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Workshop Towards Neutrino Technologies

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Stellar tomography with high energy neutrinos

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Stellar Tomography with High Energy Neutrinos

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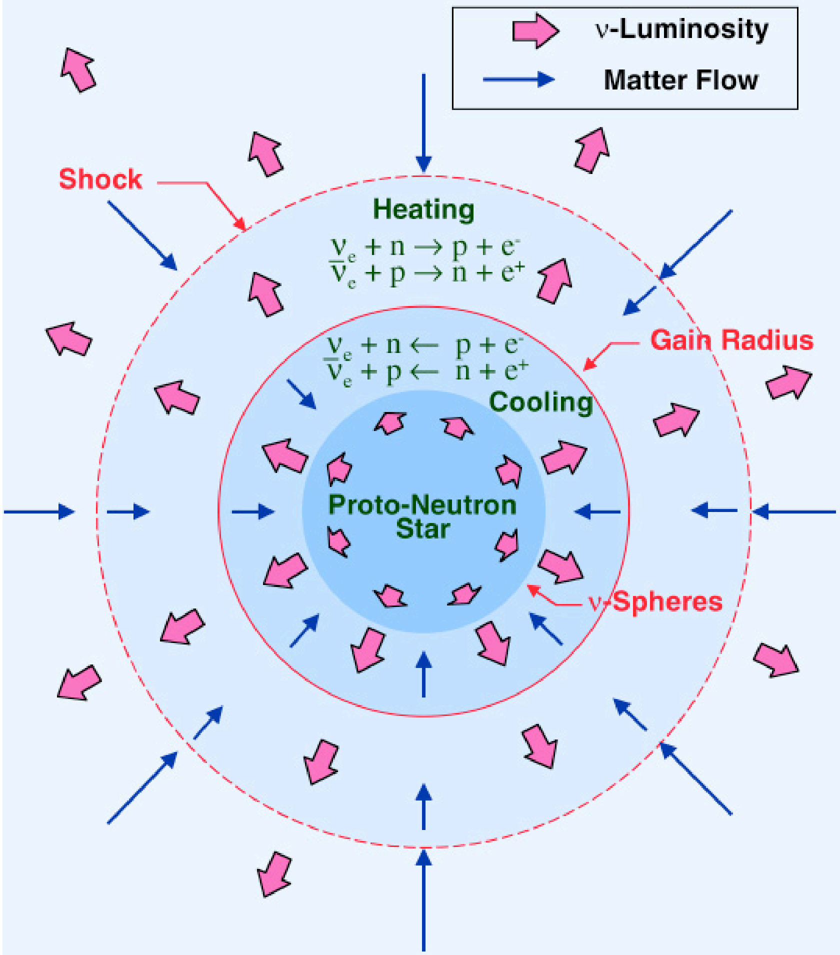
Trieste, Italy. 13-17 July, 2009

Core Collapse Supernovae

Standard Textbook picture



… and some details

- Fe core collapse of $>8M_\odot$ stars
- $\sim10^{54}$ erg of energy release in ν's
- Thermal ~10 MeV ν's
- Detection from SN 1987A
- Rate: 1 Snu = 10^{-2} yr^{-1} 10^{-10} blue $L_\odot$ or 1/yr within 20 Mpc (4000 galaxies)
- Can provide information on stellar collapse and on ν properties

No detection since 1987

Look for high energy ν signature to probe stellar interior in the rarer cousin of SNe ➔

Gamma Ray Bursts

Collapsar Model: Pioneered by Stan Woosley and collaborators

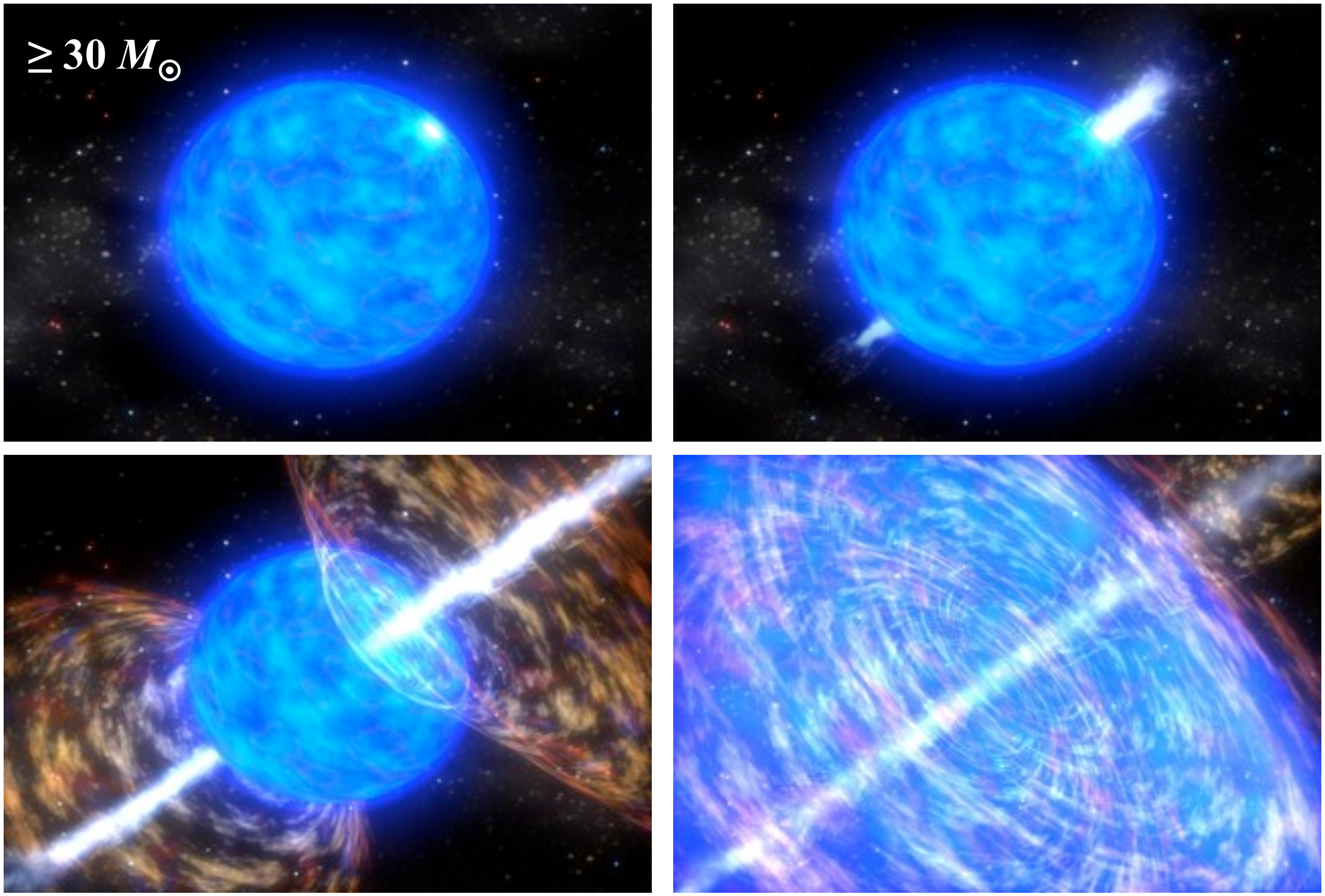
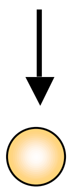


