SN1987A neutrinos: status and prospects

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4th EuCAPT Annual Symposium

based on arXiv:2308.01403 (*Phys.Rev.D* 108 (2023) 8, 8)
with M. Heinlein, H.-T. Janka, G. Raffelt, E. Vitagliano, R. Bollig

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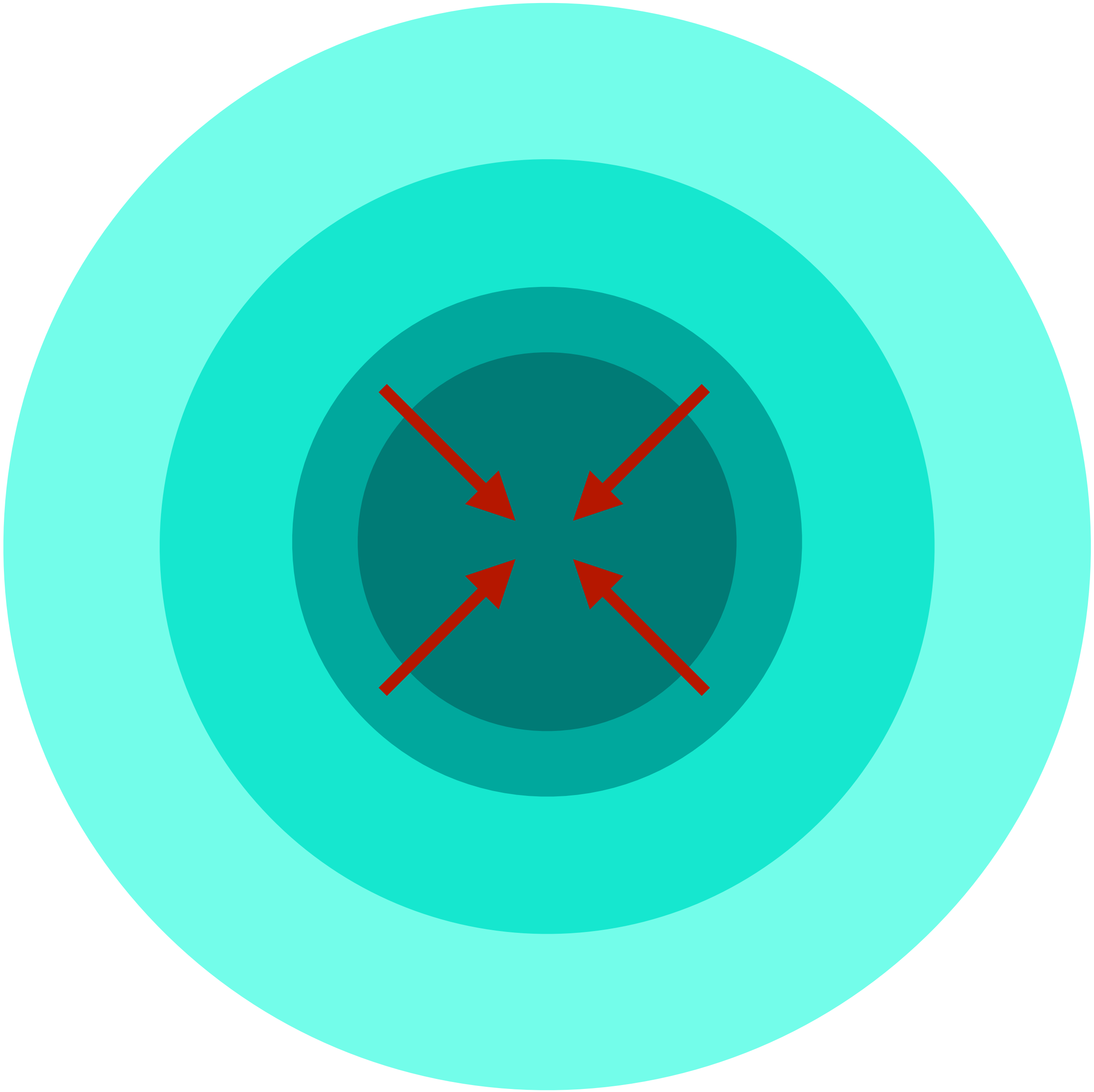
VILLUM FONDEN

Outline

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

Supernova neutrinos

Core-Collapse Supernovae

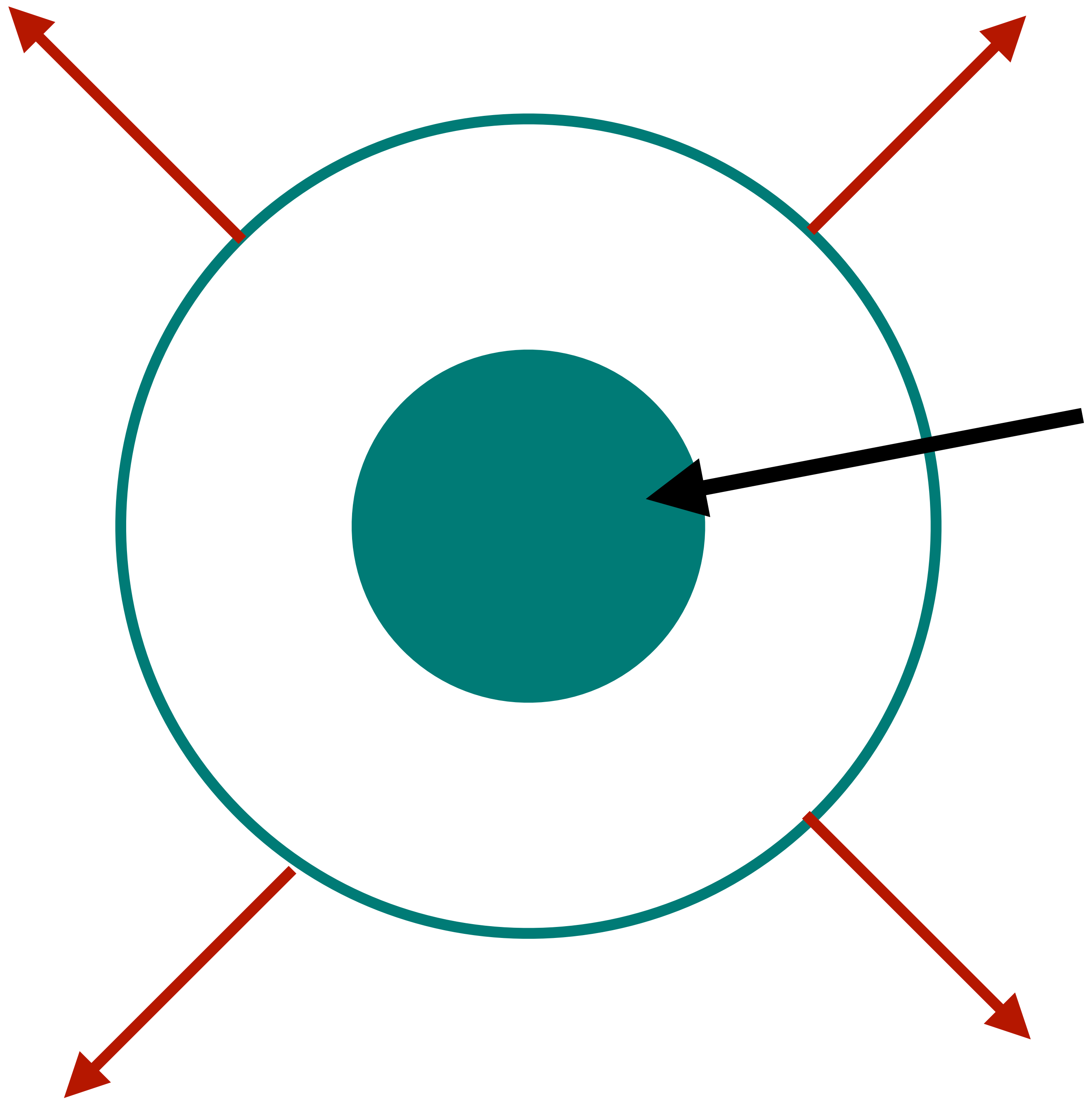


- Iron core with stopping of fusion
- Core collapses up to nuclear densities

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

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

Core-Collapse Supernovae



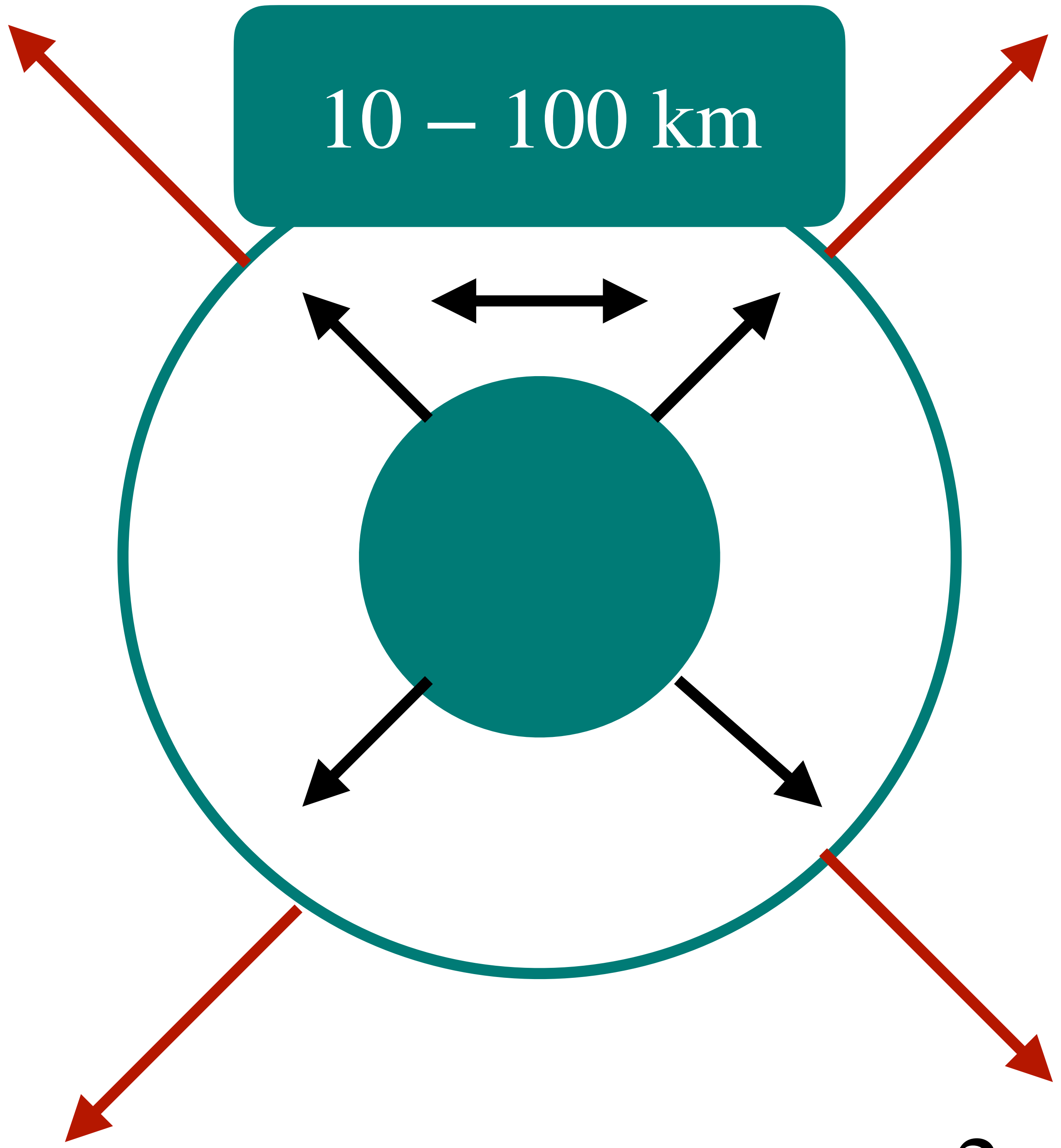
Neutrinos trapped and degenerate!

- 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

$$\Delta t \sim 0.5 - 1 \text{ s}$$

Core-Collapse Supernovae

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



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

- Iron core with stopping of fusion
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- Neutrino **cooling** of PNS

Core-Collapse Supernovae

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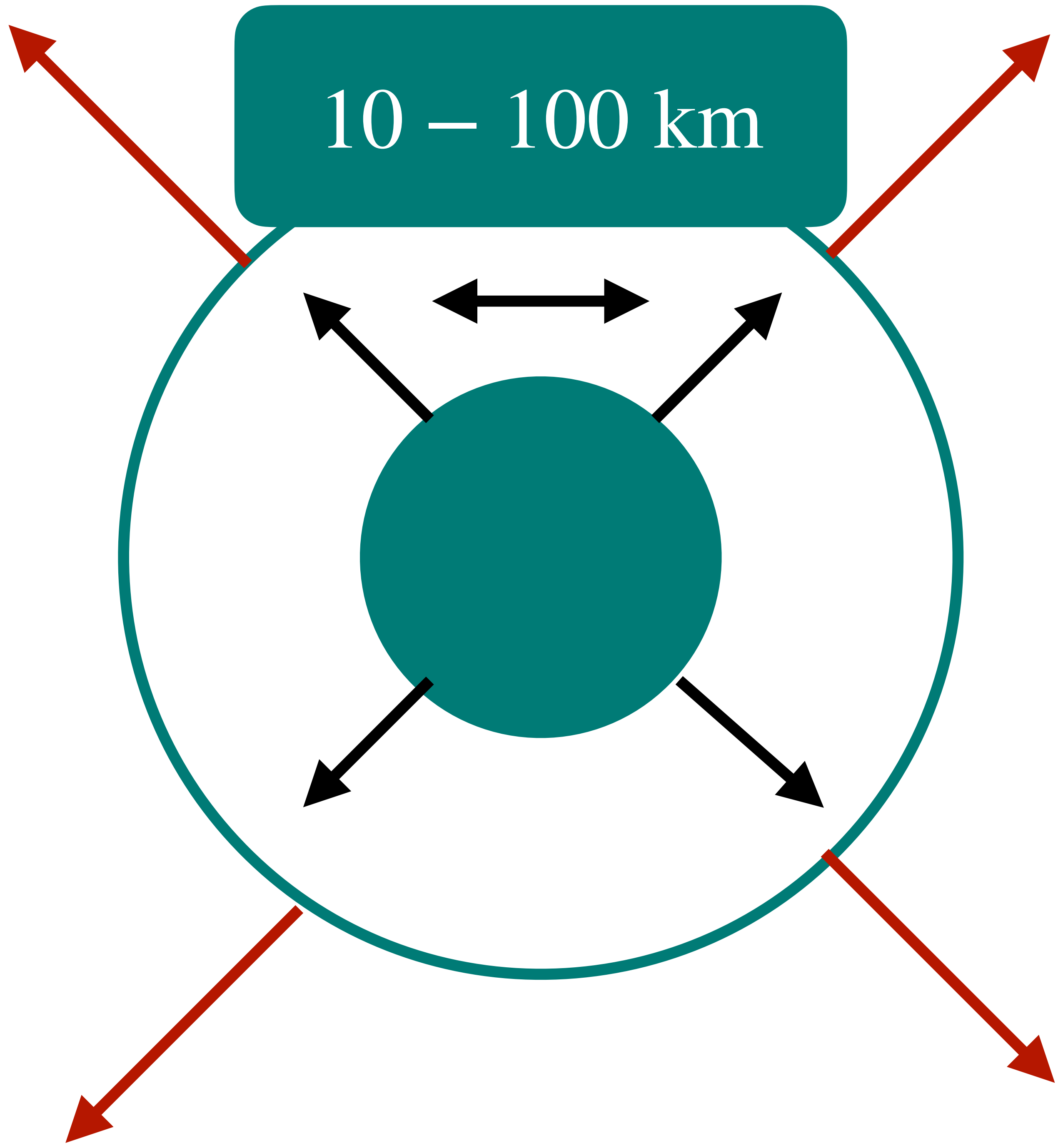

PNS mass main order parameter for neutrino flux!

- Iron core with stopping of fusion
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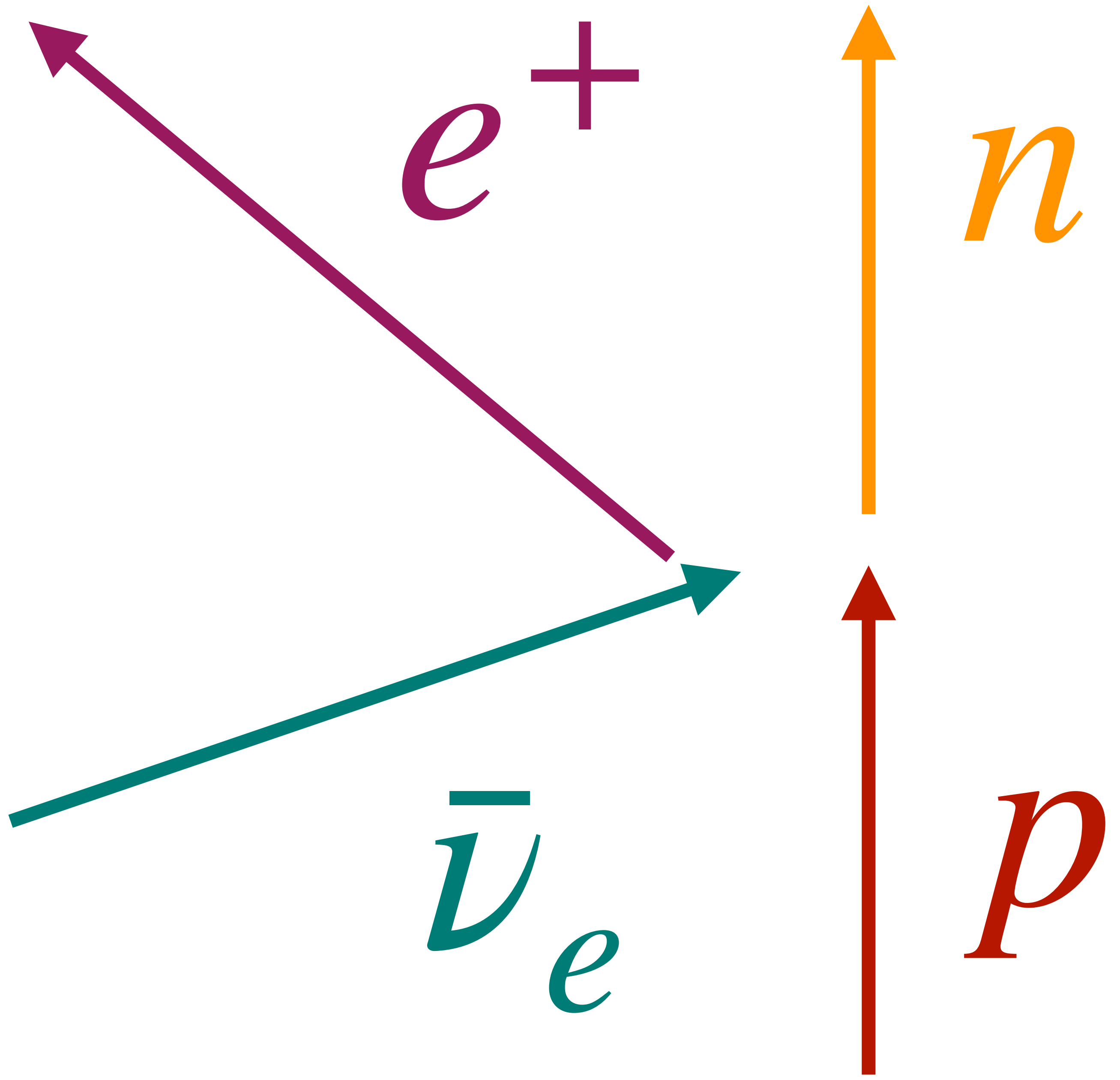
Neutrino observations from SN1987A

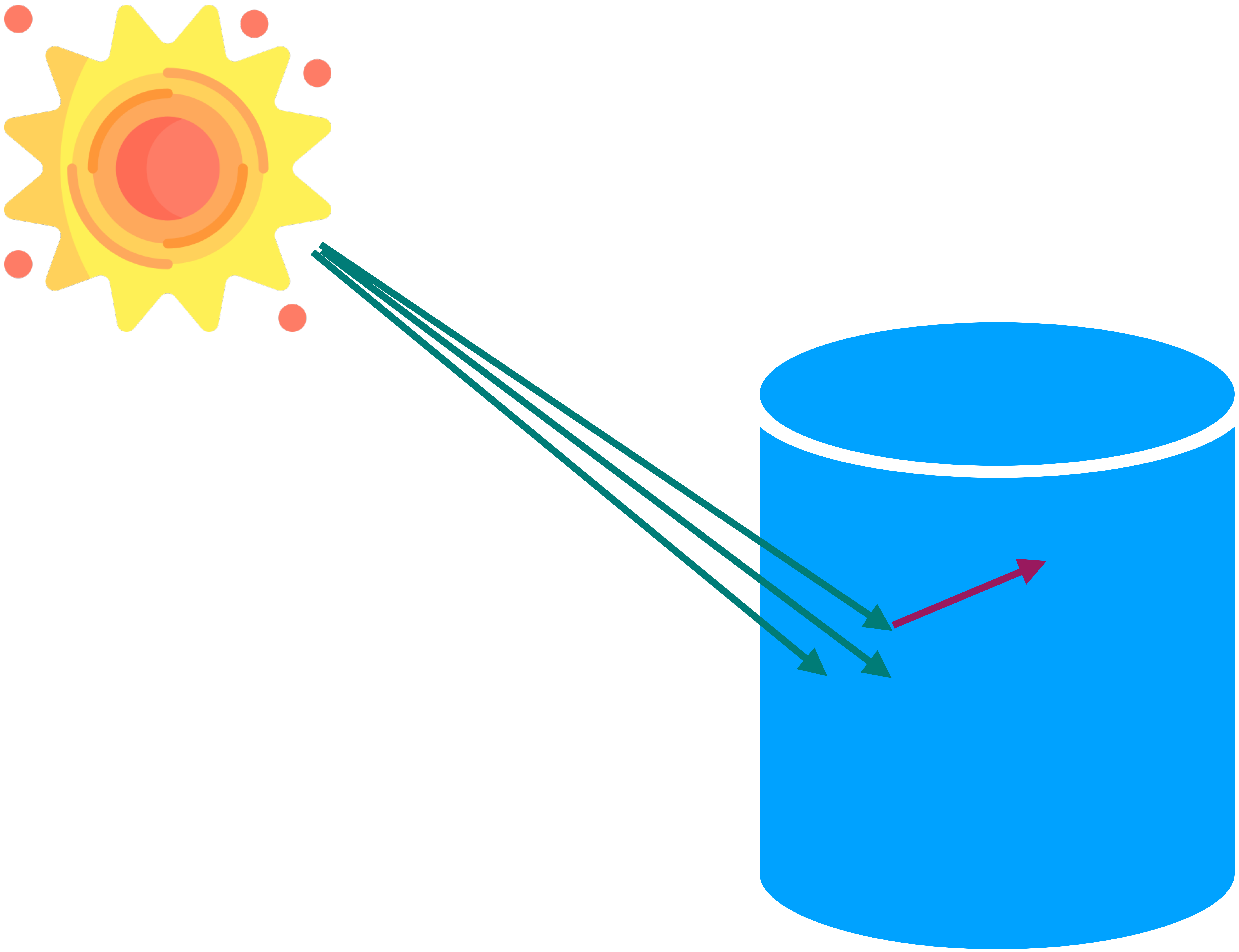
It is February 23 1987. At 49.59 ± 0.09stat ± 0.54syst kpc from Earth, blue supergiant Sanduleak -69 202 is going to explode…

Credits to E. Vitagliano

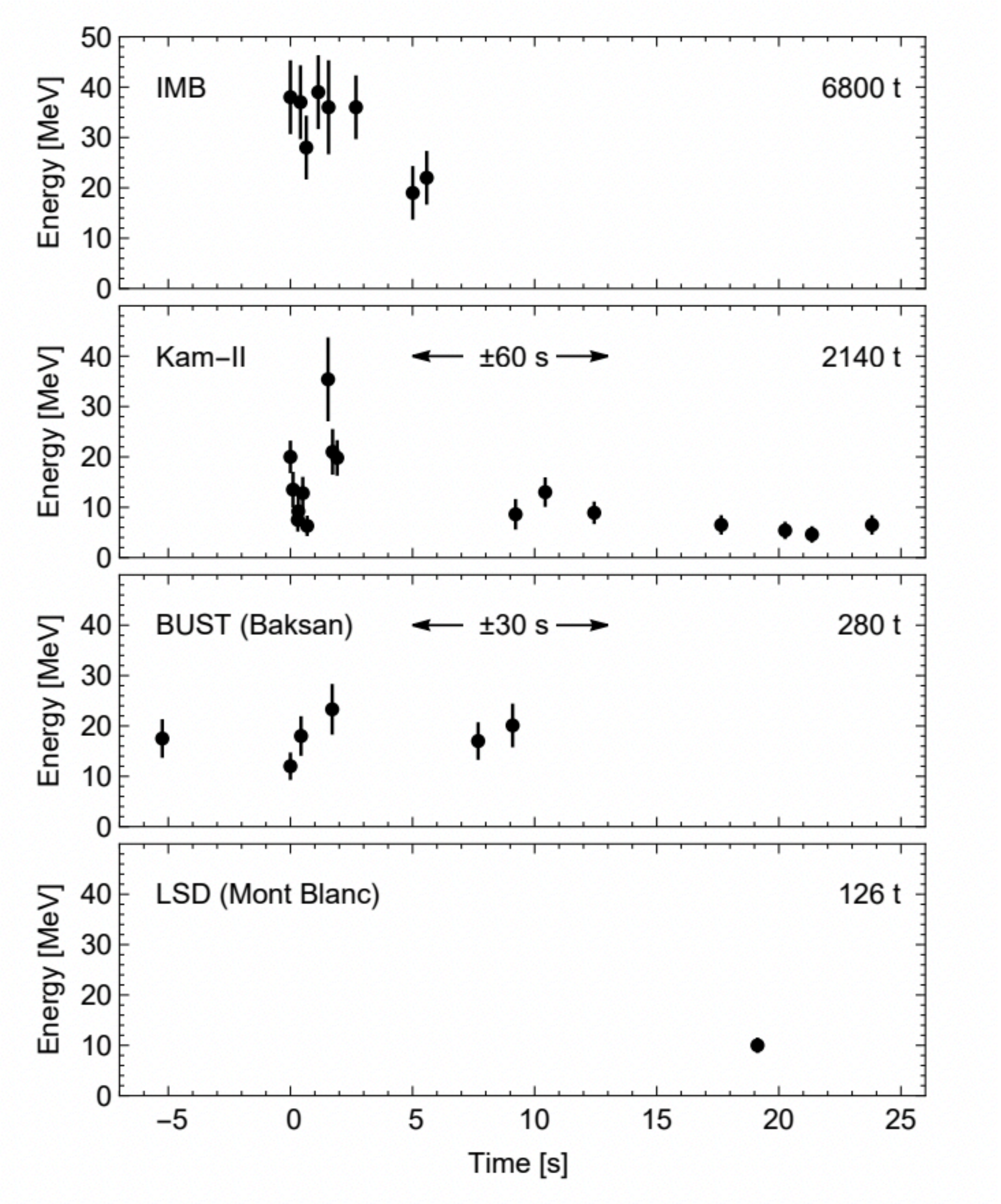
SN1987A neutrino observations



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



SN1987A neutrino observations



Several puzzles

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

Supernova simulations confront SN 1987A neutrinos

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

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

Motivation

- Increased confidence in the neutrino delayed explosion mechanism - 3D simulations show self-consistent explosions
- Boost of activity in BSM bounds
- Significant updates to the simulations
    - **Convection**
    - **Updated neutrino-nucleon opacities**

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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- 3D models have severe limitations
    - Cannot systematically scan parameter space (PNS mass)

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- 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
- 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

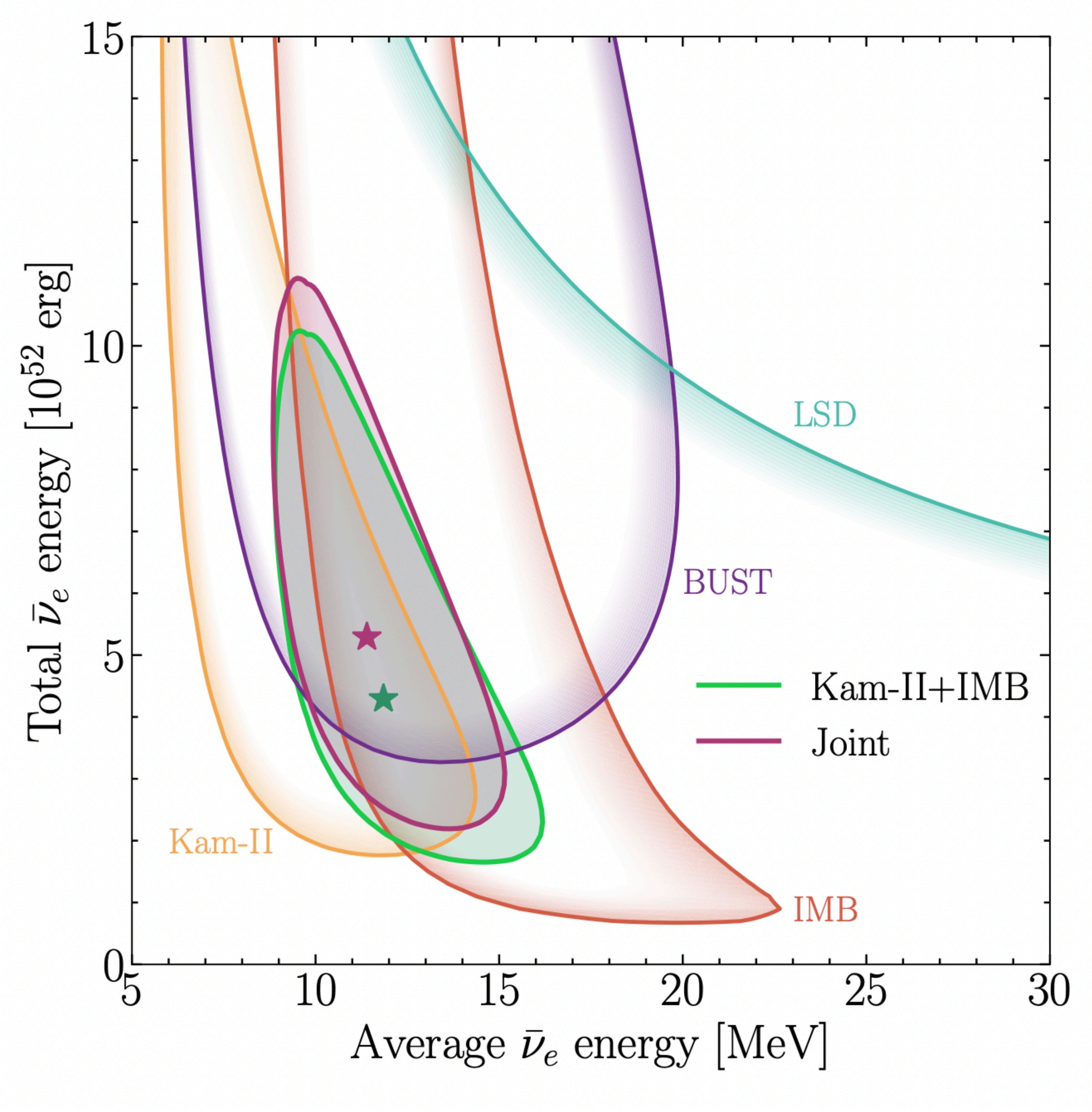
LS220

SFHo

SFHx

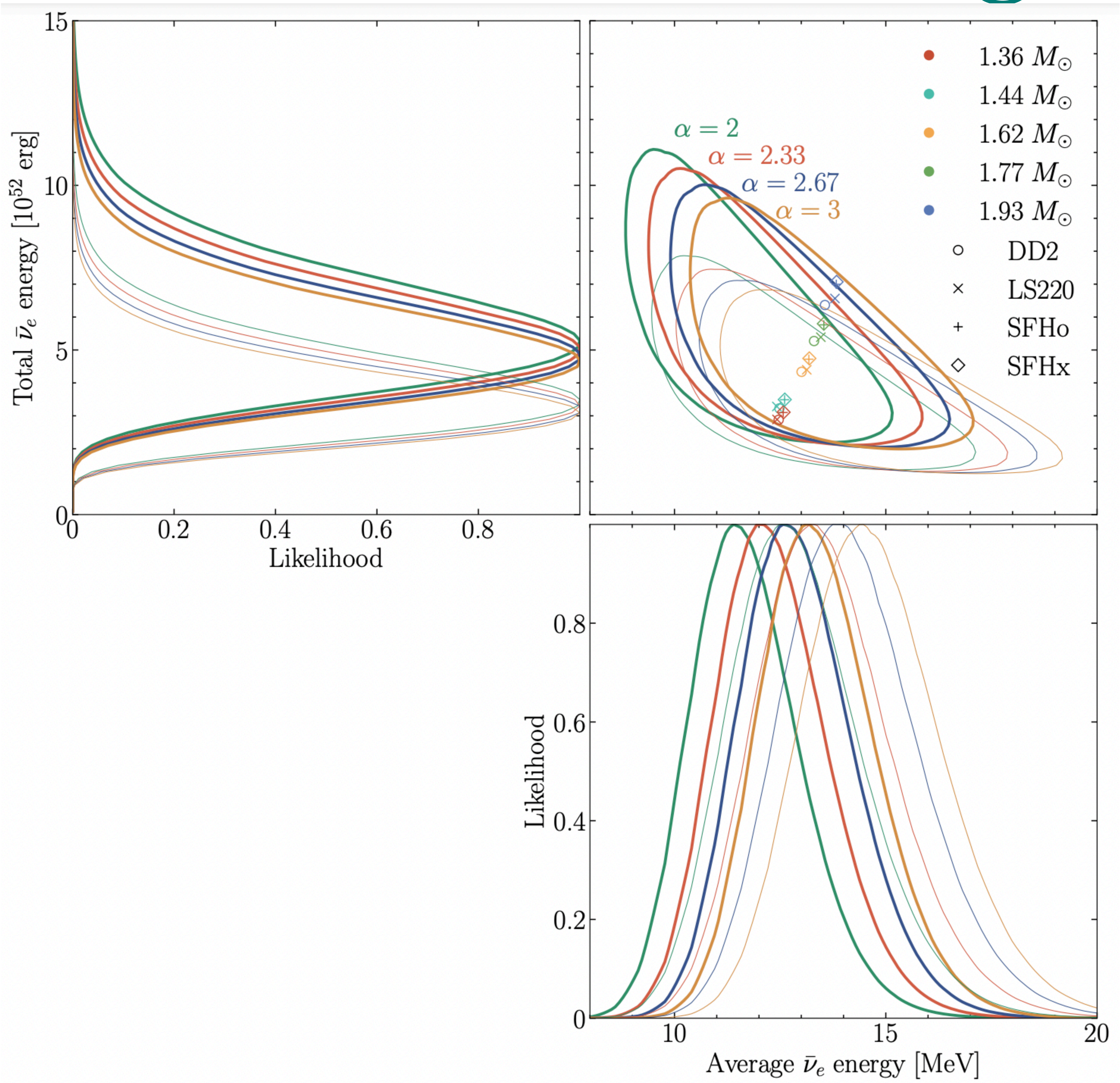
All 1D
(Reliable for the sparse data of SN 1987A!)

