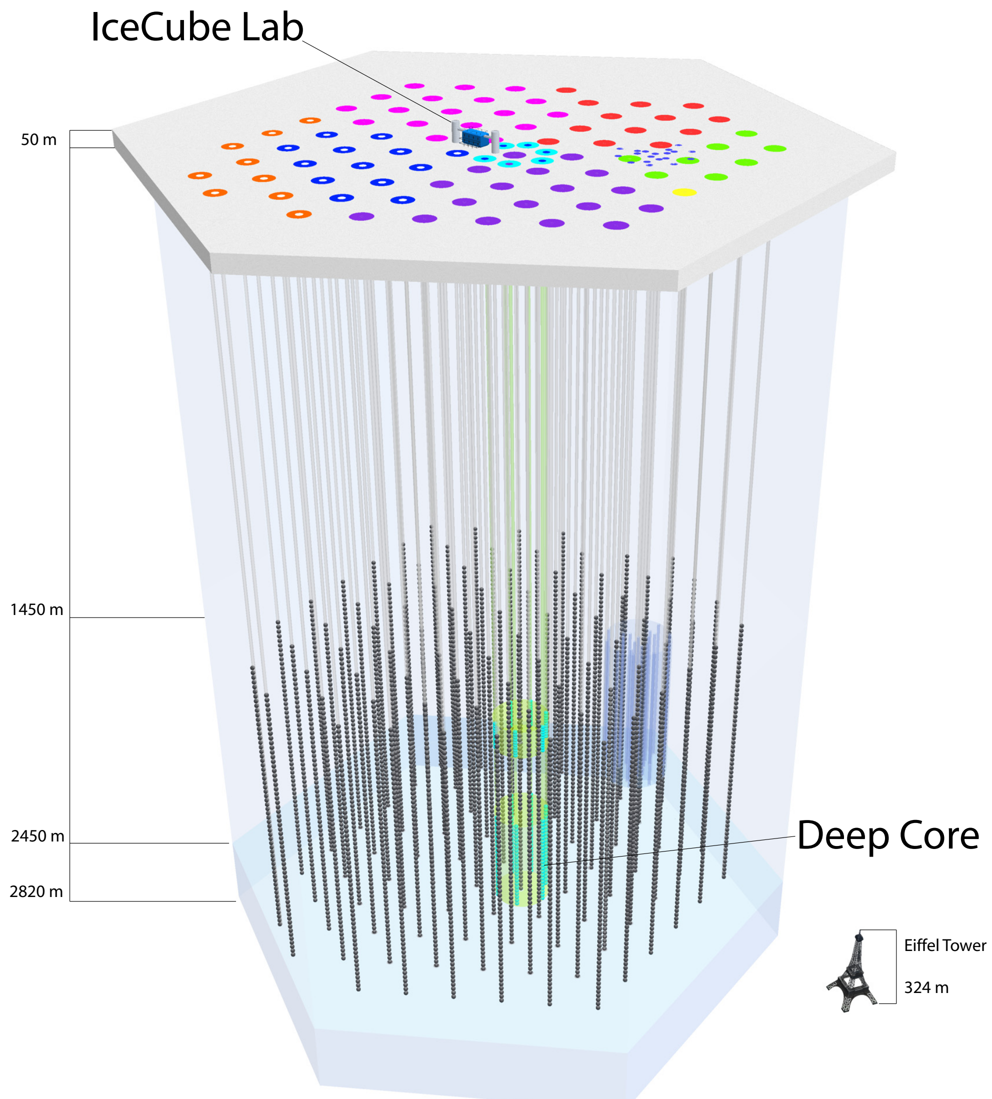
Neutron-Proton-Converter Acceleration Mechanism at Sub-Photospheres of Relativistic Outflows

Kazumi Kashiyama (PSU, JSPS fellow)

with Kohta Murase (IAS) and Peter Meszaros (PSU)

Ref.) arXiv:1304.1945 to be published in PRL

High Energy Neutrino Astronomy



Now we have two PeV events, and additional 26 sub-PeV events!

