Revealing the Deaths of Massive Stars with High-Energy Neutrinos

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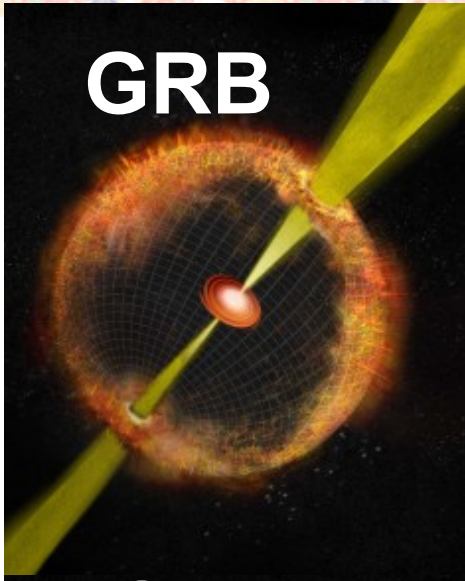
TAUP 2013 Asilomar

Outline

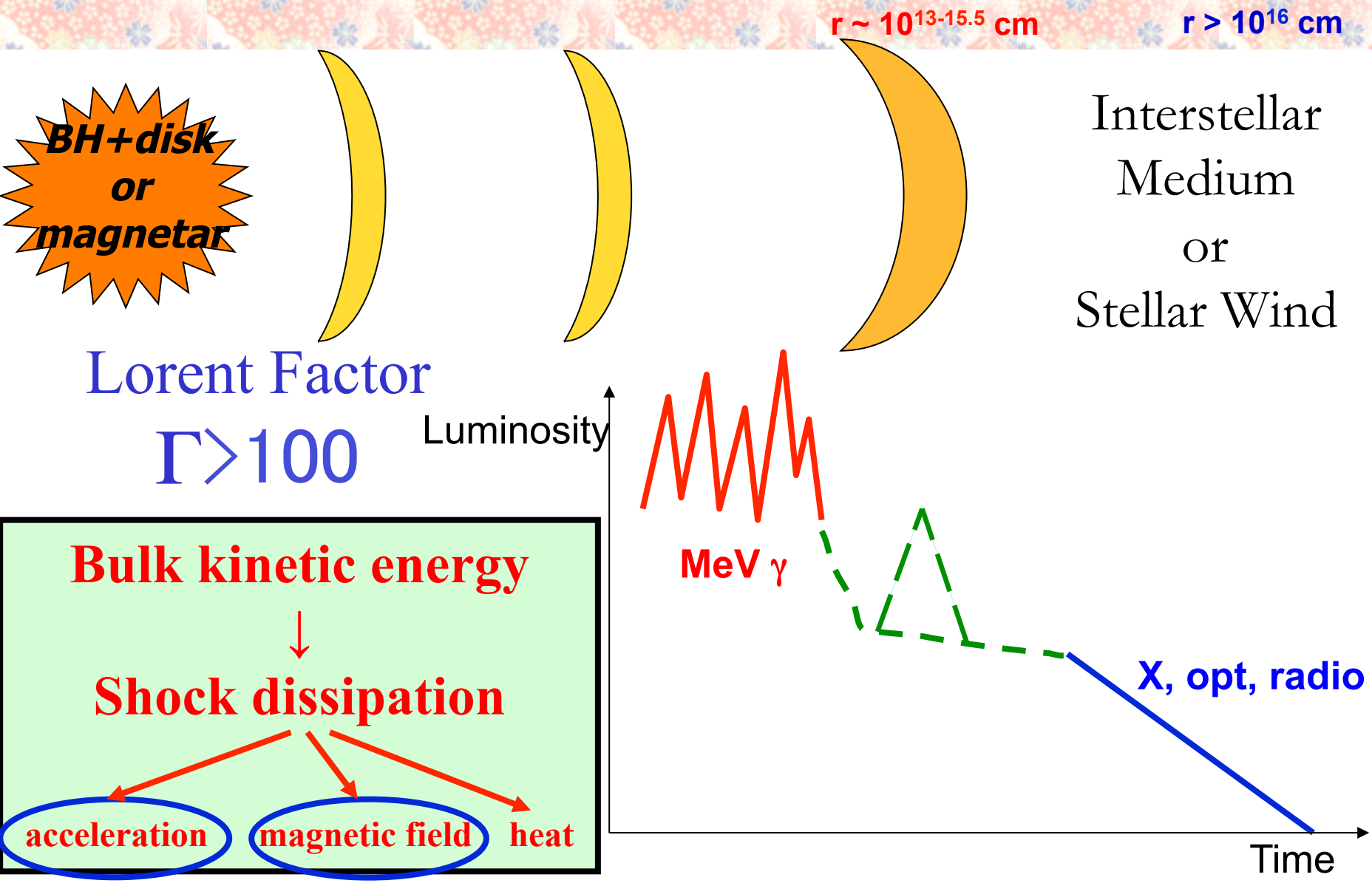
GRBs & SNe = violent cosmic explosions
at the deaths of massive stars

HE neutrinos can potentially tell us…
+ Jet dynamics, composition
+ GRB-SN relationship
+ Possible connection w. CRs
+ CR acceleration mechanisms

