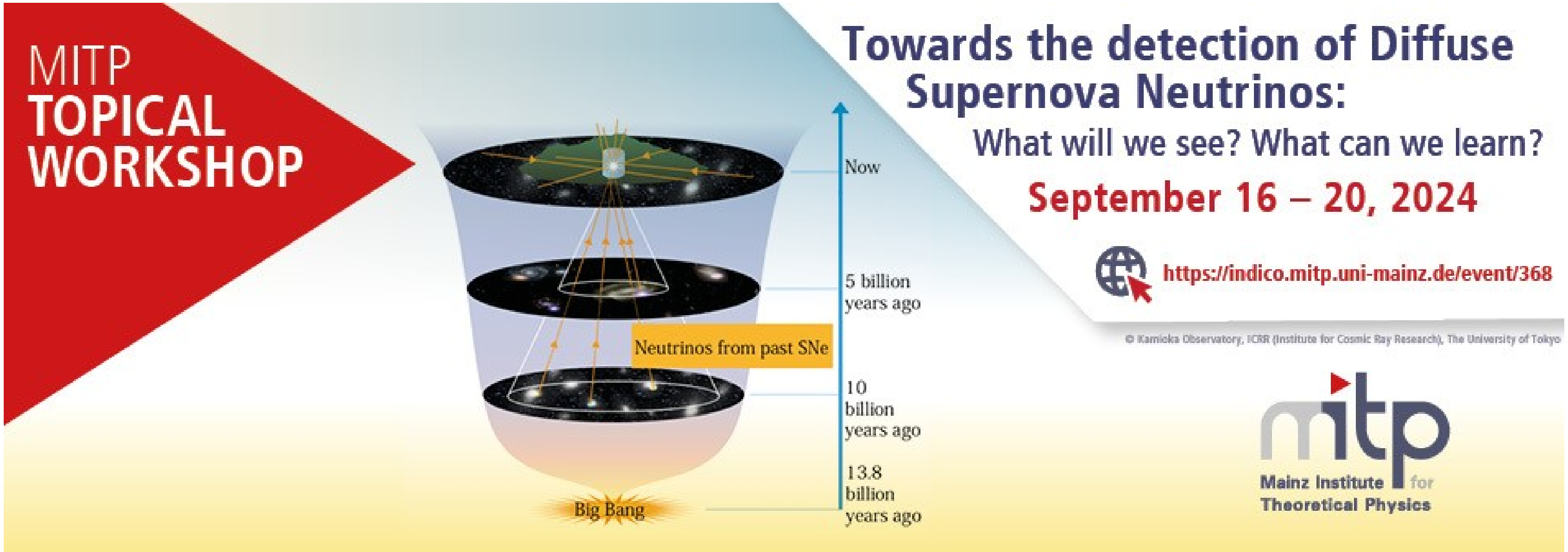
Status and prospects of DSNB modeling

MAX PLANCK INSTITUTE
FOR ASTROPHYSICS

Daniel Kresse, 2024-09-17



MITP
TOPICAL
WORKSHOP

Towards the detection of Diffuse Supernova Neutrinos:

What will we see? What can we learn?

September 16 – 20, 2024

https://indico.mitp.uni-mainz.de/event/368

© Kamioka Observatory, ICRR (Institute for Cosmic Ray Research), The University of Tokyo

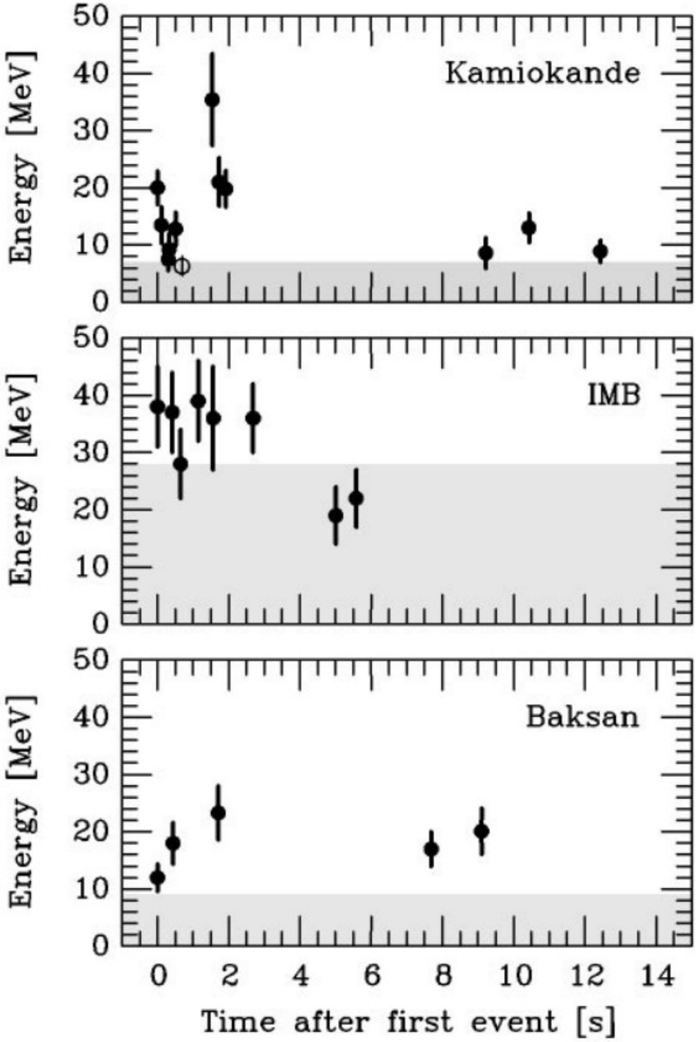
Mainz Institute for Theoretical Physics

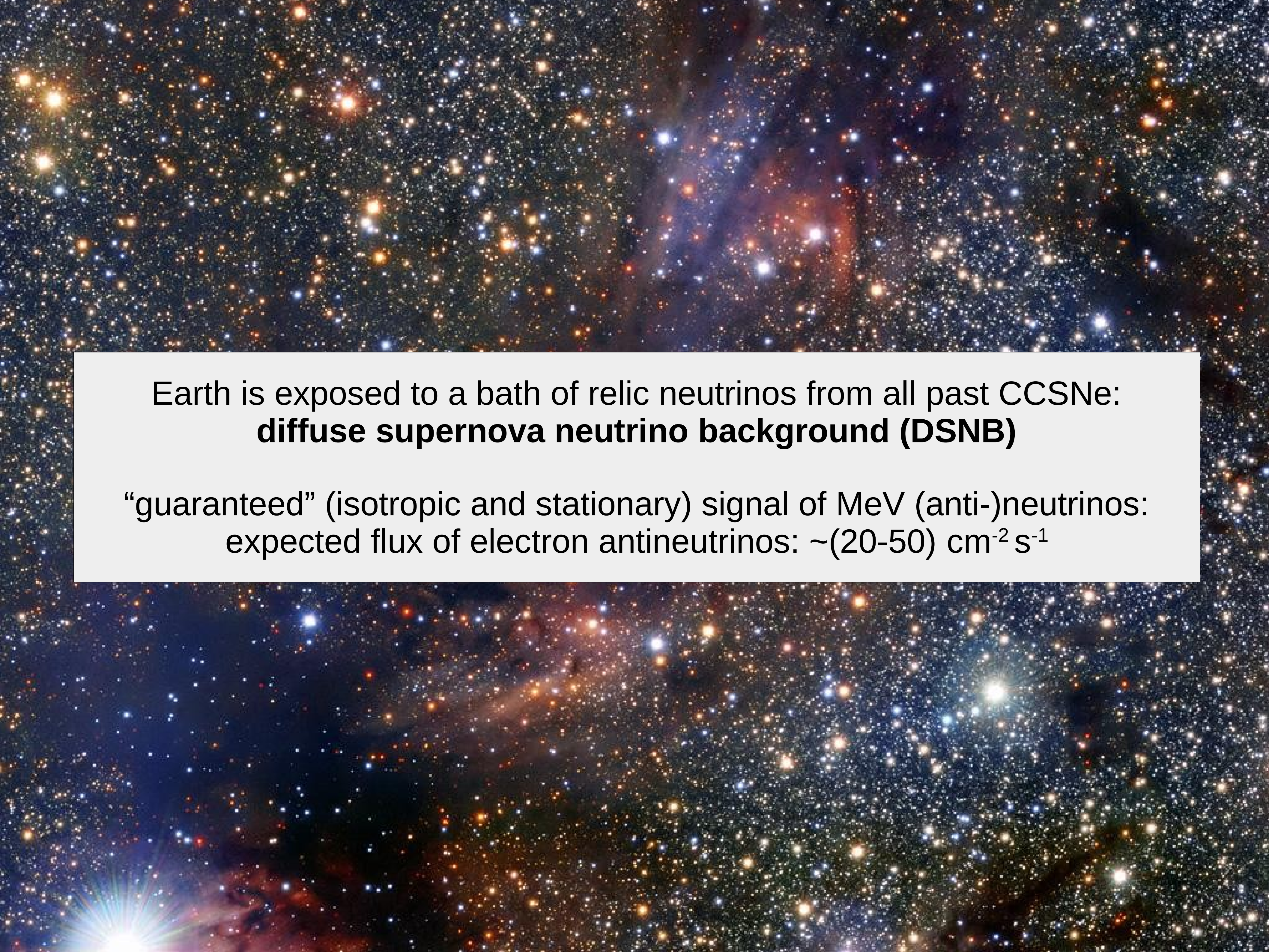
Collaborators: Thomas Janka, Thomas Ertl, Malte Heinlein, Robert Bollig, Tobias Melson, Alexander Summa, et al.

SFB 1258 Neutrinos Dark Matter Messengers

- core-collapse of massive stars (above $\sim 9\,\mathrm{M}_\odot$) → formation of a compact remnant (NS/BH)
- $\sim 99\,\%$ of released gravitational binding energy (several $10^{53}\,\mathrm{erg}$) radiated in the form of neutrinos and antineutrinos in an $\sim \mathcal{O}(10\,\mathrm{s})$ long signal → **SN 1987A**

- waiting for next galactic/nearby SN with high expected event statistics (e.g. Super-K, IceCube)
- **however:** (1.9 ± 1.1) CCSNe per century in the Milky Way (Diehl et al. 2006)

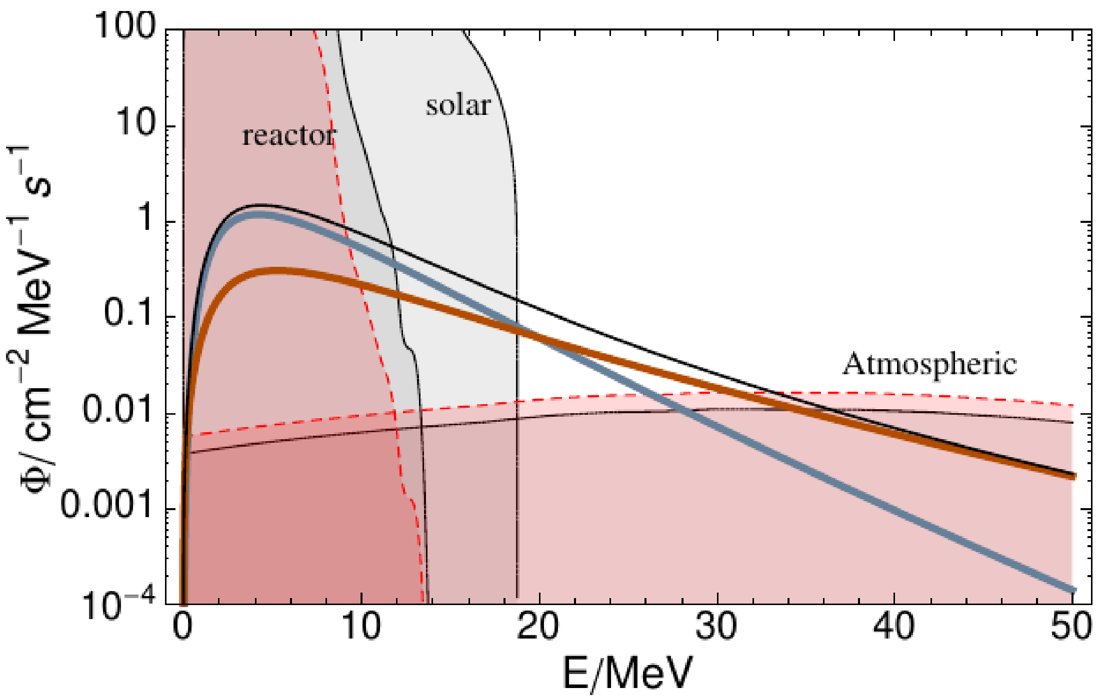

Raffelt (1999)



Earth is exposed to a bath of relic neutrinos from all past CCSNe:
diffuse supernova neutrino background (DSNB)

“guaranteed” (isotropic and stationary) signal of MeV (anti-)neutrinos:
expected flux of electron antineutrinos: ~(20-50) cm^{-2} s^{-1}

DSNB Detection Prospects

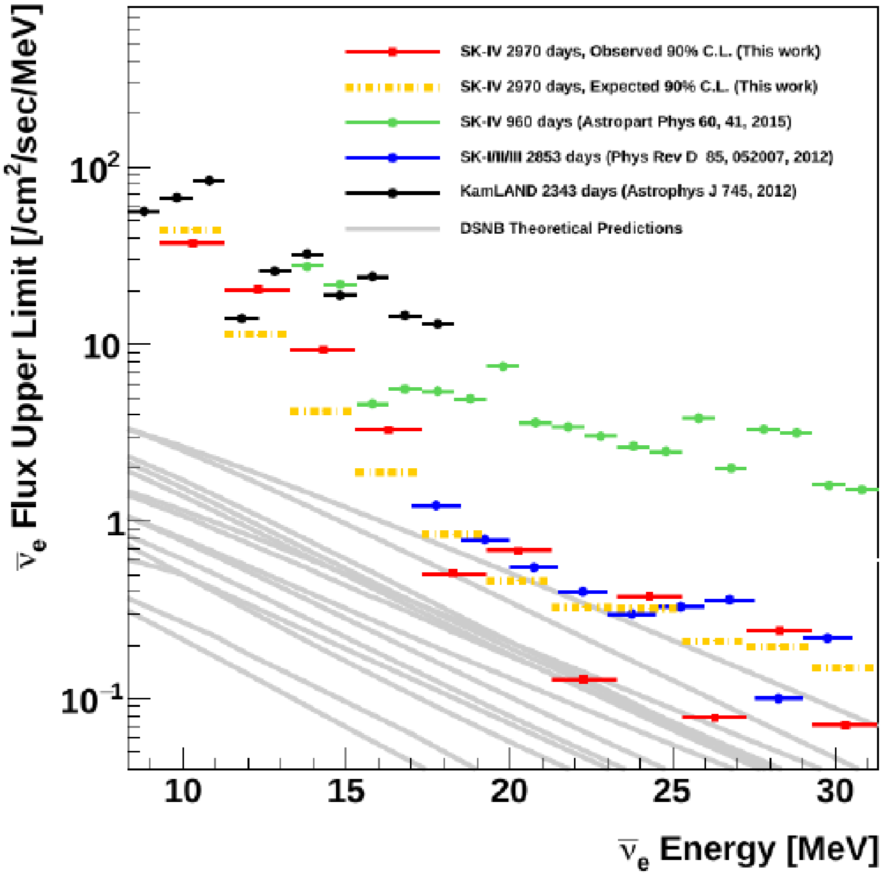


detection window:
$\sim 10 - 30\,\mathrm{MeV}$

Keehn & Lunardini 2012, PhRvD, 85, 043011

- upper flux limits (e.g., Abe et al. 2021) close to theoretical predictions → excellent discovery prospects within next decade (e.g., SK-Gd, JUNO)

DSNB Detection Prospects (Super-K flux limit)

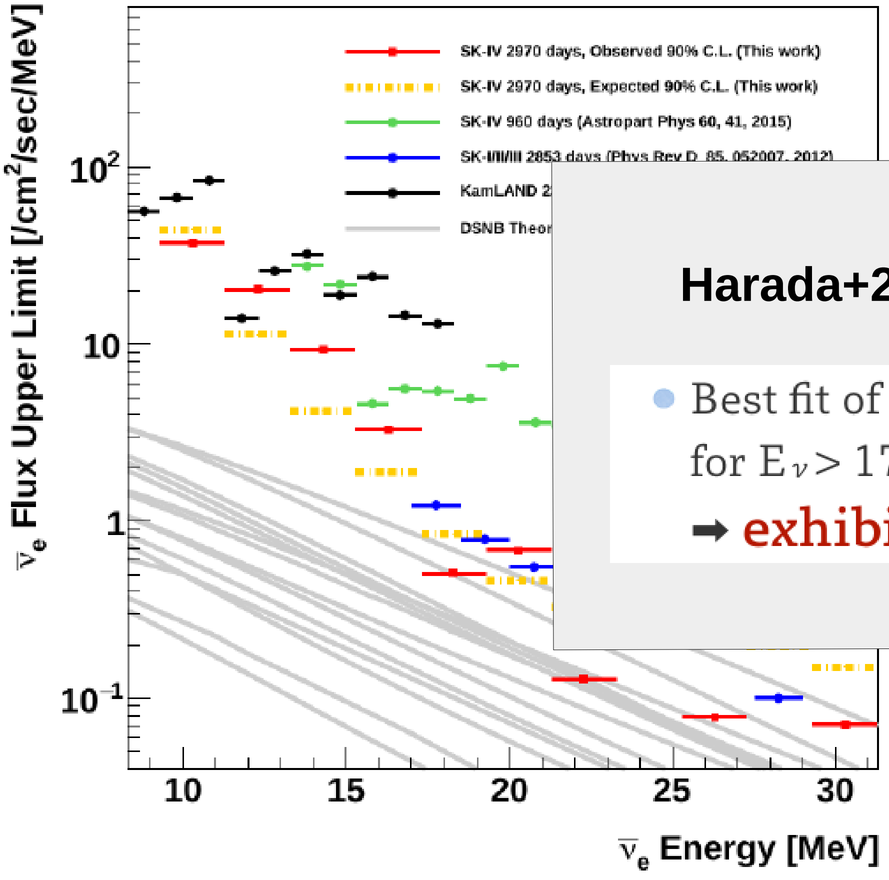


- $\Phi(E > 17.3\,\mathrm{MeV}) \lesssim 2.7\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- $\sim$ a factor of 2 above theoretical predictions
- some models already disfavored / excluded

Abe et al. 2021, arXiv:2109.11174

- upper flux limits (e.g., Abe et al. 2021) close to theoretical predictions → excellent discovery prospects within next decade (e.g., **SK-Gd**, **JUNO**)
- **theoretical models** will be needed to interpret future measurements

DSNB Detection Prospects (Super-K flux limit)



Harada+24 (SK-Gd):

- Best fit of whole SK observation is $\mathbf{1.4^{+0.8}_{-0.6}}$ **cm^{-2} s^{-1}** for $E_\nu > 17.3$ MeV
  ➡ exhibit ~2.3 σ excess!!

