NEUTRINO ASTROPHYSICS

Maria Cristina Volpe (CNRS et APC, Paris)

OUTLINE

General and historical

> Neutrinos in Nature
> Dense environments
> GW170817 and binary neutron star mergers
> SN1987A and core-collapse supernovae
> Neutrino evolution equations in matter and the MSW effect

Neutrino evolution in dense media

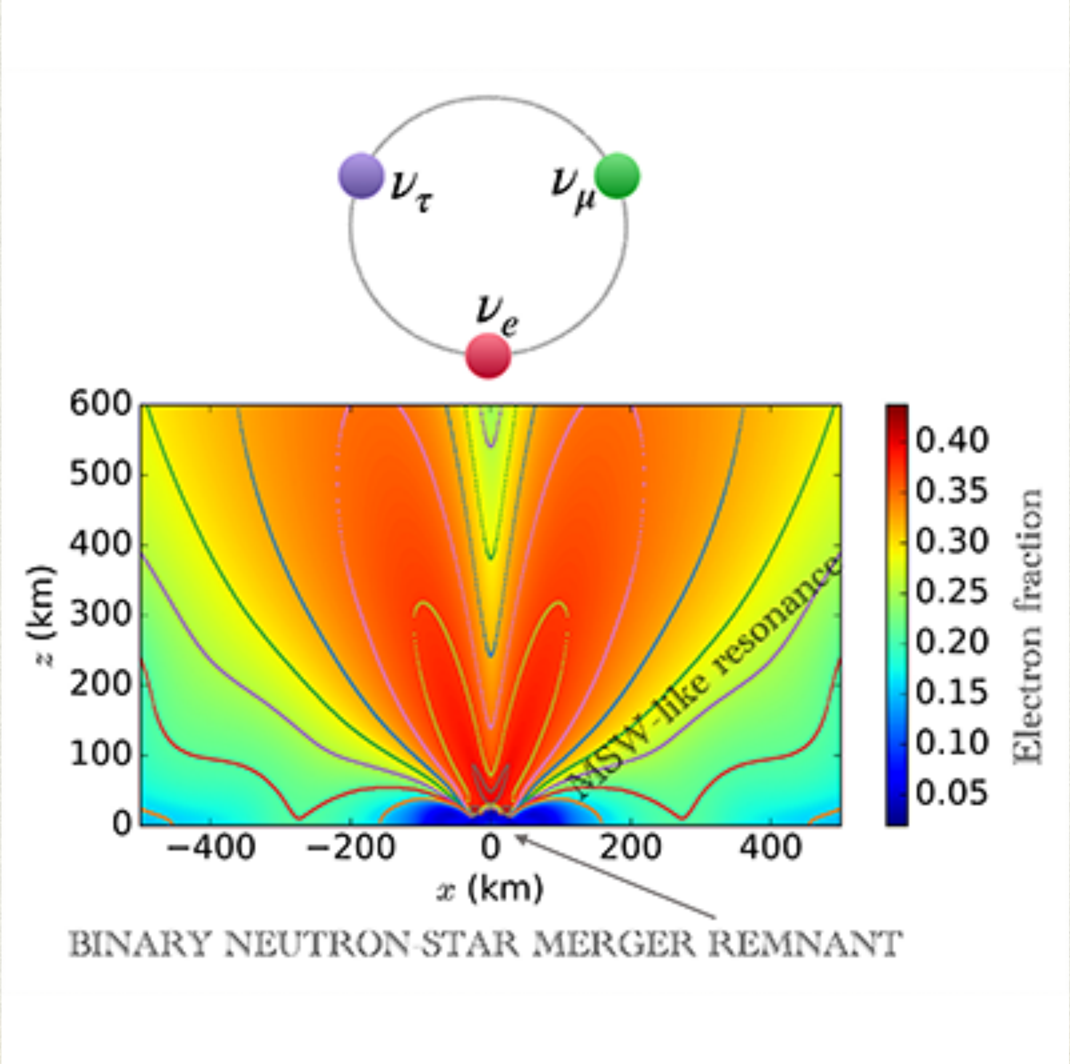
> Neutrino evolution as a many-body problem
> Novel flavor mechanisms, beyond MSW
> Theoretical approaches for neutrino evolution

Future observations

> The diffuse supernova neutrino background

REFERENCES

- Giunti, C., and C. W. Kim, 2007, Fundamentals of Neutrino Physics and Astrophysics (Oxford University Press, Oxford).
- Mohapatra, R. N., and P. B. Pal, 2004, Massive Neutrinos in Physics and Astrophysics, 3rd ed., World Scientific Lecture Notes in Physics Vol. 72 (World Scientific, Singapore).

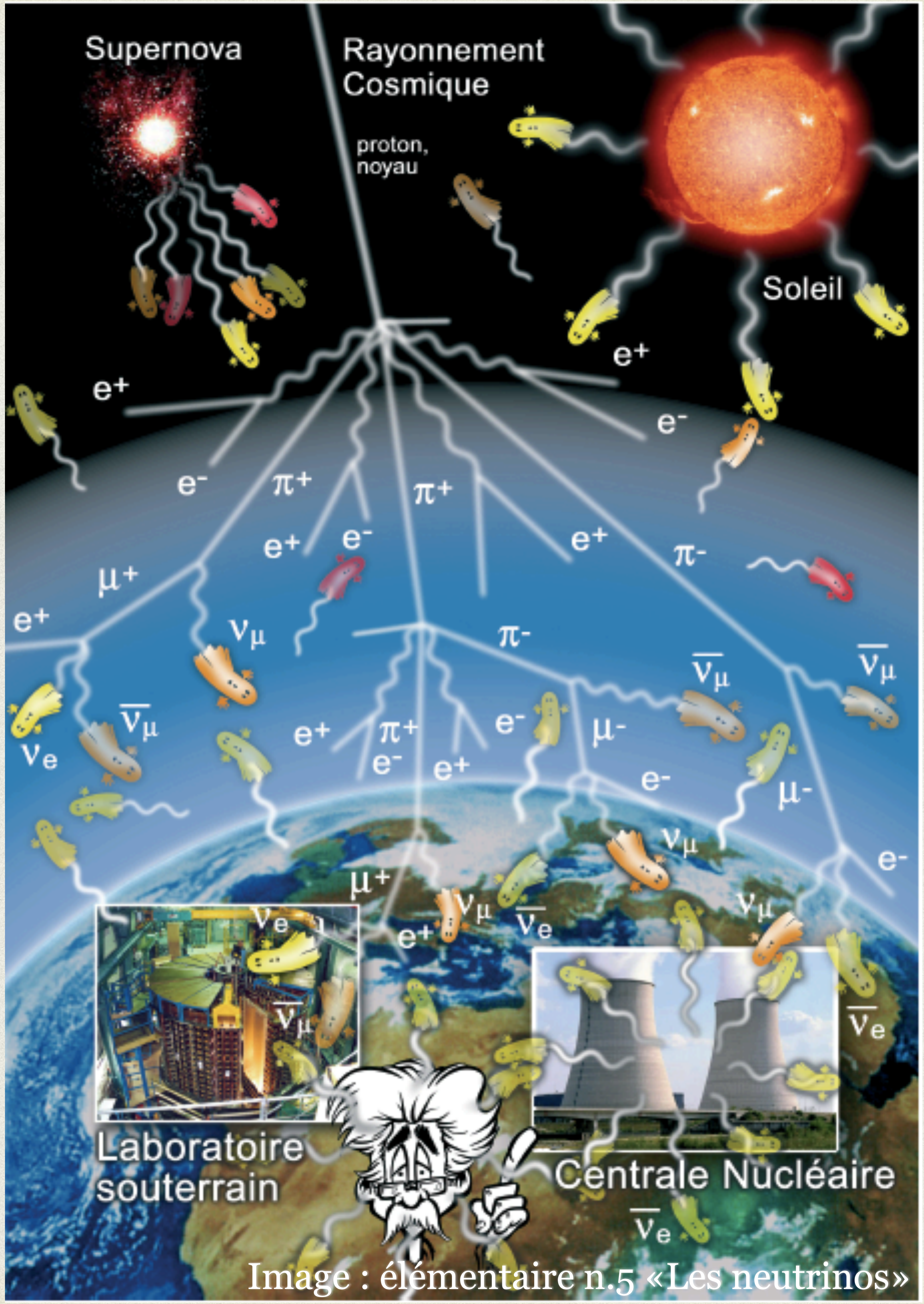


NEW ARTICLE

[Neutrinos from dense environments: Flavor mechanisms, theoretical approaches, observations, and new directions]

M. Cristina Volpe
Rev. Mod. Phys. **96**, 025004 (2024)

Des neutrinos il y en partout sur Terre
et dans l'Univers !



NEUTRINO FLUXES on Earth

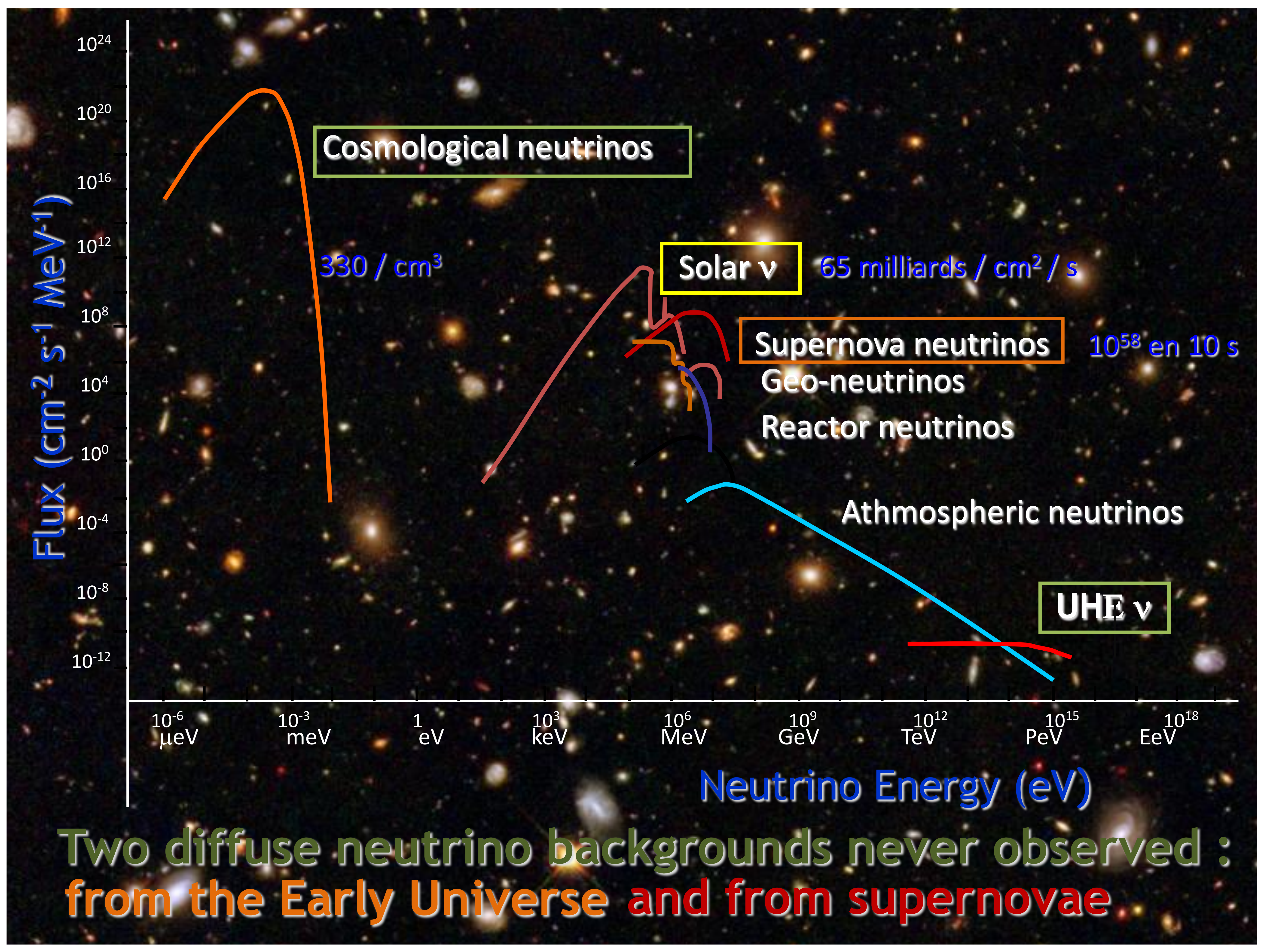
- Variety of natural and man-made sources produce neutrinos of all flavors.

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

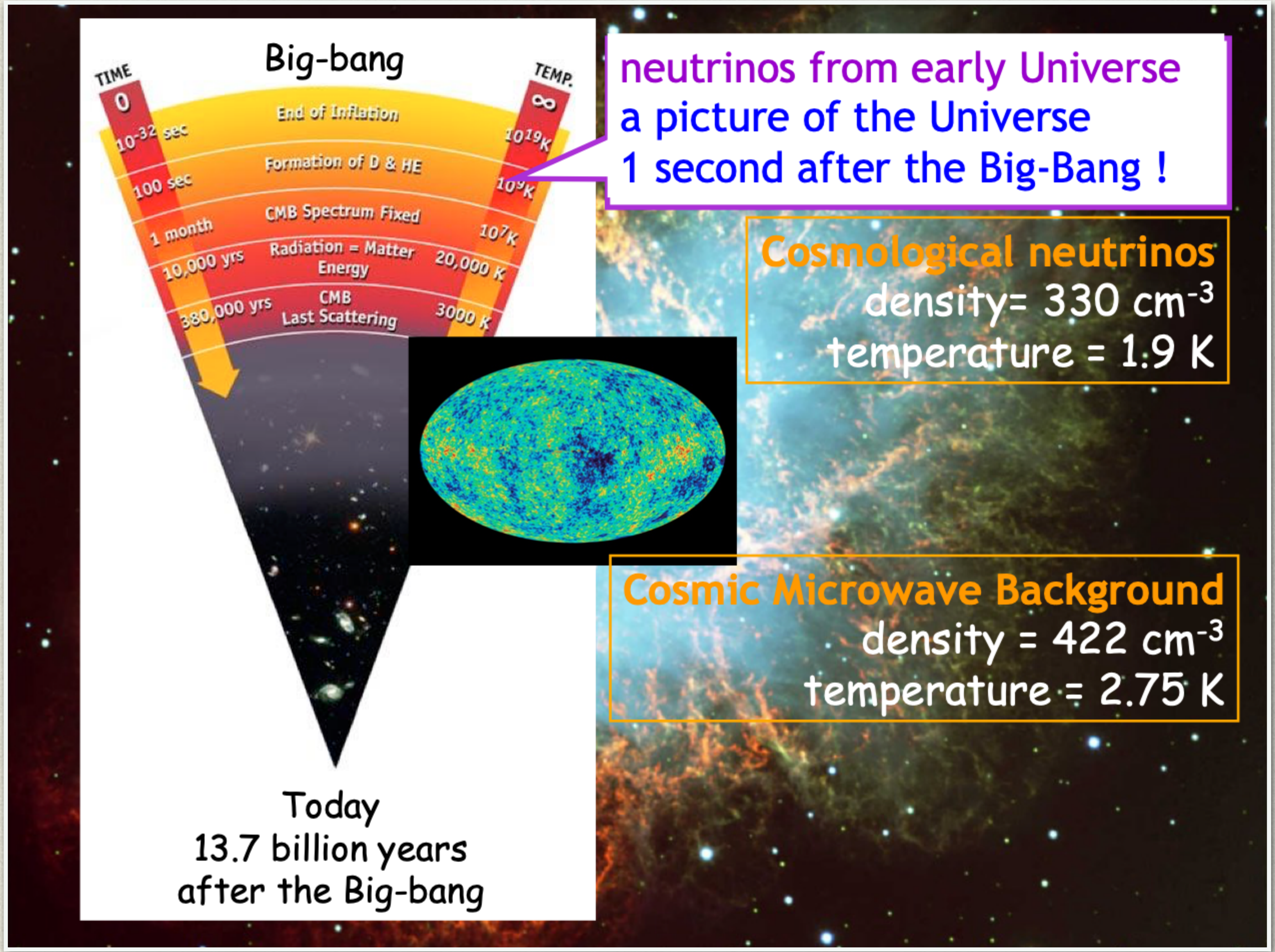
- Two diffuse neutrino backgrounds never observed :

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

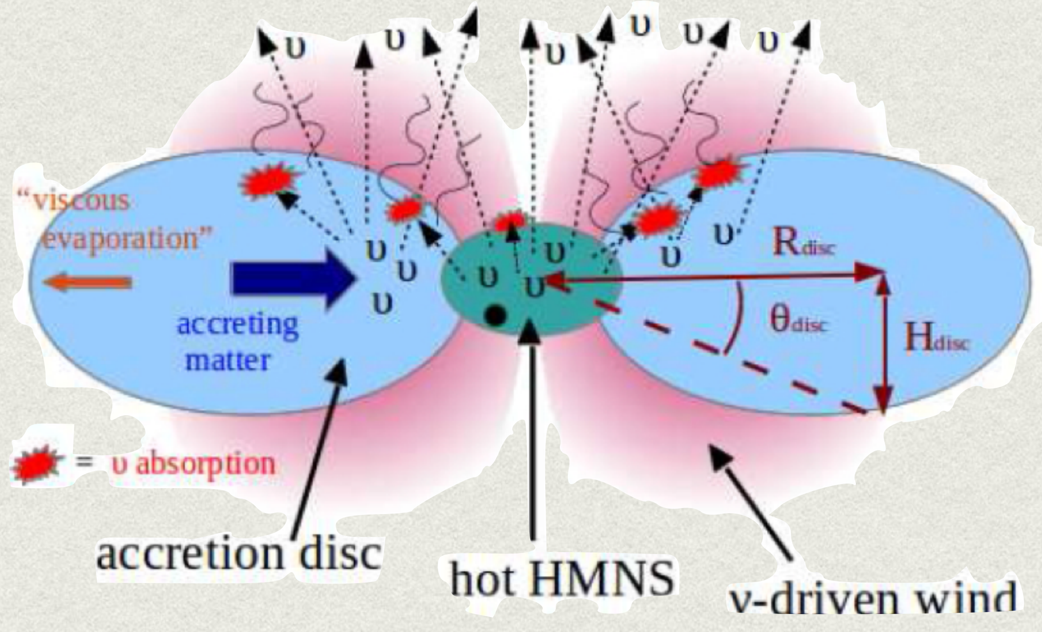
  - diffuse supernova neutrino background **(DSNB)** in the tens of MeV energy range



NEUTRINOS FROM DENSE ENVIRONMENTS

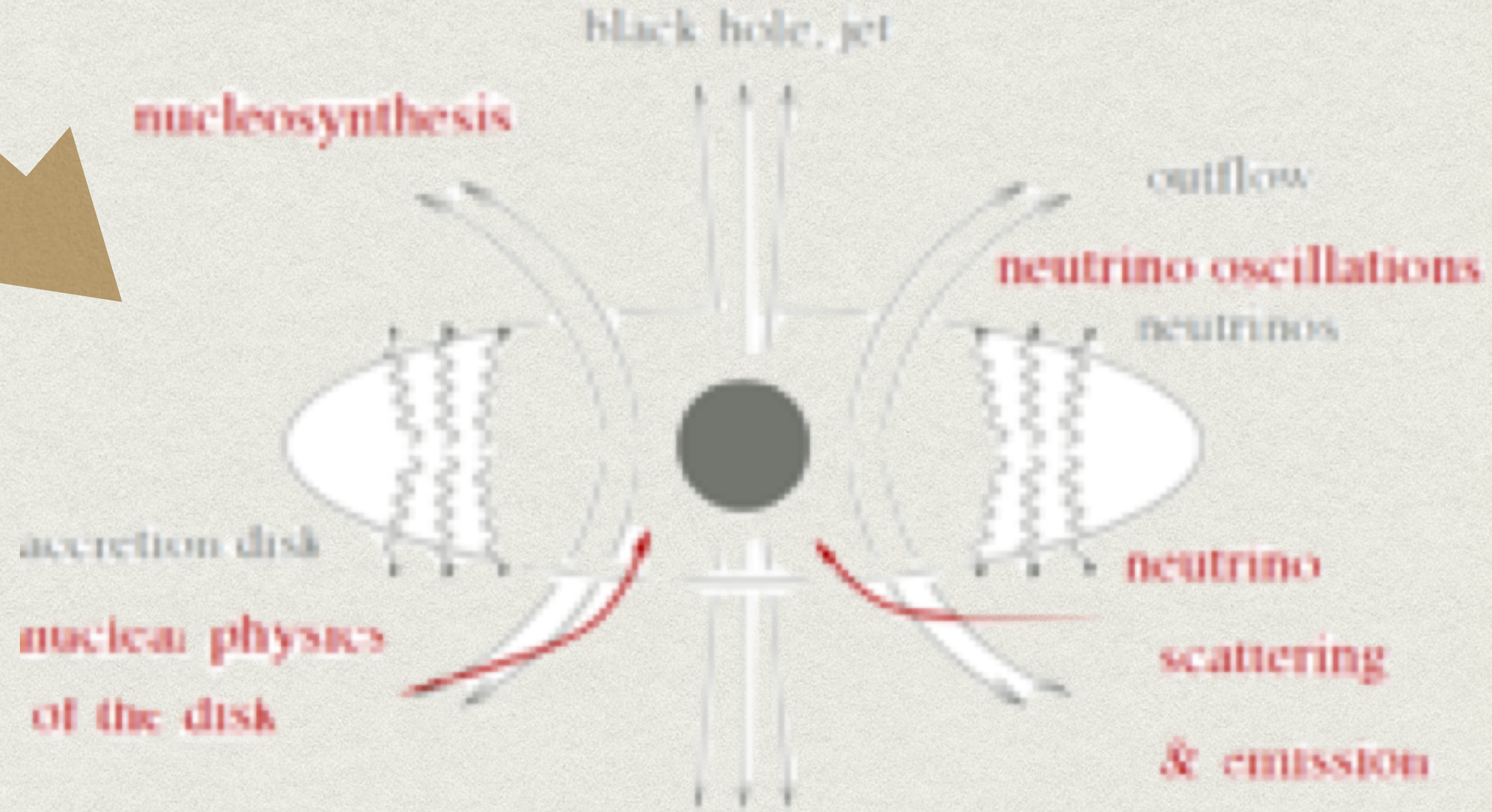


BINARY NEUTRON STAR MERGERS

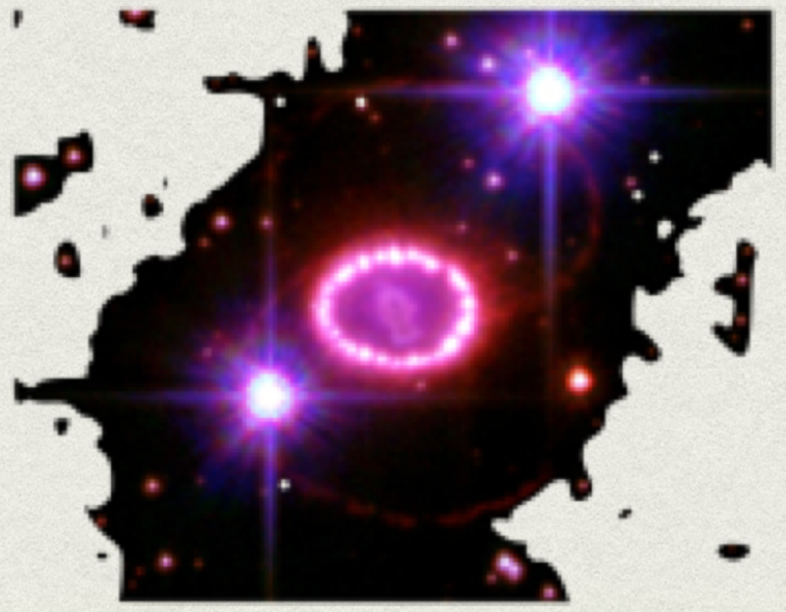


GW170817

ACCRETION DISKS AROUND BLACK HOLES



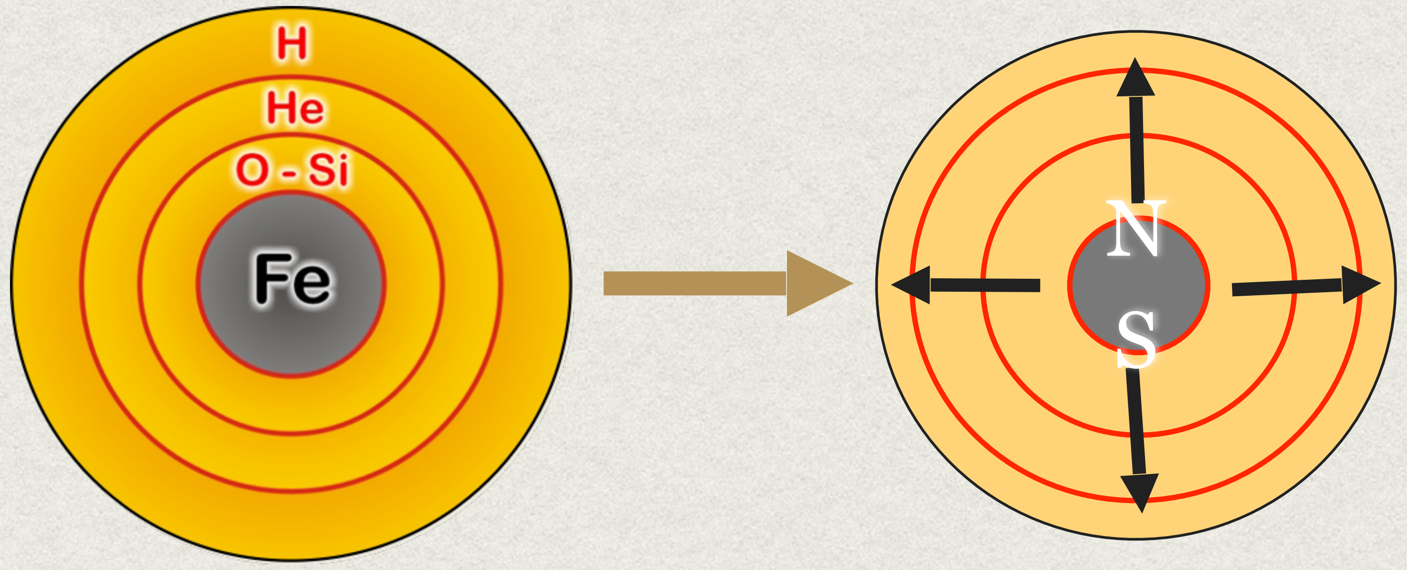
CORE-COLLAPSE SUPERNOVAE



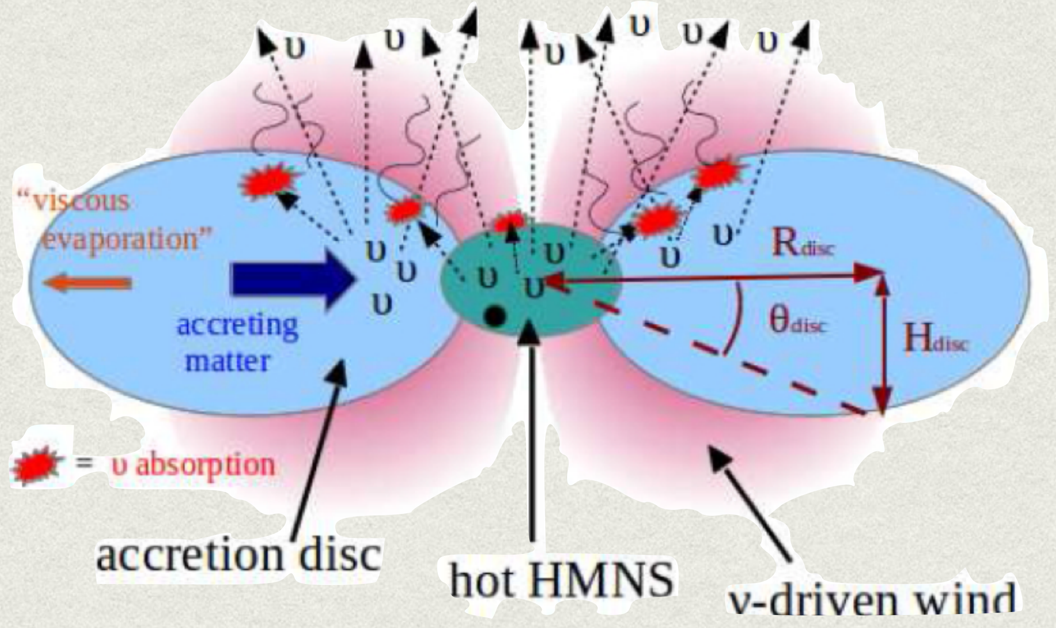
SN1987A

DENSE ENVIRONMENTS

- **« Dense» =** a medium that can reach 10^{10} g/cm^3 and more, 10^{15} - 10^{16} g/cm^3 (limits of matter compressibility), e.g. massive stars called core-collapse supernovae or binary neutron star merger remnants.



core-collapse supernova



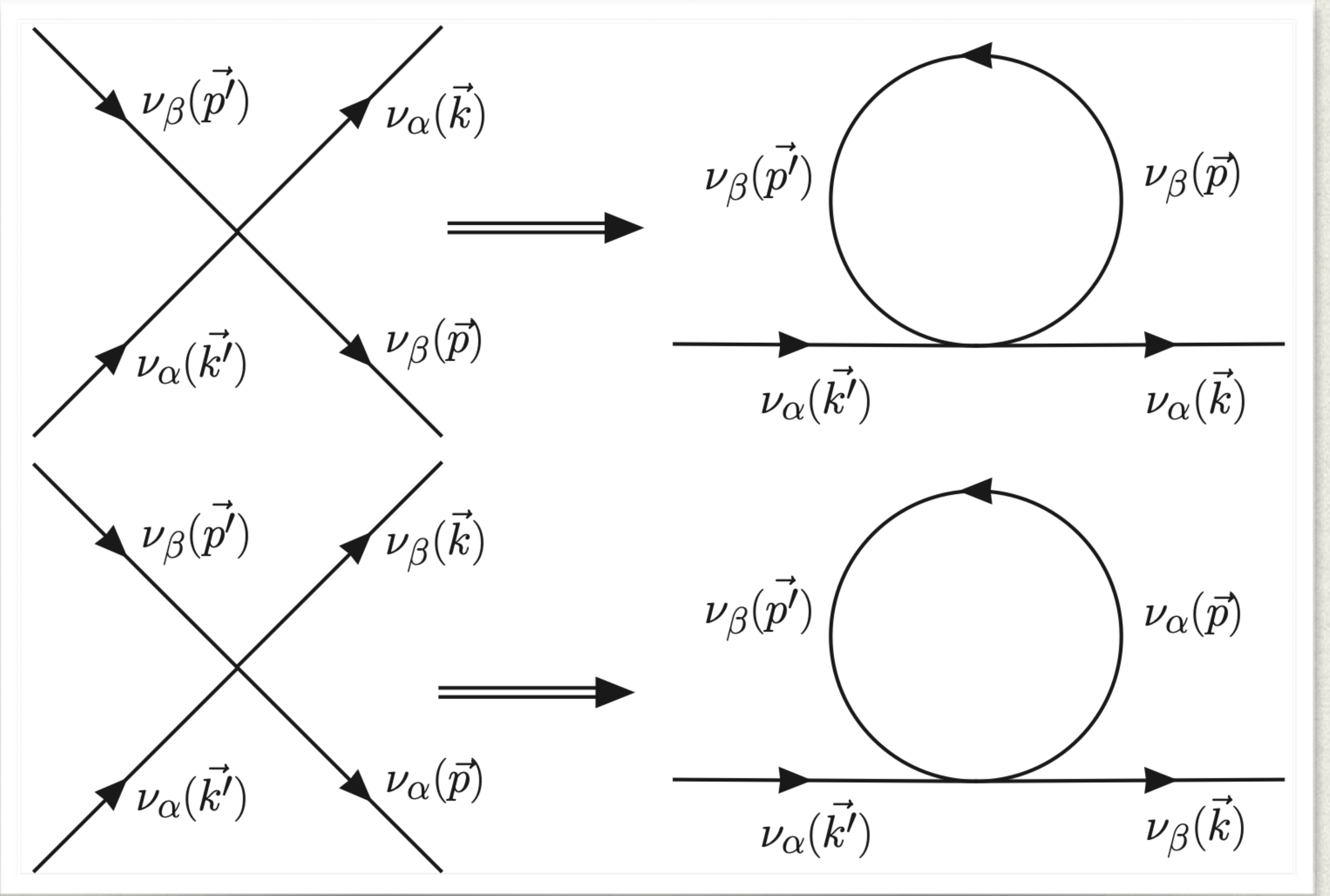
binary neutron-star merger remnant

IN MATTER

DENSE ENVIRONMENTS

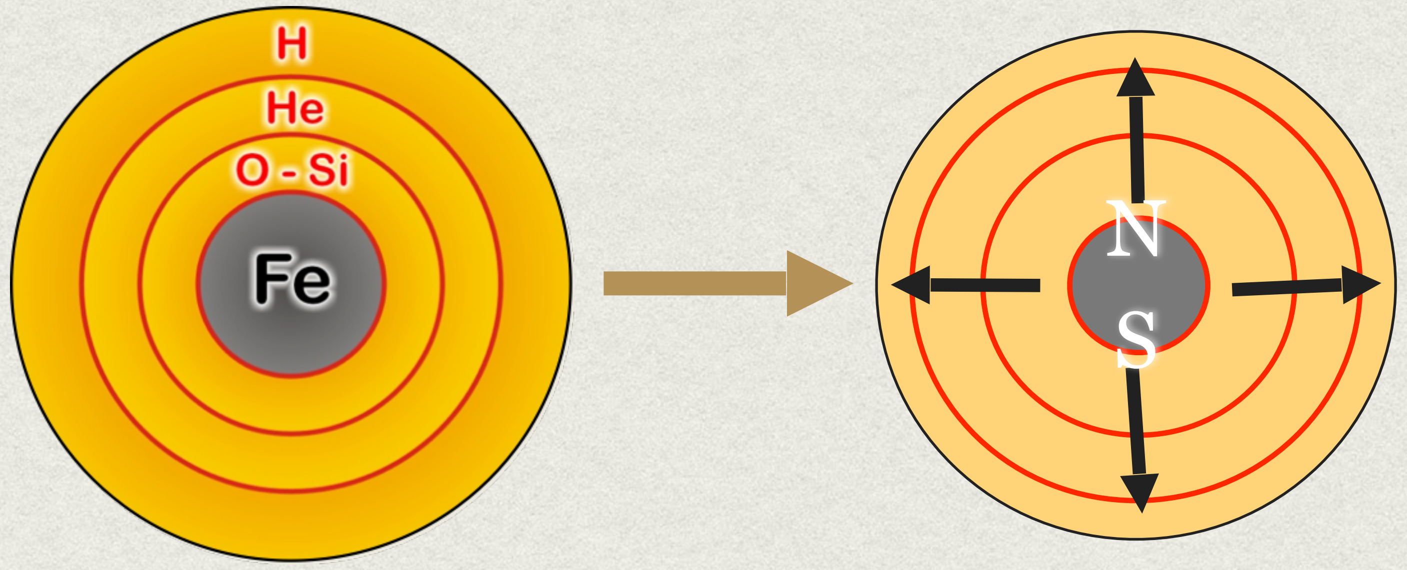
- But « dense » also means in neutrinos. In a supernova explosion about 10^{58} neutrinos with an average energy of 10 MeV produced.

