Supernova neutrino detection in DUNE

Inés Gil-Botella

Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

Workshop on core-collapse supernova neutrino detection
IPNO Orsay, July 4-5, 2018

Outline

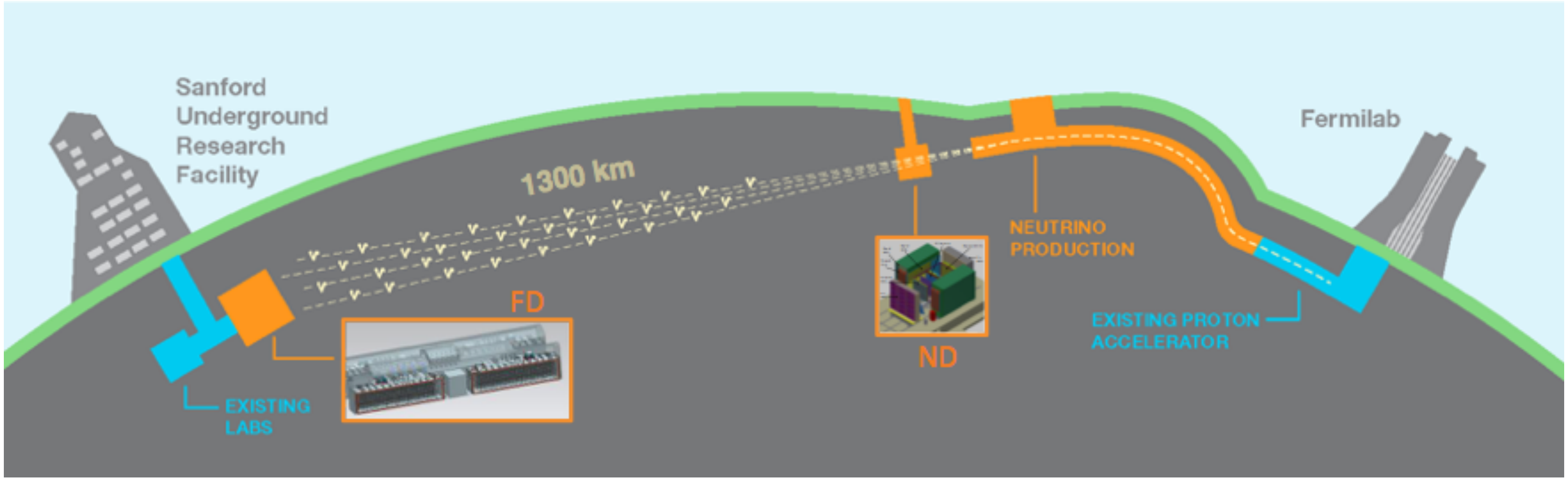
- The Deep Underground Neutrino Experiment (DUNE)
  - DUNE program
  - Liquid Argon TPC technology
  - The CERN Neutrino Platform Program
- Supernova Neutrinos in LAr TPCs
  - SN neutrino signal in LAr
  - Neutronization burst
- Status of SN neutrino reconstruction at DUNE
  - Challenges
  - MARLEY generator
  - Tagging algorithms
- Summary

DEEP UNDERGROUND NEUTRINO EXPERIMENT

Deep
Underground
Neutrino
Experiment

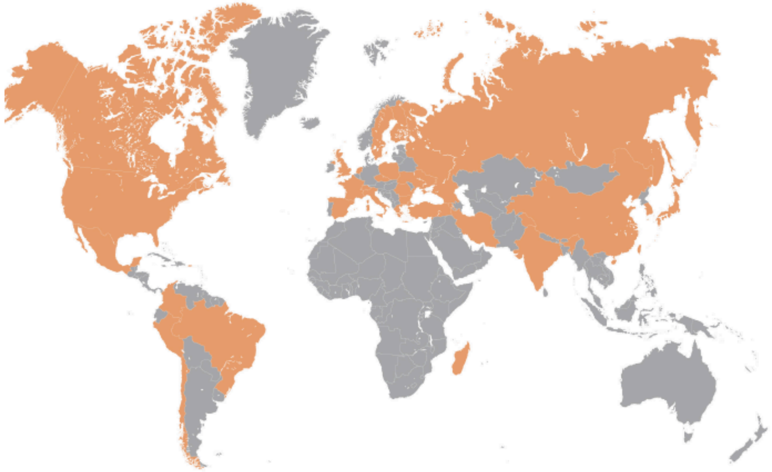
DUNE

"Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE) Conceptual Design Report Volume 2: The Physics Program for DUNE at LBNF" (arXiv:1512.06148)



- **Deep Underground Neutrino Experiment**: 40 kton LAr TPC far detector at 1480 m depth (4300 mwe) at SURF measuring neutrino spectra at 1300 km in a **wide-band** high purity ν_μ beam with peak flux at 2.5 GeV **operating at ~1.2 MW** and upgradeable to 2.4 MW
- **4 x 10 kton (fiducial) modules** (single and/or dual-phase) with ability to detect LBL oscillations, SN burst neutrinos, nucleon decay, atmospheric νs…
- Detectors will be ready before the beam arrives ⇨ **good opportunity to start with non-accelerator physics!**

The DUNE Collaboration



- Strong international collaboration: >1000 collaborators
- 32 nations
- 179 institutions

The DUNE Science Program

PRIMARY GOALS

Focus on fundamental open questions in particle physics and astroparticle physics – aim for **discoveries**:

1) **Neutrino Oscillation Physics**
   - CPV in the leptonic sector
   - Neutrino Mass Hierarchy
   - Precision Oscillation Physics & testing the 3-flavor paradigm
2) **Supernova burst physics & astrophysics**
   - Unique sensitivity to ν_e complementary to other technologies
3) **Nucleon Decay**
   - New detector technology offers sensitivity to as of yet unexplored decay channels

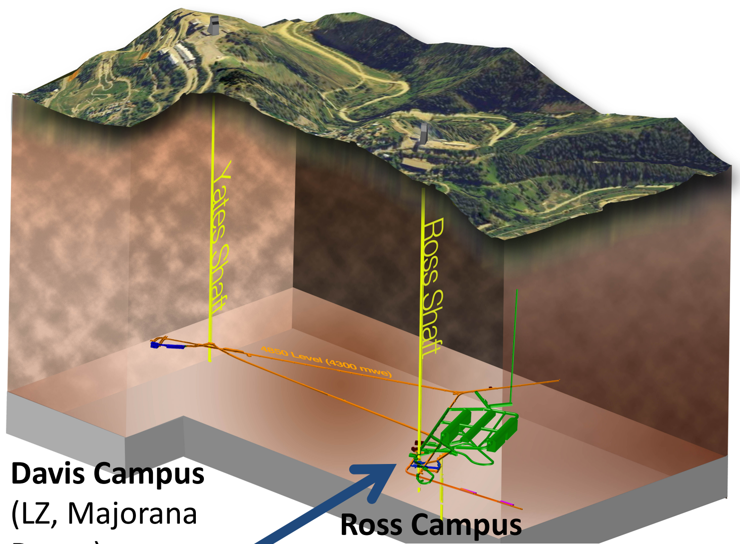
ANCILLARY GOALS

4) Atmospheric neutrino oscillation measurements
5) Neutrino Astrophysics
   - Solar neutrinos
   - Diffuse Supernova Neutrino Background
6) Precise measurements of neutrino interactions with the near detector
7) NSI, sterile neutrinos, Lorentz violation, neutrino decay, decoherence
8) Dark matter

The DUNE Far Site

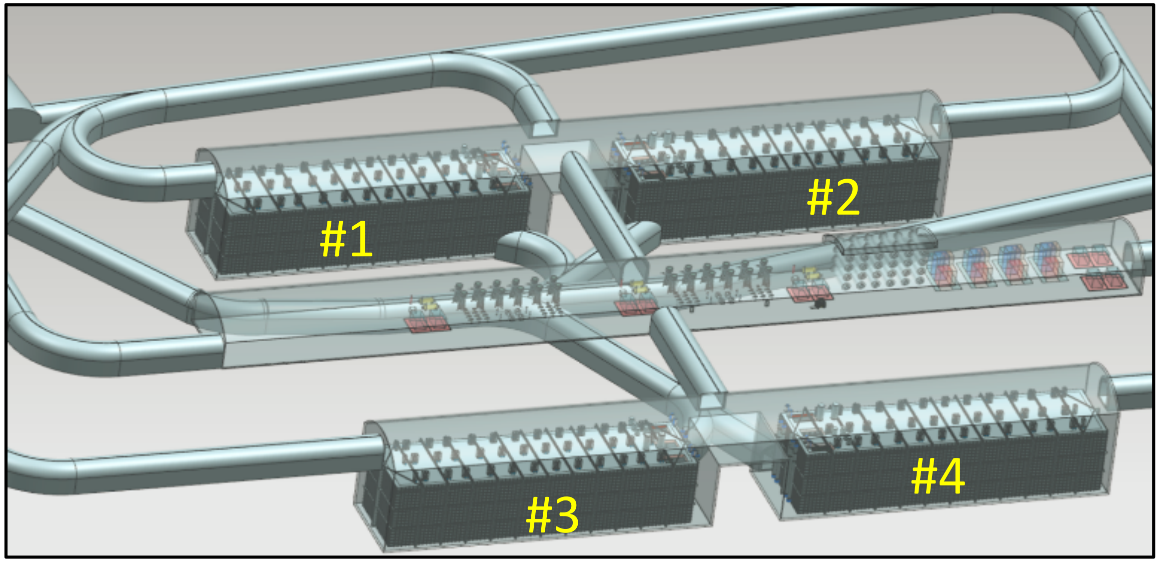
- **Sanford Underground Research Facility (SURF), South Dakota**
- Four caverns hosting four independent 10 kton (fiducial mass) FD modules
  - Assumed four identical cryostats 19 (W) x 18 (H) x 66 (L) m^3
  - Phase-in approach
  - Allows alternate designs (single vs dual-phase LAr TPCs)
- Complete TDR should be ready for 2019
- Installation of #1 module starts in 2022

Surface facilties (power, cryo systems, compressors, control room, waste rock handling system)



Davis Campus (LZ, Majorana Demo)

Ross Campus (CASPAR, Low background, Majorana Demo Electroforming lab)



LBNF and DUNE CDR Volume 4: The DUNE Detectors at LBNF (arXiv:1601.02984)

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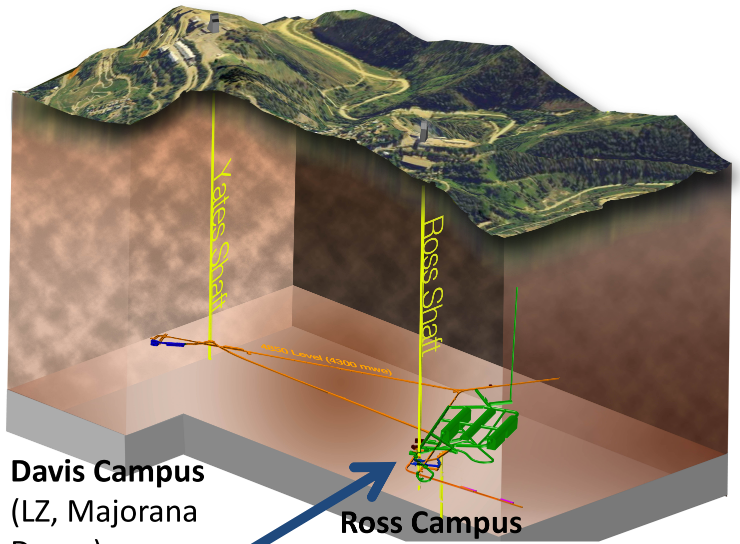

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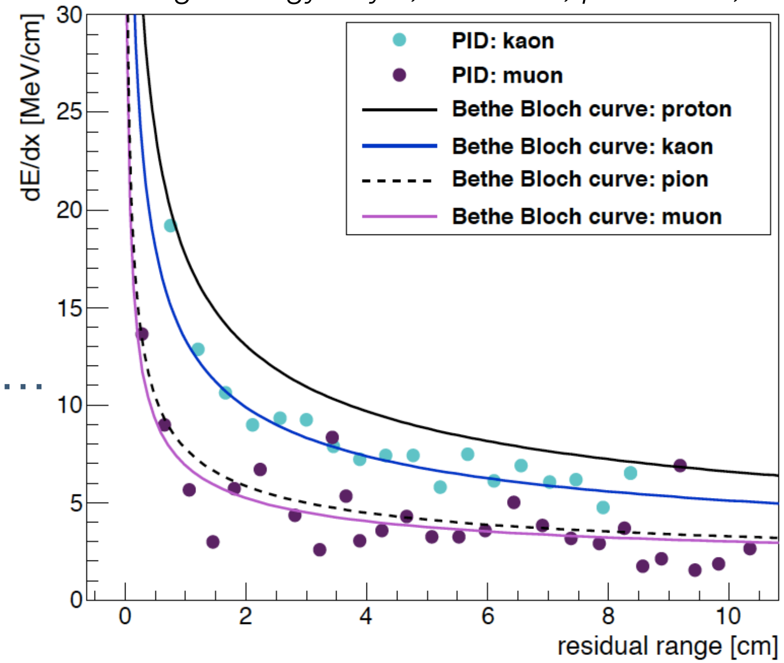
LBNF and DUNE CDR Volume 4: The DUNE Detectors at LBNF (arXiv:1601.02984)

