Magnetic Field Effects on Neutrino Oscillation in Supernovas

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1. Introduction
   - SN as neutrino laboratories
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   - SN neutrino astrophysics: SN 1987 A
2. Neutrino propagation in SN: Standard picture
3. Neutrino propagation in SN: "New effects"
   - Neutrino μ_B
     - μ_B : Dirac neutrinos Vs Majorana Netrinos
     - Magnetic fields in SN
   - Weak interaction spin coherence
4. Conclusions

Neutrinos

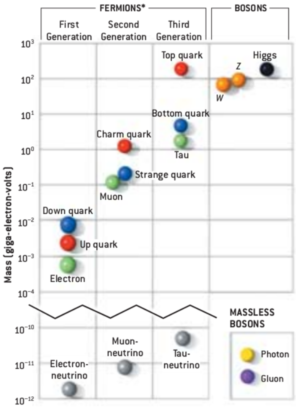


Figure: Mass spectrum of particles of the SM

Neutrinos

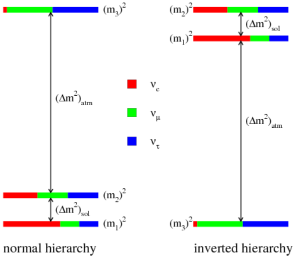
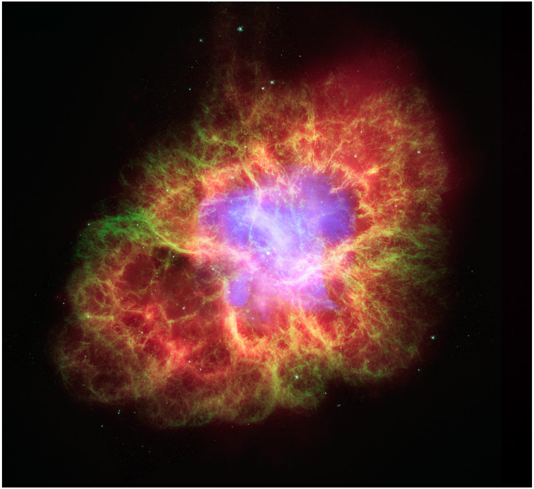


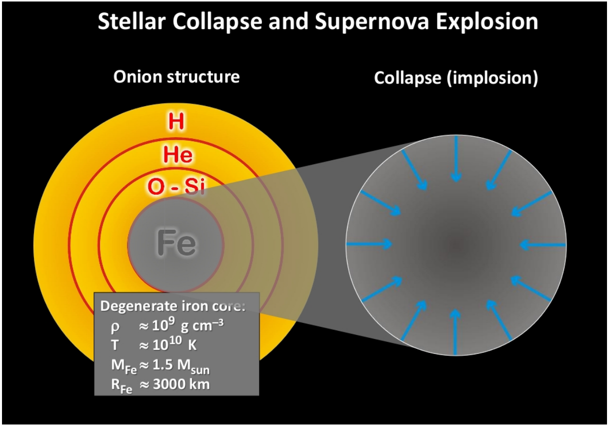
Figure: Flavour composition of mass eigenstates

$$\boxed{\bar{\nu}_\mu = U_{\mu 1}\bar{\nu}_1 + U_{\mu 2}\bar{\nu}_2 + U_{\mu 3}\bar{\nu}_3}$$

Supernovas as neutrino laboratories



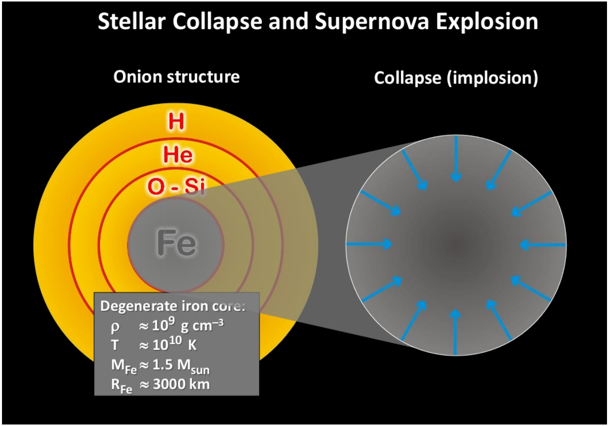
Supernovas as neutrino laboratories



Stellar Collapse and Supernova Explosion

Degenerate iron core:
$\rho \approx 10^9$ g cm^{-3}
$T \approx 10^{10}$ K
$M_{Fe} \approx 1.5\ M_{sun}$
$R_{Fe} \approx 3000$ km

