High-Energy Neutrinos from Supernovae: New Prospects for the Next Galactic Supernova

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Neutrinos: Unique Probe of Cosmic Explosions

Super-K

~10 MeV neutrinos from supernova
thermal: core’s grav. binding energy
- supernova explosion mechanism
- progenitor
- neutrino properties, new physics
Super-K can detect ~8,000 \( \nu \) at MeV (at 8.5 kpc)

IceCube

GeV-PeV neutrinos from supernova?
non-thermal: shock dissipation
- physics of cosmic-ray acceleration
- progenitor & mass-loss mechanism
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IceCube/KM3Net can detect ??? \( \nu \) at TeV
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Early Diffusive Shock Acceleration in Supernovae?

- CR and high-energy neutrino production is initially negligible; most of energy is in a kinetic form until the Sedov time.
  - uniform ISM: CR energy $\propto$ dissipation energy $\propto t^3$

- But situations are different when circumstellar material (CSM) exists.
  - many observational evidences in the recent several years

(Raffaella Margutti’s talk)
Evidence of Strong Interactions w. Dense CSM

SN 2010jl (IIn)

Fransson+14 ApJ

log \(_{10} \text{erg} \text{s}^{-1}\)

log(Days after first detection)

SN 2014C (Ib->IIn)

Margutti et al. 16

b

c

Time (days)

Time (days)

Pre-explosion Source

SN 2010jl on several occasions. The data were reduced using

Dense CSM

examples of strong interactions w. dense wind or CSM (IIn, SLSN-II)
Evidence for Dense Material in Ordinary SNe II

Extended material is common even for Type II-P SNe
→ \( \dot{M} \approx 10^{-3} - 10^{-1} \, M_\odot \, \text{yr}^{-1} \) (\(\gg 3 \times 10^{-6} \, M_\odot \, \text{yr}^{-1} \) for RSG)

early spectroscopy (Yaron+ 16 Nat. Phys.)

see also light curve modeling Morozova+ 17 ApJ
Supernovae with Interactions with CSM

kinetic energy $\rightarrow$ thermal + non-thermal via shock,

$p + p \rightarrow N\pi + X$

$\pi^\pm \rightarrow \nu_\mu + \bar{\nu}_\mu + \nu_e(\bar{\nu}_e) + e^\pm$

$\pi^0 \rightarrow \gamma + \gamma$

dense environments = efficient $\nu$ emitters (calorimeters)
equation of motion of the shocked ejecta

\[ M_{\text{sh}} \frac{dV_s}{dt} = 4\pi R_s^2 [\varrho_{\text{ej}} (V_{\text{ej}} - V_s)^2 - \varrho_{\text{cs}} (V_s - V_w)^2] \]

self-similar solution (Chevalier 82)

shock radius

\[ R_s = X(w, \delta) D^{-\frac{1}{\delta - w}} E_{\text{ej}}^{\frac{\delta - 3}{2(\delta - w)}} M_{\text{ej}}^{-\frac{\delta - 5}{2(\delta - w)}} t^{\frac{\delta - 3}{\delta - w}} \]

CSM parameter

\[ D = \frac{\dot{M}_w}{4\pi V_w} \]

\[ E_{\text{ej}} \sim 10^{51} \text{ erg}, M_{\text{ej}} \sim 10 \, M_{\odot} \]

\( w=2 \) for a wind CSM \hspace{1cm} \( \delta \sim 10-12 \) for typical progenitors

dissipation luminosity

\[ L_d = 2\pi \varrho_{\text{cs}} V_s^3 R_s^2 \propto t^{\frac{6w - 15 + 2\delta - \delta w}{\delta - w}} \]

parameters can be determined by photon (opt, X, radio) observations!
\[ E_d \sim E_{\text{ej}} (>V_s) \] in the detailed model, different from \( E_d \sim (M_{\text{cs}}/M_{\text{ej}}) E_{\text{ej}} \) by KM+11
Diversity of Core-Collapse Supernovae

