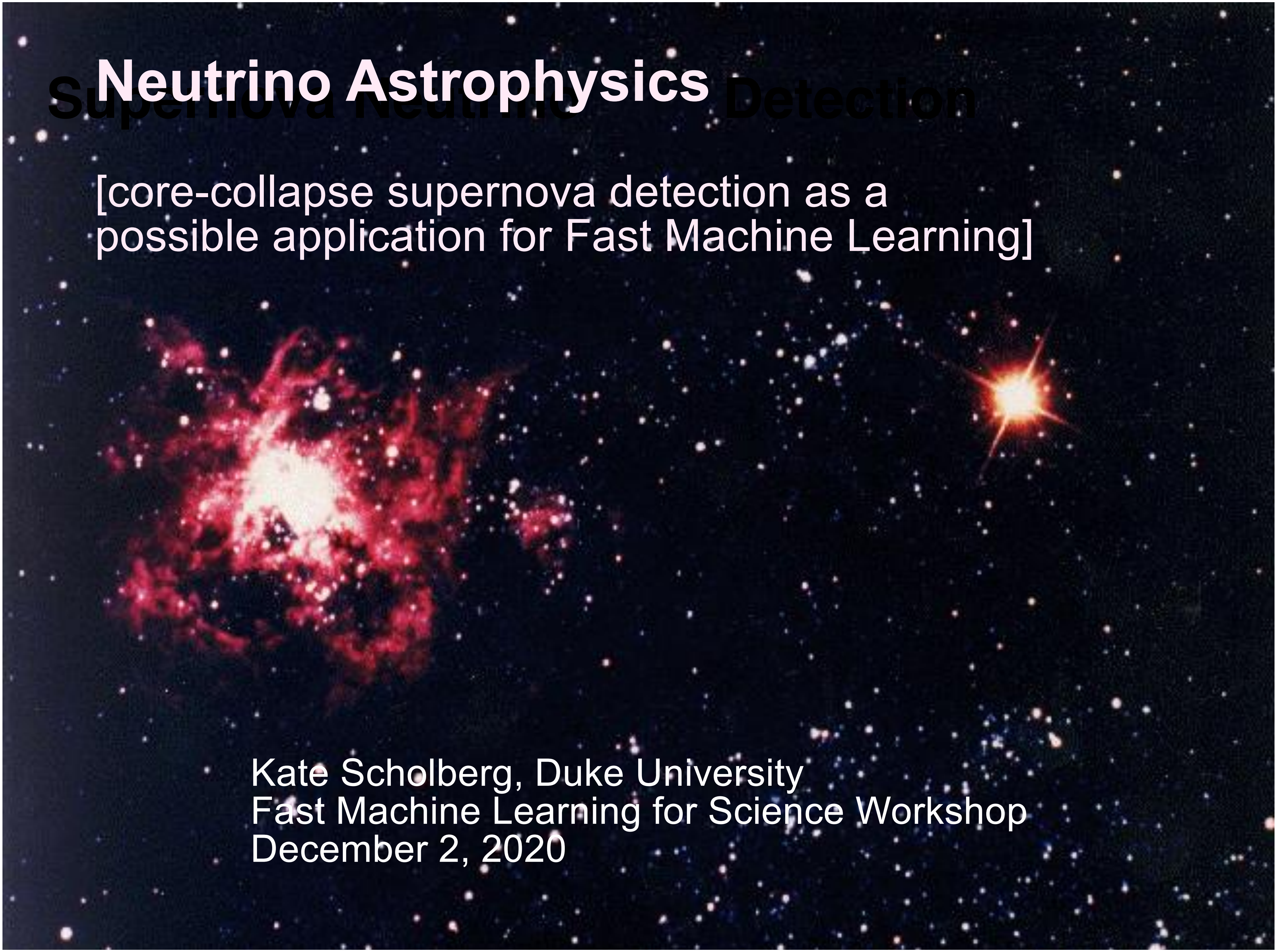


# Neutrino Astrophysics

[core-collapse supernova detection as a possible application for Fast Machine Learning]

Kate Scholberg, Duke University
Fast Machine Learning for Science Workshop
December 2, 2020

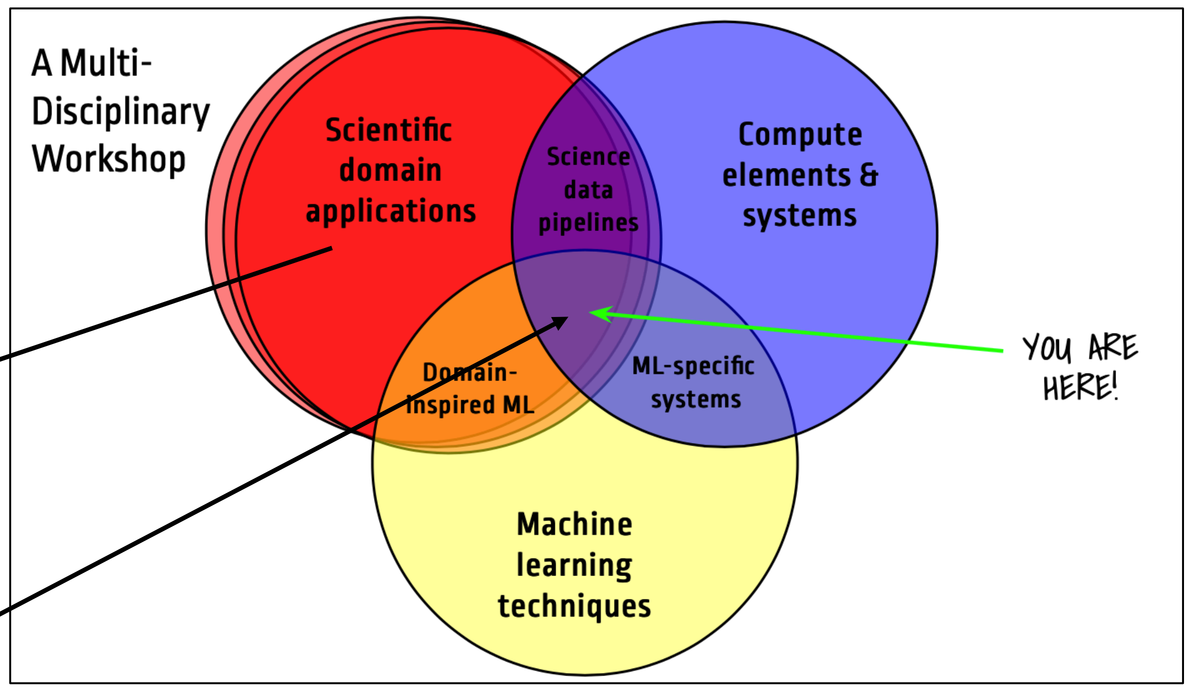

I am not a fast
machine learning expert ...

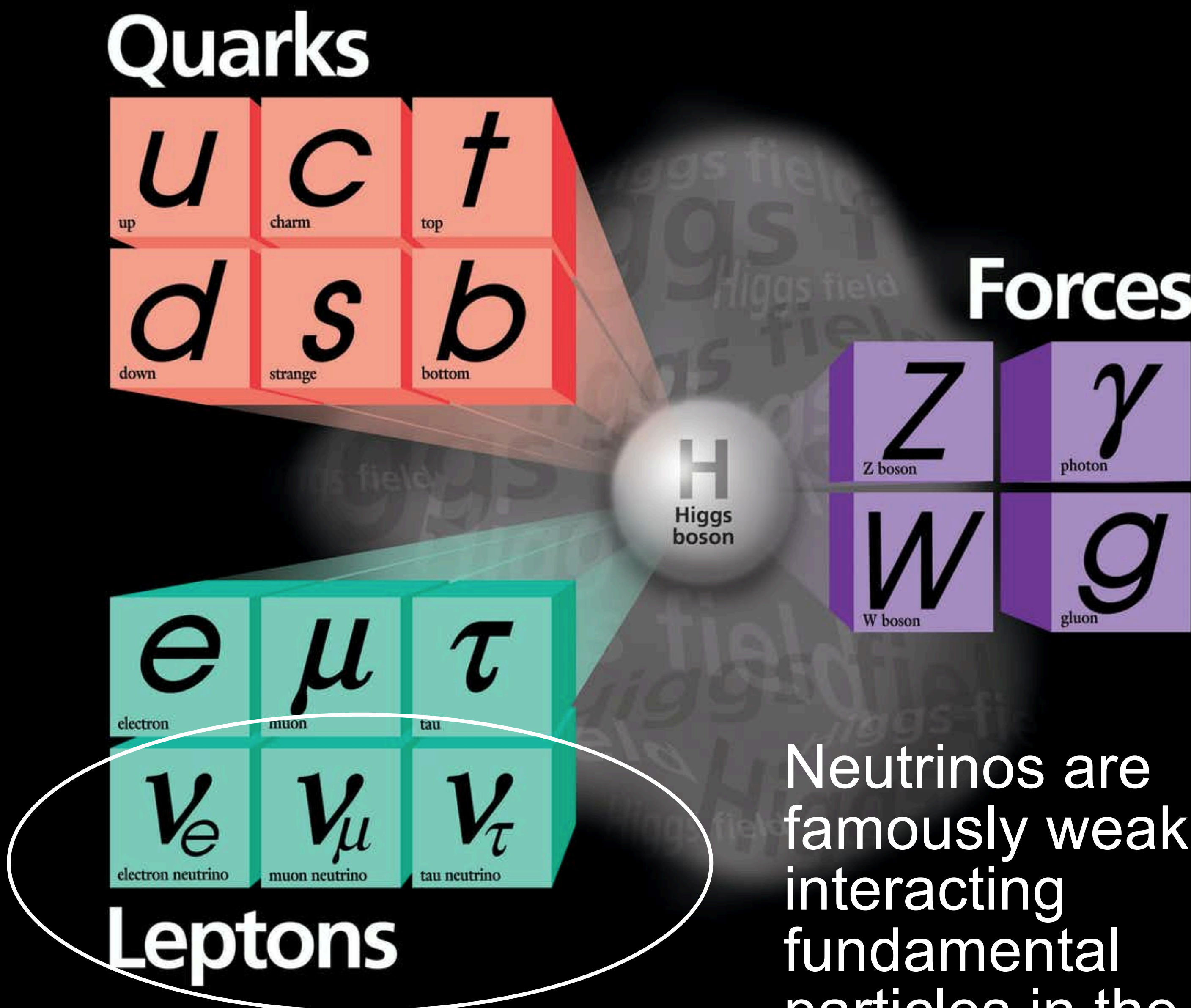
(have dabbled a little on the slow side)

Will instead describe a possible
“scientific domain application” for FastML

actually this talk will be mostly here,,,,

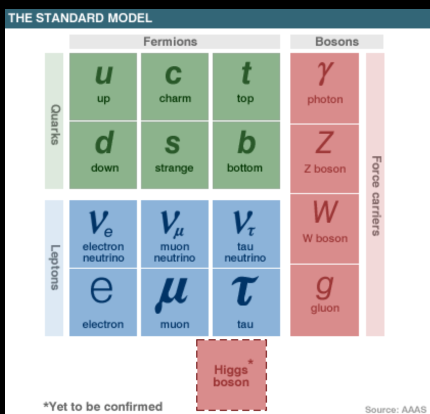
,,, but maybe someone will be inspired to go here,,,,






Neutrinos are famously weakly interacting fundamental particles in the Standard Model

