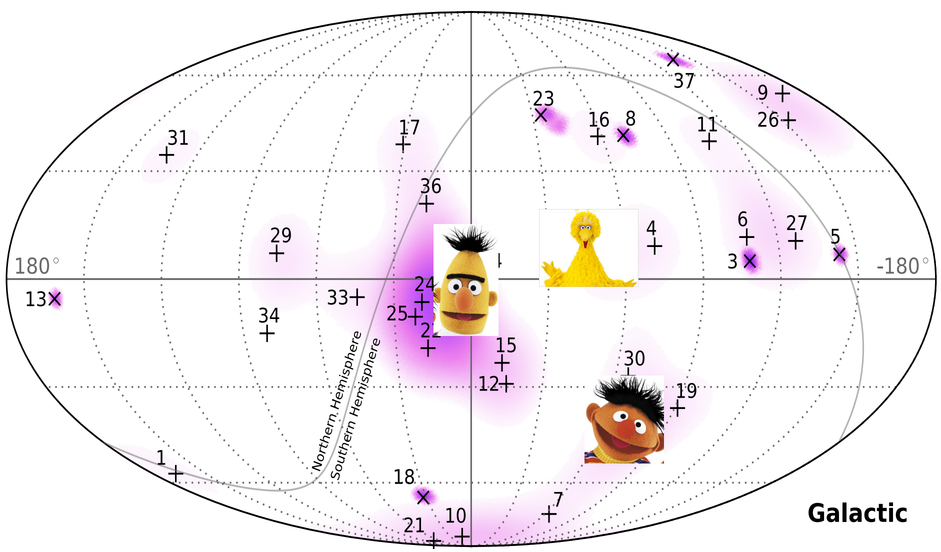
Ghostly Messengers from Relativistic Jets

Kohta Murase (Institute for Advanced Study)

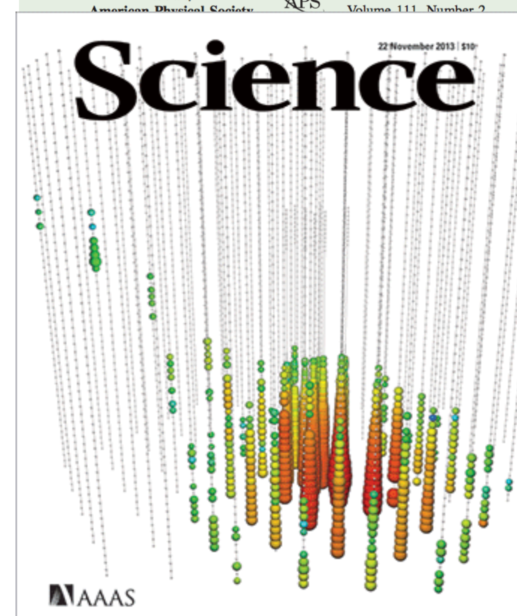
GRBs in the Multi-messenger Era, June 2014

Dawn of High-Energy Neutrino Astrophysics

#1 of top 10 breakthroughs in physics in 2013 judged by Physics World



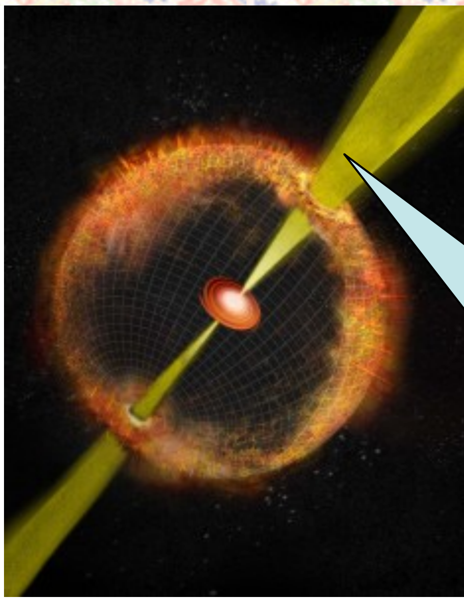
IceCube
arXiv:1405.5303



2+26+9 events (~5.7σ), 30 TeV-2 PeV

ang. resolution: ~1 deg (μ track), ~10 deg (shower)

Neutrinos & γ rays: Messengers from Cosmic-Ray Accelerators



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

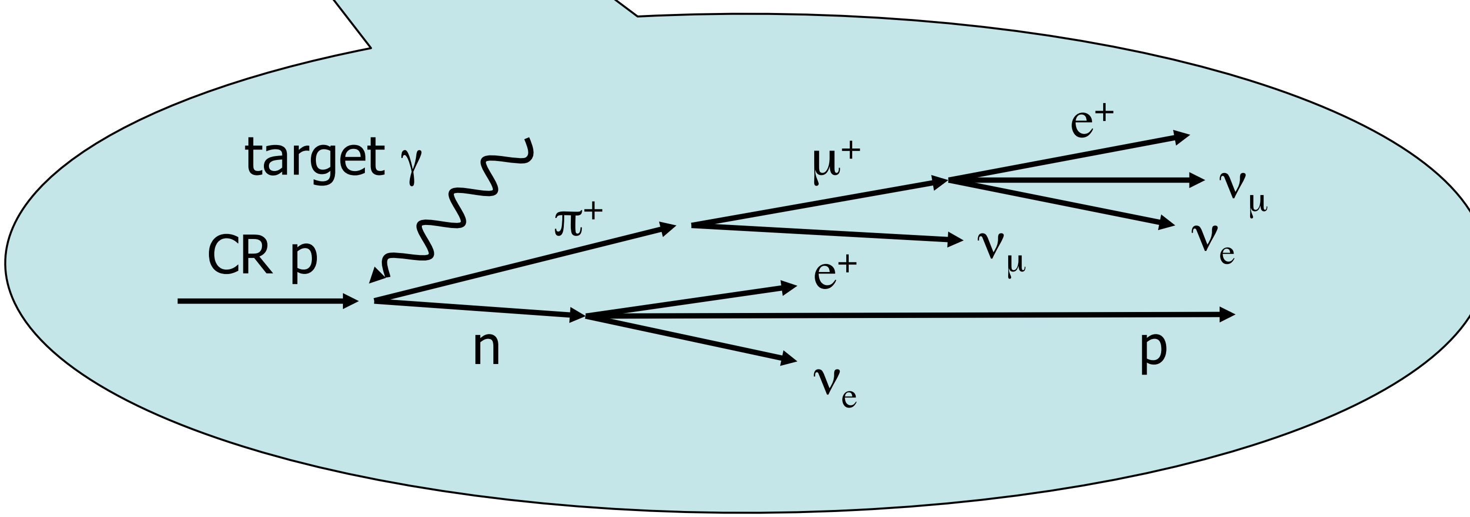
$\sigma_{pp} \sim 3 \times 10^{-26}\ \mathrm{cm}^2$