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

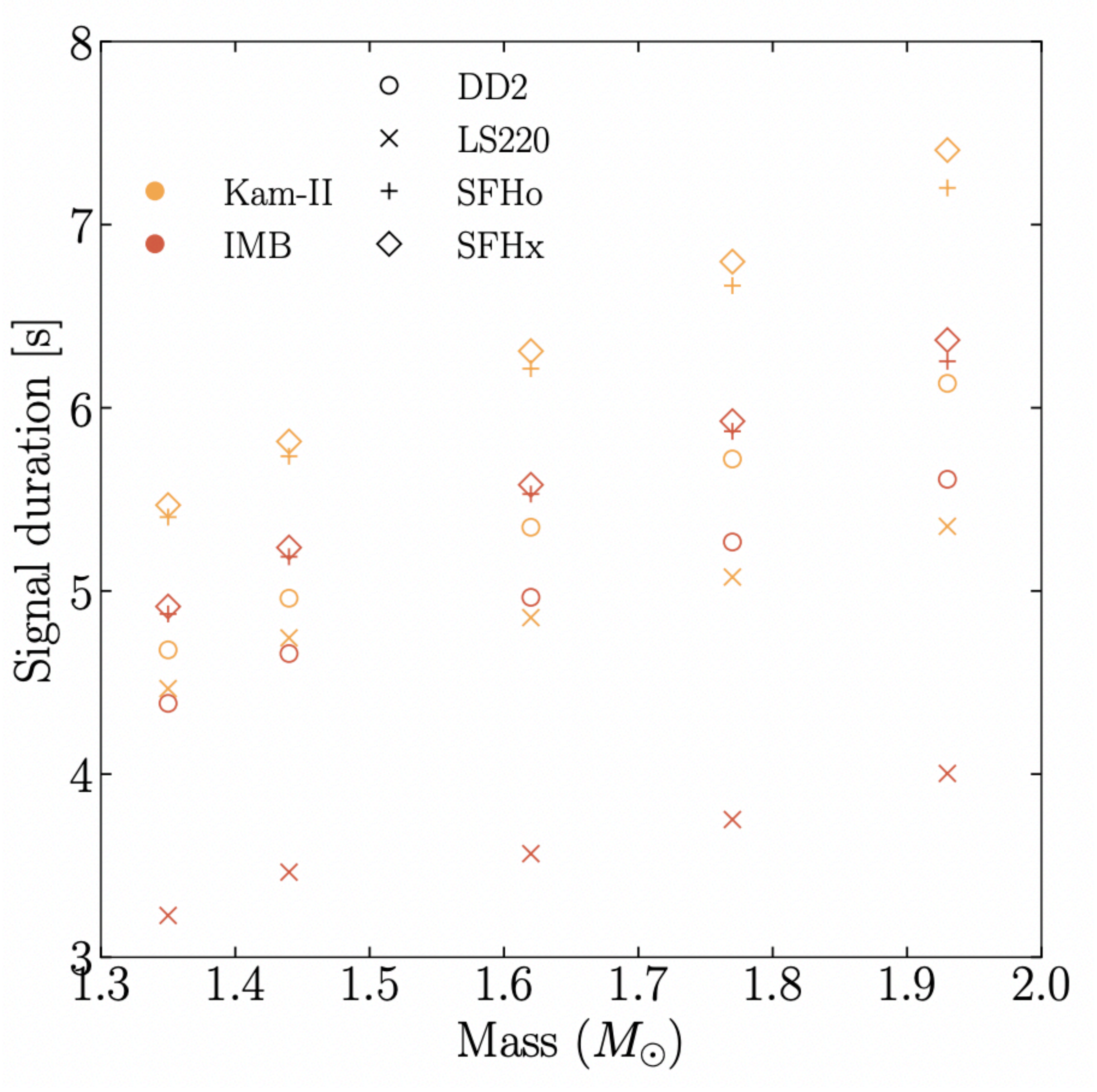


- ✦ Spectra can be pinched

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

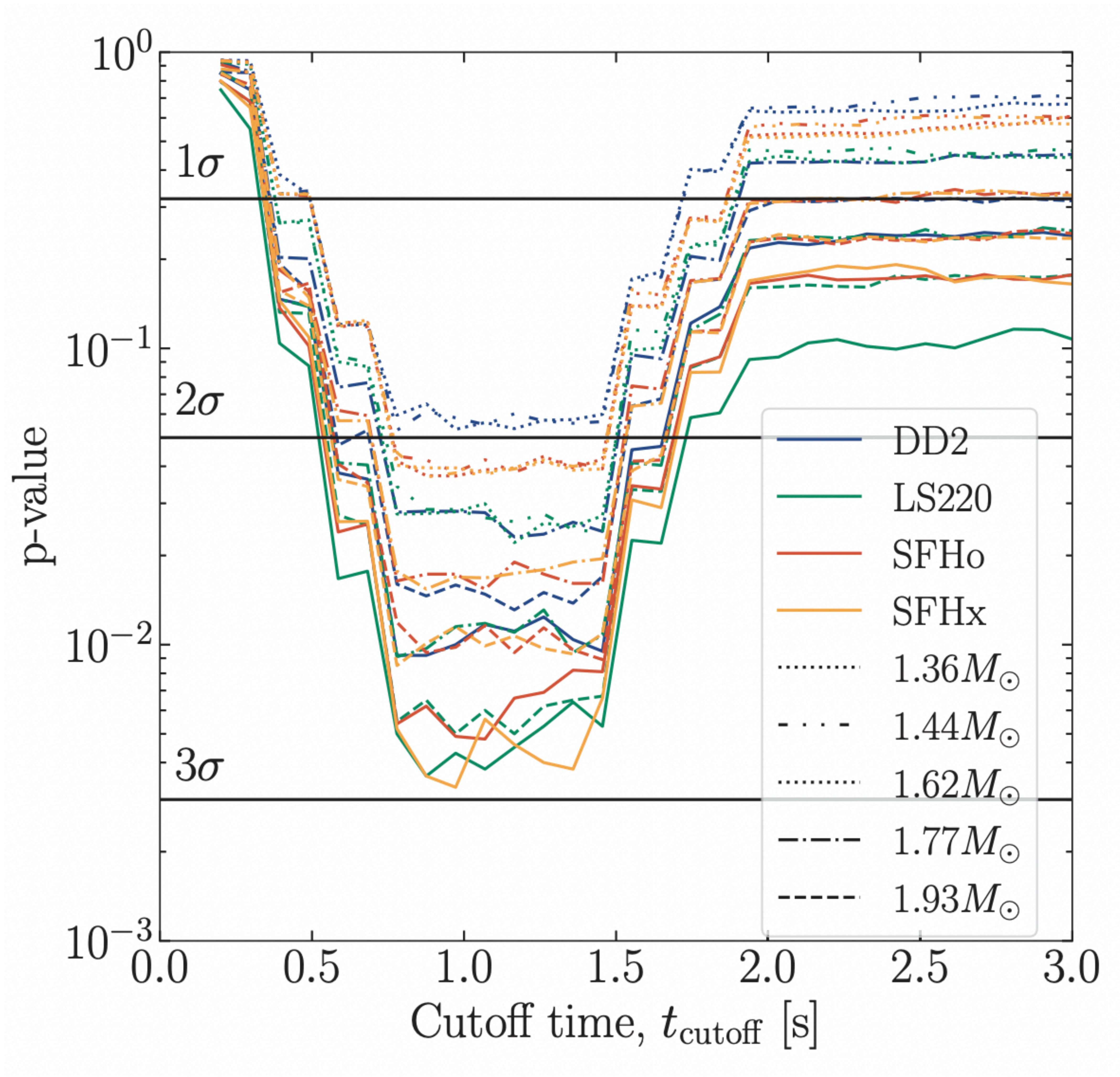
- ✦ Most SN models lie within 2σ regions — consistency with data
- ✦ Tension with heavy PNS

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



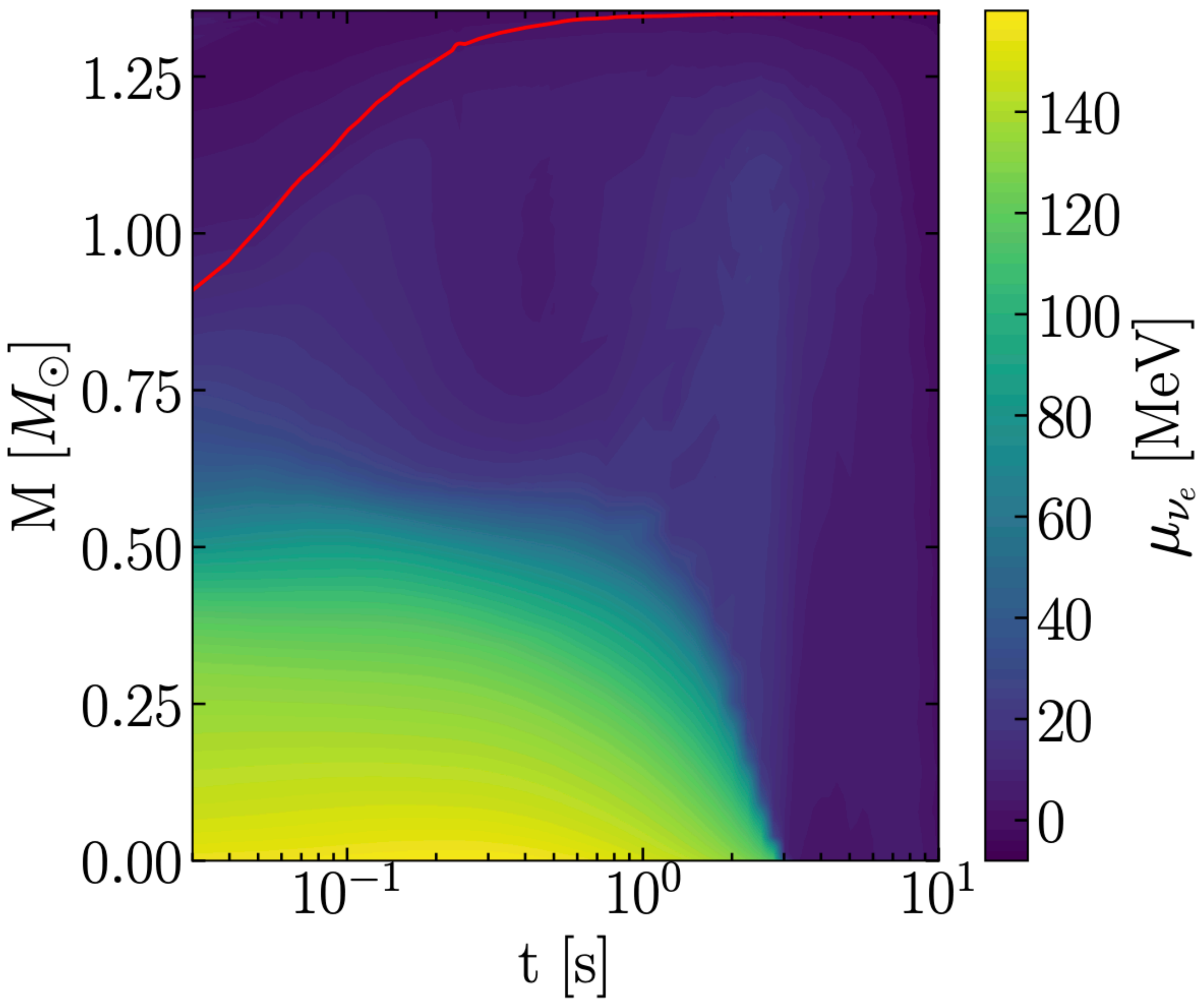
- Kolmogorov-Smirnov on first-second events to compare with Li et al., 2306.08024
- Cutting at 1 s maximizes tension (events 3 and 4 have low energy), but globally insignificant
- Models with low PNS less than 2 sigma even cutting the events

Conclusions

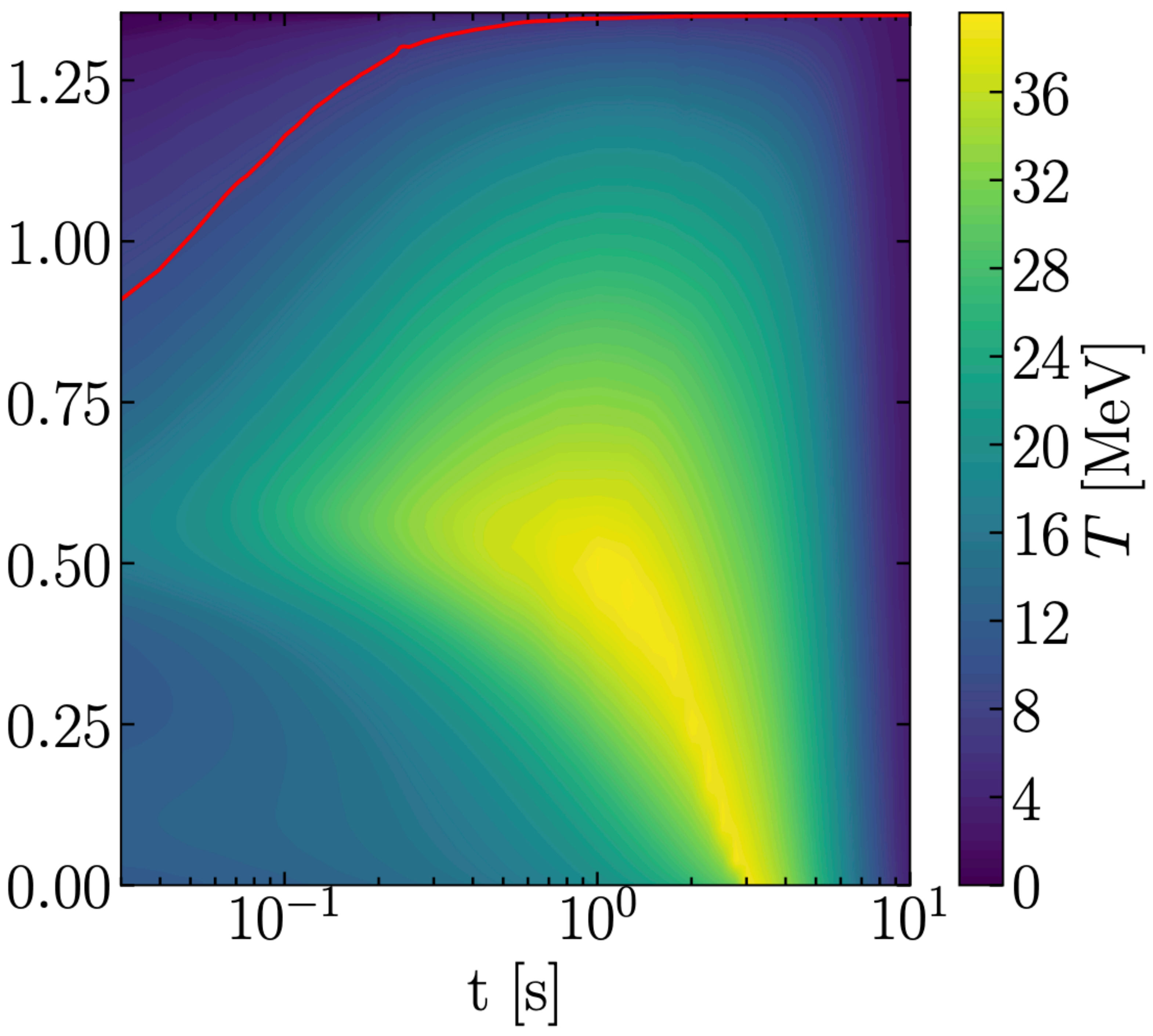
- SN 1987A: neutrinos probing the inner regions
- Generally consistent with modern simulations, both all-duration and first second
- Requires light PNS $\lesssim 1.8\,M_\odot$
- Origin of late-time events?

