Supernova simulations confront SN 1987A neutrinos

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Working Group Meeting of COST Action: Cosmic WISPers

based on arXiv:2308.01403 (Phys. Rev. D 108 (2023) 8, 083040)

with M. Heinlein, H.-T. Janka, G. Raffelt, E. Vitagliano, R. Bollig

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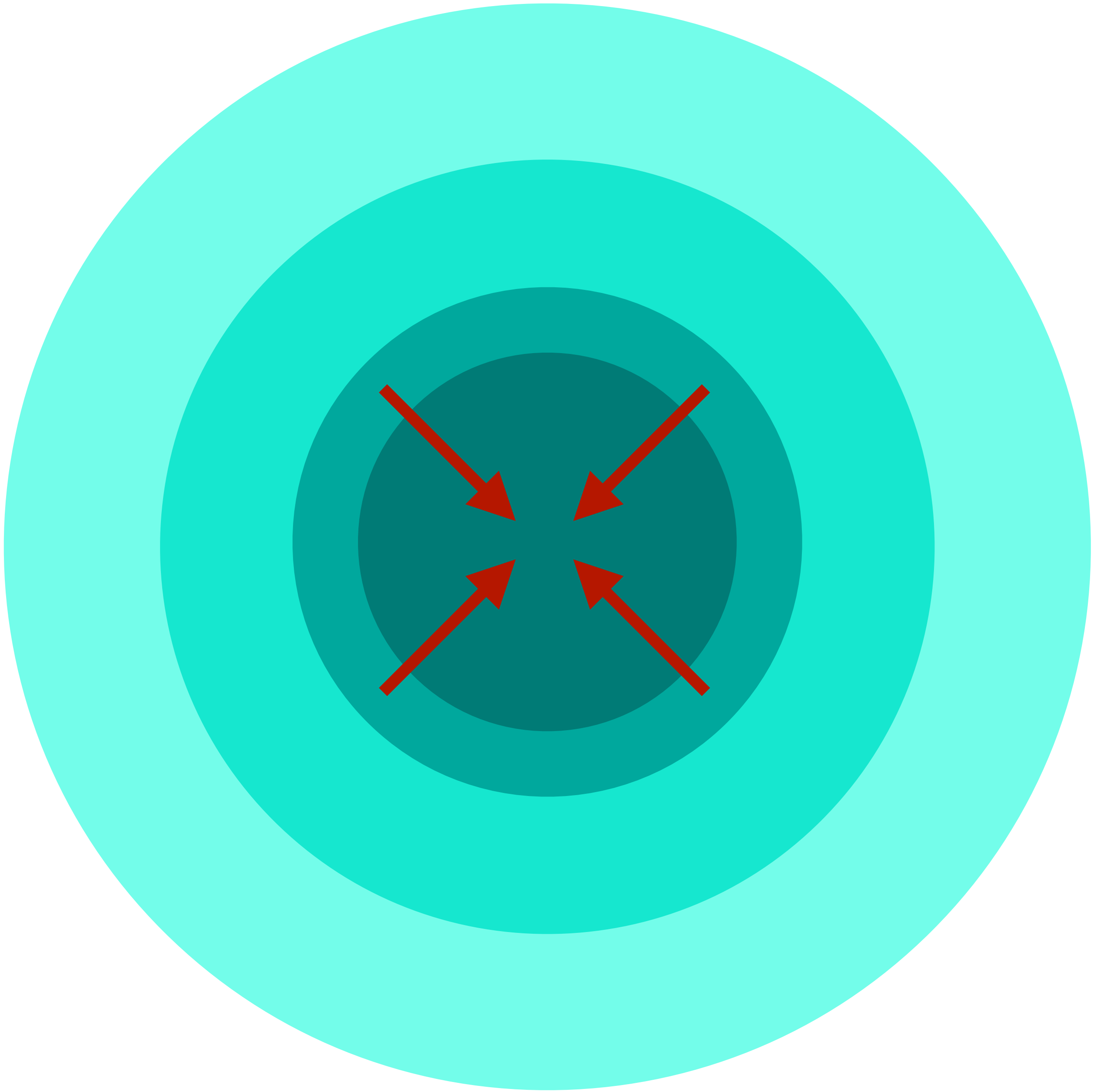
VILLUM FONDEN

Outline

- Supernova neutrinos
- SN 1987A and neutrino observations
- **Supernova simulations confront SN 1987A neutrinos**

Supernova neutrinos

Core-Collapse Supernovae

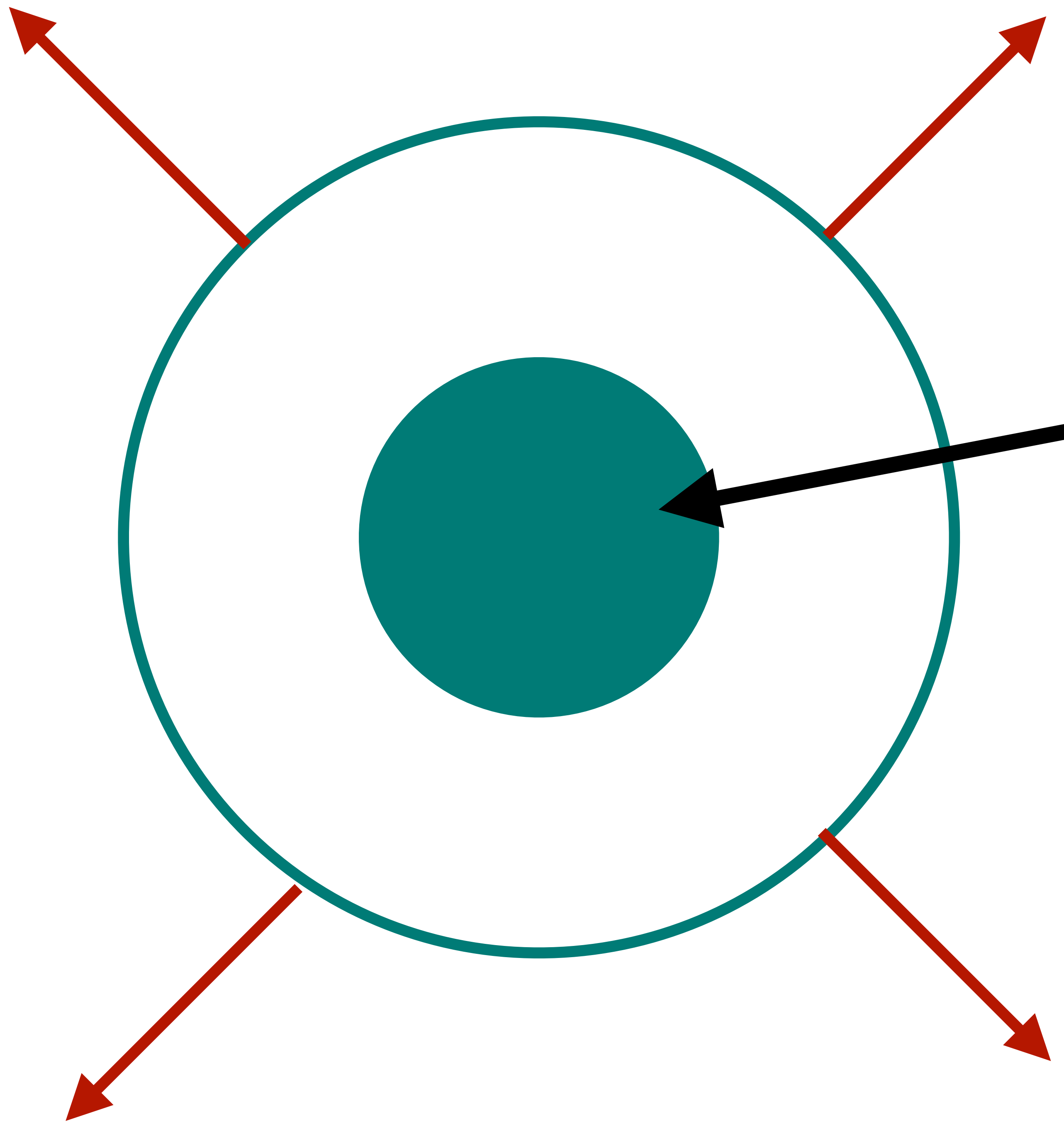


- Iron core with stopping of fusion
- Core collapses up to nuclear densities

$\rho \sim 10^{11}$ g cm^{-3} Neutrinos are trapped

$\rho \sim 10^{14}$ g cm^{-3} Rebounce

Core-Collapse Supernovae

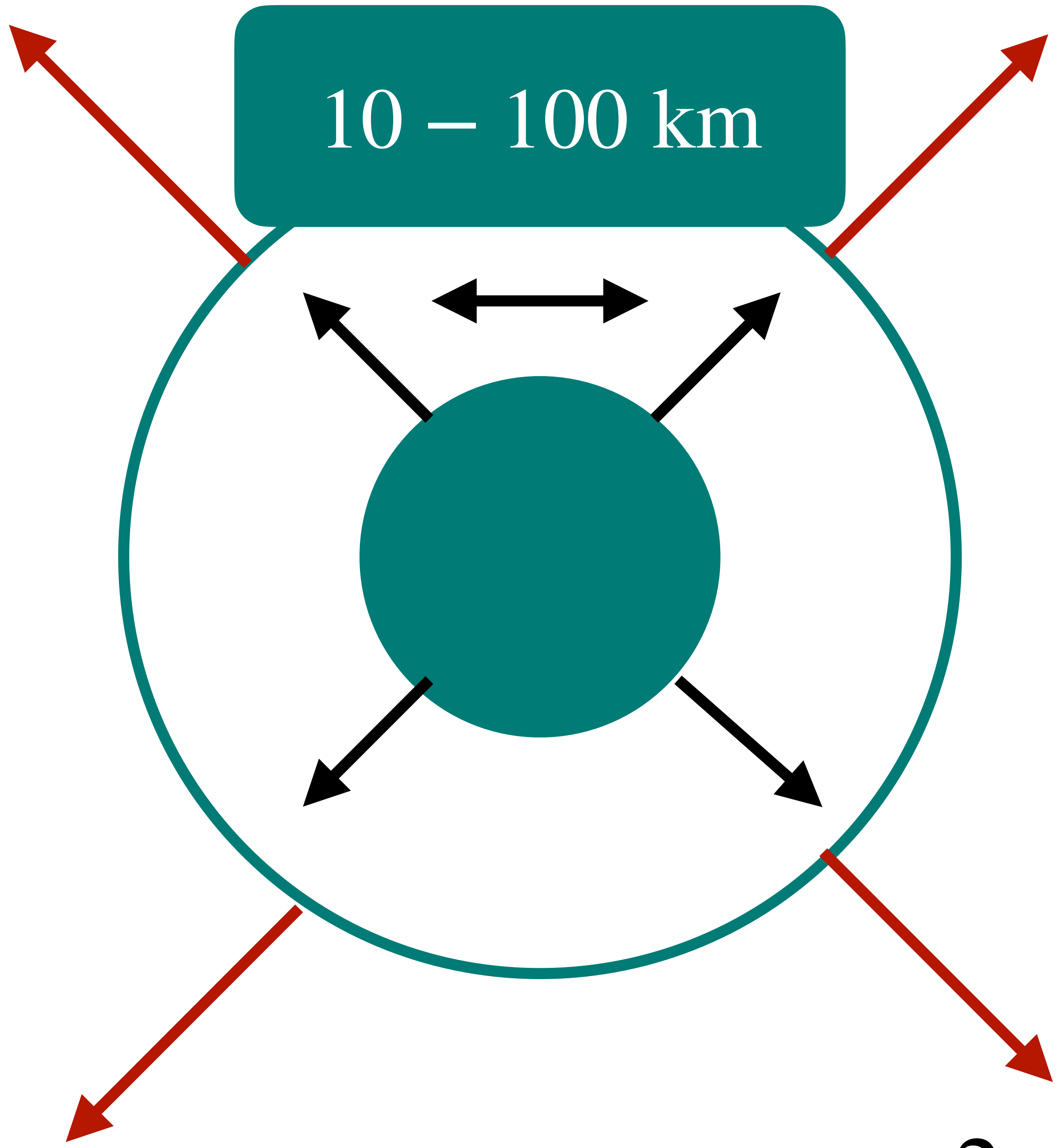


Neutrinos trapped and degenerate!