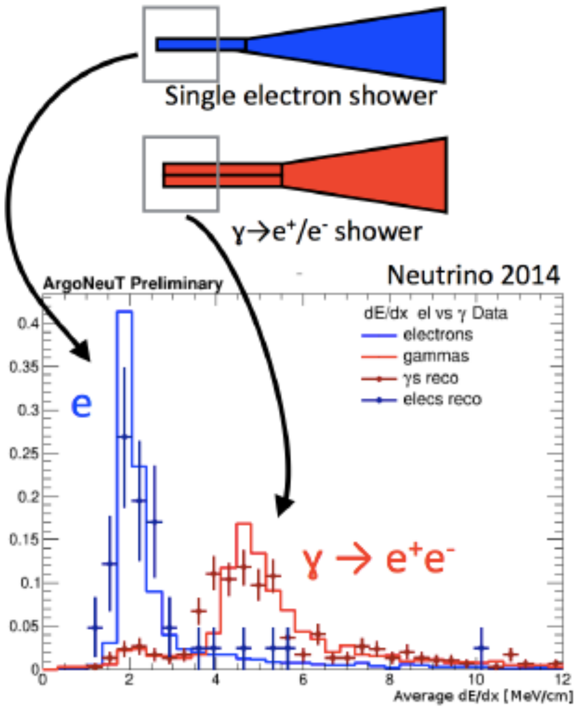
The DUNE Far Detector

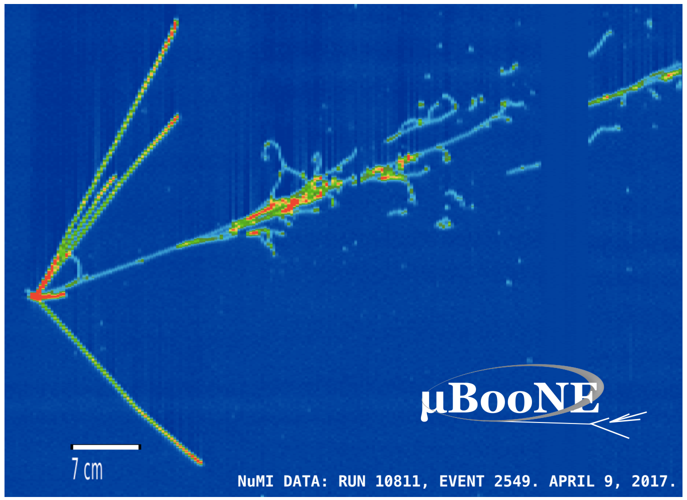
The LAr TPC technology provides:

- excellent 3D imaging capabilities
  - few mm scale over large volume detector
- excellent energy measurement capability
  - totally active calorimeter
- particle ID by dE/dx, range, event topology, …

Adv. High Energy Phys., vol. 2013, p. 260820, 2013

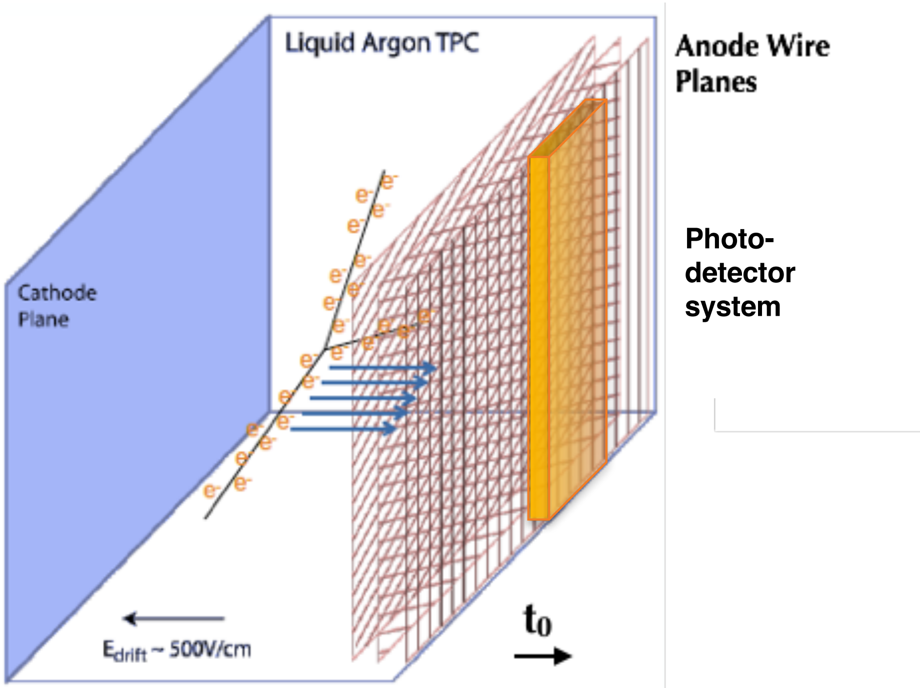


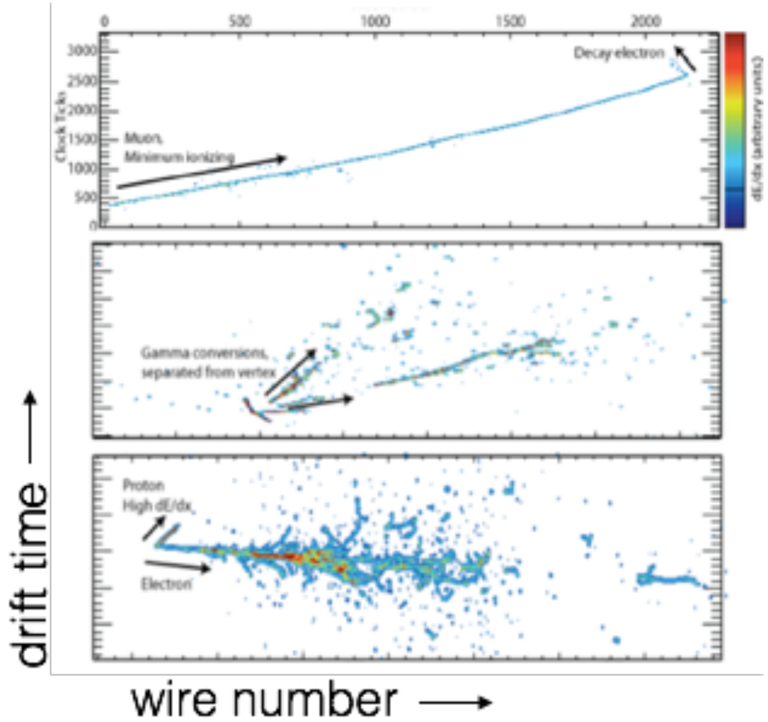




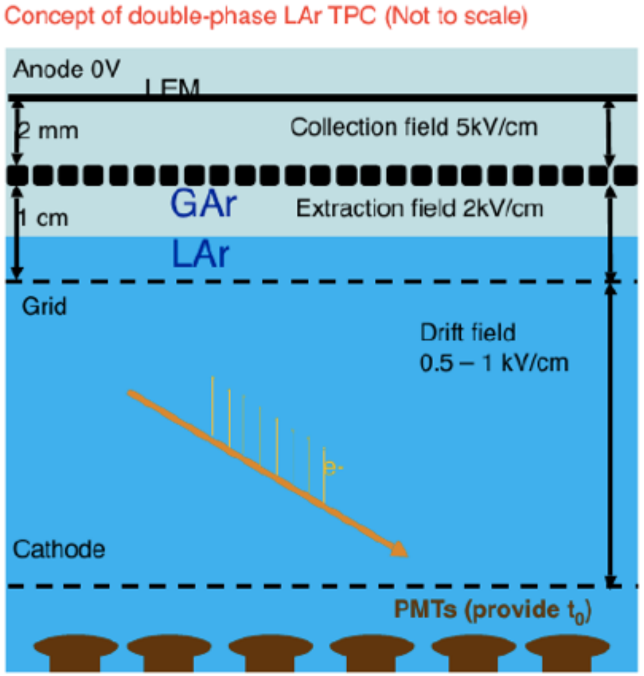
Single-phase LAr TPC technology

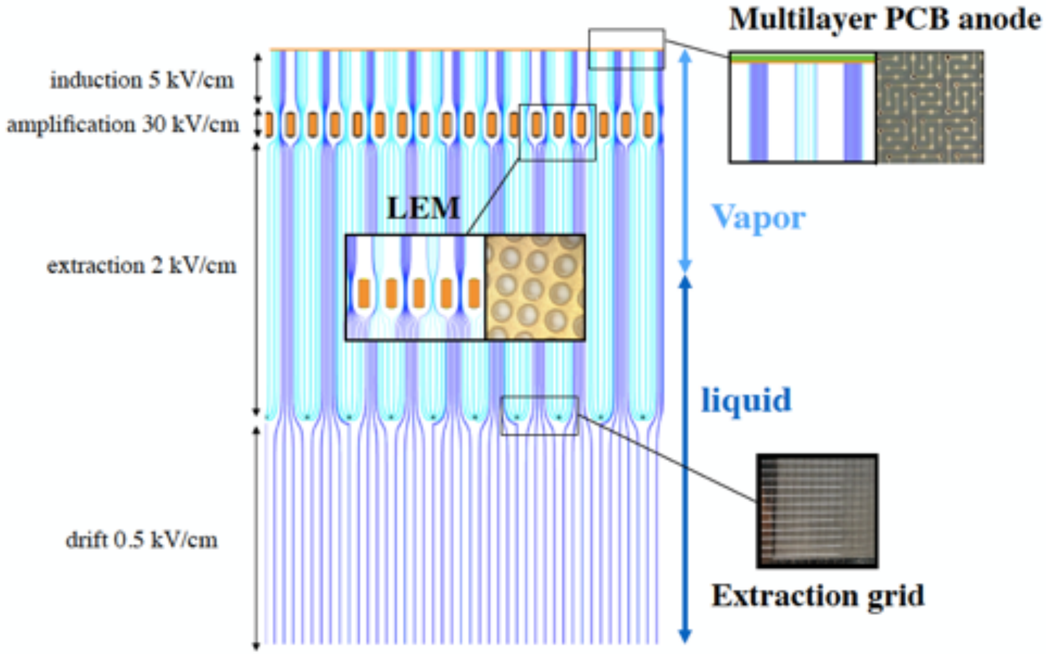
- Neutrino interactions in Ar produce charged particles that cause ionization and excitation of Argon
  - High electric field drifts electrons towards finely segmented anode wire planes
  - Excitation of Ar produces prompt scintillation light giving t_0 of the interaction
- Independent views provided by multiple wire orientations (2D position information)
- Photosensors detect the light produced providing timing information
- 3D reconstruction of tracks and showers





Dual-phase LAr TPC technology



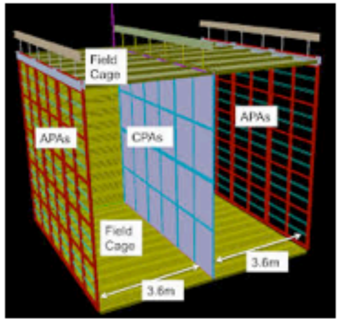


- Ionization signals are amplified and detected in gaseous argon above the liquid surface
- Two measurements:
  - Charge from ionization: tracking and calorimetry. Double-phase: multiplication in gas to increase gain and allow for long drift distances (> 5m) and low energy thresholds
  - Scintillation light: primary scintillation (trigger and t0) & secondary scintillation in gas
- Large surface instrumented with PMTs in LAr

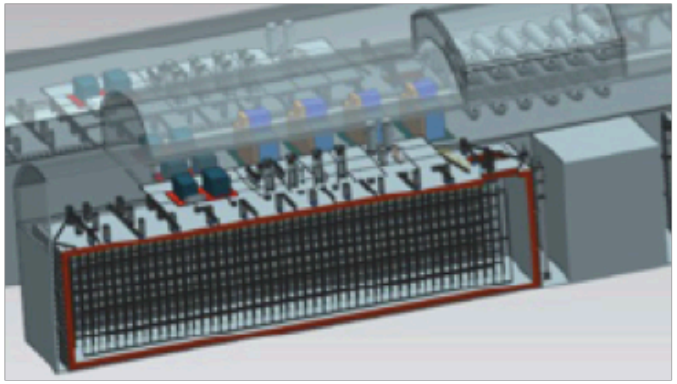
The DUNE strategy

Single-phase

DUNE **35-t** @Fermilab (2015)

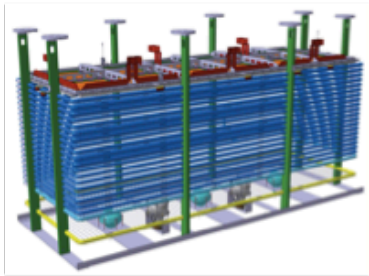


protoDUNE SP
@CERN: 300 ton
(2016-2019)

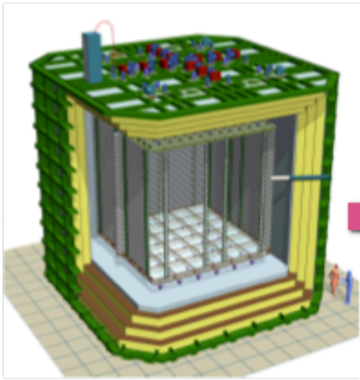


DUNE SP @SURF: 10 kton

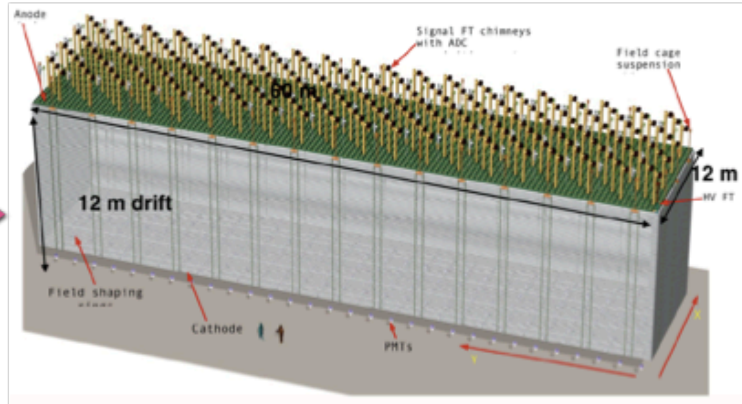
Dual-phase



WA105 **3x1x1 m^3** @CERN:
4.2 ton (2016)

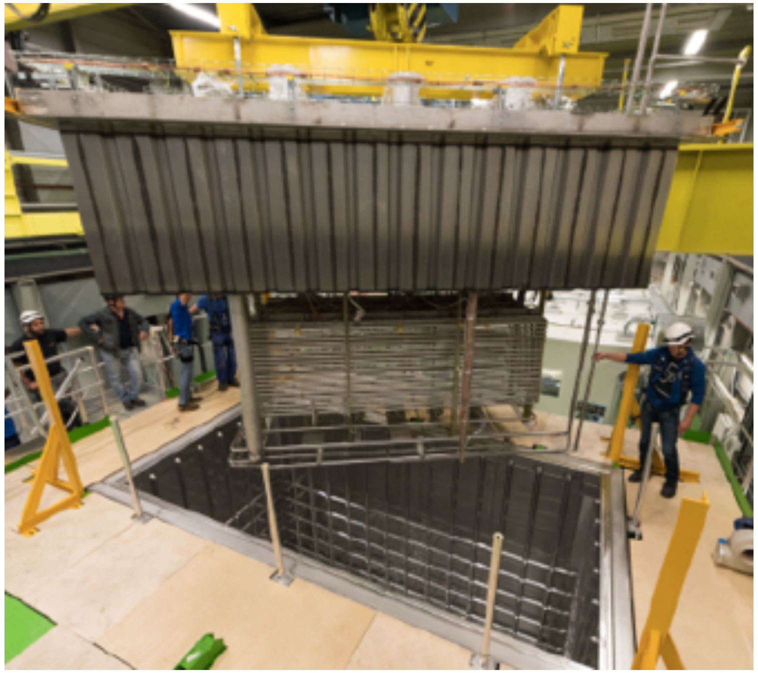


protoDUNE DP
@CERN: 300 ton
(2016-2019)

