Revealing Deaths of Massive Stars with High-Energy Neutrinos

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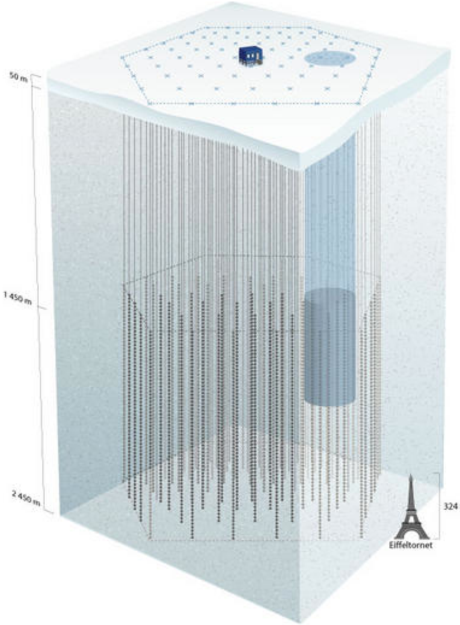
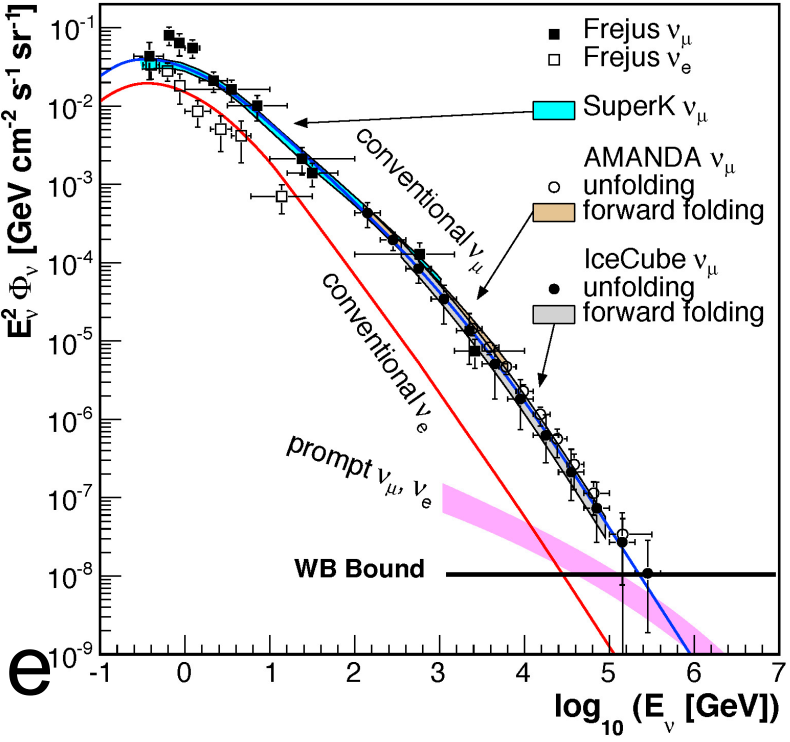
Realtime Astroparticle Physics
February 2013

High-Energy Neutrinos



Now we have IceCube
Interesting era!

>PeV: cosmic-ray origin
connection w. γ rays
<PeV: atm. ν → "transients"
more compact
γ rays may be invisible



Outline

Astrophysical scenarios for HE neutrinos from explosive phenomena such as GRBs and SNe

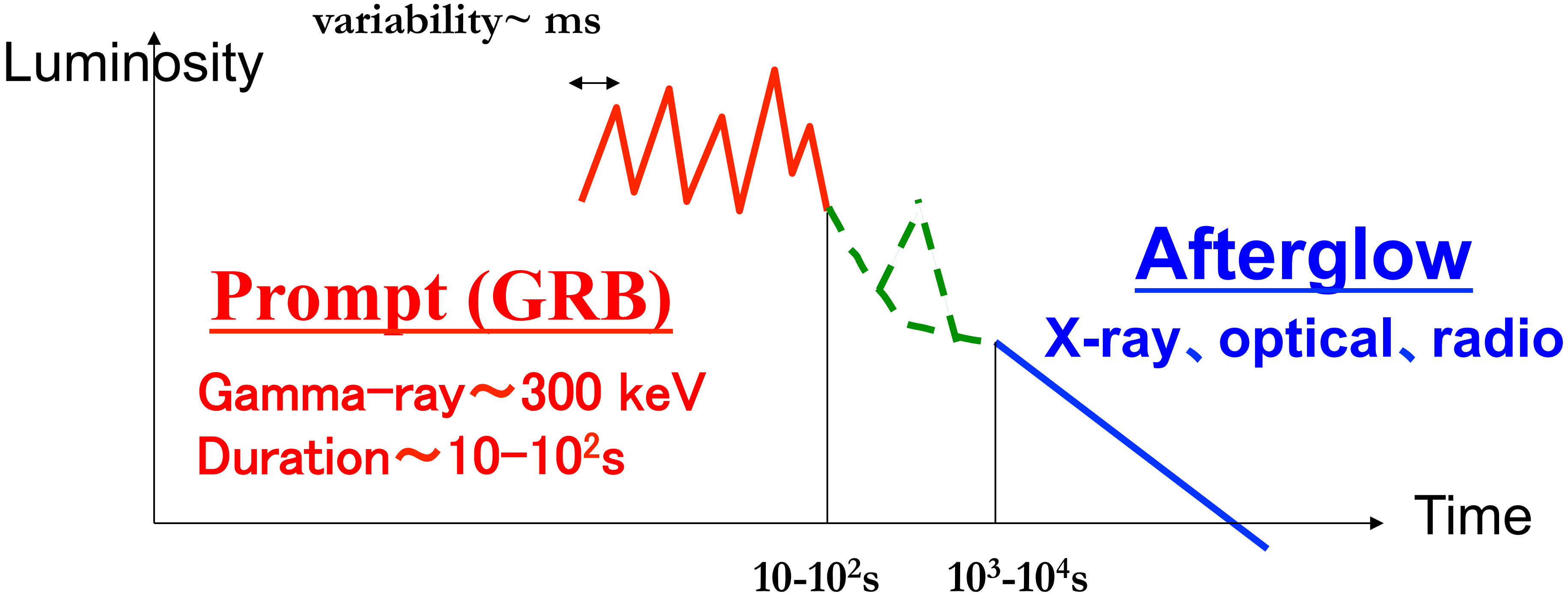
- Origin of extragalactic cosmic rays
- Physical mechanisms, GRB-SN connection etc.

1. Gamma-Ray Bursts
2. Supernovae

1. Gamma-Ray Bursts

(Long) Gamma-Ray Bursts

- The most violent phenomena in the universe ($L_\gamma \sim 10^{51\text{-}52}$ ergs s^{-1})
- Cosmological events ($z \sim 1\text{-}3$), ~1000 per year
- Relativistic jet ($\Gamma \sim 100\text{-}1000$; $\theta_{jet} \sim 0.1$ rad)
- Related to death of massive stars (association with supernovae)



Prompt (GRB)

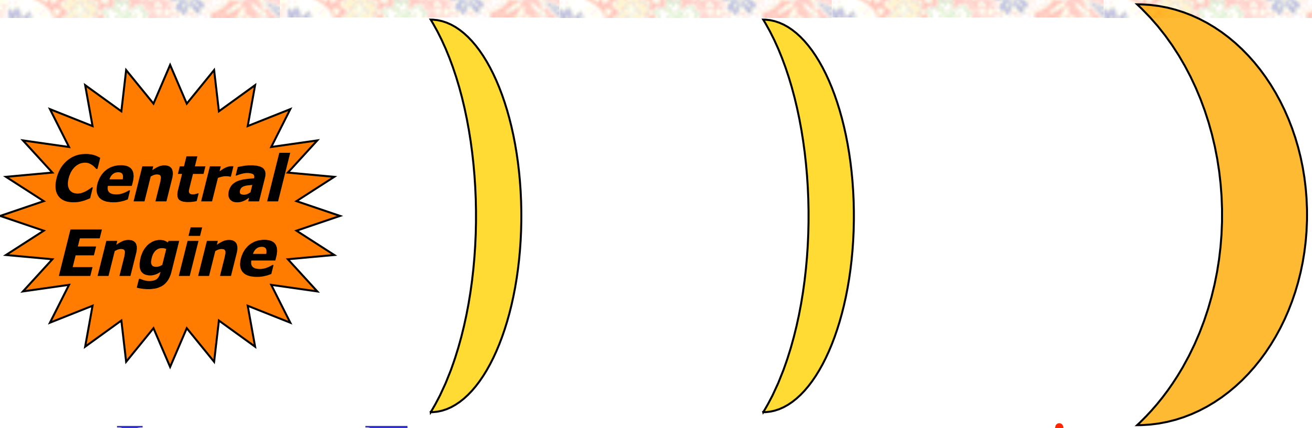
Gamma-ray～300 keV

Duration～$10\text{–}10^2$s

Afterglow

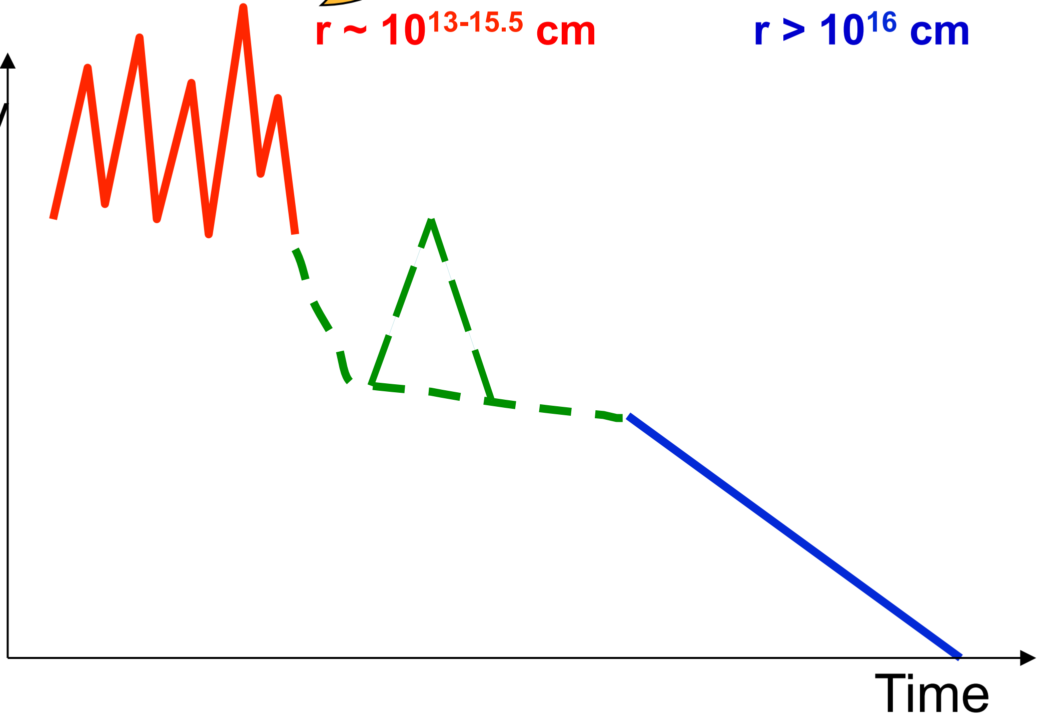
X-ray、optical、radio

“Classical” Internal-External Shock Model (Baryonic Jet Model)



interstellar medium
or
stellar wind

Lorent Factor
$\Gamma > 100$



Bulk kinetic energy

↓

Shock dissipation

acceleration **magnetic field** **heat**

Ultra-High-Energy Cosmic Rays?

