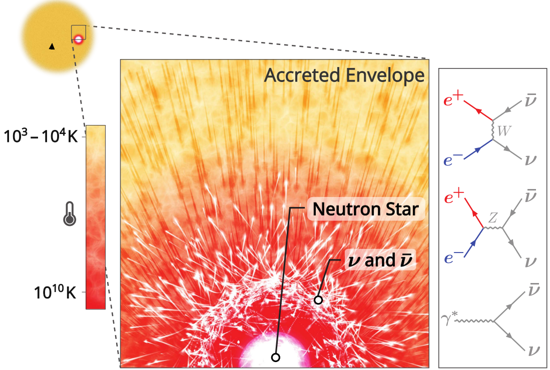
Accreting neutron stars: the potential third MeV astrophysical neutrino source



9th April 2024

Ivan Esteban

University of the Basque Country

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Neutrino astronomy

"Neutrino astronomy is interesting for the same reason it is difficult."

John Bahcall, 1989

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Neutrino astronomy

Neutrino detection is *difficult*. But, precisely because of that, neutrinos

- Provide us with the conditions deep inside sources.
- Carry out *real-time* tracking.
- Are not affected by propagation.

Neutrinos interact weakly. But, precisely because of that, neutrinos

- Are a clean probe of new, weak, interactions.
- Are a clean probe of accumulating propagation effects.
- Are a clean probe of large densities.

Introduction

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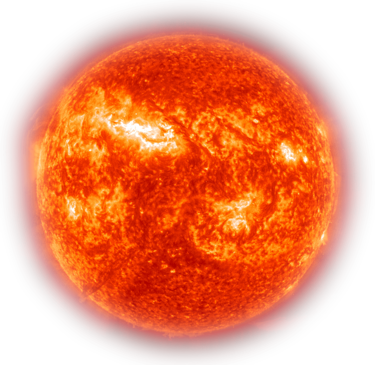
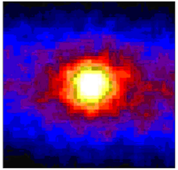
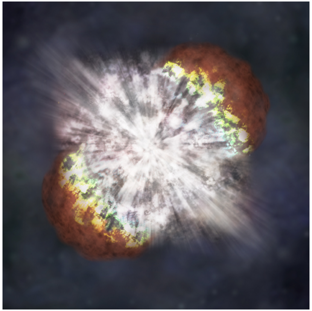
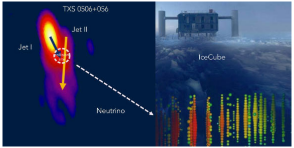
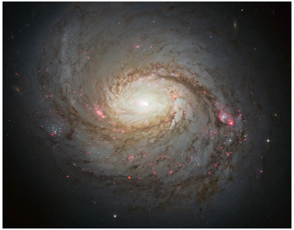
Neutrino astronomy











Neutrino astronomy: successes in astrophysics

nature

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Article | Published: 24 October 2018

Comprehensive measurement of *pp*-chain solar neutrinos

The Borexino Collaboration

Nature **562**, 505–510 (2018) | Cite this article

12k Accesses | **164** Citations | **270** Altmetric | Metrics

Abstract

About 99 per cent of solar energy is produced through sequences of nuclear reactions that convert hydrogen into helium, starting from the fusion of two protons (the *pp* chain). The neutrinos emitted by five of these reactions represent a unique probe of the Sun's internal working and, at the same time, offer an intense natural neutrino beam for fundamental physics. Here we report a complete study of the *pp* chain. We measure the neutrino–electron

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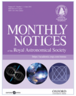

Volume 477, Issue 1
June 2018

Article Contents

JOURNAL ARTICLE

Helioseismic and neutrino data-driven reconstruction of solar properties FREE

Ningqiang Song ✉, M C Gonzalez-Garcia, Francesco L Villante, Nuria Vinyoles, Aldo Serenelli ✉

Monthly Notices of the Royal Astronomical Society, Volume 477, Issue 1, June 2018, Pages 1397–1413, https://doi.org/10.1093/mnras/sty600

Published: 06 March 2018   **Article history** ▾

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Abstract

In this work, we use Bayesian inference to quantitatively reconstruct the solar properties most relevant to the solar composition problem using as inputs the information provided by helioseismic and solar neutrino data. In particular, we

Introduction

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Neutrino astronomy: successes in astrophysics