Abe et al. 2021, arXiv:2109.11174

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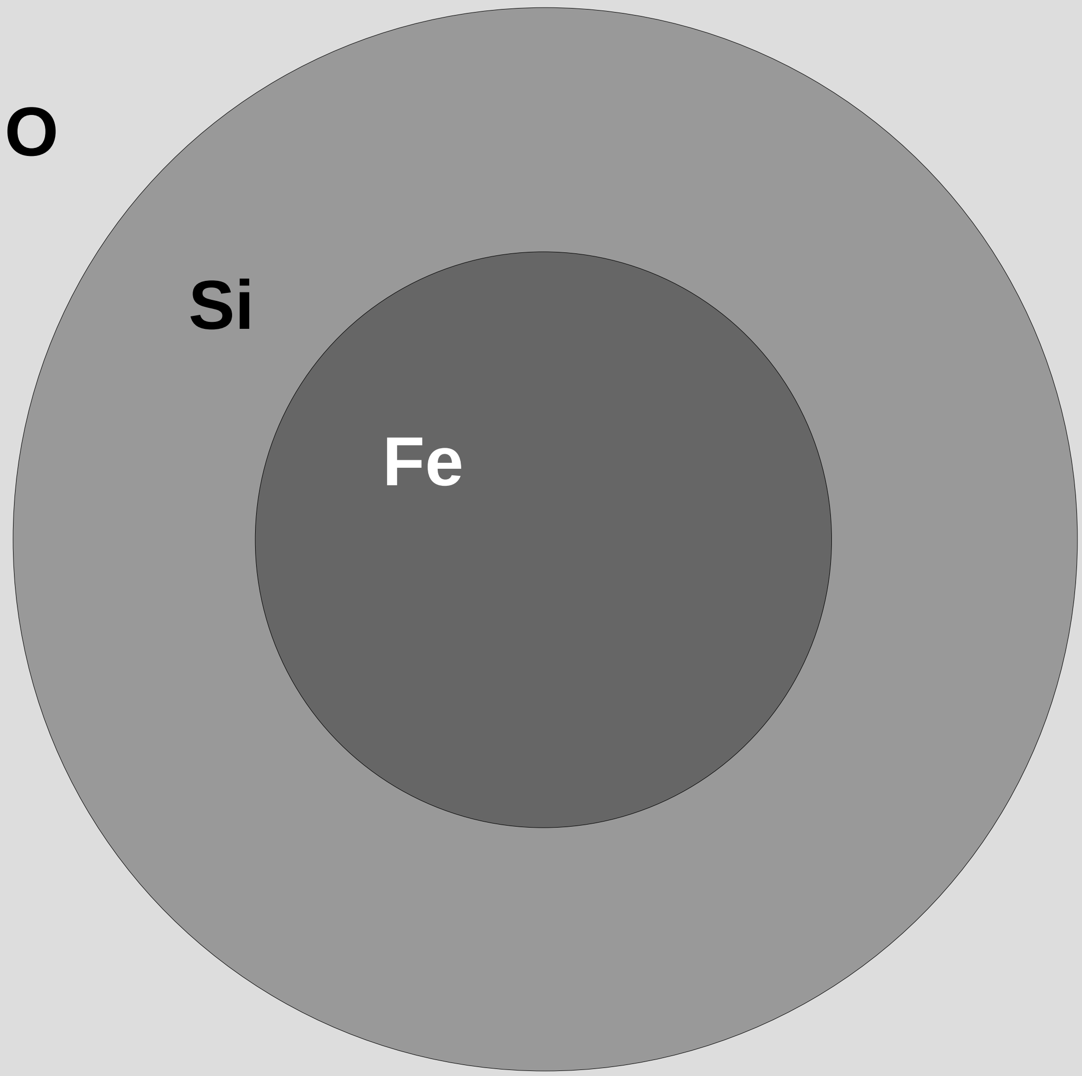
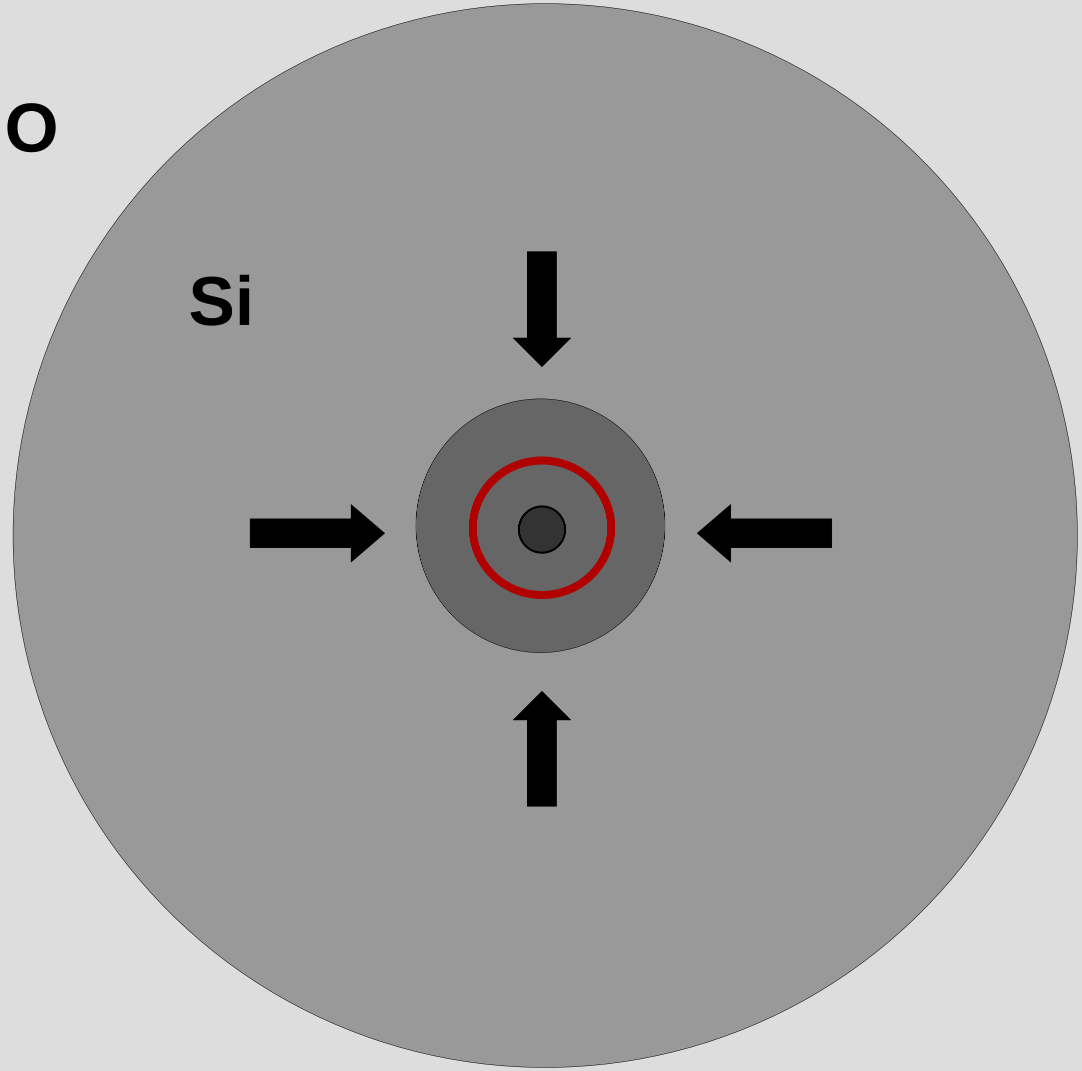
Core-collapse Supernovae in a Nutshell



- **Onion-shell-like structure**
- **Stellar radius: ~10^8-10^9 km**
- **Iron (Fe) core: ~10^3 km**

Core-collapse Supernovae in a Nutshell



- Onion-shell-like structure
- Stellar radius: $\sim 10^8$-10^9 km
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- Fe core collapses to a Proto-Neutron Star (PNS)
- Core bounce launches a shock wave (stagnates)

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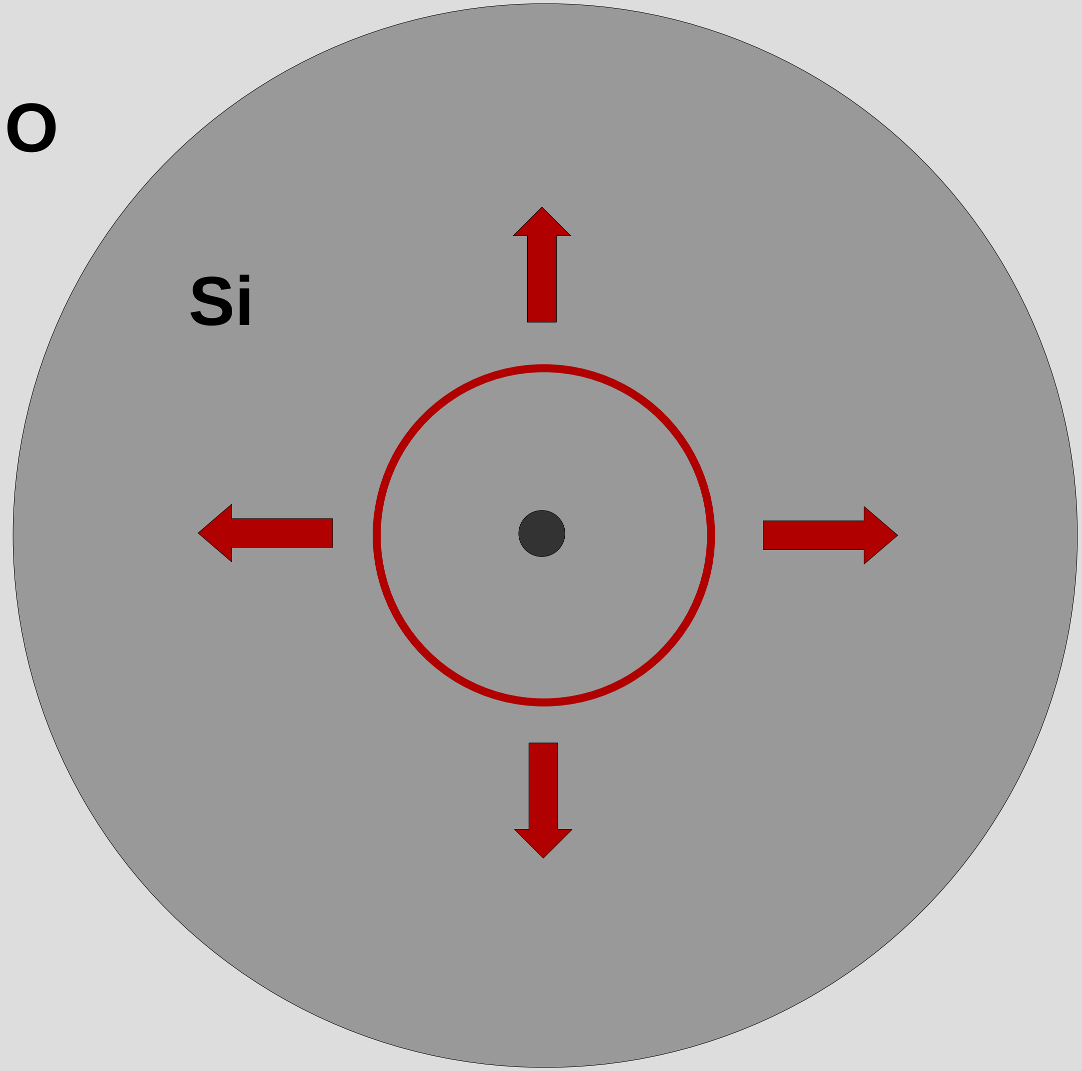

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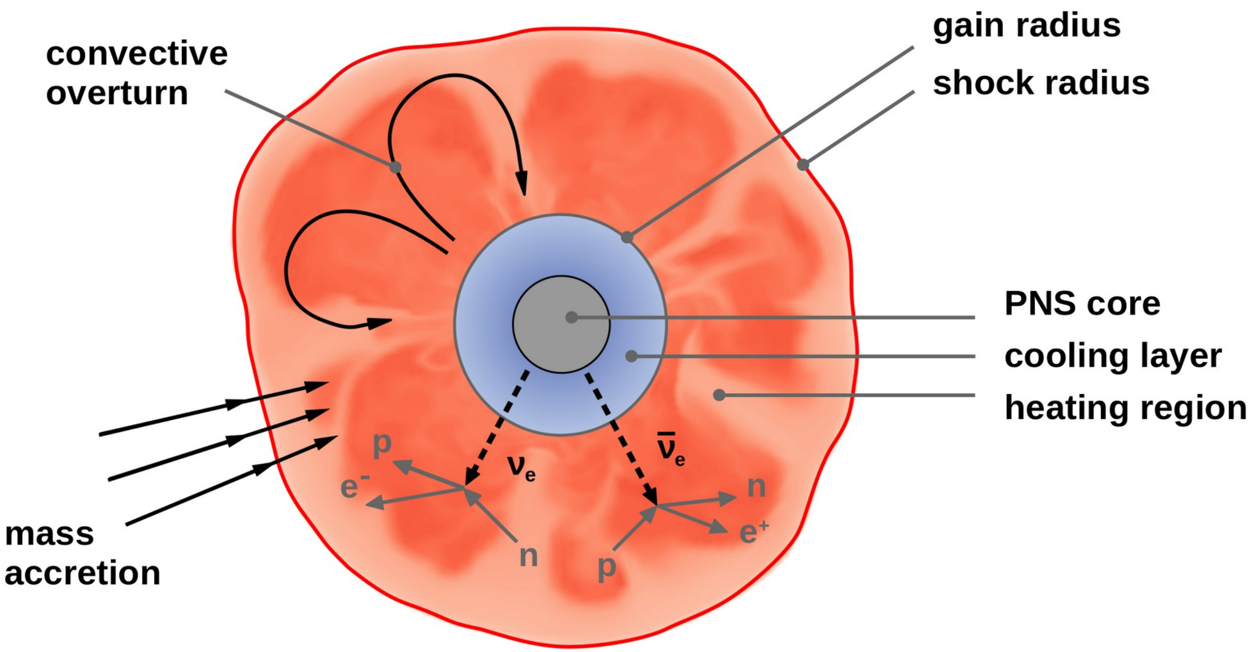
- Shock revival by neutrino energy deposition

Neutrino-driven Explosion Mechanism



convective overturn

gain radius

shock radius

PNS core

cooling layer

heating region

mass accretion

Arnett (1966)
Colgate & White (1966)
Bethe & Wilson (1985)

$$\nu_\mathrm{e} + \mathrm{n} \longleftrightarrow \mathrm{p} + \mathrm{e}^-$$
$$\bar{\nu}_\mathrm{e} + \mathrm{p} \longleftrightarrow \mathrm{n} + \mathrm{e}^+$$

- **Gravitational binding energy of the collapsed Fe core (~3–4 x 10^{53} erg) transiently stored in a hot and inflated PNS**

- **PNS contracts and cools via neutrino emission over ~10 s**
- **~1% of neutrinos reabsorbed (in “gain layer” / heating layer)**
- **Shock revival (aided by fluid instabilities: convection & SASI)**

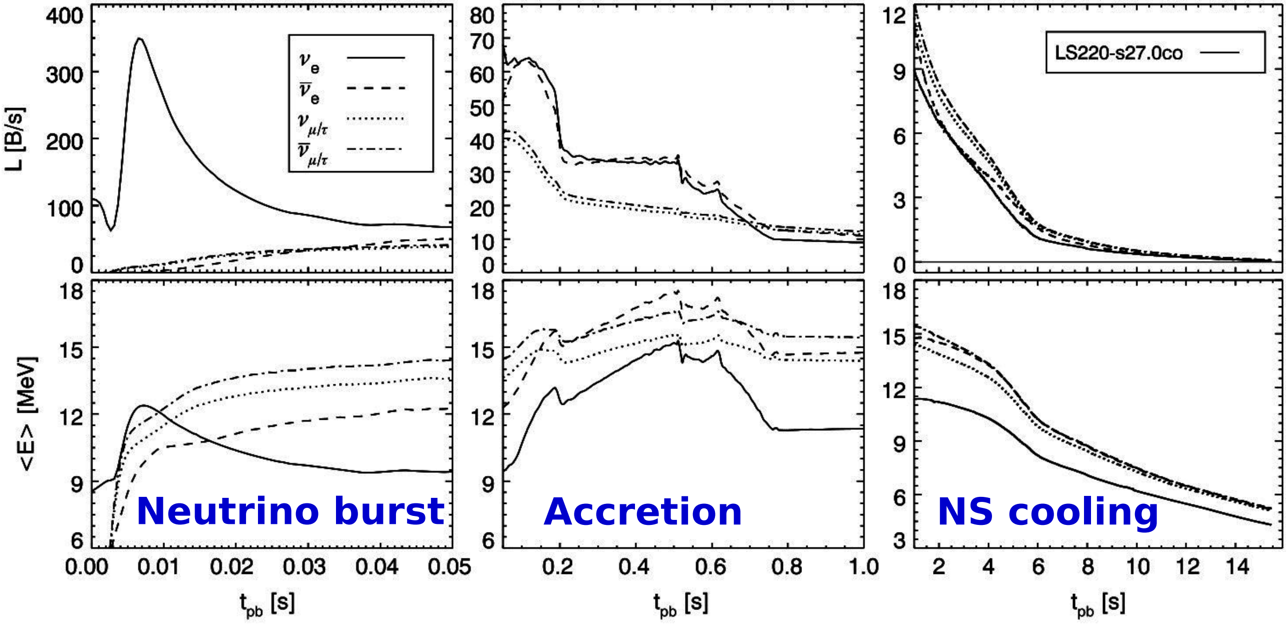
Neutrino Emission From Core-Collapse Supernovae

Neutrino energy release from SNe

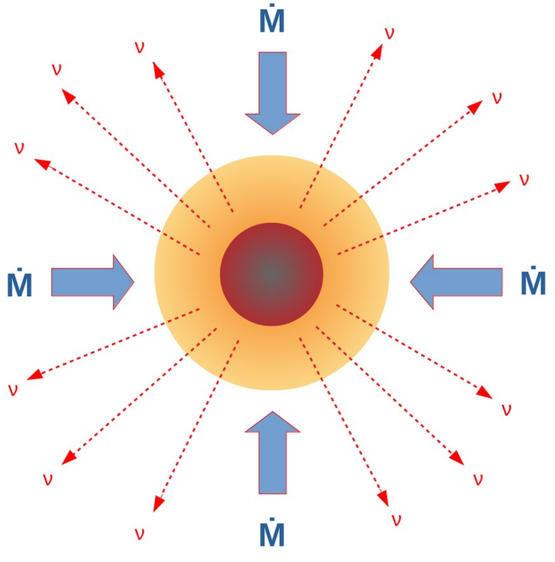
$$\begin{aligned} E_\mathrm{b} \sim E_\mathrm{g} &\approx \frac{3}{5}\frac{GM_\mathrm{ns}^2}{R_\mathrm{ns}} \\ &\approx 3.6\times10^{53}\left(\frac{M_\mathrm{ns}}{1.5\,\mathrm{M}_\odot}\right)^2\left(\frac{R_\mathrm{ns}}{10\,\mathrm{km}}\right)^{-1}\ \mathrm{erg} \end{aligned}$$

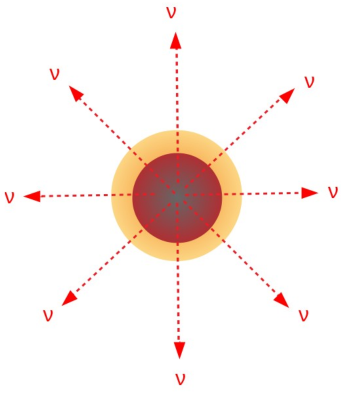
NS formation

Mirizzi, Tamborra, Janka, et al. (2016)



Neutrino burst **Accretion** **NS cooling**





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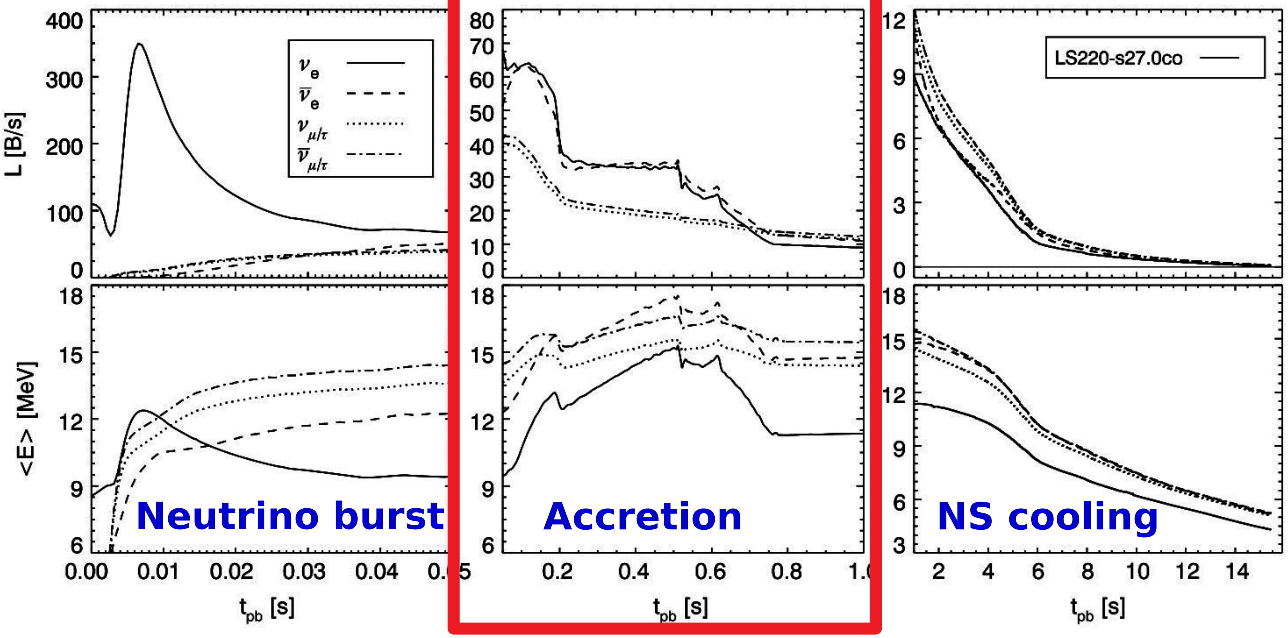

