High-Energy Neutrinos from Cosmic Explosions

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SN-GRB Conference
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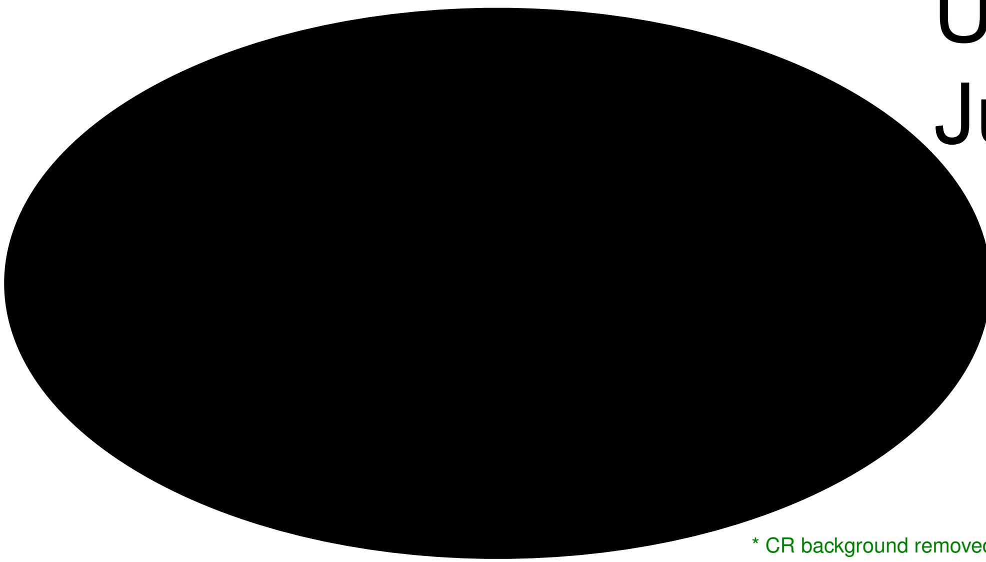
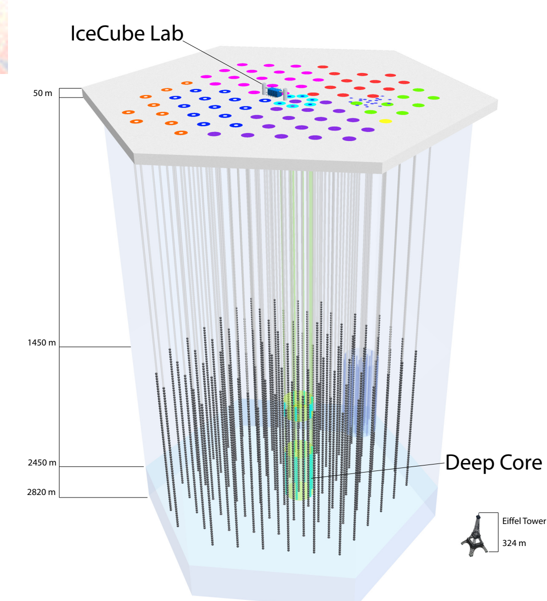
Dawn of High-Energy Neutrino Astrophysics



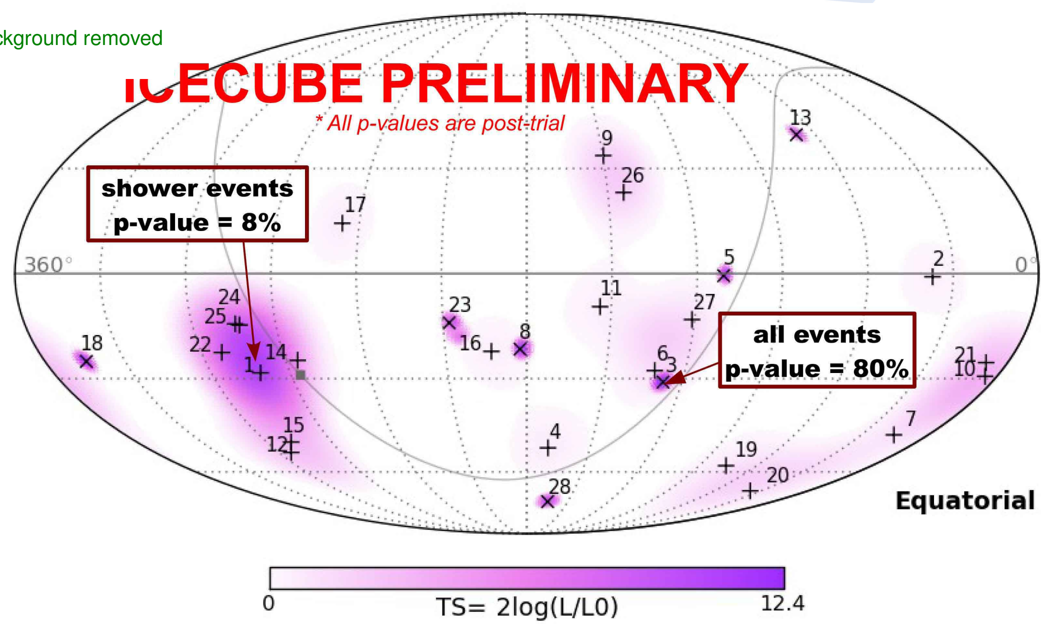
* CR background removed

Until
June 2012



June 2012
2 events at PeV
May 2013

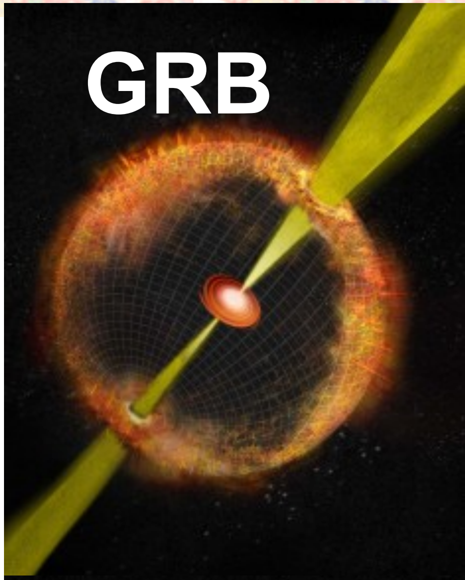
28 events > 30 TeV

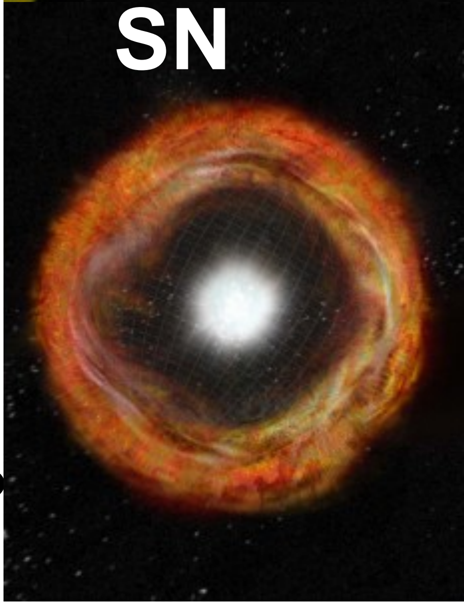


Outline

GRBs & SNe = violent cosmic explosions
at deaths of massive stars

- GRB-SN connection?, jet properties?
- CR origin?, CR acceleration?

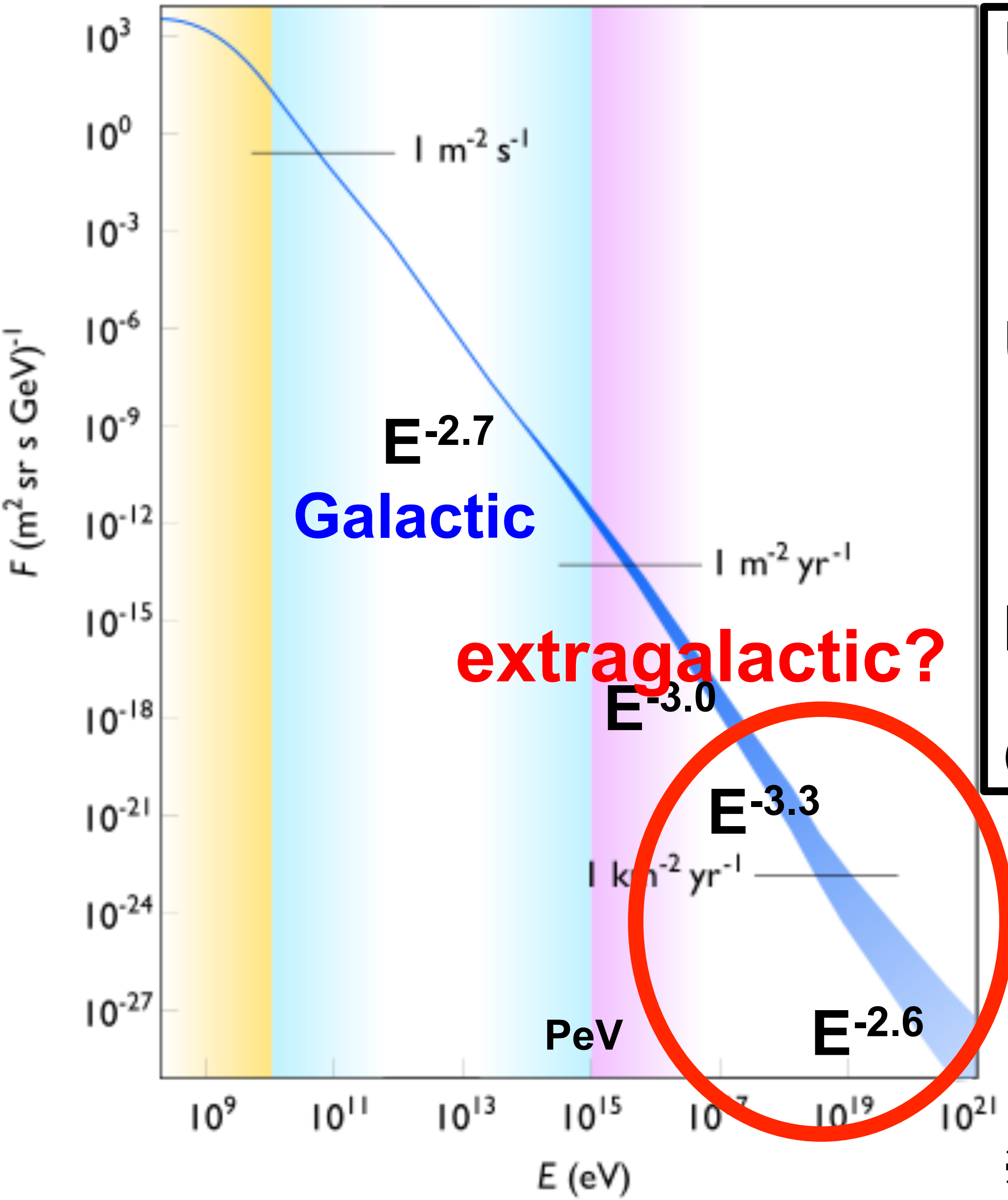




Overview of GRBs/SNe as HE ν sources

1. GRBs as UHECR origin?
2. HE neutrinos from subphotospheres?
3. Origin of sub-PeV neutrinos in IceCube?

Motivation: Cosmic Rays – A Century Old Puzzle



UHECR budget (from obs.):

$Q_{HECR} \sim 10^{44}$ erg/Mpc^3/yr

UHECR energy output ~ GRB radiation energy

$E_{HECR}^{iso} \sim E_{\gamma}^{iso} \sim 10^{53}$ erg

local GRB rate density:

~ 1 Gpc^{-3} yr^{-1}

(ex. Wanderman & Piran 10, Dermer 12)

UHECR acc. is allowed

$\varepsilon_p < erB \sim 3\times10^{20}$ eV $r_{14}B_4$

(Waxman 1995, Vietri 1995)