- Iron core with stopping of fusion
- Core collapses up to nuclear densities
- Rebounce launches shock wave, leaving **accreting** proto-neutron star (PNS) in the center
- Shock wave stalls, revived by neutrinos depositing energy

Core-Collapse Supernovae

$E_\nu \simeq 10^{53}$ erg



$$\tau \simeq \frac{R^2}{\lambda_{\nu N}} \simeq 1 - 10 \text{ s}$$

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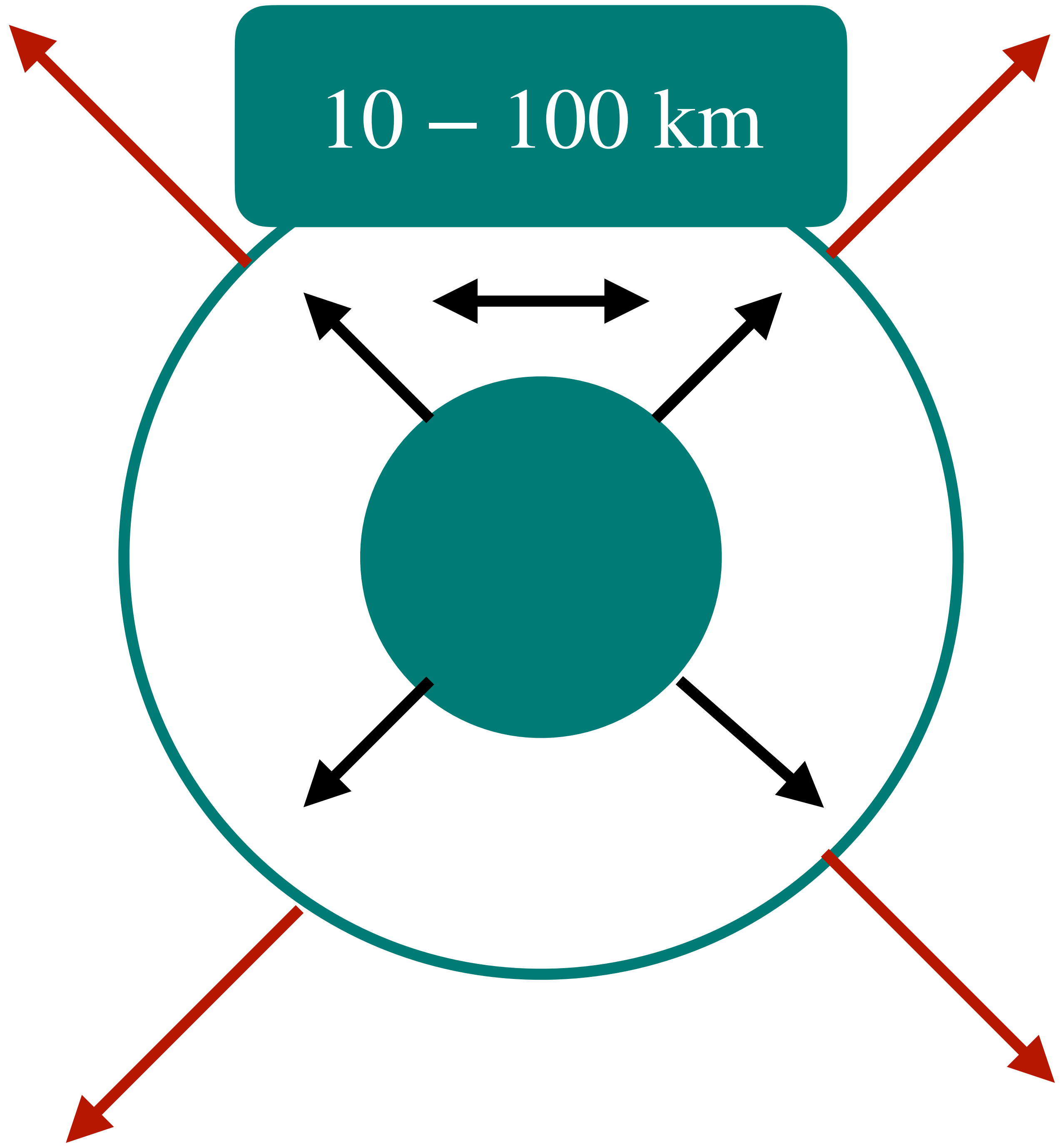

PNS mass main order parameter for neutrino flux!

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Neutrino observations from SN 1987A

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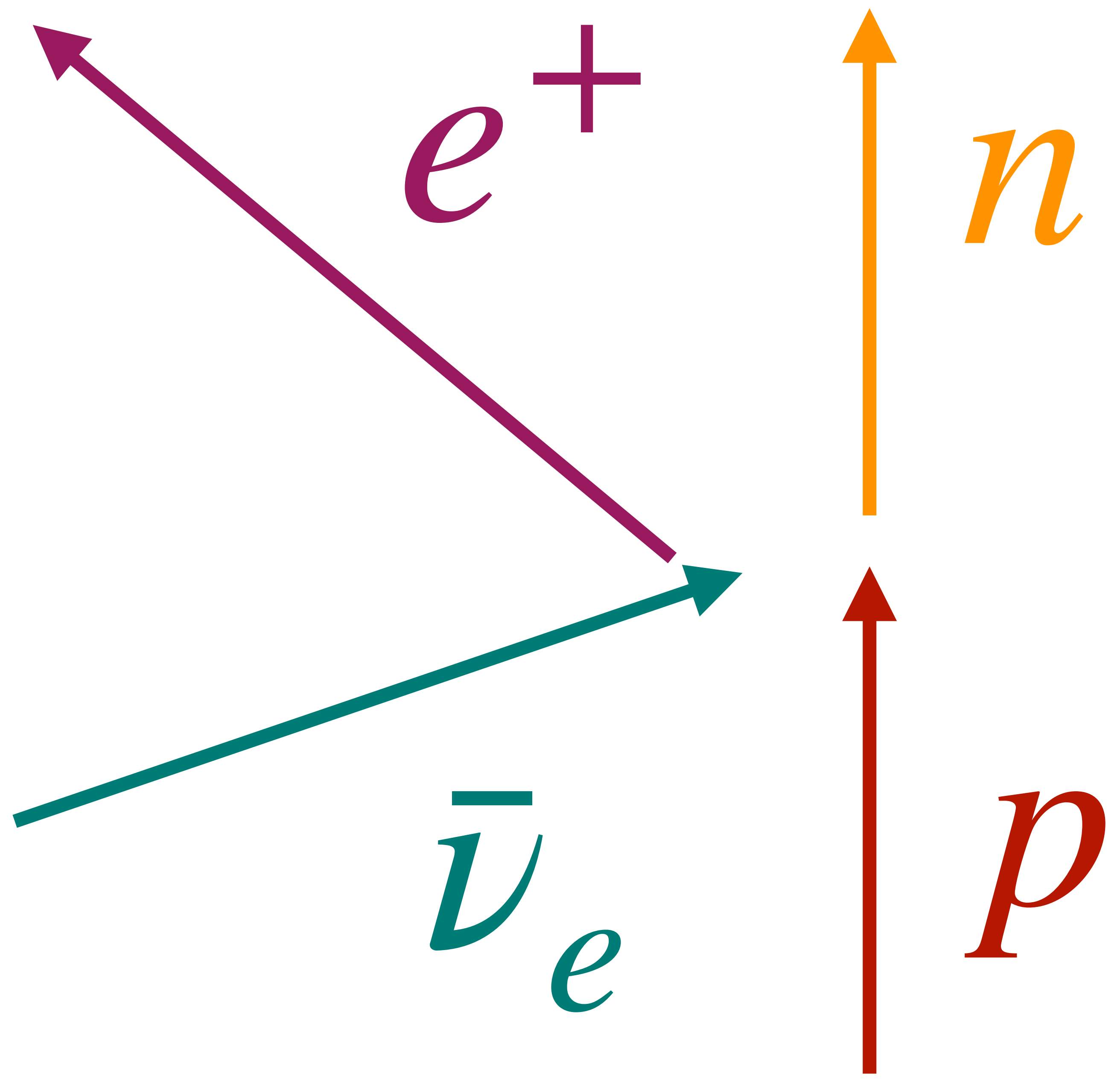
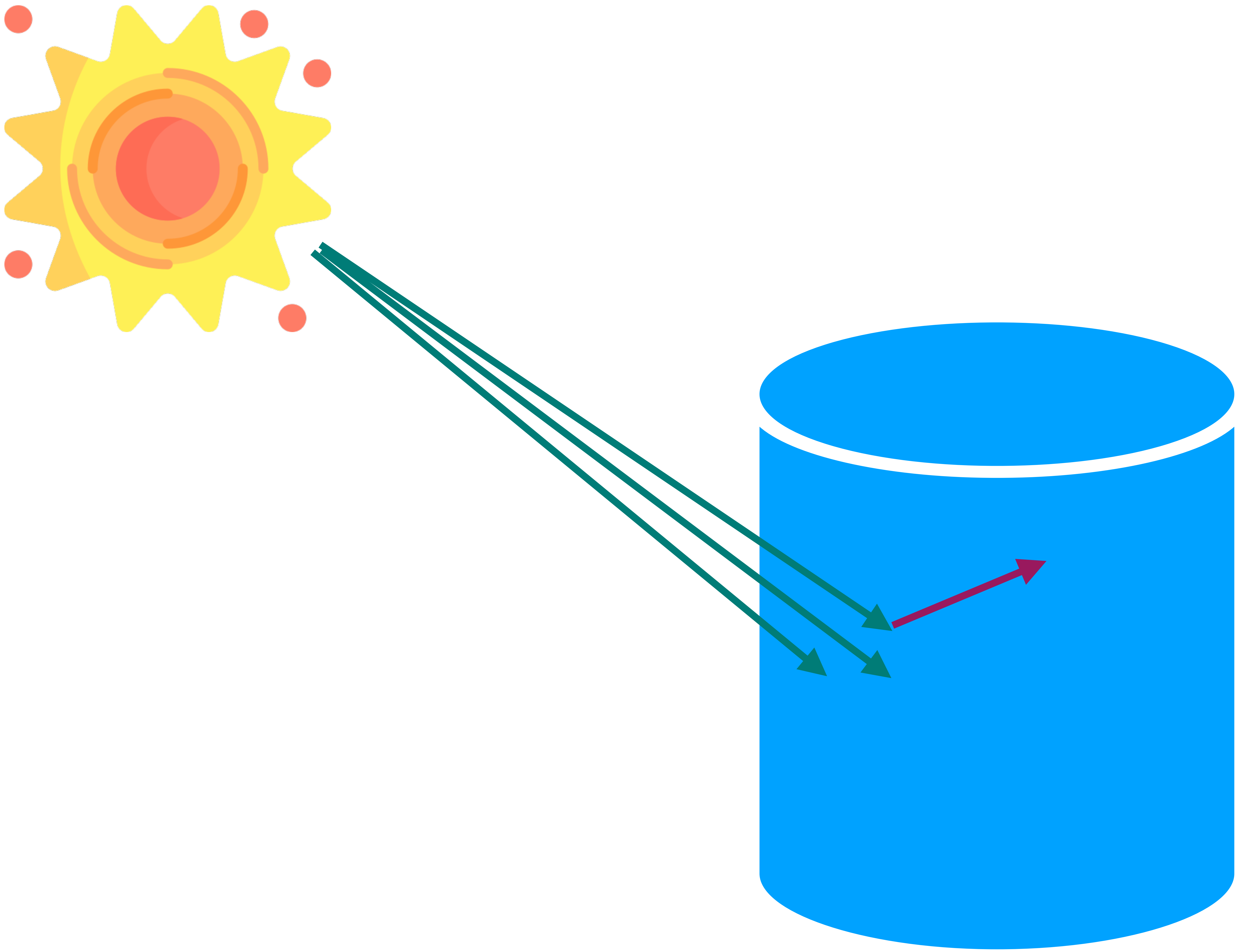
Credits to E. Vitagliano

