DTP / TALENT 2024:
Nuclear Theory For Astrophysics

Supernova Neutrinos

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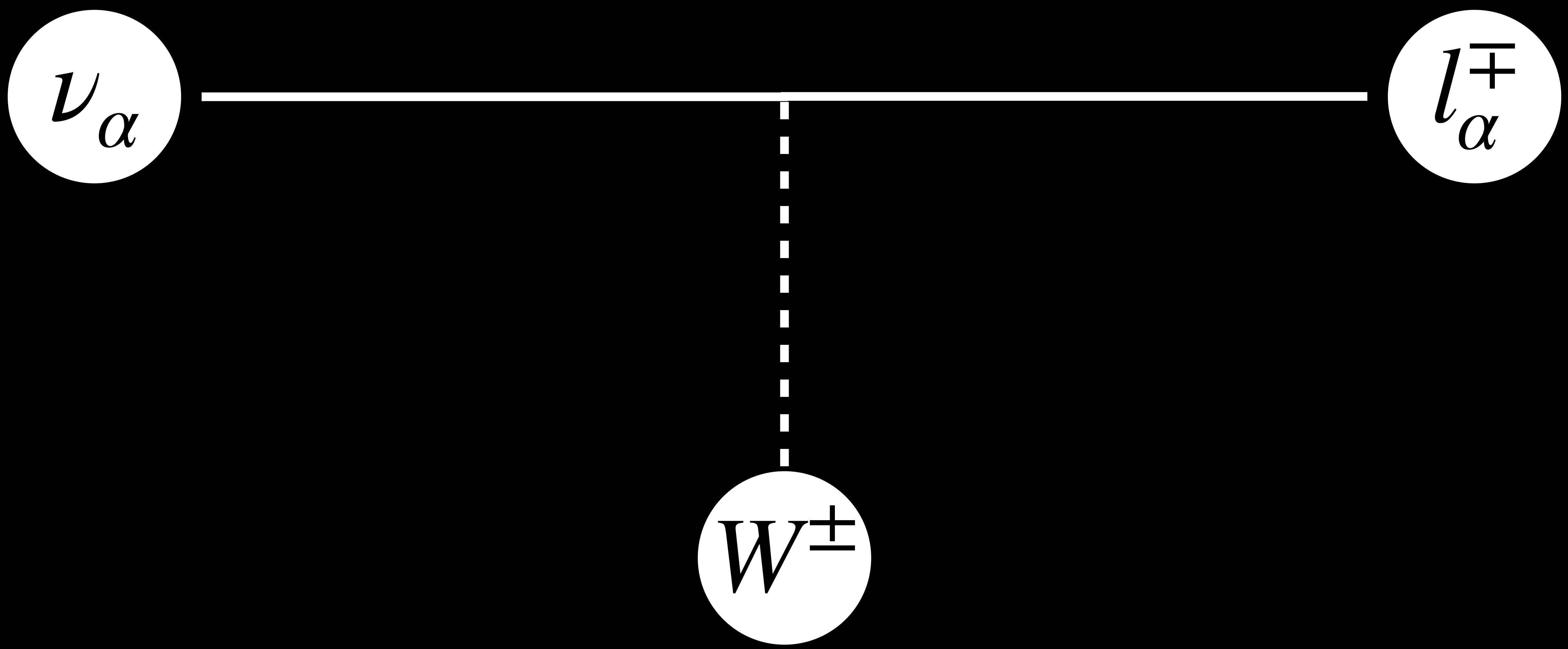
INTRODUCTION

Neutrino oscillation, production and detection

Neutrinos

Neutral fermions. Only interact through weak interactions.



They come in **three flavours**: $\nu_\alpha = (\nu_e, \nu_\mu, \nu_\tau)$

Neutrinos

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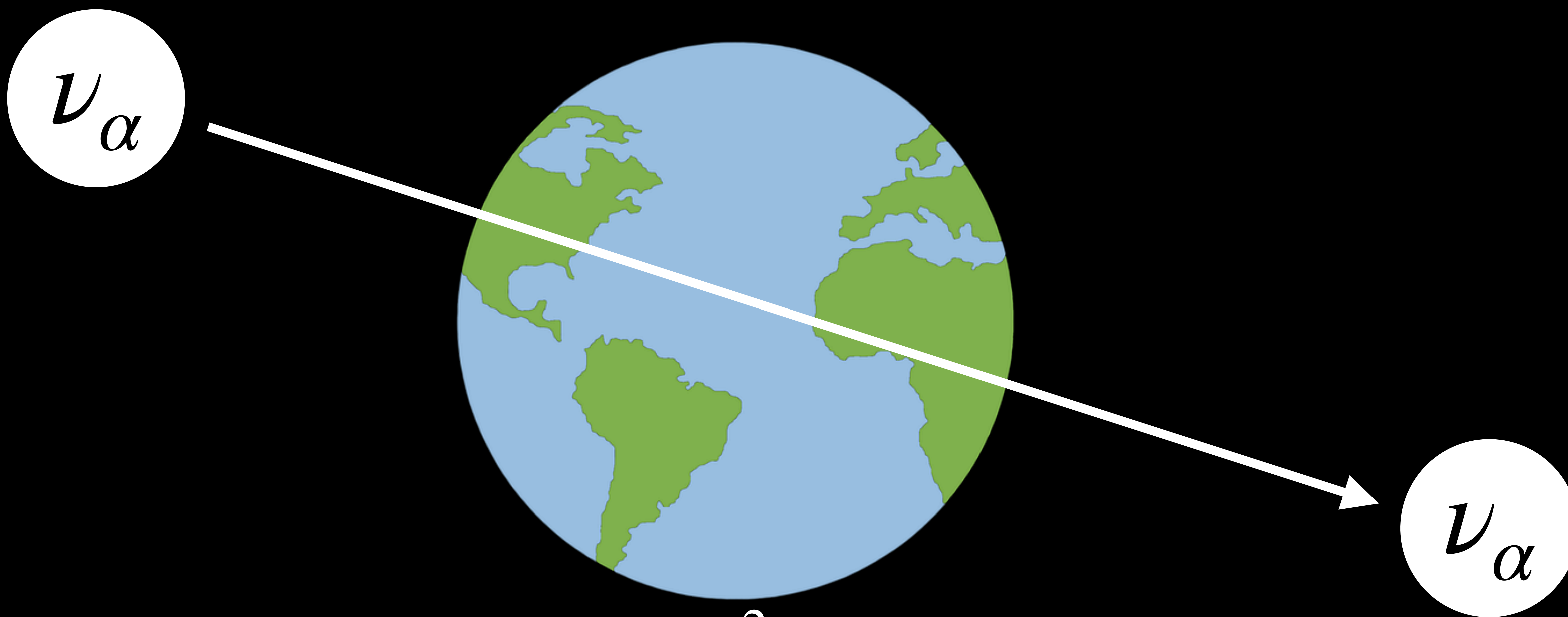

$$\sigma_{\bar{\nu}p,\nu n} \simeq 5 \times 10^{-44} \left(\frac{E_\nu}{\text{MeV}}\right)^2 \text{cm}^2 \qquad \rho_{\text{Earth}} = 5.5\,\text{gr}\,\text{cm}^{-3}$$

A 10 MeV neutrino has a mean free path of 6×10^{11} km

Neutrinos

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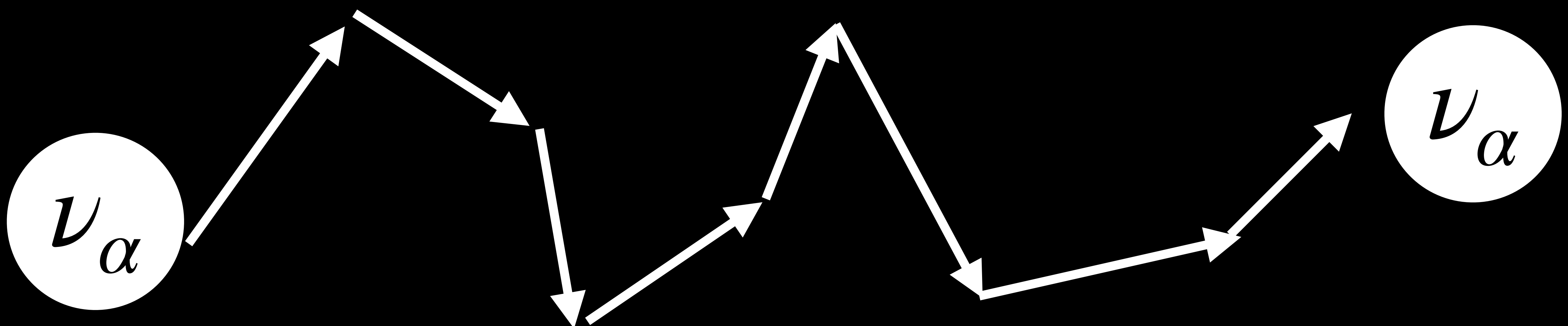
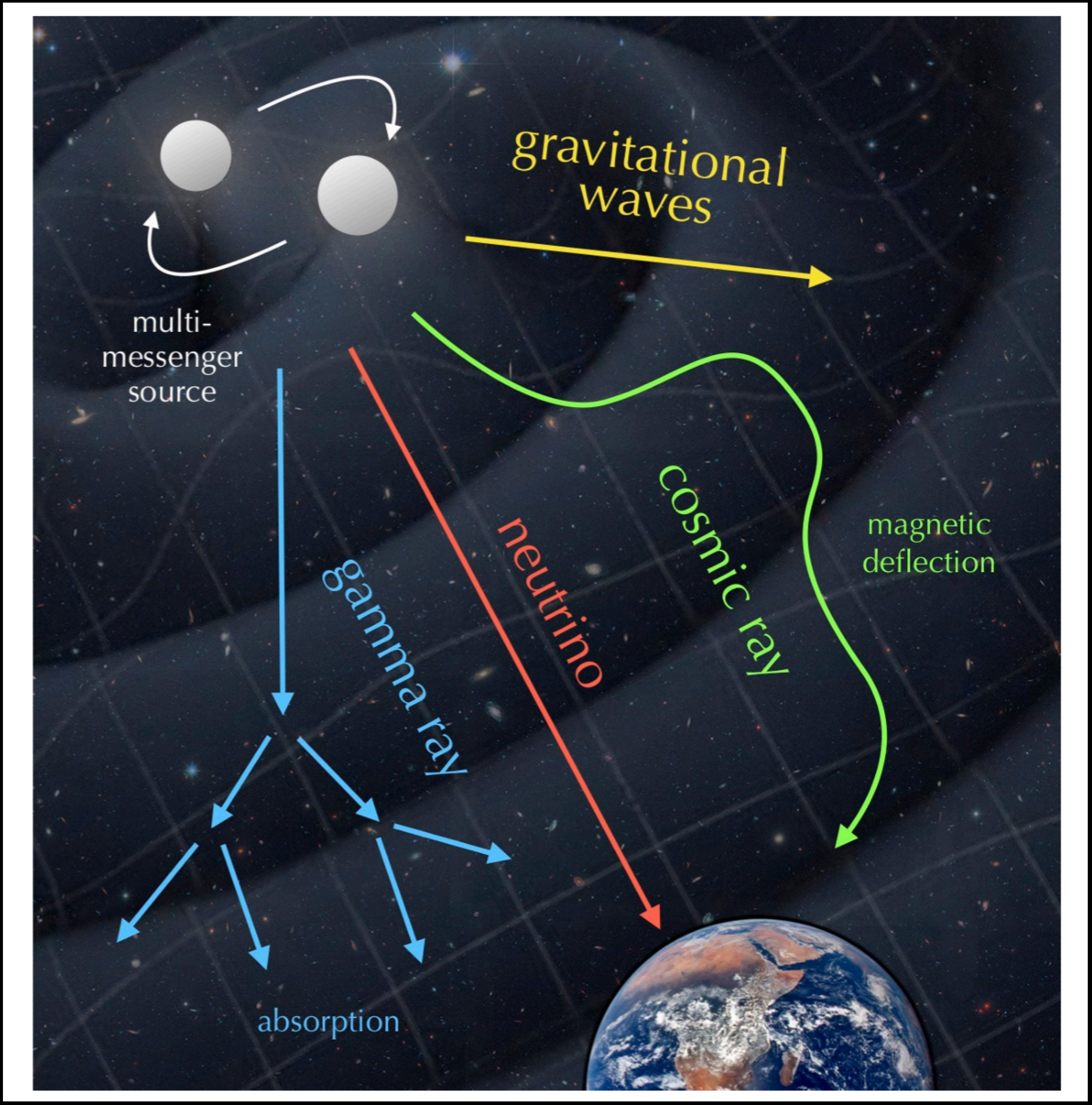


$$\sigma_{\bar{\nu}p,\nu n} \simeq 5 \times 10^{-44} \left(\frac{E_\nu}{\text{MeV}} \right)^2 \text{cm}^2 \qquad \rho = 10^{11}\,\text{gr}\,\text{cm}^{-3}$$

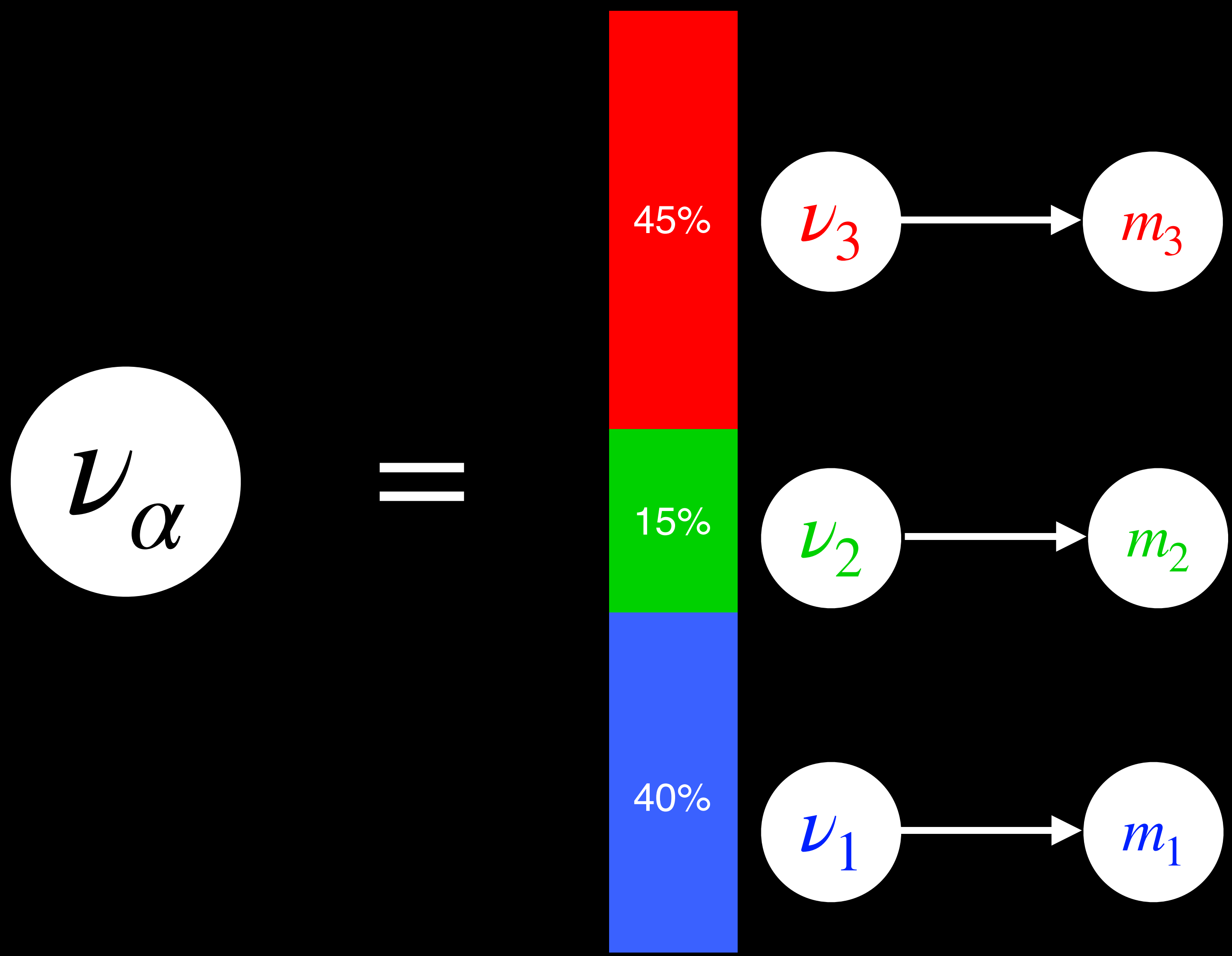
A 10 MeV neutrino has a mean free path of $O(10)\,\text{km}$

Neutrinos


gravitational waves
multi-messenger source
gamma ray
neutrino
cosmic ray
magnetic deflection
absorption

Neutrino Mixing

A neutrino is produced in a flavour eigenstate.

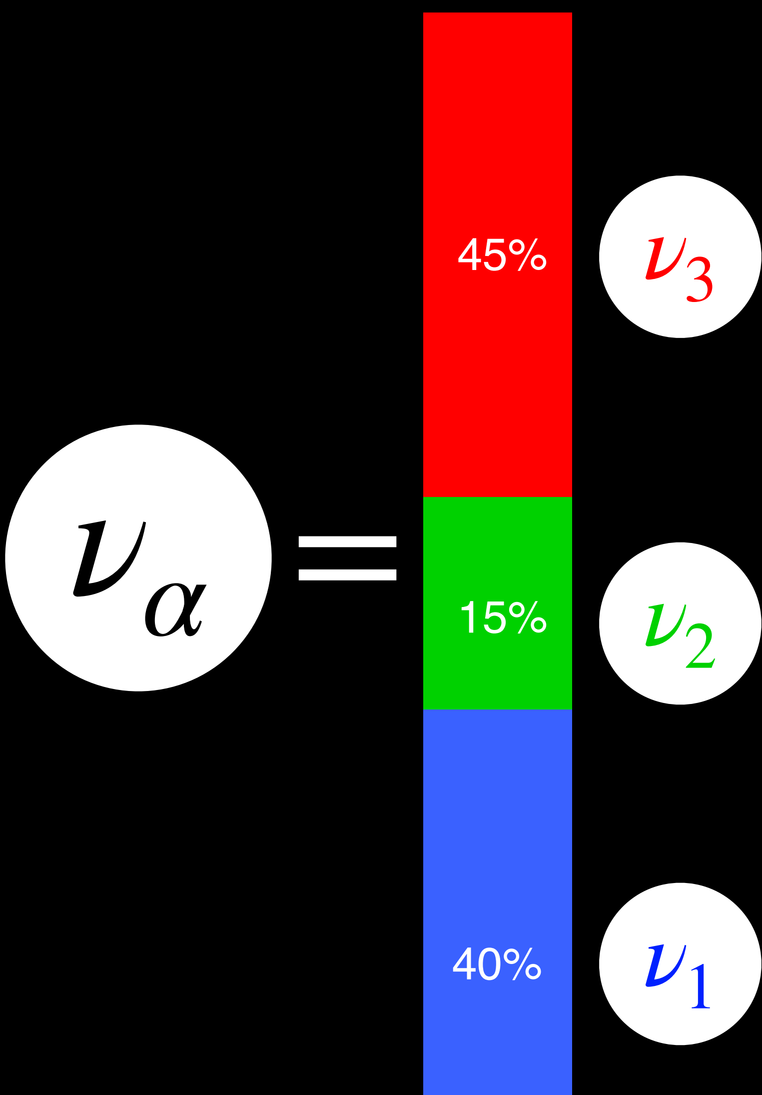


Flavour eigenstates is a superposition of mass eigenstates

$$|\nu_\alpha\rangle = \sum_k U^*_{\alpha k} |\nu_k\rangle$$

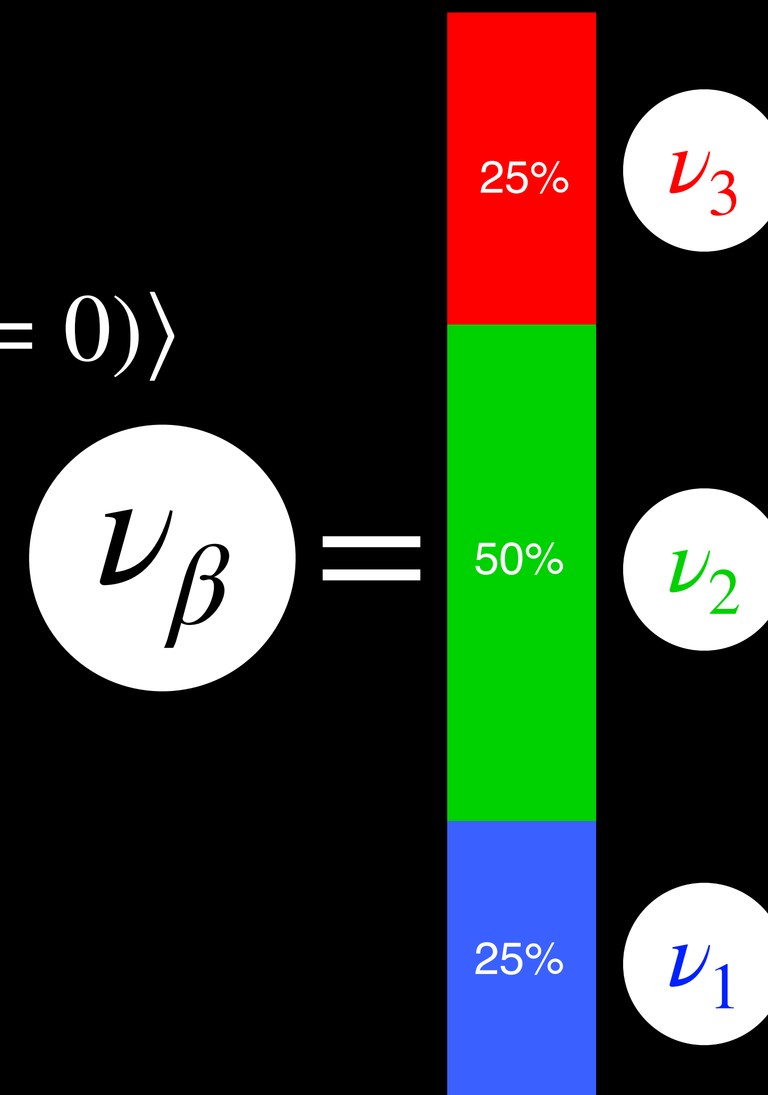
Neutrino Oscillations

Each mass eigenstate has a different time evolution



$$|\nu_k(t)\rangle = \sum_k e^{iE_k t}|\nu_k(t=0)\rangle$$

$$E_k \simeq E + \frac{m_k^2}{2E}$$



$$P(\nu_\alpha \to \nu_\beta) = \sum_{k,j} U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j} \left(-i \frac{\Delta m^2_{kj} t}{2E} \right)$$

Neutrino Oscillations

Assuming two flavours oscillations have a simple expression

θ = "mixing angle"

$$\Delta m^2 = m_2^2 - m_1^2$$

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

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$$\frac{\Delta m^2 L}{4E} = 1.27\left(\frac{\Delta m^2}{10^{-3}\,\mathrm{eV}^2}\right)\left(\frac{L}{10^3\,\mathrm{km}}\right)\left(\frac{E}{\mathrm{GeV}}\right)^{-1}$$

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$$\Delta m^2 = 2\times 10^{-3}\,\mathrm{eV}^2 \implies L \sim 10\,\mathrm{km}\,(E = 10\,\mathrm{MeV})$$

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$$\Delta m^2 = 7 \times 10^{-5}\,\mathrm{eV}^2 \implies L \sim 300\,\mathrm{km}\,(E = 10\,\mathrm{MeV})$$

Neutrino Oscillations

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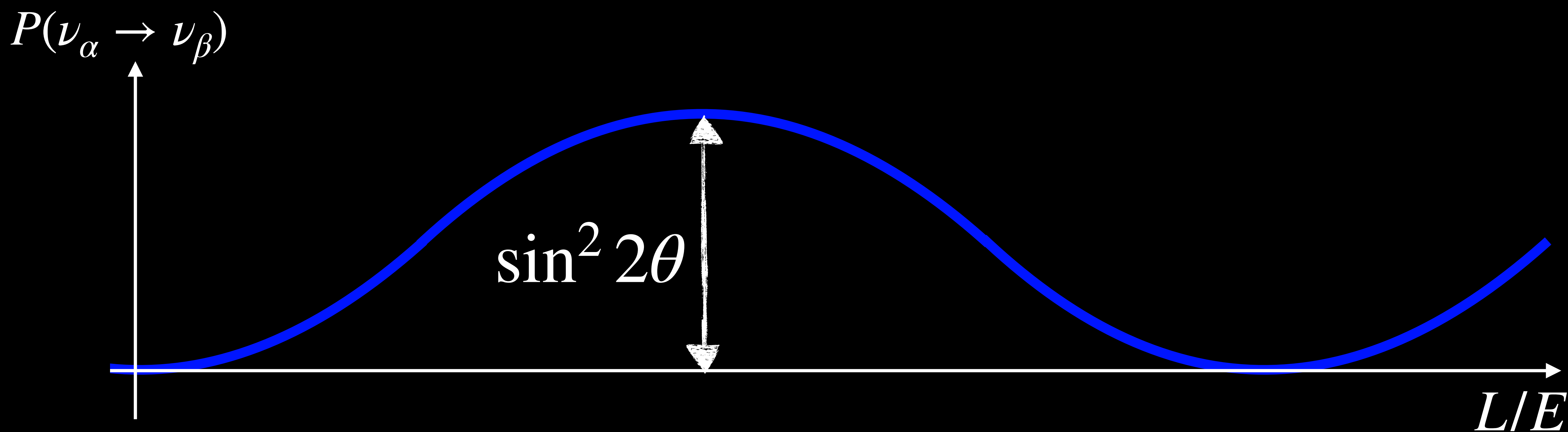

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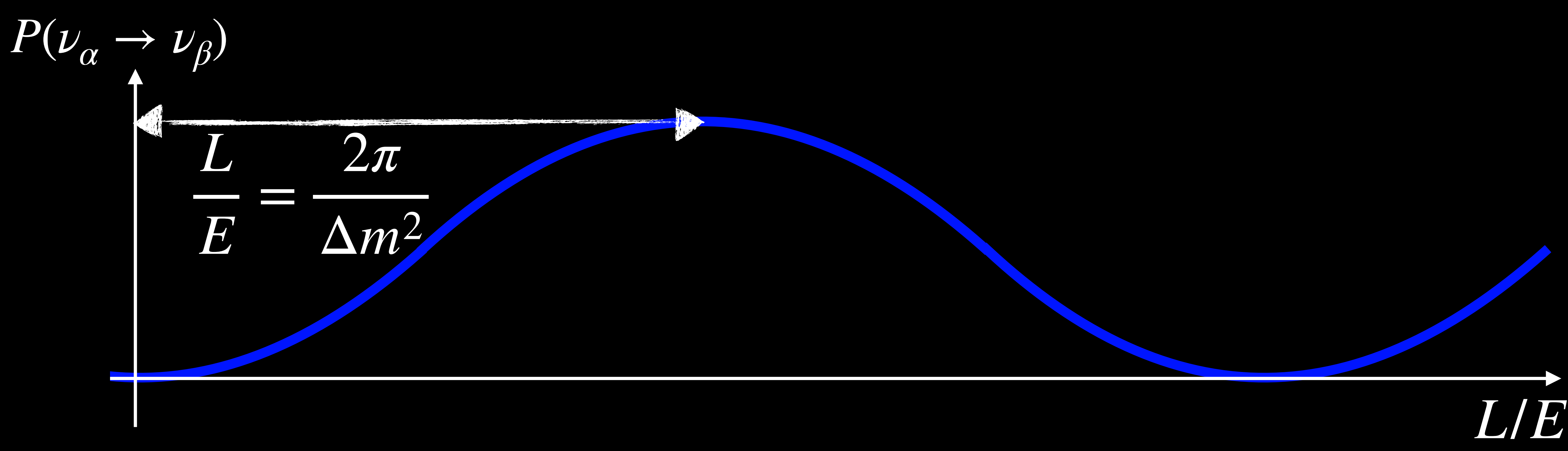


Neutrino Oscillations

In the standard three flavour scenario

$$\sin^2\theta_{13} \simeq 0.02$$

$$\sin^2\theta_{23} \simeq 0.5$$

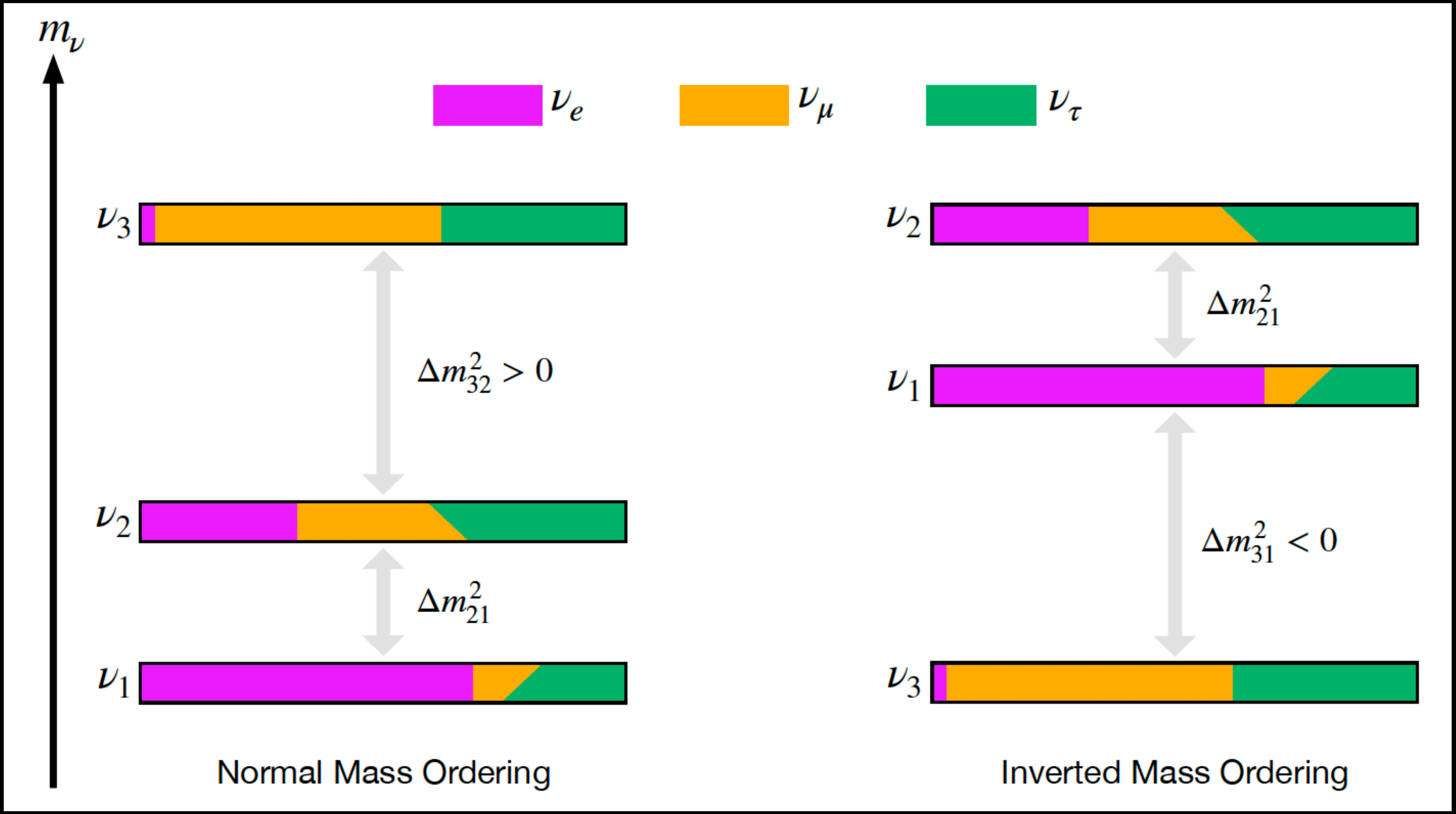
$$\sin^2\theta_{12} \simeq 0.3$$

$$|\Delta m^2_{31}| = |m^2_3 - m^2_1| \simeq 2 \times 10^{-3}\,\mathrm{eV}^2$$

$$\Delta m^2_{21} = m^2_2 - m^2_1 \simeq 7 \times 10^{-5}\,\mathrm{eV}^2$$

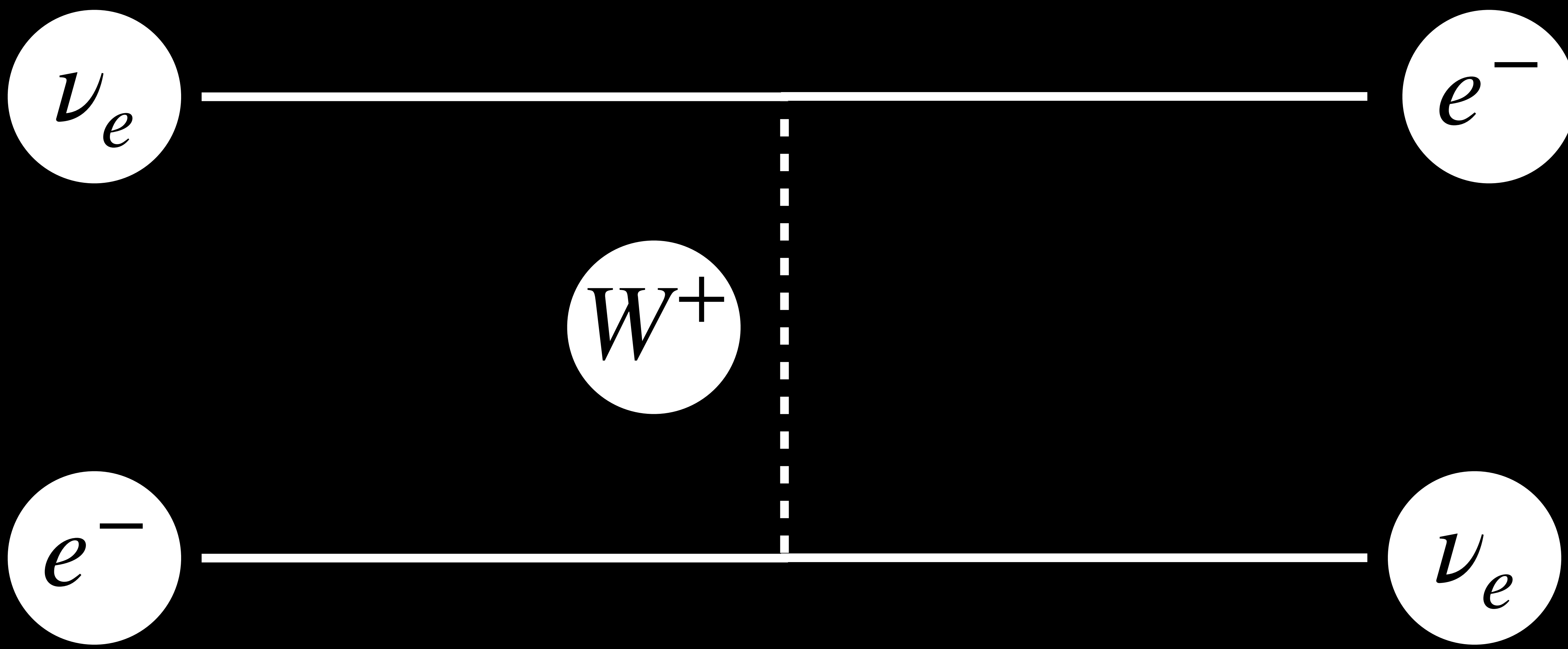
Neutrino Oscillations

In the standard three flavour scenario



Neutrino Oscillations

Propagation in matter is affected by a potential due to electrons



$$V_e = \sqrt{2} G_F N_e = 1.27 \times 10^{-37}\,\mathrm{eV} \left(\frac{N_e}{\mathrm{cm}^{-3}} \right)$$

Neutrino Oscillations

In terms of effective mixing angle in matter θ_M

$$\Delta m_M^2 = \sqrt{(\Delta m^2 \cos 2\theta - 2EV_e)^2 + (\Delta m^2 \sin 2\theta)^2}$$

$$\sin 2\theta_M = \frac{\Delta m^2 \sin 2\theta}{\Delta m_M^2}$$

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta_M \sin^2\left(\frac{\Delta m_M^2 L}{4E}\right)$$

Neutrino Oscillations

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MATTER DOMINATION

$$V_e \gg \frac{\Delta m^2}{2E} \cos 2\theta \implies \theta_M = \frac{\pi}{2}, \Delta m_M^2 = 2EV_e$$

Neutrino Oscillations

In terms of effective mixing angle in matter θ_M

$$\Delta m_M^2 = \sqrt{(\Delta m^2 \cos 2\theta - 2EV_e)^2 + (\Delta m^2 \sin 2\theta)^2}$$

$$\sin 2\theta_M = \frac{\Delta m^2 \sin 2\theta}{\Delta m_M^2}$$

VACUUM

$$V_e \ll \frac{\Delta m^2}{2E} \cos 2\theta \implies \theta_M = \theta, \Delta m_M^2 = \Delta m^2$$

Neutrino Oscillations

In terms of effective mixing angle in matter θ_M

$$\Delta m_M^2 = \sqrt{(\Delta m^2 \cos 2\theta - 2EV_e)^2 + (\Delta m^2 \sin 2\theta)^2}$$

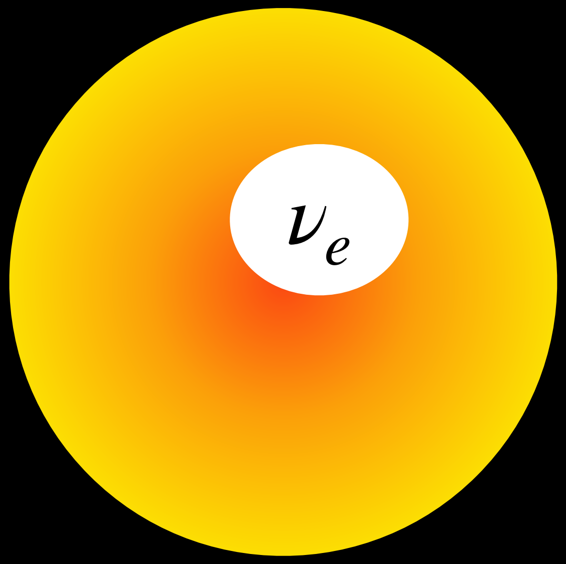
$$\sin 2\theta_M = \frac{\Delta m^2 \sin 2\theta}{\Delta m_M^2}$$

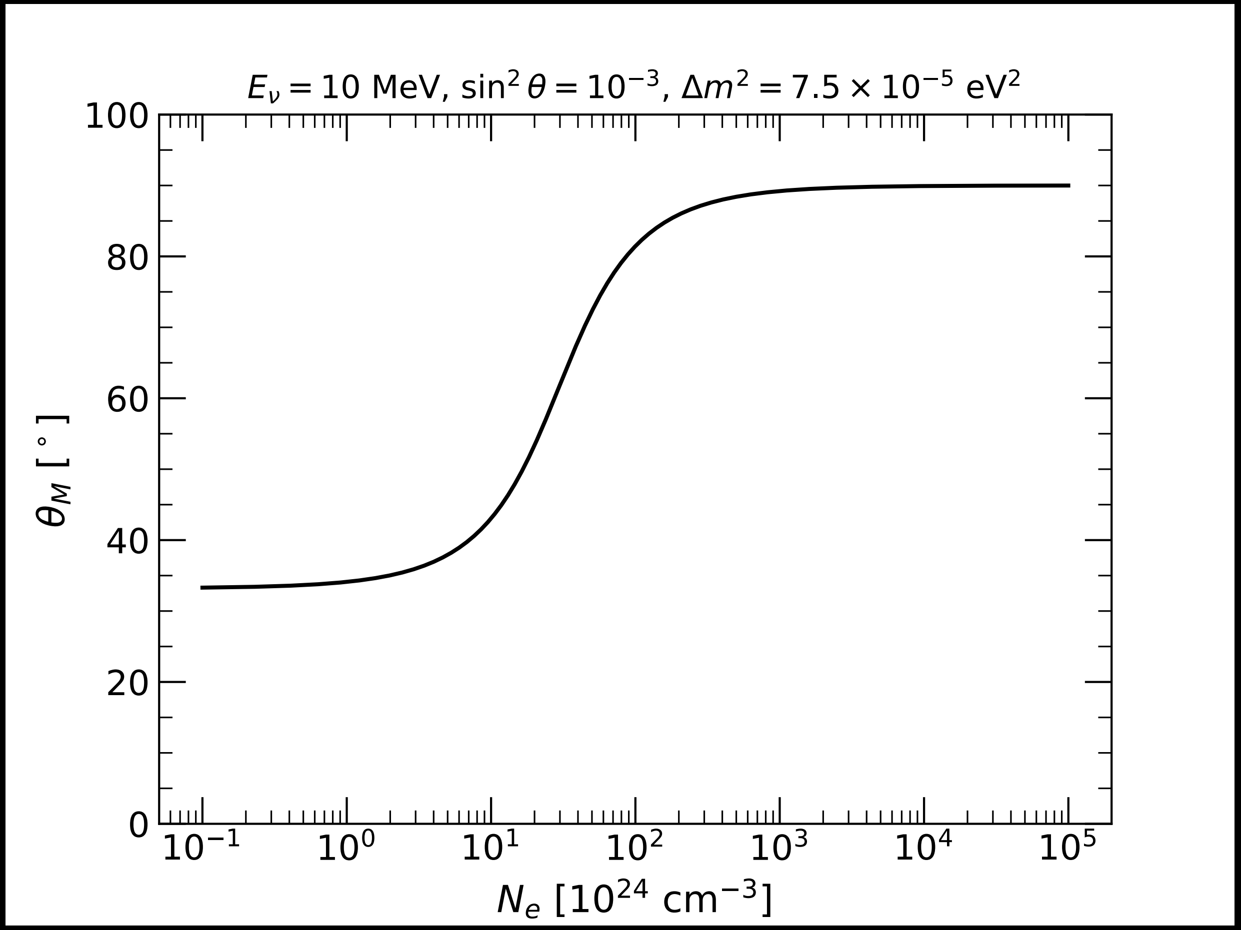
RESONANCE

$$V_e = \frac{\Delta m^2}{2E} \cos 2\theta \implies \theta_M = \frac{\pi}{4}, \Delta m_M^2 = \Delta m^2 \sin 2\theta$$

Neutrino Oscillations

Let us consider a 10 MeV ν_e produced in the core of the Sun

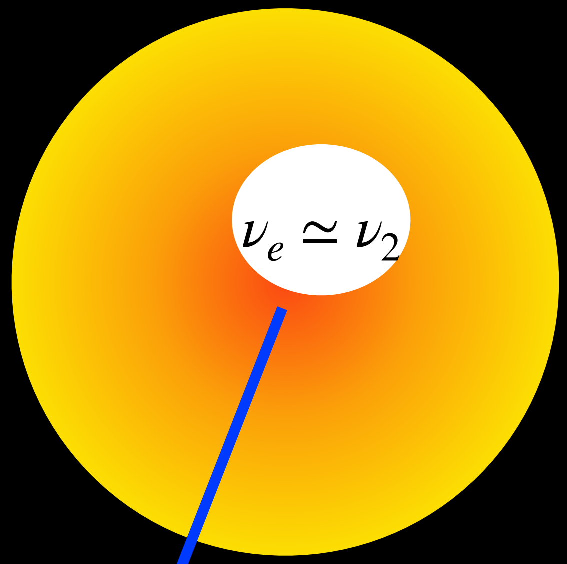


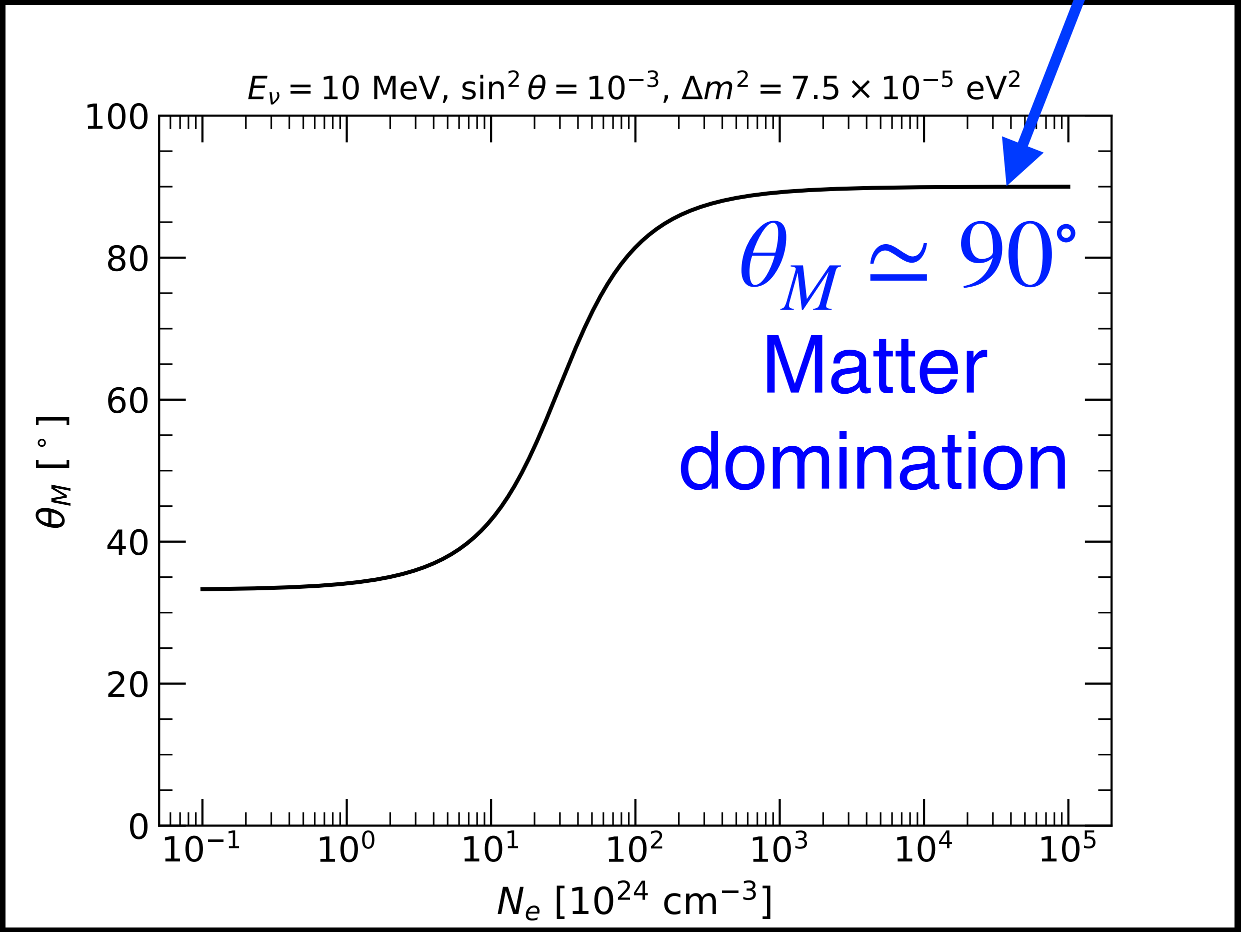


Neutrino Oscillations

Let us consider a 10 MeV ν_e produced in the core of the Sun

$$|\nu_e\rangle = \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle$$
$$|\nu_e\rangle \simeq |\nu_2\rangle$$





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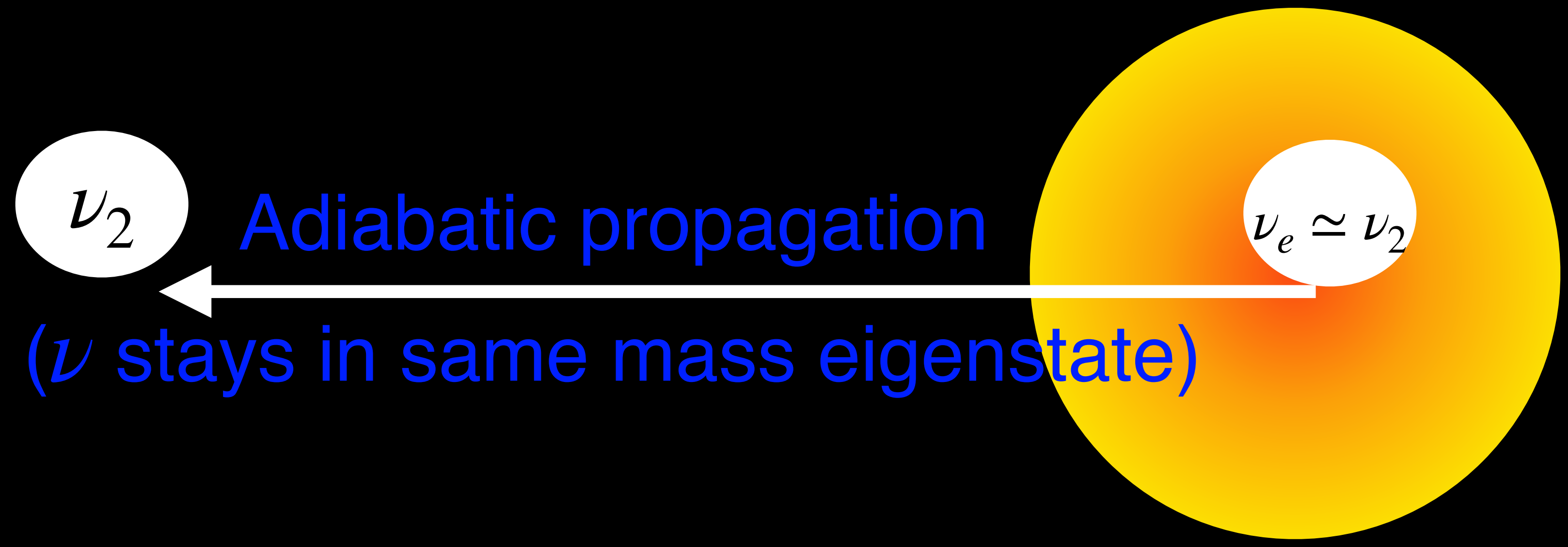

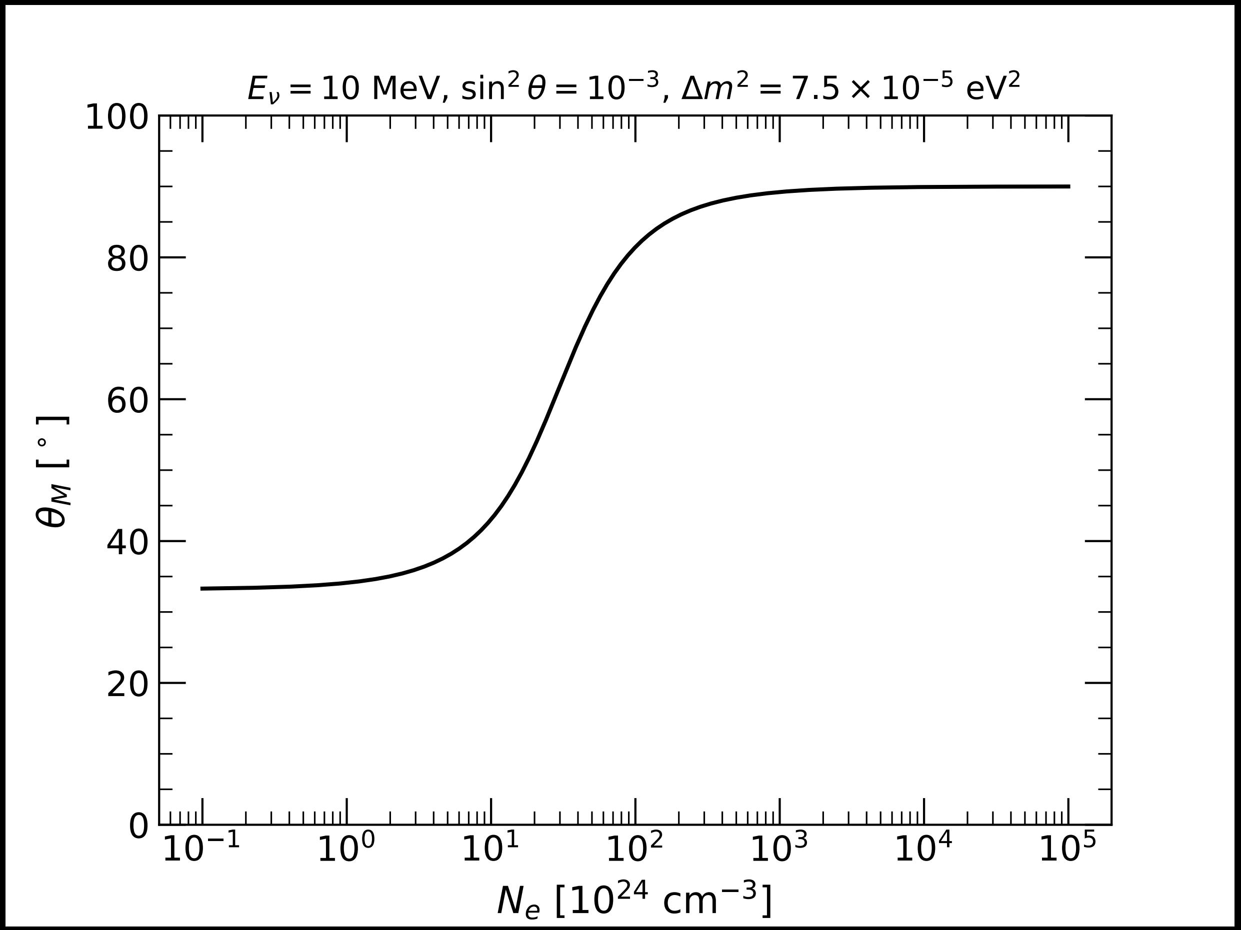

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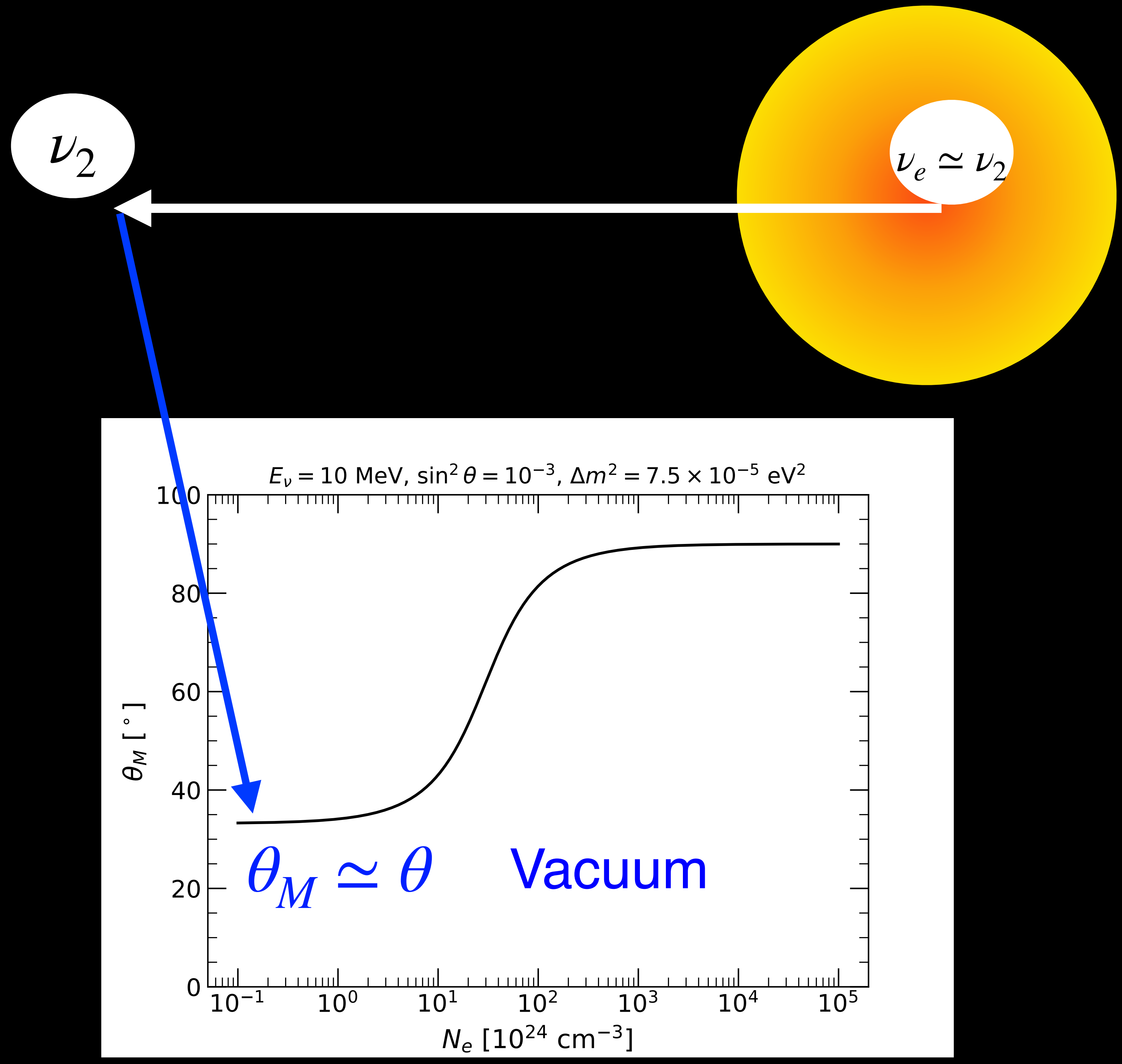

