Revealing the Supernova-GRB Connection with TeV Neutrinos
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In Collaboration with Shin'ichiro Ando
Elevator Pitch

• **GRBs and SNe, circumstantial connection:**
  GRBs have jets with $E \sim 10^{51}$ erg, $\Gamma \sim 100$
  SNe have $E \sim 10^{51}$ erg, evidence of asymmetries

• *(Some) GRBs are (some) SNe:*
  Discoveries of GRBs coincident with SNIc

• **Maybe they are a continuous family of objects?:**
  Explosion energy $E \sim 10^{51}$ erg
  GRBs have rare, highly relativistic jets
  Maybe SNe have common, mildly relativistic jets?

• **This work:**
  Vastly improved prospects for neutrino detectability
Summary of GRB properties

• Very rare (~ $10^{-3}$ of supernova rate), and so hence only distant sources are seen

• Varies rapidly (~ 0.1 s), persisting ~ 10 s

• Energetic jets characterized by:
  - $E \sim 10^{51}$ erg (after opening angle correction)
  - $\Gamma \sim 100 - 1000$

• At least some of them are connected with core-collapse supernovae
Astrophysical Motivation

Q. Can we see similar objects but with mildly relativistic jets ($\Gamma \sim a$ few) and $10^{51}$ erg?

A. No. Because...
  • Much more baryons are contained.
  • These make optical depth much larger than 1 (unlike GRB) $\rightarrow$ failed GRB / dirty fireball.

Even if such sources exist, we cannot observe gamma-rays from the jets, as we can with GRBs.
Mildly Relativistic Jets?

- E.g. radio observation of SN 2001em suggests presence of mildly relativistic jets.
  - Sharp rise of radio flux \( F_\nu \sim t^{1.9} \) may be due to the jet viewed from off-axis direction (Granot & Ramirez-Ruiz 2004).

- A significant fraction (~1-7%) of supernovae may be driven by energetic, but mildly relativistic jets (\( \Gamma \sim 3 \)).
  - See also, Totani 2003; Berger et al. 2003; Soderberg et al. 2003.
Neutrinos as a Direct Probe

- Neutrinos could be a direct probe of hidden jets in baryon-rich failed GRBs

- Fraction of supernova is estimated to be “quite high” (~ 1-7%), and so may occur in the nearby universe

- Razzaque, Meszaros & Waxman
  [PRL 93, 181101 (2004); Erratum-ibid. 94, 109903 (2005)]
  considered neutrinos from pion decay produced in those jets

- We extend this by showing that kaons make the detection prospects more promising (more than one order of magnitude!)
  [Ando, Beacom (PRL, 2005)]
Protons in the Jet

• Protons are accelerated by internal shocks, forming an \( \sim E^{-2} \) spectrum

• Protons lose energy by collisions with ambient protons, producing pions and kaons

\[ r_j \sim 2\Gamma^2 c \tau_v \sim 5 \times 10^{10} \text{ cm} \]
Meson Cooling and Decay

- Produced mesons either decay or lose energy first
- Cooling mechanisms are:
  - $\pi p$ and $Kp$ collisions (hadronic)
  - Synchrotron and inverse Compton (radiative)
Neutrino Spectrum

- Neutrino spectrum reflects the energy loss and decay processes of the parent mesons.
Pion vs. Kaon: Which is Dominant?

• Pions are more easily produced by collisions
• Advantages of kaons:
  - More massive $\Rightarrow$ radiative cooling is much less efficient ($t_{rc} \sim m^4$)
  - Shorter lifetime $\Rightarrow$ cooling break energy becomes larger
  - Also, better kinematics for decay

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<th>$E_{cb}^{(1)}$ [GeV]</th>
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<td>100</td>
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<tr>
<td>$K$</td>
<td>200</td>
<td>20,000</td>
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Neutrino Events at IceCube

- Kaon contribution dominates
- ~ 30 events in 10 s time bin and 3 deg angular bin!
- Essentially no background in the relevant bin
- Cutoff reveals the jet properties

Ando, Beacom, PRL 95, 061103 (2005)
Detection Prospects

• If everything is favorable, then in IceCube:

  3 Mpc: ~ 300 events, nice spectrum features
  10 Mpc: ~ 30 events, clear signal detection
  30 Mpc: ~ 3 events, still above background

• Multiple neutrinos in coincidence defines a ~ 10 s window, much better than the ~ 1 day optically; this could be used for gravitational wave triggers

• For close objects, AMANDA can do well also

• The only way to test it is to try, and AMANDA and IceCube groups are already working on it
Jetted Supernova Frequency

Calculated nearby ($D < 10$ Mpc) SN rate is $\sim 1$/year

Recent measured rate is about 3 times higher!

Penalty for jet direction is perhaps $\sim 1/10$

Penalty for jets in SNe is quite uncertain:
Caltech group: $< 1\%$ SNe
Gal-Yam et al., astroph/0508629
RMW: buried jets in SNII?

Ando, Beacom, Yuksel, PRL 95, 171101 (2005)
Conclusions

Razzaque, Meszaros, Waxman (PRL, 2004):
Maybe all core-collapse supernovae have energetic jets.
Commonly mildly relativistic and hidden: SNe.
Rarely highly relativistic and revealed: GRBs.

This is an intriguing but speculative proposal.
The key is the neutrino signature, and our work on
including kaons makes this proposal much more testable.

**SN/GRB connection:** Do many SNe have jets?

**neutrino astrophysics:** New extragalactic signal?

**gravitational wave trigger:** 10 s instead of 1 day?