Illustration credits: NASA

Relativistic Jet in Gamma Ray Bursts

Simulation by Zhang & Woosley

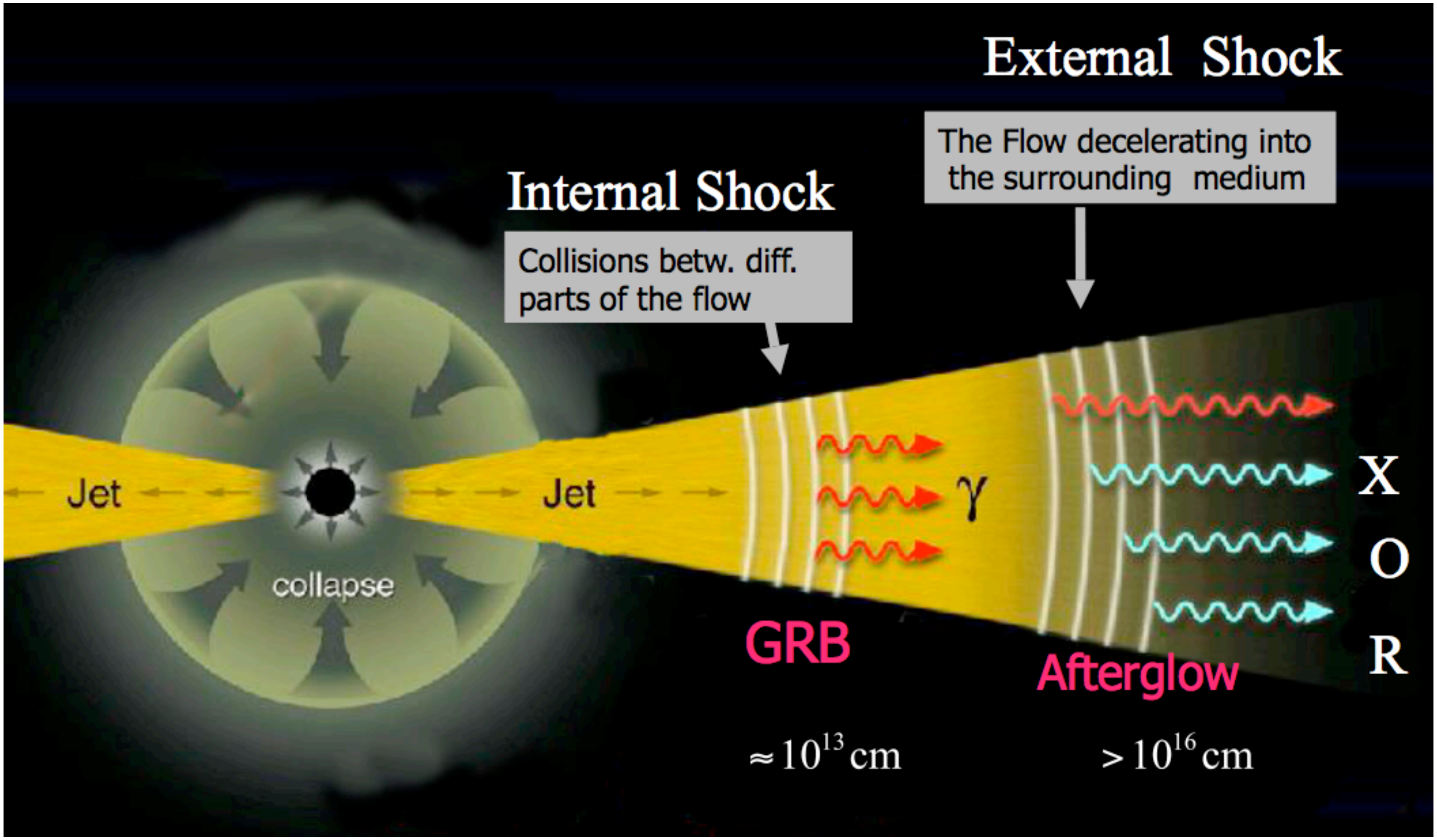
Central
Engine



Black hole/
Highly
magnetized
Neutron star

GRB Fireball Shock Model

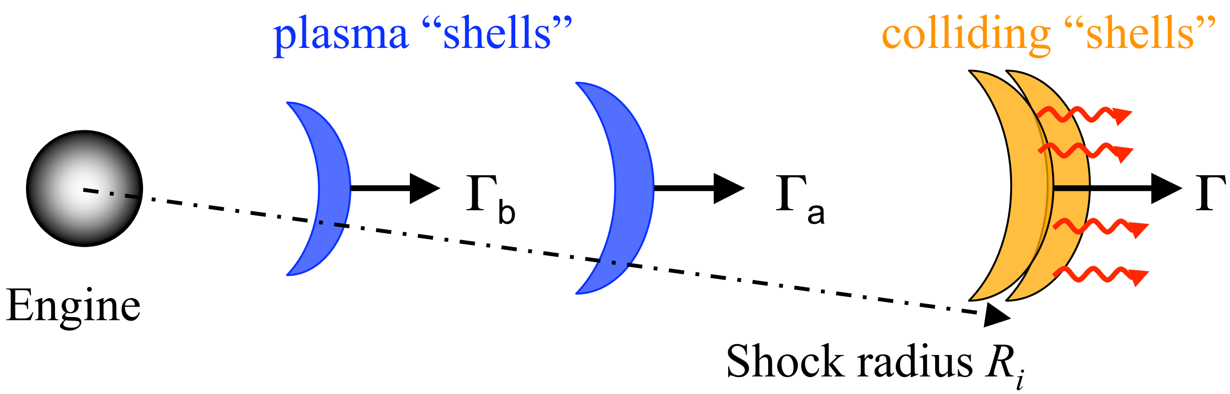
Rees, Meszaros, Piran and others …



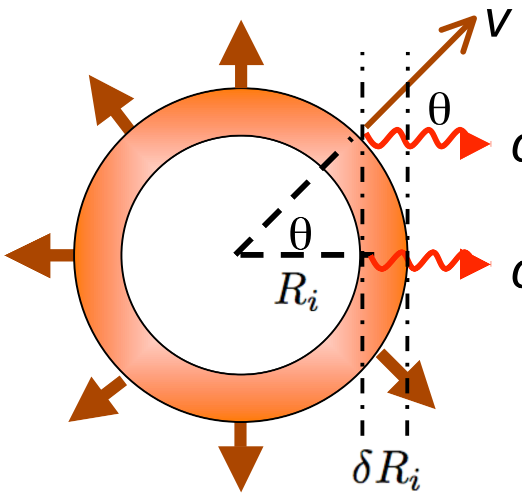
Explains non-thermal prompt MeV data and afterglow X-ray, UV,… data

Explanation of γ-ray Lightcurve

Simplest form … Discrete outflow or "shells" with variable speeds or Γ



Synchrotron radiation by electrons that are accelerated in the induced electric field



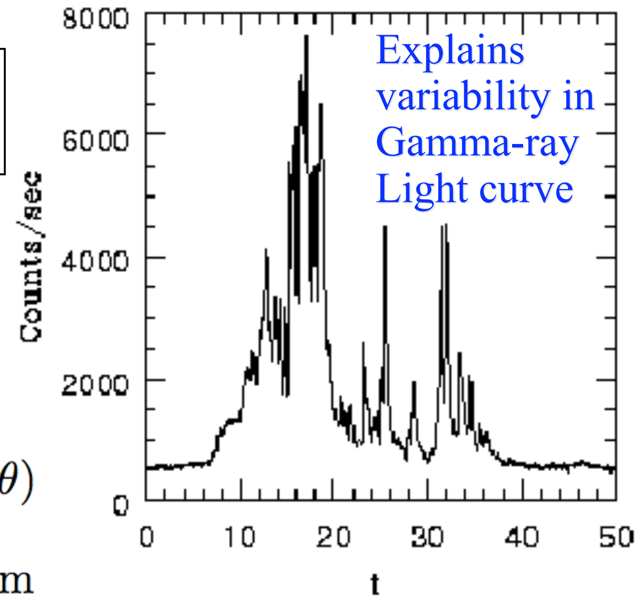
Shells can be treated as spherical when $\theta_{jet} > \Gamma^{-1}$

Flux variability time

Shell width

$$\delta t = \frac{\delta R_i}{c} = \frac{1}{c}(R_i - R_i \cos\theta)$$

$$R_i \simeq 2\Gamma_i^2 c\delta t \approx 10^{12}\text{–}10^{14}\ \text{cm}$$



Baryons are Essential in GRB Jet

Generation of "shells" with variable Γ

Entropy: $\eta = L_0/\dot{M}c^2 \geq 100$

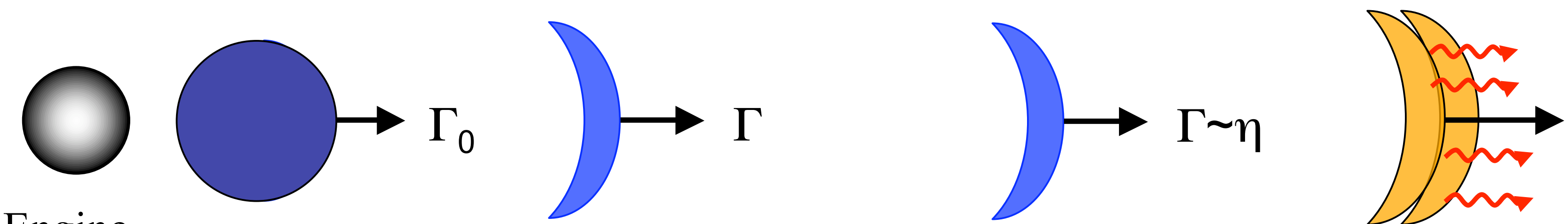
$\dot{M} = 4\pi R^2 n'_p m_p c$

Density of protons

Impulsive injection of energy (fireball)
Cavallo & Reese 1976

Expansion due to radiation pressure

Coasting fireball



Engine

Base of the jet
R_0 ~100 km
High temperature
T_0 ~10 MeV
e, γ and few p

Kinetic energy (L_k) increases, temperature decreases
$(L_\gamma + L_k)R \sim L_0 R_0 \sim$ const.
$TR \sim T_0 R_0 \sim$ const.
$\Gamma \sim R/R_0$

No more radiation pressure, kinetic energy
L_k~L_0
R_s ~10^9 cm

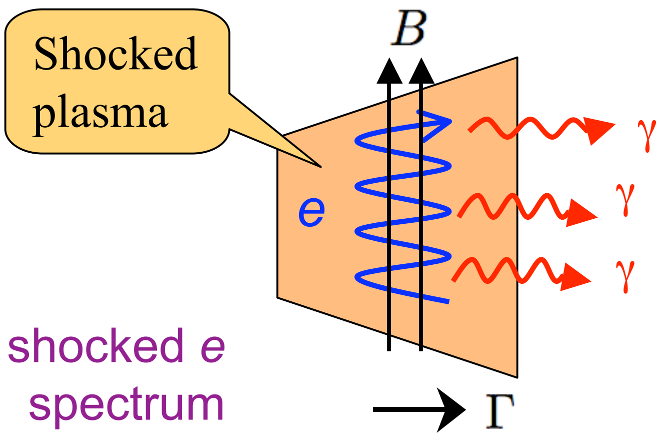
colliding "shells"

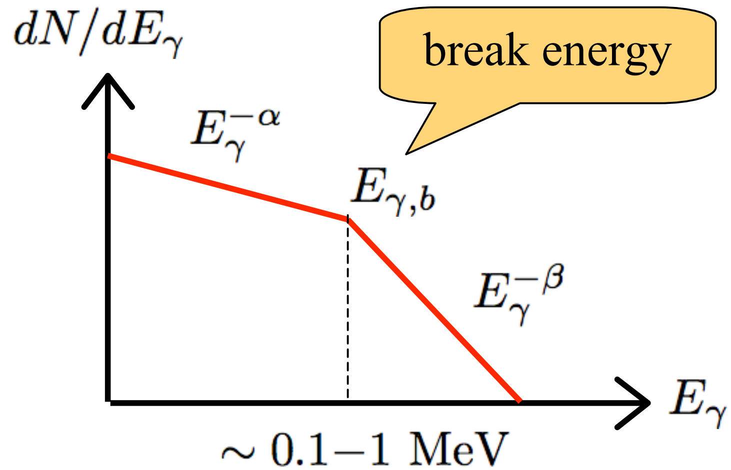
Still inside the star (~10^{11-12} cm)!

