Astroparticle Physics at the DUNE Experiment

Inés Gil-Botella
CIEMAT – Madrid
on behalf of the DUNE Collaboration

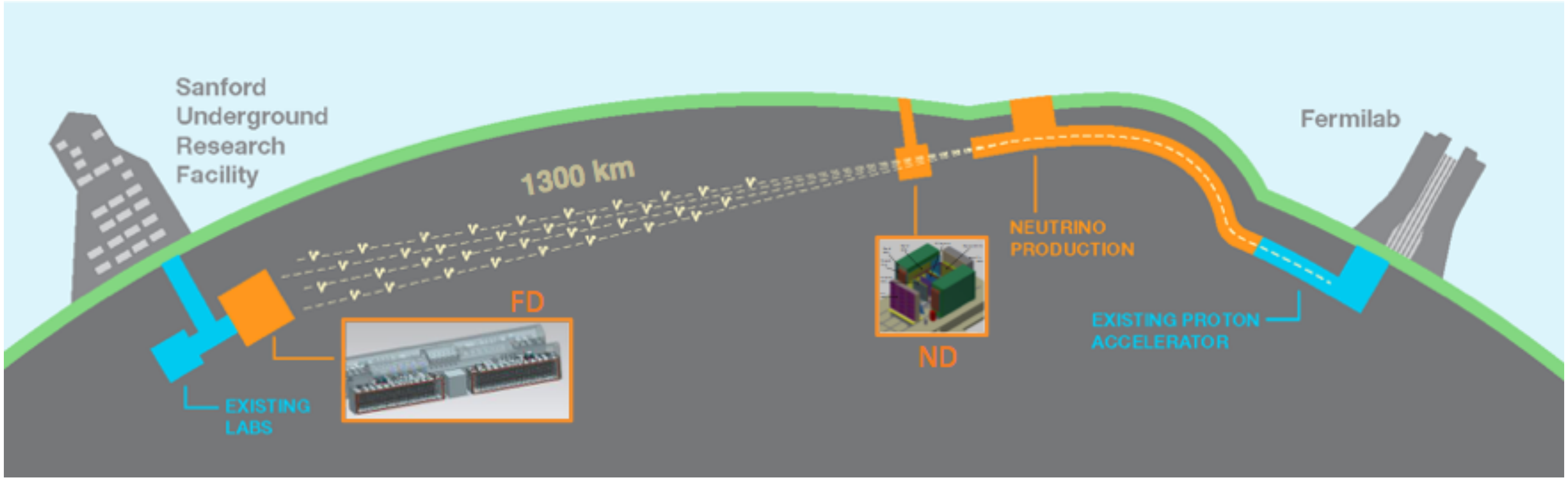
GOBIERNO DE ESPAÑA
MINISTERIO DE ECONOMÍA, INDUSTRIA Y COMPETITIVIDAD
Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
EXCELENCIA MARÍA DE MAEZTU
DUNE

Outline

- Deep Underground Neutrino Experiment
- Supernova Neutrino Detection
- Nucleon decay searches

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)



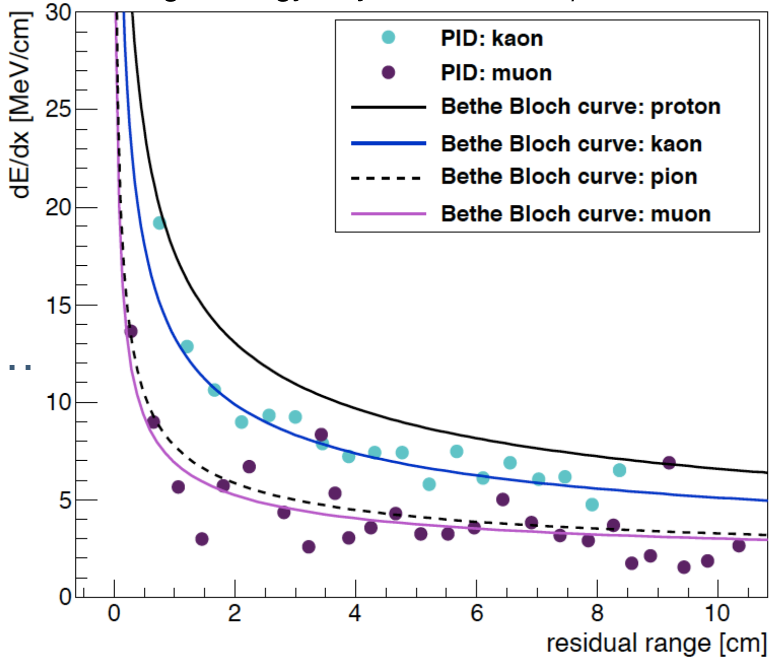
- **Deep Underground Neutrino Experiment**: 40 kton LAr TPC far detector at 1480 m depth (4300 mwe) at SURF measuring neutrino spectra at 1300 km in a **wide-band** high purity ν_μ beam with peak flux at 2.5 GeV **operating at ~1.2 MW** and upgradeable to 2.4 MW
- **4 x 10 kton (fiducial) modules** (single 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!**

