Neutrino astrophysics :
recent advances and open issues

Cristina VOLPE
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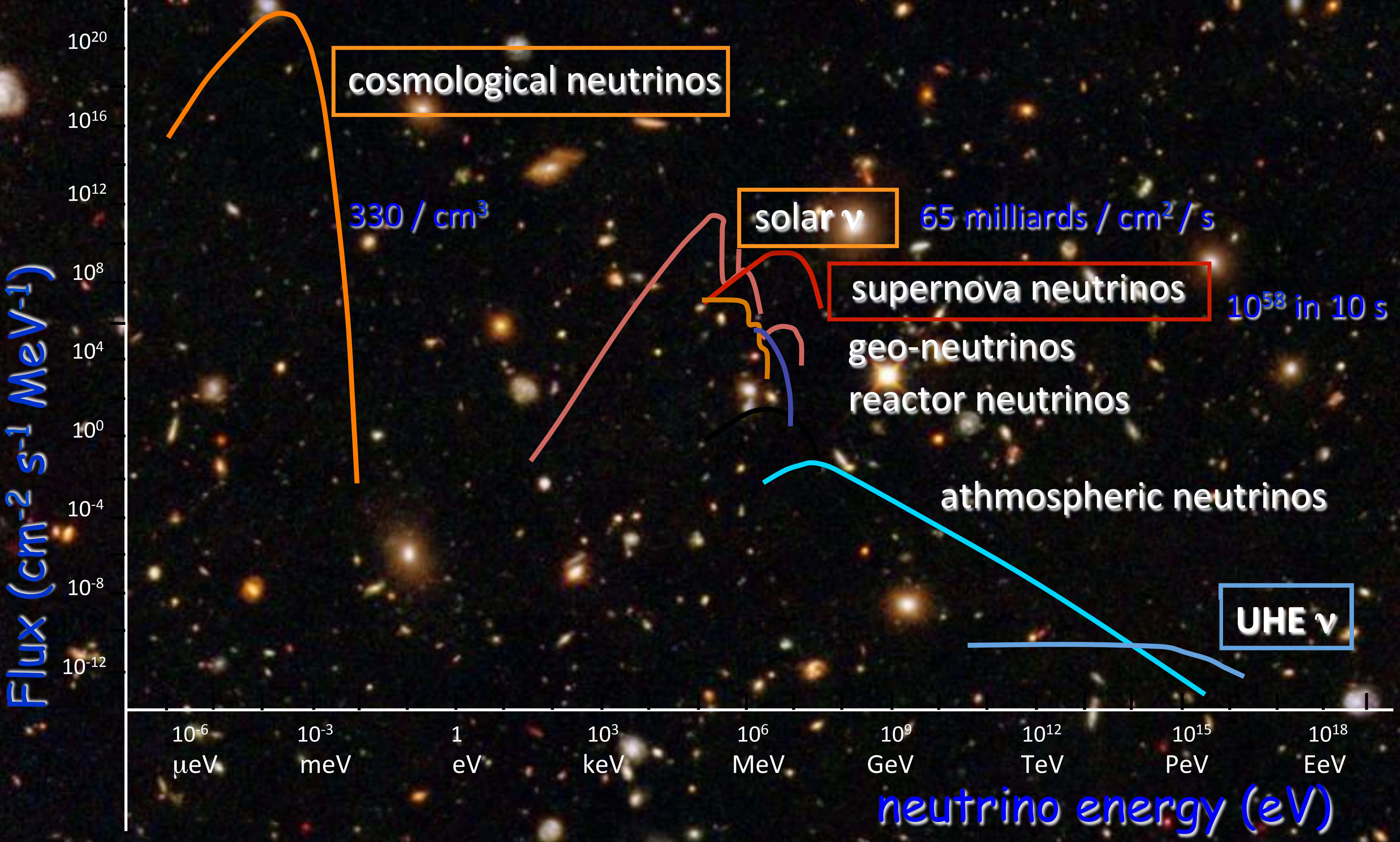
Neutrinos in Nature



Two neutrino backgrounds still to be observed :
from Early Universe and supernovae

Detecting cosmological neutrinos

Using radioactive nuclei ?

A process without threshold.

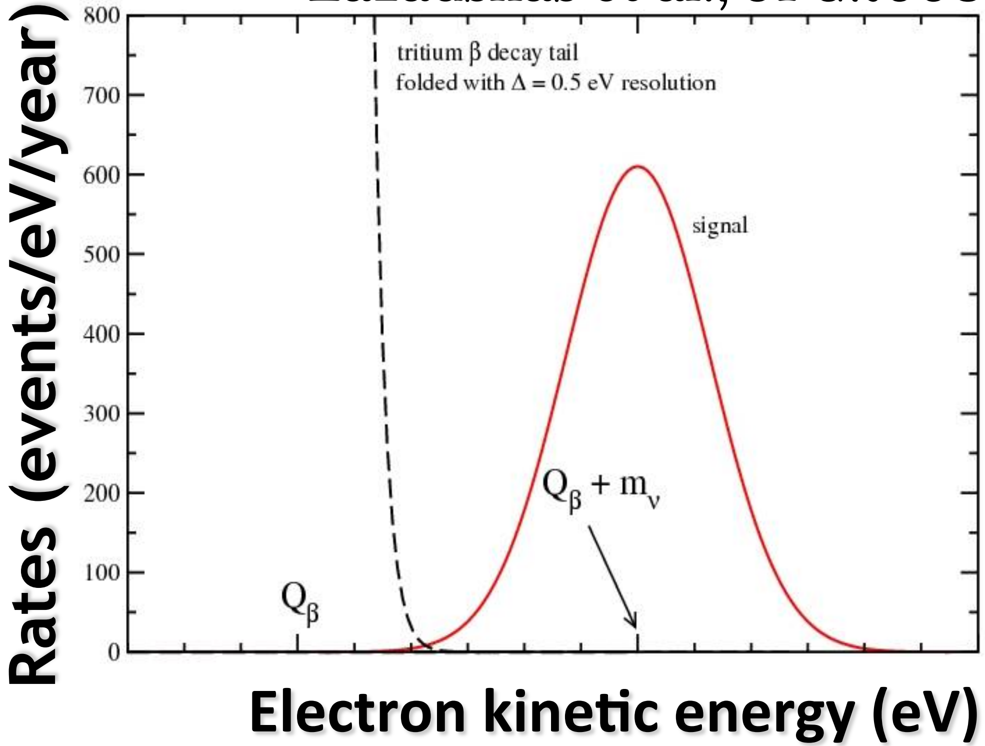
Weinberg, Phys. Rev. 1962

Today at least one neutrino is non-relativistic.

100 grams of tritium gives about 10 events/year.

Cocco et al., JCAP 2007

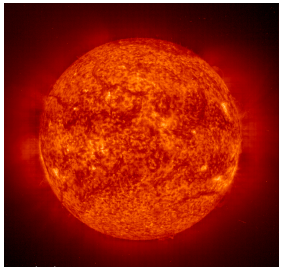
Lazauskas et al., JPG2008



PTOLEMY prototype :
Princeton Tritium Observatory
forLight, Early-Universe, Massive
Neutrino Yield, arXiv: 1307.4738.

remains a challenge !

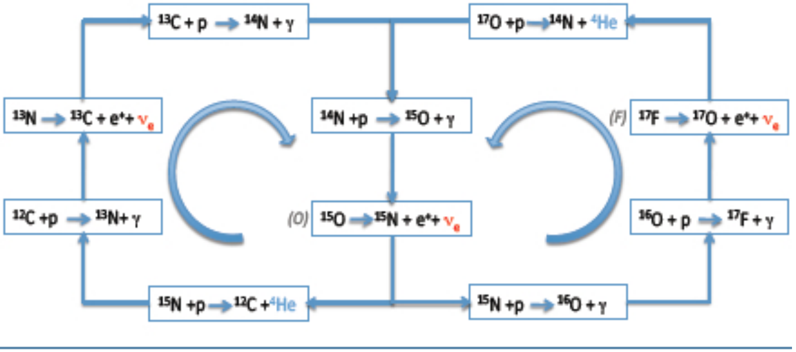
Solar neutrinos

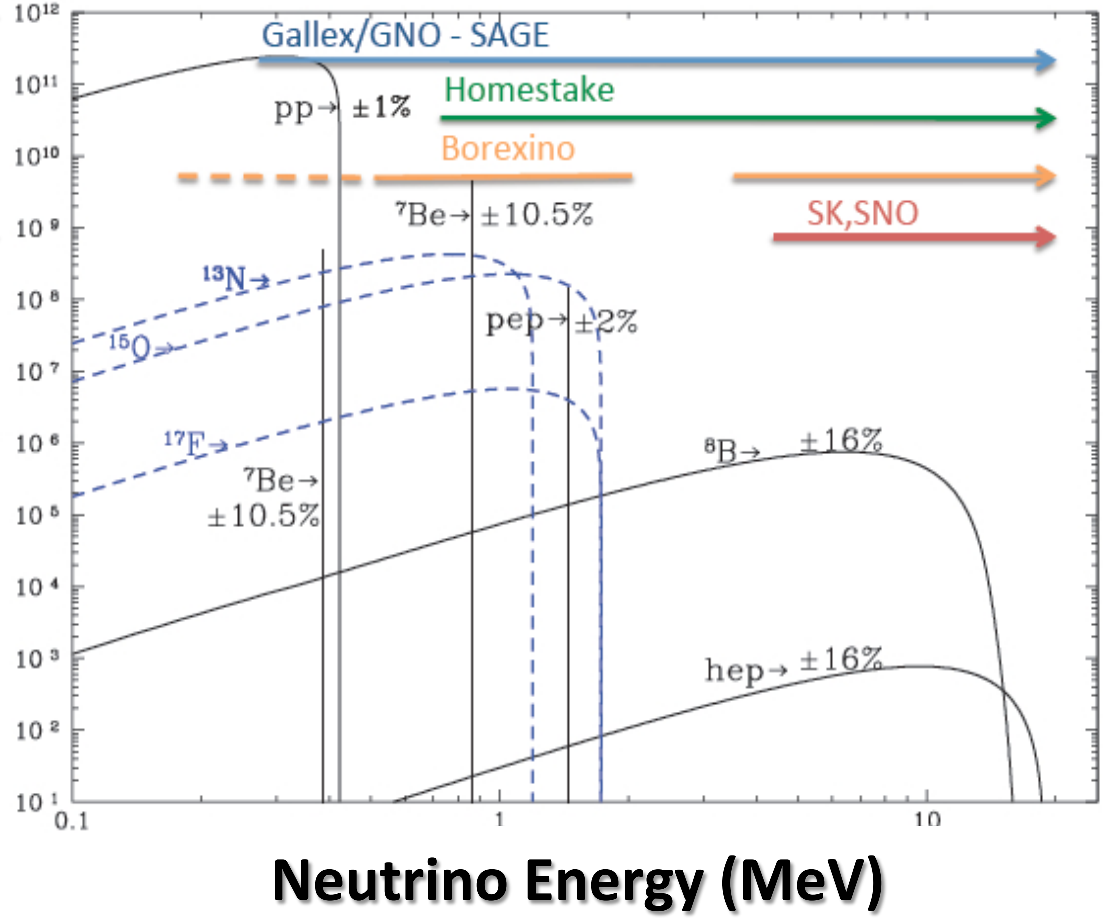


The proton-proton fusion reaction chain produces 99% of solar energy transforming H into ^{4}He.