High Energy Neutrino Factories

- pγ interaction

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

- Inelastic nuclear collision

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

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

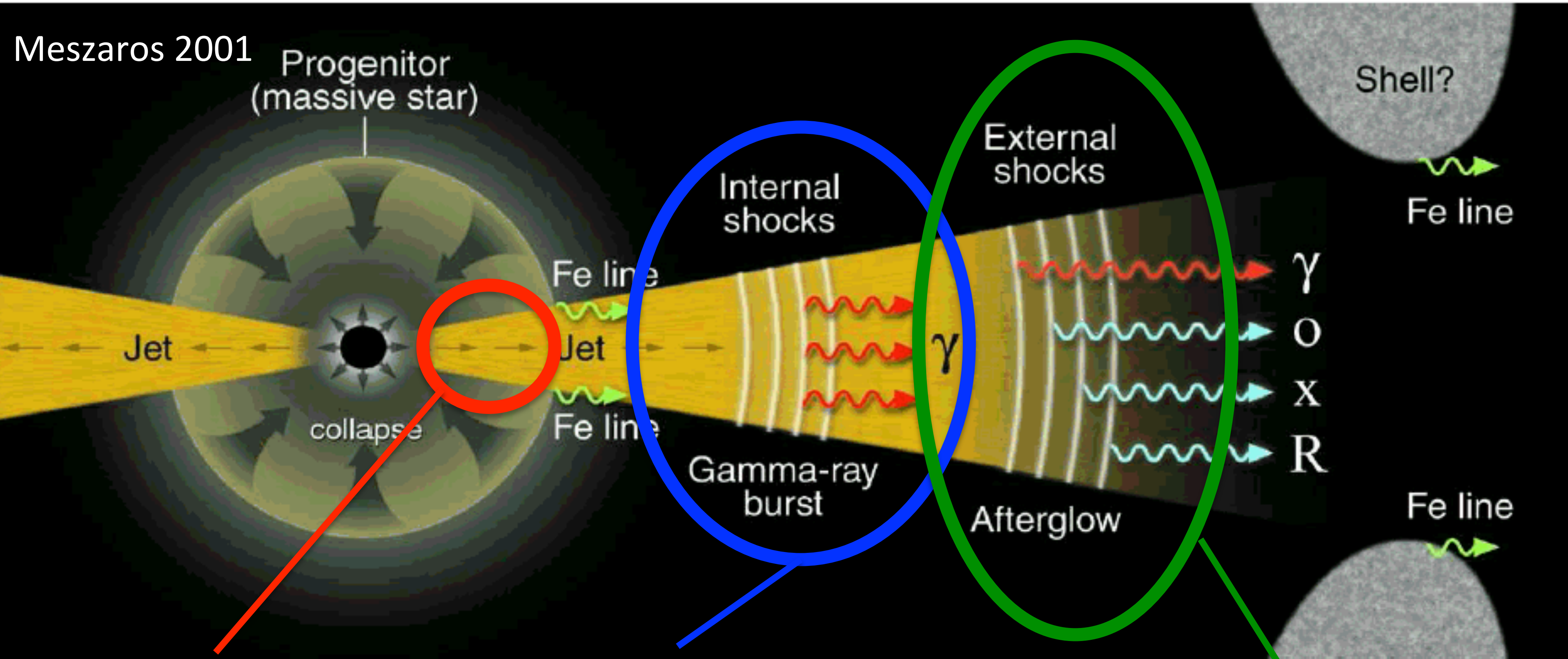
etc

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

Hadron Acceleration × Collision with Target γ or Hadrons

Neutrino × GRB

Neutrino Tomography of GRB Jet



Dissipation @ sub-photosphere

$r \lesssim 10^{12}$ cm

GeV-TeV ν

Bahcall & Meszaros 2000 and more

Dissipation @ prompt-emission radius

$r \sim 10^{12-16}$ cm

PeV ν and GeV-TeV γ

Waxman & Bahcall 1997 and more

External shock × afterglow

$r \sim 10^{16-17}$ cm

EeV ν and GeV-TeV γ

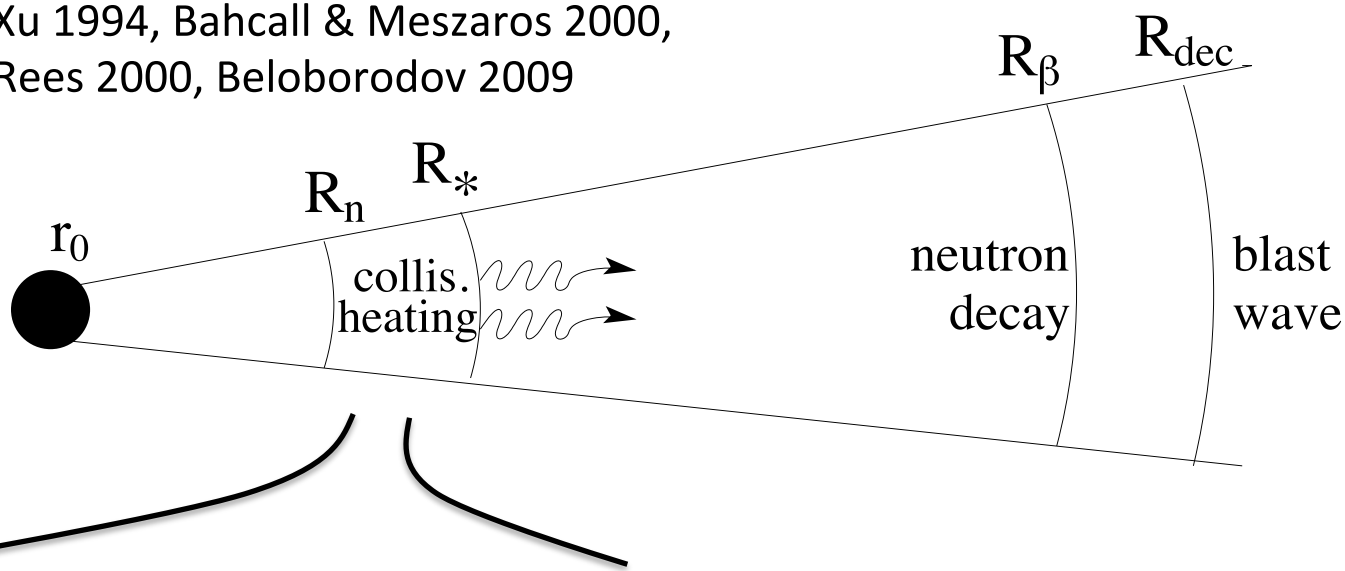
Waxman & Bahcall 2000 and more

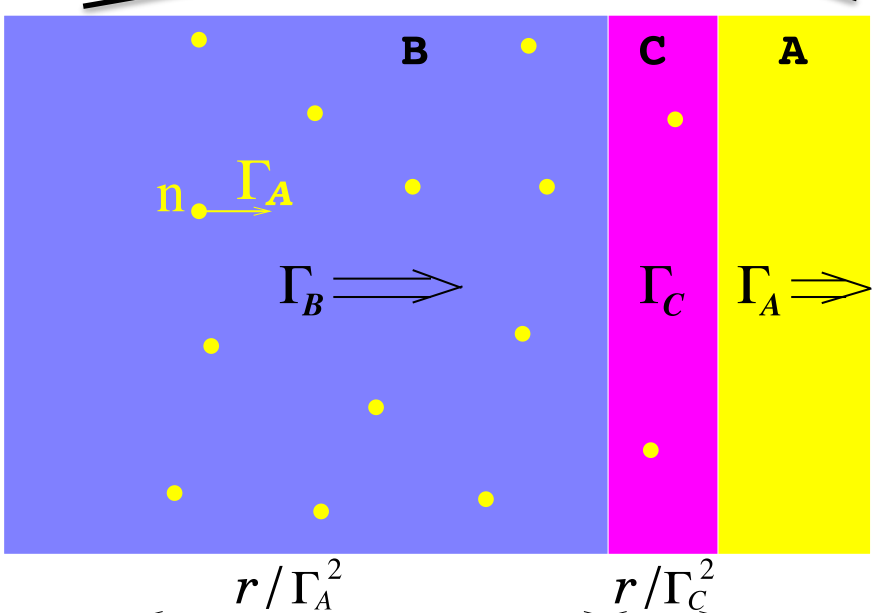
Sub-photospheric neutrinos

- Key to understand the central engine, which cannot be seen by electromagnetic waves.
- Even failed or hidden GRBs can produce them.
- Hadron nuclear collisions can also be efficient.
- Motivated by dissipative photosphere models for prompt gamma rays.
- In particular, *collisional heating scenario* predicts multi-GeV quasi-thermal neutrinos.

<u>Collisional Heating in Neutron-loaded jets</u>

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





Decoupled neutrons are swept up by the faster flow w.