Backup slides

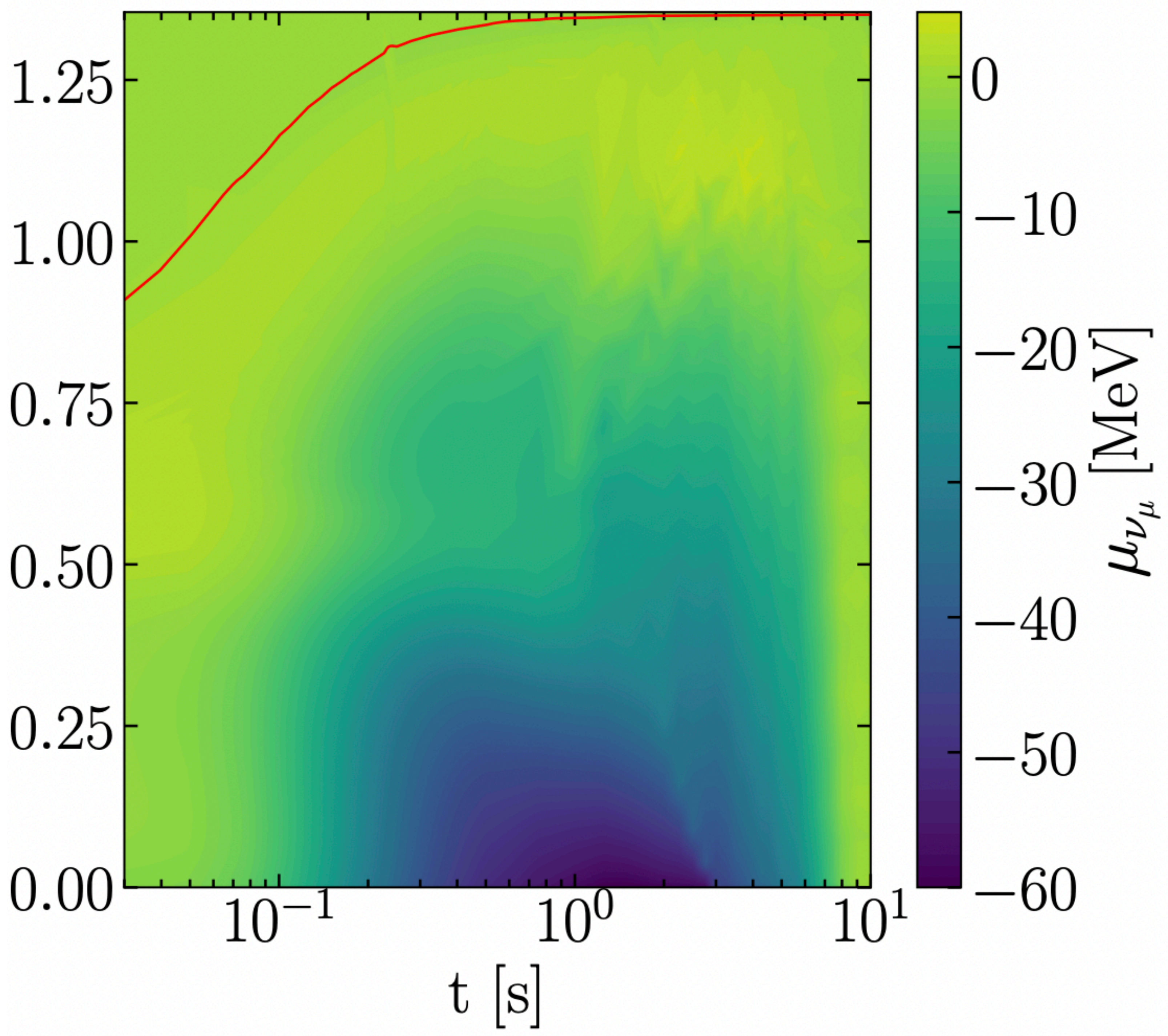
Core-Collapse Supernovae



PNS deleptonizes and cools

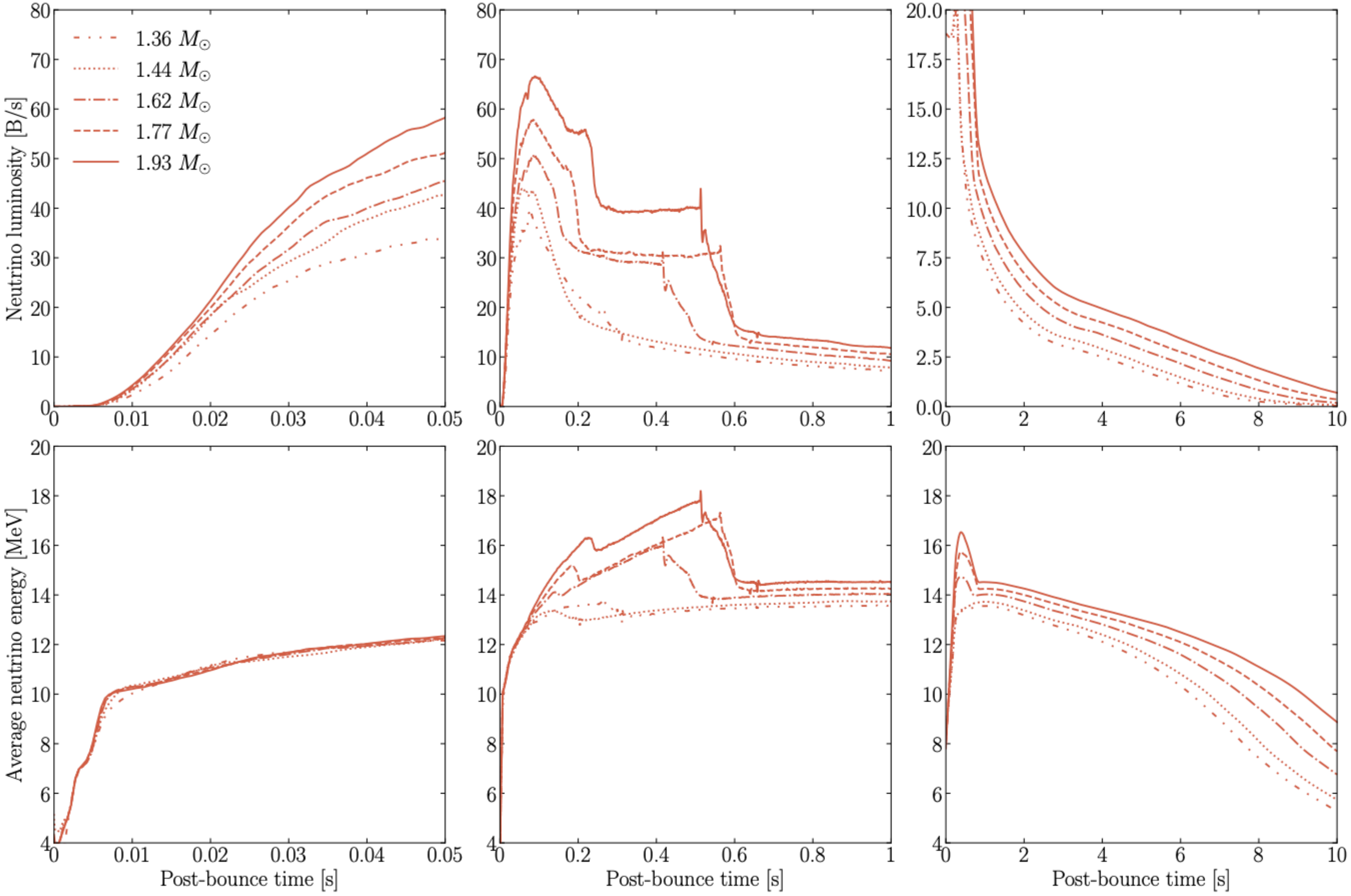


Heats up the external material

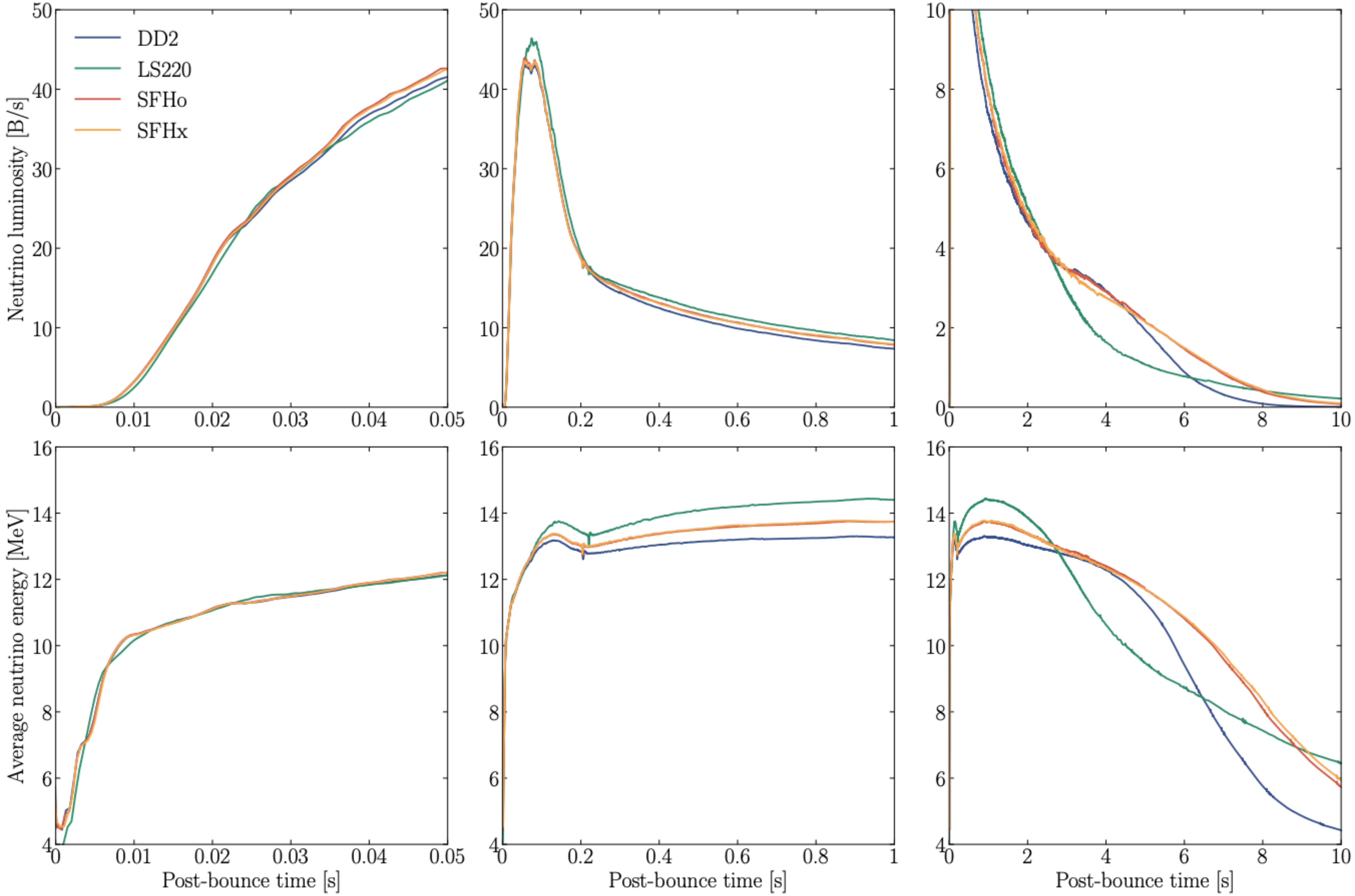


Produces muons and muon neutrinos

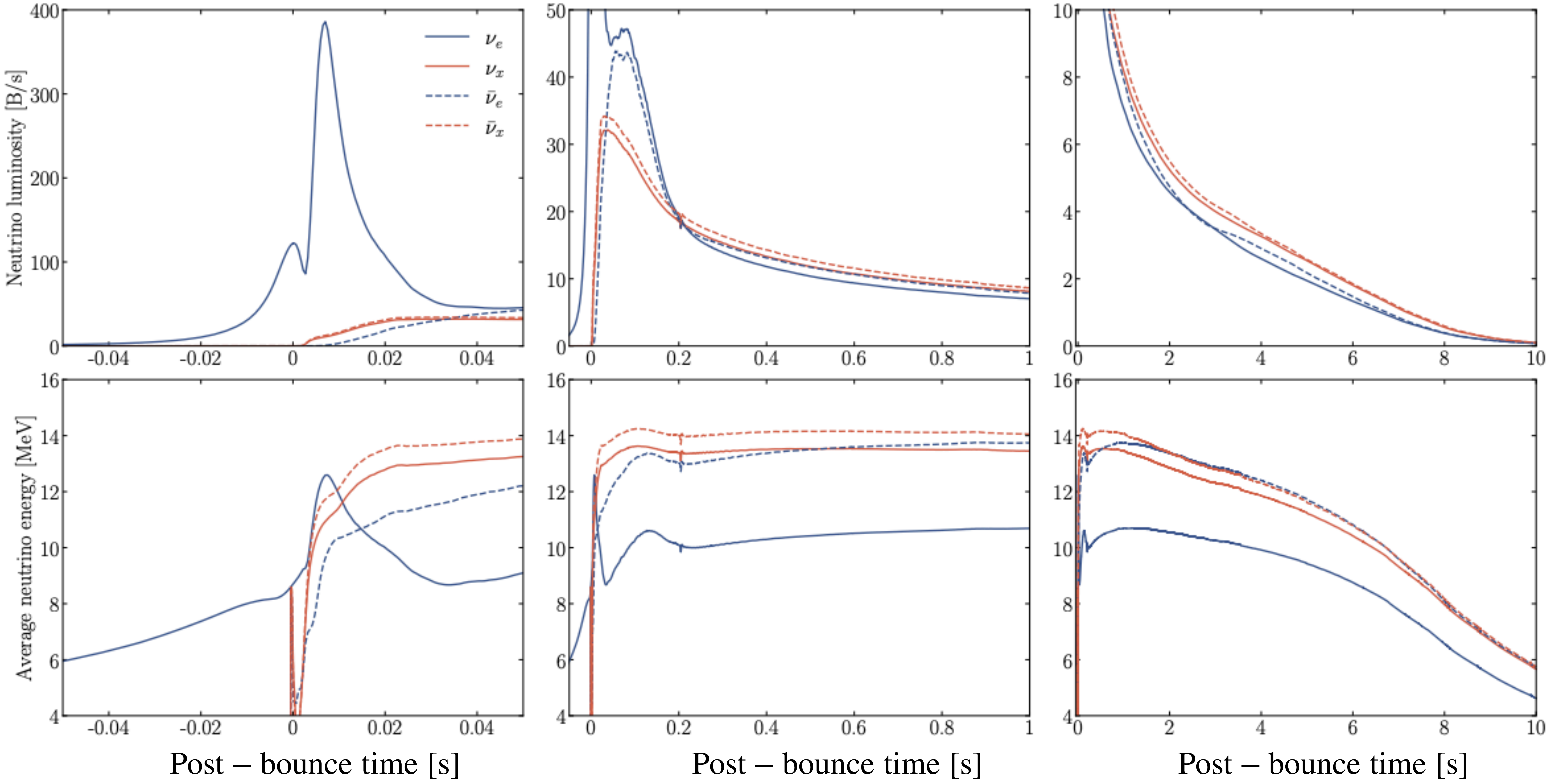
SN models - neutrino signal



SN models - neutrino signal



Flavor dependence of neutrino signal



BSM physics with SN1987A neutrinos

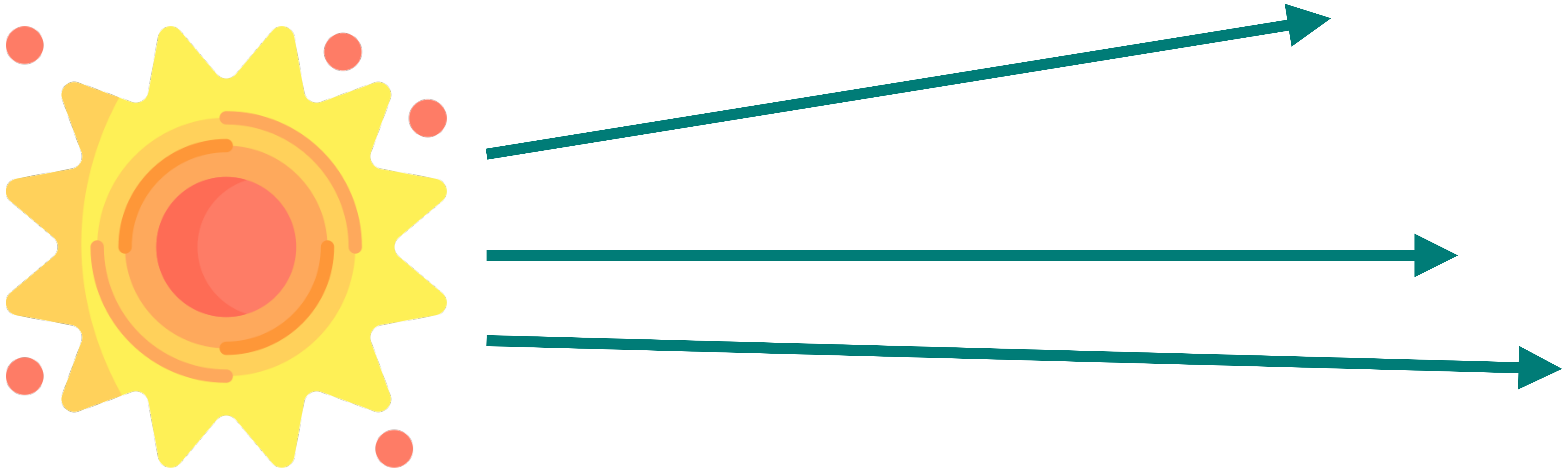
based on arXiv:2209.11773 (Phys. Rev. Lett. 131 2, 021001)

with G. Raffelt, E. Vitagliano

Testing for new physics

New particles can be produced in supernova core…

… but how do we probe them?



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

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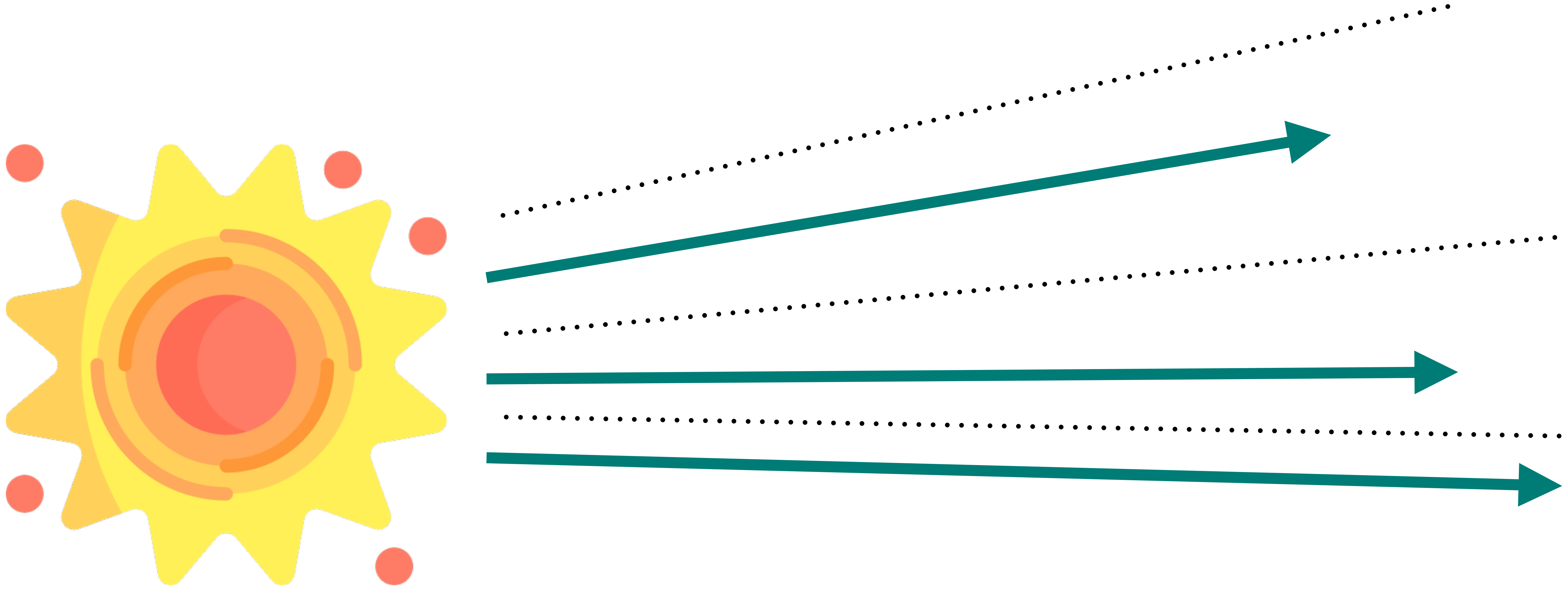


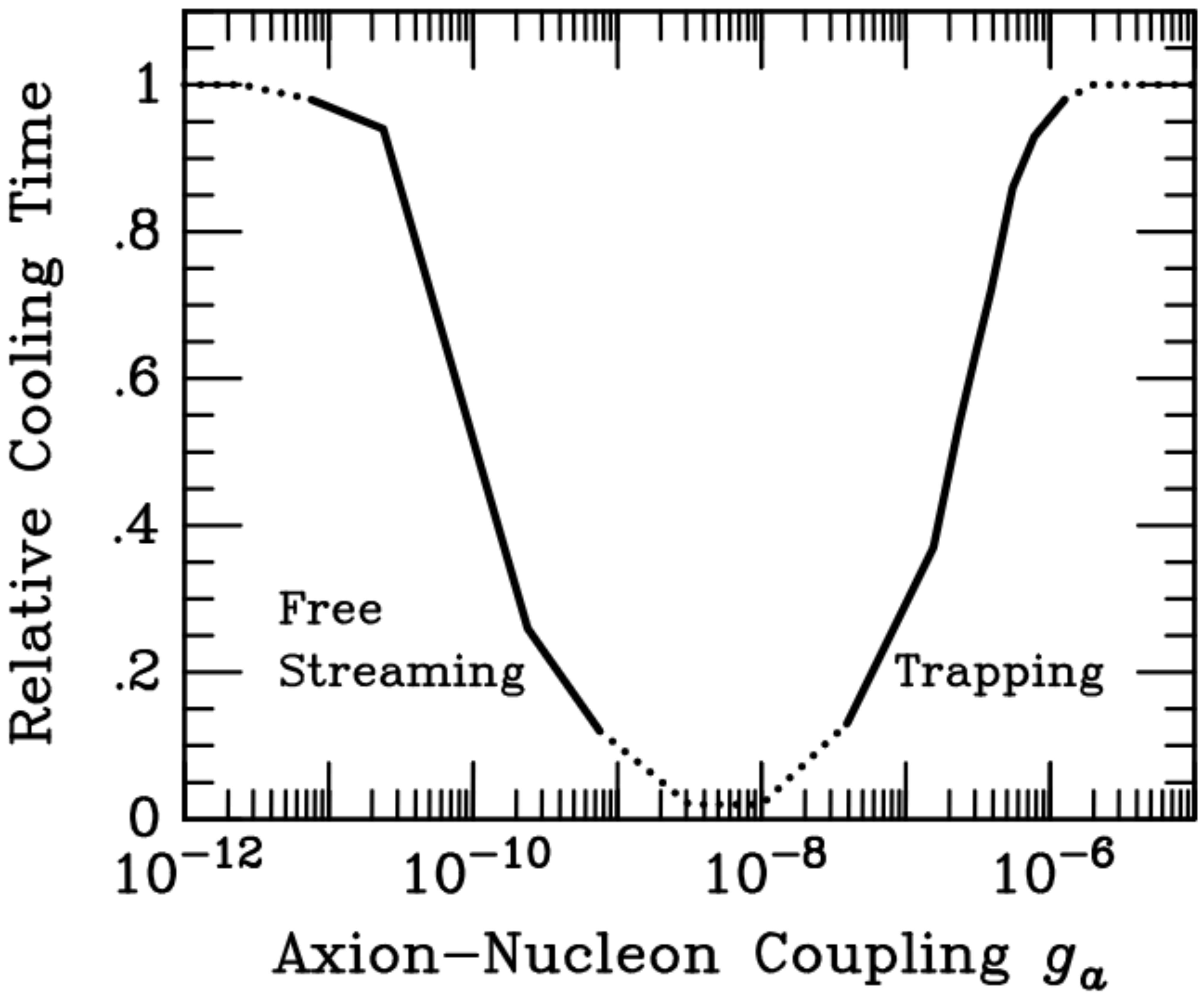
PNS cools faster,
shorter burst

Energy loss/cooling bound

$$L_\phi(1\ \mathrm{s}) < L_\nu(1\ \mathrm{s})$$

Burrows et al., 1989; Raffelt, 1996

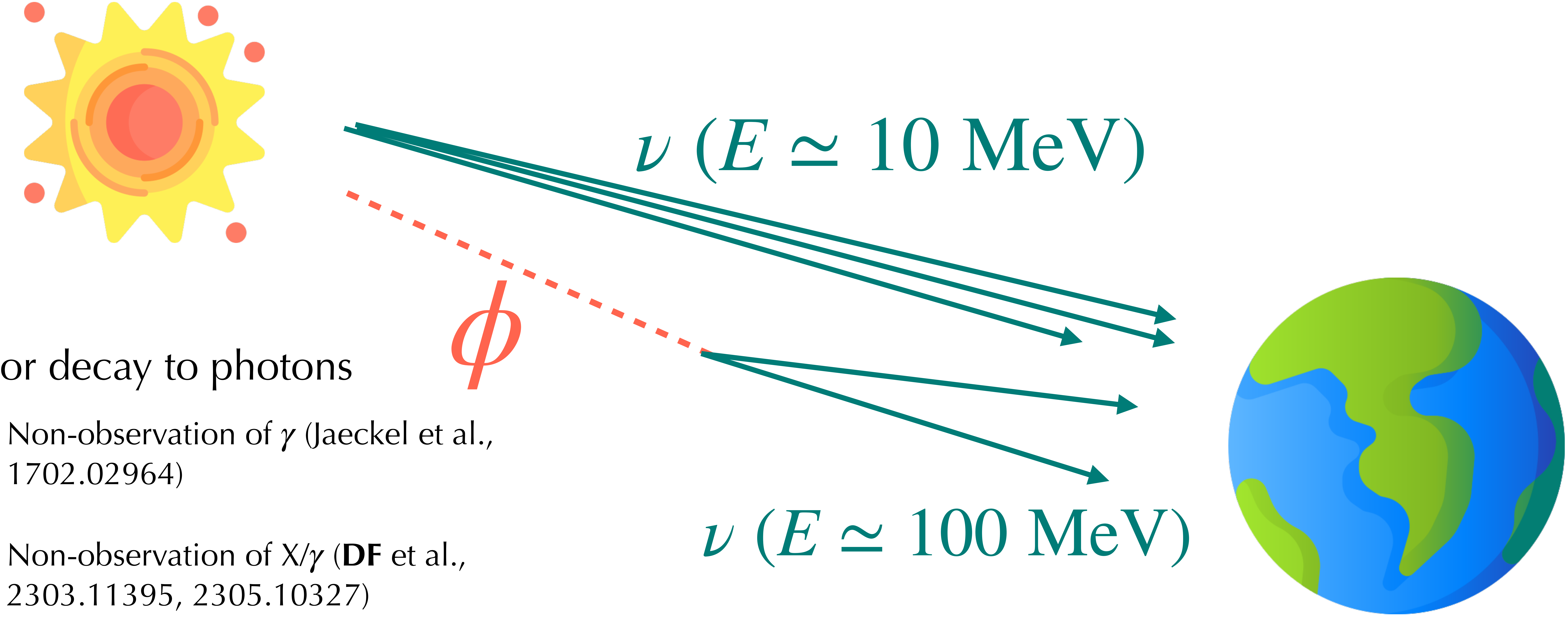
Cooling bounds



Raffelt, 1996

- Axions, new gauge bosons, millicharged particles, majorons, … (Caputo, Raffelt, 2024 and refs therein)
- Free streaming is simple volume emission
- Trapping is surface thermal emission (except for self-interacting particles, **DF**, Vitagliano, 2024)

Beyond cooling bounds?



$\nu\ (E \simeq 10\ \mathrm{MeV})$

ϕ

$\nu\ (E \simeq 100\ \mathrm{MeV})$

For decay to photons

- Non-observation of γ (Jaeckel et al., 1702.02964)
- Non-observation of X/γ (**DF** et al., 2303.11395, 2305.10327)
- Energy deposition in low-energy SNe (Caputo et al., 2201.09890)

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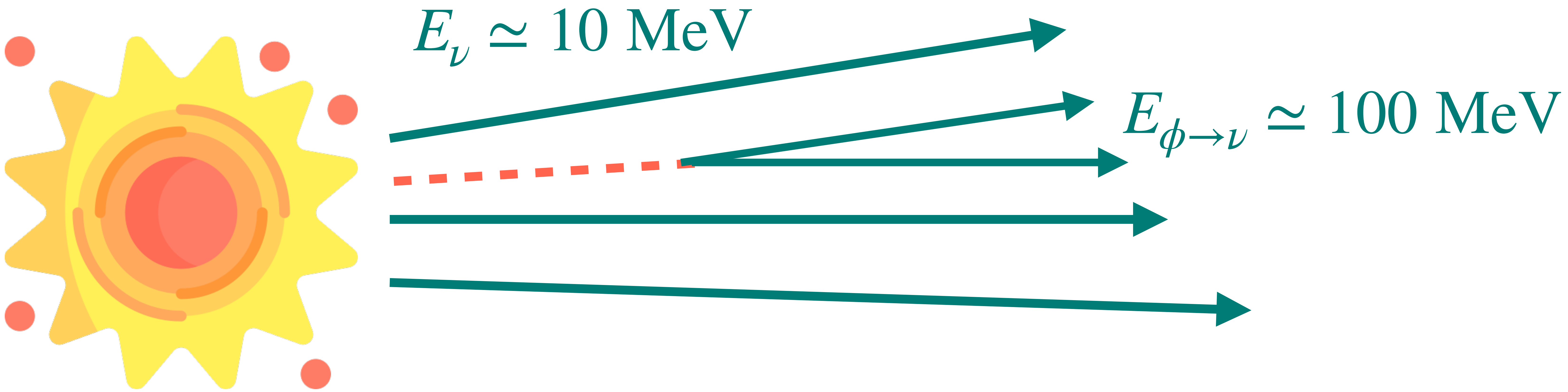
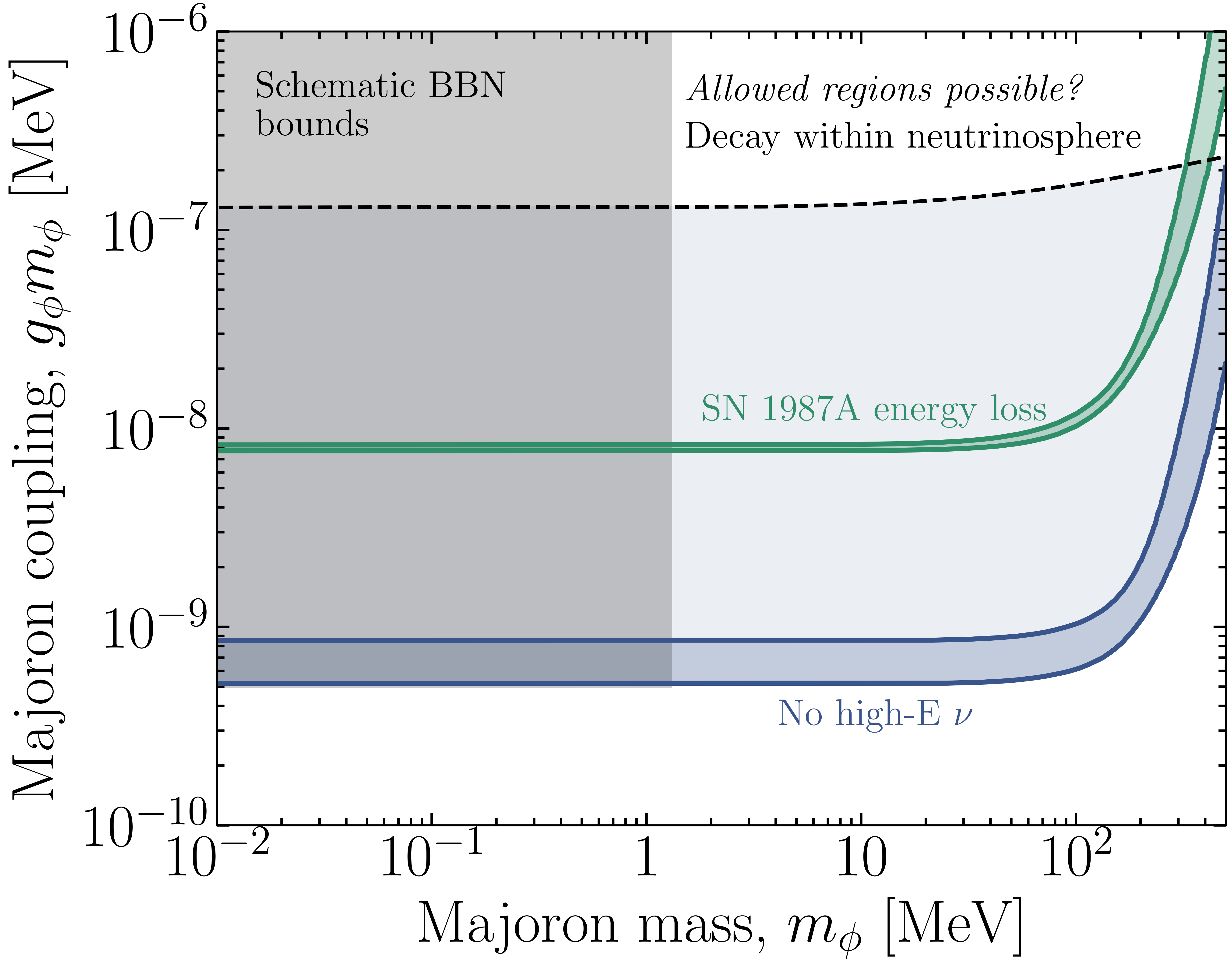


$$\frac{N^{\rm evts}_{\phi\to\nu}}{N^{\rm evts}_{\nu}} \simeq \frac{\Phi_{\phi\to\nu}}{\Phi_\nu}\frac{\sigma_{\nu N}(E_{\phi\to\nu})}{\sigma_{\nu N}(E_\nu)} \simeq \frac{L_\phi/E_{\phi\to\nu}}{L_\nu/E_\nu}\frac{E^2_{\phi\to\nu}}{E^2_\nu} \simeq 10\frac{L_\phi}{L_\nu}$$

Novel bounds



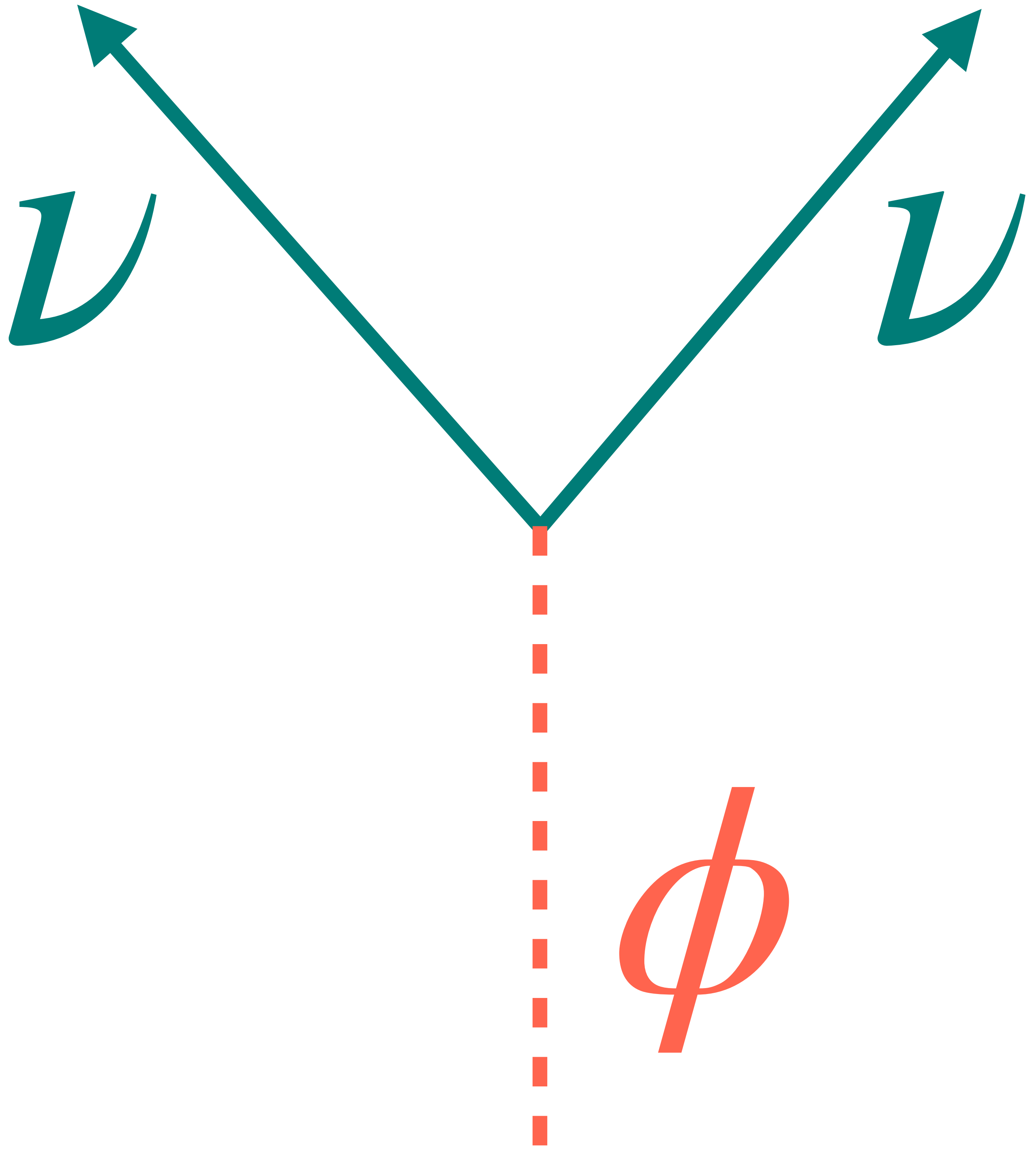
$$L_\phi < L_\nu/100$$

Impact on supernova explosion ruled out

Next galactic supernova in Akita et al., arXiv:2206.06852

Application to sterile neutrino in Brdar et al., arXiv:2302.10965

(Pseudo)-majorons



$$\mathscr{L} = \frac{g}{2}\bar{\nu}^{c}\nu\phi$$

In supernova, neutrino-neutrino and antineutrino-antineutrino coalescence

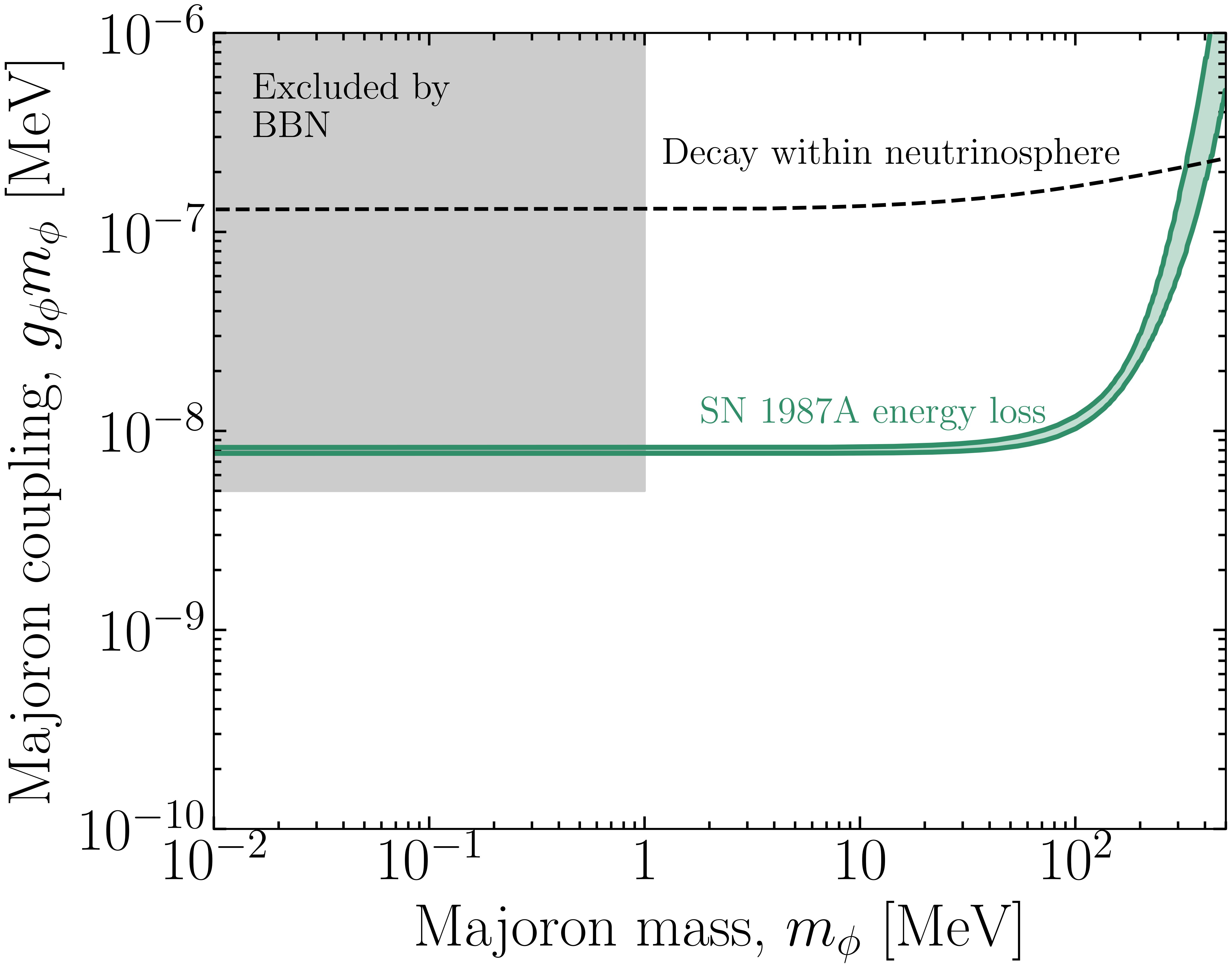
$m_\phi \gtrsim 10^{-4}$ MeV

Chicashige, Mohapatra, Peccei (1981);
Gelmini, Roncadelli (1981)