→ These neutrinos interact with each other making the neutrino-neutrino interaction sizable.

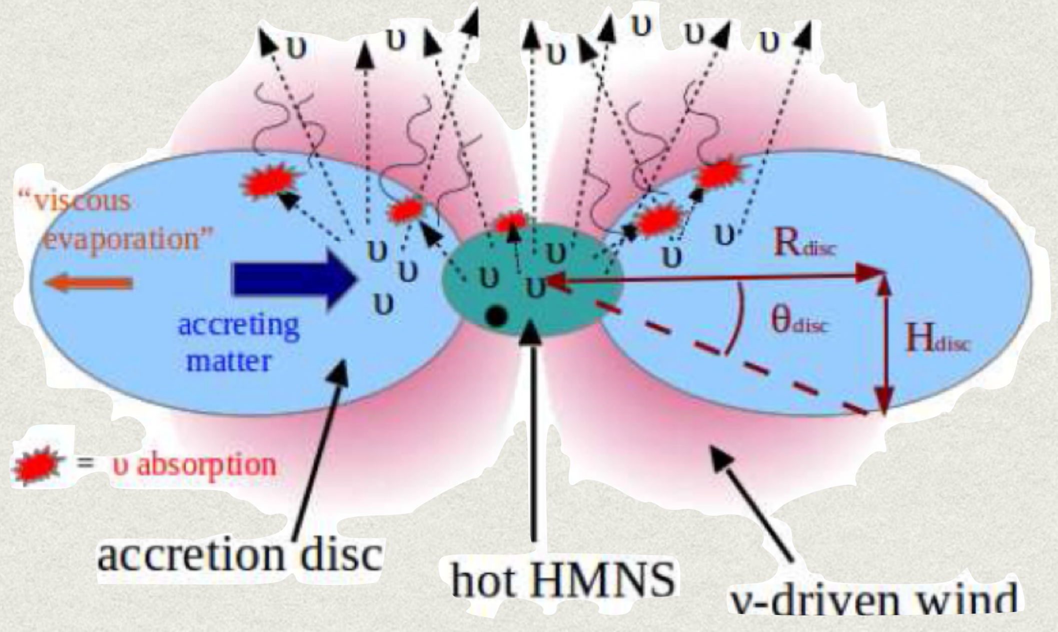


« Neutrino propagation in supernovae is a non-linear many-body problem. »

Pantaleone, PLB 1992



core-collapse supernova



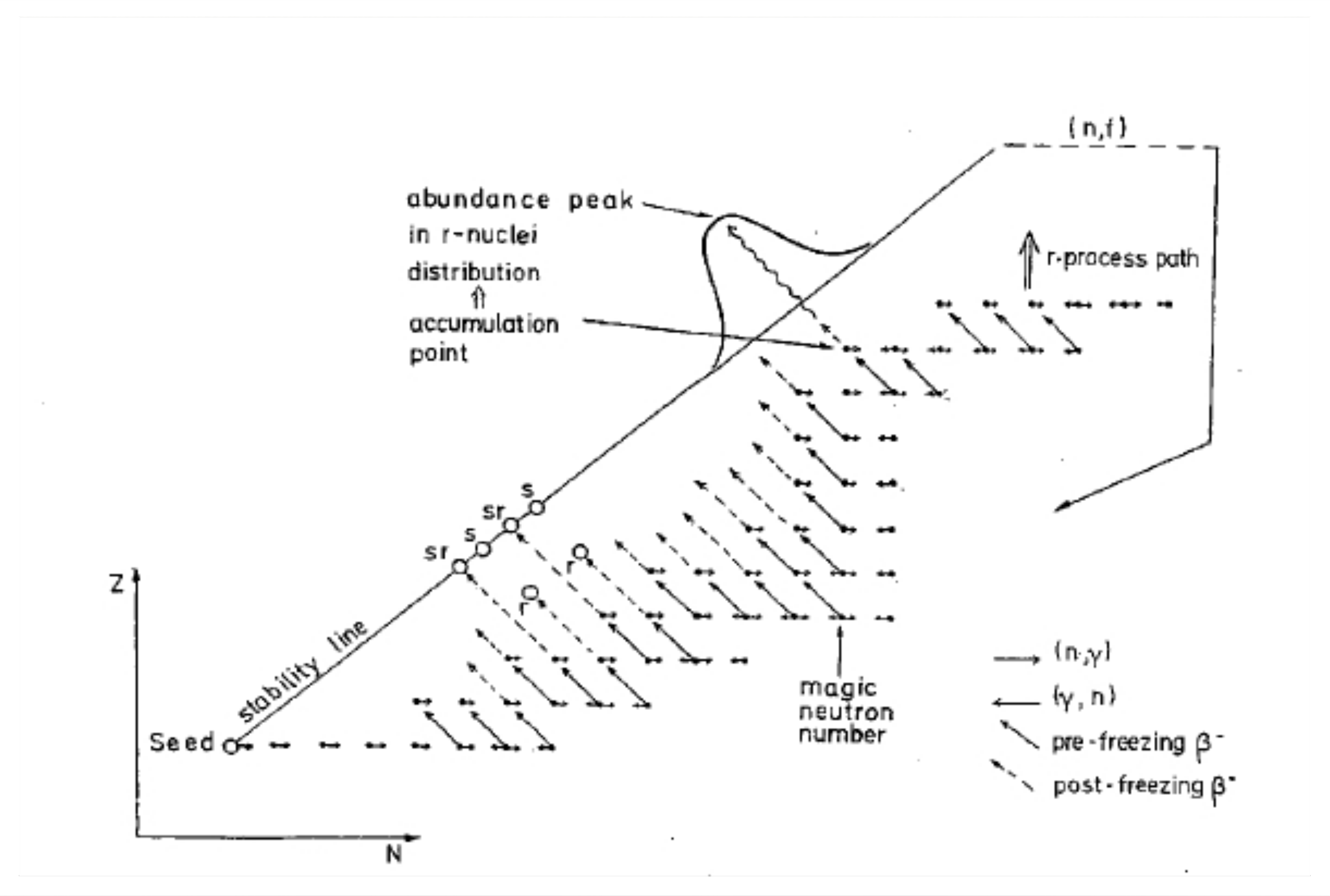
binary neutron-star merger remnant

IN MATTER AND NEUTRINOS

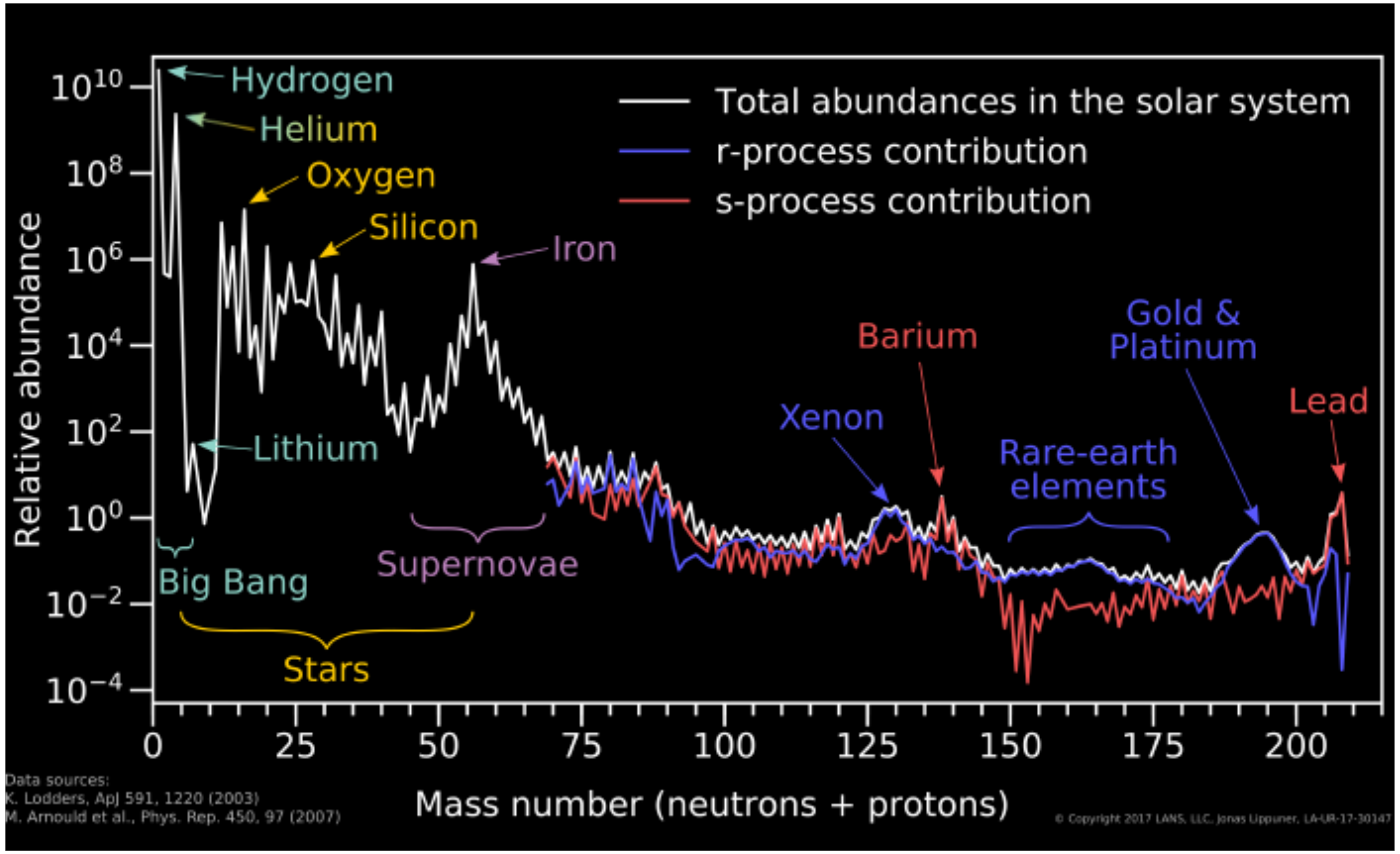
r-PROCESS NUCLEOSYNTHESIS

- 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.

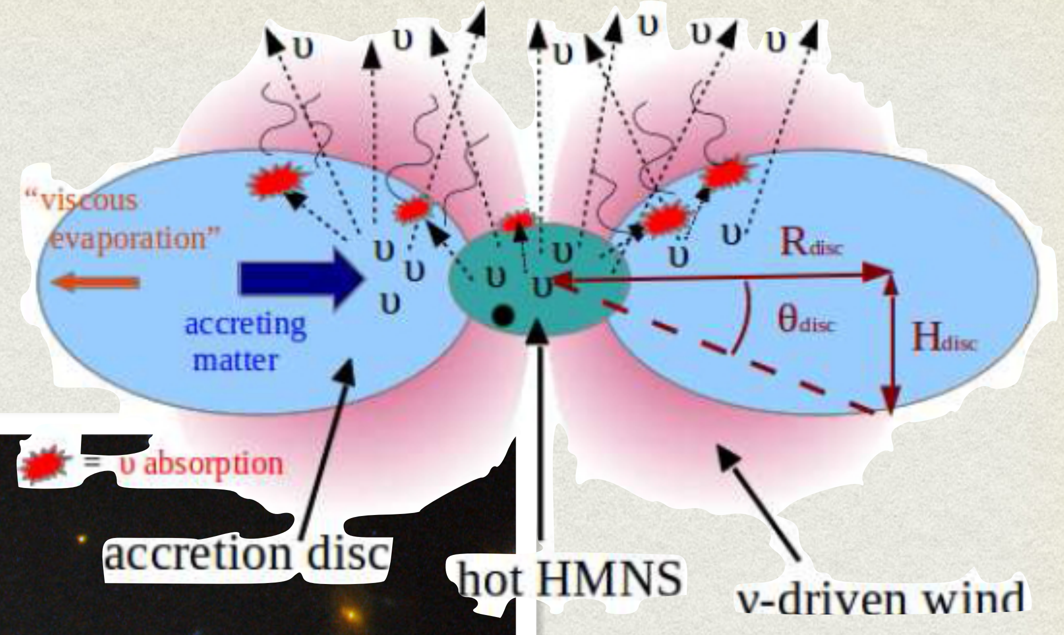


Nucleosynthetic abundances in the solar system



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

A UNIQUE EVENT : GW170817



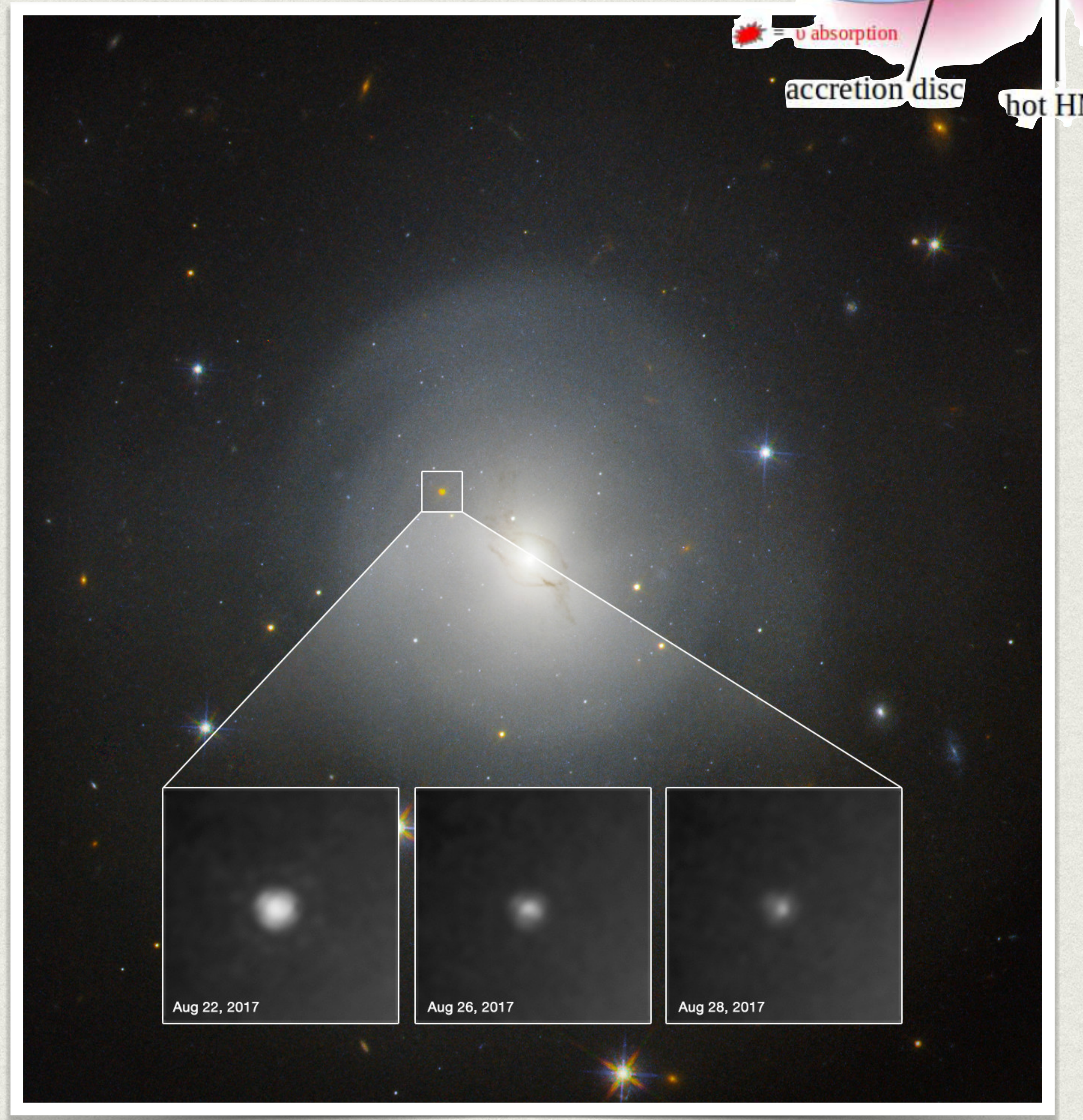
- First measurement of gravitational waves from binary neutron star mergers, in coincidence with a short gamma ray burst and a kilonova.

  Abbot et al, PRL 2017

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

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

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

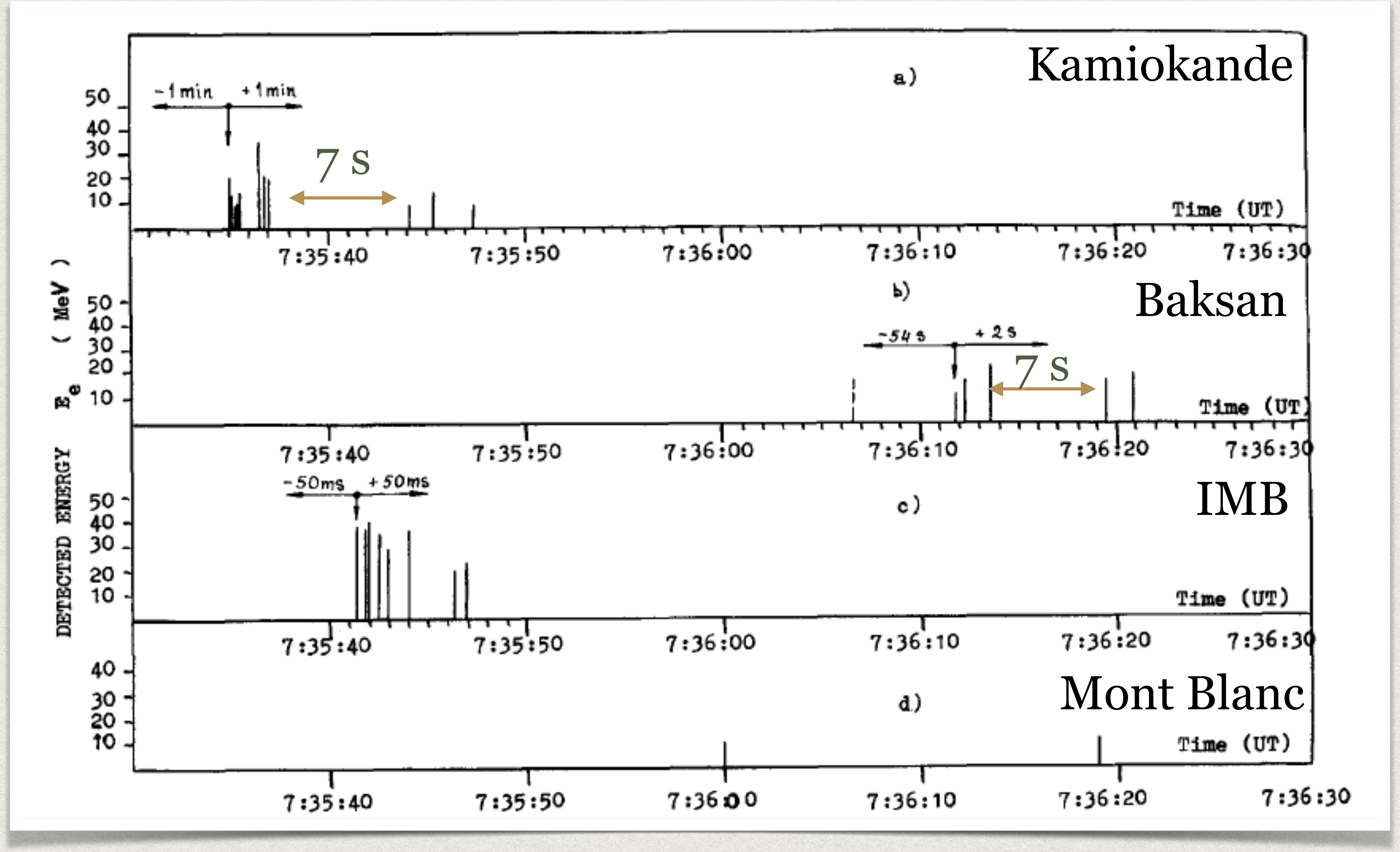


Hubble Space Telescope

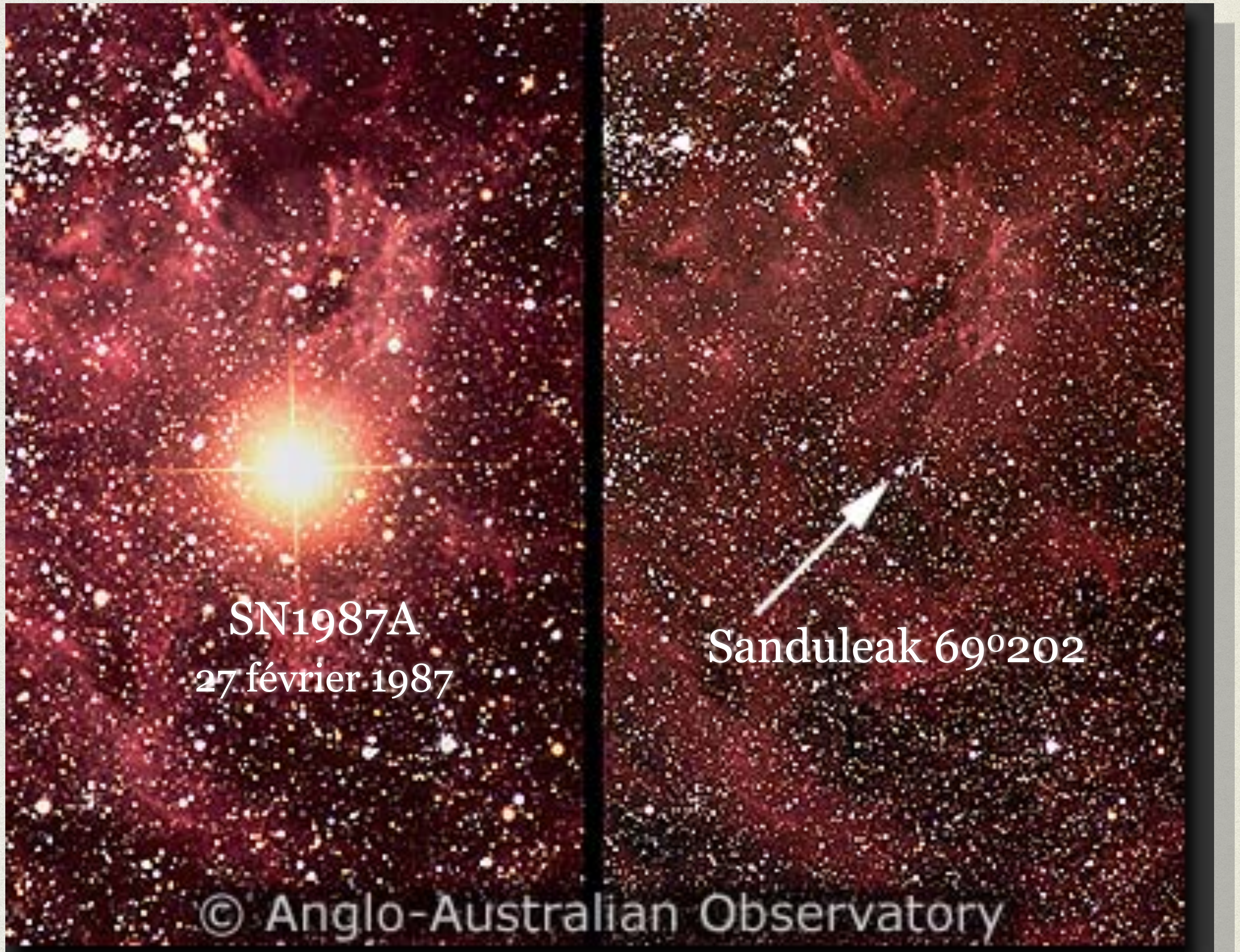
Kilonova, gradually fading away, in NGC 4993,
40 Mpc, 140 million light-years

SN1987A NEUTRINO EVENTS

- First observation of neutrinos from the death of a massive star.
  Observed in all wavelengths.
  24 events detected, plus 5 events in Mont Blanc (debated).



