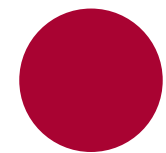


# Neutrinos from SN1987A as a probe of physics beyond the Standard Model

Damiano F. G. Fiorillo

Niels Bohr Institute, Copenhagen

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



KØBENHAVNS UNIVERSITET  
UNIVERSITY OF COPENHAGEN

VILLUM FONDEN

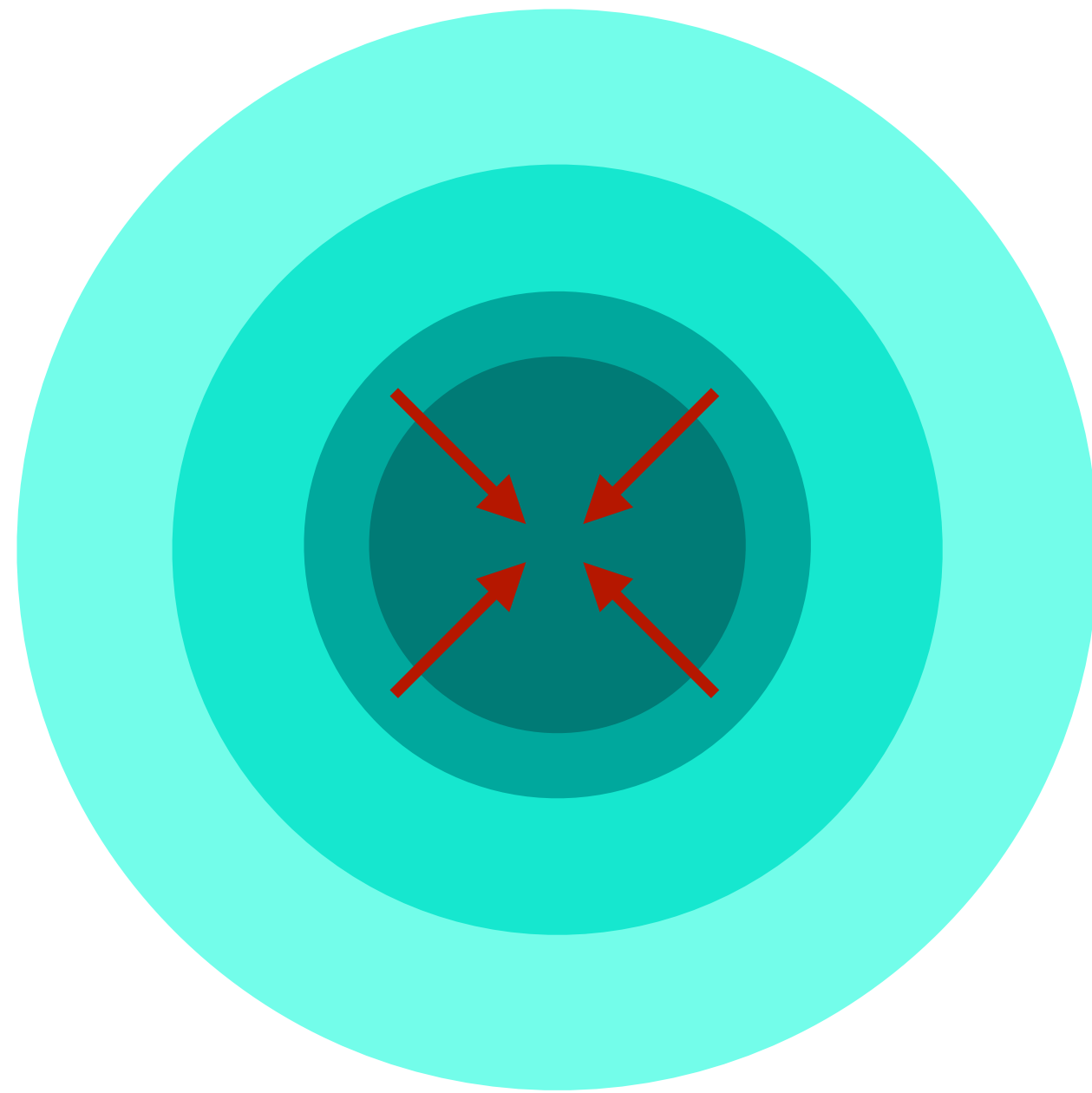


# Outline

- ◆ Supernova neutrinos
- ◆ SN 1987A and neutrino observations
- ◆ **Supernova simulations confront SN 1987A neutrinos**
- ◆ **Neutrinos probing BSM physics**
  - ◆ **Weakly interacting:** novel constraints on bosons escaping from SN
  - ◆ **Strongly interacting:** neutrino secret interactions in SN

# Supernova neutrinos

# Core-Collapse Supernovae



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

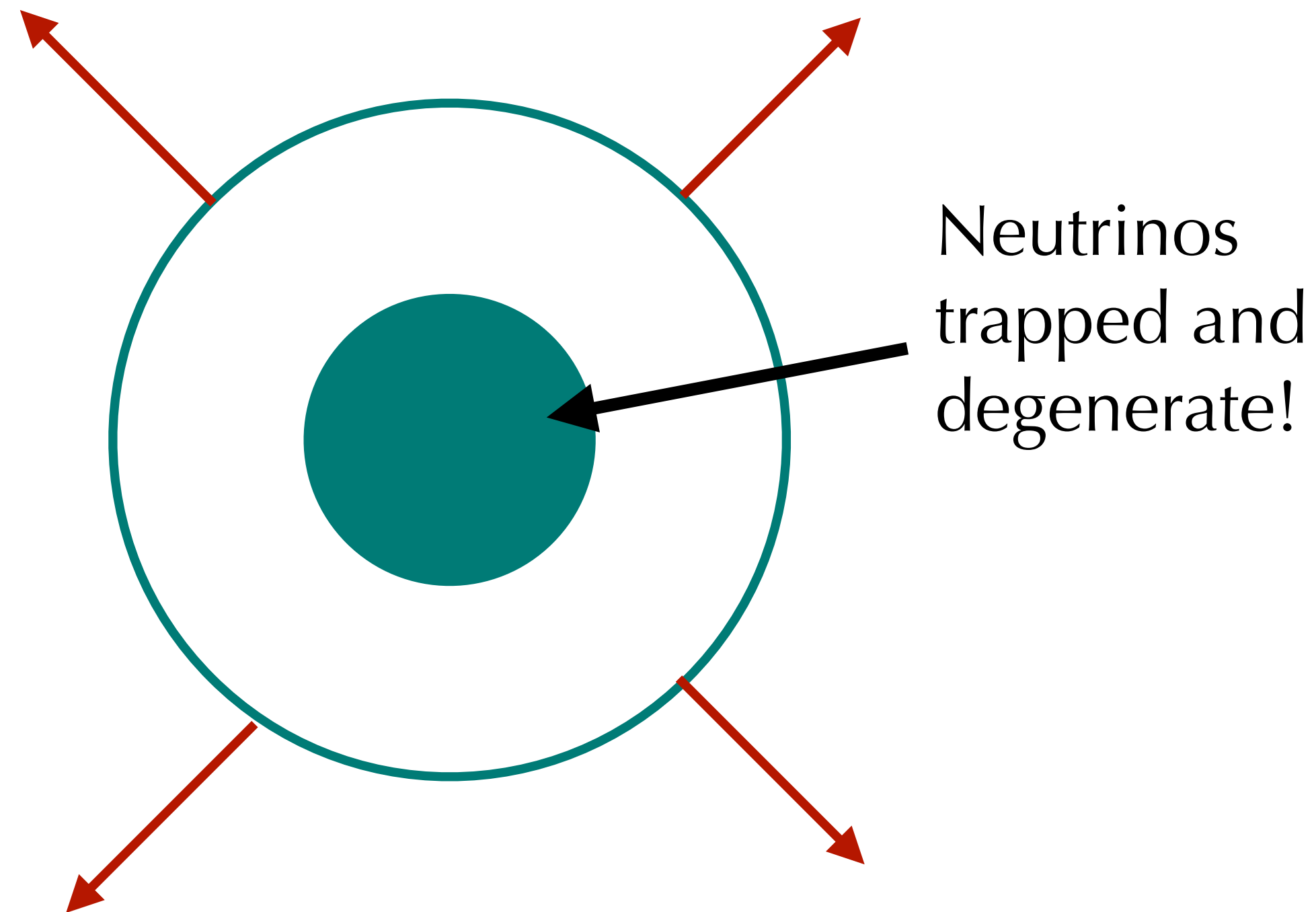
$$\rho \sim 10^{11} \text{ g cm}^{-3}$$

Neutrinos are trapped

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

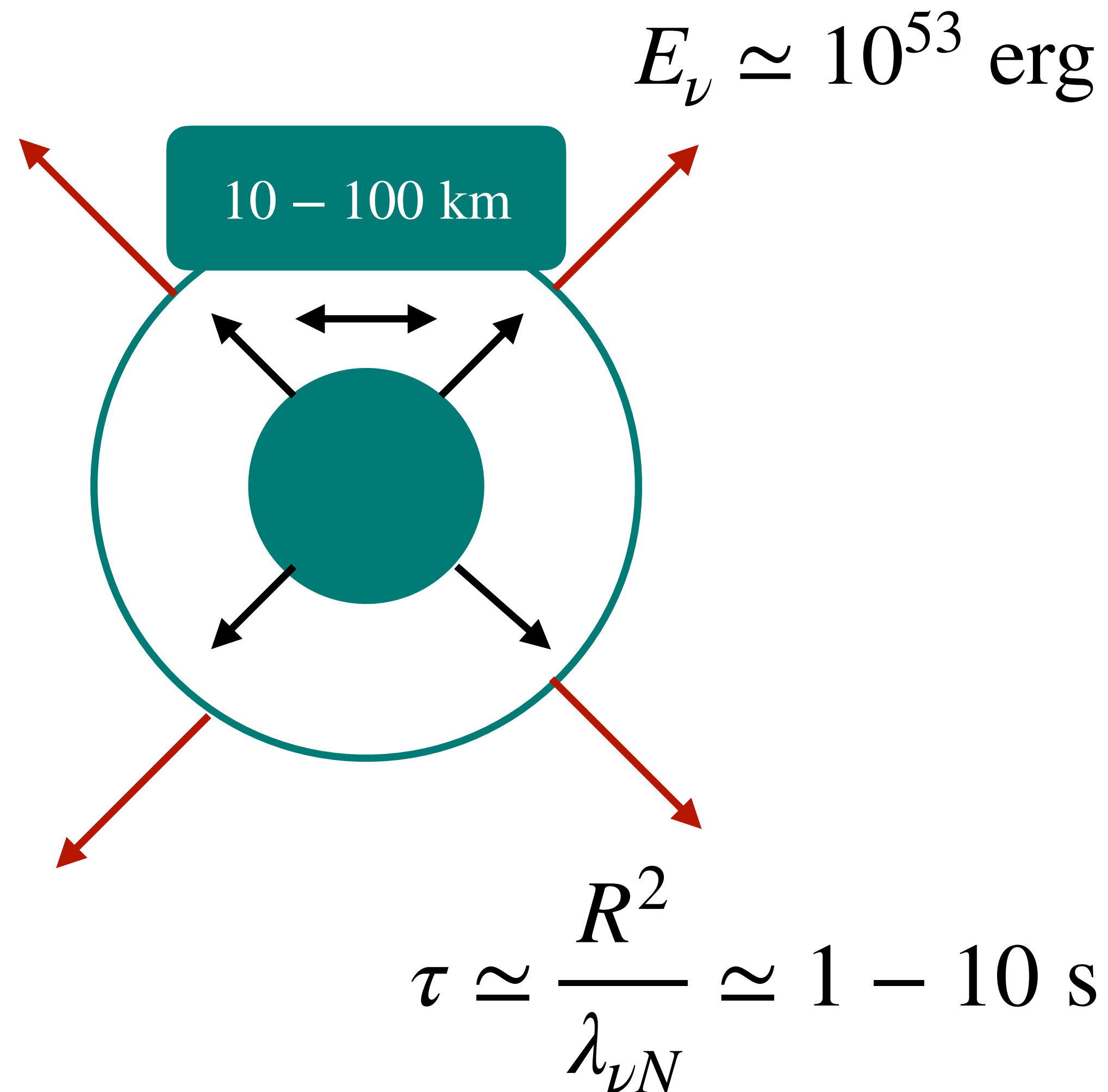
Rebounce

# Core-Collapse Supernovae



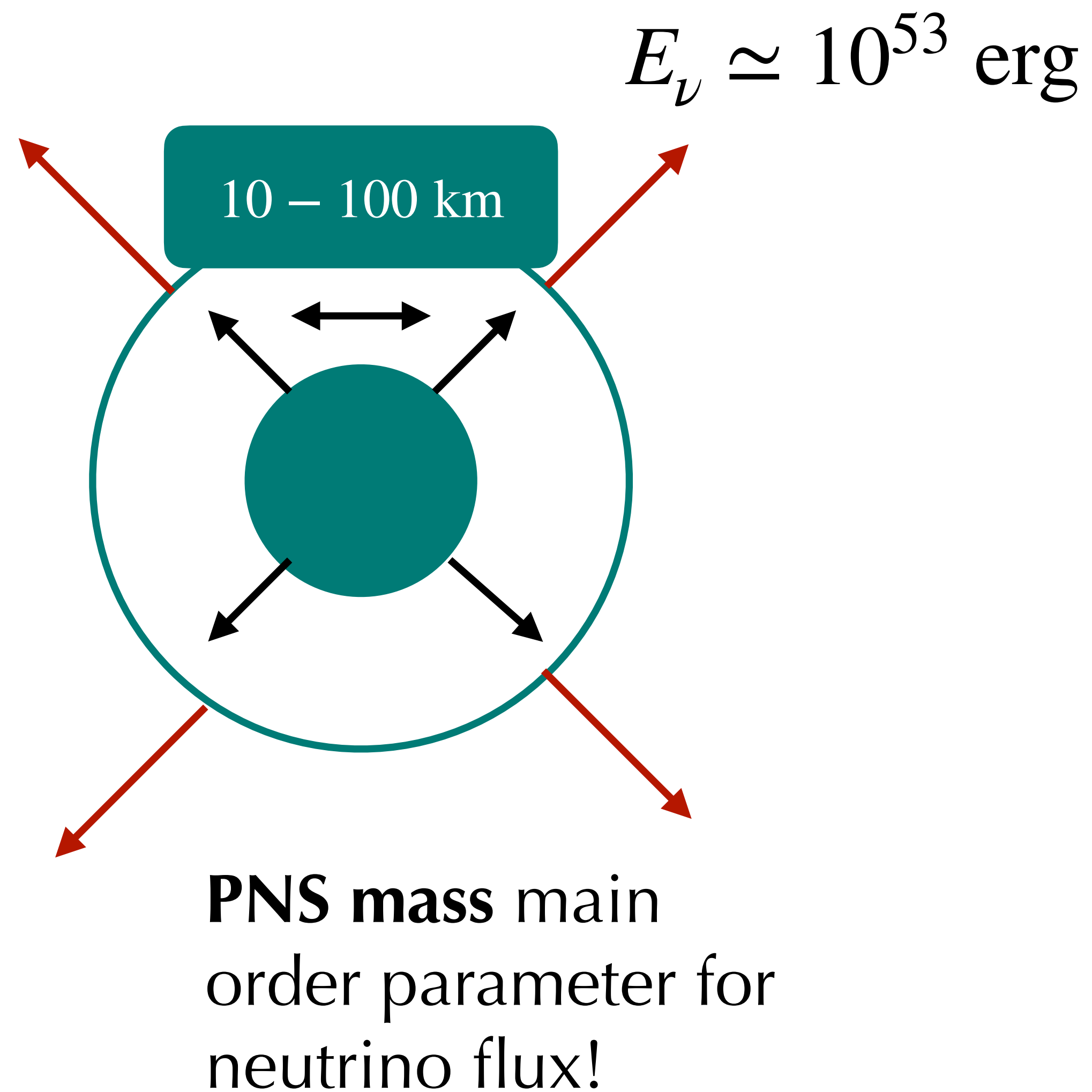
- ◆ Iron core with stopping of fusion
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- ◆ Shock wave stalls, revived by neutrinos depositing energy

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- ◆ Neutrino **cooling** of PNS

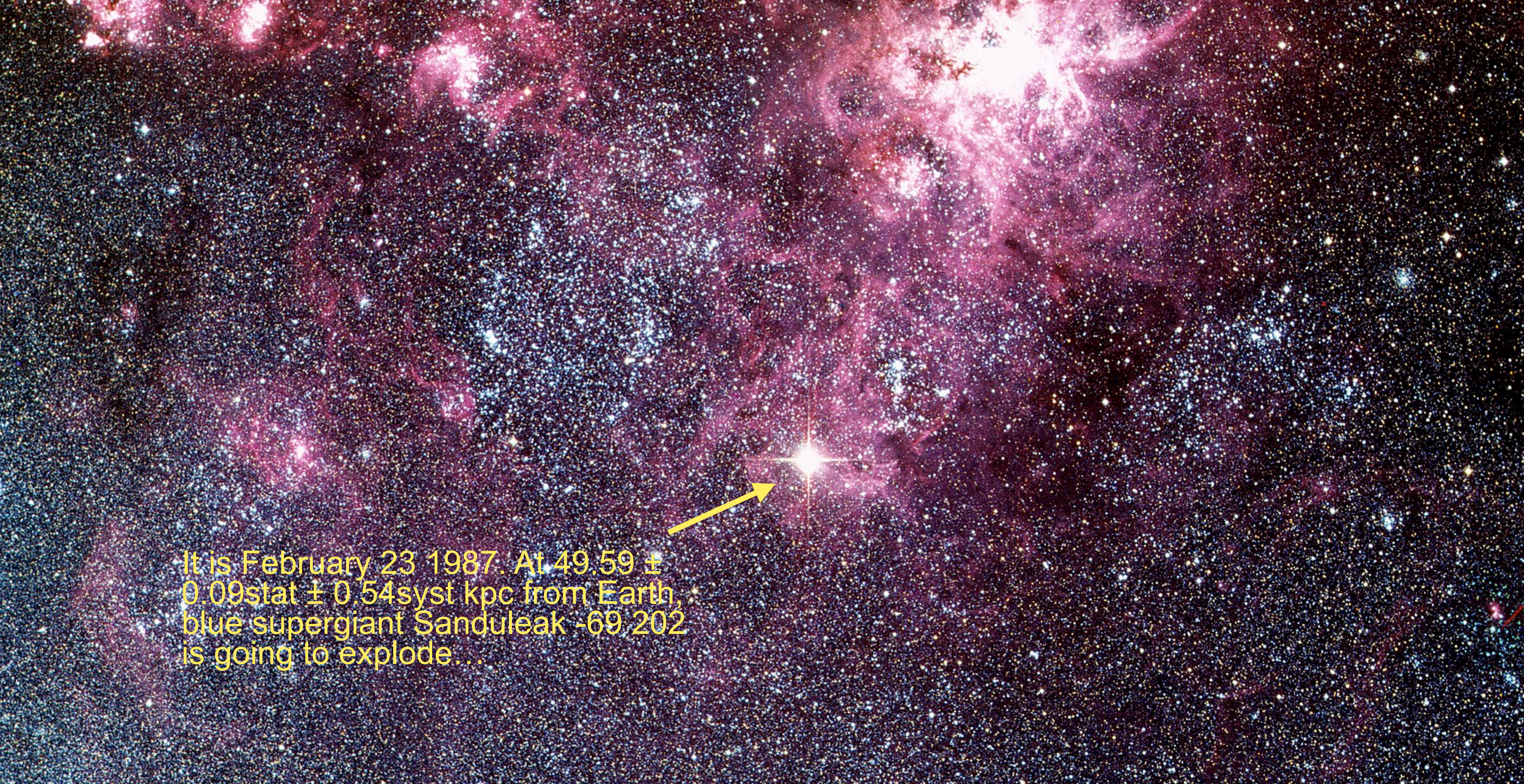
# Core-Collapse Supernovae



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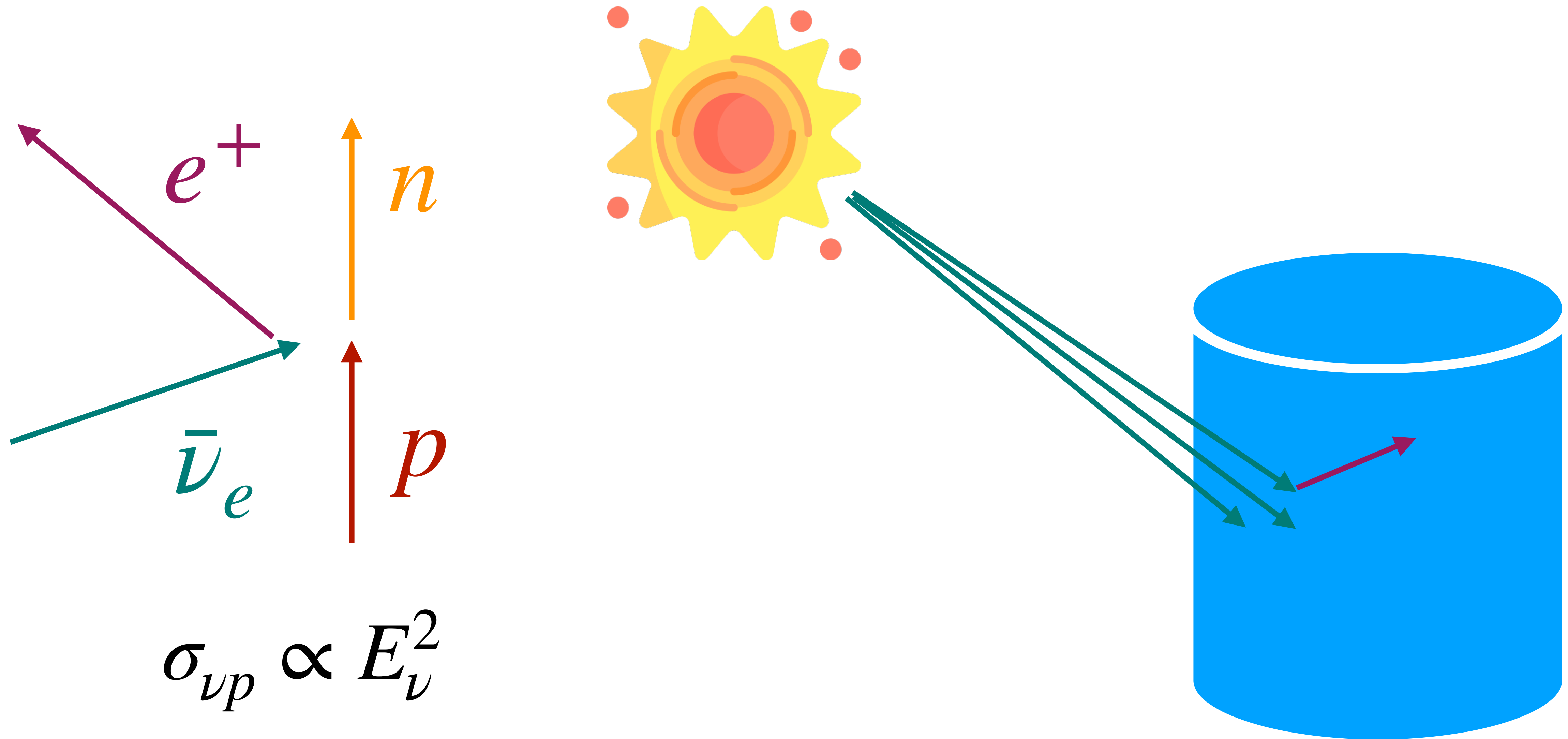
# Neutrino observations from SN1987A



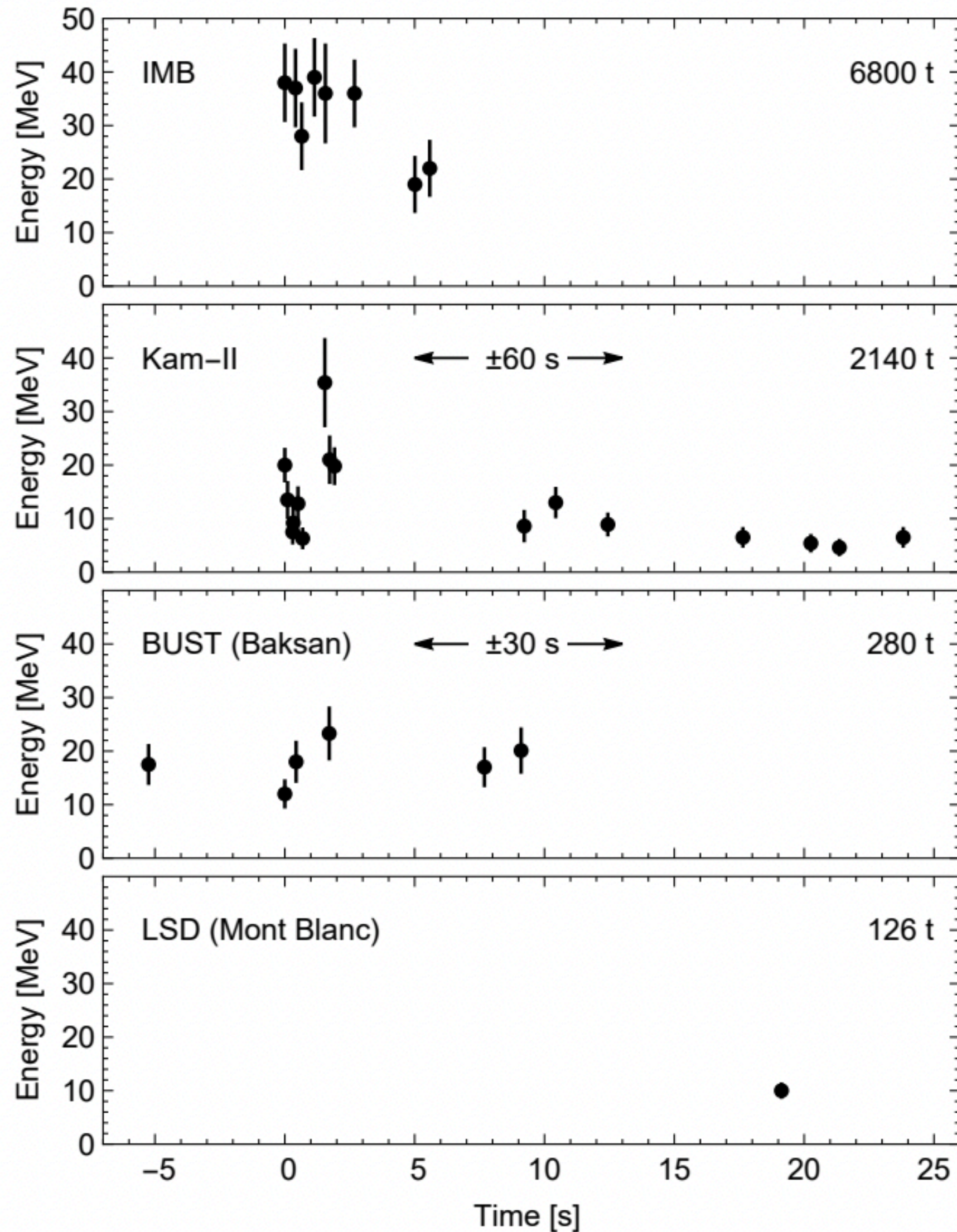


It is February 23 1987. At  $49.59 \pm 0.09_{\text{stat}} \pm 0.54_{\text{syst}}$  kpc from Earth, blue supergiant Sanduleak -69 202 is going to explode...

