High-Energy Neutrinos from Cosmic Explosions

Kohta Murase
Institute for Advanced Study, USA

IceCube Particle Astrophysics Symposium
May 2013

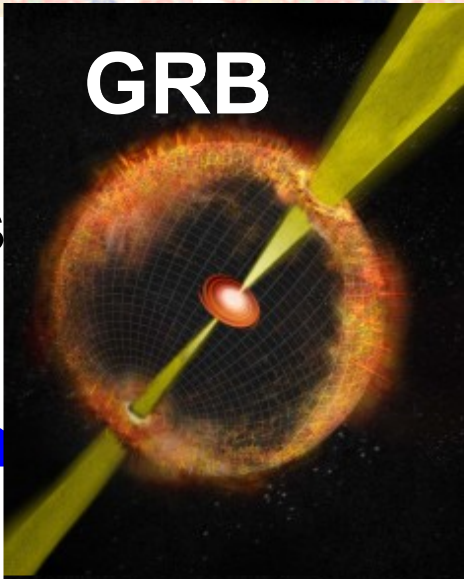
Outline

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

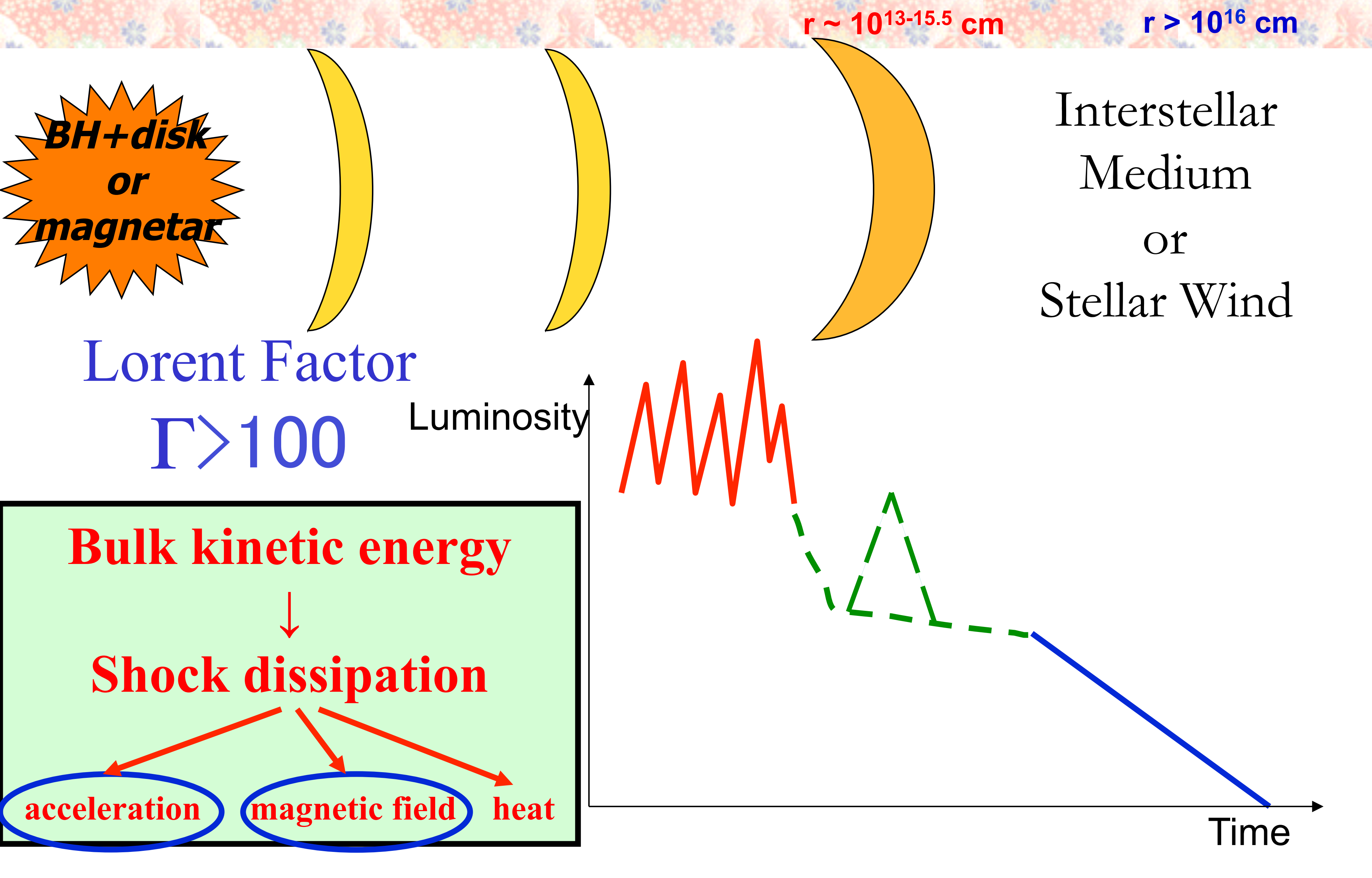
GRB-SN con., jet dynamics, composition
+ CR origin, CR acc. mechanisms

Overview of GRBs/SNe as HE ν sources

1. GRBs as UHECR sources
2. "Subphotospheric" neutrinos
3. Possibilities for PeV events (quick)



Gamma-Ray Bursts: “Classical” Pictures

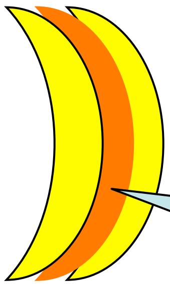


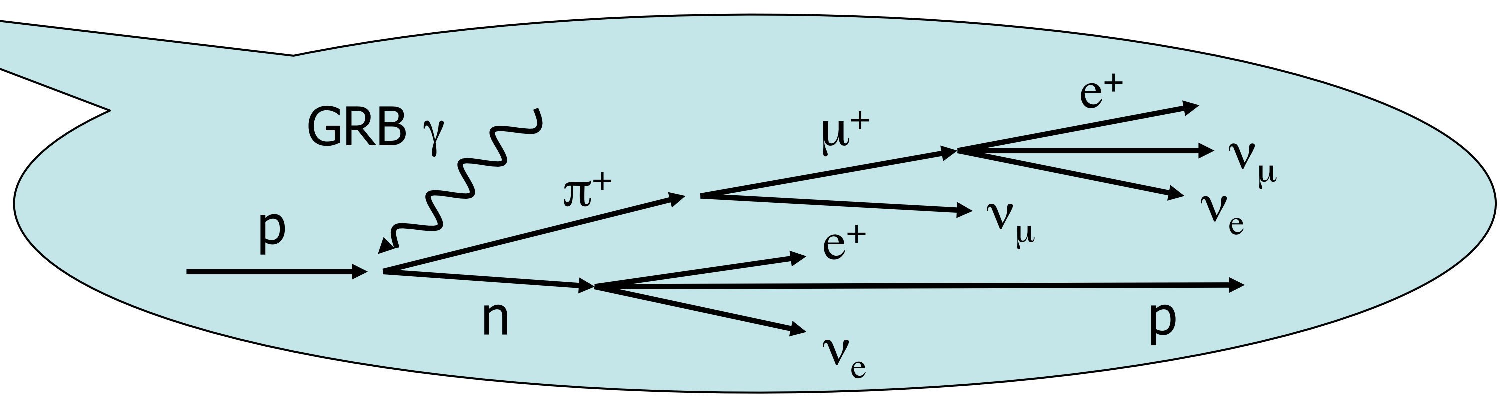
Neutrino Production in the Source

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

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

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





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

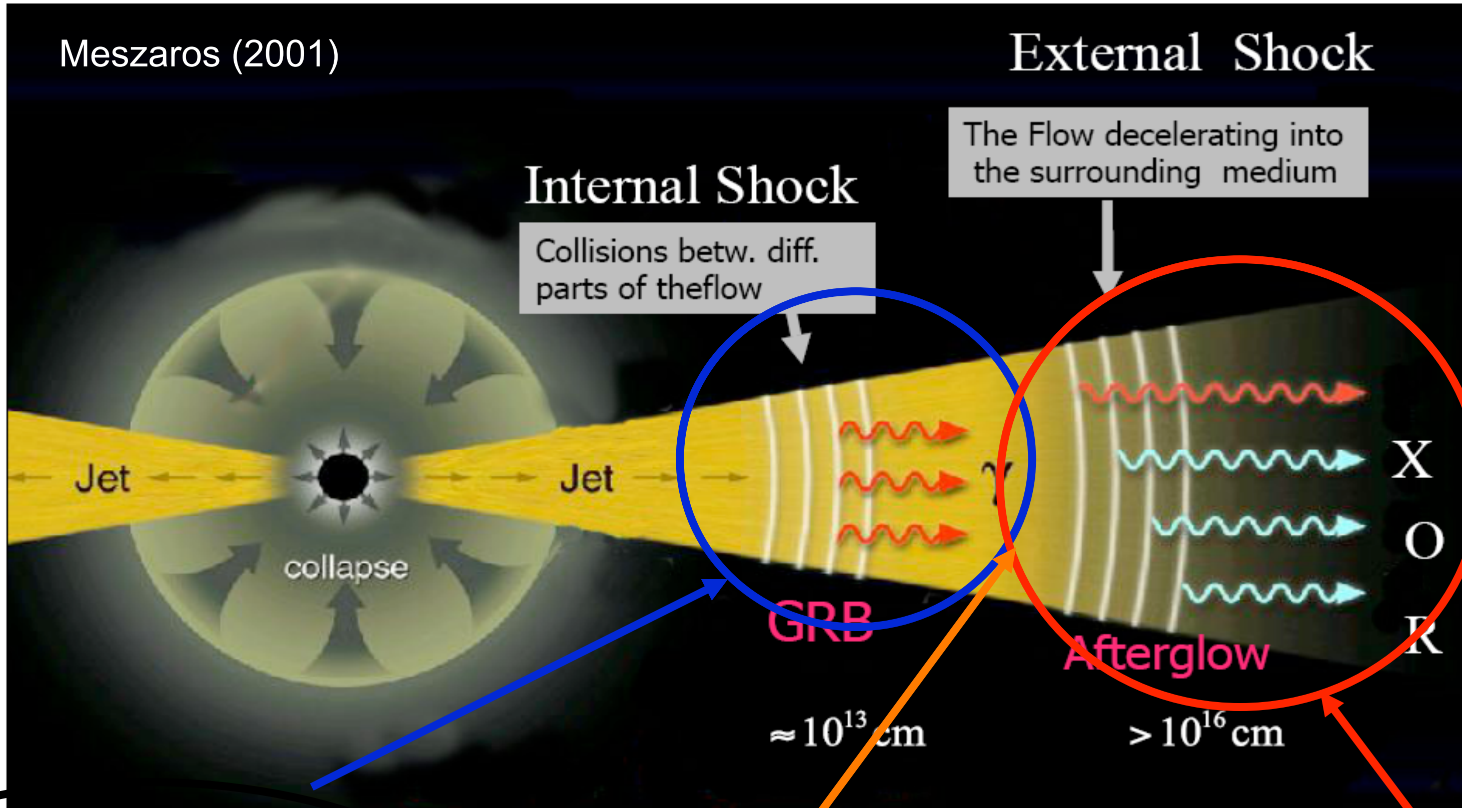
$\varepsilon_\nu^b \sim 0.05\varepsilon_p^b \sim 0.01$ GeV^2 $\Gamma^2/\varepsilon_{\gamma,pk} \sim$ 1 PeV (if $\varepsilon_{\gamma,pk} \sim$ 1 MeV)

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)

CR Acceleration in "Classical" Pictures

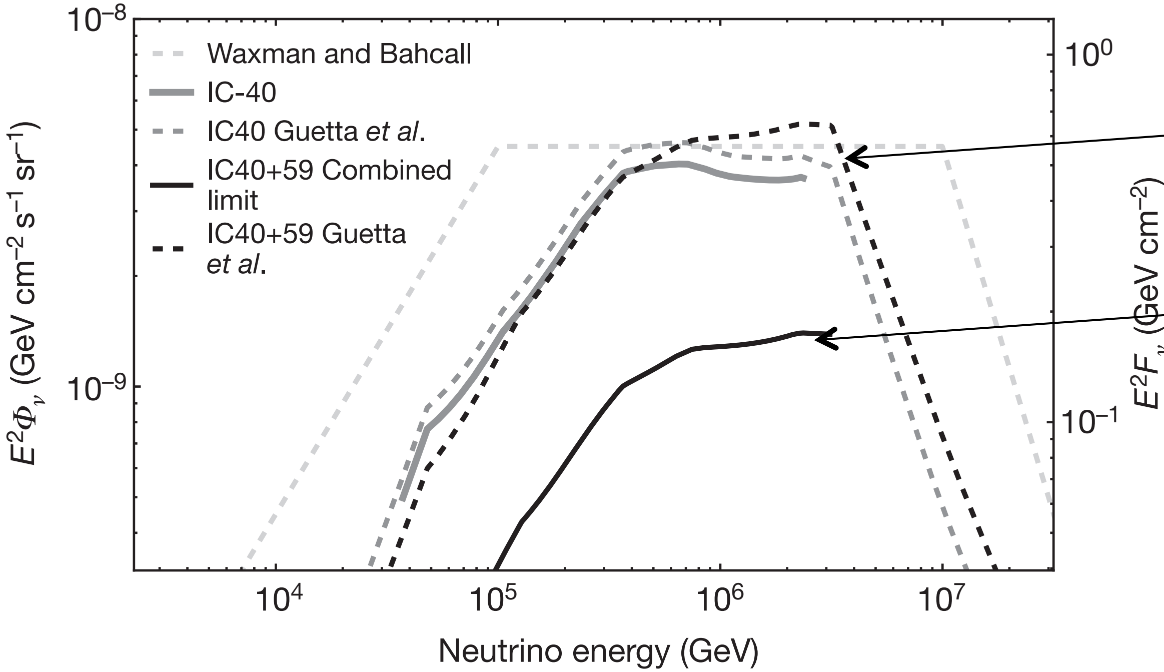


Inner jet (prompt emission)
$r \sim 10^{12}\text{-}10^{16}$ cm $B \sim 10^{2\text{-}6}$ G
PeV ν, GeV-TeV γ
Waxman & Bahcall 97 PRL
Dermer & Atoyan 03 PRL

Inner jet (flares)
$r \sim 10^{14}\text{-}10^{16}$ cm $B \sim 10^{2\text{-}4}$ G
PeV-EeV ν, GeV-TeV γ
KM & Nagataki 06 PRL

External shock (afterglow)
$r \sim 10^{16}\text{-}10^{17}$ cm $B \sim 0.1\text{-}100$ 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

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)

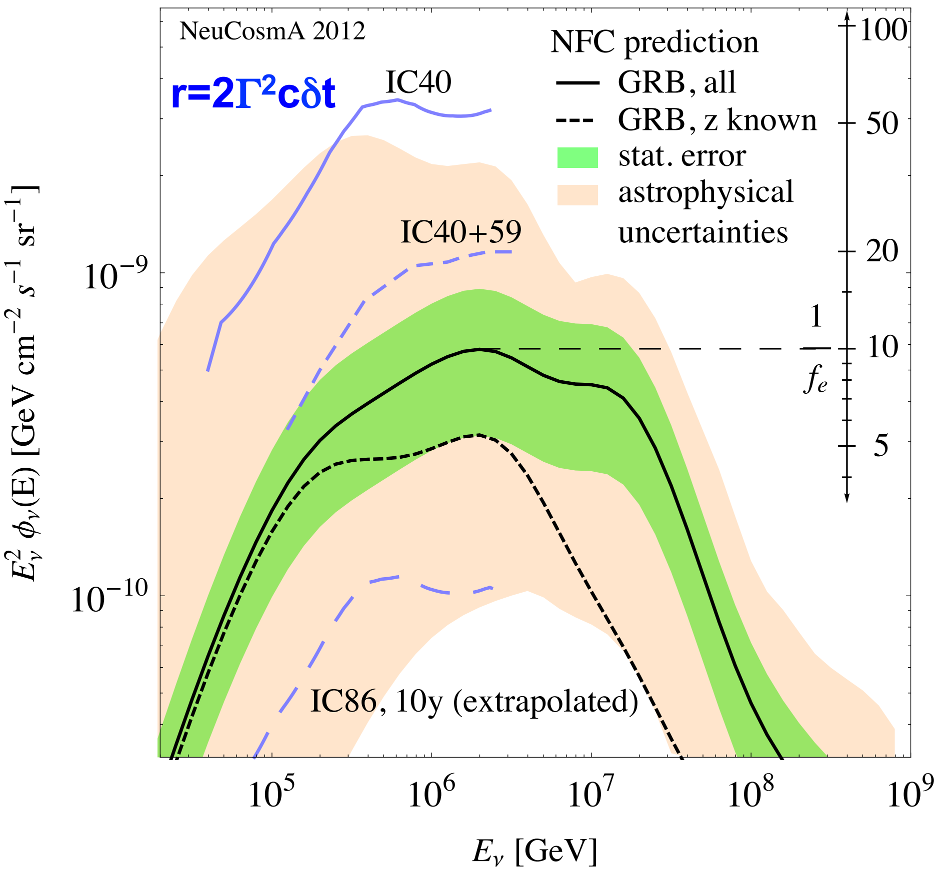
2. ($\varepsilon_\gamma^2\ \phi_\gamma$ at $\varepsilon_{\gamma,pk}$) ≠ ($\int d\varepsilon_\gamma\ \varepsilon_\gamma\ \phi_\gamma$) → ~3-6 ↓ (Hummer et al. 12 PRL, He et al. 12 ApJ)

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

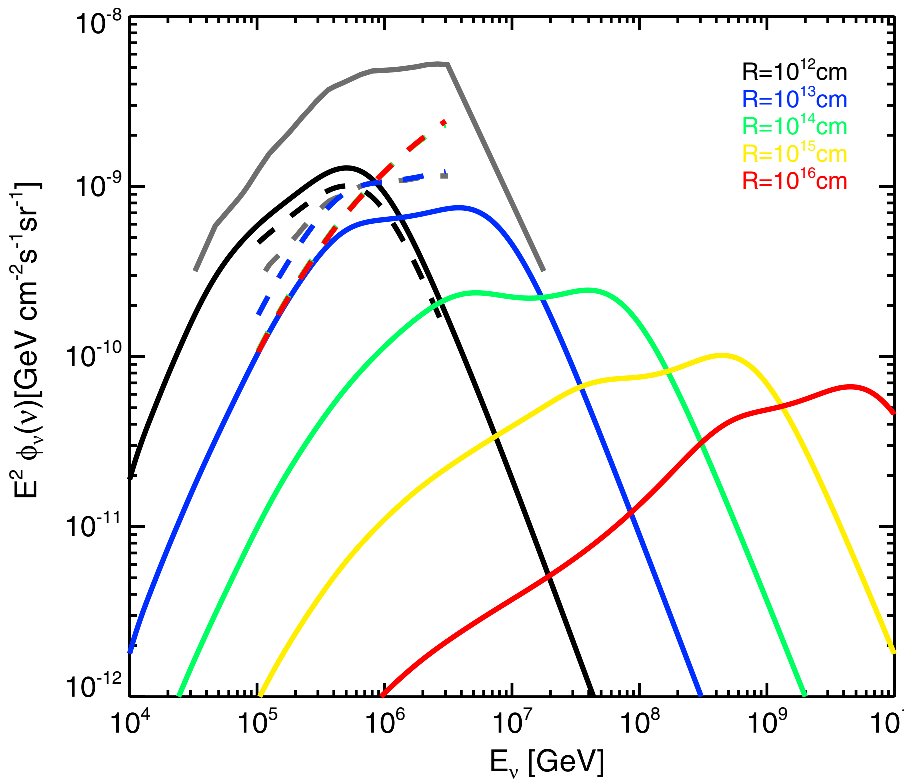
- Different from "astrophysical" model-uncertainty in calculating $f_{p\gamma}$
- Considered in earlier calculations for a given parameter set (ex. Dermer & Atoyan 03 KM & Nagataki 06)