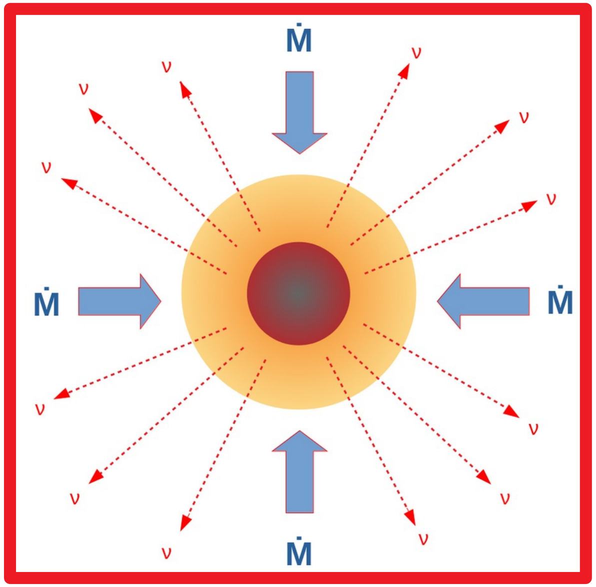

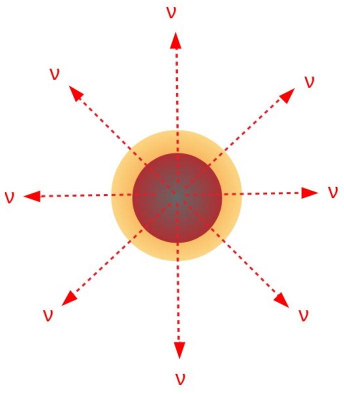

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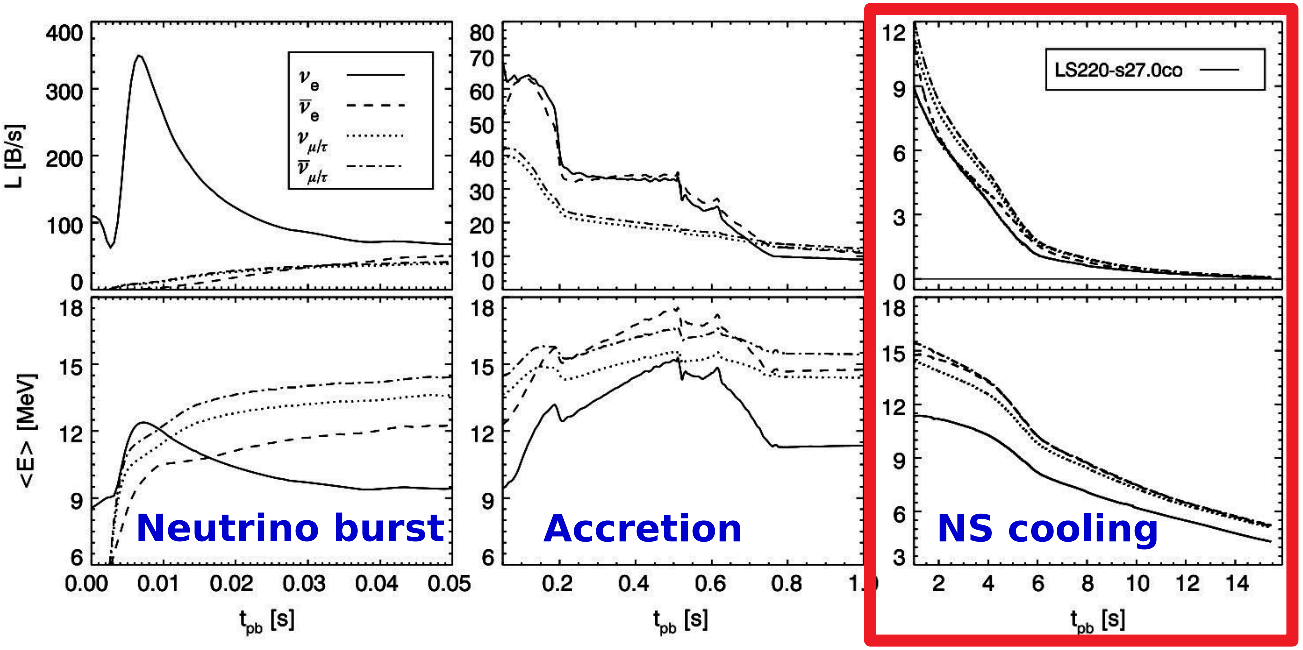

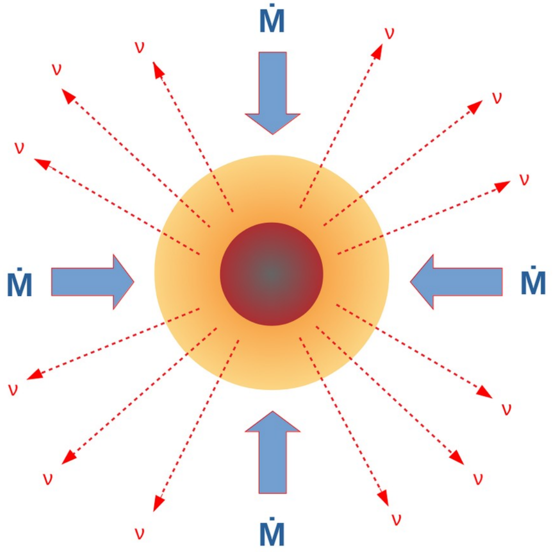

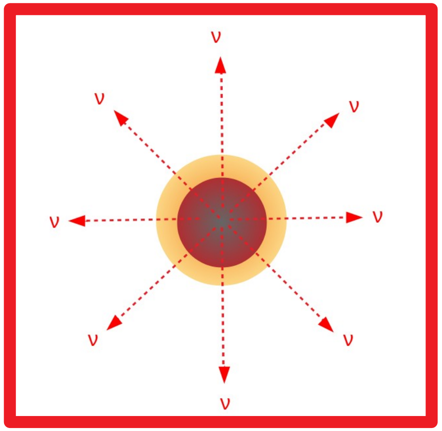

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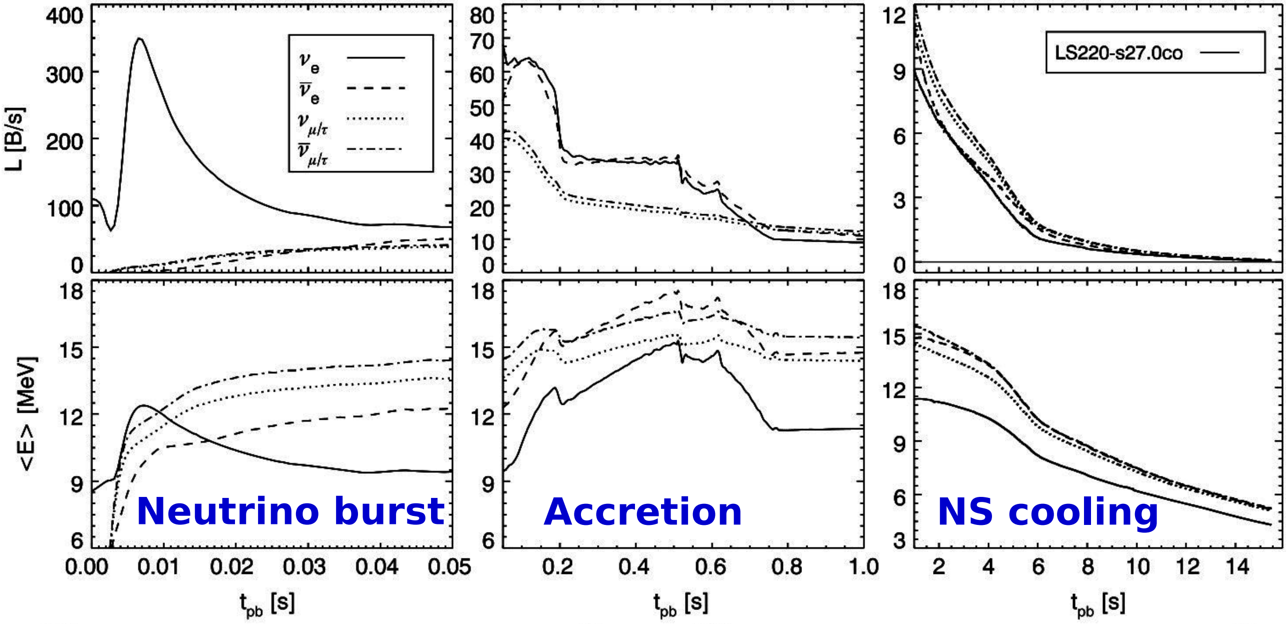
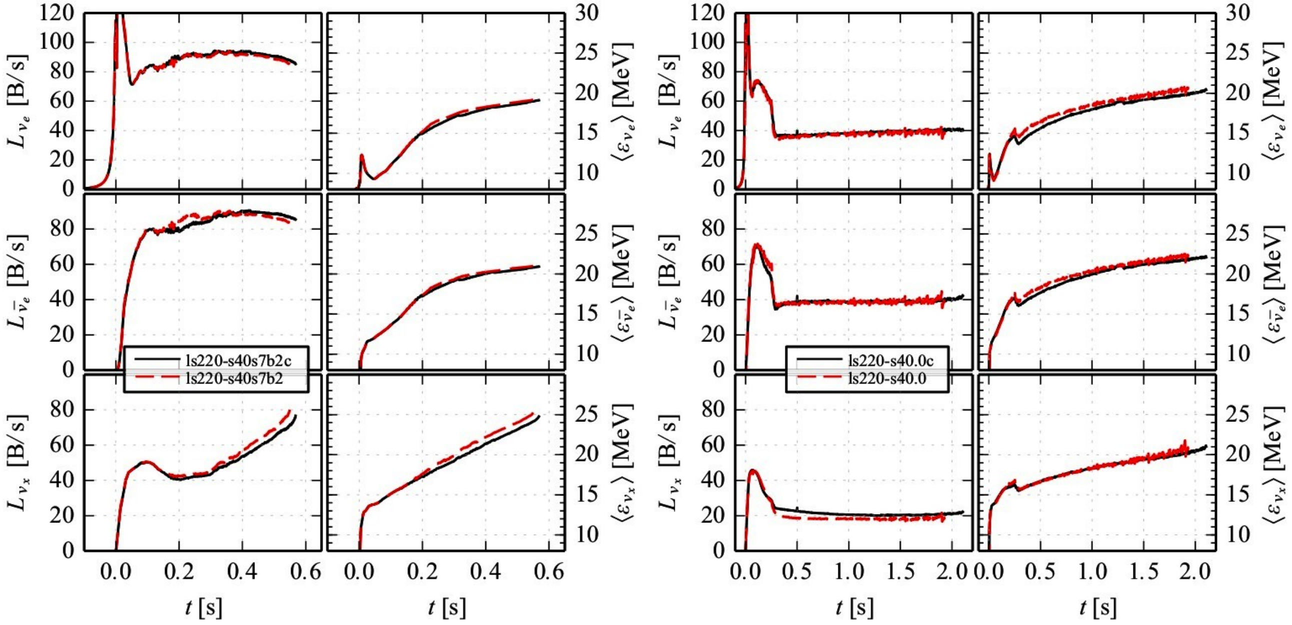
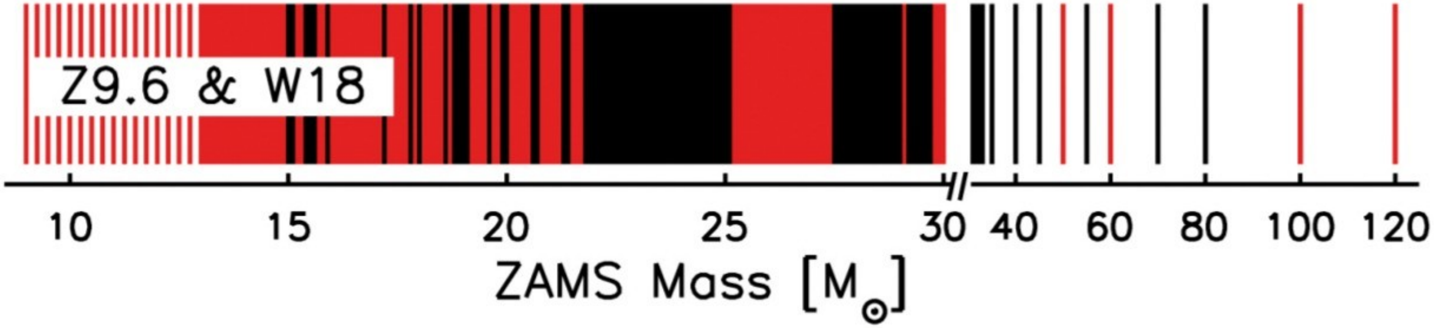


BH formation



Neutrino Emission Across the "Landscape" of Progenitors



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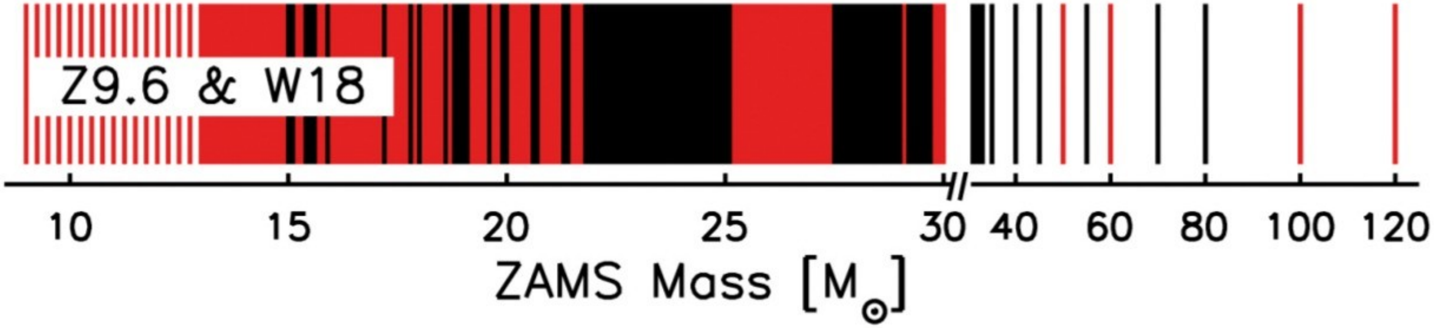

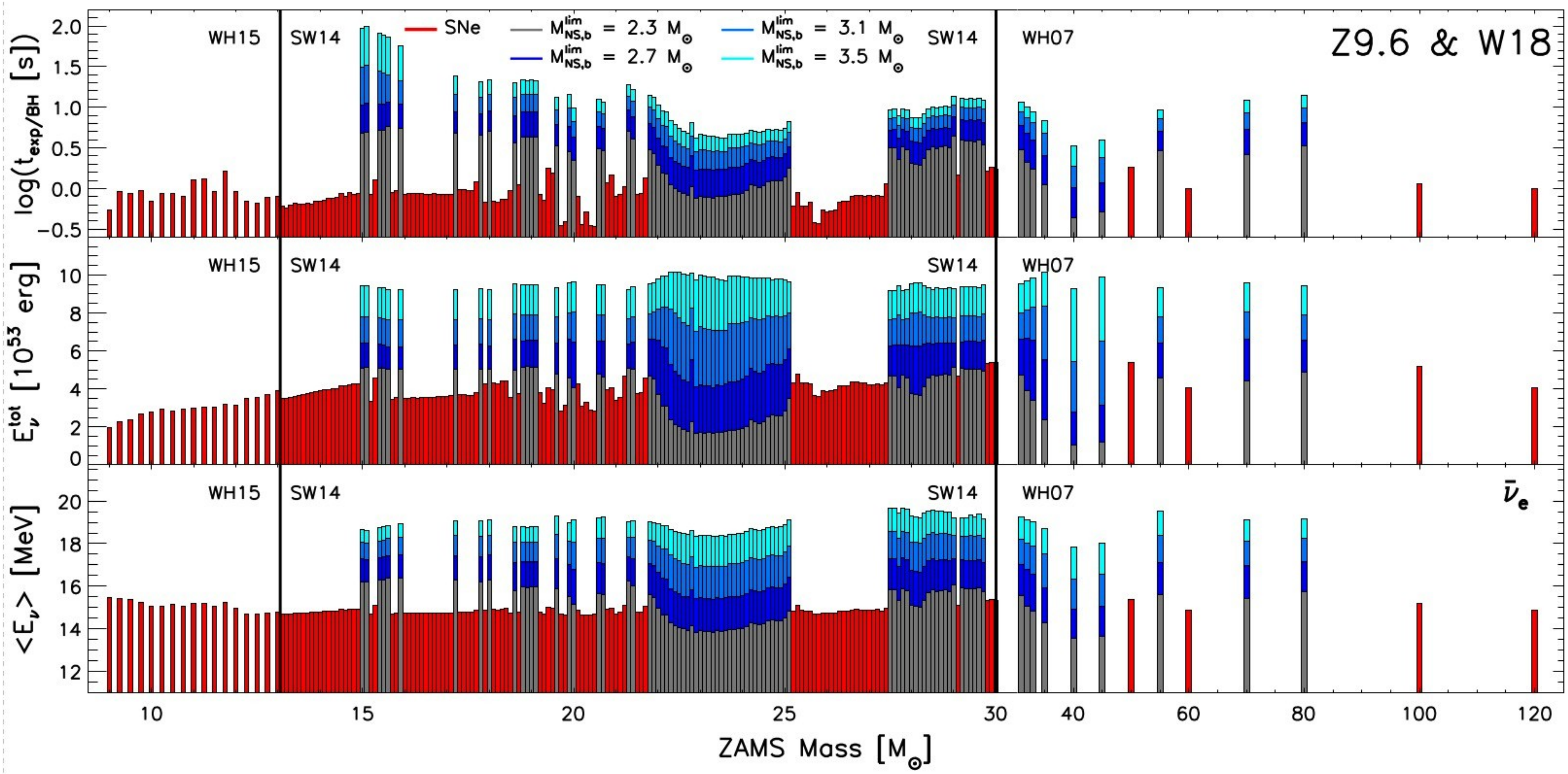

Kresse, Ertl, & Janka (2021)

DSNB modeling

$$\frac{\mathrm{d}\Phi}{\mathrm{d}E} = c \int \underbrace{\frac{\mathrm{d}N_{\mathrm{CC}}}{\mathrm{d}E'} \frac{\mathrm{d}E'}{\mathrm{d}E}}_{(1)} \underbrace{R_{\mathrm{CC}}(z)}_{(2)} \underbrace{\left|\frac{\mathrm{d}t}{\mathrm{d}z}\right| \mathrm{d}z}_{(3)}$$

(1) SN neutrino number spectrum $[\mathrm{MeV}^{-1}]$, time-integrated and IMF-folded; cosmological redshift: $E' = (1+z)E$

(2) Cosmic core-collapse rate density $[\mathrm{yr}^{-1}\mathrm{Mpc}^{-3}]$; $\sim$ SFH

(3) Cosmological time integral (ΛCDM)

DSNB modeling

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Long history of theoretical modeling:
e.g., Krauss+84, Dar 85, Hartmann+Woosley 97, Ando+Sato 03, Strigari+04/05, Hopkins+Beacom 06, Lunardini 06/07/09, Totani+09, Lunardini+Tamborra 12, Nakazato+13/15, Mathews+14, Hidaka+16/18, Horiuchi+18/21, Møller+18, Tabrizi+Horiuchi 21, Ashida+Nakazato 22/23, Suliga+22, Ekanger+22/24, Ziegler+22, Anandagoda+23, … (**non-exhaustive!!**)

Reviews:
Ando & Sato (2004), Beacom (2010), Lunardini (2016), Ando et al. (2023)

(1) IMF-averaged time-integrated neutrino source spectrum

$$\frac{\mathrm{d}\Phi}{\mathrm{d}E} = c\int \boxed{\frac{\mathrm{d}N_{\mathrm{CC}}}{\mathrm{d}E'}\,\frac{\mathrm{d}E'}{\mathrm{d}E}}\,R_{\mathrm{CC}}(z)\left|\frac{\mathrm{d}t}{\mathrm{d}z}\right|\mathrm{d}z$$

→ **many different approaches & degrees of sophistication**

- **thermal spectrum** (e.g., Horiuchi+09)
- pinched/anti-pinched **α spectrum** (e.g, Keil+03, Lunardini 07)
- numerical spectra from exemplary **CCSN simulations** (e.g., Nakazato+13/15, Møller+18, Ashida+Nakazato 22)
- considering neutrino **oscillations** (e.g., Lunardini+Tamborra 12)
- including **failed (BH-forming) SNe** for certain progenitor mass intervals (e.g., Lunardini 09, Priya+Lunardini 17, Møller+18)
- impact of **late-time** neutrino emission (e.g., Ekanger+22)
- considering large sets of numerical models, accounting for **progenitor variability** (e.g., Horiuchi+18, Kresse+21)
- considering **binary progenitors** (e.g., Horiuchi+21, Kresse+21)