Bethe, Phys. Rev. 1939

The CNO cycle, 1%, important for advanced evolutionary stages.



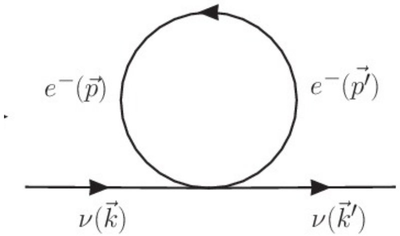


Solar neutrinos

They undergo averaged vacuum oscillations and the Mikheev-Smirnov-Wolfenstein effect.

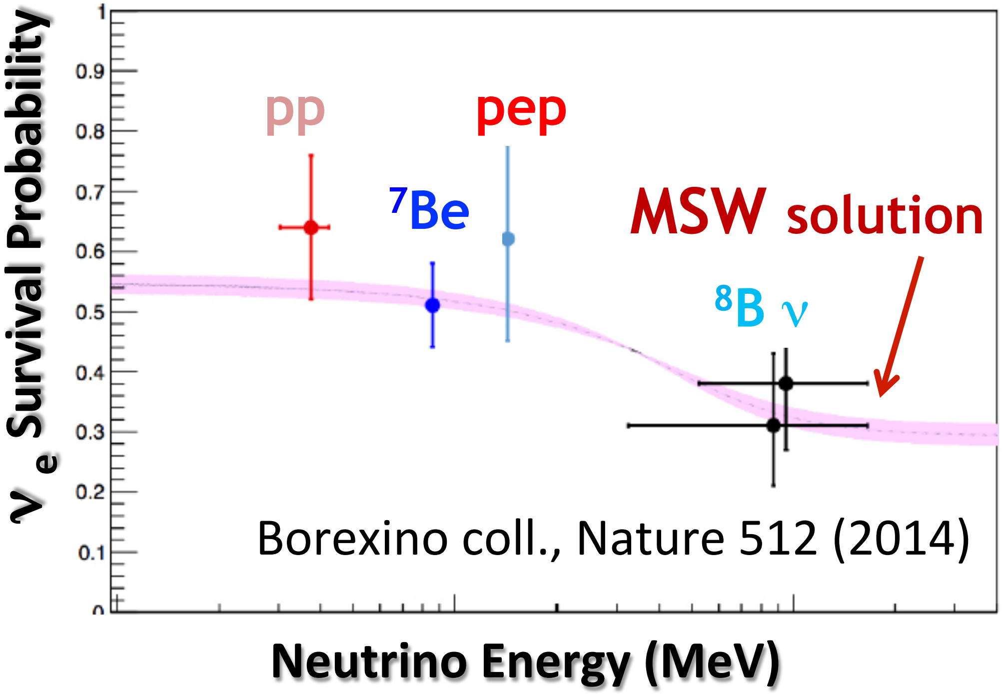
MSW effect : resonant flavour conversion due to ν-matter interaction

Wolfenstein PRD (1978)
Mikheev, Smirnov(1985)



mean-field

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



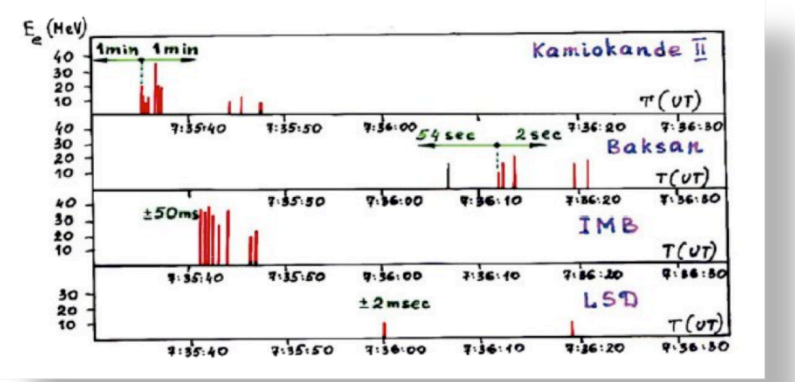
Borexino coll., Nature 512 (2014)

The transition might hide new physics.

pp neutrinos - keystone fusion reaction - measured

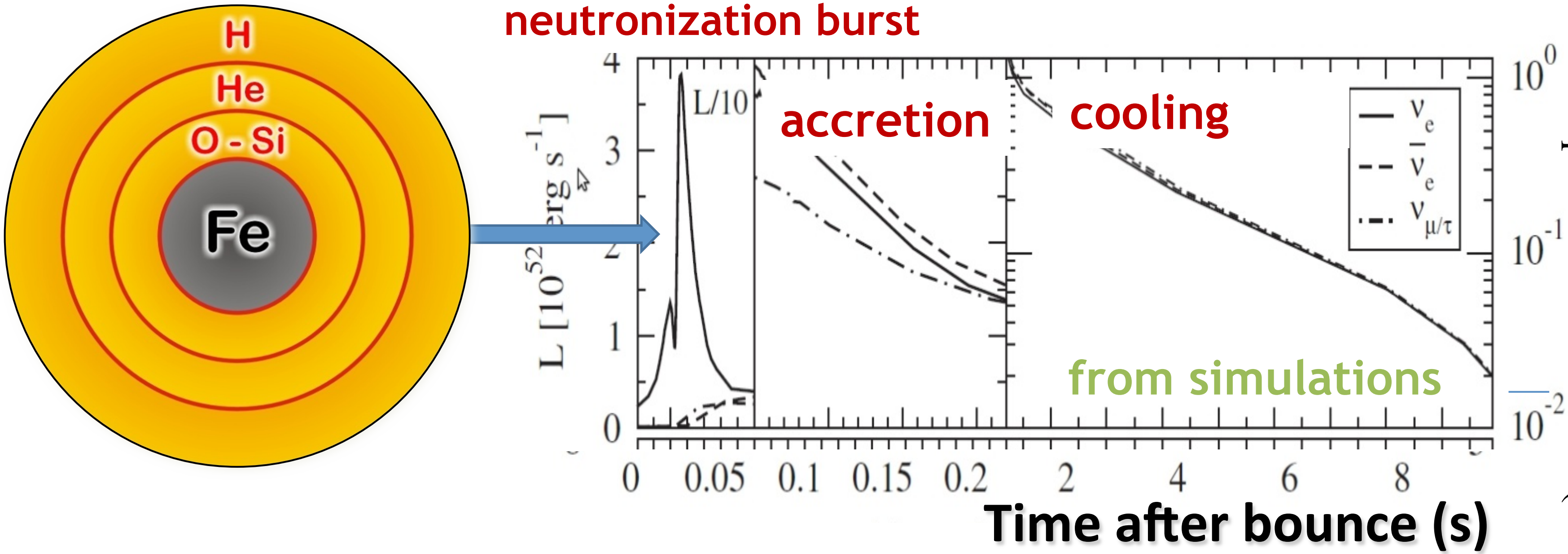
Supernova neutrinos

10^{57} ν of about 10 MeV in 10 s from the gravitational collapse of massive stars ($M > 8\,M_{sun}$).



Suzuki, J. of Phys. conf. (2008)
Vissani, JPG (2014)

SN1987A events



Hüdepohl *et al.* PRL 104 (2010)

sensitive probe of the supernova dynamics

Supernova neutrinos

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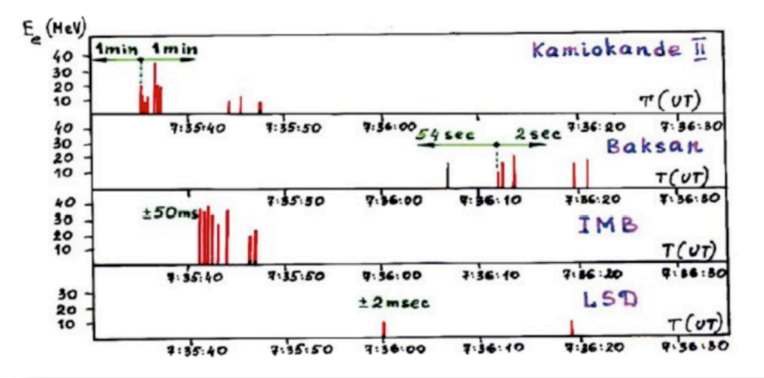
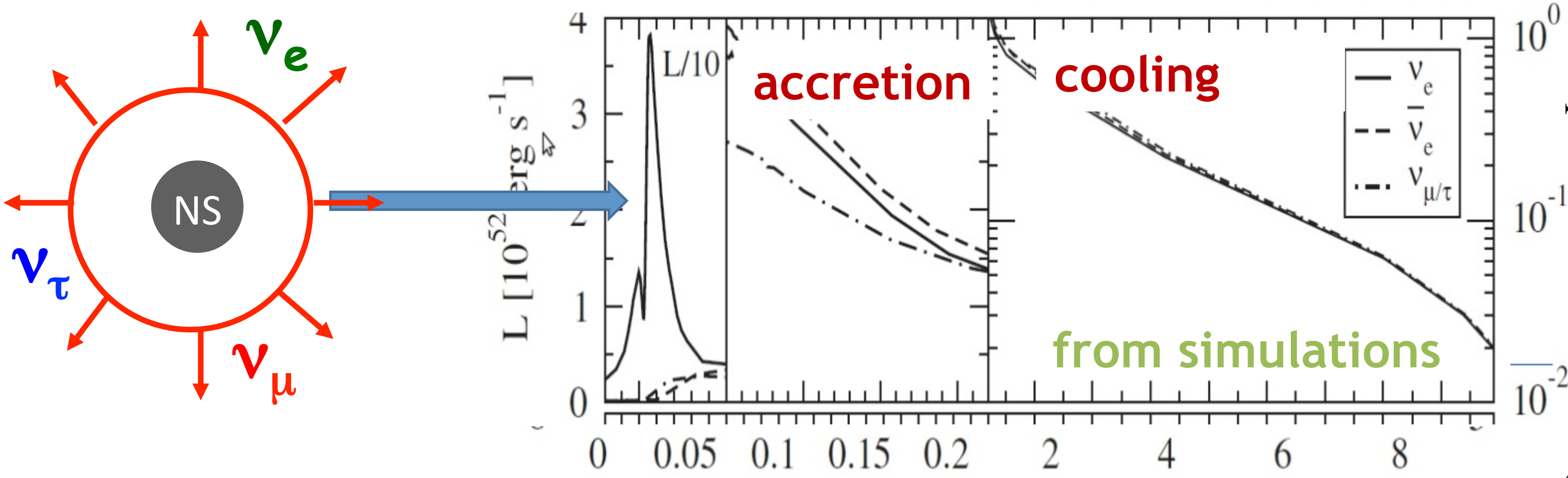