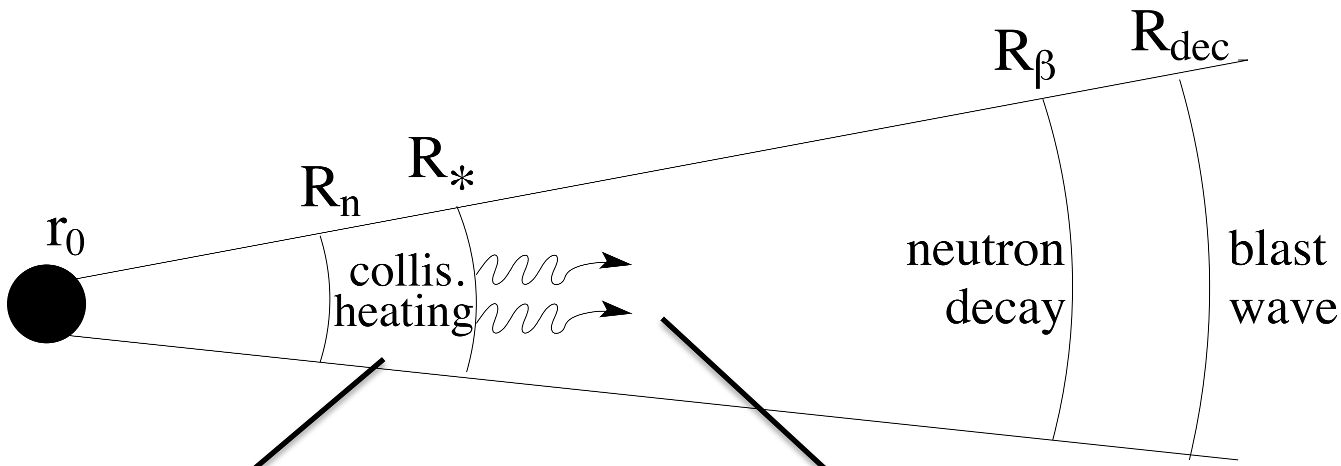
$$\Gamma_B \gg \Gamma_A = \Gamma_n$$

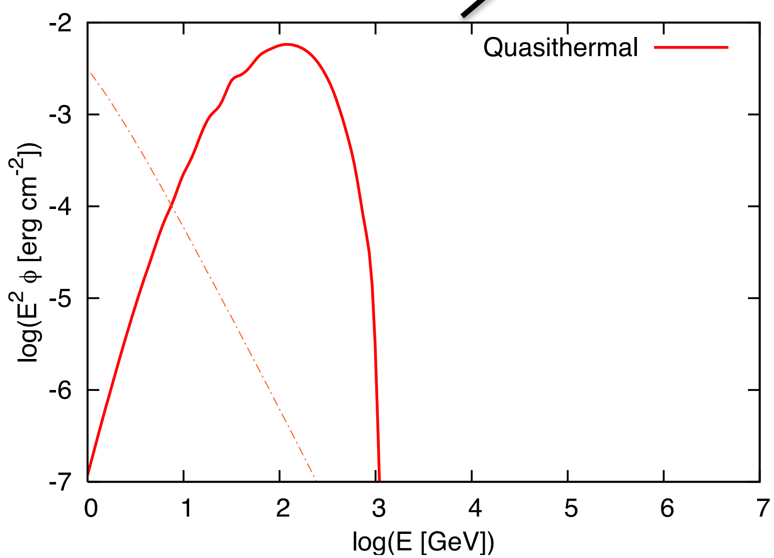
⇩

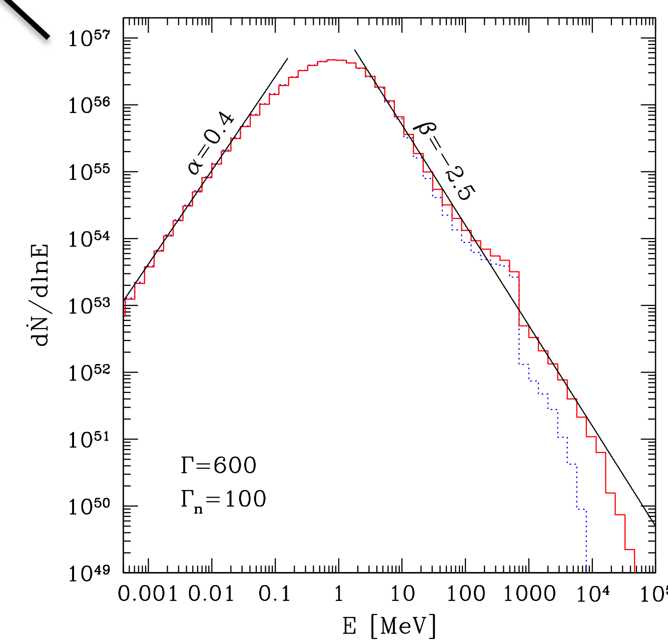
Inelastic nuclear collisions

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

Neutrinos and Gamma rays via Collisional Heating







Multi-GeV quasi-thermal neutrinos

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

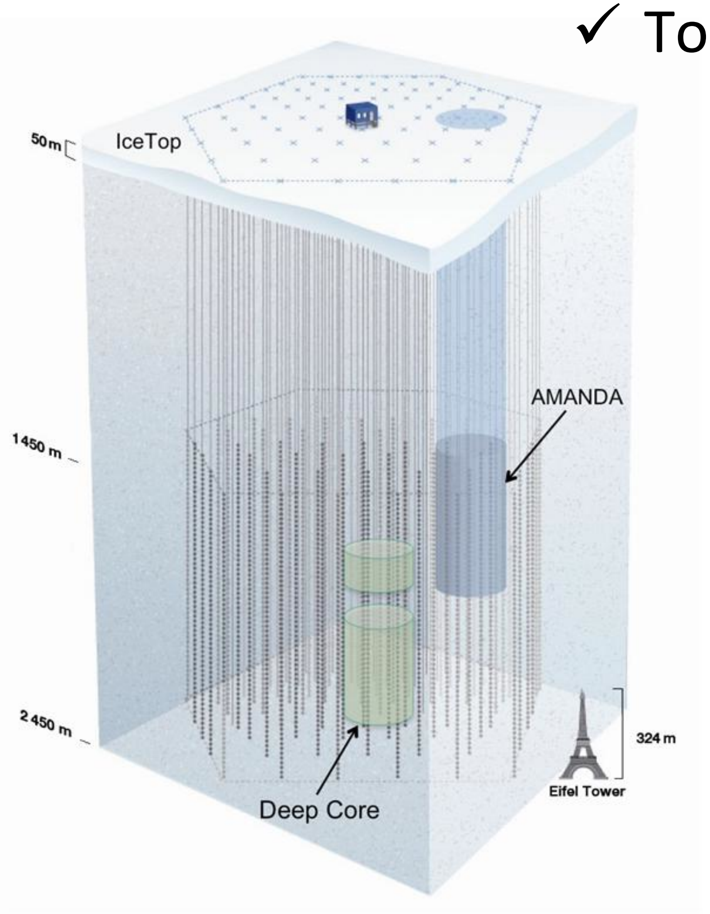
Murase, KK, Meszaros. 2013, Bartos et al. 2013

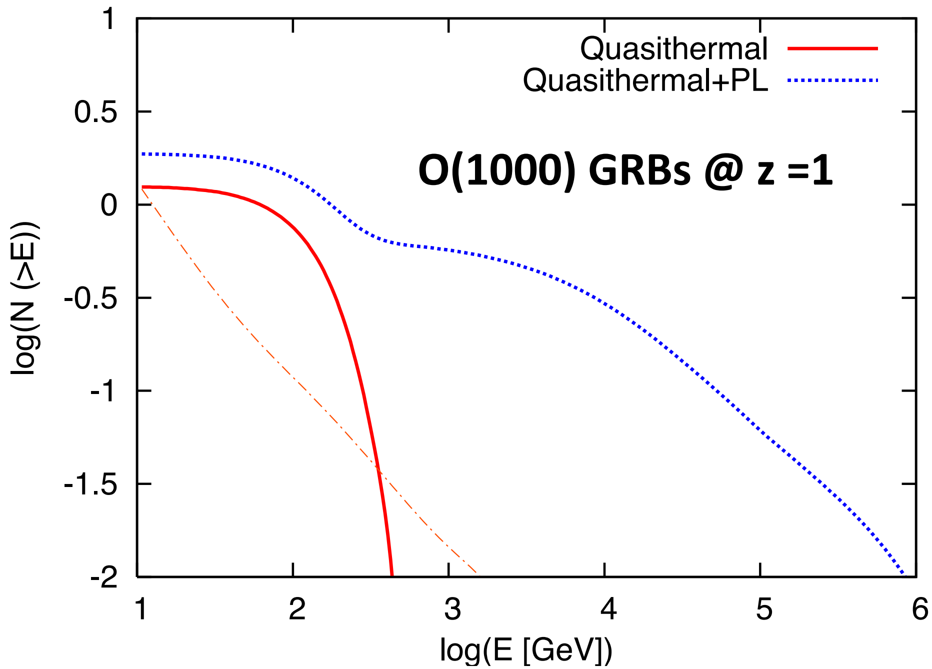
Band spectrum can be reproduced.

Beloborodov 2009

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

Higher energy neutrinos are important.
Additional acceleration process, e.g., shock acceleration?