(2) Cosmic core-collapse rate

$$\frac{\mathrm{d}\Phi}{\mathrm{d}E} = c \int \frac{\mathrm{d}N_{\mathrm{CC}}}{\mathrm{d}E'} \frac{\mathrm{d}E'}{\mathrm{d}E} \boxed{R_{\mathrm{CC}}(z)} \left| \frac{\mathrm{d}t}{\mathrm{d}z} \right| \mathrm{d}z$$

- **Deduce core-collapse rate from star-formation history (SFH)**
- **Direct measurement of visible events (excl. faint / failed SNe)**

(2) Cosmic core-collapse rate

$$\frac{\mathrm{d}\Phi}{\mathrm{d}E} = c \int \frac{\mathrm{d}N_{\mathrm{CC}}}{\mathrm{d}E'}\frac{\mathrm{d}E'}{\mathrm{d}E}\boxed{R_{\mathrm{CC}}(z)}\left|\frac{\mathrm{d}t}{\mathrm{d}z}\right| \mathrm{d}z$$

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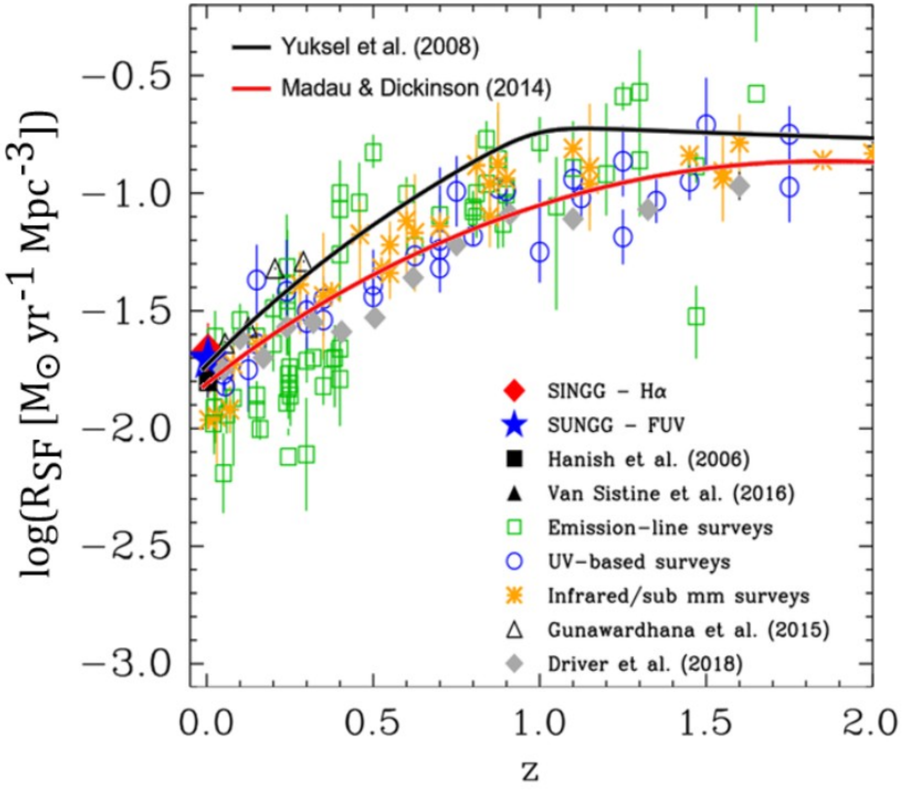
Ando+23



$$R_{\mathrm{CC}}(z) = \psi_*(z)\frac{\int_{8.7\,M_\odot}^{125\,M_\odot} dM\;\phi(M)}{\int_{0.1\,M_\odot}^{125\,M_\odot} dM\;M\phi(M)} \simeq \frac{\psi_*(z)}{116\,M_\odot}$$

(rate of successful SNe **plus** rate of failed / faint explosions)

(2) Cosmic core-collapse rate

$$\frac{\mathrm{d}\Phi}{\mathrm{d}E} = c \int \frac{\mathrm{d}N_{\mathrm{CC}}}{\mathrm{d}E'} \frac{\mathrm{d}E'}{\mathrm{d}E} \boxed{R_{\mathrm{CC}}(z)} \left| \frac{\mathrm{d}t}{\mathrm{d}z} \right| \mathrm{d}z$$

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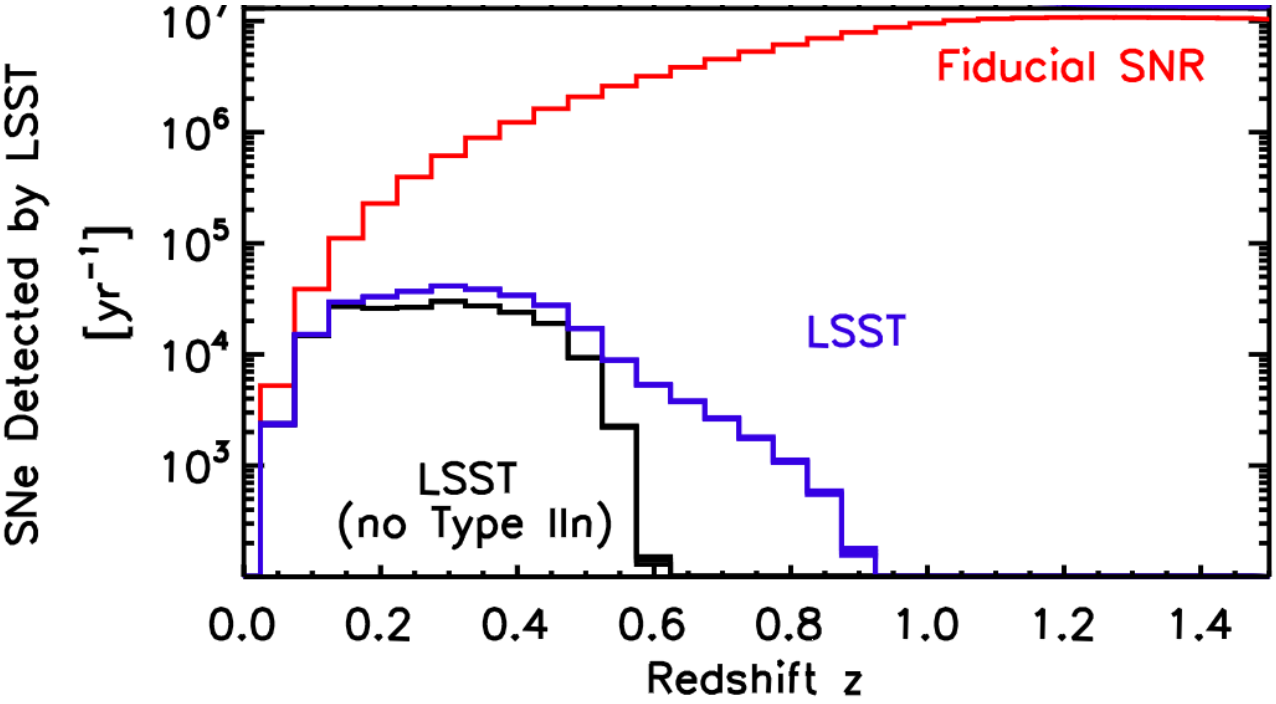
Lien, Fields, Beacom (2010)



(3) Cosmological time (redshift) integral

$$\frac{d\Phi}{dE} = c \int \frac{dN_{\mathrm{CC}}}{dE'} \frac{dE'}{dE} R_{\mathrm{CC}}(z) \boxed{\left| \frac{dt_{\mathrm{c}}}{dz} \right| dz}$$

$$= \frac{c}{H_0} \int_0^{z_{\max}} \frac{dN_{\mathrm{CC}}}{dE'} \frac{R_{\mathrm{CC}}(z)\ dz}{\sqrt{\Omega_{\mathrm{m}}(1+z)^3 + \Omega_\Lambda}}$$

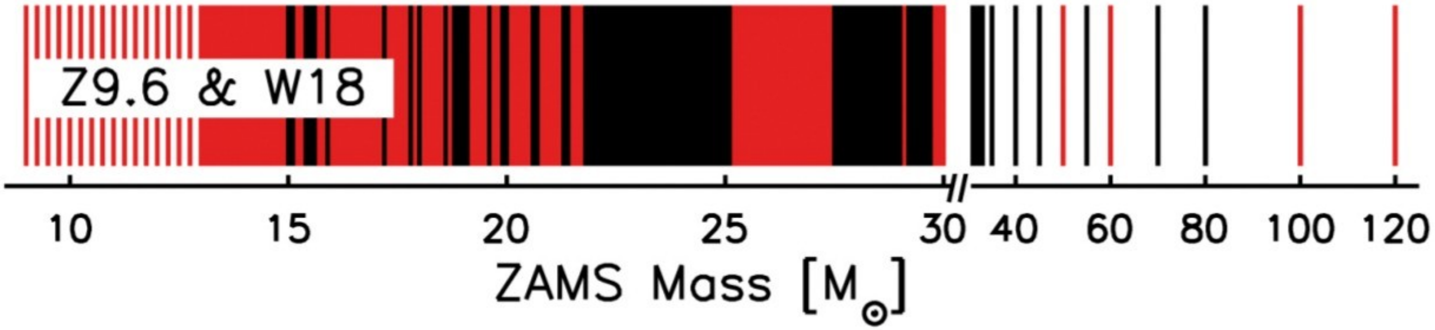
$$\boxed{\begin{gathered} H_0 = 70\,\mathrm{km\,s^{-1}\,Mpc^{-1}} \\ \Omega_{\mathrm{m}} = 0.3 \text{ and } \Omega_\Lambda = 0.7 \end{gathered}}$$

Kresse, Ertl, & Janka (2021)

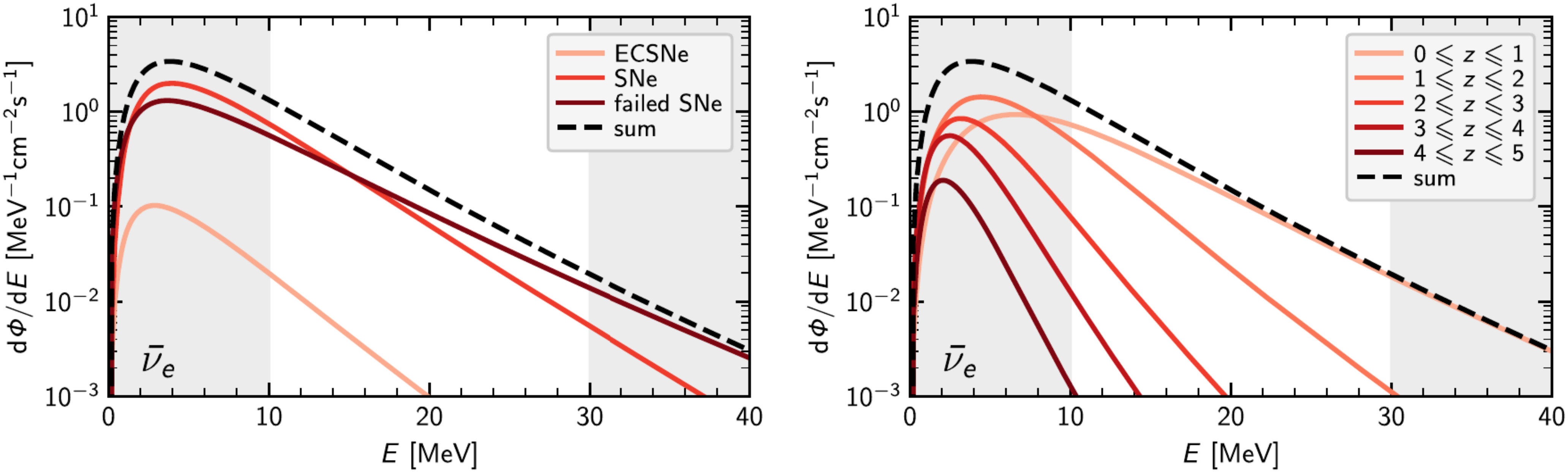
ApJ 909, 169

- DSNB predictions based on large sets of (> 200) 1D CCSN models (simulated with the *Prometheus-HotB* code)
- Models previously discussed in Ertl+16/20, Sukhbold+16

- Neutrino signals cover **long time spans** (> 10 s)
- Model set accounts for large **progenitor variability** (non-monotonic pattern of successful / failed explosions)



DSNB Source Components & Redshift Contributions

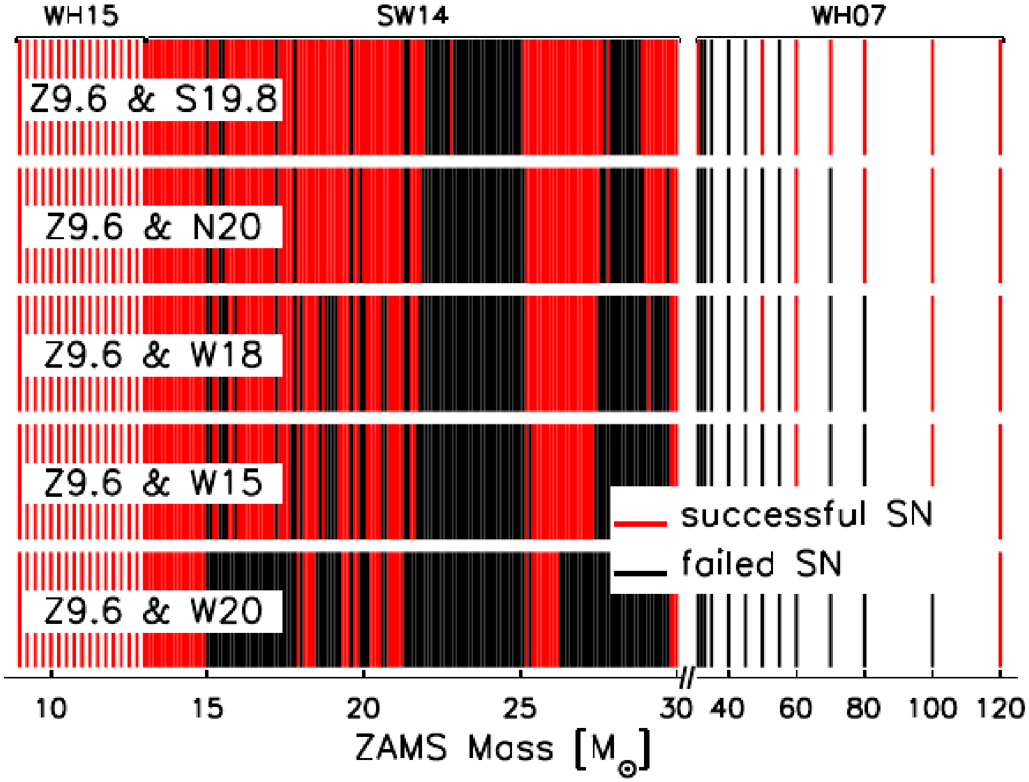


- negligible contribution from electron-capture SNe (ECSNe)
- below ∼15 MeV: dominant contribution from **successful SNe**
  above ∼15 MeV: dominant contribution from **failed SNe**
- dominant contribution to the flux from $z \lesssim 1$ (within the detection window)

Kresse+2021
(ApJ, 909, 169; arXiv:2010.04728)

Fraction of Failed Explosions

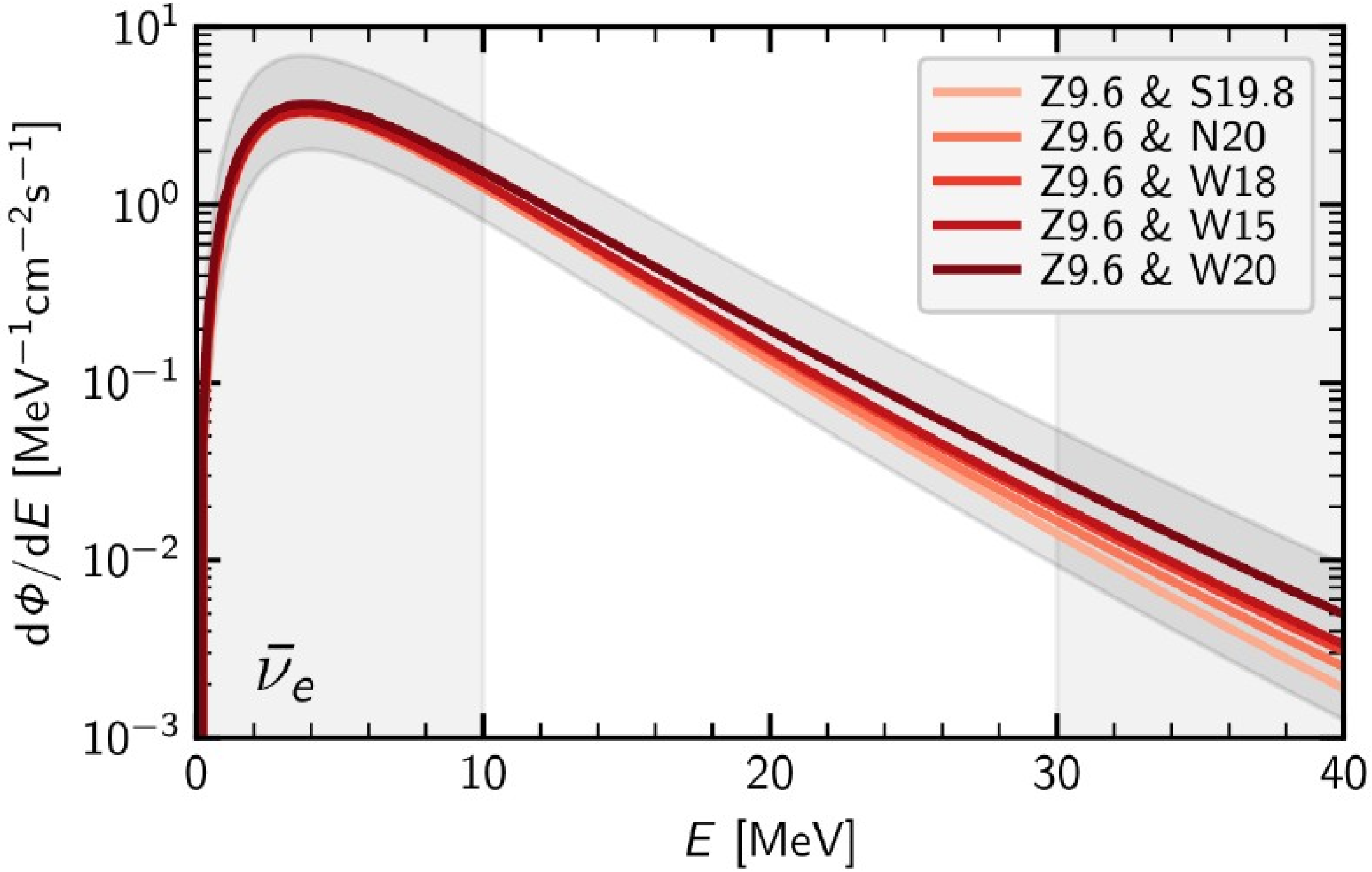
- depending on the **strength of the "neutrino engine"**
  → more/less successful explosions



Engine Model	Successful SNe	Failed SNe
Z9.6 & S19.8	82.2 %	17.8 %
Z9.6 & N20	77.2 %	22.8 %
Z9.6 & W18	73.1 %	26.9 %
Z9.6 & W15	70.9 %	29.1 %
Z9.6 & W20	58.3 %	41.7 %