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

$\sigma_{p\gamma} \sim 5 \times 10^{-28}\ \mathrm{cm}^2$

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

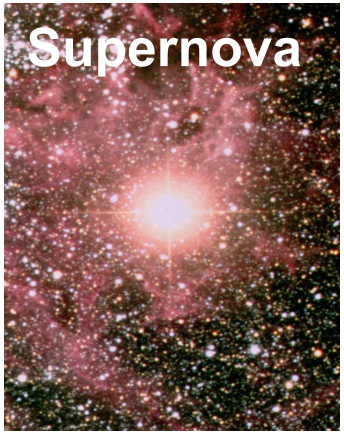
$$\pi^{0} \rightarrow \gamma + \gamma$$



Allard
Bustamante
Inoue
Petropoulou
Kouchner
Taboada

Motivation: Probe of Astrophysics & Neutrino Physics

Neutrinos can probe dense environments like the stellar interior
→ detecting even a few events can give definitive answers
→ will open new windrows of HE astrophysics & ν physics



~10 MeV neutrinos from supernova 1987A
thermal ν: stellar core's grav. binding energy

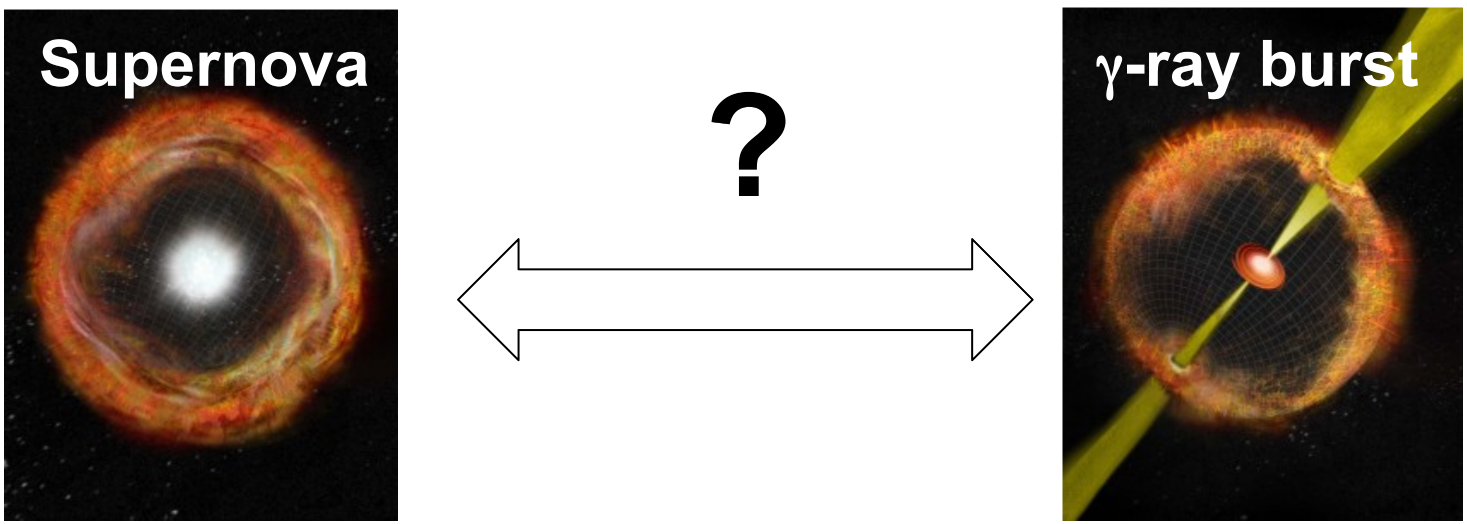
- explosion mechanisms, progenitor properties, nucleosynthesis, ν oscillation etc.

> GeV neutrinos from jets (ex. γ-ray bursts)
nonthermal ν: dissipation in relativistic jets

- relativistic jet properties, relationship with supernovae, new physics (ex. LIV, νν interactions) etc.

Talk Outline

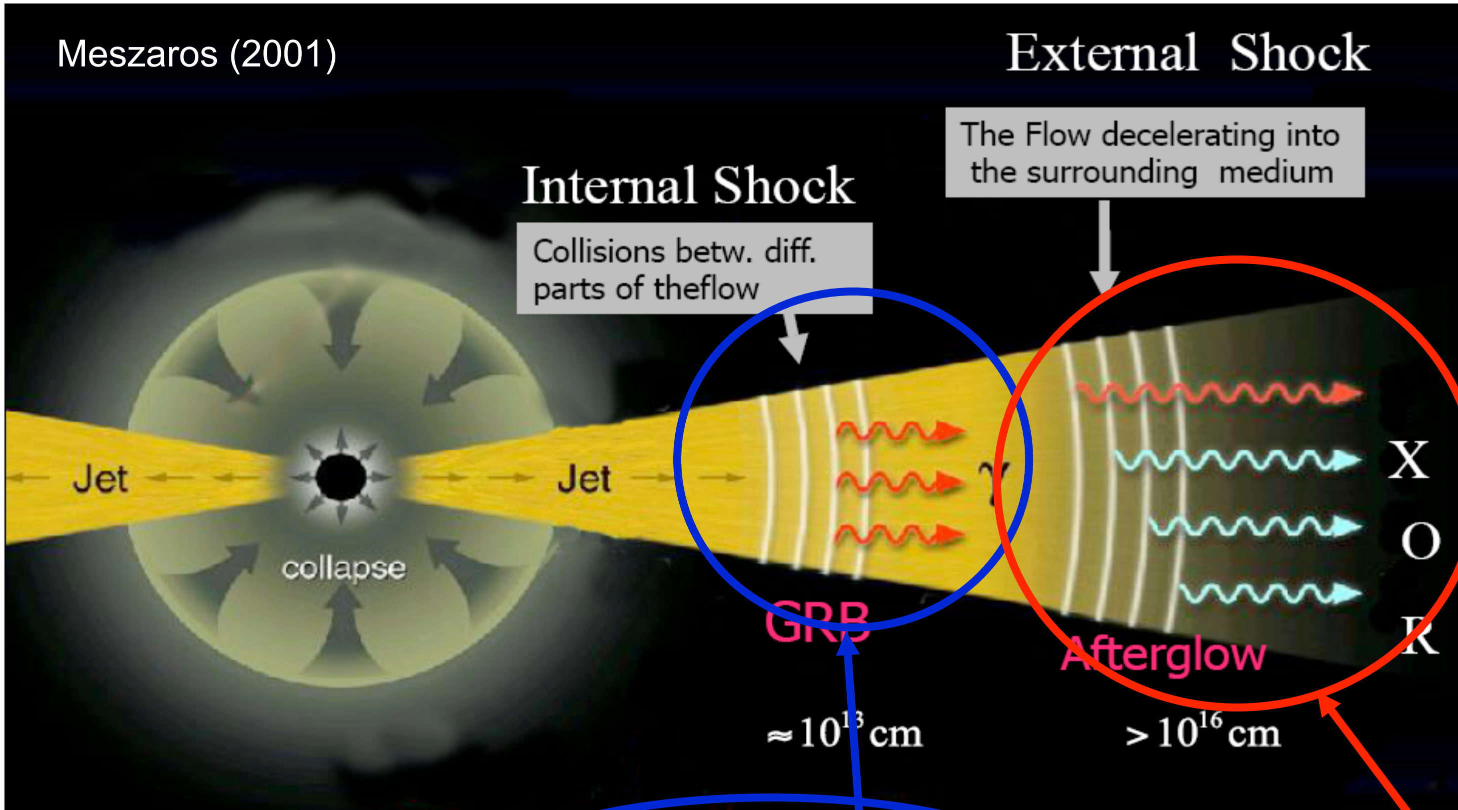
1. Prompt Gamma-Ray Burst Neutrinos
2. Neutrinos from Hidden Gamma-Ray Burst Jets
3. Summary



