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# MeV $\nu$-astronomy: Challenges and Opportunities

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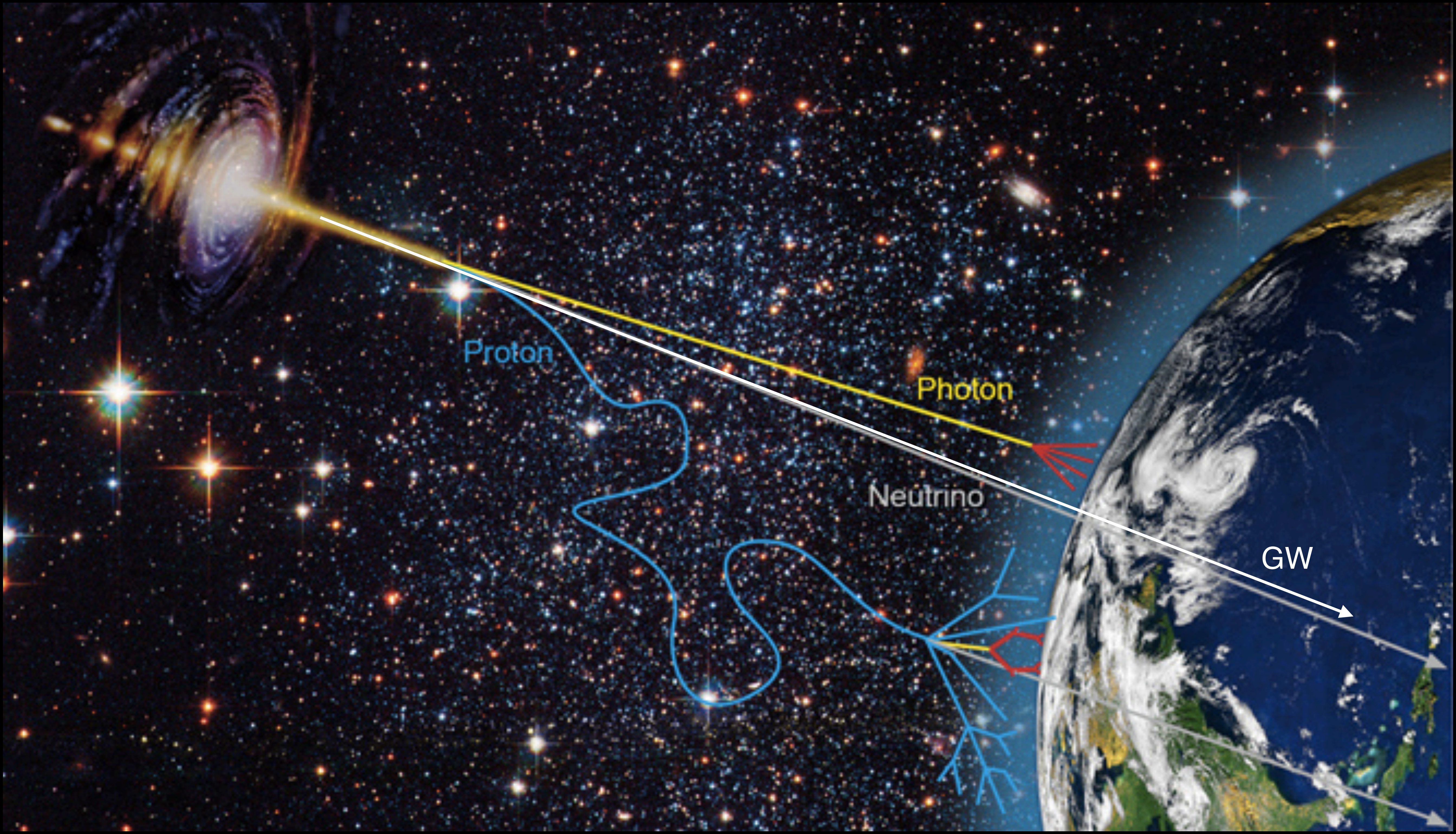
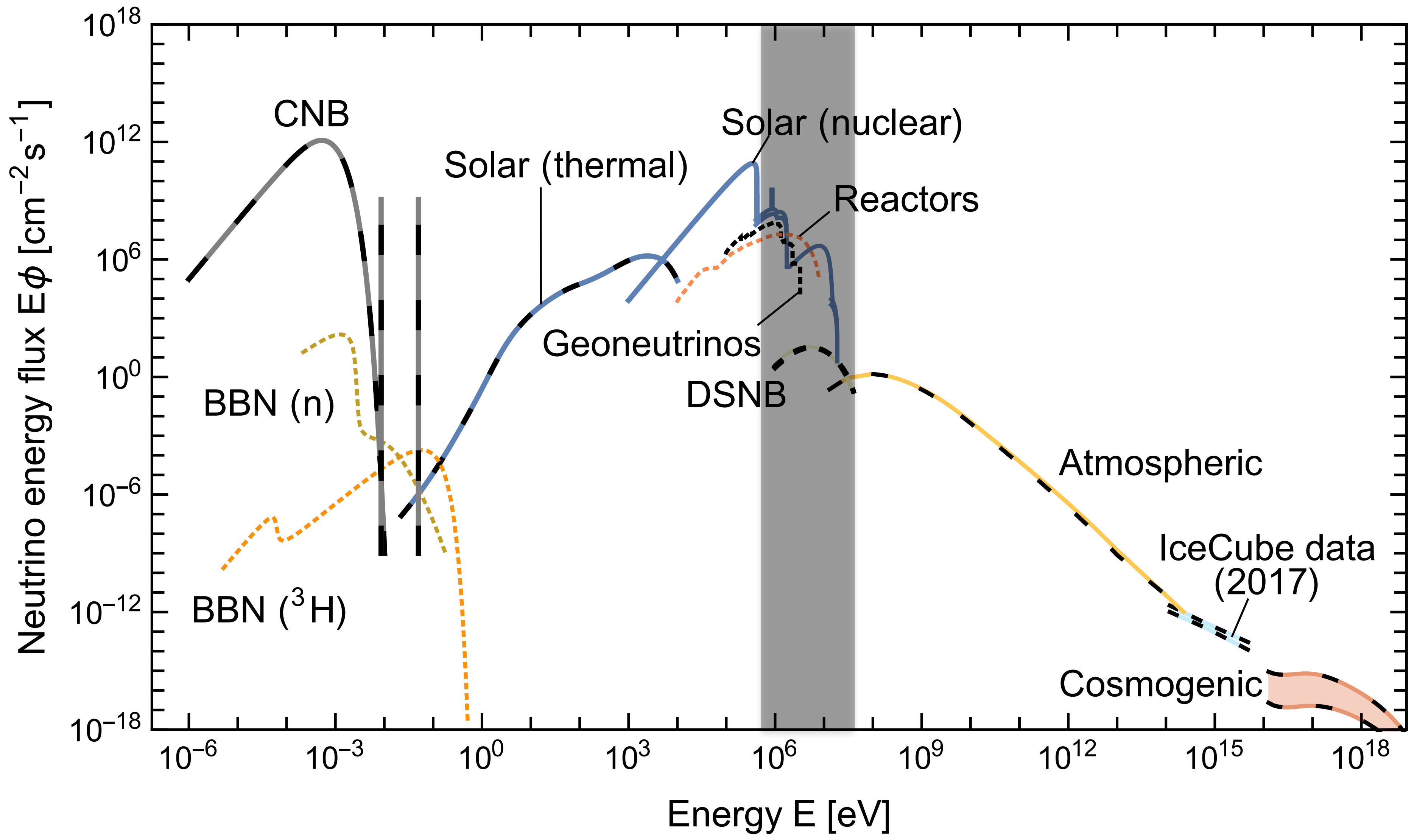
# $\nu$-Astronomy



# $\nu$-Astronomy

Plenty of sources available

Vitagliano, Tamborra, Raffelt, Rev. Mod. Phys. 92 (2020), 45006

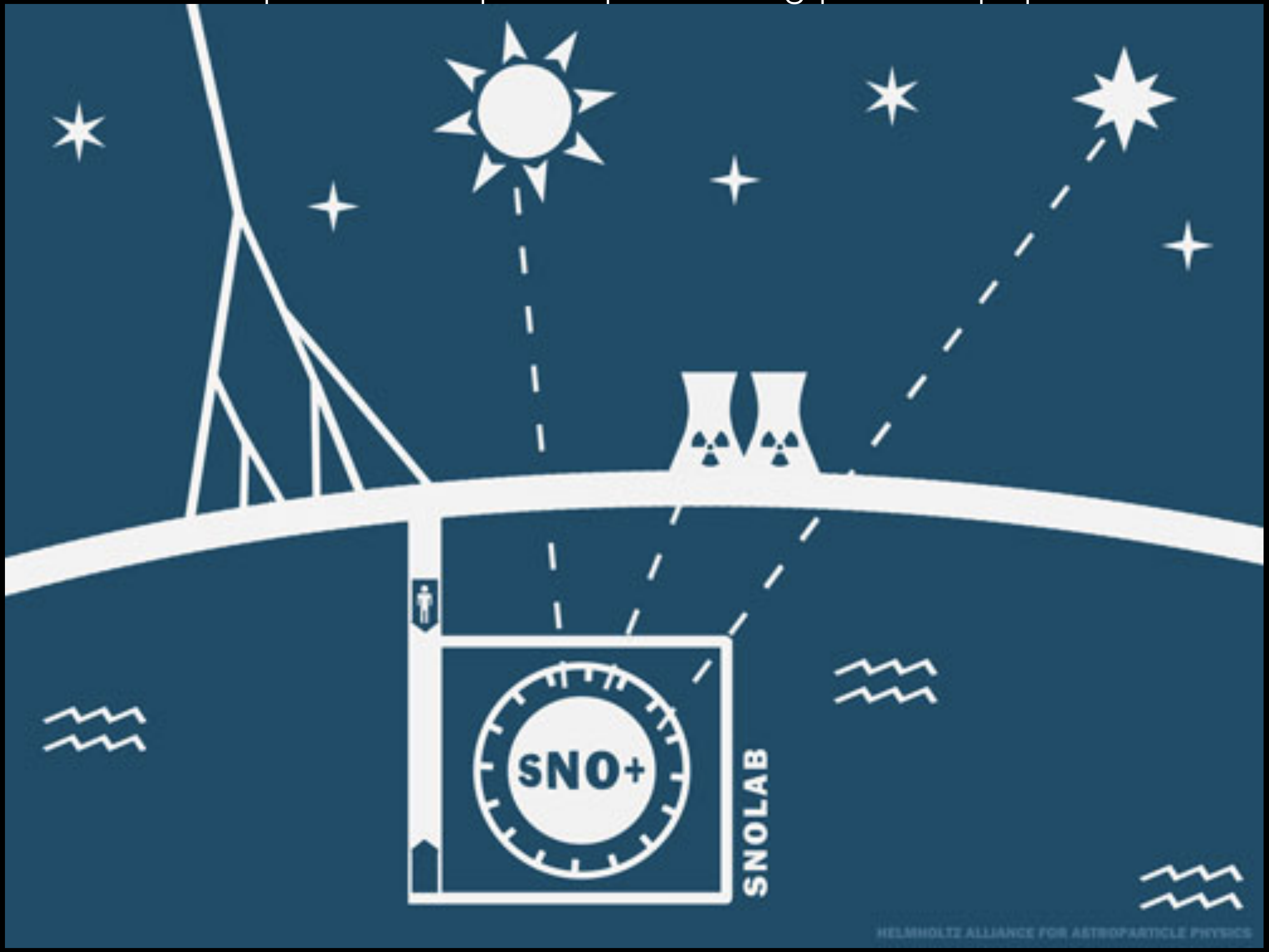


Here we only focus on MeV neutrinos

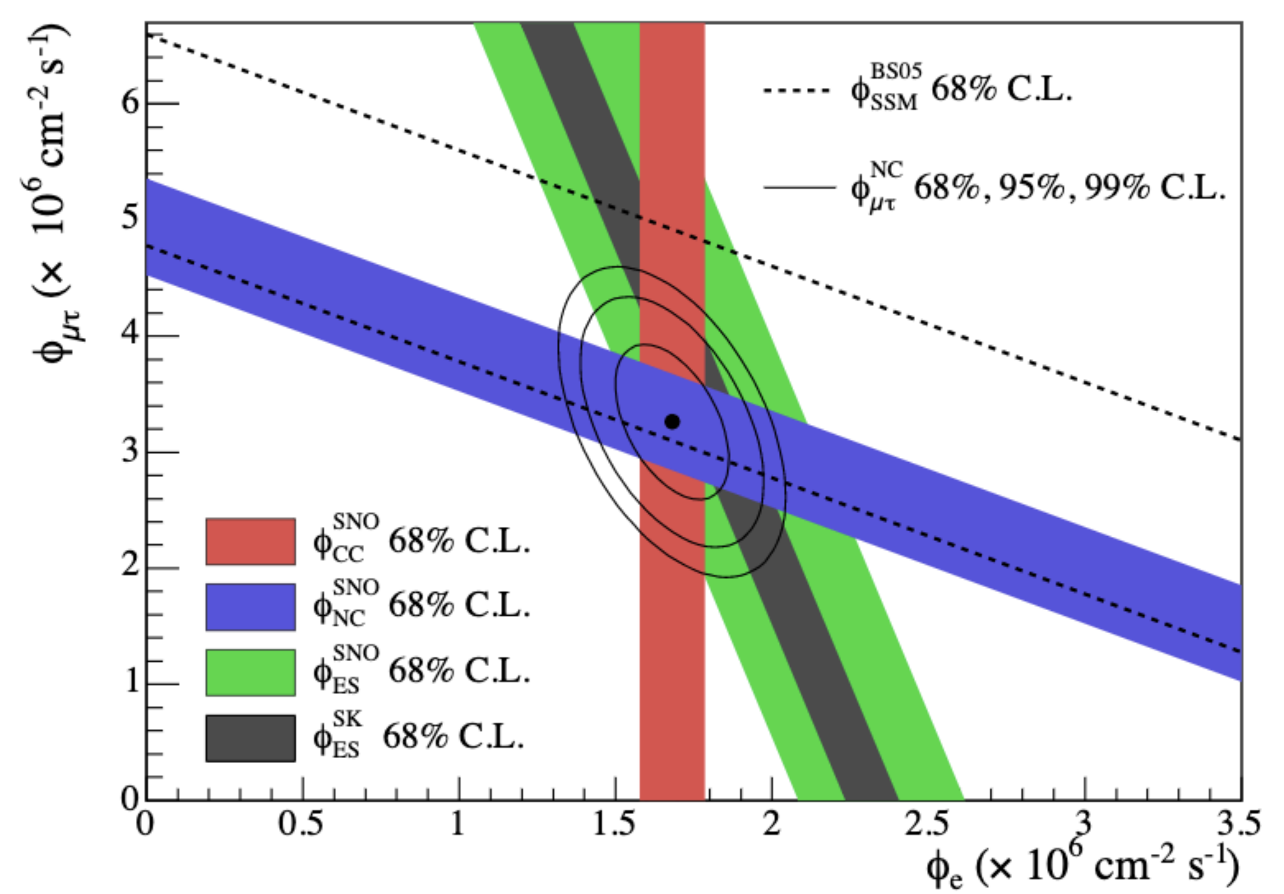
# MeV $\nu$-Astronomy: the past

Confirmation of neutrino oscillations and standard solar model

Helmholtz Alliance for Astroparticle Physics, https://www.hap-astroparticle.org/poPAHrt.php