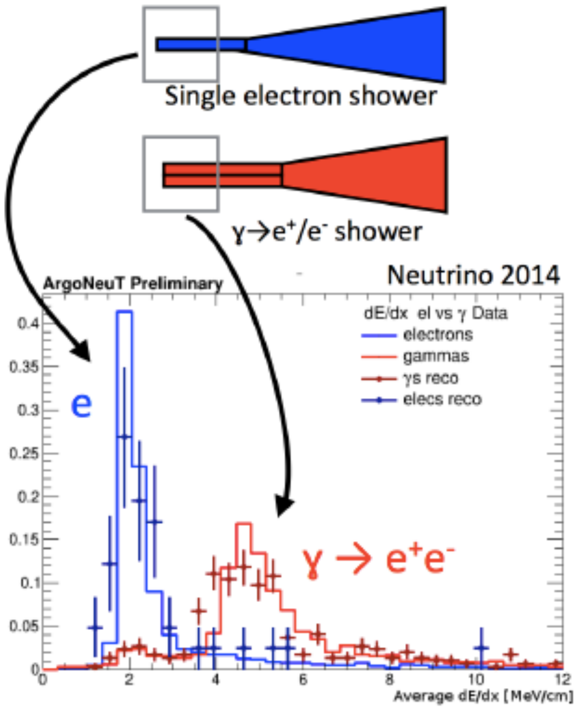
The DUNE Far Detector

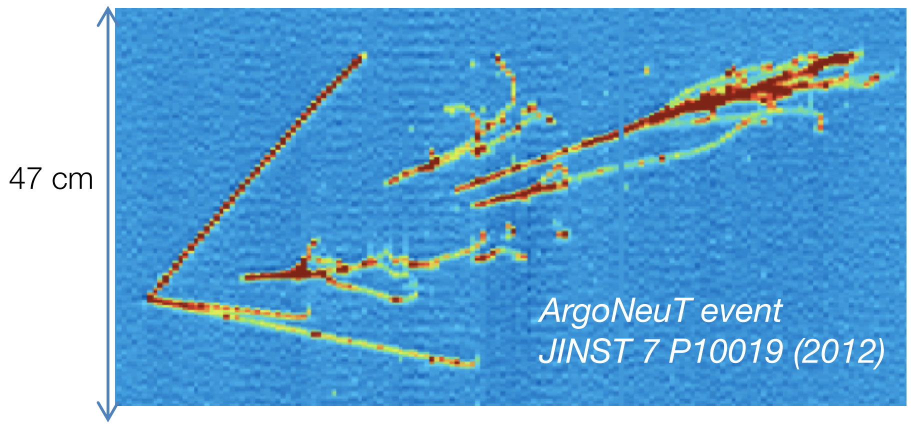
The LAr TPC technology provides:

- 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







ArgoNeuT event
JINST 7 P10019 (2012)

Supernova neutrinos

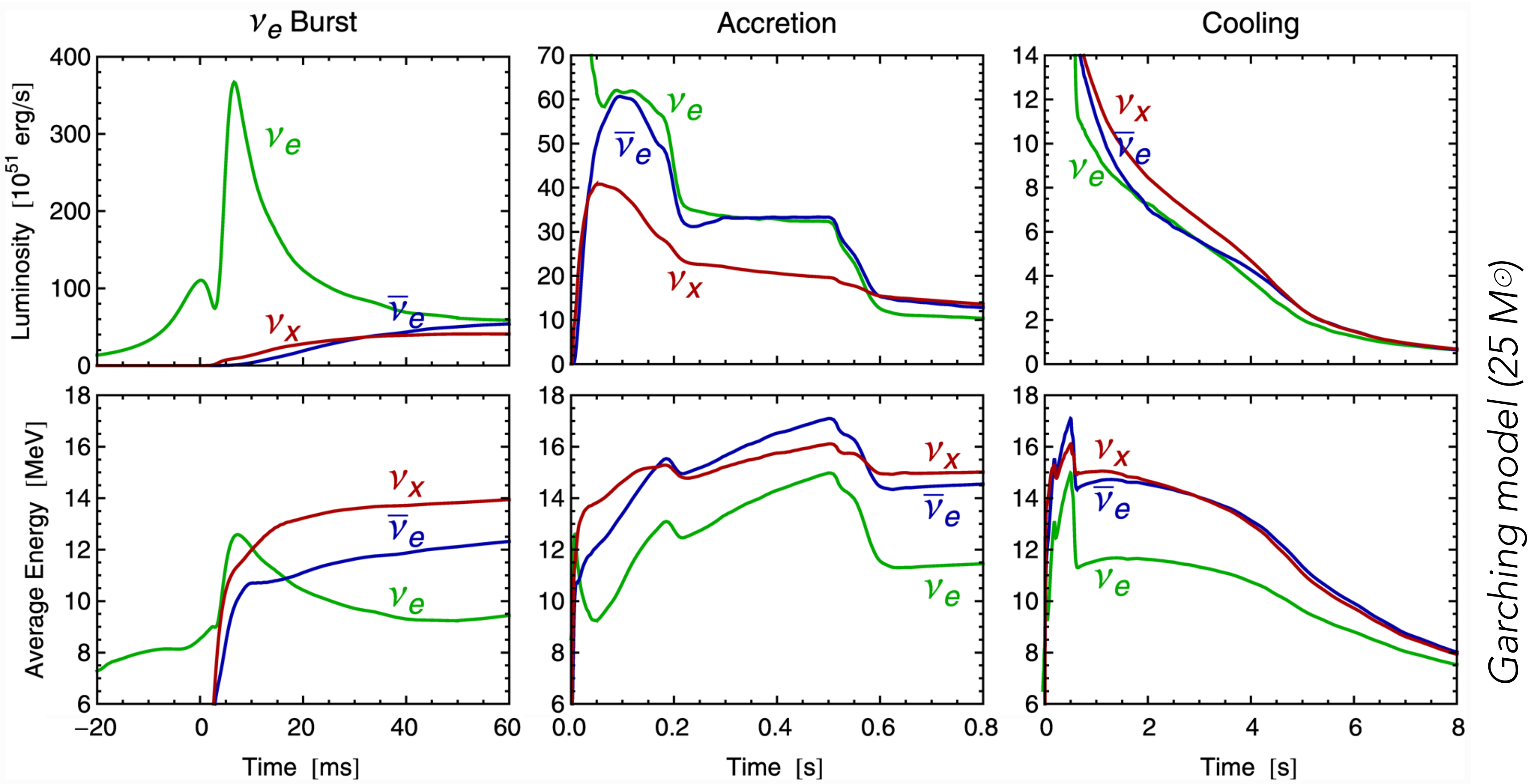
Core-collapse Supernovae

- Core-collapse supernova are a huge source of neutrinos of all flavors
- Gravitational binding energy: $E_B \approx 3 \times 10^{53}$ erg
  - 99% neutrinos
  - 1% kinetic energy of the exploding matter
  - 0.01% light
- Neutrino emission lasts ~10 sec
- Expected SNs in our Galaxy (d ≈ 10 kpc) : 1-3 SN/century

- Measurement of the neutrino energy spectra, flavor composition and time distributions from SN will provide **information about**:
  - **Supernova physics**: Core collapse mechanism, SN evolution in time, cooling of the proto-neutron star, nucleosynthesis of heavy nuclei, black hole formation
  - **Neutrino (other particle) physics**: ν flavor transformation in SN core and/or in Earth, collective effects, ν absolute mass, other ν properties: sterile νs, magnetic moments, axions, extra dimensions, …

- Neutrinos detected from SN1987A
- Kamiokande, IMB, Baksan: ~20 events in total (essentially anti-ν_e)
- Confirmed baseline model

