Neutrino Tomography of GRB Jet

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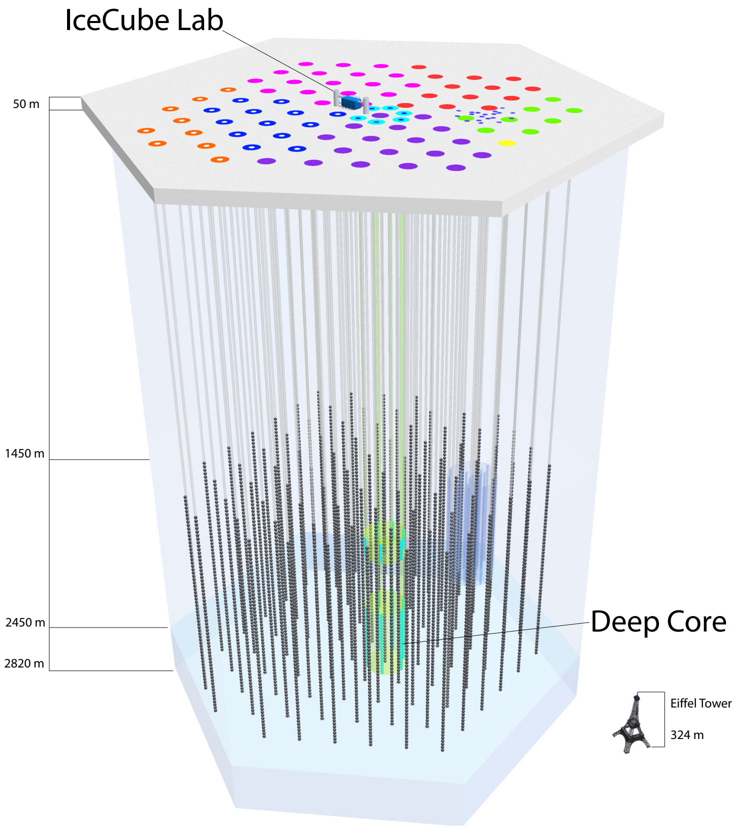
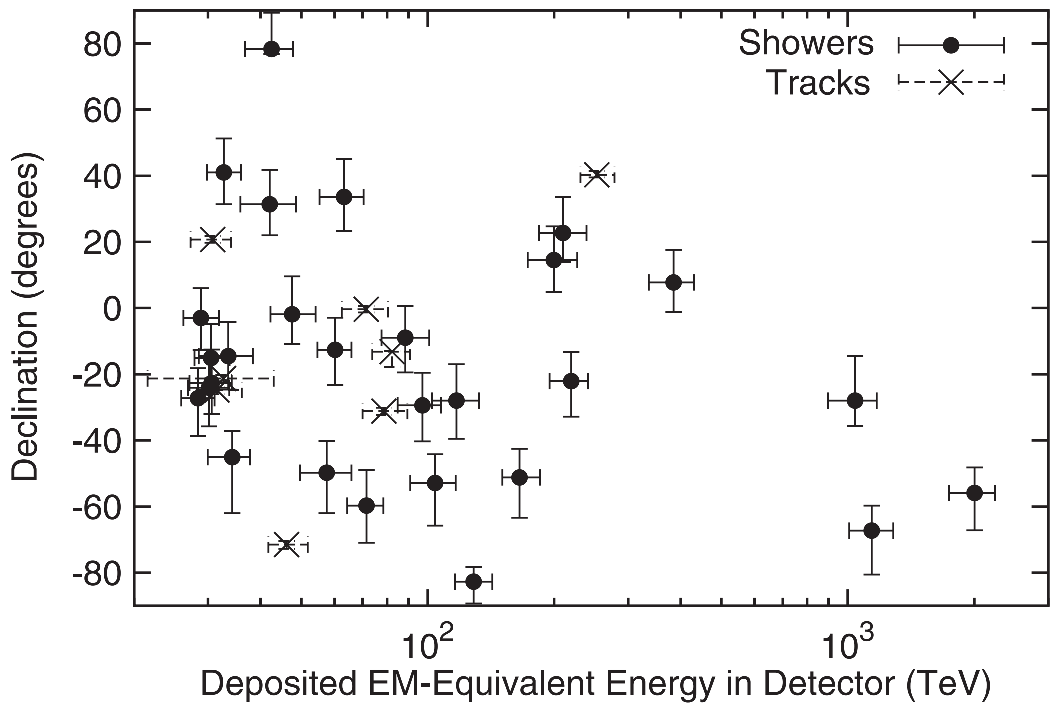
The IceCube Discovery



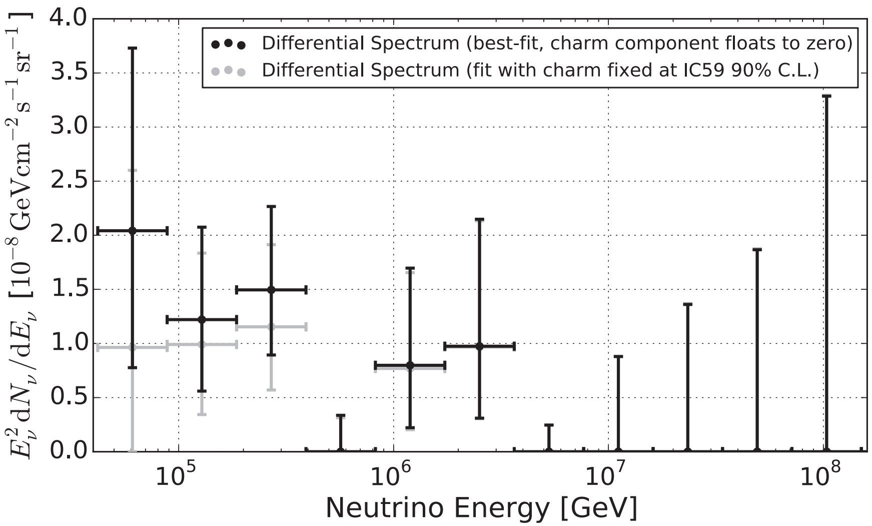
IceCube 14

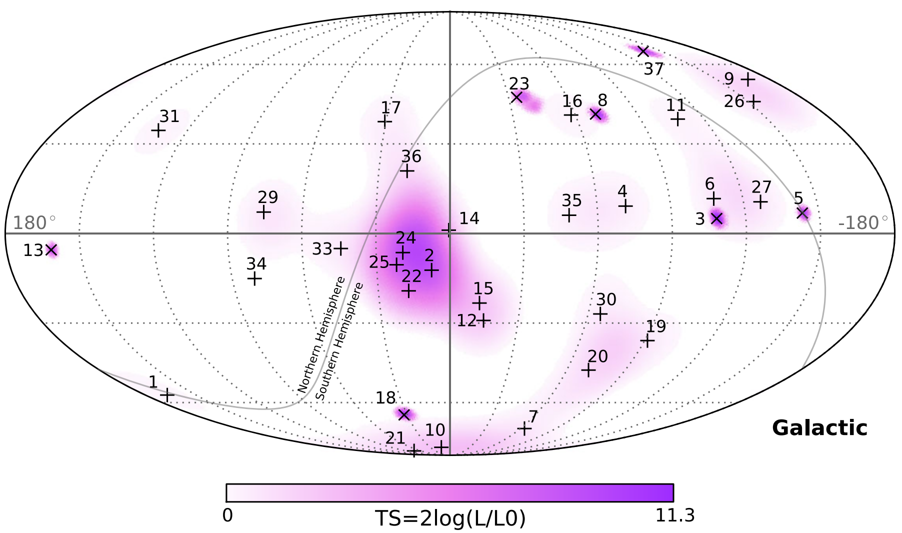


✓ **37 events ranging from ~ 30 TeV to ~ 2000 TeV per 988 days**

The IceCube Discovery

IceCube 14





- ✓ **inconsistent with atm. bg. with 5.7 σ**
- ✓ **consistent with 1:1:1 flavor ratio**
- ✓ **~ 10^{-8} GeV cm^{-2} s^{-1} sr^{-1} per flavor with a spectral index of p ~ 2**

- ✓ **No significant clustering**
- ✓ **No association with any astro source reported**

High-Energy Neutrino Production

- p γ interaction

$$p + \gamma \rightarrow p + \pi^0;\ n + \pi^+$$

- Inelastic nuclear collision

$$p + p \rightarrow p + p + \pi^0;\ n + p + \pi^+$$

$$p + n \rightarrow p + n + \pi^0;\ n + n + \pi^+$$

etc

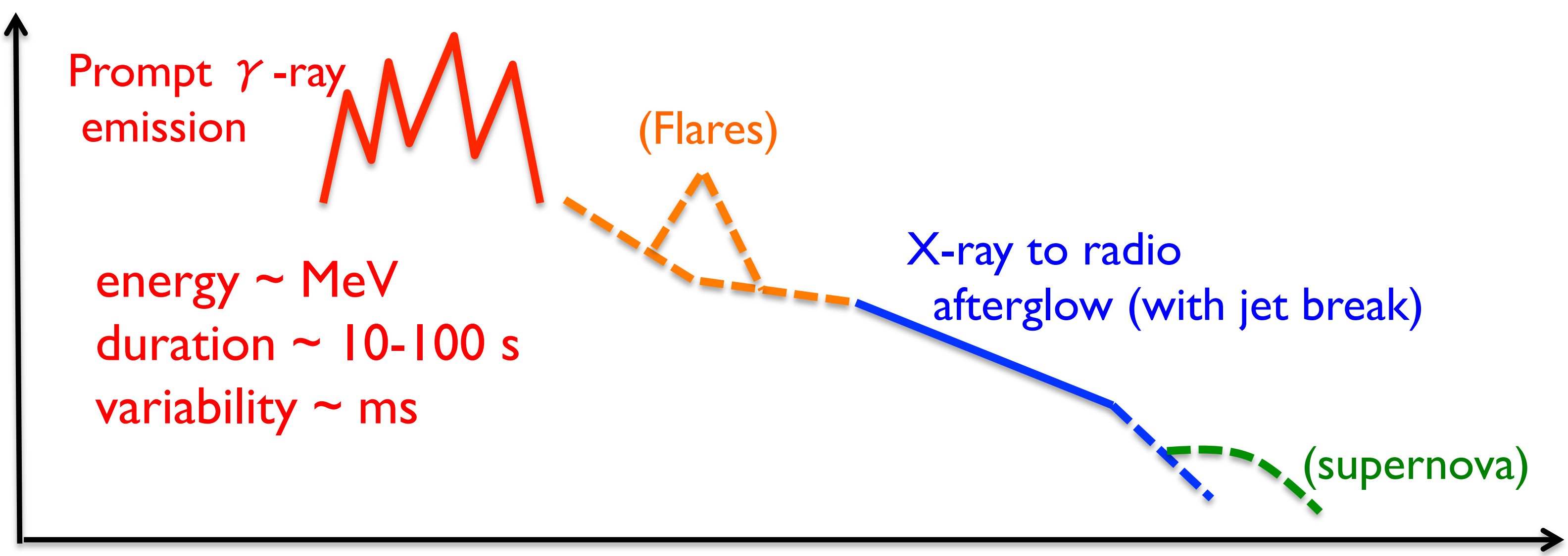
$$\pi^+ \rightarrow \mu^+ + \nu_\mu \qquad \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

Hadron Acceleration + Collision with Target Photons or Hadrons

Neutrino × GRB

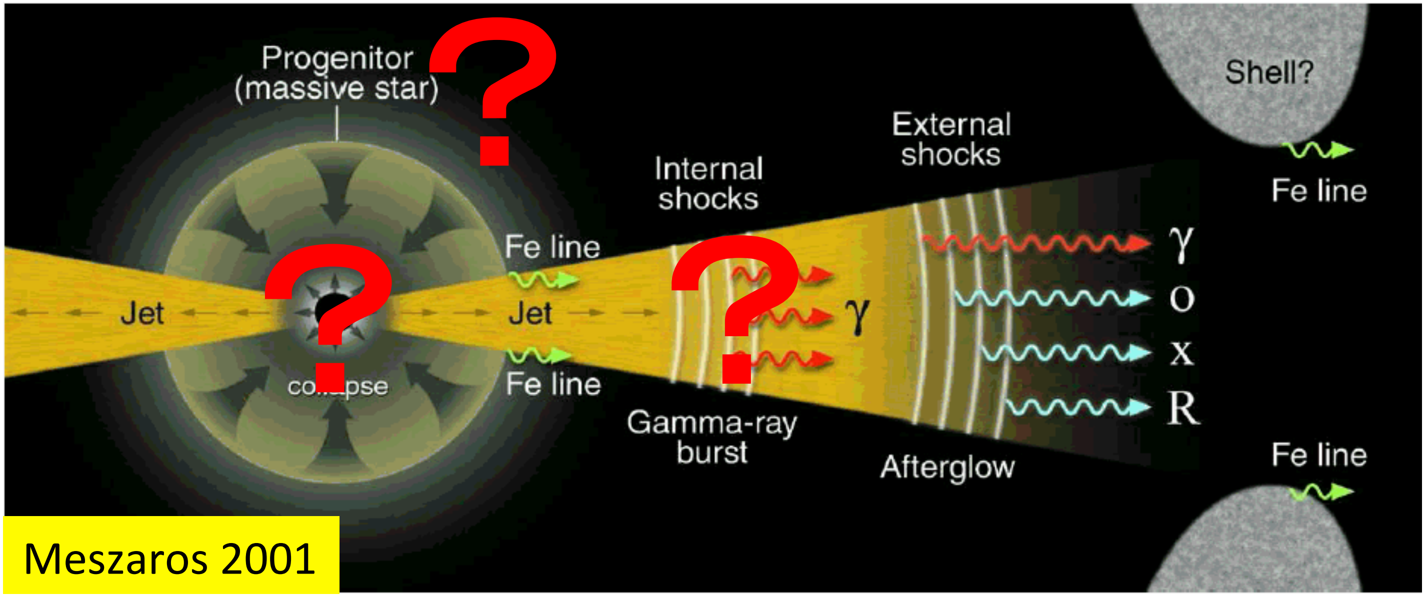
(Long) Gamma-Ray Bursts

- what we know
  - The most luminous transients ($L_\gamma \sim 10^{51\text{-}52}$ erg s^{-1})
  - Cosmological events ($z \sim 1\text{-}3$) ~ 100 per yr
  - Relativistic jets ($\Gamma \sim 10^{2\text{-}3}, \;\; \theta_j \sim 0.1$ rad)
  - Related to death of massive stars



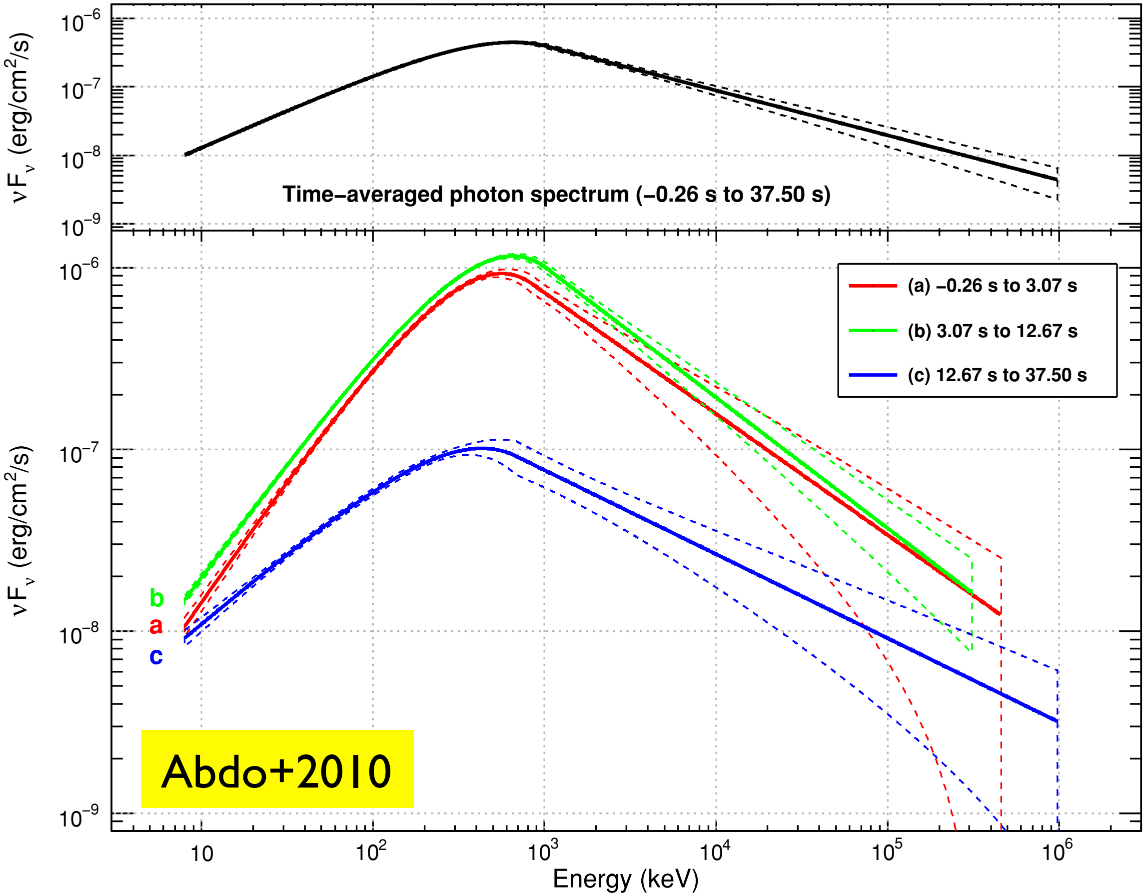
(Long) Gamma-Ray Bursts

- A standard picture



- Fundamental Questions
  - **Central engine?** → **BH and magnetar formation**
  - **Prompt emission?** → **Extreme plasma physics Origin of UHECRs**
  - **Progenitor?** → **GRB-SN connection**

Q. What is the GRB mechanism?



"Band" function
~ broken power law

✓ $\varepsilon_{peak} \sim 0.1\text{-}1$ MeV

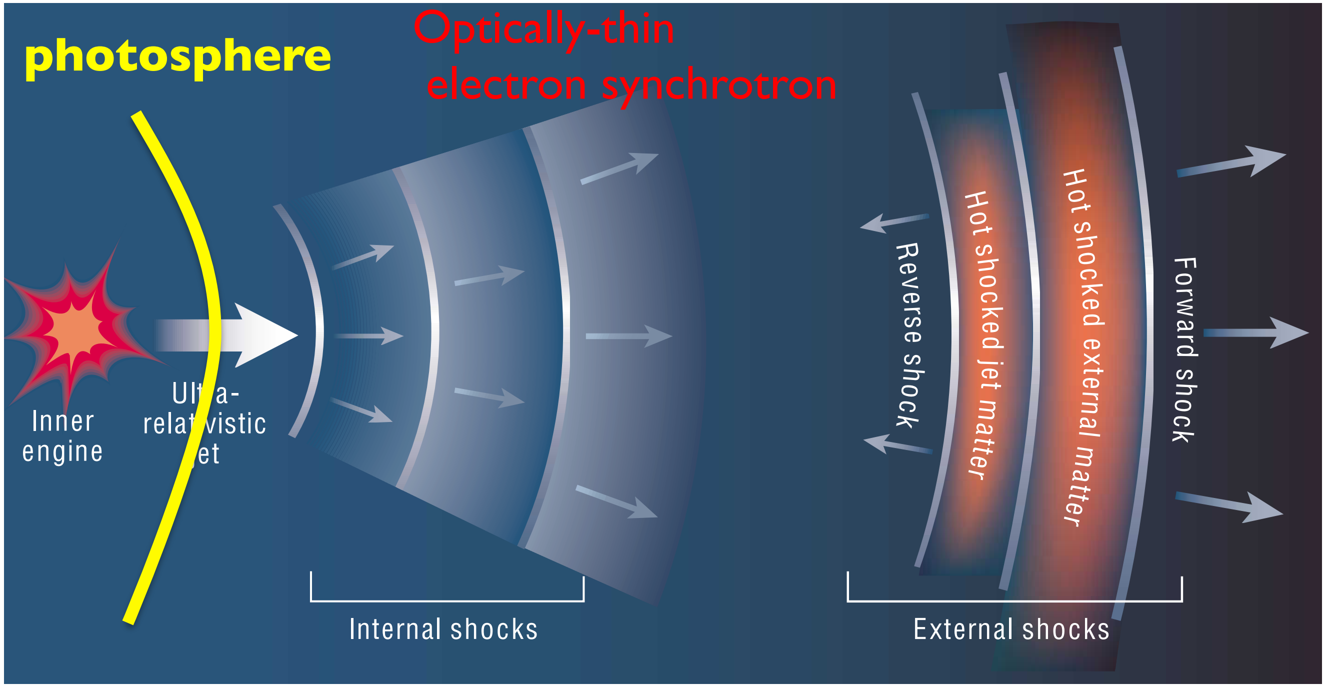
✓ @ low energy $N_E \propto E^{\alpha}$
$\alpha \sim -1$

✓ @ high energy $N_E \propto E^{\beta}$
$\beta \sim -(2\text{-}3)$

✓ non-thermal features → particle acceleration?