Aharmim et al. [SNO], Phys. Rev. C 72 (2005), 055502

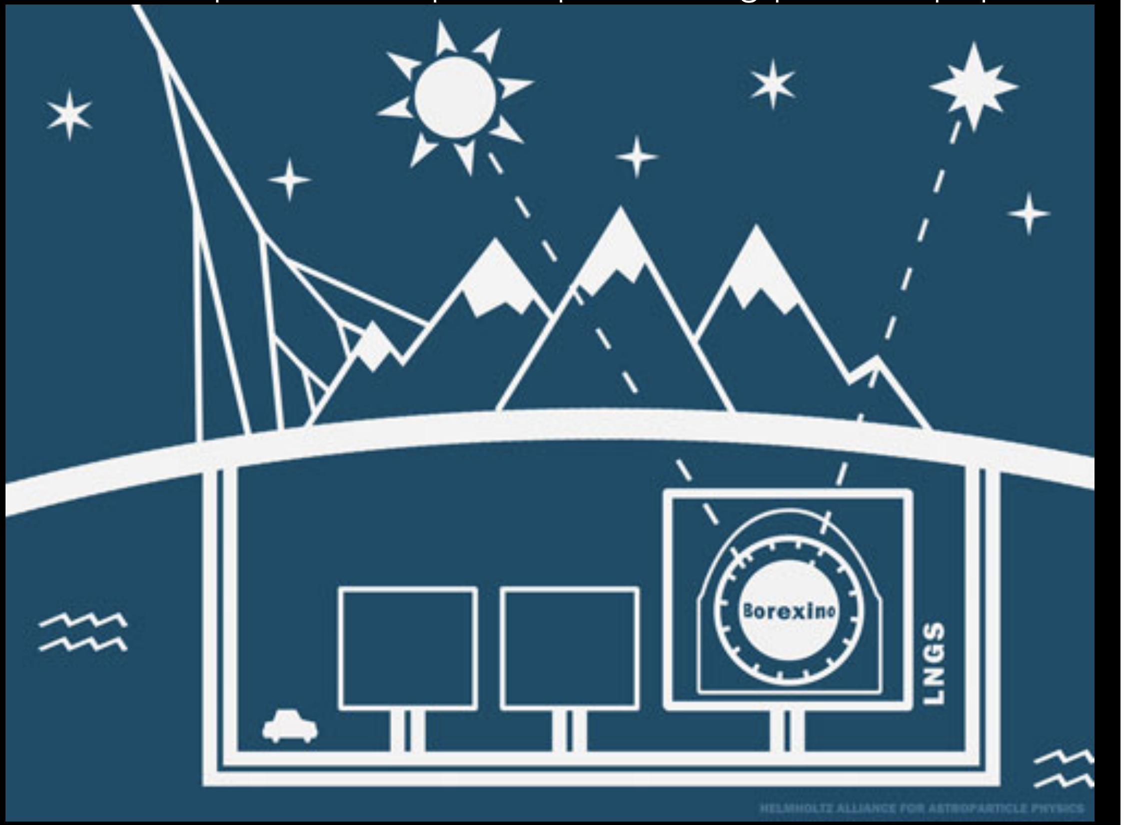


Interplay between particle and astro-particle physics

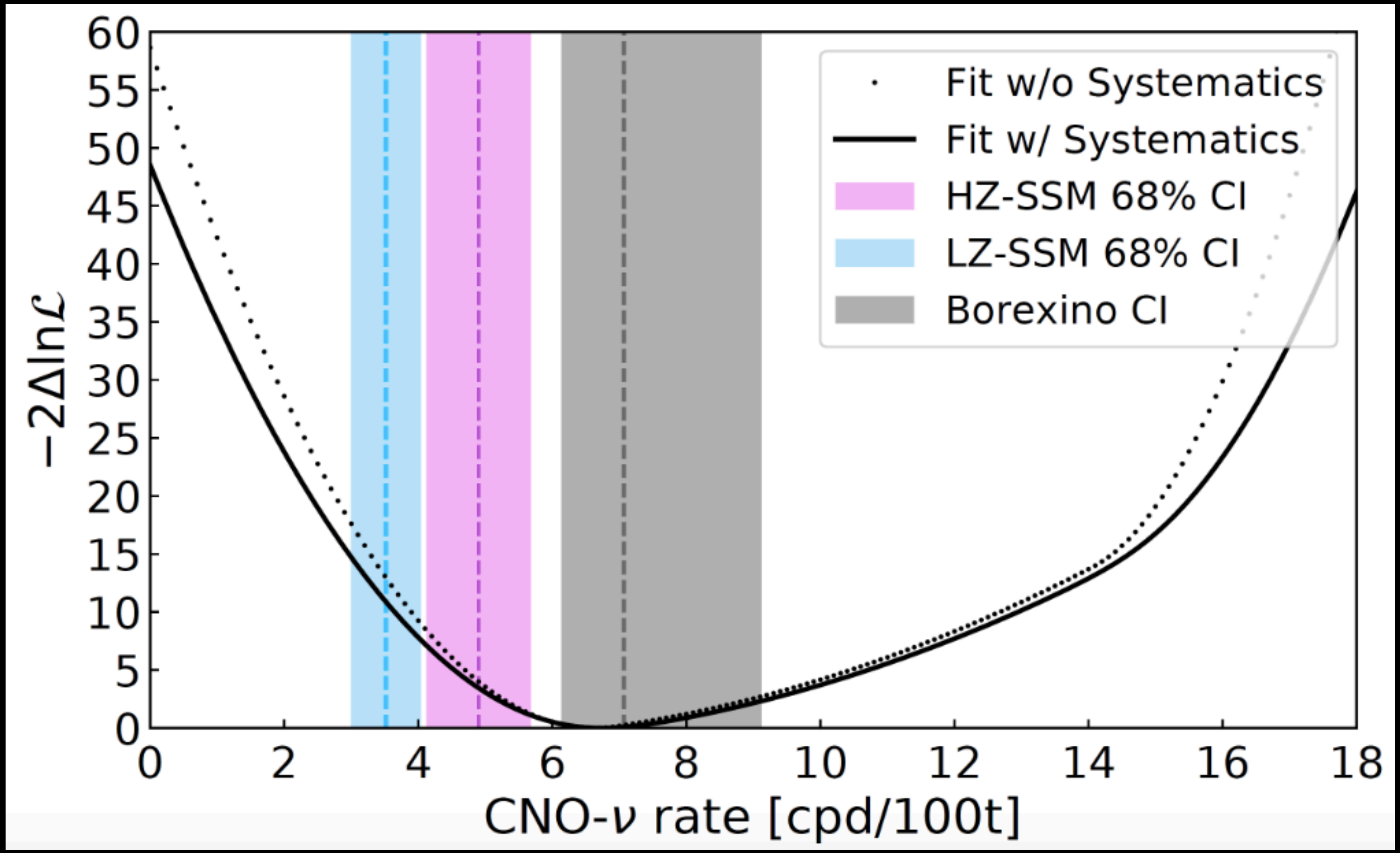
# MeV $\nu$-Astronomy: the past

First experimental evidence for CNO solar neutrinos

Helmholtz Alliance for Astroparticle Physics,
https://www.hap-astroparticle.org/poPAHrt.php



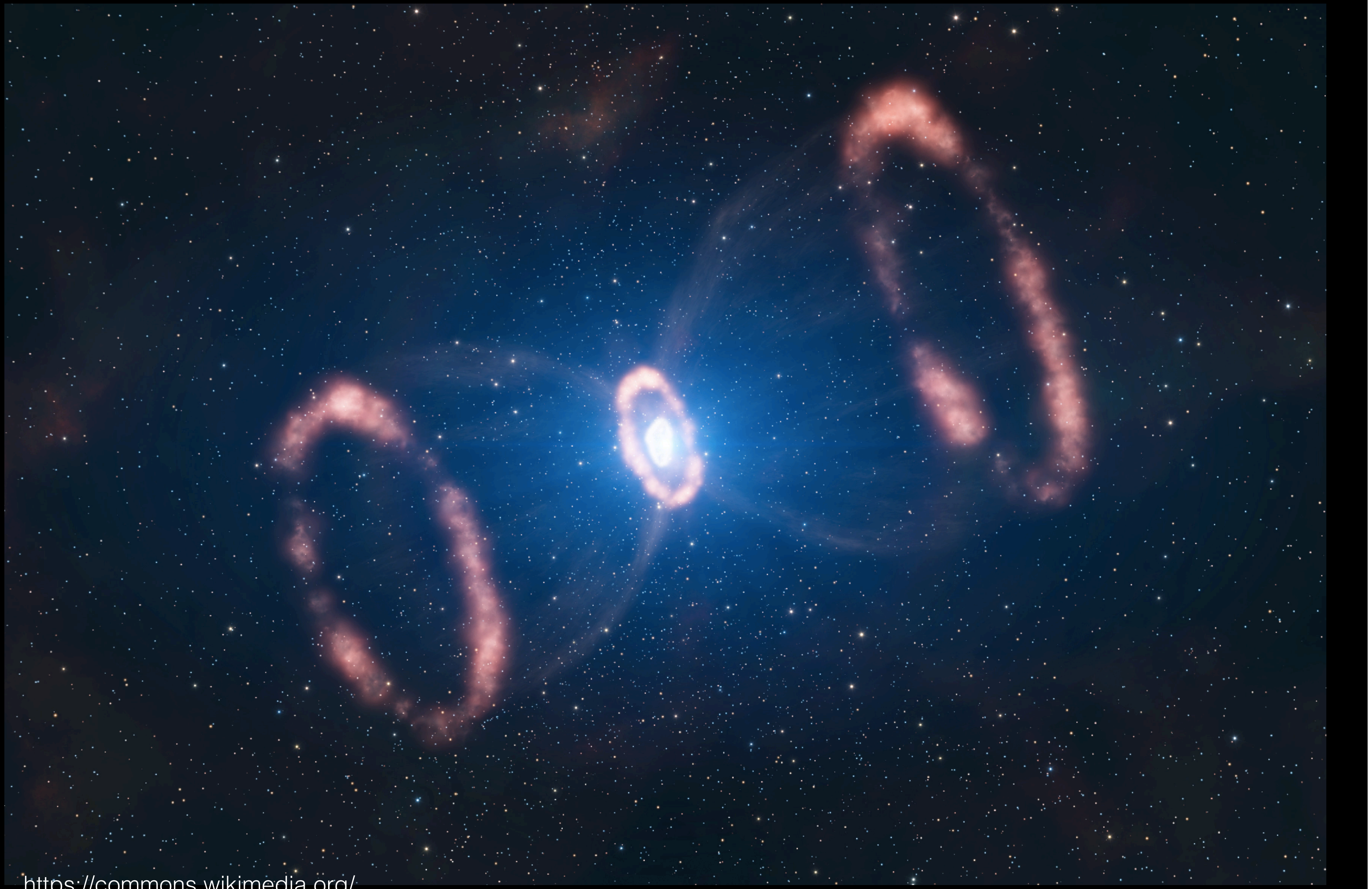
B. Caccianiga talk at Neutrino 2022



Interplay between particle and astro-particle physics

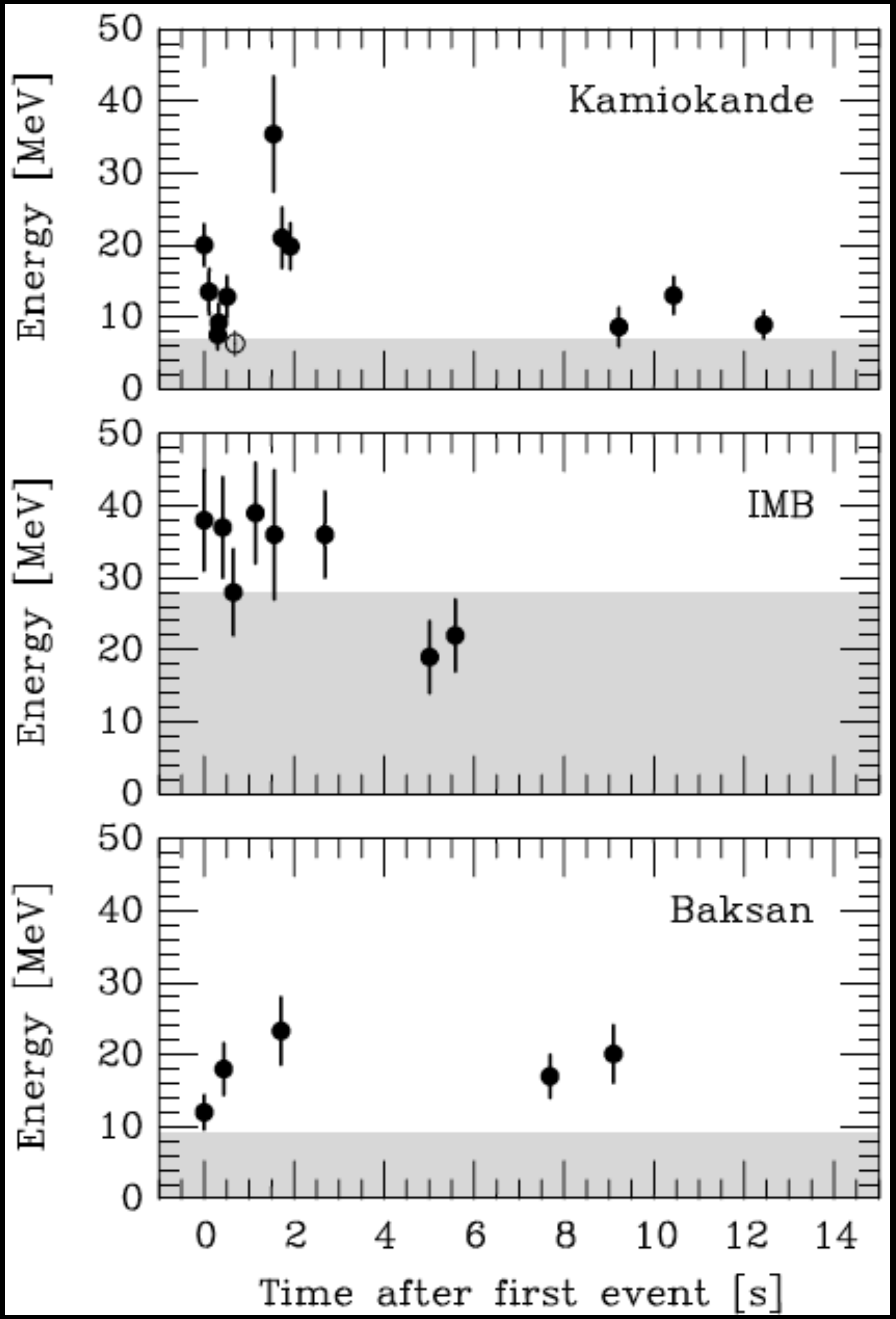
# MeV $\nu$-Astronomy: the past

SN1987a



https://commons.wikimedia.org/

Raffelt, Stars as Laboratories for Fundamental Physics



# MeV $\nu$-Astronomy: the future

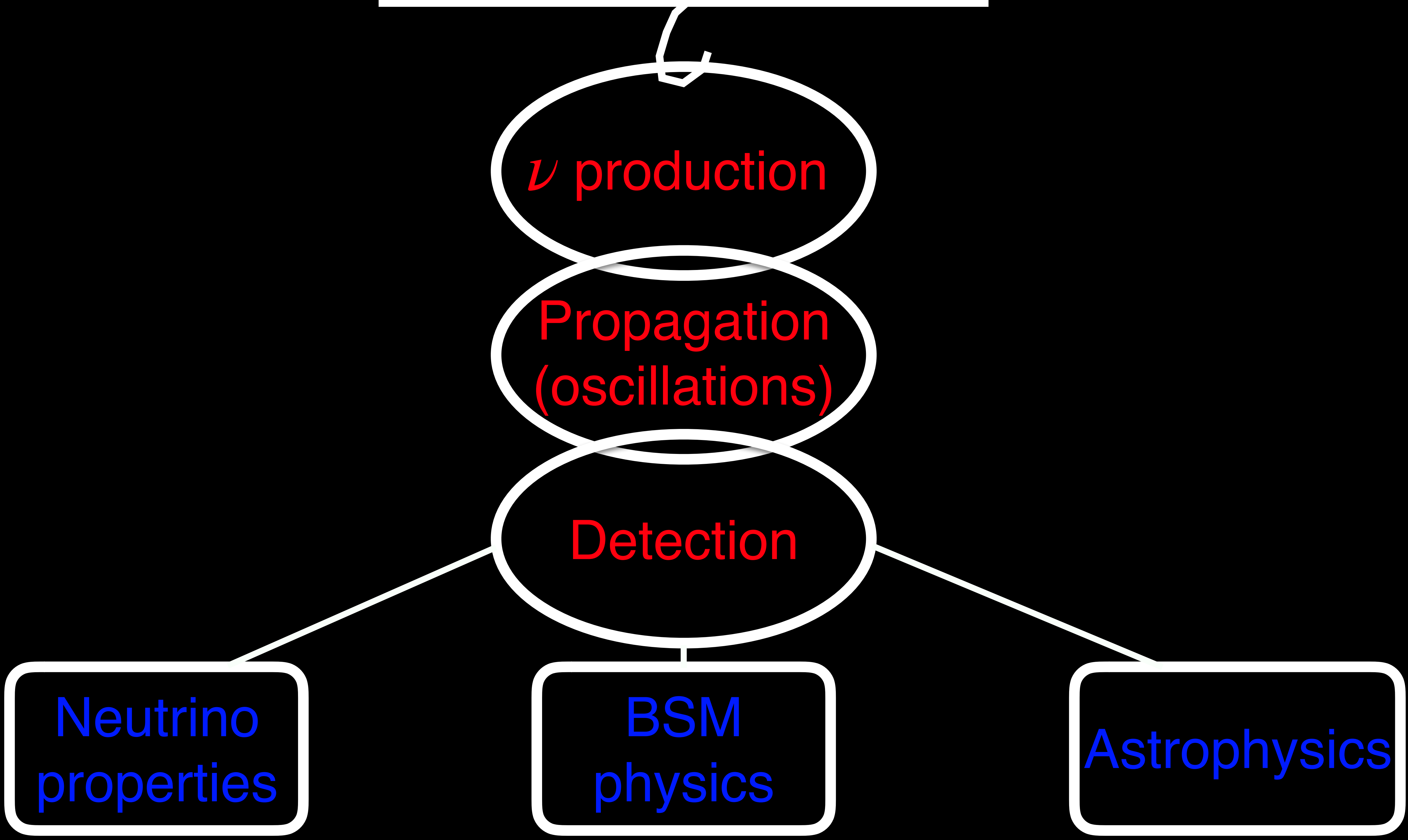
Neutrino properties

BSM physics

Astrophysics

# MeV $\nu$-Astronomy: the future

Each aspect **MUST** be well understood



$\nu$ production

Propagation (oscillations)

Detection

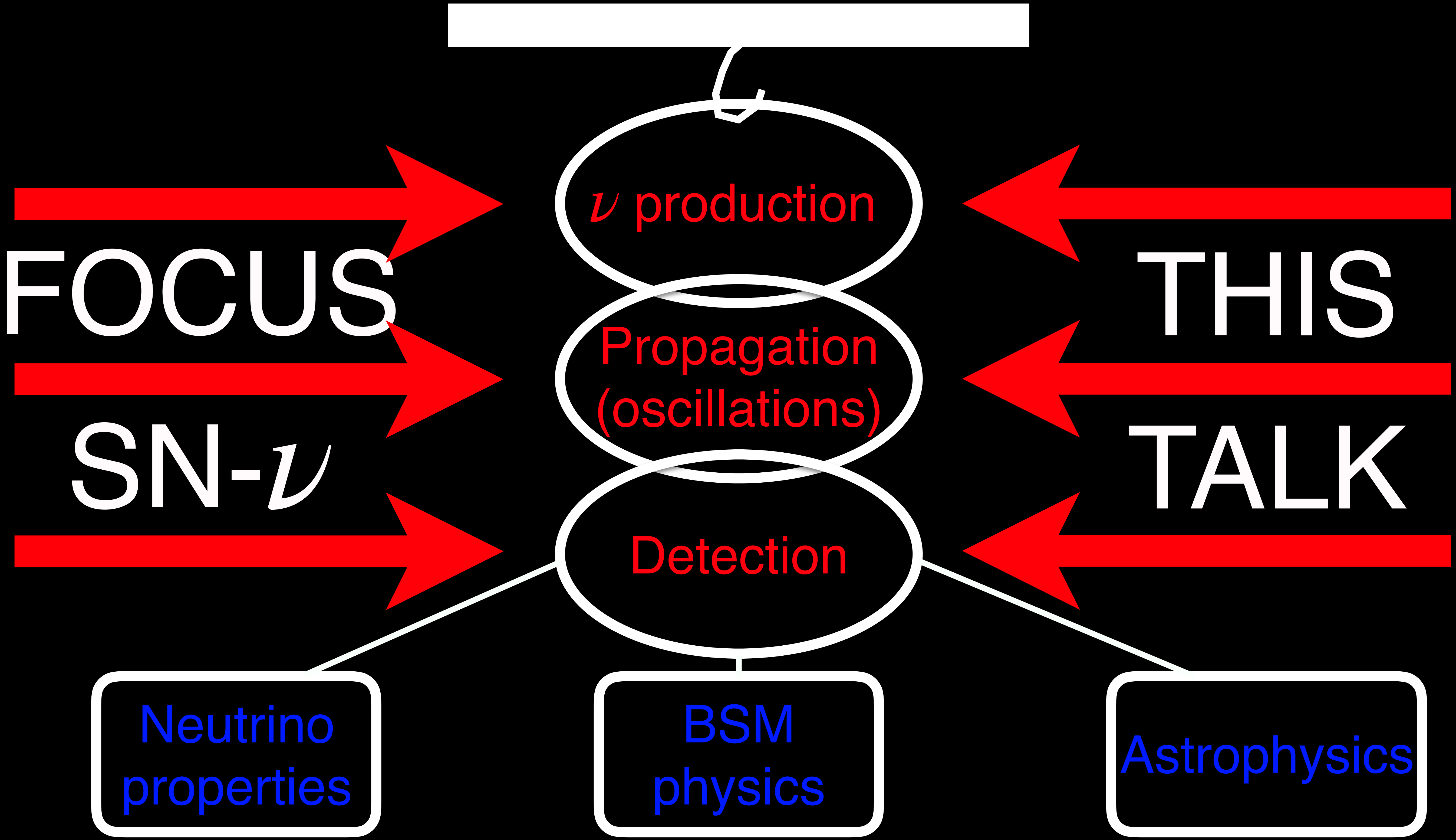
Neutrino properties

BSM physics

Astrophysics

# MeV $\nu$-Astronomy: the future

Each aspect **MUST** be well understood



FOCUS SN-$\nu$

THIS TALK

$\nu$ production

Propagation (oscillations)