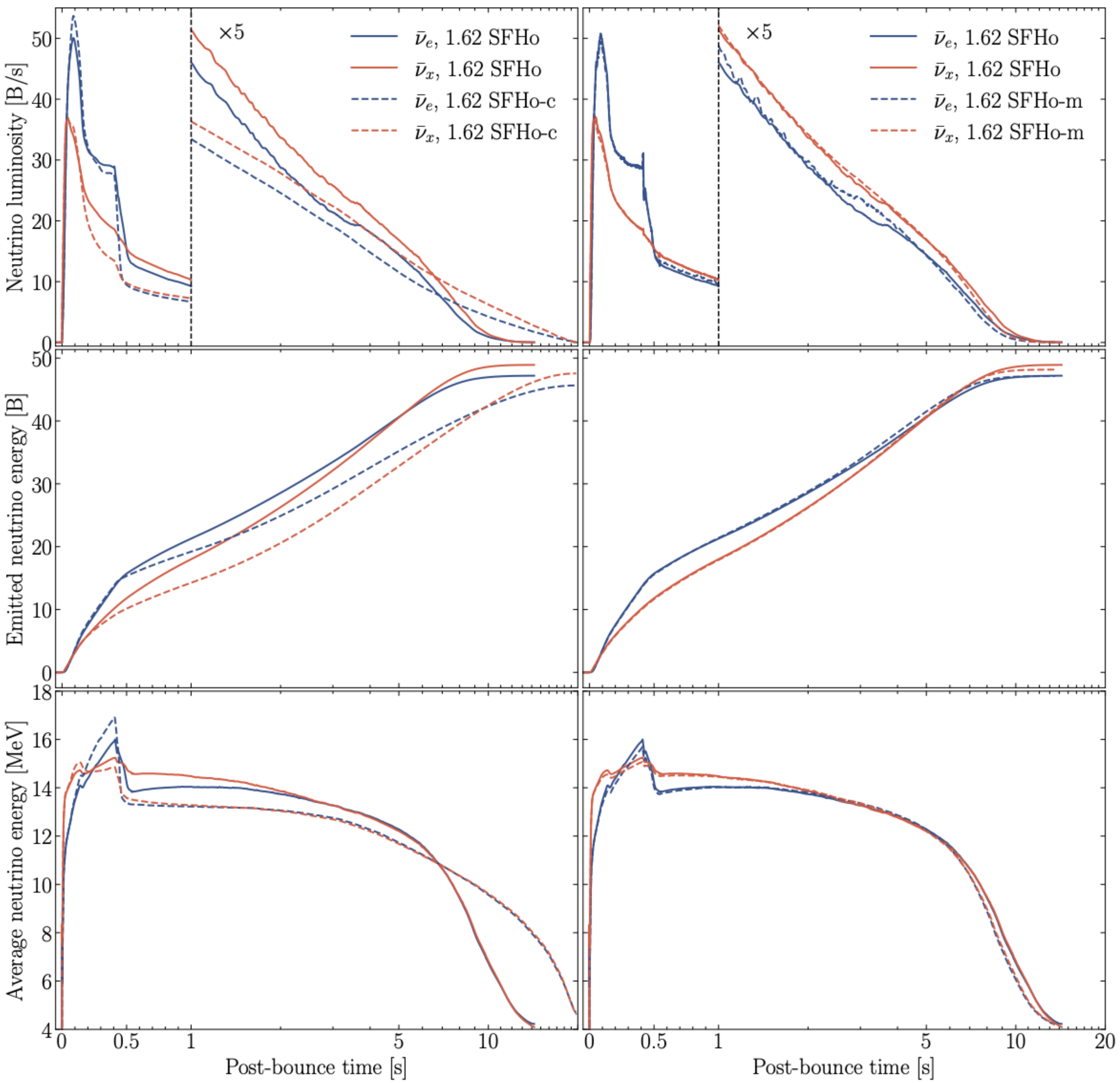
Majoron production

For small masses, signal depends only on gm_ϕ

$$\frac{dN_\phi}{dt} = \frac{(gm_\phi)^2\mu_\nu^2}{192\pi^3}$$



Convection vs. no convection



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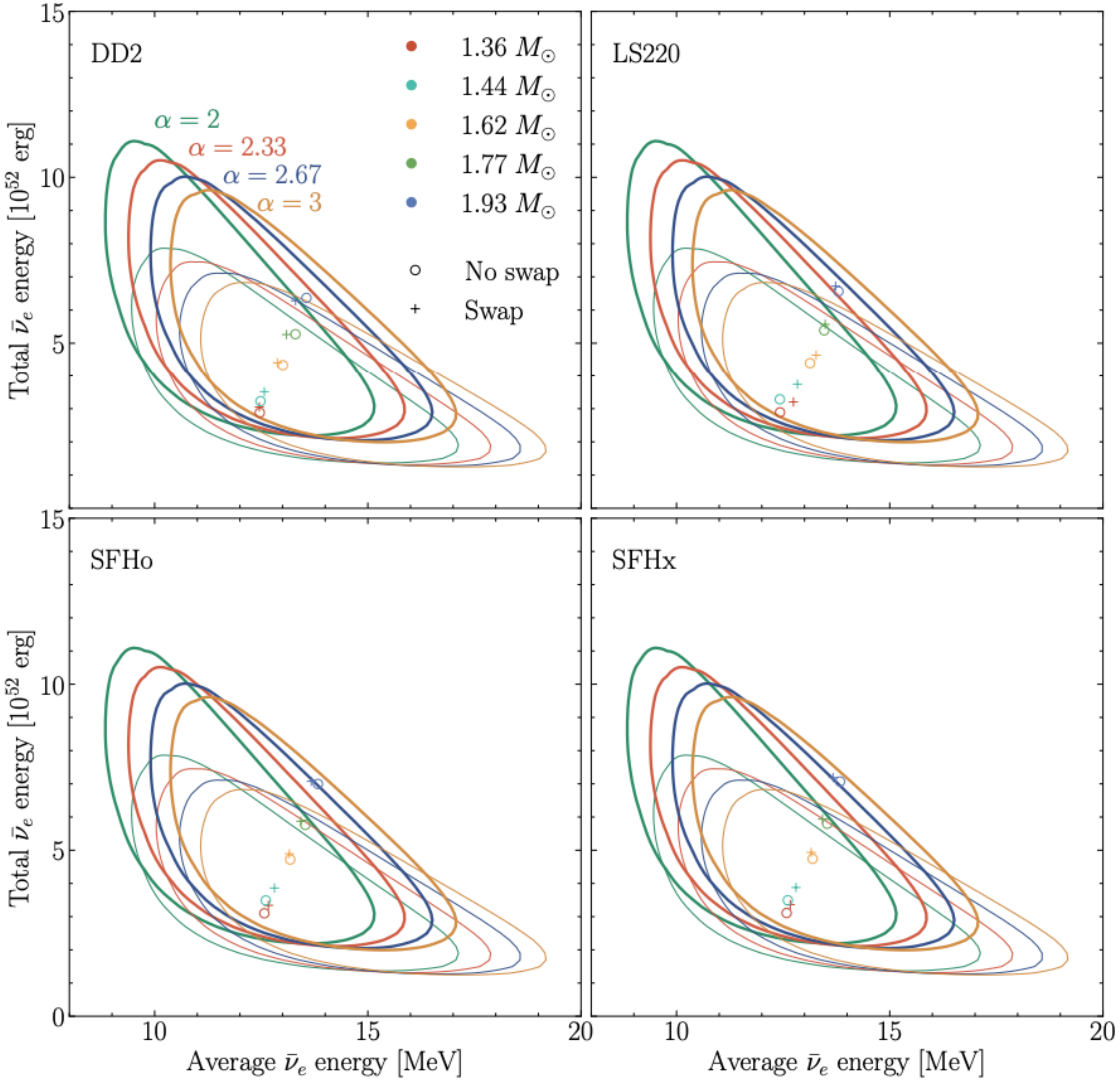
Impact of flavor conversion



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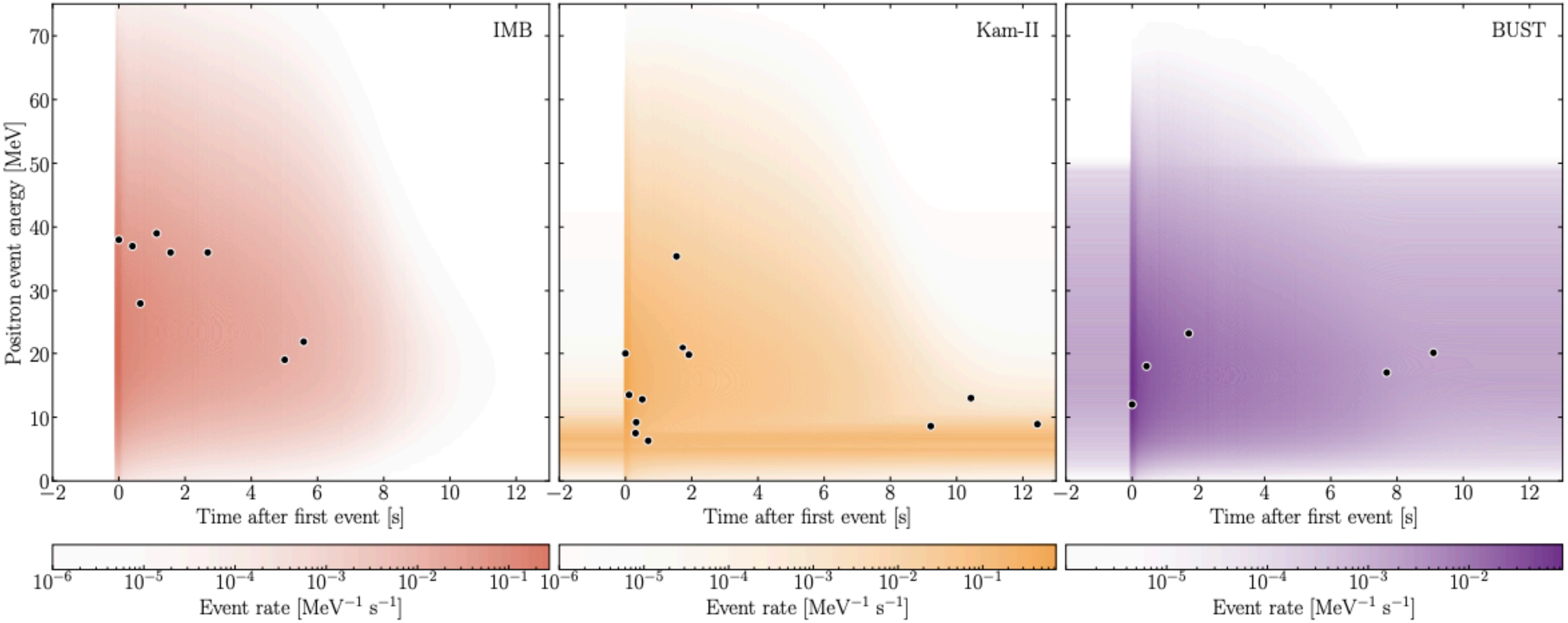
Event rates



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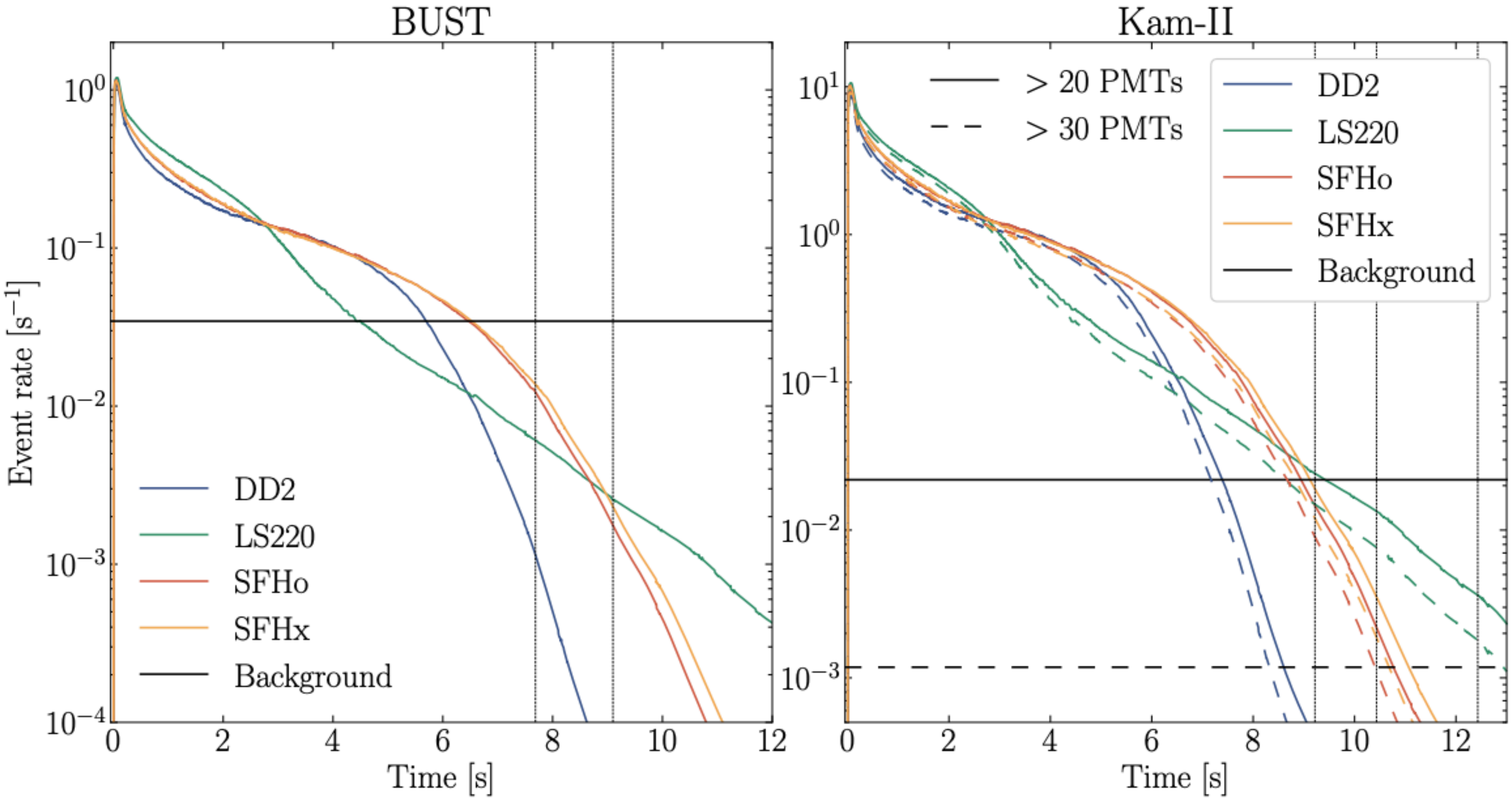
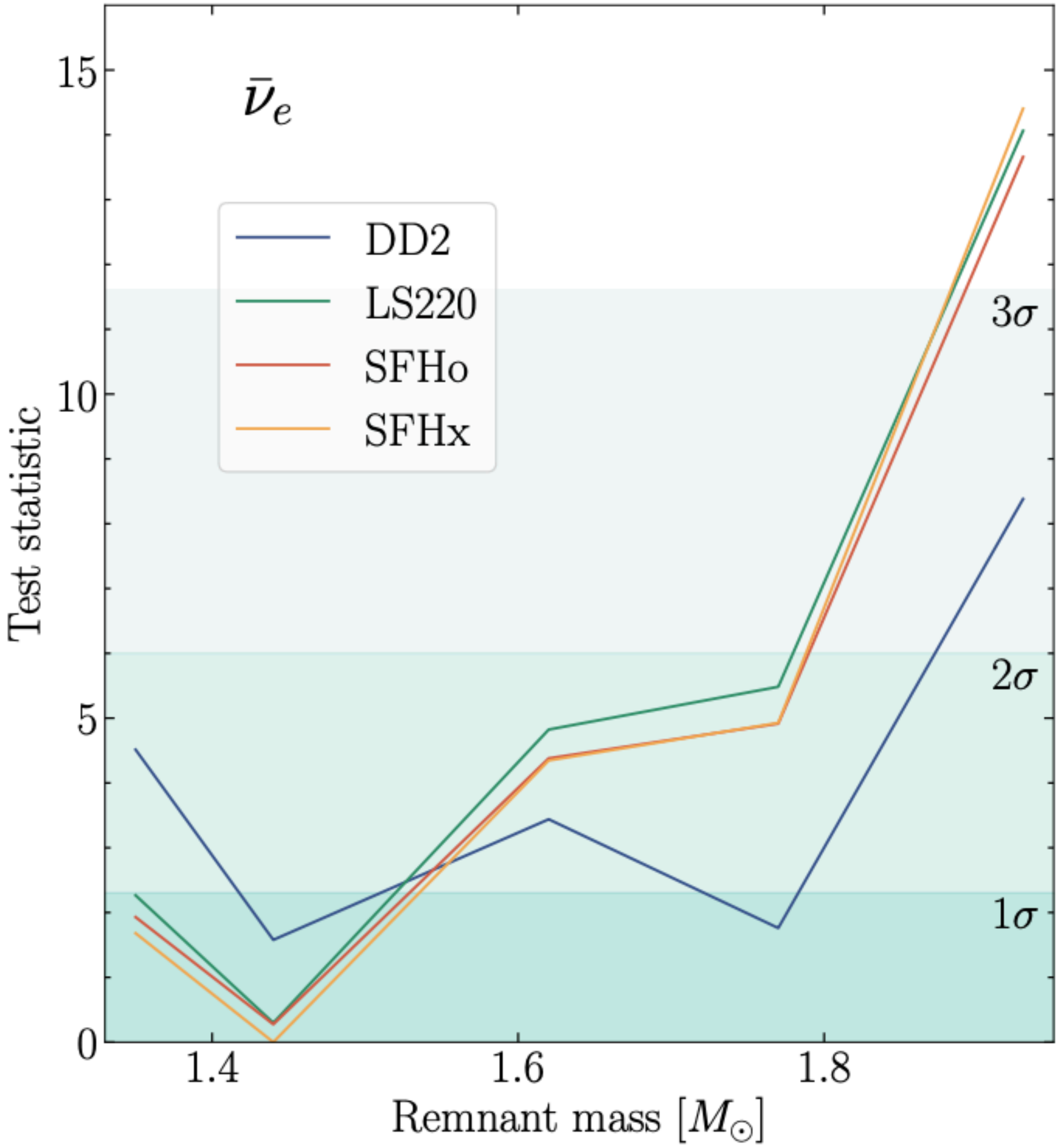
Late-time events

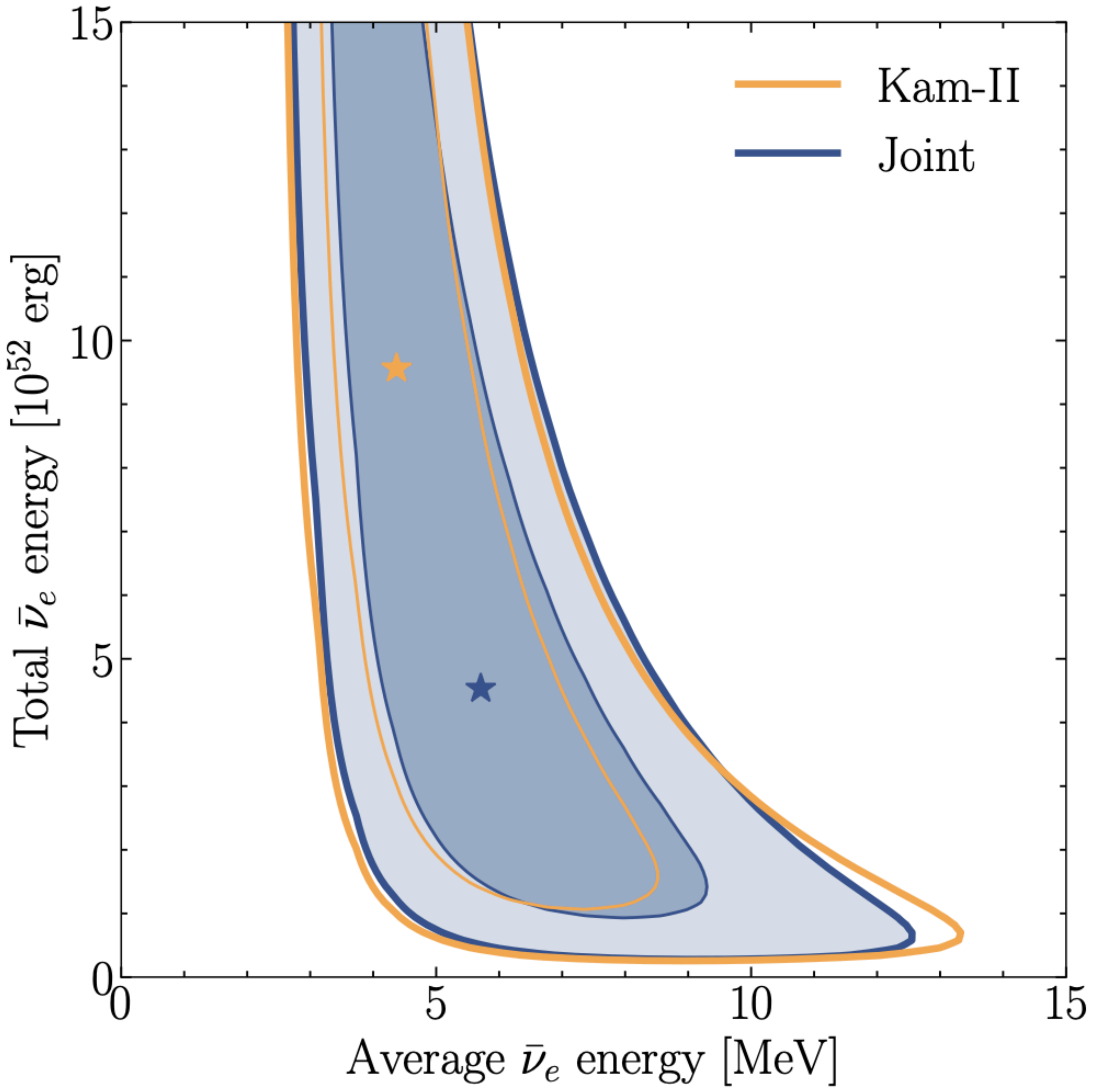


Full time and energy analysis



- 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?

Why supernova?

- ✦ Endpoint of massive stars
- ✦ Internal densities reach up to nuclear densities (10^{14} g cm^{-3})
- ✦ Internal temperatures reach up to 30 – 40 MeV
- ✦ Extreme conditions make even rare processes possible

Testing for new physics

New particles can be produced in supernova core…

Coupled to photons

- Axion-like particles
- Dark photons

Coupled to nucleons

- QCD axion
- Nucleophilic dark matter

Coupled to neutrinos

- Gauge bosons ($B-L$, $L_\mu - L_\tau$)
- Secret interactions
- Pseudo-majorons

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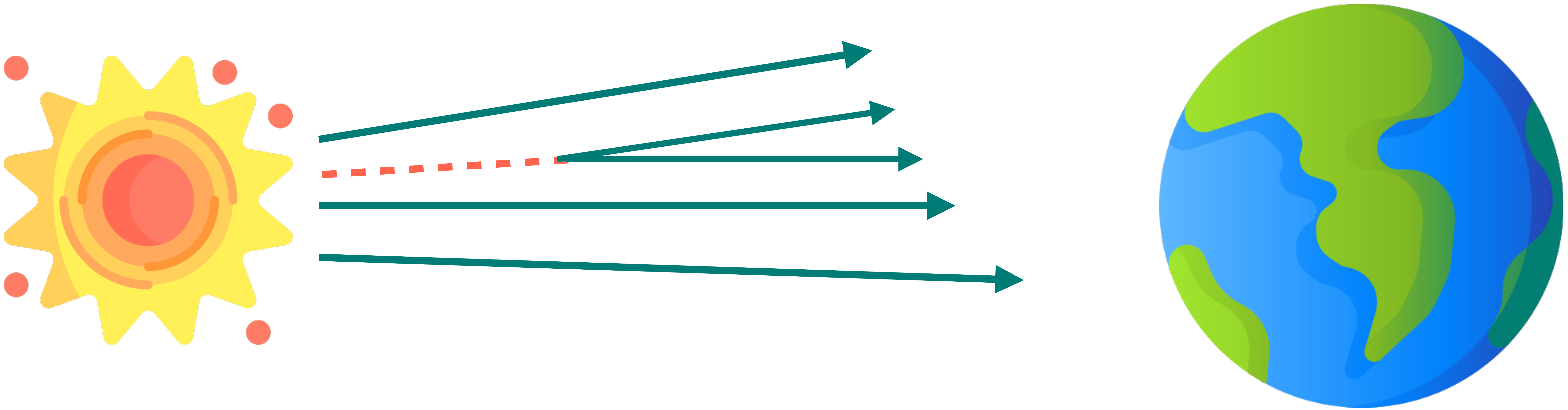
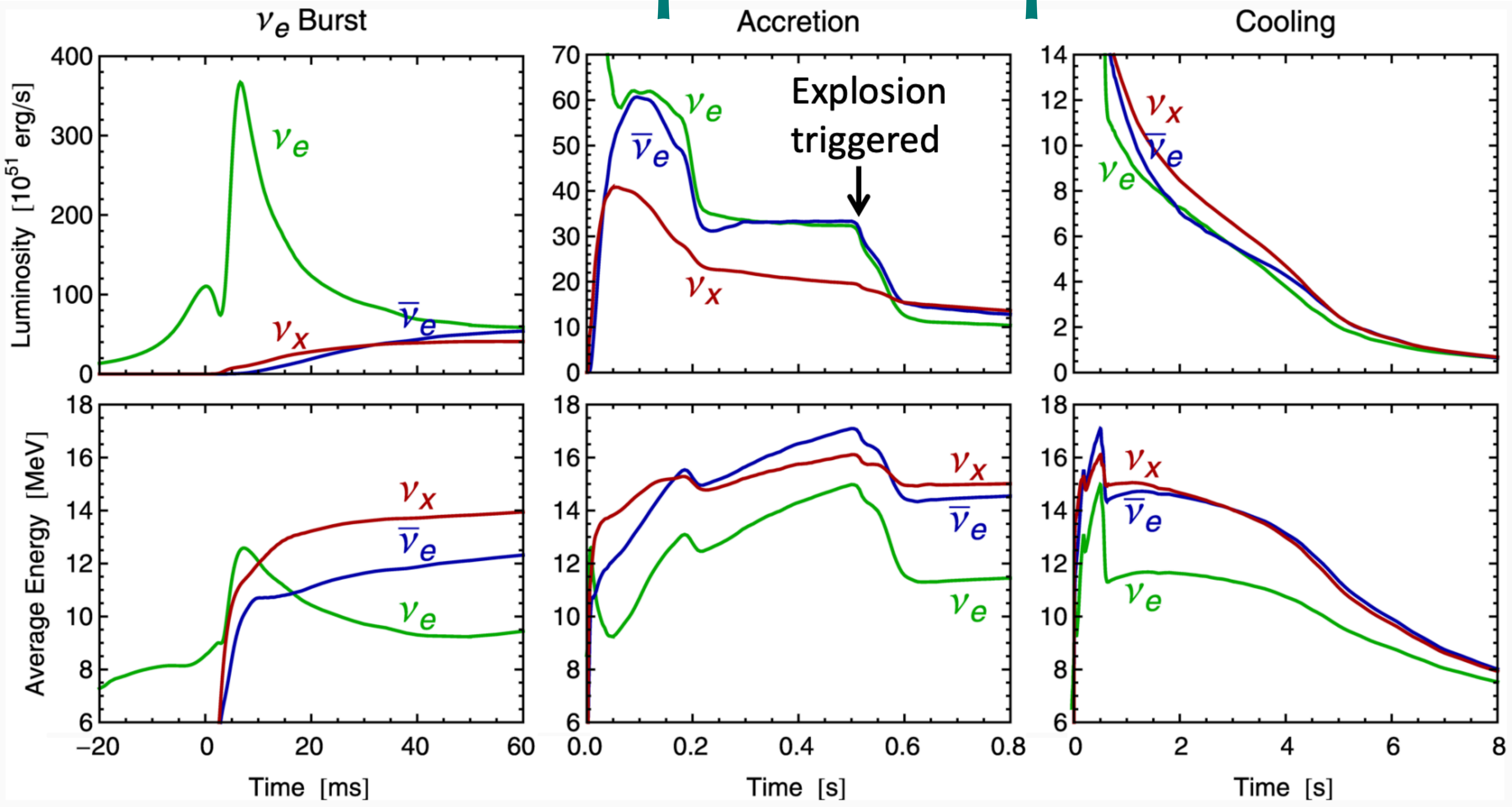


Core-Collapse Supernovae



- 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

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Testing for new physics

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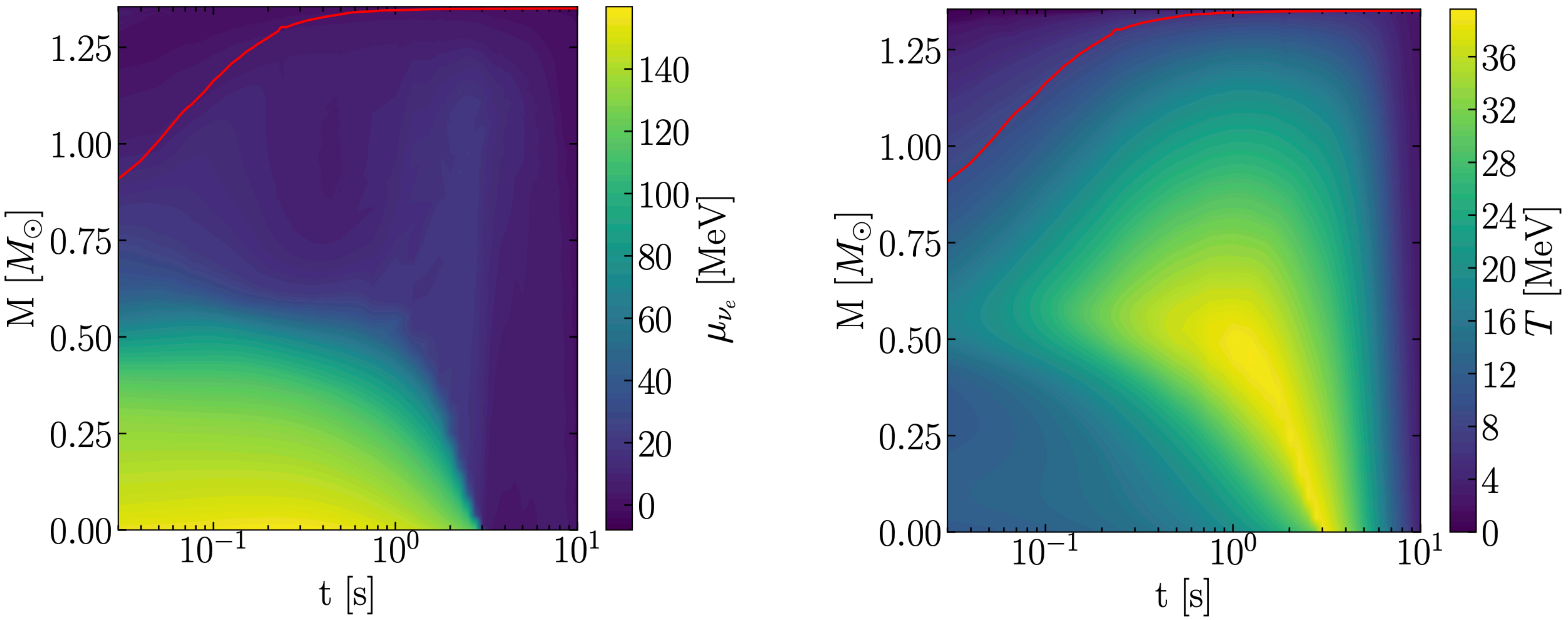