Shock Acceleration

Axford et al, Krimsky, Blandford & Ostriker, Bell

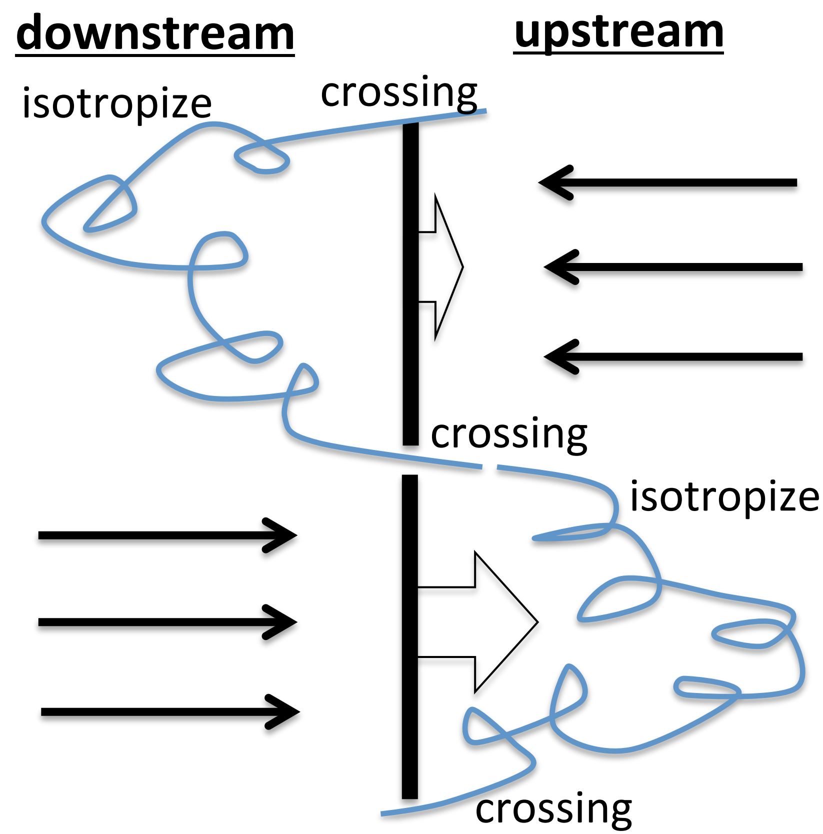
✓ Particle are accelerated by …

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 $s = 2.2$

e.g., Keshet & Waxman 2005

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

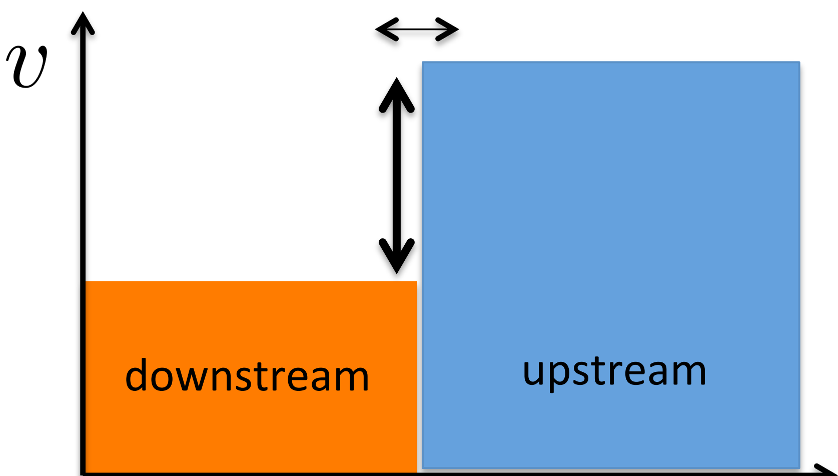
Limitation of Shock Acceleration

e.g., Levinson & Bromberg 2008, Katz+2011, Murase+2011, KK+2012

Yes ← $\tau_{\mathrm{T}} \lesssim$ 1-10 ? → No **e.g., GRB jets at sub-photosphere**

Radiation-unmediated

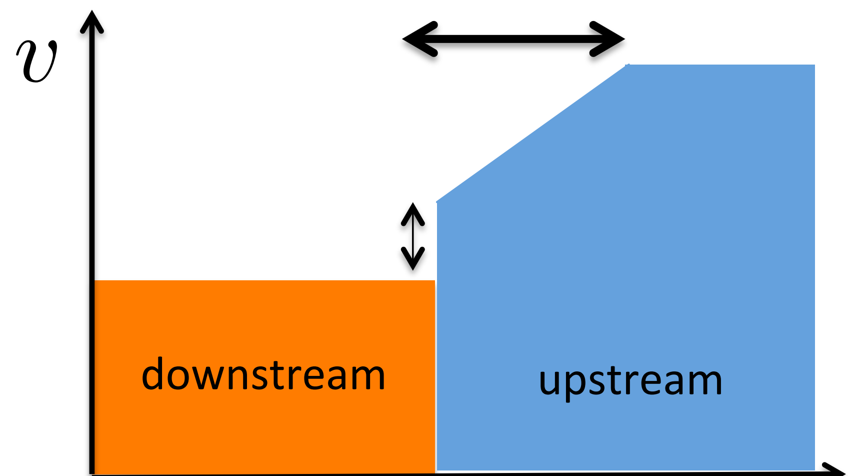
Isotropization via plasma processes $\sim c/\omega_{\mathrm{pe}}$



Shock acceleration is efficient.

Radiation-mediated

Deceleration via "precursor" photons $\sim l_{\mathrm{T}} \gg c/\omega_{\mathrm{pe}}$



Shock acceleration is inefficient.

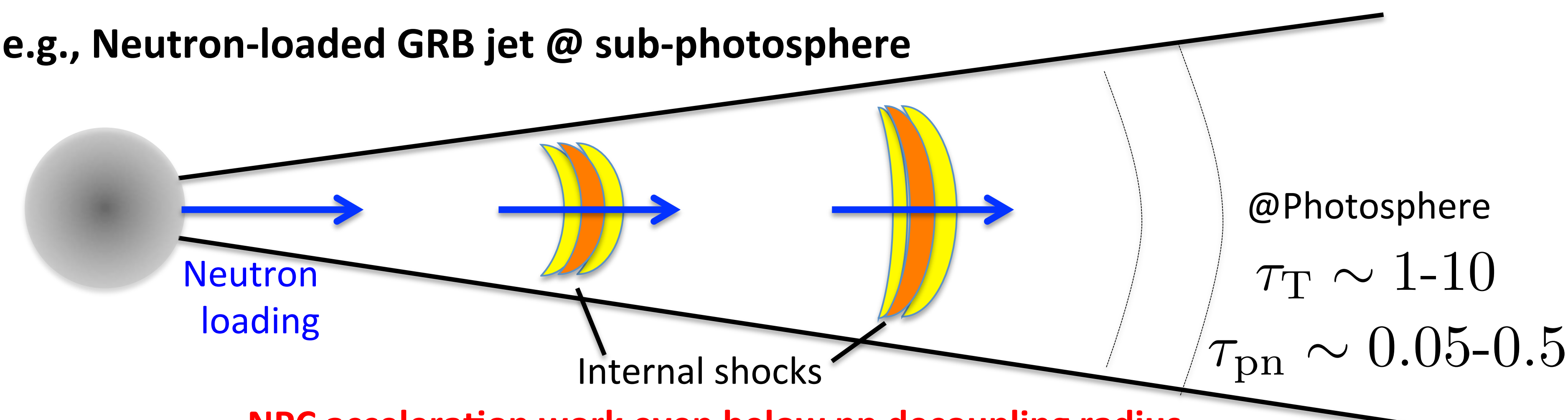
Neutron-Proton-Converter (NPC) Acceleration Mechanism

NPC Acceleration Mechanism

Kashiyama et al 2013 (originally proposed by Derishev et al. 2003)