Detection

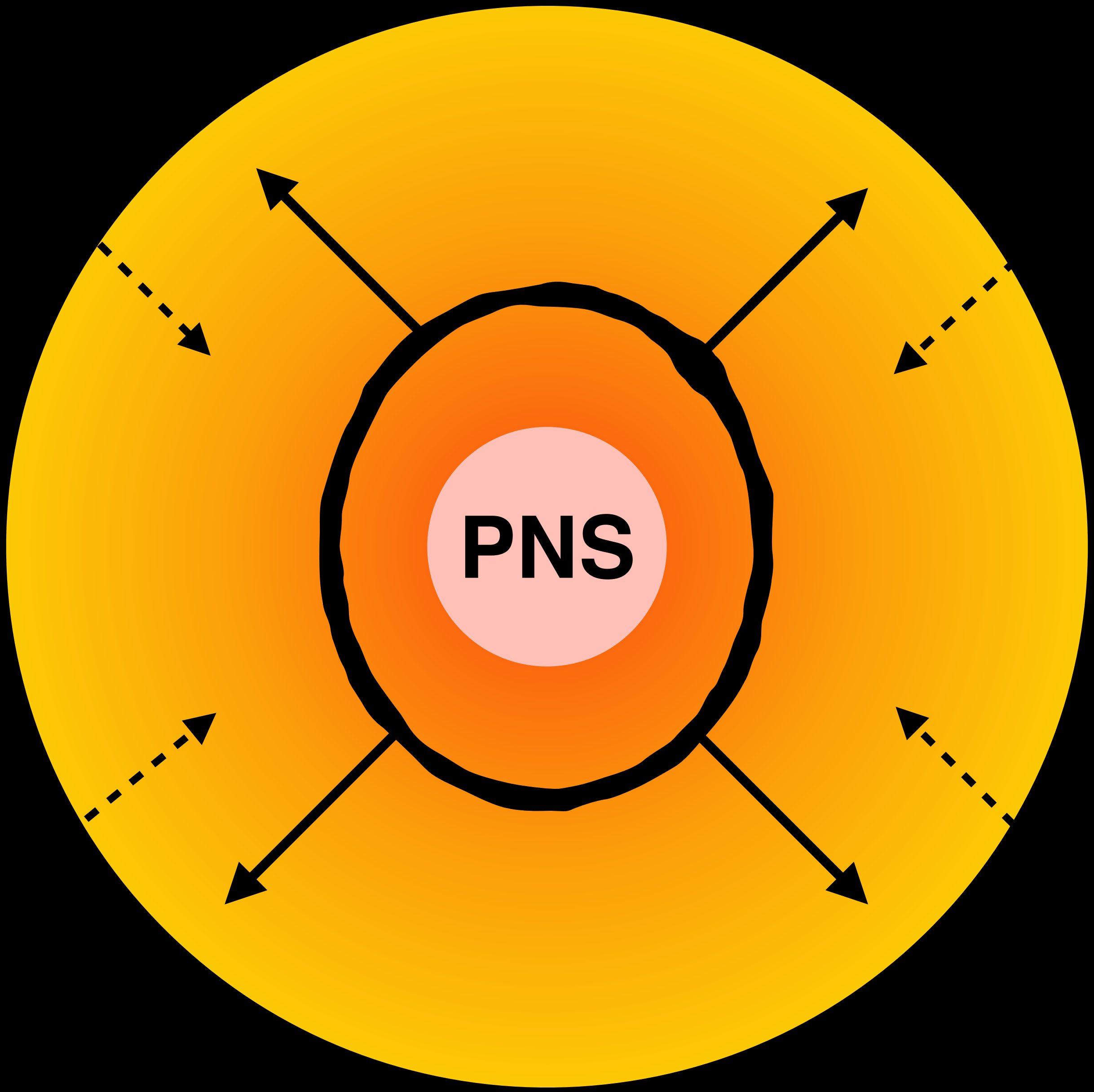
Neutrino properties

BSM physics

Astrophysics

# What are supernovae?

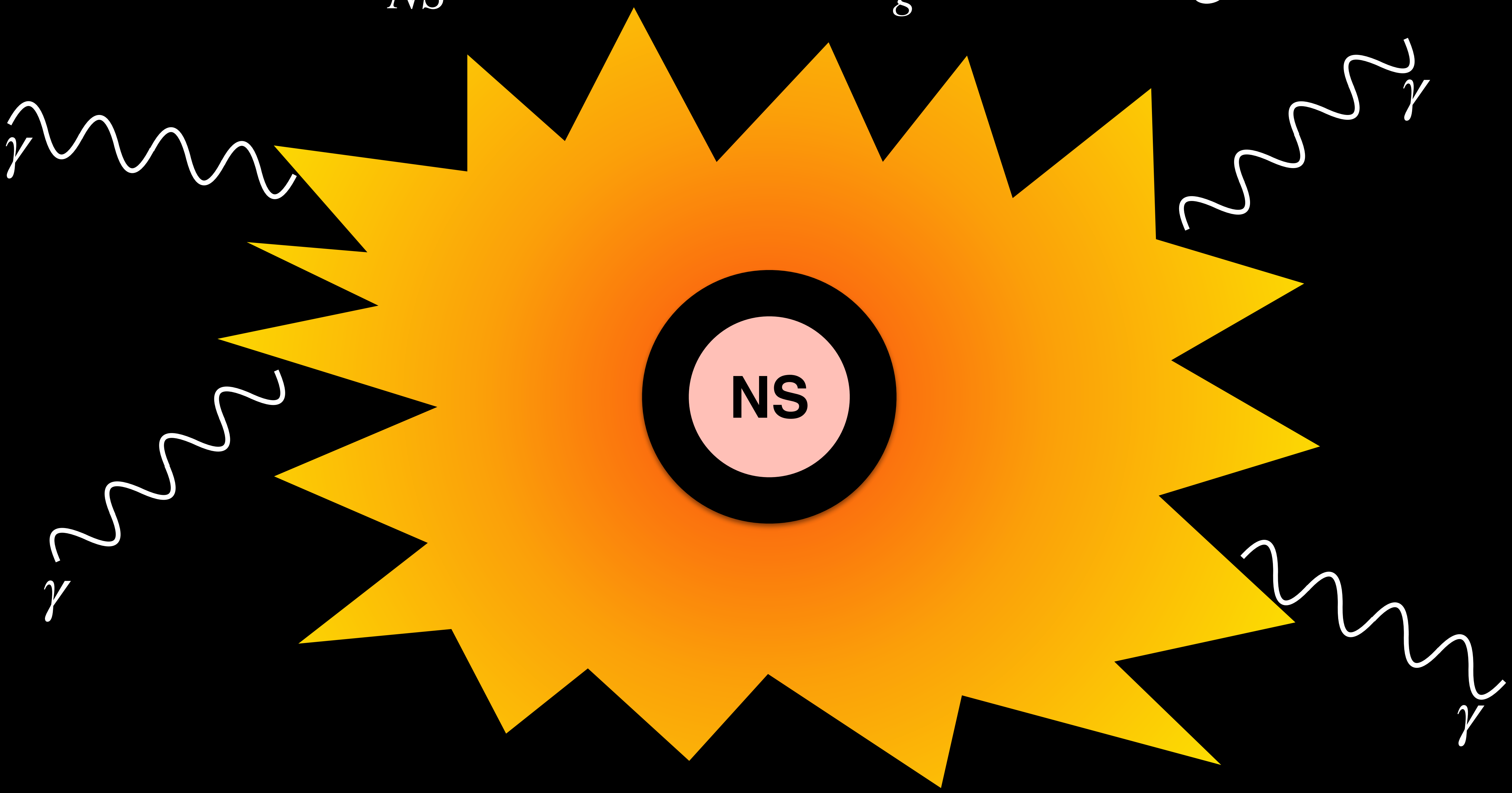
The density reaches nuclear saturation $\rho \sim 10^{14}$ g/cm$^3$



A shock wave is produced blowing up the star (Supernova)

# What are supernovae?

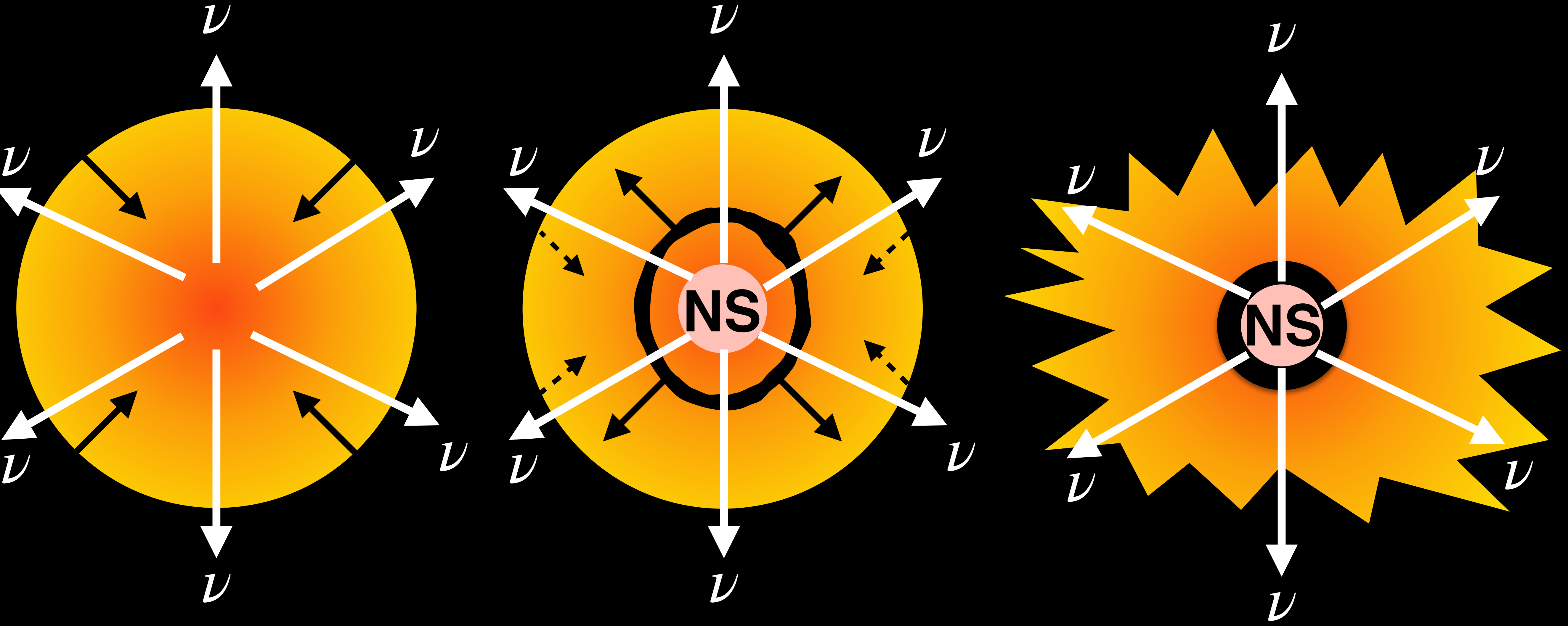
$R_{NS} \sim 10\,\mathrm{km}$ $\quad$ $E_g \sim 10^{53}\,\mathrm{erg}$



$E_{\mathrm{exp}} \sim 1\,\%\,E_g$ $\quad$ $E_\gamma \sim 0.01\,\%\,E_g$

# What is the role of neutrinos?

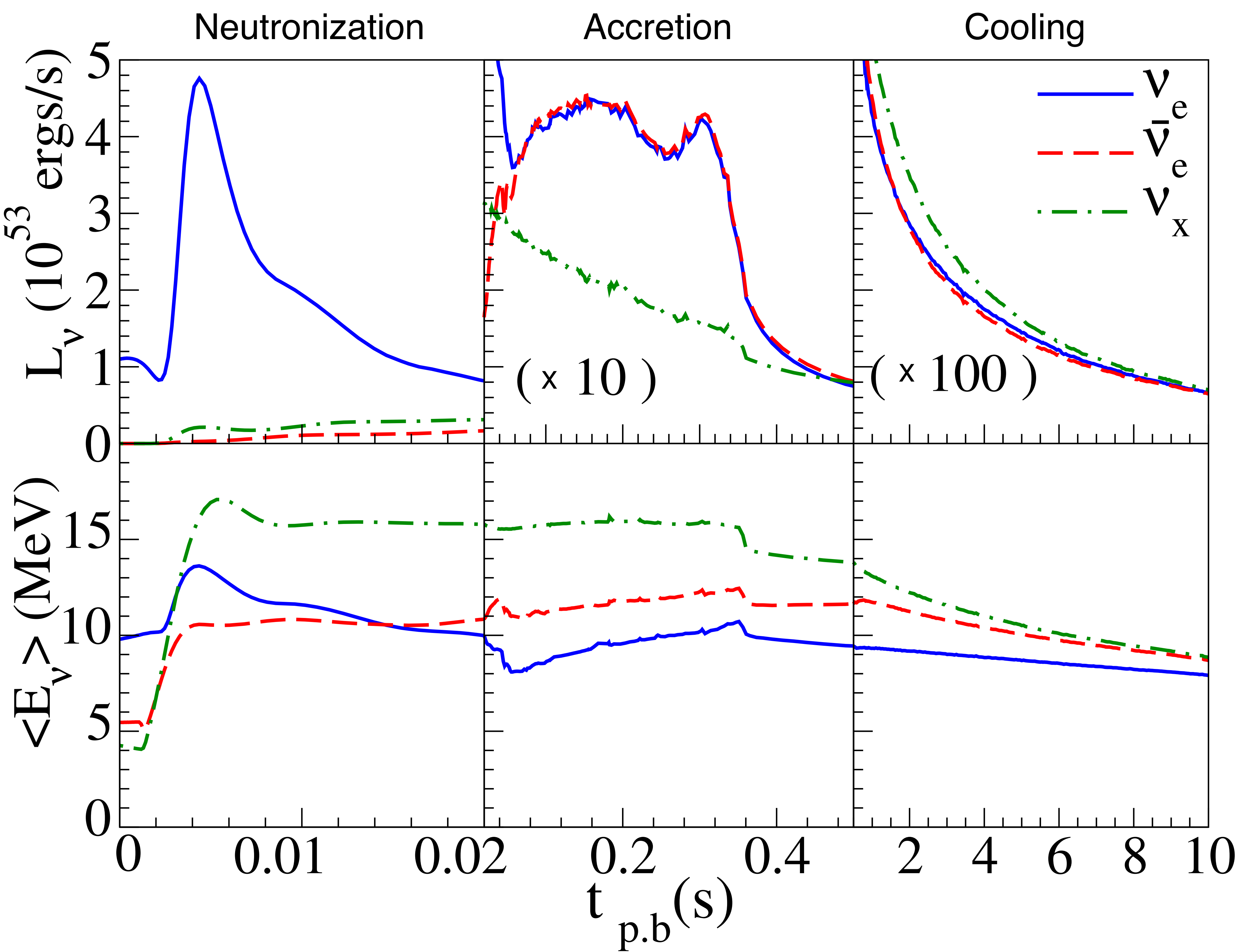
$\nu/\bar{\nu}$ of all flavor carry away 99% of $E_g$ in ~10 seconds



Neutrinos are messengers from the interior of the exploding star

# What is the role of neutrinos?

Chakraborty, Bhattacharjee, Kar, Phys. Rev. D 89 (2014) no.1, 013011, T. Fischer et al, Astron. Astrophys. 517, A80 (2010)



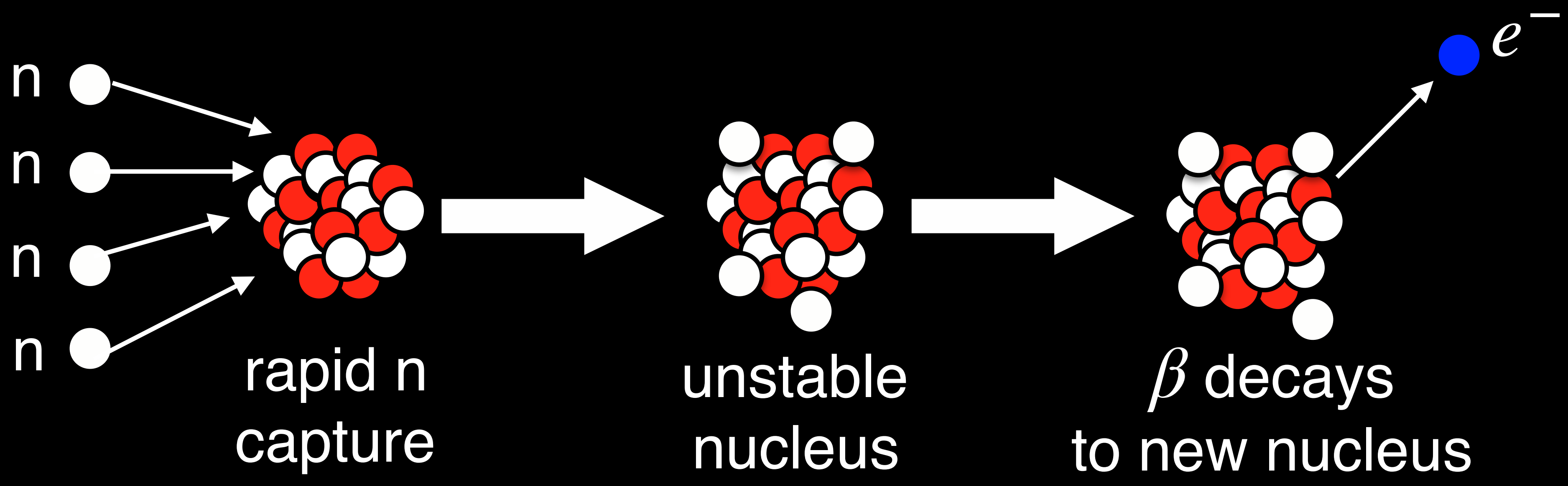
# What is the role of neutrinos?