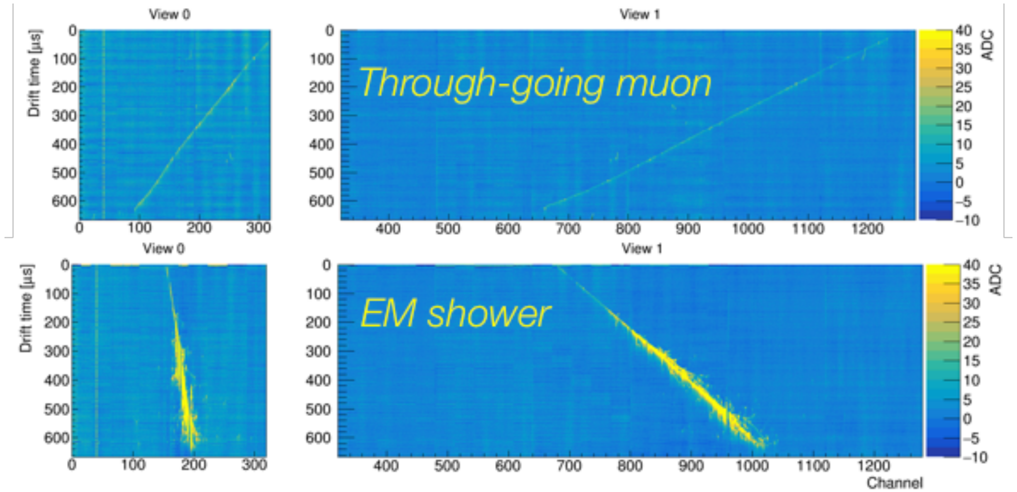


DUNE DP @SURF: 10 kton

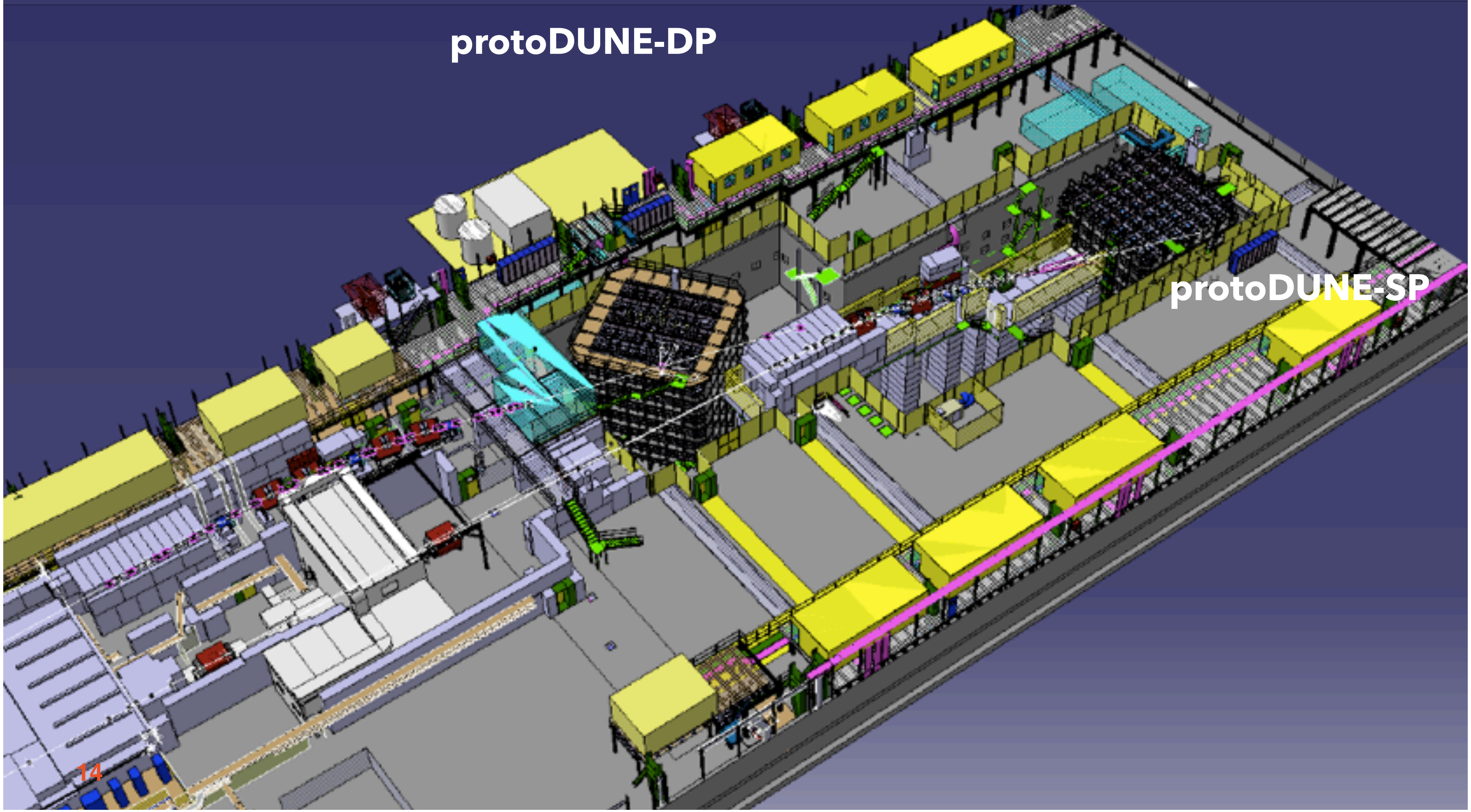
3x1x1 m^3 demonstrator at CERN



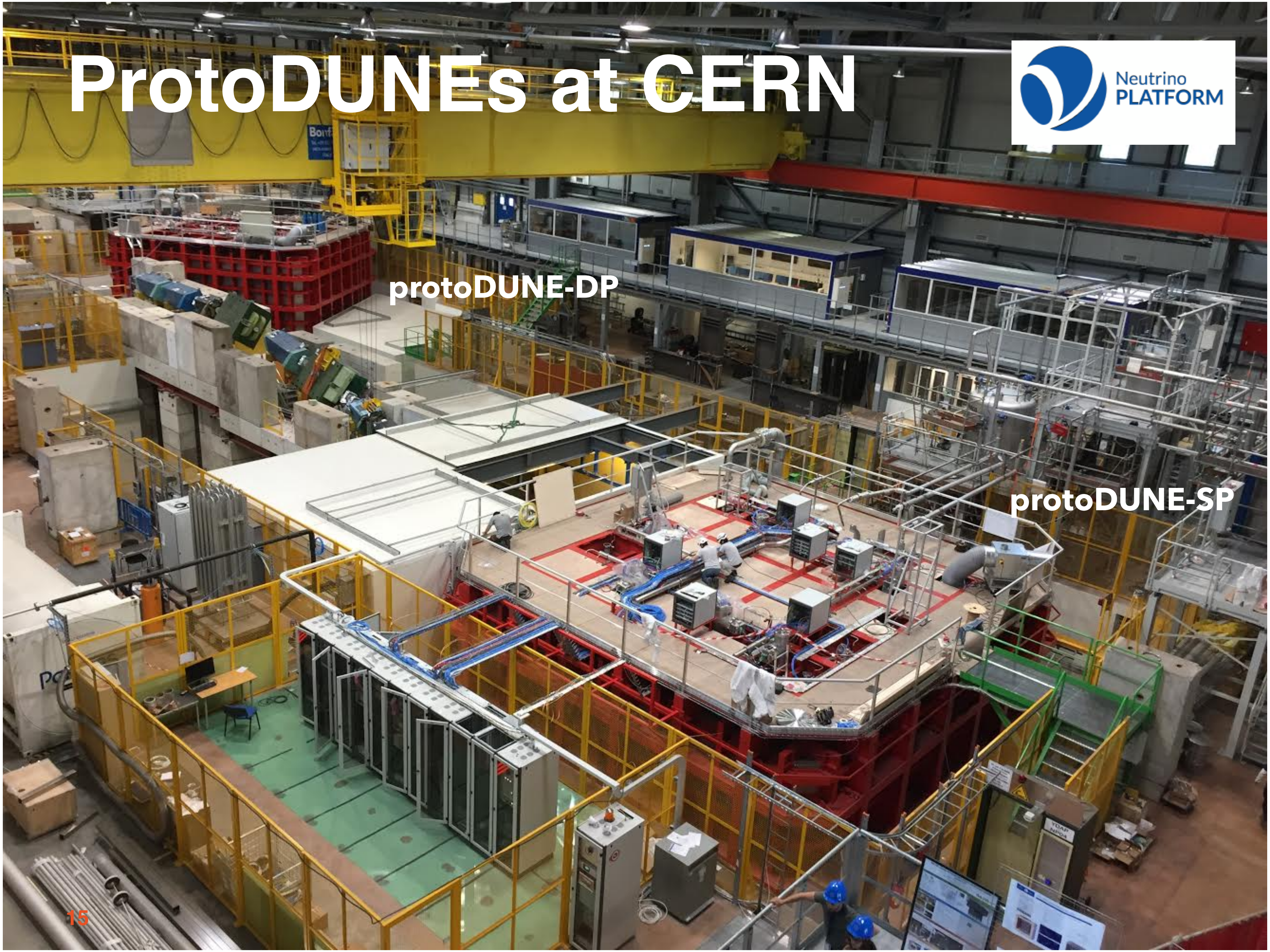
- Installed during 2016 (Bldg. 182), filled with LAr beg 2017; Data taking between June and November 2017
- 3x1x1 successful in proving the dual-phase concept for a LAr TPC at the 4 ton scale
- Technical paper (*arXiv:1806.03317*) submitted to JINST (60 p.)



