Revealing the Supernova-GRB Connection with TeV Neutrinos

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Elevator Pitch

- GRBs and SNe, circumstantial connection:

GRBs have jets with E ~ 10^{51} erg, Γ ~ 100
SNe have E ~ 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 ~ 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 (Γ ~ a few) and 10^{51} erg ?

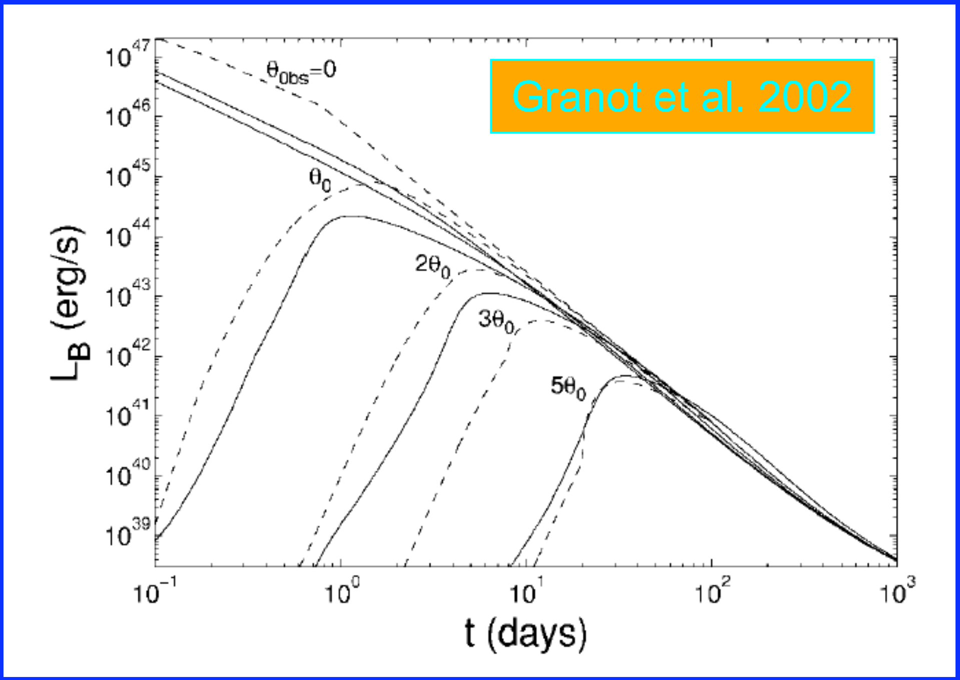
A. No. Because...

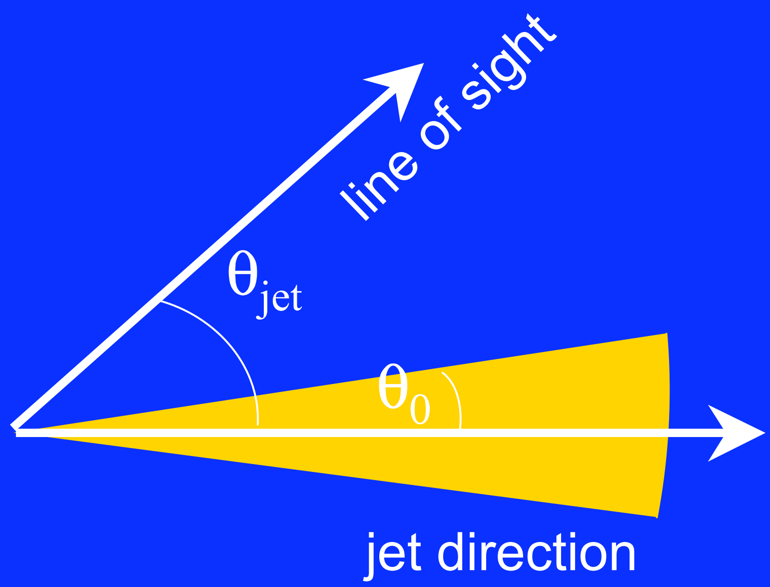
- Much more baryons are contained.
- These make optical depth much larger than 1 (unlike GRB) → failed GRB / dirty fireball.

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.