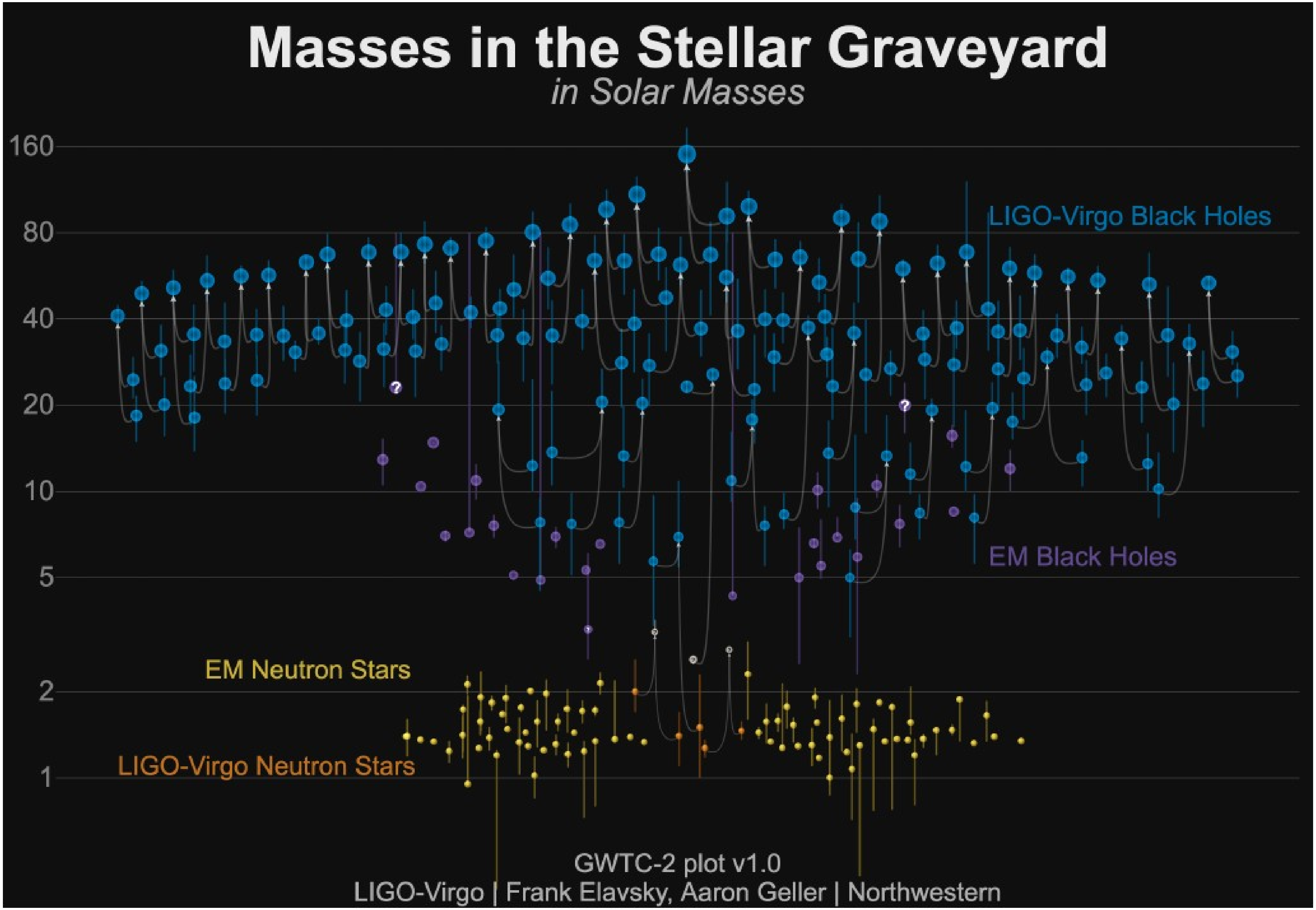
Kresse+2021
(ApJ, 909, 169; arXiv:2010.04728)

Fraction of Failed Explosions



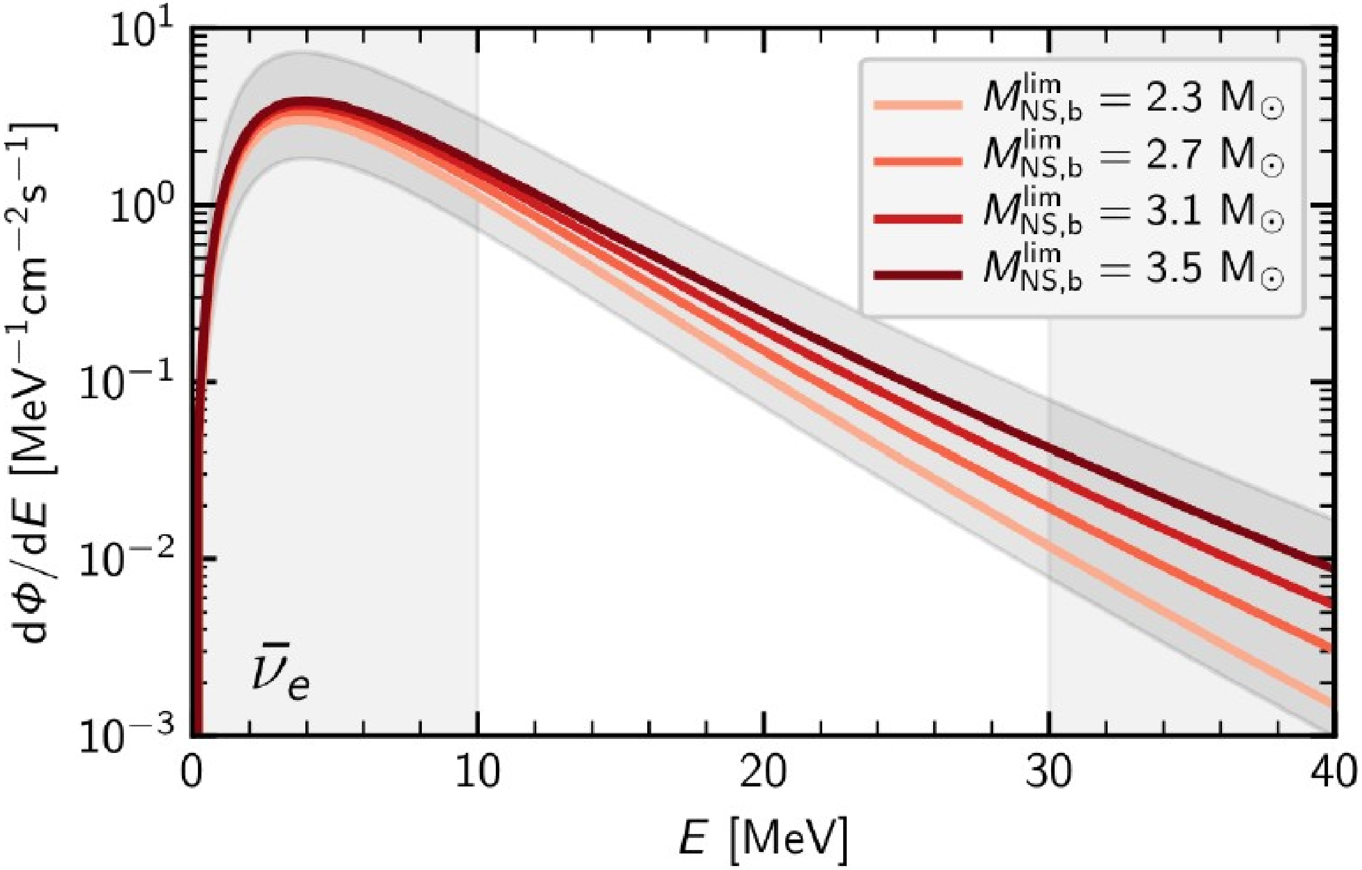
- increased fraction of failed SNe → enhancing the high-energy tail
- reference case: Z9.6 & W18

Maximum NS Mass



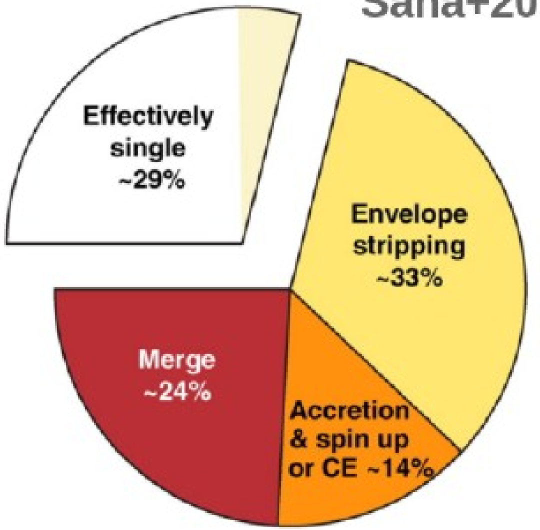
Maximum NS Mass

- neutrino signals of successful explosions simulated up to $t_{\max} = 15\,\mathrm{s}$
- BH cases up to **critical baryonic mass** $M_{\mathrm{NS,b}}^{\mathrm{lim}}$ (2.3, 2.7, 3.1, 3.5 $\mathrm{M}_\odot$)



- reference case: $M_{\mathrm{NS,b}}^{\mathrm{lim}} = 2.7\,\mathrm{M}_\odot$ (GW170817) → $M_{\mathrm{grav}} \sim 2.23\,\mathrm{M}_\odot$

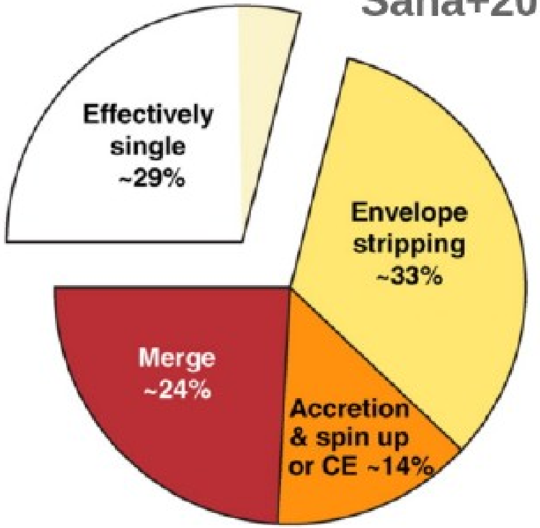
Binary Stars



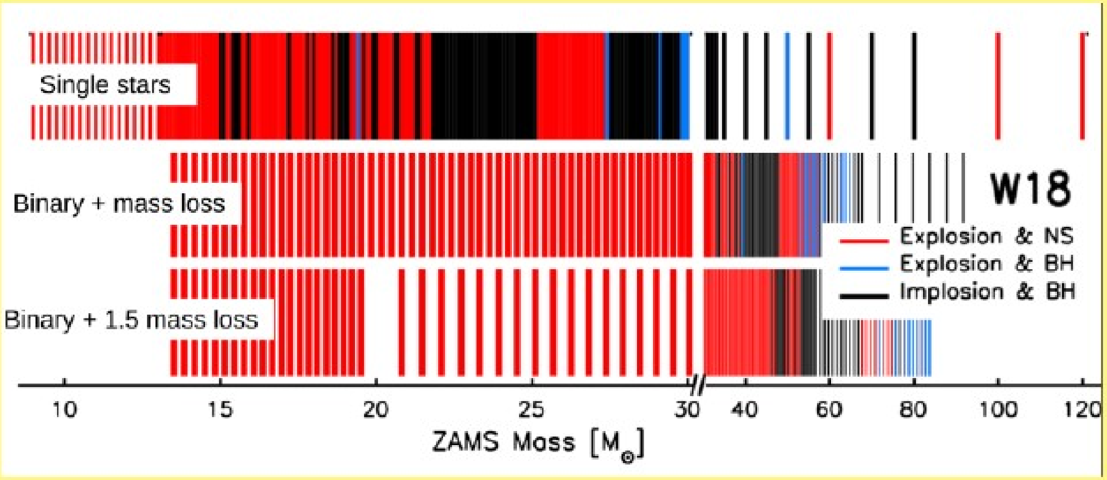
Sana+2012

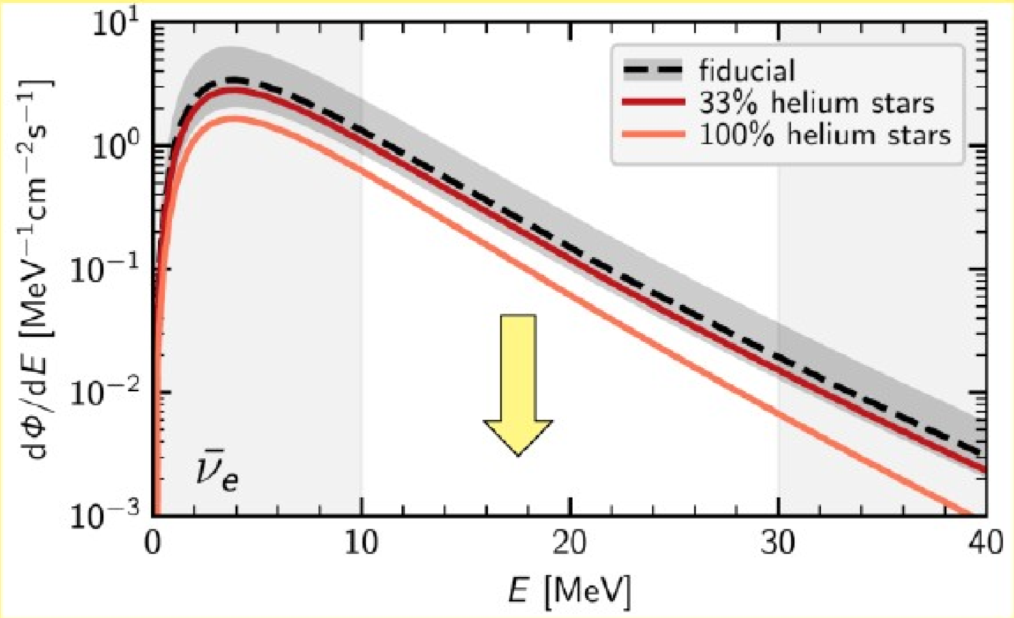
Binary Stars

Sana+2012



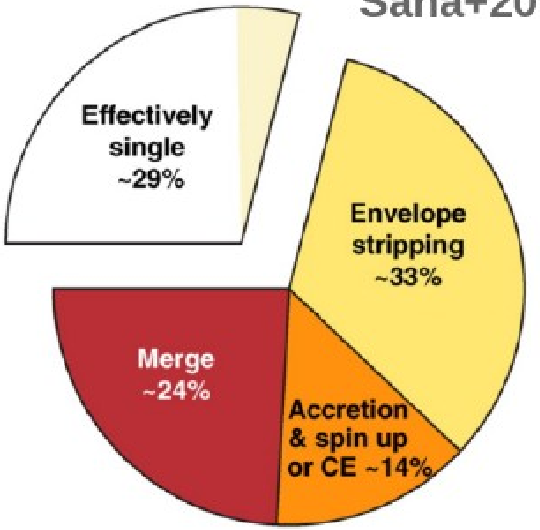
Woosley 2019, Ertl+2020



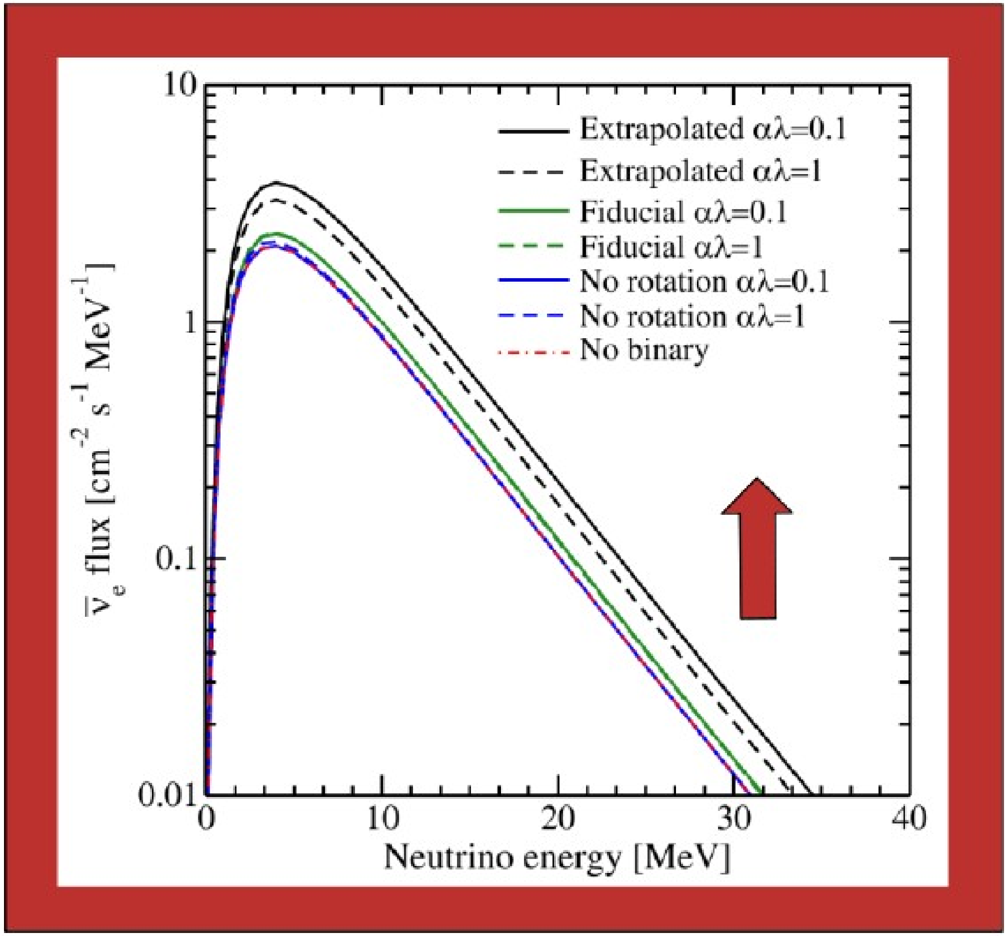


Kresse+2021

Binary Stars



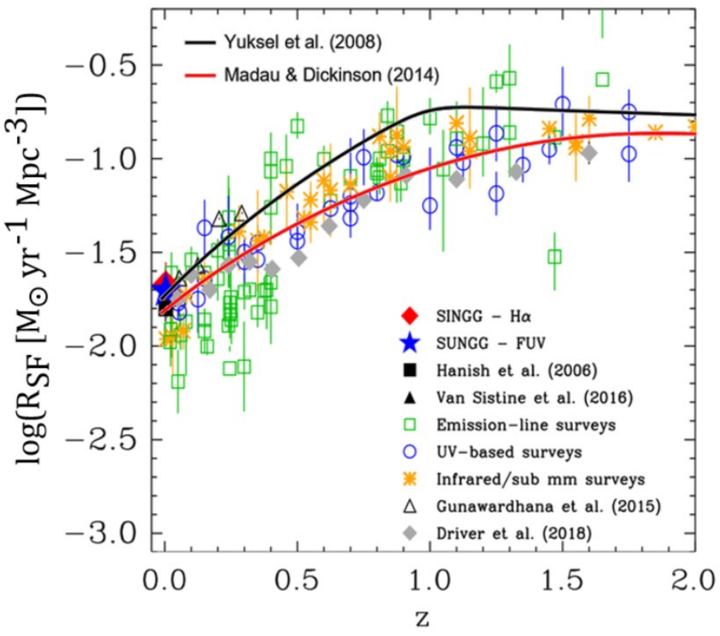
Sana+2012



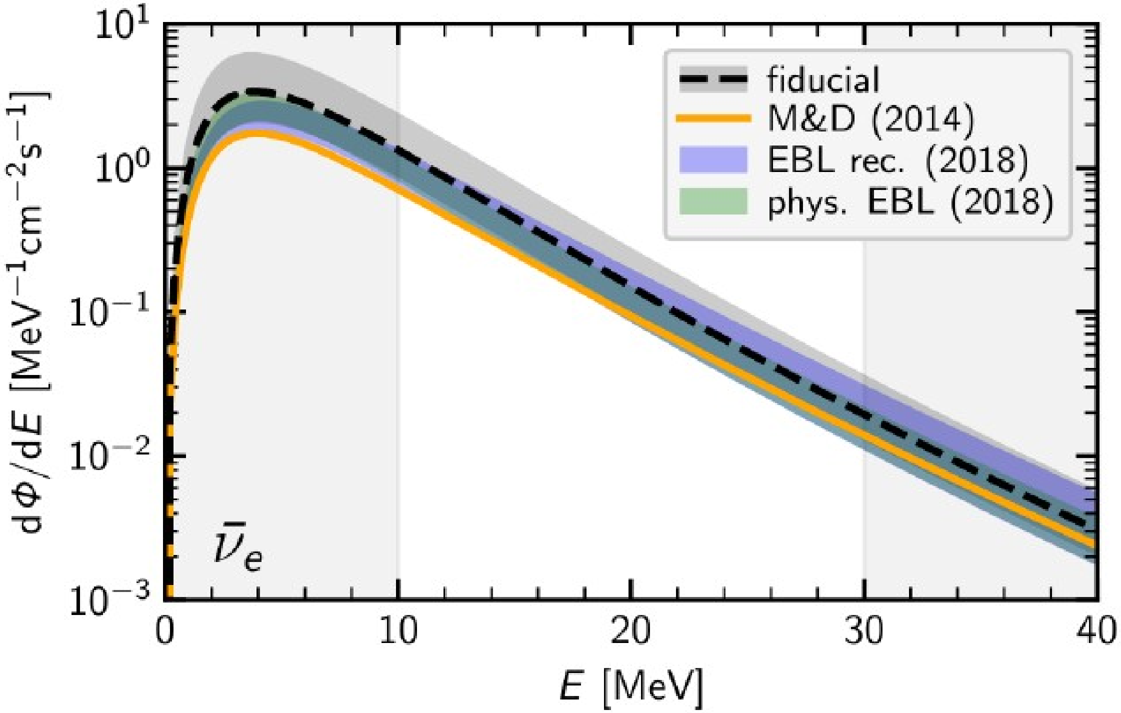
Horiuchi+2021

Major Uncertainty: Cosmic Star Formation History (SFH)