Transients: temporarily luminous and atm. bkg. reduced

Advantage of neutrinos: we can study subphotospheric phenomena ($\tau_T = n_e \sigma_T \Delta >\sim 1$)

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

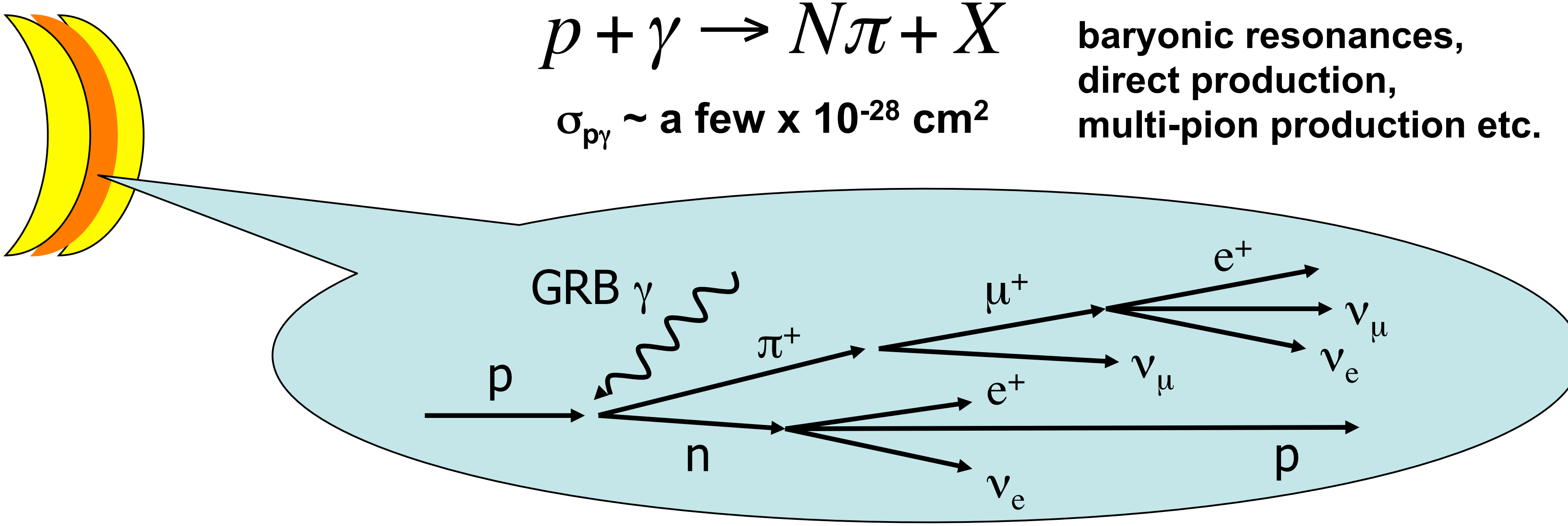
e.g., Waxman & Bahcall 00 ApJ
Dermer 02 ApJ
KM 07 PRD

$p\gamma$ Neutrinos: Basics

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

$\sigma_{p\gamma}$ ~ 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)) & CR spectrum

Neutrino Spectra

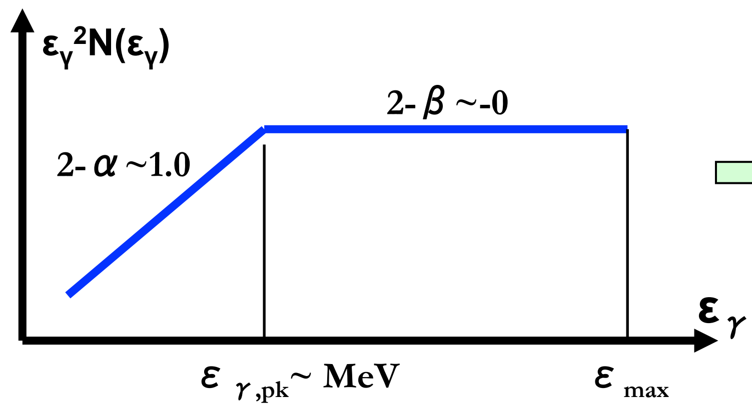
CR Spectrum (Fermi mechanism)

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

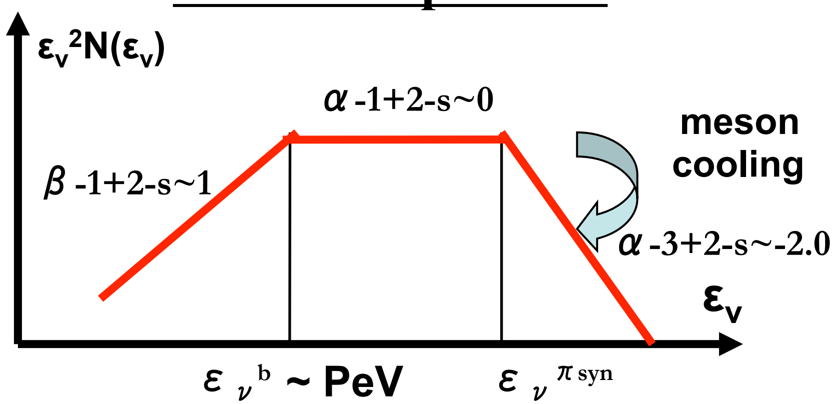
$E_{HECR} \equiv \varepsilon_p^2 N(\varepsilon_p) \sim E_\gamma$ (if UHECR origin)