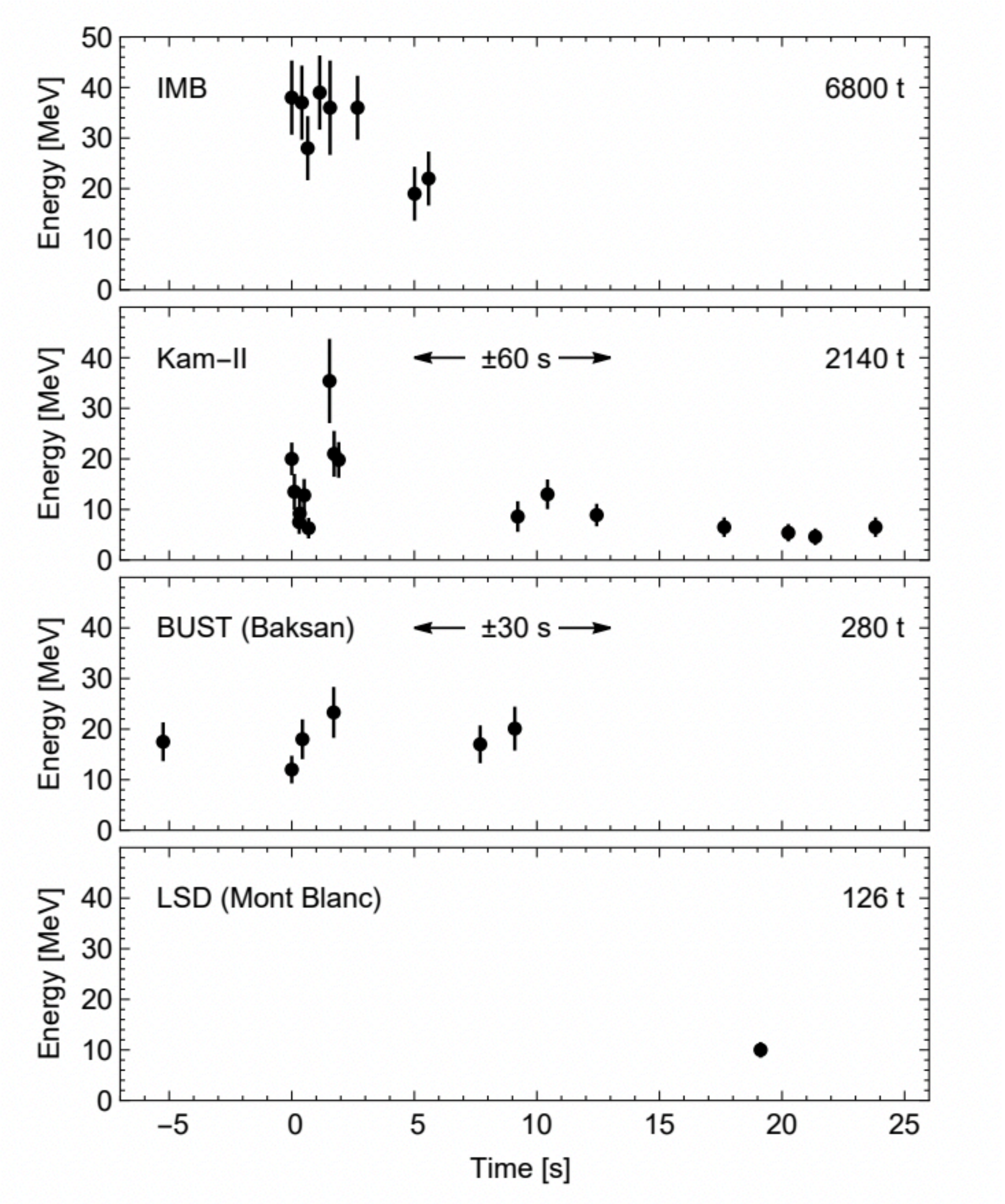
SN 1987A neutrino observations



$$\sigma_{\nu p} \propto E_\nu^2$$



SN 1987A neutrino observations



Several puzzles

- ✦ 7 seconds gap in Kamiokande
- ✦ Anisotropic angular distribution
- ✦ Precursor events at MontBlanc (not shown)

Supernova simulations confront SN 1987A neutrinos

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- Increased confidence in the neutrino delayed explosion mechanism - 3D simulations show self-consistent explosions

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- Significant updates to the simulations
    - **Convection**
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arXiv:2108.08463: Olsen, Qian

arXiv:2301.11407: Dedin Neto, de Santos, de Holand, Kemp

arXiv:2306.08024: Li, Beacom, Roberts, Capozzi

Model choice

- 3D models more reliable on the detailed time structure during first second
- 1D and 3D models consistent on the time-integrated signal during first second

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- 1D and 3D models consistent on the time-integrated signal during first second
- 3D models have severe limitations
    - Cannot systematically scan parameter space (PNS mass)
    - Cannot extend to more than 1 second (statistical pitfalls?)

Model choice

PNS mass ($M_\odot$)

1.36 1.44 1.62 1.77 1.93

Equation of state (EoS)

DD2

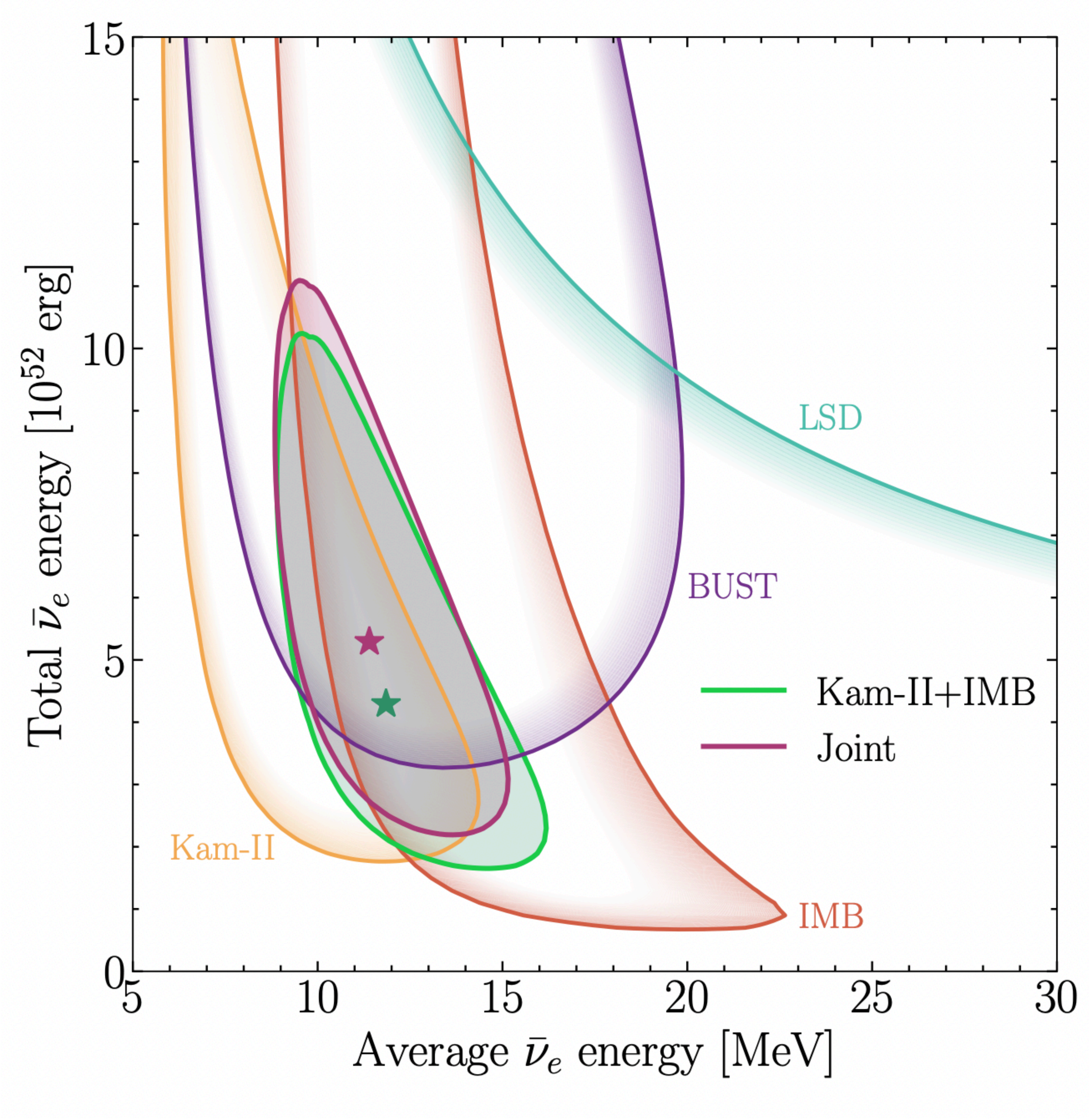
LS220

SFHo

SFHx

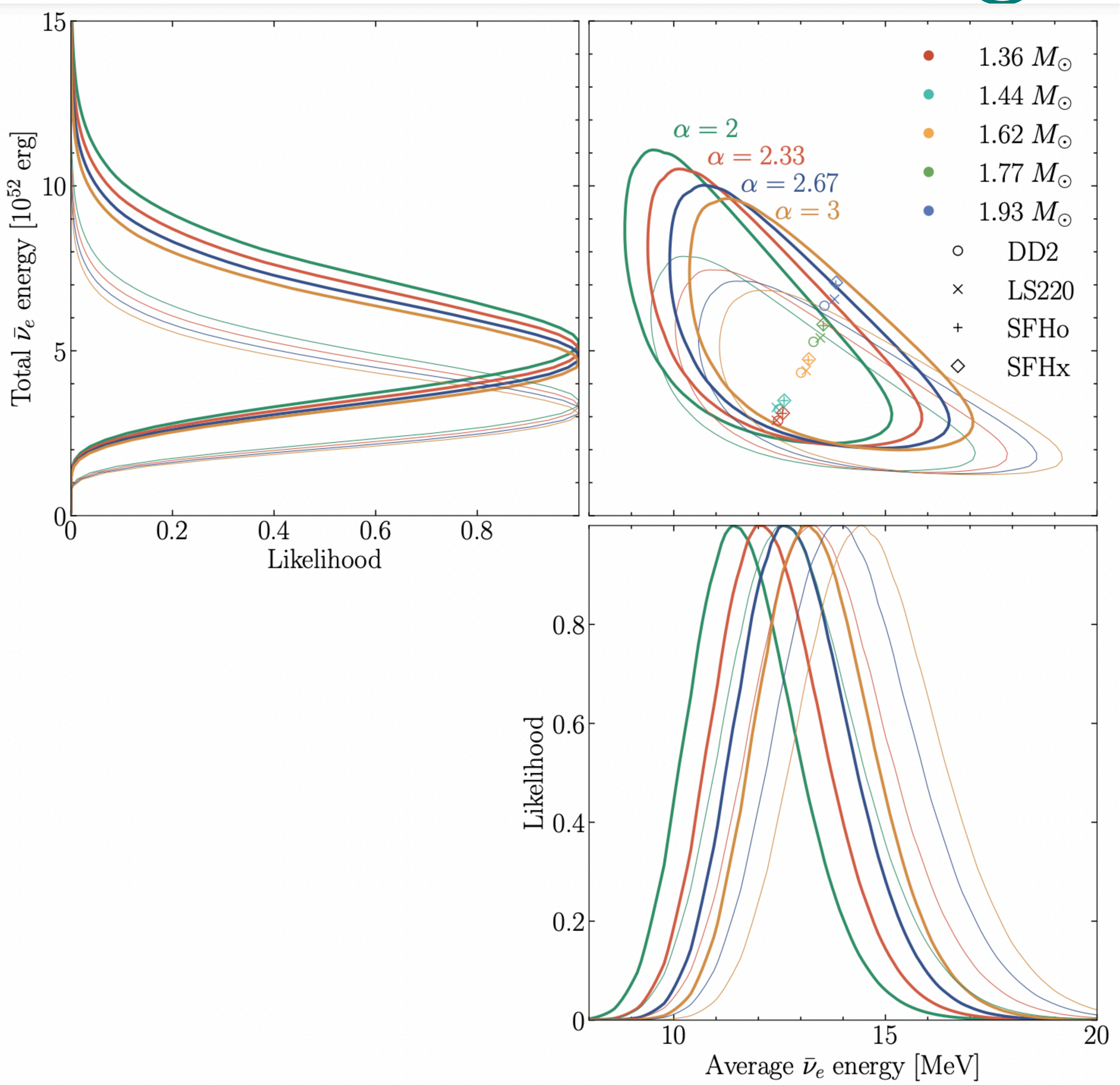
All 1D
(Reliable for the sparse data of SN 1987A!)

