Supernova Neutrinos

What have we understood so far?

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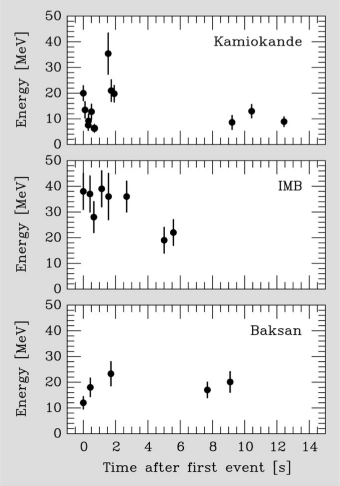
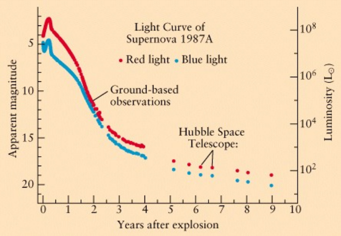
Neutrino Conference in Vietnam (NuView2025)
ICISE, Quy Nhon, Vietnam
24 July 2025

SN1987A: neutrinos and light

Neutrinos: Feb 23, 1987

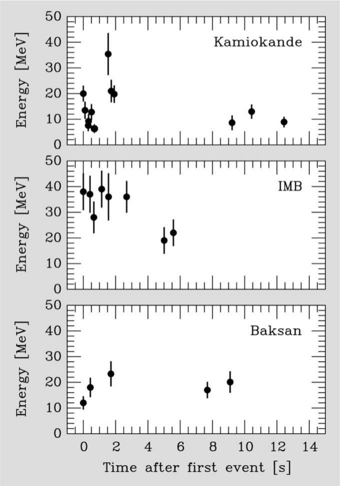


Light curve: 1987-1997



Hubble image: now

SN1987A: what did we learn ?



- Confirmed the SN cooling mechanism through neutrinos
- Number of events too small to say anything concrete about neutrino mixing
- Some constraints on SN parameters obtained
- Strong constraints on new physics models obtained (neutrino decay, Majorans, axions, extra dimensions, ...)

Also see talk by Nakahata-san

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1. Neutrino fluxes from a core-collapse SN
2. Propagation and oscillations of SN neutrinos
   - Passing through MSW resonances and vacuum
   - Nonlinear “collective” oscillations inside the core
3. Implications of SN neutrino observations
   - Early warning and mass ordering
   - Earth matter effects and shock effects
   - SN astrophysics

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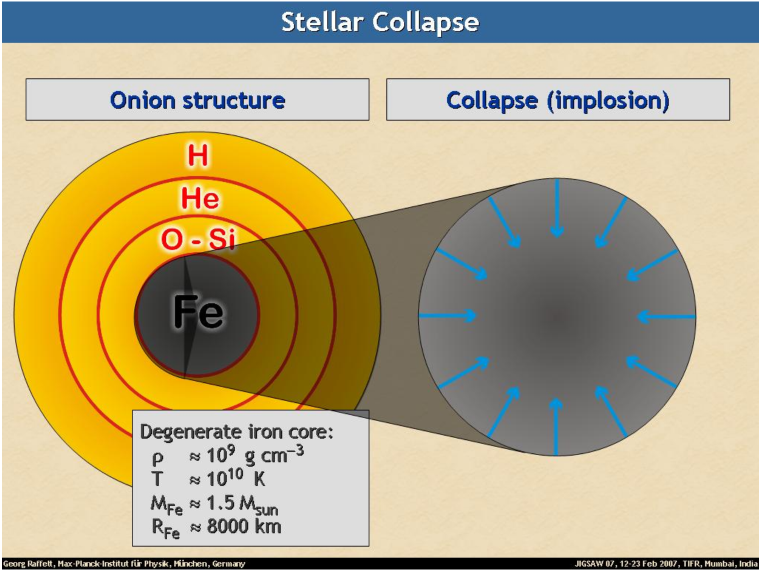
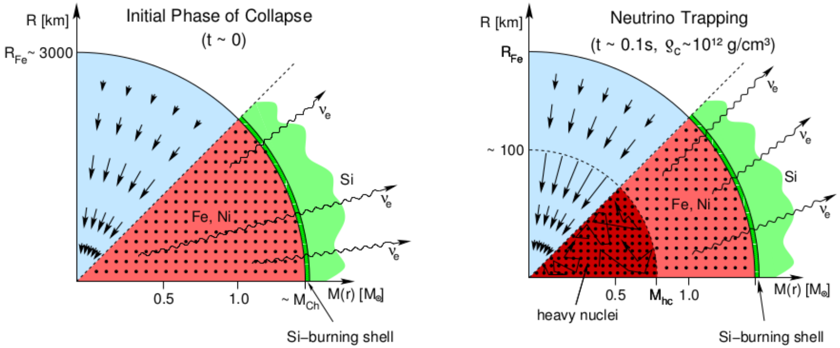
The onion ring structure