Majoron production

For small masses, signal depends only on gm_ϕ

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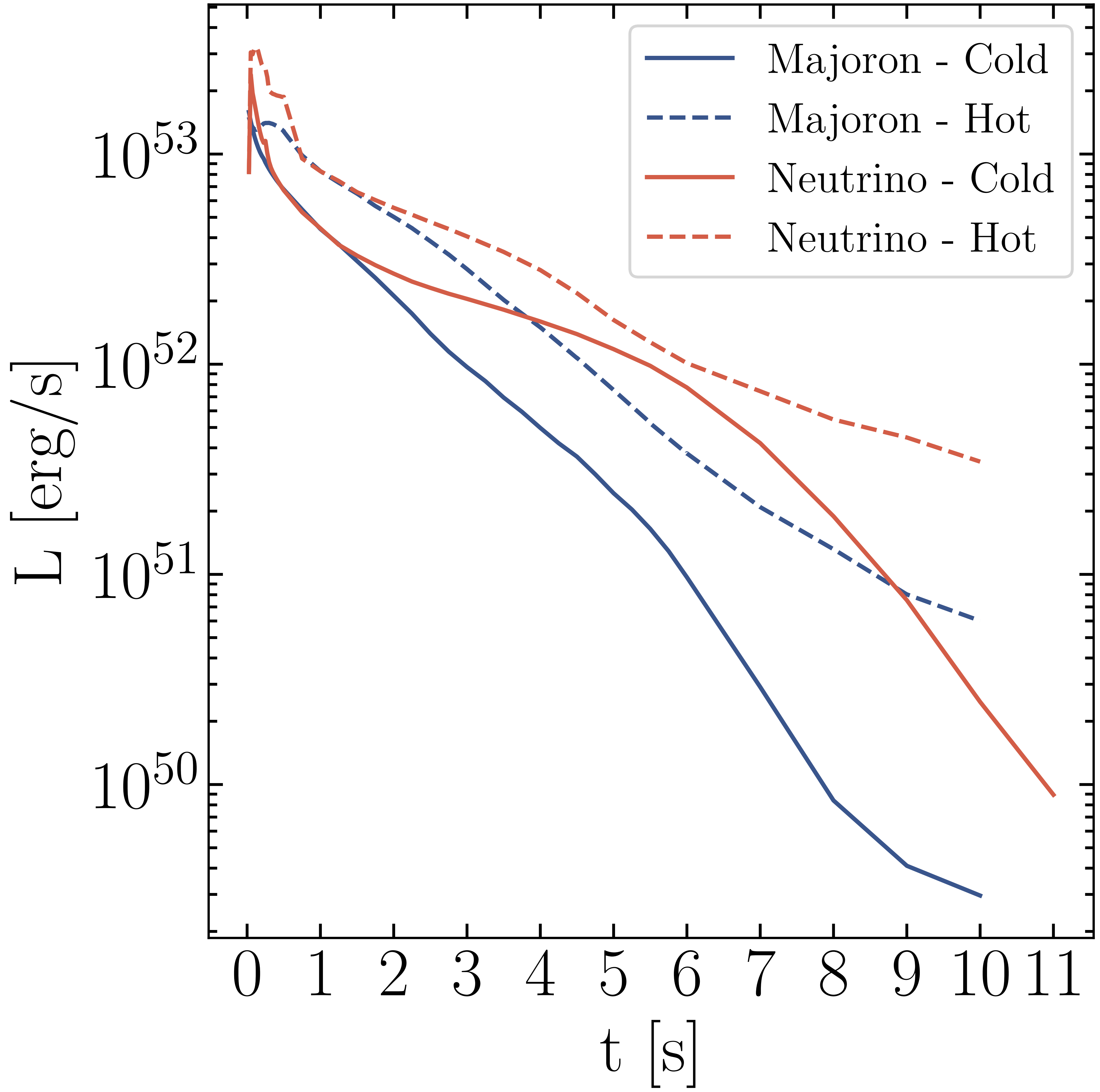

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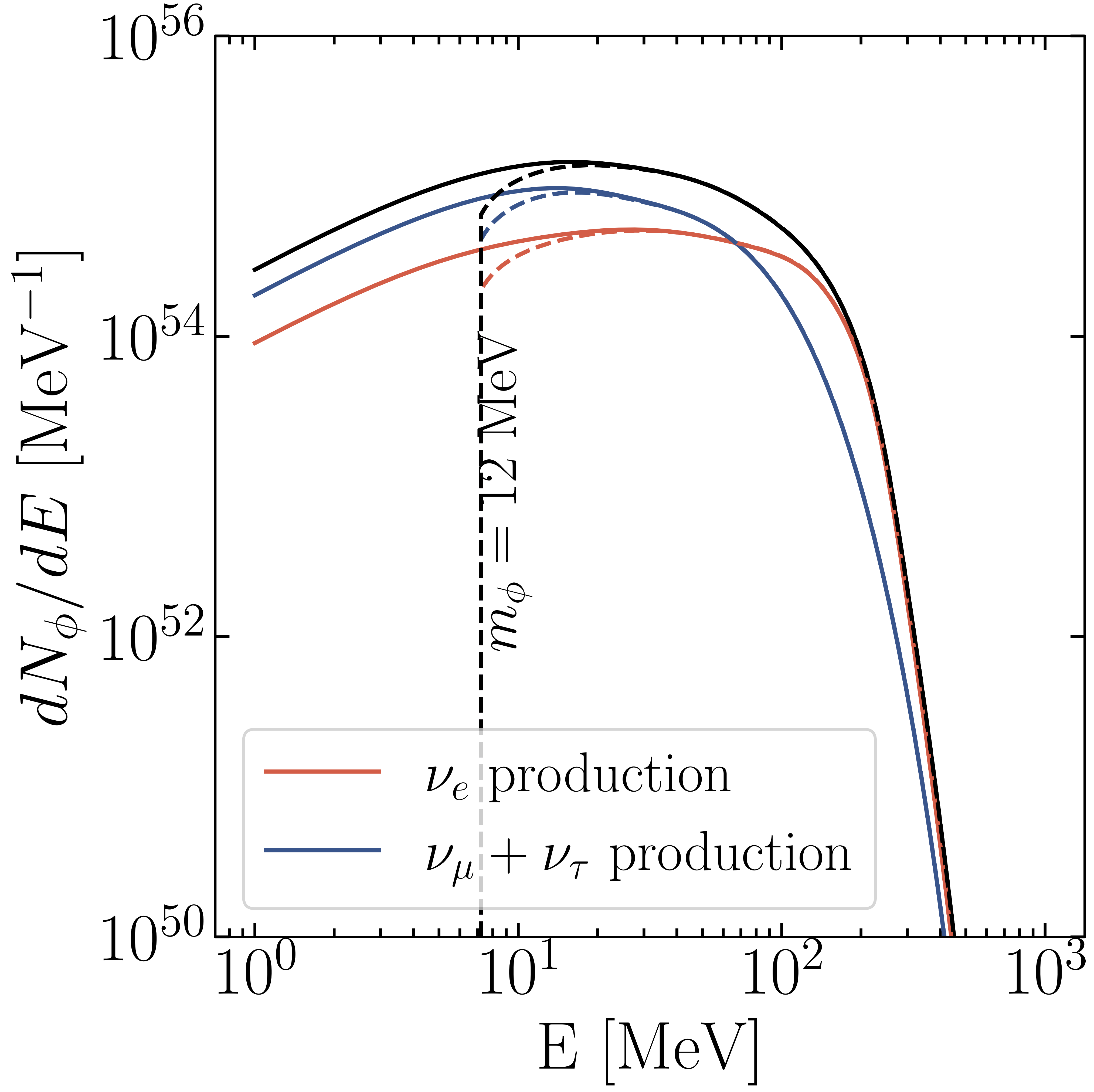
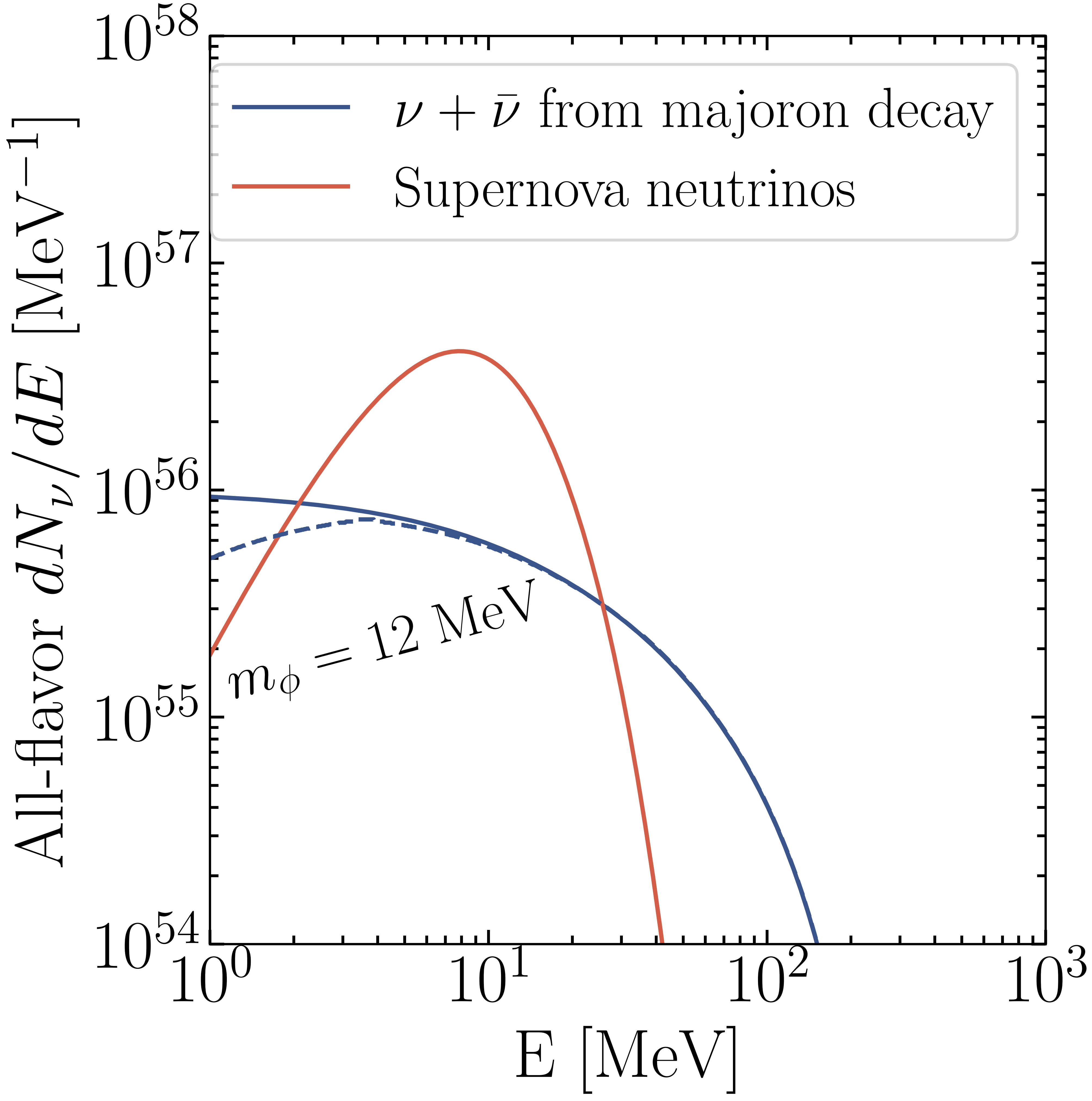
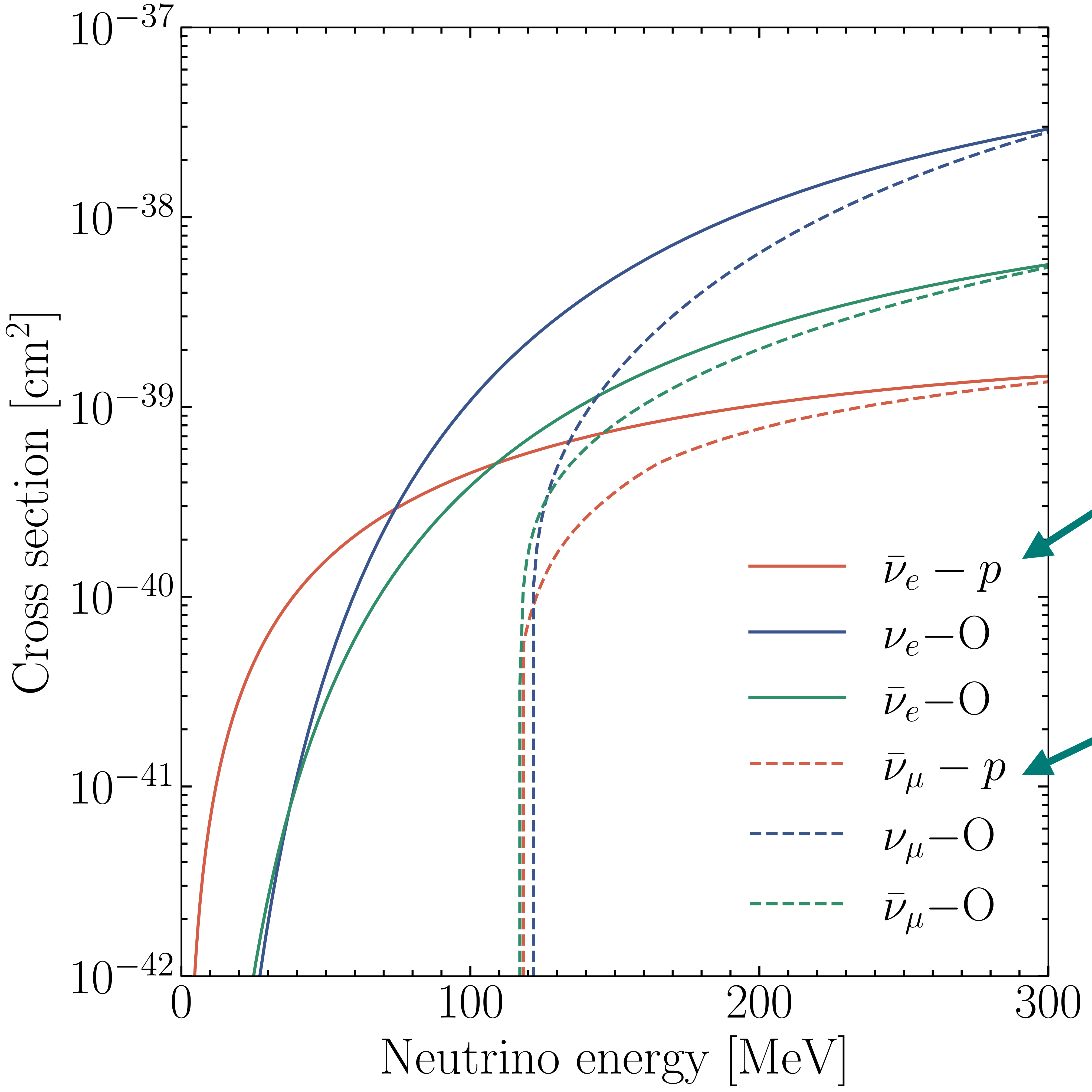




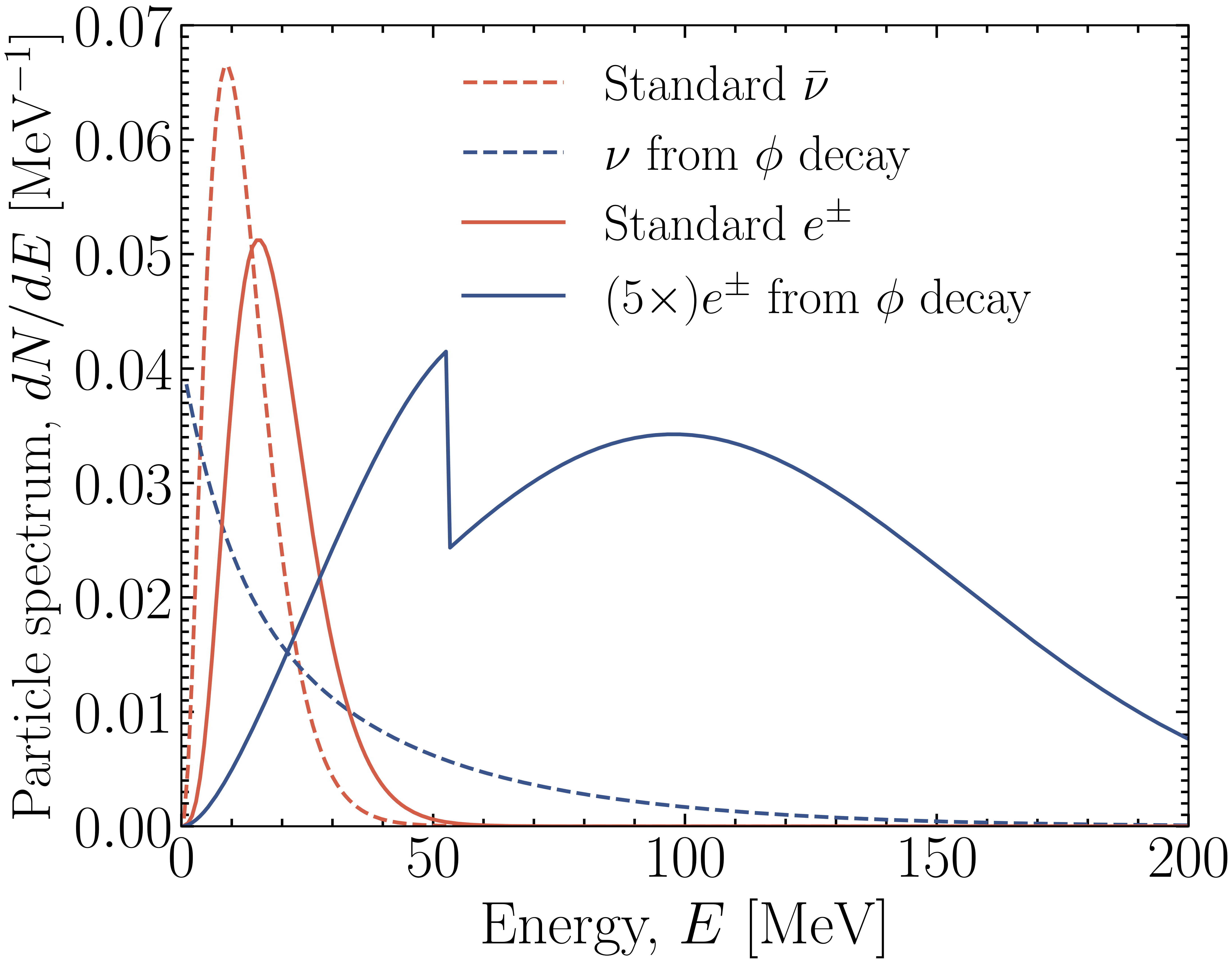
Neutrino detection



Appearing as $e^{\pm}$ Cherenkov signal

$\mu^{\pm}$ loses energy fast, appearing as $e^{\pm}$ from μ decay

Neutrino signal

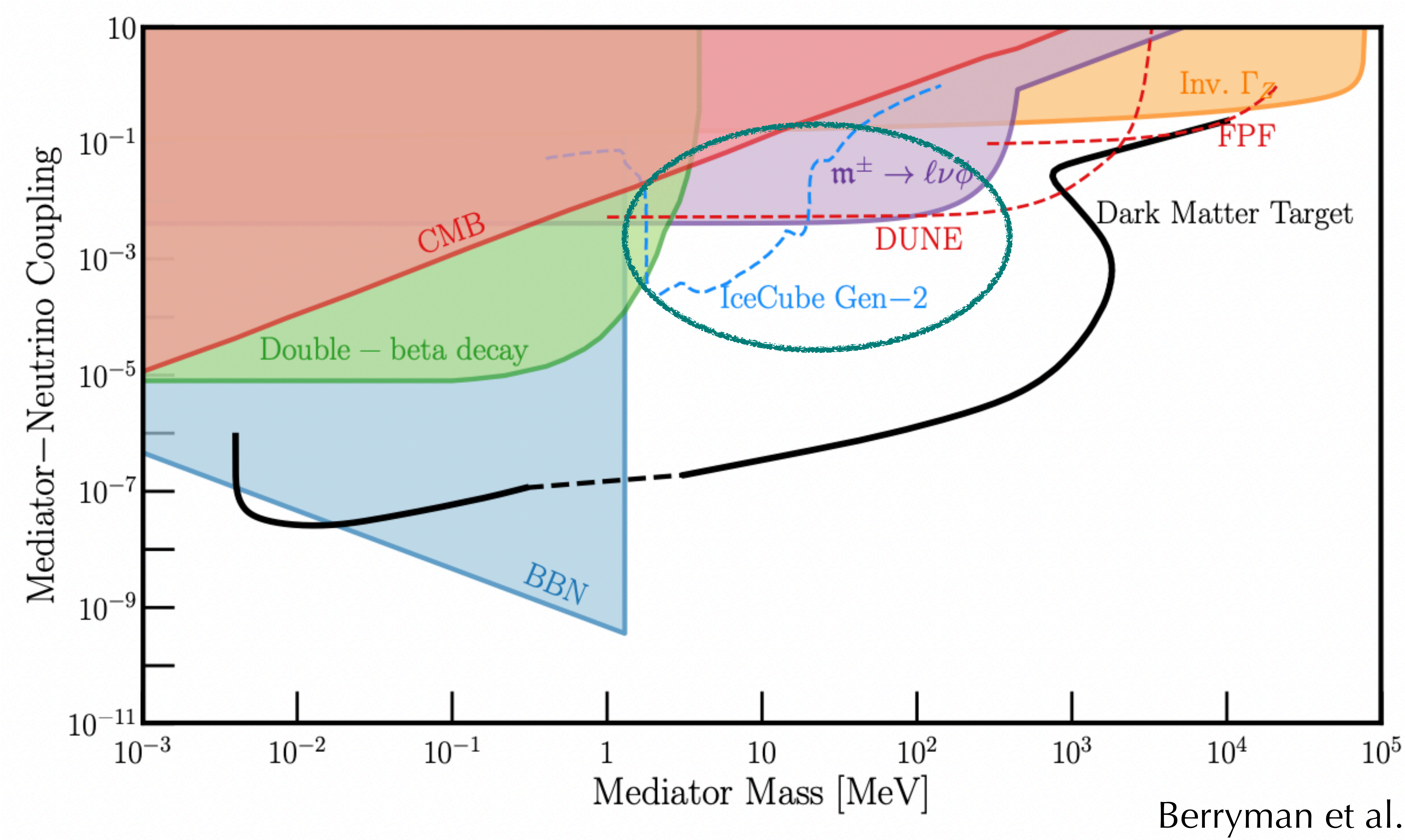


Secret interactions in supernovae

based on arXiv:2307.15122 (accepted at Phys. Rev. D) and arXiv:2307.15115 (submitted to Phys. Rev. Lett.)

with G. Raffelt, E. Vitagliano

Secret interactions

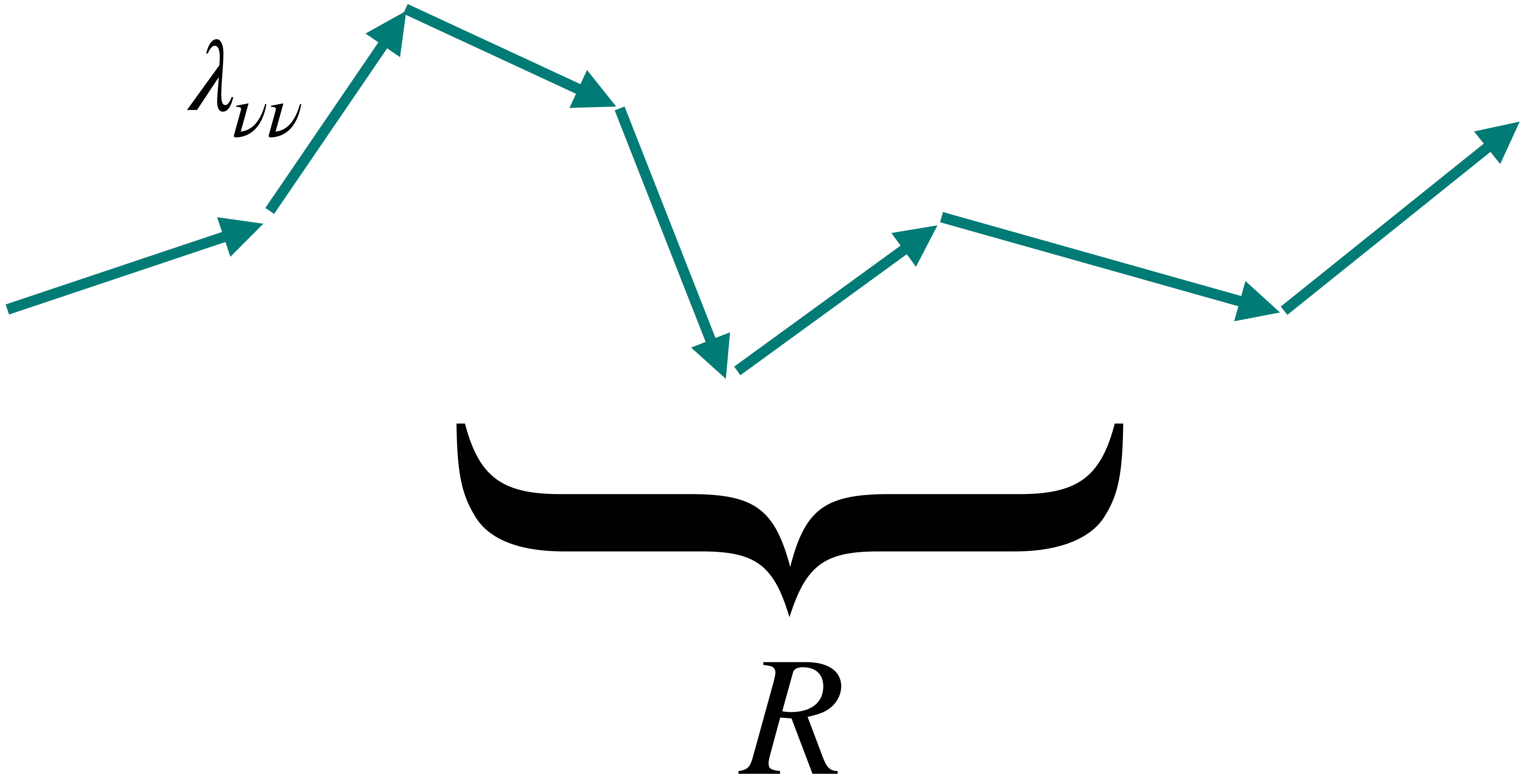


$$\mathscr{L} \propto \bar{\nu}\gamma^{\mu}\nu Z'_{\mu}$$

Berryman et al., 2203.01955

Secret interactions (νSIs) and SNe

- **Manohar (1987)**: νSI delay ν



$$\delta t \sim R\boxed{\frac{R}{\lambda_{\nu\nu}}}$$

Secret interactions (νSIs) and SNe

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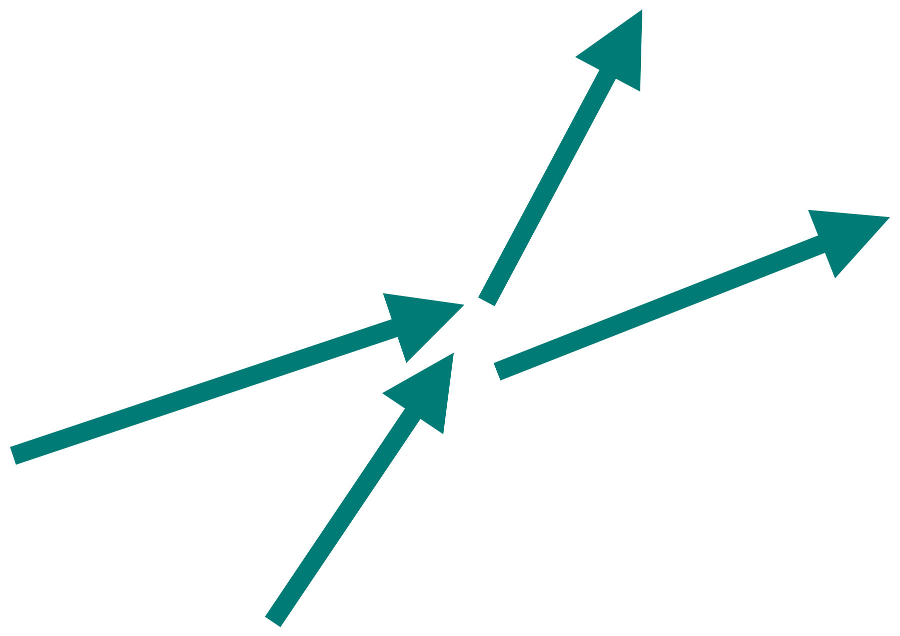
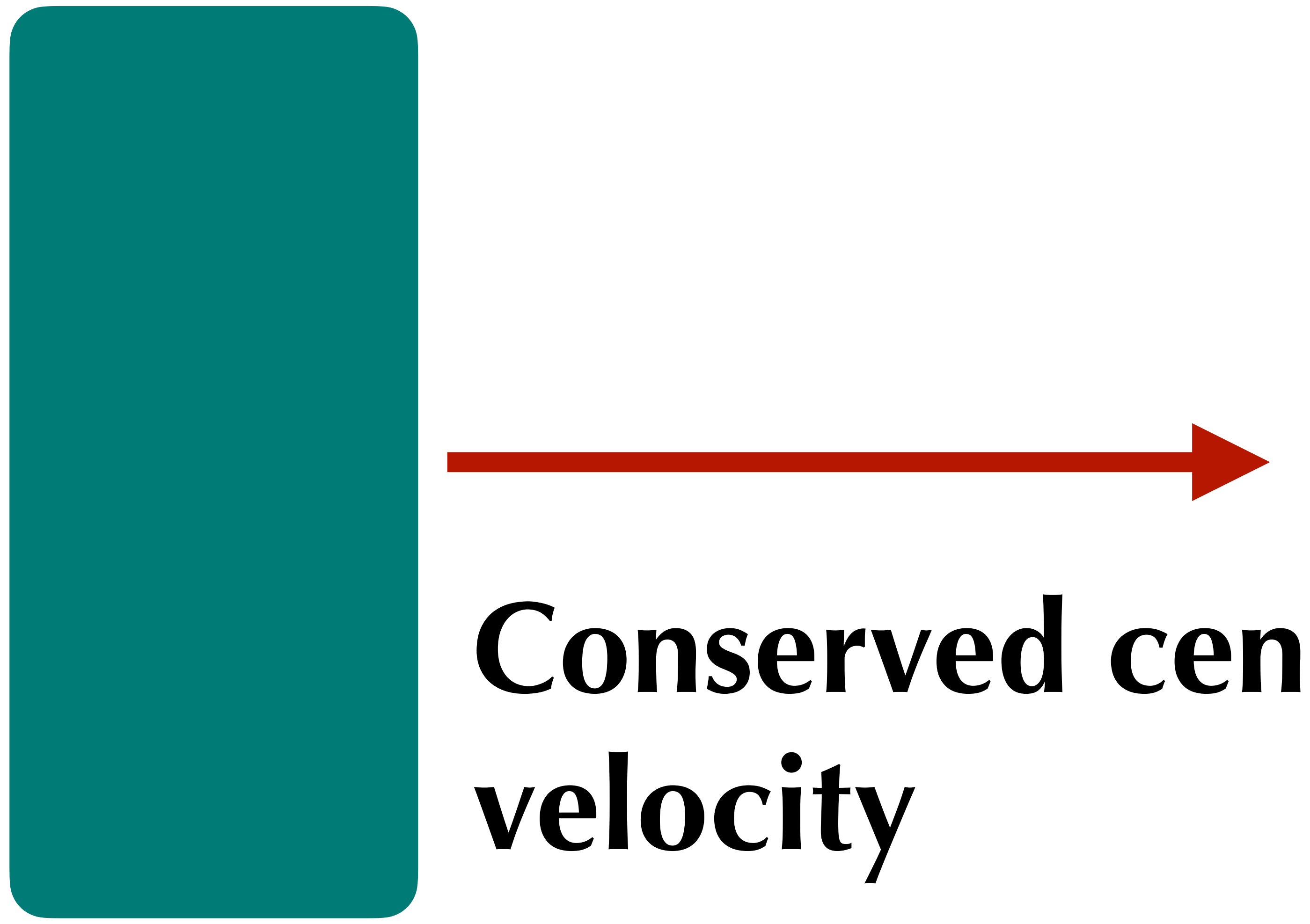
- **Dicus, Nussinov, Pal, Teplitz (1989)**: no delay, ν are a fluid