Fermi shock acceleration mechanism
-> not only electrons but protons are accelerated

$\varepsilon_p < e\ r\ B \sim 3\mathrm{x}10^{20}\ \mathrm{eV}\ r_{14}\ B_4$ **(Waxman 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: ~ 1 Gpc^{-3} yr^{-1}
(e.g., Wanderman & Piran 2010)

⇕

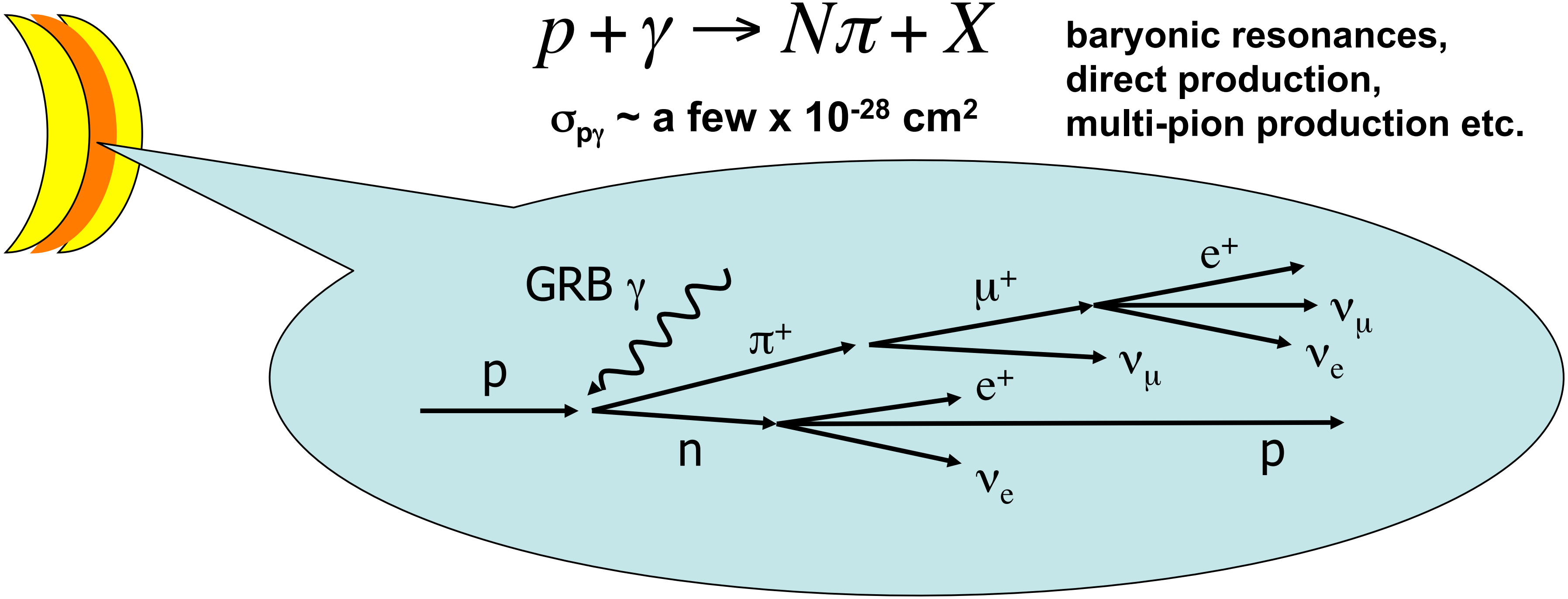
UHECR budget (from obs.): $Q_{HECR} \sim 10^{44}\ \mathrm{erg/Mpc^3/yr}$

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.



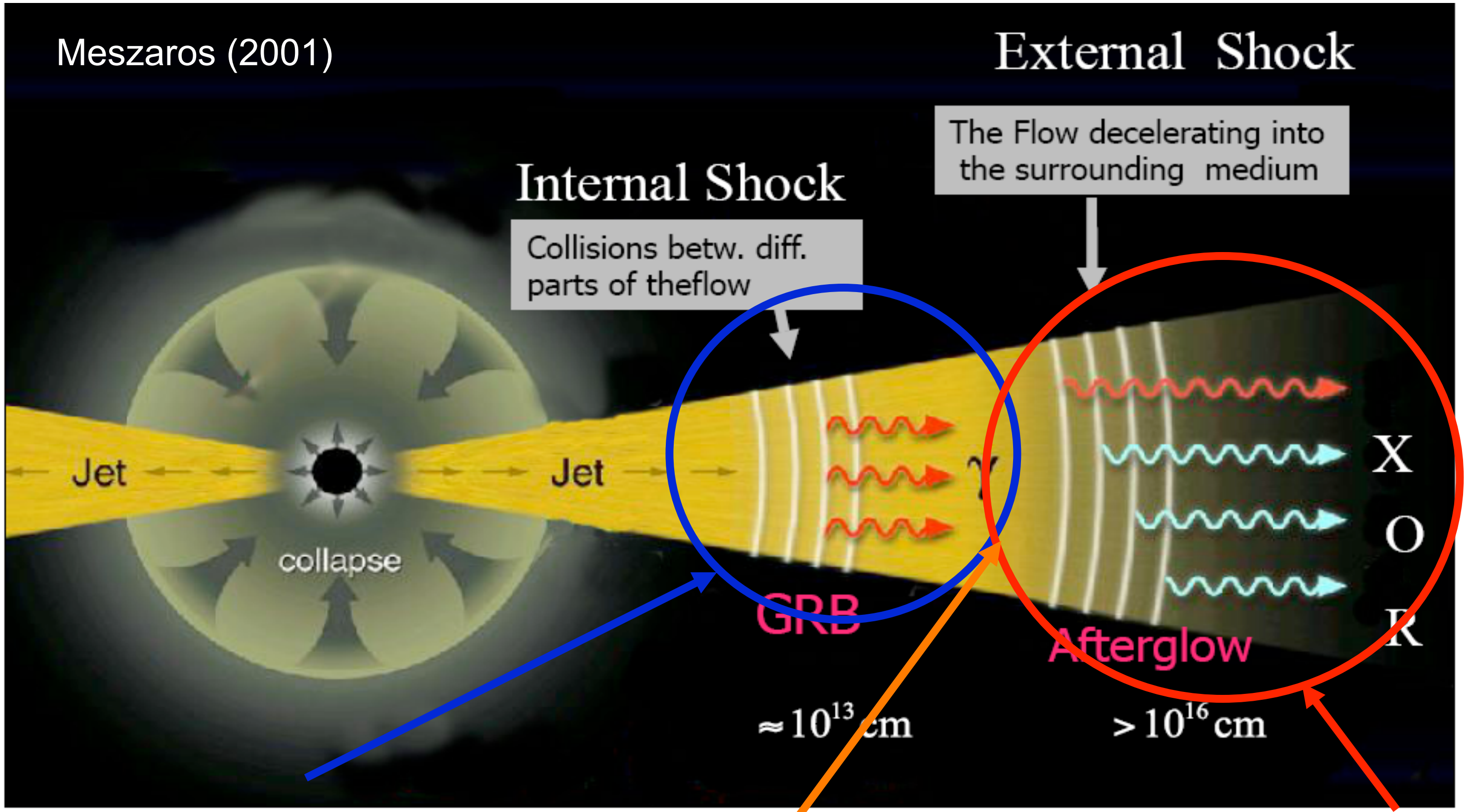
at Δ-resonance ($\varepsilon_p\ \varepsilon_\gamma \sim 0.2\ \Gamma^2$ GeV^2)

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

Meson production efficiency (large astrophysical uncertainty)

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

CR Acceleration in “Classical” Pictures



Inner jet (prompt emission)

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

PeV ν, GeV-TeV γ

Waxman & Bahcall 97 PRL

Inner jet (flares)

r ~ 10^{14}-10^{16} cm   B ~ $10^{2\text{-}4}$ G

PeV-EeV ν, GeV-TeV γ

KM & Nagataki 06 PRL

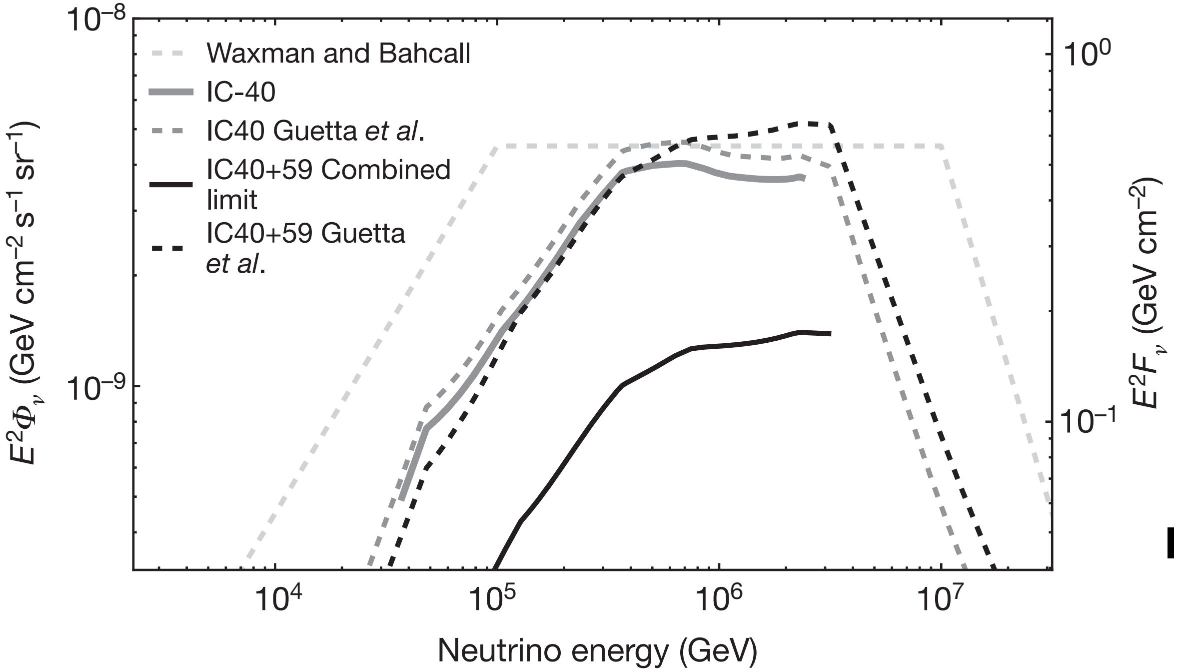
External shock (afterglow)

r ~ 10^{16}-10^{17} cm   B ~ 0.1-100 G

EeV ν, GeV-TeV γ

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

Recent IceCube Limits on Prompt ν Emission



IceCube collaboration 12 Nature

But theoretical fluxes should be lower than IceCube-Guetta et al.

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

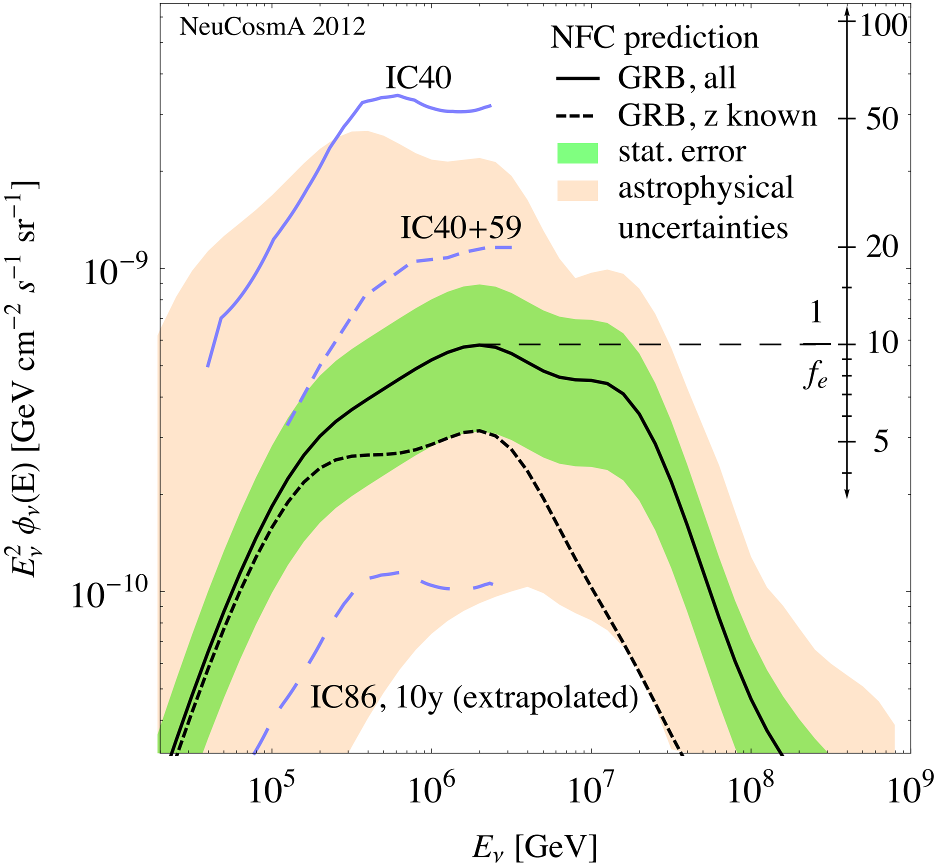
2. ($\varepsilon_\gamma^2 \phi_\gamma$ at $\varepsilon_{\gamma,pk}$) ≠ ($\int d\varepsilon_\gamma \varepsilon_\gamma \phi_\gamma$) → ~3-6 ↓ (Hummer et al. 12 PRL, He et al. 12 ApJ)