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)**

$\tau_{A\gamma} \sim n_\gamma \sigma_{A\gamma} (r/\Gamma) < 1$

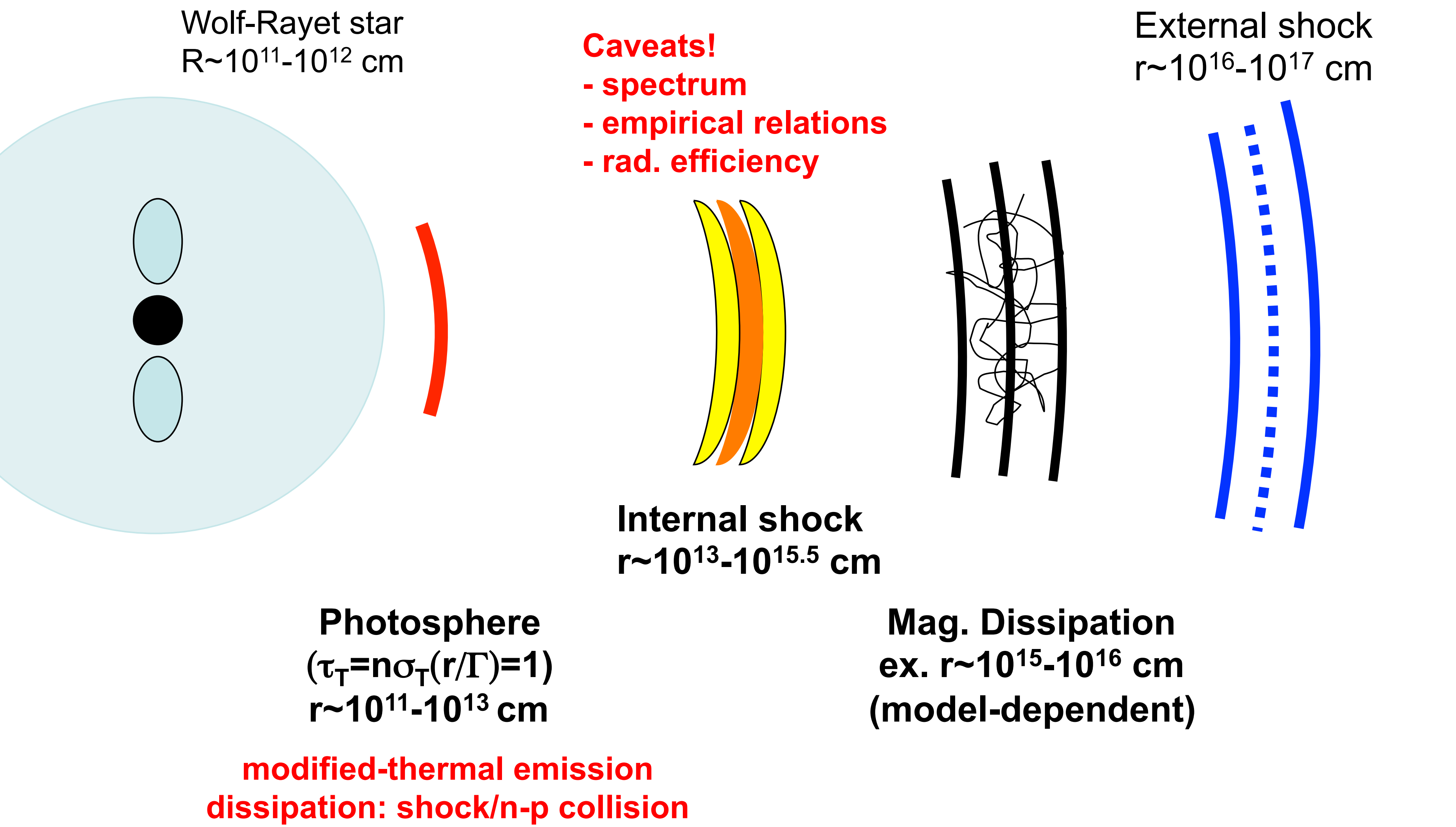
$f_{mes} \sim (0.2/A) n_\gamma A \sigma_{p\gamma} (r/\Gamma) \sim \tau_{A\gamma}(0.2\sigma_{p\gamma}/\sigma_{A\gamma}) < 10^{-3}$ (for Fe)

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

ex. ~3×10^{-11} GeV cm^{-2} s^{-1} sr^{-1} obtained in a model
below IceCube limits (but hard to test…)

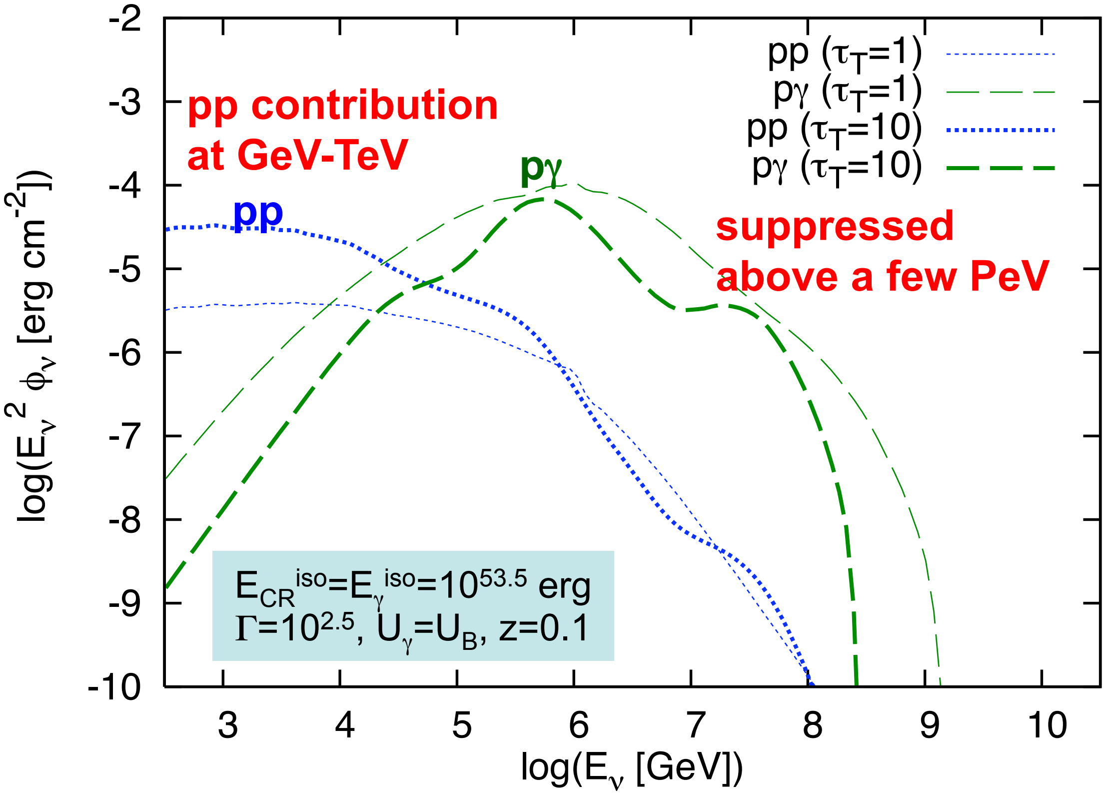
2. Subphotospheric Neutrinos (that do not require UHECRs)

Fall of "Classical" GRB Pictures



GeV-PeV Neutrinos: Subphotospheric Shock Dissipation

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



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

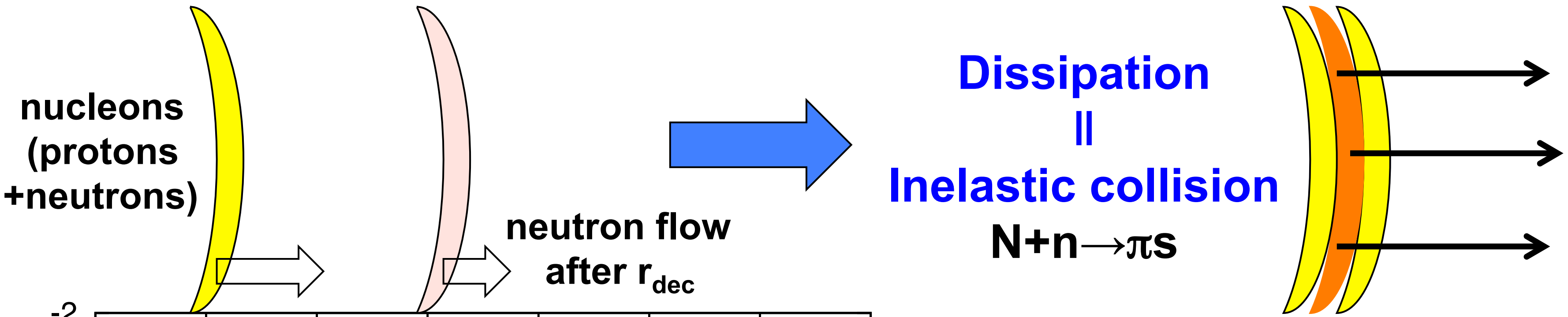
certain pp/pγ efficiencies
→ sensitive to E_{CR}

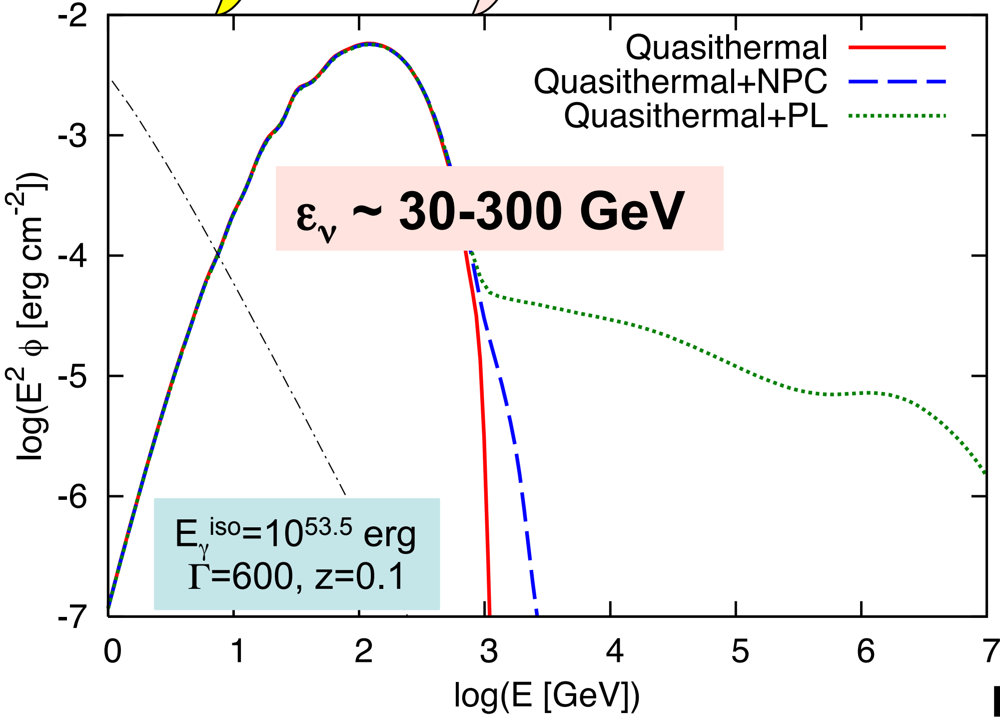
Allowed so far, but tested in 10 yrs if $E_{CR} \sim E_\gamma$ (KM+ 12 ApJ, Gao+ 12 JCAP)

※ NO UHECR acc., much radiation in jets → unlikely $E_{CR} \sim 10 E_\gamma$

Quasi-Thermal Neutrinos: Neutron-Loaded Outflows

Nn collisional model (e.g., Meszaros & Rees 00 ApJ, Beloborodov 10 ApJ)





- Inevitable νs & no CR acc. is required
- $\varepsilon_\nu^2 \phi_\nu \sim \varepsilon_\gamma^2 \phi_\gamma$ → model is testable
- with DeepCore → detectable in ~10 yrs

KM, Kashiyama & Meszaros 13, Bartos+ 13

Remarks: Subphotospheric Emissions from SNe?

SN shock breakout emission ($\tau_T \sim c/V_s >> 1$)
(super-luminous SNe, trans-relativistic SNe)

- Fermi acc. is possible at $\tau_T < c/V_s$ (NOT at radiation-mediated shocks)

KM+ 11 PRD
Katz, Sapir & Waxman 11
Kashiyama, KM+ 13 ApJL

- TeV-PeV νs, detectable up to ~10 Mpc

Neutron-loaded relativistic outflows from proto-NS
(choked jets, proto-magnetar winds)

- Inevitable νs & no Fermi acc. is needed
- Additional n-p conversion acc.

Kashiyama, KM & Meszaros 13

- GeV-TeV νs, ~100 for a Galactic SN

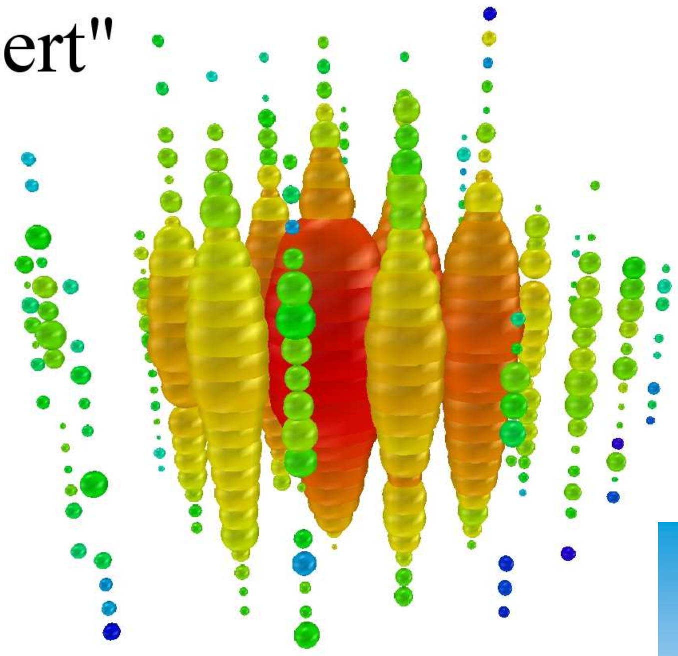
KM, Dasgupta & Thompson 13

3. Possibilities for PeV Events

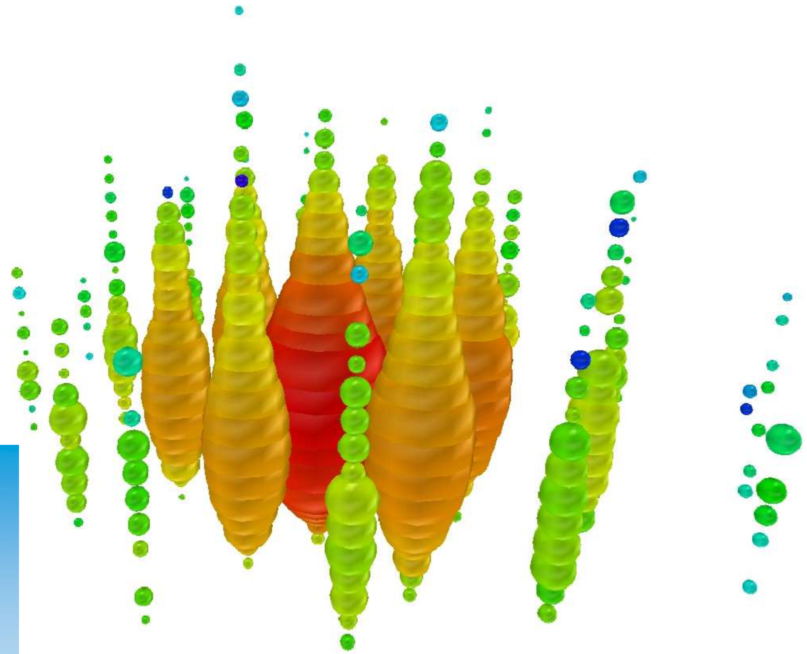
PeV Events Reported in Neutrino 2012

~ PeV neutrinos are found in UHE neutrino search
Atmospheric ν background looks small at these energies

"Bert"

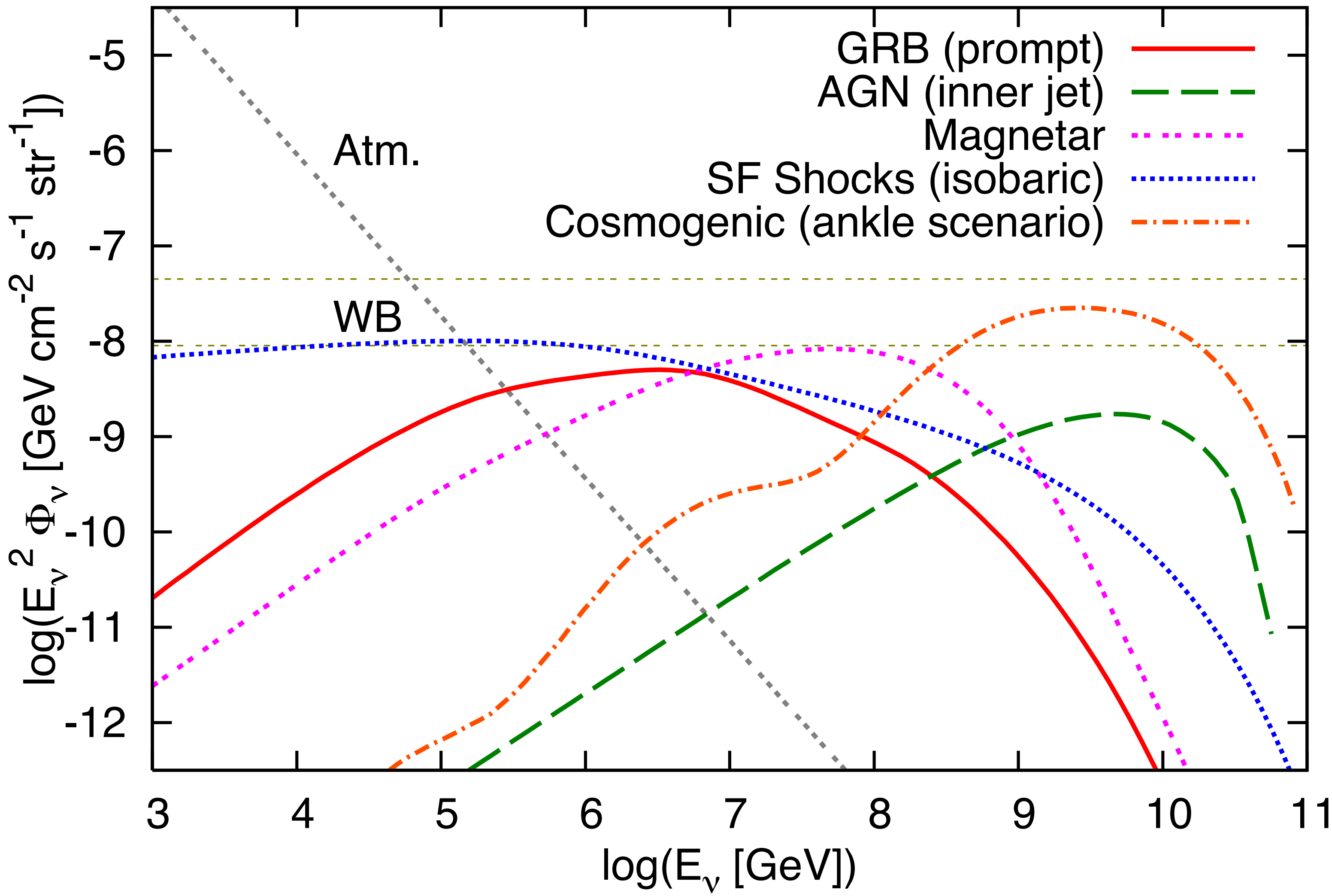


"Ernie"