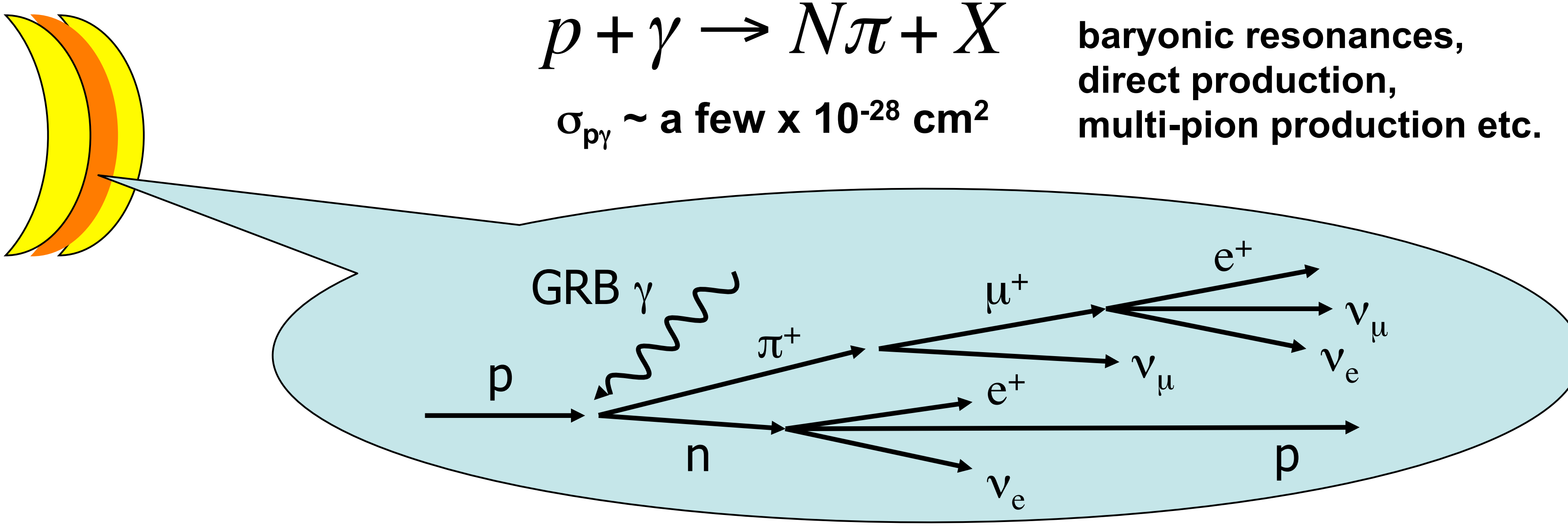
※ many theoretical issues I do not discuss

HE Neutrinos as a Smoking Gun

$$p + \gamma \rightarrow N\pi + X$$

$\sigma_{p\gamma}$ ~ a few x 10^{-28} cm^2

baryonic resonances, direct production, multi-pion production etc.



at Δ-resonance ($\varepsilon_p \varepsilon_\gamma \sim 0.2\Gamma^2$ GeV^2)

$\varepsilon_\nu^b \sim 0.05\varepsilon_p^b \sim 0.01$ GeV^2 $\Gamma^2/\varepsilon_{\gamma,pk} \sim$ 1 PeV (if $\varepsilon_{\gamma,pk} \sim 1$ MeV)

Meson production efficiency (large astrophysical uncertainty)

$f_{p\gamma} \sim 0.2 n_\gamma \sigma_{p\gamma} (r/\Gamma) \propto r^{-1}\Gamma^{-2} \propto \Gamma^{-4}\delta t^{-1}$ (if IS scenario $r \sim \Gamma^2 \delta t$)

parameters for $f_{p\gamma}$ (L_γ, photon spectrum, Γ, r (or δt)) + E_{CR} (ex. ~10 E_γ)

Neutrino Spectra

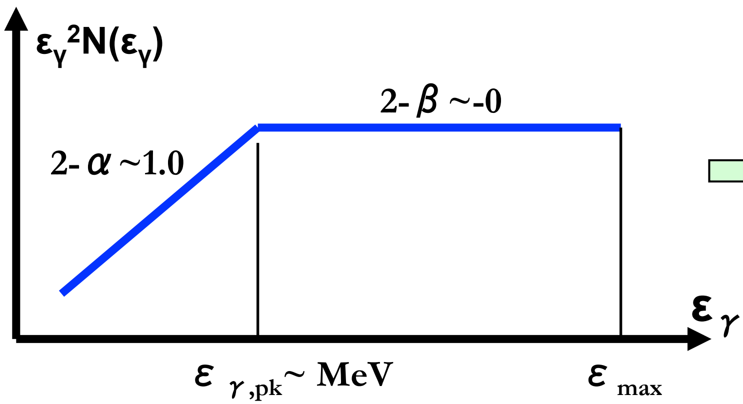
CR Spectrum (Fermi mechanism)

$N(\varepsilon_p) \propto \varepsilon_p^{-s}$ (s~2 assumed)

$E_{HECR} \equiv \varepsilon_p^2 N(\varepsilon_p) \sim E_\gamma$ (GRB-UHECR)

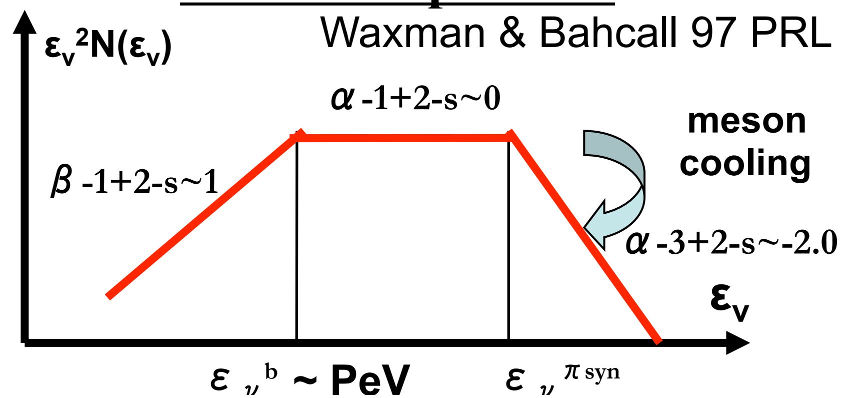
$E_{CR} = \int d\varepsilon_p\, \varepsilon_p N(\varepsilon_p) \sim 20\, E_{HECR}$

Photon Spectrum (observed)



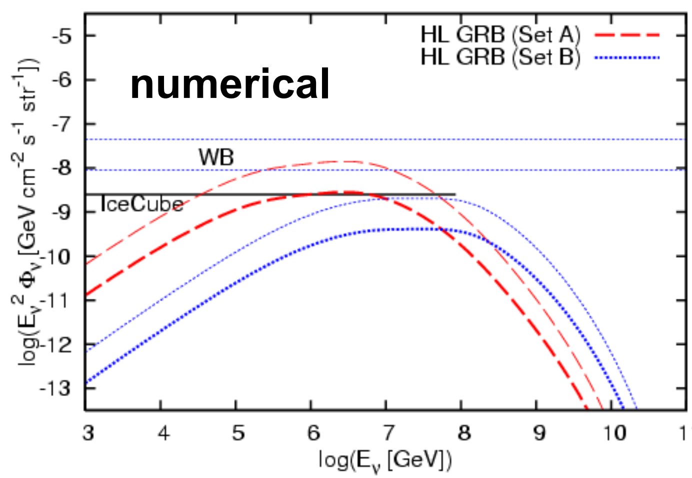
Neutrino Spectrum

Waxman & Bahcall 97 PRL

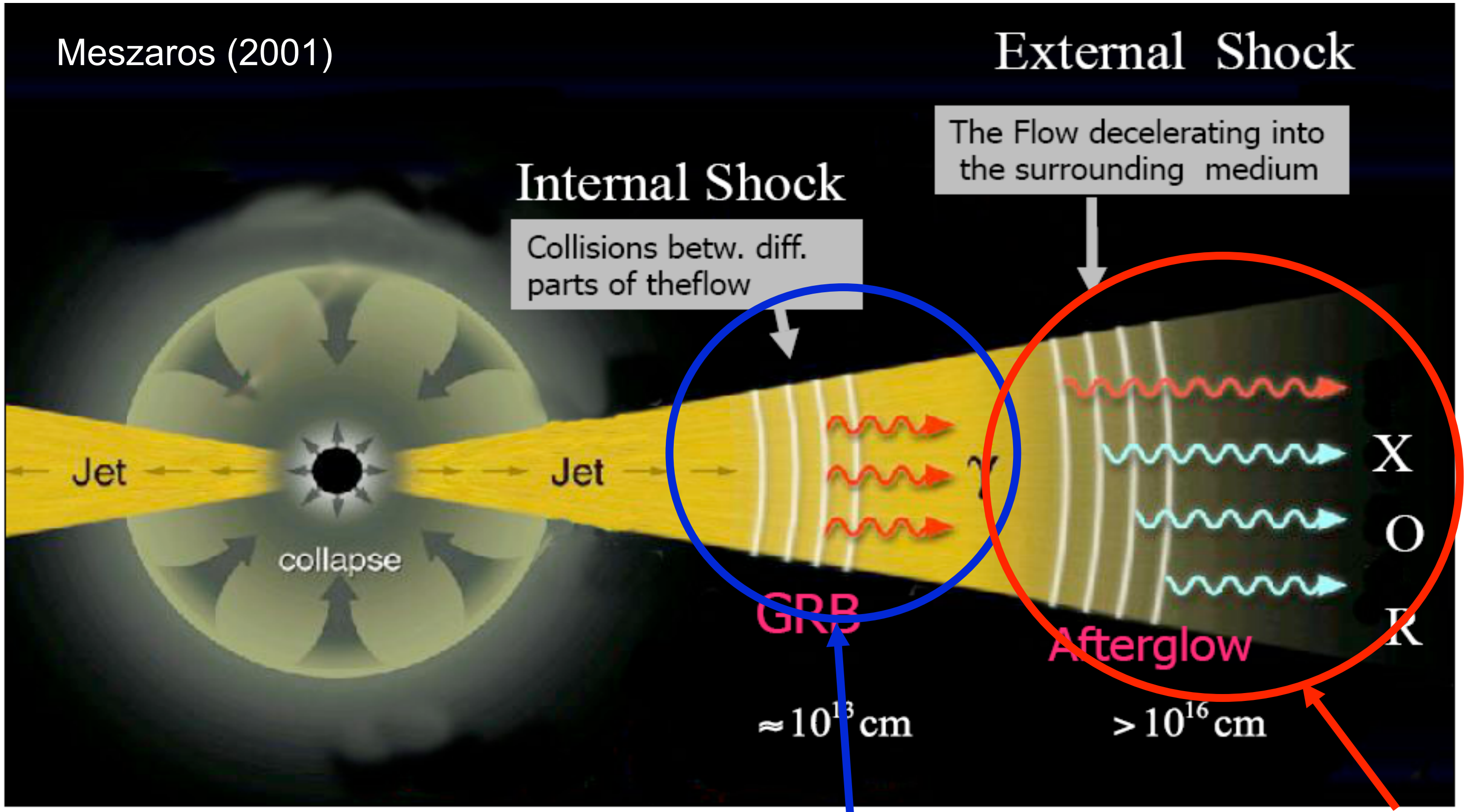


more detailed microphysics
- higher resonances & multi-pion production
- CR cooling (photomeson, photopair, syn., IC)
- muon, pion, kaon w. their cooling
- neutrino mixing

ex. KM & Nagataki 06 PRD, Baerwald+ 11 PRD



Possible Neutrino Production Sites



Inner jet (prompt/flare)