1. TeV-PeV non-thermal neutrinos
2. GeV-TeV neutrinos from “neutrons”



Gamma-Ray Bursts: "Classical" Pictures

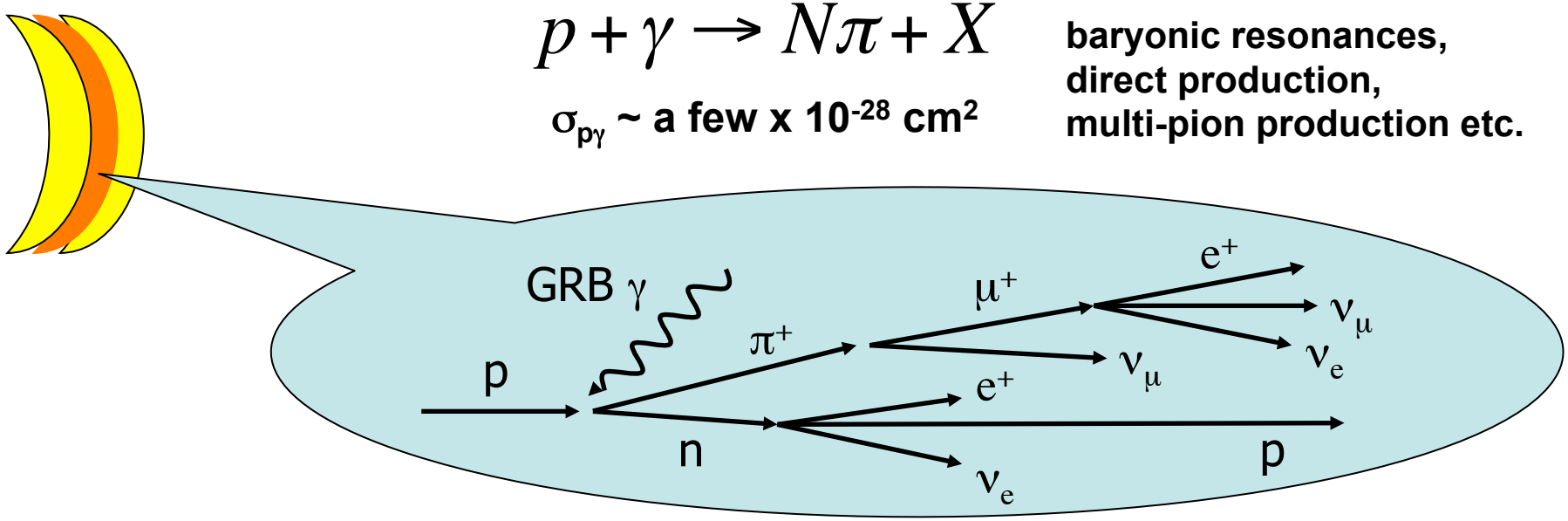


Neutrino Production in the Source

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

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

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



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

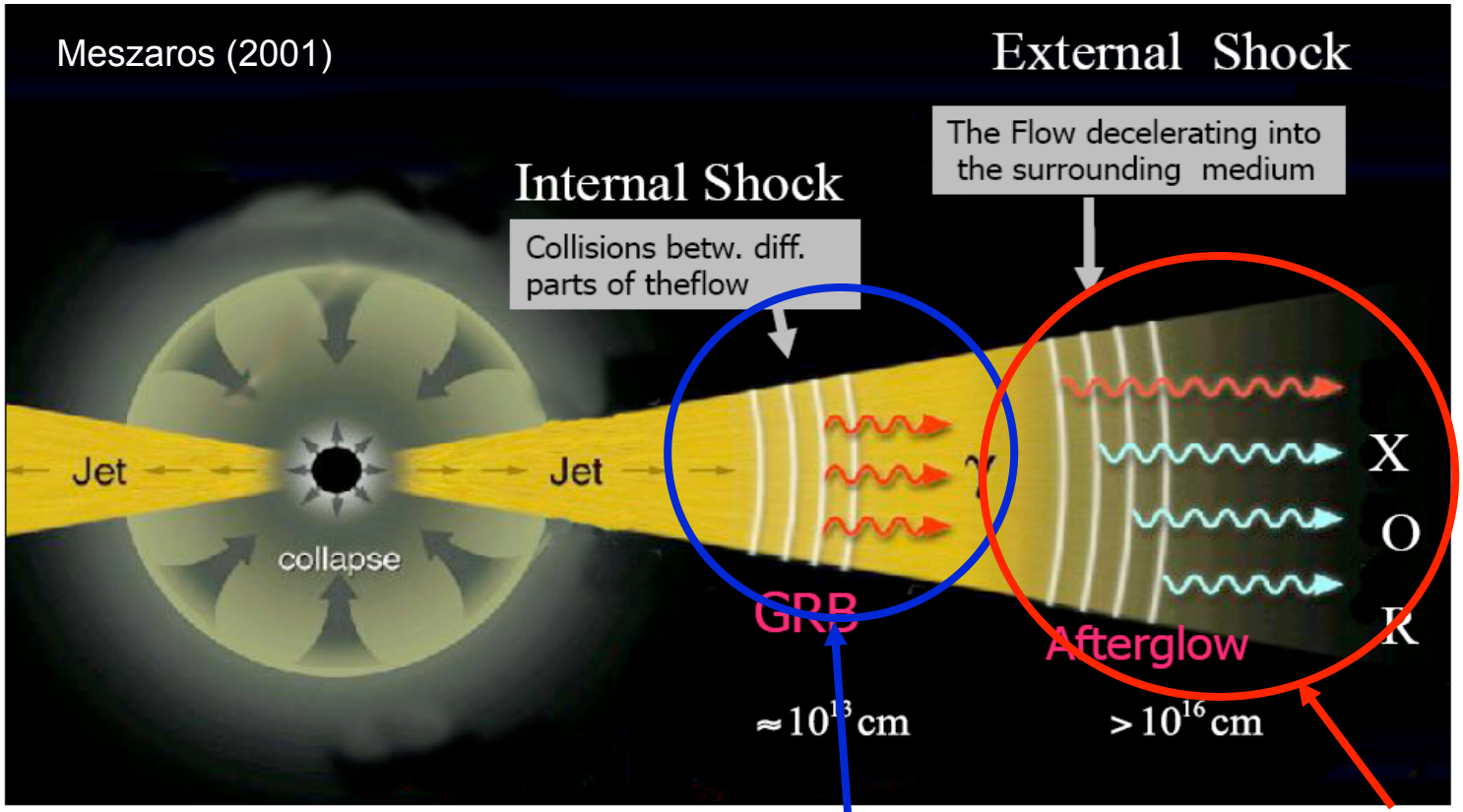
ε_ν^b ~ $0.05\varepsilon_p^b$ ~ 0.01 GeV^2 $\Gamma^2/\varepsilon_{\gamma,pk}$ ~ 1 PeV (if $\varepsilon_{\gamma,pk}$ ~ 1 MeV)

Meson production efficiency (large astrophysical uncertainty)

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

parameters for $f_{p\gamma}$ (L_γ, photon spectrum, Γ, r (or δt)) + CR normalization

Possible Neutrino Production Sites



Inner jet (prompt emission)

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

PeV ν, GeV-TeV γ

Waxman & Bahcall 97 PRL
Dermer & Atoyan 03 PRL

Afterglow

$r \sim 10^{14}$-10^{17} cm $B \sim 0.1$-100 G

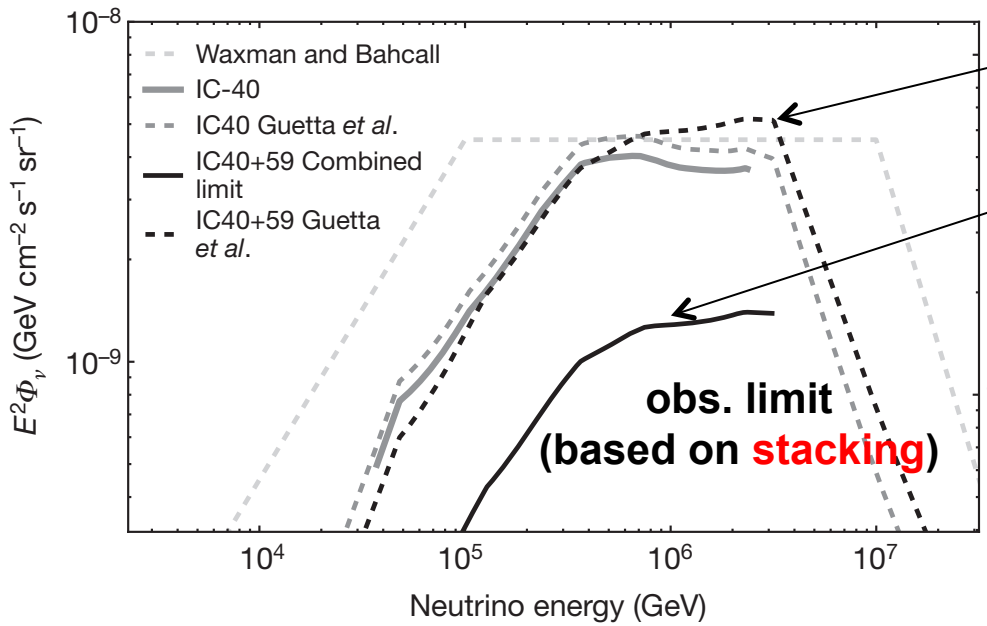
EeV ν, GeV-TeV γ

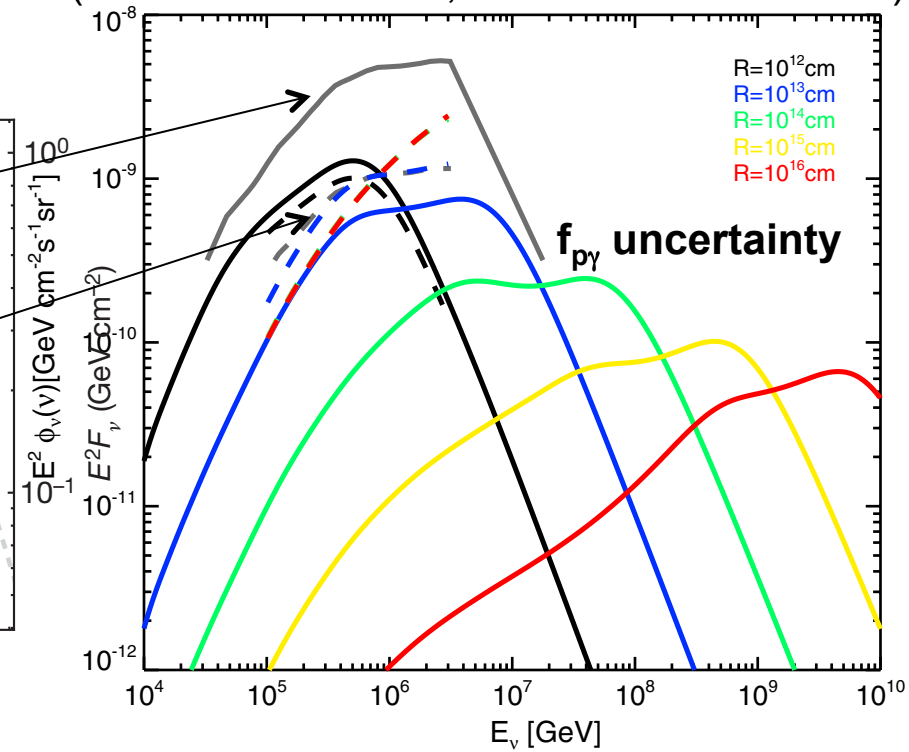
e.g., Waxman & Bahcall 00 ApJ
Dermer 02 ApJ
KM 07 PRD

IceCube Limits on Prompt GRB Neutrinos

He, Liu, Wang, Nagataki, KM & Dai 12 ApJ
(see also Li 11 PRD, Hummer et al. 12 PRL)