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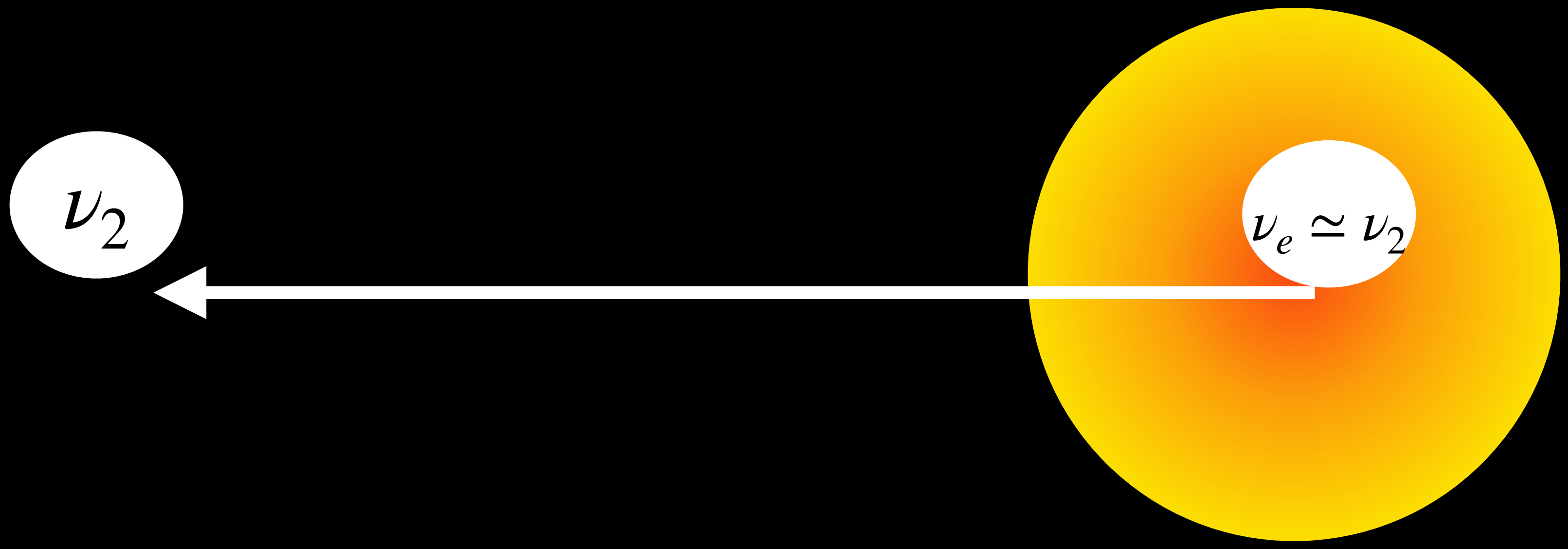


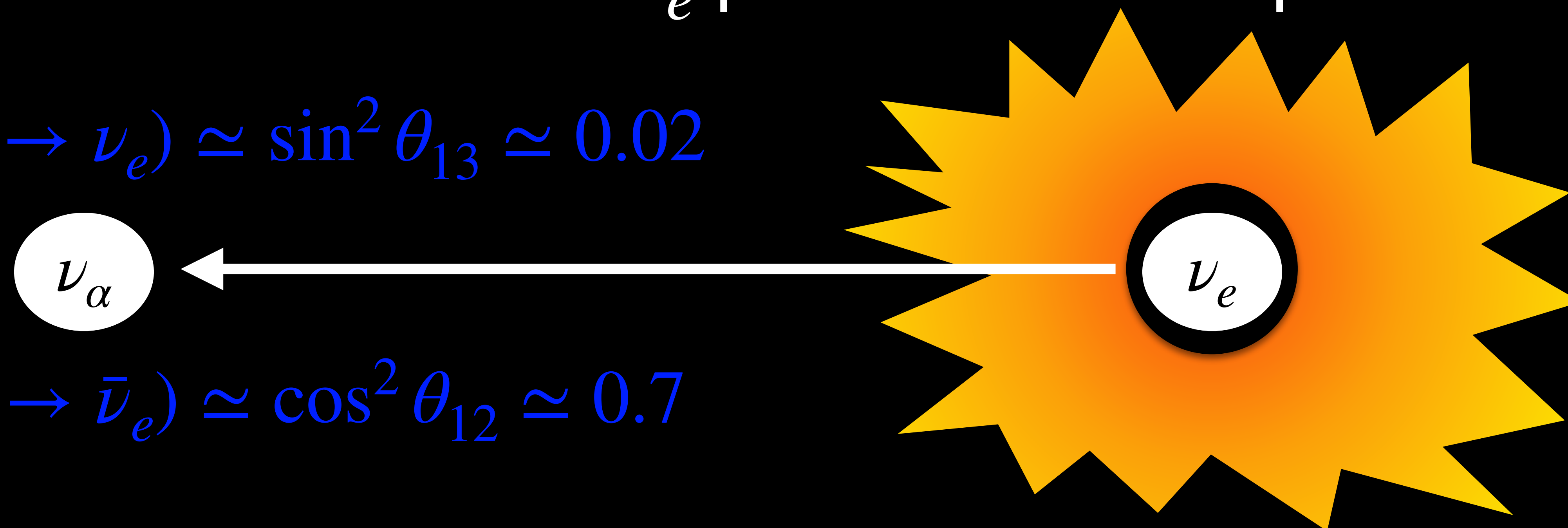
$$|\nu_2\rangle = \sin\theta\,|\nu_e\rangle + \cos\theta\,|\nu_\mu\rangle$$

$$P(\nu_e \to \nu_e) = \left|\langle\nu_e|\nu_2\rangle\right|^2 = \sin^2\theta$$

Neutrino Oscillations

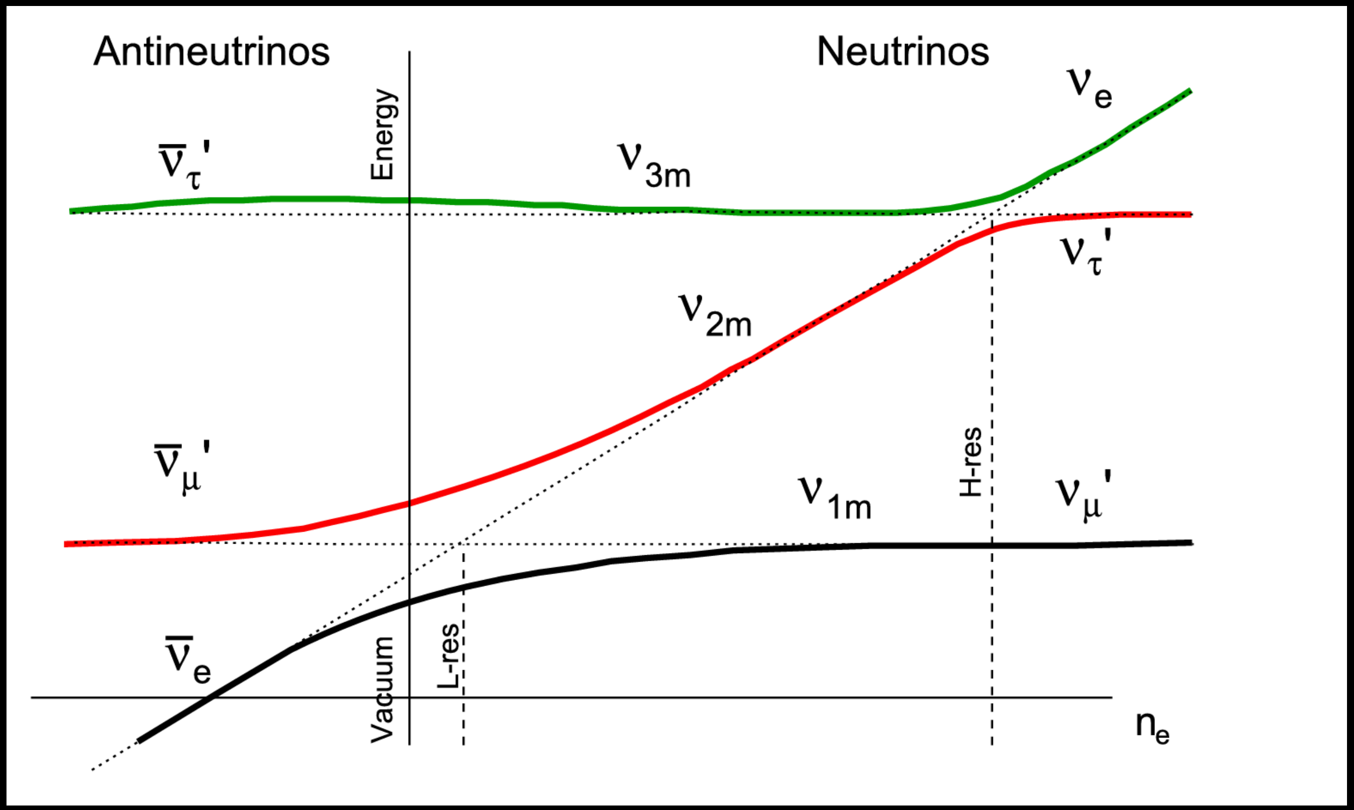
Let us consider a 10 MeV ν_e produced in a supernova

$$P(\nu_e \to \nu_e) \simeq \sin^2\theta_{13} \simeq 0.02$$



$$P(\bar{\nu}_e \to \bar{\nu}_e) \simeq \cos^2\theta_{12} \simeq 0.7$$

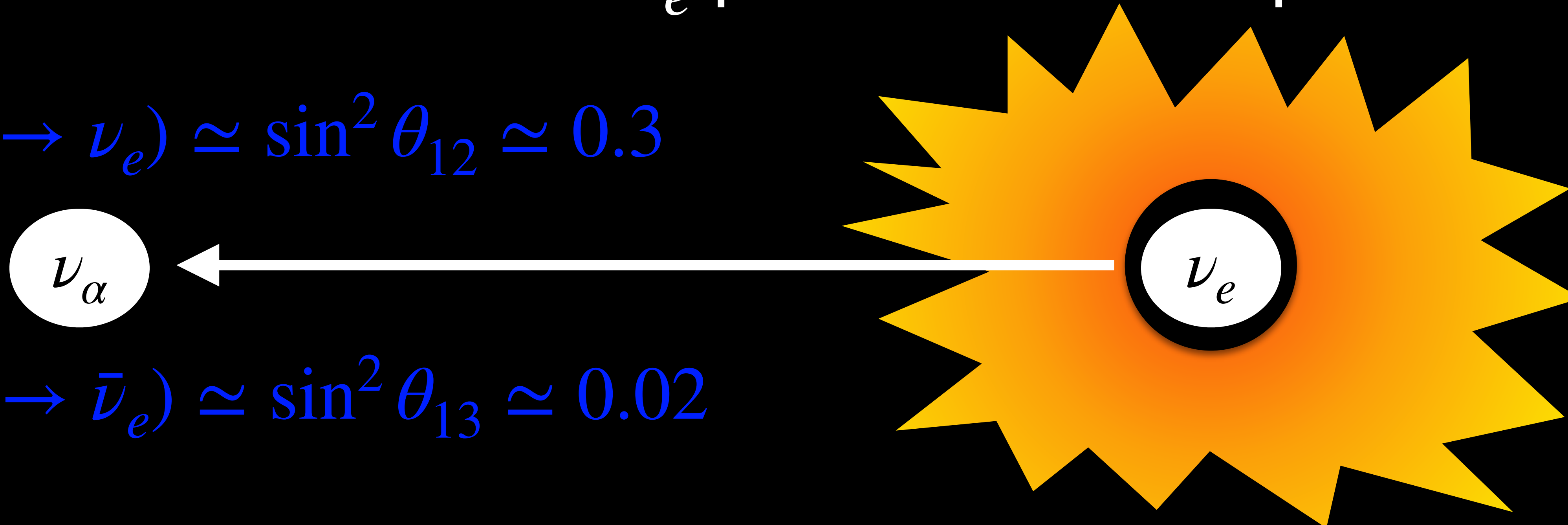
Normal Ordering



Neutrino Oscillations

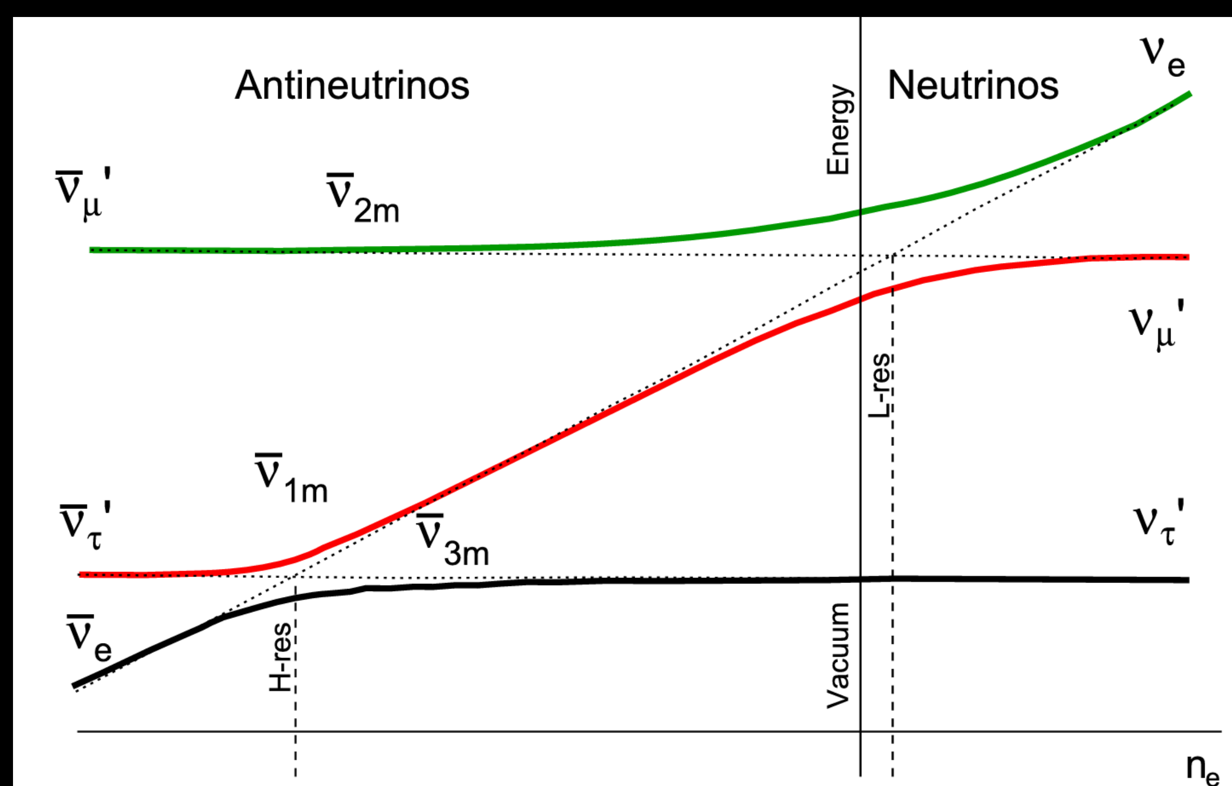
Let us consider a 10 MeV ν_e produced in a supernova

$$P(\nu_e \to \nu_e) \simeq \sin^2\theta_{12} \simeq 0.3$$



$$P(\bar{\nu}_e \to \bar{\nu}_e) \simeq \sin^2\theta_{13} \simeq 0.02$$

Inverted Ordering



Neutrino Production Processes

Beta processes

$$e^- + (A,Z) \leftrightarrow (A,Z-1) + \nu_e$$

$$(A,Z) \rightarrow (A,Z\pm 1) + e^\mp + \overset{(-)}{\nu}_e$$

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

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

Suppressed when matter is degenerate

Neutrino Production Processes

Heavier leptons/hadron decays

$$\left.\begin{array}{l}\mu^- + p \leftrightarrow \nu_\mu + n \\ \mu^+ + n \leftrightarrow \bar{\nu}_\mu + p\end{array}\right\}$$ supernova core

$$\mu^\pm \rightarrow \overset{(-)}{\nu}_\mu + e^\pm + \overset{(-)}{\nu}_e$$

$$\pi^\pm \rightarrow l_\alpha^\pm + \overset{(-)}{\nu}_\alpha$$

$$K^\pm \rightarrow l_\alpha^\pm + \overset{(-)}{\nu}_\alpha$$

Neutrino Production Processes

"Thermal" pair production in a plasma (star / supernova)

$N + N \leftrightarrow N + N + \nu + \bar{\nu}$ (nucleon bremsstrahlung)

$e^{\pm} + (A, Z) \leftrightarrow e^{\pm} + (A, Z) + \nu + \bar{\nu}$ ($e^{\pm}$ bremsstrahlung)

$\gamma + e^{-} \leftrightarrow e^{-} + \nu + \bar{\nu}$ (photoneutrinos)

$e^{-} + e^{+} \leftrightarrow \nu + \bar{\nu}$ (Pair annihilation)

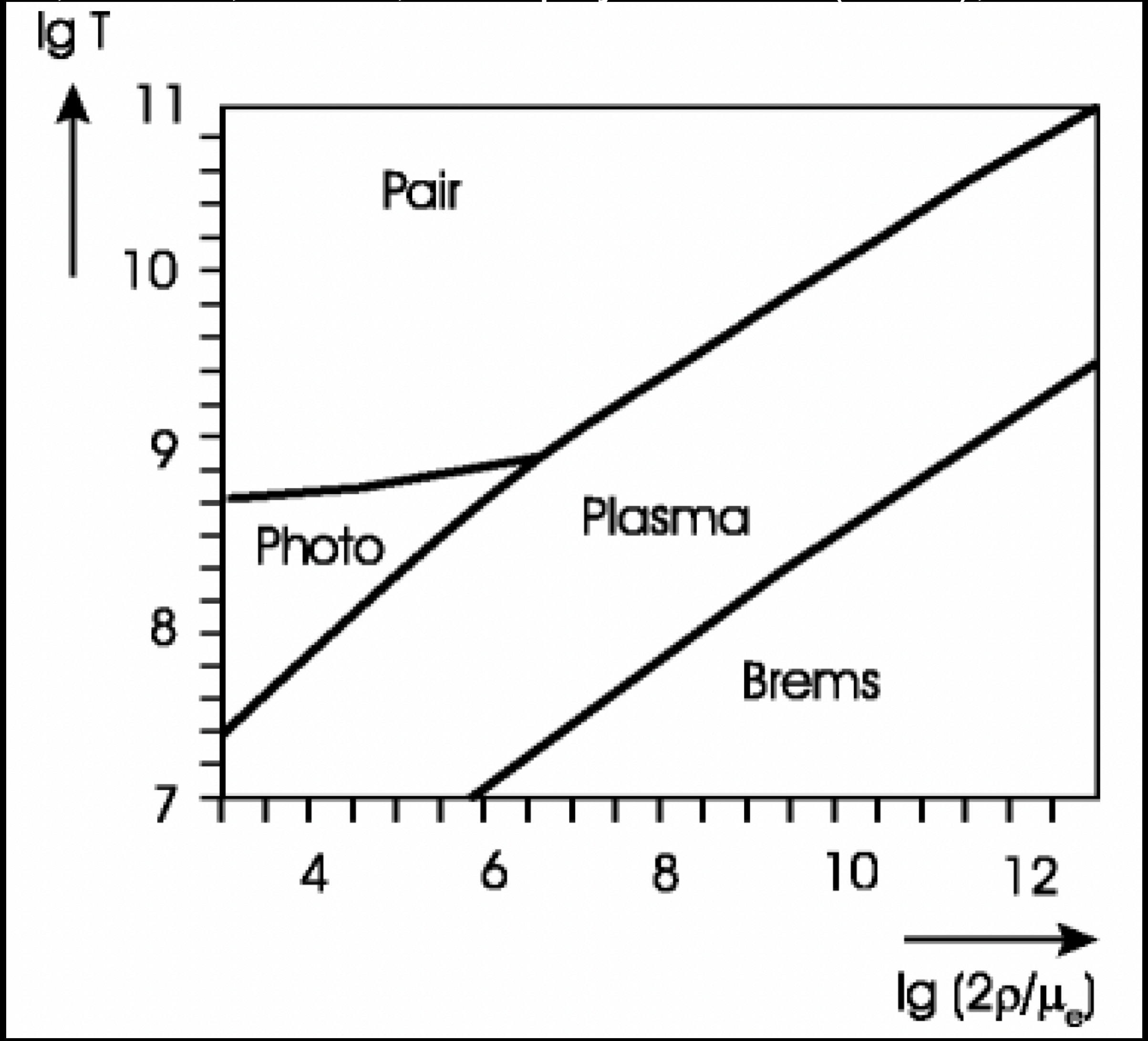
$\tilde{\gamma} \leftrightarrow \nu + \bar{\nu}$ (Plasmon decay)

Depending on the density and temperature of the medium one of these processes may dominate over the others

Neutrino Production Processes

"Thermal" pair production in a plasma (star / supernova)

Haft, Raffelt, Weiss, Astrophys. J. 425 (1994), 222-230



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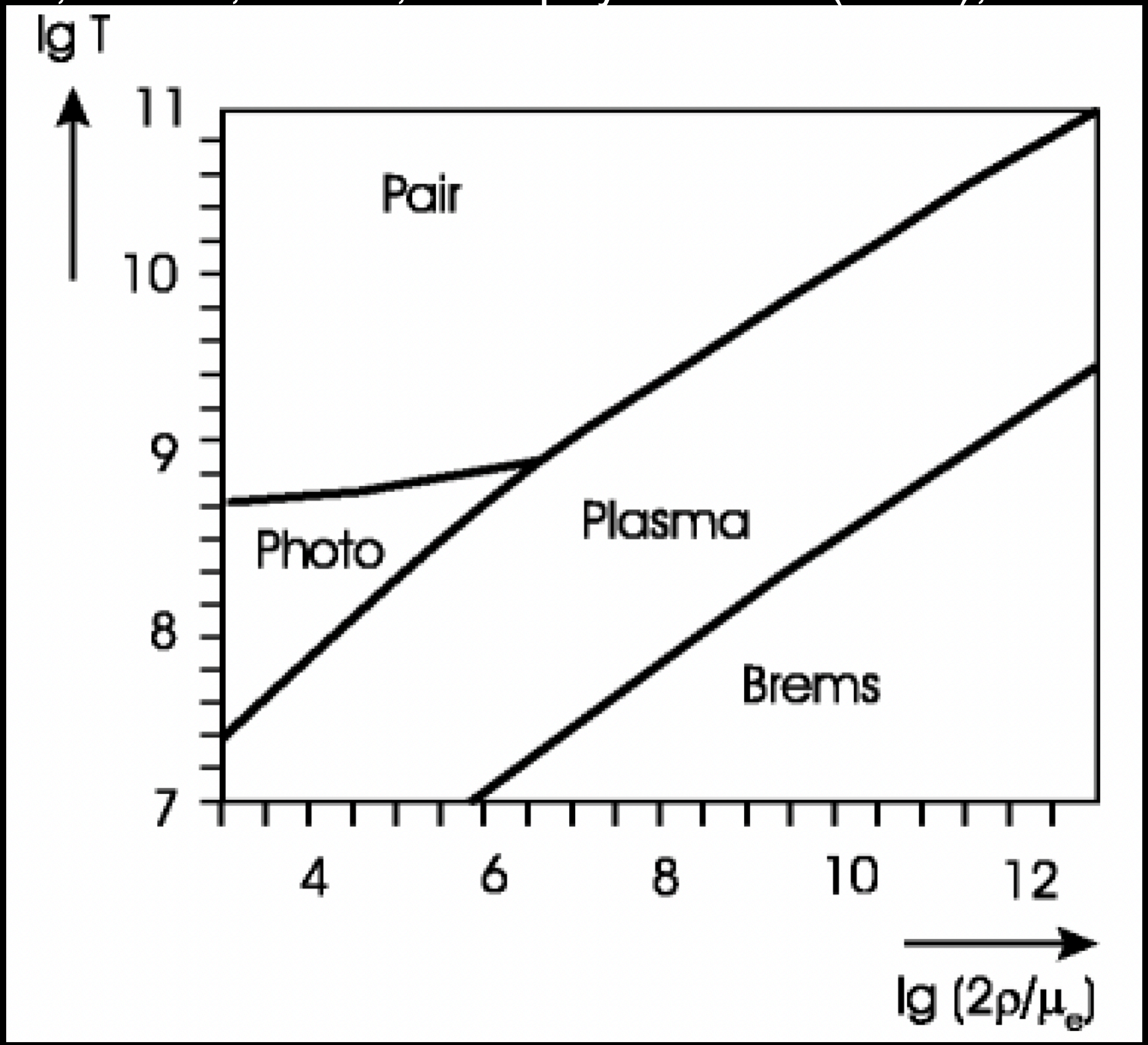


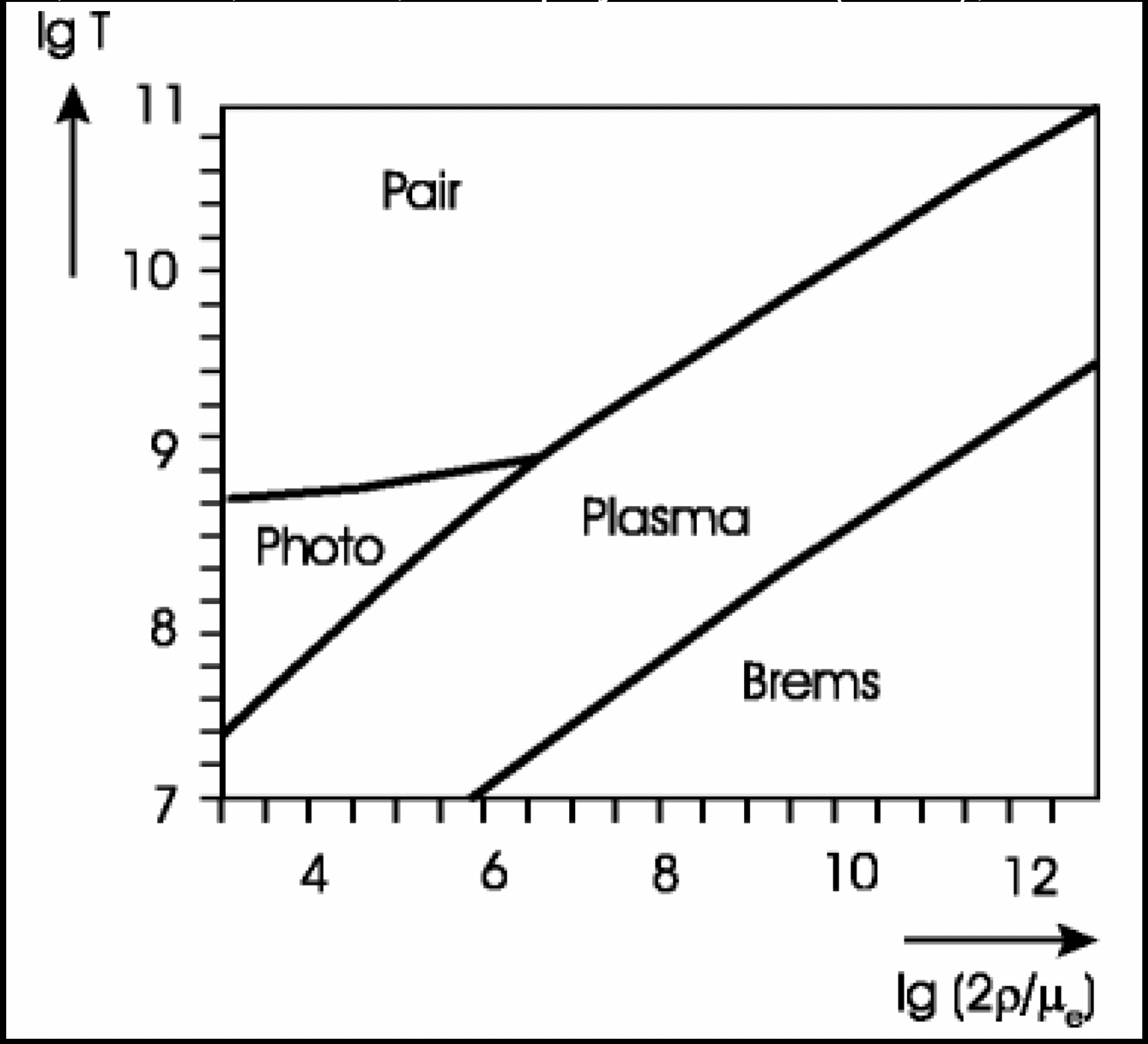
PAIR: require high T for creating e^+.

At high ρ, positron creation suppressed by degeneracy

Neutrino Production Processes

"Thermal" pair production in a plasma (star / supernova)

Haft, Raffelt, Weiss, Astrophys. J. 425 (1994), 222-230

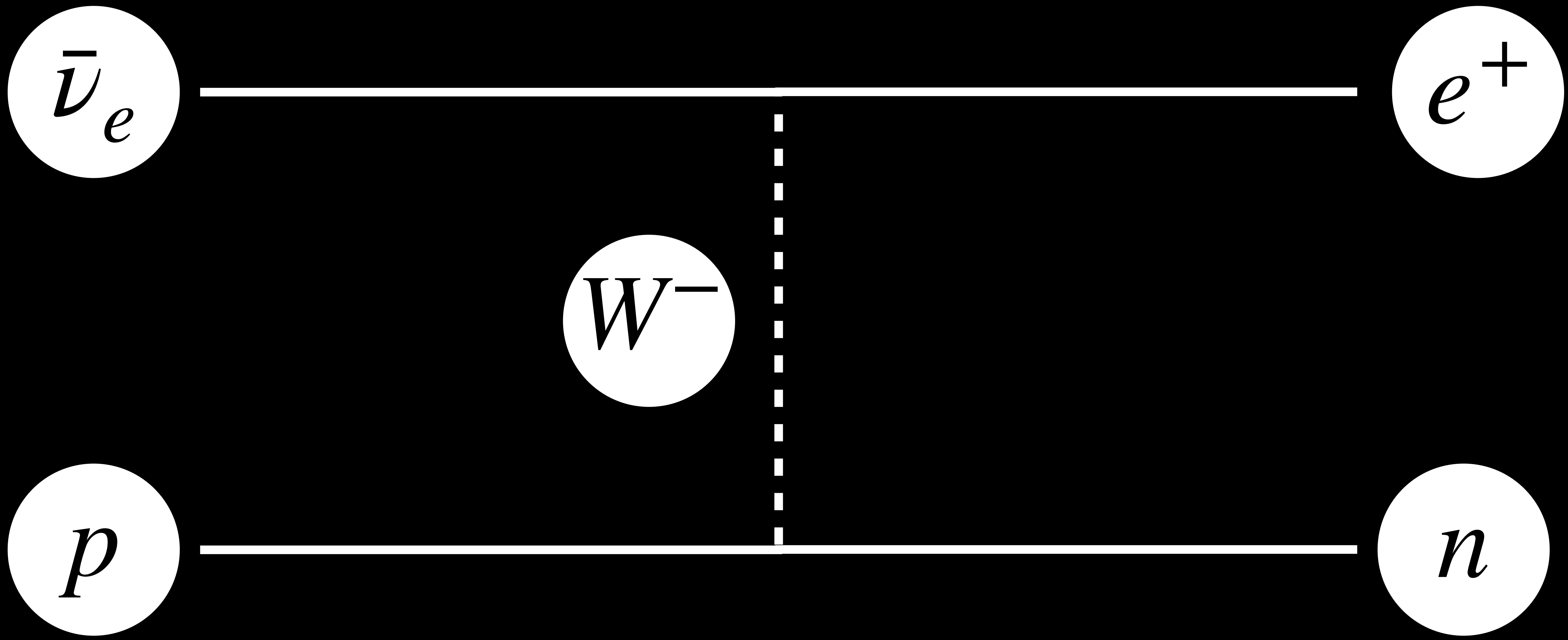


PLASMA: plasmon mass $\propto n_e^{1/2}$.

Suppression for increasing $\rho\,(n_e)$ at fixed T, because higher T is required to excite plasmons with higher mass

Neutrino Detection Processes

Inverse beta decay. Sensitive only to $\bar{\nu}_e$

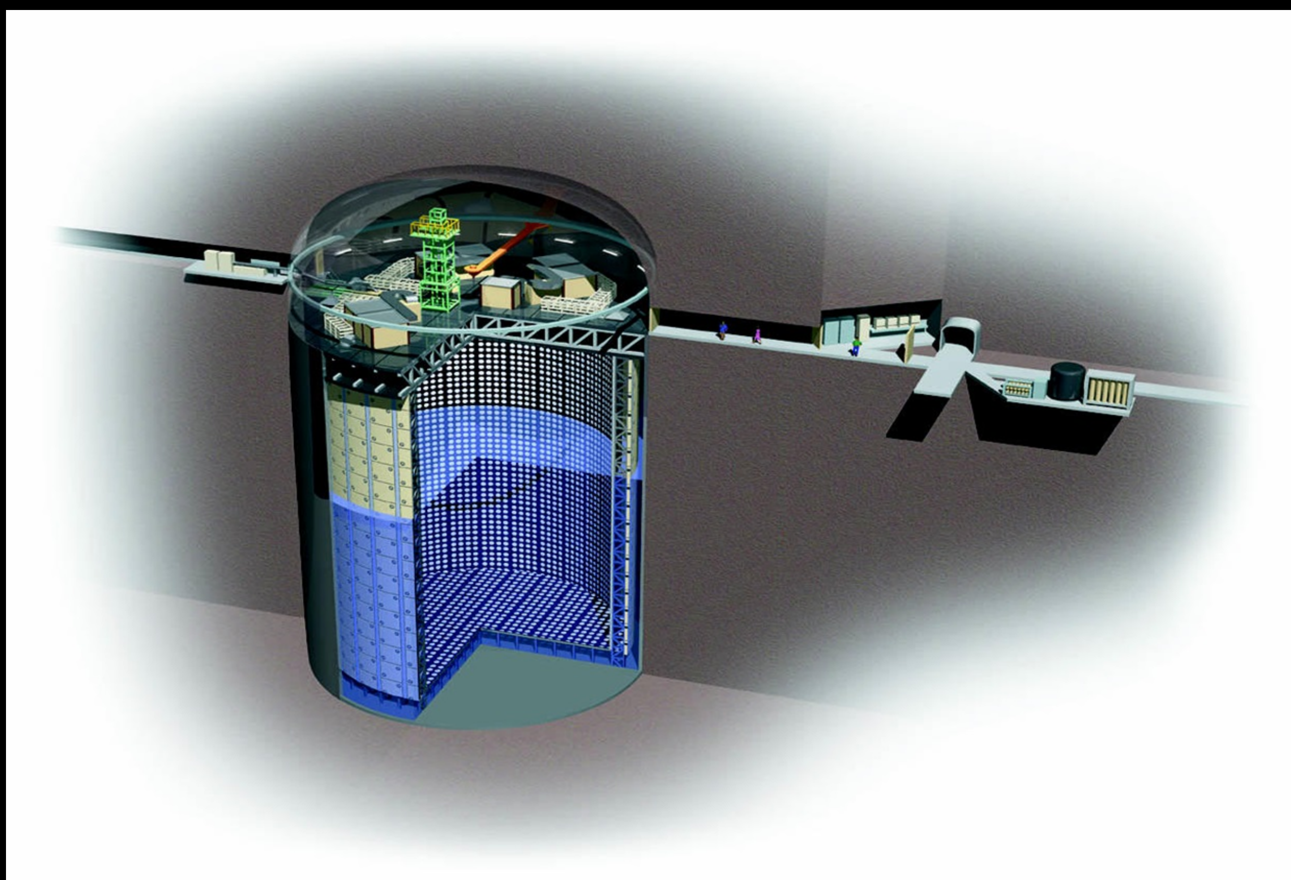


Two detectable signals: positron and the gamma ray that follows neutron capture. Positrons emitted isotropically.

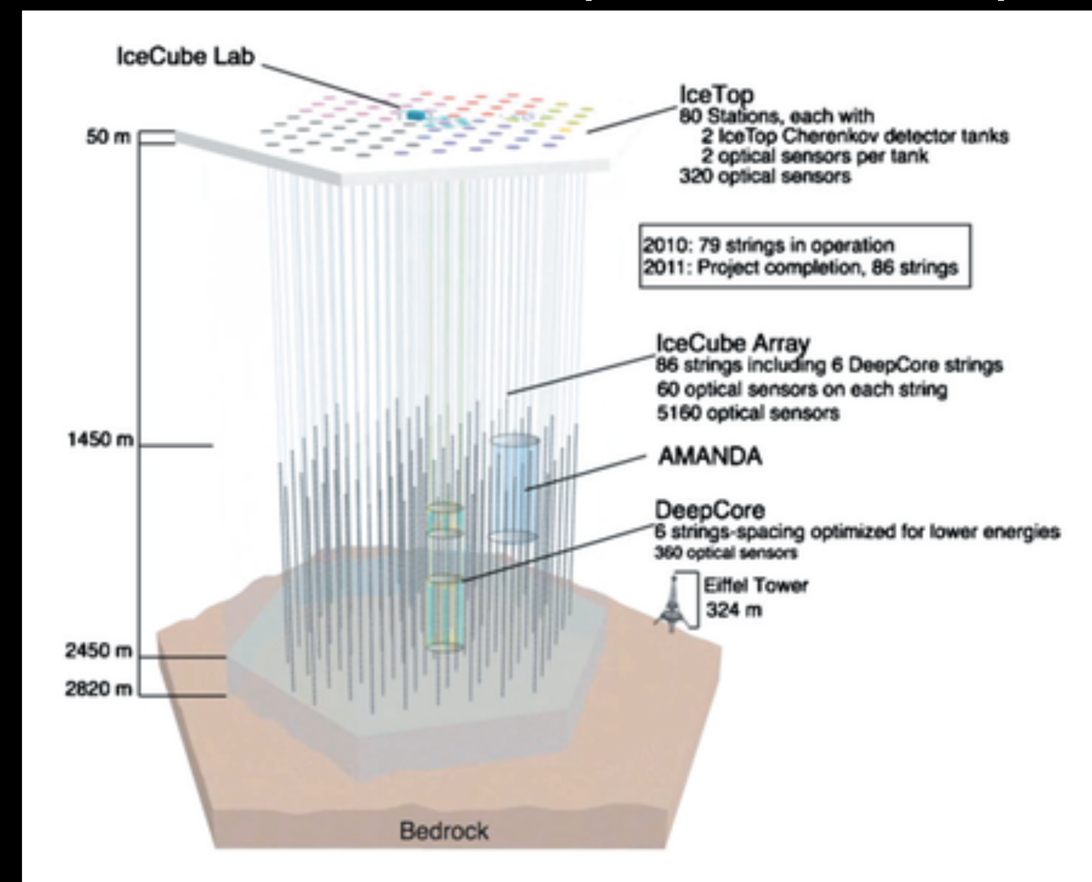
Neutrino Detection Processes

Inverse beta decay. Sensitive only to $\bar{\nu}_e$

Super-K (50 kton water)



Ice-CUBE (1 km^3 ice)

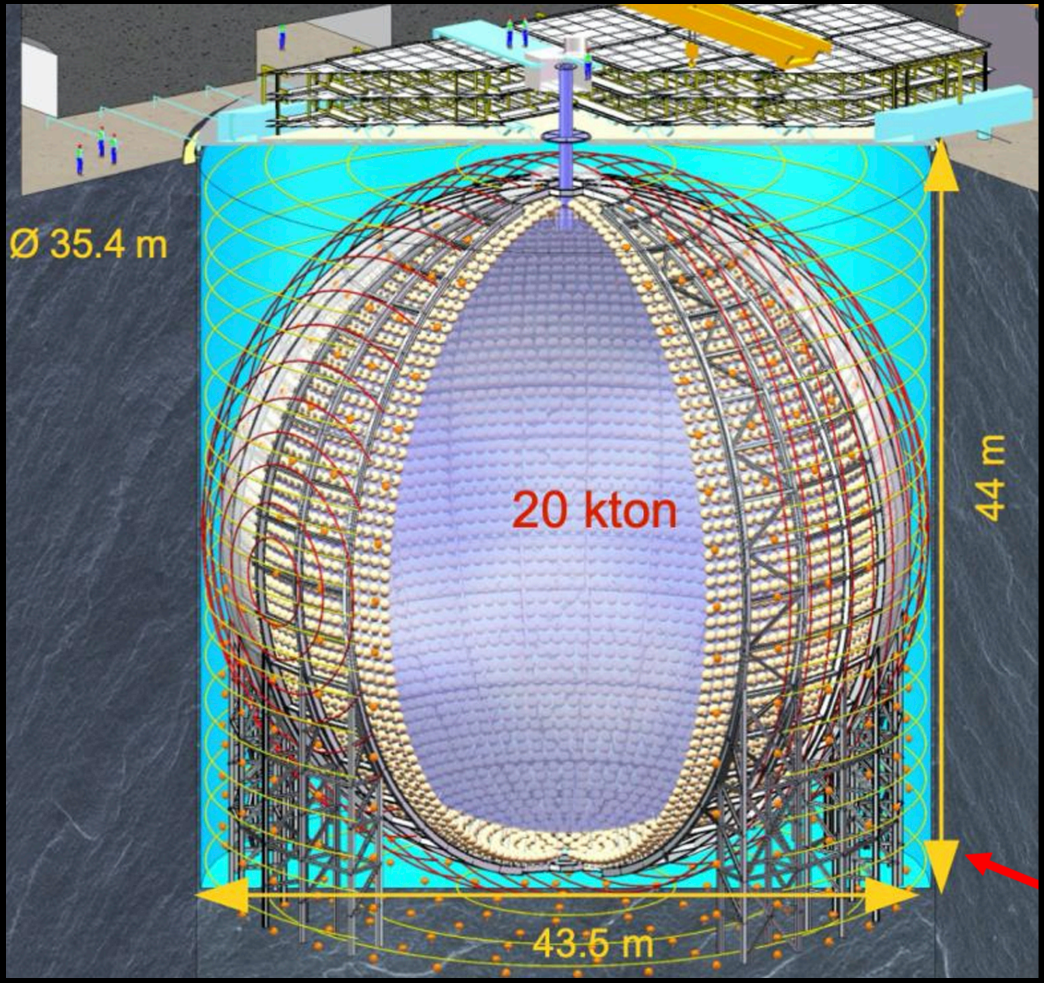


Positrons can be detected using the Cherenkov light emitted in pure water (Super-K) or in ice (Ice-CUBE)

Neutrino Detection Processes

Inverse beta decay. Sensitive only to $\bar{\nu}_e$

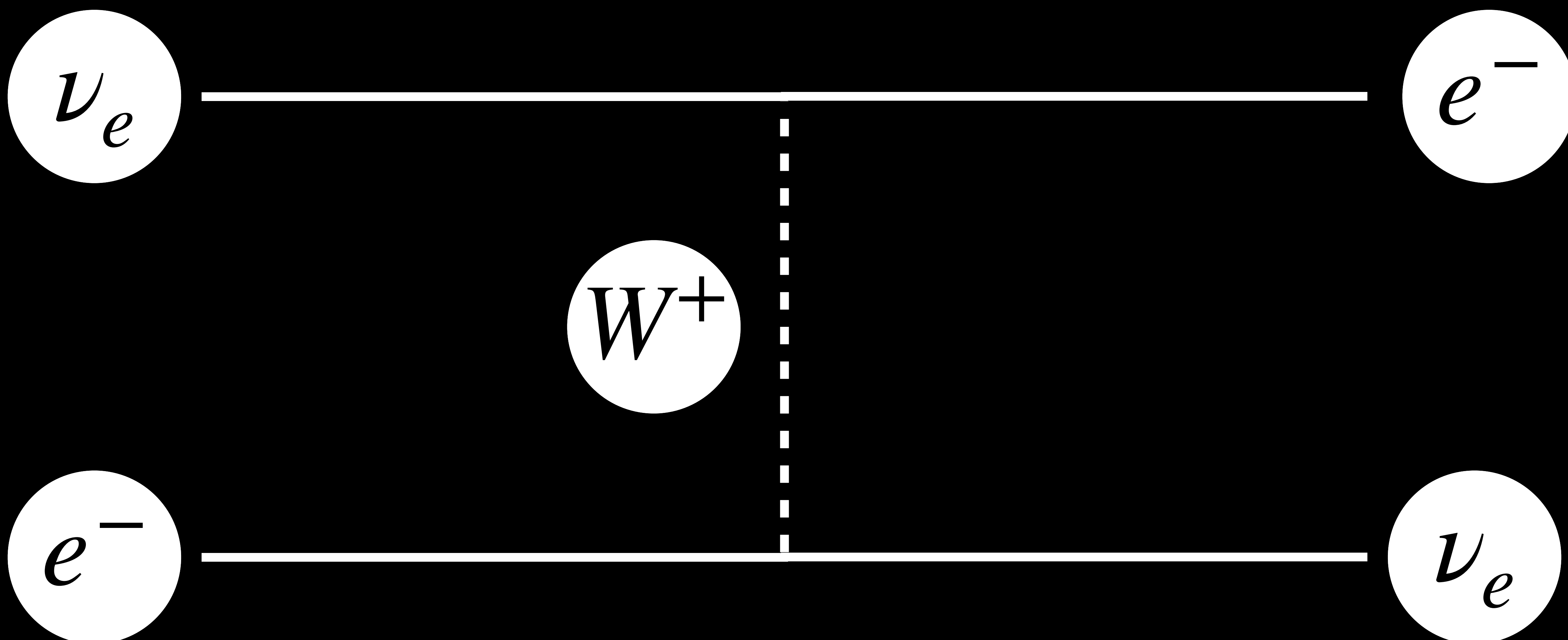
JUNO (20 kton liquid scintillator)



Positrons can be detected using scintillation light

Neutrino Detection Processes

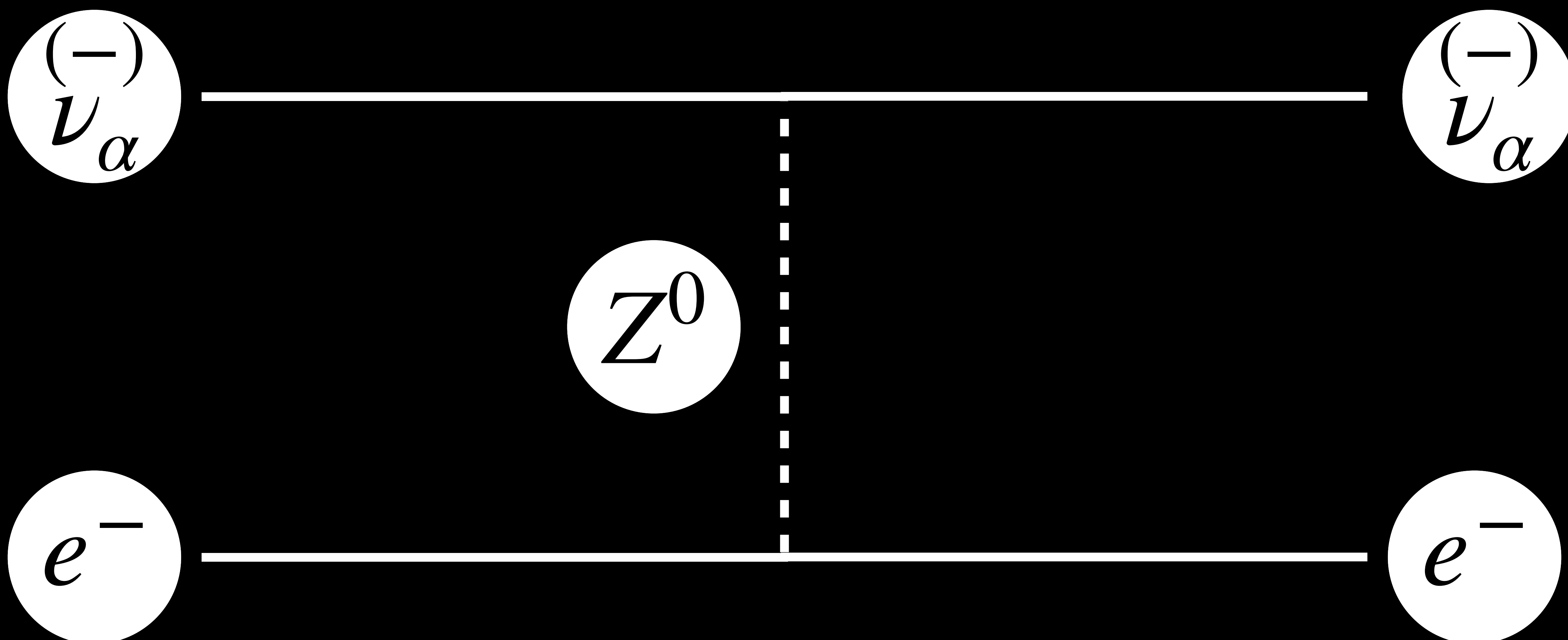
Elastic scattering on electrons.
Sensitive to all flavours, but mostly to ν_e



One detectable signals: electron.
Electrons are emitted mostly in the forward direction.

Neutrino Detection Processes

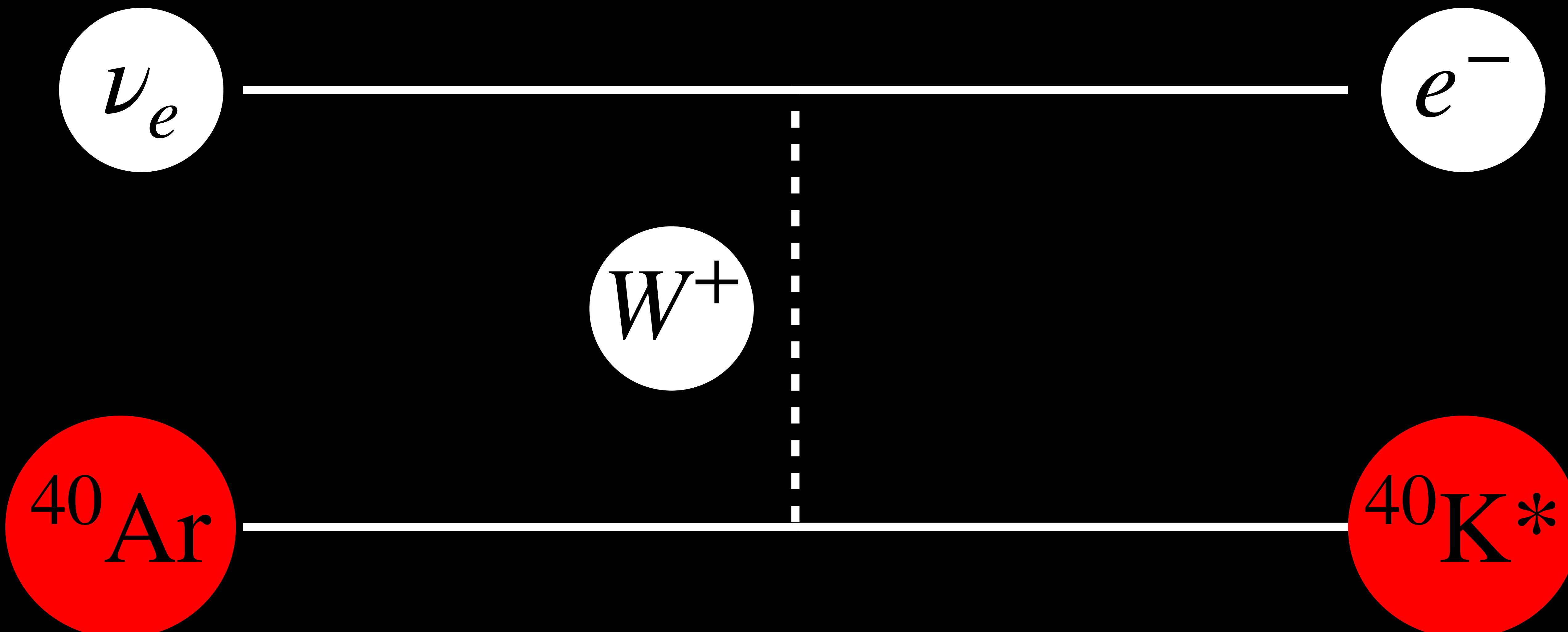
Elastic scattering on electrons.
Sensitive to all flavours, but mostly to ν_e



One detectable signals: electron.
Electrons are emitted mostly in the forward direction.