PHYSICAL REVIEW D VOLUME 38, NUMBER 2 15 JULY 1988

Observation in the Kamiokande-II detector of the neutrino burst from supernova SN1987A

The properties of the Kamiokande-II detector and the method of measurement are described in detail. The data on the neutrino burst from the supernova SN1987A on 23 February 1987 at 7:35:35 UT$\pm$1 min are presented, with records of earlier and later observation periods in which other neutrino events possibly associated with SN1987A might have occurred. There is no evidence in the data for any excess of neutrino-induced events, either in a burst of a few seconds duration or over a longer time interval, relative to the usual count rate, excepting only the neutrino burst at 7:35:35 UT. The nature of the single, observed neutrino burst coincides remarkably well with the elements of the current model of type-II supernovae and neutron-star formation. This is the first direct observation in neutrino astronomy.

Neutrino astronomy: successes in astrophysics

The Astrophysical Journal, 749:63 (15pp), 2012 April 10 doi:10.1088/0004-637X/749/1/63
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BLAZARS AS ULTRA-HIGH-ENERGY COSMIC-RAY SOURCES: IMPLICATIONS FOR TeV GAMMA-RAY OBSERVATIONS

Kohta Murase[1], Charles D. Dermer[2], Hajime Takami[3], and Giulia Migliori[4]
[1] Department of Physics, Center for Cosmology and Astro-Particle Physics, The Ohio State University, Columbus, OH 43210, USA
[2] Space Science Division, Naval Research Laboratory, Washington, DC 20375, USA
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Received 2011 July 27; accepted 2012 January 29; published 2012 March 23

ABSTRACT

The spectra of BL Lac objects and Fanaroff–Riley I radio galaxies are commonly explained by the one-zone leptonic synchrotron self-Compton (SSC) model. Spectral modeling of correlated multiwavelength data gives the

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Neutrino astronomy: successes in astrophysics

Clean, **real-time** probes of **dense interiors** of sources.

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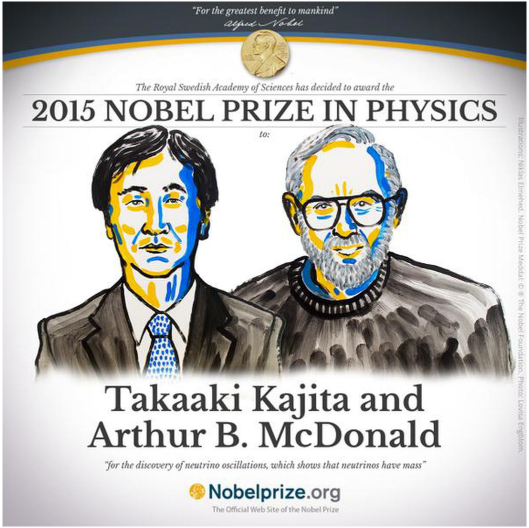
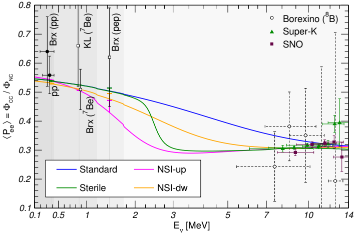
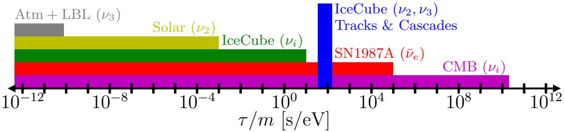
Neutrino astronomy: successes in particle physics





Maltoni & Smirnov, 2015



Abdullahi & Denton, 2020

...

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Neutrino astronomy: successes in particle physics

Clean probes of new interactions, dense matter, and/or propagation effects.

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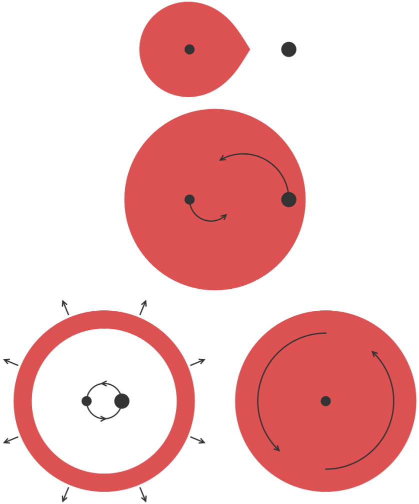
See Ivanova et al, 1209.4302, for a review



A process where two stars share a common envelope, due to expansion or orbital decrease.

