Supernova Neutrinos: Current Challenges

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What are supernovae?

When nuclear fuel ends, massive stars (> 8 M⊙) start collapsing.

The density in the core rapidly increases.
What are supernovae?

The density reaches nuclear saturation $\rho \sim 10^{14} \text{ g/cm}^3$

A shock wave is produced blowing up the star (Supernova)
What are supernovae?

\[ R_{\text{NS}} \sim 10 \text{ km} \]

\[ E_{\text{g}} \sim 10^{53} \text{ erg} \]

\[ E_{\text{exp}} \sim 1\% E_{\text{g}} \]

\[ E_{\gamma} \sim 0.01\% E_{\text{g}} \]
What is the role of neutrinos?

$\nu / \bar{\nu}$ of all flavor carry away 99% of $E_g$ in $\sim 10s$ seconds

Neutrinos are messengers from the interior of the exploding star.
What is the role of neutrinos?

The shock wave stalls after ~ few 10 ms

Neutrinos might revive the shock through energy deposition

\[ \nu_e + n \rightarrow e^- + p \]

\[ \bar{\nu}_e + p \rightarrow e^+ + n \]
What is the role of neutrinos?

What have we learnt so far?

Supernova 1987a

First and only neutrinos observed from a supernova
What have we learnt so far?

Confirmed expectation for neutrino emission

Constraints on neutrino properties and on exotic particles

Indication for an asymmetric explosion
Are we ready for SN20xy?

The supernova neutrinos chain

- Explosion mechanism
- Flavor conversions
- Neutrino detection
Are we ready for SN20xy?

The supernova neutrinos chain

Neutrino properties

Explosion mechanism

Flavor conversions

Neutrino detection
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- Astrophysics
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If even one ring breaks everything might fall apart!!!

- Neutrino properties
- BSM physics
- Astrophysics
Are we ready for SN20xy?

Each aspect of the chain to **MUST** be well understood.

- Explosion mechanism
- Flavor conversions
- Neutrino detection
- Neutrino properties
- BSM physics
- Astrophysics

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Are we ready for SN20xy?

Each aspect of the chain to **MUST** be well understood

- Explosion mechanism
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We review the status of each step in the chain
The era of 3D simulations

Successful explosions for low mass progenitors (< 10 M⊙)

Faster explosions in multi-D compared to 1D


see also


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The era of 3D simulations

Multi-D simulations allows convective / turbulent instabilities

Convective instabilities favor neutrino heating and explosions
The era of 3D simulations

Less consistent picture for heavy progenitor masses

Example: s-quark contribution in $\nu$-n NC creates explosion
The era of 3D simulations

Less consistent picture for heavy progenitor masses

Example: fast rotation induced explosion
The era of 3D simulations

Less consistent picture for heavy progenitor masses

Hypothesis 1

The delayed neutrino mechanism is **NOT** robust
The era of 3D simulations

Less consistent picture for heavy progenitor masses

Hypothesis 1

The delayed neutrino mechanism is **NOT** robust

Hypothesis 2

The delayed neutrino mechanism **IS** robust. Simulations are missing some key ingredients

More refined simulations will give the answer
Sloshing/spiraling (SASI) motion of the shock modulates $L_\nu$

Neutrinos are probe of the explosion mechanism

H.T. Janka
“Neutrino Emission from Supernovae”
arXiv:1702.08713
Multi-D neutrino signal features

Lepton number is emitted asymmetrically (LESA)

Neutrinos are probe of the explosion mechanism

confirmed by

Neutrinos are probe of the explosion mechanism
Are we forgetting something?

No 2D / 3D simulations include Flavor Conversions

Neutrino heating is flavor dependent!!!

\[ \nu_e + n \rightarrow e^- + p \]

\[ \bar{\nu}_e + p \rightarrow e^+ + n \]
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We review the status of each step in the chain
Flavor conversions: overview

Impact on detection, nucleosynthesis

PNS

$\nu_\alpha$

$\nu_\alpha$

$\nu_\beta$

$\nu_\beta$

Shock

R [km]

0 10 few 100 1000
Flavor conversions: overview

Impact on detection nucleosynthesis explosion

$\nu_{\alpha}$

$\nu_{\beta}$

$R \text{ [km]}$

PNS

few 100

1000

0 10
Well known MSW resonances happening in the outer layers

\[ P_{ee} (NO) = 0 \]
\[ P_{ee} (IO) = \sin^2 \theta_{12} \]

MSW resonance

When does it happen?

Chakraborty, Bhattacharjee, Kar, Phys. Rev. D 89 (2014) no.1, 013011
Self induced flavor conversion

$\nu\nu$ interactions are relevant: spectral splits?

Hannestad, Raffelt, Sigl, Wong, 2006, Duan, Fuller, Carlson, Qian, 2006, many others, …
Self induced flavor conversion

Instability under tiny space inhomogeneities: decoherence?

