

# Supernova Neutrinos

Production, Oscillations, Detection

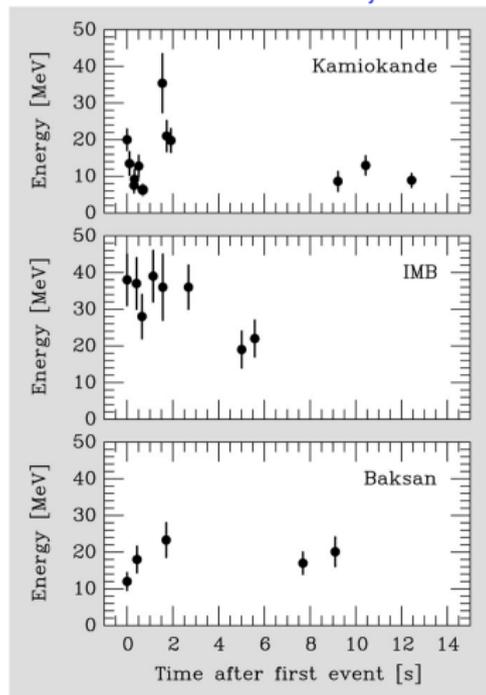
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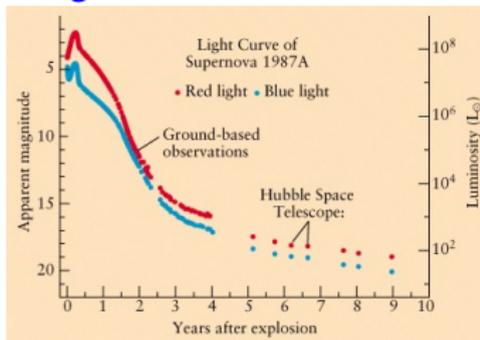
Vietnam School on Neutrinos 2025 (VSON09)  
ICISE, Quy Nhon, Vietnam  
23 July 2025

# SN1987A: neutrinos and light

## Neutrinos: Feb 23, 1987



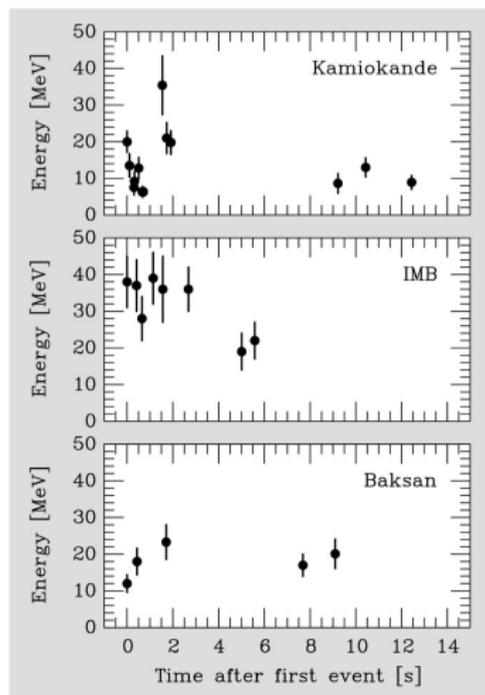
## Light curve: 1987-1997



## 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, ...)

# Why look for neutrinos from a SN ?

- Locate a supernova hours before it is seen in the sky
- Identify neutrino mass ordering
- Observe what is happening “inside” the star
- Understand supernova astrophysics

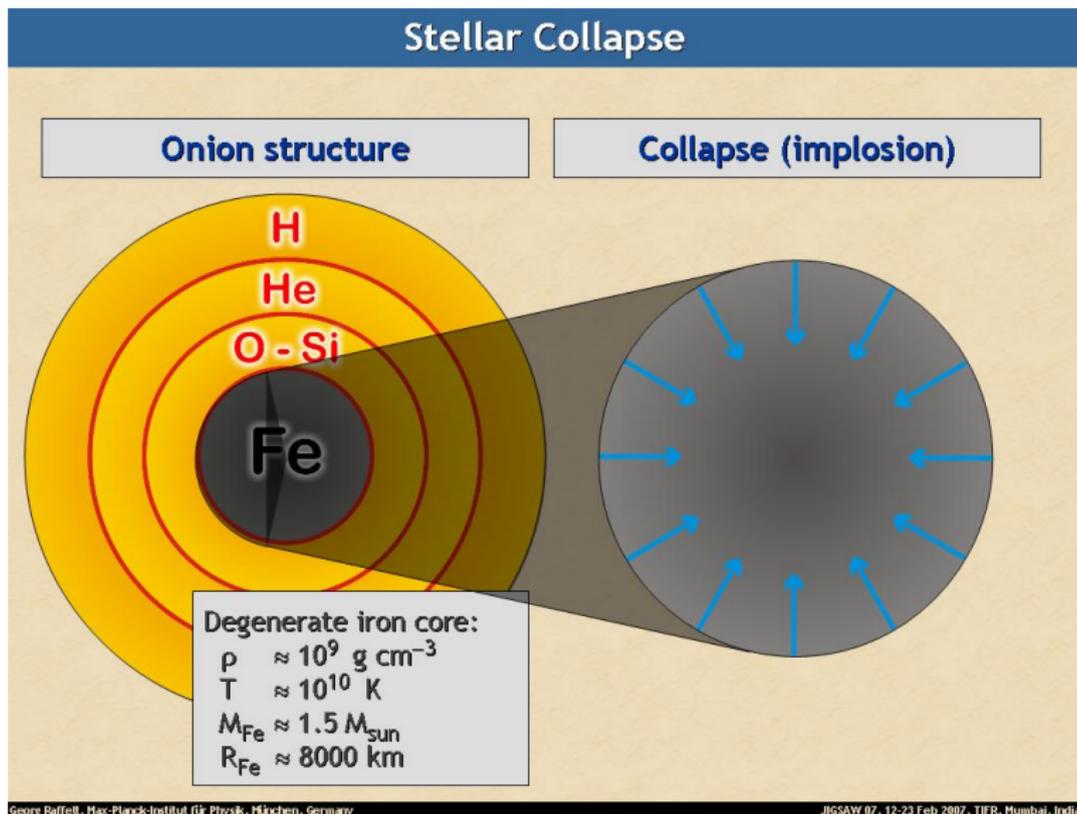
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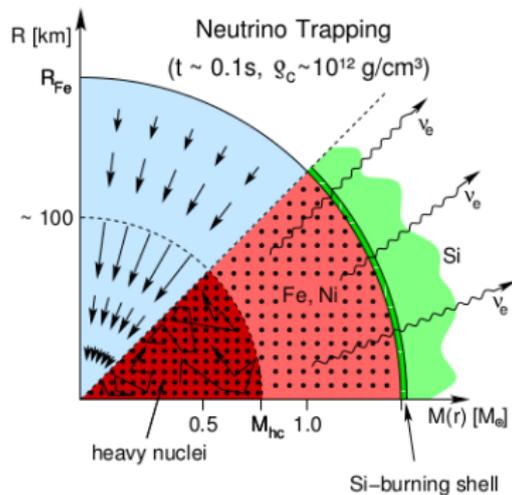
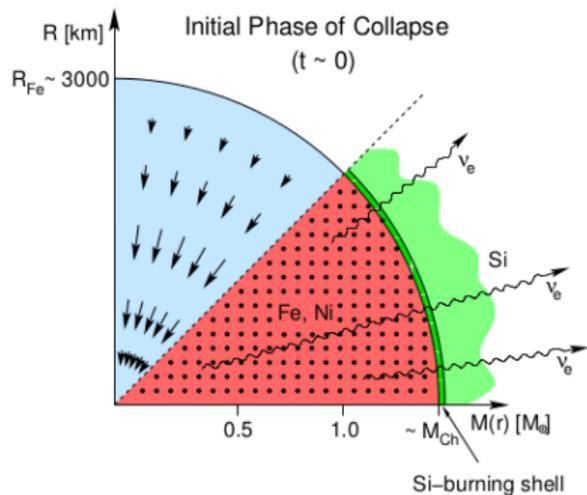
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# Pre-collapse: the onion ring structure



