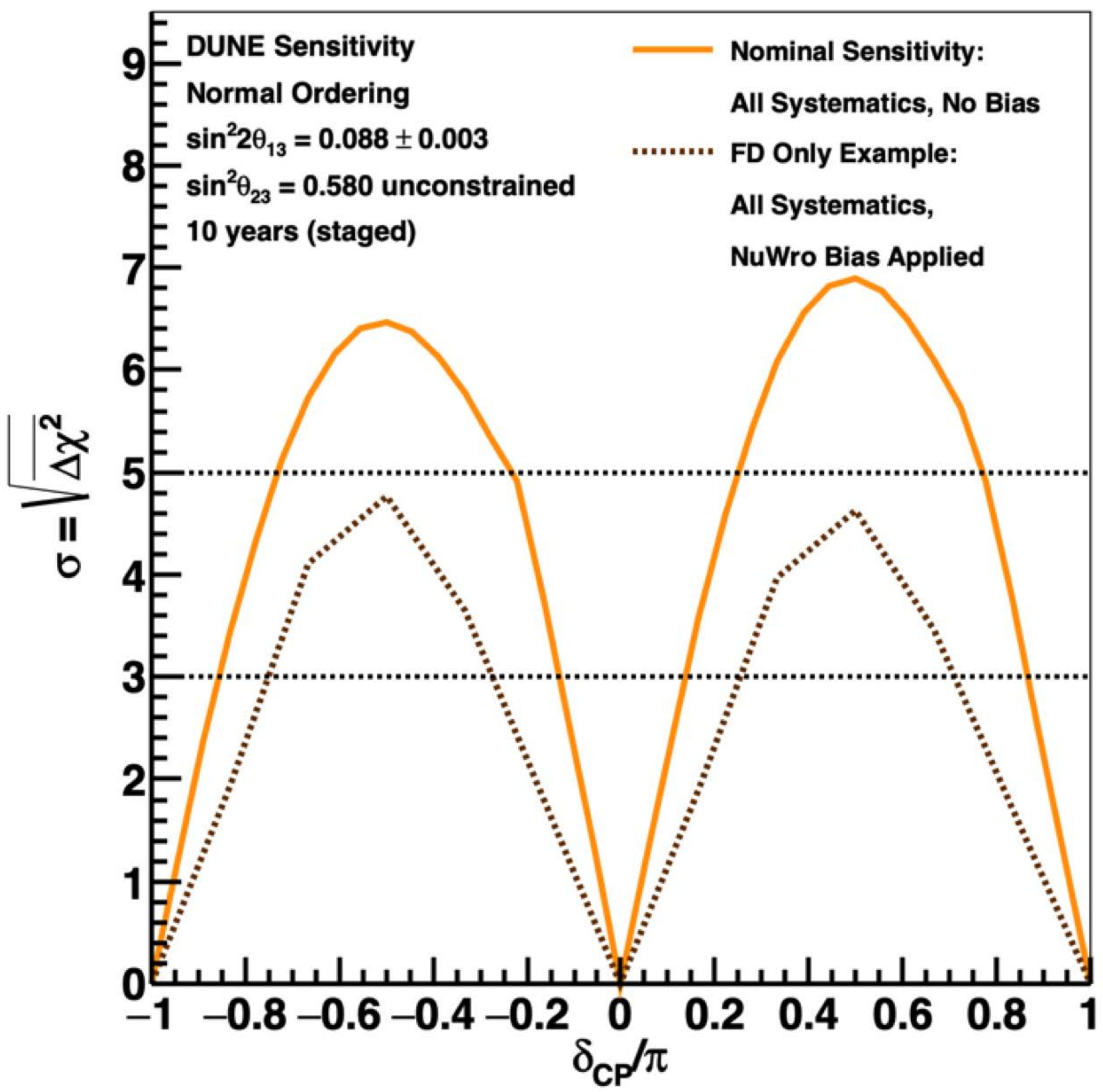
Physics Enabled by Near Detector Complex – Overview

- Primary goal of the near detector complex:

$$N^{FD}_{\nu_e}(E_{reco}) = \int P_{\nu_\mu \to \nu_e}(E_\nu) \times \Phi_{\nu_e}(E_\nu) \times \sigma_{\nu_e}(E_\nu) \times \epsilon^{FD}_{\nu_e}(E_\nu) \times S^{FD}_{\nu_e}(E_\nu \to E_{reco})\, dE_\nu$$

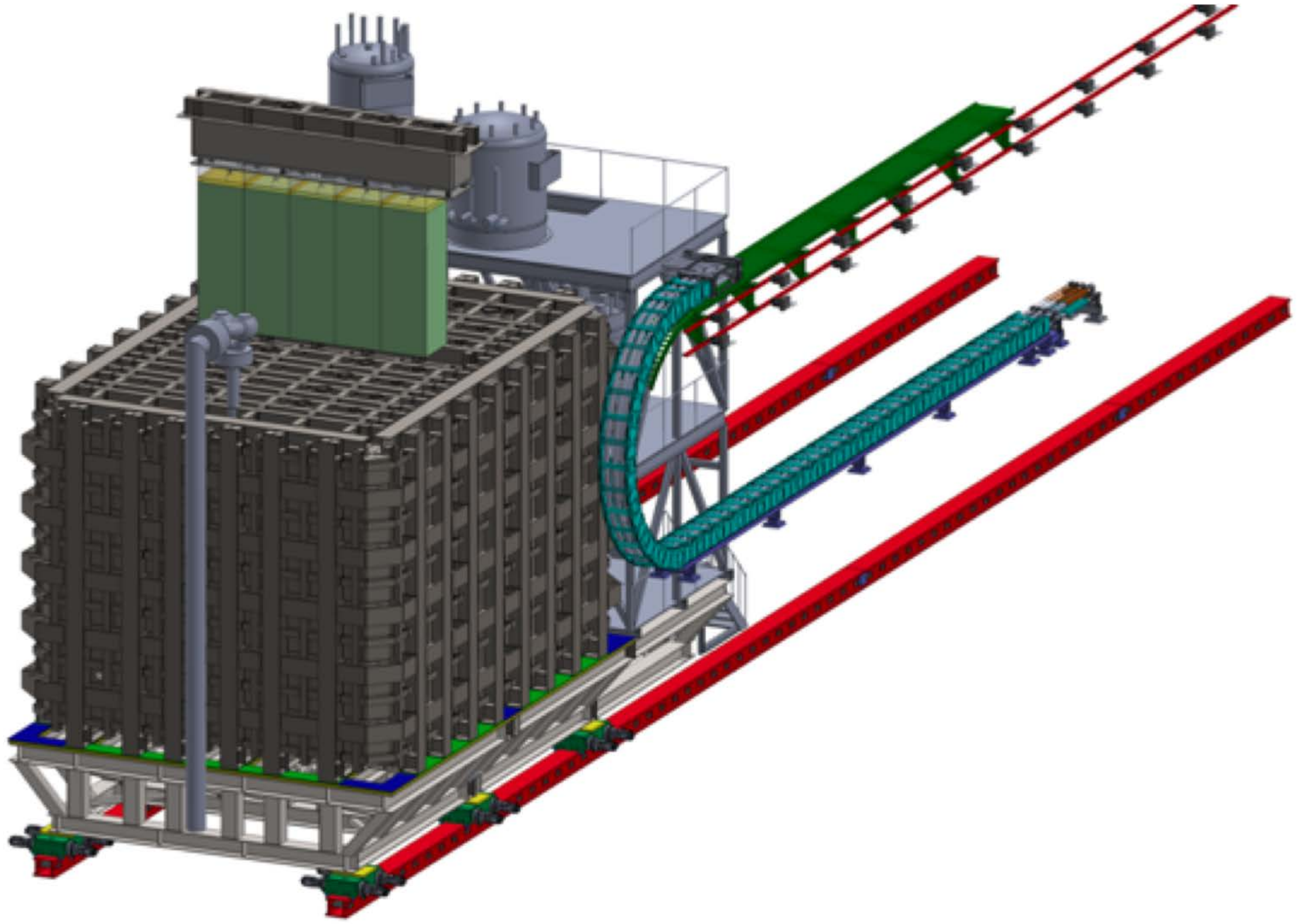
  - ★ Constraining uncertainties in near to far extrapolation + measure flux, Φ, cross section, σ, and ν-energy (migration matrix S)





ND-LAr ArgonCube – Design

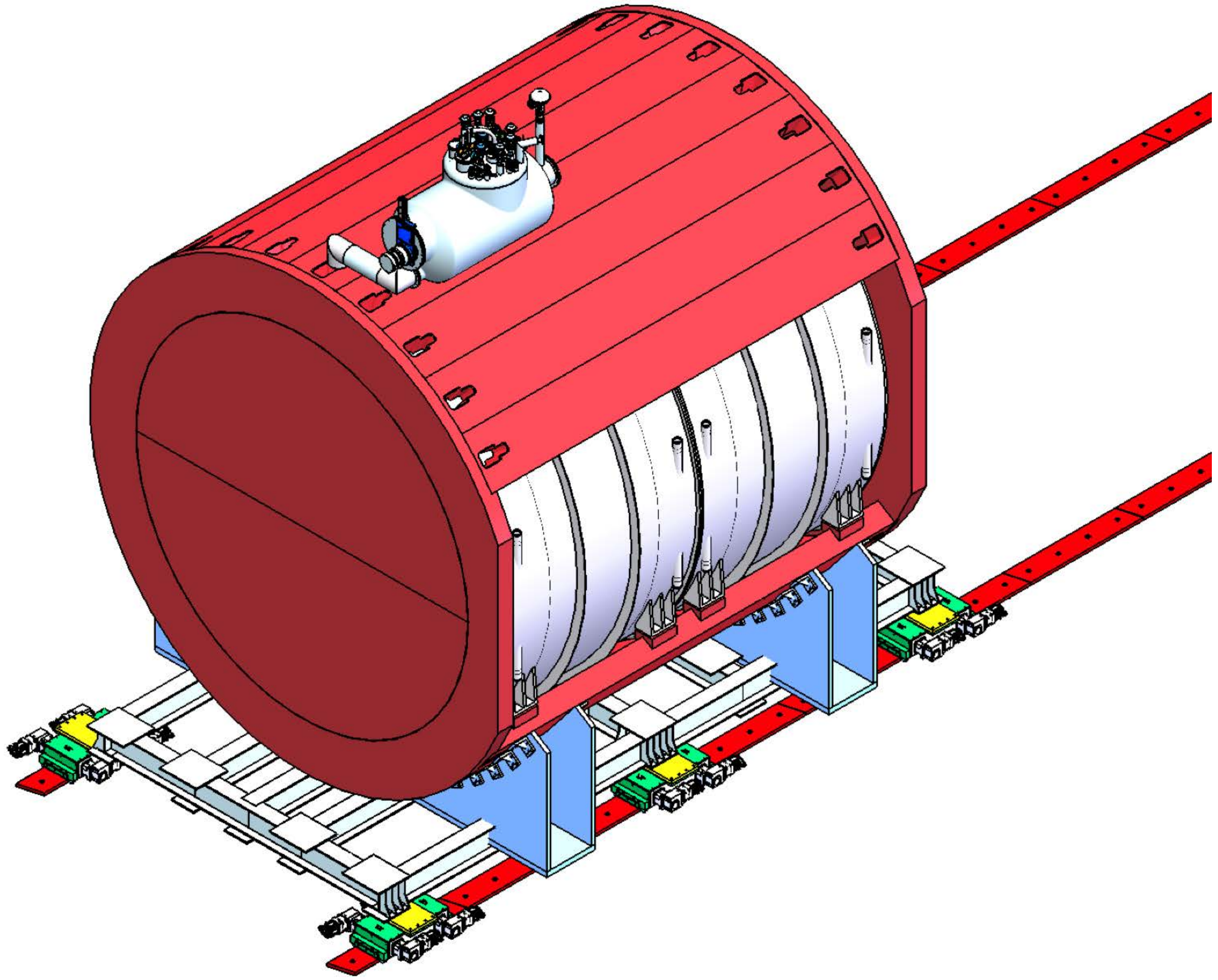
- Key design features:
  - ★ Same target nucleus as the far detector, 50t fiducial mass
  - ★ Designed to mitigate high event rates:
    - ▸ Modular design with 35 1m x 1m x 3.5m modules
    - ▸ Pixelated charge readout – LArPix



prototype module 0

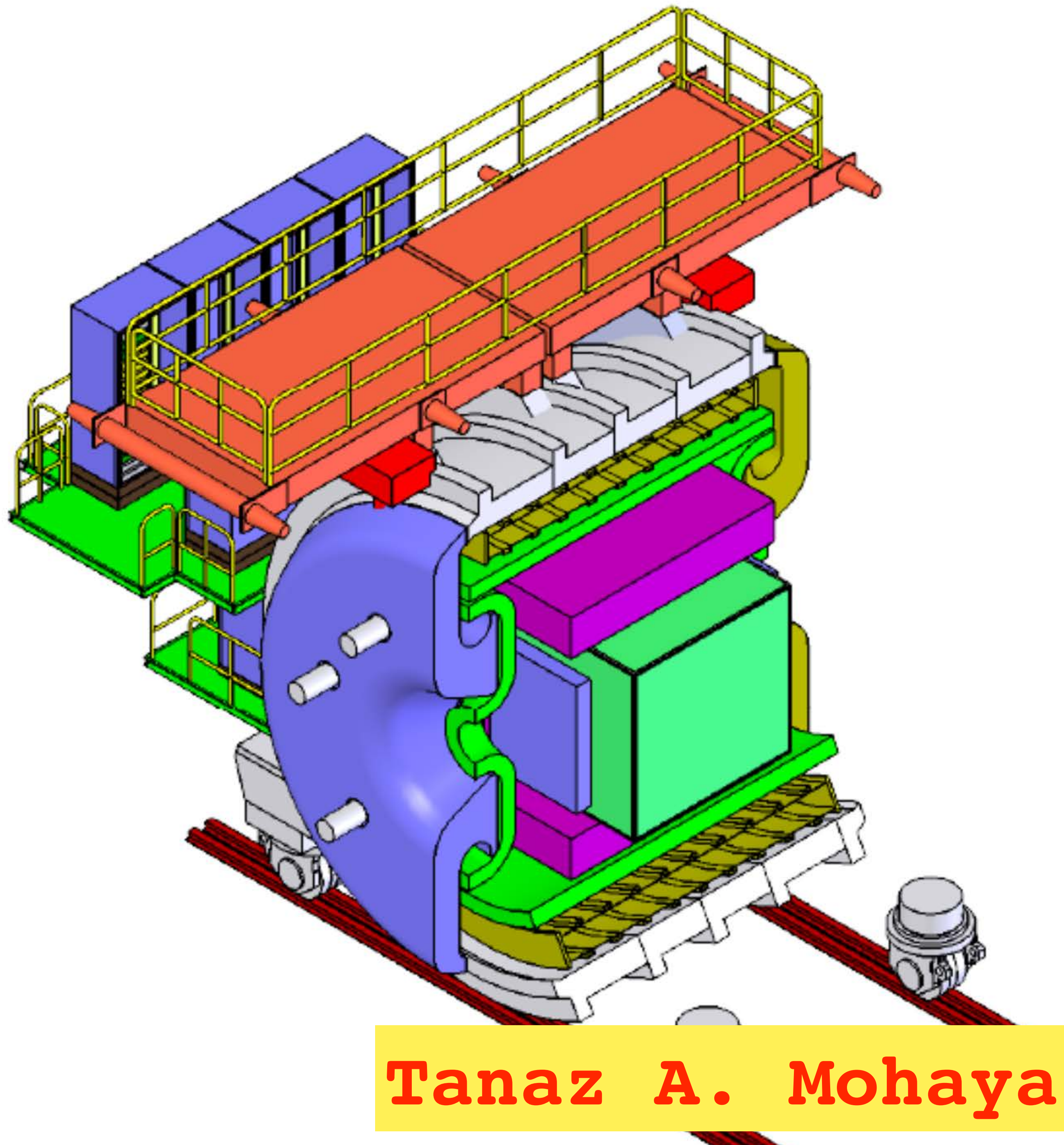
ND-GAr – Design

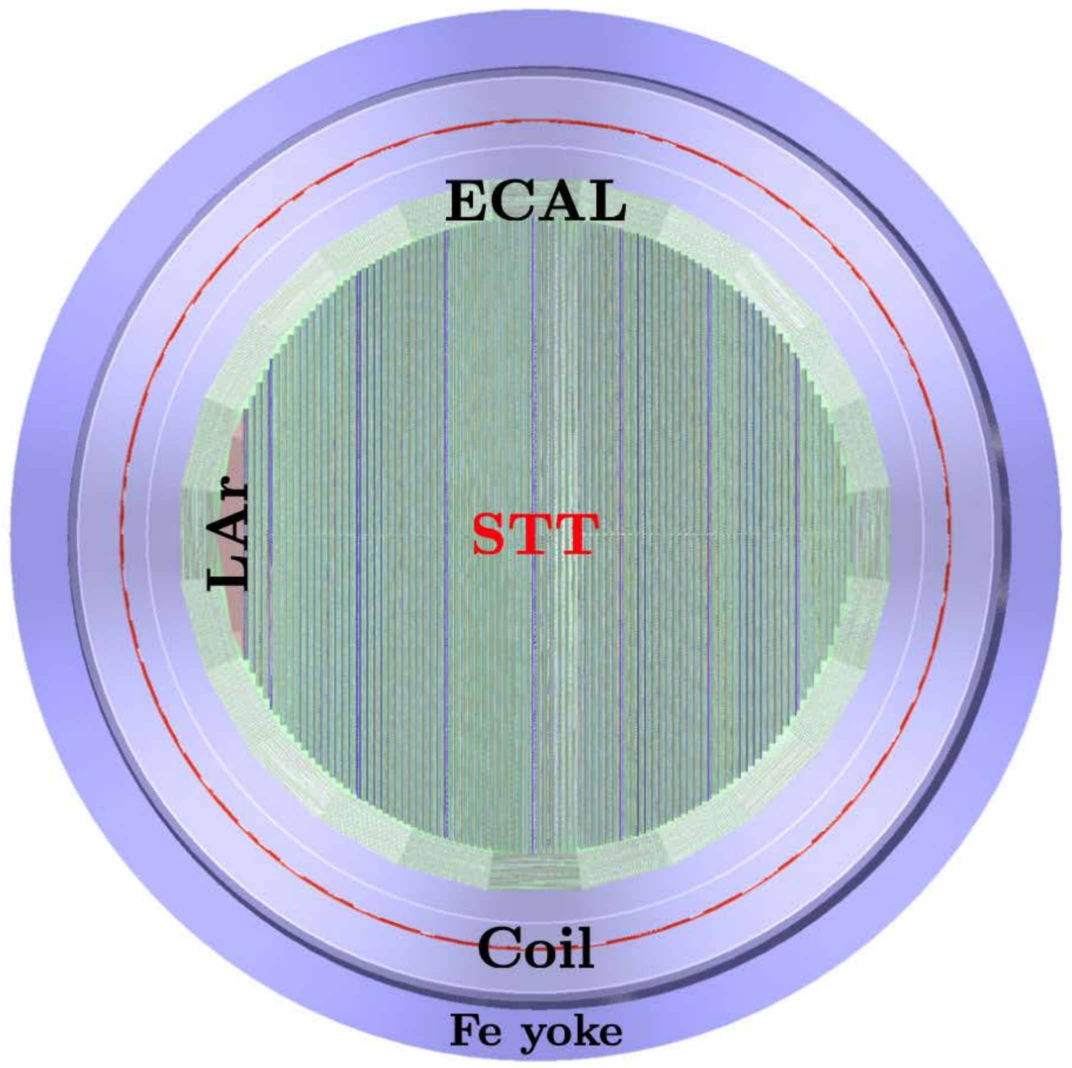
- Key design features:
  - Has a High Pressure Gas Argon TPC (HPgTPC) at its core; will be a copy of ALICE TPC (acquired ALICE’s multiwire chambers will be re-purposed for HPgTPC)
  - Ar-CH_4 90-10 baseline gas mixture (97% Ar interactions) at 10 atm
  - ECAL calorimeter & superconducting magnet surround the HPgTPC