Neutrino Detection Processes

Charged current interaction on Argon. Sensitive only to ν_e

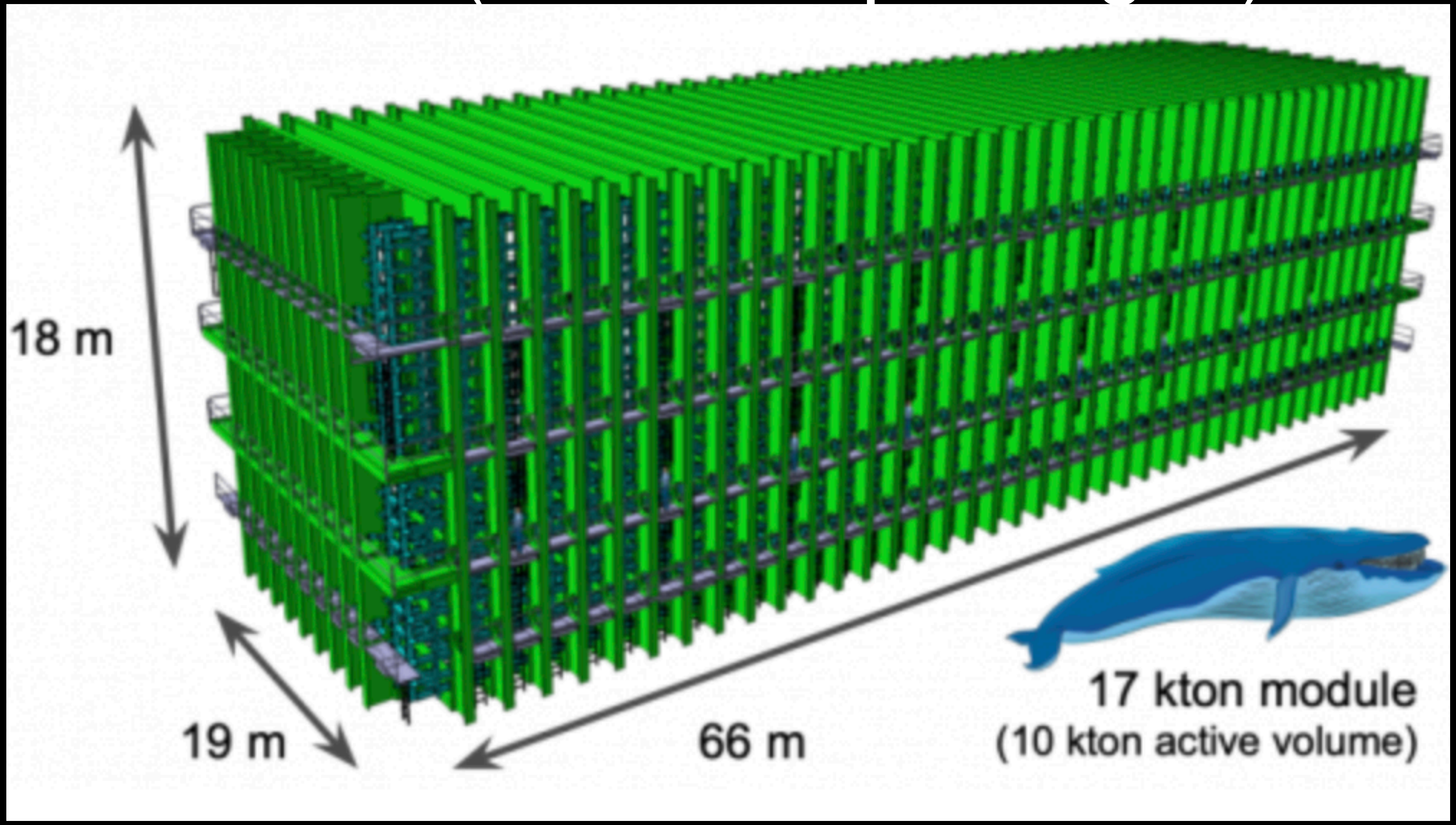


Two detectable signals: electron and the gamma ray that follows de-excitation of ^{40}K*. Electrons emitted isotropically.

Neutrino Detection Processes

Charged current interaction on Argon. Sensitive only to ν_e

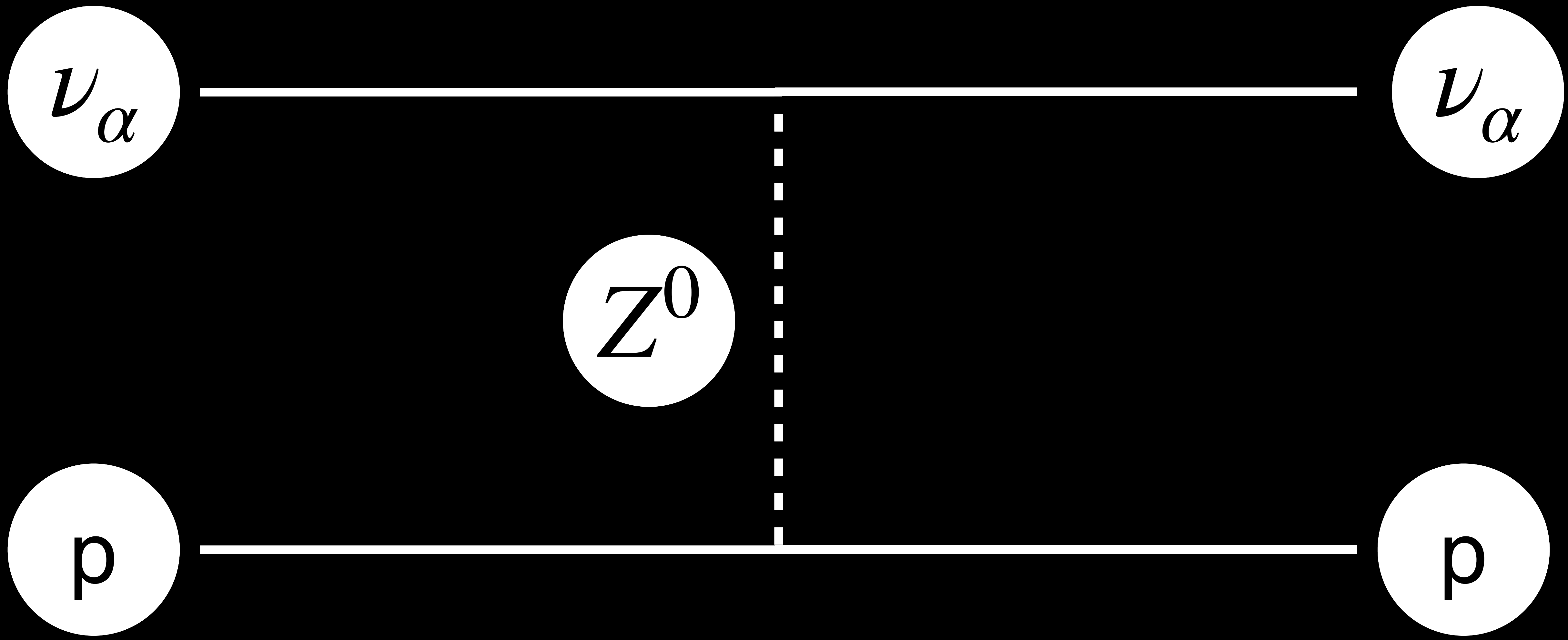
DUNE (40 kton liquid argon)



Two detectable signals: electron and the gamma ray that follows de-excitation of $^{40}\mathrm{K}*$. Electrons emitted isotropically.

Neutrino Detection Processes

Elastic scattering on protons. Sensitive to all flavours.

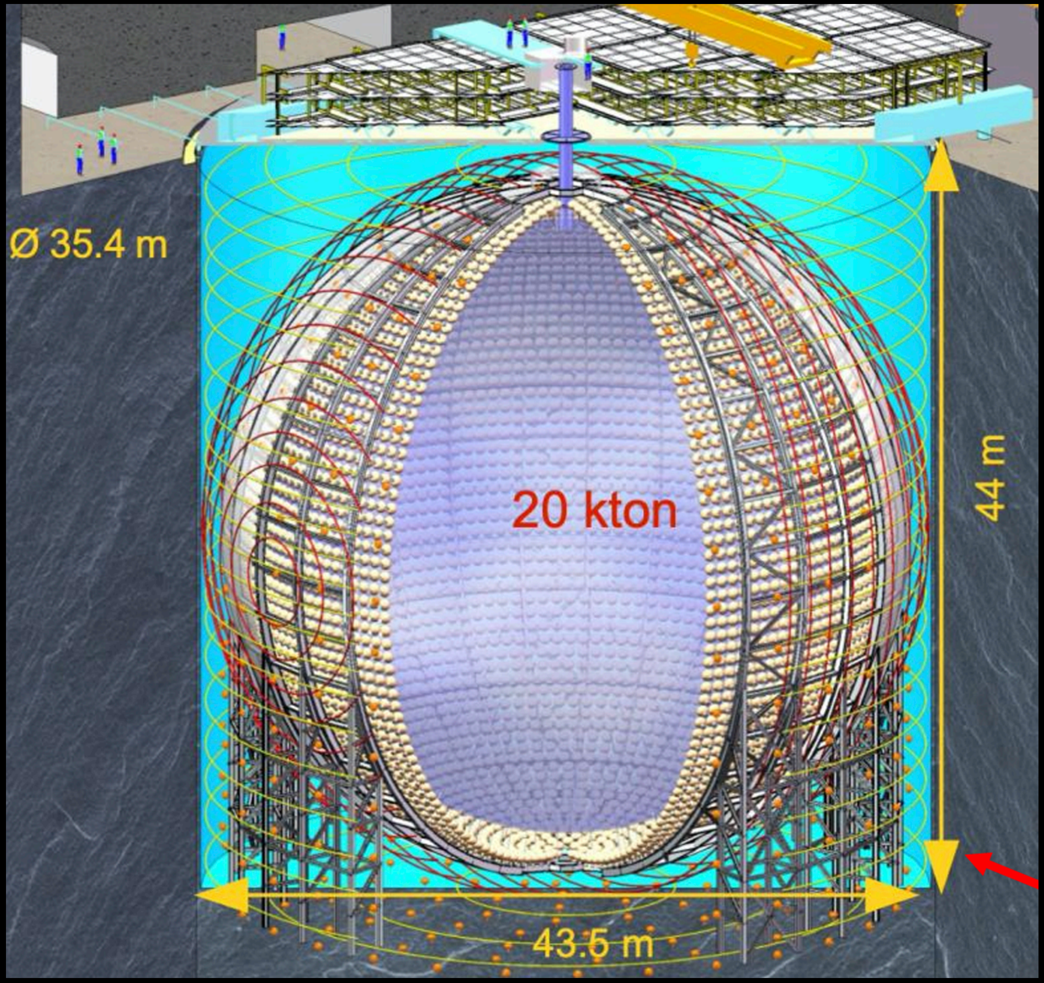


One detectable signals: proton.
Weak signal (quenching) from protons.

Neutrino Detection Processes

Elastic scattering on protons. Sensitive to all flavours.

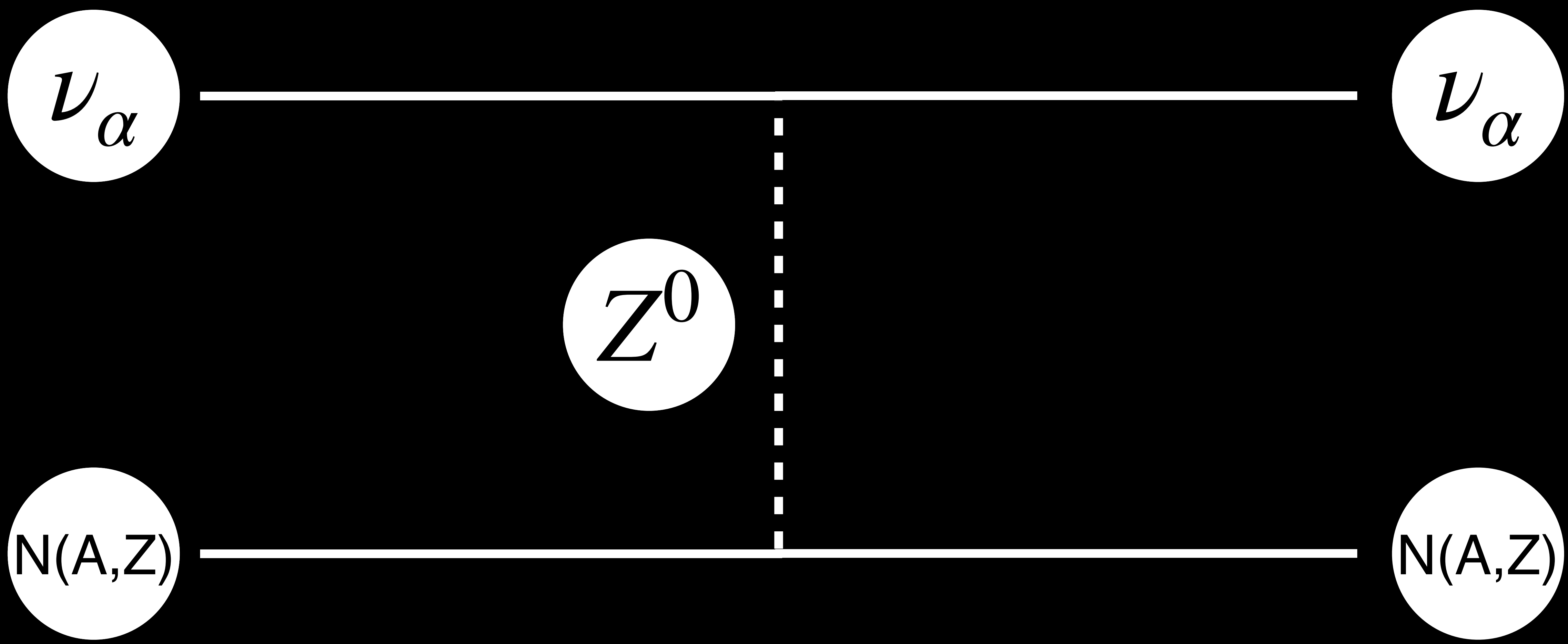
JUNO (20 kton liquid scintillator)



Protons induce scintillation, but quenching makes the signal weak. Only sensitive to high energy ν

Neutrino Detection Processes

Coherent elastic scattering on nuclei (CEνNS).
Sensitive to all flavours.



One detectable signal: nuclear recoil.
Cross section $\propto A^2$

Neutrino Detection Processes

Coherent elastic scattering on nuclei (CEνNS).
Sensitive to all flavours.

Target: CsI

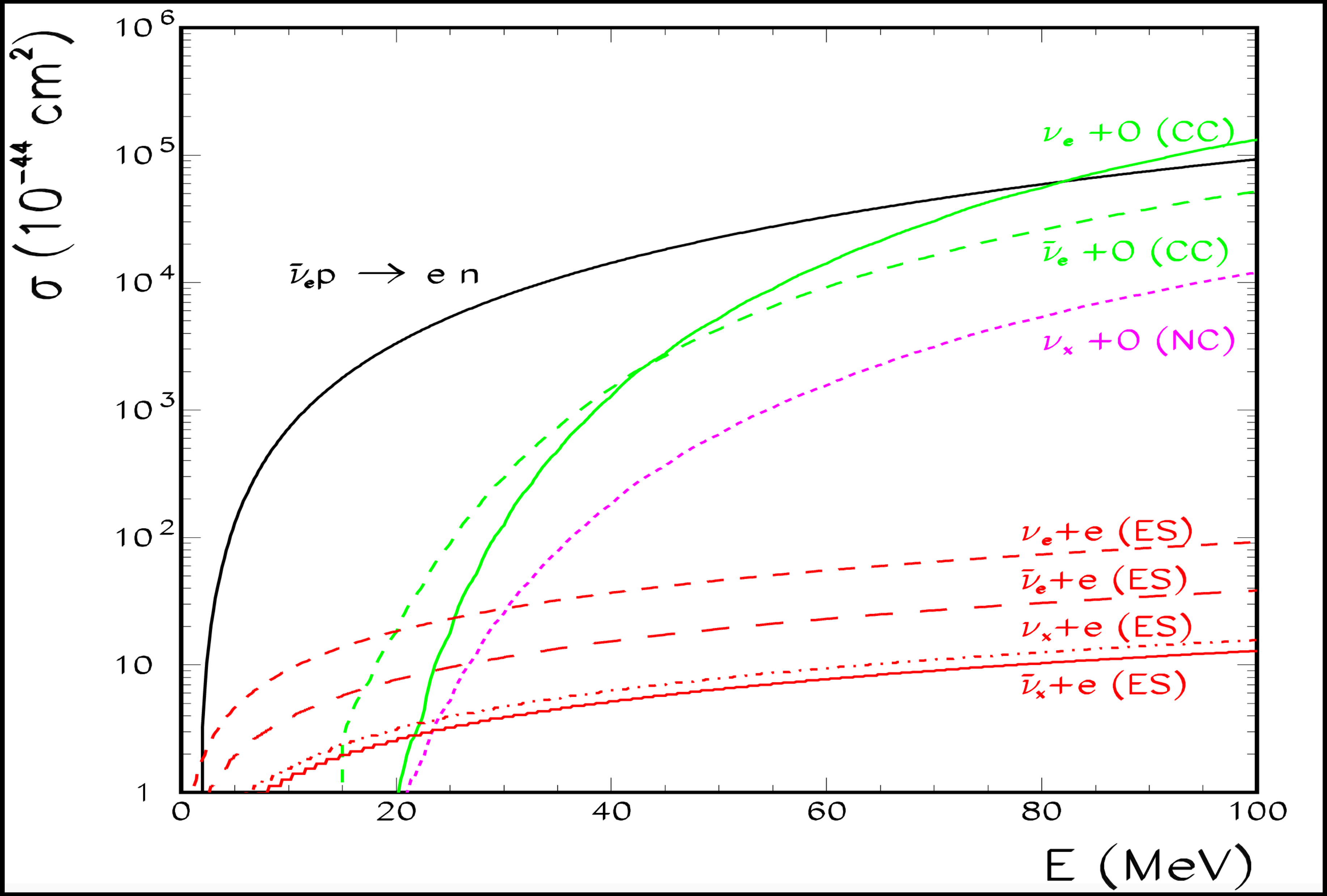
Target: cryogenic detector

Target: Liquid Xe (dark matter)

One detectable signal: nuclear recoil.
Cross section $\propto A^2$

Cross Section Comparison

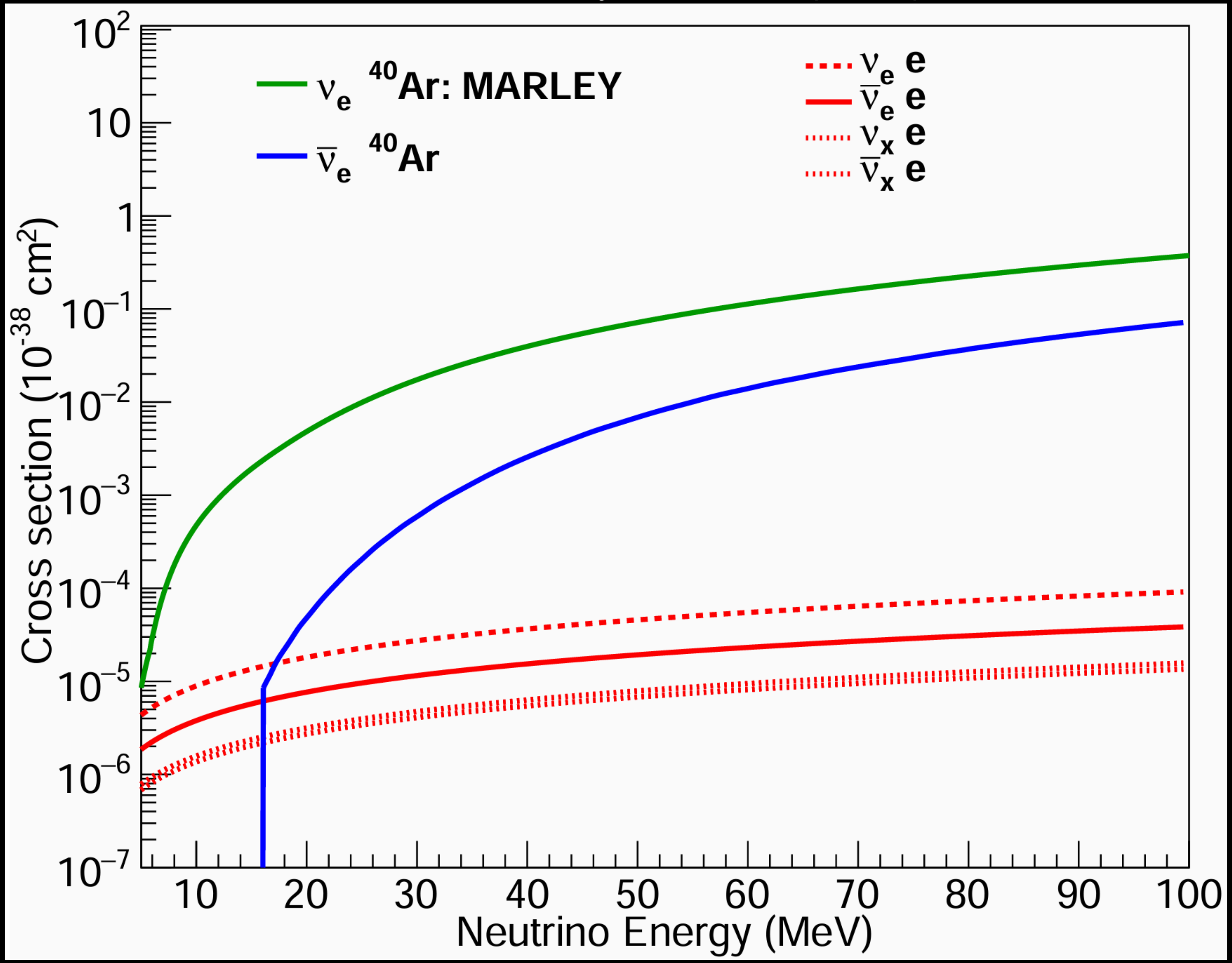
Skadhauge Zukanovich Funchal, JCAP 04 (2007), 014



Water: Dominance of $\bar{\nu}_e + p \rightarrow e^+ + n$.

Cross Section Comparison

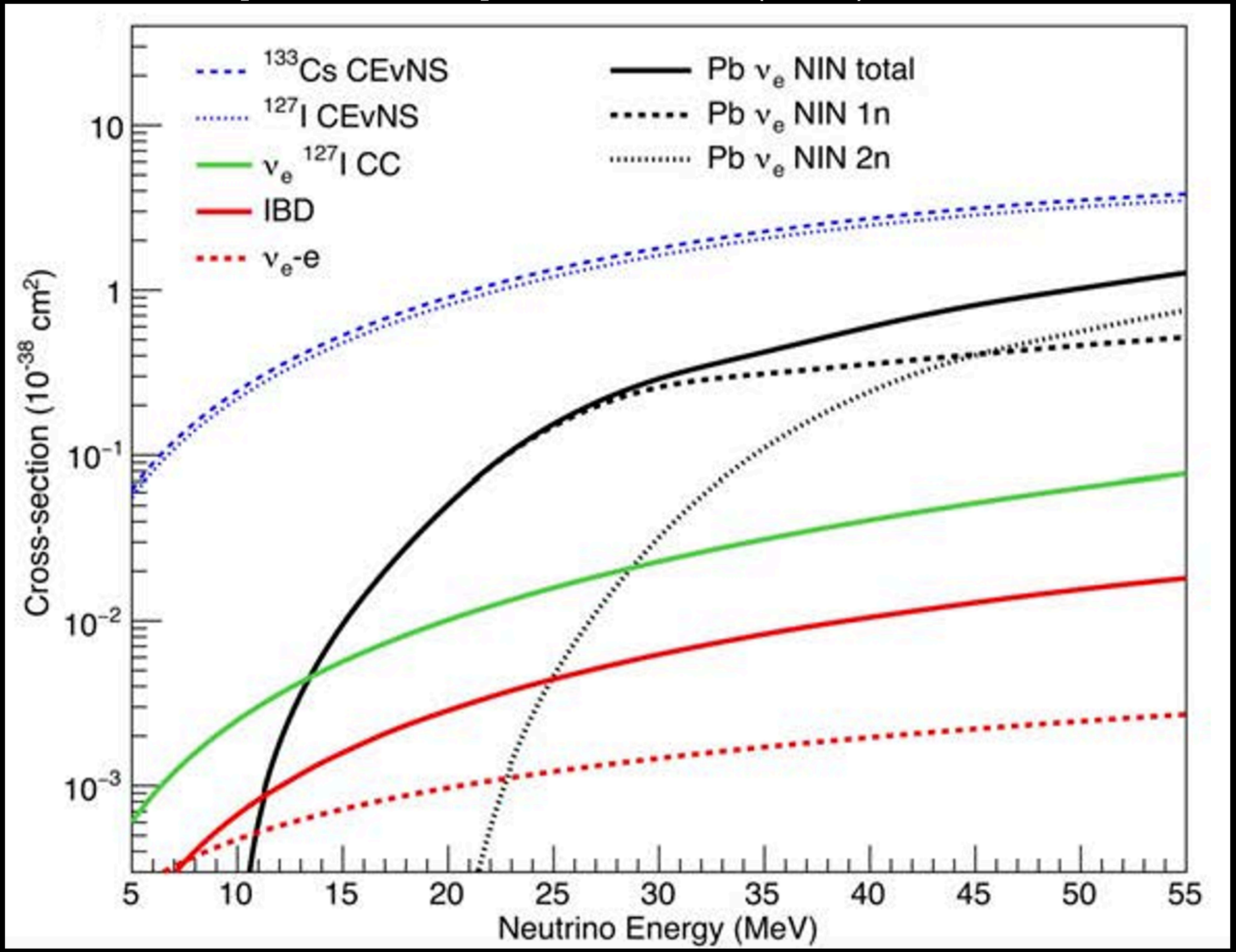
Abi et al. [DUNE], Eur. Phys. J. C 81 (2021) no.5, 423



Argon: Dominance of $\nu_e + {}^{40}\mathrm{Ar} \to e^- + {}^{40}\mathrm{K}^*$.

Cross Section Comparison

Akimov et al. [COHERENT], Science 357 (2017) no.6356, 1123-1126

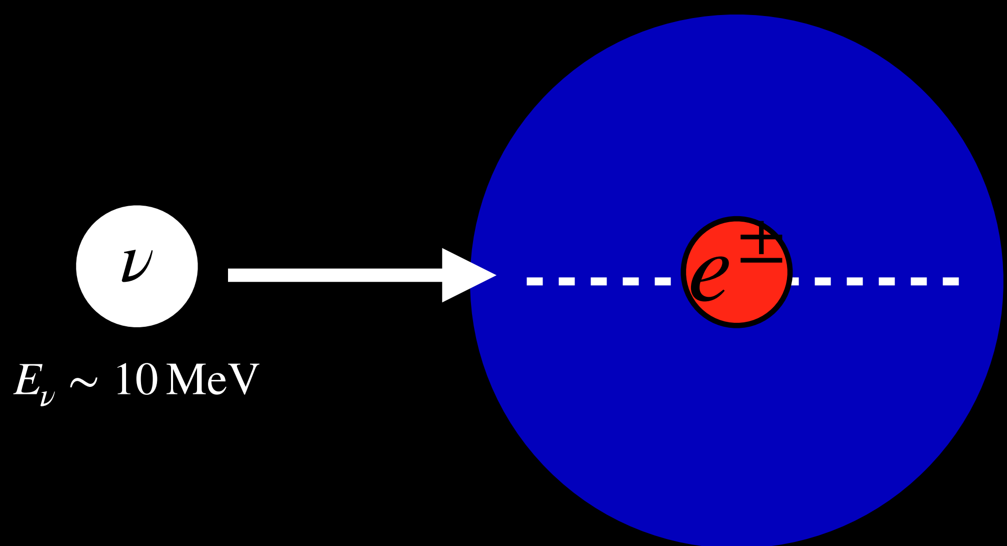


Argon: Dominance of CEνNS

Cross Section Comparison

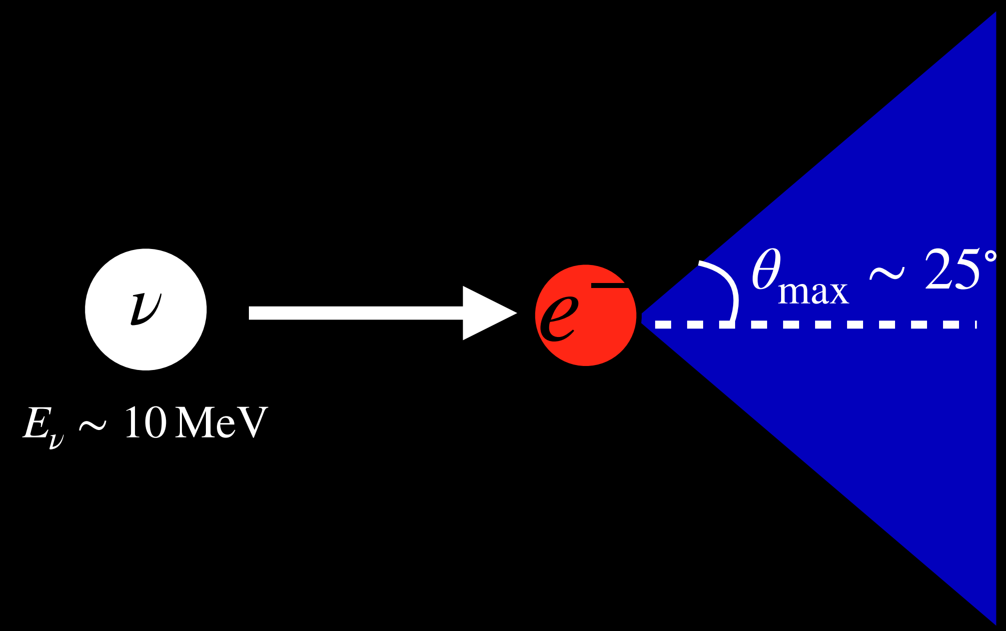
Angle of scattering for electrons in the final states

$$\bar{\nu}_e + {}^A_Z\mathrm{X} \rightarrow e^+ + {}^{A}_{Z-1}\mathrm{Y}$$
$$\nu_e + {}^A_Z\mathrm{X} \rightarrow e^- + {}^{A}_{Z+1}\mathrm{Y}$$
$$\bar{\nu}_e + p \rightarrow e^+ + n$$



Isotropic

$$\nu + e^- \rightarrow \nu + e^-$$



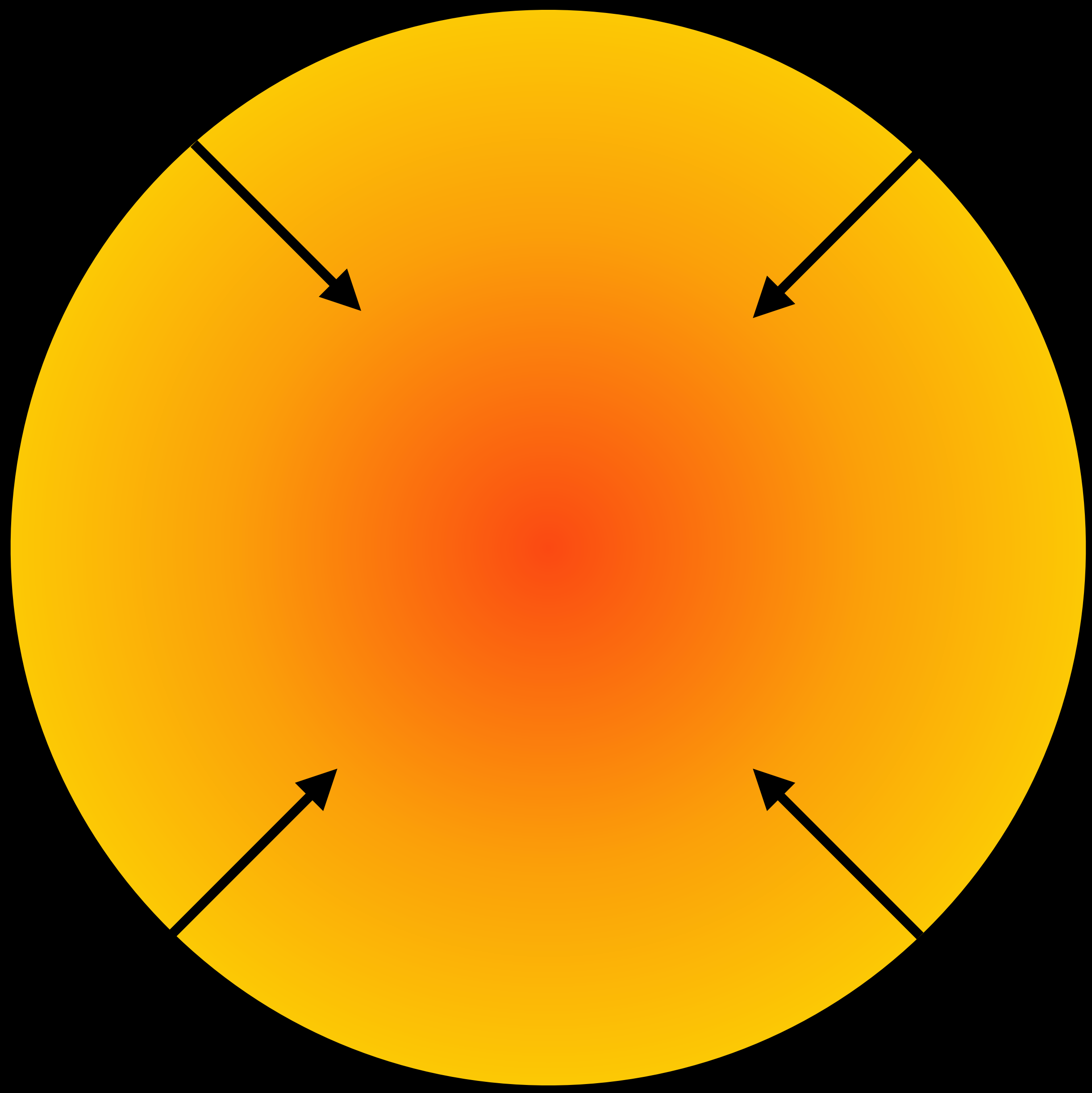
Mostly forward

CORE-COLLAPSE SUPERNOVE

Brief recap
Neutrino Emission Phases

What are supernovae?

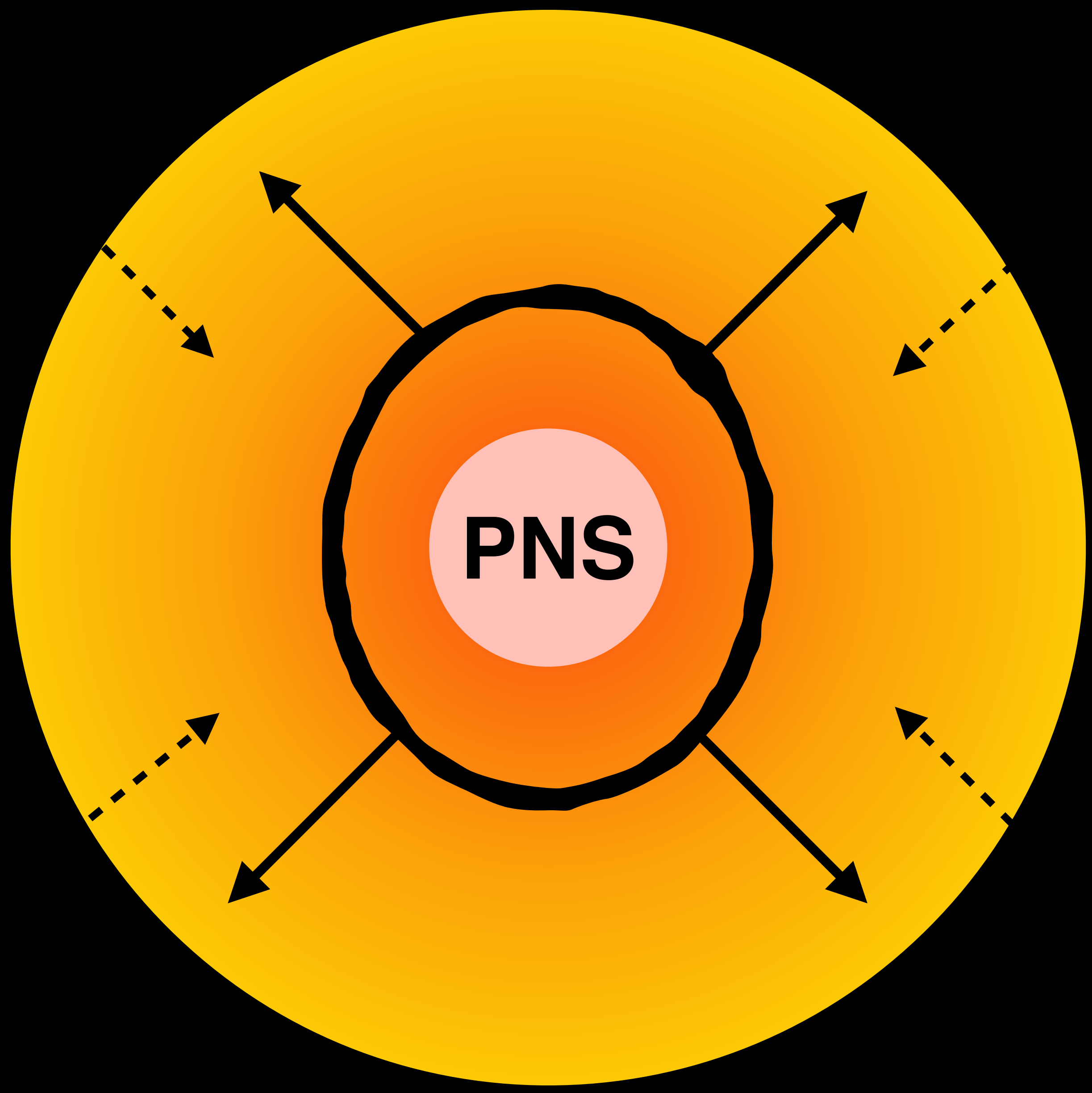
When nuclear fuel ends, massive stars ($> 8\ M_\odot$) start collapsing



The density in the core rapidly increases

What are supernovae?

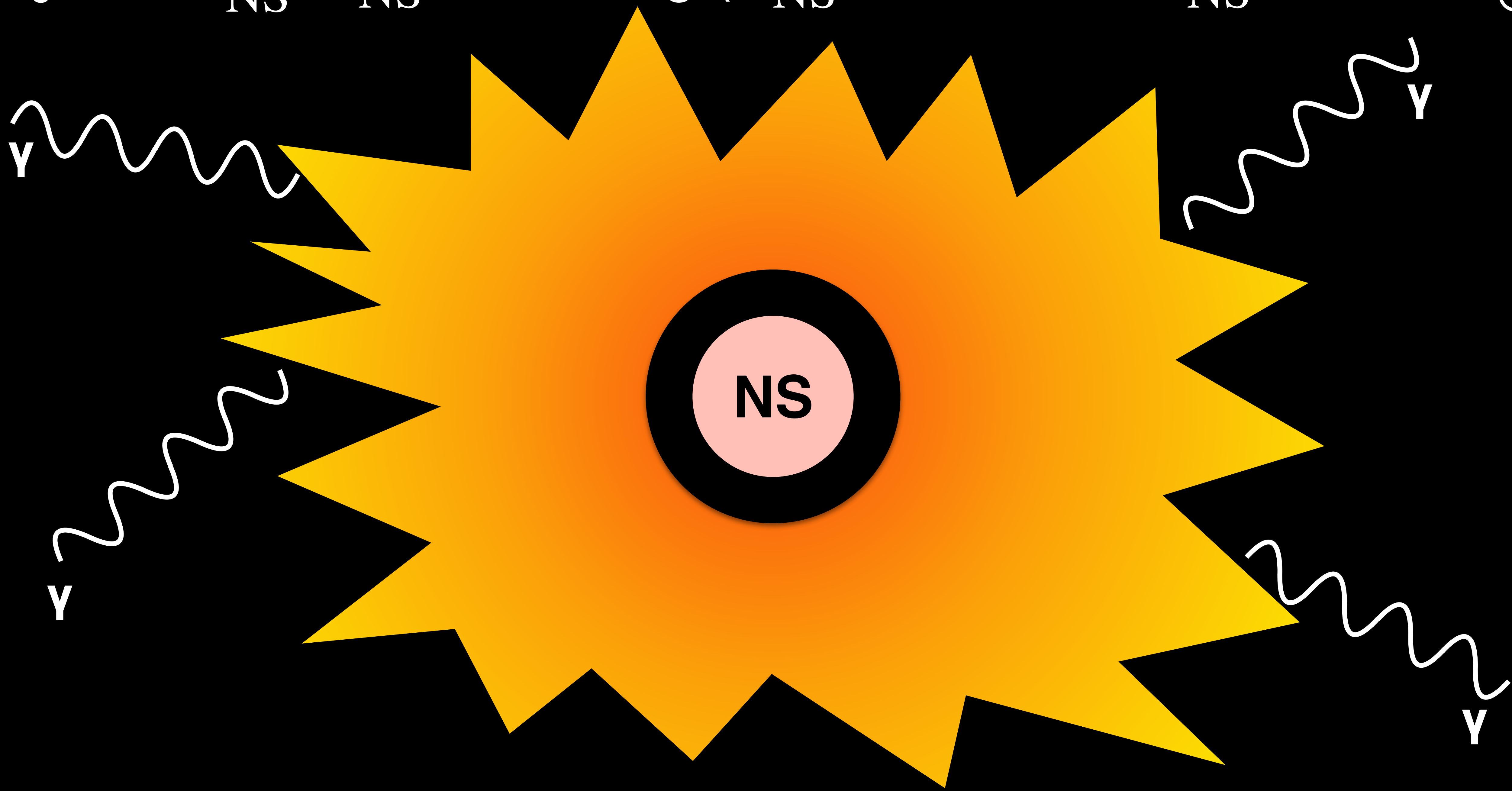
The density reaches nuclear saturation $\rho \sim 10^{14}$ g/cm^3



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

What are supernovae?

$E_g \sim GM_{NS}^2/R_{NS} \sim 10^{53}$ erg ($R_{NS} \sim 10\,\mathrm{km}$, $M_{NS} \sim 1.5\,M_\odot$)

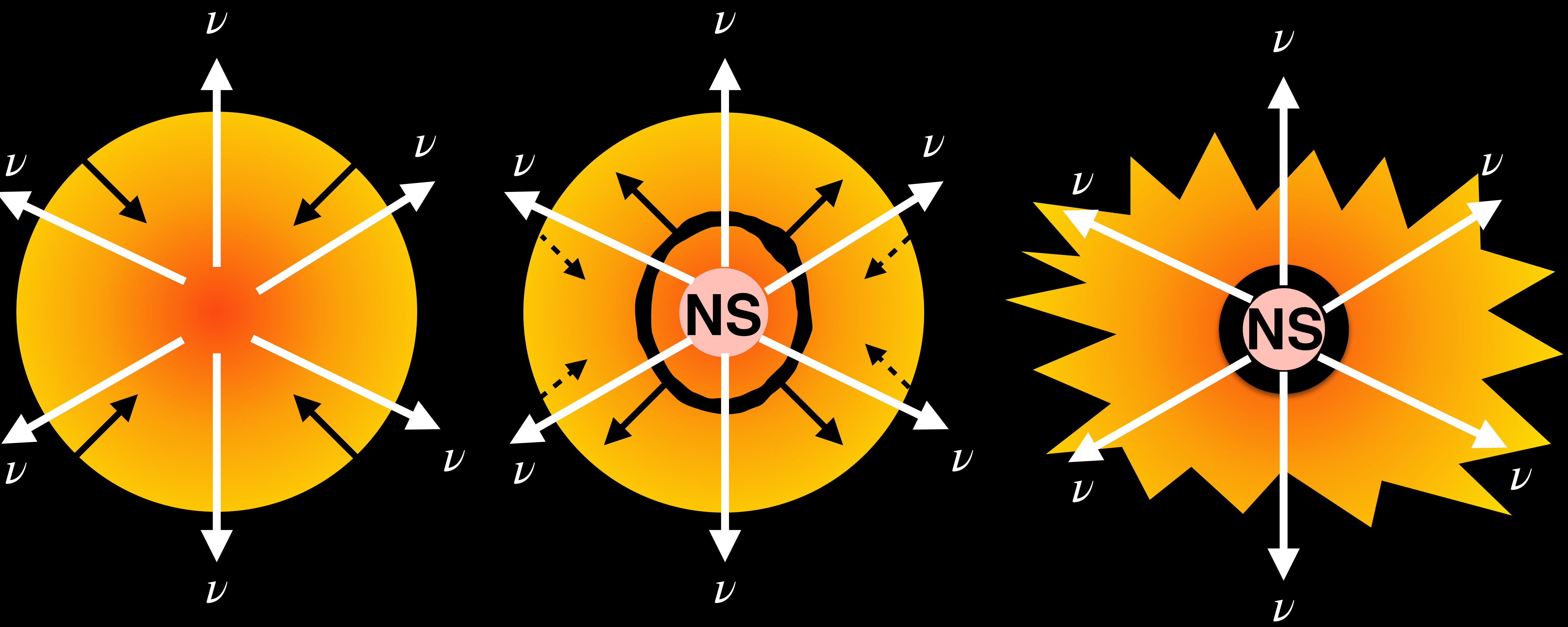


$E_{exp} \sim 1\%\ E_g$

$E_\gamma \sim 0.01\%\ E_g$

What is the role of neutrinos?

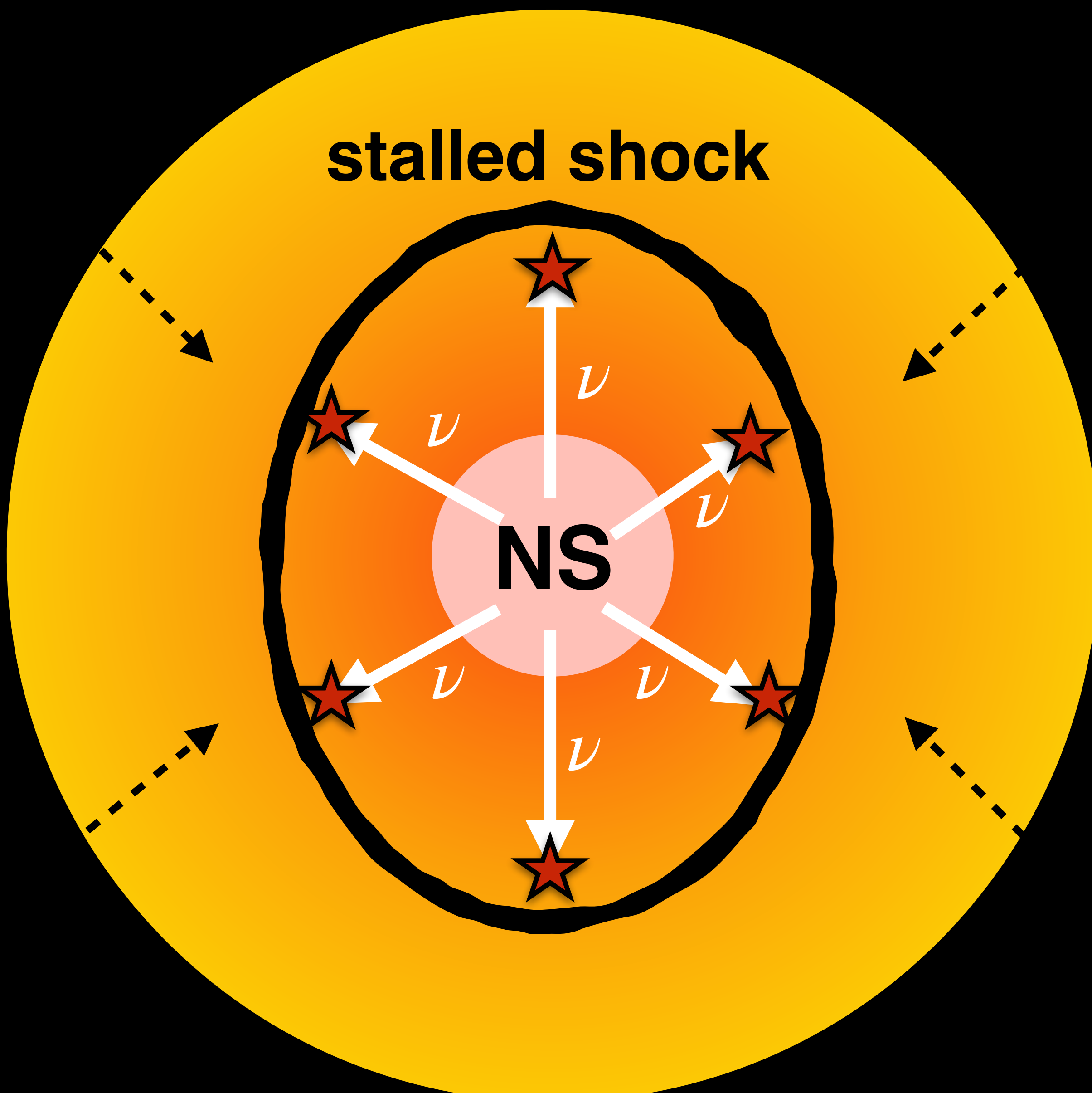
ν / $\bar{\nu}$ of all flavor carry away 99% of E_g in ~10 seconds



Neutrinos are messengers from the interior of the exploding star

What is the role of neutrinos?

The shock wave stalls after ~ few 10 ms



★ $\nu_e + n \rightarrow e^- + p$

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

Neutrinos **MIGHT REVIVE** the shock through energy deposition

What is the role of neutrinos?