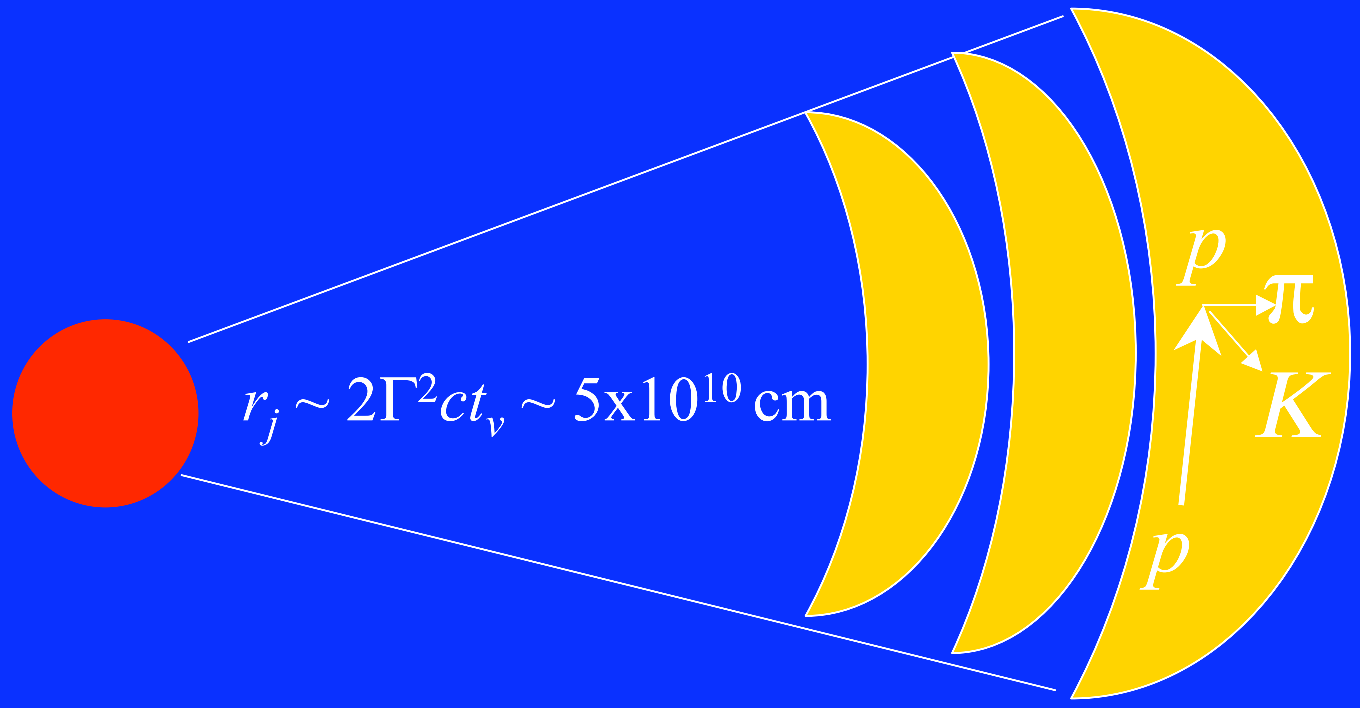
Neutrinos as a Direct Probe

- 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

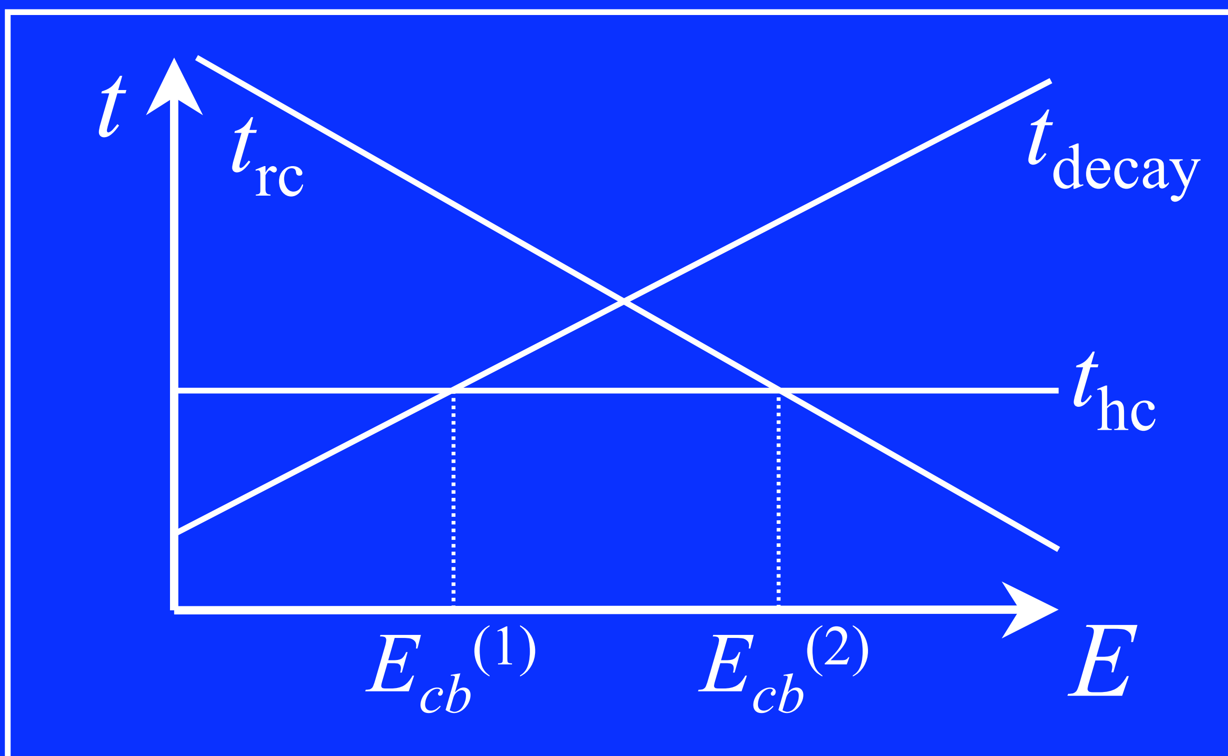
- Protons are accelerated by internal shocks, forming an ~ E^{-2} spectrum