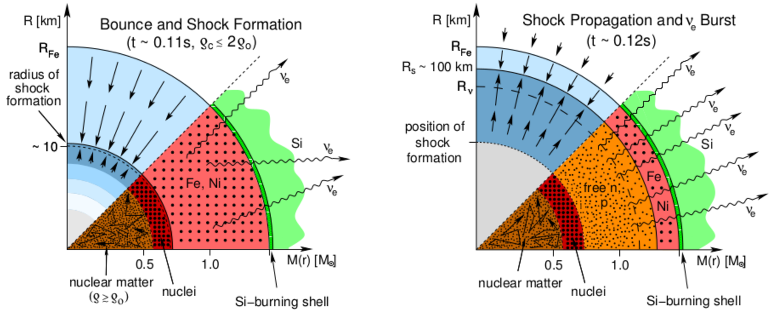
Trapped neutrinos and neutrinosphere



H.T.Janka et al. Phys. Rept 442 (2007)

- Neutrinos trapped inside “neutrinospheres” around $\rho \sim 10^{10}$g/cc.

Core collapse, Shock, Neutronization burst



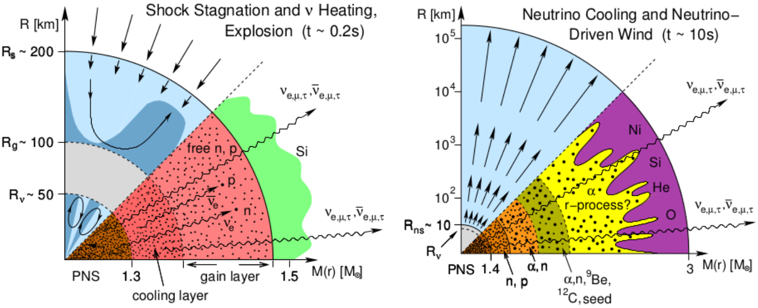
H.T.Janka et al. Phys. Rept 442 (2007)

Neutronization burst: shock breaks neutrinosphere

$$e^- + p \rightarrow n + \nu_e$$

ν_e emitted for ~ 10 ms

Neutrino cooling and explosion



H.T.Janka et al. Phys. Rept 442 (2007)

- Neutrino heating essential, but not enough
- Rotation, convection, hydrodynamic instabilities play an important role, but seeded by neutrinos
- Finally, $\sim$ 99% of the SN energy ($\sim 10^{53}$ erg) is emitted as ($\sim 10^{58}$) neutrinos

Production and scattering of neutrinos

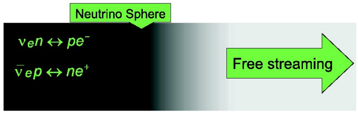
Production

$$e^- + p \to n + \nu_e \quad , \quad N_1 + N_2 \to N_3 + N_4 + \nu + \bar{\nu}$$

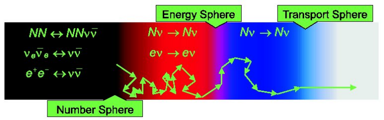
$\Rightarrow$ In general, ν_e flux is more.

Scattering

- For ν_e and $\bar{\nu}_e$:

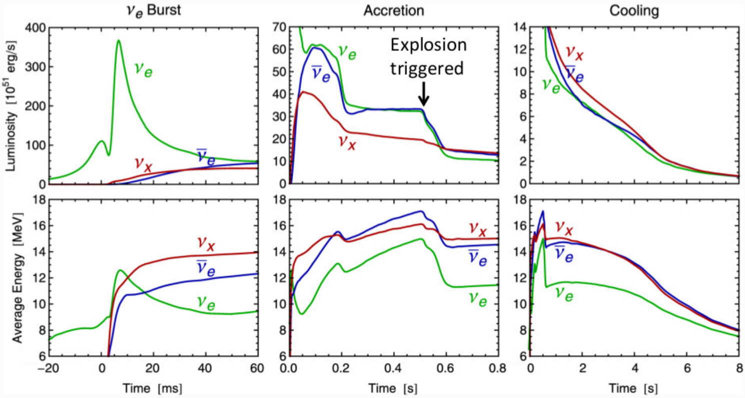


- For all neutrino species ($\nu_{e,\mu,\tau}, \bar{\nu}_{e,\mu,\tau}$):



