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CARLSBERG FOUNDATION

THE DIFFUSE SUPERNOVA NEUTRINO BACKGROUND FROM

# MAGNETOROTATIONAL CORE COLLAPSES


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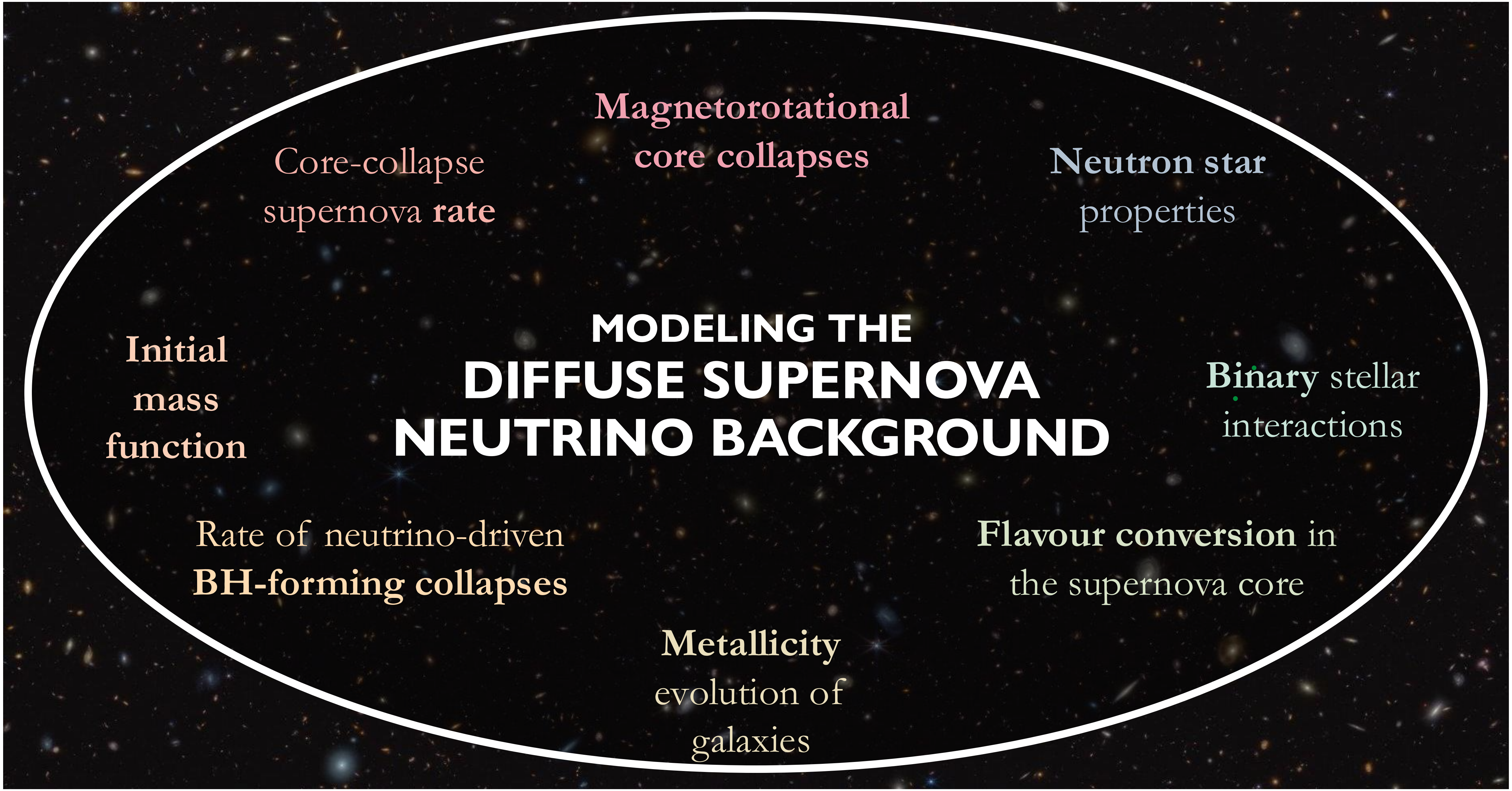
Towards the Detection of Diffuse Supernova Neutrinos: What will we see? What can we learn?

17th September 2024, MITP

Magnetorotational core collapse could contribute significantly to the diffuse supernova neutrino background.

From **present** and **future neutrino data**, numerical **simulations** and complementary **electromagnetic probes**, we can learn about the properties of the population of **magnetorotational core collapses**.


Magnetorotational core collapses
Core-collapse supernova rate
Neutron star properties
Initial mass function
MODELING THE DIFFUSE SUPERNOVA NEUTRINO BACKGROUND
Binary stellar interactions
Rate of neutrino-driven BH-forming collapses
Flavour conversion in the supernova core
Metallicity evolution of galaxies

Magnetorotational
core collapses

Core-collapse
supernova **rate**

**Neutron star**
properties

## MODELING THE
# DIFFUSE SUPERNOVA NEUTRINO BACKGROUND

**Initial mass function**

**Binary** stellar
interactions

Rate of neutrino-driven
**BH-forming collapses**

**Flavour conversion** in
the supernova core

**Metallicity**
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# MAGNETOROTATIONAL CORE COLLAPSES: **PROTOMAGNETARS & SPINARS**

**Protomagnetar:**

a post-collapsed core that develops magnetar magnetic field strengths $\geq O(10^{15})$ G and has an associated magnetar phenomenology.

**Spinar:**

when the protoneutron star mass grows rapidly due to accretion and it **collapses into a BH** after a few seconds

Morrison P., Cavaliere A., Proceedings of a *Study Week on Nuclei of Galaxies*

**Neutrino emission**

**How is the neutrino emission from magnetorotational core collapses?**

# NEUTRINO EMISSION
## FROM NEUTRINO-DRIVEN CORE COLLAPSES

- Spherically symmetric (1D) hydrodynamical simulations without muons
- Two neutrino-driven supernovae (11.2 $M_\odot$ and 27 $M_\odot$) and one neutrino-driven BH-forming collapse (40 $M_\odot$, model s4027b2)
- Lattimer and Swesty equation of state (K = 220 MeV)

Garching core-collapse supernova archive,
Mirizzi et al. Riv. Nuovo Cim. 39, 1 (2016),
Møller et al. JCAP 05 (2018) 066, Suliga et al. PRD 105 (2022) 4, 043008,
Ibanez-Ballesteros et al. PRD 107 (2023) 2, 023017, Martinez-Mirave et al. JCAP 05 (2024) 002

# NEUTRINO EMISSION

## FROM MAGNETOROTATIONAL CORE COLLAPSES

- 3D simulations combining special relativistic magnetohydrodynamics and a spectral two-moment (M1) neutrino transport.