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



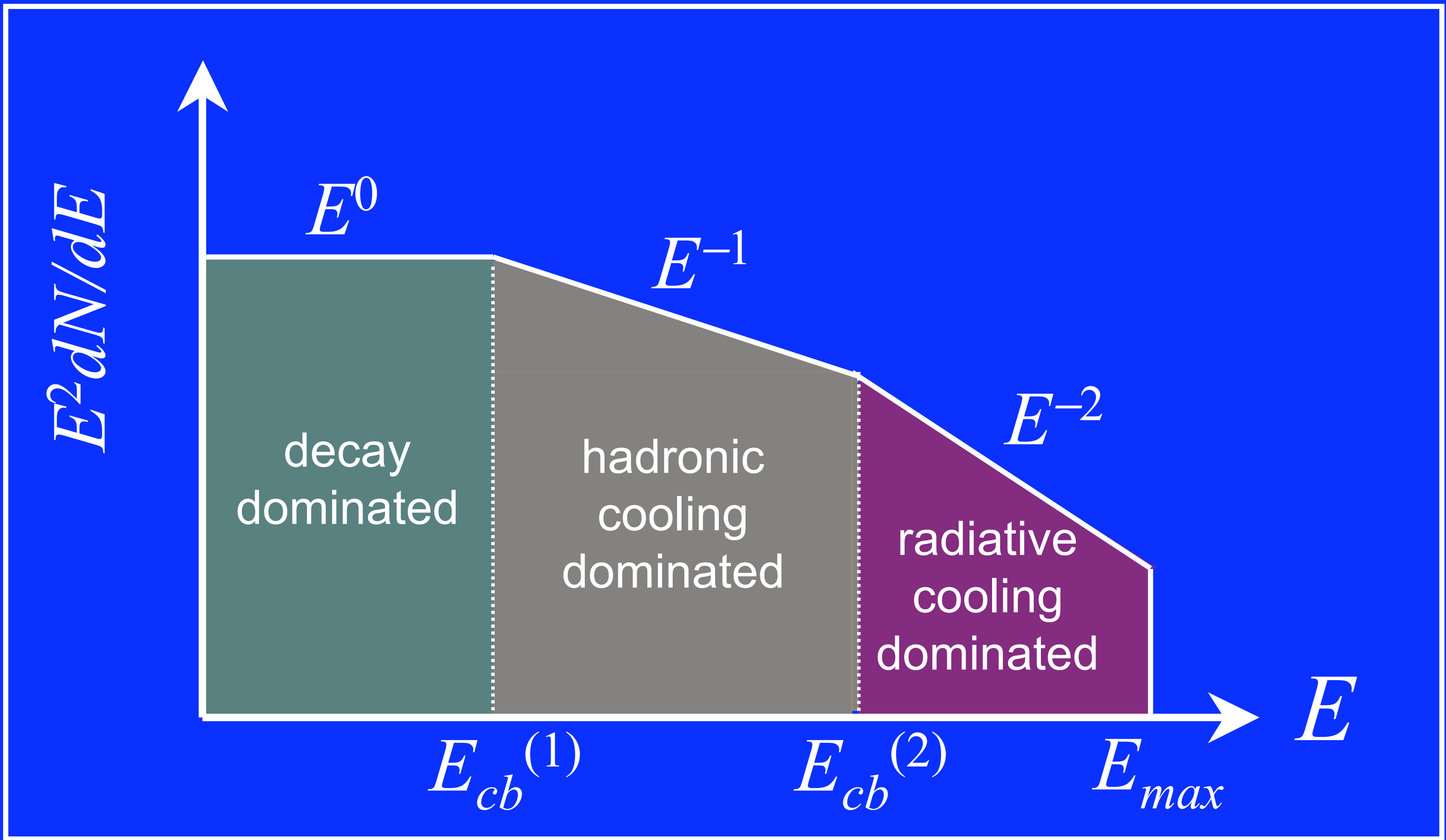
Meson Cooling and Decay

- Produced mesons either decay or lose energy first
- Cooling mechanisms are:
  - πp and Kp collisions (hadronic)
