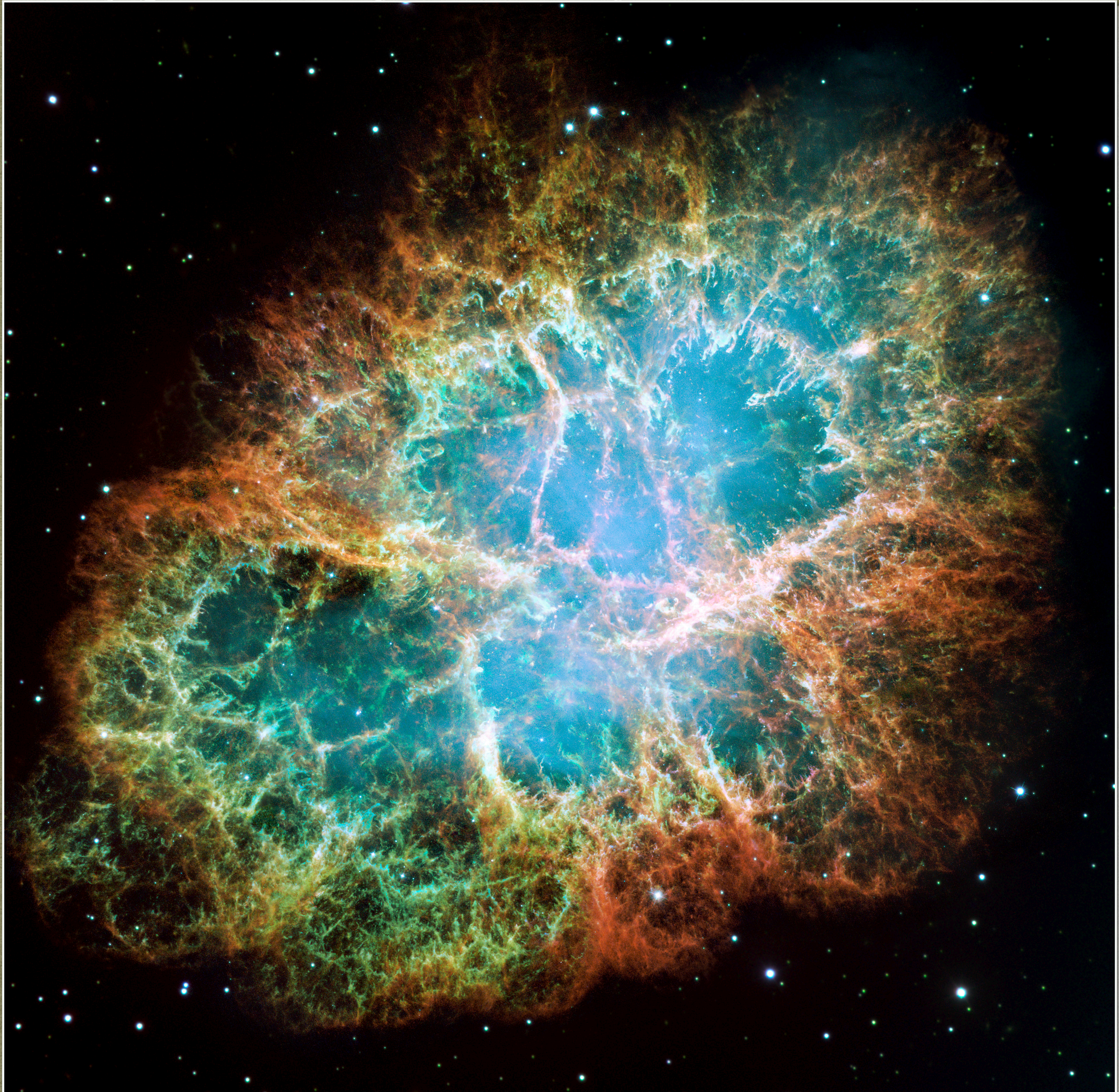
https://science.nasa.gov/asset/hubble/a-giant-hubble-mosaic-of-the-crab-nebula/

# NEUTRINO ASTROPHYSICS:
## *A window to new physics*

## Lecture III

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# OUTLINE OF THE THIRD LECTURE

> Future supernova neutrino observations
> The diffuse supernova neutrino background

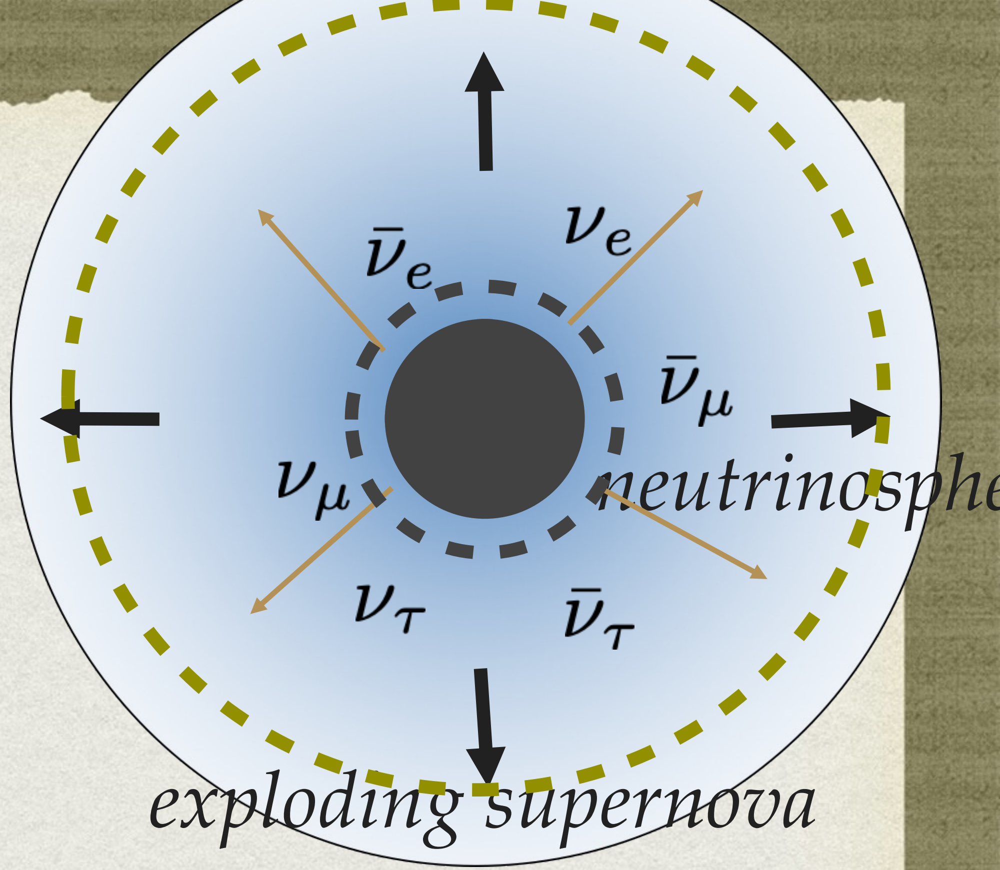
> The issue of the neutrino nature
> Neutrino masses

> Heavy elements nucleosynthesis

> The detection of cosmological neutrinos

> Conclusions

# MSW EFFECT IN SUPERNOVAE



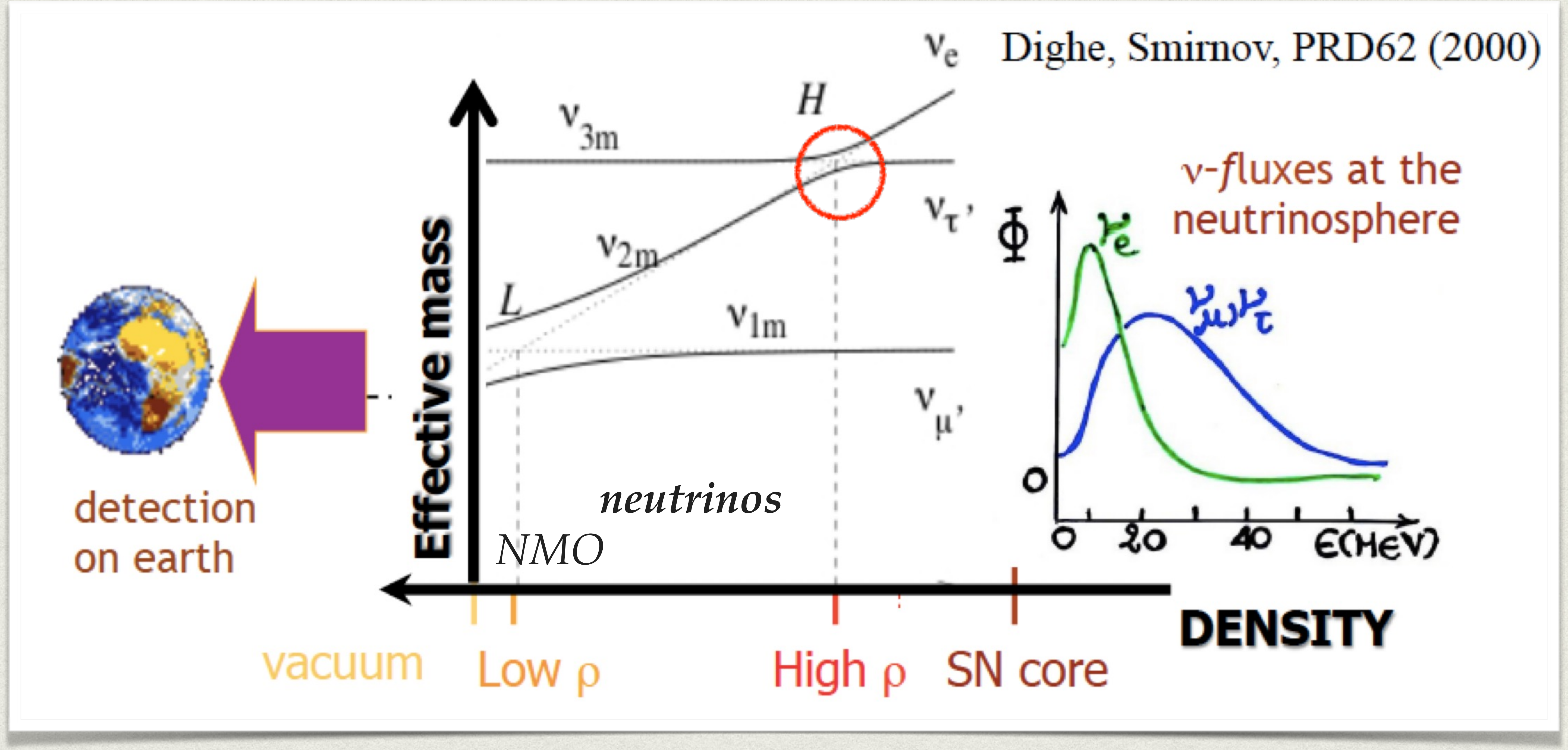

- **MSW resonance condition** $\sqrt{2}G_{\rm F}n_e - \frac{\Delta m^2}{2E}\cos 2\theta = 0$

Main resonances :
High (H) $(\theta_{13}, \Delta m^2_{13})$
Low (L) $(\theta_{12}, \Delta m^2_{12})$

- **Spectral swapping:** Modification of the neutrino spectra due to flavor conversion mechanisms

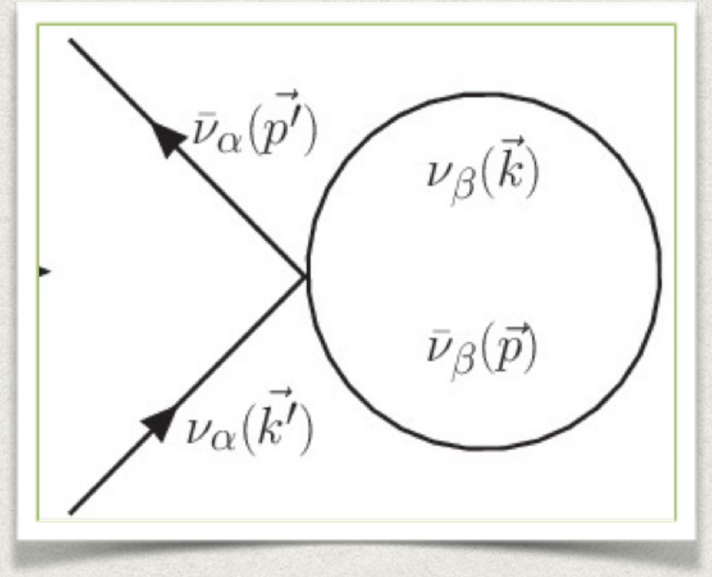
$$\phi_{\bar{\nu}_e} = p\phi^0_{\bar{\nu}_e} + (1-p)\phi^0_{\bar{\nu}_x}$$

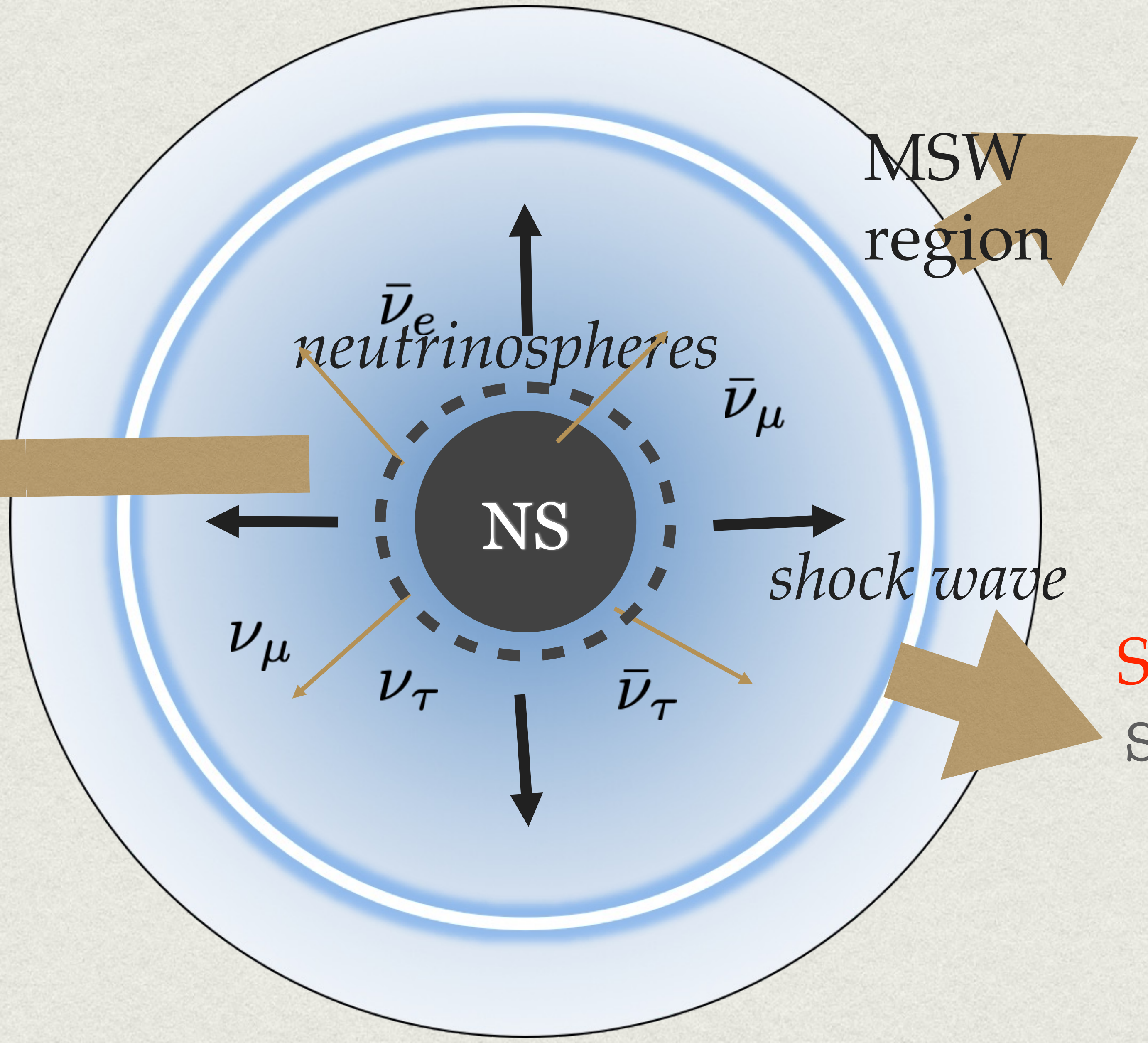
$p = 0.68 \quad NMO \qquad\qquad p = 0 \quad IMO$




→ Evolution at the H-resonance depends on the unknown sign of $\Delta m^2_{13}$

# FLAVOR CONVERSION IN DENSE ENVIRONMENTS




MSW effect

Neutrino-neutrino interactions

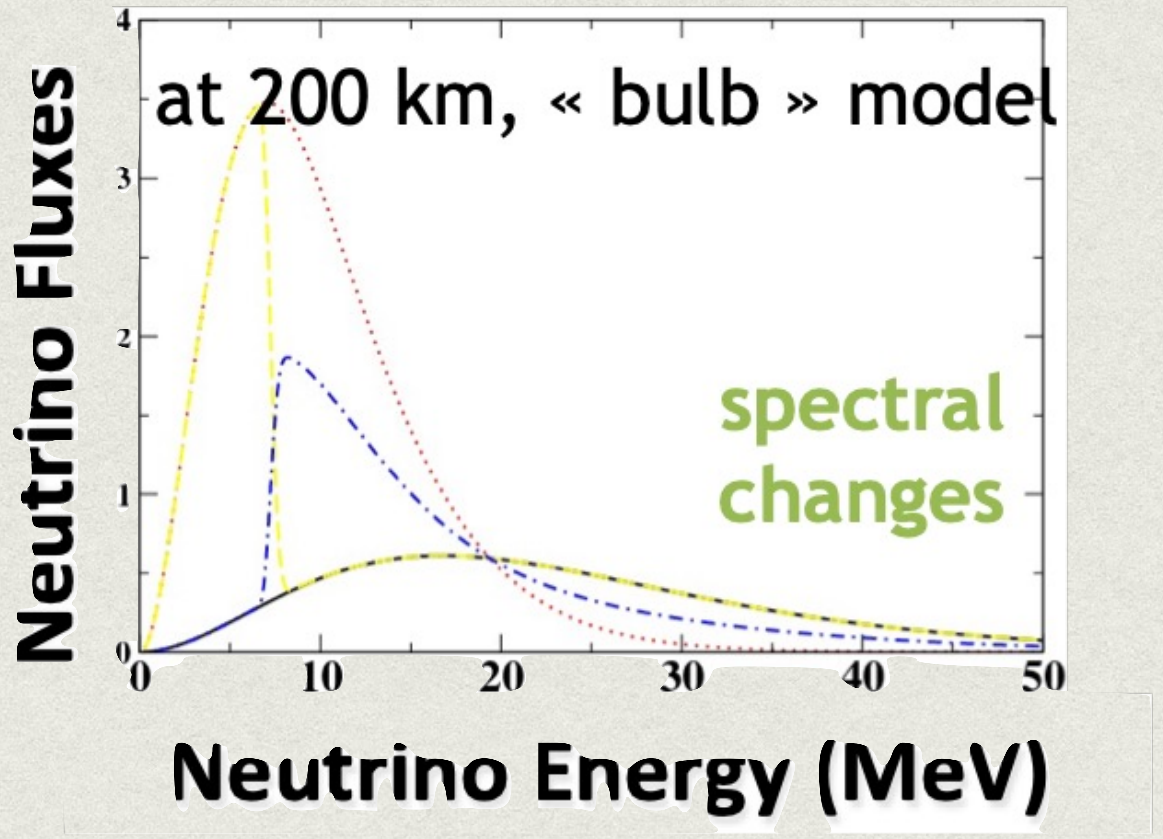
Pantaleone, PLB287 (1992).
Duan et al, PRD, 2006

*slow* **modes**
*fast* **modes (m scale or less)**

Sawyer PRD 2005, PRL 2016.

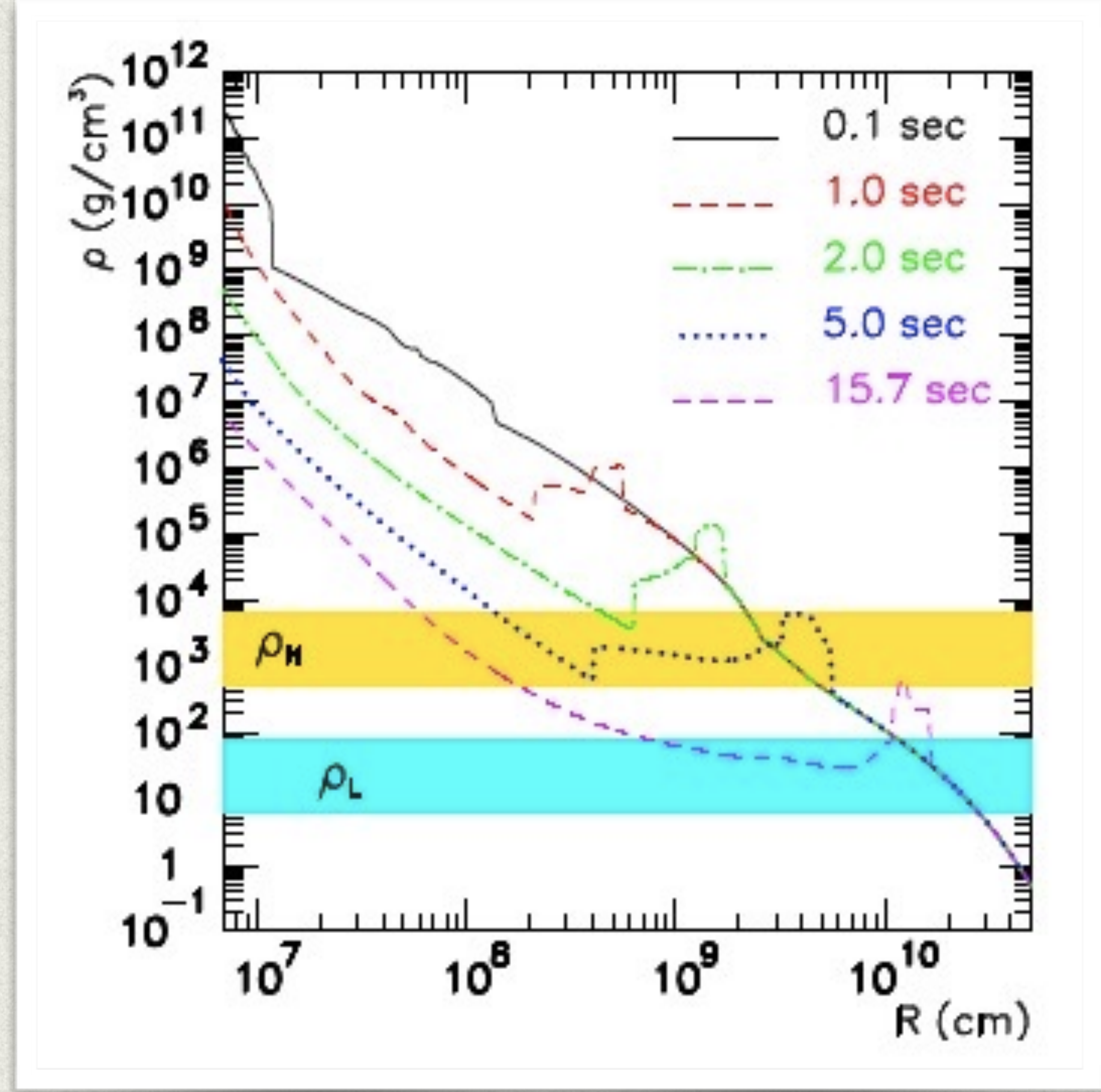
Shock wave effects

Schirato and Fuller, hep-ph/0205390



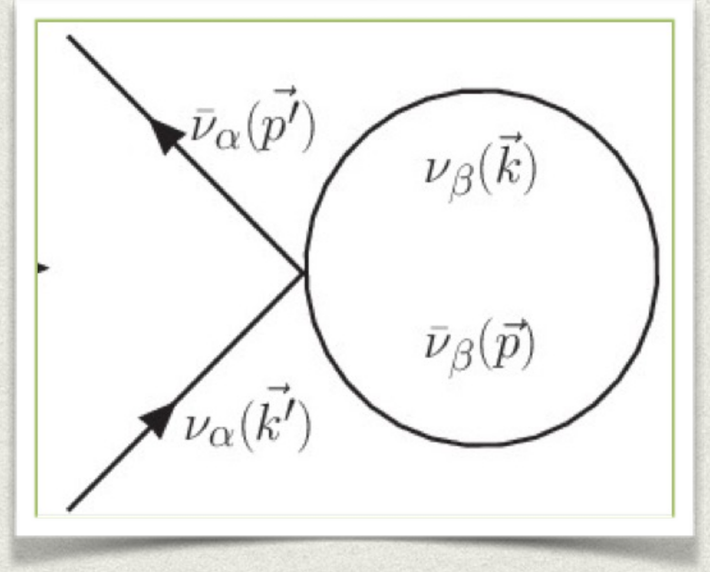

Balantekin, Gava, Volpe, PLB 662 (2008)

Tomas et al, JCAP 09 (2004)




Presence of front and reverse shocks .
MSW resonance can be met multiple times.