$\nu-$interactions: change Y_e, influence of nature of heavy nuclei

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

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

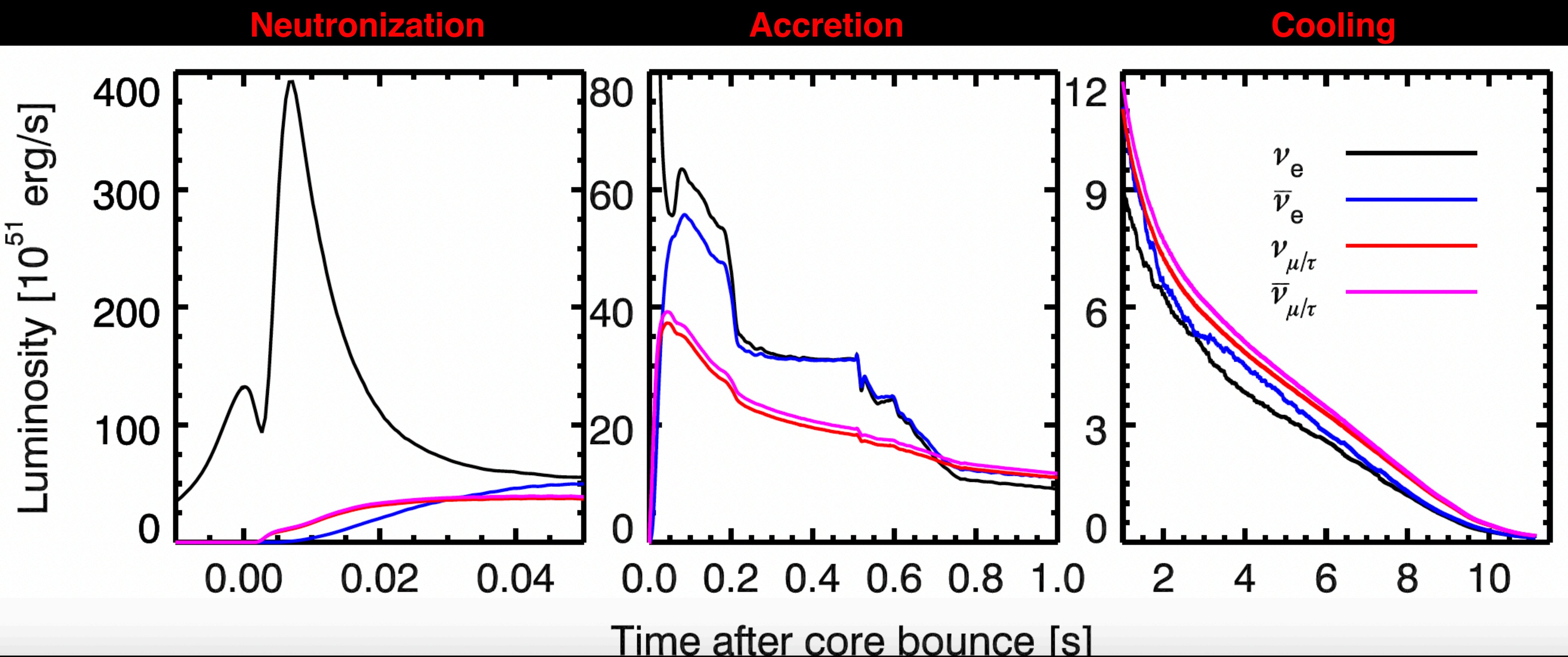
$$\nu_e + (A,Z) \rightarrow (A,Z+1) + e^-$$

$$\bar{\nu}_e + (A,Z) \rightarrow (A,Z-1) + e^+$$

ν play a role in defining the conditions for **r-PROCESS**

Neutrino Emission Phases

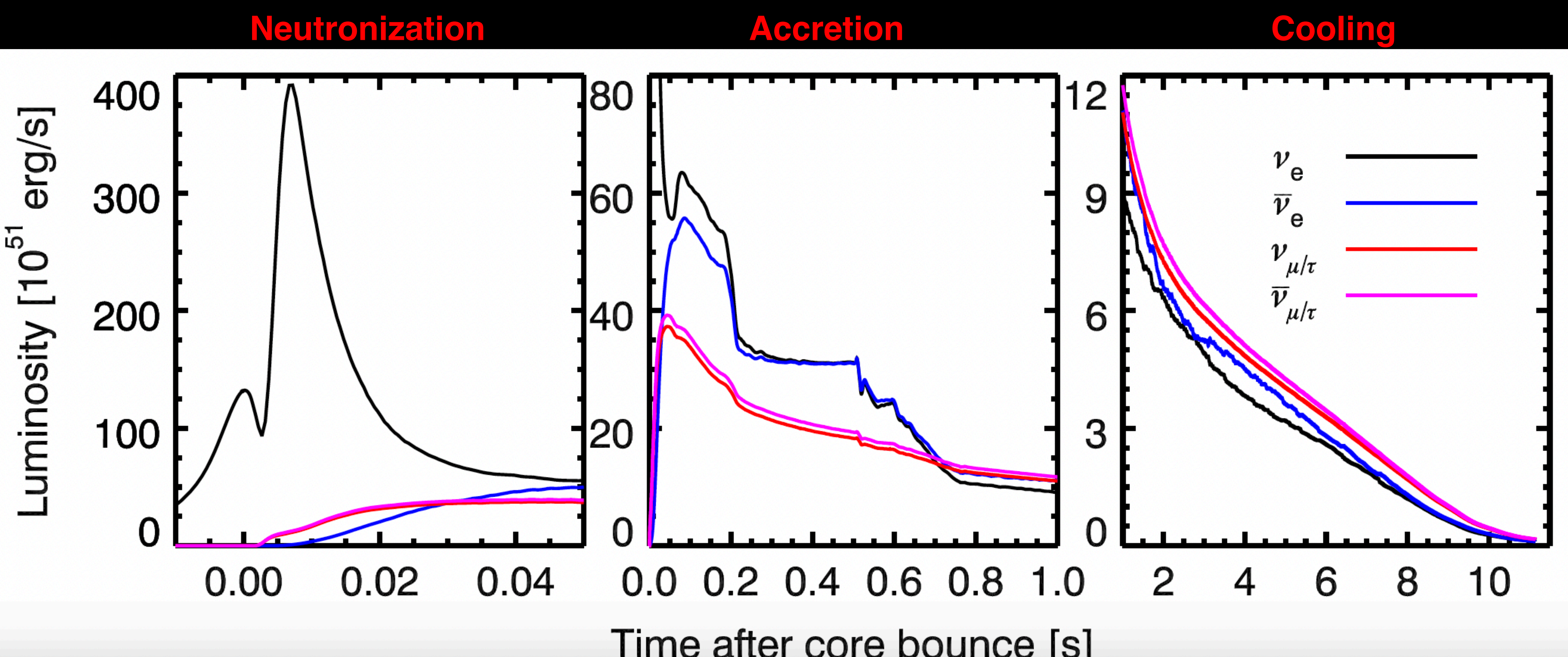
Janka, “Neutrino emission from supernovae” , arXiv:1702.08713



- Mainly ν_e from e^- capture
- ν_e trapped behind shock
- ν_e burst when density is low
- $\nu\bar{\nu}$ in shock heated matter

Neutrino Emission Phases

Janka, "Neutrino emission from supernovae" , arXiv:1702.08713

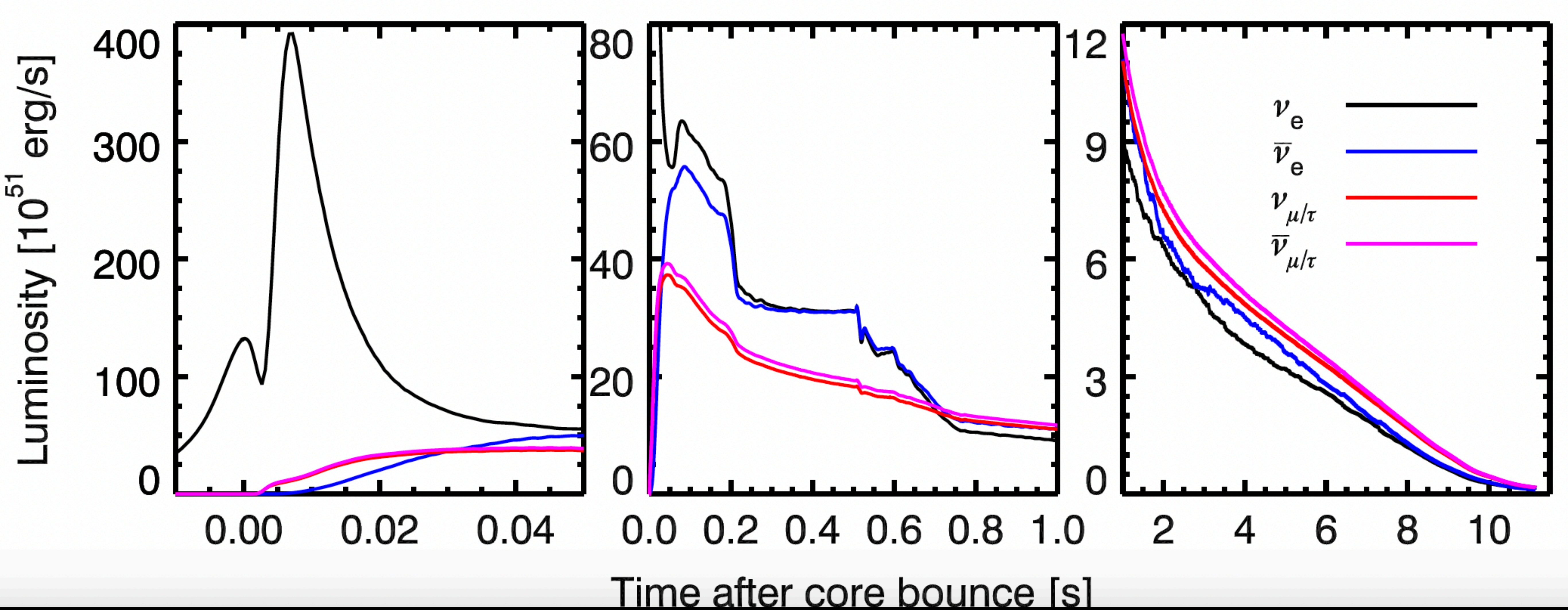


- Mainly $\nu_e, \bar{\nu}_e$ from $e^{\pm}$ capture powered by matter collapsing
- $\nu\bar{\nu}$ in shock heated matter
- shock revival by ν energy deposition

Neutrino Emission Phases

Janka, "Neutrino emission from supernovae" , arXiv:1702.08713

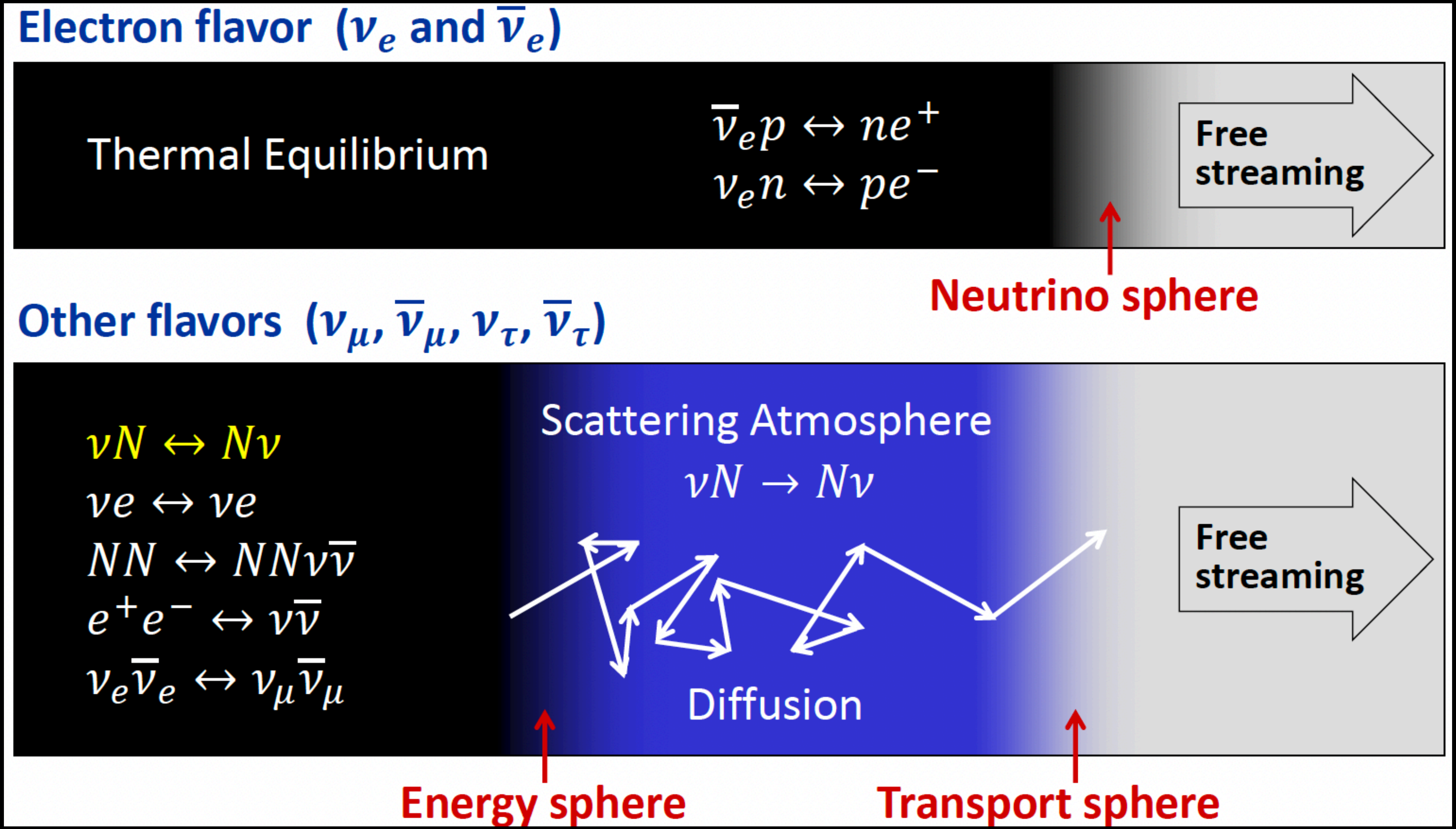
Neutronization **Accretion** **Cooling**



- only $\nu\bar{\nu}$ production
- ~ democratic flavour emission
- cooling —> luminosity decreases

Neutrino Emission Phases

Janka, "Neutrino emission from supernovae" , arXiv:1702.08713

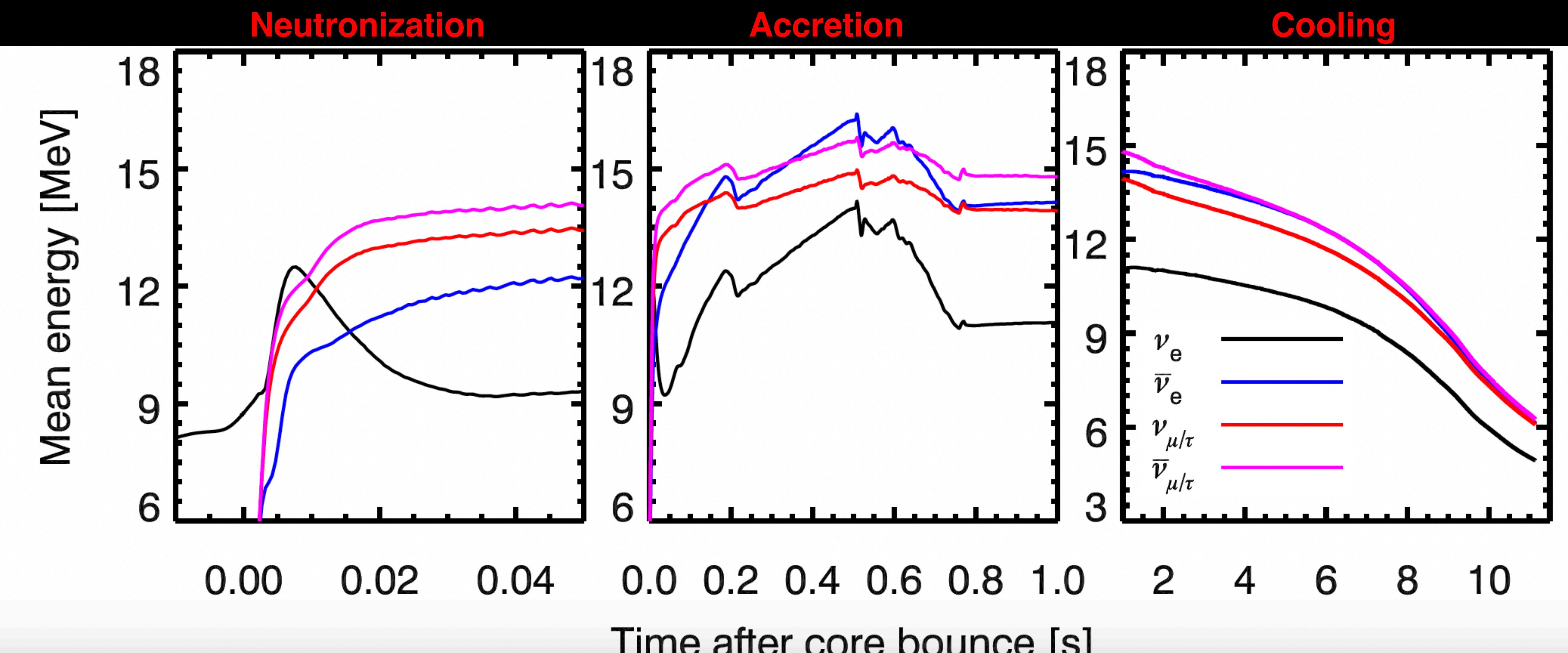


$\overset{(-)}{\nu}_e$ have stronger interactions. They decouple later.

Being in thermal equilibrium, neutrinos have ~ Fermi-Dirac energy spectrum

Neutrino Emission Phases

Janka, "Neutrino emission from supernovae" , arXiv:1702.08713



- Generally, $\langle E_{\nu_e} \rangle$ is the smallest, since ν_e are the most strongly coupled
- Differences between $\nu_{\mu,\tau}$ and $\bar{\nu}_{\mu,\tau}$ due to $\mu^\pm$ production in the core
- $\langle E_{\bar{\nu}_e} \rangle$ becomes equal to $\langle E_{\overset{(-)}{\nu}_x} \rangle$ ($\bar{\nu}_e + p \to e^+ + n$ becomes ineffective)

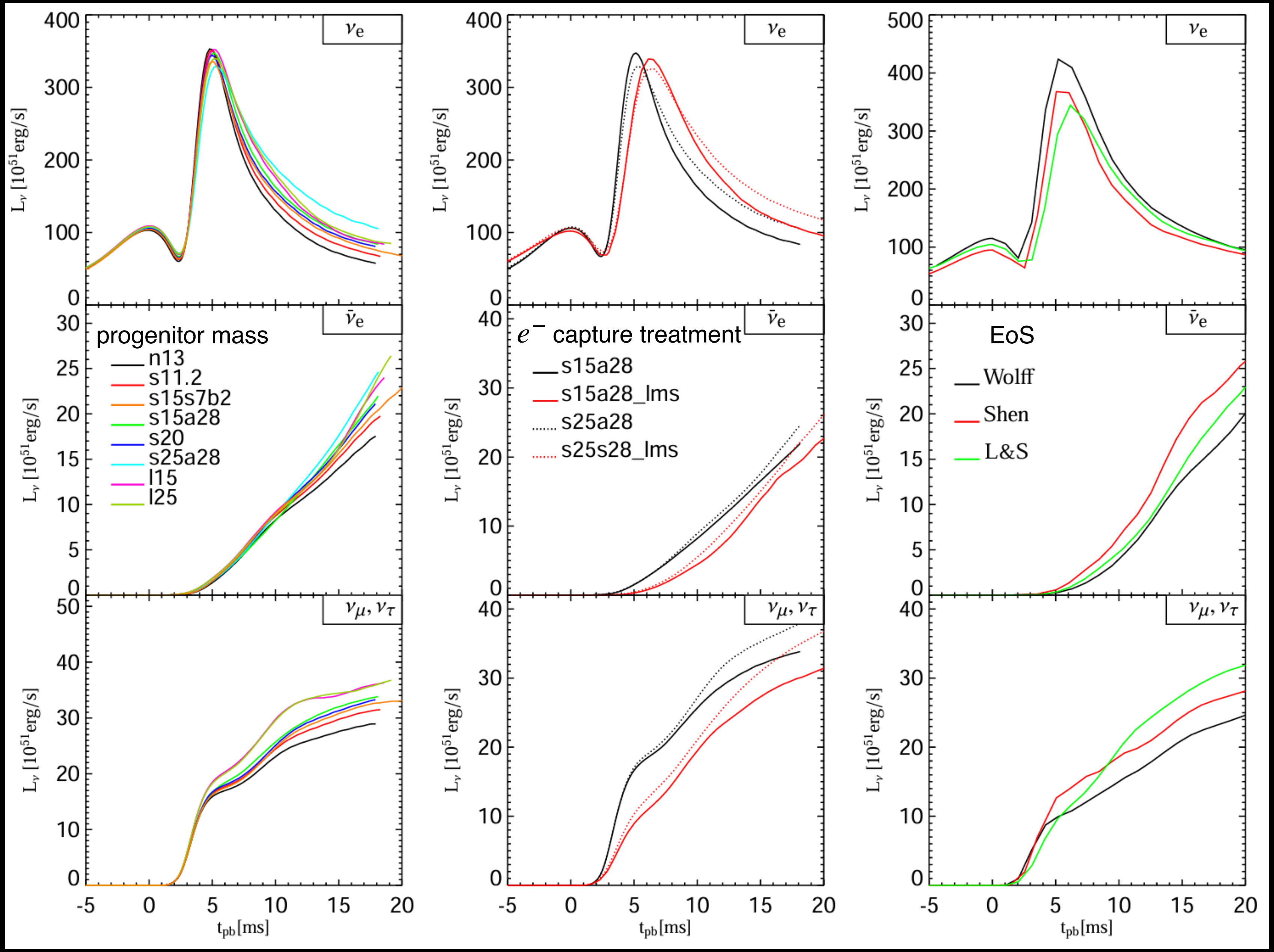
NEUTRONIZATION BURST

What can we learn?

Robustness of models

Comparison between L_ν changing some simulation details

Kachelriess, Tomas, Buras, Janka, Marek, Rampp, Phys. Rev. D 71 (2005), 063003

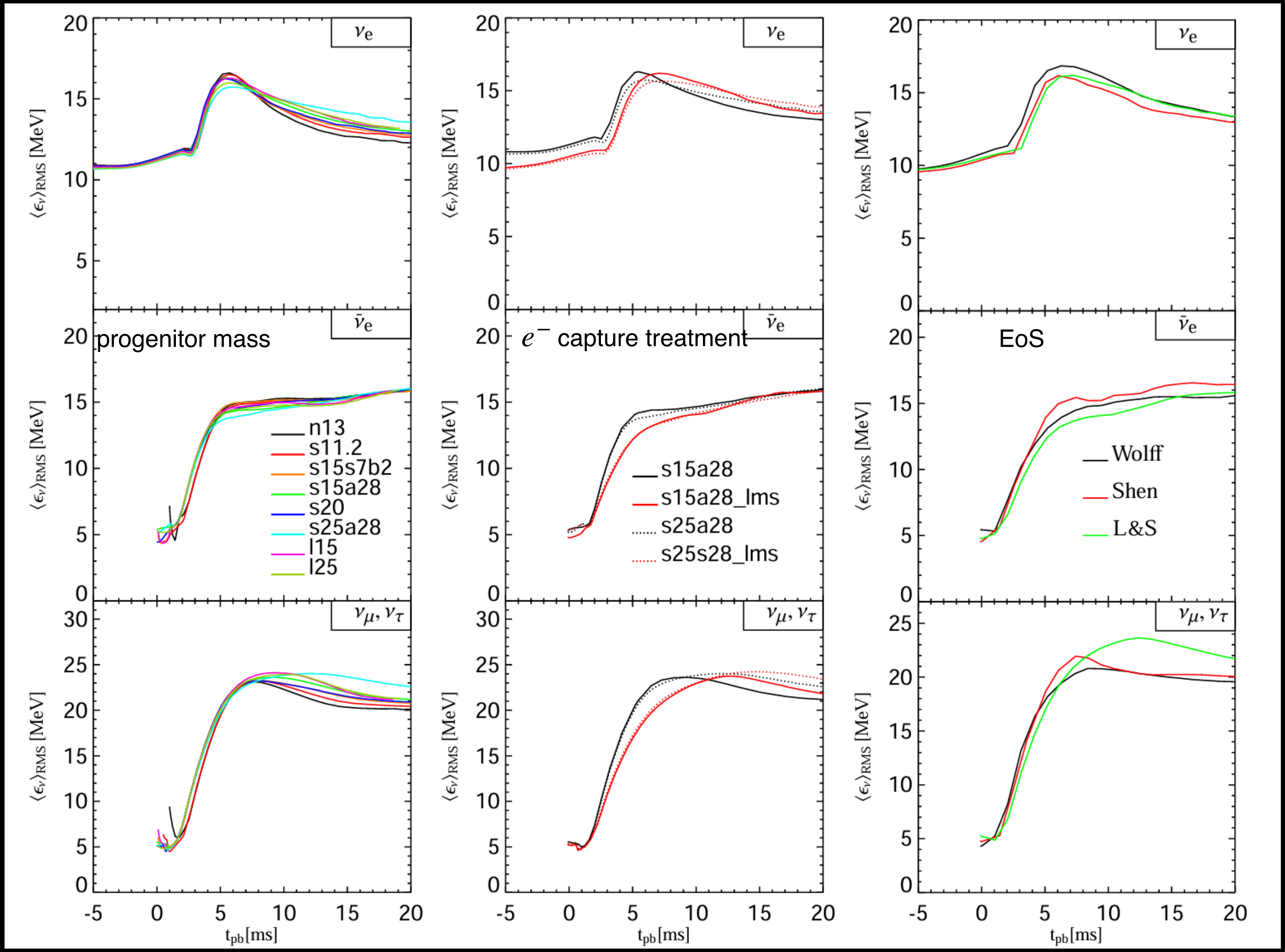


In the neutronization burst L_ν has little dependence on simulation details

Robustness of models

Comparison between L_ν changing some simulation details

Kachelriess, Tomas, Buras, Janka, Marek, Rampp, Phys. Rev. D 71 (2005), 063003

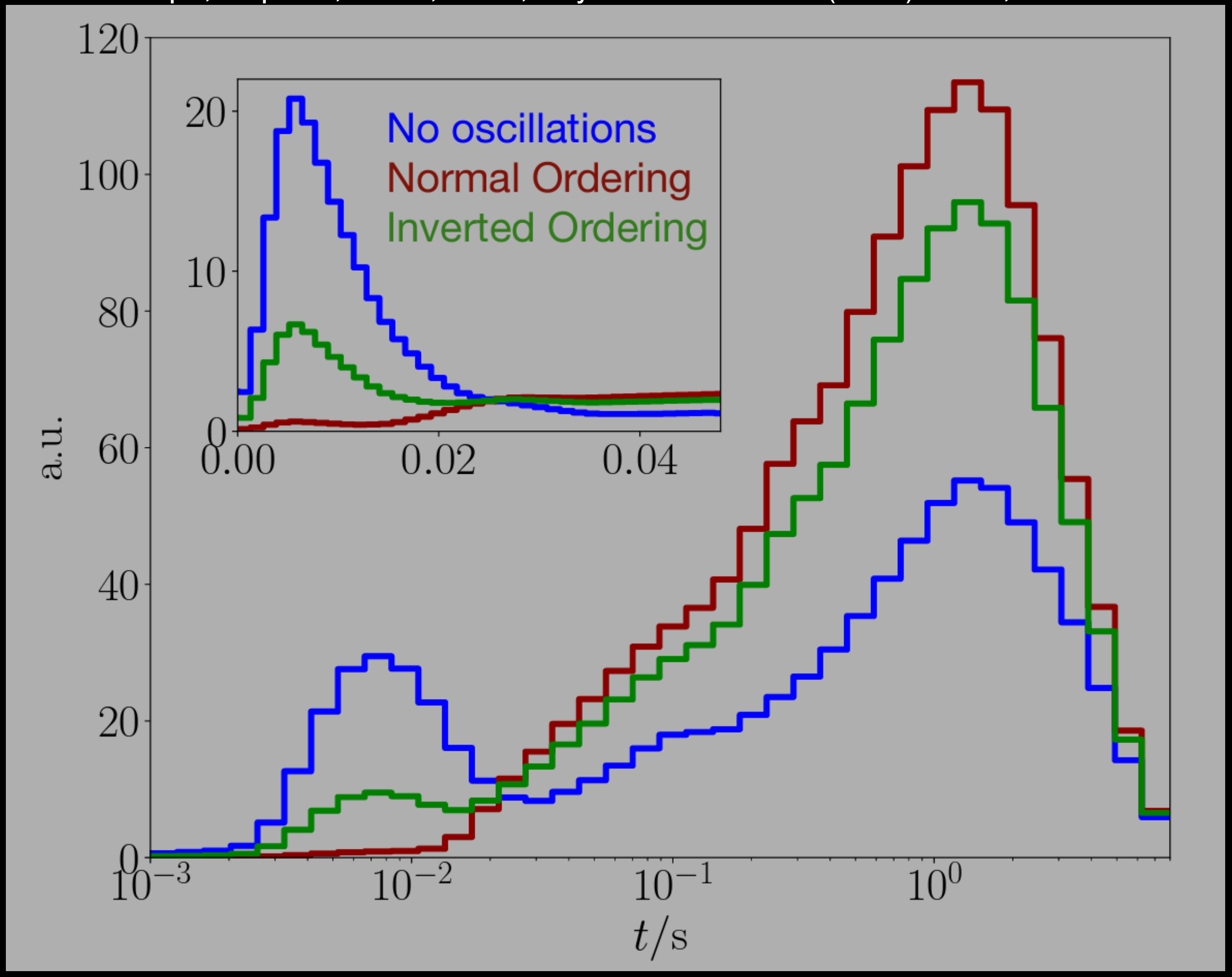


In the neutronization burst $\langle E_\nu \rangle$ has little dependence on simulation details

Neutrino Mass Ordering

DUNE will be sensitive to ν_e through $\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$

Pompa, Capozzi, Mena, Sorel, Phys. Rev. Lett. 129 (2022) no.12, 121802



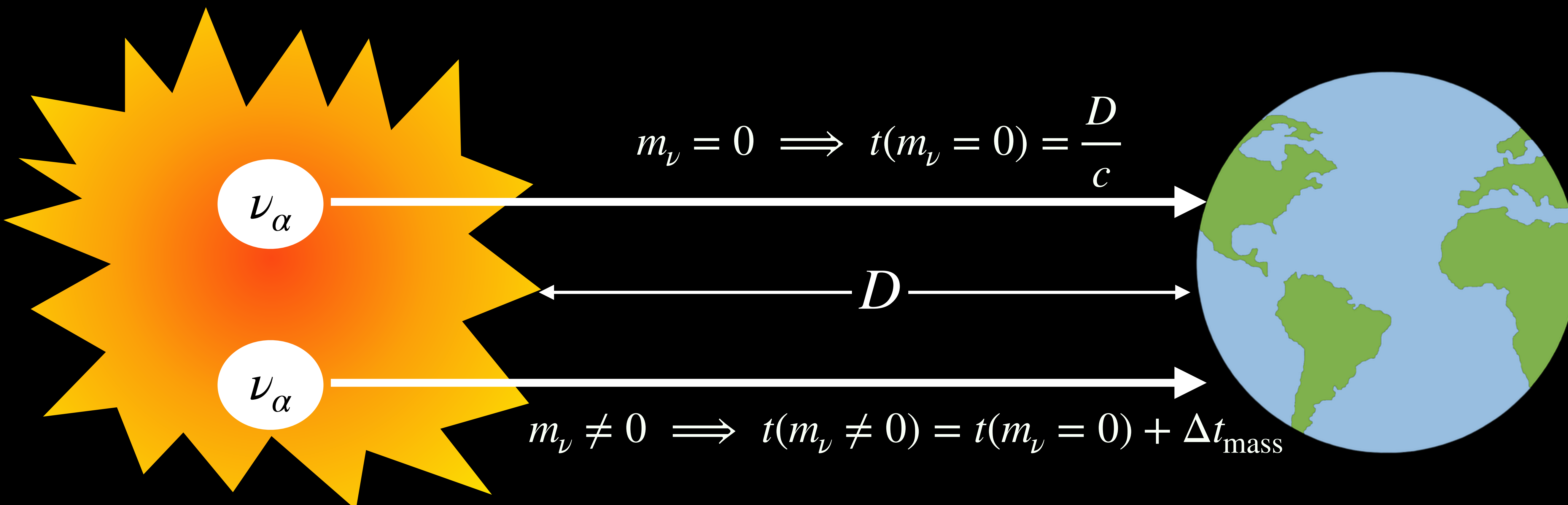
$$P(\nu_e \rightarrow \nu_e, \mathrm{NO}) \simeq \sin^2\theta_{13} \simeq 0.02$$

$$P(\nu_e \rightarrow \nu_e, \mathrm{IO}) \simeq \sin^2\theta_{12} \simeq 0.3$$

DUNE can identify the mass ordering using ν_e during the neutronization burst

Neutrino Mass

Neutrino time propagation is affected by neutrino mass

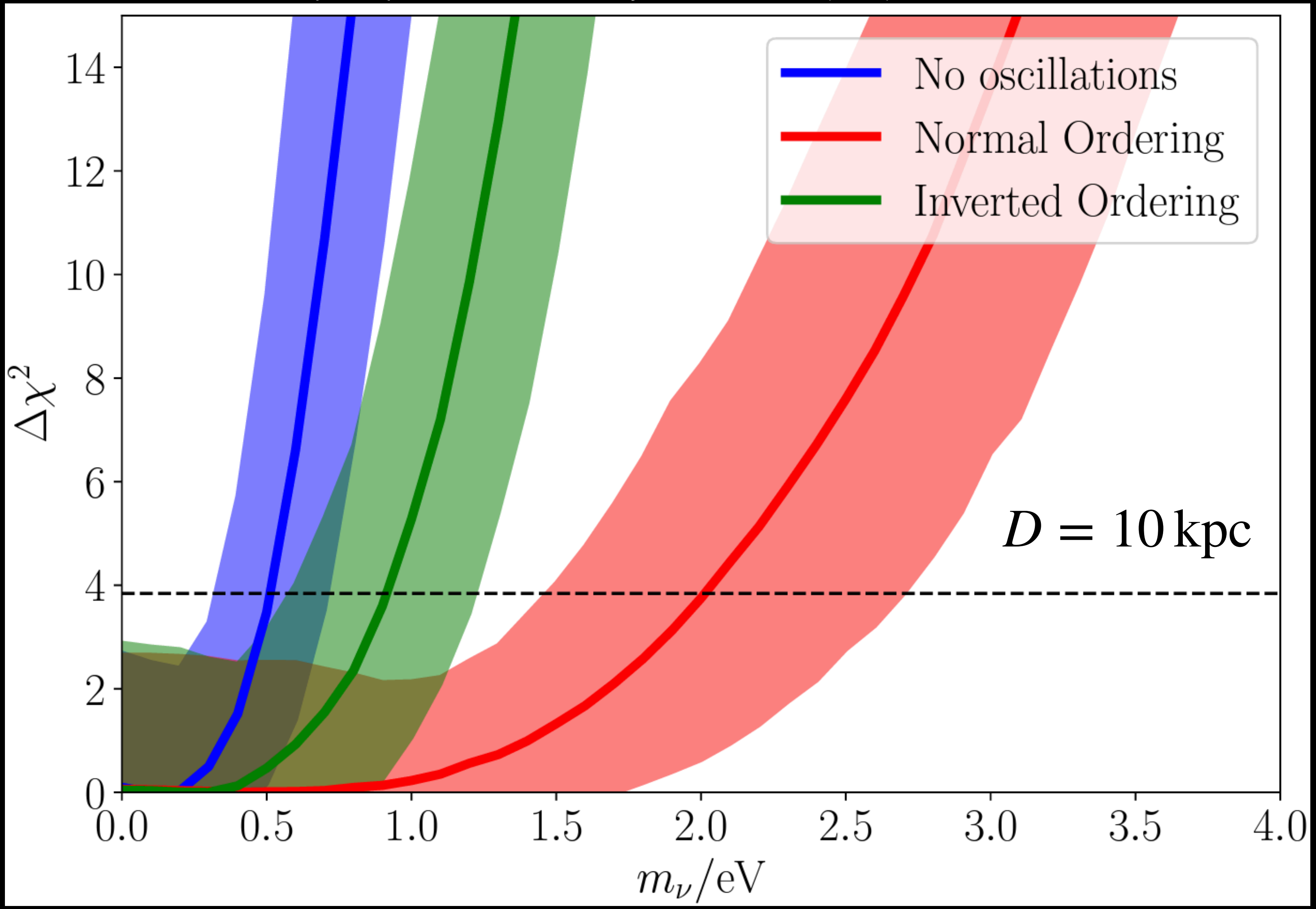


$$\Delta t_{\rm mass} \simeq \frac{D}{2c}\left(\frac{m_\nu}{E_\nu}\right)^2 \simeq 0.026\, s \left(\frac{D}{10\,{\rm kpc}}\right)\left(\frac{m_\nu}{1\,{\rm eV}}\right)^2\left(\frac{10\,{\rm MeV}}{E_\nu}\right)^2$$

Neutrino Mass

Neutrino time propagation is affected by neutrino mass

Pompa, Capozzi, Mena, Sorel, Phys. Rev. Lett. 129 (2022) no.12, 121802



DUNE can constrain neutrino mass up to ~ 1 eV

Supernova Distance

ν_e in neutronization burst is independent on simulation details

$$\Phi_\nu = \frac{\#\,\text{neutrinos}}{\text{area}} = \frac{E_{\text{grav}}}{\langle E_\nu \rangle 4\pi D^2}$$

$$N_{\text{events}} = \frac{\Phi_\nu}{6}\sigma_{\nu-\text{Ar}} N_{^{40}\text{Ar}}$$

$$D = \sqrt{\frac{E_{\text{grav}}\sigma_{\nu-\text{Ar}} N_{^{40}\text{Ar}}}{24\pi \langle E_\nu \rangle}}$$

DUNE measures the supernova distance without astrophysical observations

Neutrino Timing For GW

Apart from neutrinos also gravitational waves can be observed

$$t_{\rm GW} = t_{1{\rm st}\,\nu-{\rm evt}} - \Delta t_{\rm mass} \pm t_{\rm btw\,det} - t_{\rm resp}$$

$t_{1{\rm st}\,\nu-{\rm evt}}$ = time of first detected neutrino event

$t_{\rm btw\,det} = \vec{d}\cdot\hat{n}$, $\vec{d}$ distance $\nu-$GW detector, $\hat{n}$ SN position

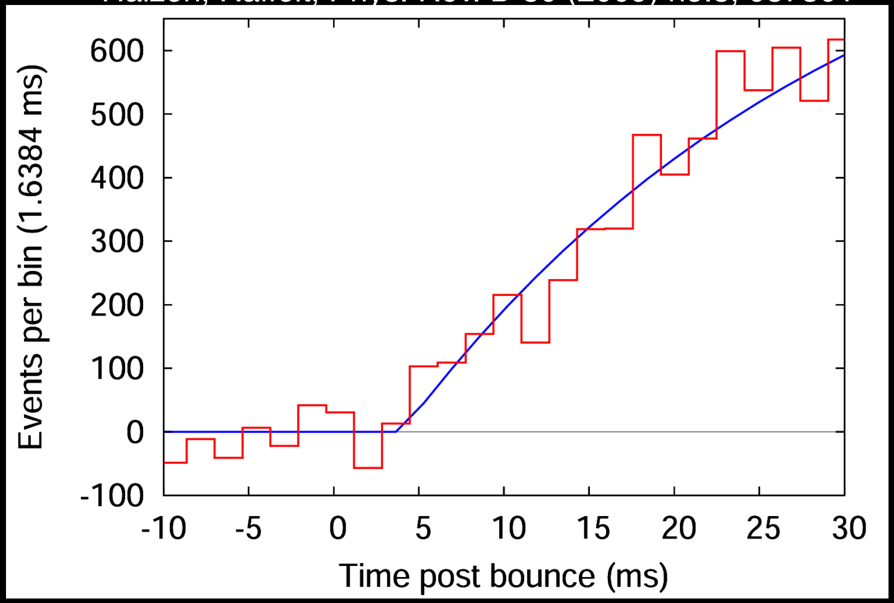
$t_{\rm resp}$ = delay between 1st ν reaches Earth and 1st event

Neutrino Timing For GW

Apart from neutrinos also gravitational waves can be observed

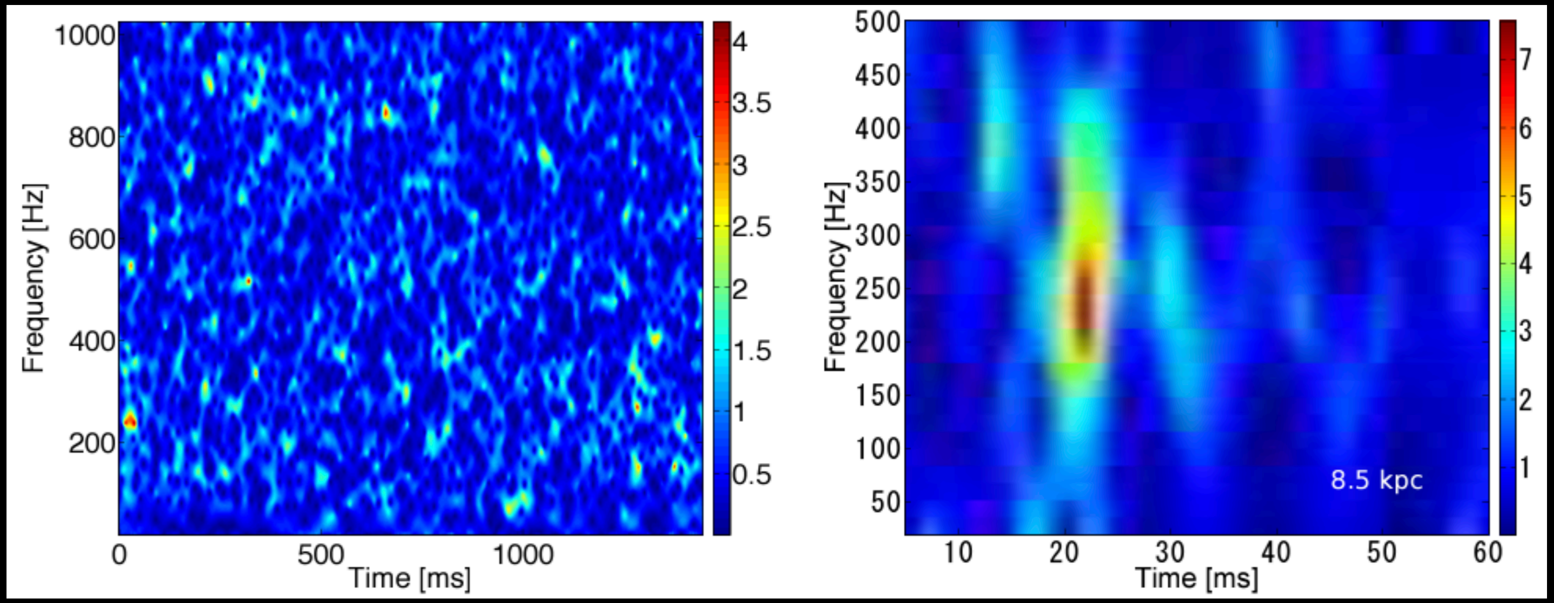
$$t_{\mathrm{GW}} = t_{1\mathrm{st}\,\nu-\mathrm{evt}} - \Delta t_{\mathrm{mass}} \pm t_{\mathrm{btw\,det}} - t_{\mathrm{resp}}$$

Halzen, Raffelt, Phys. Rev. D 80 (2009) no.8, 087301



Without ν triggering

With ν triggering



Nakamura, Horiuchi, Tanaka, Hayama, Takiwaki, Kotake, Mon. Not. Roy. Astron. Soc. 461 (2016) no.3, 3296-3313

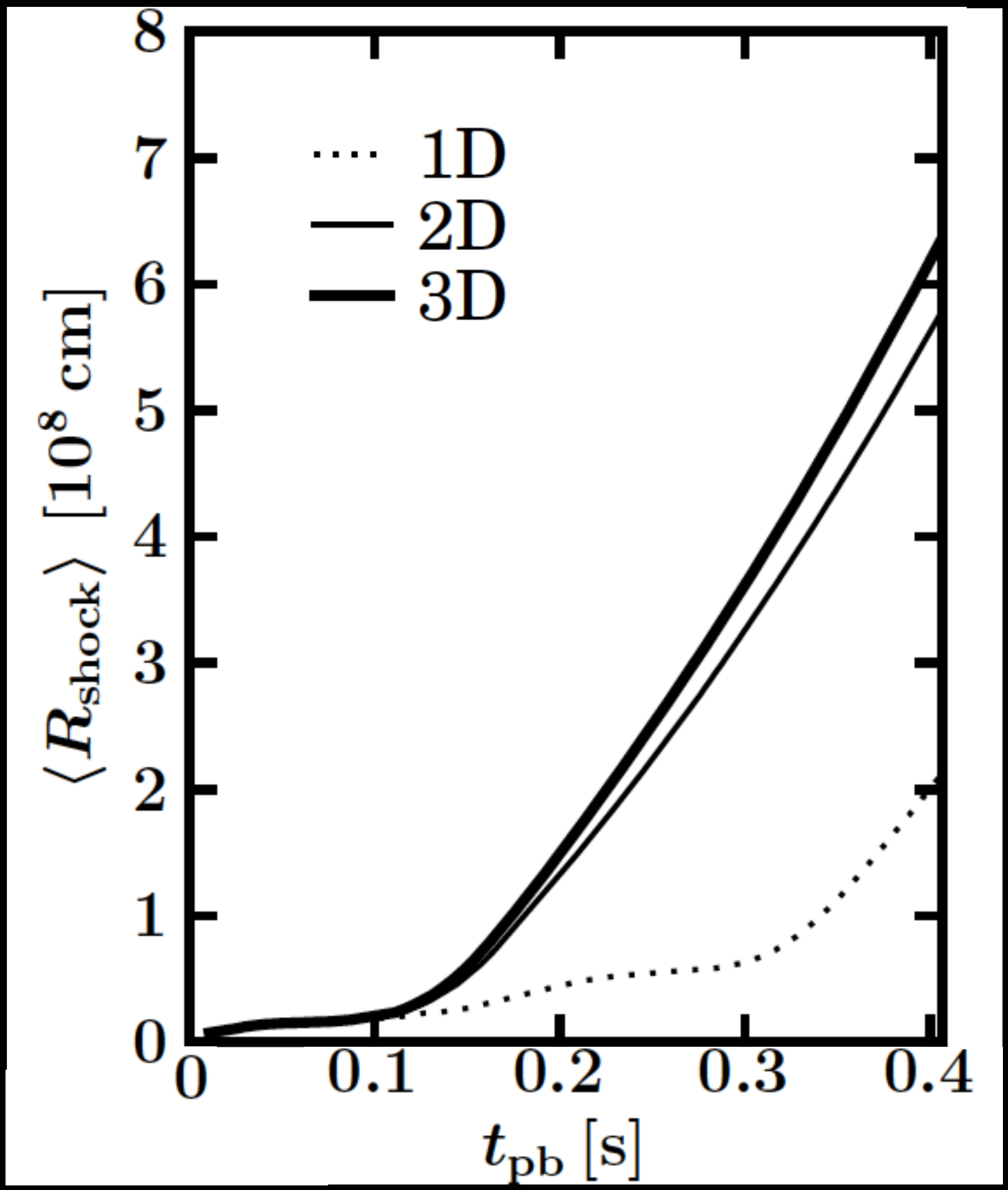
Neutrinos provide timing information for GW detectors

ACCRETION PHASE

- Current issues.
- What can we learn?

Shock revival from ν: does it work?

Successful explosions for low mass progenitors (< 10 $M_{\odot}$)



Melson, Janka and Marek, Astrophys. J. 801 (2015) no.2, L24

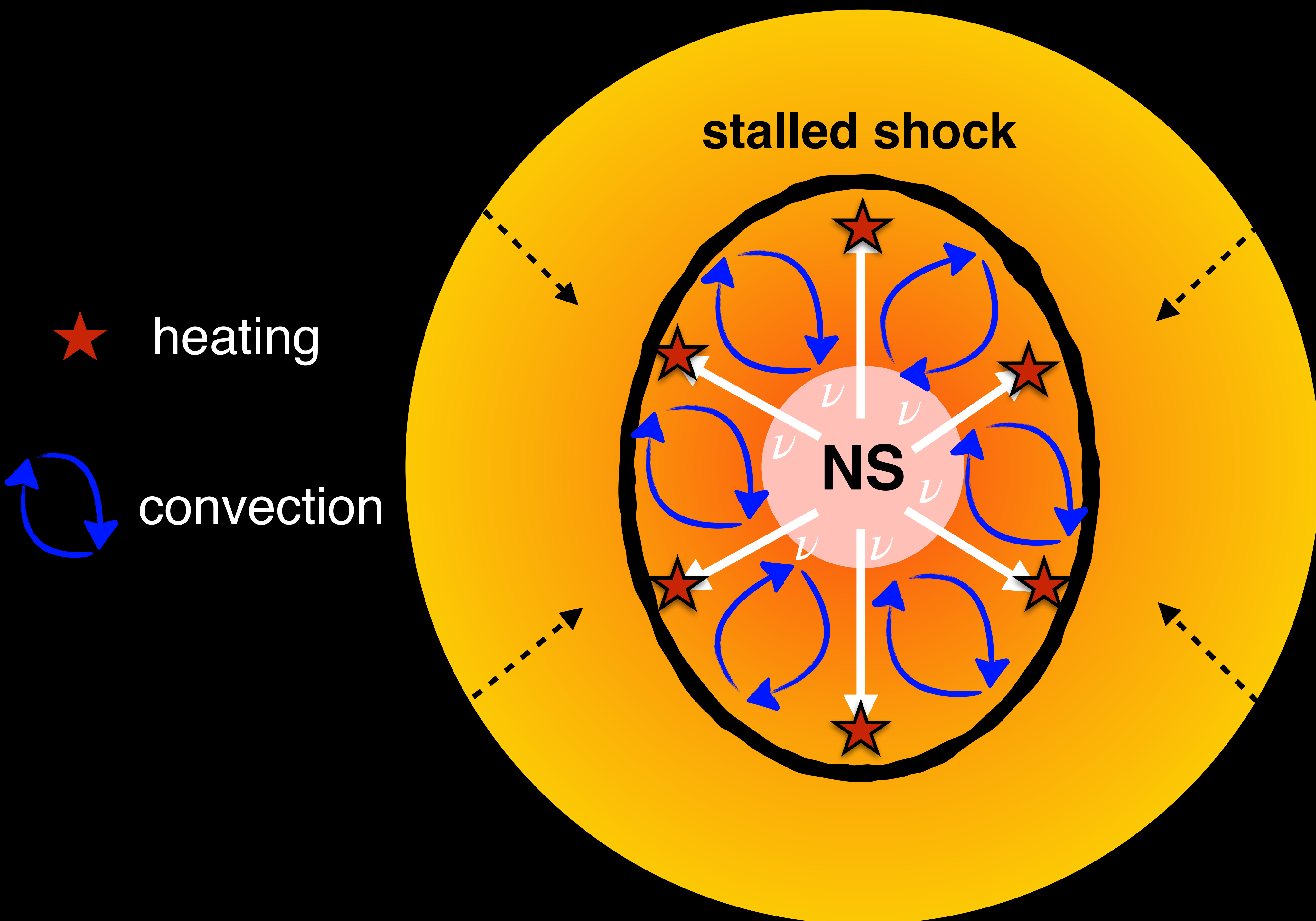
see also

Burrows, Radice and Vartanyan, MNRAS 485 (2019) no.3, 3153

Faster explosions in multi-D compared to 1D

Shock revival from ν: does it work?

Multi-D simulations allows convective / turbulent instabilities

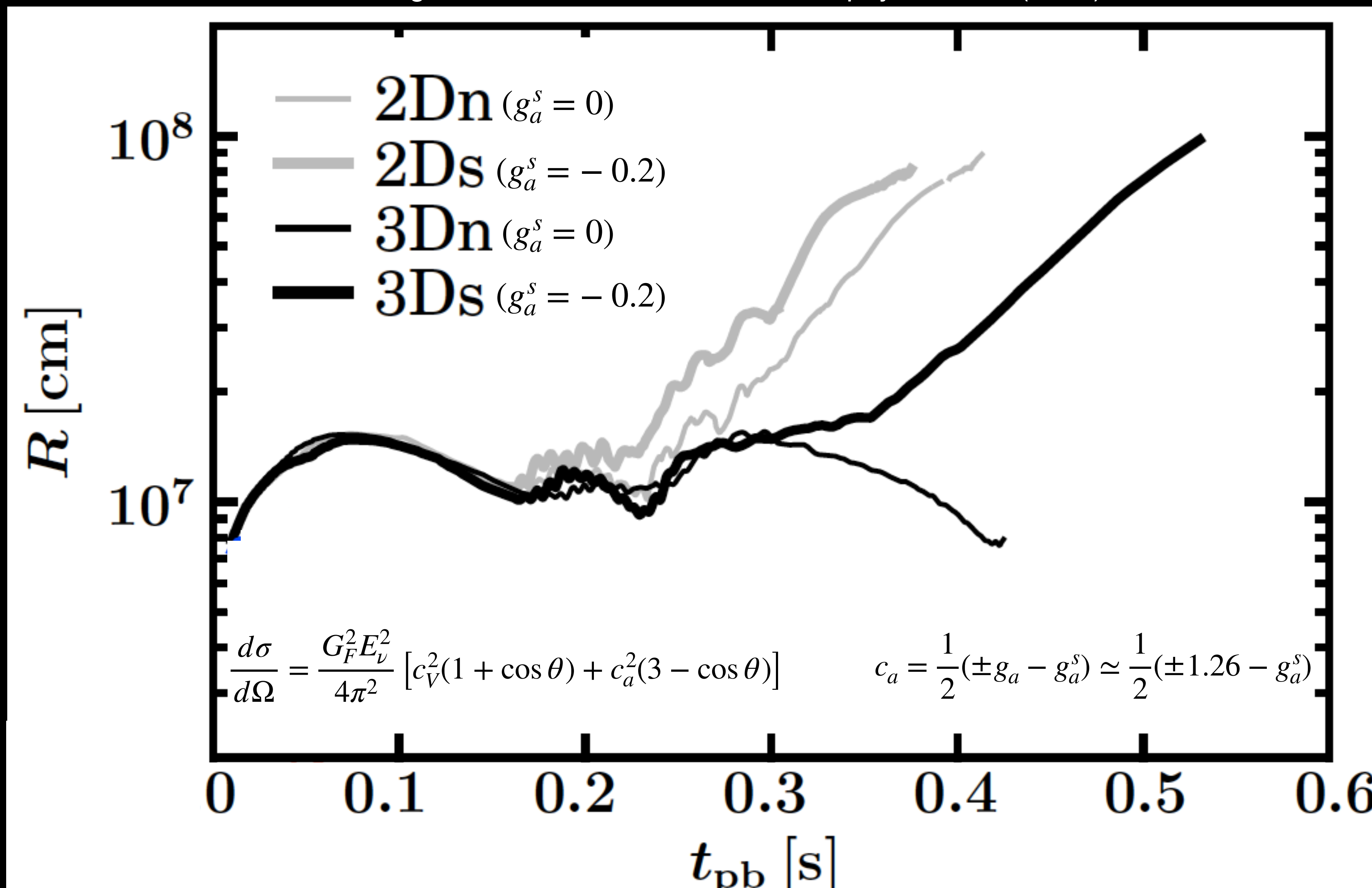


Convective instabilities “help” neutrino heating and explosions

Shock revival from ν: does it work?

Less consistent picture for heavy progenitor masses

Melson, Janka, Bollig, Hanke, Marek and Müller, Astrophys. J. 808 (2015) no.2, L42

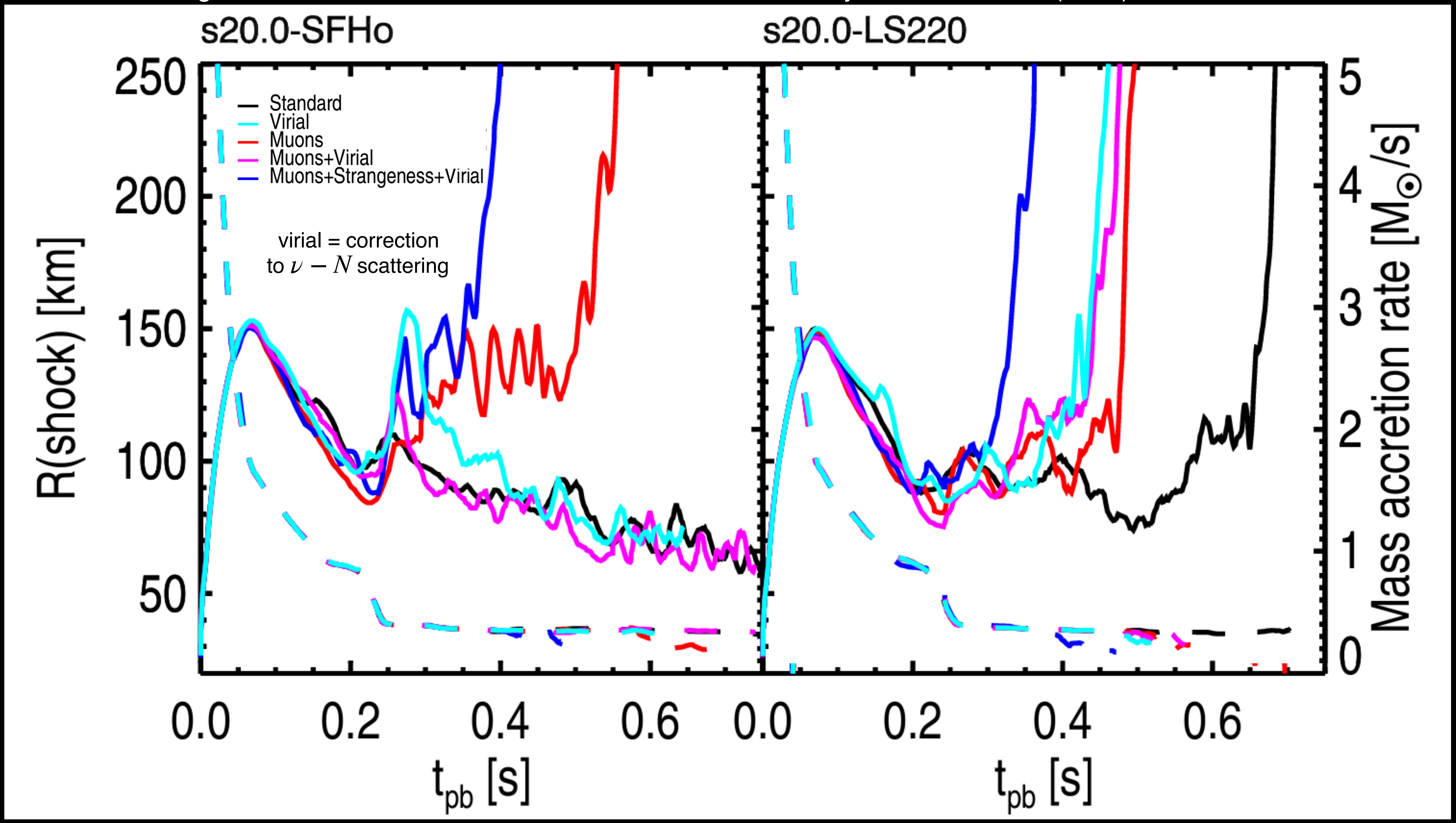


Example: s-quark contribution ν-N scattering induces explosion

Shock revival from ν: does it work?

Less consistent picture for heavy progenitor masses

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

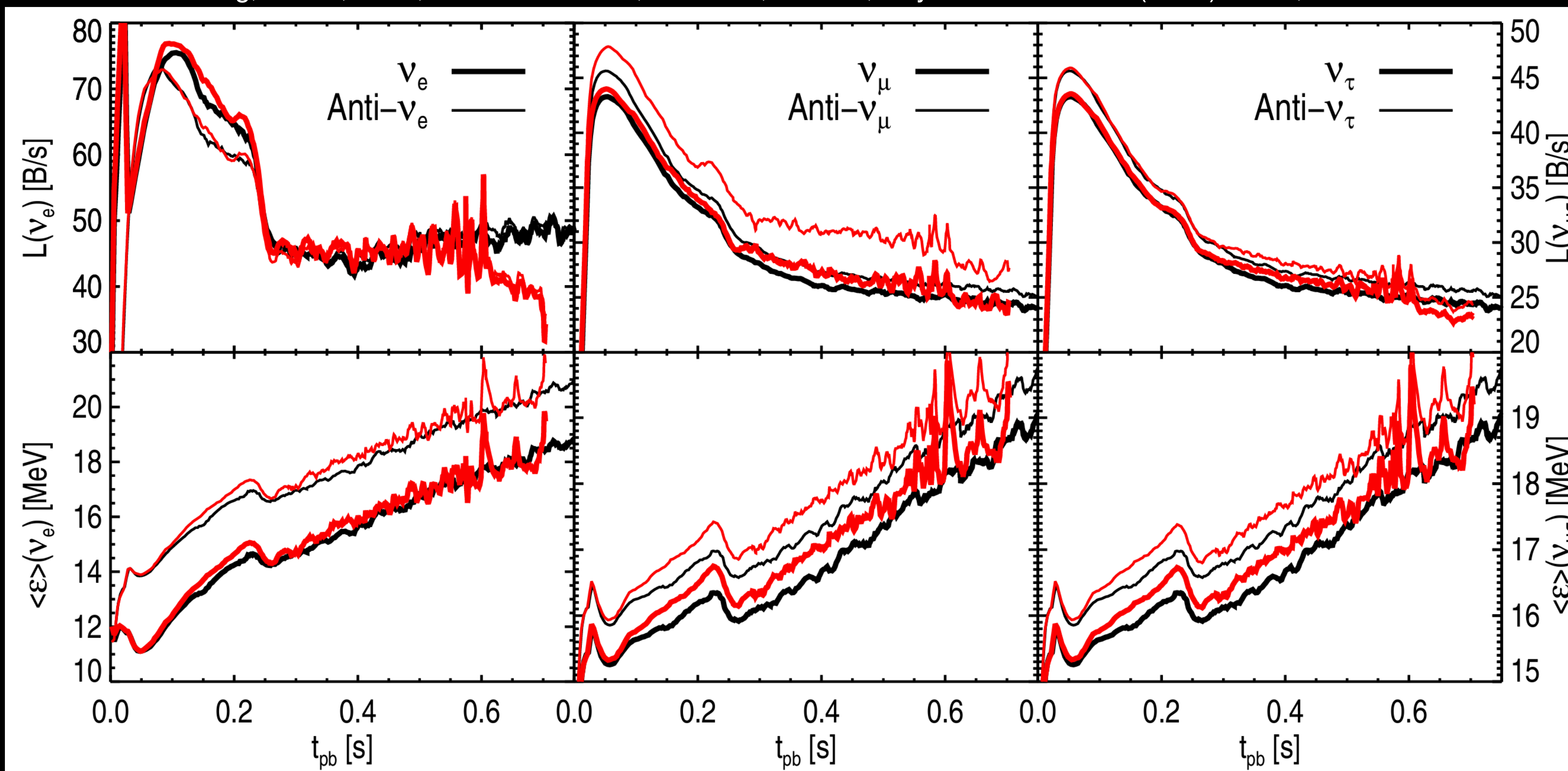


Example: muon production in the core affects explosion

Shock revival from ν: does it work?

