SUPERNOVAE:
A LABORATORY FOR NEW PHYSICS

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OUTLINE

- Neutrinos: from core-collapse supernovae
- Theoretical description: flavor mechanisms, mean field and beyond
- Future observations of supernova neutrinos
- Diffuse supernova neutrino background
- Conclusions

CORE-COLLAPSE SUPERNOVAE (SNe)

- Massive stars with

$8M_{sun} < M < 10\ M_{sun}$ O-Ne-Mg (electron-capture) SNe

$M > 10\ M_{sun}$ Iron CC supernovae

They include SNII, SN Ib (H shell lost), SN Ic (H and He shell lost)

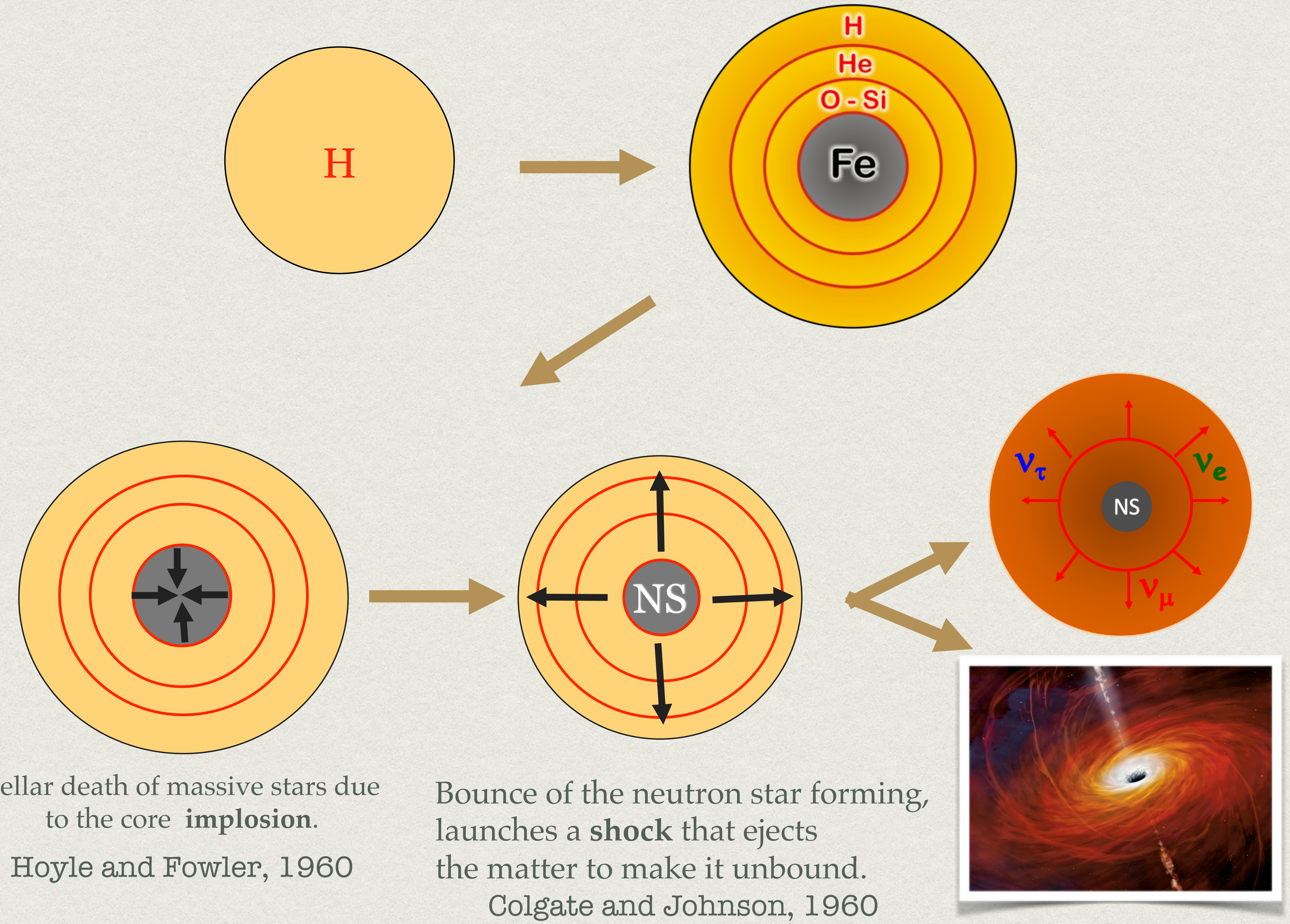
- Gravitational binding energy taken away by neutrinos.

$$E_{grav} \approx \frac{GM^2}{R} \approx 3 \times 10^{53}\ erg$$

Colgate and White, 1966

- Energy : 99 % neutrinos, 0.01% photons about 1% explosion kinetic energy

Powerful sources of all flavor neutrinos, during ten seconds' burst



Stellar death of massive stars due to the core **implosion**.

Hoyle and Fowler, 1960

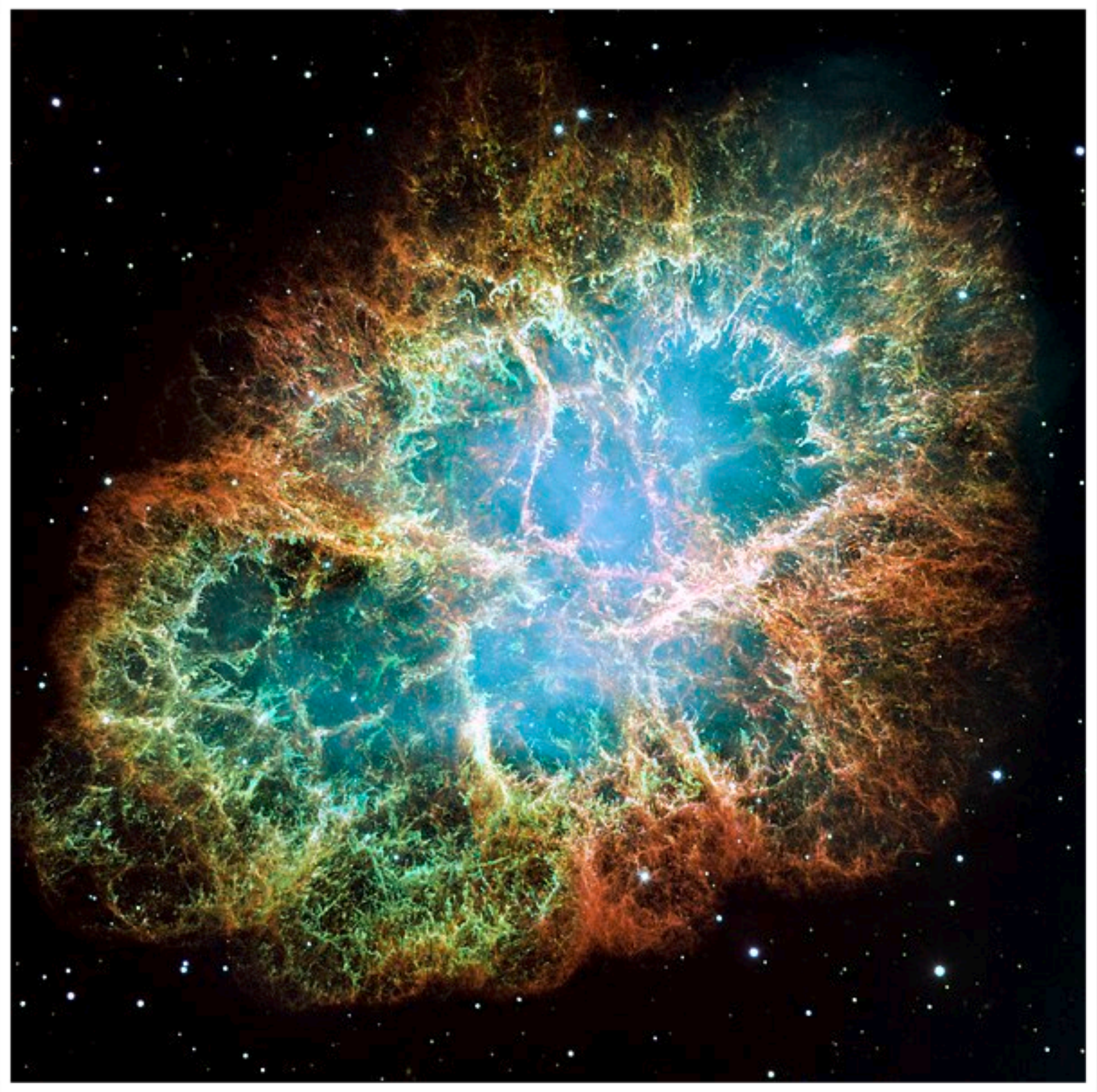
Bounce of the neutron star forming, launches a **shock** that ejects the matter to make it unbound.

Colgate and Johnson, 1960

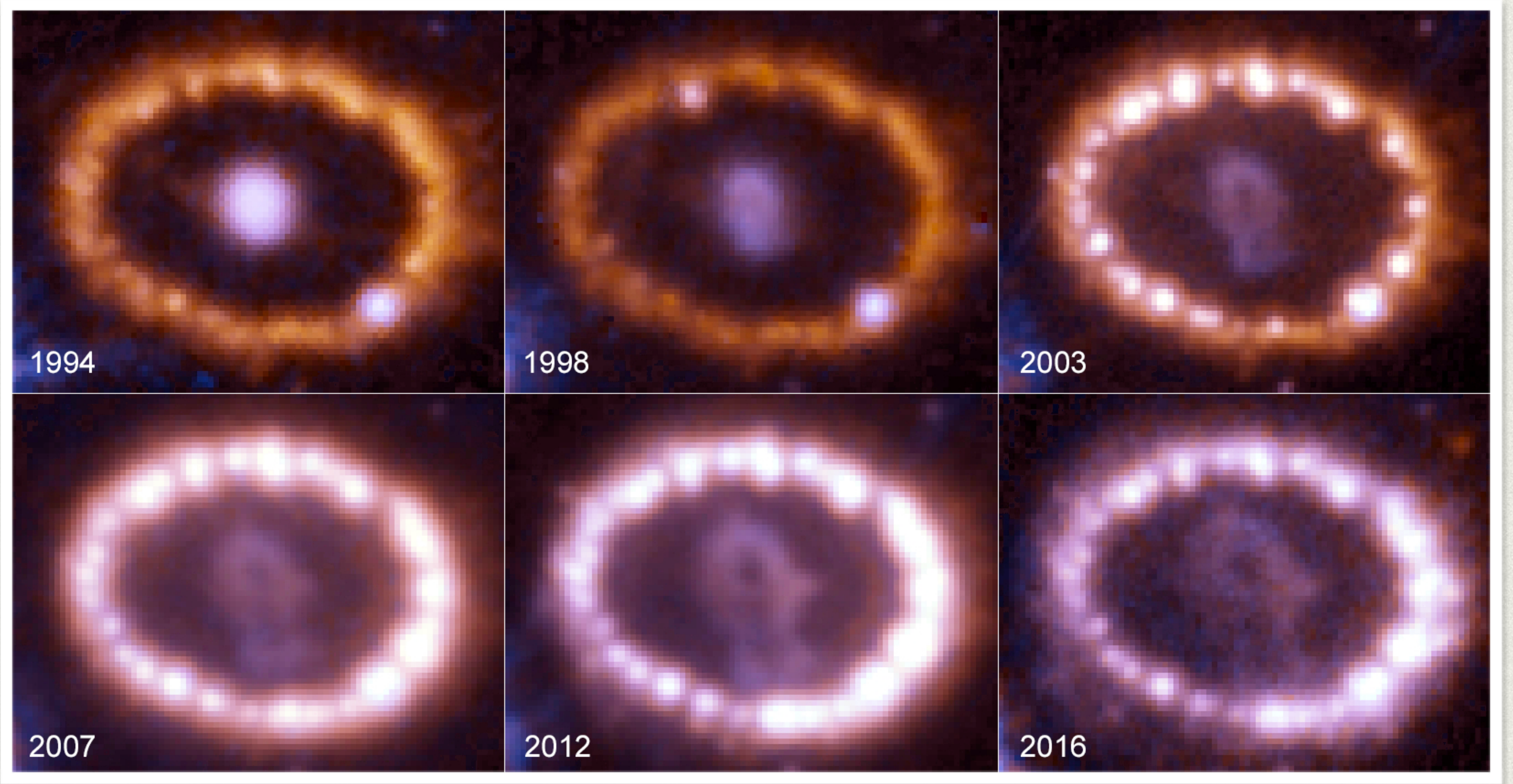
Neutrinos deposit energy behind the shock triggering the explosion (prompt explosion mechanism).

Colgate and White, 1966

RARE EVENTS



Crab Nebula, from **SN 1054,** 1.9 kpc (~6 200 light-years)



Hubble Space Telescope

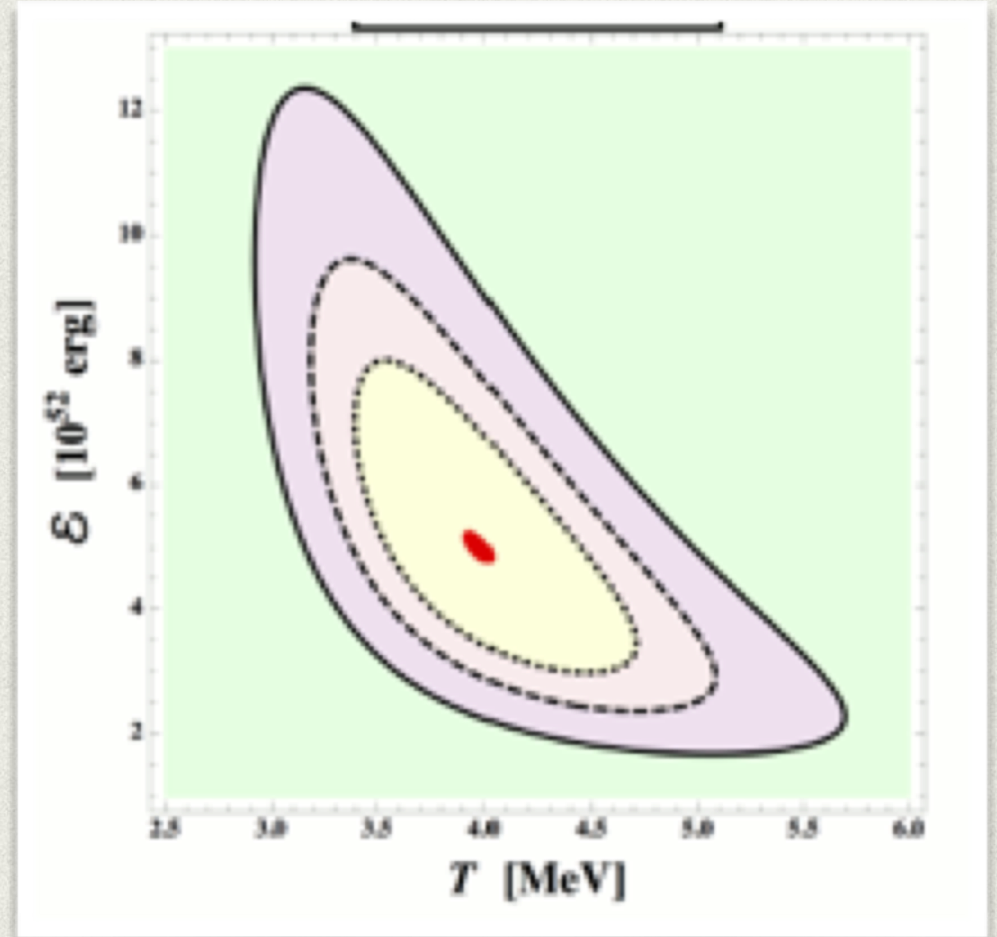
SN1987A, Sanduleak 69^0202 blue supergiant exploded,
Large Magellanic Cloud, 50 kpc (163,000 light-years)

- Expected 1-3 supernovae/century in the Milky Way
  Mean-time = 50 y pm 20 y
- SN candidate, ex. Betelgeuse 0.2 kpc (about 650 light-years).

A UNIQUE EVENT : SN1987A

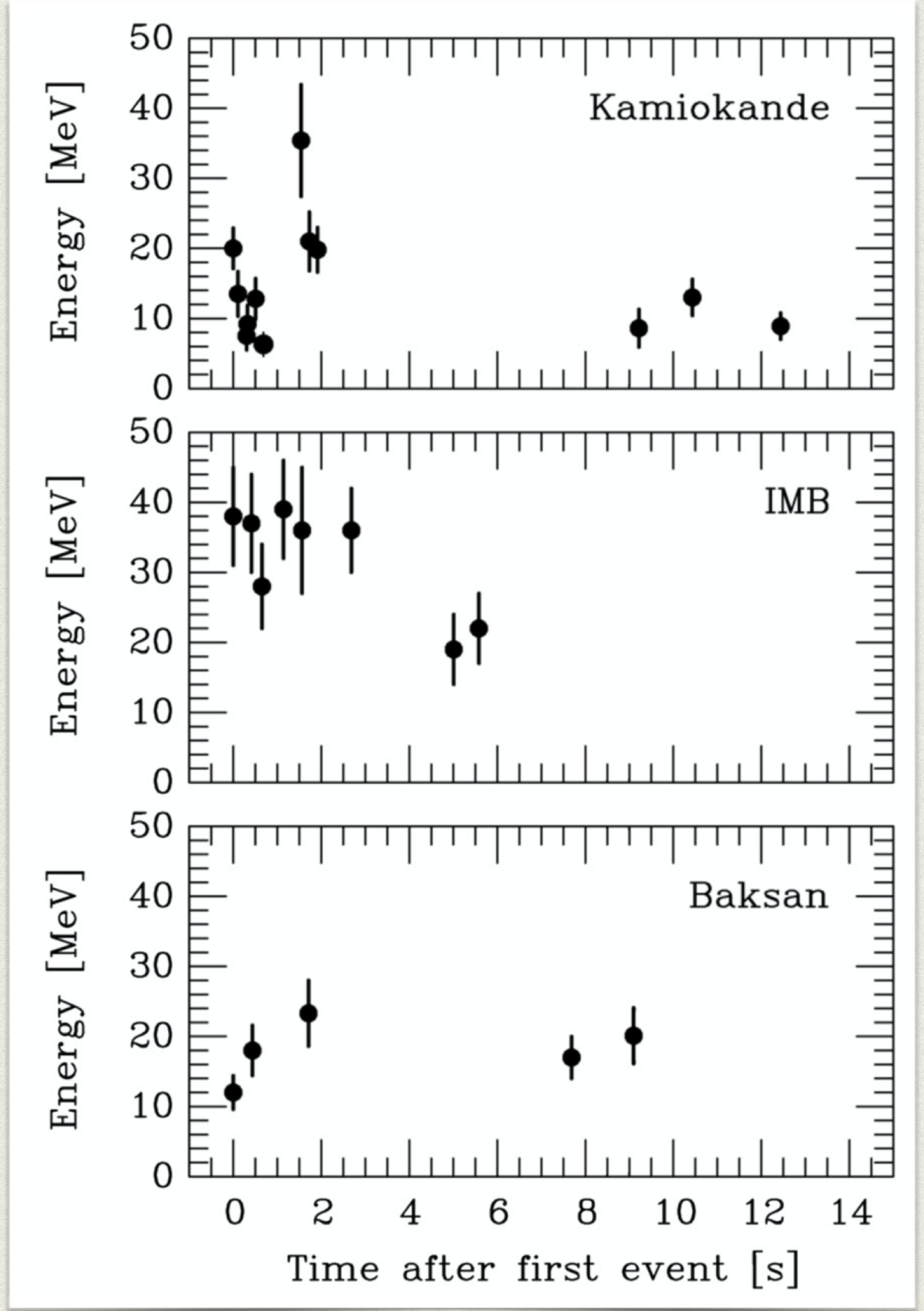
- First observation of neutrinos from the death of a massive star : 24 events detected.

- Time signal, average energies and gravitational energy, in agreement with expectations.



Vissani, JPG 2015

Information for astrophysics, on ν properties, non-standard interactions and particles



Water Cherenkov detector, 2140 tons

2002 Nobel Prize
M. Koshiba (Kamiokande),
with R. Davis (solar neutrinos),
and R. Giacconi

Irvine-Michigan-Brookhaven, Water Cherenkov, 6800 tons

Baksan Scintillator Telescope, 200 tons

SN EXPLOSION MECHANISM

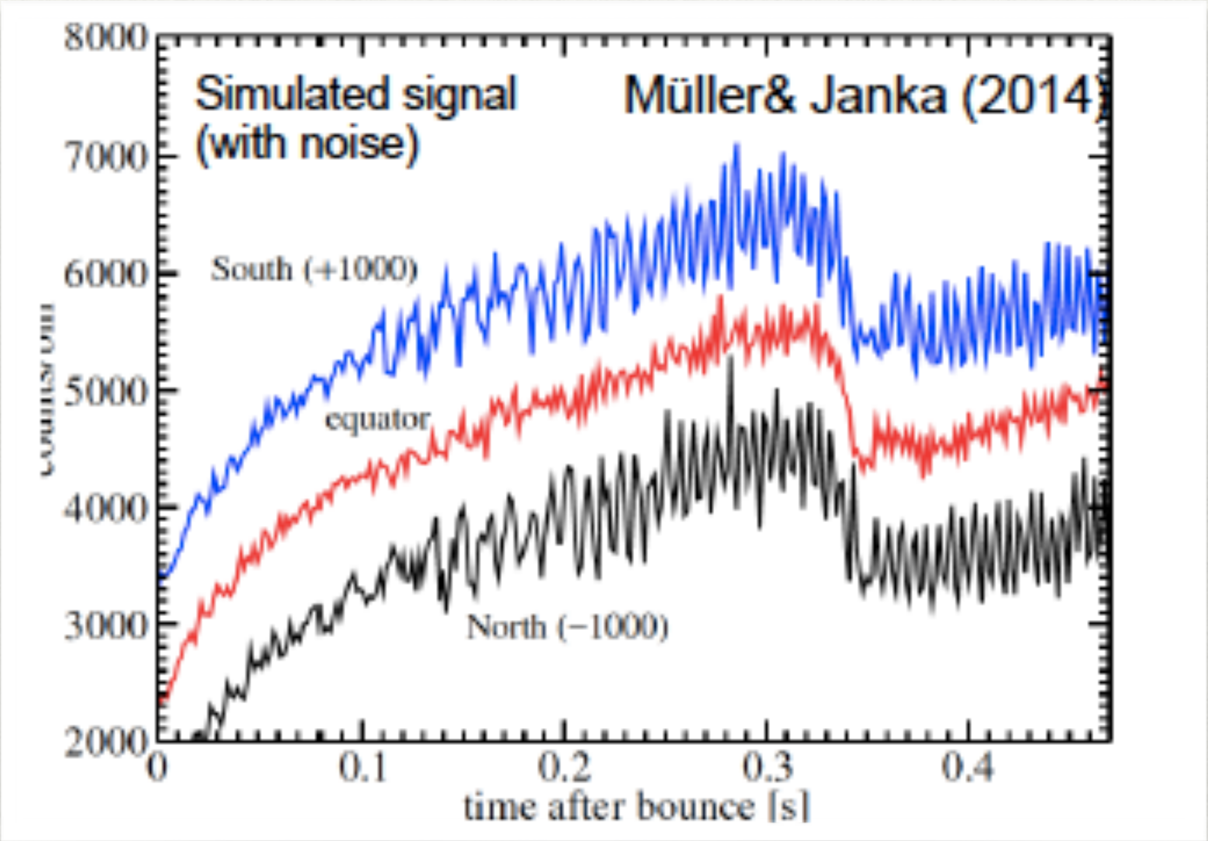
- Longstanding open question in astrophysics :
  How do massive stars explode ?

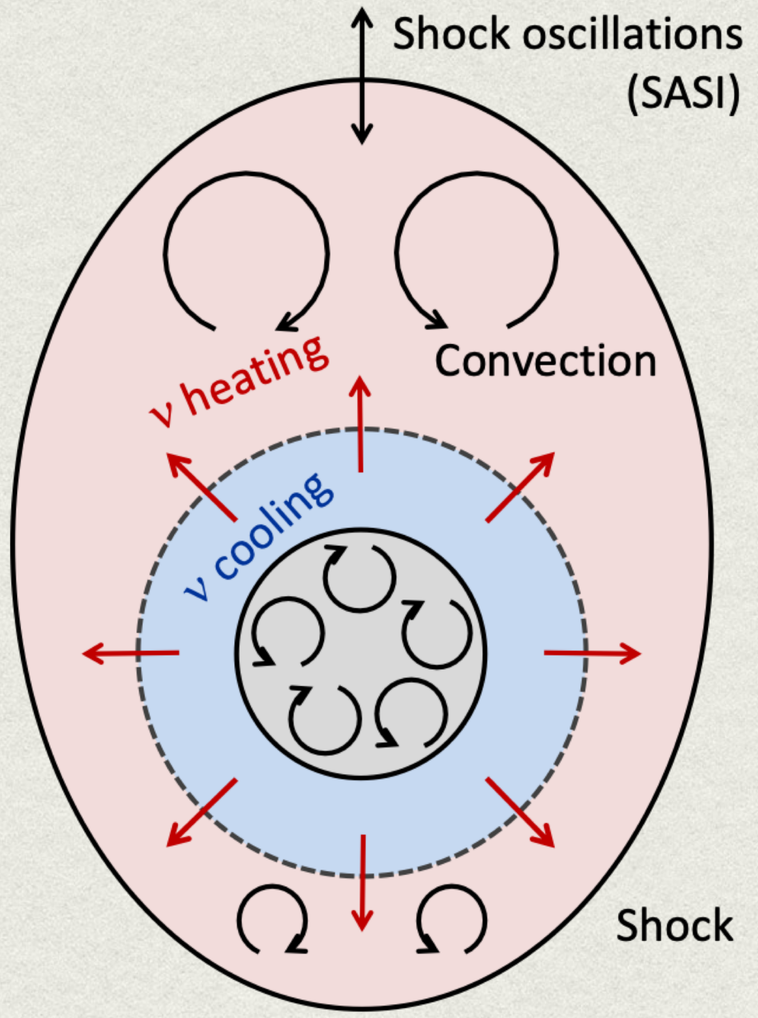
- Bayesian analysis of SN1987A time signal :
  « Prompt explosion » model refuted,
  « Neutrino delayed explosion » mechanism favored.