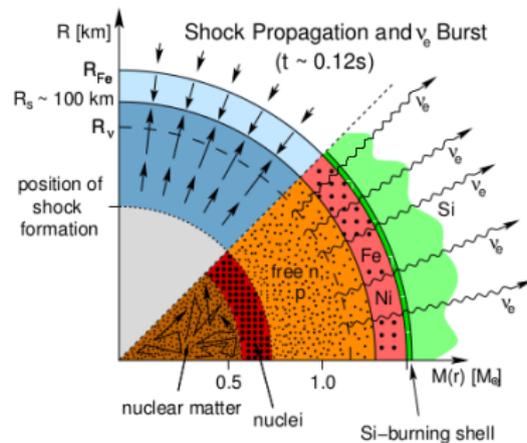
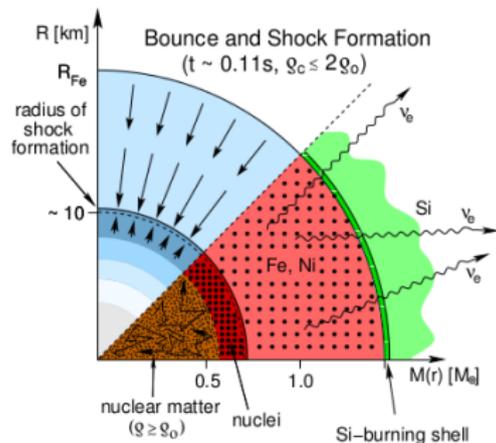
# Trapped neutrinos and neutrinosphere



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

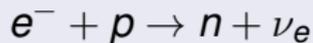
- Neutrinos trapped inside “neutrinospheres” around  $\rho \sim 10^{10} \text{ g/cc}$ .

# Core collapse, Shock, Neutronization burst



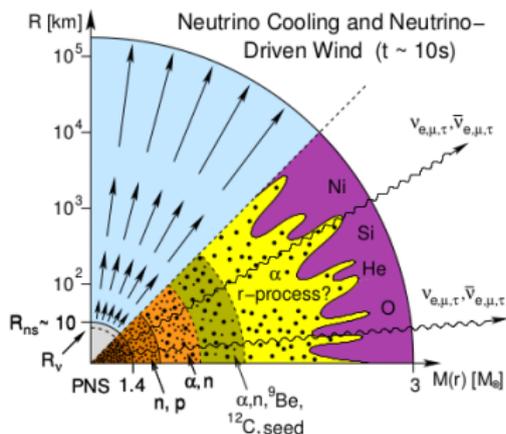
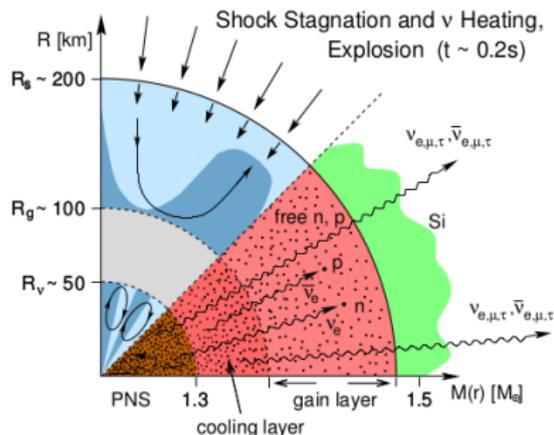
H.T.Janka et al. Phys. Rept 442 (2007)

## Neutronization burst: shock breaks neutrinosphere



$\nu_e$  emitted for  $\sim 10$  ms

# Neutrino cooling and explosion

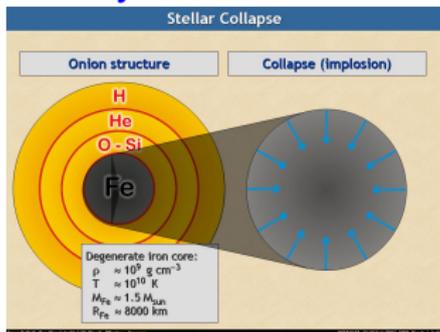


H.T.Janka et al. Phys. Rept 442 (2007)

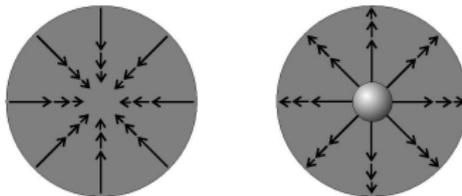
- Neutrino heating essential, but not enough
- Rotation, convection, hydrodynamic instabilities play an important role, but seeded by neutrinos
- Finally,  $\sim 99\%$  of the SN energy ( $\sim 10^{53}$  erg) is emitted as ( $\sim 10^{58}$ ) neutrinos

# Supernova: role of all fundamental forces

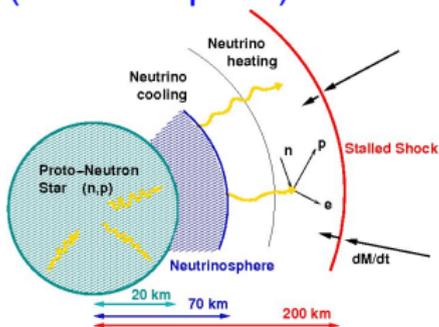
Gravity  $\Rightarrow$



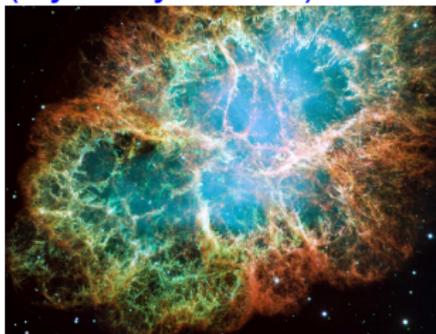
Strong nuclear force  $\Rightarrow$



Weak nuclear force  
(Neutrino push)  $\Rightarrow$



Electromagnetism  
(Hydrodynamics)  $\Rightarrow$



(Crab nebula, SN seen in 1054) 

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# Production and scattering of neutrinos

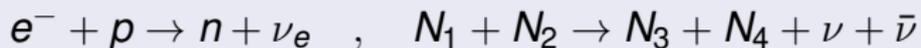
## Production

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

⇒ In general,  $\nu_e$  flux is more.