Excess of $\bar{\nu}_\mu$ over ν_μ. $\langle E_{\bar{\nu}_\mu} \rangle > \langle E_{\nu_\mu} \rangle$.

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

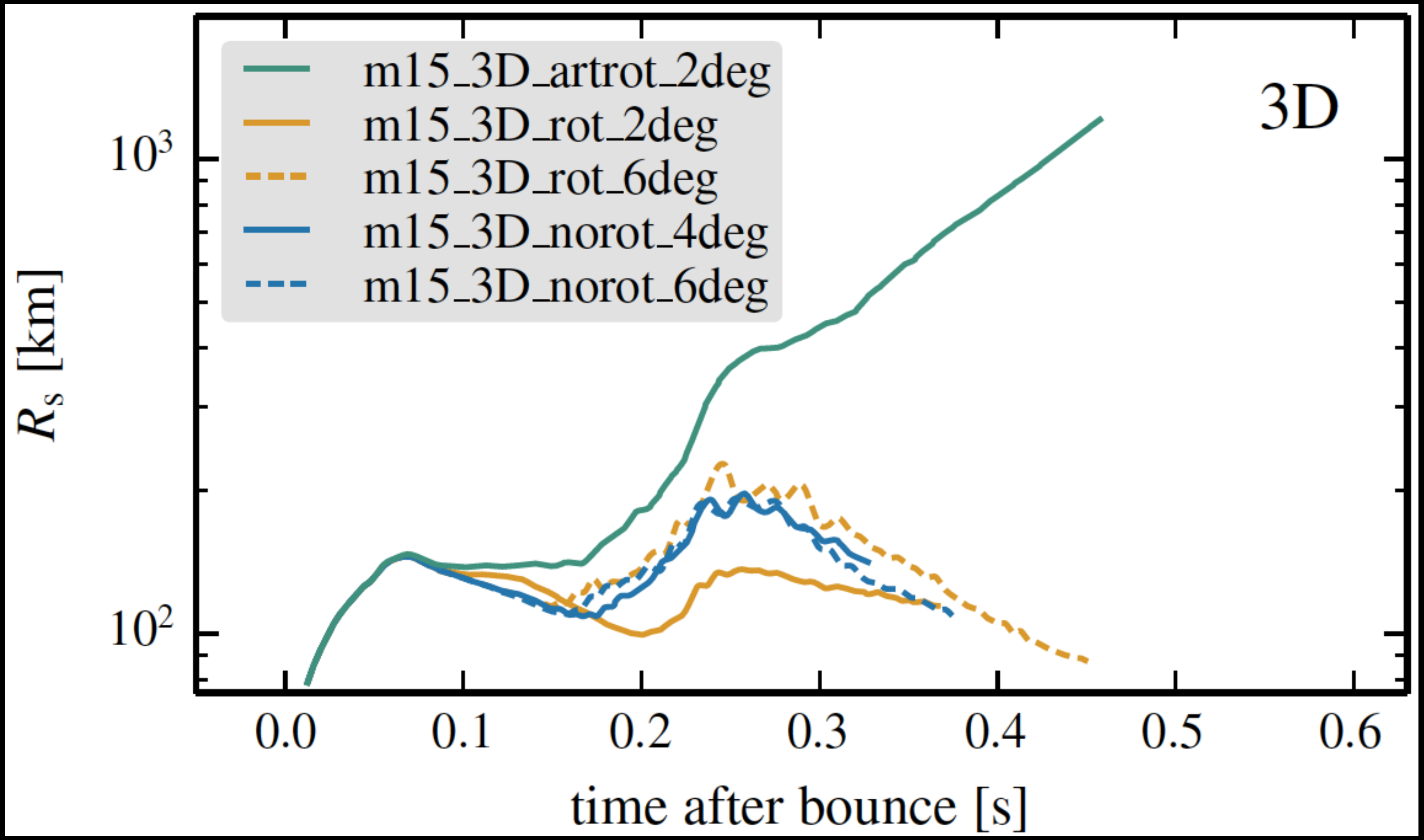


e^- degeneracy converted to $\mu^\pm$ rest mass. Faster collapse, higher temperature, more efficient ν—heating.

Shock revival from ν: does it work?

Less consistent picture for heavy progenitor masses

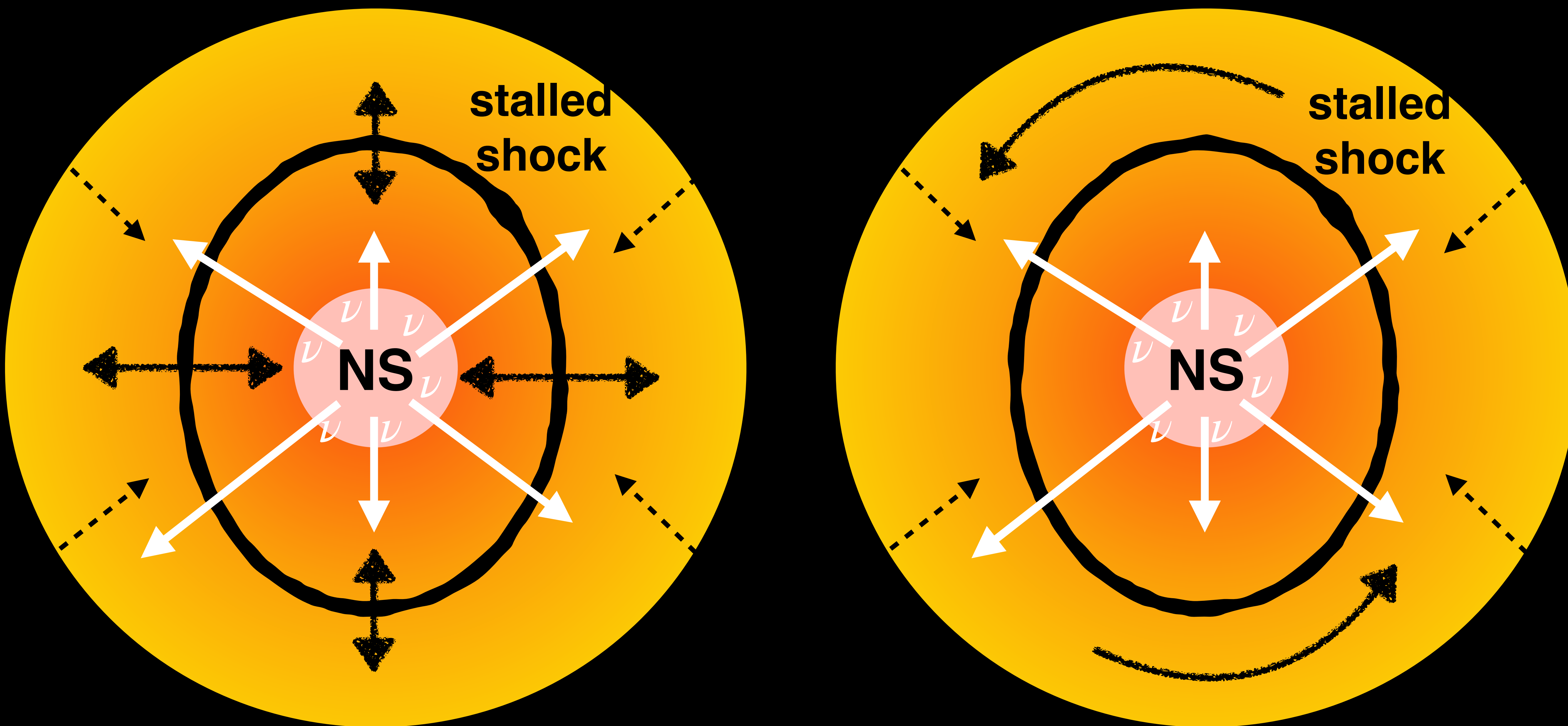
Summa, Janka, Melson and Marek, Astrophys. J. 852 (2018) no.1, 28



Example: fast rotation induced explosion

Multi-D neutrino signal features

SASI: sloshing / spiraling motion of the stalled shock

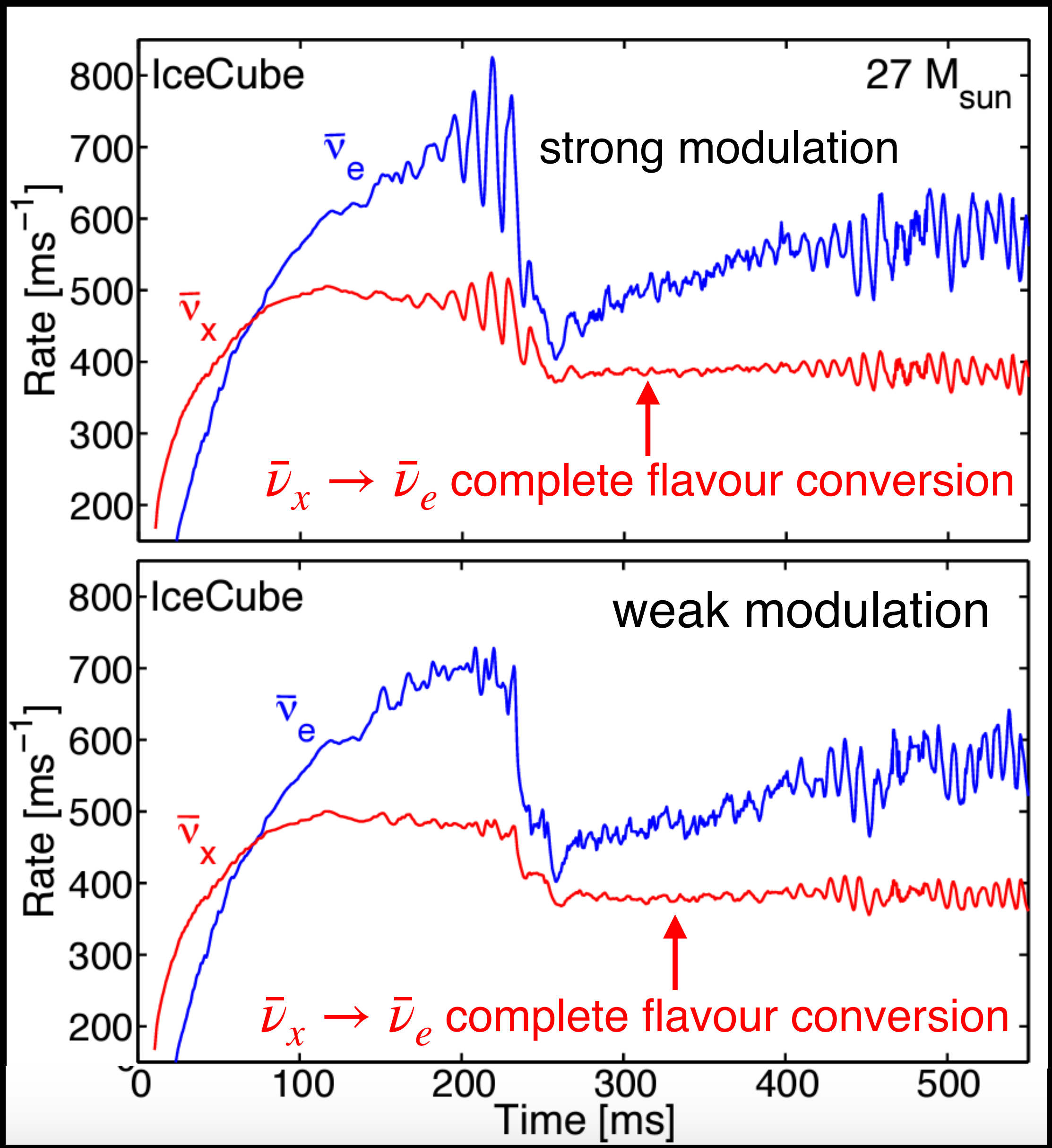


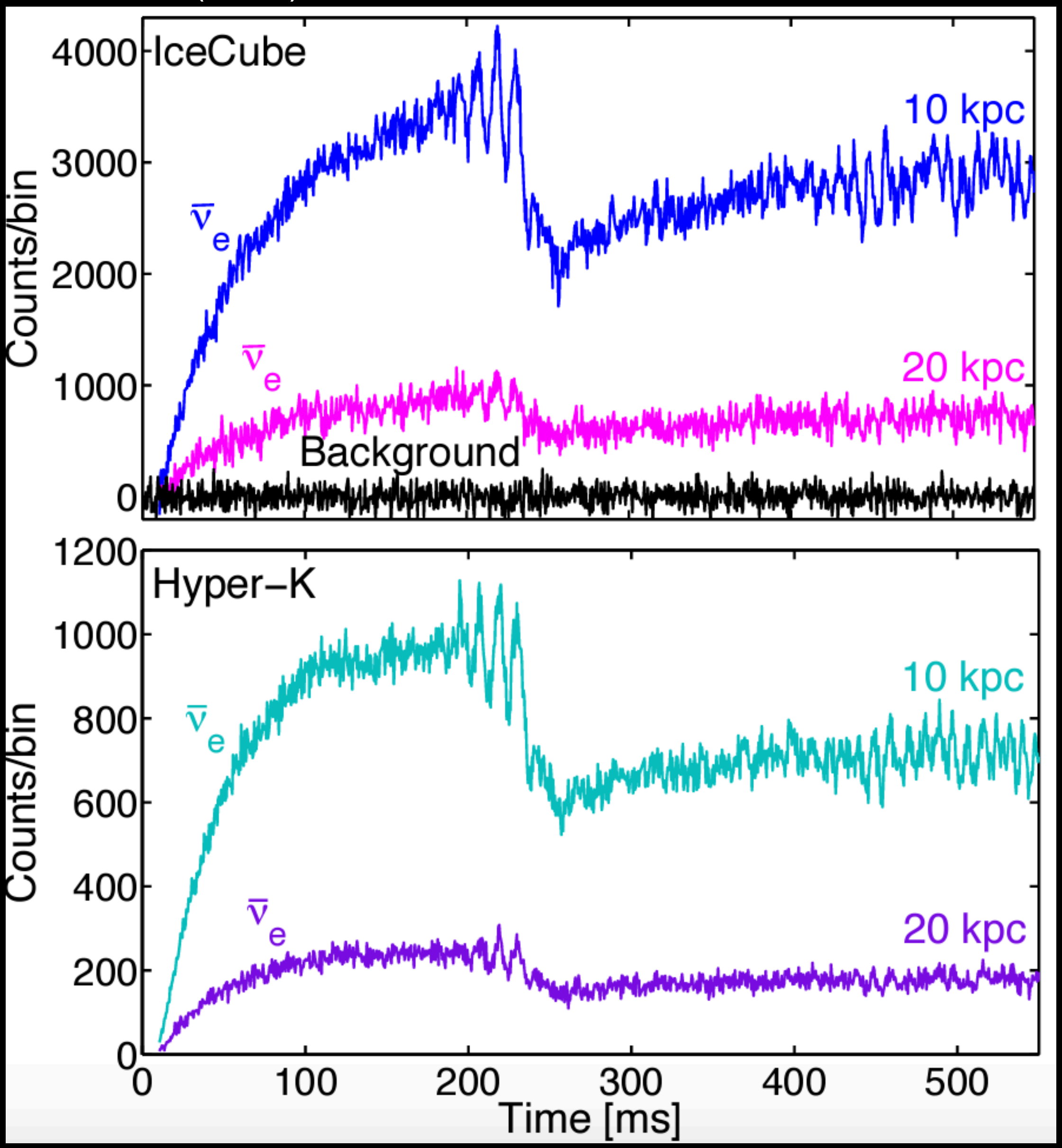
SASI induces modulation of neutrino luminosity

Multi-D neutrino signal features

SASI induces modulation of neutrino luminosity

Tamborra, Hanke, Muller, Janka, Raffelt, Phys. Rev. Lett. 111 (2013) no.12, 121104



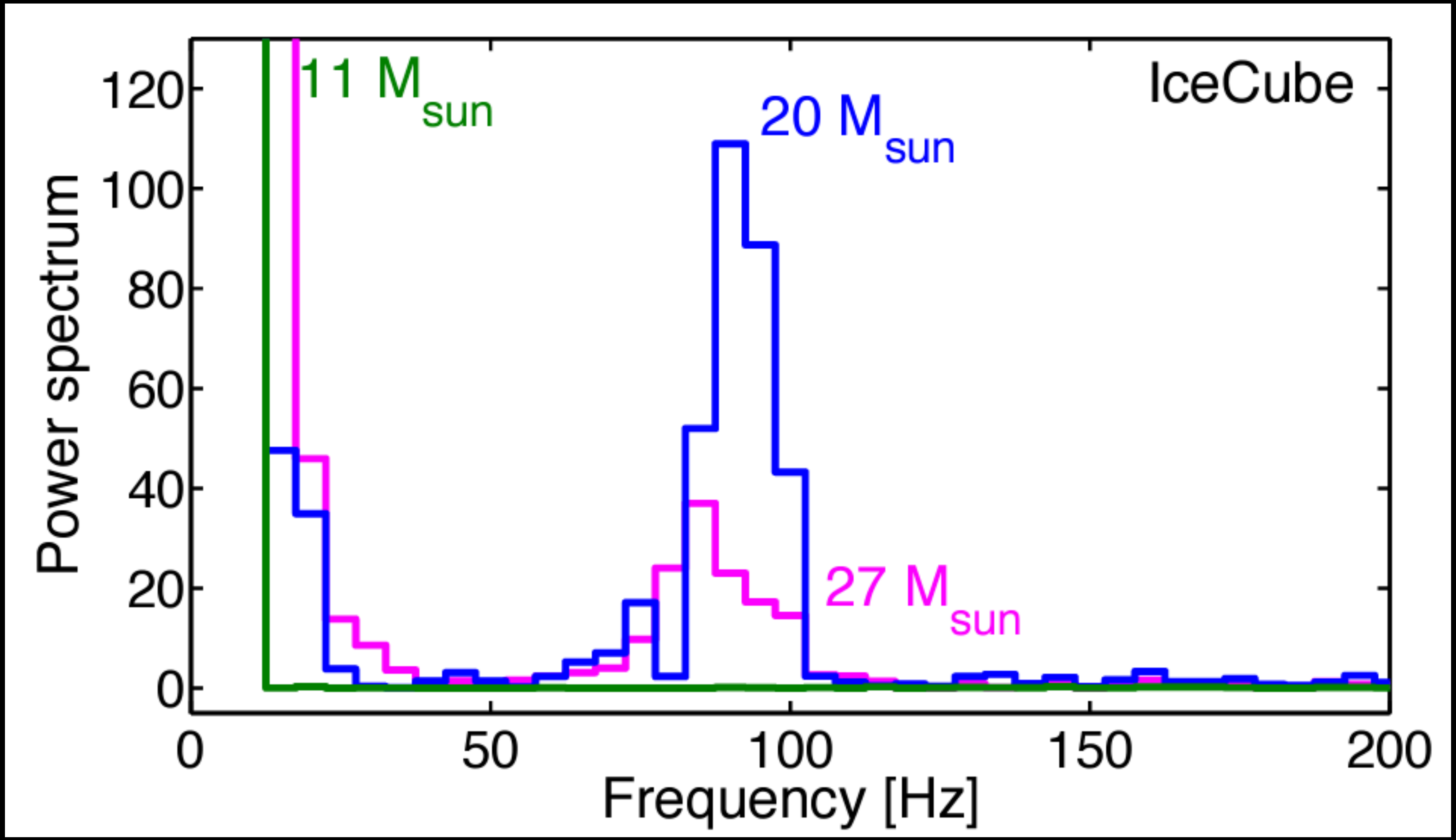


Imprints of SASI are visible with Ice-CUBE or Hyper-K

Multi-D neutrino signal features

SASI induces modulation of neutrino luminosity

Tamborra, Hanke, Muller, Janka, Raffelt, Phys. Rev. Lett. 111 (2013) no.12, 121104

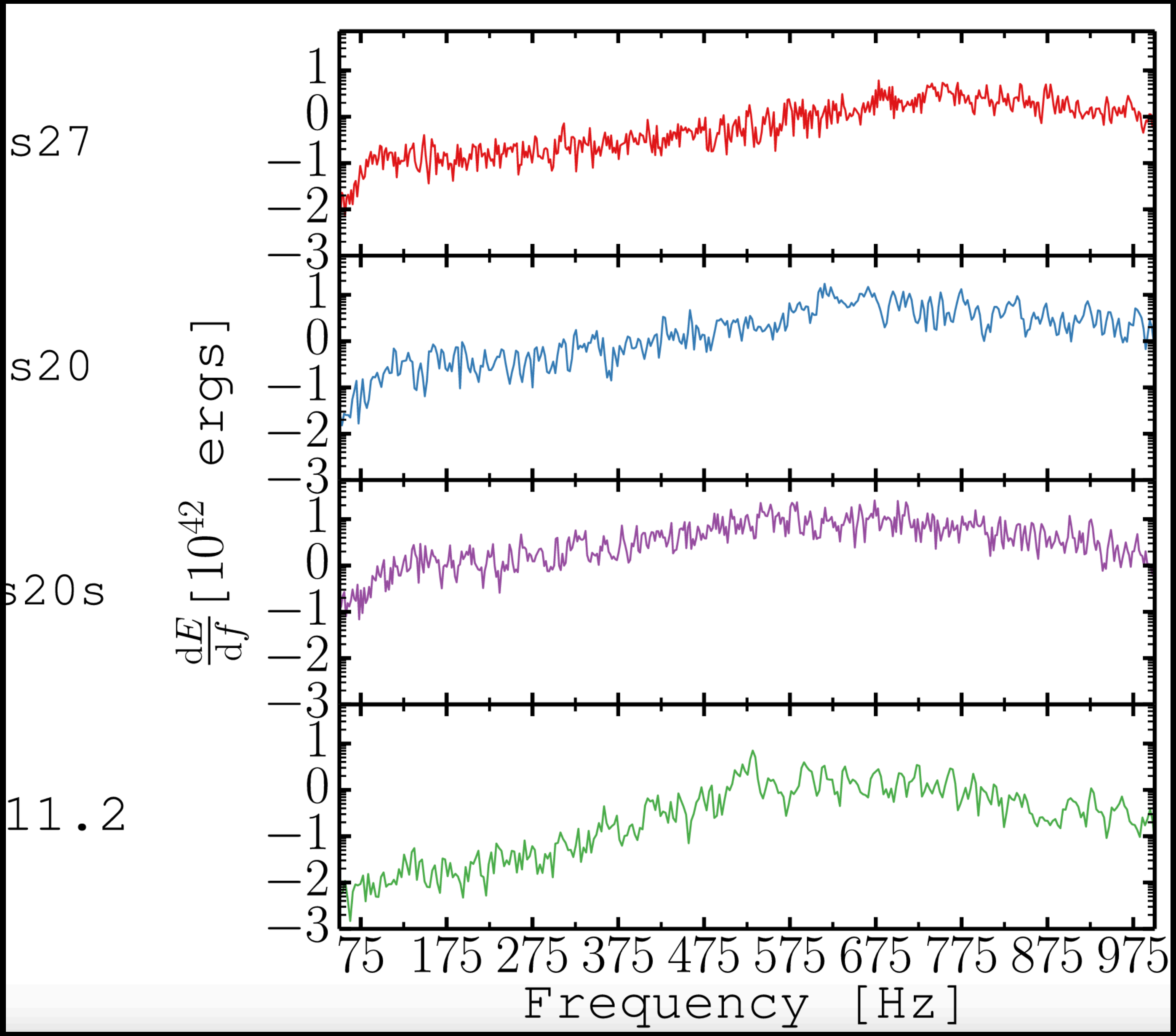


Imprints of SASI are visible with Ice-CUBE or Hyper-K

Multi-D neutrino signal features

SASI induces signatures in gravitational waves

Andresen, Muller, Muller, Janka, Mon. Not. Roy. Astron. Soc. 468 (2017) no.2, 2032-2051

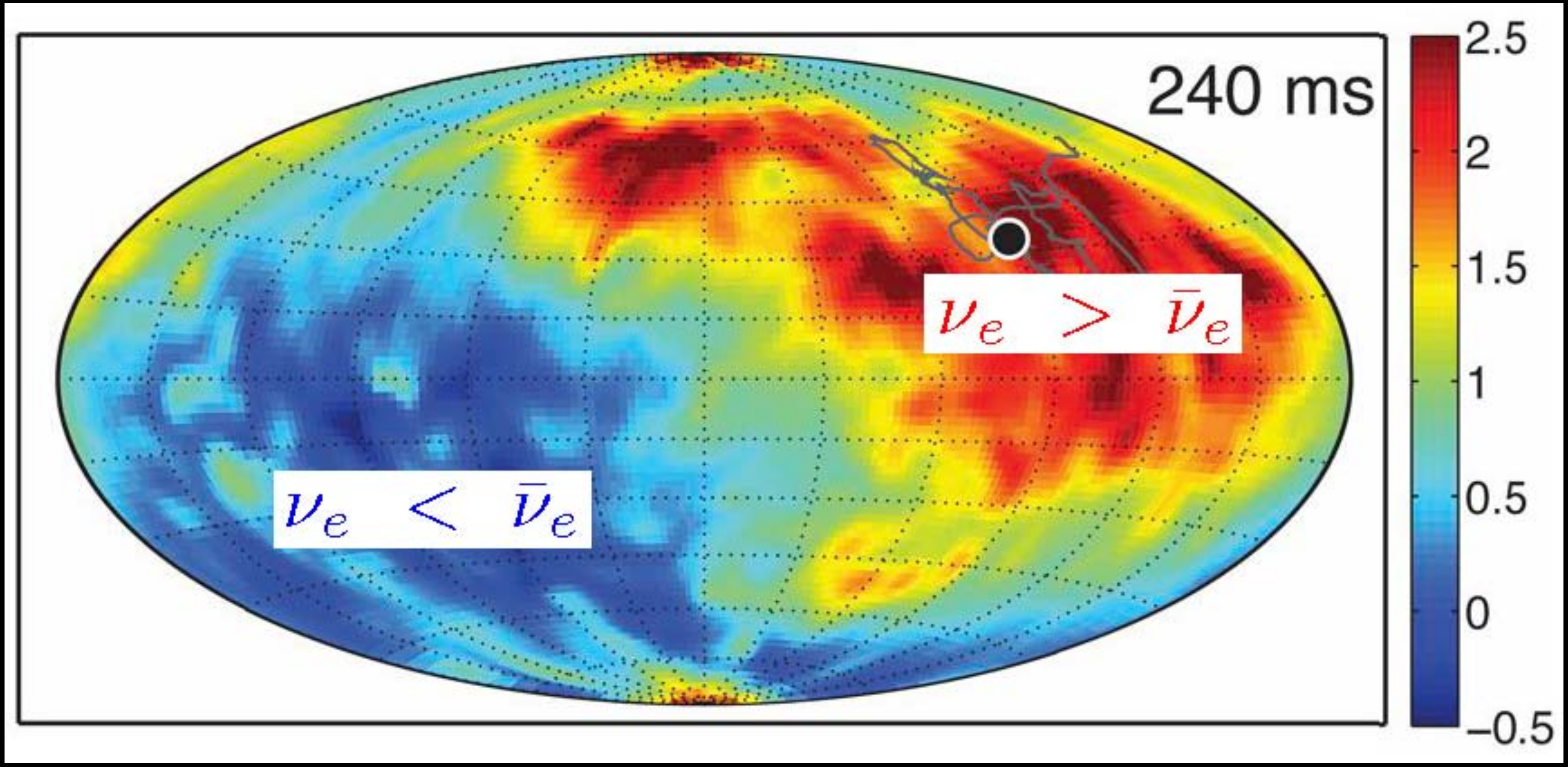


Multi-messenger information from ν + GW

Multi-D neutrino signal features

Lepton number is emitted asymmetrically (LESA)

Tamborra, et al., Astrophys. J.792 (2014) no.2, 96,
confirmed by O'Connor and Couch, Astrophys. J. 865 (2018) no.2, 81 Vartanyan, Burrows and Radice, MNRAS 489 (2019) 2, 2227

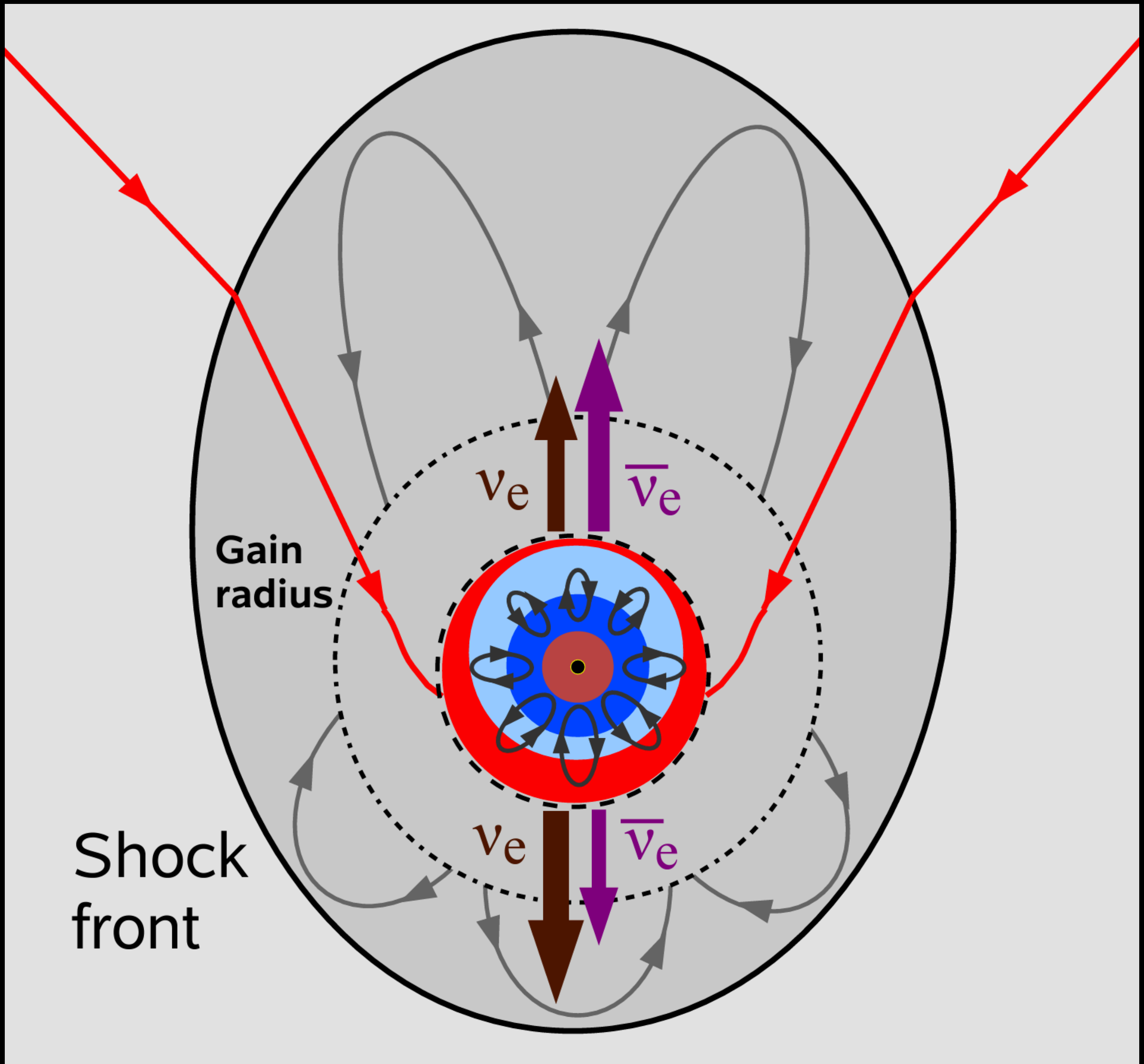


Angular dependence must be taken into account in observation

Multi-D neutrino signal features

Explosion is not spherically symmetric

Tamborra, et al., Astrophys. J.792 (2014) no.2, 96,
confirmed by O'Connor and Couch, Astrophys. J. 865 (2018) no.2, 81 Vartanyan, Burrows and Radice, MNRAS 489 (2019) 2, 2227



Non-spherical Y_e induced by asymmetric convection

Collective Flavour Conversions

Dense environments: unique conditions for flavour conversions

$\nu_\alpha(\vec{p}) \rightarrow \nu_\beta(\vec{p})$ →

<u>STANDARD OSCILLATIONS</u>

- Scale: $\Delta m^2/2E \simeq 0.5\,\mathrm{km}^{-1}$
- Requirements: $\Delta m^2, \theta \neq 0$
- Lepton number violation

Collective Flavour Conversions

Dense environments: unique conditions for flavour conversions

$$\nu_\alpha(\vec{p}) \rightarrow \nu_\beta(\vec{p})$$

STANDARD OSCILLATIONS

- Scale: $\Delta m^2/2E \simeq 0.5\,\mathrm{km}^{-1}$
- Requirements: $\Delta m^2, \theta \neq 0$
- Lepton number violation

$$\nu_e(\vec{p}) + \bar{\nu}_e(\vec{k}) \rightarrow \nu_\mu(\vec{p}) + \bar{\nu}_\mu(\vec{k})$$
$$\nu_e(\vec{p}) + \nu_\mu(\vec{k}) \rightarrow \nu_\mu(\vec{p}) + \nu_e(\vec{k})$$

COLLECTIVE EFFECTS

- Lepton number conserved
- Requirements: high $\nu-$density
- Occur even when $\Delta m^2, \theta = 0$
- Coherent effects: $O(G_F)$
- collective: same for different E_ν

Collective Flavour Conversions

Useful to work with density matrices instead of wave functions

$$(\partial_t + \mathbf{v} \cdot \partial_{\mathbf{r}})\varrho_{\mathbf{p}} = -i[H_{\mathbf{p}}, \varrho_{\mathbf{p}}] + \mathscr{C}(\varrho_{\mathbf{p}})$$

$$\varrho_{\mathbf{p}} = \begin{pmatrix} \varrho_{ee}(\overrightarrow{p}) & \varrho_{e\mu}(\overrightarrow{p}) & \varrho_{e\tau}(\overrightarrow{p}) \\ \varrho^*_{e\mu}(\overrightarrow{p}) & \varrho_{\mu\mu}(\overrightarrow{p}) & \varrho_{\mu\tau}(\overrightarrow{p}) \\ \varrho^*_{e\tau}(\overrightarrow{p}) & \varrho^*_{\mu\tau}(\overrightarrow{p}) & \varrho_{\tau\tau}(\overrightarrow{p}) \end{pmatrix}$$

Diagonal elements: number of neutrinos with a given flavour.
Off-diagonal: flavour coherence information.

Collective Flavour Conversions

Neglect standard oscillation effects in the hamiltonian

$$(\partial_t + \mathbf{v}\cdot\partial_{\mathbf{r}})\varrho_{\mathbf{p}} = -\, i[H_{\mathbf{p}}, \varrho_{\mathbf{p}}] + \mathscr{C}(\varrho_{\mathbf{p}})$$

$$H_{\mathbf{p}} = \sqrt{2}G_F \int \frac{d^3p'}{(2\pi)^3}(1 - \mathbf{v}\cdot\mathbf{v}')(\varrho_{\mathbf{p}'} - \bar{\varrho}_{\mathbf{p}'})$$

Non linear equation. Solvable only with approximations!!!

Collective Flavour Conversions

Vacuum oscillation frequency

$$\omega = \Delta m^2/(2E) \simeq 0.5\,\mathrm{km}^{-1}$$

$$(E = 10\,\mathrm{MeV}, \Delta m^2 = 2 \times 10^{-3}\,\mathrm{eV}^2)$$

$\nu - \nu$ potential

$$\mu = \sqrt{2} G_F N_\nu \simeq 1\,\mathrm{cm}^{-1}$$

$$(N_\nu \simeq 10^{36}\,\mathrm{cm}^{-3})$$

Collective Flavour Conversions

Vacuum oscillation frequency

$$\omega = \Delta m^2/(2E) \simeq 0.5\,\mathrm{km}^{-1}$$

$(E = 10\,\mathrm{MeV}, \Delta m^2 = 2 \times 10^{-3}\,\mathrm{eV}^2)$

$\nu - \nu$ potential

$$\mu = \sqrt{2}G_F N_\nu \simeq 1\,\mathrm{cm}^{-1}$$

$(N_\nu \simeq 10^{36}\,\mathrm{cm}^{-3})$

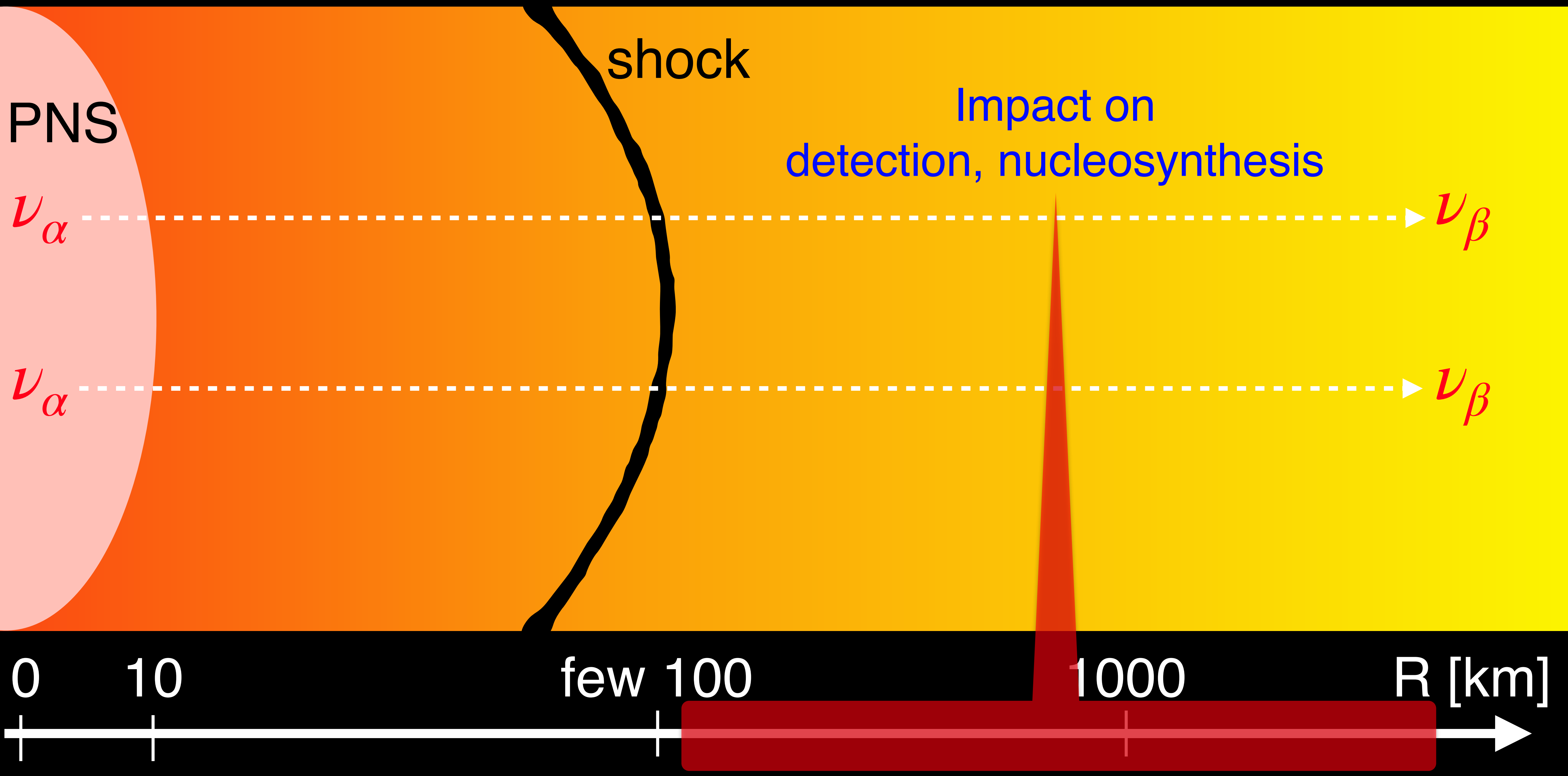
FAST CONVERSIONS

Time scale $\propto 1/\mu \simeq 10^{-9}\,\mathrm{s}$. Mixing independent!!!

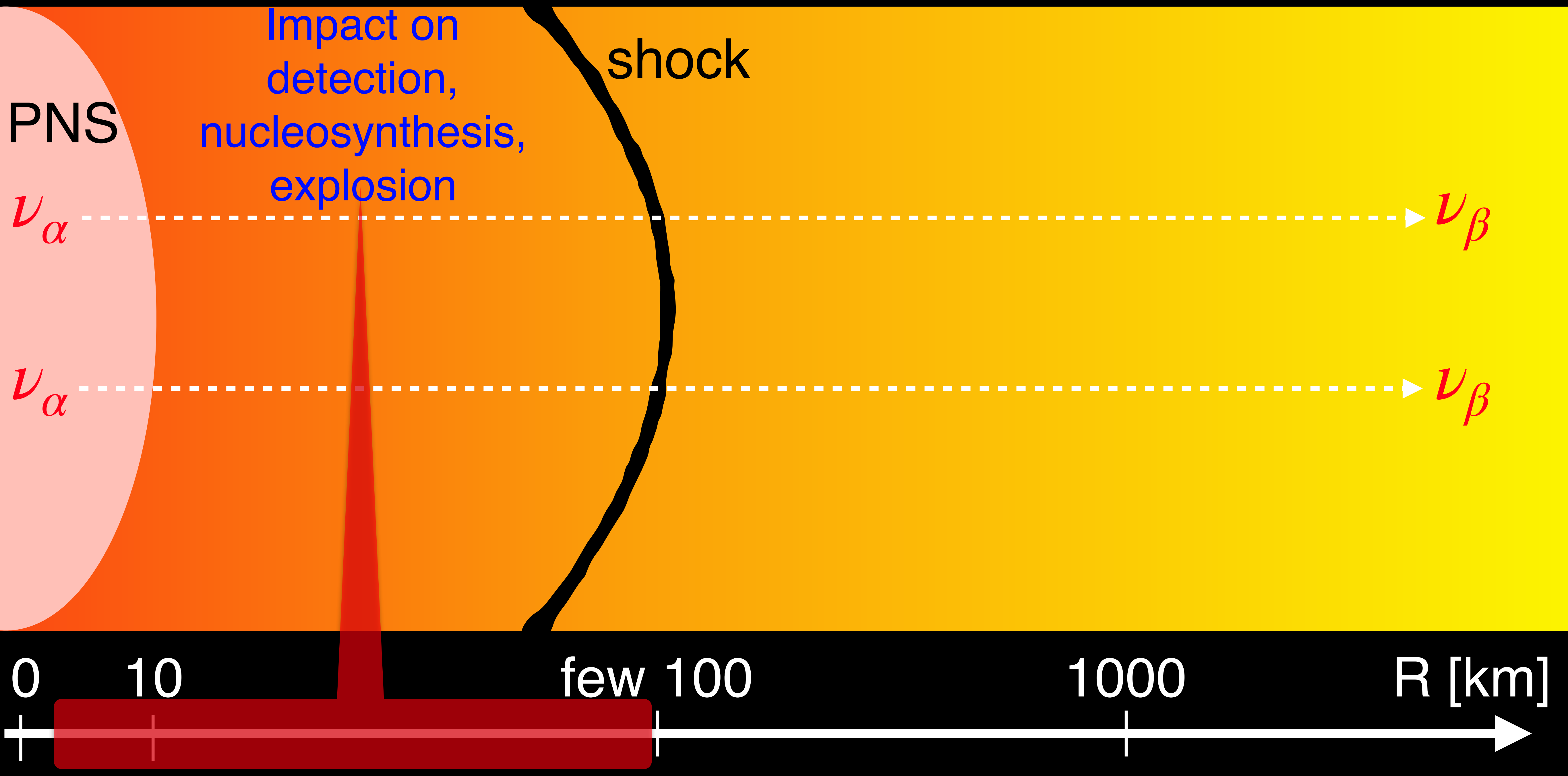
SLOW CONVERSIONS

Time scale $\propto 1/\sqrt{\omega\mu} \gg 1/\mu$. Mixing dependent!!!

Collective Flavour Conversions

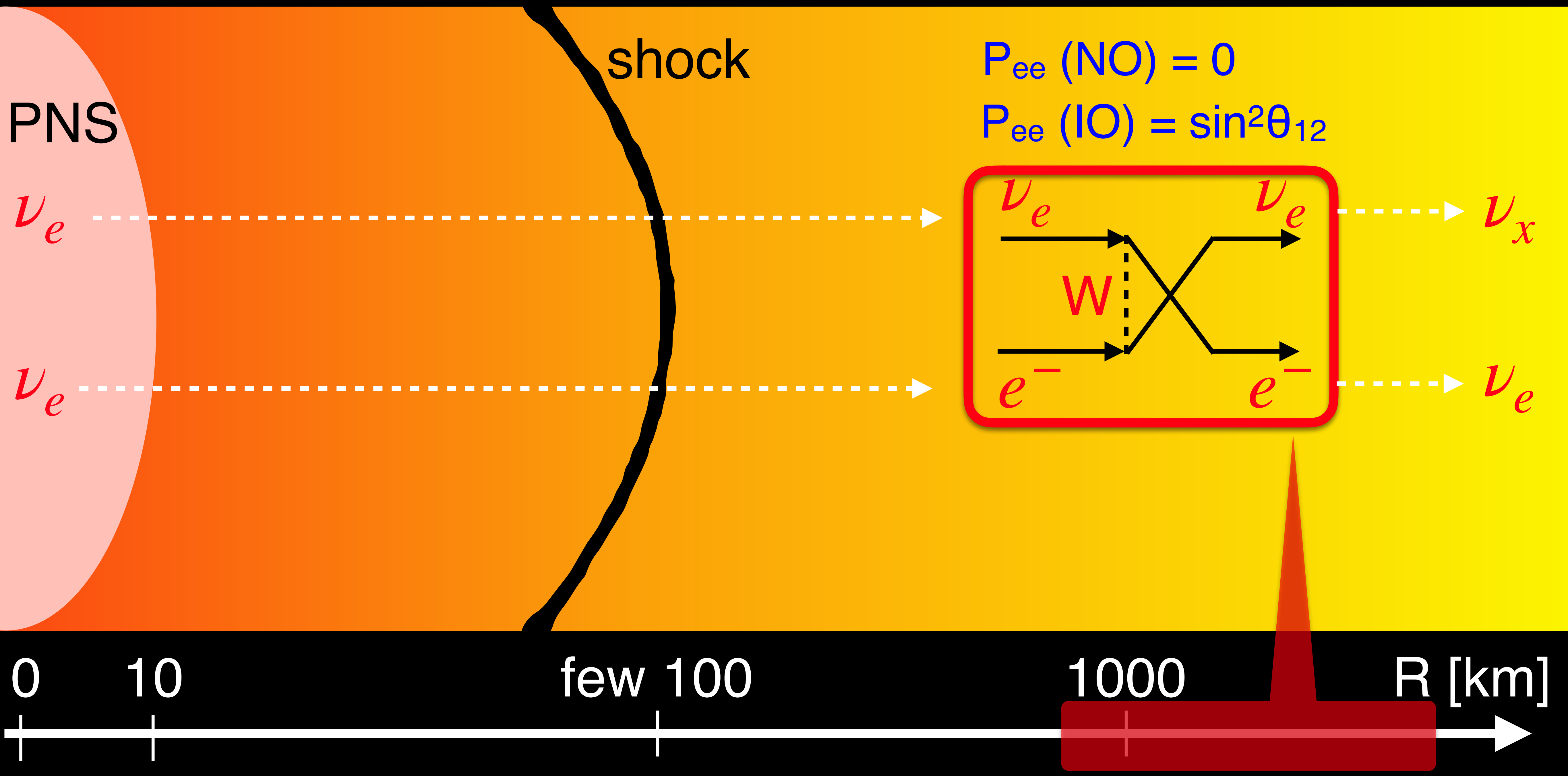


Collective Flavour Conversions



Collective Flavour Conversions

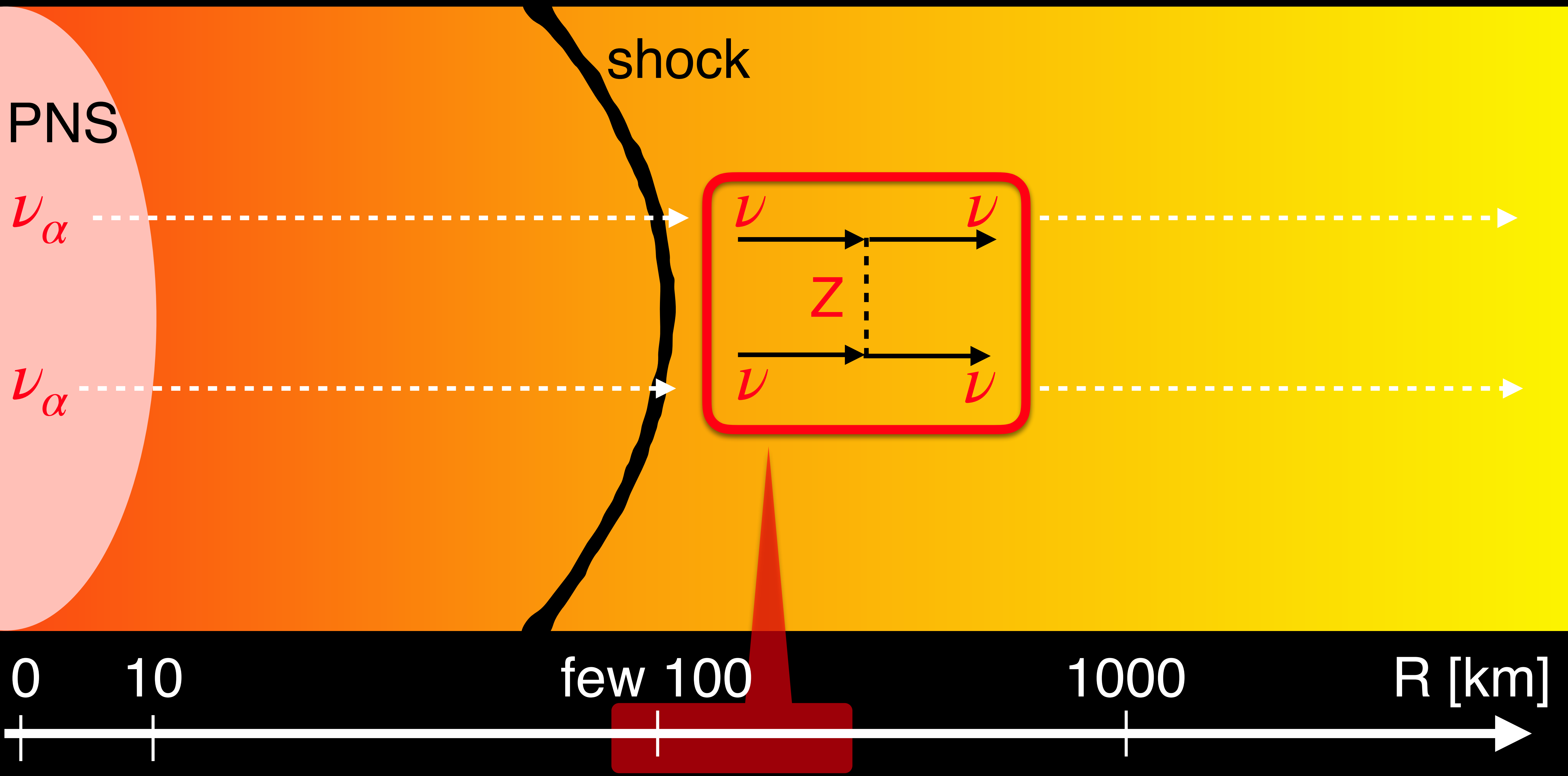
Well known MSW resonances happening in the outer layers



Dighe, Smirnov, 2000, Schirato, Fuller, 2002, Fogli, Lisi, Mirizzi, Montanino, 2002, …

Collective Flavour Conversions

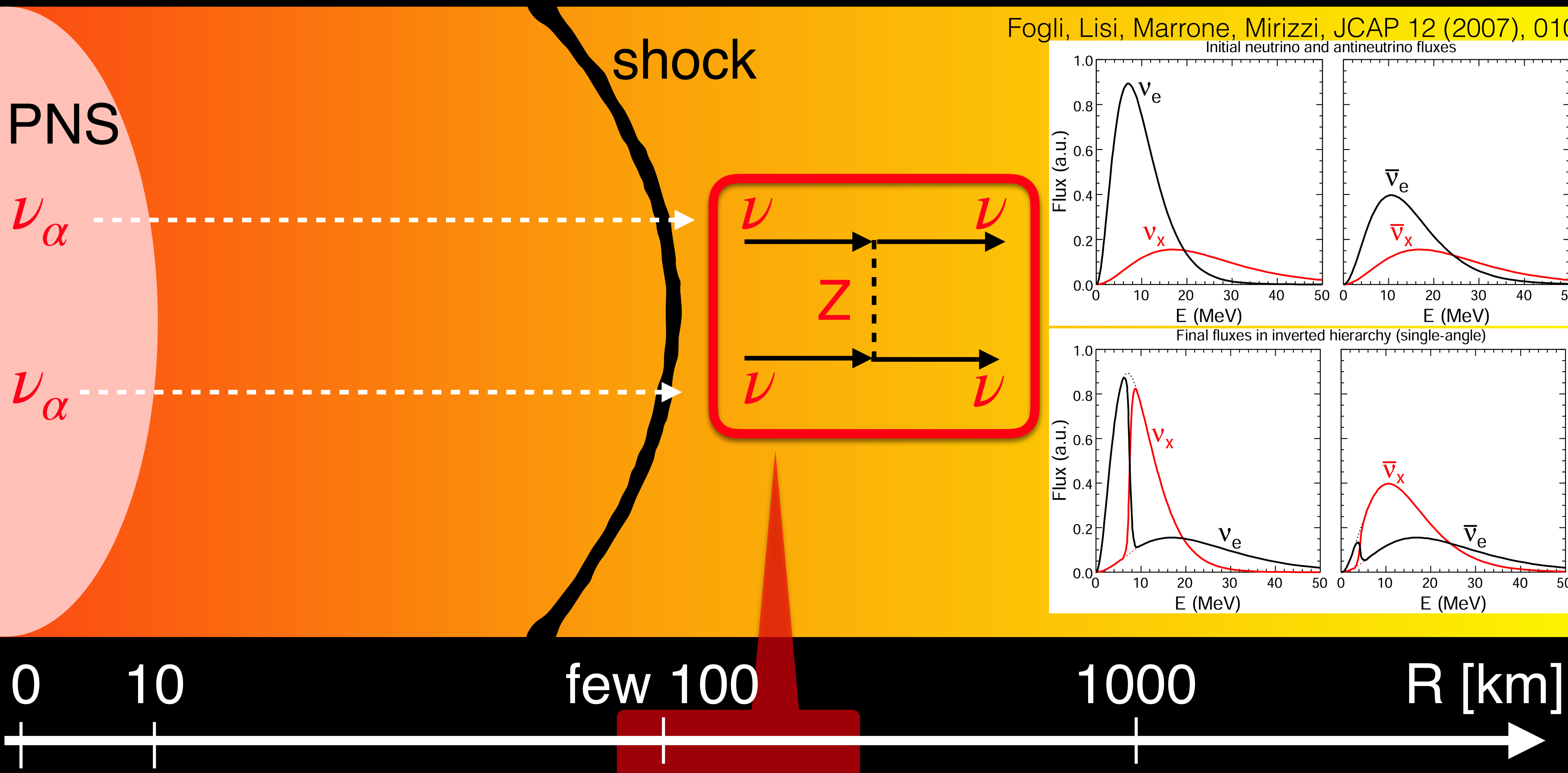
SLOW Collective effects may occur close the stalled shock



Hannestad, Raffelt, Sigl, Wong, 2006, Duan, Fuller, Carlson, Qian, 2006, many others, …

Collective Flavour Conversions

Assume spherical symmetry, stationarity and homogeneity

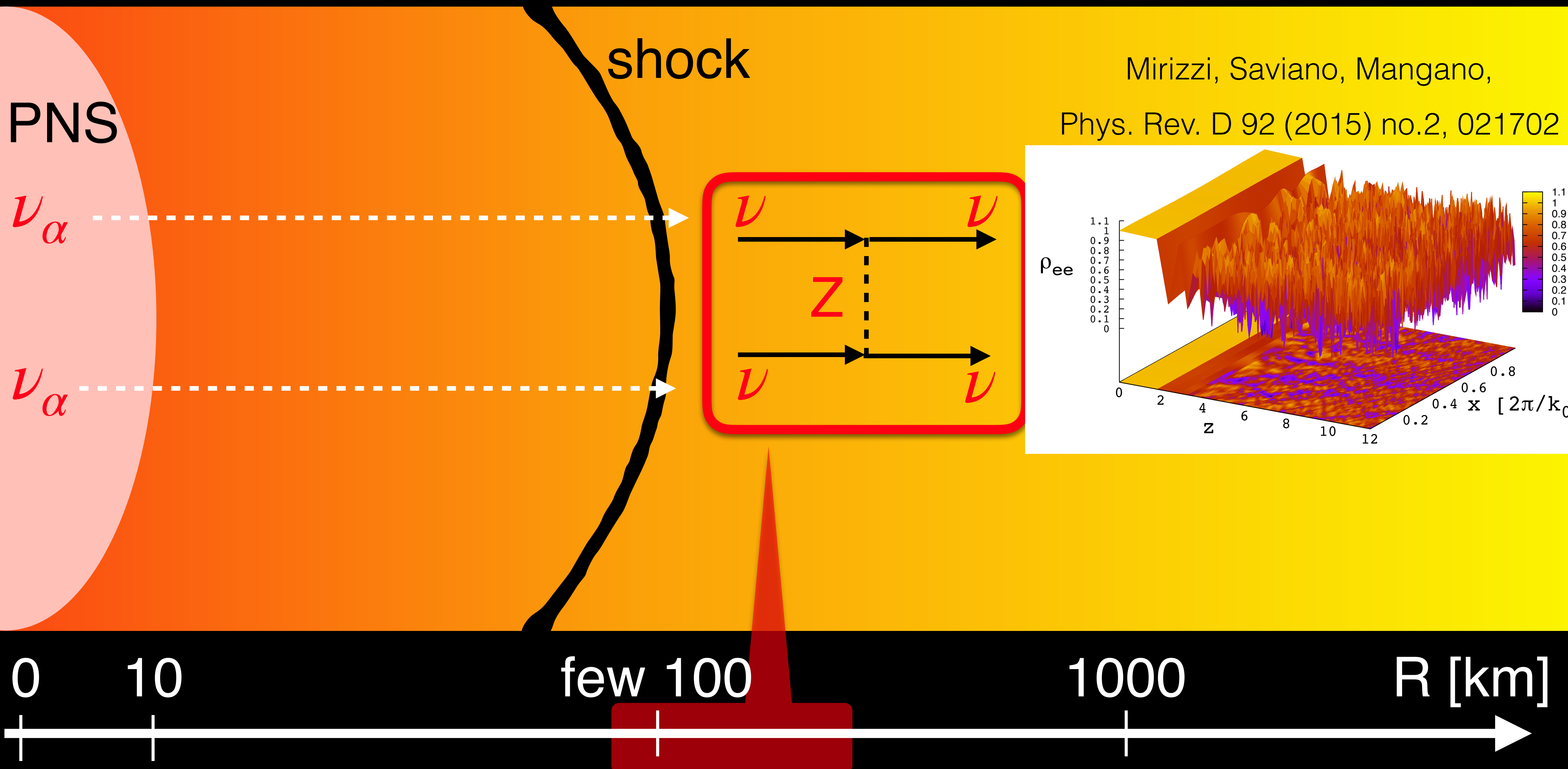


SPECTRAL SPLITS.