Suzuki, J. of Phys. conf. (2008)
Vissani, JPG (2014)

SN1987A events

neutronization burst



Time after bounce (s)

Hüdepohl *et al.* PRL 104 (2010)

sensitive probe of the supernova dynamics

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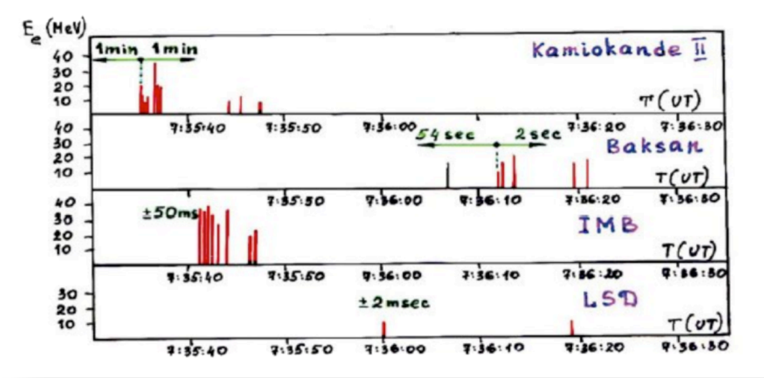

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Vissani, JPG (2014)

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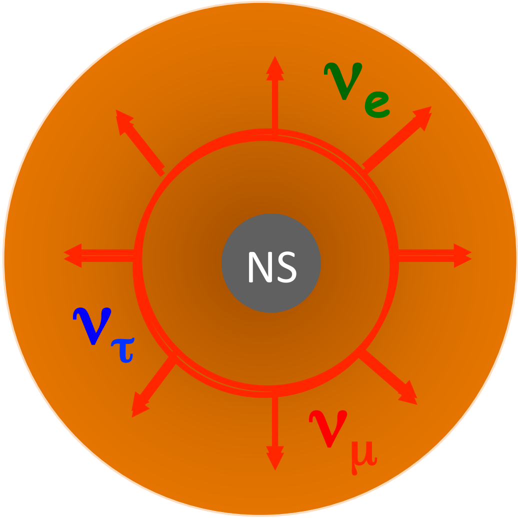
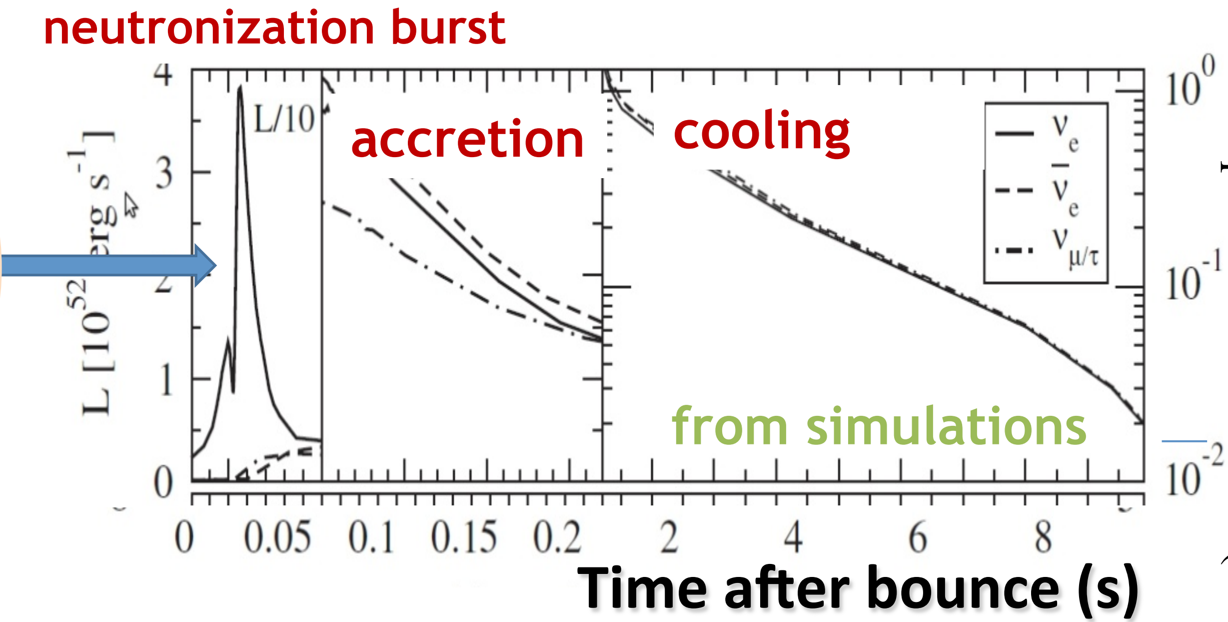




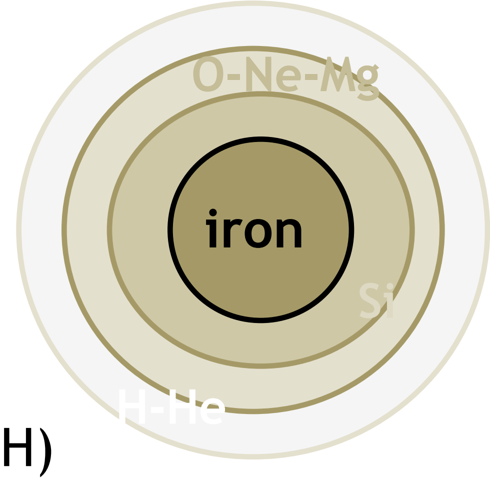
Hüdepohl *et al.* PRL 104 (2010)

sensitive probe of the supernova dynamics

Core-collapse supernovae

They comprise :

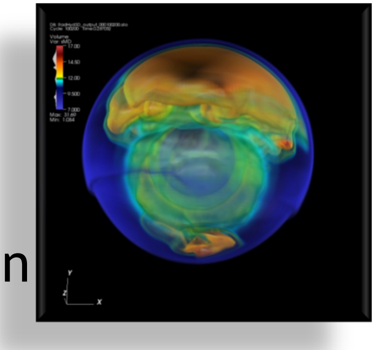
- ☐ **O-Ne-Mg supernovae**
- ☐ **Iron core-collapse supernovae**
- ☐ **Very massive**
  -> accretion-disk black hole (AD-BH)



Supernova neutrinos tightly linked to key astrophysics issues :

- How do massive stars explode ?
- What is the site where heavy elements are made ?

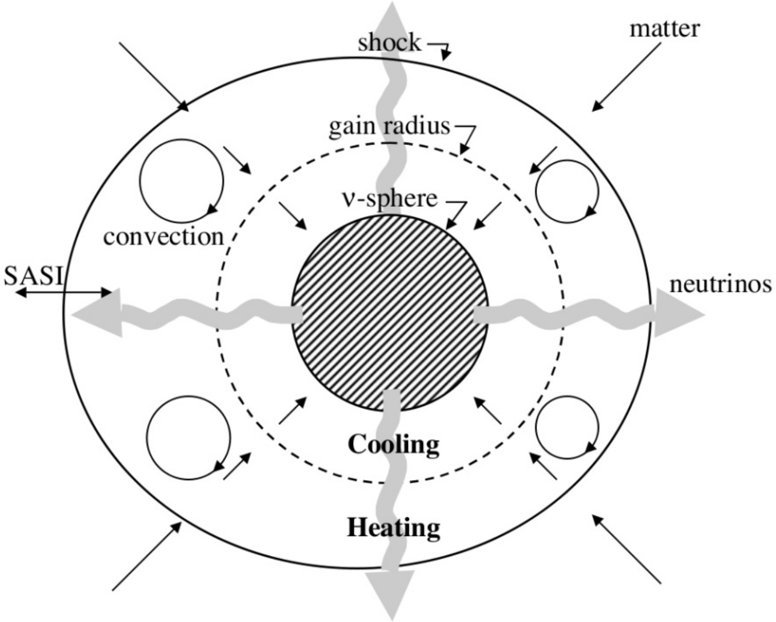
Explosion mechanism and ν



Current supernova simulations :

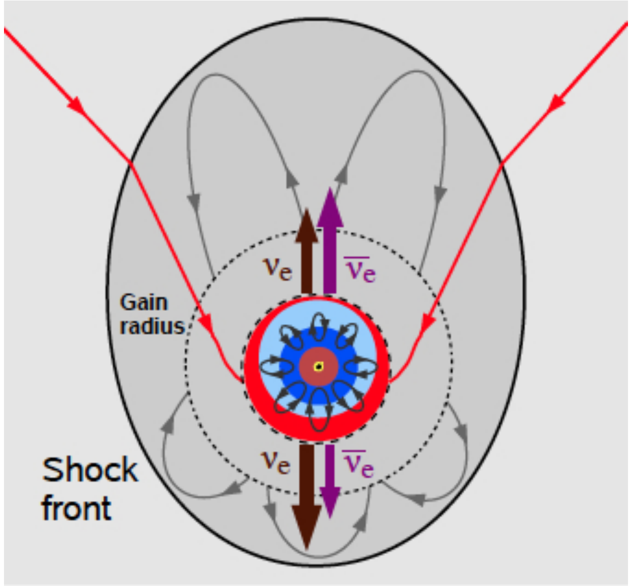
multidimensional, realistic neutrino transport, convection and turbulence, hydrodynamical instabilities (SASI).

Neutrinos play a role in revitalizing the shock.



first 3D appearing : is there any missing physics ?

Hanke et al, 1303.6269



LESA – Lepton Number Emission Self-sunstained Asymmetry

Tamborra et al, 1402.5418

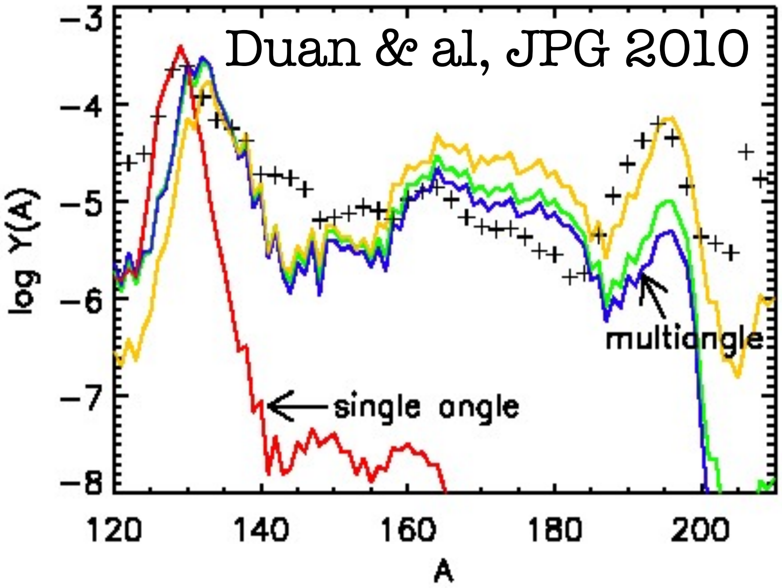
Supernova ν observations

- ❑ **Time and energy signal** from a supernova explosion. In our galaxy, 1-3 events/century; one explosion/3years at 3 Mpc.