# SN1987A neutrino observations



# 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 (in press on Phys. Rev. D)  
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

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  - ◆ **Updated neutrino-nucleon opacities**

# Motivation

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  - ◆ **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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# Model choice

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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

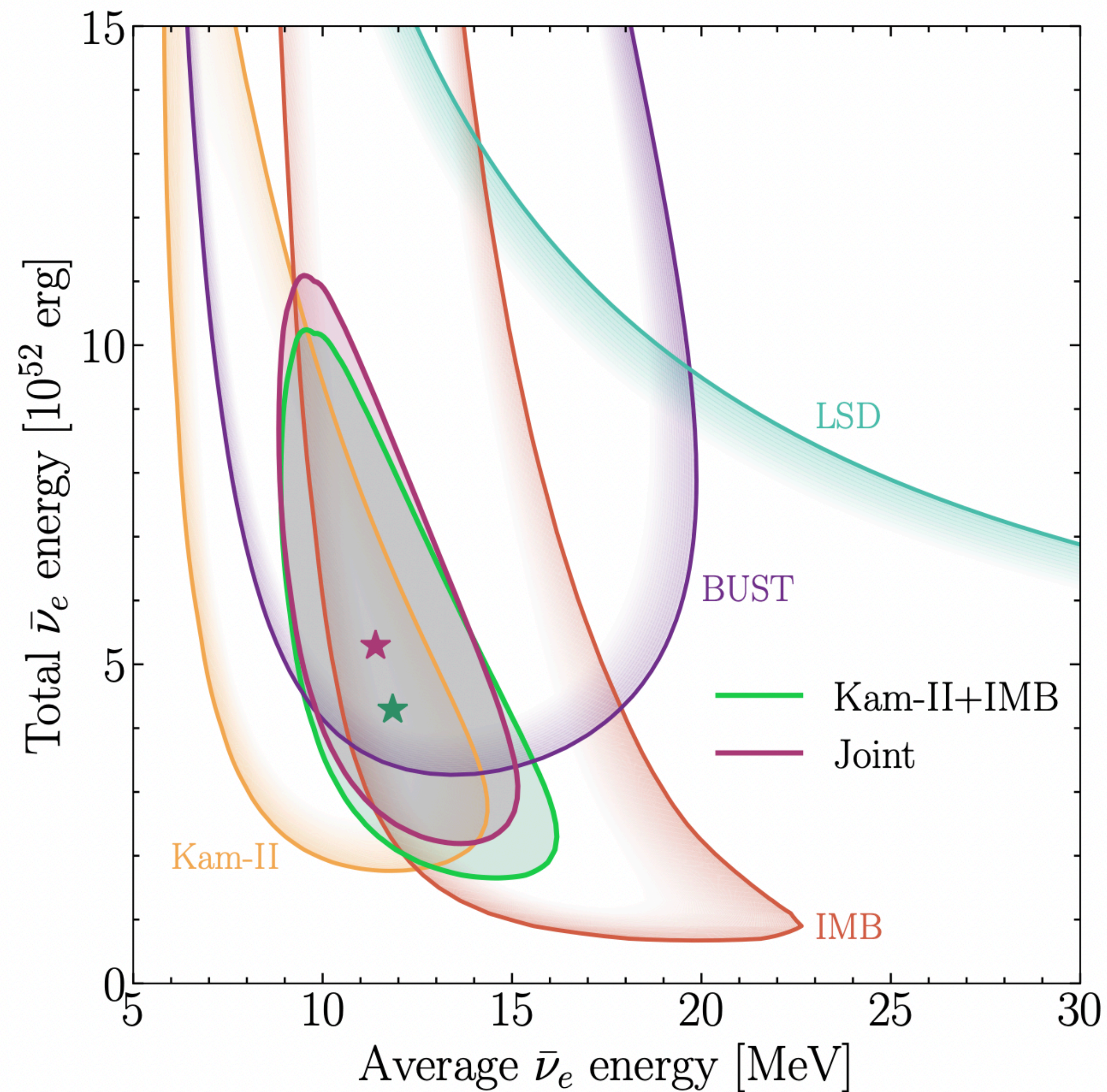
SFHo

SFHx

**All 1D**

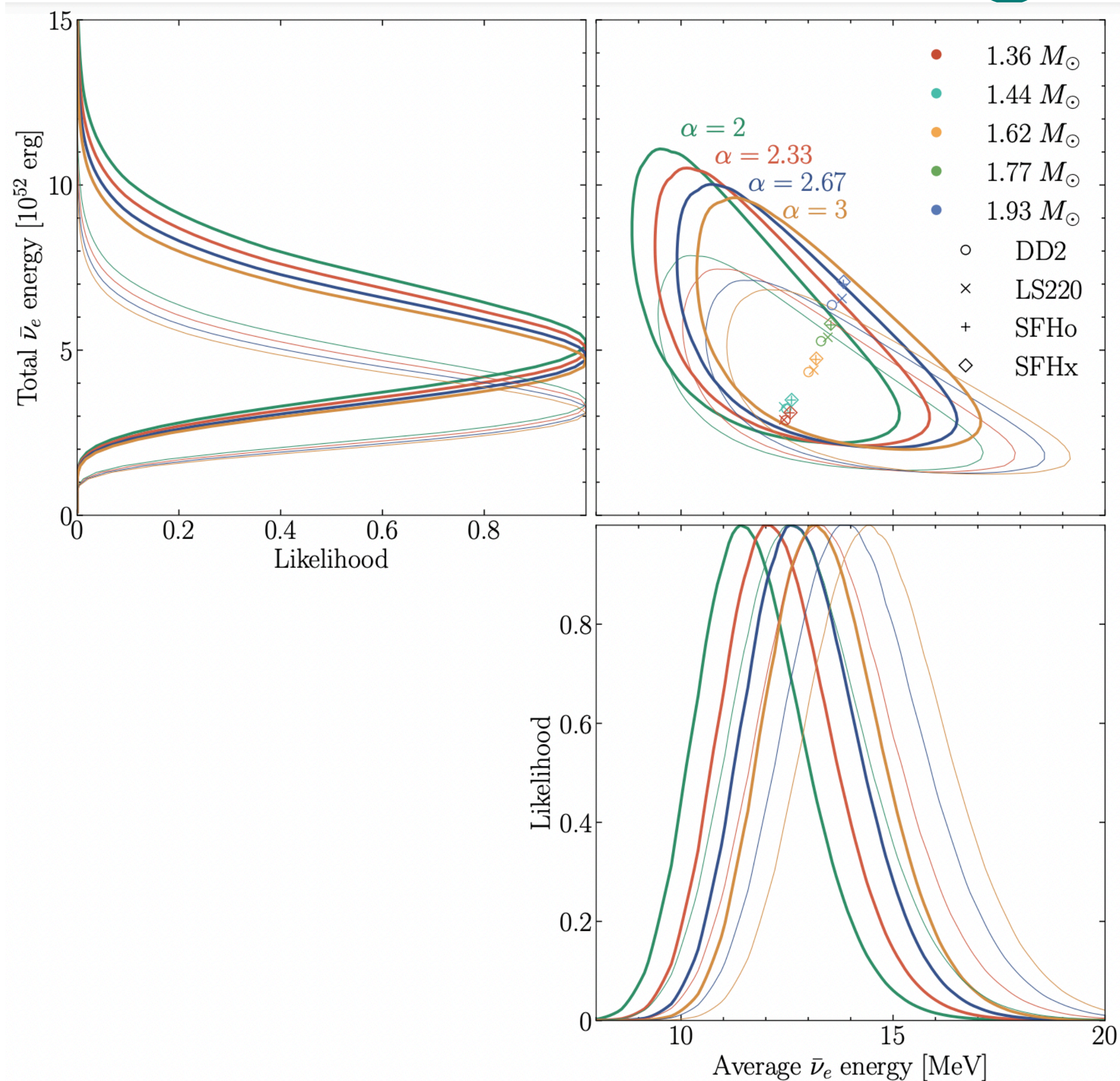
(Reliable for the sparse data  
of SN 1987A!)

# Time-integrated signal



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

# Time-integrated signal



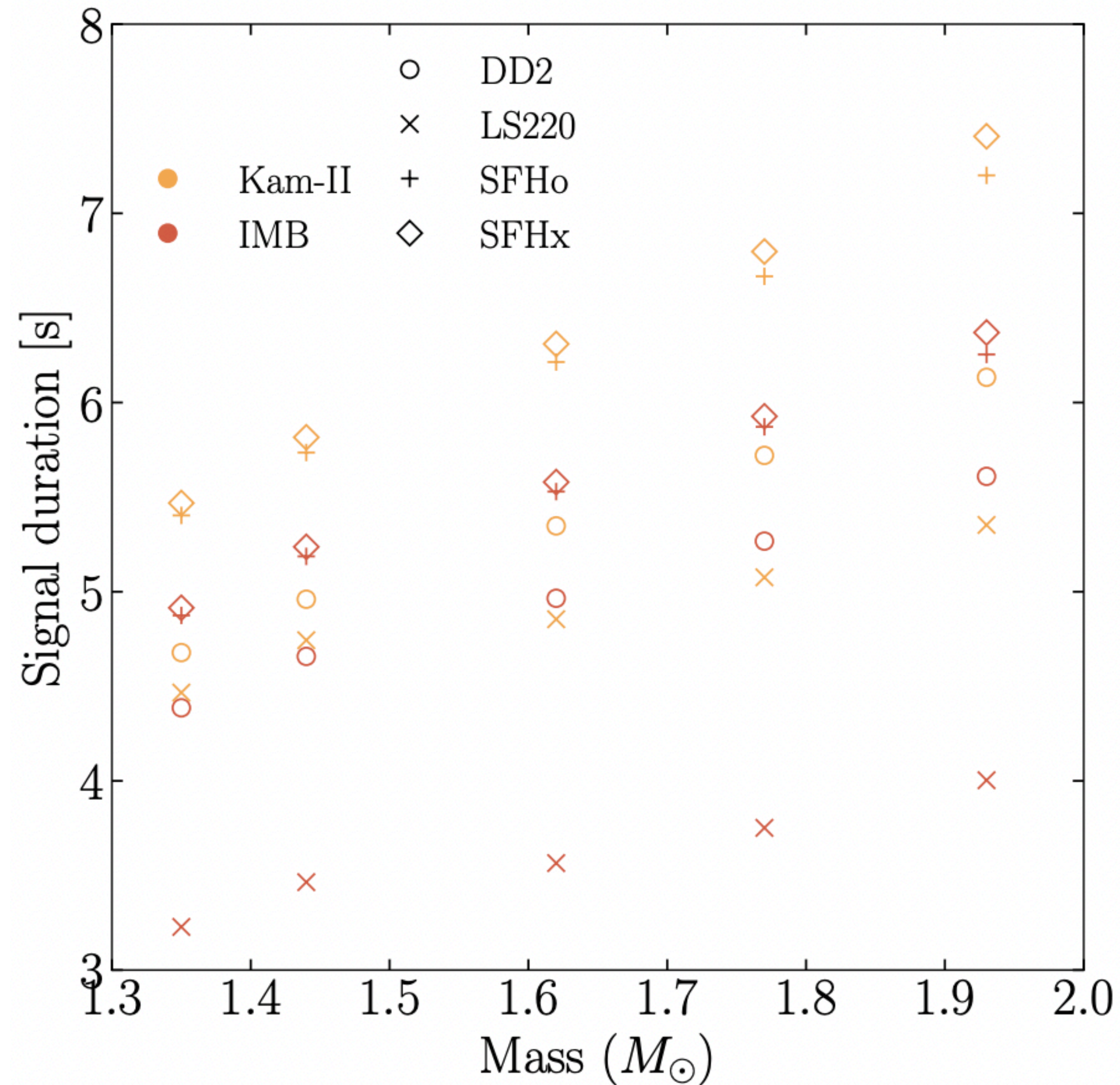
◆ Spectra can be pinched

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

◆ Most SN models lie within  $2\sigma$  regions — consistency with data

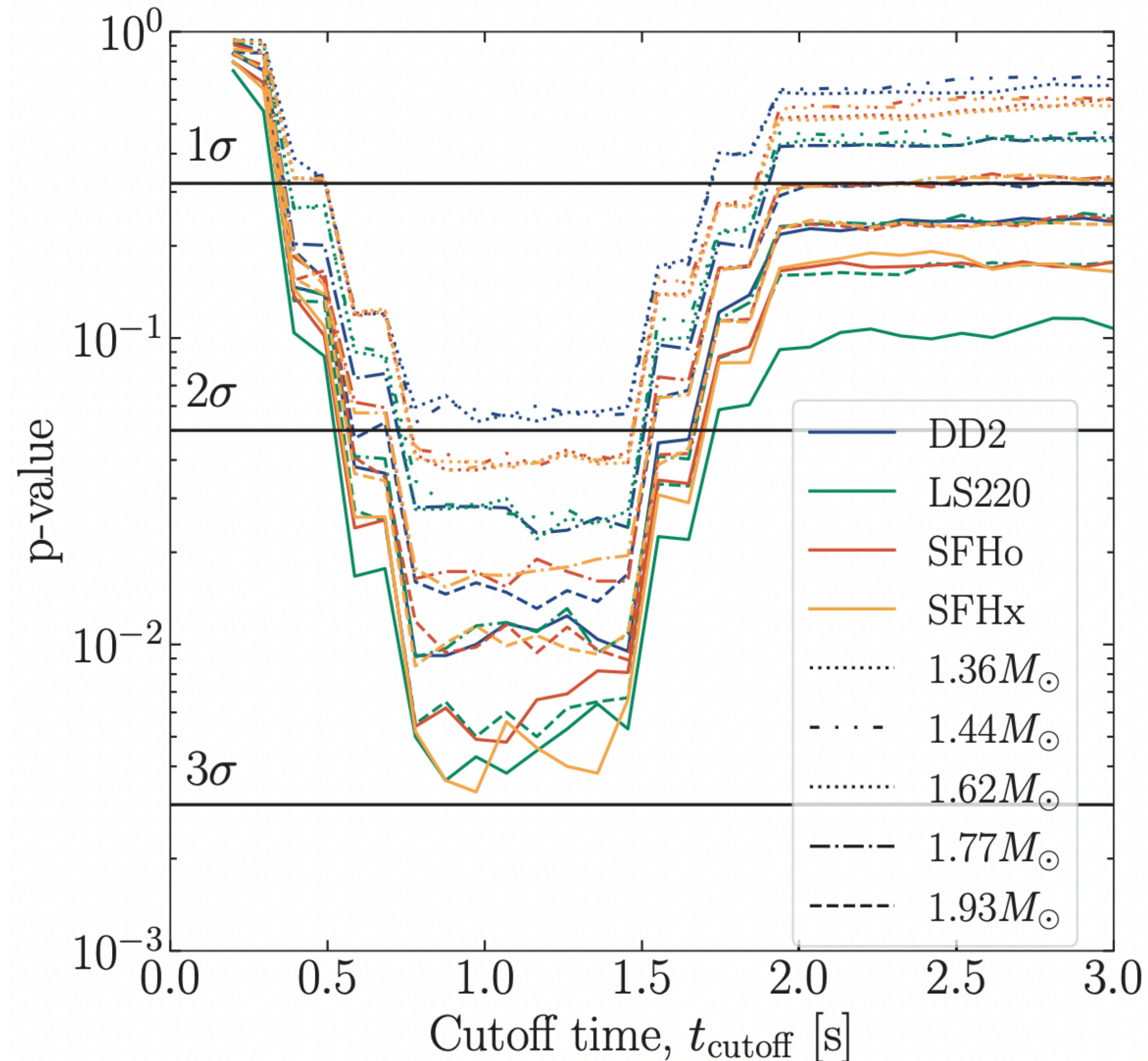
◆ Tension with heavy PNS

# 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



# Novel bounds from SN1987A

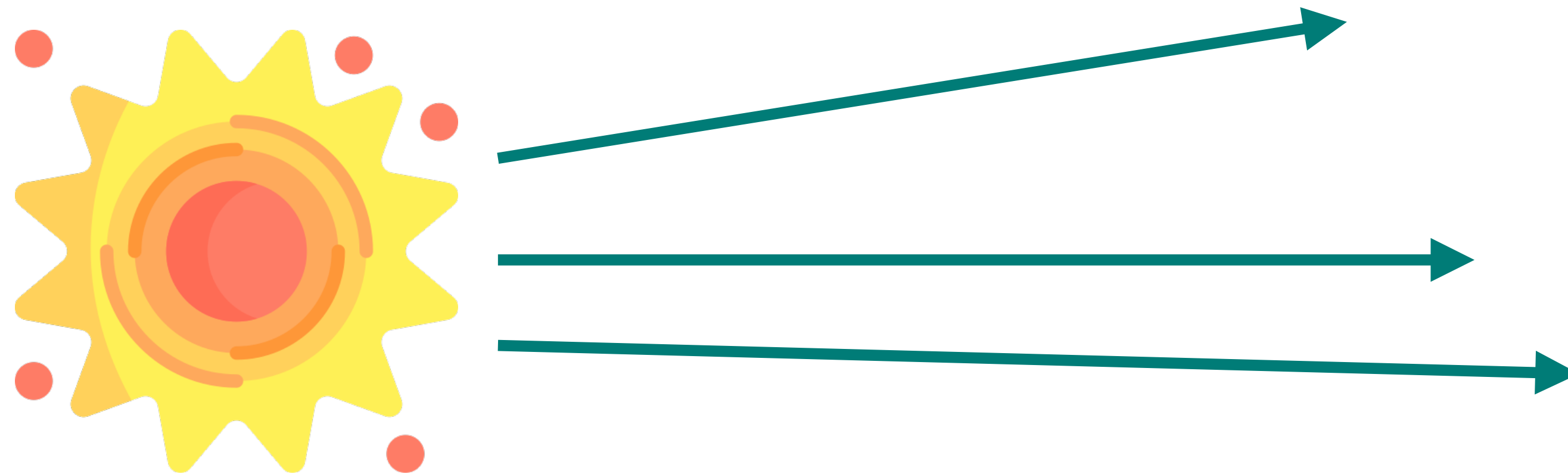
based on arXiv:2209.11773 (Phys. Rev. Lett. 131 2, 021001)

with G. Raffelt, E. Vitagliano

# Testing for new physics

New particles can be produced in supernova core...

... but how do we probe them?

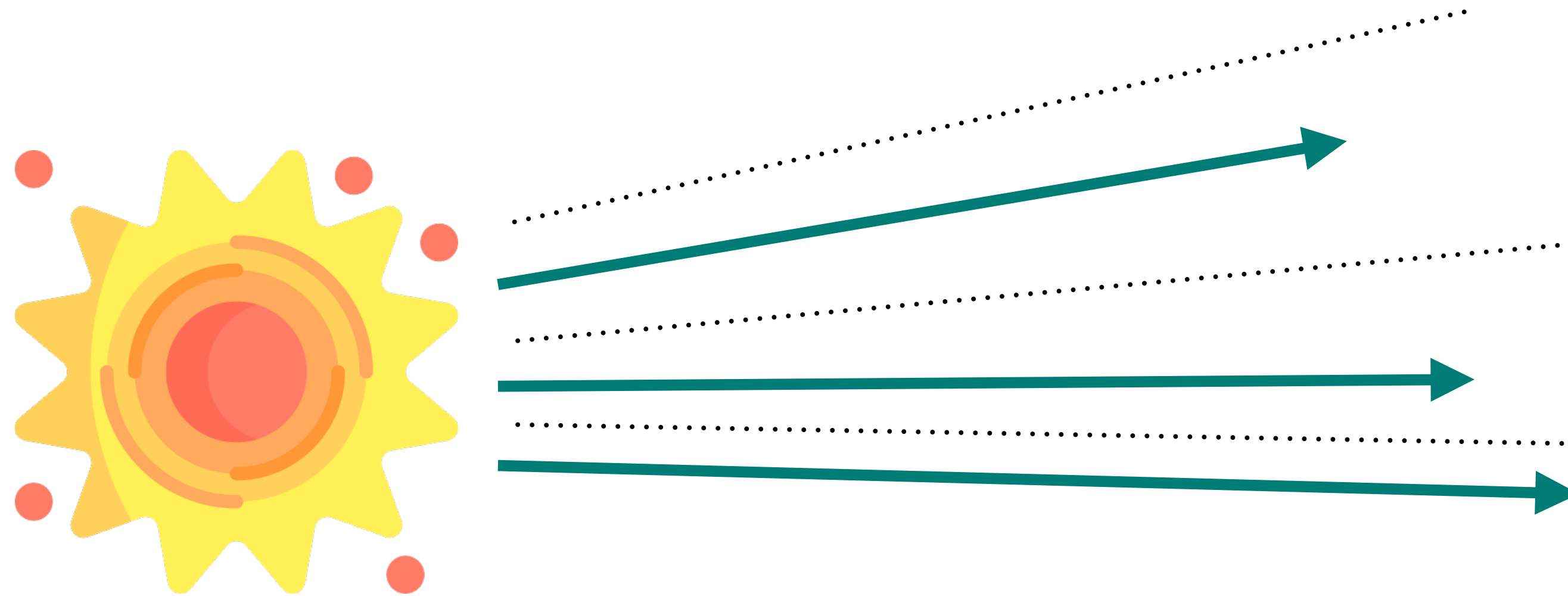


$$T \simeq \frac{R^2}{\lambda_{\nu N}} \simeq 1 - 10 \text{ s}$$

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New particles can be produced in supernova core...

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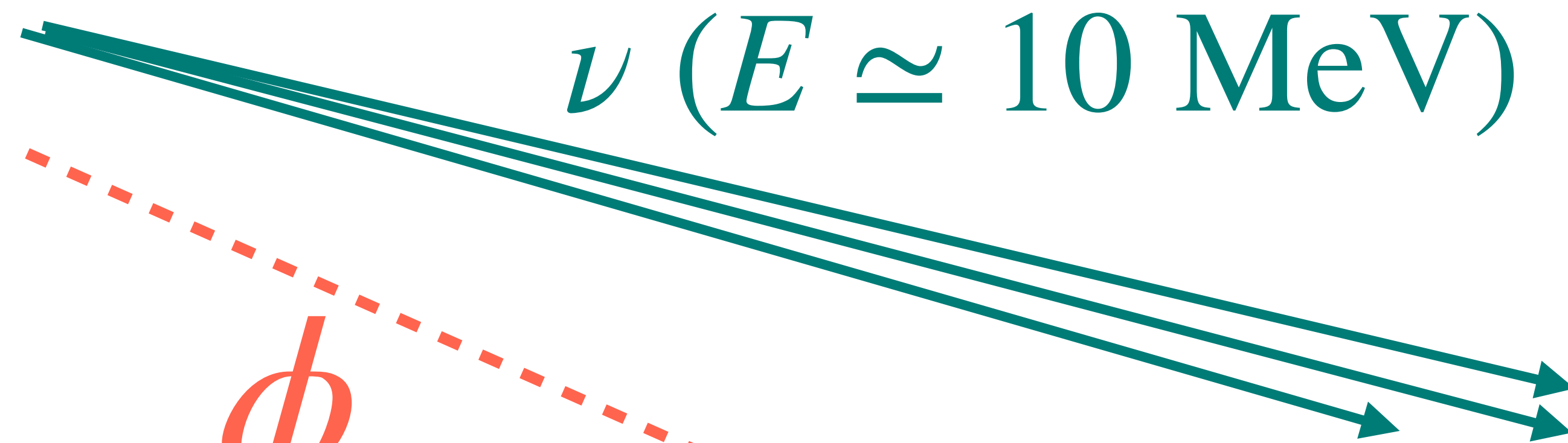
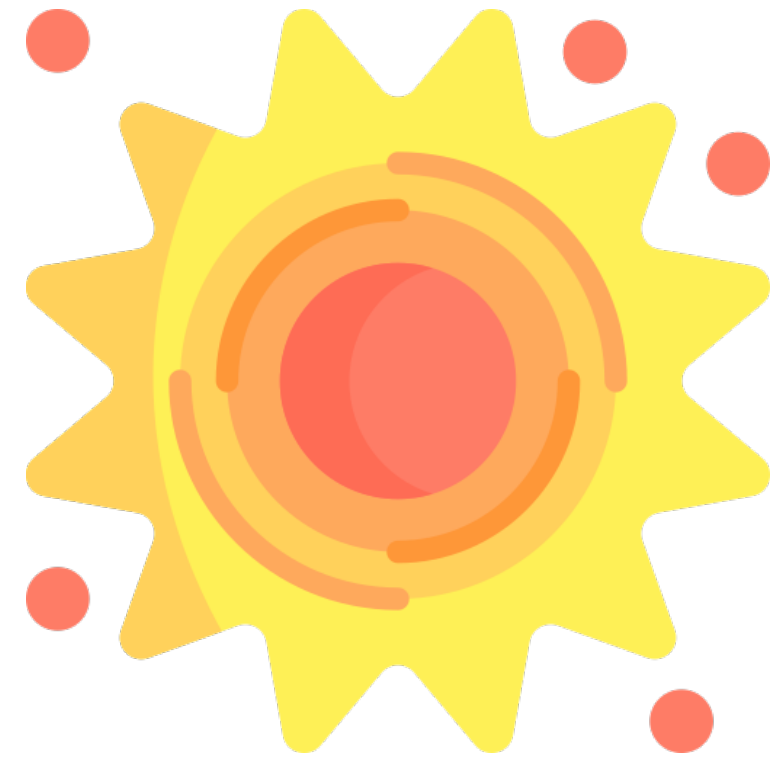
PNS cools faster,  
shorter burst

Energy loss/cooling bound

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

Burrows et al., 1989; Raffelt, 1996

# Novel bounds from SN1987A



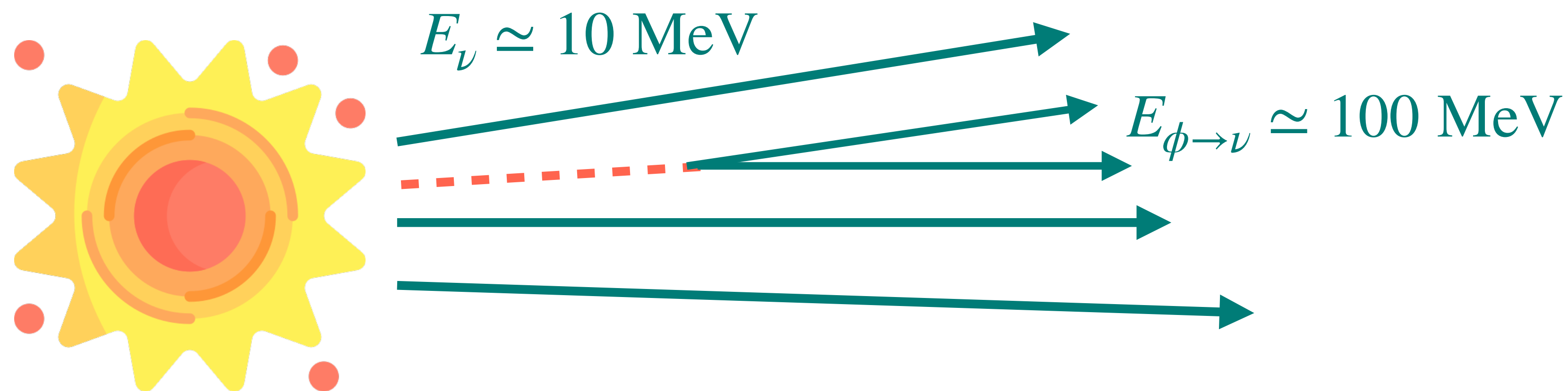
For decay to photons

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

# Testing for new physics

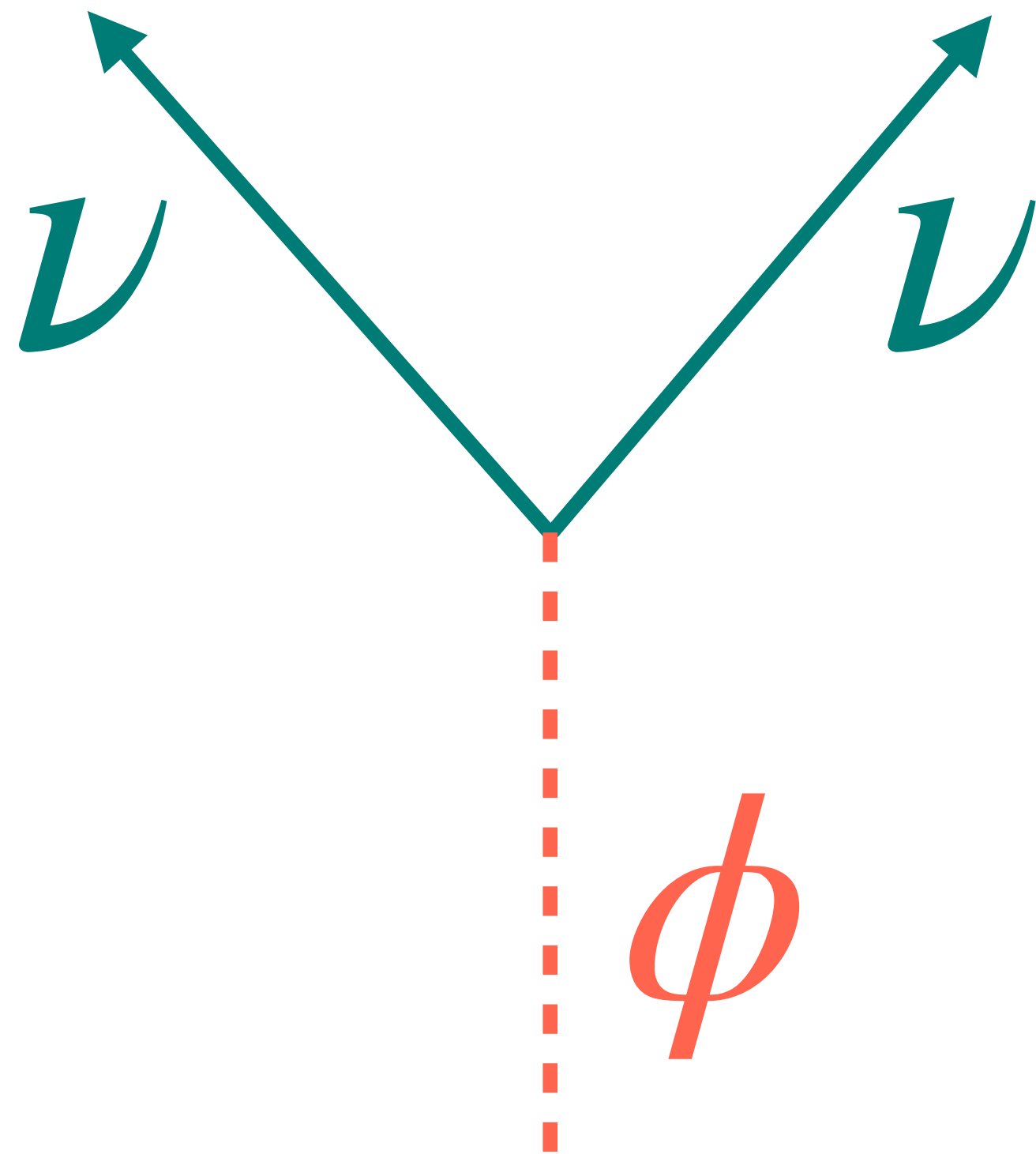
New particles can be produced in supernova core...