  - Synchrotron and inverse Compton (radiative)



Neutrino Spectrum

- Neutrino spectrum reflects the energy loss and decay processes of the parent mesons

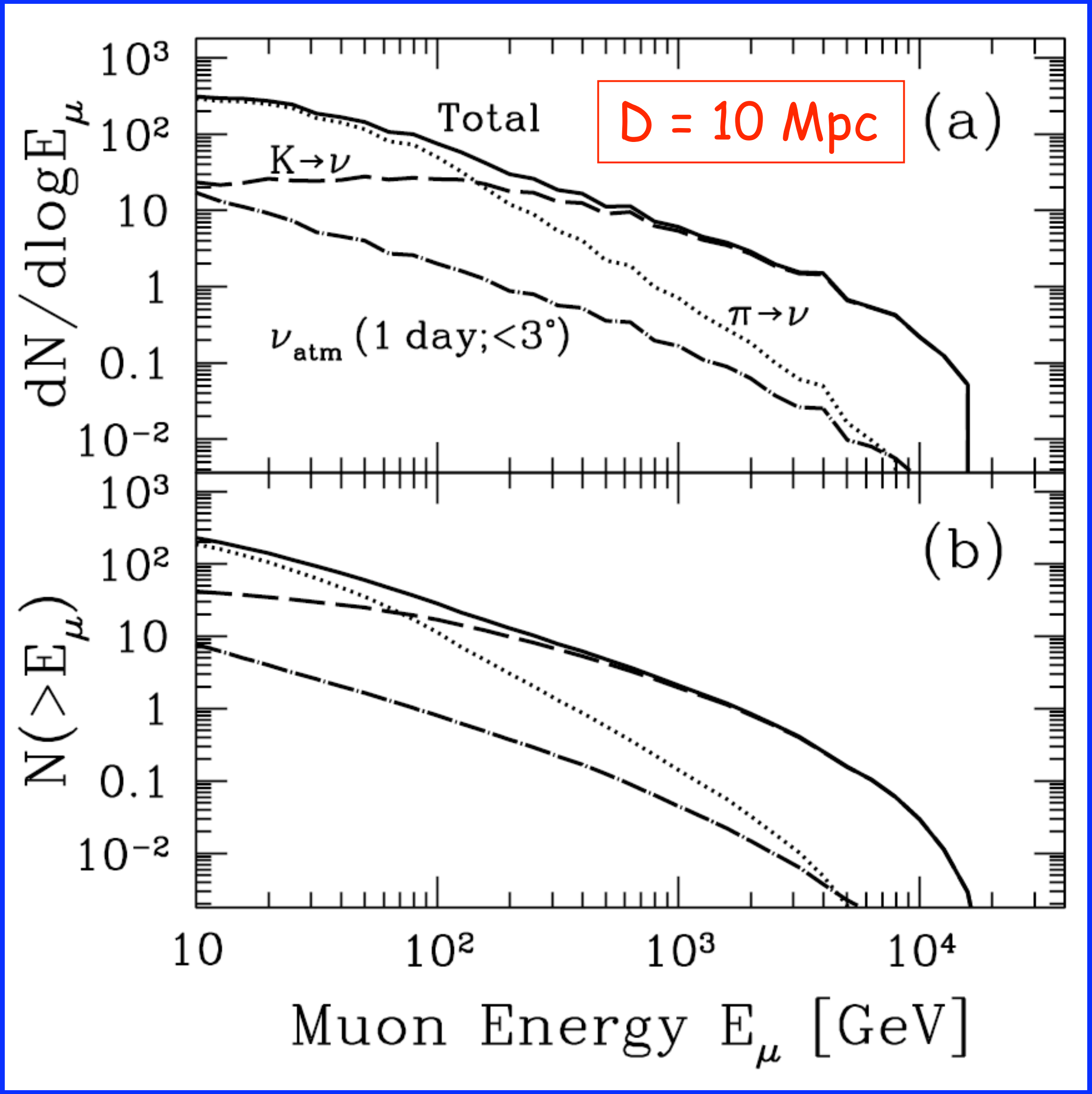


Pion vs. Kaon: Which is Dominant?