- ❑ **The Diffuse Supernova Neutrino Background**

	Events (10 y)	window	detector	
$\bar{\nu}_e$	90 (IH/NH)	9-25 MeV	50 kton	scintillator
$\bar{\nu}_e$	300	19-30 MeV	440 kton	water Cherenkov
ν_e	30	17-41 MeV	50 kton	liquid argon

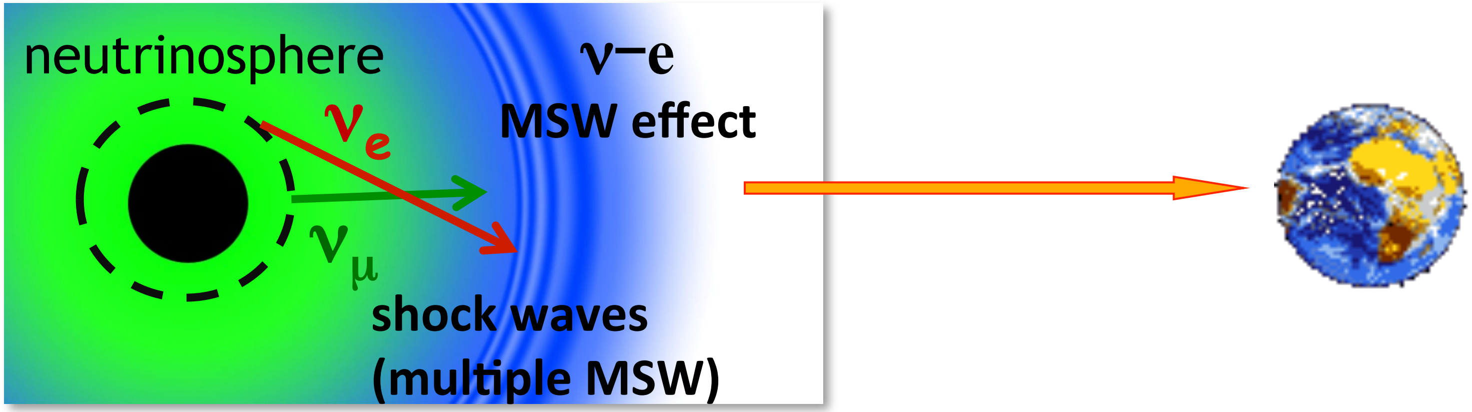
Galais, Kneller, Volpe, Gava, PRD 81(2010)


Duan & al, JPG 2010

- ❑ **Element nucleosynthesis**
  - r-process, νp-process, ν-nucleosynthesis

Focus Issue «*Neutrinos and Nucleosynthesis* », JP.G (2014)

ν flavour modification in supernovae



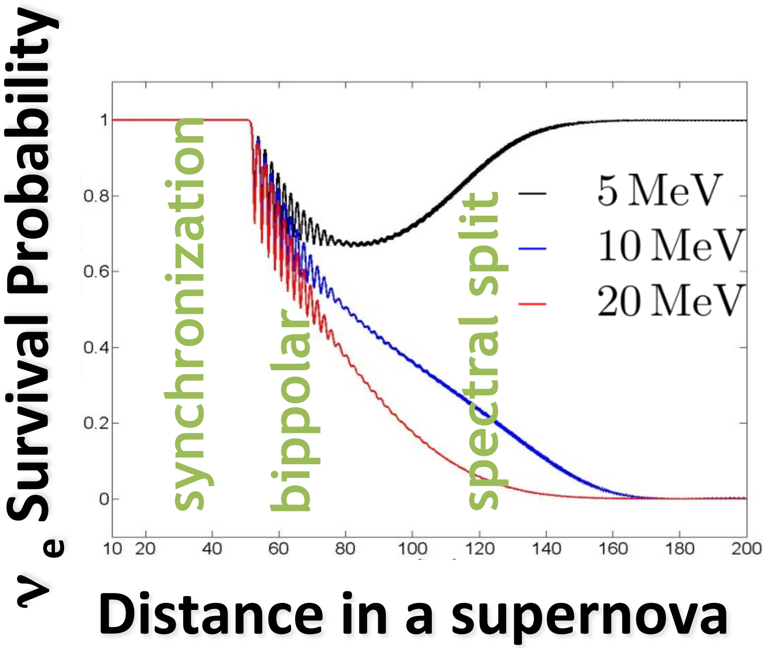
Flavour conversion due to

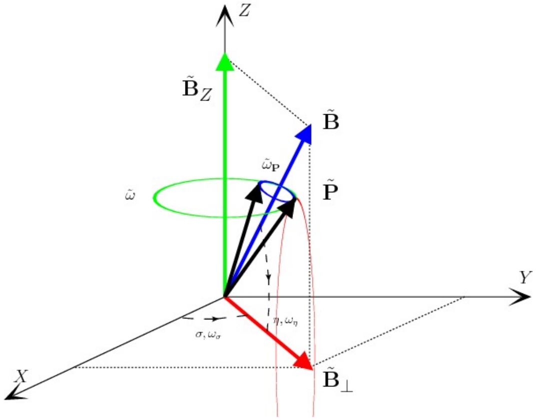
- ☐ the ν interaction with matter – MSW effect – and with ν.
- ☐ dynamical aspects - shock waves and turbulence.

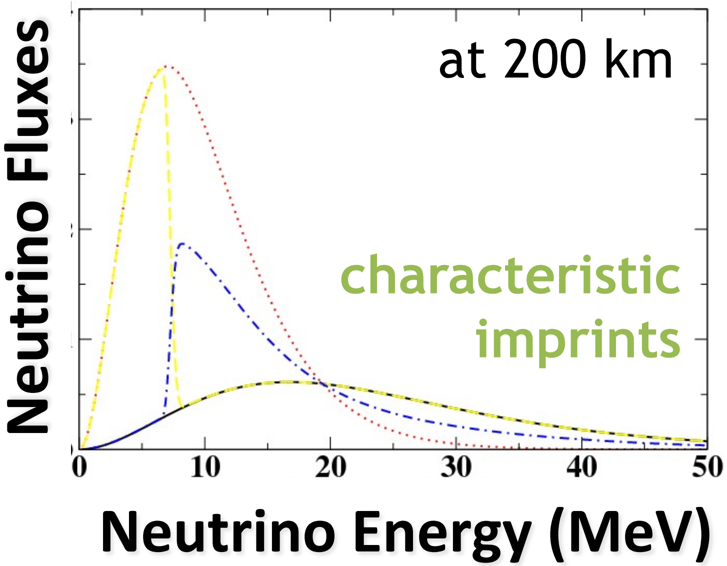
Novel phenomena discovered

The $\nu\nu$ interaction produces

Pantaleone, PLB 287 (1992)





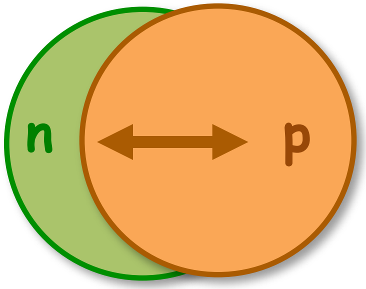


see e.g. Duan, Fuller, Qian, Ann. Rev. Nucl. Part. Sci. 60 (2010)

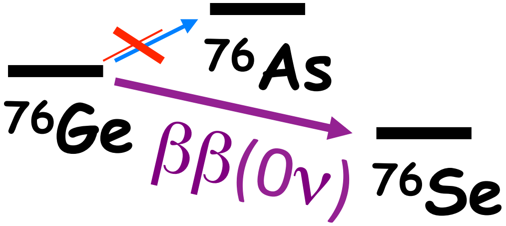
collective stable and unstable ν modes in flavor space

The connection with other systems

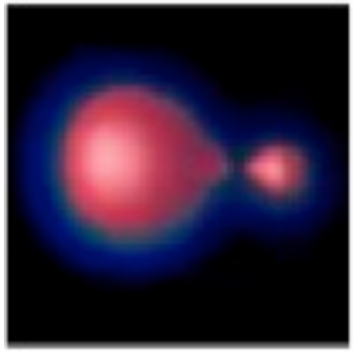
Exploring the link between ν flavour conversion in media and other many-body systems such as



giant resonances



double-beta decay



nuclear collision

phonons

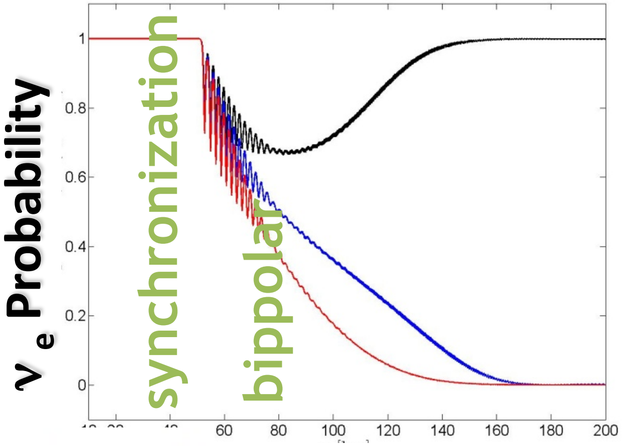
metallic clusters

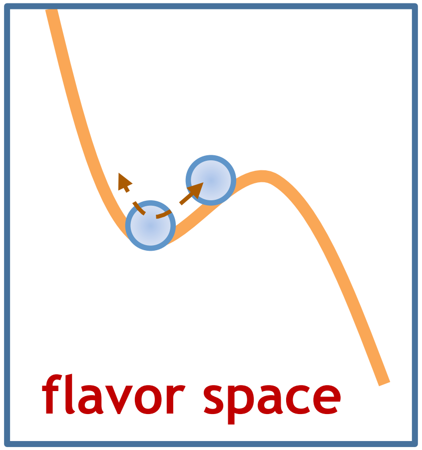
condensed matter

Collective ν modes and vibrations

Väänänen, Volpe, PRD88 (2013), arXiv: 1306.6372

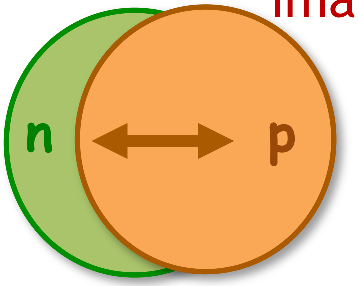
A linearized description from many-body approaches establishes the formal link to e.g. atomic nuclei



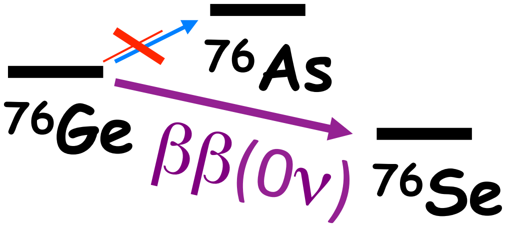


$$\boxed{\begin{pmatrix} A & B \\ \bar{B} & \bar{A} \end{pmatrix}} \begin{pmatrix} \rho' \\ \bar{\rho}' \end{pmatrix} = \omega \begin{pmatrix} \rho' \\ \bar{\rho}' \end{pmatrix}$$