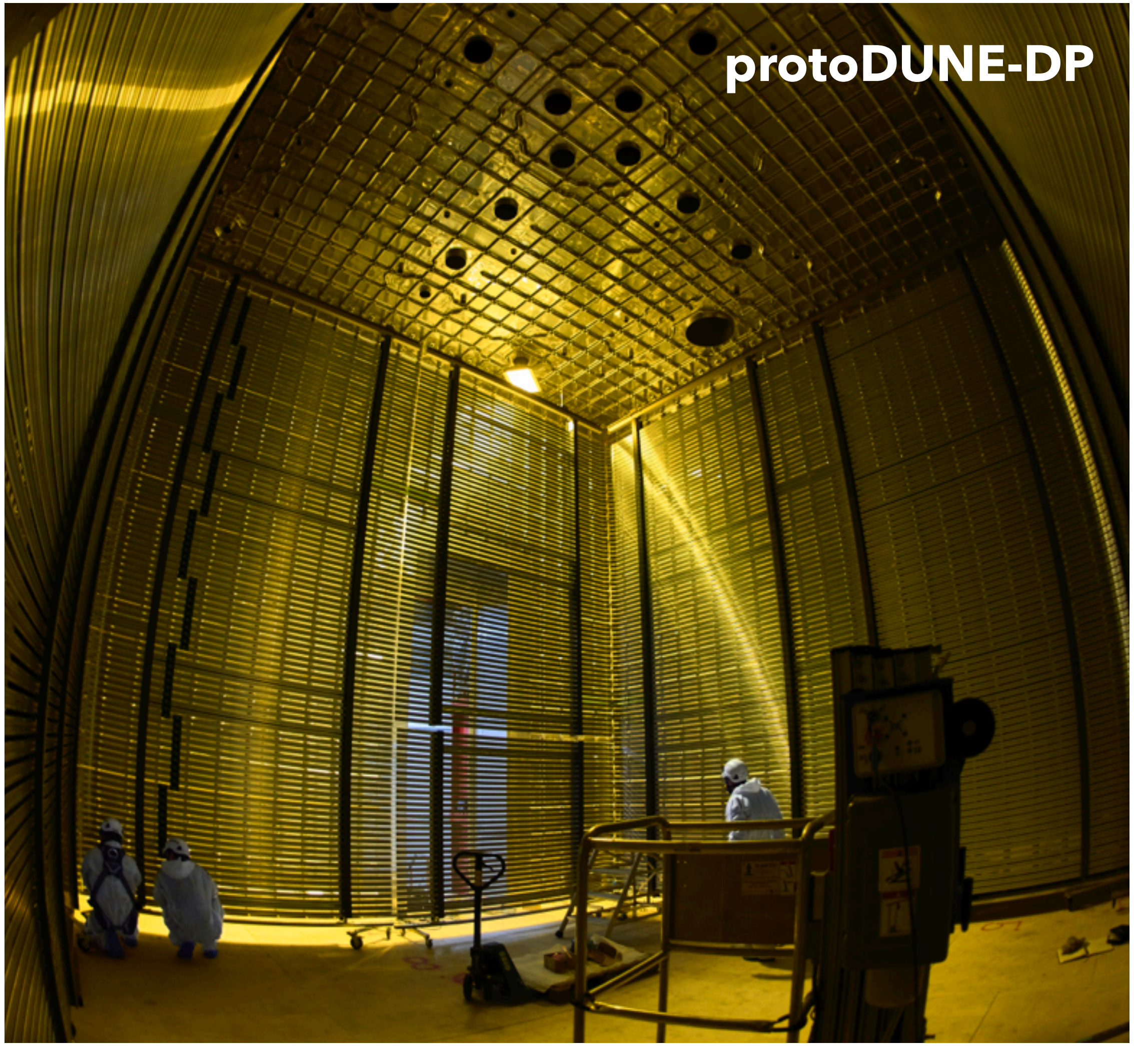
ProtoDUNEs at CERN



ProtoDUNEs at CERN

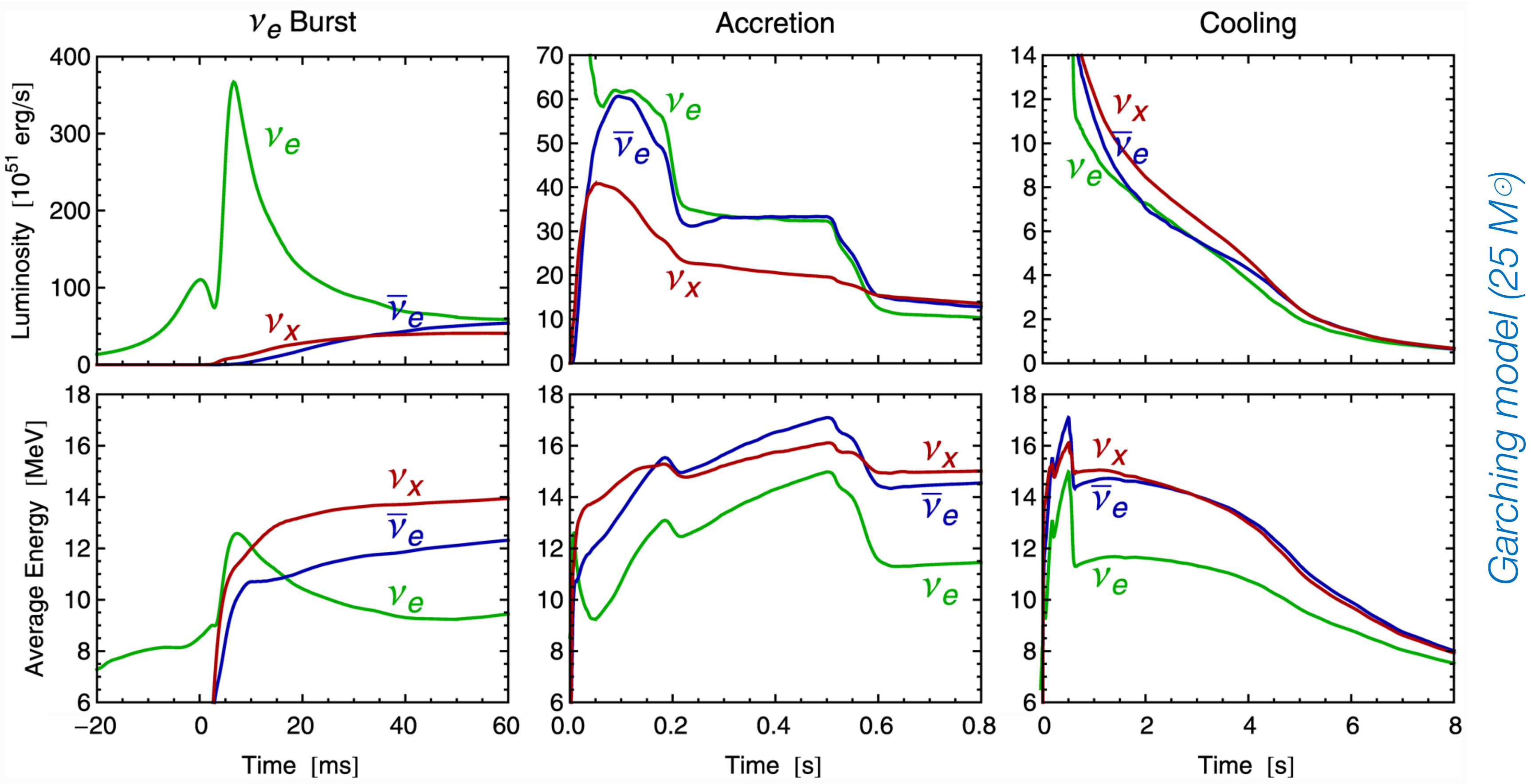


ProtoDUNEs at CERN



Supernova neutrinos in LAr TPCs

Three phases of SN ν emission



Neutronization burst

- Shock breakout
- De-leptonization of outer core layers

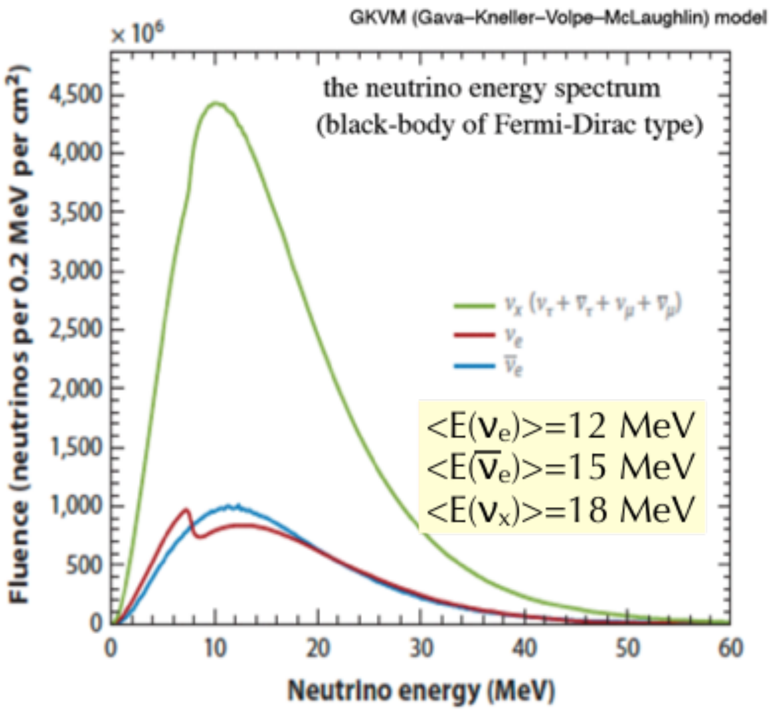
Accretion phase

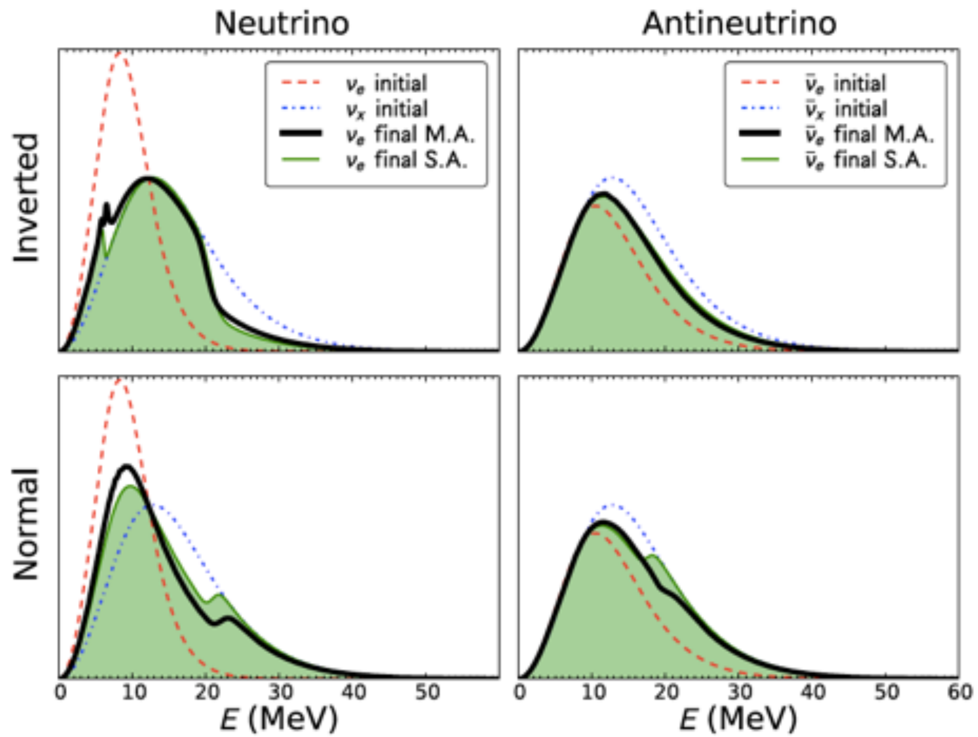
- Shock stalls ~150 km
- Neutrinos powered by infalling matter

Cooling phase

- Cooling on neutrino diffusion time scale

MSW and collective effects



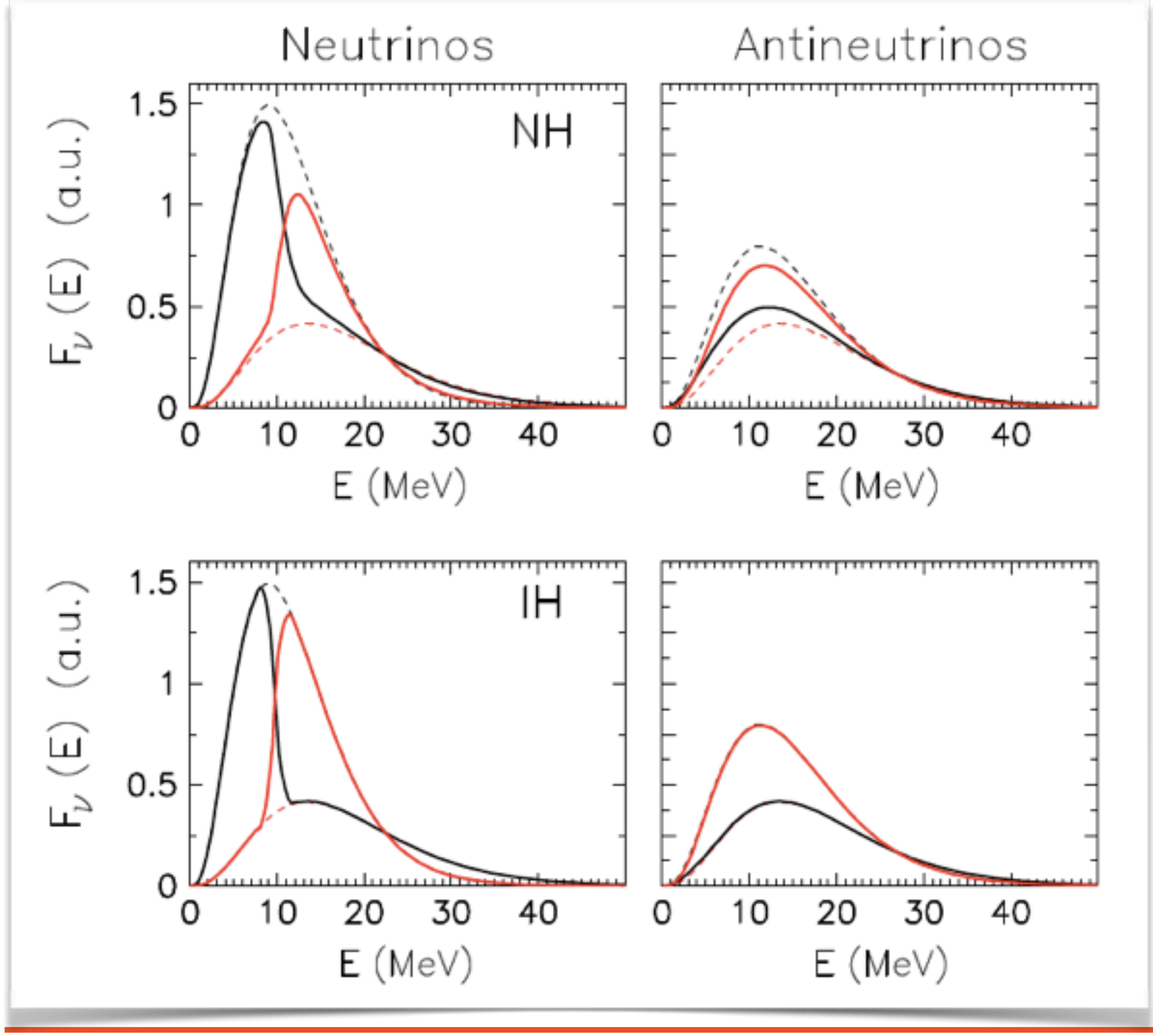


Duan & Friedland, Phys. Rev. Lett. 106 (2011) 091101

- **Collective oscillations** (r < 200 km) + **MSW flavor transformations** (r > 200 km) imprint the neutrino signal
- Information about the mass ordering (and SN mechanisms) can be obtained from the observation of the neutrino time and energy spectra evolution

Effect of collective oscillations

S. Chakraborty and A. Mirizzi, Phys. Rev. D90, 033004 (2014)



- Dashed lines: no osc.
- Solid lines: after osc. (black ν_e; red ν_x)
- Initial fluxes:

  $F\nu_e : F\bar{\nu}_e : F\nu_x = 2.4:2.0:1.5$
- **Spectral splits in certain energy intervals**

Supernova neutrino signal in LAr

1. **Elastic scattering** on electrons (**ES**)

$$\overset{(-)}{\nu} + e^- \rightarrow \overset{(-)}{\nu} + e^-$$

2. **Charged-current** (CC) interactions on Ar

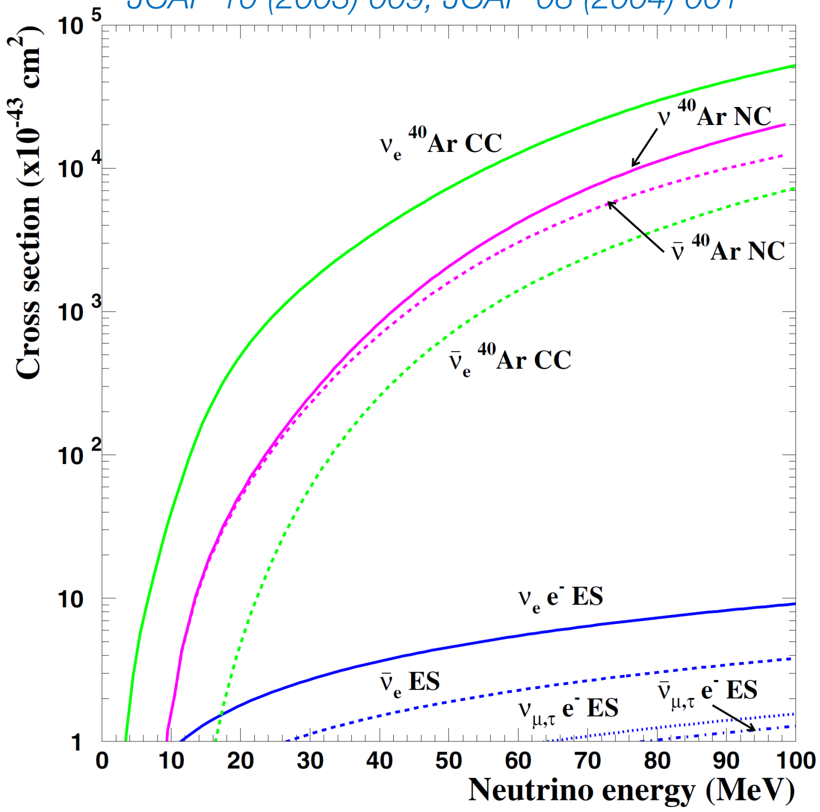
$$\nu_e + {}^{40}Ar \rightarrow {}^{40}K^* + e^-$$ $Q_{\nu eCC} = 1.5$ MeV

$$\bar{\nu}_e + {}^{40}Ar \rightarrow {}^{40}Cl^* + e^+$$ $Q_{\bar{\nu}eCC} = 7.48$ MeV