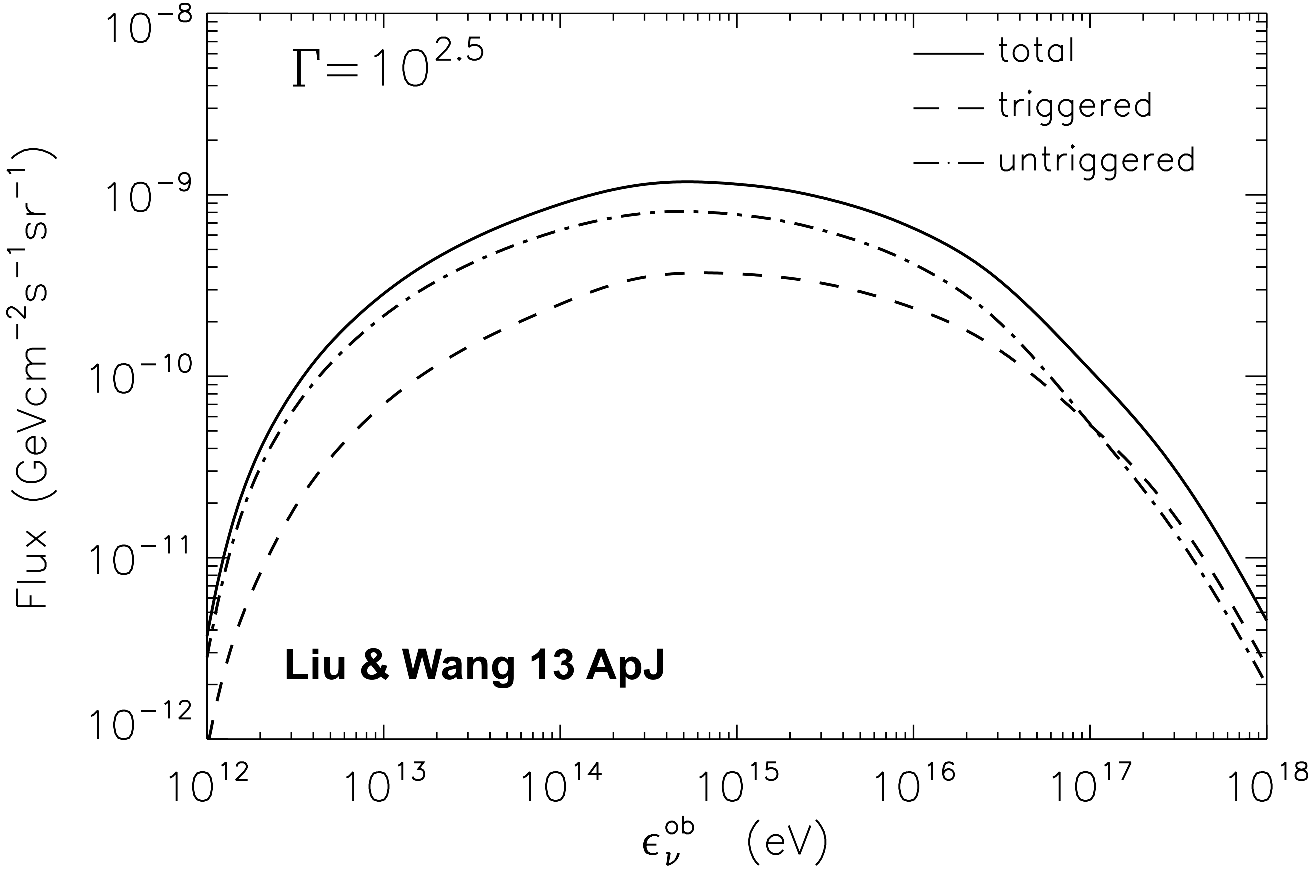
IceCube arXiv:1304.5356

Various Astrophysical Predictions



Some predictions (ex. GRBs, accretion shocks) have the right flux level w. a break/peak at ~PeV
Breaks may come from a meson cooling break or an intrinsic break in CR spectra

Can GRBs Explain Two Events?



It looks difficult (but more statistics are obviously needed)

- Untriggered ~ 2 x triggered <~ 10^{-9} GeV cm^{-2} s^{-1} sr^{-1}
- Smaller than the required flux ~ 10^{-8} GeV cm^{-2} s^{-1} sr^{-1}

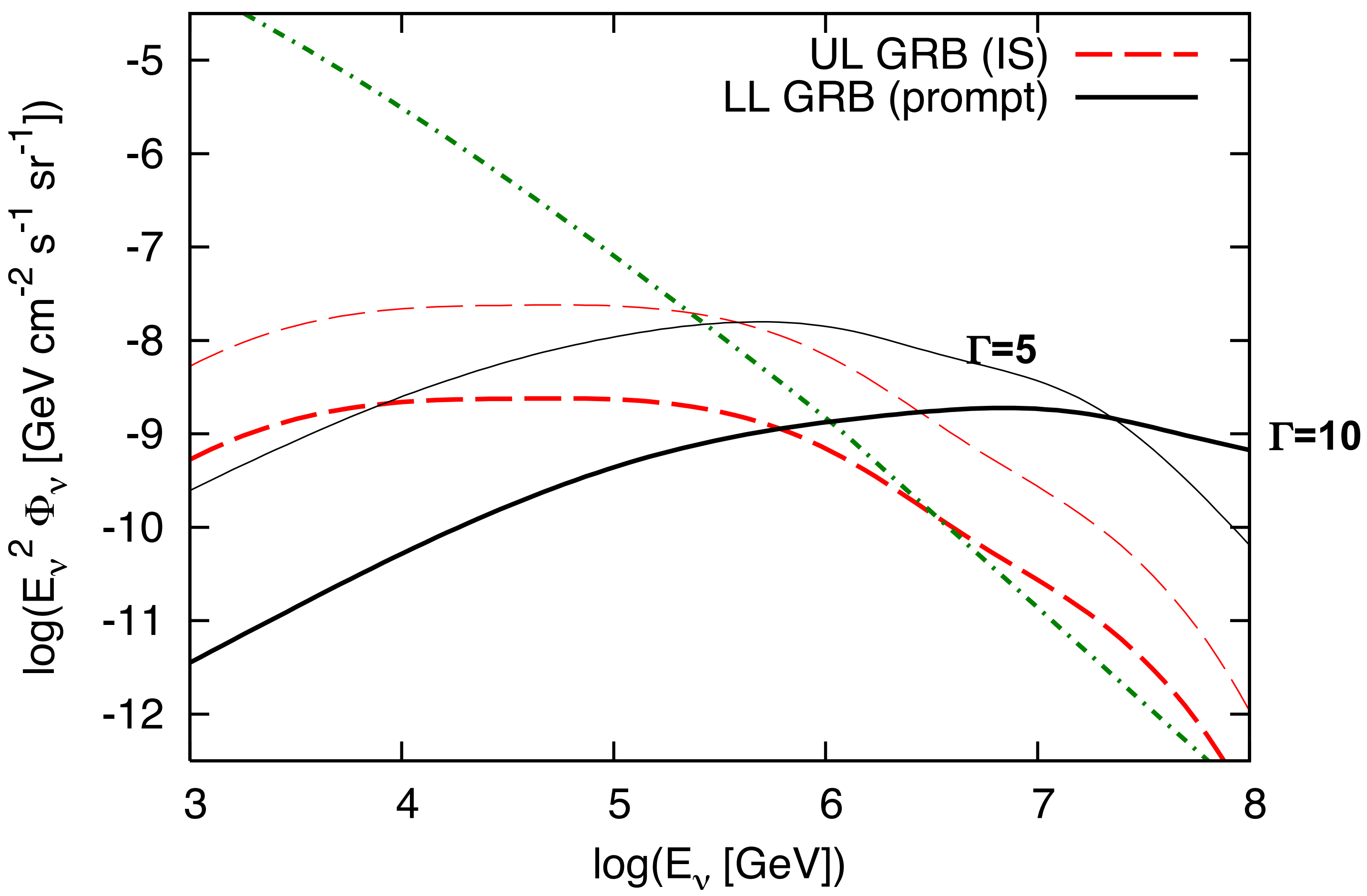
Other Classes of GRBs & SNe

We may miss a lot of "untriggered" transients

- Low-luminosity GRBs (or trans-relativsitic SNe)
  E_γ^{iso}~10^{50} erg , ρ~10^2-10^3 Gpc^{-3} yr^{-1}
  (KM+ 06 ApJL, Gupta & Zhang 07 APh, Kashiyama+ 13 ApJL)
- Ultra-long GRBs
  E_γ^{iso}~10^{53} erg, ρ~1 Gpc^{-3} yr^{-1}?
  (KM & Ioka 13)
- Hypernovae
  E_k~10^{52} erg, ρ~2000 Gpc^{-3} yr^{-1} (Wang+ 07 PRD)
- Crashing SNe (including super-luminous SNe & SNe IIn)
  E_k~10^{51} erg, ρ~1000 Gpc^{-3} yr^{-1}? (KM+ 11 PRD, Katz+ 11)

All of them might explain ~PeV events though they are uncertain

Example: Low-Luminosity GRBs



Predictions are just taken from KM et al. 06 ApJL (not renewed)

Summary

GRB-UHECR hypothesis in ”classical” GRB pictures

- Optimistic cases were excluded (ex. UHEn-escape scenario)
- Most IS parameter ranges will be covered in ~10 yr if UHEp
- Hard to exclude UHE heavy-nuclei scenario
- Do not forget afterglow neutrinos (PeV-EeV νs → ARA)

Subphotospheric emissions (GRBs & SNe)

- Probing the onset of CR acc. in GRBs, SLSNe & trans-rel. SNe
- Relevance of GeV ν detectors for quasi-thermal νs from ns

~ PeV neutrinos may start to be detected

- Less-triggered populations (ex. LL GRBs) may contribute
- Need searches for such longer-duration transients

Backup Slides

Remark I: Subphotospheric Shock Dissipation in SNe?

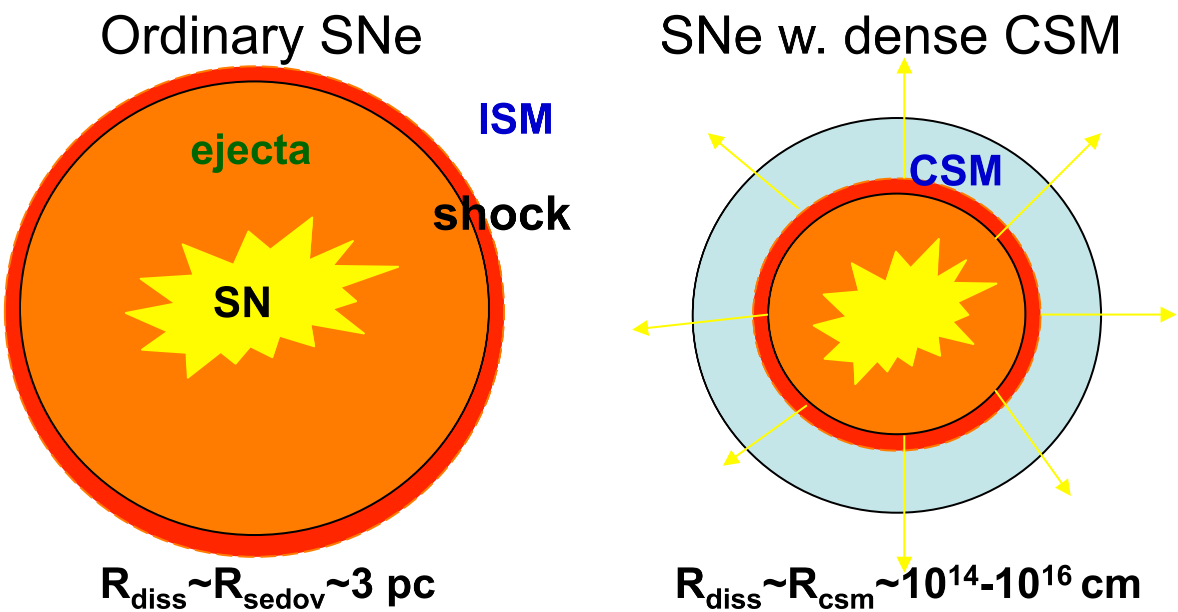
<u>SN shock breakout emission ($\tau_T \sim c/V_s >> 1$)</u>

(super-luminous SNe, trans-relativistic SNe)

- Fermi acc. is possible at $\tau_T < c/V_s$ (NOT at radiation-mediated shocks)

KM+ 11 PRD
Katz, Sapir & Waxman 11
Kashiyama, KM+ 13 ApJL

- TeV-PeV νs, detectable up to ~10 Mpc



<u>Key idea</u>

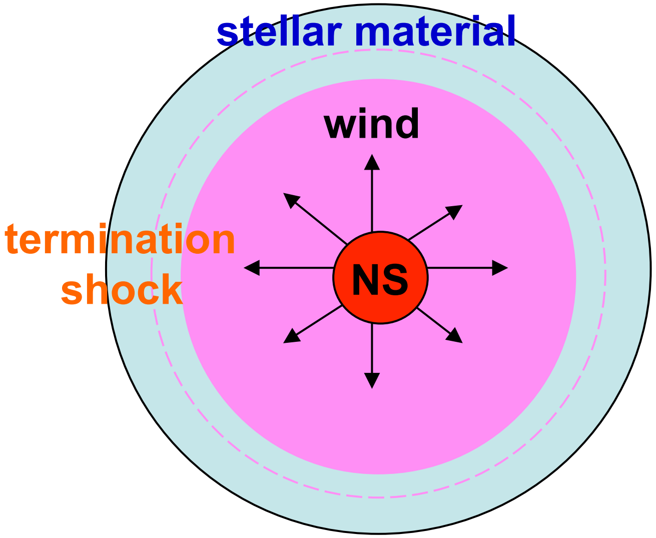
Earlier dissipation
→ higher luminosity "transients"
& efficient pp/pγ

Remark II: Neutron-Loaded Outflows in SNe?

Neutron-loaded relativistic outflows from proto-NS
(choked jets, proto-magnetar winds)

- Inevitable νs & no Fermi acc. is needed
- Additional n-p conversion acc. **Kashiyama, KM & Meszaros 13**
- GeV-TeV νs, ~100 for a Galactic SN

KM, Dasgupta & Thompson 13



Key idea

magnetic outflow acceleration
→ neutrons should be decelerated at the termination shock via n+p → Nπ

Prompt Emission

Ultra-High-Energy Cosmic Rays?

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

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

If UHECR energy output ~ GRB radiation energy

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

with local GRB rate density: ~ 1 Gpc^{-3} yr^{-1}

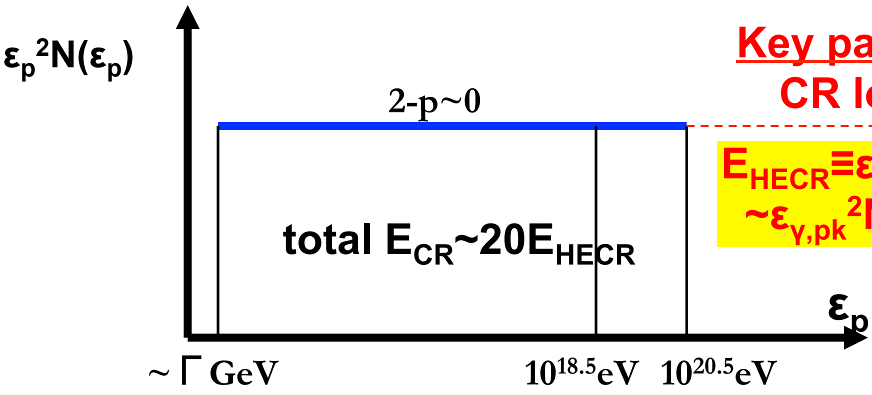
(e.g., Wanderman & Piran 2010, Dermer 12)

↕

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

Basics of ν and γ-ray Emission

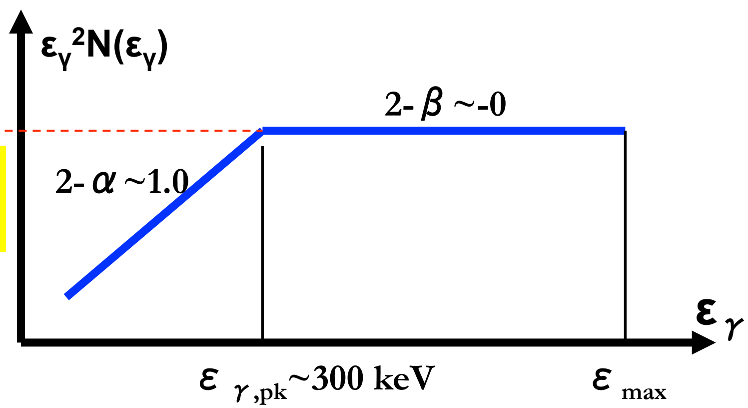
CR Spectrum (Fermi mechanism)

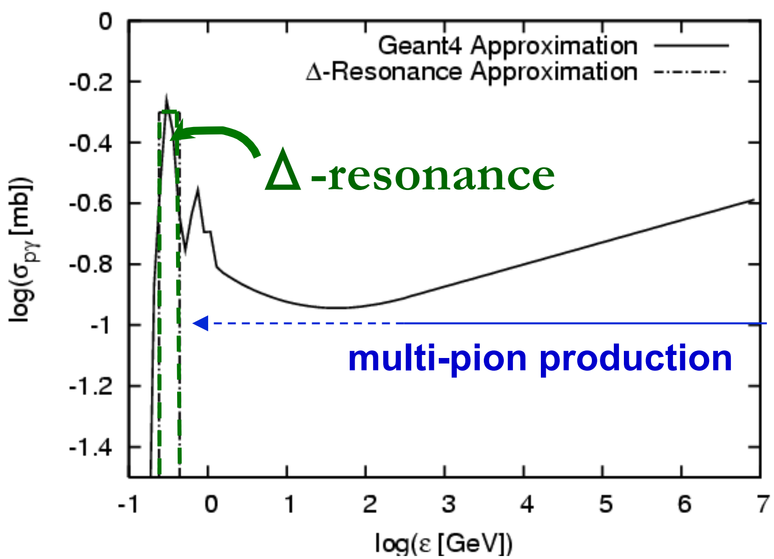


Key parameter
CR loading

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

Photon Spectrum (observed)





(in proton rest frame)

Photomeson Production

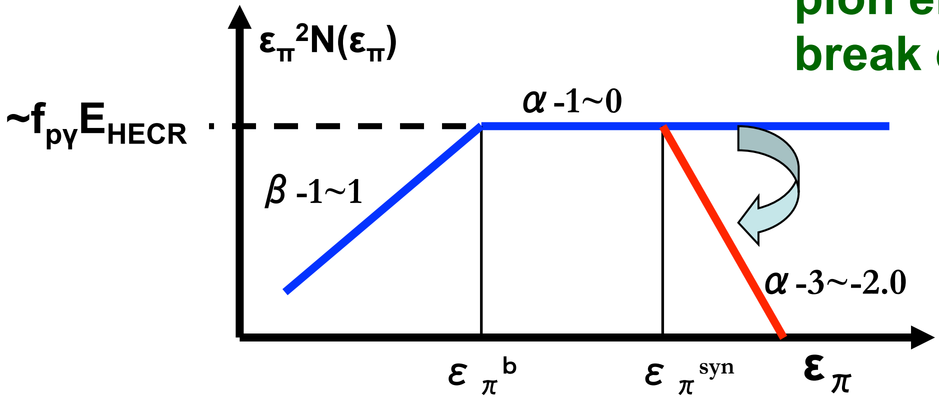
$$p + \gamma \rightarrow n + \pi^+ \quad \kappa_p \sim 0.2$$