✓ polarization? (e.g., Yonetoku+2012) → magnetic fields?

The Internal Shock Model



Bulk Kinetic energy (baryon-dominated)
$\Gamma \sim 10^{2\text{-}3}$

⇨

Shock dissipation
@ $\tau_T \ll 1$

⇨

- Magnetic filed
- Particle acceleration
- Heat

The GRB-UHECR Hypothesis

- If not only electrons but protons are accelerated,

$$\varepsilon_p < erB \sim 3 \times 10^{20} \; r_{14} B_4 \; \mathrm{eV}$$ Waxman 1995

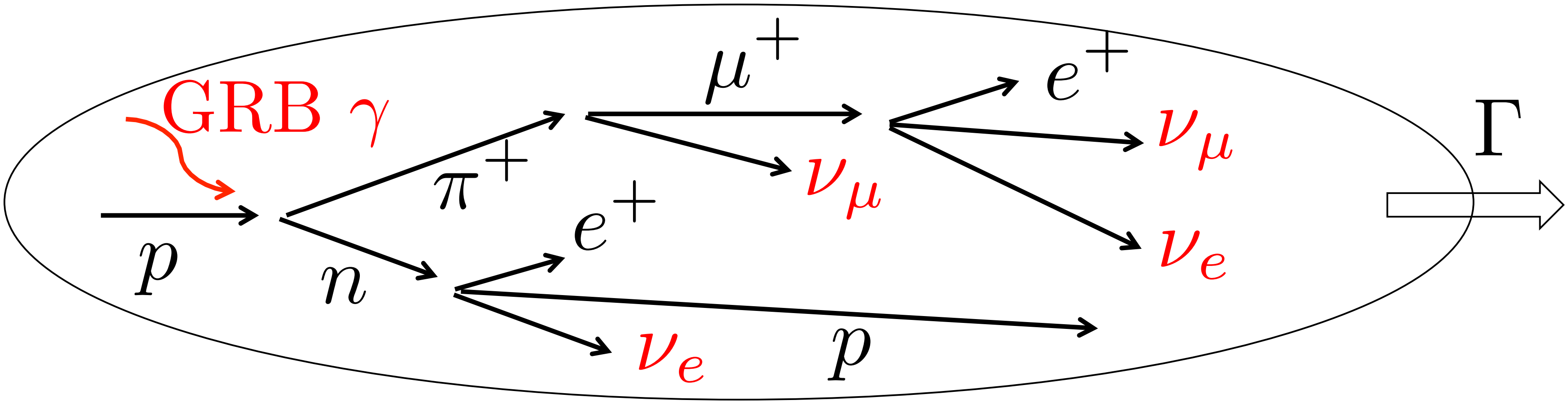
- If $E_{CR}^{iso} \sim E_{\gamma}^{iso} \sim 10^{53} \; \mathrm{erg}\,,$

with $\rho_{GRB} \sim 1 \; \mathrm{Gpc}^{-3} \mathrm{yr}^{-1}$ Wanderman & Piran 2003

$$\Longrightarrow \quad Q_{CR} \sim 10^{44} \; \mathrm{erg} \; \mathrm{Mpc}^{-3} \; \mathrm{yr}^{-1}$$

Consistent with the UHECR observations

The GRB Prompt Neutrinos



$$p + \gamma \to N\pi + X \text{ with } \sigma_{p\gamma} \sim \text{a few} \times 10^{-28} \text{ cm}^2$$

- ✓ @ Δ-resonance $\varepsilon'_p \times \varepsilon'_\gamma \sim 0.2 \text{ GeV}^2$

$$\varepsilon_{\nu,obs} \sim 0.05\, \varepsilon_{p,obs} \sim 0.01\, \Gamma^2 \varepsilon^{-1}_{\gamma,obs} \text{ GeV}^2$$

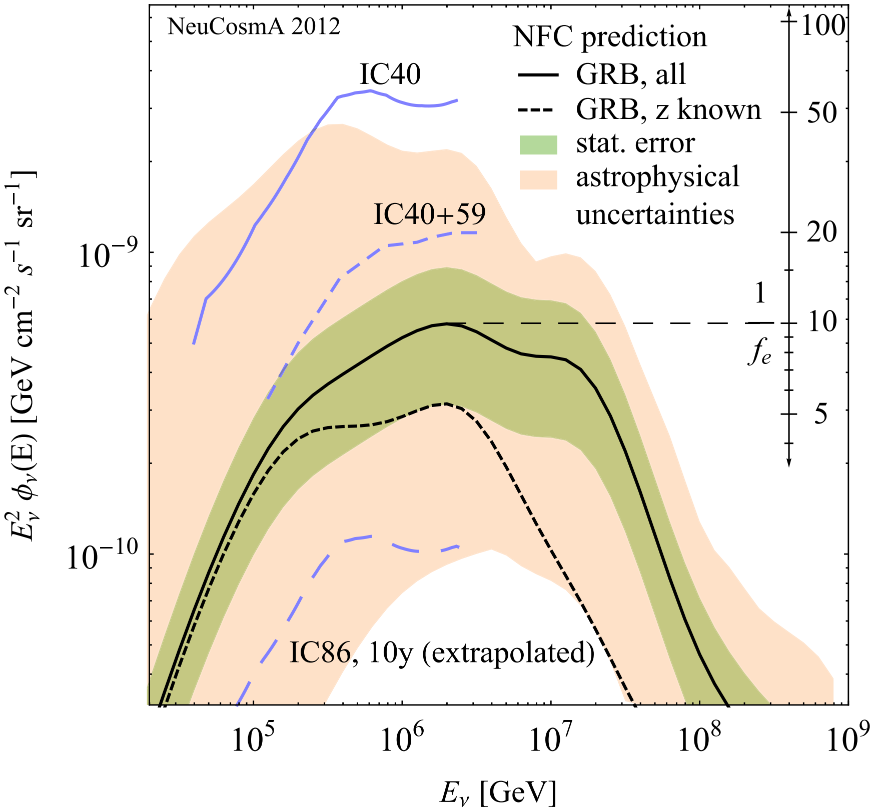
$$\sim 1 \text{ PeV } \Gamma^2_{2.5} \varepsilon^{-1}_{\gamma,obs,\text{MeV}}$$

- ✓ Meson production efficiency (large astrophysical uncertainties)

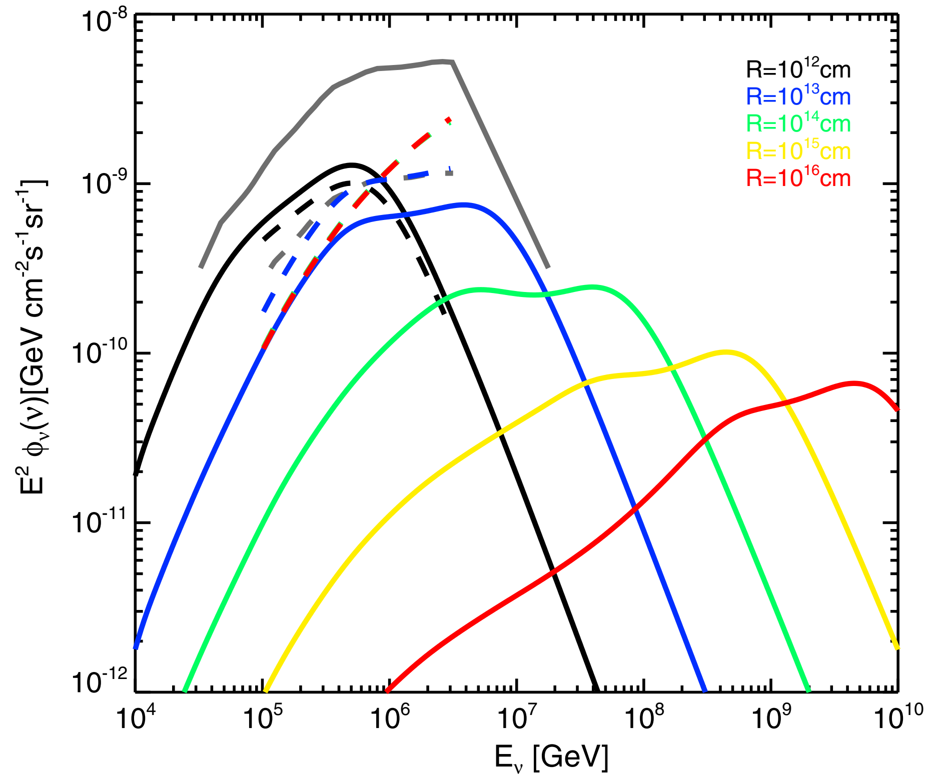
$$f_{p\gamma} \sim 0.2 n_\gamma \sigma_{p\gamma} (r/\Gamma) \propto r^{-1}\Gamma^{-2} \longrightarrow F_\nu \propto \eta_{\text{CR}} r^{-1} \Gamma^{-2}$$

The Current IceCube Limit

Hummer+ 2012



He+ 2012

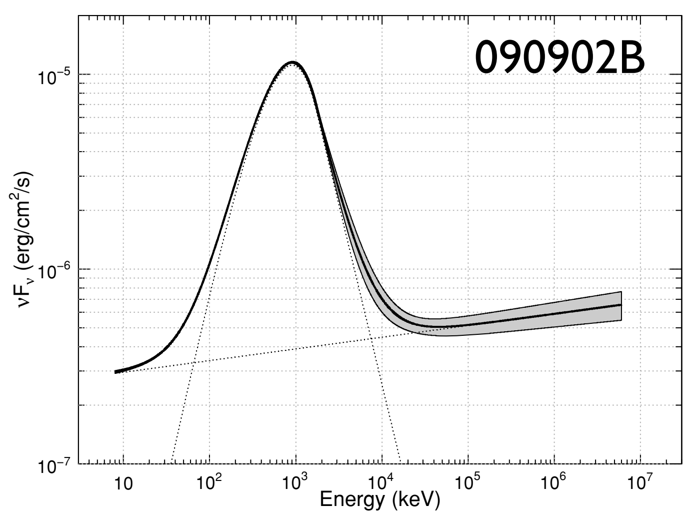


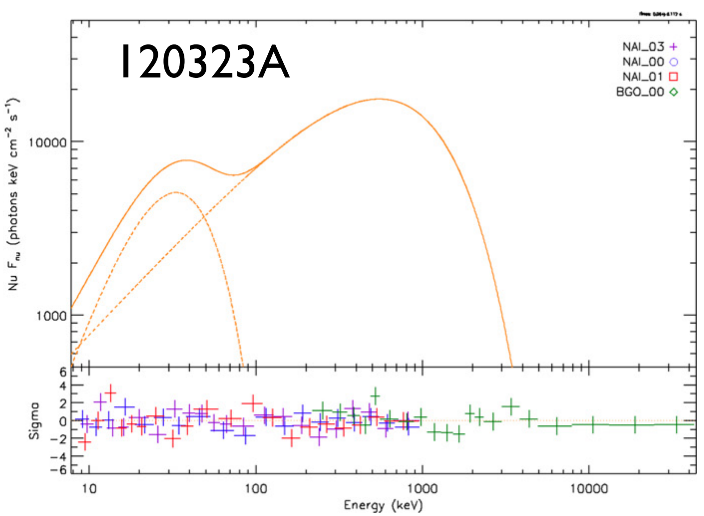
~10 yr observations by IceCube can cover reasonable parameter ranges for the GRB-UHECR scenario.

Problems in the Classical Scenario

- Low radiation efficiency
- Wrong spectrum
  - Low energy photon index incompatible with Band
  - Empirical relation (ε_{peak}-L)

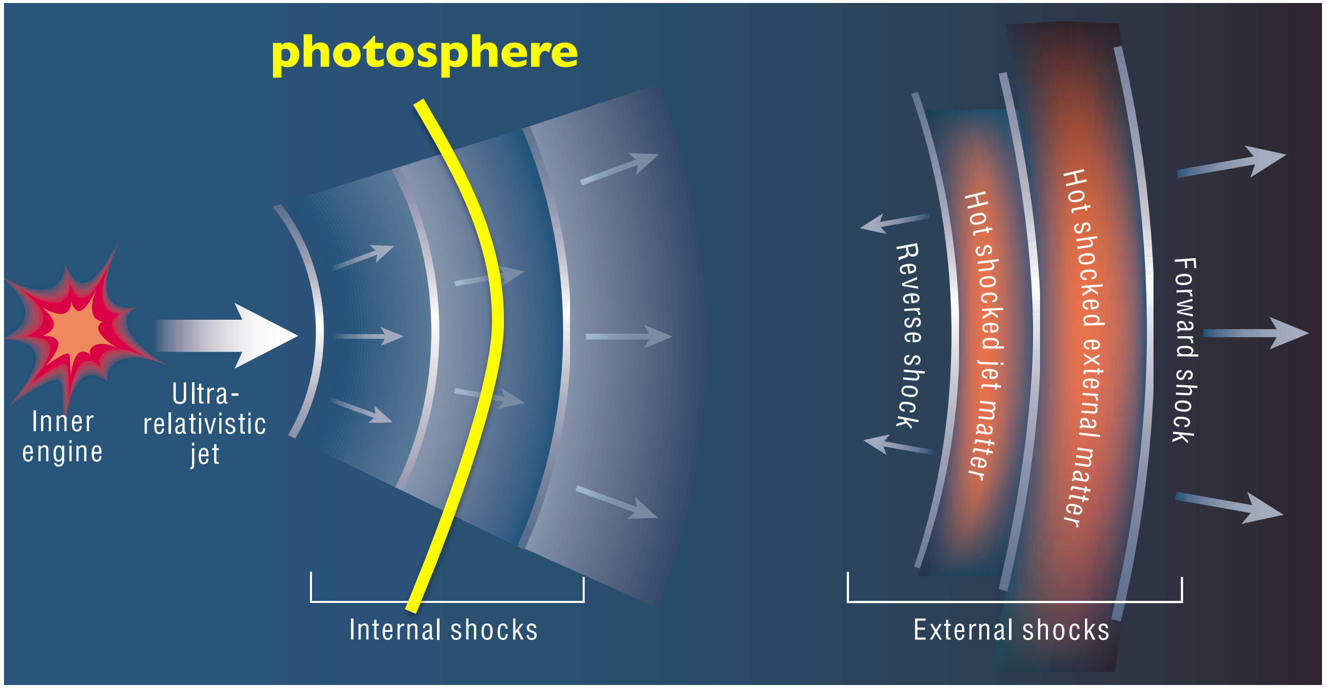
✓ Hint: GRBs with (quasi-)thermal component





Dissipative photosphere scenarios

(Re-)conversion of bulk energy to radiation energy @ $\tau_T \sim 1\text{-}10$



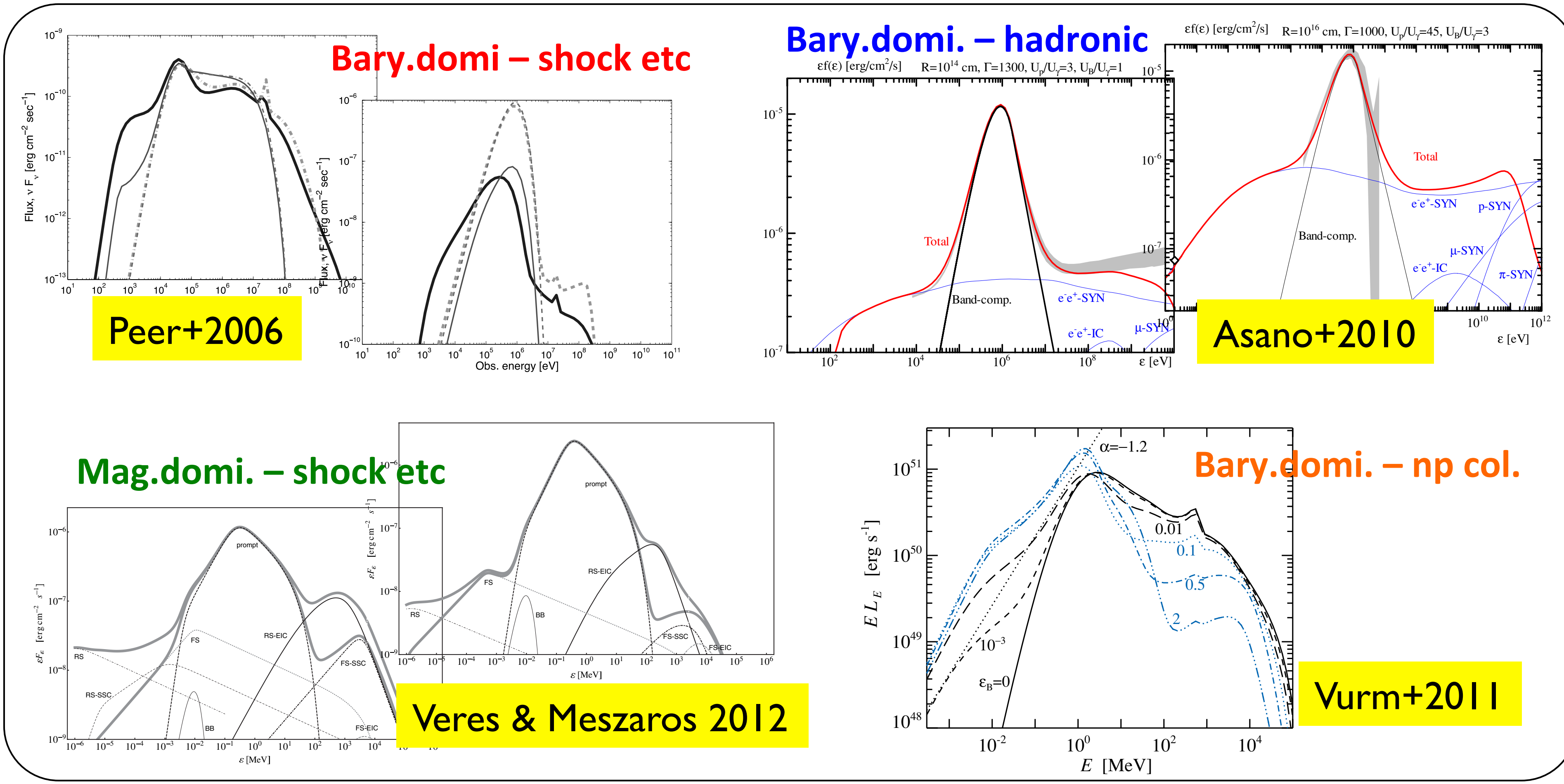
OR

magnetic reconnection,
collisions with neutrons, etc

High Radiation Efficiency & Stabilized Peak Energy

The Dissipative Photosphere Zoo

- ✓ Large variatiety ; Jet Characteristic × Dissipation Channel
- ✓ Theories can reproduce observations "with tunings" including high (GeV) to low (optical) extra-components.

