Supernova Neutrinos at the DUNE Experiment

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SNOLAB
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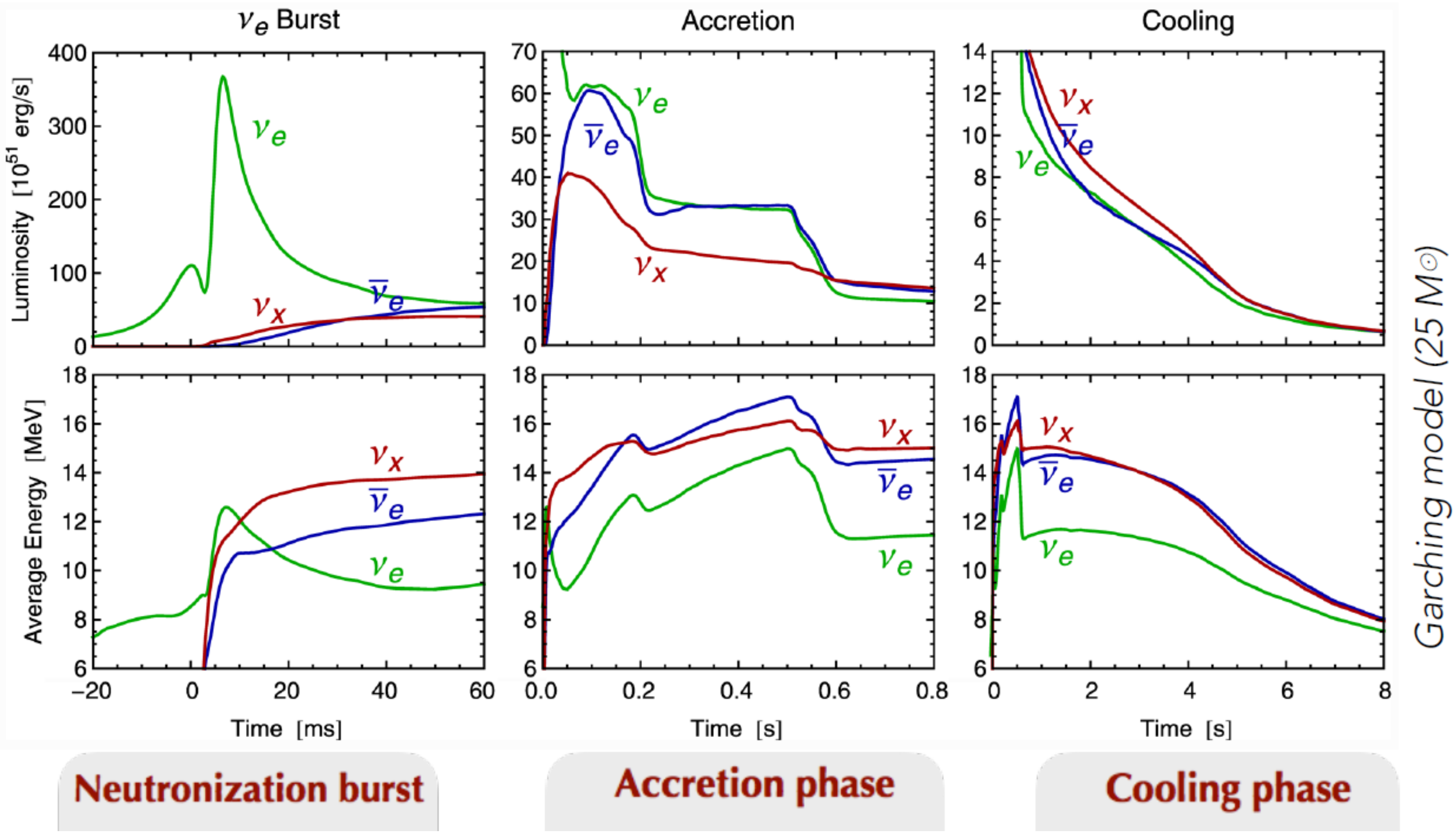
Outline

- Core-collapse supernovae as particle and astroparticle physics laboratory
- Introduction to DUNE
- CC SNe with DUNE
- Summary