- Models with mass at the zero-age main sequence time:

  $M_{ZAMS}$ = $5M_{\odot}$ (PM), $8M_{\odot}$ (PM), $13M_{\odot}$ (PM), $17M_{\odot}$ (PM), $20M_{\odot}$ (PM), $26M_{\odot}$ (SP), and $30M_{\odot}$ (SP).

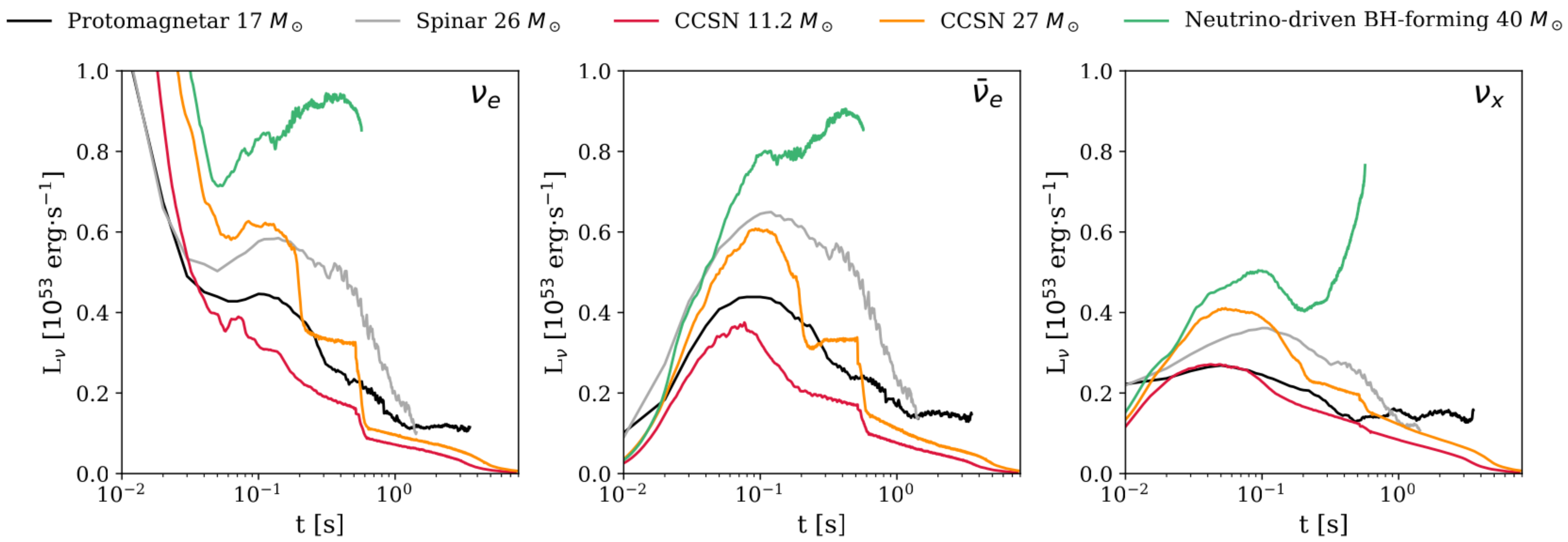
- Enhanced rotational mixing, leading to **chemically homogeneous evolution**

- SFHo EoS and include the most relevant neutrino-matter reactions

Obergaulinger et al. MNRAS 512 (2022) 2, 2489-2507, Aguilera-Dena et al. Astrophys. J. 858, 115 (2018)

# NEUTRINO EMISSION
## FROM MAGNETOROTATIONAL CORE COLLAPSES

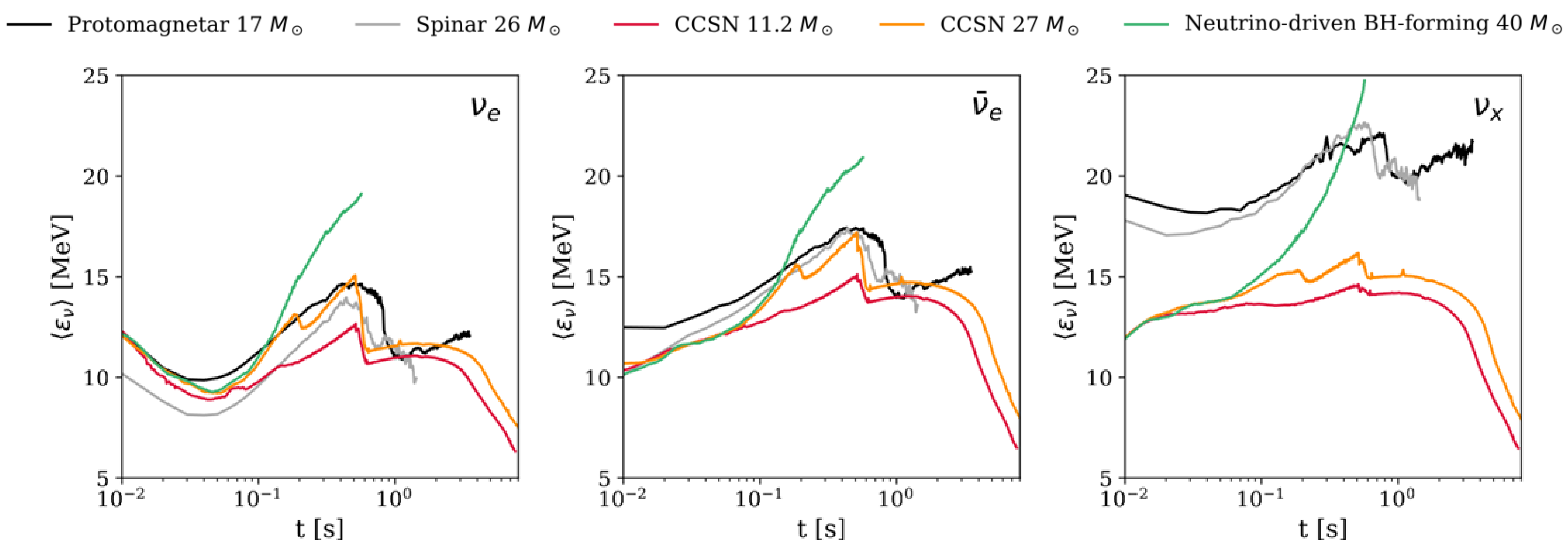
All cores produce delayed explosions.
Shock revival is powered by neutrino heating and magnetorotational stresses.