Three phases of SN ν emission



Neutronization burst

- Shock breakout
- De-leptonization of outer core layers

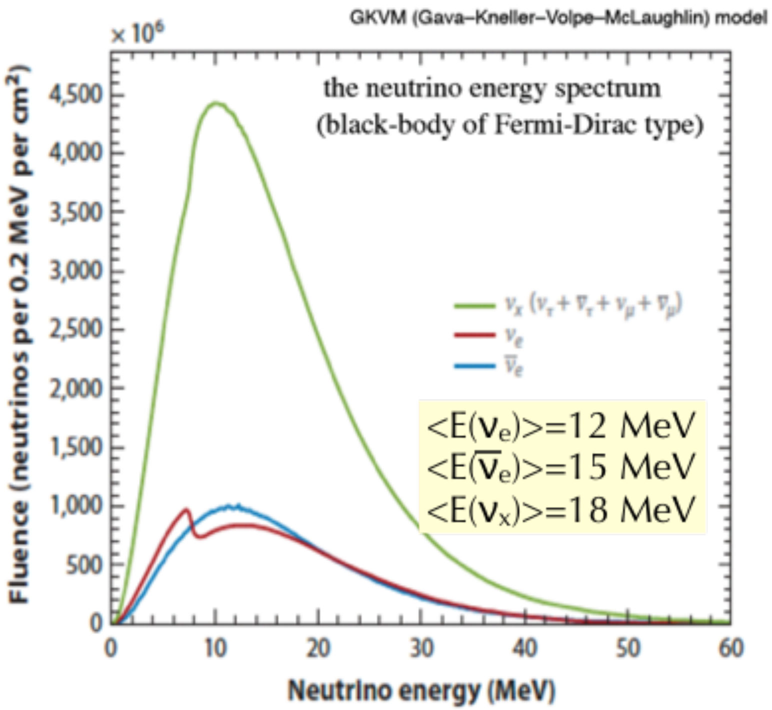
Accretion phase

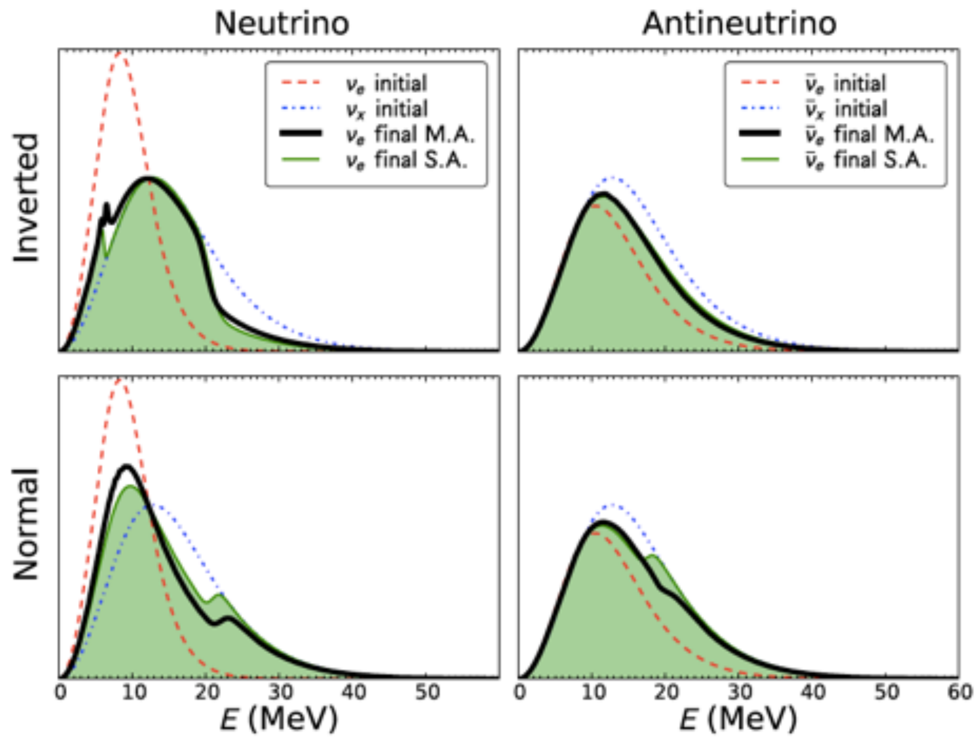
- Shock stalls ~150 km
- Neutrinos powered by infalling matter

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

Supernova neutrino signal in LAr

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

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

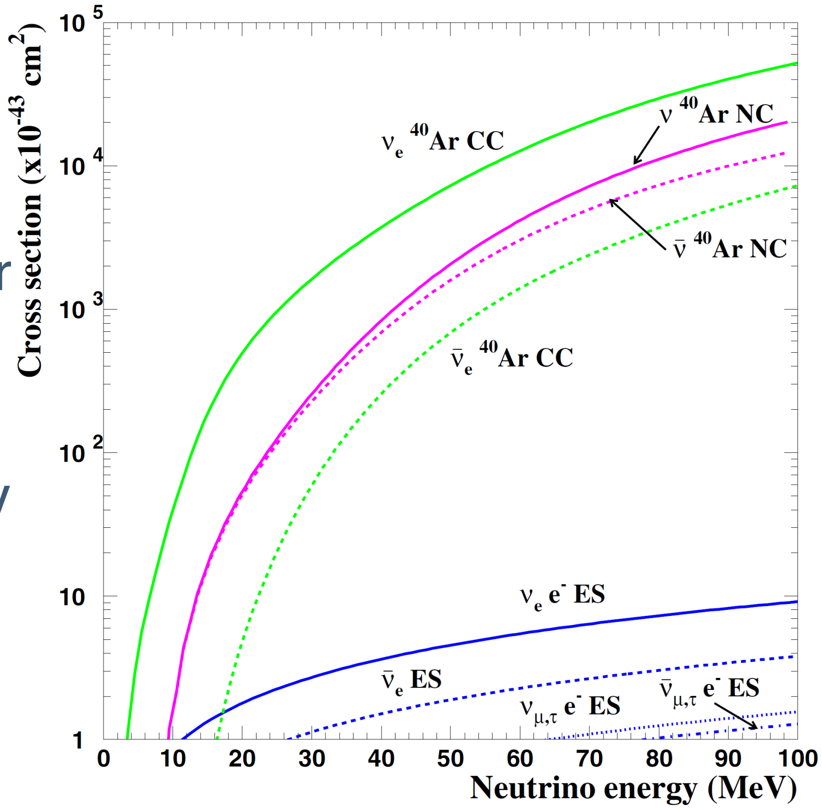
1. **Charged-current** (**CC**) interactions on Ar

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

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

1. **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**)