IceCube collaboration 12 Nature



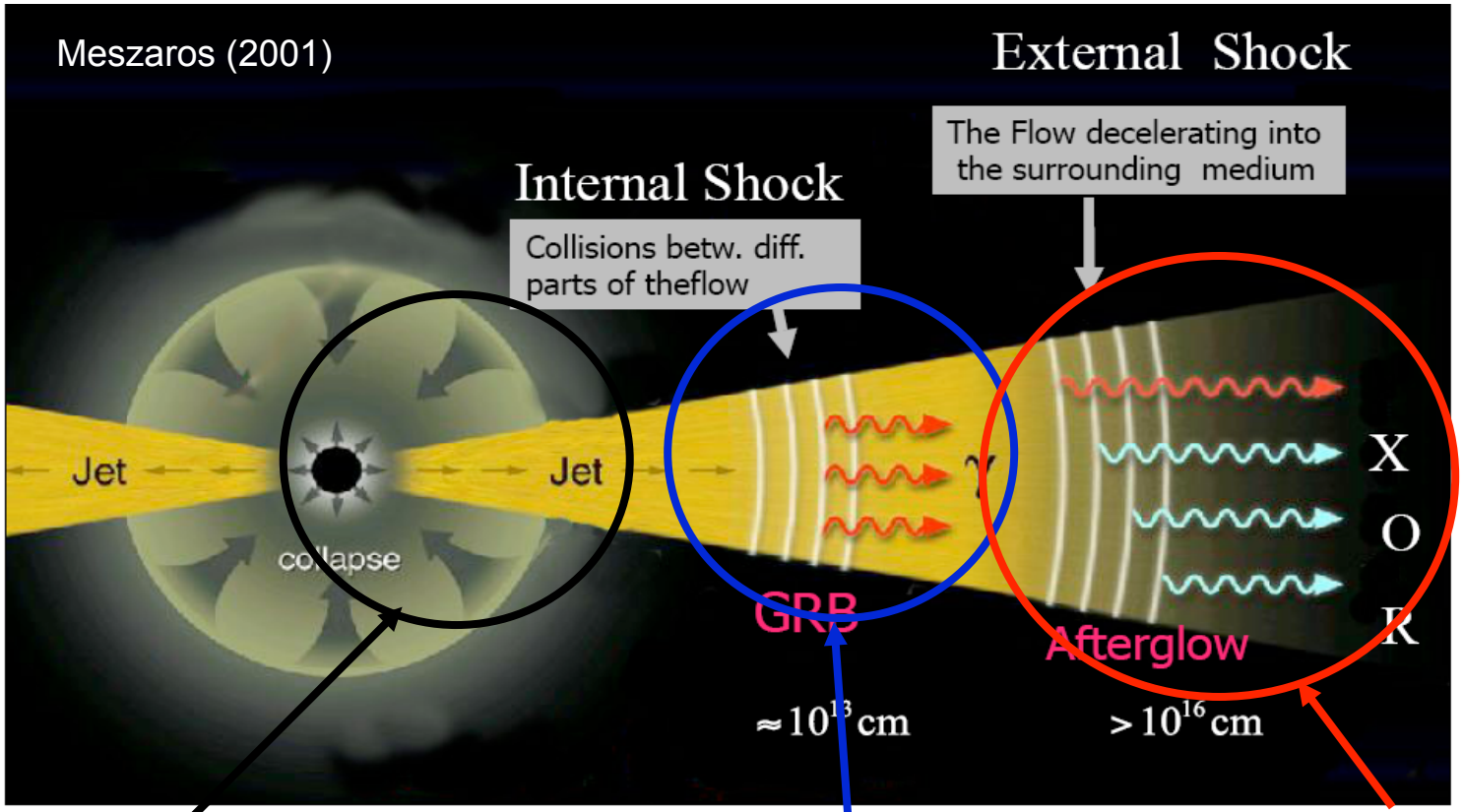


+ ~10 yr observations can cover relevant parameter space in the classical scenario w. GRB-UHEp hypothesis

※ unconstrained cases shown by earlier detailed calculations (ex. KM & Nagataki 06 PRD)

+ Difficult to explain IceCube events at PeV energies

Possible Neutrino Production Sites



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

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

Waxman & Bahcall 97 PRL
Dermer & Atoyan 03 PRL

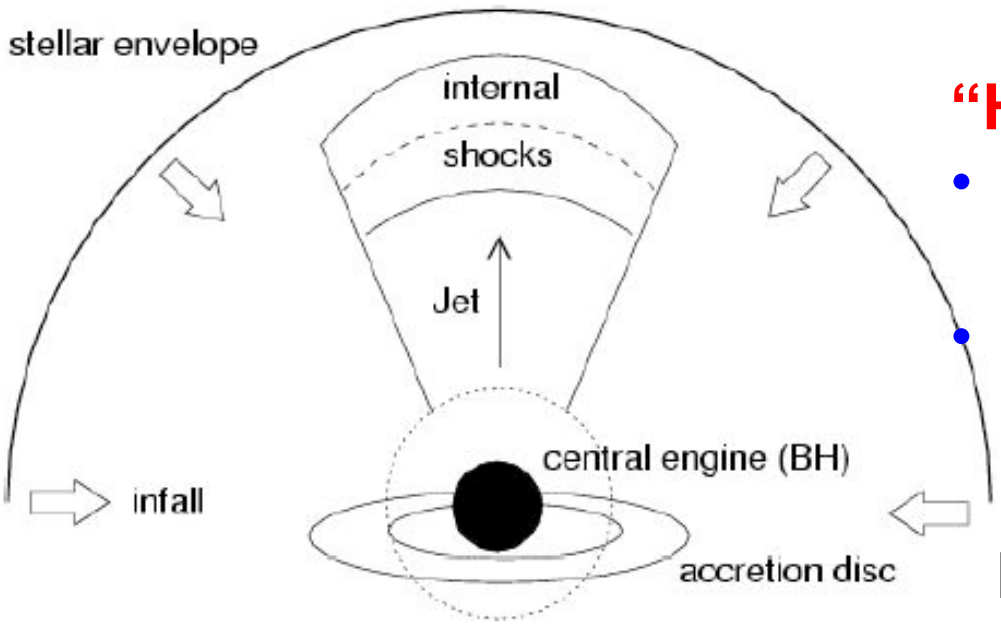
Afterglow
$r \sim 10^{14}$-10^{17} cm $B \sim 0.1$-100 G
EeV ν, GeV-TeV γ

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

Neutrinos as a Probe of Jets inside Stars

Motivations

+ Jet acceleration & composition (radiation or magnetic)
+ GRB-SN connection, progenitors: clues to GRB engine
+ Neutrino mixing including matter effects etc.



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

"Hidden" neutrino sources

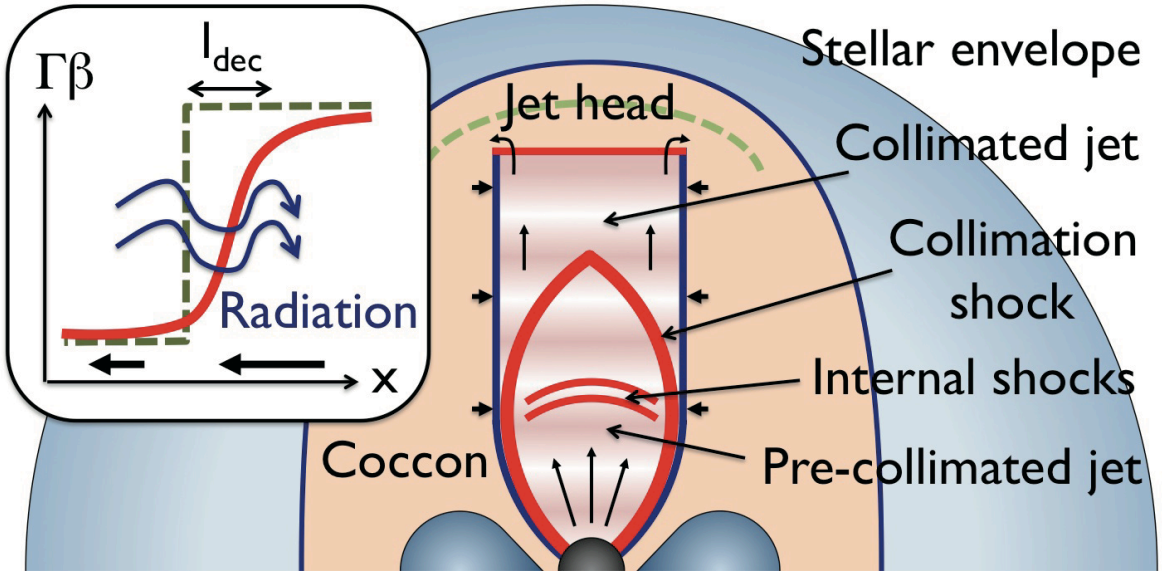
- **Jets before GRB emission "precursor neutrinos"**
- **Choked jets (failed GRBs) "orphan neutrinos"**

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

CRs damped (no UHECRs)