# Production and scattering of neutrinos

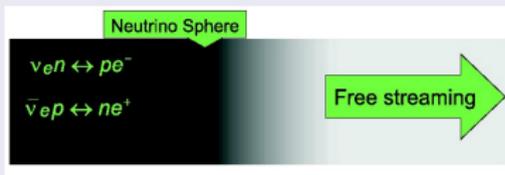
## Production



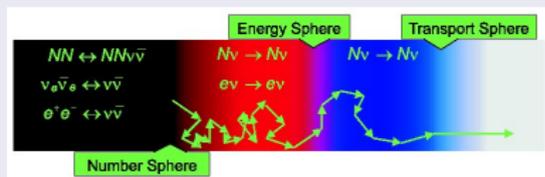
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## Scattering

- For  $\nu_e$  and  $\bar{\nu}_e$ :

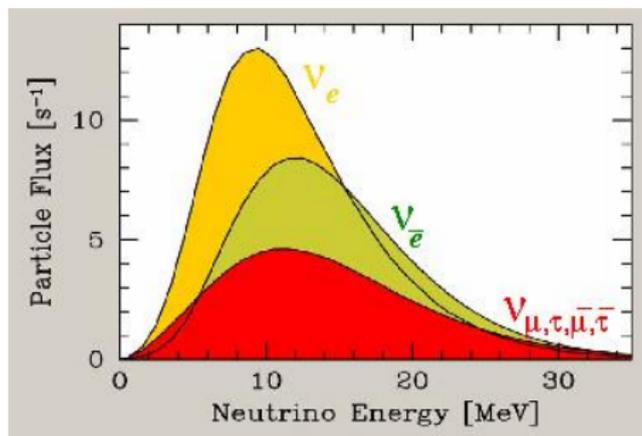


- For all neutrino species ( $\nu_{e,\mu,\tau}, \bar{\nu}_{e,\mu,\tau}$ ):



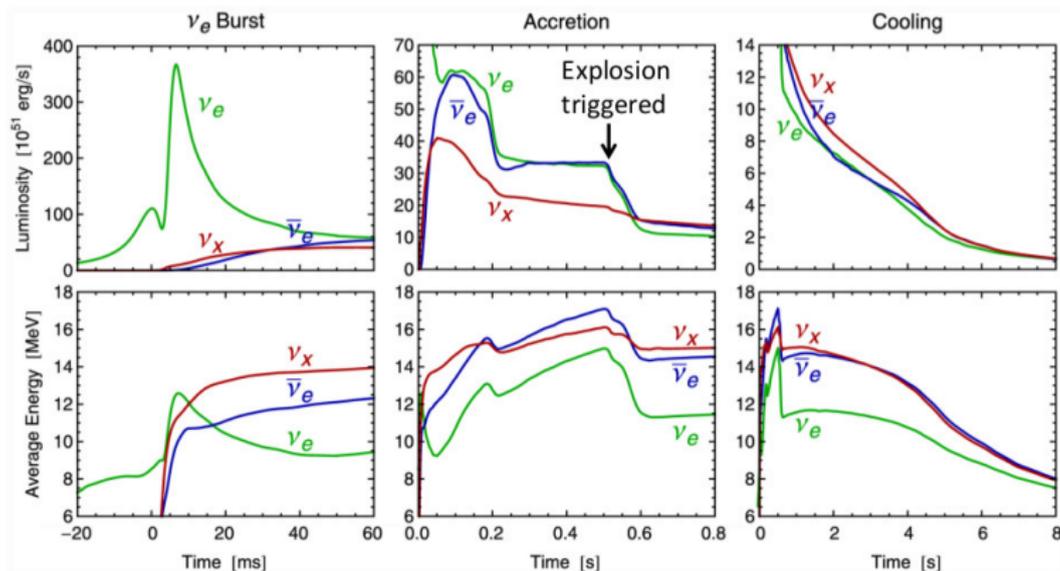
- Escaping neutrinos:  $\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_x} \rangle$

# Typical primary fluxes and spectra



- Almost blackbody spectra, slightly “pinched”
- Energy hierarchy:  $E_0(\nu_e) < E_0(\bar{\nu}_e) < E_0(\nu_x)$
- $E_0(\nu_e) \approx 10\text{--}12$  MeV
- $E_0(\bar{\nu}_e) \approx 13\text{--}16$  MeV
- $E_0(\nu_x) \approx 15\text{--}25$  MeV
- Neutrino oscillations not included

# Neutrino Luminosities and energies in three phases



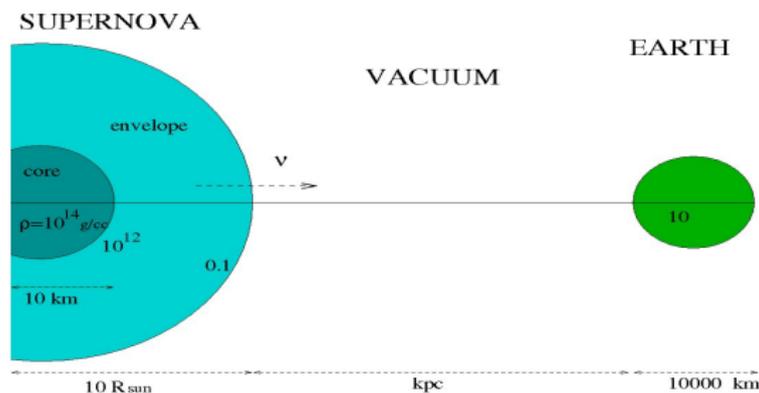
Garching group, ~ 2010

- Approximately thermal spectra
- $\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_\mu, \nu_\tau, \bar{\nu}_\mu, \bar{\nu}_\tau} \rangle$

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# The propagation of neutrinos

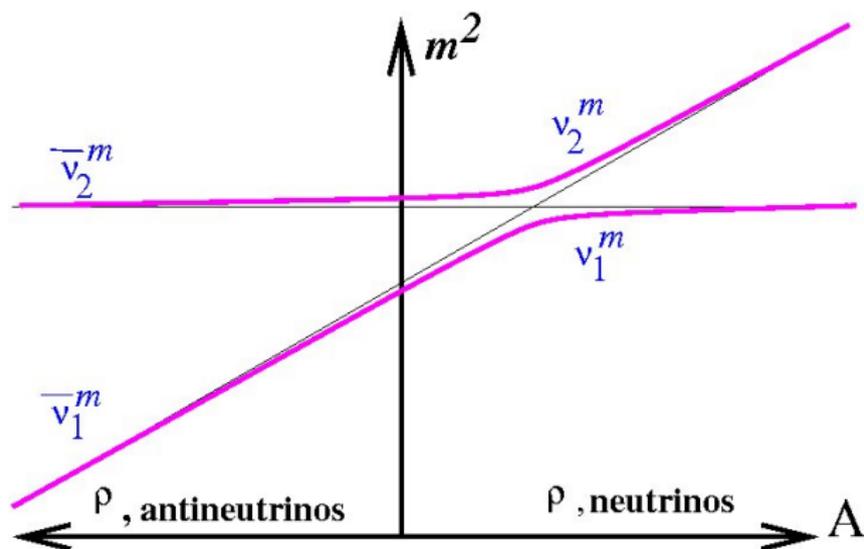


- Extremely high density inside the **core**
- Moderate / small density in the **mantle and envelope**
- **Vacuum** on the way from SN to Earth
- Possible travel through the **Earth**  
(if the detector is on the other side)