Suggested by Paczynski in 1976. Sounds exotic, but most likely necessary for

- Type Ia-supernovae
- X-ray binaries
- **Gravitational-wave sources**
- ...

Common Envelope Evolution

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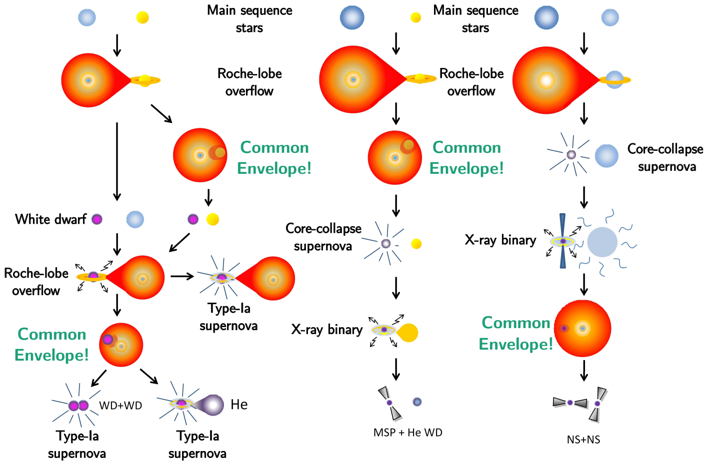

From Ivanova et al, 1209.4302

Yet still **unobserved** unambiguously (though see Dong et al., 2021, Science), and **very challenging to simulate!**

We need new signatures.

Common Envelope Evolution

For the rest of the talk, I will focus on common envelope with *neutron stars* (relevant for, e.g., X-ray binaries or gravitational wave sources).

Roughly, the main processes that happen during common envelope are

- The neutron star **inspirals** due to drag.
- The neutron star **accretes** material.

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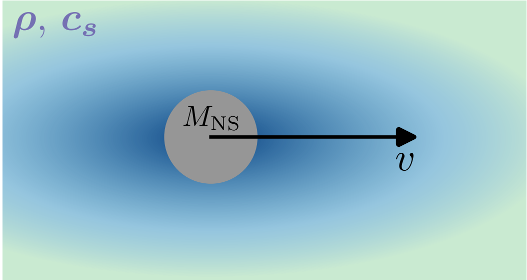
Accretion

The neutron star accretion rate can be estimated [Hoyle, Littleton (1939); Bondi (1952)]

$$\dot{M} \sim \frac{G^2 M_{\mathrm{NS}}^2 \rho}{(v^2 + c_s^2)^{3/2}} \sim 10^2\ M_{\mathrm{sun}}/\mathrm{year}$$
$$\sim 10^{25}\ \mathrm{kg/s}$$



[This is an approximation, I'll lift it in a few slides]

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Super-Eddington accretion

Usually, accretion is limited because [Eddington (1926)]

1. Inflow gains kinetic energy, heats up, and radiation pressure can compensate gravity.
2. That kinetic energy must go somewhere.

Eddington limit! $\sim 10^{-8} M_{\rm sun}/\mathrm{year}$ for a neutron star.

How can we violate it *by orders of magnitude* in common envelope?

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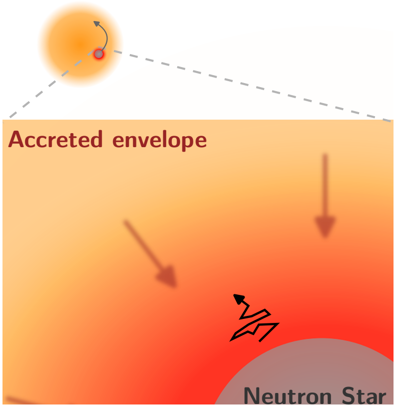
Super-Eddington accretion



Trapped light due to large inflow velocities

Basics well-understood since the 90s [Chevalier (1989); Houck & Chevalier (1991); Chevalier (1993)].