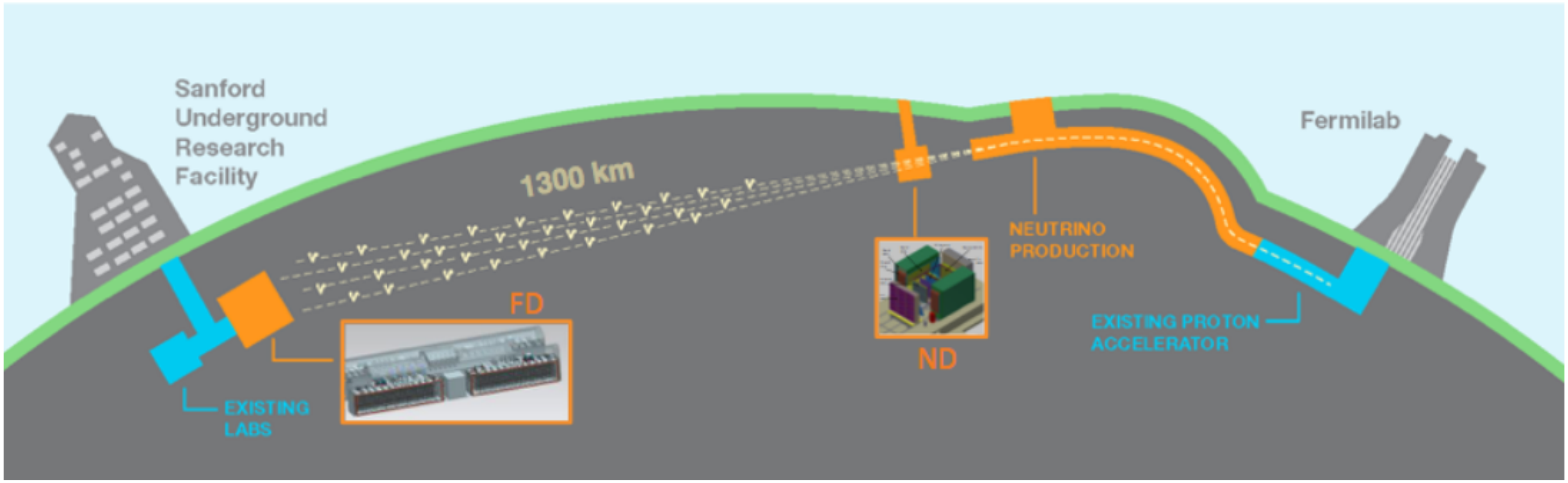
Core-collapse Supernovae

- Death of a massive star
- Expect a few (1-3) SN per century within 10 kpc (~ Galaxy)



- Neutrinos carry away 99% of gravitational binding energy (3 x 10^{53} erg) and 10% of core rest mass
- Oscillations give rise to non-thermal features
- Carries information about new physics (e.g. mass ordering) and SN processes

The DUNE Experiment



- Deep Underground Neutrino Experiment: Long baseline experiment
  - Neutrino beam from Fermilab to a large liquid argon (LAr) detector (Far Detector) at SURF in South Dakota
  - Large-scale prototypes at CERN (2018); 20-kt detector ready for beam in 2026
- Non-accelerator physics program in DUNE (supernova neutrino bursts, nucleon decay, etc.) takes advantage of period where detectors are commissioned in advance of beam.

Detection channels in LAr

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

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

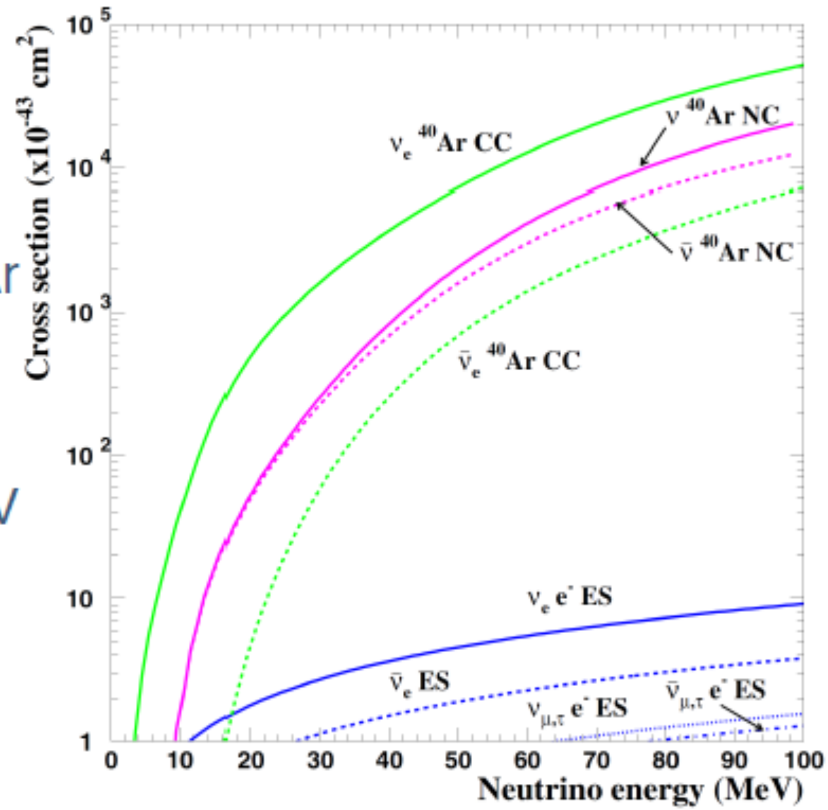
1. **Charged-current** (CC) interactions on Ar

