Detecting Supernova Neutrinos: Basics

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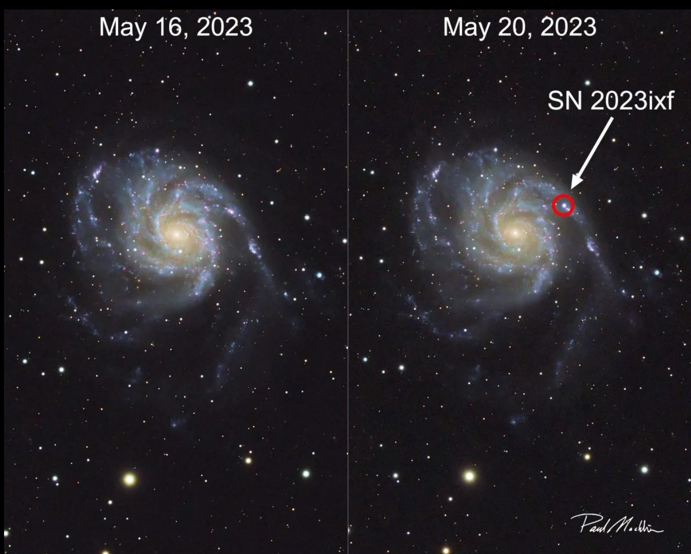
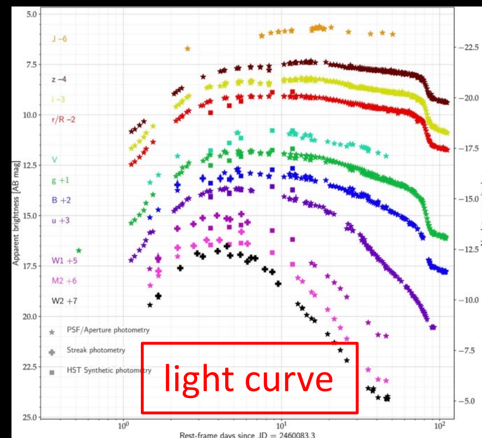
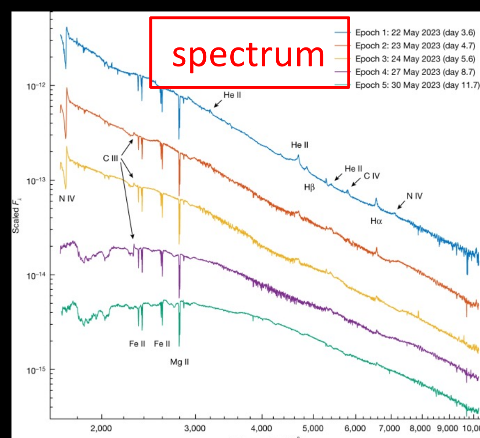
Supernova!

SN 2023ixf in M101 galaxy
~7 Mpc distance



Macklin (2023)





Zimmerman (2024)

Key characteristics of SNe:

Rare (~1/century/galaxy)
Energetic (often >10^{49} erg)
Transient (~months)
Observable (peaks in optical)
Resolvable (eventually)

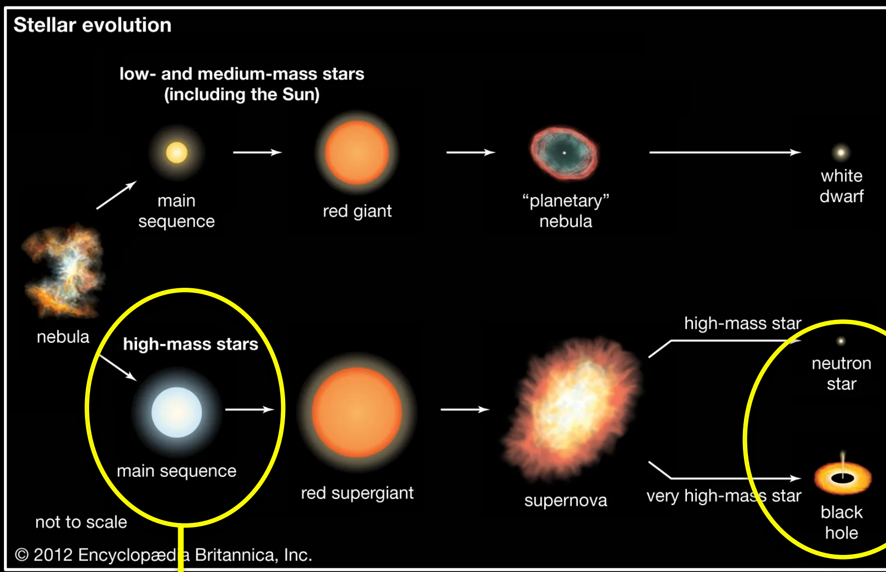
But what are they?