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

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

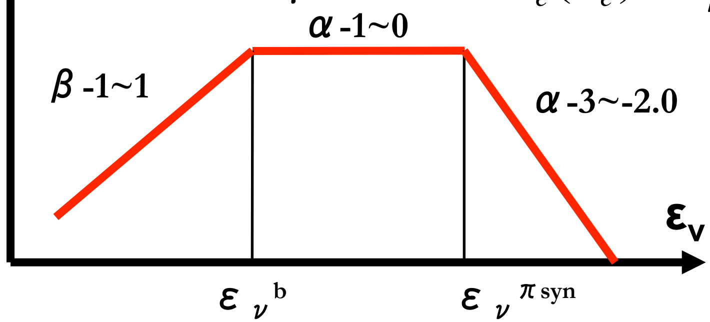
HE charged mesons
(meson cooling time) < (meson life time)
→ suppression at high energies

Waxman & Bahcall, PRL (1997)

Neutrino Spectrum

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

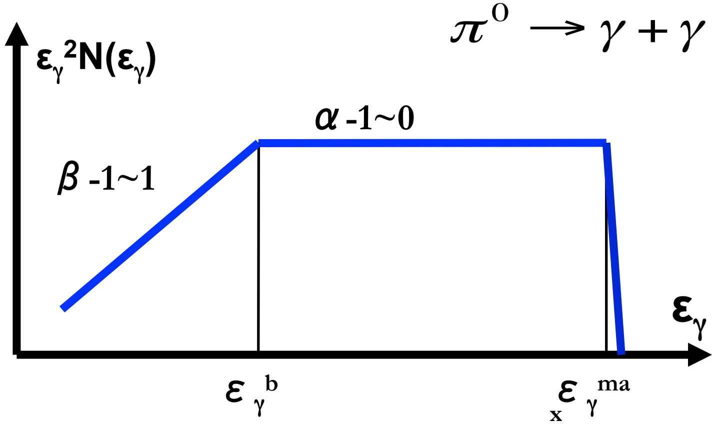
$$\mu^\pm \rightarrow e^\pm + \nu_e(\bar{\nu}_e) + \bar{\nu}_\mu(\nu_\mu)$$



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

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

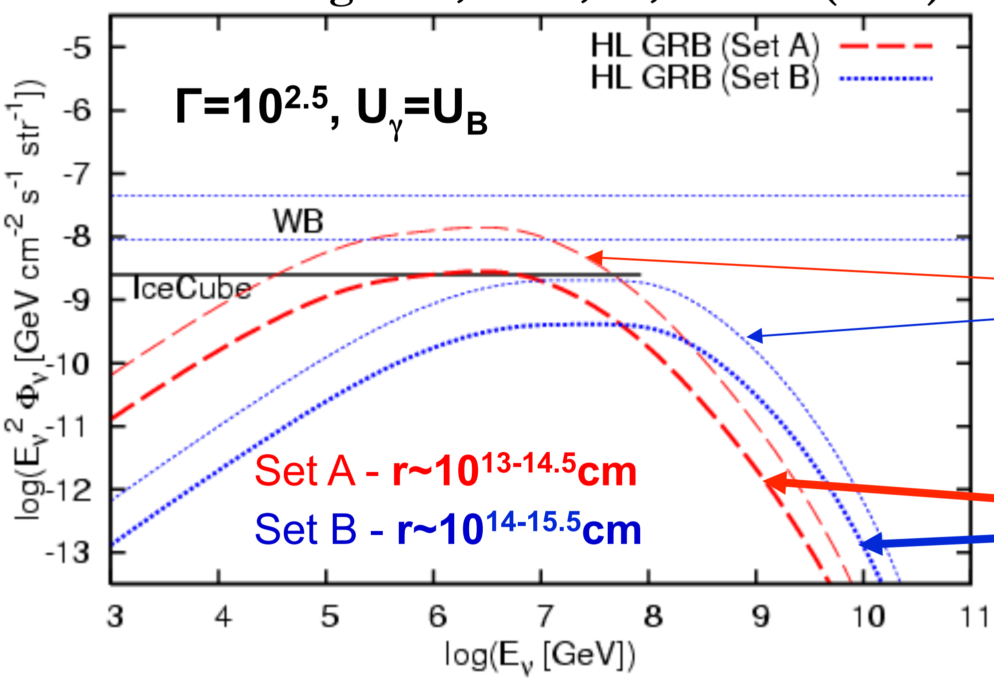


γ-ray energy $\varepsilon_\gamma \sim 0.5\ \varepsilon_\pi \sim 0.1\ \varepsilon_p$
- γ lower break energy $\varepsilon_\gamma^b \sim 5$ PeV
- γ maximum energy $\varepsilon_\gamma^{max} \sim 0.1\ \varepsilon_p^{max}$

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

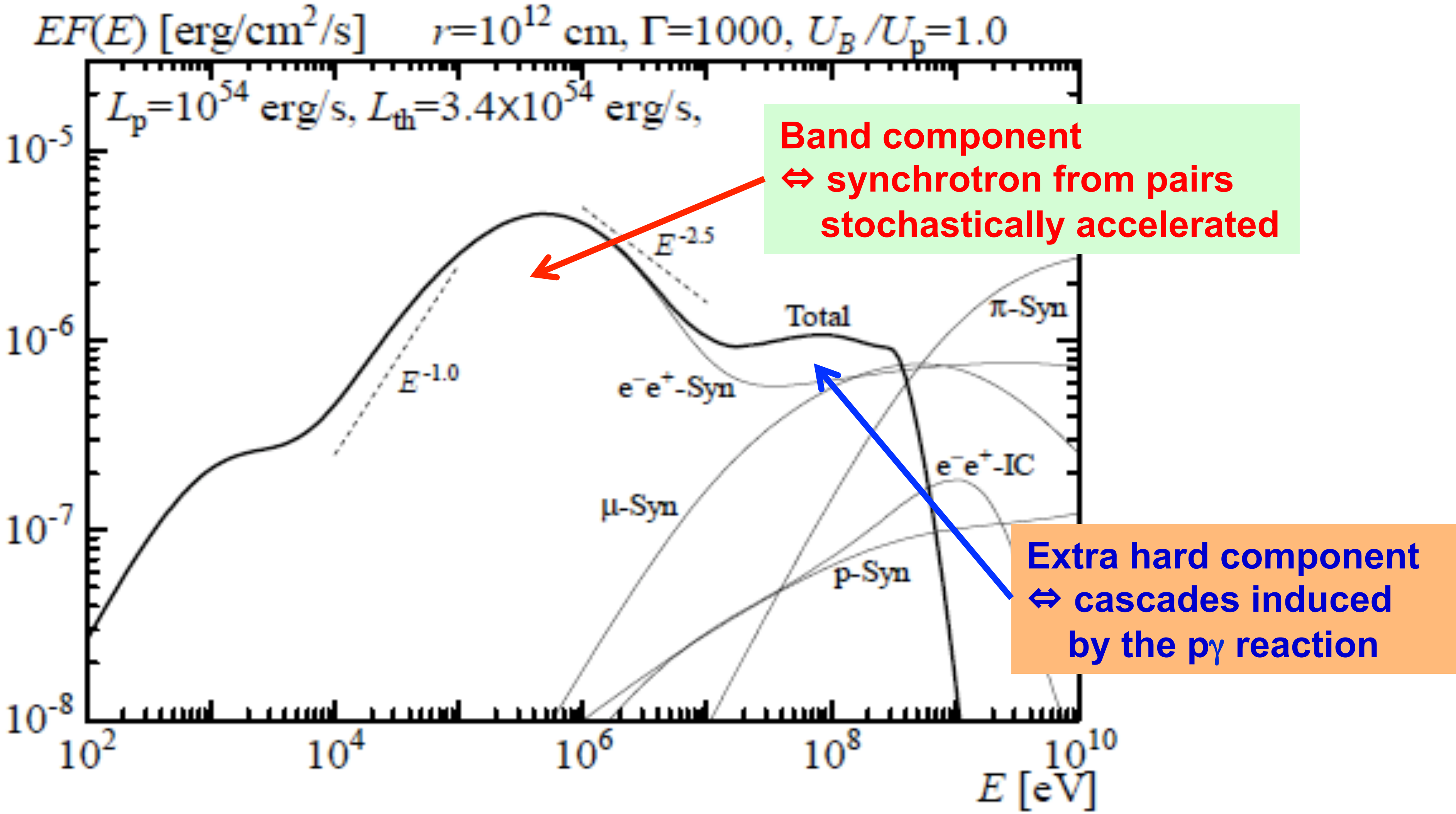
"high" CR loading
E_{HECR} ~ 2.5 $E_{GRB\gamma}$
→#~0.5-50 by IceCube

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

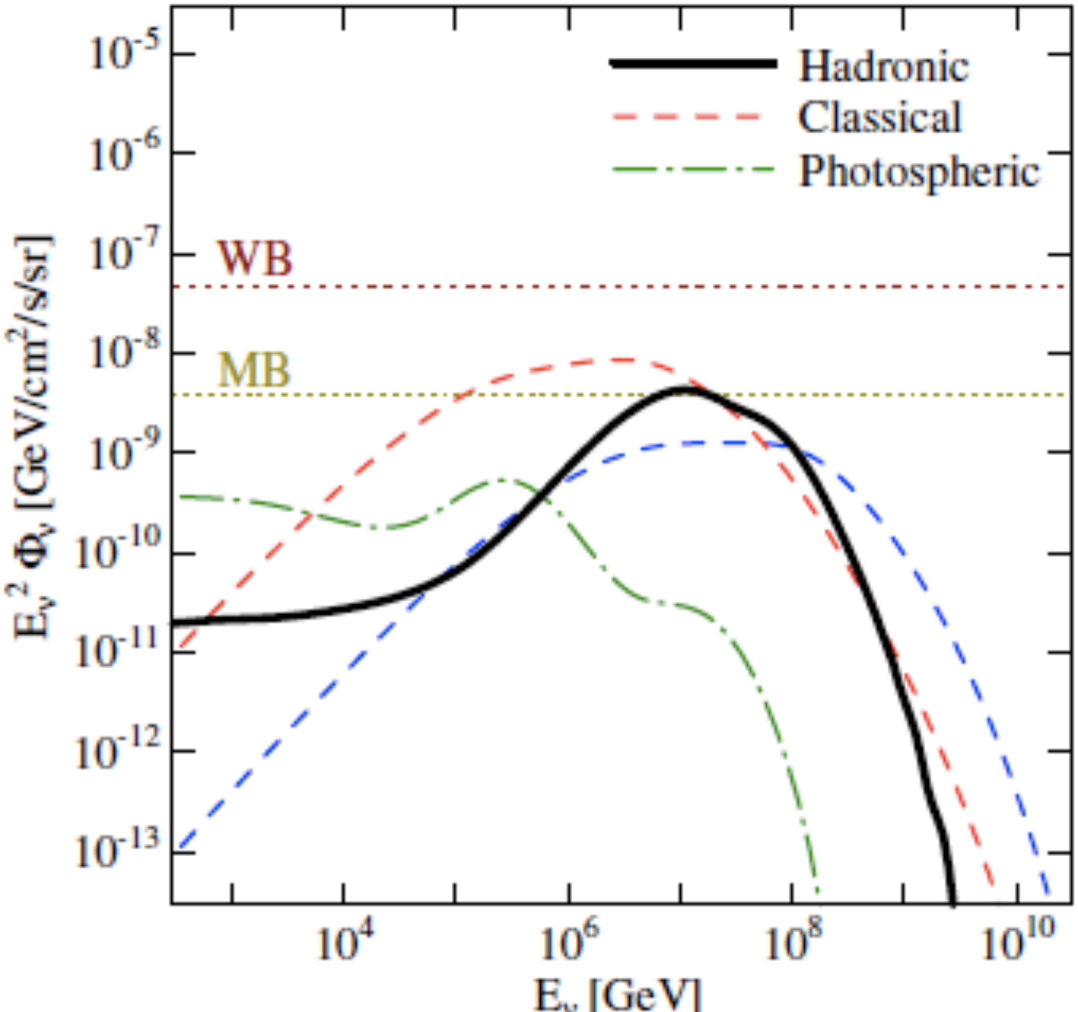
- **Testable: GRB-UHEp hypothesis ($E_{HECR}/E_{GRB\gamma}$ > 1 required)**

Hadronic Model (for Extra Component)

Murase, Asano, Terasawa, & Meszaros, ApJ, 746, 164 (2012)



Cumulative Background?

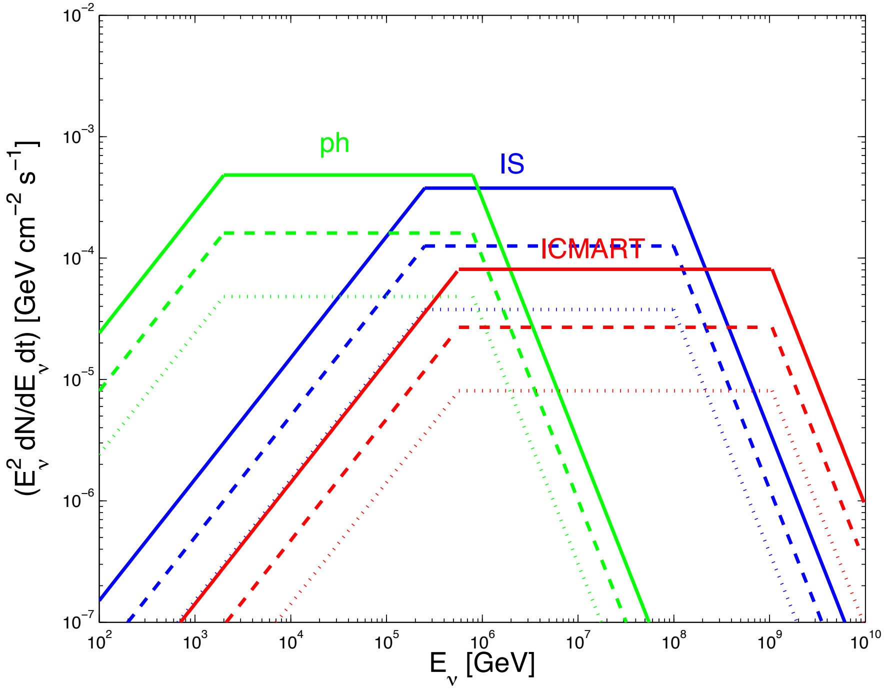


Many models are still consistent with recent upper limits by IceCube

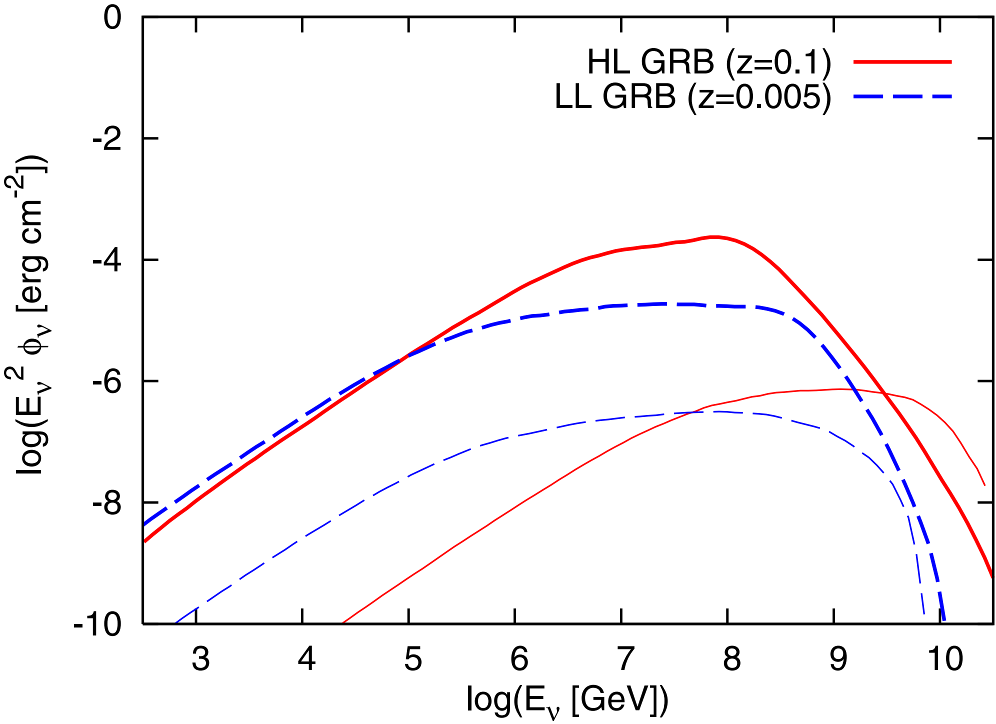
Cases of Large Emission Radii

Models predicting low neutrino fluxes were considered before IceCube were constructed