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

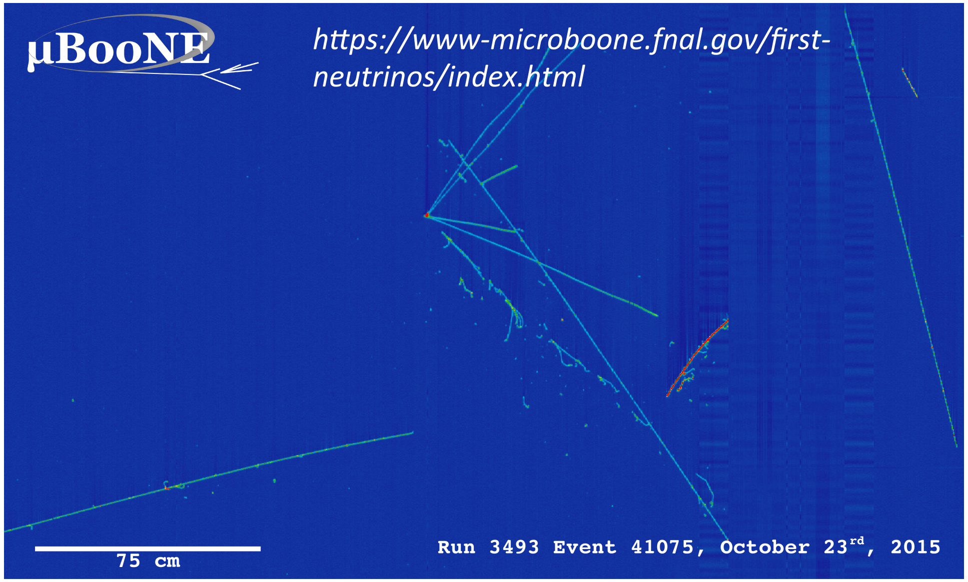


I.Gil-Botella & A.Rubbia, hep-ph/0307222, JCAP 10 (2003) 009, JCAP 08 (2004) 001

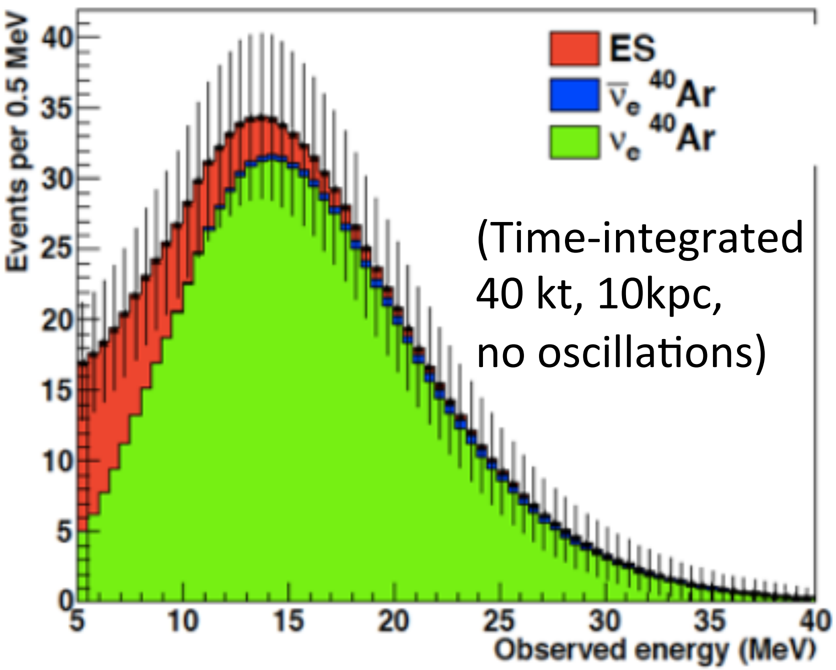
- For CC/NC, could use photons from final product de-excitation to tag channel