  Loredo, Lamb, PRD 2002

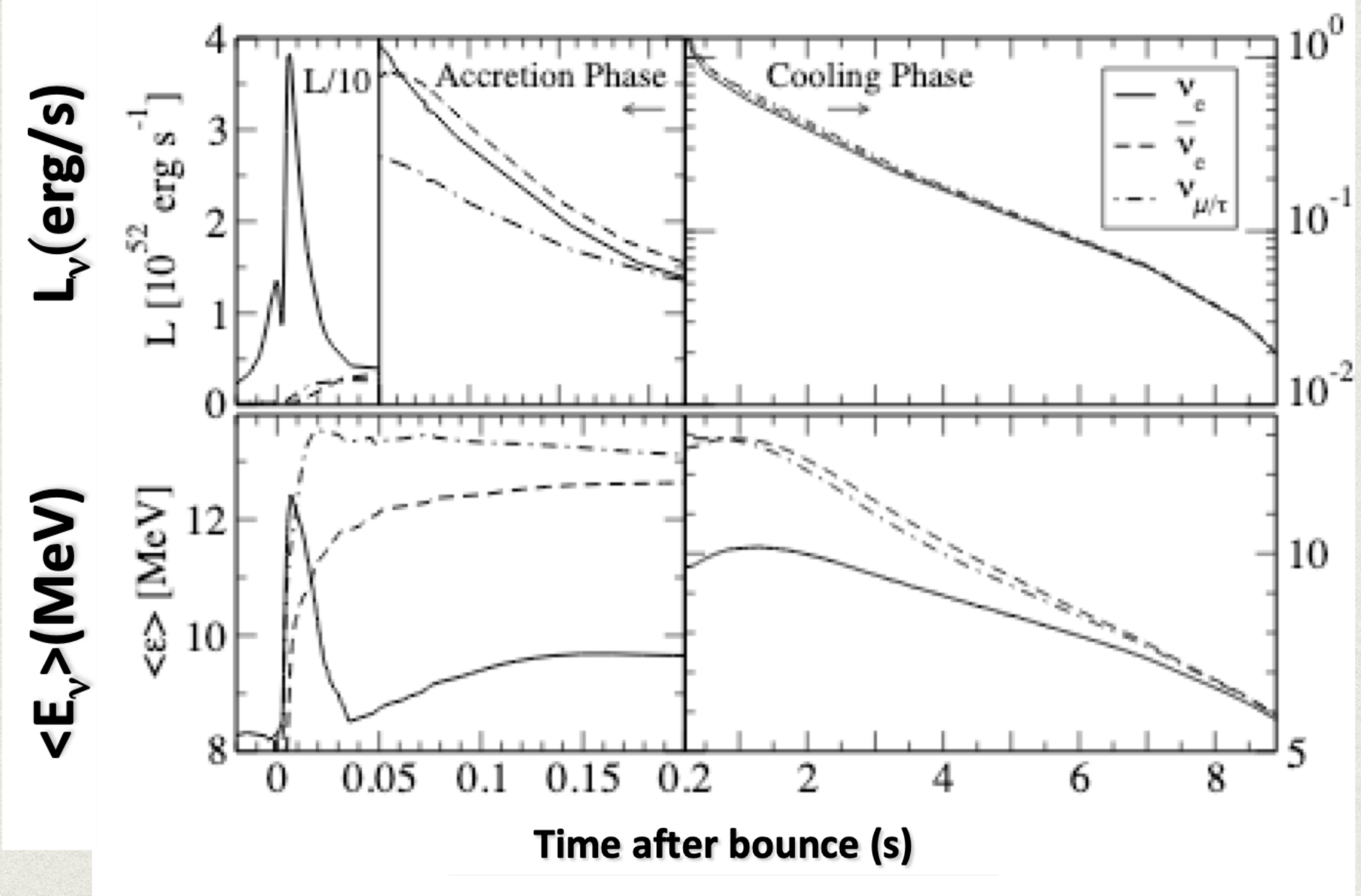
- 2D and 3D simulations include convection, turbulence, neutrino heating and hydro instabilities (SASI).

Janka 2017, Radice et al 2018, Bruenn et al, 2020, Takiwaki et al, 2021, Tamborra et al, Astrophys.J. 792 (2014) (LESA)



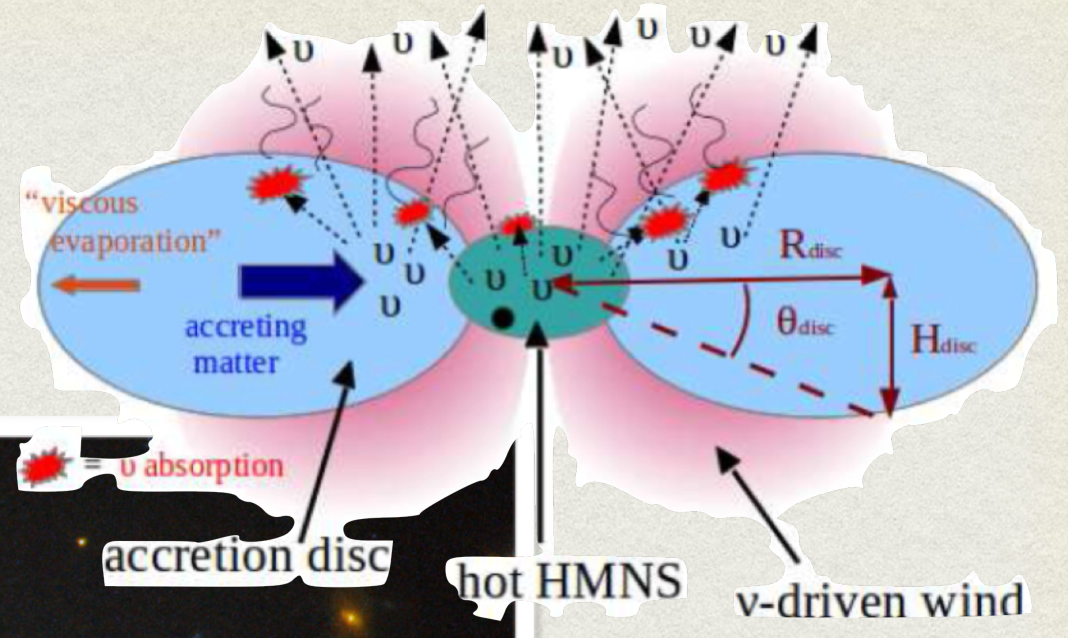


Neutronization Accretion Neutron star cooling



Characteristic imprint in neutrino signals

A UNIQUE EVENT : GW170817



- Binary neutron star mergers :
  powerful sources of tens of MeV neutrinos

- First measurement of gravitational waves, in coincidence with a short gamma ray burst and a kilonova.

  Abbot et al, PRL 2017

- Lanthanide free ejecta (blue component of the electromagnetic signal) and ejecta with lanthanides (red component).

  Vilar et al, 2017; Tanaka et al, 2017;
  Aprahamian et al, 2018;
  Nedora et al, 2021, ...

From the electromagnetic signal, indirect evidence for r-process elements in the ejecta

Hubble Space Telescope
Kilonova, gradually fading away, in NGC 4993,
40 Mpc, 140 million light-years

SN DYNAMICS, the r-process and NEUTRINOS

- 🟩 In matter (neutrino-driven winds), neutrinos interact with p/n

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

The **capture rates** are modified by spectral swappings due to flavor mechanisms and neutrino properties :

$$\frac{\lambda_{\nu_e n}}{\lambda_{\bar{\nu}_e p}} = \frac{<\sigma_{\nu_e n}>}{<\sigma_{\bar{\nu}_e p}>} \qquad <E_{\nu_e}> < <E_{\bar{\nu}_e}> < <E_{\nu_{\mu,\tau}}>$$

- 🟩 This determines the electron fraction Ye and the number of available neutrons (1- Ye). $Y_e = \frac{p}{p+n}$

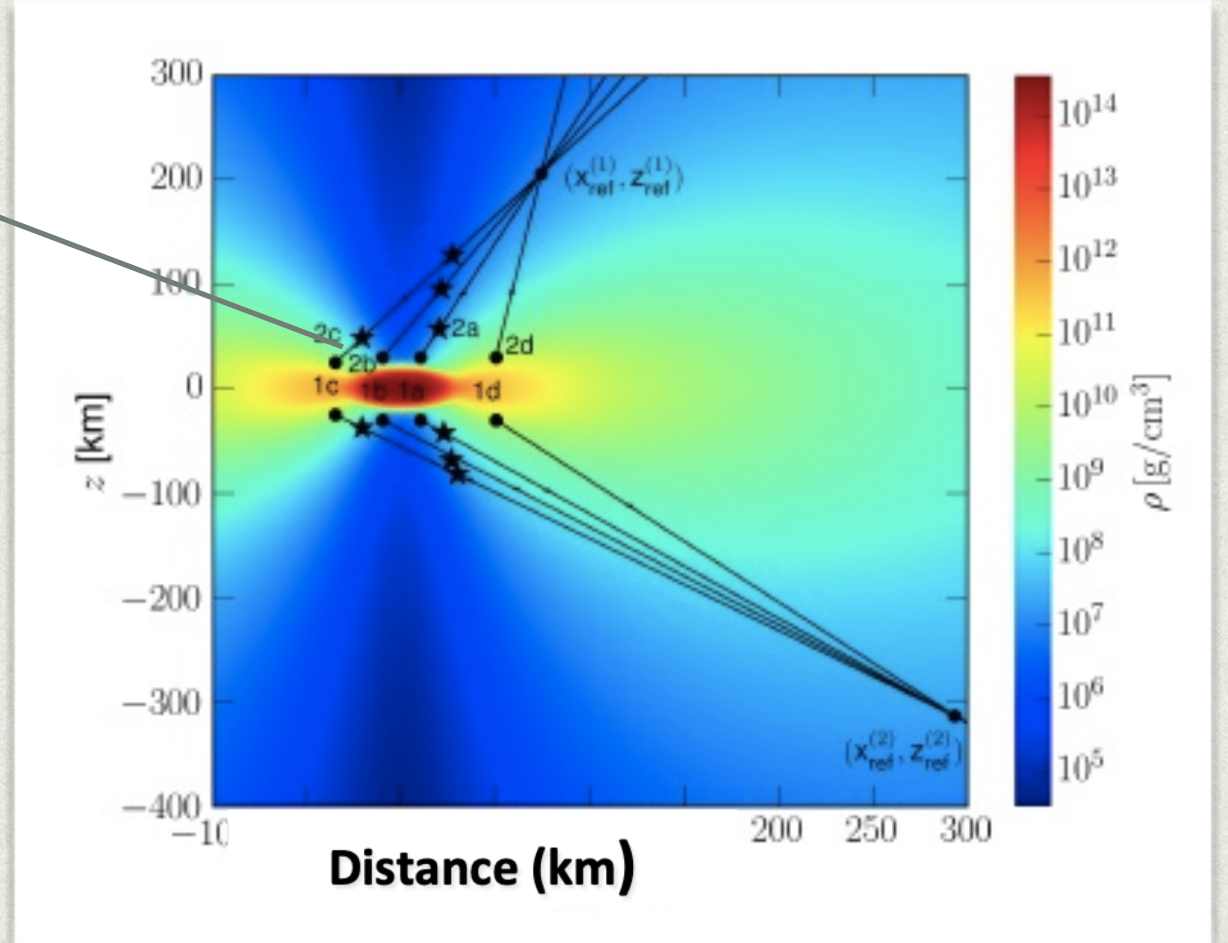
Key parameter for the r-process

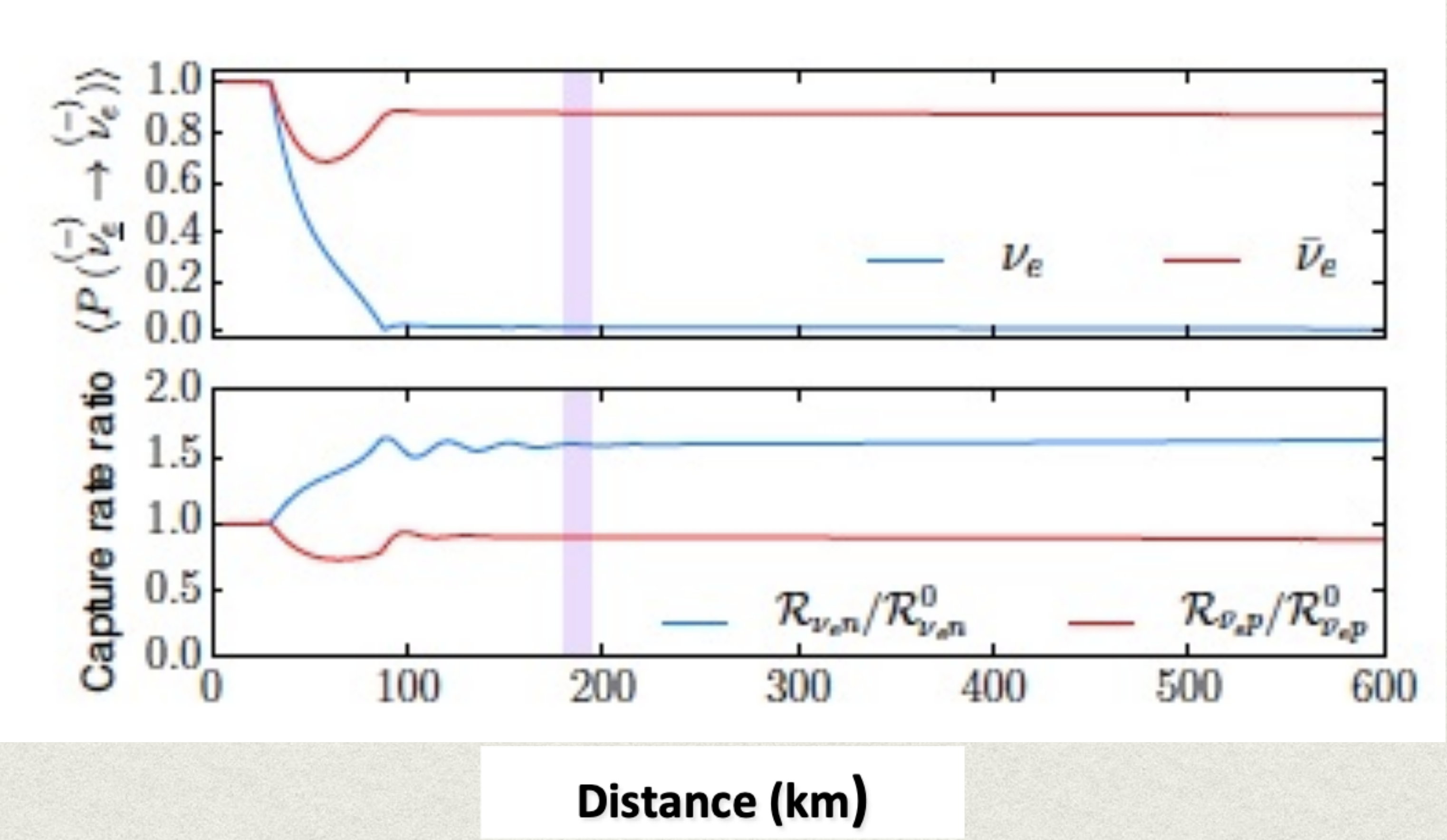
Ye > 0.5 no r-process, Ye < 0.2 strong r-process

- 🟩 Important for the SN dynamics :
Enhanced heating behind the shock.

Flavor evolution, neutrino properties impact the n/p ratio and neutrino heating

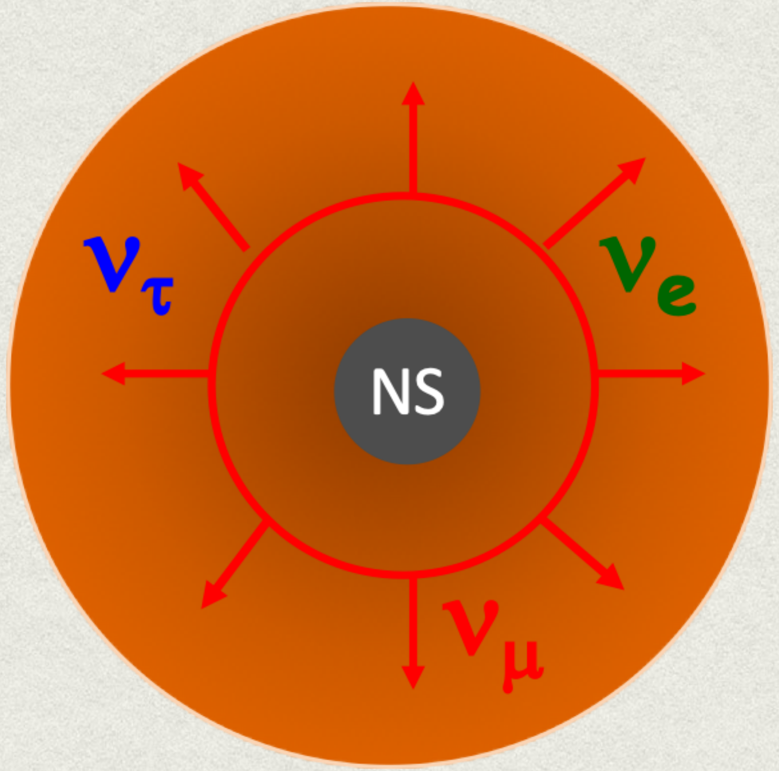
BNS remnant

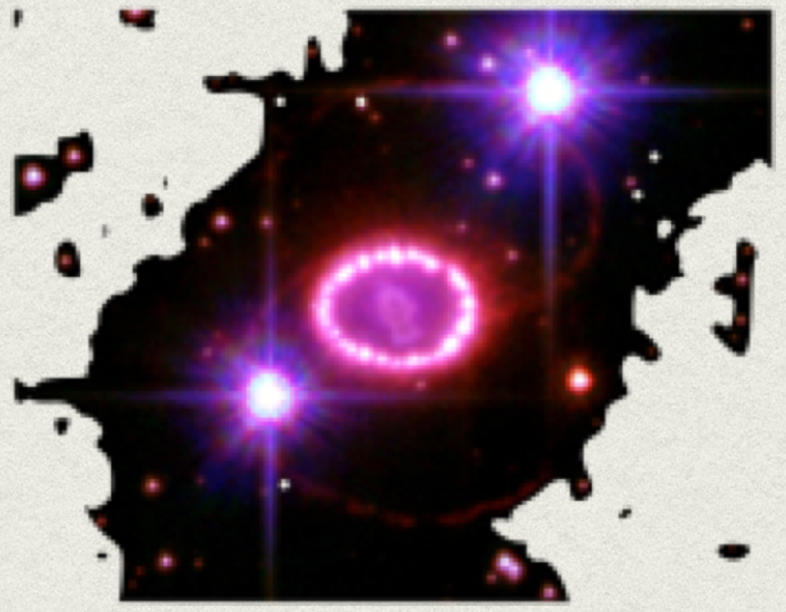




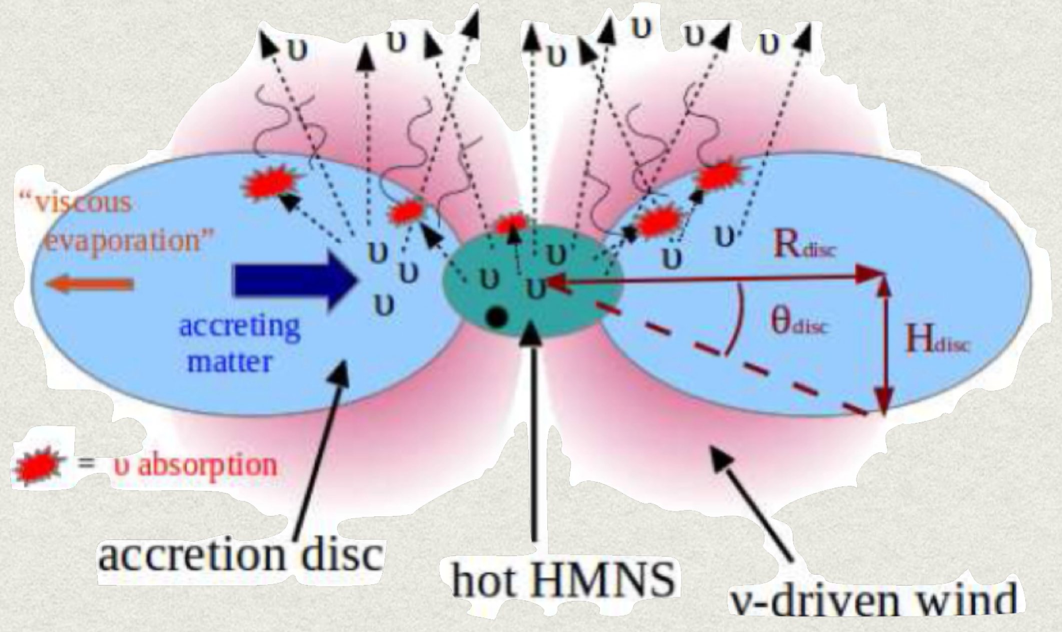
Frensel, Perego, Wu, Volpe PRD95 (2017)

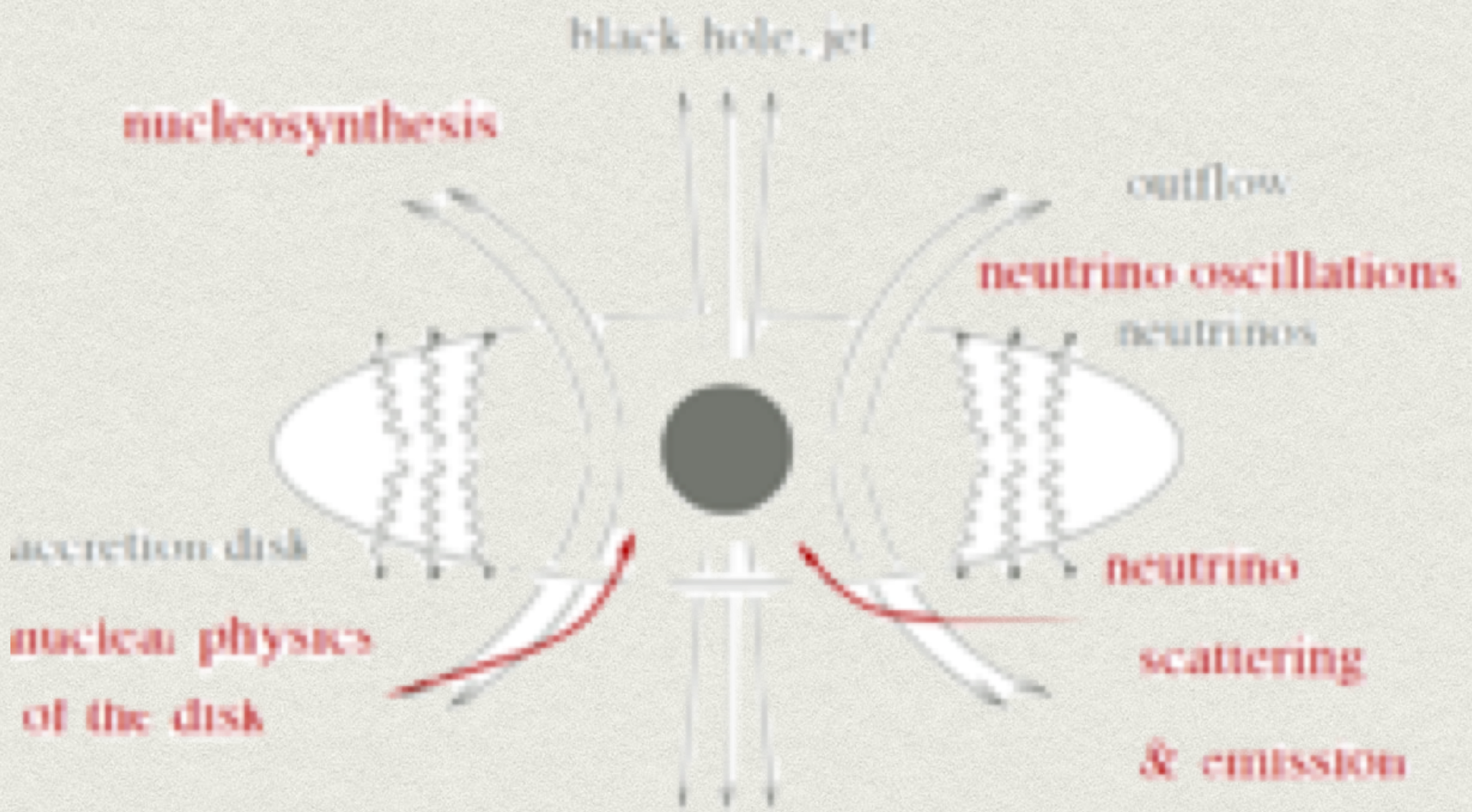
see works e.g. by Balantekin, Chatelain, Fuller, Kneller, Qian, Frensel, Yuksel, Malkus, Pastor, Raffelt, Surman, McLaughlin, Tamborra, Volpe, Wu, ...