Raffelt, Sarikas, Seixas 2013, Mangano, Mirizzi, Saviano 2014-2015, Duan, Shalgar 2014, …
Self induced flavor conversion

Time instabilities avoid matter suppression?

PNS

\[ \nu_e \rightarrow \nu_e \]

\[ \nu_e \rightarrow \nu_e \]

\[ \nu_e \rightarrow \nu_e \]

\[ \nu_e \rightarrow \nu_e \]

\[ \nu_e \rightarrow \nu_e \]

\[ \nu_e \rightarrow \nu_e \]

Less clear picture:
work needed

Dasgupta, Mirizzi 2015, Duan, Abbar, 2015, Capozzi, Dasgupta, Mirizzi 2016, …
Self induced flavor conversion

When does it happen?

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Fast self induced flavor conversion

Mixing independent, driven by vv potential: fast decoherence?


Dasgupta, Mirizzi, Sen 2017

see also

Abbar, Volpe 2018

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When does it happen?

- Neutronization
- Accretion
- Cooling

\( \langle E_\nu \rangle (\text{MeV}) \)

\( L_\nu (10^{53}\text{ ergs/s}) \)

\( t_{p.b}(s) \)

Chakraborty, Bhattacharjee, Kar, Phys. Rev. D 89 (2014) no.1, 013011

Fast self induced flavor conversion

Main requirement for FAST conversions: angular crossing

Izaguirre, Raffelt, Tamborra 2016, Capozzi, Dasgupta, Lisi, Marrone, Mirizzi 2017, Abbar, Duan 2017, Capozzi, Dasgupta, Mirizzi, Sen, Sigl 2018, Shalgar, Tamborra 2018, ...

Collisions are important!!
Fast self induced flavor conversion

Are supernovae simulations showing any sign of crossing?

Capozzi, Dasgupta, Glas, Janka, Mirizzi, Sen, Sigl, in preparation

see also
Tamborra, Huedepohl, Raffelt, Janka, 2017
Abbar, Duan, Sumiyoshi, Takiwaki, Volpe, 2018
Azari, Yamada, Morinaga, Iwakami, Okawa, Nakagura, Sumiyoshi 2019
Morinaga, Nakagura, Kato, Yamada, 2019

More work needed for a conclusive assessment
Fast self induced flavor conversion

Assuming they occur, what is their impact on the explosion?

\[ \frac{T_{\text{simul}}}{T_{\text{conv}}} \sim \frac{10^{-3}}{10^{-9}} \text{ s} \]

Very challenging numerically. Effective approach?

see Richers, McLaughlin, Kneller, Vlasenko 2019
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Water Cherenkov

SuperK (32 kton): main channel IBD

Very precise measurement of $\bar{\nu}_e$, both time and energy
Water Cherenkov

SuperK + Gd (2021): 90% tagging of $\bar{\nu}_e$

$\nu_e$ becomes accessible (~100 events)

Hyper-Kamiokande Collaboration, "Hyper-Kamiokande Design Report,"
Water Cherenkov

IceCube sees excess of DOM hits over noise (mostly $\overline{\nu}_e$)

Most precise for studying temporal evolution (SASI,…)

Liquid scintillator

Low threshold allows sensitivity for $\nu$-proton elastic scattering


Unique probe for $\nu_x$
Liquid Argon

Dominant channel: $\nu_e + {}^{40}\text{Ar} \rightarrow e^- + {}^{40}\text{K}^*$

Best precision on $\nu_e$ (need improvements on cross section)

Jost Migenda, talk at Nuphys 2017
Multi-messenger


Log (luminosity $[\text{erg s}^{-1}]$)

- pre-SN $\bar{\nu}_e$
- progenitor

Log (time relative to bounce [s])

$\nu_e$, $\bar{\nu}_e$, $\nu_x$, GW, EM, SBO, plateau
Multi-messenger

Neutrinos produce an alert for other observatories

- Water Cherenkov
- Liquid Scintillator
- Liquid Argon

Telescopes: LIGO, VIRGO, ...

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Multi-messenger

Neutrino pointing help light collection in telescopes

$\delta \theta \sim \text{few degrees for SuperK}$

Beacom, Vogel, Phys. Rev. D 60 (1999) 033007
Multi-messenger

Neutrinos and GW carry important information from the PNS

Westernacher-Schneider, O’Connor, O’Sullivan, Tamborra, Wu, Couch and Malmenbeck, arXiv:1907.01138

Oscillation modes (asteroseismology) can be probed
Conclusions

- A lot of progress made so far, but still plenty of work ahead
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- Everything is equally important: explosion, flavor, detection
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- Everything is equally important: explosion, flavor, detection

- $\nu + GW + \gamma$ are the key for a full understanding
Thank you