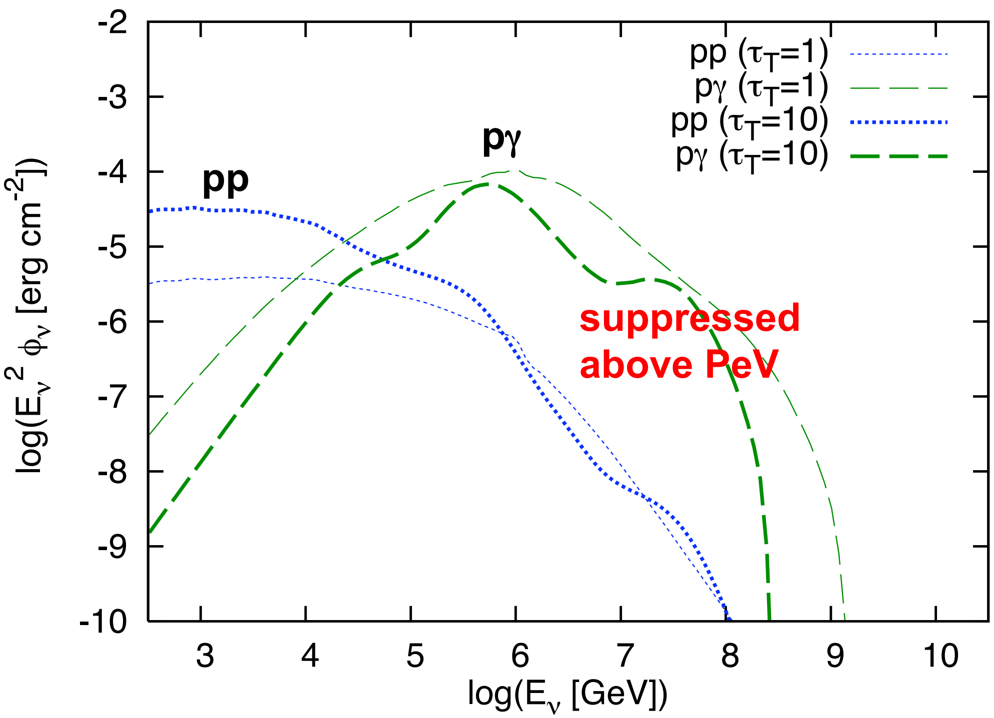


Dissipative Photospheric Neutrinos

Photosphere : $\tau_T = n_e \sigma_T (r/\Gamma) \sim$ 1-10

$\longrightarrow$ $f_{pp} = (\kappa_{pp} \sigma_{pp} / \sigma_T) \tau_T \sim 0.05\text{-}0.5$

$\longrightarrow$ If CR acc. @ photosphere, *pp* is relevant.



$E_{CR}^{iso} \sim E_\gamma^{iso} \sim 10^{53.5}$ erg

$\Downarrow$

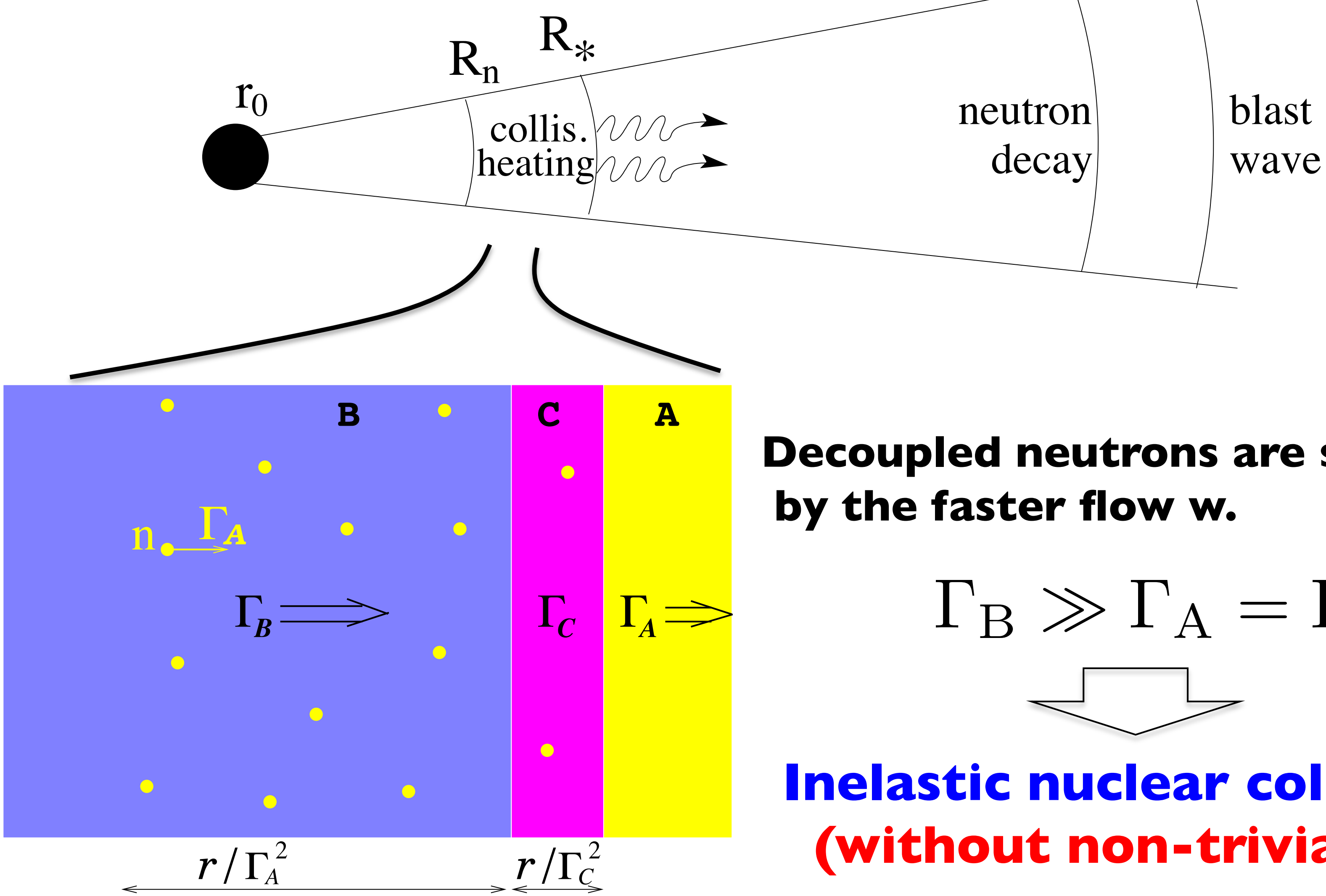
$N_\mu \sim 1\text{-}2$ from GRB @z=0.1

Murase 2008, Wang & Dai 2009

Detection of *pp* neutrinos supports dissipative photospheres.

Collisional Dissipations by Neutrons

Paczynski & Xu 1994, Bahcall & Meszaros 2000, Meszaros & Rees 2000, Beloborodov 2009



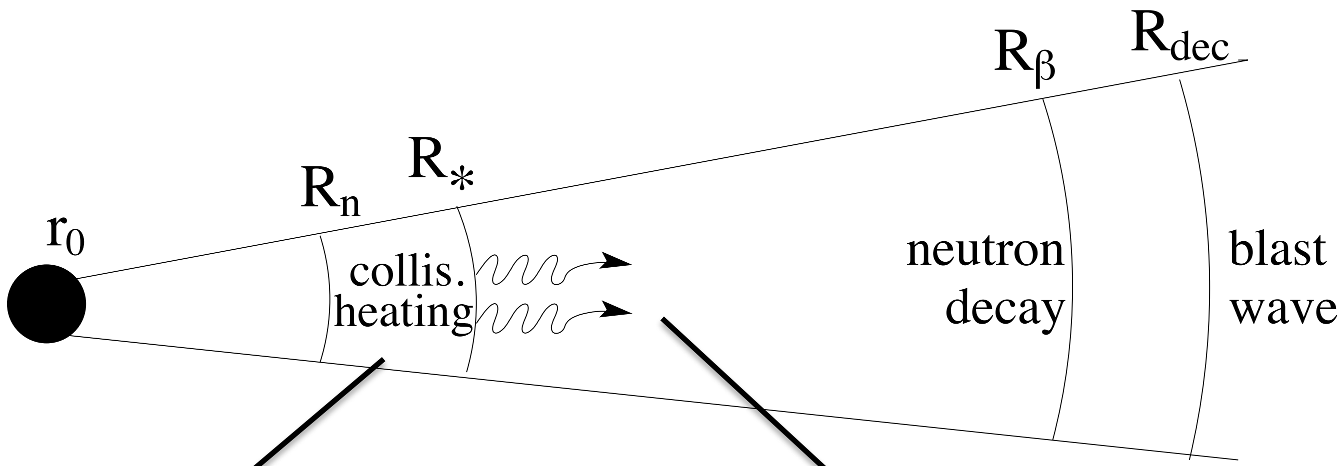
Decoupled neutrons are swept up by the faster flow w.

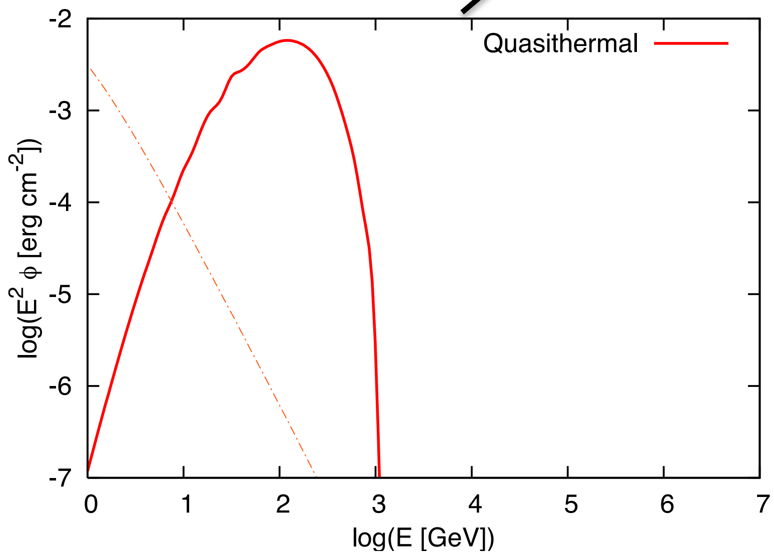
$$\Gamma_B \gg \Gamma_A = \Gamma_n$$

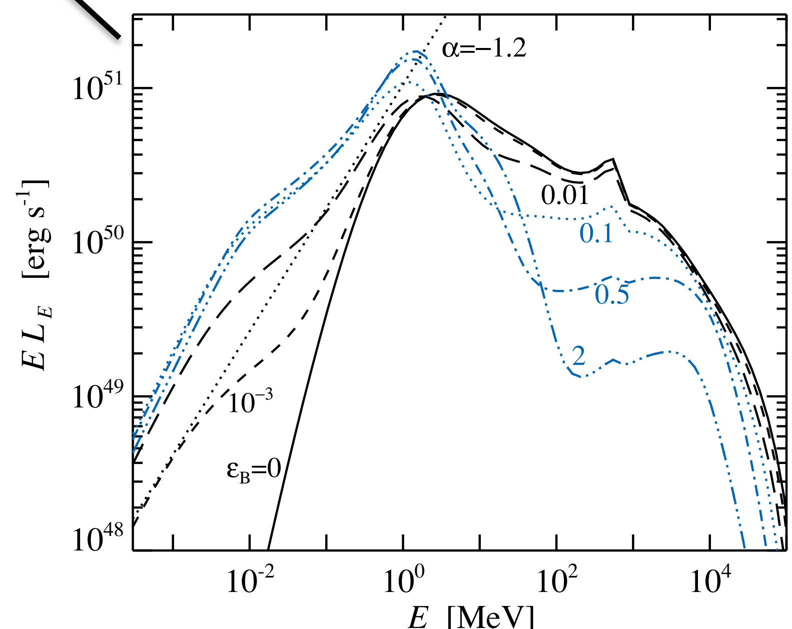
⇩

Inelastic nuclear collisions (without non-trivial acc.)

The np collisional heating scenario







Multi-GeV quasi-thermal neutrinos

$$\varepsilon_\nu \sim 100\ \mathrm{GeV}(\Gamma/500)(\Gamma_{\rm rel}/2)$$

Bartos et al. 2013, Murase, KK, Meszaros. 2013

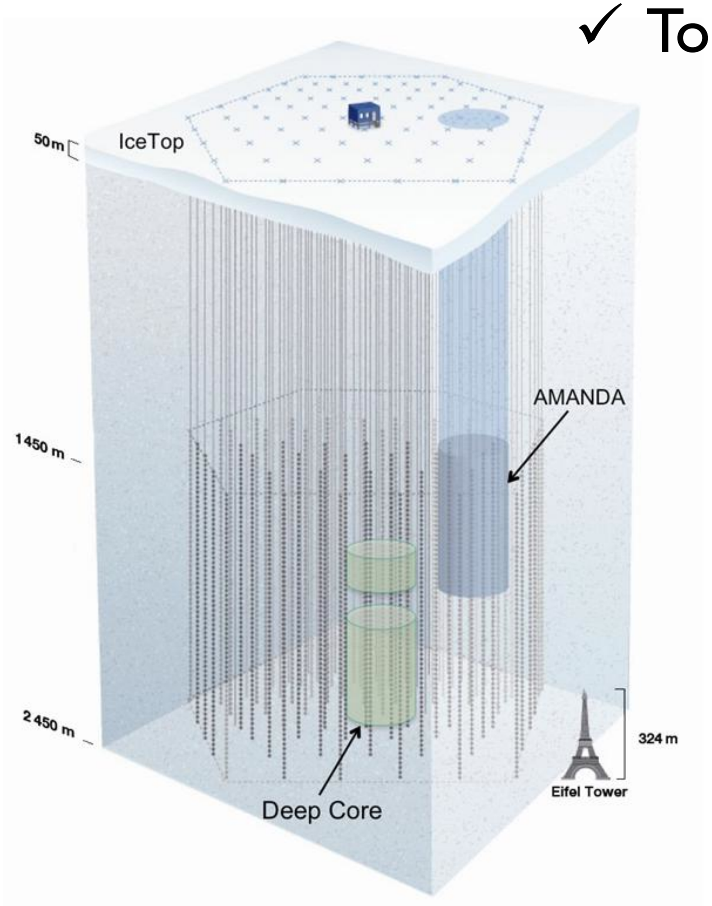
Band spectrum can be reproduced.

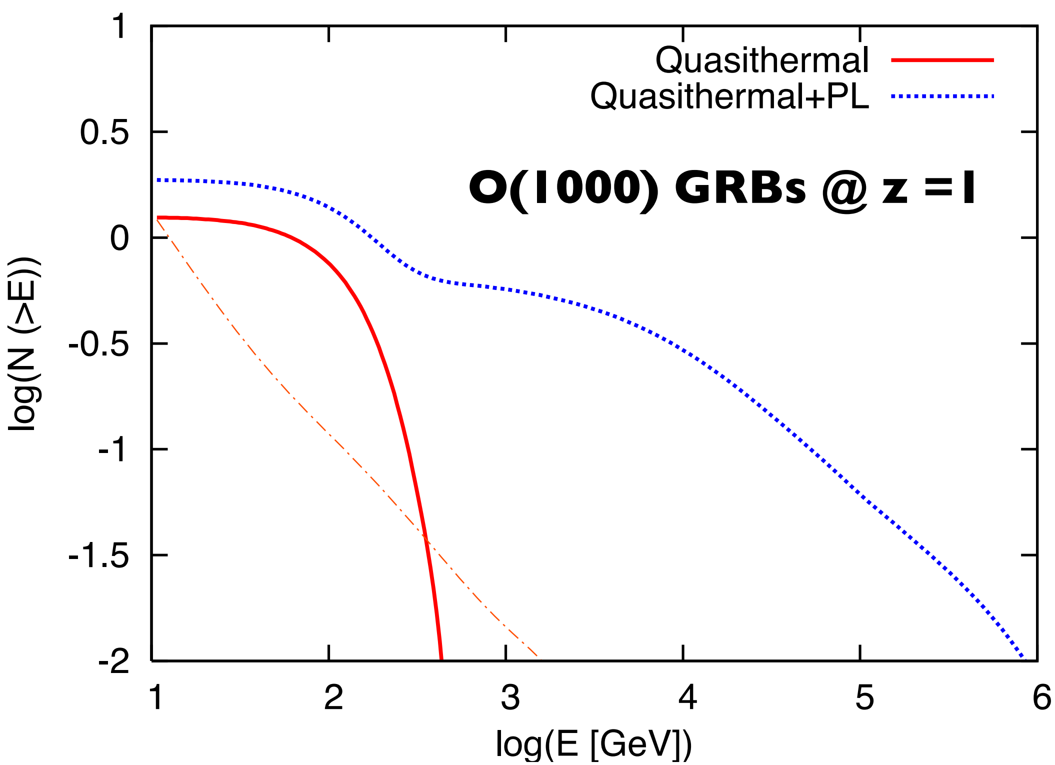
Beloborodov 2009, Vurm+2011

With DeepCore+IceCube

✓ Including DeepCore is essential @ 10-100 GeV.