# We care about them for many reasons...



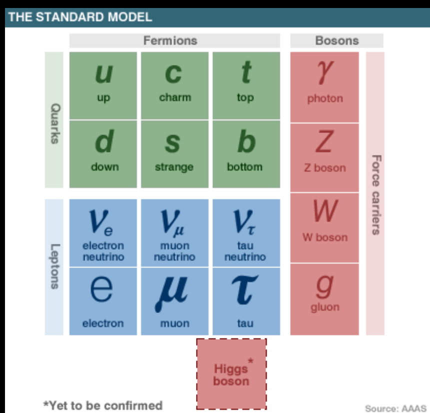

fundamental particles and interactions


astrophysical systems

cosmology

nuclear physics

# We care about them for many reasons...




fundamental particles and interactions


astrophysical systems

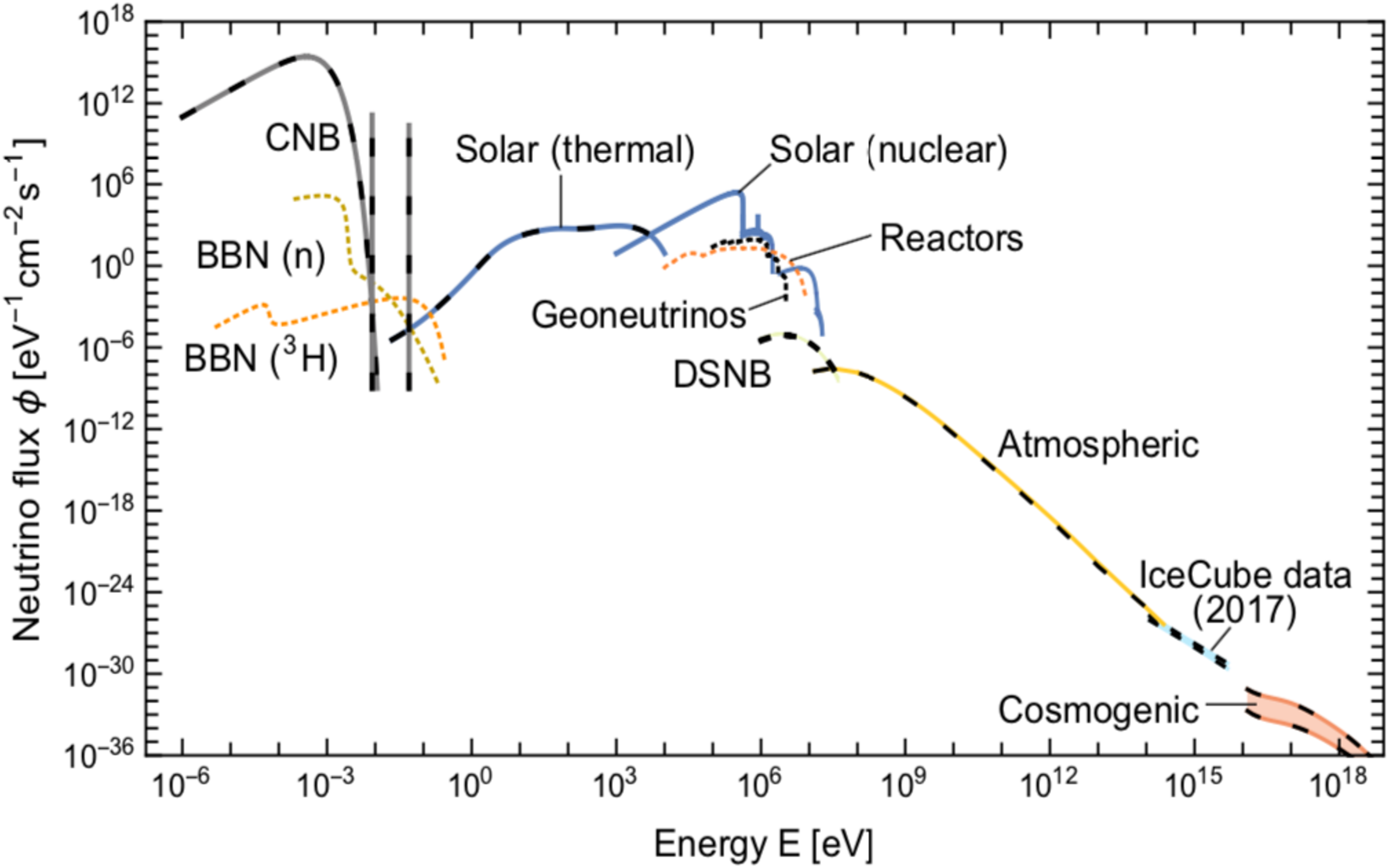
They are astrophysical messengers...
astrophysics and particle physics

cosmology

nuclear physics

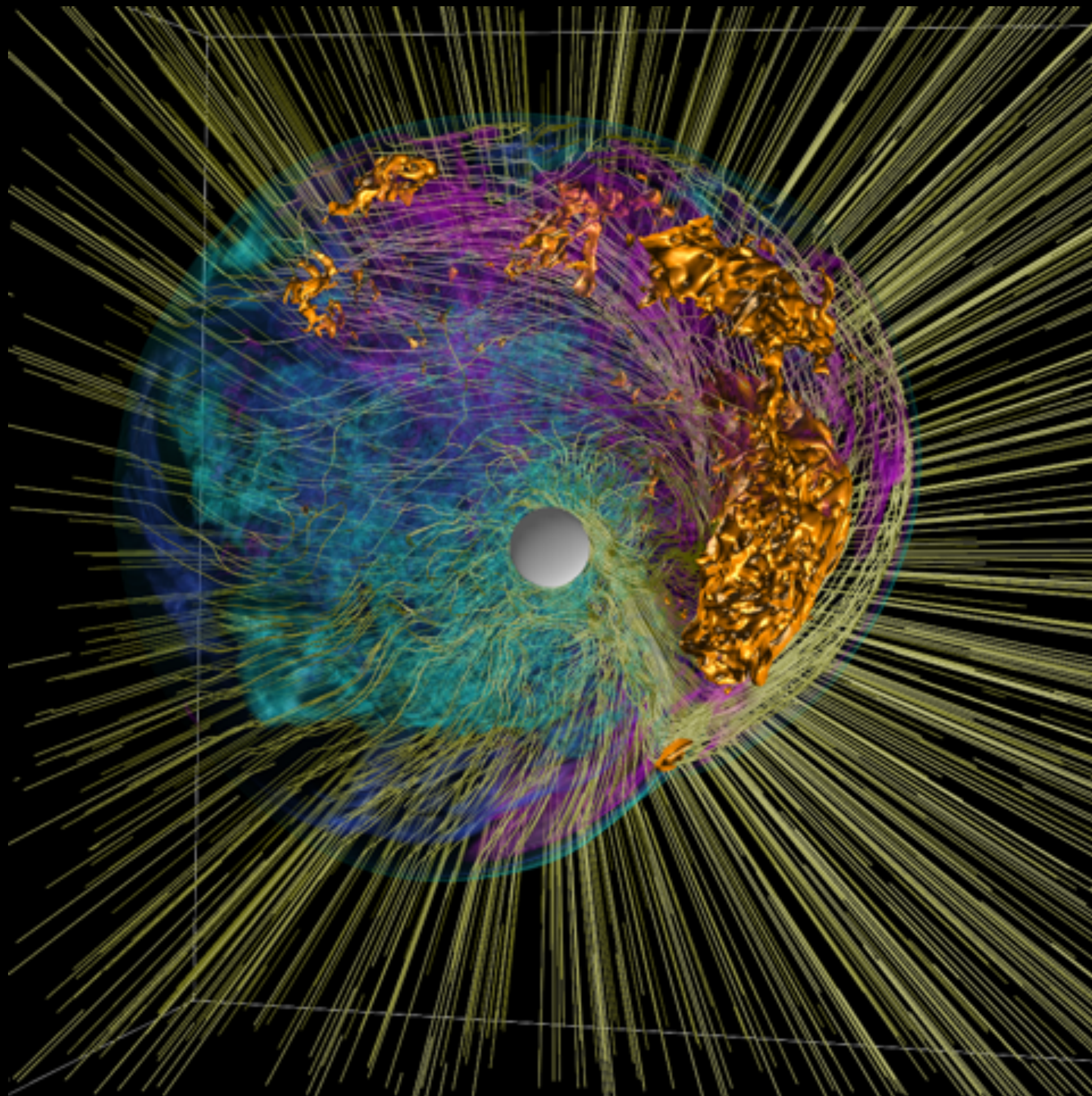
# The Steady State Neutrino Spectrum @ Earth

**Grand Unified Neutrino Spectrum at Earth**
Edoardo Vitagliano, Irene Tamborra, Georg Raffelt. Oct 25, 2019. 54 pp.
MPP-2019-205
e-Print: arXiv:1910.11878 [astro-ph.HE] I PDF



# Neutrinos arrive as **transient** sources also

When a star's core collapses, ~99% of the gravitational binding energy of the proto-neutron star remnant goes in neutrinos of all flavors,
over a timescale of
**tens of seconds**



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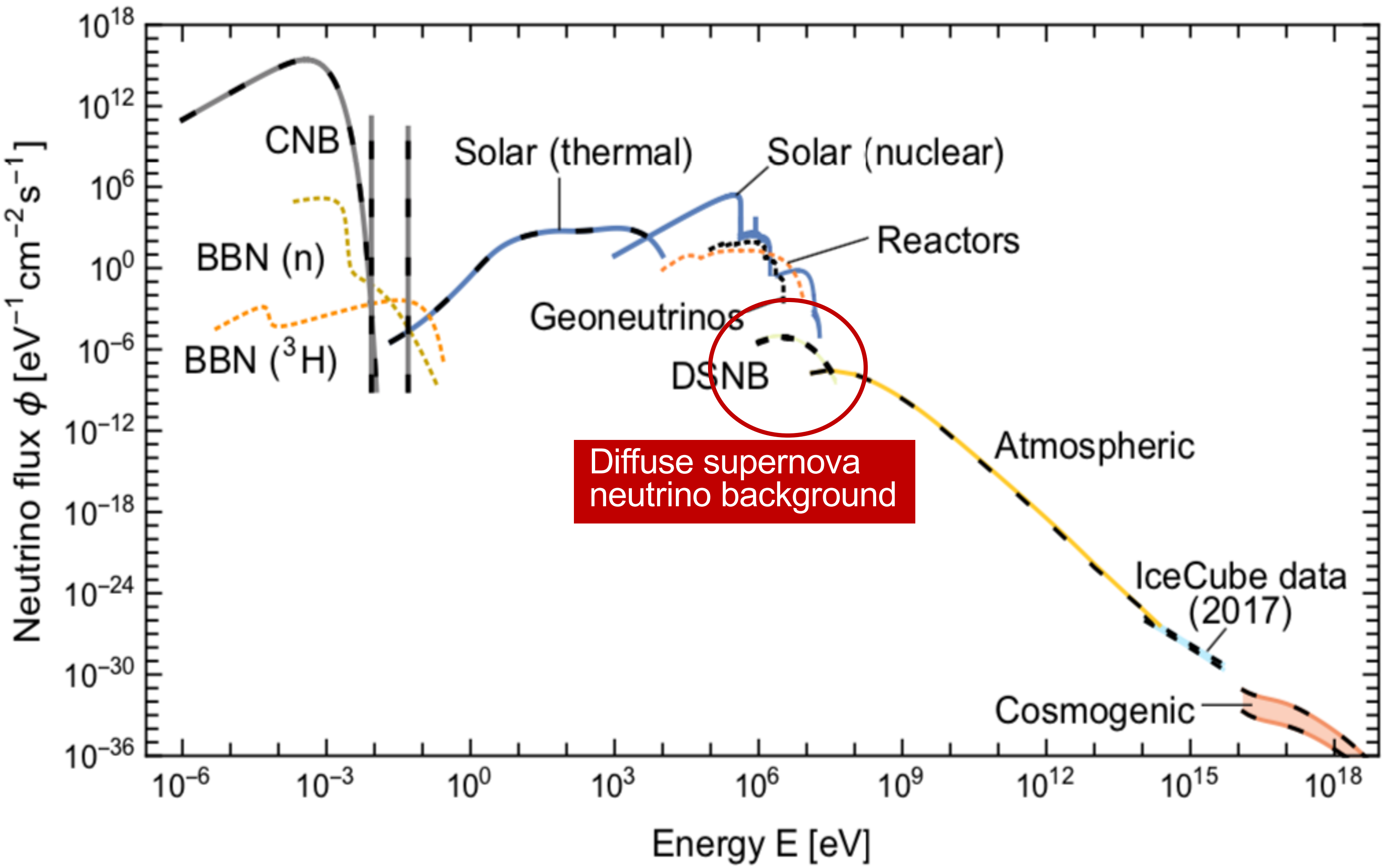

During a ~10s Galactic burst, neutrino flux can increase 9-10 orders of magnitude