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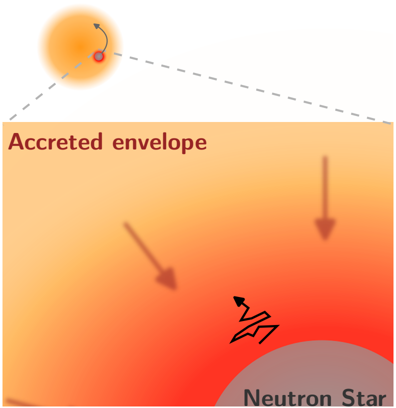
Super-Eddington accretion



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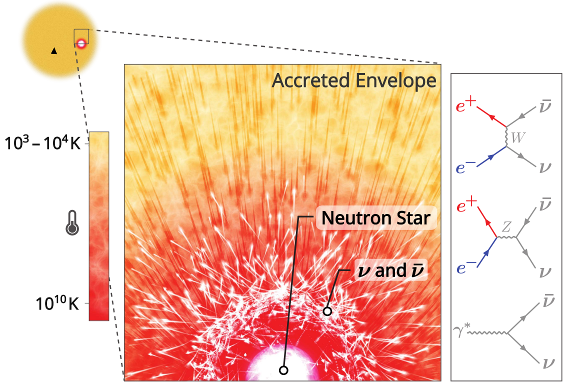

Neutrino cooling

Basics well-understood since the 90s [Chevalier (1989); Houck & Chevalier (1991); Chevalier (1993)].

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Super-Eddington accretion

The main uncertainty is the accretion rate. Simulations are **hard** (10 km neutron star vs 100 $R_{\mathrm{sun}} \sim 10^8\,\mathrm{km}$ giant)

- Angular momentum?
- How much of the energy is dissipated by neutrinos? Are jets formed?
- What are the details of the onset of super-Eddington accretion?

Fragos et al, 2019; Ivanova et al, 2012; Ricker et al, 2011; Houck & Chevalier, 1991; Brown, 1995; Ricket & Taam, 2012; Macleod & Ramirez-Ruiz, 2014; Macleod et al, 2017; Brown et al, 2000; ...

Yet recent 3D simulations still find super-Eddington accretion [Macleod & Ramirez-Ruiz, 2014; Hutchinson-Smith et al, 2023; Everson et al, 2023], with $\dot{M} \sim 0.1 M_{\mathrm{sun}}/\mathrm{year}$.

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Super-Eddington accretion

The main uncert … re **hard**
(10 km neutron s …

- Angular mo …
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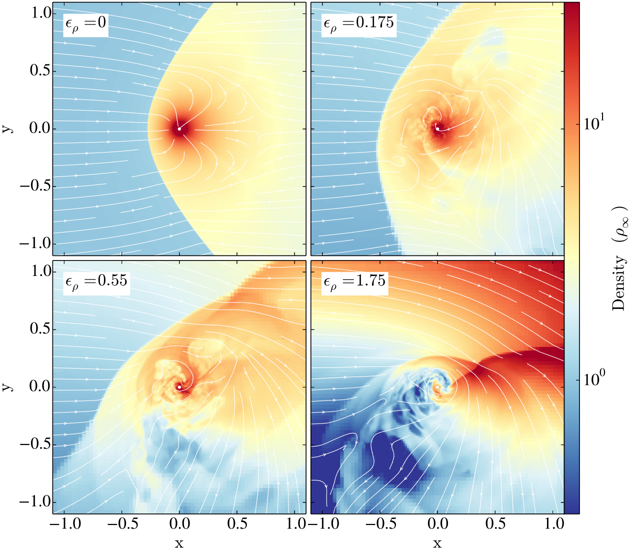
Fragos et al, 2019; Ivan … 91; Brown, 1995; Ricket
& Taam, 2012; Macleo … al, 2000; …



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Ramirez-Ruiz, 20 … on et al, 2023],
with $\dot{M} \sim 0.1 M_S$ …

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Other properties

- Duration? The neutron star momentum loss (due to drag) can be estimated by the linear momentum gained by the inflow, Macleod & Ramirez-Ruiz, 2014...

$$t \sim \textbf{month} \times \left(\frac{0.1\, M_{\rm sun}/\rm year}{\dot{M}} \right)$$

- Rate in the Milky Way? From X-ray binary catalogs, estimates are Ginat et al, 2019; Hutilukejiang et al, 2018

$$\tau \sim 10^{-2} - 1\, \textbf{century}^{-1}$$

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Wrapping up

Understanding common envelope is **key** to understand X-ray binaries, gravitational-wave sources...
But direct, unambiguous observational windows lack.