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

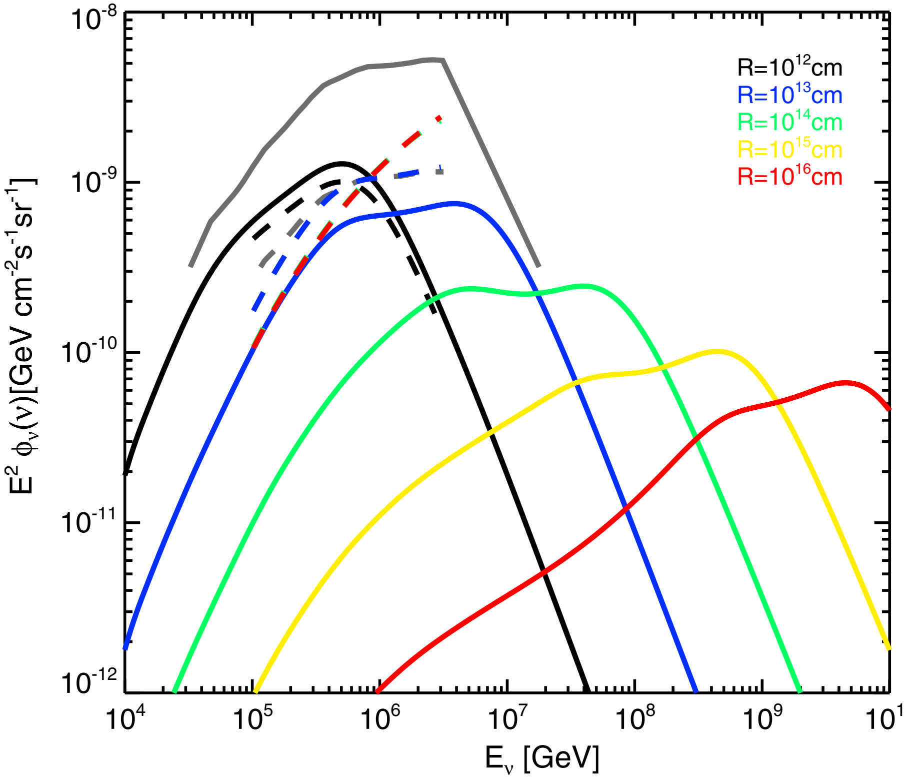
- In addition, there is "astrophysical" model-uncertainty in calculating $f_{p\gamma}$

Recent IceCube Limits on Prompt ν Emission

Hummer, Baerwald & Winter 12 PRL



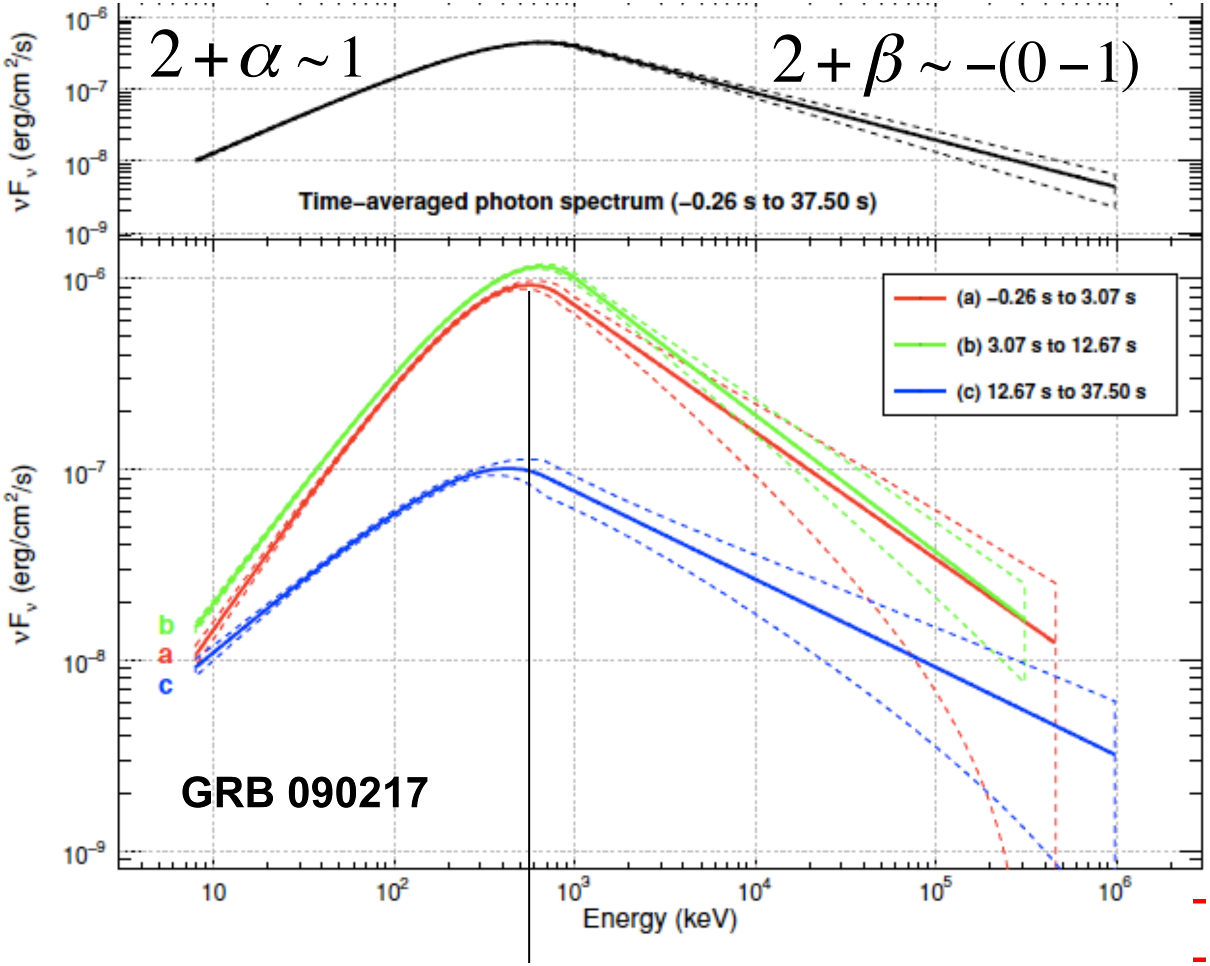
He, Liu, Wang, Nagataki, KM & Dai 12 ApJ



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

Problems in Internal-Shock-Synchrotron Scenario

Fermi collaboration 10 ApJ



$$\varepsilon_{\gamma,\mathrm{pk}} \sim 0.1\text{–}1\ \mathrm{MeV}$$

Band function
~ broken power-law

$$F_\nu \propto \nu^{\beta+1}$$

"synchrotron scenario"

$$\varepsilon_{\gamma,\mathrm{pk}} = \Gamma \hbar \gamma_{ei}^2 \frac{eB}{m_e c}$$

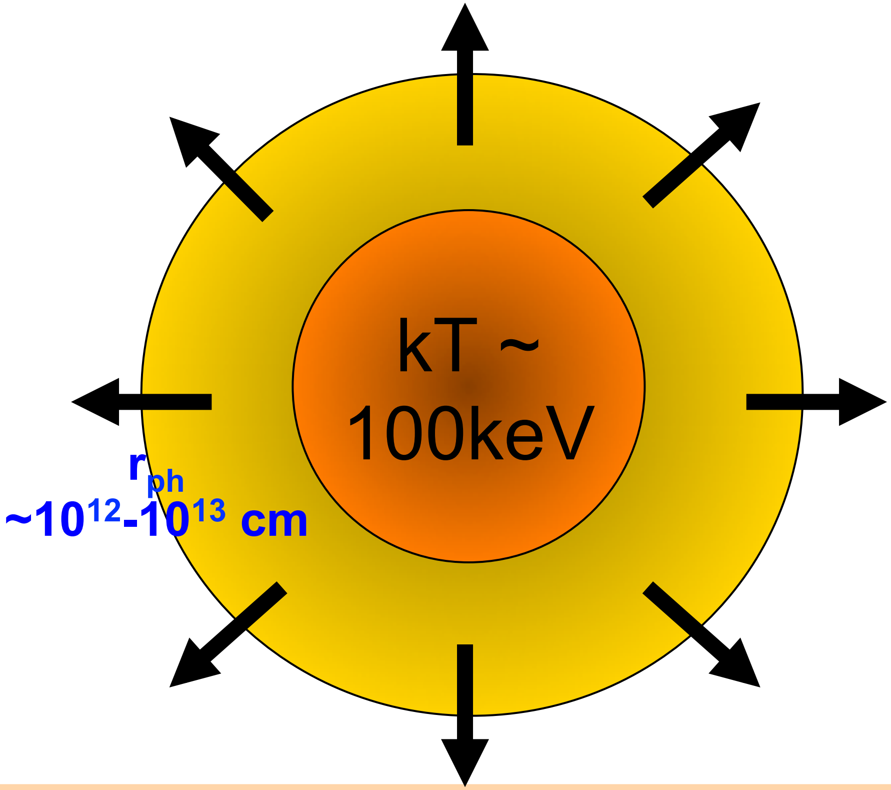
$2+\alpha$ **~ 0.5 (fast-cooling)**

Other problems

- **high radiative efficiency**
- **empirical relations ($\varepsilon_{\gamma,\mathrm{pk}}$ -L_γ)**
- **theoretical issues**

Dissipative Photosphere Scenario

e.g., Thompson 1994, Meszaros & Rees 2000, Rees & Meszaros 2005,
Peer et al. 2006, Giannios 2006, Ioka, KM et al. 2007, Beloborodov 2010



Emissions from $\tau_T \sim 1$-10

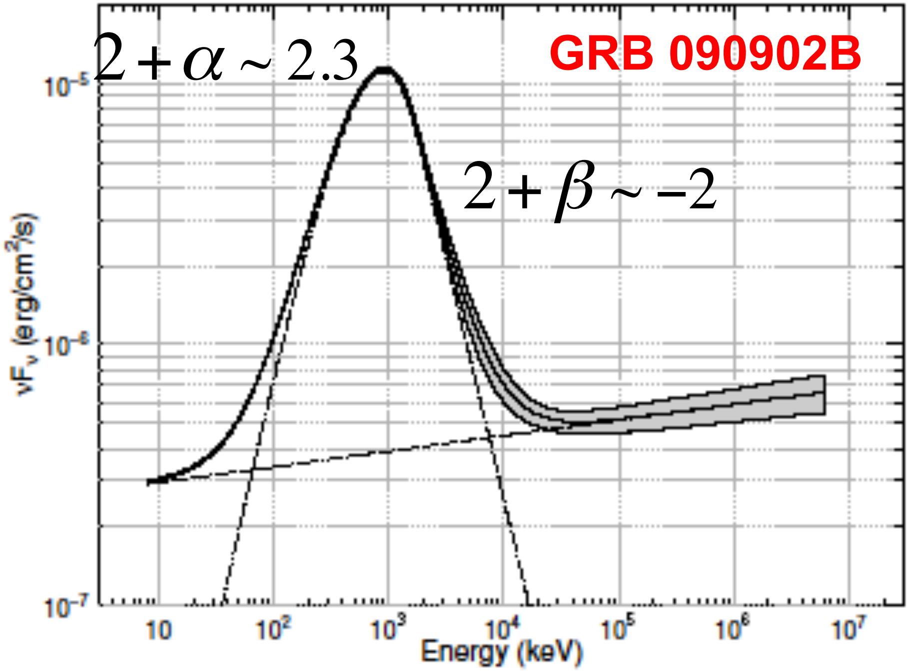
“dissipative photosphere”

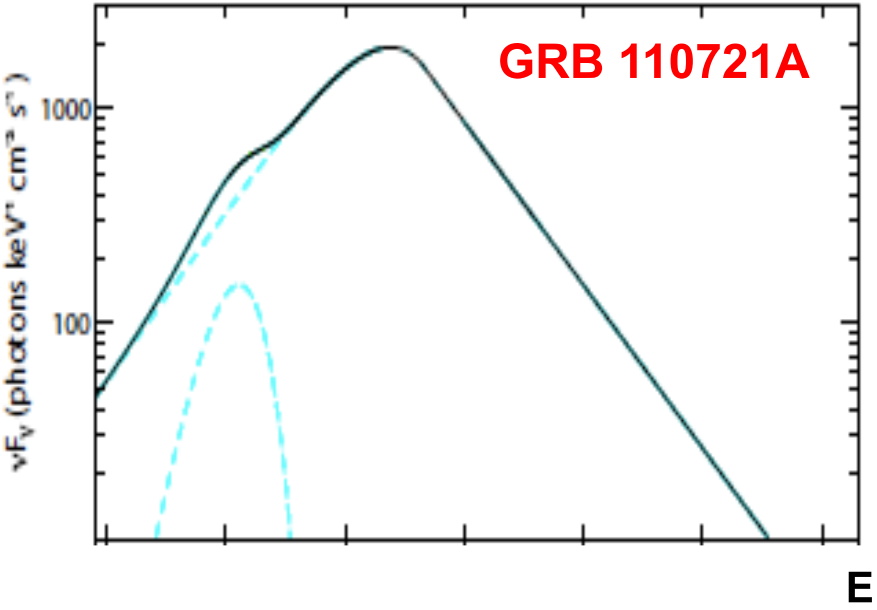
- internal shocks
- interaction with star or wind
- recollimation shocks
- magnetic reconnection
- collisions with neutrons