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$$\frac{N_{\phi \rightarrow \nu}^{\text{evts}}}{N_\nu^{\text{evts}}} \simeq \frac{\Phi_{\phi \rightarrow \nu}}{\Phi_\nu} \frac{\sigma_{\nu N}(E_{\phi \rightarrow \nu})}{\sigma_{\nu N}(E_\nu)} \simeq \frac{L_\phi / E_{\phi \rightarrow \nu}}{L_\nu / E_\nu} \frac{E_{\phi \rightarrow \nu}^2}{E_\nu^2} \simeq 10 \frac{L_\phi}{L_\nu}$$

# (Pseudo)-majorons



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

In supernova, neutrino-neutrino and antineutrino-antineutrino coalescence

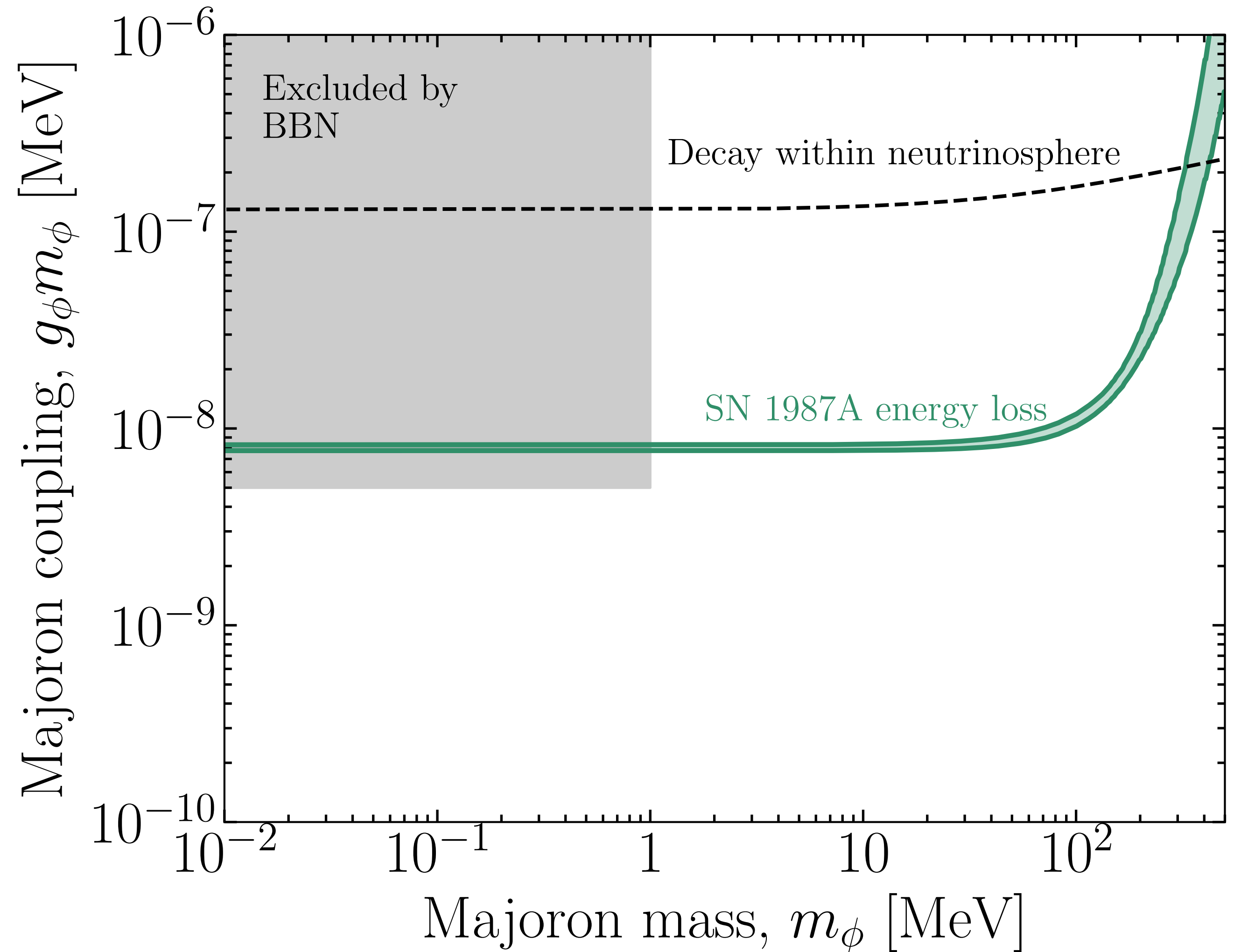
$$m_\phi \gtrsim 10^{-4} \text{ MeV}$$

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

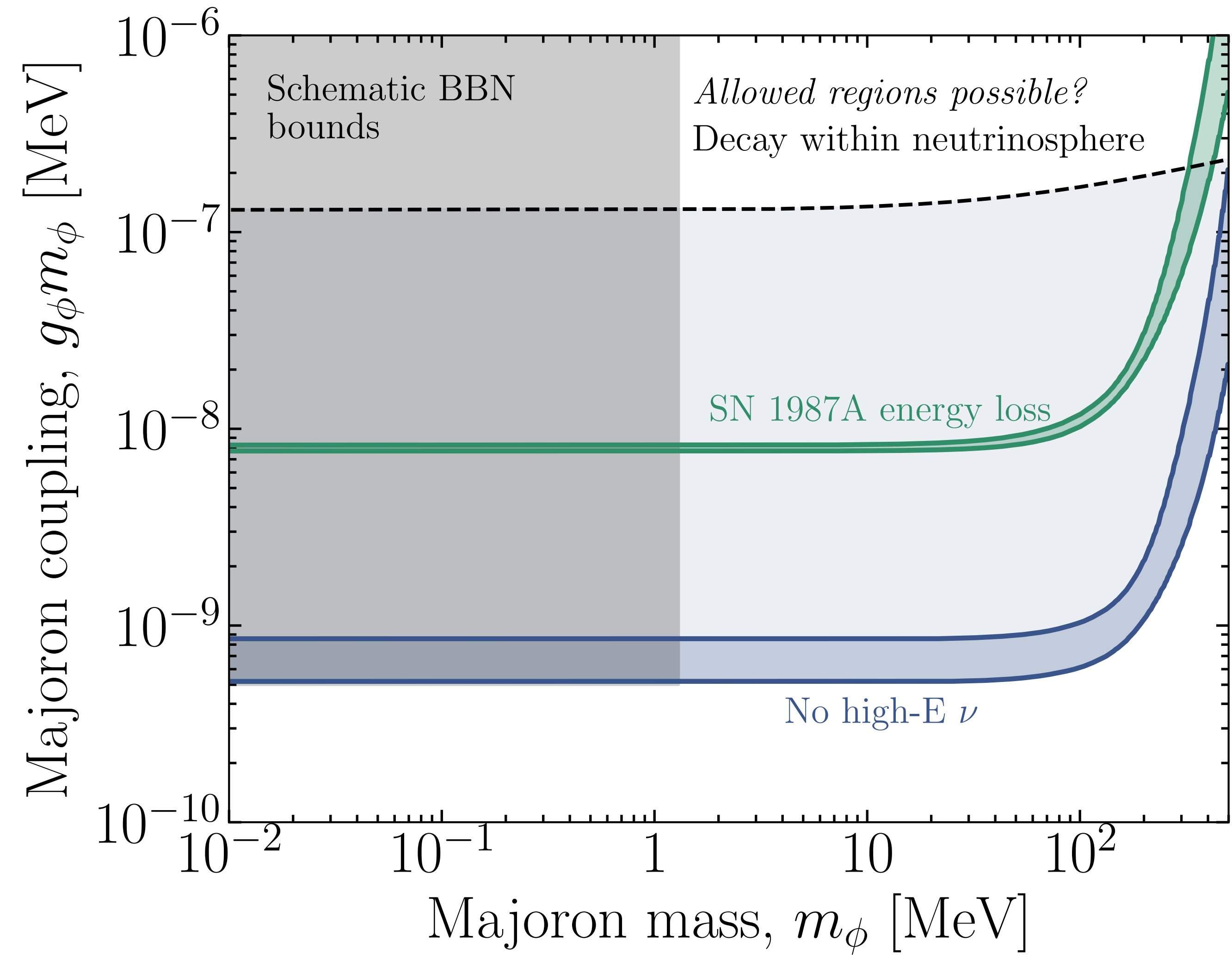
# Majoron production

For small masses, signal depends only on  $gm_\phi$

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



# 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

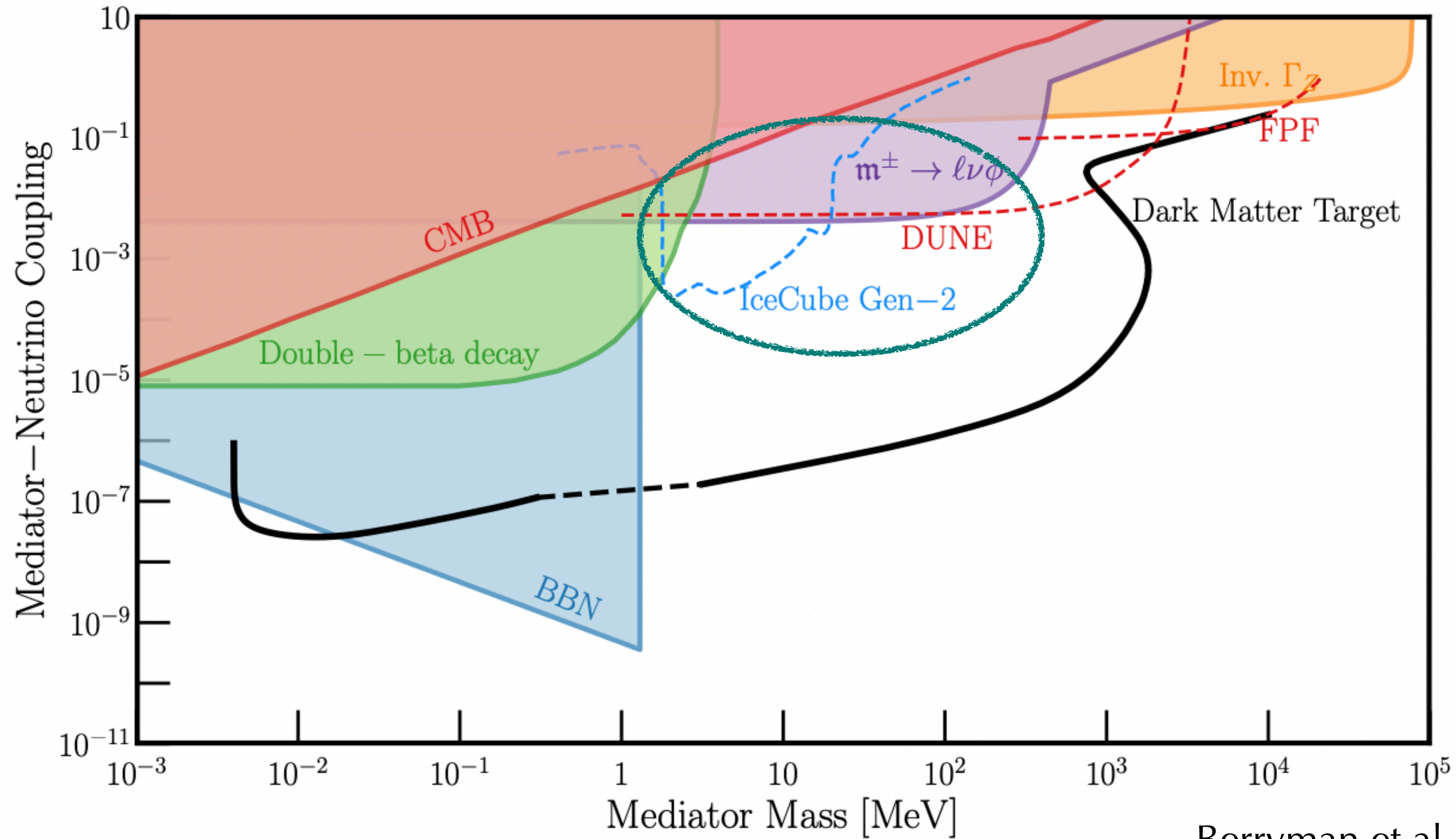


# Secret interactions in supernovae

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

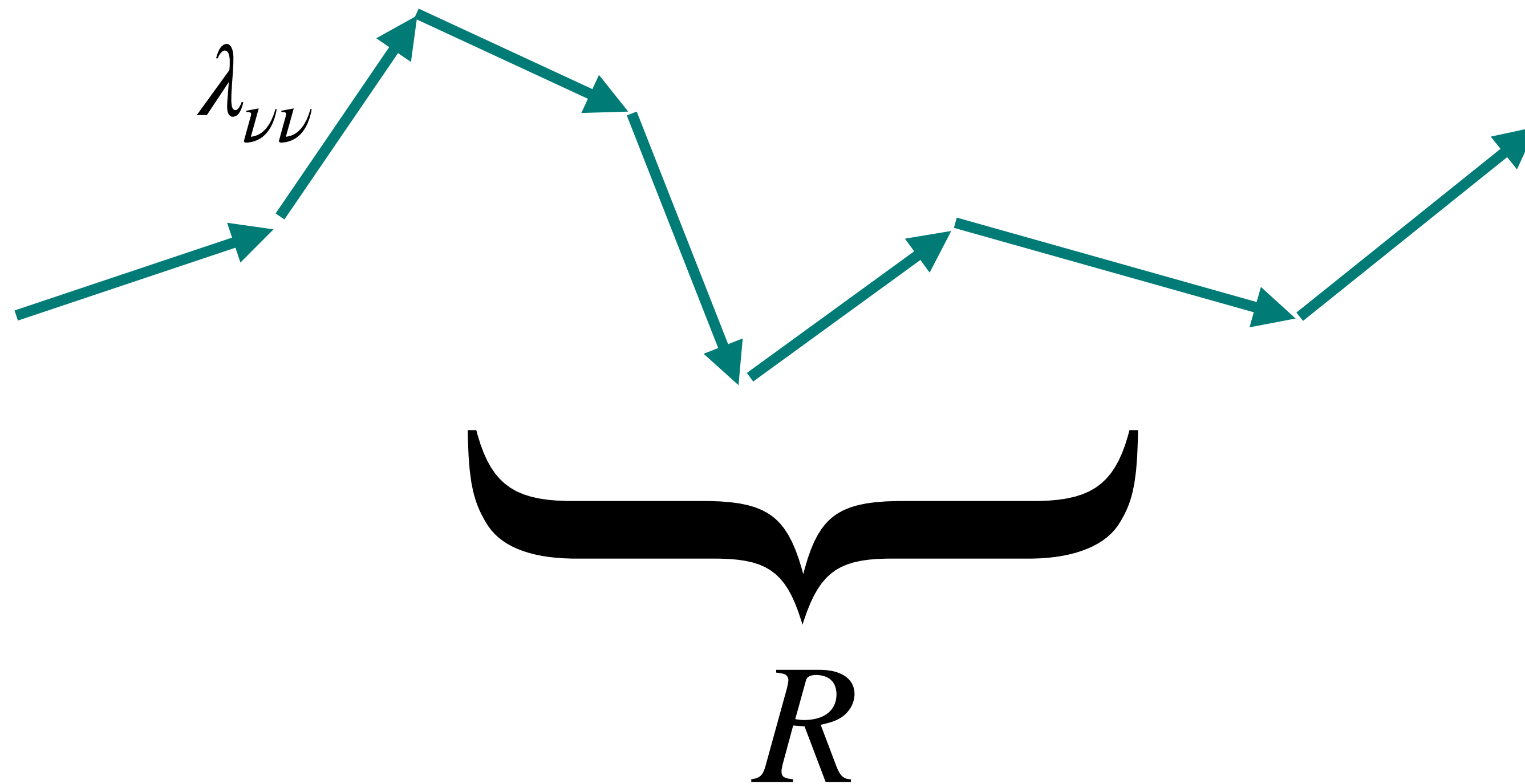


$$\mathcal{L} \propto \bar{\nu} \gamma^\mu \nu Z'_\mu$$

Berryman et al., 2203.01955

# Secret interactions ( $\nu$ SI) and SNe

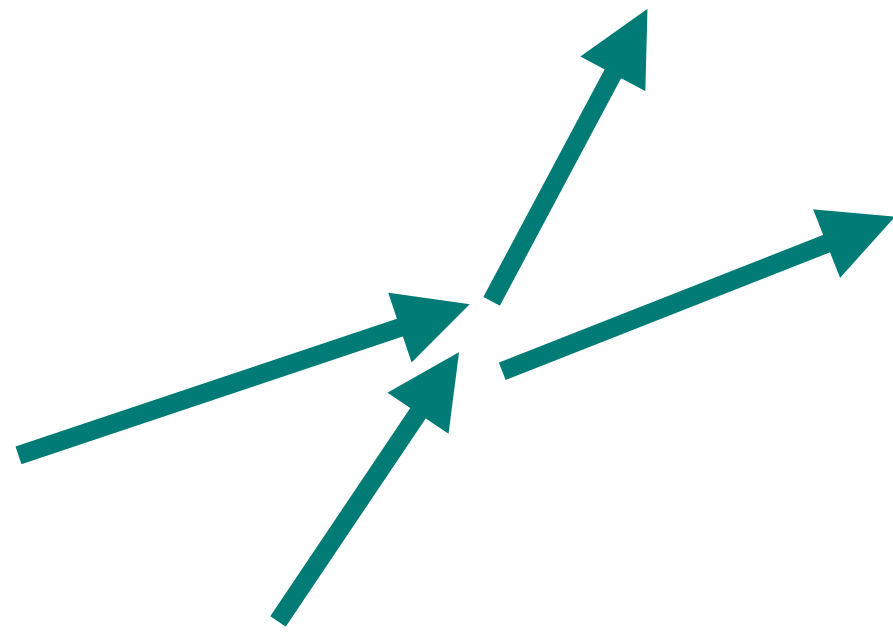
- ◆ Manohar (1987):  $\nu$ SI delay  $\nu$



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

# Secret interactions ( $\nu$ SI) and SNe

- ◆ **Manohar (1987):**  $\nu$ SI delay  $\nu$
- ◆ **Dicus, Nussinov, Pal, Teplitz (1989):** no delay,  $\nu$  are a fluid



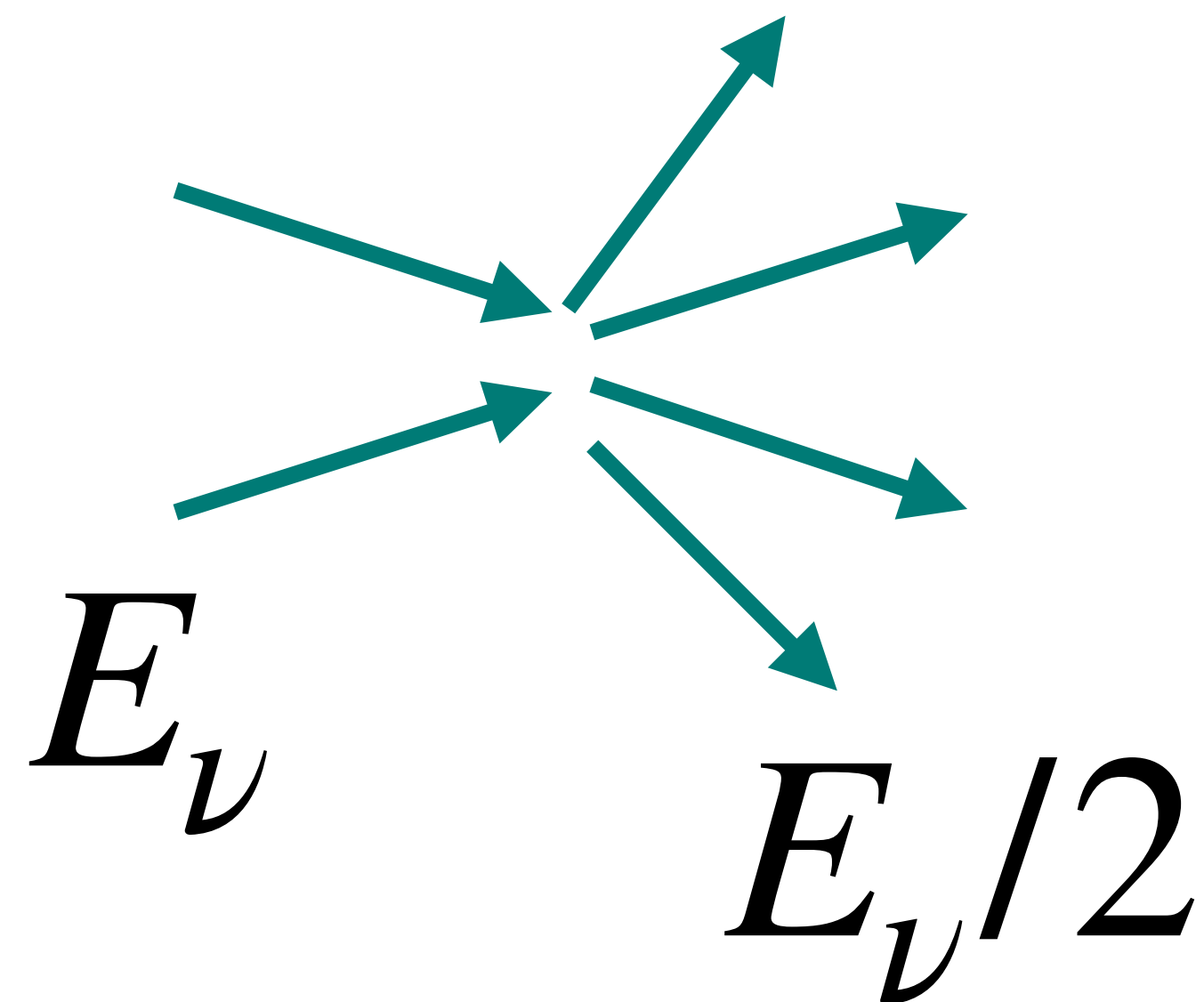
**Total momentum conserved**



**Conserved center-of-mass velocity**

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- ◆ **Shalgar, Tamborra, Bustamante (2019):**  $\nu\bar{\nu} \rightarrow \nu\bar{\nu}\nu\bar{\nu}$  reduce  $\nu$  energy



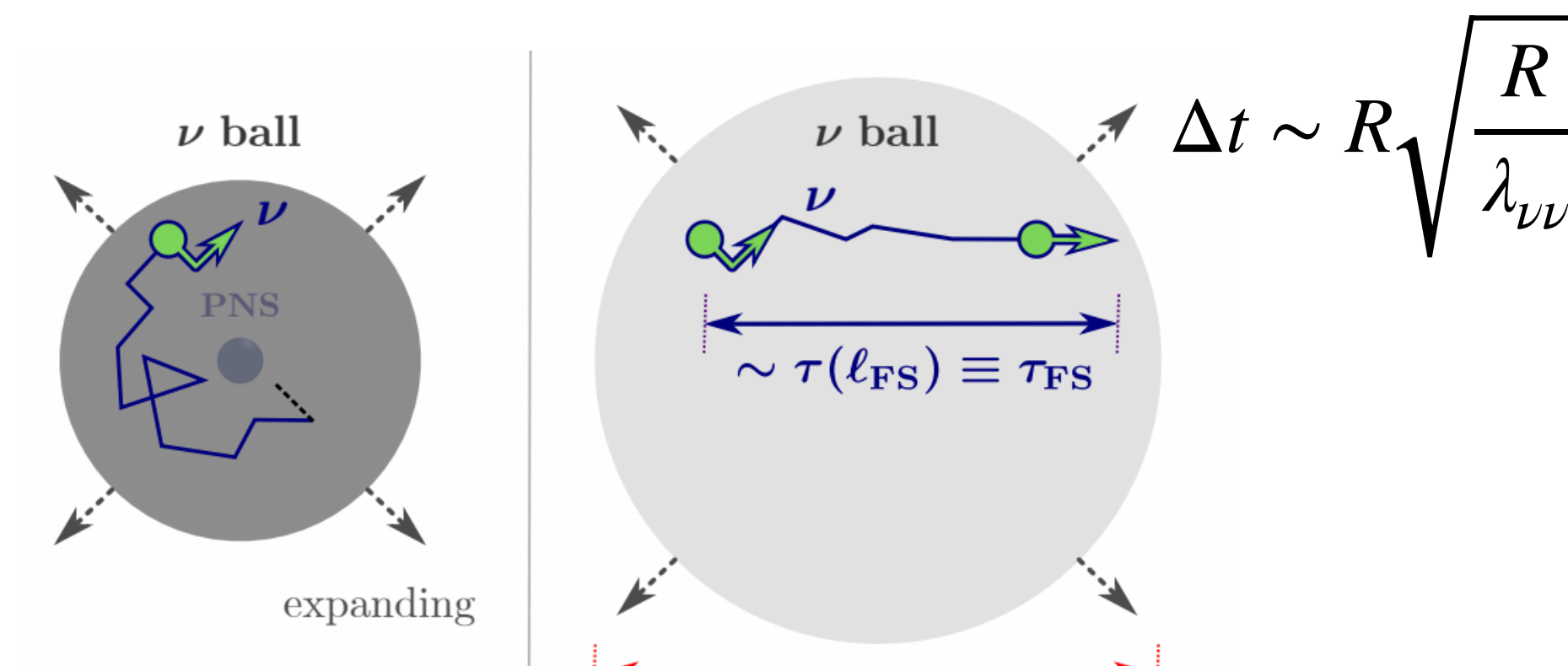
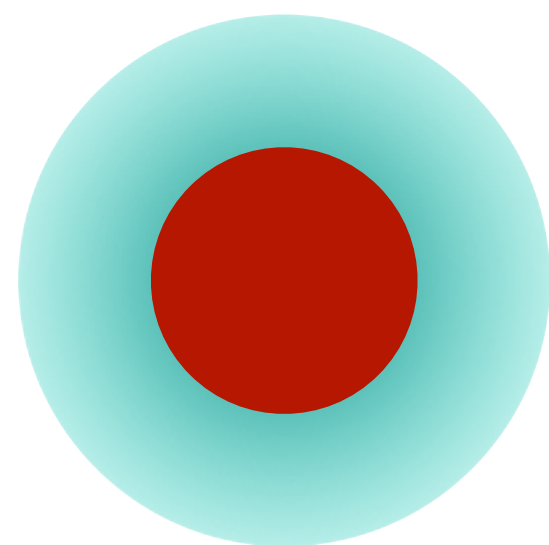
$$\frac{E_\nu}{2R/\lambda_{\nu\nu}}$$

# Secret interactions ( $\nu$ SI) and SNe

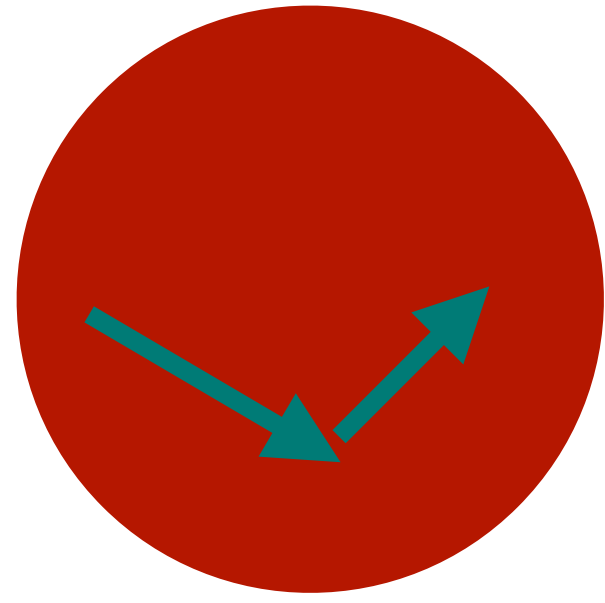
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- ◆ **Chang, Esteban, Beacom, Thompson, Hirata (2022)**: how does  $\nu$  fluid escape?