NEUTRINO FLAVOR EVOLUTION IN DENSE MEDIA





NEUTRINO EVOLUTION EQUATIONS IN DENSE MEDIA

- Neutrinos propagating in a dense astrophysical environments :
  A weakly interacting many-body problem.

- $i\dot{\rho} = [h, \rho]$ $\quad \rho = \begin{pmatrix} \rho_{ee} & \rho_{e\mu} \\ \rho_{\mu e} & \rho_{\mu\mu} \end{pmatrix}$ Density matrix

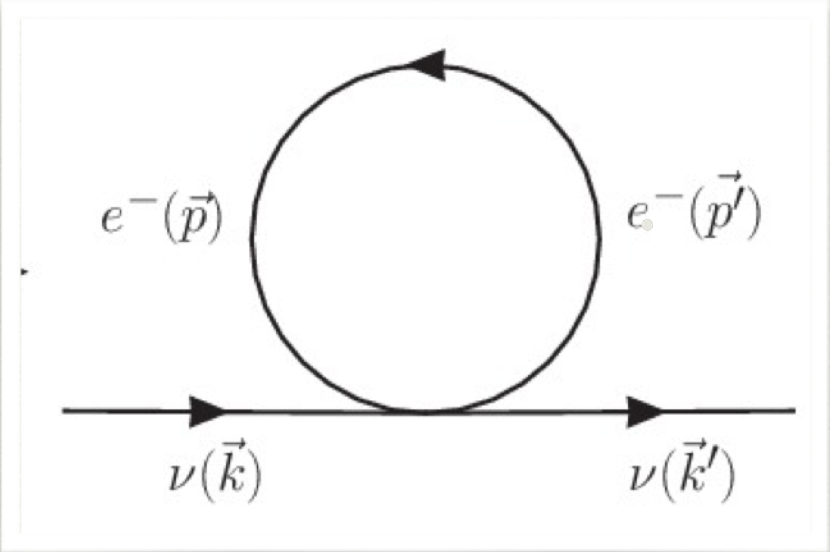
$$h = h_{vac} + h_{mat} + h_{\nu\nu} + h_{NSI}$$

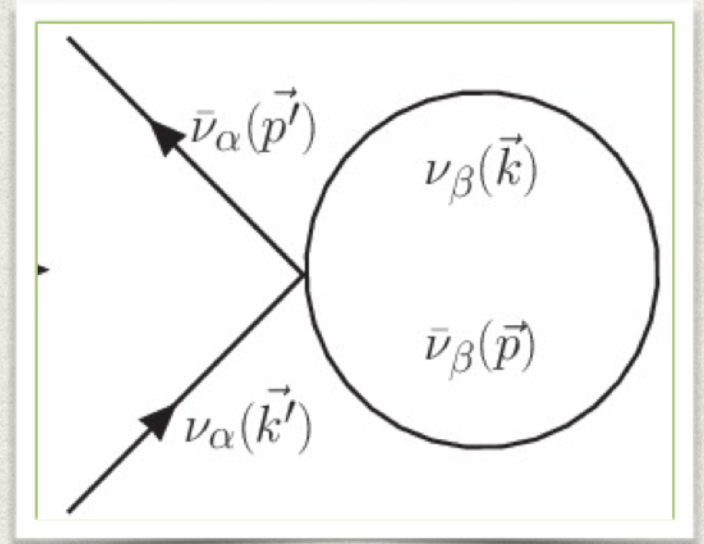
$$h_{vac} = \omega \begin{pmatrix} -c_{2\theta} & s_{2\theta} \\ s_{2\theta} & c_{2\theta} \end{pmatrix}$$

Mass term in the flavor basis : responsible for vacuum oscillations

$$h_{mat} = \sqrt{2} G_F \begin{pmatrix} N_e - \frac{N_n}{2} & 0 \\ 0 & -\frac{N_n}{2} \end{pmatrix}$$

Wolfenstein weak potential that produces MSW effect, together with the vacuum term

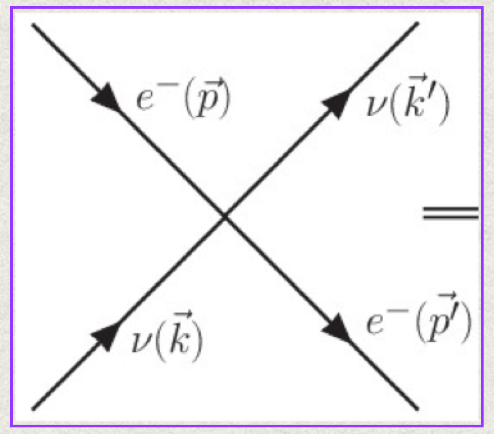




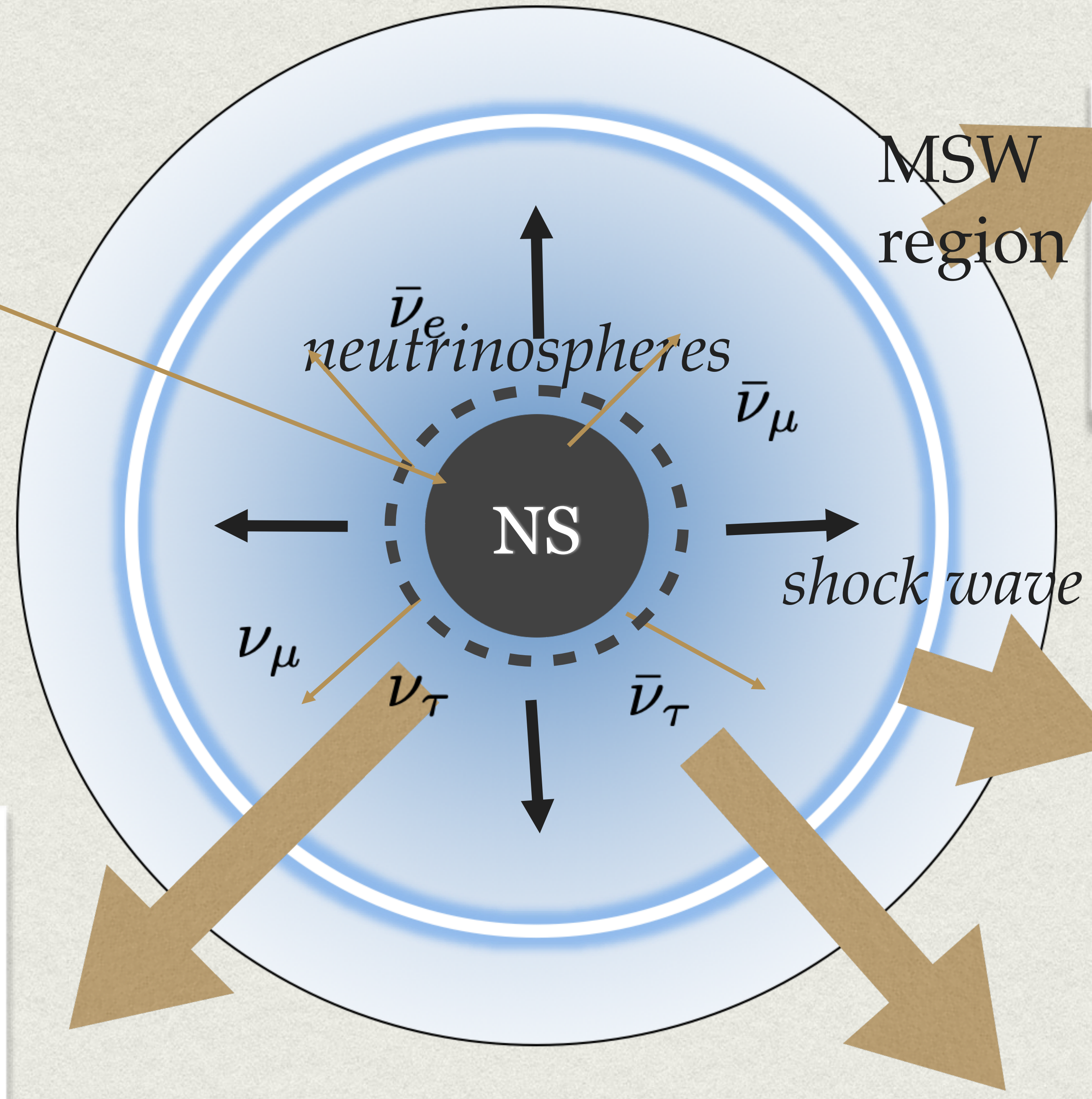
Neutrino-neutrino interactions

$$h_{\nu\nu} = \sqrt{2} G_F \sum_\alpha [\int (1 - \hat{q} \cdot \hat{p}) \times [\mathrm{d}n_{\nu_{\underline{\alpha}}} \rho_{\nu_{\underline{\alpha}}}(\vec{p}) - \mathrm{d}n_{\bar{\nu}_{\underline{\alpha}}} \bar{\rho}_{\bar{\nu}_{\underline{\alpha}}}(\vec{p})]],$$

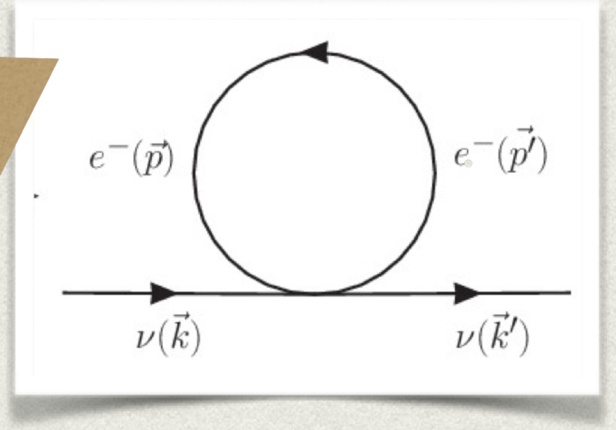
FLAVOR CONVERSION IN SUPERNOVAE



collisions dominated
Boltzmann approximation



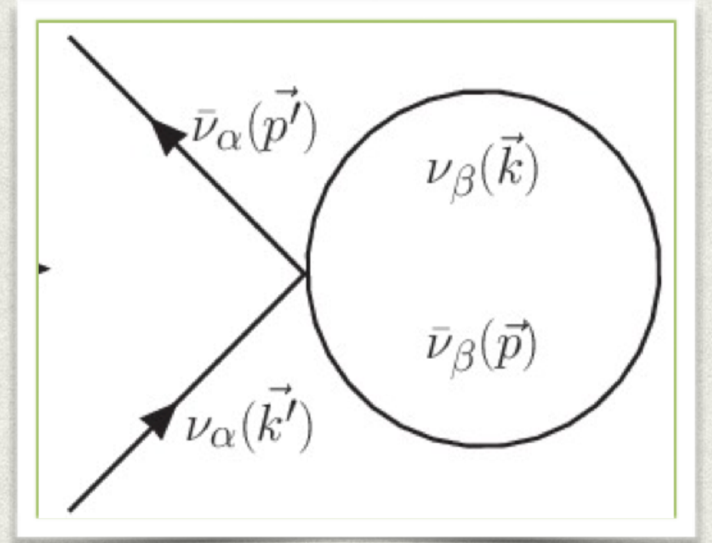
MSW effect



flavor conversion
mean-field approximation

Shock wave effects
Schirato and Fuller, hep-ph/0205390

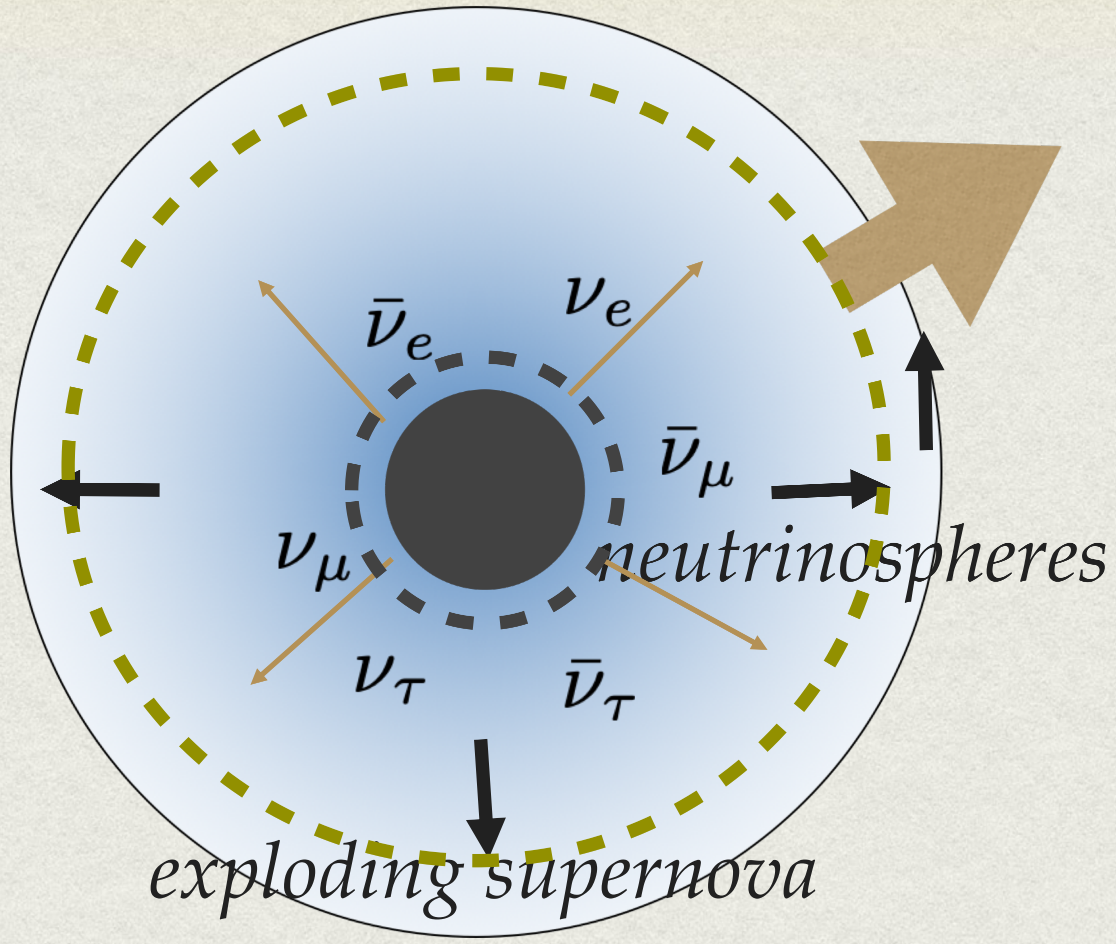
Turbulence effects
Loreti et al, PRD 52 (1995)



Neutrino-neutrino interactions
Pantaleone, PLB287 (1992)

See the reviews Duan, Fuller, Qian, Ann. Rev. 60 (2010), Volpe, Int. Journ. Of Modern Phys. E 24 (2015) Mirizzi et al, Rev. Nuovo Cimento 39 (2016), Tamborra and Shalgar (2020), Duan and Kneller, J. Phys. G36 (2009), Horiuchi and Kneller J. Phys. G 45 (2018), Volpe, in preparation.

MSW EFFECT IN SUPERNOVAE



- Main resonances :
  High (H) $(\theta_{13}, \Delta m^2_{13})$
  Low (L) $(\theta_{12}, \Delta m^2_{12})$
- Modifies supernova neutrino spectra (spectral swapping) and the time signal

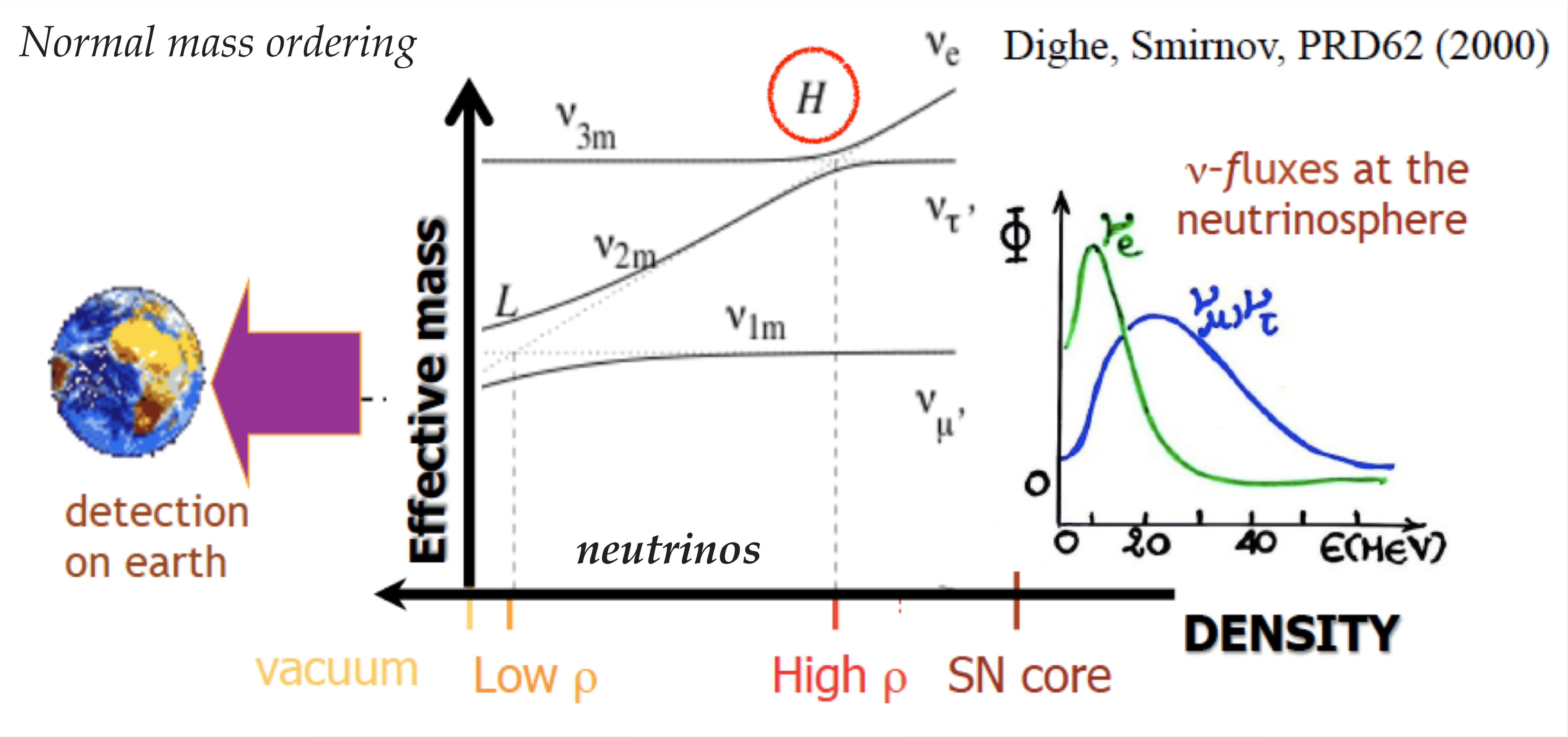
$$\phi_{\bar{\nu}_e} = p\phi^0_{\bar{\nu}_e} + (1-p)\phi^0_{\bar{\nu}_x}$$

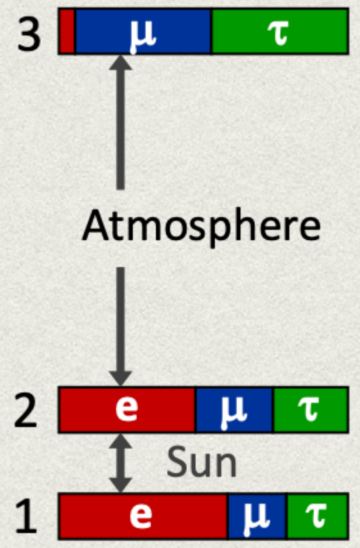
$$p = 0.68 \quad NMO \qquad p = 0 \quad IMO$$

Evolution at the H-resonance depends on the sign of Δm^2_{13}

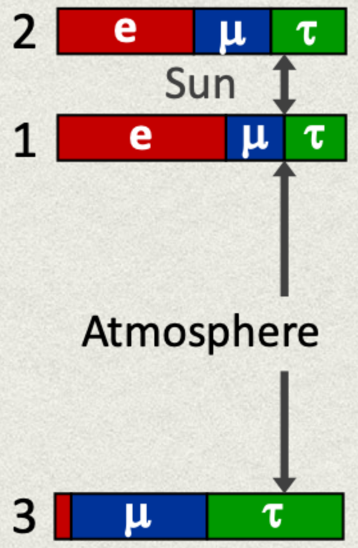
Normal mass ordering

Dighe, Smirnov, PRD62 (2000)