Time-integrated signal



- ✦ Tension between Kam-II and IMB — slightly relieved, less than 2σ
- ✦ First combined analysis including all experiments!
- ✦ Assuming neutrino blackbody spectrum

Time-integrated signal



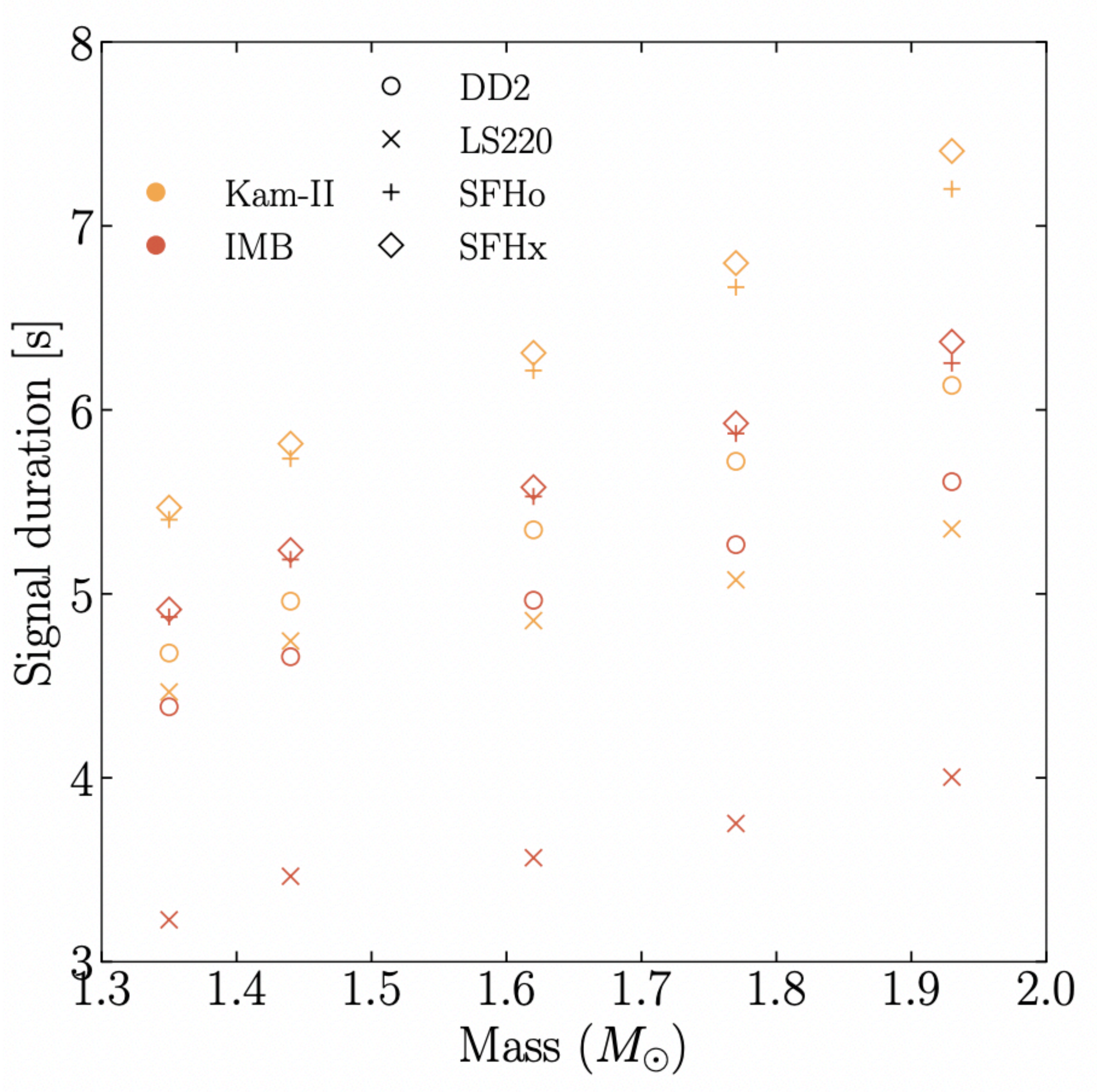
- Spectra can be pinched

$$\frac{d\mathcal{F}_{\bar{\nu}_e}}{d\epsilon_\nu} = \frac{E_{\rm tot}^{\bar{\nu}_e}}{\Gamma_{1+\alpha}\bar{\epsilon}^2} \frac{(1+\alpha)^{1+\alpha}}{4\pi d_{\rm SN}^2} \left(\frac{\epsilon_\nu}{\bar{\epsilon}}\right)^\alpha e^{-(1+\alpha)\epsilon_\nu/\bar{\epsilon}}$$

- Most SN models lie within 2σ regions — consistency with data

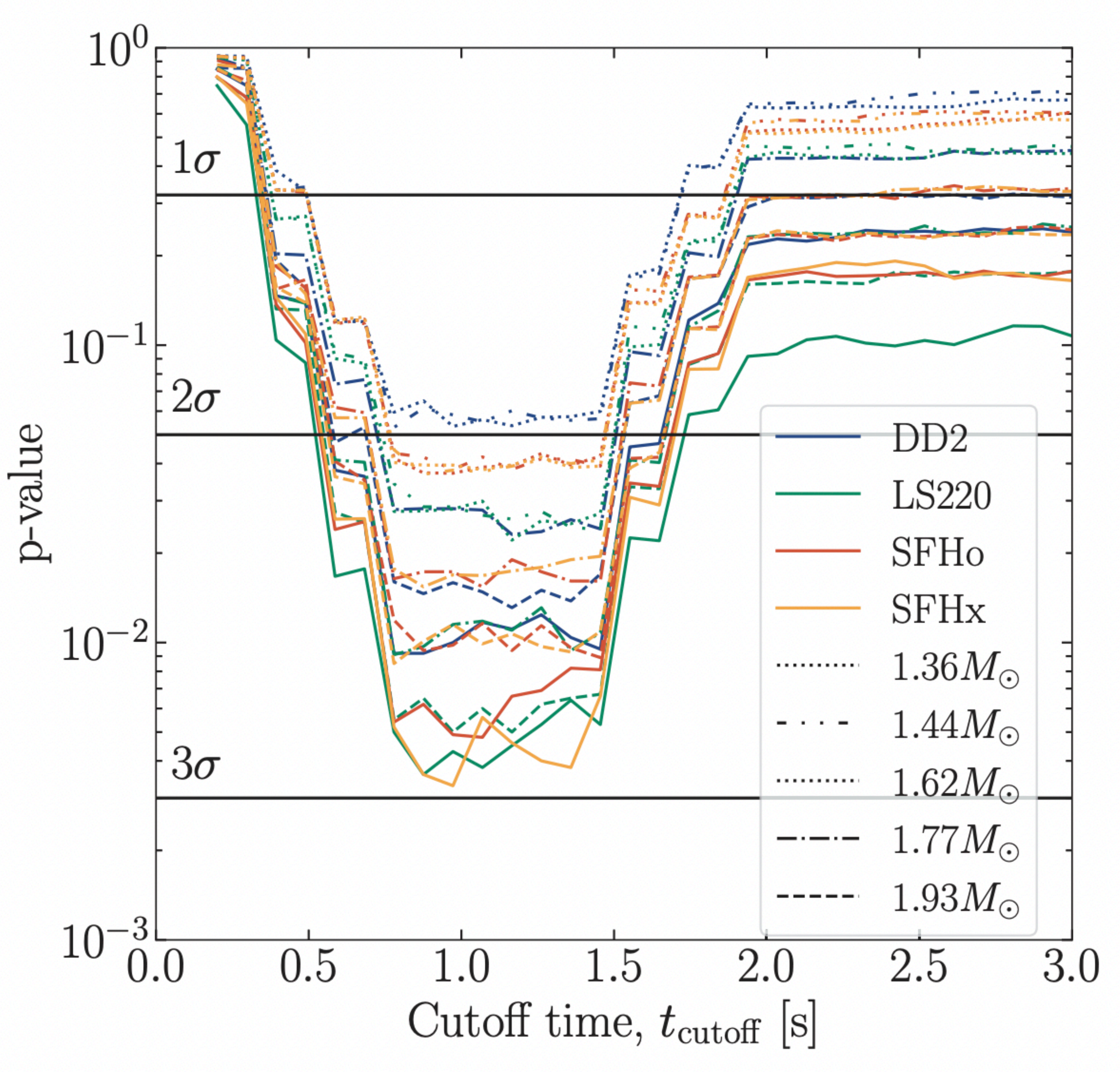
- Tension with heavy PNS

Time structure of the signal



- Signal duration less than 8 seconds for **all** models
- Tension with late-time Kam-II events
- Key role played by convection and updated neutrino-nucleon opacities

First second of emission



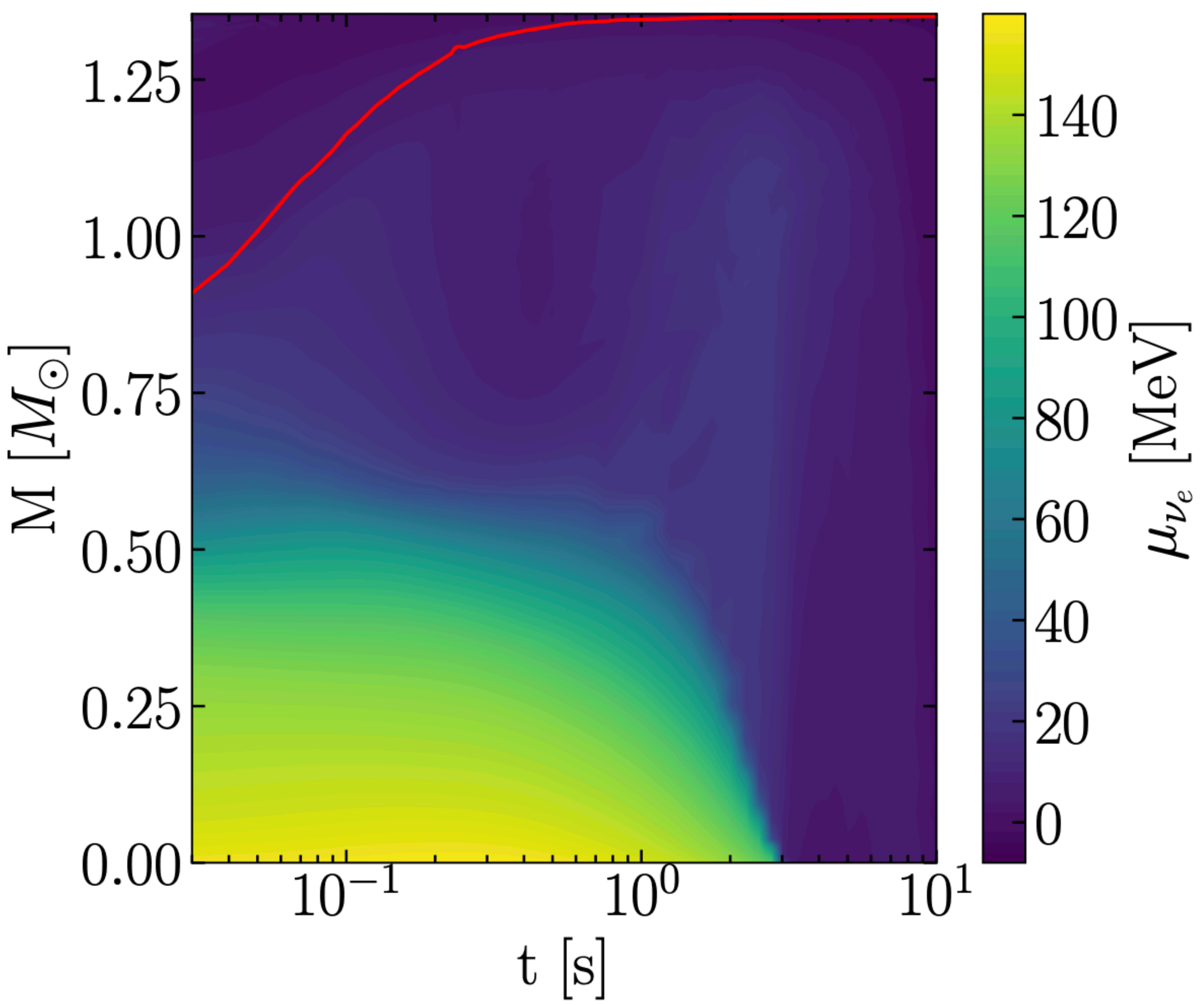
- Kolmogorov-Smirnov on first-second events to compare with Li et al., 2306.08024
- Cutting at 1 s maximizes tension (events 3 and 4 have low energy), but globally insignificant
- Models with low PNS less than 2 sigma even cutting the events