$Y_e$ in neutrino heated material affected by neutrino interactions

$$\nu_e + n \rightarrow e^- + p$$

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

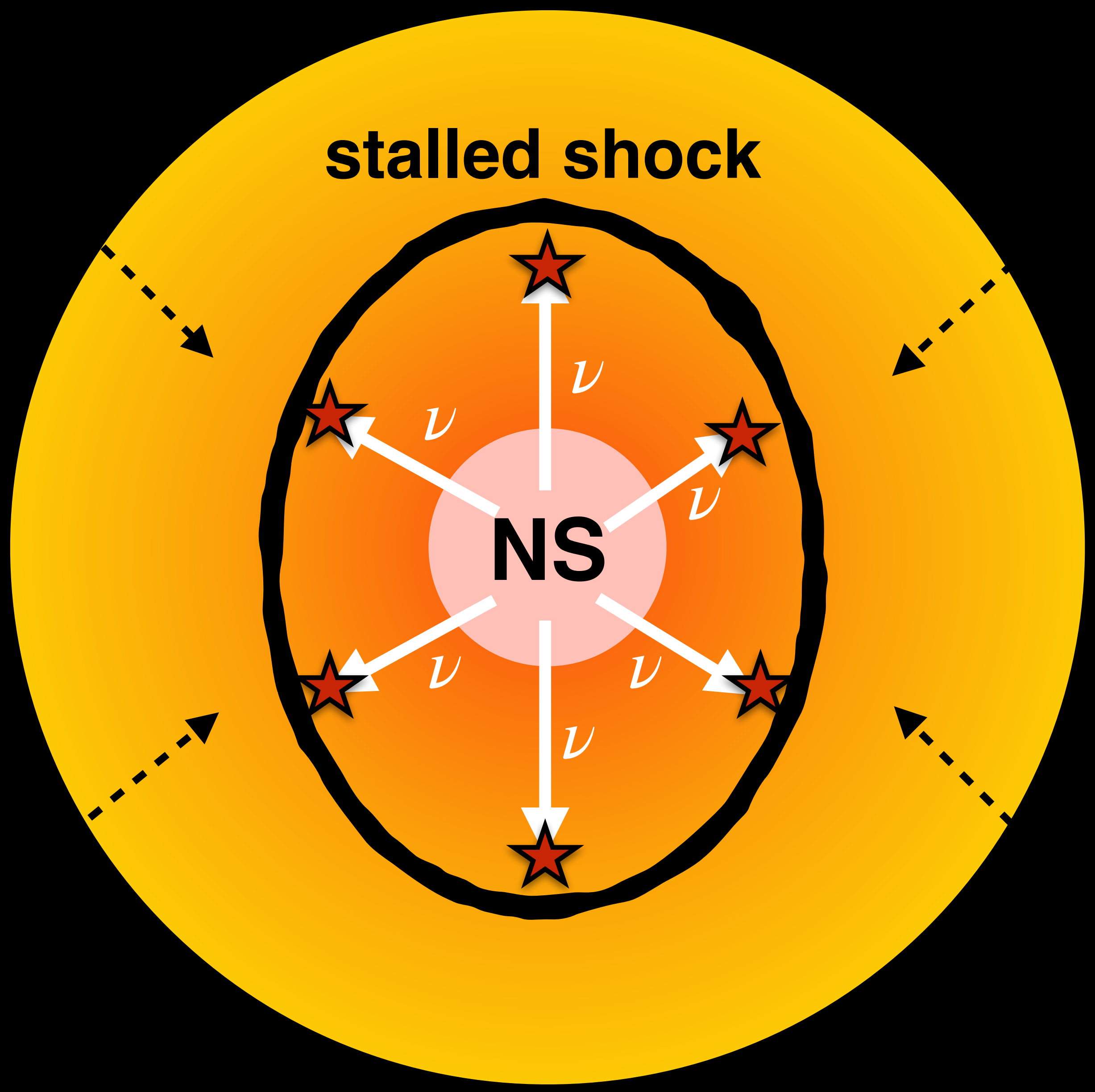
modify $Y_e = \frac{p}{n+p}$



Possible impact on r-process nucleosynthesis ($Y_e < 0.5$)

# What is the role of neutrinos?

The shock wave stalls after ~ few 10 ms



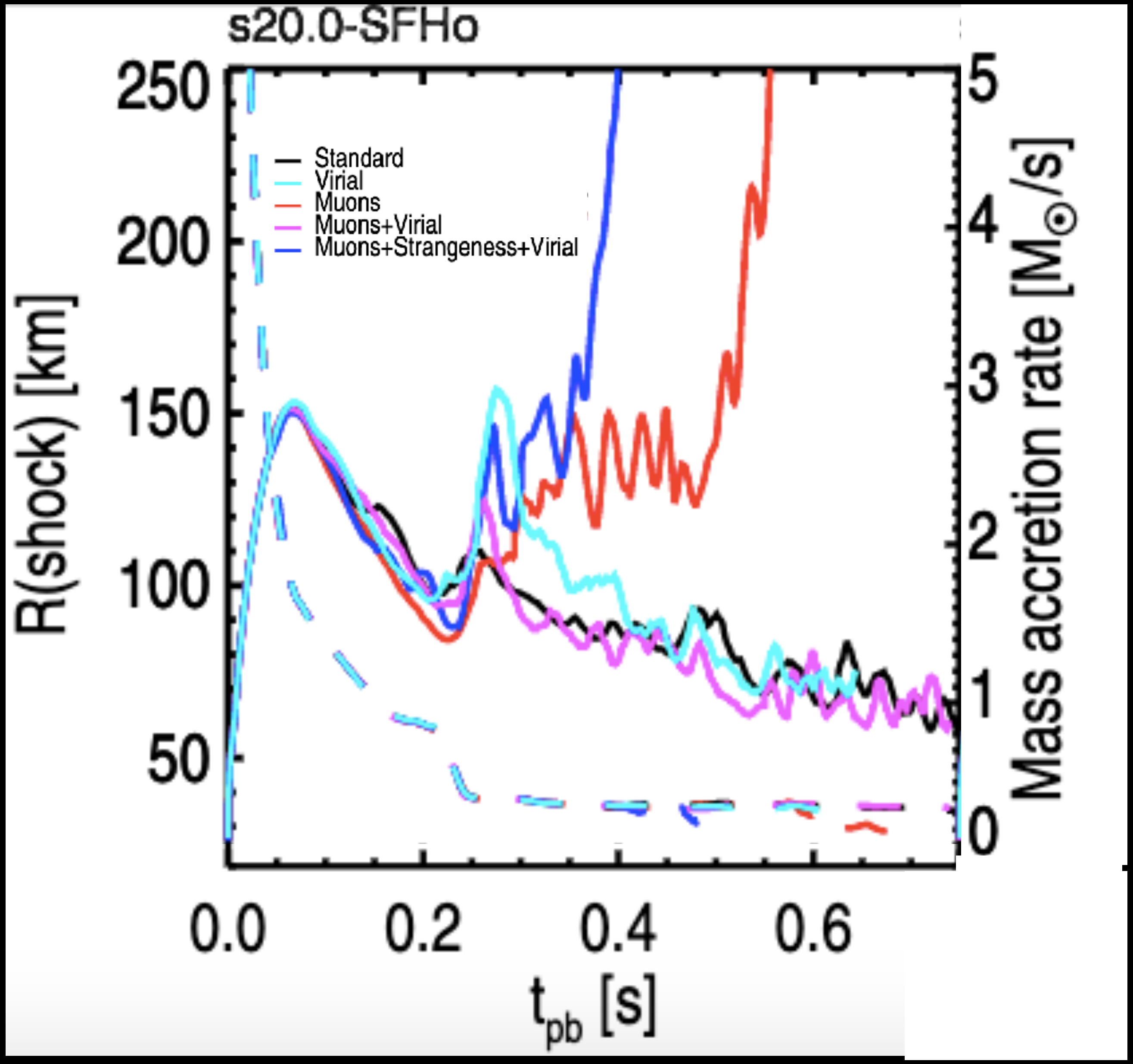
- ★ $\nu_e + n \rightarrow e^- + p$
- ★ $\bar{\nu}_e + p \rightarrow e^+ + n$

Delayed neutrino heating mechanism revives the shock

# What is the role of neutrinos?

Neutrino heating mechanism still requires confirmation in 3D

Bollig, Janka, Lohs, Martinez-Pinedo, Horowitz, Melson, Phys. Rev. Lett. 119 (2017) no.24, 242702



Dependence on details:
production of muons, s-quark corrections, …

# What is the role of neutrinos?

Neutrino heating mechanism still requires confirmation in 3D

Hypothesis 1

The delayed neutrino mechanism is **NOT** robust

# What is the role of neutrinos?

Neutrino heating mechanism still requires confirmation in 3D

Hypothesis 1

The delayed neutrino mechanism is **NOT** robust

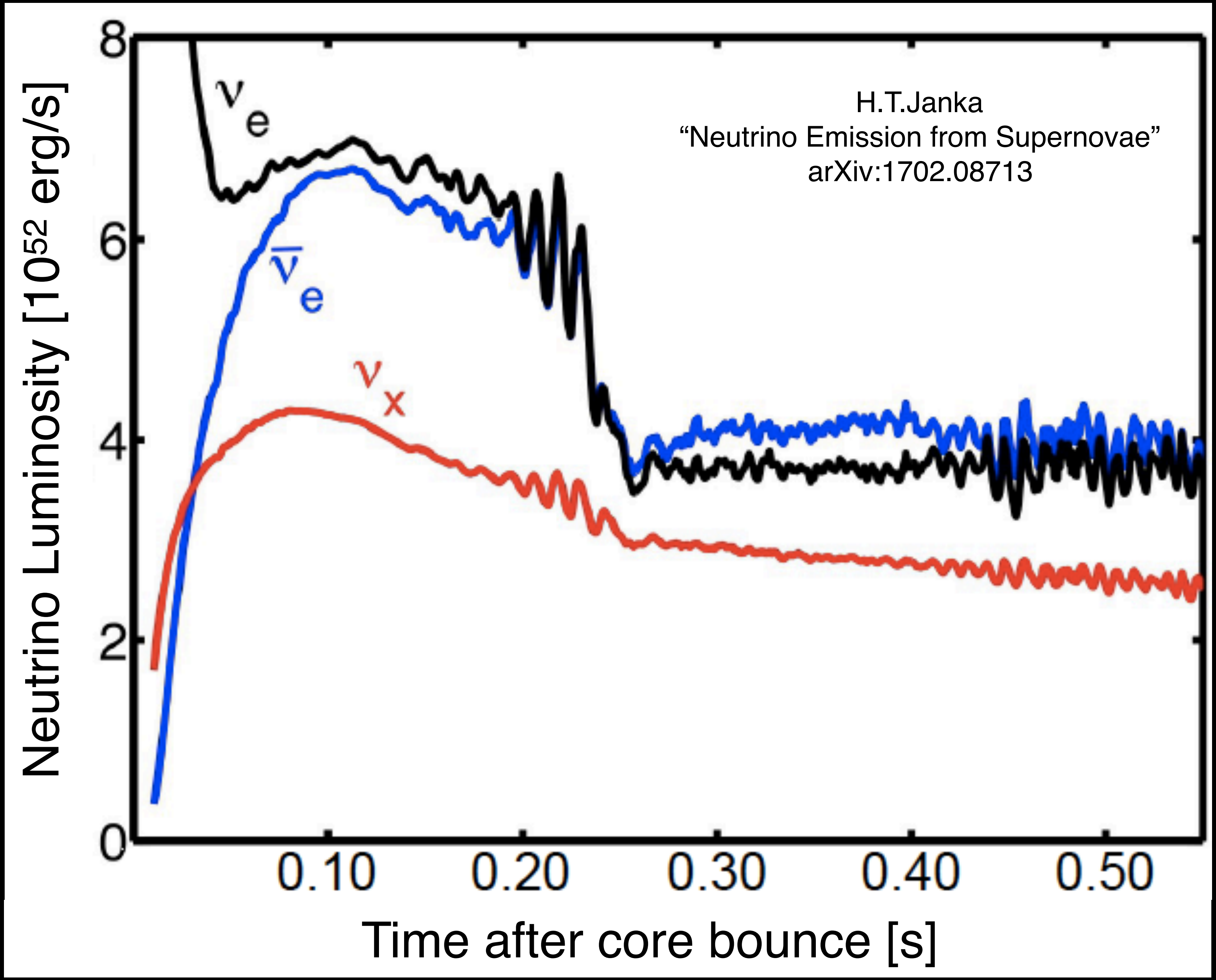
Hypothesis 2

The delayed neutrino mechanism **IS** robust.
Simulations are missing some key ingredients

More refined simulations are needed

# Multi-D neutrino signal features

Sloshing/spiraling (SASI) motion of the shock modulates $L_\nu$

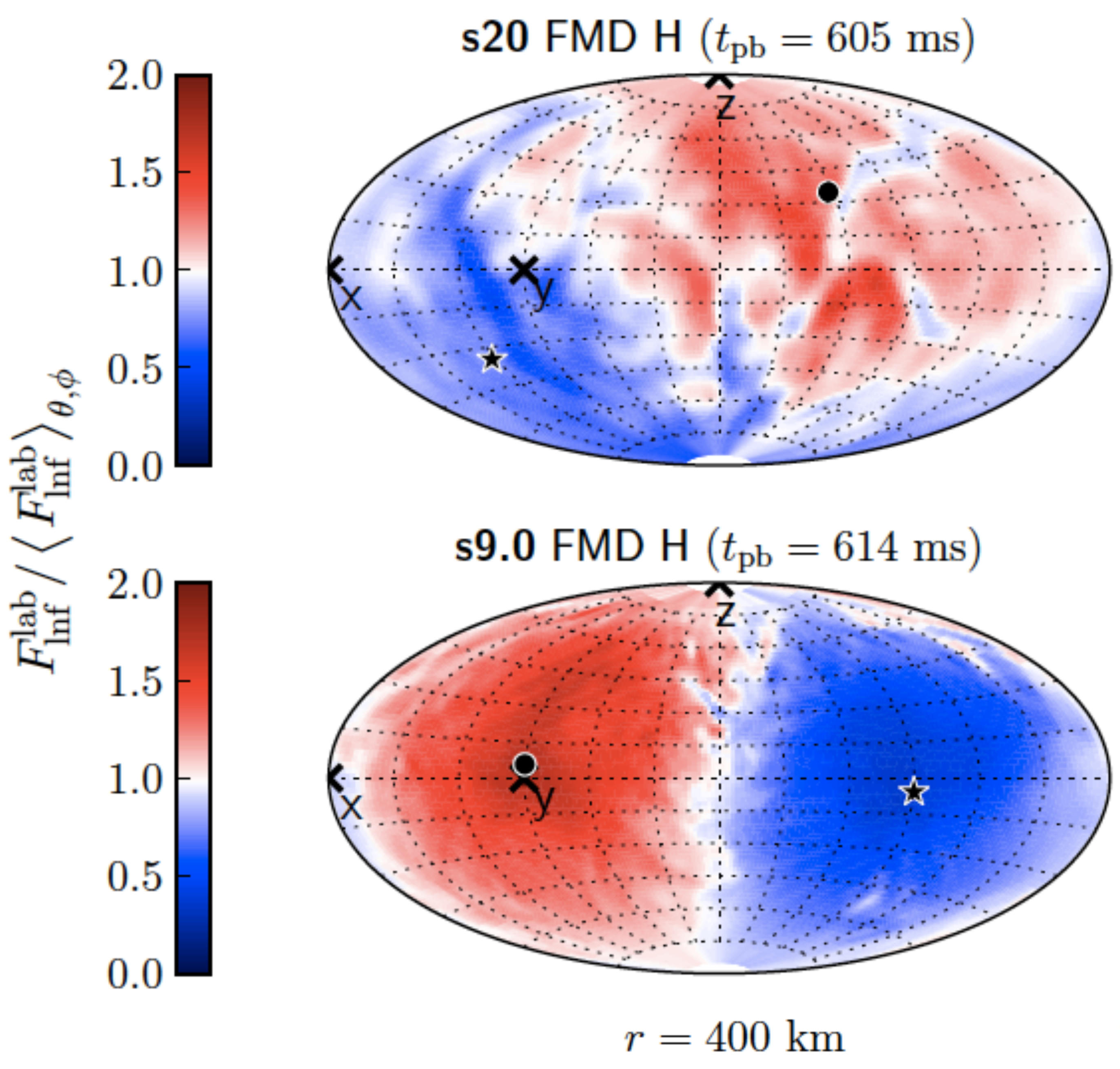


H.T.Janka
“Neutrino Emission from Supernovae”
arXiv:1702.08713

Neutrinos are probe of the explosion mechanism

# Multi-D neutrino signal features

## Lepton number is emitted asymmetrically (LESA)



Tamborra et al.,
Astrophys. J. 792 (2014) no.2, 96

Glas et al.,
Astrophys.J. 881 (2019) no.1, 36

confirmed by

O'Connor and Couch,
Astrophys. J. 865 (2018) no.2, 81

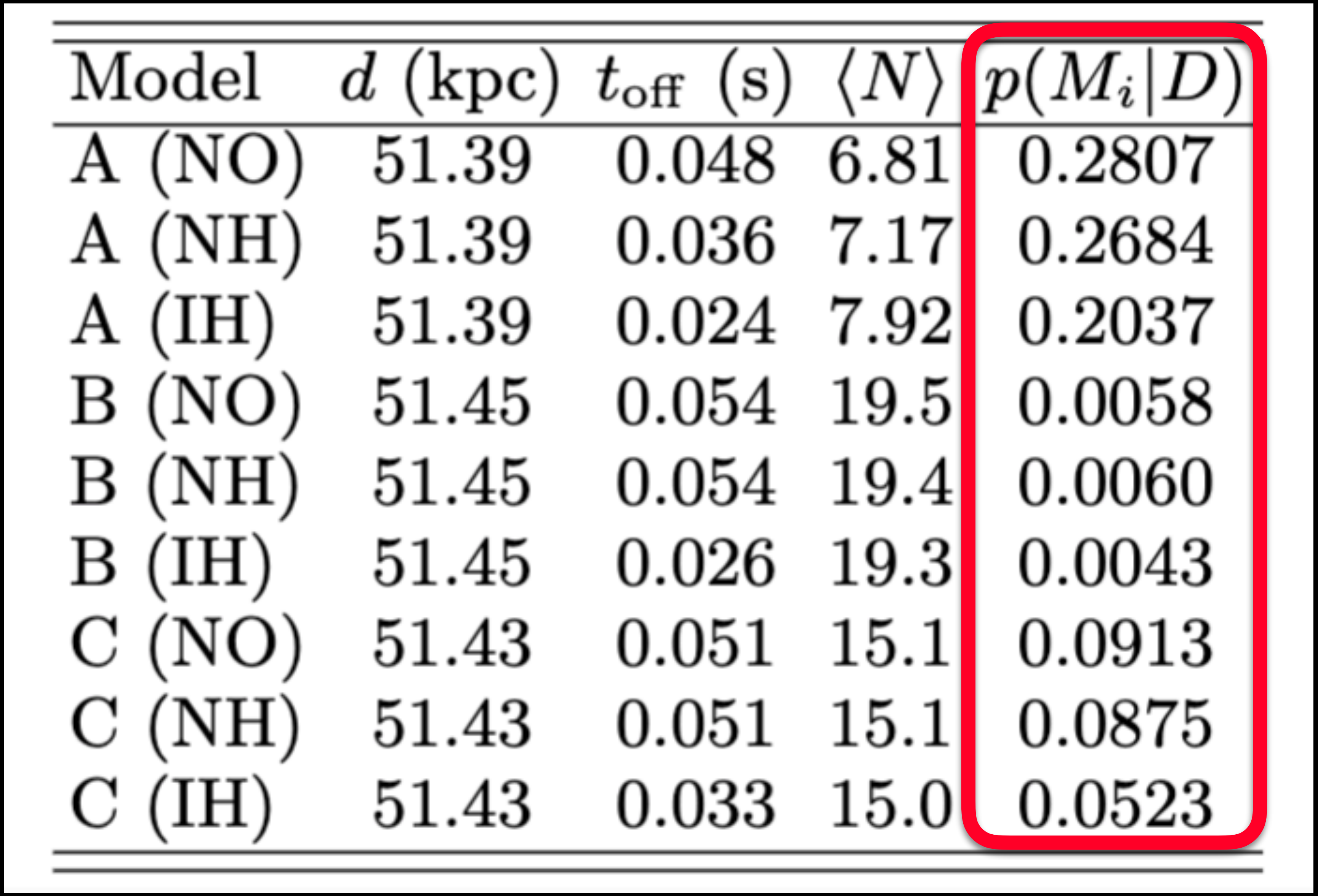
Vartanyan, Burrows and Radice,
MNRAS 489 (2019) 2, 2227

Neutrinos are probe of the explosion mechanism

# Simulations vs 1987a

Bayesian analysis comparing 1987a data with 1D models

Olsen, Qian, Phys. Rev. D 104 (2021) no.12, 123020



| | Model | $d$ (kpc) | $t_{\rm off}$ (s) | $\langle N \rangle$ | $p(M_i \vert D)$ |
|---|---|---|---|---|---|
| $9.6\,\mathrm{M}_\odot$ | A (NO) | 51.39 | 0.048 | 6.81 | 0.2807 |
| | A (NH) | 51.39 | 0.036 | 7.17 | 0.2684 |
| | A (IH) | 51.39 | 0.024 | 7.92 | 0.2037 |
| $20\,\mathrm{M}_\odot$ | B (NO) | 51.45 | 0.054 | 19.5 | 0.0058 |
| | B (NH) | 51.45 | 0.054 | 19.4 | 0.0060 |
| | B (IH) | 51.45 | 0.026 | 19.3 | 0.0043 |
| $27\,\mathrm{M}_\odot$ | C (NO) | 51.43 | 0.051 | 15.1 | 0.0913 |
| | C (NH) | 51.43 | 0.051 | 15.1 | 0.0875 |
| | C (IH) | 51.43 | 0.033 | 15.0 | 0.0523 |