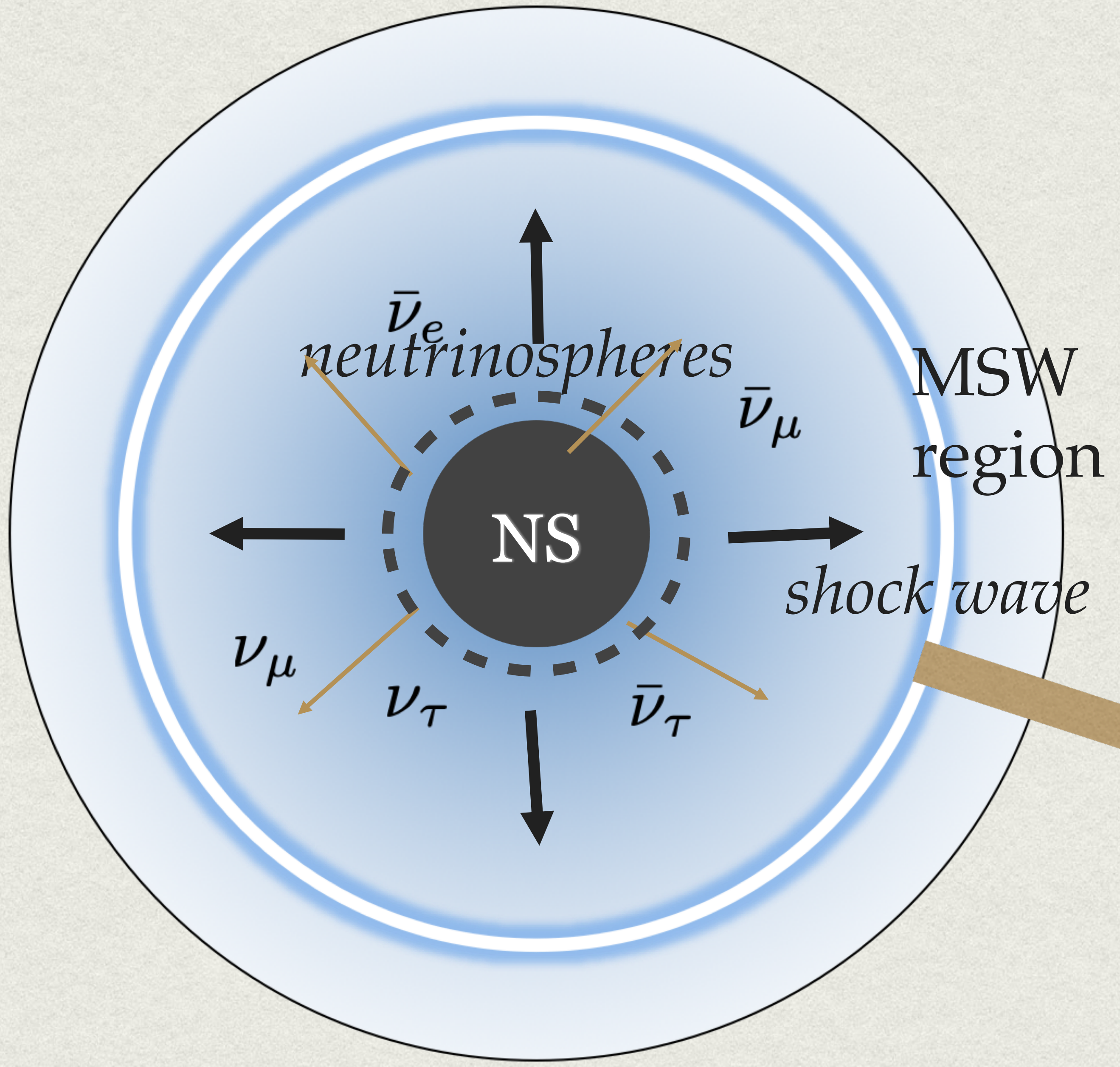


Normal mass ordering

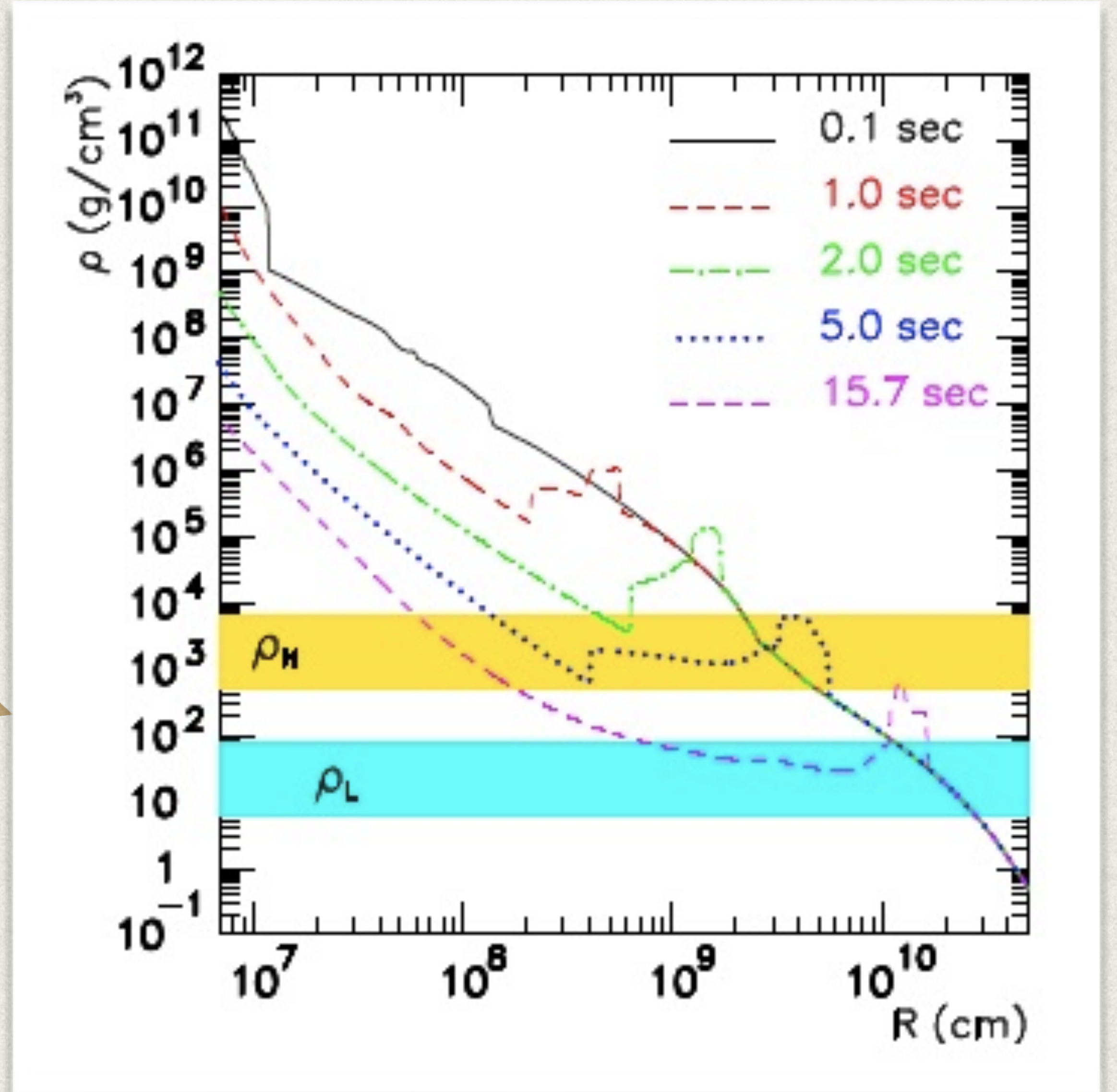


Inverted mass ordering

SHOCK WAVE EFFECTS



Presence of front and reverse shocks



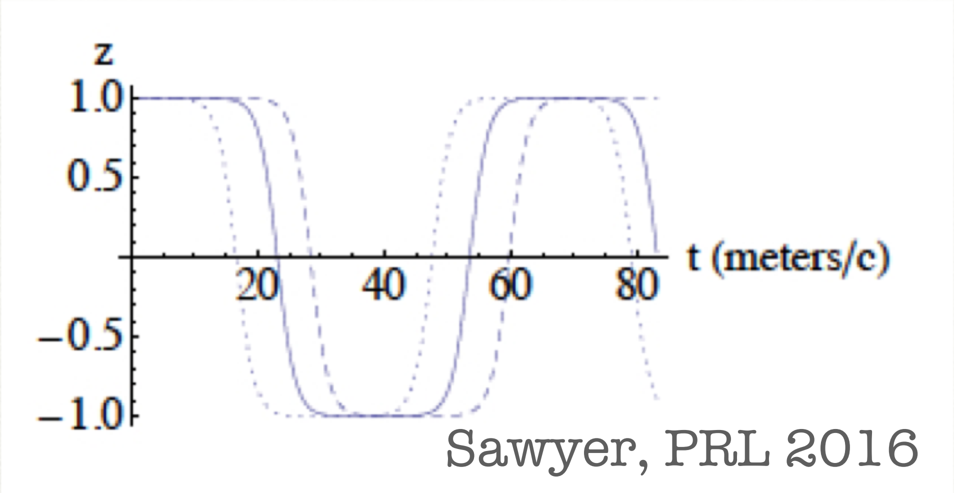
Tomas et al, JCAP 09 (2004)

MSW resonance can be met multiple times

Takahashi et al 2003, Fogli et al 2003, Kneller et al 2005,
Fogli et al 2005, Dasgupta and Dighe, PRD75 (2007),
Duan and Kneller, 2009, Gava et al 2009,
Ekinci et al 2021, ...

NEUTRINO-NEUTRINO INTERACTIONS : « fast » modes

- Very short scale flavor conversion modes, occurring when electron neutrino and antineutrino angular distributions cross each other.



Sawyer, PRL 2016

Triggered a lot of interest since they can occur behind the shock in a supernova and contribute to the explosion dynamics

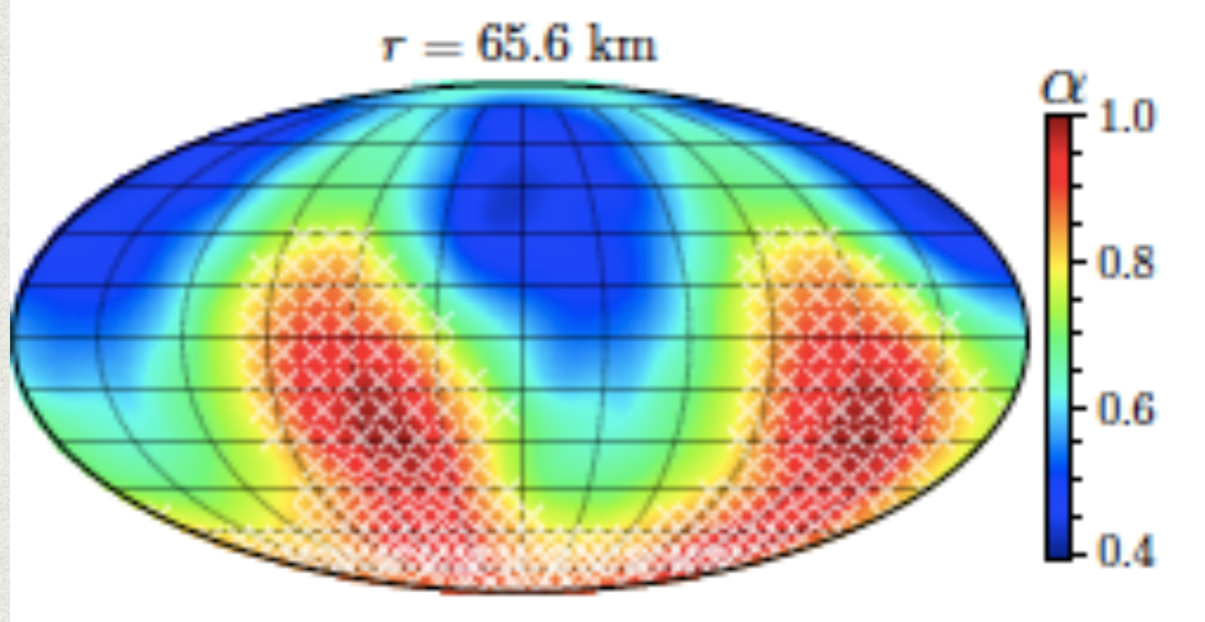
see Mirizzi, Raffelt, Chakraborty, Shalgar, Tamborra, Capozzi, ...

- Fast modes do not appear to produce flavor equilibration of the neutrino spectra (*schematic two beam model*).

Abbar and Volpe, PLB 790, 2019

- First evidence for the occurrence of « fast » neutrino flavor conversion, in 3-dimensional supernova simulations (also in the protoneutron star).

Mollweide projection for the nue-to-antinue flux ratio, t= 200 ms snapshot, 11.2 M_{sun} progenitor



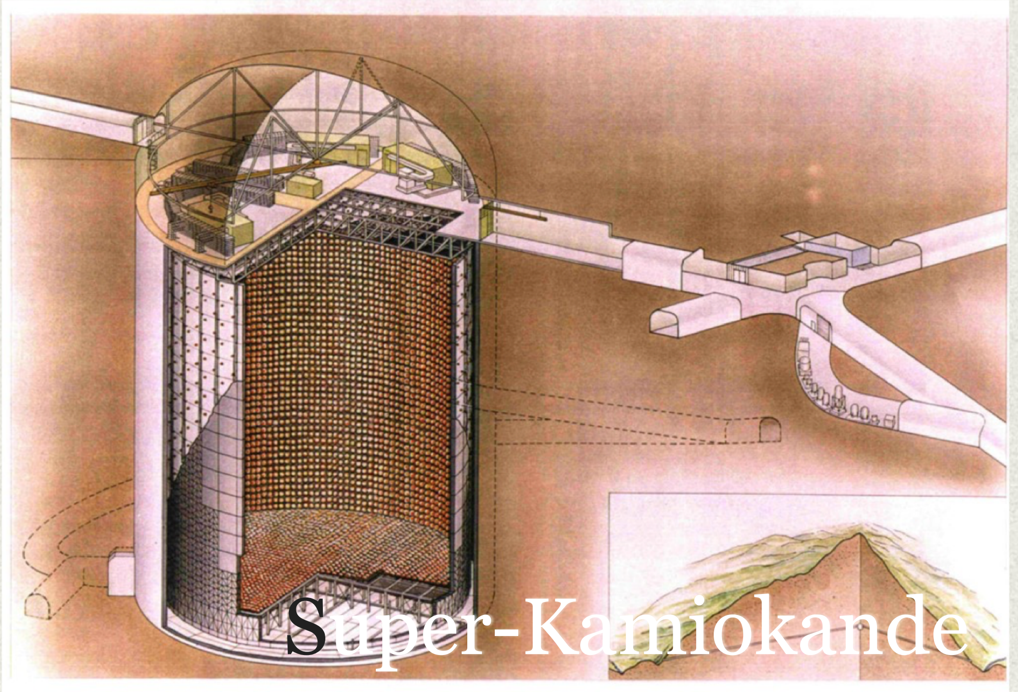
Crosses indicate fast modes

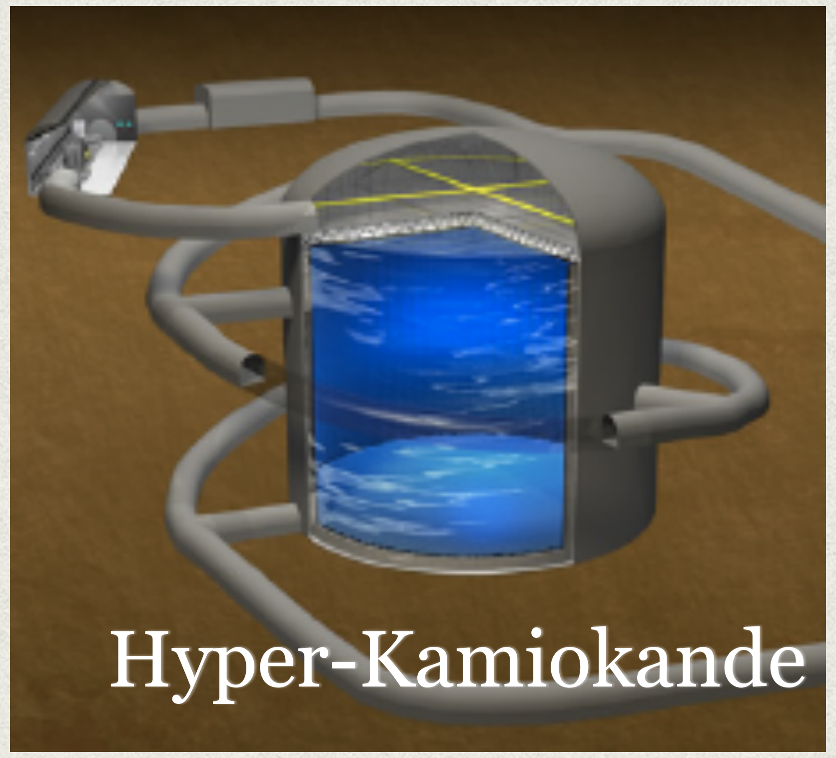
Impact on the neutrino spectra small (*already similar*).

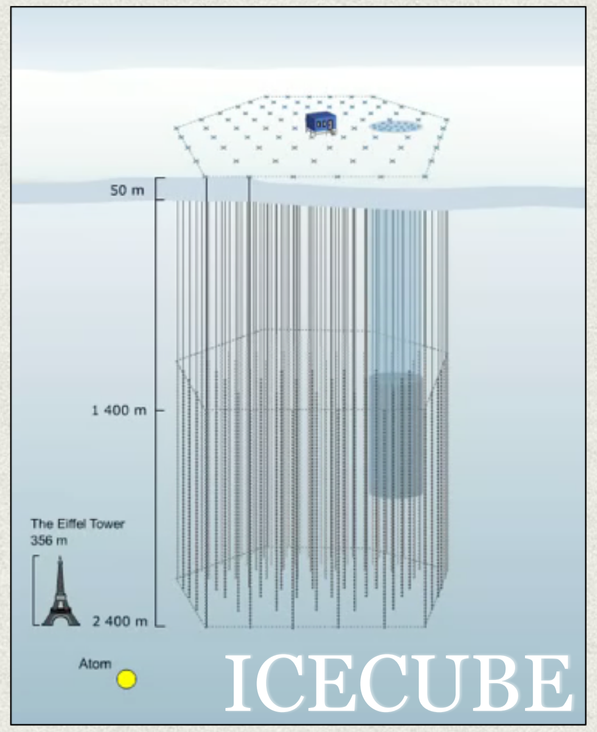
Abbar, Duan, Sumiyoshi, Takiwaki, Volpe, PRD 100, 2019; PRD 101, 2020

Evidence for the occurrence of fast modes
in different supernova simulations by several groups

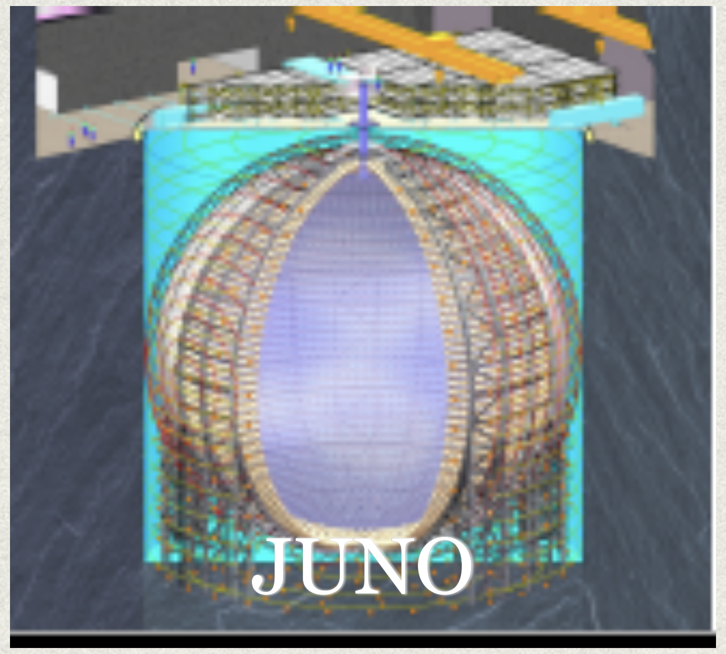
In a fully consistent description ?

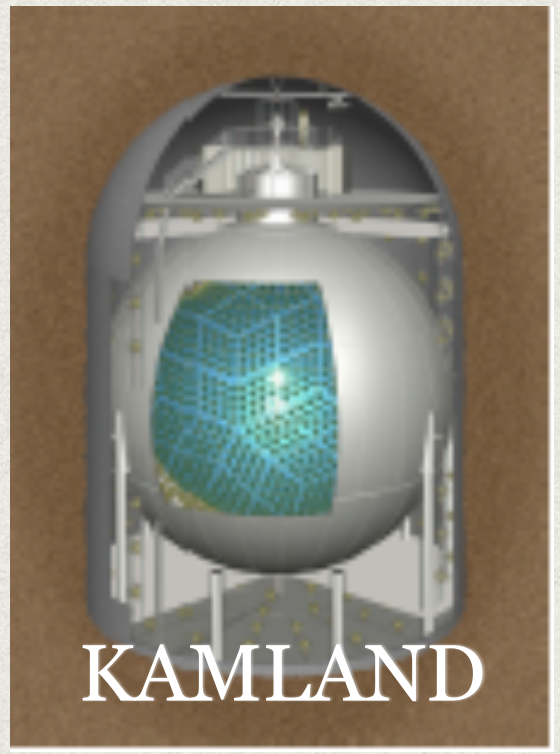


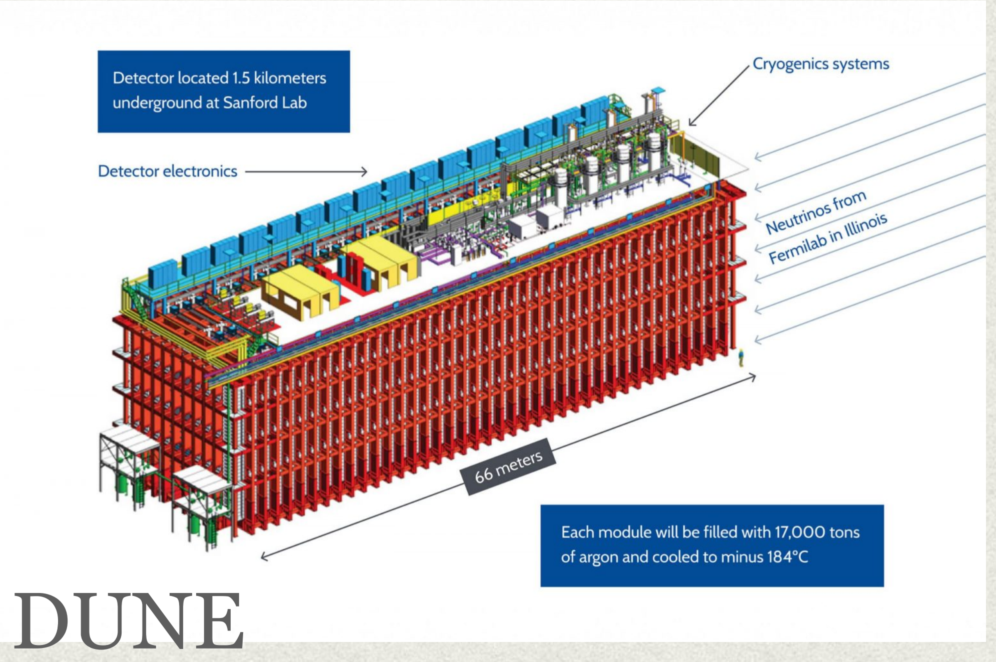




NEUTRINO PROPERTIES and FUTURE OBSERVATIONS







FROM NEXT SUPERNOVA

- Sentivity to all flavors, time and energy signal through scattering on protons, electrons, nuclei.

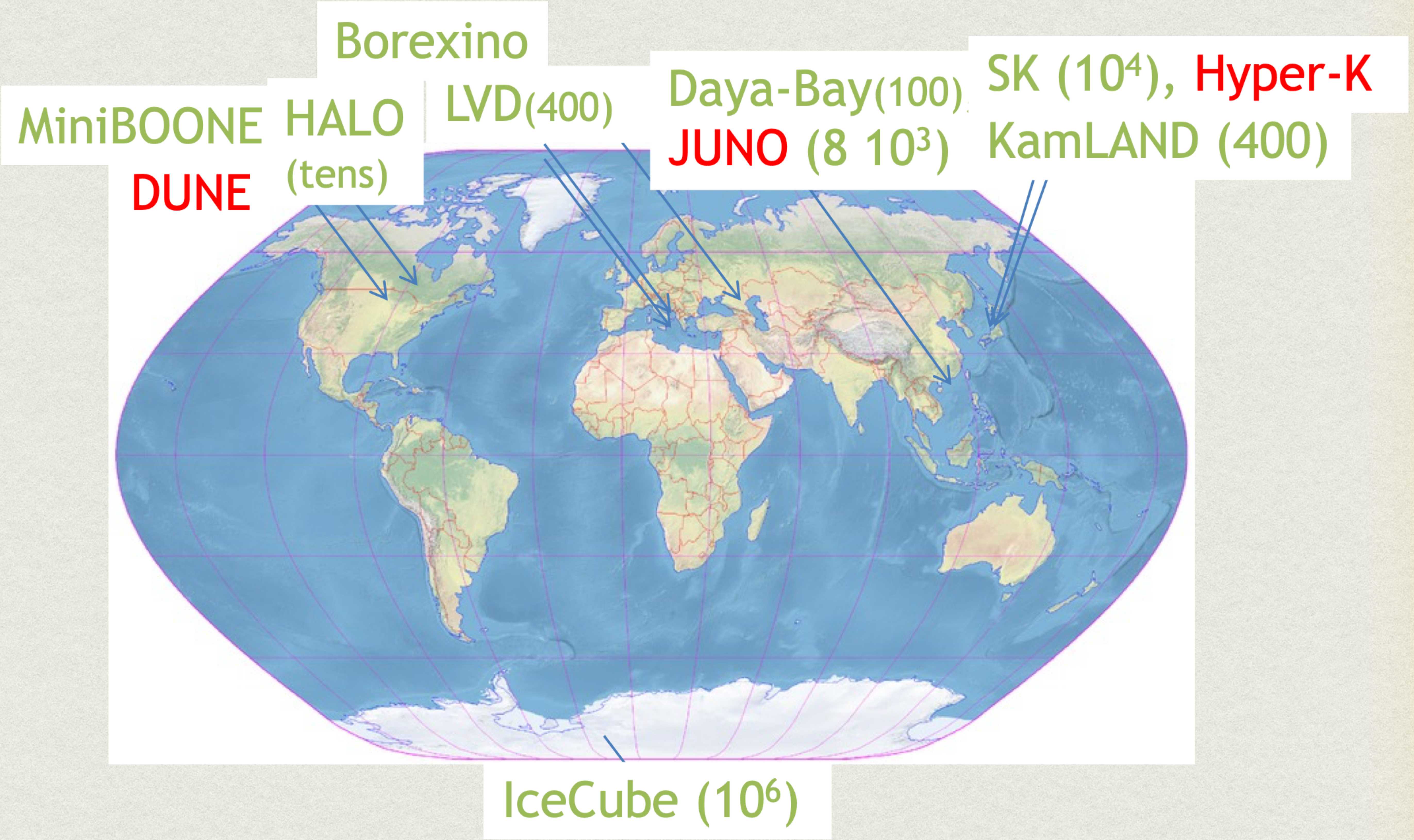
Sensitivity to electron neutrinos from neutrino-nucleus inelastic scattering

- SN localization, cooling, M-R (compactness) of the neutron star, explosion mechanism; neutrino magnetic moment, mass ordering, non-standard interactions, …

CP violation, Balantekin, Gava, Volpe, PLB B662 (2008)