r ~ 10^{12}-10^{16} cm B ~ $10^{2\text{-}6}$ G

PeV ν, GeV-TeV γ

Waxman & Bahcall 97 PRL
Dermer & Atoyan 03 PRL
KM & Nagataki 06 PRL

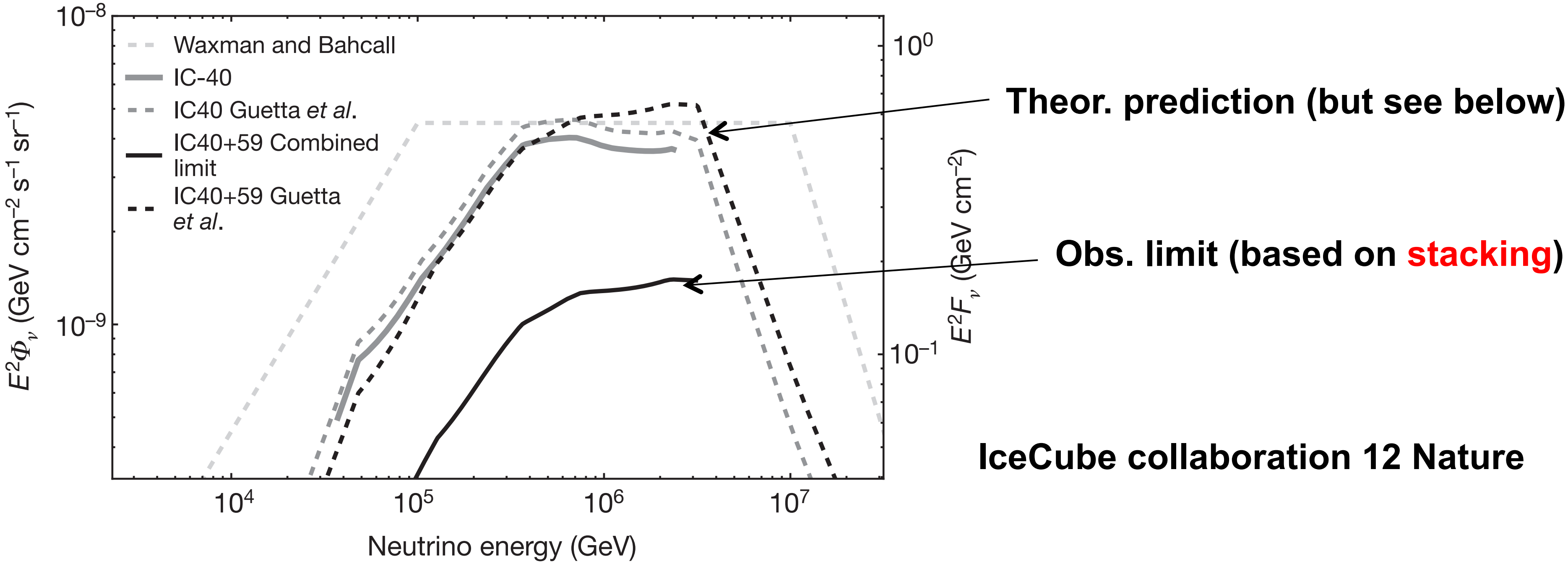
Afterglow

r ~ 10^{14}-10^{17} cm B ~ 0.1-100 G

EeV ν, GeV-TeV γ

e.g., Waxman & Bahcall 00 ApJ
Dermer 02 ApJ
KM 07 PRD

Recent IceCube Limits on Prompt ν Emission



IceCube collaboration 12 Nature

Observational limits start to be powerful but be careful

1. $f_{p\gamma}$ is energy-dependent, π-cooling → ~ 4 ↓ (Li 11, Hummer et al. 12)

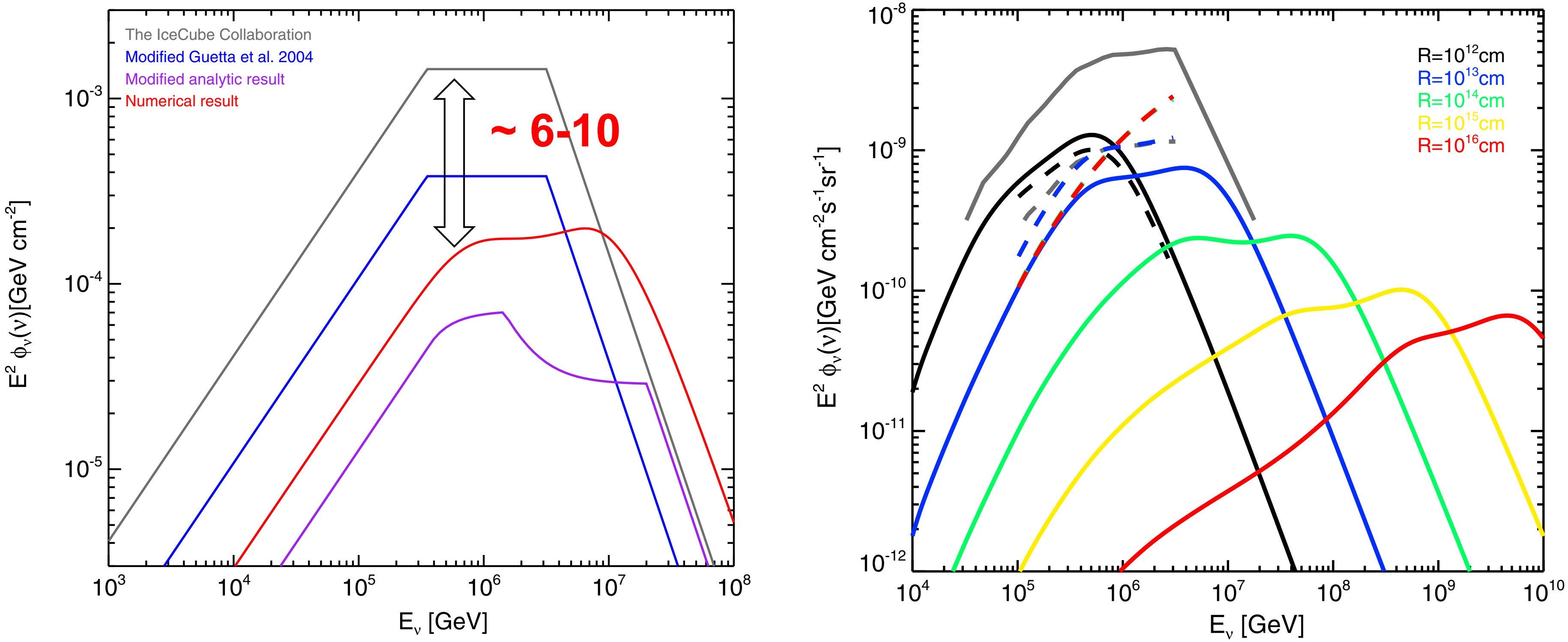
2. ($\varepsilon_\gamma^2\ \phi_\gamma$ at $\varepsilon_{\gamma,pk}$) ≠ ($\int d\varepsilon_\gamma\ \varepsilon_\gamma\ \phi_\gamma$) → ~3-6 ↓ (Hummer et al. 12, He+ KM 12)

3. details (multi-π, ν mixing etc.) → ex., multi-π ~2-3 ↑ (KM & Nagataki 06)

※ totally different from “astrophysical” model-uncertainty in calculating $f_{p\gamma}$

※ these problems do not exist in many earlier calculations (ex. Asano, KM+, Baerwald+)

Implications of IceCube "Stacking" Searches



He+ KM 12 ApJ (see also Hummer et al. 12 PRL)

+ Not ruled out yet

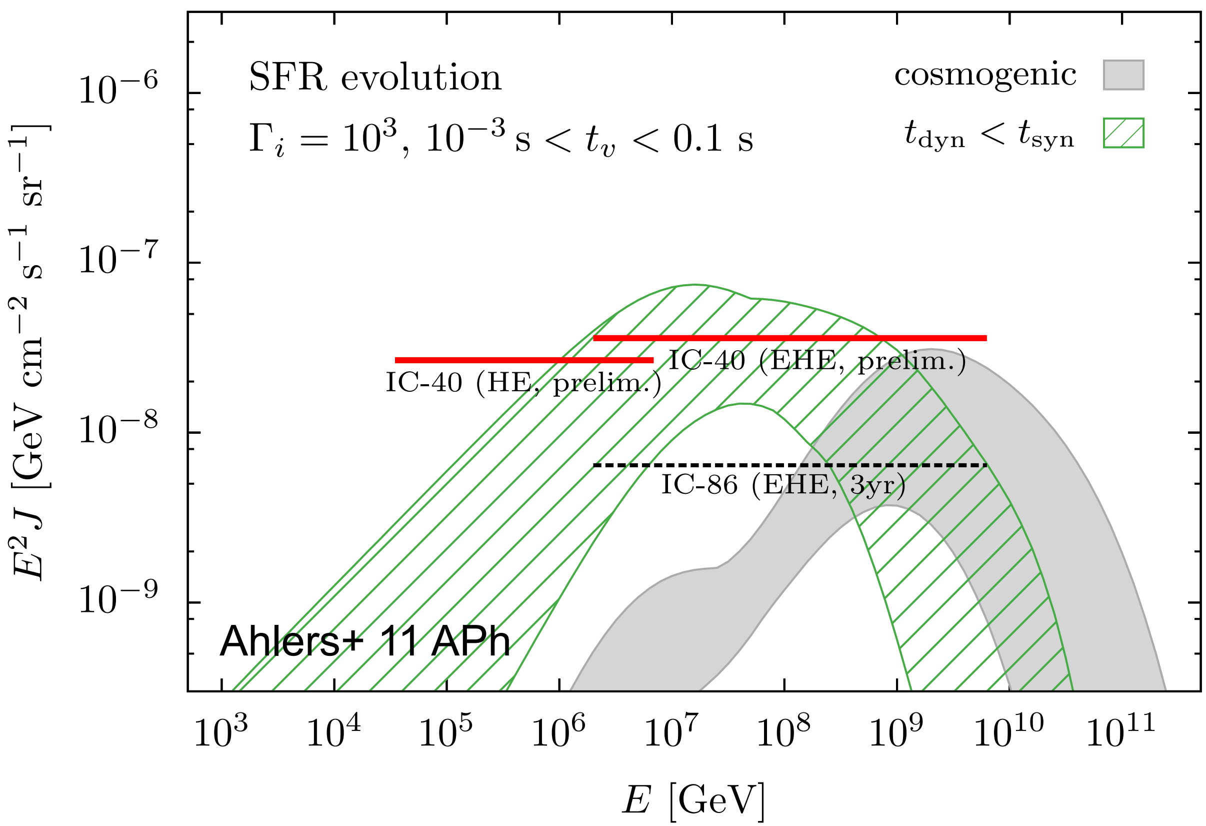
+ ~10 yr observations by IceCube can cover most of relevant parameter space for the GRB-UHECRp hypothesis

Optimistic Cases: Neutron Escape Model

Both neutrons and neutrinos should be produced

escaping UHE neutrons → UHE protons via neutron decay

$\varepsilon_\nu^2\Phi(\varepsilon_\nu) \sim \varepsilon_n^2\Phi(\varepsilon_n) \sim \varepsilon_{CR}^2\Phi(\varepsilon_{CR}) \sim$ a fewx10^{-8} GeV cm^{-2} s^{-1} sr^{-1} sr-1