# SN neutrinos: production, propagation, detection

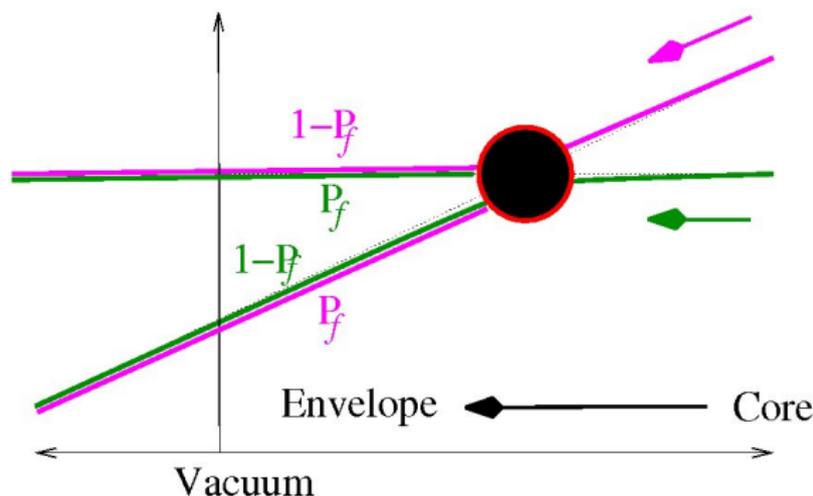
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# MSW resonance (2 flavors)



- For antineutrinos,  $A \rightarrow -A$
- $y$ -axis is vacuum ( $A = 0$ )
  - $x \rightarrow +\infty \Rightarrow$  neutrinos at high densities
  - $x \rightarrow -\infty \Rightarrow$  antineutrinos at high densities

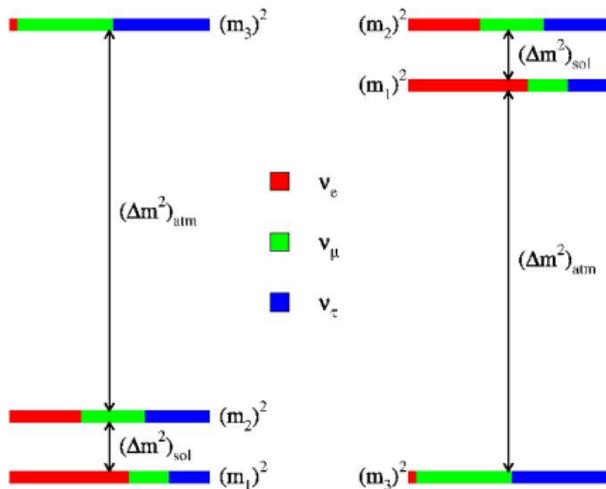
# Passing through a MSW resonance



- At large densities,  $\theta_m = 90^\circ$ ,  $\sin^2 2\theta_m = 0$
- Neutrinos start as flavour eigenstates ( $\nu_{e,\mu,\tau}, \bar{\nu}_{e,\mu,\tau}$ )
- For smooth matter density,  $P_f \approx 0$
- For sharply changing density,  $P_f \neq 0$

# The three-neutrino picture

Mixing of  $\nu_e, \nu_\mu, \nu_\tau \Rightarrow \nu_1, \nu_2, \nu_3$  (mass eigenstates)



Normal ordering

Inverted ordering

- Differences of mass squares:

$$\Delta m_{\text{atm}}^2 \approx 2.4 \times 10^{-3} \text{ eV}^2, \quad \Delta m_{\odot}^2 \approx 8 \times 10^{-5} \text{ eV}^2$$

- Mixing angles:  $\theta_{\text{atm}} \approx 45^\circ$ ,  $\theta_{\odot} \approx 32^\circ$ ,  $\theta_{\text{reactor}} \approx 9^\circ$



# The two resonances

## $H$ resonance

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

## $L$ resonance

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

# Mixing of neutrino fluxes

- Survival probabilities  $p$  and  $\bar{p}$

$$F_{\nu_e} = p F_{\nu_e}^0 + (1 - p) F_{\nu_x}^0, \quad F_{\bar{\nu}_e} = \bar{p} F_{\bar{\nu}_e}^0 + (1 - \bar{p}) F_{\nu_x}^0$$

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- Decoherence in neutrino oscillation phases  $\Rightarrow$   
 $p$  and  $\bar{p}$  approximately constant with energy  
(except during the passage of the shock wave)

$$\frac{\rho_{NH} \approx \sin^2 \theta_{13} \quad | \quad \bar{\rho}_{NH} \approx \cos^2 \theta_{12}}{\rho_{IH} \approx \sin^2 \theta_{12} \quad | \quad \bar{\rho}_{IH} \approx \sin^2 \theta_{13}}$$

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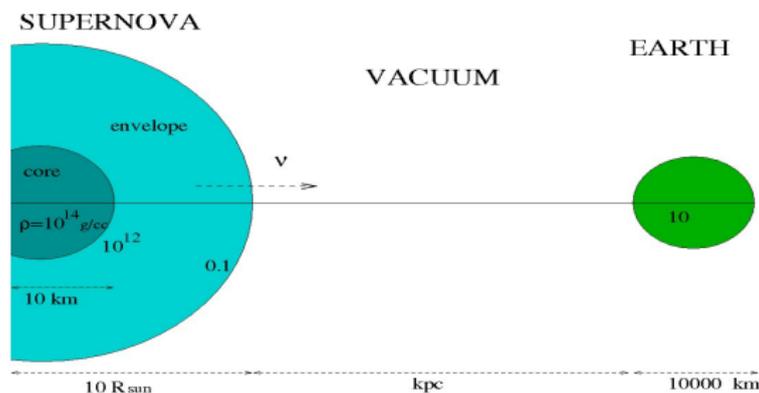
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- $p$  and  $\bar{p}$  depend on mass ordering  $\Rightarrow$   
They can help identify the ordering
- But initial fluxes have to be known accurately, and they should be different !

# Neutrino propagation in mantle, envelope and vacuum



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

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- Now, neutrino mixing depends on neutrino flavours in the background
- But neutrino flavours in the background depend on neutrino mixing !