# FLAVOR CONVERSION IN DENSE ENVIRONMENTS




Neutrino-neutrino interactions

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***slow*** **modes**
***fast*** **modes (m scale or less)**

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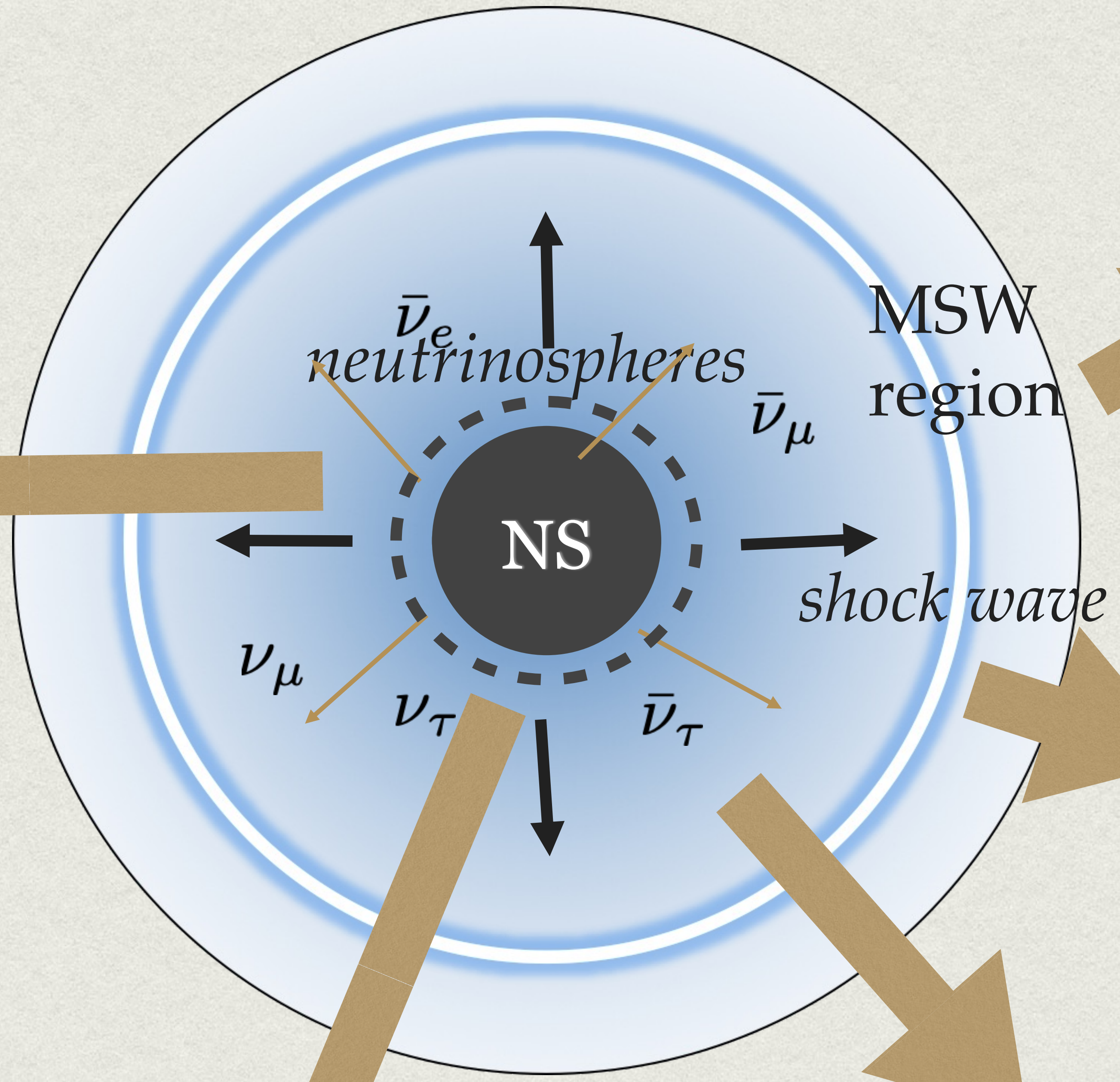
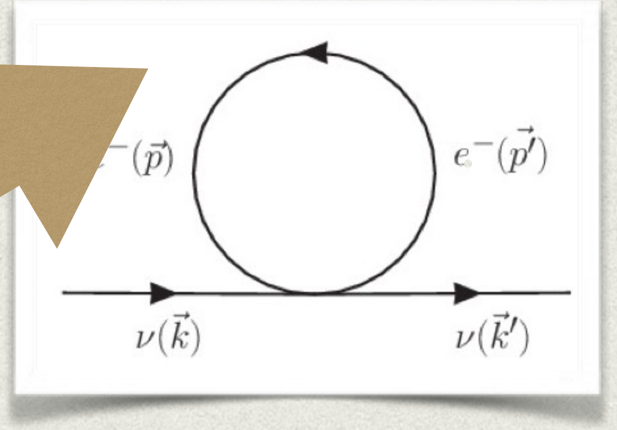



MSW effect




Shock wave effects (multiple MSW)

Schirato and Fuller,
hep-ph/0205390

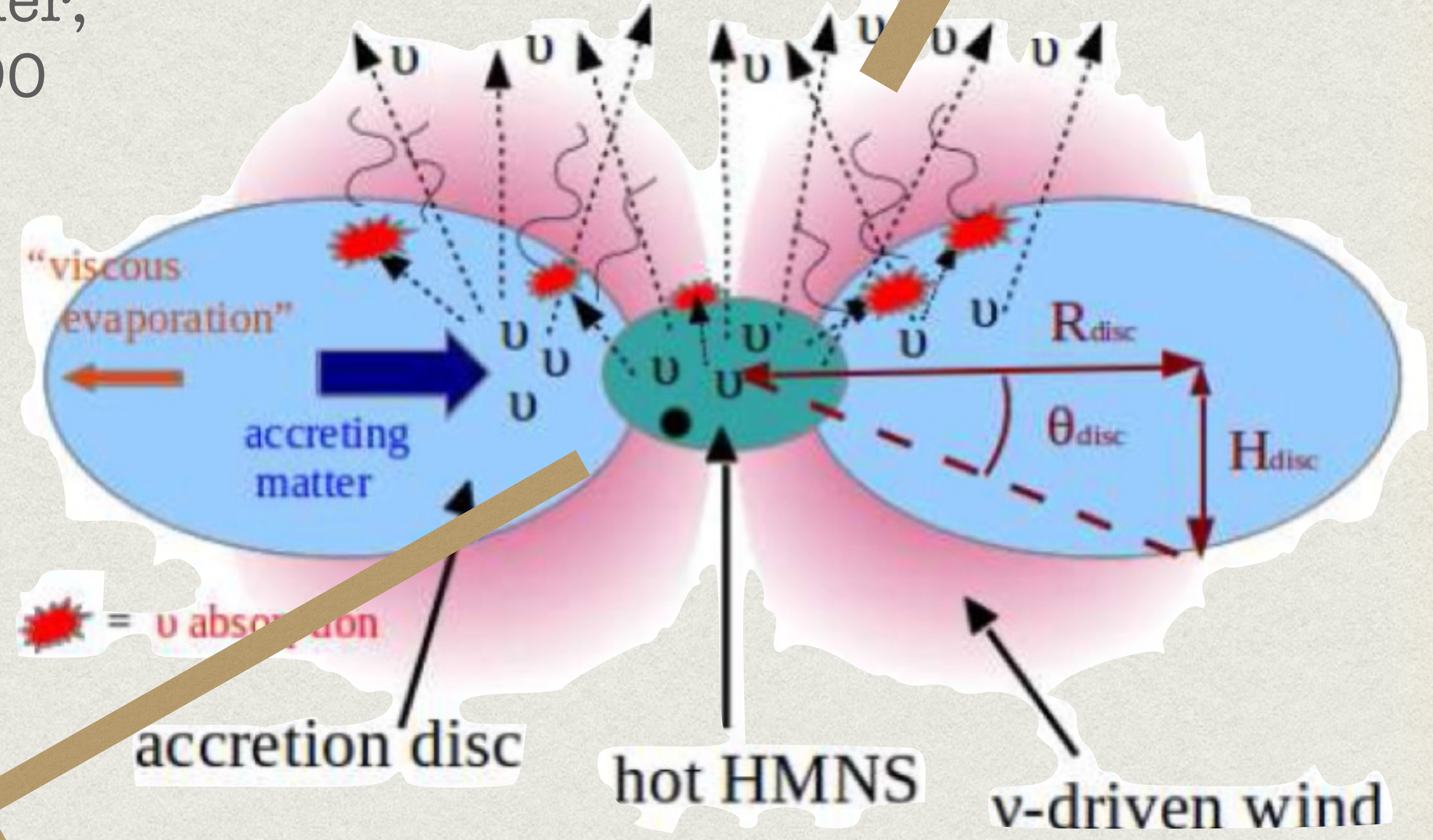
Turbulence effects

Loreti et al, PRD 52 (1995)

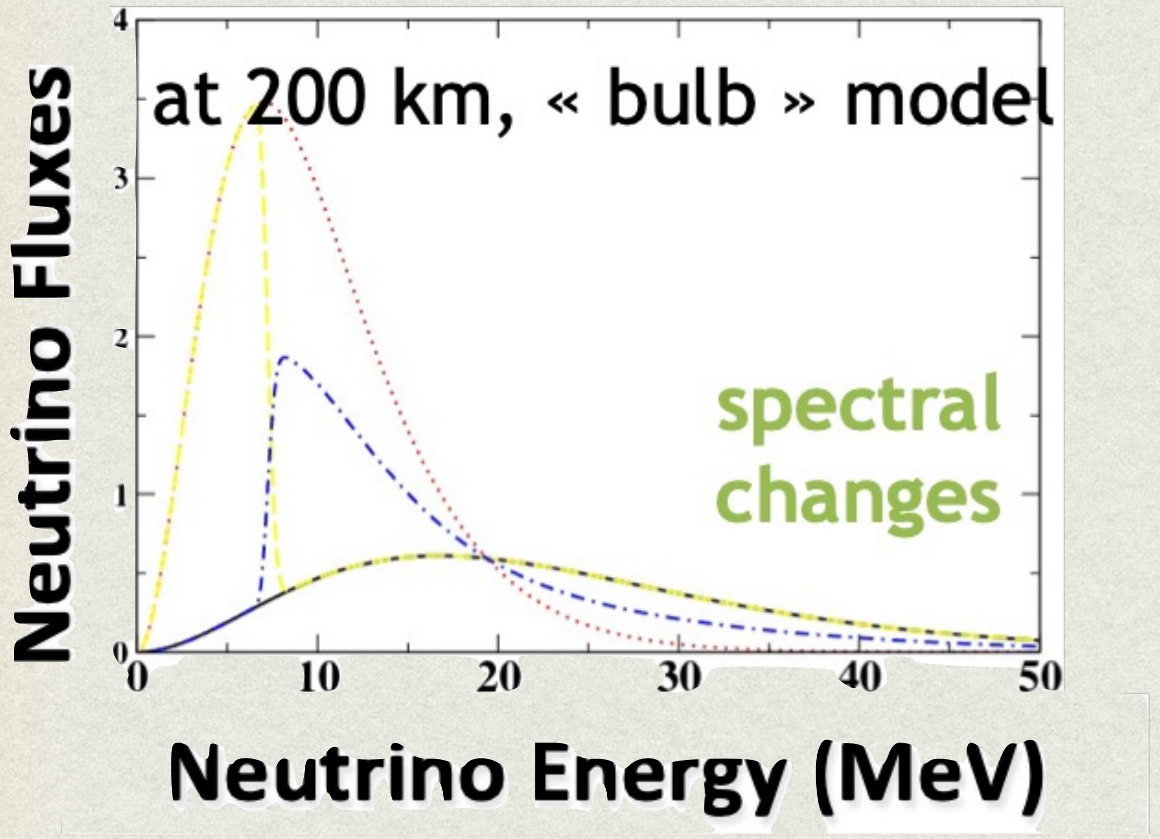
Collisional instabilities

Johns, PRL 19 (2023)

MSW effect




Neutrino-neutrino interactions




Balantekin, Gava, Volpe, PLB 662 (2008)

Many aspects understood (MSW, shock wave effects, ...)
but important questions remain (neutrino-neutrino interaction, interplay with collisions, role of correlations)

# NEUTRINOS from NEXT SUPERNOVA

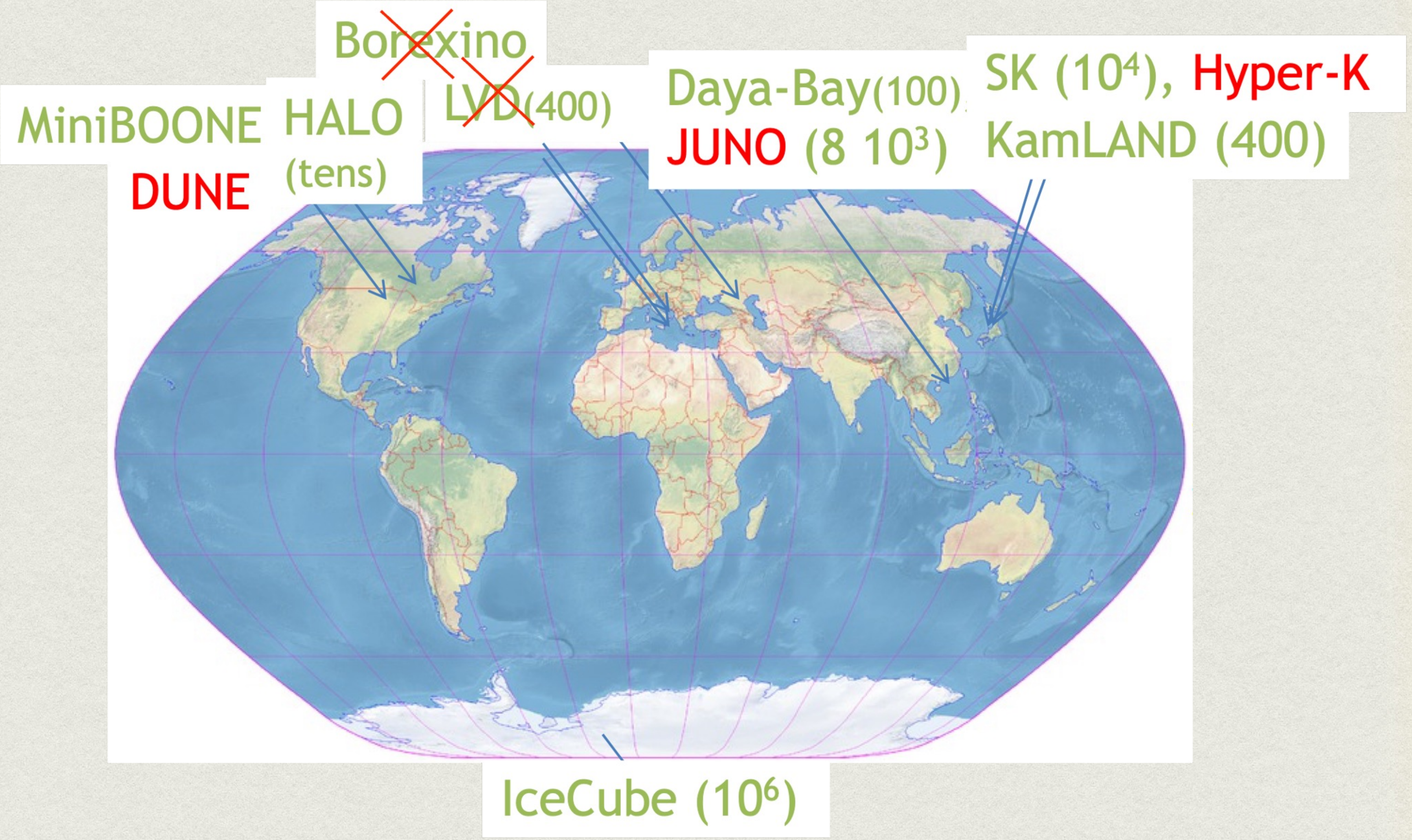
- Supernova Early Warning System (SNEWS 1.0) - prompt, positive, pointing
  Scholberg 1999, 2008; Antonioli et al, 2004
  pre-SN neutrinos, dark matter detectors, multimessenger astronomy
  SNEWS 2.0, 2021

- Expected events (supernova at 10 kpc):
  540 in HALO-2, hundreds in KamLAND,
  3000 in DUNE, 8000 (JUNO), 10000 in Super-K,
  $10^5$ in Hyper-K, $10^6$ in IceCube.

  See also SNEWPY (Baxter et al., 2022).

- Dark matter detectors:
  120 (Xenon nT, 7 tons), 700 (DARWIN, 40 tons),
  336 events (Darkside-20k, 50 tons)

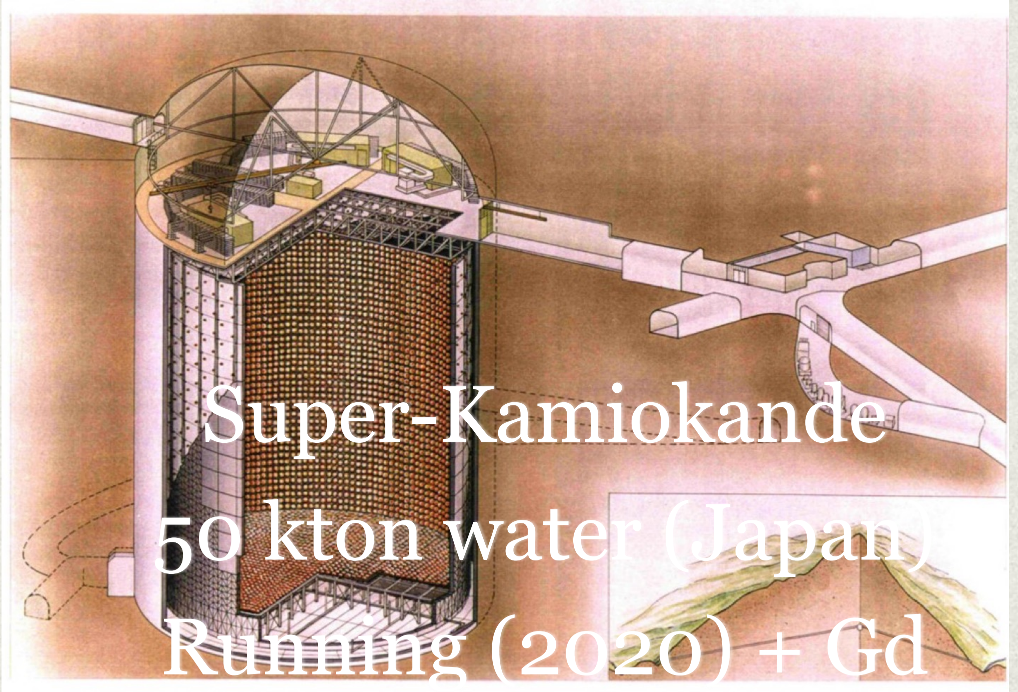
  Lang et al, 2016; Agnes 2021




Many events from the next galactic supernova (10 kpc).

# NEUTRINO DETECTORS as SN observatories

- Examples of running and upcoming detectors that will serve as supernova neutrino observatories:

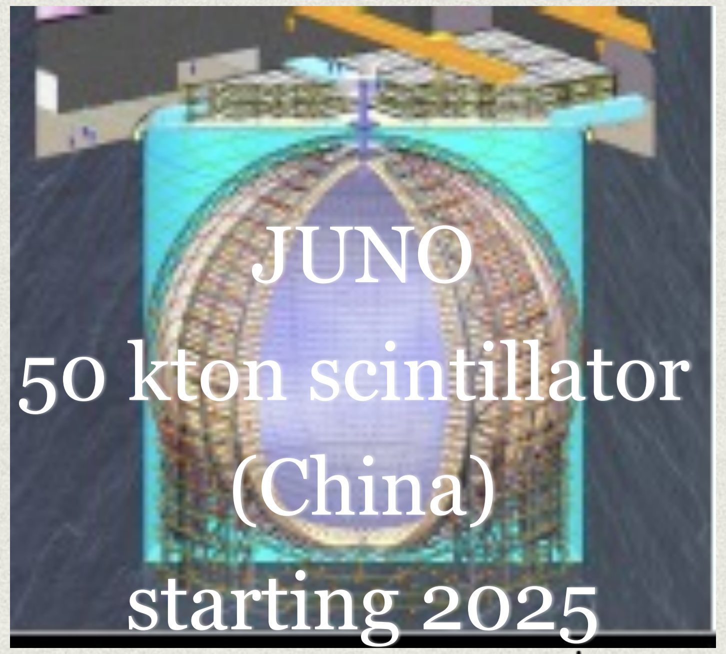


Super-Kamiokande
50 kton water (Japan)
Running (2020) + Gd

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

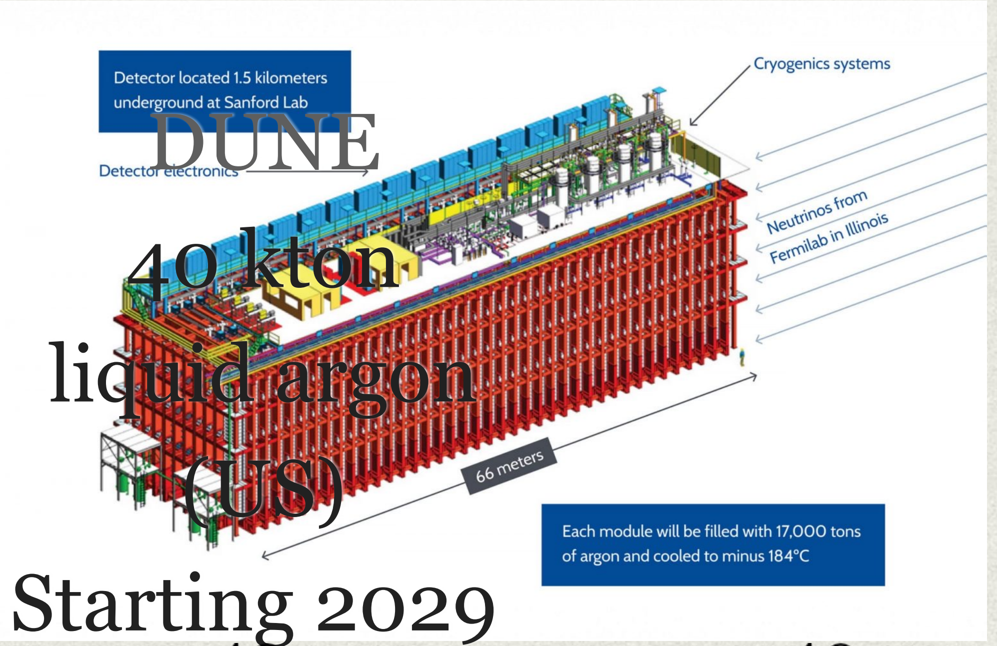
Hyper-Kamiokande
178 kton (FV) water (Japan)
Starting 2028