Core-Collapse SN Fractions

Type II SN frac. ~ 2/3

<table>
<thead>
<tr>
<th>Class</th>
<th>$D_*$</th>
<th>$M_w$ [$M_\odot$ yr$^{-1}$]</th>
<th>$V_w$ [km s$^{-1}$]</th>
<th>$R_*$ [cm]</th>
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<td>$10^{-1}$</td>
<td>100</td>
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<tr>
<td>II-P$^a$</td>
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<tr>
<td>II-P$^b$</td>
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<td>15</td>
<td>$6 \times 10^{13}$</td>
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<td>II-L/IIb</td>
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<td>$3 \times 10^{-5}$</td>
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<td>$6 \times 10^{12}$</td>
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<tr>
<td>Ibc</td>
<td>$10^{-5}$</td>
<td>$10^{-5}$</td>
<td>1000</td>
<td>$3 \times 10^{11}$</td>
</tr>
</tbody>
</table>

w. pre-SN mass loss
stellar wind only
Neutrino Light Curve

t_{onset} \sim \text{time leaving the star (typical) or breakout time (II\ln)}
slowly declining light curve while pion production efficiency \sim 1
Fluence for an integration time at which S/B^{1/2} is maximal (determined by the detailed time-dependent model)
Prospects for Neutrino Detection

~ 10-1000 events for Type II supernovae at 10 kpc
~ 0.01-0.1 events for Ibc (but see Kashiyama, KM+ 13 ApJL)
Some Remarks

- Testable & clear predictions (no need for jets, winds, shocks in a star)
  free parameters: $\varepsilon_{\text{CR}}$ & $s \Leftrightarrow$ shock acceleration theory ($\varepsilon_{\text{CR}} \sim 0.1$ & $s \sim 2.0-2.3$)

- Time window
  depends on SN types; guidelines are provided by the theory ($f_{pp} \sim t_{\text{dyn}}/t_{pp} \sim 1$)
  e.g., characteristic time window: $\sim 1$-10 day for SNe II

- Energy range
  IceCube/KM3Net: TeV-PeV (detectable Glashow res. anti-$\nu_e$ & $\nu_\tau$ events)
  Hyper-K/PINGU/ORCA: GeV

- Type II cases are different from the Type IIn case
  II-P/II-L/IIb/Ibc: shock in the CSM is collisionless & $M_{\text{csm}} \ll M_{\text{ej}}$
  IIn: shock can be radiation-mediated & $M_{\text{csm}}$ could be larger than $M_{\text{ej}}$

  $t_{\text{onset}}$ determined by photon breakout, ejecta deceleration, radiative shock, other relevant CR cooling processes…

  (for work on SNe IIn, see KM, Thompson, Lacki & Beacom 11 and Petropoulou’s talk)
Implications

• Astrophysical implications
  a. pre-explosion mass-loss mechanisms
  how does a dense wind/shell form around the star?
  b. PeVatrons
  can CRs be accelerated up to the knee energy at $10^{15.5}$ eV?
  c. real-time observation of ion acceleration for the first time
  is it consistent with the diffusive shock acceleration?
  d. promising targets of multi-messenger astrophysics
     MeV vs & possibly gravitational waves
     optical, X-rays, radio waves, and gamma rays (up to ~Mpc by Fermi)

• Particle physics implications
  neutrino flavors (matter effect is not relevant), neutrino decay,
  neutrino self-interactions, oscillation into other sterile states etc.
  cf. more lucky examples?
  Betelgeuse: $\sim 10^3$-3x$10^6$ events
  Eta Carinae: $\sim 10^5$-3x$10^6$ events
Take Away

- We provided the time-dependent model for high-energy neutrino/gamma-ray emission from different classes of SNe
- Type II: $\sim 1000$ events of $\text{TeV } \nu$ from the next Galactic SNe
- SNe as “multi-messenger” & “multi-energy” neutrino source
CRs Should Lead to Efficient Hadronic Interactions

