University of Sheffield

Particle Astrophysics

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Introduction

WHAT IS PARTICLE ASTROPHYSICS?
COURSE CONTENT

What is particle astrophysics?

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Particle astrophysics is the use of particle physics techniques (experimental or theoretical) to address astrophysical questions.

Topics included:

- early-universe cosmology
  - inflation (and alternatives), baryogenesis, dark energy
- low-energy neutrino astronomy (*coming up!*)
- dark matter (*next lecture*)
- cosmic rays
- γ-ray astronomy
- high-energy neutrino astronomy

These form a coherent field with a lot of common factors—"high-energy particle astrophysics" (cosmic rays, γ-ray astronomy, high-energy neutrino astronomy)

Course content

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Much of particle astrophysics concerns theory—especially early-Universe cosmology.

- I'm not a theorist and will not attempt to tackle this!

This lecture: low-energy neutrino astrophysics (solar and supernova neutrinos)

Lecture 2: dark matter

Lectures 3 and 4: high-energy particle astrophysics

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Low energy neutrino astrophysics

SOLAR NEUTRINOS

NEUTRINOS FROM CORE-COLLAPSE SUPERNOVAE:

- A GALACTIC SUPERNOVA
- THE DIFFUSE SUPERNOVA NEUTRINO BACKGROUND
- PRESUPERNOVA NEUTRINOS

Solar neutrinos

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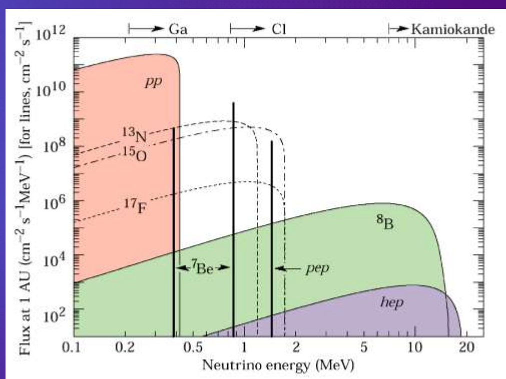
Hydrogen fusion, $4\,{}^1H \rightarrow {}^4He + 2e^+ + 2\nu_e$, necessarily produces neutrinos

- Only ν_e, because there isn't enough energy to produce muons or taus.

Historically solar neutrinos provided early evidence of neutrino oscillation, and they're the poster child for the MSW effect (see Steve Boyd's lectures).

- However, they also have potential value in astrophysics.



https://neutrino-history.in2p3.fr/solar-neutrinos/

Solar neutrinos from the CNO cycle

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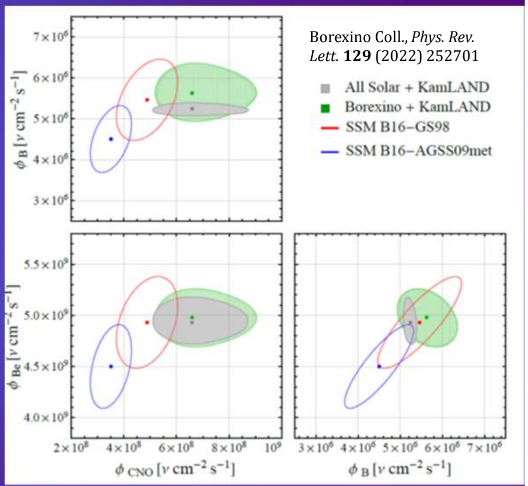
Solar neutrinos from the main pp chain have mostly provided information about neutrinos.

However, neutrinos from the CNO cycle have also been detected.

- Because this uses ^{12}C as a catalyst, it provides information about the carbon content of the Sun's core.
- This is useful because there is some tension between spectral modelling and helioseismology.



Neutrinos from core-collapse supernovae

Core-collapse supernovae emit nearly all (99%) of their energy as neutrinos:

- a pulse of ν_e from the initial formation of the proto-neutron star
- a longer burst, about 10 s, of all flavours of neutrinos and antineutrinos produced thermally in the core of the explosion.

The energies of supernova neutrinos are of order 15 MeV, slightly higher than solar neutrinos.