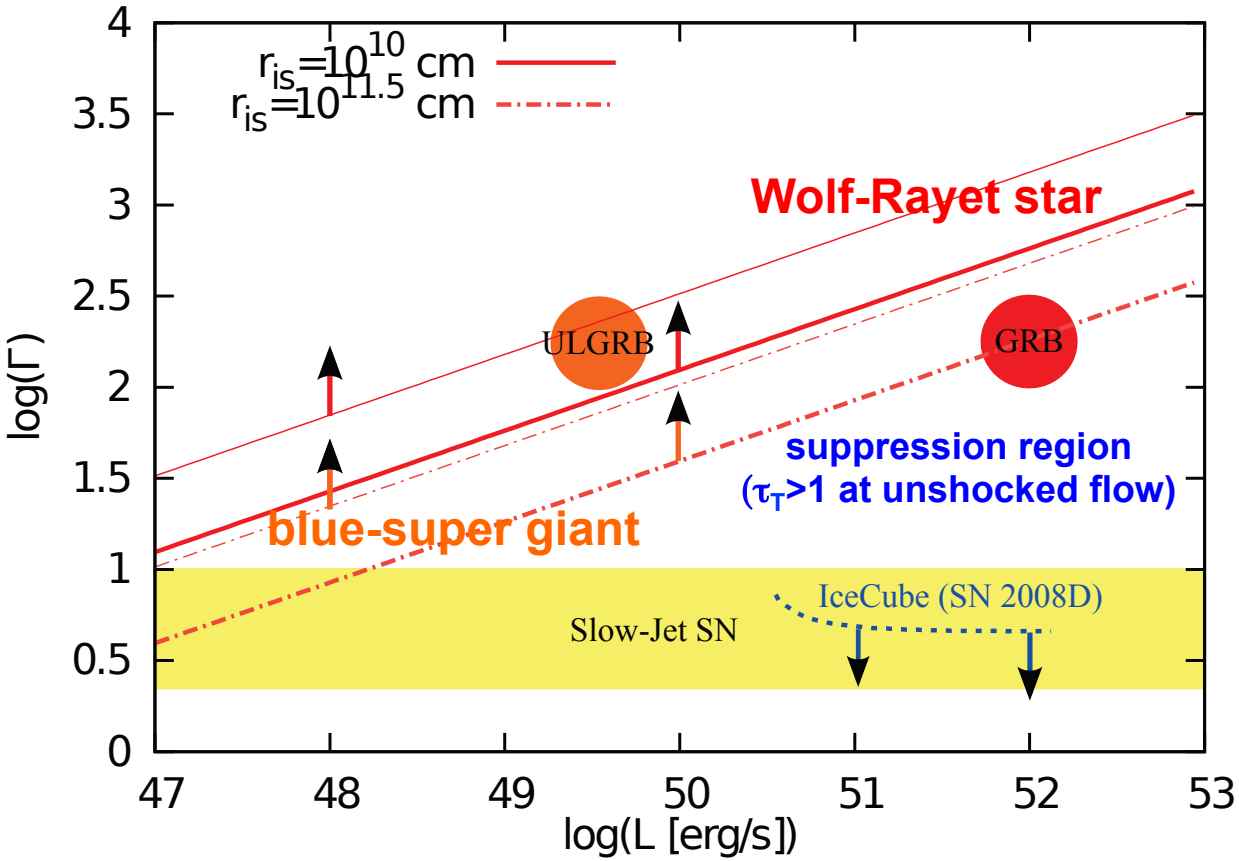
More Realistic Picture

Two pieces of important physics were overlooked



1. Ballistic jets inside stars X
   → 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 >> $T_{GRB} \sim 30$ s
→ blue-super giants?
ex. GRB 111209A

- Lower-power is better
- Bigger progenitor is better

→ favoring choked jets (difficulty of penetration)

Low-Power/Bigger Progenitor GRB Classes?

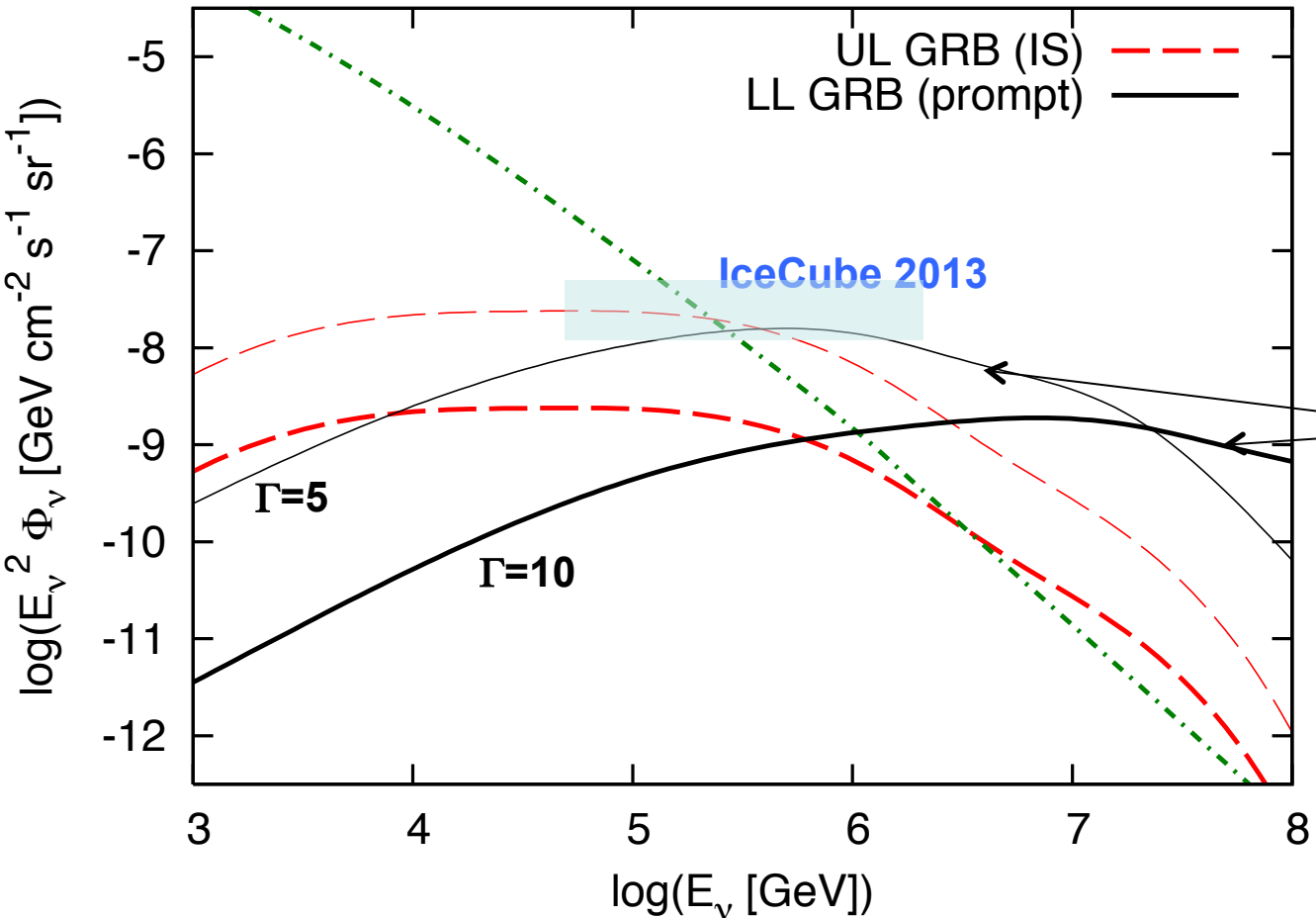
In fact, there seem distinct classes of lower-power GRBs that are largely missed by current GRB satellites like Swift and Fermi

- Low-luminosity GRBs (or trans-relativistic SNe)
  $E_\gamma^{iso} \sim 10^{50}$ erg, $\rho \sim 10^2$-10^3 ρ_{GRB} (Soderberg+ 06 Nature, Liang+ 07 ApJ)
  - intermediate nature between GRBs and SNe
  - marginally successful jets (Toma+ 07 ApJ, Bromberg+ 11 ApJ)
- Ultra-long GRBs
  $E_\gamma^{iso} \sim 10^{53}$ erg, $\rho \sim \rho_{GRB}$? (Levan+ 13)
  - ultra-long → bigger progenitors (ex. blue-super giants)
  - marginally successful jets (KM & Ioka 13 PRL)

- Clues to unveiling GRB-SN connection, progenitors etc.
- Needs for better GRB satellites and/or surveys of SNe

Possible Contributions to TeV-PeV Neutrino Background

Low-power jets could explain IceCube events at PeV energies without violating IceCube limits on GRB neutrinos



predictions by KM+ 06 ApJL

large uncertainty but interesting

Non-thermal vs Quasi-thermal

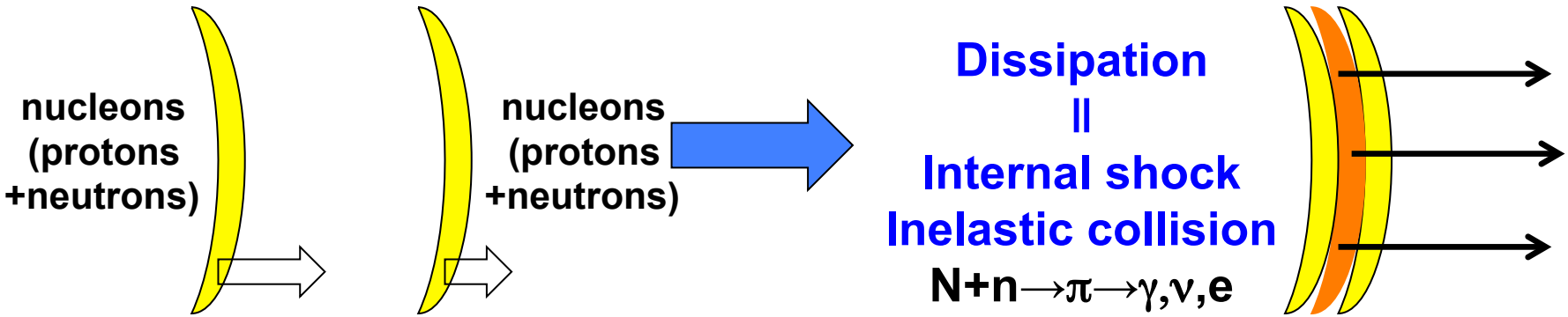
- <u>TeV-PeV non-thermal neutrinos</u>
  produced typically via $p\gamma$ interactions between CRs and photons
  $E_\nu \sim 0.01\ \Gamma^2\ (\mathrm{GeV}/\varepsilon_\gamma)$ GeV $\rightarrow$ TeV-PeV ν
  - E_p^{-2} is assumed but may not be true
  - inefficient at radiation-mediated shocks
  - complicated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