Requirement: crossing in energy, inverted mass ordering

Collective Flavour Conversions

Relax homogeneity hypothesis.

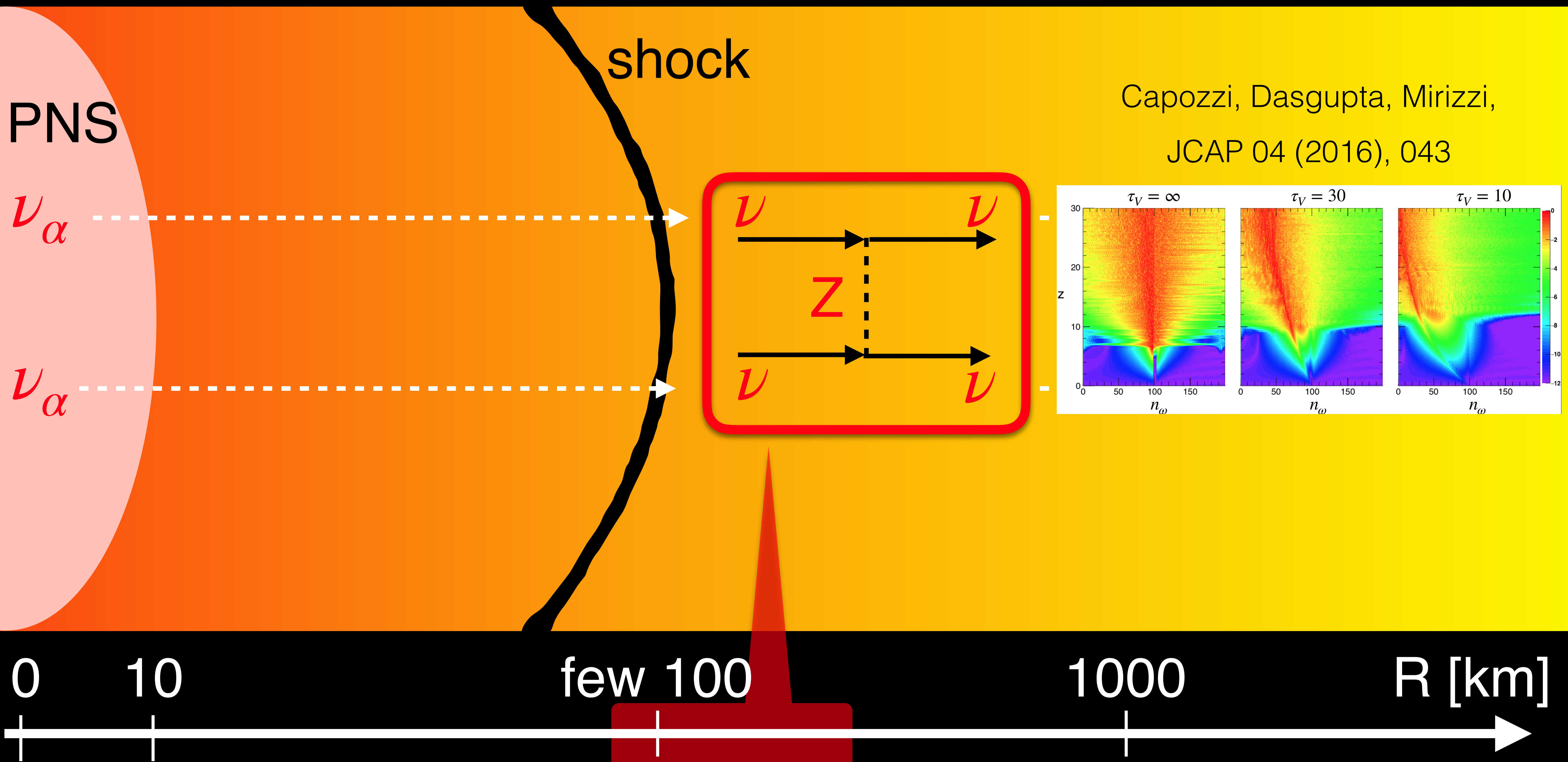


SPECTRAL SPLITS WITH INCREASING COMPLEXITY.

Requirement: crossing in energy. Both mass orderings

Collective Flavour Conversions

Relax homogeneity hypothesis and temporal stationarity.

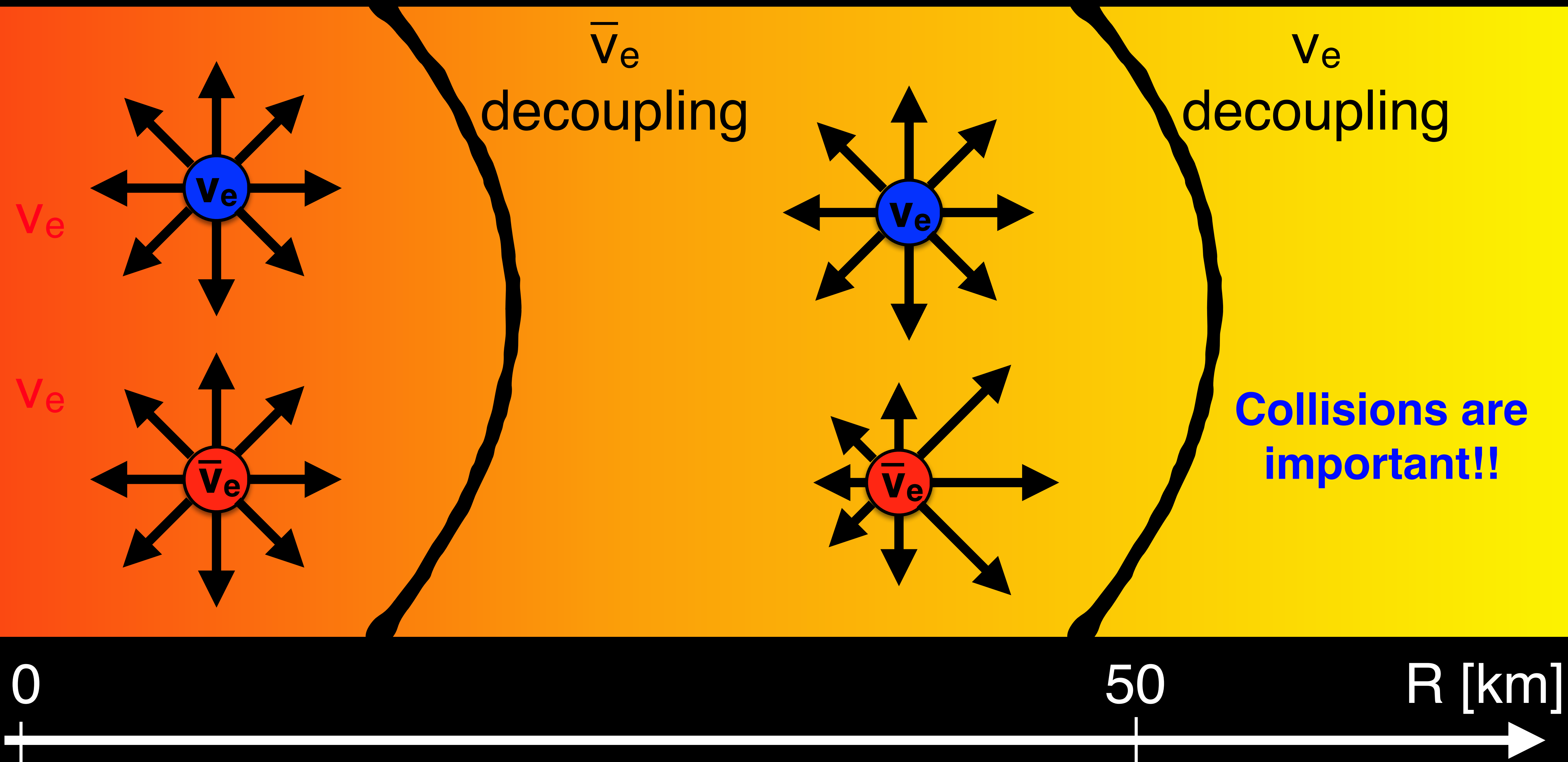


SPECTRAL SPLITS WITH INCREASING COMPLEXITY.

Relaxing hypotheses changes outcome. What's final answer?

Collective Flavour Conversions

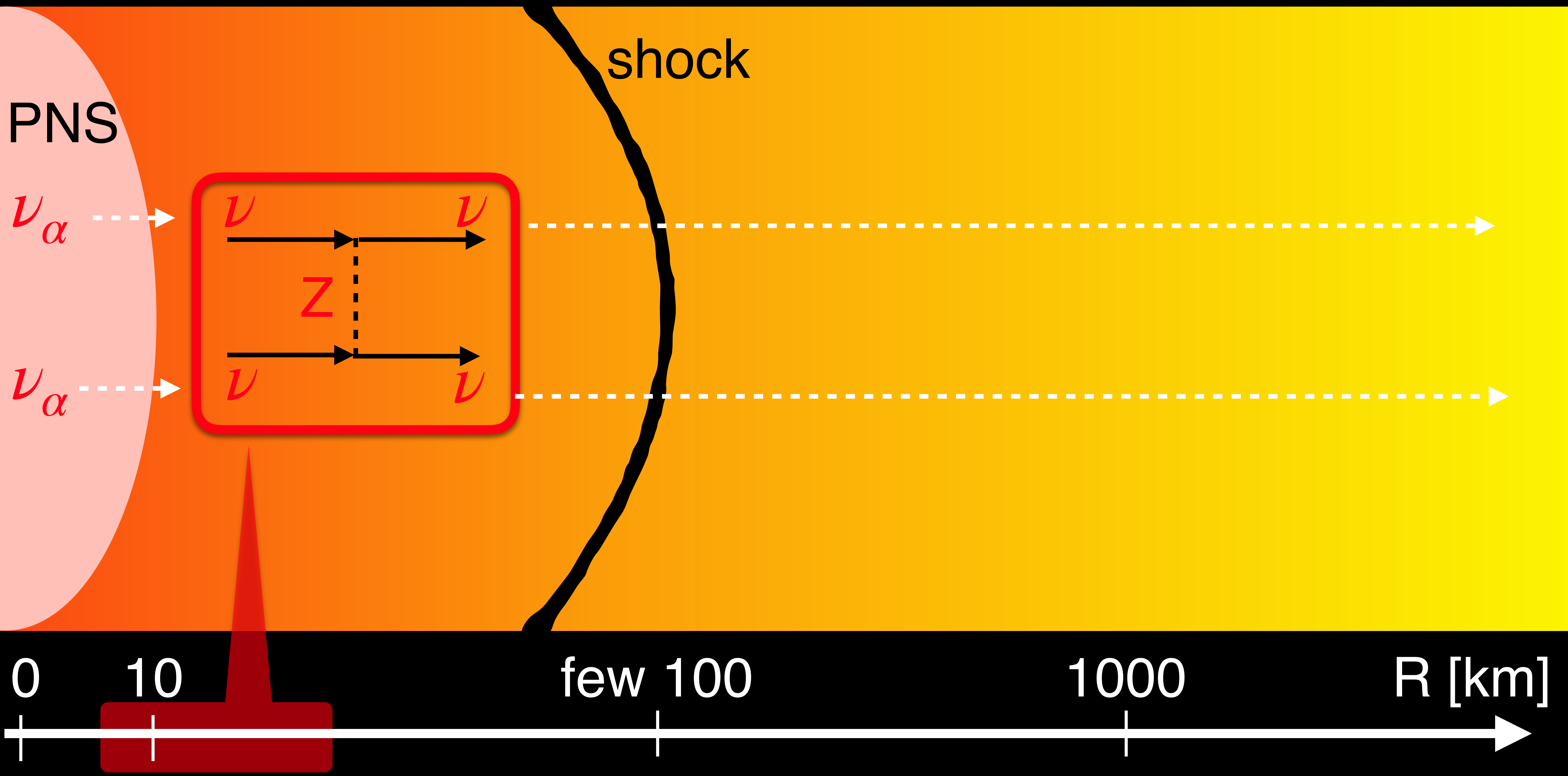
FAST conversions require an **angular crossing**



Expected to occur near the decoupling region

Collective Flavour Conversions

FAST conversions may occur in the post-shock region

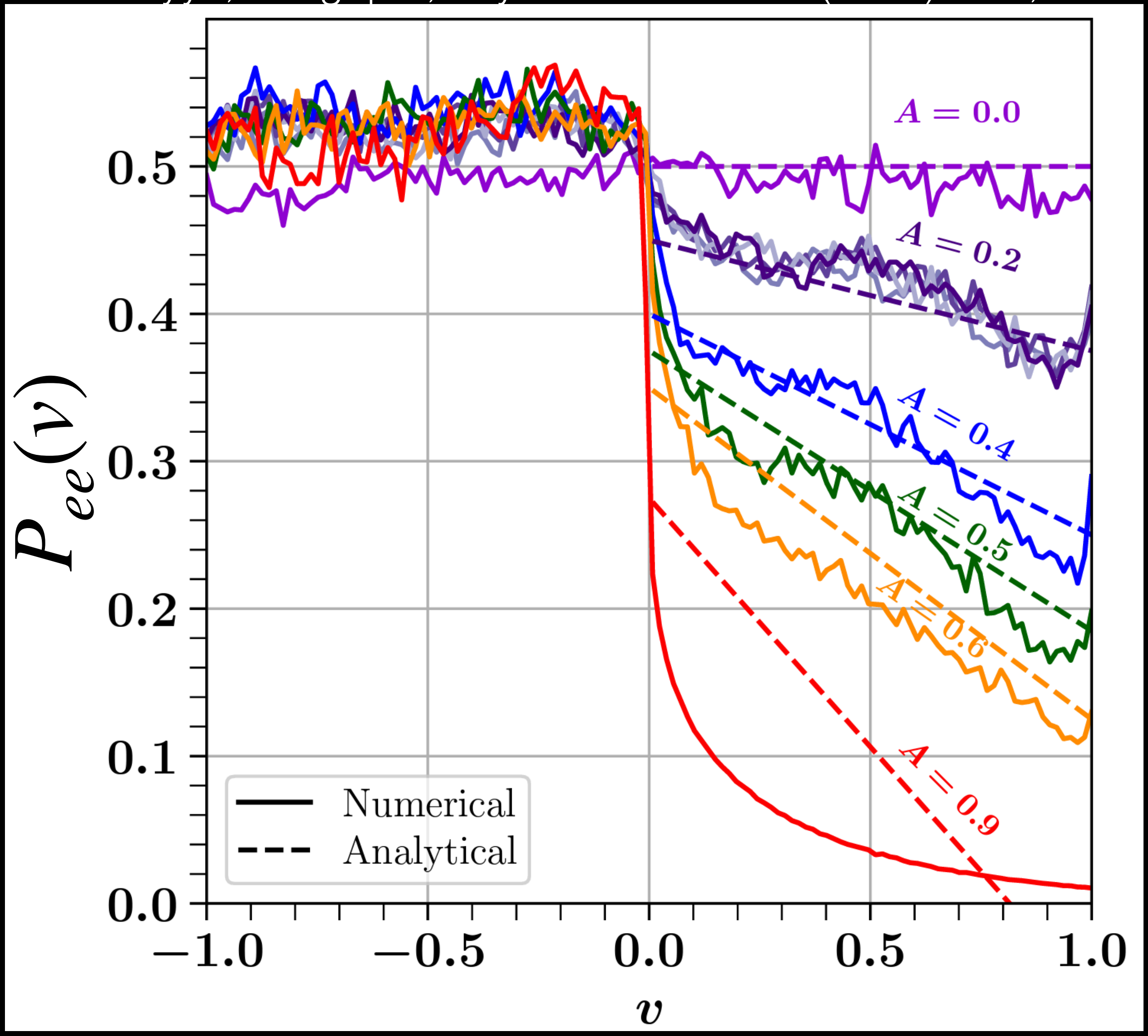


Sawyer 2005, 2009, 2015, Chakraborty, Hansen, Izaguirre, Raffelt 2016, Dasgupta, Mirizzi, Sen 2017, …

Collective Flavour Conversions

What is the outcome of fast flavour conversions?

Bhattacharyya, Dasgupta, Phys. Rev. Lett. 126 (2021) no.6, 061302

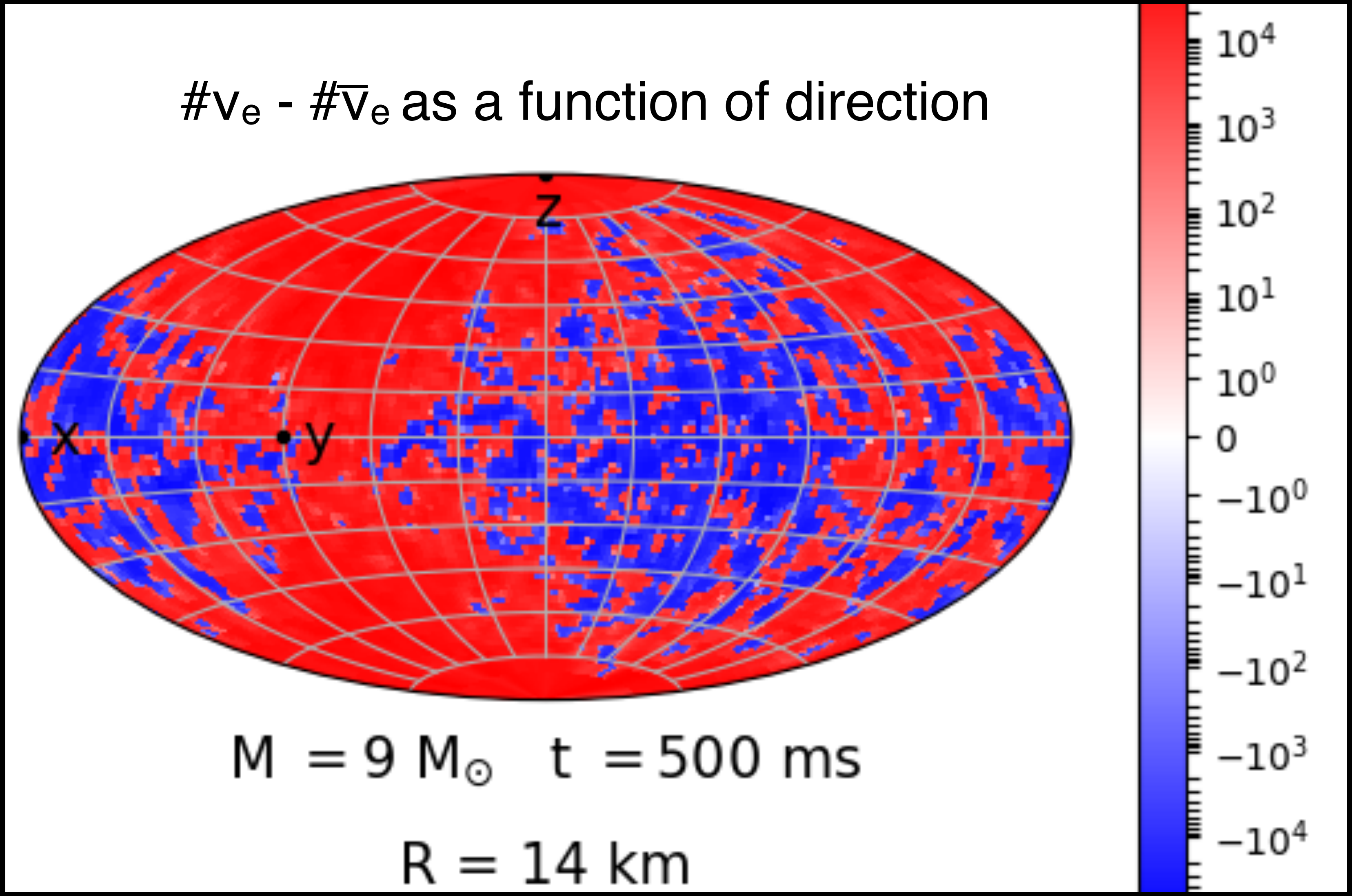


Dependence on type of crossing. Flavour equilibration possible

Collective Flavour Conversions

Are supernovae simulations showing any sign of crossing?

Glas, Janka, Capozzi, Sen, Dasgupta, Mirizzi, Sigl, Phys. Rev. D 101 (2020) no.6, 063001



see also

Tamborra, Huedepohl, Raffelt, Janka, 2017

Abbar, Duan, Sumiyoshi, Takiwaki, Volpe, 2018

Azari, Yamada, Morinaga, Iwakami, Okawa, Nakagura, Sumiyoshi 2019

Morinaga, Nakagura, Kato, Yamada, 2019

Generally, crossings are observed even beyond the decoupling region

Collective Flavour Conversions

Implementing FAST conversions in explosion simulations?

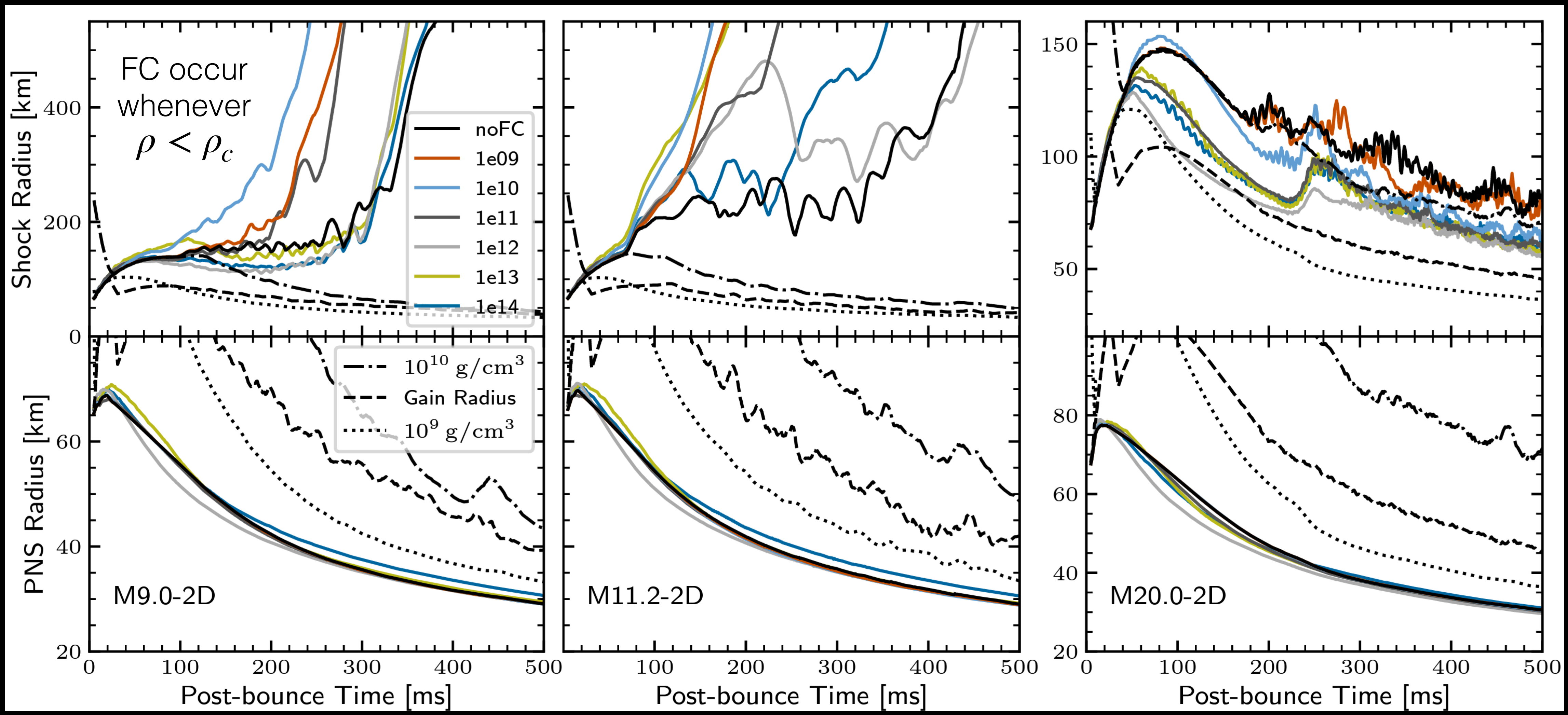
$$\frac{T_{\mathrm{simul}}}{T_{\mathrm{fl\,conv}}} \sim \frac{10^{-3}\,\mathrm{s}}{10^{-9}\,\mathrm{s}}$$

Very challenging numerically.
Use an effective approach.

Collective Flavour Conversions

FAST conversions implemented with effective approach

Ehring, Abbar, Janka, Raffelt, Tamborra, Phys. Rev. Lett. 131 (2023) no.6, 061401



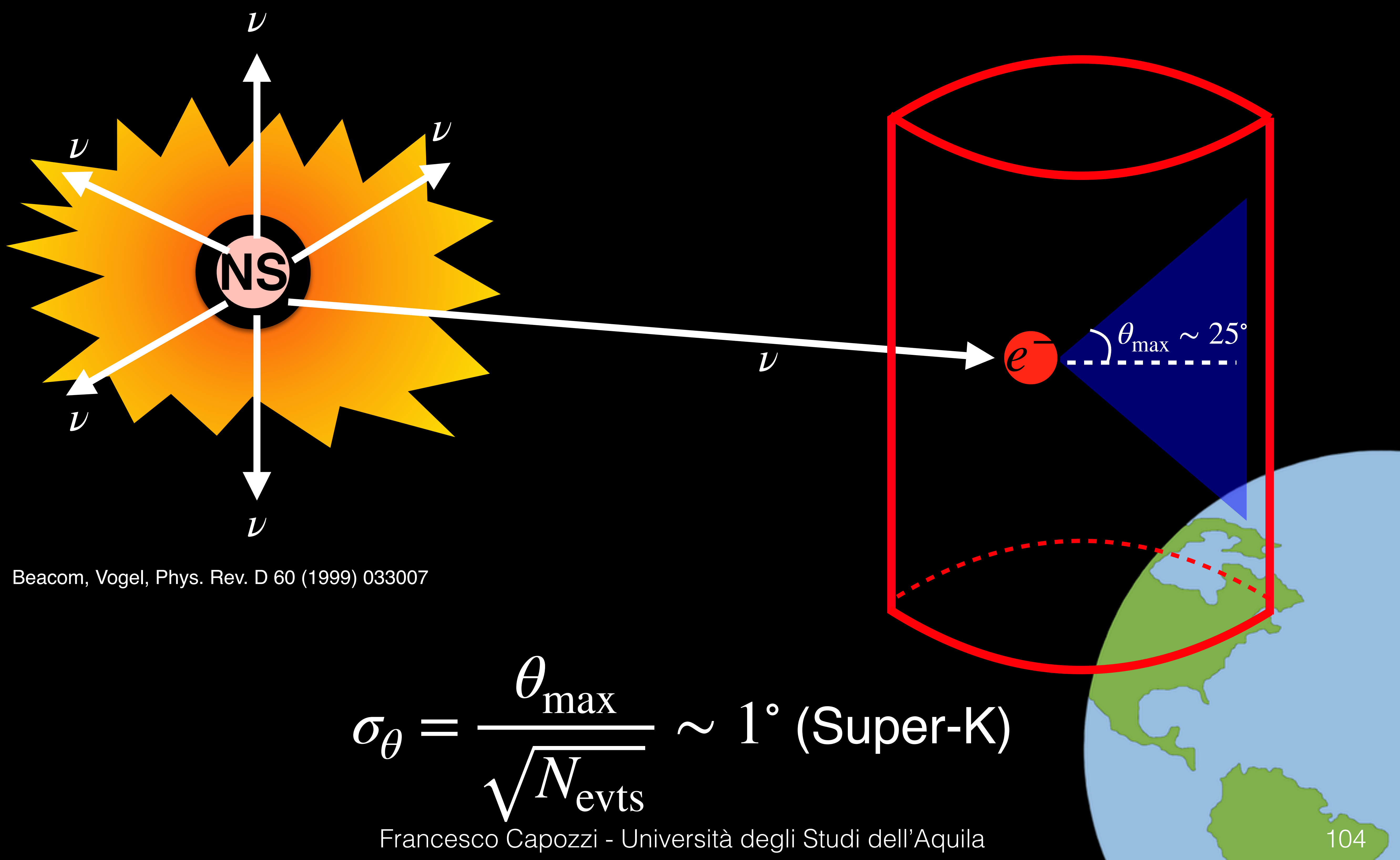
Accelerated explosion for low progenitor masses.
Further work is needed.

COOLING PHASE

- Current issues.
- What can we learn?

Supernova direction

$\nu - e^-$ scattering can be used to reconstruct SN direction



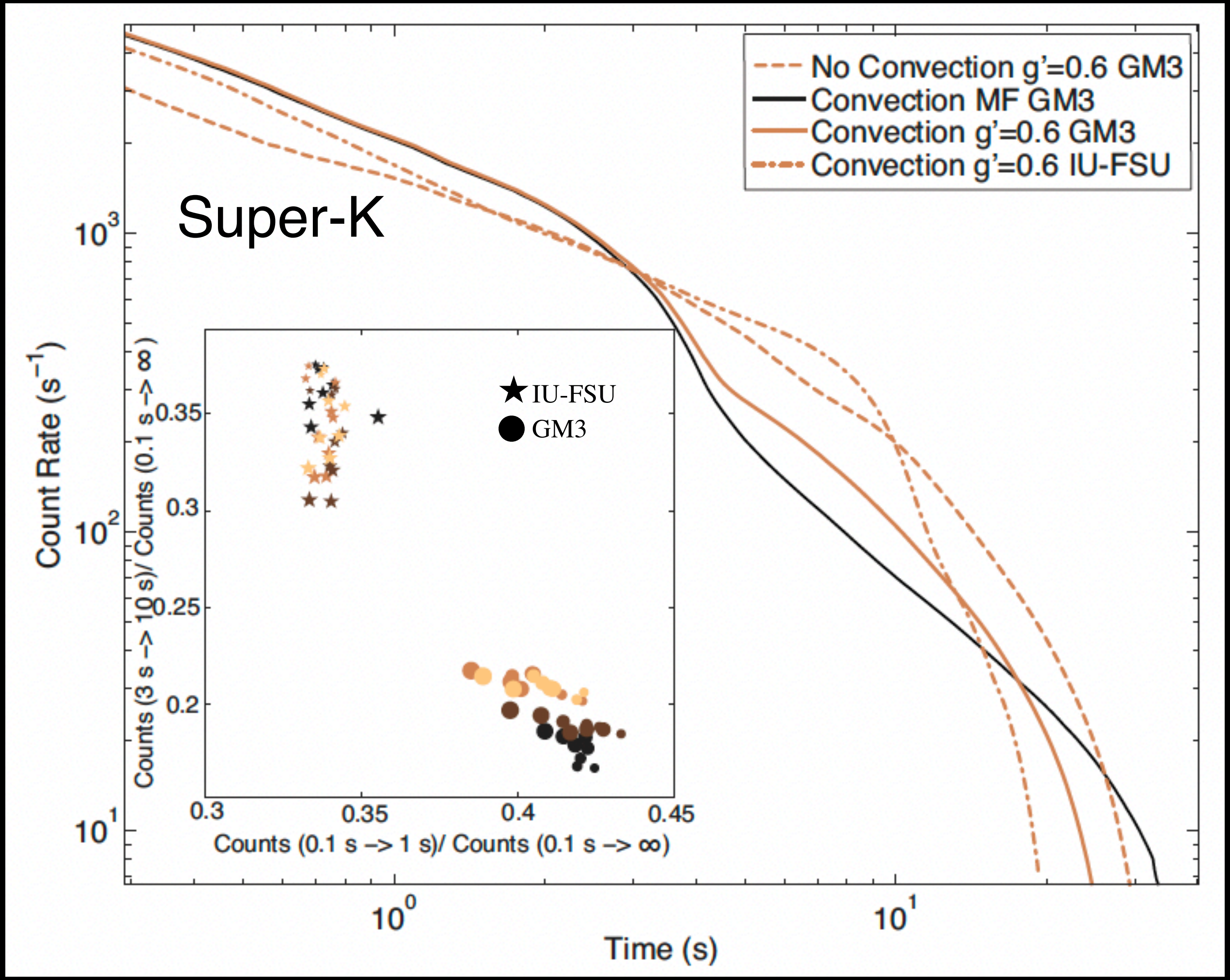
Beacom, Vogel, Phys. Rev. D 60 (1999) 033007

$$\sigma_\theta = \frac{\theta_{\max}}{\sqrt{N_{\rm evts}}} \sim 1^\circ \text{ (Super-K)}$$

Dependence on Eos

Neutrino signal in the cooling phase strongly depends on EoS

Roberts, Shen, Cirigliano, Pons, Reddy, Woosley, Phys. Rev. Lett. 108 (2012), 061103

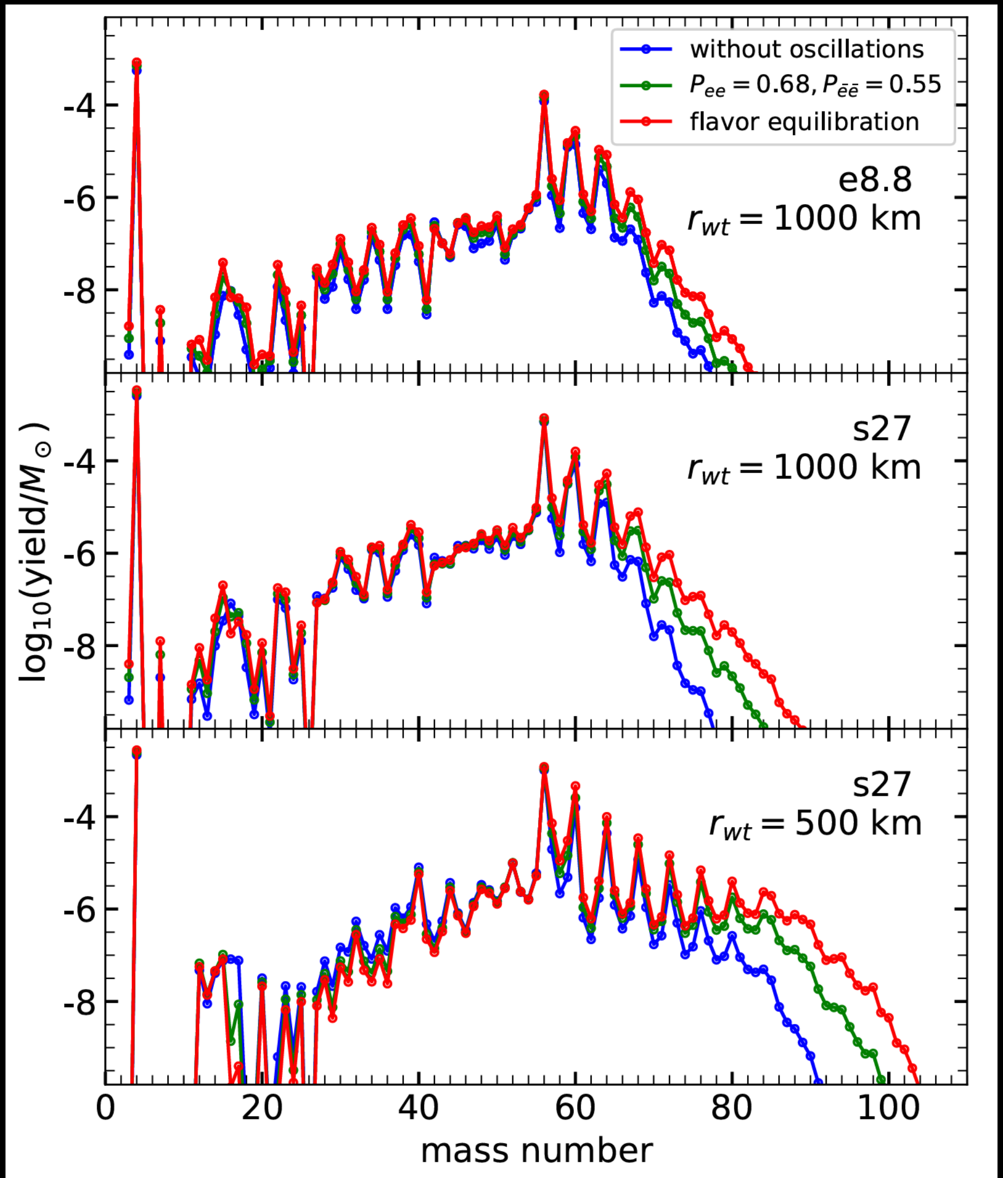


Experiments are capable of distinguishing between EoS

Impact on Nucleo-Synthesis

FAST conversions might affect nucleo-synthesis

Xiong, Sieverding, Sen, Qian, Astrophys. J. 900 (2020) no.2, 144

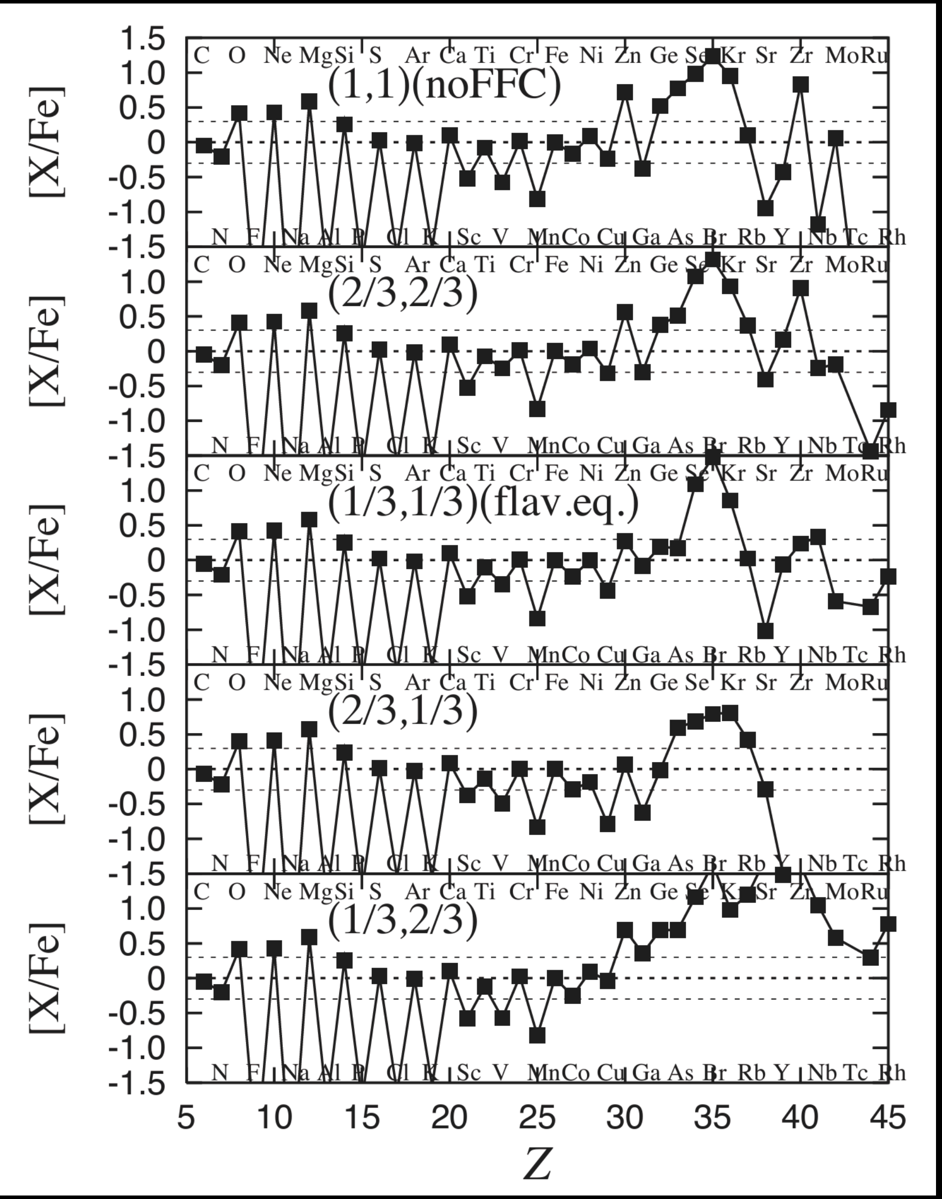


FAST conversions have a mild influence

Impact on Nucleo-Synthesis

FAST conversions might affect nucleo-synthesis

Fujimoto, Nagakura, Mon. Not. Roy. Astron. Soc. 519 (2022) no.2, 2623-2629

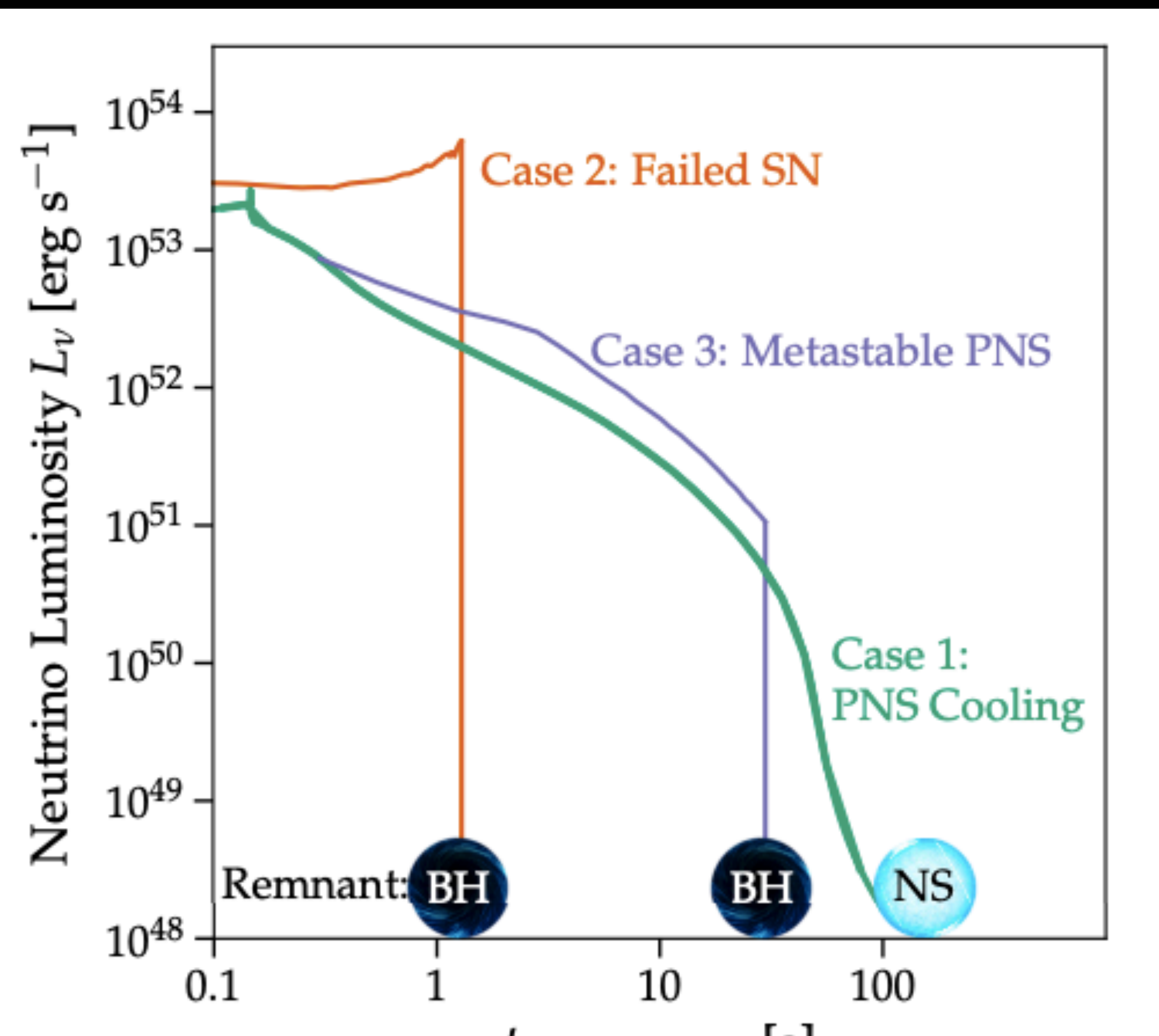


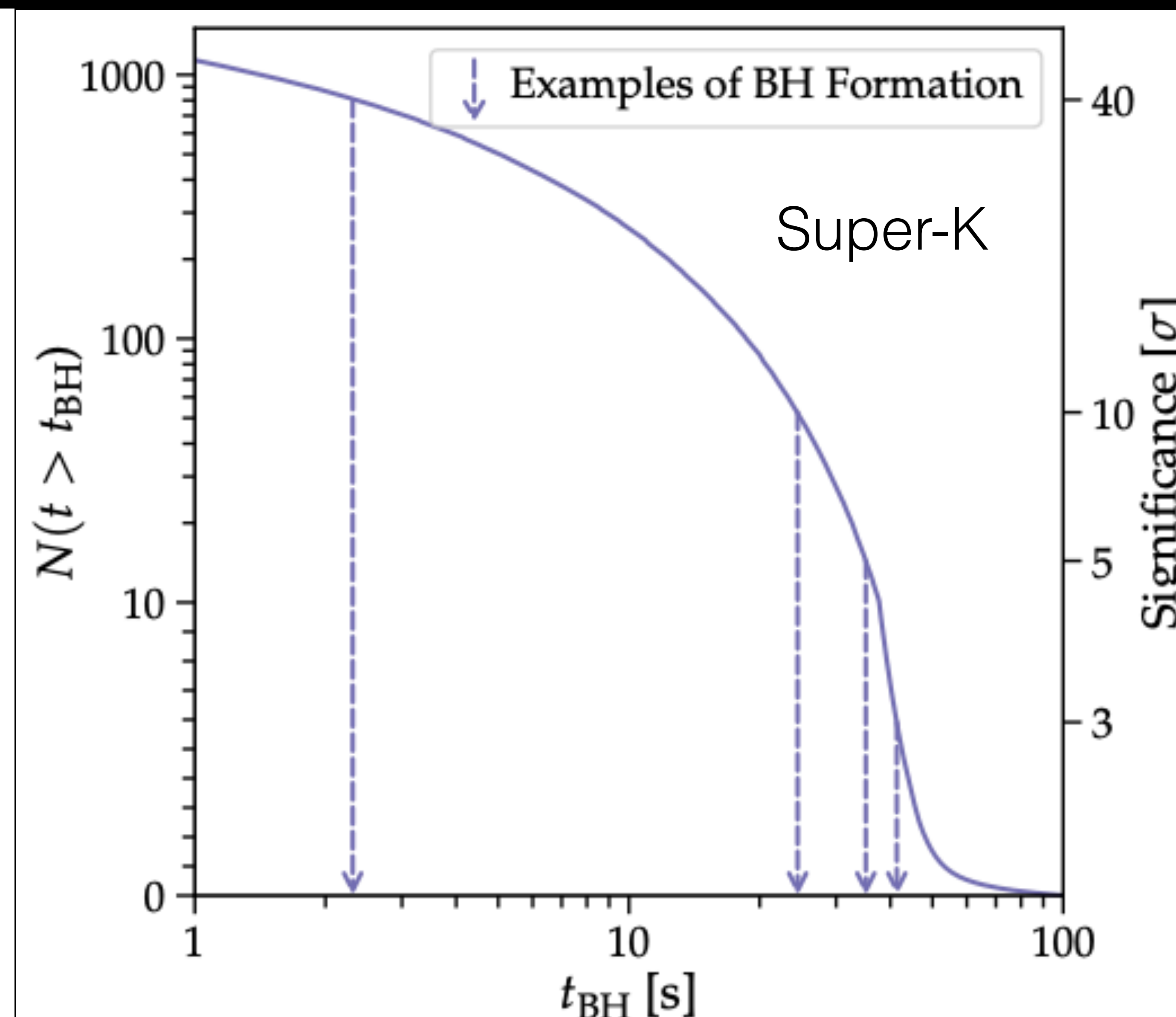
FAST conversions have a mild influence

Black Hole Formation

Black hole formation suddenly stops neutrino emission

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

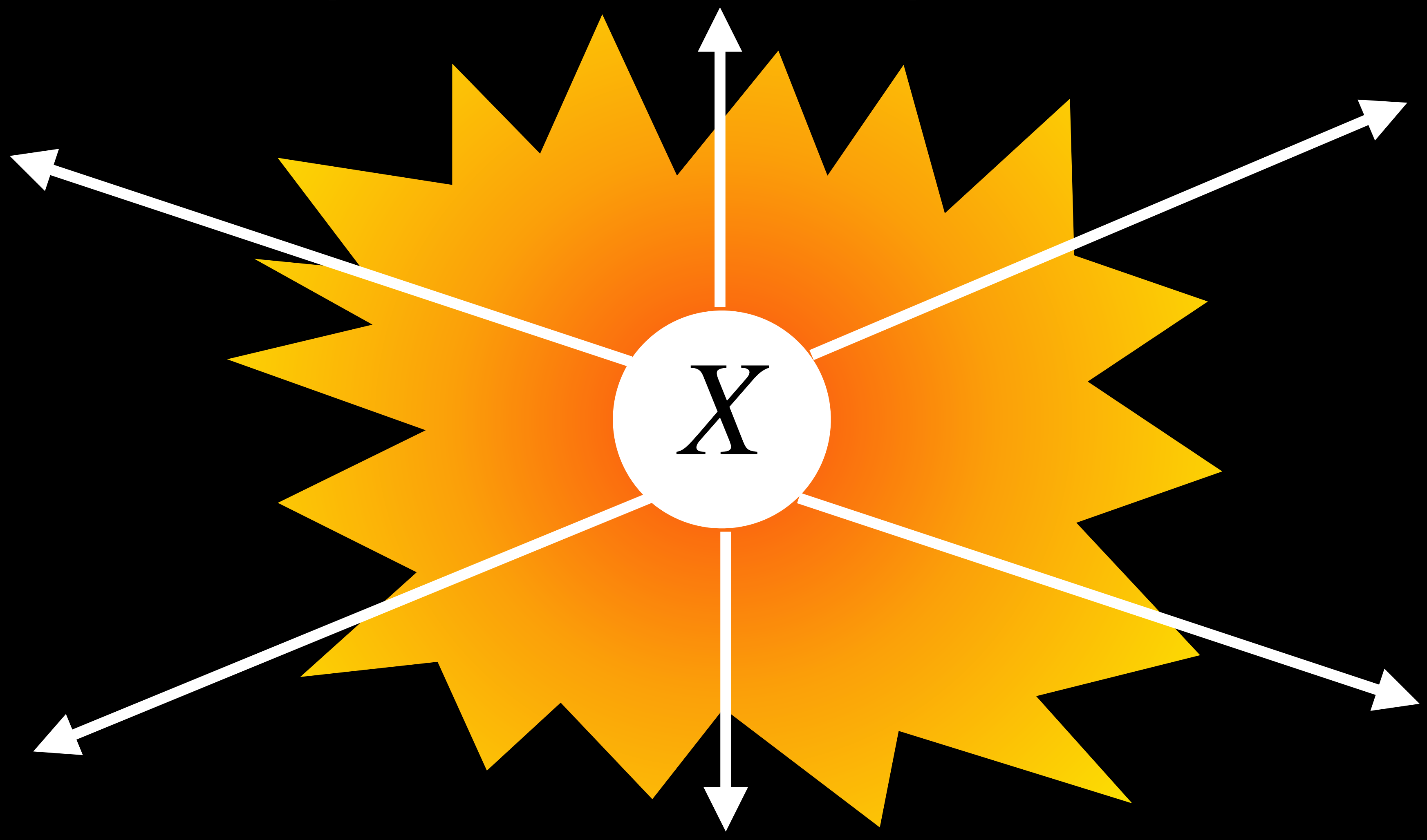




Depending on the formation time, a BH can be identified by ν

Extra Cooling

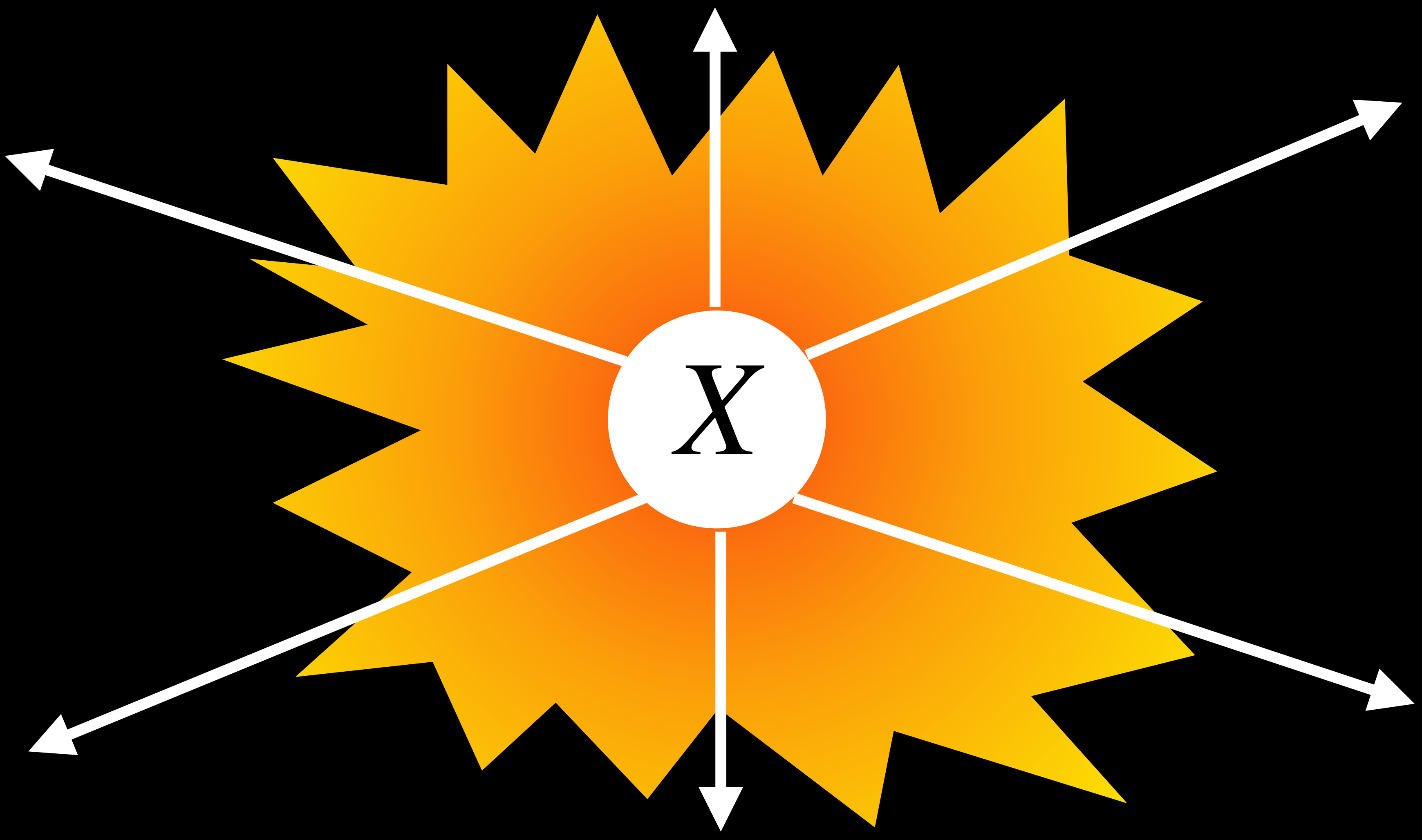
Whatever exotic X particle coupled to SM ($m_X < 100$ MeV) can be produced in a supernova core



