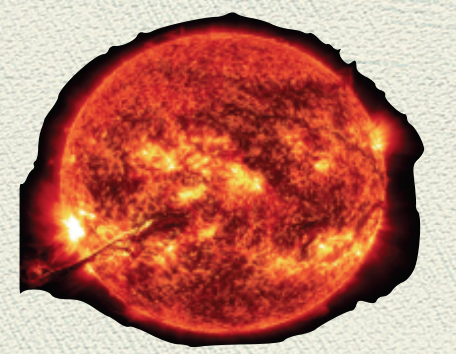
Theoretical aspects of neutrino astro-physics

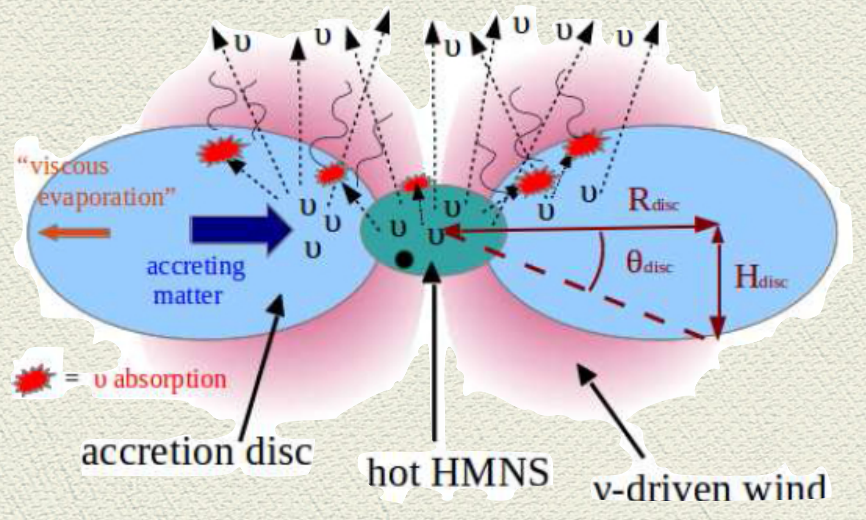
Maria Cristina Volpe
Laboratoire Astroparticule et Cosmologie (APC)



Sun

SN1987A- (LMC)

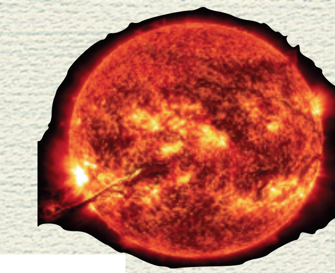
core-collapse Supernovae



Perego et al, 2014

binary neutron star mergers (remnants)

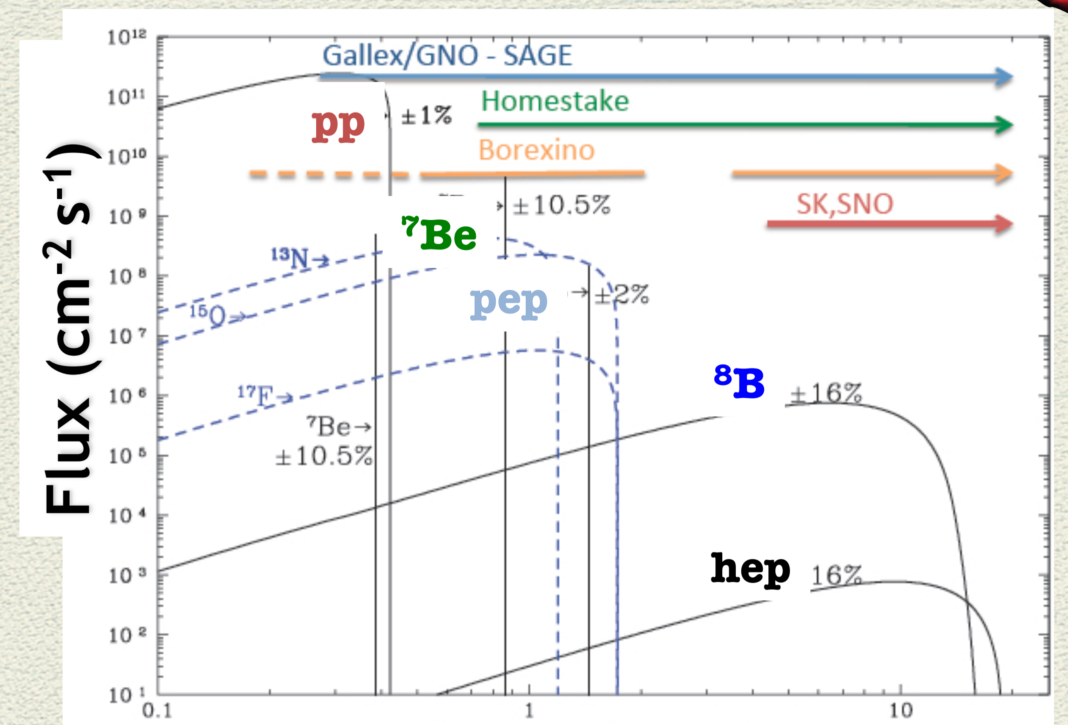
Solar neutrinos



- Our Sun burns hydrogen into helium-4 through the proton-proton reaction chain.

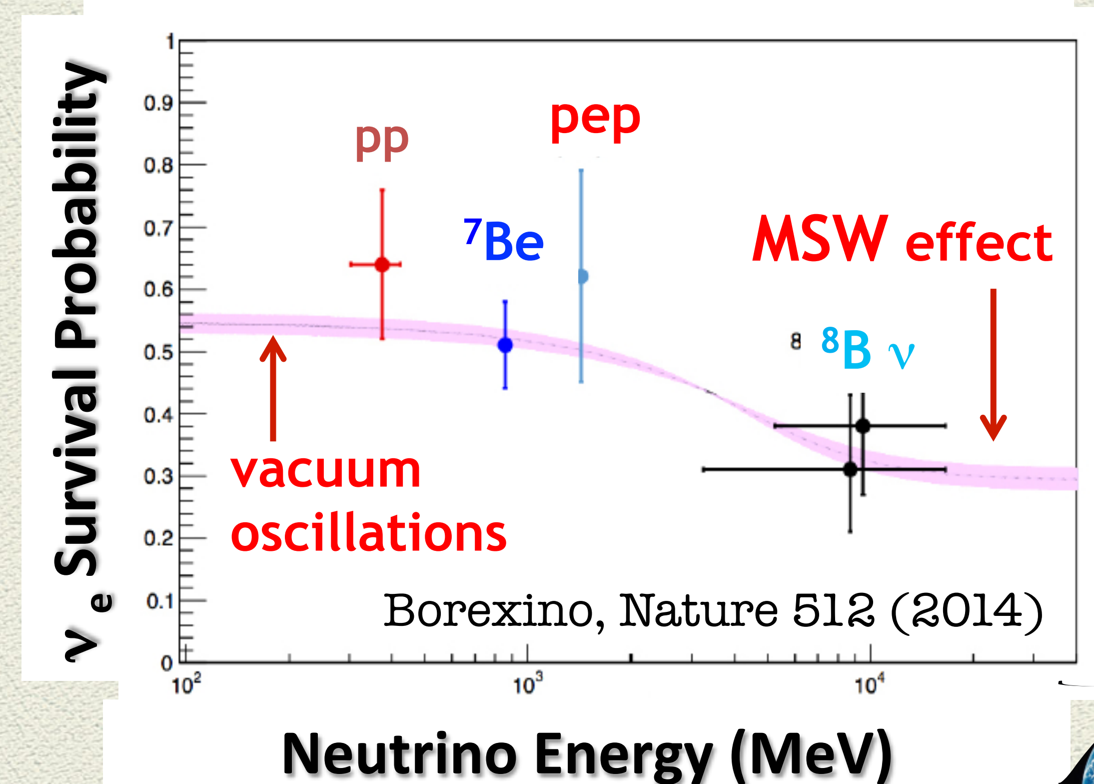
  One of the crucial results from solar neutrino experiments, *pioneered by R. Davis.*

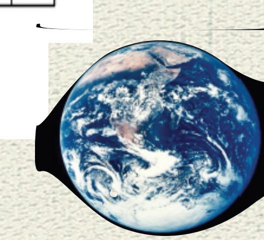
  Davis, Harmer, Hoffman, PRL20 (1968)



- Solution of the solar neutrino deficit problem : Low energy solar neutrinos are reduced by averaged vacuum oscillations.

  ^{8}B neutrinos undergo the MSW effect.

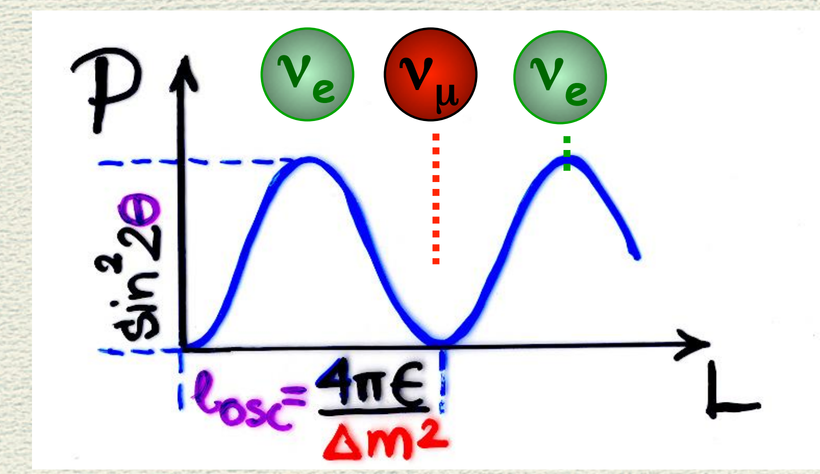




Neutrinos : vacuum oscillations

- The idea of neutrino oscillations introduced in analogy with K^0-K^0bar systems.