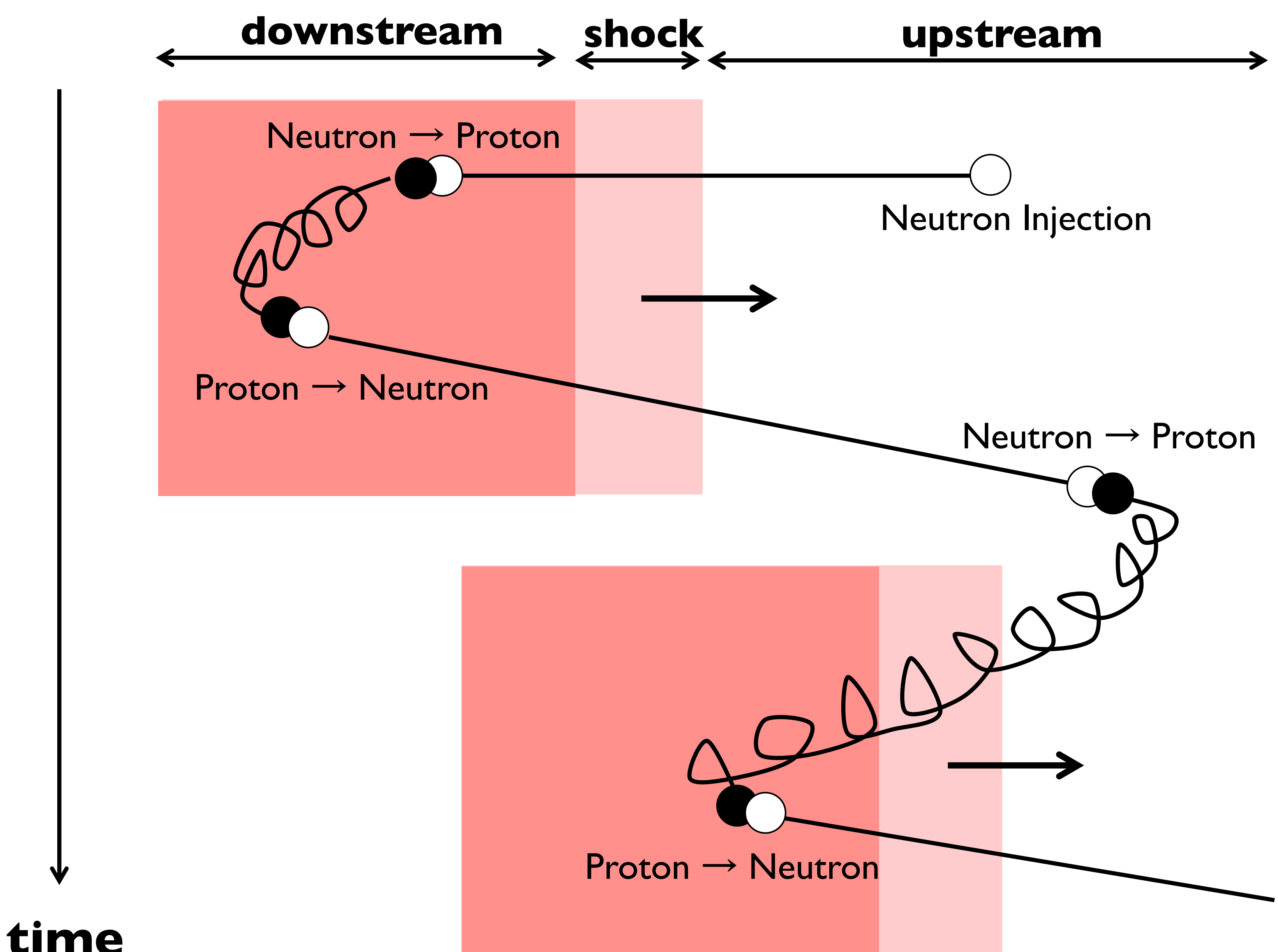
- is a shock acceleration including np conversions.
- can work with (and only with)
  1. relativistic shocks,
  2. neutron loadings,
  3. inelastic pp/pn collision optical depth,
  4. magnetic fields (not necessarily strong).
- can work even at radiation-mediated shocks.
- is slow, but efficient.
- is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

e.g., Neutron-loaded GRB jet @ sub-photosphere



NPC acceleration work even below np decoupling radius.