Total momentum conserved



Conserved center-of-mass velocity

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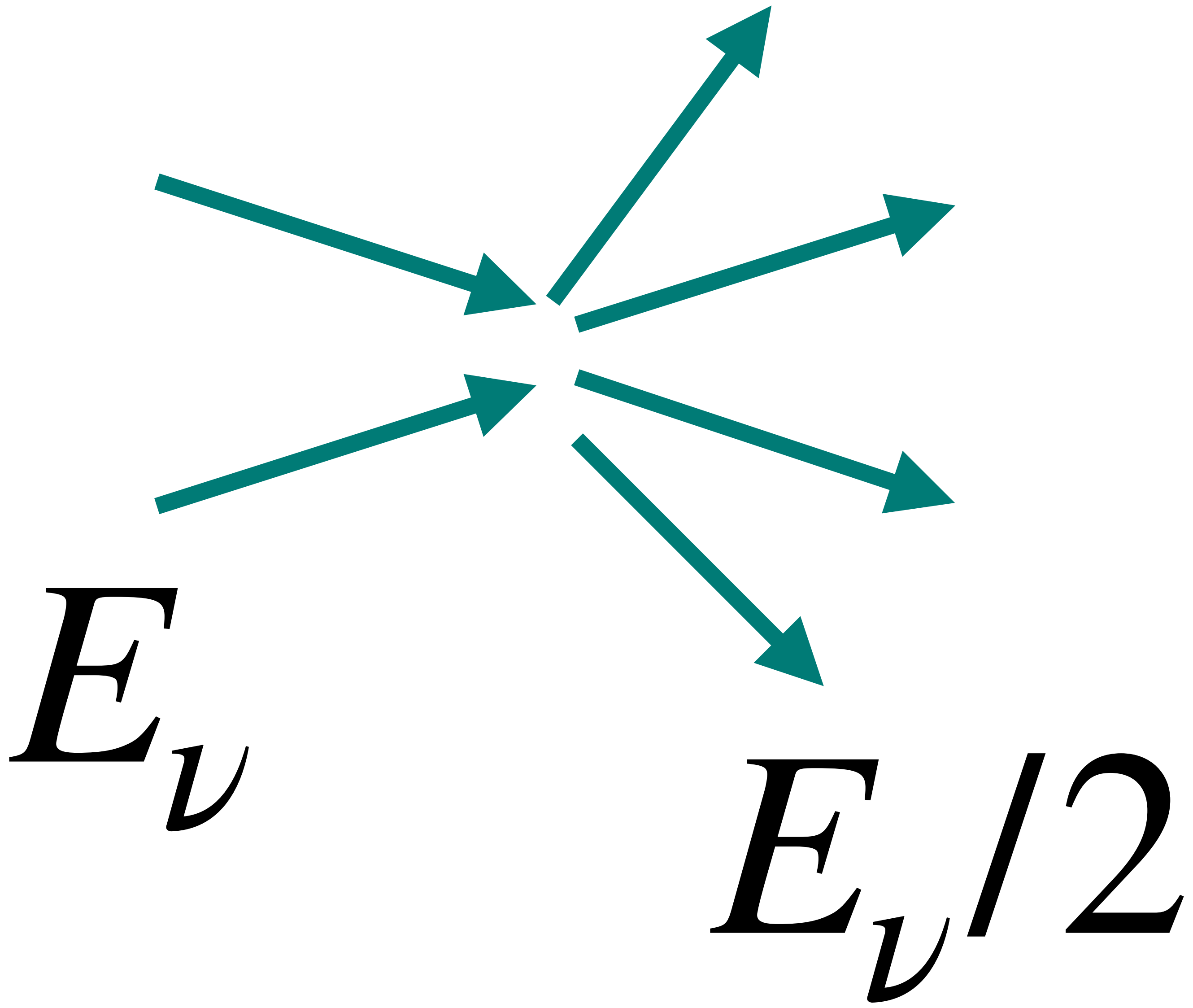

$$\frac{E_\nu}{2^{R/\lambda_{\nu\nu}}}$$

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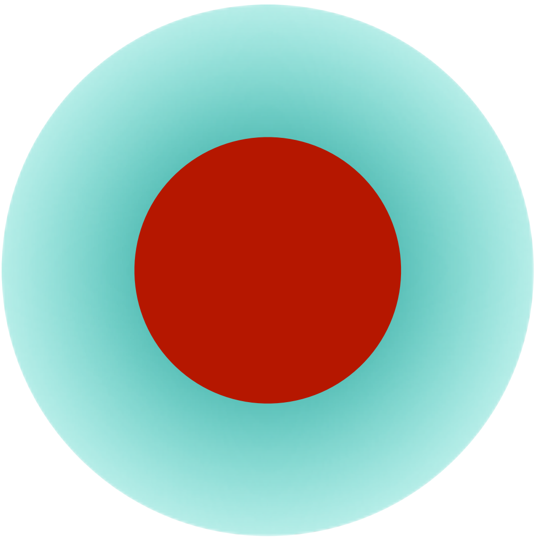
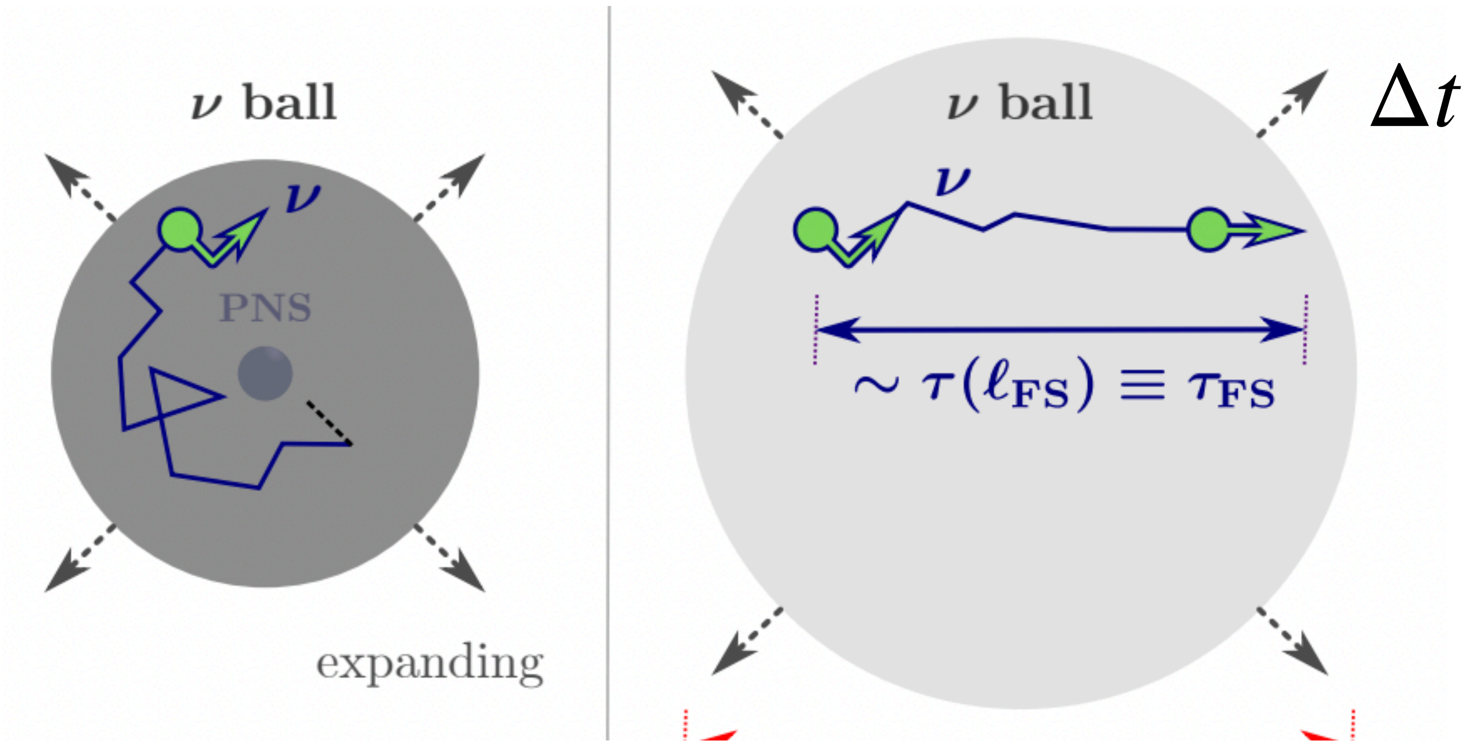
- **Chang, Esteban, Beacom, Thompson, Hirata (2022)**: how does ν fluid escape?

Wind outflow

Steady flow - incomplete picture

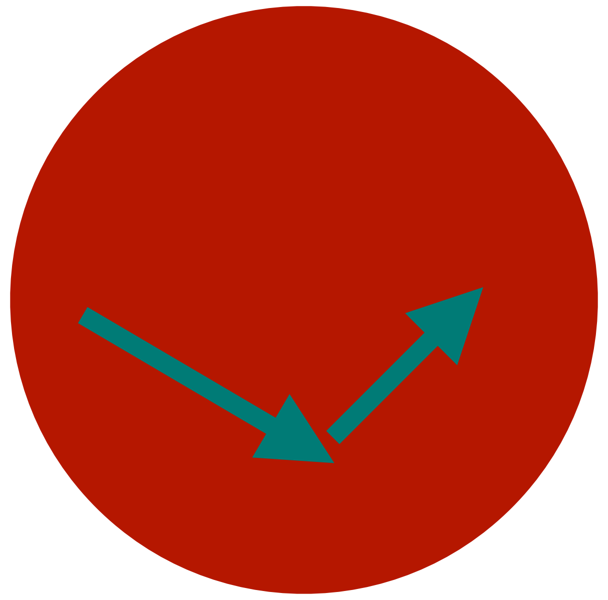




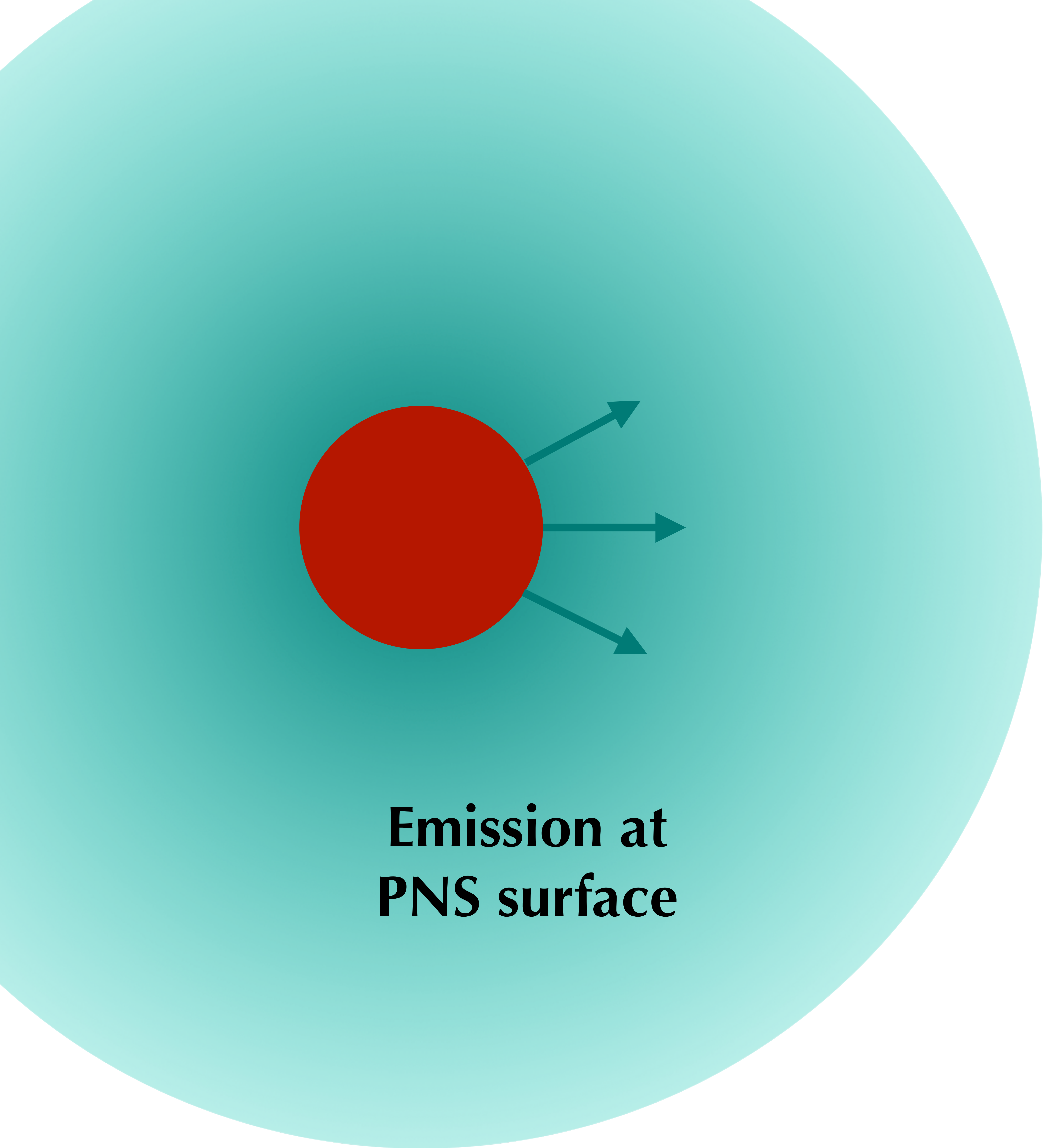
$$\Delta t \sim R\sqrt{\frac{R}{\lambda_{\nu\nu}}}$$

Burst outflow

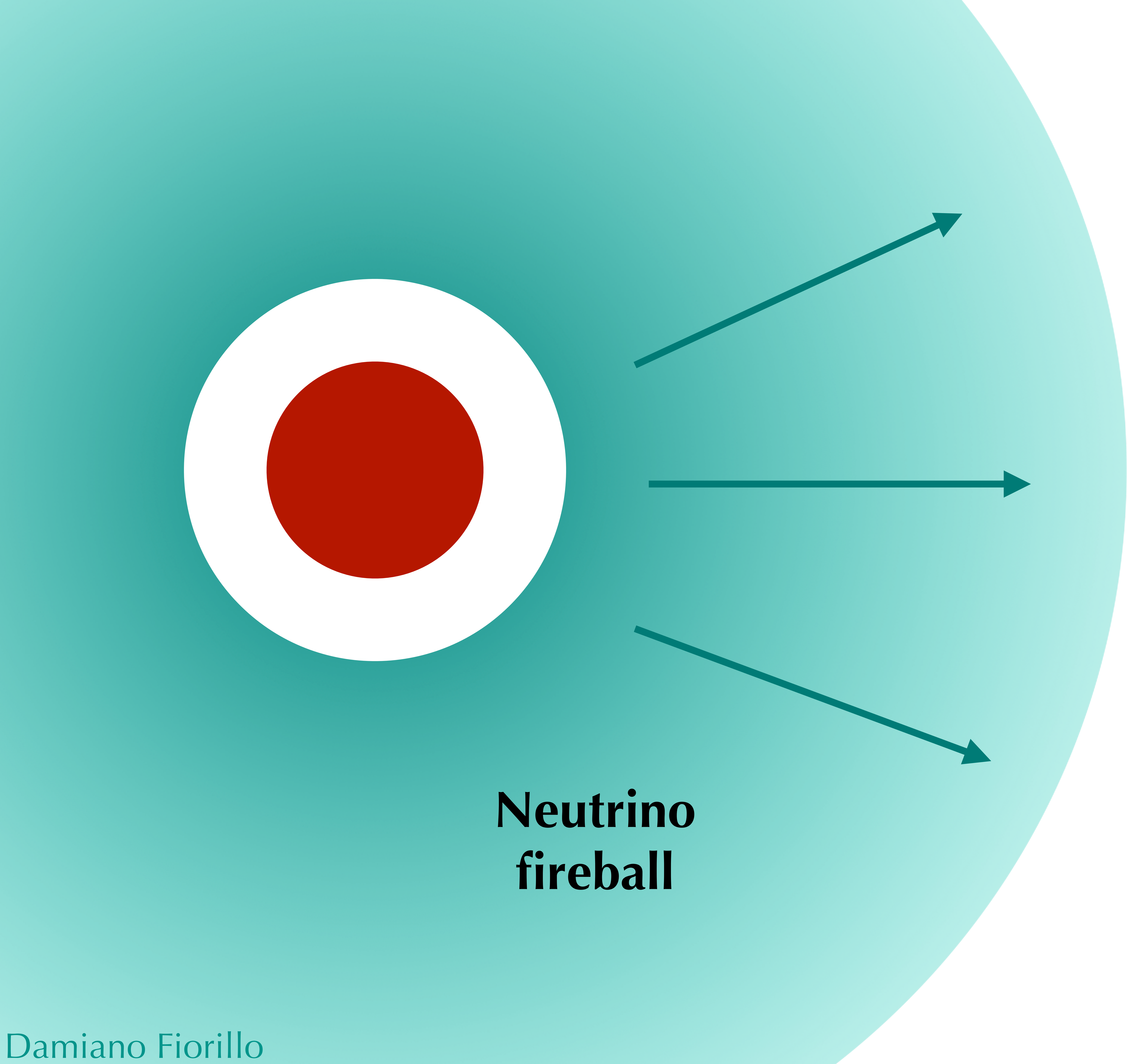
Numerical simulations in conflict with previous literature



Heat transport inside PNS



Emission at PNS surface



Damiano Fiorillo

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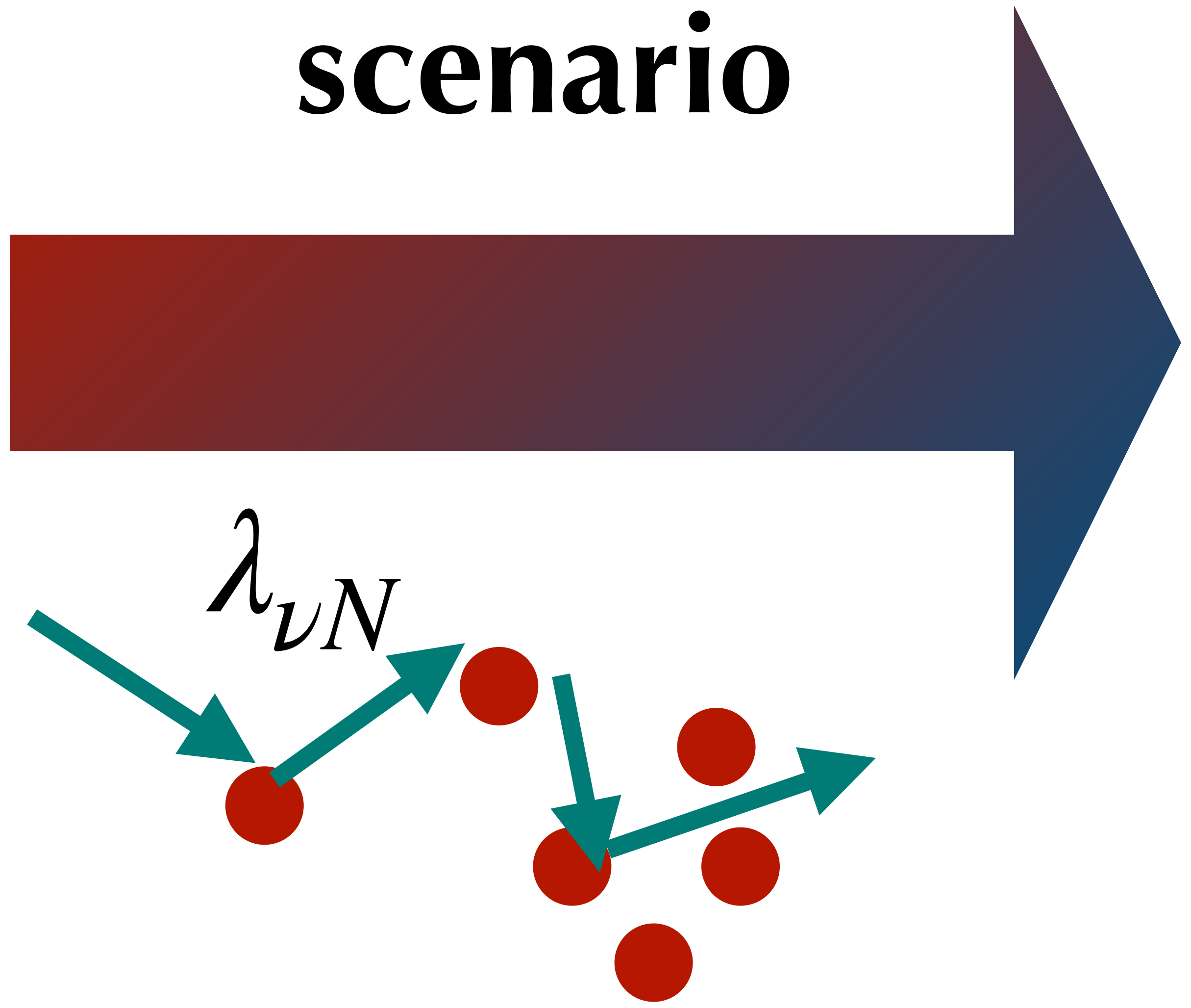
Heat transport inside PNS

Standard scenario

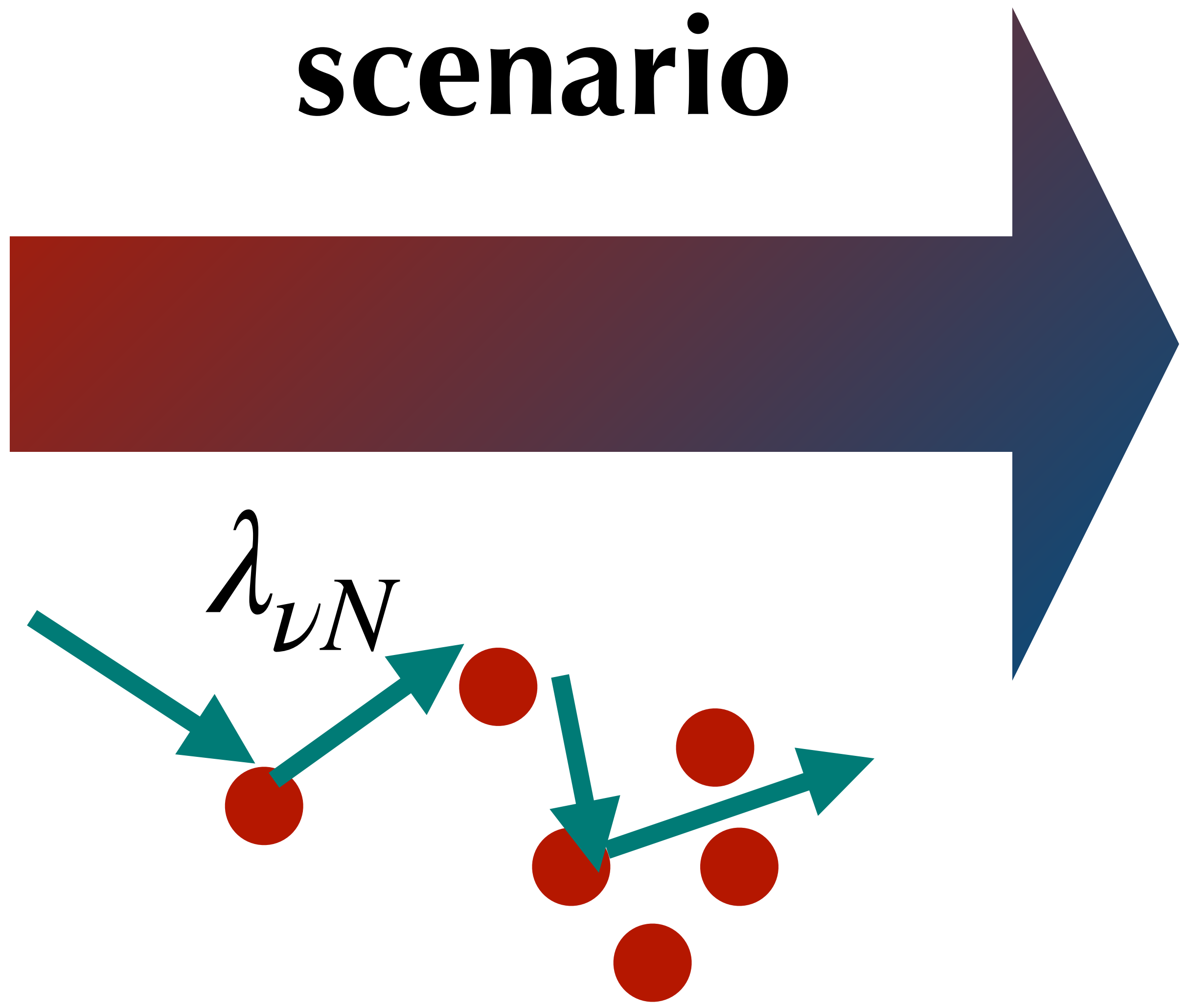


$$F \propto \lambda_{\nu N} \nabla \rho_\nu$$

Temperature gradients induce anisotropy

Heat transport inside PNS

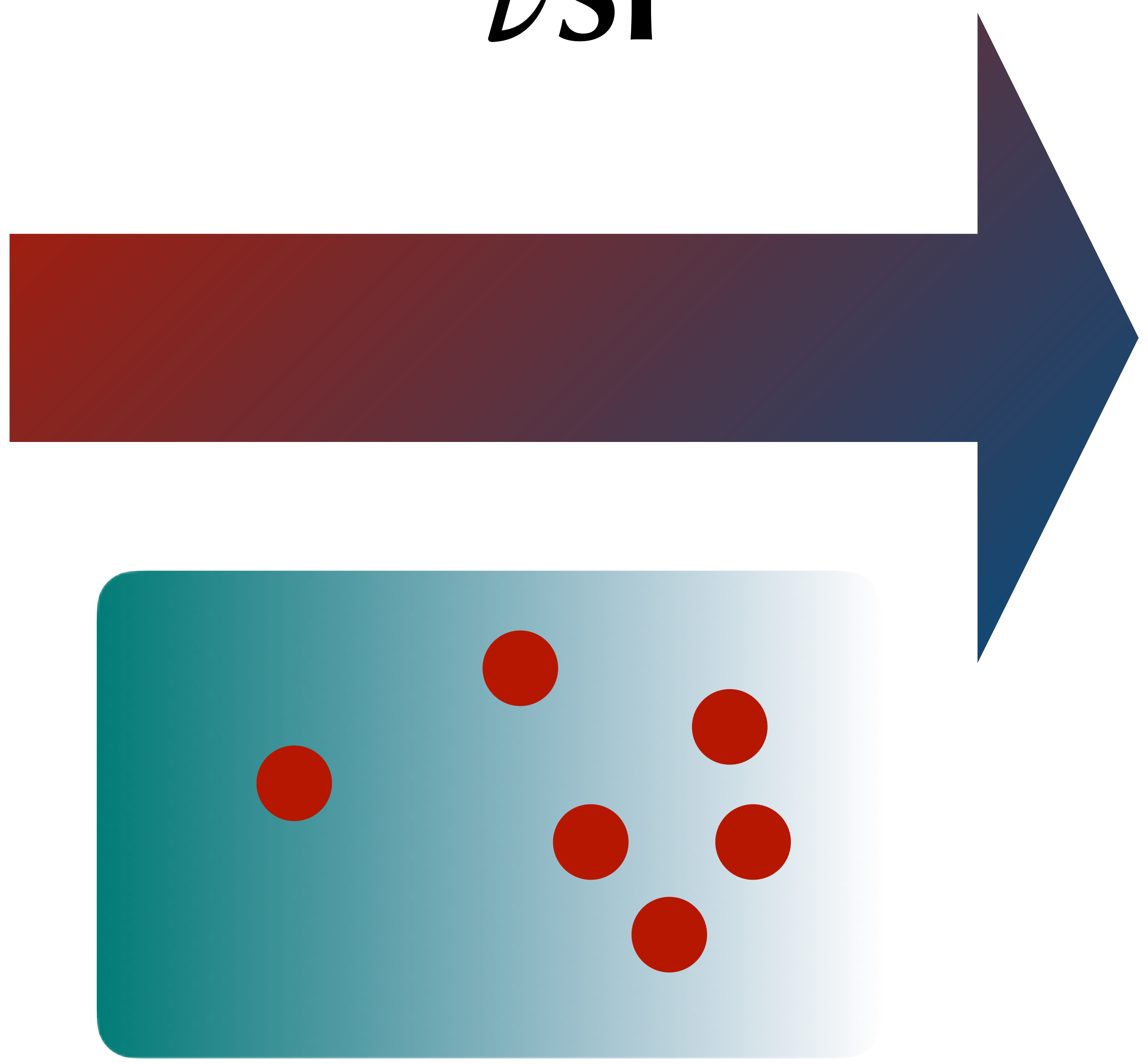
Standard scenario



$$F \propto \lambda_{\nu N} \nabla \rho_\nu$$

Temperature gradients
induce anisotropy

νSI

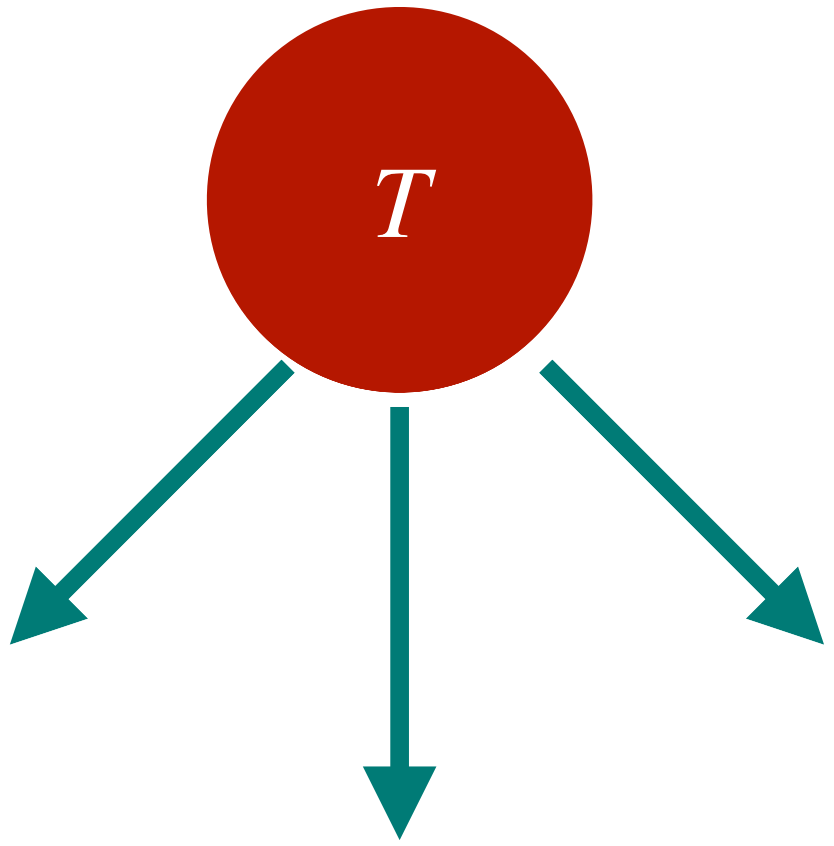


$$\nabla p \sim \frac{\rho_\nu v}{\lambda_{\nu N}} \longrightarrow F = \rho_\nu v \propto \lambda_{\nu N} \nabla \rho_\nu$$