  Pontecorvo JETP 6 (1957)



mixing angle

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \qquad \Delta m^2 = m_2^2 - m_1^2$$

mass basis

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

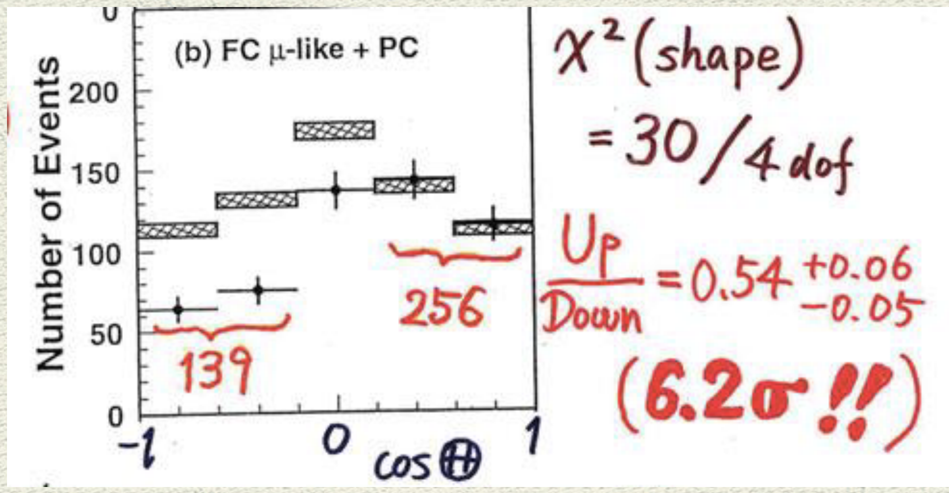
probability for neutrino oscillations

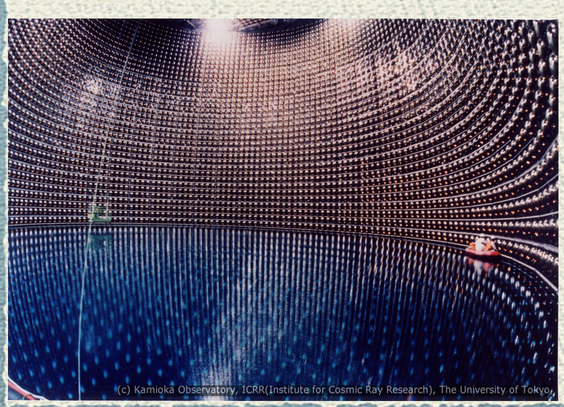
depends on mass-squared differences and mixing angles.

$|\nu_\alpha> = U^*_{\alpha k}|\nu_k>$ U - unitary Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix

- Discovered by Super-Kamiokande, using atmospheric neutrinos.

  PRL81 (1998)





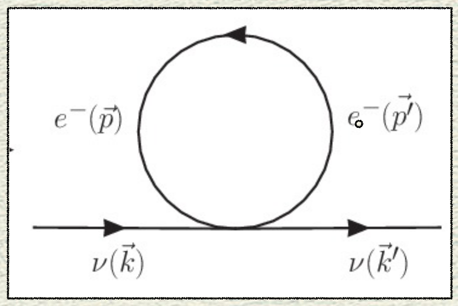
In three flavors, PMNS matrix depends on three angles, one Dirac and two Majorana CP violating phases.

Phases unknown, as the absolute mass and the mass ordering

See talks of Dominique and Thomas !

… to the Mikheev-Smirnov-Wolfenstein effect

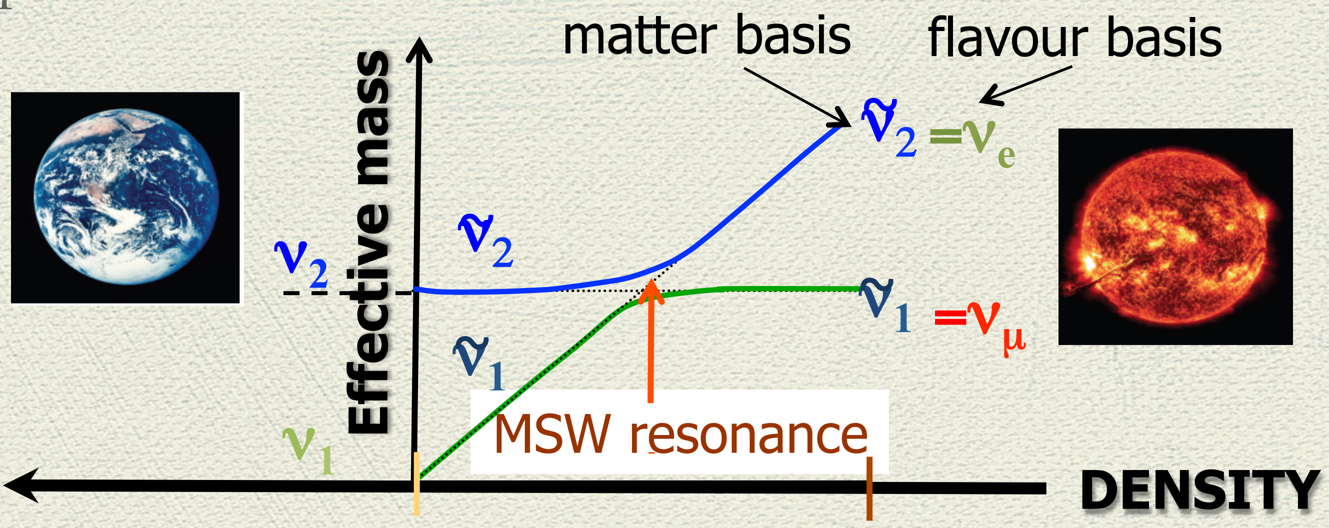
- Astrophysical neutrinos interact with the stellar environment.



$$\Gamma_{\nu_e}(\rho_e) = \sqrt{2}G_F\,\rho_e$$

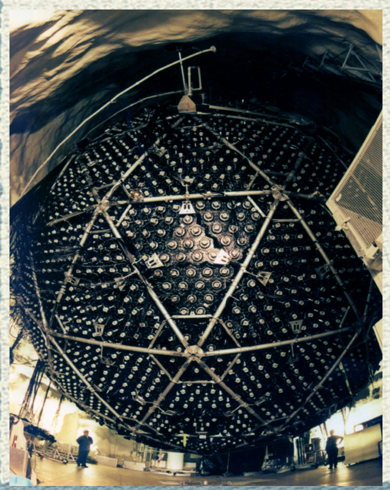
- **MSW effect**
  Neutrinos efficiently convert into other flavors, if a resonance condition is met and the evolution is adiabatic.

Wolfenstein PRD (1978)
Mikheev, Smirnov(1985)



- Defintely established by SNO, KAMLAND and solar experiments :

  explains the deficit of high energy 8B solar neutrinos



PRL89 (2002), PRL90 (2003)

It is a reference mechanism for understanding flavor evolution in media
- core-collapse supernovae, binary neutron star mergers and early Universe (BBN)

Energy production in main sequence stars

In 1939 H. Bethe predicts stars burn hydrogen into helium-4, using carbon and nitrogen as catalysts - **CN cycle :** main mechanism for energy production in <u>massive</u> main sequence stars.

MARCH 1, 1939 PHYSICAL REVIEW VOLUME 55

Energy Production in Stars*

H. A. Bethe
Cornell University, Ithaca, New York

(Received September 7, 1938)

It is shown that the *most important source of energy in ordinary stars is the reactions of carbon and nitrogen with protons*. These reactions form a cycle in which the original nucleus is reproduced, *viz.* $C^{12}+H=N^{13}$, $N^{13}=C^{13}+\epsilon^+$, $C^{13}+H=N^{14}$, $N^{14}+H=O^{15}$, $O^{15}=N^{15}+\epsilon^+$, $N^{15}+H=C^{12}+He^4$. Thus carbon and nitrogen merely serve as catalysts for the combination of four protons (and two electrons) into an α-particle (§7).

The carbon-nitrogen reactions are unique in their cyclical character (§8). For all nuclei lighter than carbon, reaction with protons will lead to the emission of an α-particle so that the original nucleus is permanently destroyed. For all nuclei heavier than fluorine, only radiative capture of the protons occurs, also destroying the original nucleus. Oxygen and fluorine reactions mostly lead back to nitrogen. Besides, these heavier nuclei react much more slowly than C and N and are therefore unimportant for the energy production.

The agreement of the carbon-nitrogen reactions with observational data (§7, 9) is excellent. In order to give the correct energy evolution in the sun, the central temperature of the sun would have to be 18.5 million degrees while integration of the Eddington equations gives 19. For the brilliant star Y Cygni the corresponding figures are 30 and 32. This good agreement holds for all bright stars of the main sequence, but, of course, not for giants.