Non-thermal γ ray Emission Mechanism

Fitted by broken power-laws

Origin: Synchrotron radiation by a population of shock-accelerated electrons





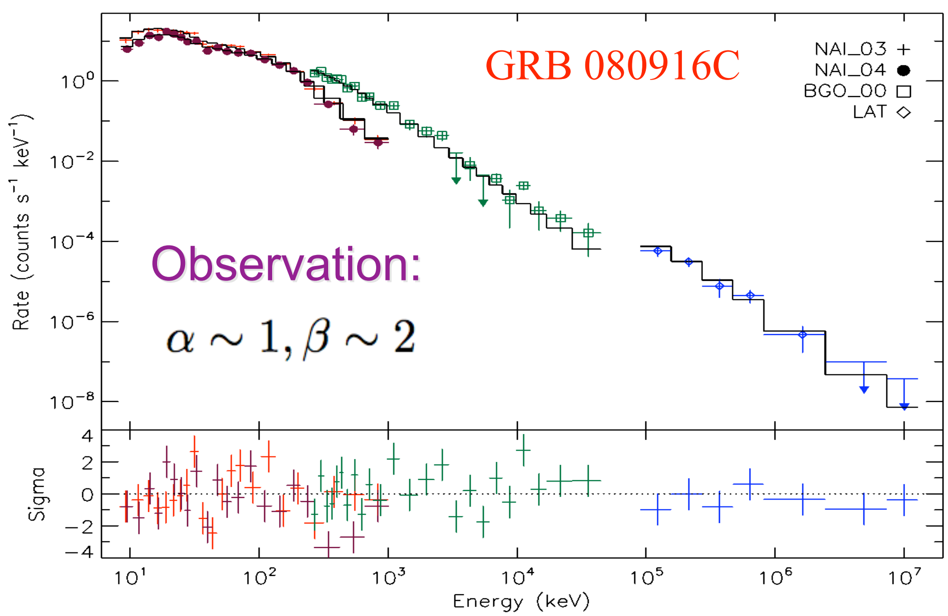
shocked *e* spectrum

$$\frac{dN}{dE_e} \propto E_e^{-q}$$

All *e* lose energy
Promptly *fast cooling*

Synchrotron radiation spectrum

$$\frac{dN}{dE_\gamma} \propto E_\gamma^{-(q+2)/2} \;;\; E_\gamma > E_{\gamma,b}$$
$$\propto E_\gamma^{-2} \;;\; q = 2$$



Evidence of Relativistic Jet

Extreme relativistic motion of the γ-ray emitting region to avoid $\gamma\gamma \rightarrow e^+e^-$ production (opacity $\tau_{\gamma\gamma}<1$) in-situ which will destroy non-thermal spectra

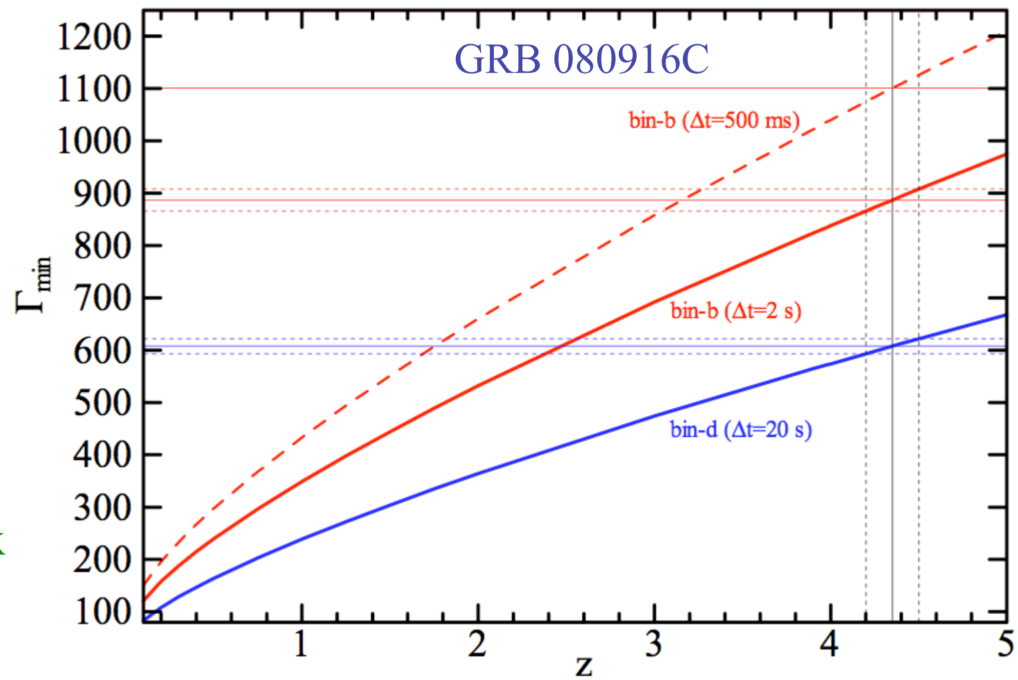
➔ Constraint on the bulk Lorentz factor: with observed variability time Δt from Fermi GBM or INTEGRAL

$\Gamma > 887$+/-21 (time bin "b", Δt ~2 s)
$\Gamma > 1100$ (time bin "b", Δt ~500 ms)

➔ Size scale of prompt emission region is large

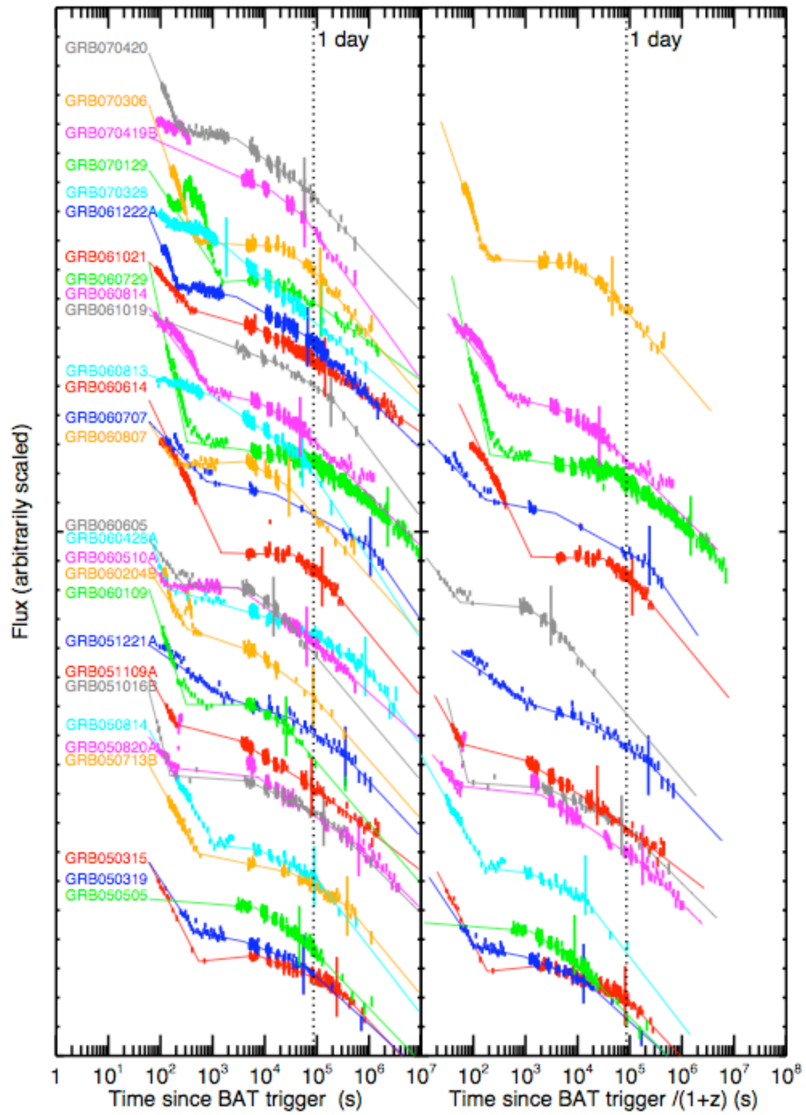
$$R \approx \frac{\Gamma^2 c\Delta t}{1+z} > 9\times 10^{15}\left(\frac{\Gamma}{890}\right)^2\left(\frac{\Delta t}{2s}\right)\left(\frac{5.35}{1+z}\right)\text{ cm}$$

High bulk Lorentz factor can relax the actual energy emission by up to $1/\Gamma$ from the observed apparent isotropic 8.8×10^{54} erg



Abdo et al. Science 2009

Further Evidence of Jetted Emission



Afterglow lightcurves of *Swift* GRBs

Racusin et al., ApJ 2009

- GRB afterglow flux evolution $F \sim t^{-\alpha} \nu^{-\beta}$ initially with $\alpha,\beta \sim 1$
- As the jet slows down by external medium the bulk Lorentz factor decreases
  - ➔ smooth light curve as long as $1/\Gamma < \theta_{jet}$ or the edge of the jet is not visible
  - ➔ for $1/\Gamma > \theta_{jet}$ the slope of the lightcurve changes "Jet break"
- Typically $\theta_{jet} \sim$5-7 degrees

The most powerful explosion in the universe

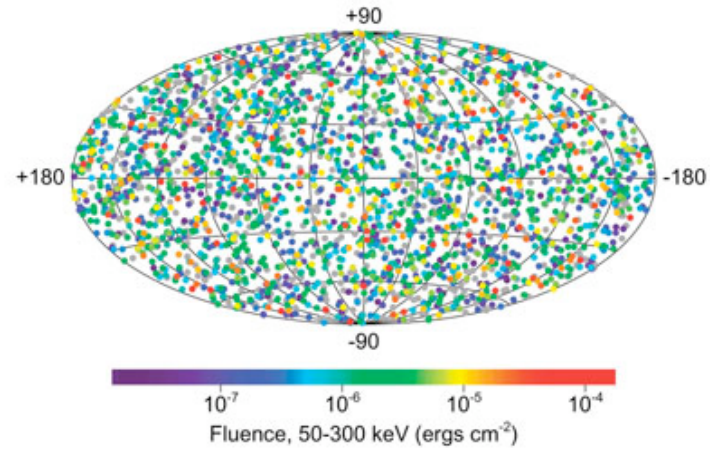
keV - MeV γ-ray flux of typical GRBs $F \sim 10^{-6}$ - 10^{-5} erg cm^{-2} s^{-1}

Isotropic distribution in sky

➔ Typical redshift z~1-2

➔ Huge energy release!

