Neutrinos from core-collapse supernovae:

flavor mechanisms and future observations

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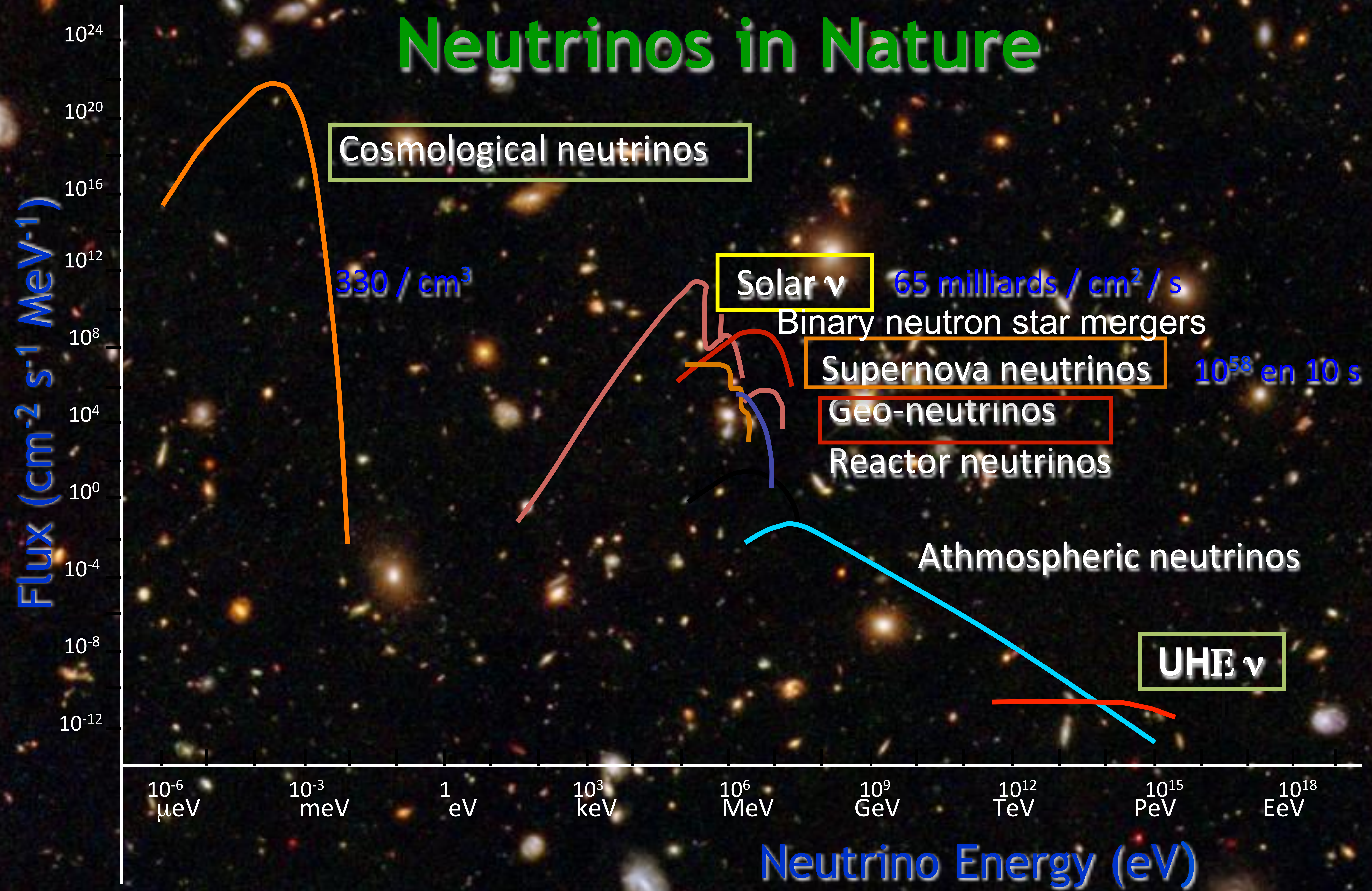
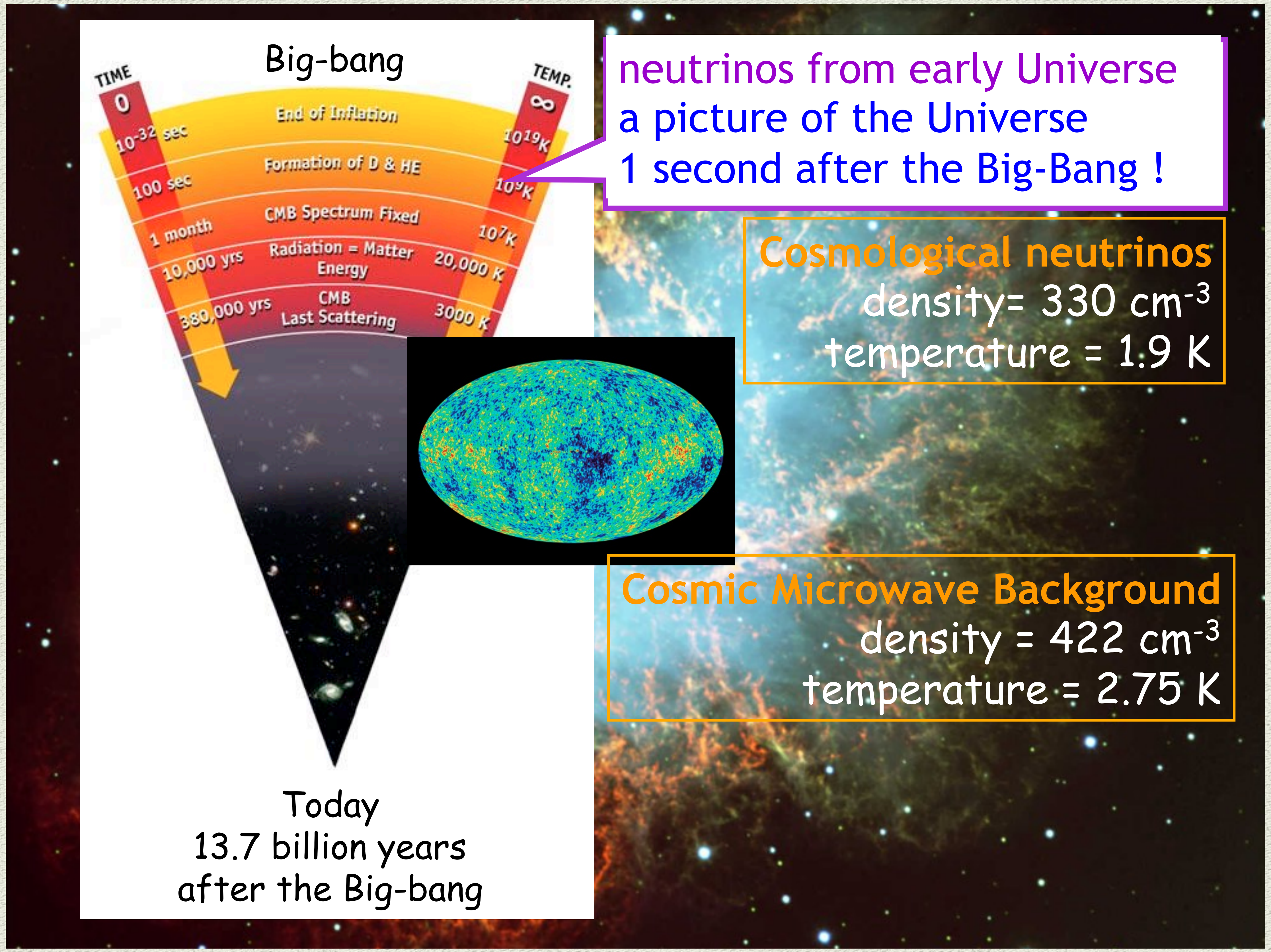
Neutrinos in Nature



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

Cosmological neutrino background



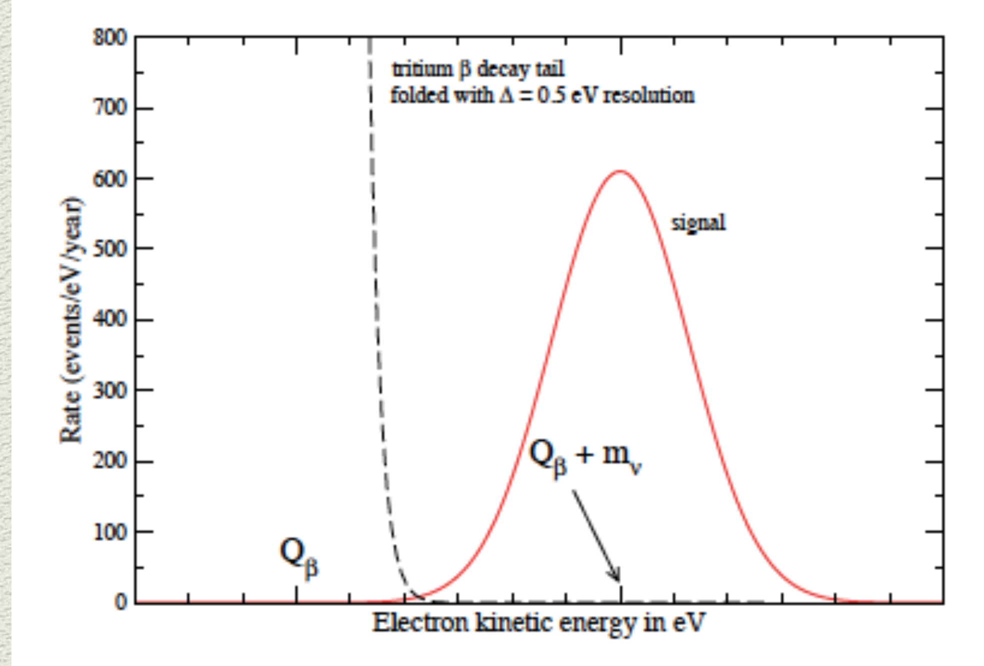
Its detection, a challenge

- Only indirect imprint of the cosmological neutrino background, on primordial nucleosynthesis and on large scale structures.
- Very cold : need for new ideas for its detection.
- *Neutrino capture on radioactive nuclei ?*

Weinberg, Phys. Rev. 1962

Idea revived by

Cocco, Mangano, Messina, JCAP 06, 2007



100 grams of tritium, 10 events/year

Lazauskas, Vogel, Volpe, J. Phys. G. 35, 2008

- Further studied.