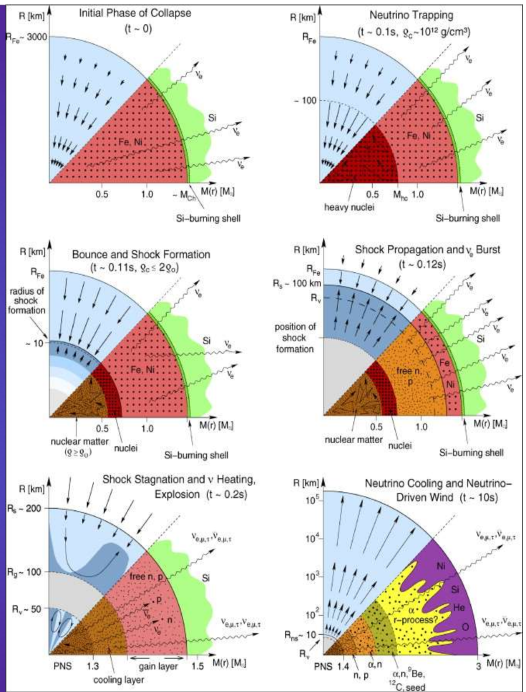


Image from Janka et al., *Phys. Rep.* **442** (2007) 38

Supernova neutrinos

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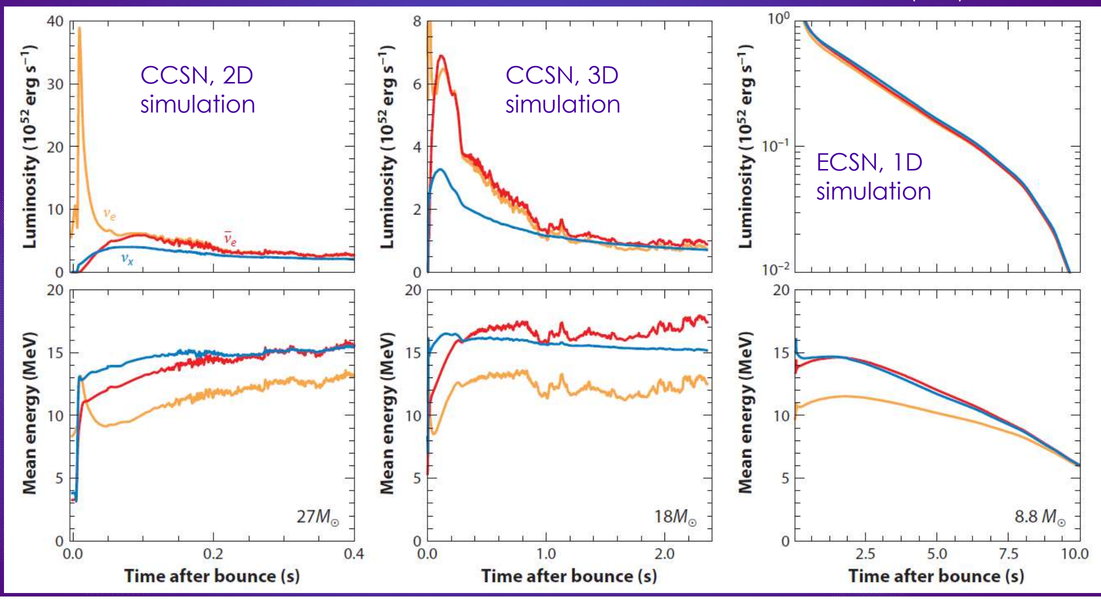
Müller, *Ann. Rev. Nucl. Part. Sci.* **69** (2019) 253



A Galactic supernova

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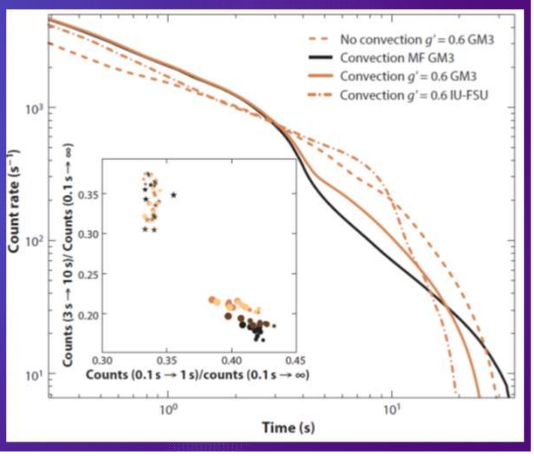
SN 1987A, 50 kpc away in the LMC, resulted in a signal of 12 neutrinos in Kamiokande-II (2140 tonnes).

Therefore a Galactic supernova (~10 kpc) would result in ~3000 neutrinos in Super-Kamiokande

- hundreds of thousands in IceCube, which can count them though it can't measure them

A signal of this size can constrain many aspects of the supernova explosion.

Müller, *Ann. Rev. Nucl. Part. Sci.* **69** (2019) 253



The Diffuse Supernova Neutrino Background

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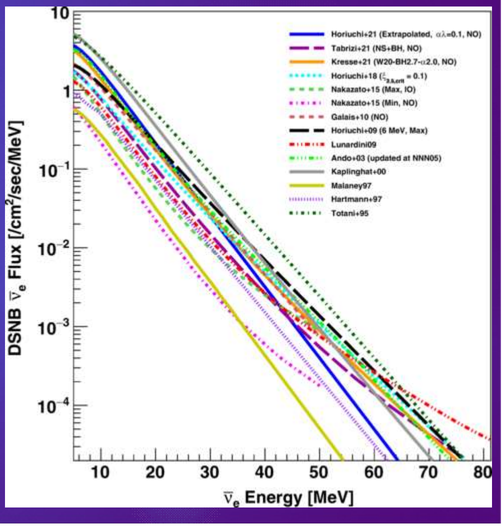
Super-K Coll., *Phys. Rev. D* **104** (2021) 122002



Neutrinos are—as far as we know—entirely stable, so neutrinos from past supernovae are still travelling through the cosmos.