Suzuki, J. Phys. Conf. Ser. (2008)



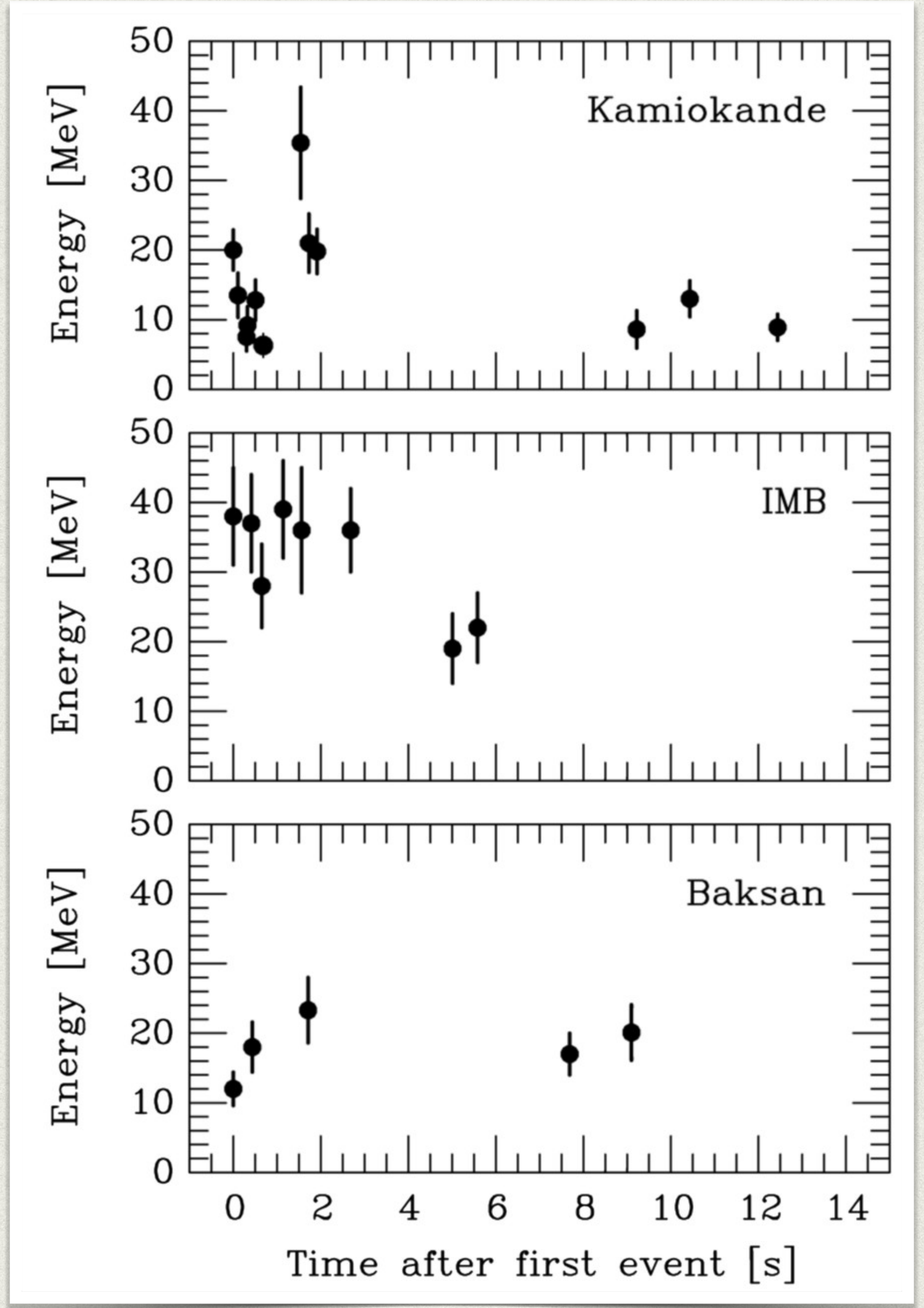
SN1987A, Sanduleak 69°202 blue supergiant exploded, Large Magellanic Cloud

50 ± 5 kpc (163,000 light-years)
Schmidt et al, 1992
49.59 ± 0.09 (stat) ± 0.54 (sys) kpc
Pietrzynski et al., 2019

Consistent with a predicted time spread of about 10 s

A UNIQUE EVENT : SN1987A

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

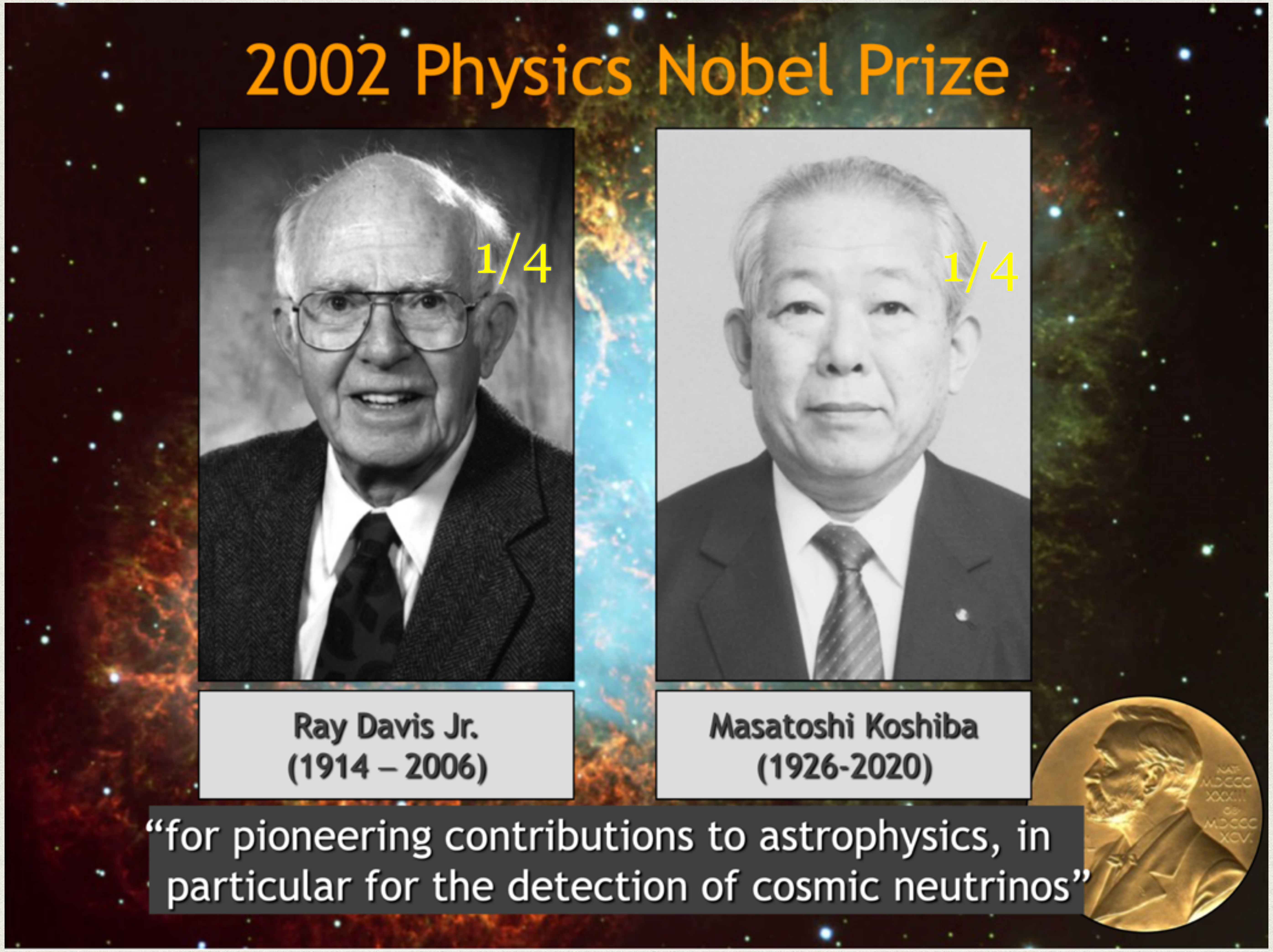


Water Cherenkov detector, 2140 tons

Irvine-Michigan-Brookhaven, Water Cherenkov, 6800 tons

Baksan Scintillator Telescope, 200 tons

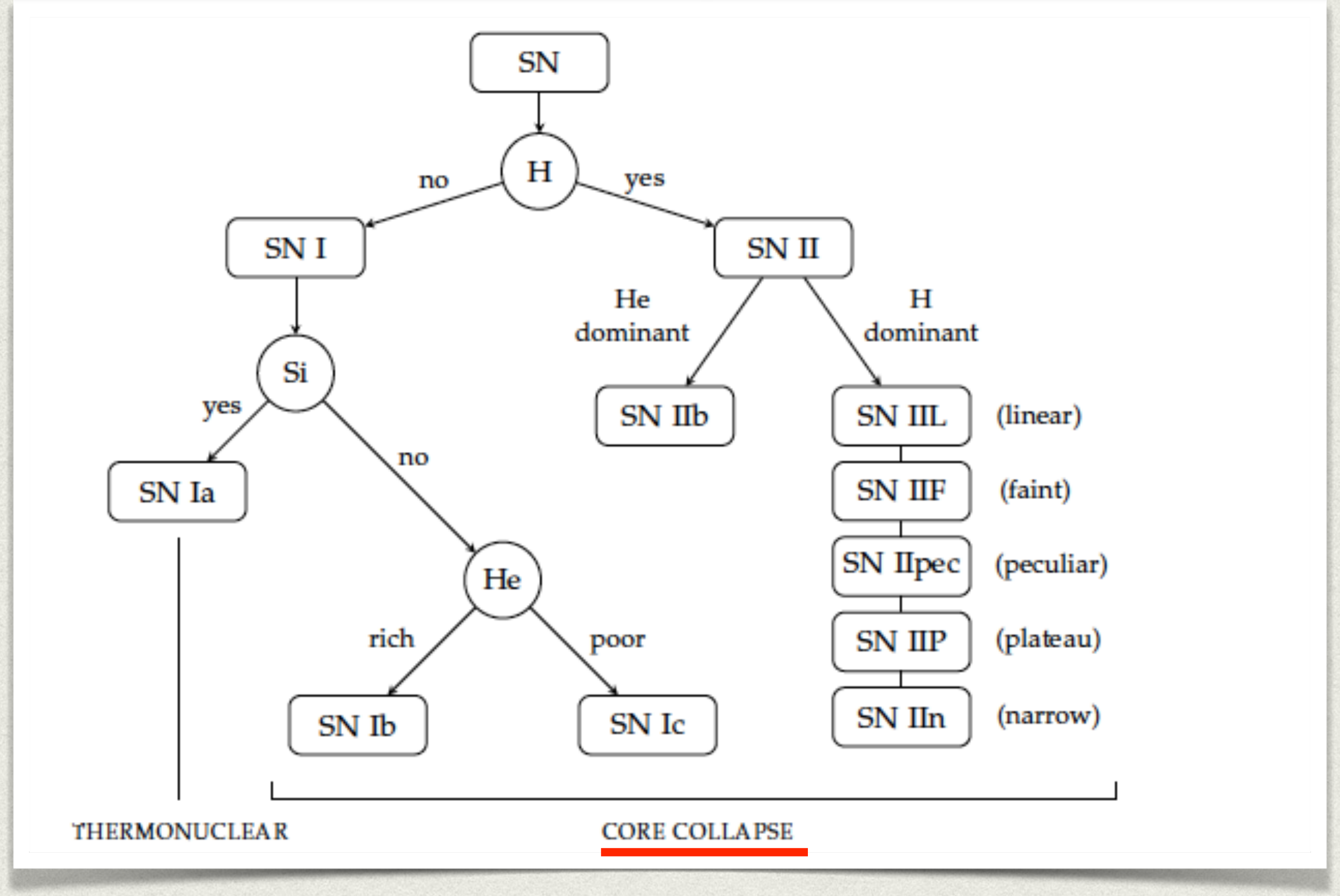
A wonderful laboratory for particle physics and astrophysics.



Prix Nobel en 2002
avec R. Giacconi (1/2)

CORE-COLLAPSE SUPERNOVAE (SNe)

- Spectral classification of supernovae



- Gravitational binding energy taken away by neutrinos.

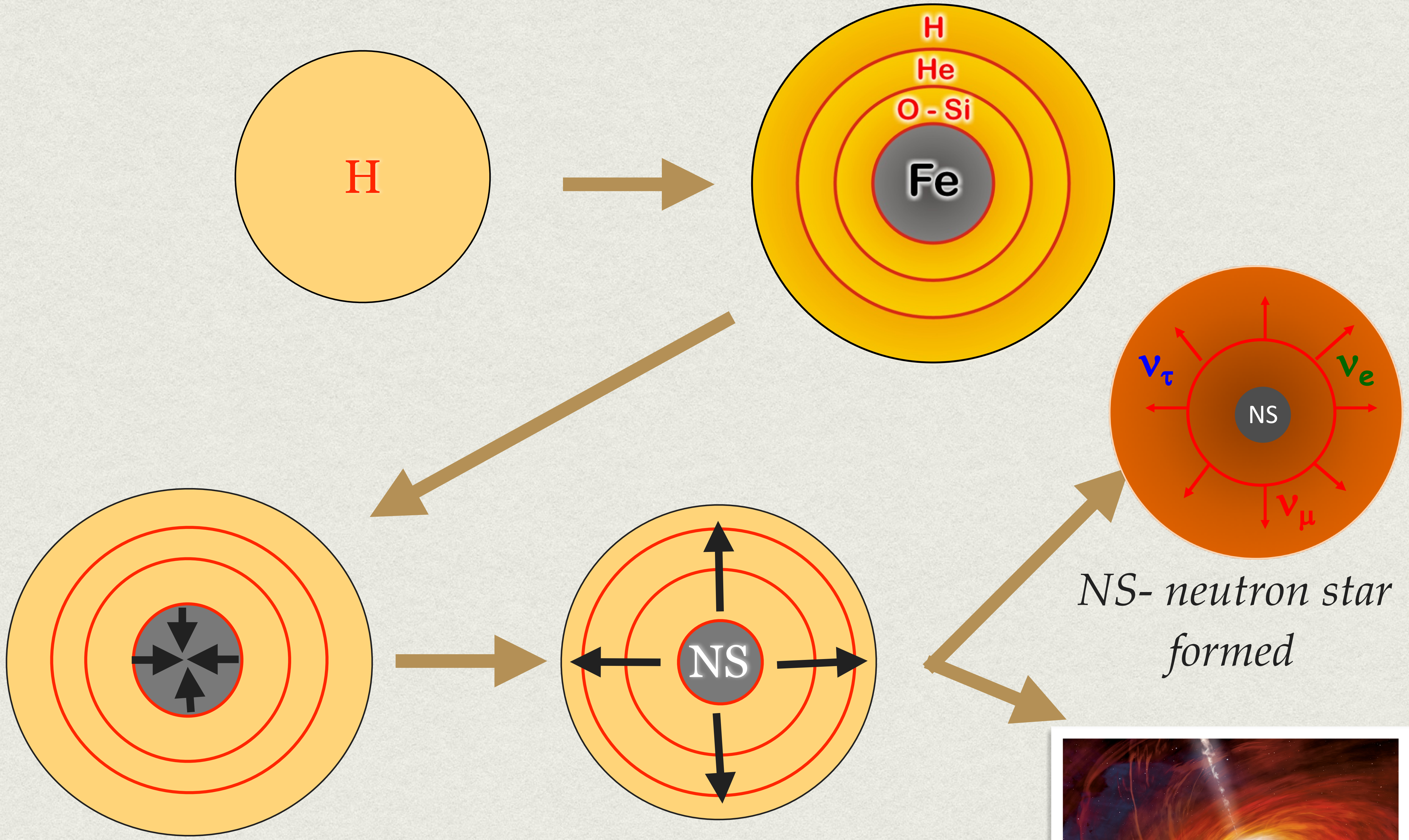
Colgate and White, 1966

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

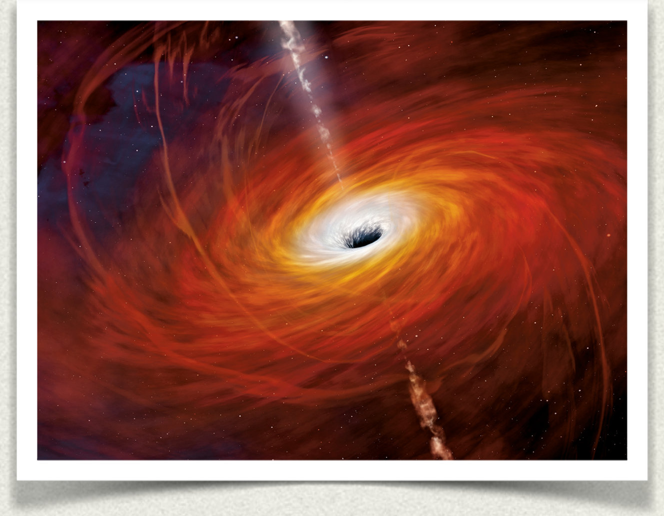
- Energy : 99 % neutrinos, 0.01% photons about 1% explosion kinetic energy

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

Evolution of massive stars - M > 8 M_{sun}



NS- neutron star formed

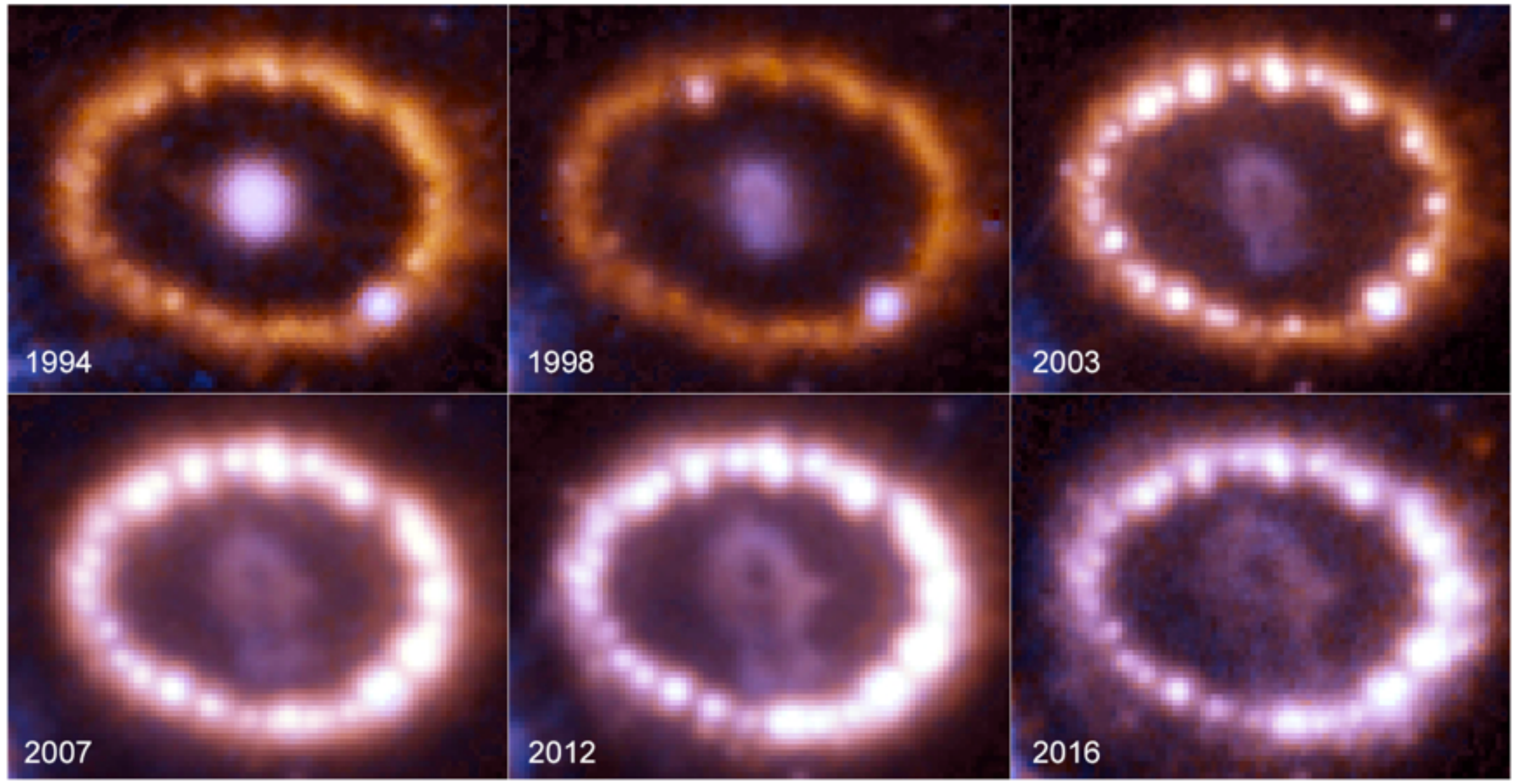


Artist image of a black-hole (BH)

Rare events : 1-3 century.
A candidate is Betelgeuse, 0.2 kpc.

What have we learnt from SN1987A?

Evolution of the ejecta and of the central object over more than 20 y.



Hubble Space Telescope

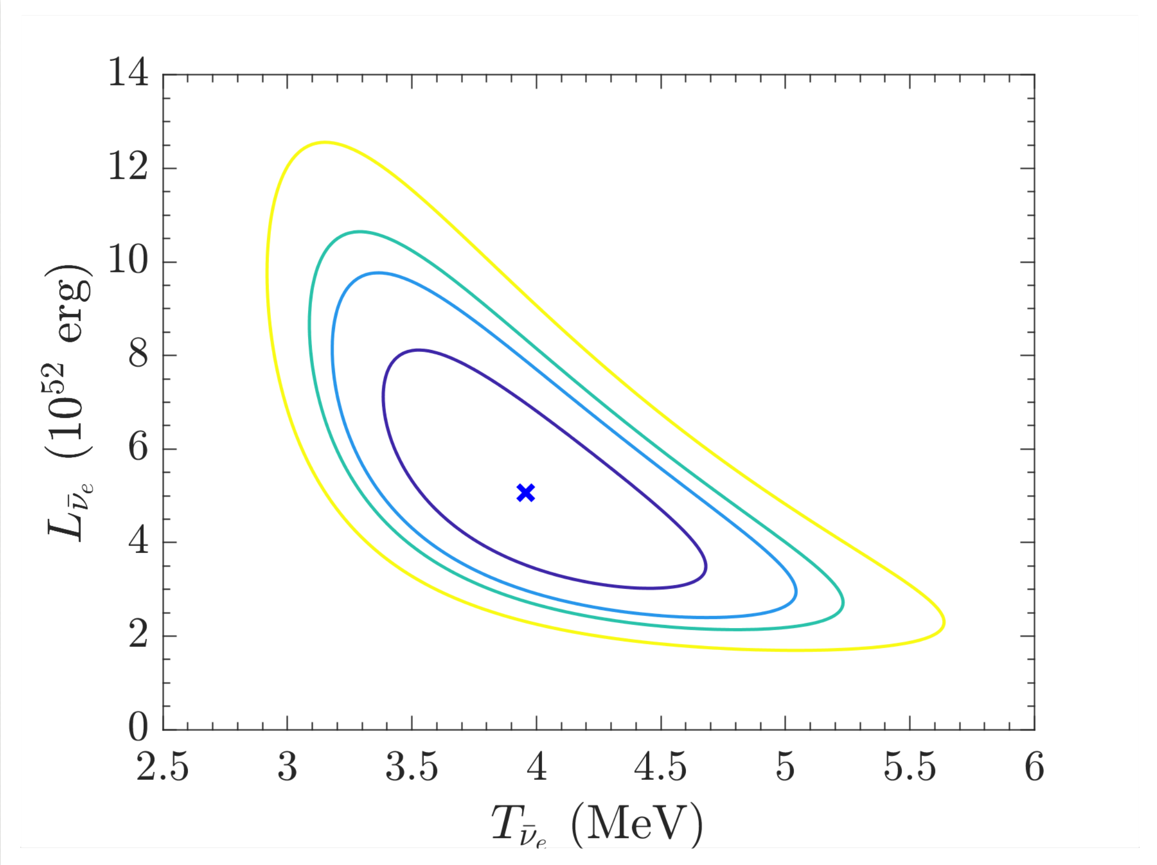
➡ Asphericity of the ejecta shows that the phenomenon is multidimensional and gave momentum to simulations in 2D and 3D.

■ After 30 years, there is finally indications for a compact object remnant: a **neutron star**.

Alp et al, 2018, Cigan et al, 2019,
Page et al., Astroph. Journ. 898, 2020

➡ The supernova neutrino spectra are expected to be quasi-thermal, i.e. (pinched) Fermi Dirac distributions. They are characterized by <u>total luminosity, average energy and width</u>.
Two-dimensional likelihoods of the 24 events: neutrino luminosity and average energy as expected.

$L_\nu = 6 \times L_{\bar{\nu}_e} = 3\ 10^{53} erg \qquad \langle E_\nu \rangle = 3.15\ T \approx 12\ \mathrm{MeV}$



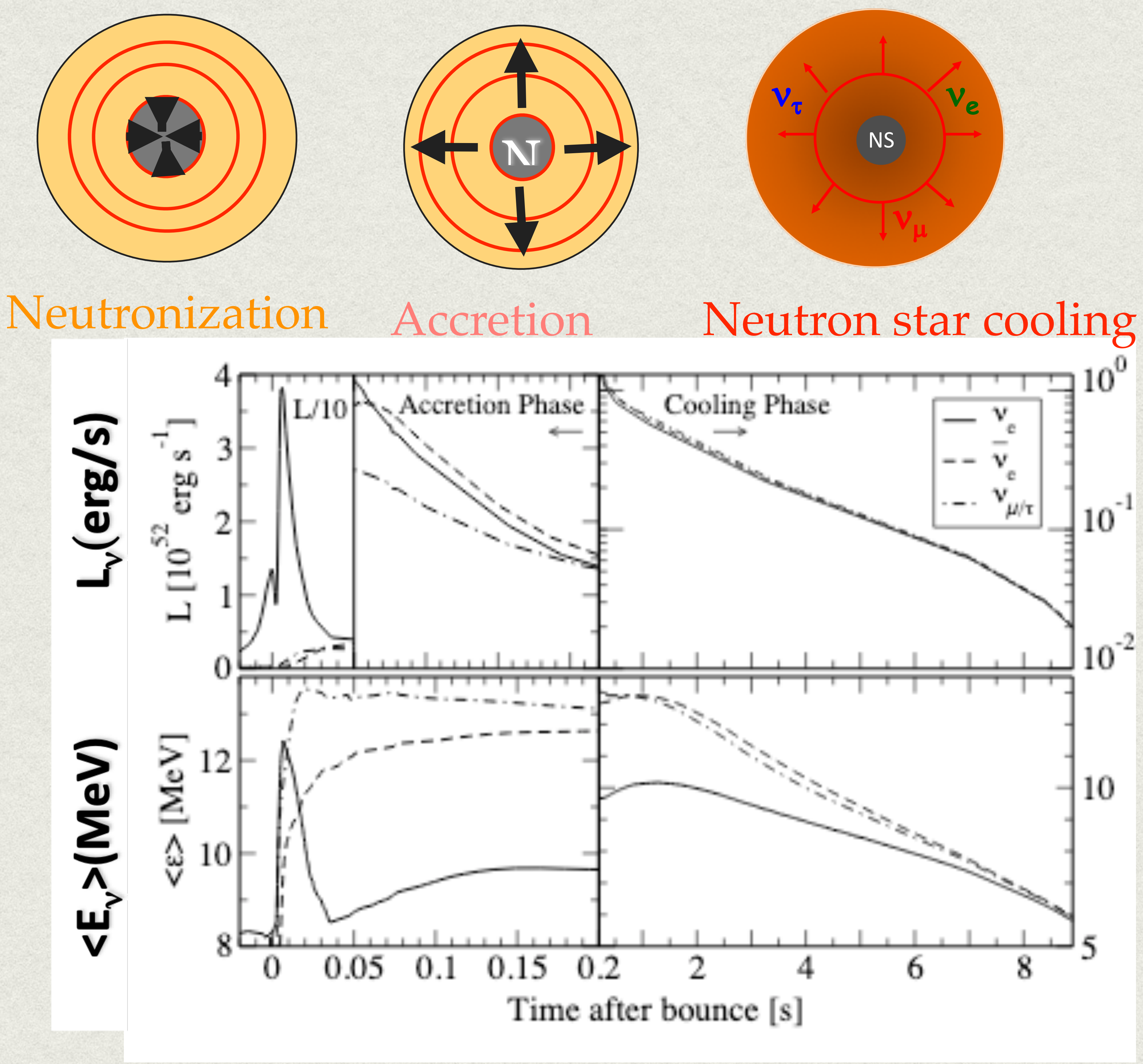
Ivanez-Ballesteros, Volpe, arXiv:2307.03549

THE SUPERNOVA EXPLOSION MECHANISM

- Hoyle and Fowler (1960) suggested that the stellar death of massive stars is due to the core implosion.
  Colgate and Johnson (1960) pointed out that the bounce of the neutron star forming, launches a shock that ejects promptly the matter to make it unbound.
  Colgate and White (1966) neutrinos deposit energy behind the shock triggering the explosion: *prompt explosion mechanism*.

  It is more than sixty years…
  There has been a crucial step forward every decade.

  see e.g. Mezzacappa (2022), arXiv: 2205.13438



- Bayesian analysis considering only cooling models or accretion+cooling models.

  «We find two-component models to be 100 more probable than single-model component. »

  Loredo and Lamb, PLB 205 (1988)

THE SUPERNOVA EXPLOSION MECHANISM: today

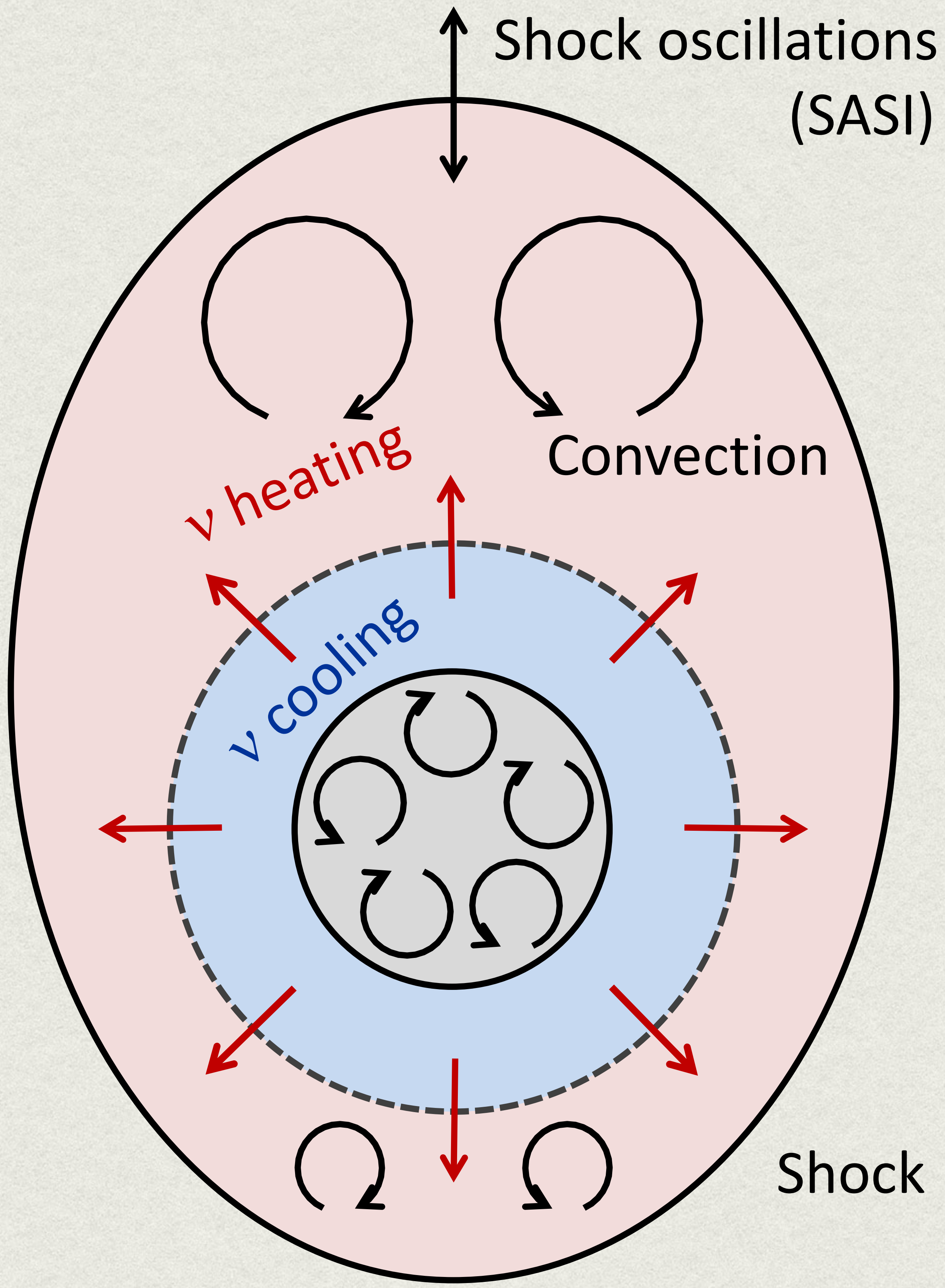
- Nowadays, 2D and 3D simulations available for different progenitors by different groups.

- Since 5-10 years there is an emerging consensus across the supernova community: the majority of supernovae explodes because of the delayed neutrino-heating mechanism, where neutrinos efficiently reheat the shock aided by turbulent-driven convection and the hydrodynamic instabilities (SASI).

Wilson (1982), Bethe and Wilson (1985)

see e.g. Mezzacappa (2022), arXiv: 2205.13438

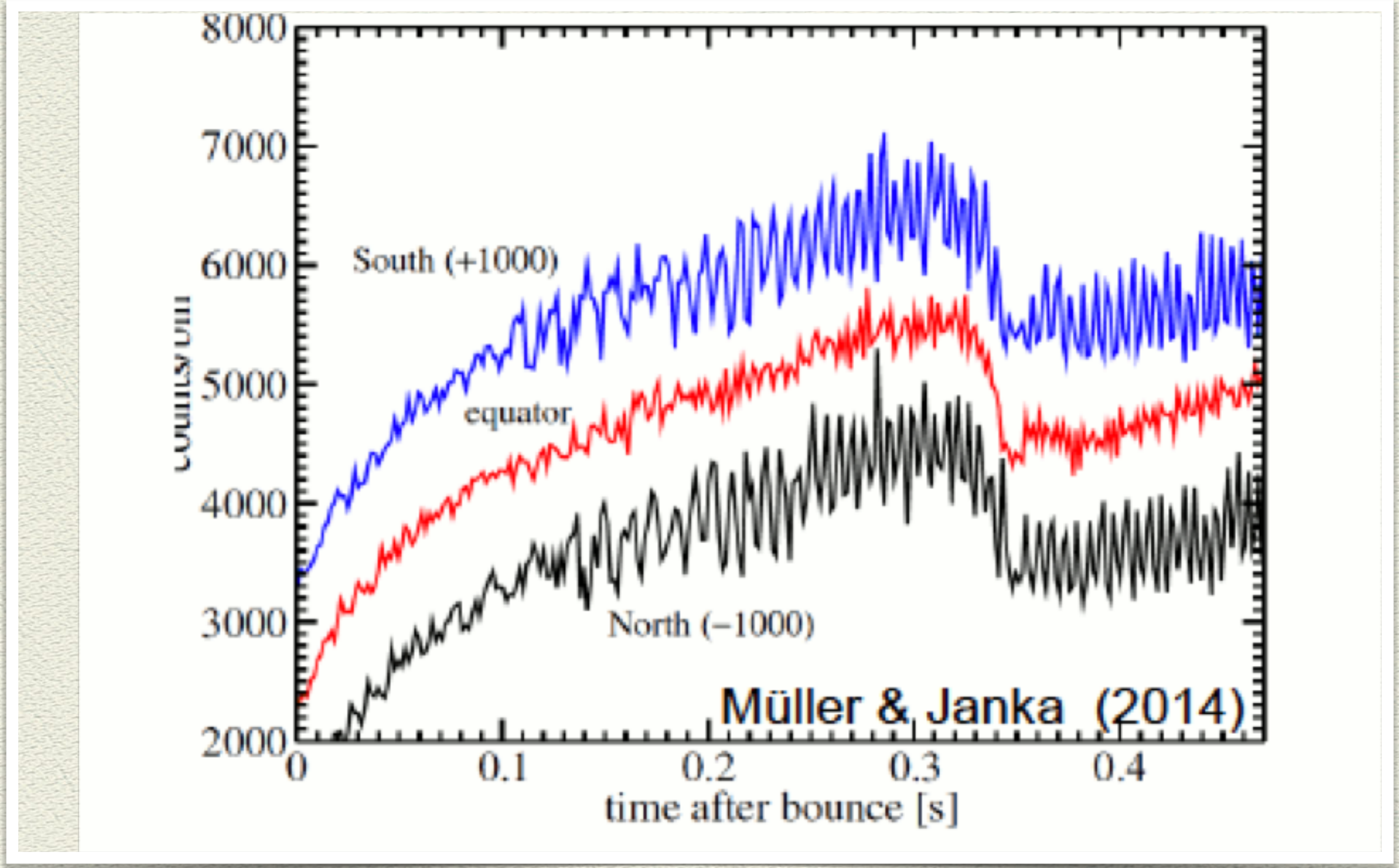
see also Foglizzo et al, arXiv:1501.01334



Explosion mechanism and neutrino signal

Supernova neutrino time signal : signature of the SASI instability (ICECUBE)

Crucial confirmation of the delayed neutrino driven mechanism for supernova explosions



SN1987A as a LABORATORY for PARTICLE PHYSICS

- Since neutrinos are massive they can decay.
  Neutrino non-radiative two-body decay:

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

ϕ a massless (pseudo)scalar particle

due to tree-level (pseudo)scalar couplings.