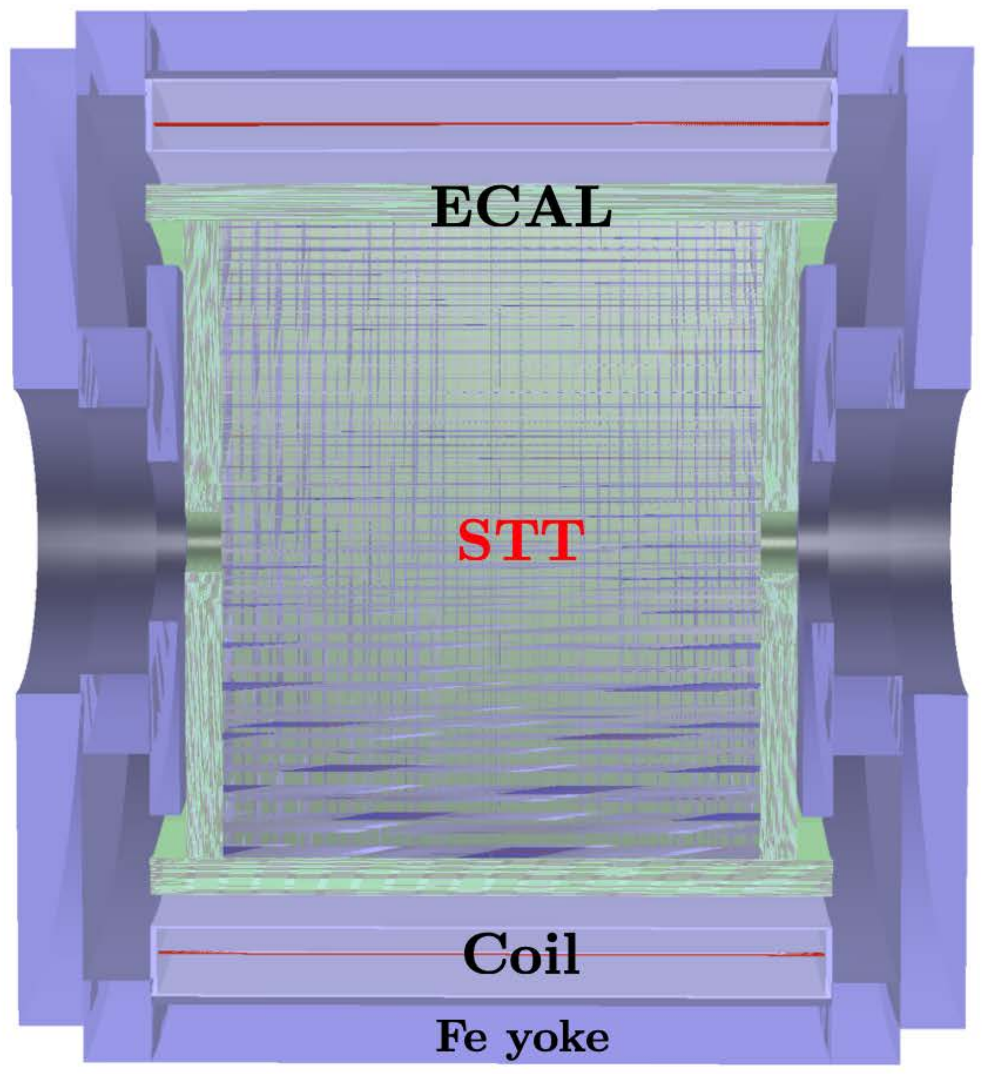


SAND – Design

- Key design features:
  - ★ Designed to measure the on-axis beam
  - ★ KLOE magnet + ECAL making up the outer layers
  - ★ Central tracking options:
    - ▶ 3D segmented plastic scintillator (3DST) + TPCs
    - ▶ 3DST + Straw Tube Tracker (STT)
    - ▶ STT-only
  - ★ Design is being finalized

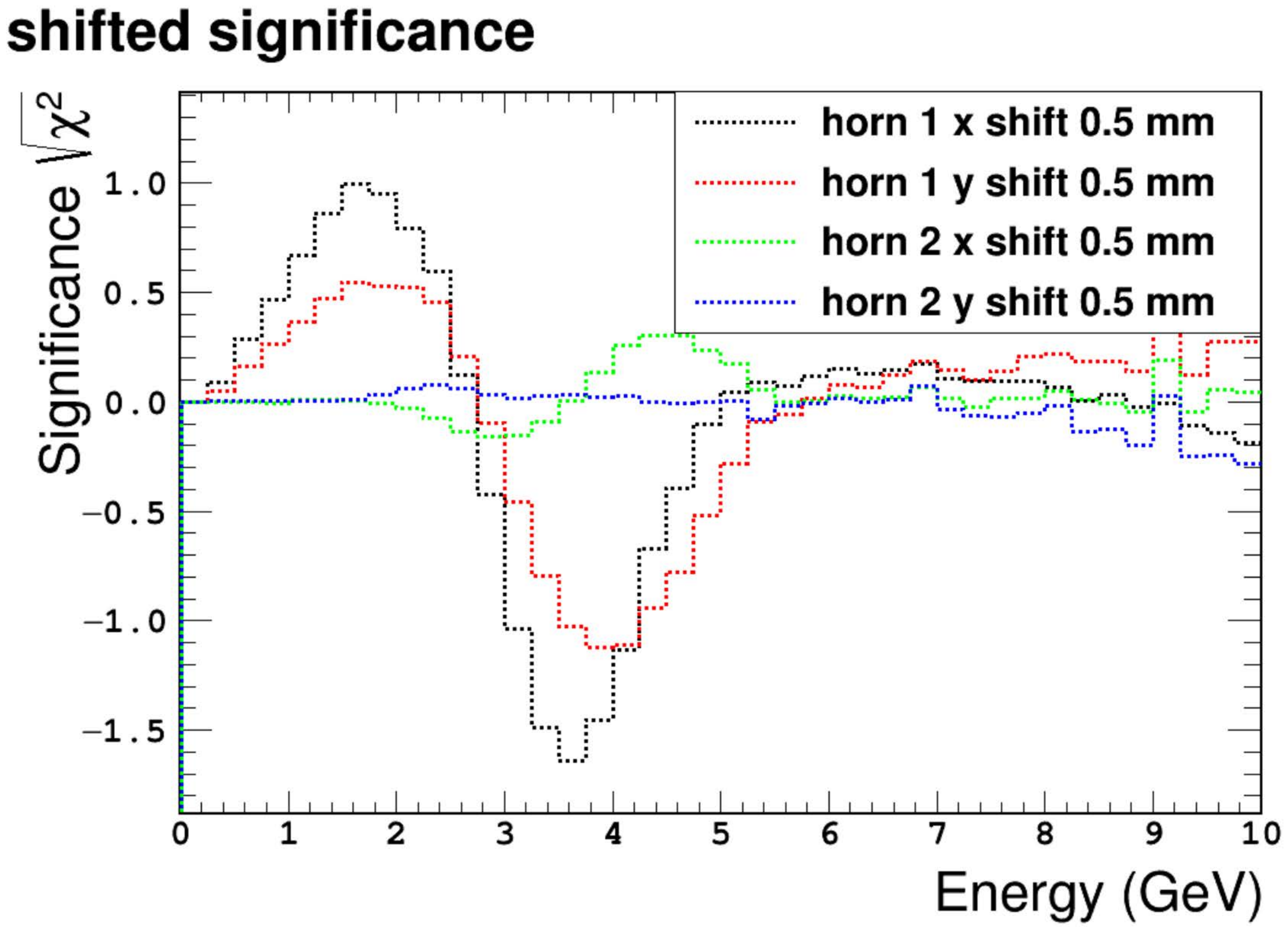






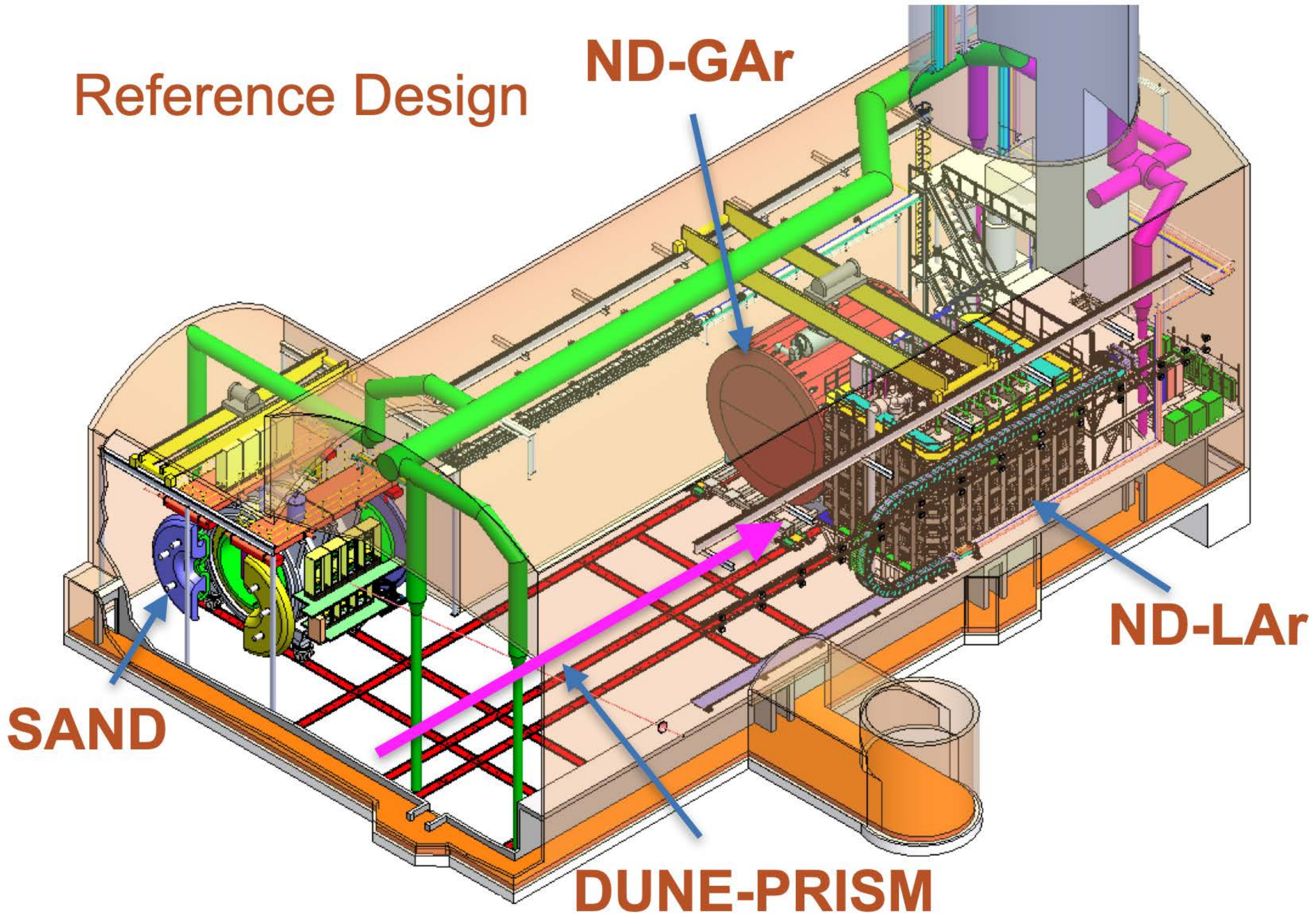
SAND – Capabilities

- With ND-LAr and ND-GAr moving to off-axis positions, SAND remains on-axis to measure any changes in the beam parameters:
  - e.g. can measure the spectral shift in the reconstructed neutrino energy for different horn shifts



Summary

- DUNE near detector components and program consist of:
  - ND-LAr
  - ND-GAr
  - SAND
  - DUNE PRISM
- Near detector components and program enable a very precise measurement of oscillation parameters
- The design of the various near detector components add unique and important capabilities to DUNE's overall physics program

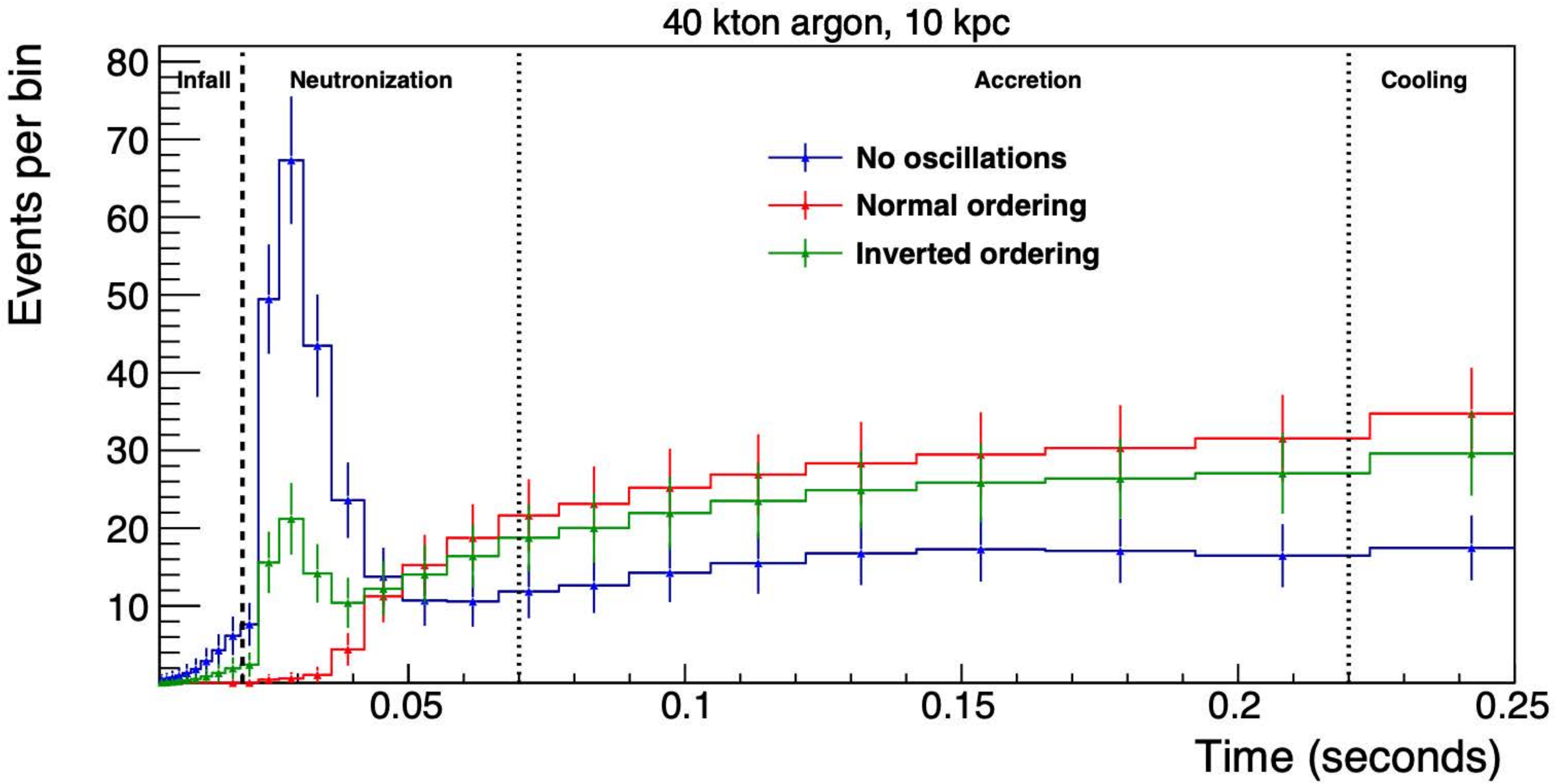


Thank you!

Questions are welcome, now or on Slack or via email (mtanaz@fnal.gov)

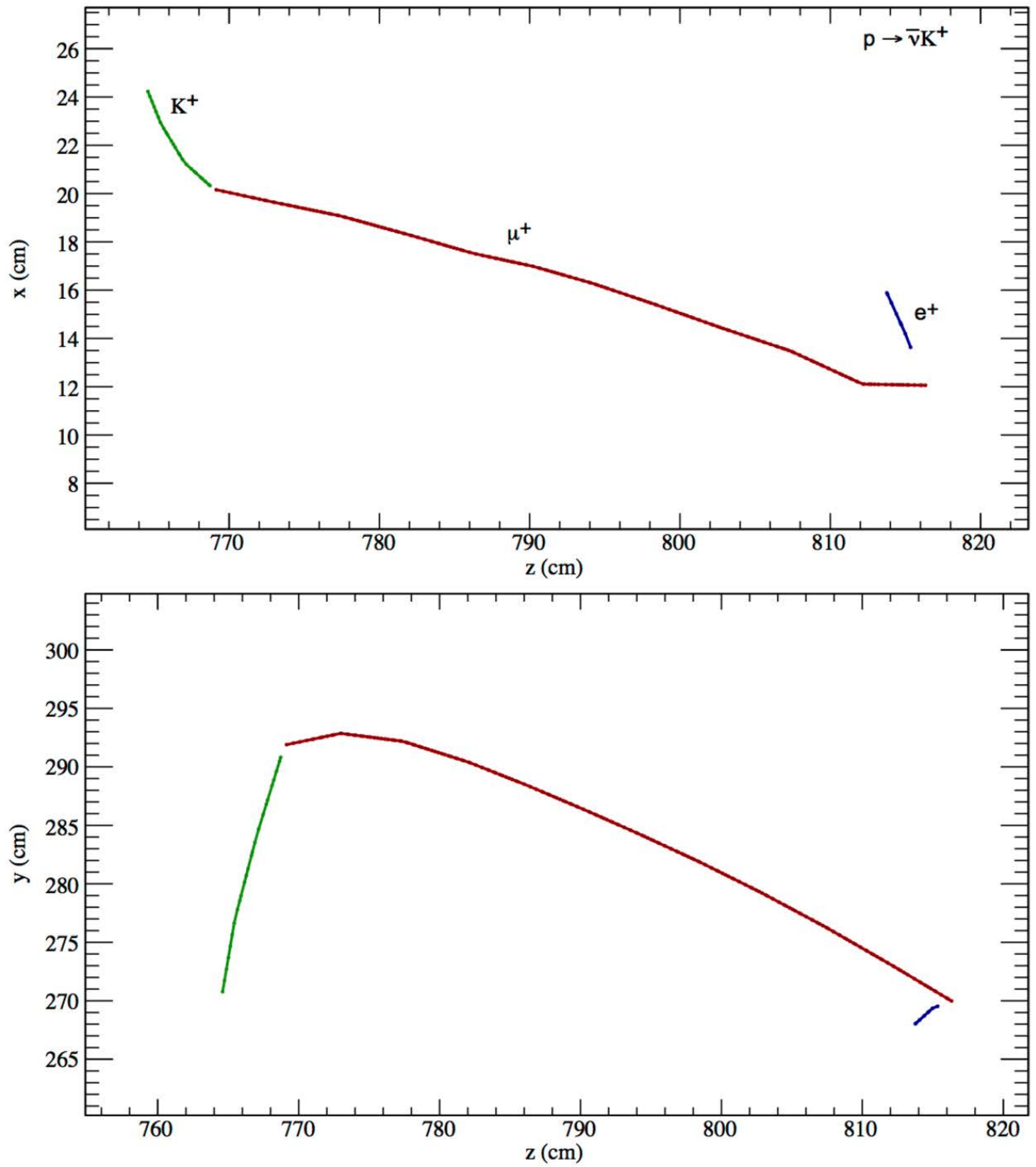
DUNE's Rich Physics Program

- Supernova physics program:
  - ★ Characterization of the time and flavor profile of supernova neutrinos for insight into collapse and evolution of supernova
  - ★ Take advantage of LArTPC's unique sensitivity to ν_e flavor



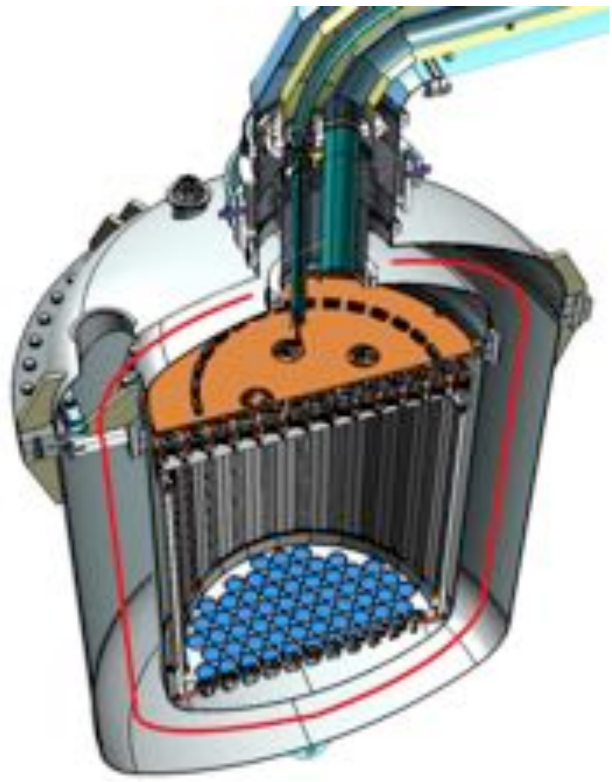
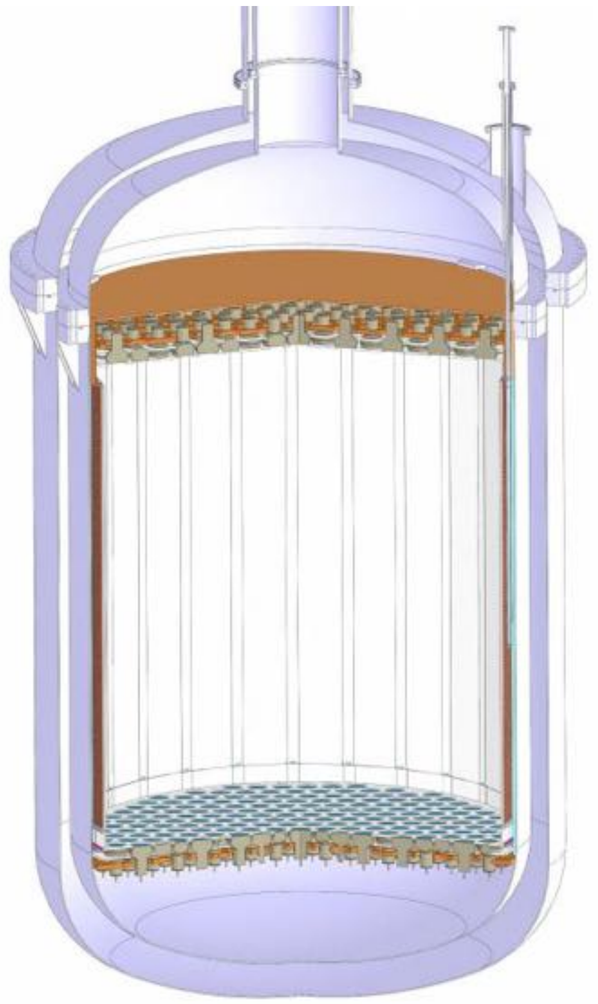
DUNE's Rich Physics Program