Scholberg, Supernova Early Warning System (SNEWS), 1999; SNEWS 2.0, 2021

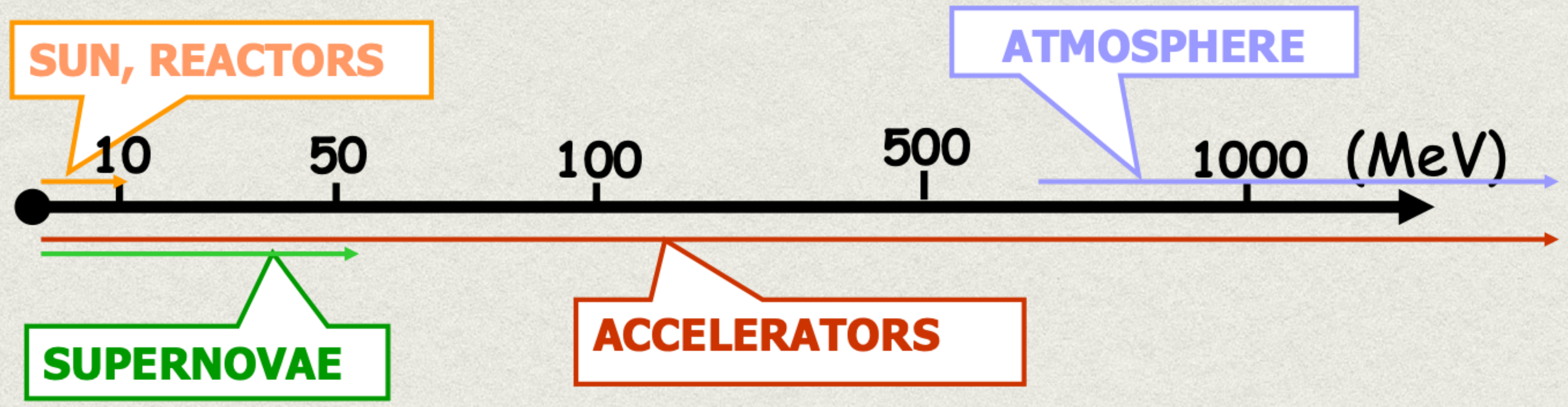
Expected events for a supernova in our galaxy (10 kpc)



Crucial information on non-standard neutrino properties, particles, interactions, on explosion dynamics, star location and properties

Low energy NEUTRINO-NUCLEUS INTERACTIONS

- From the nuclear…. to the nucleon degrees of freedom



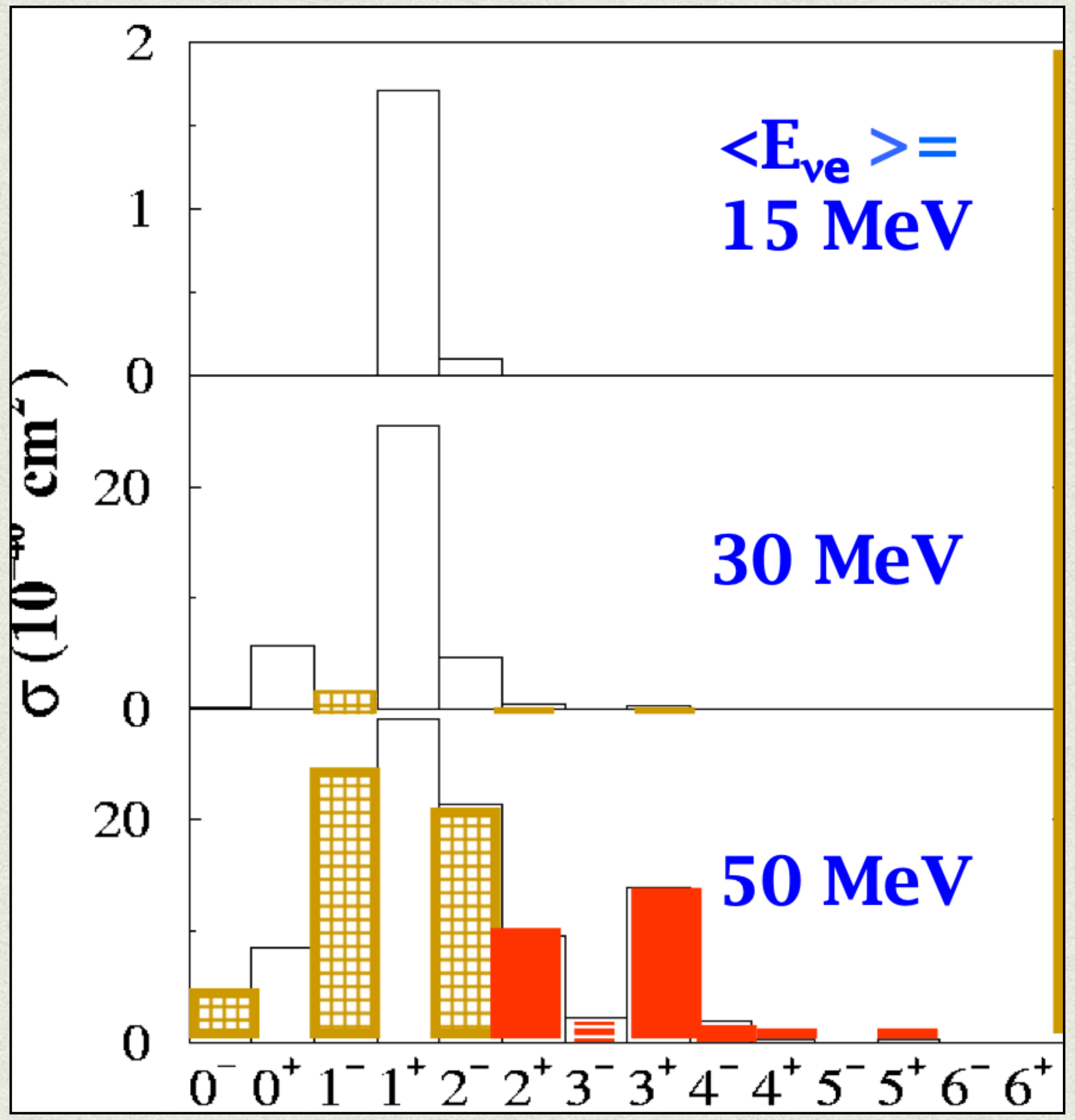
SUN, REACTORS

ATMOSPHERE

10 50 100 500 1000 (MeV)

SUPERNOVAE

ACCELERATORS

- 

$\nu_e + {}^{208}\text{Pb} \rightarrow {}^{208}\text{Bi} + e^-$

For increasing energy collective nuclear modes and forbidden transitions become important.

- Neutrino-nucleus CC cross sections : D, ^{12}C, ^{16}O, ^{40}Ar, ^{56}Fe, ^{208}Pb

  Event rate predictions rely on theoretical calculations for most of the nuclei. There are significant variations.

- Measurements at SNS by COHERENT Coll. with muon decay-at-rest ν
  - D, Ar, Ge, I, Pb

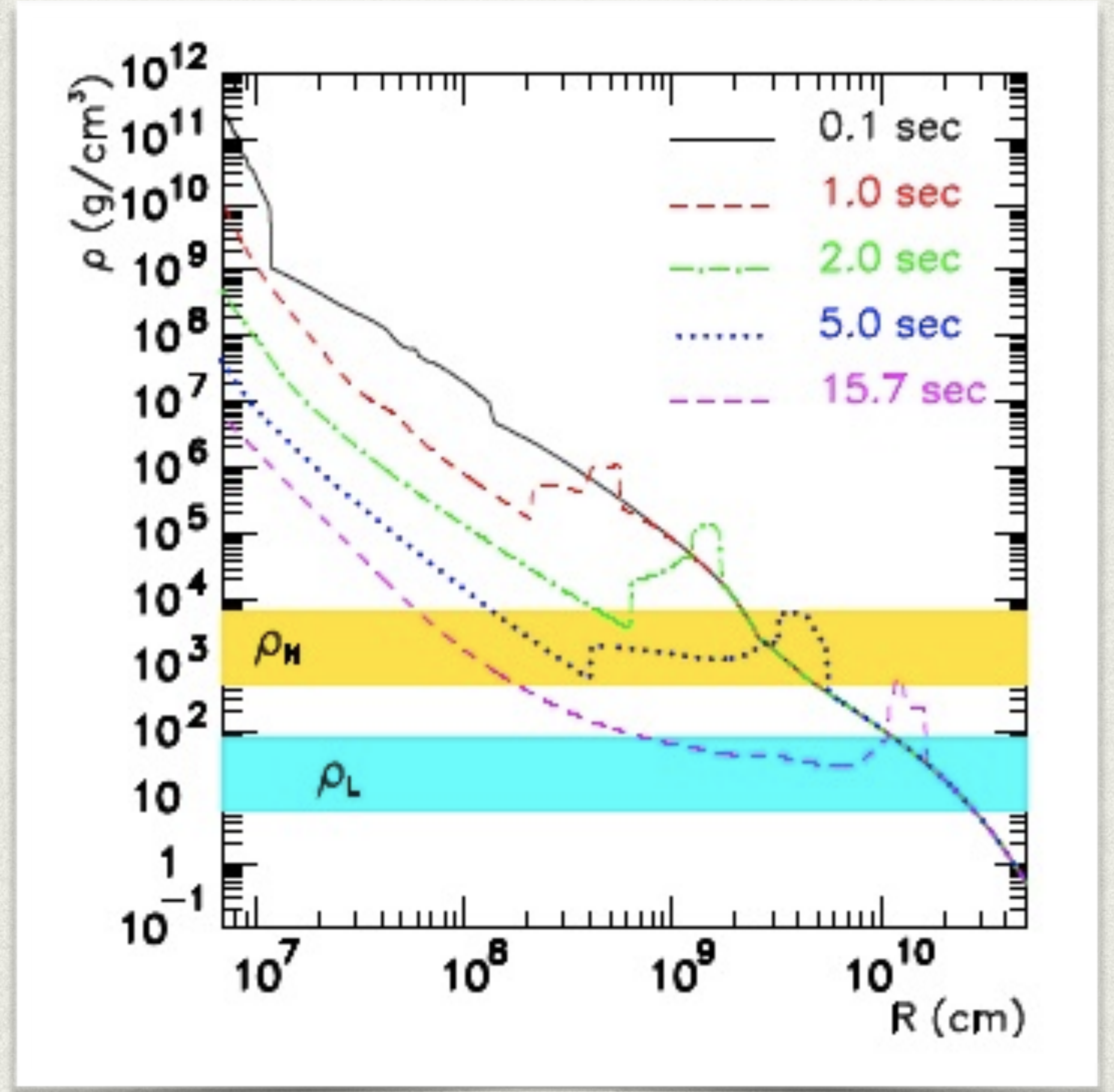
K. Scholberg

Neutrino-nucleus cross sections measurements are also of interest for neutrino-less double beta decay.

C. Volpe, J.Phys.G 31 (2005), hep-ph/0501233

NEUTRINO MASS ORDERING

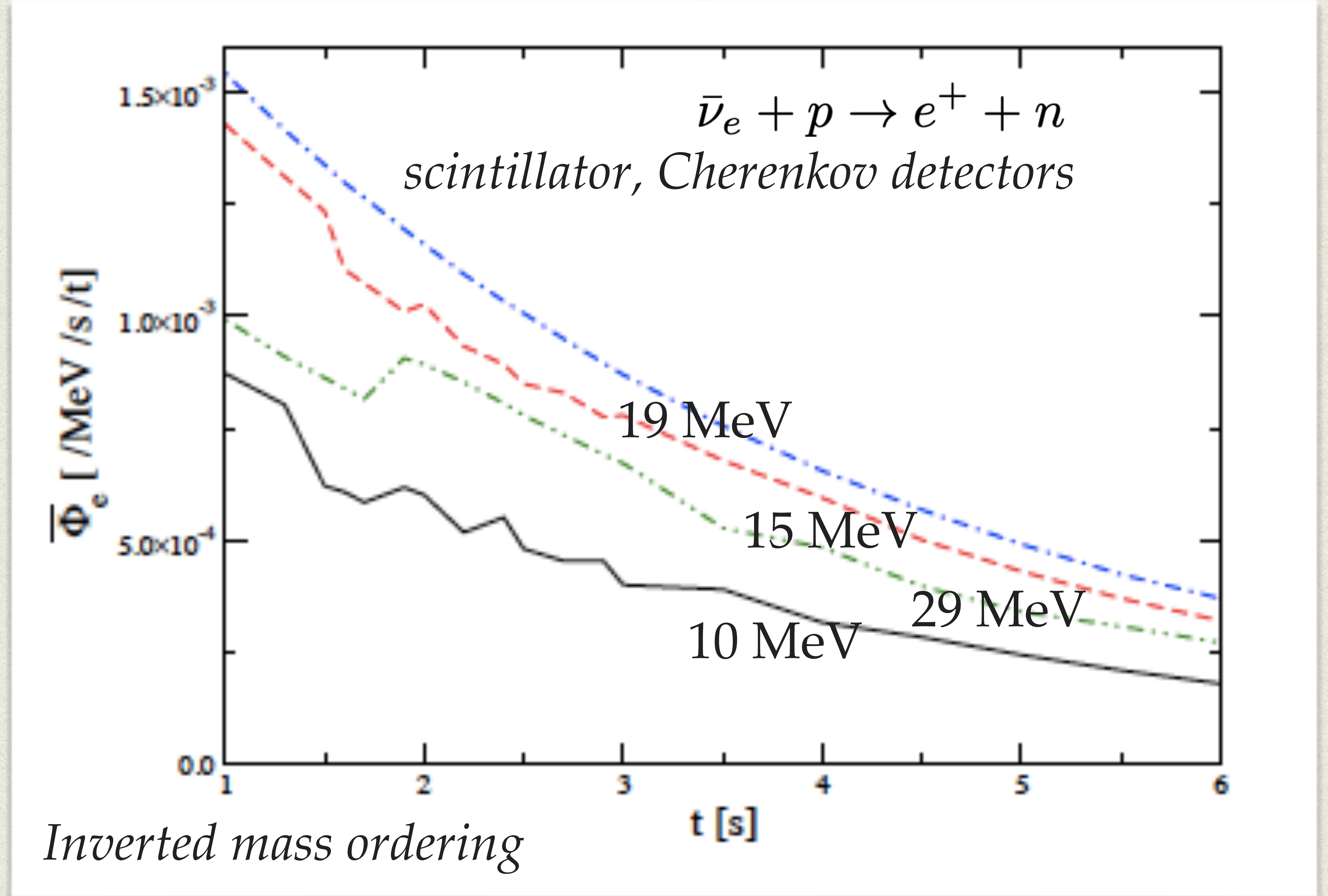
- Presence of front and reverse shocks .



Tomas et al, JCAP 09 (2004)

MSW resonance can be met multiple times.

- *Time signal in Cherenkov and scintillator detectors of a supernova in our galaxy (10 kpc)*

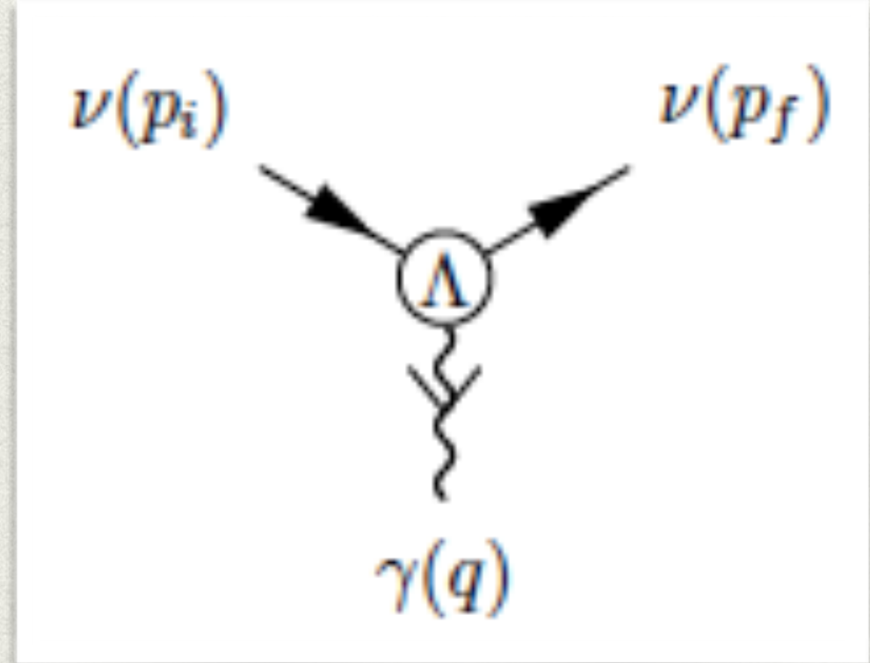


Gava, Kneller, Volpe, McLaughlin, PRL 103 (2009)

Positron time signal from $\bar{\nu}_e$ per unit tonne.
Prediction includes $\nu\nu$ interactions and shock wave effects.

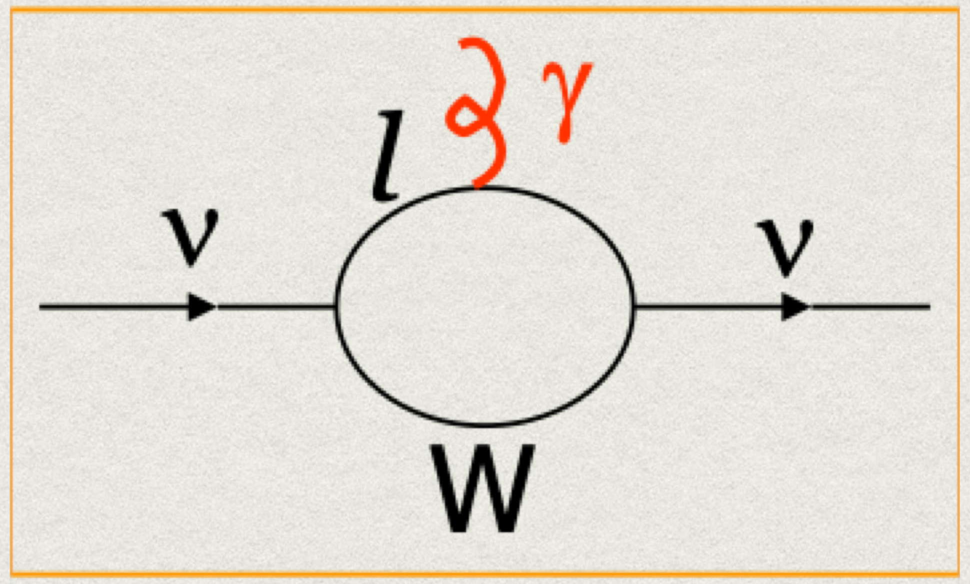
Picture of the supernova explosion from the shock wave passage in the MSW region.
Similar result for electron neutrinos in argon-based detectors (DUNE) for NMO.

Non-standard neutrino properties



Effective one-photon coupling of a neutrino with a photon

$$\mathcal{L}_{eff} = \bar{\psi} O_\lambda \psi A^\lambda$$



Neutrino magnetic moment from quantum loops

$\mu_\nu = 3.2 \times 10^{-19} (m_\nu/1\ \mathrm{eV})\ \mu_B$

- Neutrinos have electromagnetic properties from effective one-photon couplings.

- The most general vertex form, consistent with Lorentz invariance includes

$\Gamma_\lambda(p_i, p_f) = D_M(q^2)\sigma_{\lambda\rho}q^\rho$ Magnetic form factor

- Limits on the electron neutrino magnetic moment

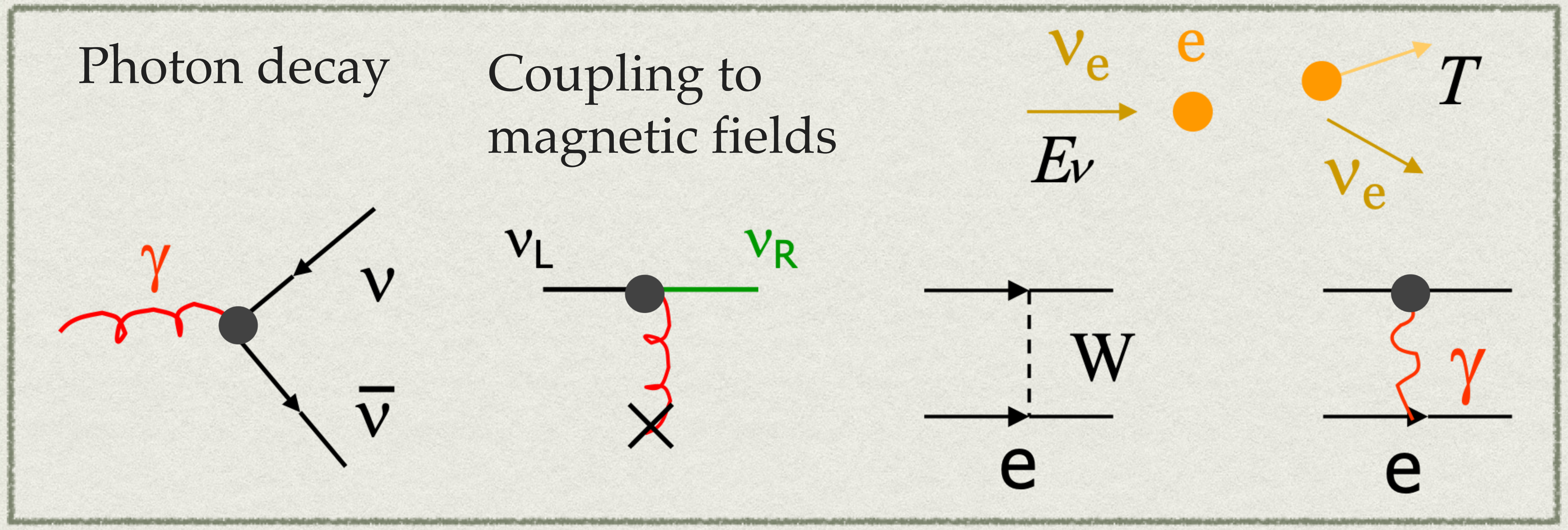
$1.1 \times 10^{-9}\mu_B$ to $2.9 \times 10^{-11}\mu_B$ reactor, accelerator experiments

$\mu_\nu < 1.5\text{-}5 \times 10^{-12}\ \mu_B$ SN1987A

Lattimer and Cooperstein (1988), Goldman et al. (1988), Notzold (1988),...

$\mu_\nu < 1 - 3 \times 10^{-12}\mu_B$ (95% $C.L.$) stellar cooling

See the review Giunti and Studenikin, RMP 87 (2015)


Photon decay

Coupling to magnetic fields

NON-STANDARD INTERACTIONS in SNe and BNS

- Current limits on NSI from solar, oscillations and as coherent neutrino-nucleus scattering.

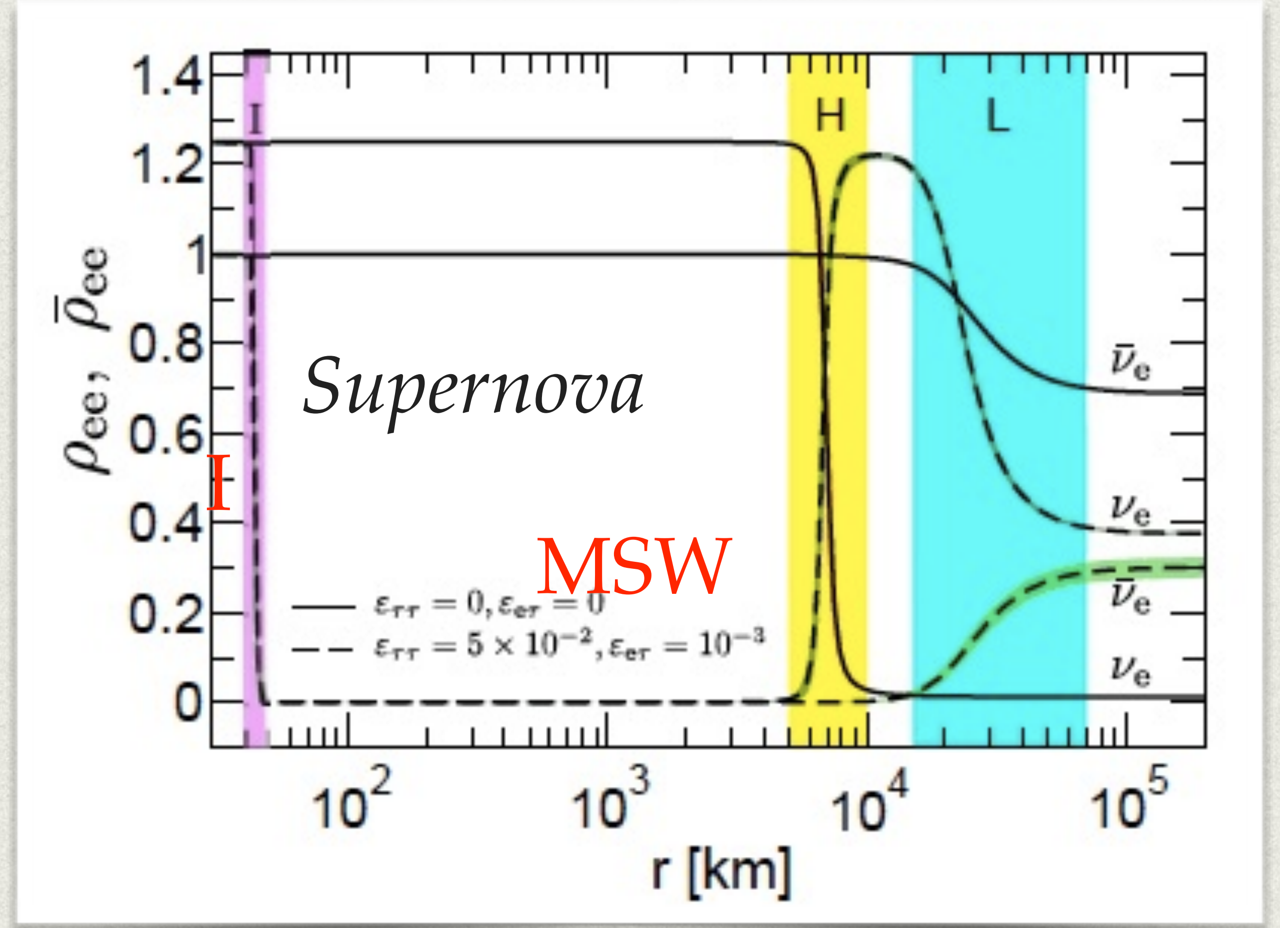
  see e.g. Biggio et al 2009, Ohlsson, 2013, Davidson et al 2013, Farzan and Tortola 2018, Bhupal-Dev et al 2019, Giunti 2020,
  Barbeau, Efremenko, Scholberg, 2111.07033, Coherent coll….