3. **Neutral current** (NC) interactions on Ar

$$\overset{(-)}{\nu} + {}^{40}Ar \rightarrow \overset{(-)}{\nu} + {}^{40}Ar^*$$ $Q_{NC} = 1.46$ MeV

I. Gil-Botella & A.Rubbia, hep-ph/0307222, JCAP 10 (2003) 009, JCAP 08 (2004) 001



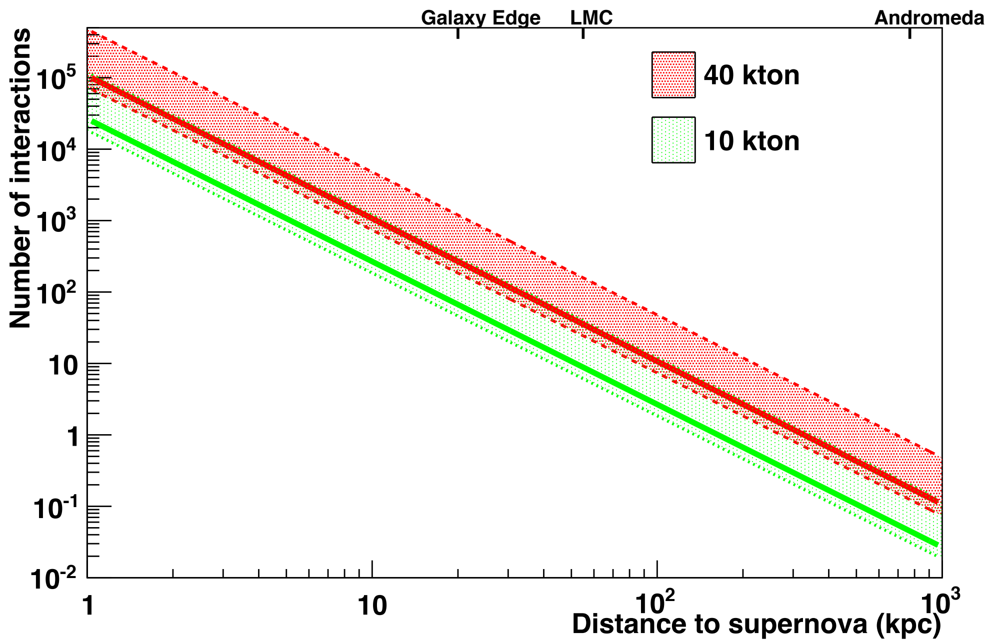
Possibility to separate the various channels by a classification of the associated **photons from the K, Cl or Ar deexcitation** (specific spectral lines for CC and NC) or by the **absence of photons** (**ES**)

SN neutrinos in DUNE

Event rates in DUNE (40 kt LAr) for a core-collapse SN at 10 kpc

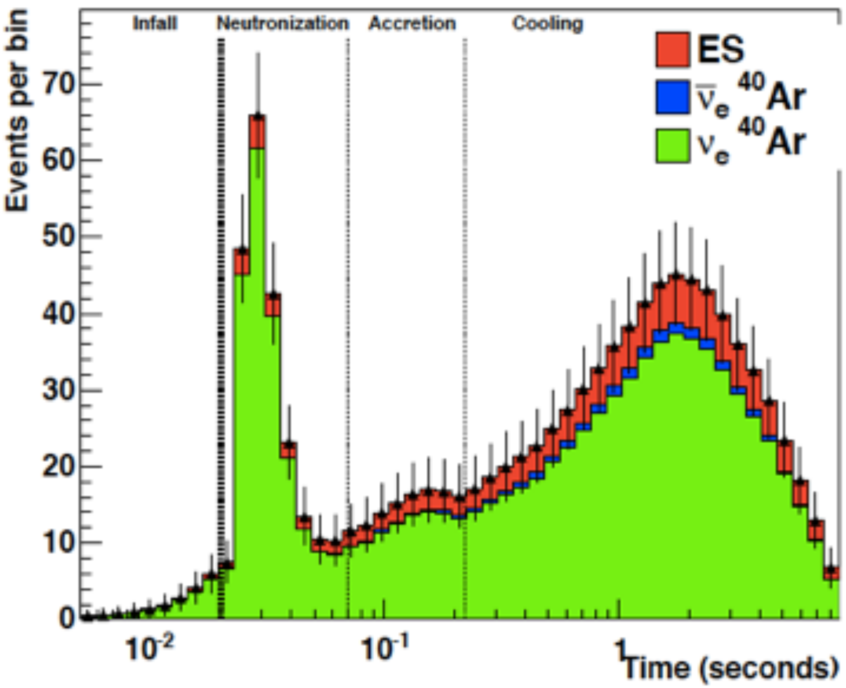
Channel	Events "Livermore" model	Events "GKVM" model
$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$	2720	3350
$\overline{\nu}_e + {}^{40}\mathrm{Ar} \rightarrow e^+ + {}^{40}\mathrm{Cl}^*$	230	160
$\nu_x + e^- \rightarrow \nu_x + e^-$	350	260
Total	3300	3770
	no oscillations	*collective effects*

- Unique sensitivity to electron neutrinos
- Width of bands represents range of models
- Solid: Garching model
  PRL104 (2010) 251101

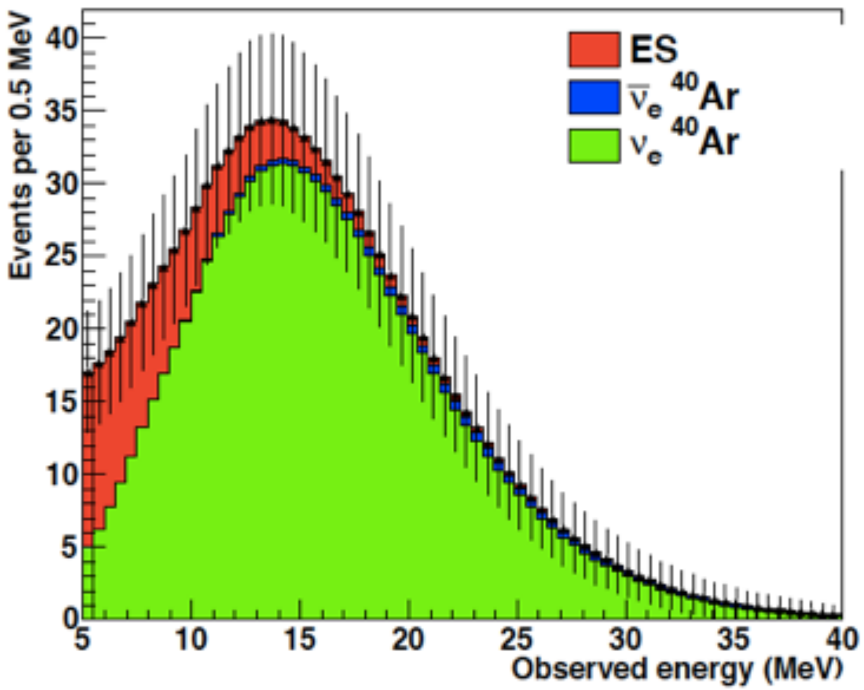


SN neutrino spectra in DUNE

- SN at 10 kpc in DUNE (40 kt LAr)
- No oscillations
- Required energy resolution < 10%
- Energy threshold ~5 MeV