# NEUTRINO EMISSION
## FROM MAGNETOROTATIONAL CORE COLLAPSES

Neutrino mean energies exhibit a characteristic hierarchy

$$\langle \varepsilon_{\nu_e} \rangle < \langle \varepsilon_{\bar{\nu}_e} \rangle < \langle \varepsilon_{\nu_x} \rangle .$$




Given that the neutrino luminosities are similar to CCSNe and that the mean energies of non-electron flavour neutrinos are large...

**How do magnetorotational core collapses modify the DSNB?**

# MODELING
## THE DIFFUSE SUPERNOVA NEUTRINO BACKGROUND

We assume the redshift dependence of the rate follows the **star formation history**

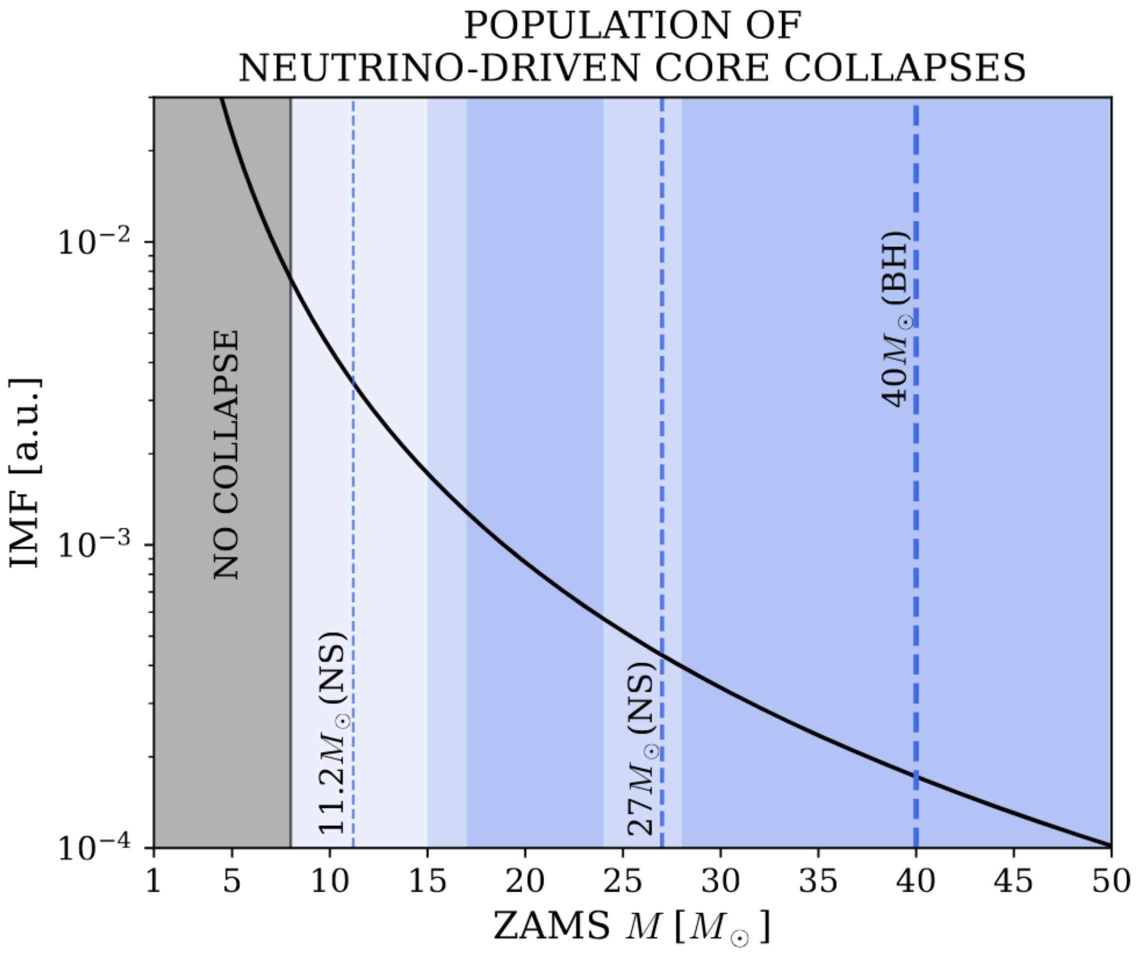
Horiuchi et al. , Phys. Rev. D 79, 083013 (2009)

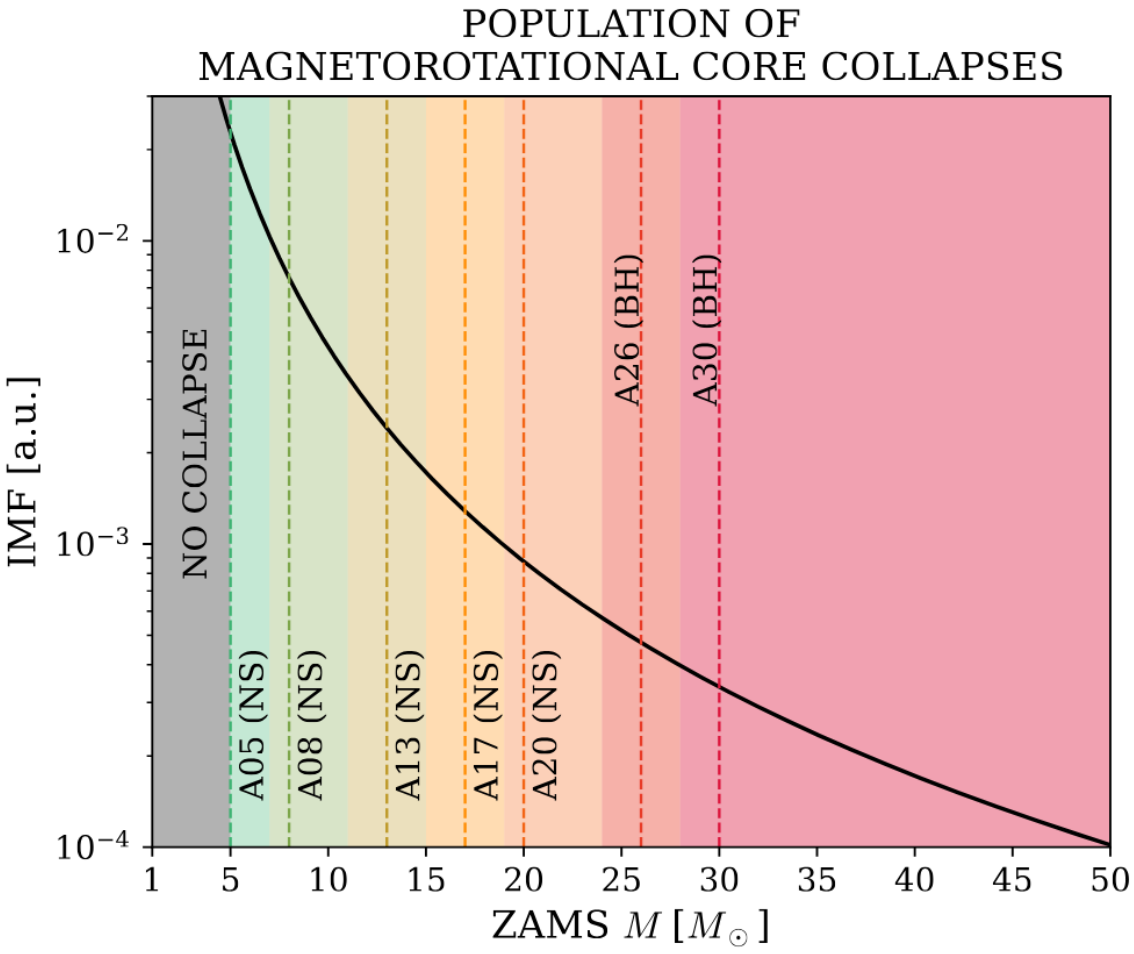
We consider a **Salpeter IMF**, both for neutrino-driven and magnetorotational core-collapses:

- Neutrino-driven core collapses for masses between 8 $M_\odot$ and 125 $M_\odot$
- **Magnetorotational core collapses** for masses between **5 $M_\odot$** and 125 $M_\odot$

# MODELING

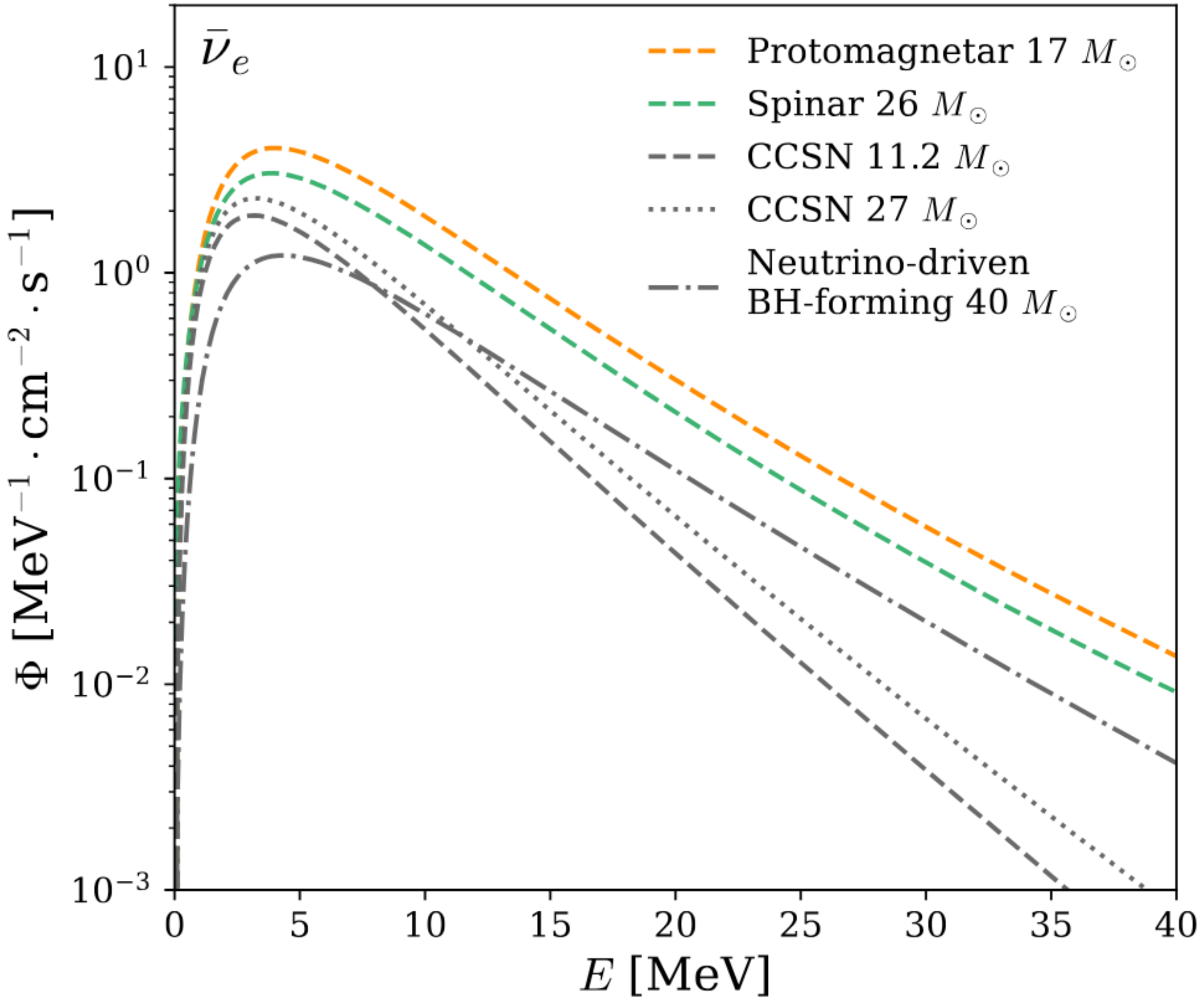
## THE DIFFUSE SUPERNOVA NEUTRINO BACKGROUND