νSI convert anisotropy in
bulk motion

Emission at the PNS surface

Blackbody emission of a fluid

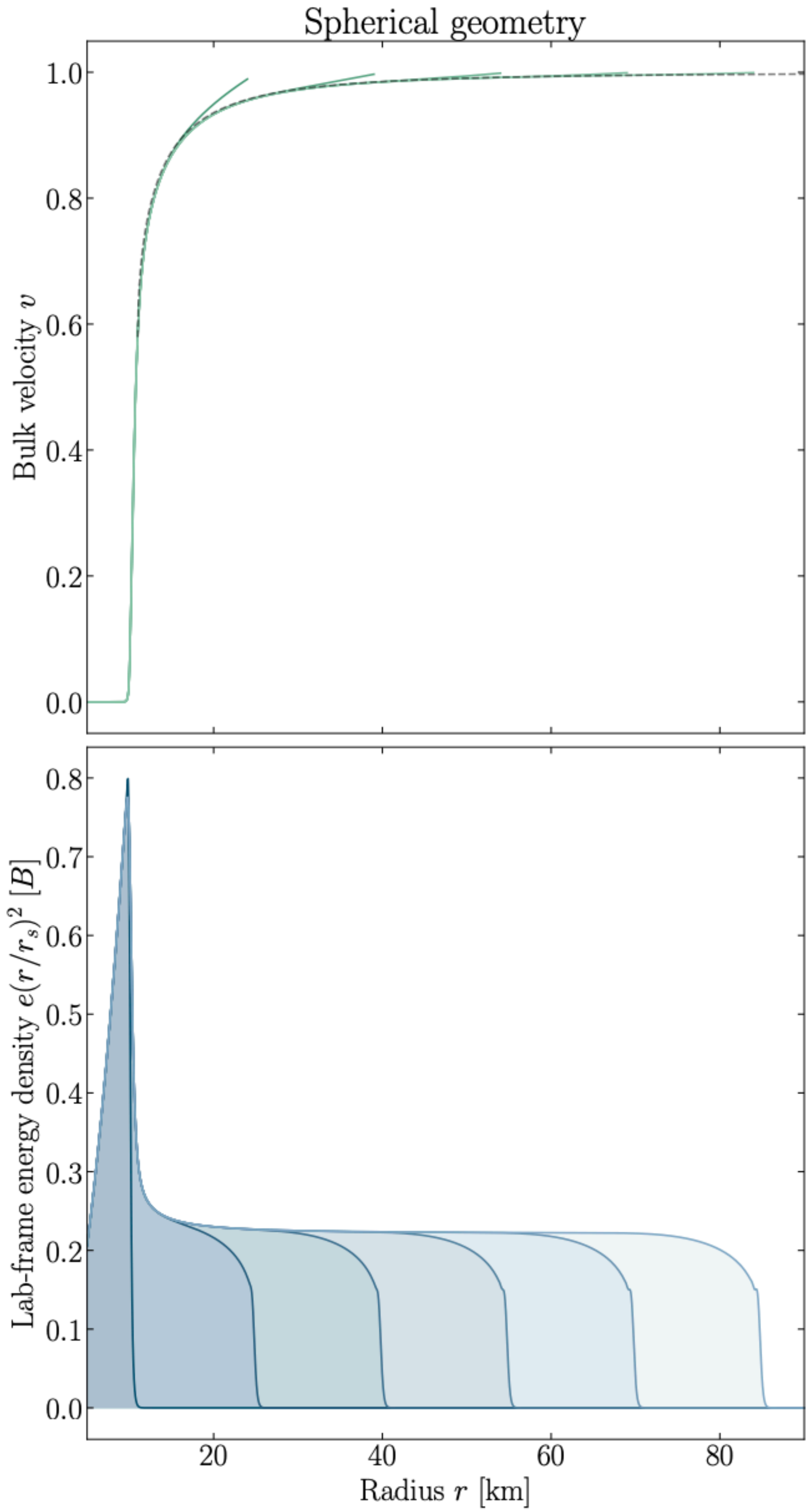


$$T_\nu \propto r^{-1}, \gamma \propto r$$

$$\overline{\epsilon} = 3.48T$$

Compare with standard

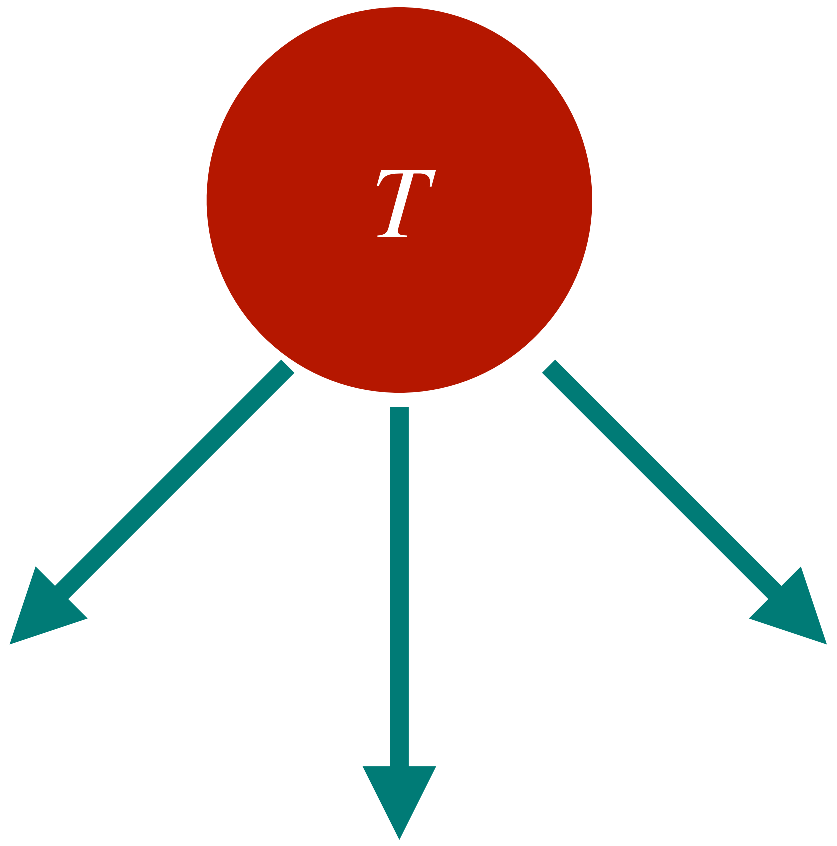
$$\overline{\epsilon} = 3.15T$$

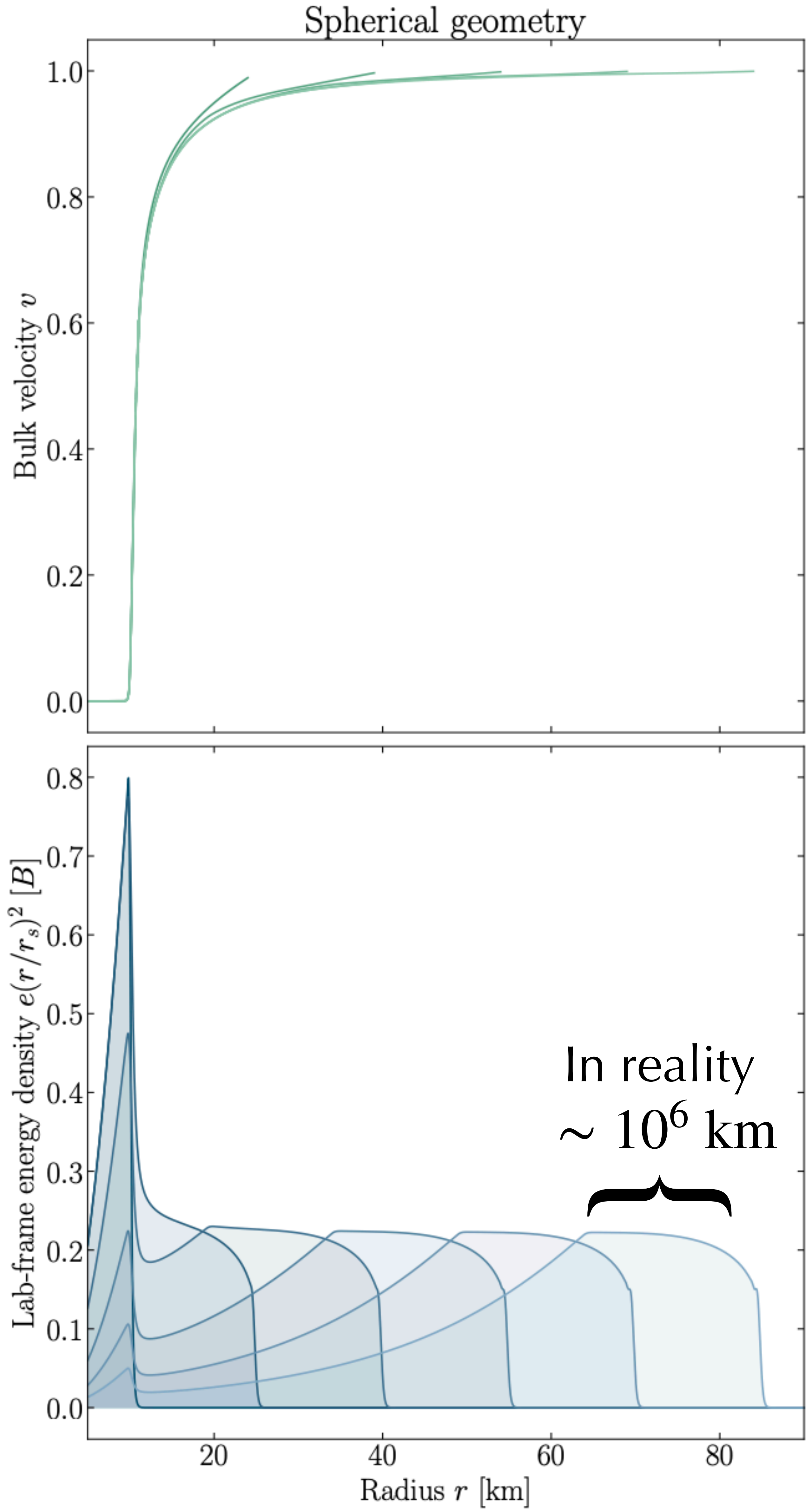


- ✦ Front emission moves with the speed of light
- ✦ Quasi-steady emission for a time $\sim 5\ \mathrm{s} \sim 10^6\ \mathrm{km} \gg R_{\mathrm{PNS}}$
- ✦ Bulk of fluid moves with speed of light

Neutrino fireball

Blackbody emission of a fluid

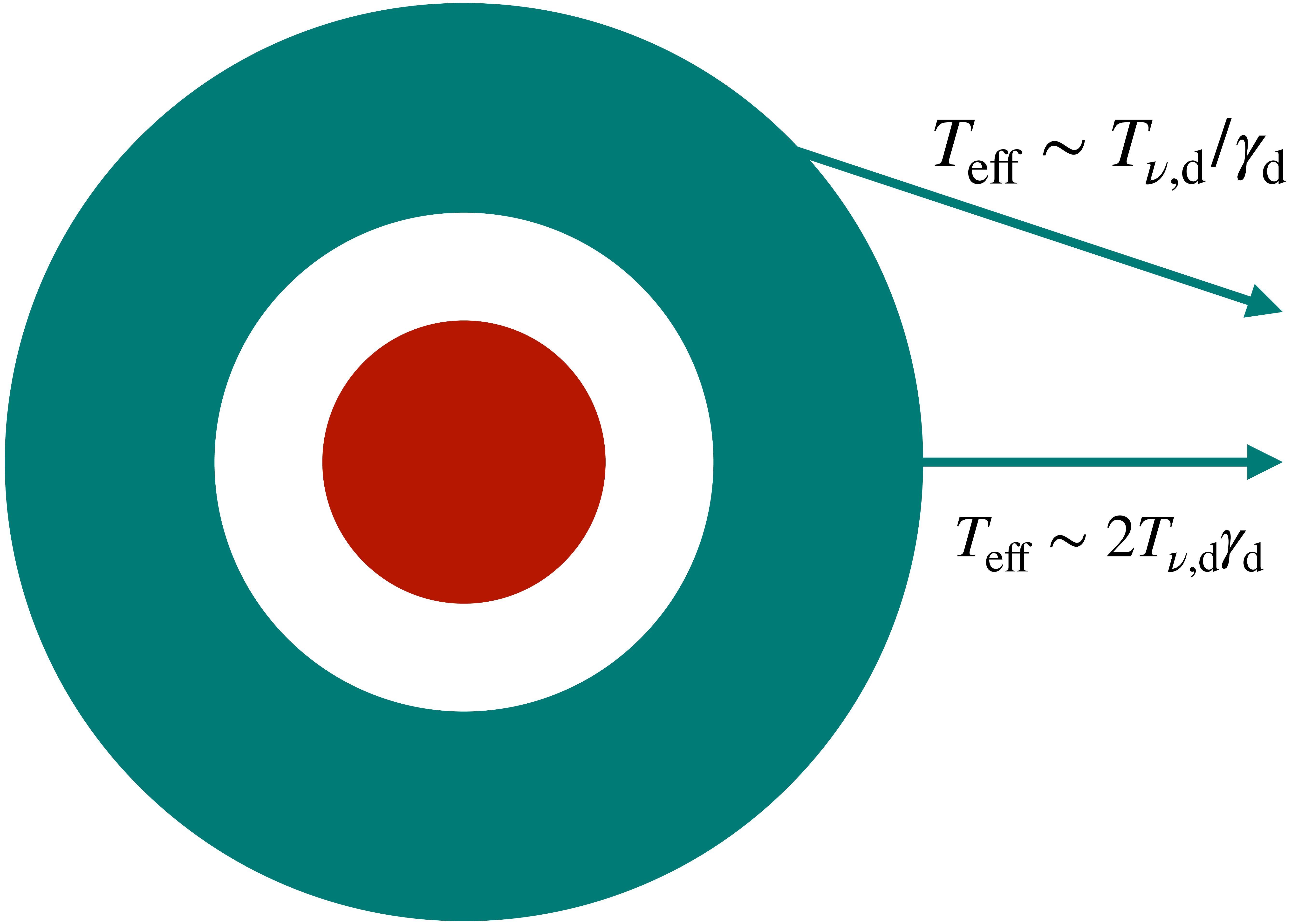




- If PNS turns off, bulk of the fluid moves so fast it does not perceive it (sound horizon)
- No change in ν thickness, since most fluid is moving with $v \sim 1$
- $\nu\bar{\nu} \to \nu\bar{\nu}\nu\bar{\nu}$ balanced by inverse reaction — detailed balance wants $\mu_\nu = -\mu_{\bar{\nu}} = 0$, already satisfied

No observable affected by large ratio $R/\lambda_{\nu\nu}$!

Decoupling



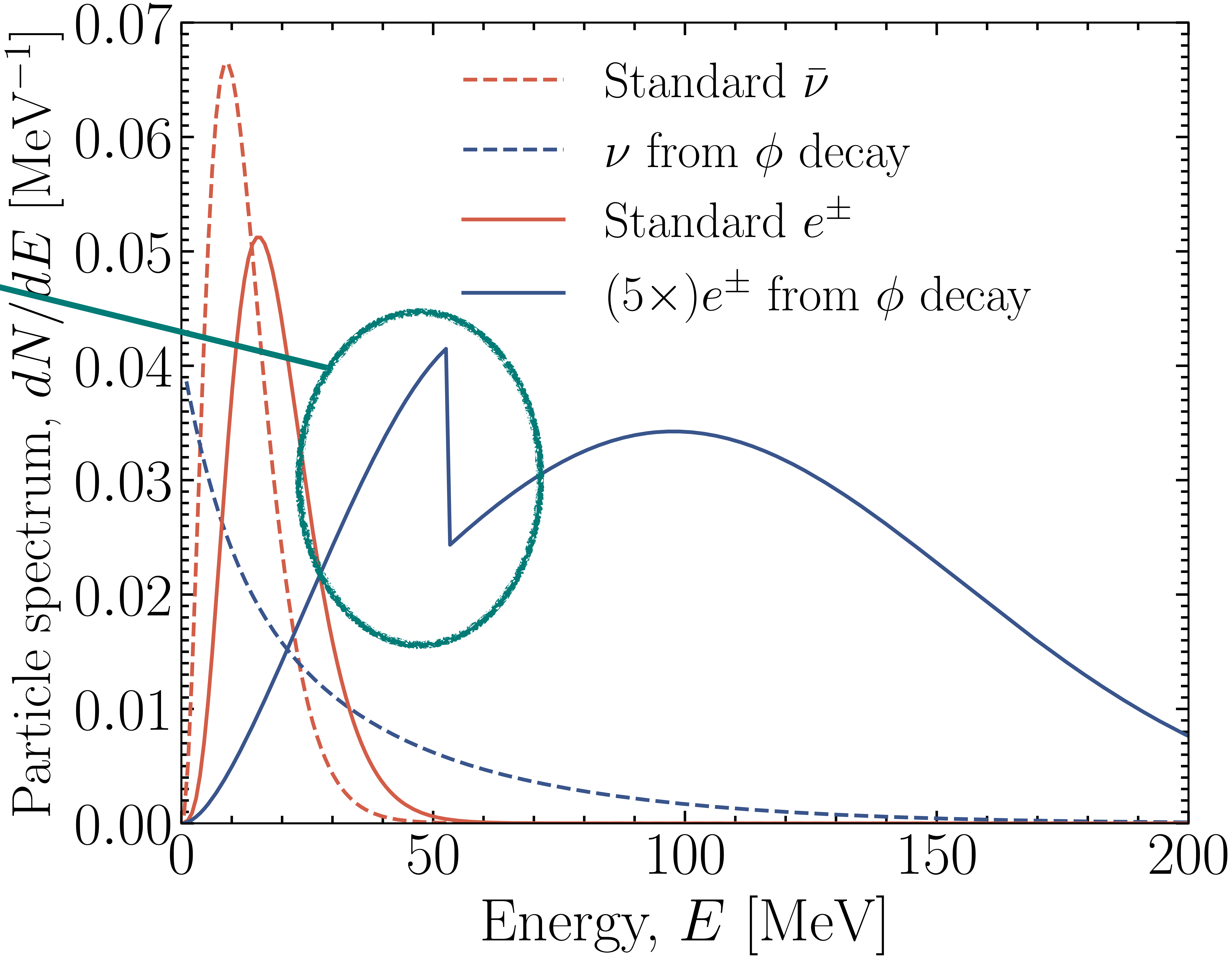
- Strongly boosted blackbody
- Superposition of different directions lead to

$$\frac{d\Phi}{d\epsilon} \propto \epsilon \log\left[1 + e^{\eta - \epsilon/2\overline{T}}\right]$$

- Obtained in **DF** et al., 2303.11395, 2305.10327

Neutrino signal

From μ decay



No event observed above 40 MeV!

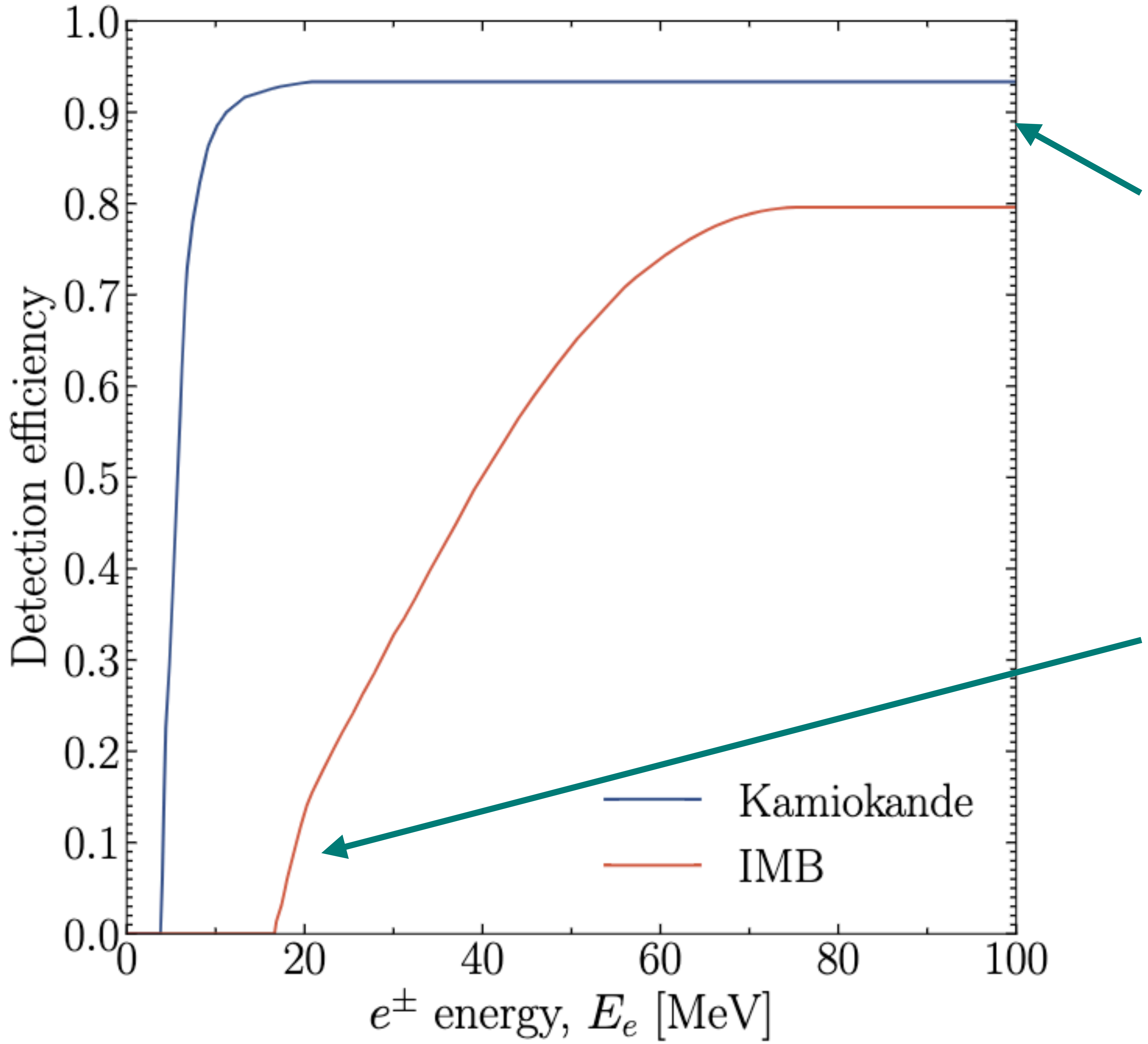
Statistical analysis

- Combined analysis of Kamiokande and IMB
- Supernova neutrino spectrum left as a fit parameter

$$\frac{dN_{\bar{\nu}_e}}{dE_\nu} = \frac{E_{\text{tot}}}{6E_0^2}\frac{(1+\alpha)^{1+\alpha}}{\Gamma(1+\alpha)}\left(\frac{E_\nu}{E_0}\right)^\alpha e^{-(1+\alpha)E_\nu/E_0}$$

- Fit performed both for cold ($\alpha = 2.39$) and hot ($\alpha = 2.07$) model

Detection efficiency

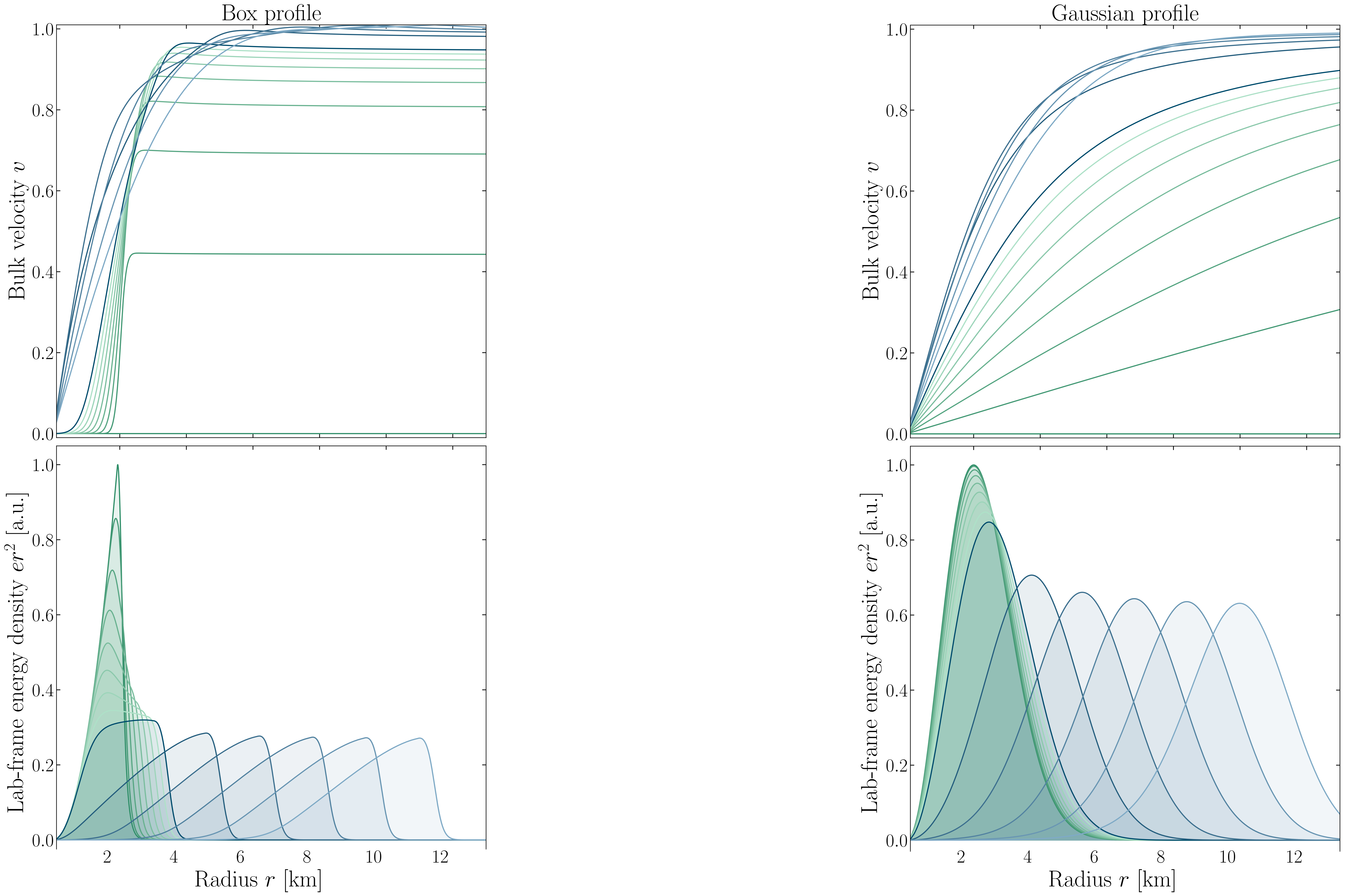


Comparable efficiencies at high energies, but IMB has larger volume

Few low-energy events at IMB

Above 75 MeV no events observed
(private communication)

Fireball formation vs. burst outflow



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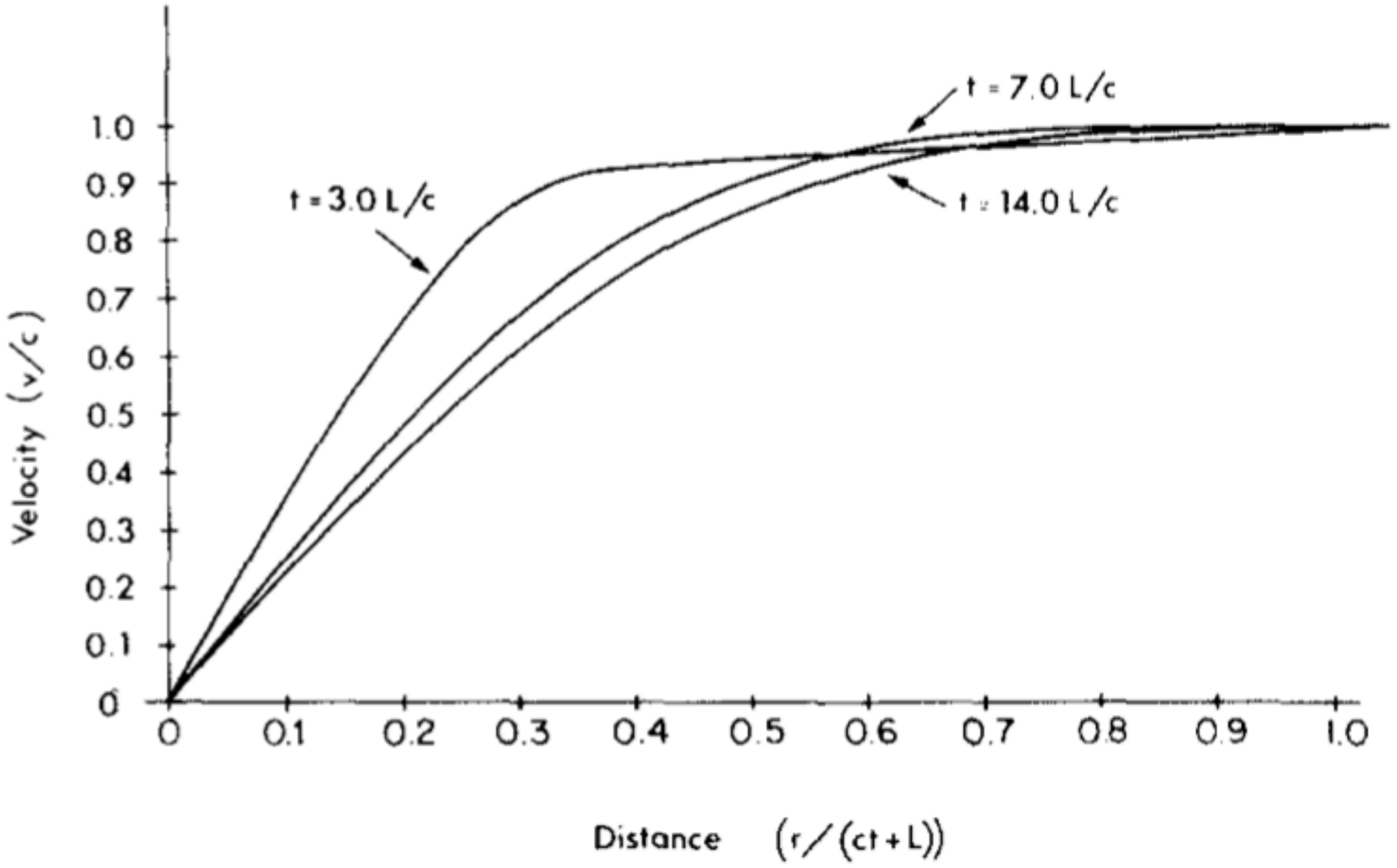
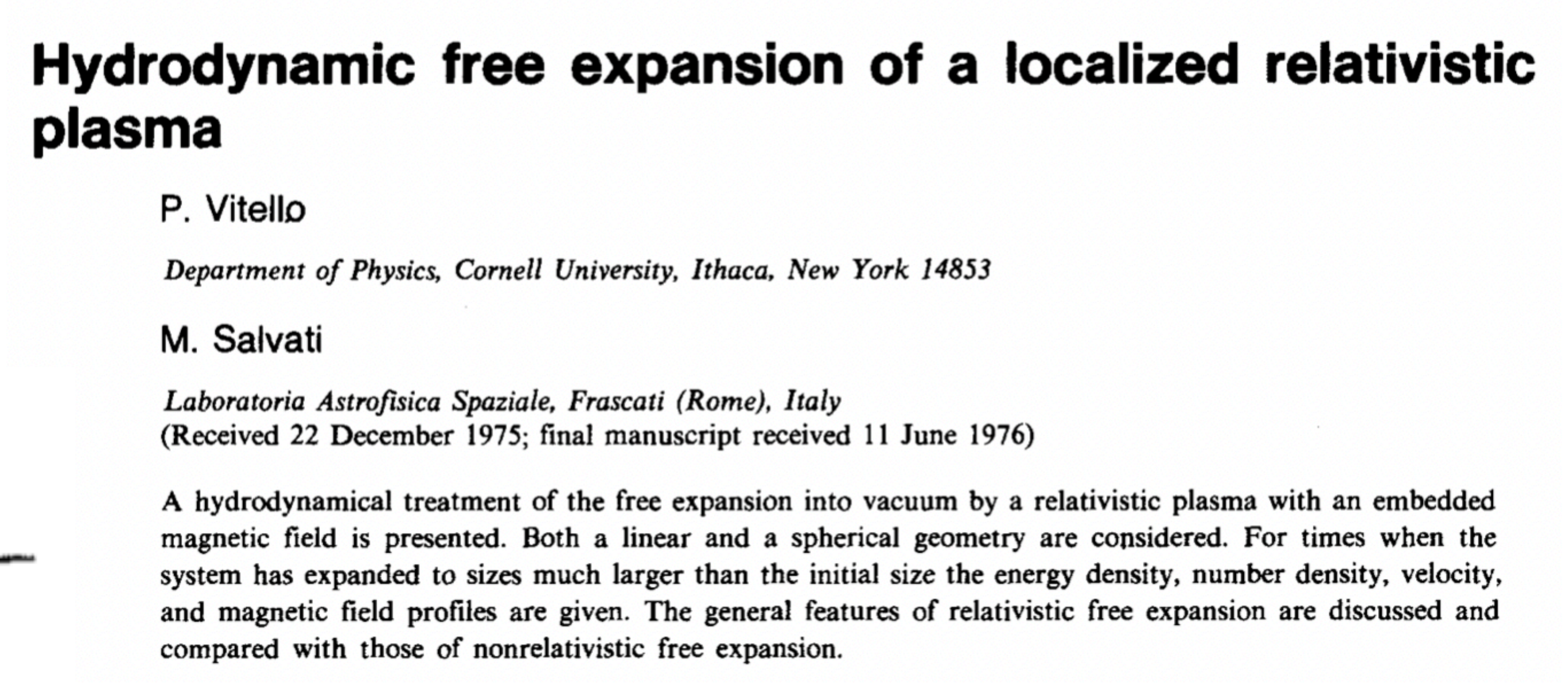
Fireball formation vs. burst outflow