For fainter stars, with lower central temperatures, the reaction $H+H=D+\epsilon^+$ and the reactions following it, are believed to be mainly responsible for the energy production. (§10)

It is shown further (§5–6) that *no elements heavier than* He^4 *can be built up in ordinary stars*. This is due to the fact, mentioned above, that all elements up to boron are disintegrated by proton bombardment (α-emission!) rather than built up (by radiative capture). The instability of Be^8 reduces the formation of heavier elements still further. The production of neutrons in stars is likewise negligible. The heavier elements found in stars must therefore have existed already when the star was formed.

Finally, the suggested mechanism of energy production is used to draw conclusions about astrophysical problems, such as the mass-luminosity relation (§10), the stability against temperature changes (§11), and stellar evolution (§12).

§1. Introduction

The progress of nuclear physics in the last few years makes it possible to decide rather definitely which processes can and which cannot occur in the interior of stars. Such decisions will be attempted in the present paper, the discussion being restricted primarily to main sequence stars. The results will be at variance with some current hypotheses.

The first main result is that, under present conditions, no elements heavier than helium can be built up to any appreciable extent. Therefore we must assume that the heavier elements were built up *before* the stars reached their present state of temperature and density. No attempt will be made at speculations about this previous state of stellar matter.

The energy production of stars is then due entirely to the combination of four protons and two electrons into an α-particle. This simplifies the discussion of stellar evolution inasmuch as the amount of heavy matter, and therefore the opacity, does not change with time.

The combination of four protons and two electrons can occur essentially only in two ways. The first mechanism starts with the combination of two protons to form a deuteron with positron emission, *viz.*

$$H+H=D+\epsilon^+. \quad (1)$$

The deuteron is then transformed into He^4 by further capture of protons; these captures occur very rapidly compared with process (1). The second mechanism uses carbon and nitrogen as catalysts, according to the chain reaction

$$\begin{array}{ll} C^{12}+H=N^{13}+\gamma, & N^{13}=C^{13}+\epsilon^+ \\ C^{13}+H=N^{14}+\gamma, & \\ N^{14}+H=O^{15}+\gamma, & O^{15}=N^{15}+\epsilon^+ \\ N^{15}+H=C^{12}+He^4. & \end{array} \quad (2)$$

The catalyst C^{12} is reproduced in all cases except about one in 10,000, therefore the abundance of carbon and nitrogen remains practically unchanged (in comparison with the change of the number of protons). The two reactions (1) and

* Awarded an A. Cressy Morrison Prize in 1938, by the New York Academy of Sciences.

The combination of four protons and two electrons can occur essentially only in two ways. The first mechanism starts with the combination of two protons to form a deuteron with positron emission, *viz.*

no neutrinos…

$$H+H=D+\epsilon^+. \quad (1)$$

The deuteron is then transformed into He^4 by further capture of protons; these captures occur very rapidly compared with process (1). The second mechanism uses carbon and nitrogen as catalysts, according to the chain reaction

$$\begin{array}{ll} C^{12}+H=N^{13}+\gamma, & N^{13}=C^{13}+\epsilon^+ \\ C^{13}+H=N^{14}+\gamma, & \\ N^{14}+H=O^{15}+\gamma, & O^{15}=N^{15}+\epsilon^+ \\ N^{15}+H=C^{12}+He^4. & \end{array} \quad (2)$$

CNO neutrinos measurement (12% precision) solves the abundance problem and confirms energy production in massive main sequence stars

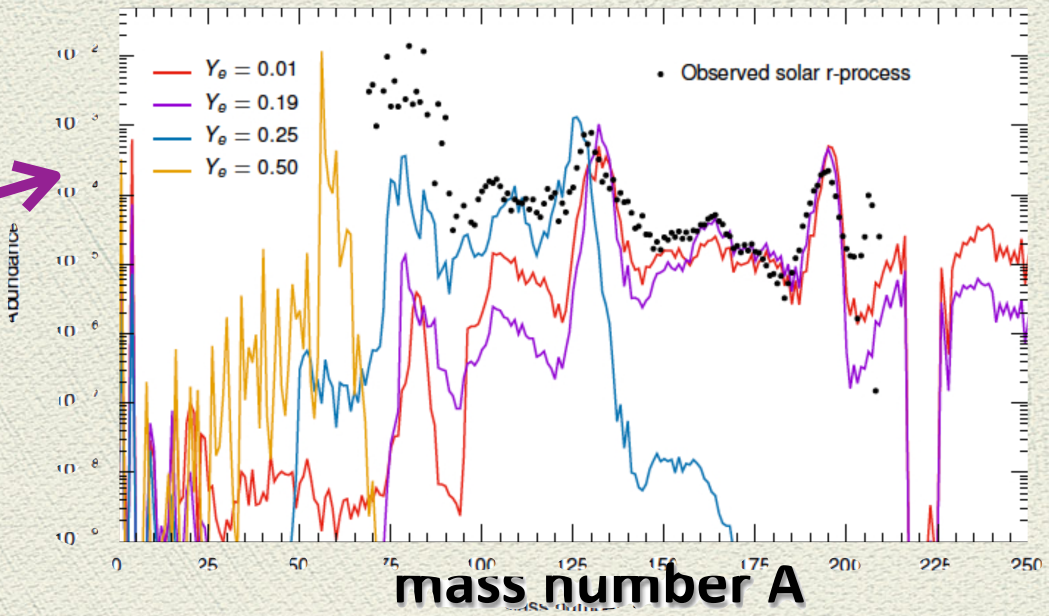
Neutrinos from dense objects and observations

Predictions for future measurements :

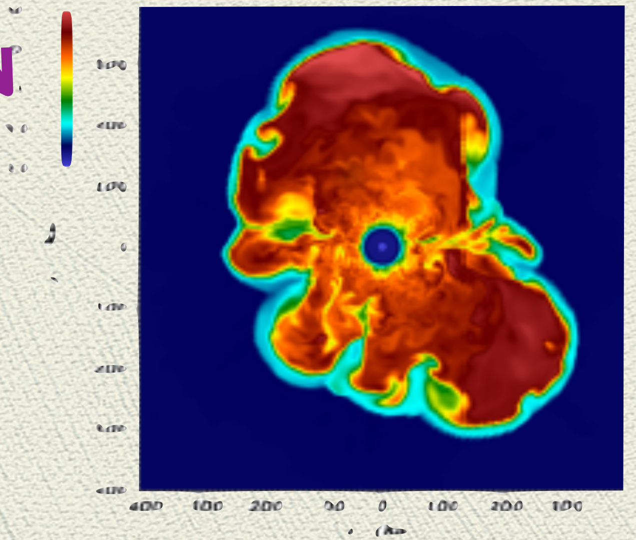
- diffuse supernova neutrino background - **Super-K + Gd**
- an (extra)galactic supernova - 10^4-10^6 events at 10 kpc - **SNEWS, Hyper-K**

Understanding the role of neutrinos and of flavor conversion in dense environments