Grand Unified Neutrino Spectrum at Earth
Edoardo Vitagliano, Irene Tamborra, Georg Raffelt. Oct 25, 2019. 54 pp.
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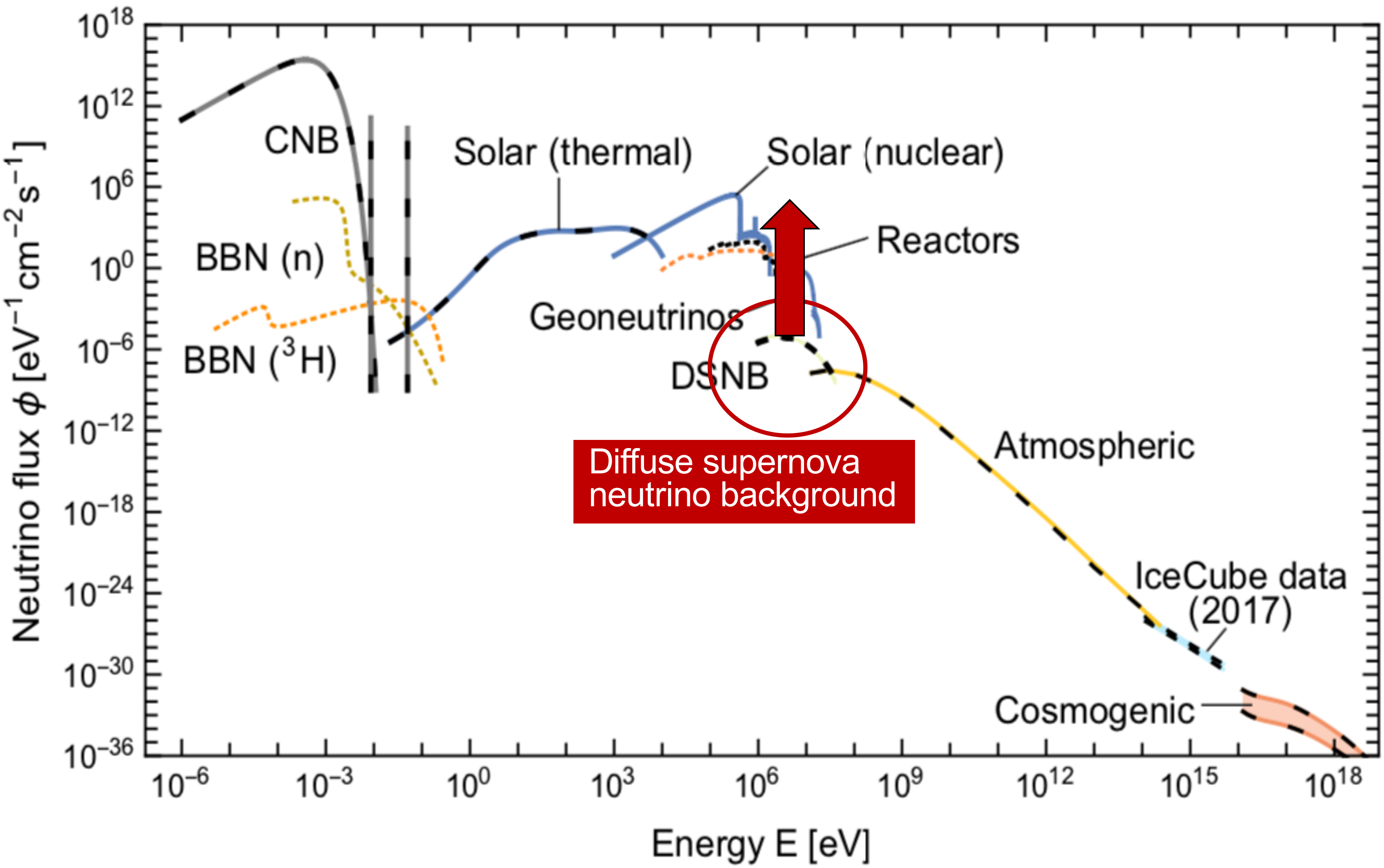
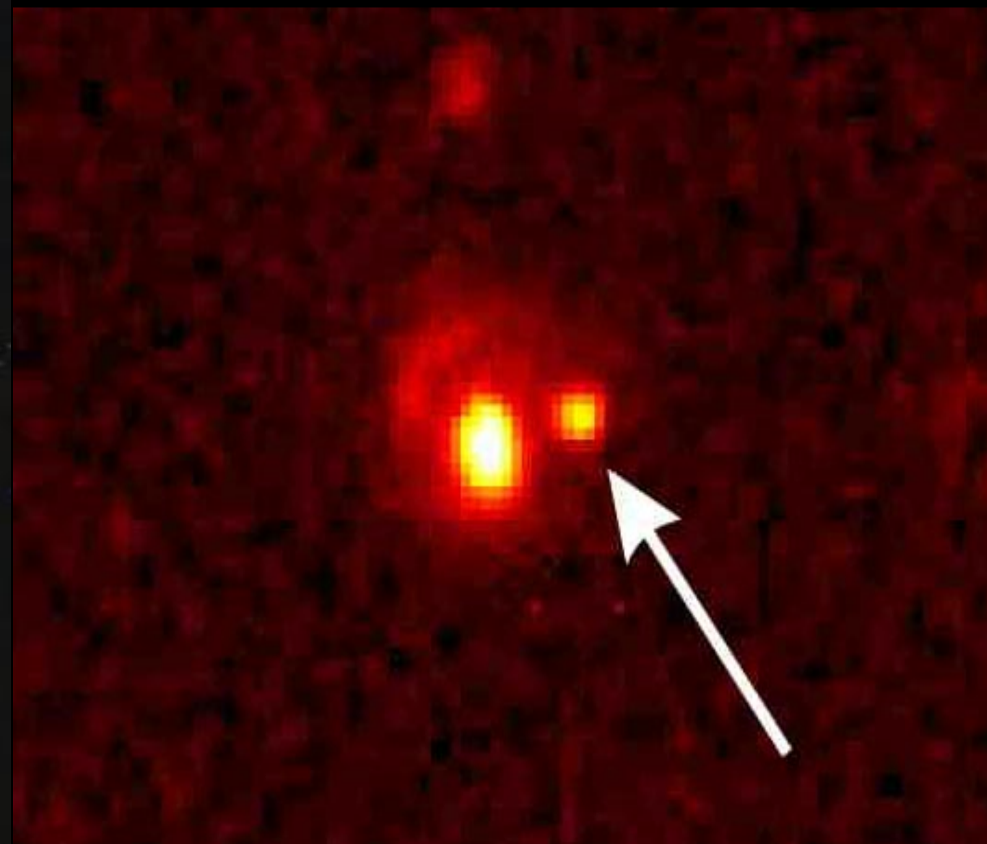



I will zoom in on this core-collapse signal....

# Such a neutrino burst heralds (in most cases) a **supernova**:

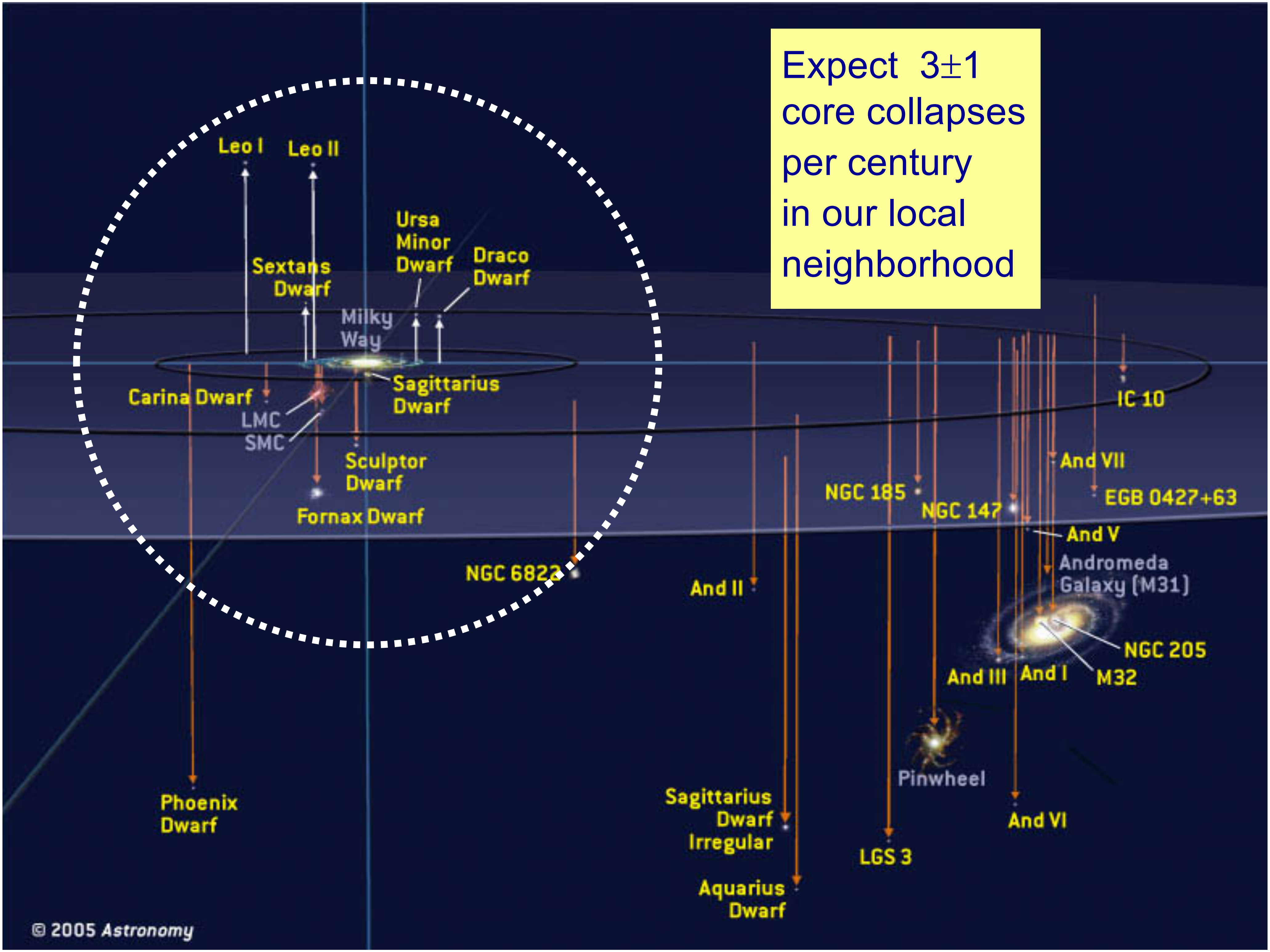



For a while, as luminous (in photons) as a galaxy*!

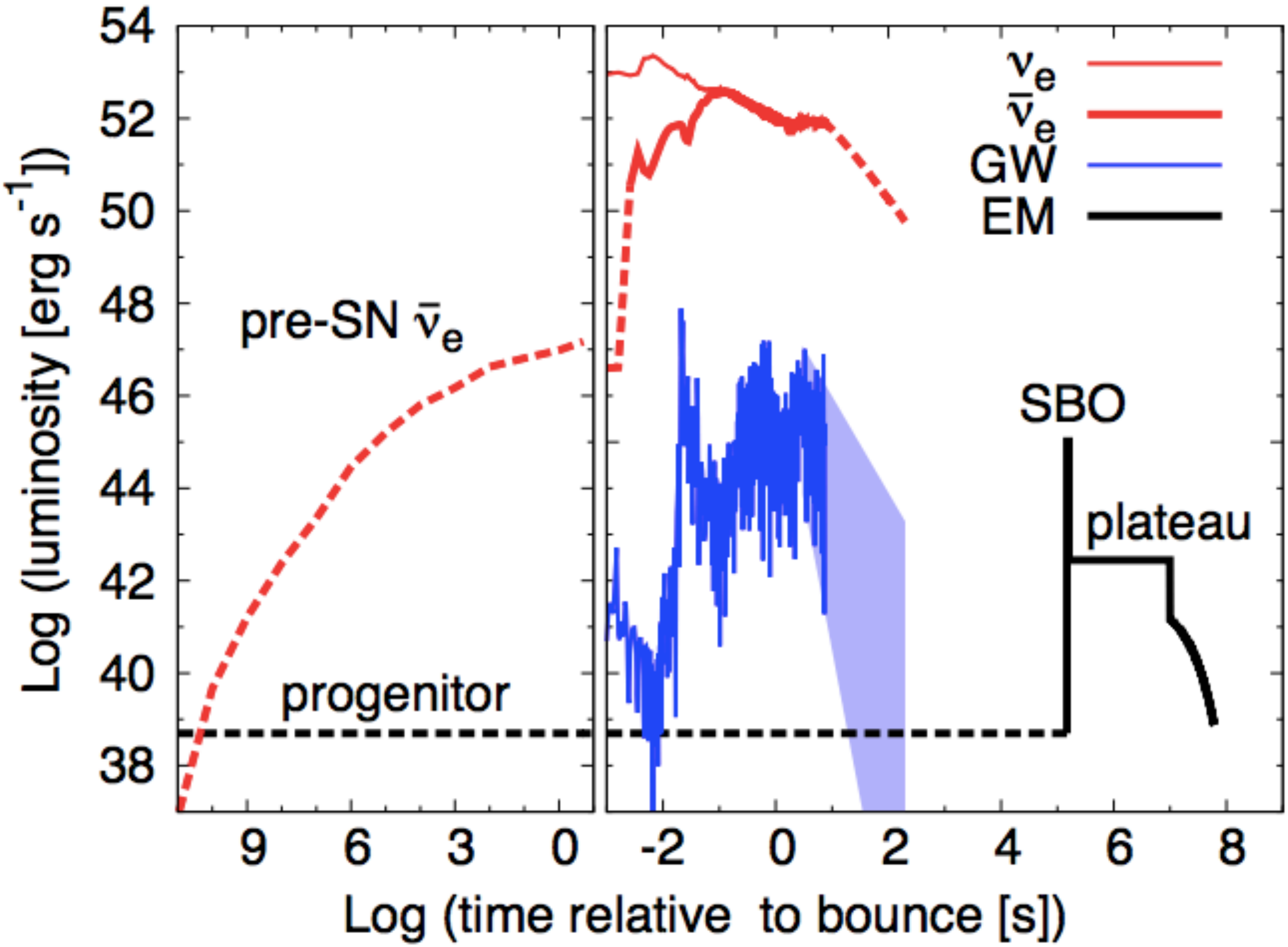
A star self-destructs a few times per century, per galaxy