Emission of X particles represent an extra source of cooling apart from that coming from standard neutrino emission

Extra Cooling

Whatever exotic X particle coupled to SM ($m_X < 100$ MeV) can be produced in a supernova core

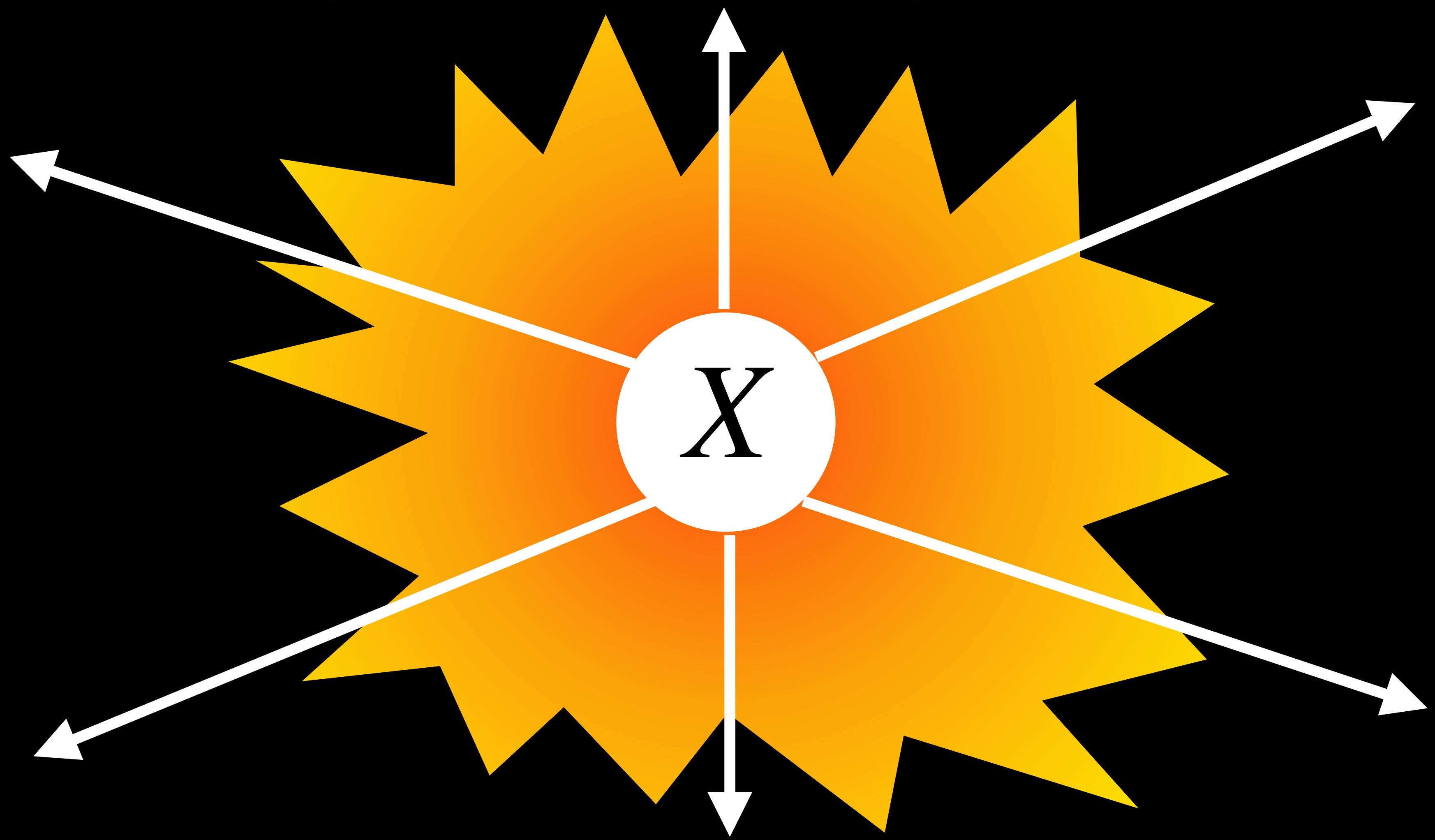


<u>**STANDARD THEORY:**</u> $E_{\text{tot},\nu} \simeq E_{\text{tot,grav}} \simeq 3 \cdot 10^{53}\,\text{erg}$ in 10 s.

To not spoil expectations, X particles must carry less energy

Extra Cooling

Whatever exotic X particle coupled to SM ($m_X < 100$ MeV) can be produced in a supernova core



Analytical Criterion

$$M_{\rm PNS} = 1.5\, M_\odot, t_{\rm cool} = 10\, {\rm s} \implies \epsilon_X \simeq 10^{19}\, {\rm erg\, g^{-1}\, s^{-1}}$$

(ϵ_X should be calculated for $\rho \simeq 10^{14}\, {\rm g\, cm^{-3}}$, $T \simeq 30\, {\rm MeV}$)

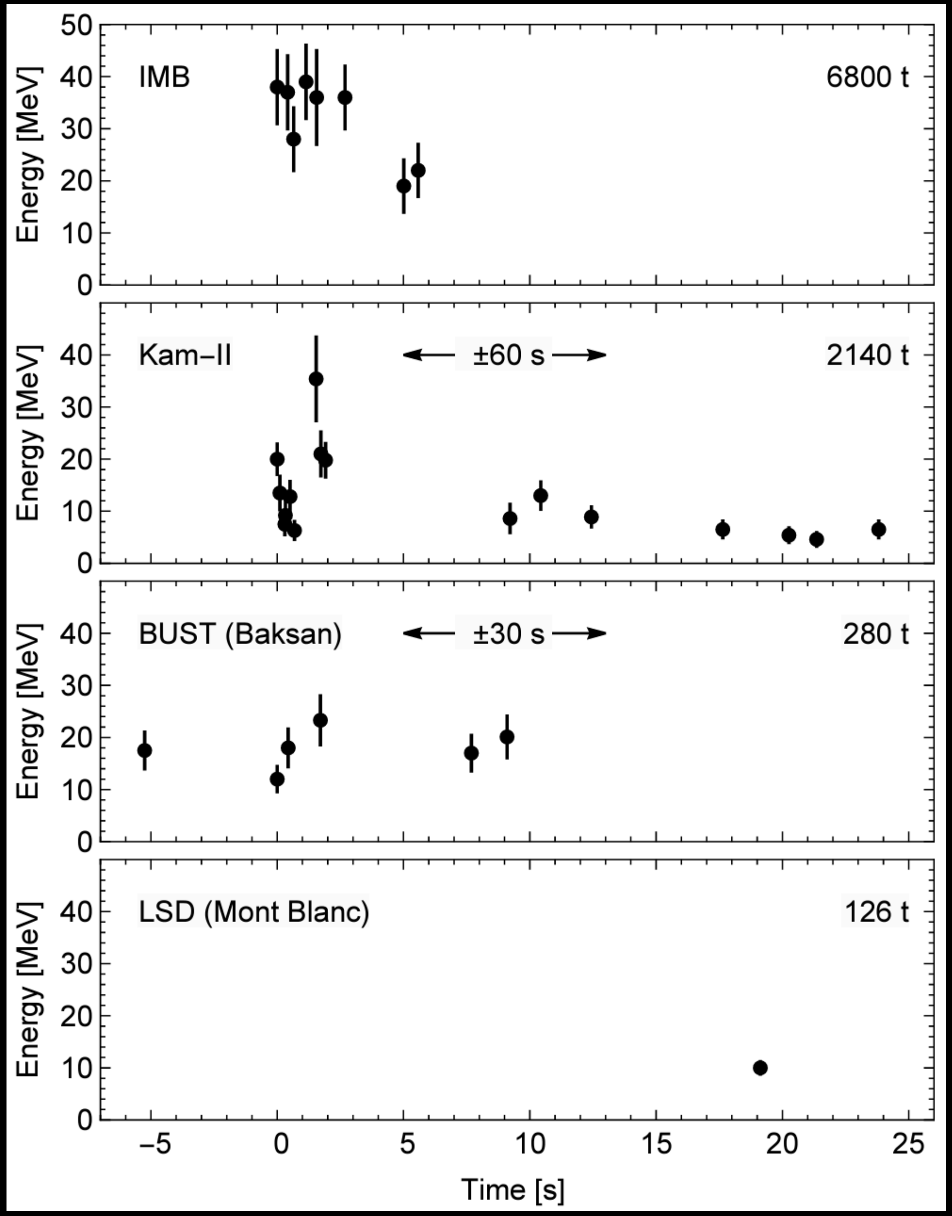
SN1987a

What have we learnt so far?

SN1987a: ν-data

24 February 1987 in the Large Magellanic Cloud (51 kpc)

Fiorillo, Heinlein, Janka, Raffelt, Vitagliano, Bollig, Phys. Rev. D 108 (2023) no.8, 8

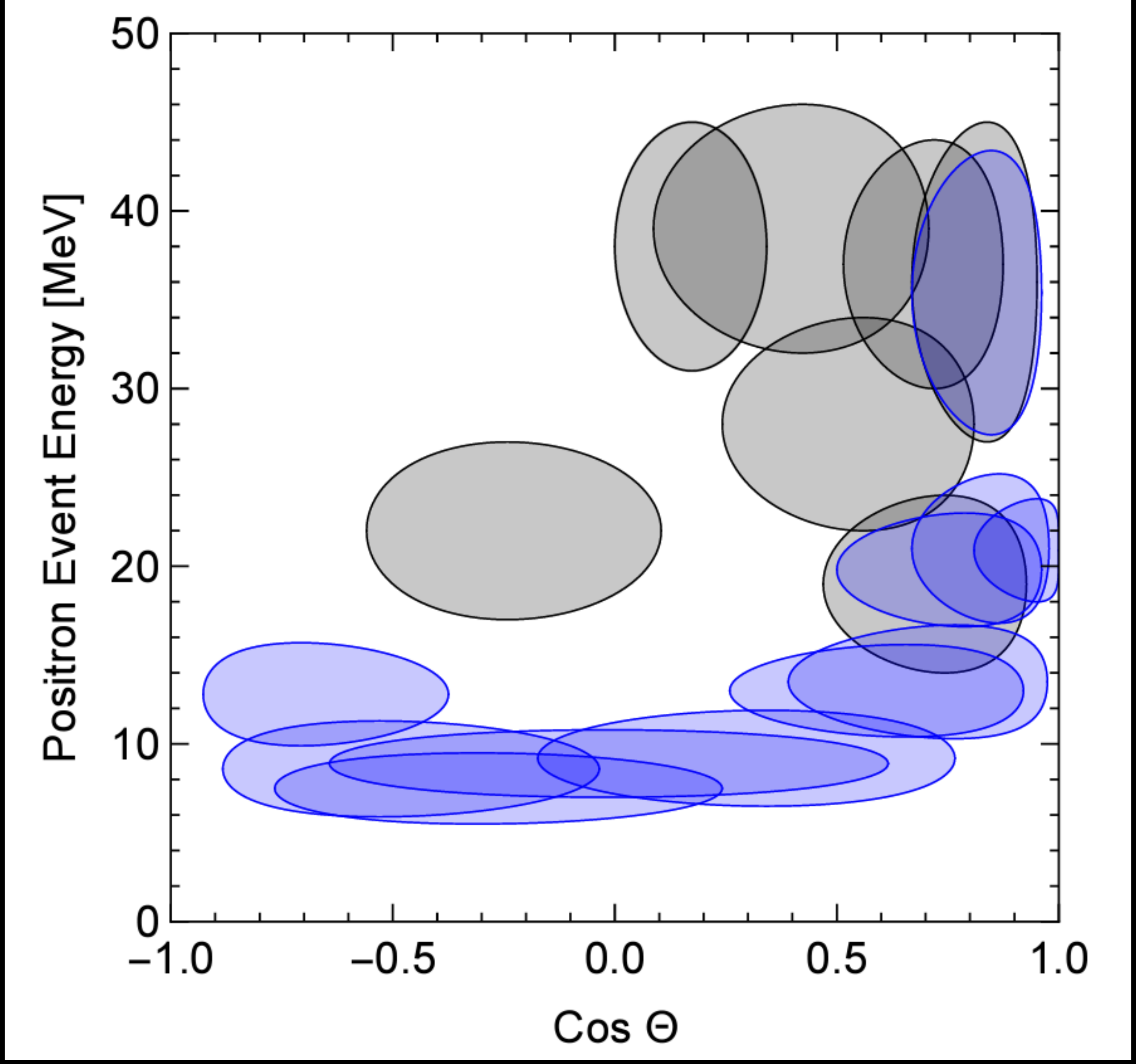


First and only neutrinos observed from a supernova

SN1987a: ν-data

Observed $e^{\pm}$: either $\bar{\nu}_e + p \to e^+ + n$ or $\nu + e^- \to \nu + e^-$

Fiorillo, Heinlein, Janka, Raffelt, Vitagliano, Bollig, Phys. Rev. D 108 (2023) no.8, 8

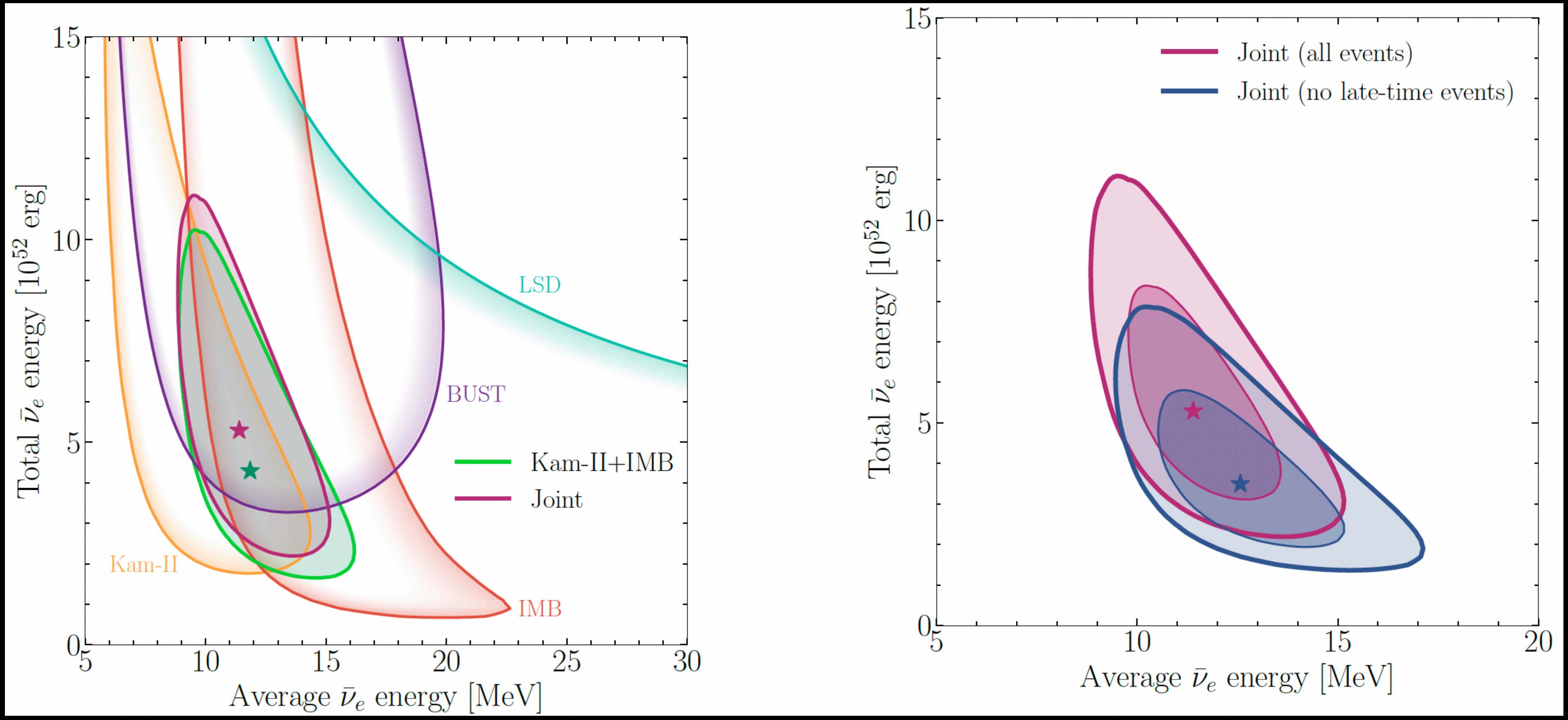


Few (forward) events can be due to $\nu + e^- \to \nu + e^-$

SN1987a: analysis of ν-data

We expect $\bar{\nu}_e$ to carry $E_{\text{tot},\bar{\nu}_e} = \frac{E_{\text{tot grav}}}{6 \text{ flavours}} \simeq \frac{3\times 10^{53}\text{ erg}}{6} = 5\times 10^{52}\text{ erg}$

Fiorillo, Heinlein, Janka, Raffelt, Vitagliano, Bollig, Phys. Rev. D 108 (2023) no.8, 8



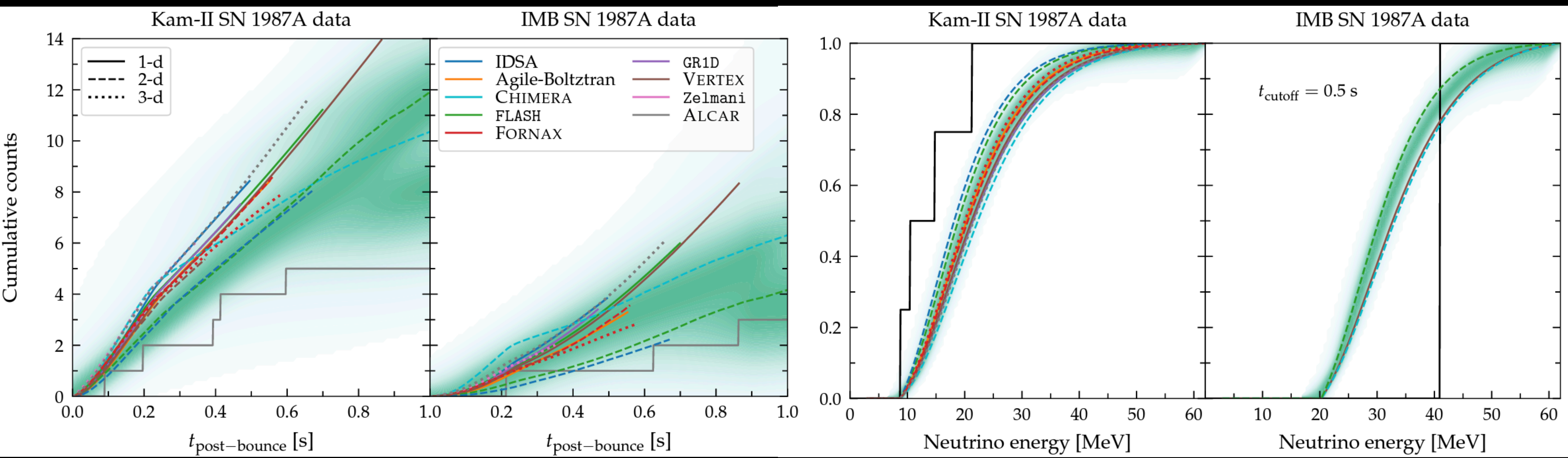
Fit done assuming thermal spectrum with free $E_{\text{tot},\bar{\nu}_e}$, $\langle E_{\bar{\nu}_e}\rangle$.

Consistent with expectation. Small tension among experiments

SN1987a: data vs simulations

What if we do a fit using outputs from numerical simulations?

Li, Beacom, Roberts, Capozzi, Phys. Rev. D 109 (2024) no.8, 083025

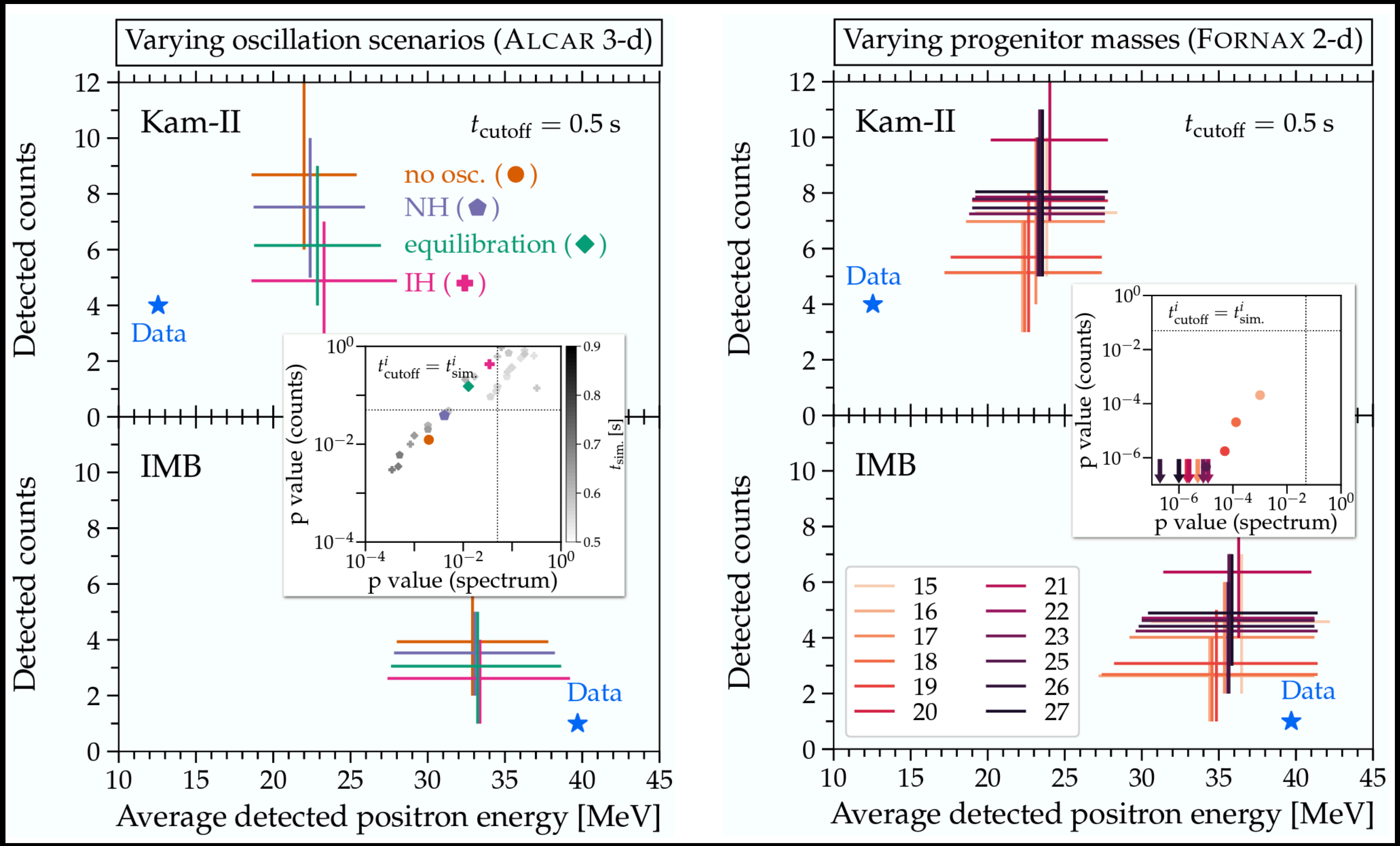


Not all models provide a good fit, using $t_{\rm cutoff} \simeq 1$ s

SN1987a: data vs simulations

What if we do a fit using outputs from numerical simulations?

Li, Beacom, Roberts, Capozzi, Phys. Rev. D 109 (2024) no.8, 083025

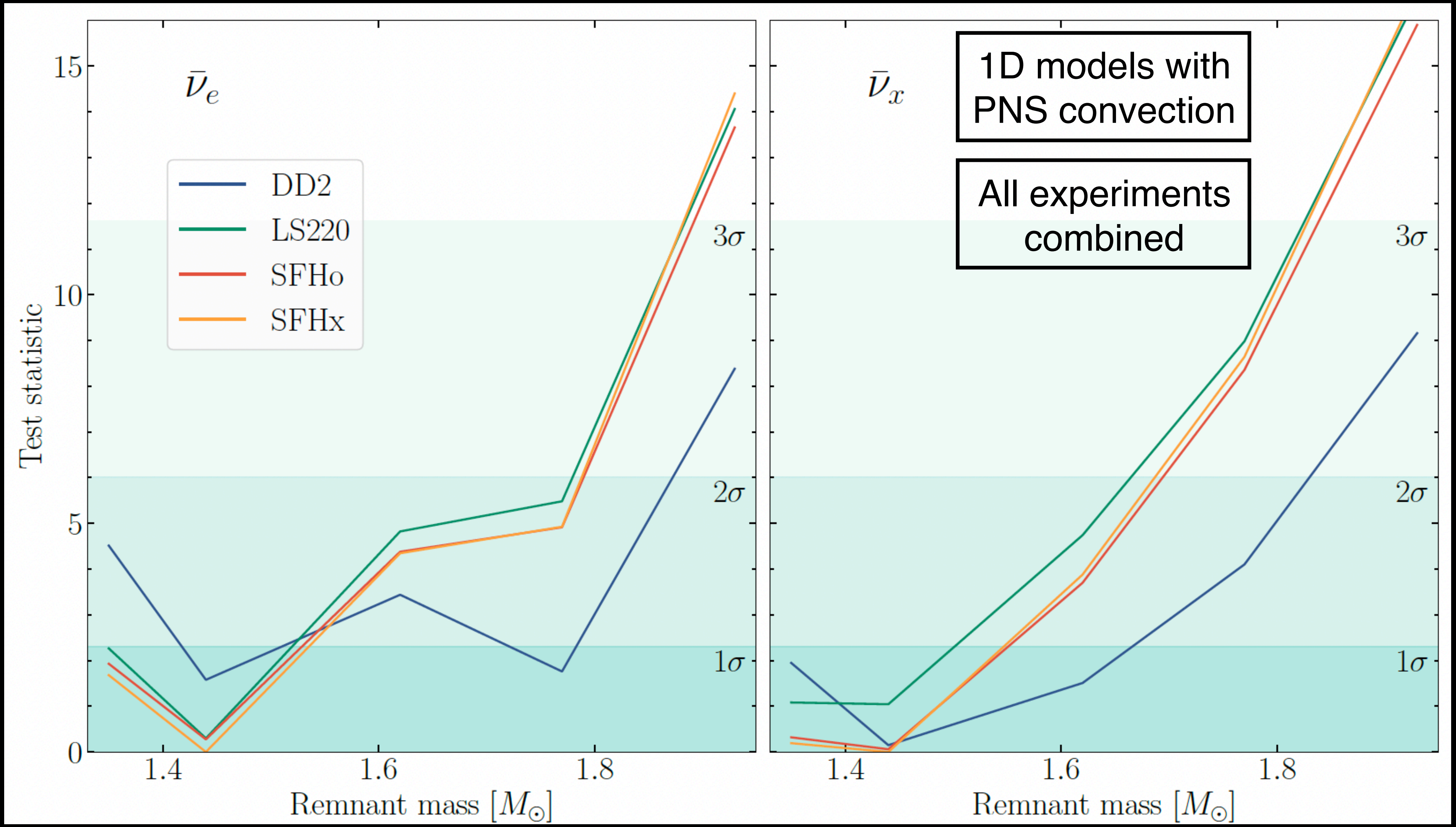


Not all models provide a good fit, using $t_{\rm cutoff} \simeq 1$ s

SN1987a: data vs simulations

What if we do a fit using outputs from numerical simulations?

Fiorillo, Heinlein, Janka, Raffelt, Vitagliano, Bollig, Phys. Rev. D 108 (2023) no.8, 8

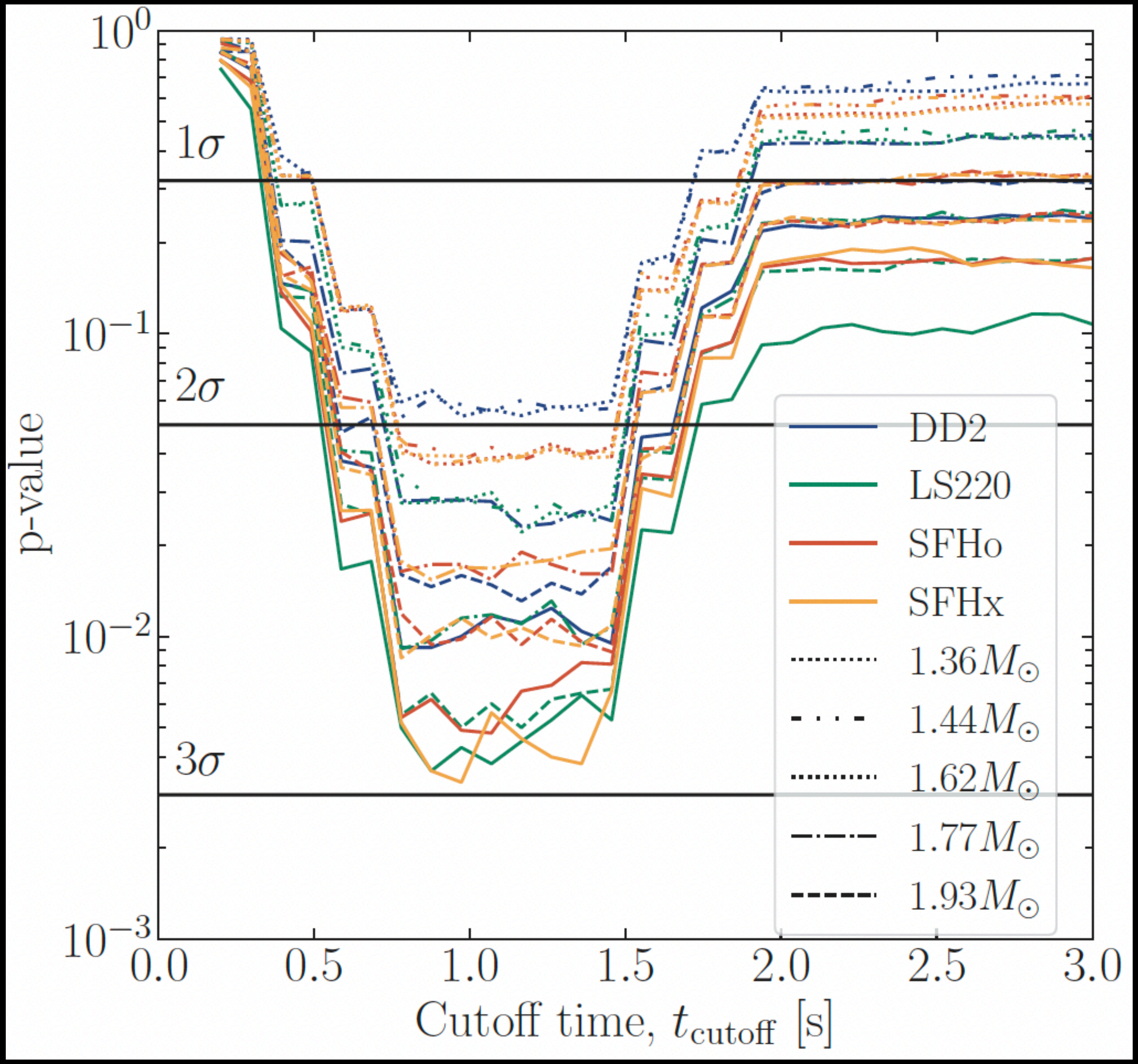


Better agreement for models with low remnant mass

SN1987a: data vs simulations

What if we do a fit using outputs from numerical simulations?

Fiorillo, Heinlein, Janka, Raffelt, Vitagliano, Bollig, Phys. Rev. D 108 (2023) no.8, 8



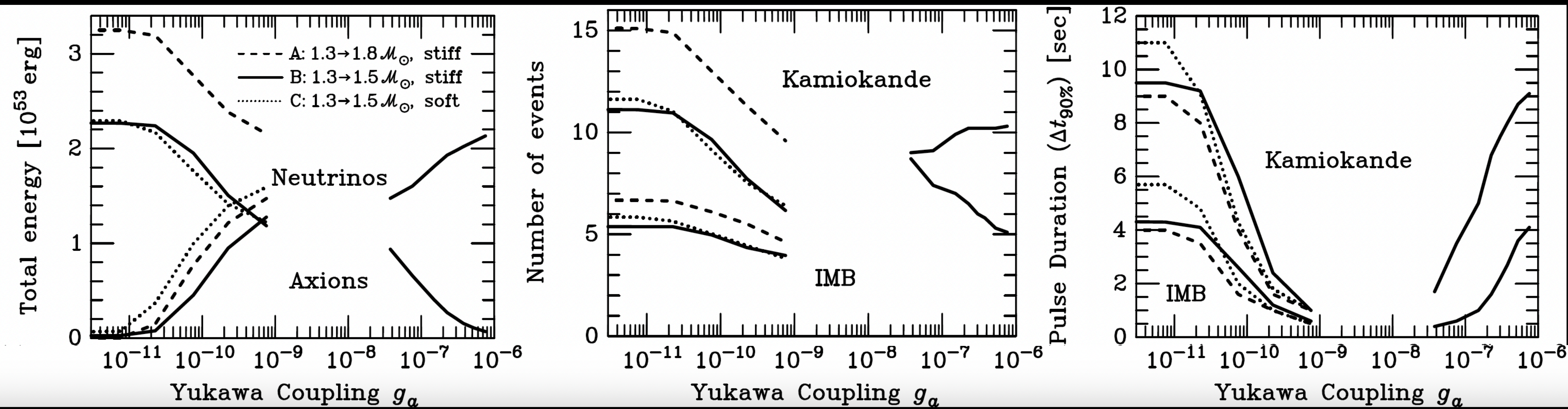
Better agreement increasing $t_{\rm cutoff}$.

Possible early time background events

SN1987a: new physics

Axion coupling to nucleons modifies neutrino signal

Raffelt, "Stars as Laboratories for Fundamental Physics", 1996, University of Chicago Press



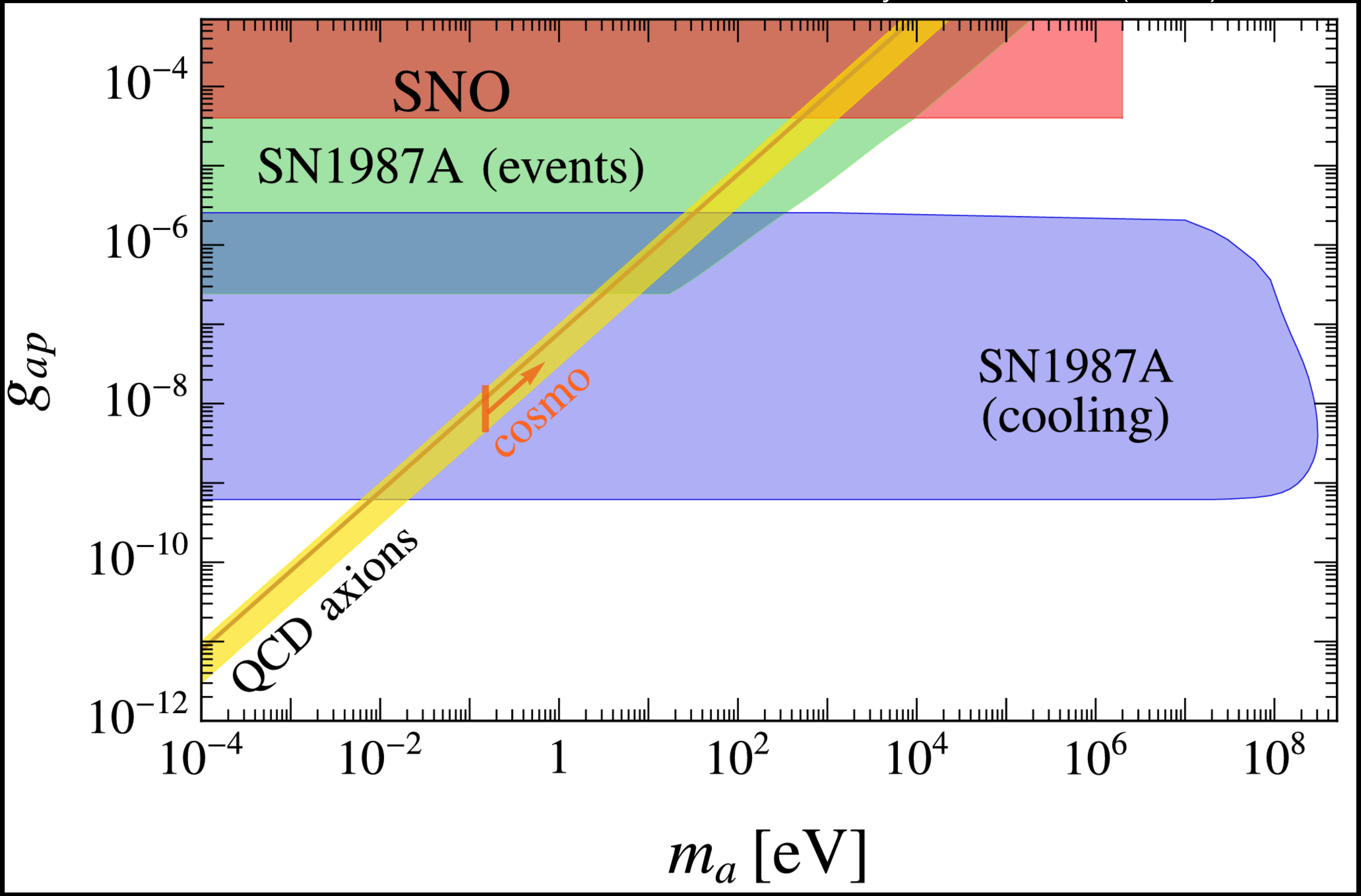
Excluded coupling $10^{-9} < g_a < 3 \times 10^{-7}$, for $m_a < 100\,\mathrm{MeV}$

SN1987a: new physics

Strong coupling could have induced events in Kamiokande II

$$a + {}^{16}\mathrm{O} \rightarrow {}^{16}\mathrm{O}^* \rightarrow {}^{16}\mathrm{O} + \gamma$$

Lella, Carenza, Co', Lucente, Giannotti, Mirizzi, Rauscher, Phys. Rev. D 109 (2024) no.2, 023001



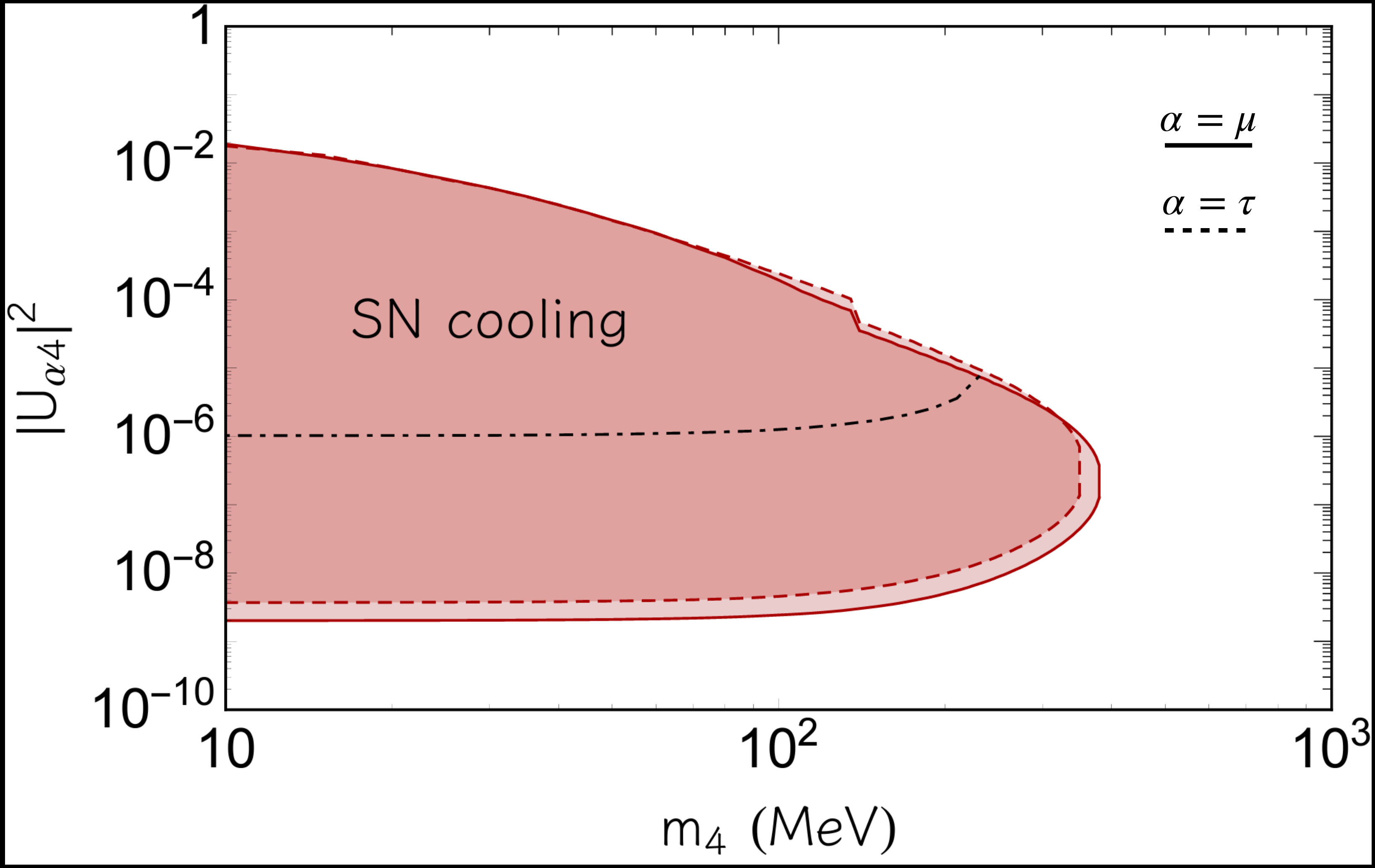
Constraints from cooling compatible with old ones.

Extension of constraints in the strong coupling regime

SN1987a: new physics

Heavy neutrinos can be produced inside a supernova

Carenza, Lucente, Mastrototaro, Mirizzi, Serpico, Phys. Rev. D 109 (2024) no.6, 063010



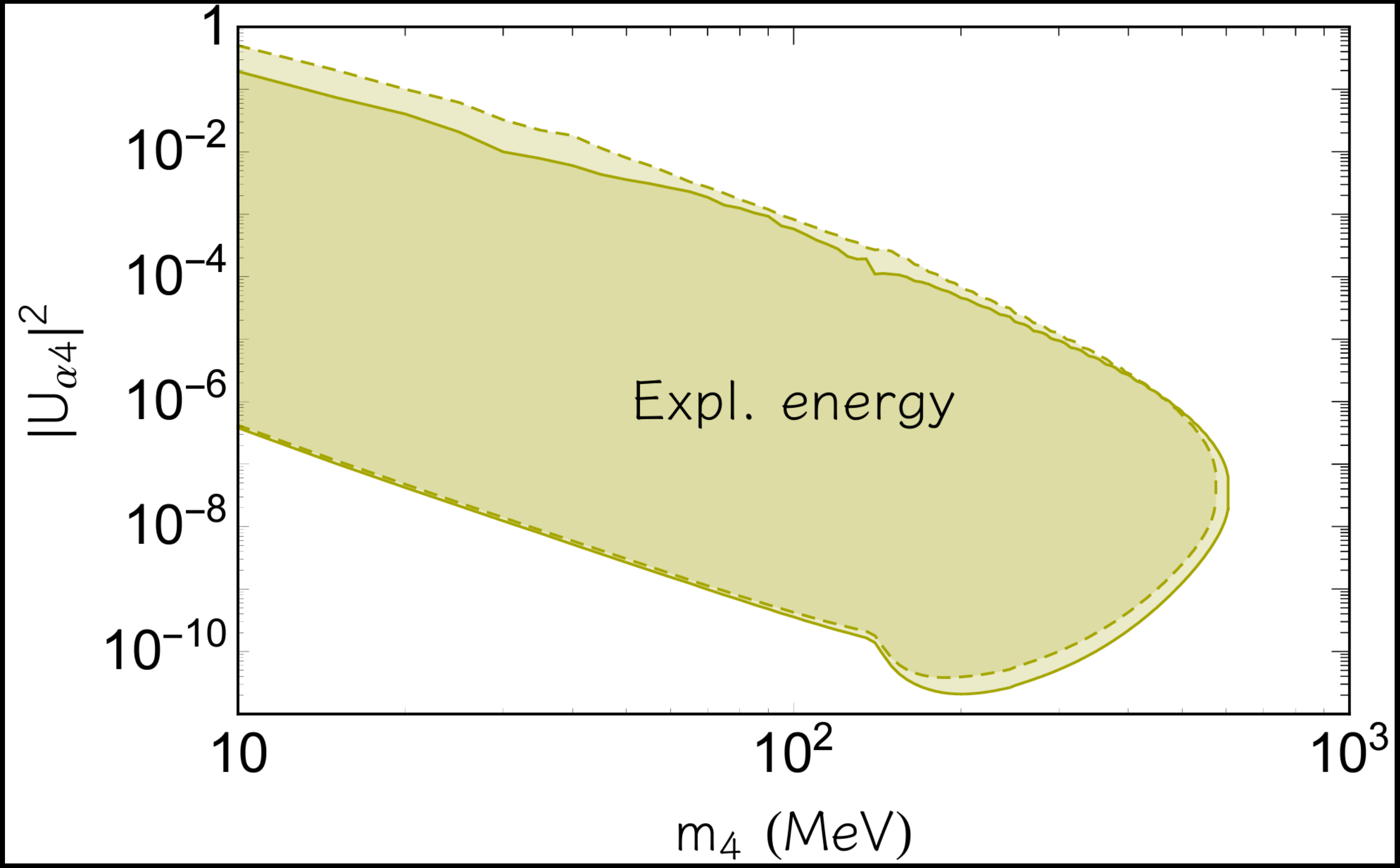
Constraint on mass-mixing obtained from usual criterium

$$\epsilon_X \lesssim 10^{19}\,\mathrm{erg\,g^{-1}\,s^{-1}}$$

SN1987a: new physics

Heavy neutrinos can be produced inside a supernova

Carenza, Lucente, Mastrototaro, Mirizzi, Serpico, Phys. Rev. D 109 (2024) no.6, 063010



Heavy neutrinos can decay contributing to explosion energy.

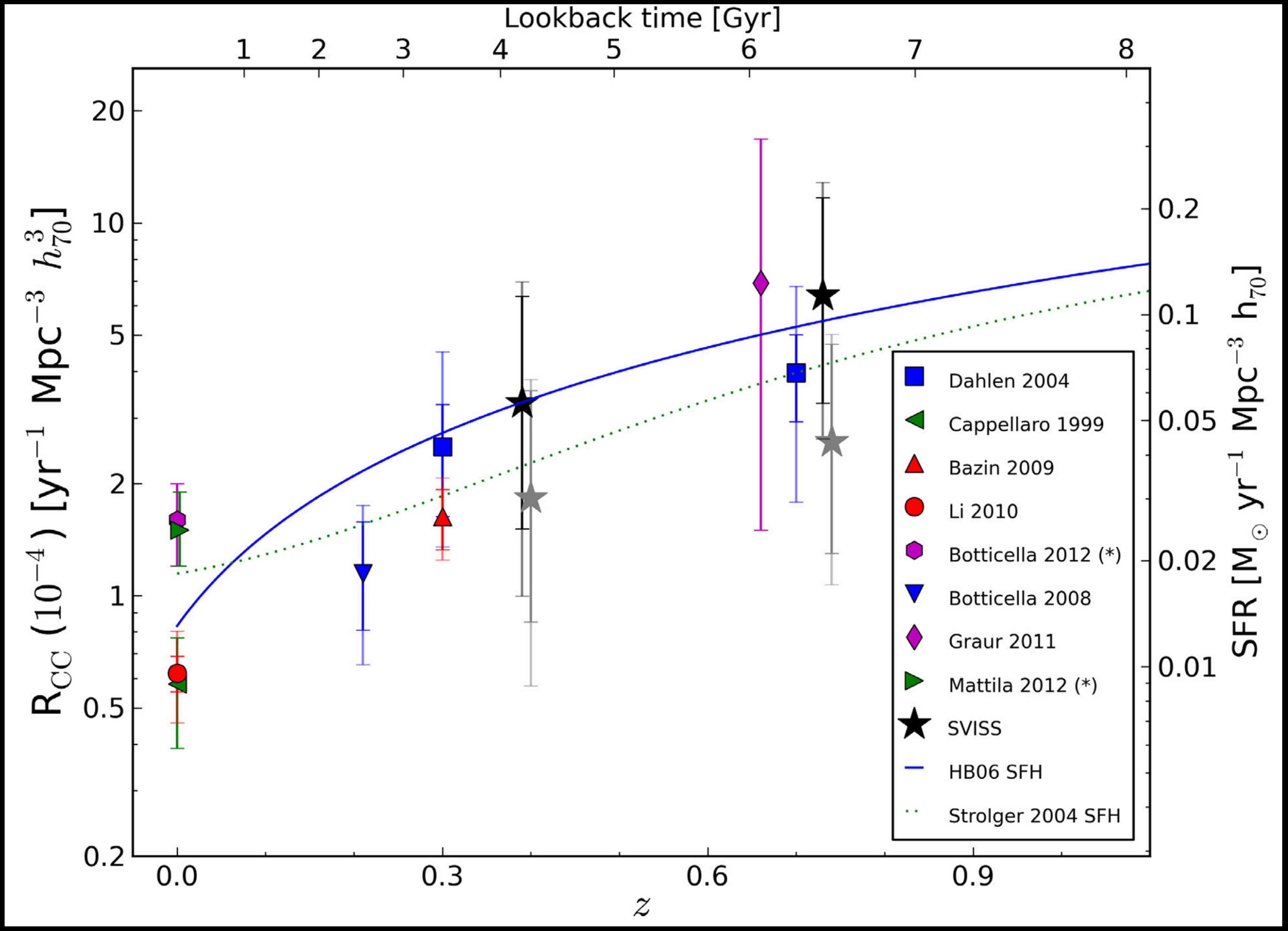
$$E_{X,\mathrm{decay}} \lesssim 10^{50}\,\mathrm{erg}$$

DIFFUSE SN-ν BACKGROUND

What is DSNB?