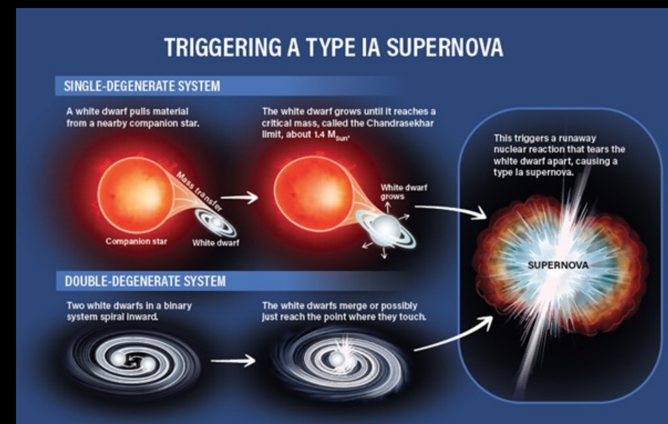
Outline

First lecture: Basics
Introducing neutrinos
Neutrino production
Neutrino propagation
Neutrino detection

Second lecture: Frontiers

Our Limited Understanding, Overall





"Massive" stars, $>8M_{sun}$

Rare, luminous, short-lived

"Core-collapse" supernovae
Our focus in these talks

Our Limited Understanding, Core Collapse

Early idea:

"Neutrino Theory of Stellar Collapse,"
Gamow and Schoenberg (1941)

- Core collapses (emitting neutrinos)
- ~~Core forms white dwarf~~
- Envelope expands (emitting light)

Modern idea:

- Core forms neutron star or black hole
- *Always* emits neutrinos
- *Usually* emits light
- *Might* emit gravitational waves

Homework problem:

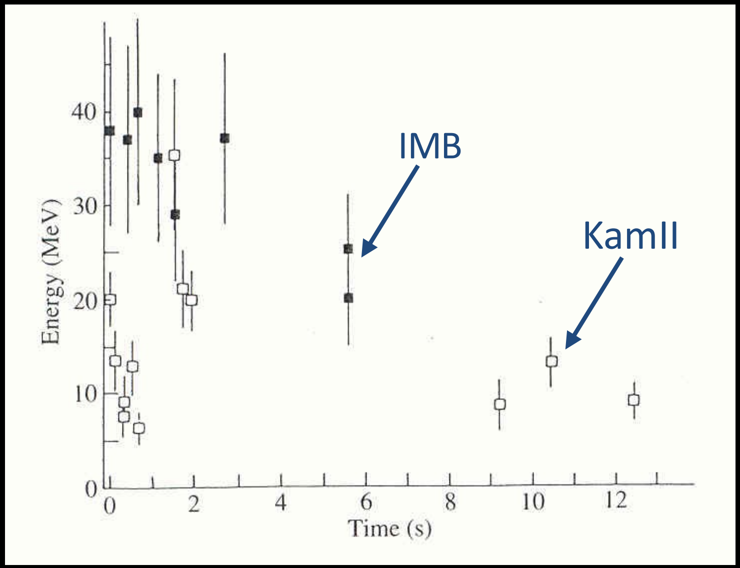
How much gravitational energy must be released in neutrinos for the core to form a neutron star?

Hints:

What is Δ(PE) for the core?
Rewrite to separate $M_{sun}\, c^2$
What is the gravitational redshift?
How many nucleons in 1 M_{sun}?
What is $E = mc^2$ for 1 M_{sun}?