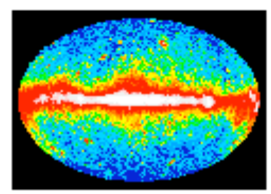
Sky map of 2512 GRBs

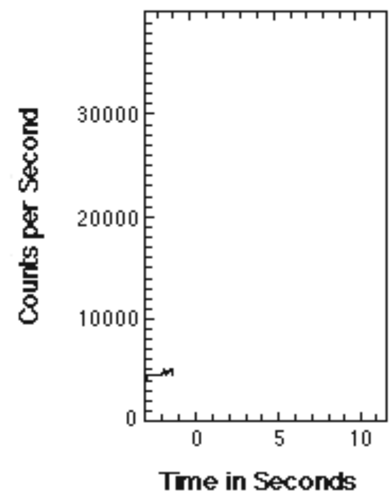


Isotropic-equivalent γ-ray luminosity $4\pi d^2 F \sim 10^{52}$ erg s^{-1}

Sizable fraction of a solar rest mass energy release!

Outshines the entire γ-ray universe





Observed rate: 600 yr^{-1} over whole sky

➔ 2 Gpc^{-3} yr^{-1} (SN rate ~10^4 Gpc^{-3}yr^{-1})

➔ 200(f_b/100) Gpc^{-3} yr^{-1} beam-corrected

➔ Follow star-formation rate

Direct Evidence of SN-GRB Connection

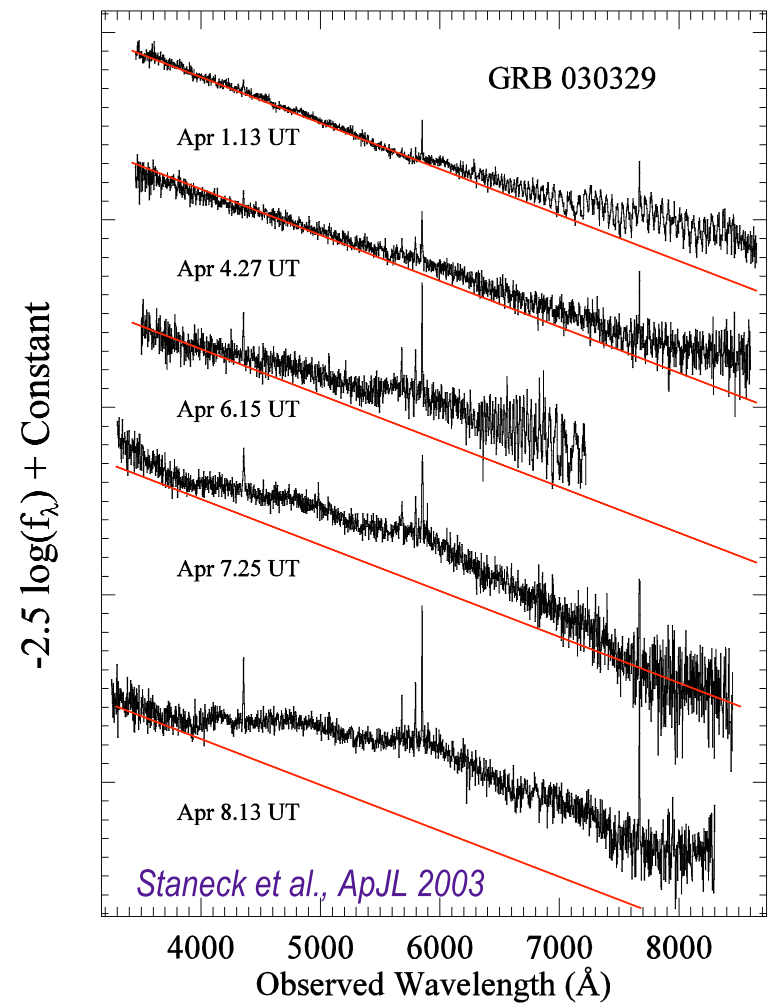
2.64 days

5.78 days

7.66 days

8.76 days

9.64 days



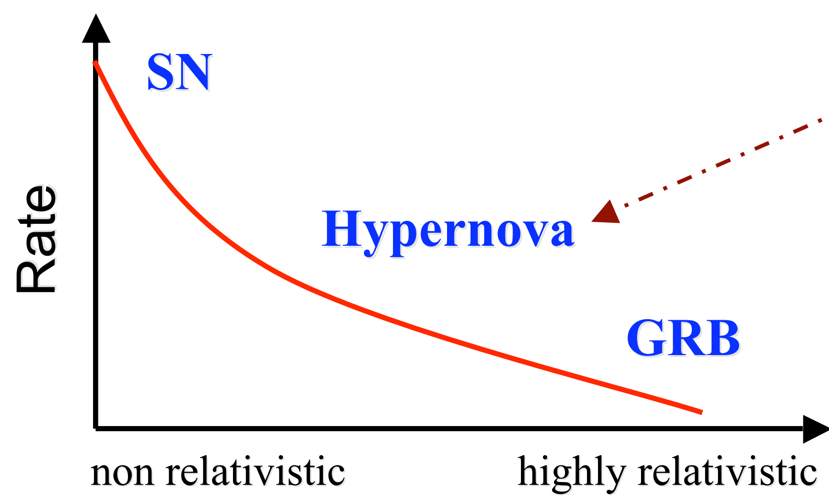
Low redshift (<0.2) GRBs have been observed as precursors to SNe: GRBs 980425, 030329, etc.

Typical afterglow power-law spectrum

SN bump (SN 2003dh) due to radioactivity appears later when the envelope is optically thin to photons as it expands

Core Collapse SN and GRB Relation

- GRBs and core-collapse SNe are related, both from collapse of massive stars
- GRBs are rare (few % of SN) ➔ more massive stars are fewer in numbers
- SN explosions are spherical with sub-relativistic shock velocity
- GRB jets are highly relativistic ➔ Highly asymmetric explosion



Intermediate class with mildly relativistic jet
➔Some observational evidence bright SN 1998bw

Stellar Tomography with High Energy ν's

Concentrate on GRBs and jetted SN with jets buried inside stars

- ❖ Shocks in relativistic jets
- ❖ Jet energy estimate from observations
- ❖ Proton acceleration and interactions, neutrino production

Discuss three models

- ❖ Supranova model ➔ SN explosion before the GRB event
- ❖ Choked GRBs ➔ Relativistic GRB jet while still inside star
- ❖ Hypernovae ➔ A fraction of SN which may have mildly relativistic buried jet

➔ Neutrino oscillation physics in play

Calculation of Energetics in GRB Shocks

Basic calculation approach (*a la Astrophysicists*)

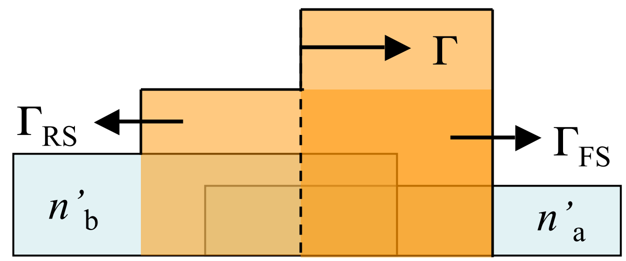
- Collision between two plasma "shells"
  - ➔ Relativistic forward & reverse shockwaves plough through the "shells"
  - ➔ Plasma instabilities, turbulent motion generate magnetic field
  - ➔ Charged particles (*test particle*) are accelerated in the induced electric field via a Fermi mechanism

Observed γ-ray luminosity

Non-thermal γ-ray energy density in the jet frame

$$u'_\gamma = \frac{L_\gamma}{4\pi R^2 c \Gamma^2}$$

Shock radius $R = 2\Gamma^2 c t_v$;
$\Gamma \sim 100\text{-}1000$, $t_v \sim 0.001\text{s-}1\text{s}$



Collision hydrodynamics

Particle energy density

$$u'_p = \varepsilon_e^{-1} u'_e = \varepsilon_e^{-1} u'_\gamma$$

Fast cooling

Energy density in magnetic field

$$u'_B = \varepsilon_B u'_p = (\varepsilon_B / \varepsilon_e) u'_\gamma$$

ε_e and ε_B are parameters to be fitted from data

Proton Acceleration and Cooling

Magnetic field $B' = \sqrt{8\pi u'_B} \approx 2\times 10^6 R_{12}^{-1}\Gamma_{2.5}^{-1}L_{\gamma,52}^{-1/2}\sqrt{\varepsilon_B/\varepsilon_e}$ G

$R = 10^{12} R_{12}$ cm; $\Gamma = 10^{2.5}\Gamma_{2.5}$

$L_\gamma = 10^{52} L_{\gamma,52}$ erg/s (isotropic)

- Acceleration time $t'_{acc} = \frac{\phi E'_p}{ecB'} \approx 1.1 \frac{\phi_1 E'_{p,9}}{B'_6}$ sec.