Best agreement with low mass progenitor model ($9.6\,\mathrm{M}_\odot$)

# Flavor evolution in dense environments

Boltzmann equation of the density matrix $\varrho_{\mathbf{p},\mathbf{x}}$

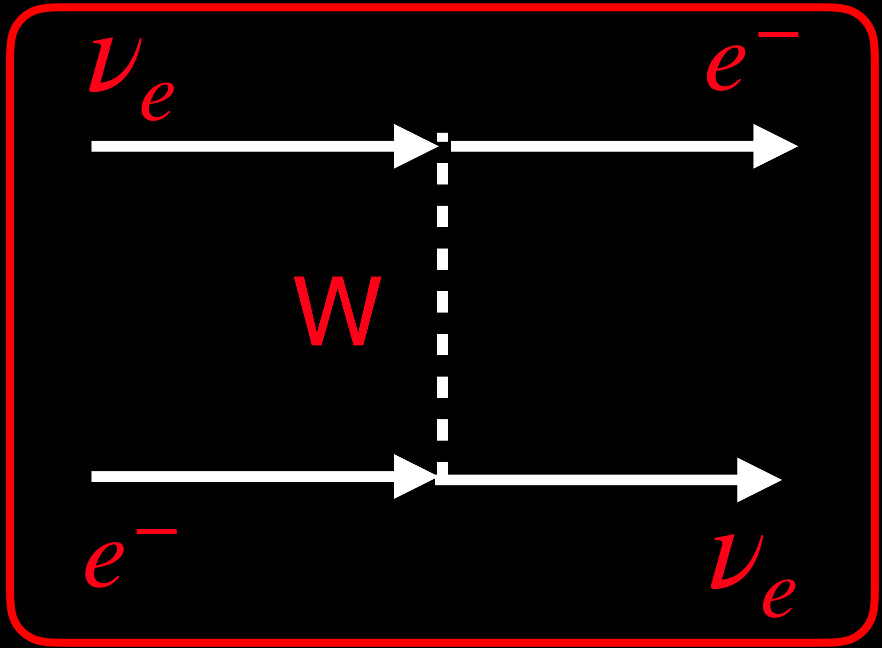
$$(\partial_t + \mathbf{v}_\mathbf{p} \cdot \nabla_\mathbf{x})\, \varrho_{\mathbf{p},\mathbf{x}} = -\, i[H^{\mathrm{vac}}_{\mathbf{p},\mathbf{x}} + H^{\mathrm{mat}}_{\mathbf{p},\mathbf{x}} + H^{\nu\nu}_{\mathbf{p},\mathbf{x}}, \varrho_{\mathbf{p},\mathbf{x}}] + \hat{\mathscr{C}}[\varrho_{\mathbf{p},\mathbf{x}}]$$

# Flavor evolution in dense environments

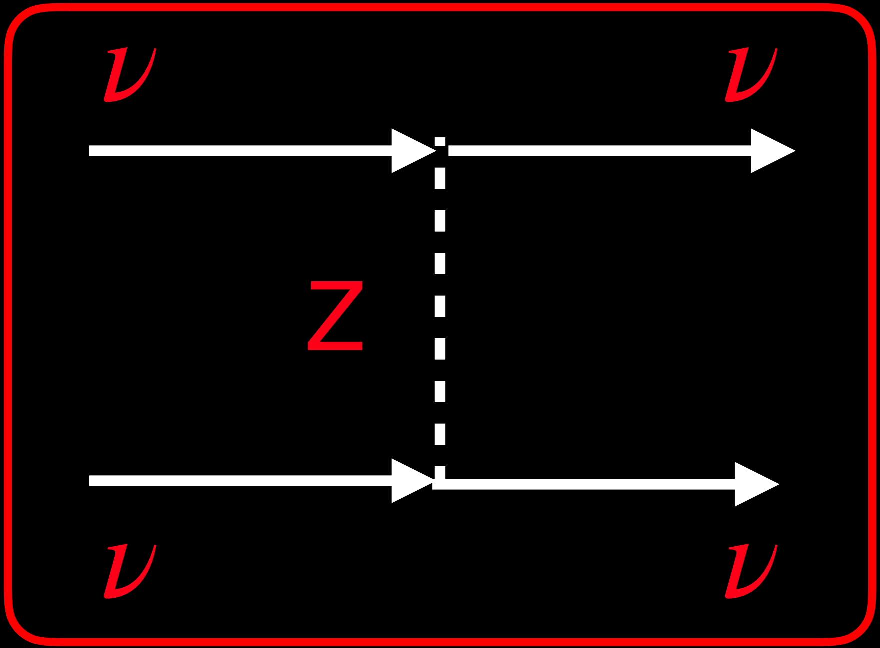
Boltzmann equation of the density matrix $\varrho_{\mathbf{p},\mathbf{x}}$

$$(\partial_t + \mathbf{v}_\mathbf{p} \cdot \nabla_\mathbf{x})\,\varrho_{\mathbf{p},\mathbf{x}} = -\,i[H^{\rm vac}_{\mathbf{p},\mathbf{x}} + H^{\rm mat}_{\mathbf{p},\mathbf{x}} + H^{\nu\nu}_{\mathbf{p},\mathbf{x}}, \varrho_{\mathbf{p},\mathbf{x}}] + \hat{\mathscr{C}}[\varrho_{\mathbf{p},\mathbf{x}}]$$

$$H^{\rm mat}_{\mathbf{p},\mathbf{x}}$$



$$H^{\nu\nu}_{\mathbf{p},\mathbf{x}}$$



Non-linear equations. Only solvable with some assumptions

# Flavor evolution in dense environments

Two ways to tackle the problem

**Linear Stability** →

1) linearize in $\varrho_{ex}$
2) Find exponential solutions

$$\varrho_{ex} \sim e^{i\mathbf{k}\cdot\mathbf{x}+i\omega t}$$

**Numerical Solution** →

# Flavor evolution in dense environments

Two ways to tackle the problem

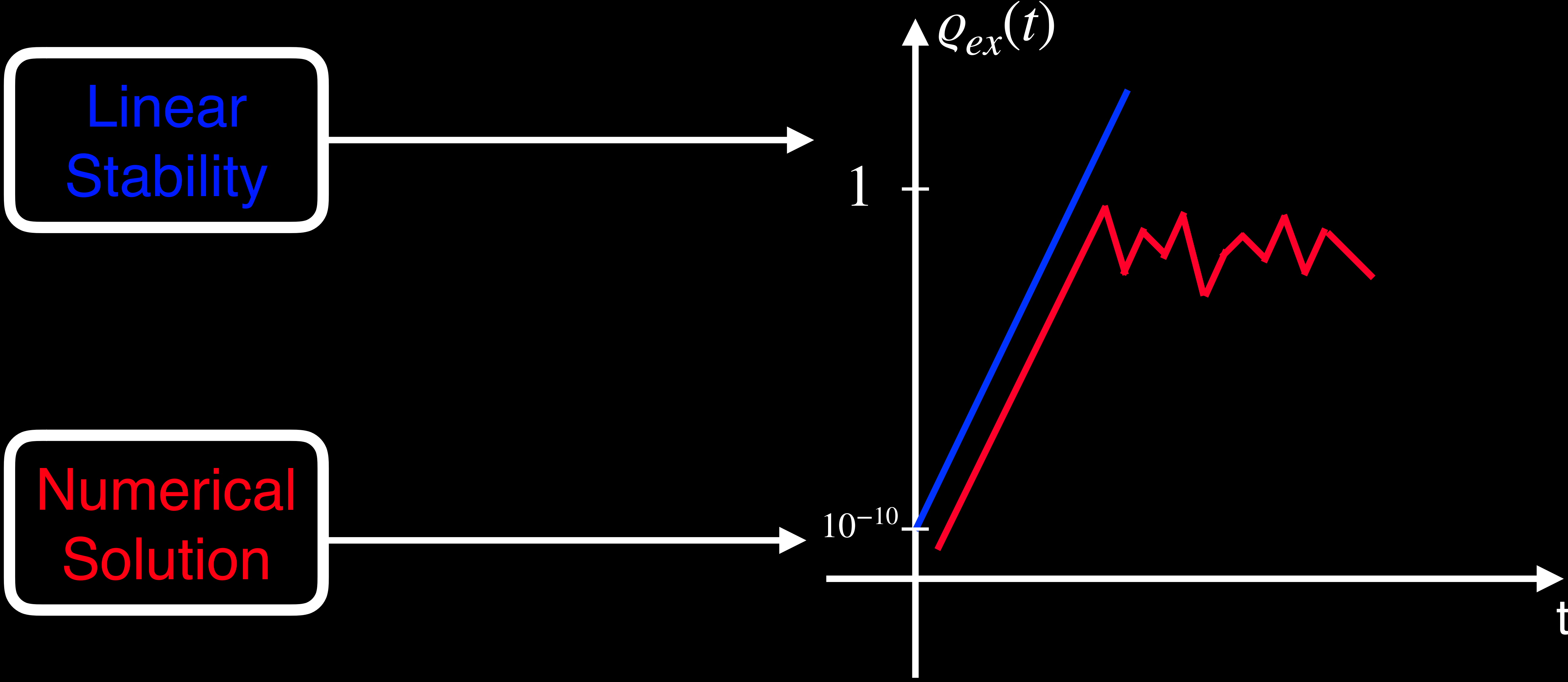
**Linear Stability**

**Numerical Solution**

1) Reduce dimensionality with some assumptions
2) Solve the system numerically

# Flavor evolution in dense environments

Two ways to tackle the problem



Linear Stability

Numerical Solution

Find instabilties, hard to know amount of flavour conversions

Numerically hard, simplifying assumptions can alter final results

# Fast and slow conversions

Linear stability analysis predicts two kind of instabilities

Fast conversions → Growth rate $\propto G_F n_\nu$

Time scale ~ 1 ns

Slow conversions → Growth rate $\propto \sqrt{\frac{\Delta m^2}{E_\nu} G_F n_\nu}$

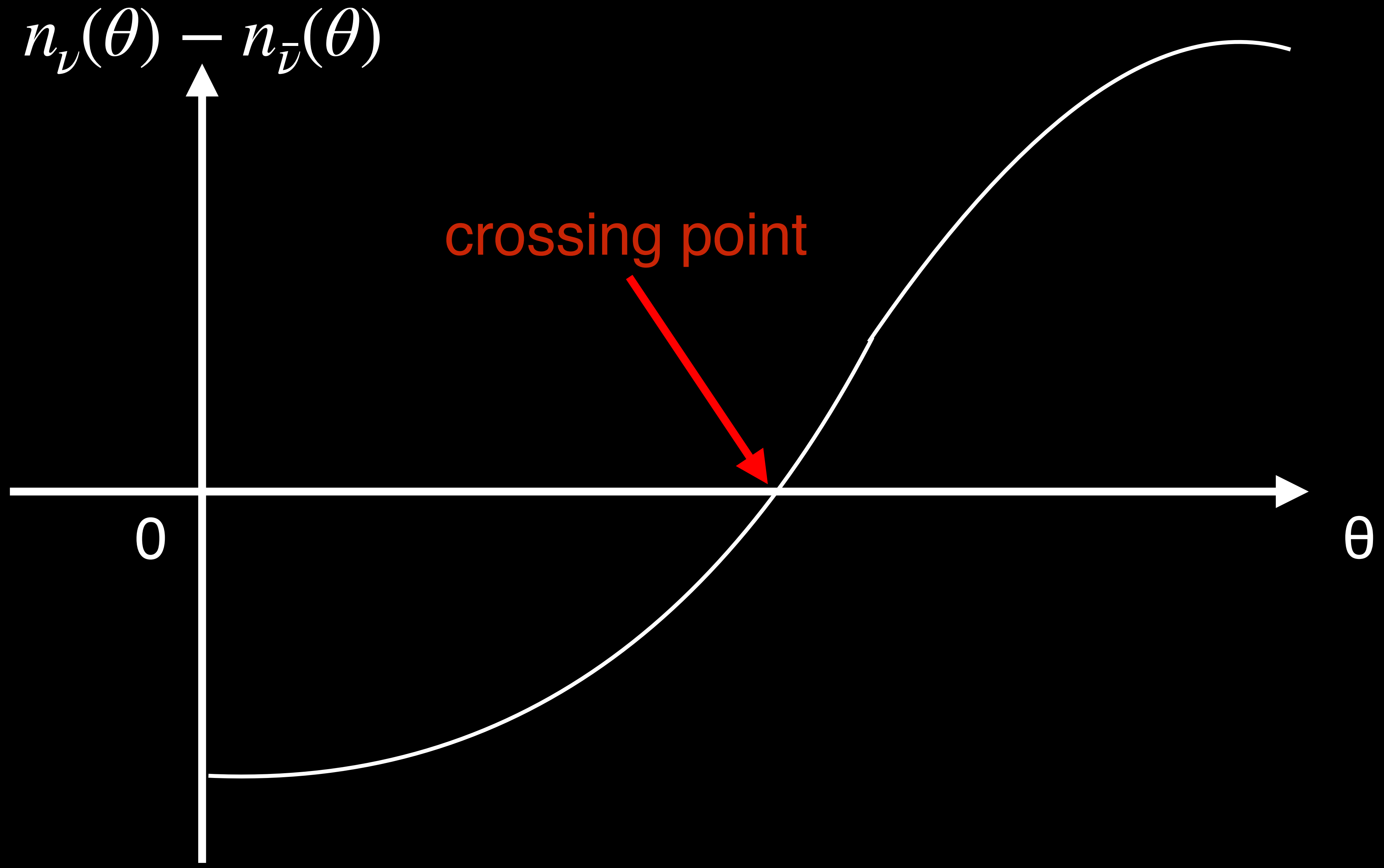
Time scale ~ 0.1 µs

Fast conversions develop on very short time scales

# Fast conversions

Necessary and sufficient condition: **angular crossing**

Morinaga, Phys. Rev. D105 (2022) no.10, L101301, Dasgupta, Phys. Rev. Lett. 128 (2022) no.8, 8

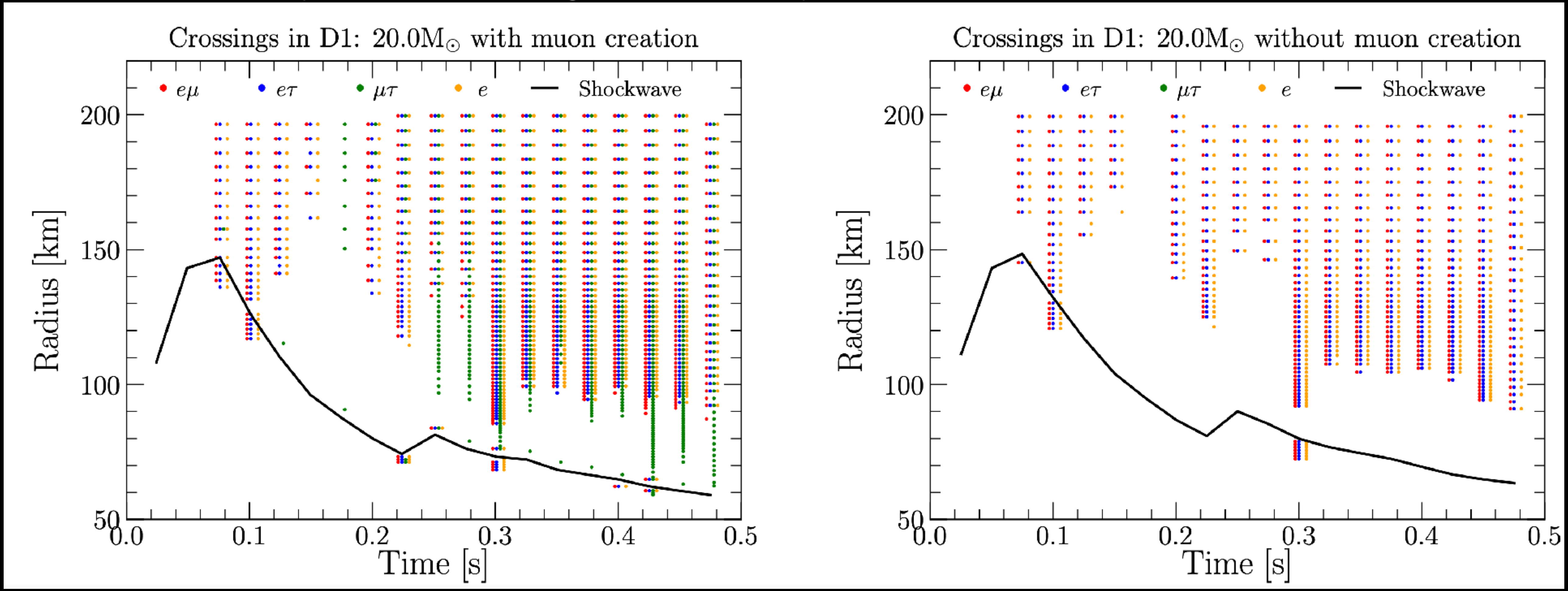


Example: $\nu$ $(\bar{\nu})$ dominate in the forward (backward) direction

# Fast conversions in real simulations

## Are crossing really happening in supernovae?

Capozzi, Abbar, Bollig and Janka, Phys. Rev. D 103 (2021) no.6, 063013



see also
Tamborra, Huedepohl, Raffelt, Janka, 2017; Abbar, Duan, Sumiyoshi, Takiwaki, Volpe, 2018; Morinaga, Nakagura, Kato, Yamada, 2019;
Azari, Yamada, Morinaga, Iwakami, Okawa, Nakagura, Sumiyoshi 2019;  Morinaga, Nagakura, Kato, Yamada 2020;
Abbar, Capozzi, Glas, Janka, Tamborra Phys. Rev. D 103 (2021) no.6, 063033

Crossings possible both below and above the shock wave

# Fast conversions in real simulations

**What is the impact of fast conversions?**

Including fast conversions in supernova simulations?

