Neutrino astrophysics: recent advances and open issues

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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

PTOLEMY prototype:

Electron kinetic energy (eV)
Rate (events/eV/year)

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 $\nu$-matter interaction

- Wolfenstein PRD (1978)
- Mikheev, Smirnov (1985)

Mean-field

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

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 ($M > 8 \, M_{\text{sun}}$).

Sensitive probe of the supernova dynamics
Supernova neutrinos

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Supernova neutrinos

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

Sensitive probe of the supernova dynamics

Hüdepohl et al. PRL 104 (2010)
Vissani, JPG (2014)
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 $\nu$

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-sustained 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/3 years at 3 Mpc.

- The Diffuse Supernova Neutrino Background

<table>
<thead>
<tr>
<th>Event</th>
<th>Window</th>
<th>Detector</th>
</tr>
</thead>
<tbody>
<tr>
<td>νe</td>
<td>90 (IH/NH)</td>
<td>9-25 MeV</td>
</tr>
<tr>
<td>νe</td>
<td>300</td>
<td>19-30 MeV</td>
</tr>
<tr>
<td>νe</td>
<td>30</td>
<td>17-41 MeV</td>
</tr>
</tbody>
</table>

Galais, Kneller, Volpe, Gava, PRD 81(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 characteristic imprints on the neutrino fluxes at 200 km.

Pantaleone, PLB 287 (1992)

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

collective stable and unstable $\nu$ modes in flavor space
The connection with other systems

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

- giant resonances
- nuclear collision
- double-beta decay
- $^{76}$Ge $\rightarrow$ $^{76}$As $\rightarrow$ $^{76}$Se $\beta\beta(0\nu)$ $^{76}$Se
- phonons
- metallic clusters
- condensed matter
Collective $\nu$ modes and vibrations


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

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

Giant resonances

Double-beta decay

$^{76}\text{Ge} \overset{\beta\beta(0\nu)}{\rightarrow} ^{76}\text{As}$

$^{76}\text{Se}$
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,
  Duan, Friedland, McLaughlin, Surman, JPG 38 (2011)

- role of decoherence (by matter, wave-packet treatment,...)
  Esteban-Pretel et al, 2007
  Akhmedov, Kopp, Lindner, 2014
The neutrino evolution equations are based on the mean-field due to matter background (MSW effect) and $\nu$ backgrounds.

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

one-body density

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

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., PRL 108 (2012) (toy model)

- wrong helicity contributions due to the $\nu$ mass - spin or helicity coherence, suppressed by $m/E$.

Volpe, Väänänen, Espinoza, PRD 87 (2013)

Vlasenko, Fuller, Cirigliano, PRD 89 (2014)

- neutrino-antineutrino pairing correlations

Volpe, Väänänen, Espinoza, PRD 87 (2013)

\[ \kappa_{ik} \equiv \langle b_k a_j \rangle \]

pairing density
In presence of pairing correlations the $\nu$ equations can be cast as

$$\mathcal{R} = \begin{pmatrix} \rho & \kappa \\ \kappa^\dagger & 1 - \bar{\rho}^* \end{pmatrix} \quad i\dot{\mathcal{R}} = [\mathcal{H}, \mathcal{R}]$$

generalised density

generalised Hamiltonian

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


**the role** of neutrino-antineutrino correlations?

*... and of the wrong helicity contributions?*

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

- **CP violation**
  

- **non-standard interactions**
- **sterile neutrinos**

- **the mass ordering**
  through earth matter effects with atmospheric \( \nu \) (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-$\nu_e$ with $p$
- $\nu_e$ with nuclei
- $\nu_x$ with $e, p$

Large scale detectors coming:
- JUNO, Hyper-K,...
Earth matter effects on the atmospheric neutrino can be used to determine the neutrino mass ordering - PINGU, ORCA

The $\nu$ mass ordering at $3 \sigma$ in 3 years

ICECUBE coll., arXiv: 1401.2046
From the early time supernova signal

SN $\nu$ fluxes at accretion phase

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.

\[
\bar{\nu}_e + p \rightarrow n + e^+
\]

inverted hierarchy

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

Gava, Kneller, Volpe, McLaughlin, PRL 103(2009)
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.
Thank you

Life tree
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.

mean-field app.
terms $\sim G_F^2$ important
transition region?

Numerical investigations necessary

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transition region?

Numerical investigations necessary
UHE neutrinos discovery

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

ICECUBE collaboration, arXiv: 1405.5303

a new window on the Universe
A novel perspective to $\nu$ conversion


**BBGKY for neutrinos:**
- a system of particles and anti-particles
- particles with mixings

\[
\begin{align*}
\rho_\nu &= \begin{pmatrix}
\langle a_{\nu\alpha,i}^\dagger a_{\nu\alpha,i} \rangle & \langle a_{\nu\beta,j}^\dagger a_{\nu\alpha,i} \rangle \\
\langle a_{\nu\alpha,i}^\dagger a_{\nu\beta,j} \rangle & \langle a_{\nu\beta,j}^\dagger a_{\nu\beta,j} \rangle
\end{pmatrix} \\
\bar{\rho}_\nu &= \begin{pmatrix}
\langle b_{\nu\alpha,i}^\dagger b_{\nu\alpha,i} \rangle & \langle b_{\nu\beta,j}^\dagger b_{\nu\alpha,i} \rangle \\
\langle b_{\nu\alpha,i}^\dagger b_{\nu\beta,j} \rangle & \langle b_{\nu\beta,j}^\dagger b_{\nu\beta,j} \rangle
\end{pmatrix}
\end{align*}
\]