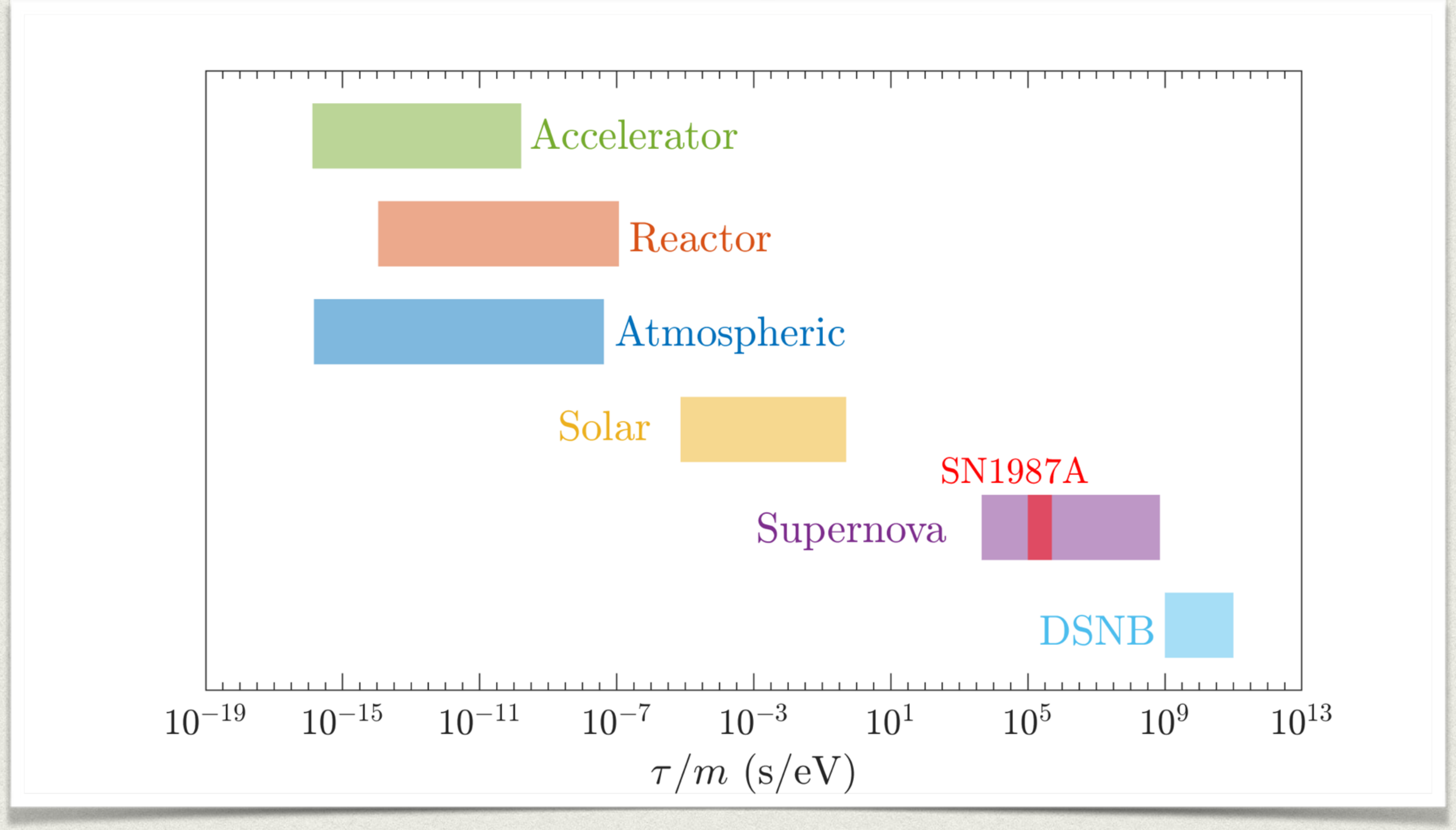
$$\mathcal{L} = g_{ij}\bar{\nu}_i\nu_j\phi + h_{ij}\bar{\nu}_i\gamma_5\nu_j\phi + H.c. \ ,$$

- The neutrino fluxes get suppressed by the factor

$$\exp\left(-\frac{L}{E}\times\frac{m}{\tau}\right)$$

L - souce-detector distance
E - neutrino energy
m - neutrino mass
τ - lifetime

Sensitivity to non-radiative decay from different neutrino sources

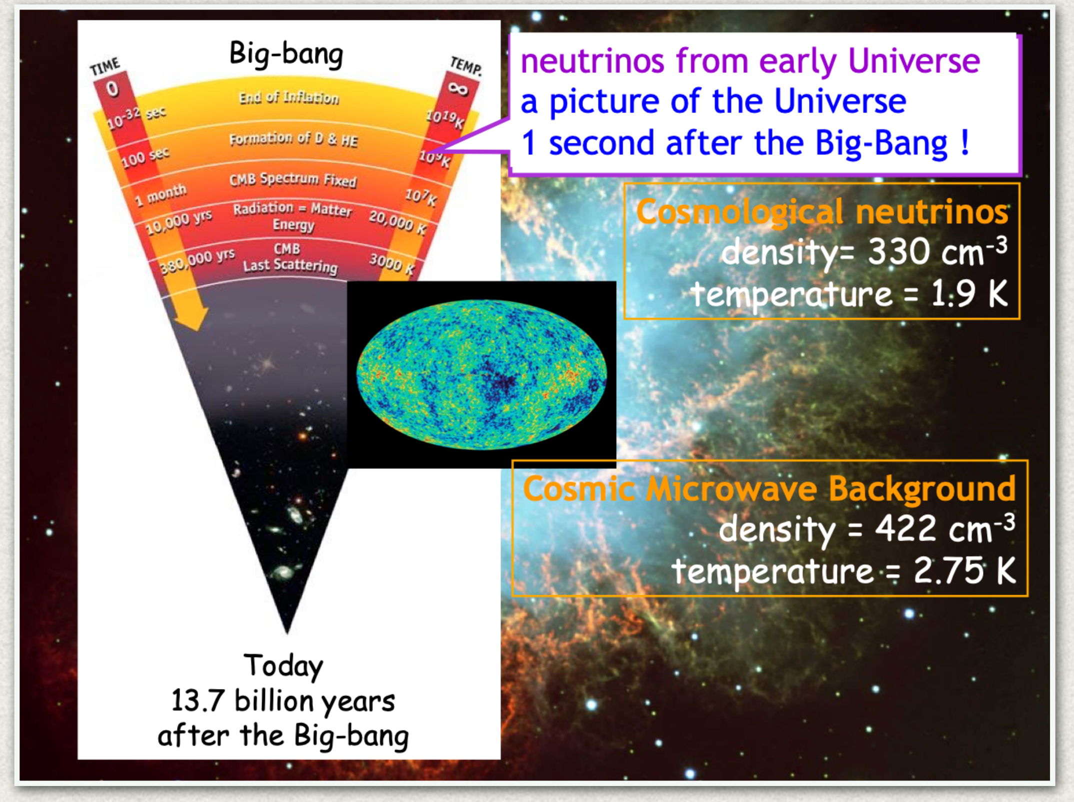


Ivanez-Ballesteros and Volpe, Phys. Lett. B (2023), arXiv: 2307.03549

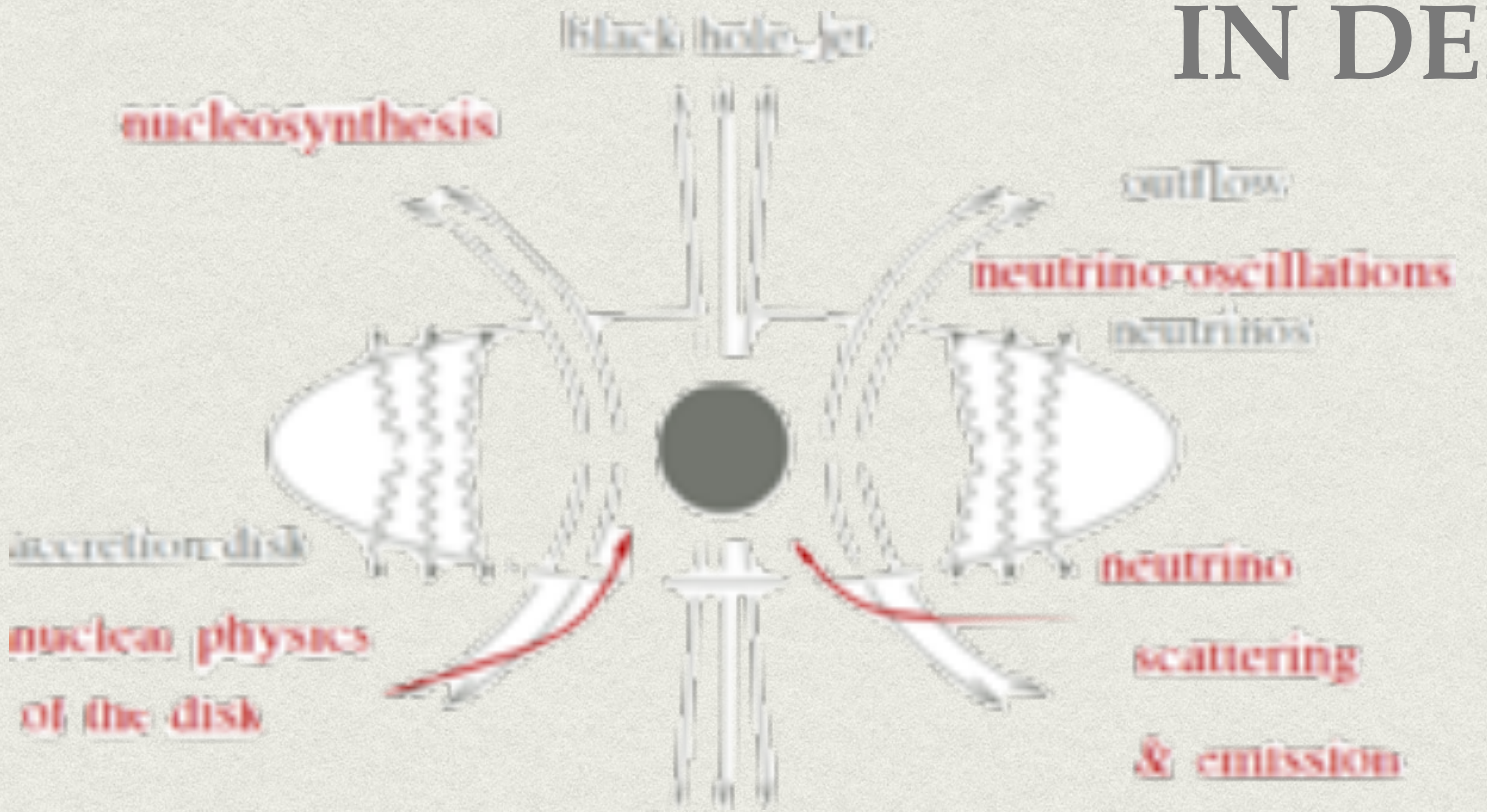
- Likelihood analysis (7D) of the 24 SN1987 neutrino events in Kamiokande, IMB and Baksan, including non-radiative decay.

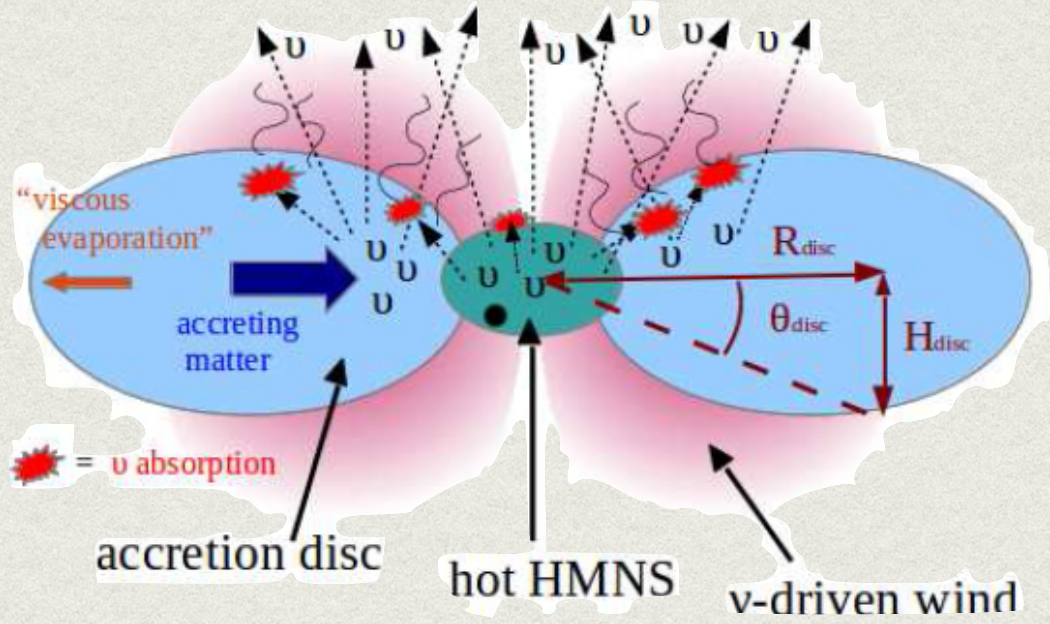
$\tau/m \geq 2.4\ (1.2)\times 10^5$ s/eV at 68 (90) % CL

A tight bound on tau/m, competitive with cosmology for inverted mass ordering



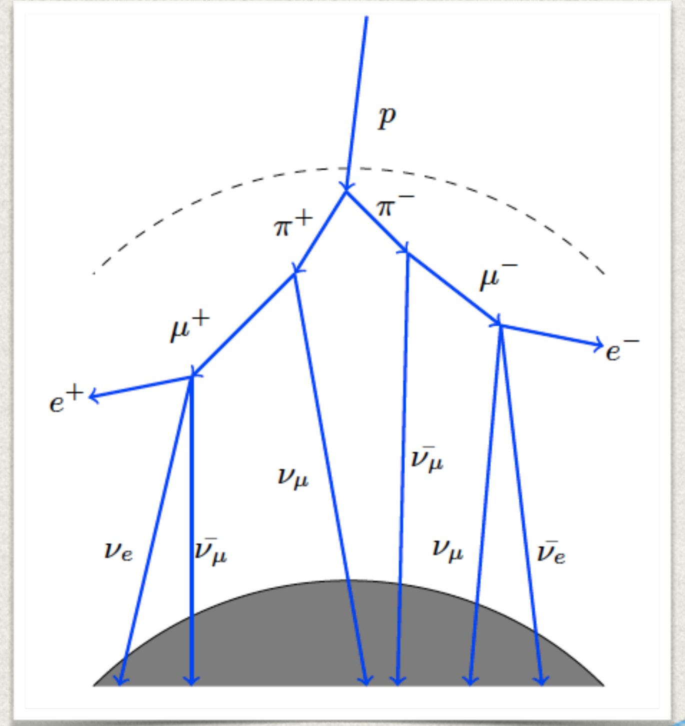
NEUTRINO EVOLUTION IN DENSE MEDIA



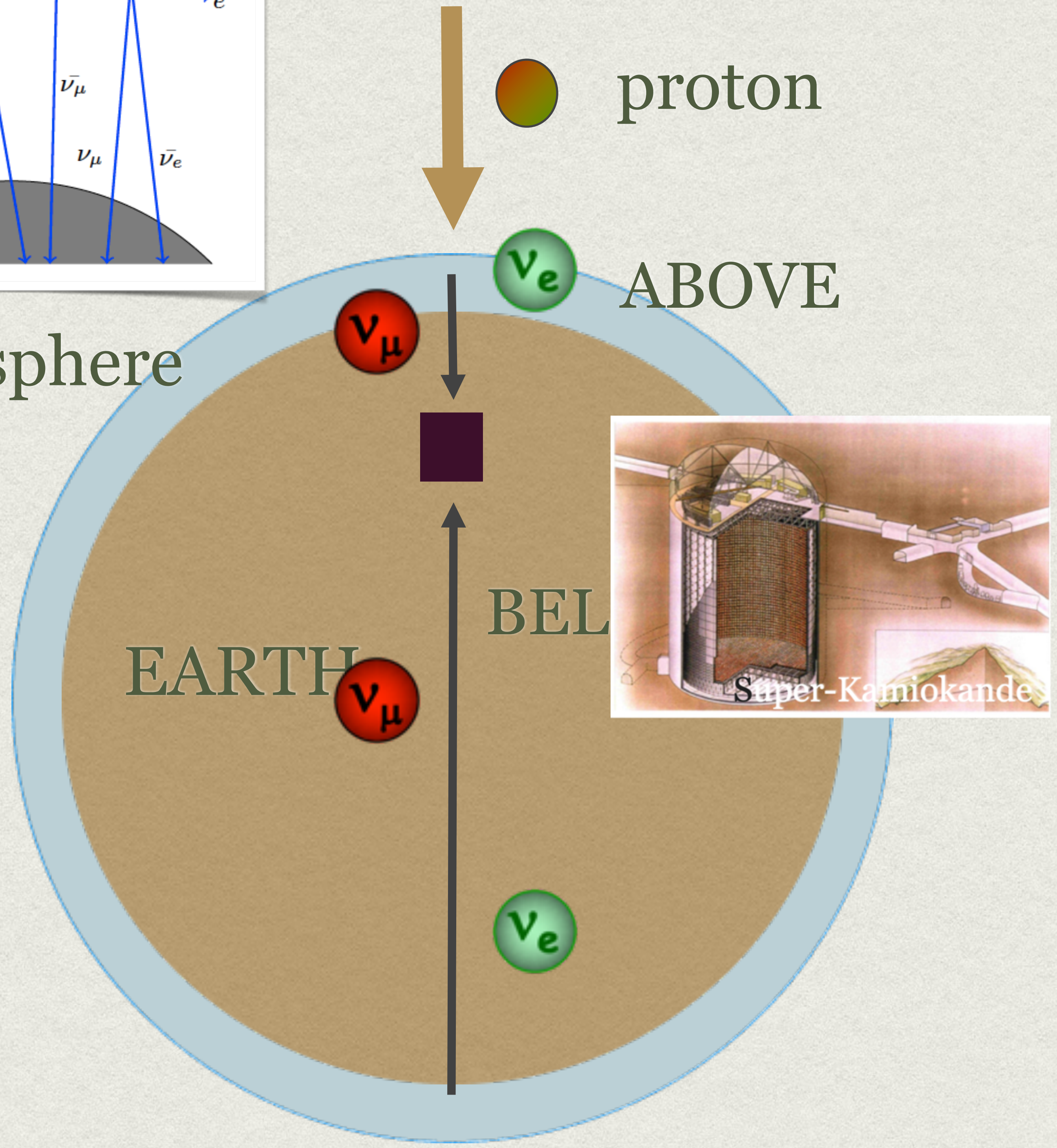


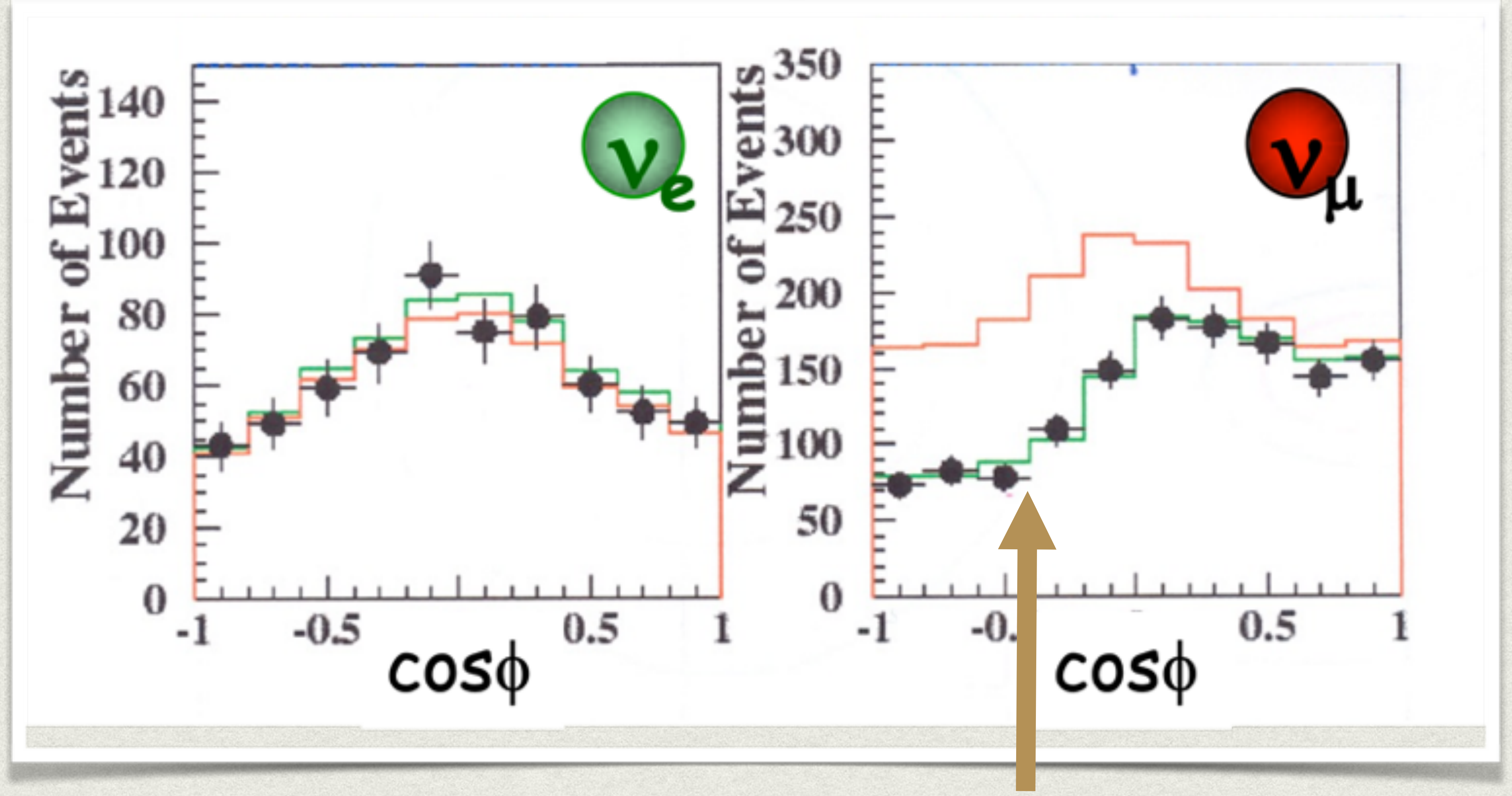
THE OSCILLATION DISCOVERY

- The Super-Kamiokande Collaboration (1998) discovered that atmospheric neutrinos oscillate while traversing the Earth

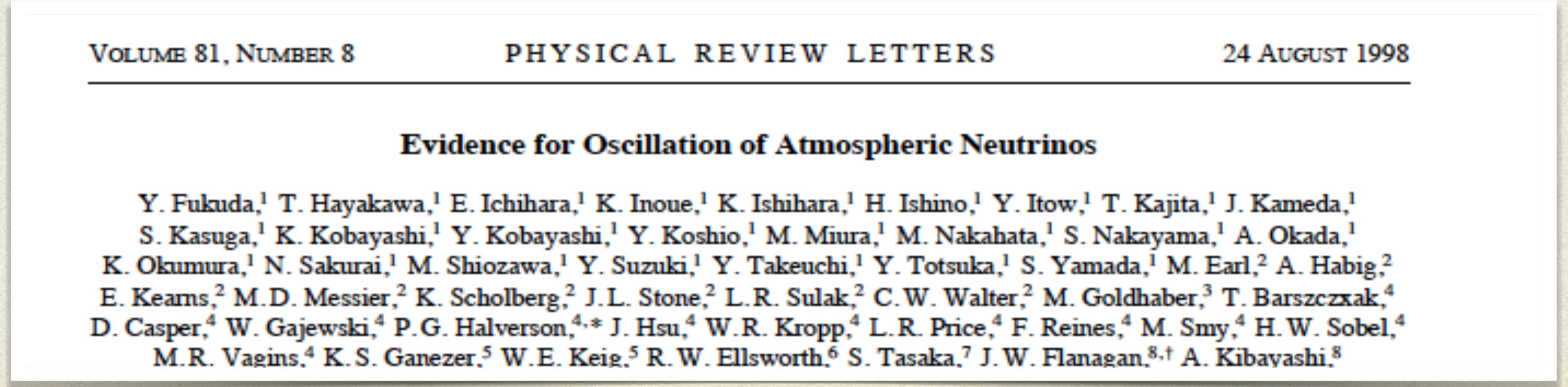


atmosphere





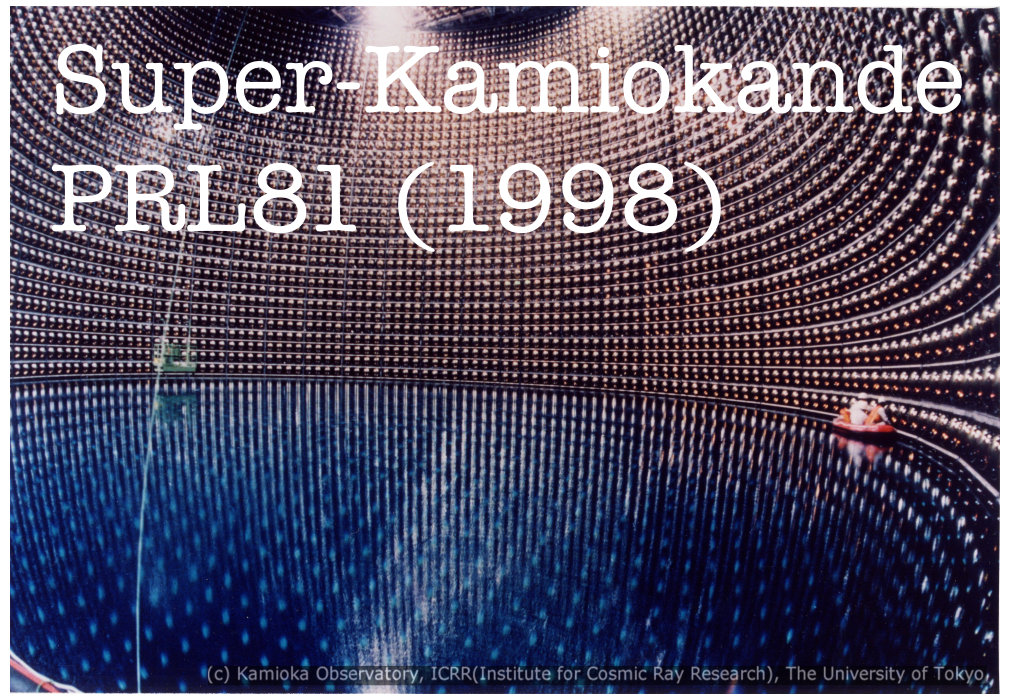
→ Muon neutrinos oscillate into tau neutrinos


Volume 81, Number 8 PHYSICAL REVIEW LETTERS 24 August 1998

Evidence for Oscillation of Atmospheric Neutrinos

Y. Fukuda,[1] T. Hayakawa,[1] E. Ichihara,[1] K. Inoue,[1] K. Ishihara,[1] H. Ishino,[1] Y. Itow,[1] T. Kajita,[1] J. Kameda,[1] S. Kasuga,[1] K. Kobayashi,[1] Y. Kobayashi,[1] Y. Koshio,[1] M. Miura,[1] M. Nakahata,[1] S. Nakayama,[1] A. Okada,[1] K. Okumura,[1] N. Sakurai,[1] M. Shiozawa,[1] Y. Suzuki,[1] Y. Takeuchi,[1] Y. Totsuka,[1] S. Yamada,[1] M. Earl,[2] A. Habig,[2] E. Kearns,[2] M.D. Messier,[2] K. Scholberg,[2] J.L. Stone,[2] L.R. Sulak,[2] C.W. Walter,[2] M. Goldhaber,[3] T. Barszczxak,[4] D. Casper,[4] W. Gajewski,[4] P.G. Halverson,[4,*] J. Hsu,[4] W.R. Kropp,[4] L.R. Price,[4] F. Reines,[4] M. Smy,[4] H.W. Sobel,[4] M.R. Vagins,[4] K.S. Ganezer,[5] W.E. Keig,[5] R.W. Ellsworth,[6] S. Tasaka,[7] J.W. Flanagan,[8,†] A. Kibayashi,[8]

Solution of the solar neutrino puzzle

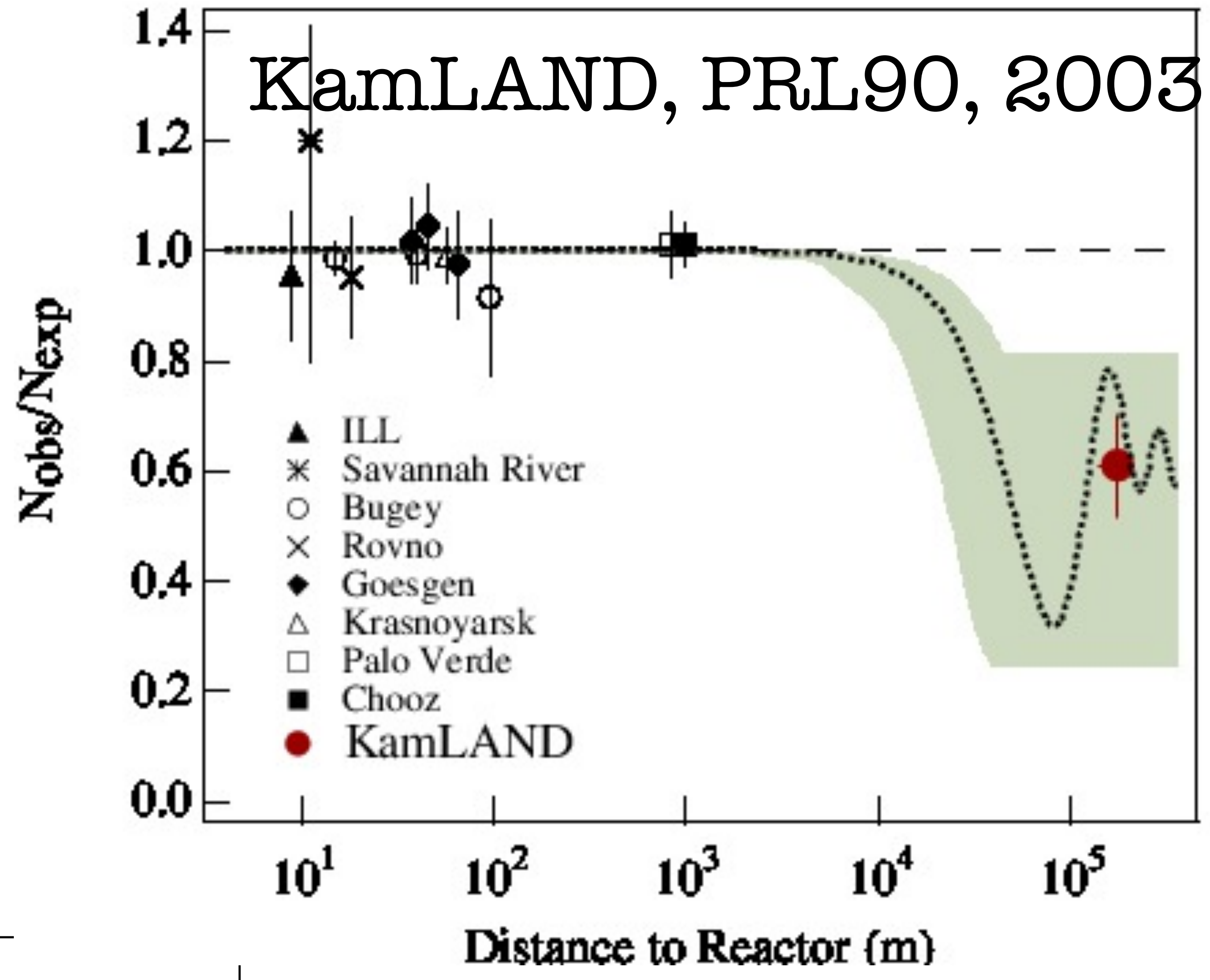


50 kton, water Cherenkov (Japan)