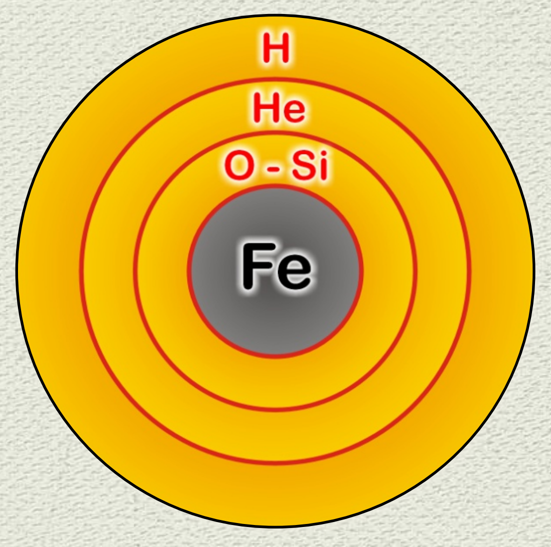
Long, Lunardini, Sabancilar, 2014; Roulet, Vissani, 2018 , ...

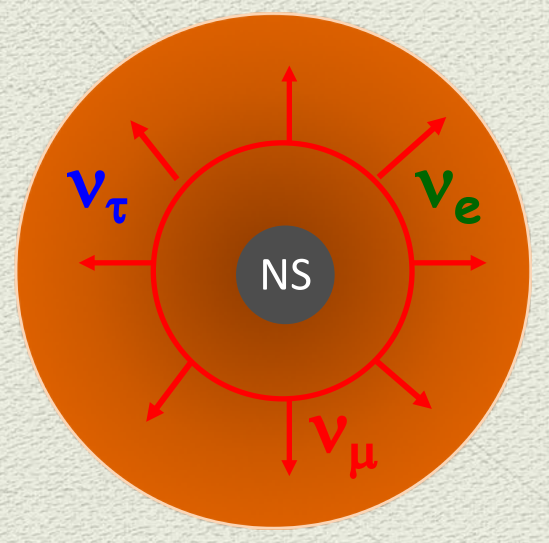
PTOLEMY project, JCAP 0, 72019

Neutrinos from dense astrophysical environments

Core-collapse supernovae

Supernovae : massive stars with $M > 8\ M_{sun}$
They undergo gravitational collapse at the end of their life.





Supernovae emit the gravitational binding energy 10^{53} ergs in 10 s, as neutrinos and antineutrinos of all flavors

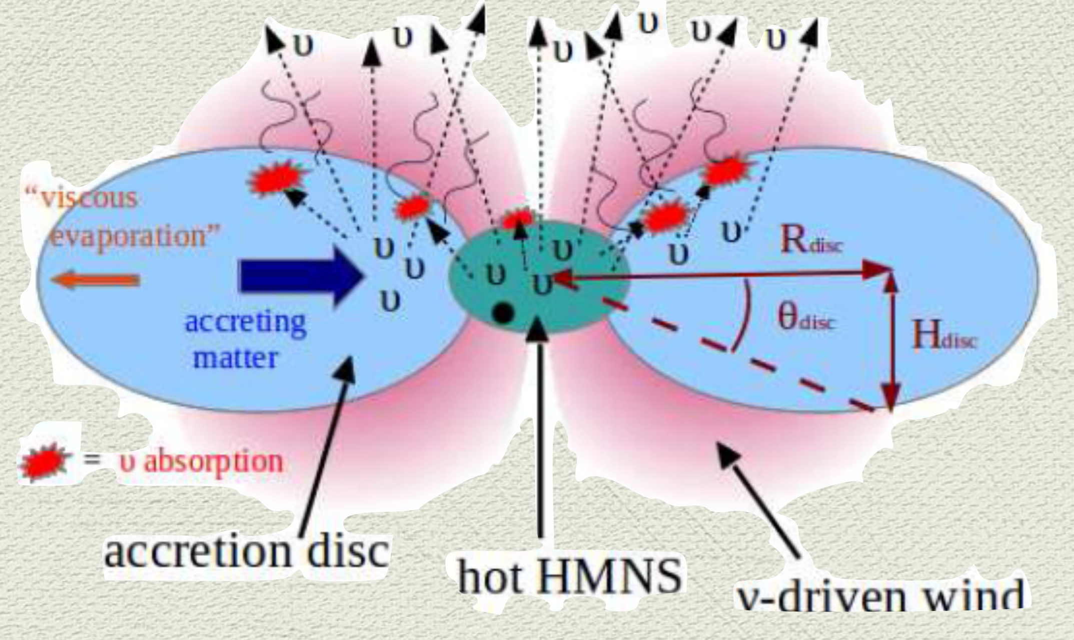
SN1987A- LMC

- On the 23rd of February 1987, Sk-69°202 exploded in the Large Magellanic Cloud at 50 kpc
- **25 events observed, in KII, IMB, BST**
  Hirata et al, 1987, Bionta et al, 1988, Alekseev et al, 1988
- Prompt explosion model discarded. Colgate and White, 1966
  Delayed shock model favored. Bethe and Wilson, 1985
  Loredo and Lamb, 2002
- Currenty multi-dimensional supernova simulations available, with convection, turbulence, realistic neutrino transport and nuclear networks.
  Bruenn et al, 2020, Janka 2017, ...

Wealth of information on non-standard neutrino properties, particles or interactions and on astrophysics

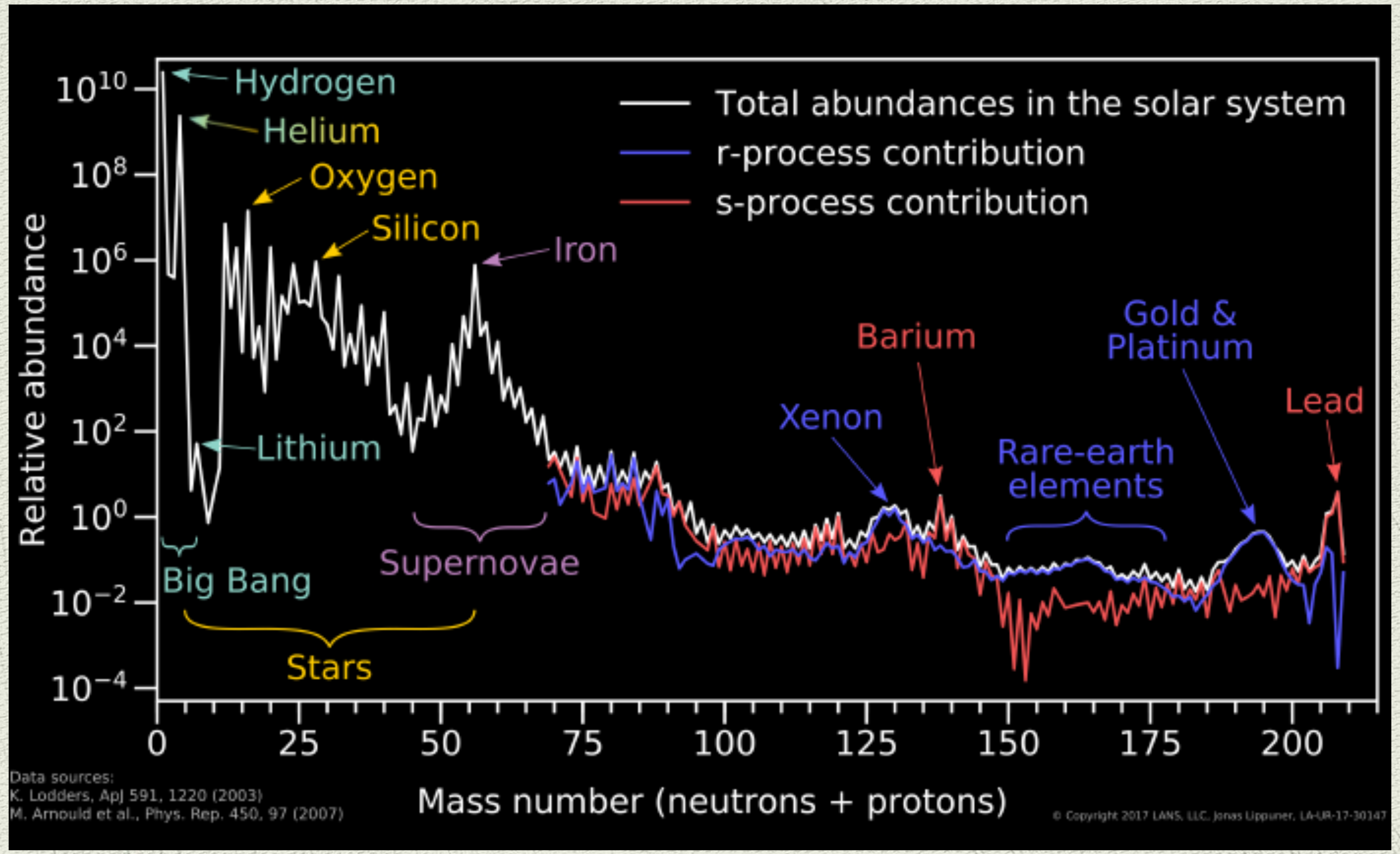
Neutrinos from dense astrophysical environments

Binary neutron star (BNS) mergers remnants



Perego et al, 2014

CCSNe and BNS are candidate sites for r-process nucleosynthesis.