✓ To reduce atmospheric ν background, select only bright GRBs w. 10^{-6} erg cm^{-2} .





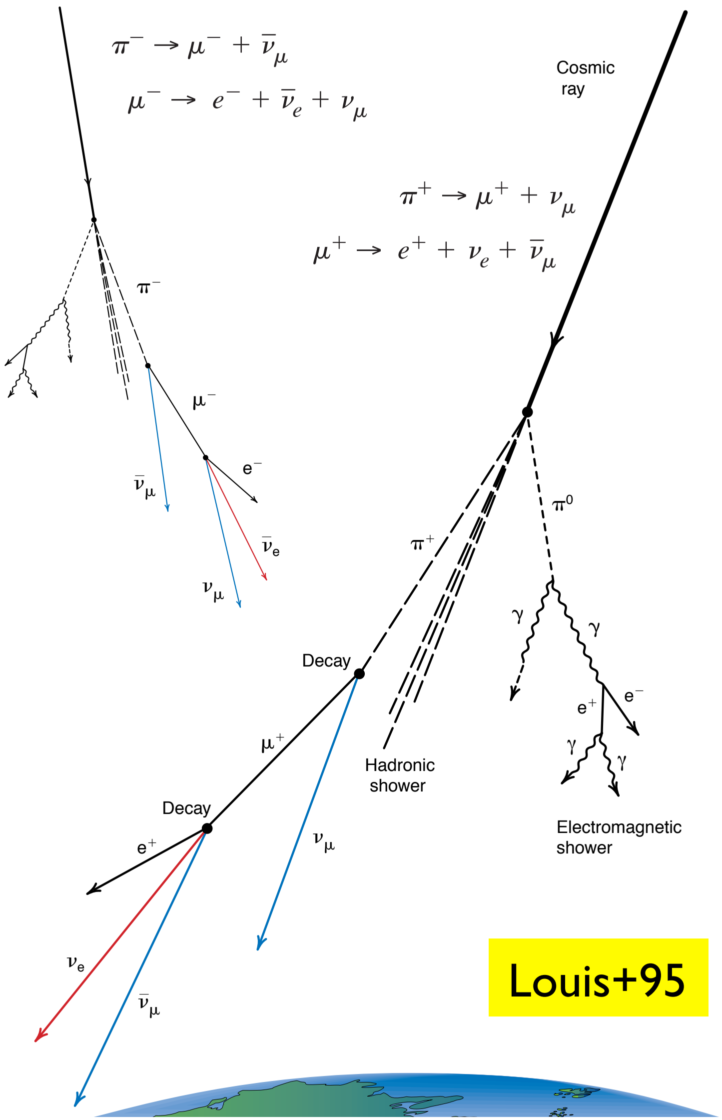
Murase, KK, Meszaros. 2013, Bartos et al. 2013

Summary

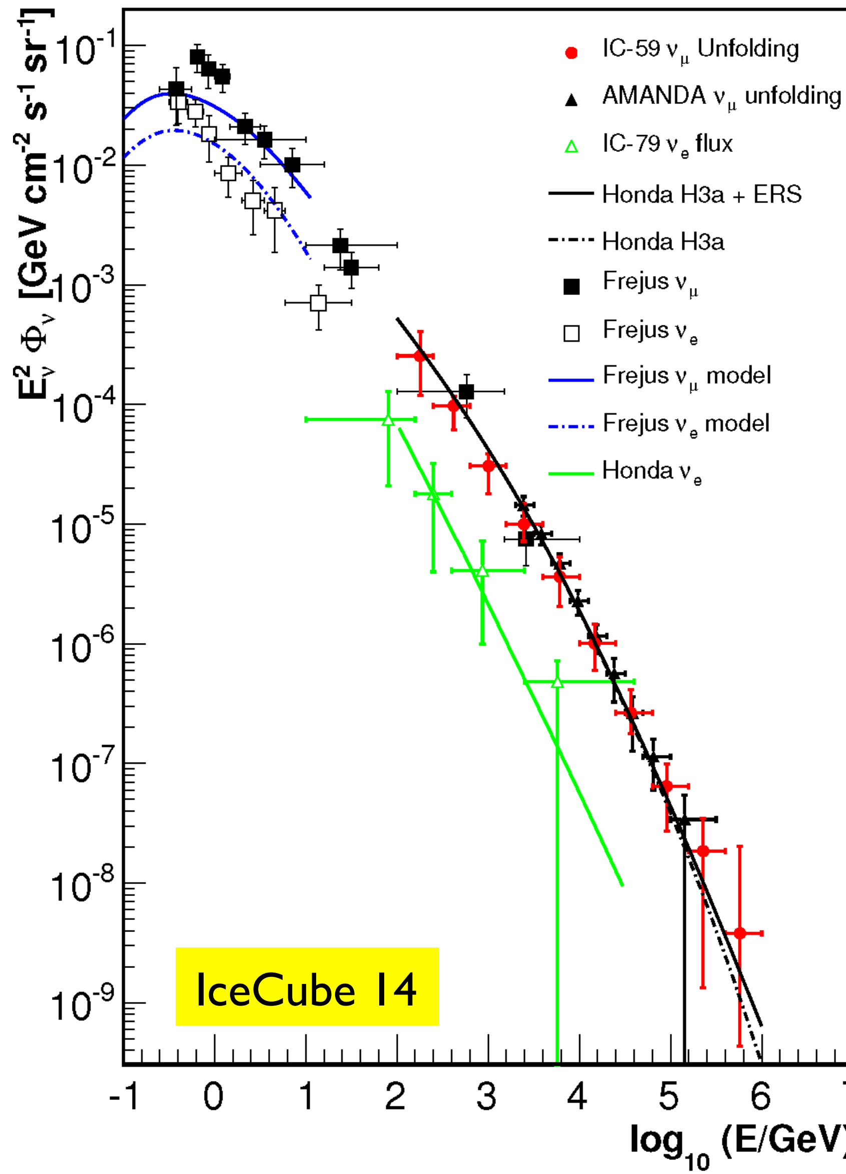
- The era of high-energy neutrino astronomy
- No detection from GRBs so far, but
- ~10yr obs. can give relevant constraints on
  1. the GRB-UHECR hypothesis from ~ PeV ν ,
  2. the dissipative photospheres from ~ TeV ν ,
  3. the neutrons in GRB jets from ~100 GeV ν .

Backups

Atmospheric Background



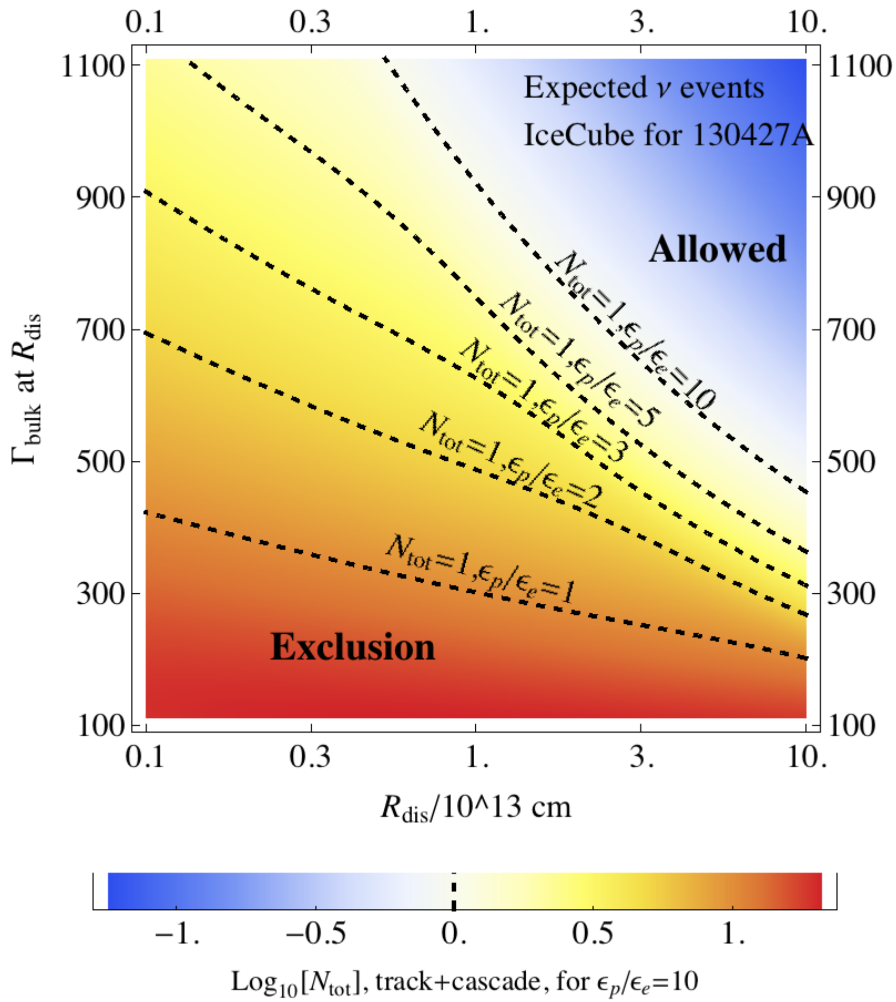
Louis+95



IceCube 14

GRB 130427A

Non detection for the brightest burst ever since the full operation



Shan, KK, & Meszaros. 2013

Low-Luminosity GRBs

- Nearby (ex. 060218@140Mpc)
- Much dimmer

$$E_{LL}^{iso} \sim 10^{50}\ \mathrm{erg} \sim 10^{-3} E_{HL}^{iso}$$

- More frequent

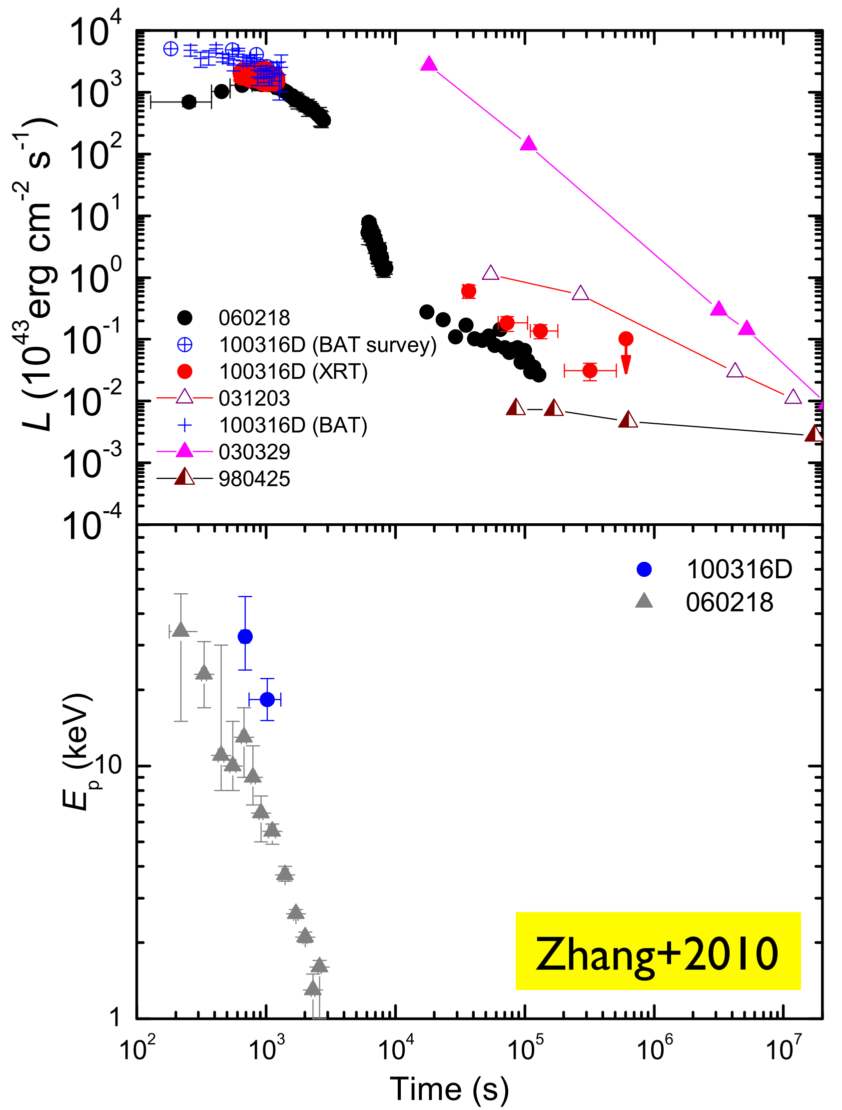
$$\rho_{LL} \sim 10^{2\text{-}3}\mathrm{Gpc}^{-3}\mathrm{yr}^{-1} \gtrsim 10^{3}\rho_{HL}$$

- Quasi-thermal soft spectrum

$$\varepsilon_{peak,LL} \sim 1\text{-}10\ \mathrm{keV} \sim 10^{-2}\varepsilon_{peak,HL}$$

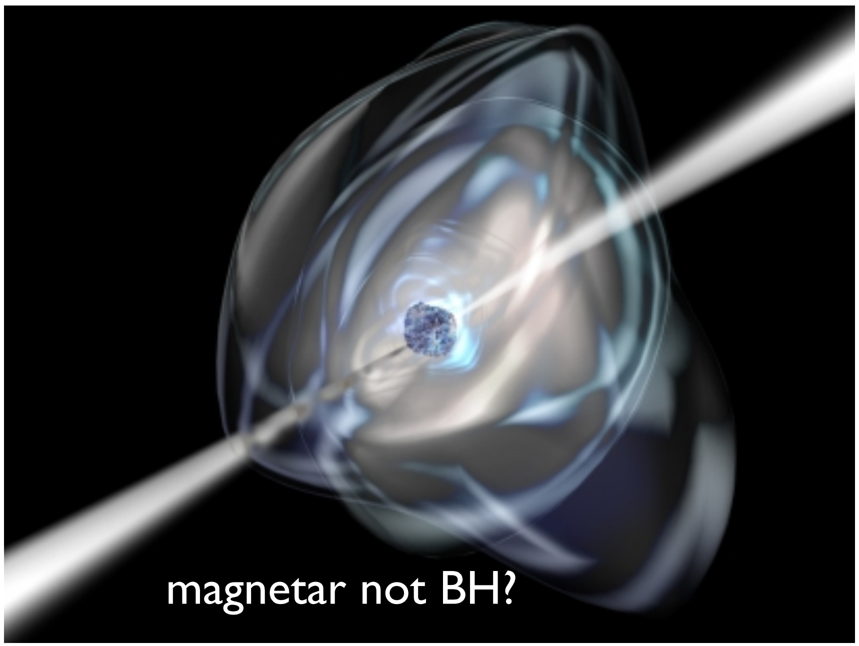
- Associate broad line type Ic SN

  → Relativistic ejecta



Two Competing Scenarios

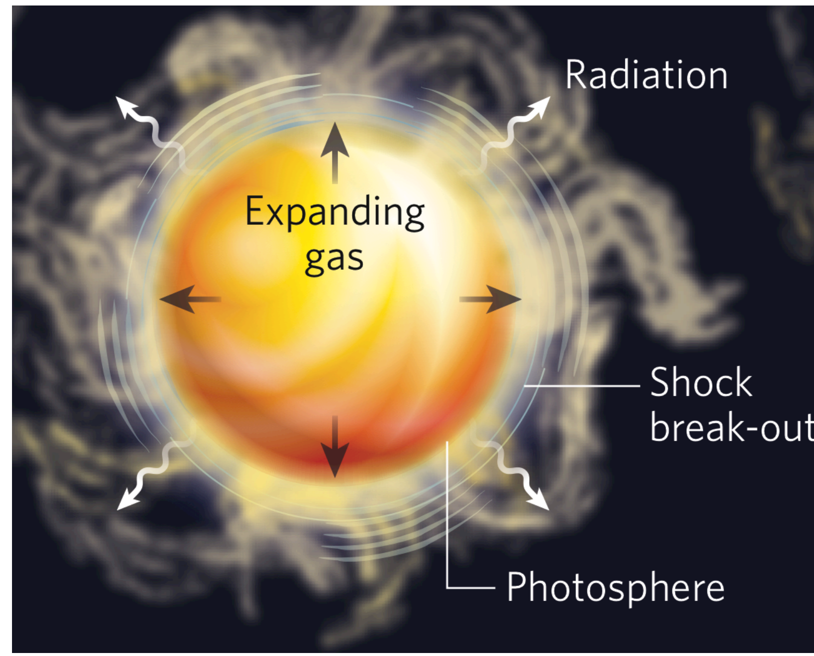
Low-power relativistic jet



Toma+2007
Fan+2010

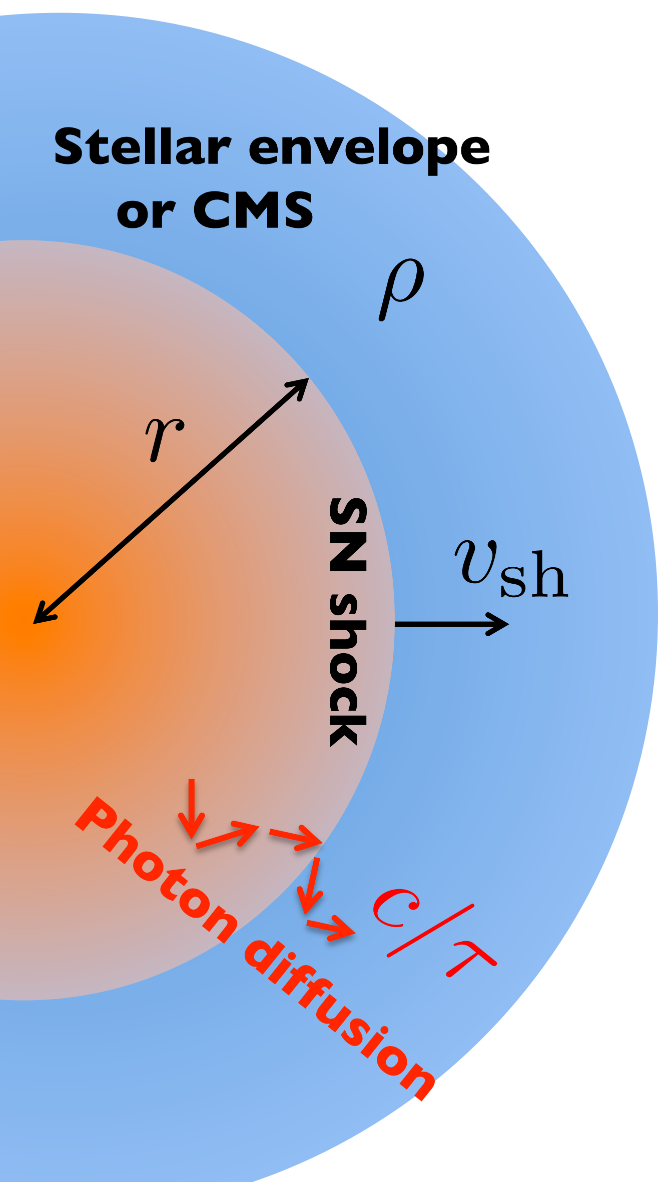
vs

Trans-relativistic shock breakout from optically-thick wind



Waxman+2010
Nakar & Sari 2012

Shock Breakouts



- ✓ The shock downstream is radiation-dominated.