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



JUNO
50 kton scintillator
(China)
starting 2025

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

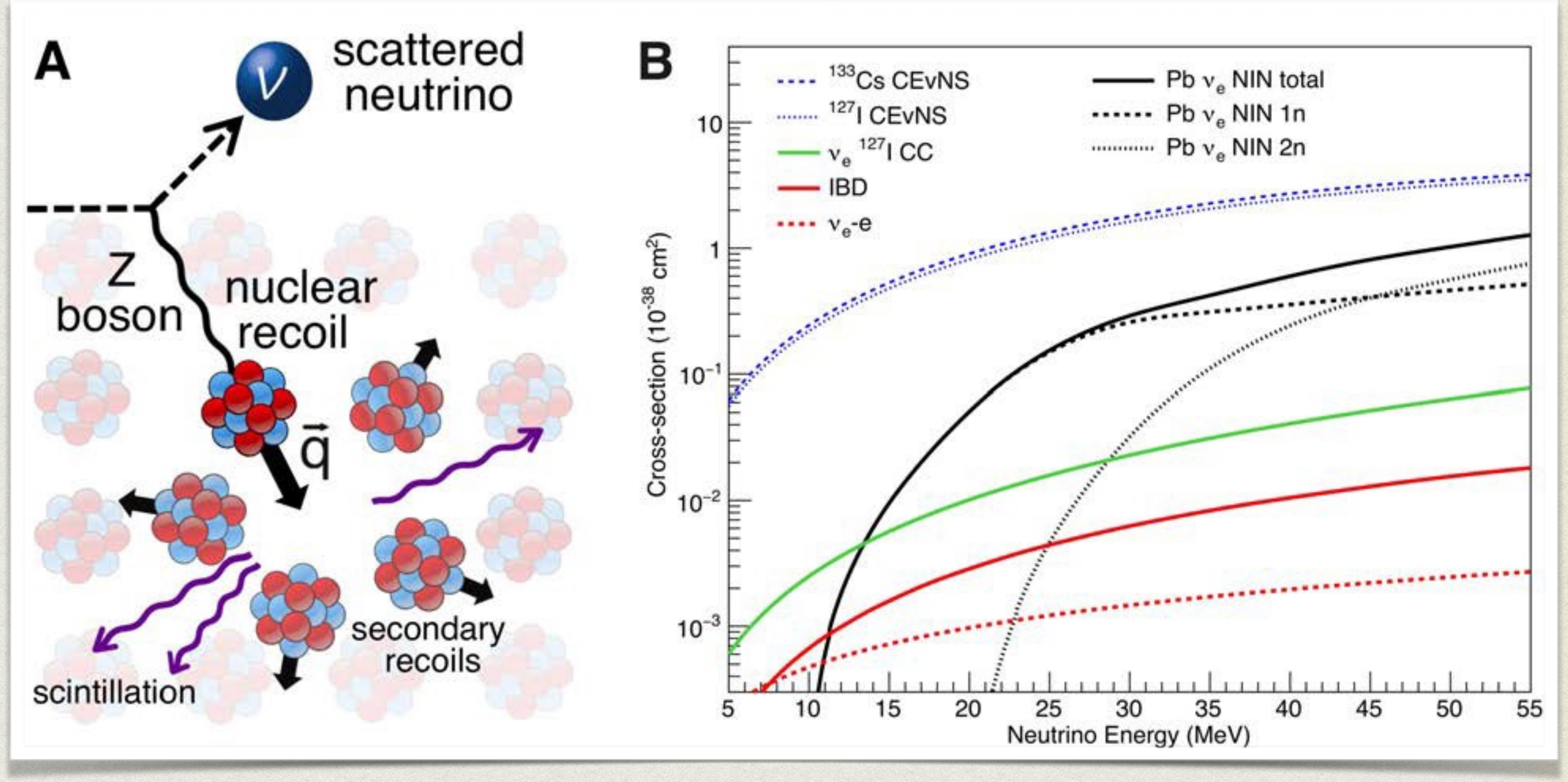



DUNE
40 kton
liquid argon
(US)
Starting 2029

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

- Neutrino-nucleus coherent scattering ($qR < 1$, R nuclear radius, few keV recoils)

D.Z. Freedman. Phys. Rev. D9, 1389 (1974)

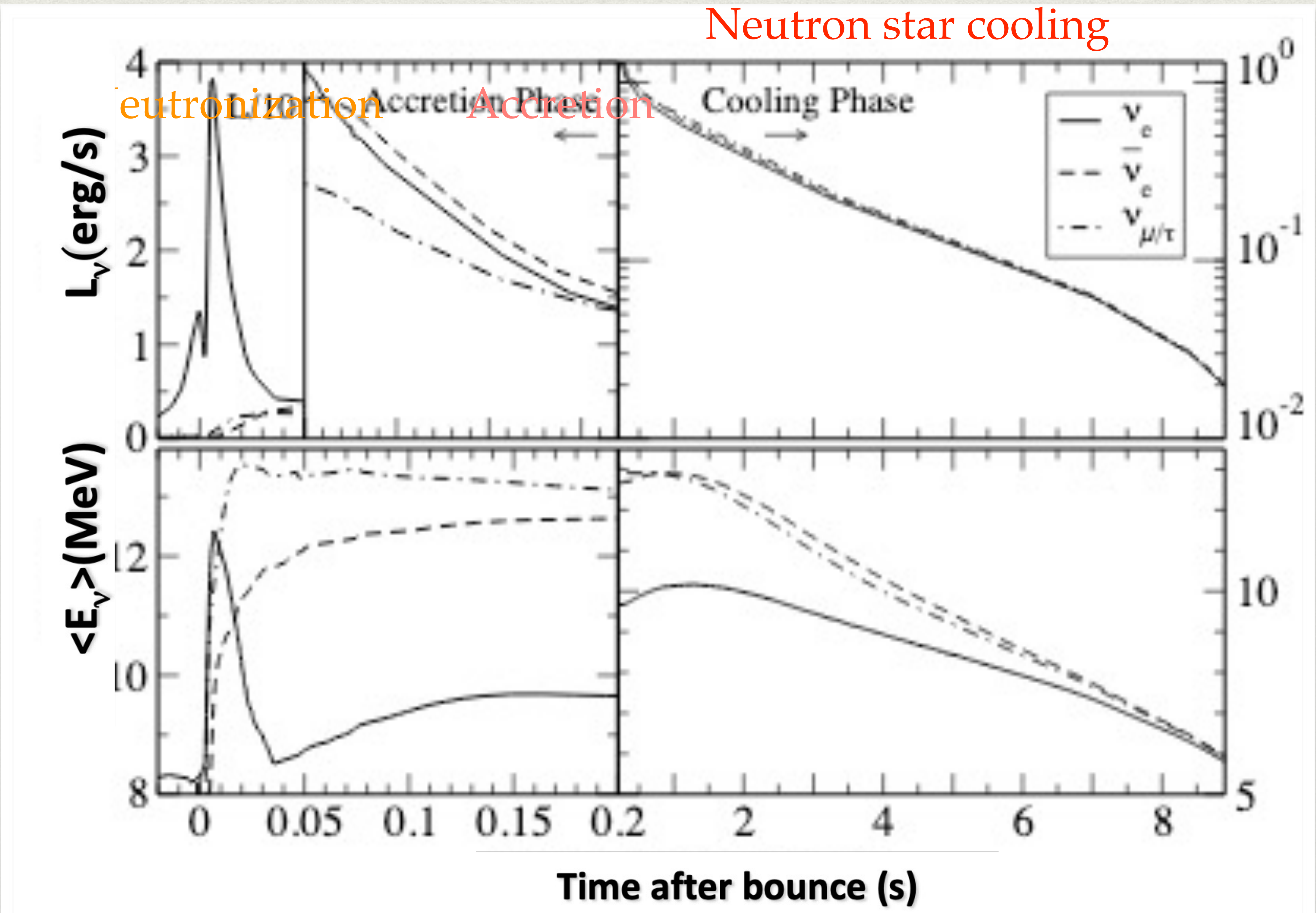



Observed in 2017 (6.7 sigma) by the COHERENT Collaboration at SNS (Oak Ridge)

COHERENT Coll, Science 357 (2017) 6356 1708.01294 [

Sentivity to all flavors, time and energy signal through nu-electrons, nu-nucleus incoherent, nu-proton and coherent nu-nucleus scattering

# SN NEUTRINO 10 s TIME SIGNAL




Hudepöhl et al PRL, 2011

Detection of each phase crucial

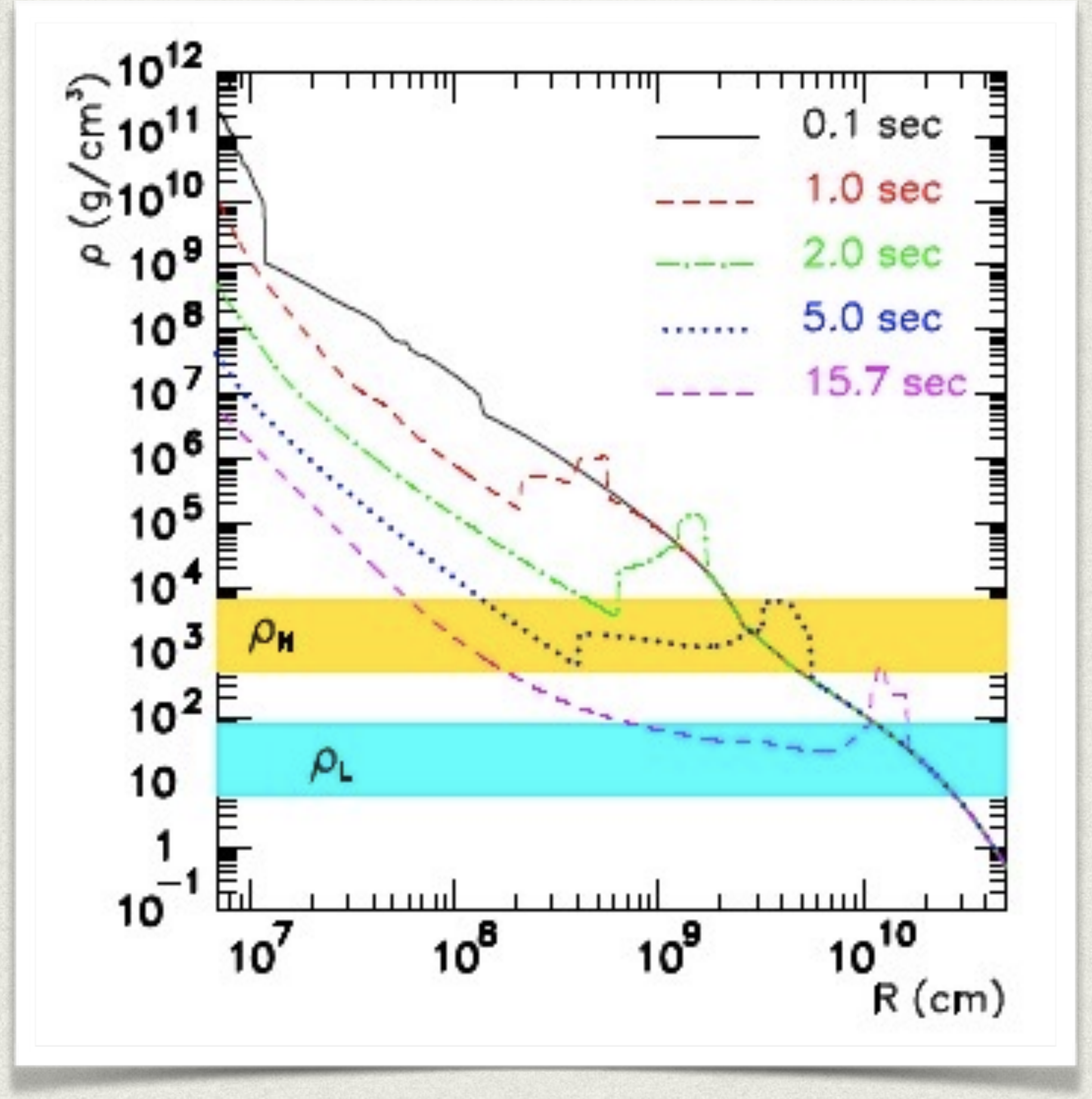
- Neutronization peak:
  > only MSW effect operates
  > non-standard properties, ex. decay or NSI
  De Gouvea et al, PRD101, 2020; Das et al, JCAP 05, 2017; etc…

- Total gravitational energy emitted in neutrino luminosity ((SN at 10 kpc):
  > 11% (SK) and 3% (HK) precision
  Gallo Rosso, Vissani, Volpe, JCAP 11, 2017

# NEUTRINO MASS ORDERING

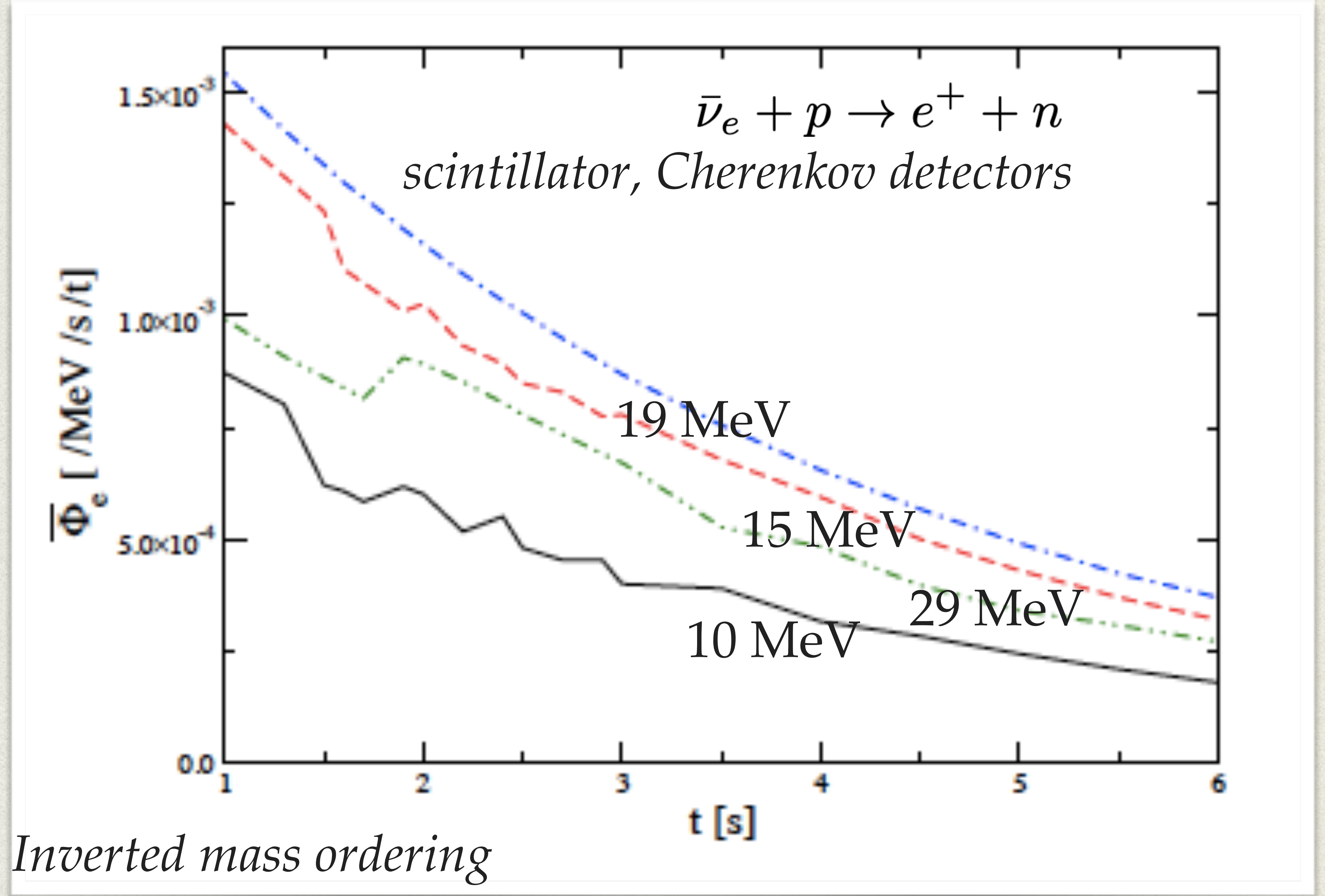
- Presence of front and reverse shocks .

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)

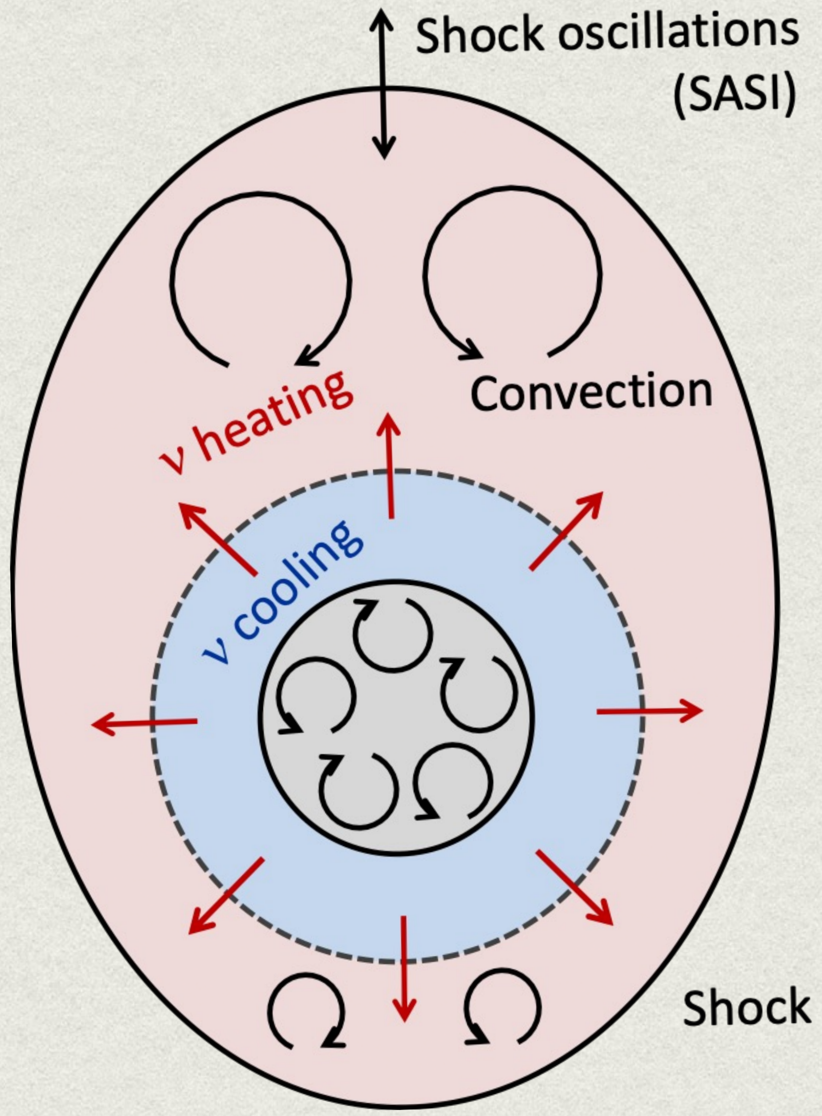
Positron time signal from $\bar{\nu}_e$ per unit tonne.
Prediction includes $\nu\nu$ interactions and shock wave effects.

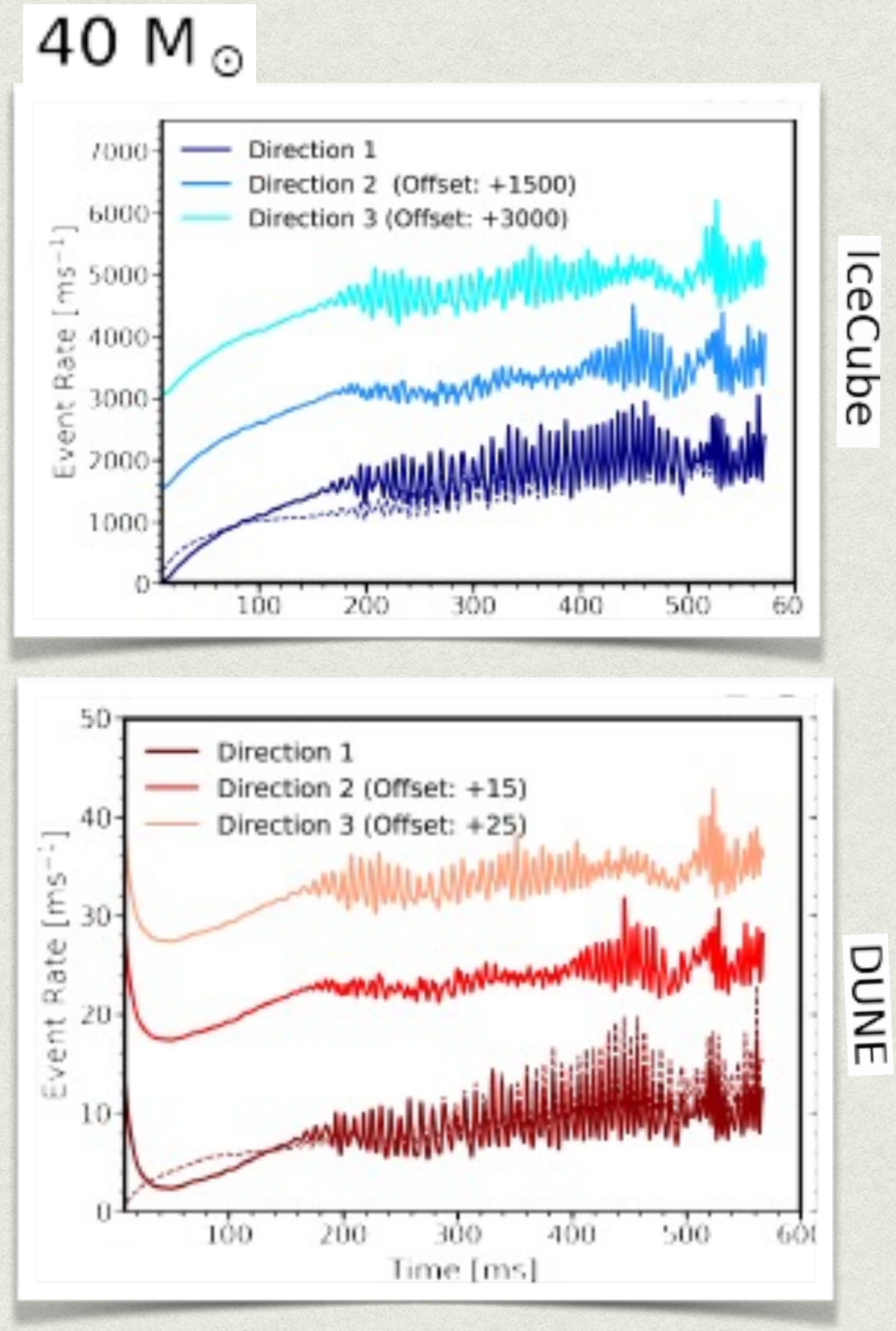
**Picture of the supernova explosion from the shock wave passage in the MSW region.**
**Similar result for electron neutrinos in argon-based detectors (DUNE) for NMO.**

# THE DELAYED NEUTRINO-HEATING MECHANISM

- *Since a decade, there is an emerging consensus : the majority of supernovae explodes due to the **delayed neutrino-heating mechanism** neutrinos efficiently reheat the shock aided by convection,* **turbulence and hydrodynamic instabilities (SASI).**

  see Mezzacappa (2022), arXiv: [2205.13438](https://arxiv.org/abs/2205.13438).