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

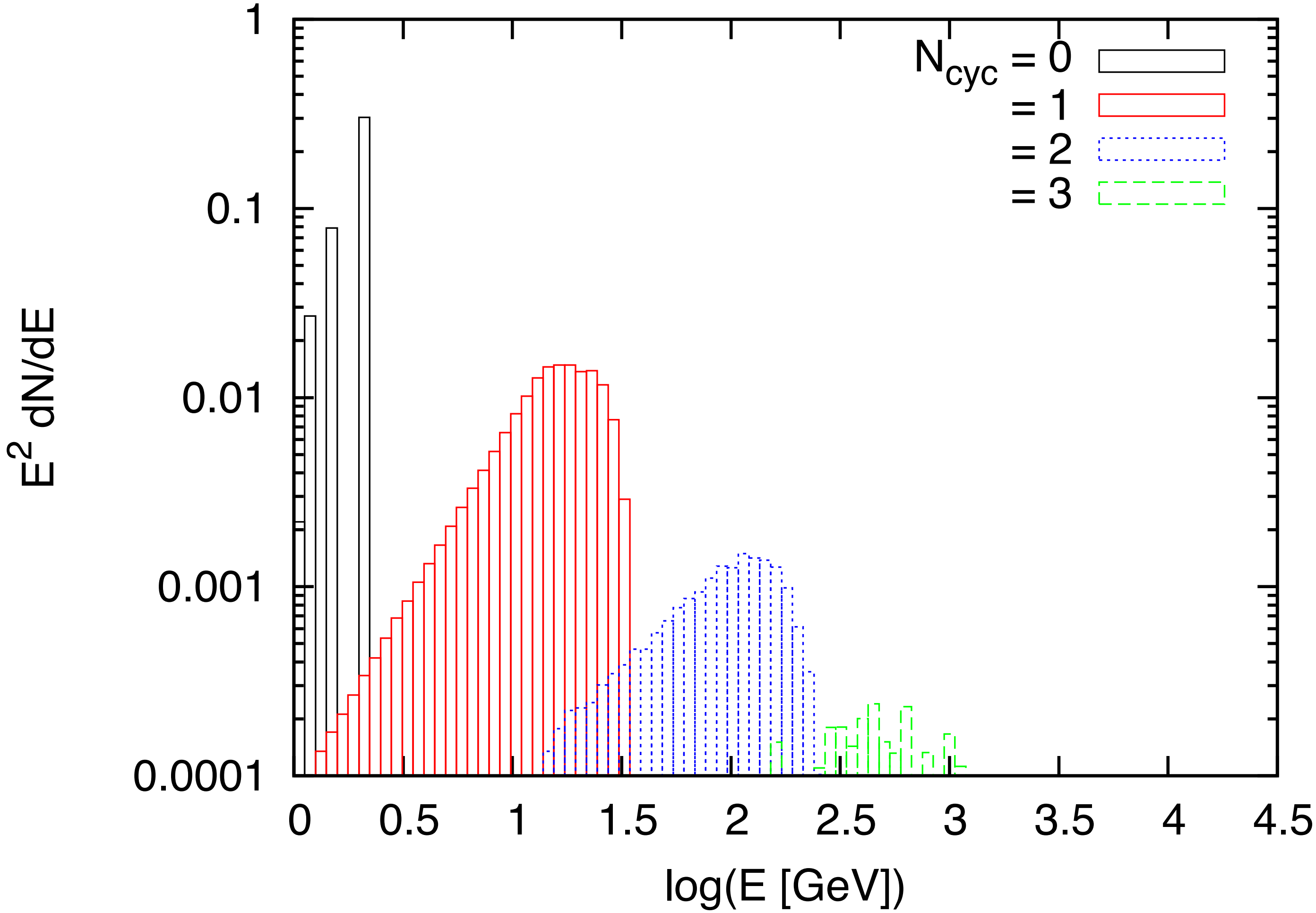
Acceleration efficiency

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

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

To be fixed by Monte-Carlo simulation

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

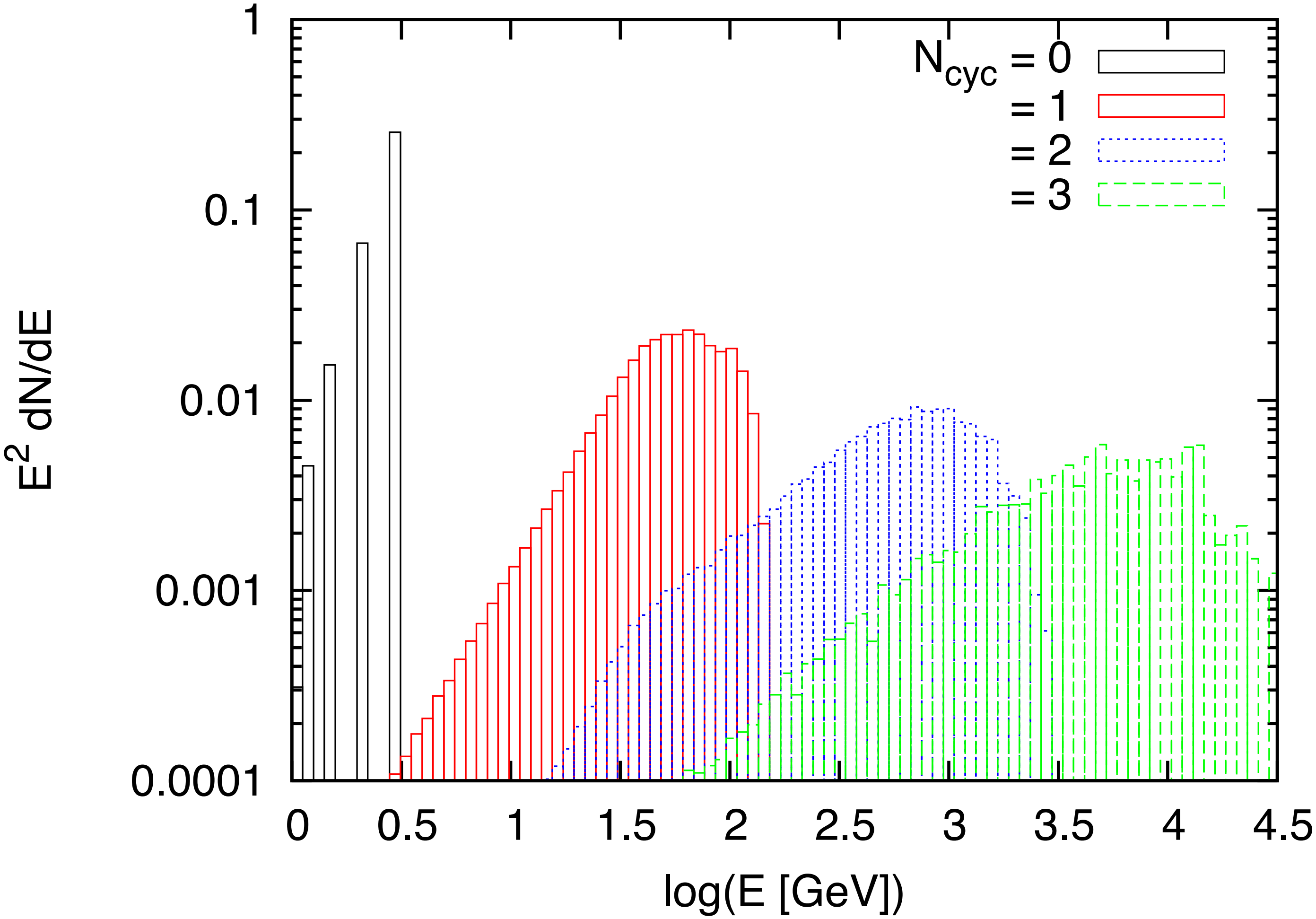


DS rest frame