Ando+23



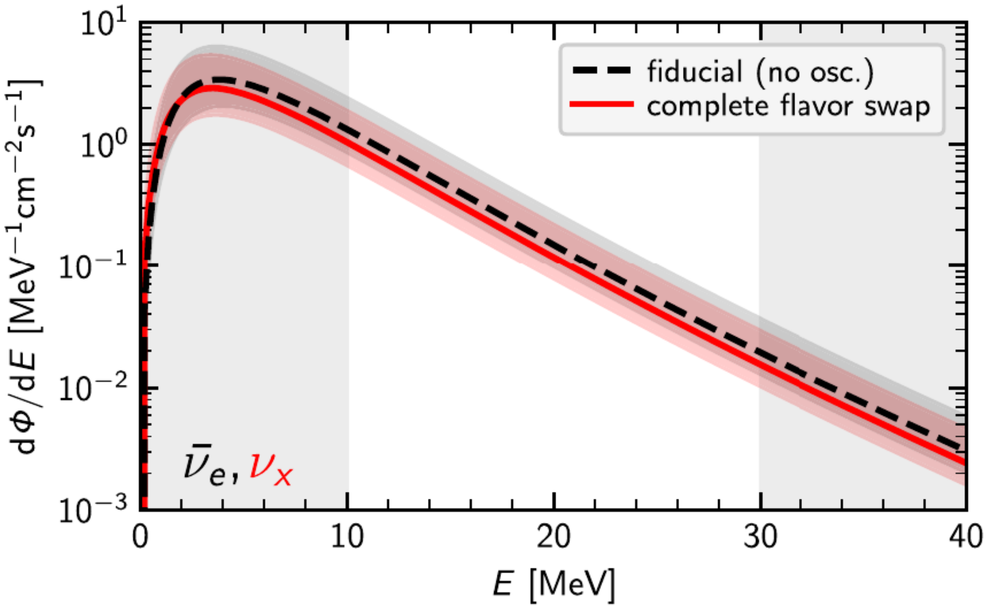
$$R_{\rm CC}(z) = \psi_*(z)\frac{\int_{8.7\,M_\odot}^{125\,M_\odot} dM\ \phi(M)}{\int_{0.1\,M_\odot}^{125\,M_\odot} dM\ M\phi(M)}$$



- Cosmic core-collapse rate density $\sim$ SFH
- DSNB flux uncertainty of a factor of $\sim$2

Mathews et al. (2014)
Madau & Dickinson (2014)
Fermi-LAT Collaboration et al. (2018)

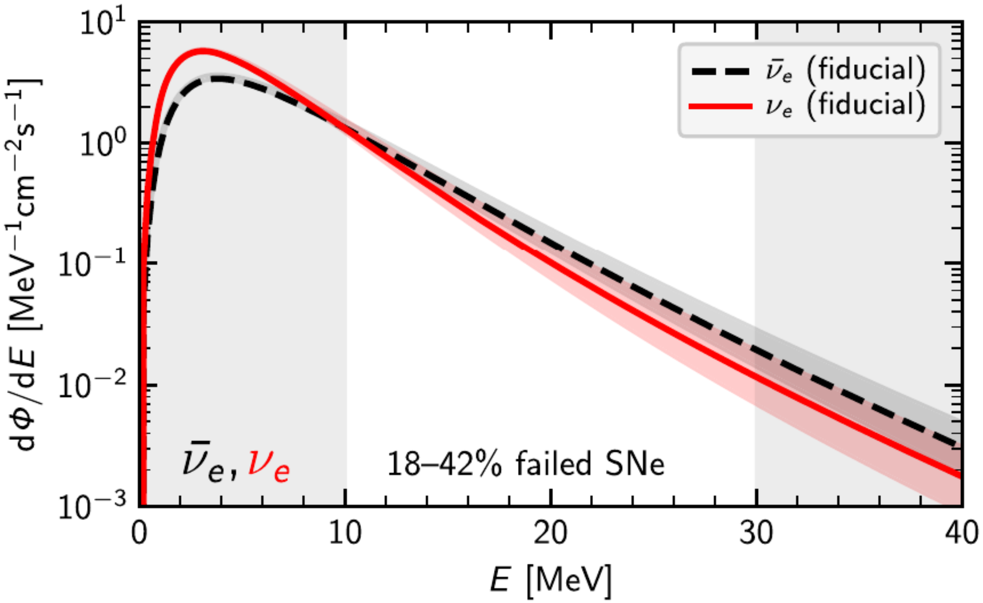
Flavor oscillations (MSW)



$$\frac{d\Phi_{\bar{\nu}_e}}{dE} = \bar{p}\,\frac{d\Phi^0_{\bar{\nu}_e}}{dE} + (1-\bar{p})\,\frac{d\Phi^0_{\nu_x}}{dE}$$

$\bar{p} \simeq 0.7$ or $\bar{p} \simeq 0$ for normal (NH) or inverted (IH)

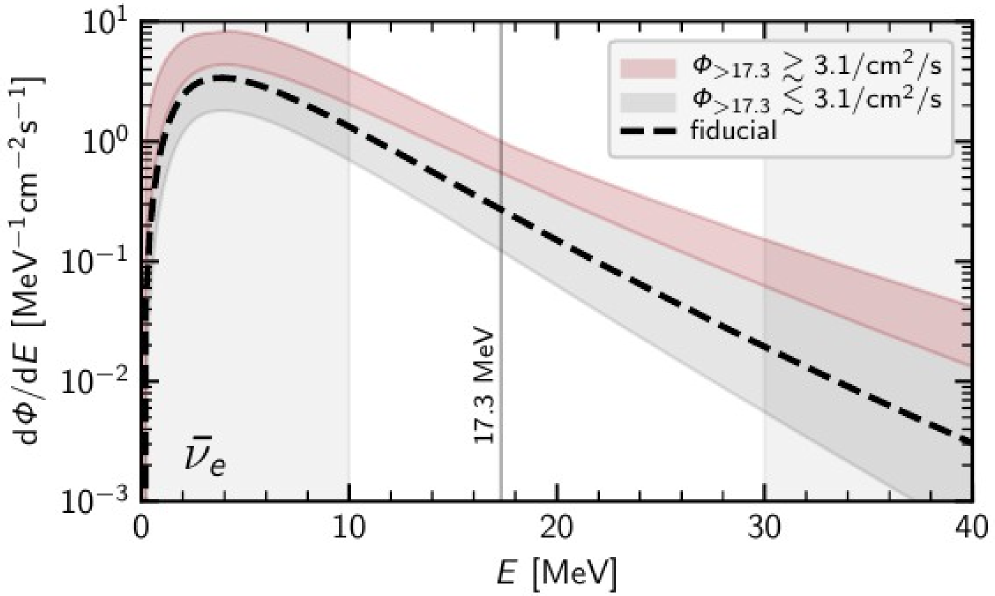
Electron neutrino DSNB component

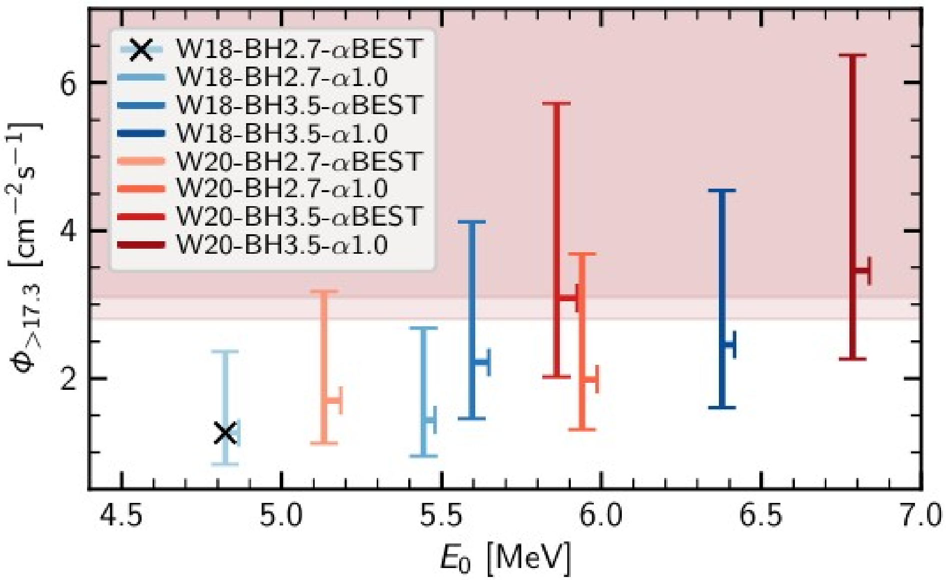


(lower mean energies of emitted electron neutrinos compared to electron antineutrinos and muon / tau neutrinos due to higher opacities and thus lower neutrinospheric temperatures)

Comparison with the Super-K flux limit

- comparison to $\bar{\nu}_e$-flux limits set by the SK experiment: $\Phi_{17.3} \equiv \Phi(E > 17.3\,\mathrm{MeV}) \lesssim (2.8 - 3.1)\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (Bays et al. 2012) (updated value: 2.7; Abe et al. 2021)
- $\mathrm{d}\Phi/\mathrm{d}E \simeq \phi_0 \exp(-E/E_0)$





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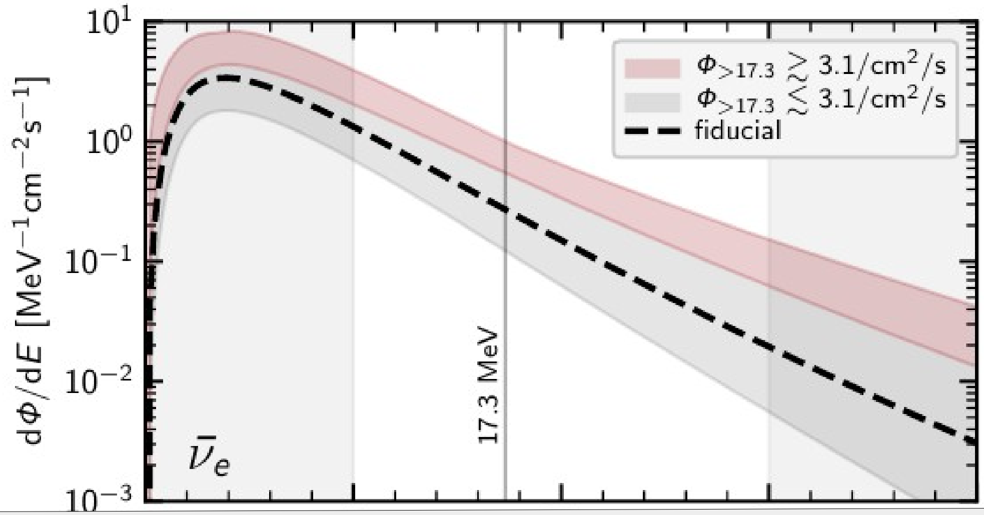
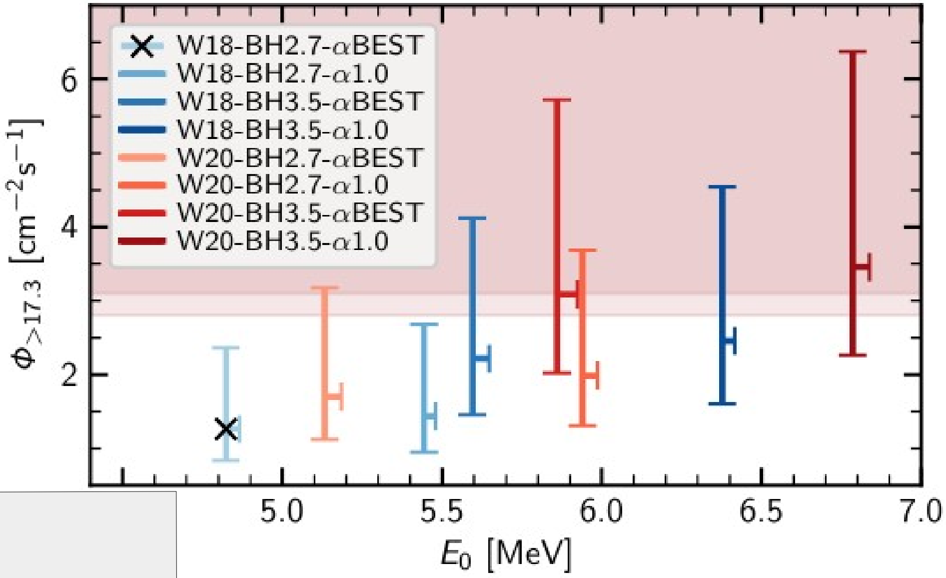


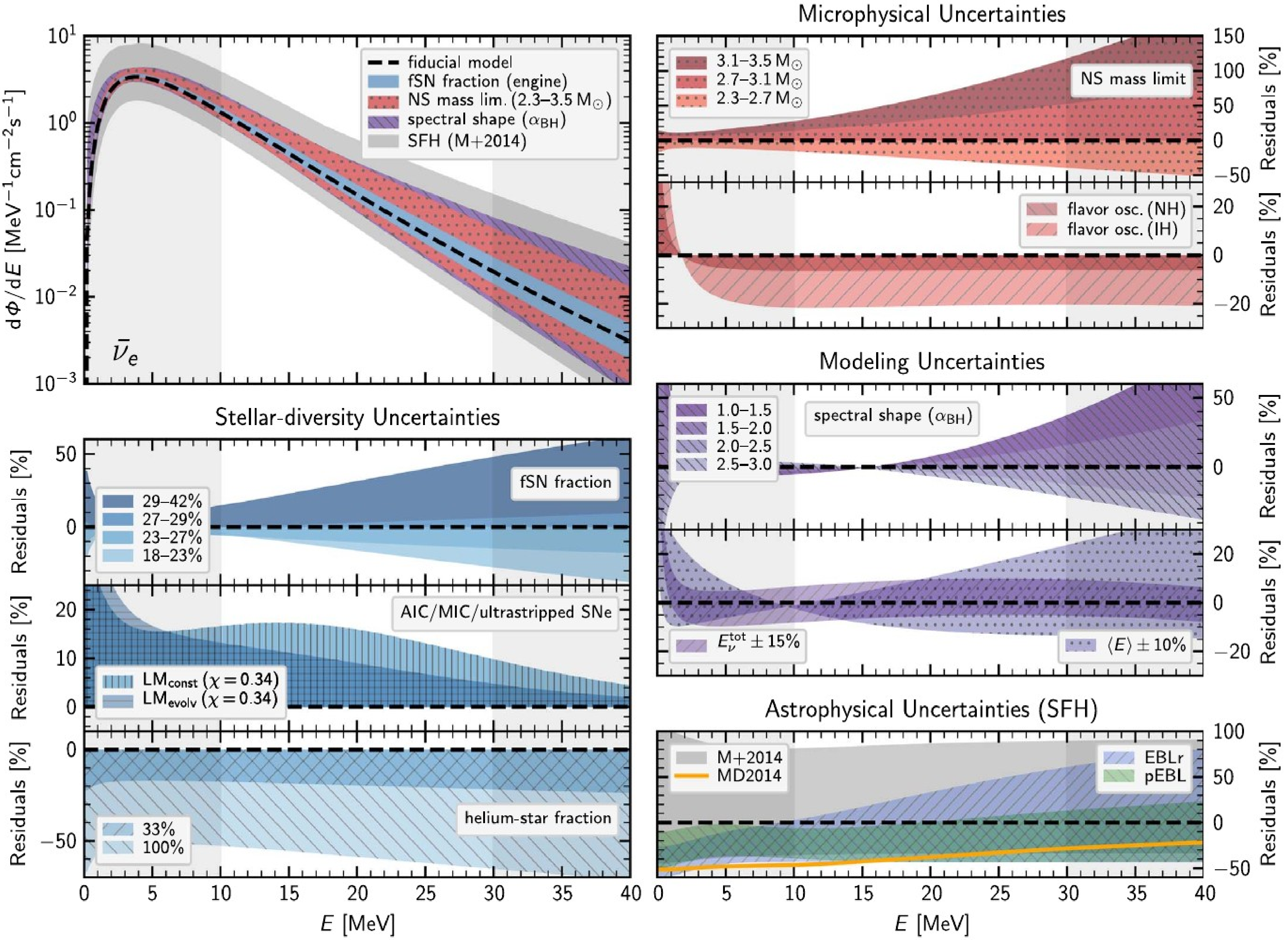


Harada+24 (SK-Gd):

- Best fit of whole SK observation is **$1.4^{+0.8}_{-0.6}$ cm^{-2} s^{-1}** for E_ν > 17.3 MeV

➡ **exhibit ~2.3 σ excess!!**

Summary of DSNB Uncertainties


Microphysical Uncertainties
Modeling Uncertainties
Stellar-diversity Uncertainties
Astrophysical Uncertainties (SFH)
$d\Phi/dE$ [MeV^{-1}cm^{-2}s^{-1}]
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
$\bar{\nu}_e$
fiducial model
fSN fraction (engine)
NS mass lim. (2.3–3.5 $M_\odot$)
spectral shape (α_{BH})
SFH (M+2014)
3.1–3.5 $M_\odot$
2.7–3.1 $M_\odot$
2.3–2.7 $M_\odot$
NS mass limit
flavor osc. (NH)
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1.0–1.5
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$E_\nu^{tot} \pm 15\%$
$\langle E \rangle \pm 10\%$
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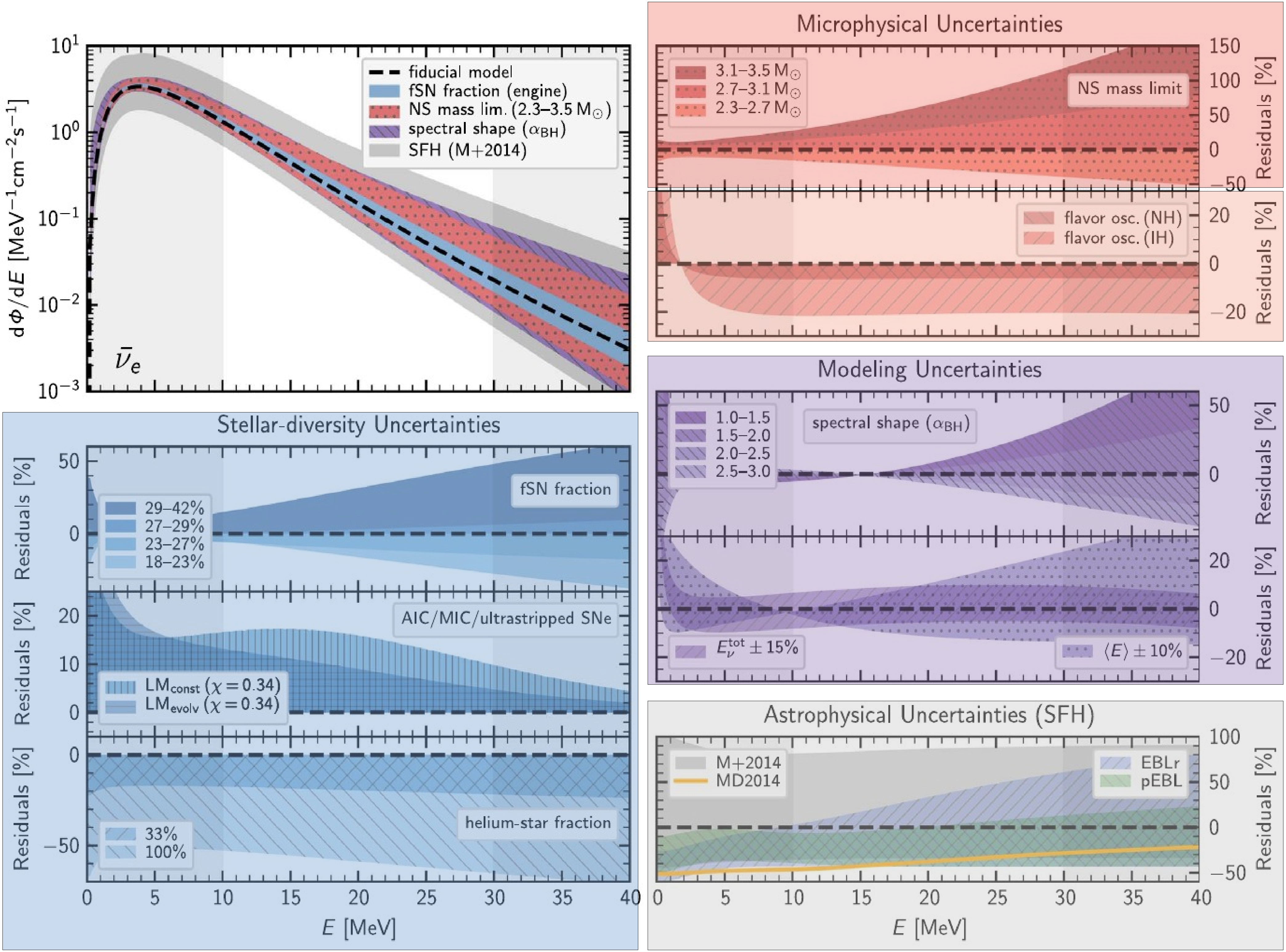
29–42%
27–29%
23–27%
18–23%
AIC/MIC/ultrastripped SNe
LM_{const} ($\chi = 0.34$)
LM_{evolv} ($\chi = 0.34$)
helium-star fraction
33%
100%
M+2014
MD2014
EBLr
pEBL
Residuals [%]
150
100
50
0
−50
20
−20
0
5
10
15
20
25
30
35
40
E [MeV]