- **GW170817 :** First measurement of gravitational waves from a binary neutron star merger, in coincidence with a short gamma ray burst and a kilonova. Abbot et al, 2017

- **Electromagnetic emission** powered by the decay of radioactive elements, with lanthanide free ejecta (blue component of the signal) and ejecta with lanthanides (red component).

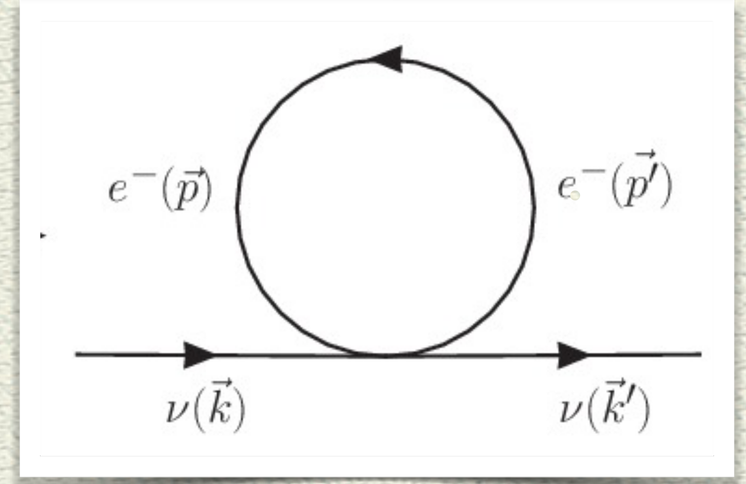
Indirect evidence for r-process elements in BNS.

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

Neutrino properties and flavor mechanisms impact r-process nucleosynthesis

Mikheev-Smirnov-Wolfenstein effect

- In matter, neutrinos interact with the particles composing the medium. These interactions can be accounted in mean-field giving



$$h_{mat} = \sqrt{2}\, G_F \rho_e$$

- In the matter basis, the neutrino hamiltonian

$$h_\nu = \begin{pmatrix} -\Delta\tilde{m}^2/4E & -i\dot{\theta}_M \\ i\dot{\theta}_M & \Delta\tilde{m}^2/4E \end{pmatrix}$$

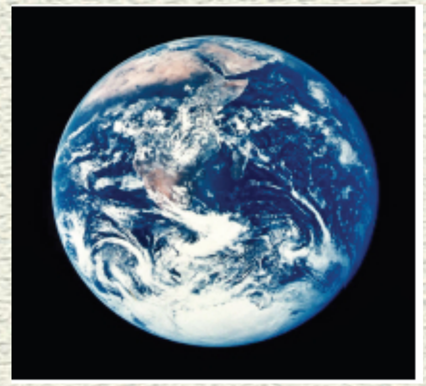
resonance condition : $h_{\nu,11} - h_{\nu,22} \approx 0$

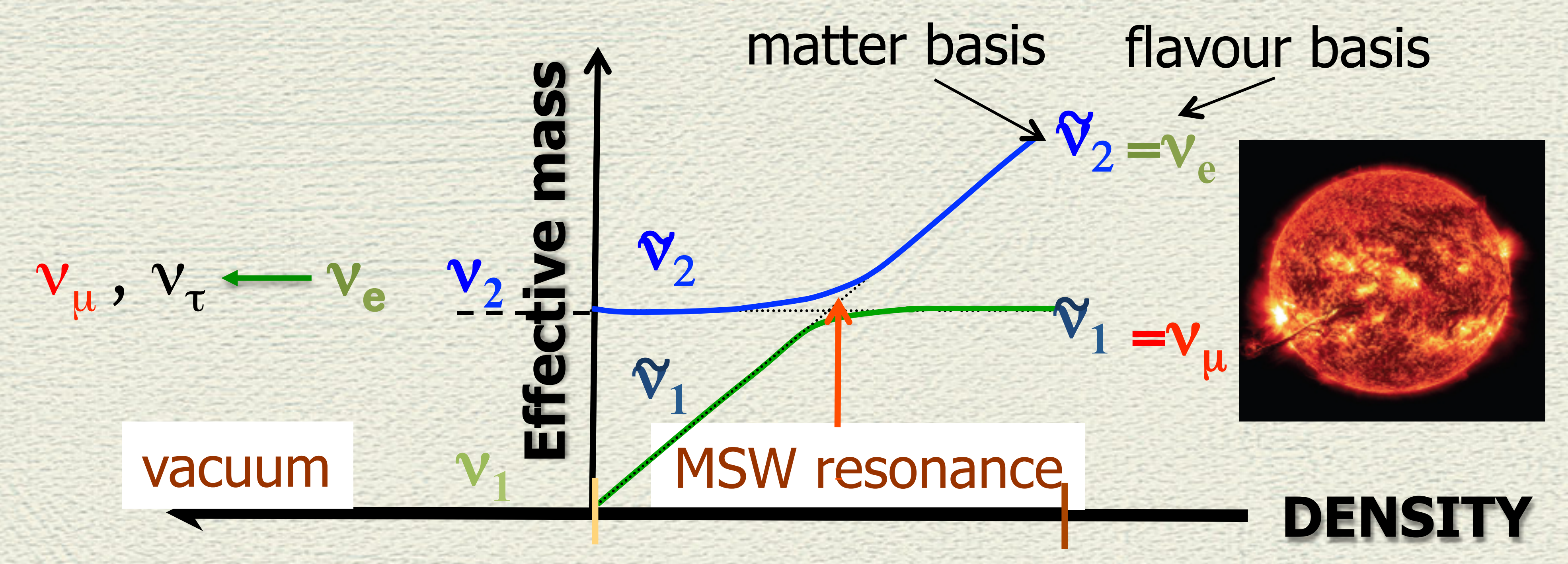
Cancellation of the vacuum and matter term.

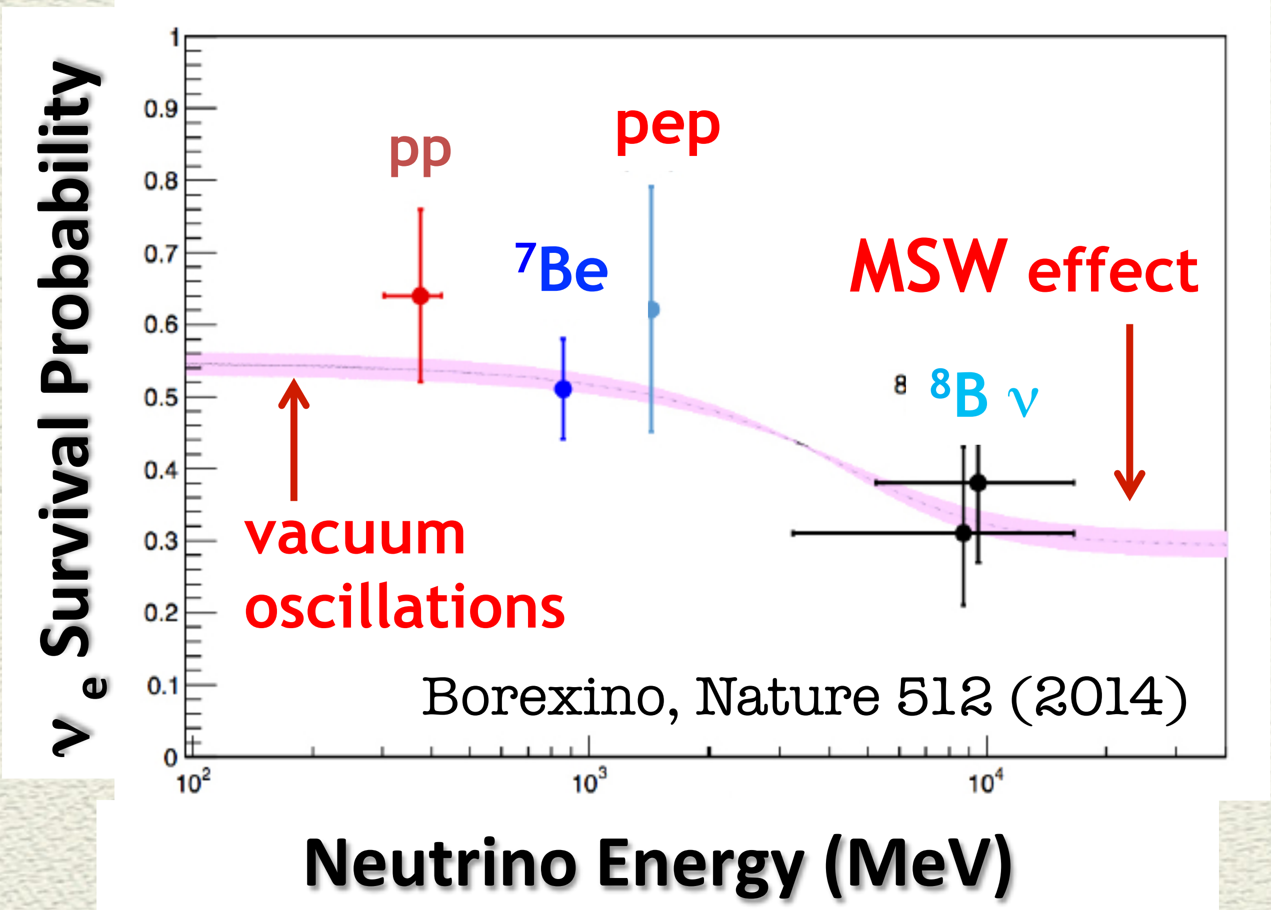
- Flavor modification can be efficient if evolution is adiabatic at the resonance location.