*well, some galaxies

Expect 3±1 core collapses per century in our local neighborhood



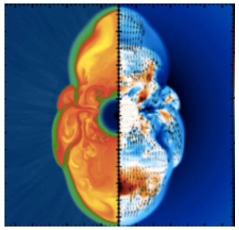
# Multimessenger core-collapse SN signals




K. Nakamura et al., MNRAS 2016

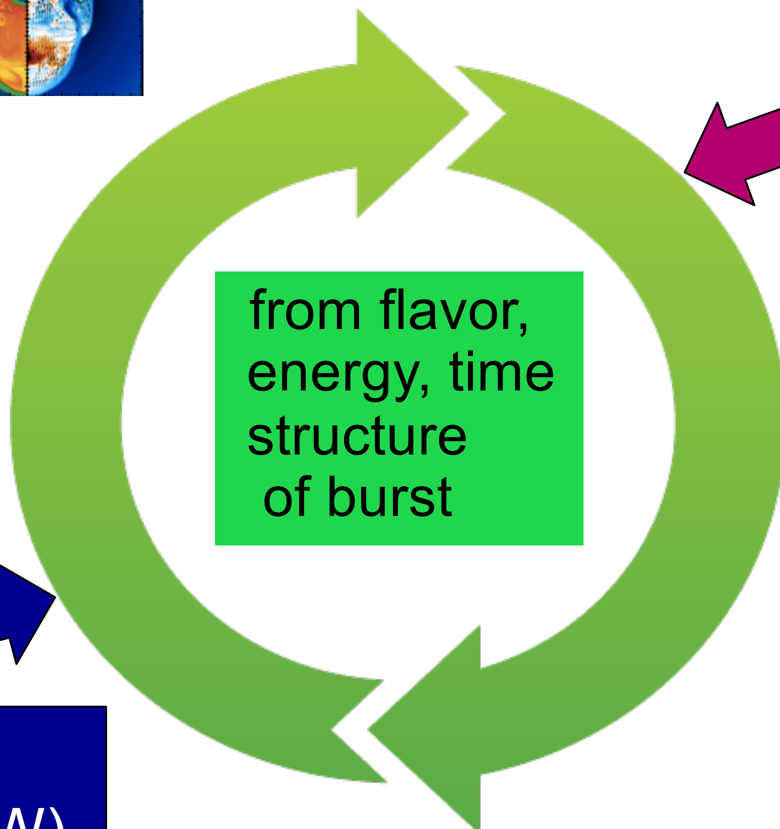
# What can we learn from the next neutrino burst?

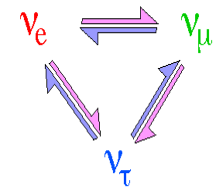
## CORE COLLAPSE PHYSICS



explosion mechanism
proto nstar cooling,
quark matter
black hole formation
accretion, SASI
nucleosynthesis
....

input from neutrino experiments




## NEUTRINO and OTHER PARTICLE PHYSICS

$\nu$ absolute mass (not competitive)
$\nu$ mixing from spectra:
flavor conversion in SN/Earth
(mass hierarchy)
other $\nu$ properties: sterile $\nu$'s,
magnetic moment,...
axions, extra dimensions,
FCNC, ...

input from photon (GW) observations

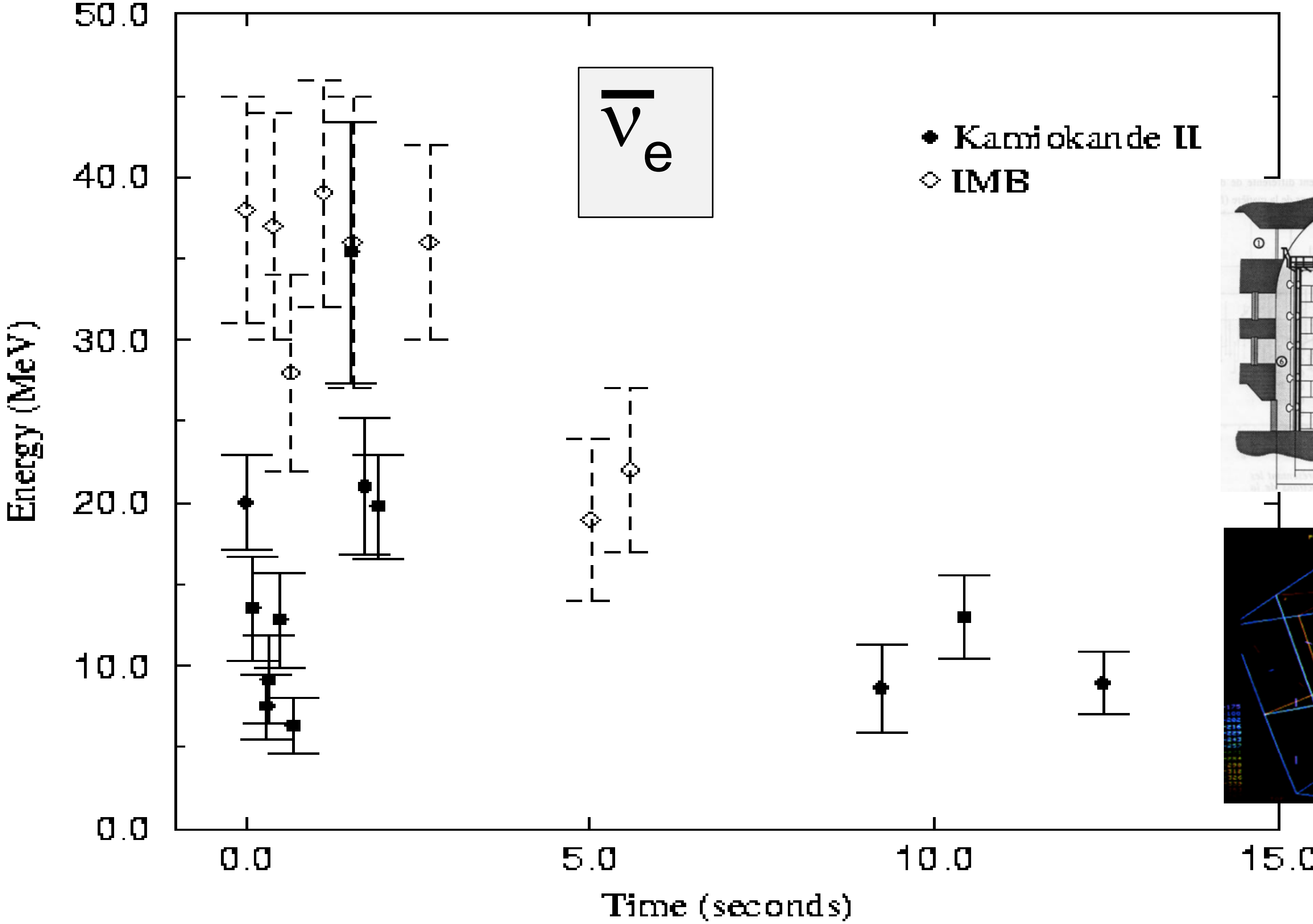
**+ EARLY ALERT**

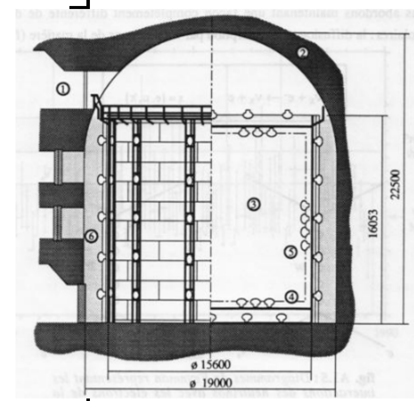
# Supernova 1987A
in the Large Magellanic Cloud (55 kpc away)

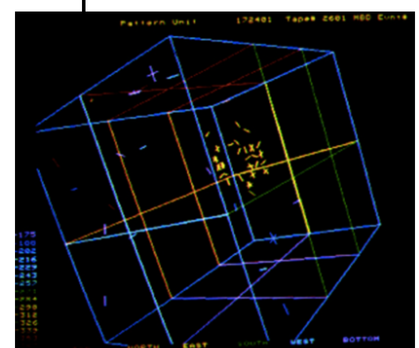

~two dozen neutrino interactions observed!

# SN1987A in LMC

ν's seen ~2.5 hours before first light



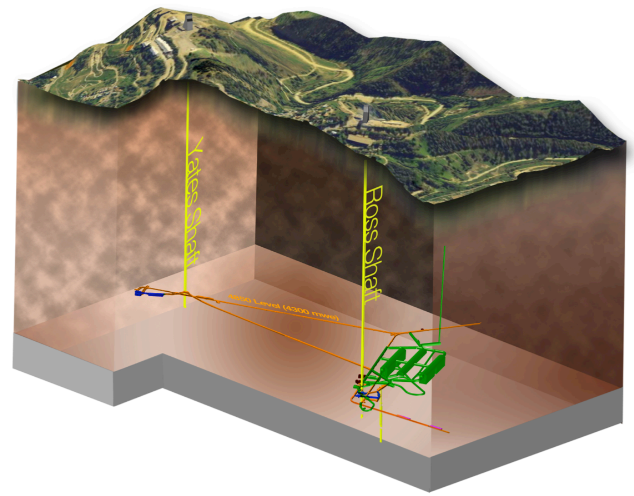



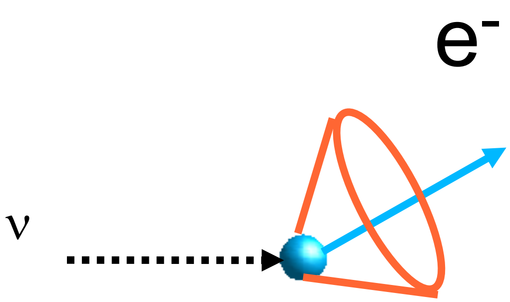


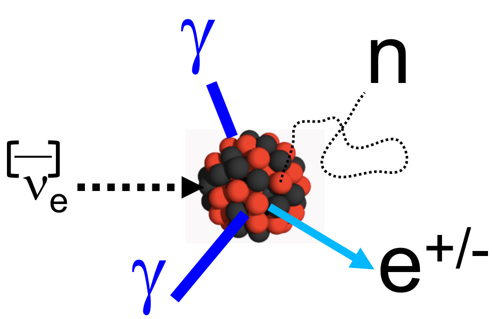
Confirmed baseline model... but still many questions

# How do we detect the SN burst neutrinos?

Need **large** detectors
(~1 kton per ~100 $\nu$ interactions
for SN @ Galactic center),
typically **underground**
(to shield from cosmic rays)

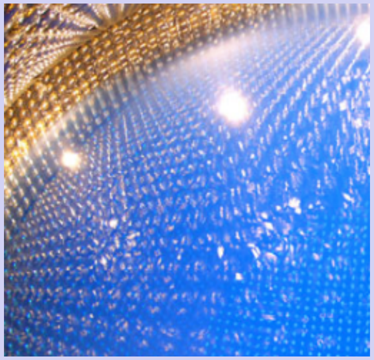
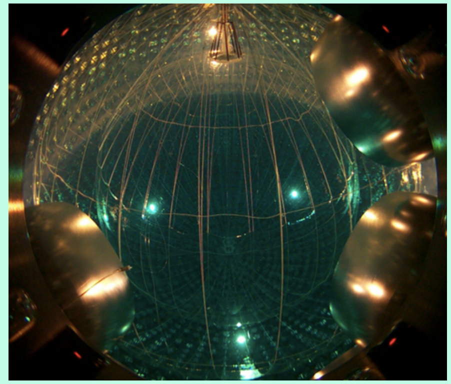