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

	$E_{cb}^{(1)}$ [GeV]	$E_{cb}^{(2)}$ [GeV]
π	30	100
K	200	20,000

Neutrino Events at IceCube



Ando, Beacom, PRL 95, 061103 (2005)

- 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

Detection Prospects

- If everything is favorable, then in IceCube:

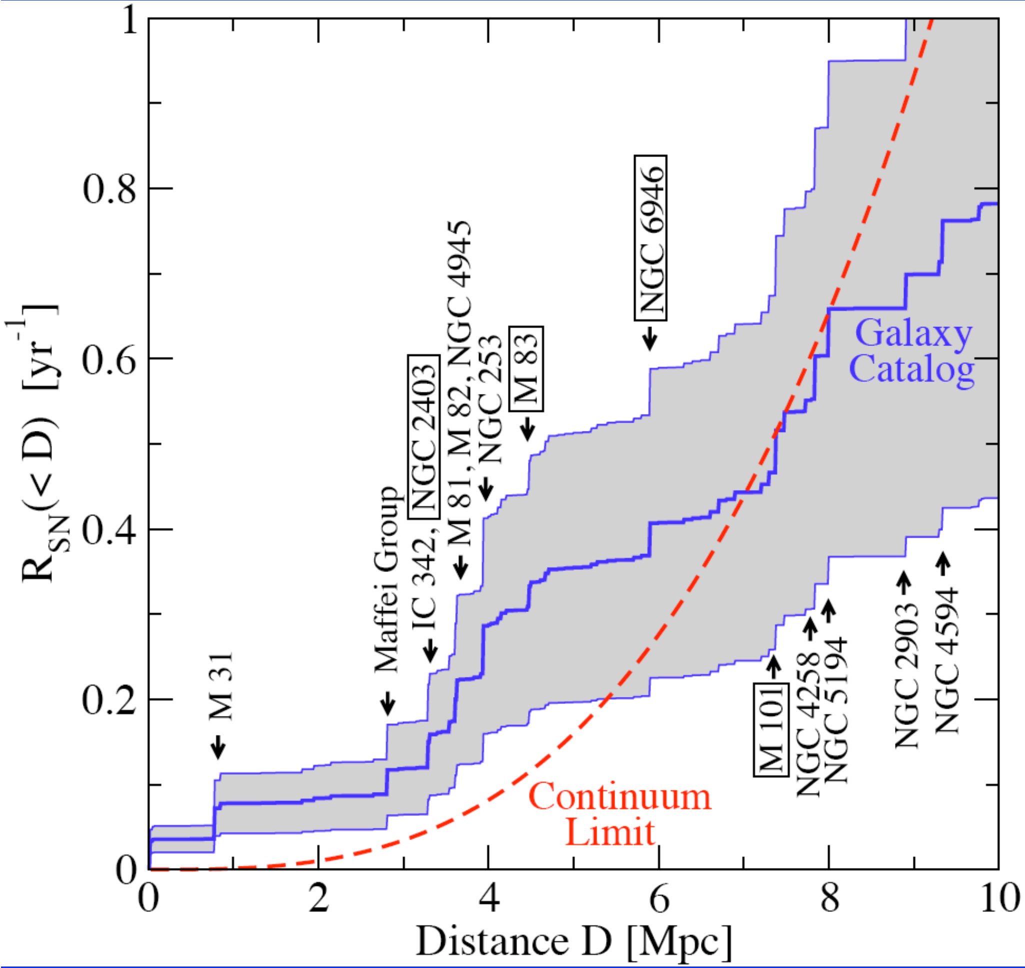
3 Mpc: ~ 300 events, nice spectrum features
10 Mpc: ~ 30 events, clear signal detection
30 Mpc: ~ 3 events, still above background

- 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



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

Calculated nearby (D < 10 Mpc) SN rate is ~ 1/year

Recent measured rate is about 3 times higher!

Penalty for jet direction is perhaps ~ 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?

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?