Time-dependent signal

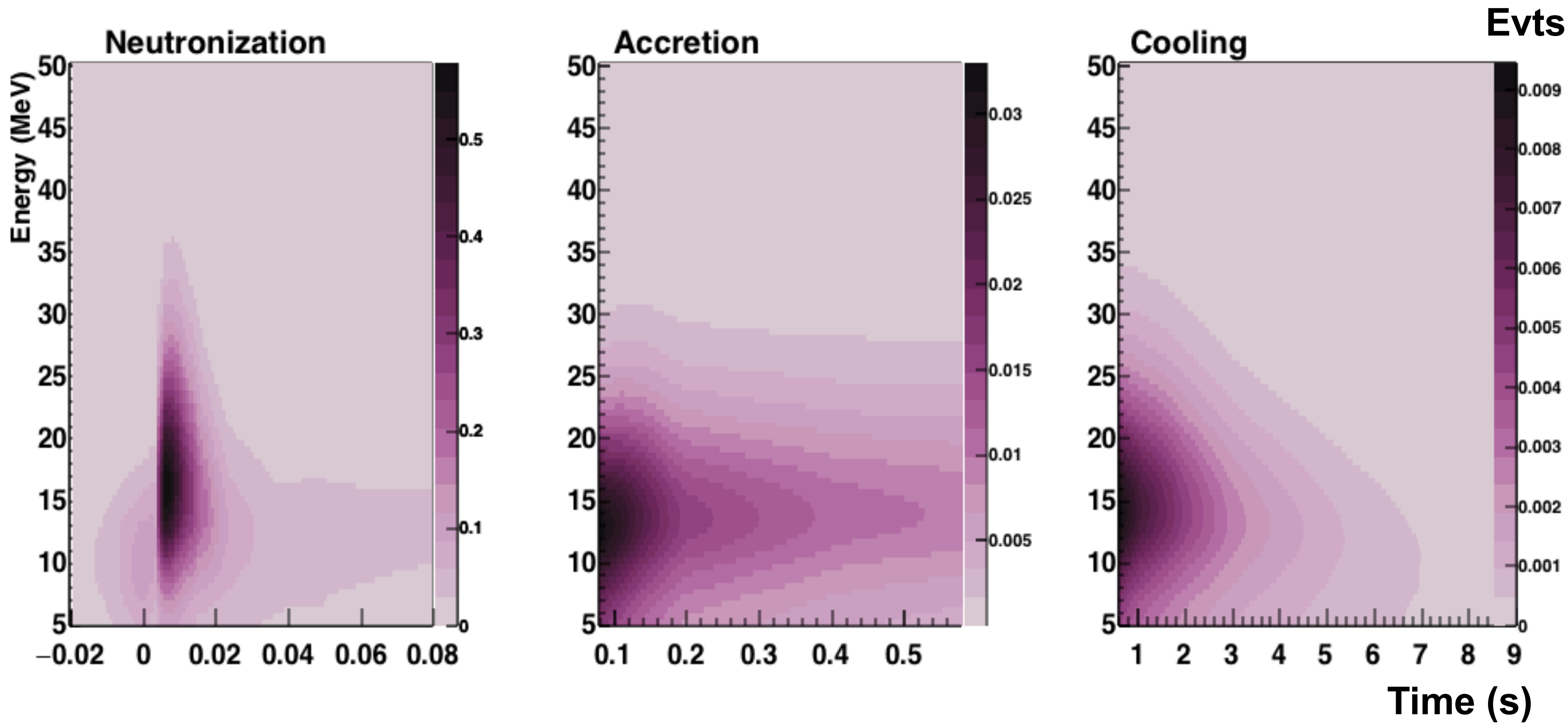


Expected event spectrum integrated over time

Garching model, ICARUS energy resolution, 5 MeV threshold

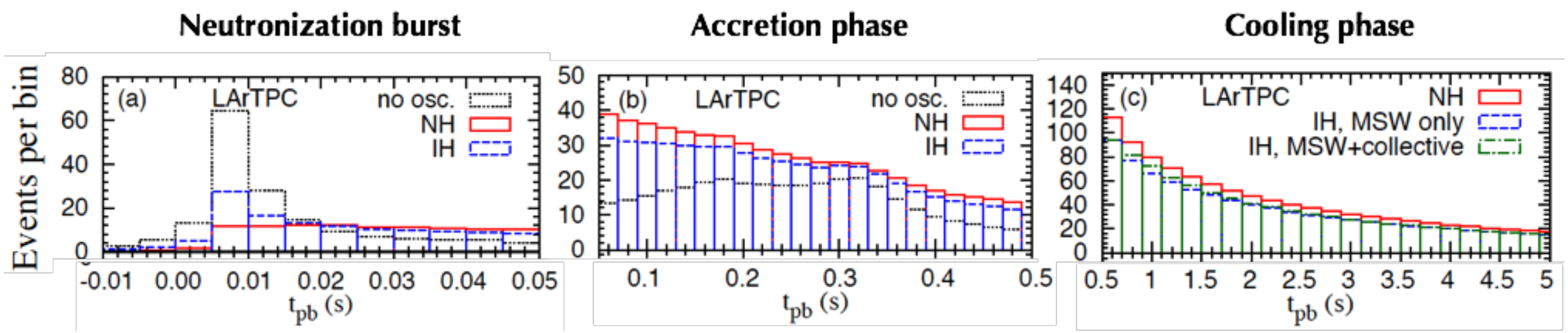
ν_eCC on Ar in DUNE

- Events per 0.5 MeV per ms, 40 kton @10 kpc
- No oscillations



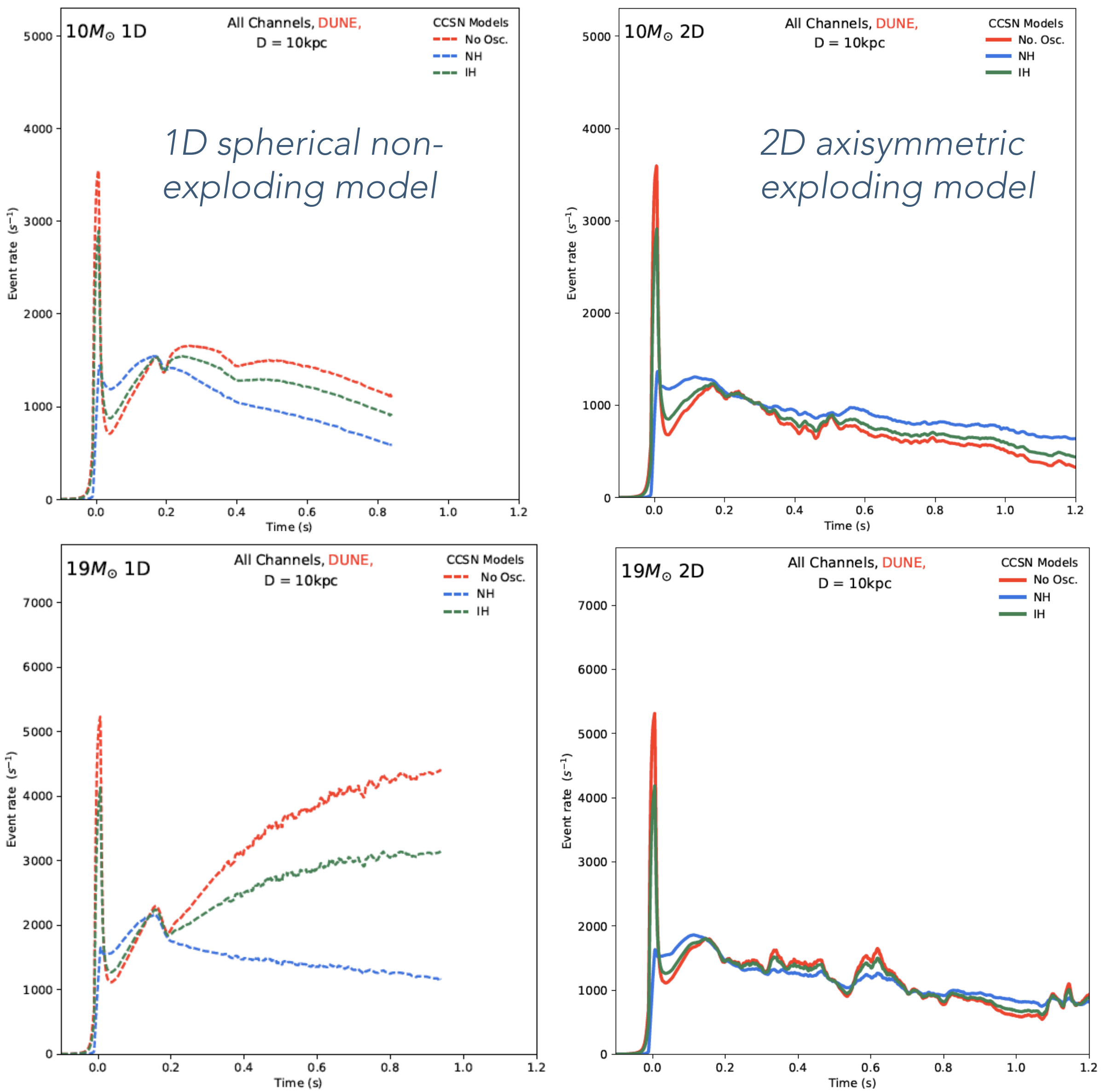
Effects of oscillations in SN ν signal

35 kton LAr **SN at 10 kpc** *Martinez-Pinedo et al., Phys. Rev. D91 (2015) 065016*



- Collective effects (important for IH) and MSW oscillations included
- Analysis of time structure and associated neutrino spectra can help to identify MH

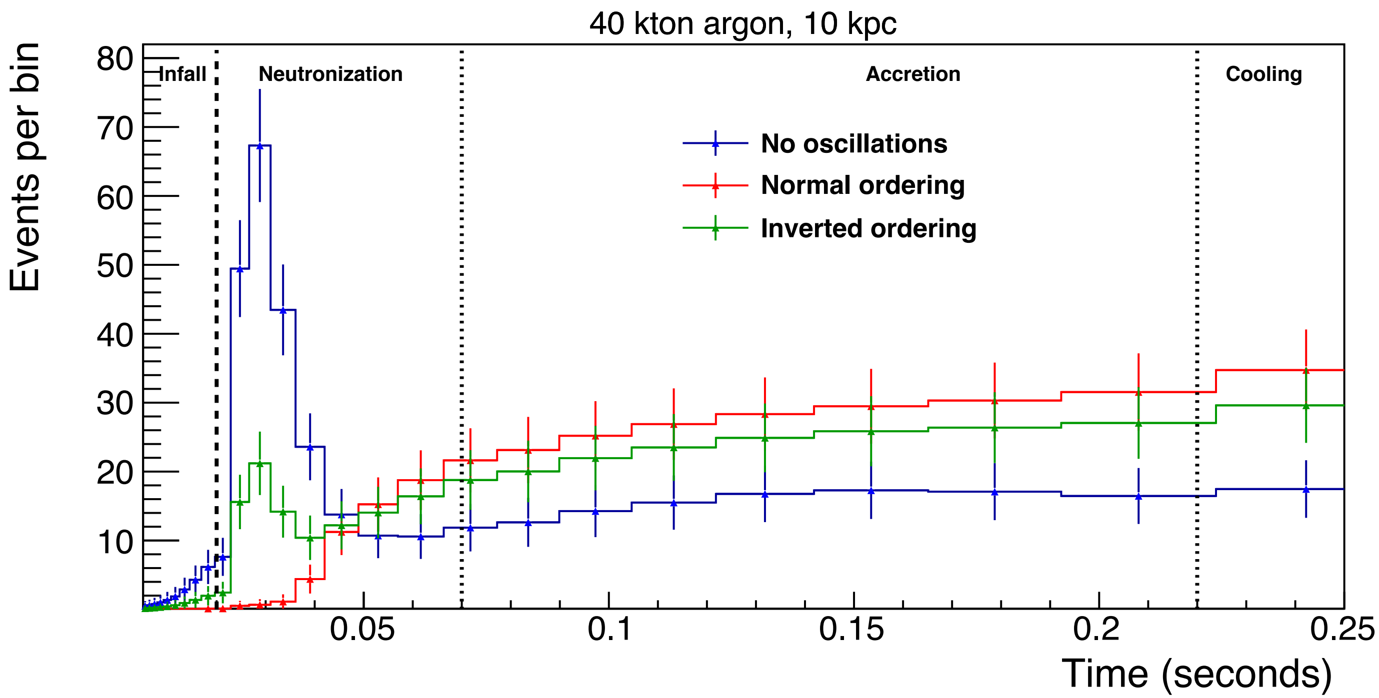
DUNE evt rates for 1D/2D models



- S. Seadrow et al. (arXiv:1804.00689)
- SN at 10 kpc
- All channels
- MSW transitions

The neutronization burst

Because of its sensitivity to electron neutrinos, LAr TPCs can provide unique information bout the early breakout pulse from next galactic SN

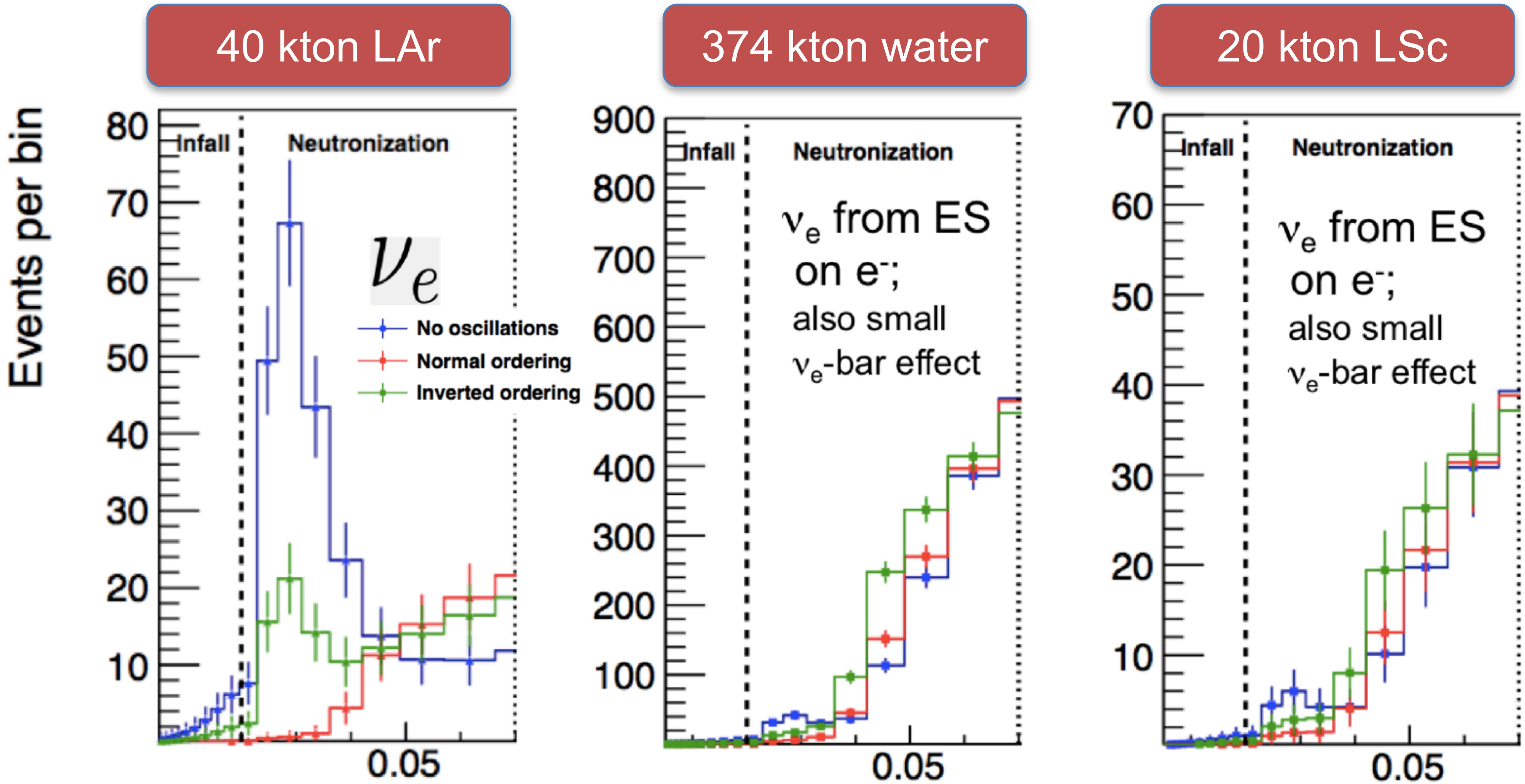


Robust MO signature

Garching model,
MSW transitions only,
total events (mostly ν_e)

The time structure of the SN signal during the first few tens of ms after the core bounce can provide a clear indication if the ν_e burst is present or absent, allowing to **distinguish the mass ordering**

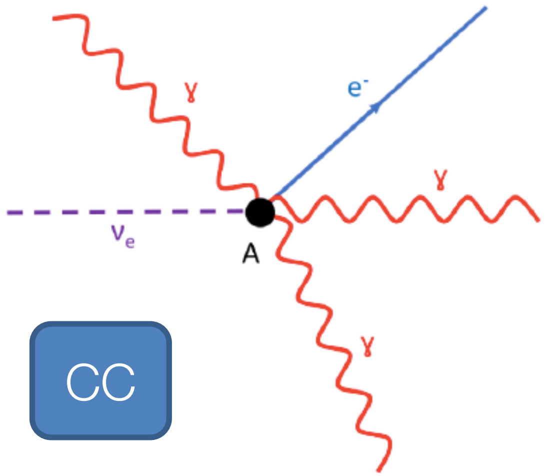
Robust mass ordering signature from ν_e burst



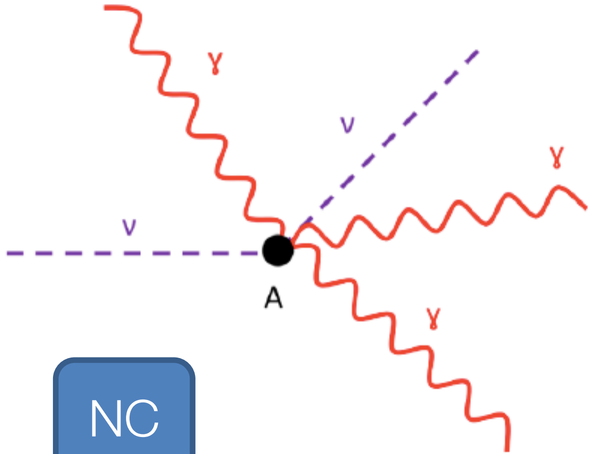
SN at 10 kpc

SN neutrino reconstruction in DUNE

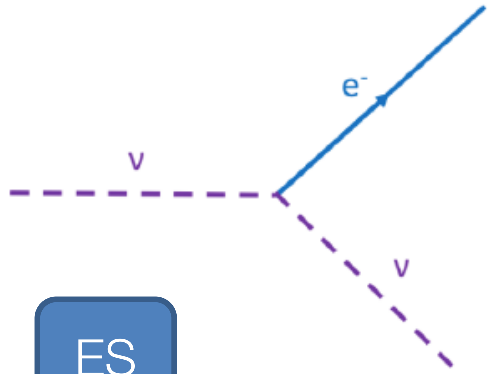
What are we looking for?