But diffusive shock acceleration is not always required

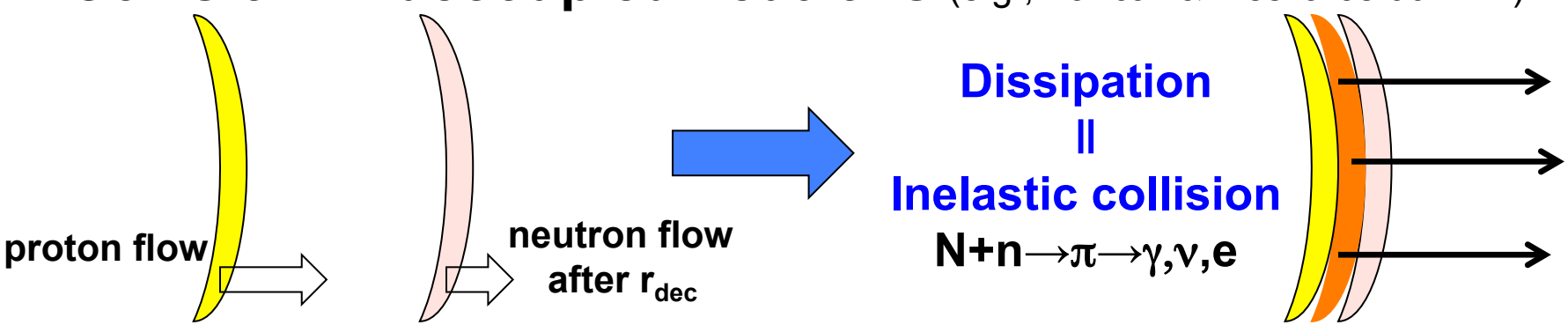
- <u>GeV-TeV quasi-thermal neutrinos</u>
  produced via pn inelastic collisions with thermal "neutrons"
  $E_\nu \sim 0.1\ \Gamma\ \Gamma_{rel}\ m_p\ c^2 \rightarrow$ ~30-300 GeV ν
  - relativistic nucleons via thermalization of neutrons
  - neutrons are naturally loaded from GRB engine
  - universal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

Subphotospheric ($\tau_T > 1$) Inelastic Collision Model

Collision w. compound flow (e.g., Meszaros & Rees 00 ApJ)



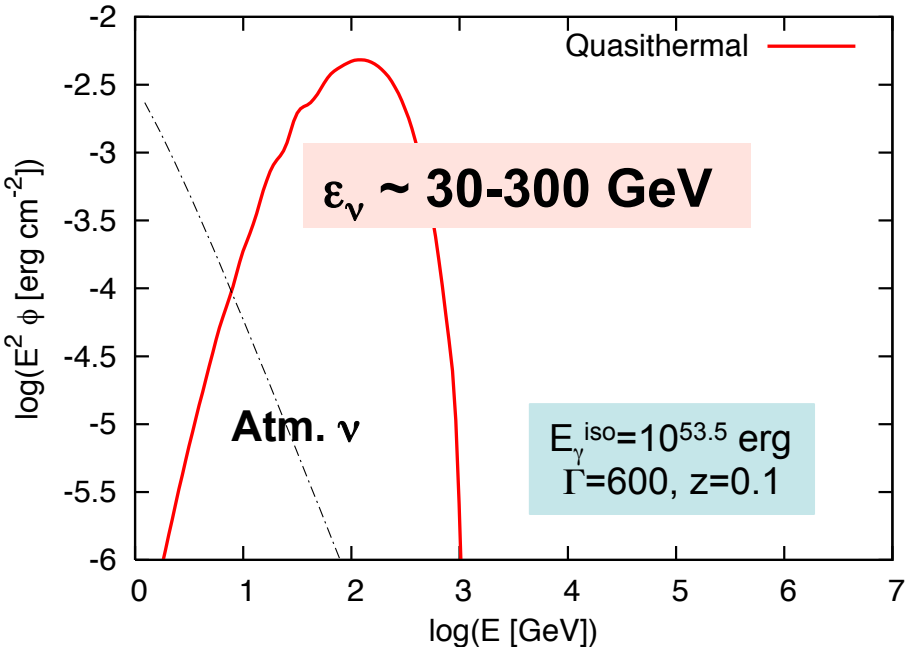
Collision w. decoupled neutrons (e.g., Bahcall & Meszaros 00 PRL)



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

(e.g., Beloborodov 10 ApJ, Vurm+ 11 ApJ)

Quasi-thermal Neutrinos are Detectable

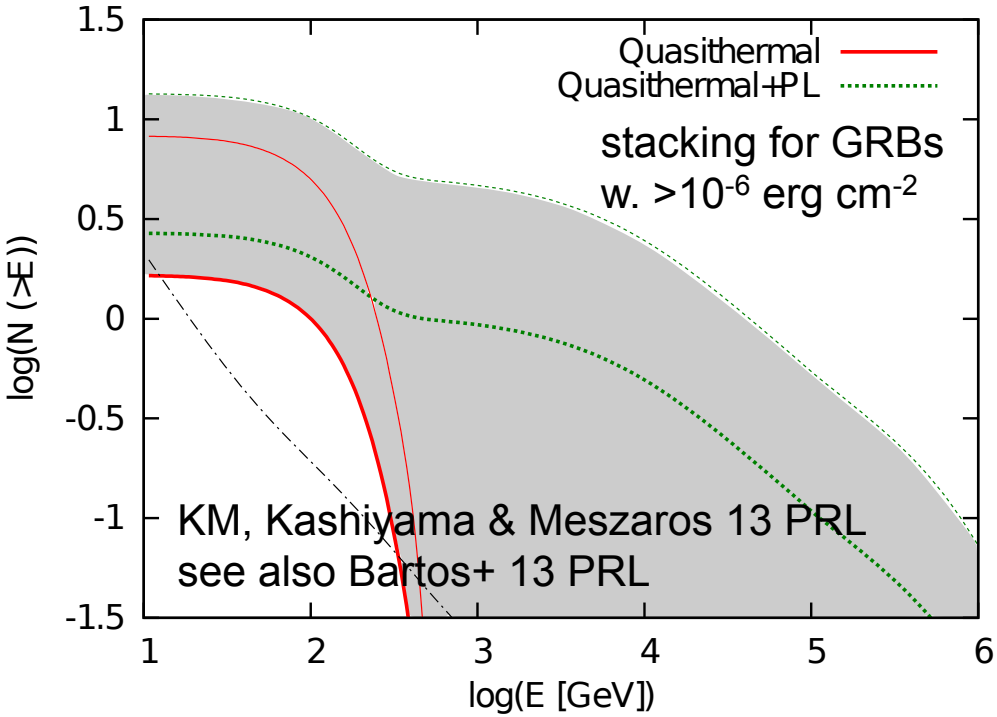


Inevitable ν emission

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

if neutrons are responsible for GRB prompt emission

"testable model"

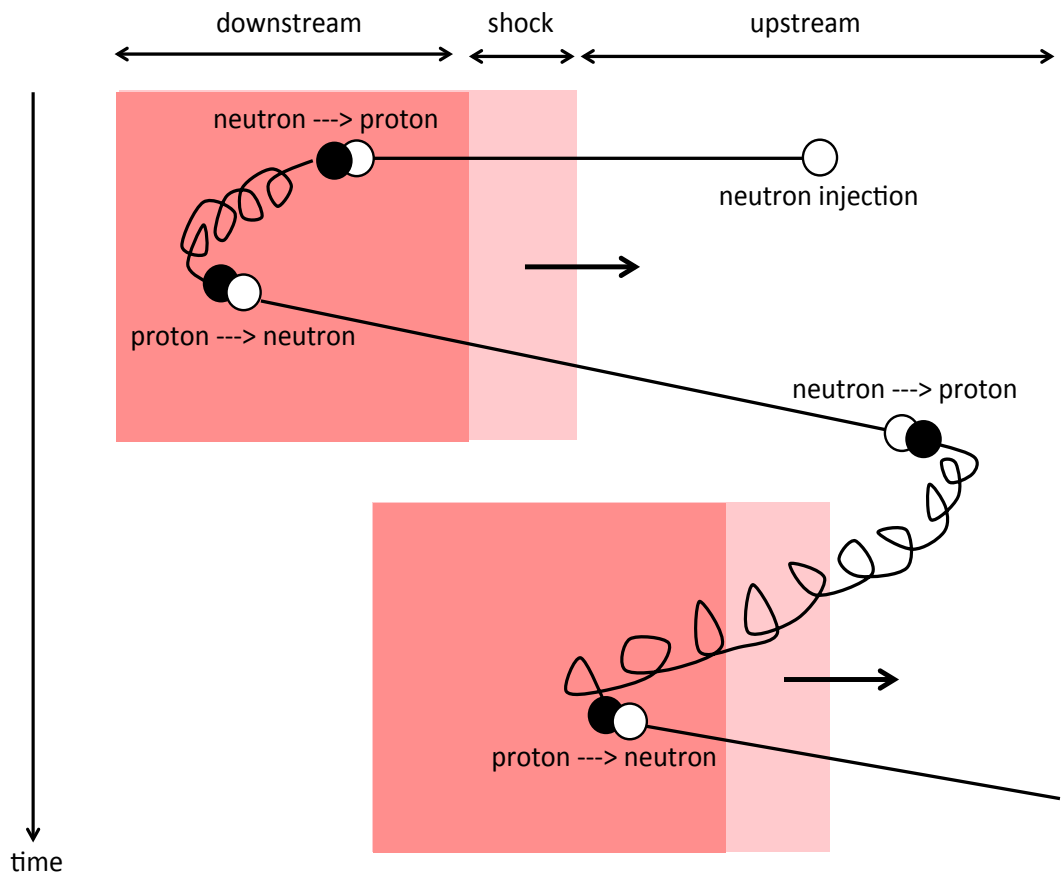


- DeepCore is crucial in the 10-100 GeV range
- Stacking ~1000-2000 GRBs (~10 yr w. current satellites)