- NSI impact studied in core-collapse supernovae and BNS.

  see e.g. Fogli et al, 2002, Esteban-Pretel et al 2007, Stapleford et al 2016, …

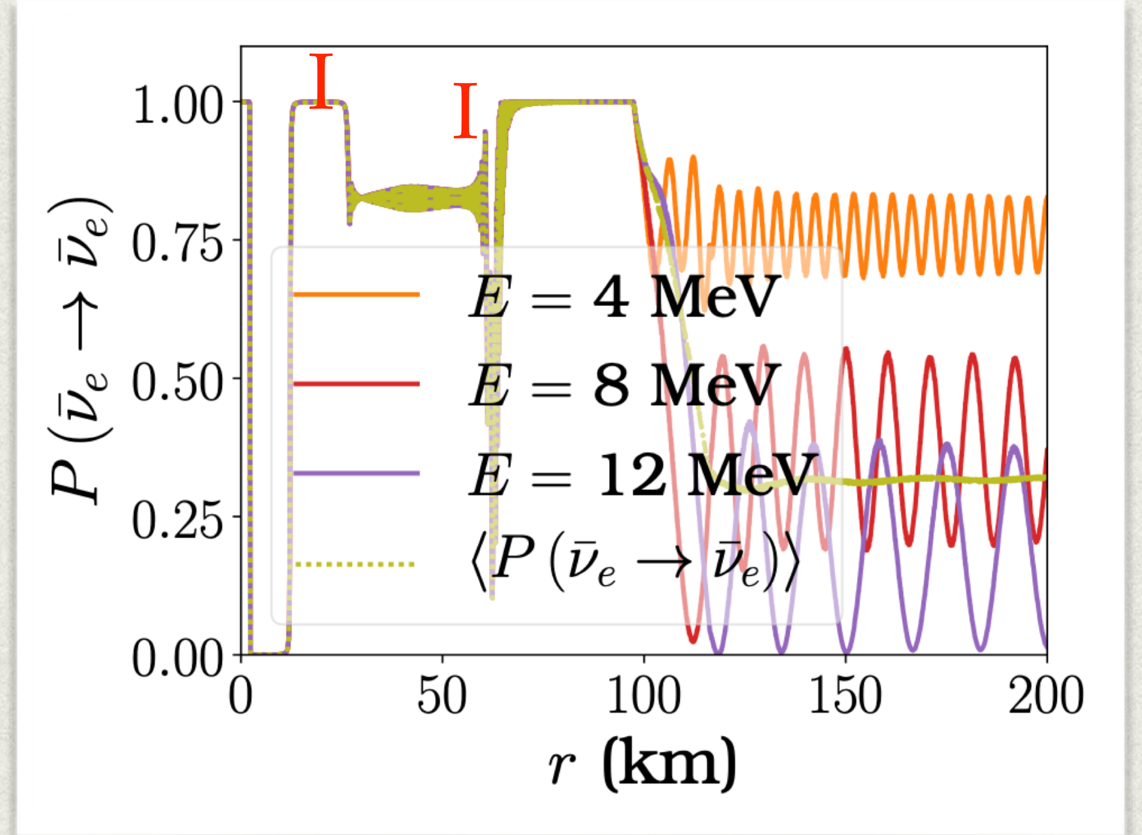
$$h_{NSI} = \sqrt{2} G_F \sum_f N_f \epsilon^f \quad f = e, d, u$$

Impact flavor evolution and potentially r-process nucleosynthesis, even for very small NSI couplings



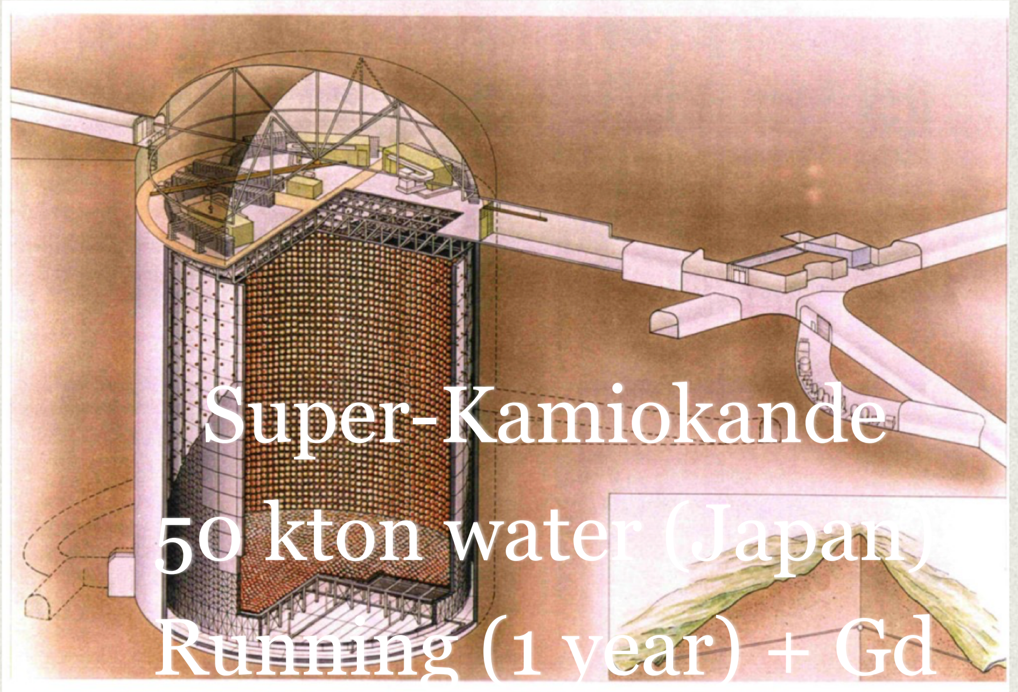
Esteban-Pretel et al, 2010

I-resonance : cancellation between standard matter and NSI



Antineutrinos

Chatelain and Volpe PRD97 (2018)



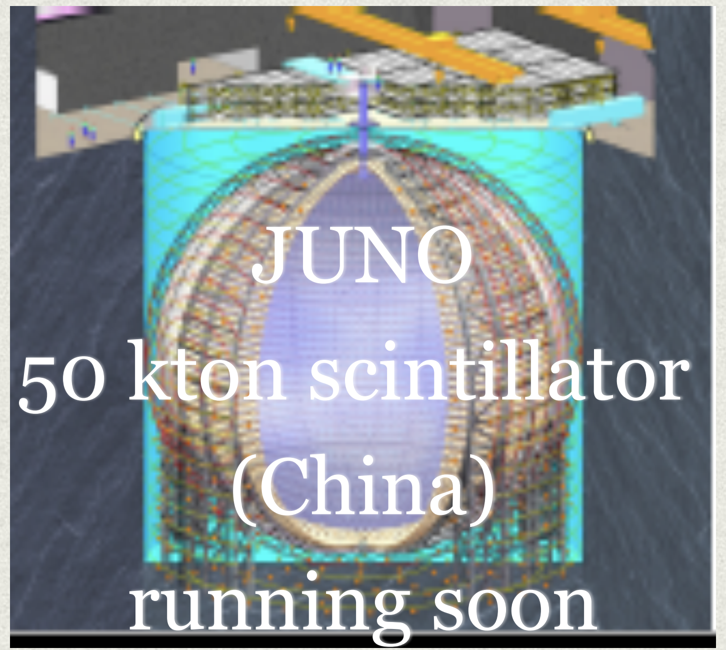
Super-Kamiokande
50 kton water (Japan)
Running (1 year) + Gd

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

Hyper-Kamiokande
178 kton (FV) water (Japan)
runnin 2027

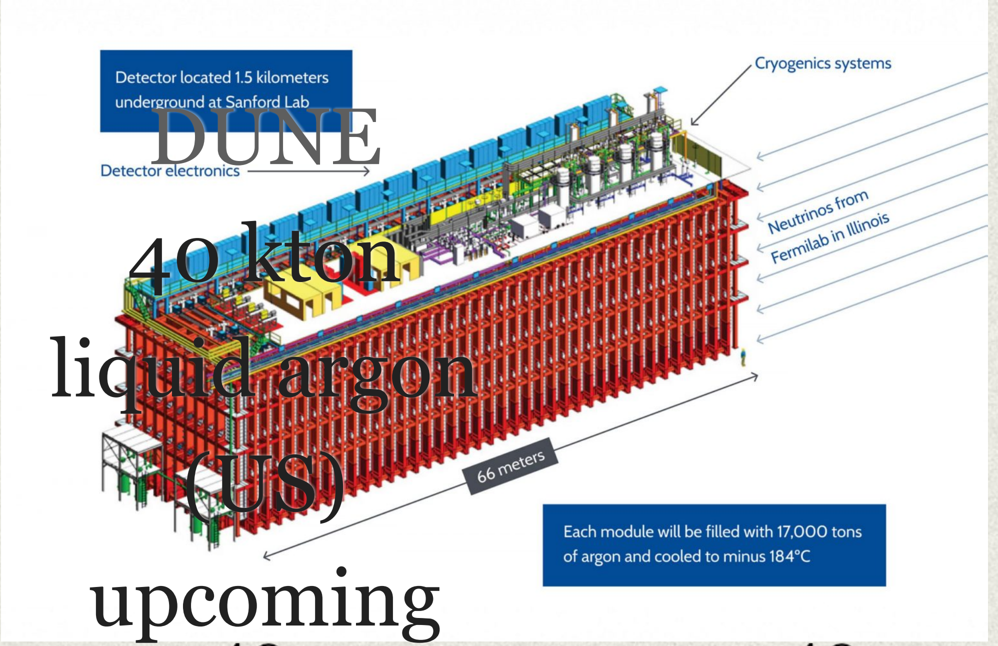
$$\bar{\nu}_e + p \rightarrow n + e^+ (IBD)$$

THE DISCOVERY OF THE DIFFUSE SUPERNOVA NEUTRINO BACKGROUND



JUNO
50 kton scintillator
(China)
running soon

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



DUNE
40 kton
liquid argon
(US)
upcoming

$$\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K$$

DIFFUSE SUPERNOVA NEUTRINO BACKGROUND

- Flux upper limits from SKI-IV and SNO data

$2.8 - 3 \ \ \bar{\nu}_e \ \ \mathrm{cm}^{-2} s^{-1} \ \ (E_\nu > 17.3 \ \ \mathrm{MeV})$

Abe et al, 2109.11174

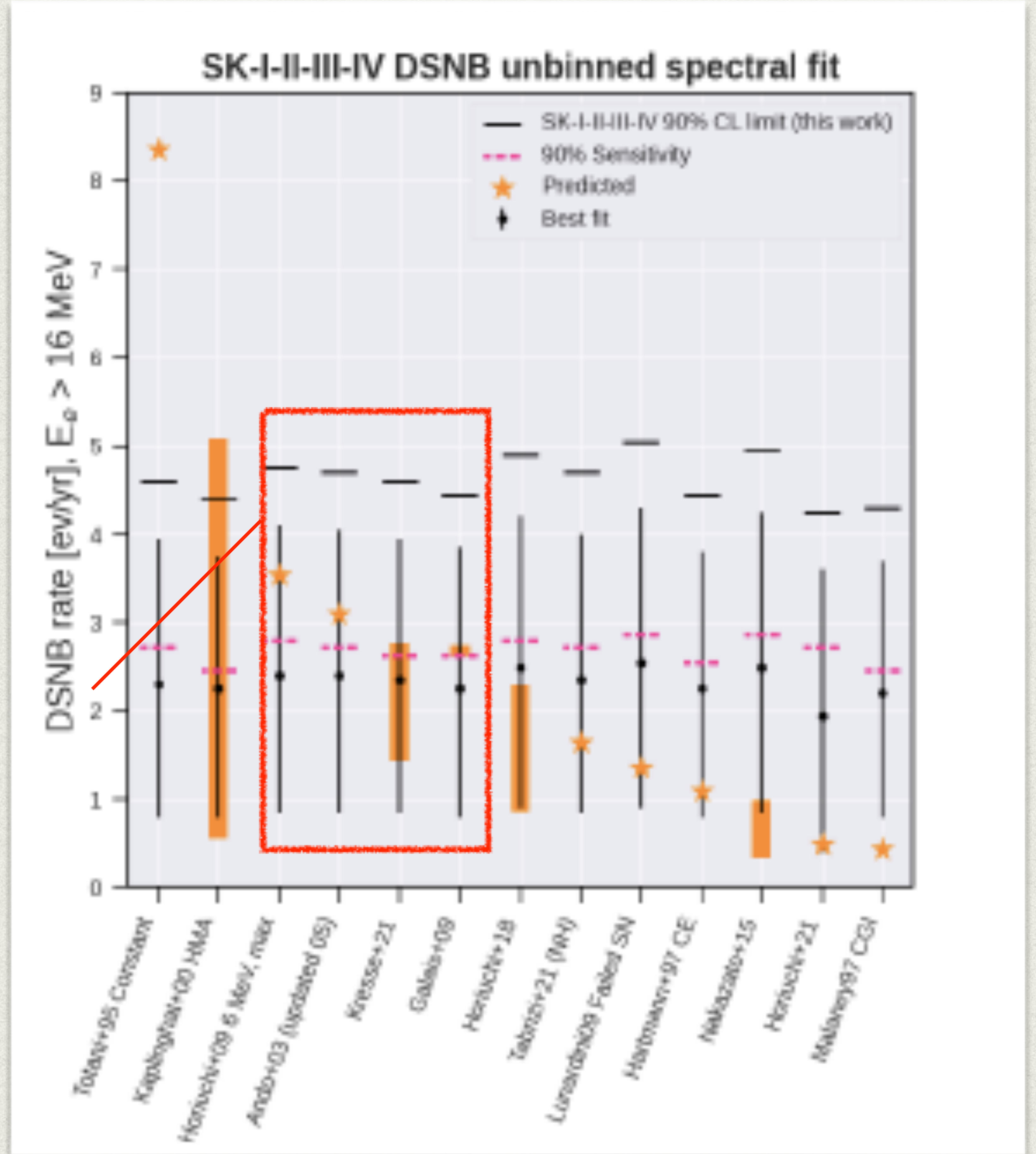
$19 \ \ \nu_e \ \ \mathrm{cm}^{-2} s^{-1} \ \ (E_\nu \in [22.9, 36.9] \ \ \mathrm{MeV})$

SNO data, Aharmim et al, Astrophys. J. 2006

$10^3 \nu_x \ cm^{-2} s^{-1}$ Peres and Lunardini,. JCAP 2008

An excess of 1.5 sigma observed in the data.

The sensitivity of the combined analysis (90 % C.L.) is on par with 4 predictions.



Expected rates, 90% C.L. upper limits, best fit values (1 sig.) and expected sensitivity from SK-I and SK-IV data

Abe et al, 2109.11174

DIFFUSE SUPERNOVA NEUTRINO BACKGROUND

- The DSNB flux depends on the evolving core-collapse supernova rate, the neutrino fluxes from a supernova, integrated over time

$$\phi^{\mathrm{DSNB}}_{\nu_\alpha}(E_\nu) = c \int\int \mathrm{dM}\; dz \left|\frac{dt}{dz}\right| \underleftrightarrow{R_{\mathrm{SN}}(z,\ \mathrm{M})}\ \underleftrightarrow{\phi_{\nu_\alpha,SN}(E'_\nu,\ \mathrm{M})}$$

$E'_\nu = E_\nu(1+z)$ redshifted neutrino energies

M mass of the supernova progenitor

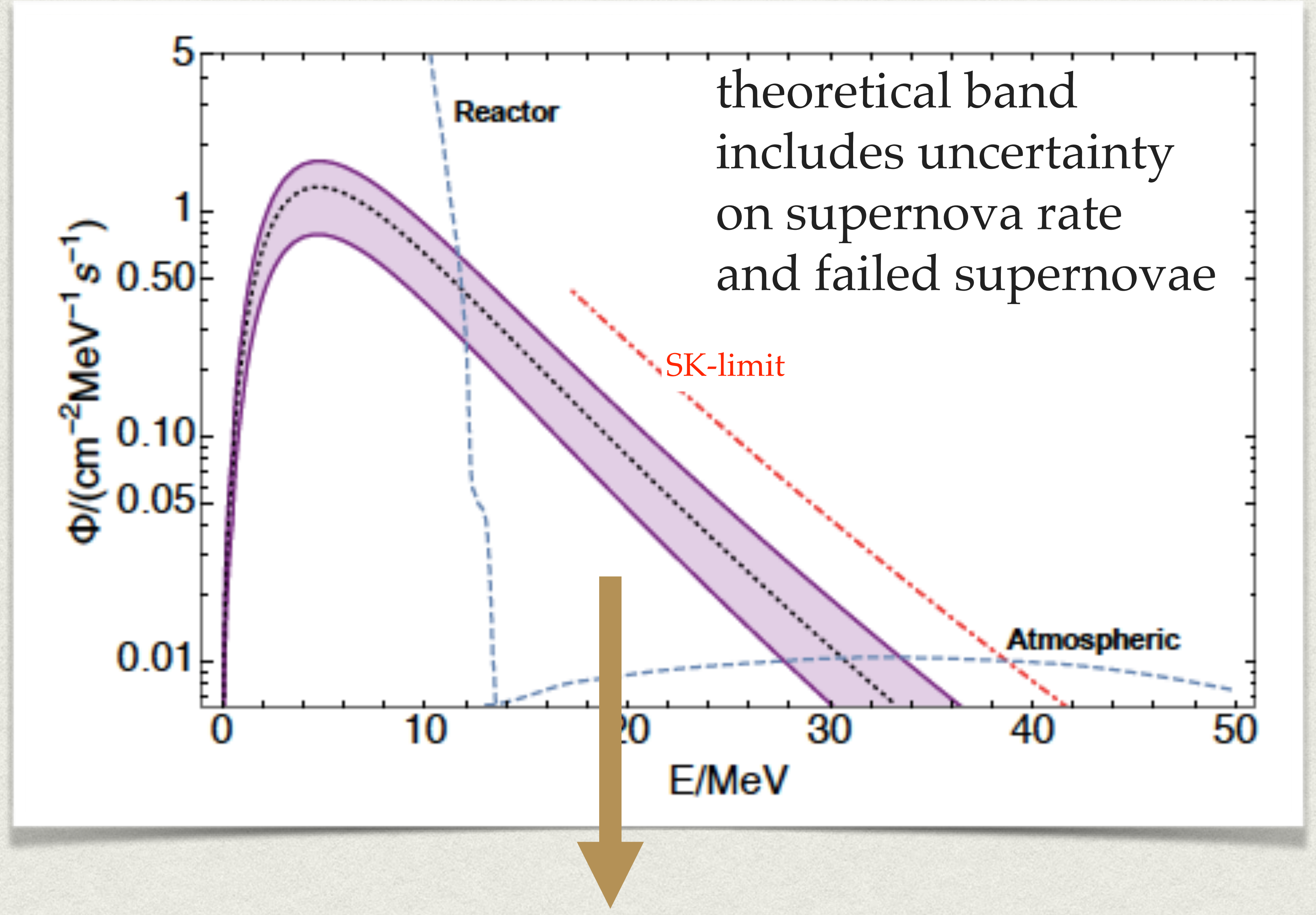
- There is a contribution from failed supernovae (black-hole): hotter energy spectrum determines the relic flux tail

Lunardini, PRL 2009

- $$\left|\frac{dz}{dt}\right| = H_0(1+z)\sqrt{\Omega_\Lambda + (1+z)^3\Omega_m}$$

$\Omega_\Lambda = 0.7 \quad \Omega_m = 0.3$ dark energy and matter cosmic energy densities

$H_0 = 67.4\ \mathrm{km\ s^{-1}Mpc^{-1}}$ ΛCDM



theoretical band includes uncertainty on supernova rate and failed supernovae

DSNB detection window

Priya and Lunardini JCAP 2017

CORE-COLLAPSE SUPERNOVA RATE

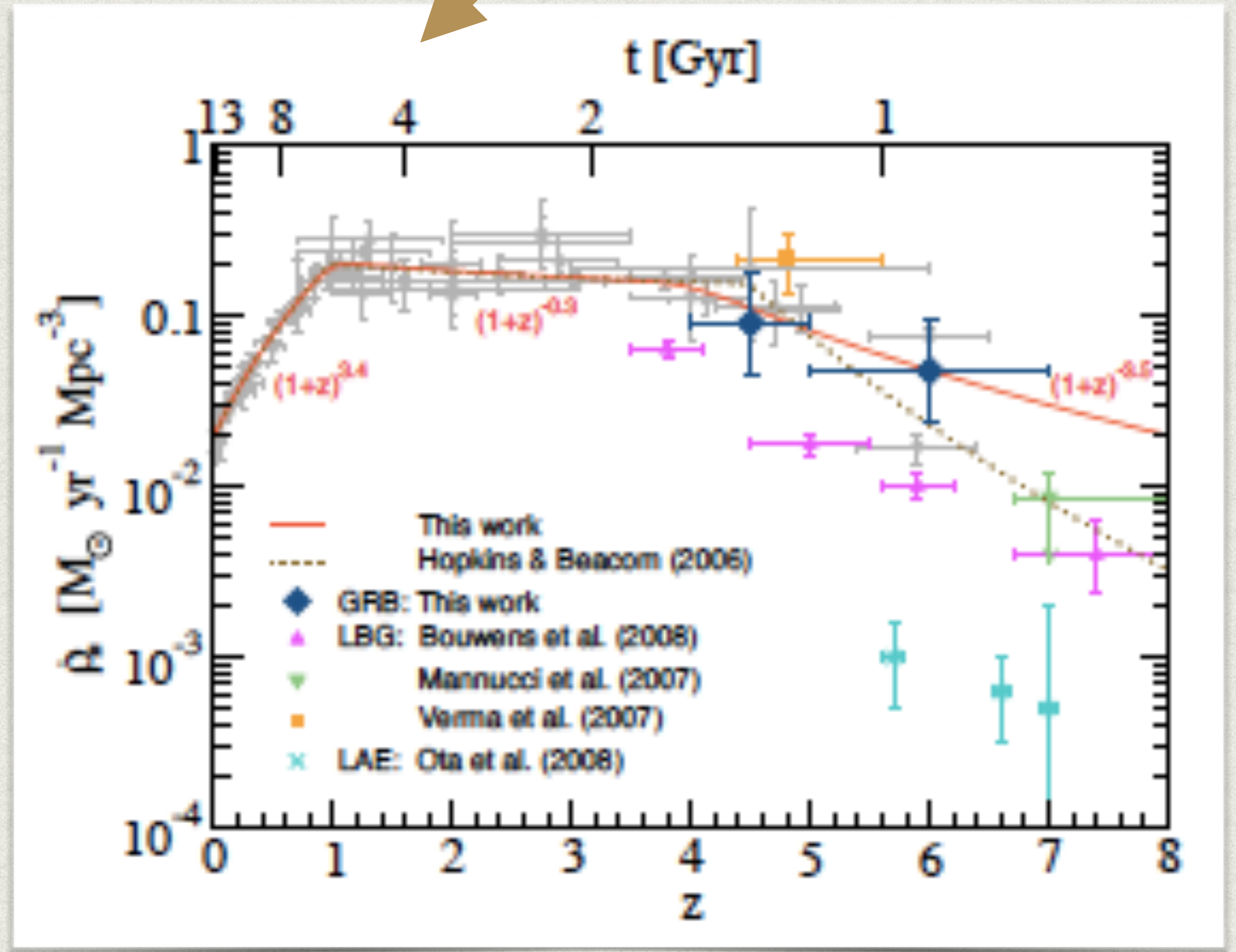
- The cosmic core-collapse supernova rate history can be deduced from the cosmic star formation rate history

$$R_{\rm SN}(z,{\rm M}) = \dot{\rho}_*(z)\frac{\phi({\rm M})d{\rm M}}{\int_{0.5\ {\rm M}_\odot}^{125\ {\rm M}_\odot}\phi({\rm M}){\rm M}d{\rm M}}$$

Salpeter Initial Mass Function (IMF) :

$$\phi({\rm M}) \sim {\rm M}^{\chi} \qquad \chi = -2.35 \qquad {\rm M} \geq 0.5{\rm M}_\odot$$

$\phi({\rm M})d{\rm M}$ is the number of stars with progenitor mass $[{\rm M}, {\rm M} + d{\rm M}]$