CC



NC



ES

- Electron track + de-excitation gammas
- Nucleon emission also possible

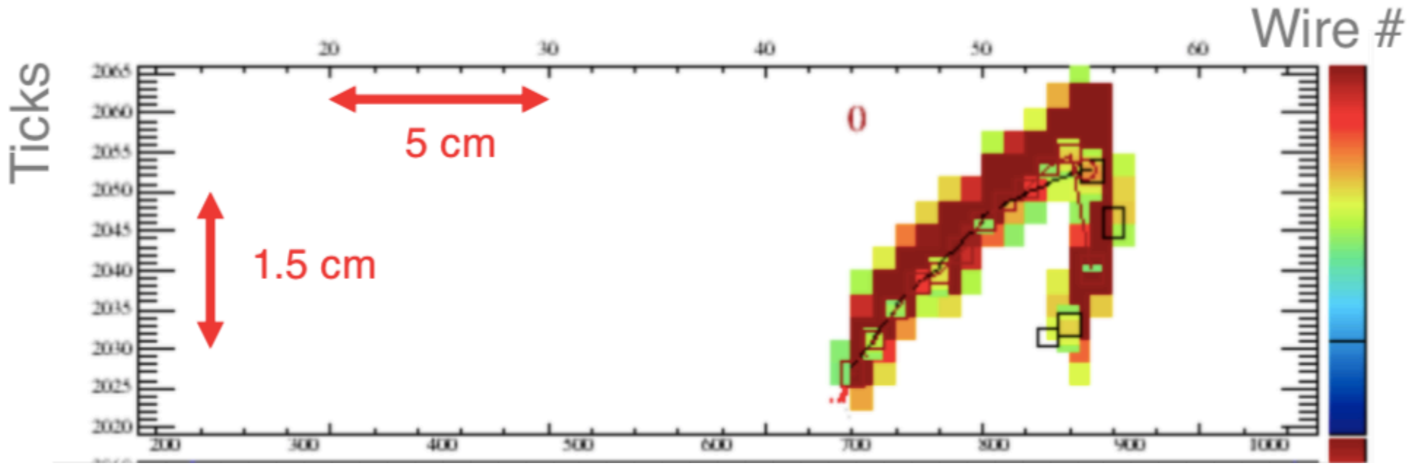
- De-excitation gammas

- Electron track
- Directionality

- Reconstruction capabilities are required to identify the interaction channels

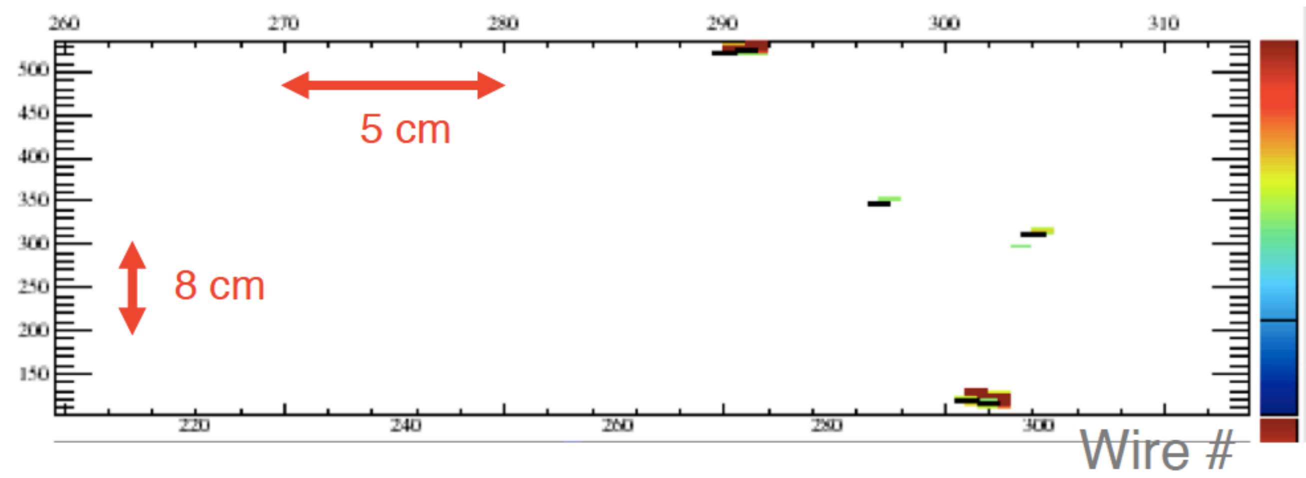
Examples of event display

- Reconstructing energy depositions - collection plane



ν_eCC

30.25 MeV veCC event



NC

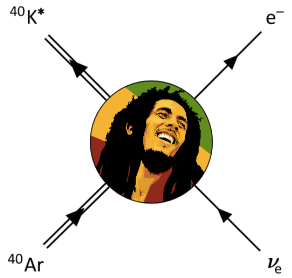
9.8 MeV gamma event

Challenges

- **Simulation:**
  - Robust SN neutrino fluxes including time profiles
  - Realistic event generators for SN neutrino interactions
  - Background simulations, electronic noise…
- **Reconstruction:**
  - Energy, vertex, angle, time reconstruction of low energy electrons and gammas
  - Interaction channels taggers
  - Extraction from background
- **SN trigger and DAQ**
  - Trigger rates
  - Data rates

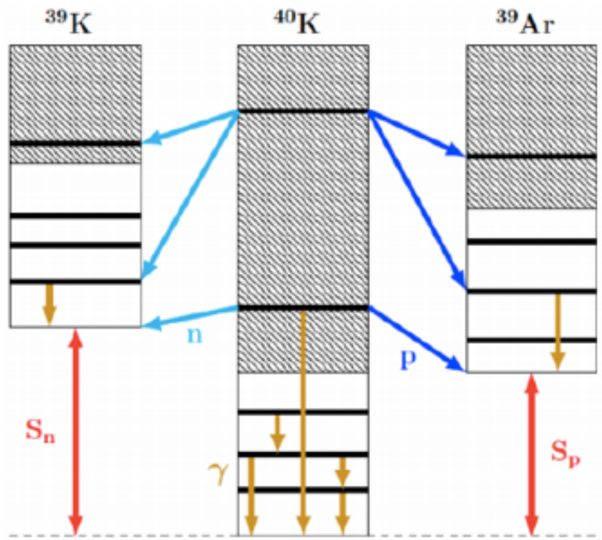
Work in progress…

- Developing reconstruction tools for low energy events
- Developing realistic simulation of SN neutrino events (including time profile)
- Developing gamma tagging algorithms
- Study of the ^{39}Ar background in the low energy reconstruction
- DAQ/triggering strategy
- Study of the capabilities of the photon detection system to trigger and reconstruct SN neutrino events
- …



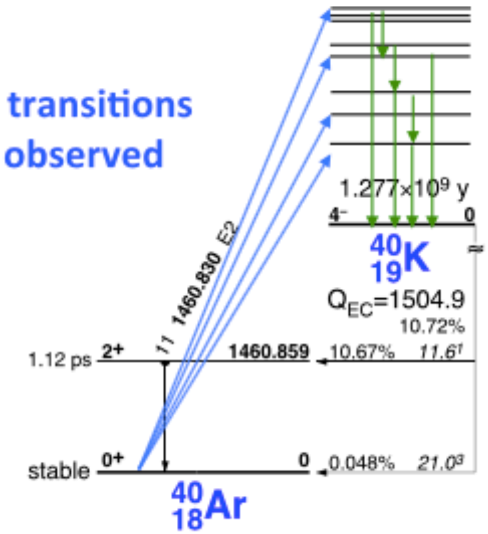
MARLEY (Model of Argon Reaction Low-Energy Yields)

- Event generator for low energy ν_eCC neutrino interactions on ^{40}Ar with realistic final state particles
- Lack of precision models of low-E neutrino argon interactions
- Transition levels are determined by observing de-excitation (gammas and nucleons)



At least 25 transitions have been observed indirectly

(g.s. to g.s. is 3rd forbidden transition)



Reconstructing true neutrino energy:

Q is determined by measuring de-excitation gammas and nucleons

Outgoing e⁻ Energy | Energy donated to transition | Recoil Energy of Nucleus (negligible)

$$E_\nu = E_e + Q + K_{\text{recoil}}$$

- Large uncertainties in nuclear data and models complicate energy reconstruction

Example of simulated SN ν event in DUNE

MARLEY

$$\nu_e + {}^{40}\text{Ar} \rightarrow e^- + {}^{40}\text{K}^*$$

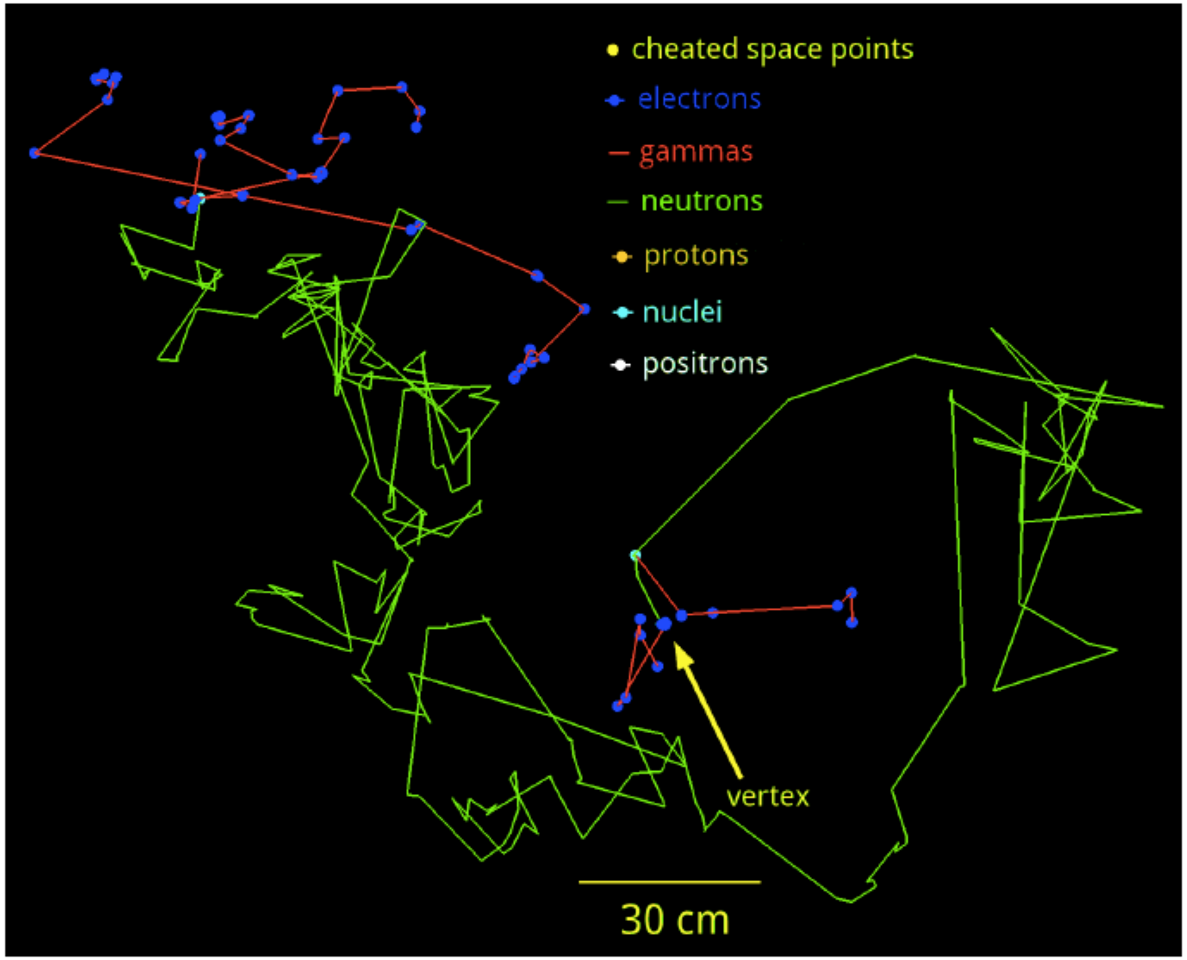
E_ν = 16.3 MeV

e^- deposited 4.5 MeV

γs from n-capture 7.6 MeV

Total visible Energy = 12.2 MeV

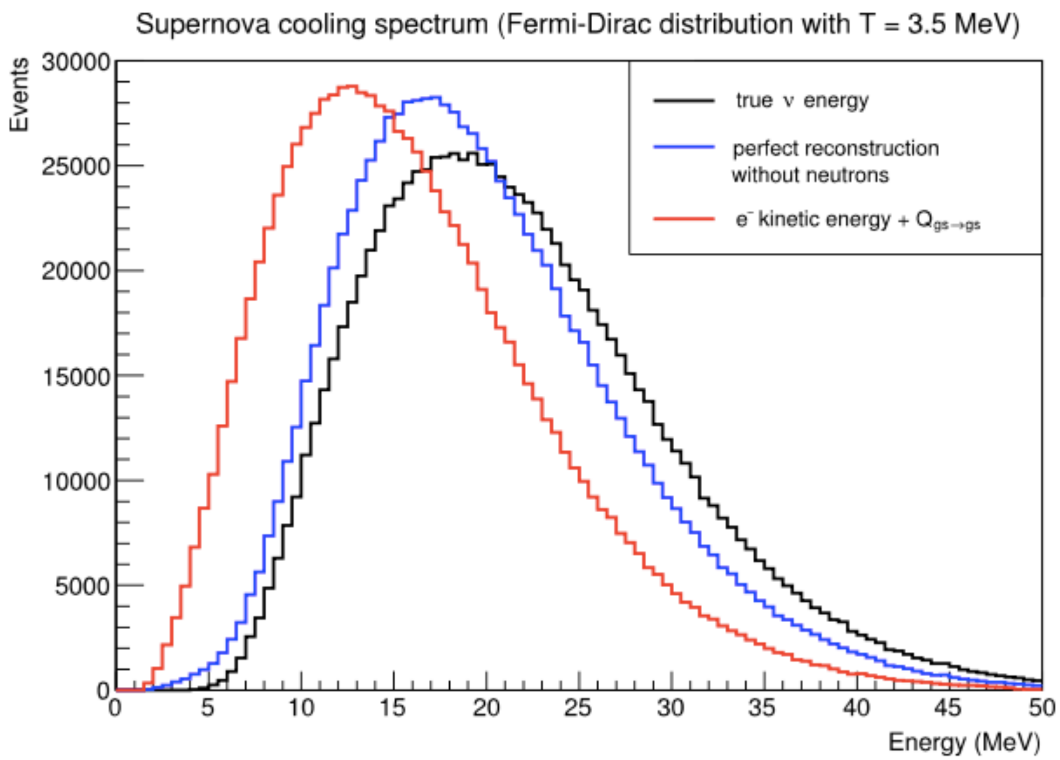
Visible event radius = 144 cm



MARLEY simulation

$^{40}K^*$ de-excitations

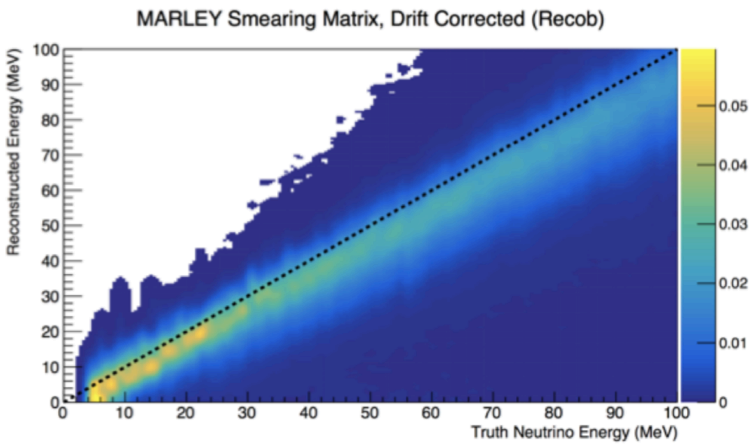
- γs only: 83.7%
- single n + γs: 14.6%
- single p + γs: 1.5%
- other: 0.2%