Wolfenstein, 1978; Mikheev and Smirnov, 1985

It's the 20th anniversary of SNO





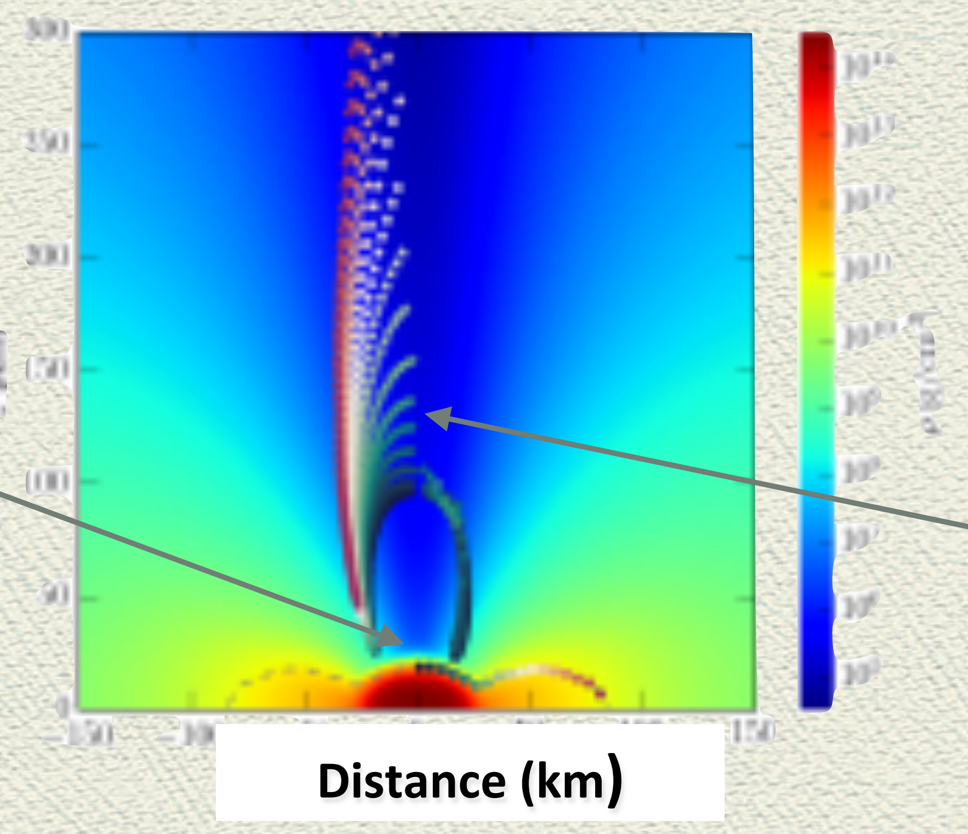


A reference phenomenon - Supernovae, in BNS, in the Earth and in the Early Universe.

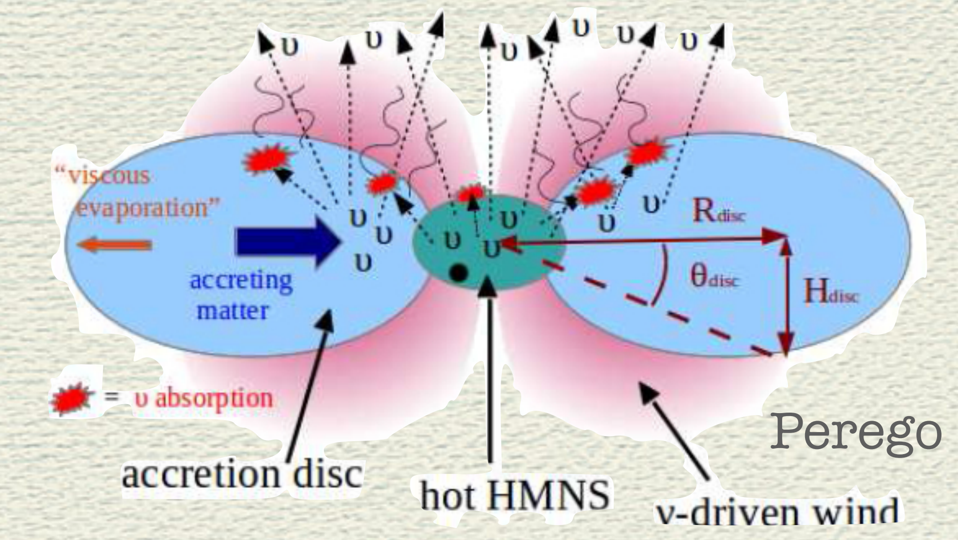
Multiple MSW resonances

Among the flavor phenomena uncovered in dense environments, there are multiple MSW resonances.

BNS remnant



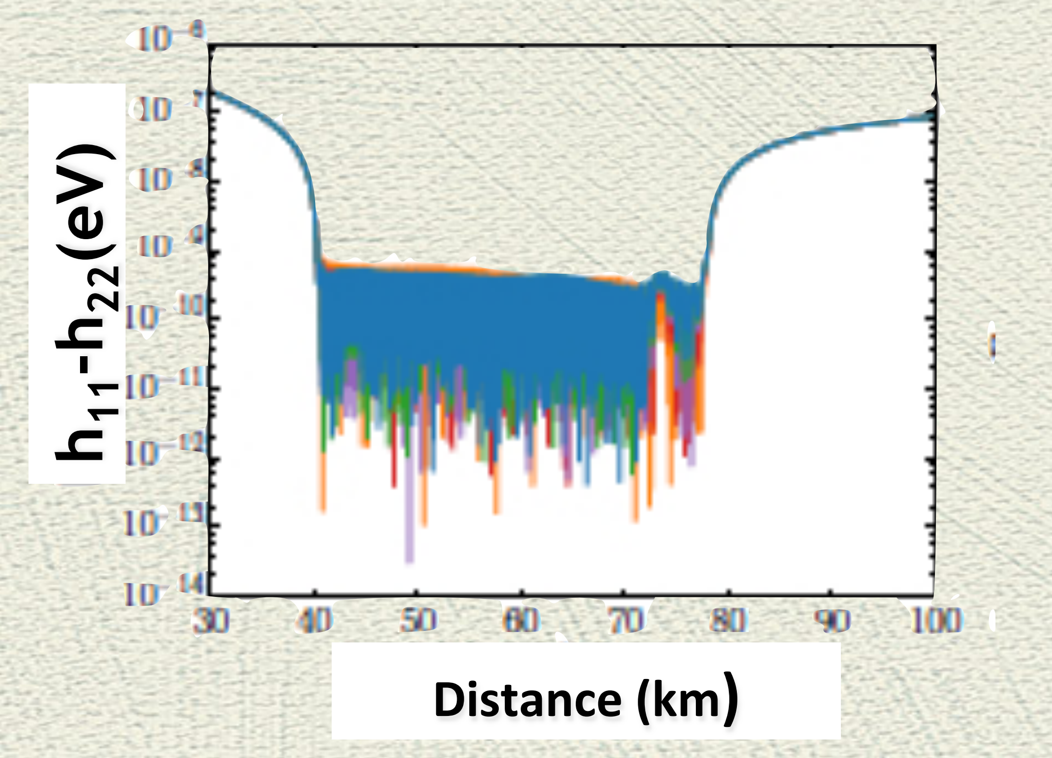
Frensel, Perego, Wu, Volpe PRD95, 2017

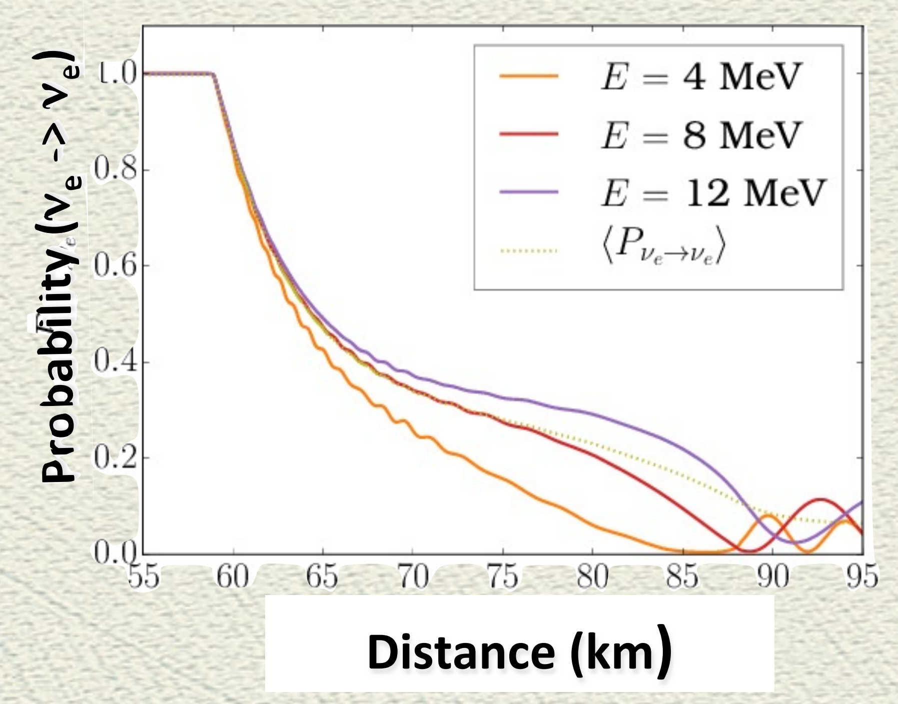


Perego et al, 2014

- In BNS, the electron antineutrino excess can produce a MSW-like resonance, the « matter-neutrino » resonance.