Heavy elements nucleosynthesis

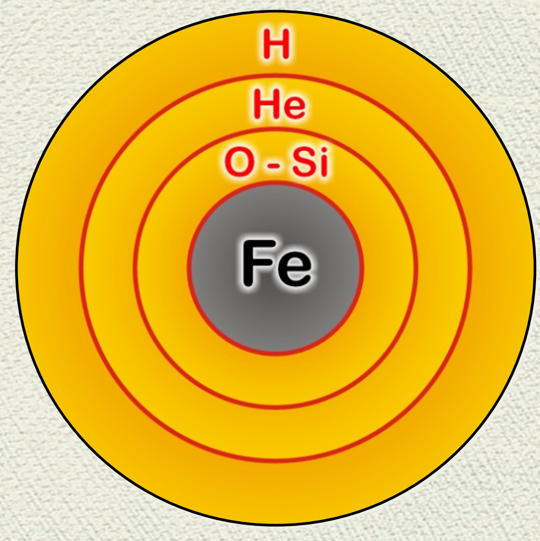


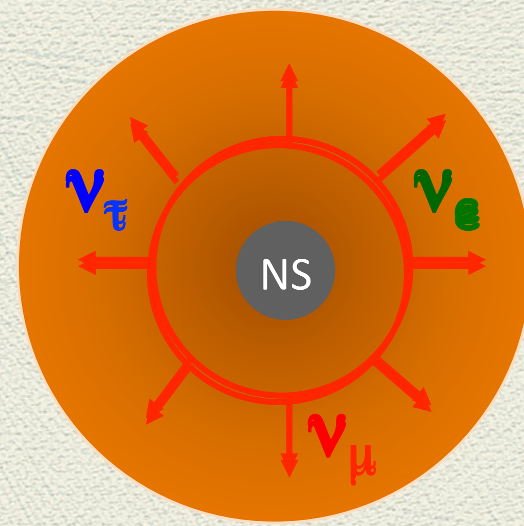
Supernova explosion mechanism



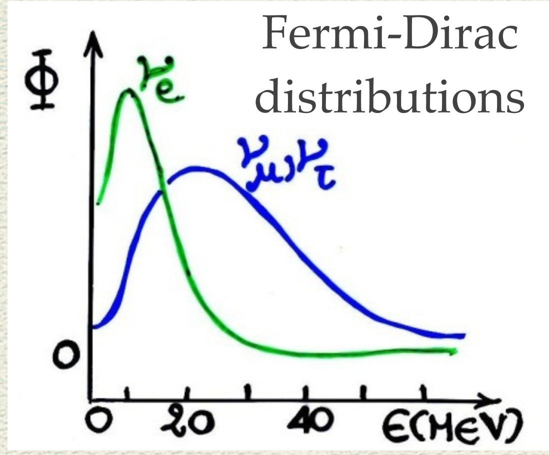
Mueller et al, 1705.00620

Supernovae (type II, Ib, Ic) and the neutrino signal

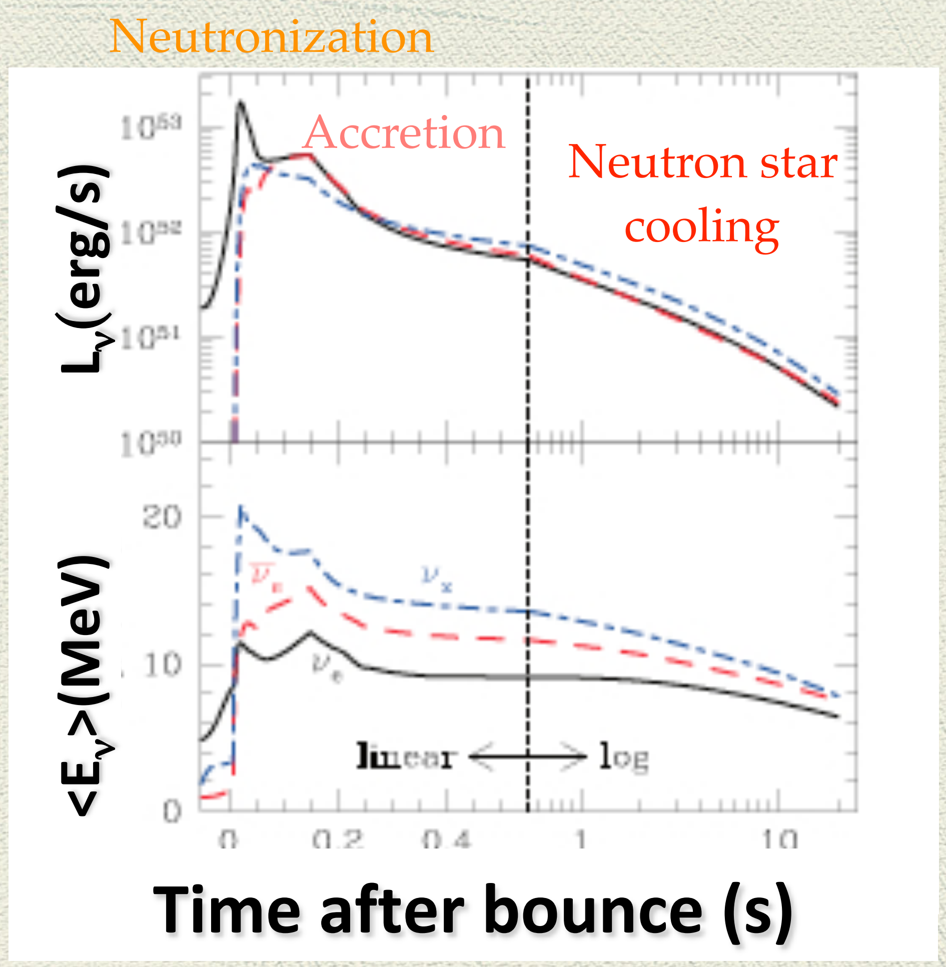




The gravitational binding energy of the nascent neutron star (99% of 10^{53} erg) as neutrinos.



$$< E_{\nu_e} ><< E_{\bar{\nu}_e} ><< E_{\nu_{\mu,\tau}} >$$



Neutrino luminosity curves and spectra bring crucial information about

- SNe explosion dynamics
- neutron star properties
- SNe location
- neutrino properties and flavor evolution
- new physics

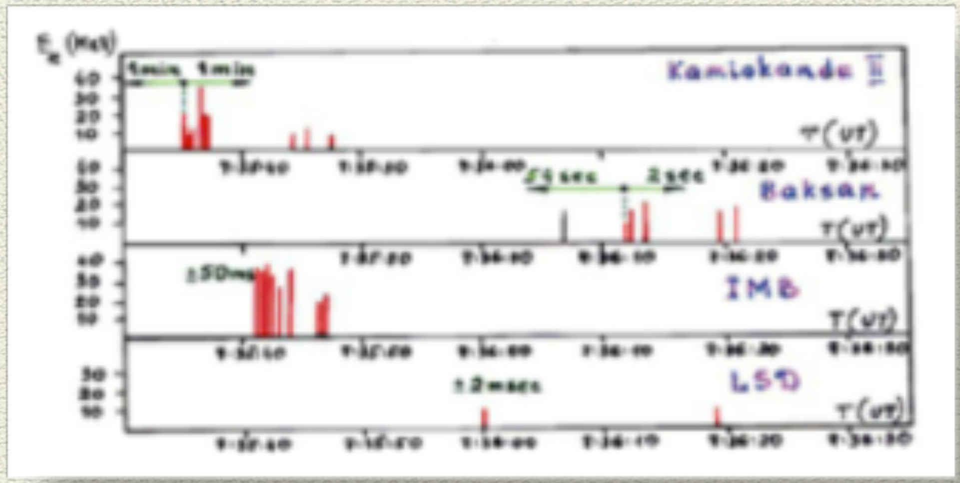
Core-collapse supernova explosion mechanisms

- One of the key questions in nuclear astrophysics tightly linked to neutrinos :
  How do massive stars explode ?

- Colgate and White (1966) : $E_{grav} \approx \frac{GM^2}{R} \approx 10^{53} ergs$
  gravitational binding energy of the newly born neutron star emitted with neutrinos. They can deposit energy behind the shock to trigger the explosion - « prompt explosion mechanism ».

- Wilson (1982), Bethe and Wilson (1985) :
  delayed accretion shock mechanism

Sanduleak 69^0202, a blue super-giant in Large Magellanic Cloud, at 50 kpc, no remnant found so far.



Suzuki, A. J. Conf. Phys. 120 (2008)

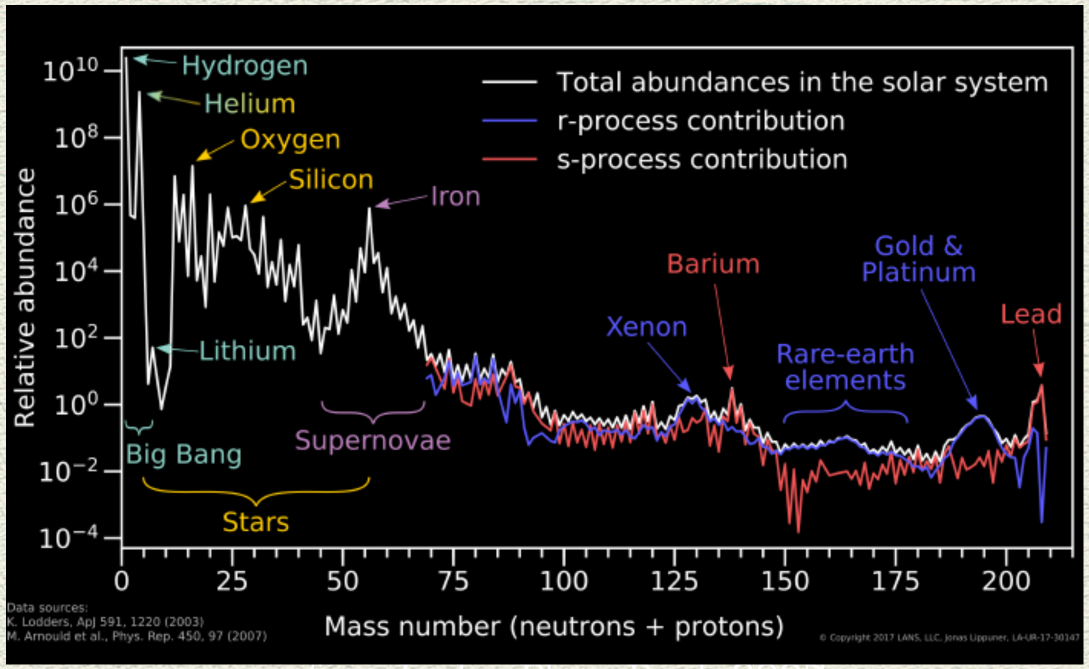
SN1987A : Delayed explosion mechanism favored over the prompt one.

Several decades of searches to unravel the explosion mechanism… close

r-process nucleosynthesis : the sites ?

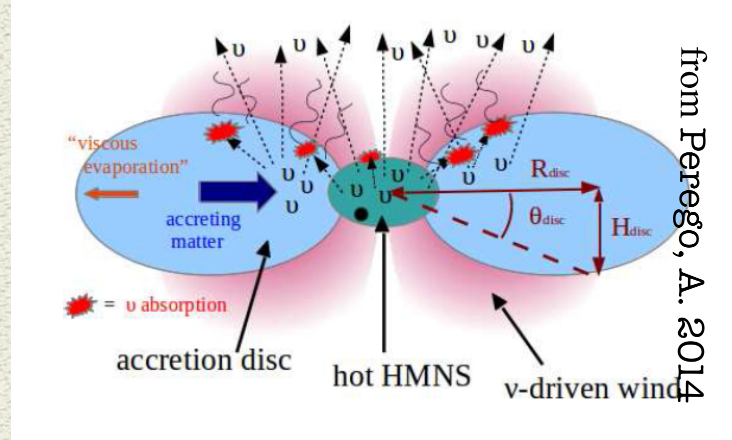
- One of the key questions in nuclear astrophysics : the origin of elements heavier than iron in our Universe, i.e. to determine the sites and the conditions under which they are made.

r-process requires neutron-rich environment, occurs in short timescales. Formation of neutron rich nuclei through neutron capture faster than beta-decay.