Super-Eddington accretion, hypothesized since the 90s, would involve

- Accretion rates $\sim 0.1 M_{\mathrm{sun}}/\mathrm{year}$.
- For about a month.
- $\sim 10^{-2} - 1\,\mathrm{century}^{-1}$ in our galaxy.
- With neutrinos playing a key role.

How can we look for this?

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Average neutrino energy

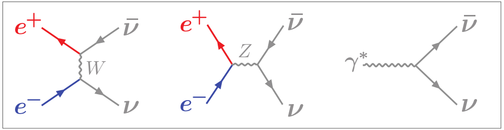
Esteban, Beacom, Kopp; 2310.19868

What are the properties of the neutrino signal?

Neutrinos dissipate the kinetic energy gained by the inflow. Simple energy conservation determines the signal properties.

$$\text{Inflow heating} \Rightarrow \frac{\mathrm{d}E}{\mathrm{d}t\mathrm{d}V} \sim \frac{G M_{\mathrm{NS}} \dot{M}}{r_{\mathrm{NS}}} \frac{1}{4\pi r_{\mathrm{NS}}^2 (r_{\mathrm{NS}}/2)}$$

$$\text{Neutrino-cooling} \Rightarrow \frac{\mathrm{d}E}{\mathrm{d}t\mathrm{d}V} \sim G_F^2 T^9. \text{ So } T \sim \left(\frac{\mathrm{d}E}{\mathrm{d}t\mathrm{d}V}\right)^{1/9}$$



Neutrino signal

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Esteban, Beacom, Kopp; 2310.19868

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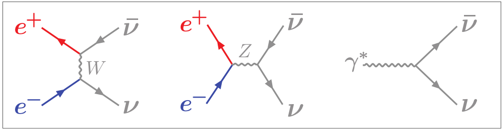

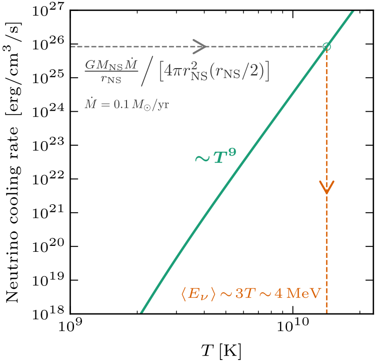

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Neutrino flux

Esteban, Beacom, Kopp; 2310.19868

Neutrinos dissipate the kinetic energy gained by the inflow. Simple energy conservation determines the signal properties.
$\langle E_\nu \rangle \sim 4\,\mathrm{MeV}$.

$$\frac{\mathrm{d}N_\nu}{\mathrm{d}t} \sim \frac{\mathrm{d}E/\mathrm{d}t}{\langle E_\nu \rangle} \sim \frac{G M_{\mathrm{NS}} \dot{M} / r_{\mathrm{NS}}}{\langle E_\nu \rangle} \sim 10^{50}\,\mathrm{neutrinos/s}$$

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Order-of-magnitude estimations

Esteban, Beacom, Kopp; 2310.19868

Neutrinos dissipate the kinetic energy gained by the inflow. Simple energy conservation determines the signal properties.
$\langle E_\nu \rangle \sim 4\,\mathrm{MeV}$, 10^{50} neutrinos/s.

At 10 kpc, $\phi_\nu \sim 10^4\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$.
Is it observable? At $\sim$ MeV energies, the most efficient detection channel is

$$\bar{\nu}_e + p \Rightarrow n + e^+$$

with $\sigma \sim 10^{-42}\,\mathrm{cm}^2$. $\phi \times \sigma \times N_{\mathrm{targets}} \sim 100\,\mathrm{events/few\ months}$ at Super-Kamiokande! (Of course, beware of backgrounds!)

Neutrino signal

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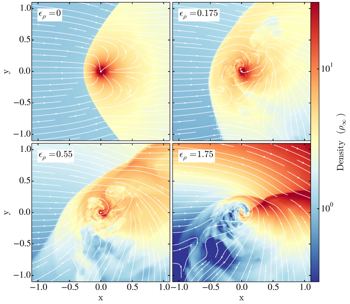
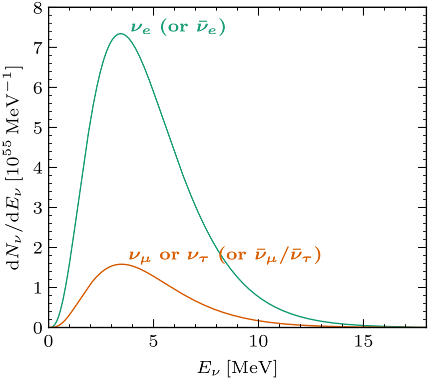
Sharpening up the predictions

Up to now, I've only given (robust) order-of-magnitude estimations.