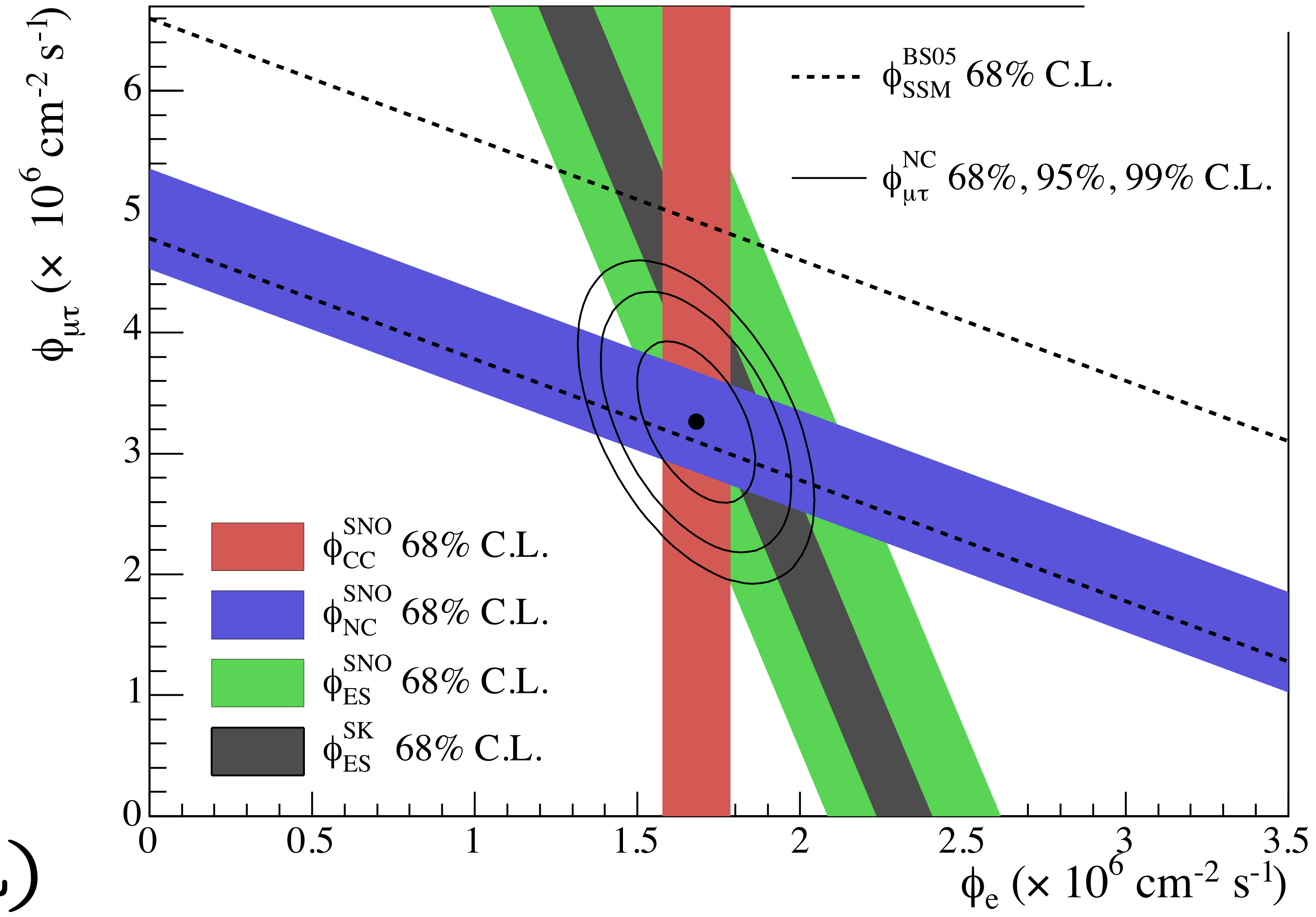
1) The ν oscillation discovery with atmospheric ν.

3) Kamland identifies the MSW large-mixing-angle (MSW) solution.

1 kton, scintillator (Japan), reactor $\overline{\nu}_e$



1 kton, heavy water (Canada)



$\nu_e + D \rightarrow p + p + e^-$ (CC)

$\nu_x + D \rightarrow \nu_x + p + n$(NC)

$\nu_x + e^- \rightarrow \nu_x + e^-$ (ES)

2) The total solar flux consistent with SSM. Non-zero ν_μ,ν_τ flux (5.3 σ).

2015 Nobel Prize

THE PMNS MATRIX

- For an arbitrary number of neutrino families N, the flavor and mass basis are related by the unitary Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix $(U^{-1} = U^{\dagger})$:

$$|\nu_\alpha\rangle = \sum U^*_{\alpha i}\, |\nu_i\rangle\, .$$

$\alpha = e, \mu, \tau, ..., N$
Flavor index

$i = 1, 2, 3, ..., N$
Mass index

- For three neutrino flavors the PMNS matrix depends on three mixing angles, one Dirac and two Majorana phases:

$$c_{ij} = \cos\theta_{ij} \quad s_{ij} = \sin\theta_{ij}$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

θ_{23} θ_{13} θ_{12}

THE CP violating phase INTRODUCES A ν-$\bar{\nu}$ ASYMMETRY.

→ For three mixing angles are precisely known, for the Dirac phase we have a hint (1.5-2 sigma), the Majorana phases are unknown (not important for oscillations).

2015 NOBEL PRIZE IN PHYSICS

6 October 2015

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2015 to

Takaaki Kajita
Super-Kamiokande Collaboration
University of Tokyo, Kashiwa, Japan

and

Arthur B. McDonald
Sudbury Neutrino Observatory Collaboration
Queen's University, Kingston, Canada

"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

Super-Kamiokande

SNO

NEUTRINO EVOLUTION EQUATIONS IN VACUUM

- **The phenomenon can be accounted for by a Schrödinger-like equation for the <u>neutrino flavor states</u>**, with $\mathcal{H}$ the neutrino Hamiltonian:

$$|\nu_\alpha(0)\rangle = |\nu_\alpha\rangle \qquad i\frac{d}{dt}|\nu_\alpha(t)\rangle = \mathcal{H}^f_{vac}\,|\nu_\alpha(t)\rangle$$

- The Hamiltonian in the mass basis is diagonal and depends on the neutrino energies:

$$|\nu_\alpha\rangle = \sum U^*_{\alpha i}\,|\nu_i\rangle\,. \qquad \mathcal{H}^f_{\text{vac}} = U\mathcal{H}_{\text{vac}}U^\dagger. \quad \mathcal{H}_{\text{vac}} = \text{diag}(E_k) \qquad E_k = \sqrt{\mathbf{p}_k^2 + m_k^2}$$

$$\rightarrow \quad i\frac{d}{dt}|\nu_\alpha(t)\rangle = [U\mathcal{H}_{vac}U^\dagger]\,|\nu_\alpha(t)\rangle$$

- **Now, we introduce the <u>neutrino flavor amplitudes</u>**, for a neutrino to remain in its flavor, or the amplitude to change into another flavor:

$$\psi_{\alpha\alpha}(t) = \langle\nu_\alpha|\nu_\alpha(t)\rangle \qquad P(\nu_\alpha \to \nu_\alpha, t) = |\psi_{\nu_{\alpha\alpha}}(t)|^2 \quad \text{disappearance probability}$$

$$\psi_{\alpha\beta}(t) = \langle\nu_\beta|\nu_\alpha(t)\rangle \qquad \psi_{\alpha\beta}(0) = \delta_{\alpha\beta} \qquad P(\nu_\alpha \to \nu_\beta, t) = |\psi_{\nu_{\alpha\beta}}(t)|^2 \quad \text{appearance probability}$$

$$\sum_\beta P(\nu_\alpha \to \nu_\beta)(t) = 1$$

NEUTRINO EVOLUTION EQUATIONS IN VACUUM

- The evolution equations for the neutrino amplitudes can be deduced from the previous equation and read

$$i\frac{d}{dt}\psi_{\alpha\beta}(t) = \sum_\eta (\sum_k U_{\beta k} E_k U^*_{\eta k})\psi_{\alpha\eta}(t)$$

I add and subtract E_1 (in the parenthesis) on the *r.h.s.* .

- Since neutrinos are relativistic, assuming equal momentum:

$$E_k = \sqrt{\mathbf{p}_k^2 + m_k^2} \qquad E_k \approx |\mathbf{p}| + \frac{m_k^2}{2E} \quad E = |\mathbf{p}| \quad k = 1, 2, ...N$$

$$p = |\mathbf{p}|$$

$$E_k - E_1 \approx (p + \frac{m_k^2}{2E}) - (p + \frac{m_1^2}{2E}) \approx \frac{(m_k^2 - m_1^2)}{2E} \approx \frac{\Delta m_{k1}^2}{2E}$$

$$\rightarrow \quad i\frac{d}{dt}\psi_{\alpha\beta}(t) = (p + \frac{m_1^2}{2E})\psi_{\alpha\beta}(t) + \sum_\eta \sum_k (U_{\beta k}\frac{\Delta m_{k1}^2}{2E}U^*_{\eta k})\psi_{\alpha\eta}(t)$$

common phase to all flavors and is irrelevant for oscillations.

NEUTRINOS IN MATTER

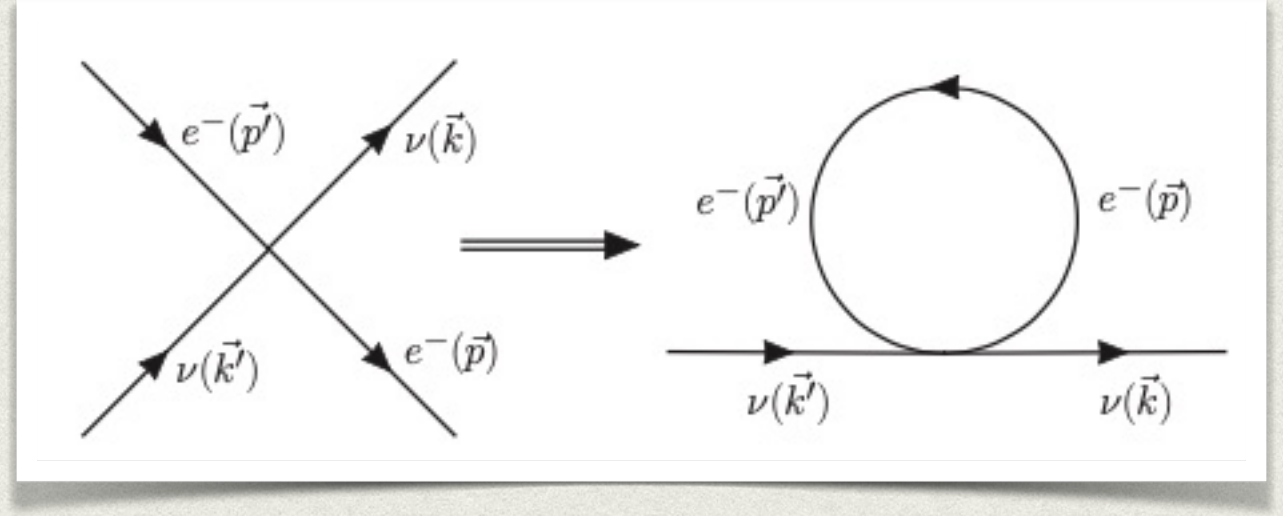
- Wolfenstein (1978) pointed out that neutrinos could change flavor in matter due to coherent forward scattering and a flavor-dependent refractive index.

  Mikheev-Smirnov (1986) suggested that flavor conversion in matter could be resonantly amplified and proposed this as **a solution of the solar neutrino problem**.

- $\nu_e - e$ - scattering in an astrophysical or cosmological environment

  $V_{\rm CC} = \sqrt{2} G_F n_e$ G_F- Fermi coupling constant

→ **MEAN-FIELD approximation**



This is similar to the Hartree or Hartree-Fock approximation in nuclear physics.
Here the interactions are the charged- and neutral-current interaction terms from
the GWS SM Lagrangian in the low energy limit (relevant range here is MeV, tens of MeV, 100 MeV).

NEUTRINO EVOLUTION EQUATIONS IN MATTER

- The evolution equations can be generalized to include the contribution from neutrino charged- and neutral-current interactions with matter:

$$i\frac{d}{dt}\psi_{\alpha\beta}(t) = \left(p + \frac{m_1^2}{2E} + V_{\rm NC}\right)\psi_{\alpha\beta}(t) + \sum_\eta \sum_k \left(U_{\beta k}\frac{\Delta m_{k1}^2}{2E}U_{\eta k}^* + \delta_{\beta e}\delta_{\eta e}V_{\rm CC}\right)\psi_{\alpha\eta}(t)$$

common phase to all flavors, irrelevant for oscillations.

- In 2 neutrino flavors, the equations with mixings and matter cast in matrix form read:

$$i\frac{d}{dt}\begin{pmatrix}\psi_{ee}\\ \psi_{e\mu}\end{pmatrix} = \begin{pmatrix} -\frac{\Delta m^2}{4E}\cos 2\theta + \sqrt{2}G_{\rm F}n_e & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{4E}\cos 2\theta \end{pmatrix}\begin{pmatrix}\psi_{ee}\\ \psi_{e\mu}\end{pmatrix}$$

beware that here the common term of the Hamiltonian (not shown) is $\mathcal{H}_{\rm com} = p + \frac{m_1^2 + m_2^2}{4}$

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

That is

$$i\frac{d}{dt}\begin{pmatrix}\psi_{ee}\\ \psi_{e\mu}\end{pmatrix} = \begin{pmatrix} -\frac{\Delta m^2}{4E}\cos 2\theta & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{4E}\cos 2\theta \end{pmatrix} + \begin{pmatrix}\sqrt{2}G_{\rm F}n_e & 0\\ 0 & 0\end{pmatrix}\begin{pmatrix}\psi_{ee}\\ \psi_{e\mu}\end{pmatrix}$$

amplitude for a neutrino to be a ν_e at time t

amplitude for a neutrino to be a ν_μ at time t

EVOLUTION EQUATIONS FOR 2 nu IN (DILUTE) MATTER

THE Mikheev-Smirnov-Wolfenstein (MSW) EFFECT

Wolfenstein, 1978; Mikheev and Smirnov, 1985

- The total Hamiltonian in 2 neutrino flavors

$$\mathcal{H}^f = \mathcal{H}^f_{\rm vac} + \mathcal{H}^f_{\rm mat} = \begin{pmatrix} -\frac{\Delta m^2}{4E}\cos^2 2\theta + \sqrt{2}G_{\rm F}n_e & \frac{\Delta m^2}{4E}\sin^2 2\theta \\ \frac{\Delta m^2}{4E}\sin^2 2\theta & \frac{\Delta m^2}{4E}\cos^2 2\theta \end{pmatrix}$$

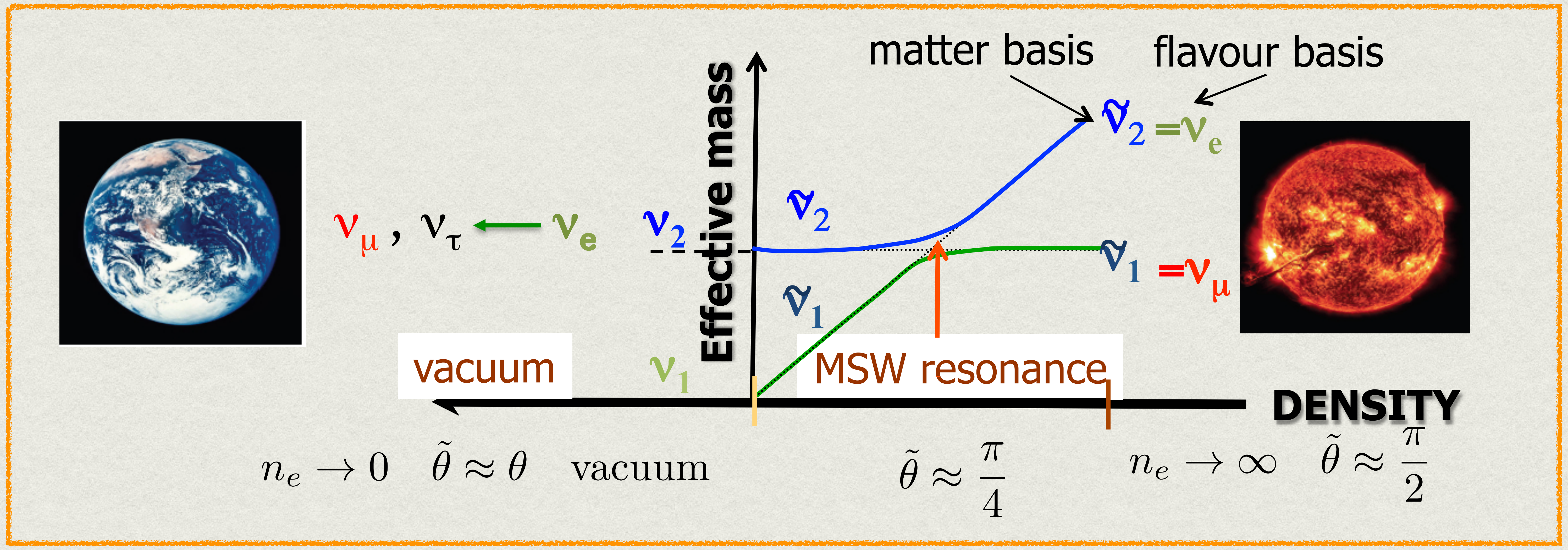
- It can be made diagonal with the rotation (giving the so called « matter basis ») :

$$\tan 2\tilde\theta = \frac{2|H_{12}|}{H_{11} - H_{22}} = \frac{\frac{\Delta m^2}{2E}\sin 2\theta}{\sqrt{2}G_{\rm F}n_e - \frac{\Delta m^2}{2E}\cos 2\theta}$$

MSW resonance condition

$$\sqrt{2}G_{\rm F}n_e - \frac{\Delta m^2}{2E}\cos 2\theta = 0$$

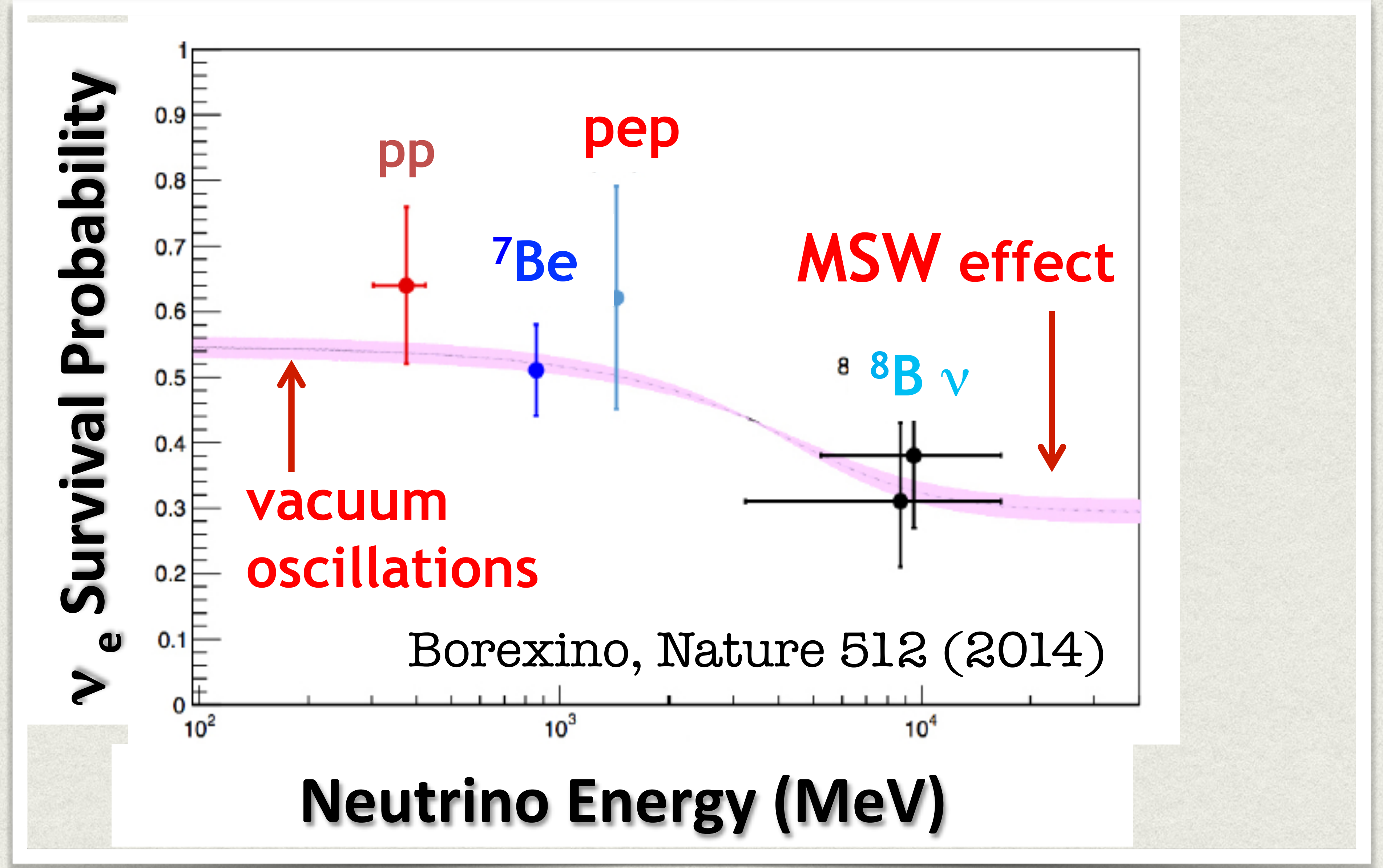
Two-level problem in quantum mechanics



If the MSW resonance is fulfilled, the resonance width is large and the evolution through resonance adiabatic, an electron neutrino will come out as a nu2.

SOLUTION OF THE SOLAR NEUTRINO PROBLEM

- Borexino experiment (Gran Sasso) measured for the first time solar neutrinos from pp, pep, 7Be… and the CNO cycle suggested by Bethe (1939) (1% of solar energy).



thanks for Super-Kamionande discovery of neutrino oscillations in vacuum, SNO measurement of the total solar neutrino flux, KamLAND measurement, but also thirty years of searches and combined data fit and Borexino results for low energy solar neutrinos

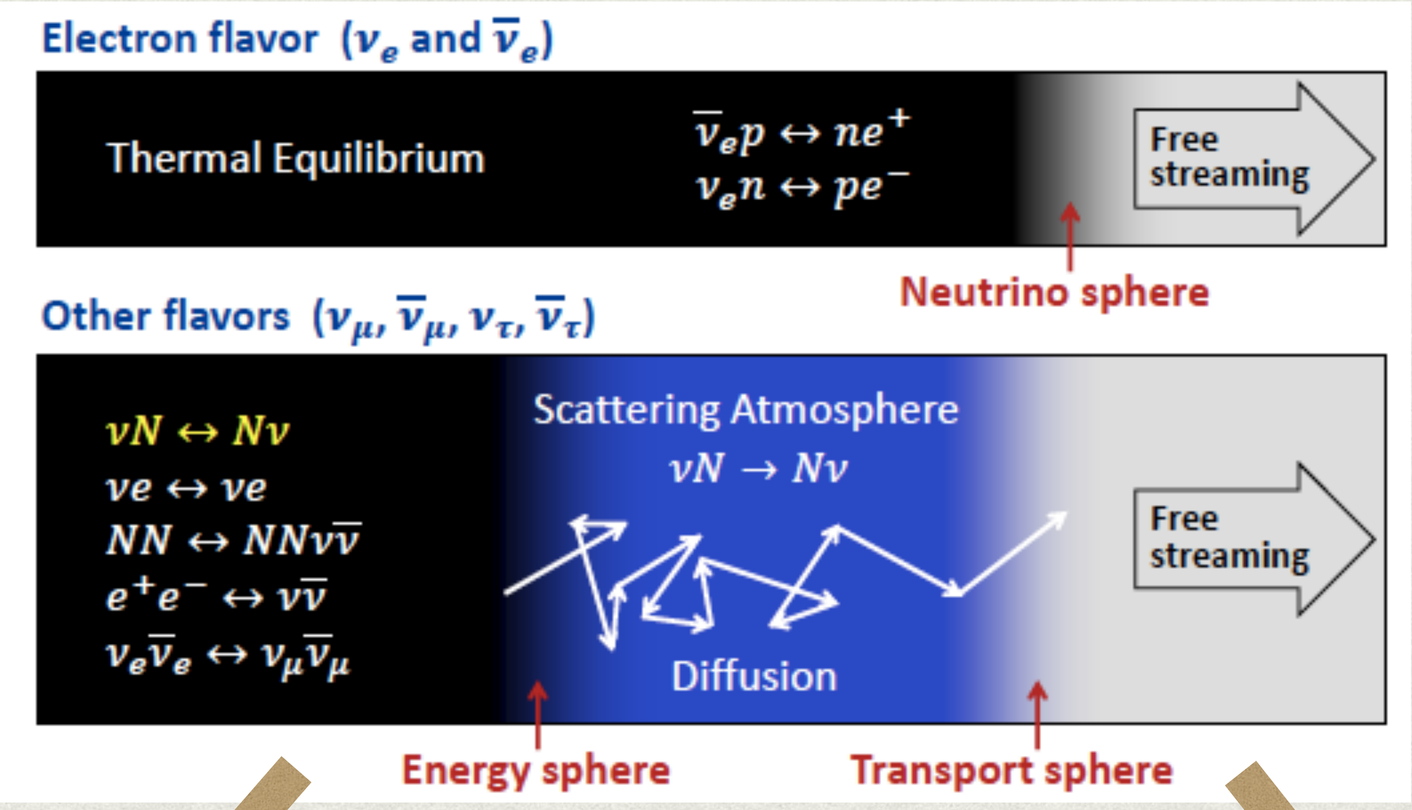
A reference phenomenon for the study of how neutrinos change flavor in dense media.

DENSE ENVIRONMENTS: FROM TRAPPED TO FREE-STREAMING

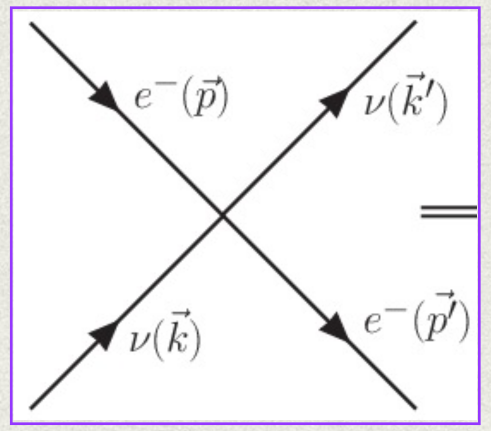
- In such environments neutrinos are <u>trapped</u>.
  $E = 10$ MeV
  Typical cross section Density Mean free path $\lambda = \frac{1}{\sigma\rho}$
  $\sigma = 6\ 10^{-41}\mathrm{cm}^2$ $\rho = 10^{14}\mathrm{g/cm}^3$ $\lambda \approx \mathrm{m}$
  $\rho = 10^{12}\mathrm{g/cm}^3$ $\lambda \approx \text{tens of km}$

  The region where neutrinos start free-streaming is called the neutrinosphere. It is energy and flavor dependent. In flavor studies, usually taken as a a sharp boundary.