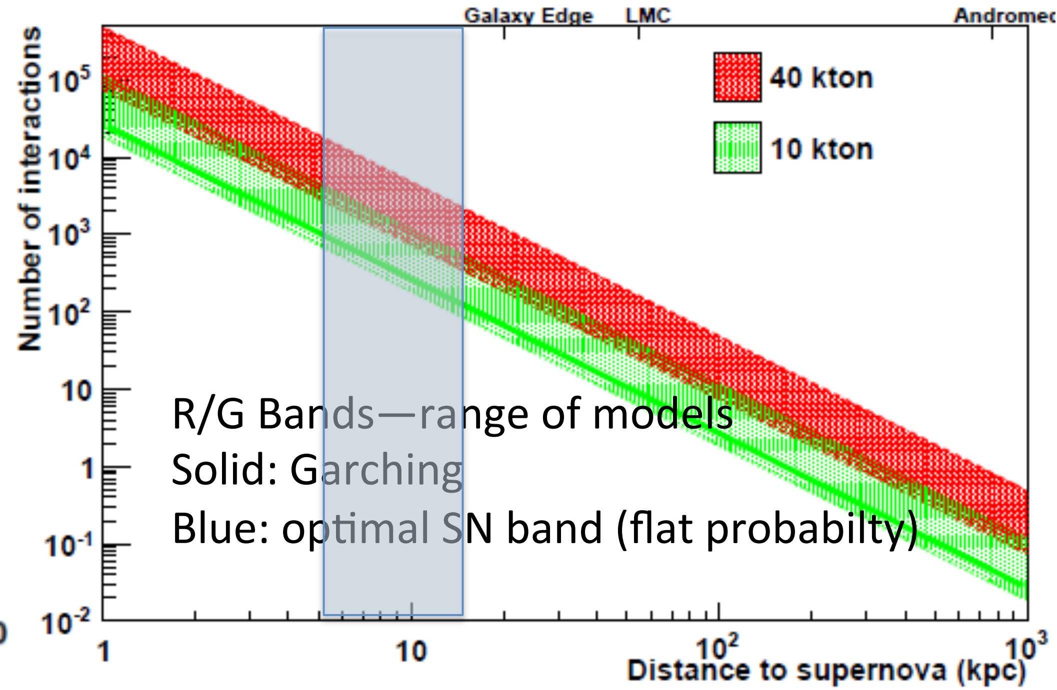
The DUNE Far Detector

- 4 10-kt Liquid-Argon Time-Projection Chamber (LArTPC) modules in SURF 4850 ft underground
- LAr TPC provides
  - Excellent 3D imaging (few mm scale)
  - Totally active calorimeter
  - Particle ID through dE/dX, event topology, etc.
  - Slow drift time (~ms)
- Modules also equipped with wavelength-shifting bars and photon detectors (SiPMs)
  - Prompt scintillation light
  - Absolute event timing for non-beam events



SNB Horizon with DUNE

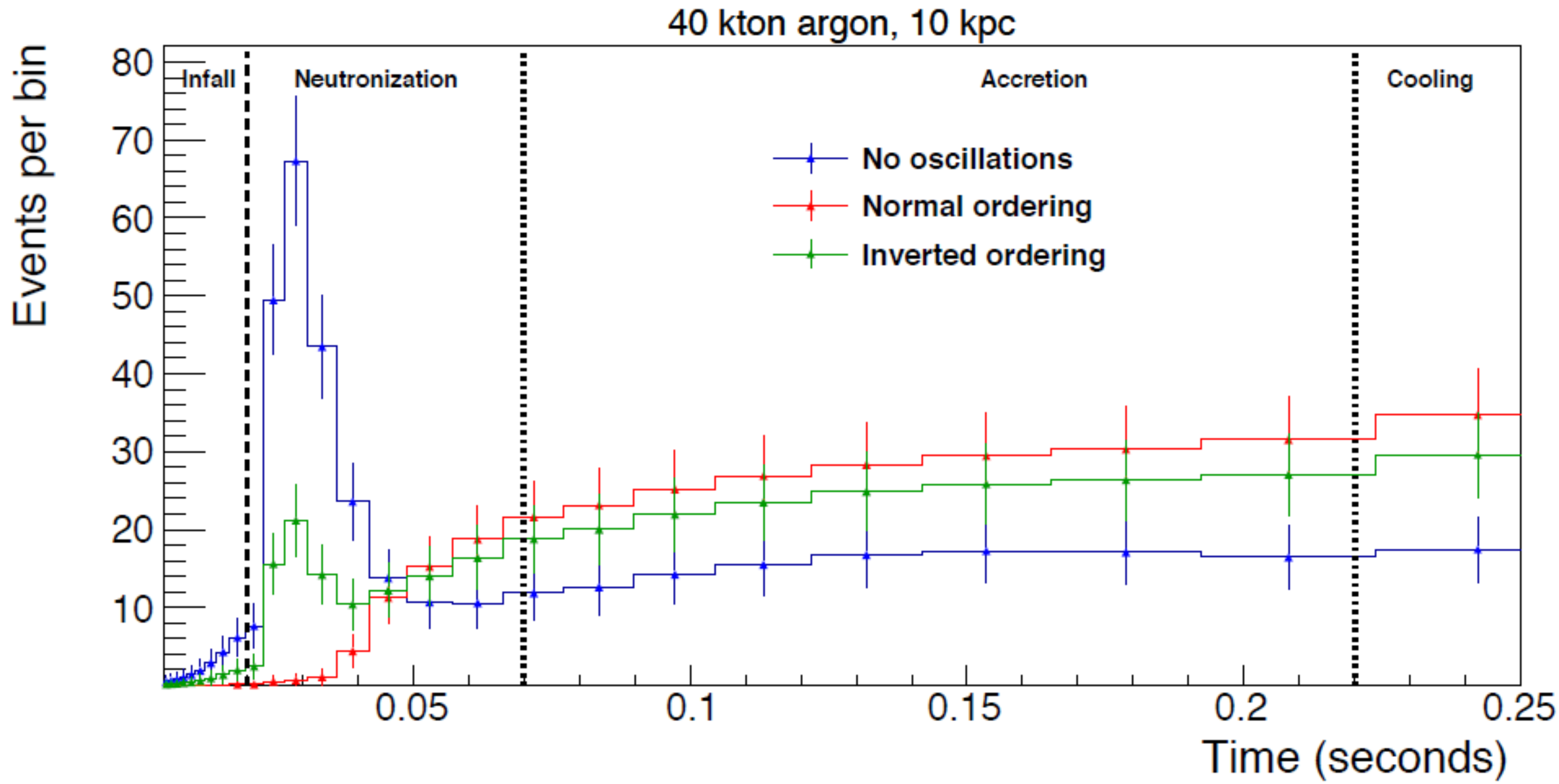




- Requirements:
  - Energy resolution <10%
  - Energy threshold ~ 5 MeV

- Physics potential statistics-driven
- Event rates scale by
  - Detector mass
  - Inverse square of SN distance