- Escaping neutrinos: $\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_x} \rangle$

Neutrino fluxes in three phases



Garching group

- Approximately thermal spectra
- $\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_\mu,\nu_\tau,\bar{\nu}_\mu,\bar{\nu}_\tau} \rangle$
- Neutrino oscillations not included

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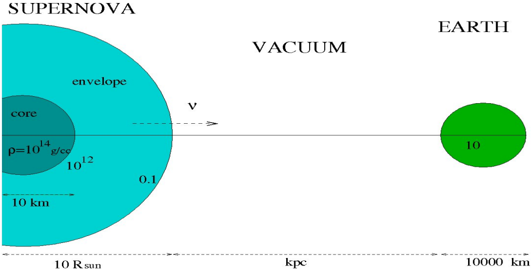
The propagation of neutrinos



- Extremely high density inside the core
- Moderate / small density in the mantle and envelope
- Vacuum on the way from SN to Earth
- Possible travel through the Earth
  (if the detector is on the other side)

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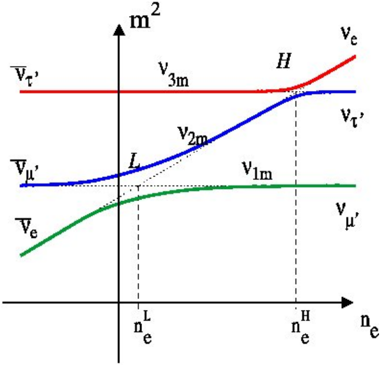
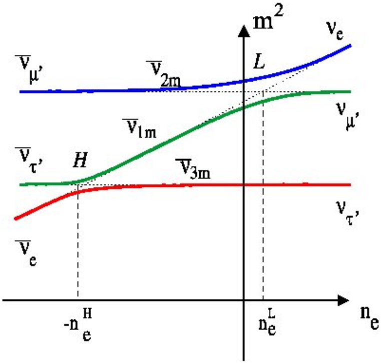
MSW Resonances inside a SN

Normal mass ordering



Inverted mass ordering



AD, A.Smirnov, PRD 62 (2000)

The two resonances

H resonance

- Depends on $\Delta m^2_{\rm atm}$ and $\theta_{\rm reactor}$
- At density $\rho \sim$ 10^3–10^4 g/cc (mantle)
- In neutrinos for normal ordering
- In antineutrinos for inverted ordering

L resonance

- Depends on $\Delta m^2_\odot$ and $\theta_\odot$
- Takes place at density $\rho \sim$ 10–100 g/cc (mantle / envelope)
- Always in neutrinos

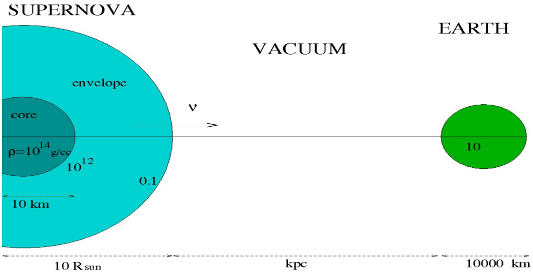
Mixing of neutrino fluxes

- Survival probabilities p and $\bar{p}$
  $F_{\nu_e} = p\, F^0_{\nu_e} + (1-p)\, F^0_{\nu_x}$, $F_{\bar{\nu}_e} = \bar{p}\, F^0_{\bar{\nu}_e} + (1-\bar{p})\, F^0_{\nu_x}$
- Decoherence of oscillations $\Rightarrow$
  p and $\bar{p}$ approximately constant with energy
  (except during the passage of the shock wave)

$p_{NH} \approx \sin^2\theta_{13}$	$\bar{p}_{NH} \approx \cos^2\theta_{12}$
$p_{IH} \approx \sin^2\theta_{12}$	$\bar{p}_{IH} \approx \sin^2\theta_{13}$

- p and $\bar{p}$ depend on mass ordering $\Rightarrow$
  They can help identify the ordering
- But initial fluxes have to be known accurately, and they should be different !