We sharpened them via simulation. Main input is accretion rate [$\langle E_\nu \rangle \propto \dot{M}^{1/9}$; $\phi_\nu \propto \dot{M}$], that we took from the 3D simulation Macleod & Ramirez-Ruiz, 2014 [$\dot{M} \sim 0.1\, M_{\rm sun}/\mathrm{year}$].
Our code is publicly available! github.com/ivan-esteban-phys/common-envelope-thermal





- 3-months integrated
- $10^{50}\nu/\mathrm{s} \times 3\,\mathrm{months} \sim 10^{56}\nu$
- Very well approximated by FD, $T \sim 1.6\,\mathrm{MeV}$ ($\langle E_\nu \rangle \sim 5\,\mathrm{MeV}$).
- No oscillations in this plot, although in our results we included adiabatic oscillations (factor of few impact).

Neutrino signal

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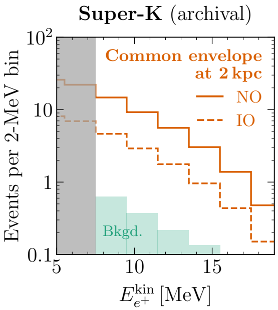
Detector signals

Archival Super-Kamiokande data: e^+ and γ from neutron capture on H.



Collaboration-estimated background from DSNB search.

Neutrino signal

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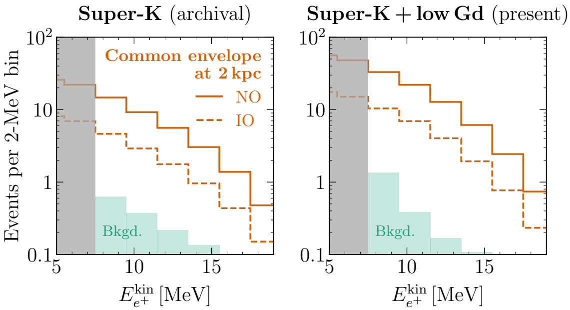
Detector signals

Super-Kamiokande with low Gd: e^+ and γ from neutron capture on Gd.



Similar, collaboration-estimated, background sources, but higher efficiency.

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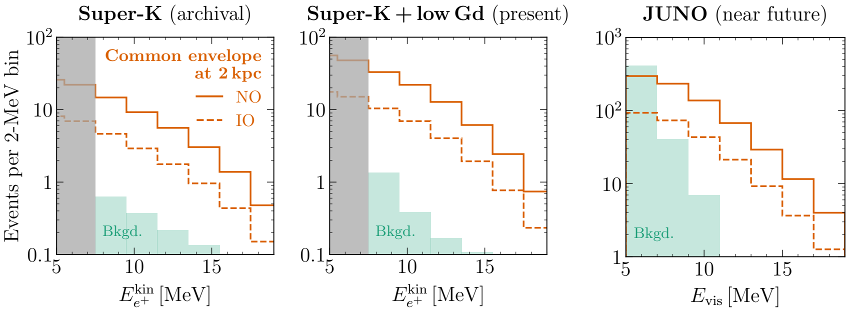
Detector signals

JUNO: e^+ and γ from neutron capture.



Collaboration-estimated background. Large efficiency due to scintillator.

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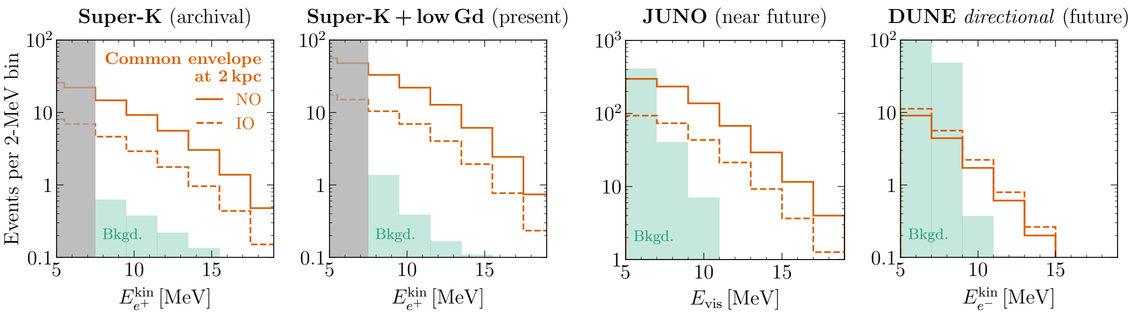
Detector signals

DUNE: ν on e^-, directional.