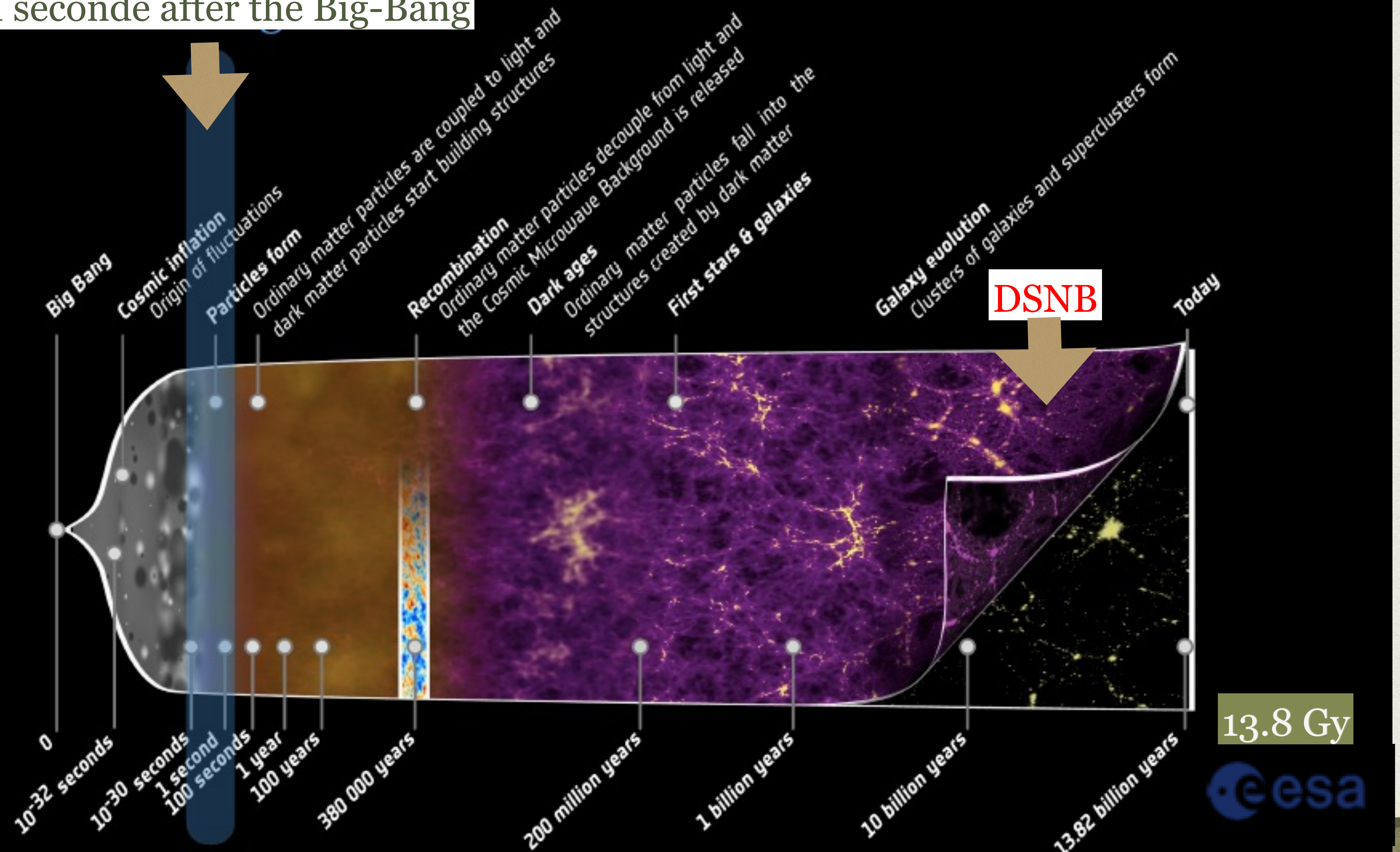

Walk et al (2020)

see also Mueller, Janka, Astr. J. (2014), Tamborra et al, Ast. Journ.(2014)

**OBSERVING THE NEXT SUPERNOVA CRUCIAL to CONFIRM/REFUTE**

# Universe evolution

1 seconde after the Big-Bang



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

*might be imminent…*

It depends on **astrophysics**, **cosmology** **and** **neutrino physics** **in a unique way.**

# Running and upcoming detectors

- There are four running or upcoming experiments with a potential sensitivity to the DSNB: Super-Kamiokande+Gadolinium (Gd), Hyerp-Kamionkande, JUNO and DUNE.

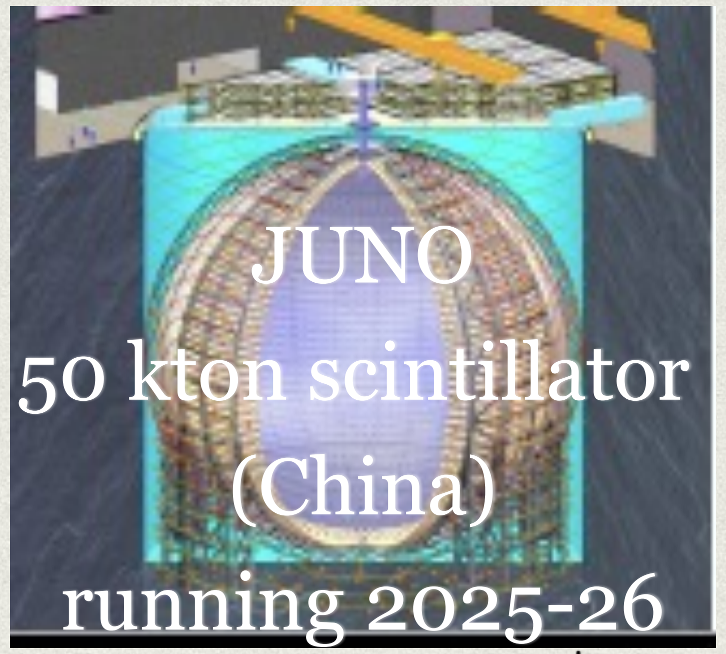
Super-Kamiokande
50 kton water (Japan)
Running (2020) + Gd

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

Hyper-Kamiokande
178 kton (FV) water (Japan)
Starting 2028

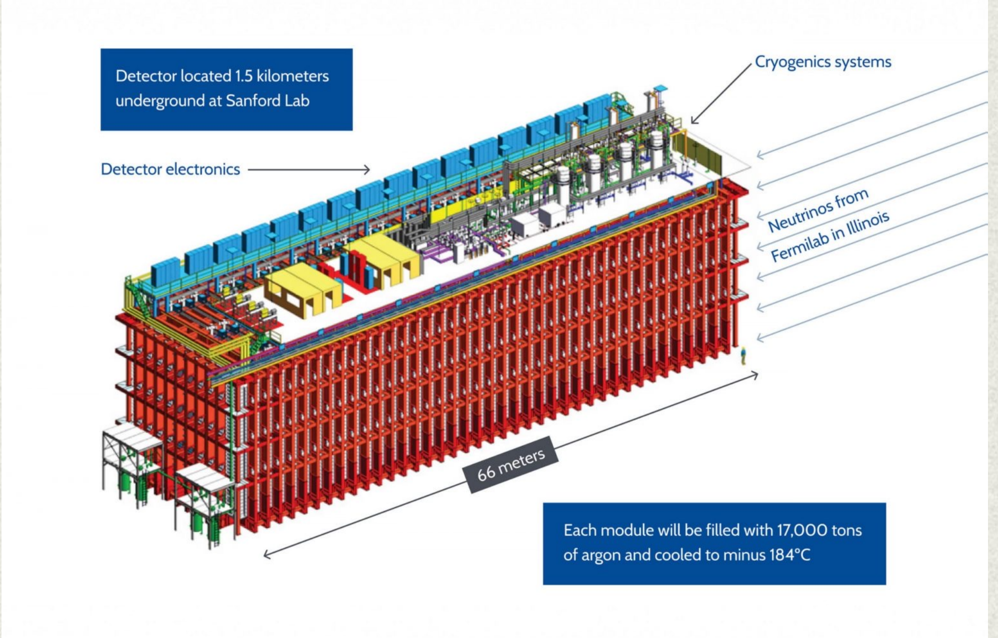
$$\bar{\nu}_e + p \rightarrow n + e^+ (IBD)$$

Active volume :
8.3 times larger
than Super-K



JUNO
50 kton scintillator
(China)
running 2025-26

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




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

DUNE, 40 kton
(4 tanks of 10 ton)
liquid argon (US)
starting in 2019

Dark matter detectors through coherent neutrino-nucleus scattering, see e.g. Suliga, Beacom, Tamborra, PRD 105 (2022), 2112.09168
The DSNB is part of the « neutrino floor » in dark matter detectors.

# Current upper limits on the DSNB flux

- Flux upper limits from SKI-IV and SNO data

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

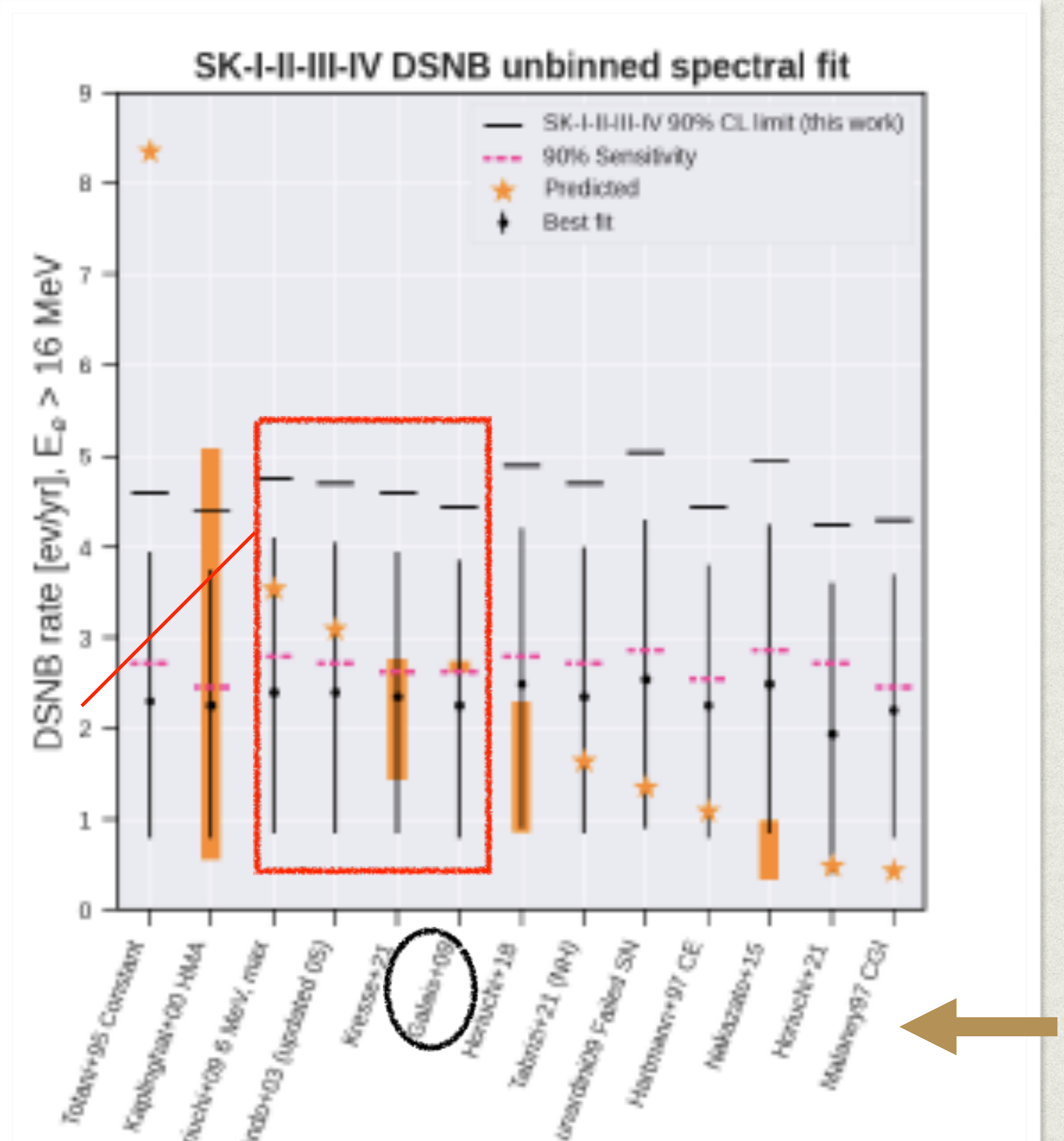
Abe et al, 2109.11174

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

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

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

The sensitivity of the combined analysis is on par with 4 predictions.




Abe et al, 2109.11174

*Sample of DSNB available predictions*

Super-Kamiokande analyses (20 years) :
DSNB rates (90% C.L.), best fit values (1 sig.)
and expected sensitivity from SK-I and SK-IV data

# The DSNB: the flux of neutrinos from past supernovae

- The diffuse supernova neutrino background (DSNB) depends on **astrophysics**, **cosmology** and **neutrino physics** **in a unique way. The information encoded is complementary to the one from individual supernovae.**

- The DSNB flux depends on the evolving core-collapse supernova rate, the neutrino fluxes from a supernova (integrated over time), the cosmological model through the cosmic time

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

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

M - mass of the supernova progenitor $\quad \mathrm{M} \in [8,100]$

$1 + z = \frac{\lambda_0}{\lambda_1} = \frac{R(t_0)}{R(t_1)}$ - redshift, ratio of detected to emitted wavelength increase in the cosmic scale factor R(t) leads to a red shift of the light of distant sources $\quad z \in [0,5]$

c - speed of light

For each supernova progenitor, one needs to calculated the neutrino flux through the supernova that depends on supernova simulations, neutrino properties and new physics. We need to look back past in the history of the Universe.

# The flux of neutrinos from past supernovae

Our ΛCDM Universe today


Heavy elements 0.03 %

Stars 0.5 %

CMB 0.001 %

Neutrinos 0.1-0.3%

- 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

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

$H_0 = \frac{\dot{R}(t_0)}{R(t_0)}$ - present expansion rate of the Universe

# EVOLVING CORE-COLLAPSE SUPERNOVA RATE

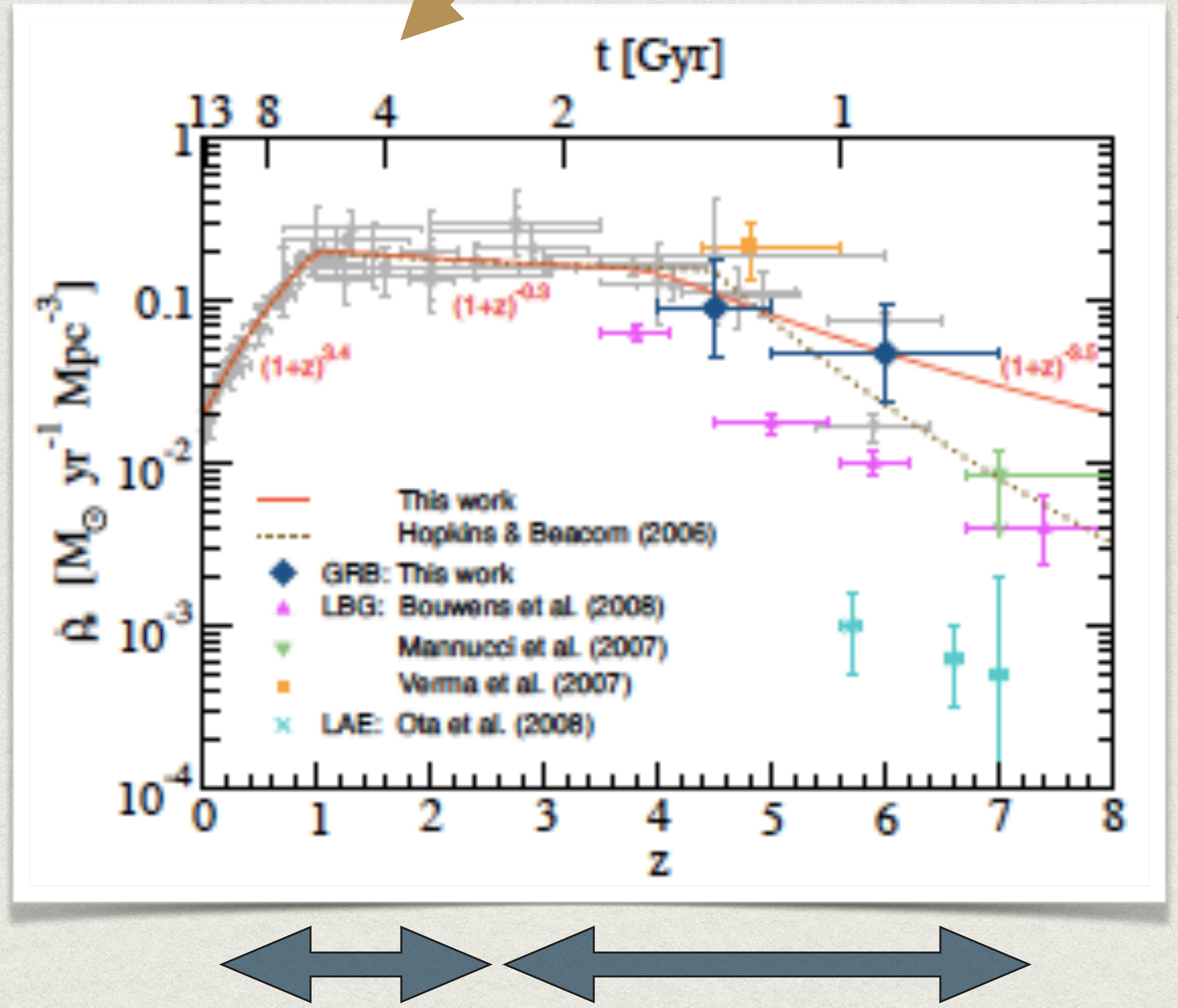
- The cosmic core-collapse supernova rate history can be deduced from the cosmic star formation rate history.

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

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

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

Salpeter Initial Mass Function (IMF)




Yuksel et al, Astrophys. J(2008)

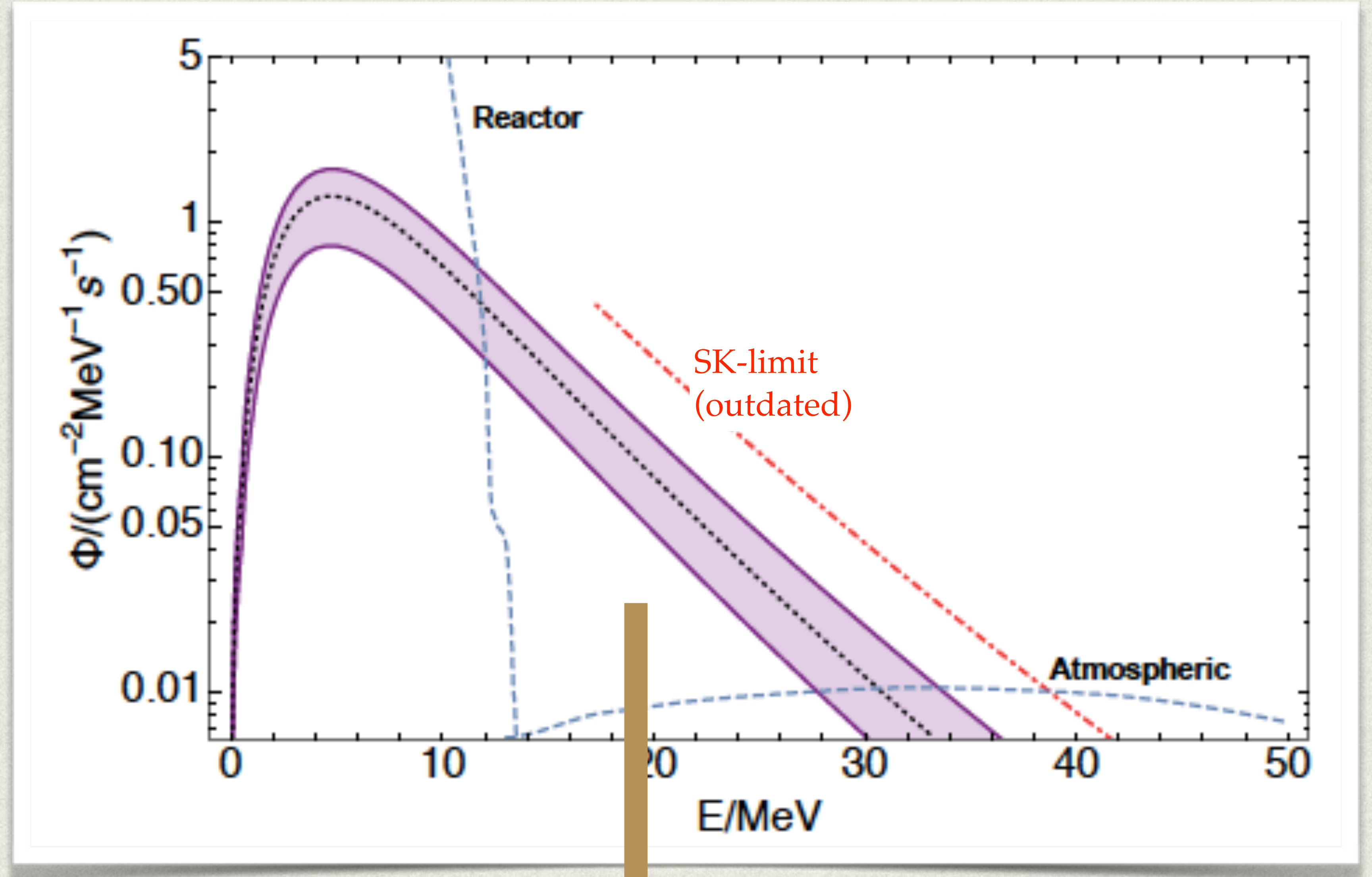
relevant for the DSNB

below detection threshold

**ONE of the main UNCERTAINTIES**

# The DSNB flux and the fraction of failed supernovae

- Predictions for the DSNB flux: the theoretical band includes the uncertainty on supernova rate and on failed supernovae