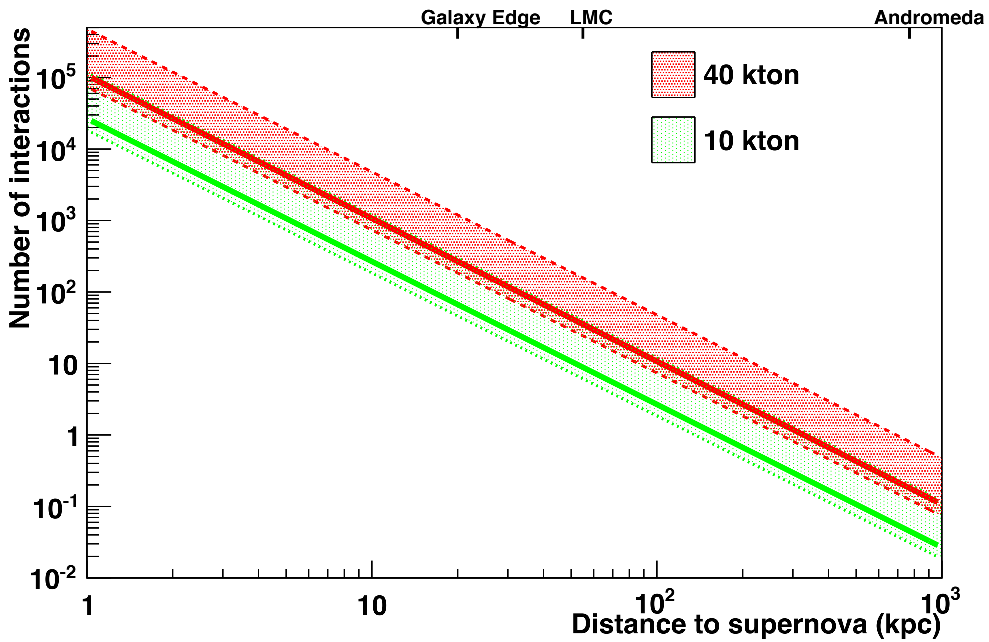
SN neutrinos in DUNE

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*

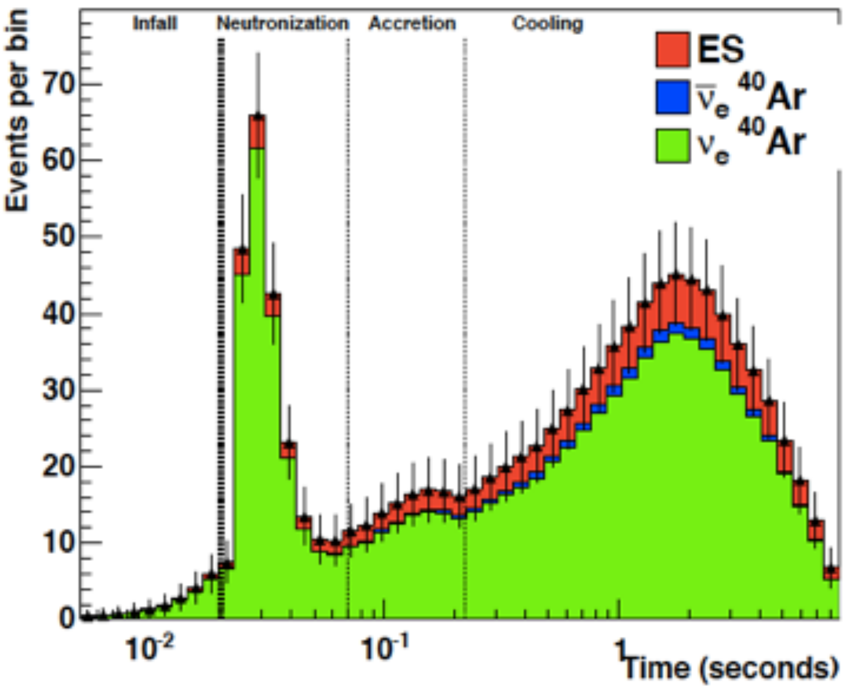
- Unique sensitivity to electron neutrinos
- Width of bands represents range of models
- Solid: Garching model *PRL104 (2010) 251101*