- Beyond standard model program, e.g. baryon number violation:
  - ★ LAr TPC technology well-suited to certain proton decay channels



DARk matter WImp search with liquid xenoN

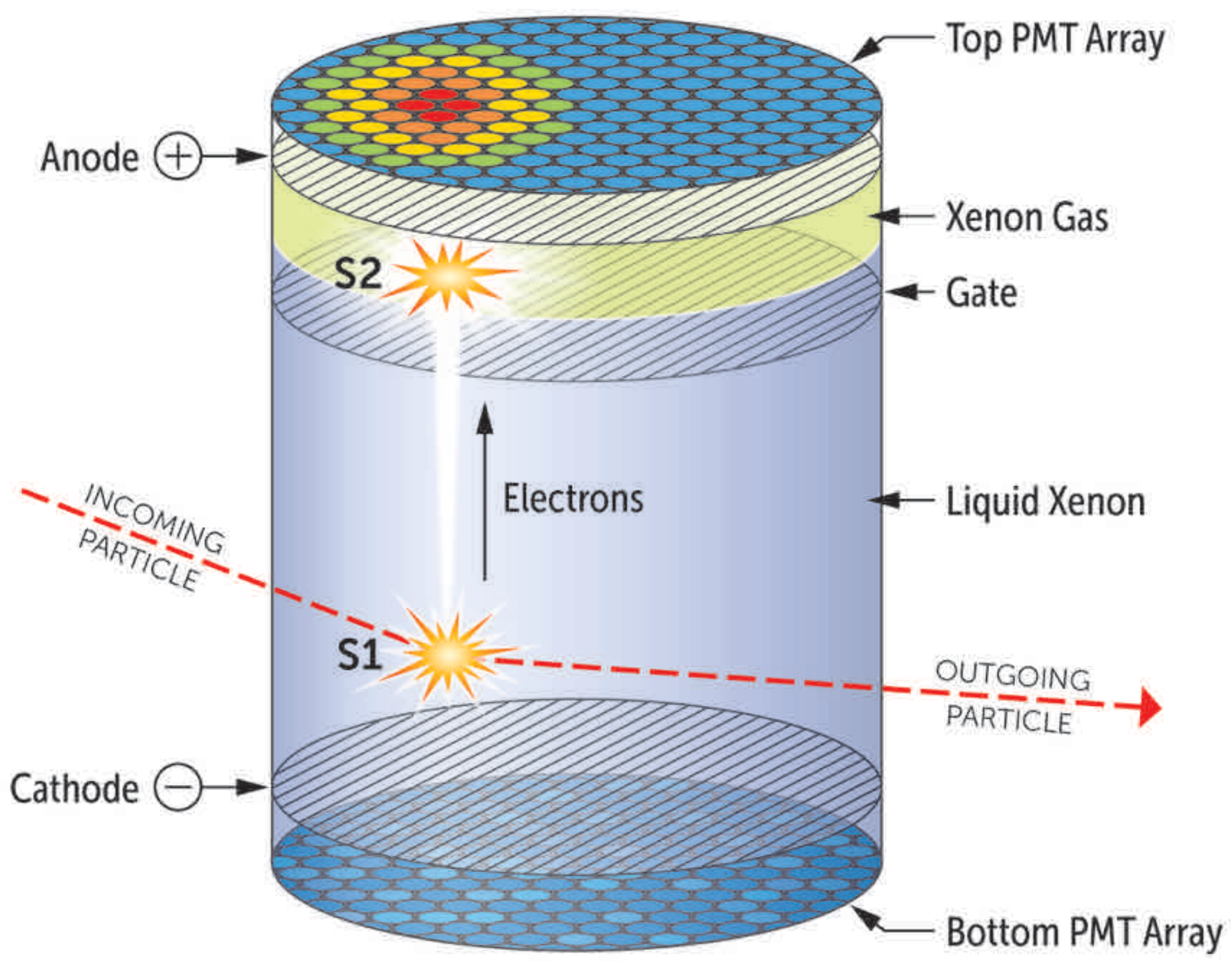
DARWIN

XENON10	XENON100	XENON1T	XENONnT	**DARWIN**
2005—2007	2008—2016	2012 – 2019	2017 – 2023	**~2023 –**
				
Past	**Past**	**Present**	**Near future**	
Total mass : 25 kg	Total mass : 161 kg	Total mass : 3.2 t	Total mass : ~8 t	**Total mass : ~50 t**
Target mass: 14 kg	Target mass: 62 kg	Target mass: 2 t	Target mass: ~6 t	**Target mass: ~40 t**
Drift TPC: 15 cm	Drift TPC: 30 cm	Drift TPC: 96 cm	Drift TPC: 144 cm	**Drift TPC: 260 cm**
Limit ~ 10^{-43} cm^2	Limit ~ 10^{-45} cm^2	Limit ~ 10^{-47}cm^2	Sensitivity ~ 10^{-48}cm^2	**Sensitivity ~ 10^{-49}cm^2**
				Future

Carla Macolino @TAUP, Sep 2019

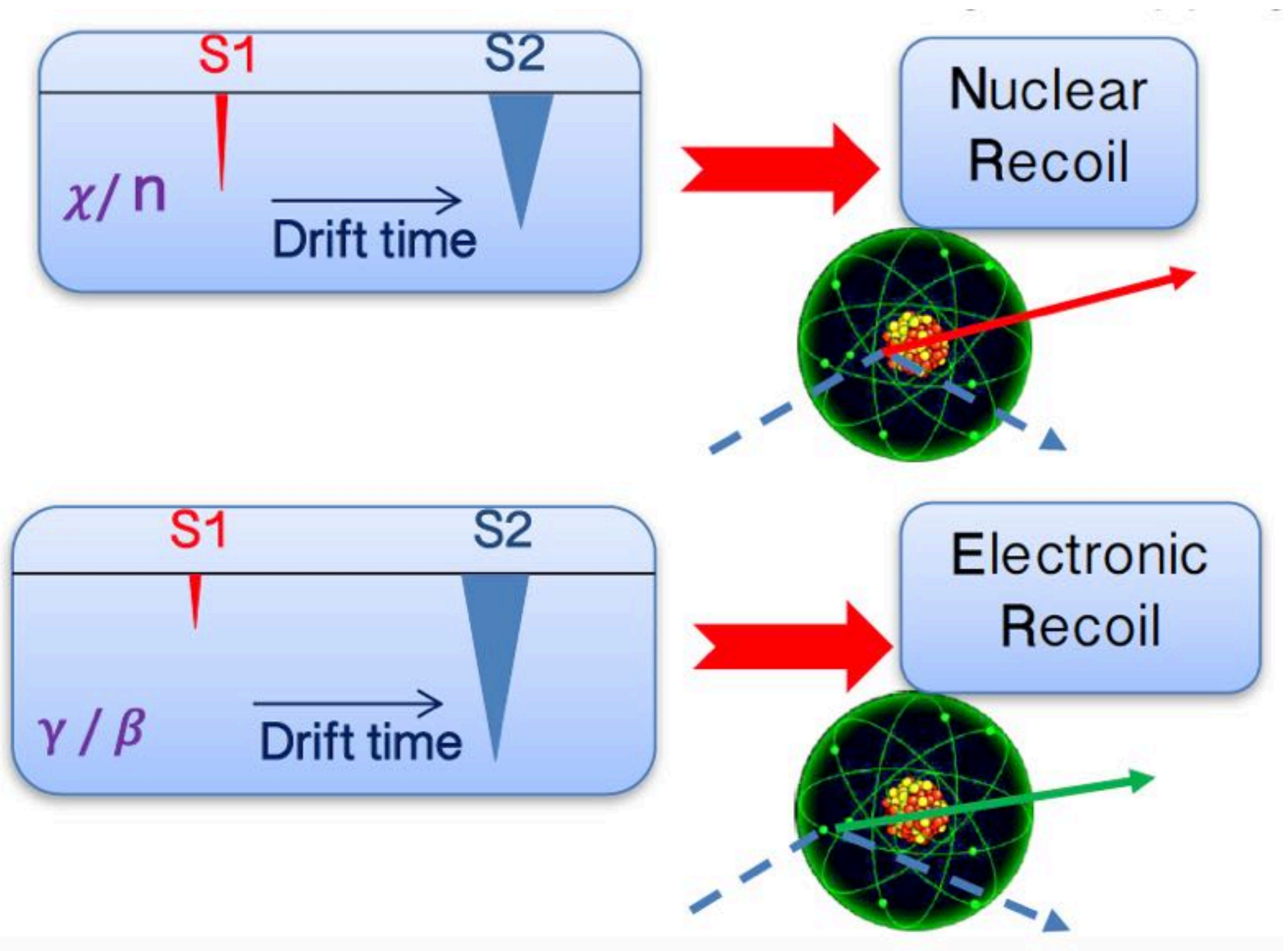
DARk matter WImp search with liquid xenoN

DARWIN



Credits: Purdue University

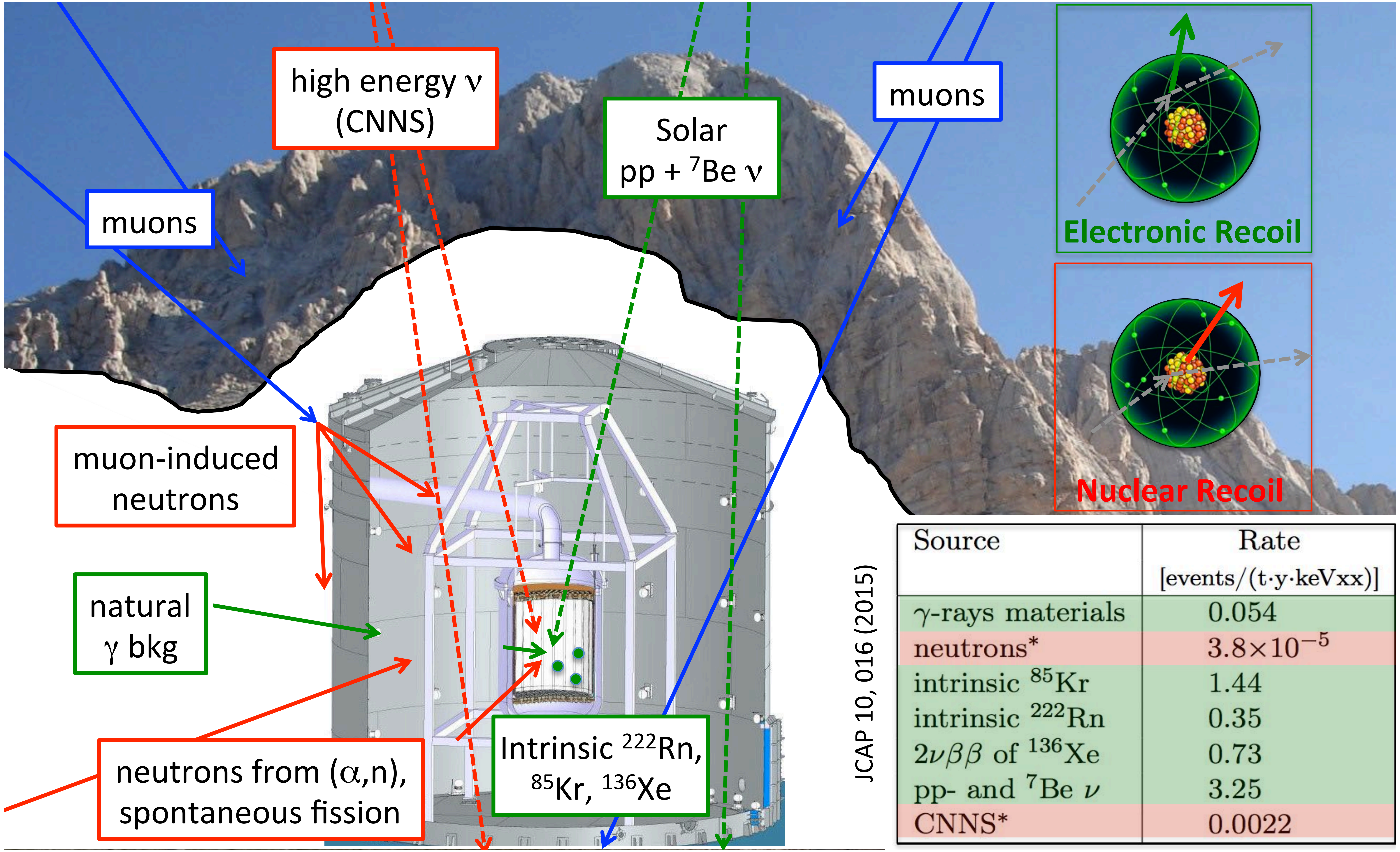
S1: prompt scintillation (light)
S2: proportional scintillation from electron drift and extraction into gas (charge)



- **Energy:** from S1 and S2
- **3D position reconstruction:**
  - x and y from S2 pattern on top PMT array
  - z from drift time
- **Electron and nuclear recoil discrimination**

$$(S2/S1)_{WIMP,n} < (S2/S1)_{\gamma,\beta}$$

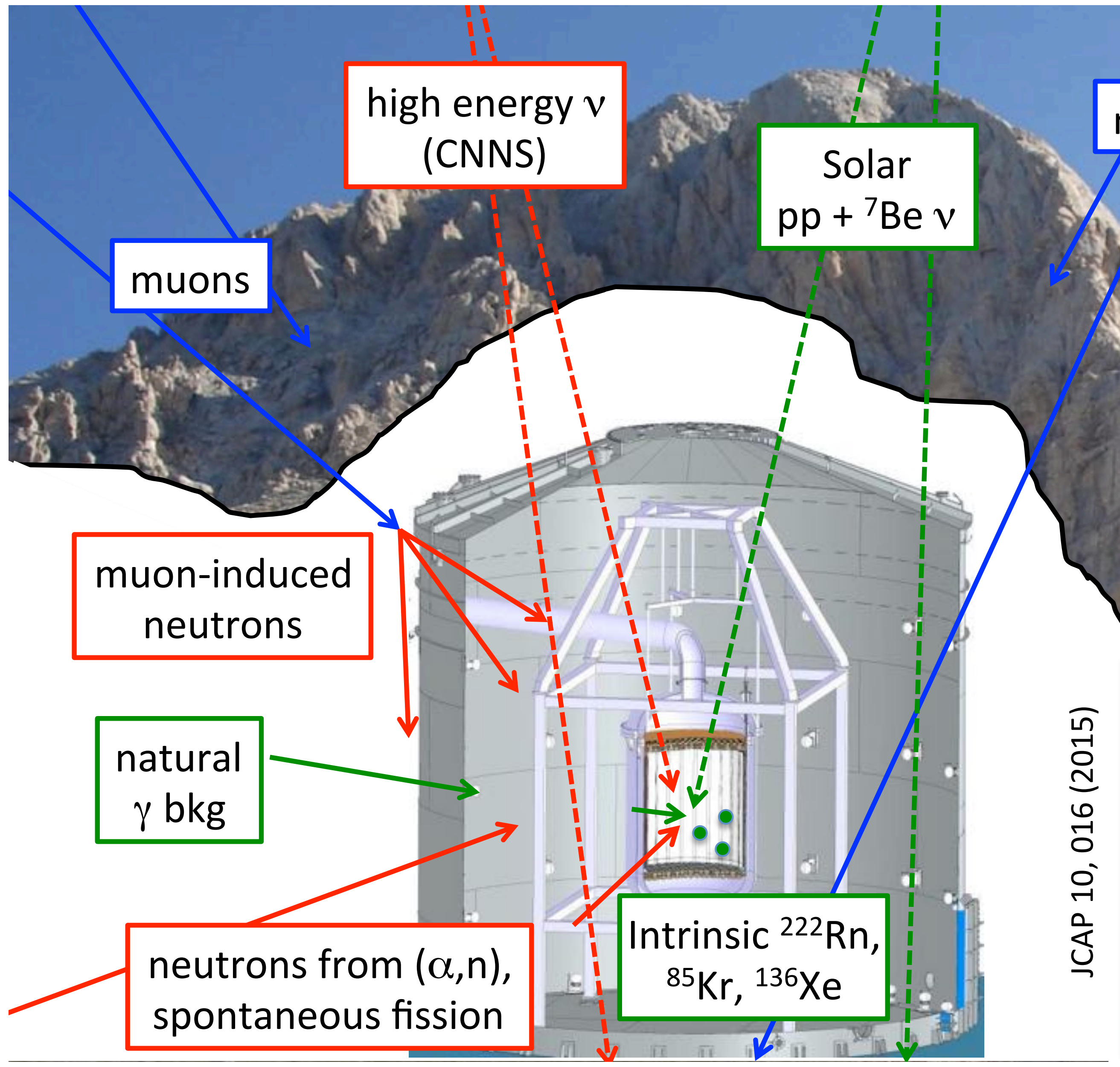
Background for DARWIN

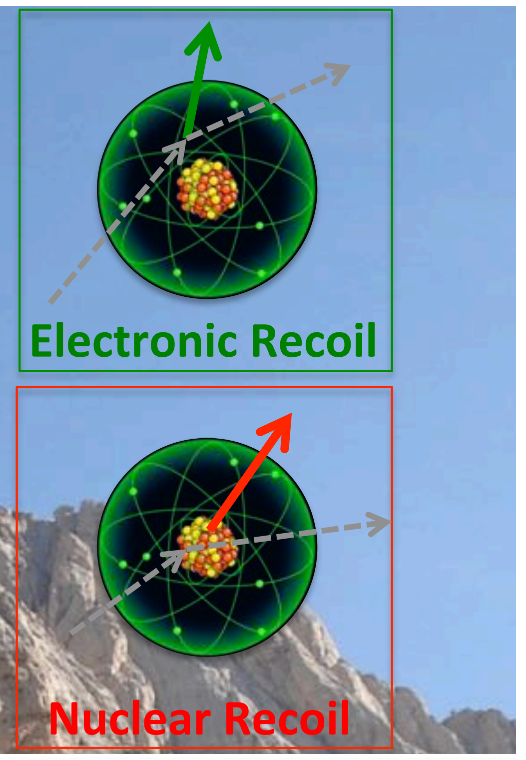


JCAP 10, 016 (2015)

Source	Rate [events/(t·y·keVxx)]
γ-rays materials	0.054
neutrons*	3.8×10^{-5}
intrinsic ^{85}Kr	1.44
intrinsic ^{222}Rn	0.35
$2\nu\beta\beta$ of ^{136}Xe	0.73
pp- and ^{7}Be ν	3.25
CNNS*	0.0022