•Re-conversion of kinetic energy to radiation energy

•High radiative efficiency & stabilization of $\varepsilon_{\gamma,pk}$

Observational Hints





"modified" black-body emission

or

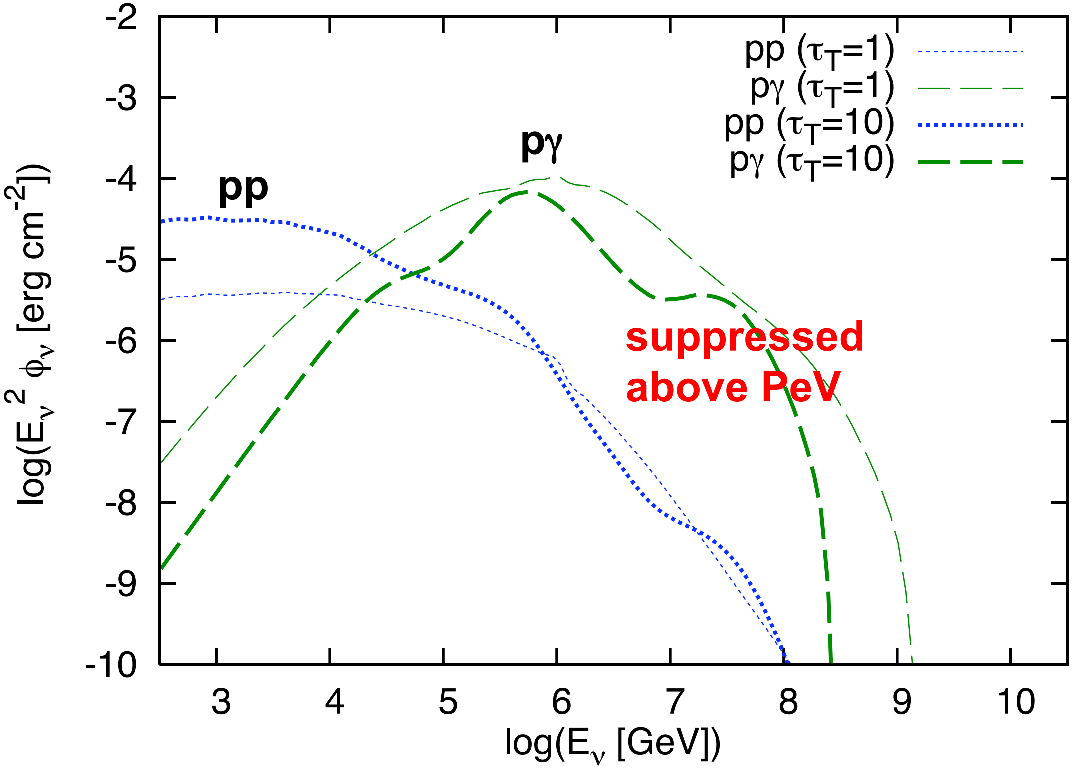
thermal + nonthermal emission

Observed spectra can be reproduced by theories

Photospheric Neutrinos

- **Dissipative photosphere** (e.g., Rees & Meszaros 05 ApJ)

$$\tau_T = n_e \sigma_T (r/\Gamma) \sim 1\text{-}10 \Leftrightarrow f_{pp} = (\kappa_{pp}\sigma_{pp}/\sigma_T)\tau_T \sim 0.05\text{-}0.5$$



τ_T=1-10 (r ~ 10^{12}-$10^{12.5}$ cm)
$\Gamma=10^{2.5}$, $U_e=U_B$

$E_{CR}^{iso} \sim E_\gamma^{iso} \sim 10^{53.5}$ erg
→ # of μs ~ 1-2 for GRB @z=0.1

KM, PRD(R), 78, 101302 (2008)
cf. Wang & Dai, ApJL, 691, L67 (2009)

Detection of pp neutrinos strongly supports dissipative photospheres

Quasi-Thermal Neutrinos?

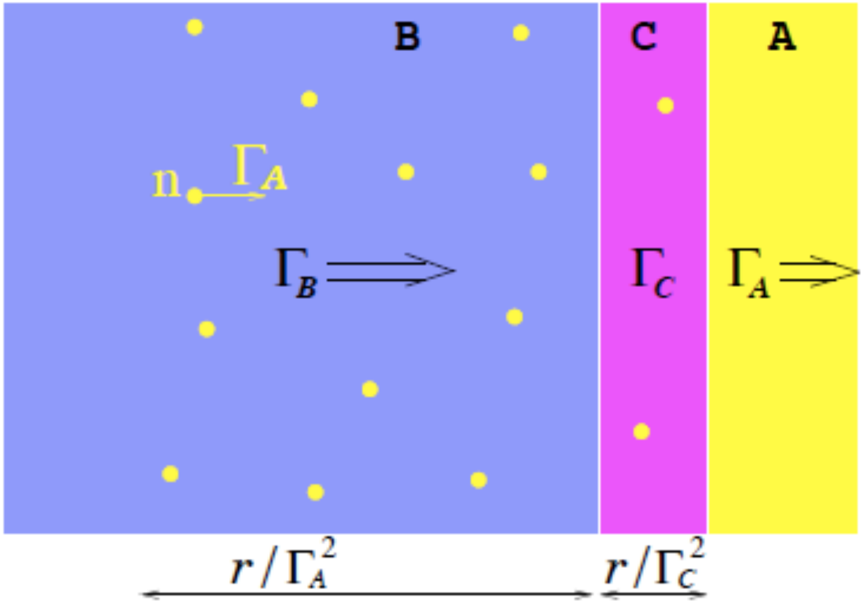
We have assumed ε_p^{-2} spectrum w. $E_{CR}^{iso} \sim E_\gamma^{iso}$
But highly uncertain….

- pγ is unimportant (pp is more important) if steeper
- non-thermal component may be absent

Q. Can we expect "thermal" neutrinos?
A. Yes! (Paczynski & Xu 1994, Bahcall & Meszaros 2000, Meszaros & Rees 2000)
inevitable when neutrons are loaded in jets

(But uncertain if not, since thermal protons would not cause inelastic collisions for radiation-mediated shocks)

Collisional Dissipation by Neutrons



- "Quasi-thermal"

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

- γs & νs come from ps

$\varepsilon_\nu^2\, \phi_\nu \sim \varepsilon_\gamma^2\, \phi_\gamma$ (normalizable)

KM, Kashiyama & Meszaros 13, Bartos et al. 13

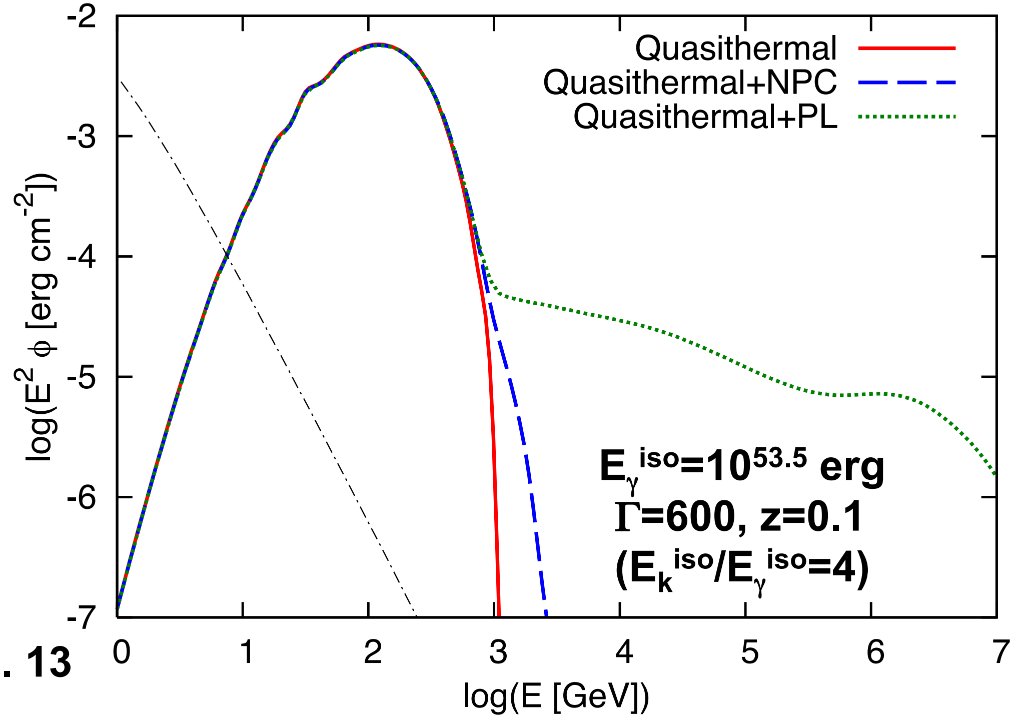
Decoupled neutrons are swept up by the faster flow w. $\Gamma_B >> \Gamma_A = \Gamma_n$

inelastic pn collision

↓

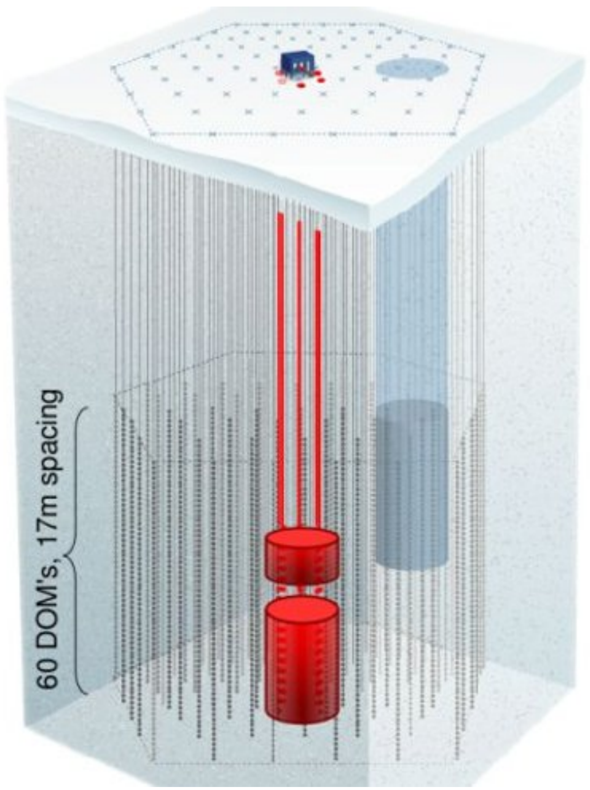
γ rays ⇔ prompt emission

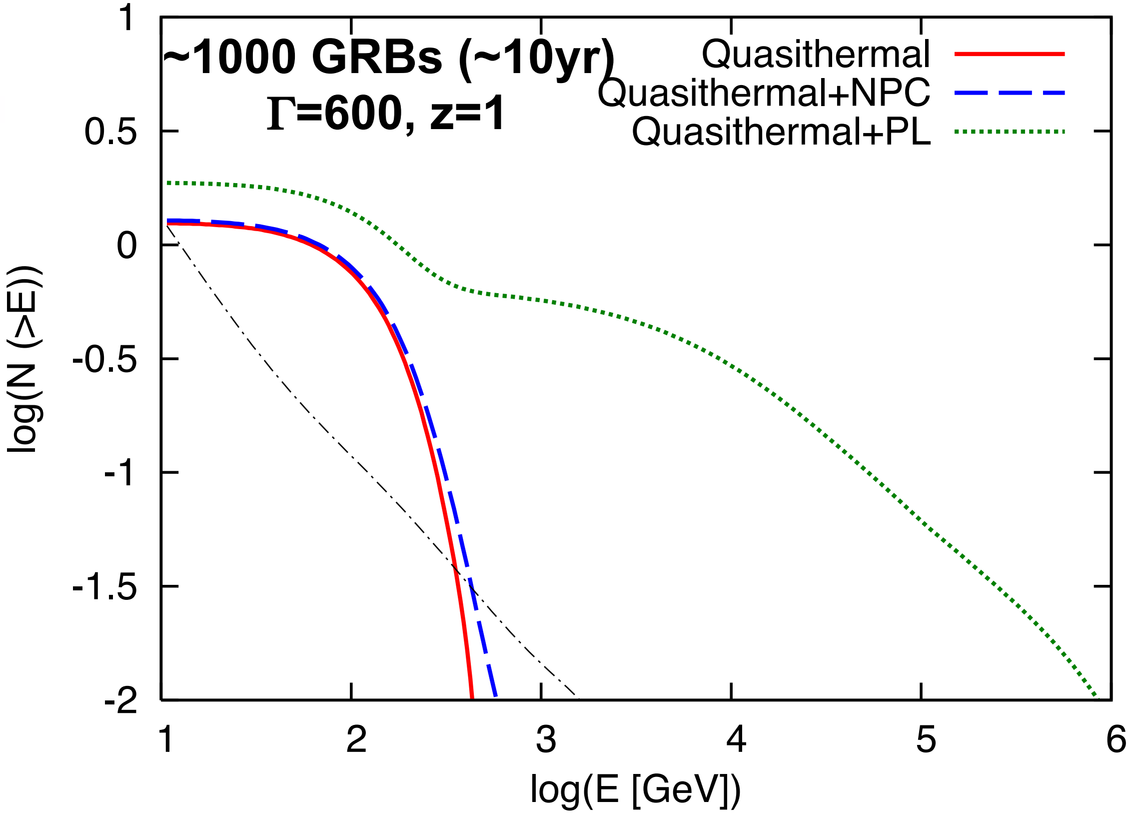
+ neutrinos!