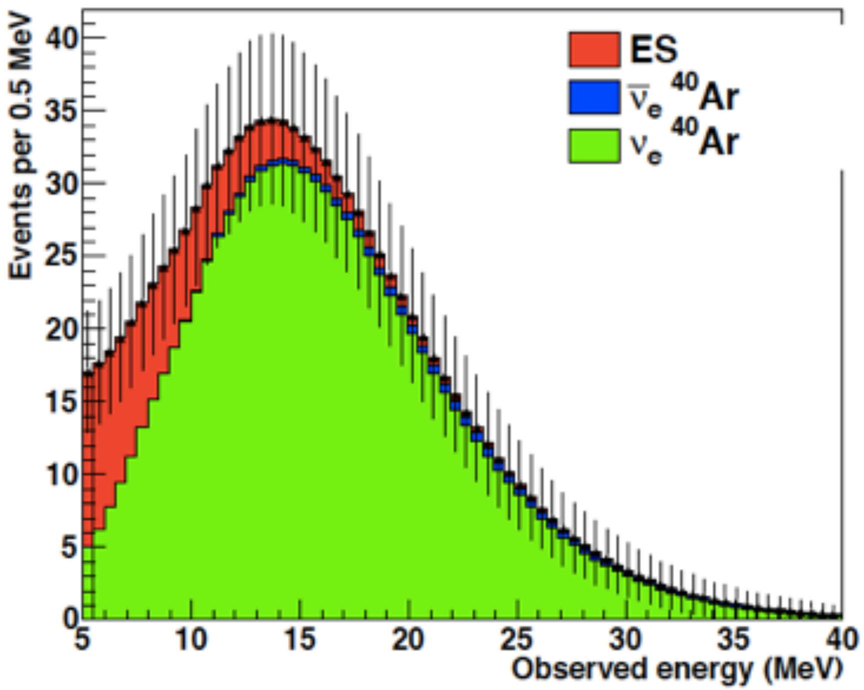
SN neutrino spectra in DUNE

- SN at 10 kpc in DUNE (40 kt LAr)
- No oscillations

- Required energy resolution < 10%
- Energy threshold ~5 MeV



Time-dependent signal

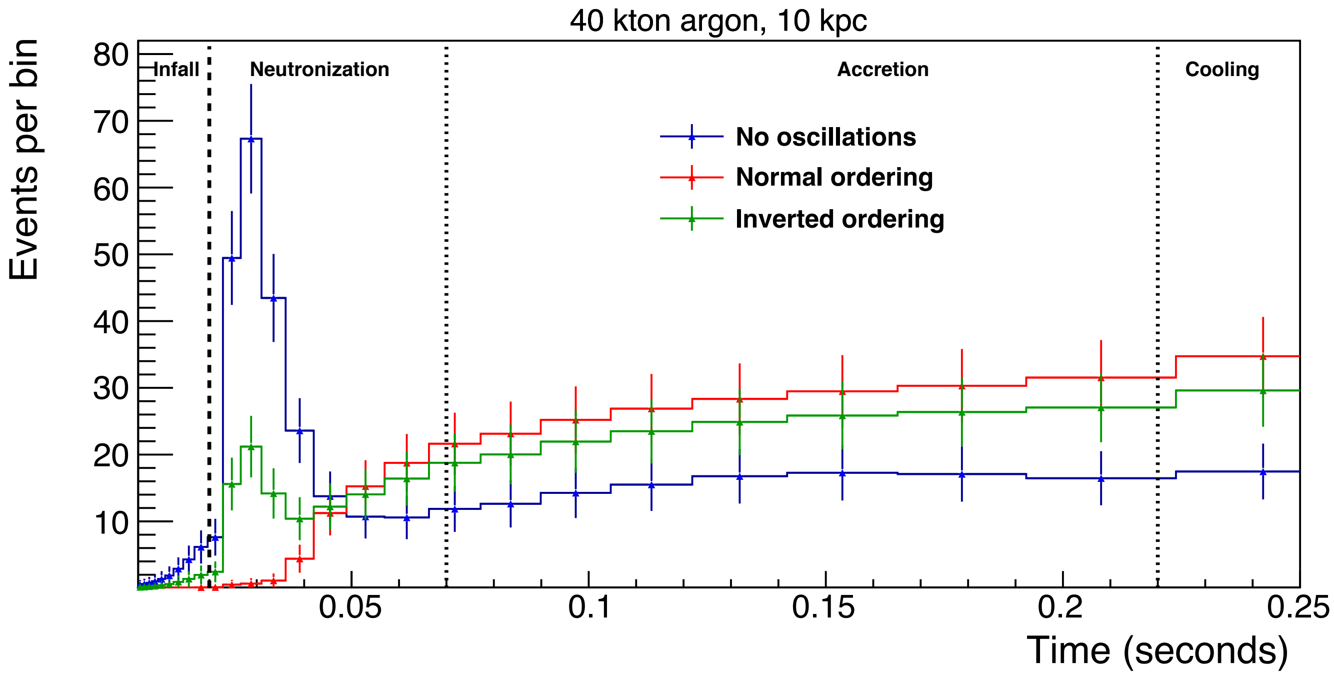


Expected event spectrum integrated over time

Garching model, ICARUS energy resolution, 5 MeV threshold

Neutronization burst

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



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 between different mixing scenarios**

Nucleon Decay Searches

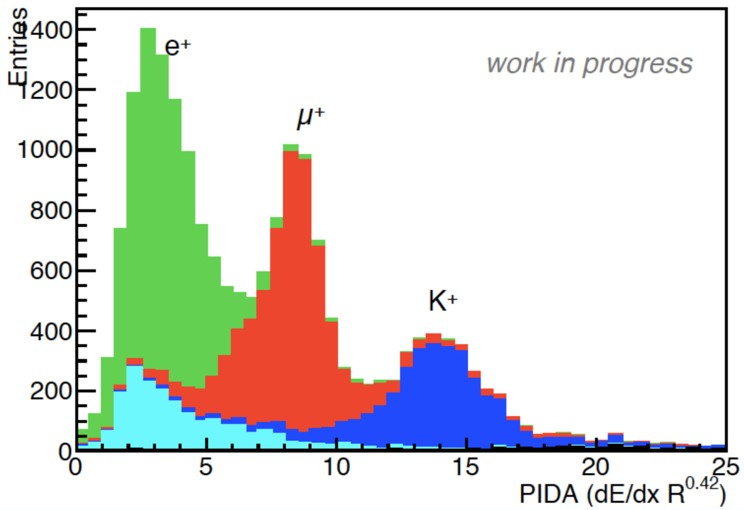
Nucleon decay channels

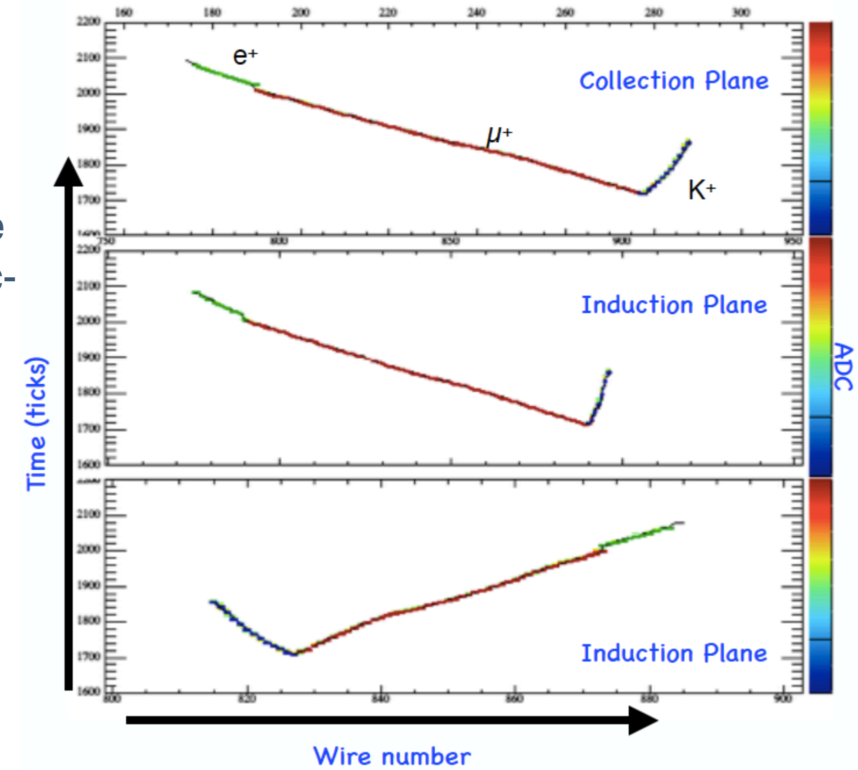
- **Many possible decay modes** (≈ 90 identified)
  - Proton decay modes, neutron decay modes, n-nbar oscillation modes
- The strength of LAr: kaon modes, e.g. **$p \rightarrow \bar{\nu} K^+$ (SUSY motivated)**
- Kaons clearly identified by dE/dx and decay chain in LAr TPCs
- Main background: atmospheric neutrinos where a proton is misidentified as kaon or cosmogenic-induced kaons