Supernovas as neutrino laboratories



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- Low E (MeV), Very high ν density

Neutrinos

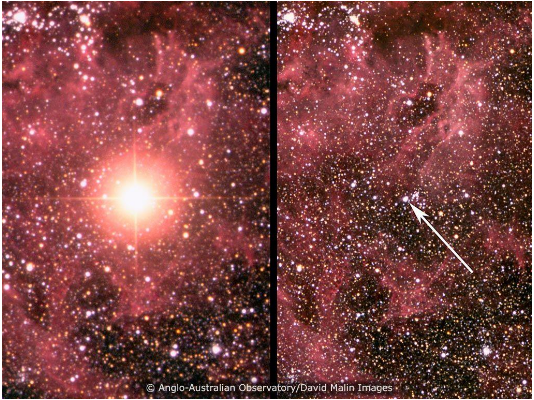
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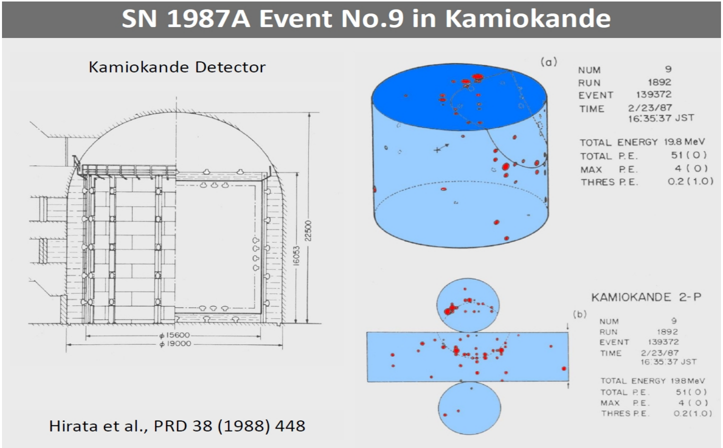
Figure: SN 1987 A

Neutrinos



SN 1987A Event No.9 in Kamiokande

Kamiokande Detector

NUM 9
RUN 1892
EVENT 139372
TIME 2/23/87
16:35:37 JST

TOTAL ENERGY 19.8 MeV
TOTAL P.E. 51 (0)
MAX P.E. 4 (0)
THRES P.E. 0.2 (1.0)

KAMIOKANDE 2-P

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RUN 1892
EVENT 139372
TIME 2/23/87
16:35:37 JST

TOTAL ENERGY 19.8 MeV
TOTAL P.E. 51 (0)
MAX P.E. 4 (0)
THRES P.E. 0.2 (1.0)

Hirata et al., PRD 38 (1988) 448

Neutrinos

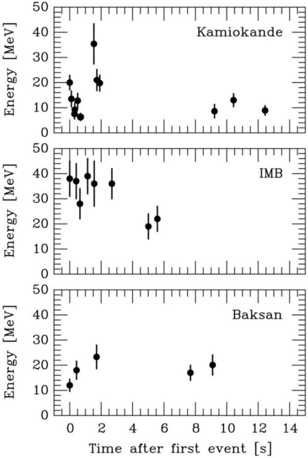

Figure: SN 1987 A

Neutrino density matrix

- $\boxed{\psi(x) = \int d\mathbf{p}(a_{\mathbf{p}}(t)u_{\mathbf{p}} + b^{\dagger}_{\text{-}\mathbf{p}}(t)v_{\text{-}\mathbf{p}})e^{i\mathbf{p}\cdot x}}$

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  - $< b_j^{\dagger}(p)a_i(p') > \propto \left(\frac{m}{E}\right) \propto 10^{-8}$

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- We neglect the following bilinears
  - $< b^{\dagger}_{j}(p)a_{i}(p') > \propto \left(\frac{m}{E}\right) \propto 10^{-8} \rightarrow$ B , Anisotropies
  - $< a^{\dagger}_{j}(p)b^{\dagger}_{i}(p') > \longrightarrow$ Inhomogeneus enviroment