* In the homework problems, you should approximate like *crazy*.

SN 1987A — A Rosetta Stone



Observation: Type II supernova progenitors are massive stars

Observation: The neutrino precursor is very energetic

Theory: Core collapse makes a proto-neutron star and neutrinos

Why Are Supernovae Interesting?

What happens?

What do they reveal?

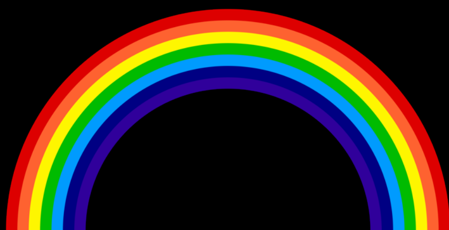
What do they destroy?

What do they make?

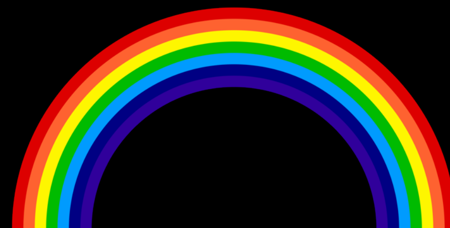
What reach beyond the lab?

How Do We Want to Find Supernovae?

Neutrinos



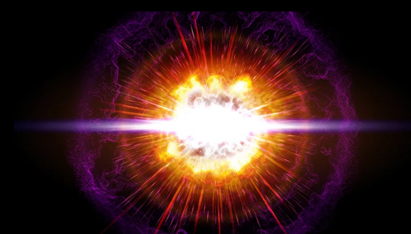
Electromagnetic



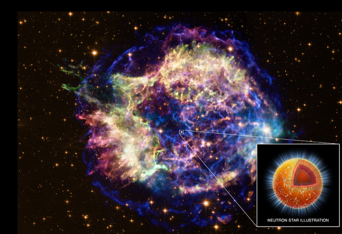
Gravitational Waves

Before

During



After



This is the only way to answer all the questions about supernovae

What Do We Hope to Learn?

Total energy emitted in neutrinos?
Partition between flavors?
Spectrum of neutrinos?
Neutrino mixing effects?
Emission in other particles?

…

Supernova explosion mechanism?
Nucleosynthesis yields?
Neutron star or black hole?
Electromagnetic counterpart?
Gravitational wave counterpart?

…

and much more!

What Are the Obstacles and Ways Forward?

Supernovae rates are too low / signals are too hard to detect

We need more sensitive detectors

Supernovae are really complicated!

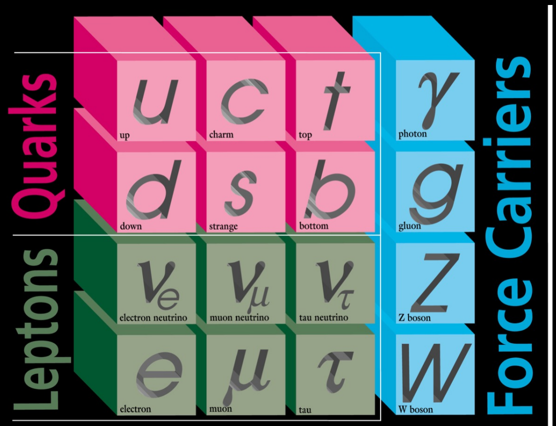
We need a multi-messenger approach in a theoretical framework

Neutrino and gravitational wave signals are faint

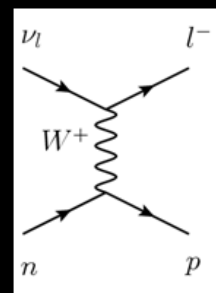
Yes, but they greatly leverage electromagnetic signals

Introducing Neutrinos

What Are Neutrinos?

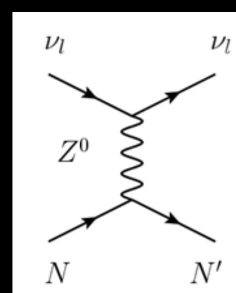


Neutral
May be own antiparticles
Nominally massless
Only weak interactions



Charged-current (CC; W exchange)
$\nu_e + n \rightarrow e^- + p$, etc.