$$P_{\rm rad} \gtrsim P_{\rm gas}$$

- ✓ The shock is initially inside optically-thick media.

$$\tau \approx \rho \kappa_{\rm T} r \gg 1$$

⇩

Radiation-mediated shock

e.g., Weaver 1976

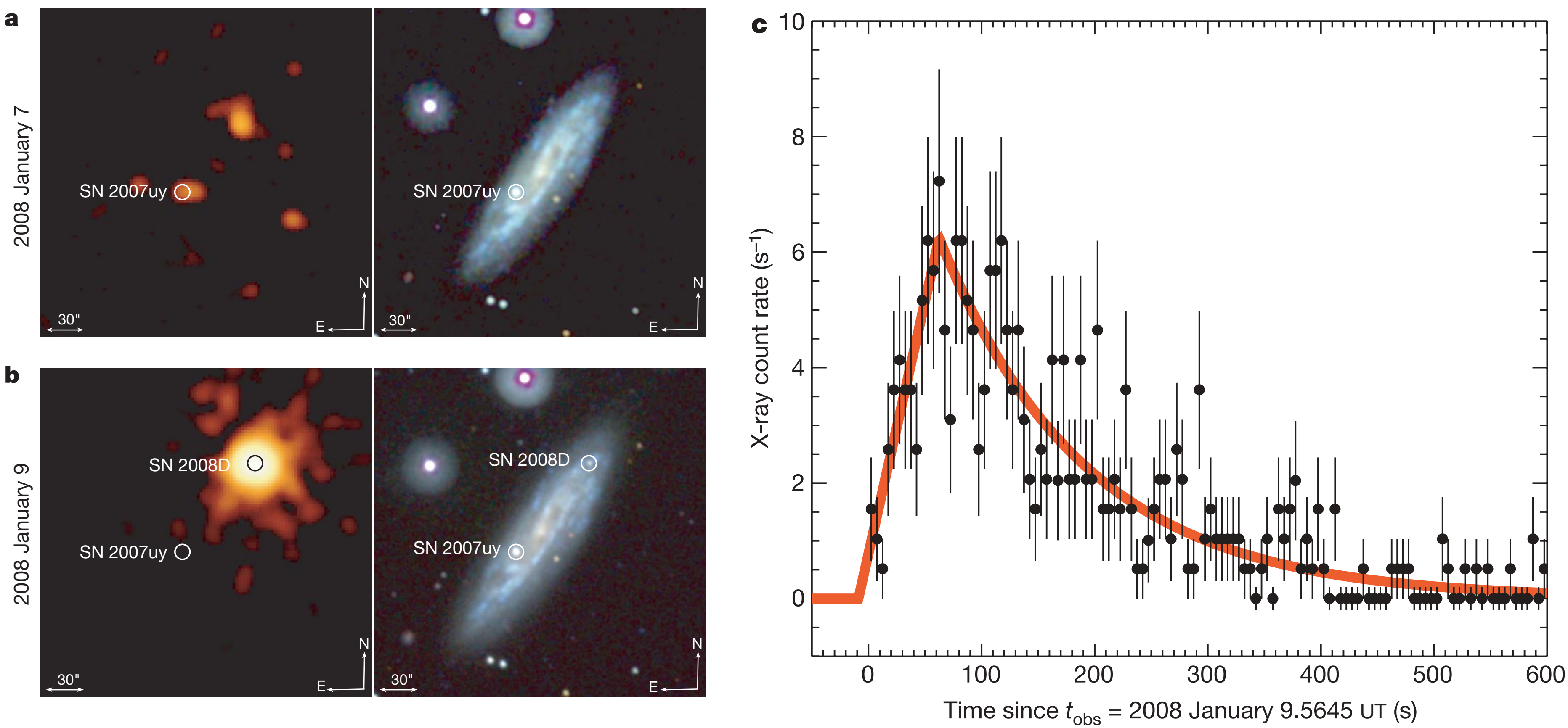
Shock breakout @ $r = r_{\rm sb}$
where $c/\tau \approx v_{\rm sh}$

⇩

The downstream photons begin to escape.

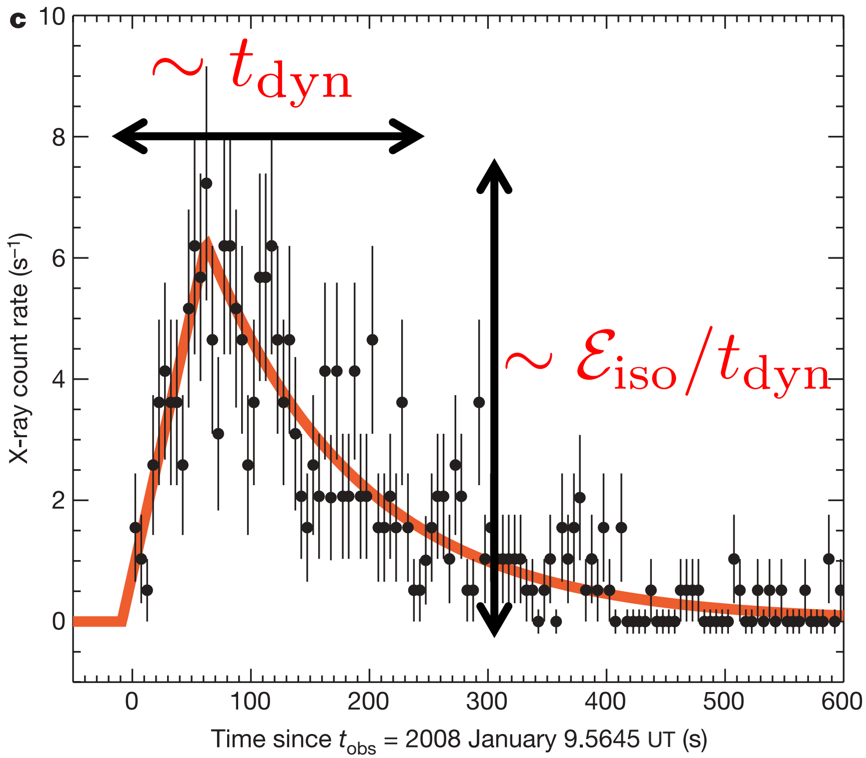
→
- ✓ Shock breakout emission
- ✓ No longer radiation-mediated

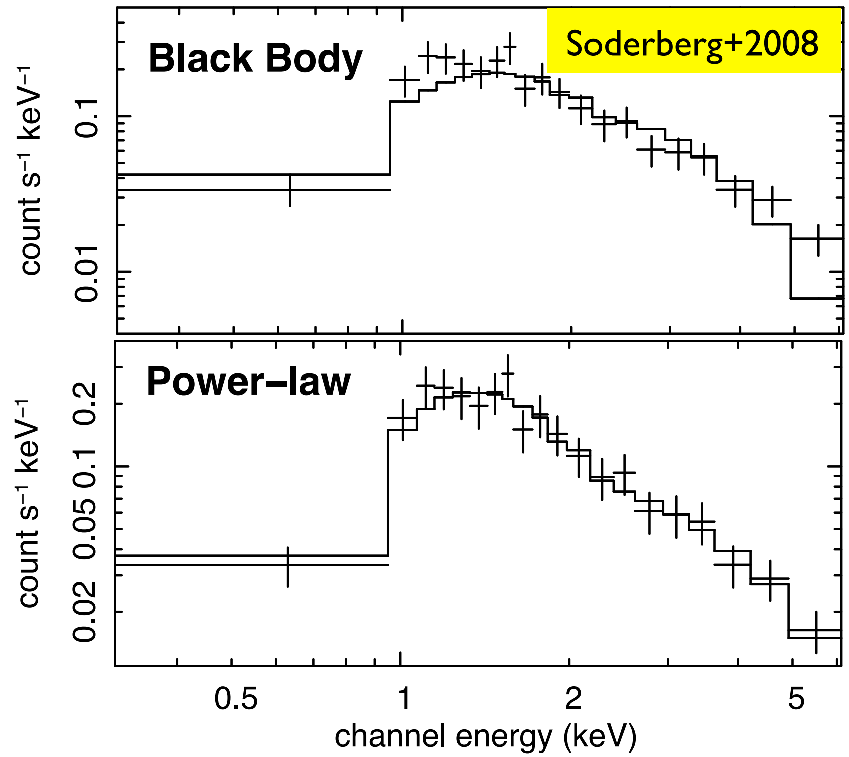
Discovery of X-ray outburst



Soderberg+2008

What Shock Breakouts Tell Us





$$t_{\rm dyn} \sim r_{\rm sb}/c\beta_{\rm sh}$$

$$\mathcal{E}_{\rm iso} \sim 2\pi\rho {r_{\rm sb}}^3 {\beta_{\rm sh}}^2 c^2$$

$$\rho \sim 1/\kappa_{\rm T} r_{\rm sb}\beta_{\rm sh}$$

Light curve $\longrightarrow$ $r_{\rm sb}$, $\beta_{\rm sh}$

Spectrum: quasi-thermal

The temperature and the power low tail depends on the details of plasma.

($e^{\pm}$ Is relevant for $\beta_{\rm sh} \gtrsim 0.1$.)

Shock Breakout Scenario for LL GRBs

$E_{\gamma,iso} \sim 10^{50}$ erg $t_\gamma \sim 3000$ s

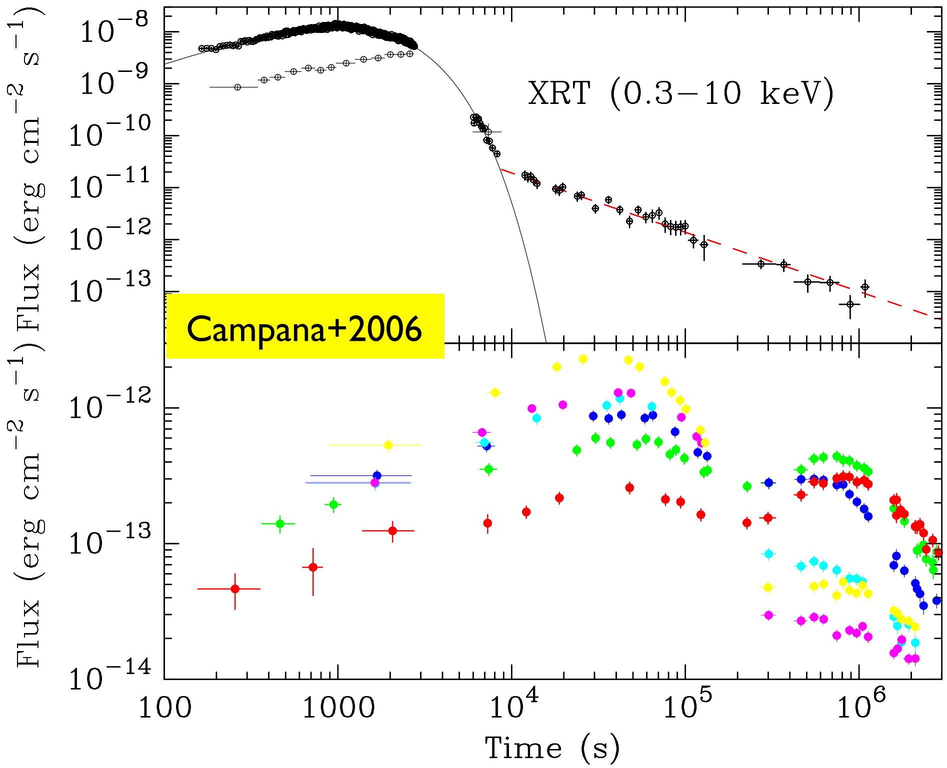
⇩

$\beta_{sh} \sim 1$ $r_{sb} \sim 9 \times 10^{13}$ cm

(Too large for a C-O WR $\sim 10^{11}$ cm)

$\rho(r_{sb}) \sim 10^{-14}$ g cm^{-3}

$\longrightarrow \dot{M} \sim 0.1\ M_\odot$ yr^{-1}



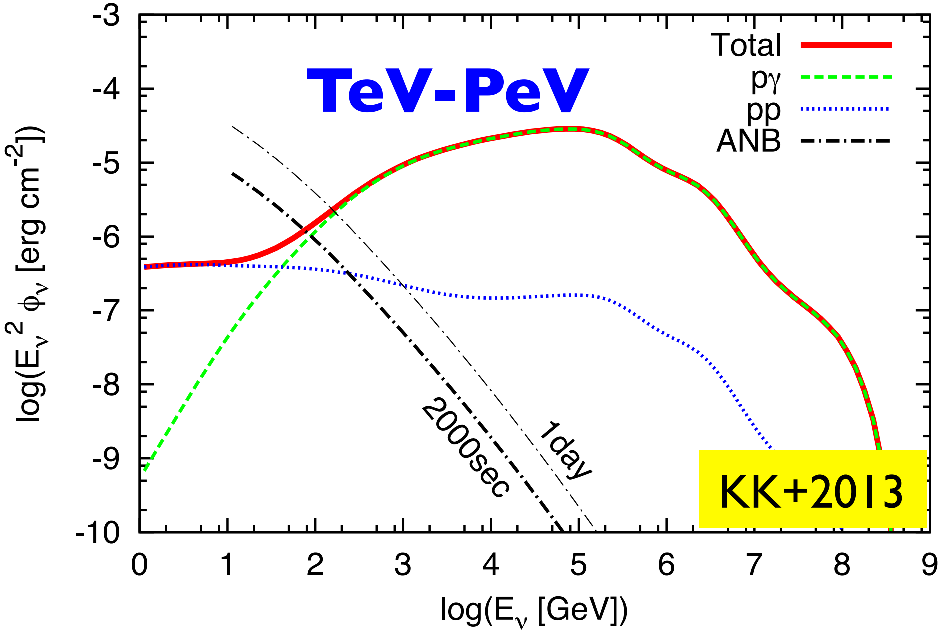
A trans-relativistic shock breakout from an optically-thick envelope formed by a strong wind

Smoking Gun Neutrinos

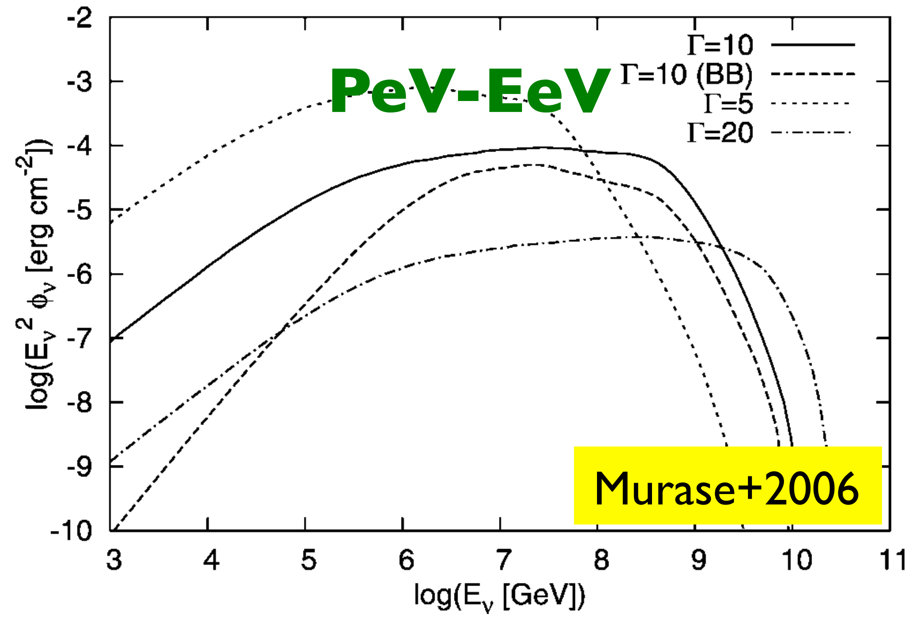
proton acc. @ collisionless sh. + s.b.o ph. → $p\gamma$ int. → neutrinos

similar to HL GRB photospheric neutrinos $E_{\nu,obs} \propto \varepsilon_{\gamma,obs}^{-1}\Gamma^2$