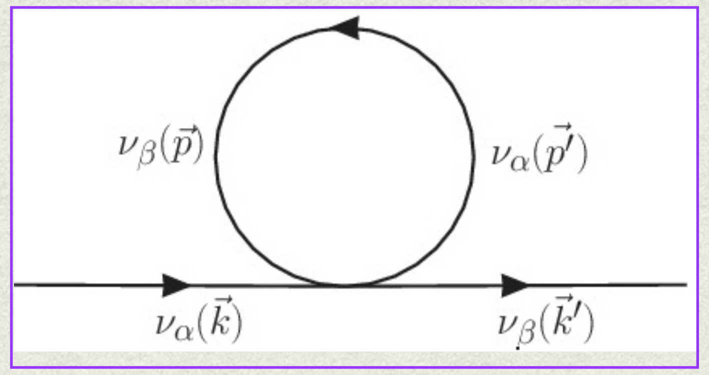
- Neutrinos are emitted with quasi-thermal spectra (Fermi-Dirac distributions)



Raffelt (2012)

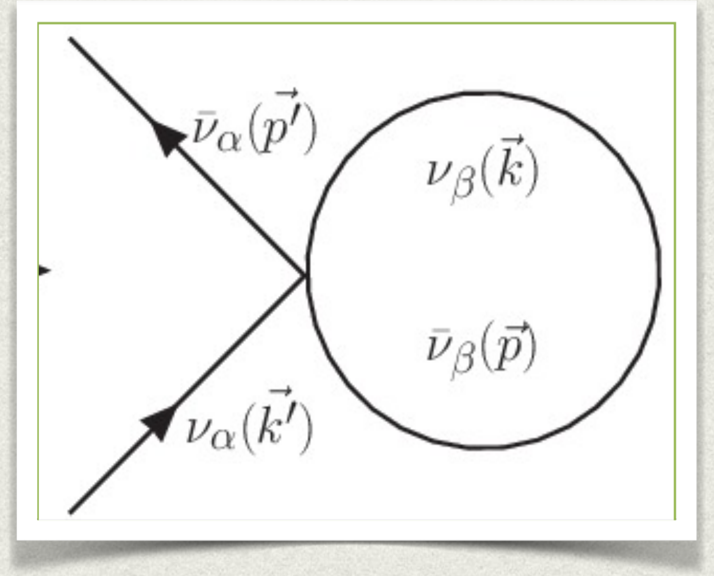


collisions dominated



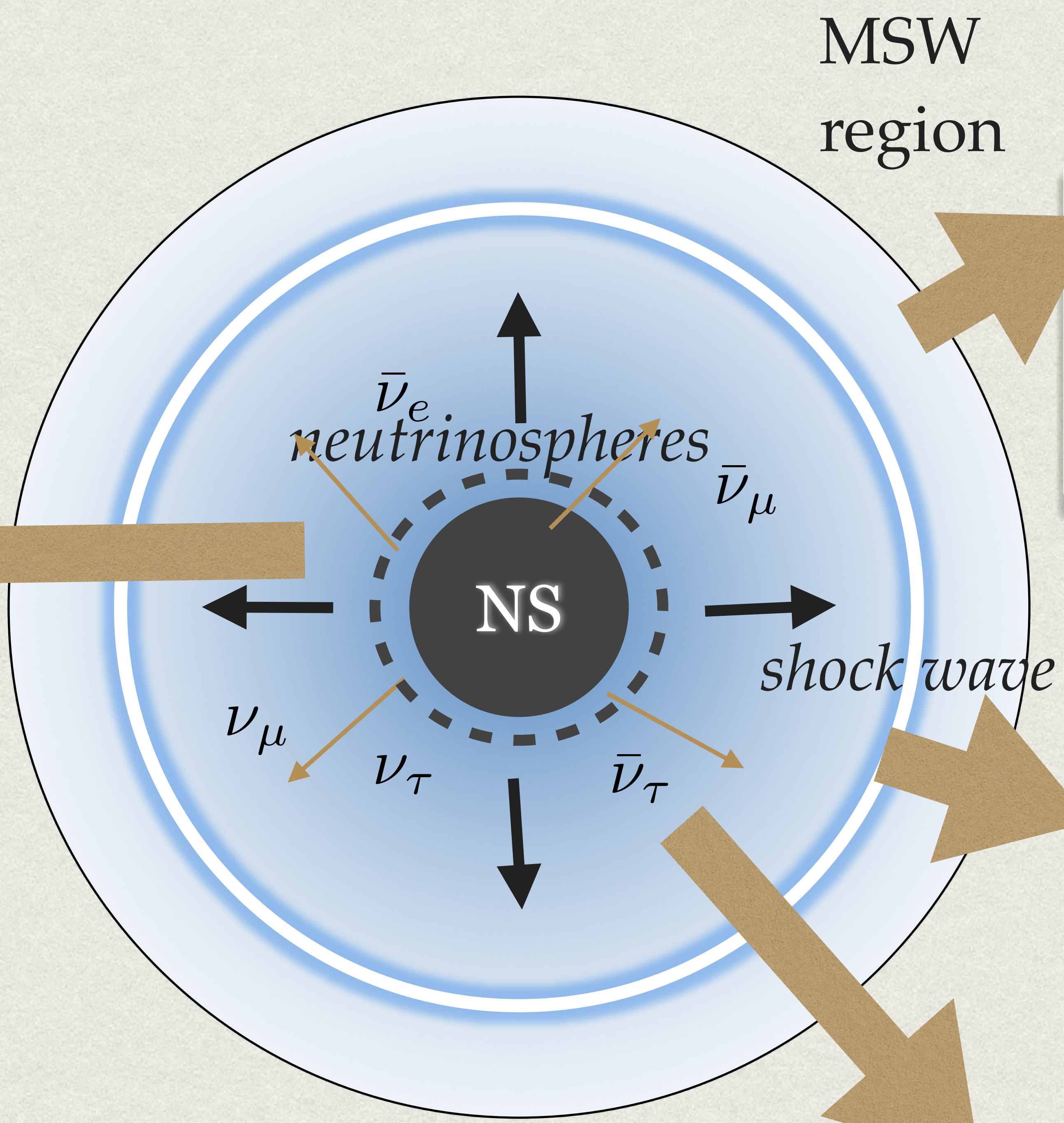
flavor conversion

FLAVOR CONVERSION IN DENSE ENVIRONMENTS

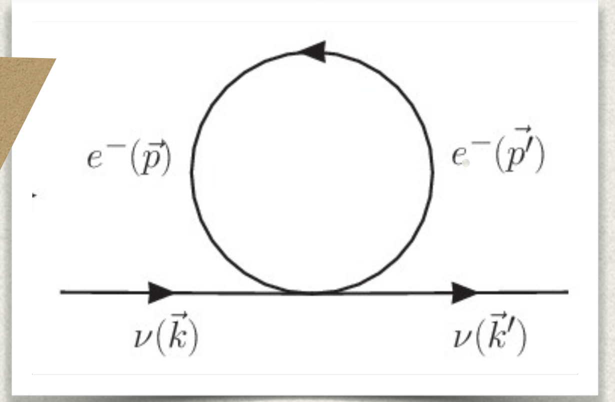


Neutrino-neutrino interactions

Pantaleone, PLB287 (1992).
Studied intensively since 2006



MSW effect



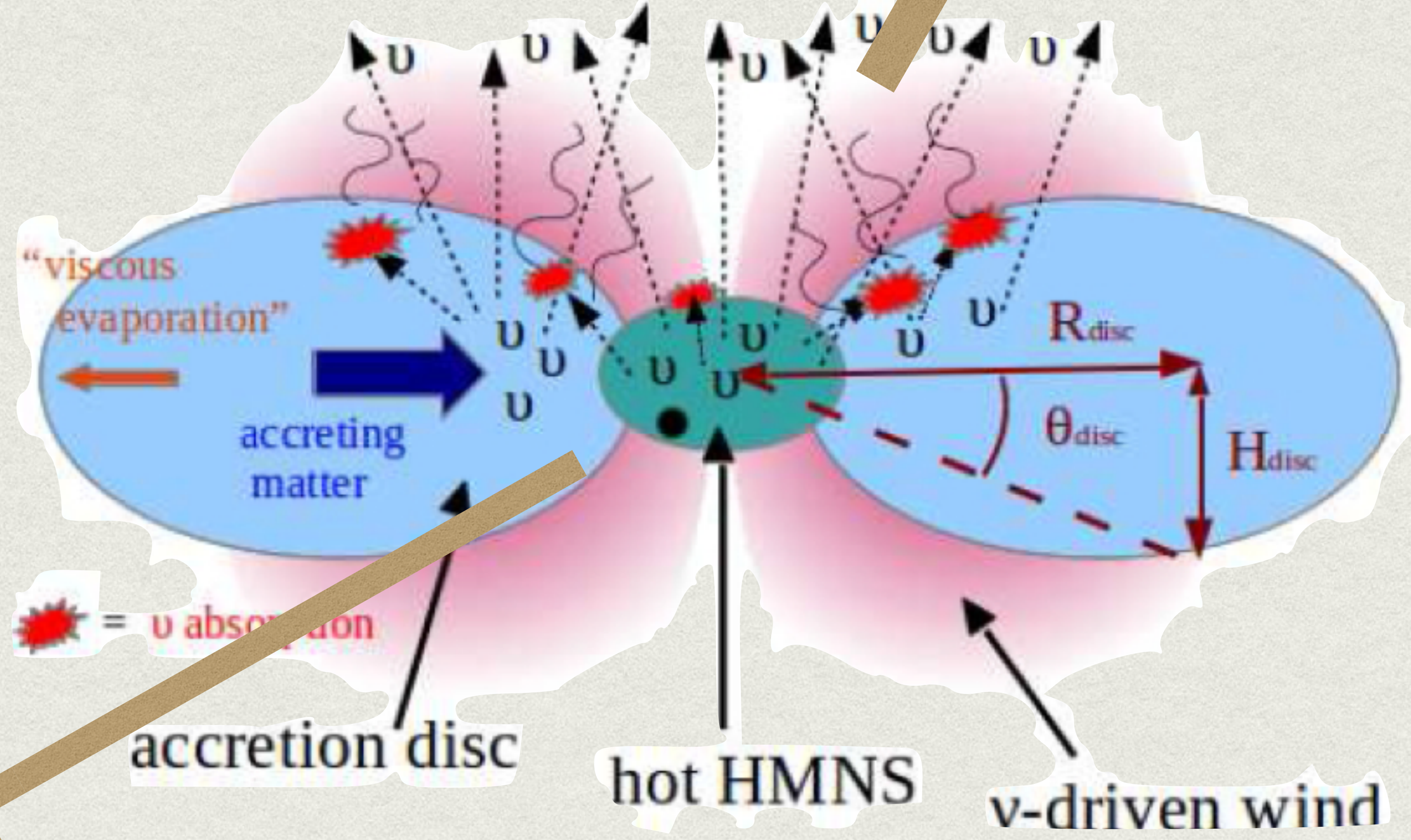
Shock wave effects

Schirato and Fuller,
hep-ph/0205390

Turbulence effects

Loreti et al, PRD 52 (1995)

MSW effect



Neutrino-neutrino interactions

THEORETICAL DESCRIPTION OF NEUTRINO EVOLUTION IN DENSE ENVIRONMENTS

In astrophysical and cosmological environments, neutrinos interact with the particles in the medium.

- One-body density matrix for 2 neutrinos:

$$\rho = \begin{pmatrix} \rho_{ee} & \rho_{e\mu} \\ \rho_{\mu e} & \rho_{\mu\mu} \end{pmatrix}$$

Diagonal elements are the expectation value of the number operator :

$$\alpha = \beta \qquad \rho_{\alpha\alpha} = \langle a_\alpha^\dagger a_\alpha \rangle$$

$$N_\alpha = \int \frac{d\vec{p}}{(2\pi)^3} \rho_{\alpha\alpha}$$

Non-diagonal elements account for the mixings (flavor modification)

$$\alpha \neq \beta \qquad \rho_{\alpha\beta} = \langle a_\beta^\dagger a_\alpha \rangle$$

- The neutrino evolution equations in media in the density matrix approach (Liouville equation).

$$i(\partial_t + \mathbf{v} \cdot \nabla_{\mathbf{x}} + \mathbf{F} \cdot \nabla_{\mathbf{p}}) \varrho_{\mathbf{x},\mathbf{p}} = [h_{\mathbf{x},\mathbf{p}}, \varrho_{\mathbf{x},\mathbf{p}}] \ ,$$

The full Liouville operator is 7-dimensional.

- The full description employs the neutrino quantum kinetic equations:

$$i(\partial_t + \mathbf{v} \cdot \nabla_{\mathbf{x}}) \varrho_{\mathbf{x},\mathbf{p}} = [h_{\mathbf{x},\mathbf{p}}, \varrho_{\mathbf{x},\mathbf{p}}] + iC[\varrho, \bar{\varrho}] \ ,$$

Necessary for the early Universe - epoch of primordial nucleosynthesis (10 MeV - 0.1 MeV, neutrinos set n/p ratio key for the build up to He4, D, He3, Li7).

THEORETICAL DESCRIPTION OF NEUTRINO EVOLUTION IN DENSE MEDIA

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

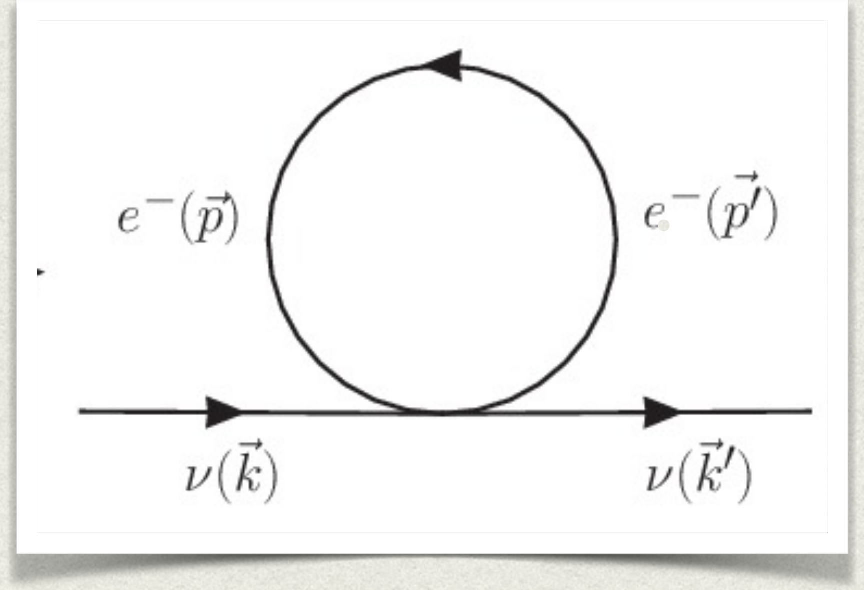
- $h = h_{vac} + h_{mat} + h_{\nu\nu} + h_{NSI}$

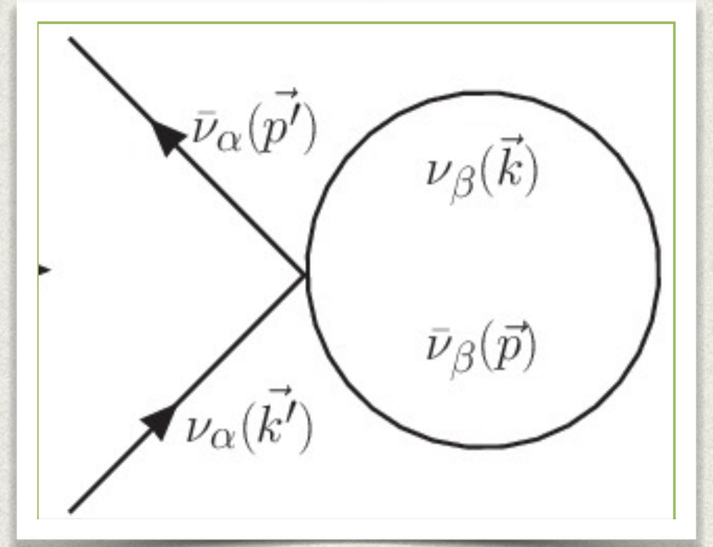
$$h_{vac} = \omega \begin{pmatrix} -c_{2\theta} & s_{2\theta} \\ s_{2\theta} & c_{2\theta} \end{pmatrix}$$

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

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

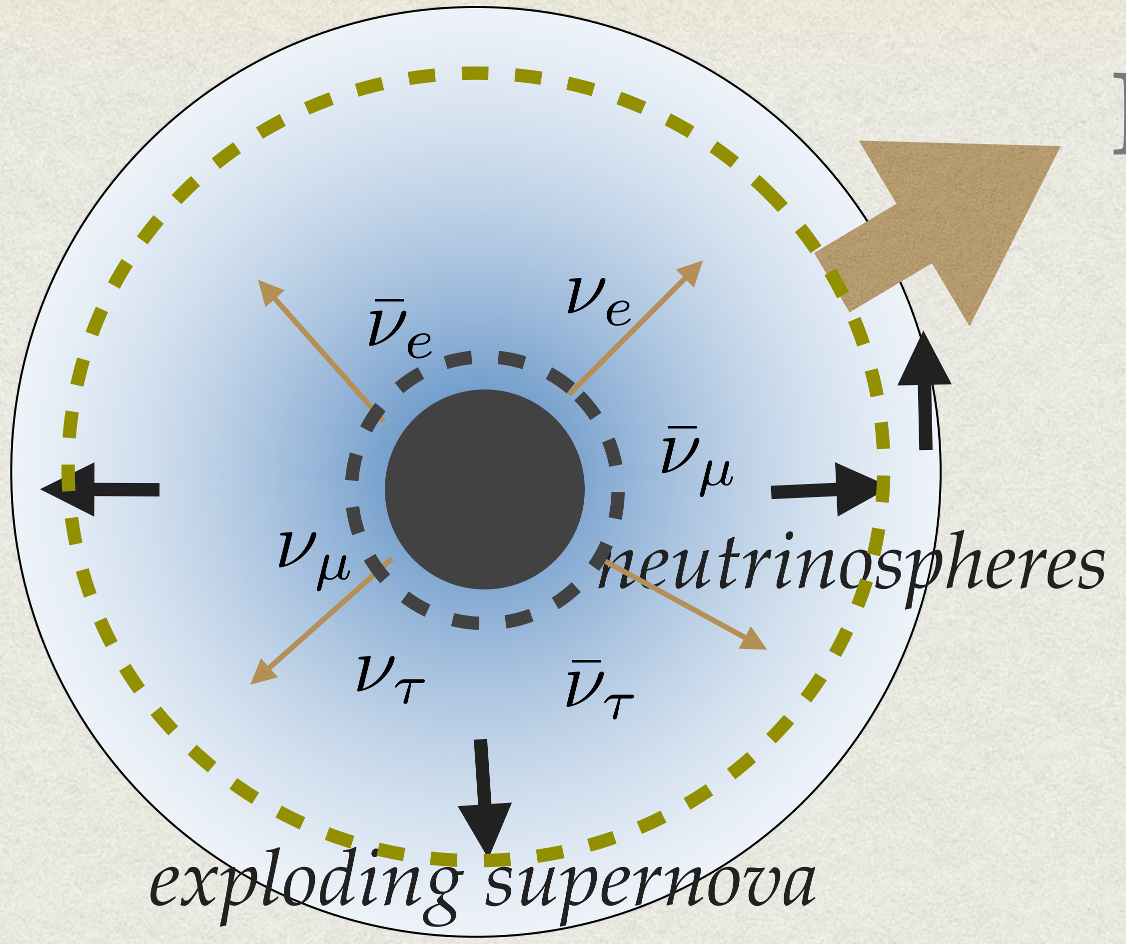
$$h_{NSI} = \sqrt{2} G_F \sum_f N_f \epsilon^f \quad f = e, d, u$$

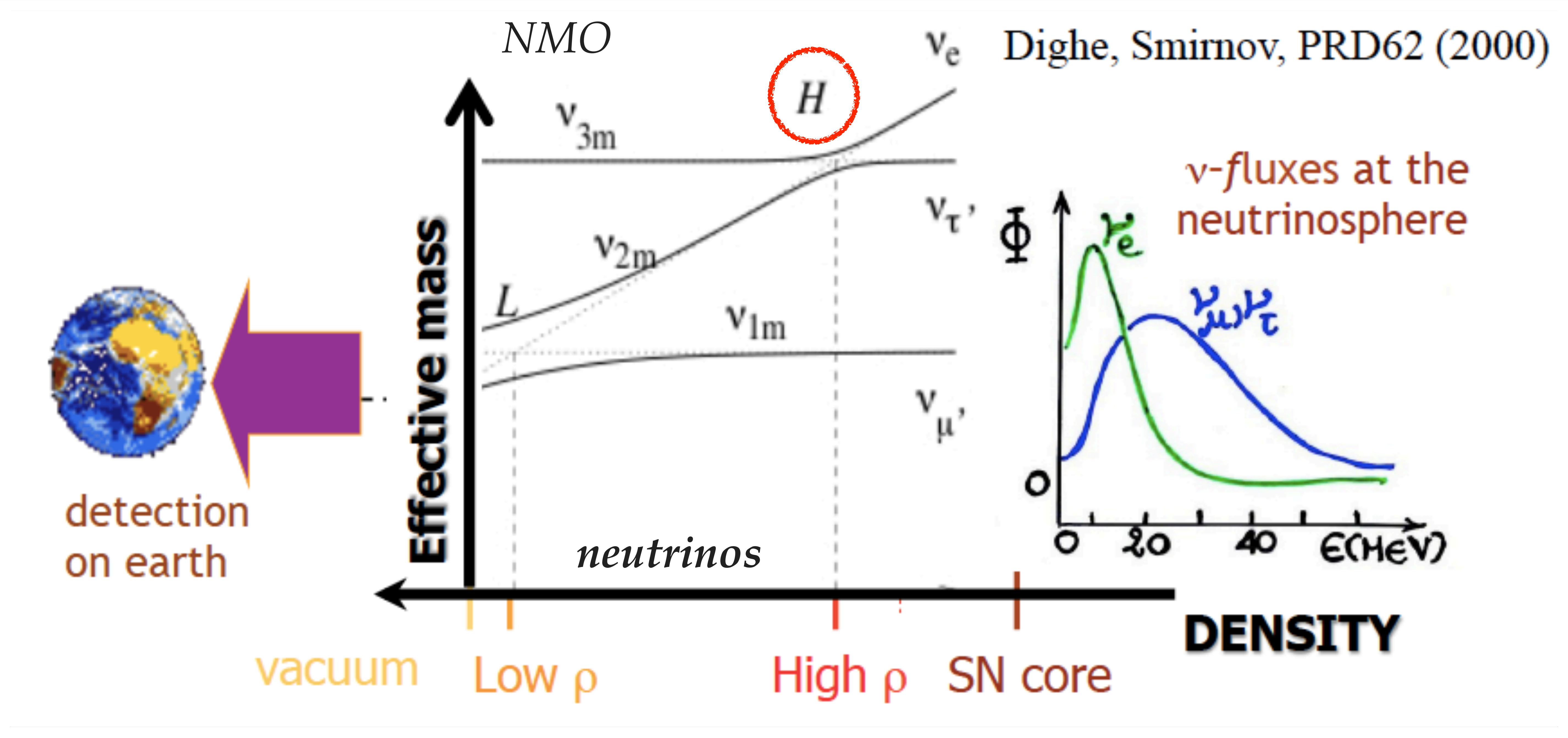
Non-standard interactions

$$\begin{pmatrix} \mid \epsilon_{ee} \mid < 2.5 & \mid \epsilon_{e\tau} \mid < 1.7 \\ & \mid \epsilon_{\tau\tau} \mid < 9.0 \end{pmatrix}$$

limits for neutral solar-like matter

MSW EFFECT IN DENSE MEDIA





- 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

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

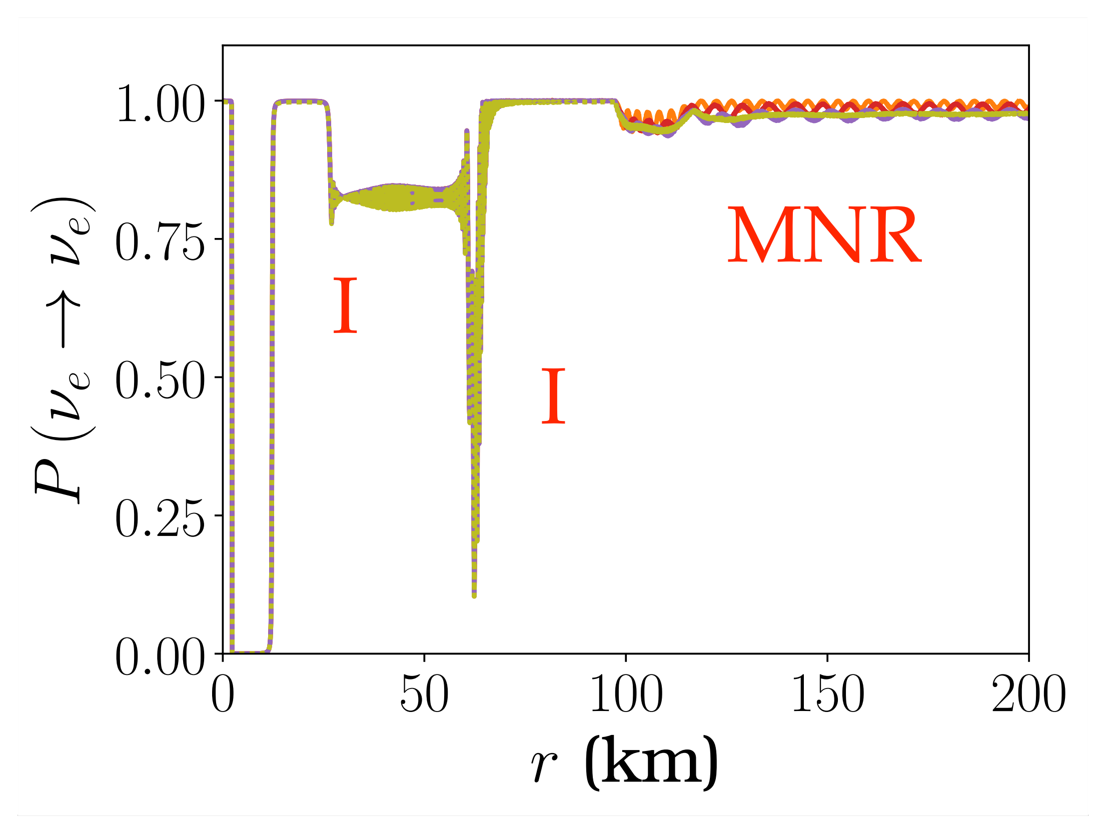
$$p = 0.68 \quad NMO \qquad p = 0 \quad IMO$$

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

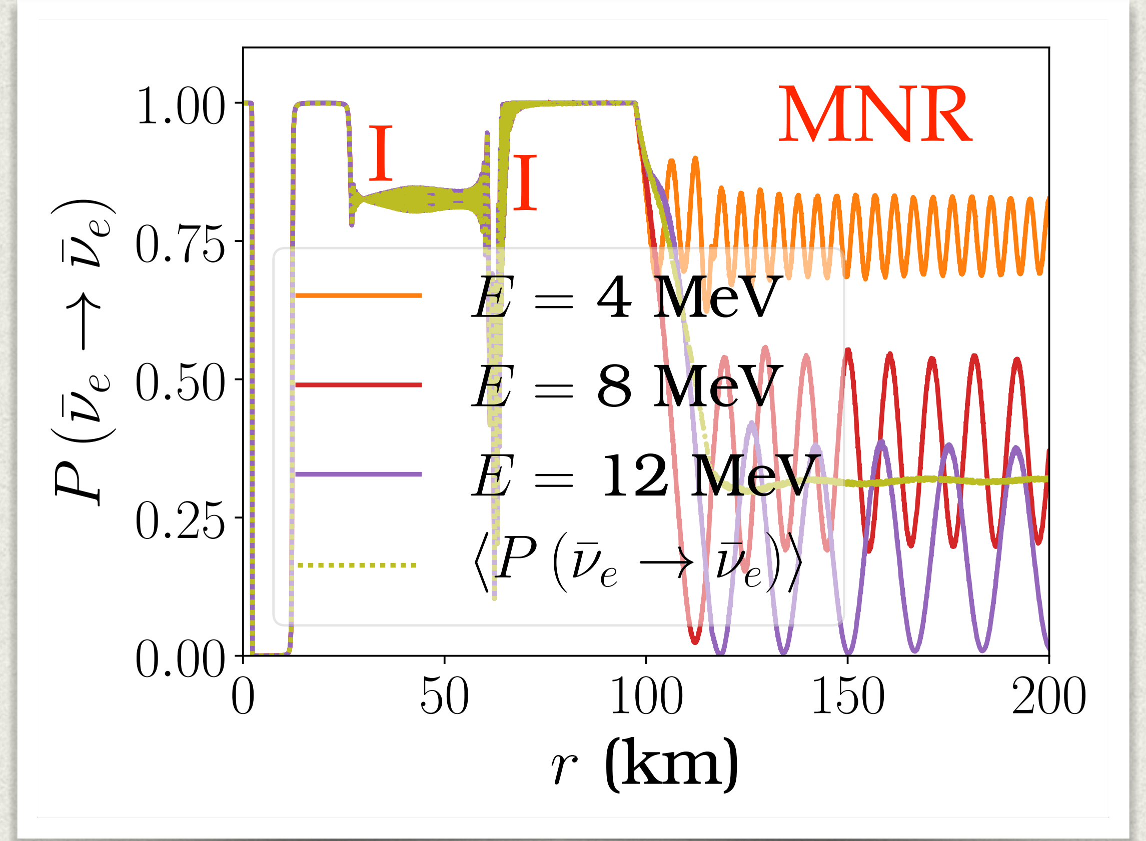
Normal mass ordering (NMO) *Inverted mass ordering (IMO)*

NON-STANDARD INTERACTIONS in Binary Neutron Star Mergers

- A large set of neutrino trajectories investigated : an example..



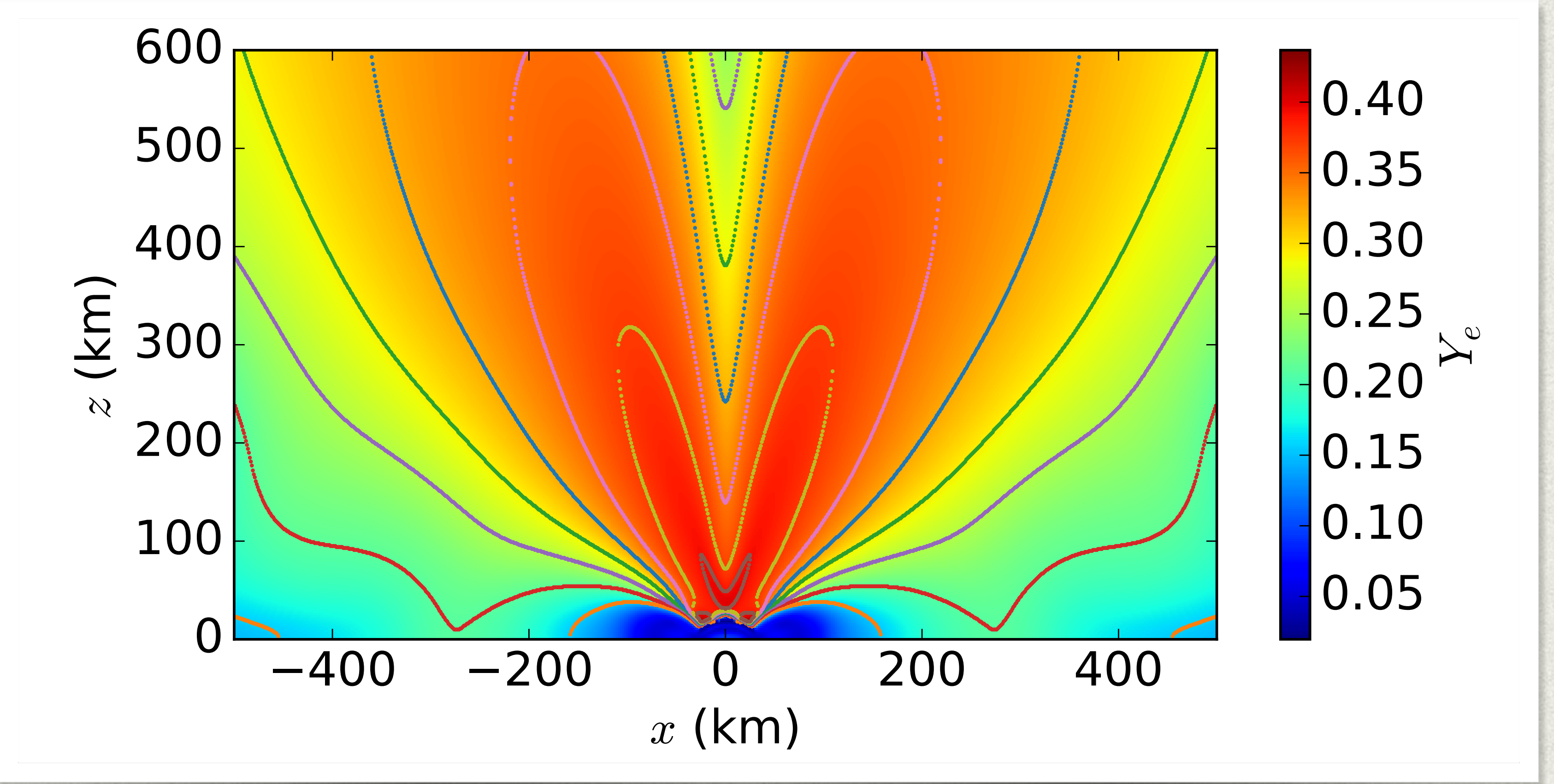
Neutrinos



Antineutrinos

Complex patterns of flavor evolution mechanisms emerge, even for small NSI couplings which produces spectral modifications, with a possible impact on Ye.