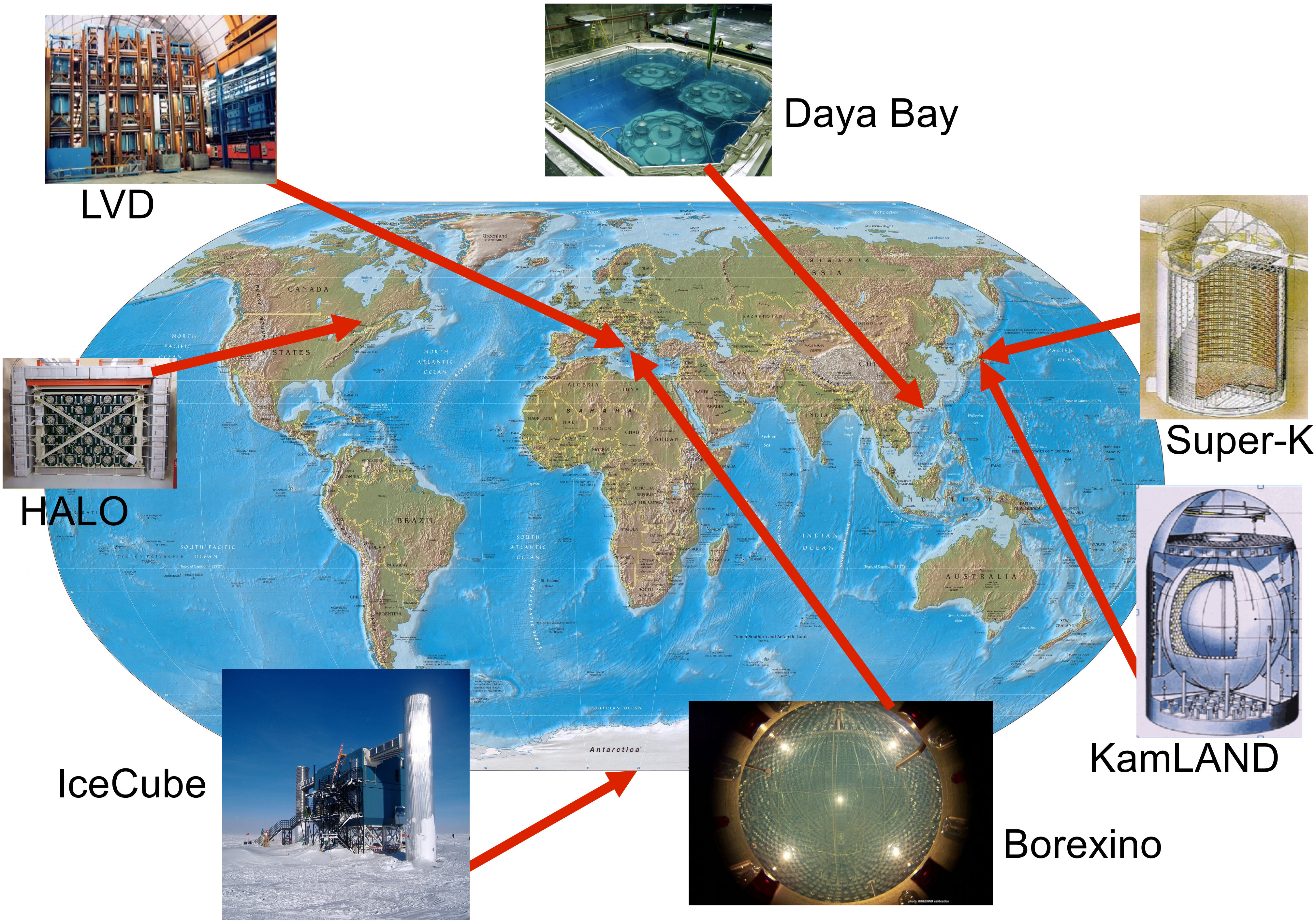




Neutrinos interact
with electrons or nuclei;
energy loss of resulting
created or kicked
charged particles
is collected and digitized

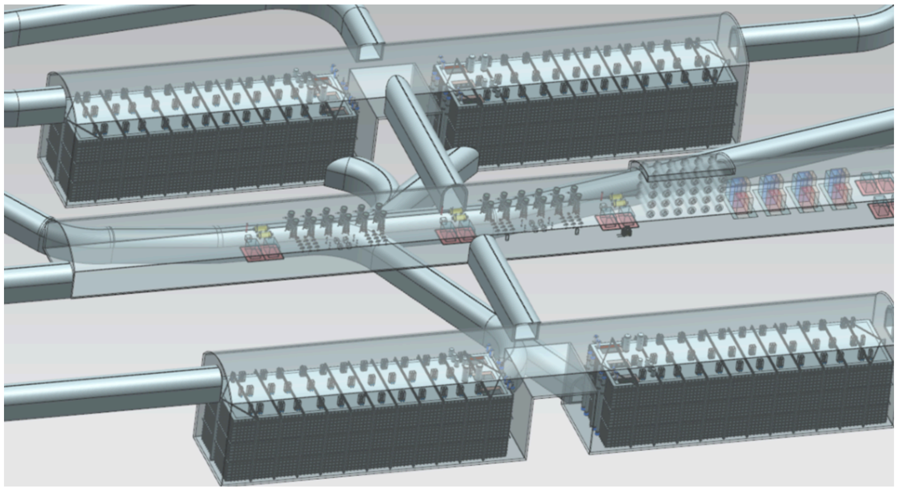
# Current main supernova neutrino detector types

| Water | Scintillator |
| --- | --- |
|   |  |
| **Argon** | **Lead** |
|  |  |

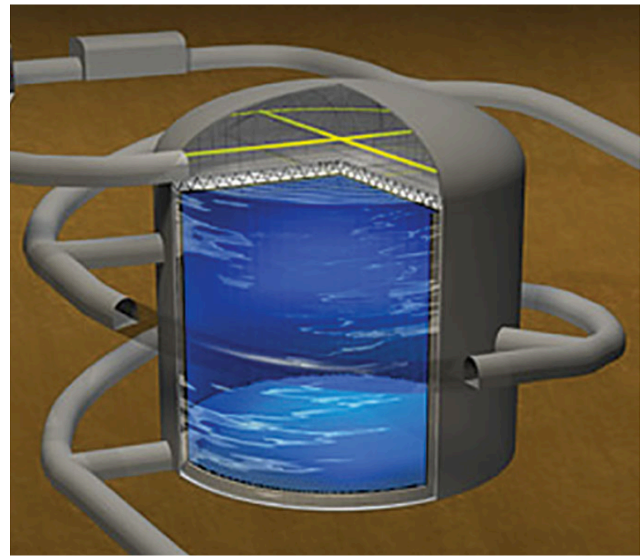


LVD
Daya Bay
Super-K
HALO
KamLAND
IceCube
Borexino

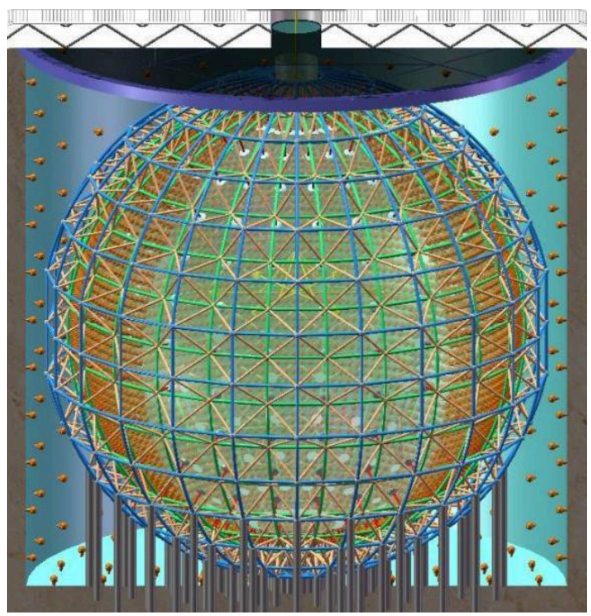
# Future Supernova-Burst-Sensitive Neutrino Detectors



**DUNE**
40 kton argon
USA



**Hyper-Kamiokande**
374 kton water
Japan



**JUNO**
20 kton scintillator
(hydrocarbon)
China

# The Supernova Early Warning System


snews.bnl.gov

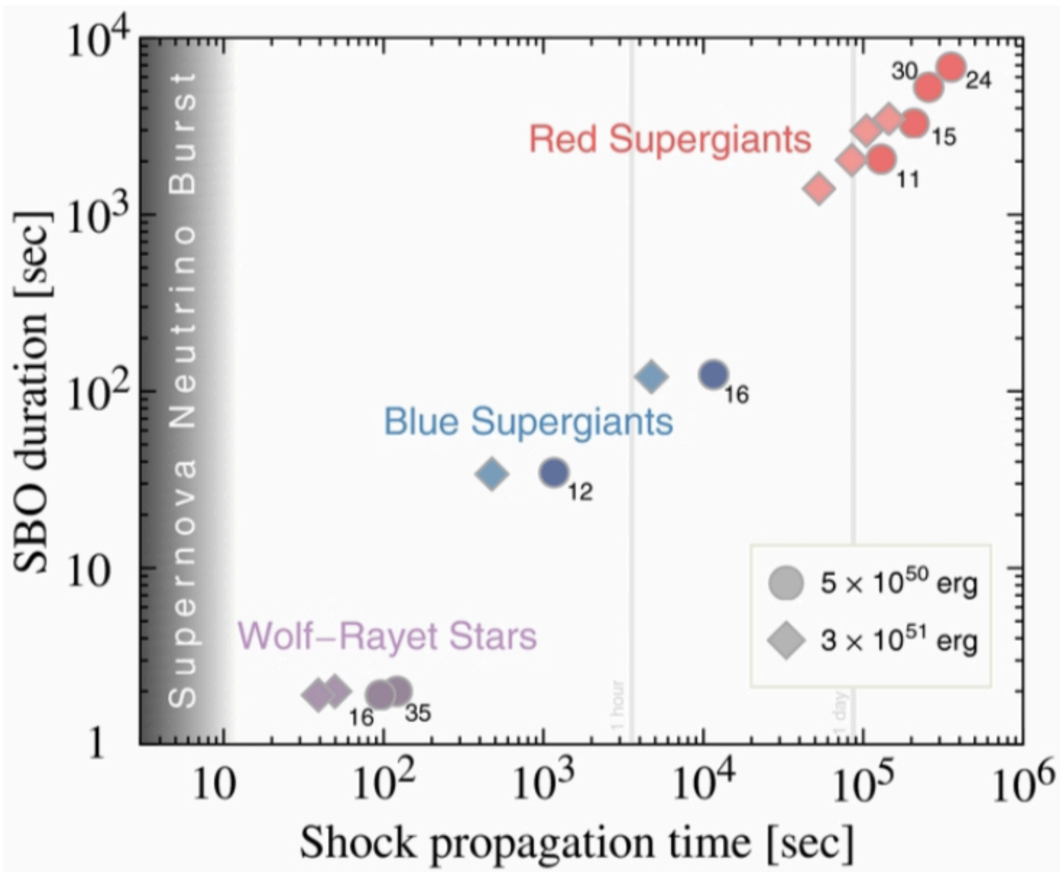
Nature Reviews

Current configuration: future will have more!

Can the neutrinos point to the supernova?

# Find the supernova!

Early light observations are valuable….




Matthew D. Kistler, W. C. Haxton, and Hasan Yüksel. Tomography of Massive Stars from Core Collapse to Supernova Shock Breakout. ApJ, 778:81, 2013, arXiv:1211.6770.

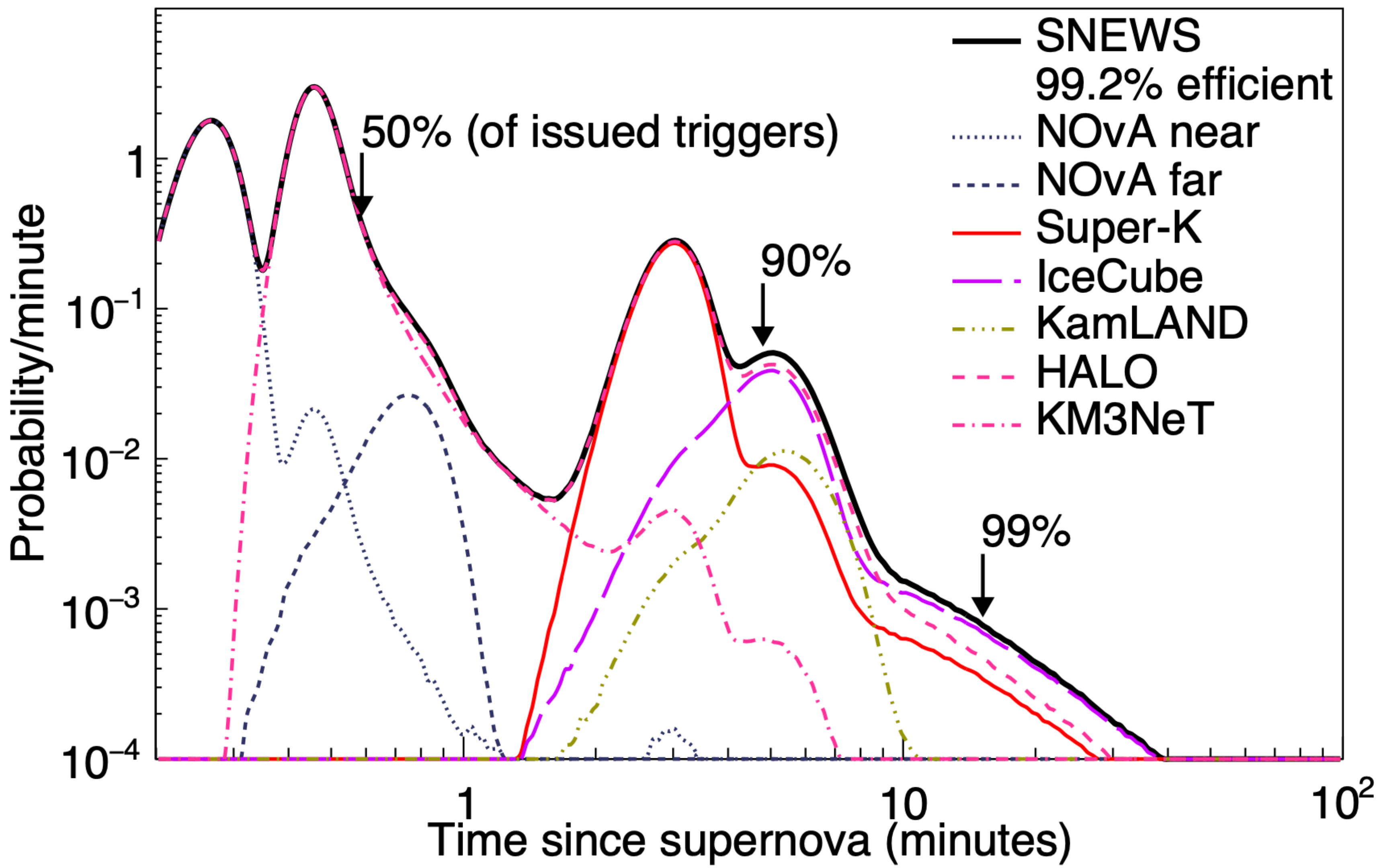
We're racing the shock!