Neutronization burst with DUNE

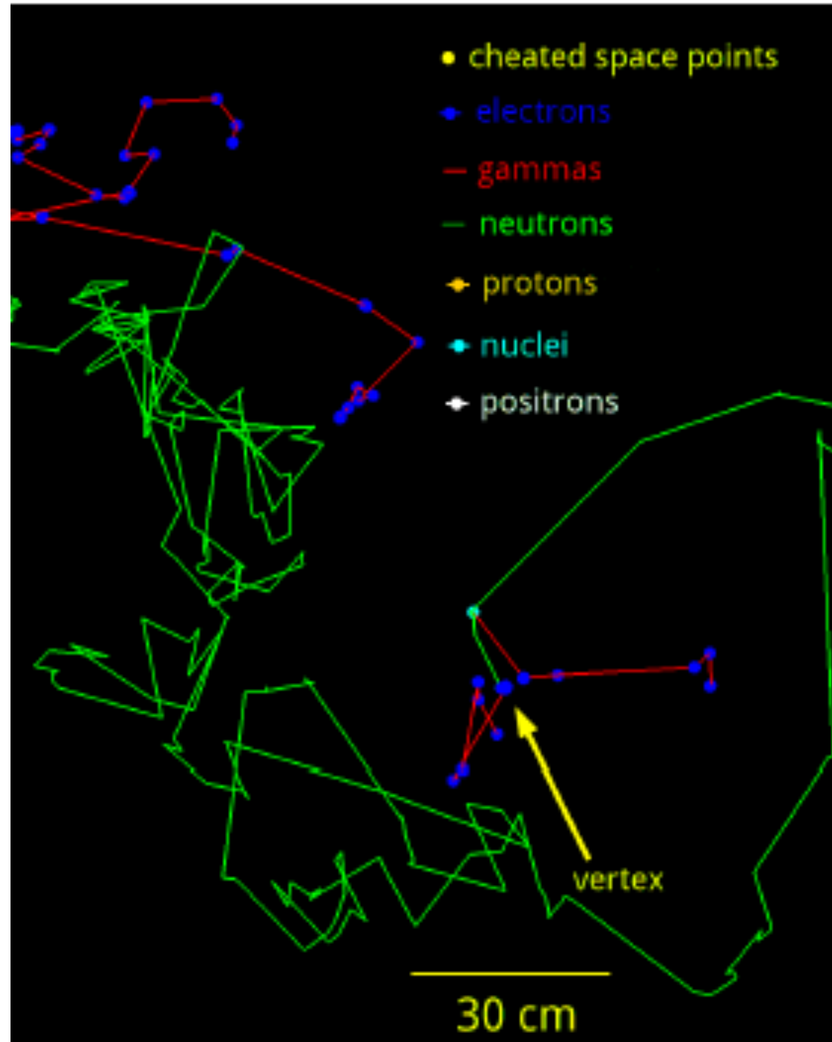


- Early time structure of SN neutrino flux (presence or absence of neutronization burst) highly sensitive to mass hierarchy.

Technical Challenges

- Spectral distortion due to missing energy
- Accurate modeling of charged-current interactions in LAr
  - Poorly known cross sections
  - Mismatch between measurement and theory
  - A great deal of work ongoing in this area (Svoboda, Gardiner)
- Improve reconstruction using timing information
  - Light detection system efficiency
- Radiological backgrounds
  - Due to use of natural Ar, Ar 39 in particular
    - Mimics light from low-E interactions (e.g. 10 MeV SN ν's)
    - suppress with spatial information?