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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 !
- $\Rightarrow$  Non-linear problem !! (very hard)

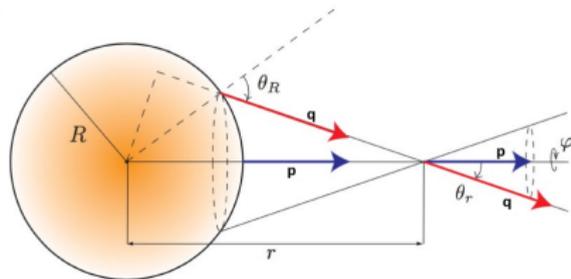
# Non-linearity from neutrino-neutrino interactions

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

$$H_{vac}(\vec{p}) = M^2/(2p)$$

$$H_{MSW} = \sqrt{2}G_F n_{e^-} \text{diag}(1, 0, 0)$$

$$H_{\nu\nu}(\vec{p}) = \sqrt{2}G_F \int \frac{d^3q}{(2\pi)^3} (1 - \cos \theta_{pq}) (\rho(\vec{q}) - \bar{\rho}(\vec{q}))$$



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

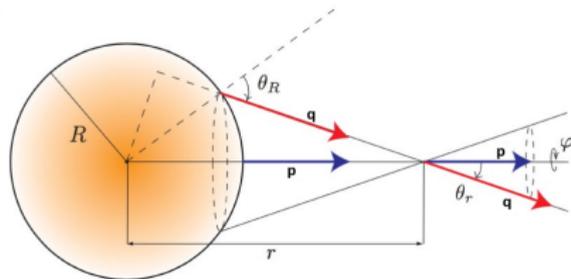
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A.Mirizzi et al. Riv. Nuovo Cim 39 (2016)

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

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

# Nonlinear “Collective” effects: new phenomena

## Synchronized oscillations:

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

NOT like  $\sin^2(\Delta m^2/2E)$

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

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## 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)

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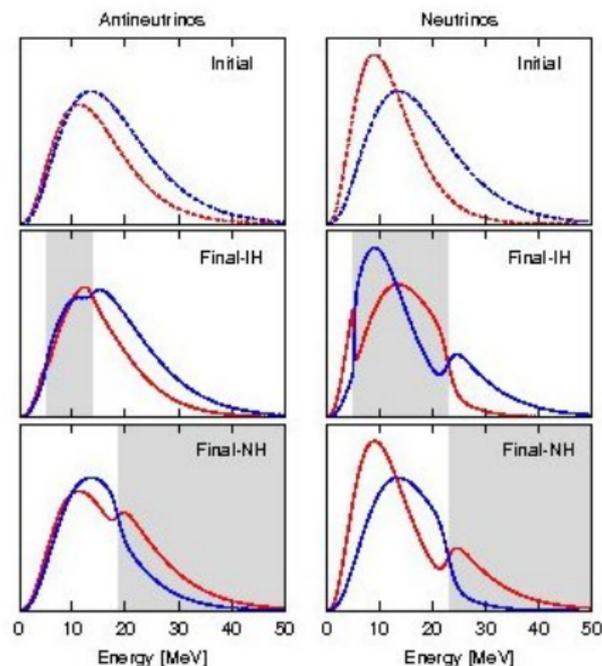
## Spectral split/swap:

$\nu_e$  and  $\nu_x$  ( $\bar{\nu}_e$  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)

# Multiple spectral splits



- Spectral splits as boundaries of swap regions
- Splits possible both for  $\nu_e$  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)

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

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

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

S.Shalgar and I.Tamborra JCAP 2024

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

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- Is that necessary and sufficient ?

B.Dasgupta and D.Mukherjee, arXiv 2025

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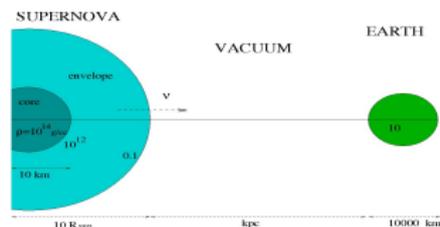
- Is that necessary and sufficient ?

B.Dasgupta and D.Mukherjee, arXiv 2025

- What is the effect of collisions ?

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

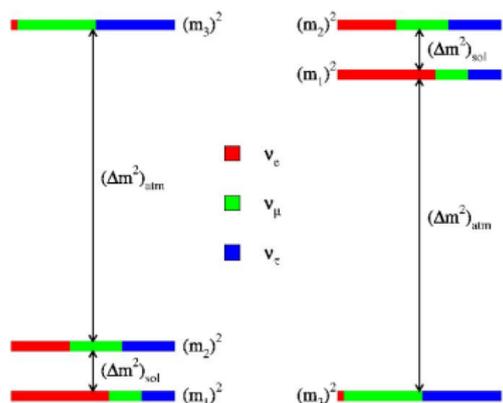
# The net picture



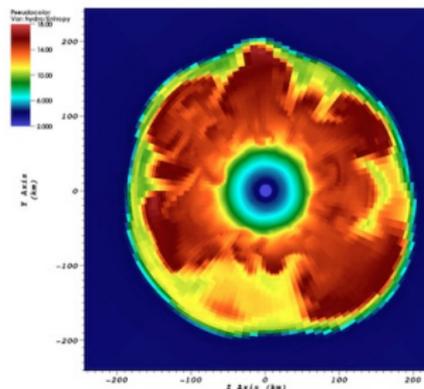
- Deep inside the SN core, neutrinos trapped
- After collapse, neutrinos of different flavours emitted
- While still inside the core  $r \sim 10$  km, they can undergo fast collective non-linear oscillations due to  $\nu-\nu$  interactions
- Around  $r \sim 1000$  km, matter effects, H and L resonances
- 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



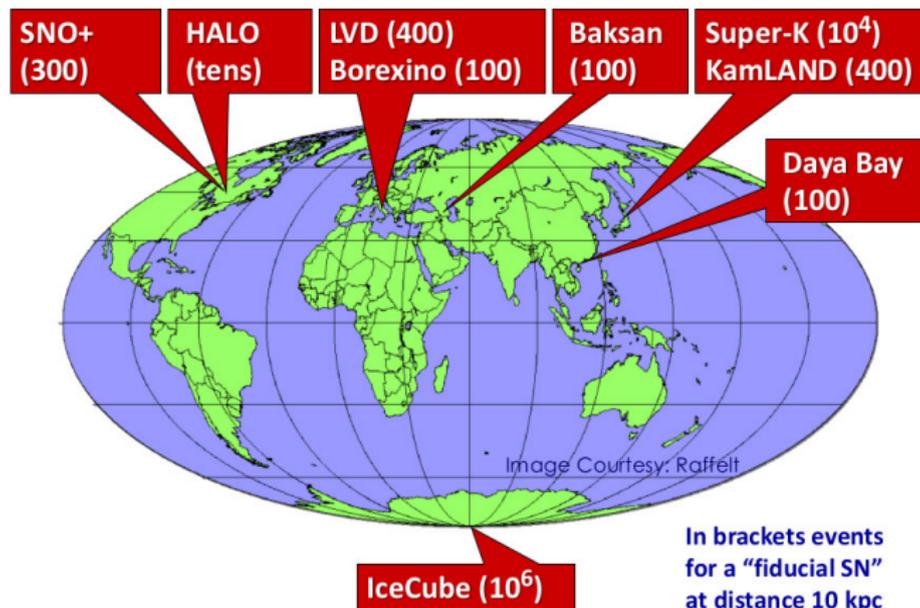
## About supernova interior



# SN neutrinos: production, propagation, detection

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# SN detectors around the globe