$\tau_{\rm pn} = 1$

Kashiyama et al. 2013

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



DS rest frame

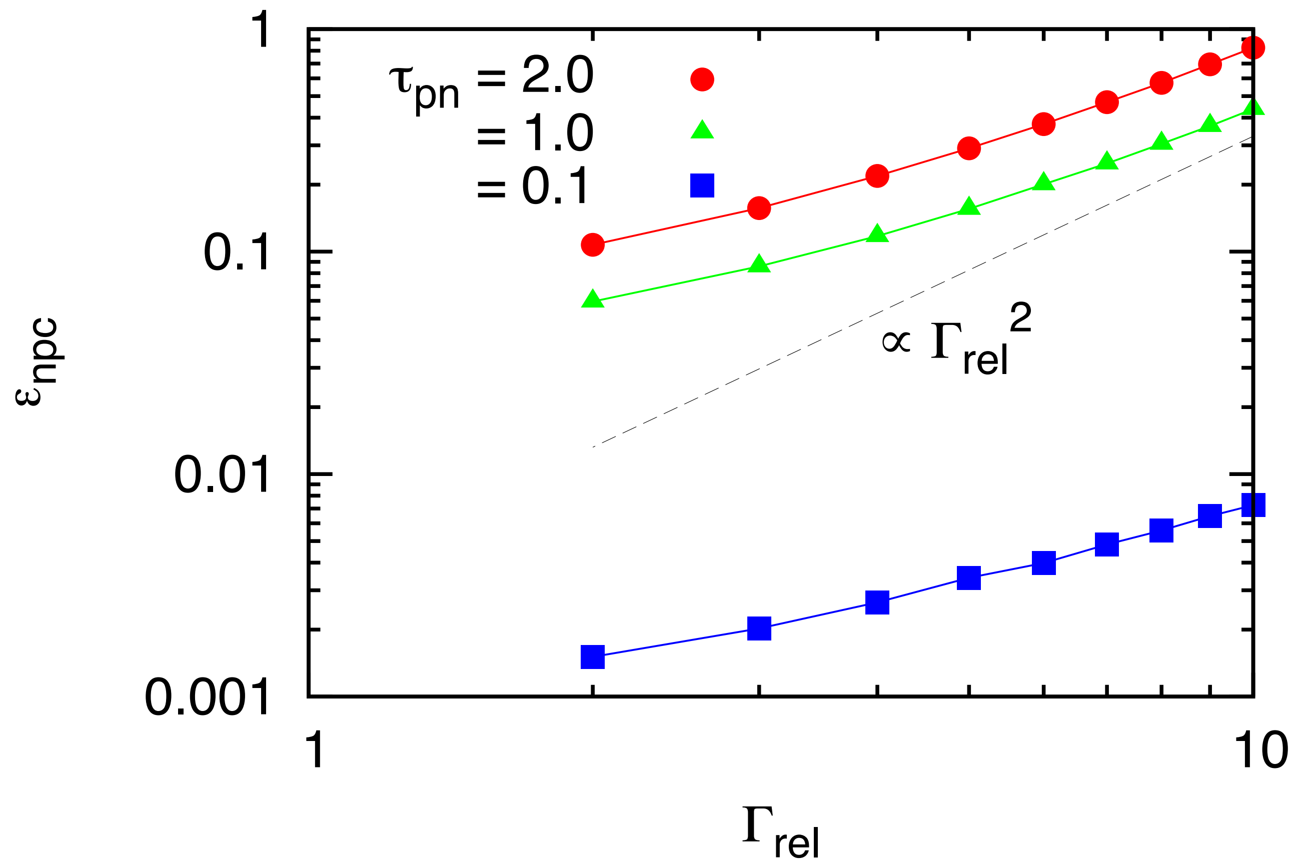
$\tau_{\rm pn} = 1$

Harder for larger $\Gamma_{\rm rel}$

Kashiyama et al. 2013

Acceleration Efficiency of NPC

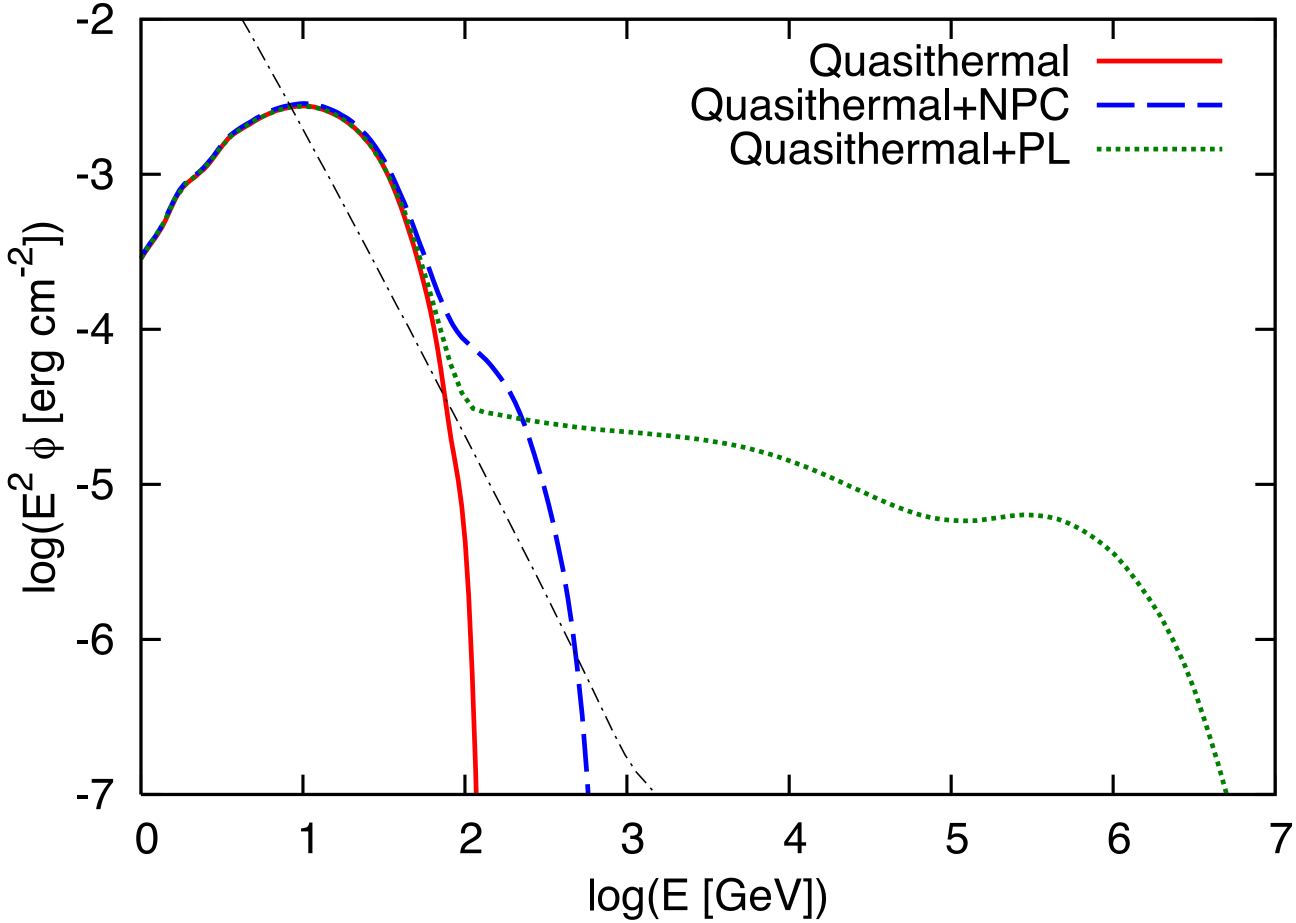
$$\varepsilon_{\rm npc} = \frac{\text{Accelerated Baryons}}{\text{Neutron Injection}}$$