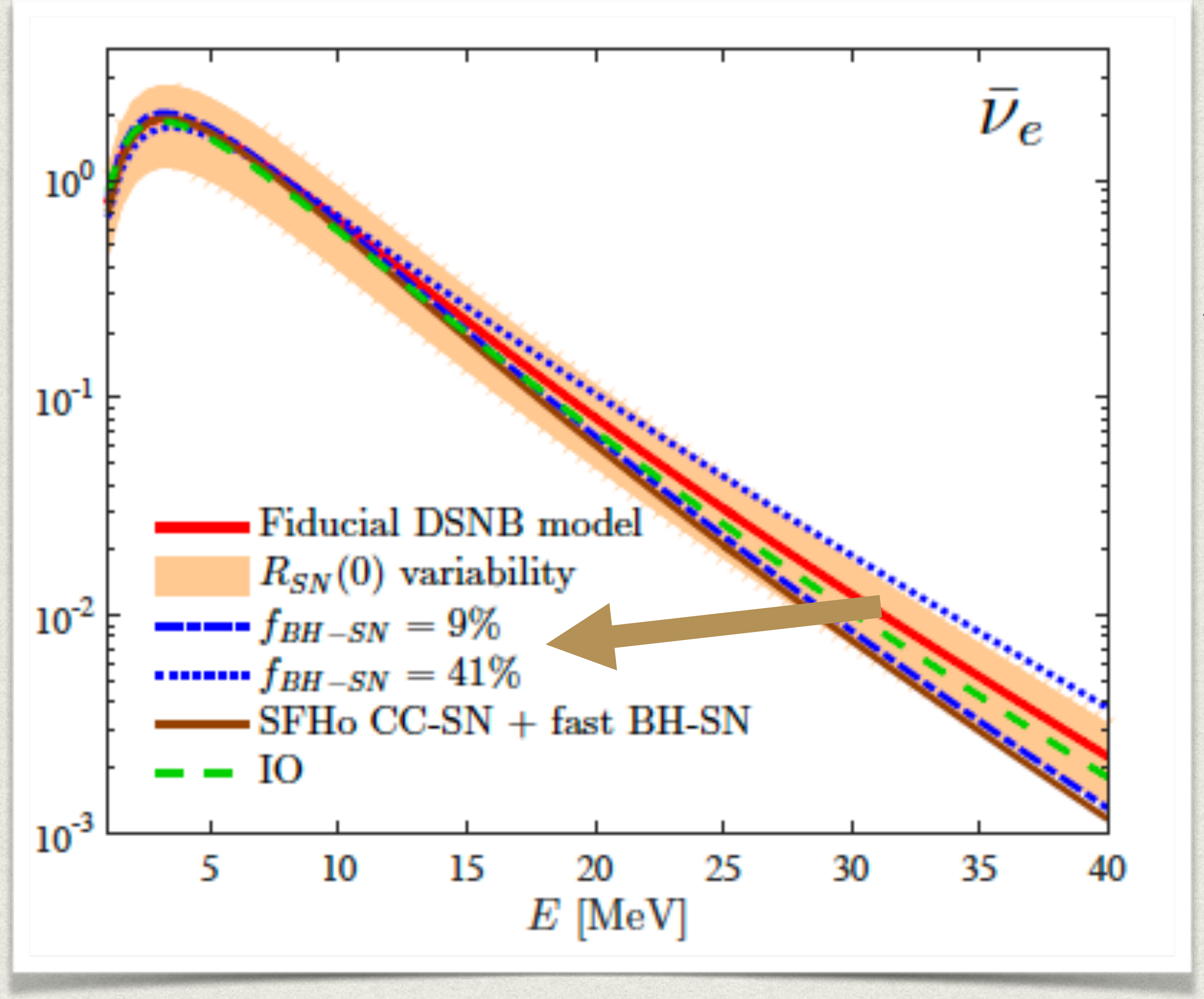

Priya and Lunardini JCAP 2017

*DSNB detection window*

- The supernova progenitor can give either a neutron star or a black hole

Lunardini, PRL 2009

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




Möller et al, JCAP 2018

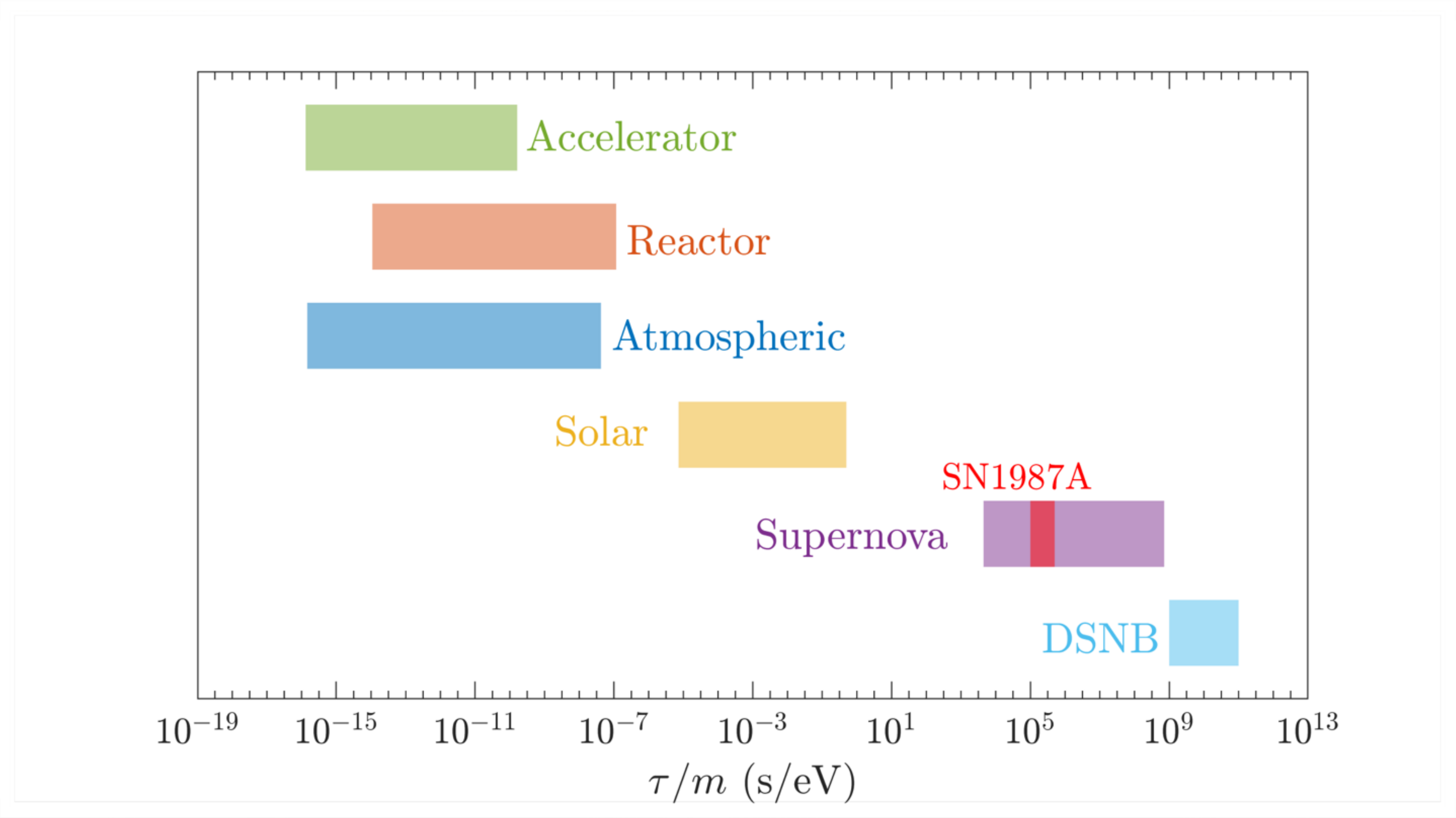
*The BH fraction is a debated astrophysical input.*

# The DSNB and new physics: an example

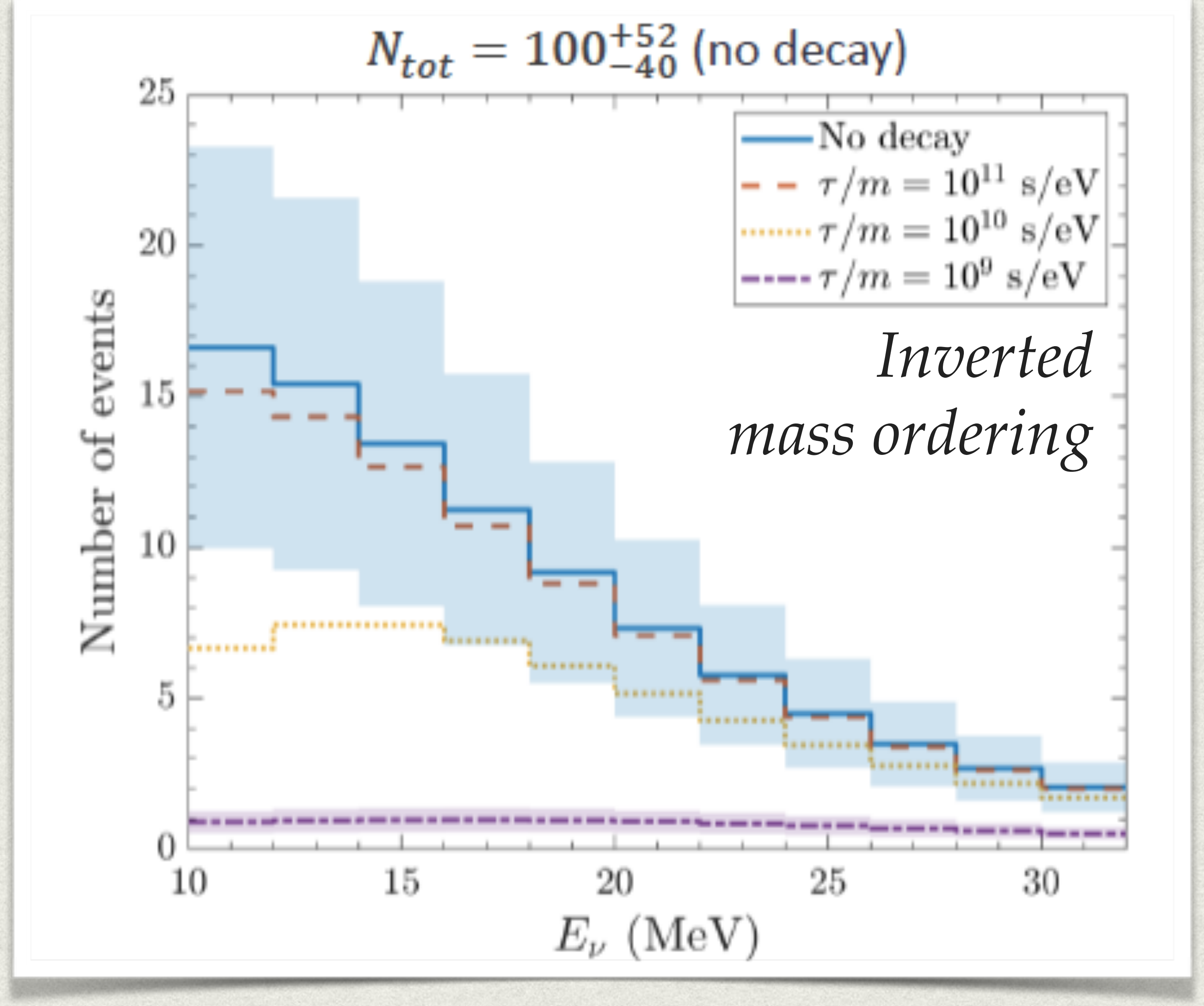
- The DSNB is sensitive to non-standard properties.
  It has a unique sensitivity to neutrino non-radiative two-body decay:

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

$\phi$ a massless scalar particle




Hyper-Kamiokande



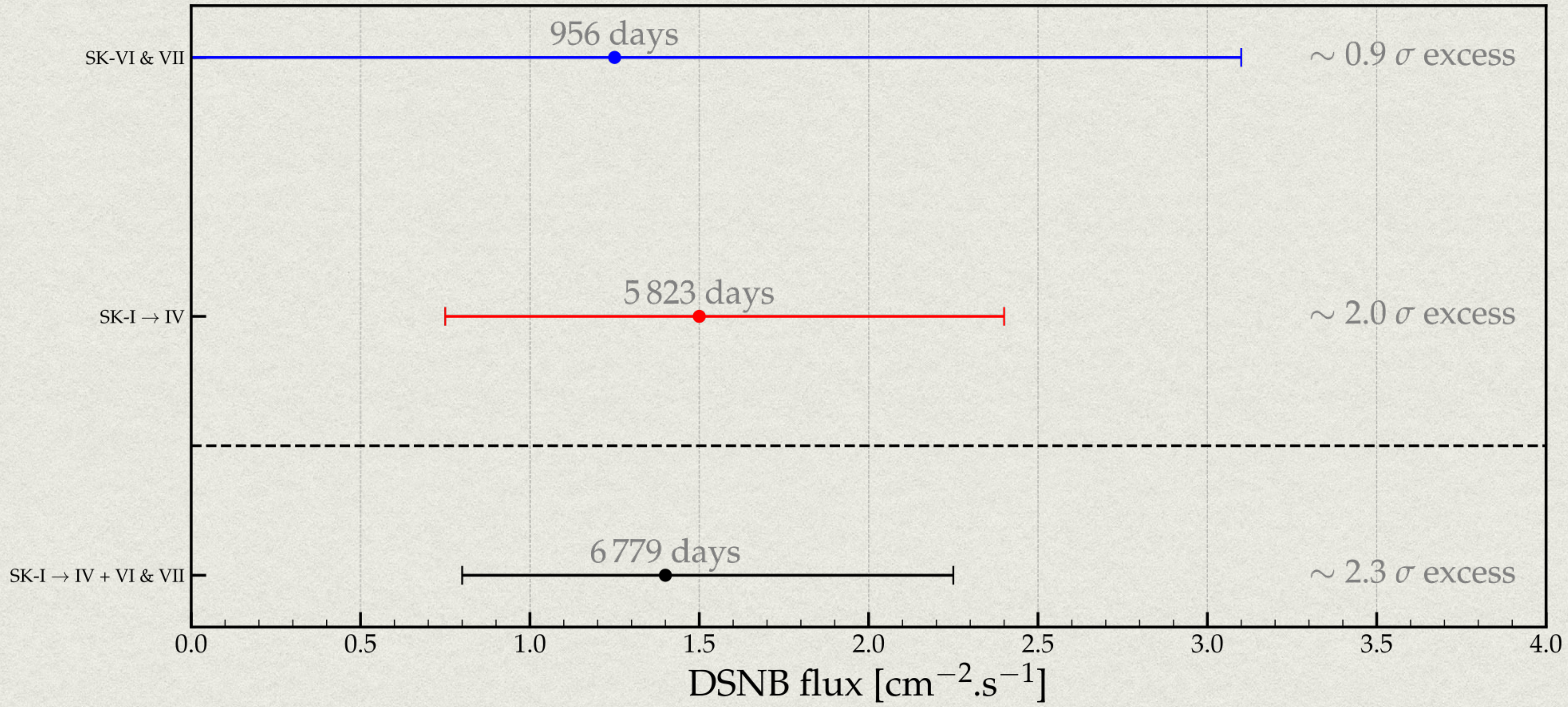

Ivanez-Ballesteros and Volpe,
PRD107 (2023), arXiv:2209.12465

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

**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).

The DSNB observation would open a completely new window in neutrino astrophysics.
Crucial information on the evolving core-collapse supernova rate, the fraction of failed supernovae, supernova neutrinos and new physics.

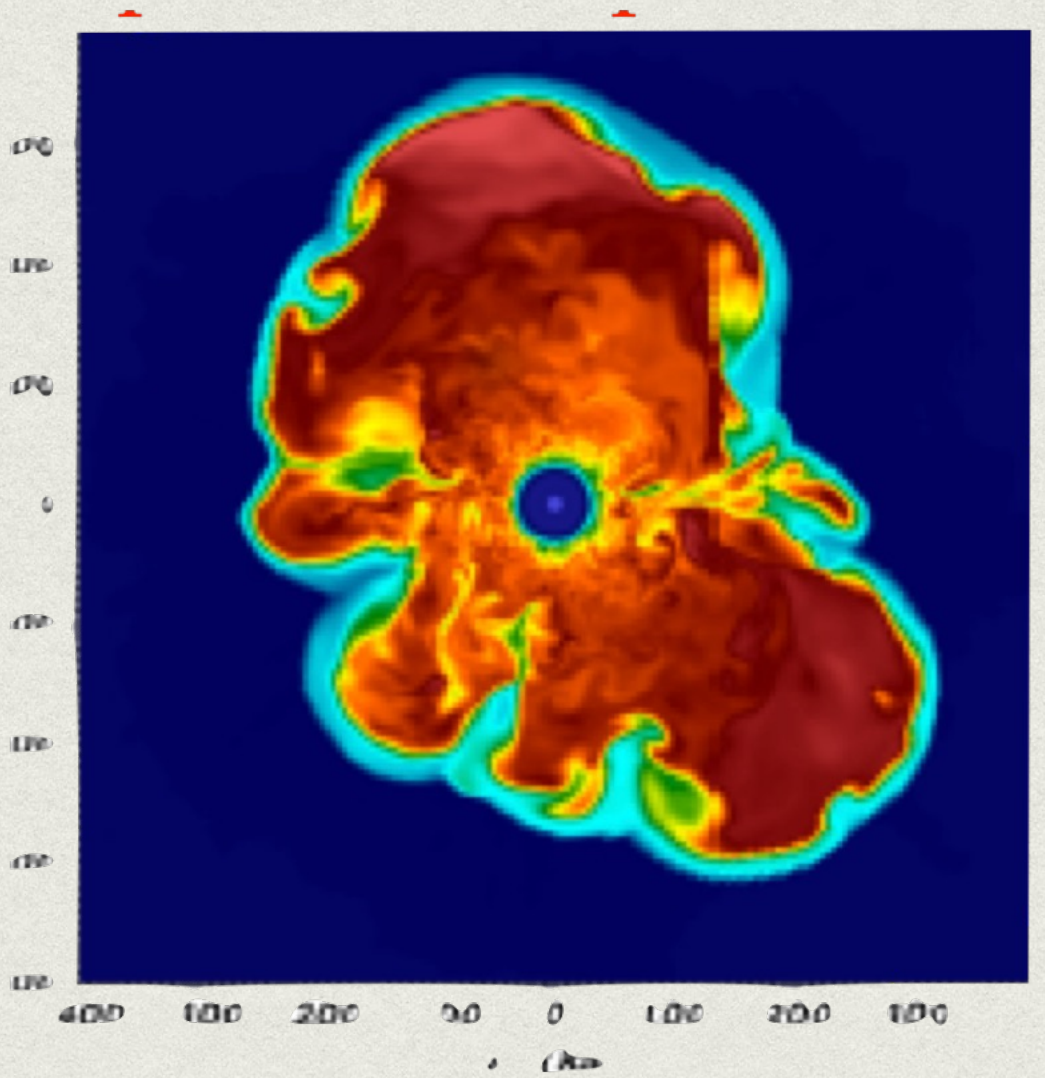
# Super-Kamiokande results with Gadolinium (June 2024)




*Courtesy of A. Beauchêne*

There is currently a hint for the DSNB at 2.3 sigma, from all previous Super-Kamiokande data, plus two years running with gadolinium.

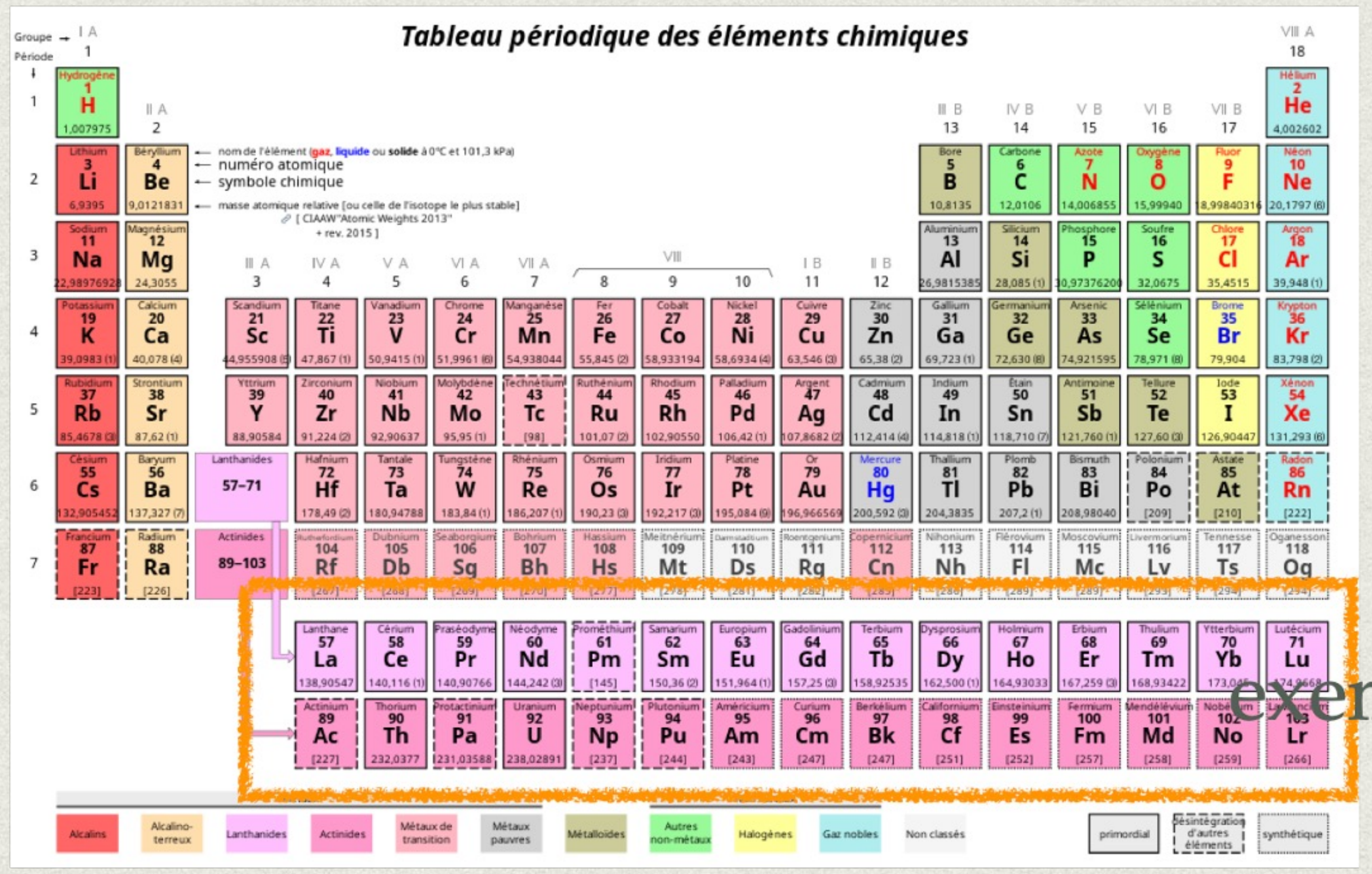
# **WHY** are we *interested* in **neutrinos from dense environments**?



Mueller et al, 1705.00620

How do supernovae explode?

Neutrinos from dense environments



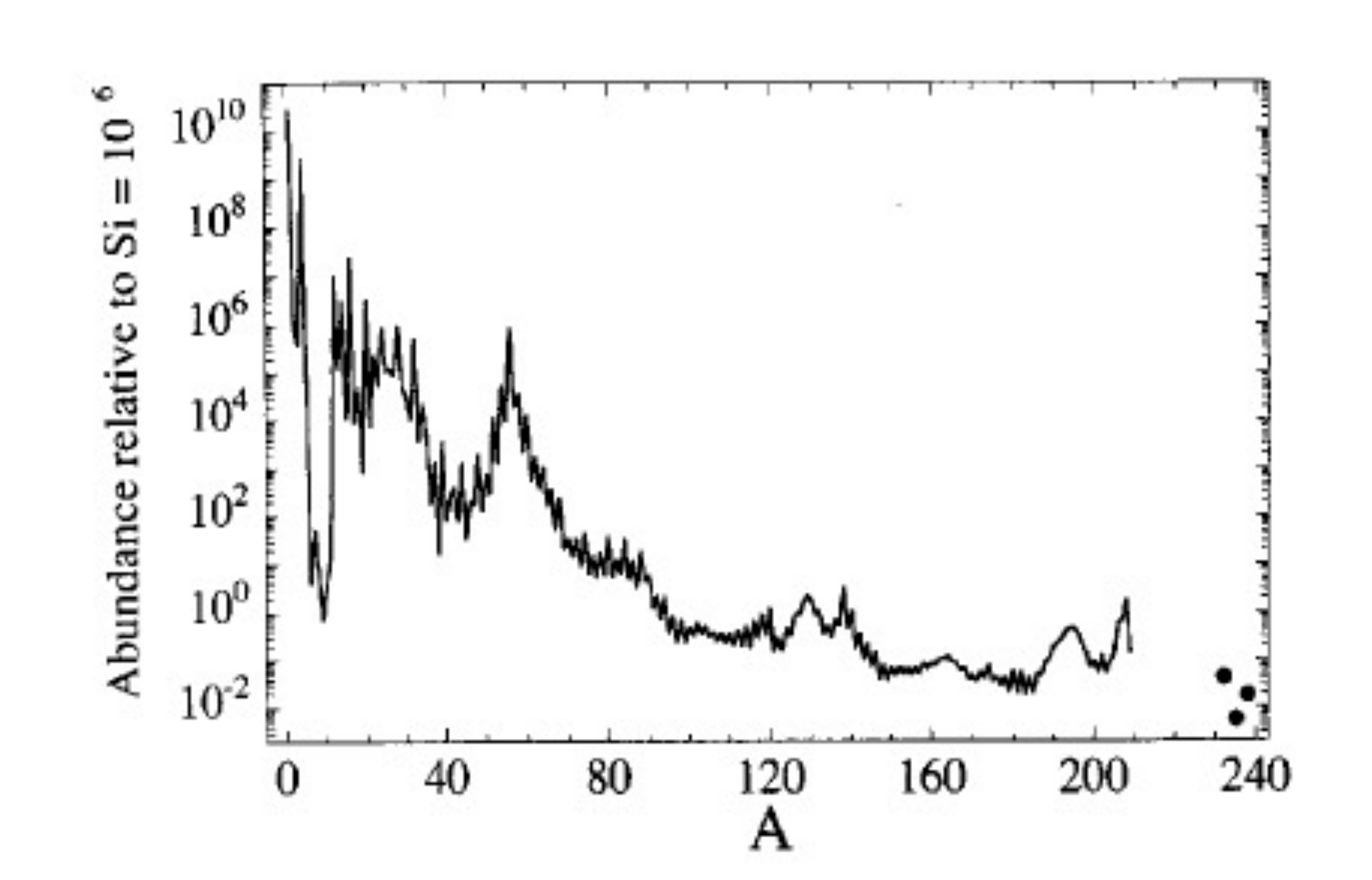

Where are the heavy elements made?