Other flavors only at high energies



Neutral-current (NC; Z exchange)
$\nu_e + n \rightarrow \nu_e + n$, etc.

Possible for all flavors at all energies

Plus similar interactions with electrons, etc.

Neutrinos — As Messengers

Neutrinos reveal:

Nuclear reactions; hot, dense matter; hadronic acceleration

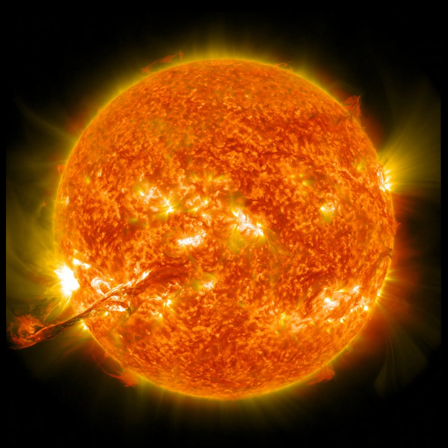
Can see:

- deep insides of sources, not the outsides
- initial energies, not reduced by scattering
- original timescales, not delayed by diffusion
- distant sources, not attenuated en route

The only thing is that neutrino signal detection is hard

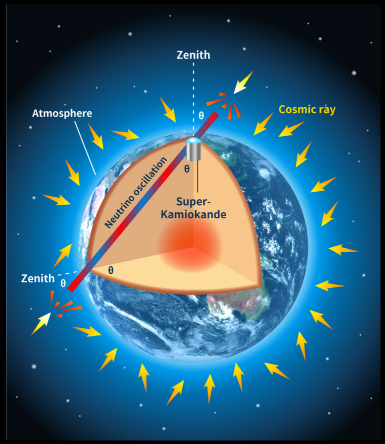
Neutrino Astronomy is Real

Sun

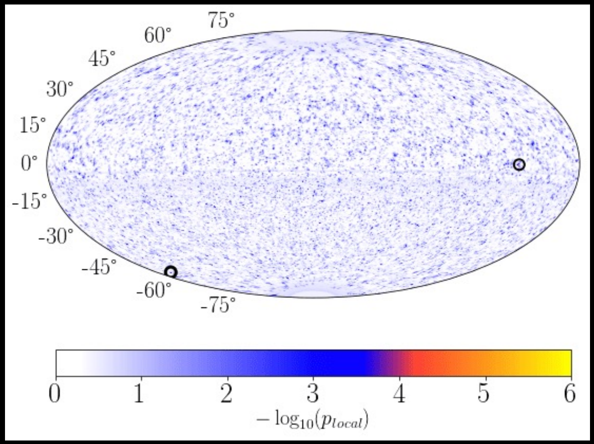


Supernova

Atmosphere

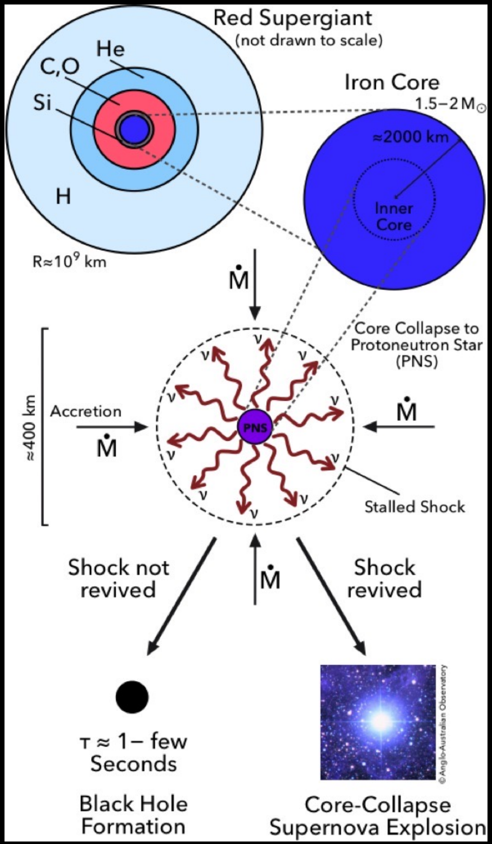


Extragalactic Sources



Neutrino Production

What Produces the Neutrinos?