# MODELING

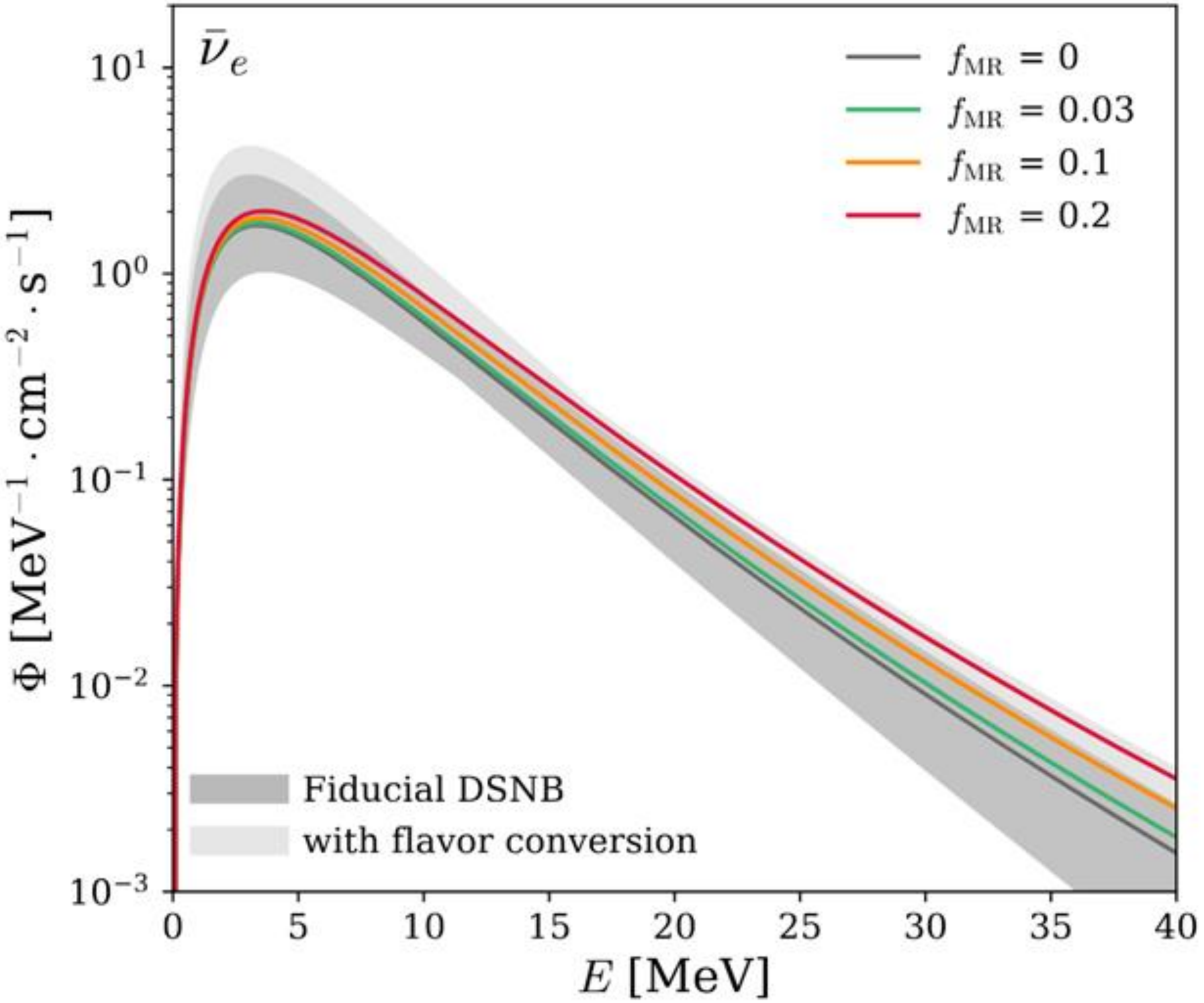
## THE DIFFUSE SUPERNOVA NEUTRINO BACKGROUND




The high-energy tail of the flux from magnetorotational core collapses has a soft slope, as neutrino-driven black hole-forming core collapses.

# MODELING

## THE DIFFUSE SUPERNOVA NEUTRINO BACKGROUND




Let us introduce the fractional contribution from magnetorotational core collapse, $f_{\mathrm{MR}}$,

$$\Phi_{\mathrm{diffuse}} = (1 - f_{\mathrm{MR}})\Phi_{\nu\mathrm{CCSN}} + f_{\mathrm{MR}}\Phi_{\mathrm{MR}}$$

A non-zero fraction of spinars and protomagnetars would change the tail of the DSNB.

# WHAT DO WE KNOW NOW?

The fraction of fast-rotating Be stars could be considered as an upper bound on the fraction of massive stars expected to form protomagnetars.

(4.4 ± 0.9)% for stars with mass between 2–16 $M_\odot$

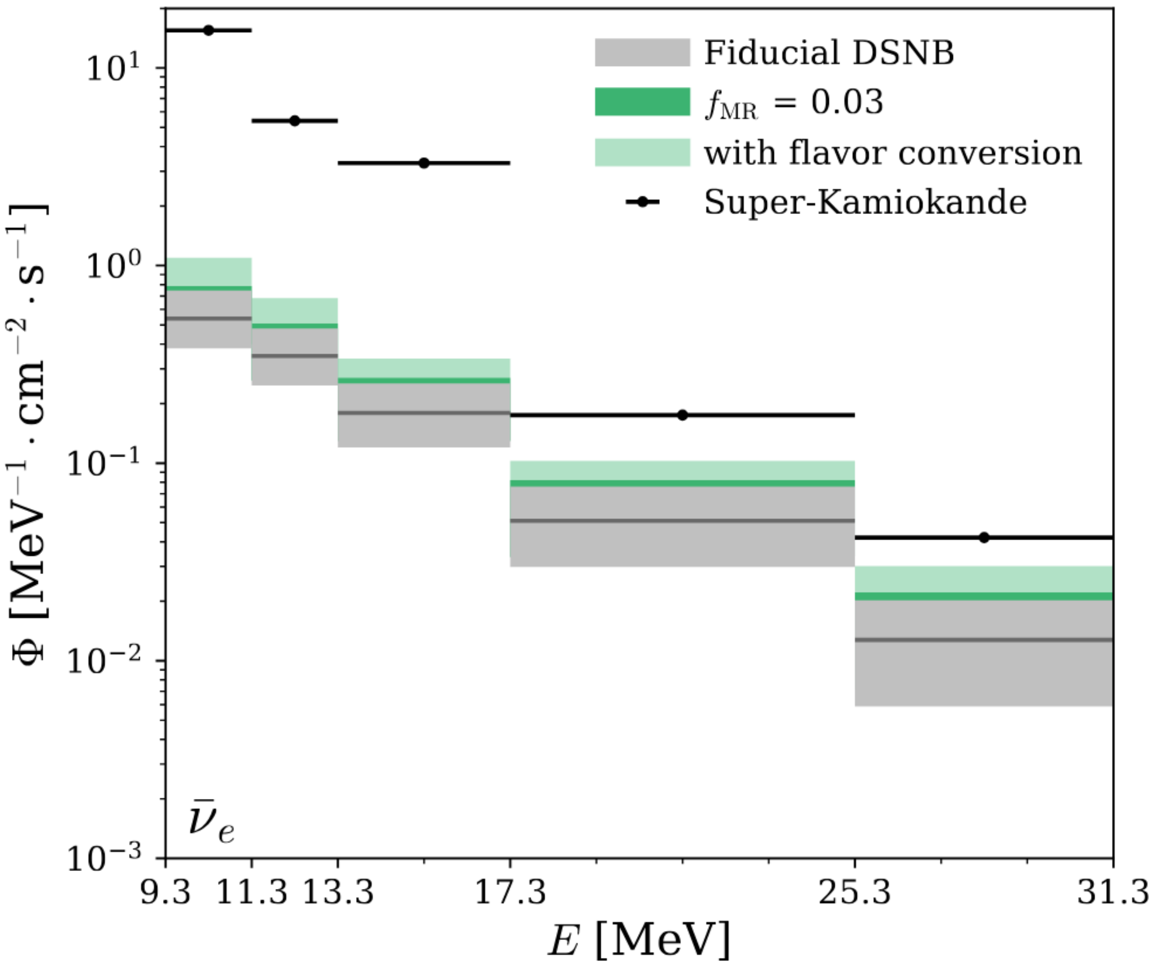
(32.8 ± 3.4)% for stars with mass above 15–16$M_\odot$