Neutrino propagation in mantle, envelope, vacuum



- H and L resonances in mantle + envelope
  $\Rightarrow$ survival probabilities p and $\bar{p}$
- Neutrinos exit the star as approximate mass eigenstates
- Mass eigenstates do not oscillate $\Rightarrow$
  p and $\bar{p}$ do not change during SN $\rightarrow$ Earth travel

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New phenomena inside SN core

- Neutrino densities grow to 10^{30-35} per cc
- Extremely large densities $\Rightarrow$
  Neutrino-neutrino interactions become significant !

New phenomena inside SN core

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  Neutrino-neutrino interactions become significant !

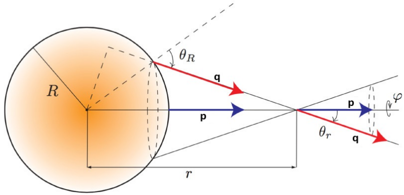
- Earlier, neutrino mixing depended on electron density
- Now, neutrino mixing depends on neutrino flavours in the background
- But neutrino flavours in the background depend on neutrino mixing !

- Non-linear problem !! (very hard)

Non-linearity from neutrino-neutrino interactions

- Effective Hamiltonian: $H = H_{vac} + H_{MSW} + H_{\nu\nu}$

$$\begin{aligned} H_{vac}(\vec{p}) &= M^2/(2p) \\ H_{MSW} &= \sqrt{2} G_F n_{e^-} \, diag(1,0,0) \\ H_{\nu\nu}(\vec{p}) &= \sqrt{2} G_F \int \frac{d^3q}{(2\pi)^3} (1 - \cos\theta_{pq}) \left(\rho(\vec{q}) - \bar{\rho}(\vec{q})\right) \end{aligned}$$



A.Mirizzi et al. Riv. Nuovo Cim 39 (2016)

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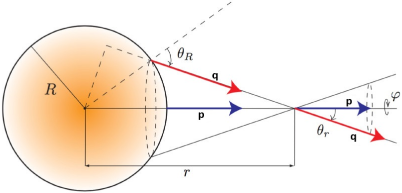

A.Mirizzi et al. Riv. Nuovo Cim 39 (2016)

- Equation of motion: (Density matrix formalism of QM)

$$\frac{d\rho}{dt} = i\,[H(\rho), \rho]$$

Nonlinear "Collective" effects: new phenomena

Synchronized oscillations:

ν and $\bar{\nu}$ of all energies oscillate with the same frequency

S. Pastor, G. Raffelt and D. Semikoz, PRD 65 (2002)

Bipolar/pendular oscillations:

Coherent $\nu_e\bar{\nu}_e \leftrightarrow \nu_x\bar{\nu}_x$ oscillations

S. Hannestad, G. Raffelt, G. Sigl, Y. Wong, PRD 74 (2006)

Spectral split/swap:

ν_e and ν_x ($\bar{\nu}_e$ and $\bar{\nu}_x$) spectra swap completely,
but only within certain energy ranges.

G.Raffelt, A.Smirnov, PRD 76 (2007)

B. Dasgupta, AD, G.Raffelt, A.Smirnov, PRL 103 (2009)

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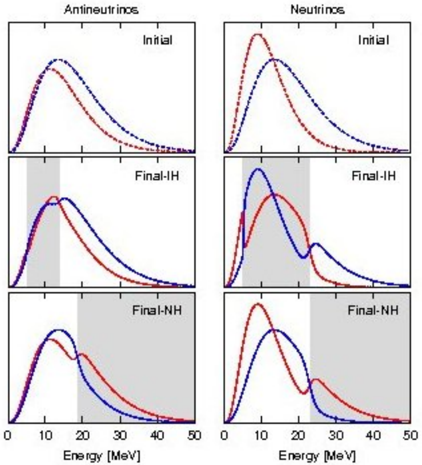
Multiple spectral splits



- Spectral splits as boundaries of swap regions
- Splits possible both for ν_e and $\bar{\nu}_e$
- Split positions depend on Normal (NH) / Inverted (NH) ordering

B. Dasgupta, AD, G.Raffelt, A.Smirnov, PRL 103 (2009)

Recent developments: “fast collective oscillations”

- MSW resonances (H and L): $r \sim 1000$ km
- Nonlinear collective transformations: $r \sim 100$ km
- Fast collective transformations: $r \sim 10$ km
  - Possible if certain symmetries are broken
  - Still being investigated
- If flavours change deep inside, explosion may be affected (Neutrinos will push shock wave with different strength)

Latest on fast collective oscillations

- How soon do the fast oscillations start (numerical) ?

  S.Bhattacharya and B.Dasgupta, PRL 126 (2021)

- What is the long-term behaviour of fast oscillations?