Yuksel et al, i Astrophys. J(2008)

relevant for the DSNB

below detection threshold

- $$R_{SN}(0) = \int_{8\ {\rm M}_\odot}^{125\ {\rm M}_\odot} R_{\rm SN}(0,{\rm M})d{\rm M}$$

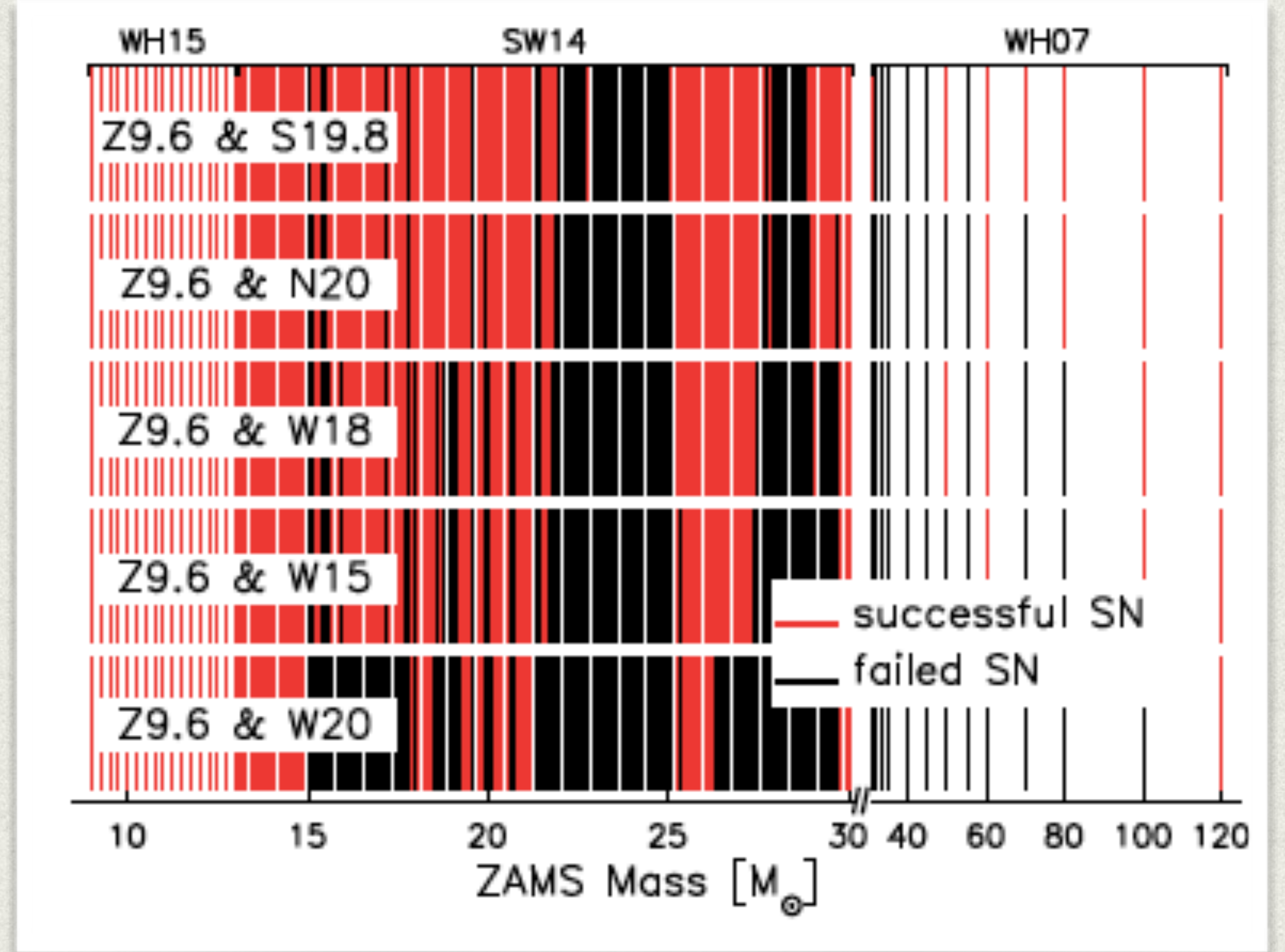
$$= 1.25 \pm 0.5 \times 10^{-4} yr^{-1} Mpc^{-3}$$

An uncertainty by about a factor of 2.

$R_{\rm SN}(z)$ MAIN UNCERTAINTY

DIFFUSE SUPERNOVA NEUTRINO BACKGROUND

- The fraction of « dark » collapses is debated.



Kresse et al 2021

- Therefore the DSNB is sensitive to :
  - the cosmic core-collapse supernova rate, the fraction of failed supernovae, the EOS;

see e.g. Priya and Lunardini 2017,
Moller et al 2018, Kresse et al 2021,
Horiuchi et al 2021, ...

- flavor conversion phenomena beyond MSW, e.g. shock waves and self-interaction. Event rates can be modified by 10-20 %.

Galais, Kneller, Gava, Volpe, PRD81, 2010

- non-standard neutrino properties such as neutrino decay.

Ando 2003, Lisi et al 2004,
De Gouvea et al 2020,
Tabrizi et Horiuchi 2021,
Ivanez-Ballesteros and Volpe, 2022.

DSNB and neutrino non-radiative decay

- The DSNB is sensitive to non-standard neutrino properties such as neutrino non-radiative (invisible) two-body decay

$$\nu_i \to \nu_j + \phi \quad \text{or} \quad \nu_i \to \bar{\nu}_j + \phi$$

a massless scalar particle ϕ

$$\tau_i^{-1} = \tilde{\Gamma}_i = \sum_{m_j < m_i} \tilde{\Gamma}(\nu_i \to \nu_j) + \tilde{\Gamma}(\nu_i \to \bar{\nu}_j)$$

$\tau_{lab} = \frac{\tau}{m} E$ lifetime in the laboratory frame

- Limits on from Earth experiments, solar neutrinos and cosmology.

$\frac{\tau}{m} \leq 10^{11} \frac{s}{eV}$ $\quad \Gamma \geq H_0$ decay observability (rule of thumb)

- Neutrino fluxes deplete because of decay over a distance L by the factor

$$\exp(-\frac{t}{\tau_{lab}}) = \exp(-\frac{L}{E} \times \frac{m}{\tau})$$

Typical values for different neutrino sources:

	$\frac{\tau}{m}$
Accelerator	$10^{-14}\ s/eV$
Atmosphere	$10^{-10}\ s/eV$
Sun	$10^{-4}\ s/eV$
Supernovae	$10^{5}\ s/eV$

DSNB : $\frac{\tau}{m} \in [10^9, 10^{11}] \frac{s}{eV}$

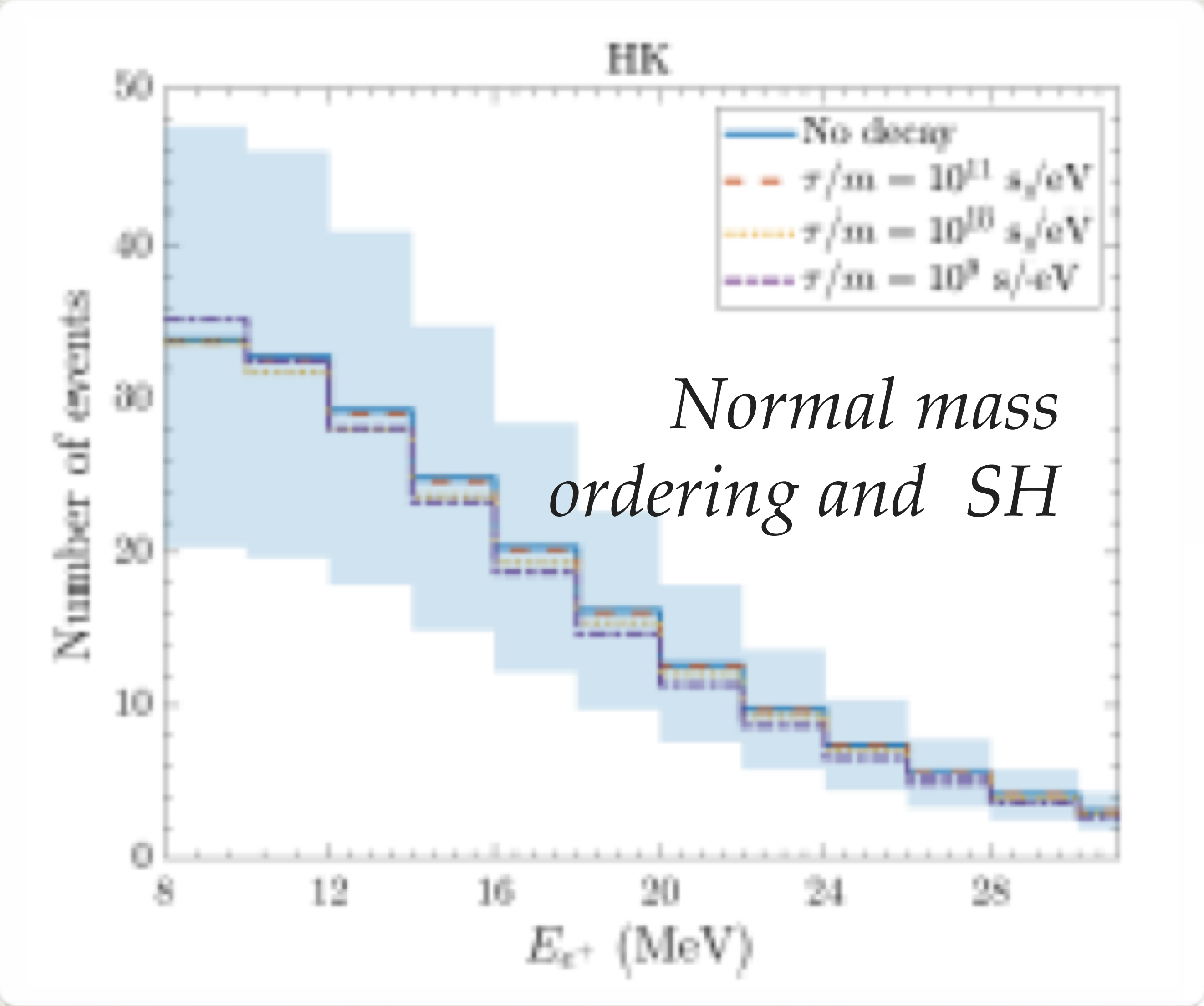
- Studies used simple Fermi-Dirac distributions for the neutrino fluxes, or no supernova progenitor dependence or only 2 neutrino flavors.

The DSNB has a sensitivity to a unique sensitivity window for tau/m

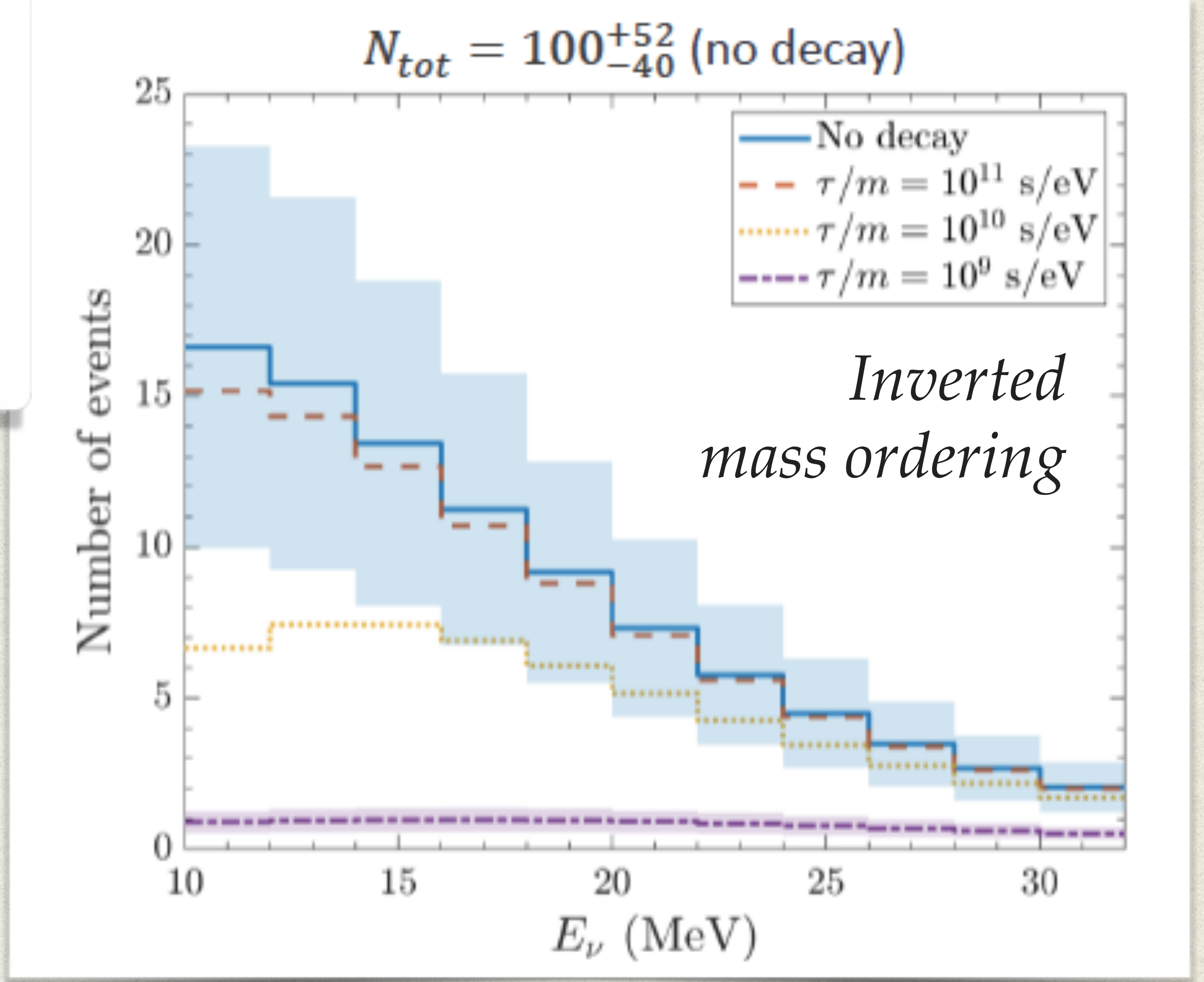
DSNB and neutrino non-radiative decay

- Performed a 3 neutrino flavor study including the dependence on the supernova progenitors and the uncertainty from the cosmic core-collapse supernova rate (bands).
- Rates can be significantly reduced due to neutrino decay. The impact of decay goes beyond astrophysical uncertainties in some cases.

Expected events (no decay) from about 10 for SK-Gd (10 year), and DUNE (20 years), 10-40 for JUNO (20 years) and a few hundreds for Hyper-Kamiokande (20 years).



Hyper-Kamiokande



P. Ivanez-Ballesteros and M.C. Volpe, arXiv:2209.12465

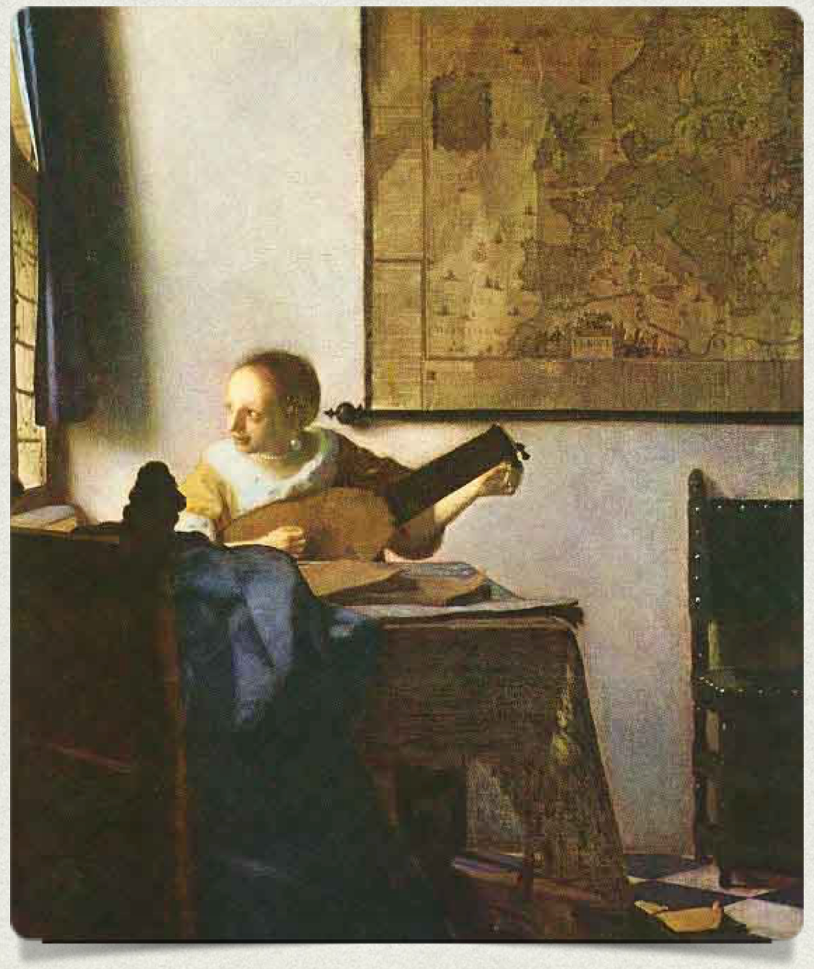
In case DSNB not observed, it could be due to neutrino non-radiative two-body decay

Conclusions and Perspectives

- Neutrinos change flavor in dense environments, i.e. supernovae and compact objects in unexpected ways. Impressive progress in the last fifteen years in uncovering flavor mechanisms, on the evolution equations and more.

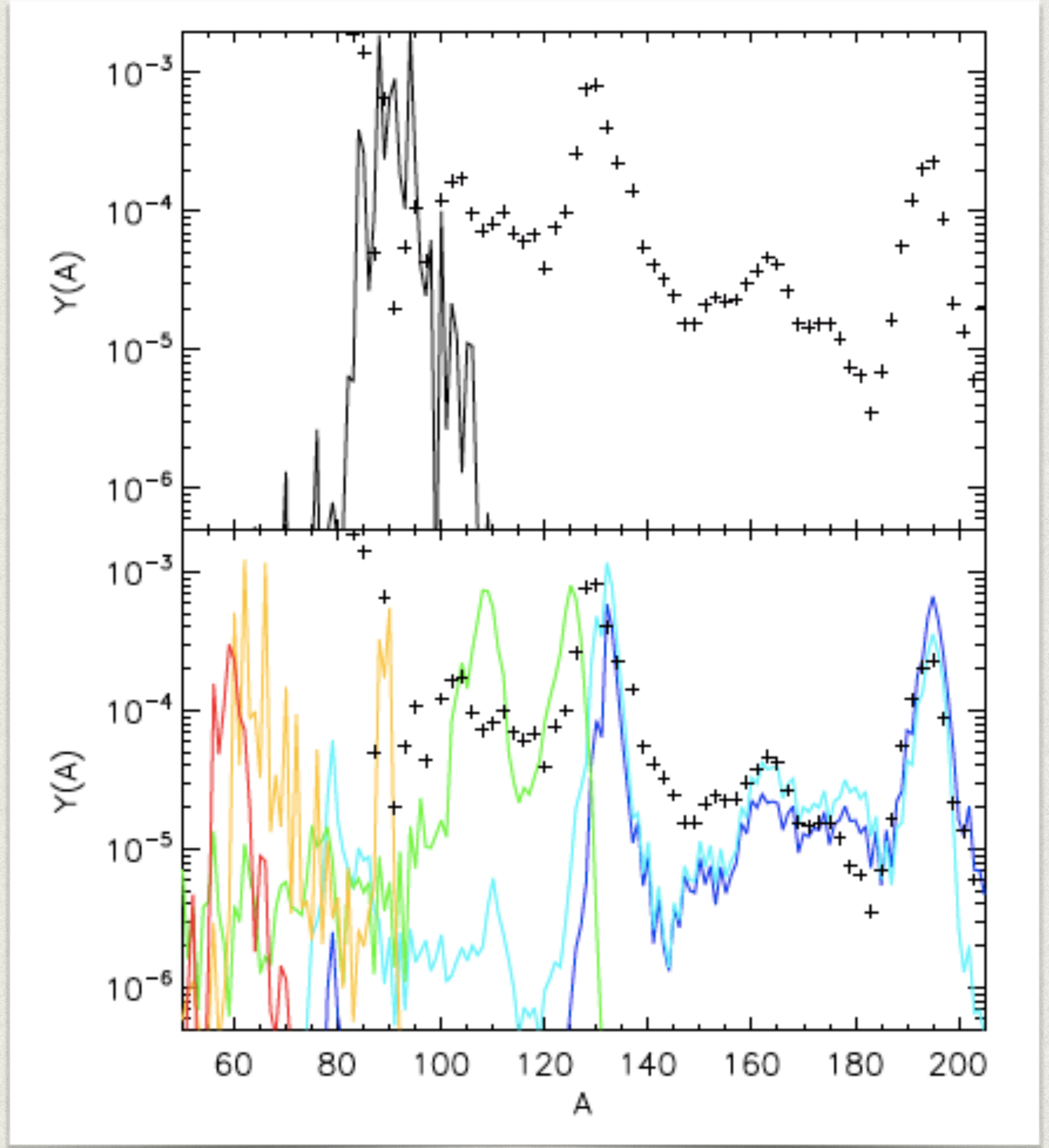
- Supernovae remain a laboratory for new physics. Both non-standard neutrino properties and interactions can significantly impact neutrino evolution in dense environments.

- The discovery of the diffuse supernova neutrino background will bring unique information for astrophysics and particle physics, e.g. on neutrino decay.



« La *femme au luth*», Vermeer, 1663

FLAVOR EVOLUTION
with STANDARD INTERACTIONS in BNS



no flavor evolution
included

flavor evolution included
(different initial mu and
tau neutrino fluxes)

Malkus et al, PRD 93, 2016

Impact r-process nucleosynthesis

NEUTRINO FLUXES on Earth

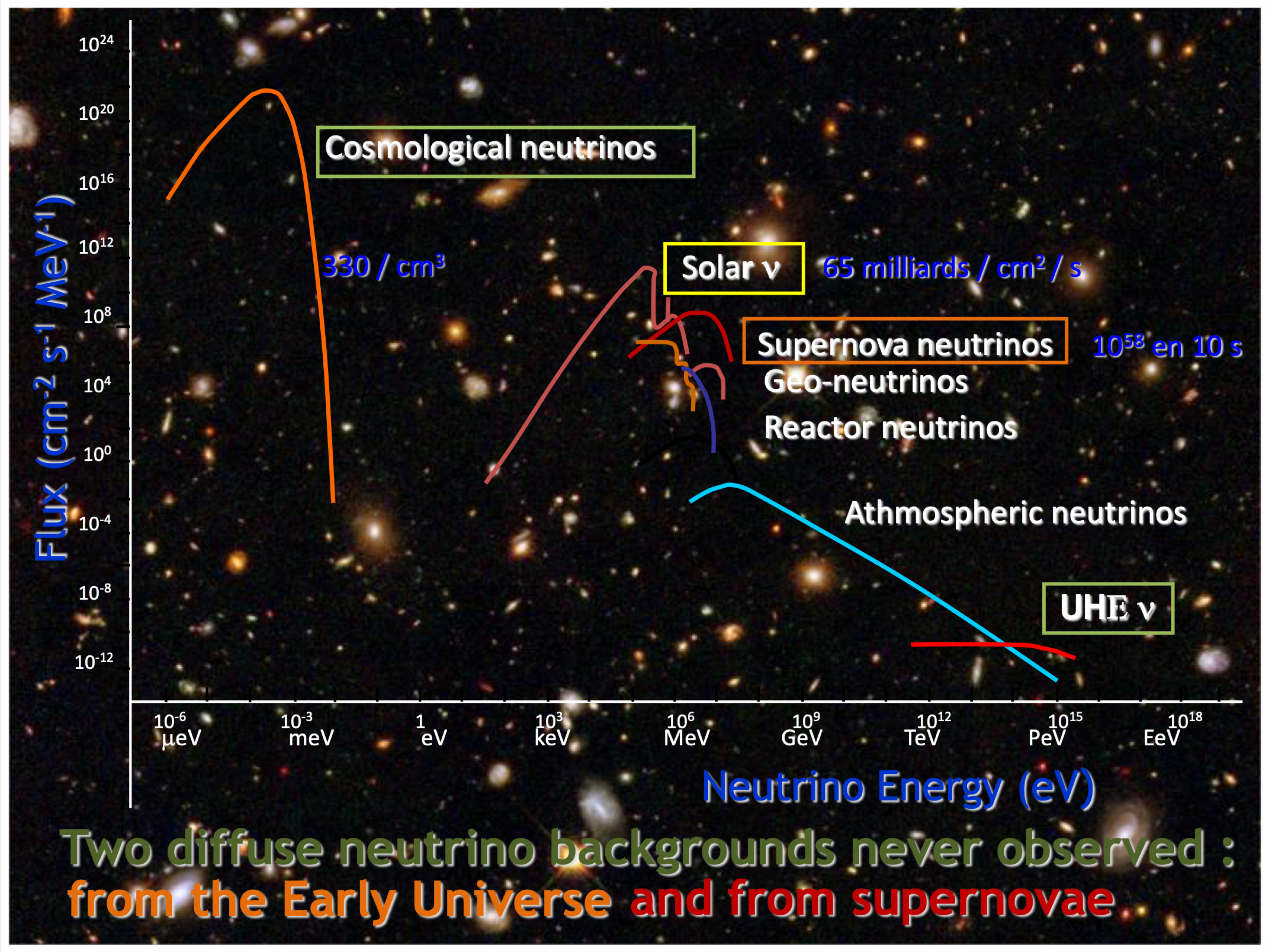
- Variety of natural and man-made sources produce neutrinos of all flavors.