Neutrino density matrix EoM

- Density matrix evolution equation

$$\dot{\rho}_{\mathbf{p}} = -i\left[H_{\mathbf{p}}, \rho_{\mathbf{p}}\right]$$

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Neutrino density matrix EoM

- Density matrix evolution equation

$$\dot{\rho}_{\mathbf{p}} = -i\,[H_{\mathbf{p}}, \rho_{\mathbf{p}}]$$

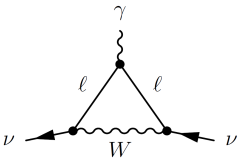
- Where $H = H_{vac} + H_{matter} + H_{self}$
  - $H_{vac} = \frac{\Delta m^2}{2E} \begin{pmatrix} -cos(2\theta_{vac}) & sin(2\theta_{vac}) \\ sin(2\theta_{vac}) & cos(2\theta_{vac}) \end{pmatrix}$
  - $H_{matter} = \sqrt{2} G_F n_e \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix}$
  - $H_{self} = \sqrt{2} G_F \int d^3p'(1 - p \cdot p')(\rho_{p'} - \bar{\rho}_{p'})$

Neutrino density matrix EoM

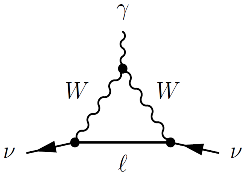
- Density matrix evolution equation

$$i\begin{pmatrix} \dot{\rho} & 0 \\ 0 & \dot{\bar{\rho}} \end{pmatrix} = \left[\begin{pmatrix} \rho & 0 \\ 0 & \bar{\rho} \end{pmatrix}, \begin{pmatrix} H & 0 \\ 0 & -H^* \end{pmatrix}\right]$$

Neutrino magnetic moment μ_B



(a)



(b)

- The form factor for the μ_B is proportional to $f_M(q)\sigma_{ij} \longrightarrow$ chirality changing operators

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Dirac spinor	**Majorana spinor** $(\nu_R = \nu_L^C)$
$\nu = \begin{pmatrix} \chi_L \\ \chi_R \end{pmatrix}$	$\nu = \begin{pmatrix} \chi_L \\ \chi_L^C \end{pmatrix}$
μ_{ij}	$\mu_{i,j} \quad (i \neq j)$
Active $\rightleftharpoons$ sterile neutrino	**Neutrino $\rightleftharpoons$ antineutrino**
$\mu_D = 10^{-19}\mu_B$	$\mu_M = 10^{-24}\mu_B$

Supernova core colapse (arXiv:astro-ph/0601261)

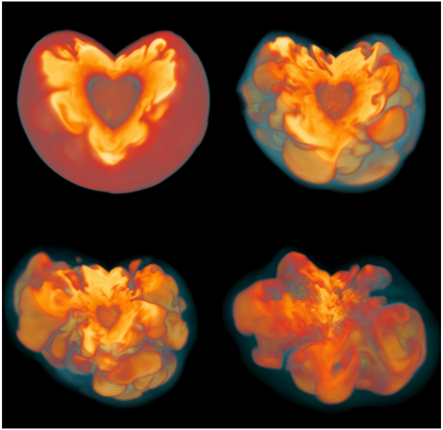


Figure: Supernova Core. From top left to bottom right: structure at 0.1, 0.2, 0.3, and 0.5 seconds after the shock is born. The shock has an average radius of about 200, 300, 500, and 2,000 kilometers, respectively

Supernovas: Magnetic fields

$$\boxed{B \backsimeq 10^{12} \cdot \left(\frac{50km}{r(km)}\right)(G)}$$

Supernovas: Magnetic fields

$$\boxed{B \backsimeq 10^{12} \cdot \left(\frac{50km}{r(km)}\right) (G)}$$

- Hamiltonian $H = \begin{pmatrix} 0 & \mu B_T \\ -\mu B_T & 0 \end{pmatrix}$

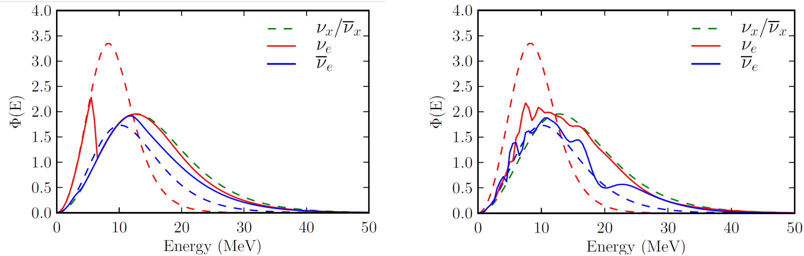
Neutrino density matrix: a generalization