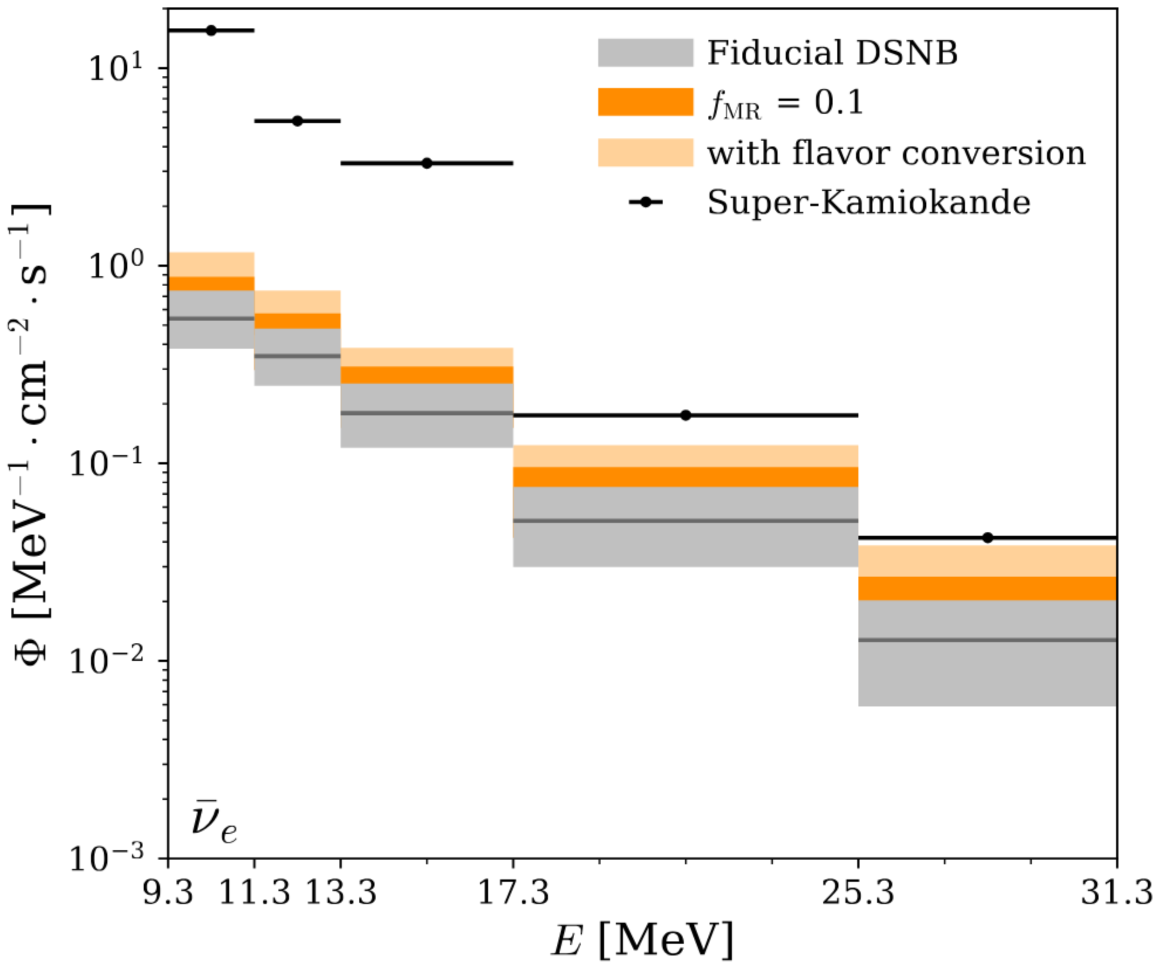
Navarrete et al. Astrophys. J. 970, 113 (2024)

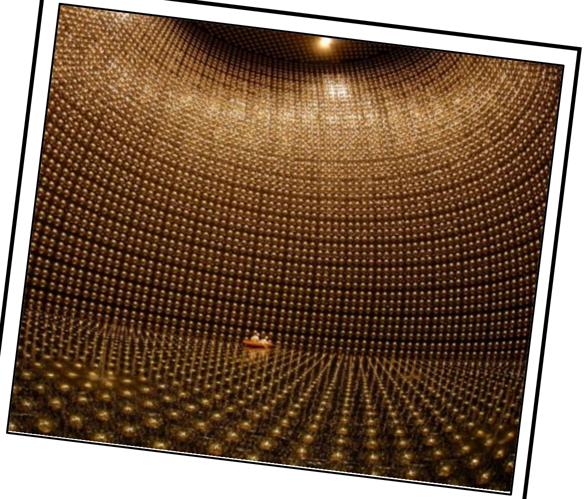
**The IMF-weighted fraction in the range [5 $M_\odot$, 26 $M_\odot$] is ~ 8% .**