Prospects for DeepCore+IceCube

- Including DeepCore is essential at 10-100 GeV
- Reducing atmospheric ν background is essential
  → select only bright GRBs w. > 10^{-6} erg cm^{-2}





KM, Kashiyama & Meszaros 13, Bartos et al. 13

Summary: Testable Cases for GRB Neutrinos

νs in GRB-UHECR hypothesis

- Prompt νs: PeV
  - ~10 yr to cover parameter space in classical scenario
  - maybe difficult in magnetic scenarios
- Afterglow cases are allowed (→ Askaryan Radio Array)

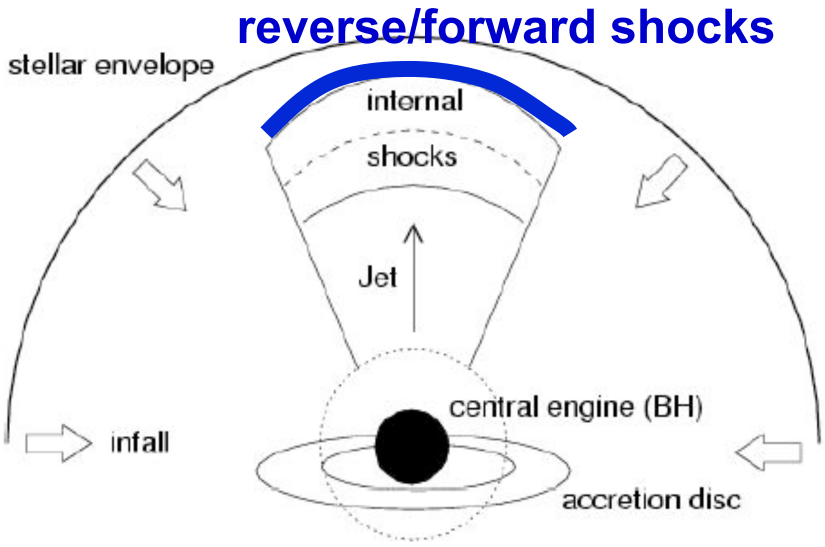
Prompt νs in dissipative photosphere scenario

- Different predictions (GeV-TeV from pp, suppression at > PeV)
- Consistent w. non-observations by IceCube
- Better things
  - pp(or pn)/pγ efficiencies are fixed by τ_T ~1-10
  - inevitable quasi-thermal νs in pn collisional dissipation

→ searches w. DeepCore, improving ang. resolution for cascades

2. Supernovae

TeV Neutrinos from Choked Jets



Razzaque et al. 2005

- **Jet penetration?**

  GRBs=successful jets

  failed GRBs=SNe w. choked jets

  (Meszaros & Waxman 01 PRL)

- **Slow jets embedded in SNe?**

  Some SNe may be driven by a slow jet

  (Razzaque et al. 04 PRL,
  Ando & Beacom 05 PRL, Horiuchi & Ando 08 PRD)

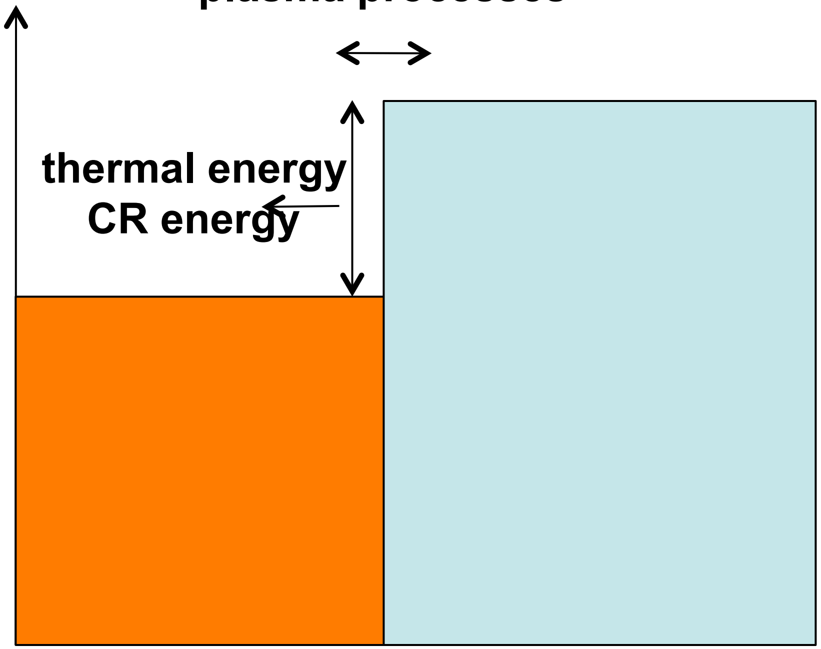
If CRs carry E_{CR}^{iso}~0.5x10^{53} erg (GRB)
→ # of μs ~30 for SN@10Mpc

Neutrinos from such SNe are interesting if detected
(neutrino tomography, neutrino mixing etc.)

But can we expect CR acceleration deep inside stars?

Limitation of Shock Acceleration

Collisionless shock



Velocity

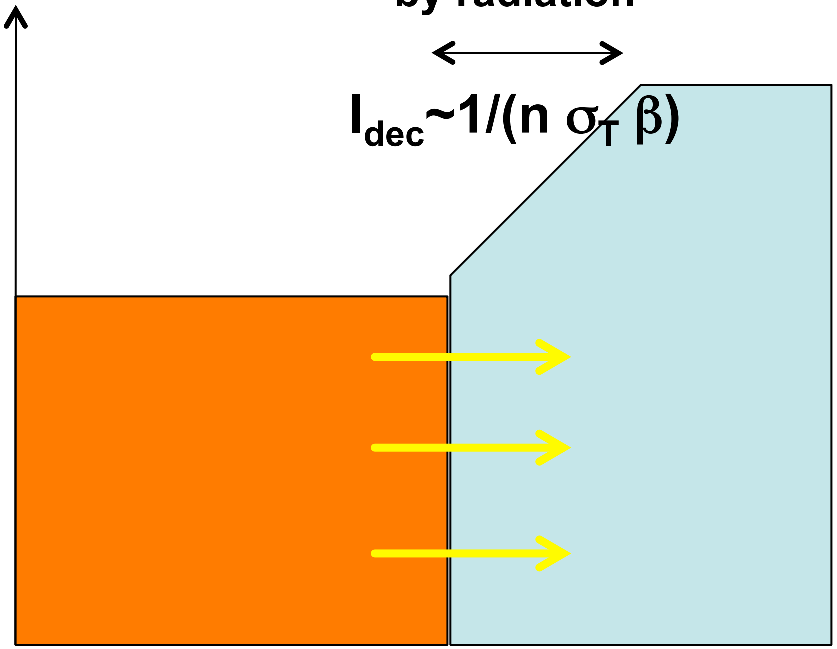
plasma processes

thermal energy
CR energy

downstream **upstream**

Radiation-mediated shock

(ex. Weaver 76 ApJ, Katz+ 10 ApJ,
Nakar & Sari 12 ApJ)



Velocity

deceleration
by radiation

$l_{dec} \sim 1/(n\,\sigma_T\,\beta)$

downstream **upstream**

Shock Breakout & Collisionless Shocks

- Necessary condition for collisionless shocks
  $l <\sim l_{dec} \sim (1/n\,\sigma_T\,\beta) \Leftrightarrow \tau_T <\sim 1/\beta$
  (not sufficient condition: ex. steep density profile)

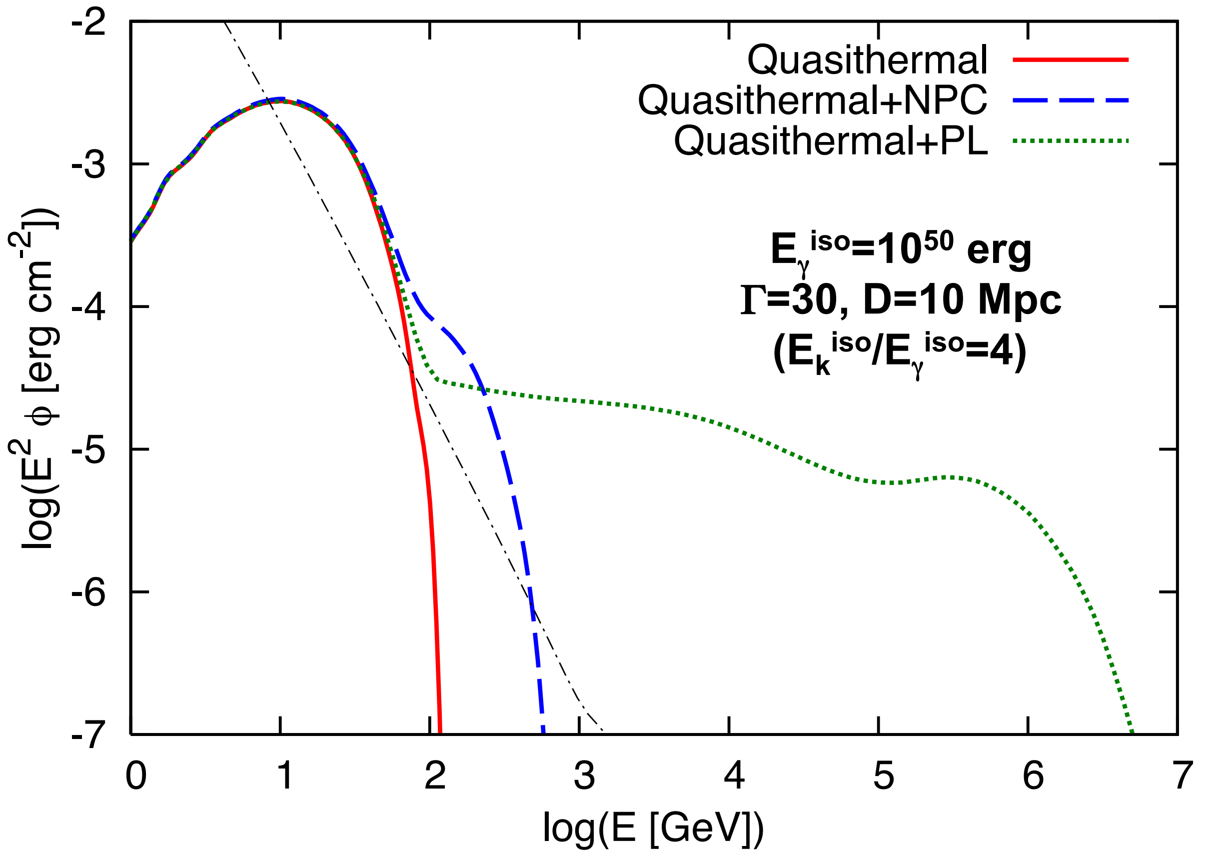
(Waxman & Loeb 01 PRL, KM et al. 11 PRD, Katz, Sapir & Waxman 11)

- Shock breakout: $t_{diff} \sim t_{dyn} \Leftrightarrow \tau_T \sim 1/\beta$
  $t_{diff} \sim l^2/\kappa$ $(\kappa \sim (c/n\,\sigma_T))$
  $t_{dyn} \sim l/\beta c$
  wind CSM $\rightarrow r_{bo} \sim l_{bo} \sim (1/n\,\sigma_T\,\beta)$ (unless ultra-relativistic)

Ex. int./rev. shock at $r=10^9$ cm in choked jets ($L_k=10^{48}$ erg/s, $\Gamma=10$)
$\rightarrow \tau_T \sim 10^3$, CR acc. is difficult (see also Levinson & Bromberg 08 PRL)

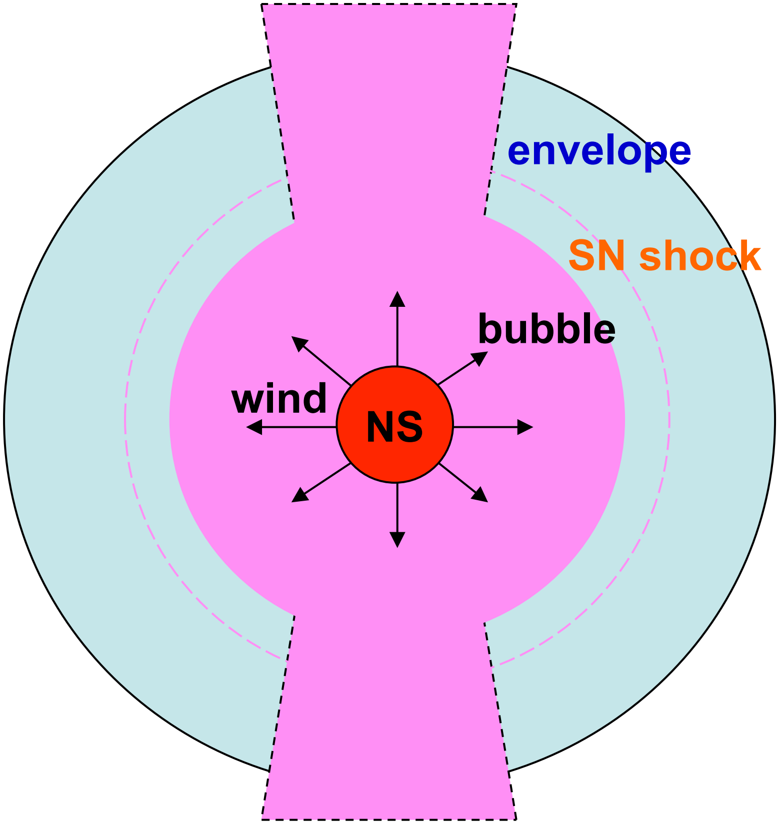
Possibility: Quasi-Thermal Neutrinos

KM, Kashiyama & Meszaros 13



- pn collisions in LL GRBs → possible detections up to <~ 3 Mpc

Possibility: Non-Shock Acceleration?