Malkus et al, PRD 86, 2012; PRD 93, 2016





Chatelain, Volpe, PRD 95, 2017

- Flavor conversion mechanism : multiple MSW resonances. Multiple cancellation of the self-interaction and the matter term, due to non-linear feedback.

Chatelain, Volpe, PRD 95, 2017

Multiple MSW resonances found in supernovae and BNS

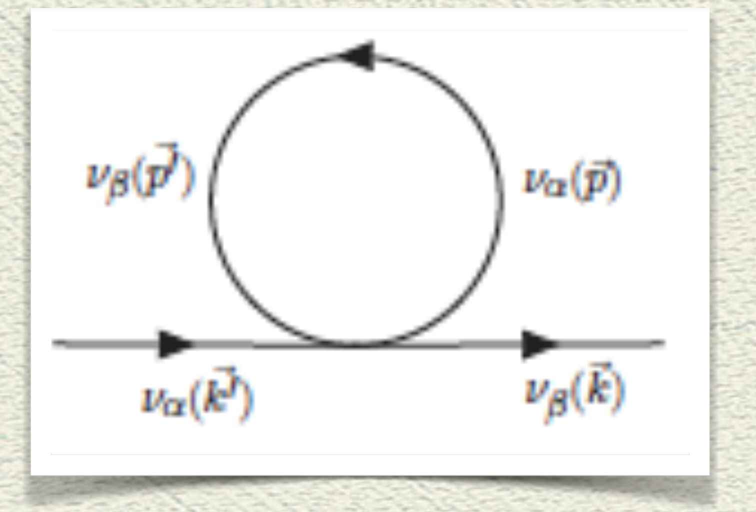
Neutrino self-interactions in dense environments

The investigation of neutrino self-interactions has triggered an intense theoretical activity since 2006.

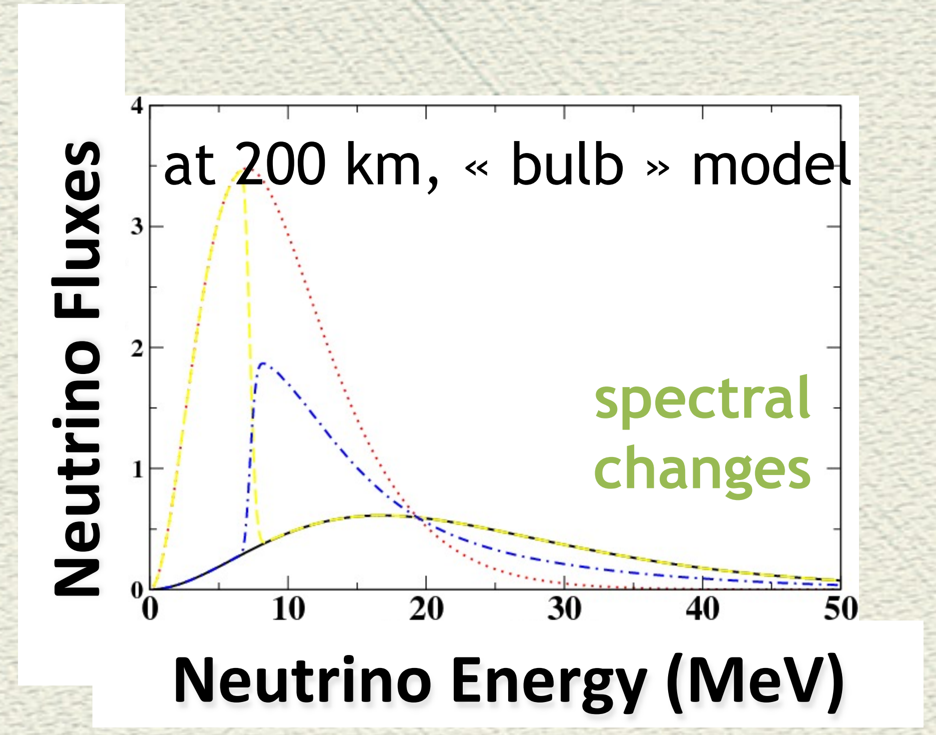
Duan, Fuller, Carlson, Qian, PRD74, 2006; also Yuksel, Balantekin, New Your. Phys. 7, 2005

- Neutrino self-interactions are sizeable and make neutrino propagation a non-linear many-body problem.

Pantaleone, 1992



- The « bulb » model has uncovered new large scale conversion modes. No impact on the explosion dynamics, impact on the r-process and on observations.



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

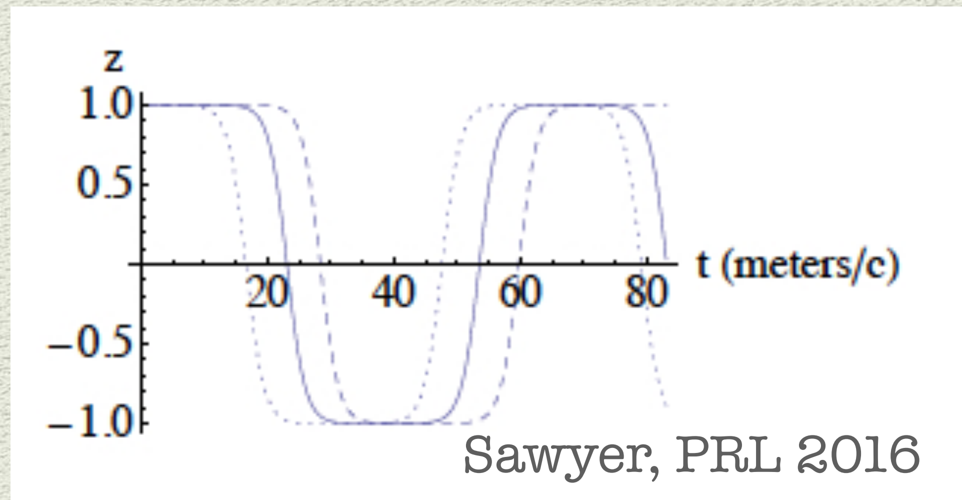
$$\frac{\lambda_{\nu_e n}}{\lambda_{\bar{\nu}_e p}} = \frac{< \sigma_{\nu_e n} >}{< \sigma_{\bar{\nu}_e p} >}$$

see the reviews Duan, Fuller, Qian, 2010;
Mirizzi, et al, 2016;
Horiuchi, Kneller, 2018

Slow modes influence r-process and observations.

Fast modes

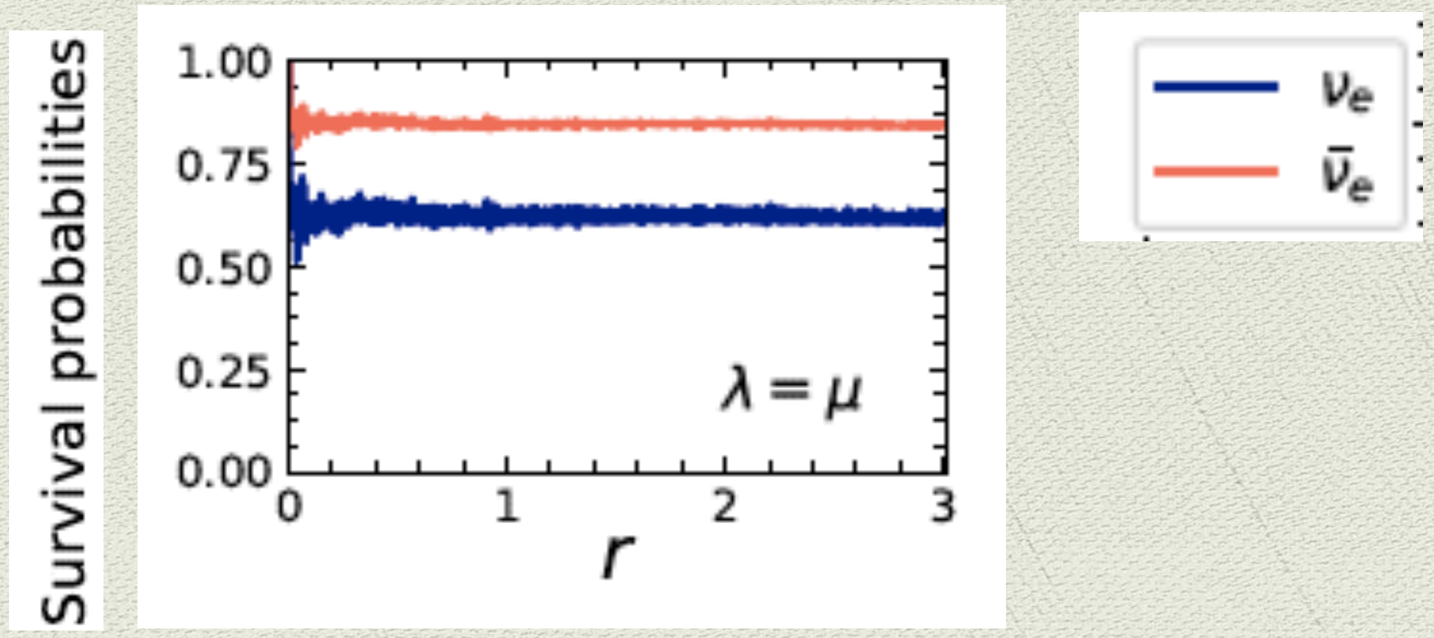
- Very short scale flavor conversion modes, occurring when electron neutrino and antineutrino angular distributions cross each other.