## Wind outflow

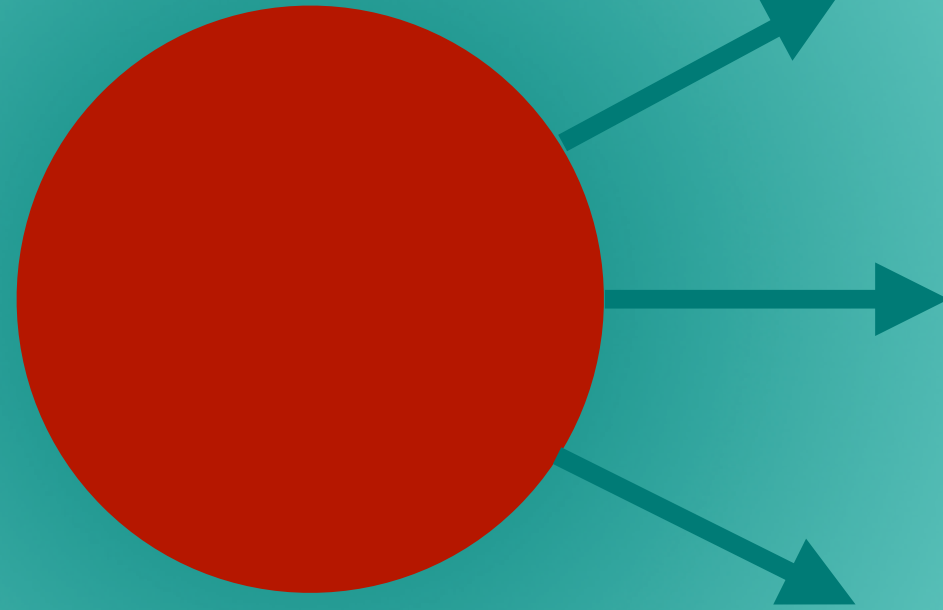
Steady flow -  
incomplete  
picture



**Burst outflow**  
Numerical  
simulations in  
conflict with  
previous literature



**Heat transport  
inside PNS**



**Emission at  
PNS surface**





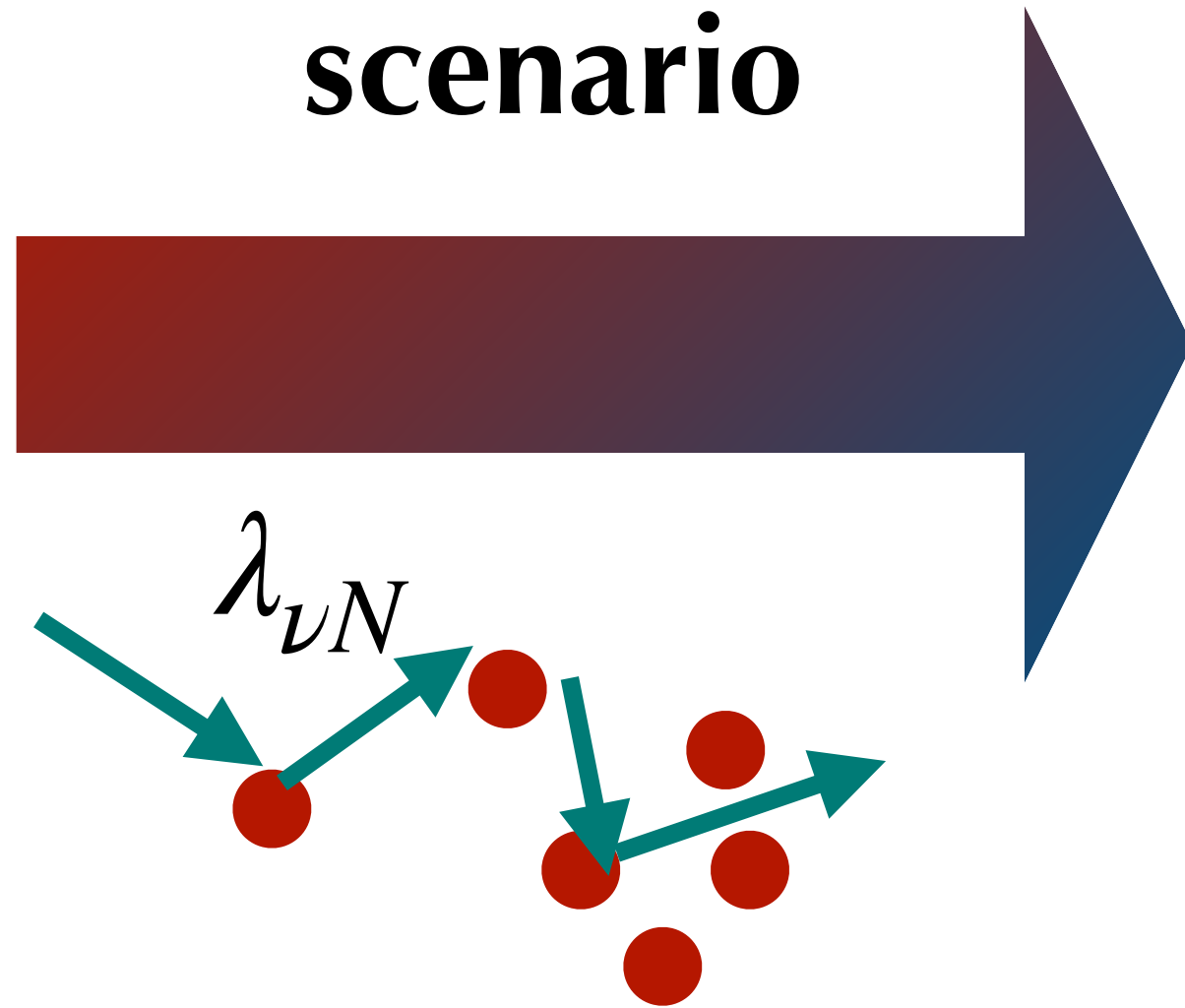
**Neutrino  
fireball**



**Decoupling**

# Heat transport inside PNS

**Standard  
scenario**

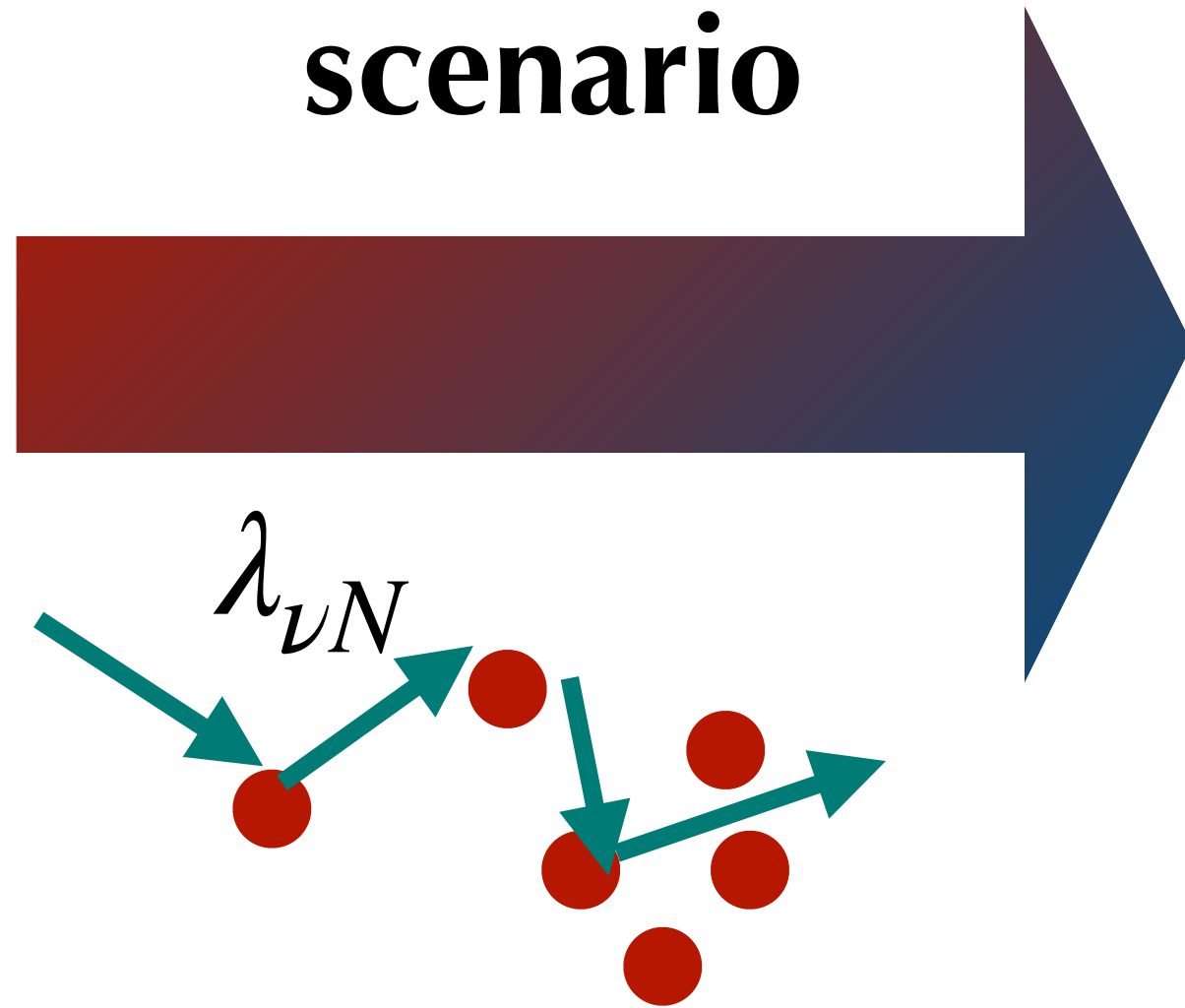


$$F \propto \lambda_{\nu N} \nabla \rho_{\nu}$$

Temperature gradients  
induce anisotropy

# Heat transport inside PNS

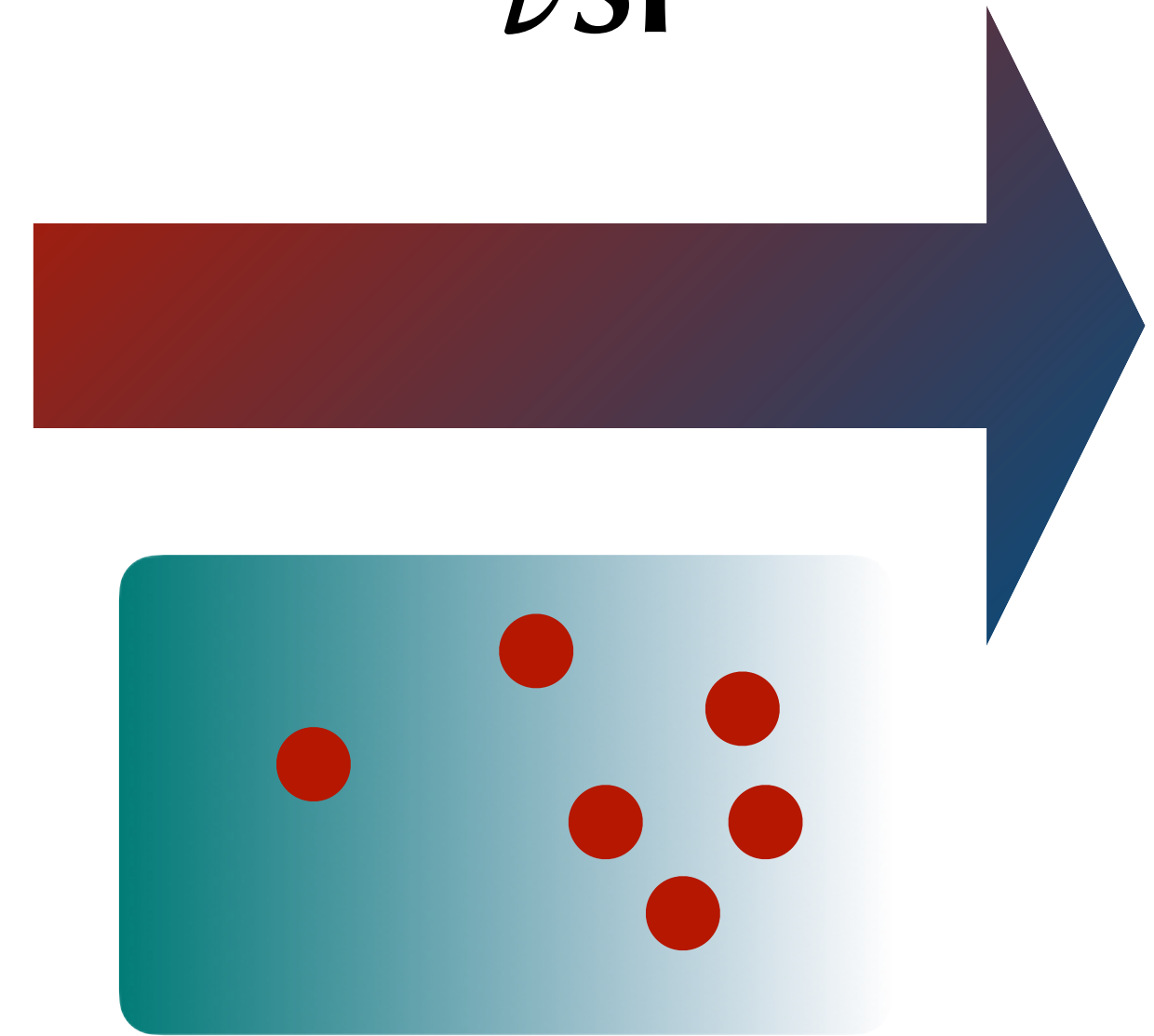
Standard scenario



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

Temperature gradients induce anisotropy

$\nu$ SI

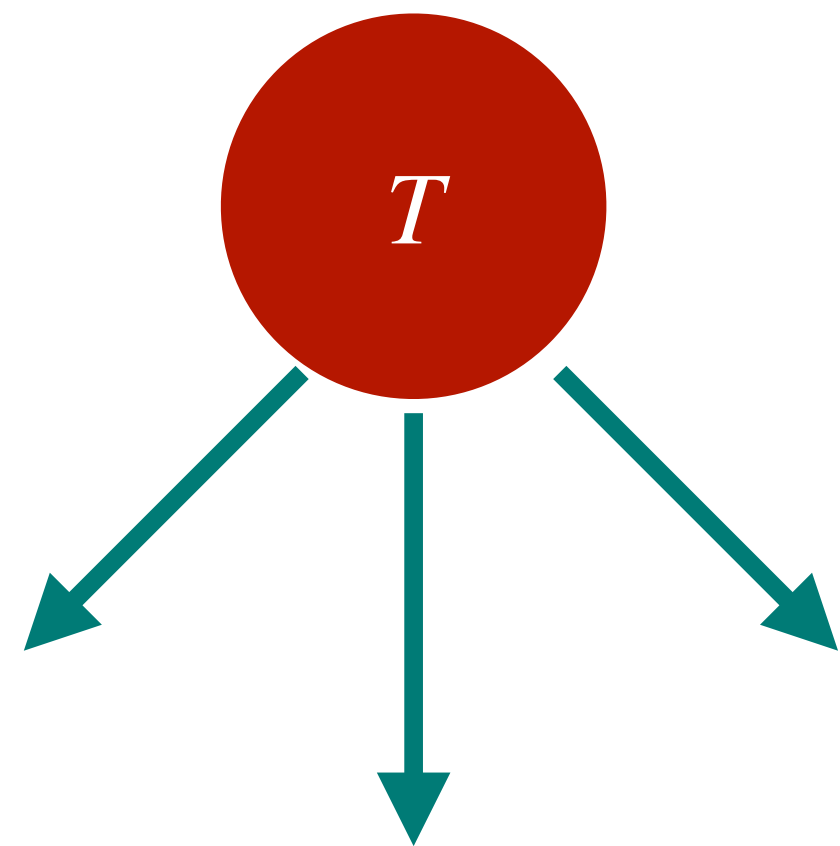


$$\nabla p \sim \frac{\rho_{\nu} v}{\lambda_{\nu N}} \longrightarrow F = \rho_{\nu} v \propto \lambda_{\nu N} \nabla \rho_{\nu}$$

$\nu$ SI convert anisotropy in bulk motion

# Emission at the PNS surface

Blackbody  
emission of a  
fluid

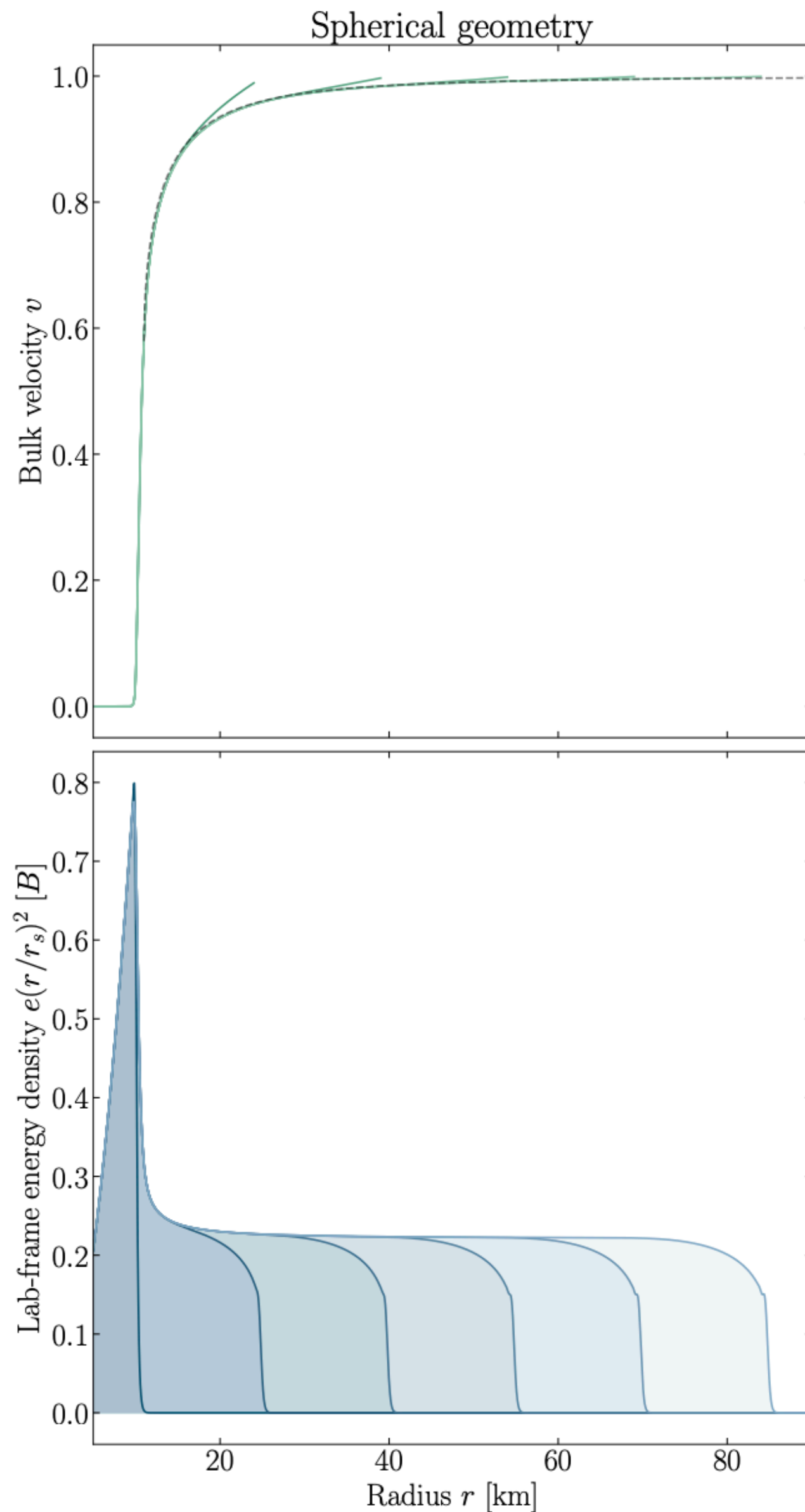


$$T_\nu \propto r^{-1}, \gamma \propto r$$

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

Compare with standard

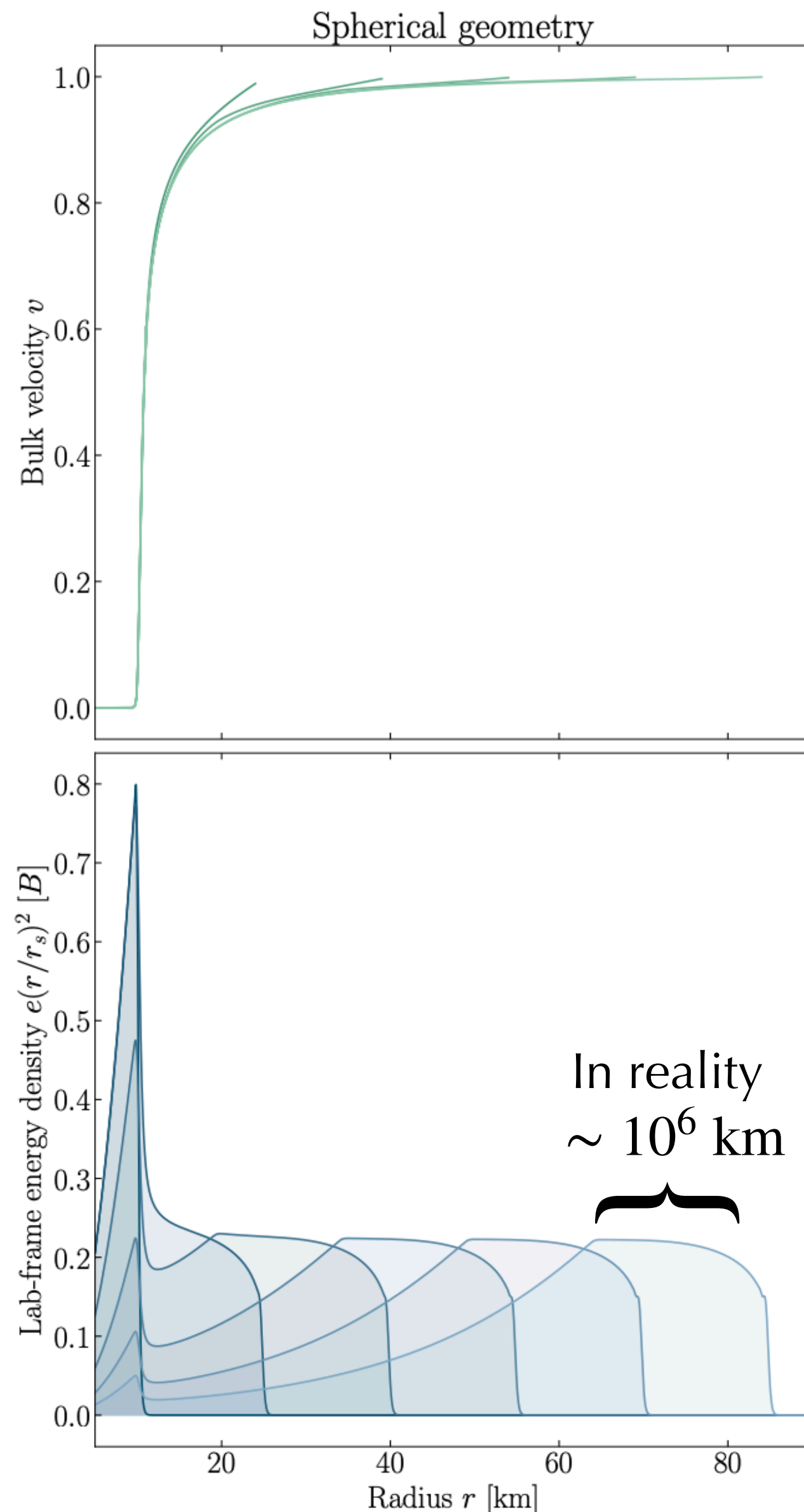
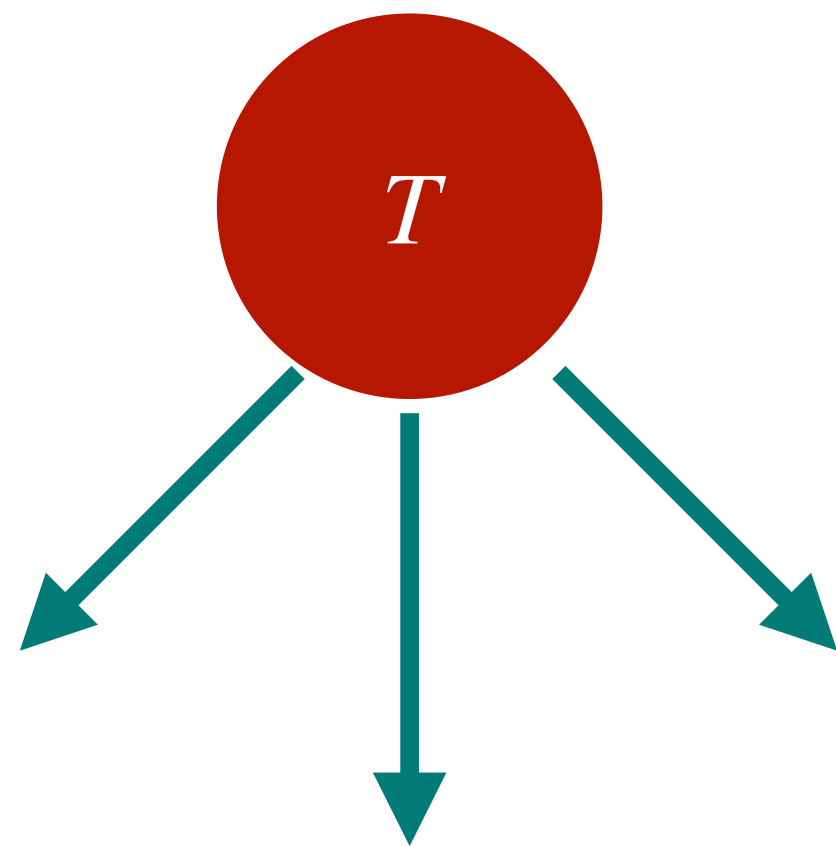
$$\bar{\epsilon} = 3.15T$$



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

# Neutrino fireball

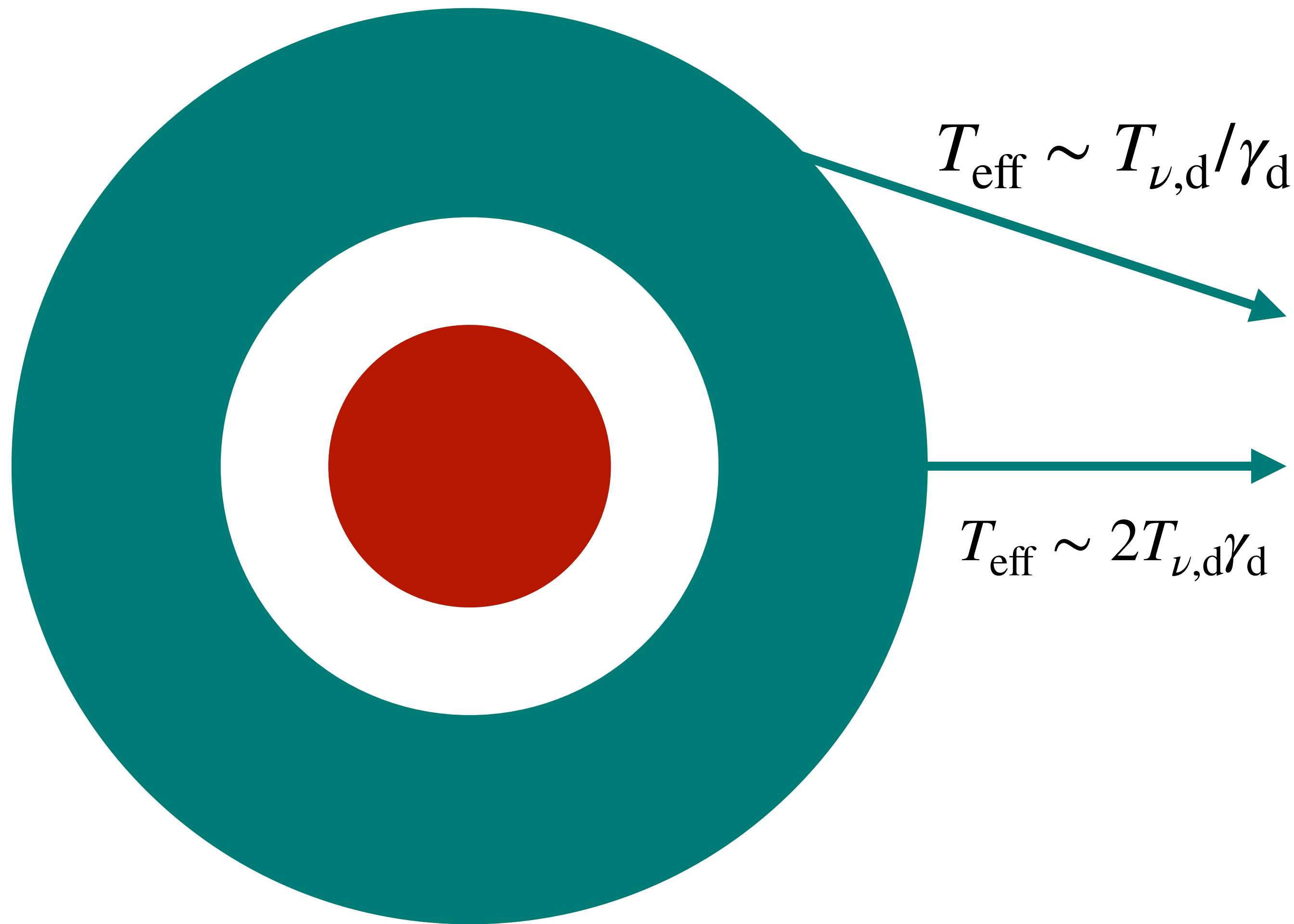
Blackbody emission of a fluid



- ◆ If PNS turns off, bulk of the fluid moves so fast it does not perceive it (sound horizon)
- ◆ No change in  $\nu$  thickness, since most fluid is moving with  $v \sim 1$
- ◆  $\nu\bar{\nu} \rightarrow \nu\bar{\nu}\nu\bar{\nu}$  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

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

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

# Astrophysical conclusions

- ◆ SN 1987A ideal laboratory for astrophysics
- ◆ Generally consistent with modern simulations, both all-duration and first second
- ◆ Requires light PNS  $\lesssim 1.8 M_{\odot}$
- ◆ Origin of late-time events?

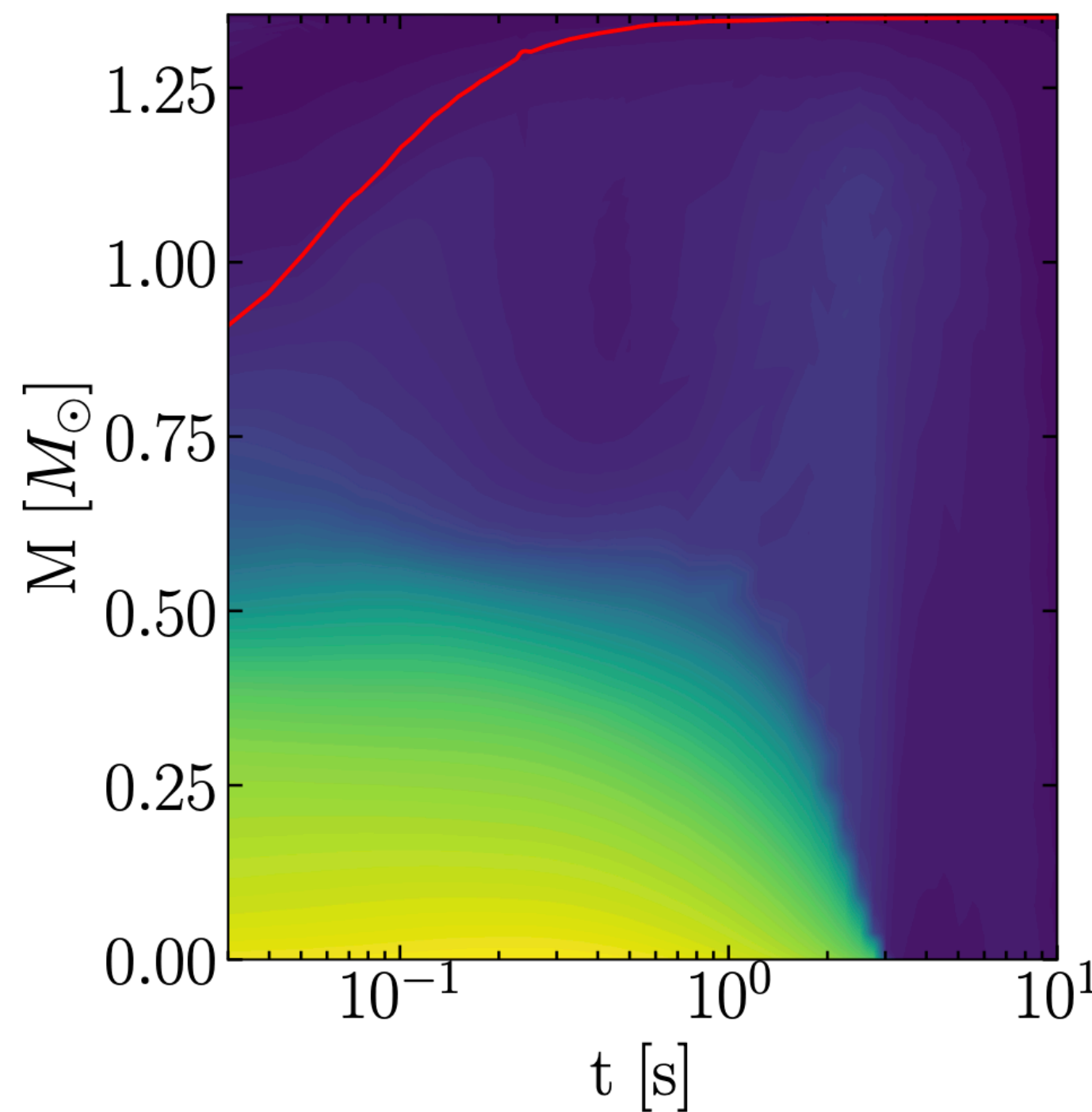


# BSM conclusions

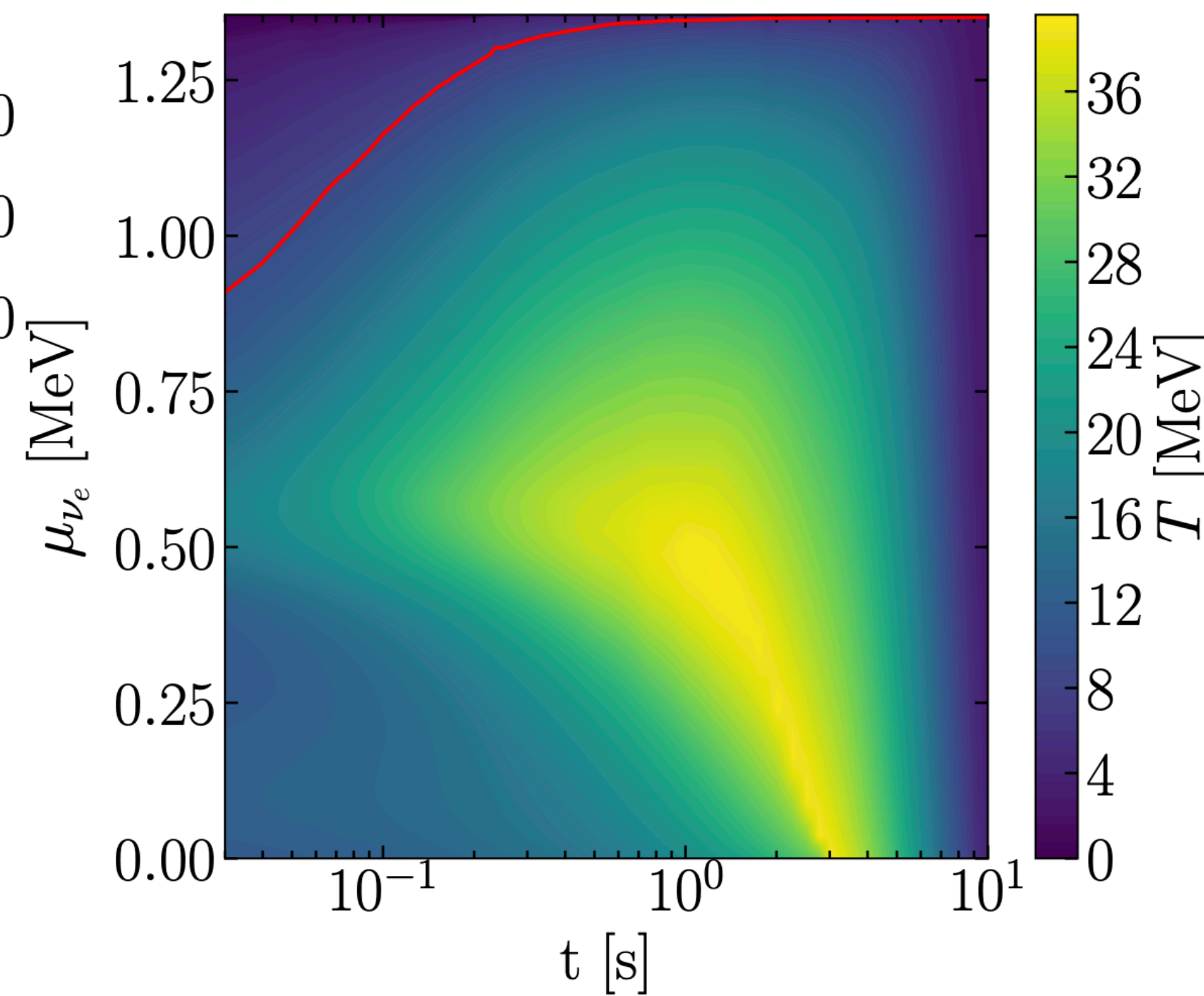
- ◆ SN 1987A ideal laboratory for BSM physics in neutrino sector
- ◆ Cooling bound complemented by decay bounds — stronger by 1 order of magnitude, more robust
- ◆ Trapped mediators produce  $\nu$ SI, but only  $\mathcal{O}(1)$  changes to observables