$E'_p = 10^9 E'_{p,9}$ GeV; $B' = 10^6 B'_6$ G

- Synchrotron cooling $t'_{acc} = \frac{3}{4}\left(\frac{m_p}{m_e}\right)^2 \frac{m_p^2 c^3}{\sigma_T u'_B E'_p} \approx \frac{0.0045}{B_6'^2 E'_{p,9}}$ sec.

- Compton cooling ➔ may be important if $u'_B << u'_\gamma$
- Photopion production ➔ Dominant channel for high-energy neutrino production

$p\gamma \to \Delta^+ \to n\pi^+/p\pi^0$ at resonance $E_p E_\gamma \simeq 0.3\ GeV^2$

- Hadronic interactions $pp/pn \to \pi^\pm/K^\pm$
- Bethe-Heitler process

Neutrino production

$\pi^+/K^+ \to \mu^+\nu_\mu \to e^+\nu_e\bar{\nu}_\mu\nu_\mu$

Similar to atmospheric ν's
Seconaries may suffer further losses

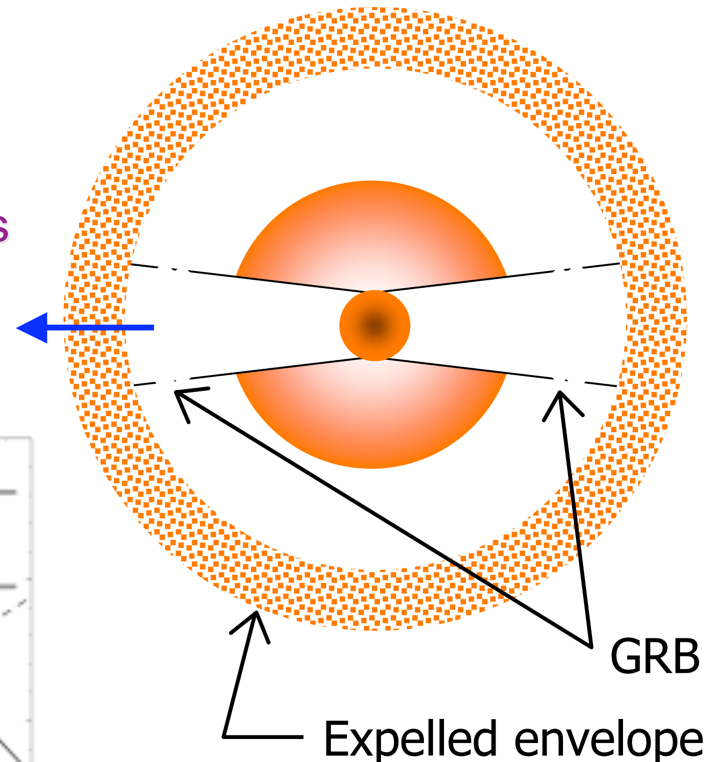
Supranova GRB Model

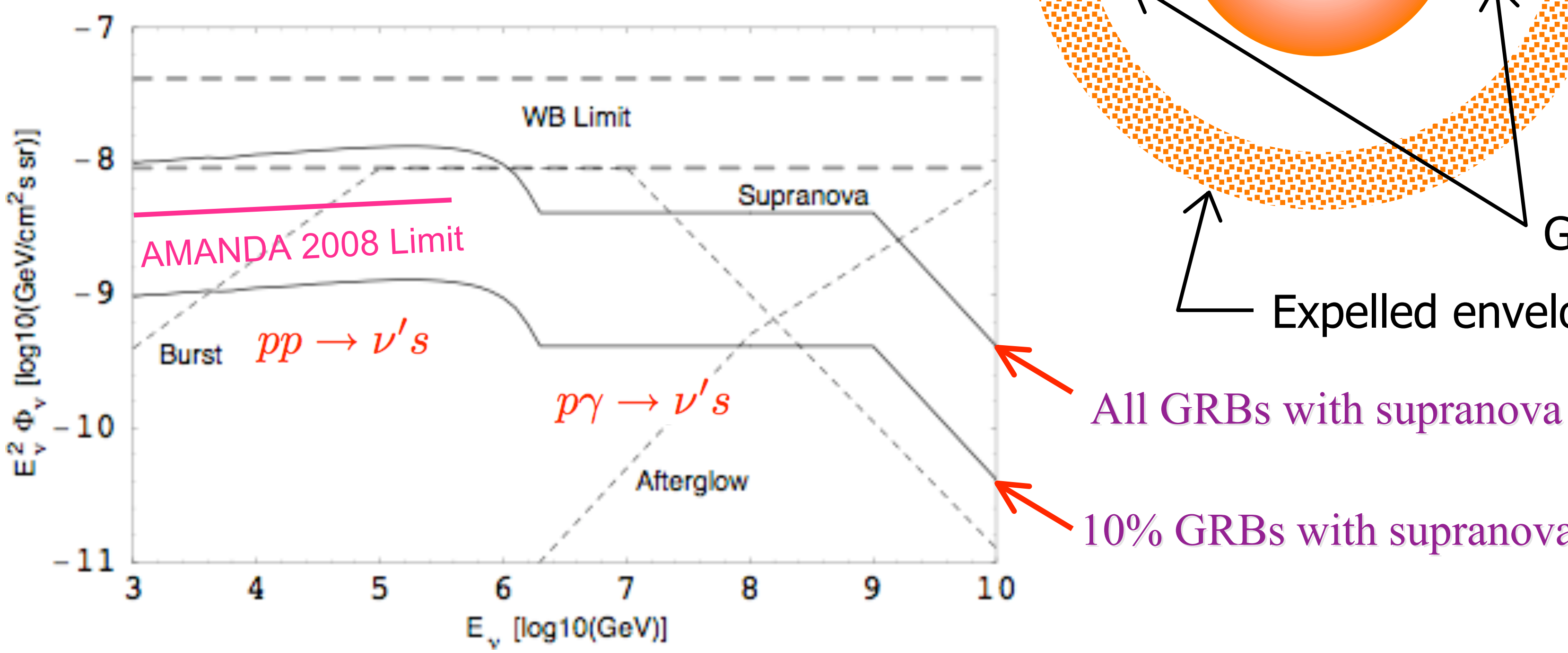
Razzaque, Meszaros & Waxman, PRL 2003

Two step stellar collapse model:
stellar collapse ➔ SN ➔ GRB
Time-delay between SN and GRB ~ hours-days

- Electromagnetic limit ~days
- Neutrinos ~hours

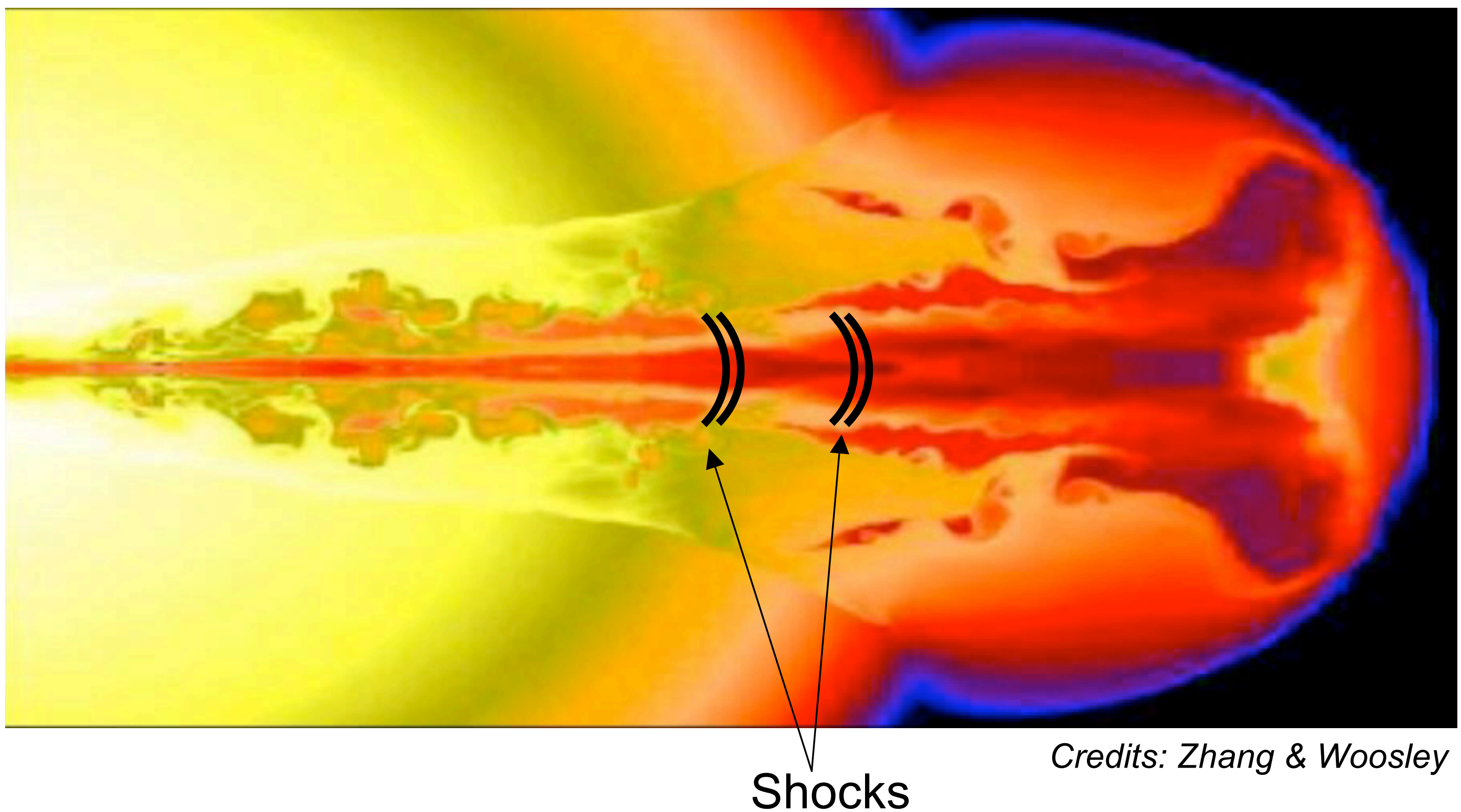
$pp, p\gamma \rightarrow \nu' s$





Buried Relativistic GRB Jet

Relativistic GRB-like jet inside star ➔ Successful or *choked* GRB
➔ Choked GRBs may be related to orphan afterglows
Shocks in the jet ➔ particle acceleration ➔ high-energy ν production