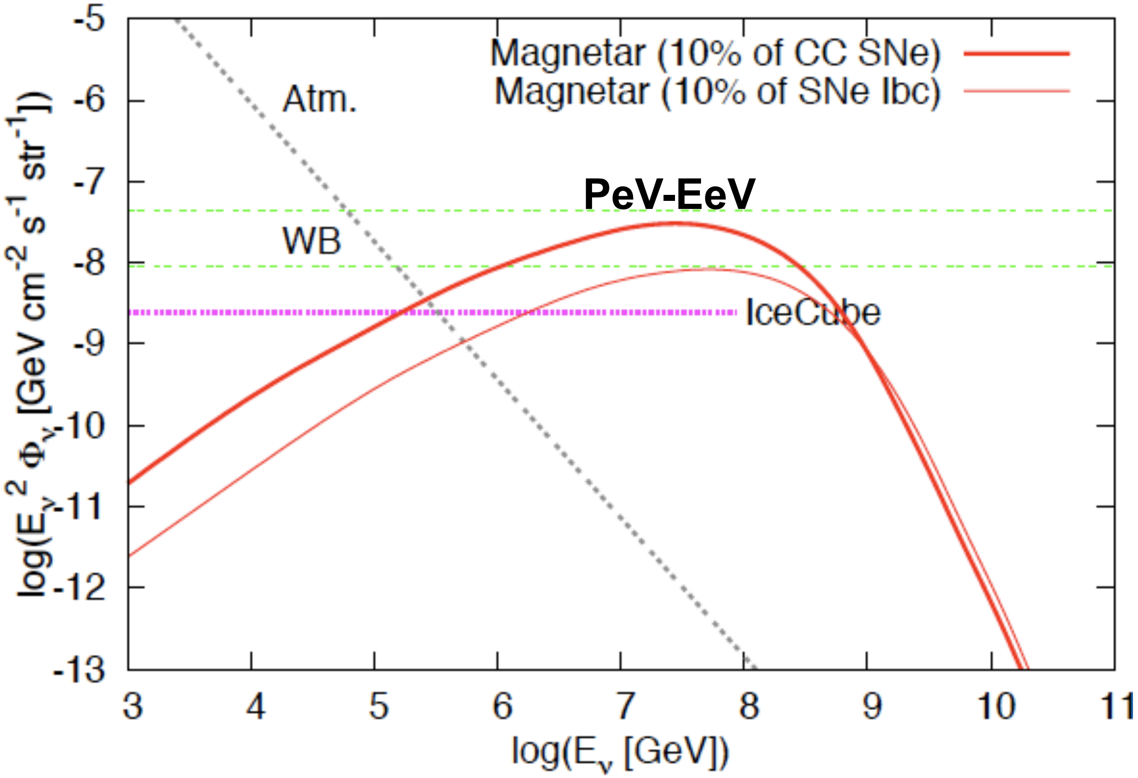


- **Magnetar-UHECR hypothesis**
  UHECR acc. may occur in wind in ~hrs after the birth (Arons 03 ApJ)

- **Accelerated CRs should interact with stellar material and rad. field**
  → pp/pγ reactions
  → νs should be produced

- **Escape of UHECRs？**
  ex. puncturing envelope by jets

Neutrinos from Fast-Rotating Magnetars



KM, Meszaros, & Zhang, PRD, 79, 103001 (2009)

Time scale ~ day
soft-hard-soft time-evolution

Detectable for D < 5 Mpc
Probe of the magnetar birth
(birth rate ~ 0.02-0.05 yr^{-1})

Magnetar-UHECR hypothesis can be tested by IceCube

Possibility: Post-Shock-Breakout?

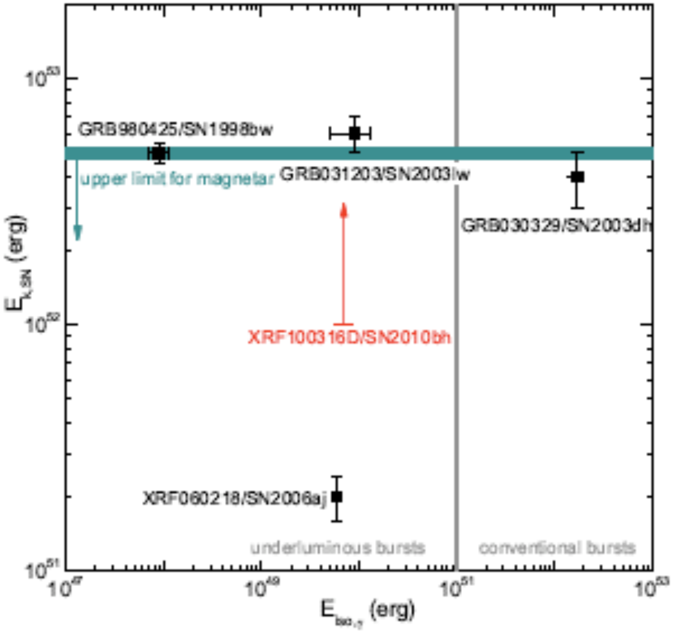
Expect formation of collisionless shocks & CRs

pp cooling: $t_{pp} = 1/(n\,\kappa_{pp}\,\sigma_{pp}\,c)$
dynamical: $t_{dyn} = l/\beta c$
→ $f_{pp} = (l/\beta)\,n\,\kappa_{pp}\,\sigma_{pp}$

$f_{pp}(r_{bo}) \sim \beta^{-2}\,(\kappa_{pp}\,\sigma_{pp}/\sigma_T) \sim 0.03\,\beta^{-2}$

$\beta \sim 1$ ⇔ trans-relativistic SNe
(pγ efficiency ~ 1: dominant)
$\beta \sim 0.01\text{-}0.03$ ⇔ typical SN velocity
pp efficiency ~ 1

Trans-Relativistic SNe (Low-Luminosity GRBs)



from Fan et al. 10

Nearby GRBs (ex. 060218@140Mpc, 980425@40Mpc) may form another class

- much dimmer ($E_{LL\gamma}^{iso}$ ~10^{50} erg ⇔ $E_{GRB\gamma}^{iso}$ ~10^{53} erg/s)
- more frequent (ρ_{LL} ~$10^{2\text{-}3}$ Gpc^{-3} yr^{-1} ⇔ ρ_{GRB} ~0.05-1 Gpc^{-3} yr^{-1})
- relativistic ejecta (the other GRB-SNe + 2009bb) (Soderberg+ 10 Nature)
- more baryon-rich? (e.g., Zhang & Yan 11 ApJ), relevant for UHECRs? (KM et al. 06 ApJ)

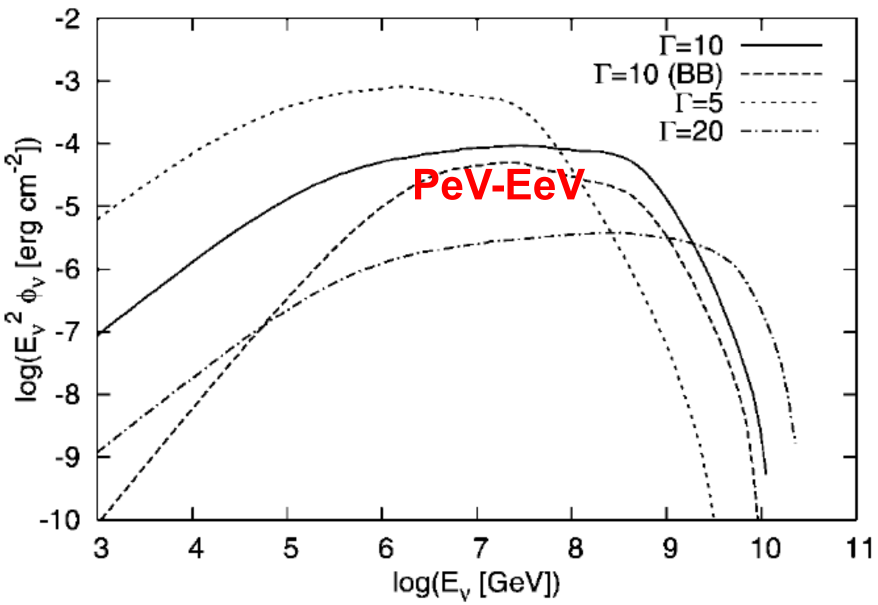
Two Competing Scenarios

- Inner jet dissipation (similar to GRBs)

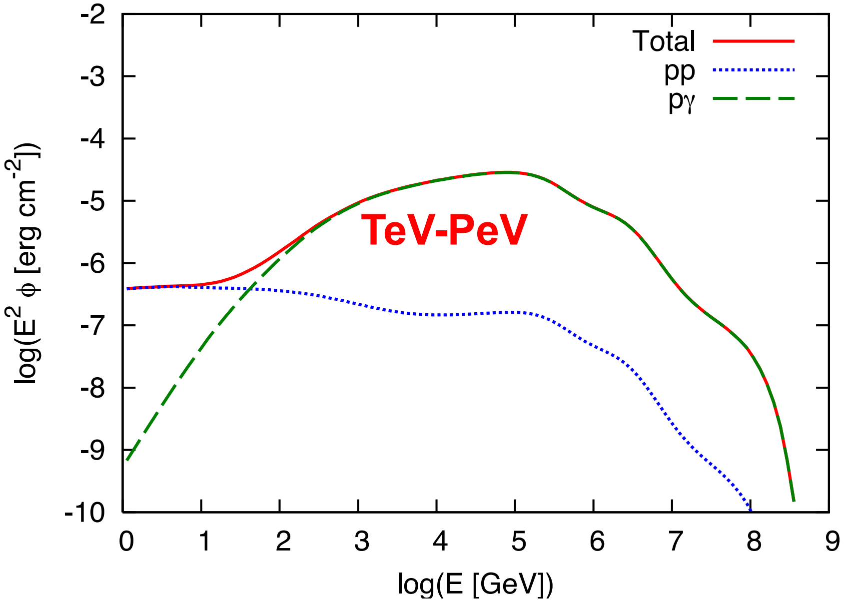
(Toma et al. 07 ApJ, Fan et al. 10 ApJL)

- Shock breakout from optically-thick wind

(Waxman et al. 07 ApJ, Nakar & Sari 12 ApJ)