$p \rightarrow K^+ \bar{\nu}$

$K^+ \rightarrow \mu^+ \bar{\nu}_\mu$

$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$

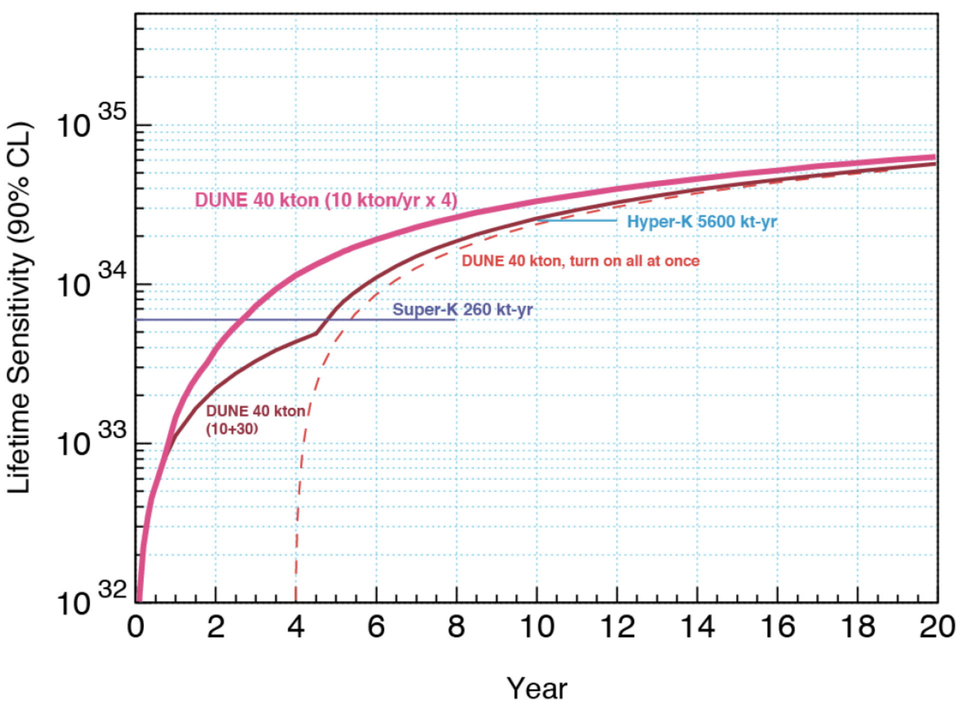


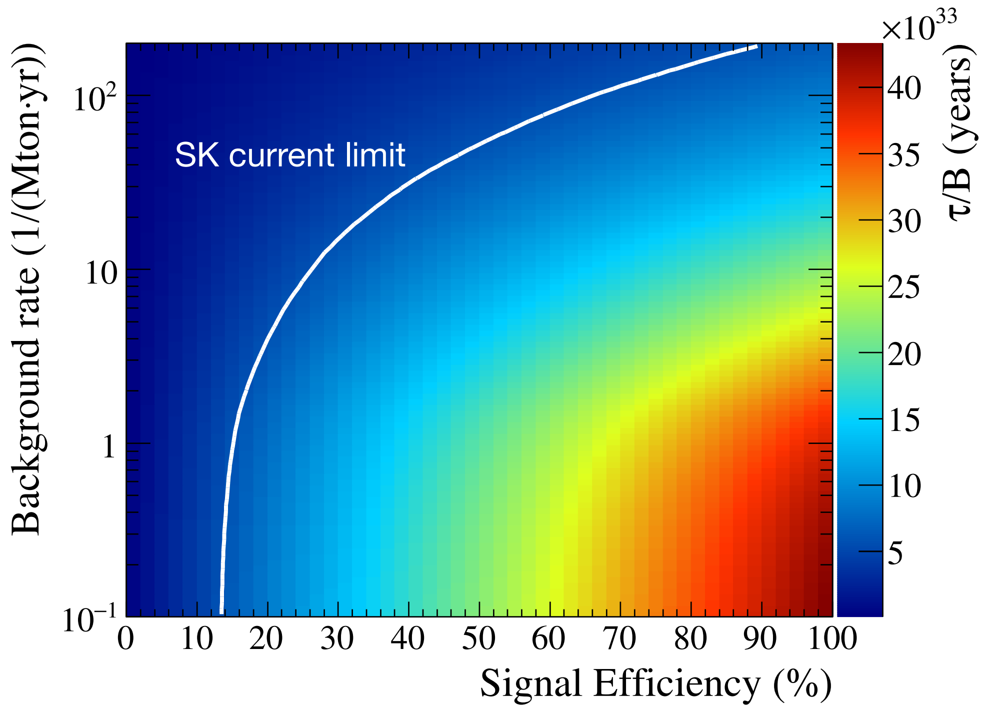


Simulation and reconstruction of proton decay at DUNE

Expected DUNE Sensitivity for p → $K^+ \bar{\nu}$

- **Low-background** mode with **high detection efficiency**
- DUNE will do well in decay modes with kaons, and modes with neutrinos or with complicated topologies