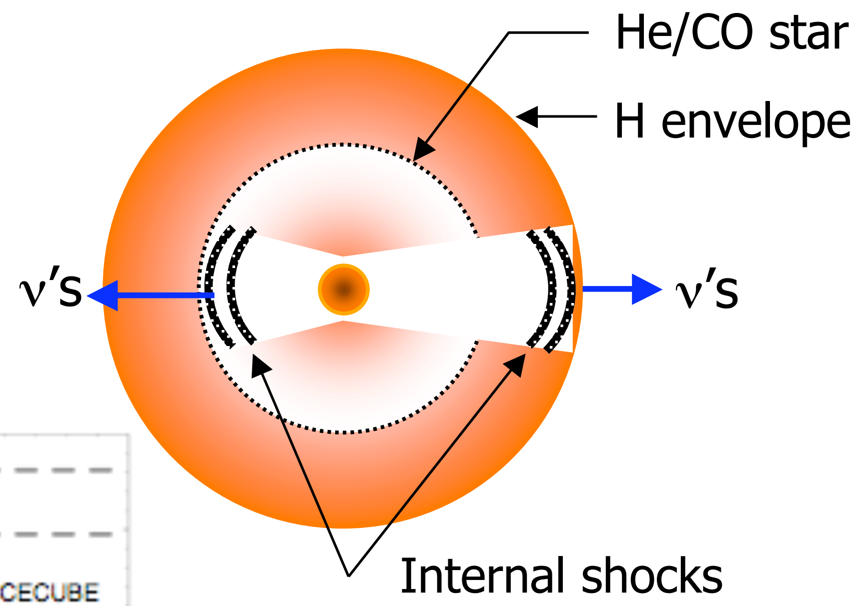


Credits: Zhang & Woosley

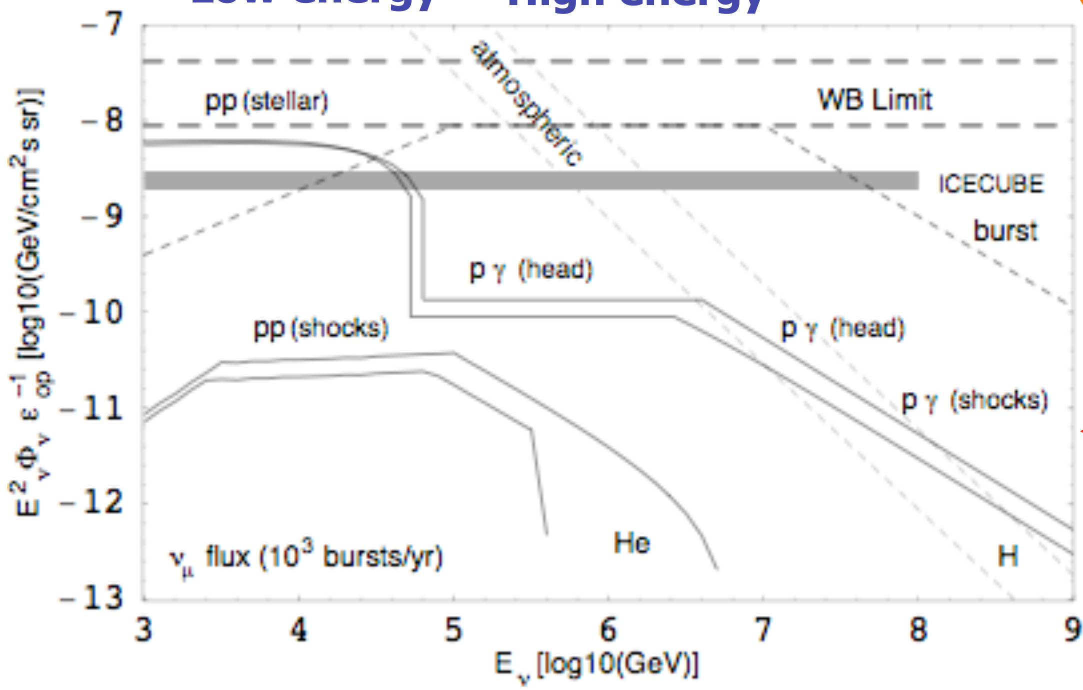
ν's precursor to GRB or Orphan Afterglow

Razzaque, Meszaros & Waxman, PRD 2003

→ Optically thick shocks
→ High density of thermal γ-rays and target protons



$pp \rightarrow \nu's$ **Low energy** $p\gamma \rightarrow \nu's$ **High energy**



$$R_i < R_\star \approx \begin{cases} 10^{11}\ cm\ (He) \\ 10^{12.5}\ cm\ (H) \end{cases}$$

Diffuse flux

No. of choked jets can be Larger than the no. of GRBs

High Energy GRB ν Detection Prospects

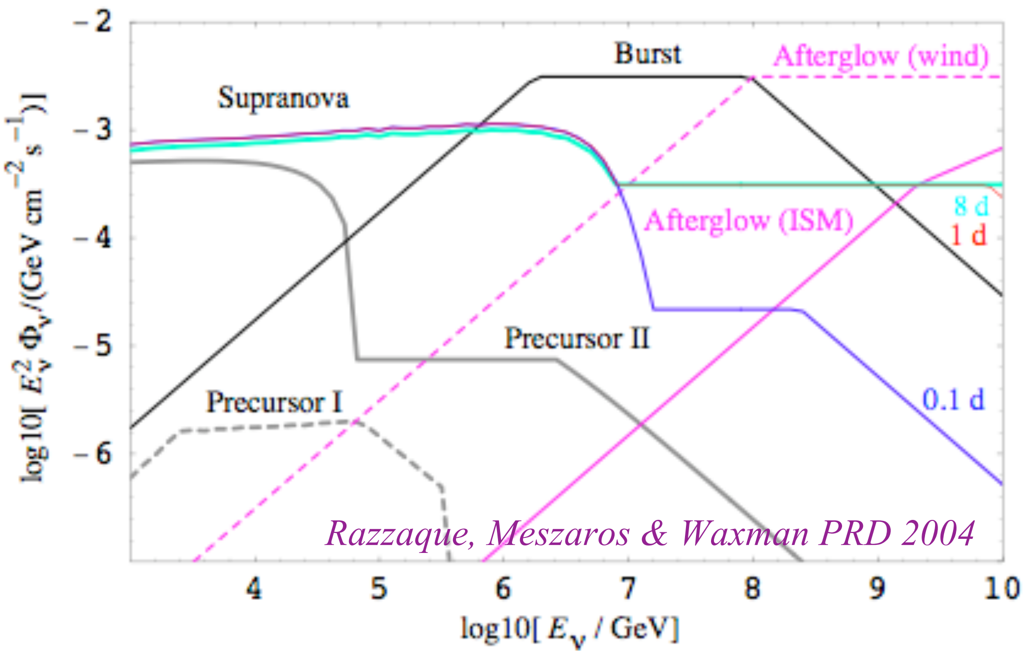
Projected ν events for IceCube		
Flux model	ν_μ	ν_e
Precursor I (He)	-	-
Precursor II (H)	4.1	1.1
Burst/prompt	3.2	0.3
Afterglow (ISM)	-	-
Afterglow (wind)	0.1	-
Supranova (>0.1 d)	13	2.4

E_ν > TeV, no oscillation

GRB 030329/SN 2003dh

Typical long duration GRB with bright SN

~10^{51} ergs/s luminosity at redshift $z = 0.17$



Neutrino flux models:

Dai & Lu 2000 (afterglow wind)

Razzaque, Meszaros & Waxman, PRL 2003 (supranova)

Razzaque, Meszaros & Waxman, PRD 2003 (precursor)

Waxman & Bahcall 2000 (afterglow ISM)

Waxman & Bahcall 1997 (burst/prompt)

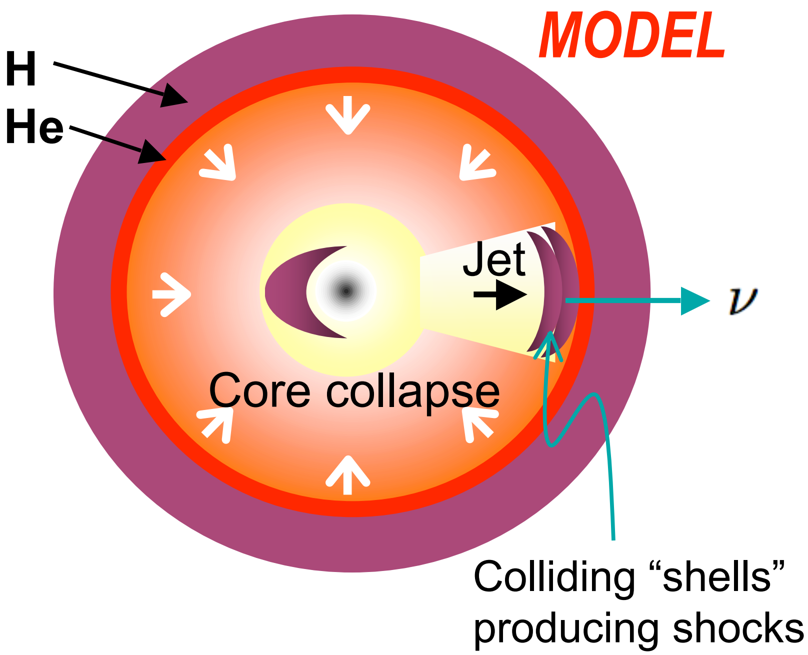
Conclusion

- Distinguish between H and He envelope
- Rule out >0.1 day delay between SN and GRB