Background for DARWIN





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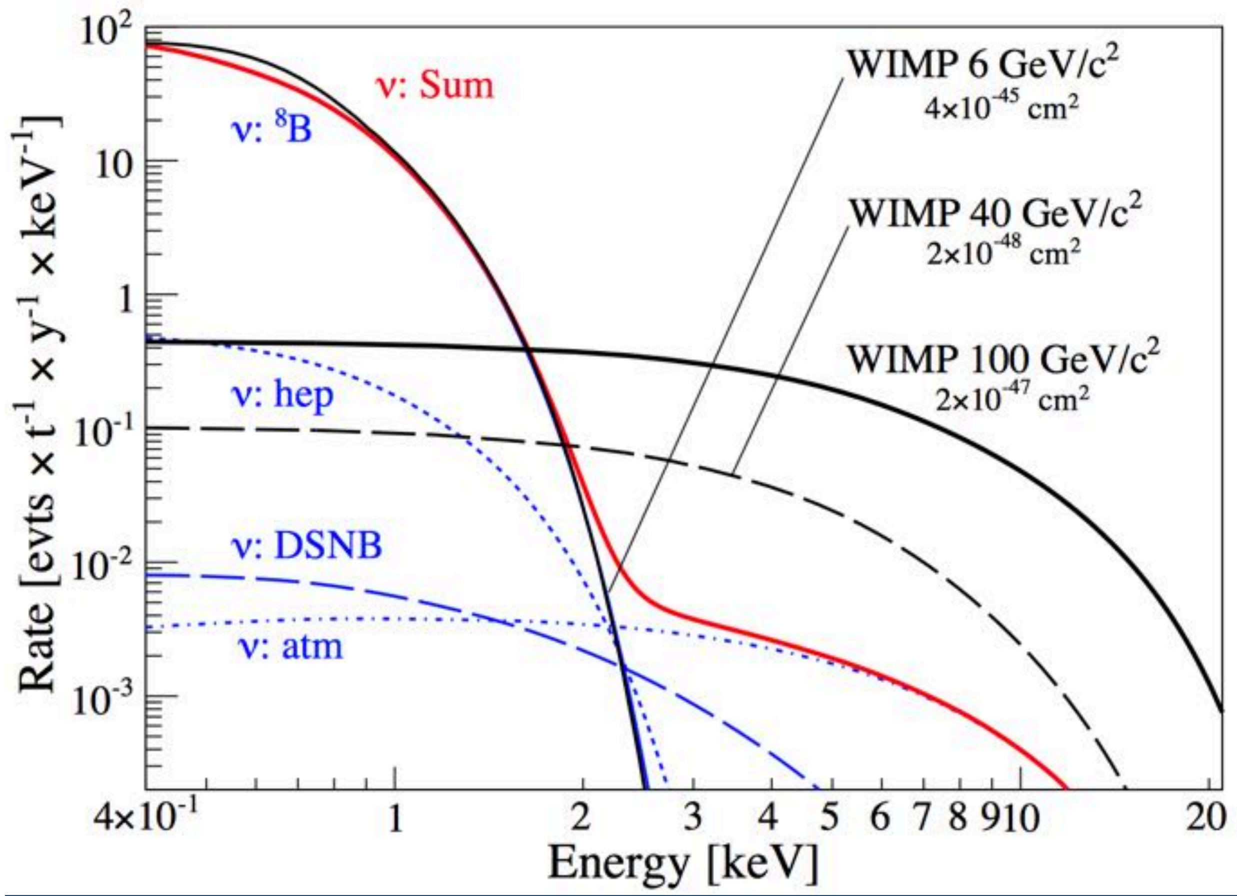
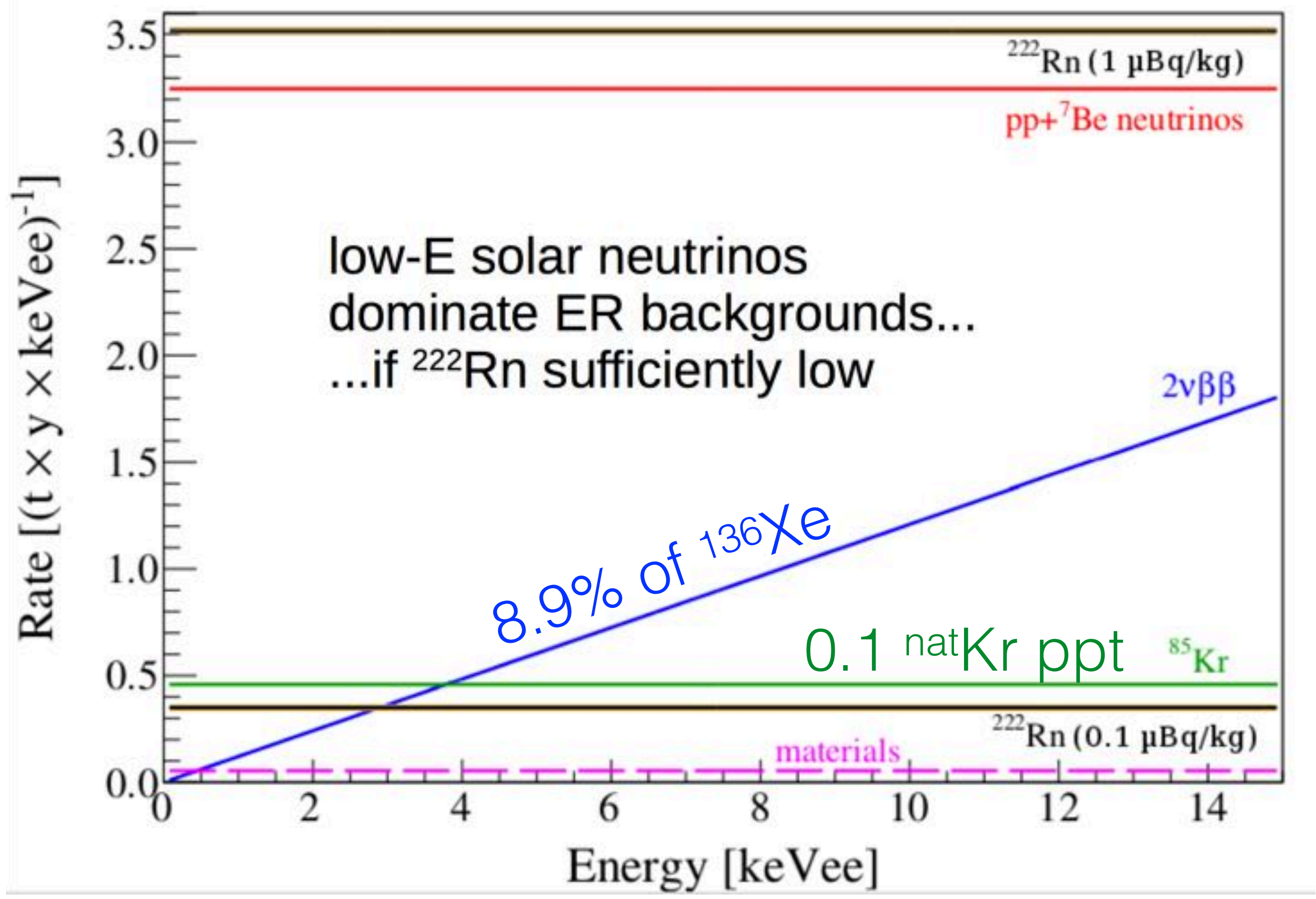
pp- and ^{7}Be ν	3.25
CNNS*	0.0022

NR: neutrinos from coherent neutrino-nucleus scattering



ER: intrinsic ^{85}Kr, ^{222}Rn

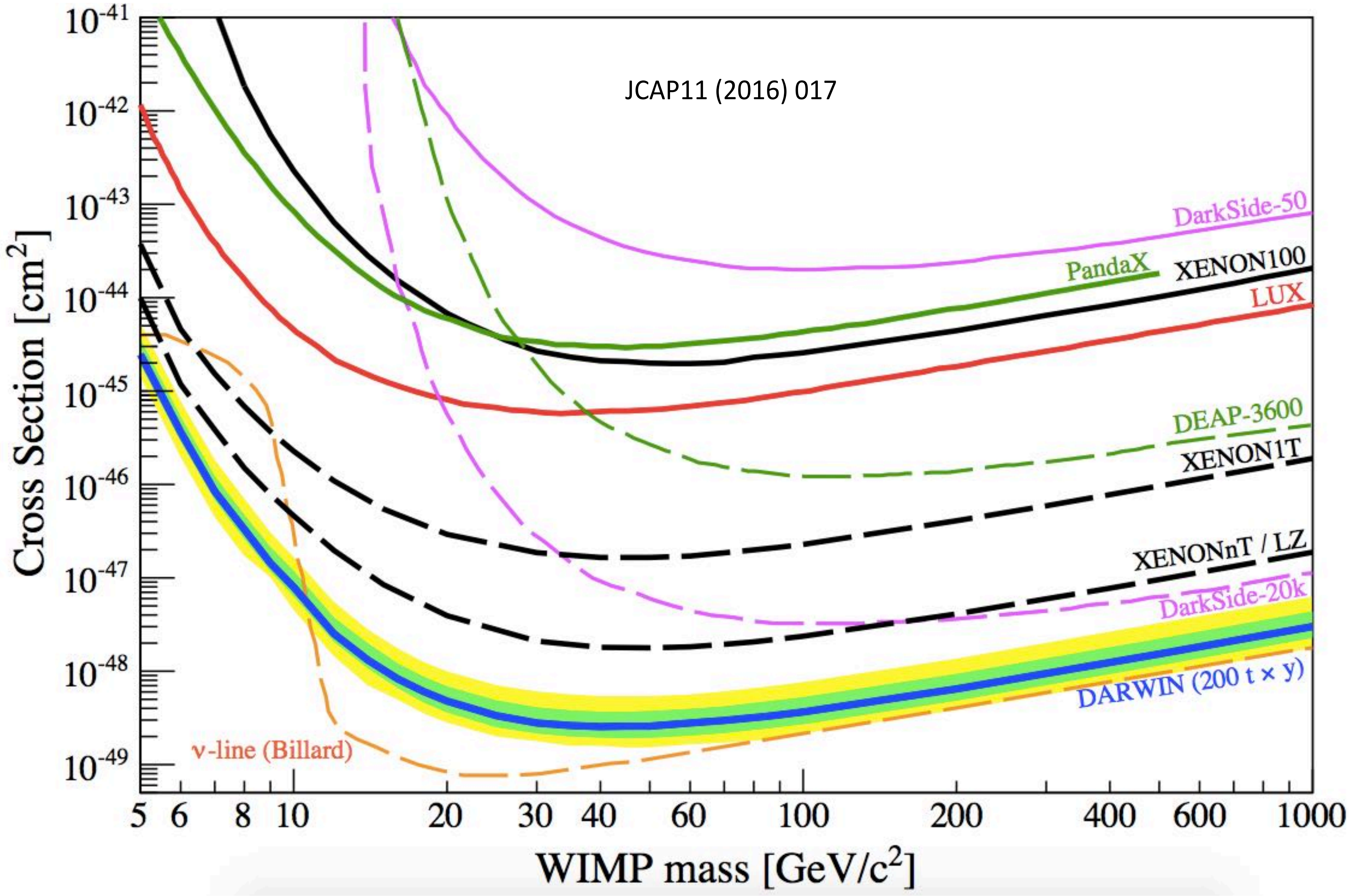
JCAP 10, 016 (2015)



WIMP search

DARWIN

Spin-independent WIMP-nucleon interaction

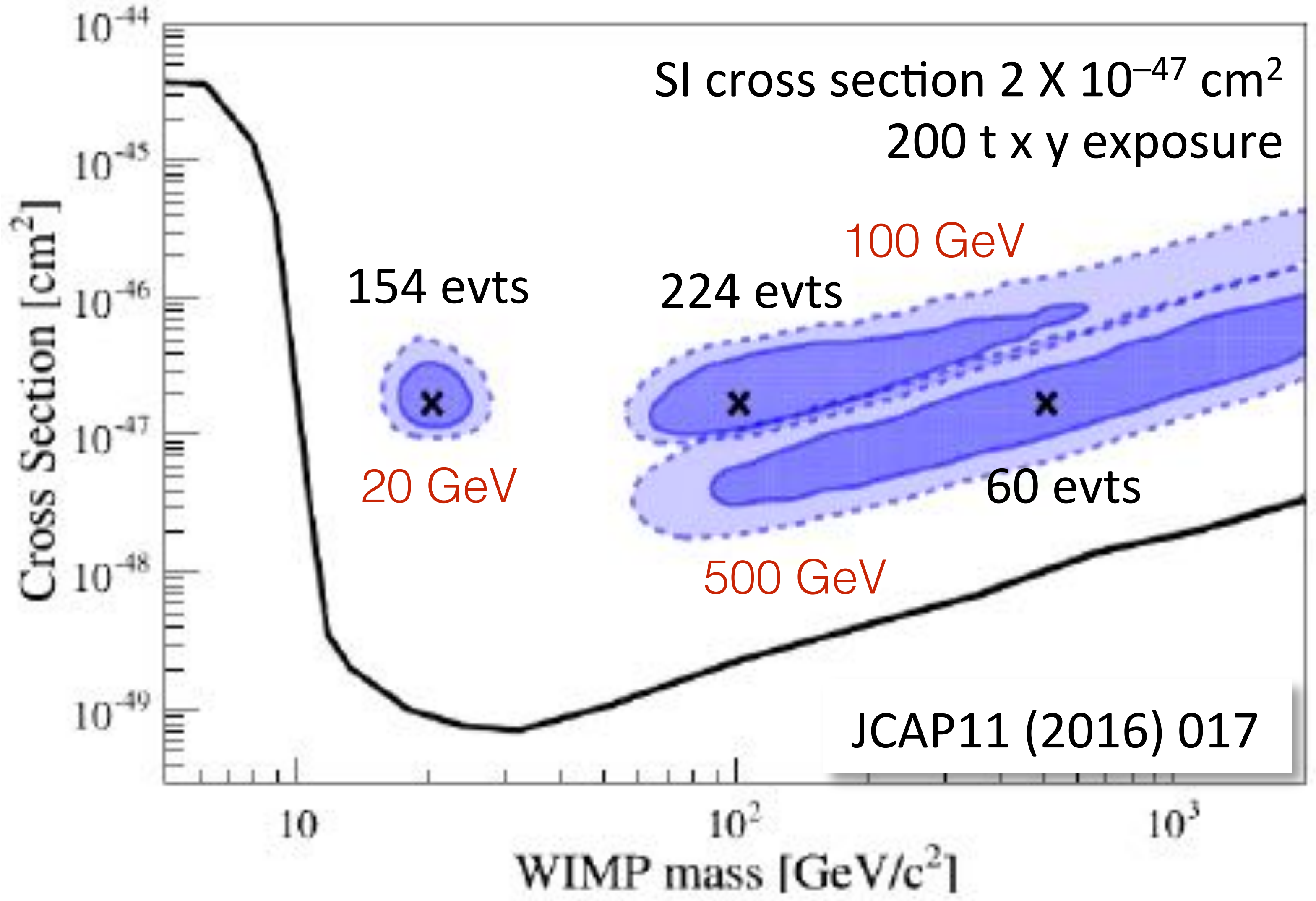


- **30 tons of fiducial volume**
- **99.98% ER rejection at 30% NR acceptance**
- **Light yield 8 PE/keV at 122 keV, Energy window 5-35 keV_{NR}**
- **Sensitivity: ~10^{-49} cm^2**

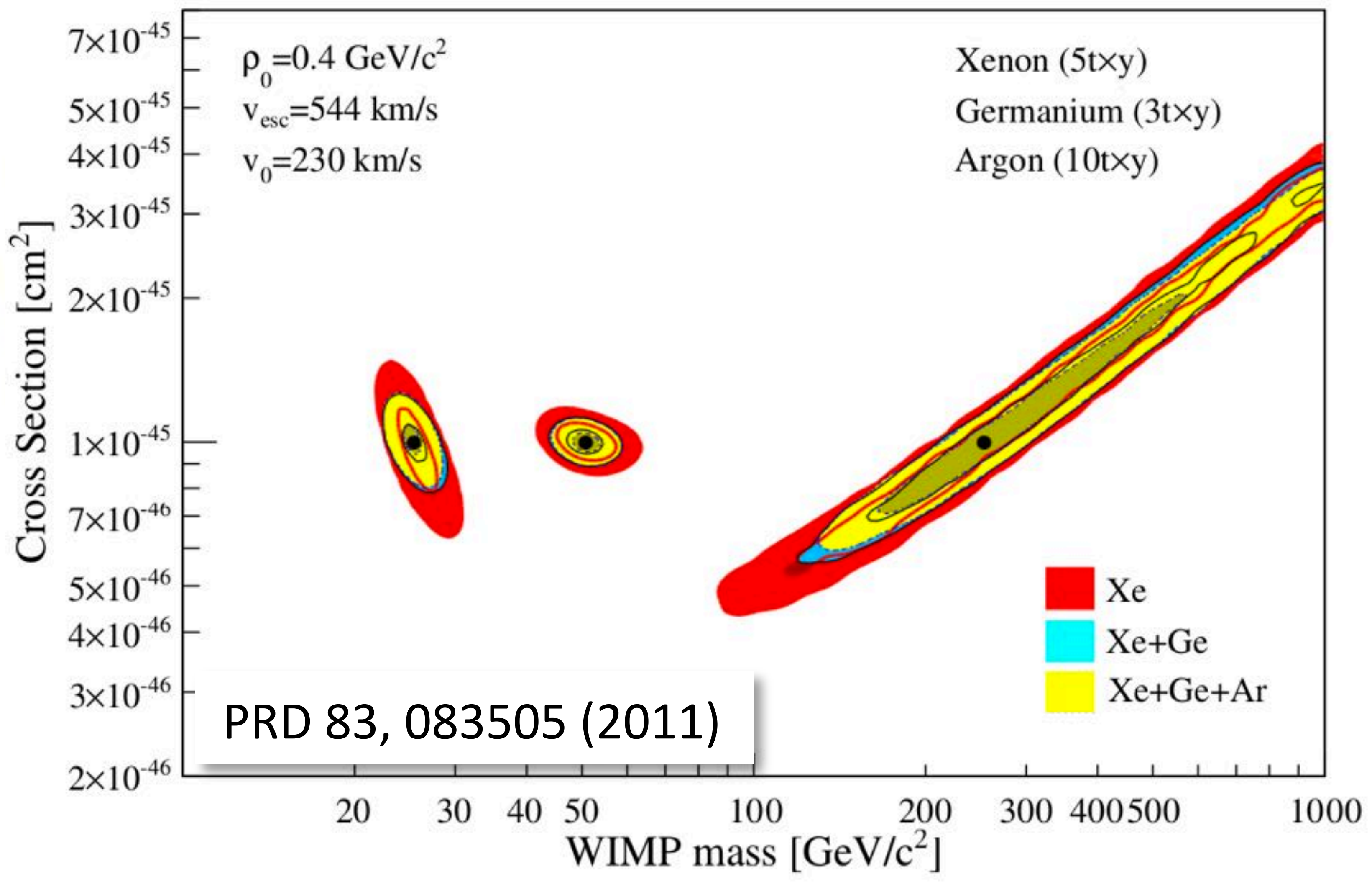
WIMP spectroscopy

DARWIN

WIMP properties



Target complementarity



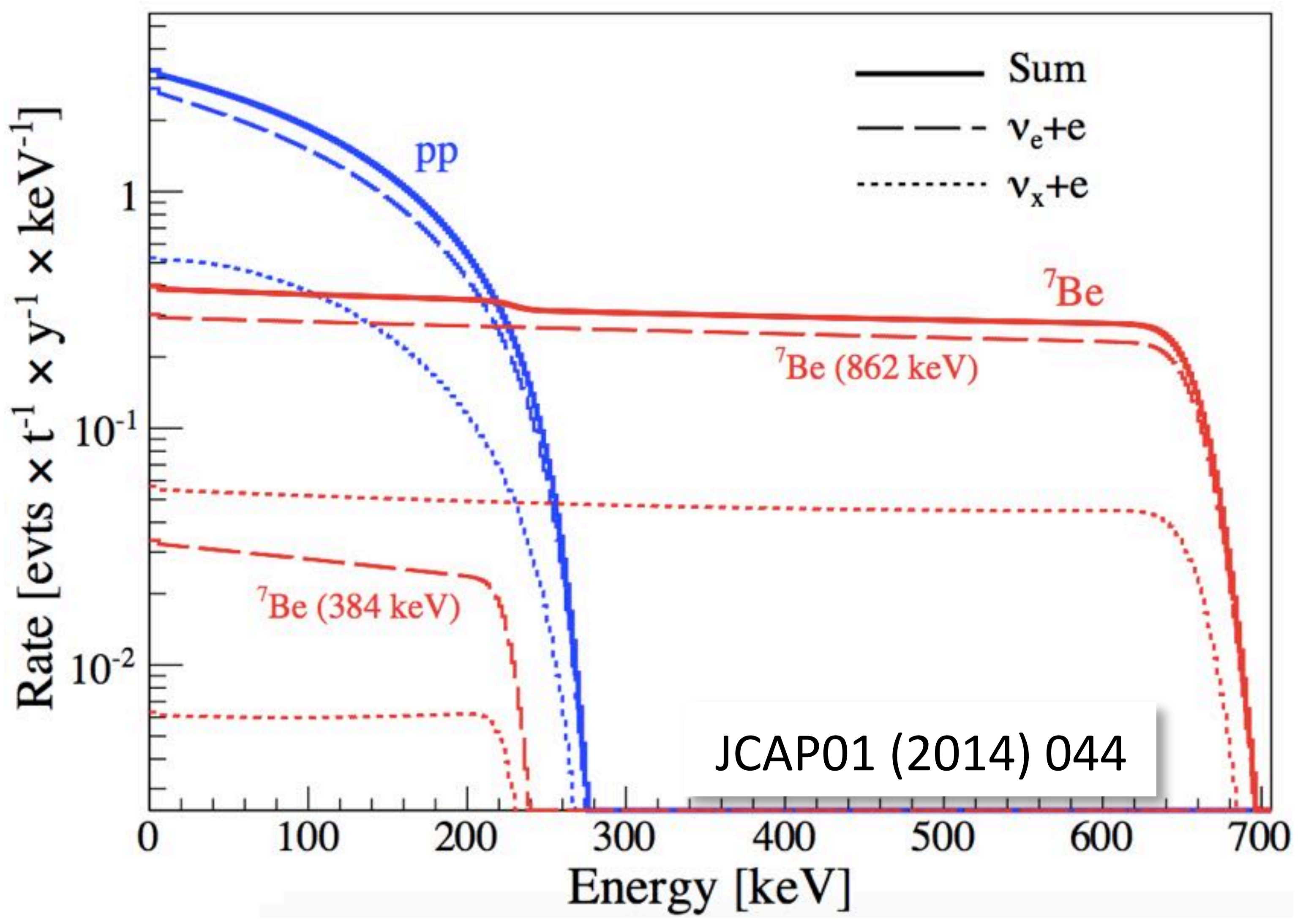
- Reconstruction of WIMP mass and scattering cross section
- 1σ, 2σ credibility regions for 20, 100 and 500 GeV/c^2 marginalised over astrophysical parameters uncertainties
- Few 100 GeV can be constrained