May have less than a half hour, or even just minutes

For this application, want to point with ***low latency***

# SNEWS Alert Latency

From A. Habig, M. Strait




(will improve with SNEWS 2.0)

arXiv: 2011.00035

Now, the example where FastML may help!

## Methods for Pointing Using Neutrinos

- **Anisotropic neutrino interactions**
  combined with detector technology that can exploit it,
  using the burst neutrino signal
- **Triangulation**
  using inter-detector timing
- **Oscillation pattern pointing**
  in high-energy resolution detectors
- **High-energy (~GeV) neutrino follow-on pointing**
  in directional detectors, using later neutrinos
- **All of the above!**

# Neutrino Pointing Methods

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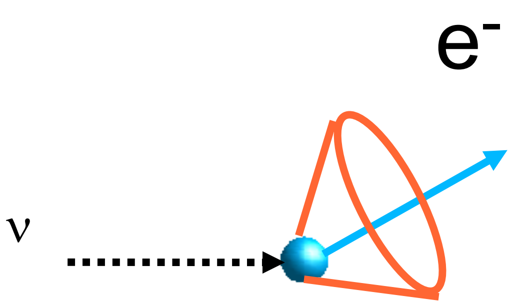
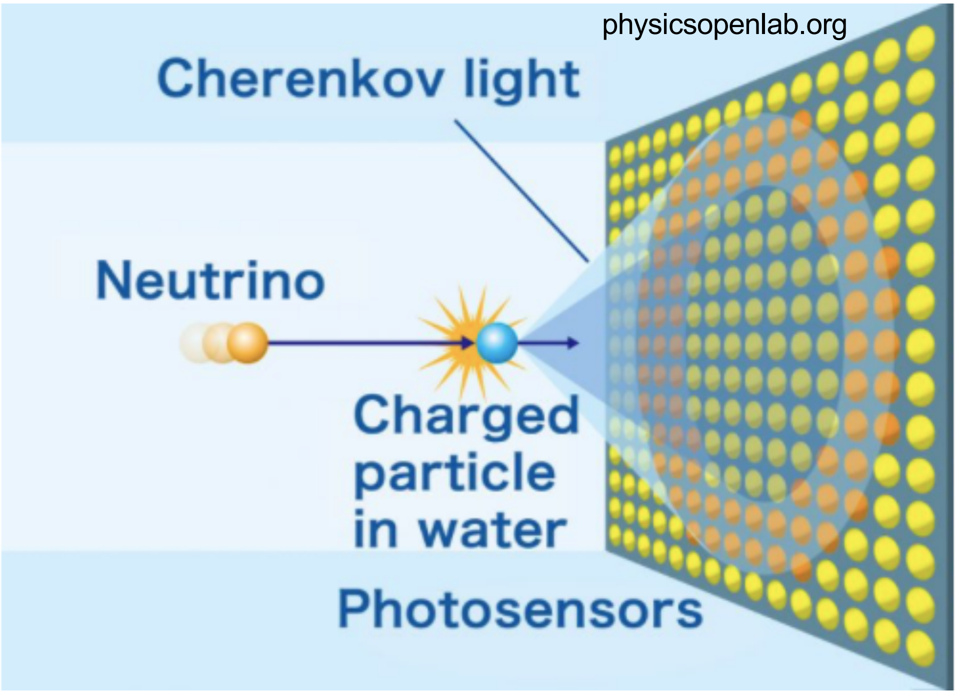
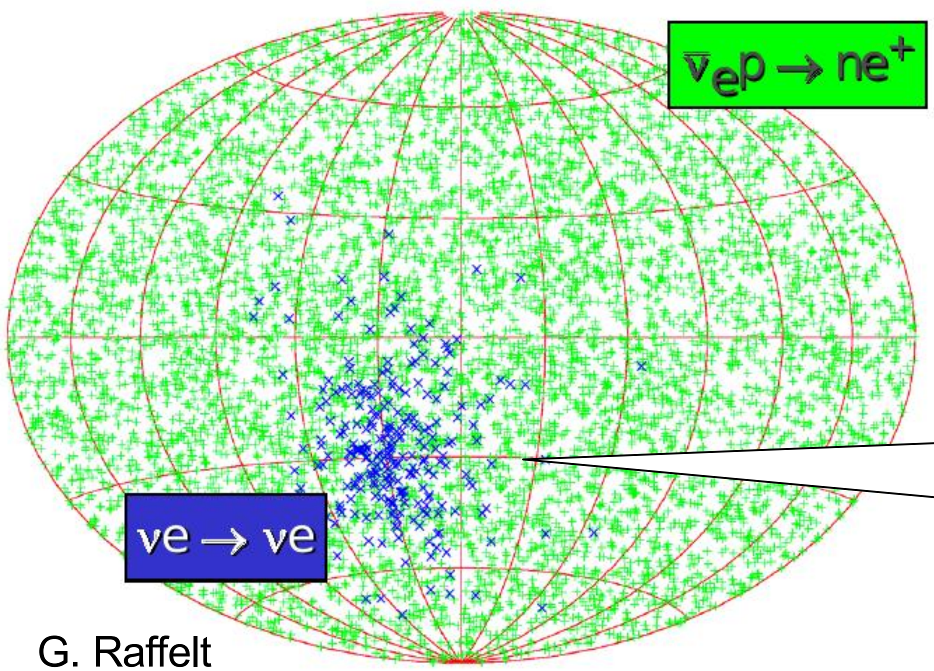



Final-state particle may remember the neutrino direction...
detector must be able to exploit the directionality!

# Water Cherenkov Detectors

Excellent intrinsic directionality, including head-tail disambiguation

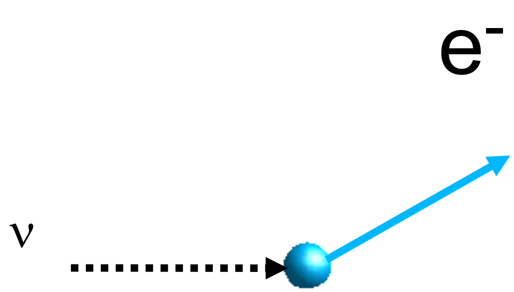


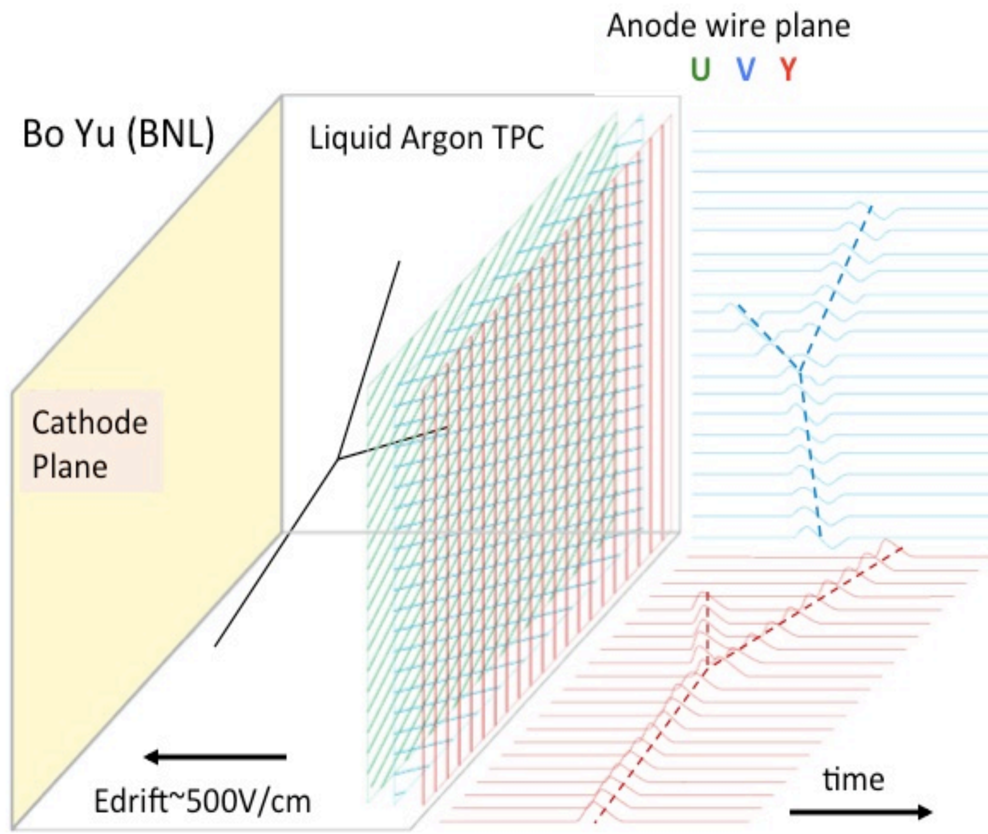




Should work well in Super-K (few degrees for Galactic center)