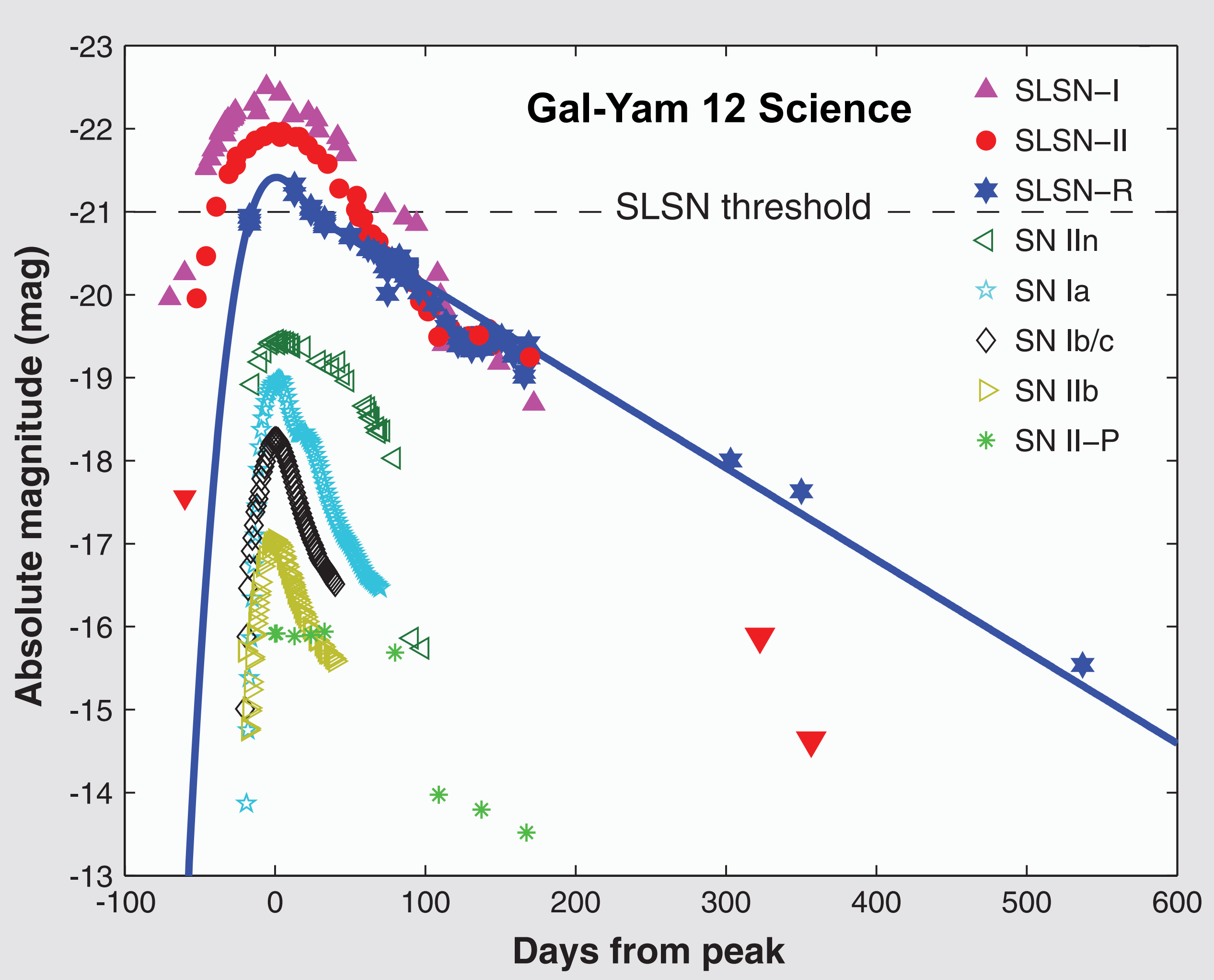
KM et al. 06 ApJL



Kashiyama et al. 12

The signal is detectable for nearby SNe at D < 10 Mpc

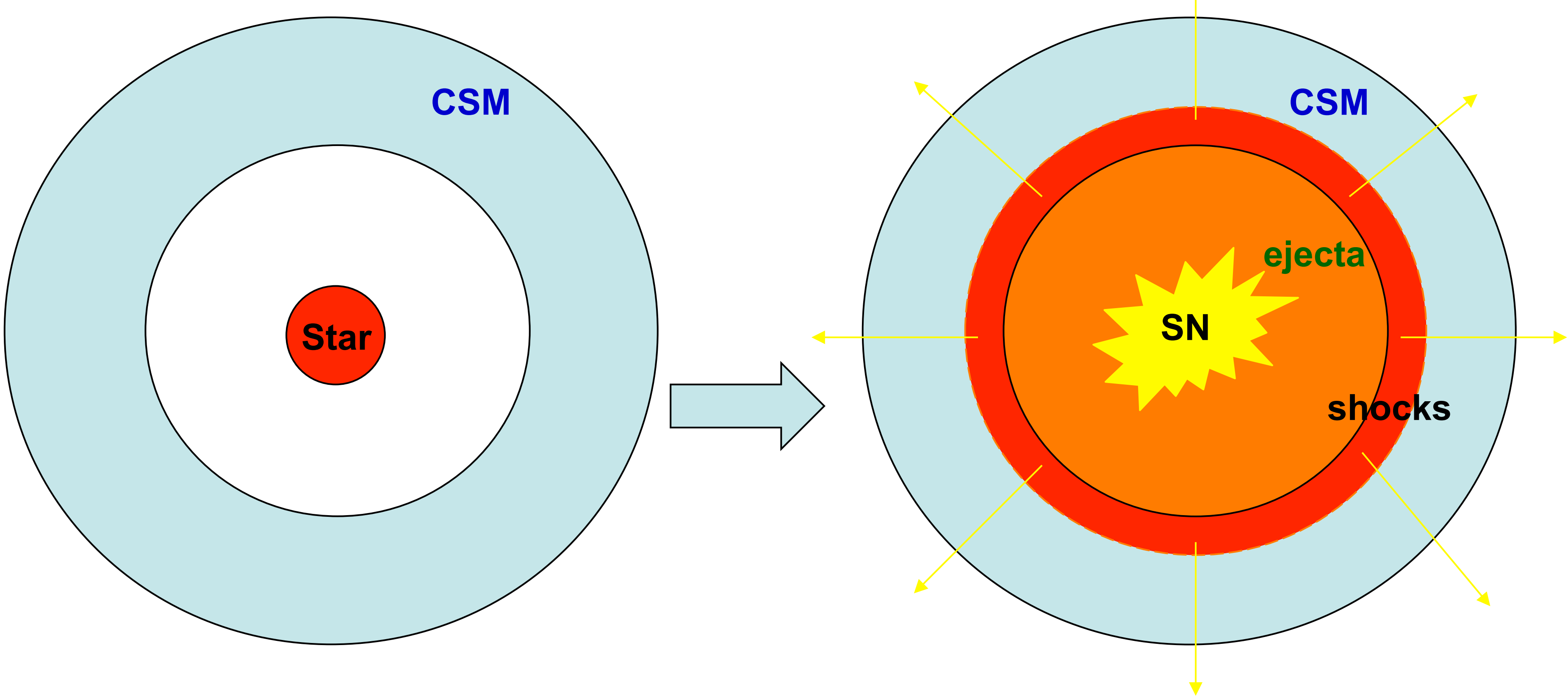
SNe IIn & Super-Luminous SNe



Circumstellar-Material-Collision Scenario

CSM eruptions before explosion

True SN explosion



kinetic energy → thermal + radiation

$$E_{\rm rad} \simeq \frac{\alpha M_{\rm CSM}}{M_{\rm ej} + M_{\rm CSM}} E_{\rm ej}.$$

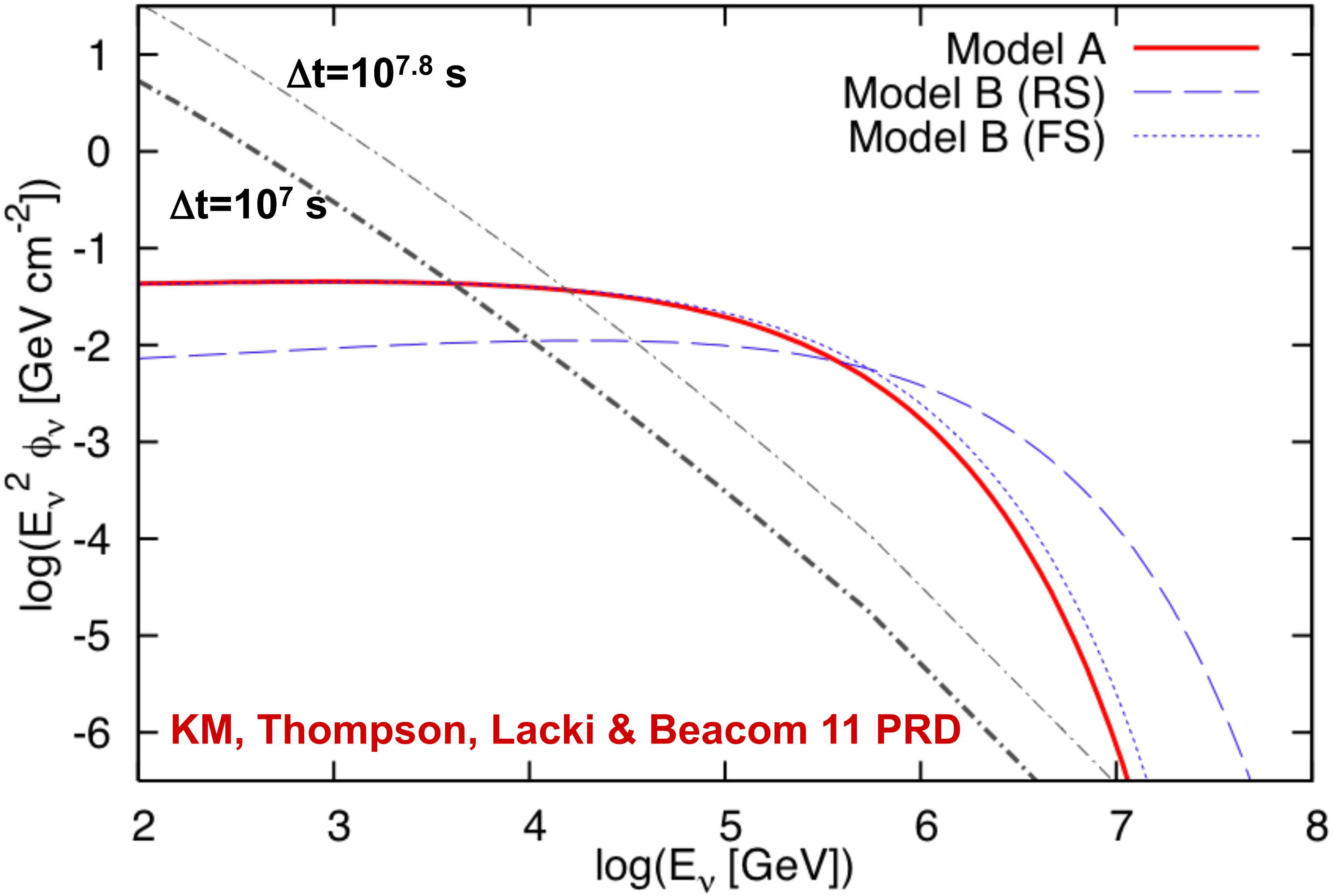
Similar to SNe IIn mechanism
for luminous SNe,
Smith & McCray 07 ApJL, Woosley+ 07 Nature

From SNe IIn to Luminous SNe

- $\tau_T >> 1$ collision → luminous SNe
  strong thermalization (optical, infrared)
  ex. SN 2006gy
  $R \sim 3\text{x}10^{15}$ cm, $V \sim 5000$ km/s
  $n_{CSM} \sim 3\text{x}10^{10}\ \text{cm}^{-3}$ ($M_{CSM} \sim 10\ M_{sun}$)
  characteristic timescale: $t_{bo} \sim t_{diff} \sim t_{dyn} \sim 60$ day

- $\tau_T < 1$ collision → SNe IIn
  weaker thermalization (optical + x rays, radio)
  ex. SN 2006jd
  $R \sim 3\text{x}10^{16}$ cm, $V \sim 5000$ km/s
  $n_{CSM} \sim 3\text{x}10^{6}\ \text{cm}^{-3}$ ($M_{CSM} \sim 1\ M_{sun}$)
  characteristic timescale: $t_{dyn} \sim 2$ yr