Zhang & Kumar 13 PRL



KM et al. 08 PRD



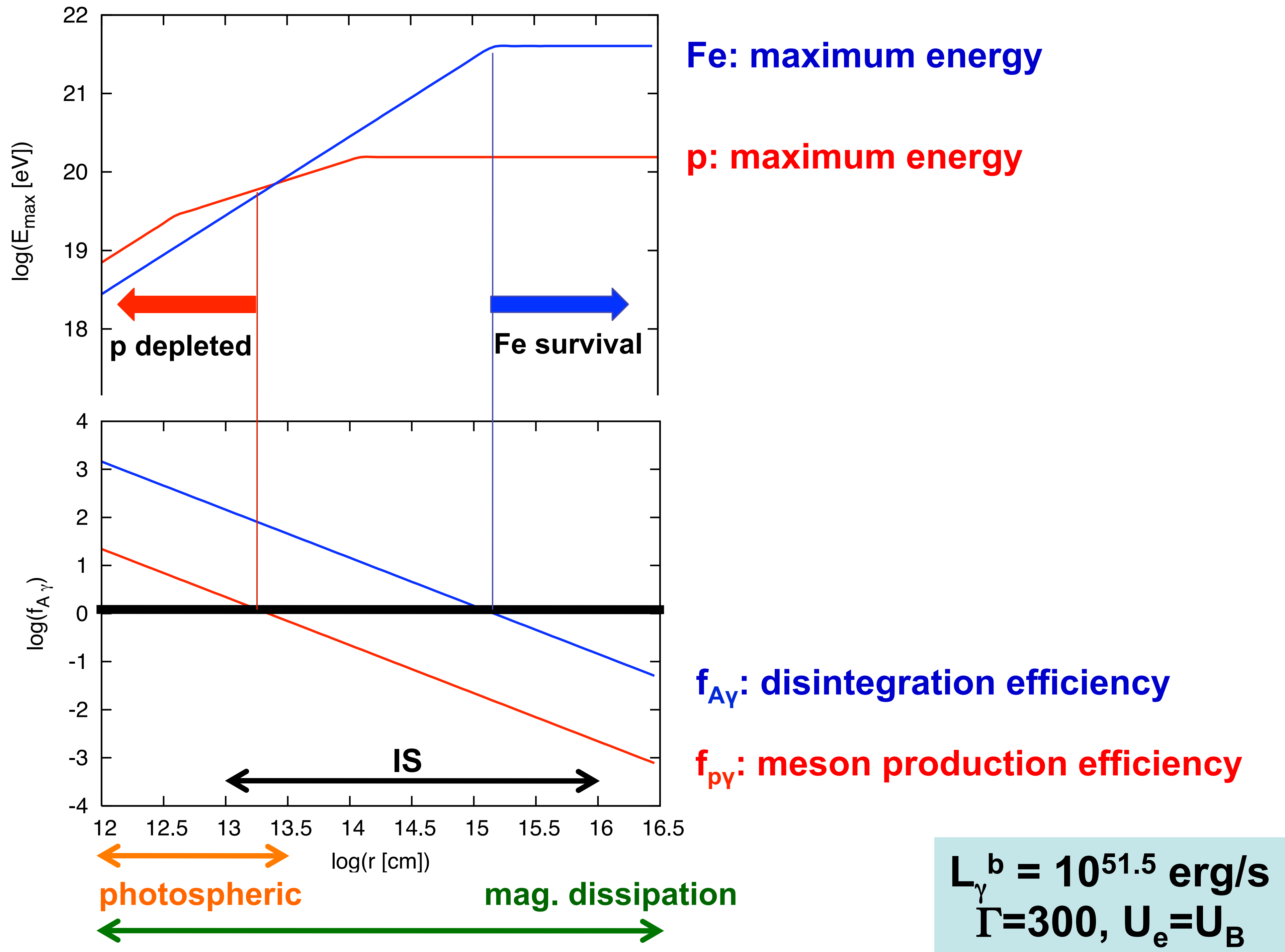
Comments on UHE Nuclei Sources

- **Motivation: PAO composition (interpretation is not settled)**
- ***If* heavy-rich at Earth, most nuclei must survive *in* sources**
  survival from photodisintegration gives

$$\tau_{A\gamma} \sim n_\gamma \, \sigma_{A\gamma} \, \Delta < 1$$

photon density should be small

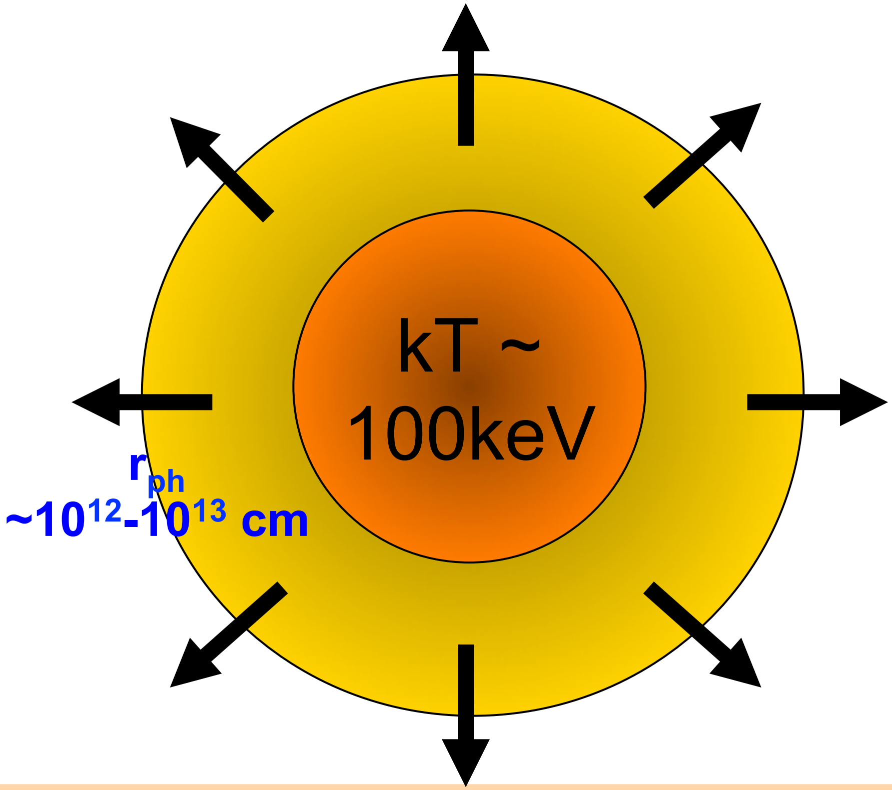
Aside from issues on escape & abundance (e.g., Metzger+ 11)
survival is allowed only at sufficiently large radii,
GRB (Wang et al. 08 ApJ, KM et al. 08 PRD)
AGN (Peer, KM, & Meszaros 09 PRD, KM et al. 12 ApJ)
but ν production should be inefficient



Fe: maximum energy
p: maximum energy
p depleted
Fe survival
log(E_max [eV])
22
21
20
19
18
4
3
2
1
0
-1
-2
-3
-4
log(f_Aγ)
IS
12
12.5
13
13.5
14
14.5
15
15.5
16
16.5
log(r [cm])
photospheric
mag. dissipation
f_Aγ: disintegration efficiency
f_pγ: meson production efficiency
L_γ^b = 10^51.5 erg/s
Γ=300, U_e=U_B

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 τ_T~1-10

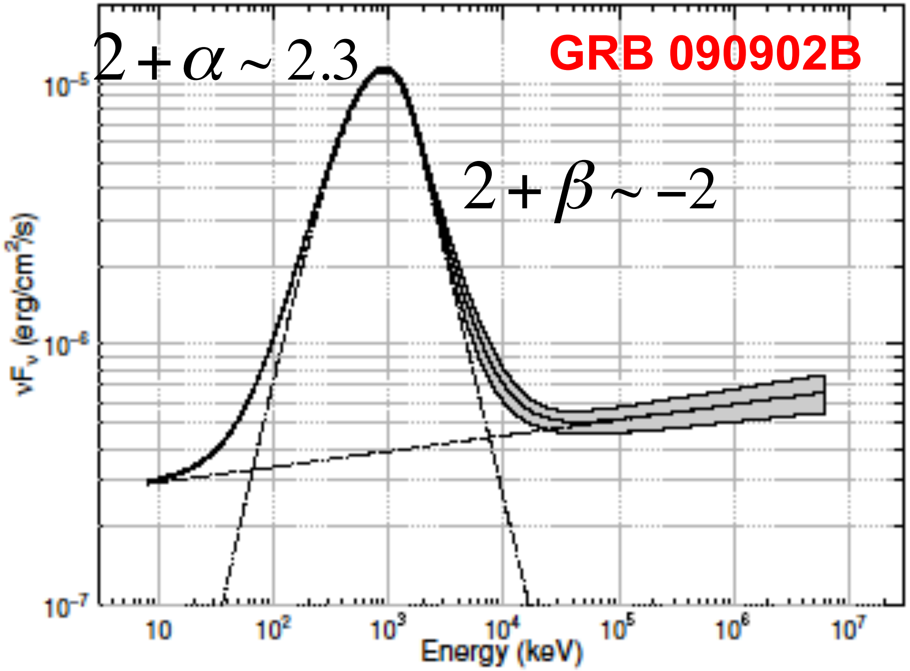
"dissipative photosphere"

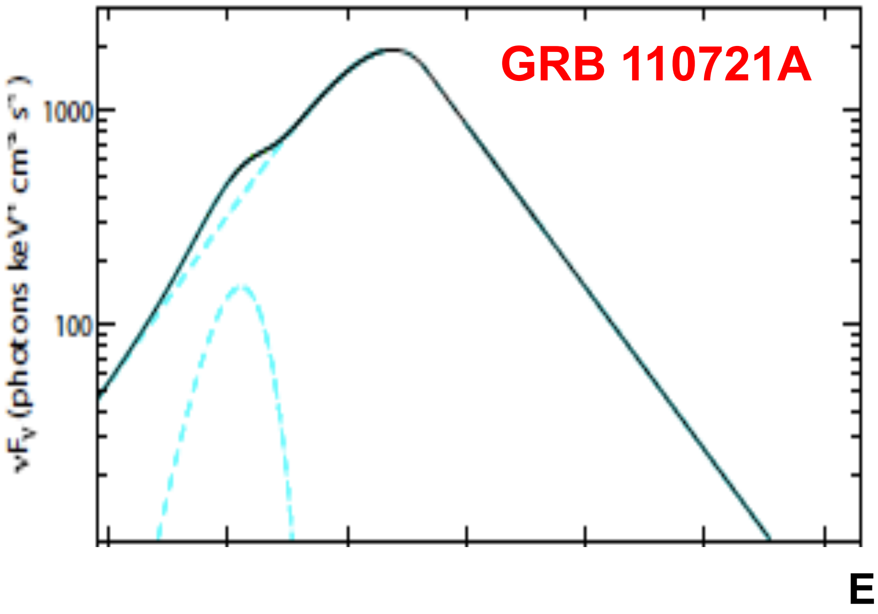
- internal shocks
- interaction with star or wind
- recollimation shocks
- magnetic reconnection
- collisions with neutrons

•Re-conversion of kinetic energy to radiation energy

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

Observational Hints





“modified” black-body emission

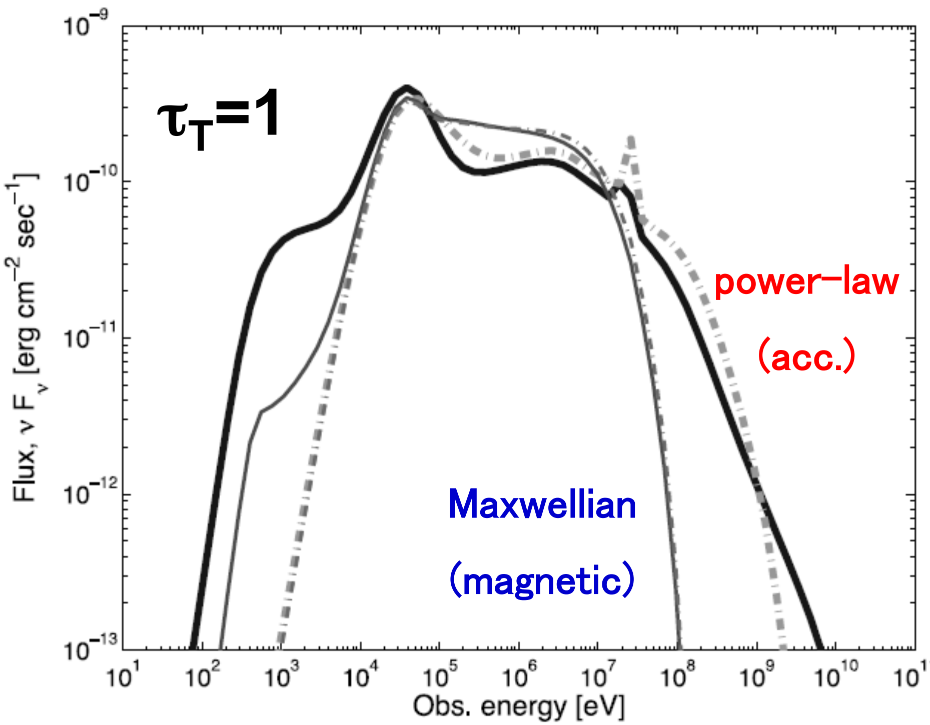
or

thermal + nonthermal emission

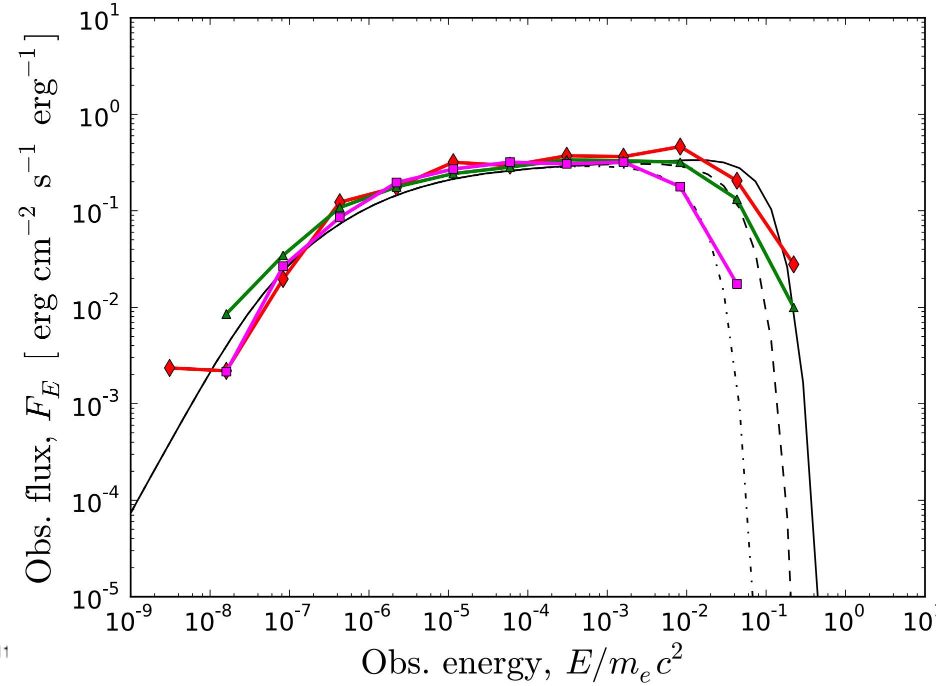
Observed spectra can be reproduced by theories

Theory: Quasi-Thermal Emission

- Comptonized thermal/geometrical effect
  → **α ~ -1 or harder** is possible (w. some tuning)



Peer, Meszaros & Rees 06 ApJ

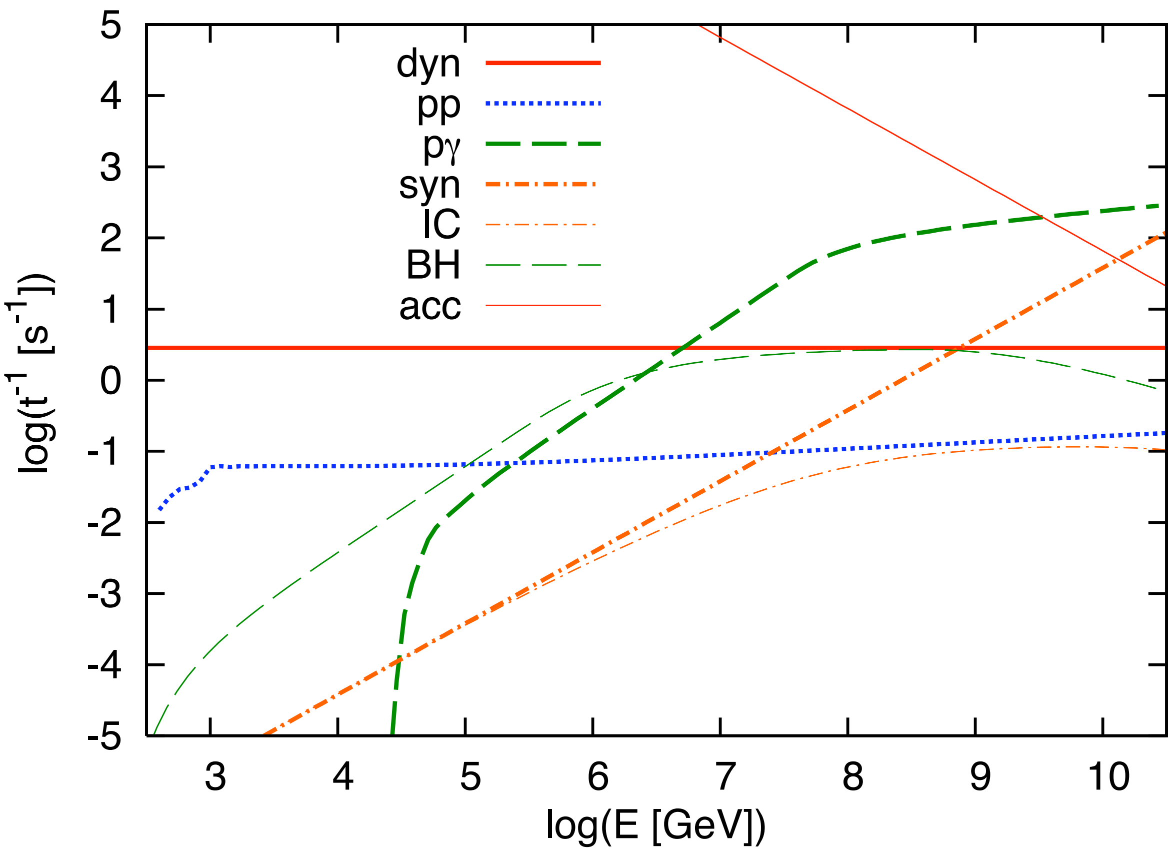


Lundman, Peer & Ryde 13 MNRAS

Cosmic-Ray Acceleration?

• In either shock acc. or magnetic reconnection, Fermi mechanisms lead to acceleration of both p and e

Hillas condition + t_{acc} < max[t_{cool}, t_{dyn}] + t_{dyn} < t_{cool}



KM, PRD(R), 78, 101302 (2008)

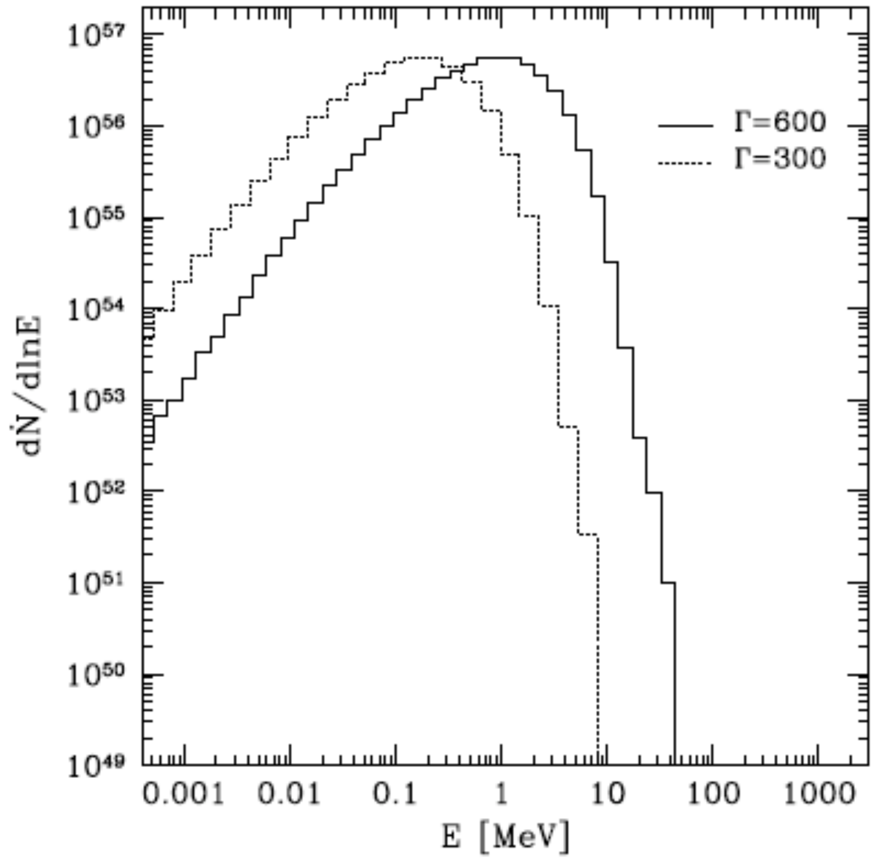
τ_T=1 (r ~ $10^{12.5}$ cm)
$\Gamma=10^{2.5}$
$U_e=U_B$

※UHECRs cannot be produced around the photosphere

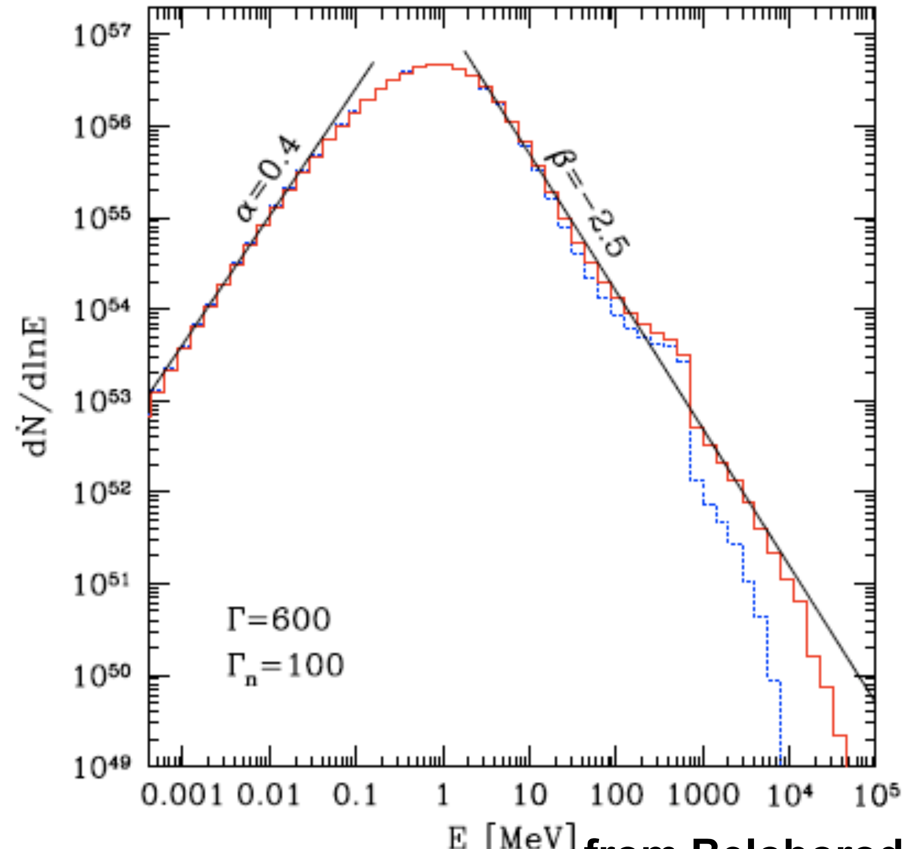
+ meson/muon cooling
synchrotron, IC, adiabatic, πp, μp
(kinetic eq.)