## Upcoming:

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

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

## Water Cherenkov detector: (events at SK)

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

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

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

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

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

# What are the observables ?

- The spectrum of  $\nu_e$  (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)

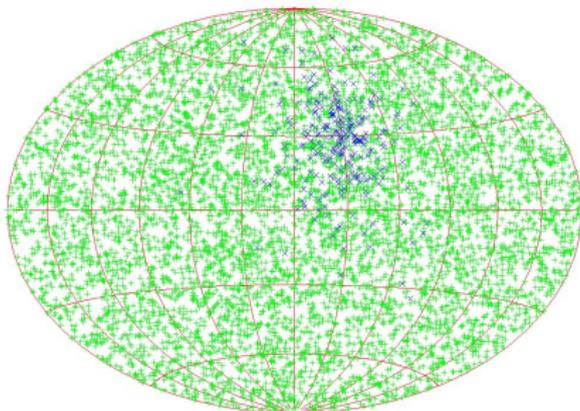
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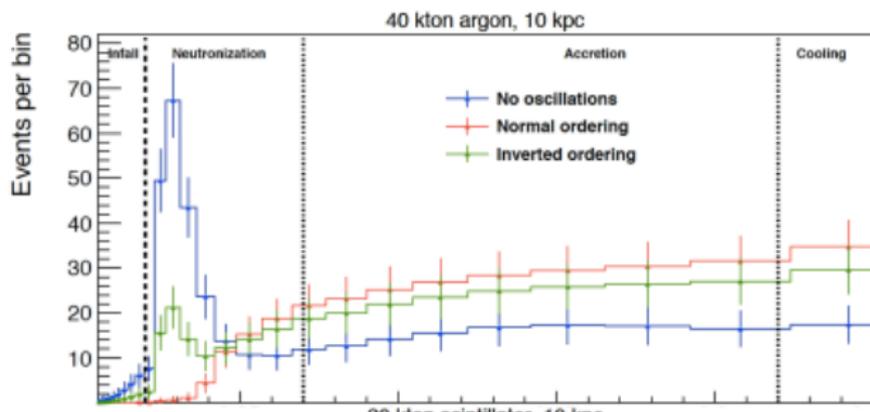
# Pointing to the SN in advance

- 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
- The Gd added to SK makes the pointing much better...

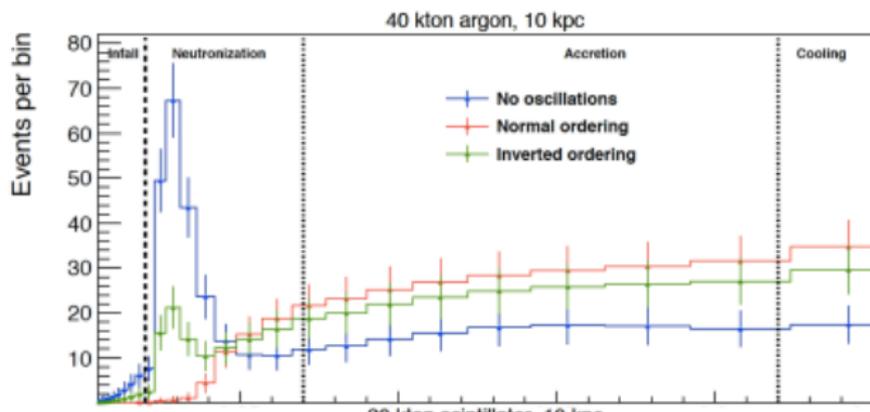
J.Beacom and P.Vogel, PRD 60 (1999), R.Tomas et al PRD 68 (2003)



# Suppressed neutronization ( $\nu_e$ ) burst



# Suppressed neutronization ( $\nu_e$ ) burst



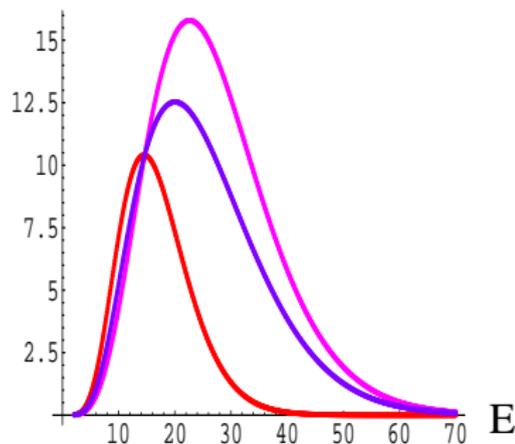
DUNE collaboration, Preliminary

## Mass hierarchy identification

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

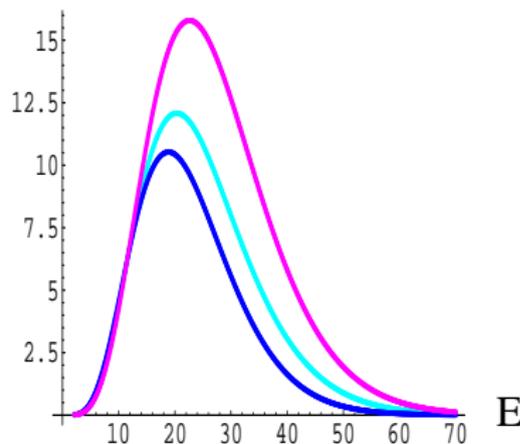
# Is observing the fluxes enough ?

Neutrino spectrum



( $\nu_e$ ,  $\nu_x$ , mixed  $\nu$ )

Antineutrino spectrum



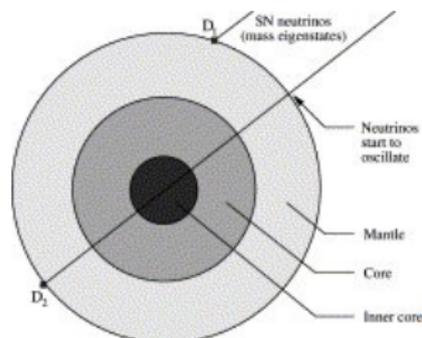
( $\bar{\nu}_e$ ,  $\bar{\nu}_x$ , mixed  $\bar{\nu}$ )

- If initial fluxes are not well known, difficult to find  $p$  or  $\bar{p}$  by just looking at final fluxes

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# If neutrinos reach the detector through the earth

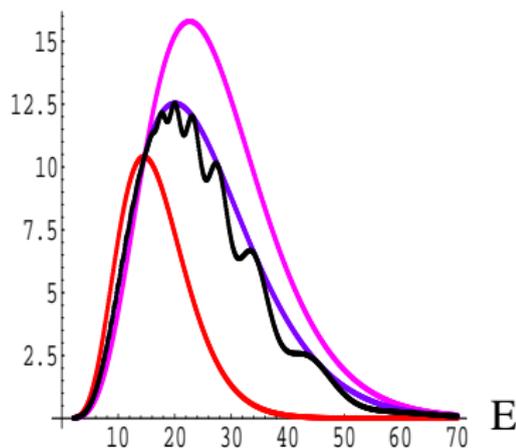


- Mass eigenstates no longer remain mass eigenstates (matter effect)
- Neutrinos start oscillating again !
- $p$  and  $\bar{p}$  start having oscillating energy dependence