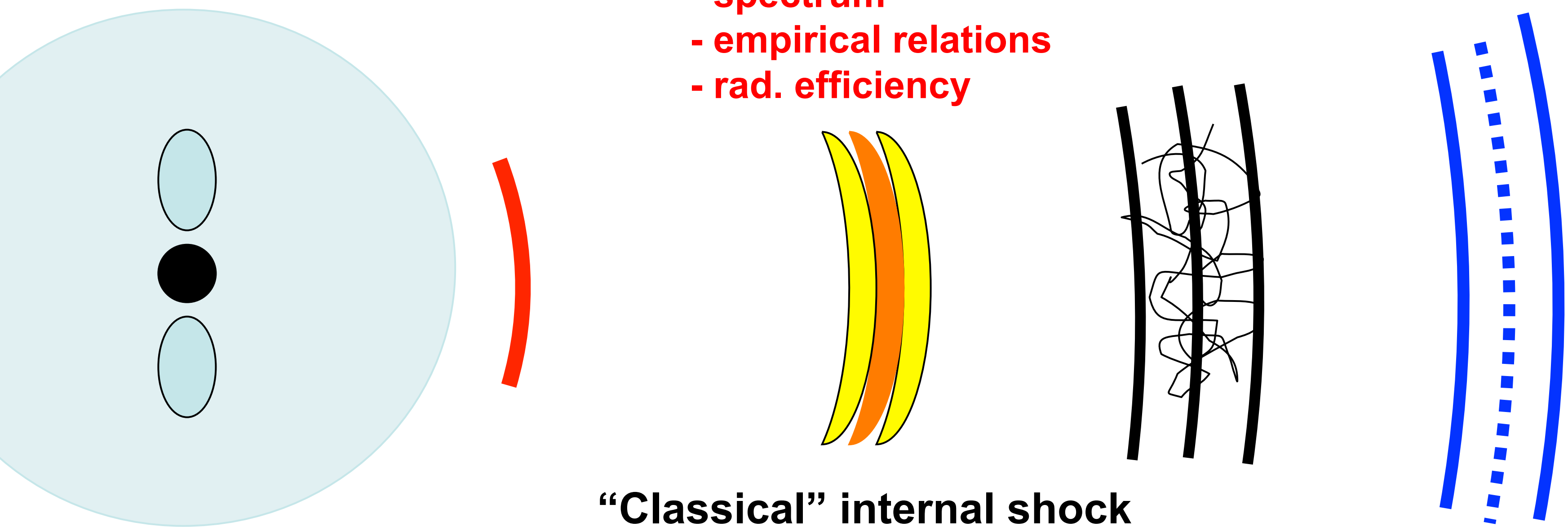
Excluded by IceCube

Fall of Classical GRB Picture

Wolf-Rayet star
$R \sim 10^{11}$-10^{12} cm

Problems!
- spectrum
- empirical relations
- rad. efficiency

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



"Classical" internal shock
$r \sim 10^{13}$-$10^{15.5}$ cm

talk by Daigne

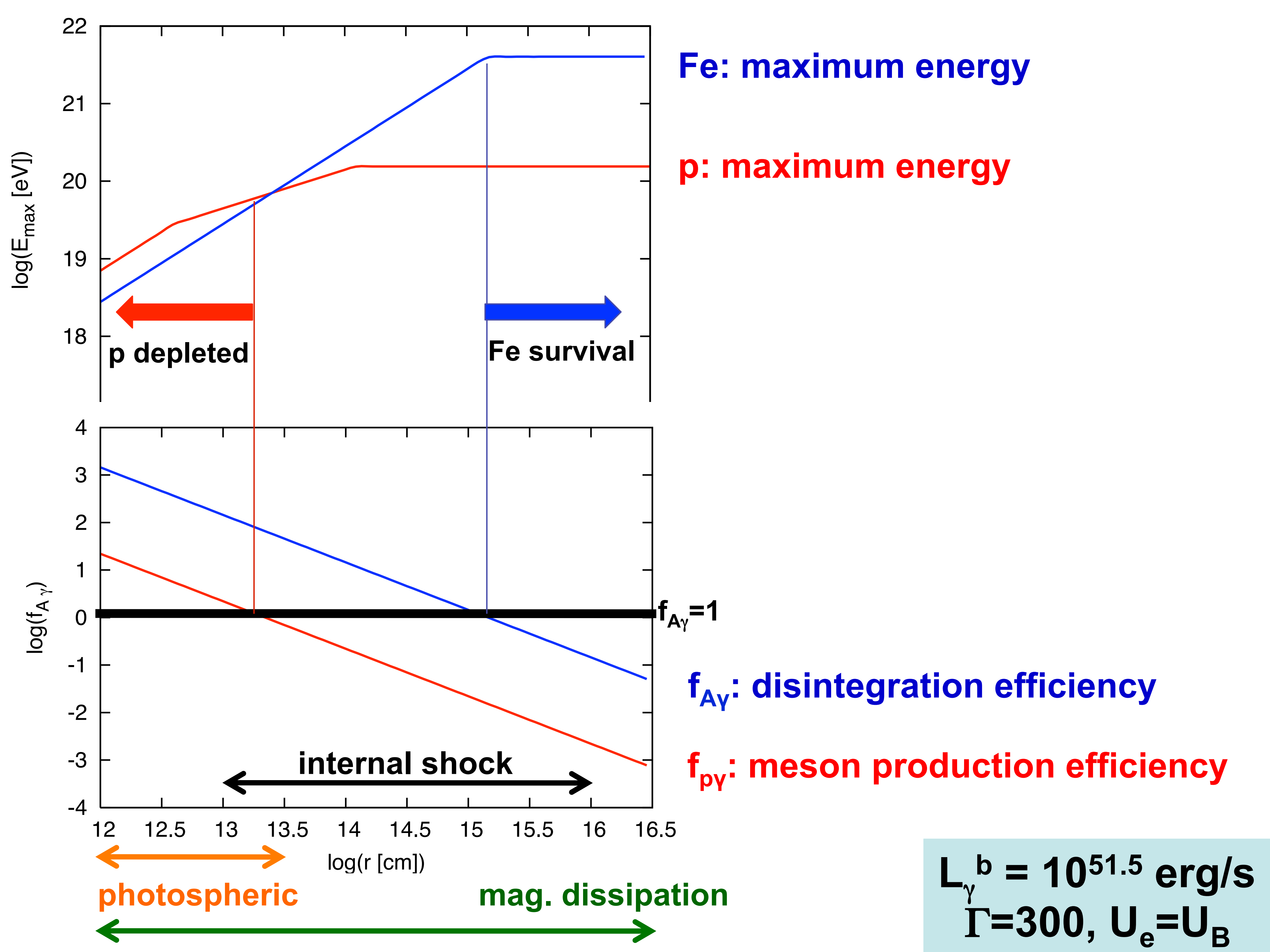
Photosphere
($\tau_T = n\sigma_T(r/\Gamma) = 1$)
$r \sim 10^{11}$-10^{13} cm

modified-thermal emission
dissipation: shock/mag./n-p collision

talks by Pe'er, Beloborodov, Ryde

Mag. dissipation
ex. $r \sim 10^{15}$-10^{16} cm
(model-dependent)

talk by Zhang

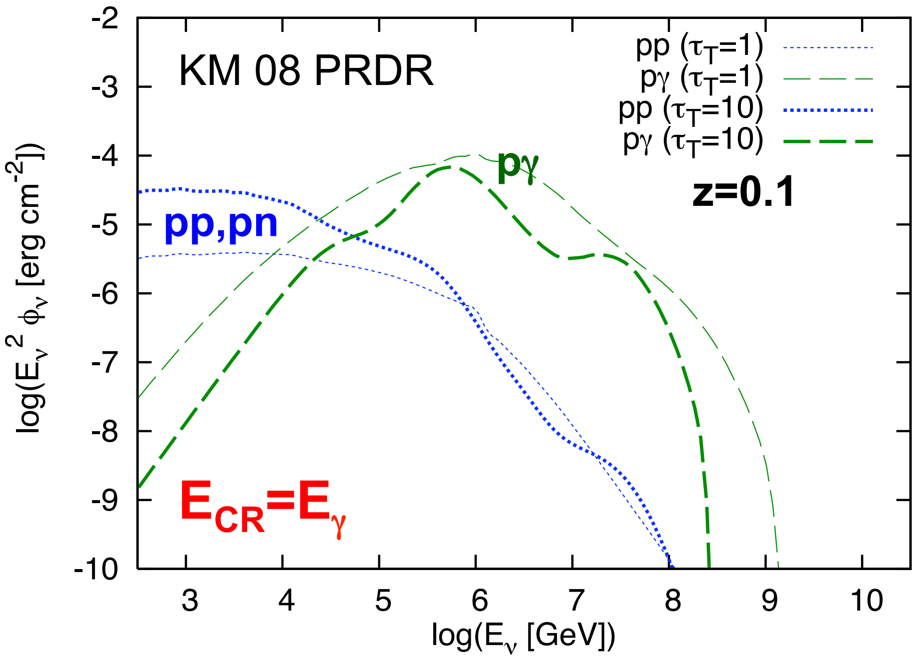


Fe: maximum energy
p: maximum energy
p depleted
Fe survival
log(E_max [eV])
log(f_Aγ)
f_Aγ=1
f_Aγ: disintegration efficiency
f_pγ: meson production efficiency
internal shock
log(r [cm])
photospheric
mag. dissipation
L_γ^b = 10^51.5 erg/s
Γ=300, U_e=U_B

Model-Dependent Predictions

Dissipative photosphere

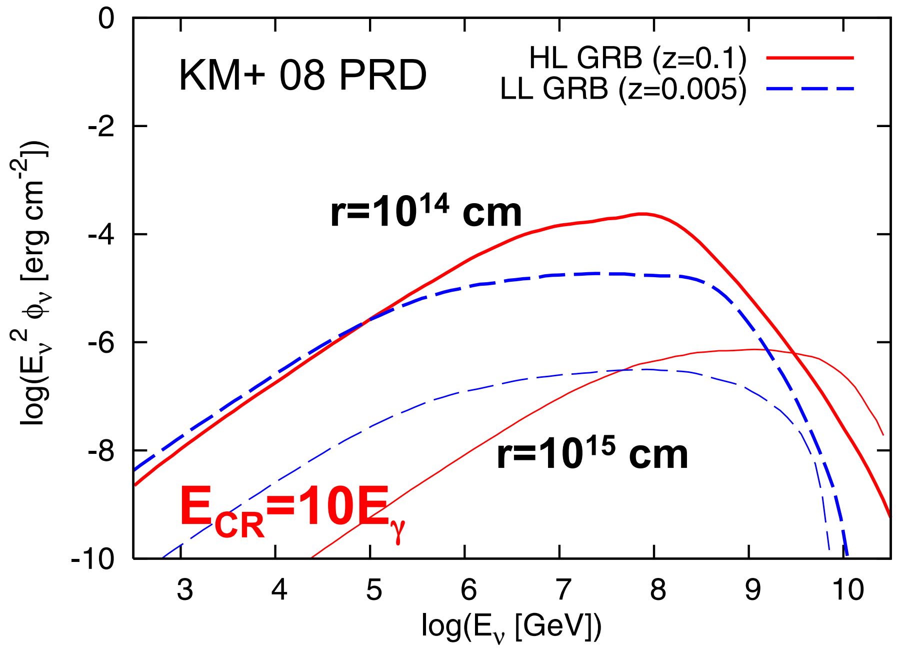
- GeV-TeV due to pp
- (UHE)CRs depleted



see also Wang & Dai 09 ApJL
Gao, Asano & Meszaros 13 JCAP

Large r models

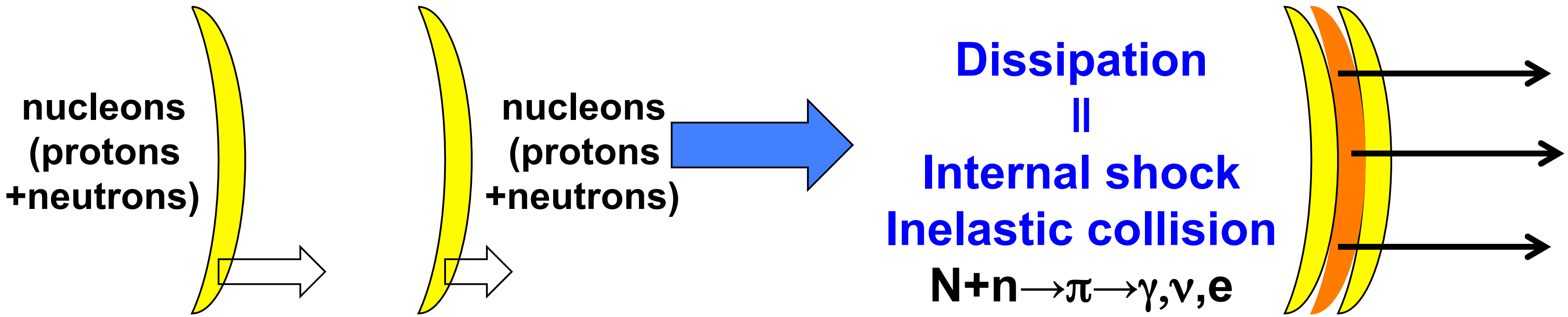
- PeV-EeV (undetectable)
- UHE "nuclei" possible