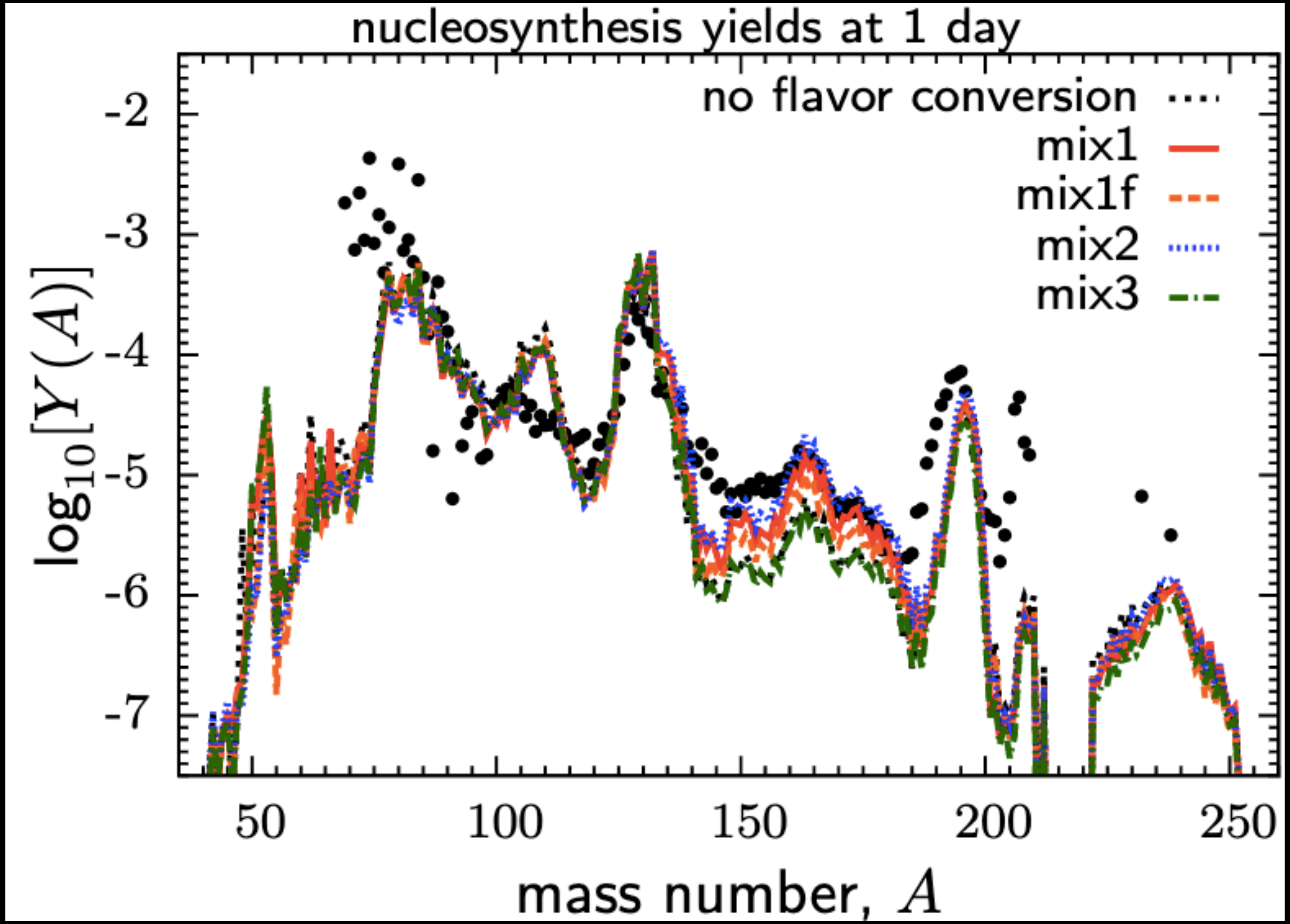
xxxx, et al. Phys. Rev. Lett. nn (20yy) mm, ll

Still a lot of work ahead

# Digression: neutron star mergers

Implementation of fast conversions in an “effective” way

Just, Abbar, Wu, Tamborra, Janka, Capozzi, Phys. Rev. D 105 (2022) no.8, 083024



see also  Wu, Tamborra, Phys. Rev. D 95 (2017) no.10, 103007, Wu, Tamborra, Just, Janka, Phys. Rev. D 96 (2017) no.12, 123015, George, Wu, Tamborra, Ardevol-Pulpillo, Janka, Phys. Rev. D 102 (2020) no.10, 103015, Li, Siegel, Phys. Rev. Lett. 126 (2021) no.25, 251101

Mild impact of fast conversions on r-process yields.
This is stable to changing the model parameters

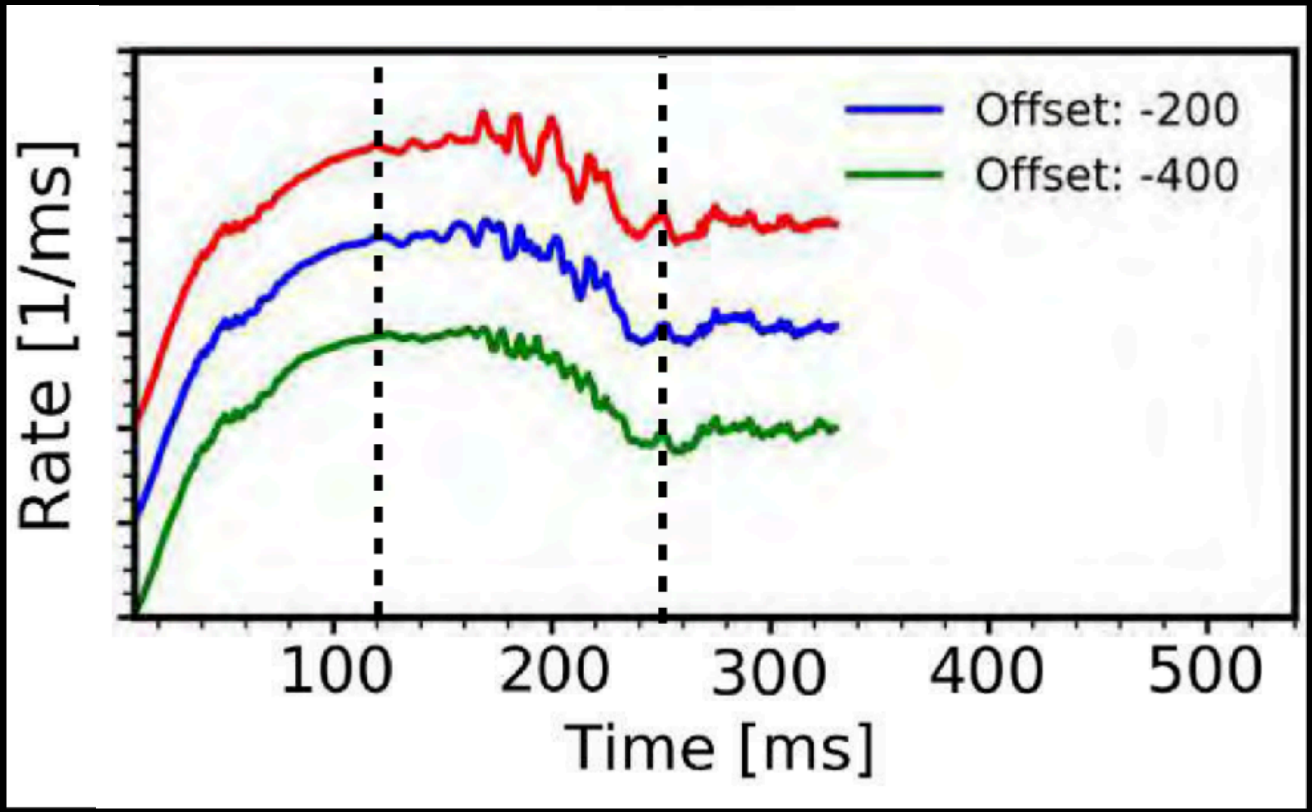
# Detecting Supernova Neutrinos

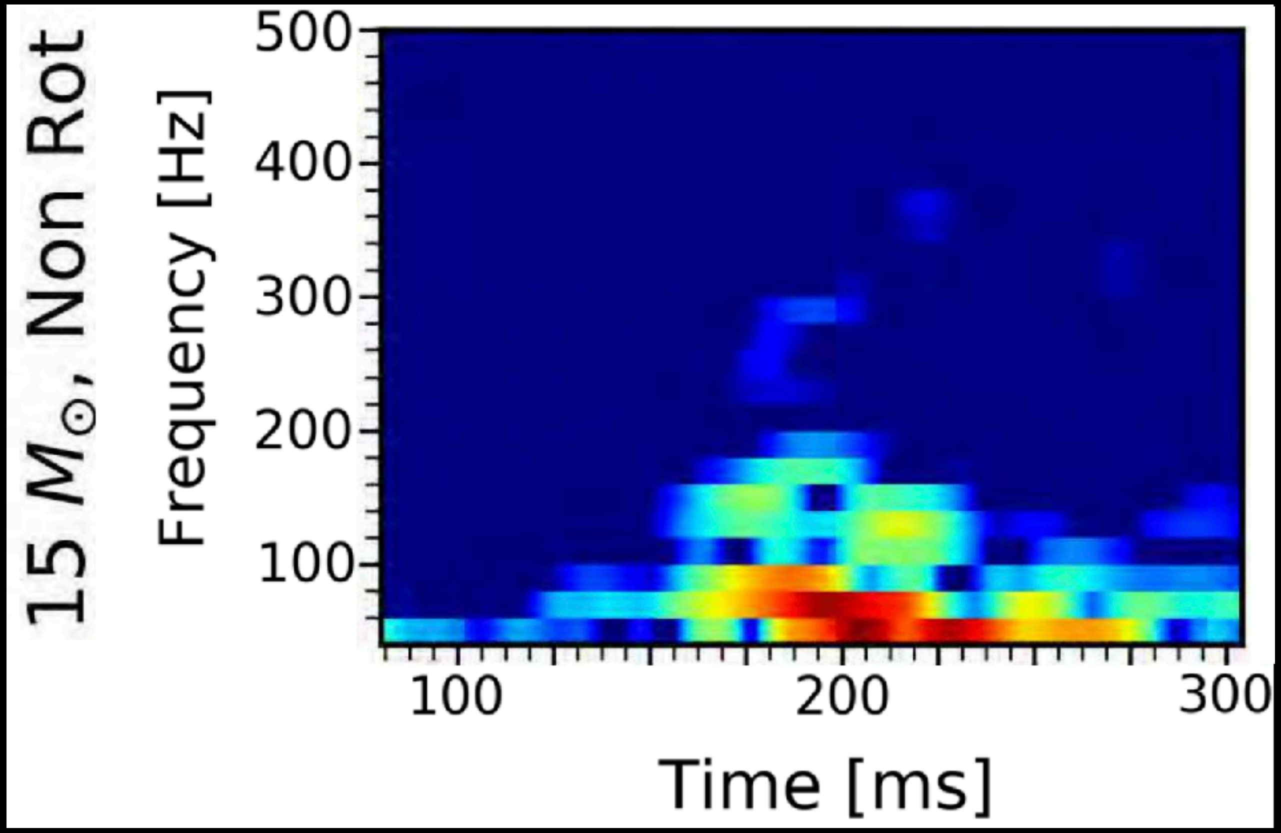
| Flavor | Detection channel | Experiments | Events (10 kpc) |
|---|---|---|---|
| $\bar{\nu}_e$ | $\bar{\nu}_e + p \rightarrow n + e^+$ | SuperK, HyperK<br>IceCUBE<br>JUNO | $10^4 - 10^5$<br>$10^6$<br>$\text{few} \times 10^3$ |
| $\nu_e$ | $\nu_e + {}^{40}\text{Ar} \rightarrow e^- + {}^{40}\text{K}^*$ | DUNE | $10^3$ |
| $\nu_x$ | $\nu + p \rightarrow \nu + p$<br>$\nu + {}^{N}X \rightarrow \nu + {}^{N}X$ | JUNO<br>Dark matter, Lead | $10^2$<br>$10 - 10^3$ |

# What can we learn?

Water Cherenkov will have high statistics and precise time info

Walk, Tamborra, Janka, Summa, Phys. Rev. D 98 (2018) no.12, 123001



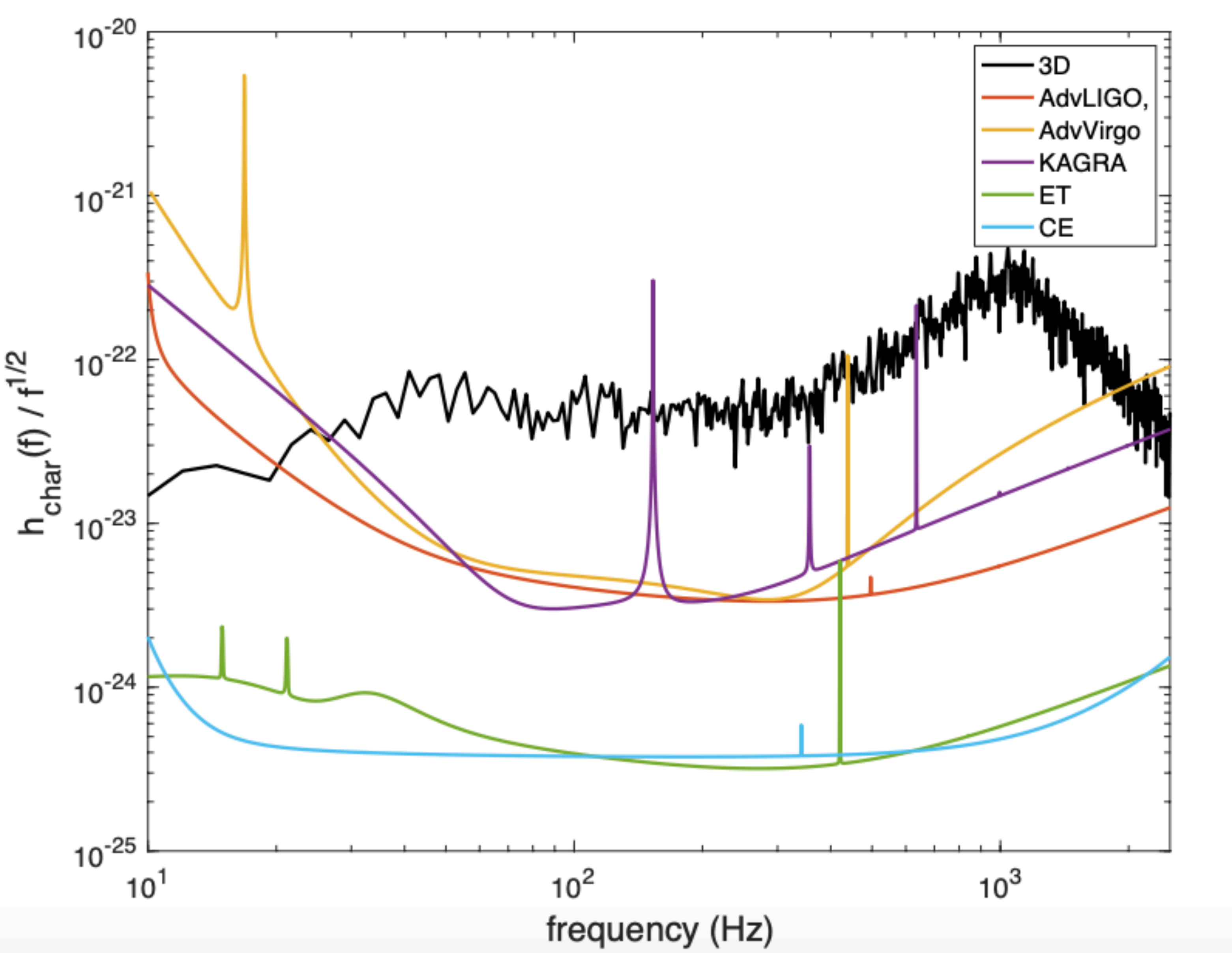


Time variations in the neutrino signal (SASI) can be studied

# What can we learn?

Neutrinos and GW carry important information from the PNS

Mezzacappa, et al., Phys. Rev. D 102 (2020) no.2, 023027



see also

Westernacher-Schneider,an,
Phys. Rev. D 100 (2019) no.12, 123009

Vartanyan, Burrows,
Astrophys. J. 901 (2020) no.2, 108

Pan, Liebendorfer, Couch, Thielemann,
arXiv:2010.02453

Abdikamalov, Pagliaroli, Radice,
arXiv:2010.04356

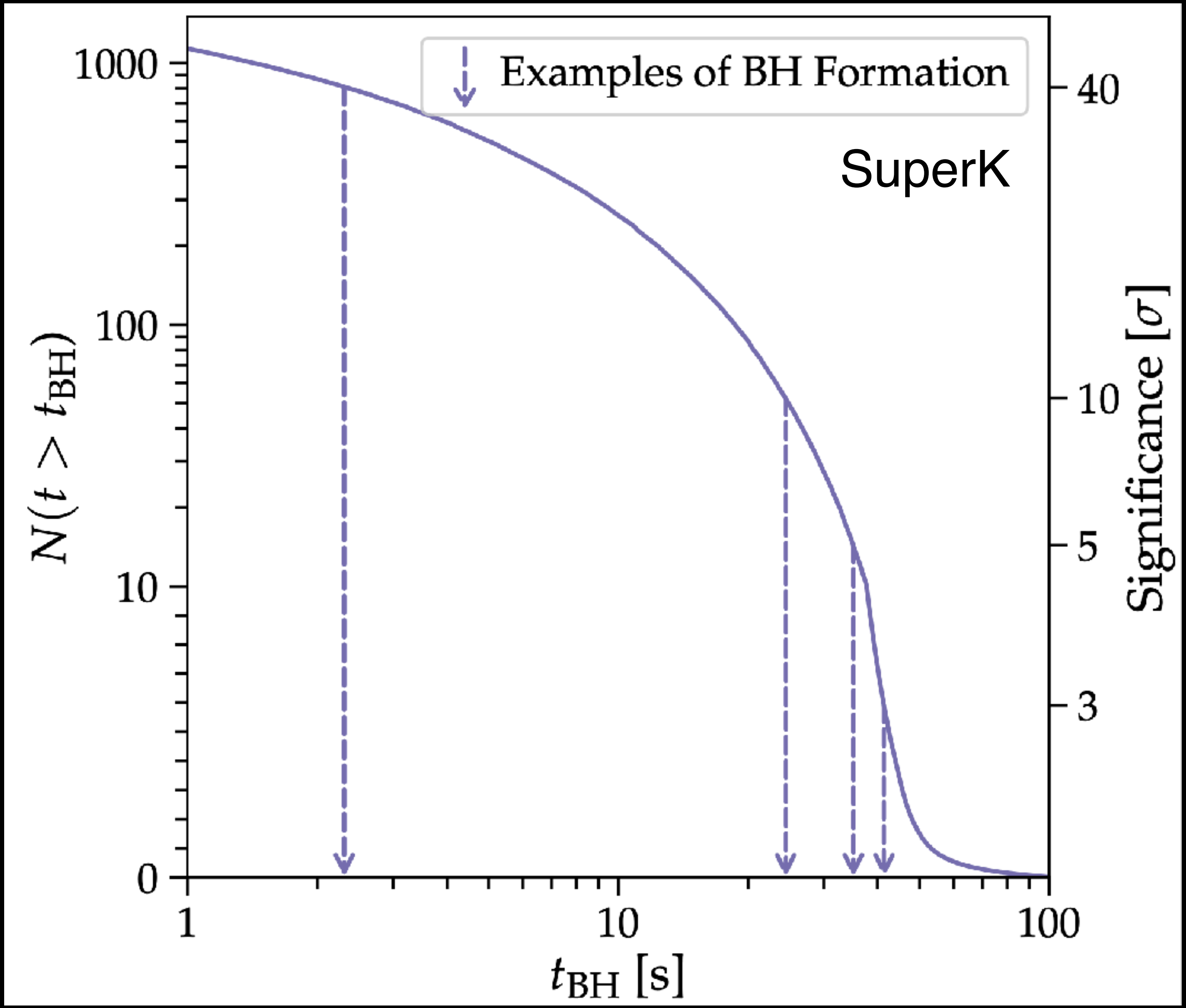
….