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

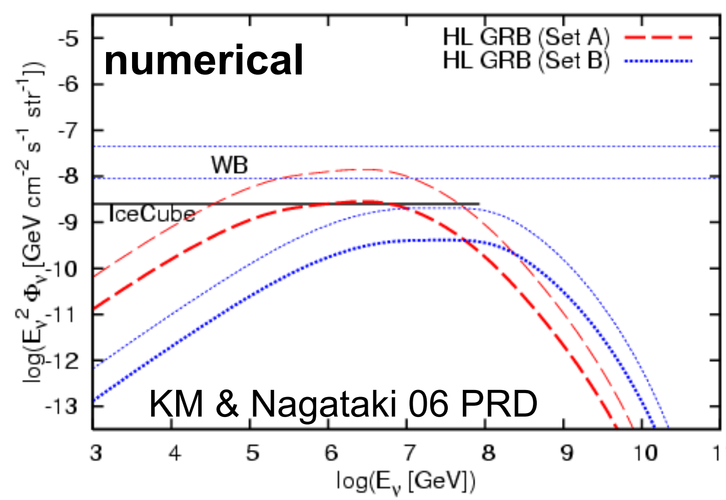
Photon Spectrum (observed)



Neutrino Spectrum

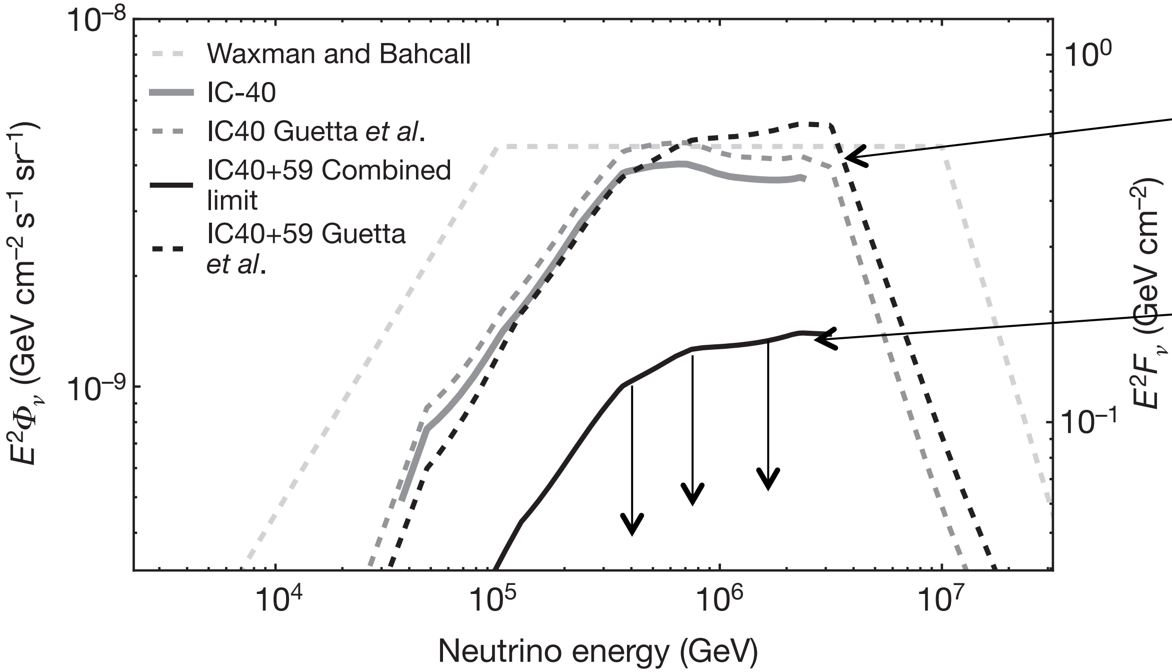


more detailed microphysics
- higher resonances & multi-pion production
- CR cooling (photomeson, photopair, syn., IC)
- muon, pion, kaon w. their cooling
- neutrino mixing



Recent IceCube Limits on Prompt ν Emission

IceCube collaboration 12 Nature



Observational limits start to be powerful but be careful about interpretations

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

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

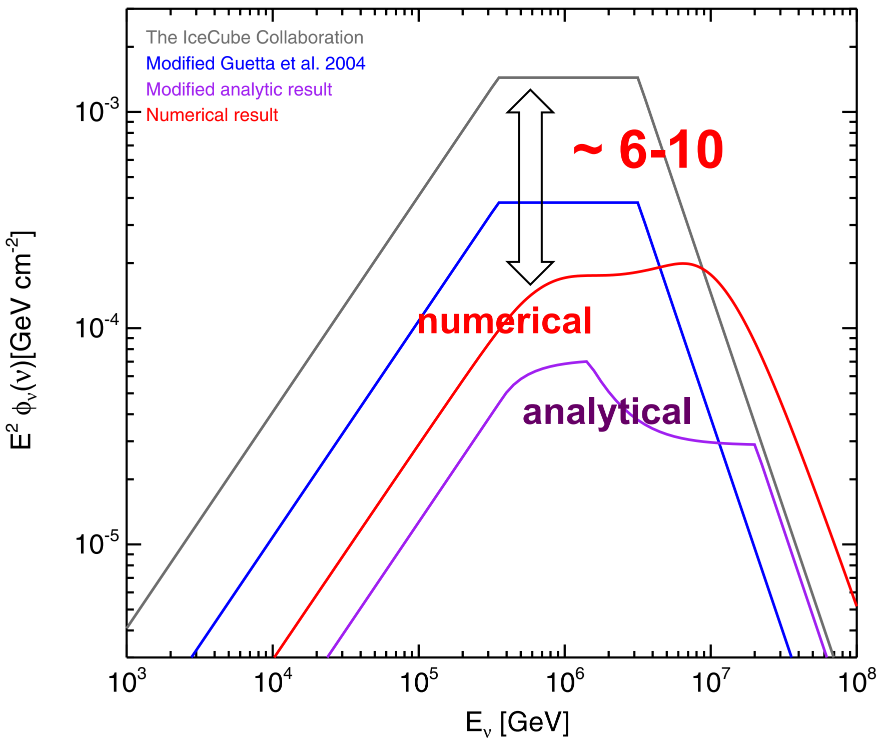
3. details (multi-π, ν mixing etc.) → ex., multi-π ~2-3 ↑ (KM & Nagataki 06)