Future observations of core-collapse supernova neutrinos and the diffuse supernova neutrino background (DSNB)

Search for new physics, e.g. dark matter particles, and multimessenger physics

# Stellar nucleosynthesis

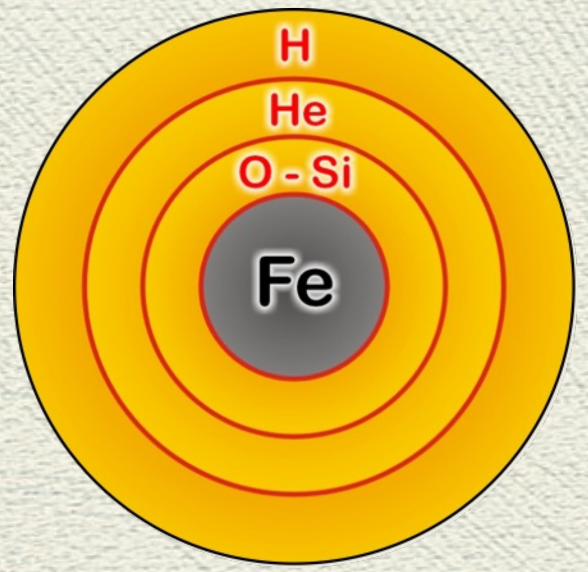
- One of the key questions in nuclear astrophysics is to understand the origin of elements heavier than iron in our Universe, i.e. to determine the site and the conditions under which they are made.

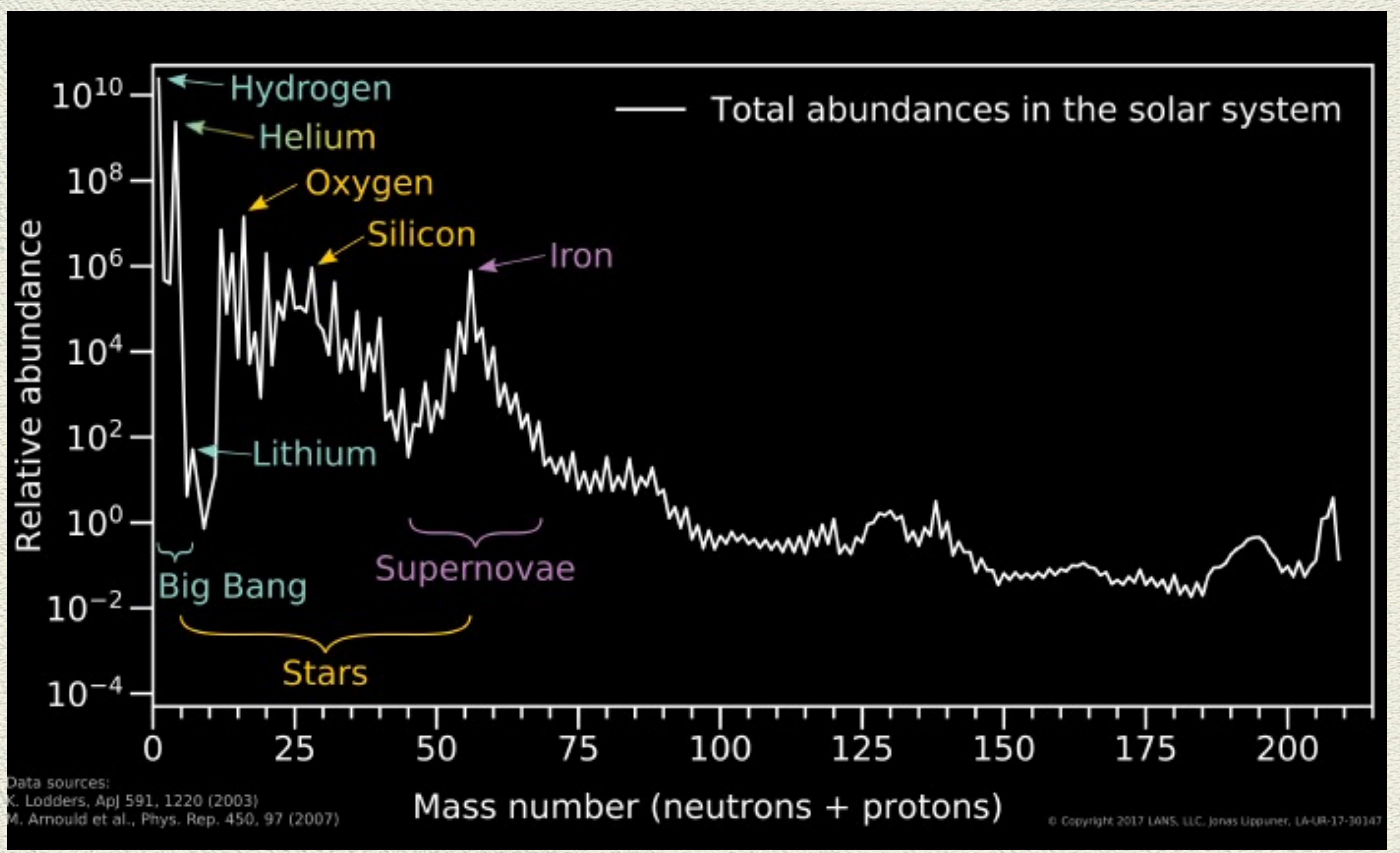



Element abundance of the solar system at the time of his formation (4.6 milliards years).

- Based mainly on meteorites (matière solaire primitive) and electromagnetic spectrum of stars such as one Sun (abundance in protosolar nebula of volatile elements) and e.g. old metal poor stars.

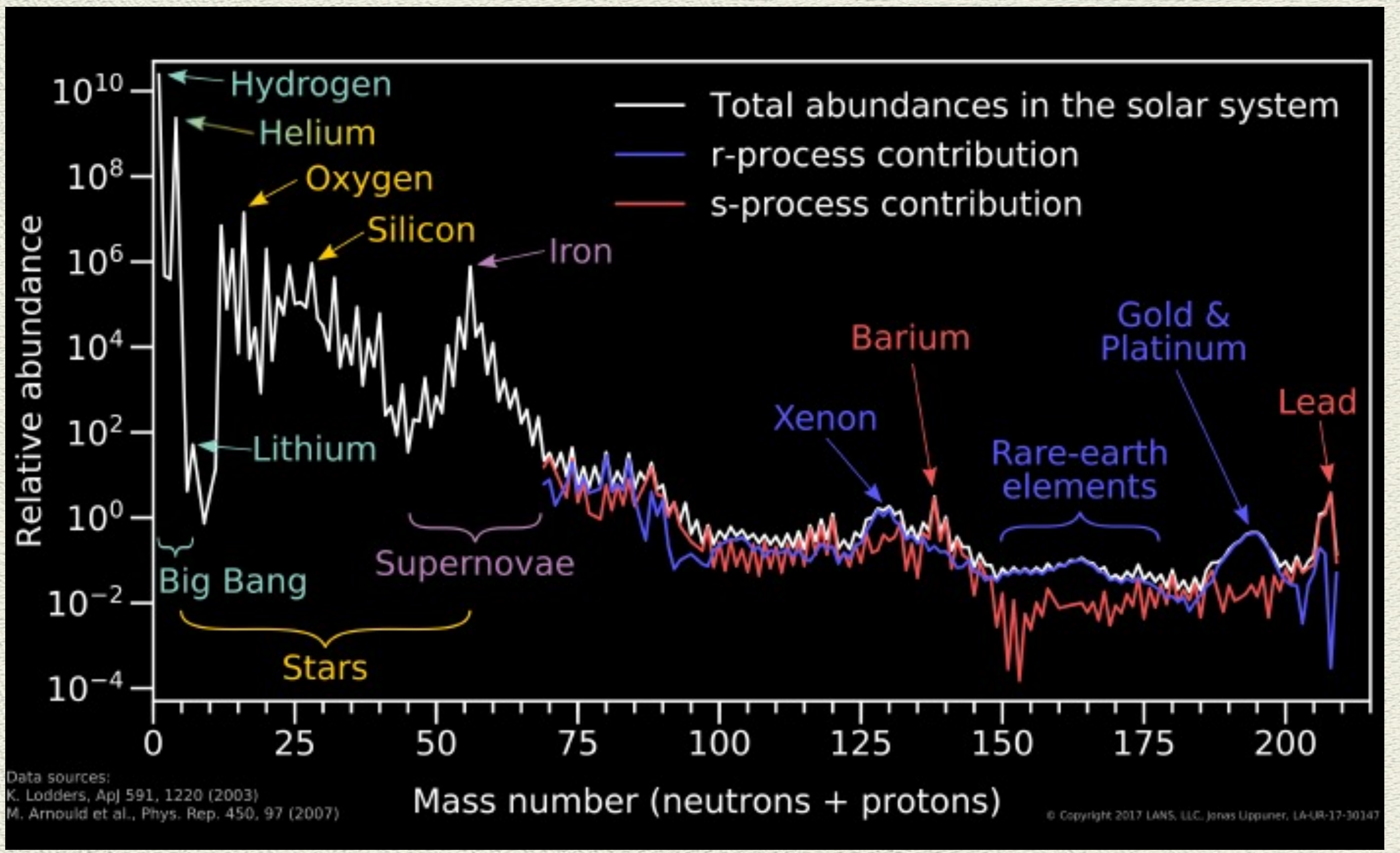
- H, He are the most abundant elements.
  Li, Be, B are the least abundant compared to nearby nuclei.
  Beyond C abundances decrease with the atomic number.
  Superimposed are abundance peaks, the iron one (Z=26).
  A large peak is observed at 80 < A < 90, two double peaks at A=130-138 and A=195-208.



- Neutron captures is responsible for the synthesis of elements heavier than iron.
- Three different mechanisms are at their origin :
  the s-process (s for slow), the r-process (r for rapid) and the p-process (p for proton).

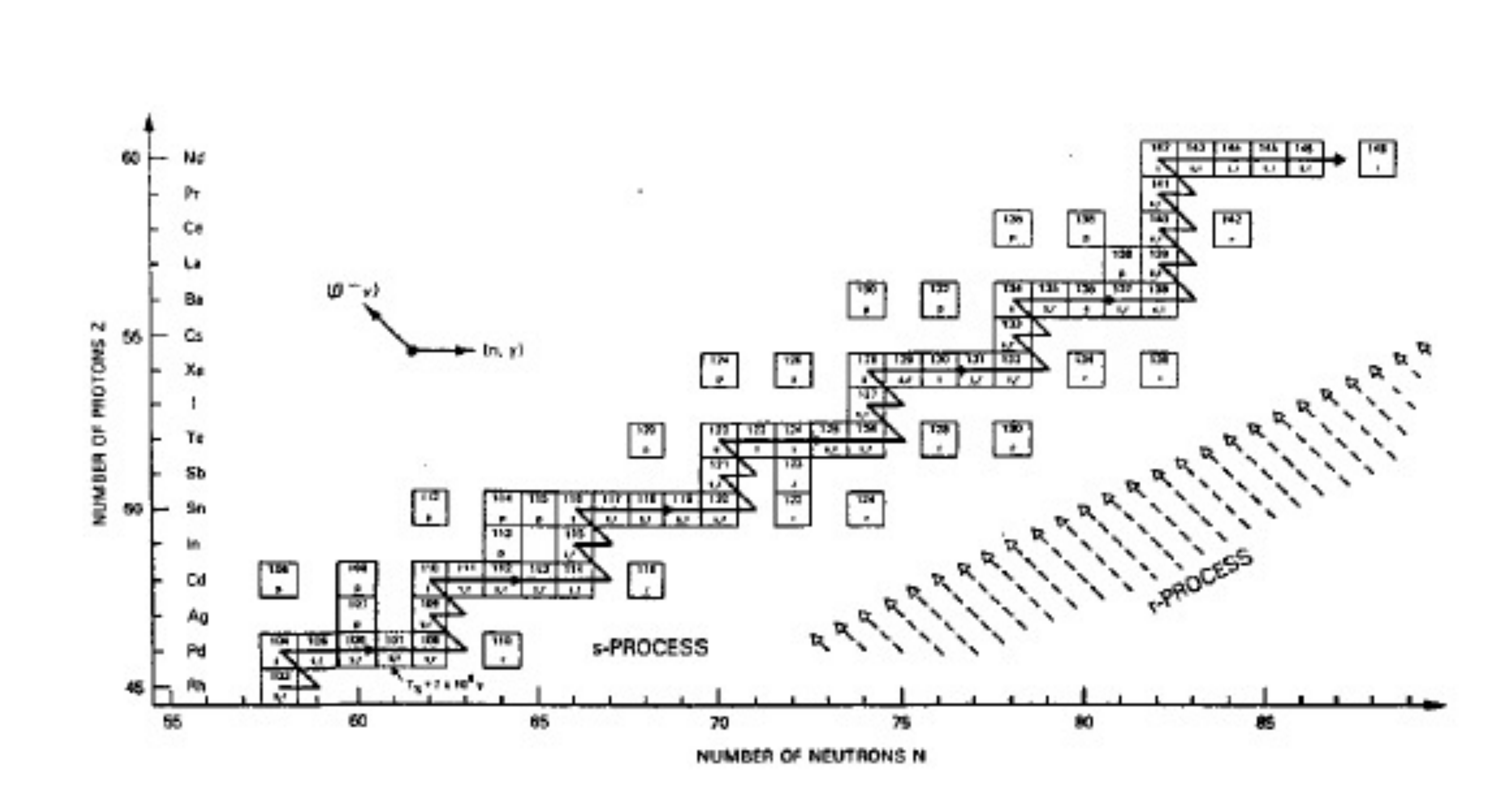
- The double pic structures at the first A=90, the second A=130 and third A=190 peaks are due to the fact that both the s-process and the r-process contribute to produce such elements. The s-process is responsible for the heavier A=138 and A=208 component, while the r-process for the lighter A=130 and A=200 ones.



# The s-process

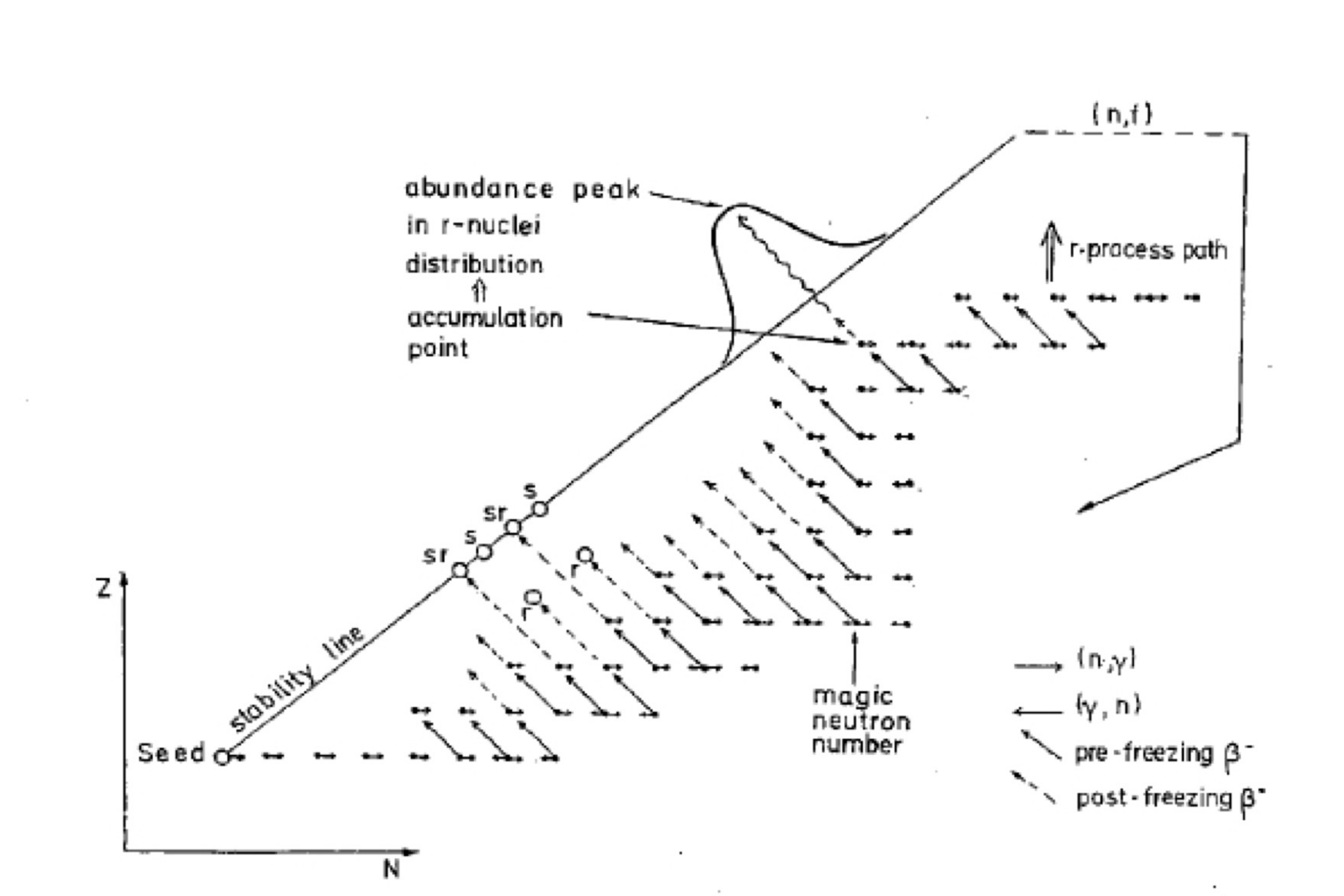
- The s-process occurs when the neutron-capture (mainly on Fe nuclei) is slow compared to half-lives of the unstable nuclei produced in the process. They decay before capturing a neutron, constraining the nuclear flow to follow the stability line.

- The s-process involves hundreds of nuclei. Many of their properties are measured in laboratories. The sites are massive stars (first peak) and Asymptotic Red Giants (AGB) with different metallicities (Z < 0.01, main peak and Z < 0.001, third peak).



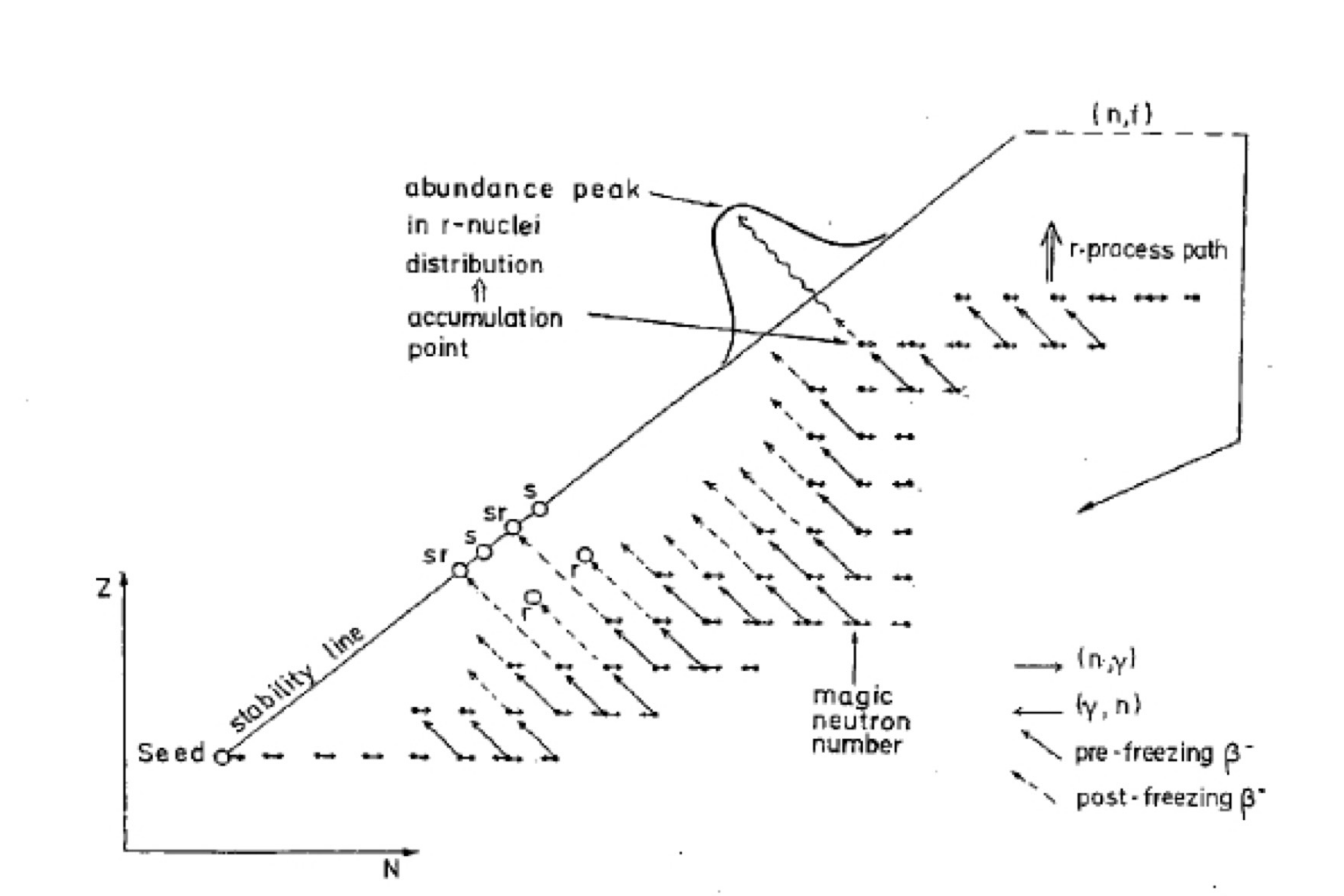
# The r-process

- The r-process is responsible for 50% of nuclei heavier than iron in the solar system and our Galaxy.
- The r-process occurs when the neutron-capture (mainly on Fe nuclei) is fast compared to half-lives of the unstable nuclei produced in the process. The nuclear flow goes far away from the stability line producing thousands of exotic nuclei, close to the neutron drip line.