Conclusions

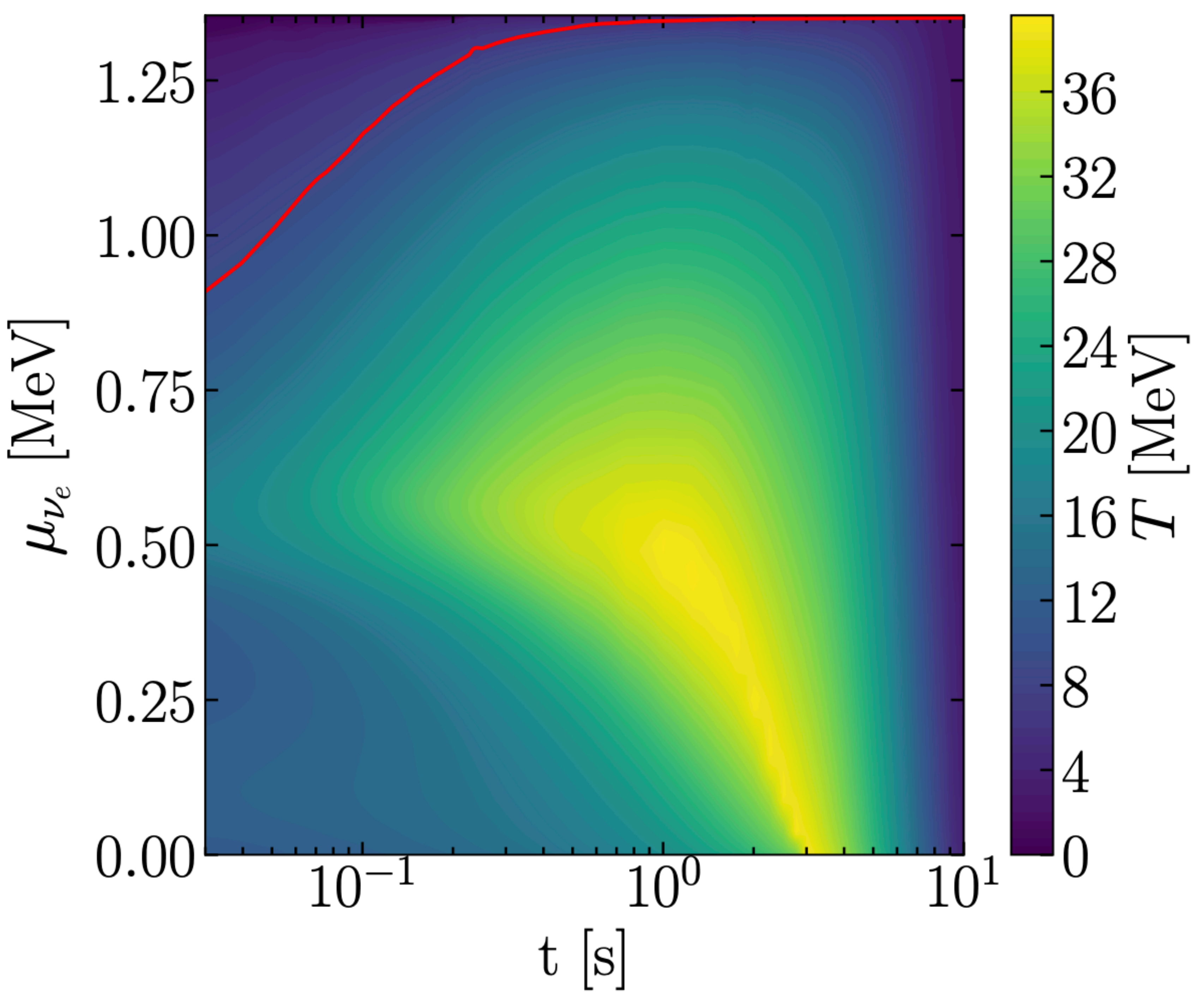
- SN 1987A generally consistent with modern simulations, both all-duration and first second
- Requires light PNS $\lesssim 1.8\ M_\odot$
- Origin of late-time events?