Prompt Emission (Quasi-Thermal)

Passive cooling



Hadronic injection+Coulomb heating



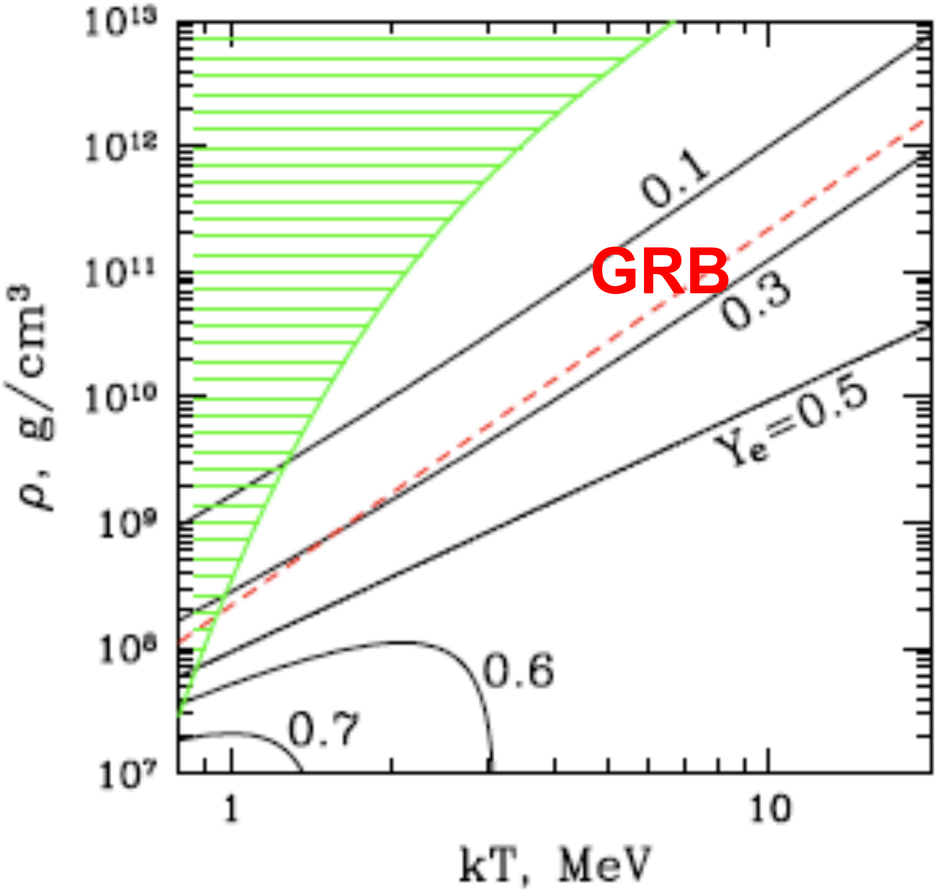
from Beloborodov

- Collisional heating leads to the tail emission

Neutron-Loaded Outflow

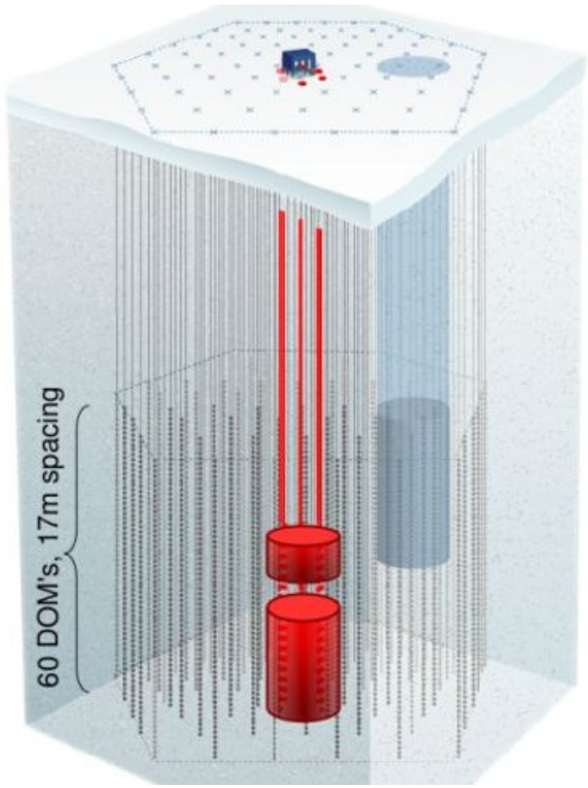
- GRB engine BH+accretion disk
- Neutron-rich disk
- Powerful magnetar
- Maybe entrained in the jet

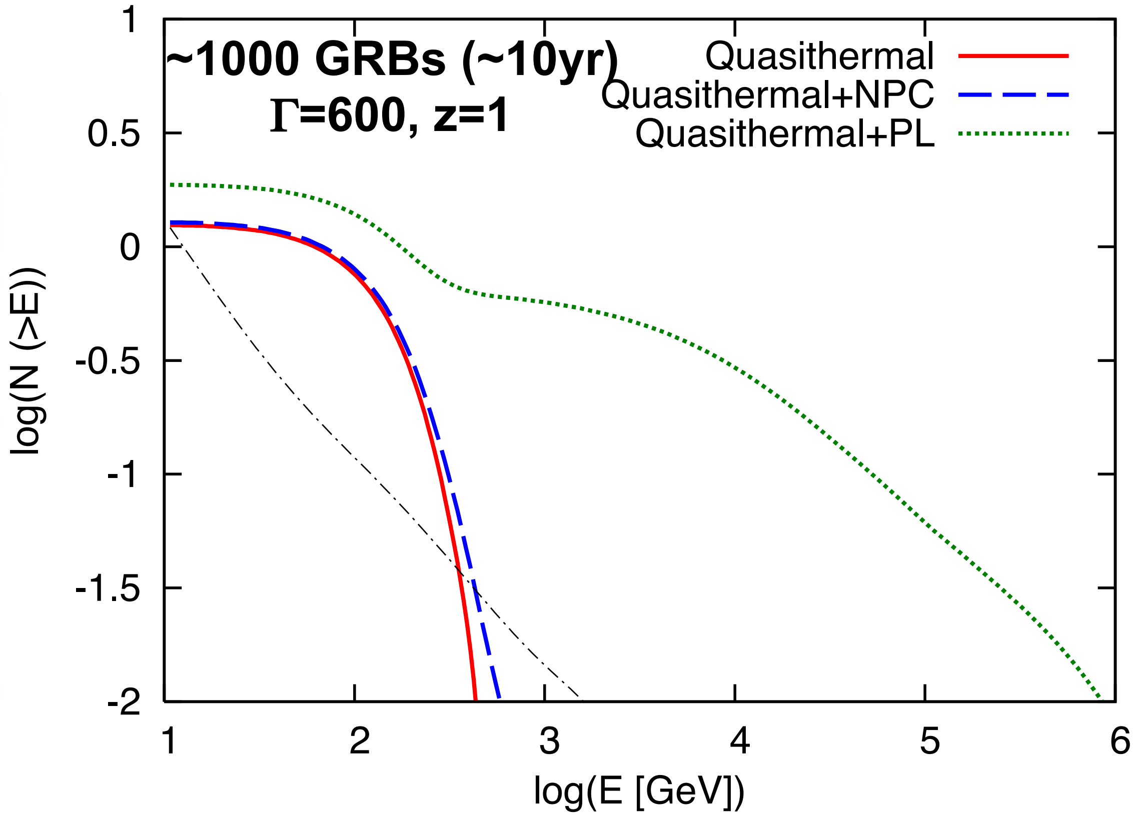
from Beloborodov



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}



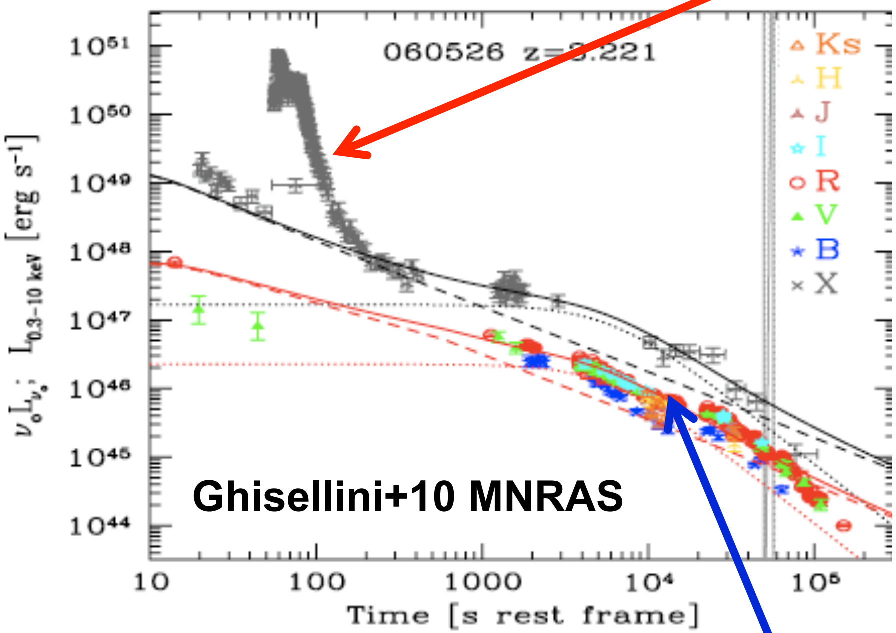


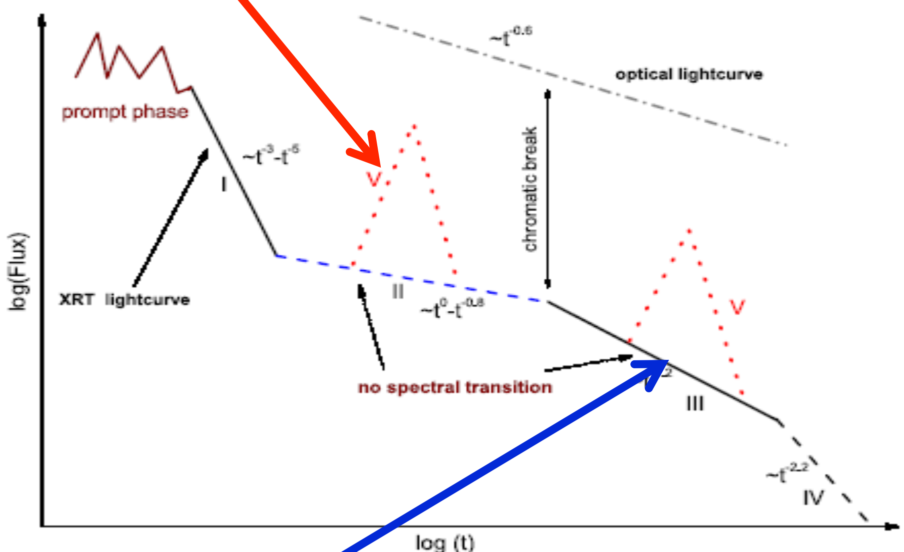
KM, Kashiyama & Meszaros 13, Bartos et al. 13

Afterglows

GRB Afterglow Emission

X-ray/FUV Flare: "late" internal dissipation like prompt emission



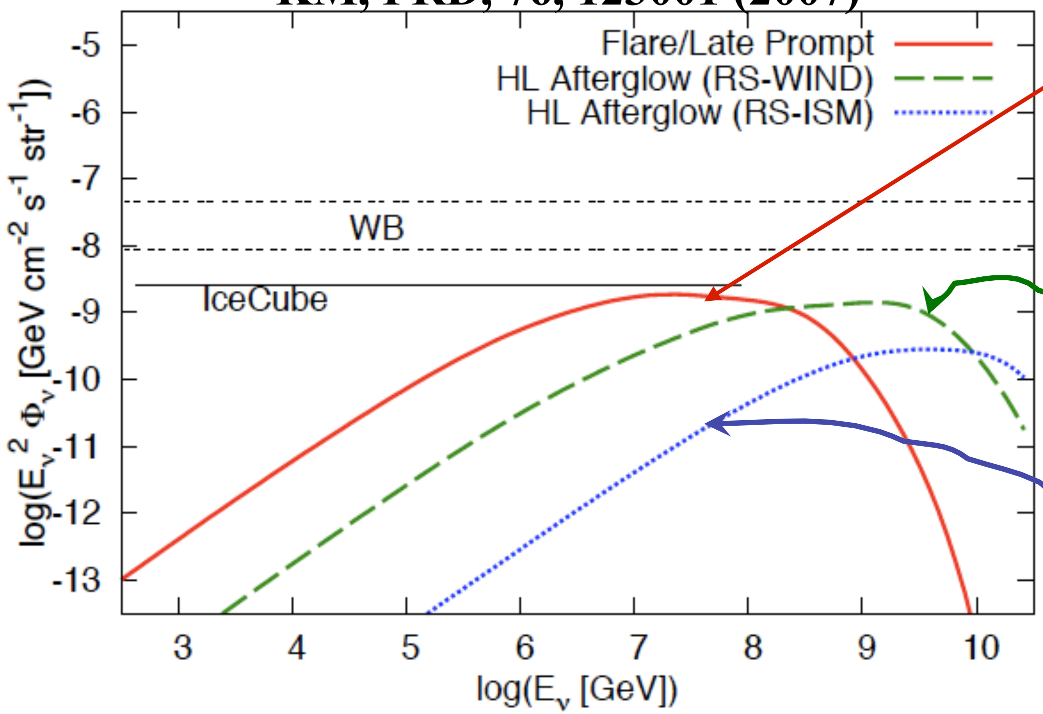


Afterglow: syn. emission from electrons accelerated at ext. shock

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)

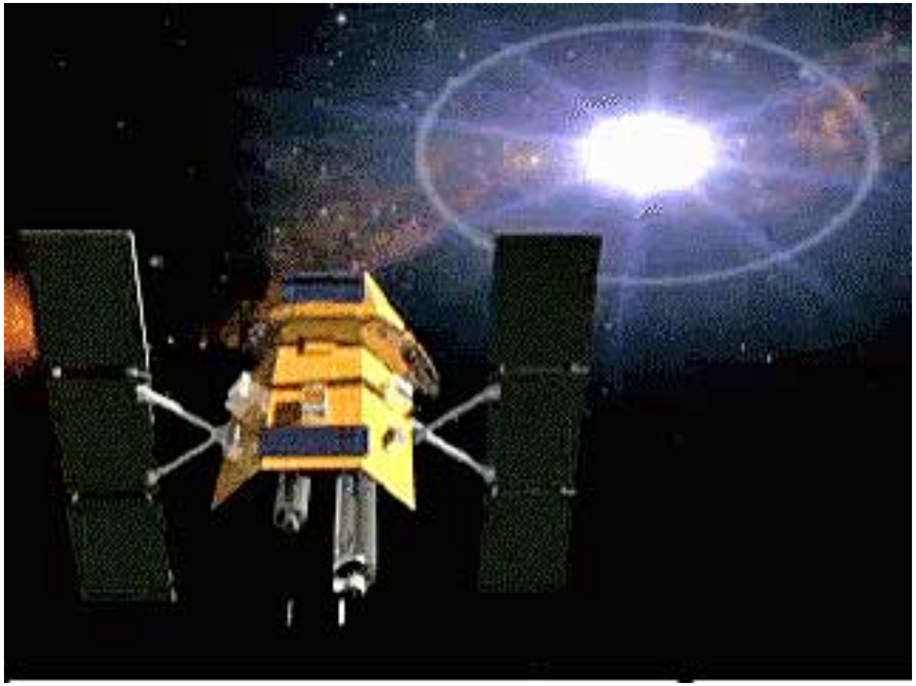
ES protons + ES opt-x rays
stellar wind medium
(normalized by UHECR budget)

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**

Flares and Low-Luminosity GRBs

Swift

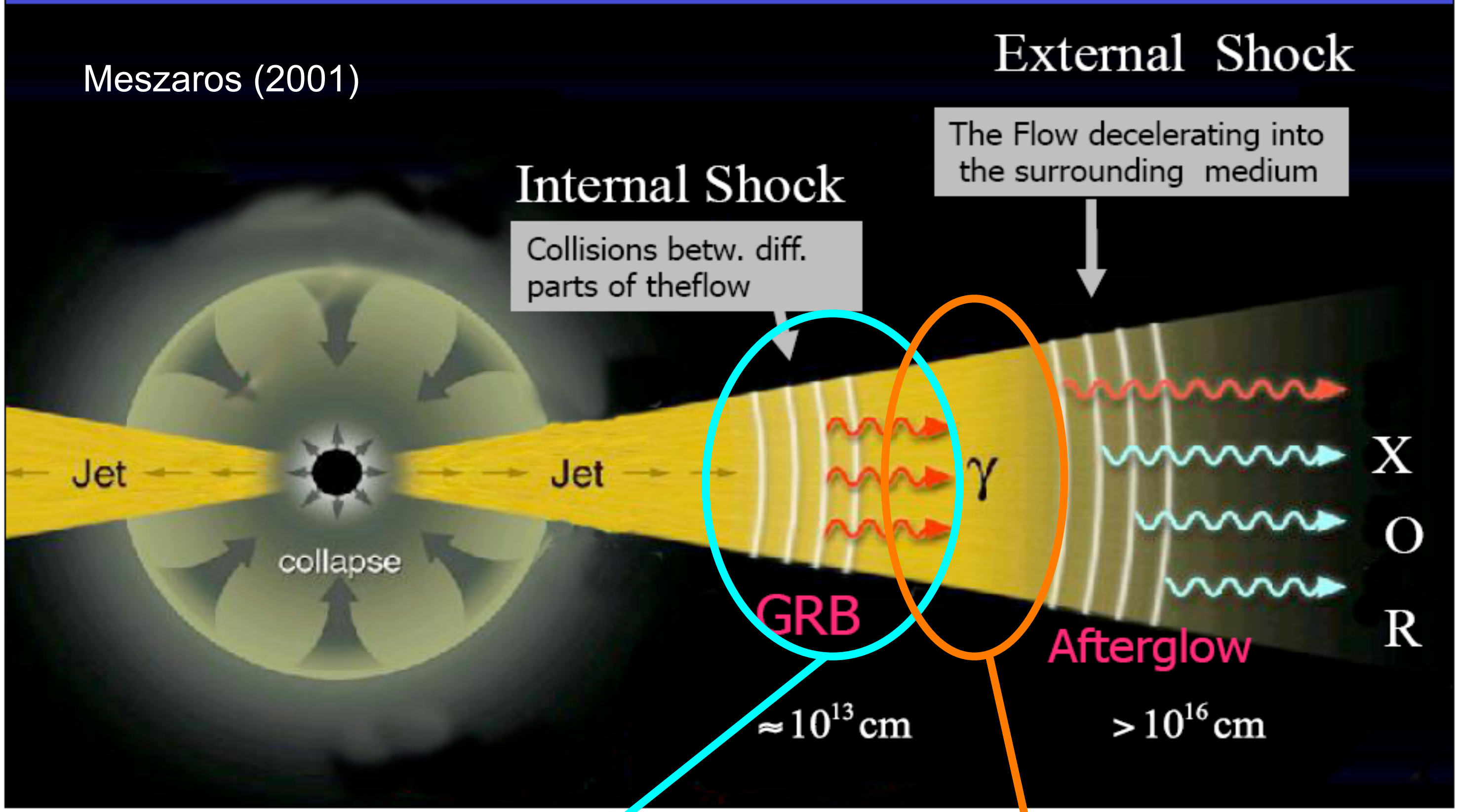


Swift brought us many novel results

↓

Additional possibilities of CR production and ν/γ emission!