STABILITY MATRIX : if eigenvalues real or imaginary, stable or unstable modes

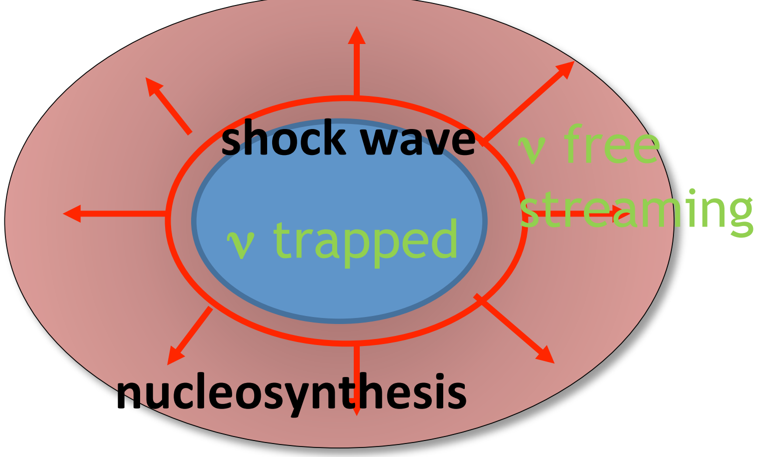


giant resonances



double-beta decay

key questions



Further work needed to finally assess :

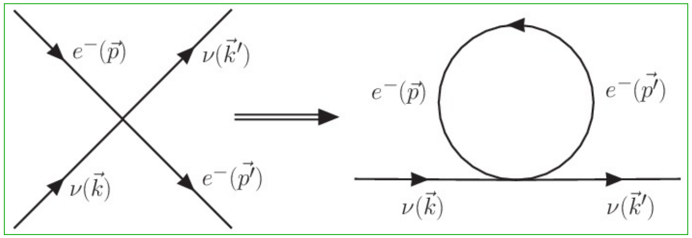
- ☐ impact on the shock wave
  Dasgupta, o'Connor, Ott, PRD 85 (2012)

- ☐ impact on (heavy elements) stellar nucleosynthesis,
  Balantekin and Yuksel, New J. Phys. 7, 51 (2005)
  Duan, Friedland, McLaughlin, Surman, JPG 38 (2011)

- ☐ role of decoherence (by matter, wave-packet treatment,…)
  Esteban-Pretel et al, 2007
  Akhmedov, Kopp, Lindner, 2014

is mean-field sufficient ?

The neutrino evolution equations are based on the mean-field due to matter background (MSW effect) and ν backgrounds.



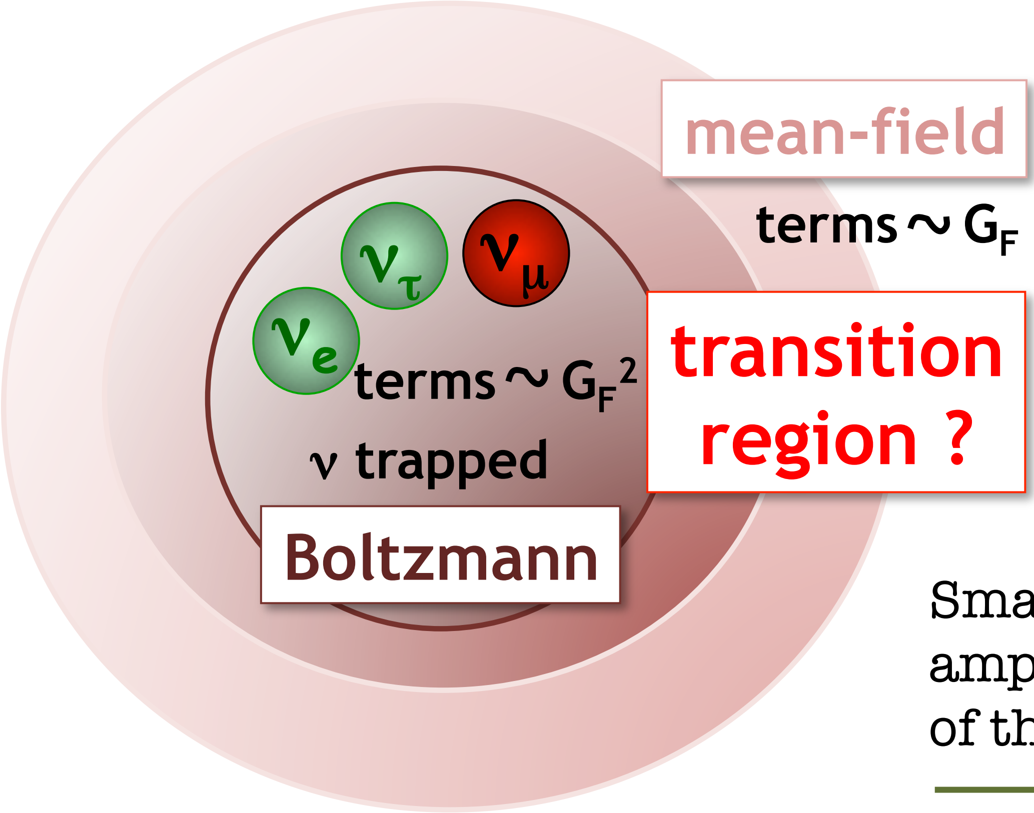
$$\rho_1 = \langle \psi(t)|a_1^\dagger a_1|\psi(t)\rangle$$

one-body density

$$i\dot{\rho}_1 = [h_1(\rho), \rho_1]$$

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

ex. electron mean-field



ν_τ ν_μ ν_e

mean-field

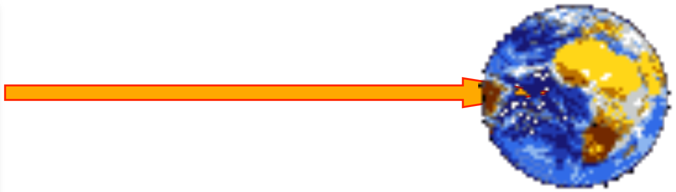
terms ~ G_F

terms ~ G_F^2

ν trapped

Boltzmann

transition region ?



Small contributions can be amplified by the non-linearity of the equations.

Extended mean-field description

The role of (two-body) correlations is under investigation :

- collisions

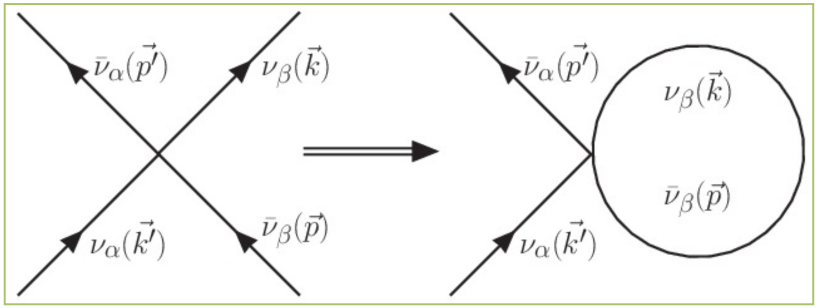
Cherry et al., PRL108 (2012) (toy model)

- wrong helicity contributions due to the ν mass – spin or helicity coherence, suppressed by m/Eν.

Volpe, Väänänen, Espinoza, PRD 87 (2013)
Vlasenko, Fuller, Cirigliano, PRD89 (2014)

- neutrino-antineutrino pairing correlations

Volpe, Väänänen, Espinoza, PRD 87 (2013)



$$\kappa_{ik} \equiv \langle b_k a_j \rangle$$

pairing density

Extended mean-field description

Volpe, Väänänen, Espinoza, PRD 87 (2013)

In presence of pairing correlations the ν equations can be cast as

$$\mathcal{R} = \begin{pmatrix} \rho & \kappa \\ \kappa^\dagger & 1-\bar{\rho}^* \end{pmatrix}$$

generalised density

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

$$\mathcal{H} = \begin{pmatrix} h & \Delta \\ \Delta^\dagger & -\bar{h}^* \end{pmatrix}$$

generalised Hamiltonian

Most general mean-field equations, including both contributions. Both type of correlations need anysotropic backgrounds and introduce neutrino-antineutrino mixing.

Serreau, Volpe, arXiv: 1409.3591.

the role of neutrino-antineutrino correlations?
... and of the wrong helicity contributions?

Numerical investigations necessary.

interplay with unknown properties

Neutrino properties leave an imprint on supernova neutrino fluxes and and on nucleosynthesis processes. Among the key unknown properties :

❑ CP violation

Balantekin, Gava, Volpe, PLB662, (2008).

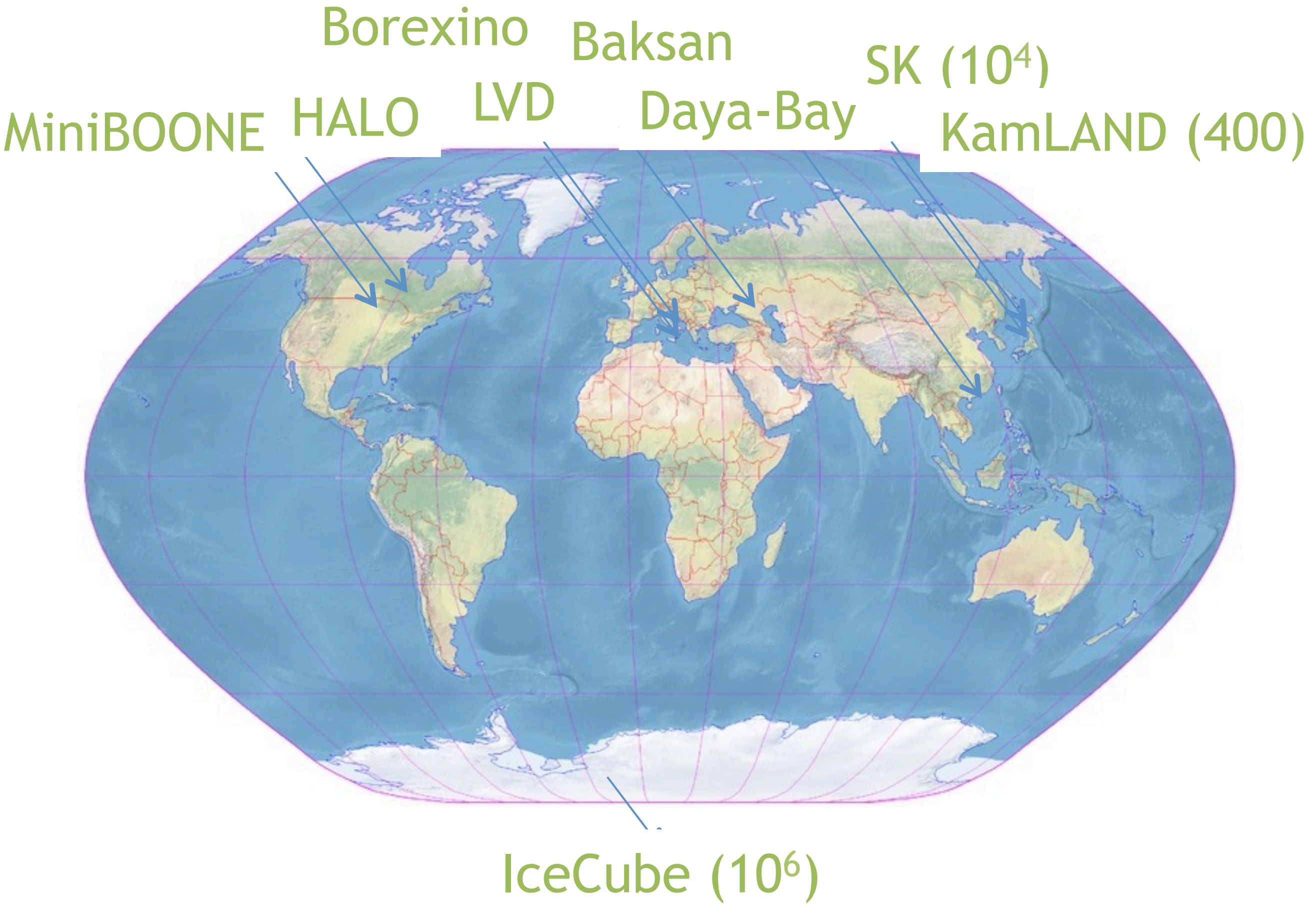
❑ non-standard interactions
❑ sterile neutrinos

❑ the mass ordering

through earth matter effects with atmospheric ν (PINGU, ORCA)
or the early time supernova signal,

or the full time and energy signal of the explosion.