Sawyer, PRL 2016

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

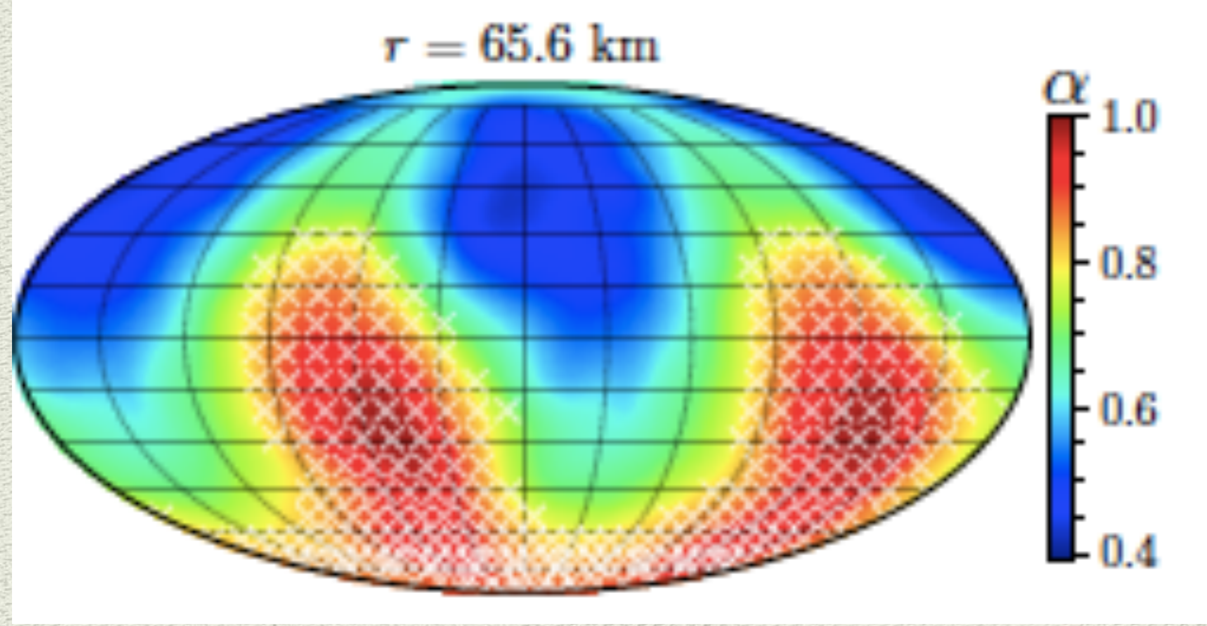
- Fast modes do not appear to produce flavor equilibration of the neutrino spectra (*schematic two beam model*).



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 supernova simulations by several groups using different supernova simulations

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

In a fully consistent description ?

Theoretical aspects of neutrino propagation in dense environments

- *Connections to other domains investigated.*

The Hamiltonian for self-interacting neutrinos (under some assumptions) same as for Bardeen-Cooper-Schrieffer superconductivity.

Pehlivan, Balantekin, Kajino, Yoshida, PRD84, 2011; PRD90, 2014

The (linear and non-linear) evolution equations of a weakly interacting ensemble of neutrinos and antineutrinos propagating in dense matter can be formally connected to the ones of atomic nuclei (BBGKY hierarchy).

Volpe, Väänänen, Espinoza, PRD87, 2013; Väänänen, Volpe, PRD88, 2013

- Mean-field equations and quantum kinetic equations derived with numerous approaches.

Volpe, Int. J. Mod. Phys., E24, 2015

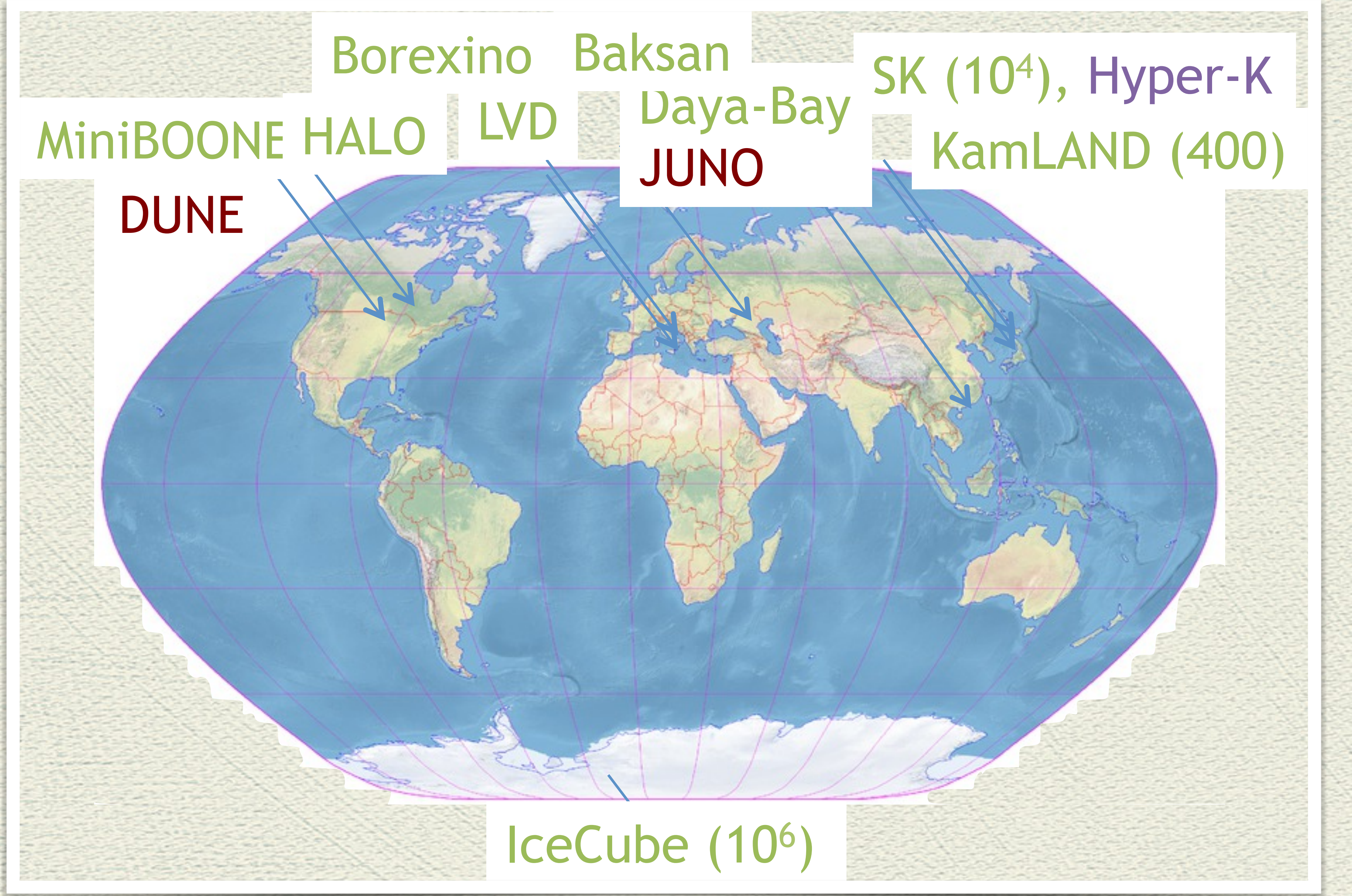
Rederiveation QKE for the Early Universe (BBGKY) and first calculation implementing the full collision term to derive a precise value of Neff = 3.0440.

Froustey, Pitrou, Volpe, JCAP 12, 2020

Connections to other domains uncovered.