Background estimates from solar neutrino studies (Capozzi et al, 2018; Zhu, Li & Beacom, 2019).

Neutrino signal

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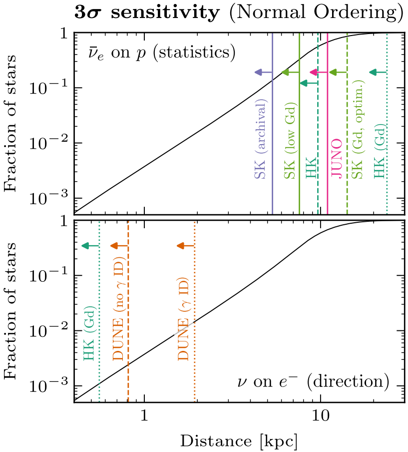
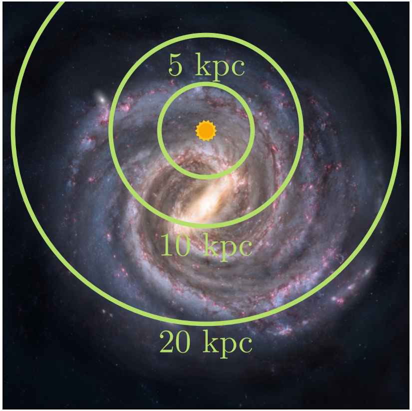
Distance reach

Improvable! (More Gd, dedicated background reduction strategies . . .)





For Inverted Ordering, currently disfavored by ∼ 2–3 sigma, distance reach worsens by a factor ∼ 2.

Neutrino signal

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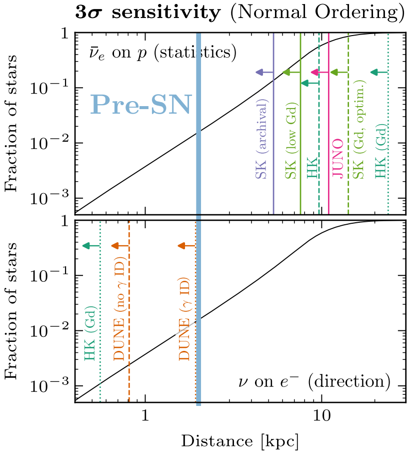
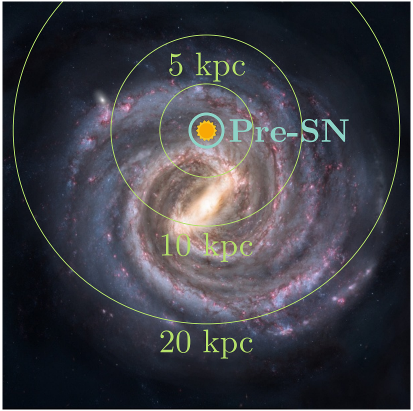
Distance reach

Improvable! (More Gd, dedicated background reduction strategies ...)





For Inverted Ordering, currently disfavored by $\sim$ 2–3 sigma, distance reach worsens by a factor $\sim$ 2.

Summary

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- Neutron-star common-envelope is key to understand many binary systems. But it has never been observed unambiguously.
- If accretion is super-Eddington, cooling proceeds emitting neutrinos.
- A Milky Way event ($\sim 10^{-2}\text{–}1\,\mathrm{century}^{-1}$) would produce **detectable**, **months-long**, **MeV** neutrino signals.
  The *third* MeV astrophysical neutrino source, after the Sun and supernovae. It is rare, but **we won't see it unless we look for it!**

Outlook

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In case of a detection,

- Common-envelope would be observationally established.
- Super-Eddington accretion would be observationally established.
  Even a non-detection with an electromagnetic/gravitational wave counterpart would be useful!

What's next?

- *Astrophysics*: more simulation. Accretion on white dwarfs?
- *Experiments*: dedicated searches, *including archival data*.
- *Theory*: neutrino properties? Particle physics?

We extensively detail how to predict the neutrino flux.