Novel Acceleration Mechanism in Neutron-Loaded Flows

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

another Fermi acceleration mechanism without diffusion



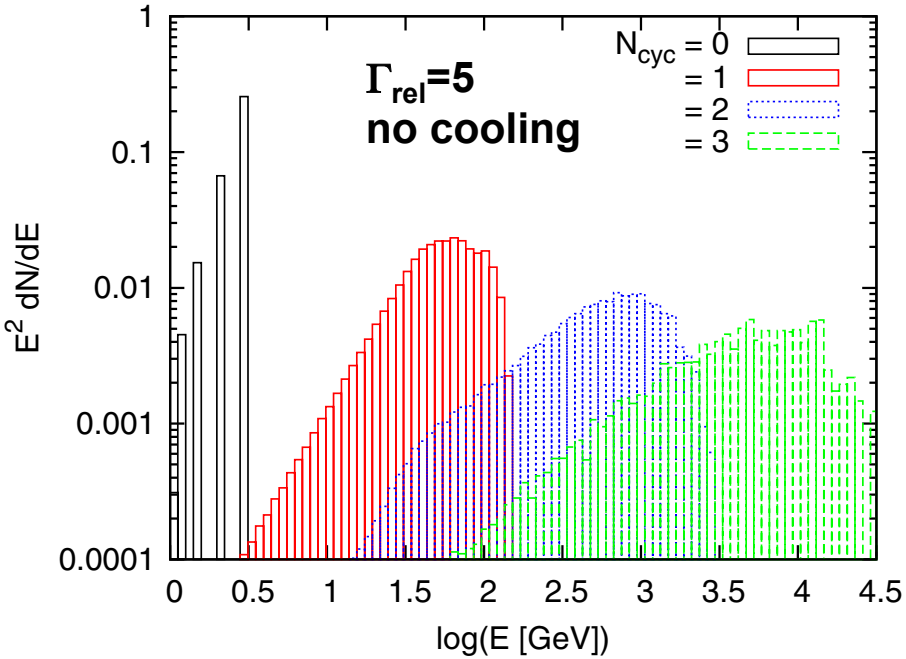
Points

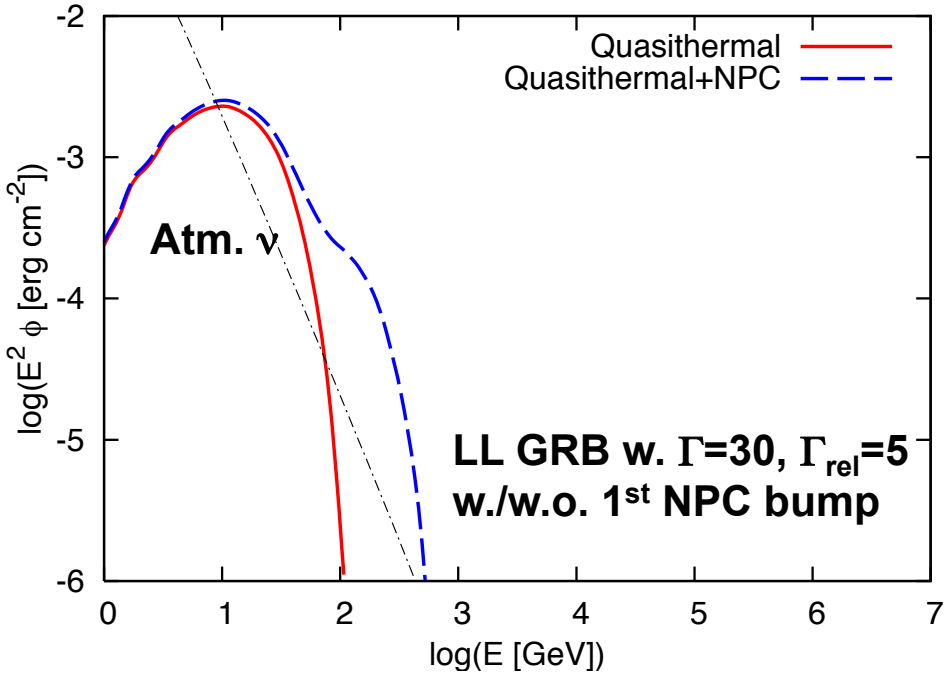
- **naturally injected (neutron mean free path > internal shock length)**
- **guaranteed for n-loaded flows (B is needed for isotropization)**
- **crucial if radiation-mediated ($\sigma_{np} < \sigma_T$)**
- **slow process → TeV ν**

Kashiyama, KM & Meszaros 13 PRL in press

NPC Acceleration: Spectra & Effects

+ First demonstration by Monte Carlo simulations
+ Spectra consisting of bumps rather than a power law
+ >10% of injected neutron energy can be used for acceleration
+ Enhancing the detectability of GeV-TeV neutrinos





Summary

TeV-PeV non-thermal neutrinos

Prompt ν

+ If UHEp origin, relevant parameters can be covered in ~10 yr

Precursor/orphan ν

+ General radiation constraints: low-power GRBs are favored

+ Detecting TeV ν signal may support big progenitors

Low-power GRBs can contribute to PeV ν bkg. seen by IceCube

GeV-TeV neutrinos from "neutrons"

Inevitable quasi-thermal ν/γ emission (without CR acceleration)

Detectable in ~10 yr if neutrons are responsible for GRB emission

NPC acceleration can enhance detectability

Needs: better surveys for GRB-SNe & searches for GeV-TeV ν

Backup Slides

Prompt Emission

Ultra-High-Energy Cosmic Rays?

Fermi shock acceleration (in "classical" pictures)
-> not only electrons but protons are accelerated

$\varepsilon_p < erB \sim 3\times10^{20}\ \mathrm{eV}\ r_{14}B_4$ (Waxman 1995, Vietri 1995)

If UHECR energy output ~ GRB radiation energy

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

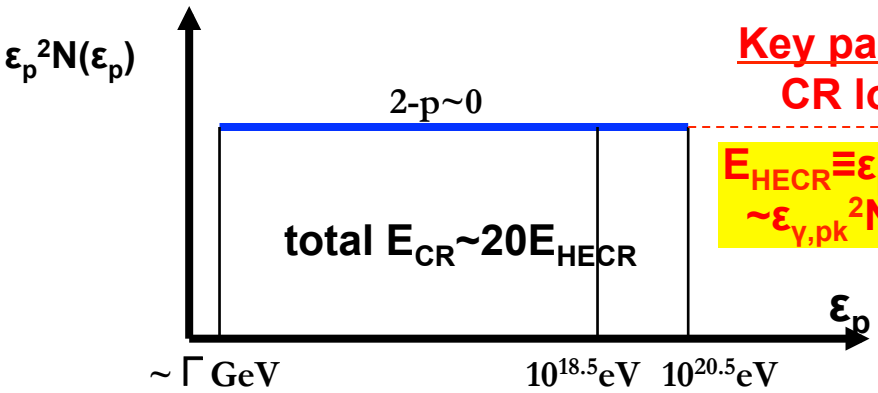
with local GRB rate density: $\sim 1\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$

(e.g., Wanderman & Piran 2010, Dermer 12)

UHECR budget (from obs.): $Q_{HECR} \sim 10^{44}\ \mathrm{erg/Mpc^3/yr}$

Basics of ν and γ-ray Emission

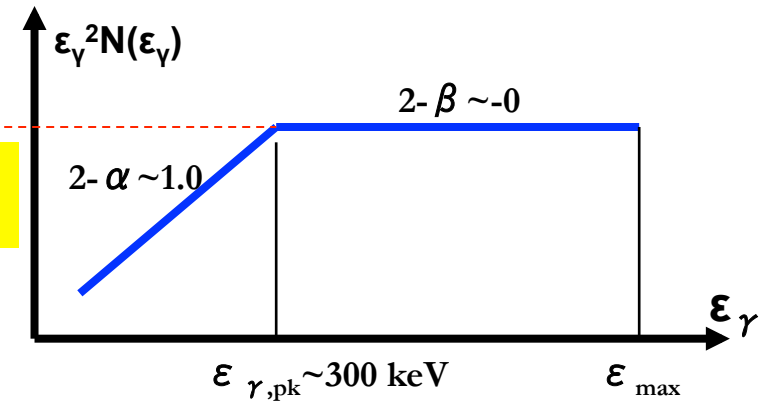
CR Spectrum (Fermi mechanism)

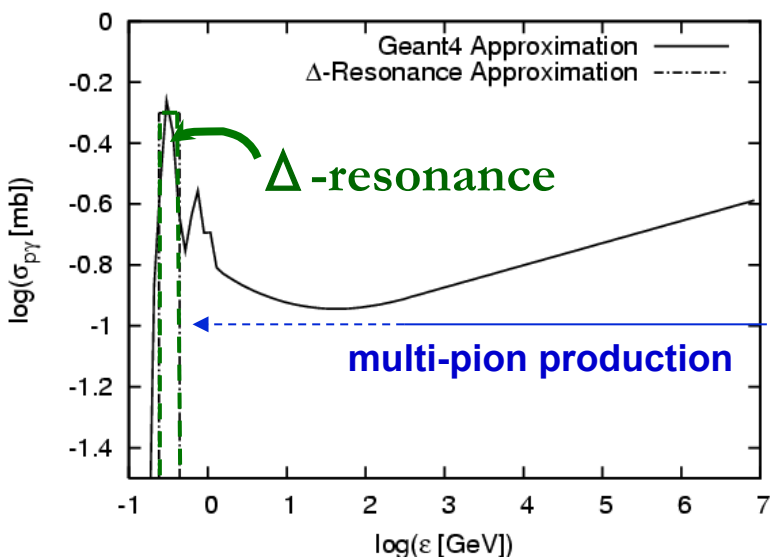


Key parameter
CR loading

$E_{HECR} \equiv \varepsilon_p^2 N(\varepsilon_p) \sim \varepsilon_{\gamma,pk}^2 N(\varepsilon_{\gamma,pk})$