Missing energy example: neutrons



Summary

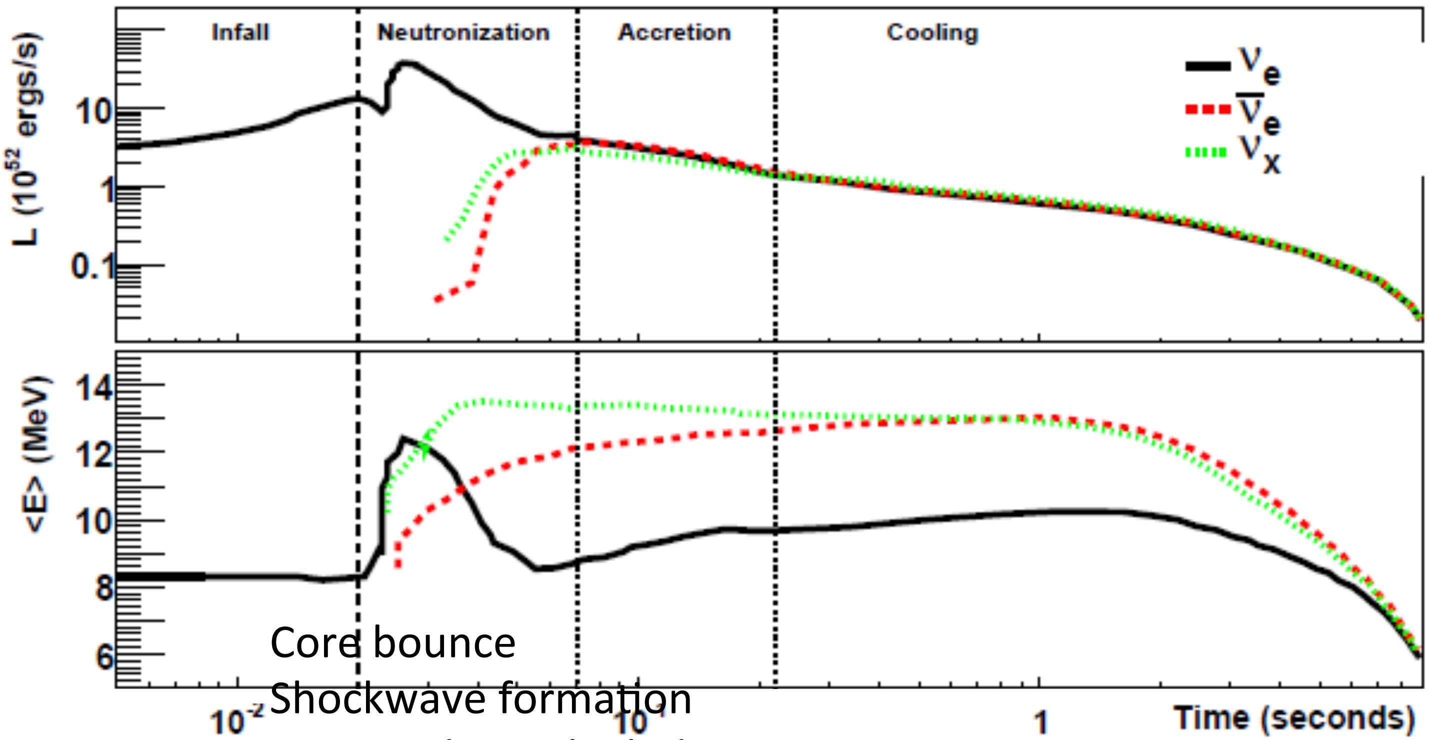
- A nearby Galactic SN is a neutrino physics laboratory
  - Measurements of the time, flavor, and energy structure of the neutrino flux from a nearby Galactic SN provide a window on neutrino physics as well as the astrophysical dynamics.

- In addition to beam physics, DUNE has a rich program of particle physics and astrophysics done without beam and relying on the unique capabilities of the Far Detector.
  - As a LAr TPC the DUNE Far Detector offers unique access to the electron neutrino component and unique technical challenges.
  - The supernova neutrino burst program remains a key science goal (and a design driver) for DUNE

BACKUP

Core-collapse Supernovae

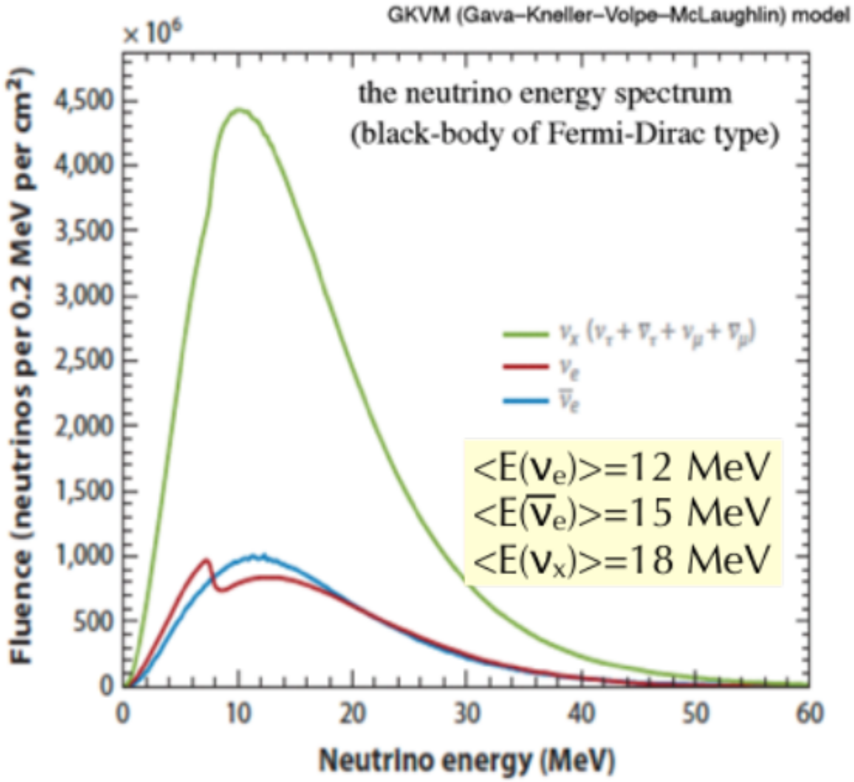
- Death of a massive star
- Expect a few (1-3) SN per century within 10 kpc (~ Galaxy)