GW are complementary to neutrinos

# What can we learn?

Water Cherenkov will have high statistics and precise time info

Li, Beacom, Roberts, Phys. Rev. D 103 (2021) no.2, 023016



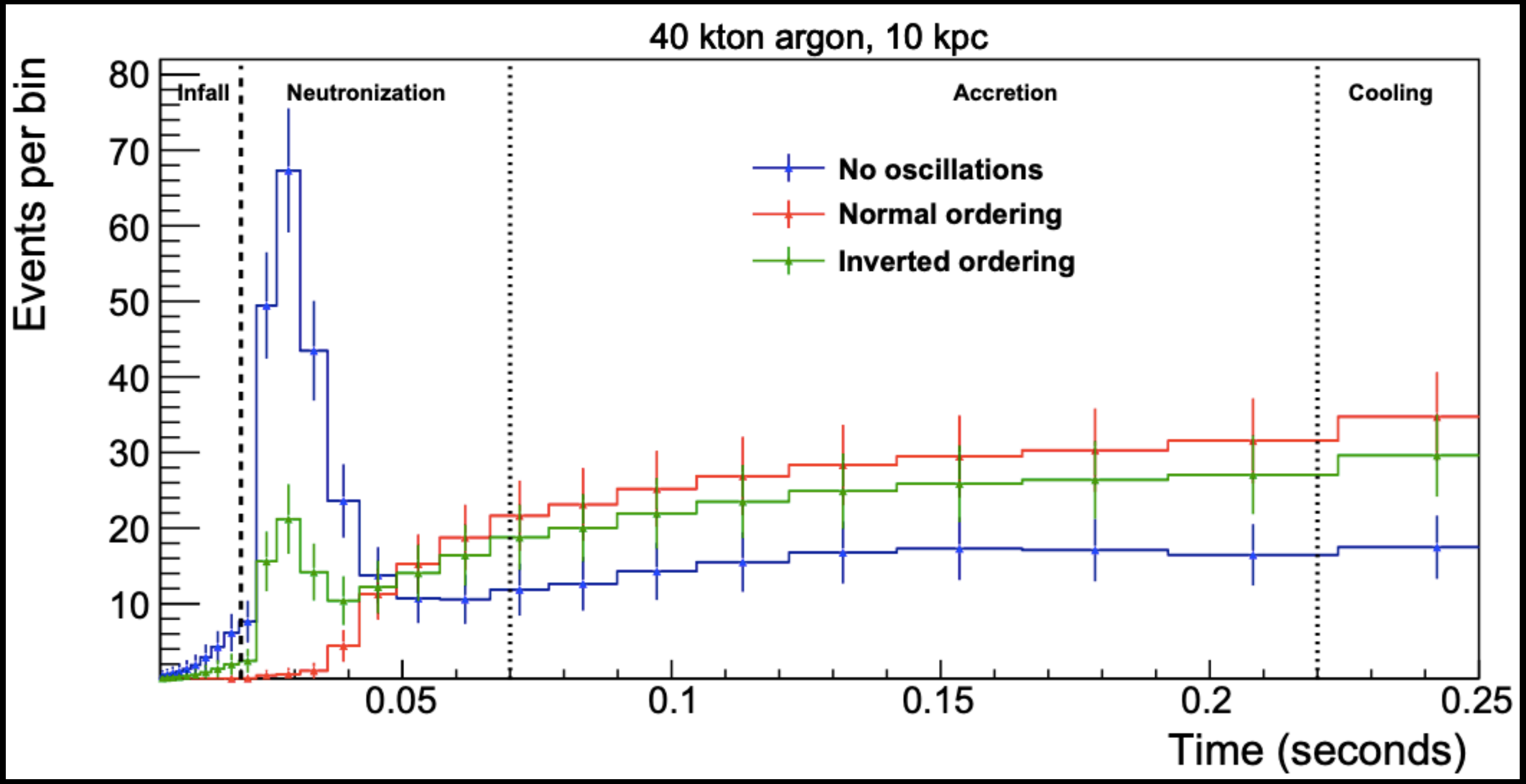
Evidence of black hole formation

# What can we learn?

DUNE has direct access to the neutronization burst

DEEP UNDERGROUND NEUTRINO EXPERIMENT

Jost Migenda, talk at Nuphys 2017

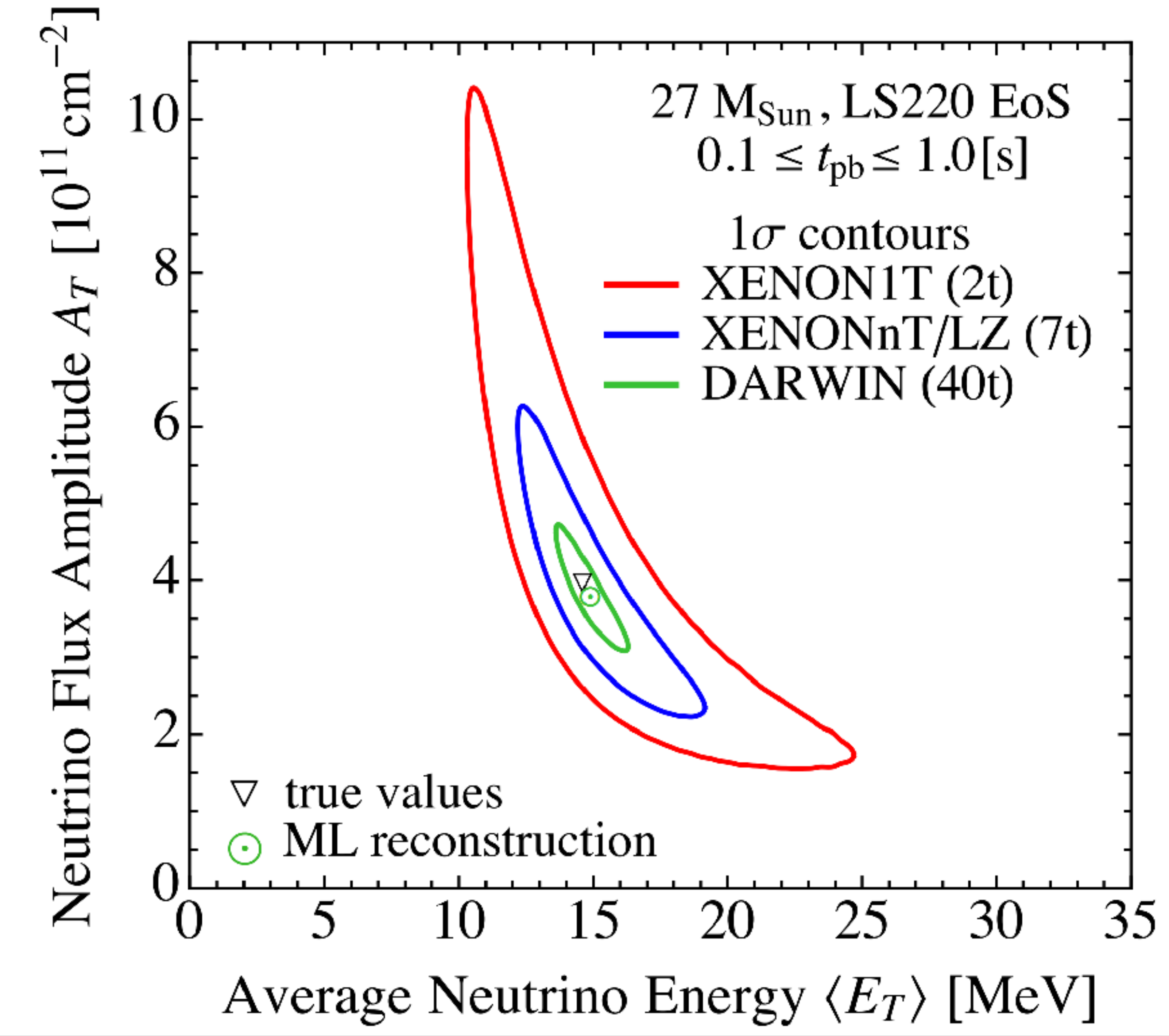


Study the neutronization burst:
distance, light sterile, neutrino mass (see poster by F. Pompa)

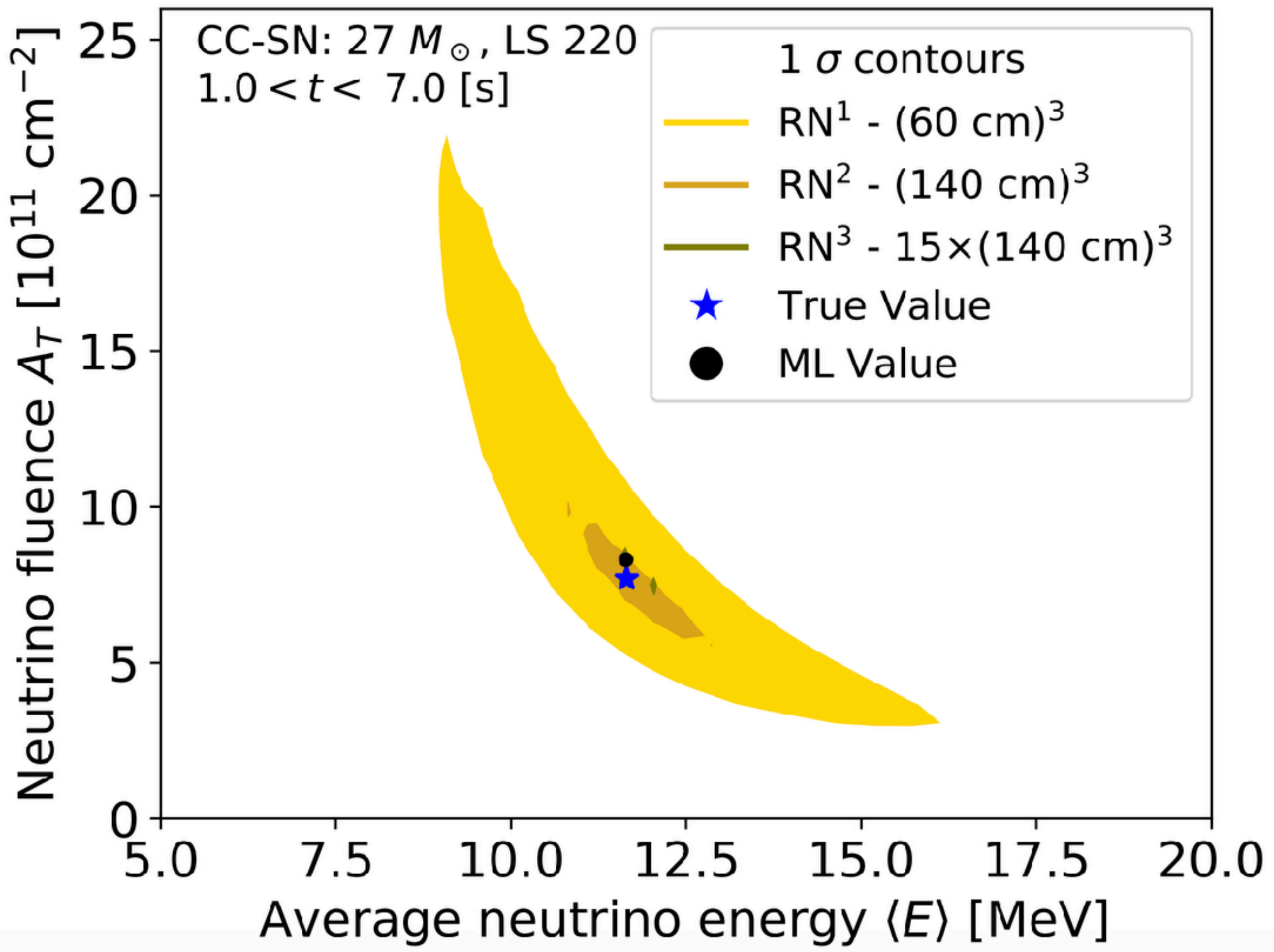
# What can we learn?