Ott (2016)

What you learned in school:

$e^- + p \rightarrow \nu_e + n$, "neutronization"

This does happen, but is subdominant

Total energy is $\sim 10^{52}$ erg

What really happens:

$e^- + e^+ \rightarrow \nu_e$ + anti-ν_e, etc.

$N + N \rightarrow N + N + \nu_e$ + anti-ν_e, etc.

Total energy is $\sim 3 \times 10^{53}$ erg

Why neutrinos?

Nothing else can effectively remove energy!

What Can We Learn By Estimating?

Homework problems about the PNS:

What is the mass density?

What is the number density?

What is the column density?

If the neutrino cross section is $\sim 10^{-41}$ cm^2, what does this imply?

Again, approximate like *crazy*.

Other key estimates:

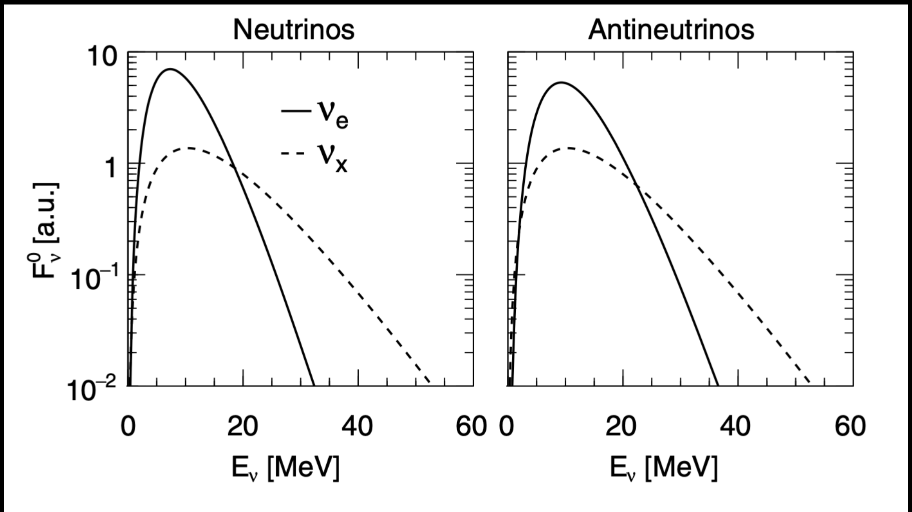
$\langle E_\nu \rangle \sim$ 100 MeV in core

$\langle E_\nu \rangle \sim$ 10 MeV at surface

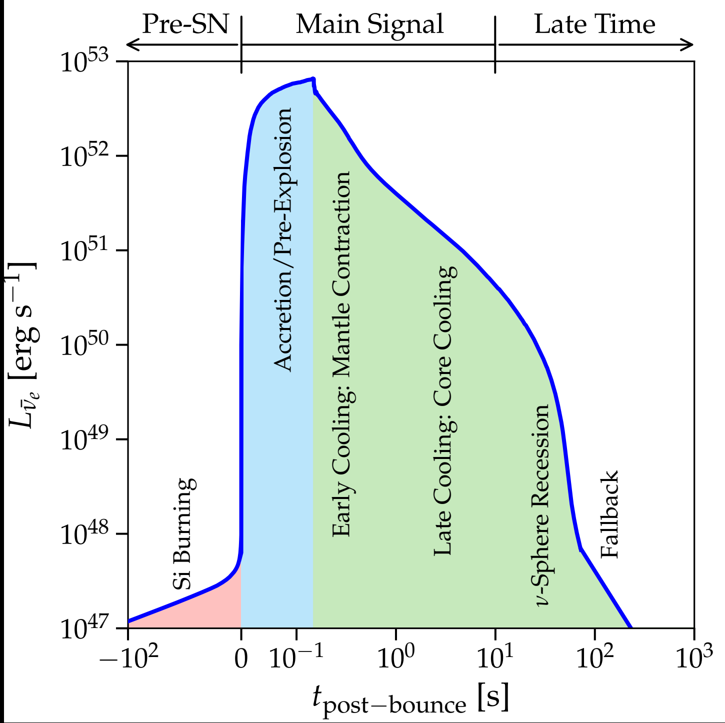
Diffusion over seconds

See Chang et al., 2206.12426

Spectra and Time Profiles



Capozzi, Dasgupta, Mirizzi (2018)