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

\[ \rho_1 = \langle \psi(t)|a_1^\dagger a_1|\psi(t)\rangle \quad \rho_{12} = \langle \psi(t)|a_2^\dagger a_1^\dagger a_1 a_2|\psi(t)\rangle \]

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

The two-body density matrix can be written as:

\[ \rho_{12} = \rho_1 \rho_2 + C_{12} \]

**two-body correlation function**

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

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

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

\[ \langle 11, ij | \rho \rangle = \sum_{mn} u_{im,jn} \rho_{2,nm} \]

**MEAN-FIELD**

the mean-field approximation
Deriving the $\nu$ evolution equations in presence of
- a $\nu$ and $\nu$ backgrounds --- early Universe, supernovae, AD-BH

\[ i\dot{\rho} = [h(\rho), \rho] \]
\[ \Gamma_{1,ij}(\rho) = \sum_{mn} v_{(im,jn)} \rho_{2,nm} \]

\[ H_{NC} = \frac{G_F}{2\sqrt{2}} \int d^3\vec{x} [\bar{\phi}_{\nu_e} \gamma_\mu (1 - \gamma_5) \phi_{\nu_e}], [\bar{\phi}_{\nu_y} \gamma_\mu (1 - \gamma_5) \phi_{\nu_y}] \]

\[ \phi(\vec{x}) = \sum_h \int \frac{d^3\vec{p}}{(2\pi)^3 2E_p} \left[ a(p, h) u_{p,h} e^{i\vec{p} \cdot \vec{x}} + b^\dagger(p, h) \nu_{p,h} e^{-i\vec{p} \cdot \vec{x}} \right] \]

\[ |m\rangle = a_m^\dagger | \]

\[ \Gamma_{\nu_\alpha,\nu_\beta}(\rho_\nu) = \frac{G_F}{2\sqrt{2}} \int \frac{d^3\vec{p}}{(2\pi)^3 2E_p} \int \frac{d^3\vec{p}'}{(2\pi)^3 2E_{p'}} \int \frac{d^3\vec{\nu}}{(2\pi)^3 2E_\nu} \delta^3(\vec{p} + \vec{k} - \vec{p}' - \vec{k}') \]
\[ \times [\bar{u}_{\nu_\beta}(\vec{k}, h_\beta) \gamma_\mu (1 - \gamma_5) u_{\nu_\alpha}(\vec{k}', h'_\alpha)] \]
\[ \times [\bar{u}_{\nu_\alpha}(\vec{p}, h_\alpha) \gamma_\mu (1 - \gamma_5) u_{\nu_\beta}(\vec{p}', h'_\beta)] \]
\[ \times \langle a_{\nu_\alpha}^\dagger (\vec{p}, h_\alpha) a_{\nu_\beta} (\vec{p}', h'_\beta) \rangle \]
BBGKY for neutrinos: mean-field equations

\[ \rho^{\nu_{\beta}, \nu_{\alpha}}_{\vec{p}', h', \vec{p} h} = \langle a_{\nu_{\alpha}}^{\dagger}(\vec{p}, h_{\alpha}) a_{\nu_{\beta}}(\vec{p}', h'_{\beta}) \rangle \]

\[ \rho^{\nu_{\beta}, \nu_{\alpha}}_{\vec{p}', h', \vec{p} h} = (2\pi)^3 2E_p \delta_{hh'} \delta^3(\vec{p} - \vec{p}') \rho^{\nu_{\beta}, \nu_{\alpha}}_{\vec{p}}. \]

\[ \Gamma(\rho_{\nu}, \bar{\rho}_{\nu}) = \sqrt{2} G_F \sum_{\nu_{\alpha}} \int \frac{d^3 \vec{p}}{(2\pi)^3 2E_p} (\rho_{\nu_{\alpha}, \vec{p}} - \bar{\rho}_{\nu_{\alpha}, \vec{p}}^*) (1 - \hat{p} \cdot \hat{k}) \]

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

Mean-field equations - MSW and \( \nu \nu \) - reDERIVED consistent with previous derivations

Diagonal contribution

Off-diagonal contribution

A matter background - MSW effect
Beyond the mean-field approximation

\[ \rho_{12} = \rho_1 \rho_2 + c_{12} \]

The evolution equation for the two-body correlation function:

\[
\dot{c}_{12} = [h_1 + h_2, c_{12}]
\]

\[
+ (1 - \rho_1)(1 - \rho_2)v_{12}\rho_1 \rho_2 - v_{12}\rho_1 \rho_2 (1 - \rho_1)(1 - \rho_2)
\]

\[
+ (1 - \rho_1 - \rho_2)v_{12}c_{12} - c_{12}v_{12}(1 - \rho_1 - \rho_2)
\]

\[
+ \text{Tr} (v_{13}, (1 - P_{13})\rho_1 c_{23}(1 - P_{12}))
\]

\[
+ \text{Tr} (v_{23}, (1 - P_{23})\rho_2 c_{13}(1 - P_{12}))
\]

\[
+ \text{Tr} (v_{13} + v_{23}, c_{123})
\]