Particle collisions with CSM

\[ t_{pp} = \frac{1}{(n \kappa_{pp} \sigma_{pp} c)} \]
\[ t_{dyn} = \frac{R}{\beta c} \]

\[ f_{pp} = (\frac{R}{\beta}) n \kappa_{pp} \sigma_{pp} \]

\[ (\sigma_{pp} \sim 3 \times 10^{-26} \text{ cm}^2) \]

\[ f_{pp}(r_{bo}) \sim \beta^{-2} (\kappa_{pp} \sigma_{pp} / \sigma_T) \sim 0.03 \beta^{-2} \]

At breakout: \( \tau_T = 1/\beta \)

\( \beta \sim 0.1-1 \) ⇔ transrelativistic SNe

\( \beta \sim 0.01-0.03 \) ⇔ nonrelativistic SNe

Most CR energy goes to pions

\[ \pi^0 \rightarrow \gamma + \gamma \]
\[ \pi^\pm \rightarrow \nu_\mu + \bar{\nu}_\mu + \nu_e (\bar{\nu}_e) + e^\pm \]

New probes!
Transrelativistic SNe (β~1)

Nearby GRBs (ex. 060218@140Mpc, 980425@40Mpc) may form another class

- much dimmer \( (E_{\text{LL}^{\gamma}}^{\text{iso}} \sim 10^{50} \text{ erg} \Leftrightarrow E_{\text{GRB}^{\gamma}}^{\text{iso}} \sim 10^{53} \text{ erg/s} ) \)
- more frequent \( (\rho_{\text{LL}} \sim 10^{2-3} \text{ Gpc}^{-3} \text{ yr}^{-1} \Leftrightarrow \rho_{\text{GRB}} \sim 0.05-1 \text{ Gpc}^{-3} \text{ yr}^{-1} ) \)
- relativistic ejecta (the other GRB-SNe + 2009bb) (Soderberg+ 10 Nature)
- maybe more baryon-rich? (e.g., Zhang & Yan 11 ApJ)
Neutrinos from Transrelativistic SNe

Kashiyama, KM+ 13 ApJL

- Detectable by IceCube up to ~10 Mpc
- Stacking analyses may be possible
**Gamma Rays from Transrelativistic SNe**

- Detectable by CTA up to \( \sim 100 \) Mpc
- Detection \( \rightarrow \) SN-GRB connection, physics of breakout and CRs
Shock Breakout Emission from Dense CSM

**Photon diffusion time**

\[ t_{\text{diff}} \approx \frac{R^2}{\kappa_{\text{rad}}} \sim n\sigma_T R^2/c \]

**Dynamical time**

\[ t_{\text{dyn}} \approx \frac{R}{\beta c}, \beta = \frac{V}{c} \]

**Shock breakout**

\[ t_{\text{rise}} = t_{\text{diff}} = t_{\text{dyn}} \Leftrightarrow \tau_T = \frac{1}{\beta} = \frac{c}{V} \]

**CSM mass**

\[ M_{cs} \approx \frac{4\pi R^2}{3\sigma_T} m_p \tau_T \]

**Dissipation energy**

\[ E_{\text{rad}} \approx \frac{1}{2} M_{cs} V^2 \]

Example: SN 2009ip

- \( t_{\text{rise}} = 10 \) d, \( R = 0.5 \times 10^{15} \) cm
- \( \rightarrow M_{cs} \approx 0.05 M_{\odot} \)
- \( \rightarrow E_{\text{rad}} \approx 2 \times 10^{49} \) erg

Consistent with observations!
Neutrinos from Type IIb SNe

- If CRs carry ~10% of $E_{ej} \rightarrow \# \text{ of } \mu\text{s} \sim \text{a few for SN@10Mpc}
- Stacking analyses for nearby SNe ($\sim O(100)$ needed)

KM, Thompson, Lacki & Beacom 11 PRD

Model A - optically thick collision
Model B - optically thin collision

$\Delta t = 10^7$ s
$\Delta t = 10^{7.8}$ s

$d = 10 \text{Mpc}$

$\Phi_\nu$ within $1^\circ$
• GeV $\gamma$ rays can be seen by Fermi up to $\sim$30 Mpc
• TeV $\gamma$ rays are detectable by CTA up to $\sim$30-100 Mpc