Current SN observatories

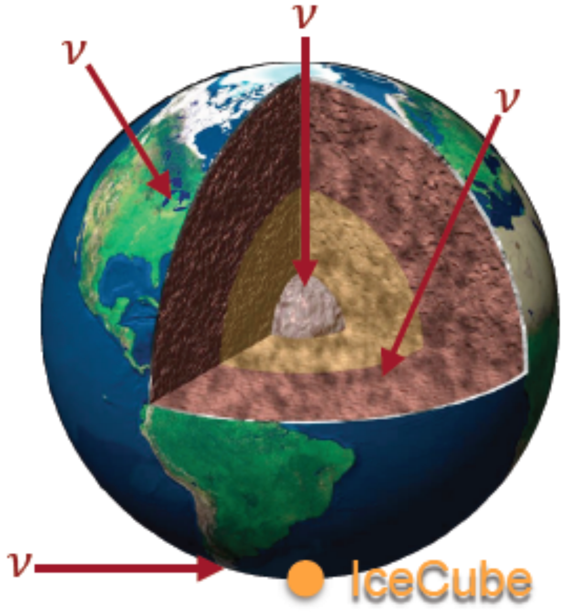


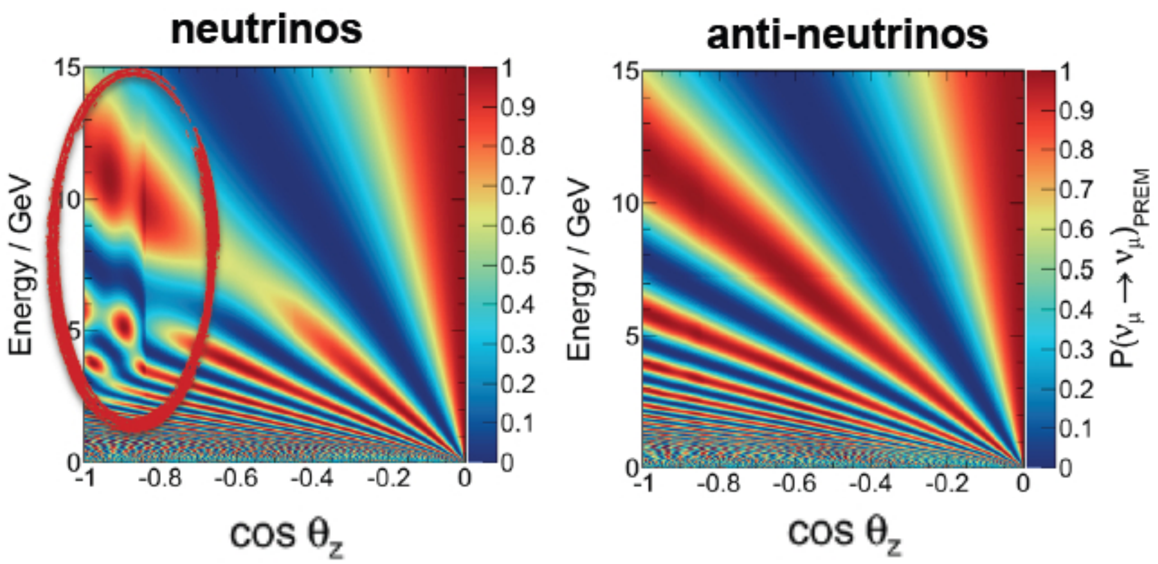
Different detection channels available :
scattering of anti-ν_e with p, ν_e with nuclei, ν_x with *e*, *p*

Large scale detectors coming -- JUNO, Hyper-K,…

Mass ordering from atmospheric ν

Earth matter effects on the atmospheric neutrino can be used to determine the neutrino mass ordering – PINGU, ORCA



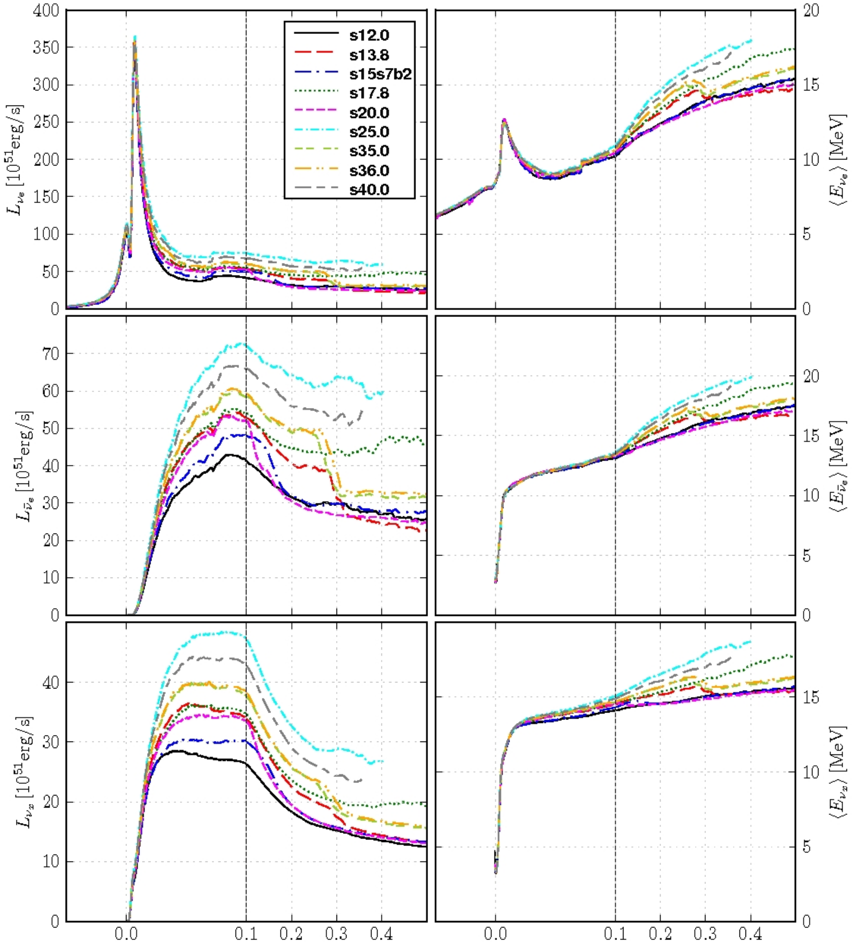


The ν mass ordering at 3 σ in 3 years

ICECUBE coll., arXiv : 1401.2046

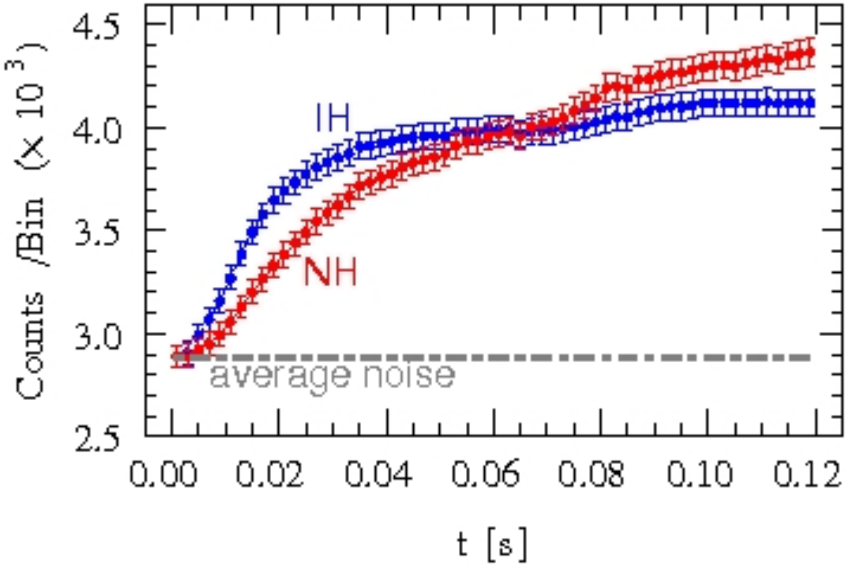
From the early time supernova signal

SN ν fluxes at accretion phase



Serpico, et al. PRD 85 (2012).

Predictions for the time rise in Icecube

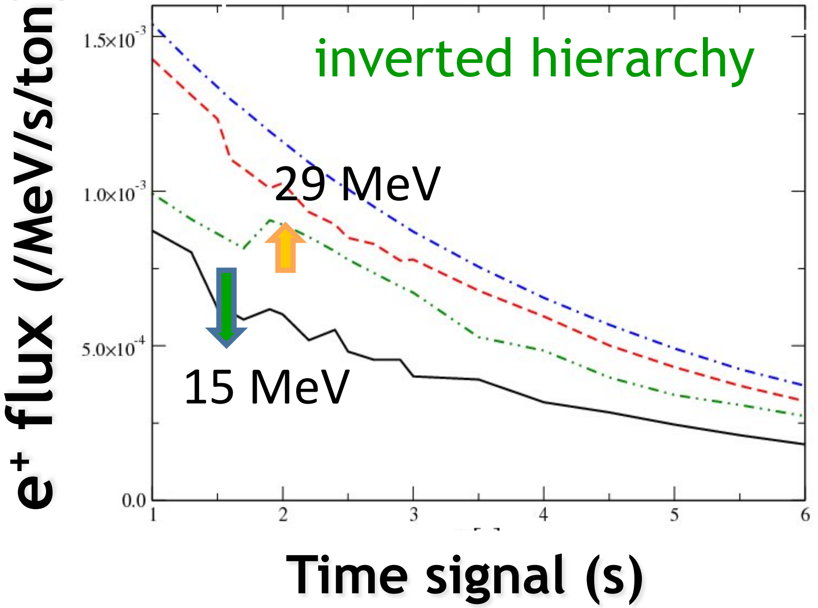


The hierarchy appear to be distinguishable.