Photon Spectrum (observed)





(in proton rest frame)

Photomeson Production

$$p + \gamma \rightarrow n + \pi^+ \quad \kappa_p \sim 0.2$$

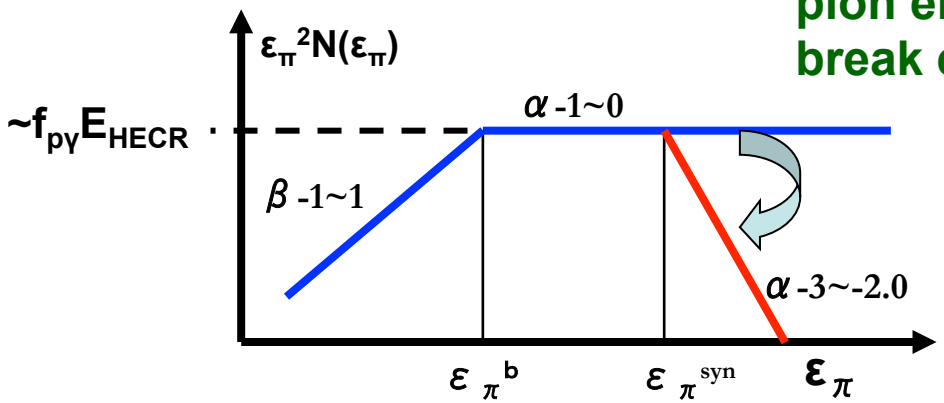
$$p + \gamma \rightarrow N\pi^\pm + X \quad \kappa_p \sim (0.4 - 0.7)$$

at Δ-resonance ($\varepsilon_p\, \varepsilon_\gamma$ ~ 0.3 Γ^2 GeV^2)
ε_p^b~ 0.15 GeV $m_p c^2\, \Gamma^2/\varepsilon_{\gamma,pk}$ ~ 50 PeV

Photomeson production efficiency
~ effective optical depth for pγ process
$f_{p\gamma}$ ~ 0.2 $n_\gamma \sigma_{p\gamma}$ (r/Γ): func. of r&Γ

Meson Spectrum

pion energy $\varepsilon_\pi \sim 0.2\ \varepsilon_p$
break energy $\varepsilon_\pi^b \sim 0.07\ \mathrm{GeV}^2\ \Gamma^2/\varepsilon_{\gamma,pk} \sim 10$ PeV



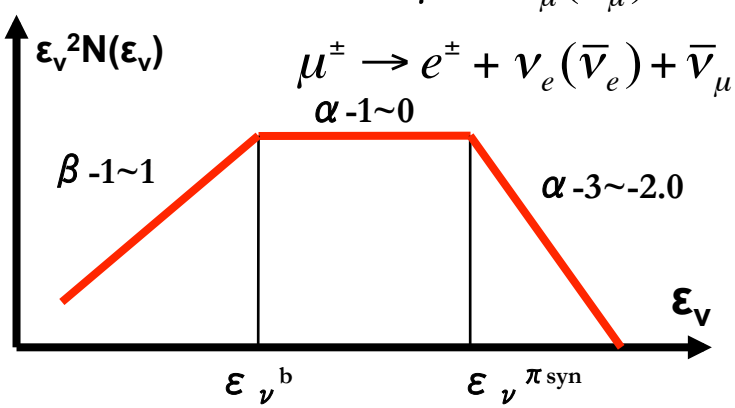
HE charged mesons
(meson cooling time) < (meson life time)
→ suppression at high energies

Waxman & Bahcall, PRL (1997)

Neutrino Spectrum

$$\pi^\pm \rightarrow \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$$

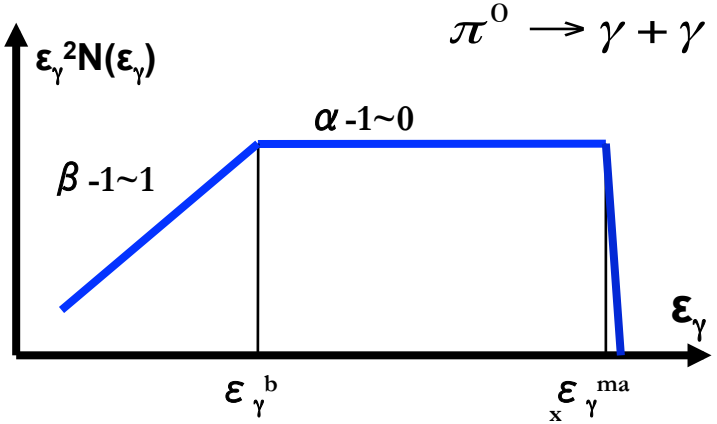
$$\mu^\pm \rightarrow e^\pm + \nu_e(\bar{\nu}_e) + \bar{\nu}_\mu(\nu_\mu)$$



neutrino energy $\varepsilon_\nu \sim 0.25\ \varepsilon_\pi \sim 0.05\ \varepsilon_p$
•ν lower break energy $\varepsilon_\nu^b \sim 2.5$ PeV
•ν higher break energy $\varepsilon_\nu^{\pi syn} \sim 25$ PeV

Gamma-Ray Spectrum

$$\pi^0 \rightarrow \gamma + \gamma$$

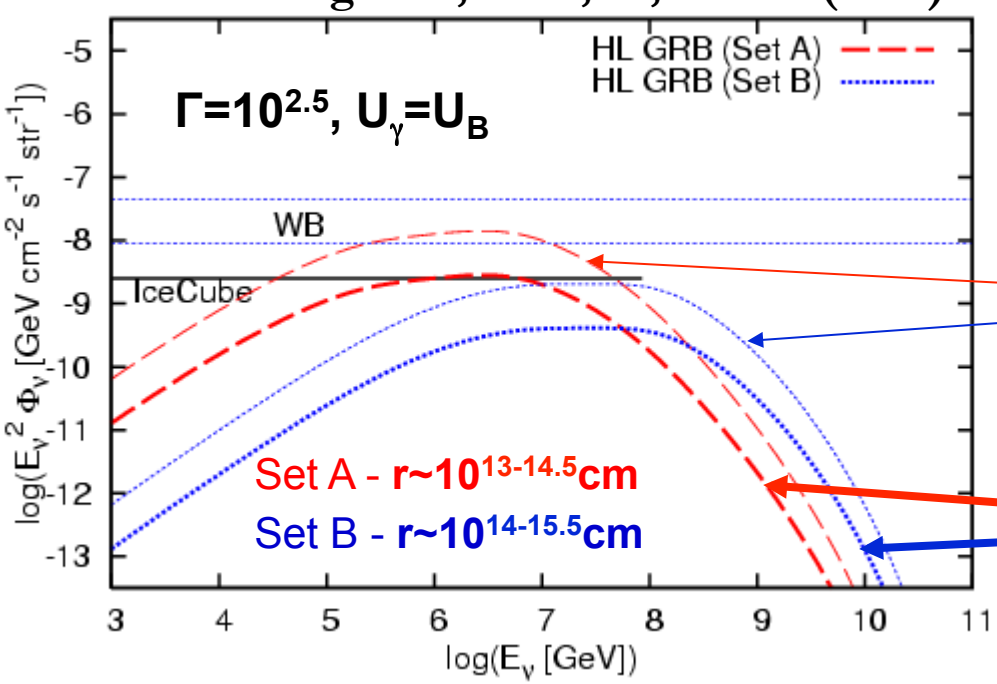


γ-ray energy $\varepsilon_\gamma \sim 0.5\ \varepsilon_\pi \sim 0.1\ \varepsilon_p$
•γ lower break energy $\varepsilon_\gamma^b \sim 5$ PeV
•γ maximum energy $\varepsilon_\gamma^{max} \sim 0.1\ \varepsilon_p^{max}$

GRB Prompt ν Emission

Event rates by IceCube for 1 GRB @ z~1 ~ 10^{-3}-10^{-1}
→ Cumulative ν background (time/space coincidence)

KM & Nagataki, PRD, 73, 063002 (2006)