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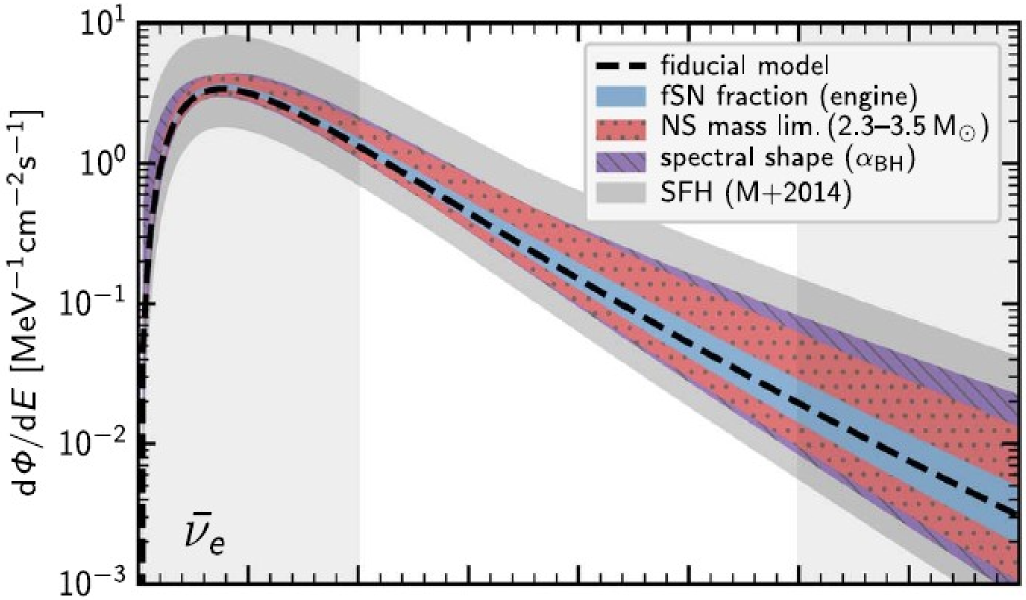
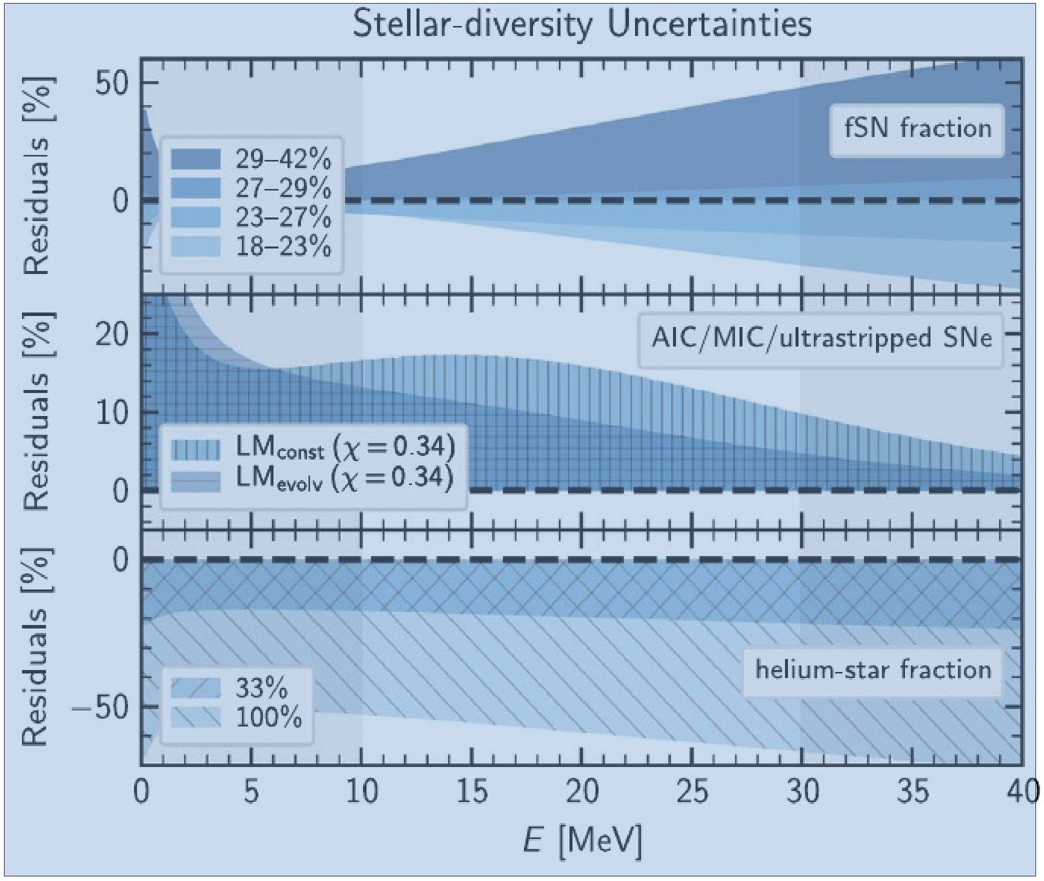
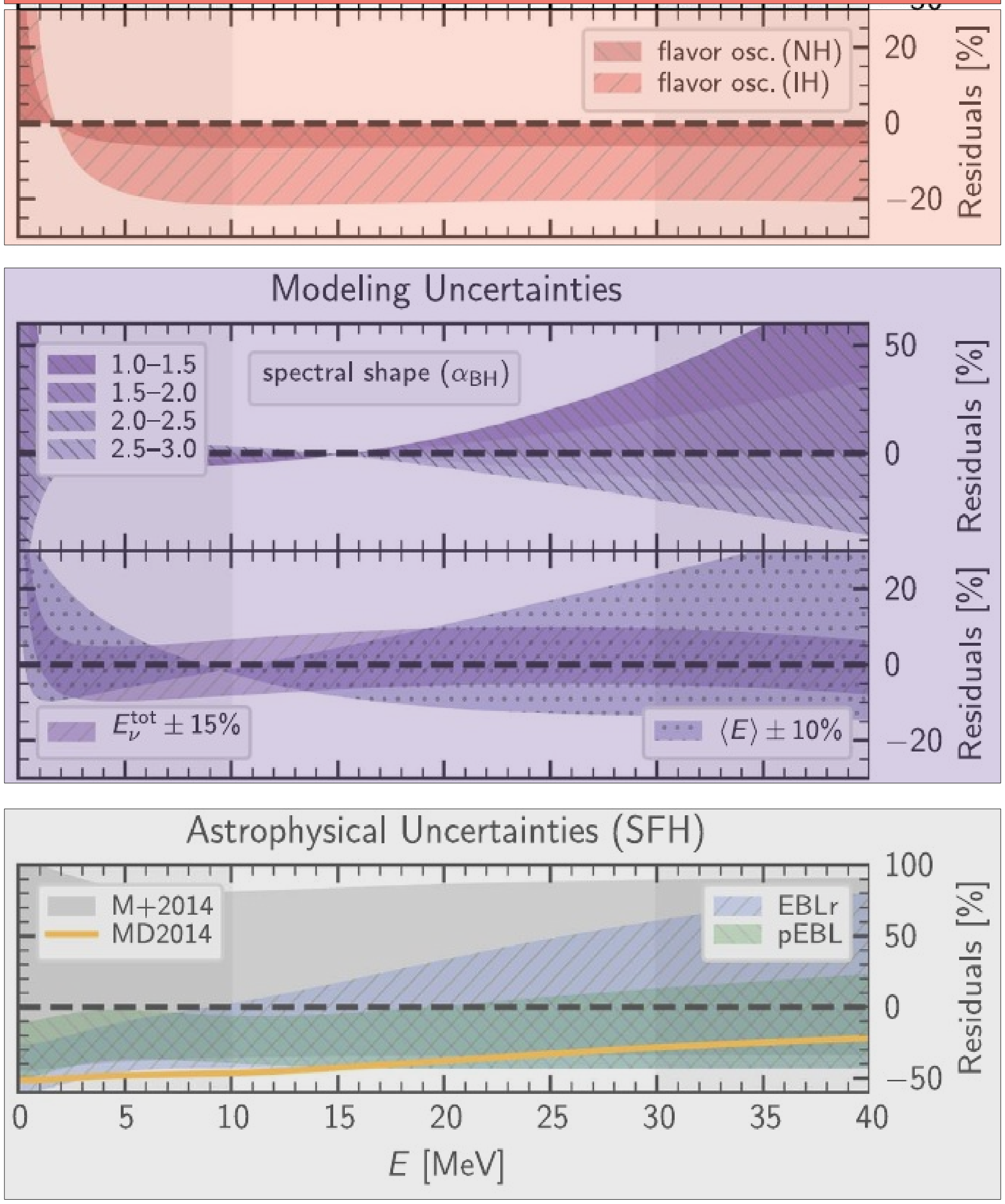
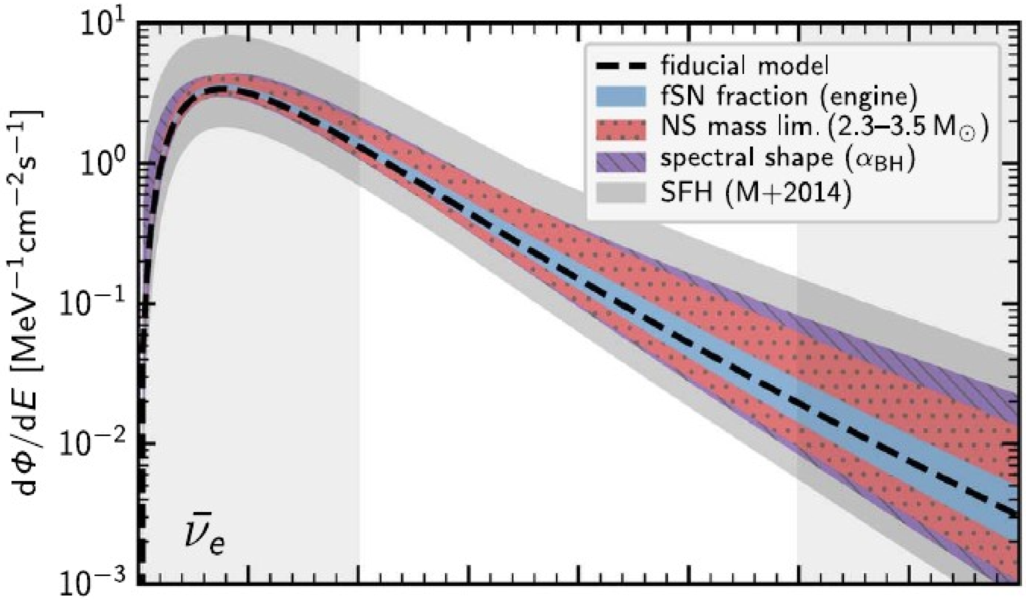
E [MeV]

GWs from binary NS mergers (LIGO, VIRGO, KAGRA) & observations by NICER → **constraints on max. NS mass / NS radii / high-density EoS**









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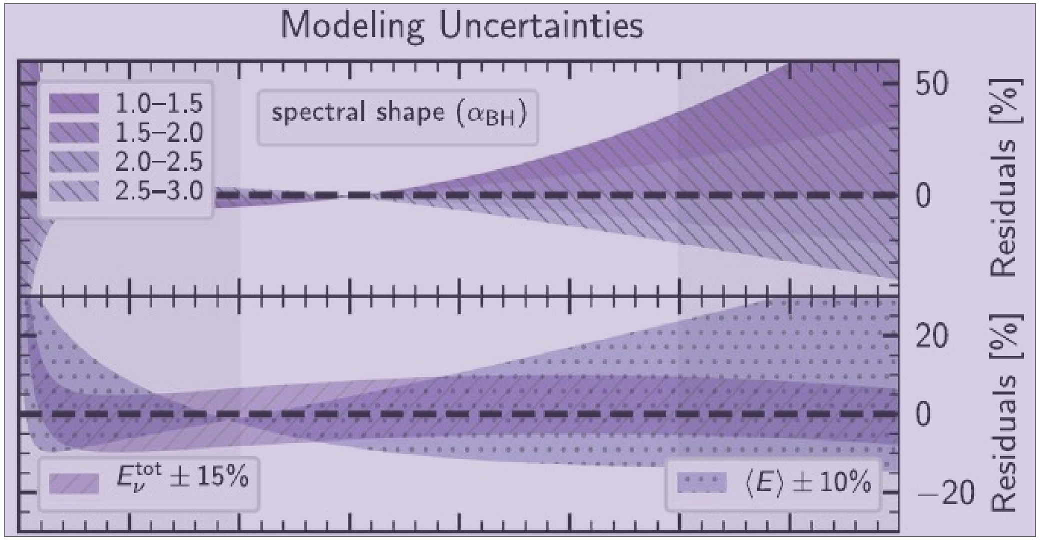
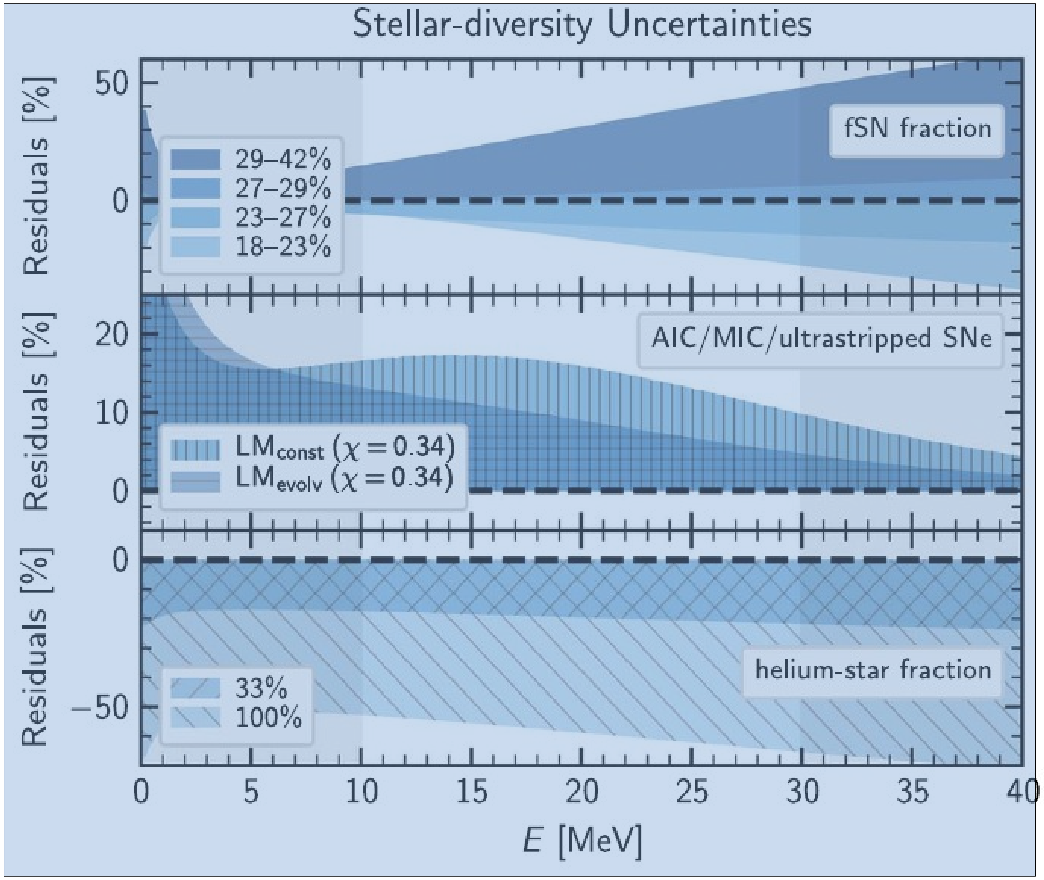
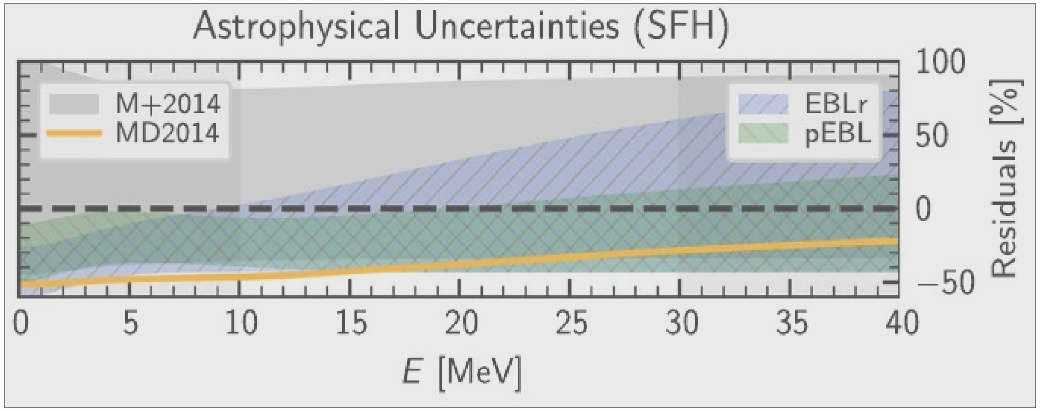
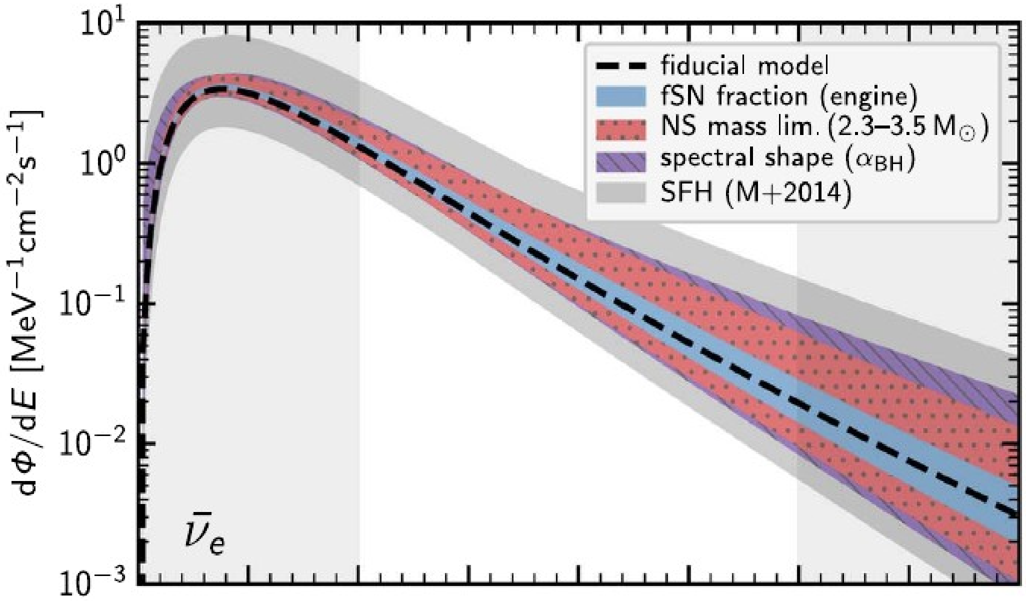
Long-baseline oscillation experiments (JUNO) → **neutrino mass hierarchy** → constraints on flavor conversions