Waiting for the next (extra)galactic supernova

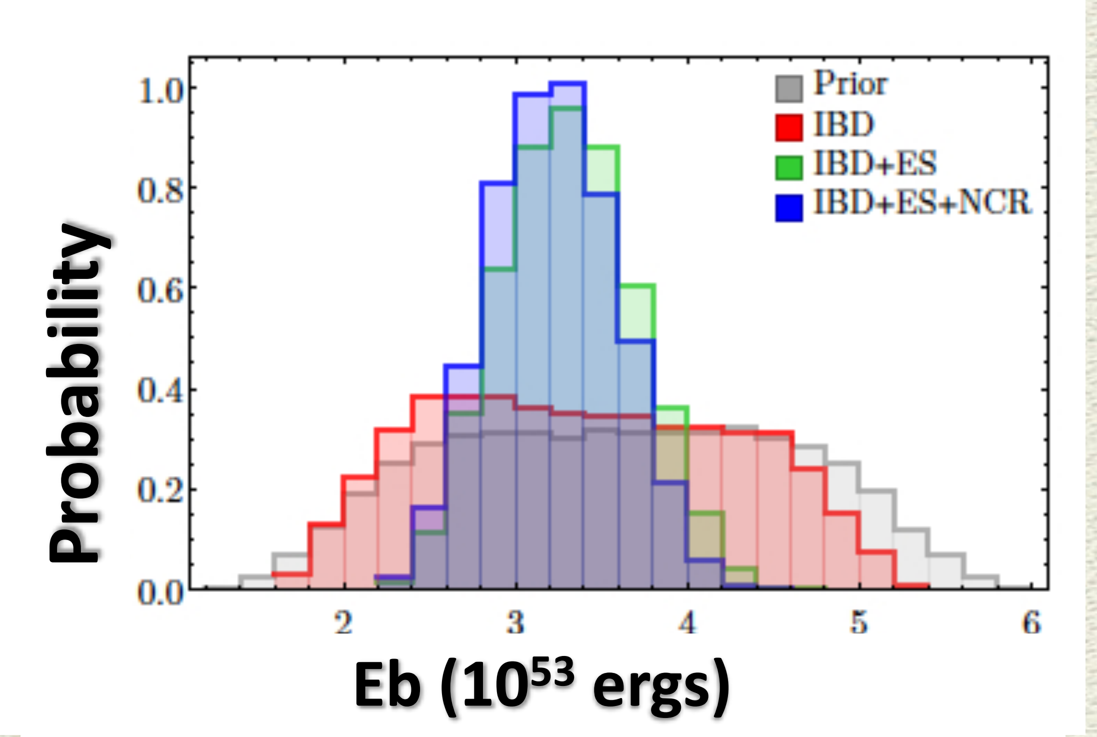
- Expected events for a supernova in our galaxy (10 kpc) up to 10^6



- Detection channels : scattering on protons, electrons, nuclei. Sentivity to all flavors, time and energy signal will be measured.

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

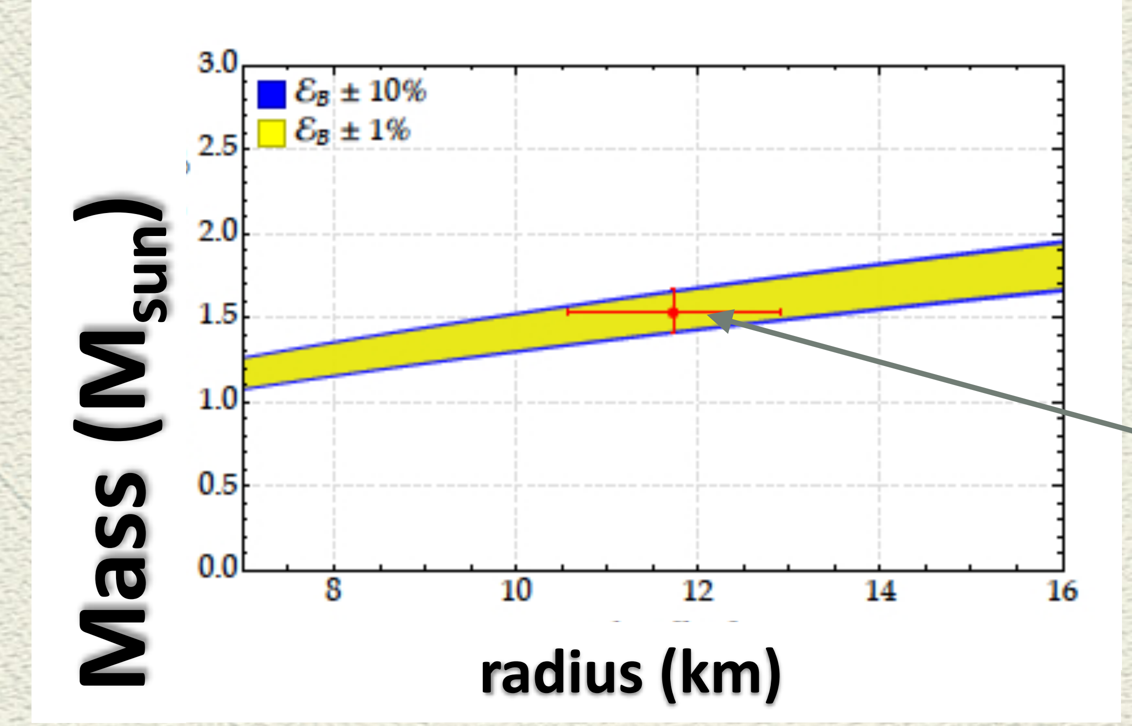
- A likelihood analysis of the events in a galactic supernova shows the gravitational binding energy can be reconstructed with 11% accuracy in Super-K, 3% accuracy in Hyper-K



Gallo Rosso, Vissani, Volpe, JCAP11, 2017; JCAP 04, 2018

Fit to EOS for NS $\frac{\mathcal{E}_B}{Mc^2} \approx \frac{(0.60 \pm 0.05)\,\beta}{1 - \beta/2}$, $\beta = \frac{GM}{Rc^2}$, Lattimer, Prakash

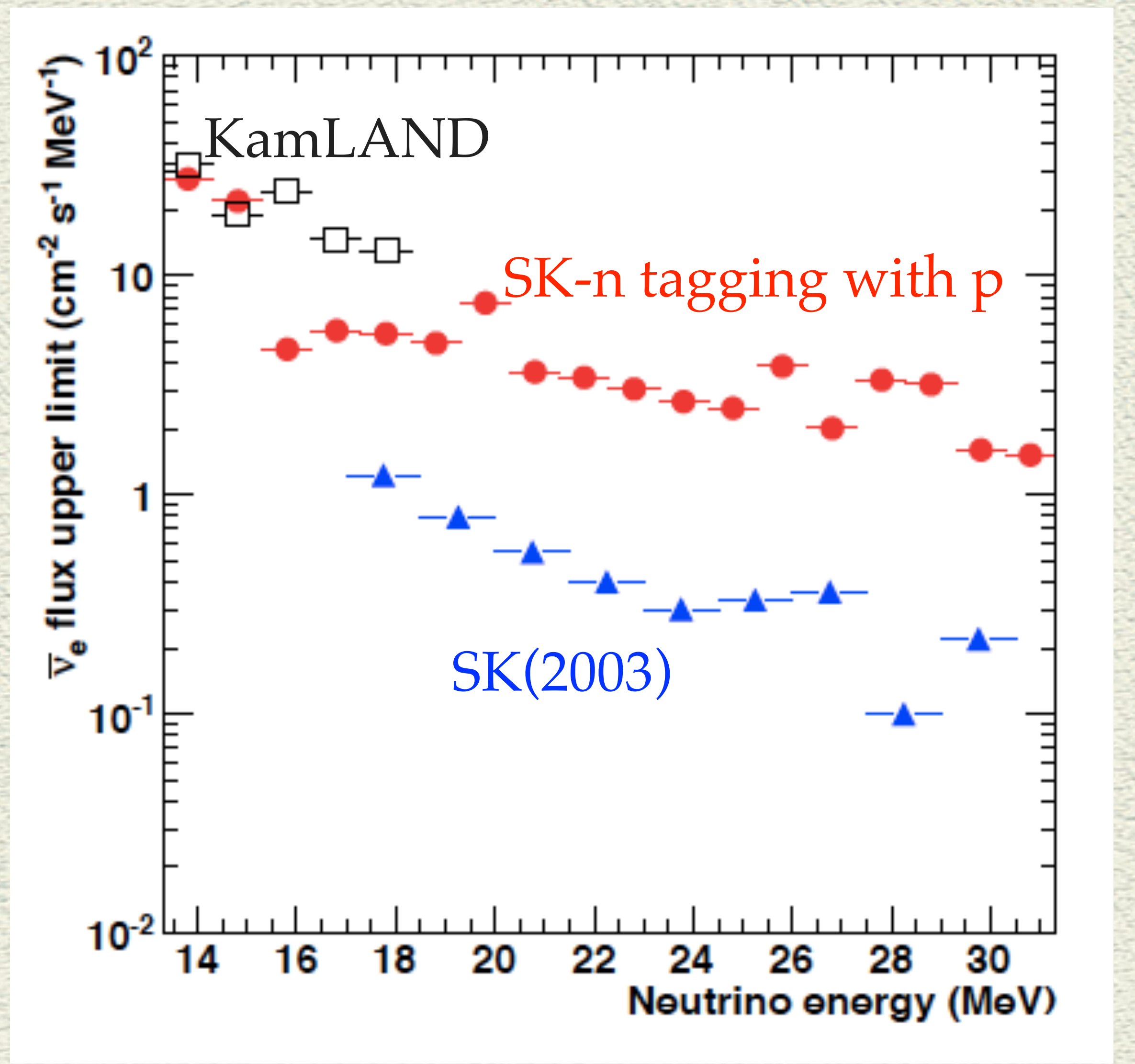
compactness



A star like SN1987A

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

Diffuse Supernova Neutrino Background (DSNB)



Zhang et al, Astr. Phys. 60 (2015)

- The DSNB neutrino flux depends on the core-collapse supernova rate (related to the star formation rate), the supernova neutrino fluxes integrated over redshift

$$F_\alpha(E_\nu) = \int dz \left| \frac{dt}{dz} \right| (1+z) R_{\rm SN}(z) \frac{dN_\alpha(E'_\nu)}{dE'_\nu},$$

$$E'_\nu = (1+z)E_\nu,$$

redshifted neutrino energy
mostly sensitive to z = 0,1,2

- Addition to Gd to water Cherenkov detectors to better identify the neutron by capture on Gd and increase signal/background.