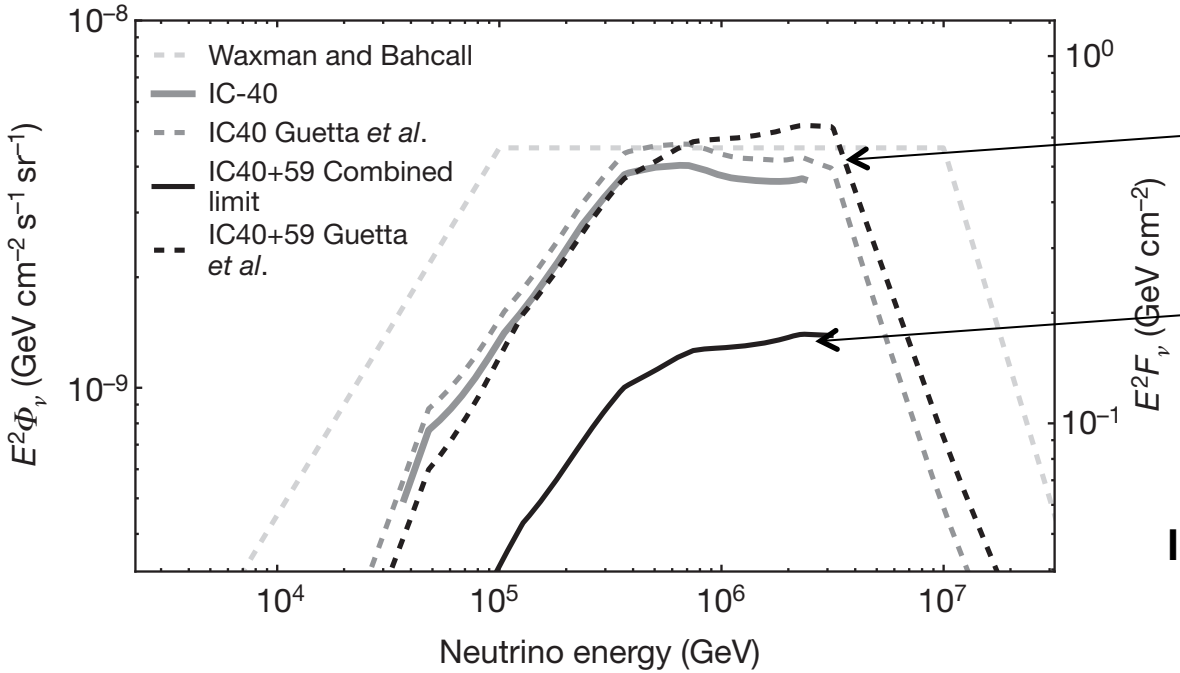
CR loading parameter
$E_{HECR} \equiv \varepsilon_p^2 N(\varepsilon_p)$

"high" CR loading
E_{HECR} ~ 2.5 $E_{GRB\gamma}$
→#~0.5-50 by IceCube

"moderate" CR loading
E_{HECR} ~ 0.5 $E_{GRB\gamma}$
→#~0.1-10 by IceCube

- **Testable: GRB-UHEp hypothesis ($E_{HECR}/E_{GRB\gamma}$ > 1 required)**

Recent IceCube Limits on Prompt ν Emission



Prediction (but see below)

Limit (based on stacking)

IceCube collaboration 12 Nature

Limits start to be powerful but the above is optimistic by ~ 6-10

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

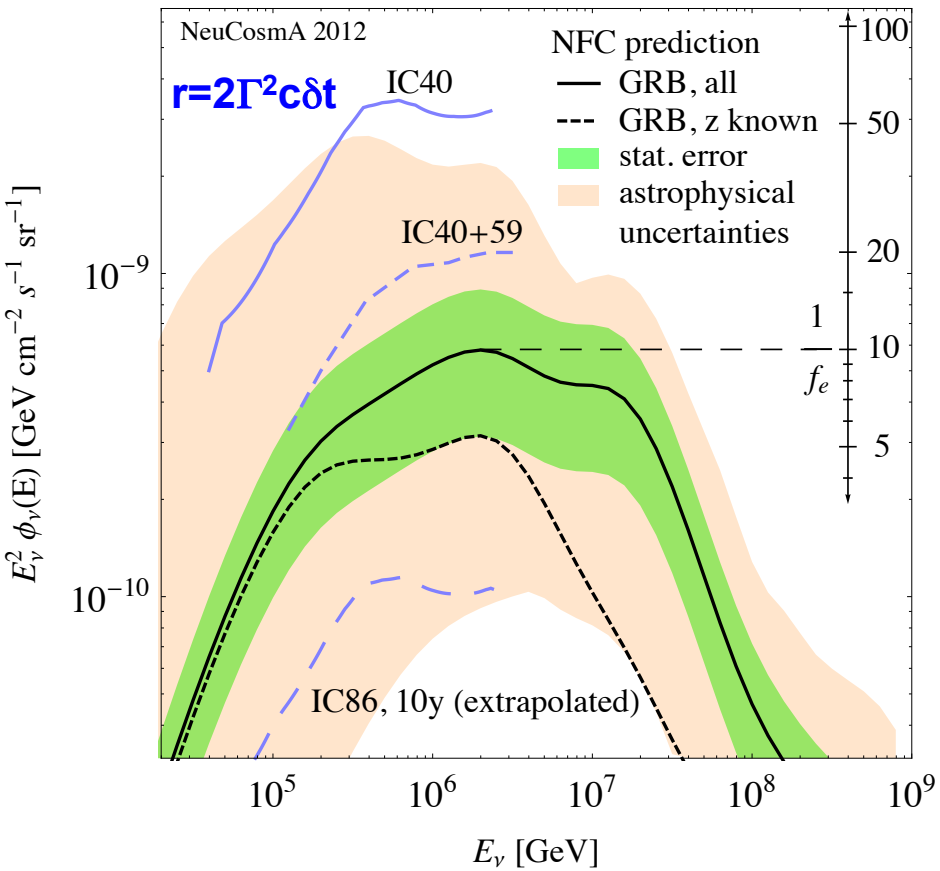
2. ($\varepsilon_\gamma^2\ \phi_\gamma$ at $\varepsilon_{\gamma,pk}$) ≠ ($\int d\varepsilon_\gamma\ \varepsilon_\gamma\ \phi_\gamma$) → ~3-6 ↓ (Hummer et al. 12 PRL, He et al. 12 ApJ)

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

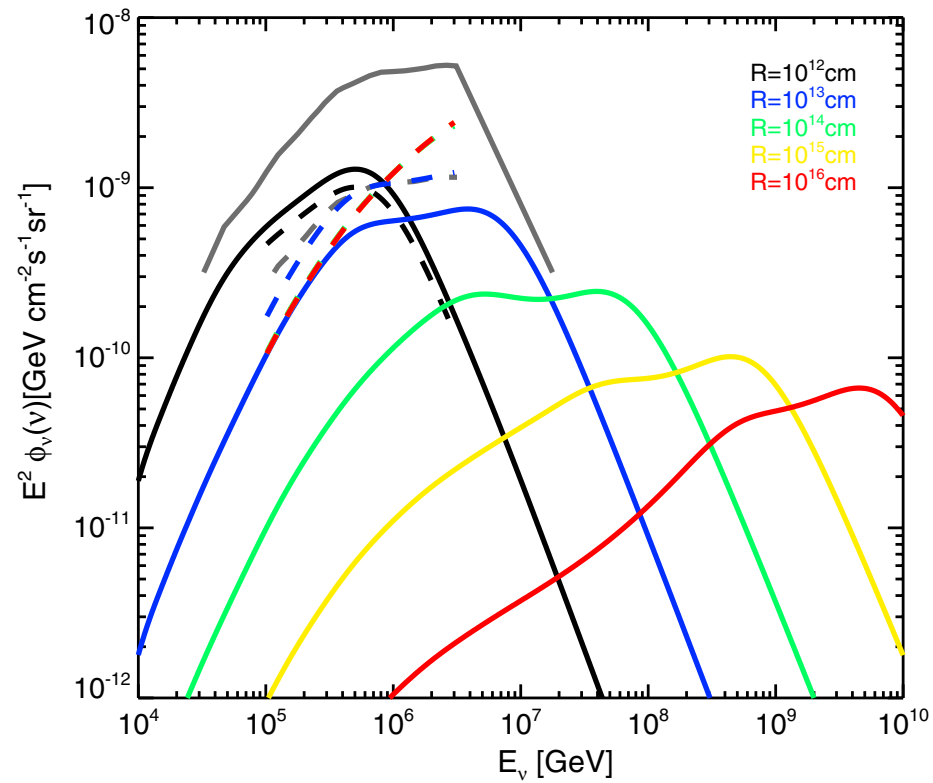
- Different from "astrophysical" model-uncertainty in calculating $f_{p\gamma}$
- Considered in earlier calculations for a given parameter set (ex. Dermer & Atoyan 03 KM & Nagataki 06)

Applications to Individual GRBs

Hummer, Baerwald & Winter 12 PRL



He, Liu, Wang, Nagataki, KM & Dai 12 ApJ



~10 yr observations by IceCube can cover relevant parameter space in the IS scenario w. GRB-UHEp hypothesis

Remarks: Two Important Cases

- **GRBs=UHEn sources (optimistic case)**

Escaping UHEn → UHEp 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}

→ ruled out by IceCube **Ahrels et al., APh, 35, 87 (2011)**

- **GRBs=UHE heavy-nuclei sources (pessimistic case)**

"Nucleus-survival bound" **KM & Beacom, PRD, 81, 123001 (2010)**

$\tau_{A\gamma} \sim n_\gamma \sigma_{A\gamma}(r/\Gamma) < 1 \rightarrow f_{mes} \sim \tau_{A\gamma}(0.2\sigma_{p\gamma}/\sigma_{A\gamma}) < 10^{-3}$ (for Fe)

$\varepsilon_\nu^2\Phi(\varepsilon_\nu) < 10^{-3}\, \varepsilon_\nu^2\Phi_{WB}(\varepsilon_\nu) \sim$ a fewx10^{-11} GeV cm^{-2} s^{-1} sr^{-1}

→ below IceCube limits (but hard to test…)