# Backup slides

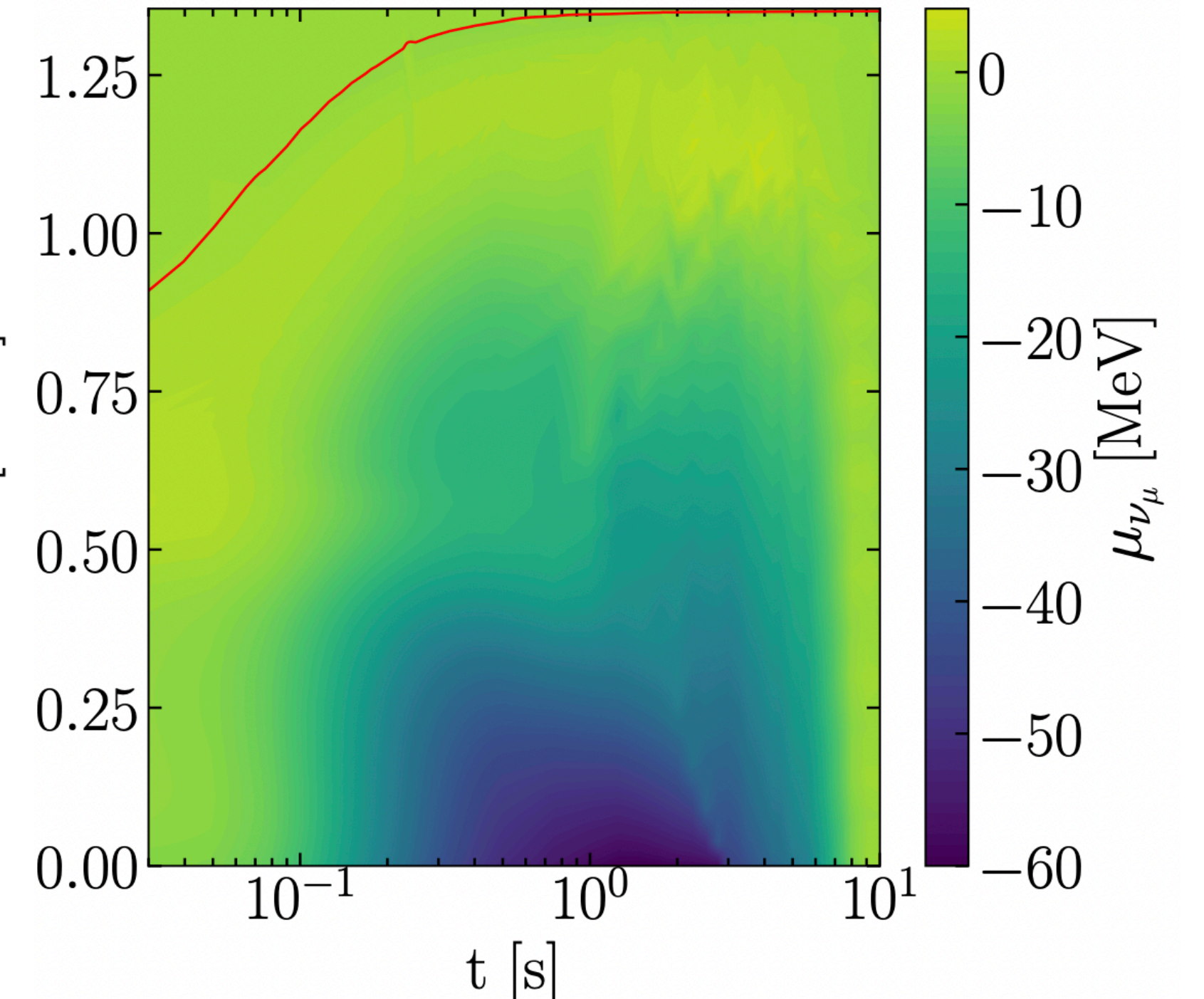
# Core-Collapse Supernovae



PNS de-leptonizes  
and cools

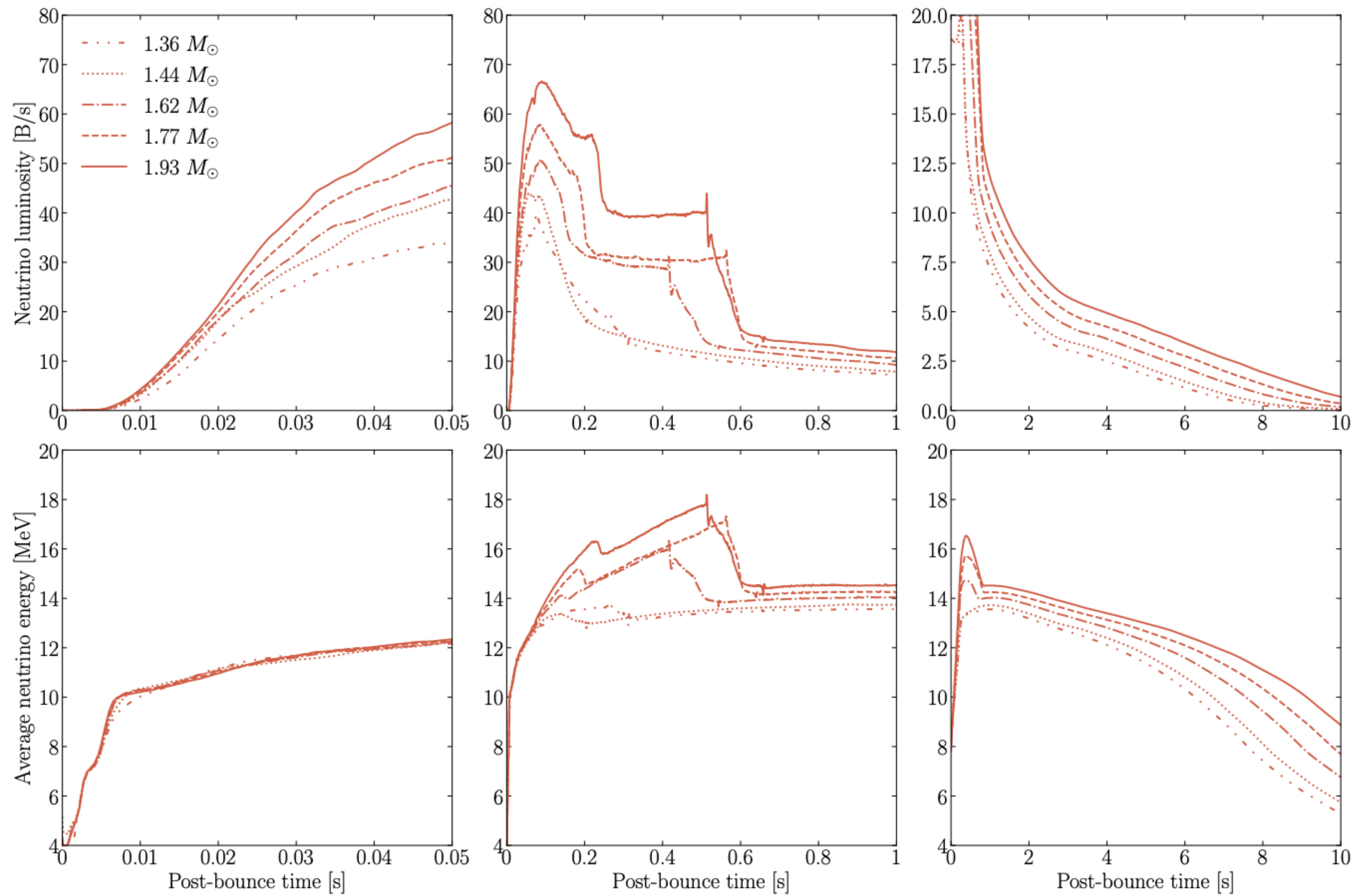


Heats up the  
external material

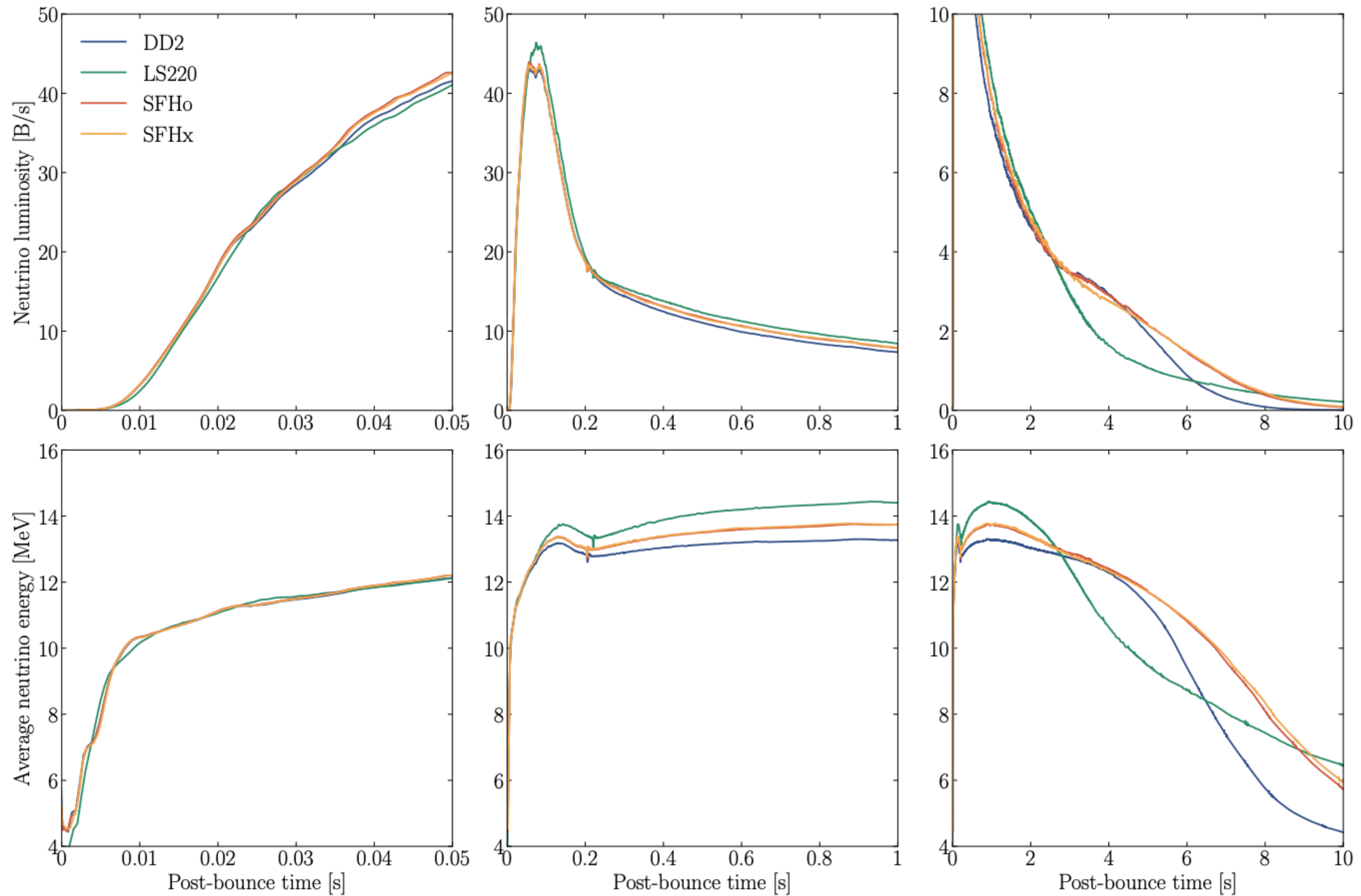


Produces muons  
and muon  
neutrinos

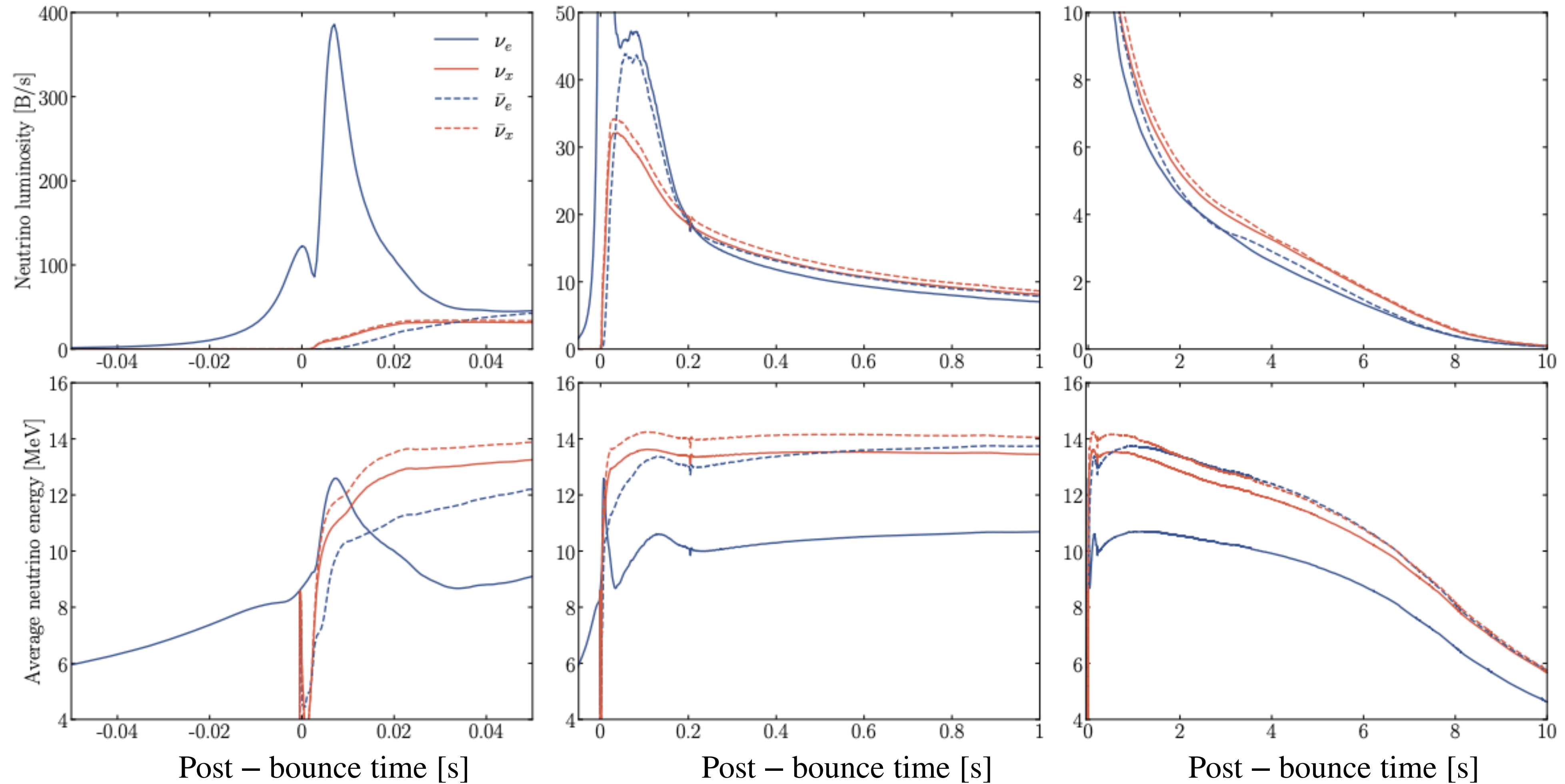
# SN models - neutrino signal



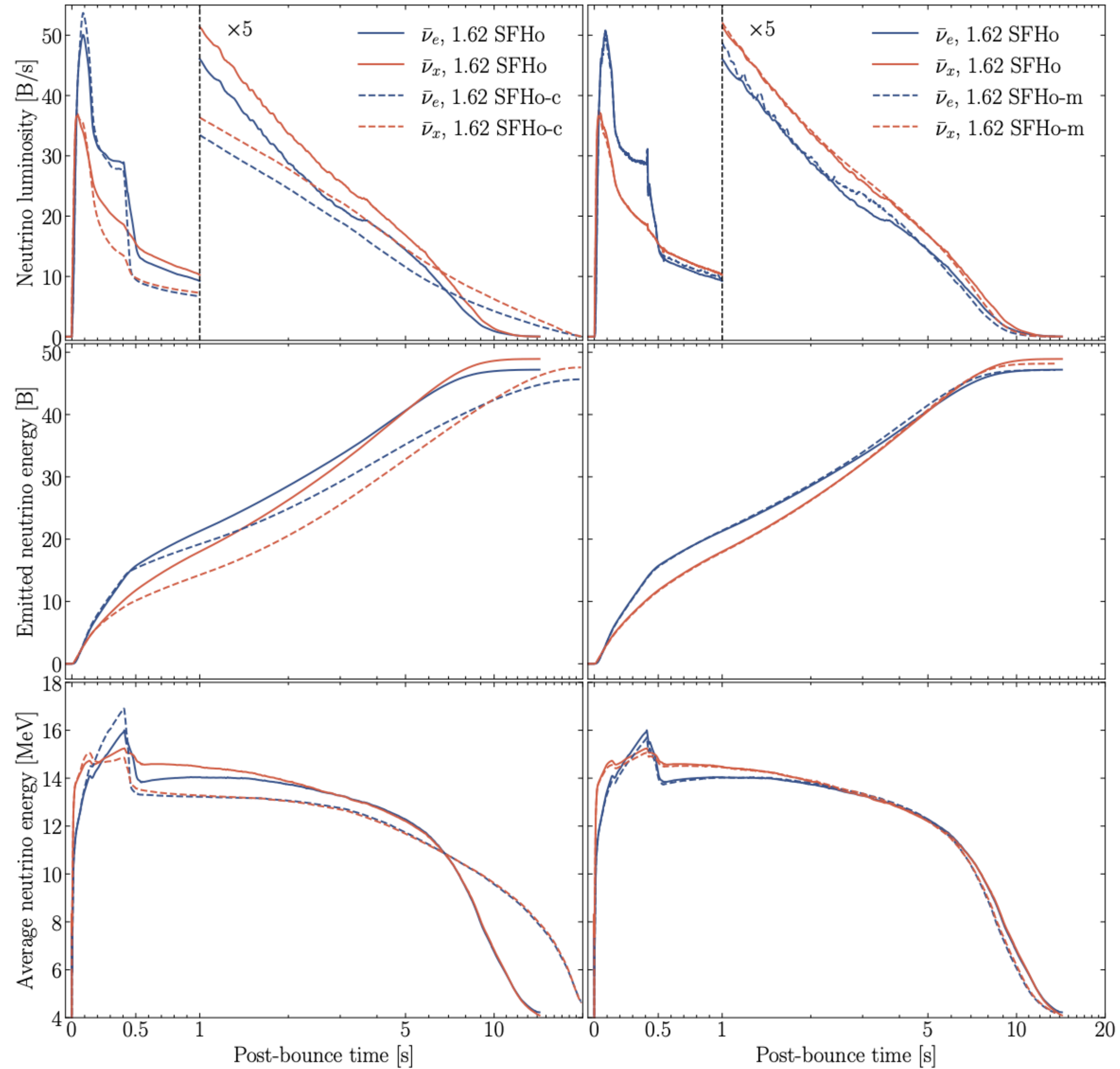
# SN models - neutrino signal



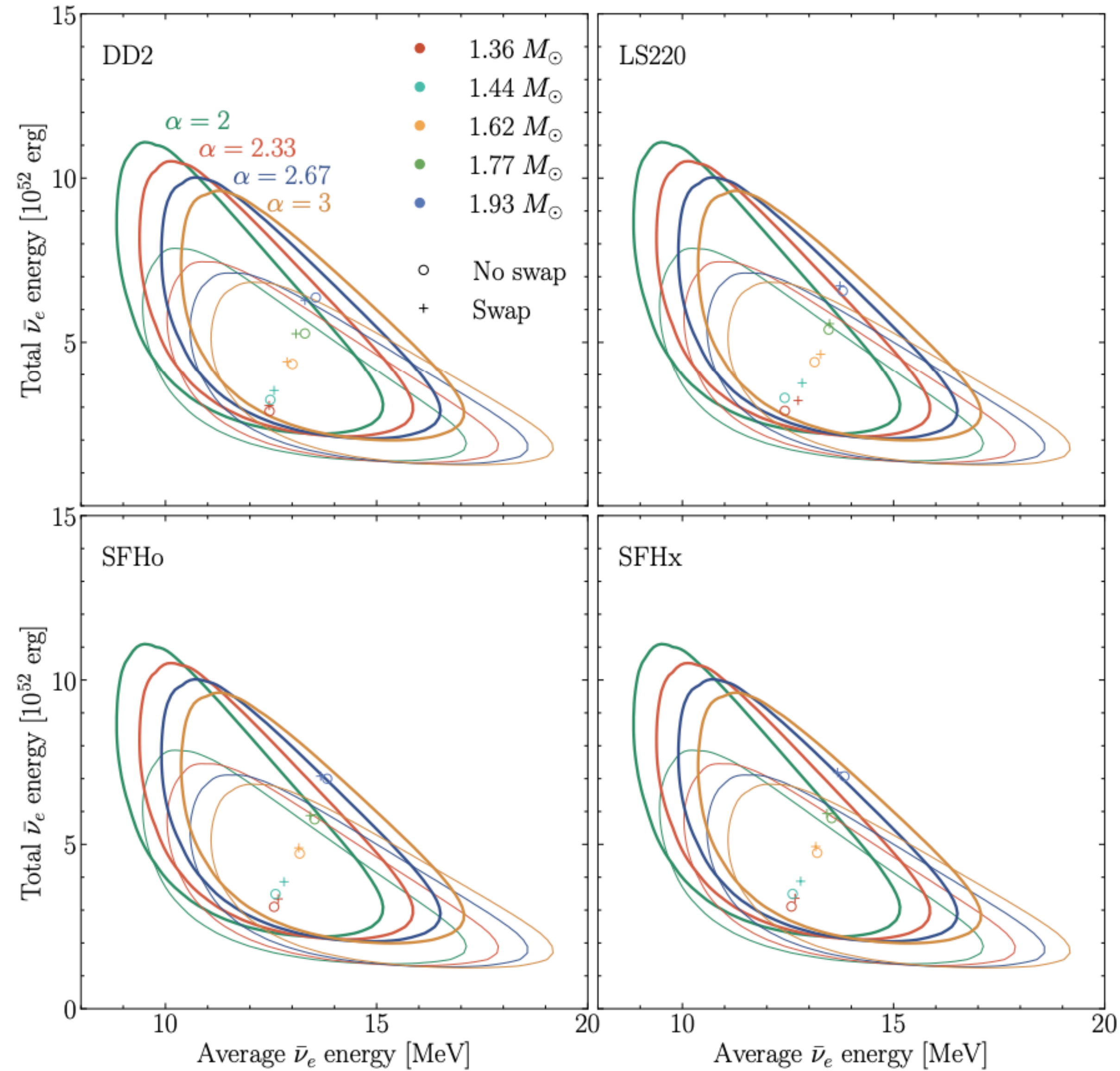
# Flavor dependence of neutrino signal



# Convection vs. no convection

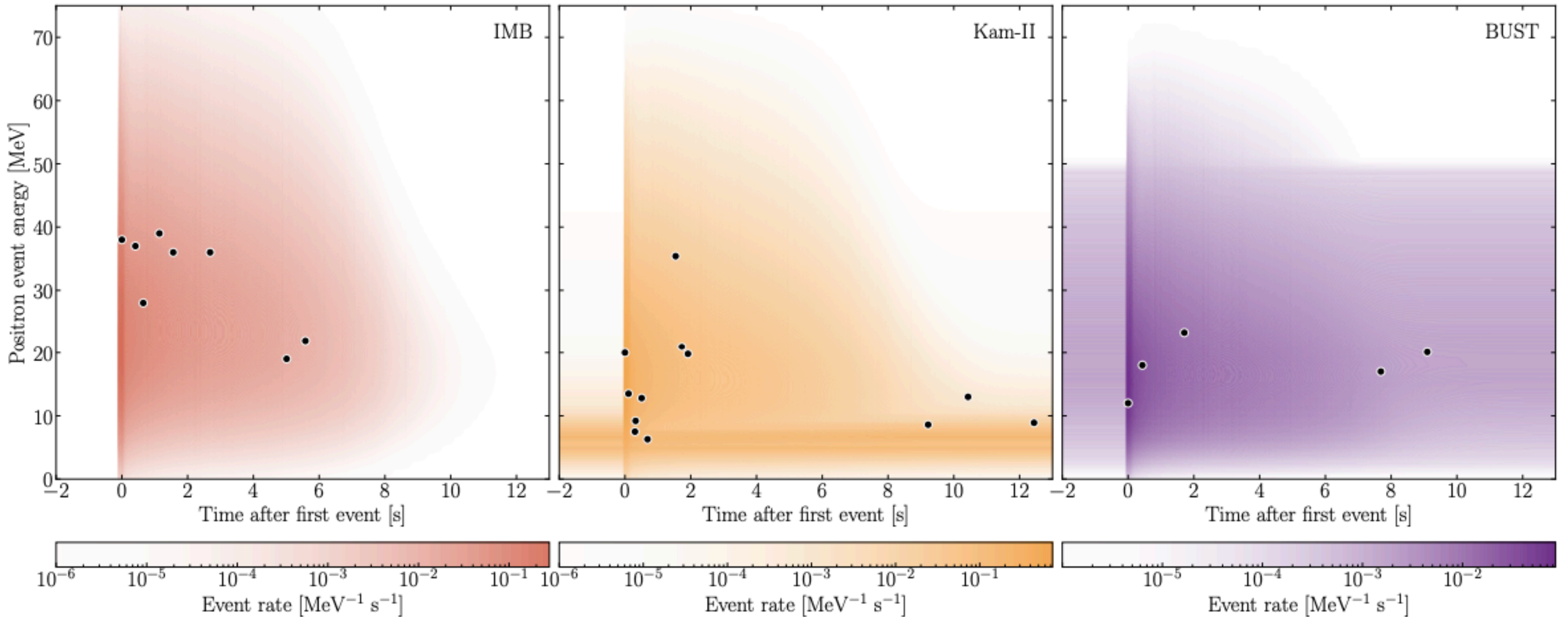


# Impact of flavor conversion

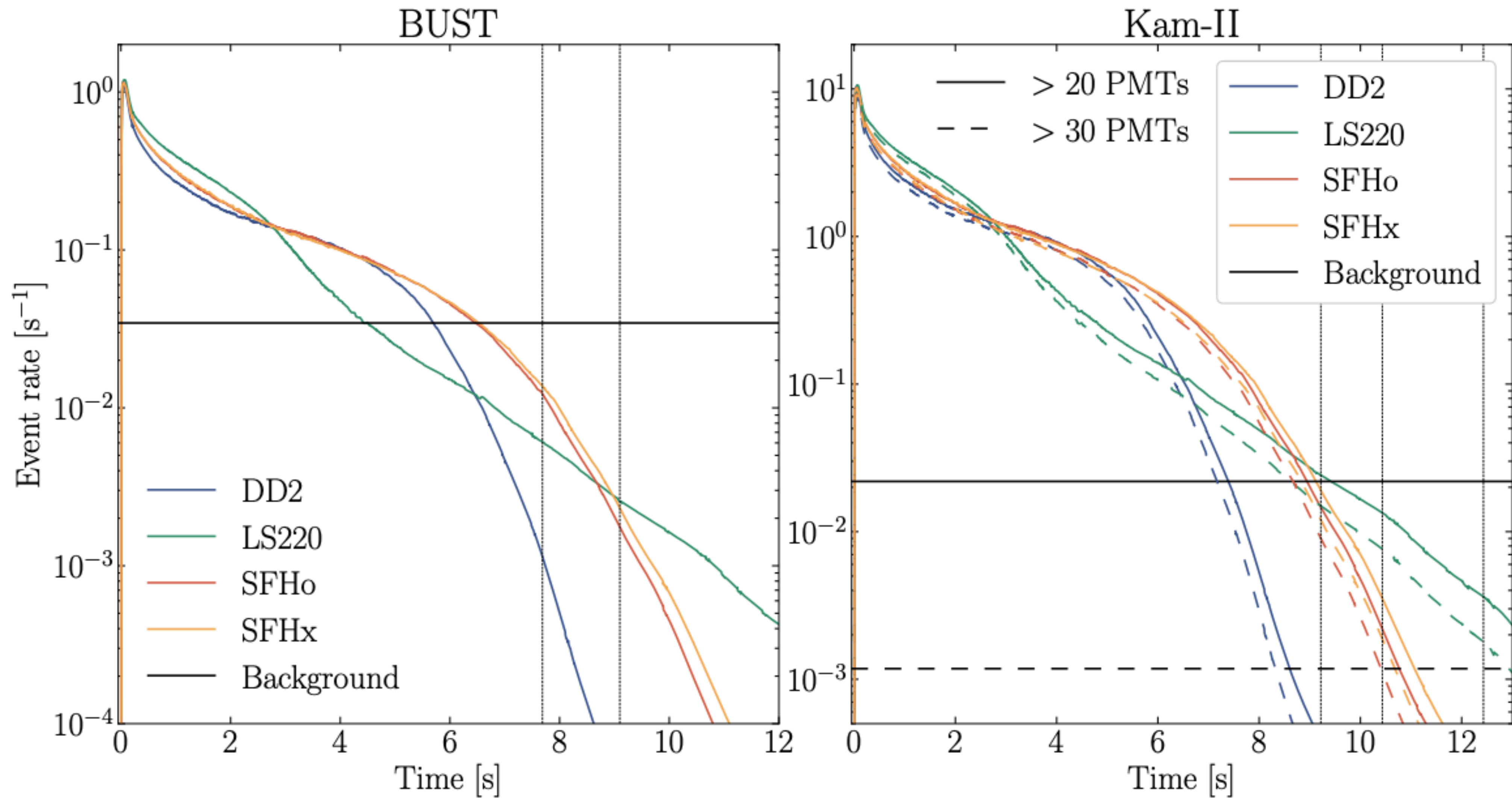




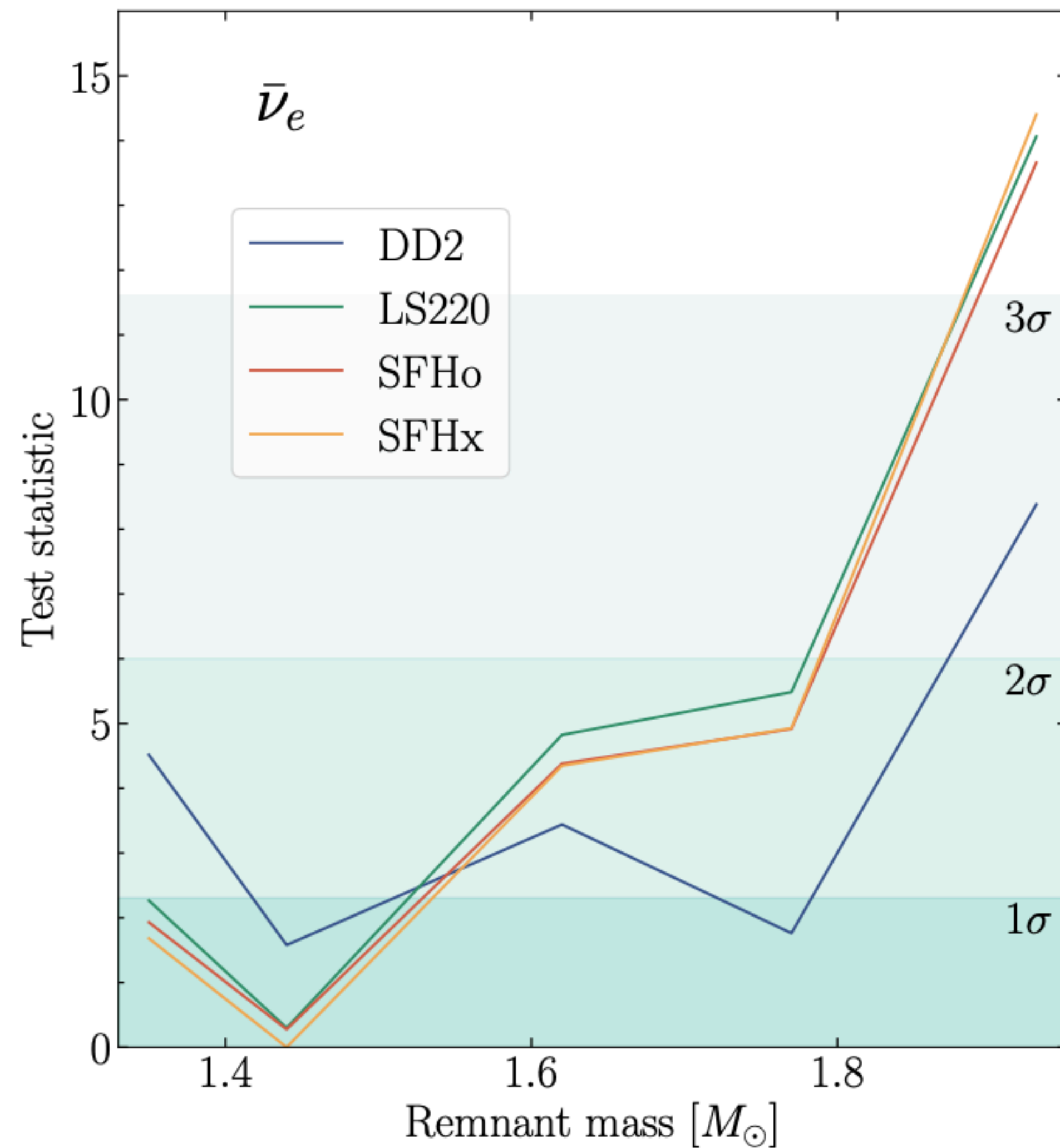
# Event rates



# Late-time events

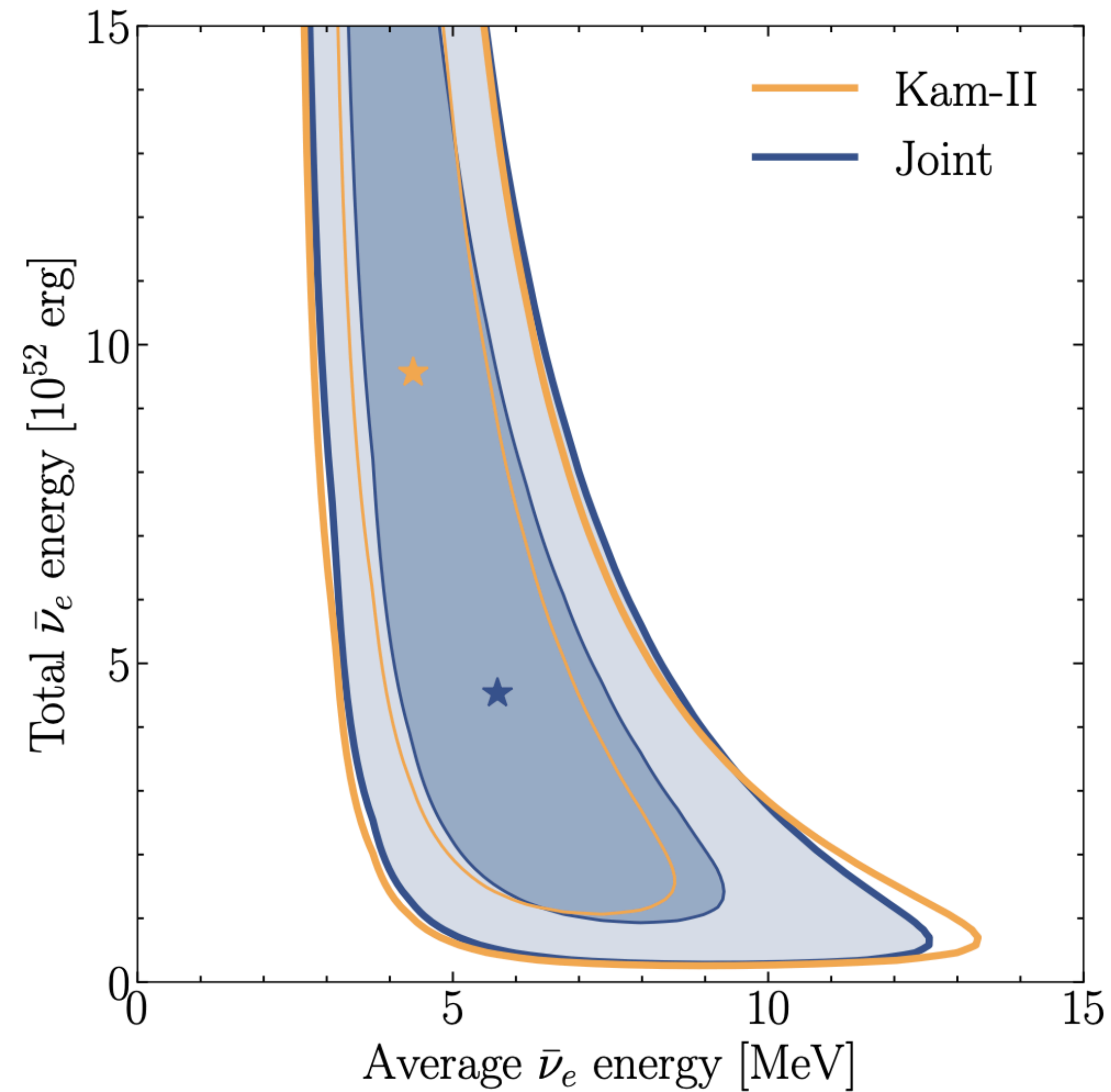


# Full time and energy analysis



- ◆ 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

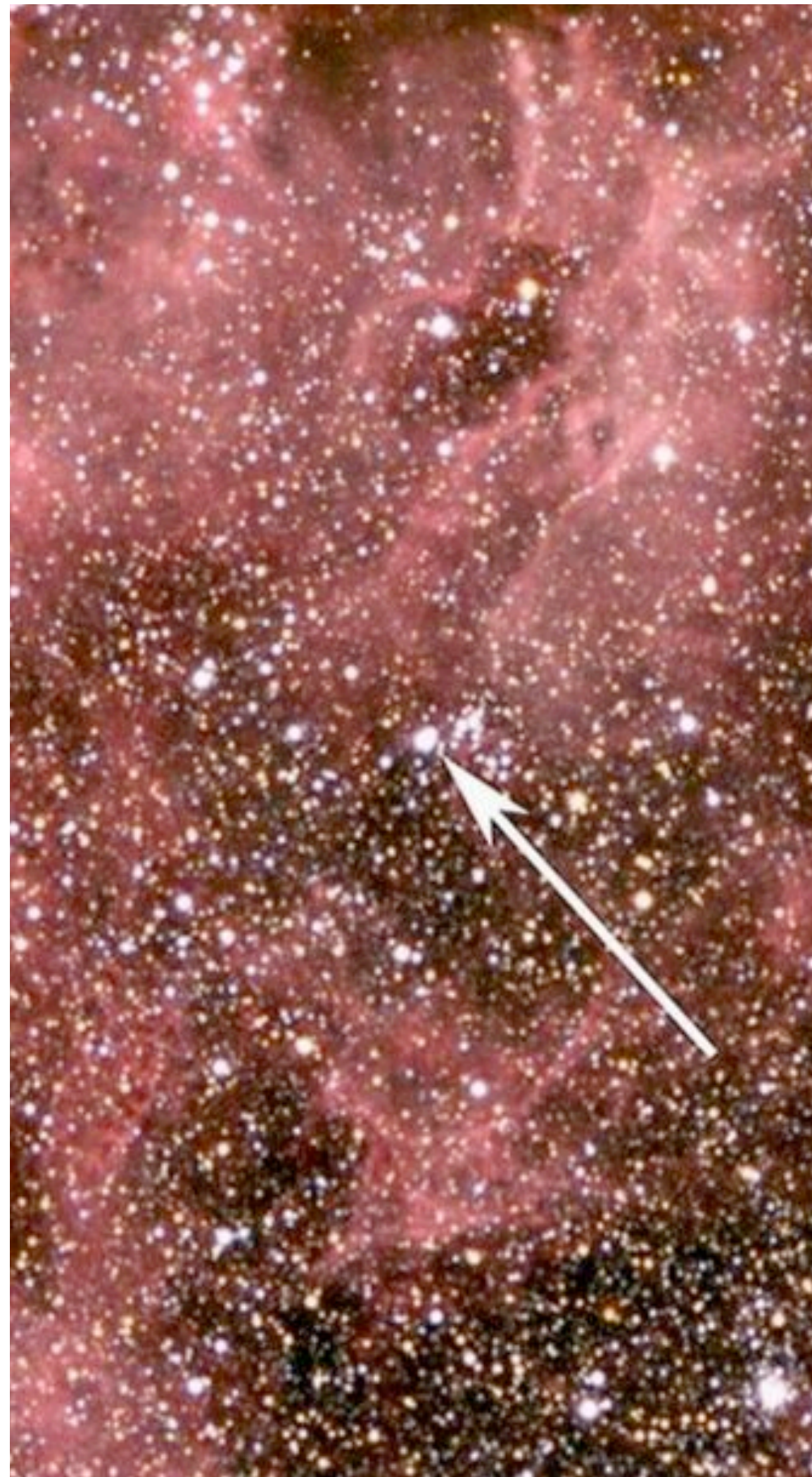


◆ Origin of late-time events is an open question

◆ Background?

◆ Late-time fallback accretion?

# Why supernova?



- ◆ Endpoint of massive stars