Li, Roberts, and Beacom (2021)

Neutrino Propagation

Neutrino Mixing in Vacuum

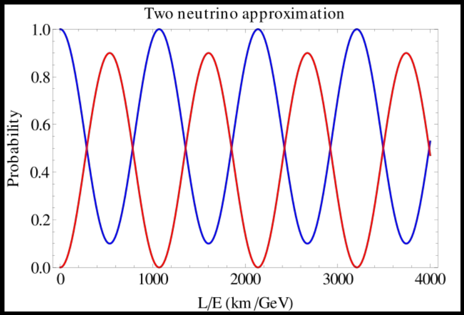
Neutrino flavor states:
An electron neutrino couples to an electron, e.g., $\nu_e + n \rightarrow e^- + p$, etc.

Neutrino mass states:
Neutrino masses are tiny but have small mass differences

How are the different states related?
Transform between them with a unitary matrix, take limit of m << E

$$P(\nu_e \to \nu_e)(t) = |\Psi_e(t)|^2 = 1 - \sin^2 2\theta_v \sin^2 (\pi t / L_{\rm osc}) \,,$$

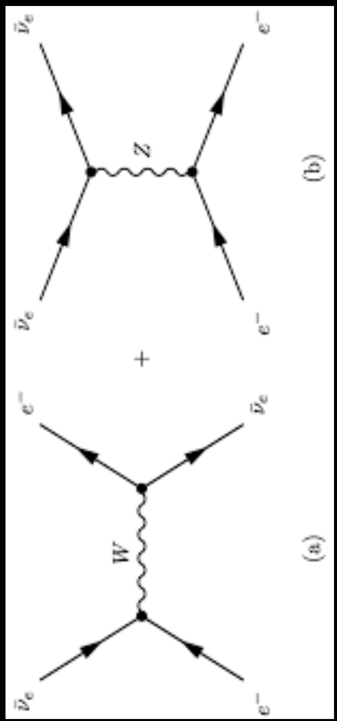
$$L_{\rm osc} = 4\pi E\hbar/\delta m^2,$$



Neutrinos can change flavor in vacuum!

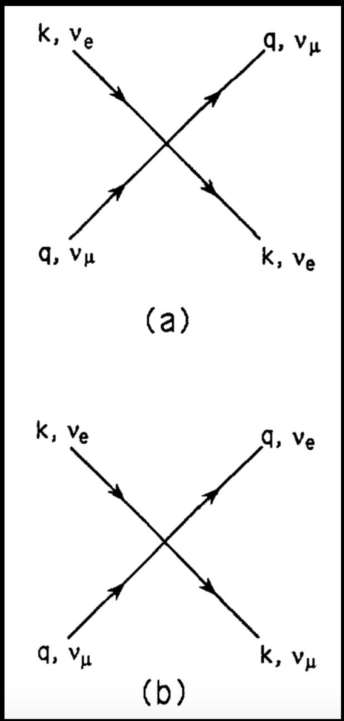
Neutrino Mixing in Matter

Neutrino-Electron



MSW effect

Neutrino-Neutrino



Pantaleone (1992)

→

Very complex consequences for mixing and maybe for the supernova explosion!

Unsolved problem, beyond reach of the lab

Is This Uncertainty a Problem?