- Density matrix evolution equation

$$i\begin{pmatrix} \dot{\rho} & \dot{\sigma} \\ \dot{\bar{\sigma}} & \dot{\bar{\rho}} \end{pmatrix} = \left[\begin{pmatrix} \rho & \sigma \\ \dot{\sigma} & \bar{\rho} \end{pmatrix}, \begin{pmatrix} H & \mu B_T \\ -\mu B_T & -H^* \end{pmatrix}\right]$$

Where: $\sigma_{ij} =< b_j^\dagger(p) a_i(p') >$, $(i \neq j)$

Neutrino magnetic moment μ_B



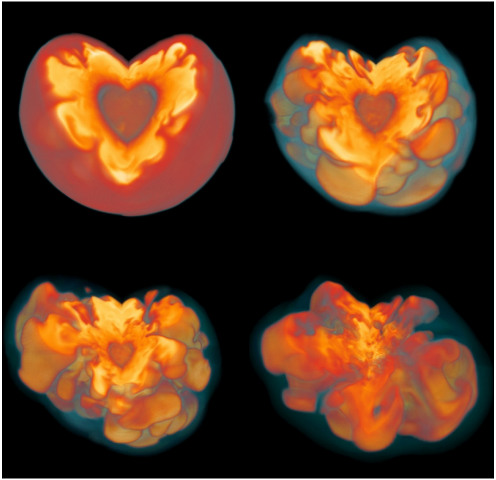
(a) No μ_B effects included

(b) μ_B effects included

Anisotropy as spin coherence inducer

- **Weak interaction spin flip transitions**
  - Also introduces $\sigma_{ij} =< b_j^\dagger(p) a_i(p') >$
  - The effects are suppressed by a factor $\left(\frac{m_\nu}{E}\right) \backsimeq 10^{-8}$
  - However, due to nonlinear feedback effects, they might have an non negligible impact in the final result

Supernova core colapse (arXiv:astro-ph/0601261)



Anisotropy as spin-flip transition inducer

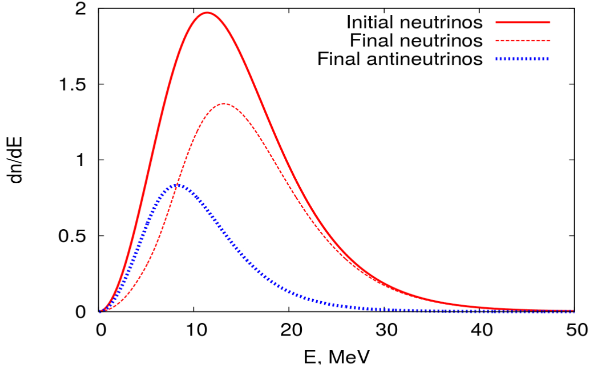
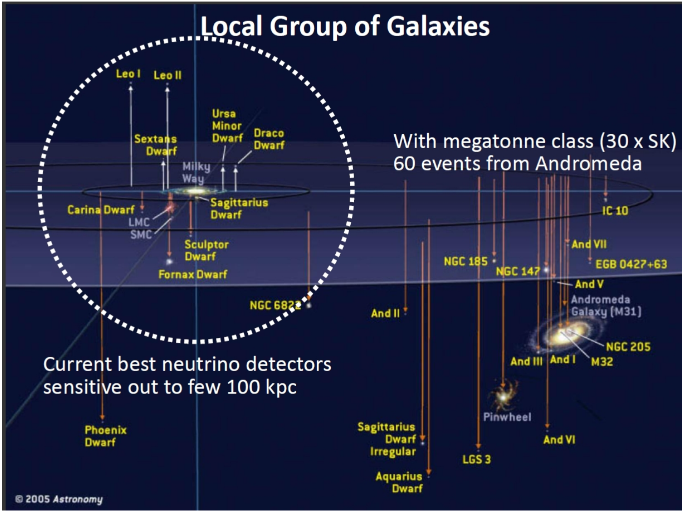


Figure: arXiv:1406.6724 (25 June 2014)

Next SN event?



Local Group of Galaxies

With megatonne class (30 x SK) 60 events from Andromeda

Current best neutrino detectors sensitive out to few 100 kpc

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Conclusions

- Supernovas are the perfect neutrino laboratories.
- Effects initially neglected (μ_B, Spin-flip transitions, wave packet decoherence, non stationary solutions...) might have a strong impact
    - $\boxed{\text{Are we using the right equations?}}$
    - $\boxed{\text{Collective neutrino oscillations theory must be re-examined}}$
        - ▶ The new models have to be tested numerically
    - We should be prepared for the next SN!

Thank you for your attention