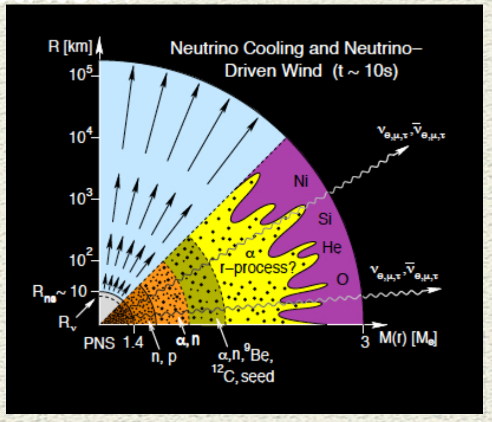


- Candidate sites for r-process nucleosynthesis : core-collapse supernovae and compact objects — accreting disks around black holes and binary neutron star mergers (BNS).

These sites emit 10^{51} to 10^{52} ergs with tens of MeV neutrinos There are neutrino driven winds.



from Perego, A. 2014



- GW170817 : gravitational wave signal from a BNS, in coincidence with a short gamma ray burst and a kilonova.

kilonova : first evidence that r-process elements are produced in BNS. Electromagnetic emission compatible with lanthanide free ejecta (cold, blue component)and ejecta with lanthanides (hot, red). Dynamical ejecta pre-merging phase, viscous and neutrinodriven winds from post-merger phase.

r-process nucleosynthesis and neutrinos

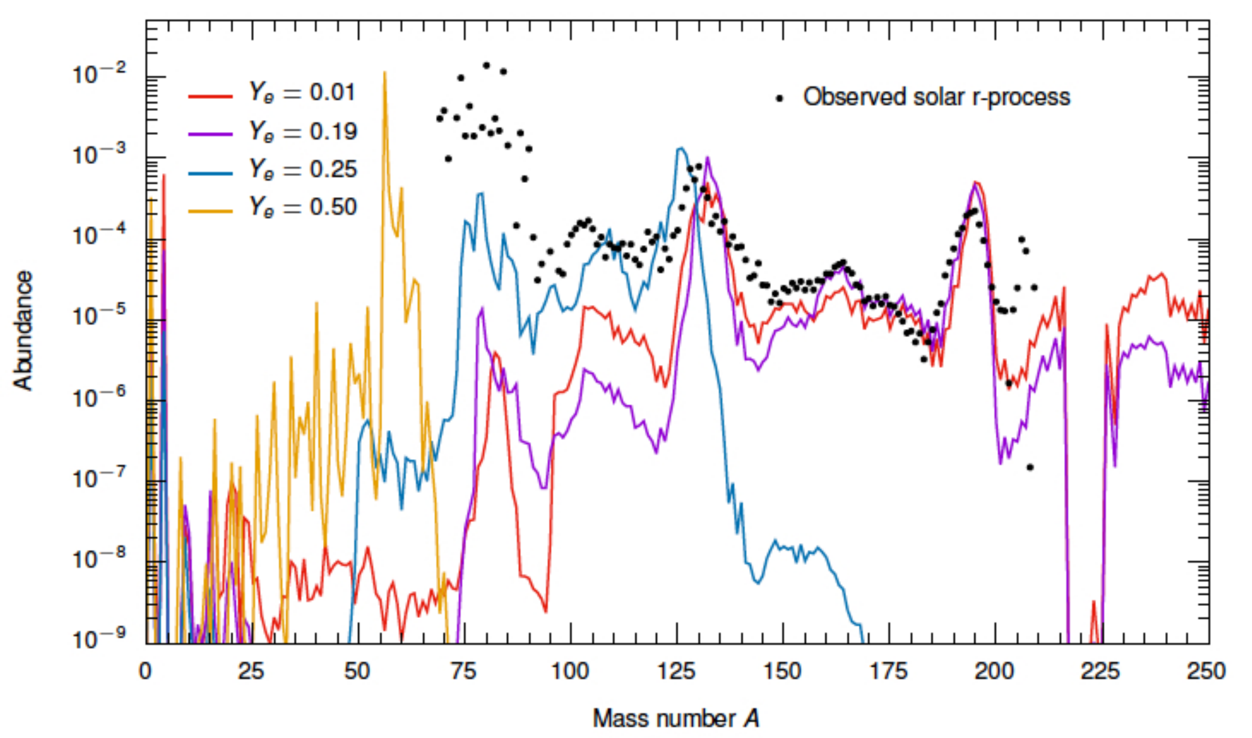
- Neutrinos impact neutron richness of matter :

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

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

sets the neutron-to-proton ratio :

$Y_e = \frac{p}{p+n}$ $Y_n = 1 - Y_e$

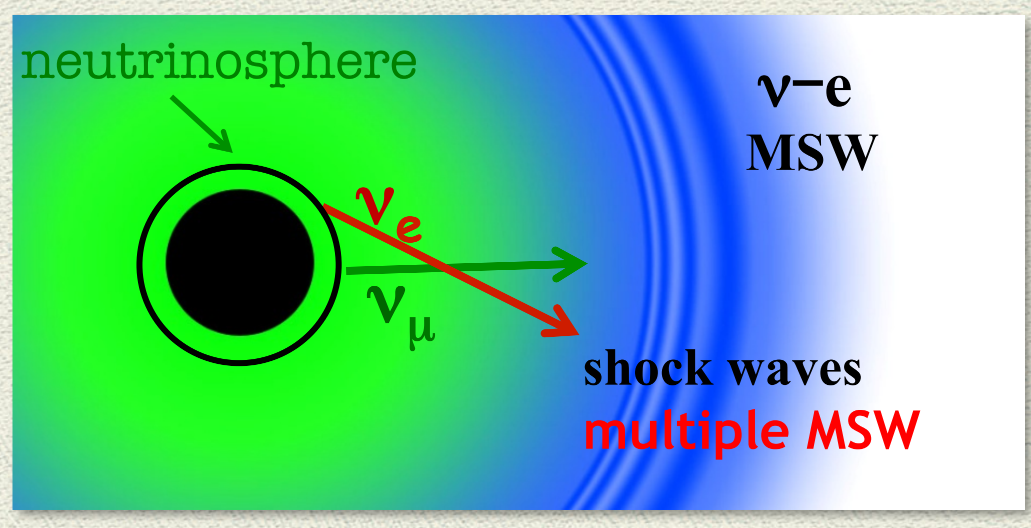


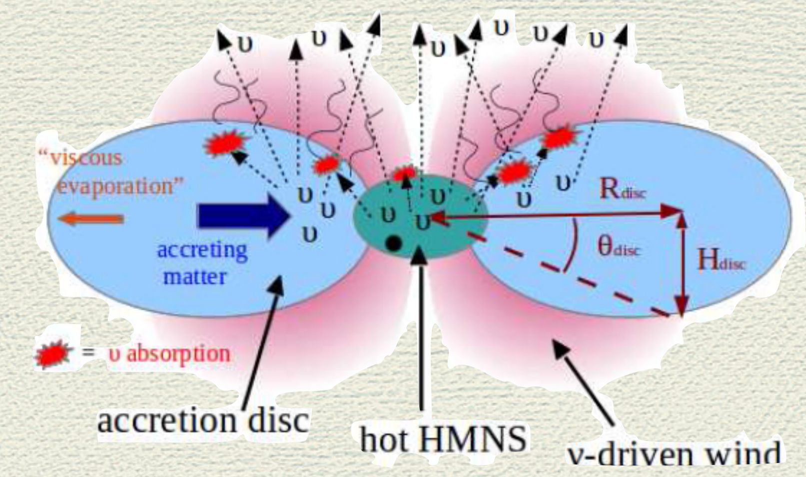
- For Ye = 0.5, no r-process elements.

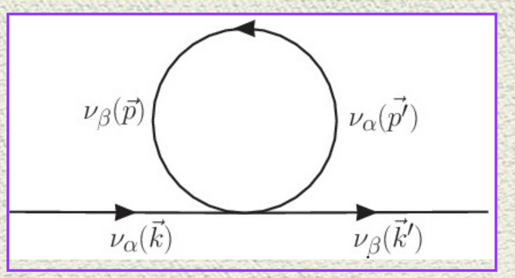
For Ye < 0.25, rare-elements plateau and third element peak (strong r-process).