# WHAT DO WE KNOW NOW?

Harada, Neutrino 2024



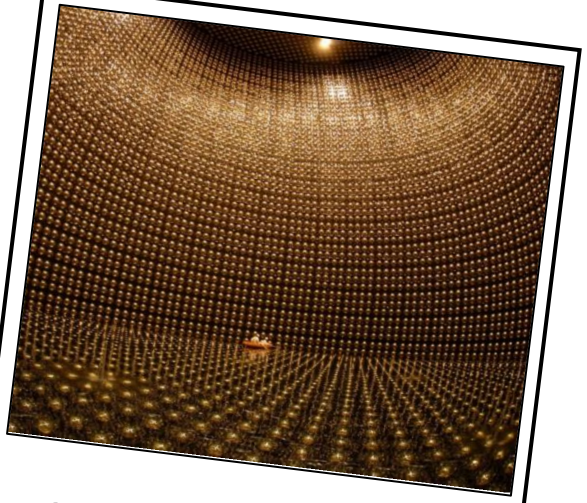





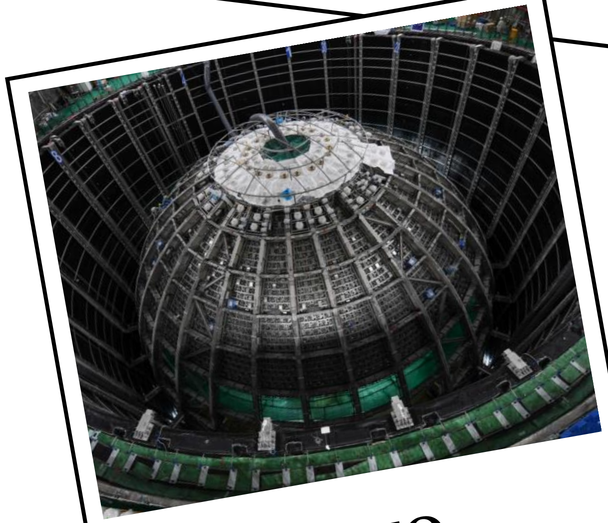
Super-Kamiokande

# WHAT DO WE KNOW NOW?

**Super-Kamiokande** data already excludes a **fraction of magnetoratoational core collapses** larger **13%** and **full flavor conversion** for the **highest local star formation rate**, and for a fixed fraction of BH-forming collapses of 30%.



Super-Kamiokande



JUNO

# WHAT WILL WE LEARN IN THE NEAR FUTURE?

**A non-zero fraction of magnetorotational core collapses could lead to an early detection of the DSNB.**

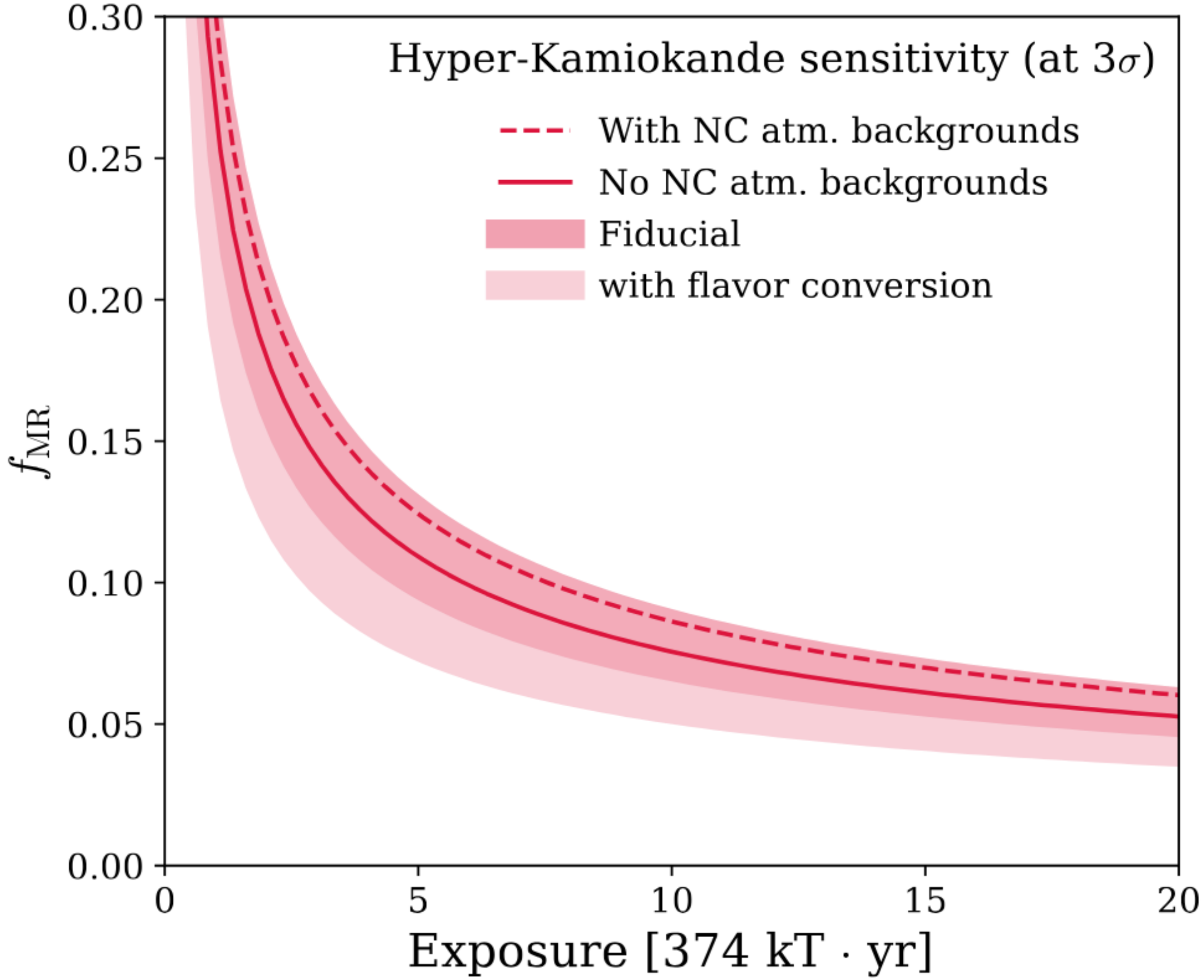
For a fraction around 10%, the background-only hypothesis could be rejected 2-4 years earlier than for $f_{\mathrm{MR}} = 0$ at Super-Kamiokande and JUNO, i.e than for our standard DSNB prediction.

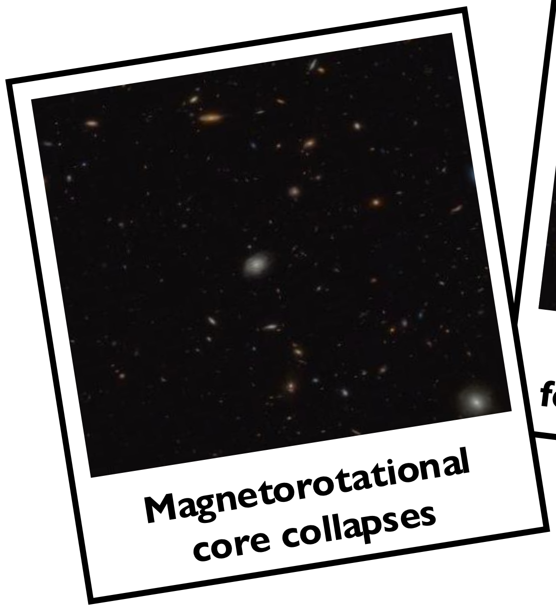
# AND IN THE LONG TERM?