I-resonance locations in a BNS remnant



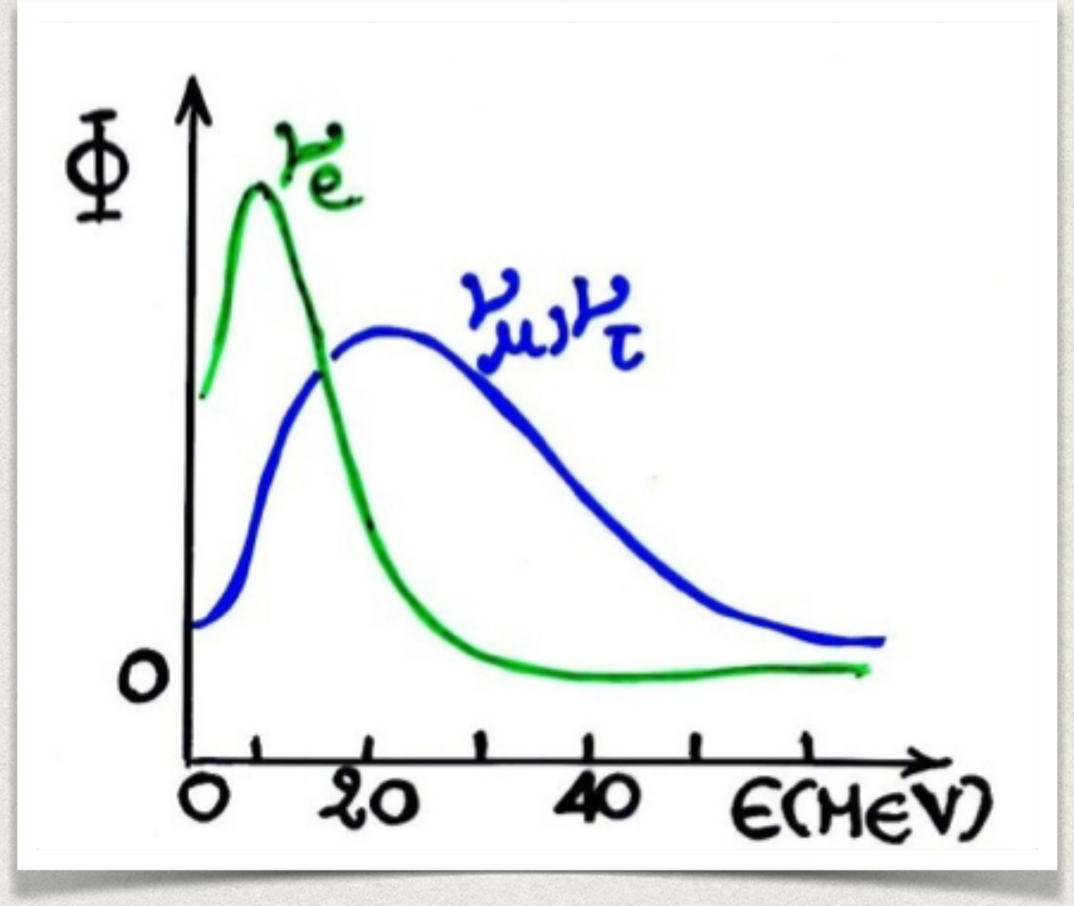
Chatelain and Volpe PRD97 (2018)

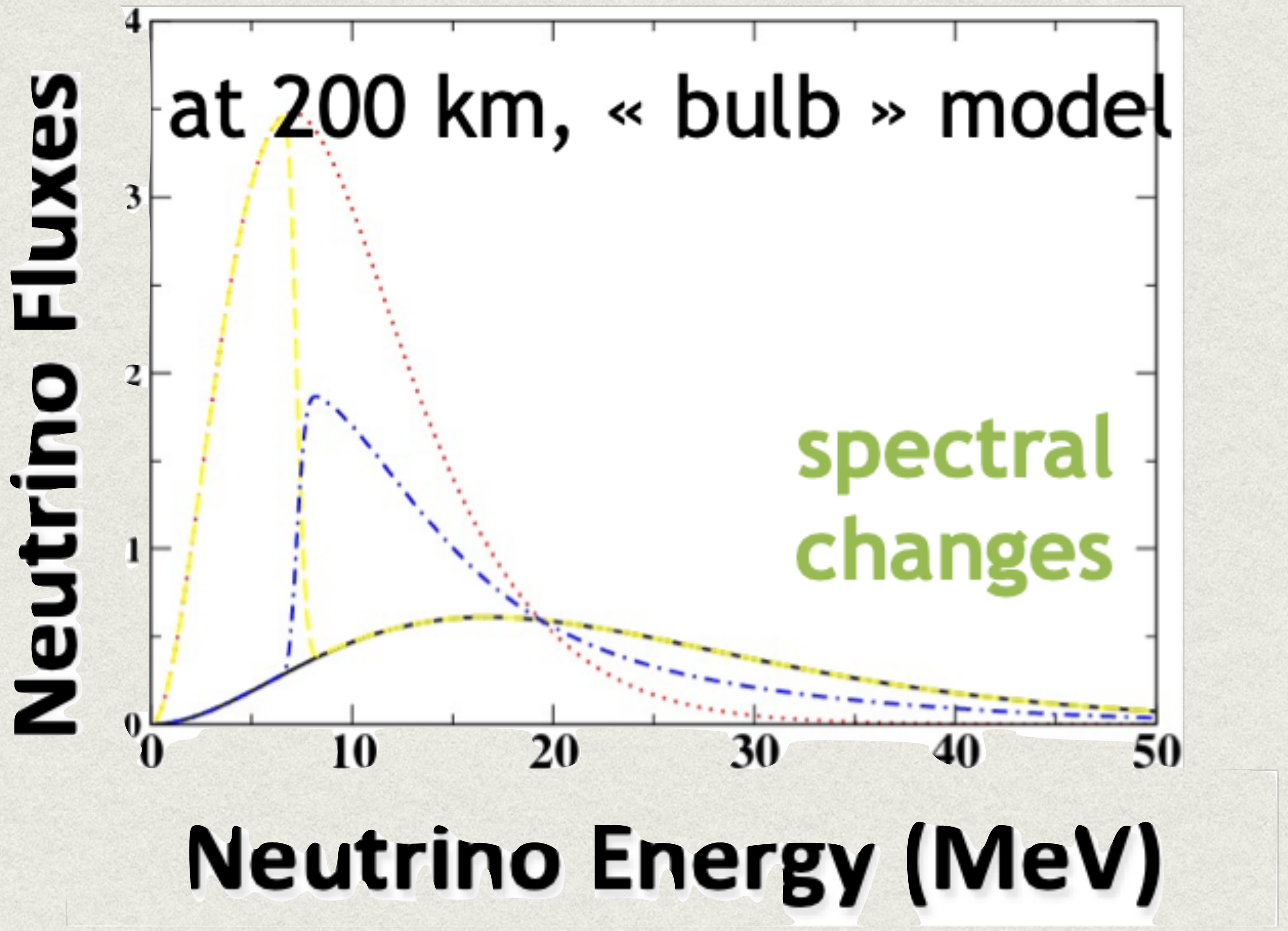
$$Y_e = \frac{p}{p+n}$$

electron fraction

Key parameter for the r-proces

SPECTRAL SWAPPING DENSE MEDIA





An example due to the neutrino-neutrino interaction

IMPACT OF SPECTRAL SWAPPING

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 :

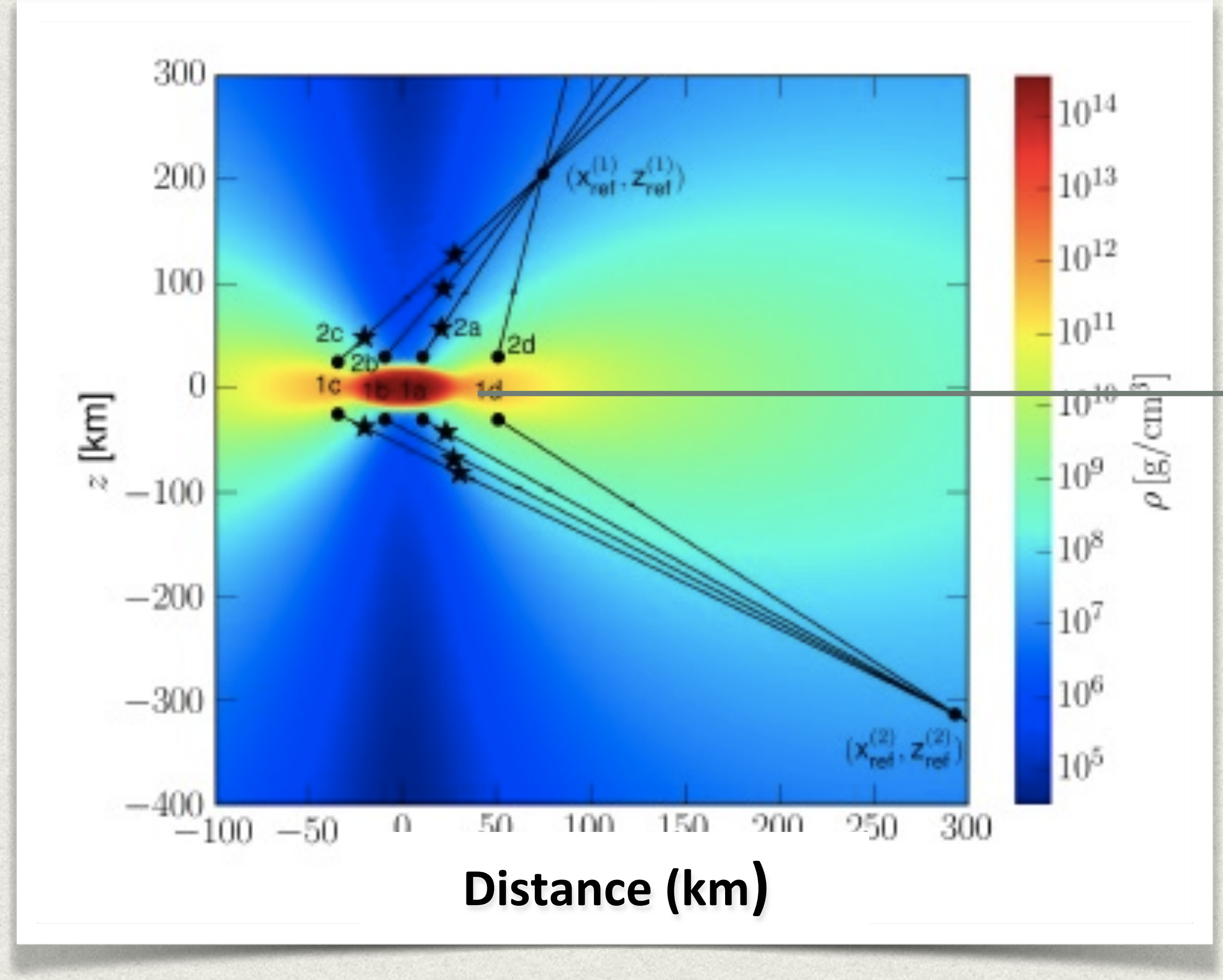
$$\frac{\lambda_{\nu_e n}}{\lambda_{\bar{\nu}_e p}} = \frac{<\sigma_{\nu_e n}>}{<\sigma_{\bar{\nu}_e p}>} \qquad <E_{\nu_e}><<E_{\bar{\nu}_e}><<E_{\nu_{\mu,\tau}}>$$

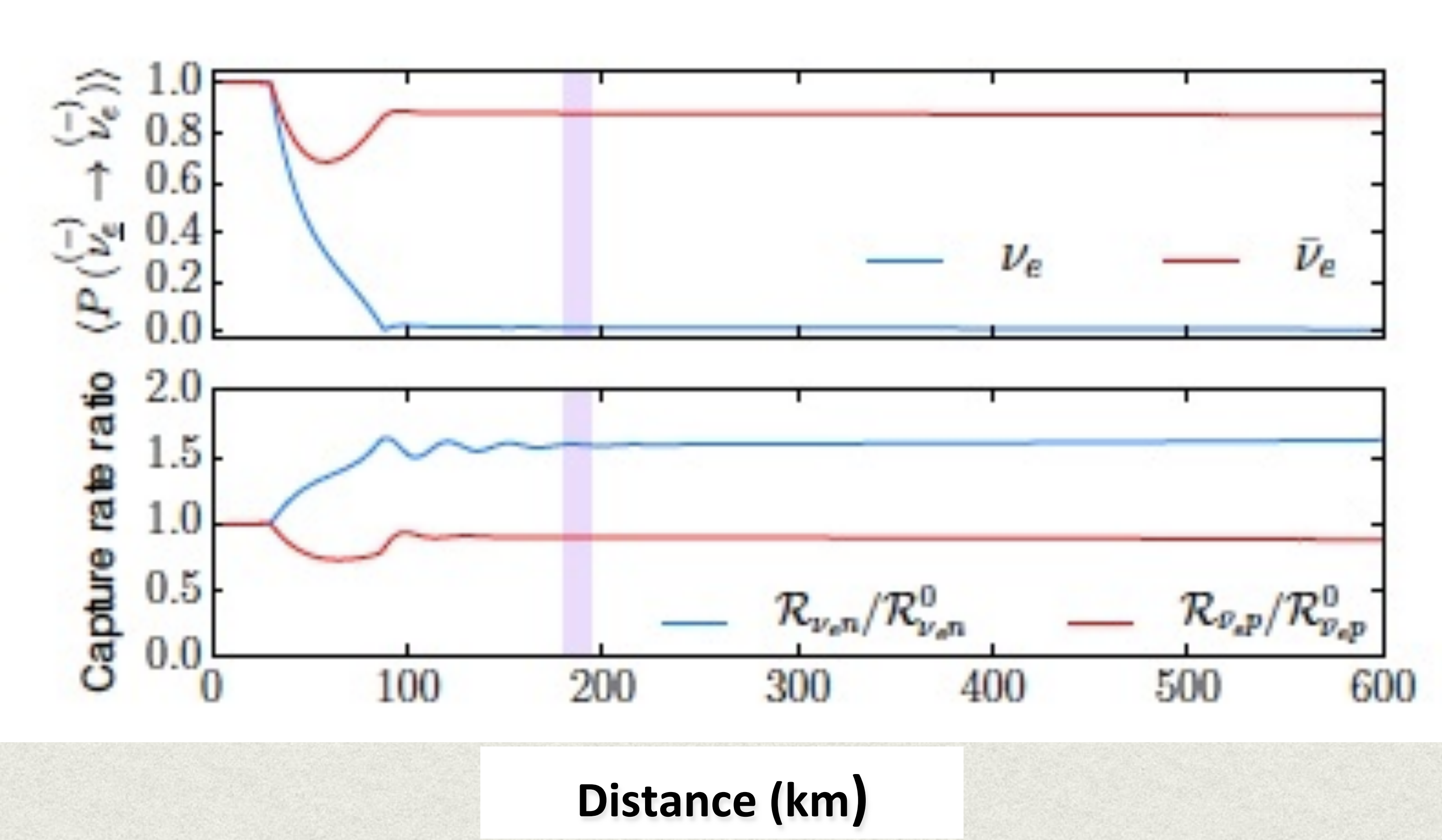
- This determines the electron fraction Ye and the number of available neutrons (1- Ye). $Y_e = \frac{p}{p+n}$

  Key parameter for the r-proces (elements heavier than iron)

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

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

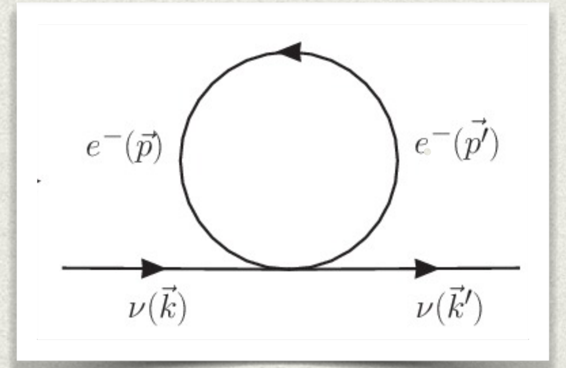




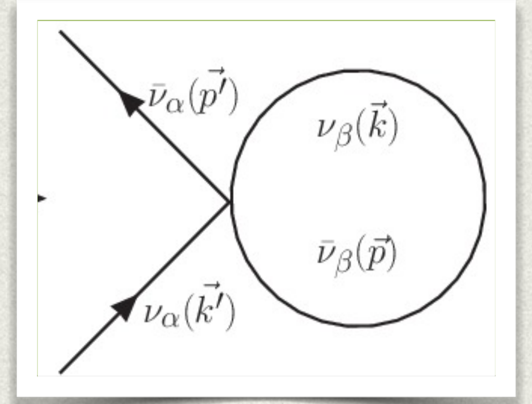
Frensel et al PRD95 (2017)

Flavor evolution and neutrino properties impact
the n/p ratio (nucleosynthesis), neutrino heating (SN dynamics) and observations

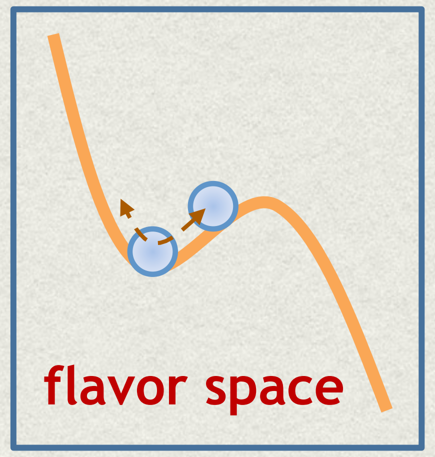
THEORETICAL APPROACHES



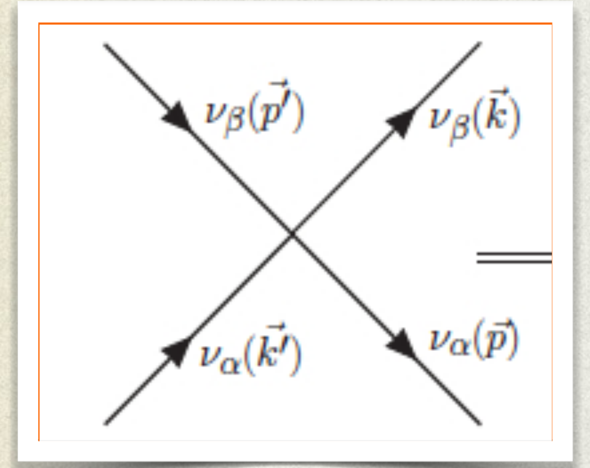
Mean-field approximation



Mean-field and extended mean-field



Linearised mean-field equations



Towards the many-body solution

Quantum kinetic equations

Mean-field equations

$$i(\partial_t + \mathbf{v} \cdot \nabla_{\mathbf{x}})\varrho_{\mathbf{x},\mathbf{p}} = [h_{\mathbf{x},\mathbf{p}}, \varrho_{\mathbf{x},\mathbf{p}}] \ ,$$

Extended mean-field equations

$$i\dot{\mathcal{R}} = [\mathcal{H}, \mathcal{R}] \ ,$$

$k_{\alpha\beta} = \langle b_\beta a_\alpha \rangle$ - pairing correlators

$\zeta = \langle a_+^\dagger a_- \rangle$ - spin or helicity coherence

Linearised equations

$$\delta\rho = \rho_0 + \delta\rho(t) = \rho^0 + \rho' e^{-i\omega t} + \rho'^\dagger e^{i\omega^* t}$$

$$\begin{pmatrix} A & B \\ \bar{B} & \bar{A} \end{pmatrix} \begin{pmatrix} \rho' \\ \bar{\rho}' \end{pmatrix} = \omega \begin{pmatrix} \rho' \\ \bar{\rho}' \end{pmatrix}$$

S eigenvalues :
-> real : stable collective
-> imaginary : instabilities

Quantum kinetic equations

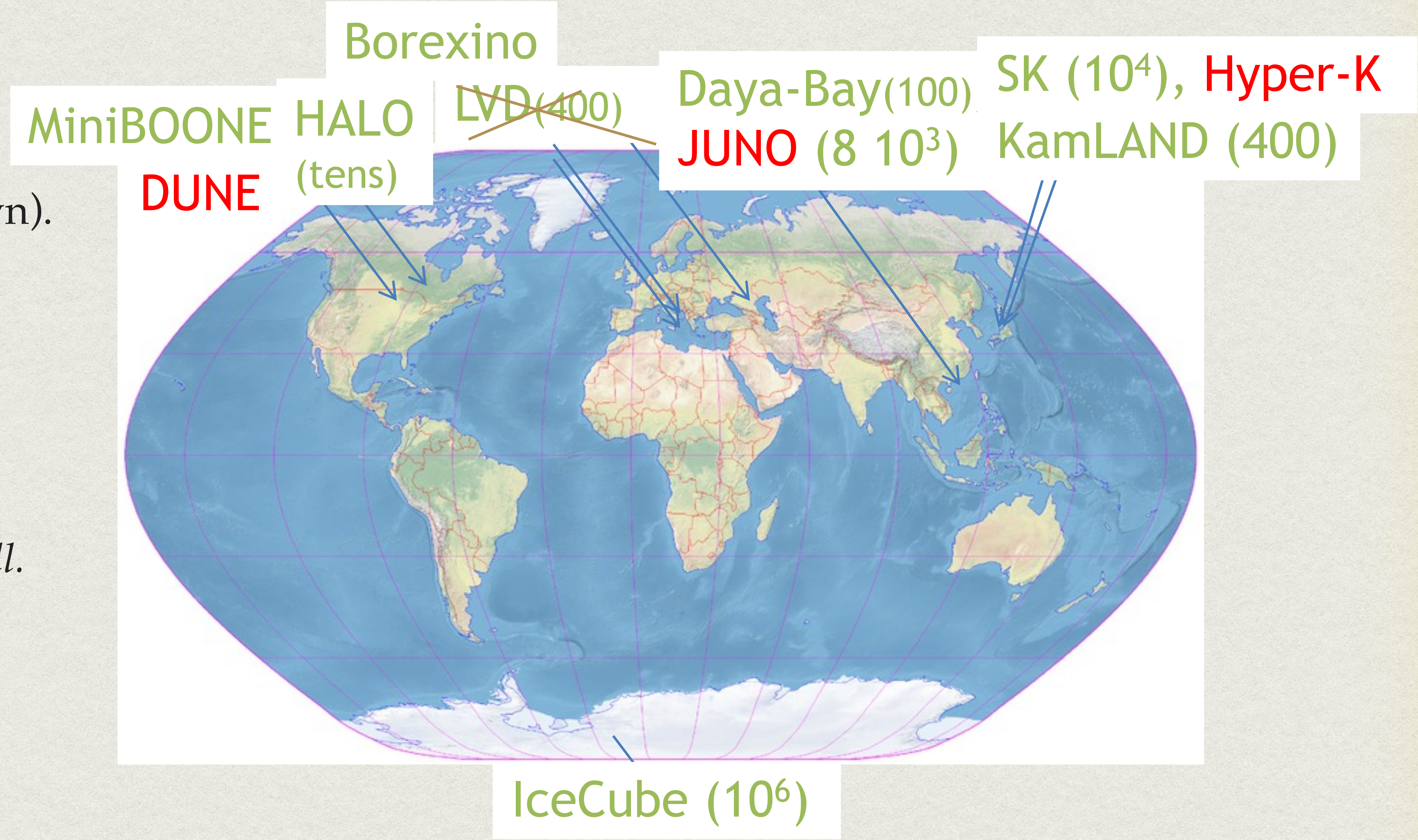
$$i(\partial_t + \mathbf{v} \cdot \nabla_{\mathbf{x}})\varrho_{\mathbf{x},\mathbf{p}} = [h_{\mathbf{x},\mathbf{p}}, \varrho_{\mathbf{x},\mathbf{p}}] + iC[\varrho, \bar{\varrho}] \ ,$$

-full collision term

THE DETECTION OF NEUTRINOS FROM A FUTURE SUPERNOVA

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

- We will reconstruct the neutrino time and energy signal for all neutrino flavors through scattering on protons, electrons, nuclei and neutrino-nucleus coherent scattering (in dark matter detectors, not shown).



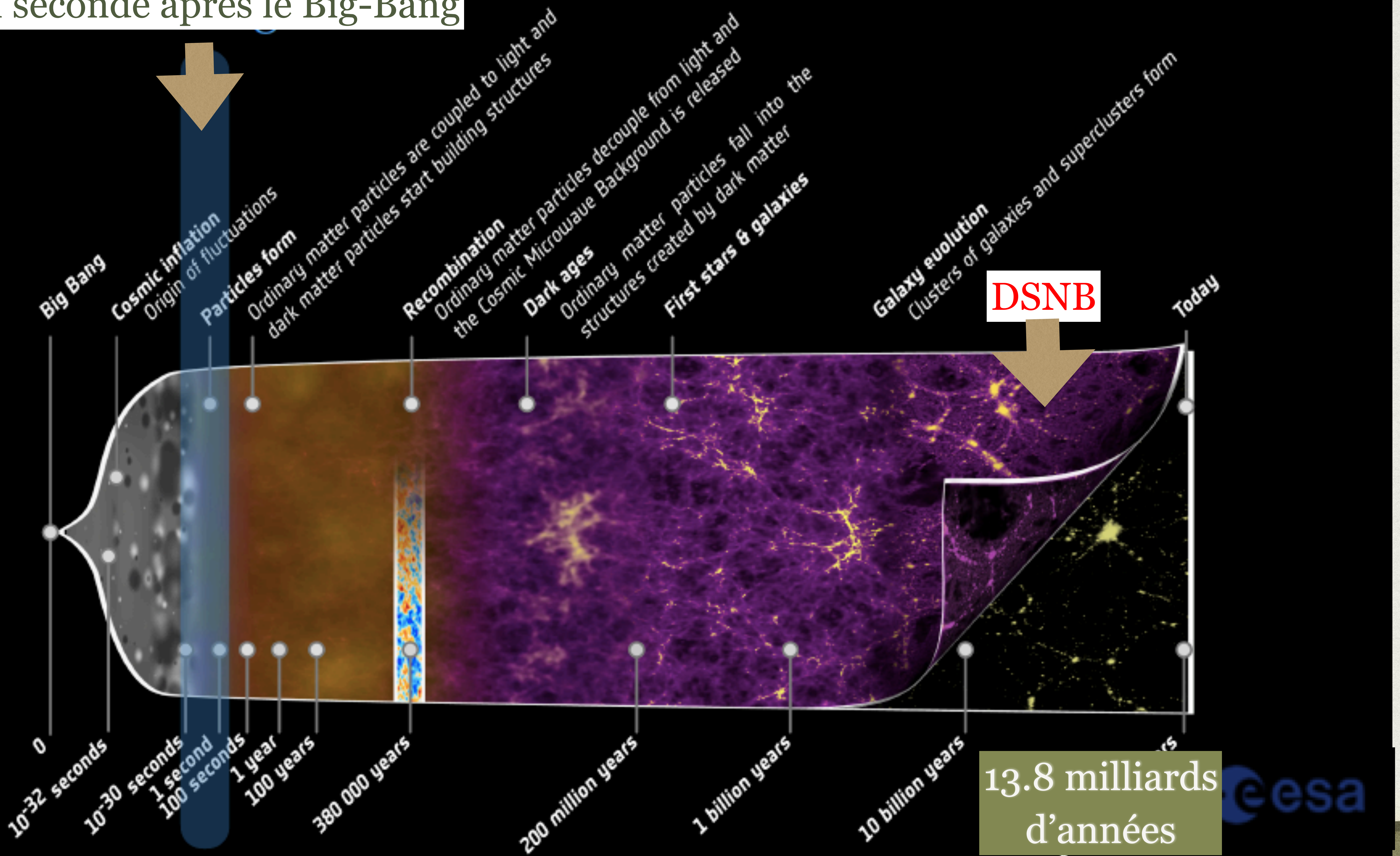
- Neutrino-nucleus CC cross sections :
  D, ^{12}C, ^{16}O, ^{40}Ar, ^{56}Fe, ^{208}Pb

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

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

EVOLUTION DE L'UNIVERS

1 seconde après le Big-Bang



DSNB

13.8 milliards d'années

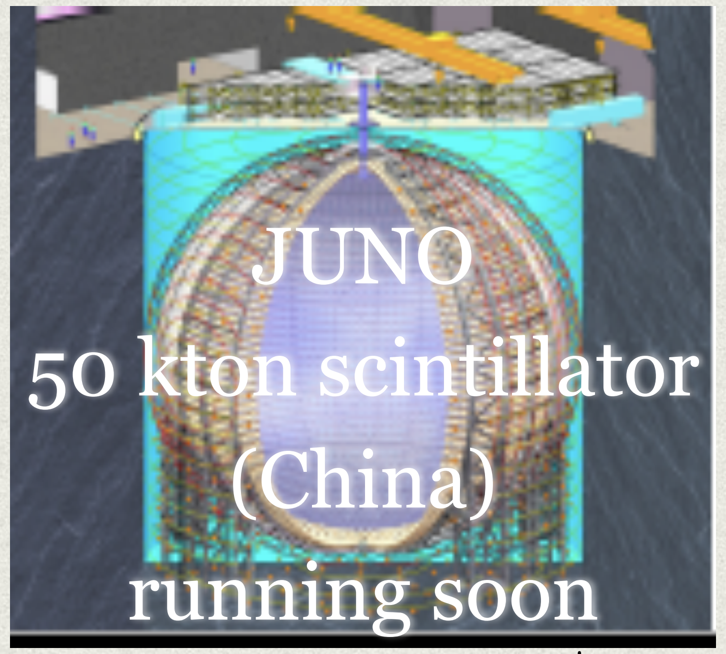
Super-Kamiokande
50 kton water (Japan)
Running (2020) + Gd

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

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

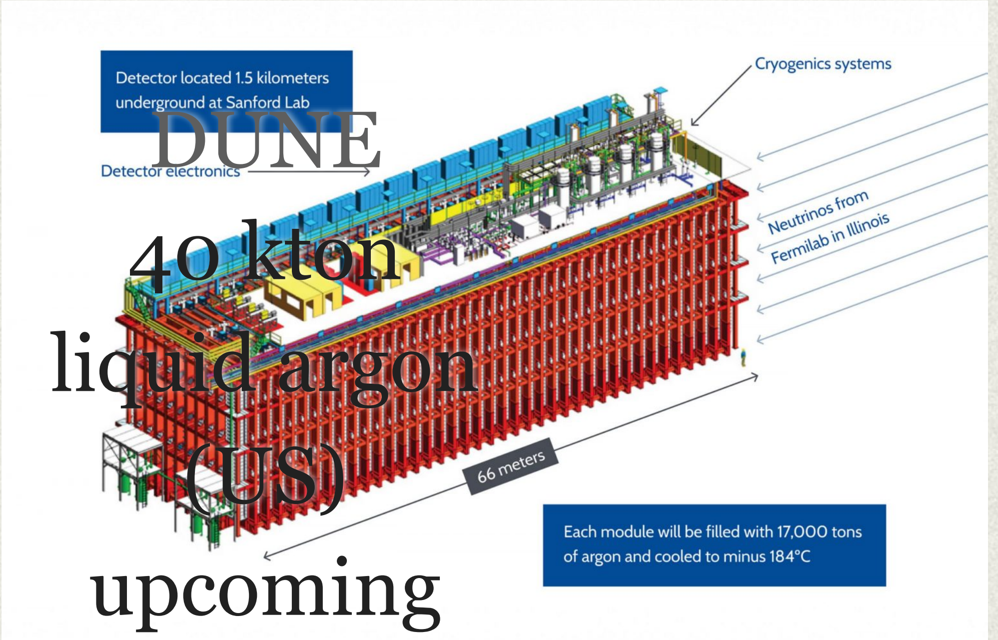
$$\bar{\nu}_e + p \rightarrow n + e^+ (IBD)$$

THE UPCOMING DISCOVERY OF THE DIFFUSE SUPERNOVA NEUTRINO BACKGROUND (DSNB)