Yes
If we want to compare neutrino data to theory
If we want to precisely test new physics

No
If we want to compare neutrino data to data
If we want to roughly test new physics

Why?
Nothing happens to the neutrinos en route!
The extreme conditions give us a great lever arm

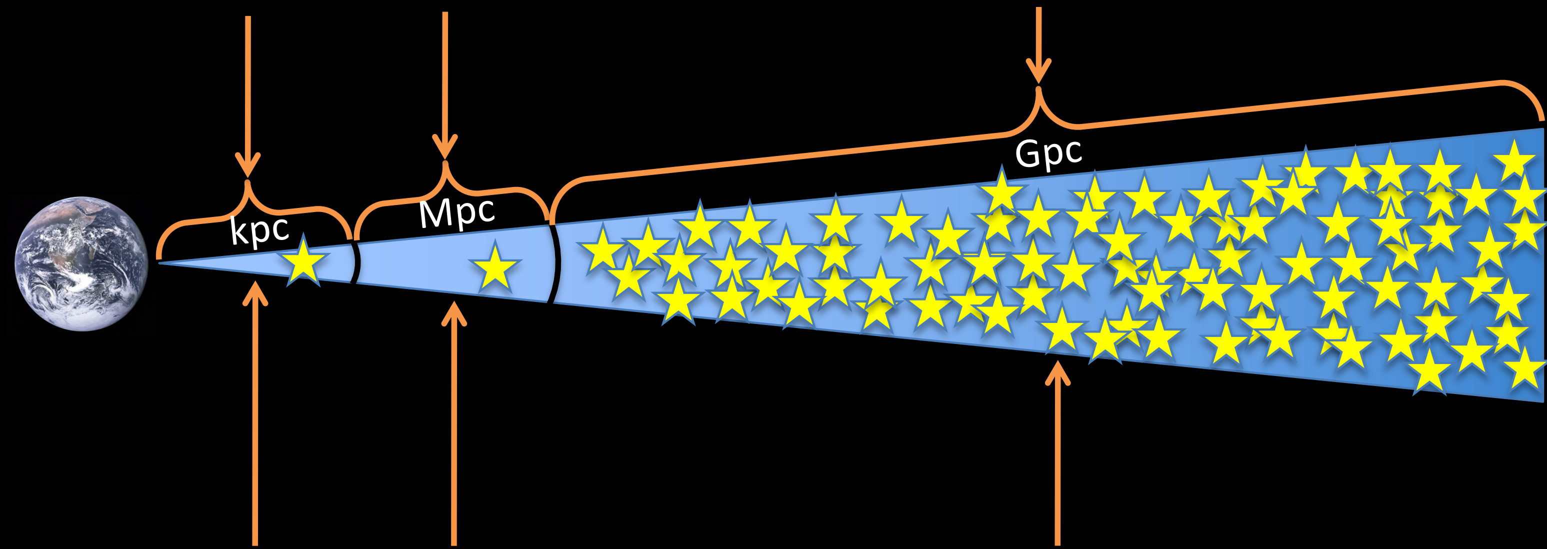
Neutrino Detection

How Do We Find Core Collapses With Neutrinos?

N >> 1 : Burst

N ~ 1 : Mini-Burst

N << 1 : DSNB



Rate ~ 0.01/yr

high statistics,
all flavors

Rate ~ 1/yr

object identity,
burst variety

Rate ~ 10^8/yr

cosmic rate,
average emission

How Do Neutrino Detectors Work?

Like gravitational-wave detectors:

Synoptic (passive, all-sky, no focusing), waiting for "events"

Unlike gravitational-wave detectors:

Sensitivity falls as $1/r^2$, discrete particle interactions, low backgrounds

Example: anti-ν_e + p → e^+ + n

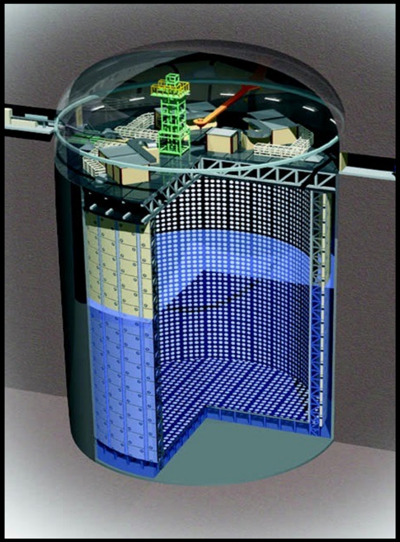
- $\sigma \sim 10^{-43}$ cm^2 $(E_\nu/\mathrm{MeV})^2$, "big"
- positron is mostly isotropic
- $E_e \sim E_\nu - 1.3$ MeV
- Flavor identification with neutron
- Timing often to few-ns level