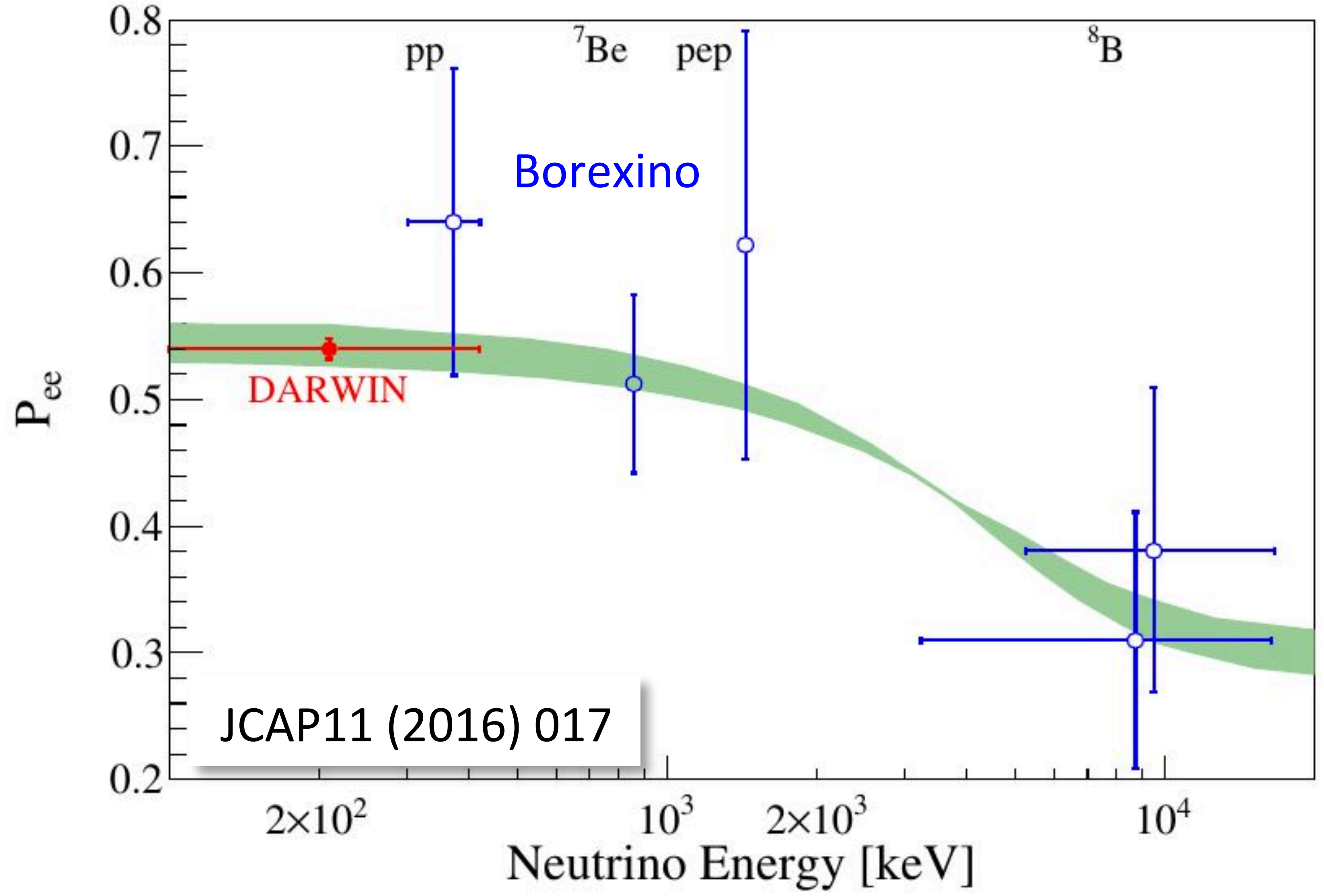
- Parameters reconstruction improves with information from Ge detectors

Solar neutrinos

DARWIN

Solar pp and ^{7}Be neutrinos





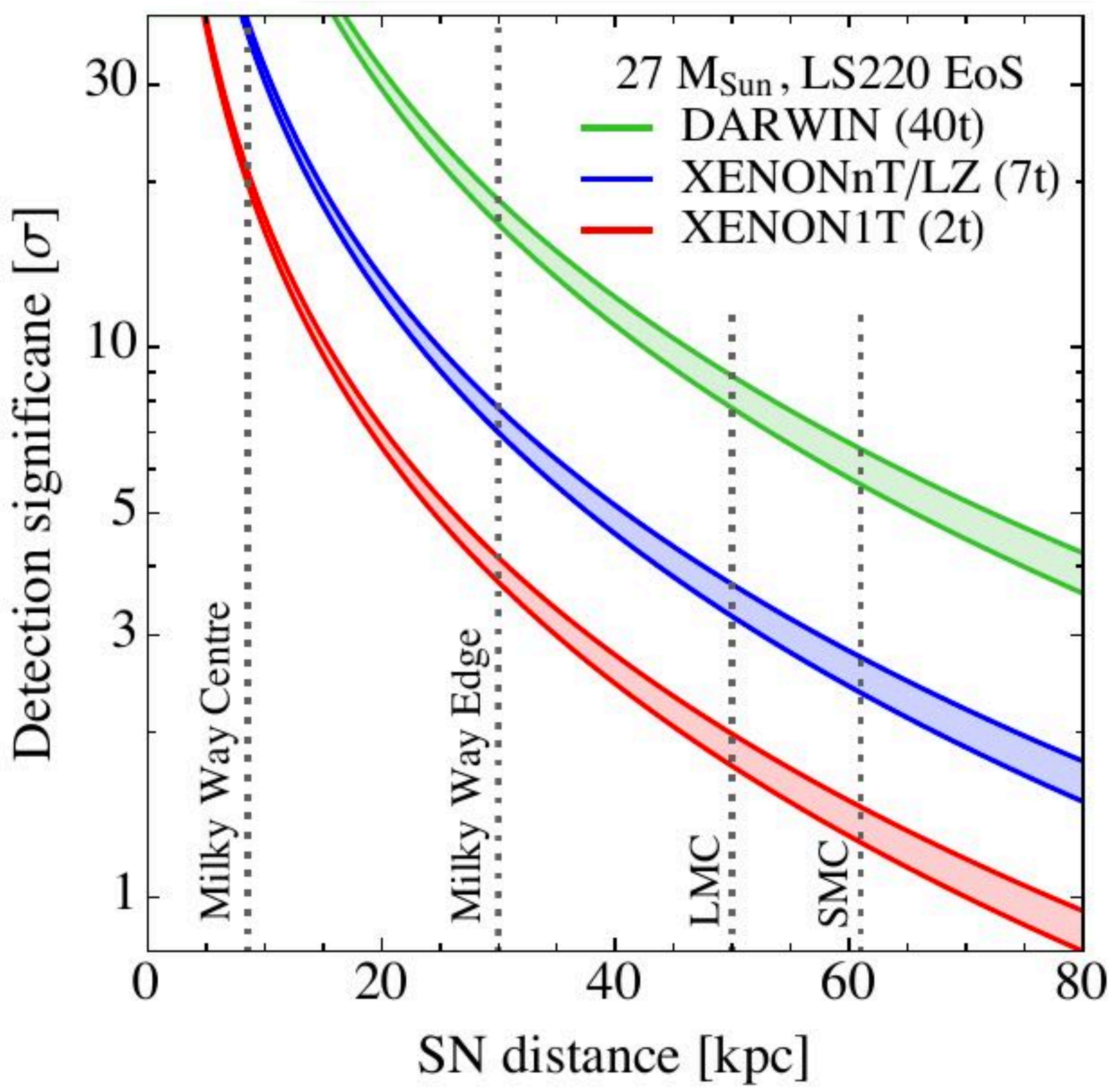
- Continuous recoil spectrum at low energy
- Expected events at 2-30 keV and 30 t fiducial mass:
  - 7.2 cts/day for pp neutrinos
  - 0.9 cts/day for ^{7}Be neutrinos
- 2%(1%) stat. precision after 1 year (5 years)

- Neutrinos survival probability
- 2850 pp neutrinos/year
- 1% stat. precision with 100 ton x year exposure

SuperNova neutrinos

- Coherent neutrino-nucleus scattering
- Low threshold with S2-only events
- 5σ significance to a SN burst up to ~65 kpc from Earth
- ~700 events from a SN progenitor at 10 kpc
- Can get precise time evolution informations and constrain SN models

Phys. Rev. D 94 (2016) no.10, 103009



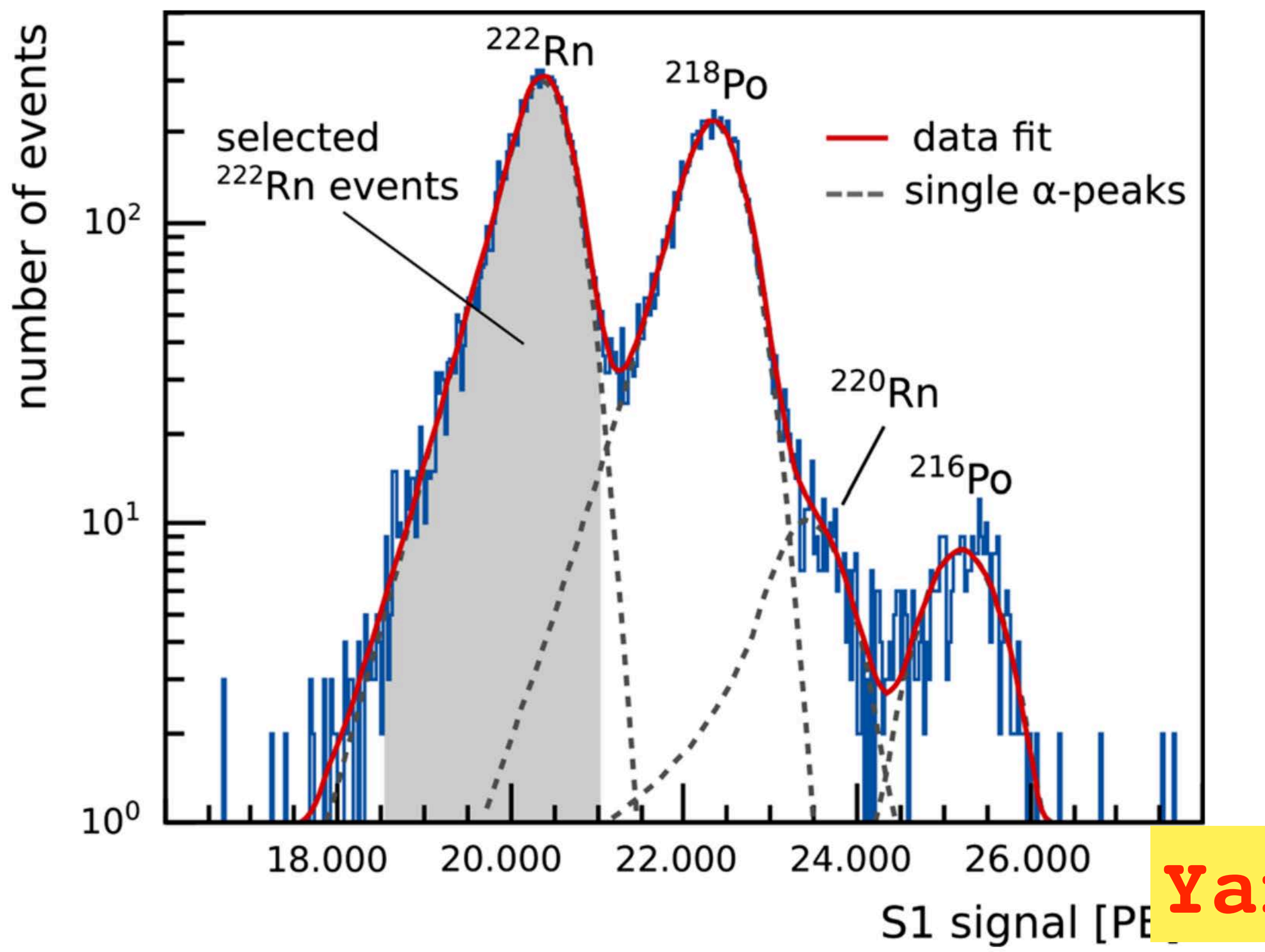
BACKGROUND CONTRIBUTIONS AROUND ^{136}XE Q-VALUE

DARWIN

Contaminants in LXe

- The noble gas ^{222}Rn ($T_{1/2} \approx 3.8$ days) from ^{226}Ra ($T_{1/2} \approx 1600$ years), mixes with the xenon with beta decays from this chain.
- ^{214}Pb and daughters a**dhere** to material surfaces (**plate-out**) and can lead to **(α, n) reactions**
- Contamination assumption $0.1\mu Bq/kg$

XENON Collaboration, Eur. Phys. J. C (2017) 77:358

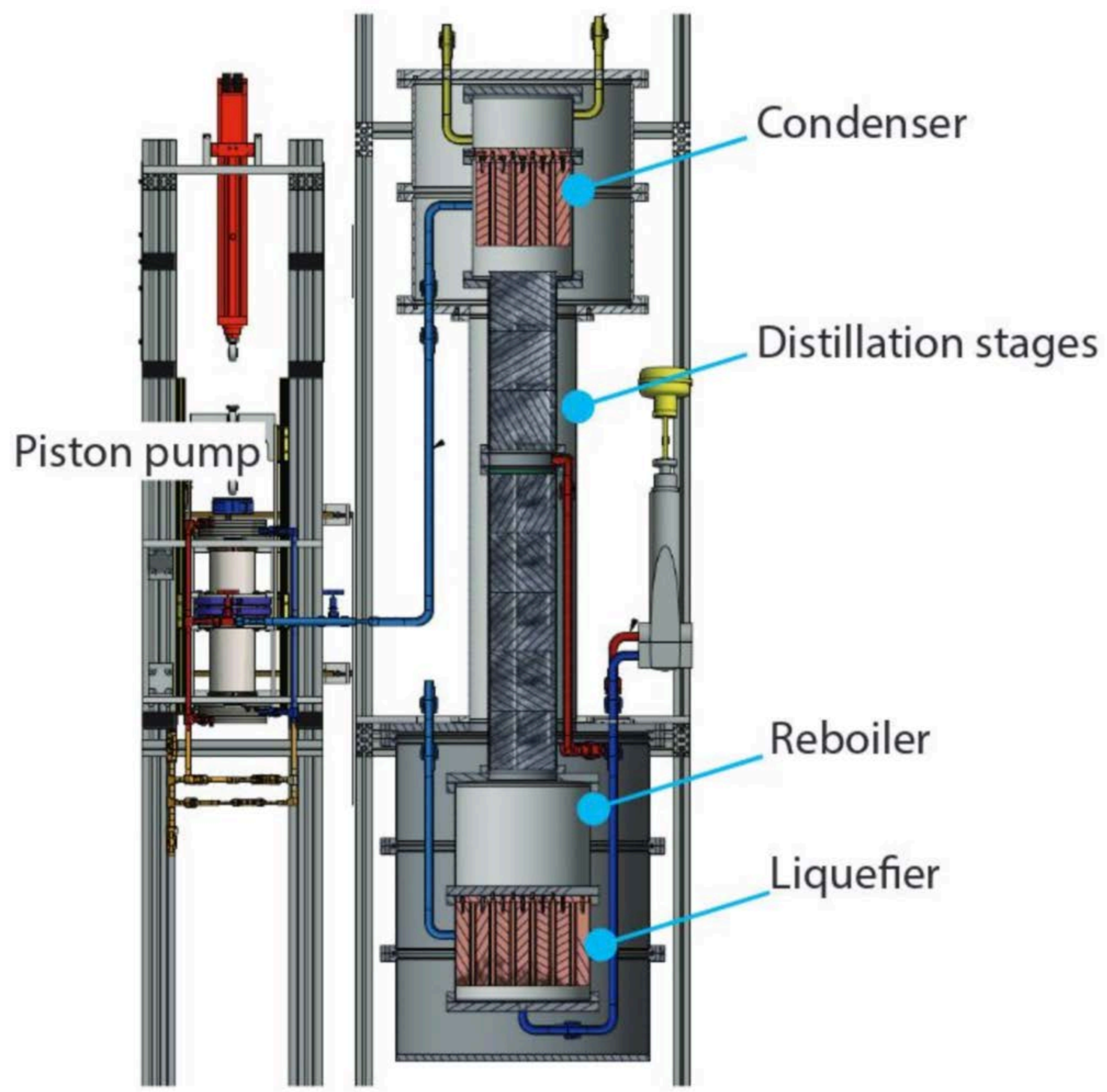


Bi-Po : 99.8% tagging efficiency and suppression

Removal by cryo-distillation columns

More info in Michael Murra's Poster

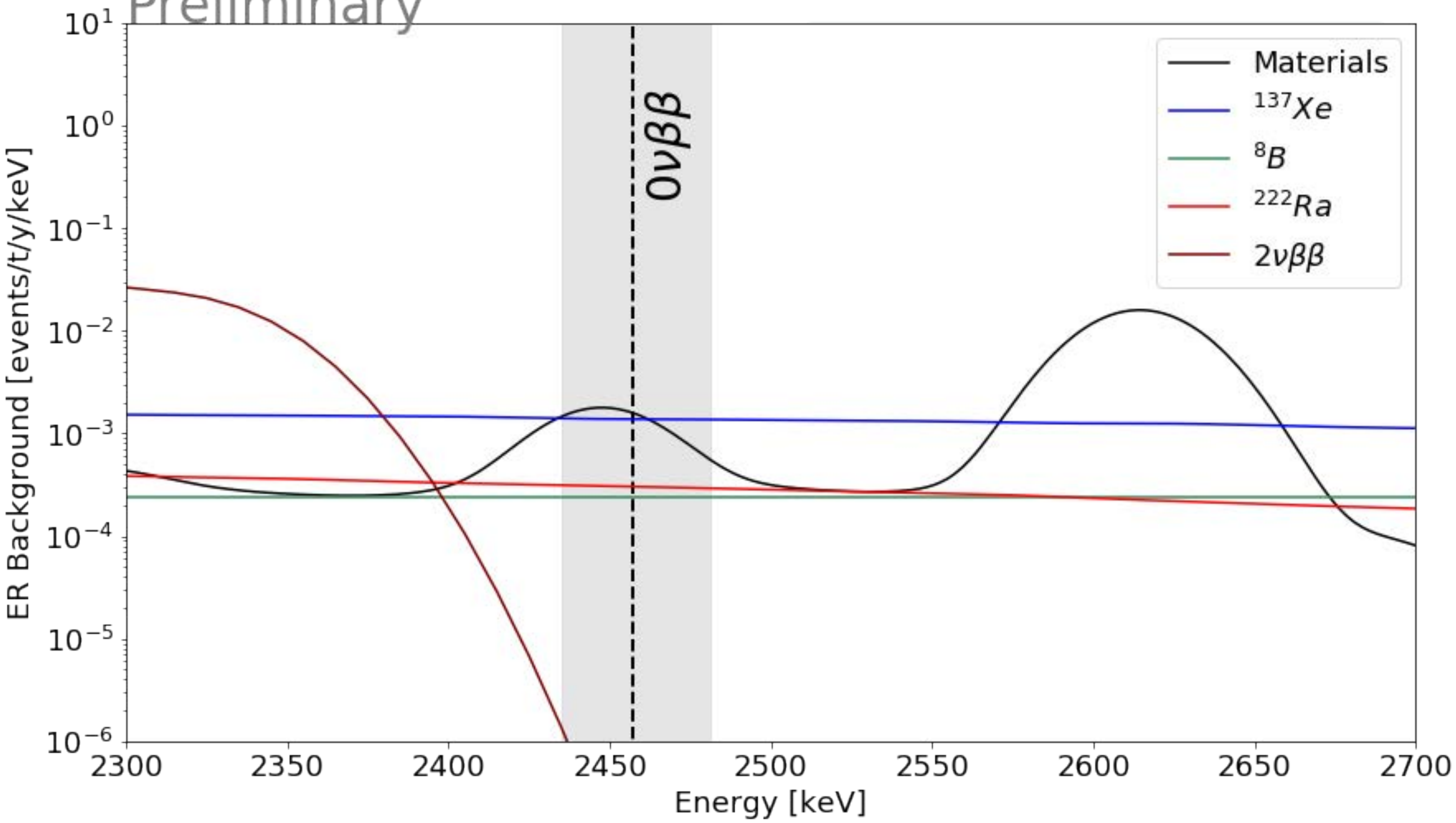
XENON Collaboration



Yanina Biondi @TAUP, Sep 2019

DARWIN'S BACKGROUND BUDGET

6 tonne fiducial mass



Contributions in
ROI 2435-2481 keV*:

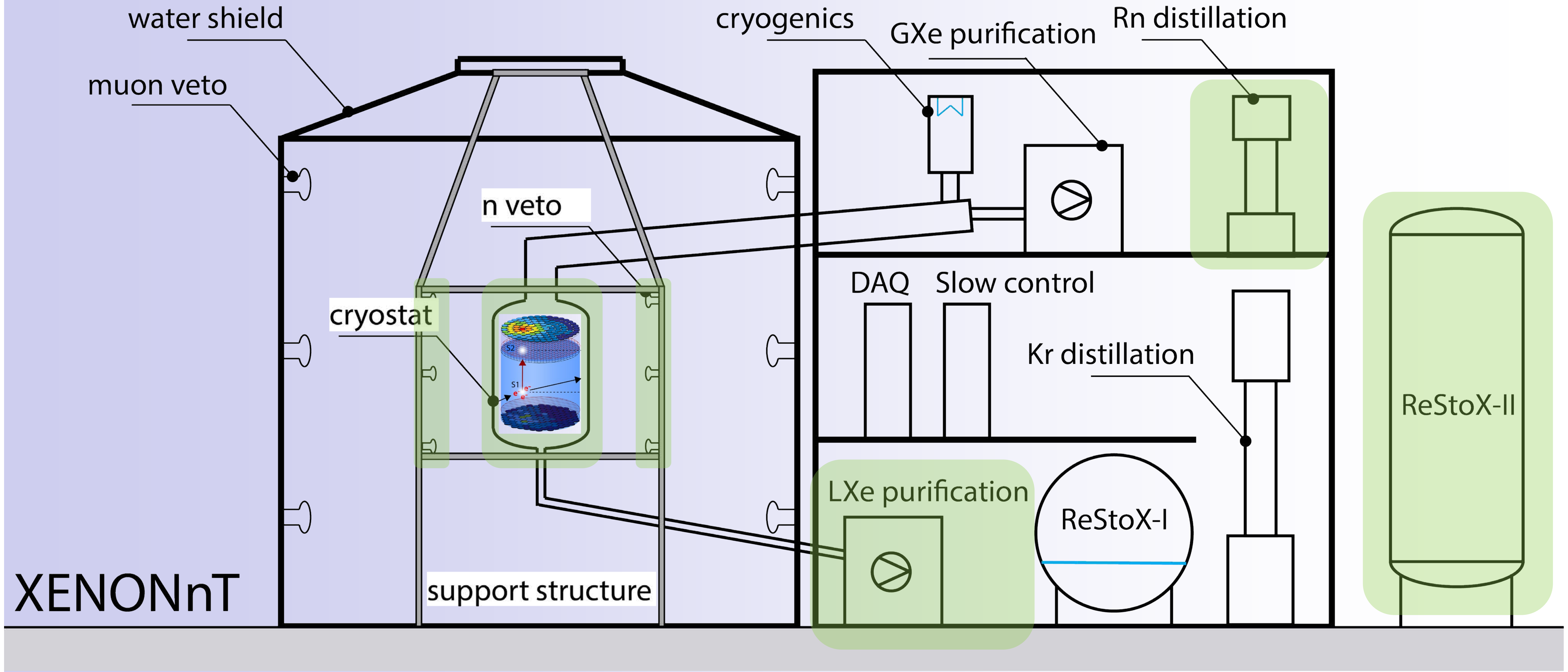
Background	Events/(t y keV)
^{8}B	2.4×10^{-4}
^{137}Xe	1.4×10^{-3}
^{136}Xe	3.7×10^{-7}
^{222}Rn	3.0×10^{-4}
Materials	$1.3 \pm 0.2 \times 10^{-3}$

* FWHM with energy resolution 0.8%, PMT for both arrays scenario

Currently performing a profile likelihood test to calculate the sensitivity with the optimal mass

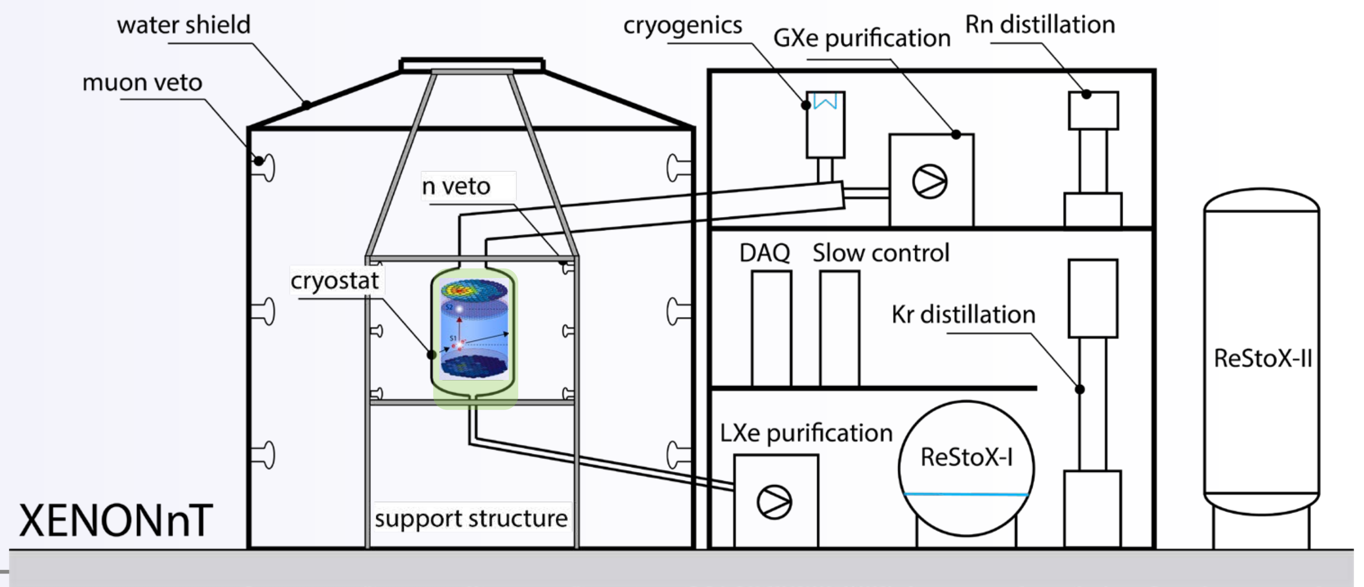
Yanina Biondi @TAUP, Sep 2019

From XENON1T to *XENONnT*



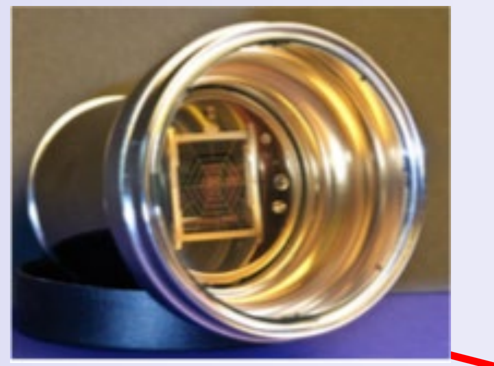
Auke Colijn @TAUP, Sep 2019

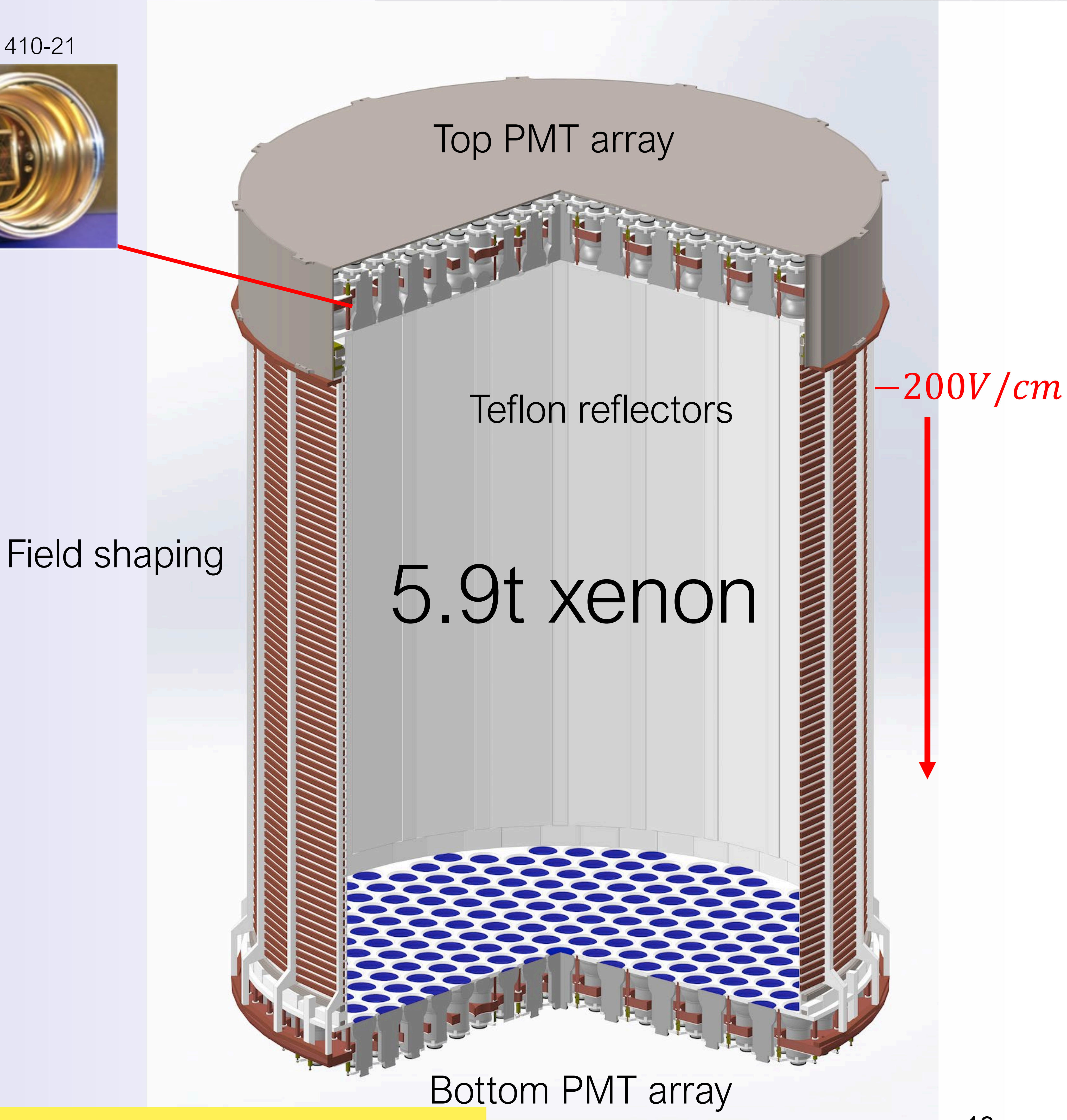
Time Projection Chamber (new)



- 5.9 t liquid target in TPC
- 494 PMTs
    1. Hamamatsu 3” R11410-21
    2. 253 top + 241 bottom
    3. 1T recycled + new
- 1.48 m drift length
- 1.33 m diameter
- PTFE reflectors & Cu field shaping rings

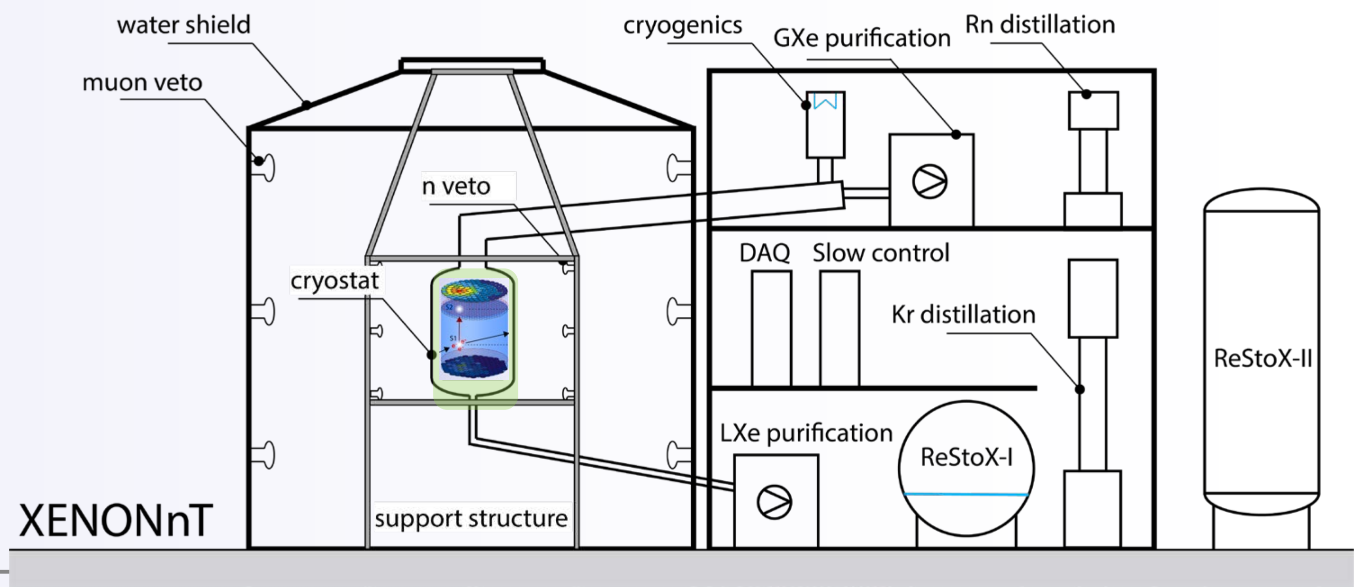
3” R11410-21



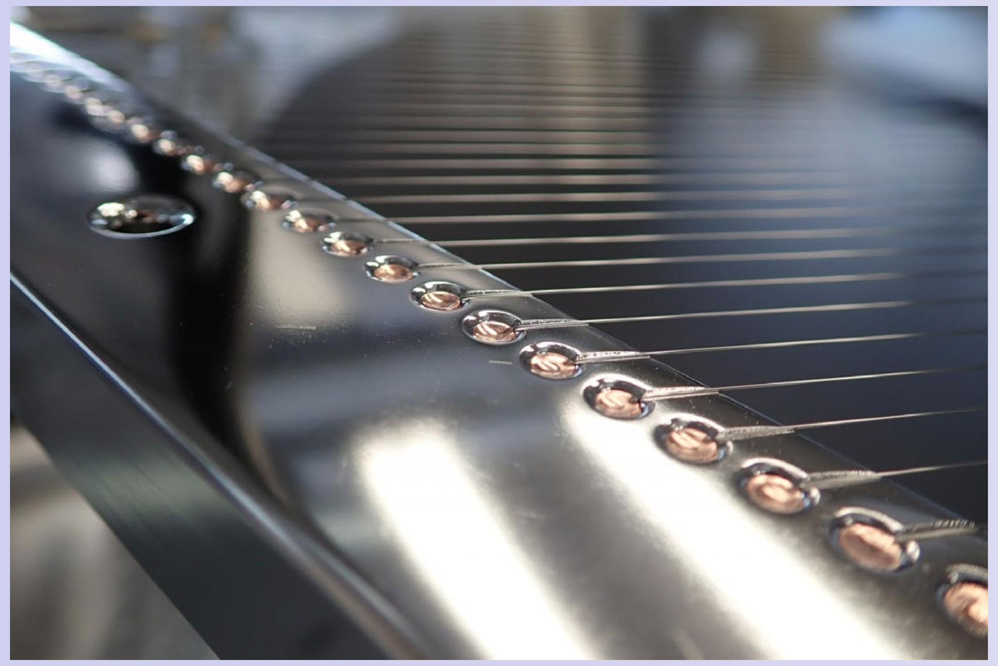


Auke Colijn @TAUP, Sep 2019

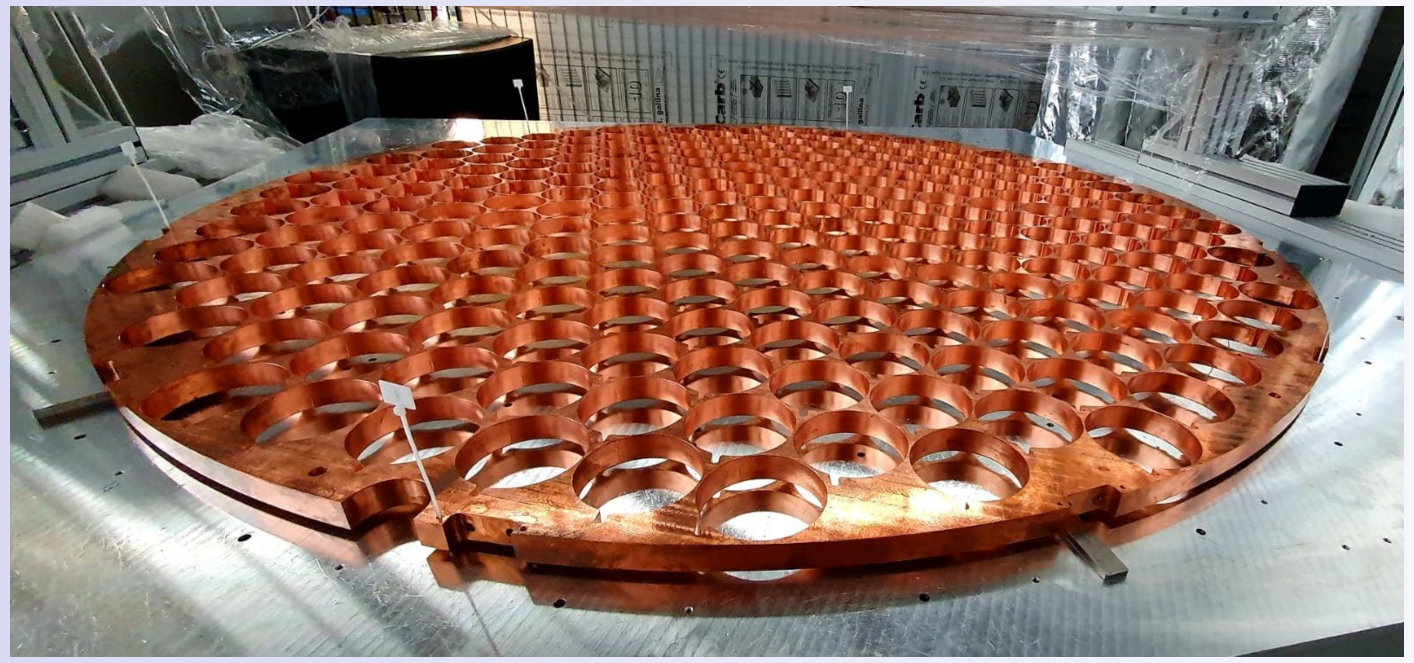
Time Projection Chamber (new)



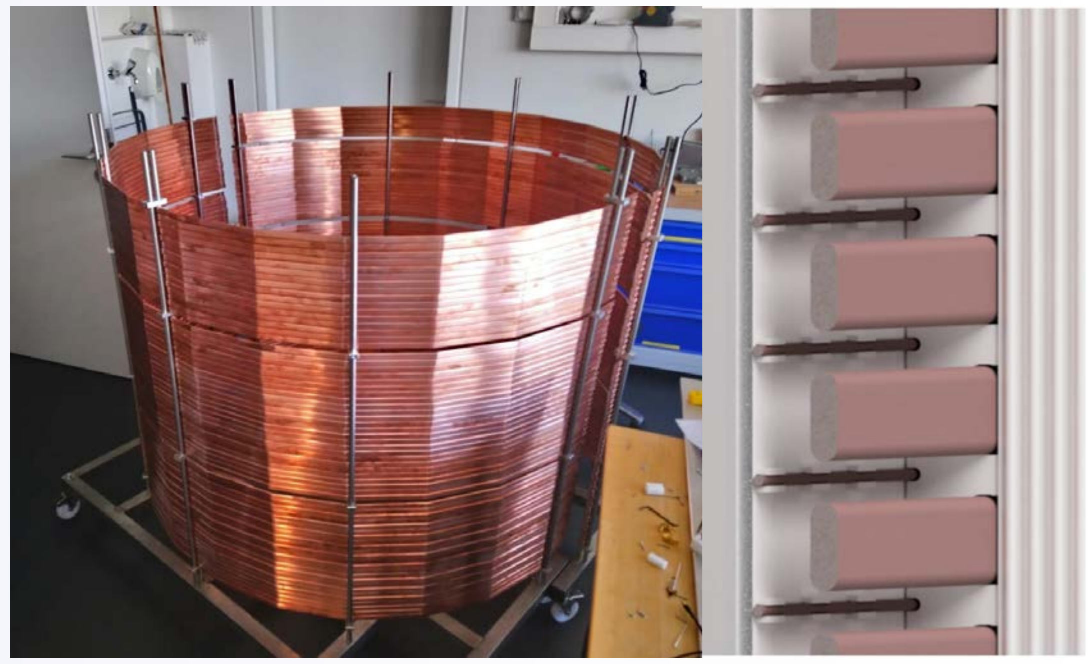
Five electrodes Poster C. Macolino



PMT array – still without the PMTs

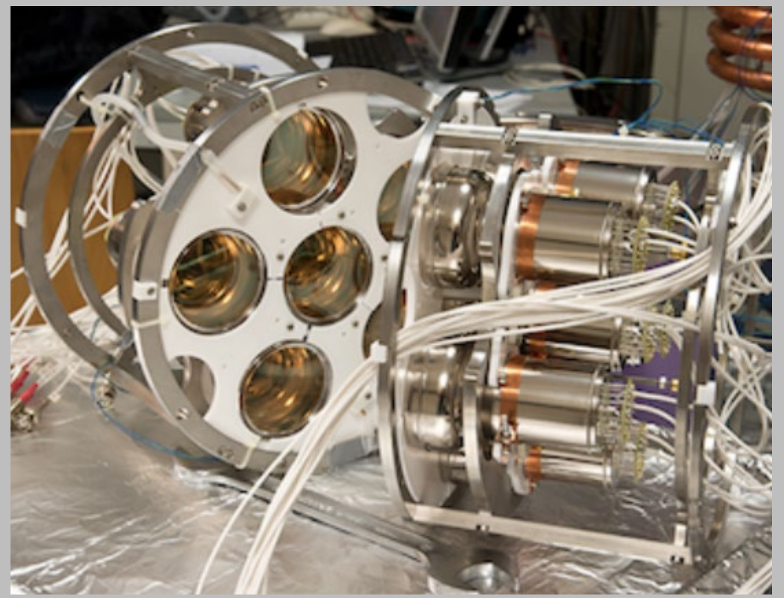


Field shaping rings – novel design



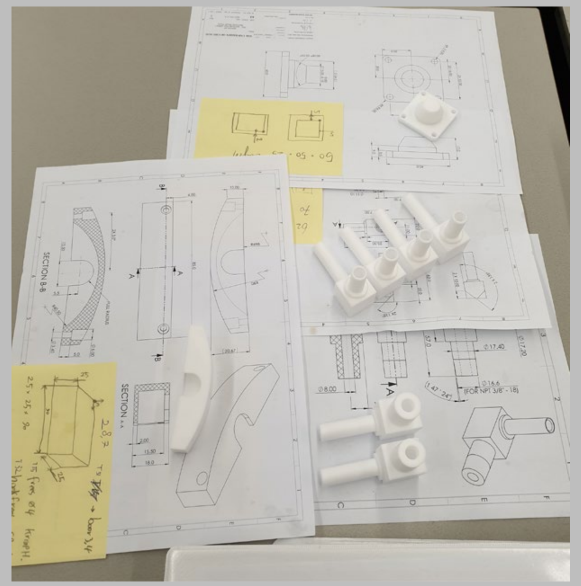
PMTs for nT

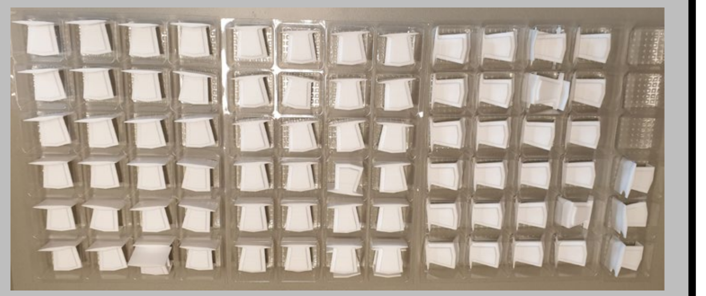
1. Improved leakrate
2. Improved light emission