Jetted Supernova: Hypernova

Razzaque, Meszaros & Waxman, PRL 2004

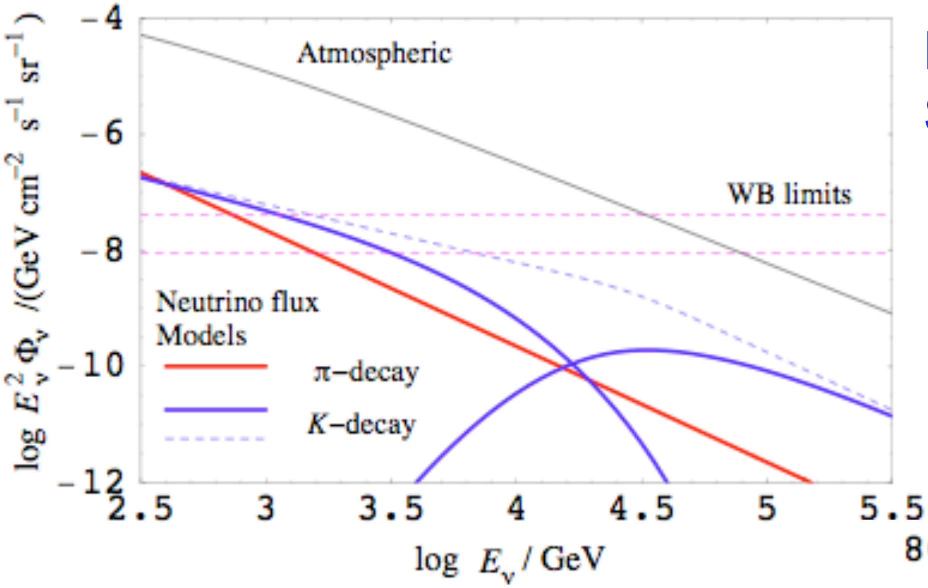
A dirty fireball model of SN explosion
➔ A weak semi-relativistic jet (Γ~3) forms after core collapse
➔ Jet chokes inside



Motivation

- High expansion velocity (30-40 x 1000 km/s) of SN remnant shell as seen in SN 1998bw
- Radio afterglow not associated with gamma-ray emission
- Asymmetric explosion inferred polarimetry observations of SN type Ib/c

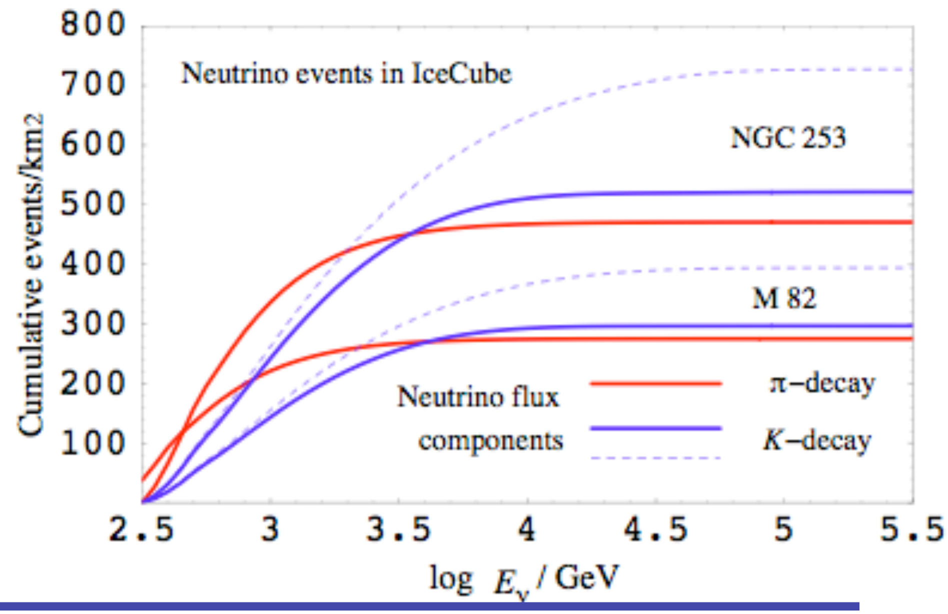
High Energy ν's from Jetted SNe



Diffuse Neutrino flux assuming all SNe with semi-relativistic jets

Prospects for individual source detection is much better from hypernovae within ~20 Mpc and if their rate is a significant fraction of the SNe rate of 1/yr

Razzaque, Meszaros & Waxman 2004; 2005
Ando & Beacom 2005

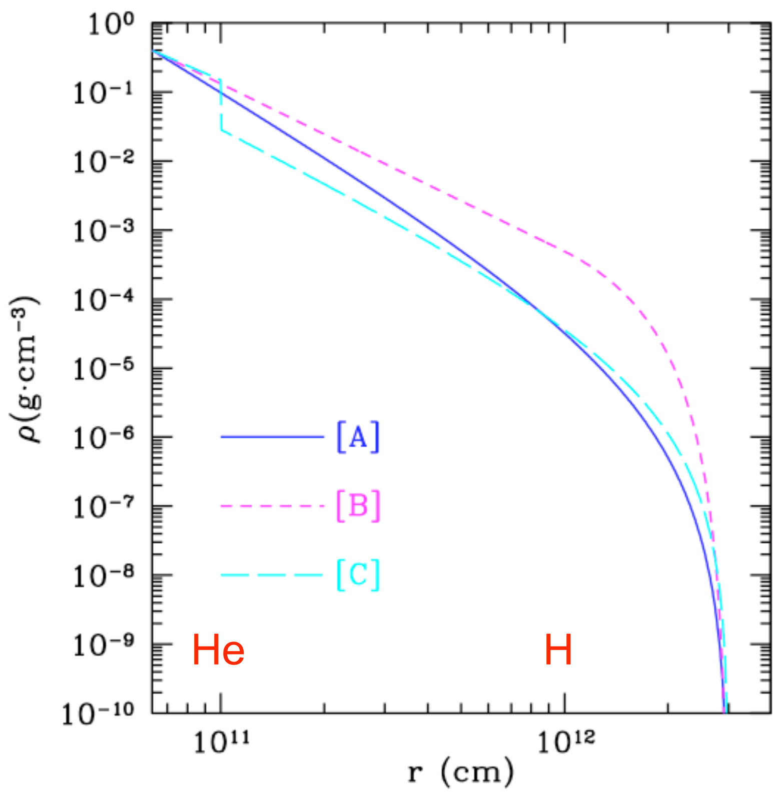


Recent progress by

Farzan & Smirnov, 2008
Enberg, Reno & Sarcevic, 2009

Oscillation Effects on Neutrino Fluxes

Mena, Mocioiu & Razzaque, PRD 2007



Density profiles of pre-SN stellar envelopes of a Blue Super Giant

High energy ν's are produced inside the He envelope and propagate through the He and H envelopes

$N_e = 2.4\times10^{23}$ cm^{-3} at $r = r_{\rm jet} = 10^{10.8}$ cm

Comprehensive study on MSW oscillation effects for thermal SN ν's by *Dighe & Smirnov 2000*

Resonant densities

$$N_e^L = \frac{\Delta m^2_{\rm sol}\cos 2\theta_{12}}{2\sqrt{2}G_F E} \simeq \frac{3\times10^{23}}{E[\mathrm{GeV}]}\ \mathrm{cm}^{-3}$$

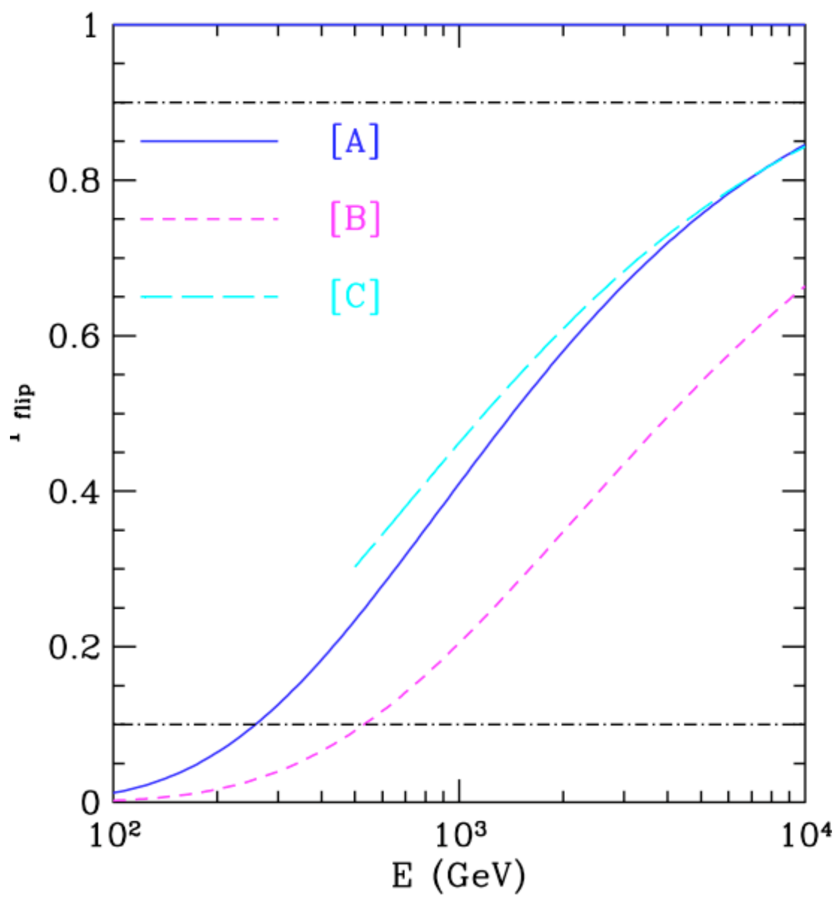
$\sin^2 2\theta_{13} = 0.15$

$$N_e^H = \frac{|\Delta m^2_{\rm atm}|\cos 2\theta_{13}}{2\sqrt{2}G_F E} \simeq \frac{9\times10^{24}}{E[\mathrm{GeV}]}\ \mathrm{cm}^{-3}$$