  S.Bhattacharya and B.Dasgupta PRD 102 (2020), PRD 106 (2022)

  S.Shalgar and I.Tamborra JCAP 2024

  C. Kato, H.Nagakura, M.Zaizen, J.Liu, L.Johns, et al. 2021-25

- Can we find analytic conditions for the onset of fast oscillations ? (Suspected: “Spectral crossing”)

  T.Morinaga, PRD 105 (2022), B. Dasgupta PRL 128 (2022), D.Fiorillo, G.Raffelt, et al, 2023-25

  ‘

- Is that necessary and sufficient ?

  B.Dasgupta and D.Mukherjee, arXiv 2025

- What is the effect of collisions ?

  L.Johns, PRL 130 (2023), Zaizen PRD 111 (2025)

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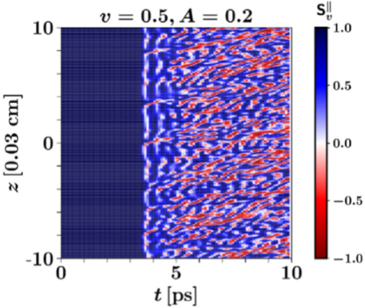
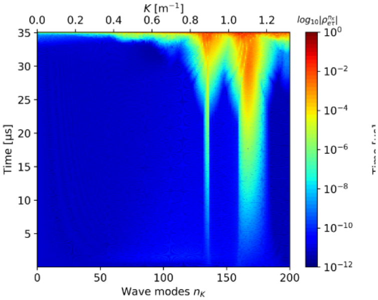
How fast do fast oscillations start

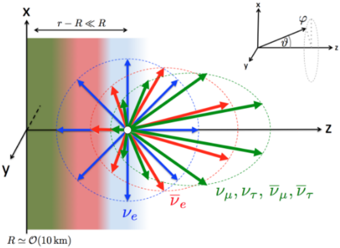


S.Bhattacharya and B.Dasgupta PRD 102 (2020)

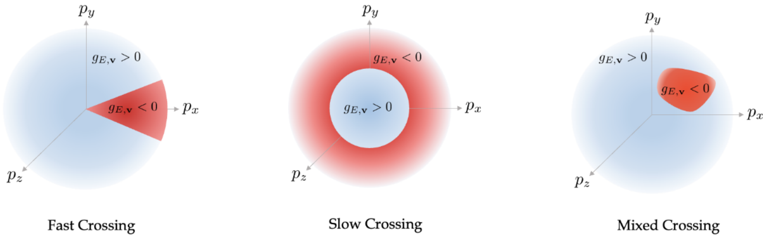


M.Zaizen and T.Morinaga, PRD 104 (2021)

What is this “spectral crossing”?

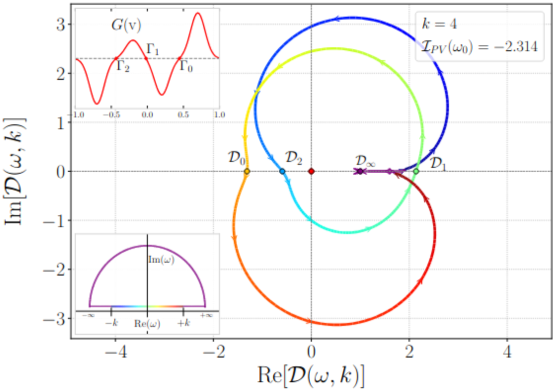


B.Dasgupta, A.Mirizzi and M.Sen, JCAP 02 (2017)



B.Dasgupta and D.Mukherjee, arXiv 2025

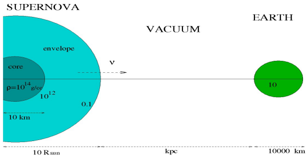
The necessary and sufficient condition



$$\mathcal{D}(\omega, \vec{\mathbf{k}}) \equiv 1 + \int d\Gamma \frac{g_\Gamma}{\omega - \vec{\mathbf{k}} \cdot \vec{\mathbf{v}} - \omega_E}$$