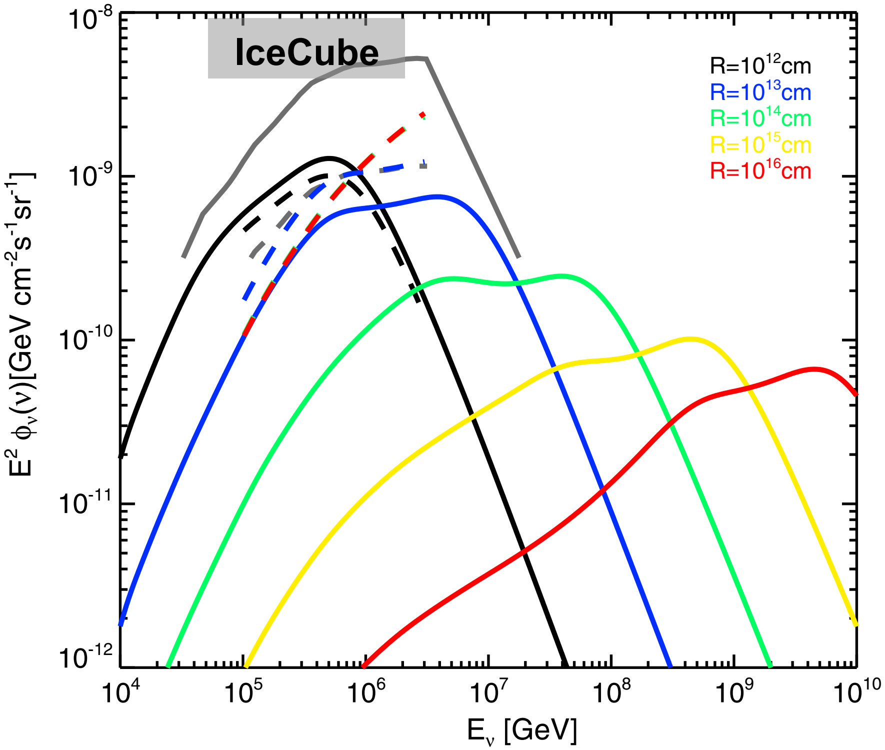
independent of "astrophysical" model-uncertainty in calculating $f_{p\gamma}$

※ The above issues do NOT exist in some pre-IceCube models (ex. KM & Nagataki 06)

Implications of IceCube "Stacking" Searches

He, Liu, Wang+ KM 12 (see also Hummer+12)

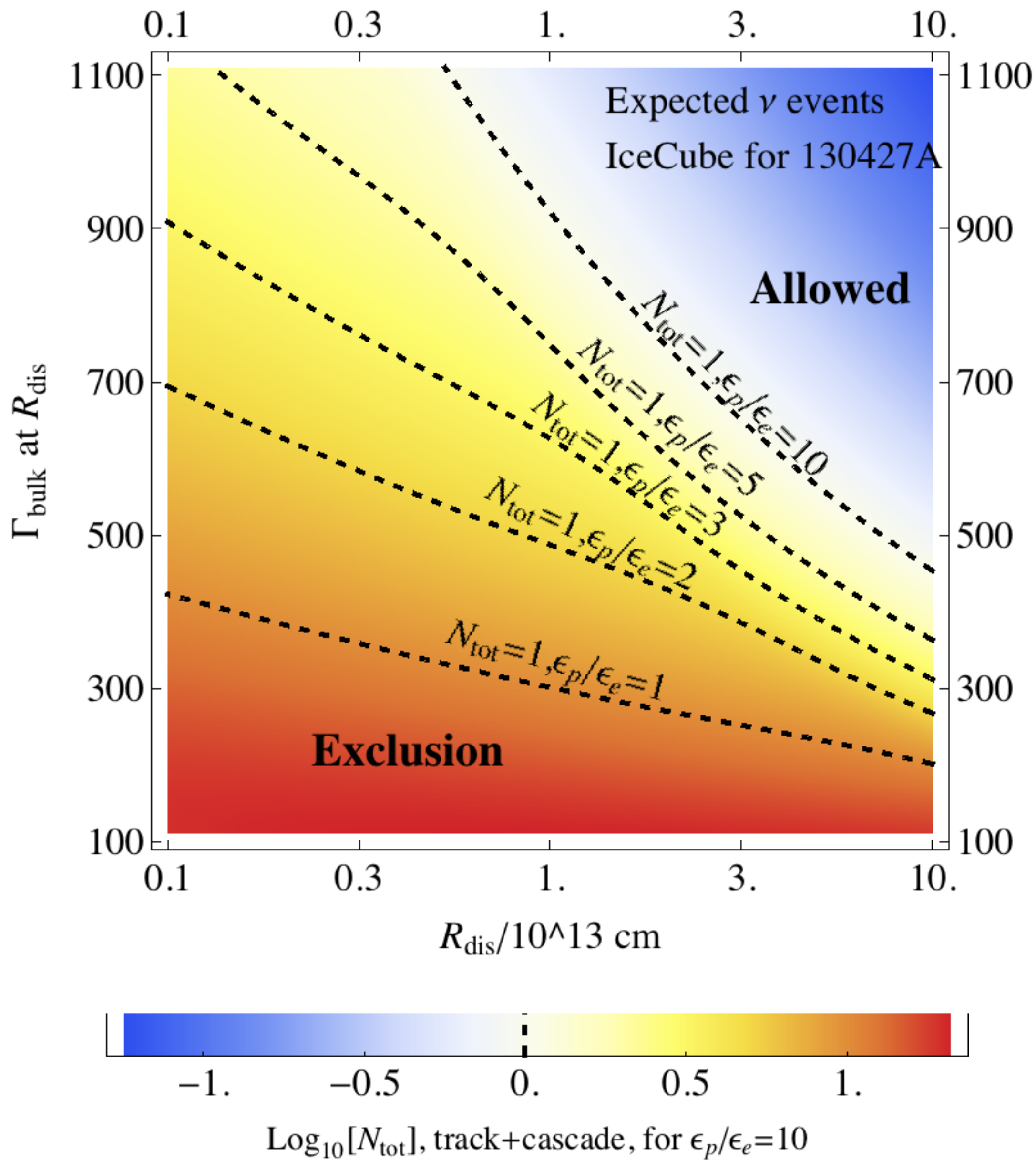




- GRB-UHECR(proton) hypothesis: not ruled out yet
- ~10 yr obs. can cover most of relevant parameter space
- Observed diffuse ν flux cannot be explained by typical GRBs