Neutrinos from SNe Colliding with Massive CSM



Model A
- optically thick collision

Model B
- optically thin collision

V_s ~ $10^{3.5}$-10^4 km/s
If ε_B~10^{-3}-10^{-2} → E_{max} ~ PeV

If CRs carry ~10% (E_{CR} ~ 10^{50} erg c.f. SNR)
→ # of μs ~a few for SN@10Mpc

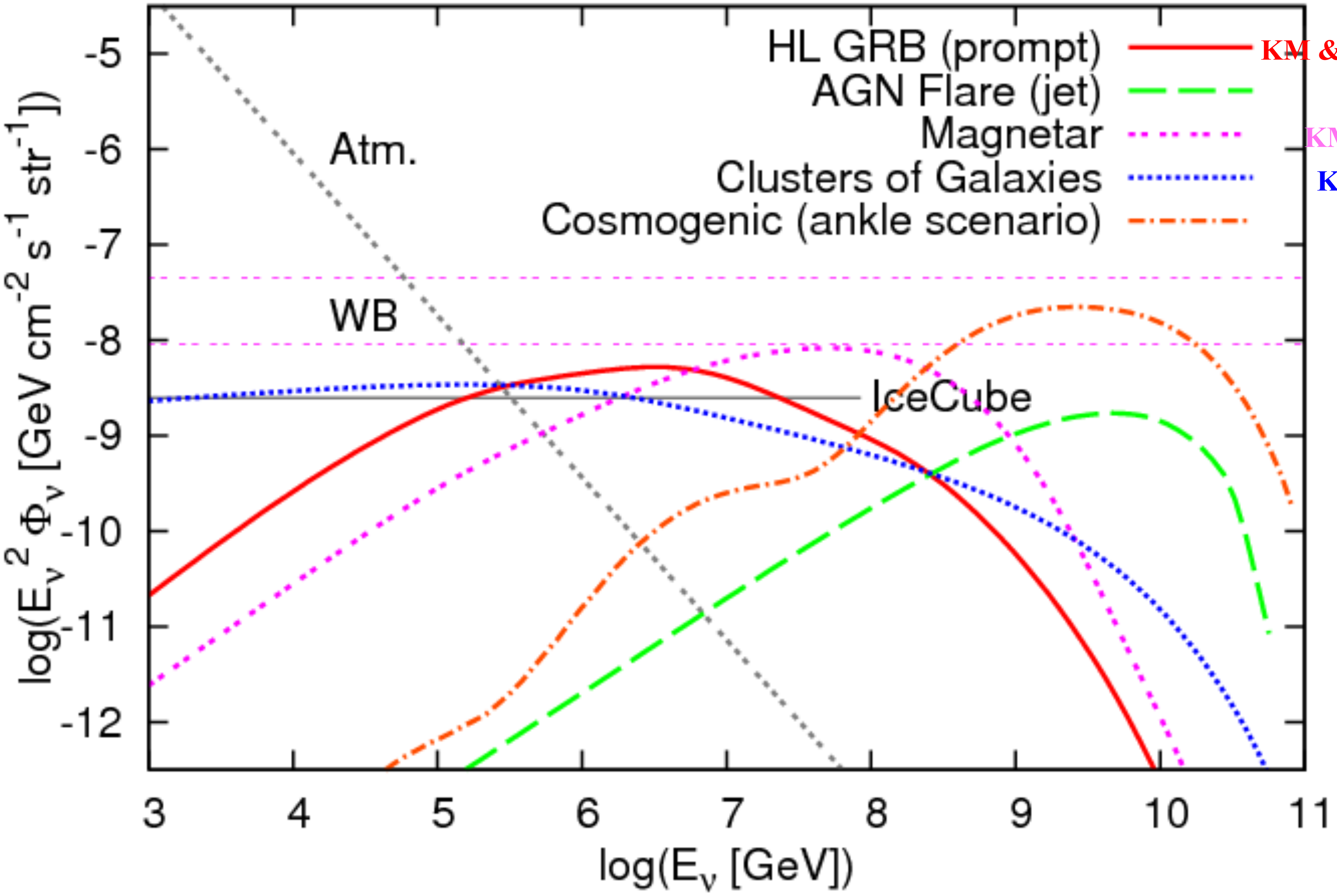
Summary: SN Neutrinos

- Shock acc. may occur after **τ_T ~ c/V** → **TeV-PeV** νs (νs from slow jets are unlikely since $\tau_T >> 1$)
- Possible non-shock acc. in magnetars → **PeV-EeV** νs
- Detectable typically up to **< ~10 Mpc**
- Timescales longer than GRBs → fight w. atm. νs…
  - trans-relativistic SNe (~ hr)
  - magnetar-driven SNe (~ day)
  - SN colliding with CSM (~ month-to-year)

  → counterparts in opt./IR (+ x rays, radio and γ rays)

→ probes of emission mechanisms, mass loss, progenitors and GRB-SN connection

Various Predictions for Neutrino Background



KM & Nagataki 06 PRD, KM 08 PRD

KM 08 AIPC

KM, Zhang & Meszaros 09 PRD

KM, Inoue & Nagataki 08 ApJL

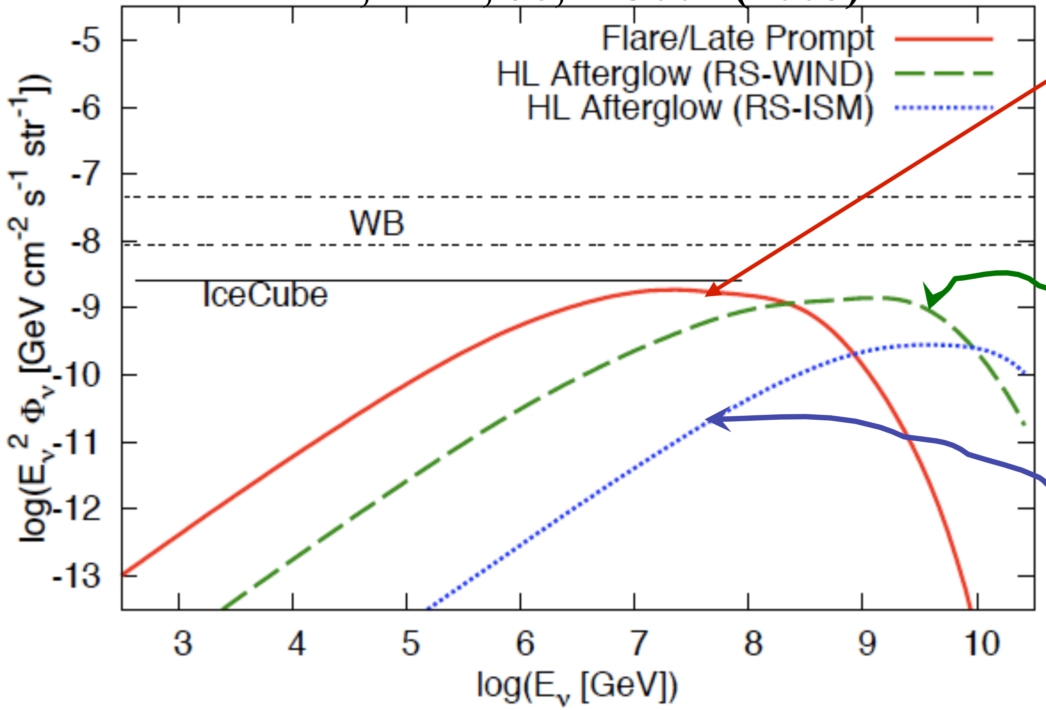
Takami, KM et al. 09 APh

Backup Slides

GRB Early Afterglow Emission

- Most νs are radiated in ~0.1-1 hr (physically max[T, T_{dec}])
- Afterglows are typically explained by external shock scenario
- But flares and early afterglows may come from internal dissipation

KM, PRD, 76, 123001 (2007)



Inner jet protons + flare x rays
(normalized by 10% of UHECR budget)

KM & Nagataki, PRL, 97, 051101 (2006)

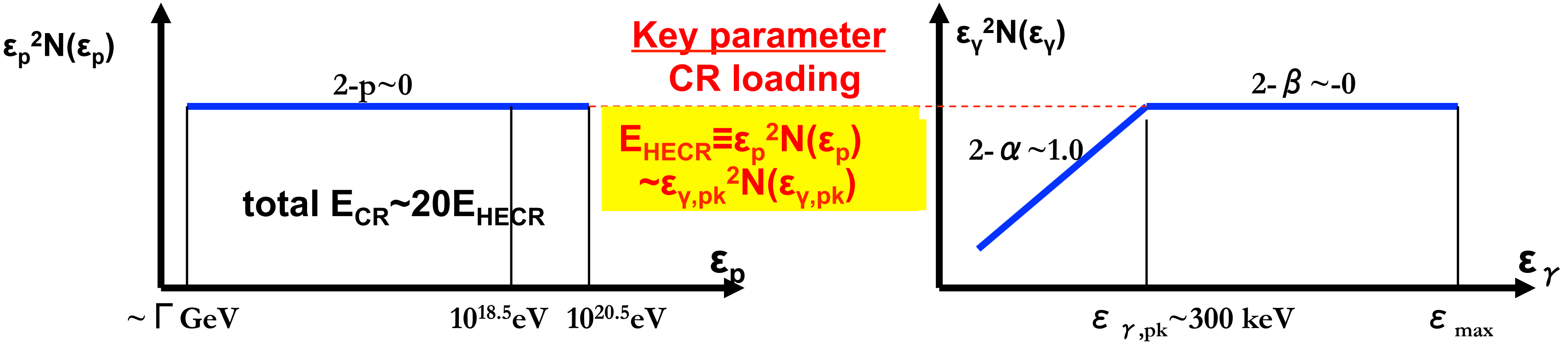
ES protons + ES opt-x rays
stellar wind medium
(normalized by UHECR budget)

ES protons + ES opt-x rays
interstellar medium
(normalized by UHECR budget)

- Flares – efficient meson production ($f_{p\gamma}$ ~ 1-10), maybe detectable
- External shock – not easy to detect both νs and hadronic γ rays

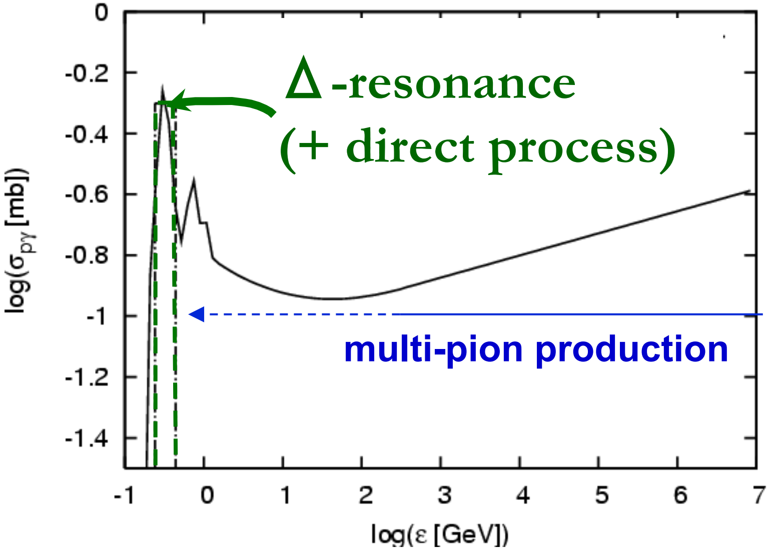
Basics of Neutrino Emission

CR Spectrum (Fermi mechanism) **Photon Spectrum (observed)**



Key parameter
CR loading

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



(in proton rest frame)

Photomeson Production

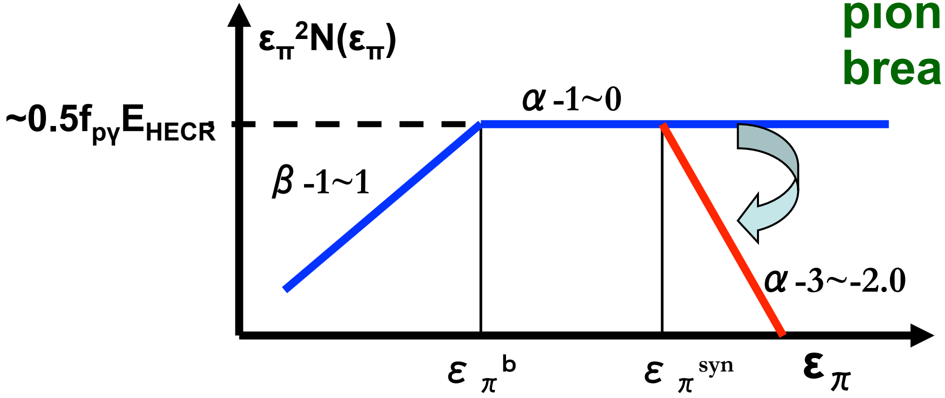
at Δ-resonance
$\varepsilon_p \, \varepsilon_\gamma \sim 0.3 \, \Gamma^2 \, \mathrm{GeV}^2$
$\varepsilon_p^b \sim 0.15 \, \mathrm{GeV} \, m_p c^2 \, \Gamma^2 / \varepsilon_{\gamma,pk} \sim 50 \, \mathrm{PeV}$

Photomeson production efficiency
~ effective optical depth for pγ process

$f_{p\gamma} \sim 0.2 \, n_\gamma \sigma_{p\gamma} \, (r/\Gamma)$

※multi-pion effect ~3-6 (KM & Nagataki 06 PRD)

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

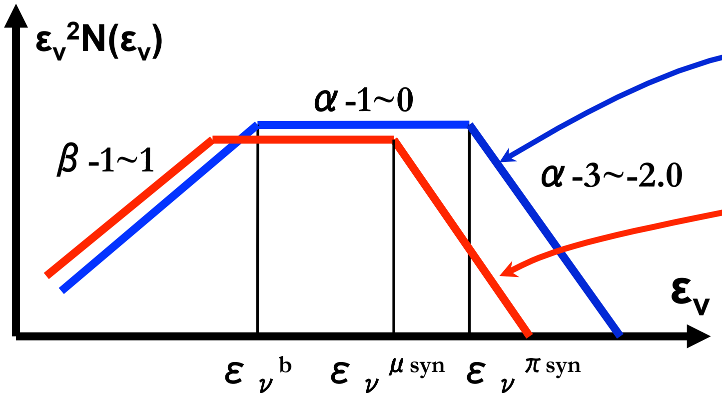
meson cooling before decay

(meson cooling time) ~ (meson life time)

→ break energy in neutrino spectra

Neutrino Spectrum

“Waxman-Bahcall” type spectrum (Waxman & Bahcall 97 PRL)



$$\pi^\pm \to \mu^\pm + \nu_\mu(\overline{\nu}_\mu)$$

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

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

Neutrino oscillation

$$\begin{tikzcd} & \nu_e:\nu_\mu:\nu_\tau=1:1:1 & \text{No loss} \\ \nu_e:\nu_\mu:\nu_\tau=1:2:0 \arrow[ur] \arrow[dr] & & \\ & \nu_e:\nu_\mu:\nu_\tau=1:1.8:1.8 & \text{High } \varepsilon_\nu \text{ Loss limit} \end{tikzcd}$$

(e.g., Kashti & Waxman 05 PRL)