# The r-process

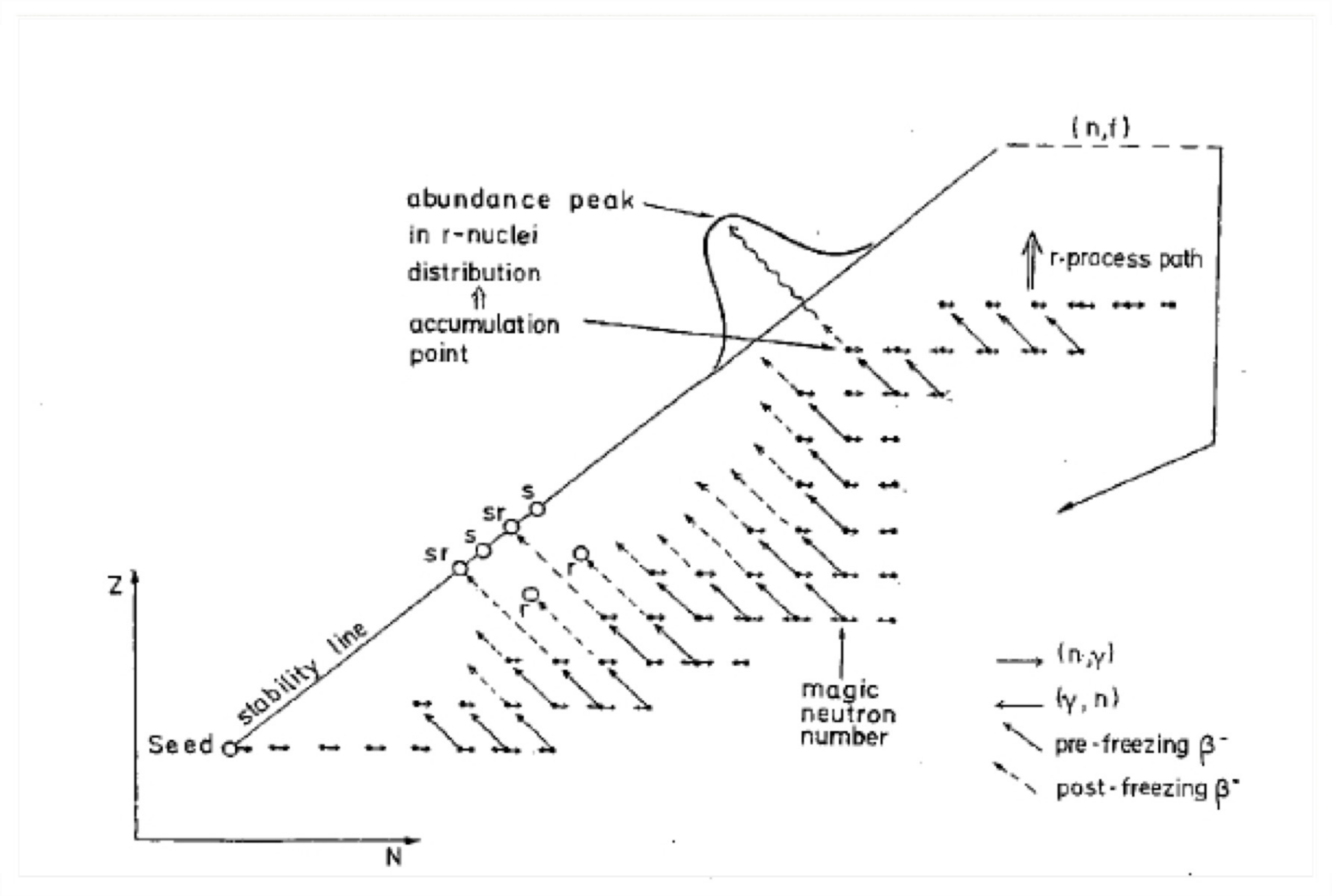
- Nuclei that have closed neutron shells (magic nuclei) are « waiting point » nuclei. Neutron capture less favorable (more stable) and beta-decay is slower than for non-magic ones. This induces peaks in the nucleosynthetic abundances. The three peaks correspond to the magic neutron numbers N=50, N=82 and N=126.
- Nuclear properties on mainly exotic nuclei are necessary : nuclear masses, beta-decay half-lives, neutron-capture $(n,\gamma)$ and photo-disintegration rates $(\gamma n)$ and neutrino CC and NC cross sections.



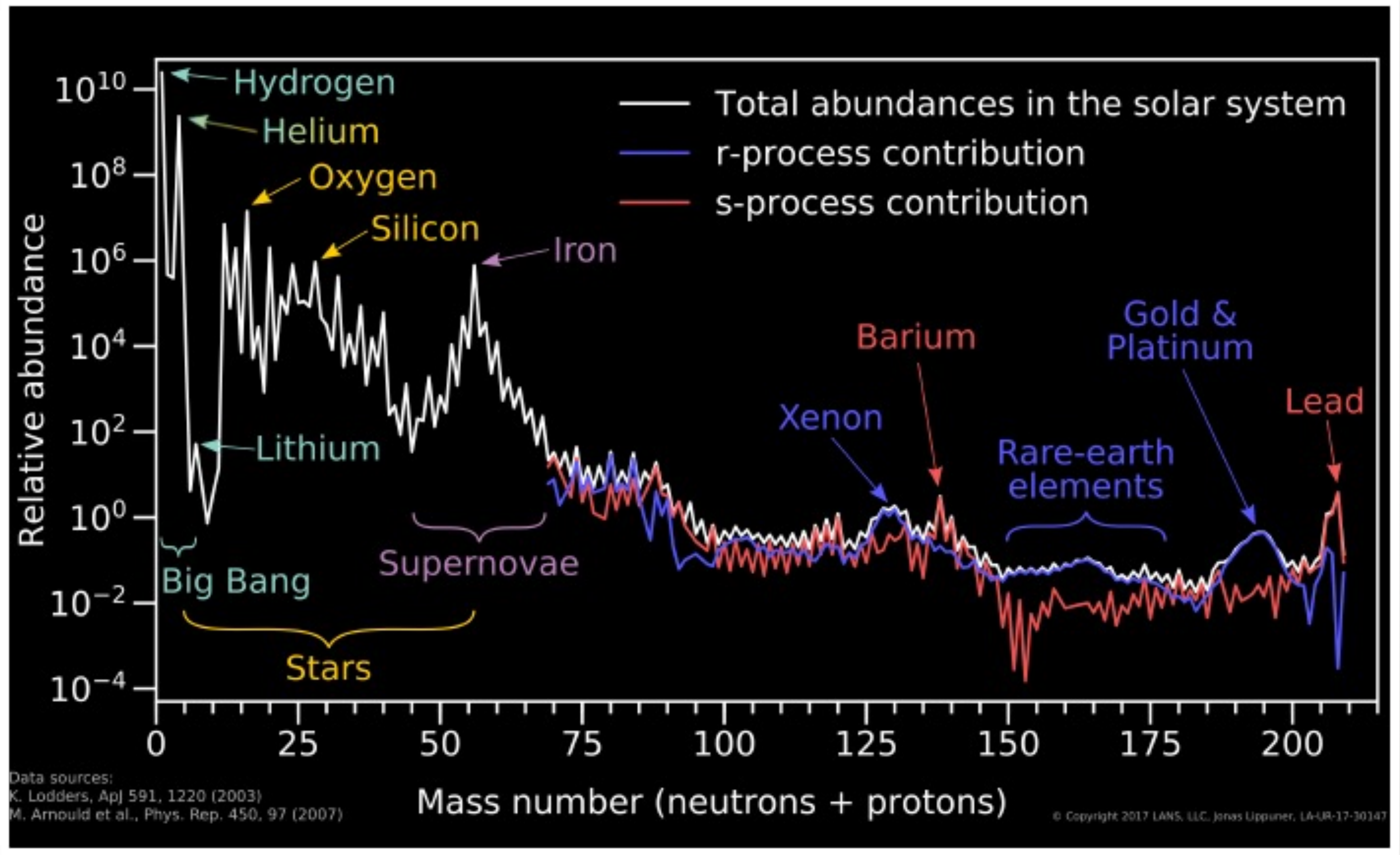
# r-PROCESS NUCLEOSYNTHESIS: the site is unknown

- 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*




- Neutrino driven winds can occur around black holes, in binary neutron star mergers or core-collapse supernovae. Matter leaves the gravitational potential because of neutrino energy deposition.

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

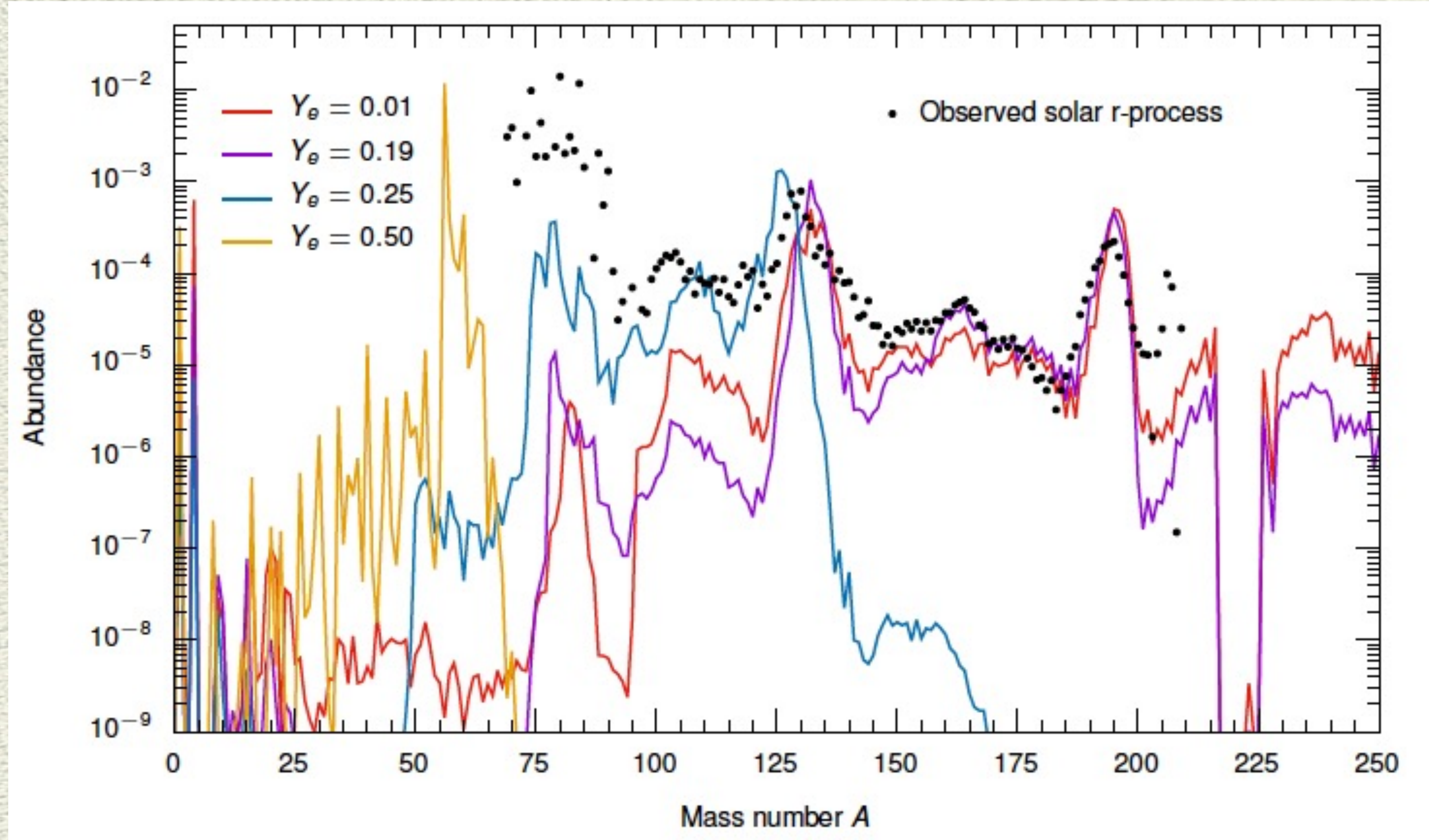
# r-process nucleosynthesis and neutrinos

- Most importantly neutrinos influence the neutron richness of the material through :

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

that sets the neutron-to-proton ratio or electron fraction - $Y_e = \dfrac{p}{p+n}$

- Neutrinos tend to harm a successful r-process by converting neutrons into protons and driving Ye towards the critical value of 0.5.




no flavor evolution included (here)

- For Ye = 0.5, no r-process elements.

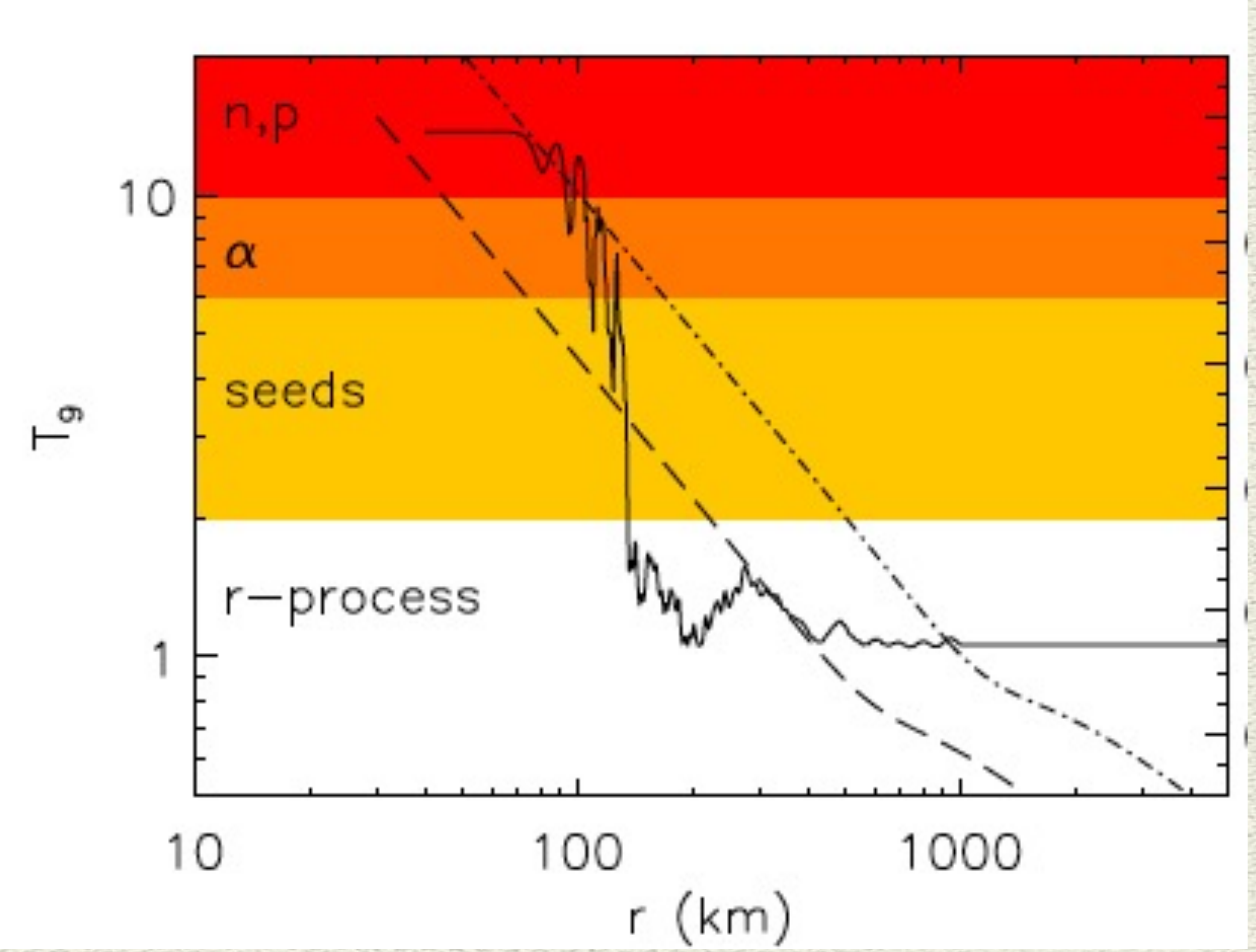
  For Ye > 0.25, the first and second peak elements are produced (weak and main r-process).

  For Ye < 0.25, rare-elements plateau and third element peak (strong r-process).

# The r-process elements in supernovae

- Core-collapse supernovae were thought to be responsible for most of r-process elements.
  Two processes are evoked - external shells (He and C rich) or the neutrino driven winds (hot and dense bubble) formed at the ejecta basis, above the supernova residue (black hole or neutron star).

- Most frequent events compared to binary compact systems.
  Rule of thumb :
  if $10^{-4}$ $M_\odot$ each event and 3 supernova/100 years (average) x $10^{10}$ years $\approx 3\ 10^4$ $M_\odot$ r-elements.

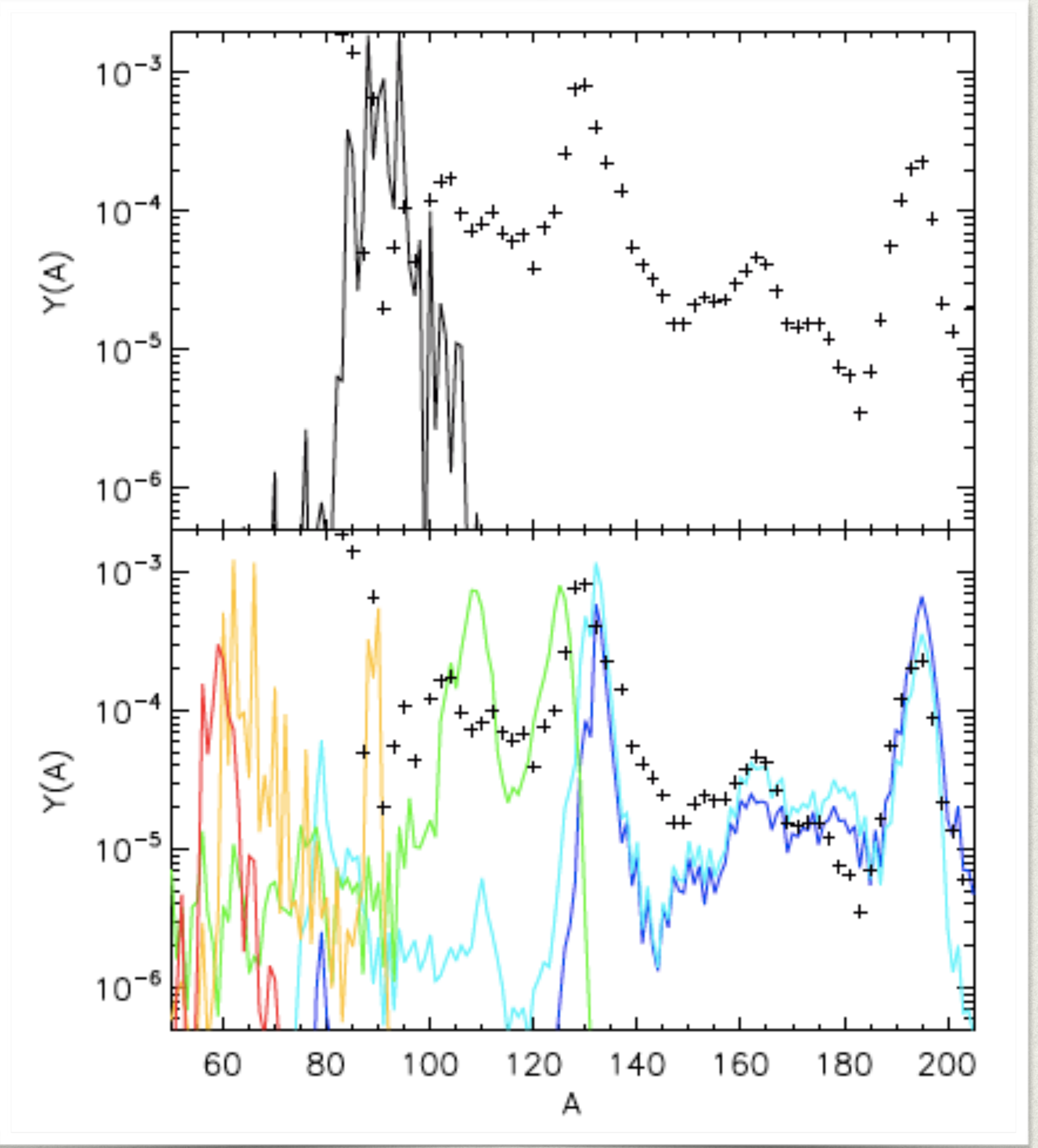
- 


Duan et al, J.Phys. G38 (2011)

In a core-collapse supernova :
- $T > 10^{10}$ K, only n, p
- A few $10^9$ K, n, p start forming $\alpha$
- $2\ 10^9$ K $< T < 7\ 10^9$ K $\alpha$ start forming seeds nuclei.
- $T < 2\ 10^9$ K « $\alpha$ process » stops, $(\alpha$,n) is too slow.
- The wind contains $\alpha$, neutrons and heavy nuclei. High entropy is necessary to have enough neutrons per seed nuclei in order to obtain a strong r-process (up to third peak).

- However the astrophysical conditions are not met in supernova simulations - too low entropies, too few neutrons to have a strong r-process, except for the most energetic events.

# FLAVOR EVOLUTION with STANDARD INTERACTIONS in BNS



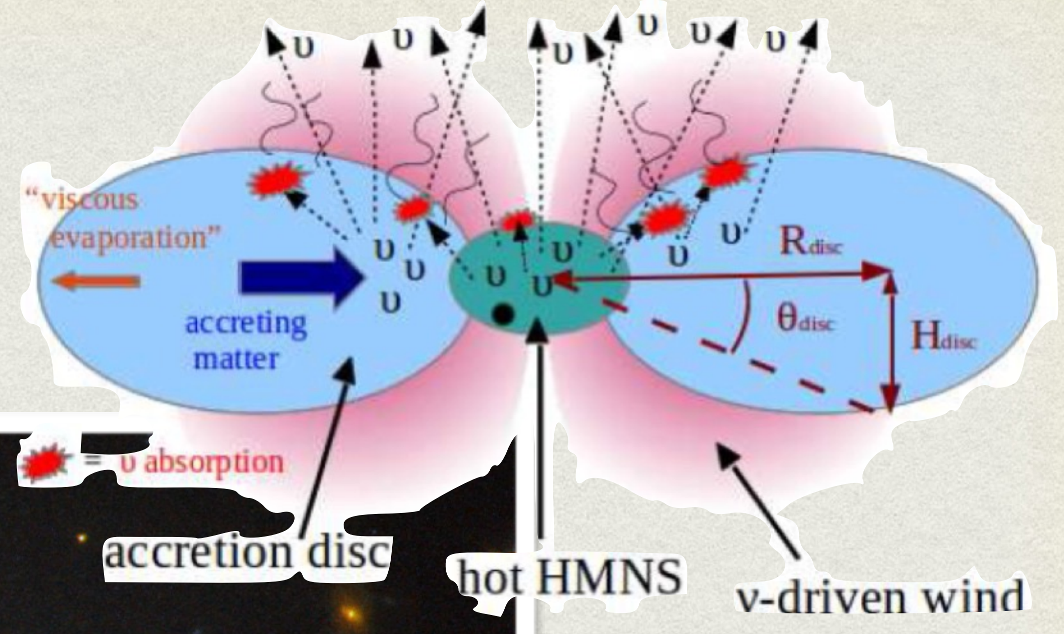

no flavor evolution included

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

Malkus et al, PRD 93, 2016

**Impact r-process nucleosynthesis**

# A UNIQUE EVENT : GW170817




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

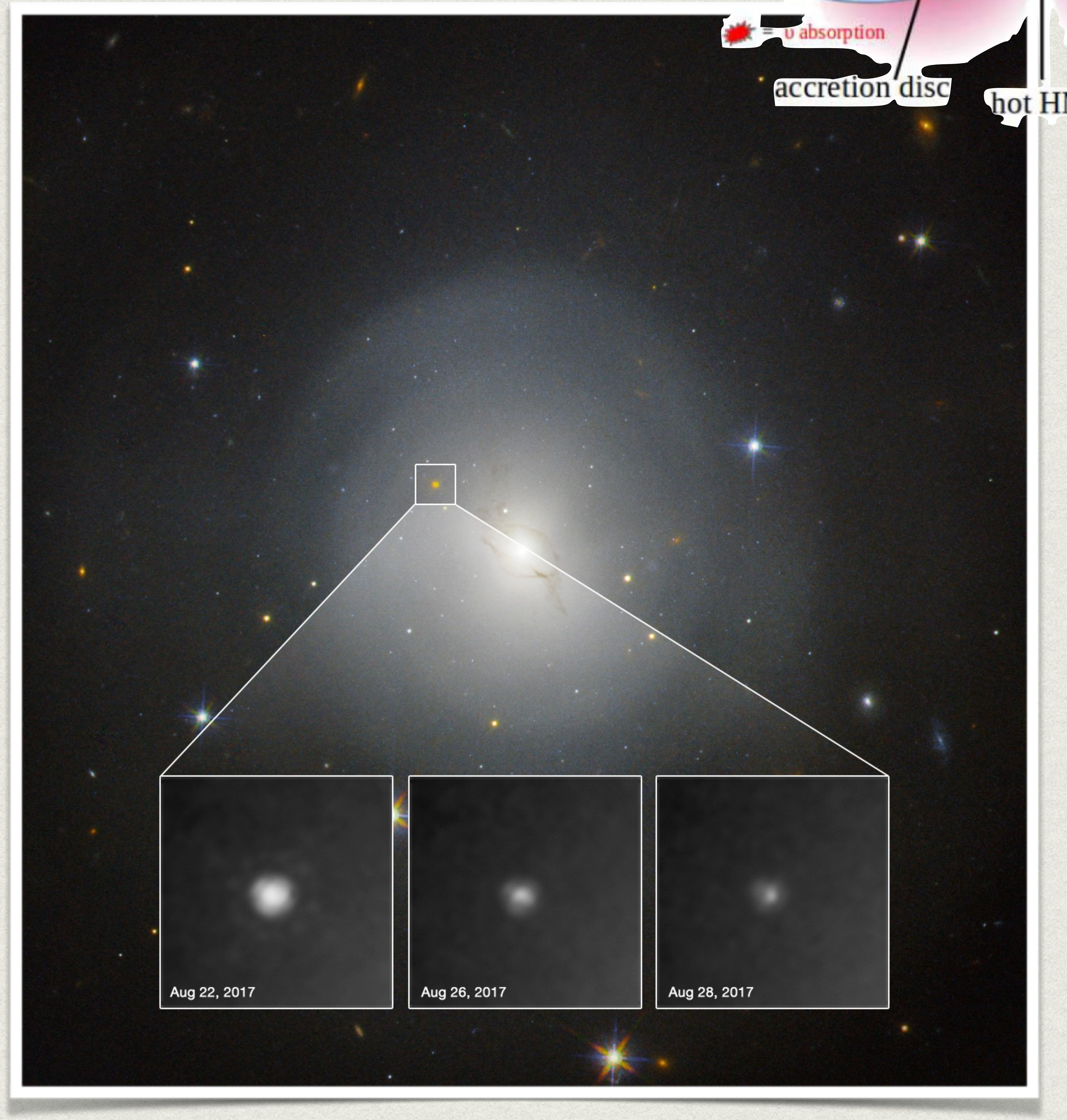
- First measurement of gravitational waves, in coincidence with a short gamma ray burst and a <u>kilonova</u>.