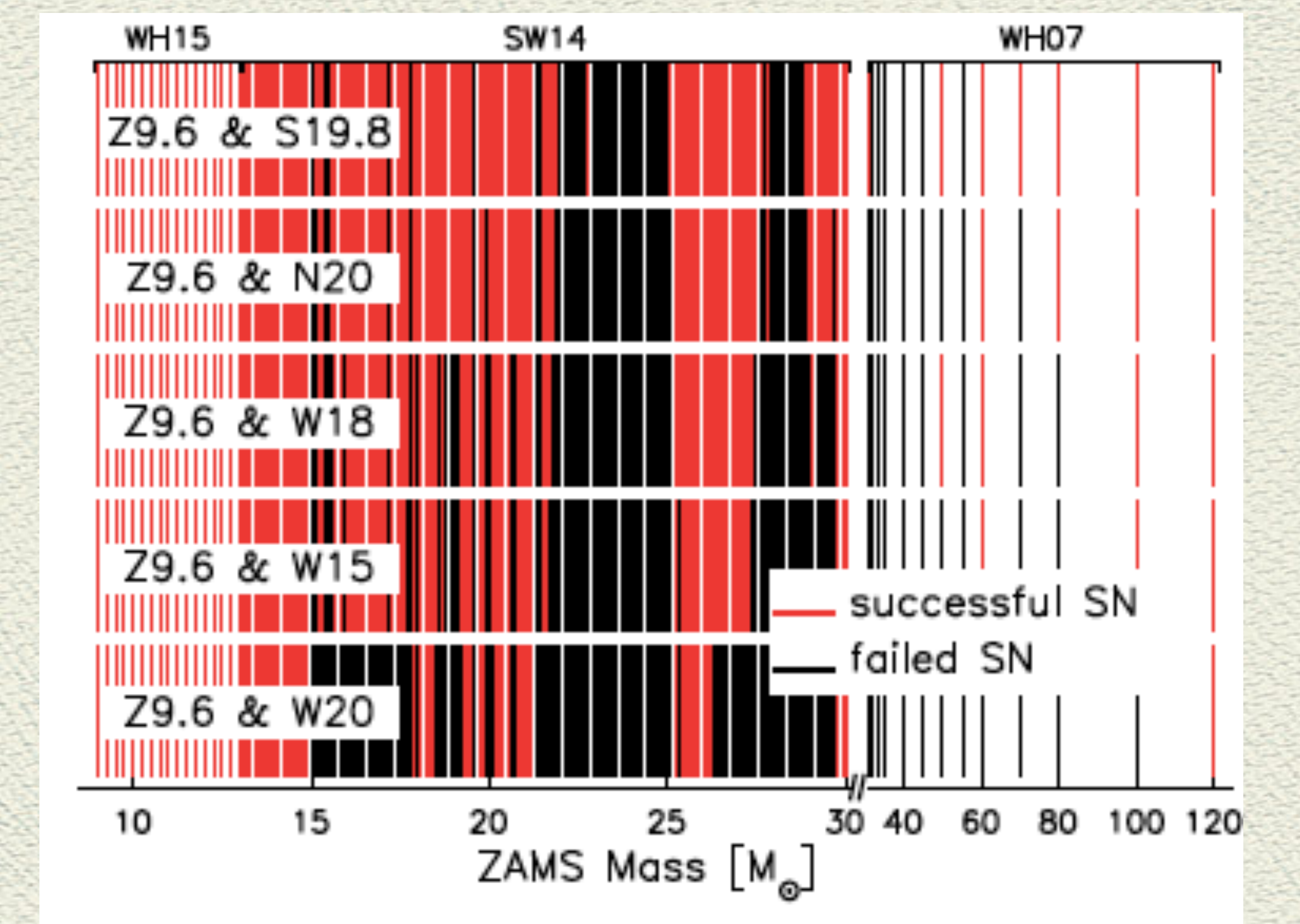
Beacom and Vagins, PRL 93, 2004

EGADS prototype worked fine.

A atmospheric NC events, a dangerous background.

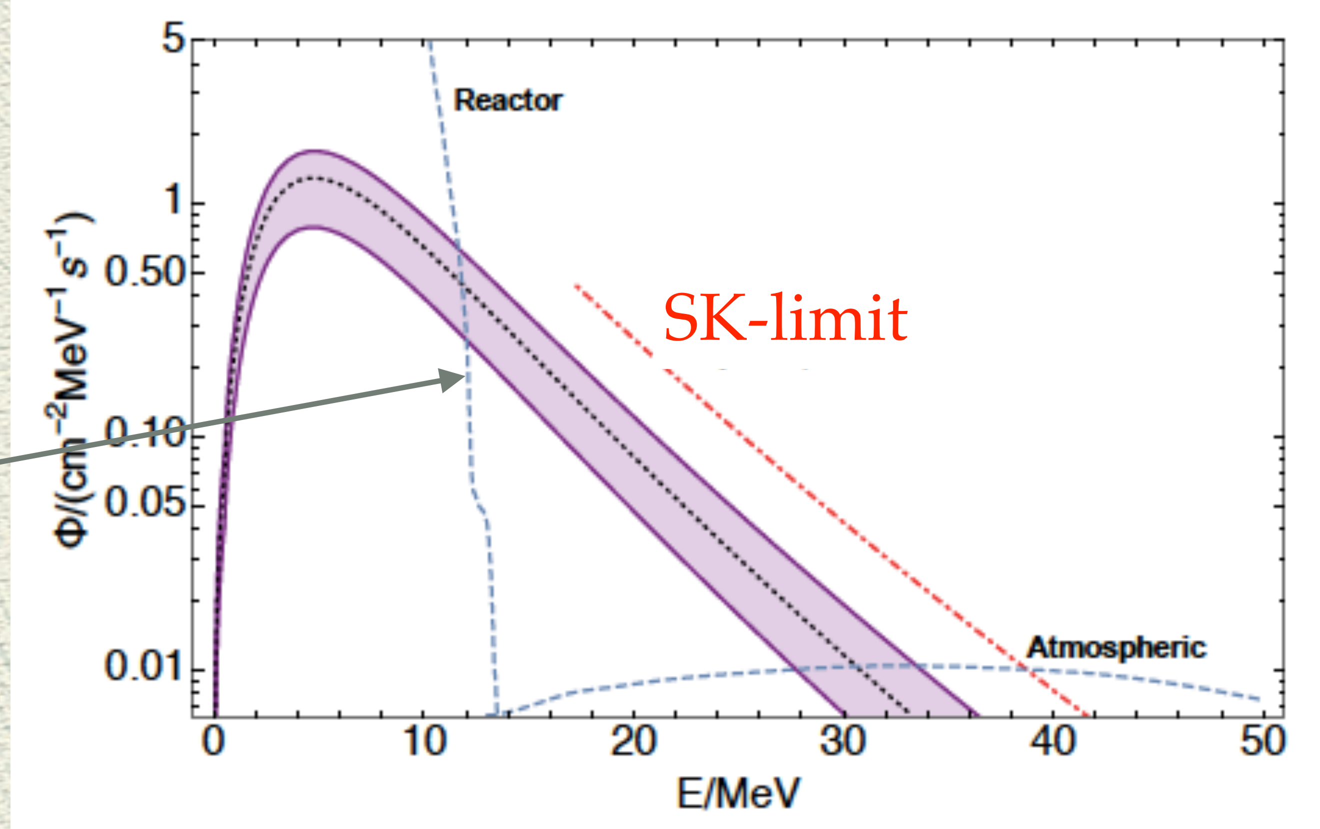
Priya and Lunardini JCAP 11, 2017

The detection of the DSNB



Kresse et al, Astrophys. J. 909, 2021

theoretical band includes uncertainty on supernova rate and failed supernovae



Priya and Lunardini JCAP 2017

- The DSNB is sensitive to :

  > the fraction of failed supernovae, subdominant contribution but hotter energy spectrum, determines the relic flux tail.
  Lunardini, PRL102, 2009

  > the EOS Moller et al, JCAP05, 2018

  > to single stars and helium stars (proxy for binary systems)
  Kresse et al, Astrophys. J. 909, 2021

  > non-standard neutrino properties (e.g. decay)
  De Gouvea et al, PRD 102, 2020

  > flavor conversion phenomena - MSW, shock waves and self-interaction effects.
  Galais, Kneller, Gava, Volpe, PRD 2010

- **Predictions close to the current SK limit.**
  Tens (SK+Gd) to hundreds (Hyper-K) events expected (10 years).

SK+Gd experiment started (August 2020), JUNO under construction, Hyper-K approved (2020)

Conclusions and perspectives

Neutrino flavor evolution in dense environments is still an open problem.

Last two decades have brought key steps forward, showing the richness of this complex domain, uncovered a variety of flavor conversion mechanisms, the last being fast modes.

Flavor conversion impacts r-process nucleosynthetic abundances and supernova neutrinos fluxes, important for observations.

Numerous open questions need to be fully addressed, including the interplay between flavor and collisions, the impact of fast modes, the role of decoherence and of strong gravitational fields, the final impact on observations.

Waiting for the next supernova and for the discovery of the diffuse supernova neutrino background which will bring key information on core-collapse supernova rate, on the fraction of failed supernovae, on non-standard neutrino properties and on flavor evolution.

Luth player, 1615, O. Gentileschi