Shock Breakout Scenario

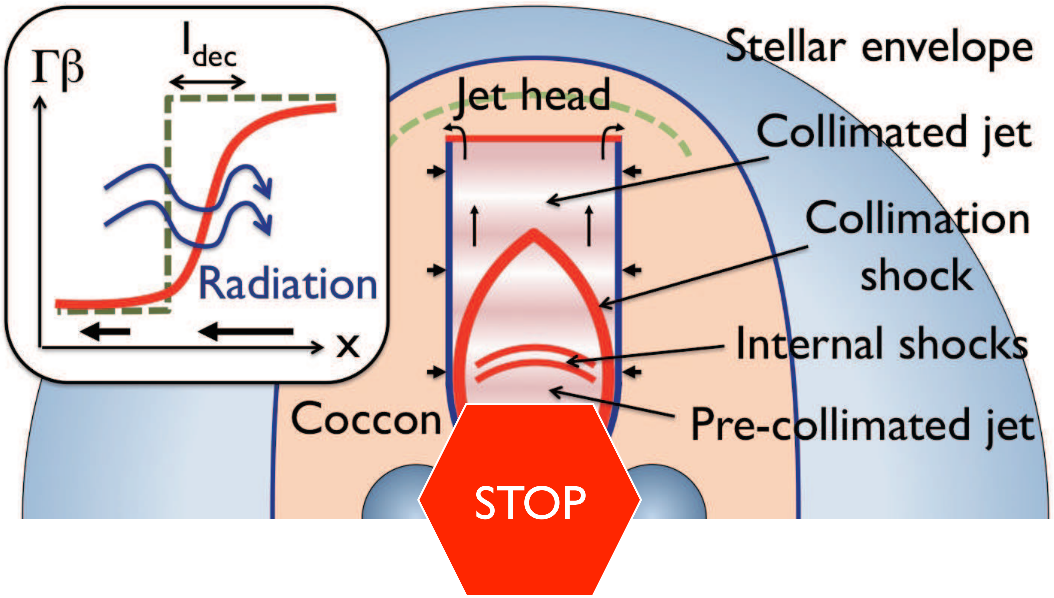


Jet Scenario



Detectable from10 Mpc by IceCube/KM3Net

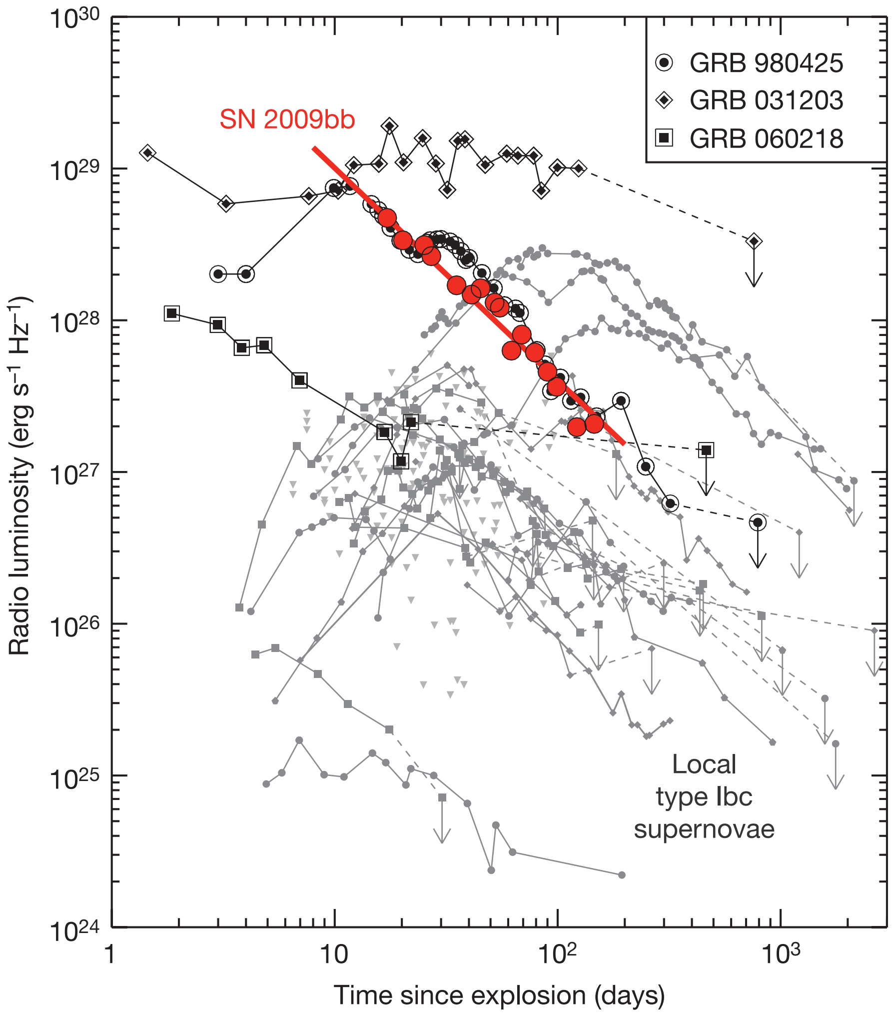
Corked Jet SNe or Failed GRBs

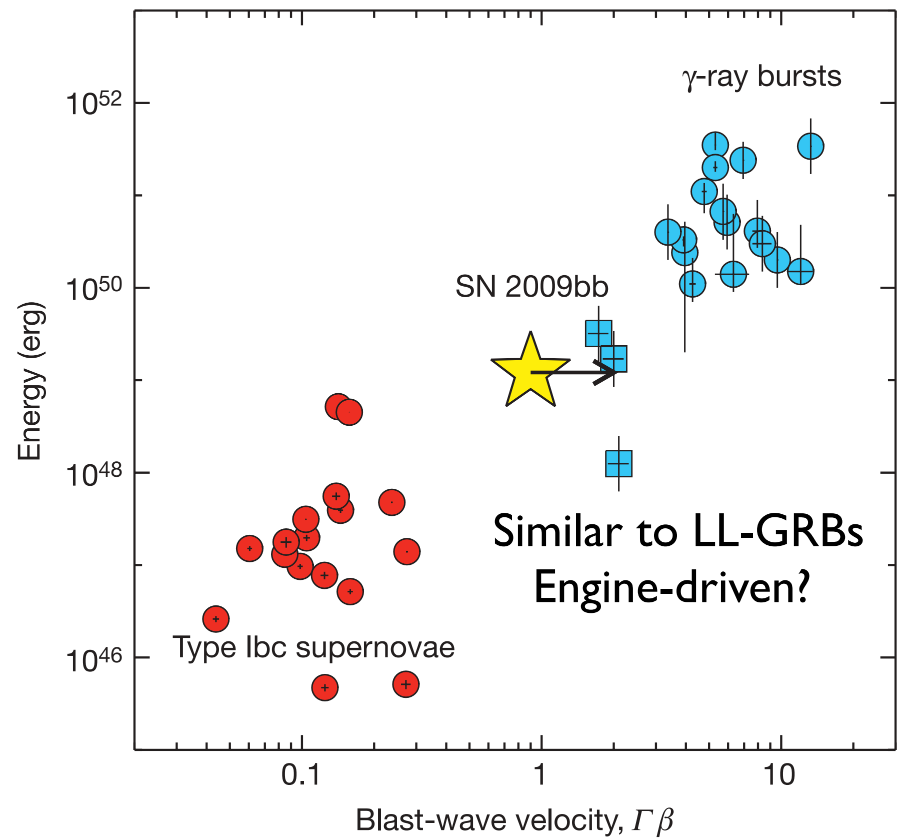


Murase & Ioka 2013

- though still speculative (some implications),
- can be more frequent than successful bursts,
- produce similar (dim) GWs and neutrinos.
- Shock breakouts and SNe can be more energetic.

Discovery of Relativistic SNIc without GRB



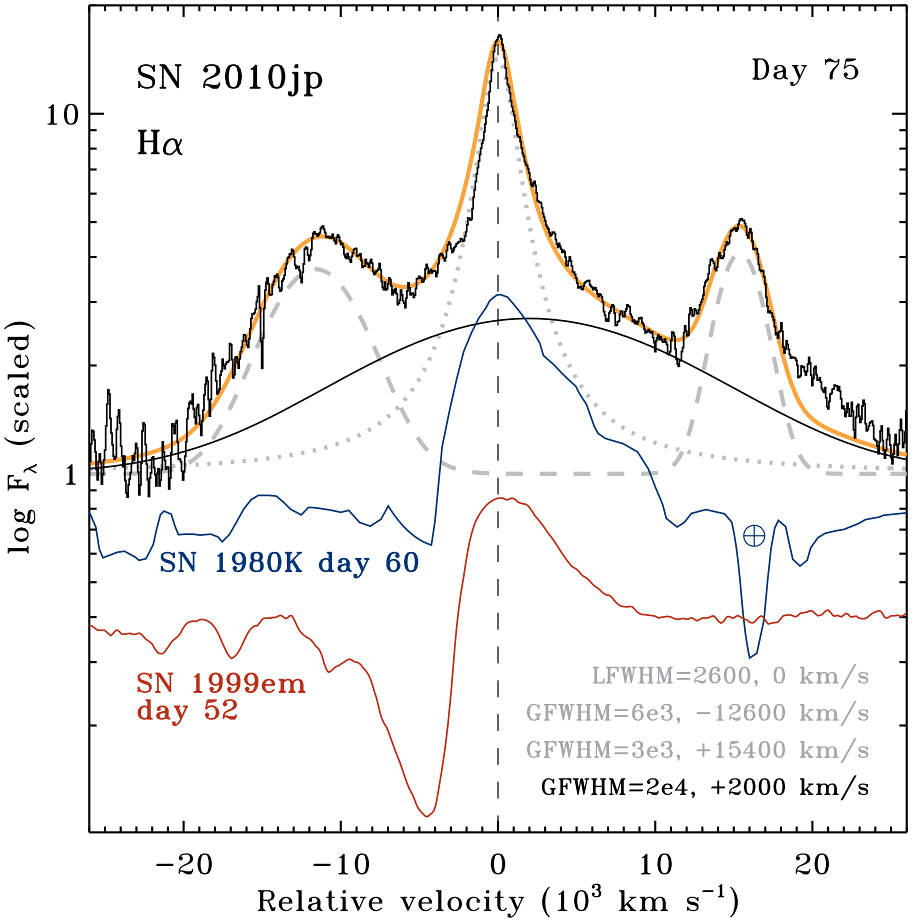


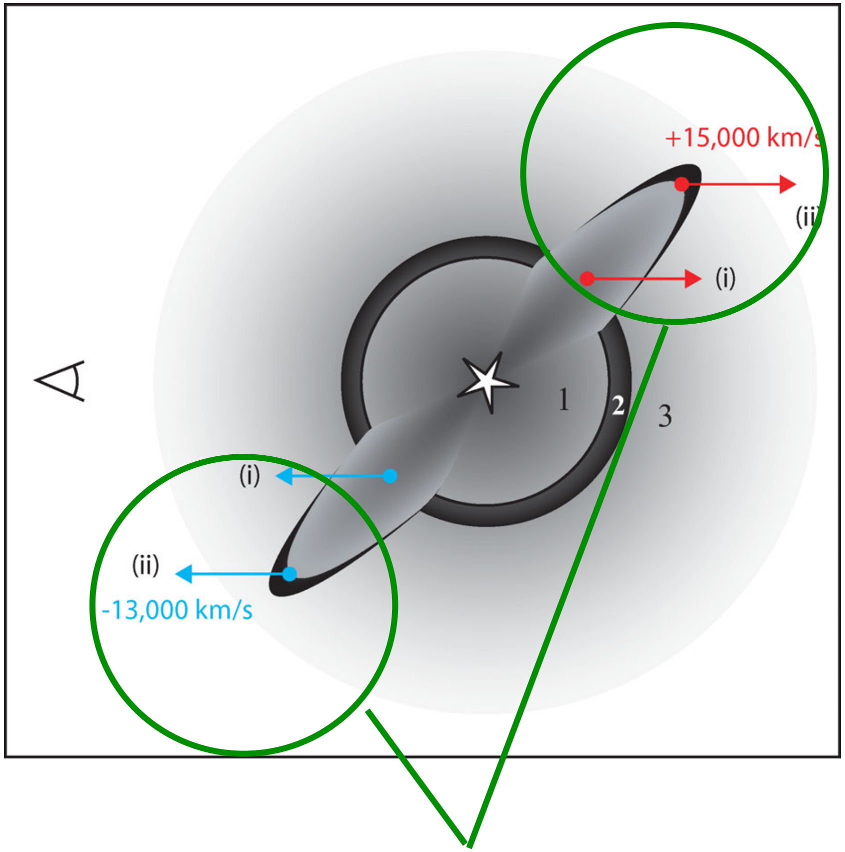
Similar to LL-GRBs
Engine-driven?

2009bb-like events are at most ~1% of SNIc ~ GRB

Soderberg+2010

SN 2010jp: A jet in a type II SN



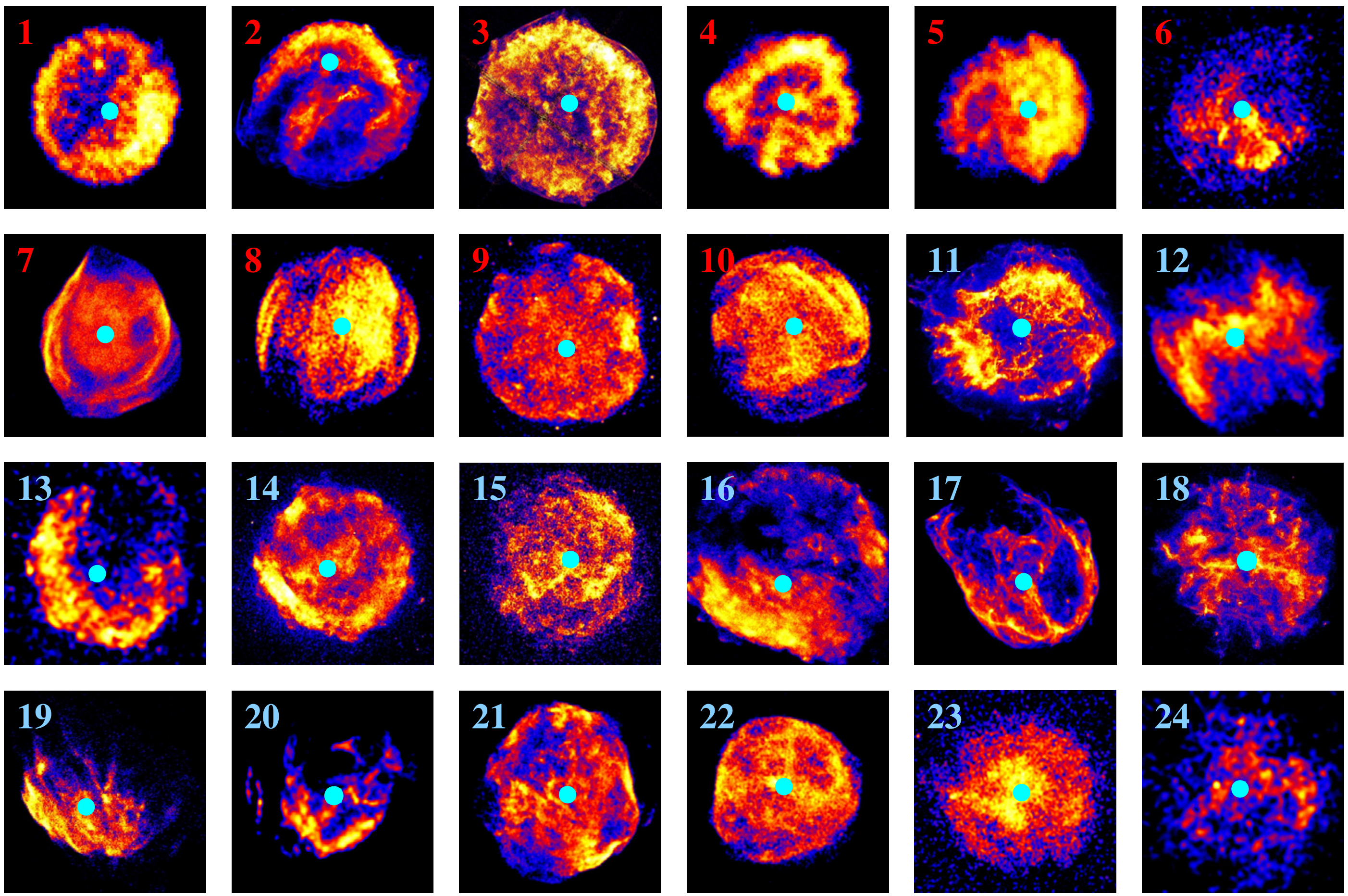


Trans-Relativistic!

Smith+2011

CC SNR are asymmetric?

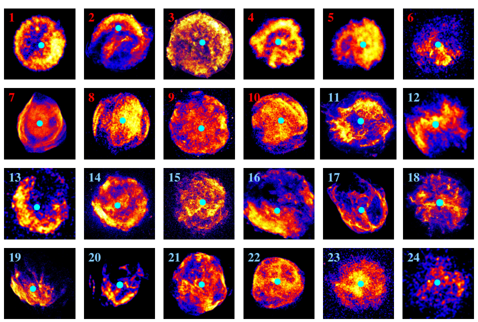
Chandra X-ray soft-band (0.5–2.1 keV)

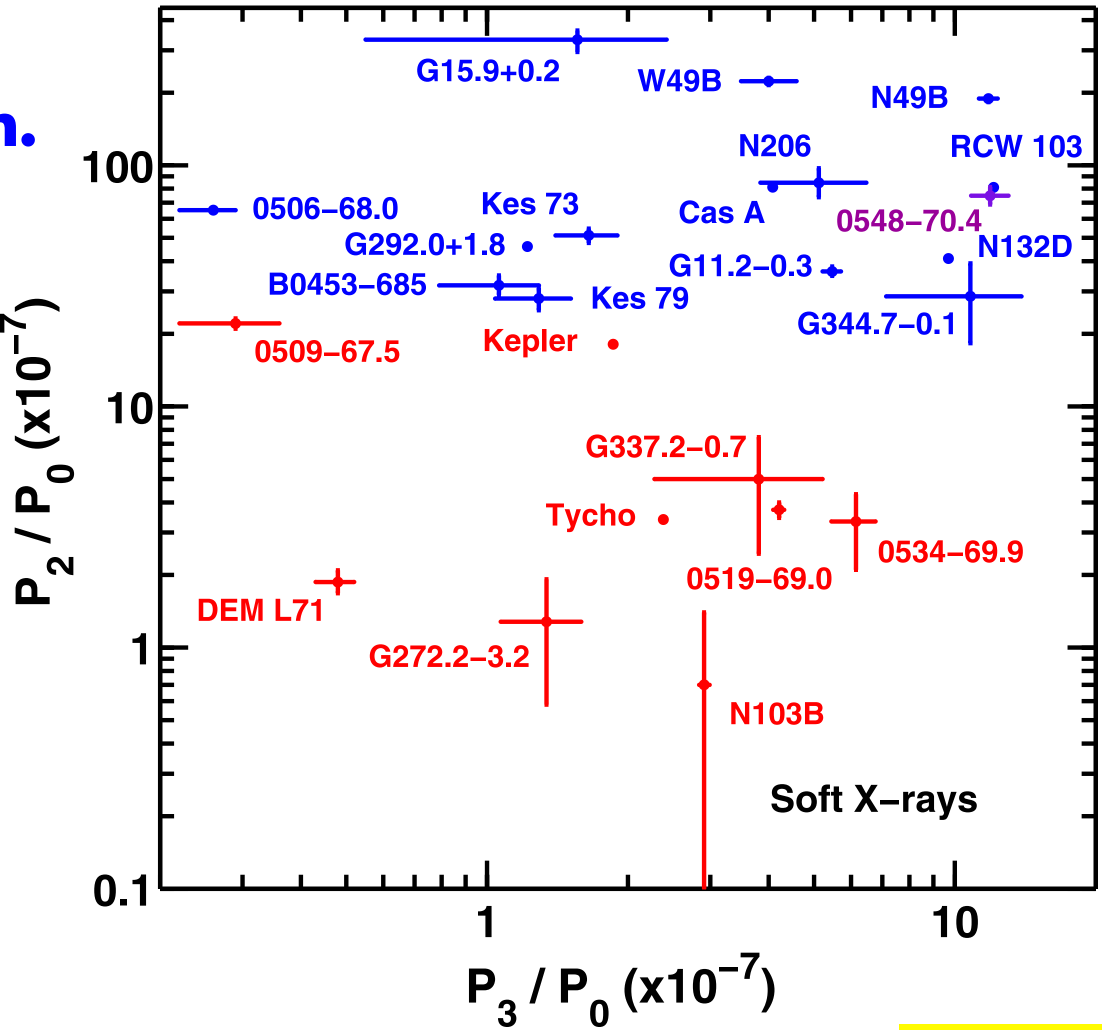


Lopez+2011

CC SNR are asymmetric?