  Fluxes vary over more than 30 orders of magnitudes and go from meV to PeV energies.

- Two diffuse neutrino backgrounds never observed :

  - cold cosmological one (decoupling at BBN epoch, 1 s after Big-Bang)

  - diffuse, or relic, supernova neutrino background (DSNB) in the tens of MeV energy range

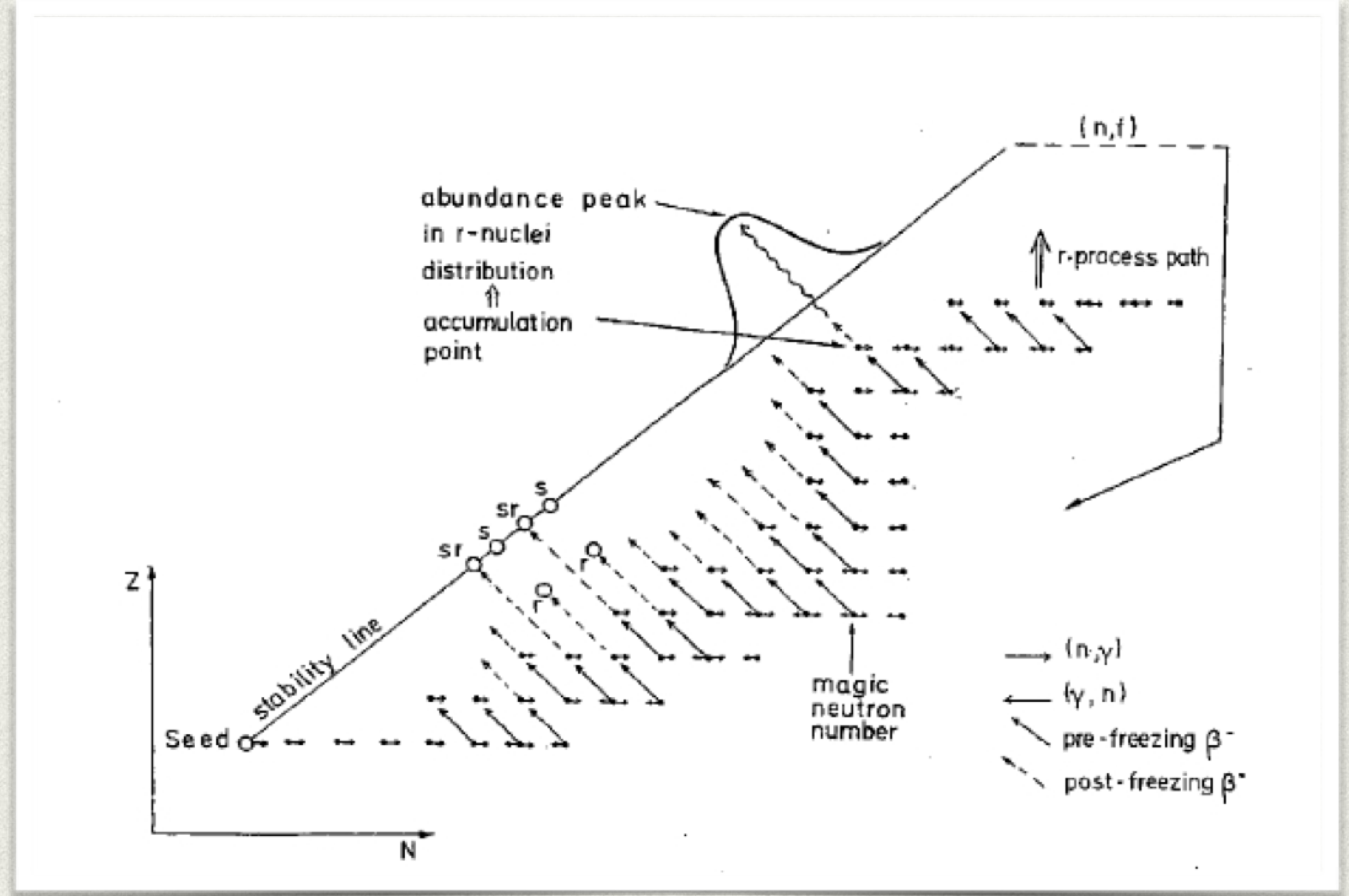


Two diffuse neutrino backgrounds never observed :
from the Early Universe and from supernovae

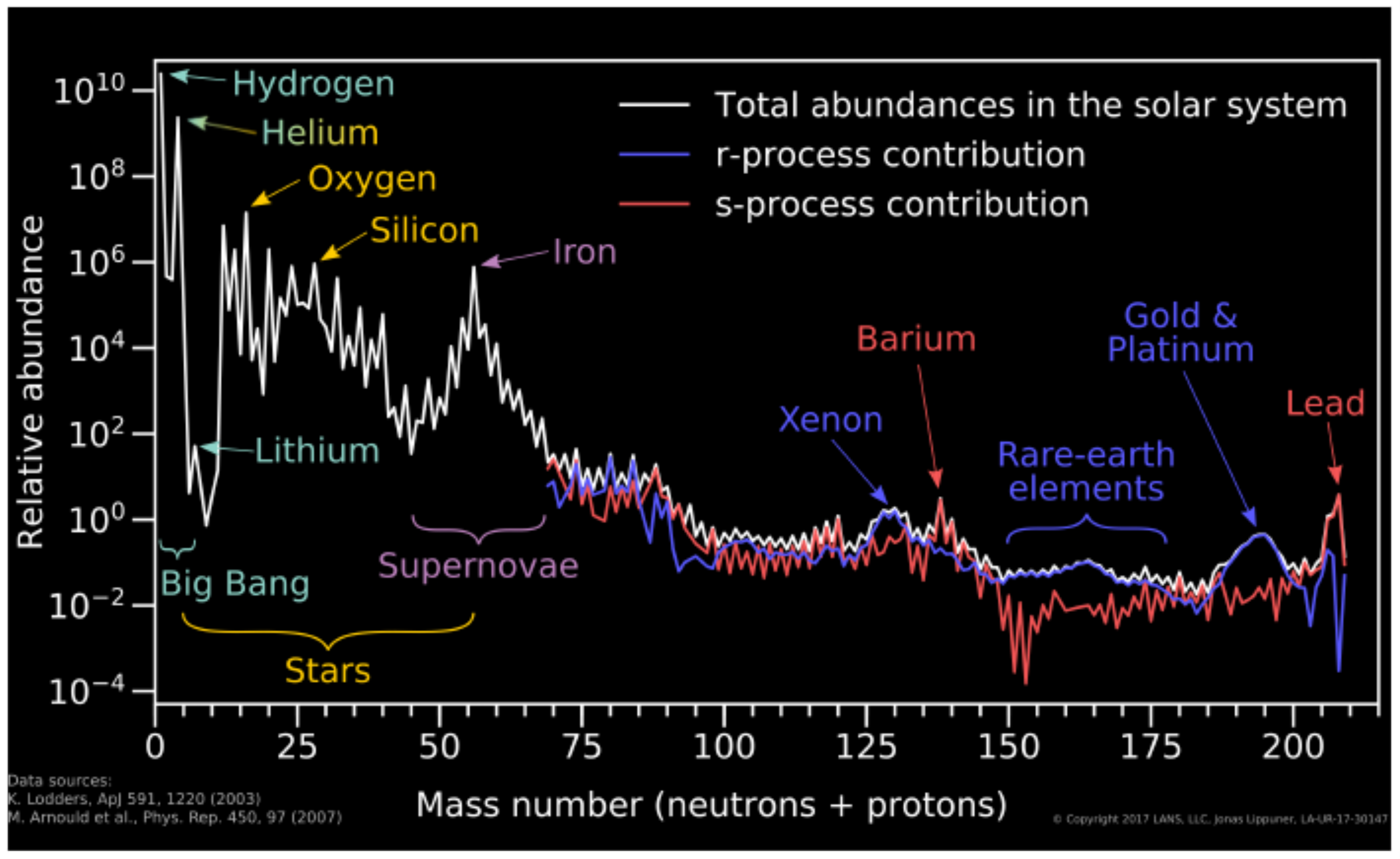
r-PROCESS NUCLEOSYNTHESIS

- Key open question in astrophysics :
  the origin (i.e. the sites and conditions) of elements heavier than iron.

- Two main mechanisms : s-process (s for slow), r-process (r for rapid neutron capture) where neutron rich nuclei capture neutrons faster than beta-decay to the stability valley.

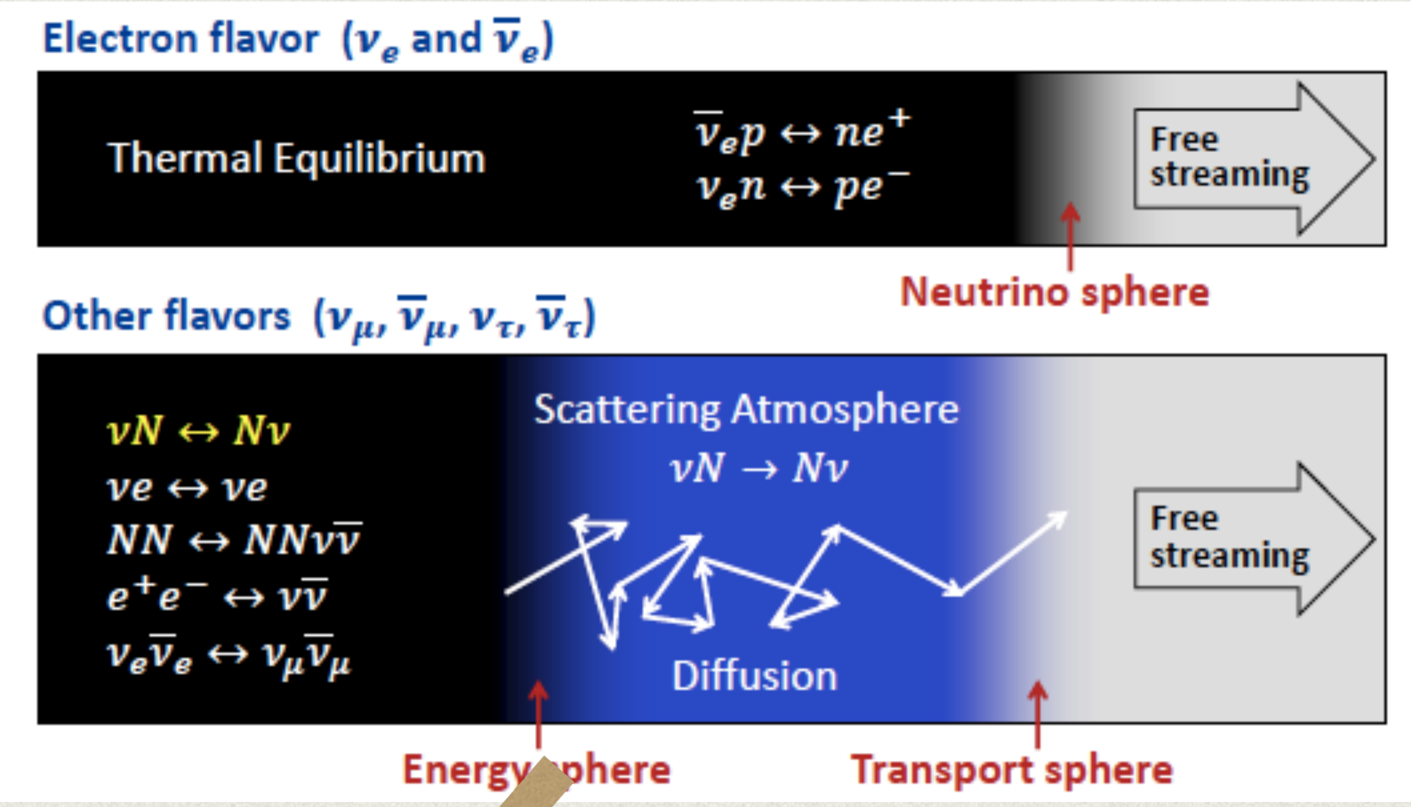


Nucleosynthetic abundances in the solar system

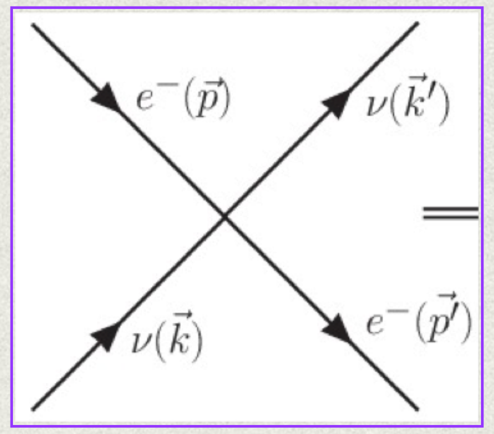


Main candidate sites : supernovae and neutron star-neutron star mergers

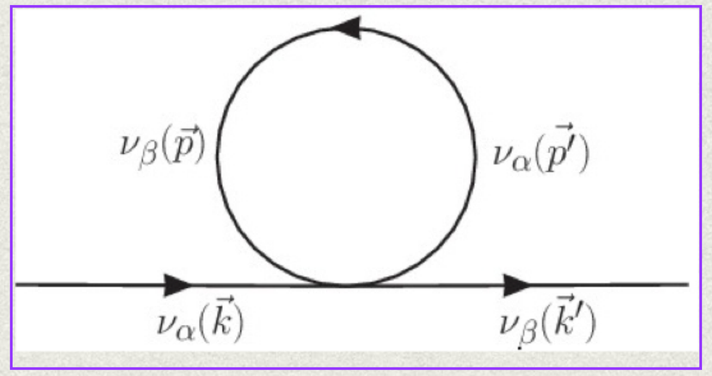
From dense to dilute: the neutrinosphere, Boltzmann and mean-field



Raffelt (2012)



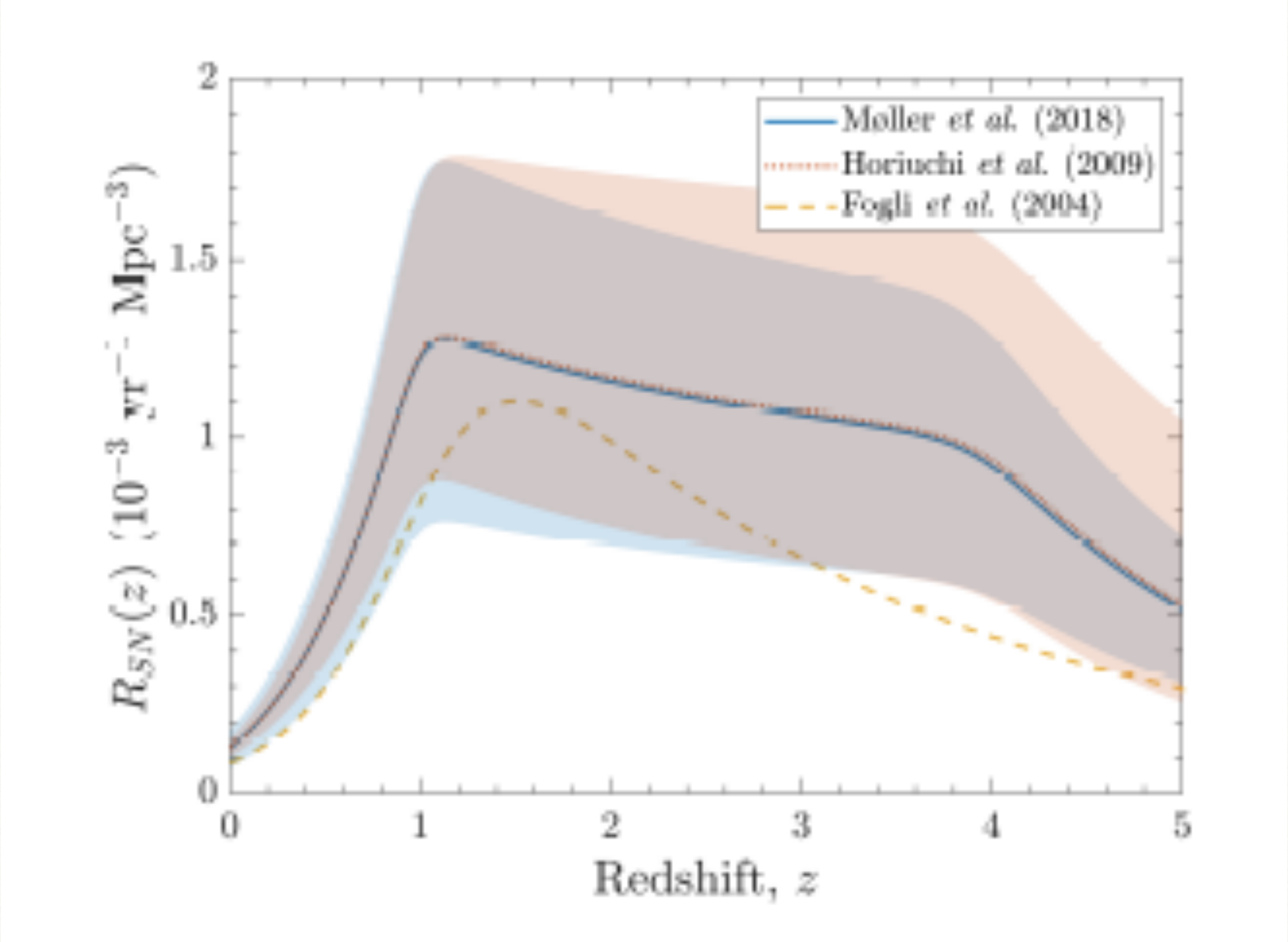
collisions dominated
Boltzmann approximation

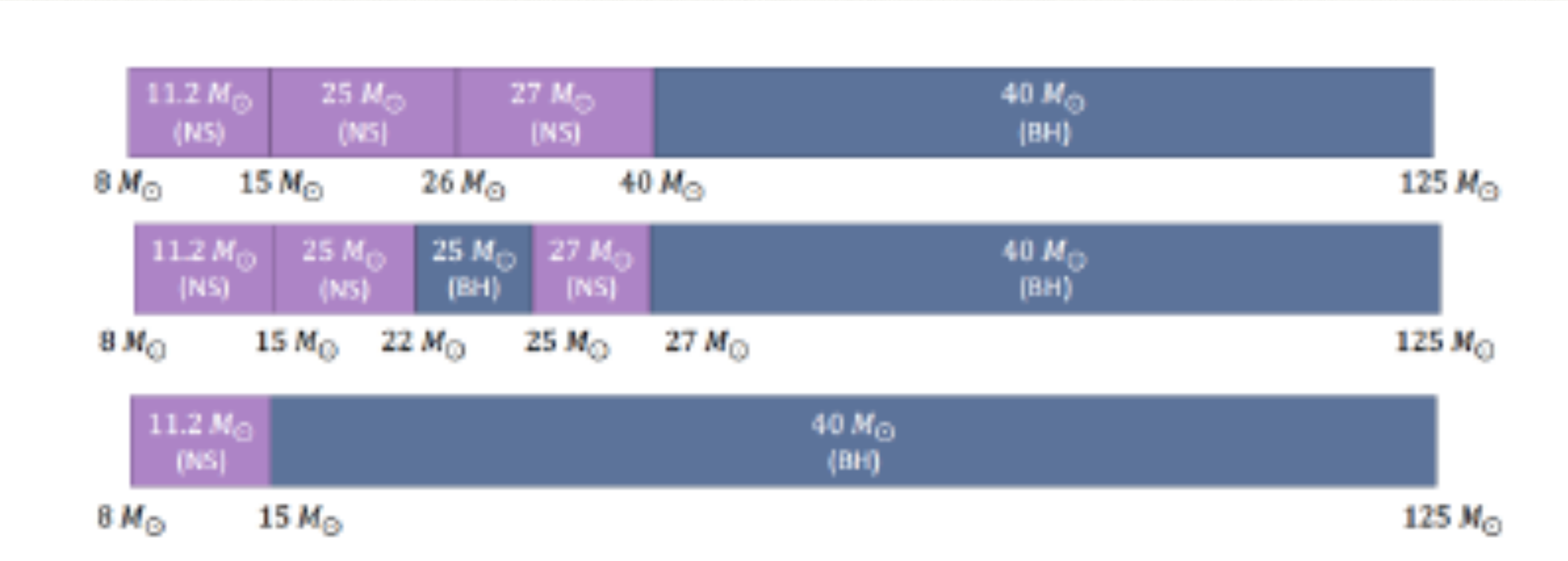


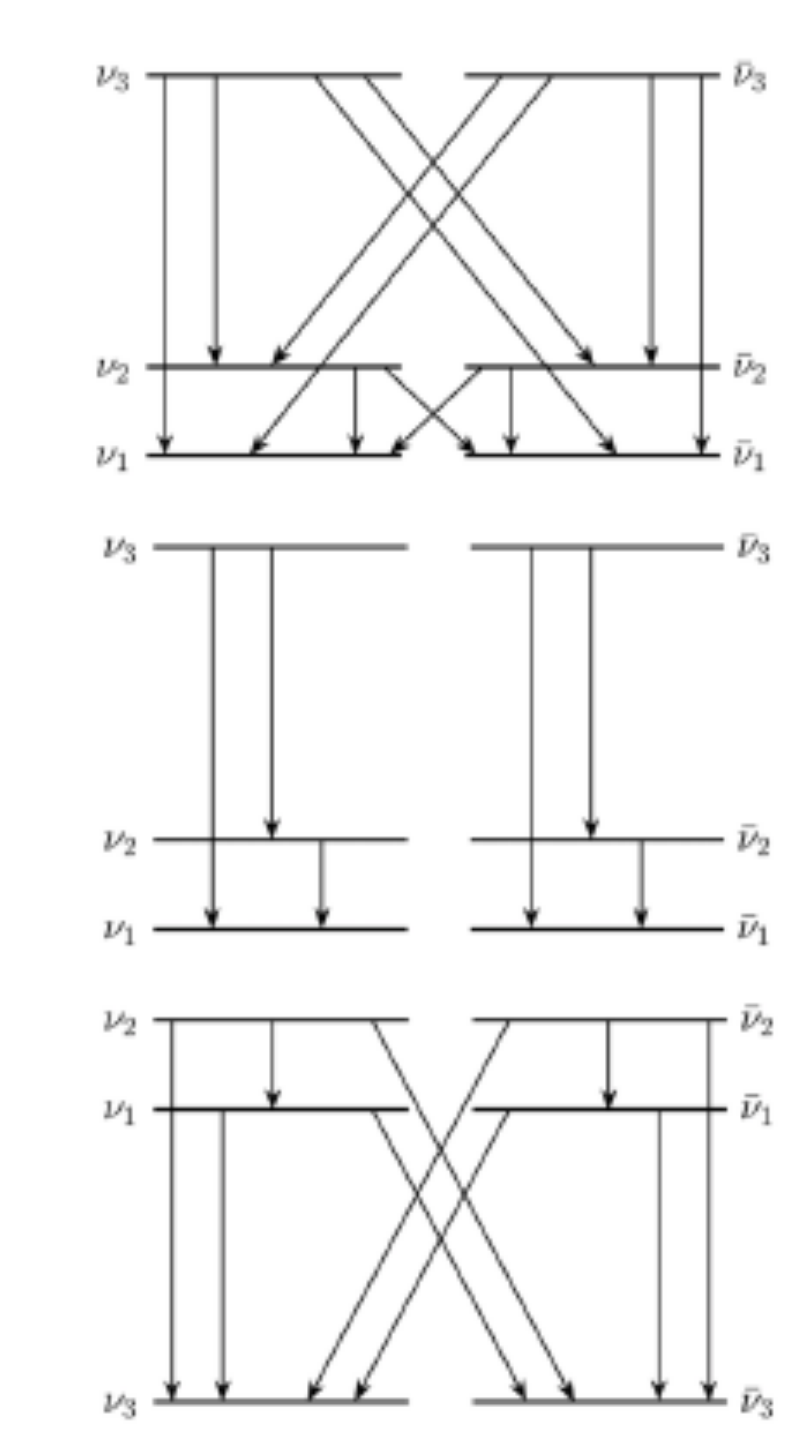
flavor conversion
mean-field approximation

separation of scales
does not necessarily hold…

Neutrinosphere : energy and flavor dependent region where neutrinos start free-streaming







Normal mass ordering and strongly-hierarchical
$m_h \gg m_l \simeq 0$

Normal mass ordering and quasi-degenerate
$m_h \simeq m_l \gg m_h - m_l$

Inverted mass ordering