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

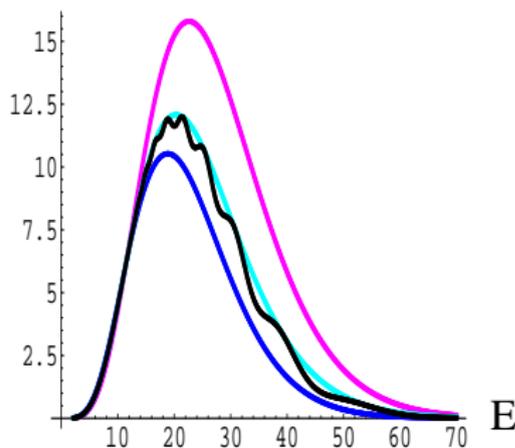
# Earth effects through spectral modulations

Neutrino spectrum



( $\nu_e$ ,  $\nu_x$ , mixed  $\nu$ )

Antineutrino spectrum



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

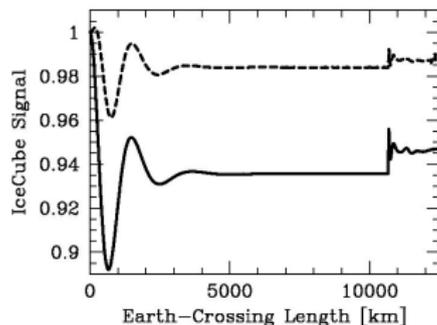
- Now the mixed spectra can be (sometimes) identified ...
- Peak expected in Fourier transforms...

AD, M.Keil, G.Raffelt, JCAP 06 (2003)

E.Boriello et al. PRD 86 (2012)

# 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.



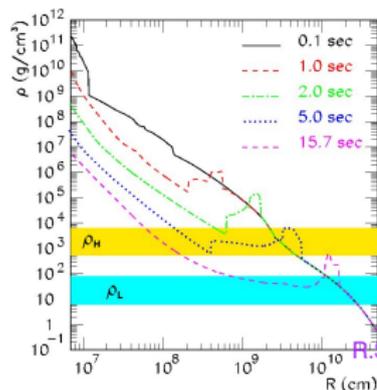
- The extent of Earth effects changes by 3–4 % between the **accretion phase** (first 0.5 sec) and the **cooling phase**.
- Absolute calibration not essential.

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

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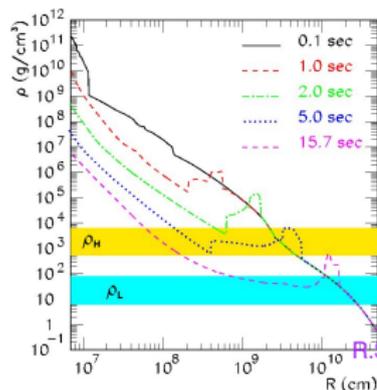
# Shock wave imprint on neutrino spectra



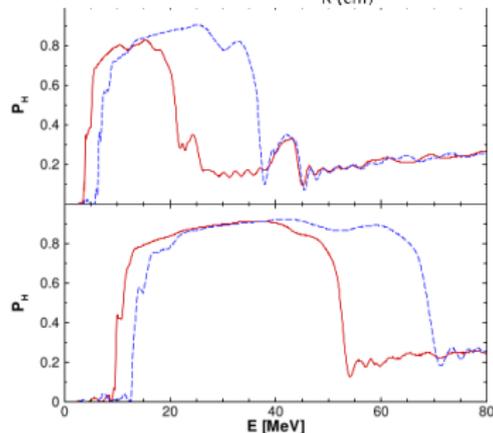
R. Schirato and G. Fuller, astro-ph/0205390, G. Fogli et al., PRD 68 (2003)

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

# Shock wave imprint on 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

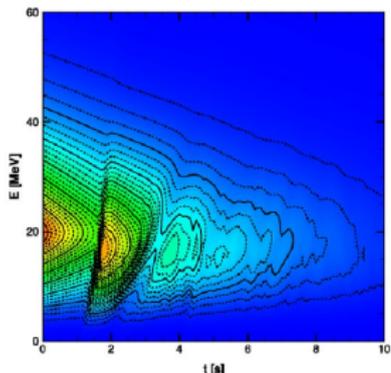
- When shock wave passes through a resonance region, **adiabaticity may be momentarily lost**
- Sharp, time-dependent changes in the neutrino spectra

- With time, affected (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

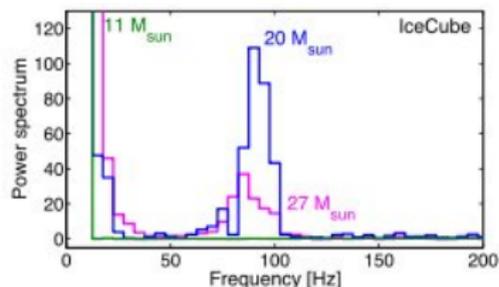
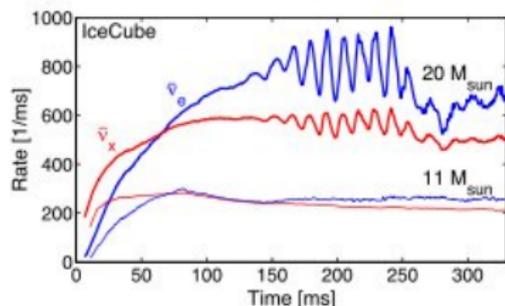
- Shock effects present in  $\nu_e$  only for NH
- Shock effects present in  $\bar{\nu}_e$  only for IH
- Absence of shock effects gives no concrete signal.  
primary spectra too close ? turbulence ?

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

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# Detection of SASI instabilities



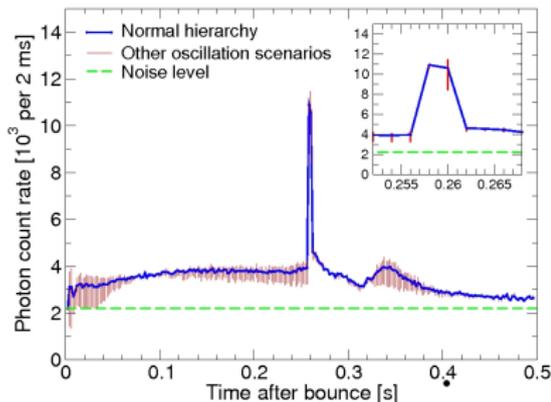
- **Standing Accretion Shock Instability:** global dipolar and quadrupolar deformations at the shock front
- Imprints even on top of the turbulent motion of matter
- Observable in Icecube event rate, as a high-frequency signal