G. Raffelt

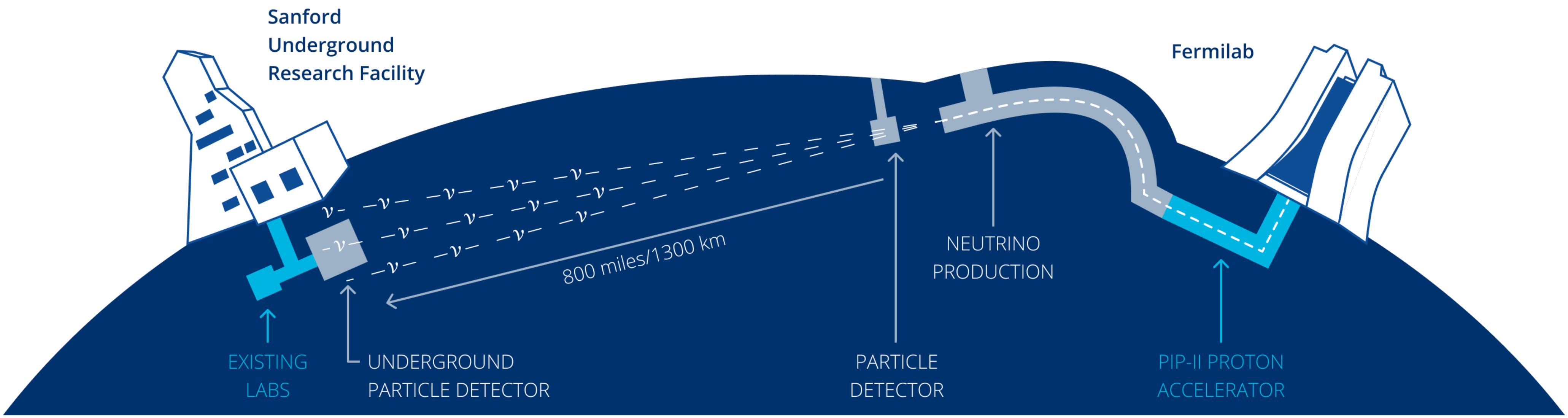
# Liquid Argon Time Projection Chambers

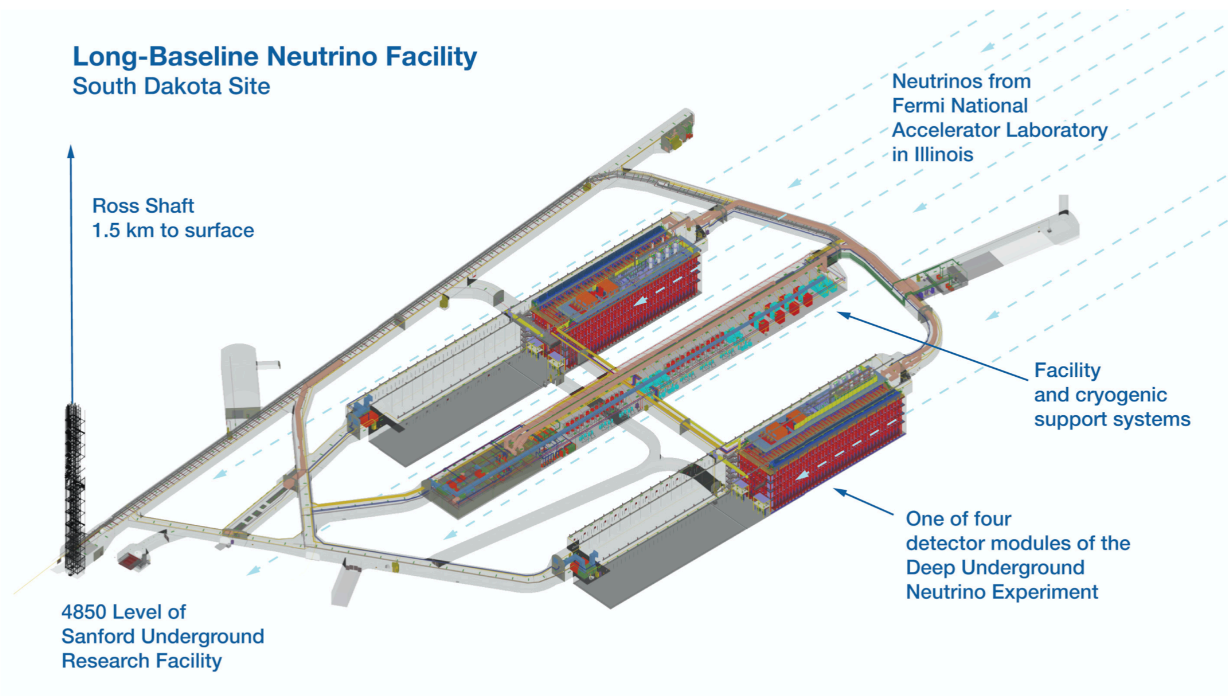



- Fine-grained tracking of final-state particles
- Machine learning (not "fast")has been used for neutrino event classification in LArTPCs, e.g.
  - MicroBooNE: arXiv:2011.01375v1
  - DUNE: 10.1103/PhysRevD.102.092003, https://zenodo.org/record/4122909#.X8e2My9h3s0

# DUNE (Deep Underground Neutrino Experiment)

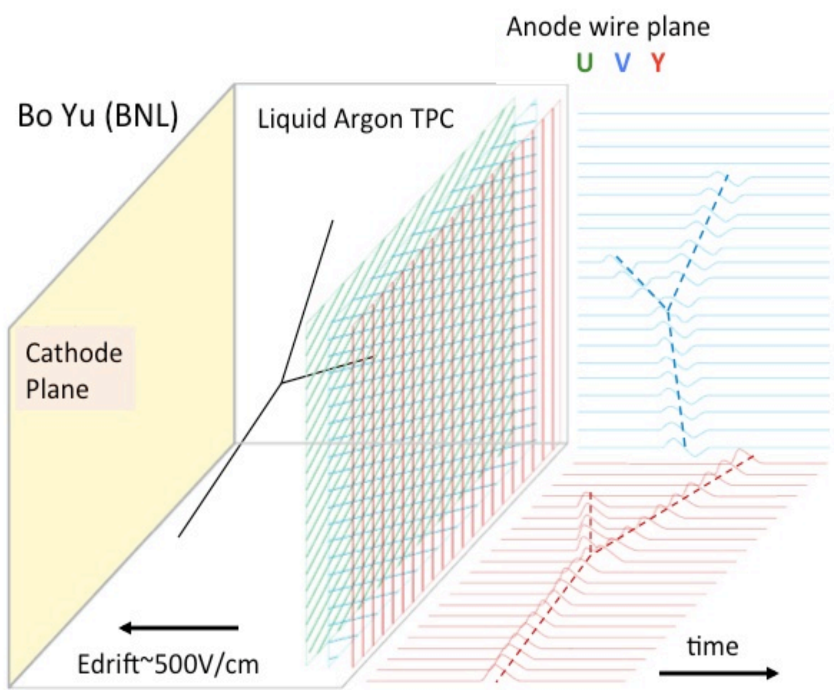


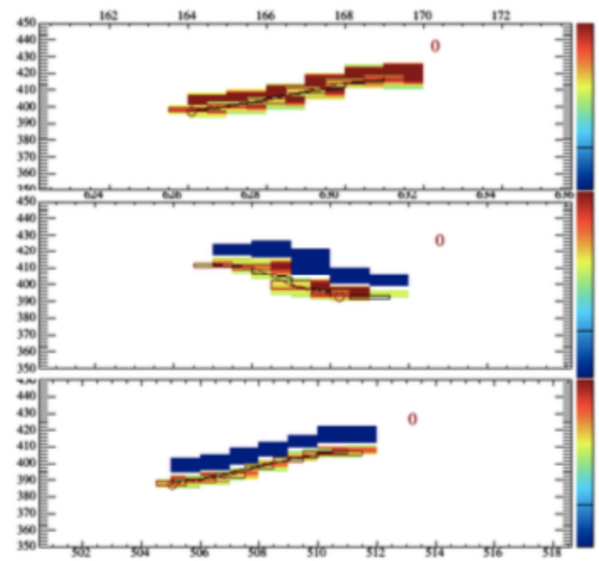

- neutrino oscillations w/beam from Fermilab
- **supernova burst neutrinos**
- proton decay

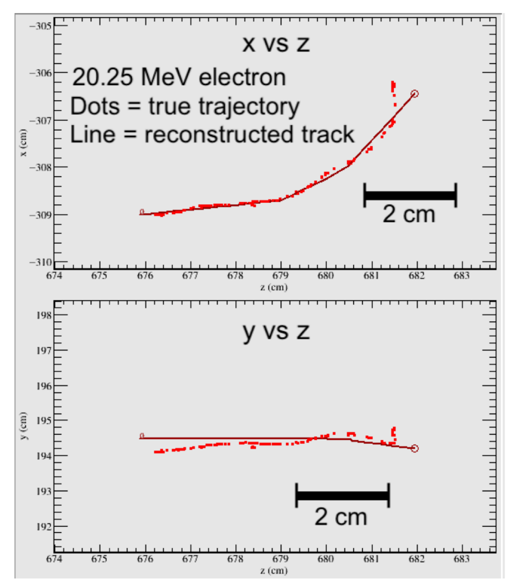
...

# Pointing to the supernova with LArTPCs




10.25 MeV electron

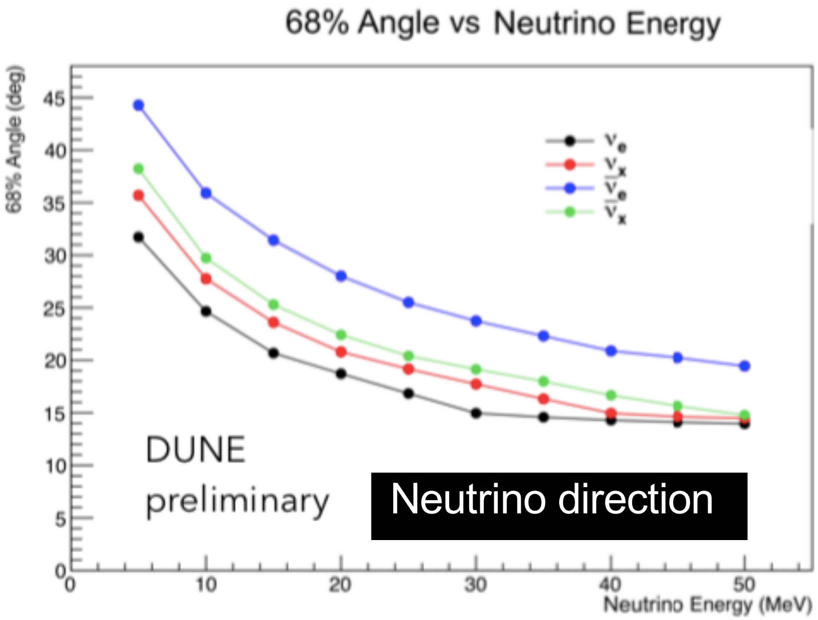


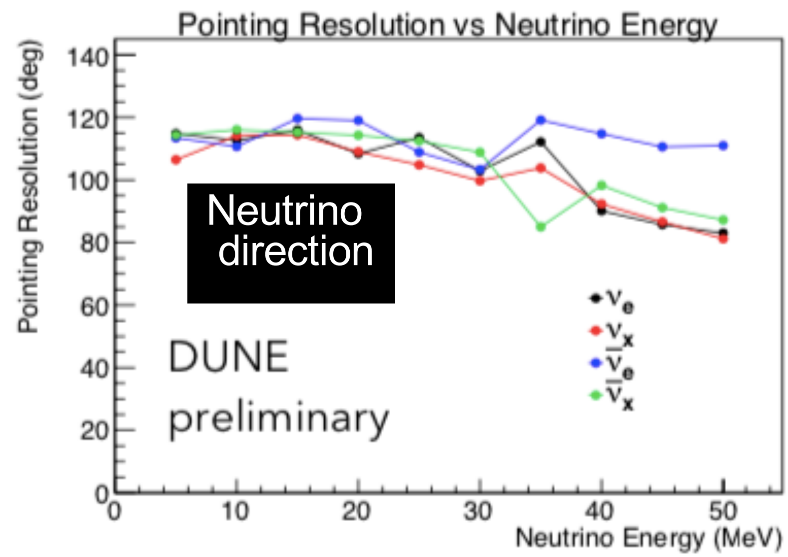



Tracks can be reconstructed,
but note direction ambiguity,
unlike Cherenkov!

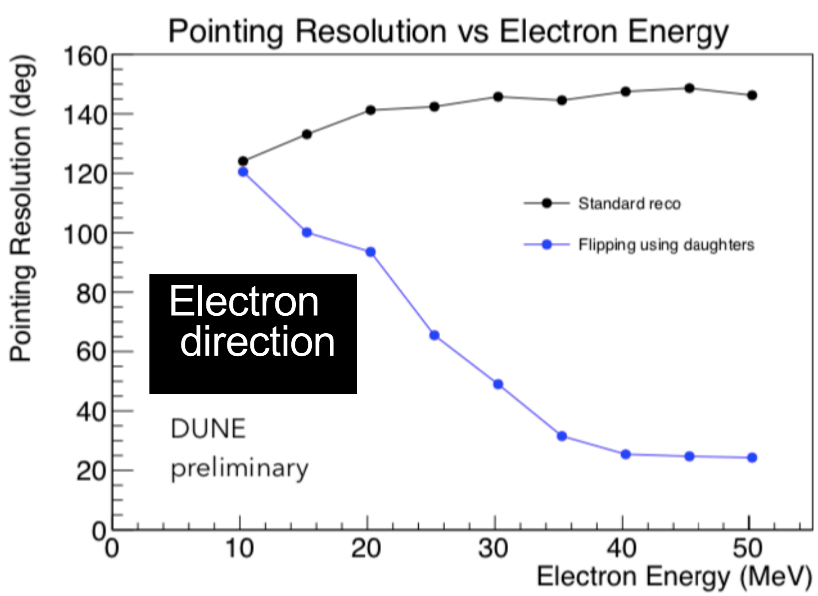
... but can resolve statistically
using bremsstrahlung
directionality and multiple scattering