Neutrino flavor evolution in dense environments modifies neutrino spectra and impacts are r-process nucleosynthesis in neutrino driven winds

Neutrino flavor evolution in dense environments



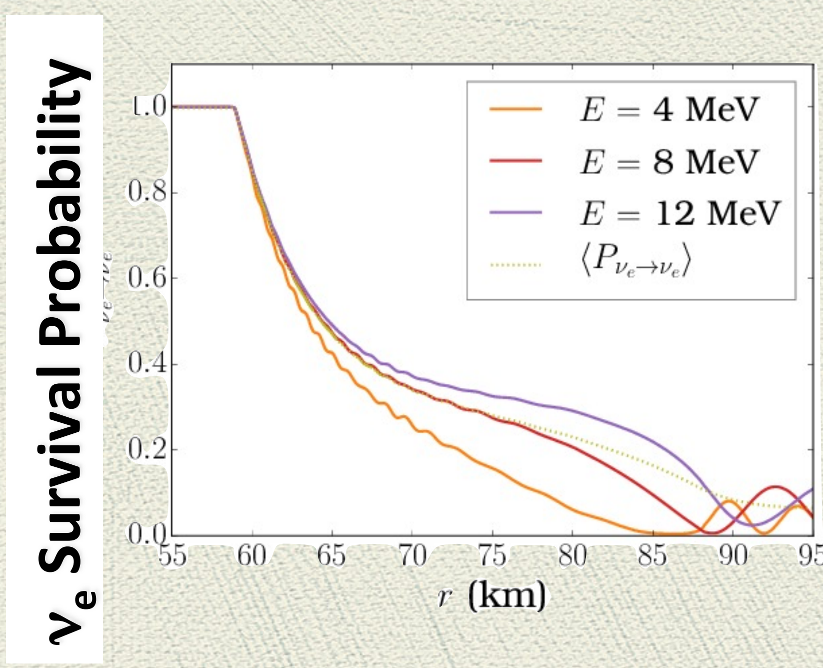




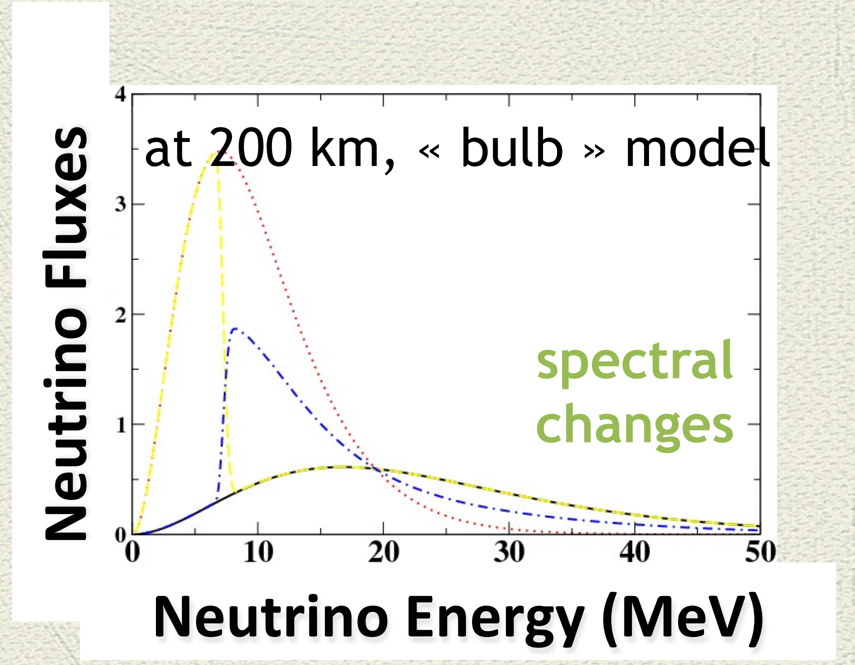
Neutrino
self-interactions
sizeable

Pantaleone, PLB287 (1992)

A weakly many-body system…



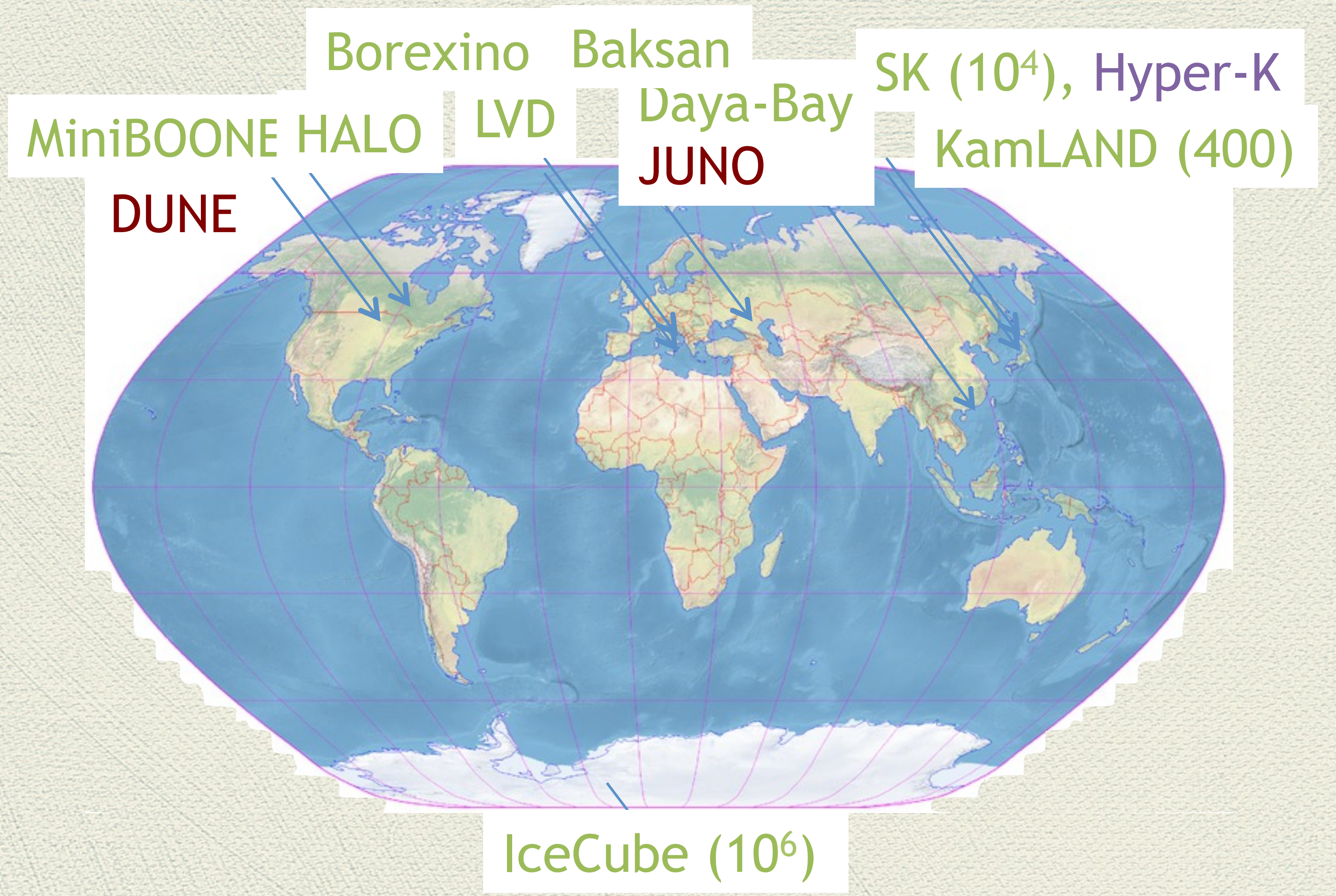
Chatelain, Volpe, PRD 95, 2017



A variety of novel flavor conversion phenomena (MSW-like, multiple MSW and beyond…)

Supernova Early Warning System and SNe observations

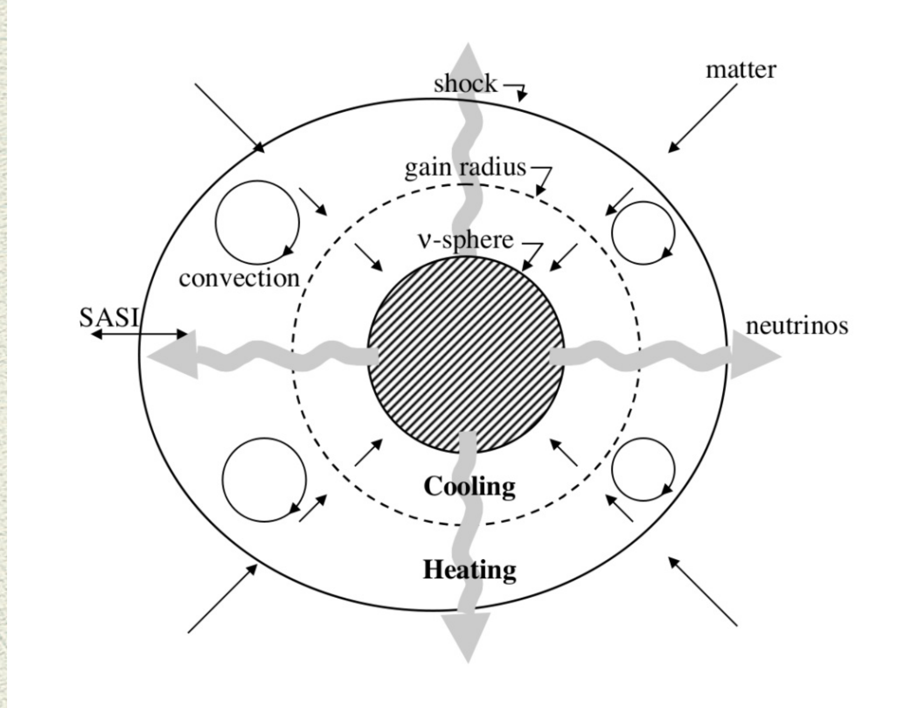
Expected events for a supernova in our galaxy (10 kpc) up to 10^6