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

Kashiyama et al. 2013

NPC enhances the detectability



$$\Gamma_{\rm rel} = 3.0$$

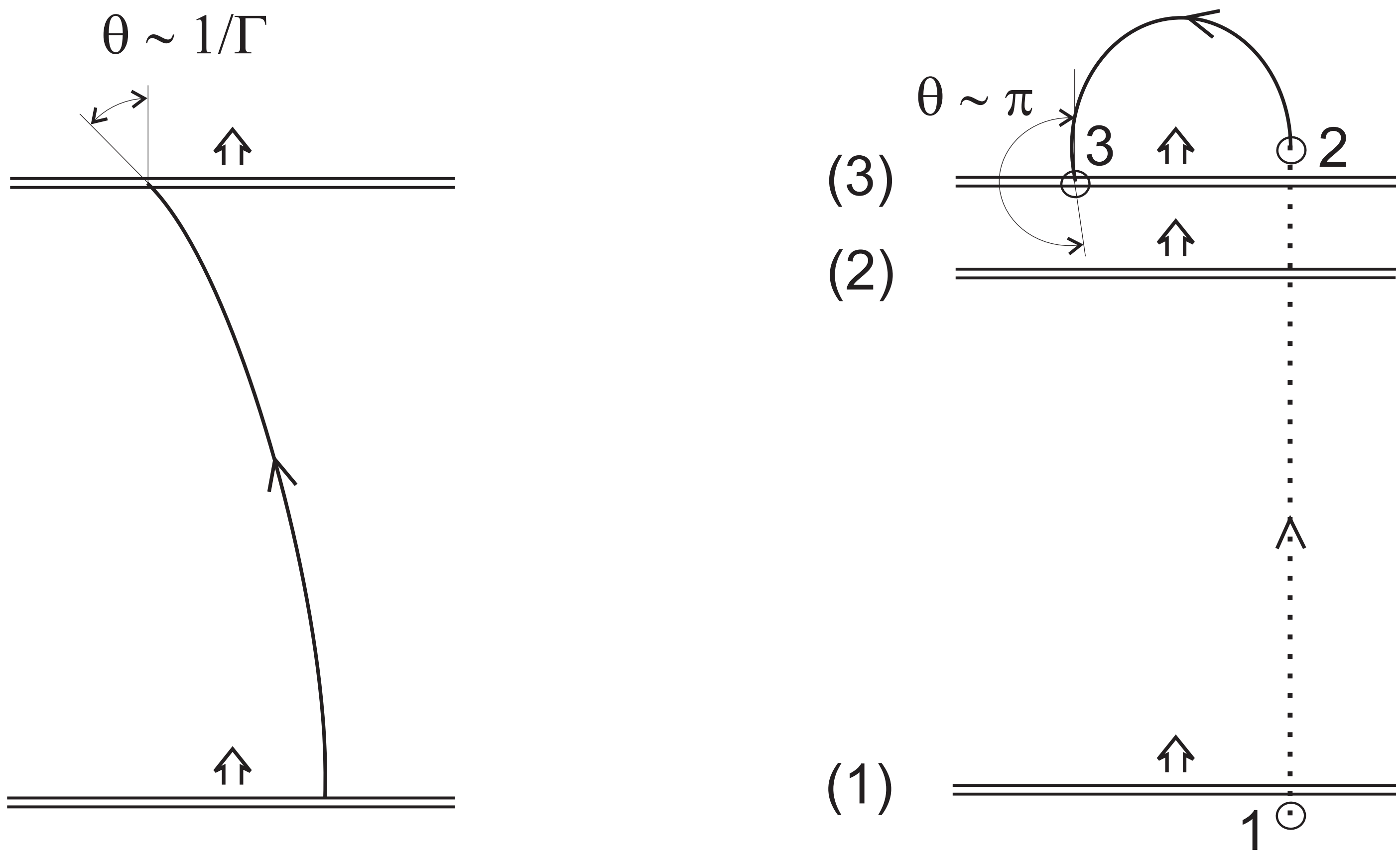
Murase, KK, Meszaros 2013

Summary

- Era of neutrino astronomy
  - TeV-PeV neutrinos are now detected.
  - GeV-TeV neutrino astronomy is also possible.
- GRB is still an interesting target
  - Neutrinos from sub-photospheric dissipation
    - A key to understand the central engine
    - Leading model of prompt emission.
    - Even failed or hidden GRBs can produce.
- NPC mechanism
  - is inevitable at sub-photosphere of GRB jets.
  - is slow, but efficient.
  - can enhance the detectability of GeV-TeV neutrinos by IceCube DeepCore.

Back-up

1st order Fermi vs NPC



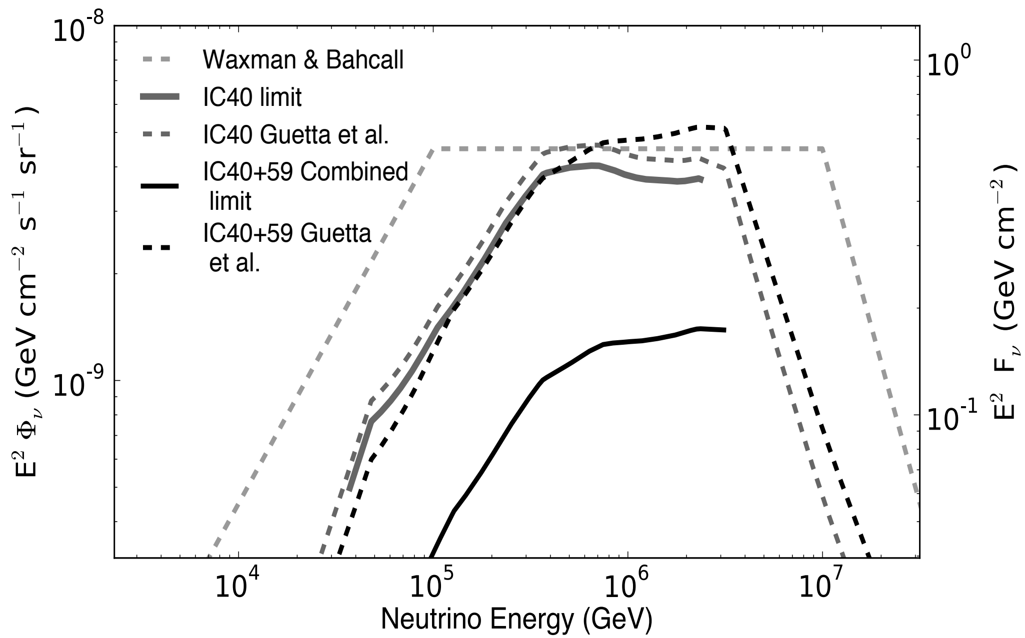
Derishev et al. 2003

Prompt pγ neutrino: Staking Analysis

No detection by stacking O(100) of GRBs

→ **model dependent constraints on prompt pγ neutrinos**

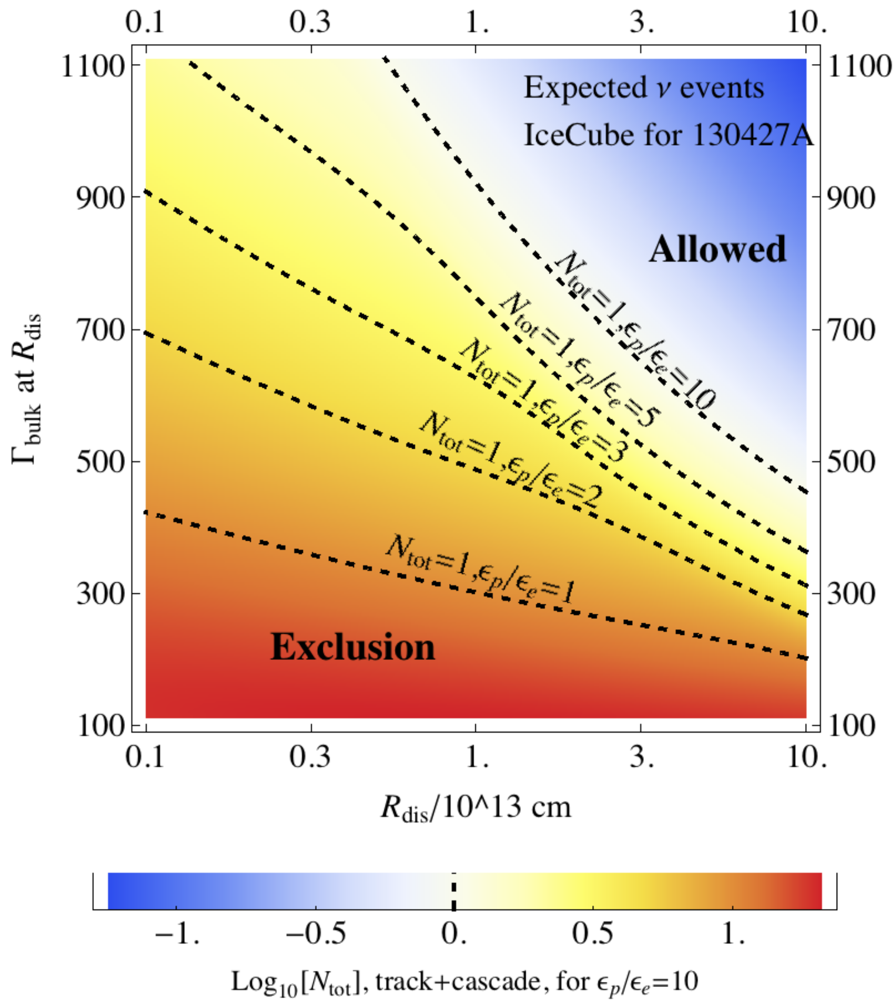
→ **Testing *GRB-UHECR hypothesis***



IceCube collaboration 2012 (see, also Hummer+12, He+12)

Prompt pγ neutrino : GRB 130427A

Non detection for the brightest burst ever since the full operation



Shan, KK, & Meszaros. 2013

NPC Acceleration Cycle