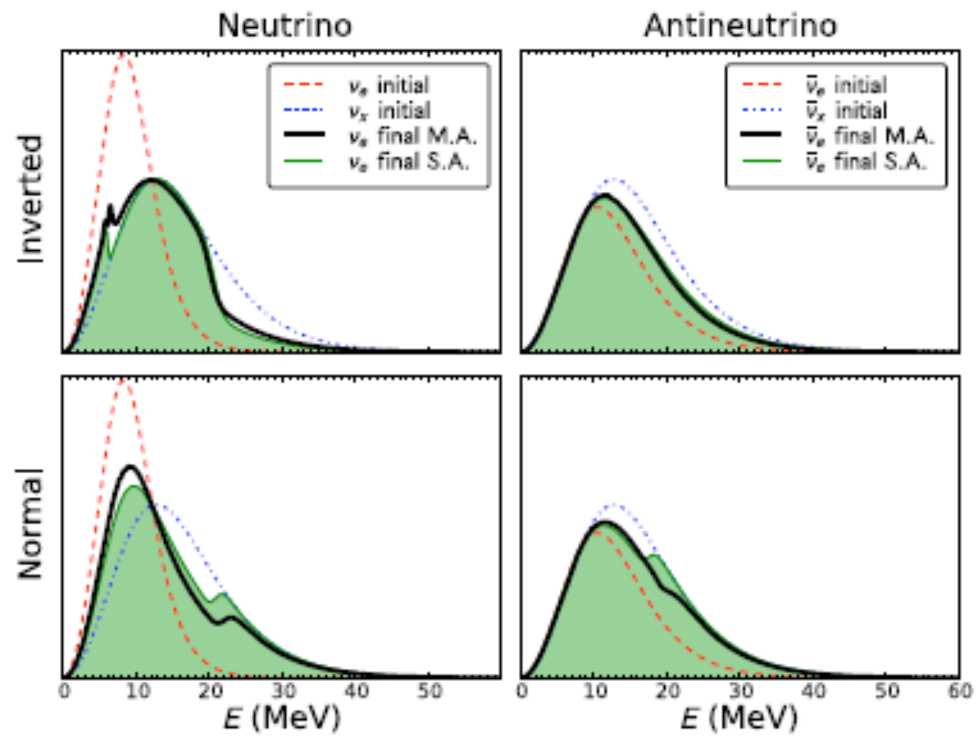
Core bounce
Shockwave formation
Opacity due to high density

- Important neutrino counterpart to EM signal
- Neutrinos carry away 99% of gravitational binding energy (3 x 10^{53} erg) and 10% of core rest mass

Physics Imprints



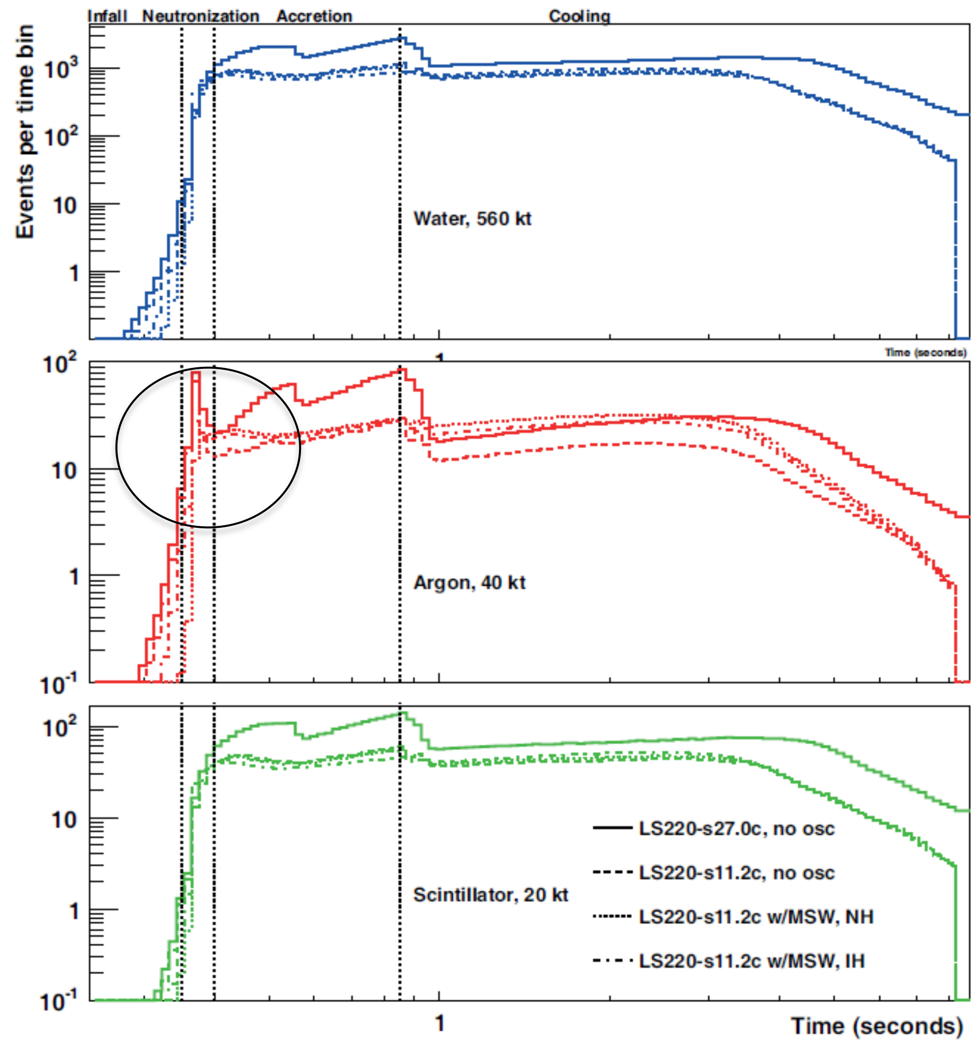
Duan and Friedland Phys. Rev. Lett. 106 (2011) 091101