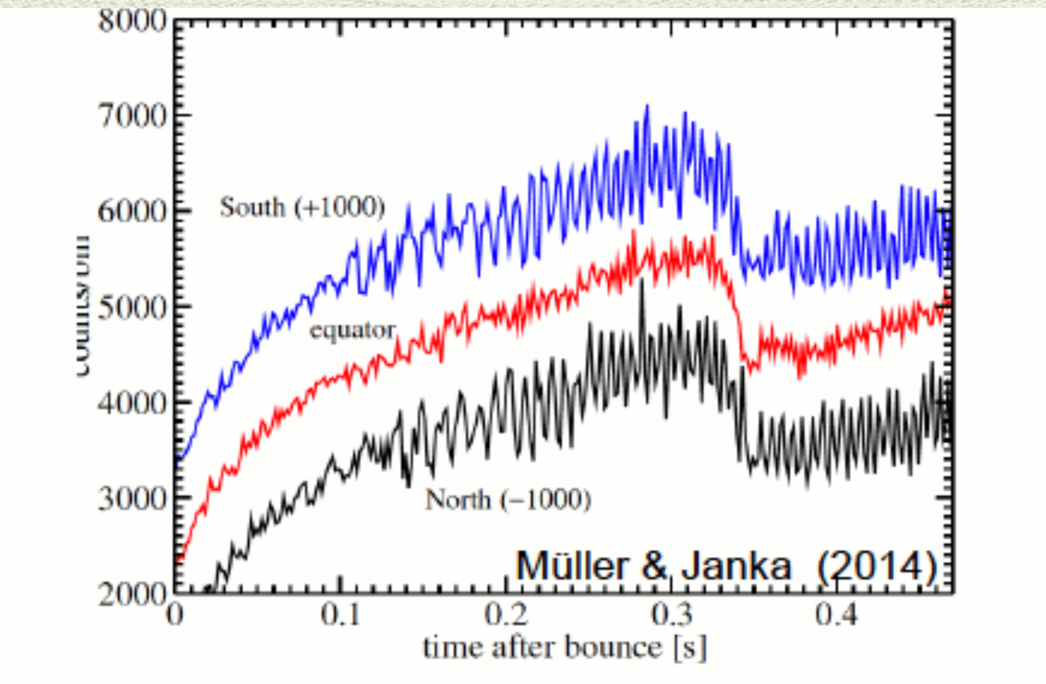
Detection channels : scattering on protons, electrons, nuclei.
Sentivity to all flavors, time and energy signal will be measured.

Explosion mechanism and neutrino signal

- Core-collapse supernova simulations : Three-dimensional simulations running for several progenitors, with realistic neutrino transports, convection and Standing-Accretion-Shock-Instabilities (SASI)



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

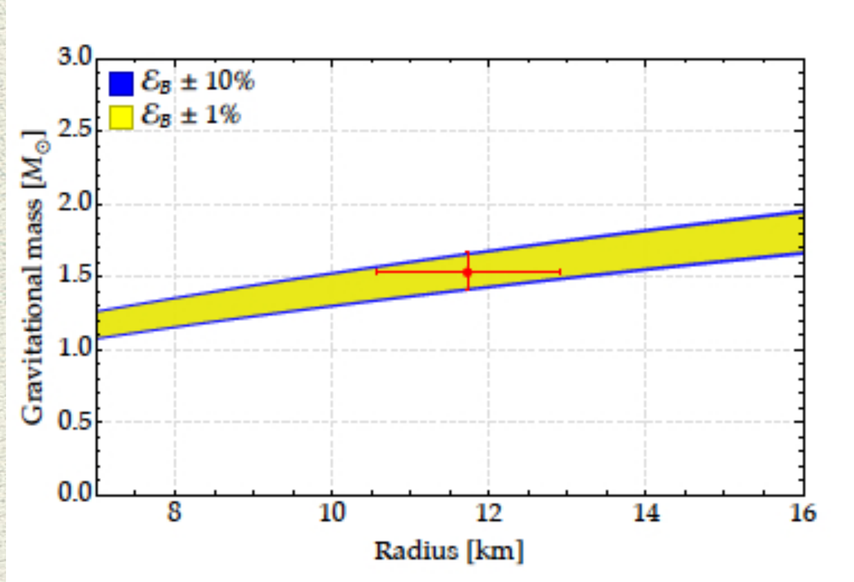


Crucial confirmation of the delayed accretion shock mechanism for supernova explosions

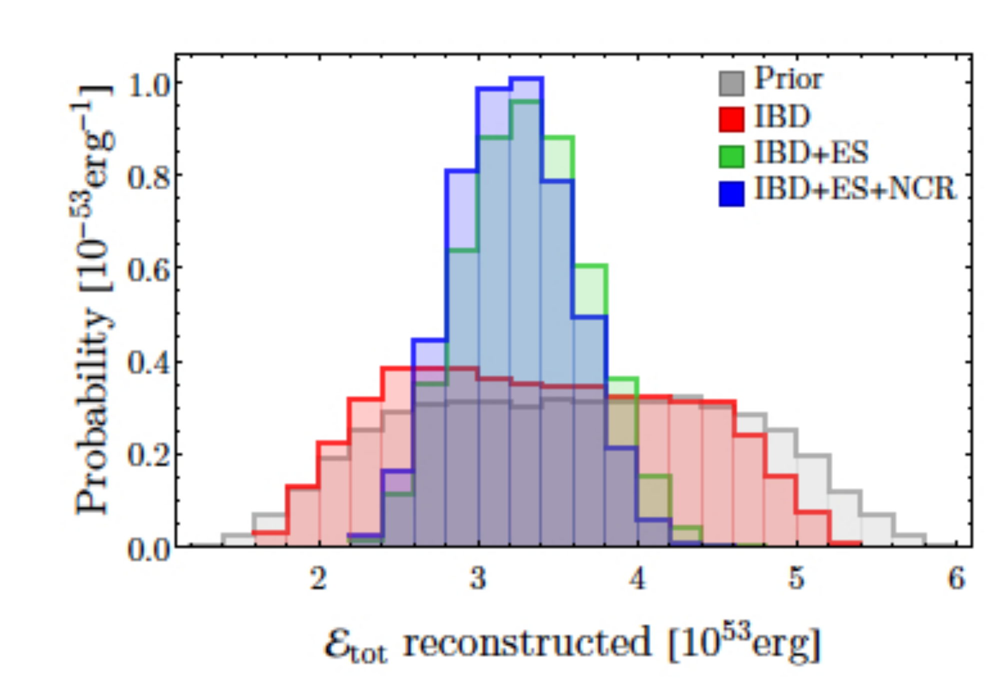
Reconstructing the gravitational binding energy of the neutron star and neutrino spectra

Likelihood analysis for a neutrino signal from a galactic supernova.

- Combining inverse beta-decay, elastic scattering (and neutral current) allows to reconstruct the gravitational binding energy at a few percent accuracy - 11% in Super-Kamiokande, 3% in Hyper-Kamiokande.



(b) Mass–Radius constraint



Gallo Rosso, Vissani, Volpe, JCAP 1711 (2017)

- The spectra of electron anti-neutrinos and muon and tau neutrinos can be reconstructed : 2% and 7% for the average energy and width of electron anti-neutrino spectra.

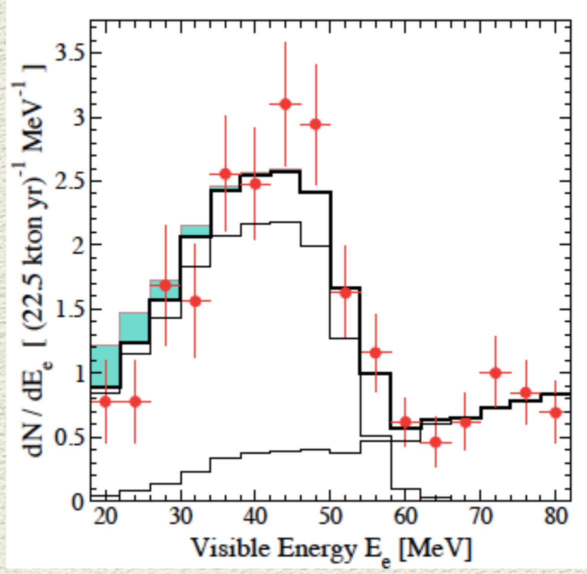
Diffuse Supernova Neutrino Background discovery

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

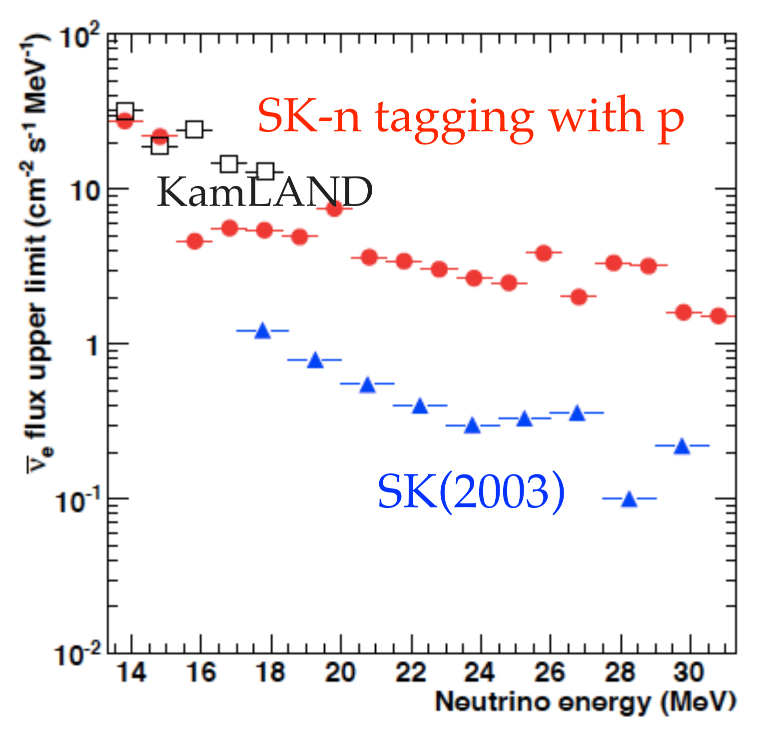
$$F_\alpha(E_\nu) = \int dz \left| \frac{dt}{dz} \right| (1+z) R_{\rm SN}(z) \frac{dN_\alpha(E'_\nu)}{dE'_\nu},$$