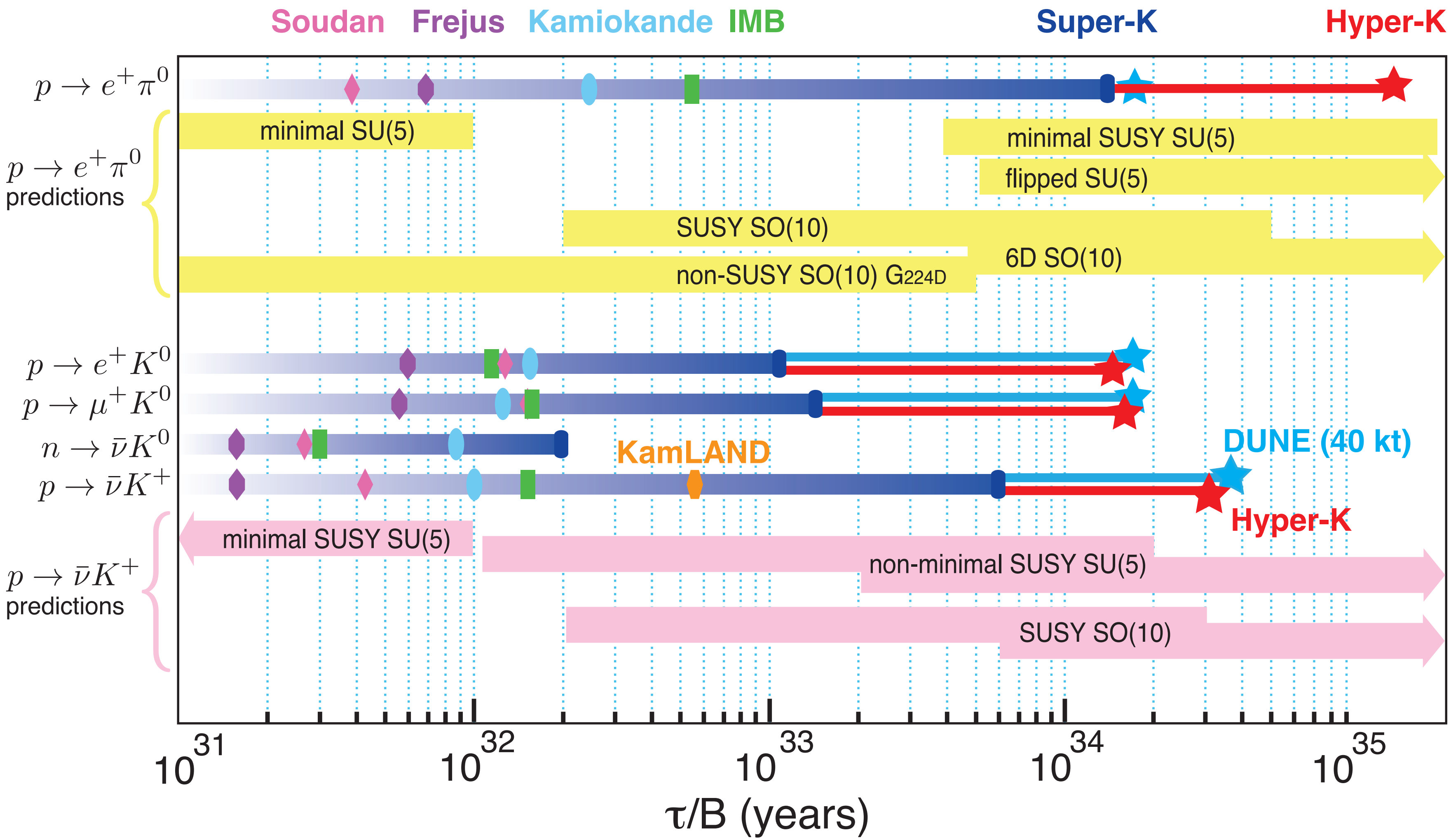




Partial lifetime sensitivity at 90% CL for a 400 kton-year exposure

Experimental Limits and Theoretical Predictions

Example “benchmark” decay modes, but **many others will also be searched**



Conclusions

Astroparticle physics with DUNE

- DUNE will have a **broad program** on neutrino physics and astrophysics including the test of fundamental symmetries **beyond the beam measurements**
- Unique measurements of **supernova neutrinos**
  - 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.
- **Nucleon decay** observation will be a **major discovery**
  - DUNE will search for proton decay in the range of proton lifetimes predicted by a wide range of GUT models

END

The DUNE Science Program

PRIMARY GOALS

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

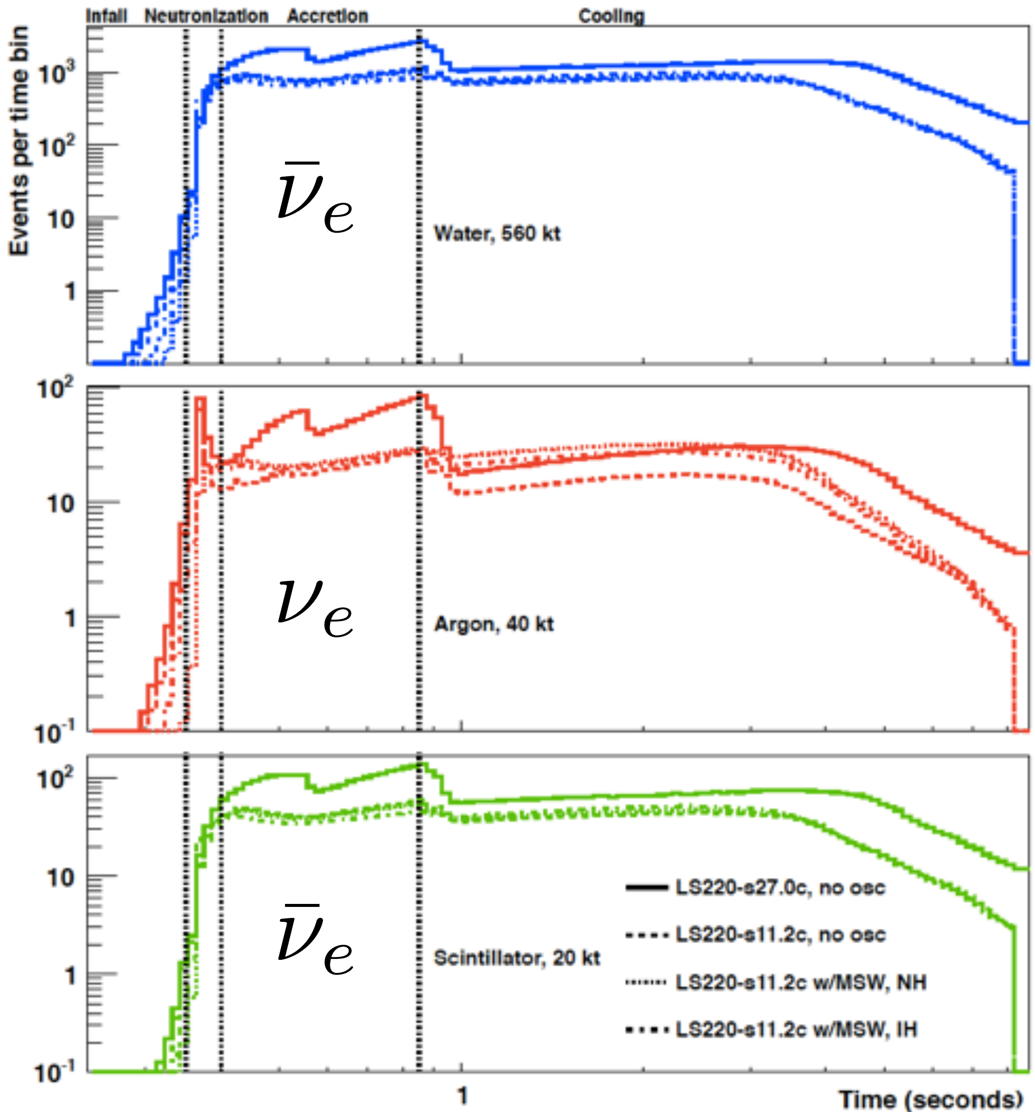
1) **Neutrino Oscillation Physics**
   - CPV in the leptonic sector
   - Neutrino Mass Hierarchy
   - Precision Oscillation Physics & testing the 3-flavor paradigm
2) **Supernova burst physics & astrophysics**
   - Unique sensitivity to ν_e complementary to other technologies
3) **Nucleon Decay**
   - 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, decoherent
8) Dark matter