B.Dasgupta and D.Mukherjee, arXiv 2025

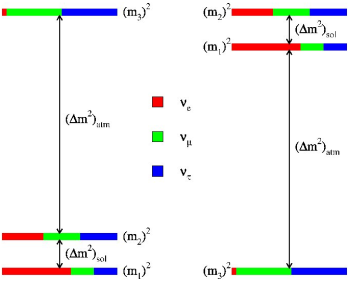
The net picture



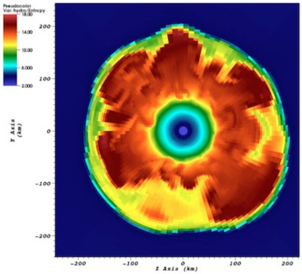
- Deep inside the SN core, neutrinos trapped
- After collapse, neutrinos of different flavours emitted
- While still inside the core $r \sim 10$ km, they can undergo fast collective non-linear oscillations due to ν–ν interactions
- Around $r \sim 1000$ km, matter effects, H and L resonances
- After leaving the star, travel in vacuum: no oscillations
- If passage through Earth, further flavour oscillations

What can SN neutrinos tell us?

About neutrino mixing



About supernova interior



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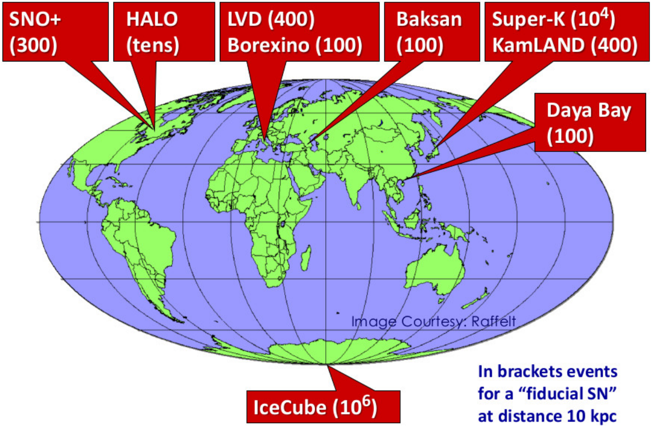
SN detectors around the globe



Upcoming:

- Hyper-Kamiokande (Japan): $\mathcal{O}(10^5)$
- DUNE (USA): $\mathcal{O}(10^4)$

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Major reactions at the large detectors (SN at 10 kpc)

Water Cherenkov detector: (events at SK)

- $\bar{\nu}_e p \to n e^+$: $(\sim 7000 - 12000)$
- $\nu e^- \to \nu e^-$: $\approx 200 - 300$
- $\nu_e +^{16} O \to X + e^-$: $\approx$ 150–800

Carbon-based scintillation detector: $\sim$ 300 events/kt

- $\bar{\nu}_e p \to n e^+$ ($\sim$ 300 per kt)
- $\nu + {}^{12}C \to \nu + X + \gamma$ (15.11 MeV)
- $\nu p \to \nu p$

Liquid Argon detector: $\sim$ 300 events /kt

- $\nu_e + {}^{40}Ar \to {}^{40}K^* + e^-$ ($\sim$ 300 per kt)

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What are the observables ?

- The spectrum of ν_e (Liquid Ar: DUNE)
- The spectrum of $\bar{\nu}_e$ (Water Cherenkov: SuperKamiokande)
- Total luminosity of $\bar{\nu}_e$ (Ice Cherenkov: IceCube)
- The total flux of $\nu_{e,\mu,\tau}$ and $\bar{\nu}_{e,\mu,\tau}$ (Scintillation: ??)

Inferred quantities

- Average energy, spectral shape
- Time modulation of flux
- Time dependent, relative luminosities at two detectors
- Oscillatory spectral modulations (e.g. Earth effects)

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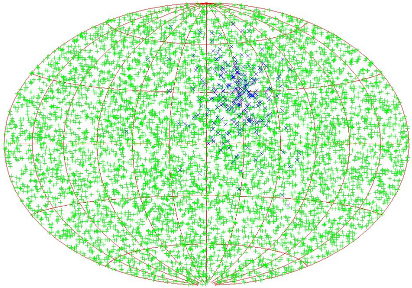
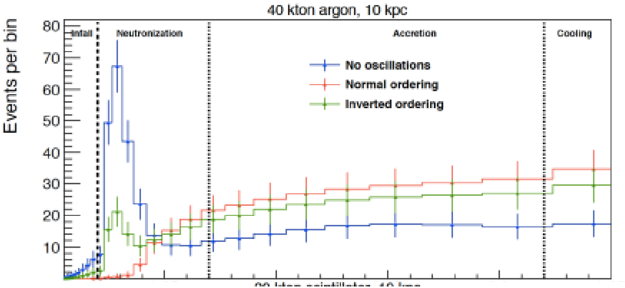
Pointing to the SN in advance

- Neutrinos reach 6-24 hours before the light from SN explosion (SNEWS network)
- $\bar{\nu}_e p \rightarrow n e^+$: nearly isotropic background
- $\nu e^- \rightarrow \nu e^-$: forward-peaked "signal"
- Background-to-signal ratio: $N_B / N_S \approx 30$–50
- SN at 10 kpc may be detected within a cone of $\sim 5^\circ$ at SK
- Adding Gd may make the pointing much better...