Backup slides

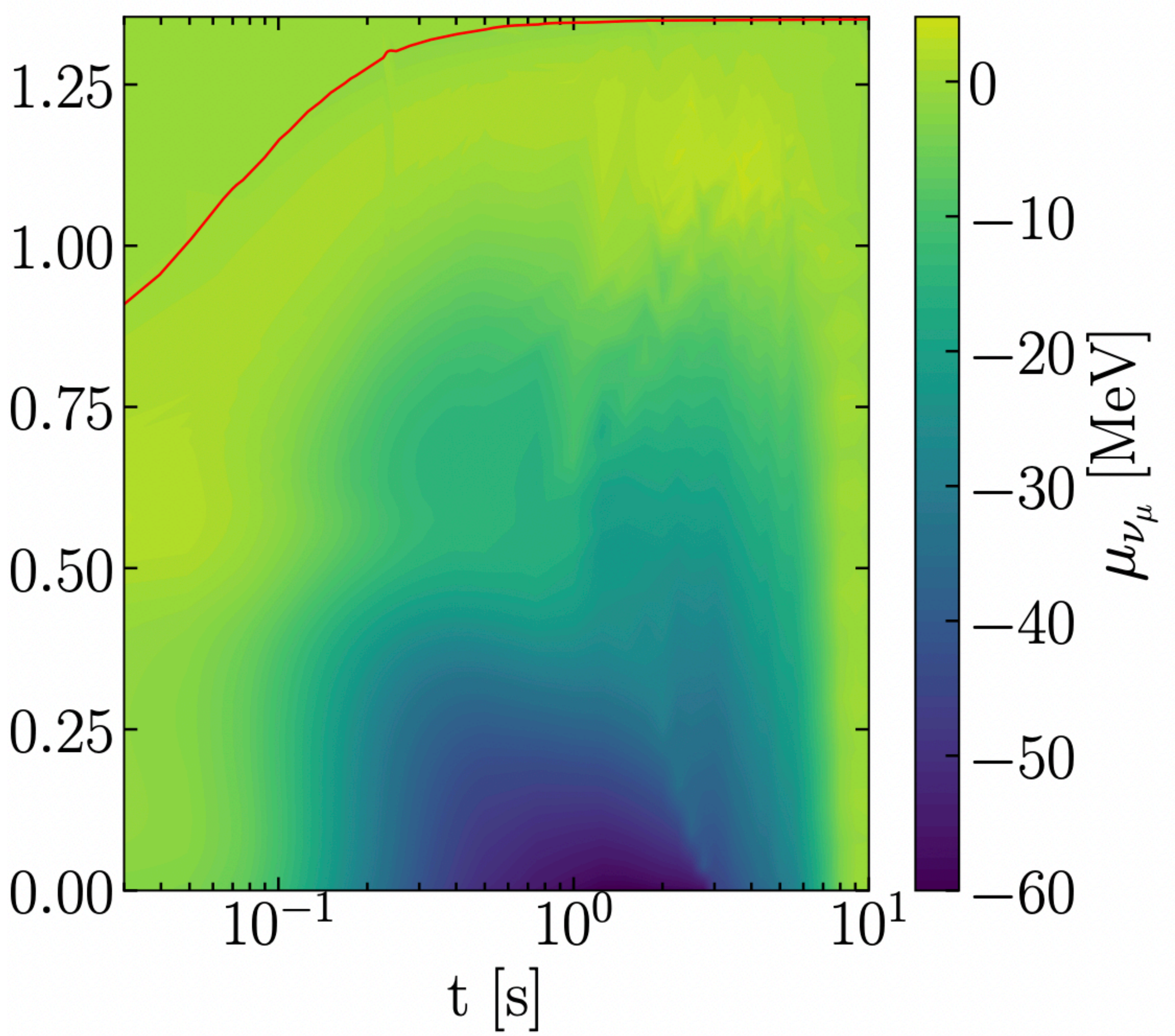
Core-Collapse Supernovae



PNS deleptonizes and cools

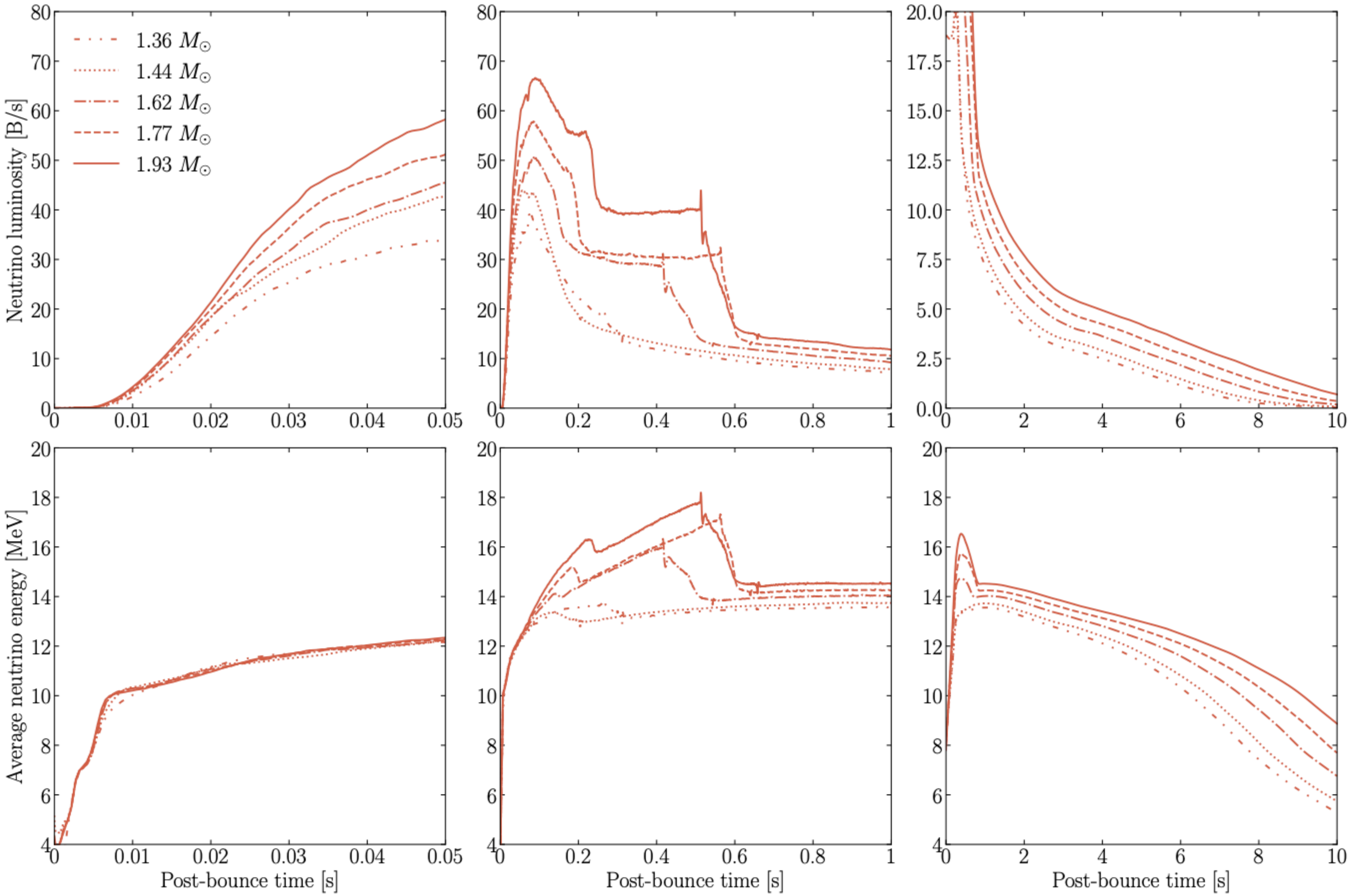


Heats up the external material



Produces muons and muon neutrinos

SN models - neutrino signal



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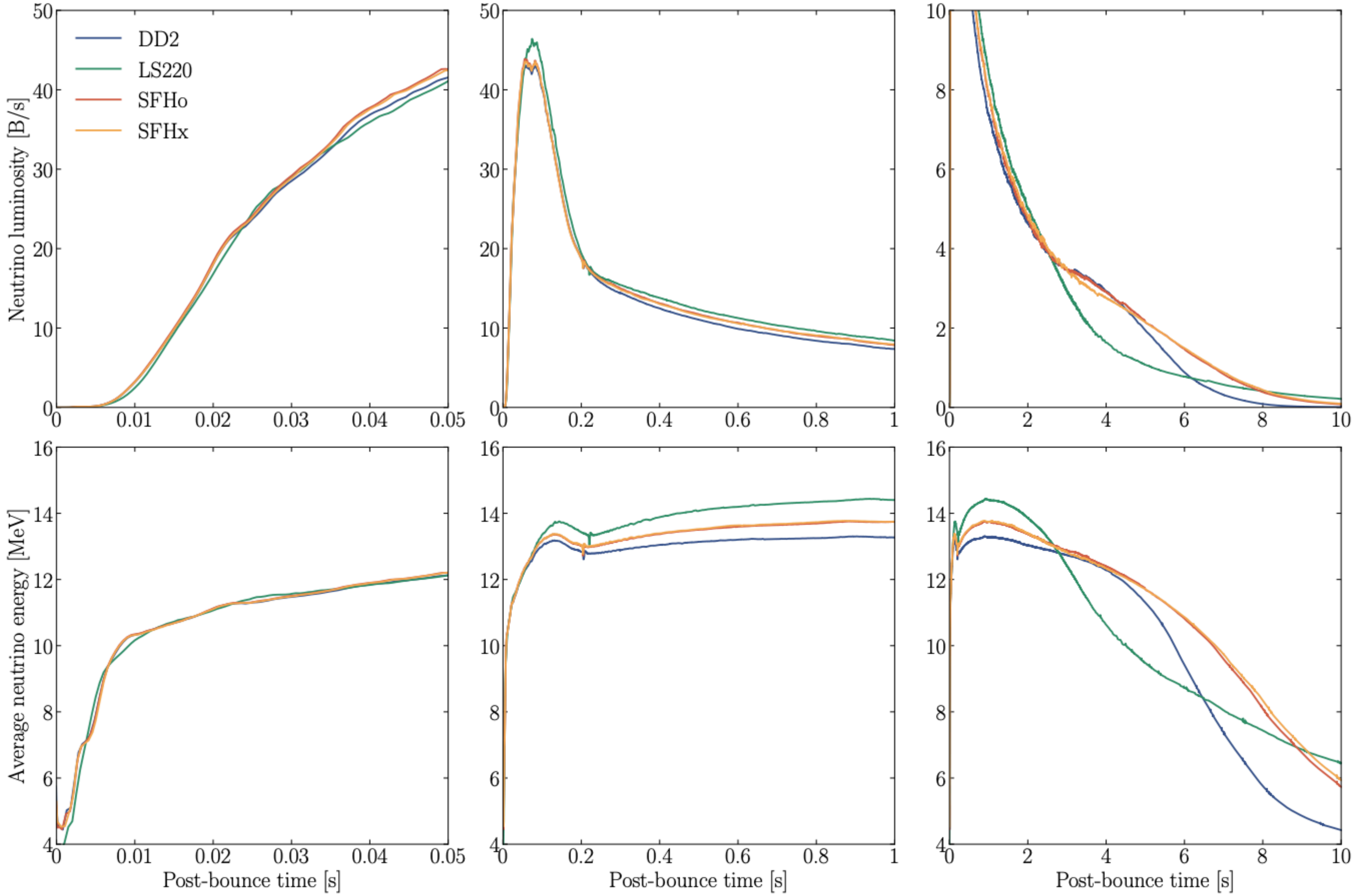

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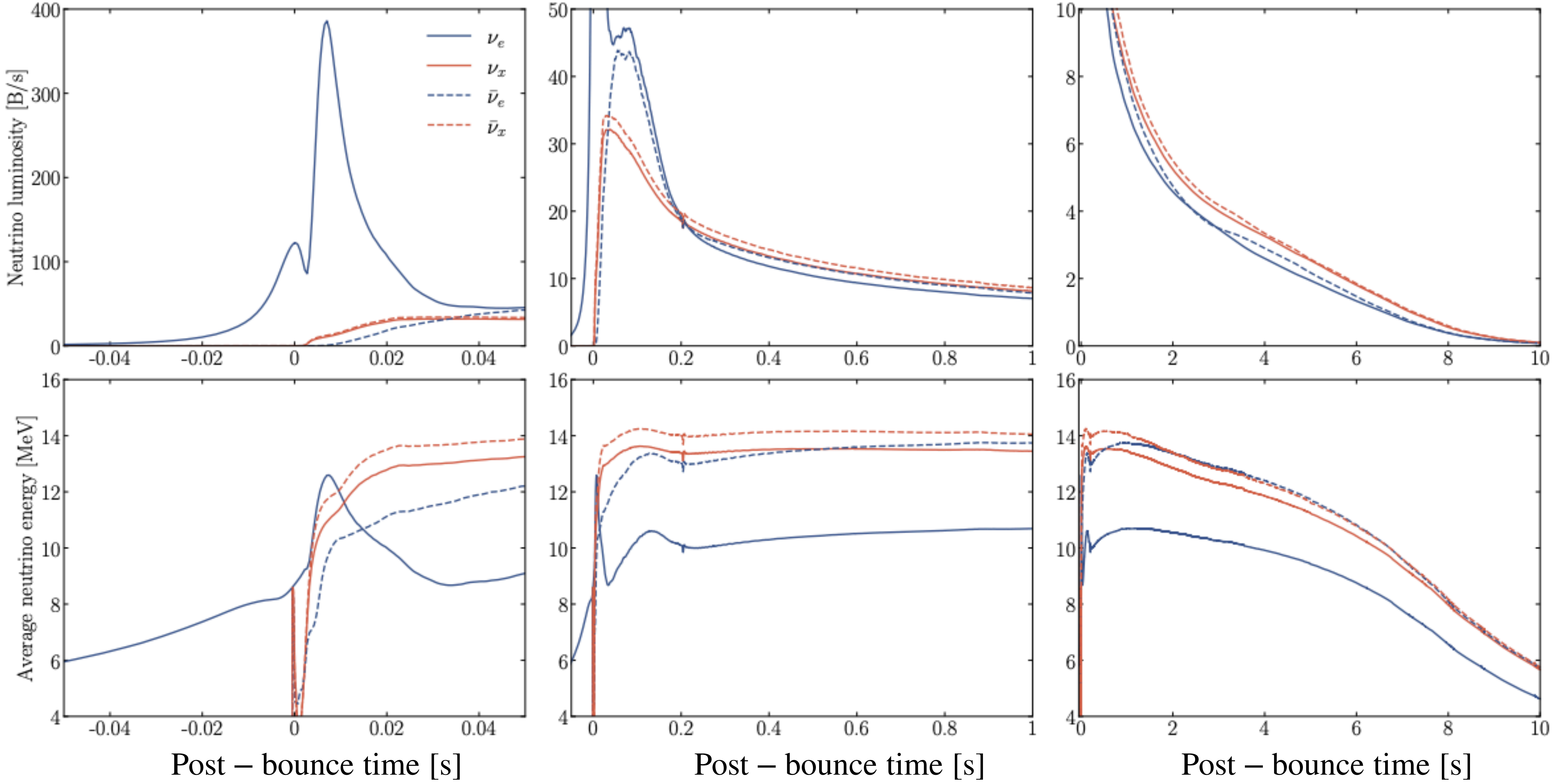
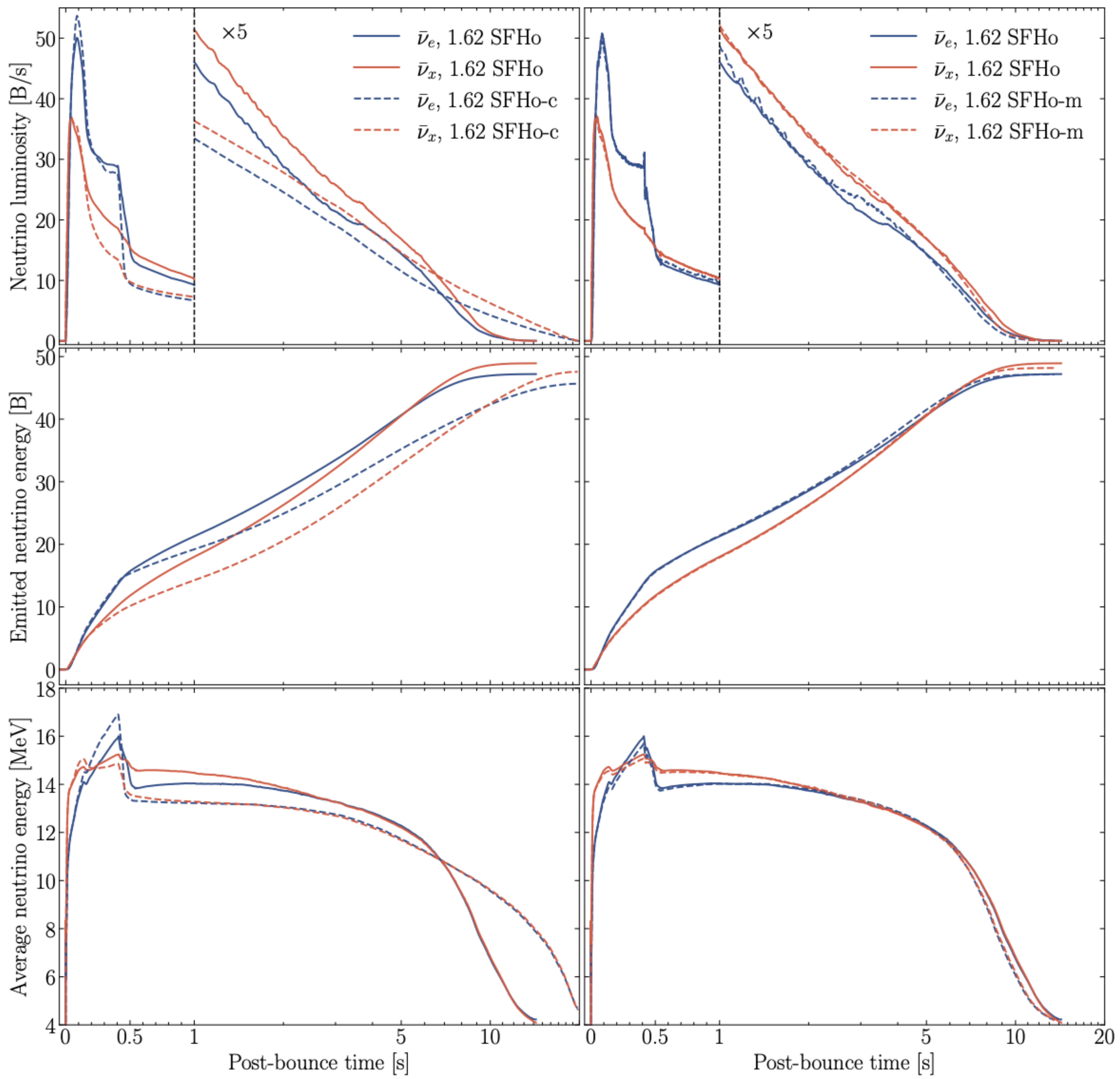
Flavor dependence of neutrino signal