$E'_\nu = (1+z)E_\nu,$ neutrino redshifted energy (only the tails of the neutrino spectra matter) $z = 0,1,2$

First SK limit on relic neutrinos (2003) :
some SN rate models excluded,
also incompatible with high average energies



Malek et al, PRL90 (2003)

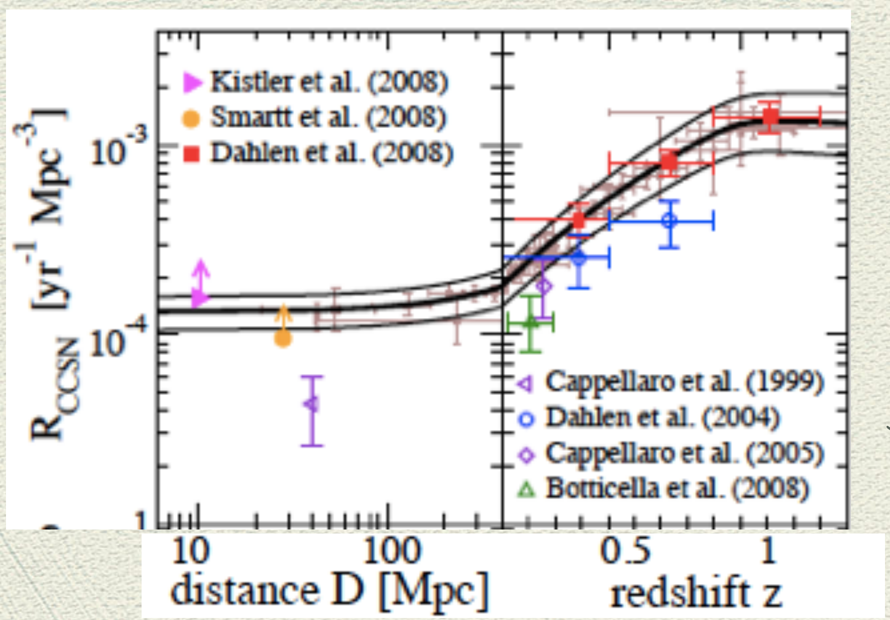


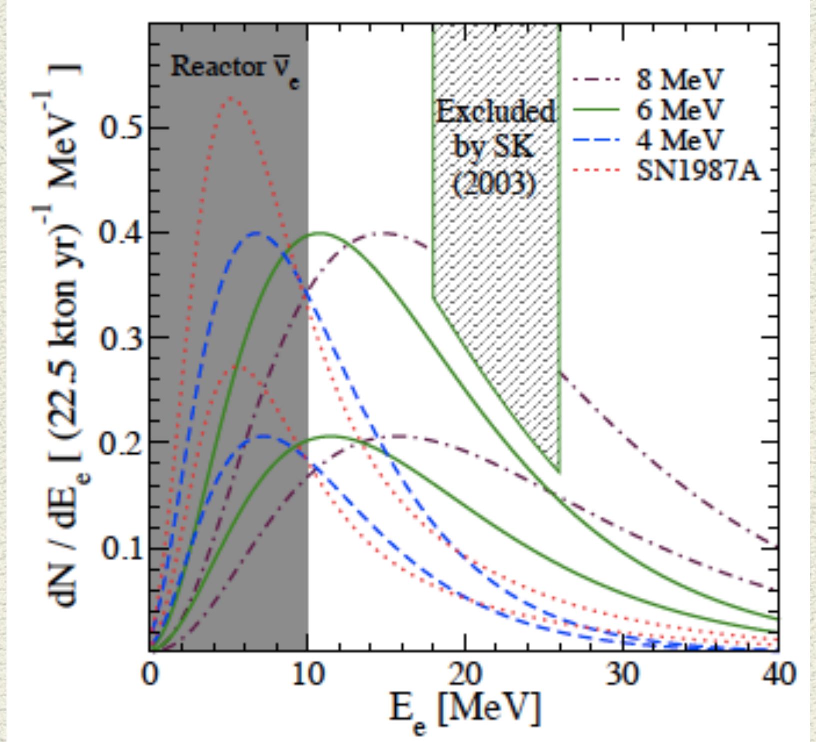
Zhang et al, Astr. Phys. 60 (2015)

Diffuse Supernova Neutrino Background discovery

- The supernova rate well constrained.
  The points below the prediction of the supernova rate from the star formation rate are affected by incompleteness (dust, faint galaxies, ...)

  About 20% uncertainty at z=0.
  A factor of 2 much hight redshifts,
  not relevant for the relic background.





Beacom, Ann. Rev. 60 (2010)

Super-Kamiokande with Gd
- neutron tagging (reduced backgrounds)
  Beacom, Vagins, PRL 93 (2004)

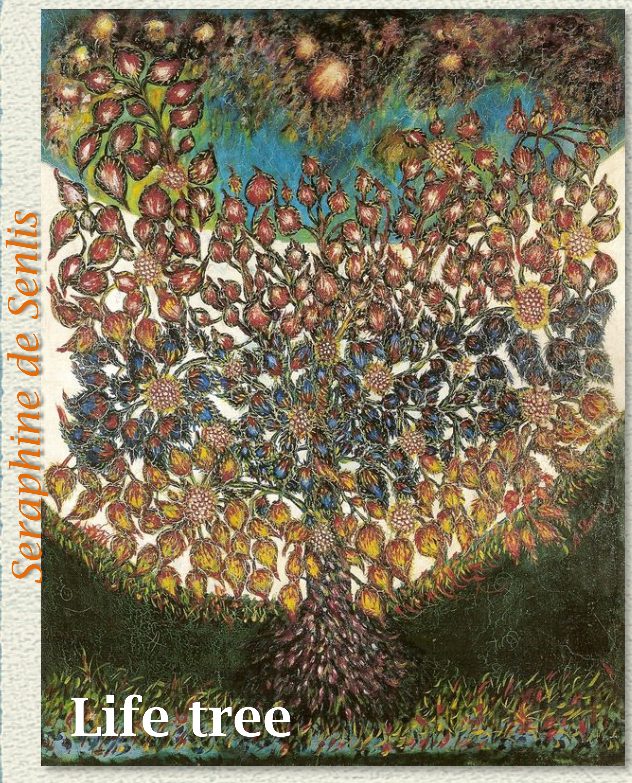
from EGADS to **SuperK-VI+Gd (2019/20)**

Hyper-K (258 ktons) - several hundreds

Crucial measurement of the R_{SN} and the (average) neutrino fluxes

Conclusions et Prospectives

- Important open questions remain and will be addressed in the future : the origin of neutrino masses, the neutrino mass ordering, CP violating phases, the absolute neutrino mass, the neutrino Dirac or Majorana nature.



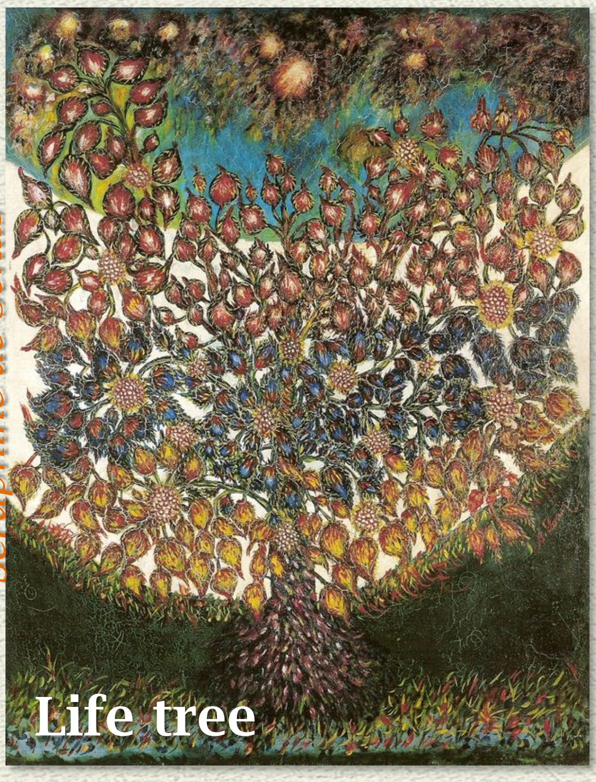
- The future measurement of solar neutrinos from the CNO cycle is needed to solve the abundance problem an.d confirm energy production in massive main sequence stars

- Gravitational waves from BNS and kilonova observations will bring clue information to identify where heavy elements are made. Neutrino flavor evolution impacts nucleosynthetic abundances and might influence the supernova dynamics.

Conclusions et Prospectives

- Future observations of neutrino signals from a galactic supernova will bring crucial information on open issues in astrophysics and on neutrino properties.
  For example, the explosion mechanism from the time signal (ICECUBE).

Seraphine de Senlis



- The neutrino spectra reconstruction for electron, muon and tau (anti)neutrino flavors with
  - Super-K, Hyper-K, JUNO, DUNE .
  Crucial to improve understanding of flavor evolution in dense environments.

- The DSNB discovery by Super-Kamiokande + Gd !!!!