JUNO
50 kton scintillator
(China)
running soon

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



DUNE
40 kton
liquid argon
(US)
upcoming

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

STATUS on the DSNB

- Flux upper limits from SKI-IV and SNO data

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

Abe et al, 2109.11174

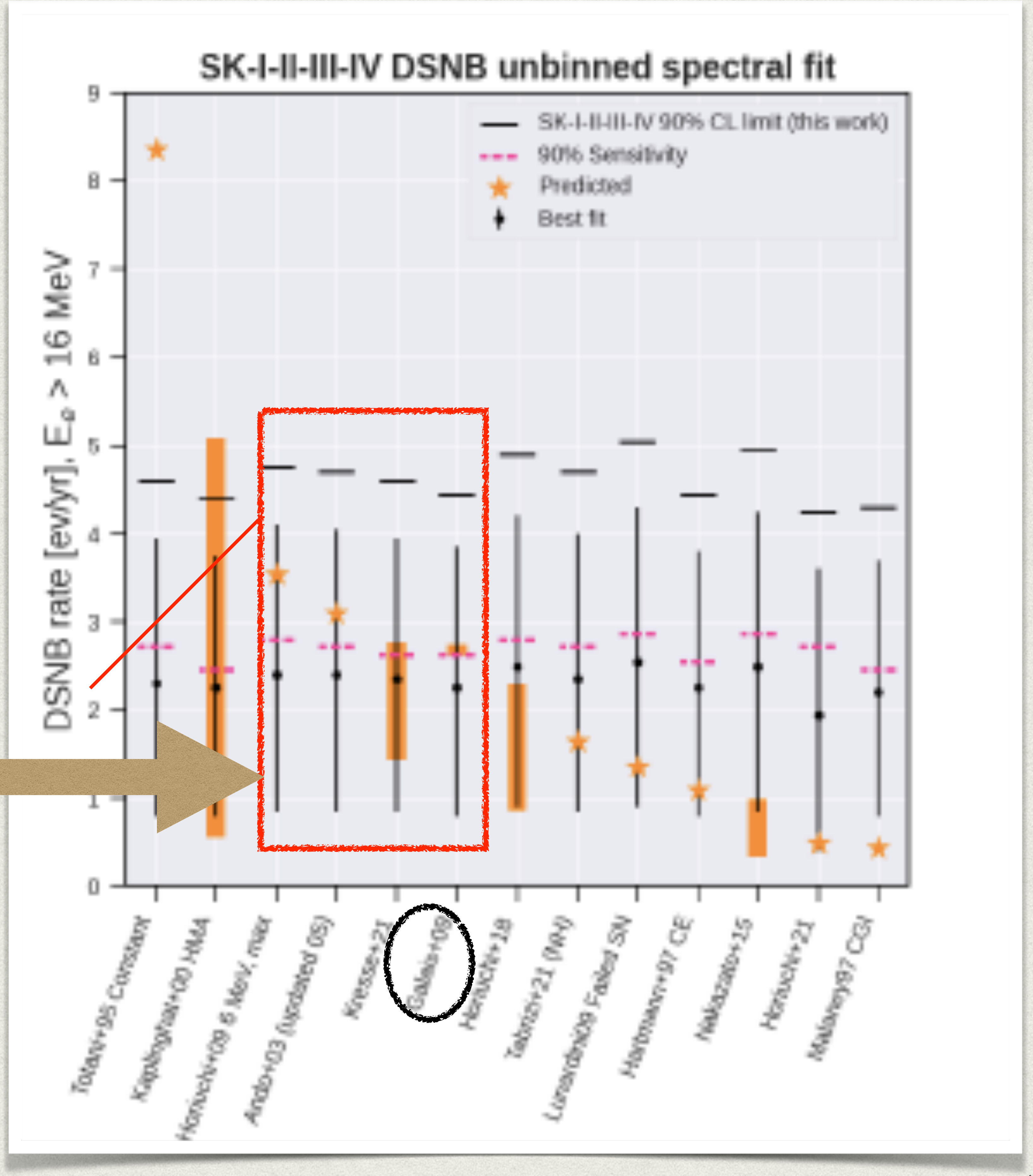
$$19 \quad \nu_e \quad \mathrm{cm}^{-2} s^{-1} \quad (E_\nu \in [22.9, 36.9] \quad \mathrm{MeV})$$

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

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

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

EXCESS (1.5 sigma) over BACKGROUND OBSERVED

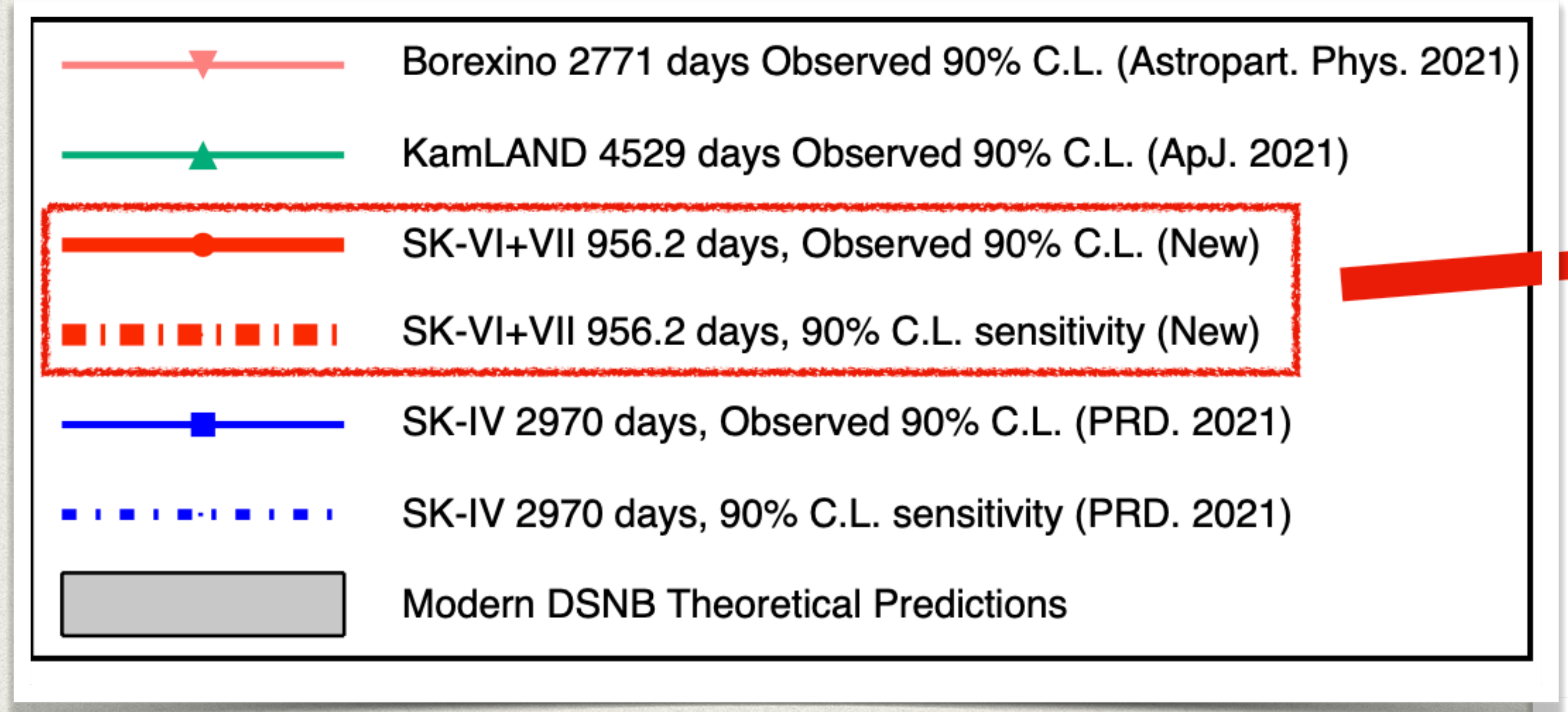


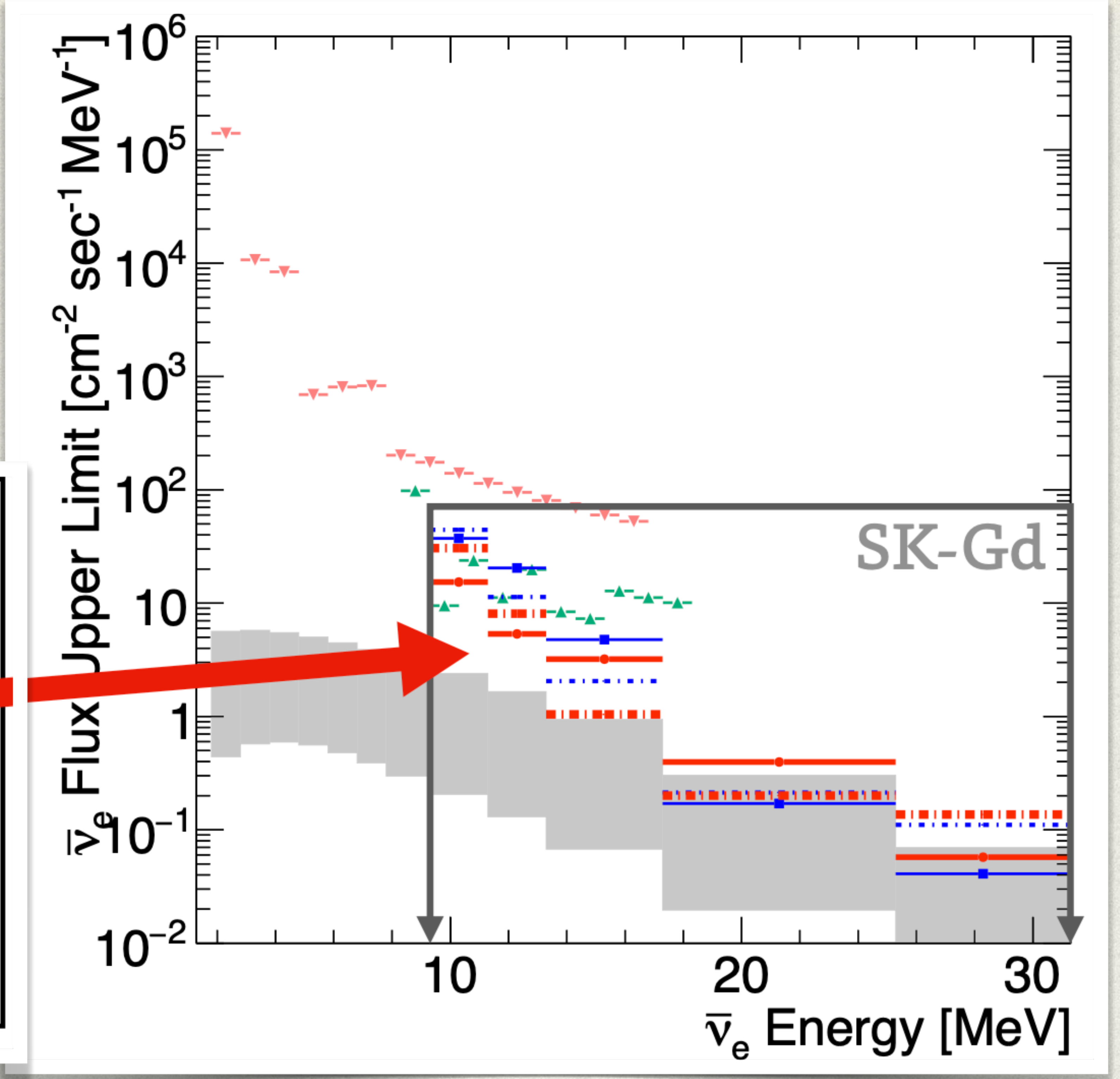
Expected rates, 90% C.L. upper limits, best fit values (1 sig.) and expected sensitivity from SK-I and SK-IV data

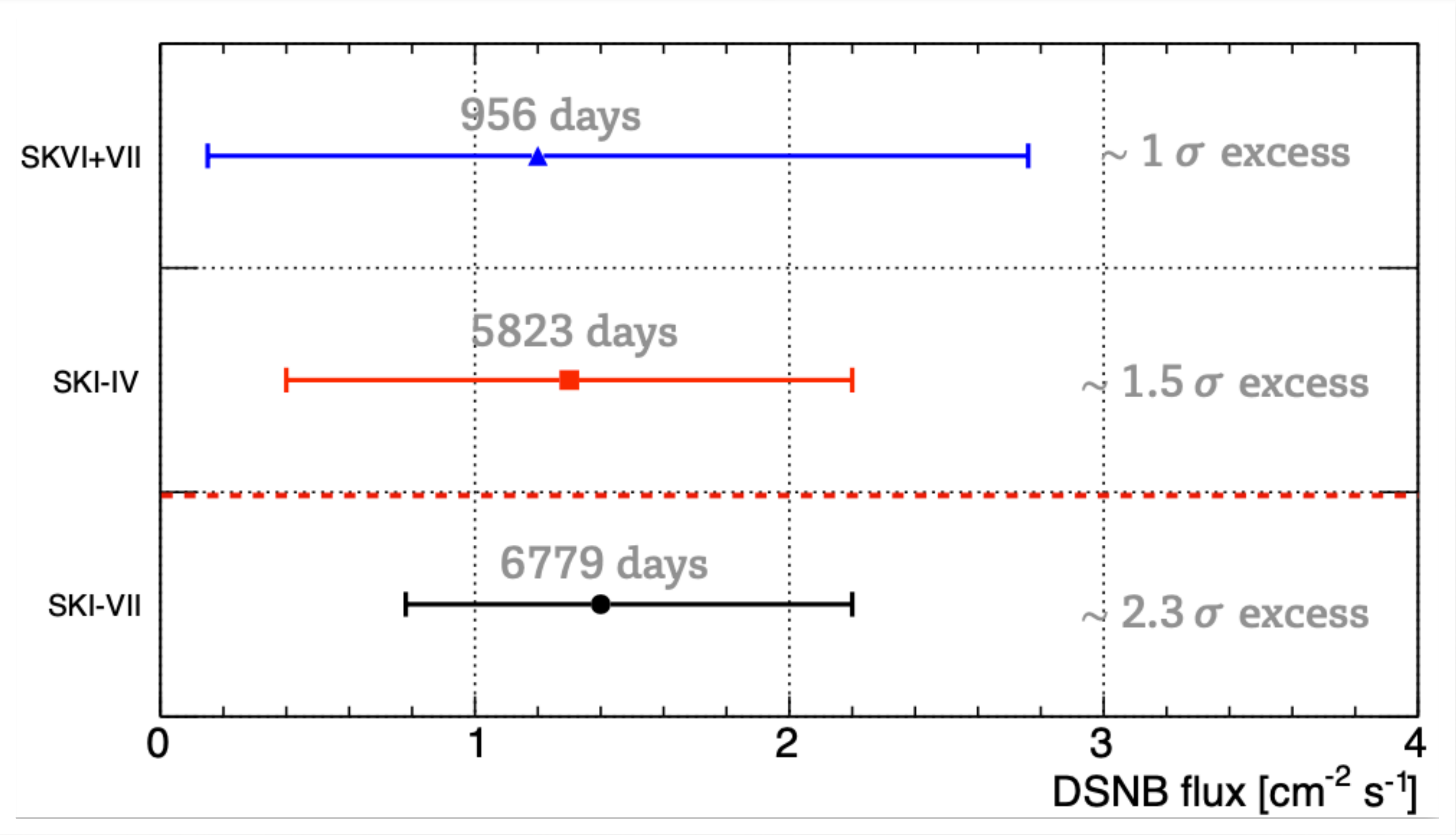
Abe et al, 2109.11174

NEUTRINO 2024

First results of SK+Gadolinium (running since 2020)







Highlight:

- Sensitivity of SK-Gd ~1000 days exposure is already comparable level it with ~6000 days of pure-water SK
- Best fit of whole SK observation is **$1.4^{+0.8}_{-0.6}$ cm^{-2} s^{-1}** for $E_\nu > 17.3$ MeV

  ➡ **exhibit ~2.3 σ excess!!**

DIFFUSE SUPERNOVA NEUTRINO BACKGROUND

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

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

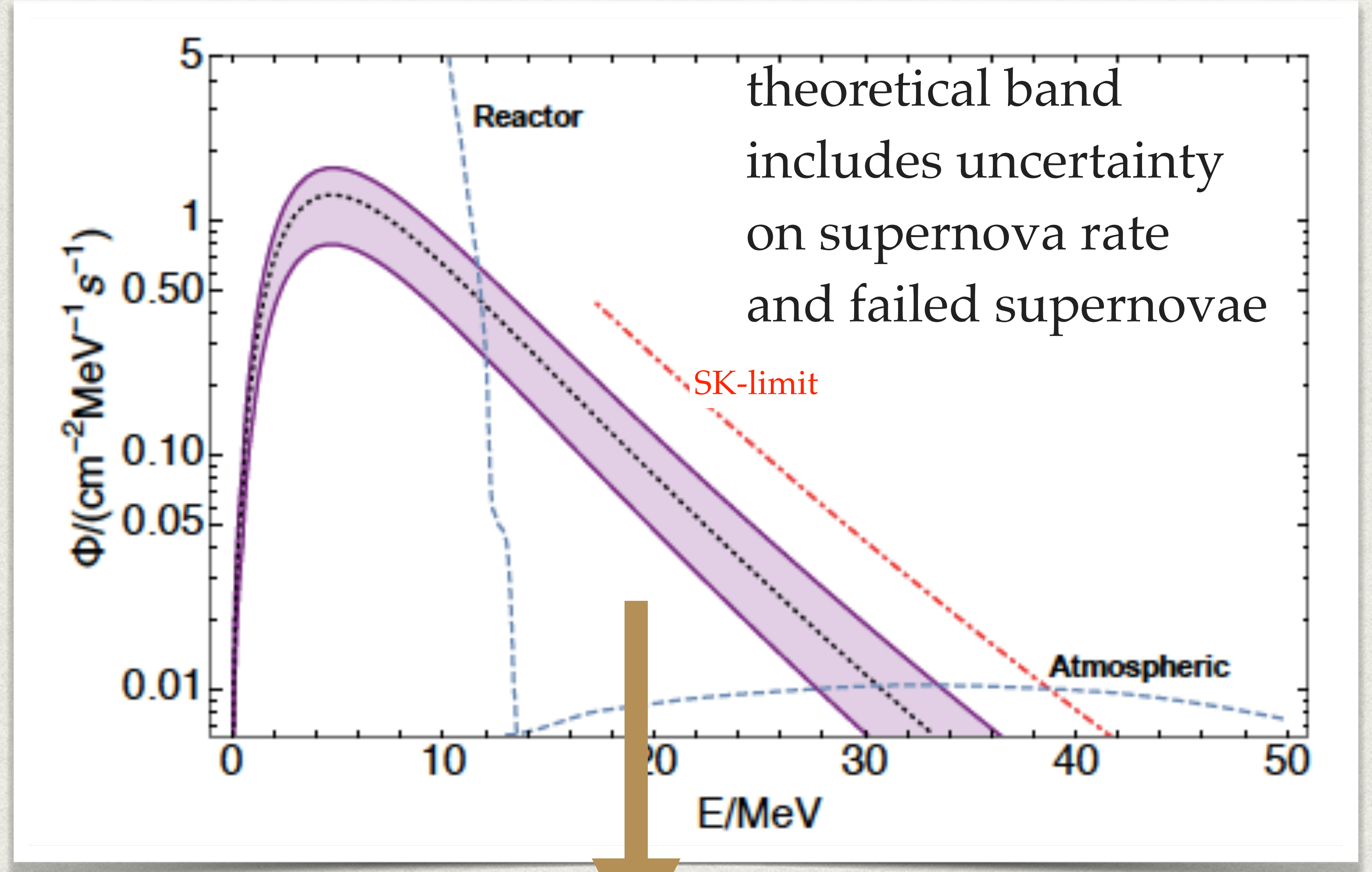
$E'_\nu = E_\nu(1+z)$ redshifted neutrino energies

M mass of the supernova progenitor giving either a neutron star or a black hole

Contribution from failed supernovae (black-hole):
hotter energy spectrum determines the relic flux tail.

Lunardini, PRL 2009

The BH fraction is a debated astrophysical input.



Priya and Lunardini JCAP 2017

DSNB detection window

- Dependence on the cosmological model ΛCDM

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

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

$H_0 = 67.4$ km s^{-1}Mpc^{-1} Hubble constant

CORE-COLLAPSE SUPERNOVA RATE

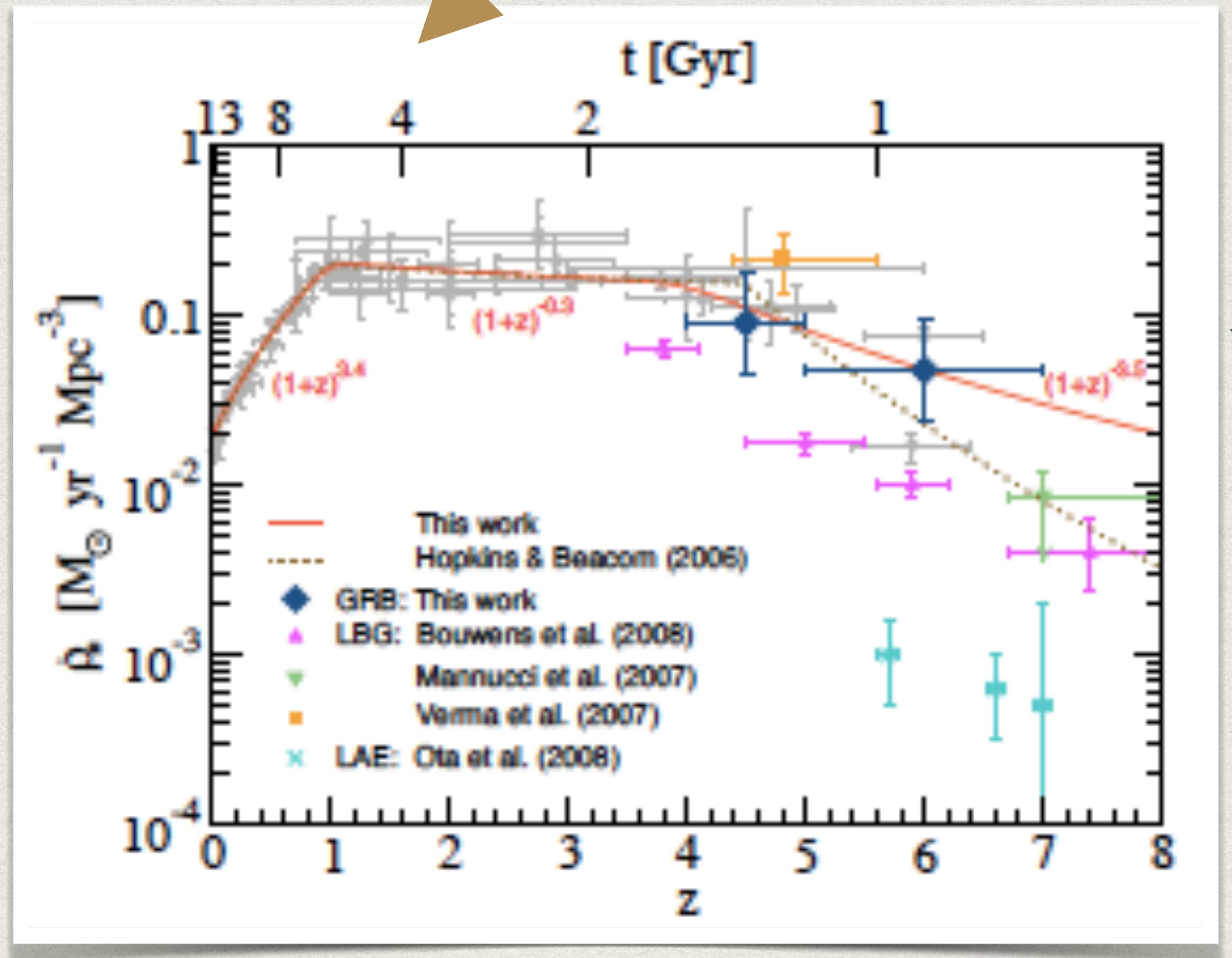
- The cosmic core-collapse supernova rate history can be deduced from the cosmic star formation rate history.

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

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

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

Salpeter Initial Mass Function (IMF)



Yuksel et al, i Astrophys. J(2008)

relevant for the DSNB

below detection threshold

- **Local SN rate uncertain by a factor of 2:**

$$R_{SN}(0) = \int_{8\ {\rm M}_\odot}^{125\ {\rm M}_\odot} R_{\rm SN}(0,{\rm M})d{\rm M}$$
$$= 1.25 \pm 0.5 \times 10^{-4} yr^{-1} Mpc^{-3}$$

ONE of the main UNCERTAINTIES

DSNB ENCODES INFORMATION on

Expected DSNB events (no decay) :
10 for SK-Gd (10 year), and DUNE (20 years),
10-40 for JUNO (20 years)
several hundreds for Hyper-Kamiokande (10-20 years).

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.

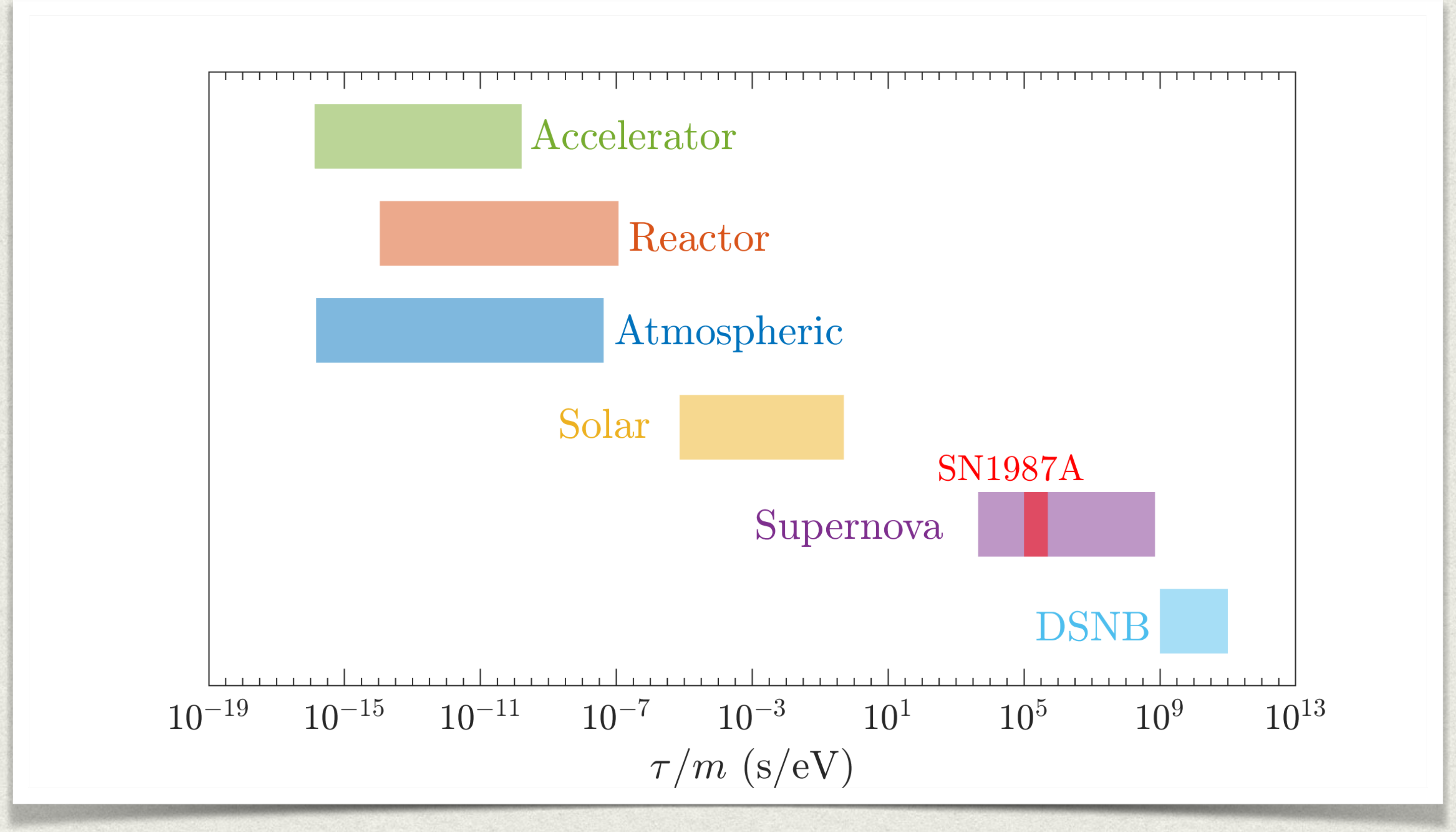
  Ando 2003, Lisi et al 2004,
  De Gouvea et al 2020,
  Tabrizi et Horiuchi 2021,
  Ivanez-Ballesteros and Volpe, 2022.

DSNB and NEUTRINO DECAY

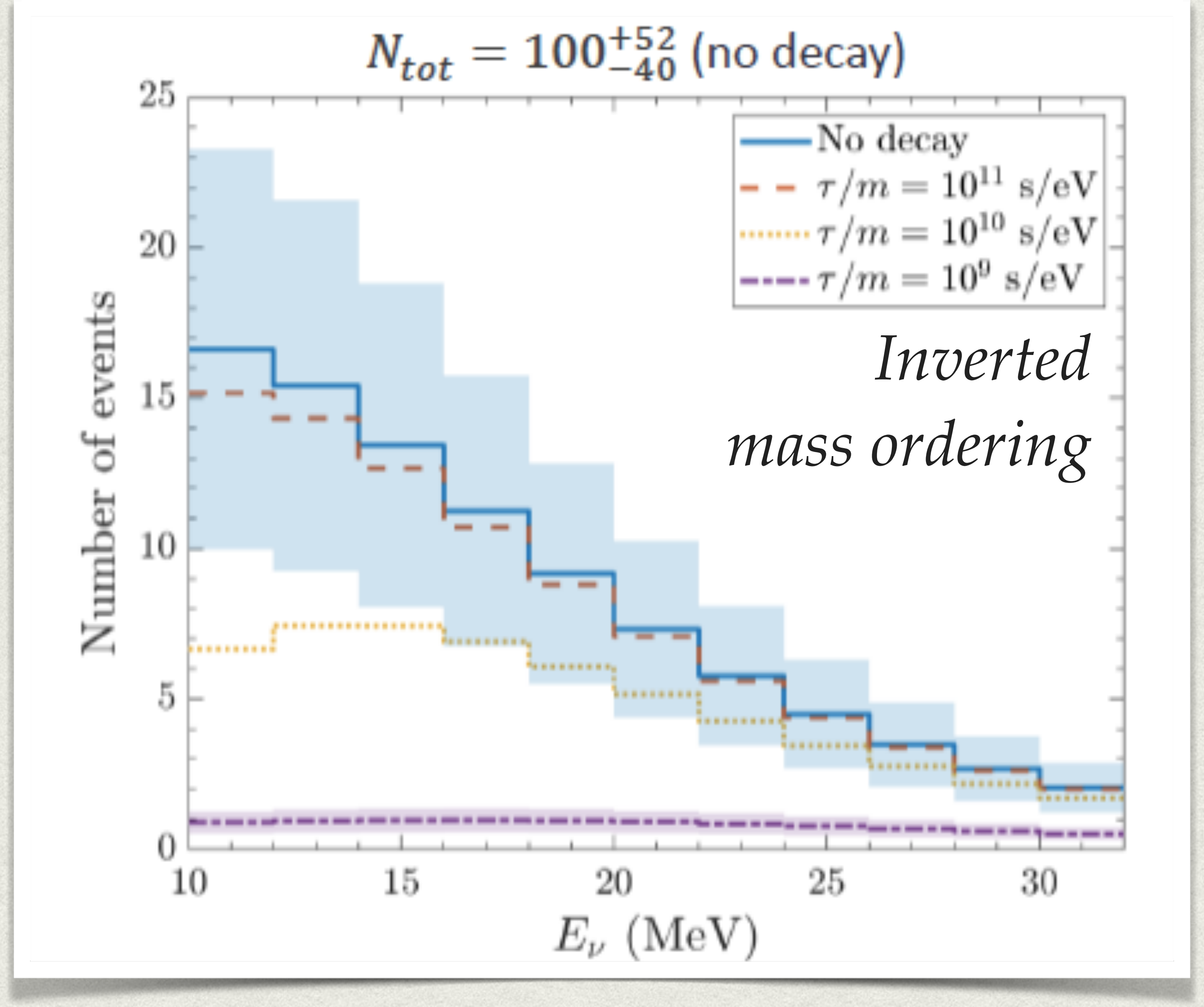
- The DSNB is sensitive to non-standard properties. It has a unique sensitivity to neutrino non-radiative two-body decay:

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

ϕ a massless scalar particle



Hyper-Kamiokande



Ivanez-Ballesteros and Volpe, PRD107 (2023), arXiv:2209.12465

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

Conclusions and Perspectives

Neutrino astrophysics brought milestones in astrophysics and for fundamental physics.
Future observations of neutrinos from a galactic or extragalactic supernova will, as SN1987A, be essential to confirm/refute the current understanding of supernova explosions, and will bring key information on unknown neutrino properties and non-standard physics.

Neutrinos in dense media is a complex weakly interacting many-body system.
A variety of novel flavor mechanisms, beyond the Mikheev-Smirnov-Wolfenstein effect have been discovered in the last two decades.

Progress in the theoretical approaches, on flavor mechanisms, interplay with non-standard neutrino properties, or interactions, are common to dense environments.

A lot of open questions and ongoing developments: role of correlations, interplay between collisions and flavor modification, effects of strong gravitation fields, …

The upcoming discovery of the diffuse supernova neutrino background will open a new window in neutrino astronomy.

« *Une femme jouant de guitare* », Vermeer, 1672