Mass hierarchy from late SN signal

Imprint of the mass hierarchy in a water Cherenkov and scintillator detector, if a supernova at 10 kpc explodes.

$$\bar{\nu}_e + p \longrightarrow n + e+$$



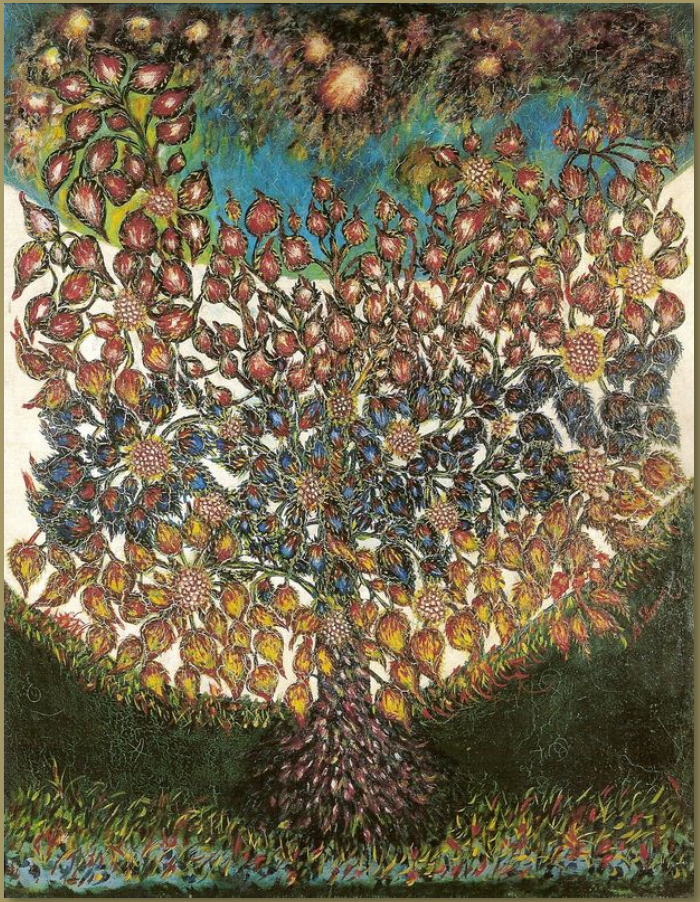
Gava, Kneller,
Volpe, McLaughlin,
PRL 103(2009)

Bump (dip) at 3.5 (1) sigma in Super-Kamiokande or large size detectors

Conclusions and perspectives

- Important progress in neutrino astrophysics in the last years. Novel flavor conversion phenomena uncovered in supernovae but key open questions remain.

- Astrophysical neutrinos keep bringing surprises both on the environments that produce them and on fundamental open issues.



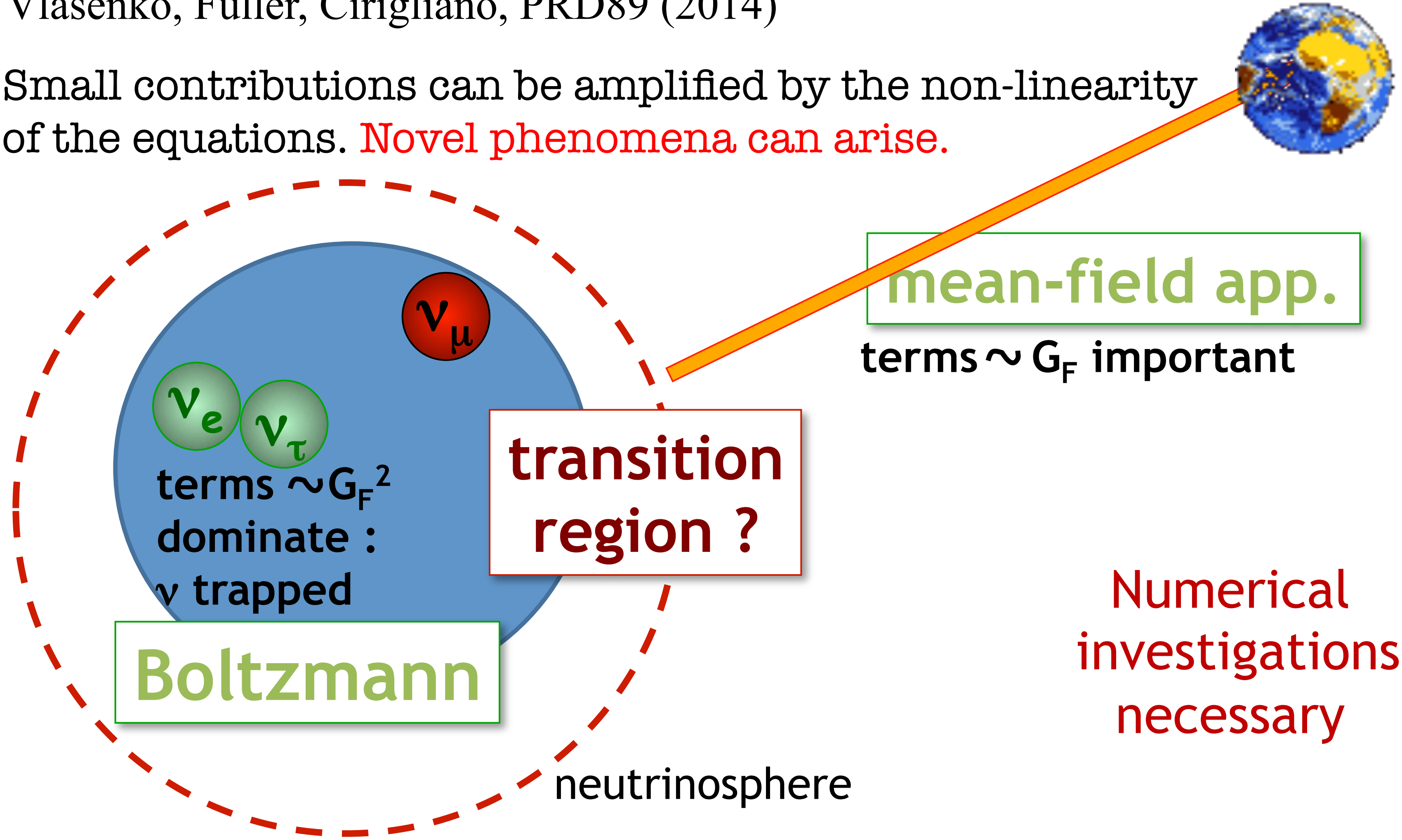
Life tree

Thank you

Is mean-field sufficient ?

Balantekin and Pehlivan, JPG 34 (2007)
Cherry et al., PRL108 (2012) - **back-scattered neutrino**
Volpe, Väänänen, Espinoza, PRD87 (2013) -**neutrino -antineutrino correlations**
Vlasenko, Fuller, Cirigliano, PRD89 (2014)

Small contributions can be amplified by the non-linearity of the equations. Novel phenomena can arise.



terms $\sim G_F^2$ dominate : ν trapped

Boltzmann

transition region ?

mean-field app.

terms $\sim G_F$ important

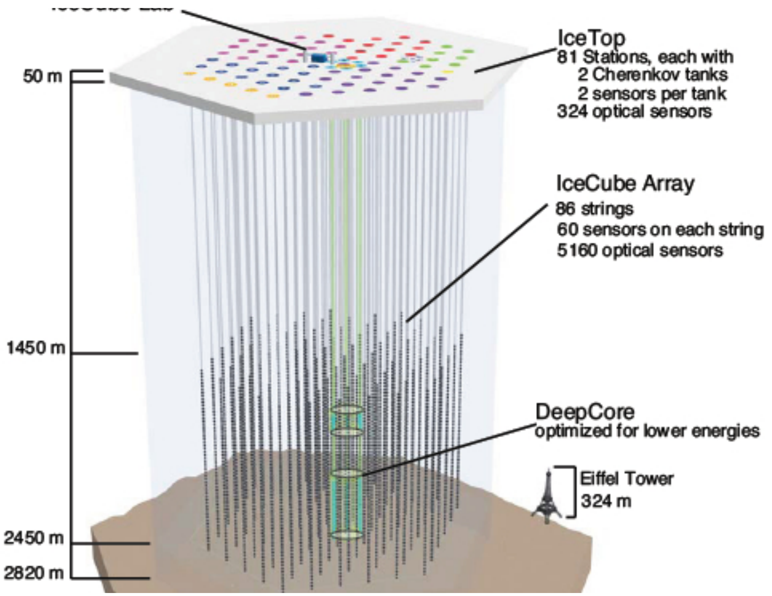
neutrinosphere

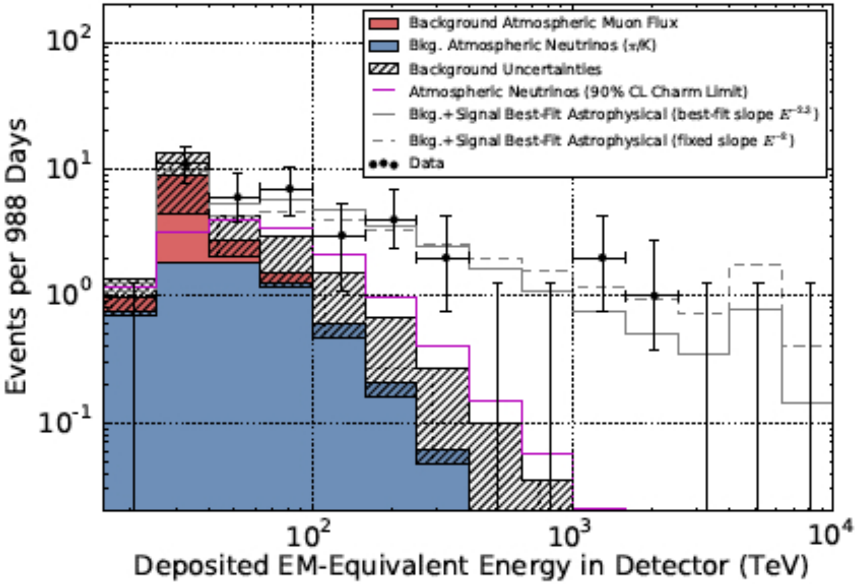
Numerical investigations necessary

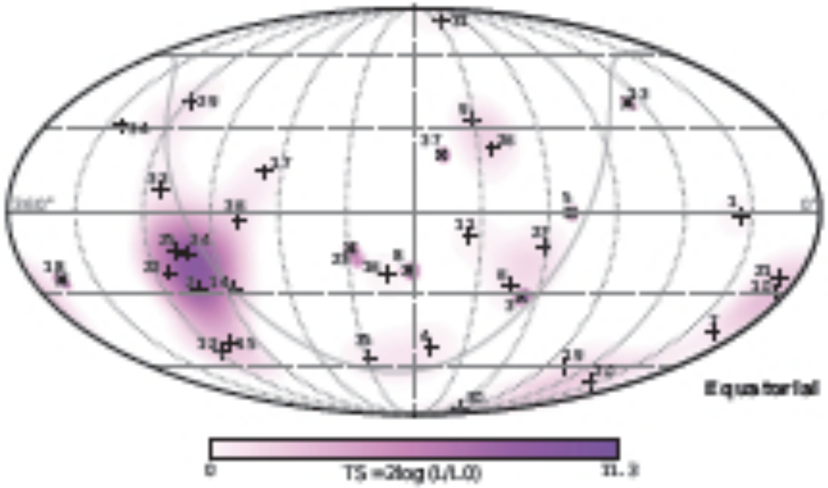
UHE neutrinos discovery

Observation of 37 events (combined 3 years data) at 5.7 σ.