## Dark matter (Xe) and Lead detectors

Lang, McCabe, Reichard, Selvi, Tamborra, Phys. Rev. D 94 (2016) no.10, 103009

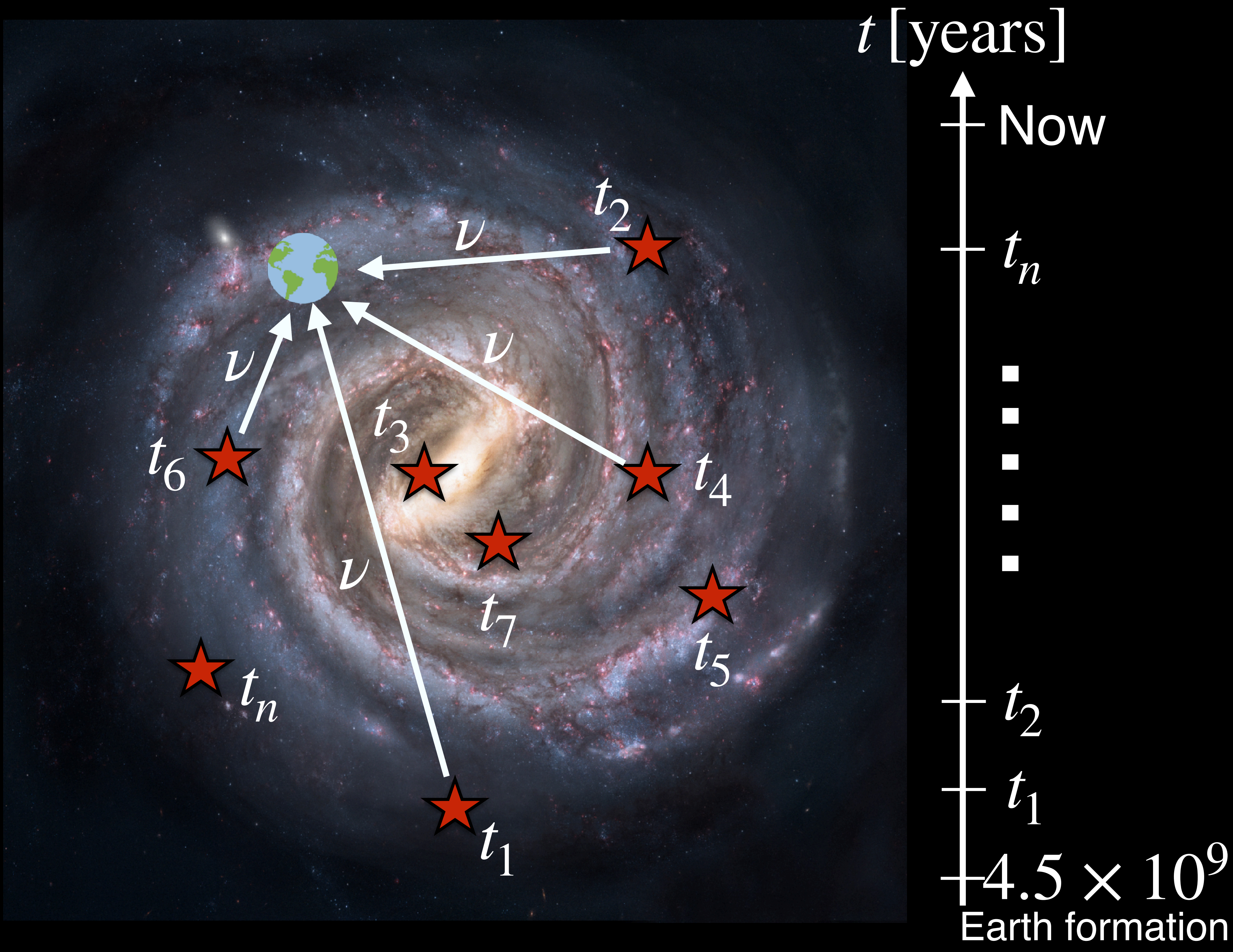


Pattavina, Ferreiro Iachellini, Tamborra, Phys. Rev. D 102 (2020) no.6, 063001



Great potential for $\nu_x$

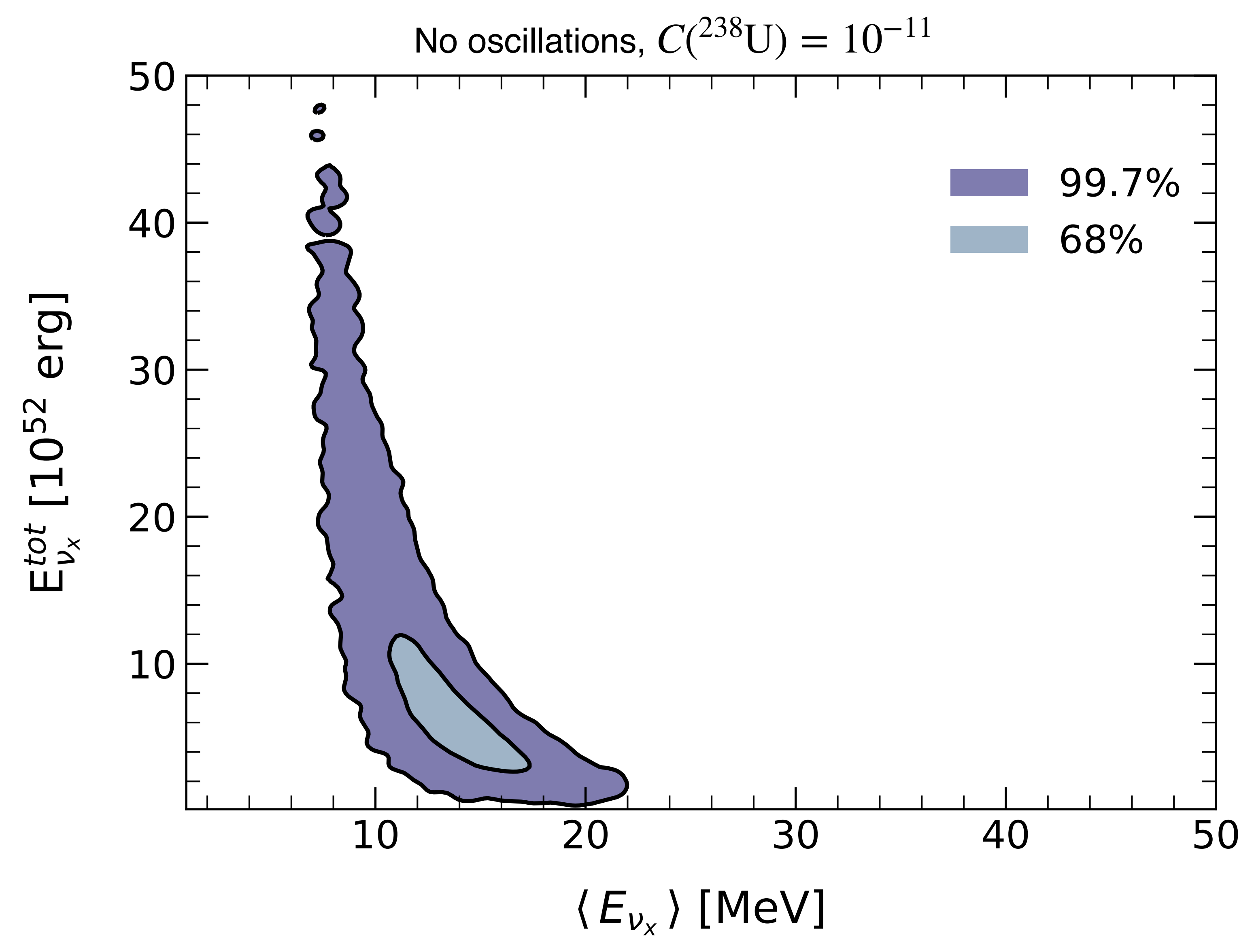
# Time Integrated Signals: Galactic



# Time Integrated Signals: Galactic

The sum of neutrinos emitted by all SN exploded in our galaxy

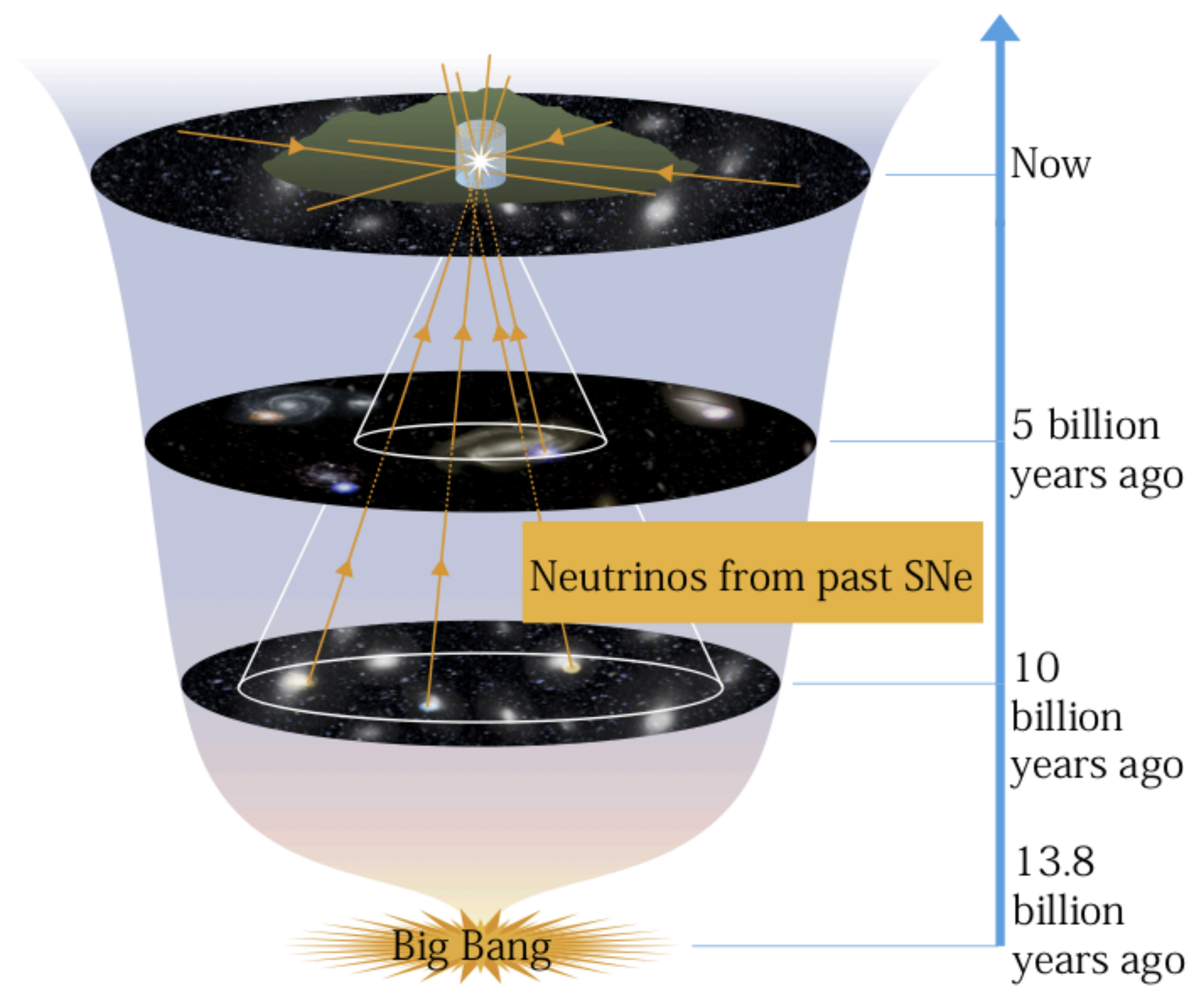
Baum, Capozzi, Horiuchi, arXiv:2203.12696v1



Potential detection using paleo-detectors.
Low background sample needed

# Time Integrated Signals: Diffuse

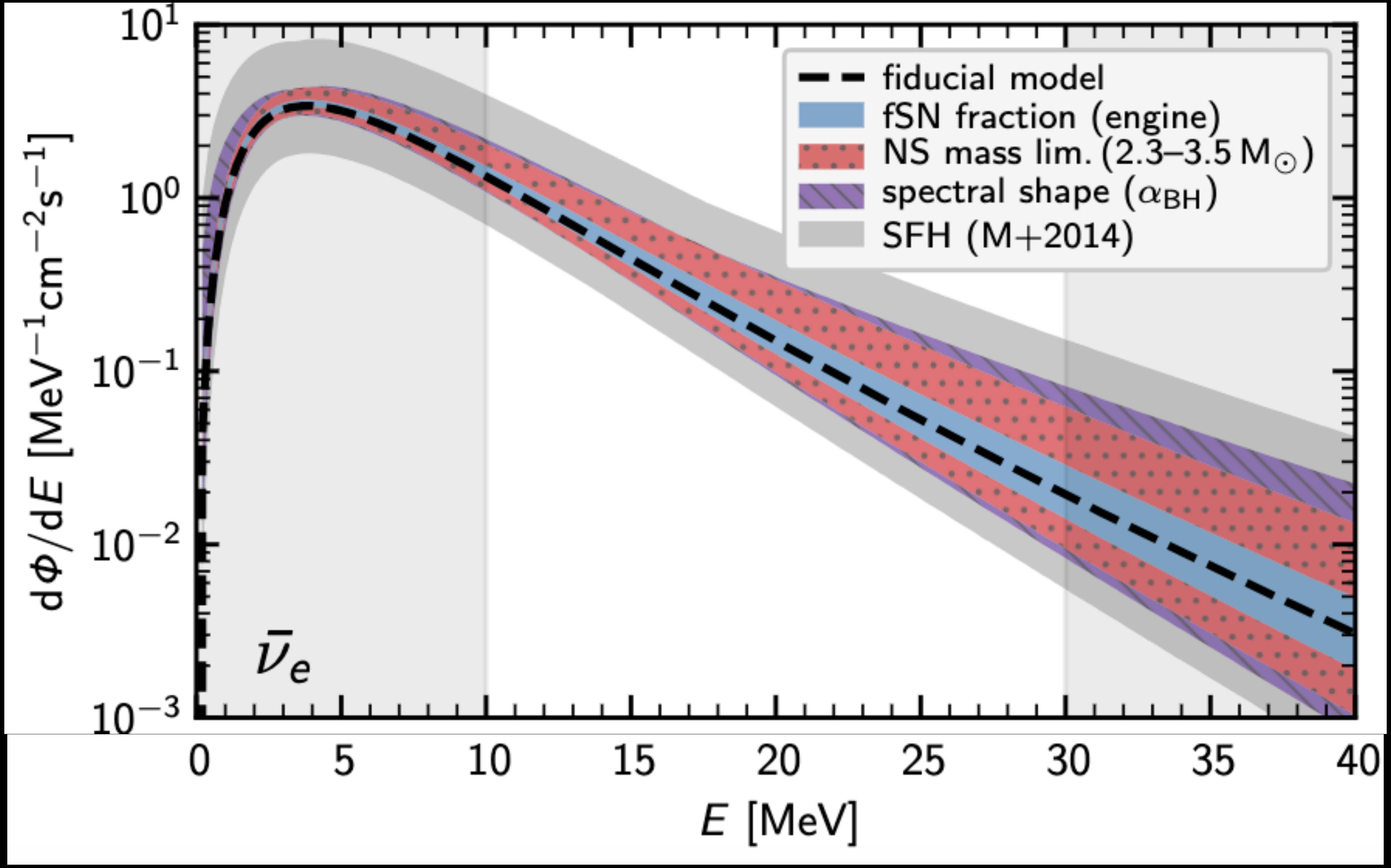
https://www-sk.icrr.u-tokyo.ac.jp/sk/news/2020/08/sk-gd-detail-e.html



# Time Integrated Signals: Diffuse

Diffuse flux sensitive to astrophysical ingredients

Kresse, Ertl, Janka, Astrophys. J. 909 (2021) no.2, 169

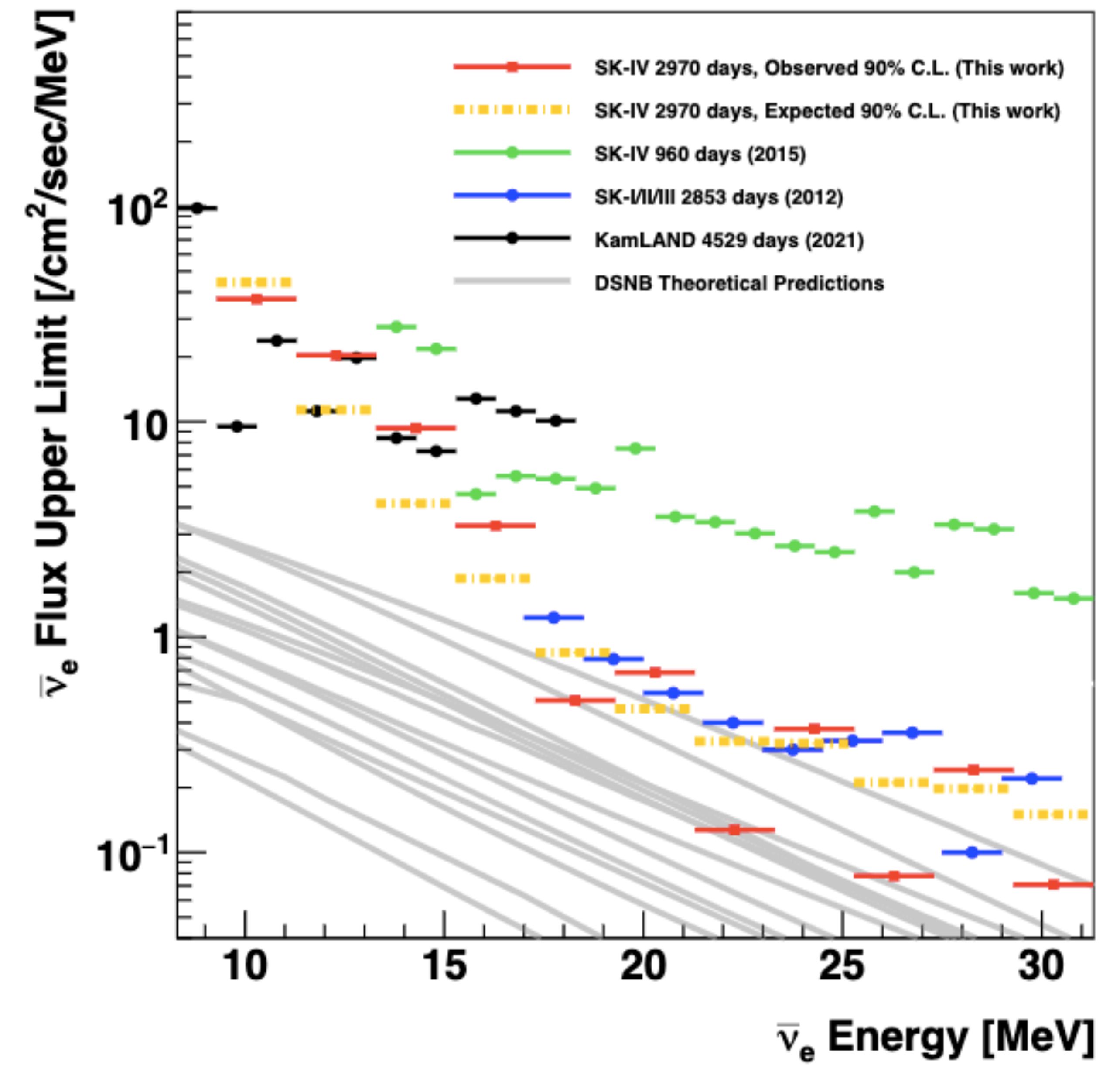


Measure star formation and failed supernova rates

# Time Integrated Signals: Diffuse

SuperK has currently the best sensitivity to DSNB

Abe  et al. [Super-Kamiokande], Phys. Rev. D 104 (2021) no.12, 122002

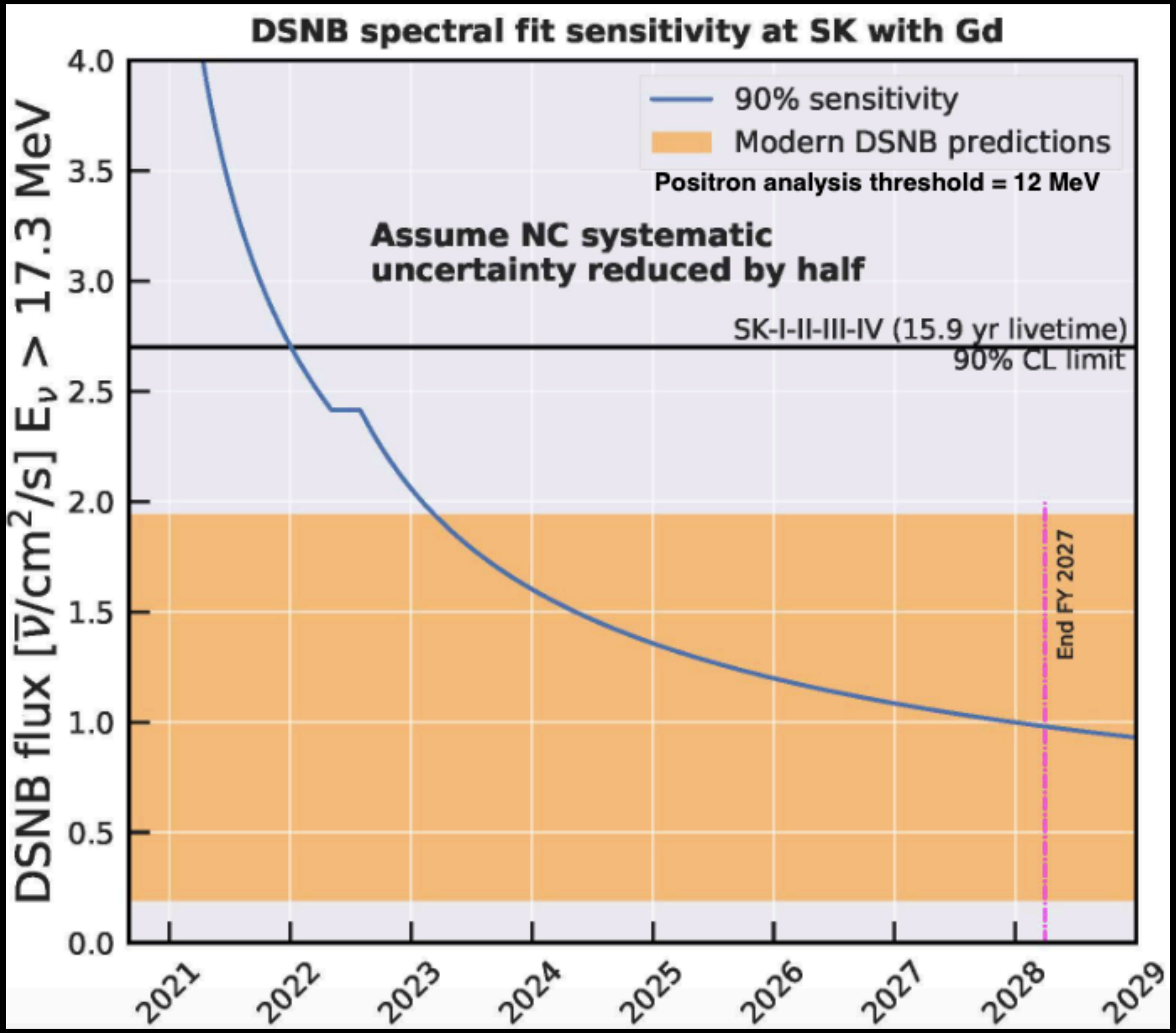


Some theoretical predictions are currently excluded

# Time Integrated Signals: Diffuse

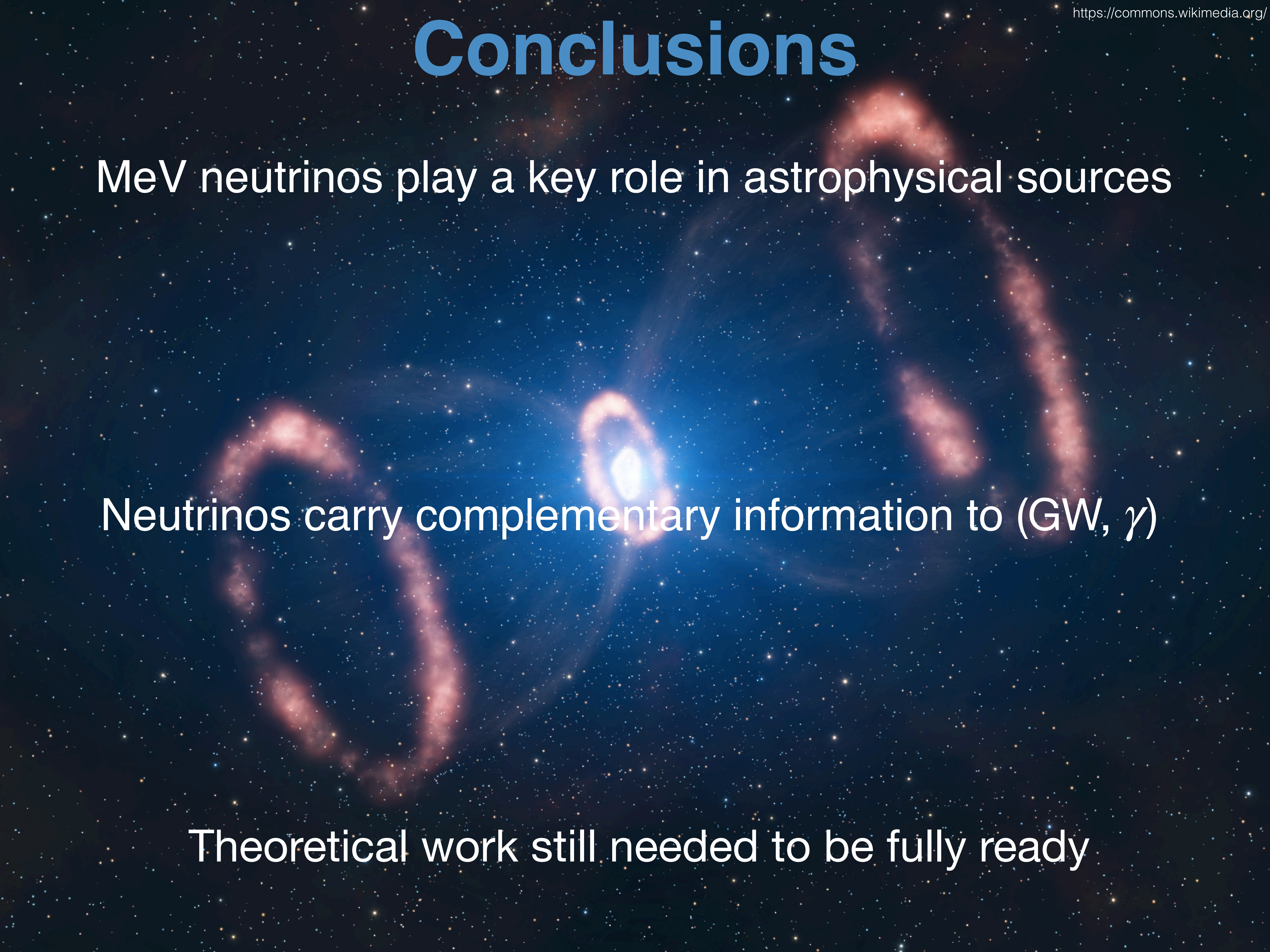
SuperK is currently adding more Gadolinium to the detector

M. Vagins talk at Neutrino 2022



Improvements in sensitivity expected in the next few years

# Conclusions



https://commons.wikimedia.org/

MeV neutrinos play a key role in astrophysical sources

Neutrinos carry complementary information to (GW, $\gamma$)

Theoretical work still needed to be fully ready

# Thank you!