- ◆ Internal densities reach up to nuclear densities ( $10^{14} \text{ g cm}^{-3}$ )
- ◆ 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

# Testing for new physics

New particles can be produced in supernova core...

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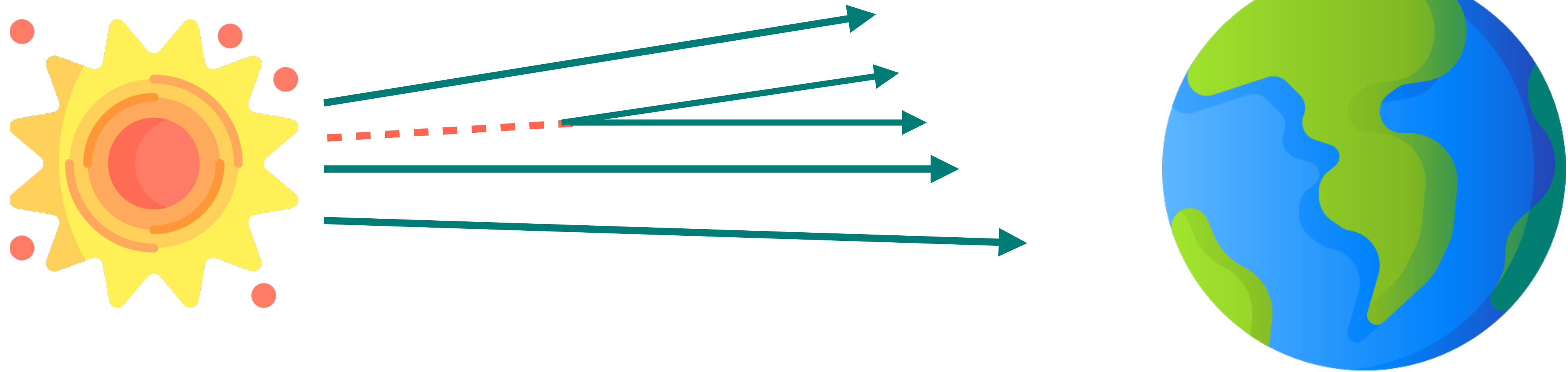
... but how do we probe them?



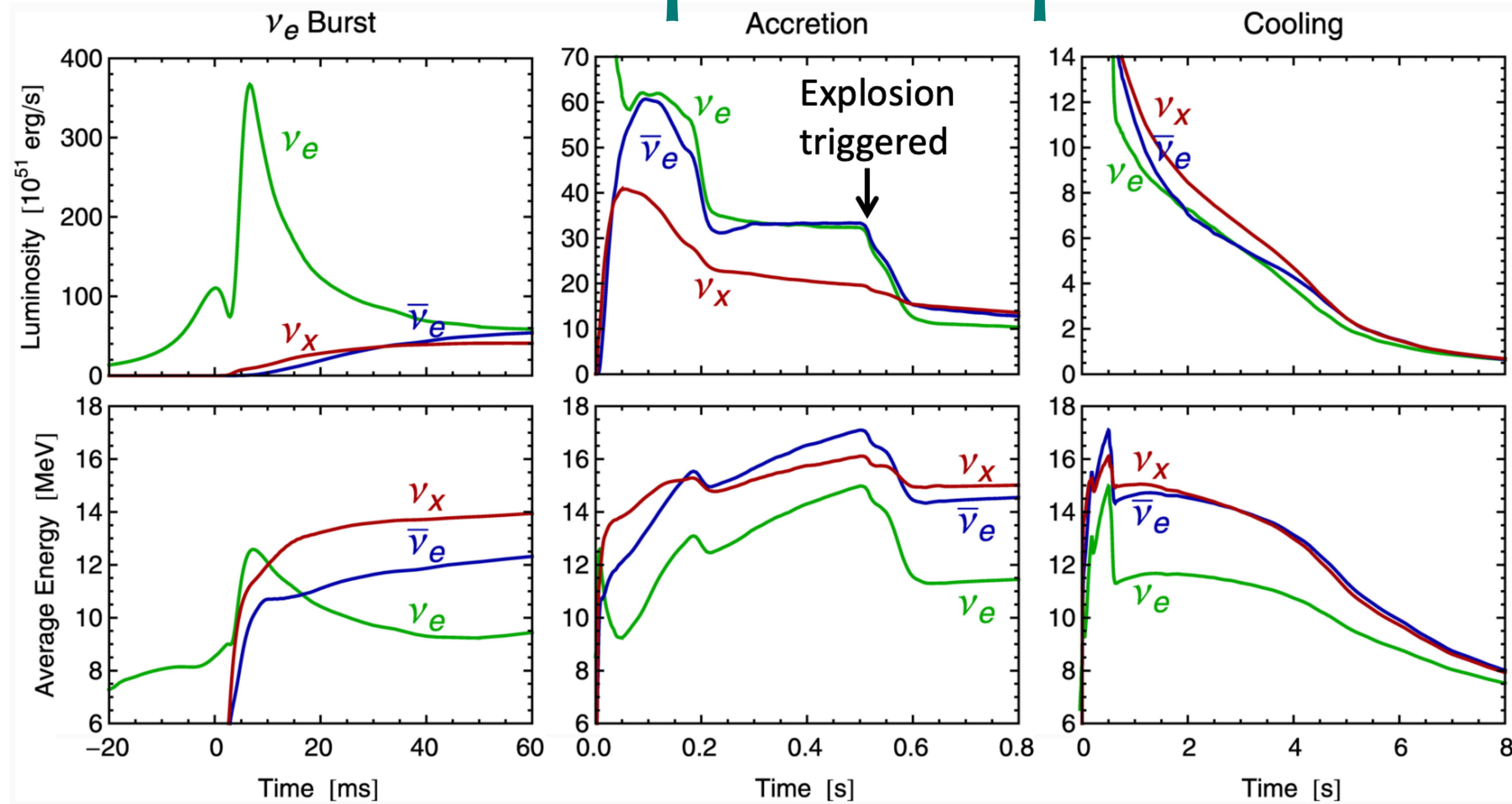
# Testing for new physics

New particles can be produced in supernova core...

... but how do we probe them?



# Core-Collapse Supernovae



- Shock breakout
- De-leptonization of outer core layers

- Shock stalls  $\sim 150$  km
- Neutrinos powered by infalling matter

Cooling on neutrino diffusion time scale

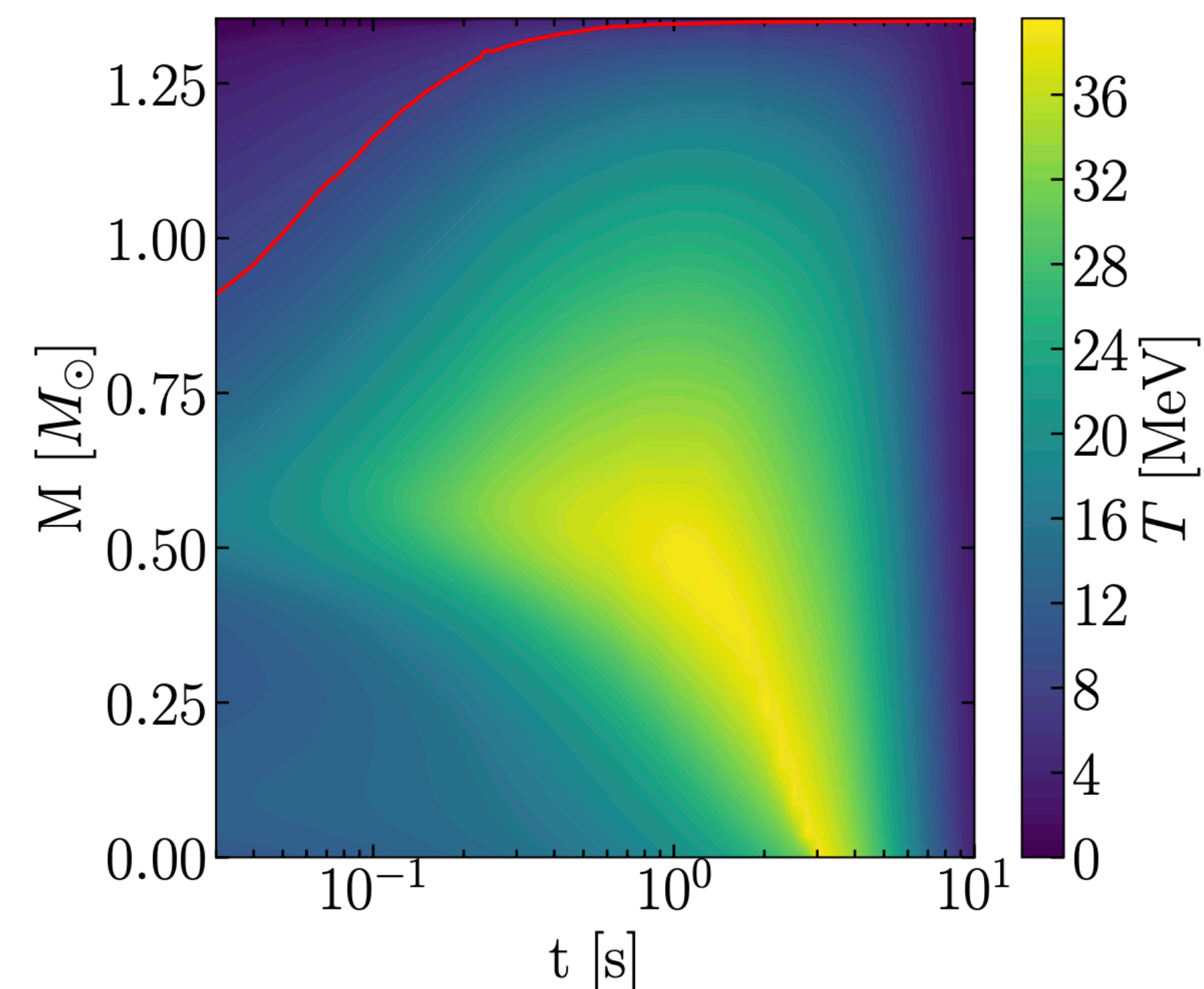
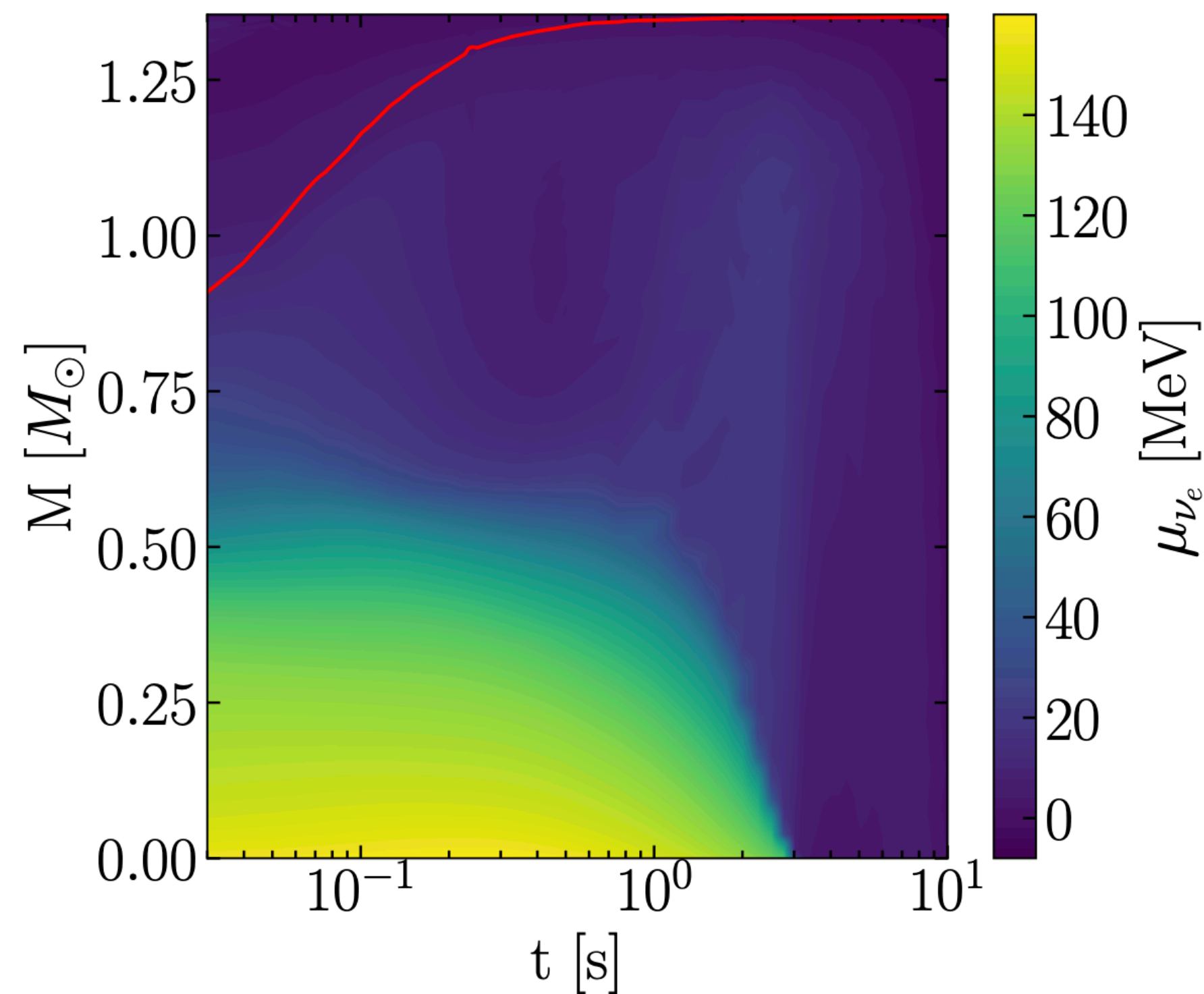
Credits to G. Raffelt

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

# Testing for new physics

New particles can be produced in supernova core...

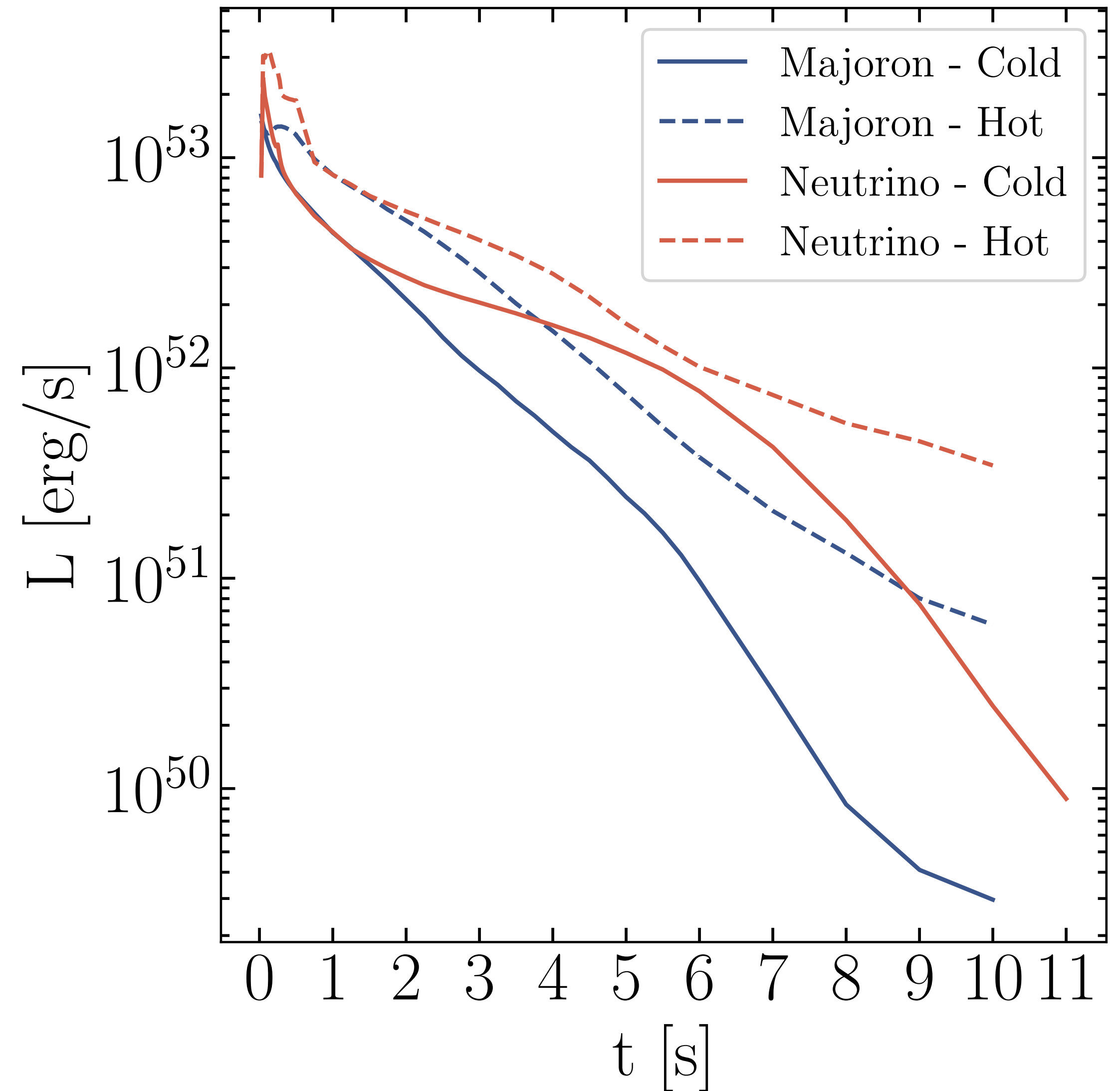
... but how do we probe them?