Fractions of magnetorotational core collapses larger than 7% could be measured after 20 years of data taking at Hyper-Kamiokande. * $

*with Gadolinium and two-tanks

$assuming the fraction of neutrino-driven BH-forming collapses is known







Both the **fraction of neutrino-driven BH-forming collapses** and the **fraction of magnetorotational core collapses** enhance the high-energy tail of the spectrum.

**Can we break that degeneracy?**

# COMPLEMENTARY CONTRAINTS

Observed **rate** of core-collapse and stripped-envelope supernovae vs predicted rate of neutrino-driven CCSN, protomagnetars and spinars

**Palomar Transient Facility**

$f_{MR}$ - $f_{\nu BH}$

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Observed **rate** of core-collapse and stripped-envelope supernovae vs predicted rate of neutrino-driven CCSN, protomagnetars and spinars

**Palomar Transient Facility**

$f_{MR}$ - $f_{\nu BH}$

The observed **rate of stripped-envelope supernovae** can be compared to the predicted rate of magnetorotational core-collapses

**Palomar Transient Facility**

$f_{MR}$

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**Palomar Transient Facility**
$f_{MR}$ - $f_{\nu BH}$

Searches for **disappearing luminous stars** vs predicted rate of neutrino-driven BH-forming collapses

**Neustadt et al. (2021)**
$f_{\nu BH}$

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$f_{MR}$

Searches for **disappearing luminous stars** vs predicted rate of neutrino-driven BH-forming collapses

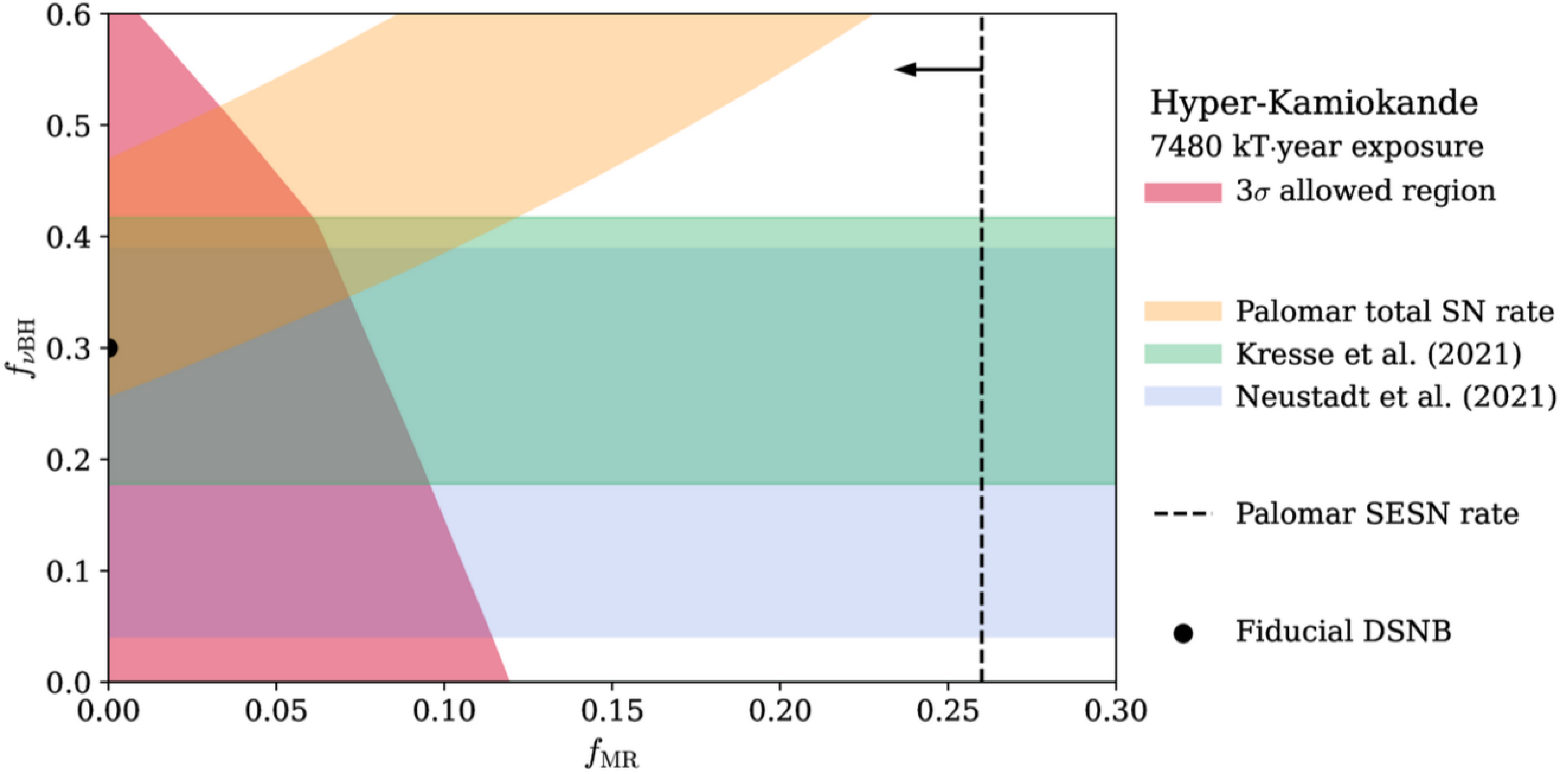
**Neustadt et al. (2021)**
$f_{\nu BH}$

1D **simulations** of neutrino-driven engines for single-star and helium-star progenitor

**Kresse et al. (2021)**
$f_{\nu BH}$

Rate of long gamma-ray bursts and superluminous supernovae (with some caveats)

# COMPLEMENTARY CONTRAINTS



Magnetorotational core collapse could contribute significantly to the diffuse supernova neutrino background.

From **present** and **future neutrino data**, numerical **simulations** and complementary **electromagnetic probes**, we can learn about the properties of the population of **magnetorotational core collapses**.


Can we identify signatures of Beyond the Standard Model (BSM) physics given the astrophysical uncertainties?

If so, could we discriminate between different BSM predictions?

**Miller MacDonald,** Pablo Martinez-Mirave, and Irene Tamborra

**To appear soon**

**Diffuse Neutrino Background from Magnetorotational Stellar Core Collapses**

Pablo Martinez-Mirave, Irene Tamborra, Miguel Angel Aloy, and Martin Obergaulinger

arxiv: 2409.09126 [astro-ph.HE]

# WHAT WILL WE LEARN IN THE NEAR FUTURE?