- These form the ***diffuse supernova neutrino background***.
- This is a much lower flux than a Galactic supernova, but is guaranteed to exist.
- The rate is primarily determined by the rate of formation of massive stars over the history of the Universe.

Detecting the DSNB

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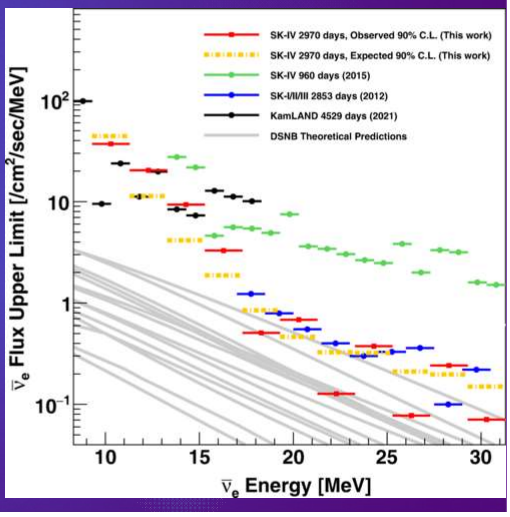
Super-K Coll., *Phys. Rev. D* **104** (2021) 122002



Water Cherenkov experiments detect the DSNB through inverse beta decay, $\bar{\nu}_e + p \rightarrow e^+ + n$ (threshold 1.8 MeV).

- Main backgrounds are electrons produced by decays of sub-threshold muons (15–50 MeV), and decays of radioactive isotopes produced by cosmic-ray spallation reactions (< 20 MeV).
- Most backgrounds can be reduced by neutron tagging (hence the decision to add Gd to Super-K), but a few isotopes, especially ^{9}Li, have $\beta + n$ decays.

Presupernova neutrinos

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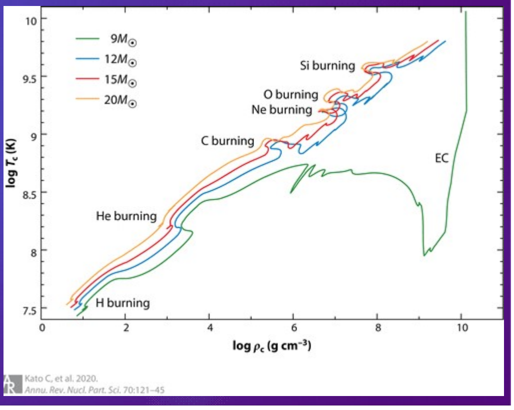
The later stages of massive star evolution require higher core temperatures to overcome the higher Coulomb barriers involved.

- At these high temperatures, neutrinos are produced via a range of interactions, e.g.

$$e^+ + e^- \to \nu + \bar{\nu}$$
$$e^- + p \to n + \nu_e$$
$$e^- + {}^A_Z X \to {}_{Z-1}^{A}X' + \nu_e$$

- If they could be detected, these neutrinos would provide early warning of an imminent supernova.



Detection of presupernova neutrinos

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Presupernova neutrinos have lower energies than neutrinos from the supernova proper, are not emitted in a single brief burst, and are not as numerous.

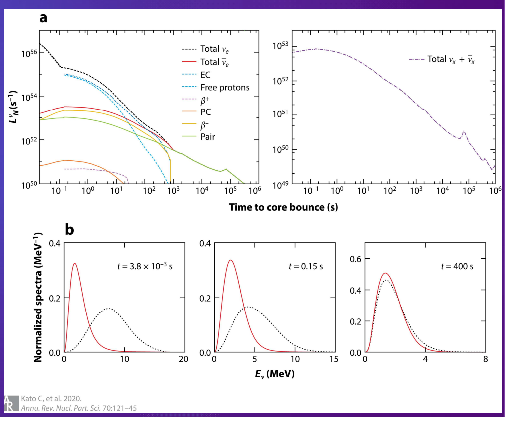
- They are therefore harder to detect.

KamLAND and SK-Gd can detect the signal at distances up to ~400 pc.

- The only really plausible presupernova stars in this range are Antares and Betelgeuse.

JUNO could reach around 1 kpc.

- DUNE could do better, if it can reconstruct such low-energy events, because it sees ν_e rather than $\bar{\nu}_e$.



Summary

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Low-energy neutrinos (~MeV) are produced by processes in stars

- fusion in main-sequence stars, thermal production in presupernova stars and supernovae.

The flux from a normal main-sequence star is low enough that we are only able to study the Sun.

- Solar neutrinos were very important in the early days of oscillation studies, and can also probe the heavy-element content of the solar core.

Presupernova stars can be detected out to a few hundred parsecs, and supernova bursts to a few hundred kpc.

- The diffuse supernova neutrino background is also potentially detectable.