# Pointing to the supernova with DUNE



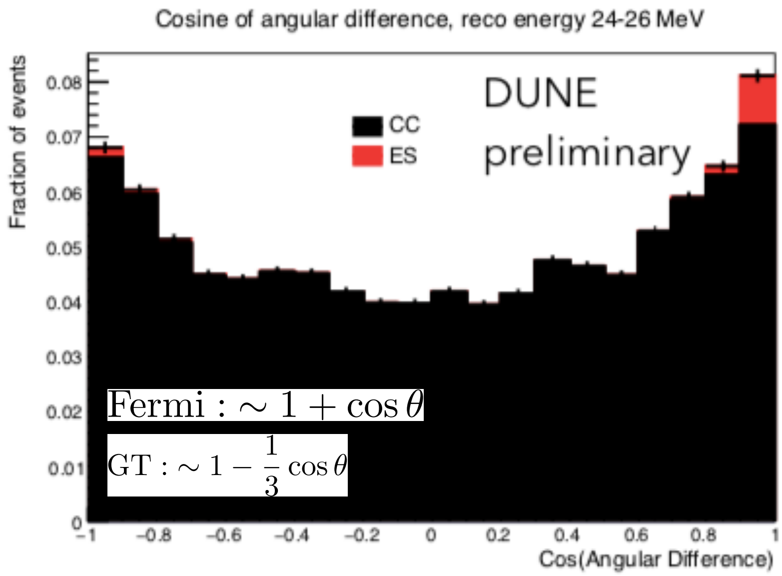

After daughter flipping

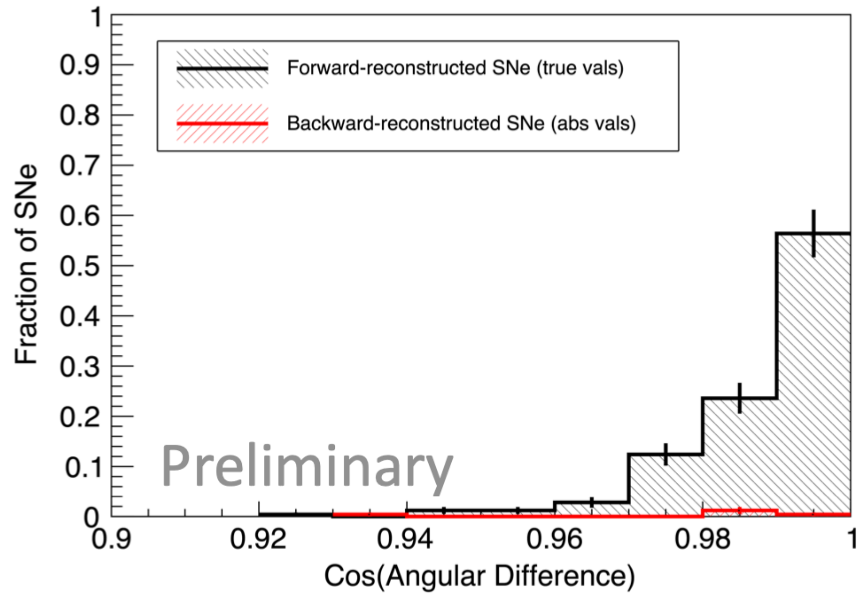



AJ Roeth, ICHEP 2020

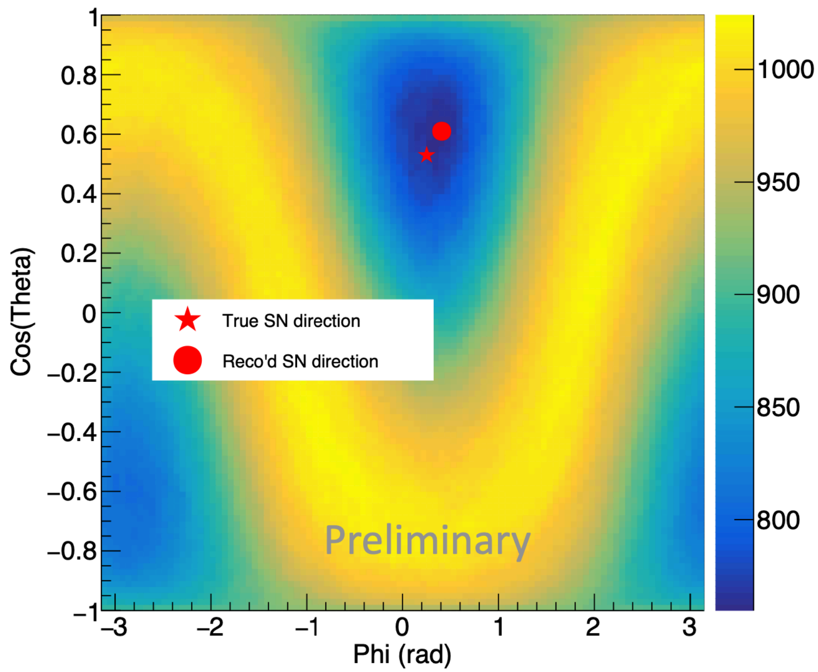
https://indico.cern.ch/event/868940/contributions/3813598/attachments/2081577/3496427/Point_Res_ICHEP_2020_07_AJRoeth.pdf

# Making use of interactions on both Ar and electrons:




Maximum likelihood method

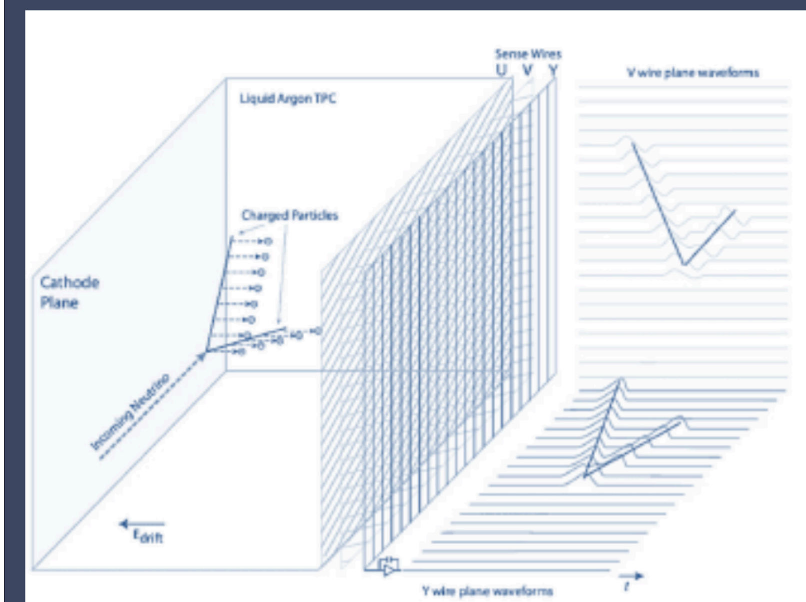



Overall pointing using an ensemble of events from a ~10 kpc supernova → ~7.5°
...improvements still possible

So decent pointing in DUNE is possible
... but this study is for offline processing of selected events
... needs to be ***fast!***

Slide from Georgia Karagiorgi:

# DUNE's Data (Selection) Challenge




High-resolution "video" streams:

- from up to 4x150 independent detector volumes
- 11.5 megapixel frames (all 3 planes) per 2.25ms
- 12-bit resolution

A total of **~40 terabits per second**

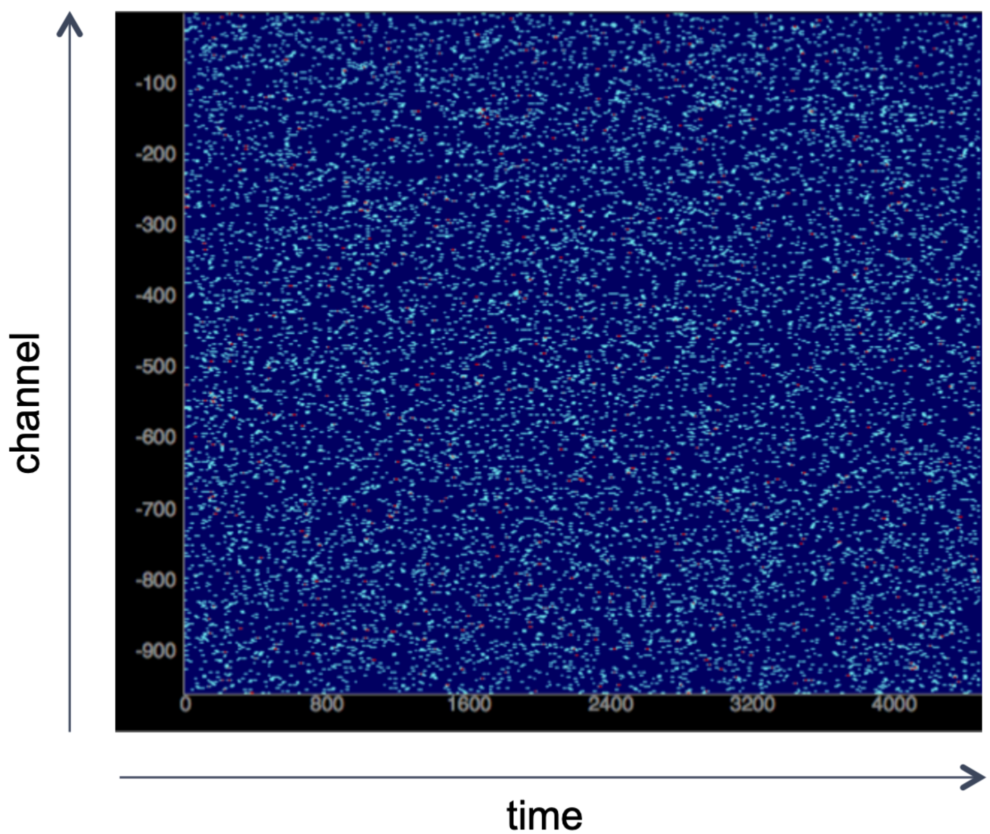
**100% live time**
**continuous operation for more than a decade**

# *Real-time* data selection is a challenge...

Slide from Georgia Karagiorgi:

## DUNE signatures

**Deep Underground = “quiet” environment**



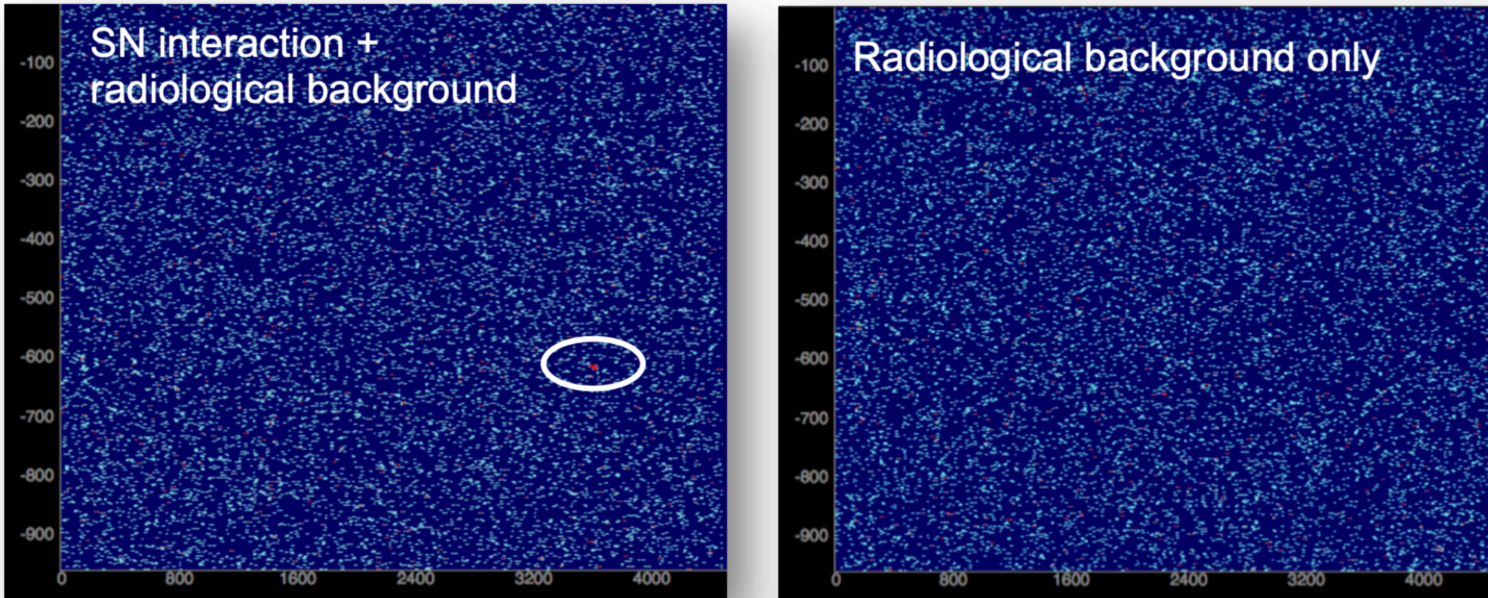

**Single frame from high-resolution video: One of three 2D views from one of hundreds of cells in the detector**

“Static” is noise and small energy deposits from radiological impurities in the detector

Slide from Georgia Karagiorgi:

Special challenge: **neutrinos from supernova core collapse**

Very low energy and small (in extent) topology, similar to radiological background activity in the detector




Need O($10^4$) overall background suppression, while maintaining high efficiency to a frame containing a supernova neutrino interaction

[simulation]





E.g., **Convolutional Neural Networks (CNNs)*** could be applied for real-time image classification, using hardware acceleration (FPGA), or online in GPU or CPU.

**translation-invariant feature extraction*

can address directional reconstruction too
(only very preliminary work so far)

# To recap: the supernova burst problem (not just DUNE) is:

**1. Trigger on the supernova burst** (easy, maybe...)

**2. Swallow all the data** (save everything! also doable)

... all this so far can be done for leisurely later perusal and sophisticated event reconstruction, but the shock isn't going to wait! So next steps must be done *fast:*

**3. Select the neutrino events from background**

**4. Reconstruct the direction to the supernova** using the ensemble of selected events

} challenge! where FastML can help

# Summary

- Neutrinos bring unique information from
 astrophysical objects
 (particle physics & astrophysics)

- Core-collapse supernovae create intense,
 few-tens-of-second, few-tens-of-MeV neutrino bursts,
 a few times per century in the Milky Way
 .... the next one will be a multimessenger extravaganza

- The neutrinos emerge before the photons, so an
 early alert is possible; delays can be days, or just minutes

- Detectors around the world are sensitive to the burst

- The SuperNova Early Warning System
 will provide a low-latency alert

- Some detectors can use the neutrinos to point to the SN

- **Fast selection of the burst neutrinos
 and reconstruction of the SN direction
 is a challenge that FastML can address**