Convection vs. no convection



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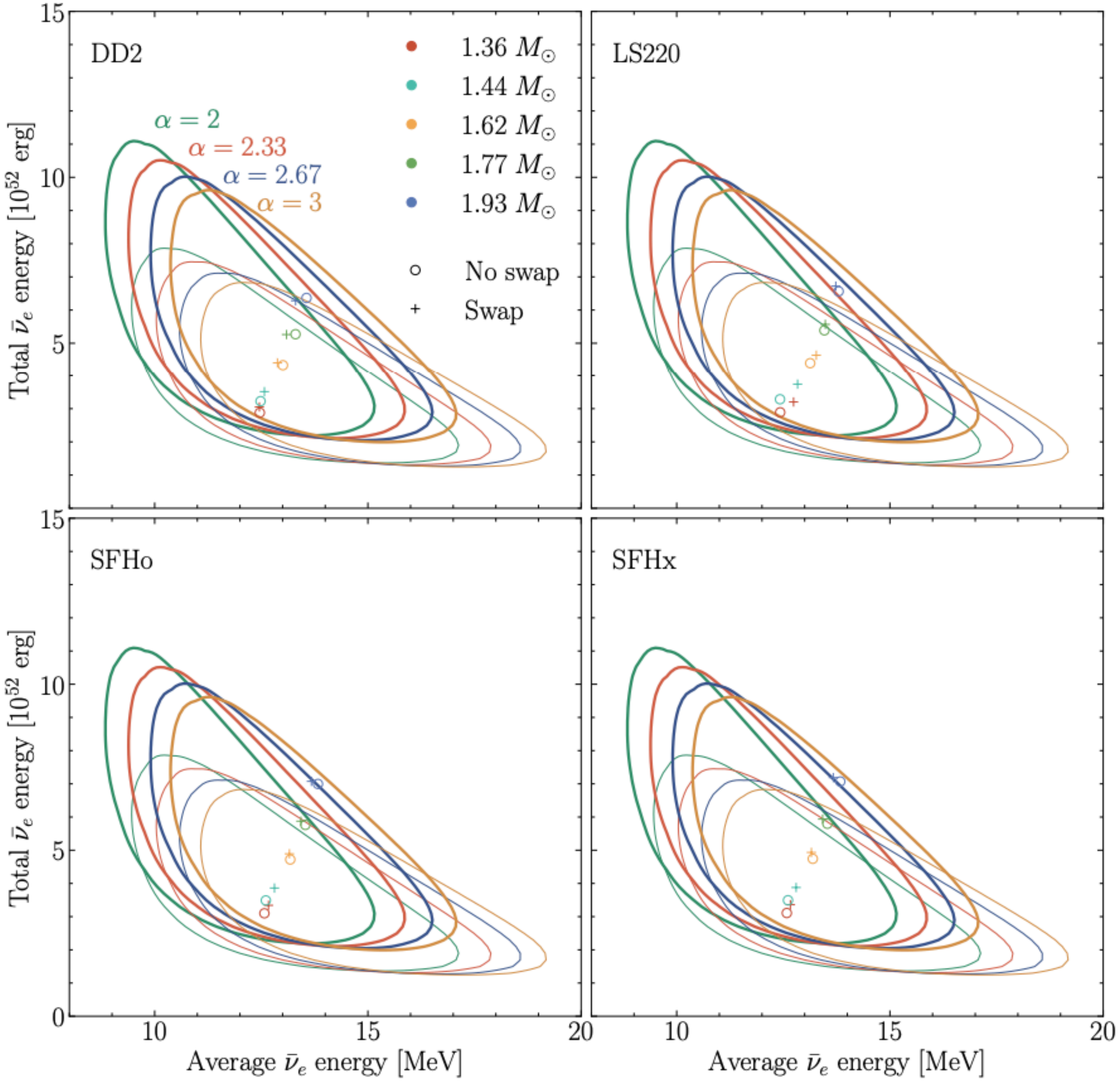
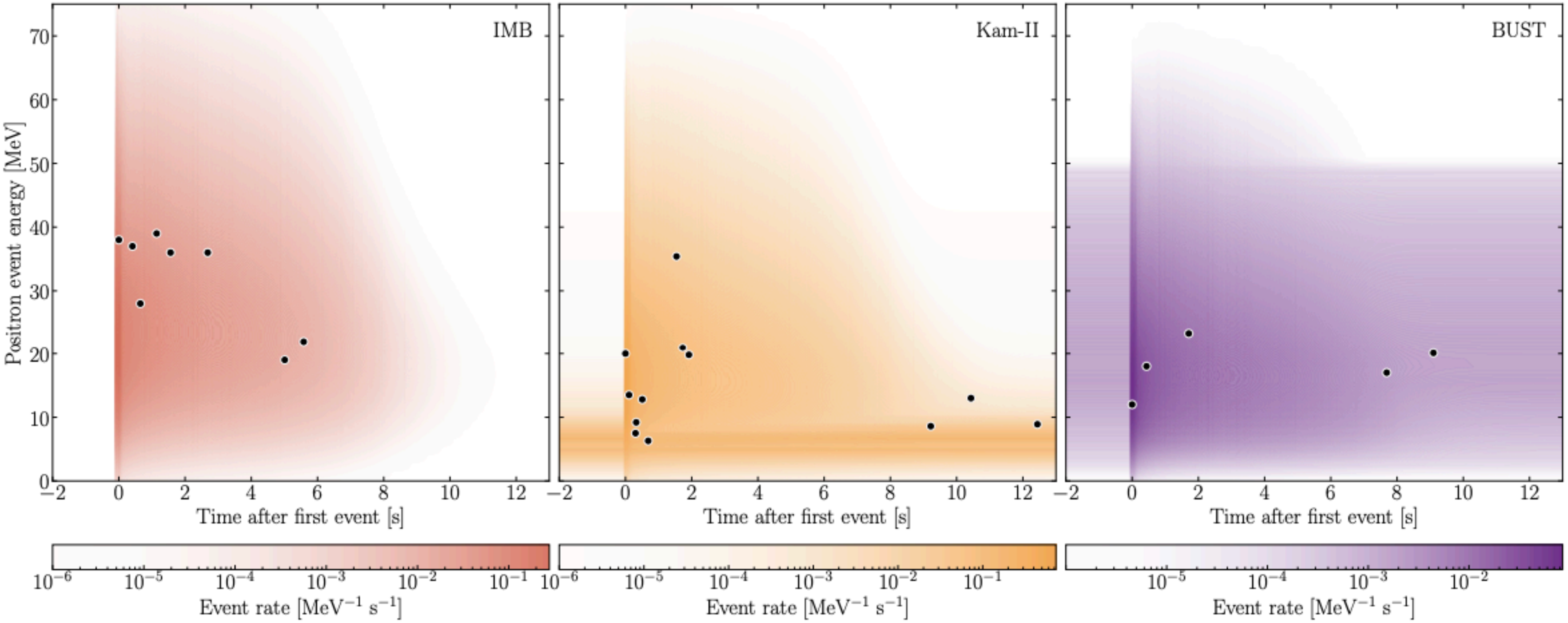
Impact of flavor conversion