Local rate of supernovae is relatively low

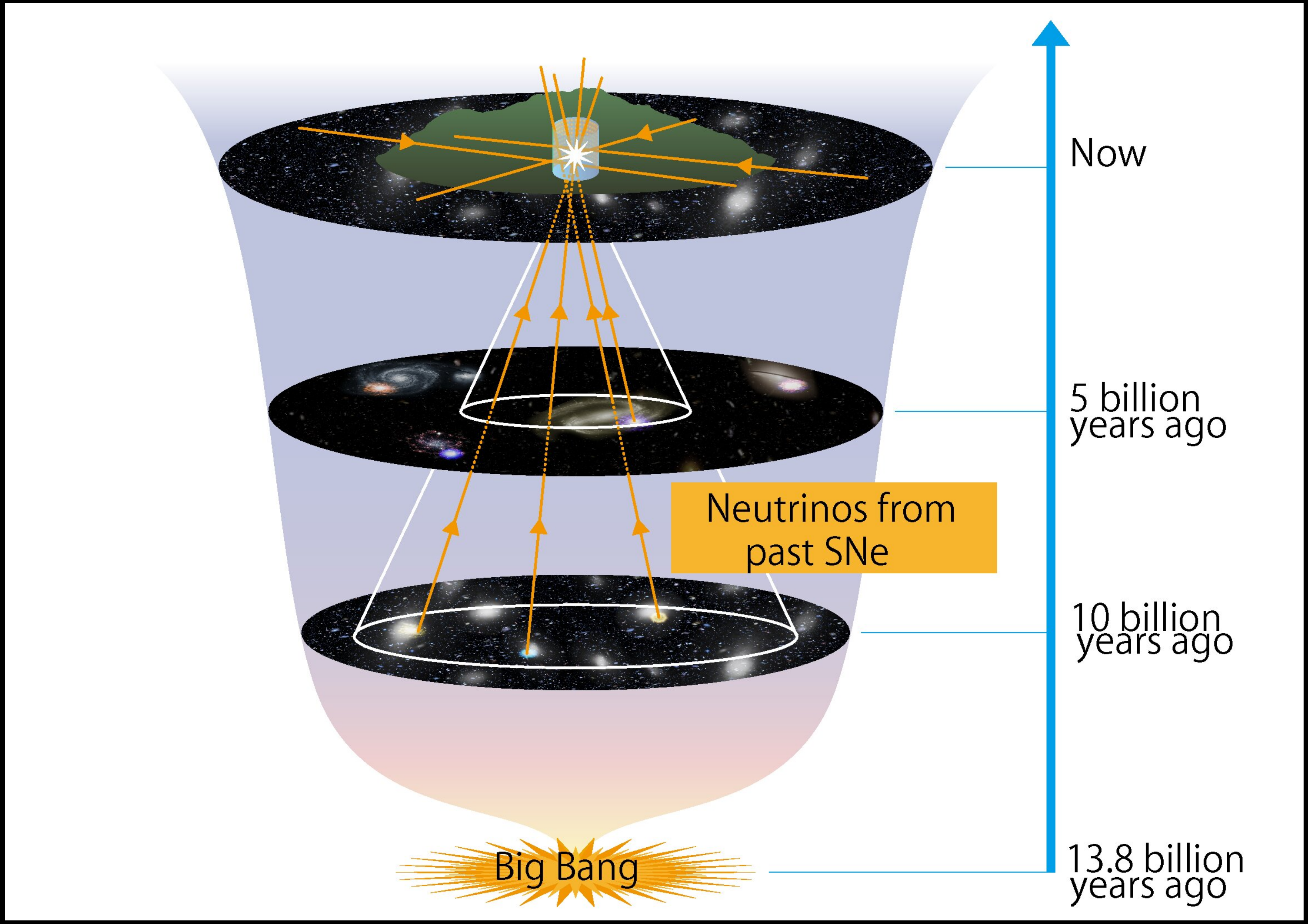
Melinder, et al, Astronomy and Astrophysics 545 (2012) A96



A supernova is a relatively rare event locally

What is DSNB?

What if we look at all supernovae exploded so far?



DSNB: combination of neutrinos from past supernovae

DSNB: expectations

How do we calculate the expected flux of DSNB on Earth?

$$\Phi_{\nu_\beta}(E) = \frac{c}{H_0}\int_{8M_\odot}^{125M_\odot} dM \int_0^{z_{\max}} dz \frac{R_{\rm SN}(z,M)}{\sqrt{\Omega_M(1+z)^3+\Omega_\Lambda}}\left[f_{\rm CC-SN}F_{\nu_\beta,{\rm CC-SN}}(E',M) + f_{\rm BH-SN}F_{\nu_\beta,{\rm BH-SN}}(E',M)\right]$$

fraction of supernovae successfully exploding

time-integrated ν_β-energy spectrum from a SN explosion

DSNB: expectations

How do we calculate the expected flux of DSNB on Earth?

$$\Phi_{\nu_\beta}(E) = \frac{c}{H_0}\int_{8M_\odot}^{125M_\odot} dM \int_0^{z_{\max}} dz \frac{R_{\rm SN}(z,M)}{\sqrt{\Omega_M(1+z)^3+\Omega_\Lambda}}\left[f_{\rm CC-SN}F_{\nu_\beta,{\rm CC-SN}}(E',M) + f_{\rm BH-SN}F_{\nu_\beta,{\rm BH-SN}}(E',M)\right]$$

fraction of supernovae going into black-hole

time-integrated ν_β-energy spectrum from a failed SN

DSNB: expectations

How do we calculate the expected flux of DSNB on Earth?

$$\Phi_{\nu_\beta}(E) = \frac{c}{H_0} \int_{8M_\odot}^{125M_\odot} dM \int_0^{z_{\max}} dz \frac{\boxed{R_{\mathrm{SN}}(z, M)}}{\sqrt{\Omega_M (1+z)^3 + \Omega_\Lambda}} \left[f_{\mathrm{CC-SN}} F_{\nu_\beta, \mathrm{CC-SN}}(E', M) + f_{\mathrm{BH-SN}} F_{\nu_\beta, \mathrm{BH-SN}}(E', M) \right]$$

rate of supernovae as a function
of redshift and progenitor mass

DSNB: expectations

How do we calculate the expected flux of DSNB on Earth?

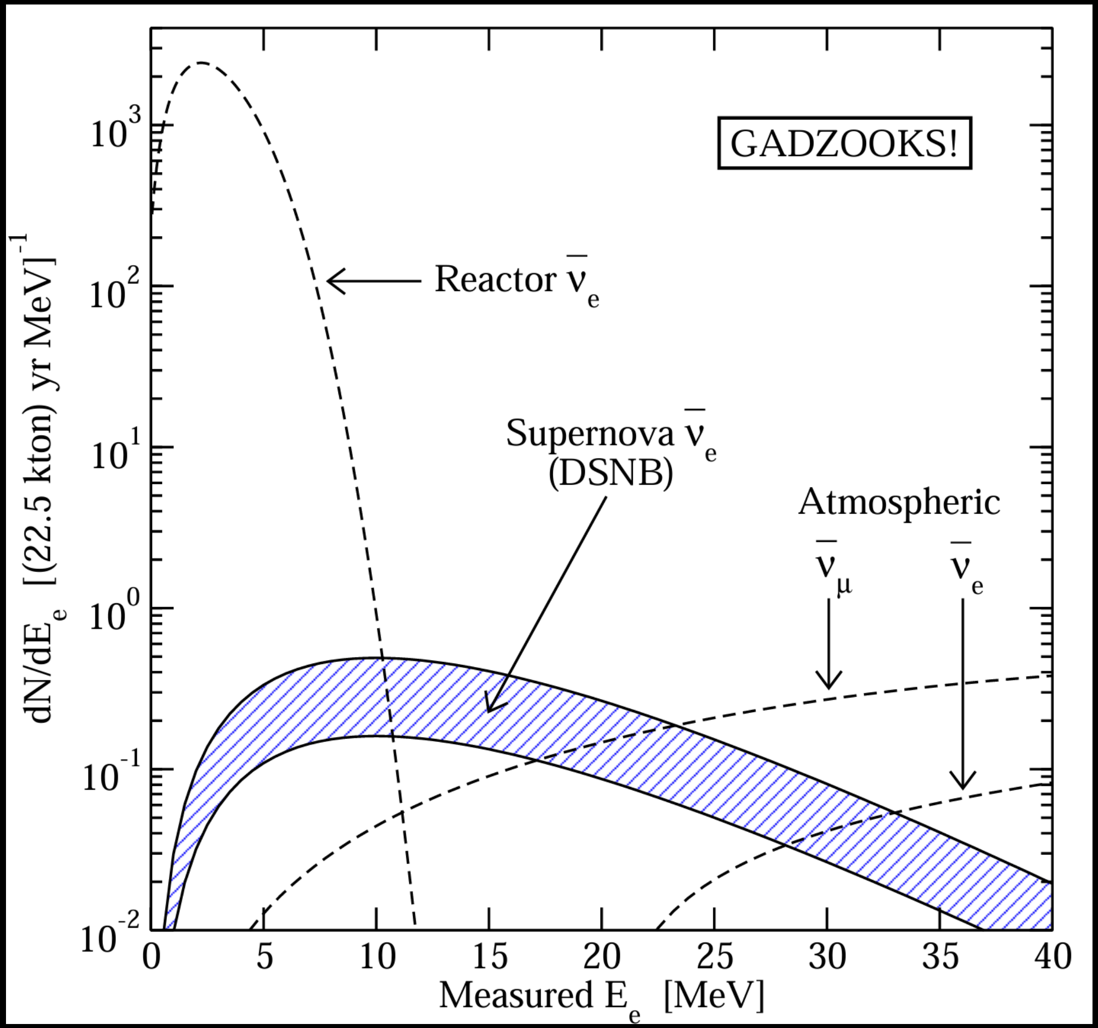
$$\Phi_{\nu_\beta}(E) = \frac{c}{H_0}\int_{8M_\odot}^{125M_\odot} dM \int_0^{z_{\max}} dz \frac{R_{\rm SN}(z,M)}{\sqrt{\boxed{\Omega_M(1+z)^3+\Omega_\Lambda}}}\left[f_{\rm CC-SN}F_{\nu_\beta,\rm CC-SN}(E',M)+f_{\rm BH-SN}F_{\nu_\beta,\rm BH-SN}(E',M)\right]$$

expansion rate of the universe changing with redshift. $\Omega_M \simeq 0.3, \Omega_\Lambda \simeq 0.7$

DSNB: expectations

Background is important for detecting DSNB

Beacom, Vagins, Phys. Rev. Lett. 93 (2004), 171101

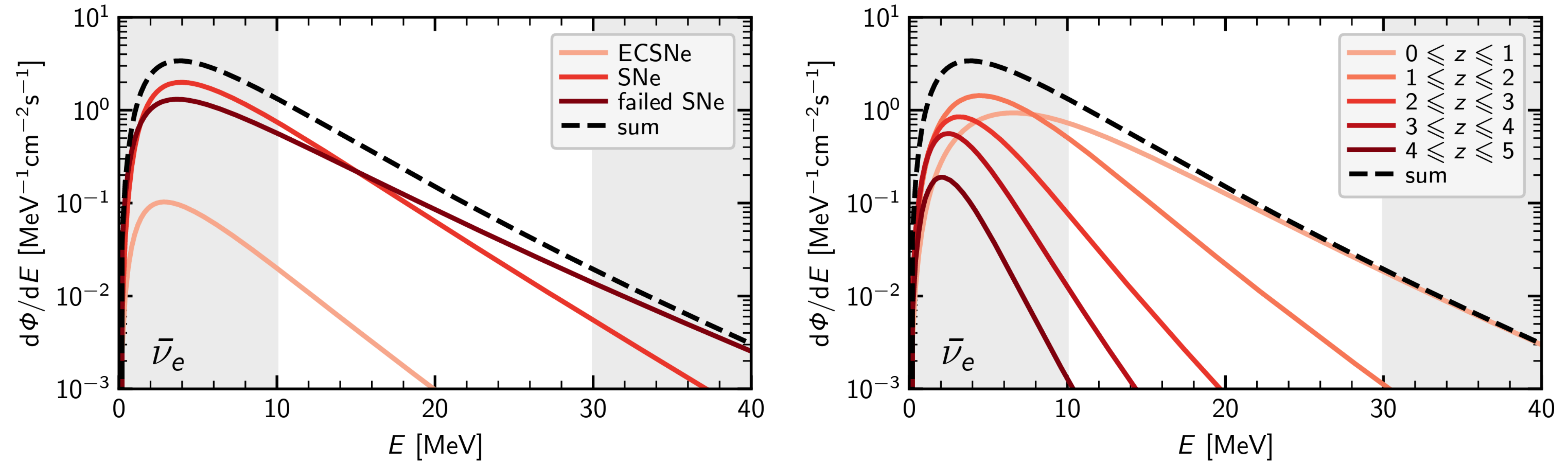


Region of observation ~ 10 - 25 MeV

DSNB: expectations

Main uncertainties: supernova rate, fraction of failed supernova

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



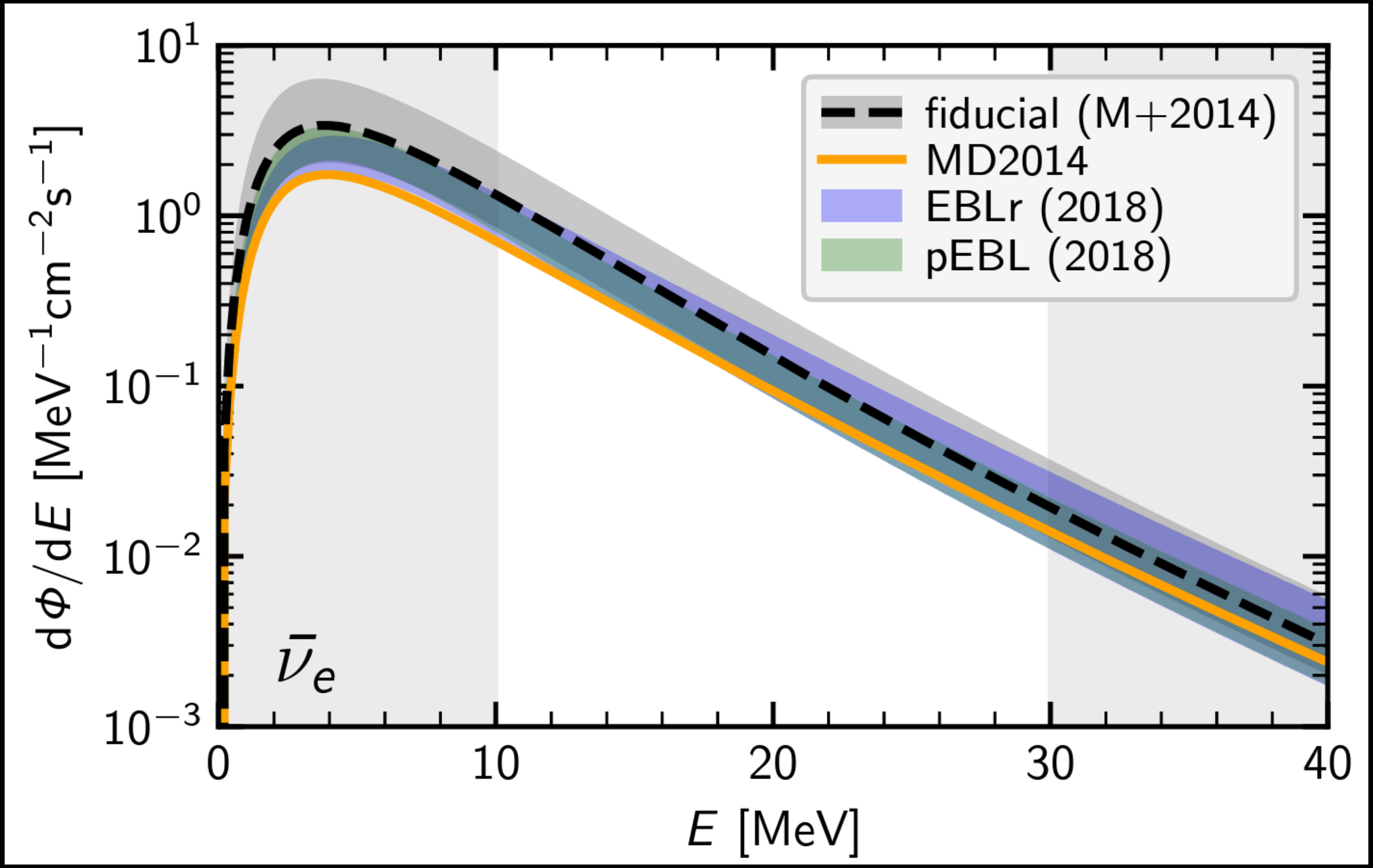
Main contribution: $z < 1$.

High energy: Failed SN. Low energy: Successful SN

DSNB: expectations

Main uncertainties: supernova rate, fraction of failed supernova

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

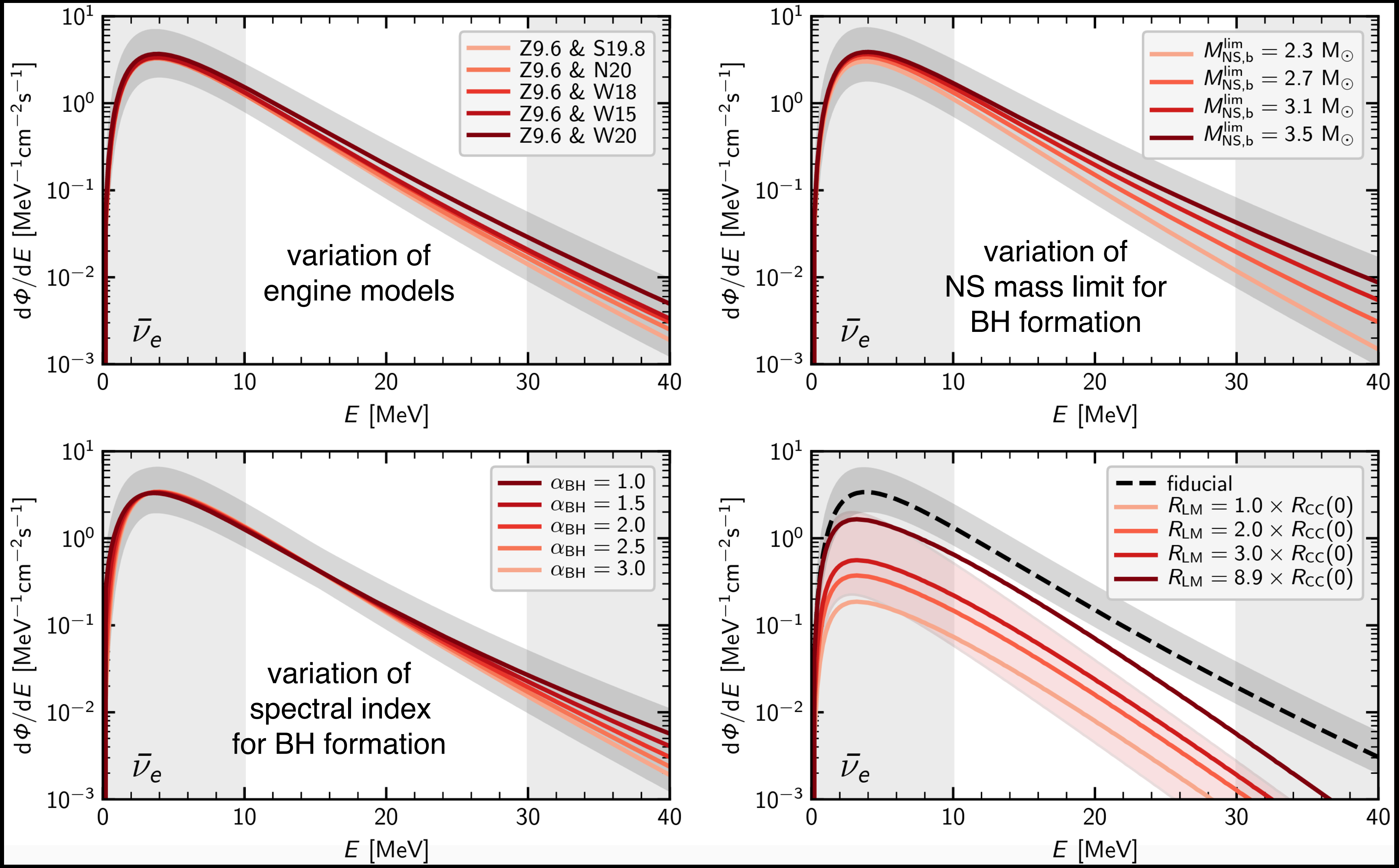


Significant dependence on star formation rate model

DSNB: expectations

Main uncertainties: supernova rate, fraction of failed supernova

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

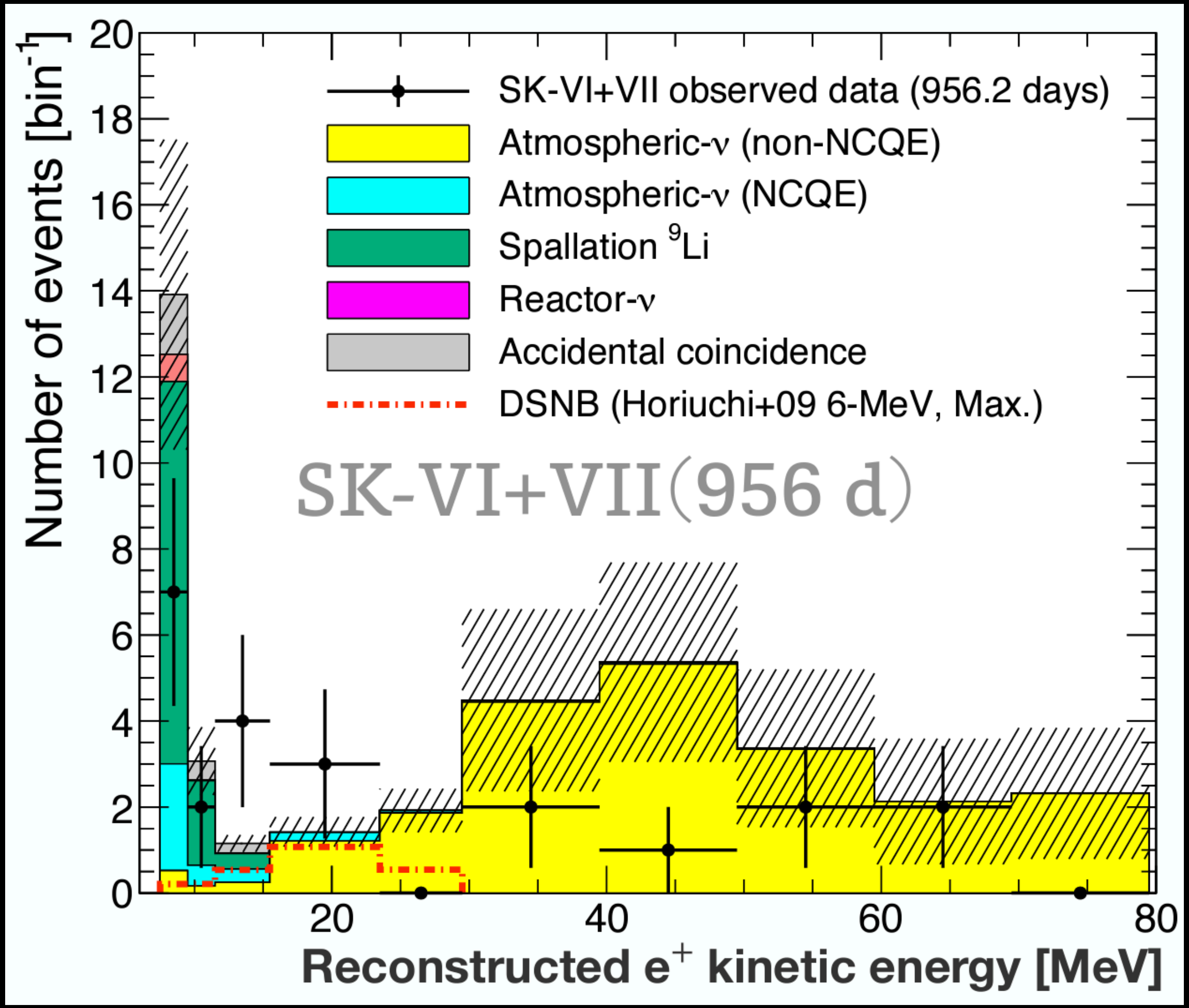


Significant dependence on simulation details

DSNB: measurements

Super-K with the addition of Gd is the most sensitive

Masayuki Harada, “Review of Diffuse SN Neutrino Background”, Talk at Neutrino 2024

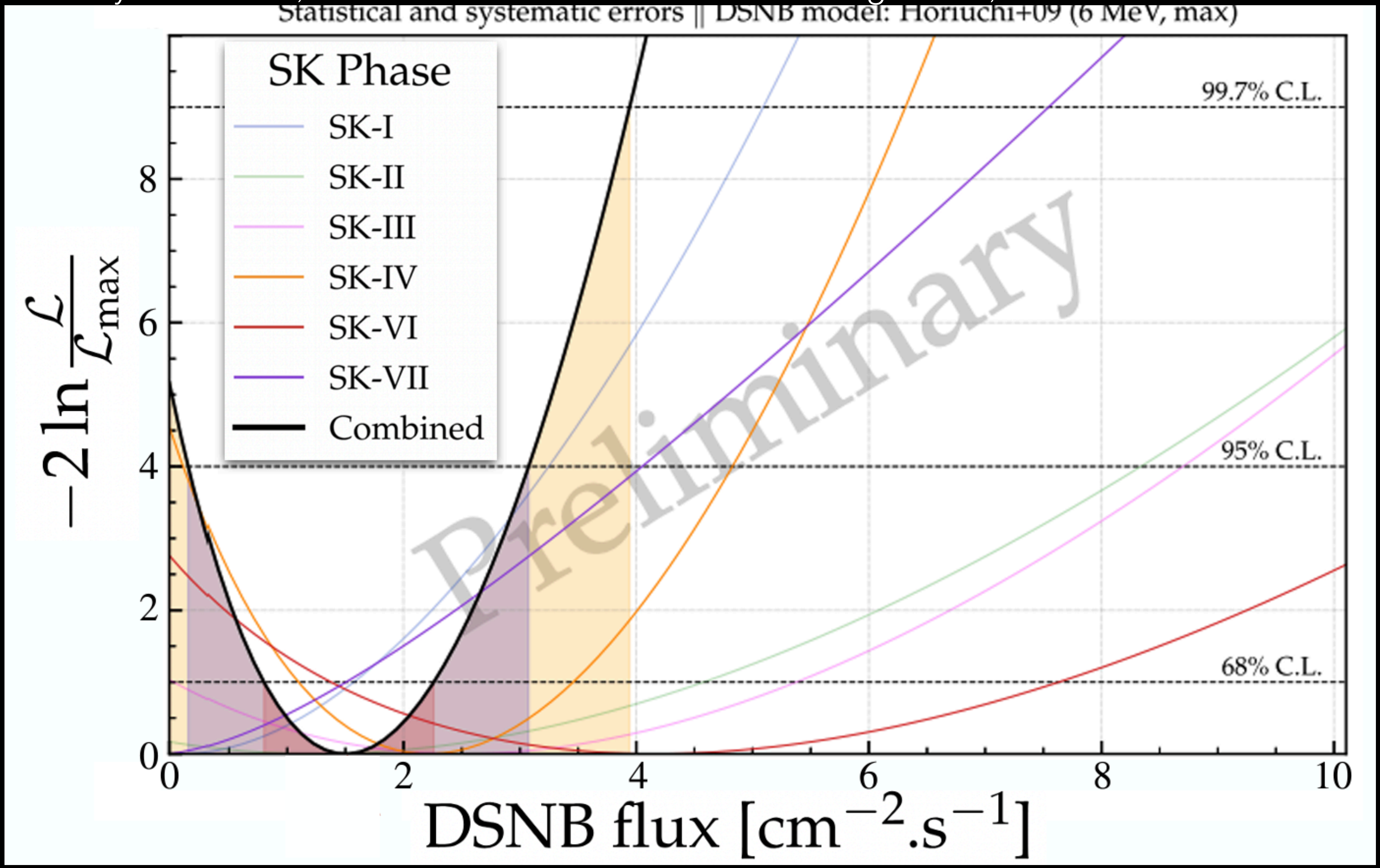


Small excess in the region 10 - 20 MeV

DSNB: measurements

Super-K with the addition of Gd is the most sensitive

Masayuki Harada, “Review of Diffuse SN Neutrino Background”, Talk at Neutrino 2024

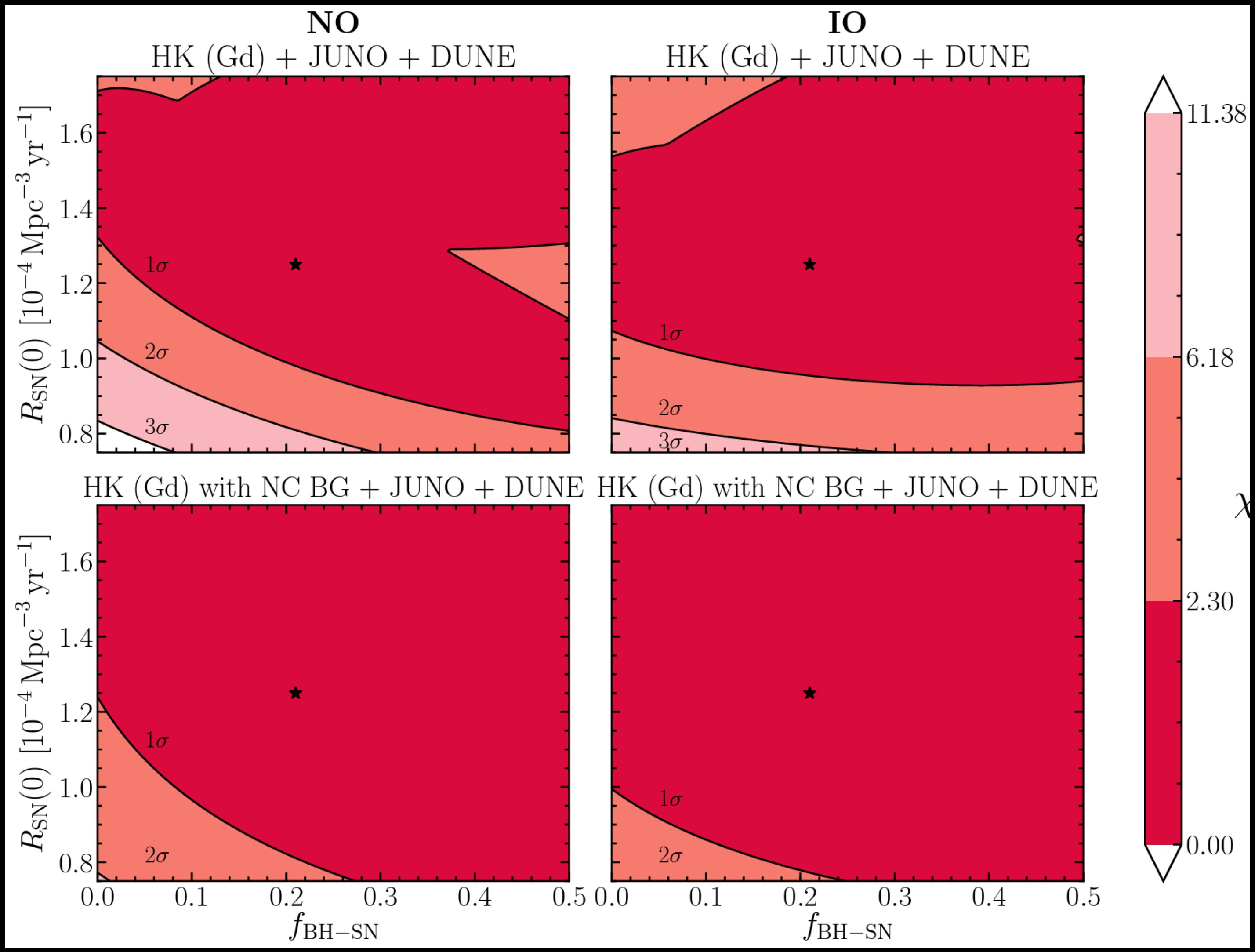


Best fit for non-zero DSNB flux. 2.3σ evidence!!!!

DSNB: future measurements

What about the future?

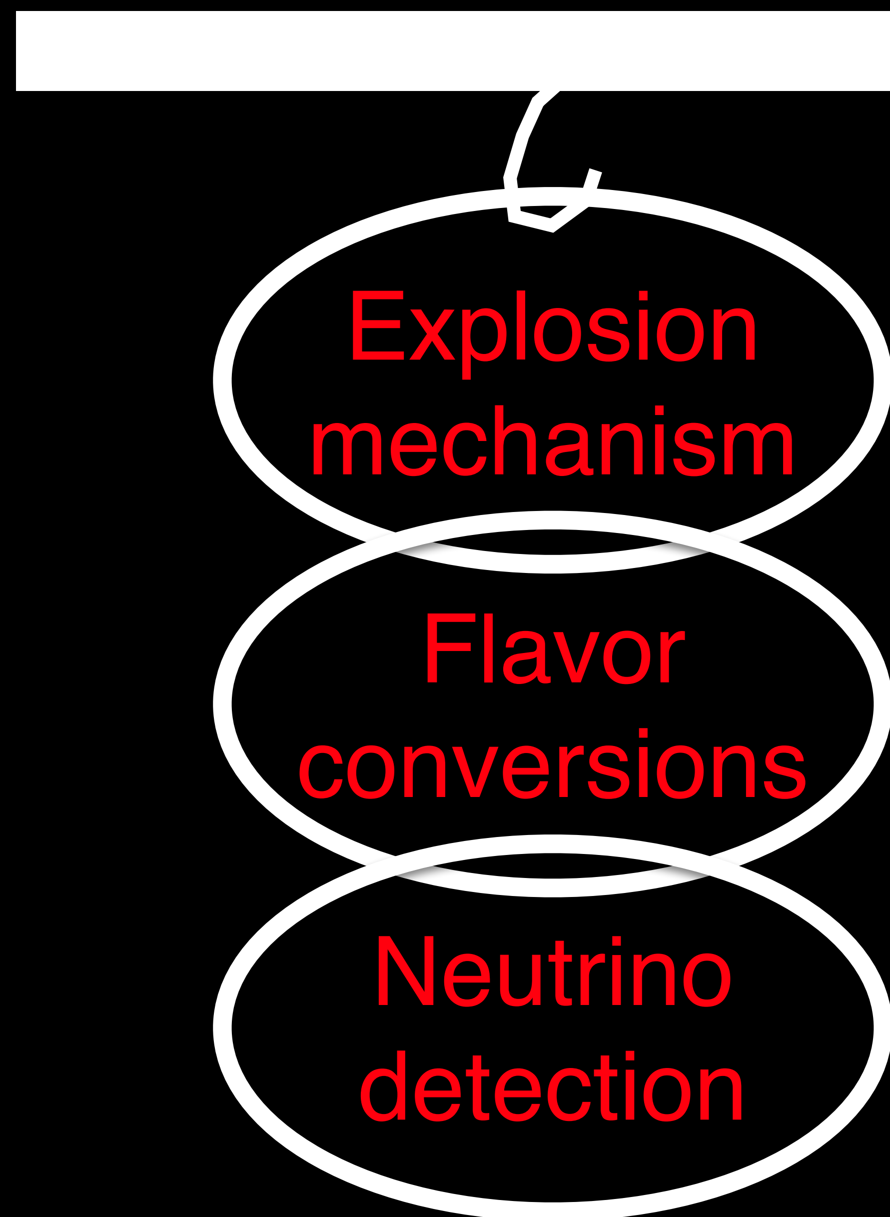
Moller, Suliga, Tamborra, Denton, JCAP 05 (2018), 066



Future experiments can shed light on main uncertainties

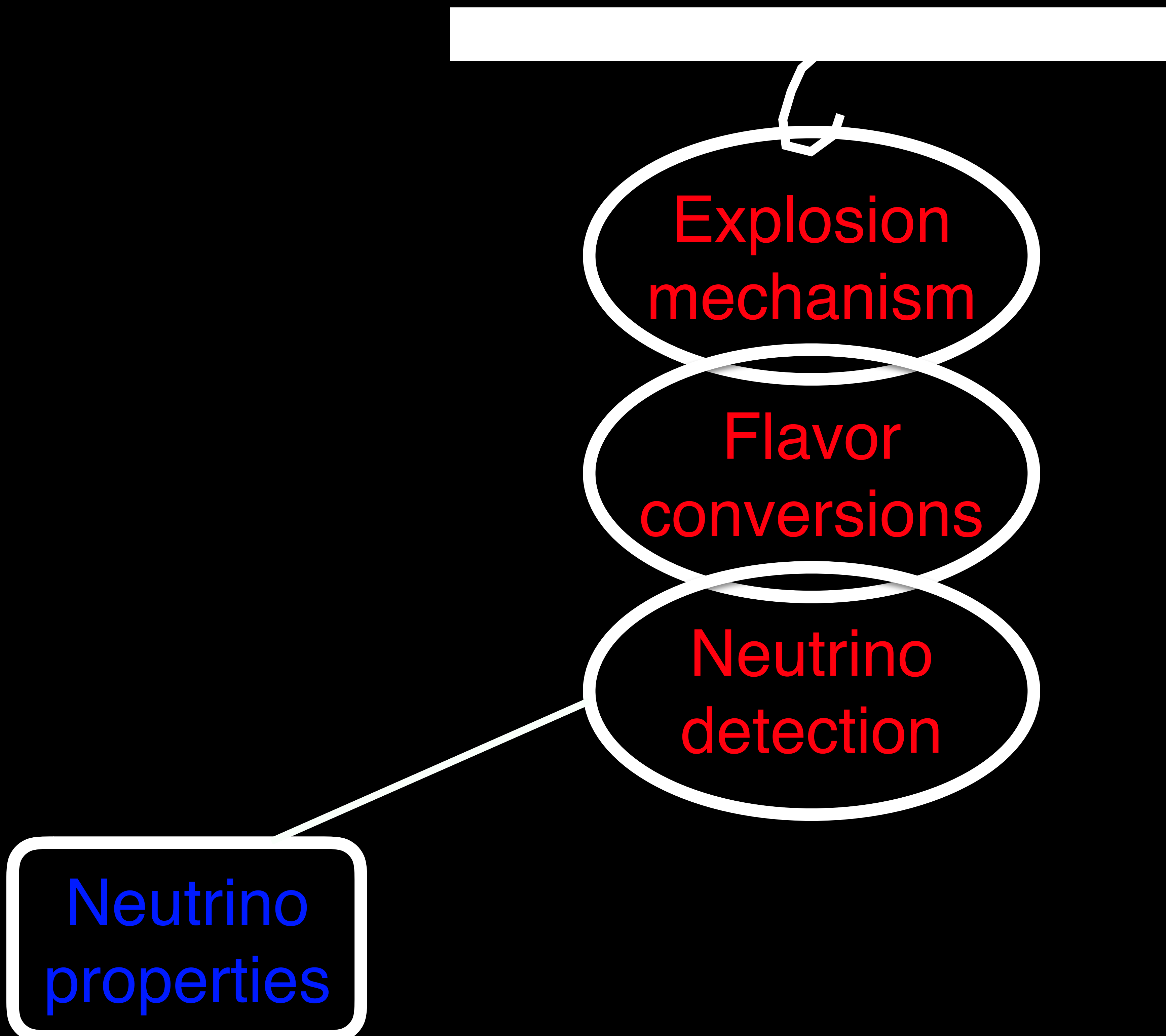
Are we ready for SN20xy?

The supernova neutrinos chain



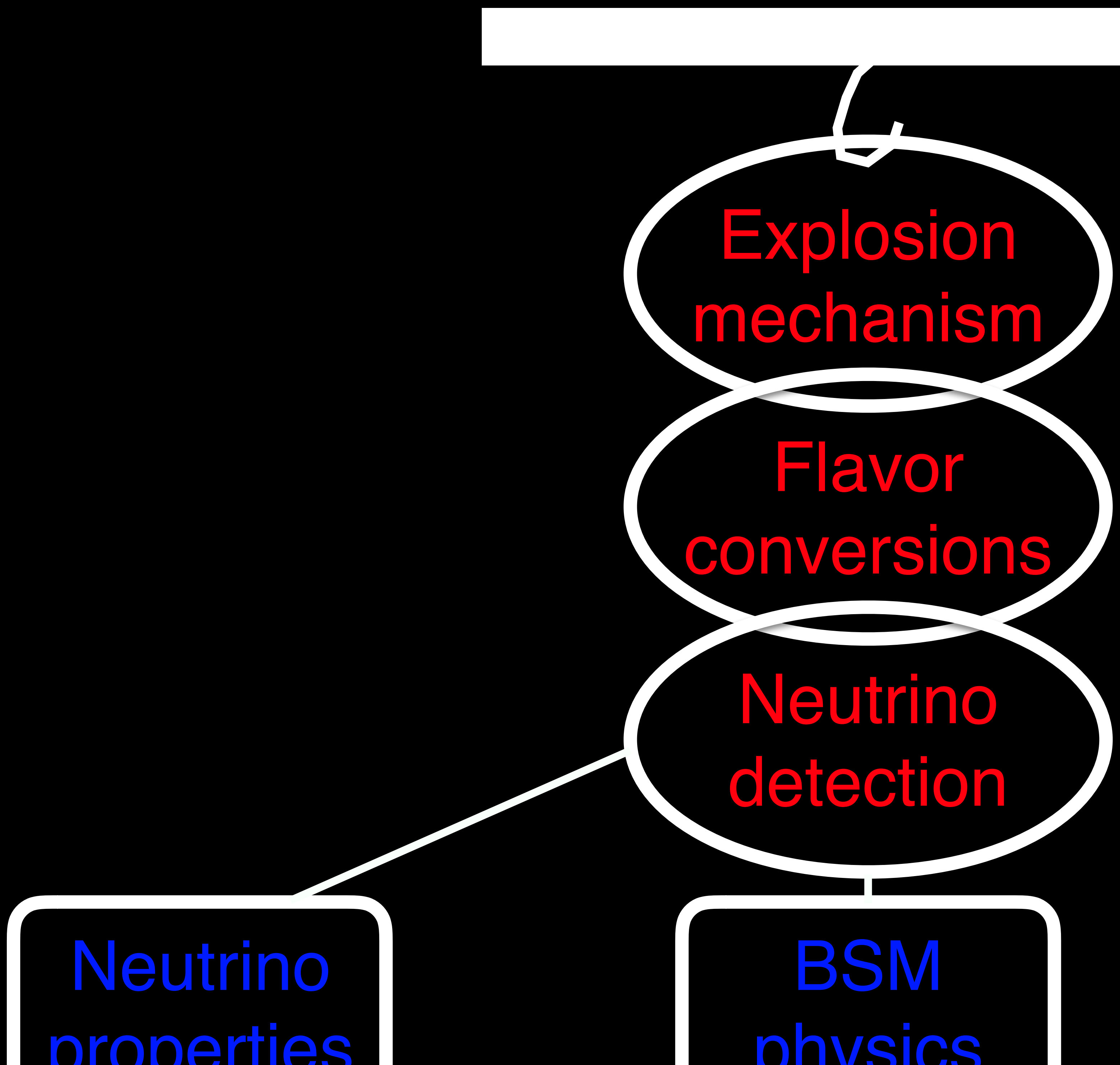
Are we ready for SN20xy?

The supernova neutrinos chain



Are we ready for SN20xy?

The supernova neutrinos chain



Are we ready for SN20xy?

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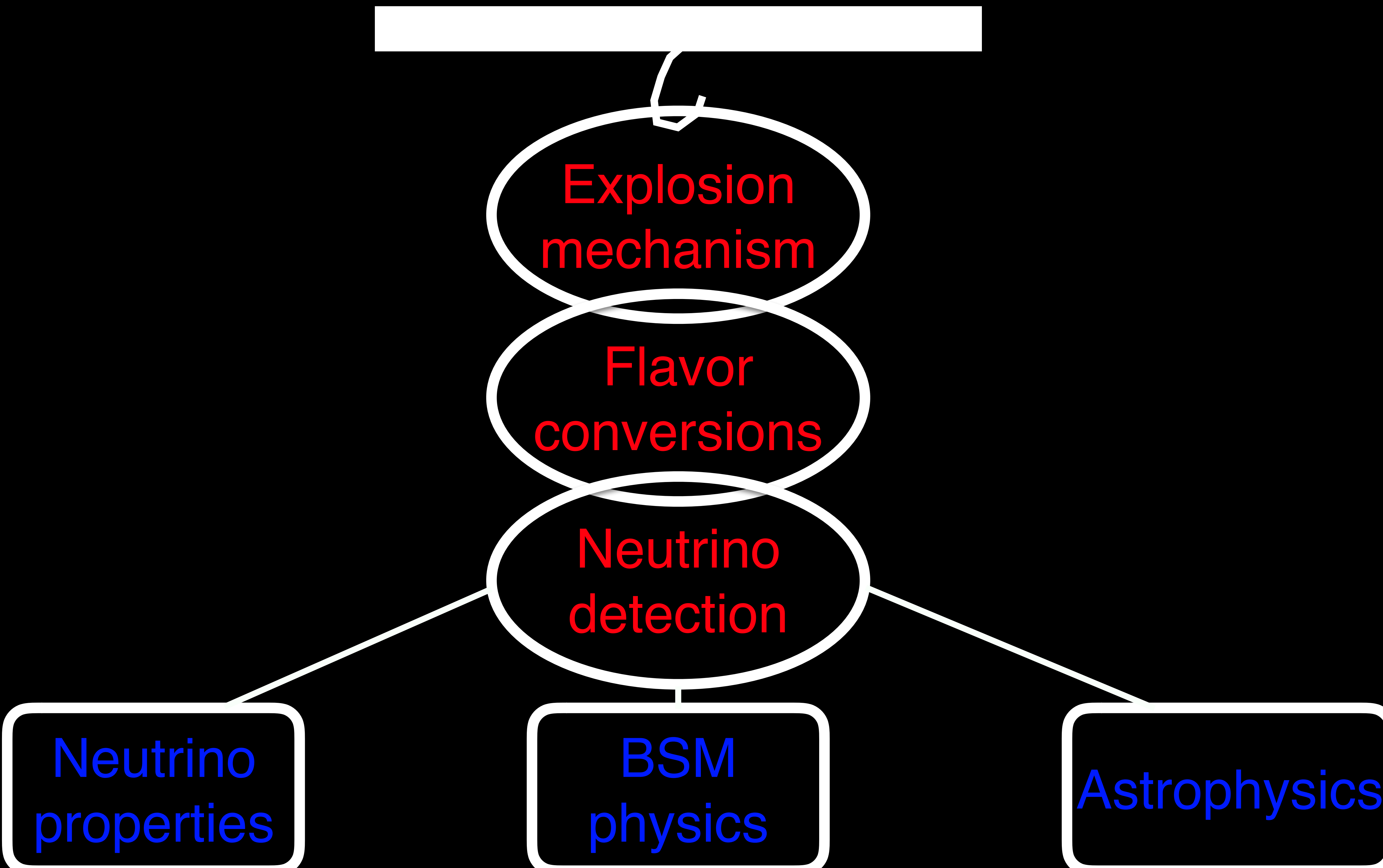
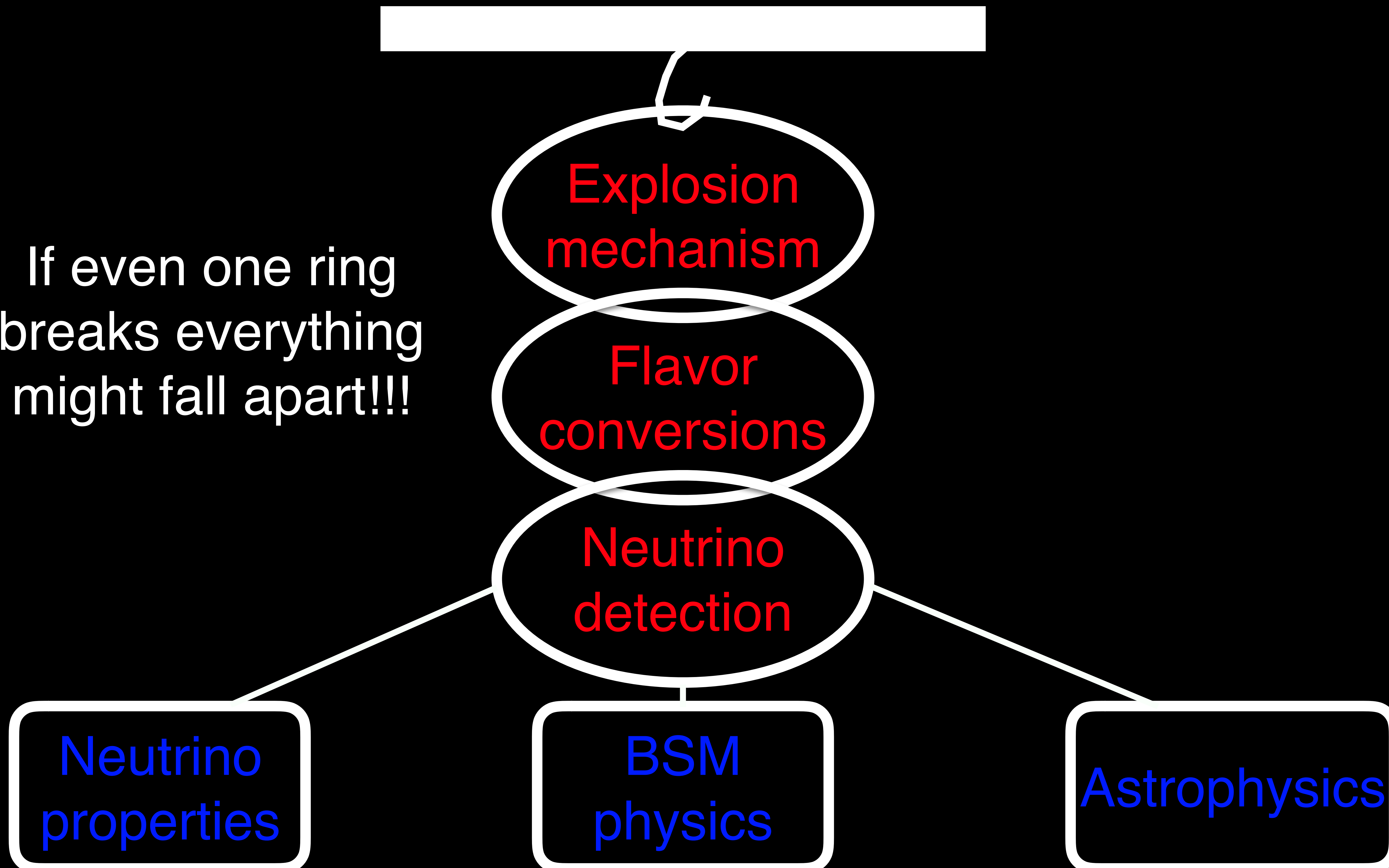


Are we ready for SN20xy?

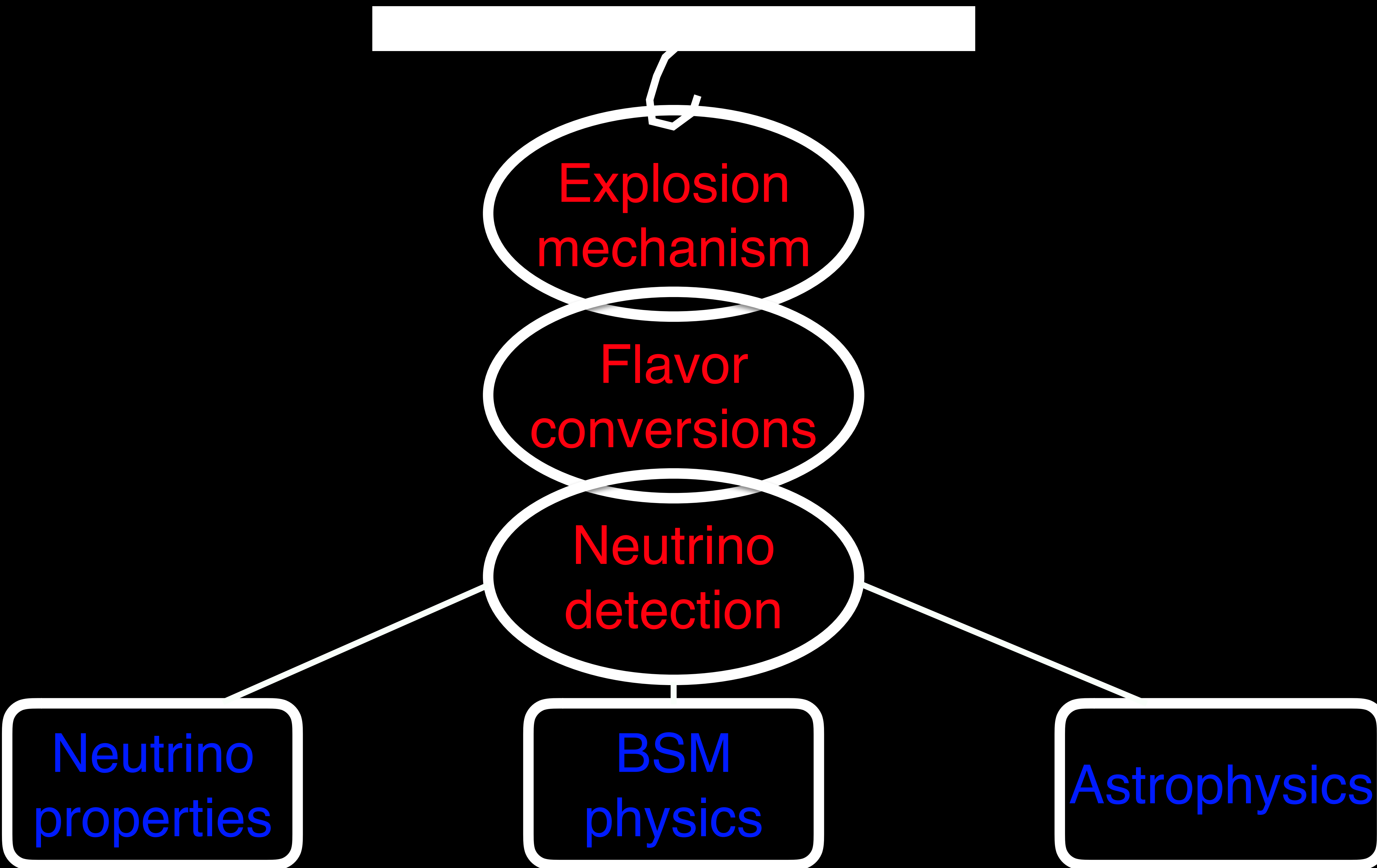
The supernova neutrinos chain

If even one ring breaks everything might fall apart!!!



Are we ready for SN20xy?

Each aspect of the chain to **MUST** be well understood



Thank you