All PMTs in hand & qualified

TPC part production – lots of Tefon





…. and material screening

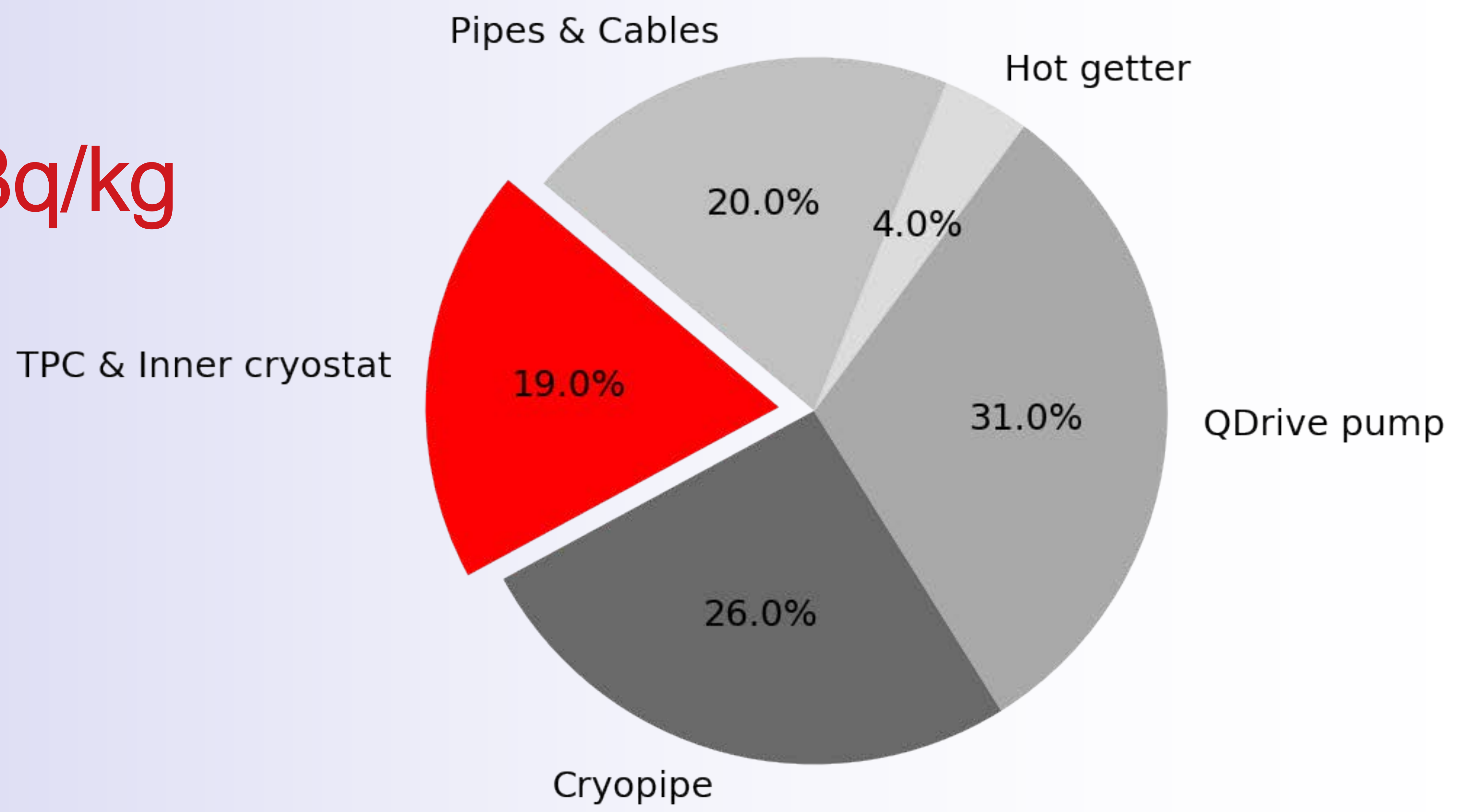
1. Rn emanation
2. U, Th daughters, K, Co,….

Purification: ^{222}Rn in XENON1T

Type I sources (a.k.a. worst radon)

- Emanation of Rn *inside* the TPC & inner cryostat: ~19%
- **diluted** by fast recirculation through Rn removal system

Total Type I+II: ~10 µBq/kg



Type II sources (a.k.a. bad radon)

- Emanation of Rn *outside* the TPC
- **fully removed** by extraction of GXe and pass through Rn removal system

Auke Colijn @TAUP, Sep 2019

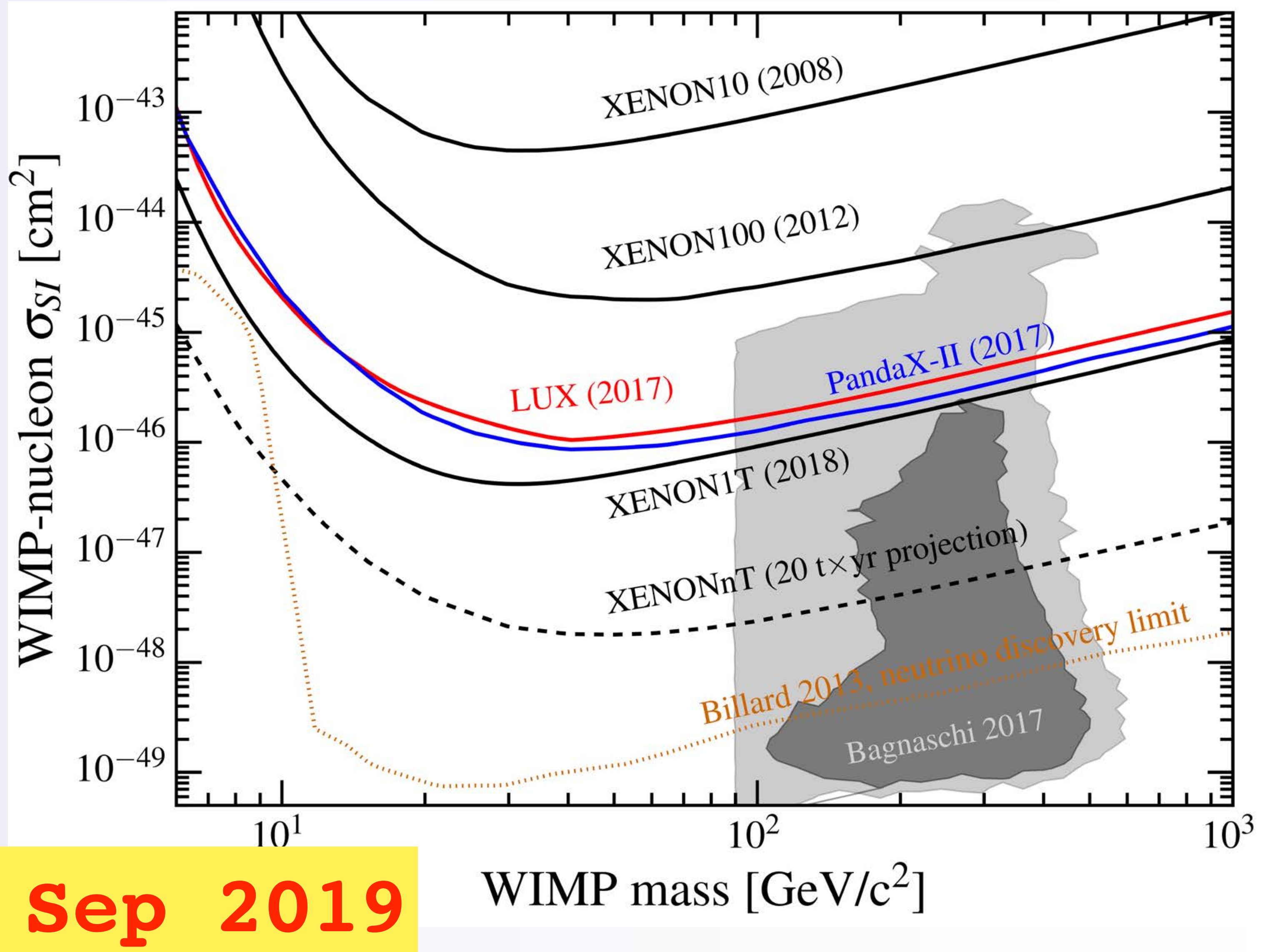
Conclusion & Outlook

1. XENONnT: discovery machine for dark matter

2. XENONnT: neutrino physics program – $0\nu\beta\beta$, ECEC, solar ν, …..

3. XENONnT: pushes low-background technology to next level

4. XENONnT: first results within one year



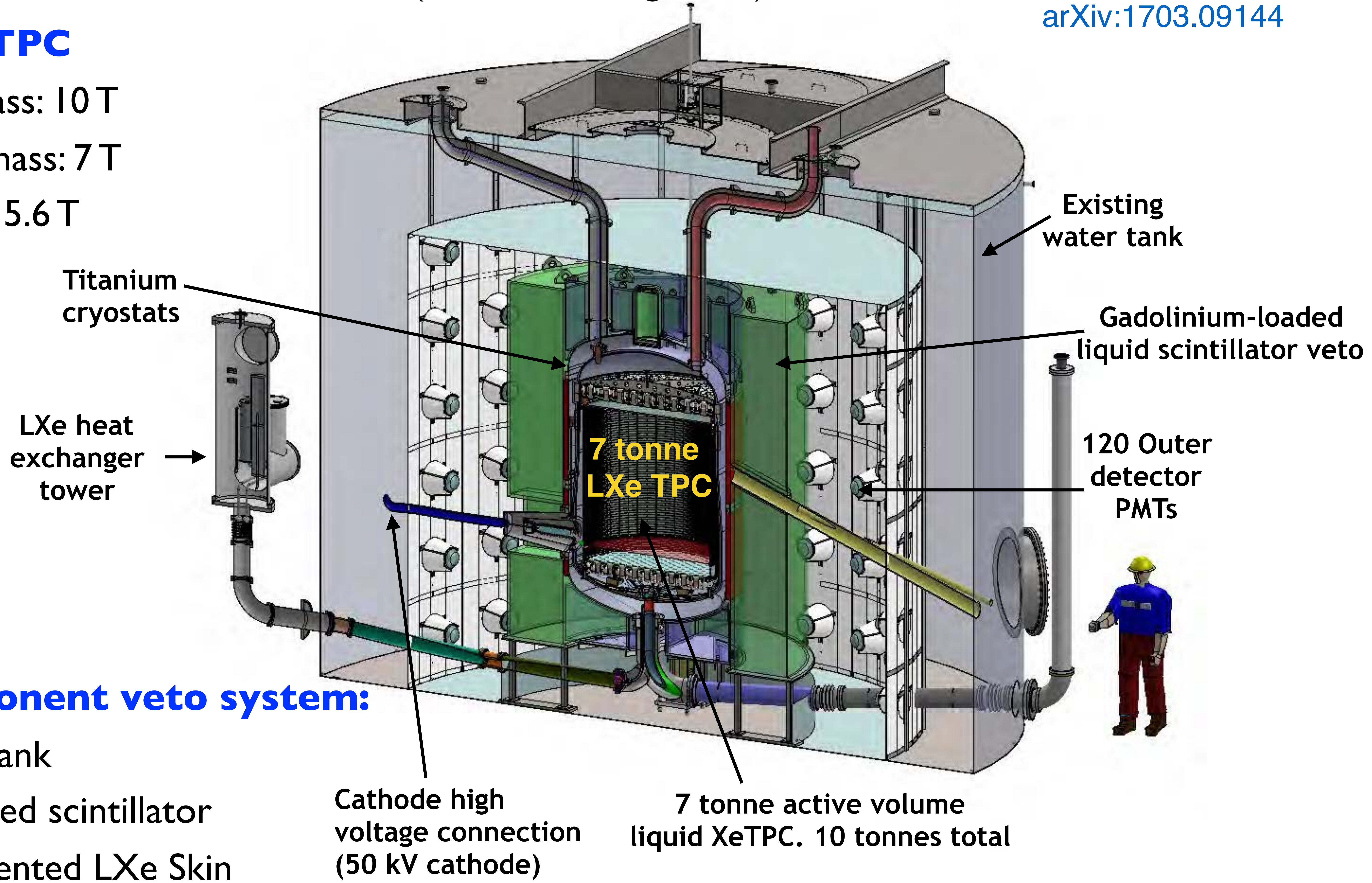
Auke Colijn @TAUP, Sep 2019

LZ Detector Overview

- LZ experiment at SURF, in Lead SD (~1 mile underground)

Technical Design Report:
arXiv:1703.09144

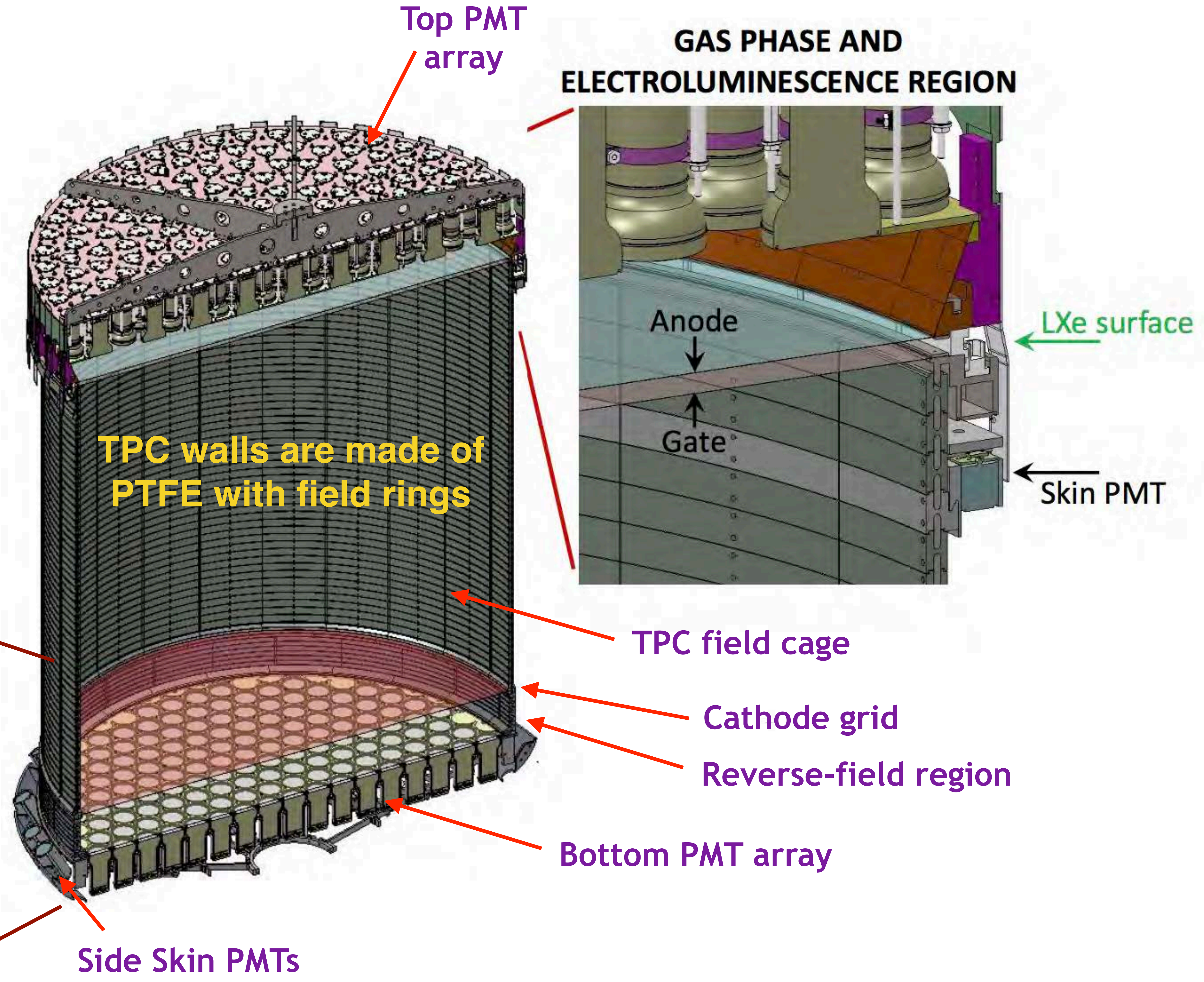
- **Xenon TPC**
  - ✦ Total mass: 10 T
  - ✦ Active mass: 7 T
  - ✦ Fiducial: 5.6 T

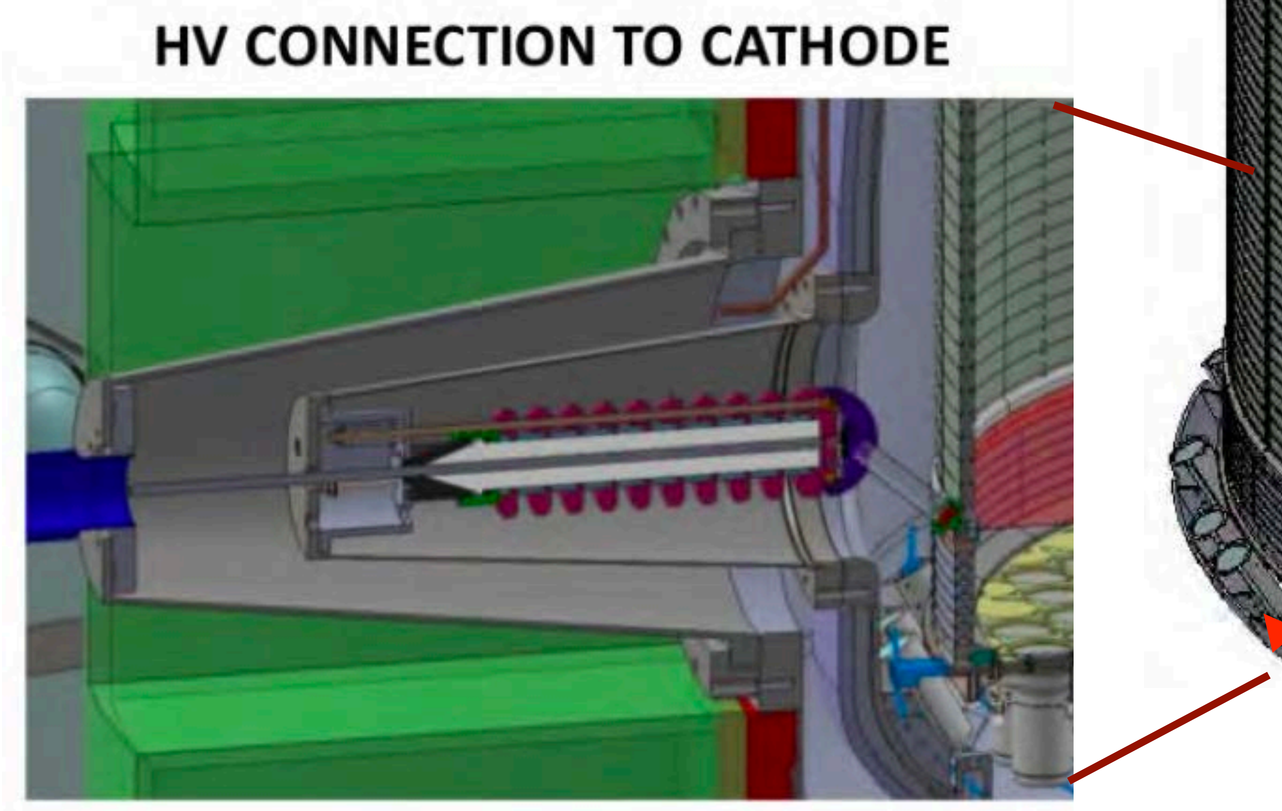


- **3-component veto system:**
  - ✦ Water tank
  - ✦ Gd-loaded scintillator
  - ✦ Instrumented LXe Skin