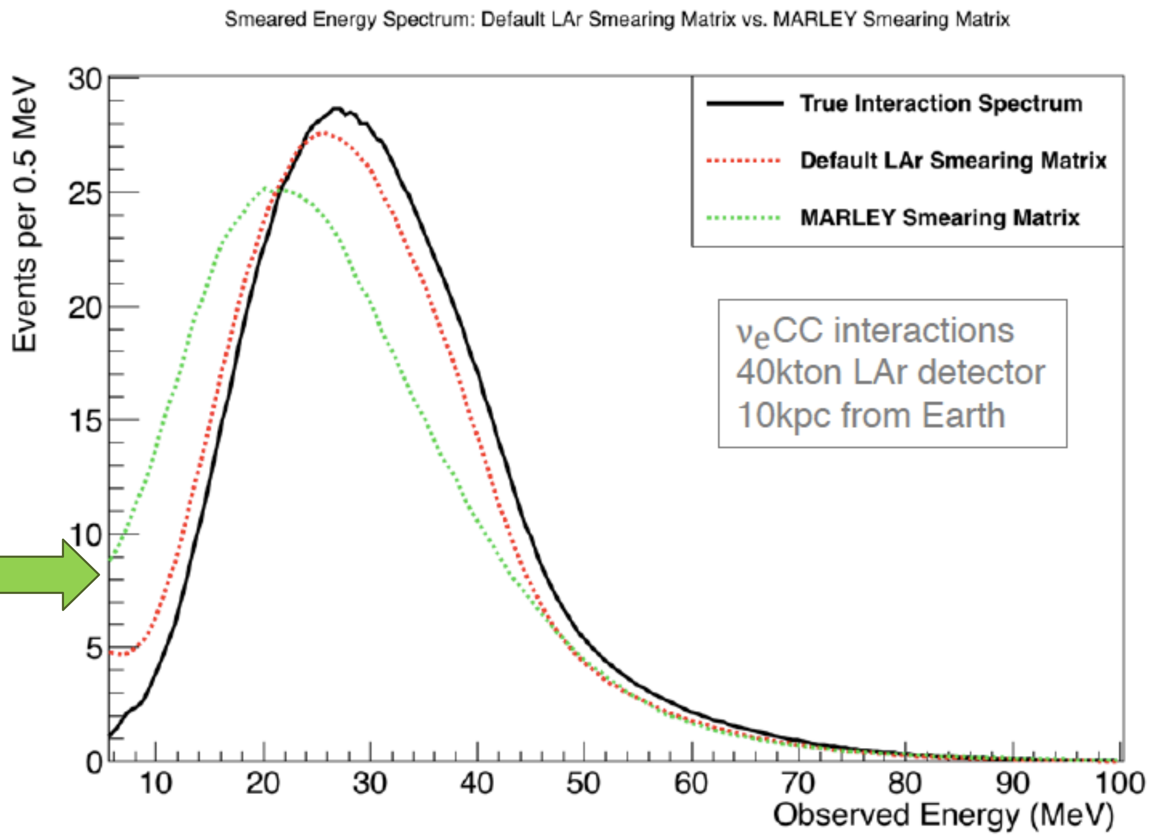


Loss of neutrons has an impact on the energy spectrum

Smearing matrix with MARLEY

- More realistic prediction is obtained with MARLEY
- “true interaction spectrum” = interaction rates before smearing

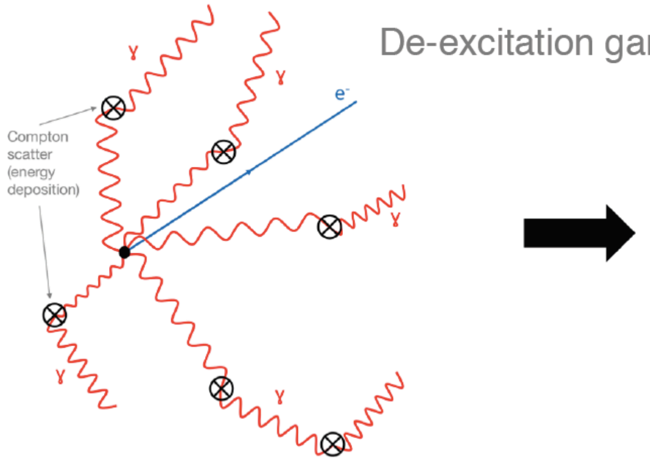


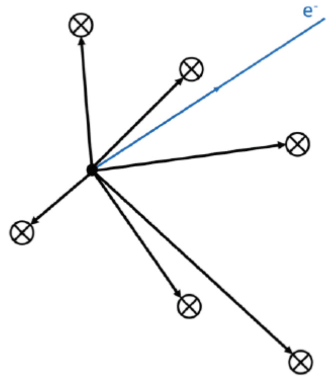


Gamma tagging algorithms

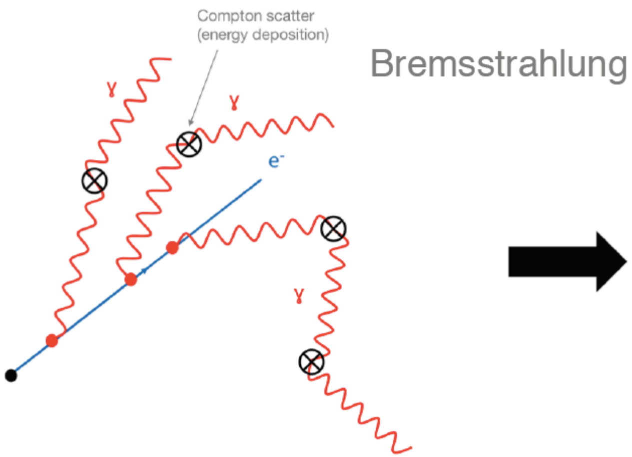
- Working on an algorithm to distinguish between bremsstrahlung and de-excitation gammas

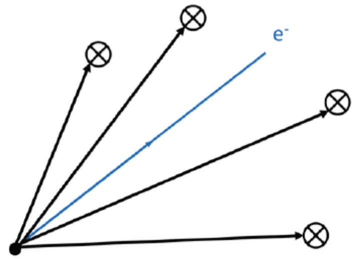
De-excitation gammas: “isotropic cloud”





Bremsstrahlung gammas: “Forward-moving jet”



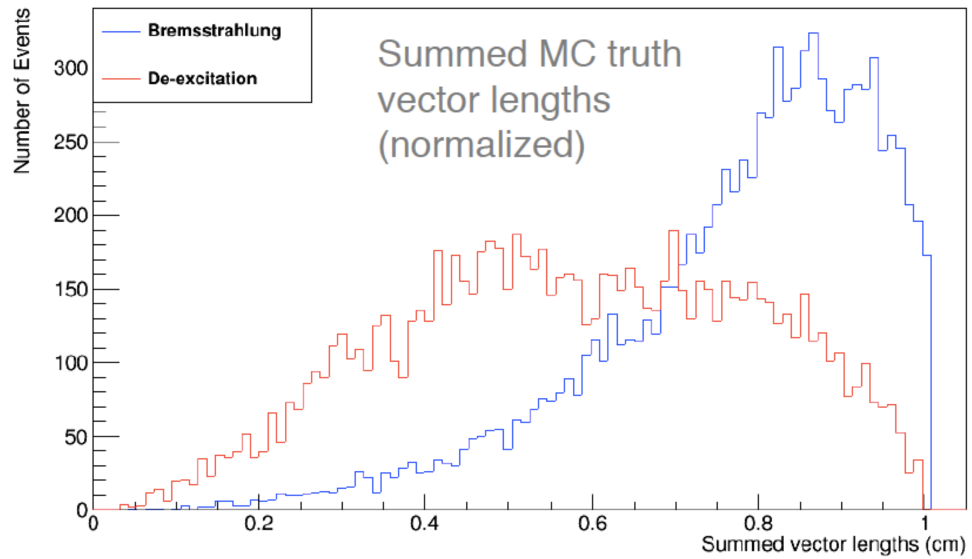


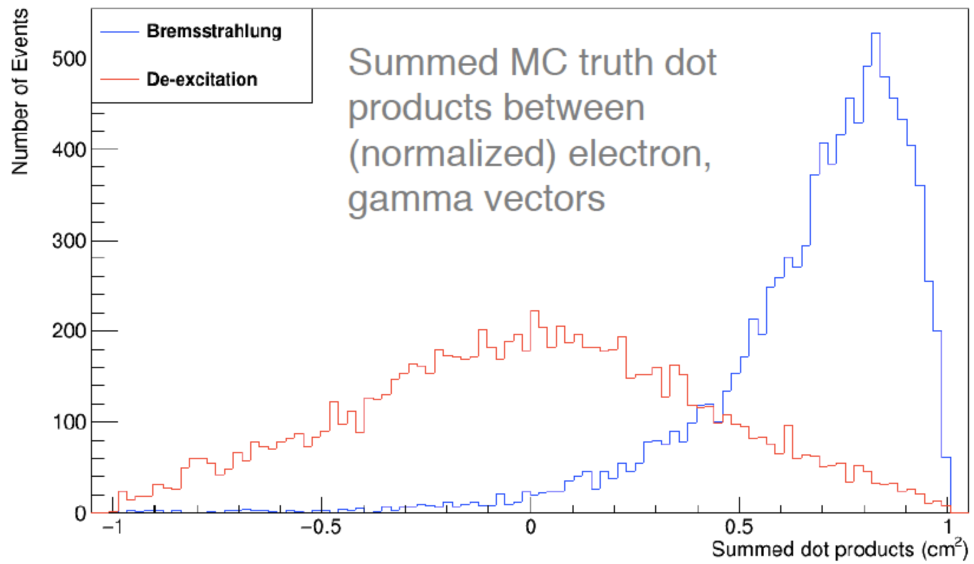
MC truth gamma-tagging parameters

- Bremsstrahlung distribution shows ”forward-moving behaviour”
- De-excitation distribution shows more isotropic behaviour

Promising information for a reconstruction algorithm

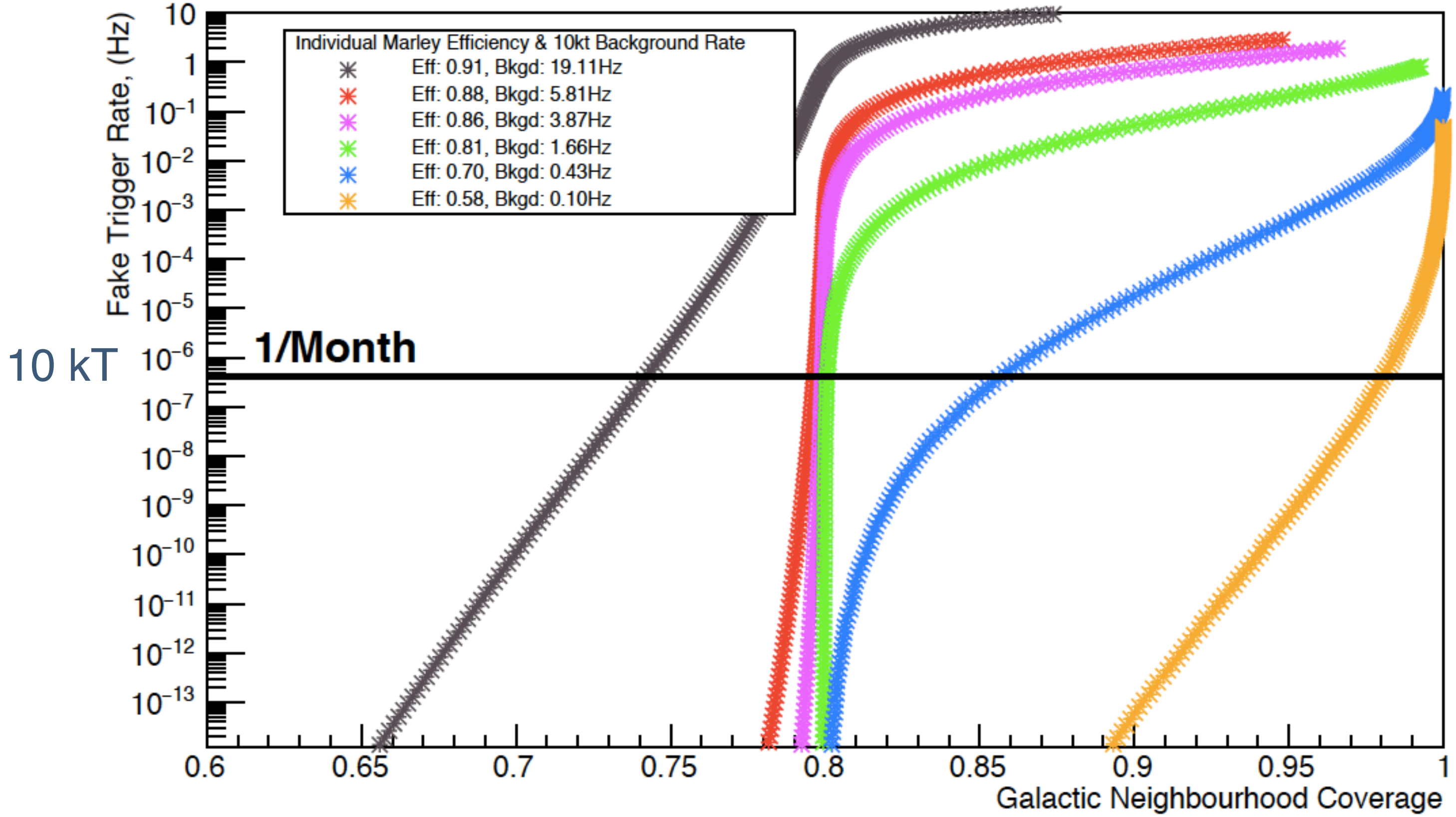
30.25 MeV ν_eCC events





Triggering on SN neutrinos

- Trigger on 98% of supernovae in Milky Way and LMC, issuing 1 fake trigger per month on average due to radiological backgrounds



Summary

Summary

- DUNE will have a **broad program** on neutrino physics and astrophysics including the test of fundamental symmetries **beyond the beam measurements**
  - **SN neutrino burst program is a key science goal for DUNE**
- Unique measurements of **supernova neutrinos**
  - Mainly sensitive to ν_e (neutronization burst)
  - Measurements of the time, flavor and energy structure of the neutrino burst will be critical for understanding the **dynamics** of this important **astrophysical phenomenon**, as well as providing information on **neutrino properties** and other particle physics.
- **Excellent progress** on low energy interaction models, reconstruction, tagging algorithms, trigger, radiological backgrounds, etc.
- **Preparing the detectors** for next SN neutrino burst!!