Exceptions: low-luminosity (LL) GRBs & choked jets inside a star (see ex. KM & Ioka 13 PRL)

Constraints from One Burst



Too small Γ and/or r are excluded

Gao, Kashiyama, & Meszaros 13 ApJL

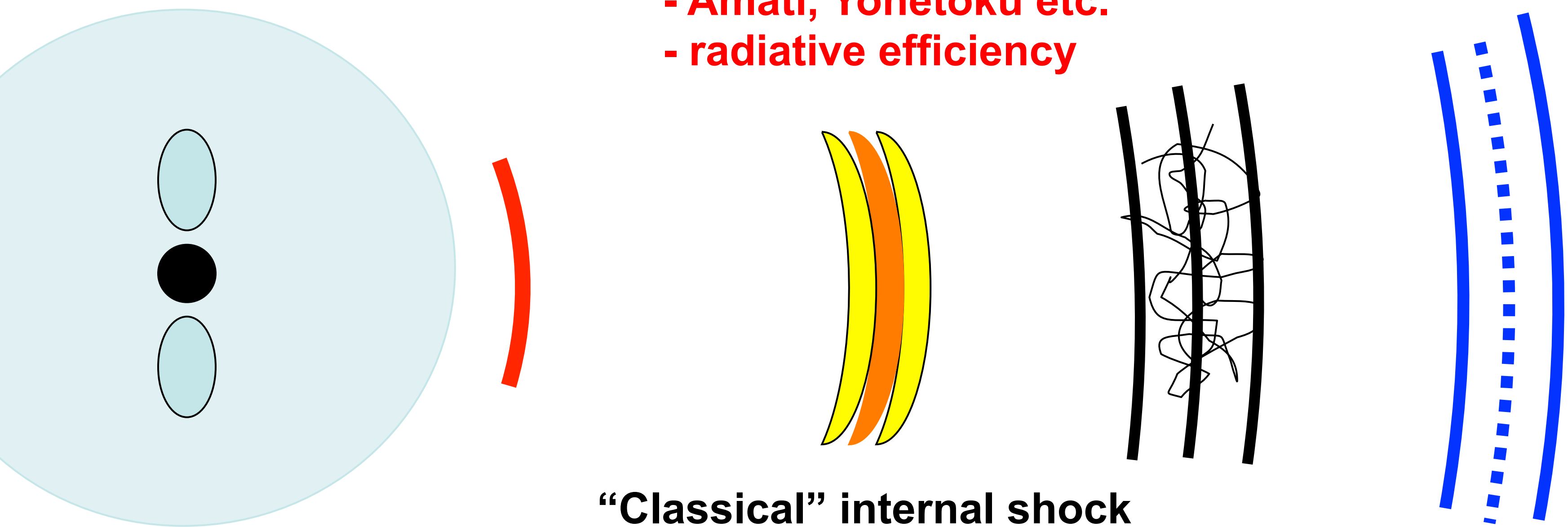
GRB 130427A

Classical GRB Picture Has Been Challenged

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

<u>**Problems!**</u>
- low-energy index
- Amati, Yonetoku etc.
- radiative efficiency

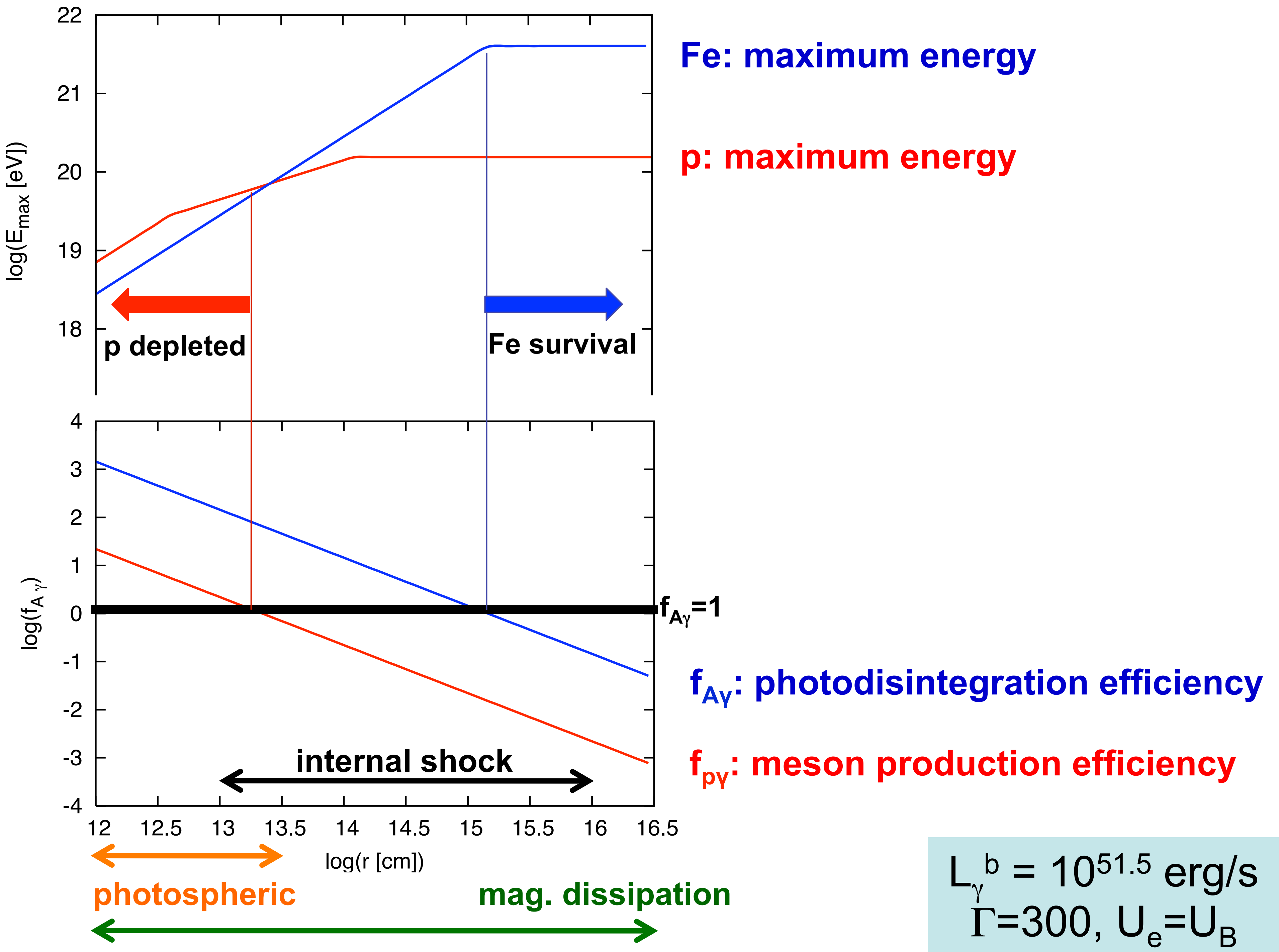
External shock
$r \sim 10^{16}$-10^{17} cm