Xenon TPC

- 1.5 m diameter x 1.5 m height
- 7T active LXe (5.6T fiducial)
- 50 kV cathode HV
  - See talk by J. Watson! (April 19, H14, at 11:21am)
- 494x 3” PMTs
- Gas circulation @ 500 slpm (turnover full mass in 2.5 days)
- Instrumented Xe skin region, outside the field cage



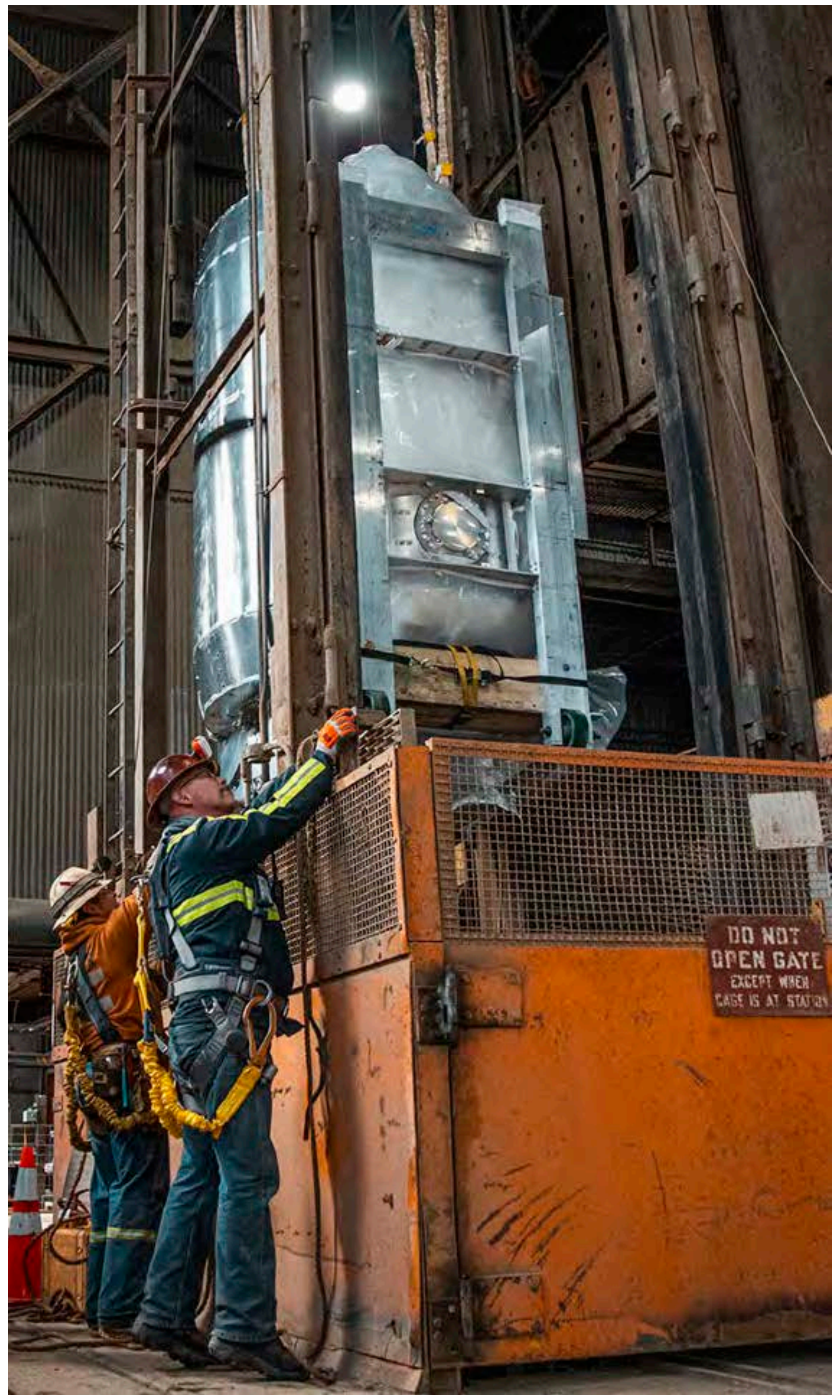


Assembled TPC

Insertion into inner cryostat vessel

Transport of TPC Underground

October 2019

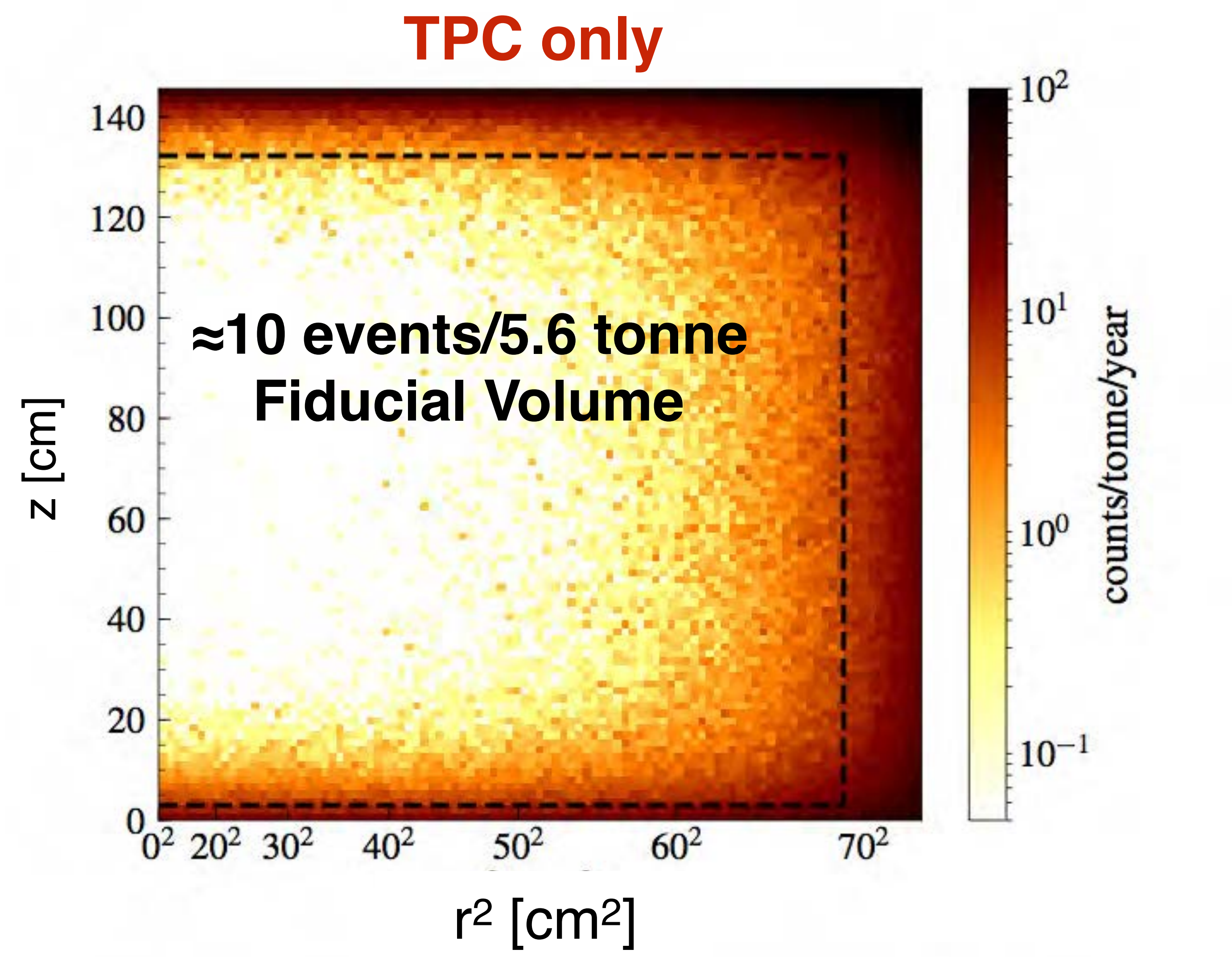


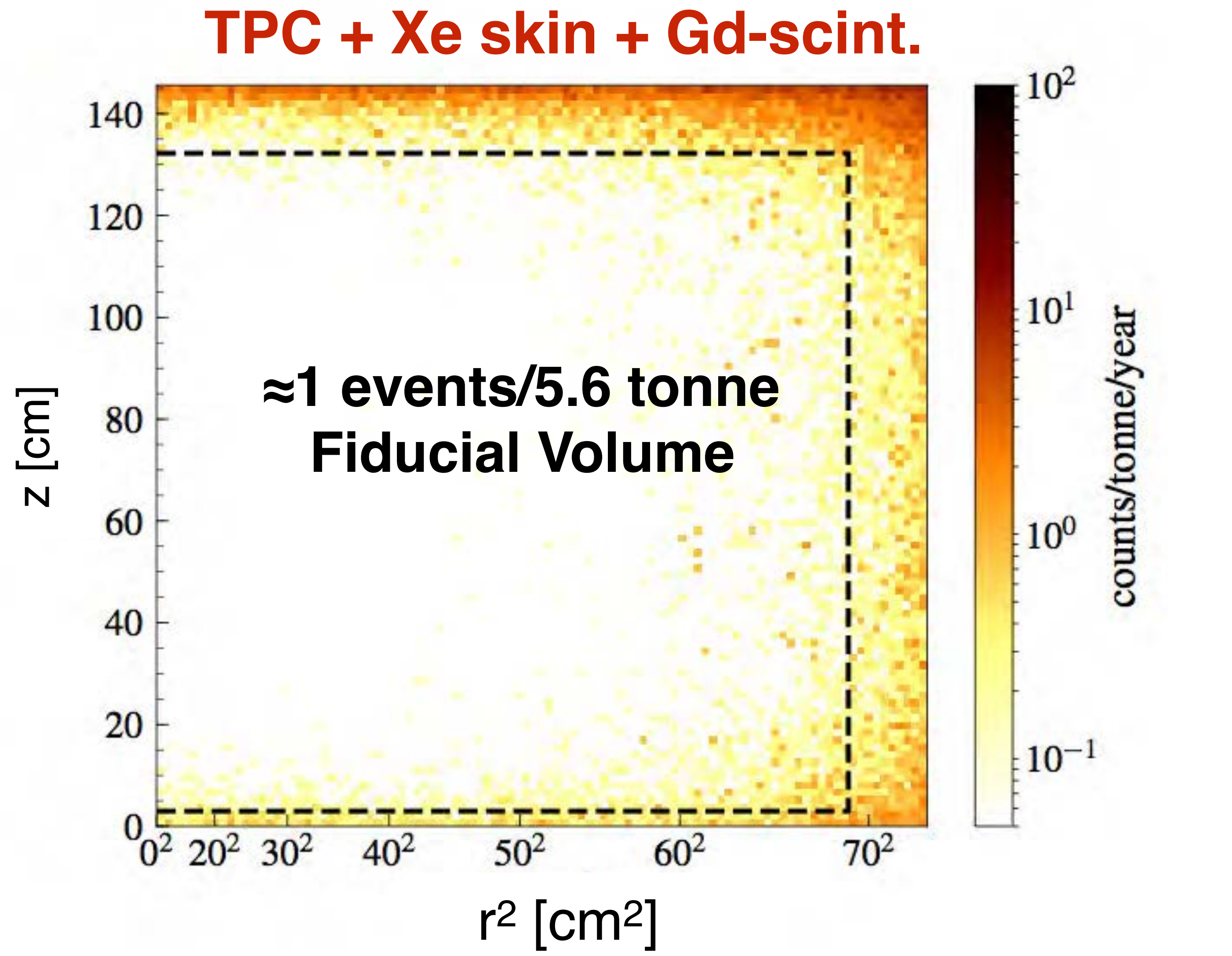
Expected backgrounds for 5.6 T fiducial - 1000 days

Background Source	ER (cts)	NR (cts)
Detector Components	**9**	**0.07**
Surface Contamination	**40**	**0.39**
Laboratory and Cosmogenics	**5**	**0.06**
Xenon Contaminants	**819**	**0**
222Rn	681	0
220Rn	111	0
natKr (0.015 ppt g/g/)	24.5	0
natAr (0.45 pub g/g)	2.5	0
Physics	**258**	**0.51**
136Xe 2νββ	67	0
Solar neutrinos (pp+7Be+13N)	191	0*
Diffuse supernova neutrinos	0	0.05
Atmospheric neutrinos	0	0.46
Total	**1131**	**1.03**
with 99.5% ER discrim., 50% NR eff.	**5.66**	**0.52**

Radon is the dominant background!

* 6 keV NR threshold used

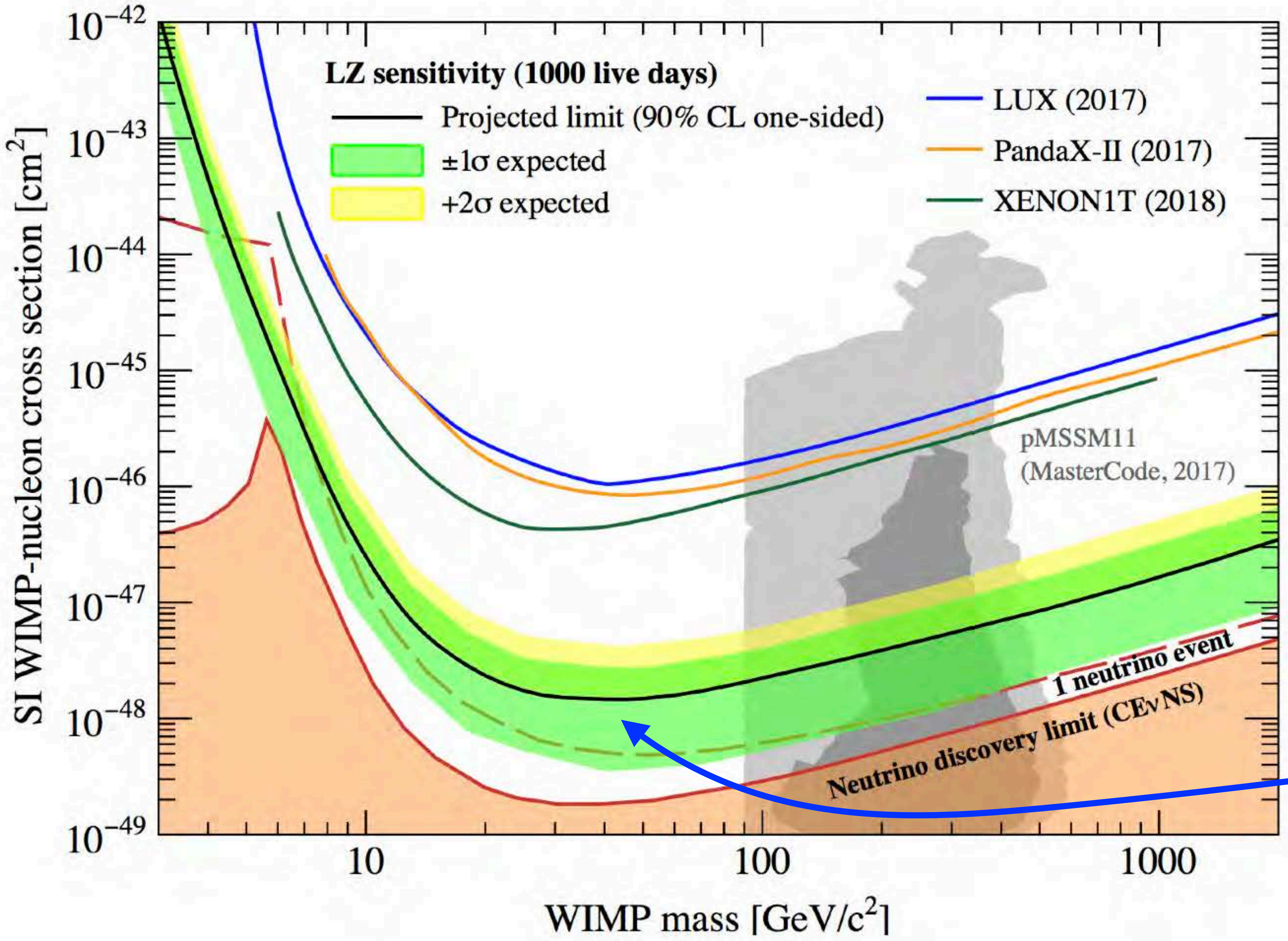


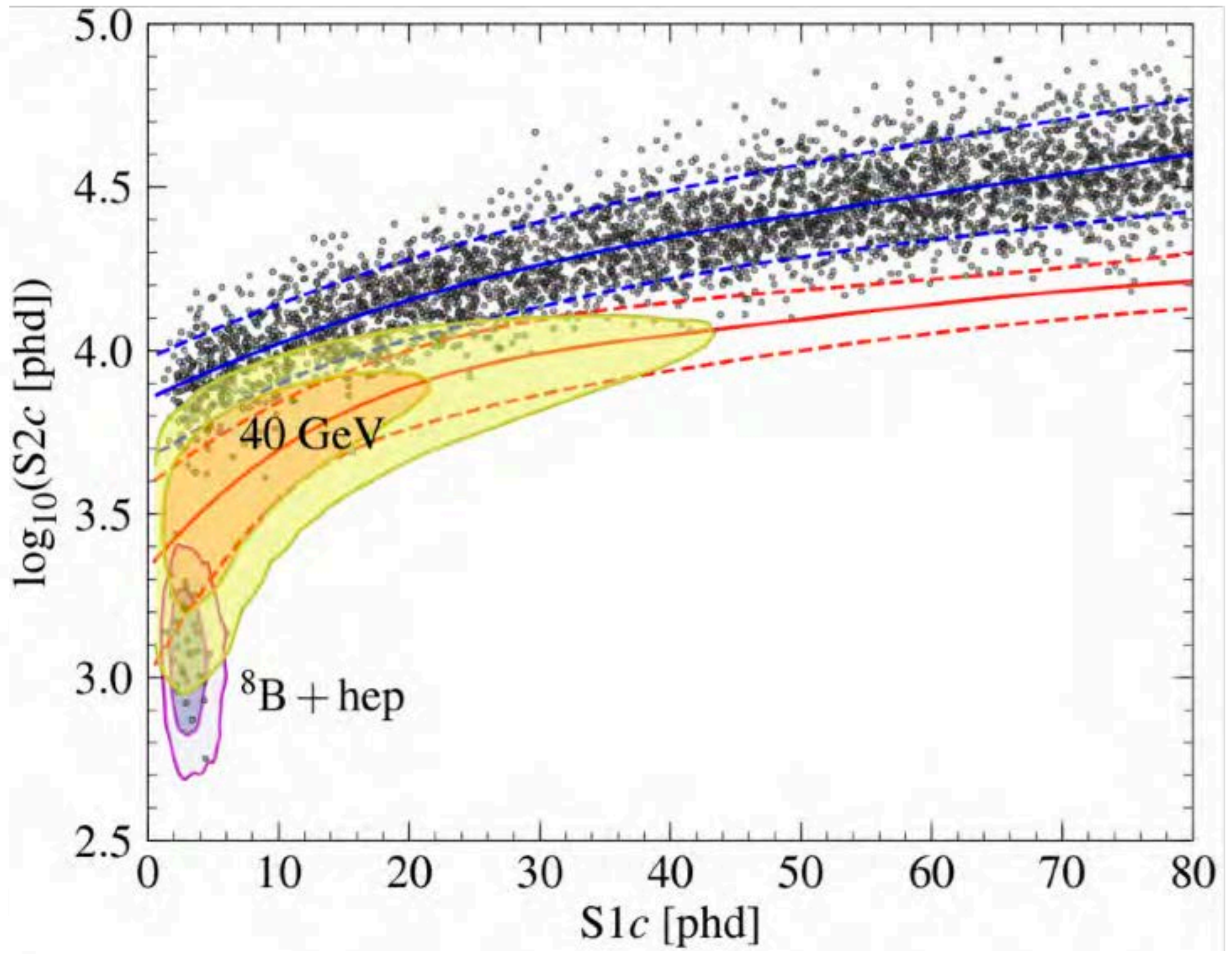


D.S. Akerib et al (LZ collaboration) Phys. Rev. D 101, 052002 (2020)

Projected Sensitivity (5.6 T exposure, 1000 live days)

Approaches coherent neutrino scattering background!





90% CL minimum of 1.6 x 10^{-48} cm^2 at 40 GeV/c^2

D.S. Akerib et al. (LZ collaboration) Phys. Rev. D 101, 052002 (2020)

The End