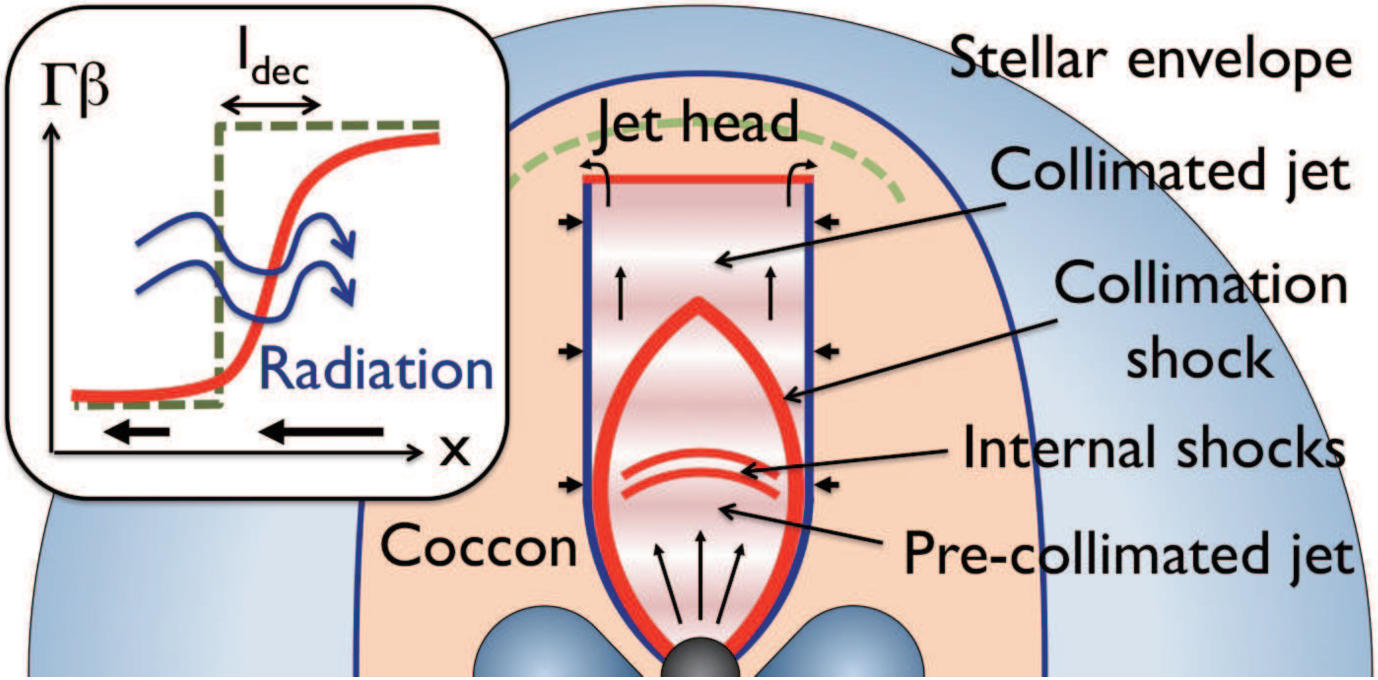
CC SNR are elliptic!
Jets may be common.





Lopez+2011

Jets inside Stars



Various shocks exist → particle acceleration → neutrinos?

Not So Fast!

Shock Acceleration

Axford et al, Krimsky, Blandford & Ostriker, Bell

✓ Particle are accelerated by …

crossing the shock from up. to down.

↓

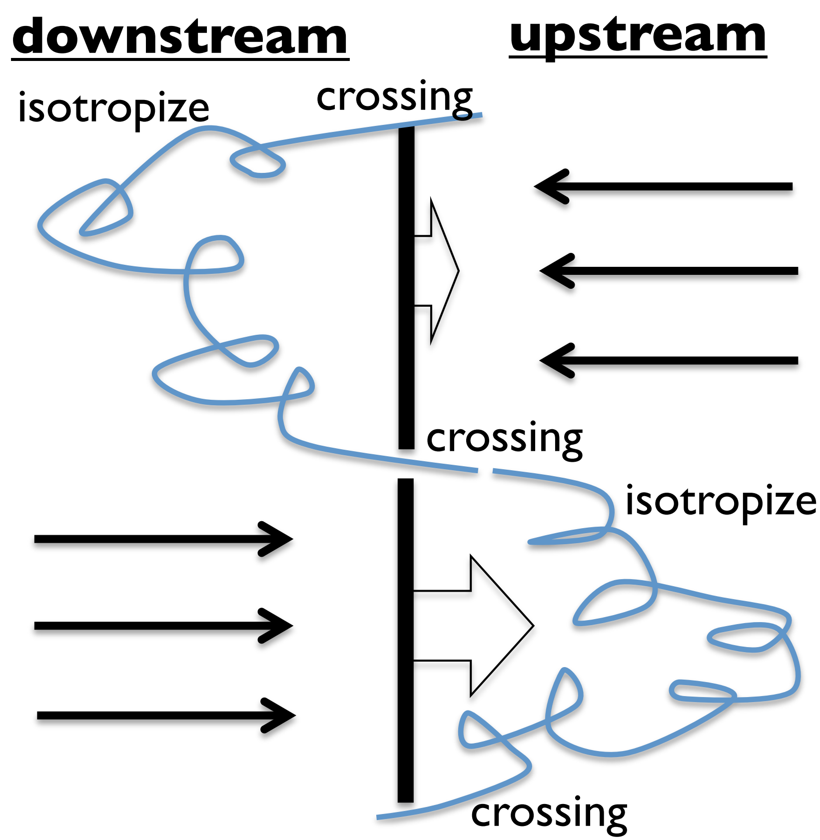
being isotropized in down.

↓

crossing the shock from down. to up.

↓

being isotropized in up.



✓ energy gain + escape probability per cycle

→ power low index

- non-rela strong shock $s = 2.0$
- ultra-rela shock $s = 2.2$

$$dN/dE \propto E^{-s}$$

e.g., Keshet & Waxman 2005

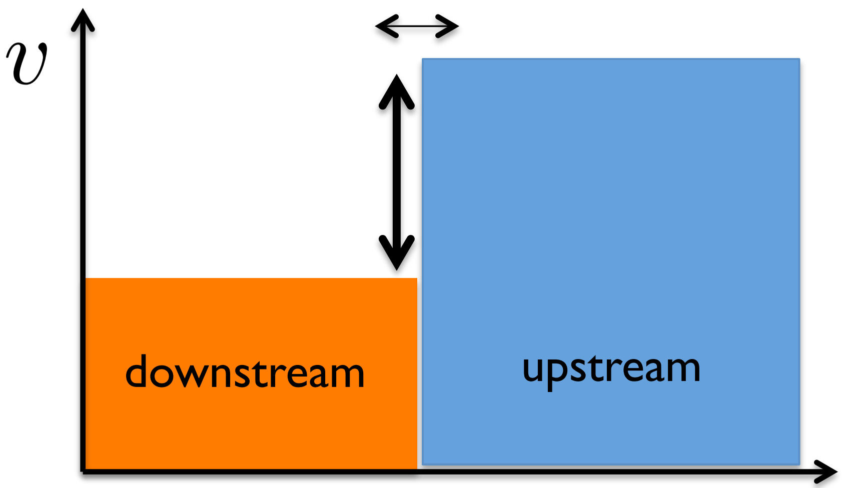
Limitation of Shock Acceleration

e.g., Levinson & Bromberg 2008

Yes $\tau_{\rm T} \lesssim$ 1-10 ? No **e.g., GRB jet in stars**

Radiation-unmediated

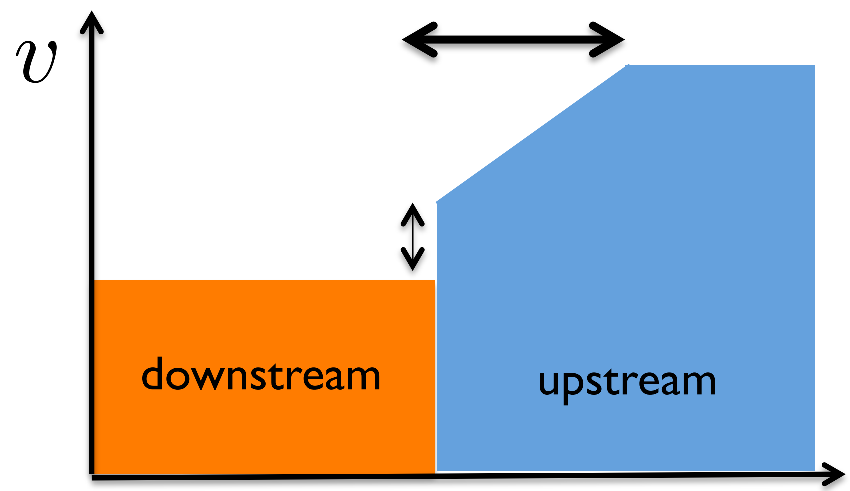
Isotropization via plasma processes $\sim c/\omega_{\rm pe}$



Shock acceleration is efficient.

Radiation-mediated

Deceleration via “precursor” photons $\sim l_{\rm T} \gg c/\omega_{\rm pe}$



Shock acceleration is inefficient

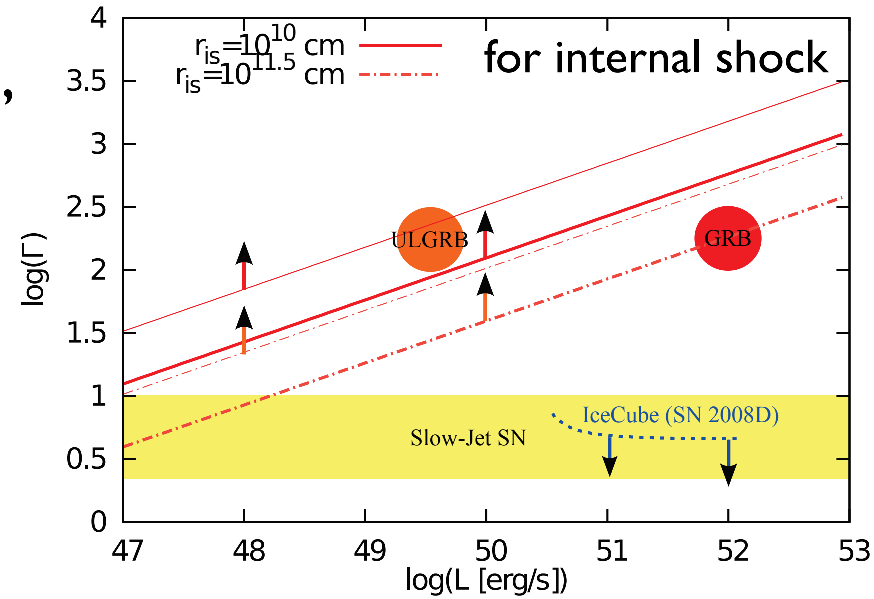
if $r_g \lesssim l_T$

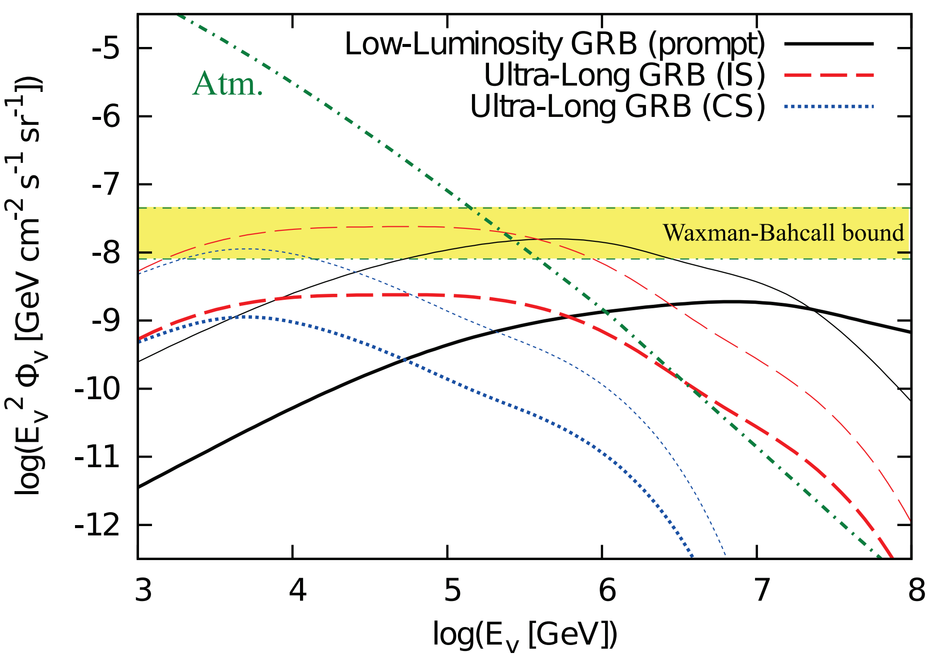
TeV-PeV Neutrinos from Jet inside Stars

"Radiation-mediated Shock Condition"

→ Shock accelerations inside stars
work only in low-power jets.

Murase & Ioka 2013





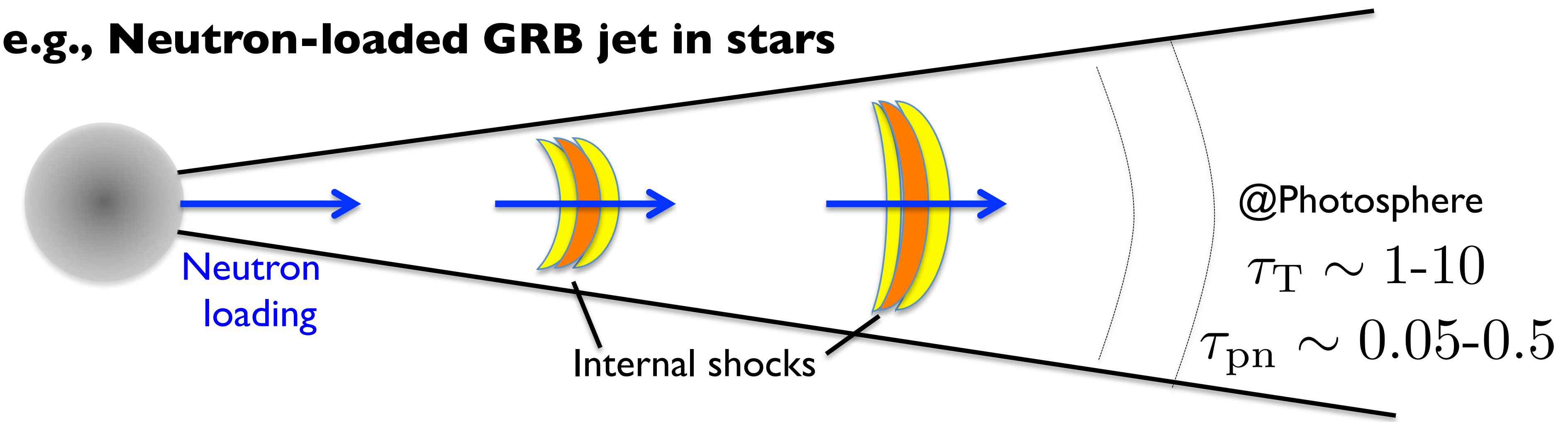
The IceCube neutrinos
can be explained by
Ultra-L-GRB jet in BSGs.

Neutron-Proton-Conversion Acceleration

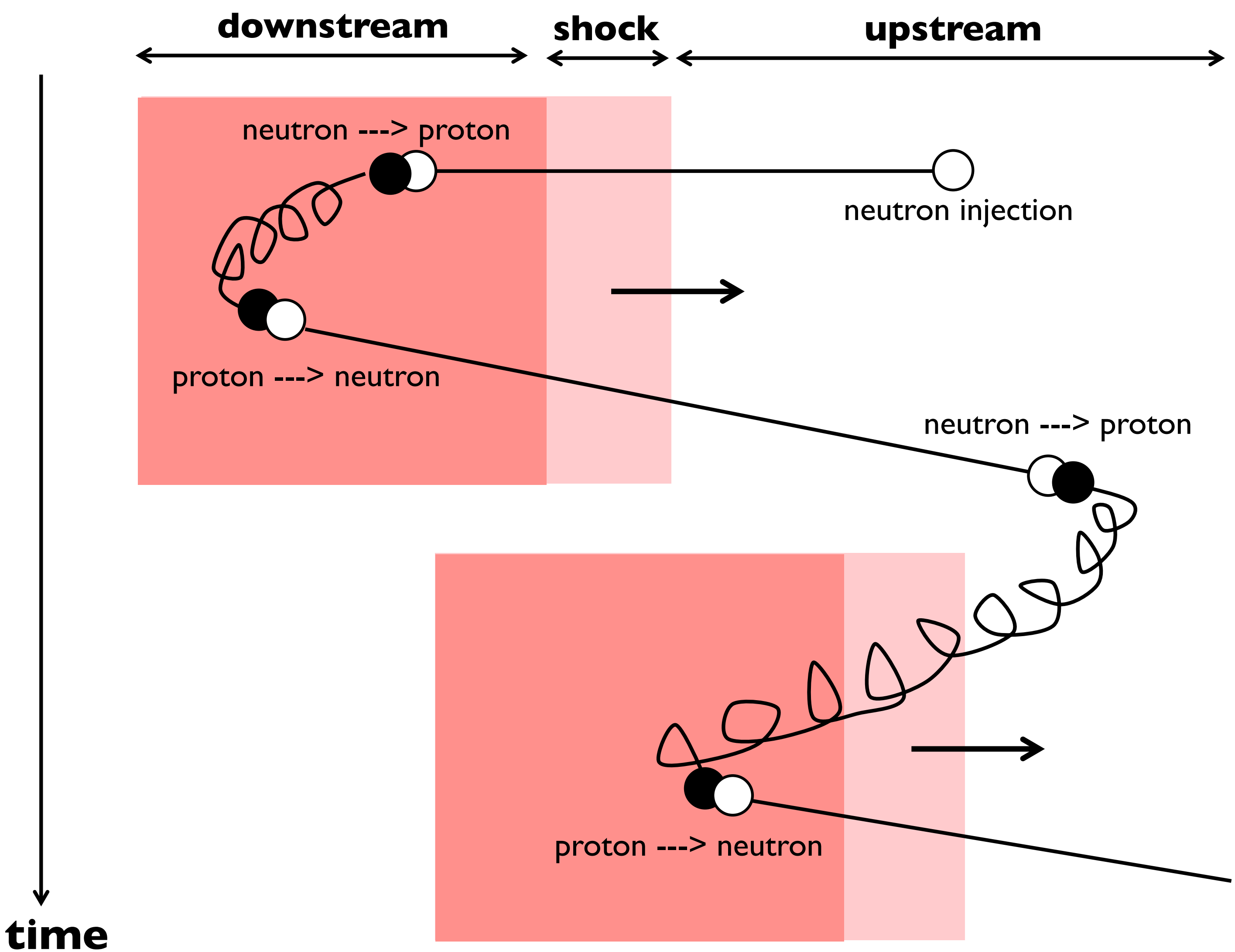
- is a shock acceleration including np conversions.
- can work with (and only with)
  1. relativistic shocks,
  2. neutron loadings,
  3. inelastic pp/pn collision optical depth,
  4. magnetic fields (not necessarily strong).
- can work even at radiation-mediated shocks.
- is slow, but efficient.
- Is accompanied by non-thermal GeV-TeV neutrinos.