J.Beacom and P.Vogel, PRD 60 (1999), R.Tomas et al PRD 68 (2003)



Suppressed neutronization (ν_e) burst



DUNE collaboration, Preliminary

Mass hierarchy identification

- Burst in CC suppressed by
  $p_{NH} \approx \sin^2\theta_{13} \approx 0.025$ for Normal Ordering,
  $p_{IH} \approx \sin^2\theta_{12} \approx 0.3$ for Inverted Ordering
- Need liquid-Ar detector (DUNE !)
- Flux during the neutronization burst well-predicted
- Oscillations not affected by nonlinear collective effects

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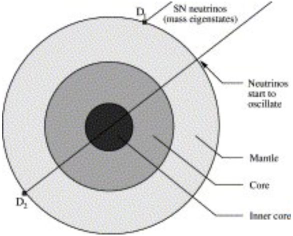
If neutrinos reach the detector through the earth

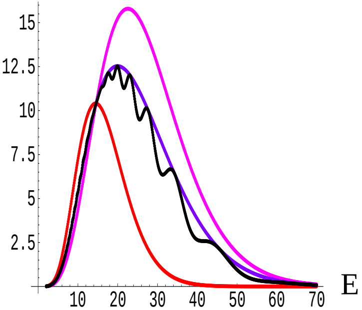


- Mass eigenstates no longer remain mass eigenstates (matter effect)
- Neutrinos start oscillating again !
- p and $\bar{p}$ start having oscillating energy dependence

$$p \approx p_0 + \sin 2\theta_{12}^{\oplus} \sin(2\theta_{12}^{\oplus} - 2\theta_{12}) \sin^2\left(\frac{\Delta m_{\oplus}^2 L}{4E}\right)$$

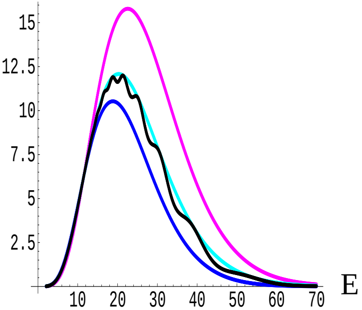
Earth effects on neutrino spectra

Neutrino spectrum



$(\nu_e, \nu_x, \text{mixed } \nu)$

Antineutrino spectrum

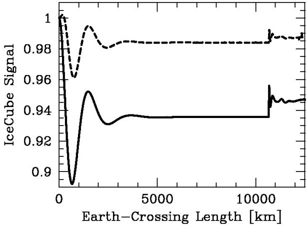


$(\bar{\nu}_e, \bar{\nu}_x, \text{mixed } \bar{\nu})$

- Now the mixed spectra can be (sometimes) identified ...
- Spectral modulations / comparison between two detectors

Earth effects through luminosity comparison

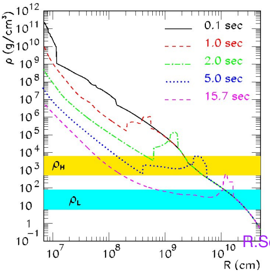
- IceCube primarily meant for neutrinos with $E \gtrsim 150$ GeV
- The number of Cherenkov photons in IceCube increases beyond statistical background fluctuations during a SN burst
- This signal (luminosity) can be determined to a statistical accuracy of $\sim 0.25\%$ for a SN at 10 kpc.



- The extent of Earth effects changes by 3–4 % between the accretion phase (first 0.5 sec) and the cooling phase.
- Absolute calibration not essential.