I. Tamborra et al, PRL 111 (2013)

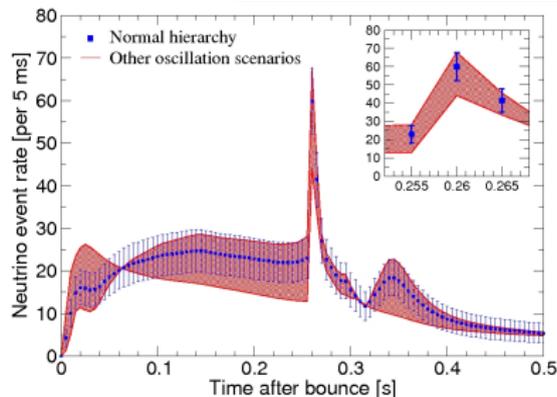
# QCD phase transition

- 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

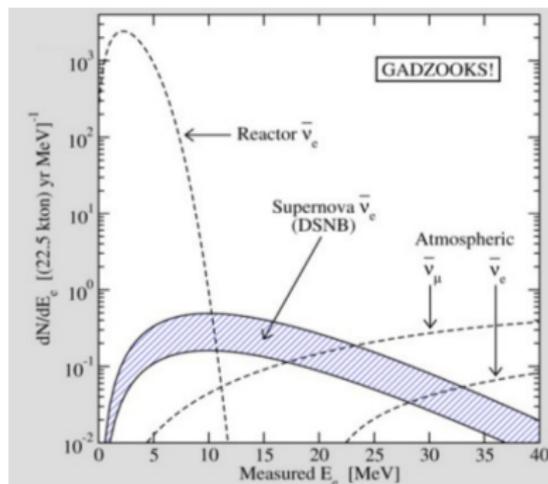


B.Dasgupta et al, PRD 81 (2010)

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# Diffused SN neutrino background



- Collective effects affect predictions of the predicted fluxes by up to  $\sim 50\%$

S.Chakraborty, S.Choubey, B.Dasgupta, K.Kar, JCAP 08 (2009)

- Shock wave effects can further change predictions by  $10 - 20\%$

S.Galais, J.Kneller, C.Volpe, J.Gava, 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

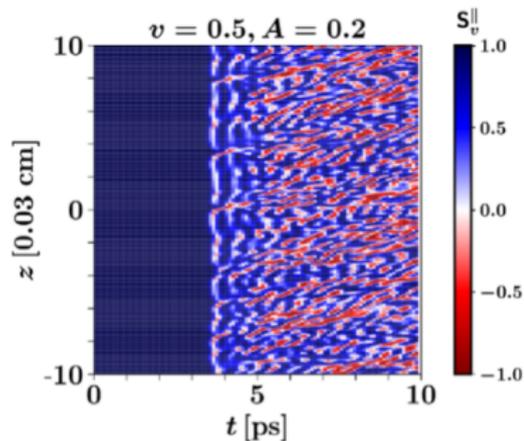
- Pointing to the SN many hours before it is seen
- Tracking the shock wave in neutrinos
- SASI instabilities, explosion mechanism
- Possible QCD phase transition
- Primary fluxes: energies, luminosities

# Question for thinking...

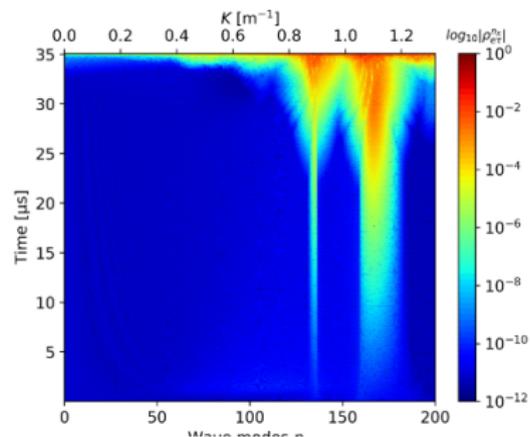
- What kind of detectors do we need to build ?
- What do we need to understand theoretically, to be able to extract maximum possible information ?  
(Collective effects not yet fully understood)
- How would neutrino flavour conversions affect SN explosion ?
- When would the next SN occur in our galaxy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

# Backup slides

# How fast do fast oscillations start

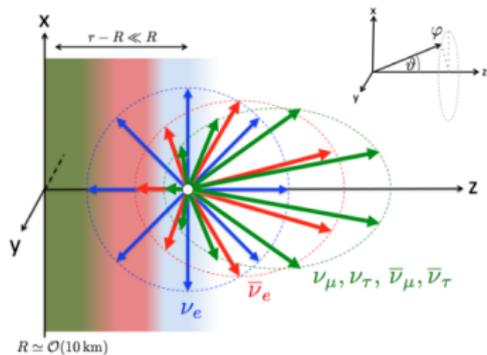


S.Bhattacharya and B.Dasgupta PRD 102 (2020)

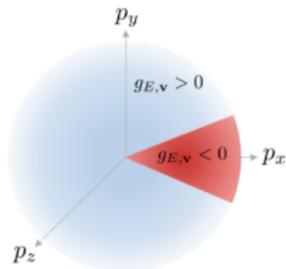


M.Zaizen and T.Morinaga, PRD 104 (2021)

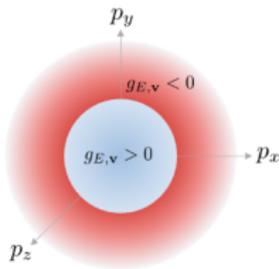
# What is this “spectral crossing”?



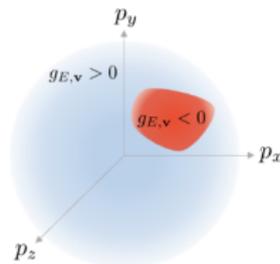
B.Dasgupta, A.Mirizzi and M.Sen, JCAP 02 (2017)



Fast Crossing



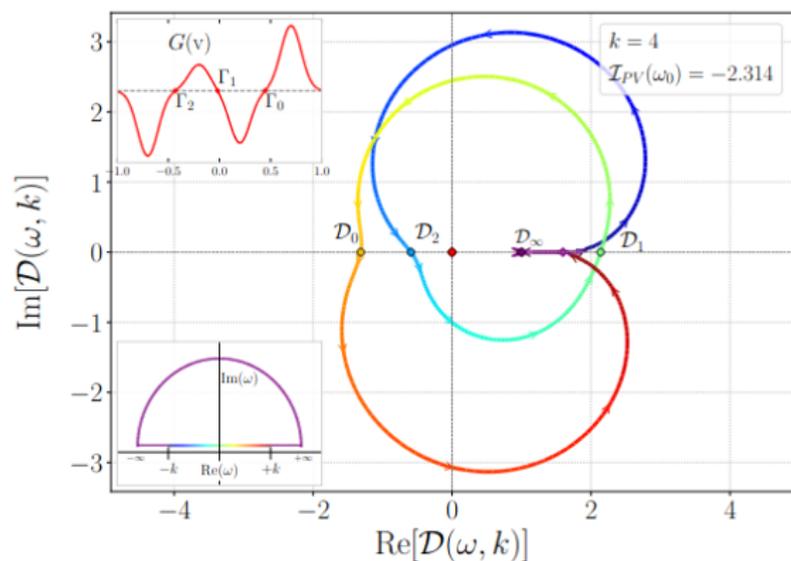
Slow Crossing



Mixed Crossing

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