ICECUBE collaboration, arXiv : 1405.5303







a new window
on the Universe

A novel perspective to ν conversion

Volpe, Väänänen, Espinoza, PRD87 (2013), arXiv: 1302.2374

BBGKY for neutrinos :

- a system of particles and anti-particles
- particles with mixings

ν

$$\rho_\nu = \begin{pmatrix} \langle a^\dagger_{\nu_\alpha,i} a_{\nu_\alpha,i} \rangle & \langle a^\dagger_{\nu_\beta,j} a_{\nu_\alpha,i} \rangle \\ \langle a^\dagger_{\nu_\alpha,i} a_{\nu_\beta,j} \rangle & \langle a^\dagger_{\nu_\beta,j} a_{\nu_\beta,j} \rangle \end{pmatrix}$$

occupation number op.

anti-ν

$$\bar{\rho}_\nu = \begin{pmatrix} \langle b^\dagger_{\nu_\alpha,i} b_{\nu_\alpha,i} \rangle & \langle b^\dagger_{\nu_\beta,j} b_{\nu_\alpha,i} \rangle \\ \langle b^\dagger_{\nu_\alpha,i} b_{\nu_\beta,j} \rangle & \langle b^\dagger_{\nu_\beta,j} b_{\nu_\beta,j} \rangle \end{pmatrix}$$

decoherence or mixing terms

The BBGKY is a rigorous theoretical framework :

- ✓ to go from the N-body to the 1-body description
- ✓ that is very general, equivalent the Green's function formalism (equal-time limit)

UNIFIED APPROACH for ASTROPHYSICAL and COSMOLOGICAL APPLICATIONS

that allows to go beyond current approximations

The first BBGKY equation

$$\rho_1 = \langle \psi(t) | a_1^\dagger a_1 | \psi(t) \rangle \qquad \rho_{12} = \langle \psi(t) | a_2^\dagger a_1^\dagger a_1 a_2 | \psi(t) \rangle$$

one-body density **two-body density**

The two-body density matrix can be written as :

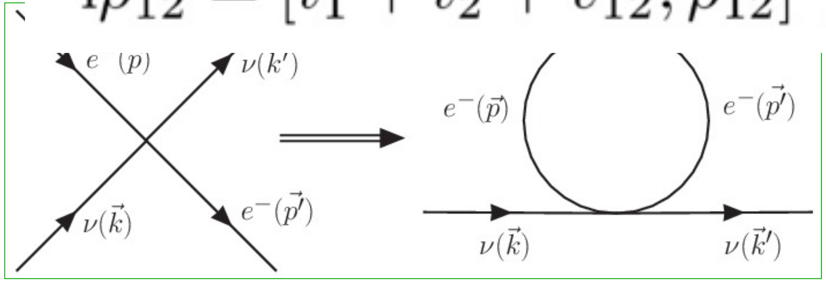
$$\rho_{12} = \rho_1 \rho_2 + \cancel{C_{12}}$$

two-body correlation function

The first BBGKY equations gives for the mean-field evolution equations

$$i\dot{\rho}_1 = [t_1, \rho_1] + \mathrm{Tr}_{(2)} \{[v_{12}, \rho_{12}]\}$$

~~$i\dot{\rho}_{12} = [t_1 + t_2 + v_{12}, \rho_{12}] + \mathrm{Tr}_{(3)} \{[v_{13} + v_{23}, \rho_{123}]\}$~~



$$\Gamma_{1,ij}(\rho) = \sum_{mn} v_{(im,jn)} \rho_{2,nm}$$

MEAN-FIELD

the mean-field approximation

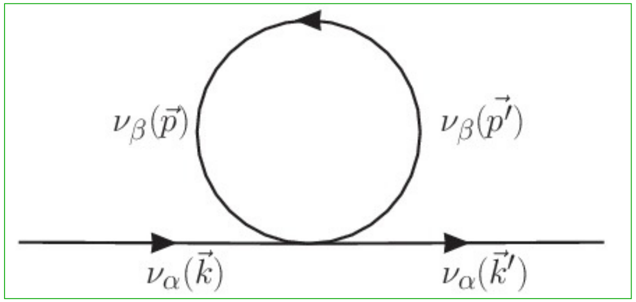
BBGKY for neutrinos : mean-field equations

Deriving the ν evolution equations in presence of

✓ a ν and ν backgrounds --- early Universe, supernovae, AD-BH

- $i\dot{\rho} = [h(\rho), \rho]$

$$\Gamma_{1,ij}(\rho) = \sum_{mn} v_{(im,jn)}\rho_{2,nm}$$



- $H_{NC} = \frac{G_F}{2\sqrt{2}}\int d^3\vec{x}[\bar{\phi}_{\nu_e}\gamma_\mu(1-\gamma_5)\phi_{\nu_e}],[\bar{\phi}_{\nu_y}\gamma^\mu(1-\gamma_5)\phi_{\nu_y}]$ **interaction H**
- $\phi(\vec{x}) = \sum_h \int \frac{d^3\vec{p}}{(2\pi)^3 2E_p}[a(\vec{p},h)u_{\vec{p},h}e^{i\vec{p}\cdot\vec{x}} + b^\dagger(\vec{p},h)v_{\vec{p},h}e^{-i\vec{p}\cdot\vec{x}}]$ **field**
- $|m\rangle = a_m^\dagger|\rangle$ **single particle states**
- $\Gamma_{\nu_\alpha,\nu_\beta}(\rho_\nu) = \frac{G_F}{2\sqrt{2}}\int \frac{d^3\vec{p}}{(2\pi)^3 2E_p}\int \frac{d^3\vec{p}'}{(2\pi)^3 2E_{p'}}(2\pi)^3\delta^3(\vec{p}+\vec{k}-\vec{p}'-\vec{k}')$

x $[\bar{u}_{\nu_\beta}(\vec{k},h_\beta)\gamma_\mu(1-\gamma_5)u_{\nu_\alpha}(\vec{k}',h'_\alpha)]\ [\bar{u}_{\nu_\alpha}(\vec{p},h_\alpha)\gamma^\mu(1-\gamma_5)u_{\nu_\beta}(\vec{p}',h'_\beta)]$

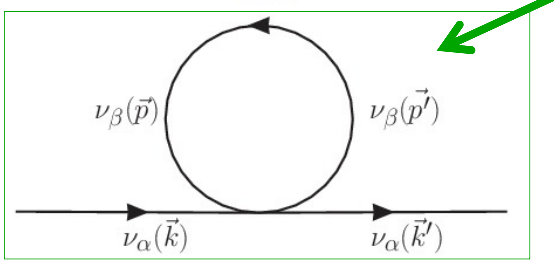
x $\langle a^\dagger_{\nu_\alpha}(\vec{p},h_\alpha)a_{\nu_\beta}(\vec{p}',h'_\beta)\rangle$ **mean-field**

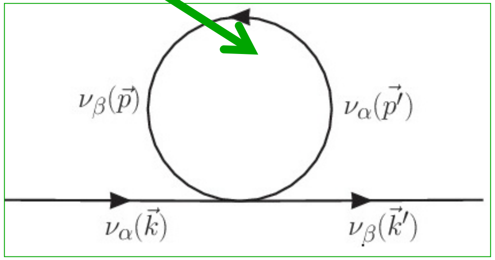
BBGKY for neutrinos : mean-field equations

- $\rho^{\nu_\beta,\nu_\alpha}_{\vec{p}'h',\vec{p}h} \equiv \langle a^\dagger_{\nu_\alpha}(\vec{p},h_\alpha) a_{\nu_\beta}(\vec{p}',h'_\beta)\rangle$ (normal) density matrix
- $\rho^{\nu_\beta,\nu_\alpha}_{\vec{p}'h',\vec{p}h} = (2\pi)^3 2E_p \delta_{hh'}\delta^3(\vec{p}-\vec{p}')\rho^{\nu_\beta,\nu_\alpha}_{\vec{p}}$ homogeneous background
- $\Gamma(\rho_\nu,\bar{\rho}_\nu) = \sqrt{2}G_F \sum_{\underline{\nu_\alpha}} \int \frac{d^3\vec{p}}{(2\pi)^3 2E_p} (\rho_{\underline{\nu_\alpha},p} - \bar{\rho}^*_{\underline{\nu_\alpha},p}) \left(1 - \hat{\vec{p}}\cdot\hat{\vec{k}}\right)$

ν mean-field

diagonal contribution



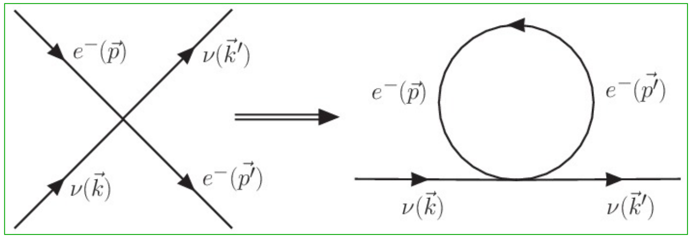


off-diagonal contribution

✓ a matter background - MSW effect

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

electron mean-field



MEAN-FIELD EQUATIONS - MSW and νν – reDERIVED

consistent with previous derivations

Beyond the mean-field approximation

$$\rho_{12} = \rho_1 \rho_2 + c_{12} \longleftarrow$$ **two-body correlations**

The evolution equation for the two-body correlation function :

$$\begin{aligned}
i\dot{c}_{12} = {} & [h_1 + h_2, c_{12}] \\
& + (1-\rho_1)(1-\rho_2)v_{12}\rho_1\rho_2 - v_{12}\rho_1\rho_2(1-\rho_1)(1-\rho_2) \\
& + (1-\rho_1-\rho_2)v_{12}c_{12} - c_{12}v_{12}(1-\rho_1-\rho_2) \\
& + \mathrm{Tr}_{(3)}\left\{[v_{13}, (1-P_{13})\rho_1 c_{23}(1-P_{12})]\right\} \\
& + \mathrm{Tr}_{(3)}\left\{[v_{23}, (1-P_{23})\rho_2 c_{13}(1-P_{12})]\right\} \\
& + \mathrm{Tr}_{(3)}\left\{[v_{13} + v_{23}, c_{123}]\right\}
\end{aligned}$$