  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, ….

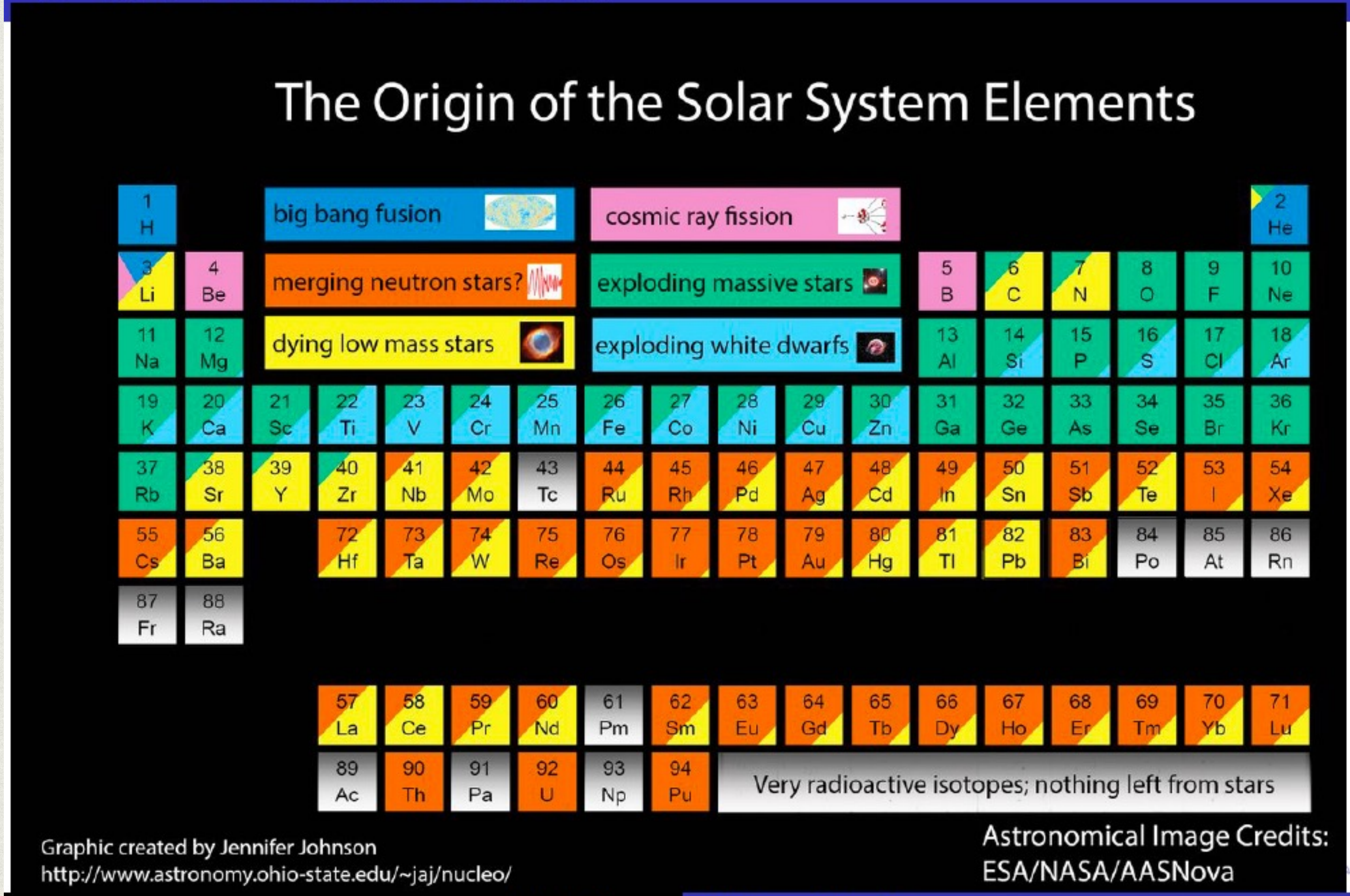
From the electromagnetic signal, indirect evidence for r-process elements in the ejecta




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

x

# Is the Problem Solved?



# NEUTRINO MASS TERMS

- The most general Lagrangian contains <u>two types of mass terms</u>: the Dirac ones and the Majorana ones.

- To write down the <u>Dirac mass terms</u> one needs to introduce right-handed singlets $N_R$ that are absent in the Standard Model. Thus already to include neutrino masses of the Dirac type, one needs to go beyond the Standard Model.

These read $-\mathcal{L}_{\mathrm{D}} = m_{\mathrm{D}}(\overline{\nu_L} N_R + \overline{N_R}\nu_L)$ Remember that $\overline{\nu_L} = (\nu_L)^\dagger \gamma^0$ $\overline{\nu_L} = \bar{\nu}_R$

- Last week we saw that we can build Majorana fields using a chiral field and CP conjugation. In particular we wrote the two Majorana fields:

$$\psi_{\mathrm{M1}} = \nu_L + \eta_1 {\nu_L}^C \qquad \psi_{\mathrm{M2}} = N_R + \eta_2 {N_R}^C$$

- If neutrinos are Majorana particles we can write the following mass terms:

$$-\mathcal{L}_{\mathrm{M1}} = \frac{m_L}{2}(\overline{\nu}_L {\nu_L}^C + \overline{{\nu_L}^C}\nu_L) \qquad -\mathcal{L}_{\mathrm{M2}} = \frac{m_L}{2}(\overline{N}_R {N_R}^C + \overline{{N_R}^C} N_R)$$

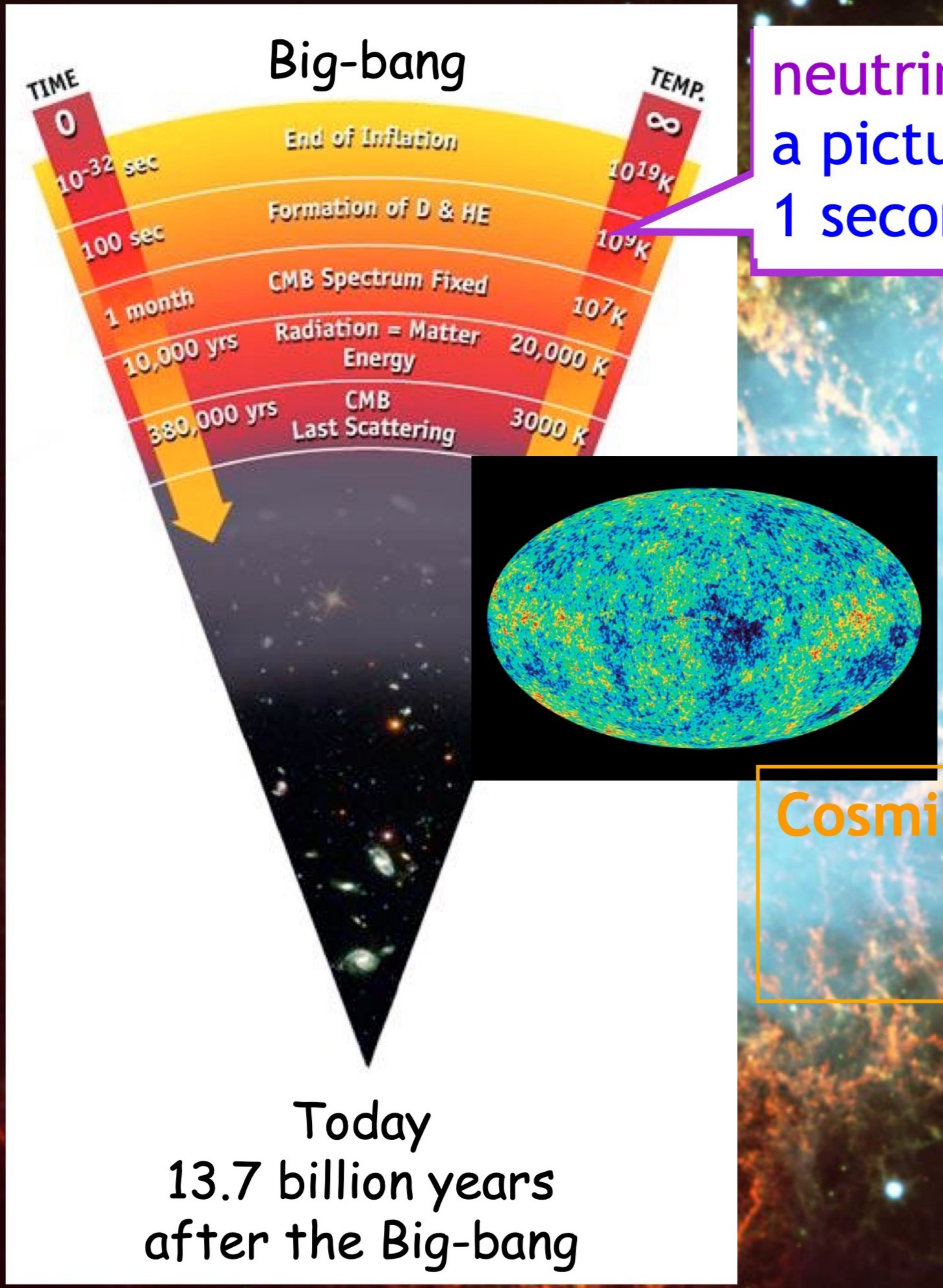
Remember that, e.g. ${N_R}^C = (N^C)_L$

- Therefore the most general Lagrangian including all terms is

$$-\mathcal{L}_{\mathrm{D+M}} = \frac{1}{2}(m_L \overline{\nu_L}{\nu_L}^C + m_R \overline{N}_R {N_R}^C + h.c.) + m_{\mathrm{D}}(\overline{\nu_L} N_R + \overline{N_R}\nu_L)$$

It can be cast in matrix form (see slide 12), using the relation $\overline{{N_R}^C}{\nu_L}^C = \overline{\nu_L} N_R$

The Majorana mass term $M_L$ is not allowed in the SM since the terms require a weak isospin triplet with Y = 2, the SM does not have any.



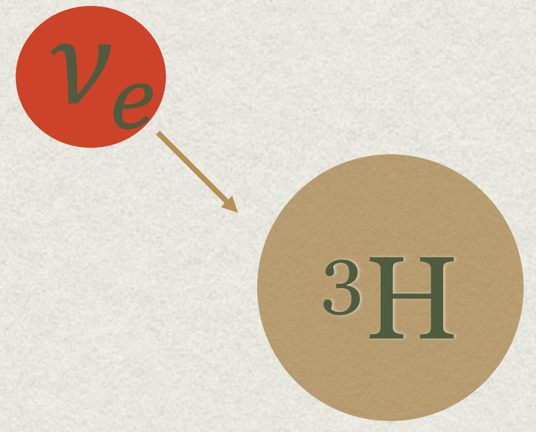

neutrinos from early Universe
a picture of the Universe
1 second after the Big-Bang !

**Cosmological neutrinos**
density= 330 $cm^{-3}$
temperature = 1.9 K

**Cosmic Microwave Background**
density = 422 $cm^{-3}$
temperature = 2.75 K

# The detection of the cosmological neutrino background…

*cosmological neutrino*



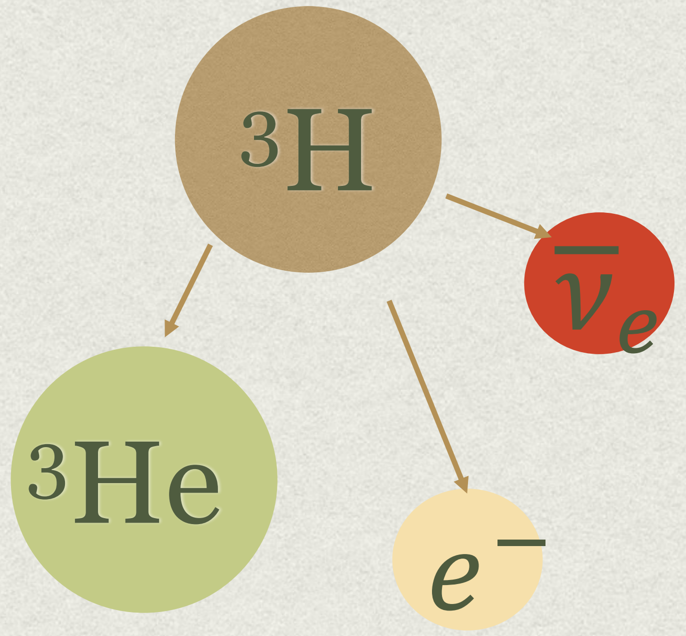

*unstable nucleus*

- The cosmological neutrino background is very cold. Established detection techniques cannot be used.
- The neutrino capture on radioactive nuclei could be used to detect cosmological neutrinos. It has no threshold.

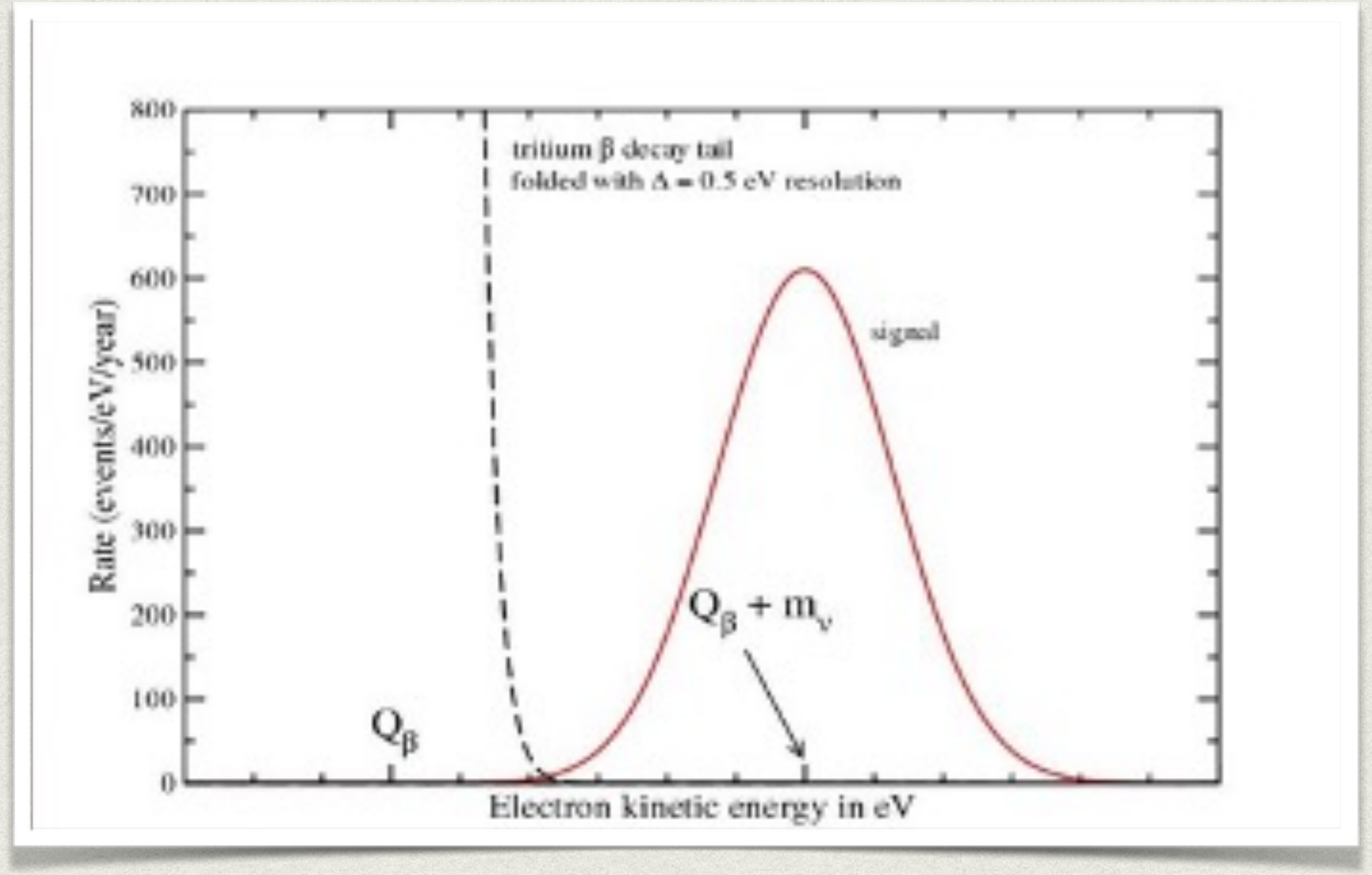
Weinberg, Phyd. Rev. 1962

- This idea was revived and potential nuclei searched through many candidates.

Cocco, Mangano, Messina, JCAP 2007




*nucleus decay*




Lazauskas, Vogel, Volpe, J. Phys. G 2007

Example: 100 g of tritium.
10 events/year

One would look for a small peak at the end-point of the beta-decay spectrum. The tritium beta decay would represent a serious background.

Challenging energy resolution needed.

*PTOLEMY project in R & D (embed tritium on graphene).* See e.g. [1808.01892]

**New ideas and techniques !**

# NEUTRINO FLUXES on Earth

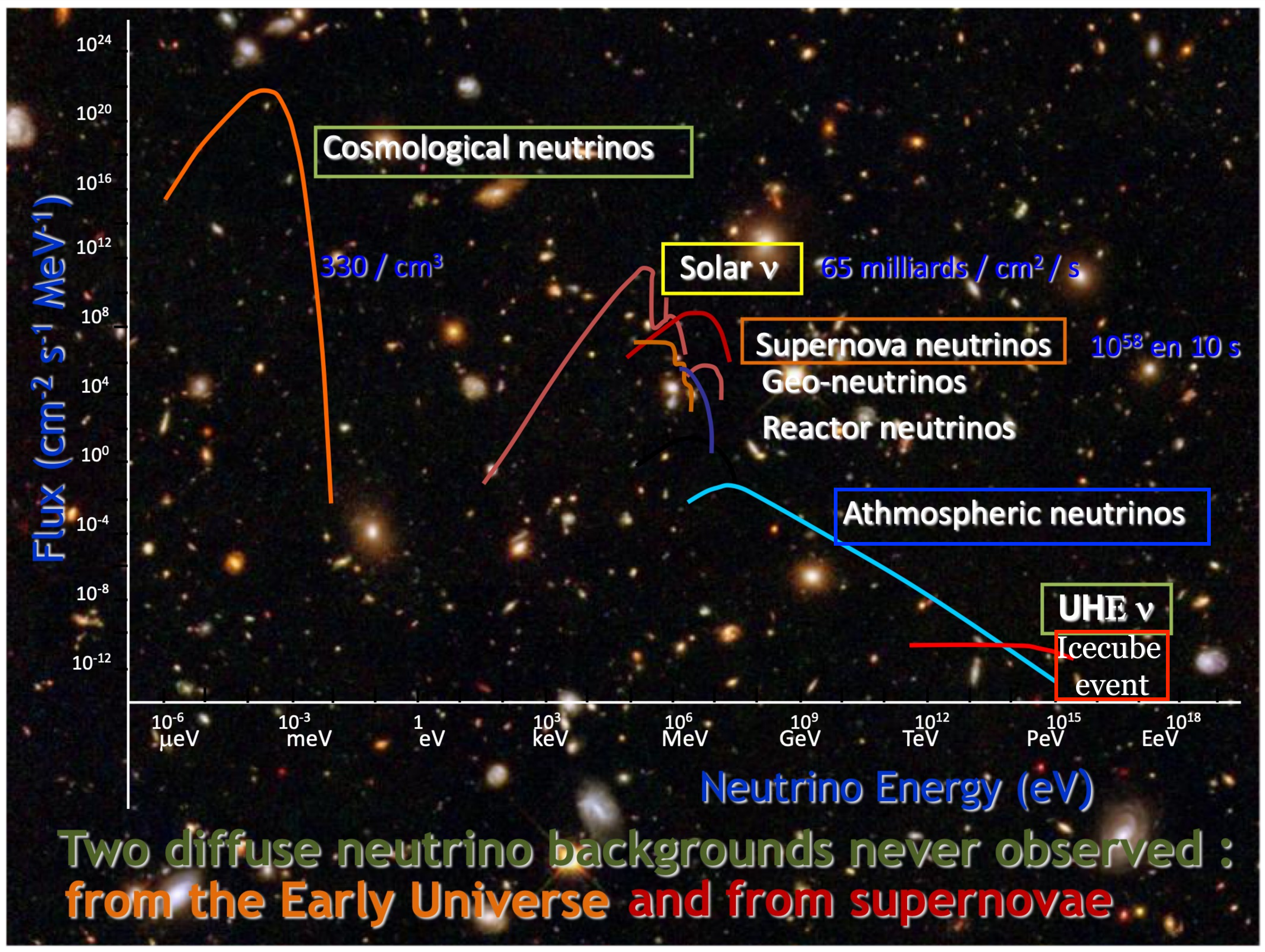
- Variety of natural and man-made sources produce neutrinos of all flavors.

  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




https://science.nasa.gov/mission/hubble/multimedia/hubble-images/

# General Conclusions

**Vacuum oscillations and the MSW firmly established and understood. Descriptions in terms of QM or QFT convey consistent descriptions under the same assumptions. Corrections beyond wave packets are not important for interpreting experiments in vacuum.**

The mass ordering and CP violation are being determined.

Flavor conversion phenomena in dense environments has numerous open questions, including the impact on the supernova dynamics, r-process nucleosynthesis and future observations (SNe, DSNB, kilonovae).
There are flavor mechanisms from neutrino-neutrino interactions, shock waves and turbulence. This is a very active domain of research.

The origin of neutrino masses is still unknown.
See saw mechanisms (Type-I) would offer a possible explanation for the smallness of neutrino masses. They require the existence of very heavy Majorana neutrinos.

The neutrino Dirac versus Majorana nature is another crucial open question. Majorana neutrinos have half the degrees of freedom and differ just for the helicity. Majorana conditions require a Majorana field to be the conjugate of itself (up to a phase), implying particles identical to antiparticles.
Apart from neutrino less double beta decay it can impact astrophysical observations, e.g. through the neutrino magnetic moment and in cosmology (baryogenesis via leptogenesis).
Its observation implies total lepton number violation and would be a breakthrough.

Neutrinos and neutrino properties impact cosmological observations, including big-bang nucleosynthesis, the cosmic microwave background and large scale structures. Moreover they could explain the baryon asymmetry of the universe via leptogenesis scenarios.

Detecting the neutrino background challenging !

**Crossing knowledge among particle physics, astrophysics and cosmology will be crucial to foster our knowledge in the fields.**

The discovery of the DSNB could be imminent. Its detection would bring crucial information on the evolving supernova rate, the black hole fraction, on supernova neutrinos and new physics.

**Neutrino physics will bring many surprises…**

Thank you for your attention !