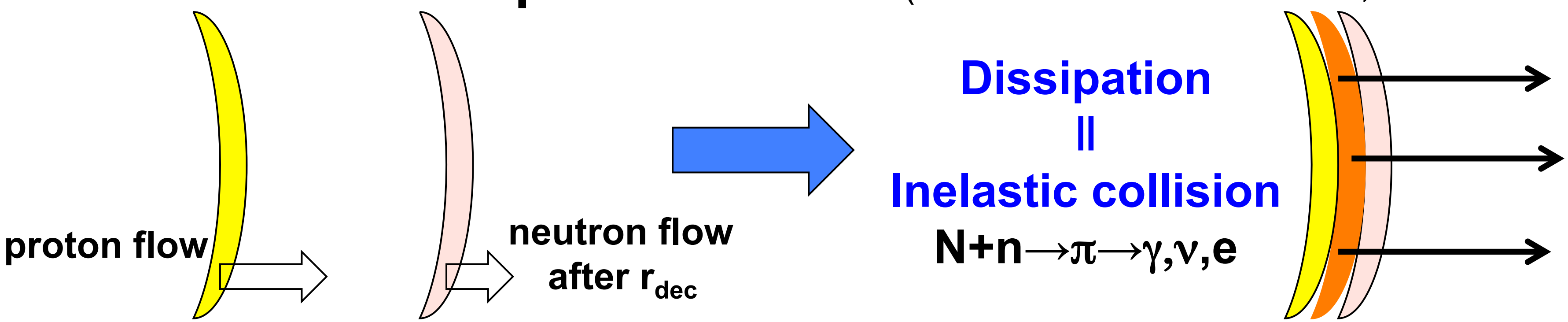
see also He et al. 12 ApJ
Zhang & Kumar 13 PRL

The Role of Neutrons at Subphotospheres: GeV Neutrinos

Collision w. compound flow (ex. Meszaros & Rees 00)



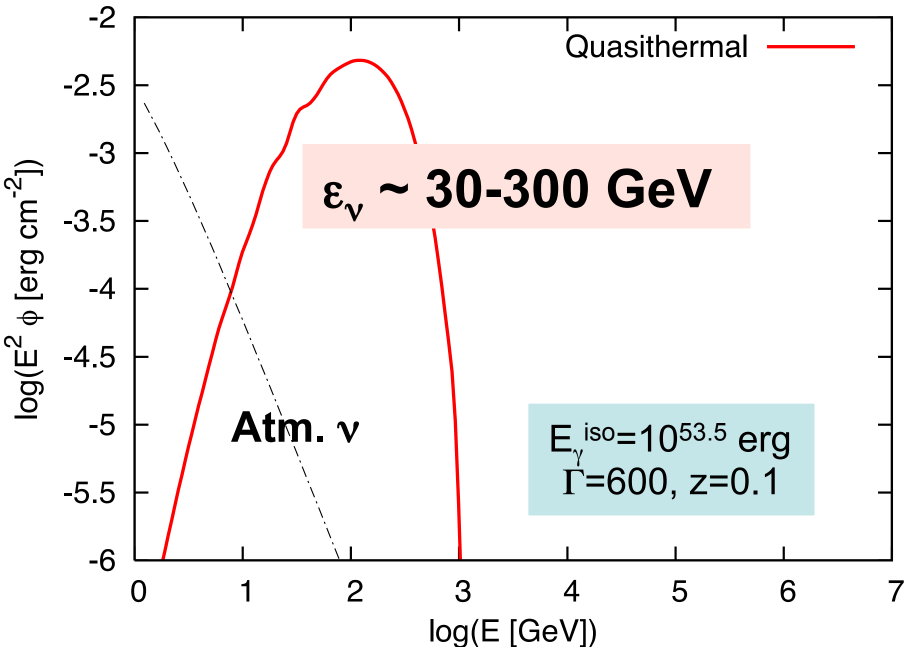
Collision w. decoupled neutrons (ex. Bahcall & Meszaros 00, Beloborodov 10)



- Quasi-thermal emission explain observed GRB spectra (via EM cascades, Coulomb heating & synchrotron)

(see talks by Meszaros, Pe'er, Beloborodov, Ryde)

Quasi-thermal Neutrinos are Detectable

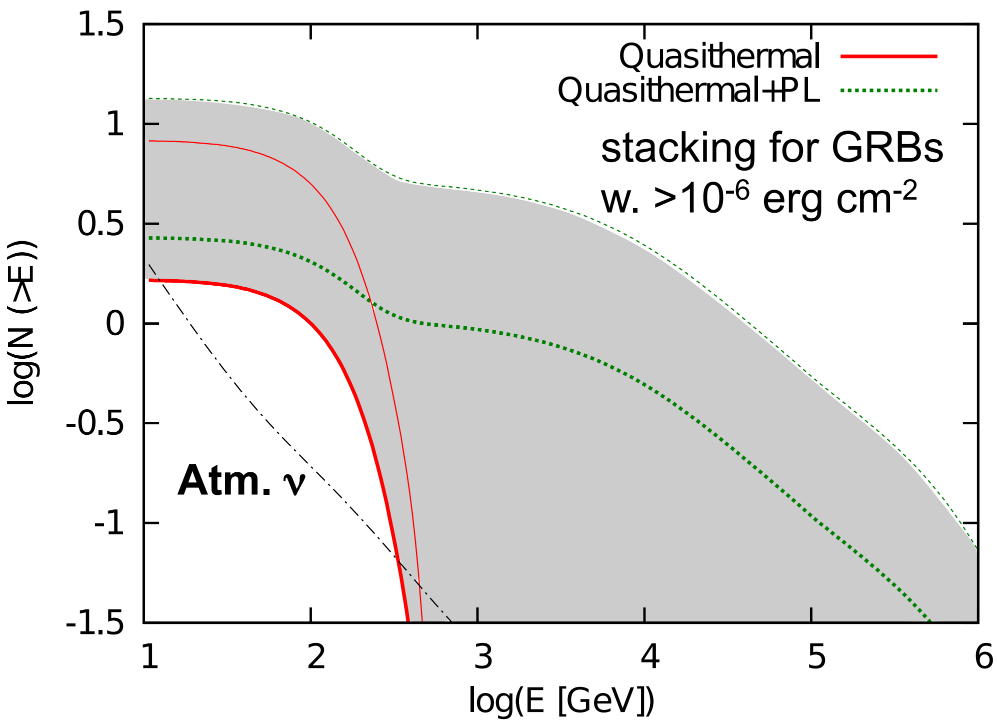


$\varepsilon_\nu \sim 0.1\ \Gamma\,\Gamma_{rel}\, m_p\, c^2$

inevitable, CRs not required

If dissipation comes from neutrons

$\varepsilon_\nu^{\ 2}\, \phi_\nu \sim \varepsilon_\gamma^{\ 2}\, \phi_\gamma$



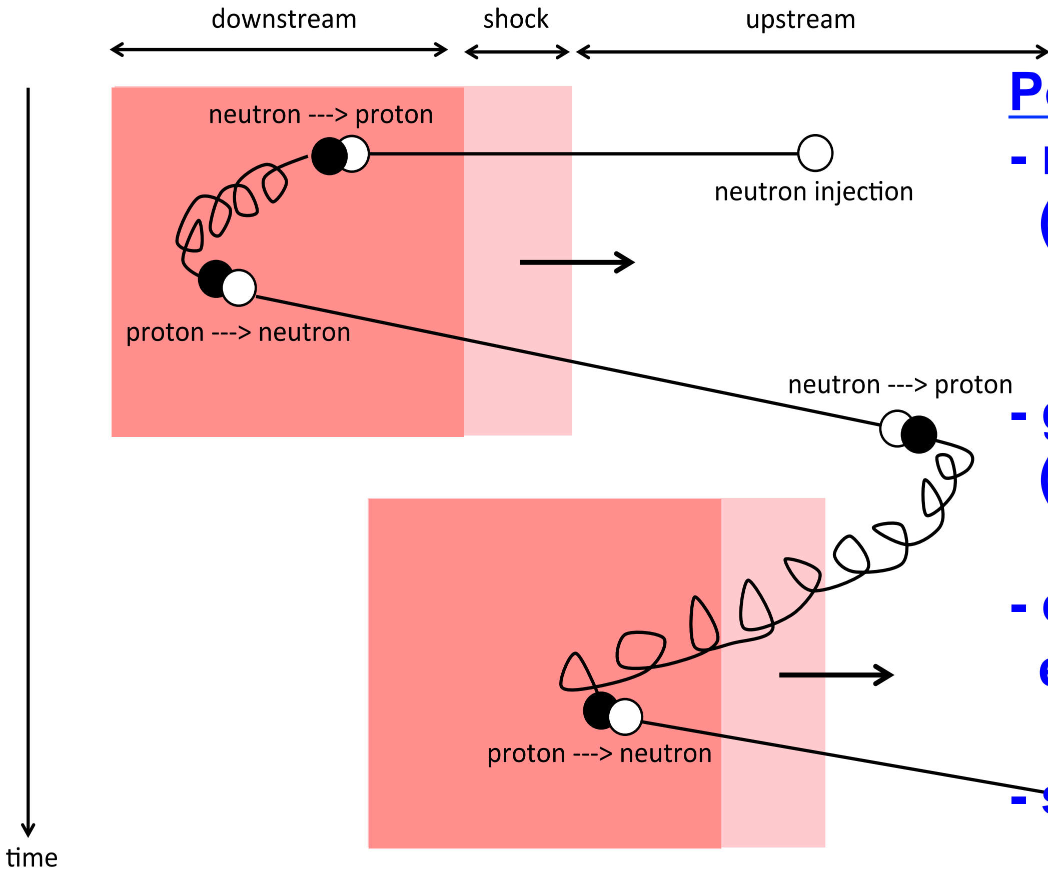
- DeepCore is crucial in the 10-100 GeV range
- Stacking ~1000-2000 GRBs (~10 yr w. current satellites)

KM, Kashiyama & Meszaros 13 PRL
see also Bartos, Beloborodov+ 13 PRL

Novel Acceleration Mechanism in Neutron-Loaded Flows

"Neutron-Proton-Converter Acceleration" (Derishev+ 03 PRD)

another Fermi acceleration mechanism without diffusion



Points

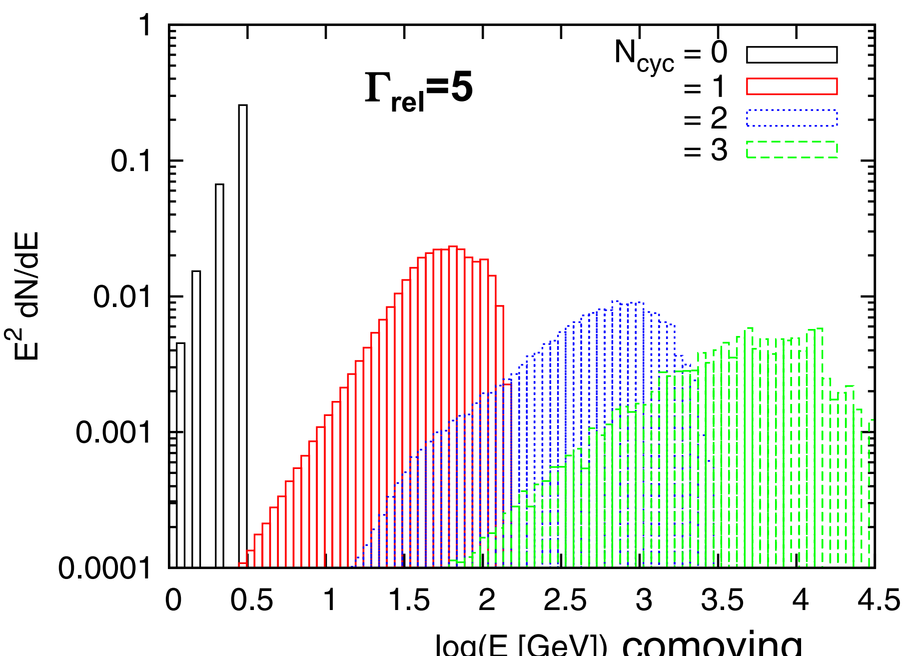
- **naturally injected (neutron mean free path > internal shock length)**
- **guaranteed for n-loaded flows (weak B is enough)**
- **crucial if shock acc. is inefficient ex. radiation-mediated ($\sigma_{np} < \sigma_T$)**
- **slow process → TeV ν**