Hydrodynamic free expansion of a localized relativistic plasma

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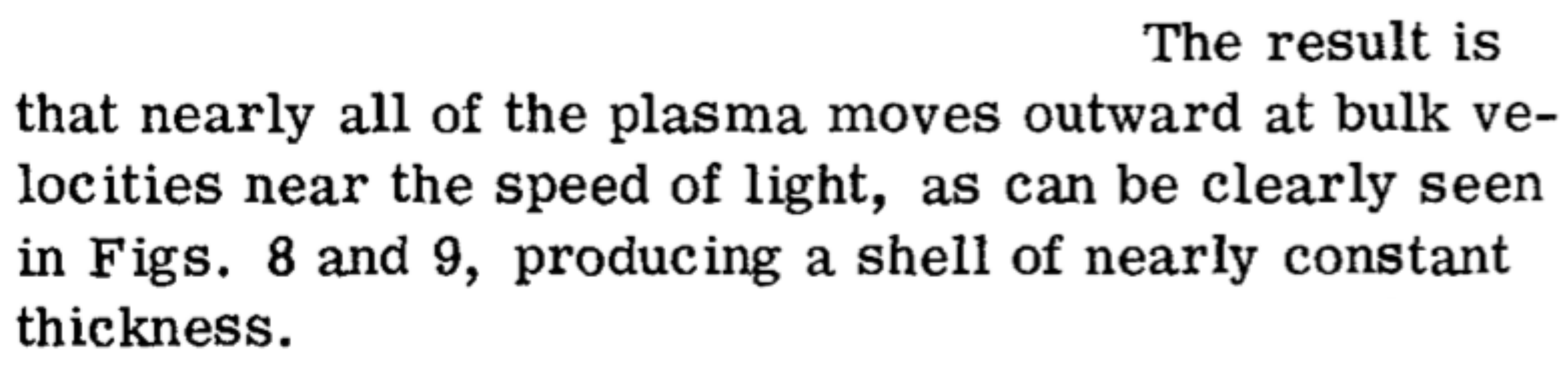
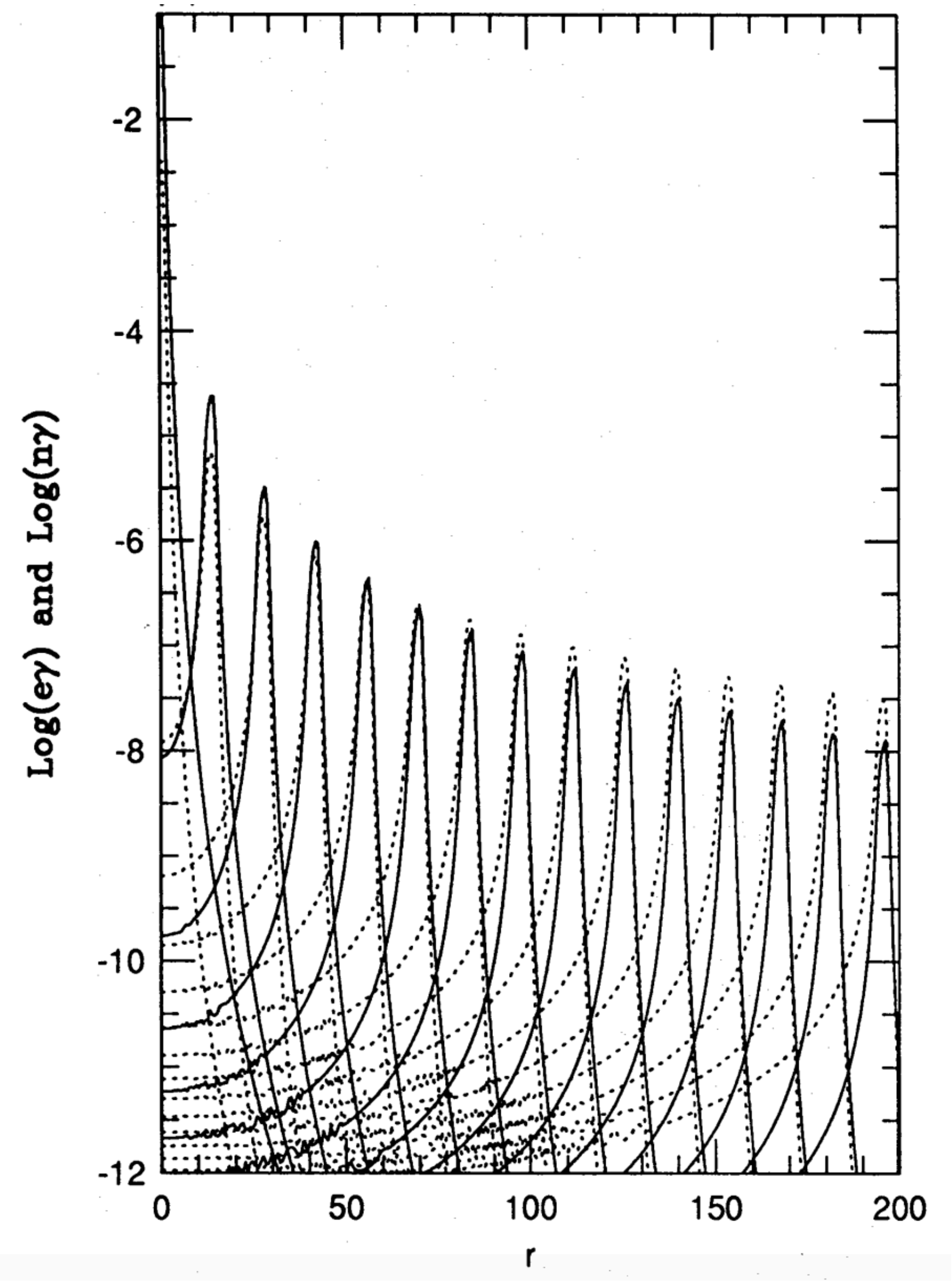
(Received 22 December 1975; final manuscript received 11 June 1976)

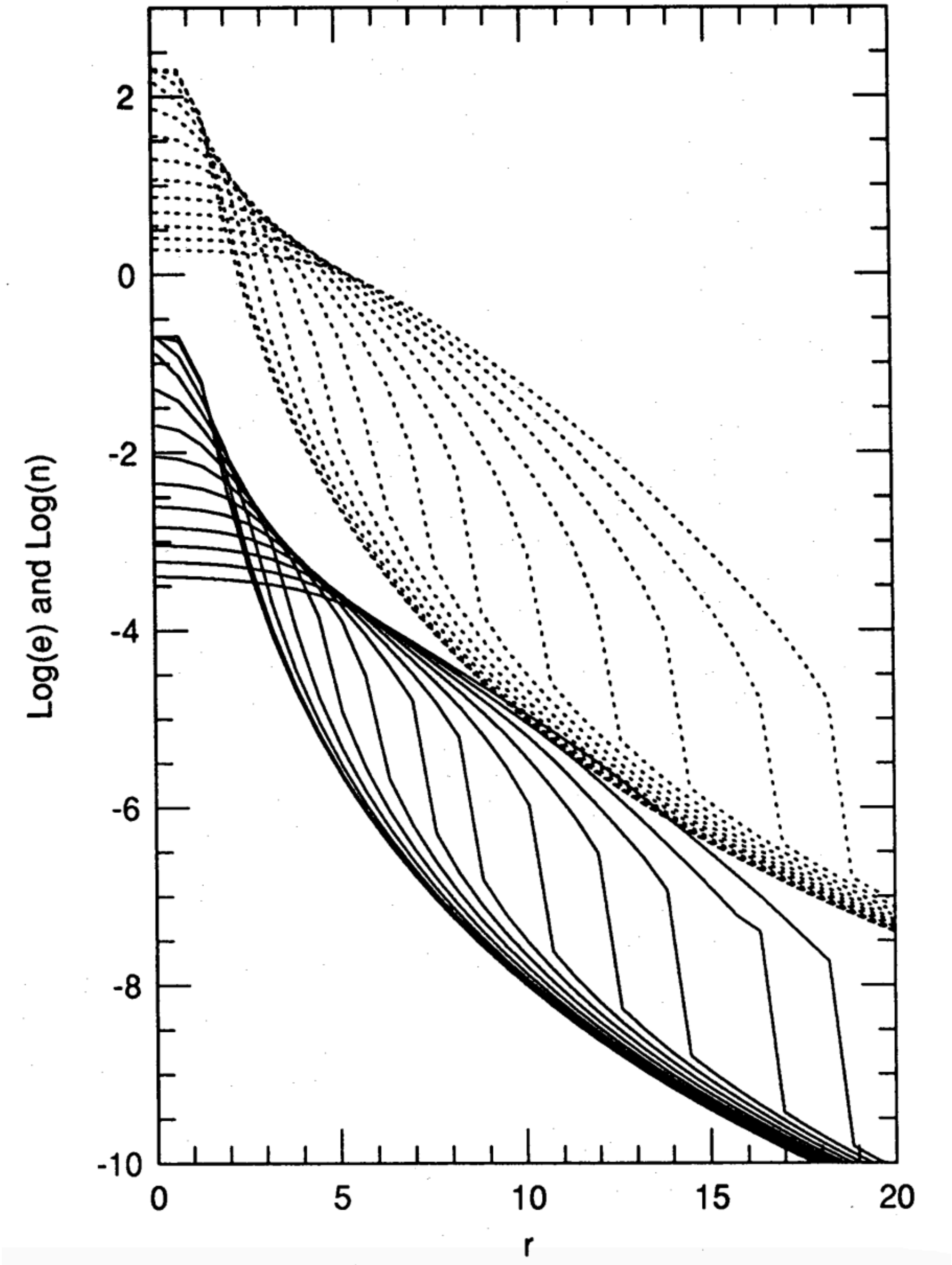
A hydrodynamical treatment of the free expansion into vacuum by a relativistic plasma with an embedded magnetic field is presented. Both a linear and a spherical geometry are considered. For times when the system has expanded to sizes much larger than the initial size the energy density, number density, velocity, and magnetic field profiles are given. The general features of relativistic free expansion are discussed and compared with those of nonrelativistic free expansion.



The result is that nearly all of the plasma moves outward at bulk velocities near the speed of light, as can be clearly seen in Figs. 8 and 9, producing a shell of nearly constant thickness.

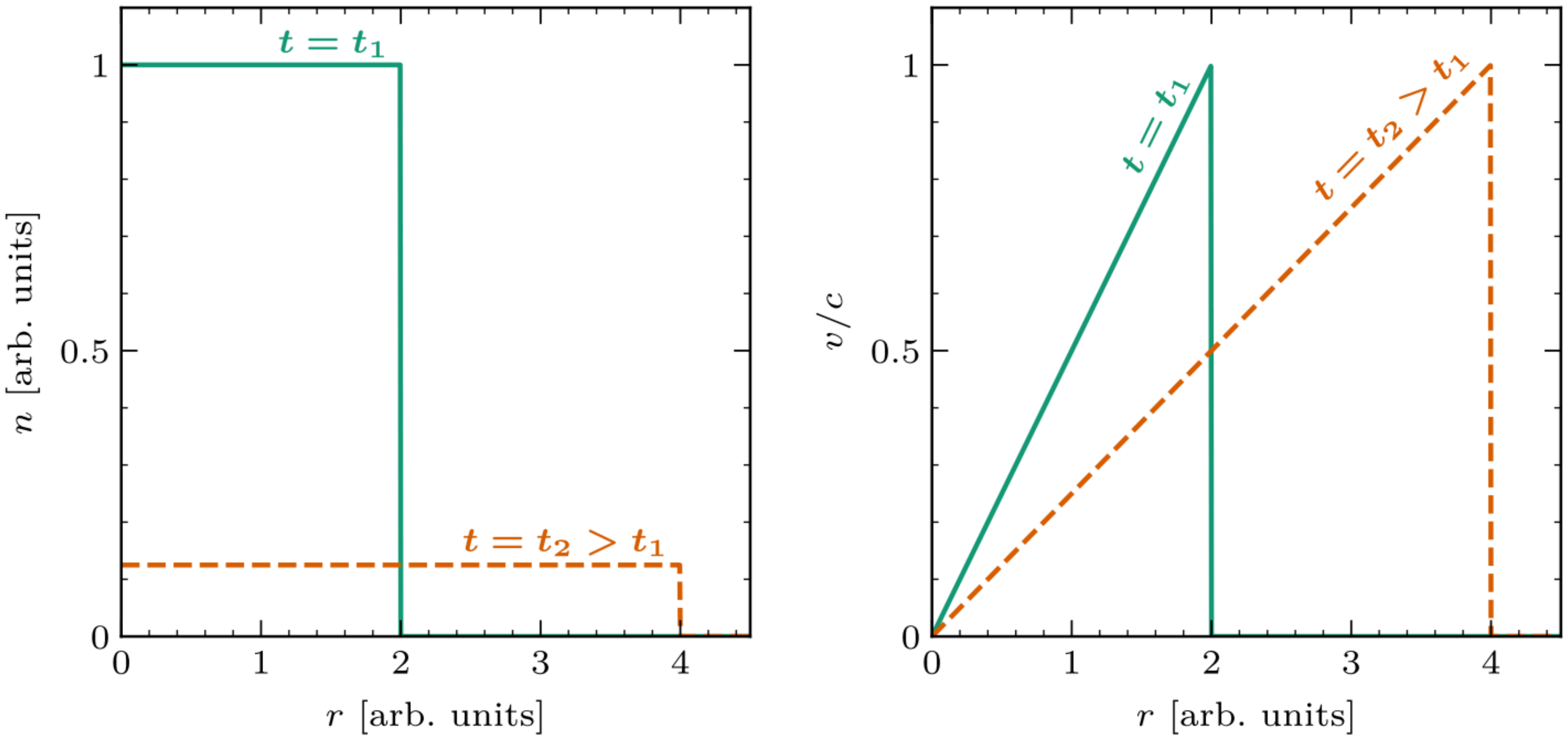
Fireball formation vs. burst outflow



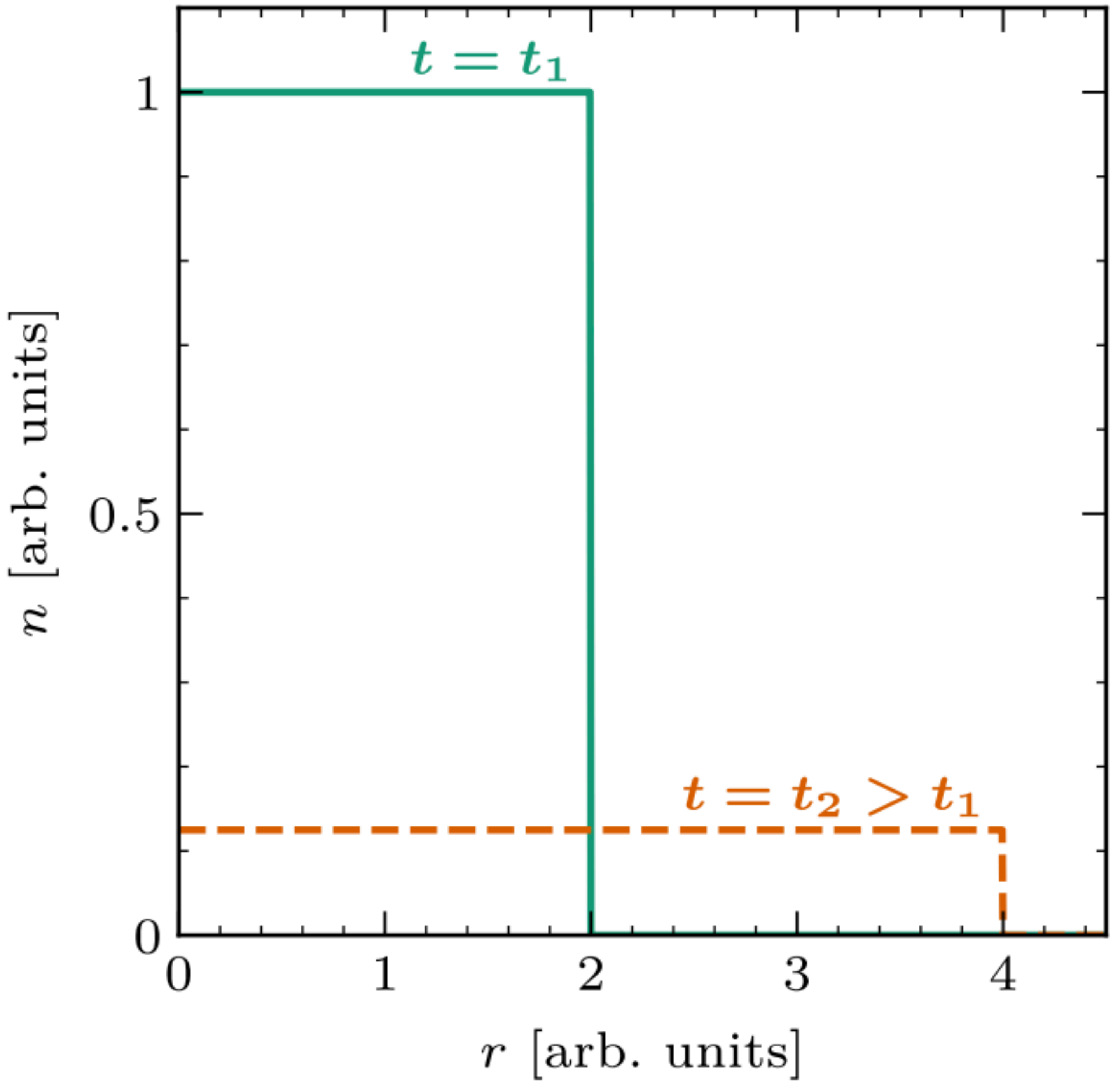


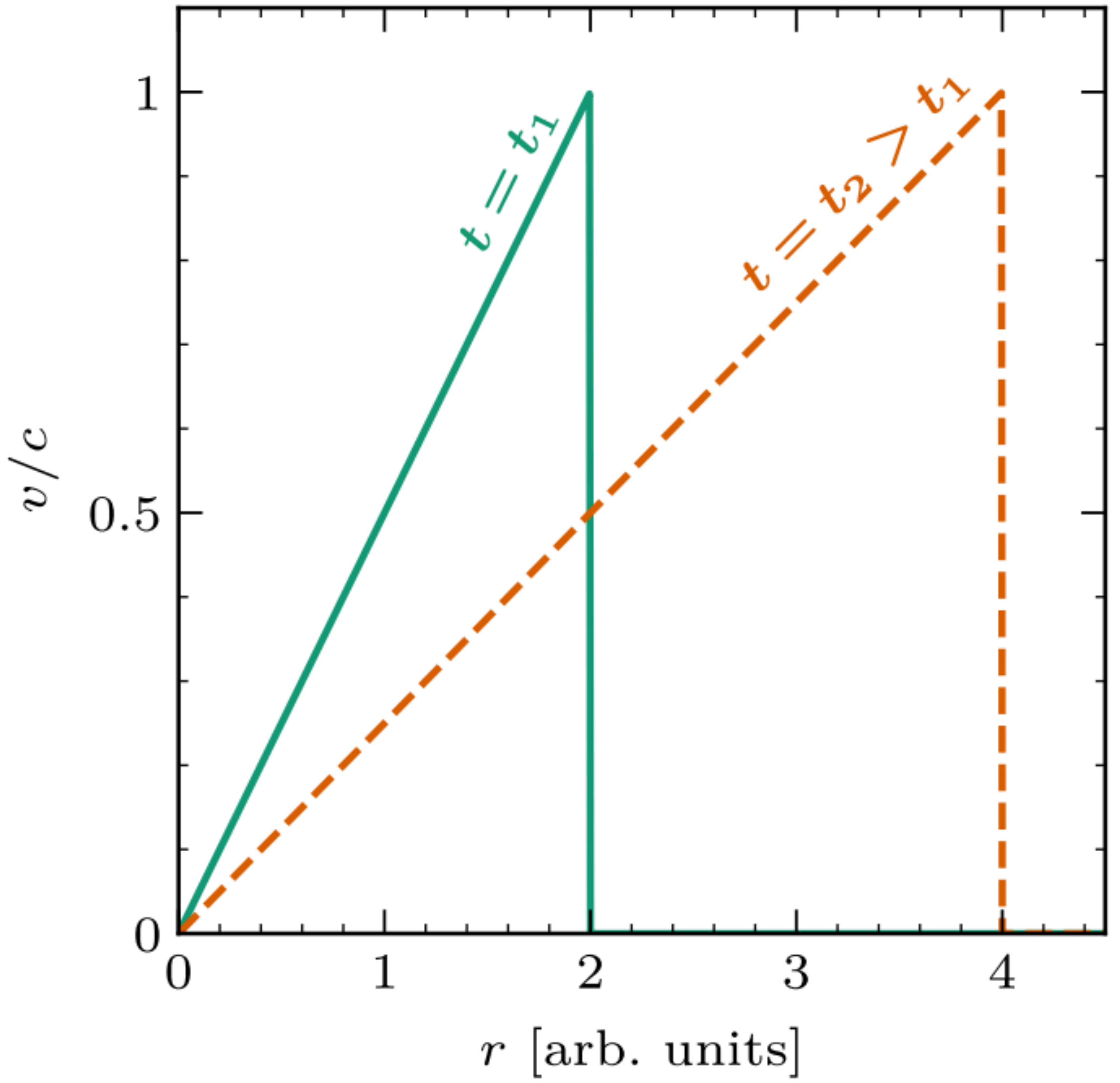
Piran et al., arXiv:9301004

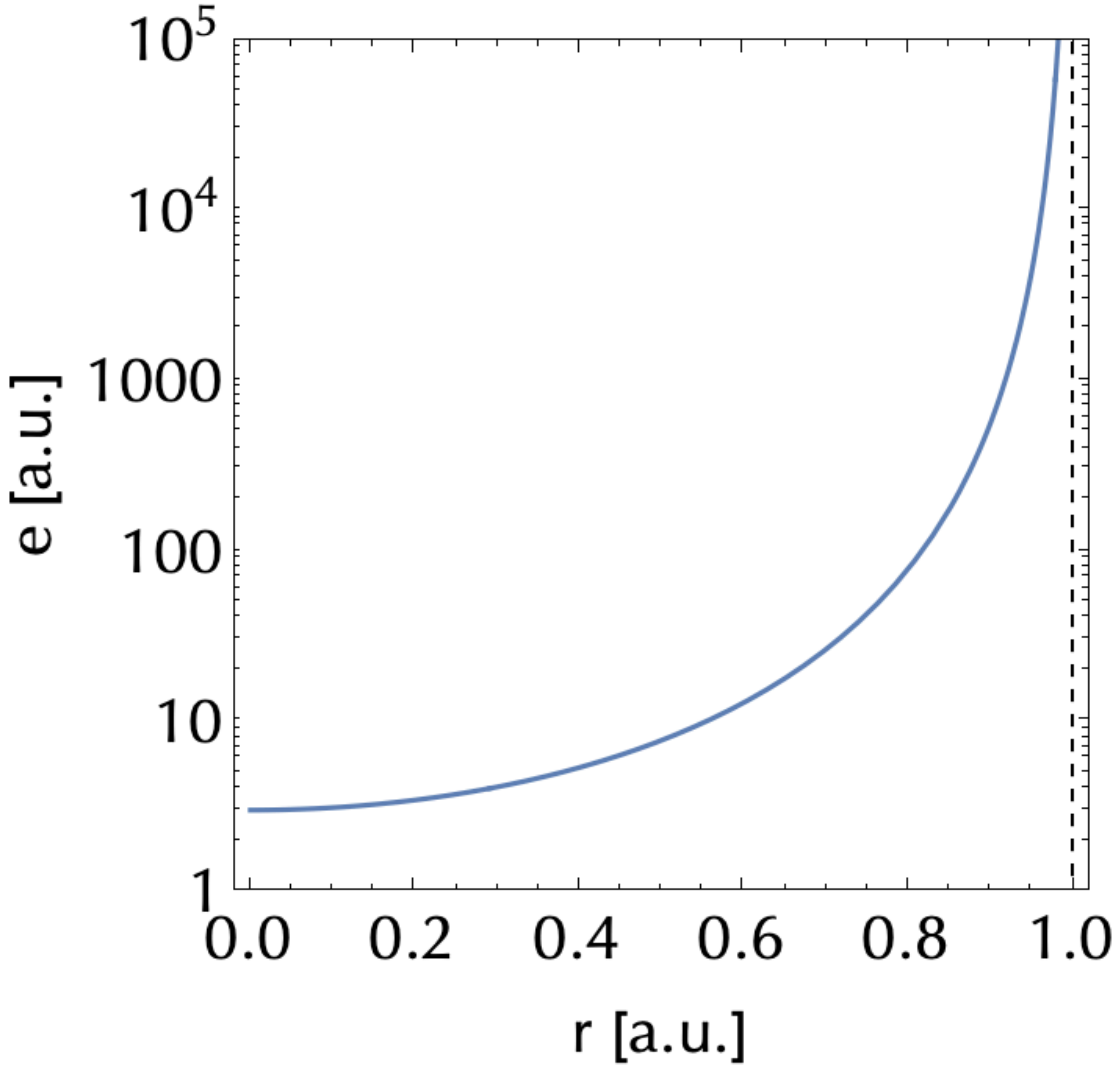
Burst outflow - analytical solution



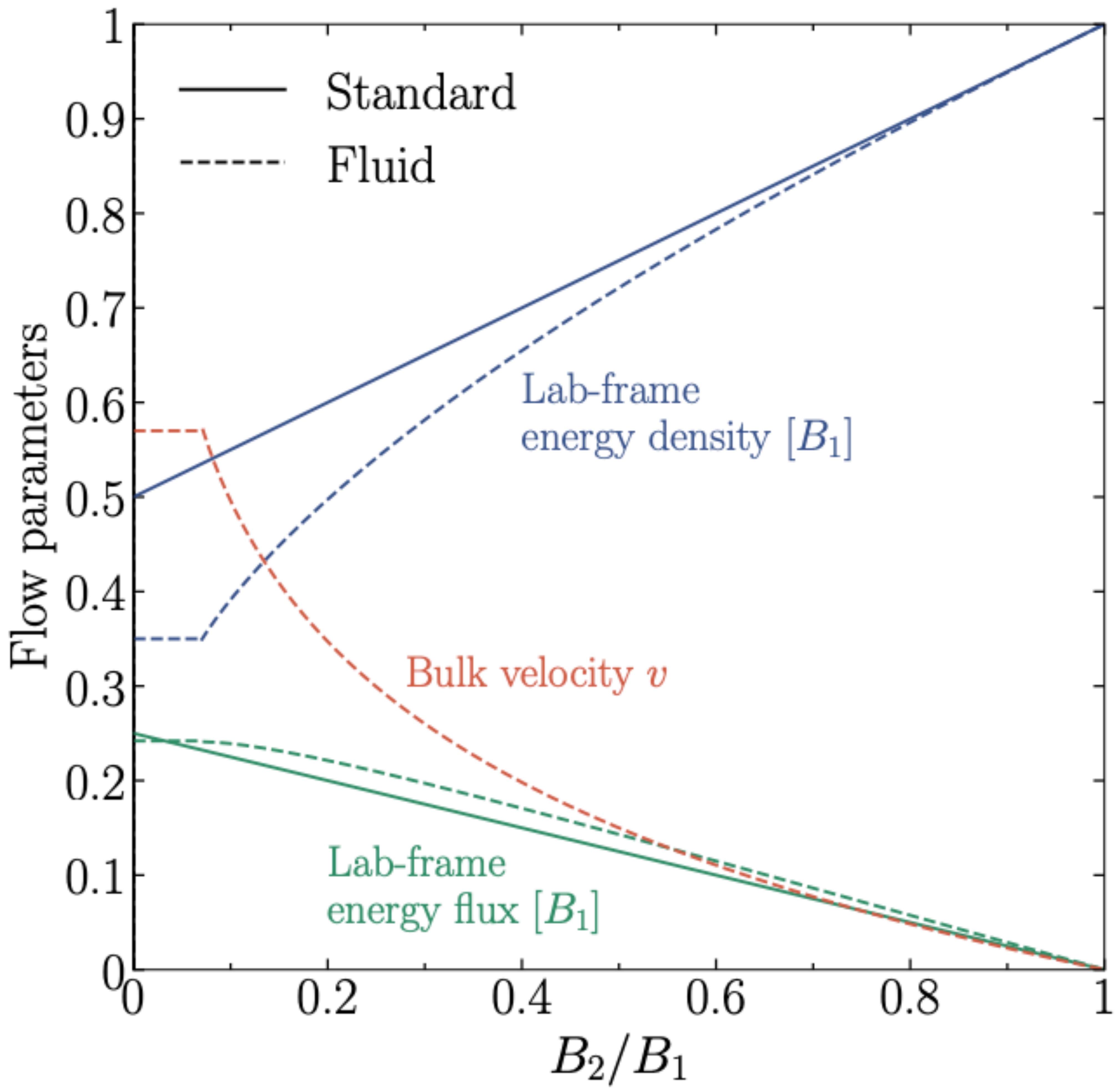
Burst outflow - analytical solution







Cooling time with νSI



- ✦ Energy flux emitted is nearly identical to the standard case
- ✦ Fluid flows with speed of sound
- ✦ Energy density is somewhat higher than in the standard case

BSM conclusions

- SN 1987A ideal laboratory for BSM physics in neutrino sector
- Cooling bound complemented by decay bounds — stronger by 1 order of magnitude, more robust
- Trapped mediators produce νSI, but only $O(1)$ changes to observables

Spectrum with νSI