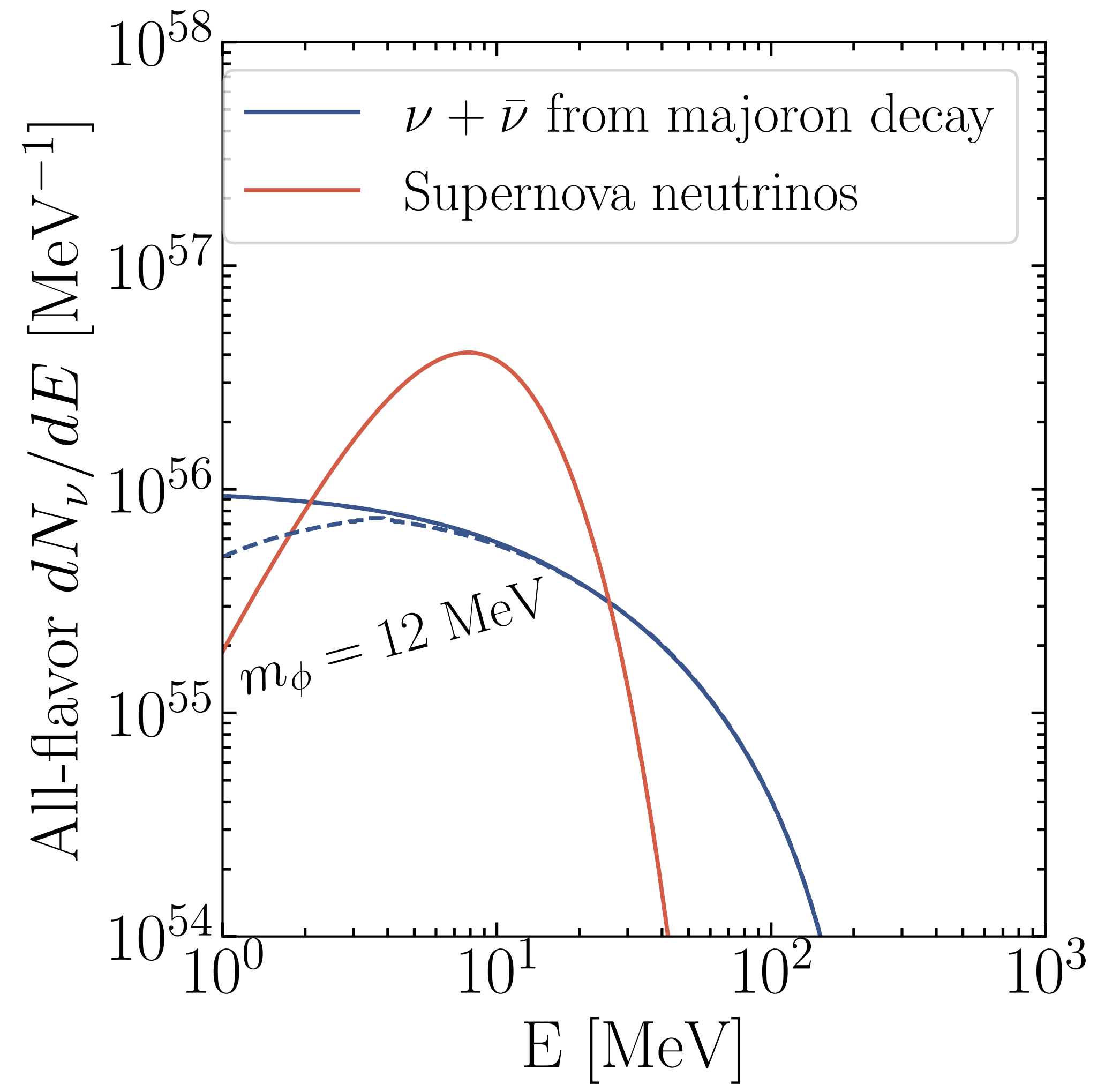
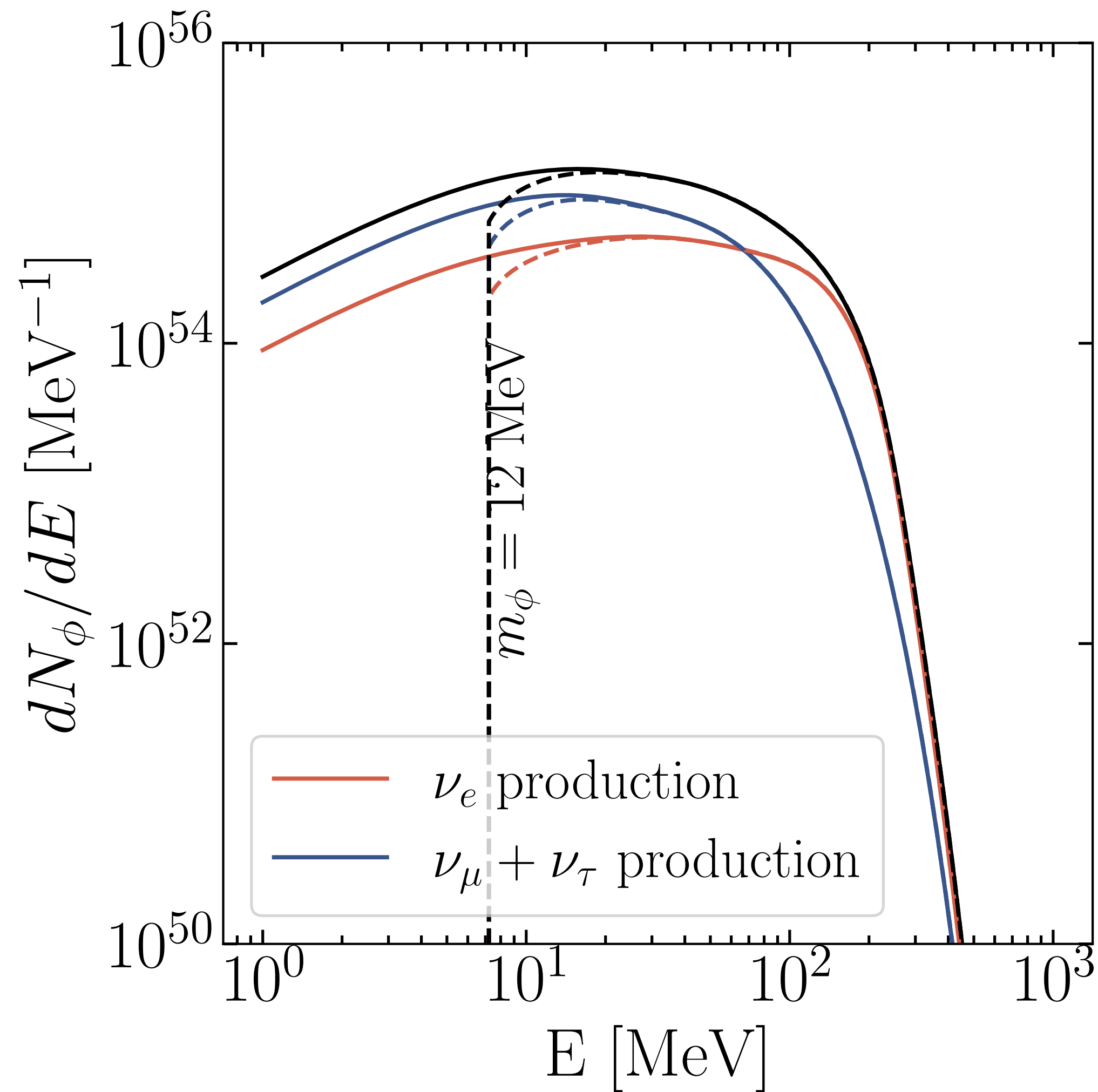
# Majoron production

For small masses, signal depends only on  $gm_\phi$

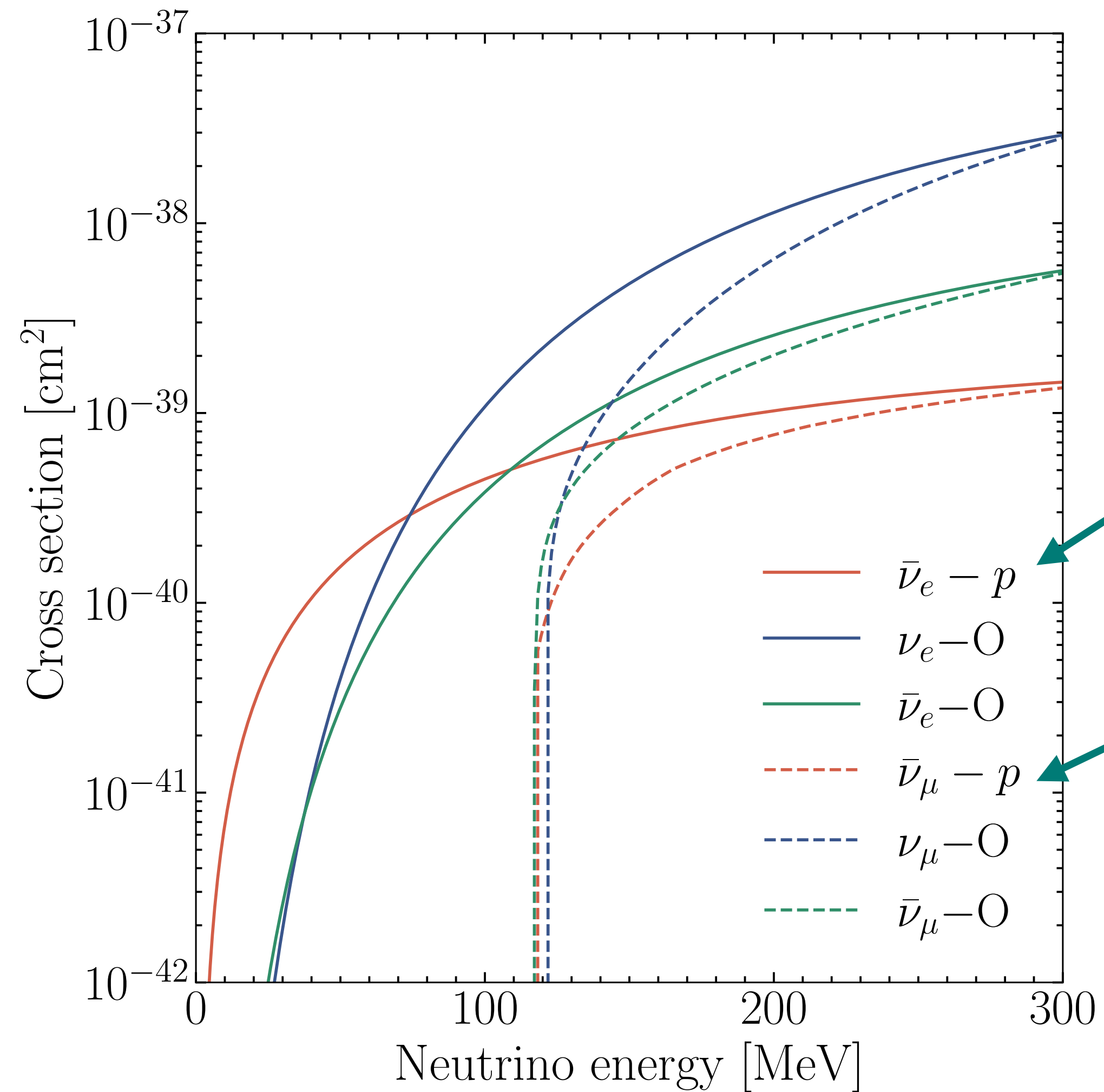
$$\frac{dN_\phi}{dt} = \frac{(gm_\phi)^2 \mu_\nu^2}{192\pi^3}$$



# Majoron production



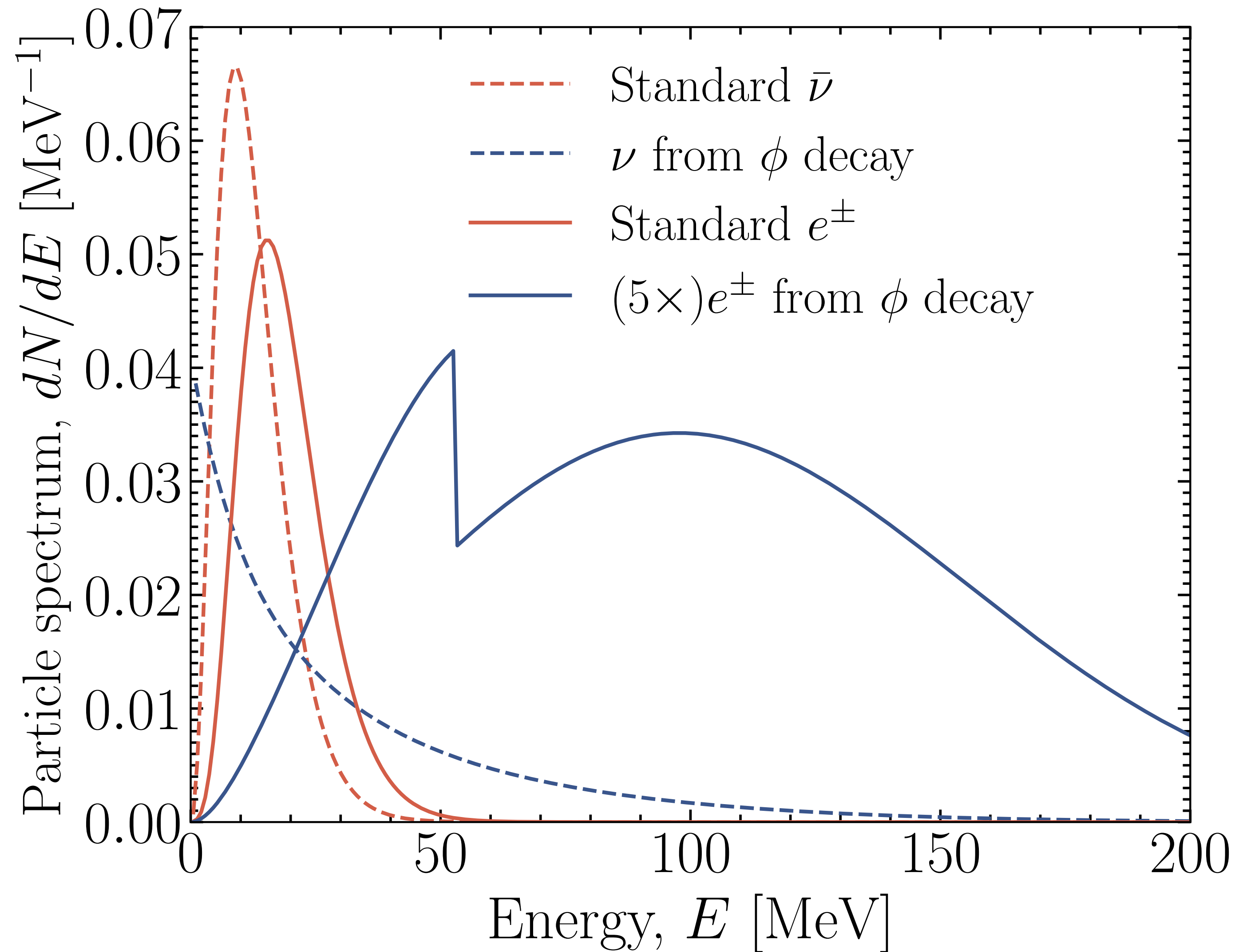
# Neutrino detection



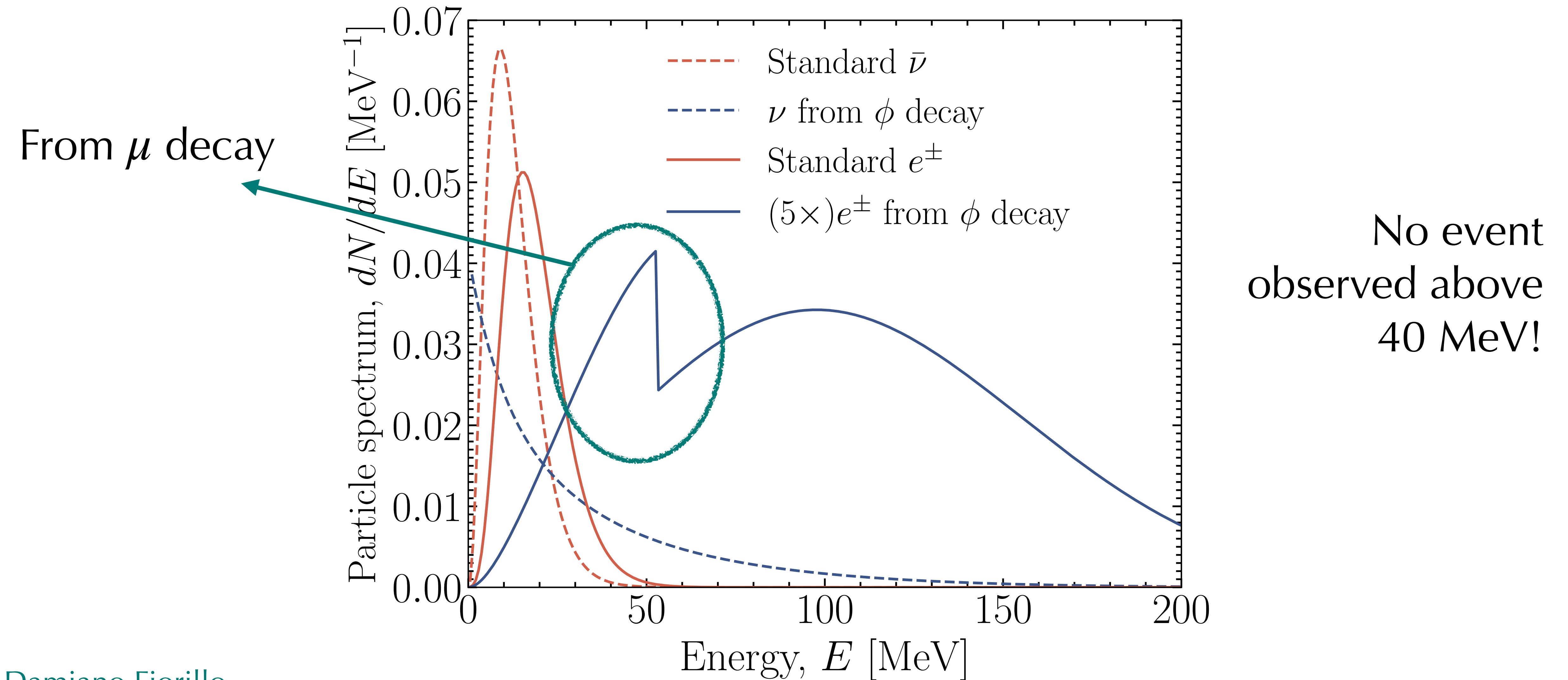
Appearing as  $e^\pm$  Cherenkov signal

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

# Neutrino signal



# Neutrino signal





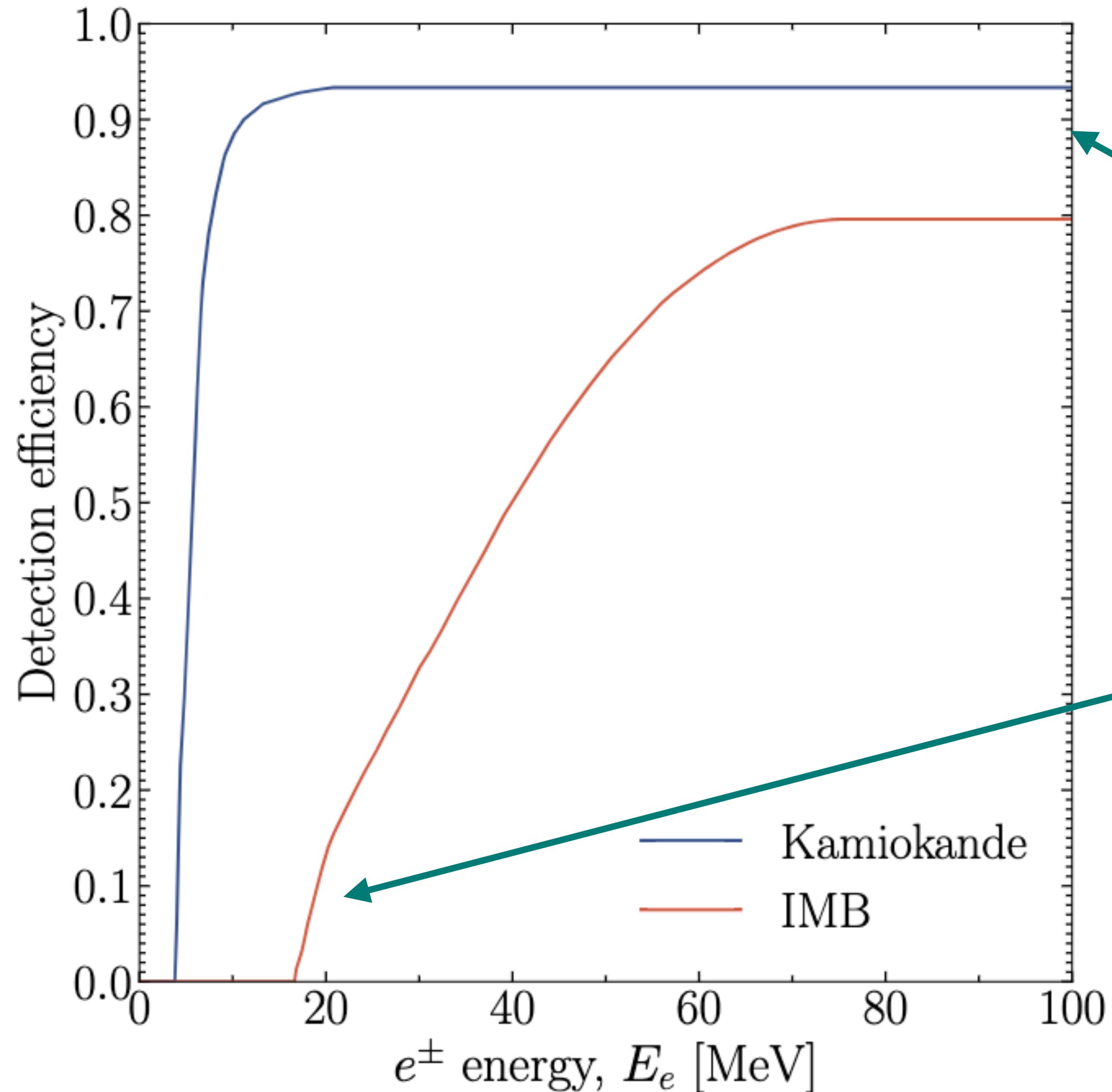
# Statistical analysis

- ◆ 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

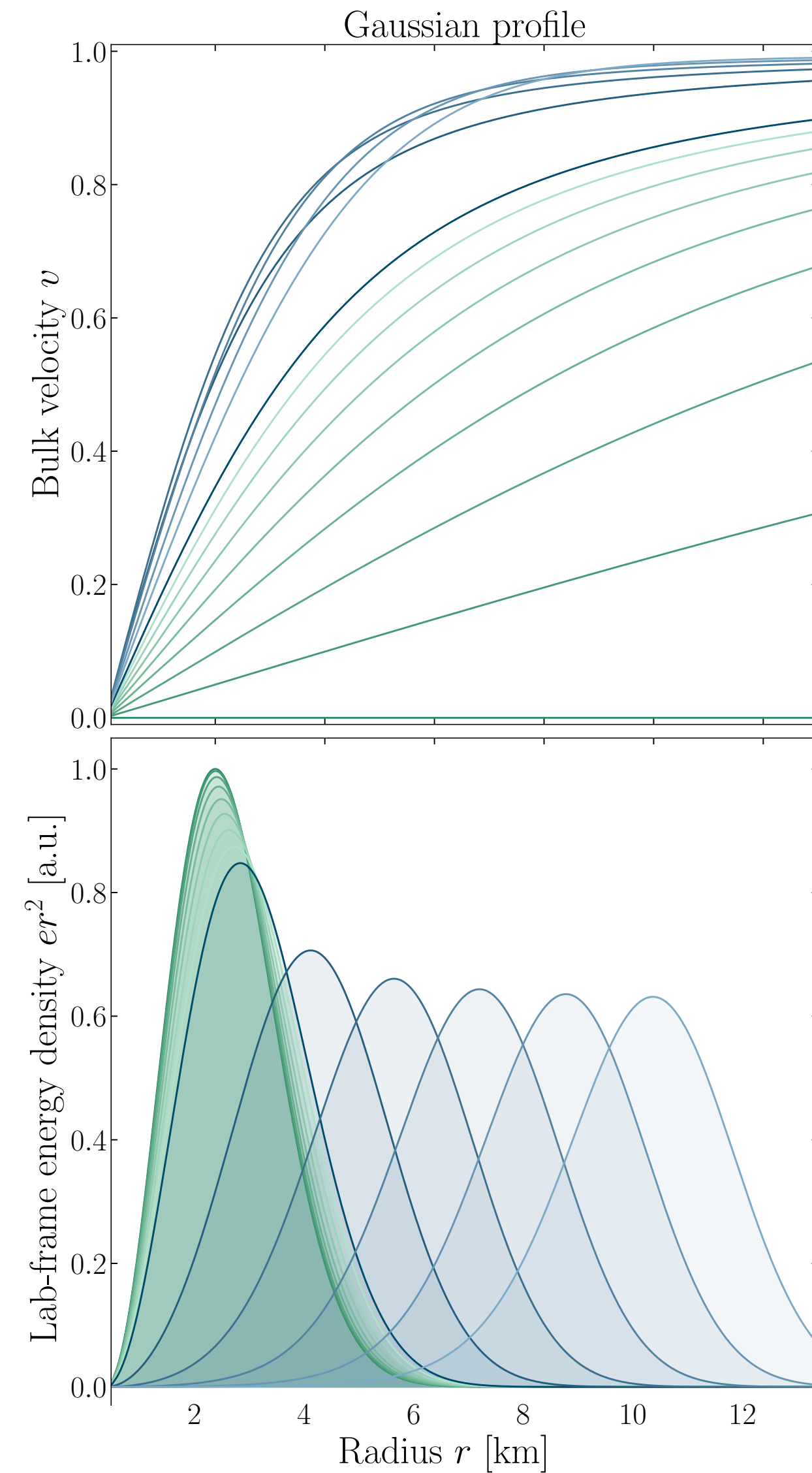
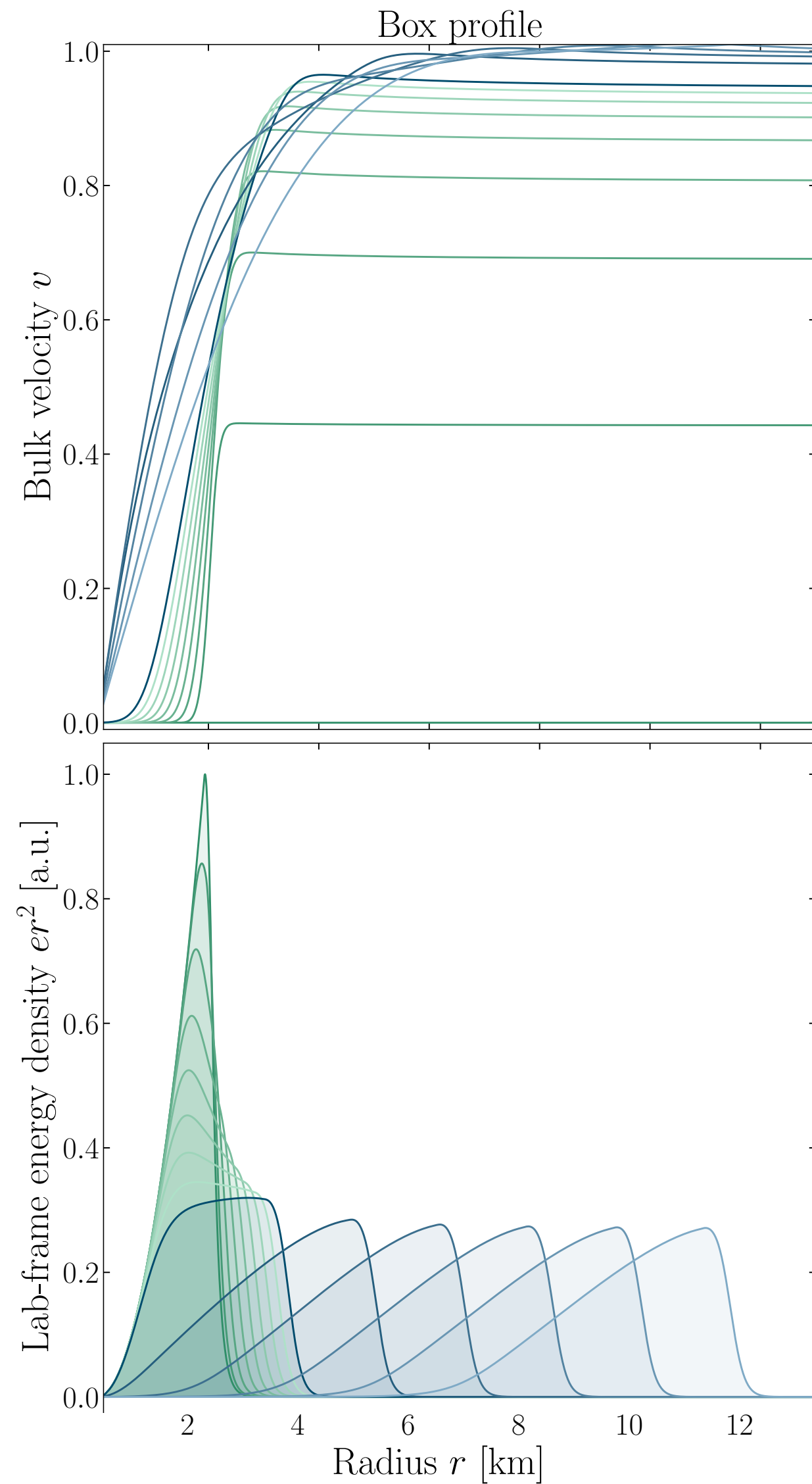


Comparable efficiencies at high energies, but IMB has larger volume

Few low-energy events at IMB

Above 75 MeV no events observed (private communication)

# Fireball formation vs. burst outflow



# Fireball formation vs. burst outflow

## Hydrodynamic free expansion of a localized relativistic plasma

P. Vitello

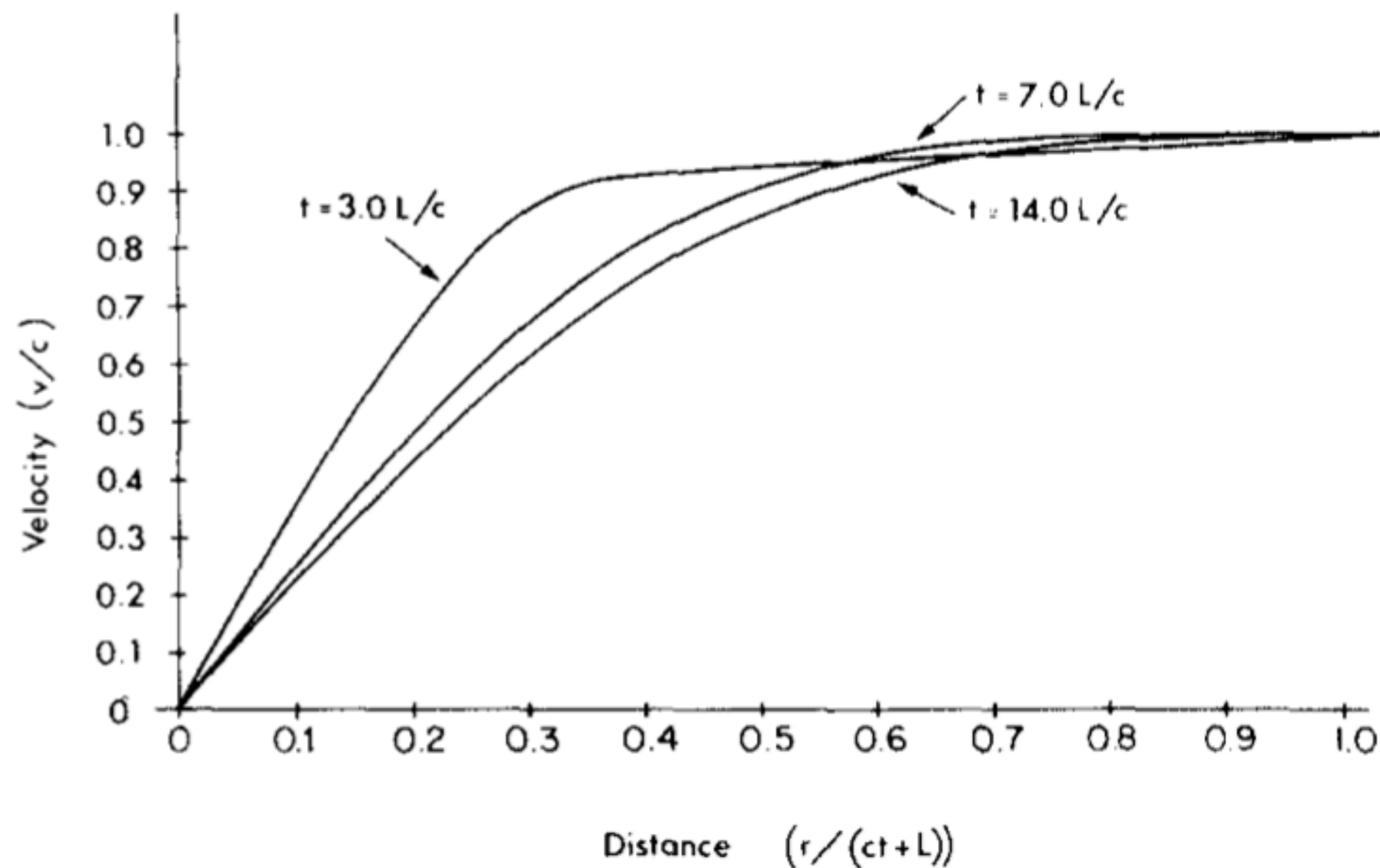
*Department of Physics, Cornell University, Ithaca, New York 14853*