Comparison between technologies

Total event rates per time bin for 27 and 11 $M_\odot$ SN progenitors models



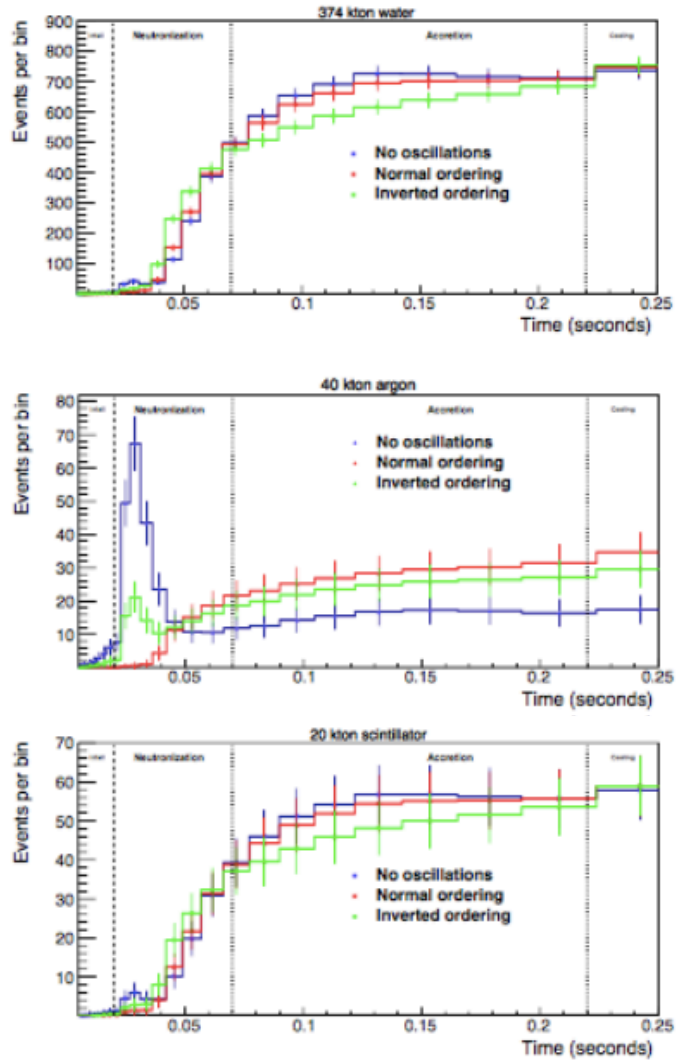
K. Scholberg et al., Rivista del Nuovo Cimento Vol. 39, N. 1-2 (2016)

WC

LAr

LSc

Neutronization burst



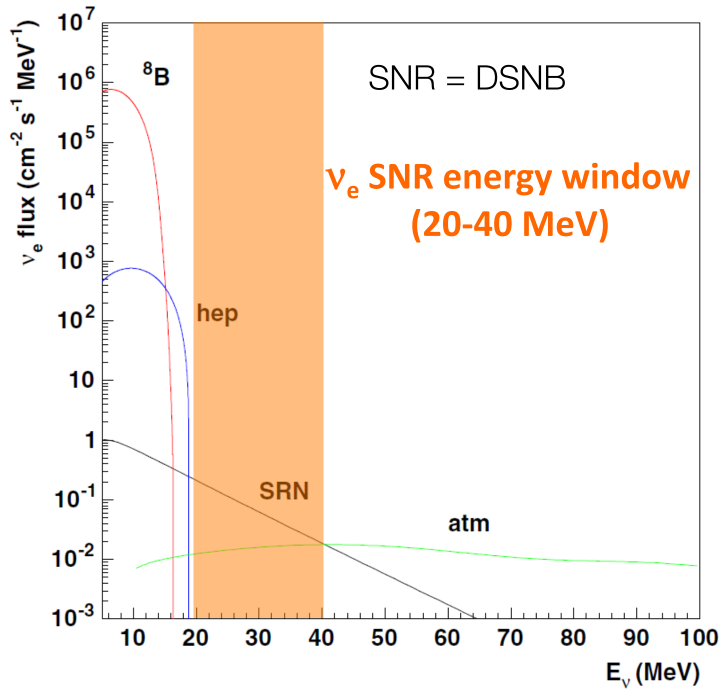
Diffuse Supernova Neutrino Background

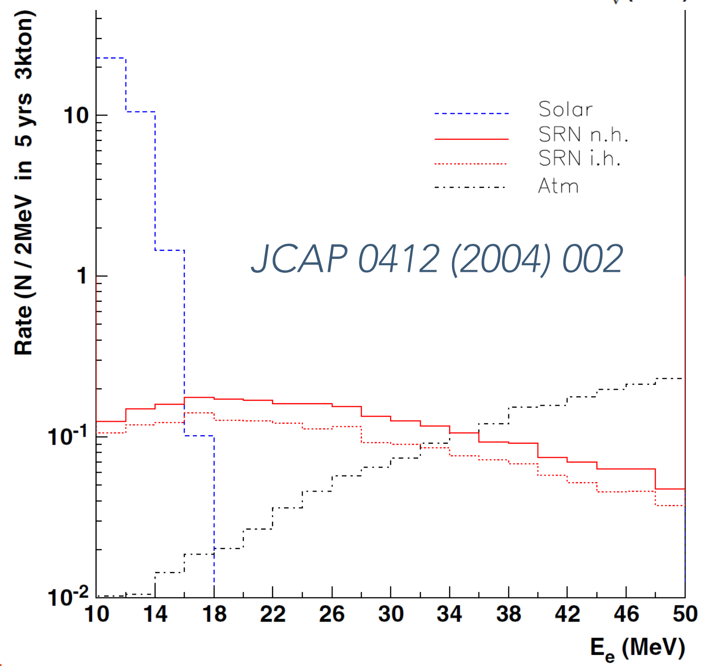
- Diffuse SN neutrino background (DSNB) from all the SN explosions in the Universe

  → **guaranteed steady source of SN neutrinos**

- **Not detected yet** (same detection channels as for burst νs)
- LAr TPCs can detect DSNB mainly through ν_eCC interactions
- Main experimental issue: **backgrounds**
  - Main background for LAr TPCs: solar and atmospheric neutrinos
- DUNE, in 10 years, n.h.

N_{DSNB}= 46 ± 10 (16 MeV ≤ E_e ≤ 40 MeV)





SNR flux prediction based on Strigari et al., JCAP03 (2004) 007