Example: ν + e^- → ν + e^-

- $\sigma \sim 10^{-44}$ cm^2 (E_ν/MeV), "small"
- electron is mostly forward
- E_e ranges over 0–E_ν
- No flavor information
- Timing often to few-ns level

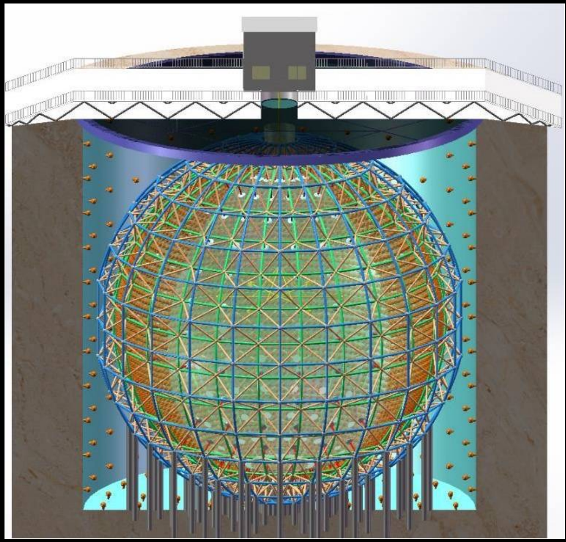
New Multi-kton Neutrino Detectors

Super-K Gd



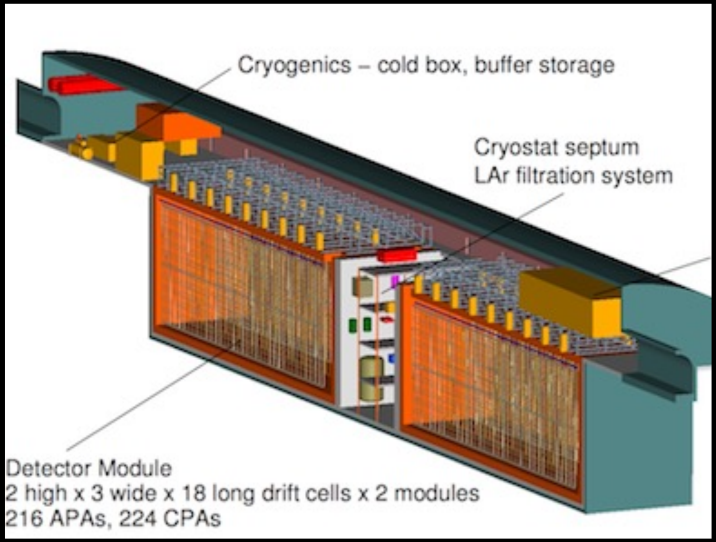
32 kton water+Gd
running (Japan)

JUNO



20 kton scintillator
starts 2025 (China)

DUNE



34 kton liquid argon
starts ~2030 (United States)

+
Hyper-K (260 kton) starts 2028

Yields For a Milky Way Burst

Super-Kamiokande (32 kton water)

~10^4 inverse beta decay on free protons
~10^2 CC and NC with oxygen nuclei
~10^2 neutrino-electron elastic scattering

Best for anti-ν_e

JUNO (20 kton mineral oil)

~10^4 inverse beta decay on free protons
~10^3 neutron-proton elastic scattering
~10^2 CC and NC with carbon nuclei
~10^2 neutrino-electron elastic scattering

Best for ν_x

IceCube (10^6 kton water)

Burst is increase over background rate
Possibility of precise timing information

DUNE (34 kton liquid argon)

~10^3 CC and NC with argon nuclei
~10^2 neutrino-electron elastic scattering

Best for ν_e

Closing Message

We can't understand supernovae without detecting neutrinos