Fireball Model: long GRBs



Prompt Emission from Low-Luminosity GRBs
PeV ν, GeV-TeV γ
(KM et al. 06)
(Gupta & Zhang 07)

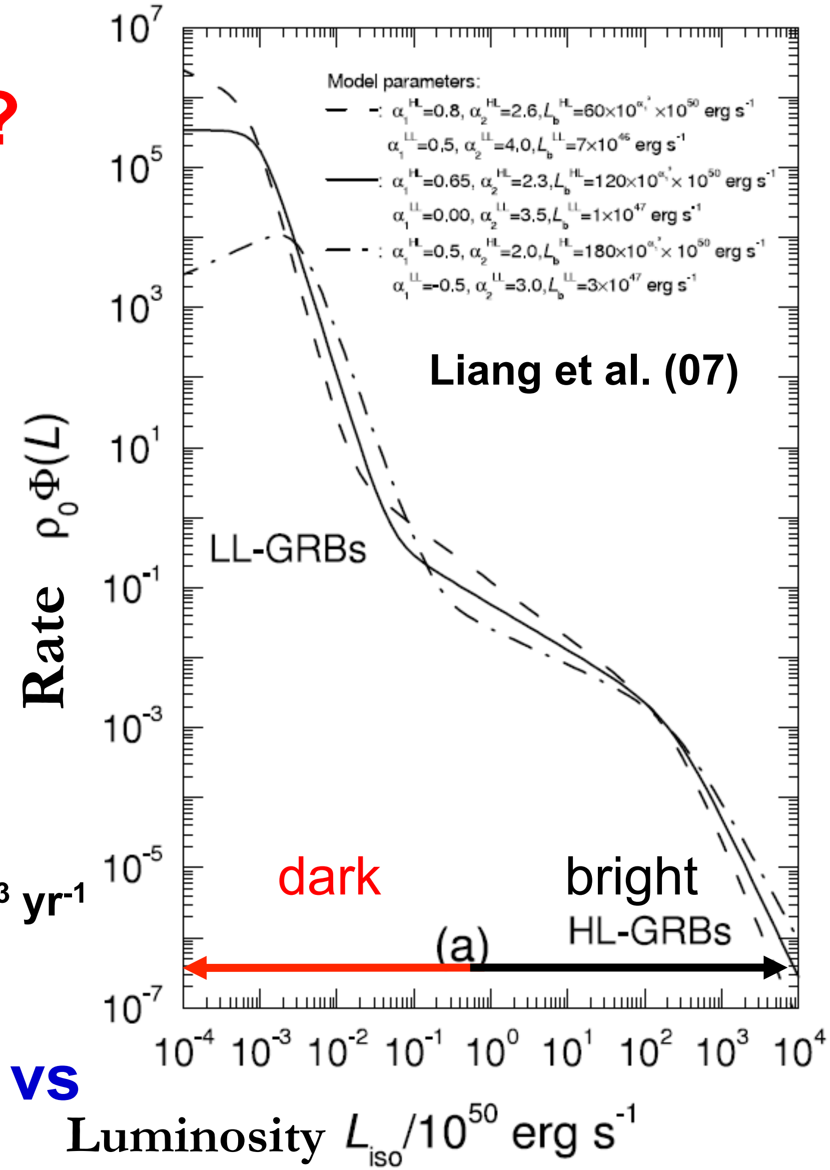
Flares
PeV-EeV ν, GeV γ
(KM &Nagataki 06)

Novel Results of Swift (GRB060218)

1. Low-luminosity (LL) GRBs?

- **GRB060218 (XRF060218)**
  - **The 2nd nearby event (~140 Mpc)**
  - **Associated with a SN Ic (optical)**
  - **Much dimmer than usual GRBs ($E_{LLGRB\gamma}$ ~ 10^{50} ergs ~ 0.001 $E_{HLGRB\gamma}$)**

- **LL GRBs (e.g., XRF060218, GRB980425)**
  more frequent than HL GRBs
  local Rate ~ $10^{2\text{-}3}$ Gpc^{-3} yr^{-1} >> (0.01-1) Gpc^{-3} yr^{-1}
  (Soderberg et al. 06, Liang et al. 07 etc…)



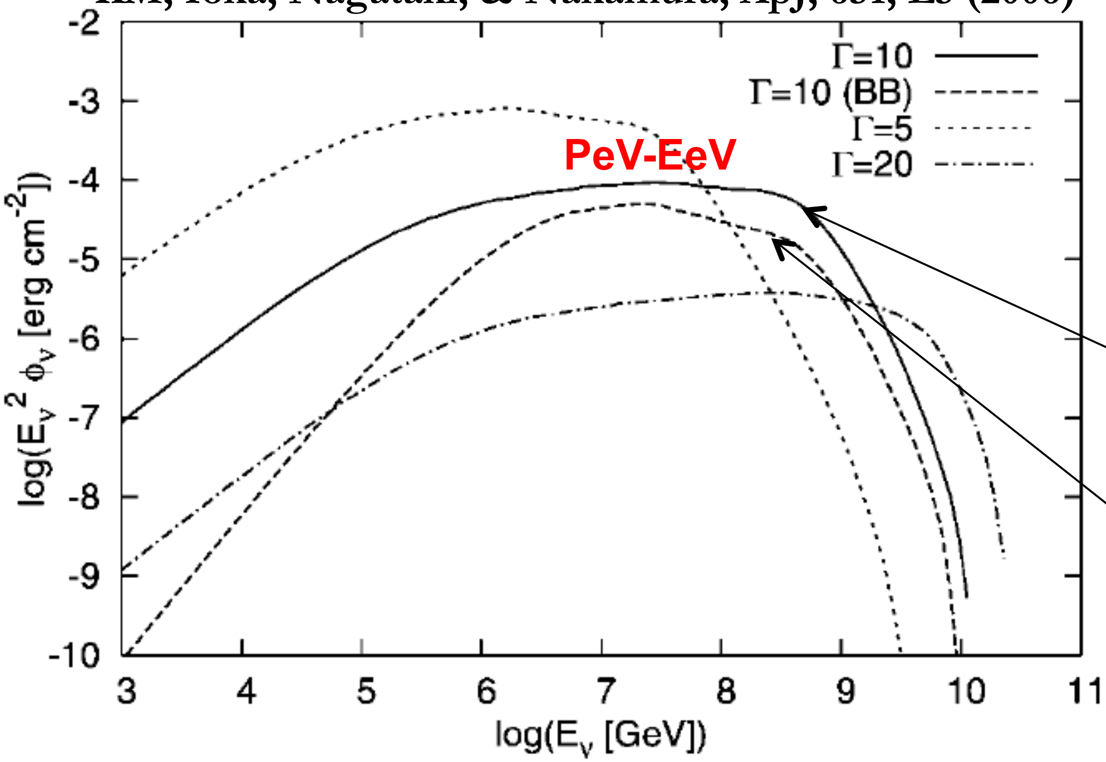
If true → contribution to HECRs & νs

Neutrinos in Jet Scenario

pγ production efficiency

$$f_{p\gamma} \simeq 0.06 \frac{L_{\max,47}}{r_{15}(\Gamma/10)^2 E^b_{5\,\mathrm{keV}}} \begin{cases} (E_p/E_p^b)^{\beta-1} & (E_p < E_p^b), \\ (E_p/E_p^b)^{\alpha-1} & (E_p^b < E_p), \end{cases}$$

KM, Ioka, Nagataki, & Nakamura, ApJ, 651, L5 (2006)



$E_{CR}^{iso}/E_\gamma^{iso}$=10
U_e=U_B
D=10 Mpc

If Γ=10 w. prompt emission
→ # of μs ~ 1-2
→ optical follow-up!

If Γ=10 w. thermal X rays
(stellar shock breakout or cocoon)
→ # of μs ~ 0.1-0.2

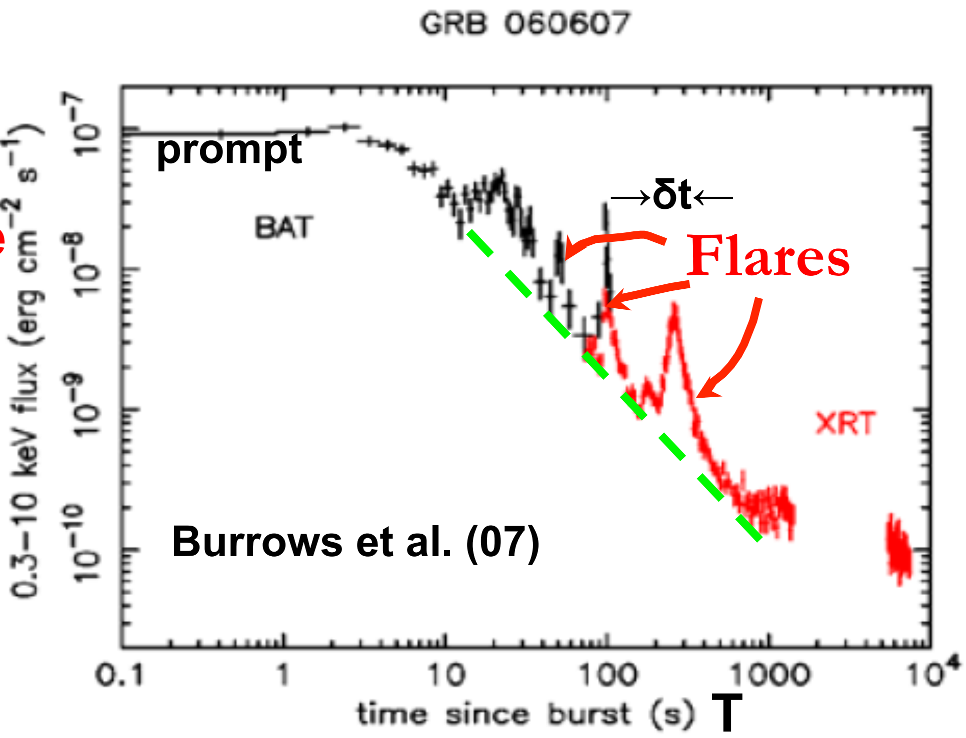
※LL GRBs accompanying relativistic SNe may produce UHECRs

KM+ 06 ApJ (energetics), Wang+ 07 PRD (ext. free exp. shock), KM + 08 PRD (int. or ext. dec. shock)

Novel Results of Swift (Flares)

2. Flares in the early afterglow phase

- Energetic ($E_{flare\gamma} \sim 0.1\ E_{GRB\gamma}$) (e.g., Falcone et al. 07)
  ($E_{flare\gamma} \sim E_{GRB\gamma}$ for some flares such as GRB050502B
  potentially comparable to energy of prompt emission)
- $\delta t >\sim 10^{2\text{-}3}$ s, $\delta t/T < 1 \rightarrow$ internal dissipation models
  (e.g. late internal shock model
  vs
  magnetic dissipation model)
- Flaring in the far-UV/x-ray range
  $\varepsilon_{pk} \sim (0.1\text{-}1)$ keV
- Lower Lorentz factors (likely)
  $\Gamma \sim$ a few×10
- Flares are common
  (at least 1/3-1/2 of LGRBs)
  (also seen in SGRBs)



Energetics

Neutrino Energy Flux ∝ Rate × Photomeson ($p \rightarrow \pi$) Production Efficiency × Nonthermal Baryon Energy

↓ Normalizing all the typical values for HL GRBs to 1

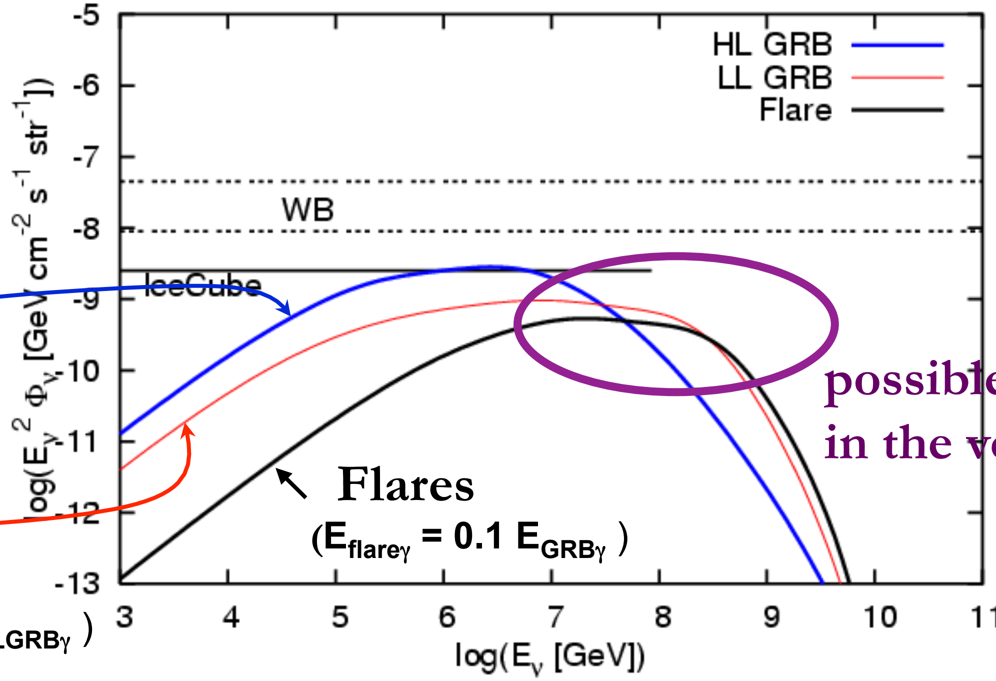
	HL GRB (Waxman & Bahcall 97)	Flare (Murase & Nagataki 06)	LL GRB (Murase et al. 06) (Gupta & Zhang 07)
Isotropic energy	1	~0.01-0.1	0.001
Meson Production Efficiency	1	10	1
Apparent Rate	1	1	~100-1000
The contribution to neutrino background	1	~0.1-1	~0.1-1

Hence, we can expect flares and LL GRBs are important!

Neutrino Predictions in the Swift Era

KM & Nagataki, PRL, 97, 051101 (2006)
KM, Ioka, Nagataki, & Nakamura, ApJL, 651, L5 (2006)

See also, Gupta & Zhang 07



Baryon loading
E_{HECR} ~ 0.5 E_γ

HL GRBs

LL GRBs
($E_{LLGRB\gamma}$ ~ 0.001 $E_{HLGRB\gamma}$)

possible dominant contribution in the very high energy region

ν flashes → Coincidence with flares/early AGs, a few events/yr

ν s from LL GRBs → little coincidence with bursts, a few events/yr

Approaches to GRBs through high-energy neutrinos

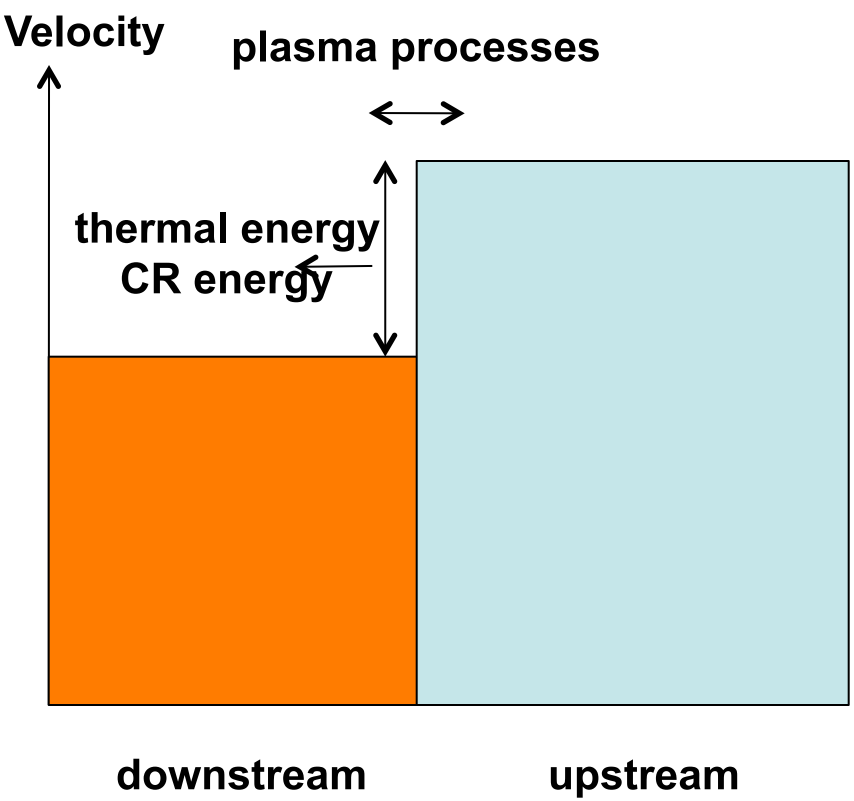
Flares → potentially more baryon-rich and efficient neutrino emitters

LL GRBs → possible indicators of SNe followed by opt. telescopes

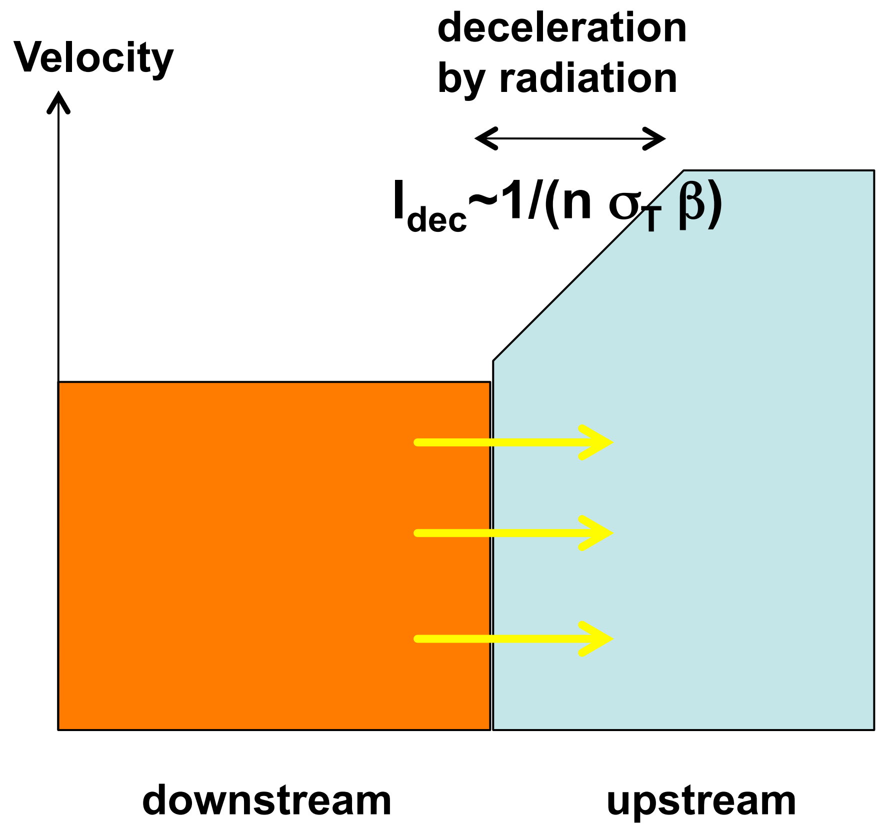
Supernovae

Limitation of Shock Acceleration

Collisionless shock



Radiation-mediated shock
(ex. Weaver 76 ApJ, Katz+ 10 ApJ, Nakar & Sari 12 ApJ)



Shock Breakout & Collisionless Shocks

- Necessary condition for collisionless shocks
  $l \lesssim l_{dec} \sim (1/n\,\sigma_T\,\beta) \Leftrightarrow \tau_T \lesssim 1/\beta$
  (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: Post-Shock-Breakout?