Kashiyama, KM & Meszaros 13 PRL

NPC Acceleration: Spectra & Effects

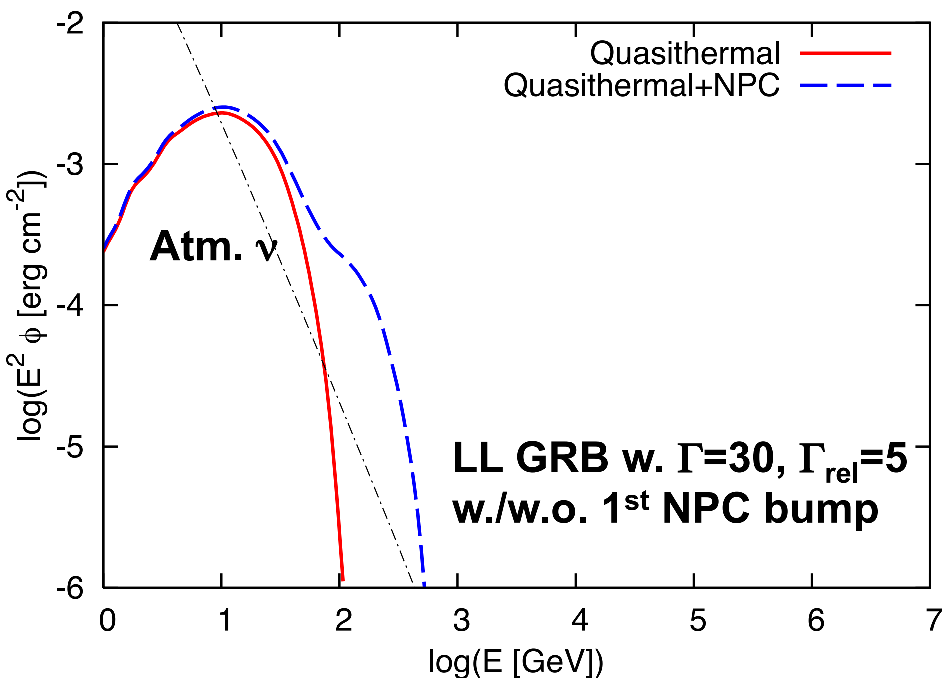
Monte Carlo simulations for test particles

- spectra consisting of bumps rather than a power law
- >10% of incoming neutron energy can be used for NPC acc.
- enhancing the detectability of GeV-TeV neutrinos



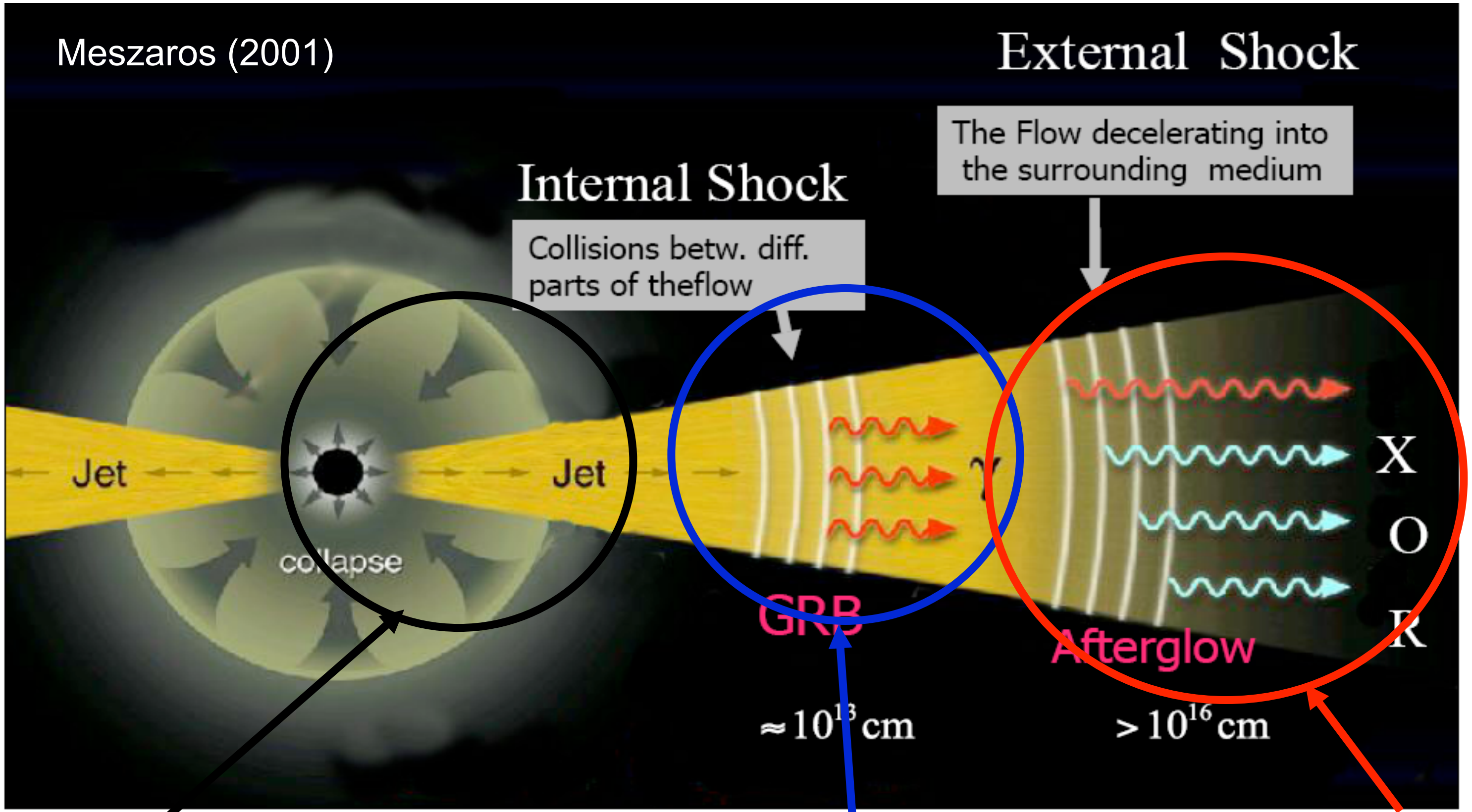
comoving

nucleon spectra w.o. cooling



neutrino spectra

Possible Neutrino Production Sites



Inner jet inside a star
$r < 10^{12}$ cm, $B > 10^6$ G
TeV-PeV ν, no γ

Meszaros & Waxman 01 PRL
Razzaque et al. 03 PRL
KM & Ioka 13 PRL

Inner jet (prompt/flare)
$r \sim 10^{12}$-10^{16} cm $B \sim 10^{2\text{-}6}$ G
PeV ν, GeV-TeV γ

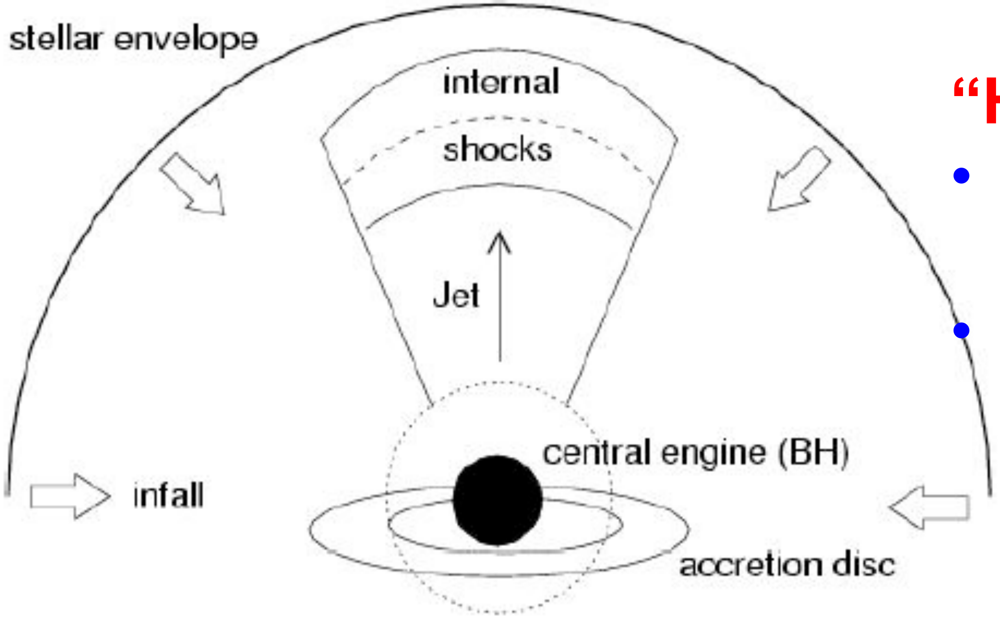
Waxman & Bahcall 97 PRL
Dermer & Atoyan 03 PRL
KM & Nagataki 06 PRL

Afterglow
$r \sim 10^{14}$-10^{17} cm $B \sim 0.1$-100 G
EeV ν, GeV-TeV γ

e.g., Waxman & Bahcall 00 ApJ
Dermer 02 ApJ
KM 07 PRD

TeV-PeV Neutrinos as a Probe of Jets inside Stars

<u>Motivations</u>
- Jet acceleration & composition (radiation or magnetic)
- GRB-SN connection, progenitor: clues to GRBs & jet-driven SNe
- Neutrino mixing including matter effects etc.