➔ Expect MSW effect for ~TeV ν's

Numerical Calc. of Oscillation Probabilities

Flip probabilities due to atmospheric transition for $\sin^2 2\theta_{13} = 0.15$



Transitions are mostly non-adiabatic at ~TeV energy due to rapid change in density

➔ Analytic estimates are unreliable

➔ Numerically solve propagation equation

$$i\frac{d}{dr}|\nu_\alpha\rangle = U H_m U^\dagger |\nu_\alpha\rangle$$

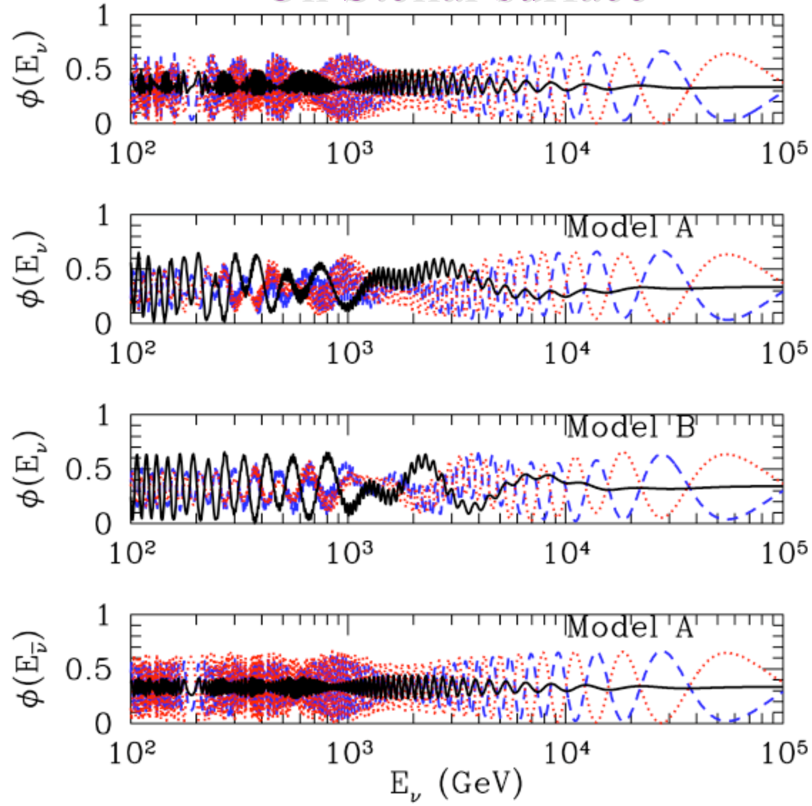
With different matter potentials

$$V_{e,CC} = \sqrt{2} G_F N_e$$

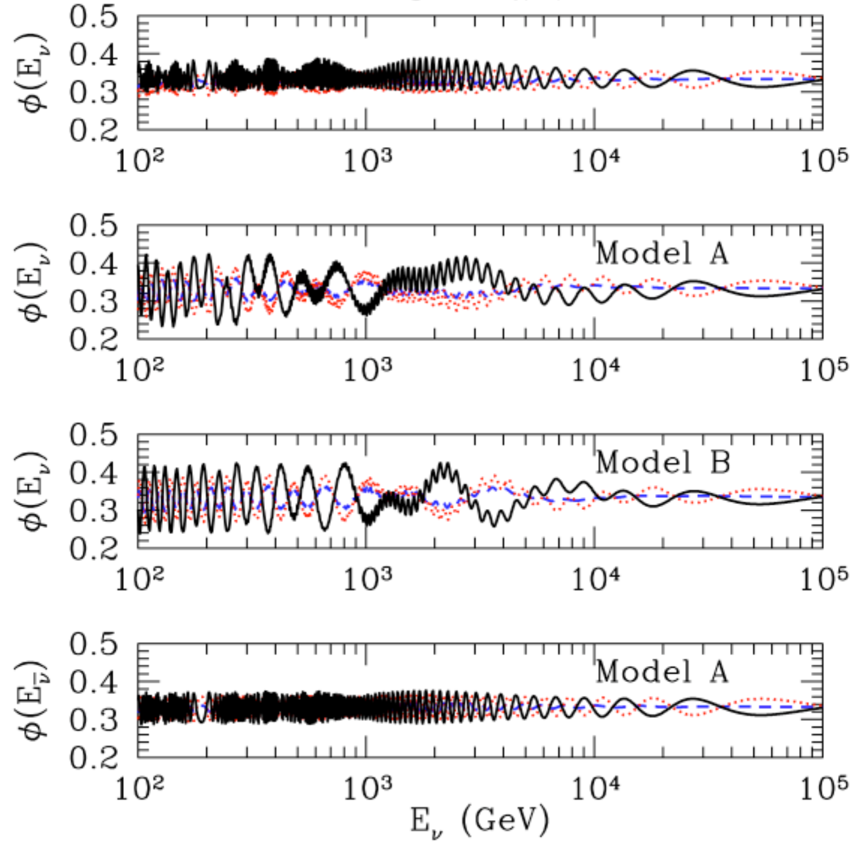
Fluxes at Production and on Earth

Production ratios in the jet for both neutrinos and anti-neutrinos in the 100 GeV - 100 TeV range: $\Phi_{\nu\mu} = 2\Phi_{\nu e}$

On Stellar surface



On Earth



Solid black: ν_e

Dashed blue: ν_μ

Dotted red: ν_τ

Probing Oscillation Effects in ν Telescopes

Calculate neutrino events in a km-scale water/ice Cherenkov detector

➔ Neutrino "telescopes" can not distinguish between ν_e and ν_τ at these energies

Construct an Observable

$$R = \frac{N_{\nu_e} + N_{\nu_\tau}}{N_{\nu_\mu}}$$

No matter effect: $R = 2$

R depends on the astrophysics

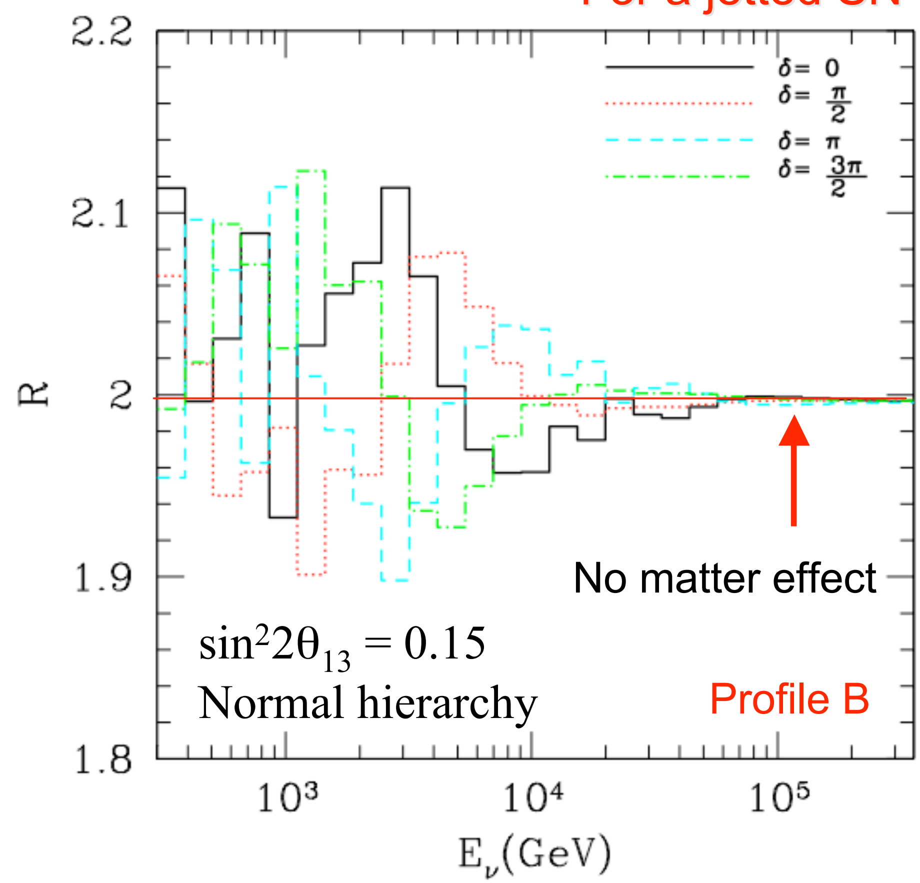
- Neutrino flux at production
- Density profile of the envelope

and on neutrino oscillation physics

- Mass hierarchy
- Oscillation parameters, θ_{13}

Small effect ➔ high event rate from nearby jetted SN can help

For a jetted SN



Summary

Only neutrinos carry information from inside stars

High energy neutrinos can probe jetted SN/GRB models

- ❖ Observations of GRBs provide evidence of relativistic jet formation from massive stellar collapses, SN and GRBs are connected
- ❖ Supranova model can be constrained or ruled-out from neutrino telescope (such as IceCube) data
- ❖ Precursor neutrino from buried GRB jet can distinguish progenitor star model, better detection prospect than burst neutrinos
- ❖ Jetted SN or hypernova may constitute a new class of collapse
  - ➔ Can only be probed with high-energy neutrinos
  - ➔ Probe MSW effect for TeV neutrinos for the first time!

Not sure if SN/GRB science will lead to ν technology though …