- MSW effects: matter modifies neutrino mass and hence oscillations (r > 200 km)
- "Collective oscillations:" forward coherent ν-ν scattering (r < 200 km)
- Flavor-specific burst evolution carries information about mass ordering and SN processes

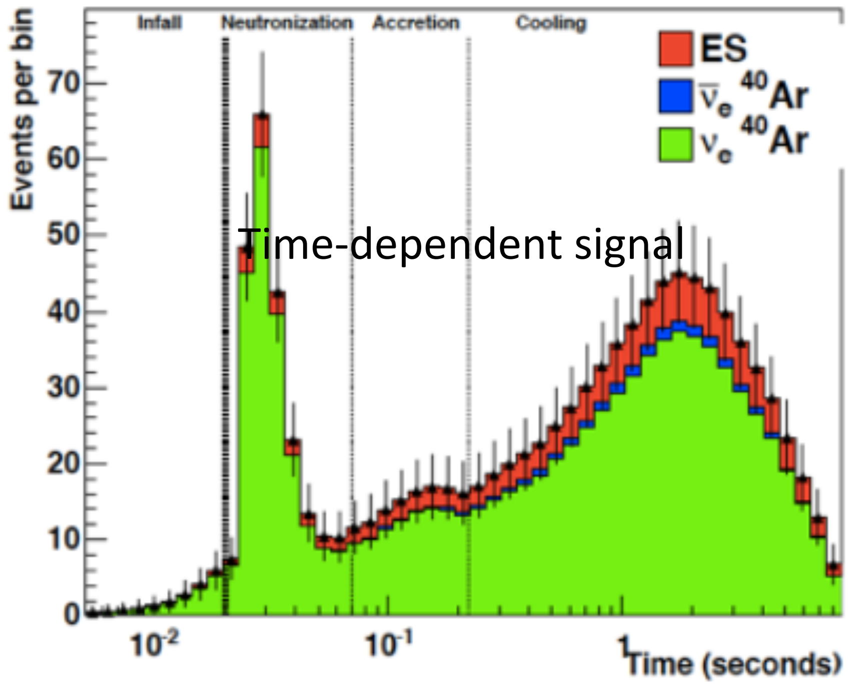
LAr TPCs and the power of ν_e

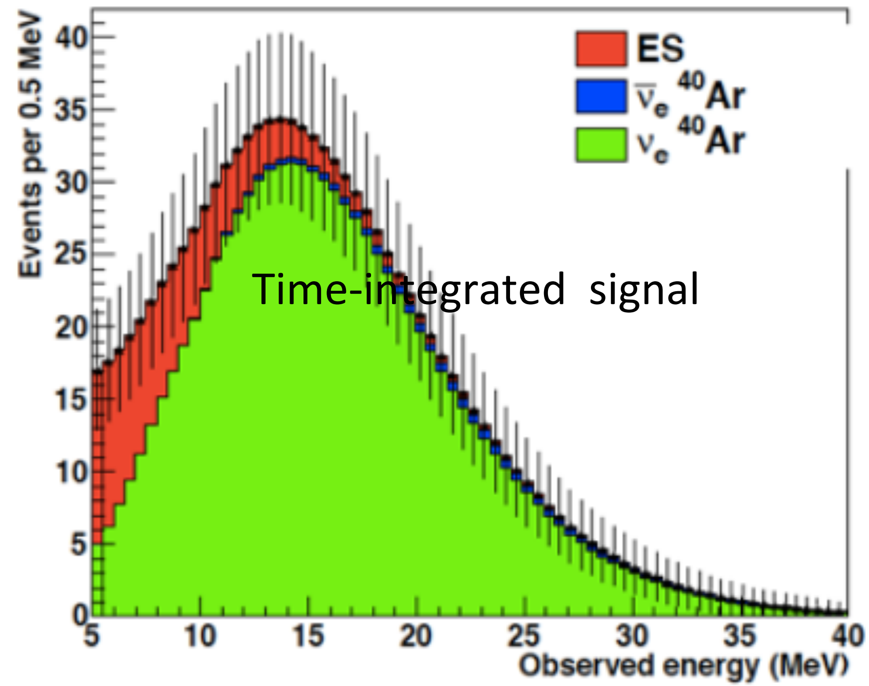
- The sensitivity of LAr TPCs to the electron neutrino component provides unique information about the early phase of the SN



Mirizzi et al. Rivisti del Nuovo Cimento Vol. 39, N. 1-2 (2016)

SN neutrinos in DUNE cont.





- SN at 10 kpc in 40 kt LAr
- Garching model (no oscillations)

- Requirements:
  - Energy resolution <10%
  - Energy threshold ~ 5 MeV

Missing energy: Neutron headaches

- Simulated event
- E_ν 16.3 MeV
- Electron deposits 4.5 MeV
- No primary photons from vertex
- Neutron deposits 7.6 MeV (primarily from capture γs)
- Total visible energy 12.2 MeV over 1.44 m radius
  - (neutrons wander)