Meszaros & Waxman 01 PRL
Razzaque, Meszaros & Waxman 04 PRL
Ando & Beacom 05 PRL

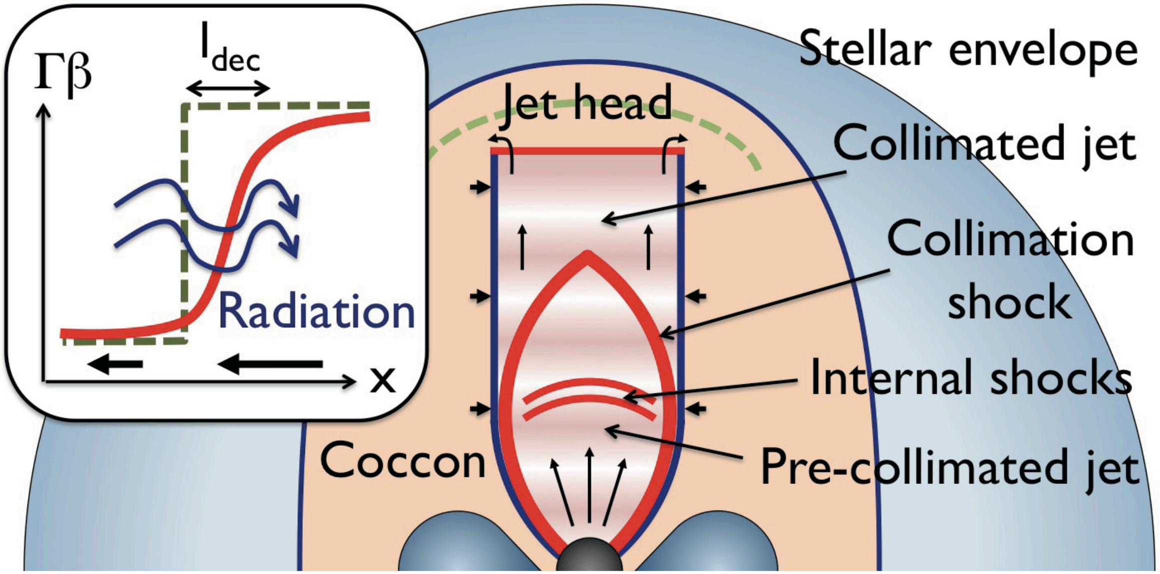
"Hidden" neutrino sources
- **Jets before GRB emission "precursor neutrinos"**
- **Choked jets (failed GRBs) "orphan neutrinos"**

high density → $f_{p\gamma}$ >> 1 "calorimetric"

CRs damped (no UHECRs)

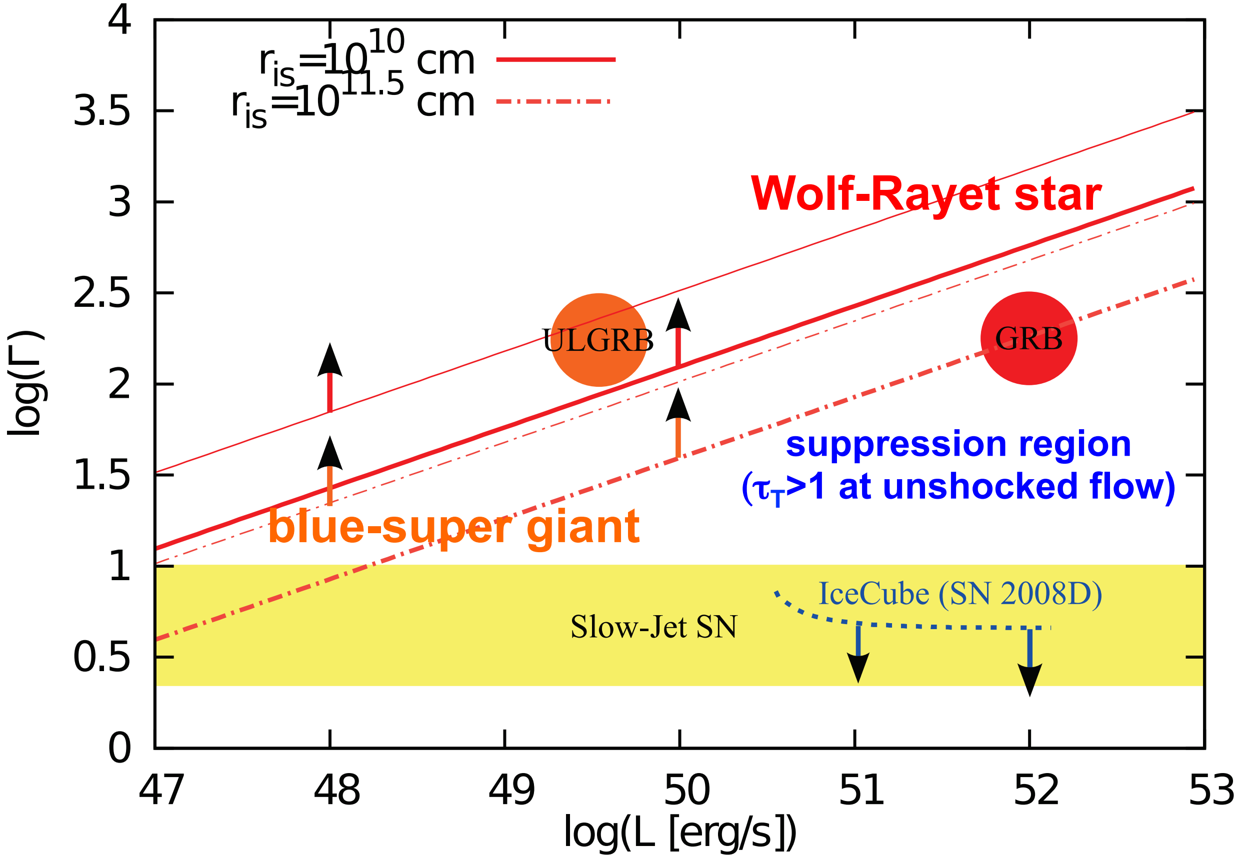
More Realistic Picture

Two pieces of important physics were overlooked



1. Ballistic jets inside stars ❌
   → collimation shock & collimated jet
2. CR acceleration at collisionless shocks ◯❌
   → inefficient when mediated by radiation

“Radiation Constraints” on Non-thermal Neutrino Production



KM & Ioka 13 PRL

UL GRB: ultra-long GRB
$T \sim 10^4$ s >> ~ 30 s
→ blue-super giants?
ex. GRB 111209A
(but see Zhang, Zhang, KM+ 13)

- Lower-power is better
- Bigger progenitor is better

⇨

- **favoring choked jets (difficulty of penetration)**
- **inefficient for HL GRBs**

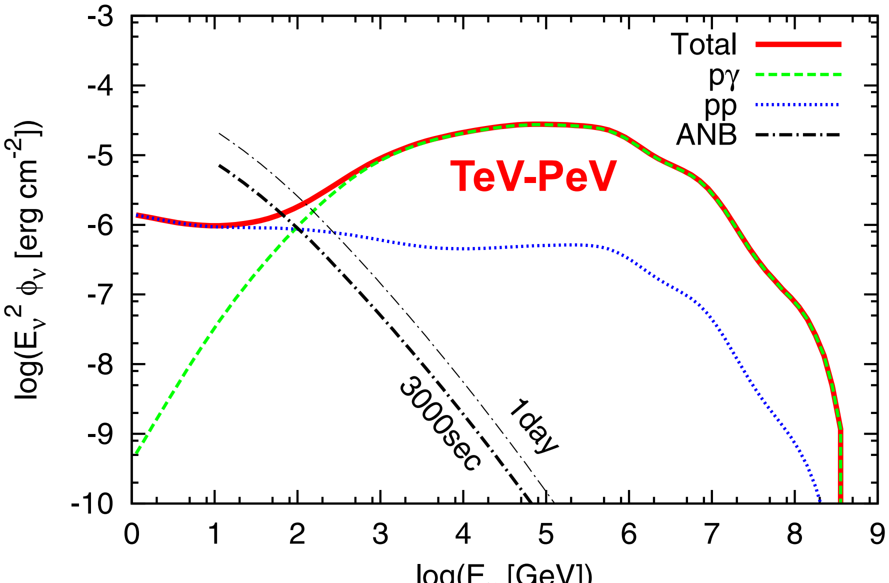
Non-Jet Case: TeV-PeV Neutrinos around Shock Breakout

- Trans-relativistic SNe (w. optically-thick wind)

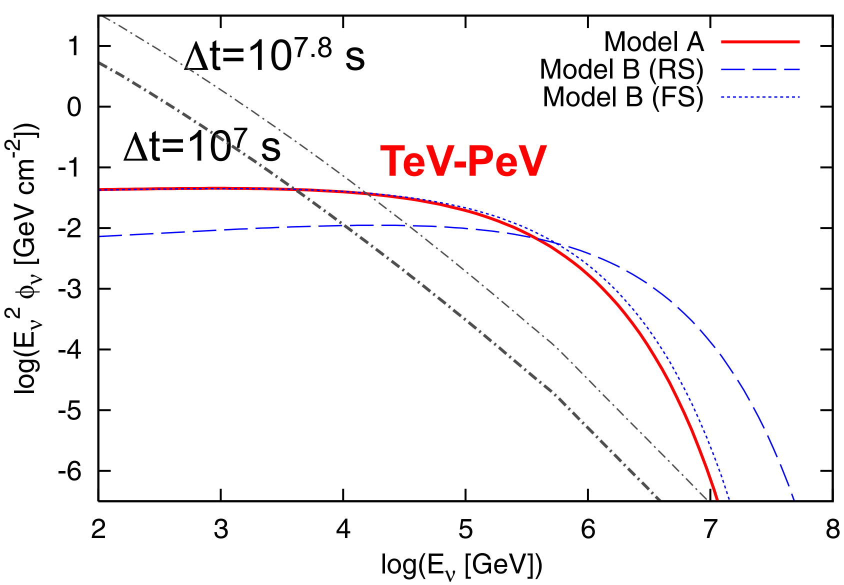
  (ex. Waxman+ 07, Nakar & Sari 12)

- Interaction-powered SNe (w. massive CSM)

  (ex. Smith & McCray 07, Chevalier & Irwin 12)



Kashiyama+ 12



KM+ 11, Katz+ 11

The signal is detectable for nearby SNe at D < 10 Mpc
stacking analyses & gamma-ray obs. are also relevant

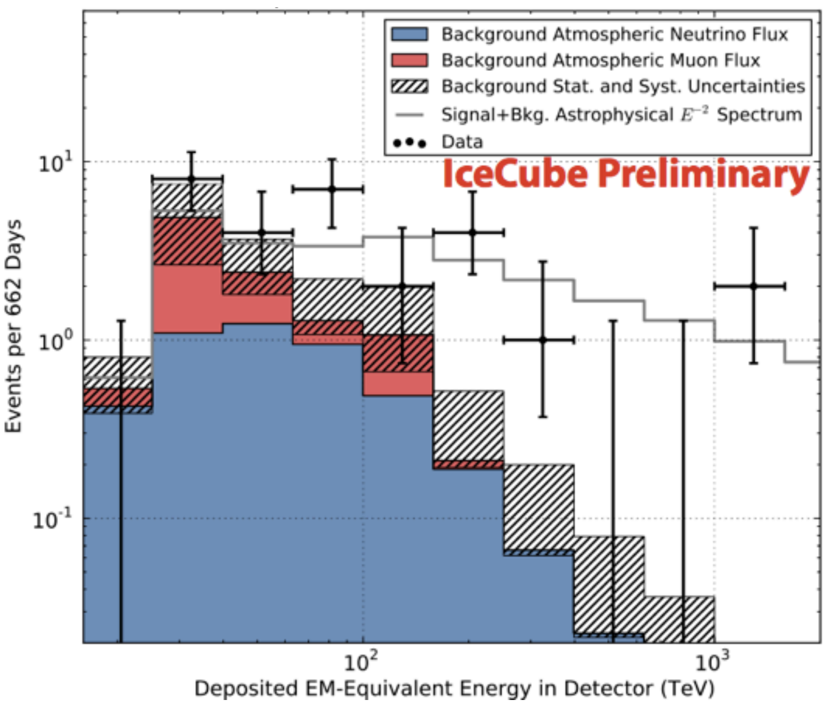
Origin of PeV Neutrinos Observed by IceCube?

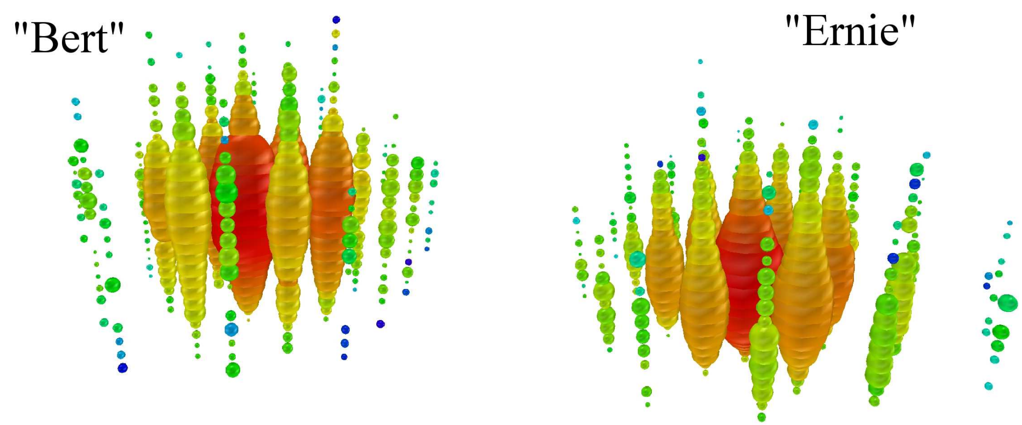
Diffuse Neutrino Flux: Now Observed

2 events with PeV energies are found in UHE neutrino search
26 more events are identified by a later analysis

$E^2 \Phi_\nu \sim 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1} per flavor
w. break/cutoff at ~2 PeV (for $\Gamma \sim 2$)

IceCube collaboration 13 PRL, Whitehorn 13 IPA
※also supported by Laha+ KM 13 PRD





consistent w. isotropic dist.