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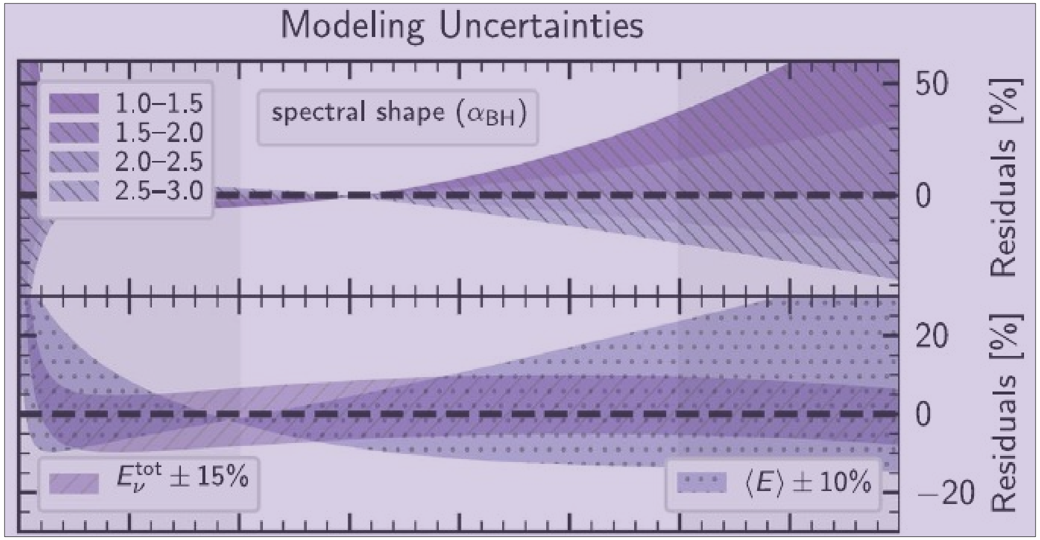
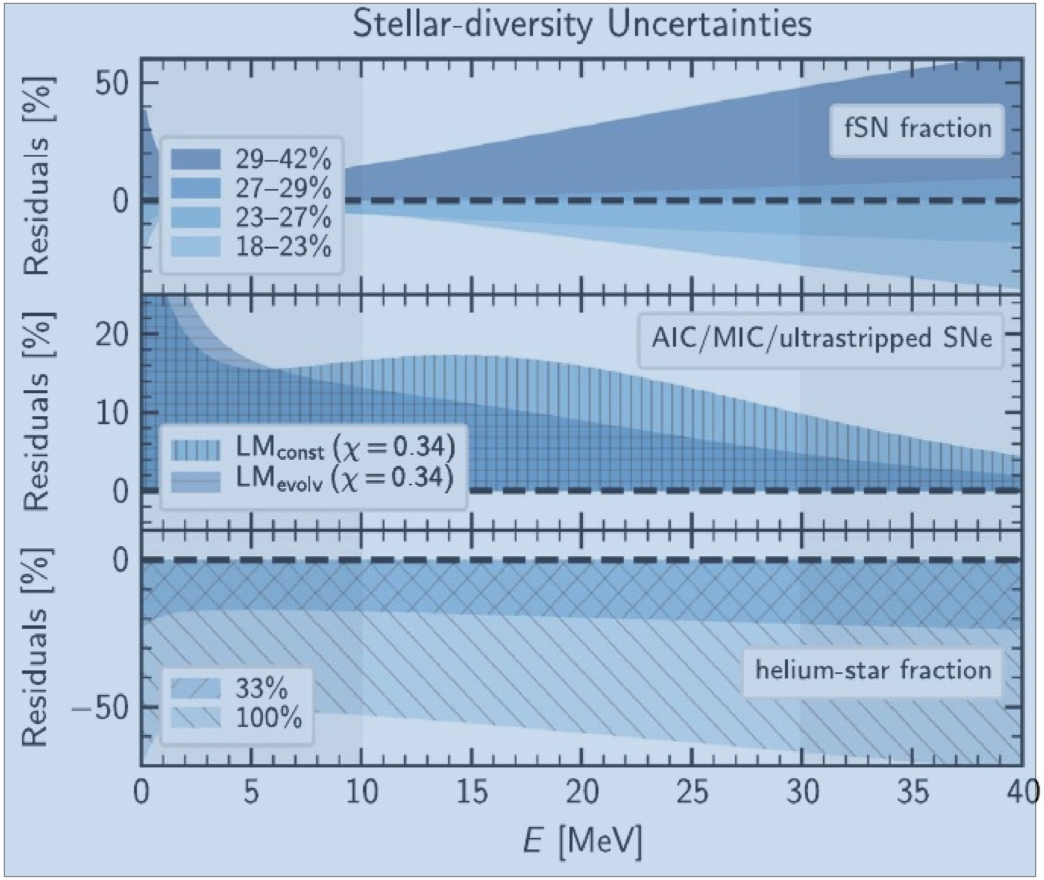
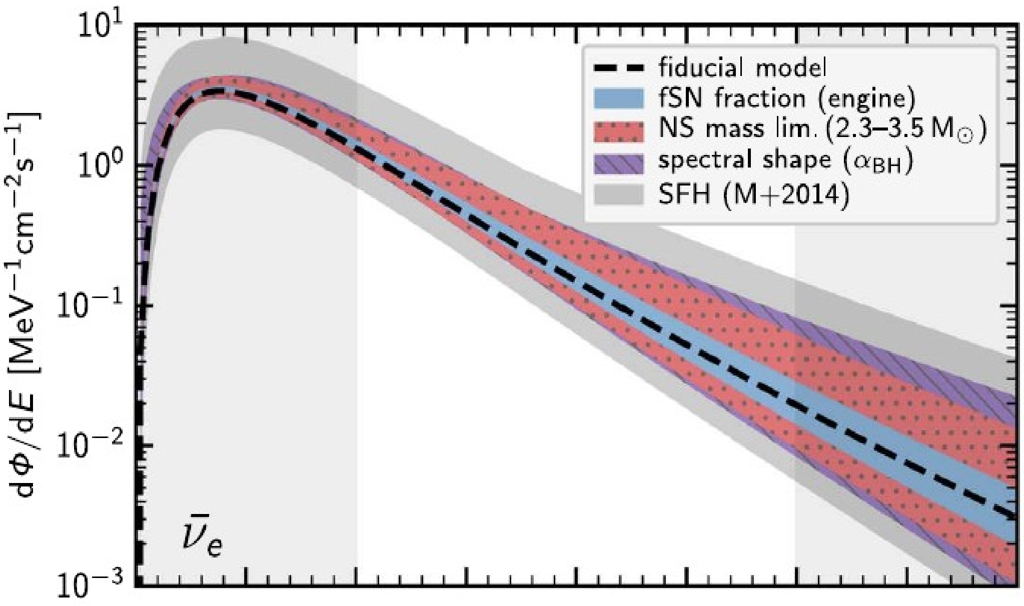




Upcoming wide-field surveys (e.g. Rubin LSST) → **rate of visible SNe**



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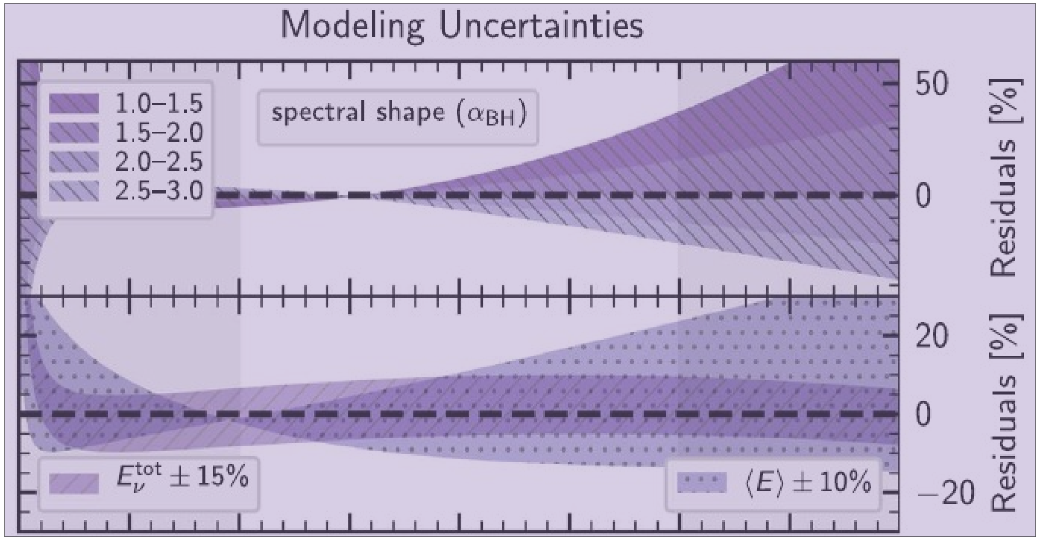

Future DSNB measurements (SK-Gd, JUNO, HK, DUNE):

- probe the **entire population of stellar collapse events** with its full diversity (incl. faint & failed explosions)
- Imprints of **new physics**?? (e.g., de Gouvêa et al. 2020, Tabrizi & Horiuchi 2021)

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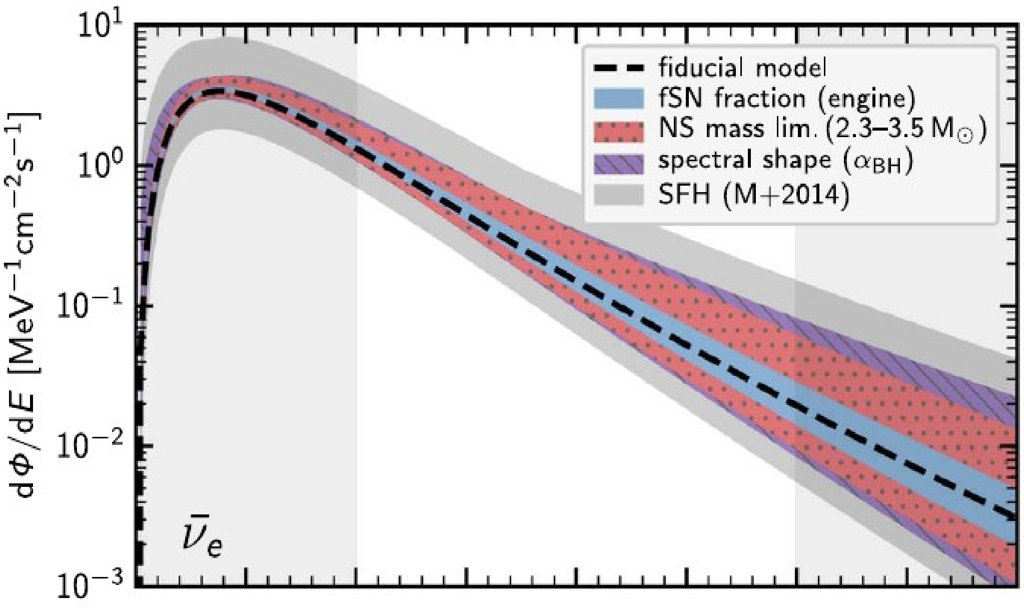

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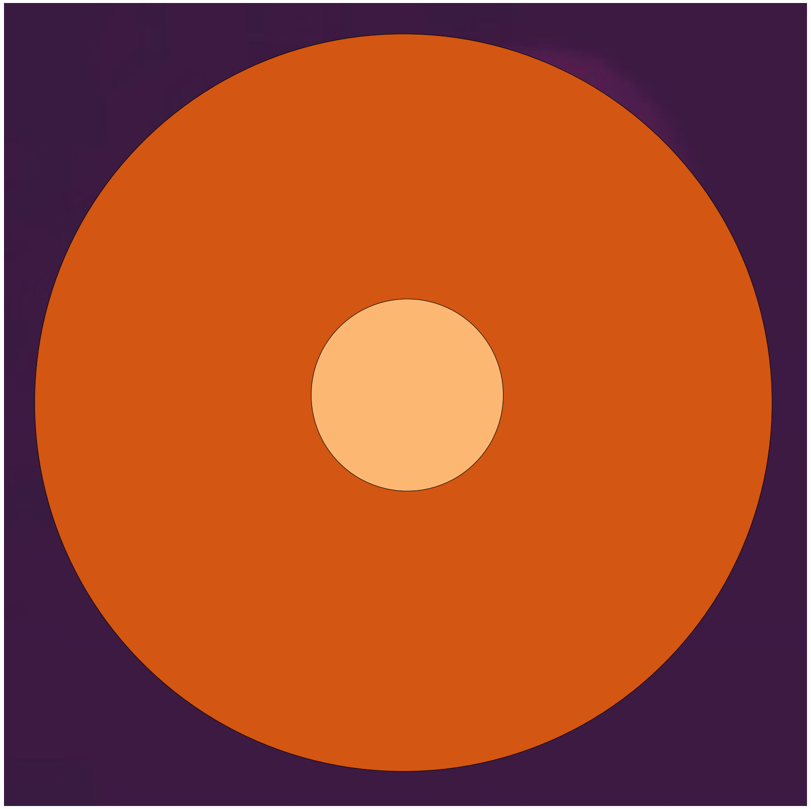
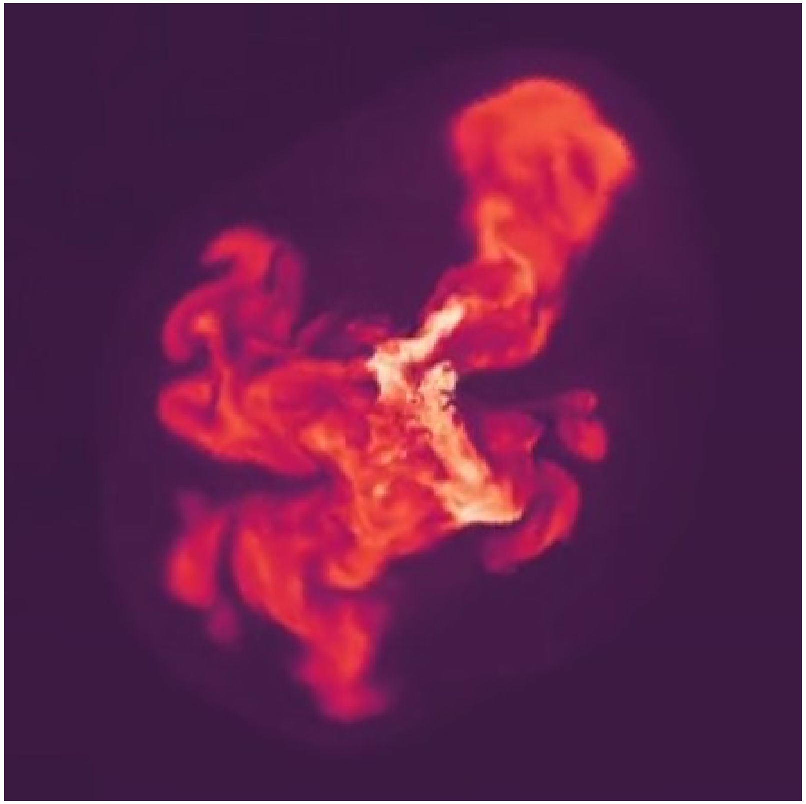
1D vs 3D (work in progress)



- models often computed under assumption of spherical symmetry (1D) due to computational costs



- Nature is intrinsically multi-dimensional (3D), e.g., hydro-dynamical fluid instabilities

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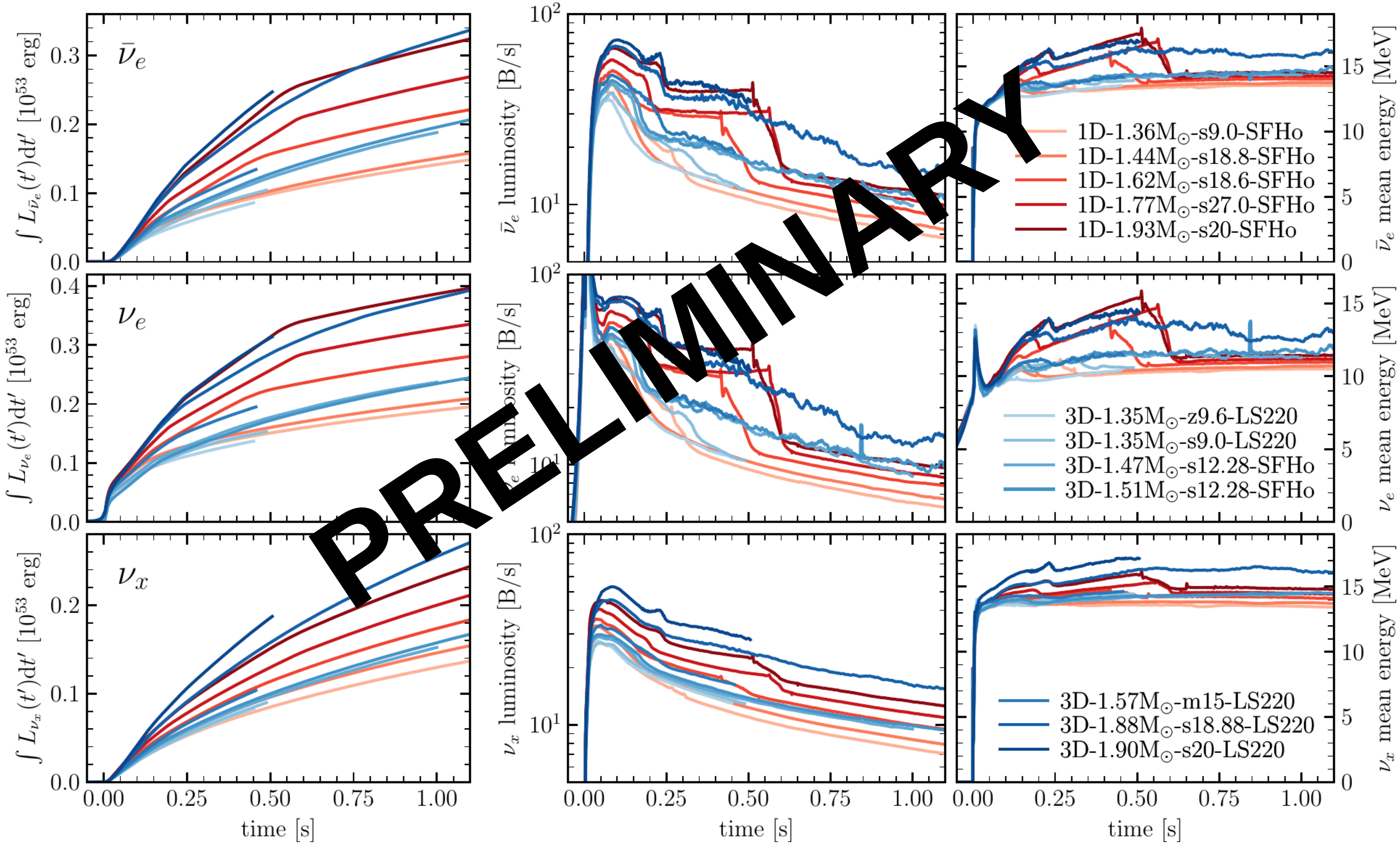

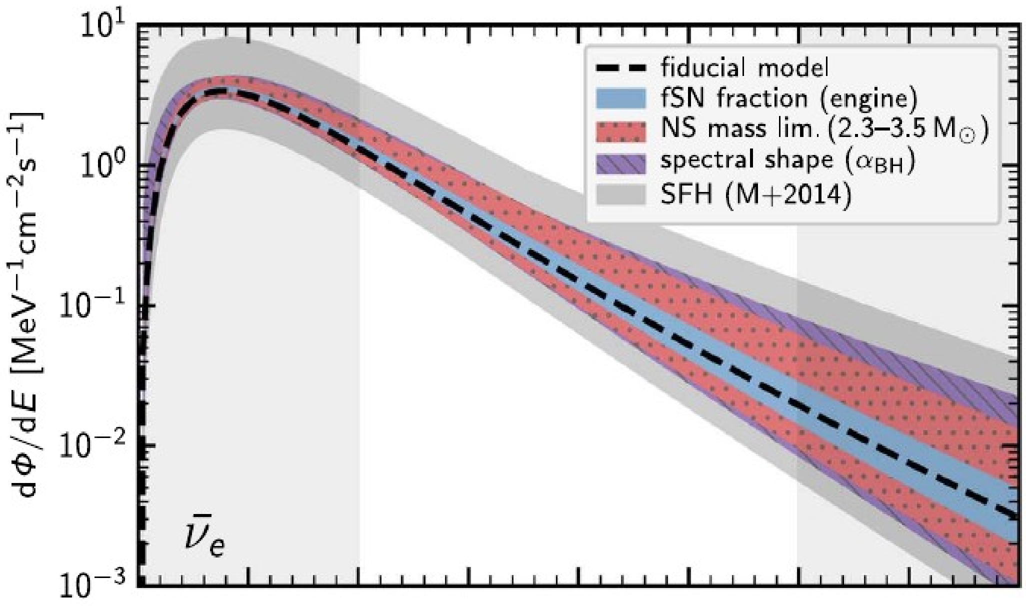

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Thank you!

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