KK+2013
originally
Derishev+2003

e.g., Neutron-loaded GRB jet in stars



NPC Acceleration Cycle



Slow Slugger

Energy gain per NPC cycle

1. Shock crossing from up to down: $\gamma \to \gamma \times \Gamma_{\rm rel}(1 - \mu_{\rm d \to u})$
2. Shock crossing from down to up: $\gamma \to \gamma \times \Gamma_{\rm rel}(1 + \mu_{\rm u \to d})$
3. np or pn conversion: $\gamma \to \gamma \times \kappa_{\rm pn}$

$$\langle \gamma_{\rm f} / \gamma_{\rm i} \rangle \approx \kappa_{\rm pn}^2 {\Gamma_{\rm rel}}^2 (1 - \mu_{\rm d \to u})(1 + \mu_{\rm u \to d}) \sim {\Gamma_{\rm rel}}^2$$

unless $1 - \mu_{\rm u \to d} \approx 1$ i.e., $t_{\rm pn}/t_{\rm gyro} \gg 1$ (realized in GRB jet)

NPC cycle timescale $\sim t_{\rm pn} \gg t_{\rm gyro} \sim$ 1st Fermi cycle timescale

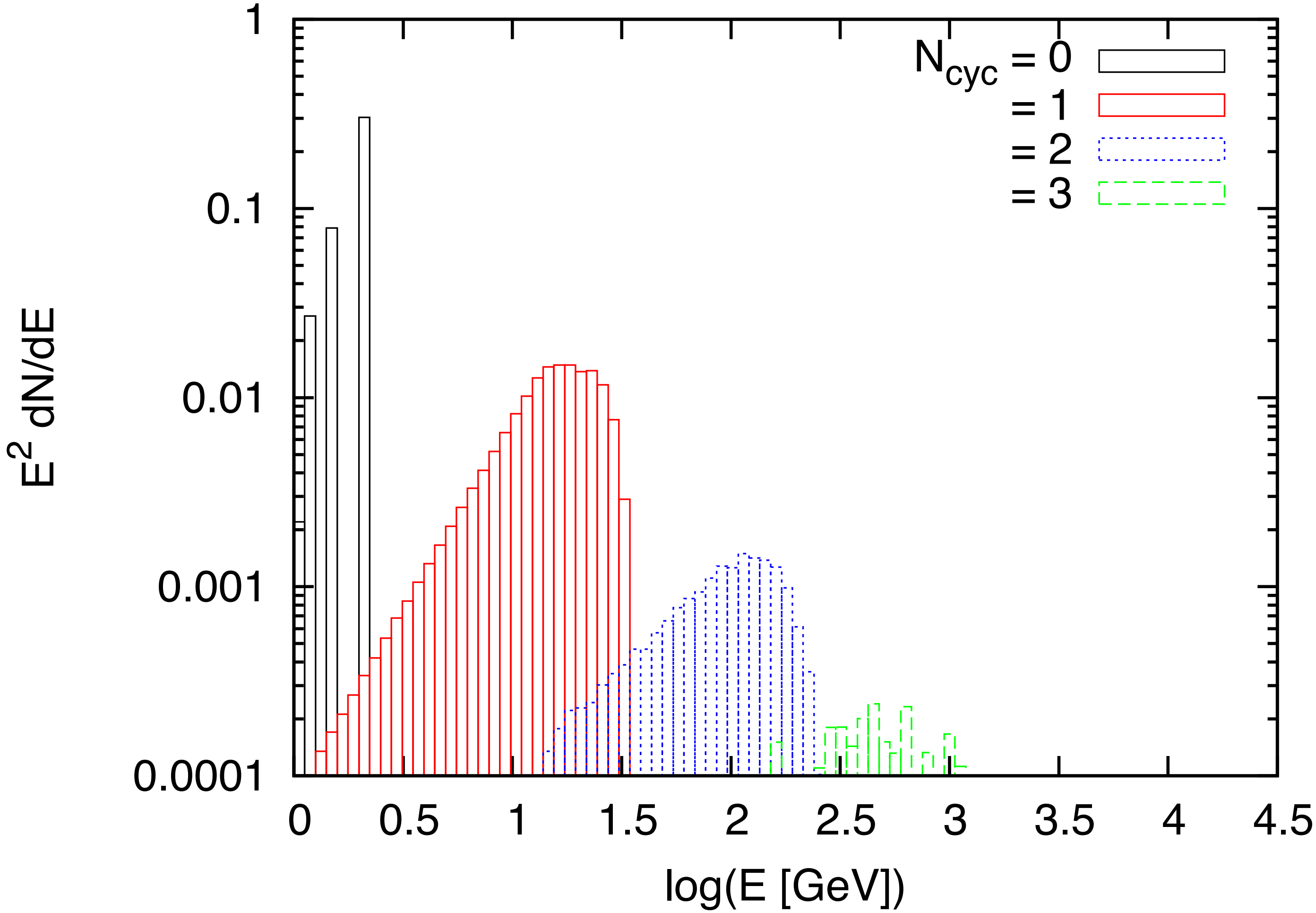
Acceleration efficiency

$\epsilon_{\rm npc} \sim \langle \gamma_{\rm f} / \gamma_{\rm i} \rangle \times P_{\rm ret}$

$P_{\rm ret}$ = return probability per cyc.

To be fixed by Monte-Carlo simulation

MC simulation of NPC : $\Gamma_{\rm rel} = 3.0$

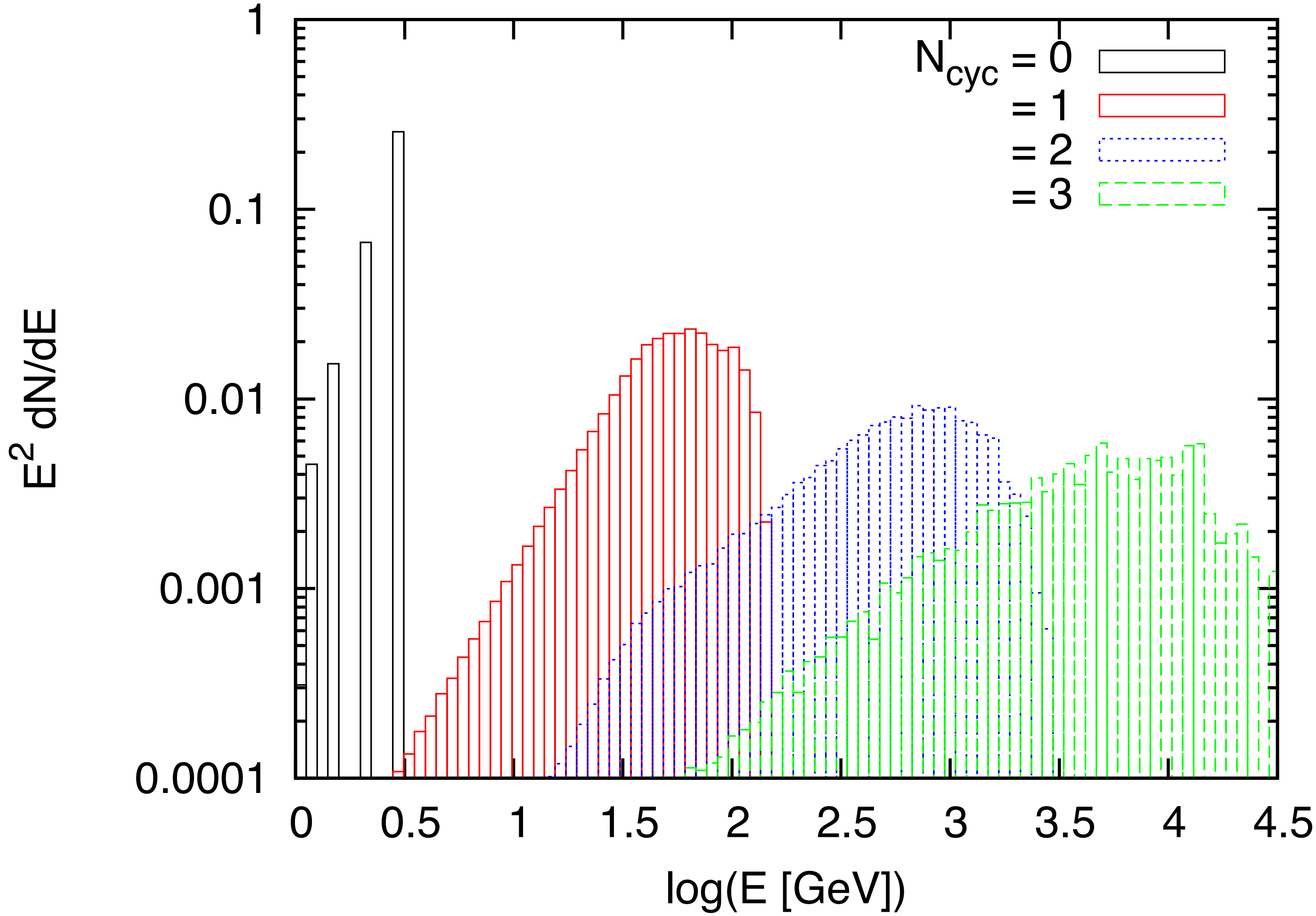


DS rest frame

$\tau_{\rm pn} = 1$

KK 2013

MC simulation of NPC : $\Gamma_{\rm rel} = 5.0$



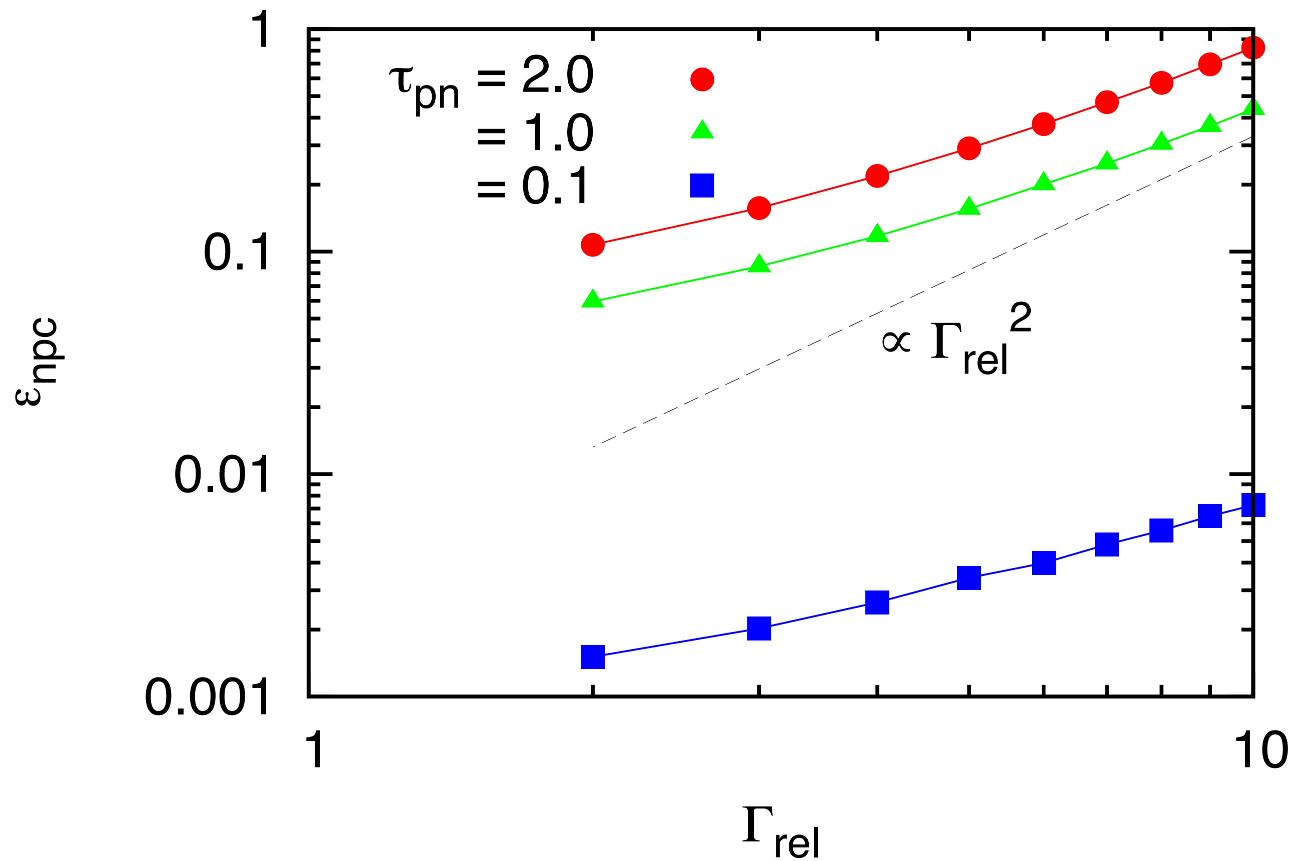
DS rest frame

$\tau_{\rm pn} = 1$

KK+2013

Acceleration Efficiency of NPC

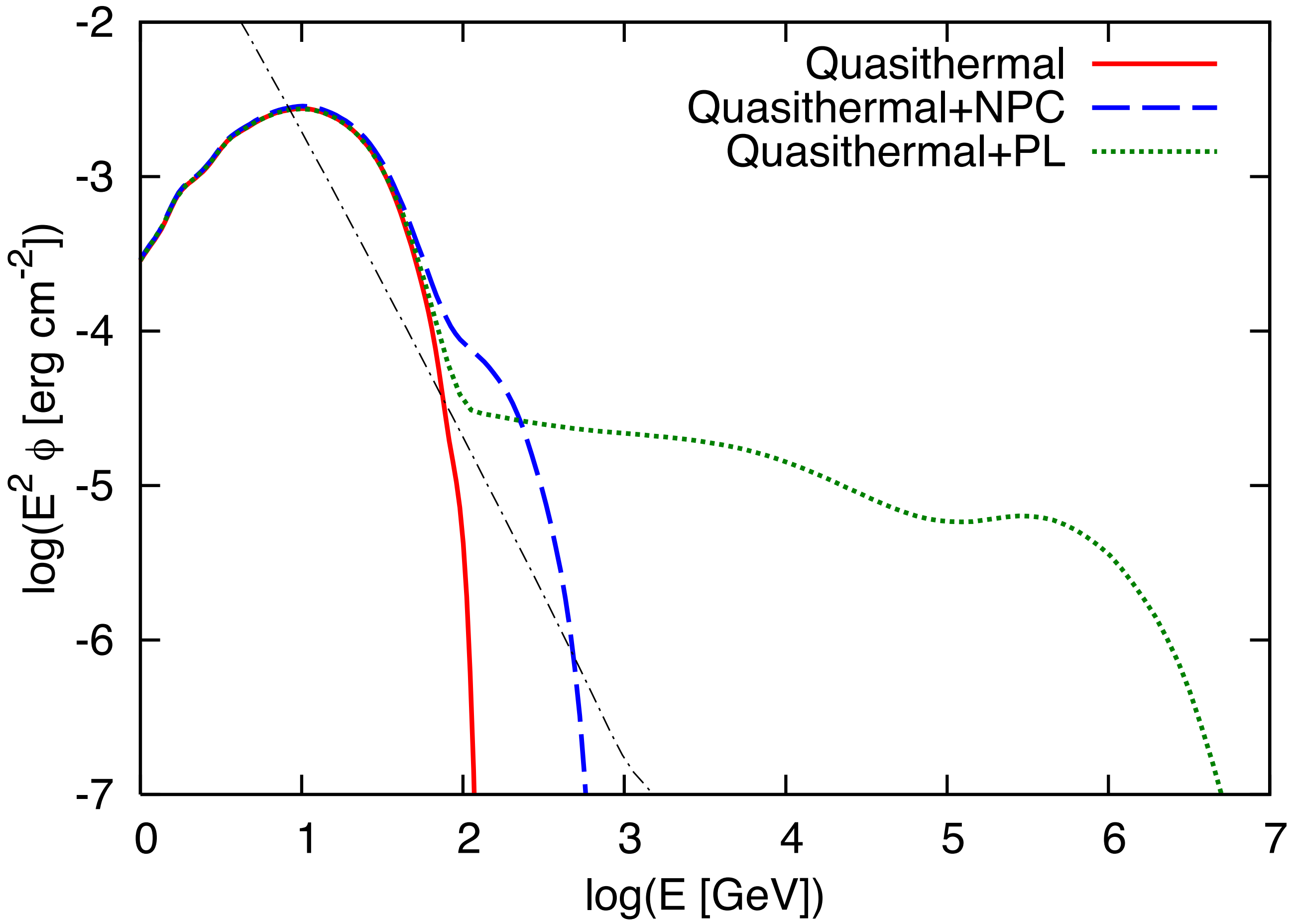
$$\varepsilon_{\rm npc} = \frac{\text{Accelerated Baryons}}{\text{Neutron Injection}}$$



$$P_{\rm ret} \sim 0.01 \times \tau_{\rm pn}$$

KK+2013

NPC enhances the detectability!



Murase, KK, Meszaros 2013