Can GRBs Explain IceCube Events?

Unknown origin (diffuse flux mostly comes from distant sources)
pp: star-forming galaxies, galaxy clusters (KM, Ahlers & Lacki 13 PRDR)

Q. Can pγ scenarios such as GRBs and AGN be the origin?

A. Yes (at present), but difficult for high-luminosity (HL) GRBs
∵ IceCube stacking for GRBs: <~ 10^{-9} GeV cm^{-2} s^{-1} sr^{-1}

(ex. IceCube collaboration 12 Nature, Liu & Wang 13 ApJ)

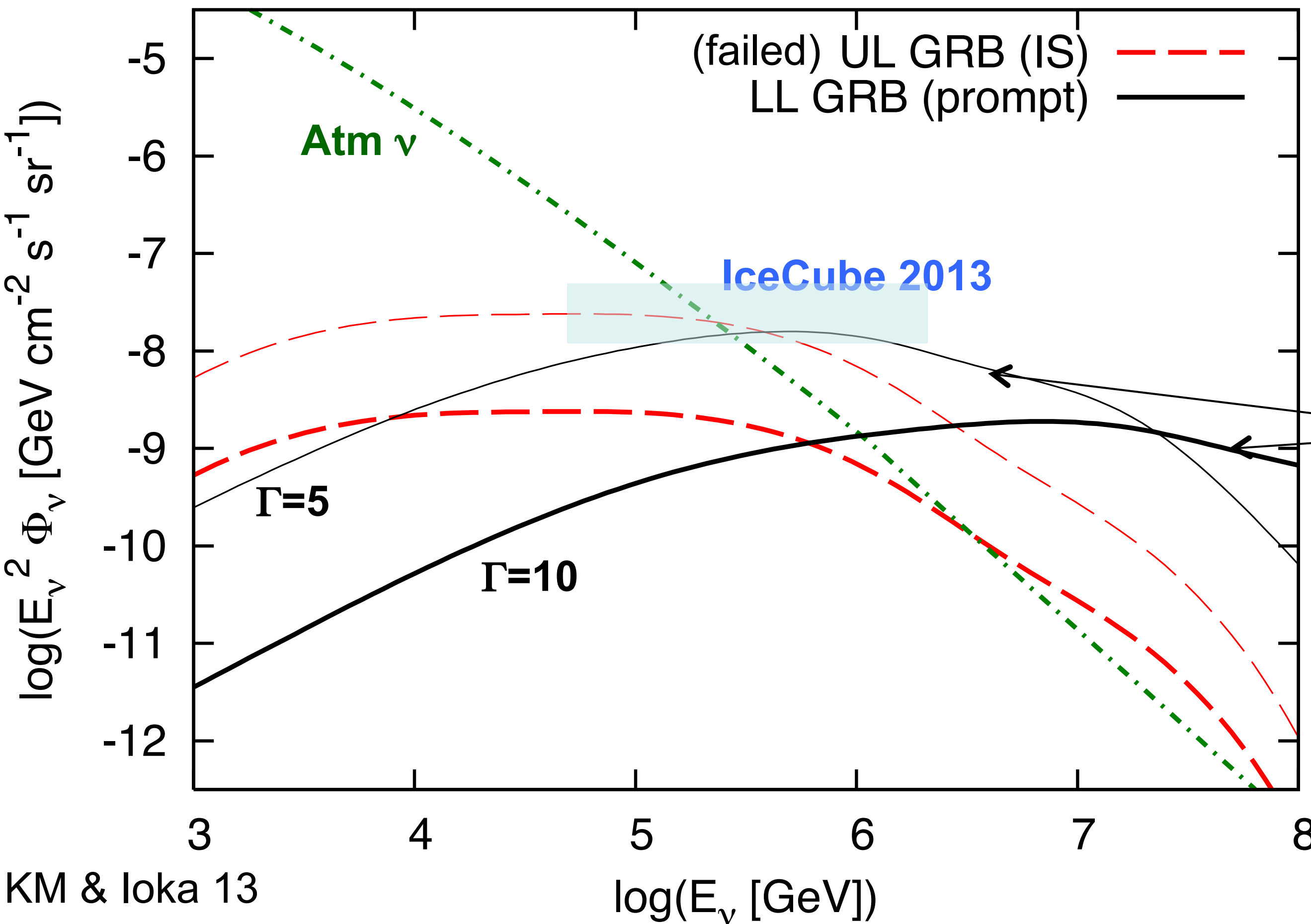
But we may miss a lot of untriggered, dimmer or failed GRBs

- Low-luminosity GRBs (or trans-relativistic SNe)
  E_γ^{iso}~10^{50} erg , ρ~10^2-10^3 Gpc^{-3} yr^{-1}
- Ultra-long GRBs
  E_γ^{iso}~10^{53} erg, ρ~1 Gpc^{-3} yr^{-1}??

※ Emission mechanisms may be different

Possible Contributions to Diffuse TeV-PeV Neutrino Flux

Low-power jets could explain IceCube events at PeV energies without violating IceCube limits from GRB stacking



KM & Ioka 13

predictions by KM+ 06 ApJL

see also Gupta & Zhang 07 APh

large uncertainty but interesting

Now HE Neutrinos as a Powerful Messenger

GRB as the UHECR origin? → allowed at present but…

- Optimistic cases were killed (ex. UHEn-escape scenario)
- Most parameter space will be covered in ~10 yr if UHEp
- But hard to exclude UHE heavy-nuclei scenario
- Afterglow scenario might be possible (→ Askaryan Radio Array)

HE neutrinos from subphotospheres? → more promising

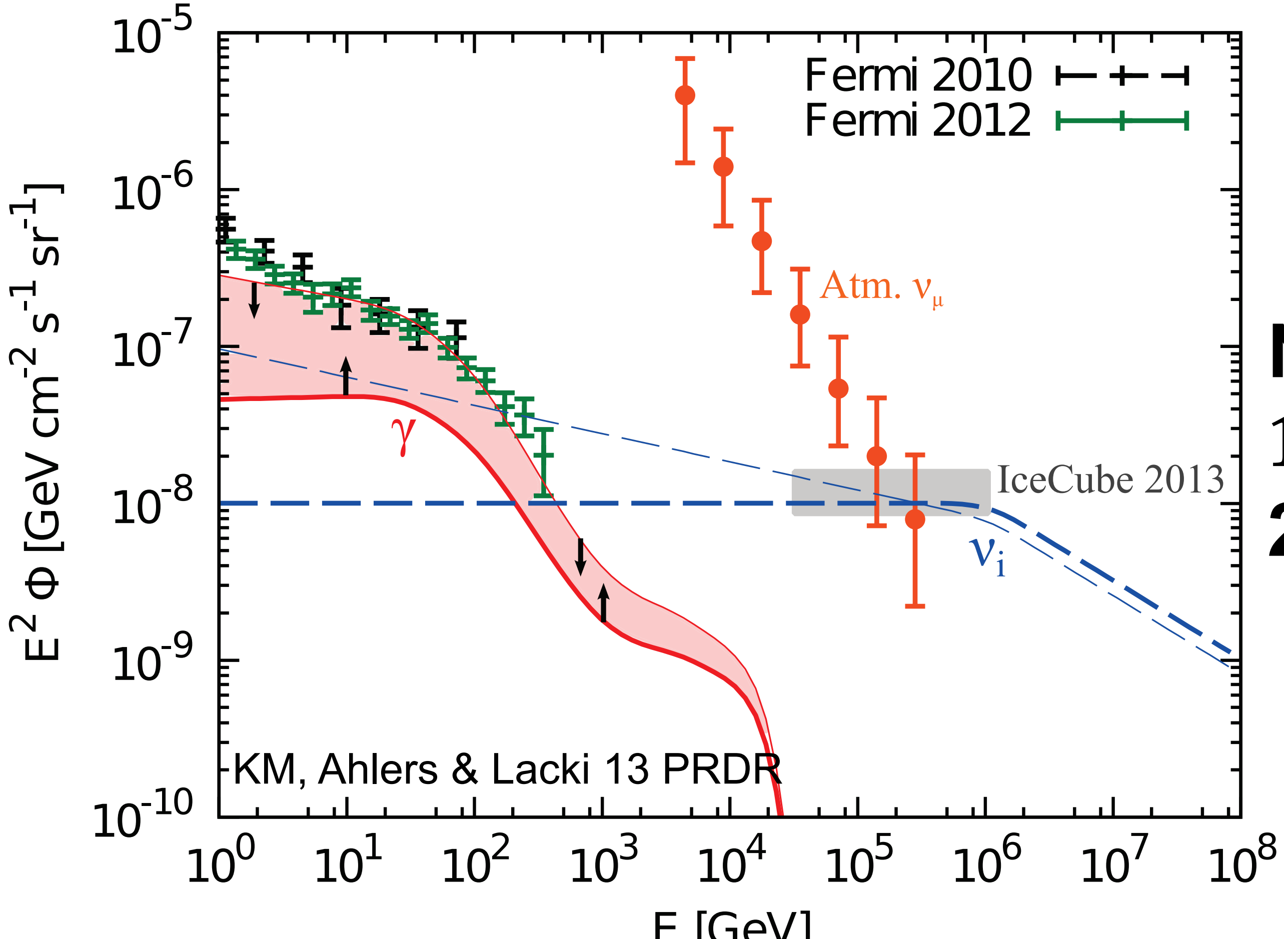
- GeV-TeV neutrinos from neutrons (→ DeepCore, PINGU etc.)
- Detectable in ~ 10 yr if dissipation comes from neutrons
- NPC acc. can enhance detectability of TeV neutrinos
- TeV-PeV neutrinos expected for choked low-power jets and peculiar SNe

Origin of sub-PeV neutrinos in IceCube? → possible

- Low-power jet populations (ex. LL GRBs) might contribute
- Need further studies on such longer-duration transients

Other Possibilities: pp Sceanrios?

pp: intergalactic shocks, star-forming galaxies etc.- viable



New constraints

1. $\Gamma < 2.2$

2. >30% to DGB

First strong example of $\nu-\gamma$ connection with *"measured"* ν & γ fluxes

Implications

Question: pp or pγ?

We can test pp scenarios

- Γ can be determined in several years
  If $\Gamma > 2.2 \rightarrow$ pp scenarios are disfavored
- Understanding DGB is important
  40%-100% from blazars $\rightarrow \Gamma \sim 2.0$-2.1 or disfavored
- Individual sources should show γ-ray spectra ($\rightarrow$ CTA)

※pγ scenarios are unbounded due to threshold effect
more studies are needed but quite model-dependent

Non-thermal vs Quasi-thermal

- TeV-PeV non-thermal neutrinos
  produced typically via pγ interactions between CRs and photons
  $E_\nu \sim 0.01\ \Gamma^2\ (\mathrm{GeV}/\varepsilon_\gamma)$ GeV → TeV-PeV ν
  - E_p^{-2} is assumed but may not be true
  - inefficient at radiation-mediated shocks
  - complicated spectra due to meson/muon cooling

But diffusive shock acceleration is not always required

- GeV-TeV quasi-thermal neutrinos
  produced via pn inelastic collisions with thermal "neutrons"
  $E_\nu \sim 0.1\ \Gamma\ \Gamma_{rel}\ m_p\ c^2$ → ~30-300 GeV ν
  - relativistic nucleons via thermalization of neutrons
  - neutrons are naturally loaded from GRB engine
  - universal spectra due to irrelevance of meson/muon cooling