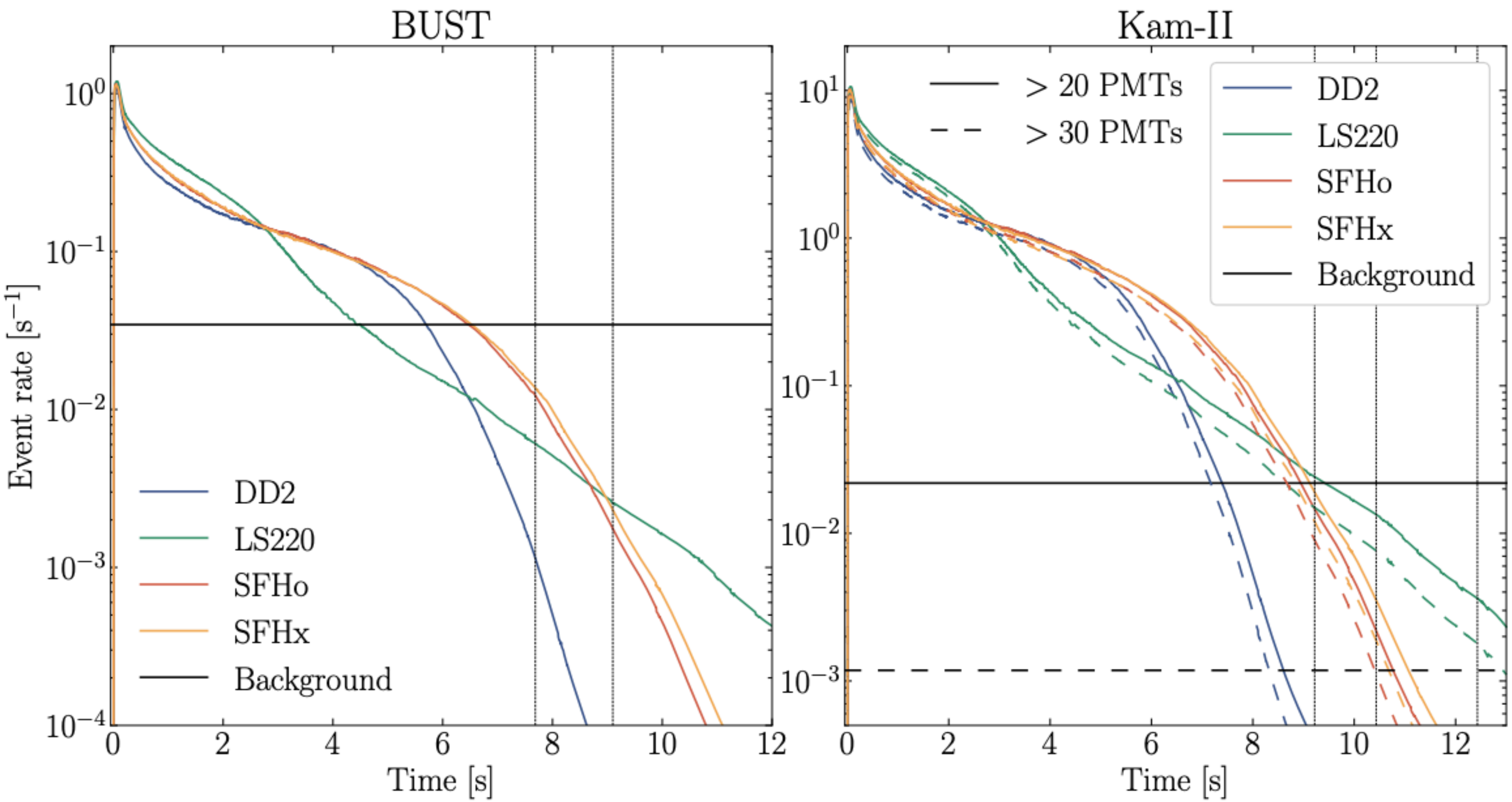


Event rates

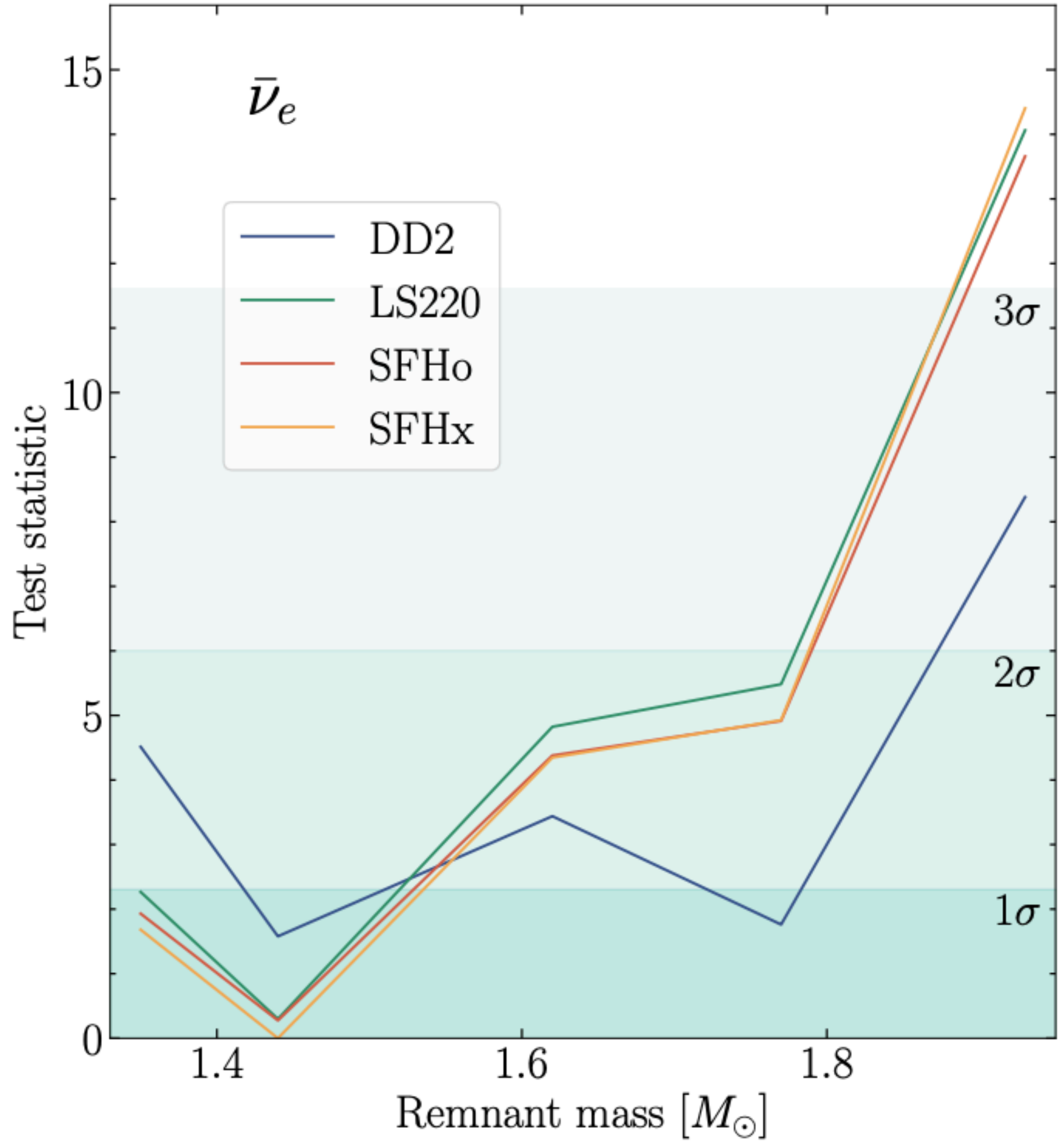


IMB
Kam-II
BUST
Positron event energy [MeV]
Time after first event [s]
Time after first event [s]
Time after first event [s]
Event rate [MeV^{-1} s^{-1}]
Event rate [MeV^{-1} s^{-1}]
Event rate [MeV^{-1} s^{-1}]

Late-time events

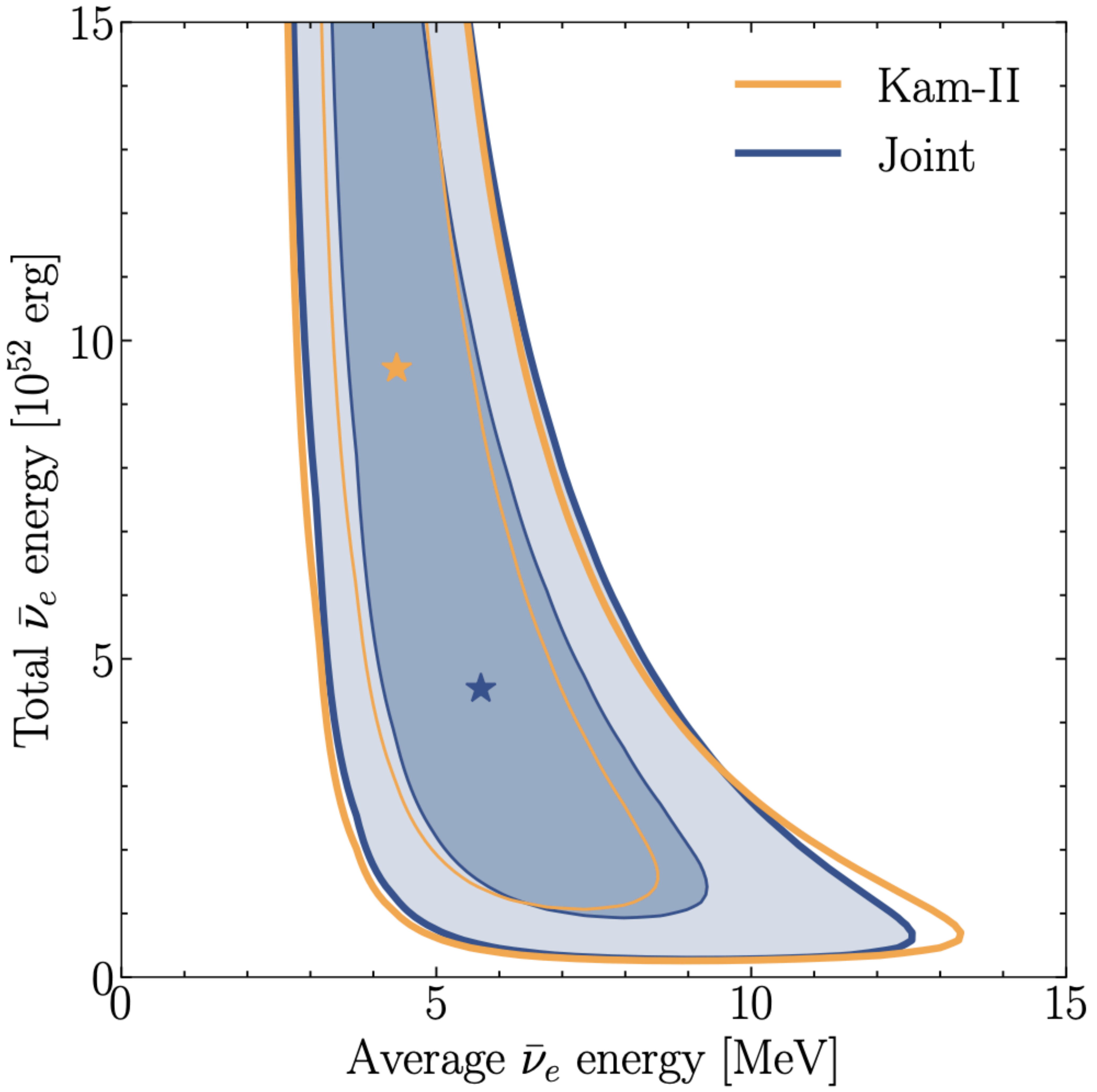


Full time and energy analysis



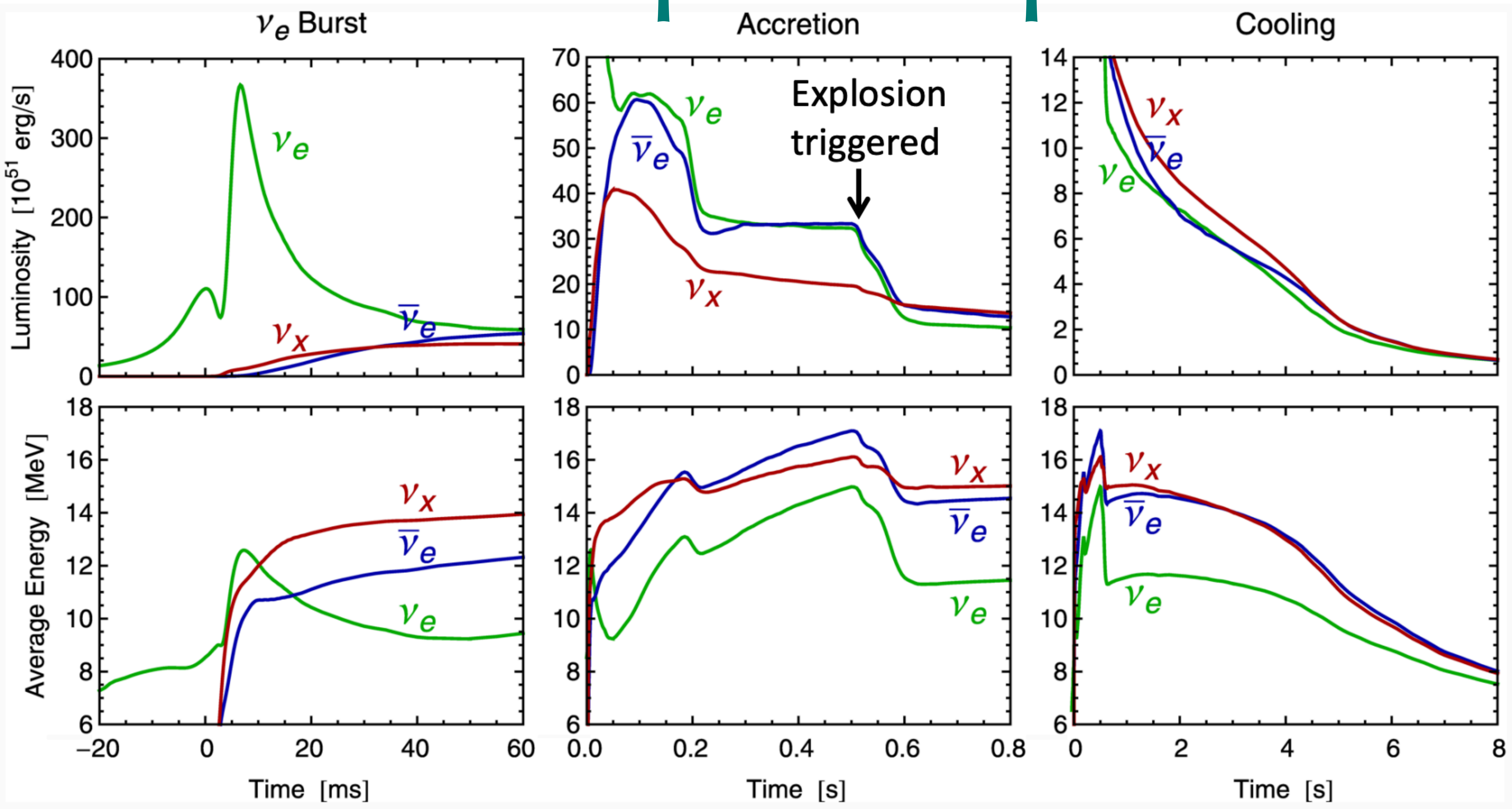
- Bimodal tendency — Kam-II and LSD point to light PNS, IMB and BUST to heavy PNS
- PNS mass of 1.93 $M_\odot$ excluded
- Weak sensitivity to EoS

Time structure of the signal



- Origin of late-time events is an open question
  - Background?
  - Late-time fallback accretion?

Core-Collapse Supernovae



- Shock breakout
- De-leptonization of outer core layers

- Shock stalls ~ 150 km
- Neutrinos powered by infalling matter

Cooling on neutrino diffusion time scale

Credits to G. Raffelt

Spherically symmetric Garching model (25 $M_\odot$) with Boltzmann neutrino transport