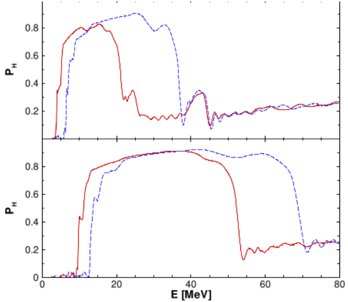
AD, M. Keil, G. Raffelt, JCAP 0306:005 (2003)

Shock wave imprint on neutrino spectra



- When shock wave passes through a resonance region, adiabaticity may be momentarily lost
- Sharp, time-dependent changes in the neutrino spectra

R.Schirato and G.Fuller, astro-ph/0205390, G.Fogli et al., PRD 68 (2003)



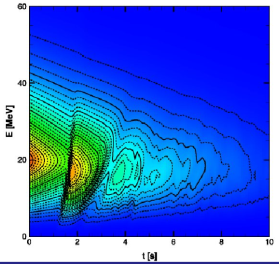
$t = 3, 3.5, 4, 4.5$ sec

- With time, resonant energies increase
- Possible in principle to track the shock wave to some extent

R.Tomas et al., JCAP 09 (2004)

J.Kneller et al., PRD 77 (2008)

Shock wave effects



2D simulation
Positron spectrum
(inverse beta reaction)

Kneller et al., PRD 77 (2008)

Observable shock signals

Time-dependent dip/peak features in $N_{\nu_e,\bar{\nu}_e}(E)$, $\langle E_{\nu_e,\bar{\nu}_e} \rangle$, ...

R.Tomas et al., JCAP 09 (2004), J.Gava et al., PRL 103 (2009)

Identifying mixing scenario: independent of collective effects

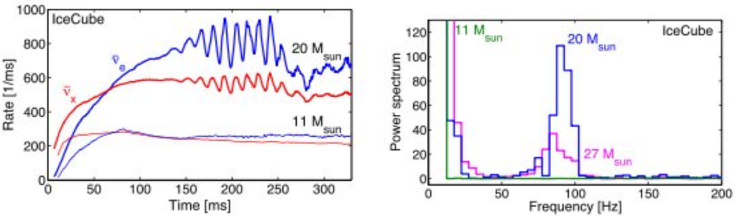
- Shock effects present in ν_e only for NH
- Shock effects present in $\bar{\nu}_e$ only for IH
- Absence of shock effects gives no concrete signal.
  primary spectra too close ? turbulence ?

J.Kneller and C.Volpe, PRD 82 (2010)

Supernova neutrinos

1. Neutrino fluxes from a core-collapse SN
2. Propagation and oscillations of SN neutrinos
   - Passing through MSW resonances and vacuum
   - Nonlinear "collective" oscillations inside the core
3. Implications of SN neutrino observations
   - Early warning and mass ordering
   - Earth matter effects and shock effects
   - SN astrophysics

Detection of SASI instabilities



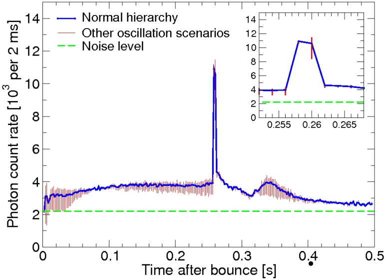
- Standing Accretion Shock Instability: global dipolar and quadrupolar deformations at the shock front
- Imprints even on top of the turbulent motion of matter
- Observable in Icecube event rate, as a high-frequency signal

I.Tamborra et al, PRL 111 (2013)

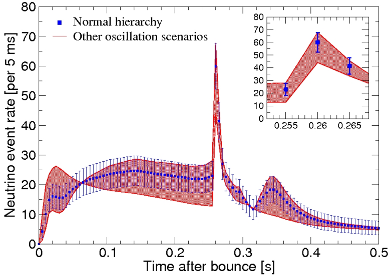
QCD phase transition

- Sudden compactification of the progenitor core during the QCD phase transition
- Prominent burst of $\bar{\nu}_e$, visible at IceCube and SK

IceCube



Super-Kamiokande



B.Dasgupta et al, PRD 81 (2010)

What a single SN can tell us

SN neutrinos for particle physics

- Identification of mass ordering
- Neutronization burst suppression
- Shock wave effects / earth matter effects
- Collective effects and flavour conversion instabilities

SN astrophysics through neutrinos

- Pointing to the SN many hours before it is seen
- Traking the shock wave in neutrinos
- SASI instabilities, explosion mechanism
- Possible QCD phase transition
- Primary fluxes: energies, luminosities

Reviews: F.Capozzi and N.Saviano, Universe 8 (2022), M.C.Volpe, RMP 96 (2024)

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Neutrinos from all past SN: Talk by Y. Ashida

Some open questions...

- What kind of detectors do we need to build ?
- What do we need to understand theoretically,
  to be able to extract maximum possible information ?
  (Collective effects not yet fully understood)
- How would neutrino flavour conversions affect SN explosion ?
- When would the next SN occur in our galaxy ?

tifr