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

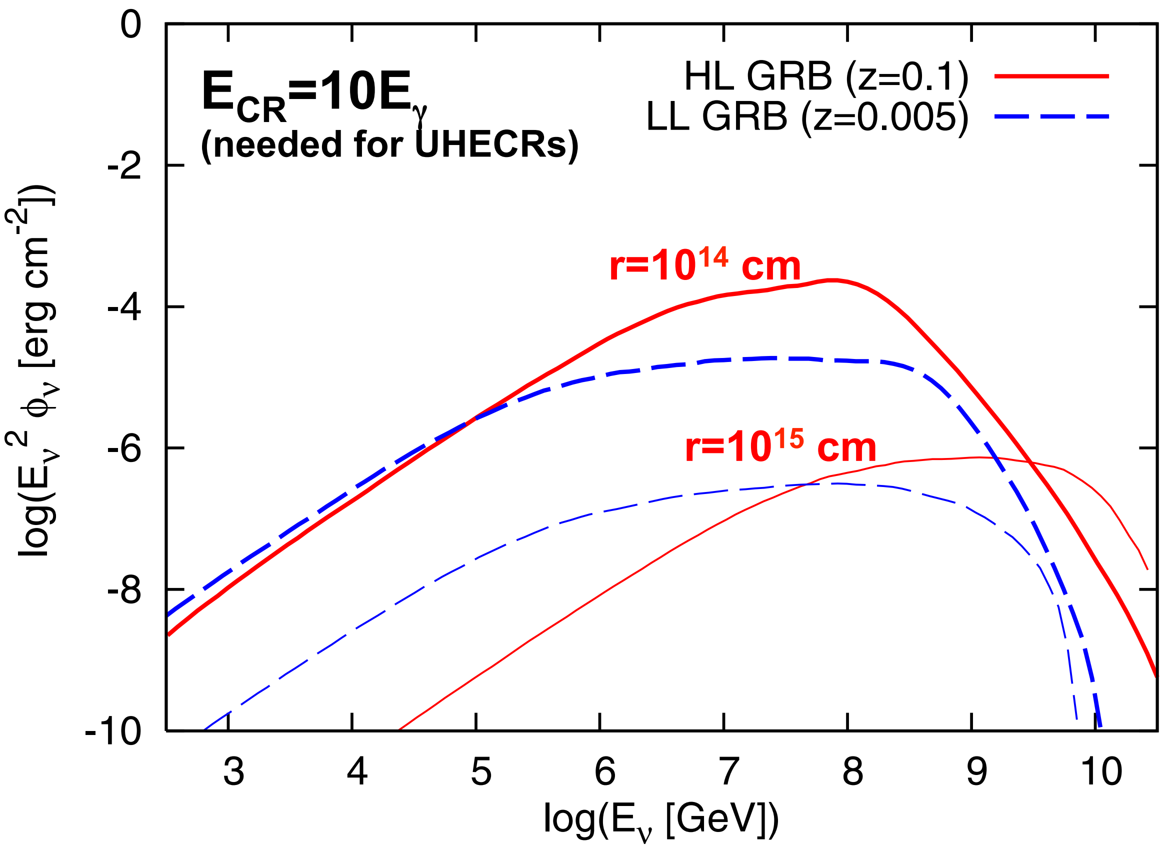
Photosphere
($\tau_T = n\sigma_T(r/\Gamma) = 1$)
$r \sim 10^{11}$-10^{13} cm
modified-thermal emission
dissipation: shock/mag./n-p collision

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



Fe: maximum energy
p: maximum energy
p depleted
Fe survival
log(E_max [eV])
$f_{A\gamma}=1$
log($f_{A\gamma}$)
$f_{A\gamma}$: photodisintegration efficiency
$f_{p\gamma}$: meson production efficiency
internal shock
log(r [cm])
photospheric
mag. dissipation
$L_\gamma^b = 10^{51.5}$ erg/s
$\Gamma=300$, $U_e=U_B$

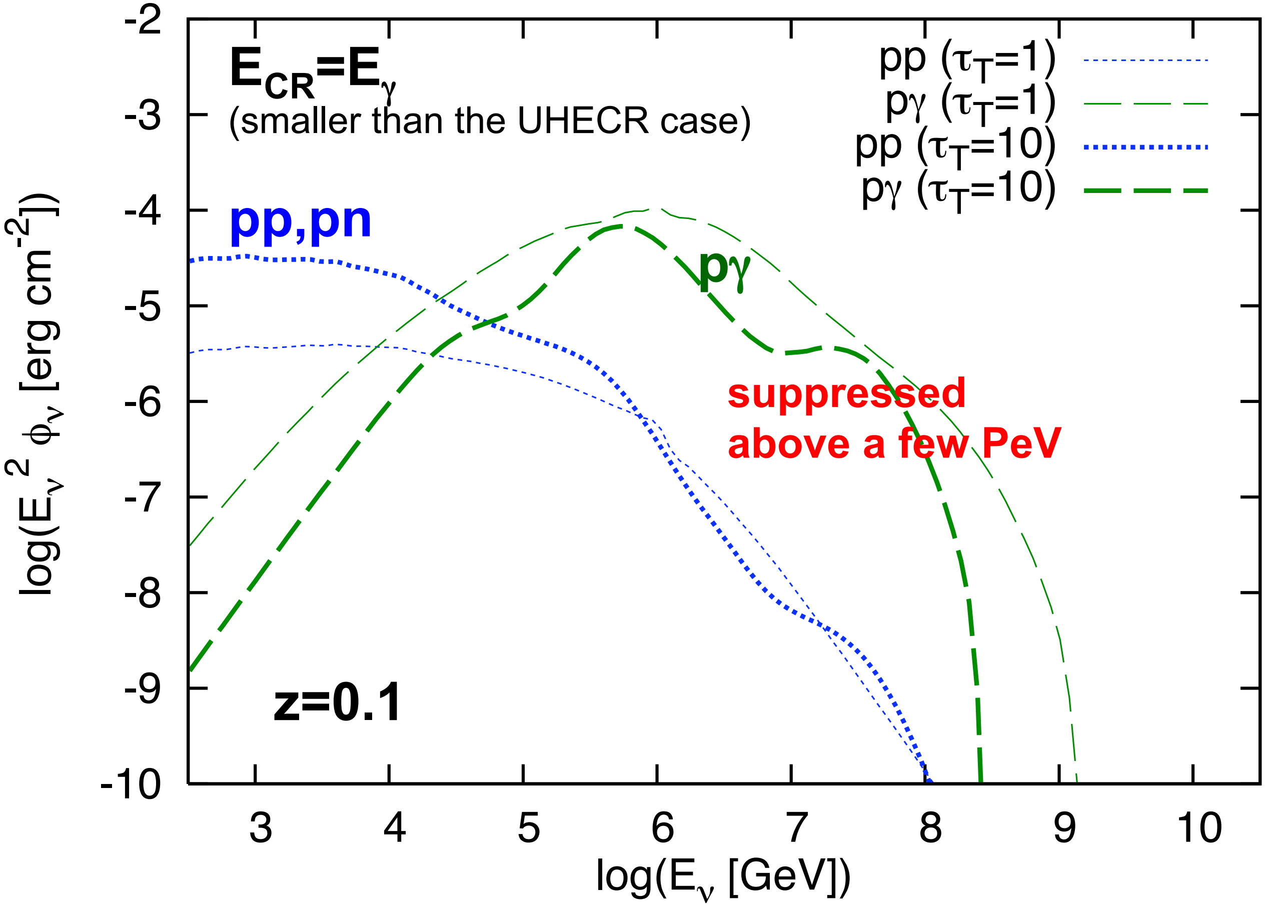
Model-Dependent Predictions: Large r Models