Expect formation of collisionless shocks & CRs

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

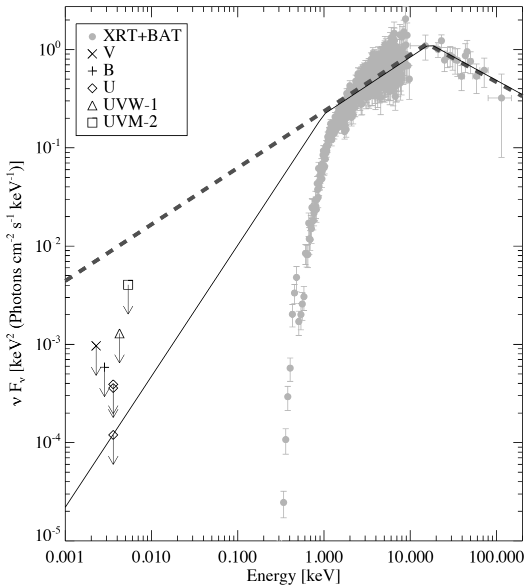
$f_{pp}(r_{bo}) \sim \beta^{-2}\, (\kappa_{pp}\, \sigma_{pp}/\sigma_T) \sim 0.03\, \beta^{-2}$

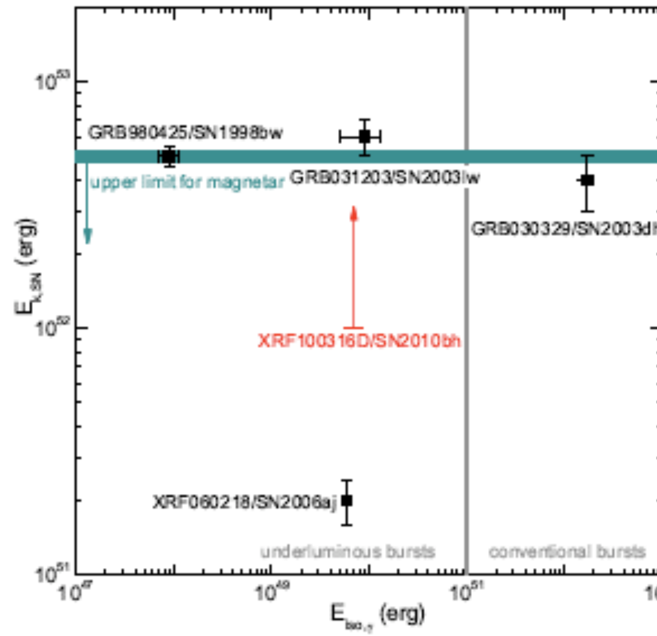
$\beta \sim 1$ ⇔ trans-relativistic SNe
($p\gamma$ efficiency ~ 1: dominant)
$\beta \sim 0.01$-0.03 ⇔ typical SN velocity
pp efficiency ~ 1

LL GRBs & Relativistic SNe

from Fan et al. 10

XRF 100316D





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

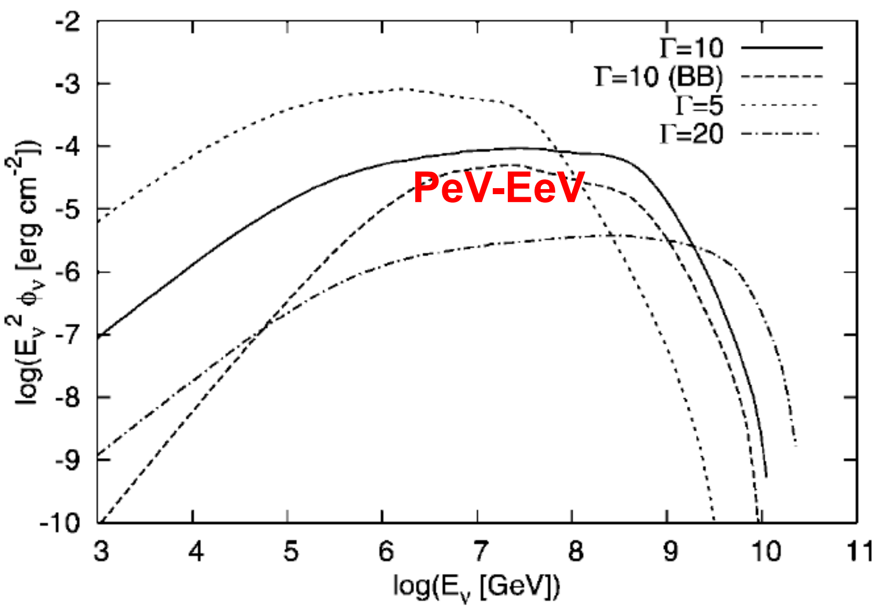
- much dimmer ($E_{GRB\gamma}^{iso}$ ~10^{50} erg ⇔ $E_{GRB\gamma}^{iso}$ ~10^{53} erg/s)
- more frequent (ρ_0 ~10^{2-3} Gpc^{-3} yr^{-1} ⇔ ρ_0 ~0.05-1 Gpc^{-3} yr^{-1})

\- maybe more baryon-rich? (e.g., Zhang & Yan 11 ApJ)

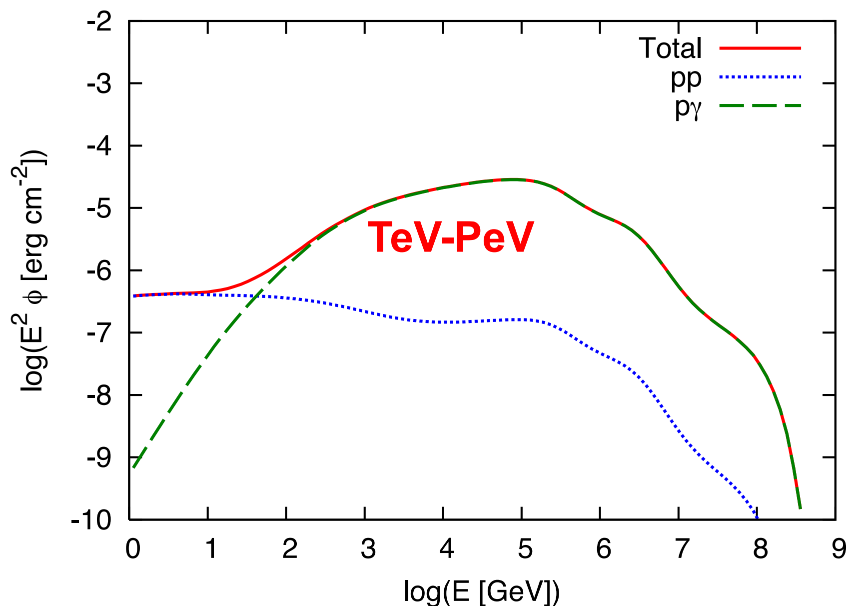
\- relativistic ejecta → same class as SNe 2009bb? (Soderberg+ 10 Nature)

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)



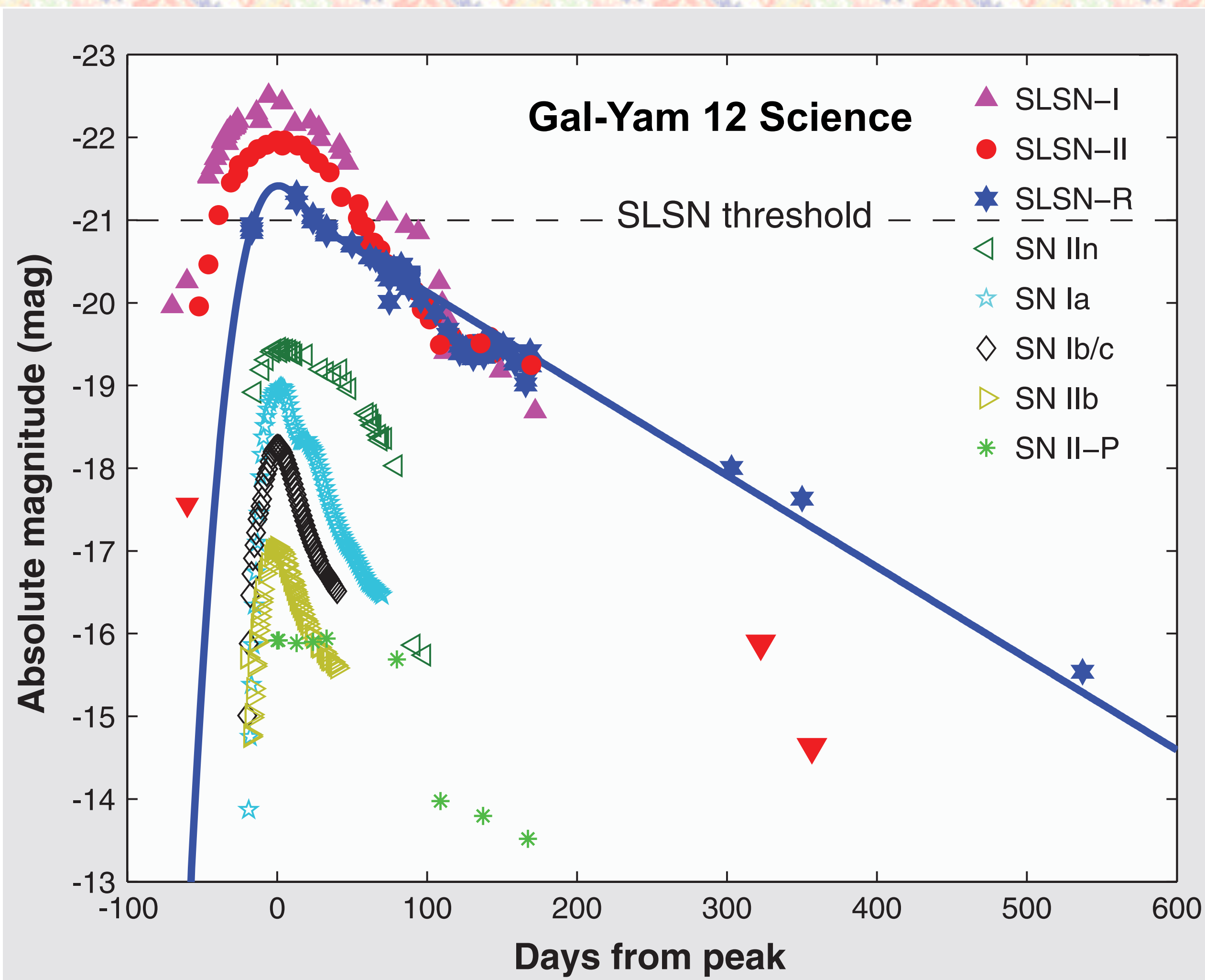
KM et al. 06 ApJL



Kashiyama et al. 12

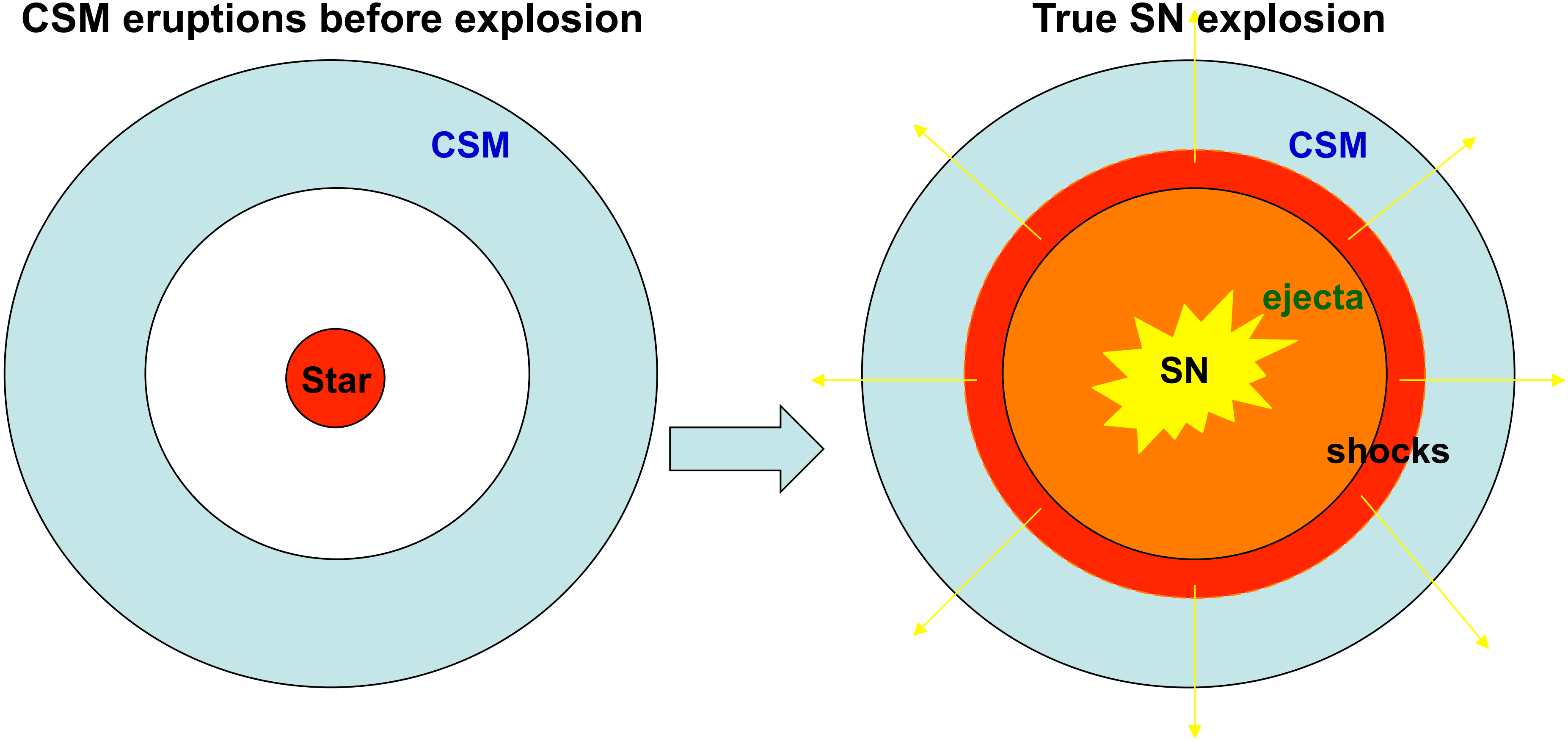
The signal is detectable for nearby SNe at D < 10 Mpc

SNe IIn & Super-Luminous SNe



Circumstellar-Material-Collision Scenario

CSM eruptions before explosion | **True SN explosion**



kinetic energy → thermal + **radiation**

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

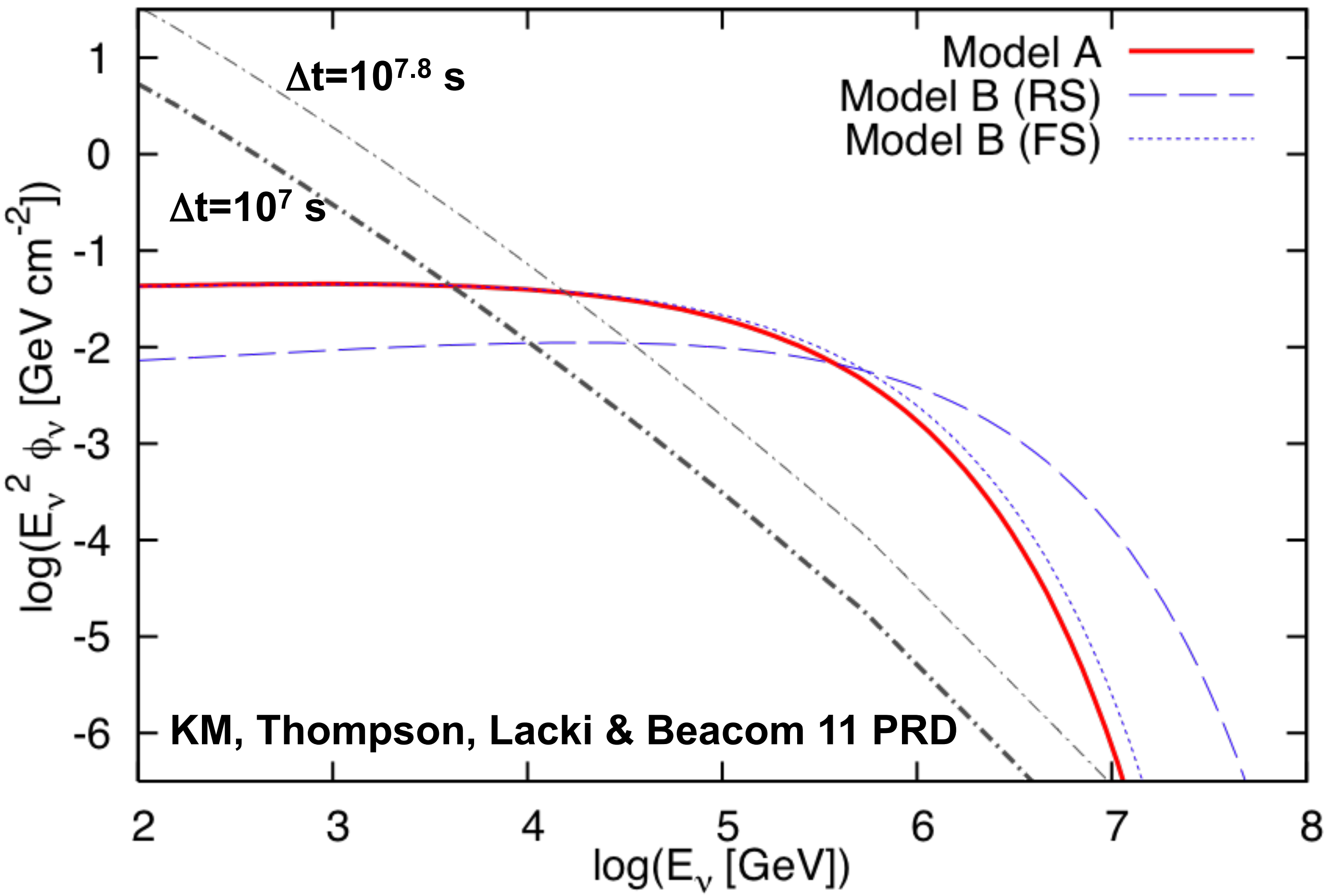
Similar to SNe IIn mechanism
for luminous SNe,
Smith & McCray 07 ApJL, Woosley+ 07 Nature

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
  $n_{CSM} \sim 3\text{x}10^{10}$ 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
  $n_{CSM} \sim 3\text{x}10^{6}$ 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

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

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