M. Salvati

*Laboratoria Astrofisica Spaziale, Frascati (Rome), Italy*

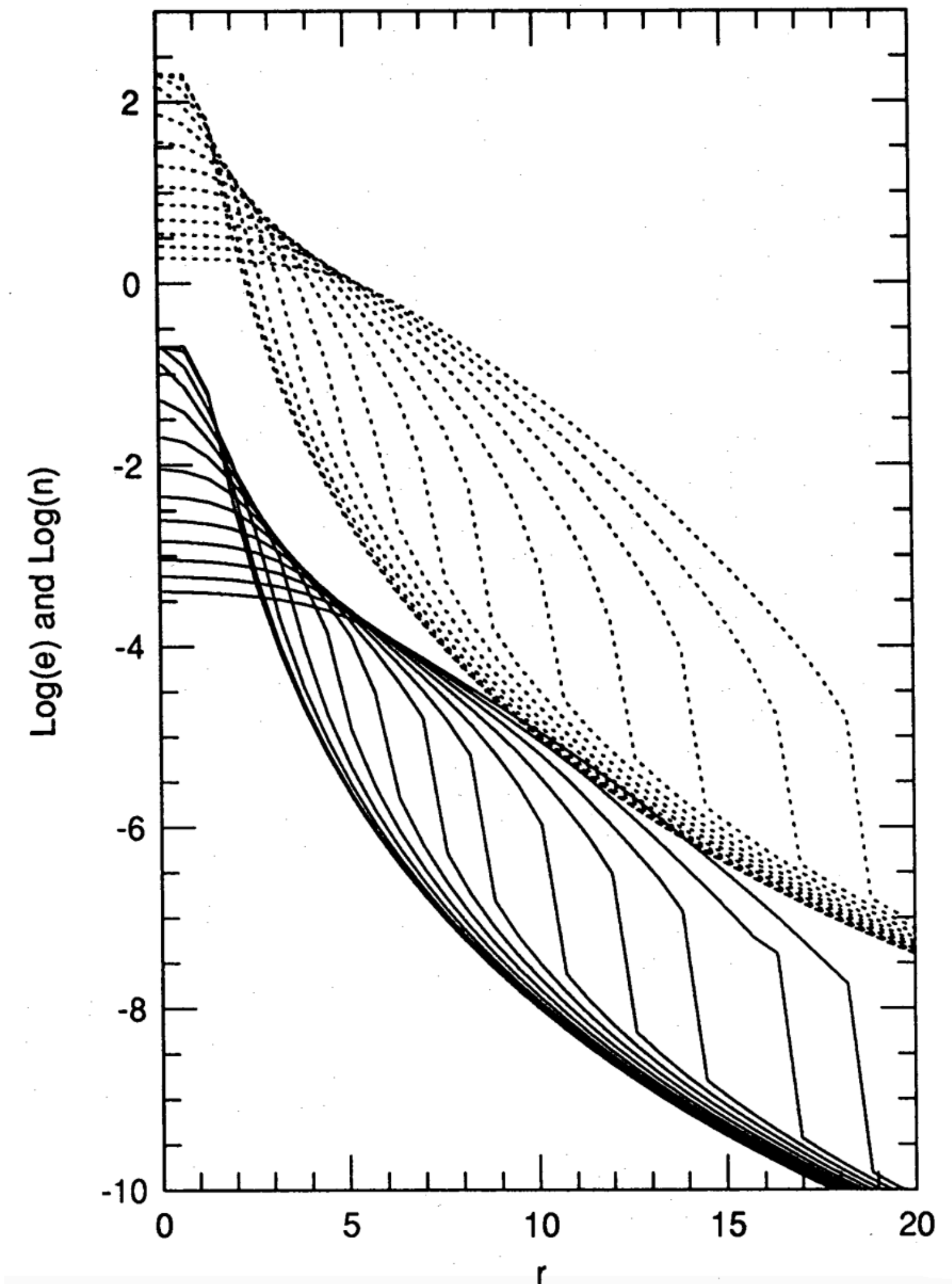
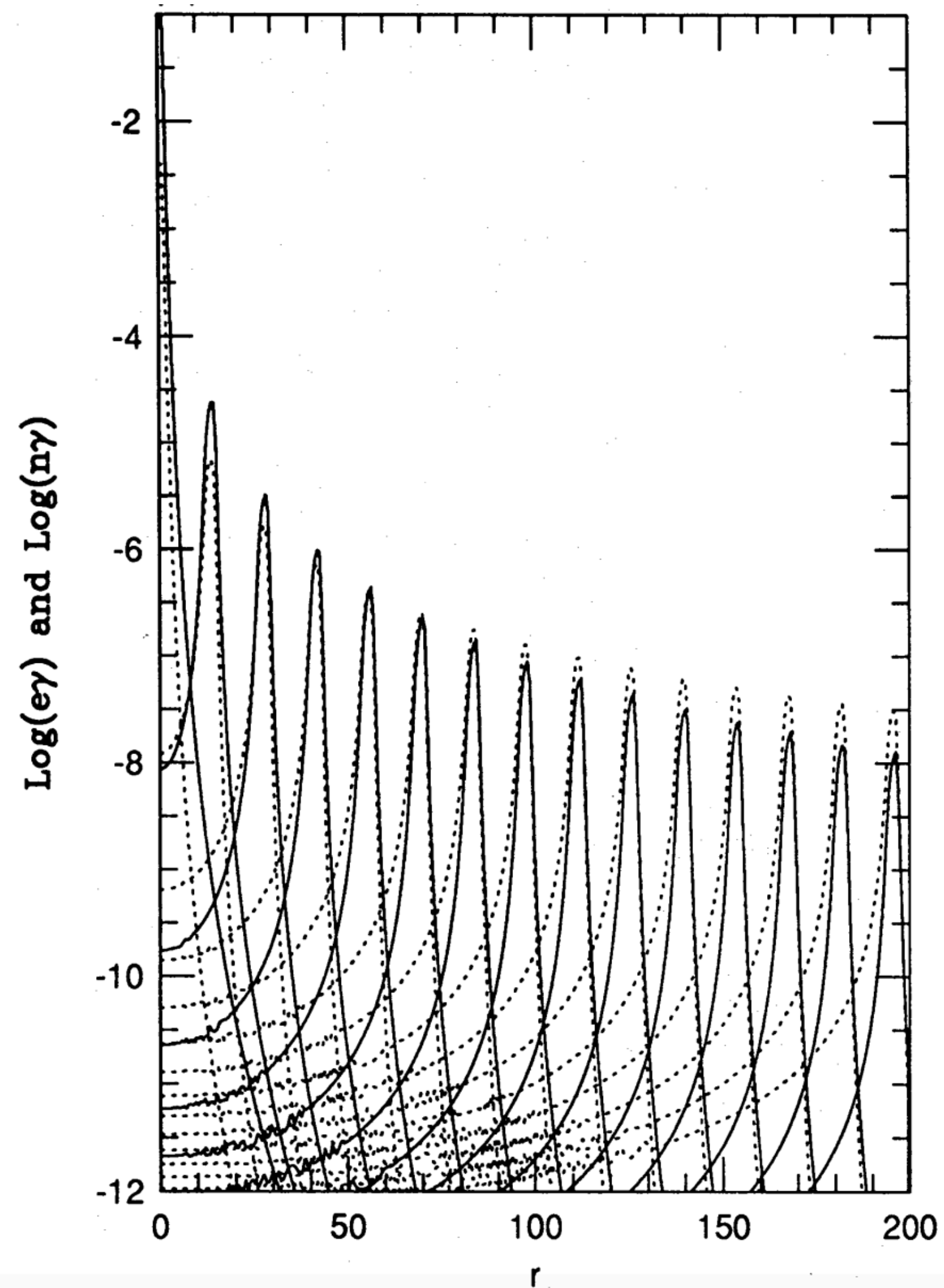
*(Received 22 December 1975; final manuscript received 11 June 1976)*

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.



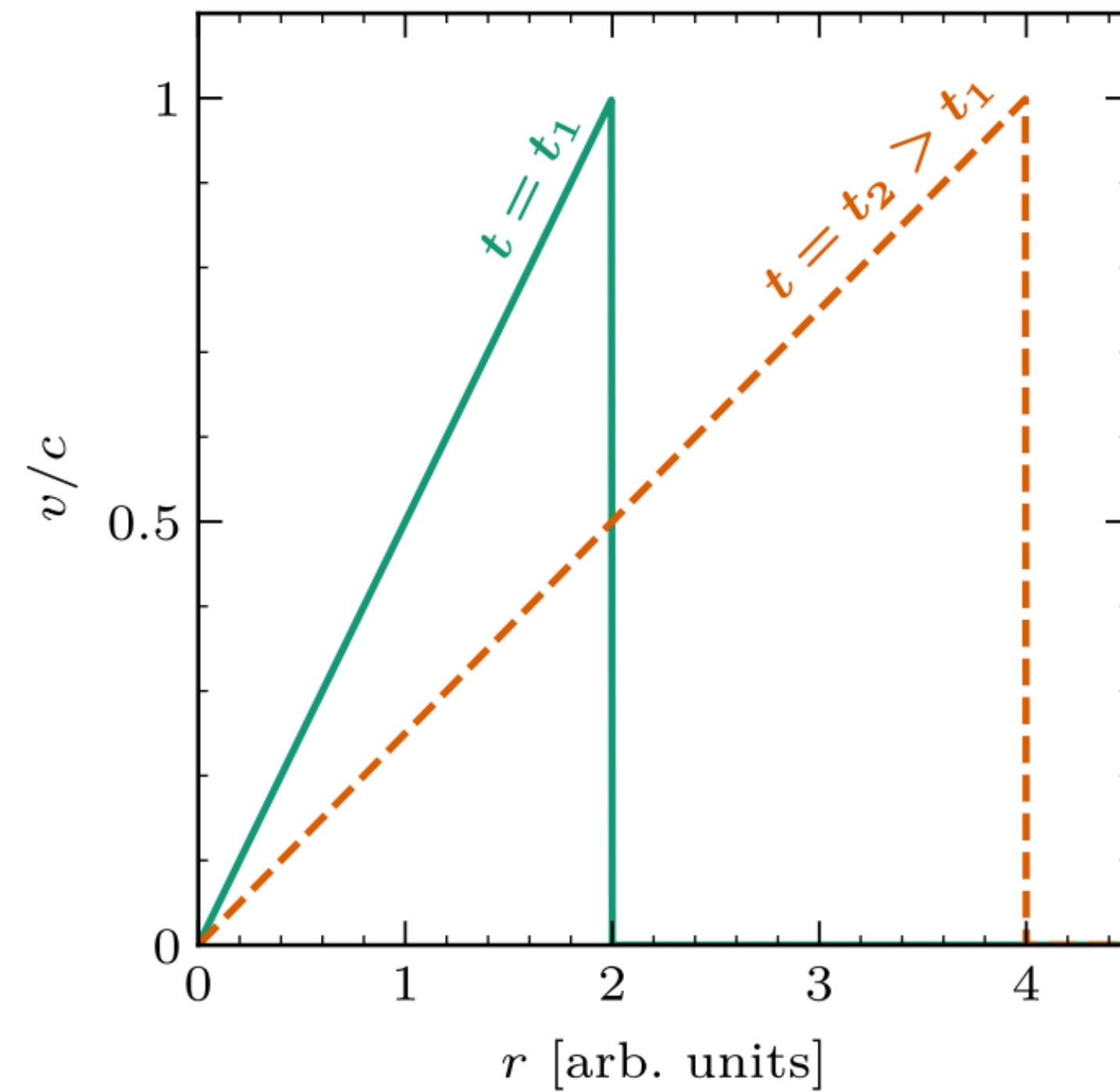
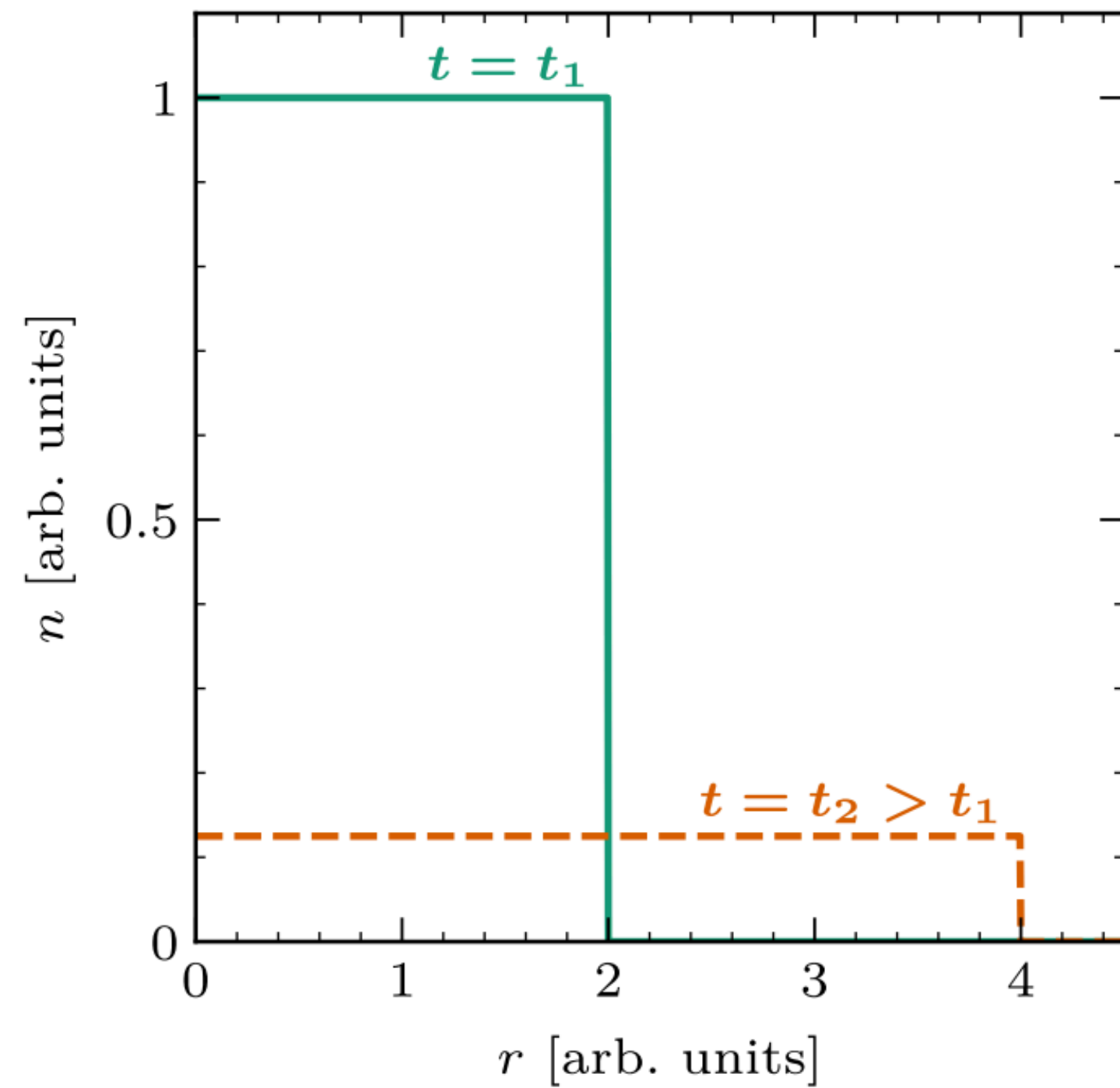
The result is that nearly all of the plasma moves outward at bulk velocities near the speed of light, as can be clearly seen in Figs. 8 and 9, producing a shell of nearly constant thickness.

# Fireball formation vs. burst outflow

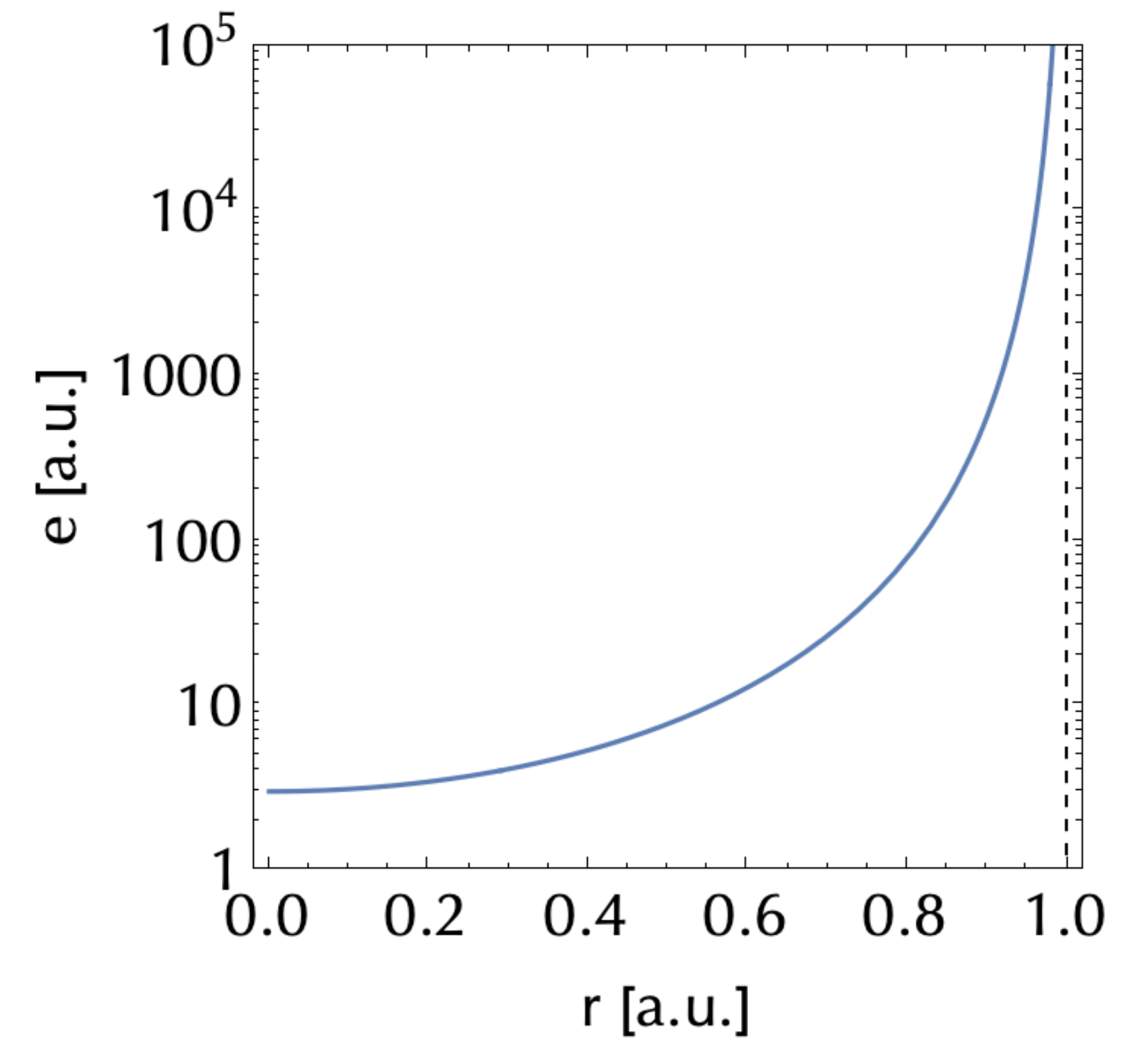
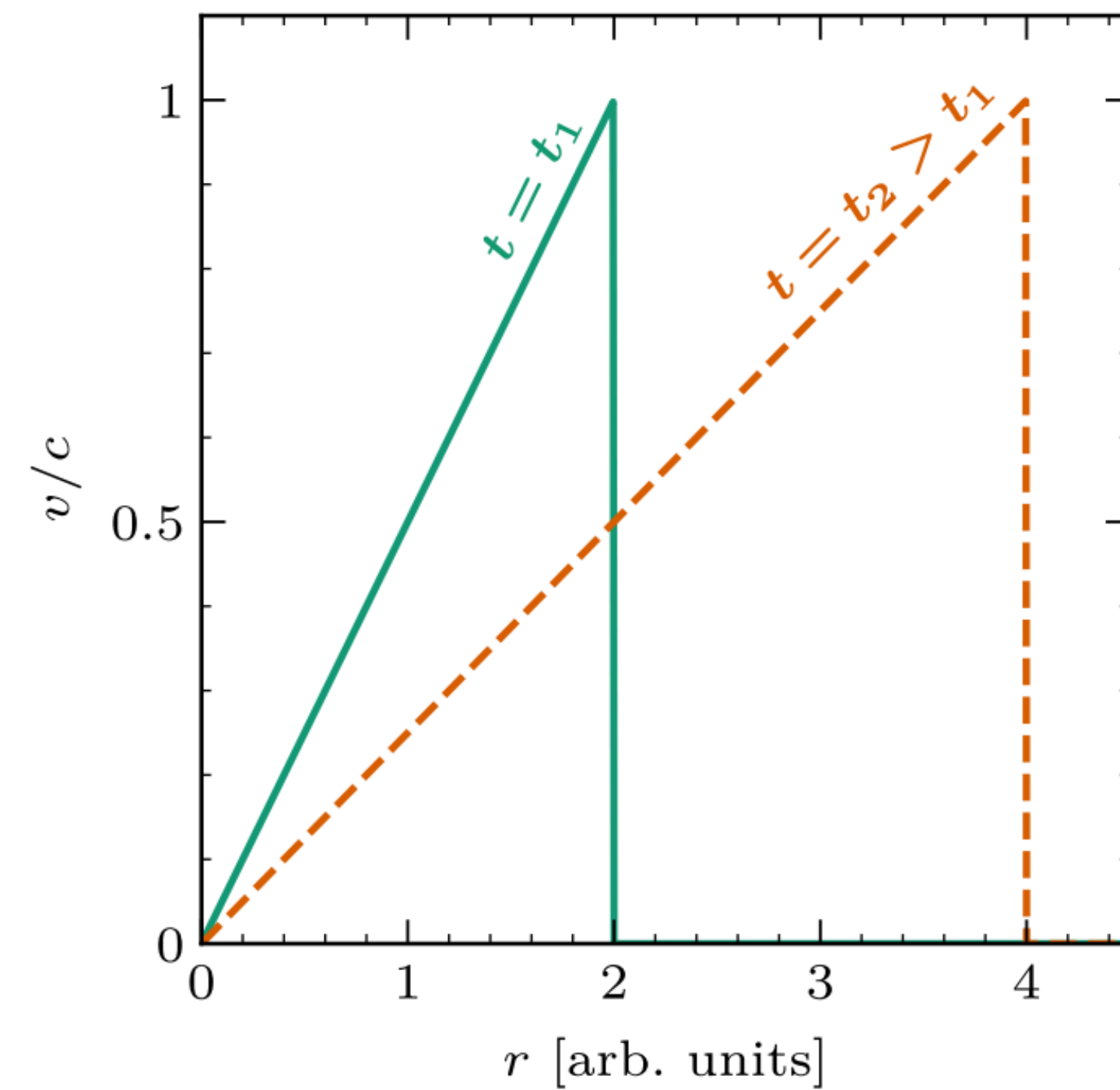
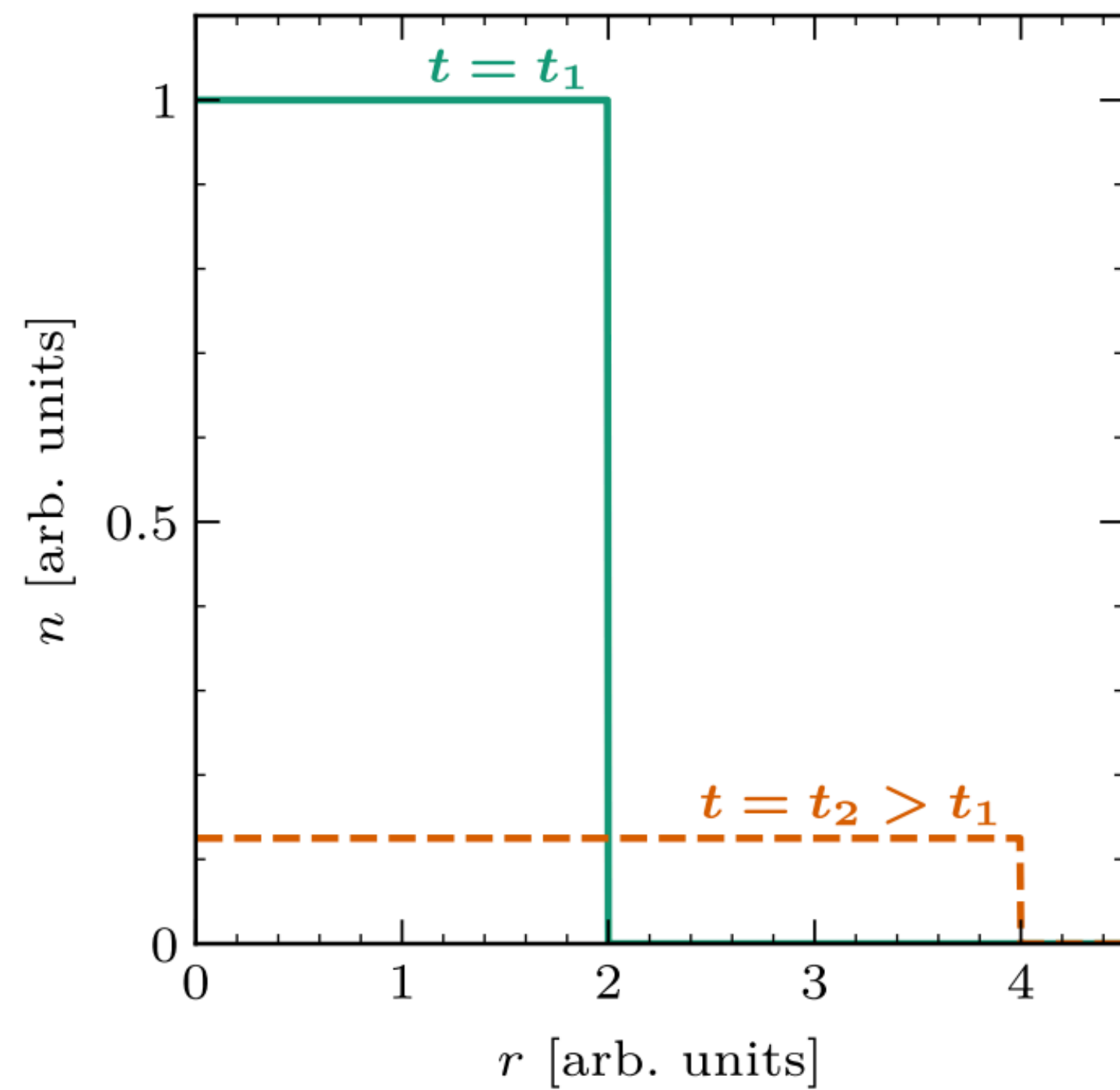


Piran et al., arXiv:9301004

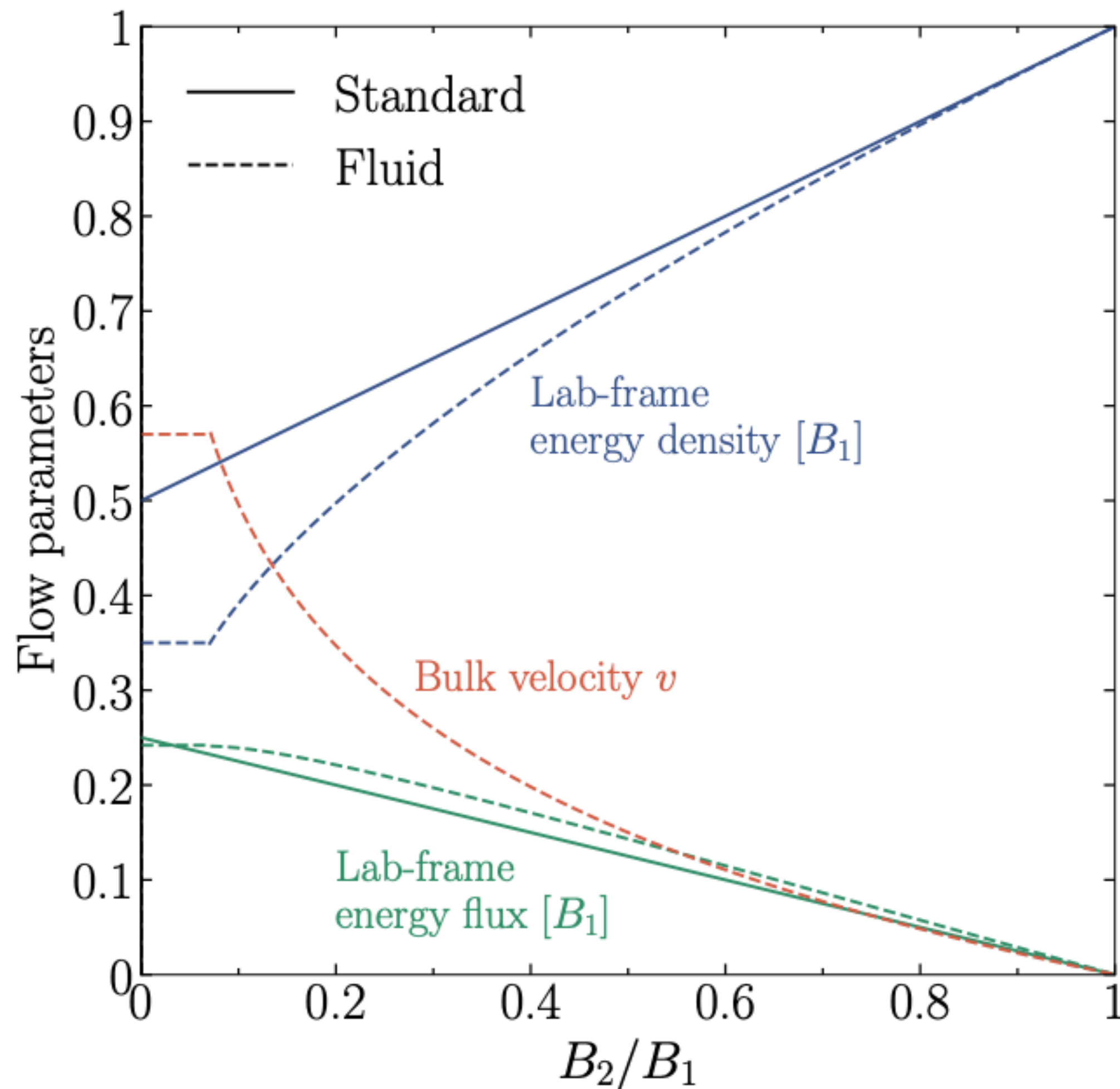
# Burst outflow - analytical solution



# Burst outflow - analytical solution



# Cooling time with $\nu SI$



- ◆ 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



# Spectrum with $\nu SI$