KM et al. 08 PRD
see also Zhang & Kumar 13 PRL

- Large r models required if GRBs are UHE nuclei sources
- $\sigma_{A\gamma} >> \sigma_{p\gamma} \rightarrow$ nucleus-survival=inefficient ν prediction
  if $\tau_{A\gamma} <\sim 1 \rightarrow \varepsilon_\nu^2 \Phi(\varepsilon_\nu) <\sim 3\times10^{-11}$ GeV cm^{-2} s^{-1} sr^{-1} (KM & Beacom 10)
- Magnetic models? multi-zone IS? (Zhang's, Allard's & Bustamante's talk)

Model-Dependent Predictions: Dissipative Photospheres



※ **still consistent with the latest IceCube limits**
$\varepsilon_{\nu\mu}^2\Phi_{\nu\mu}\sim10^{-10}$ GeV cm^{-2} s^{-1} sr^{-1}

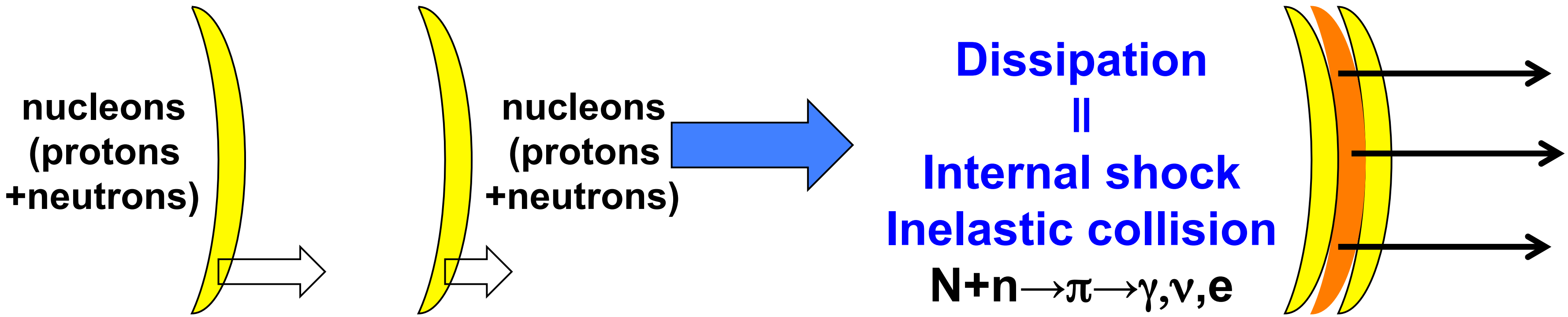
KM 08 PRDR
see also Wang & Dai 09 ApJL

pp: $\tau_T=n_e\sigma_T(r/\Gamma)\sim1\text{-}10 \Leftrightarrow f_{pp}=(\kappa_{pp}\sigma_{pp}/\sigma_T)\tau_T\sim0.05\text{-}0.5 \rightarrow$ GeV-TeV ν

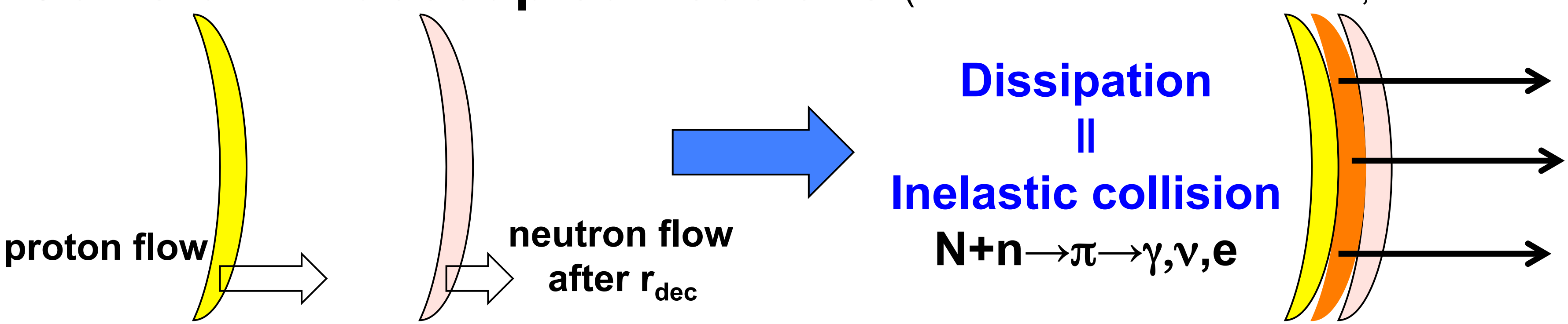
pγ: $f_{p\gamma} >> 1 \Leftrightarrow$ efficient ν production (calorimetric, UHEp depleted)

Internal Dissipation by Neutron-Loaded Outflows

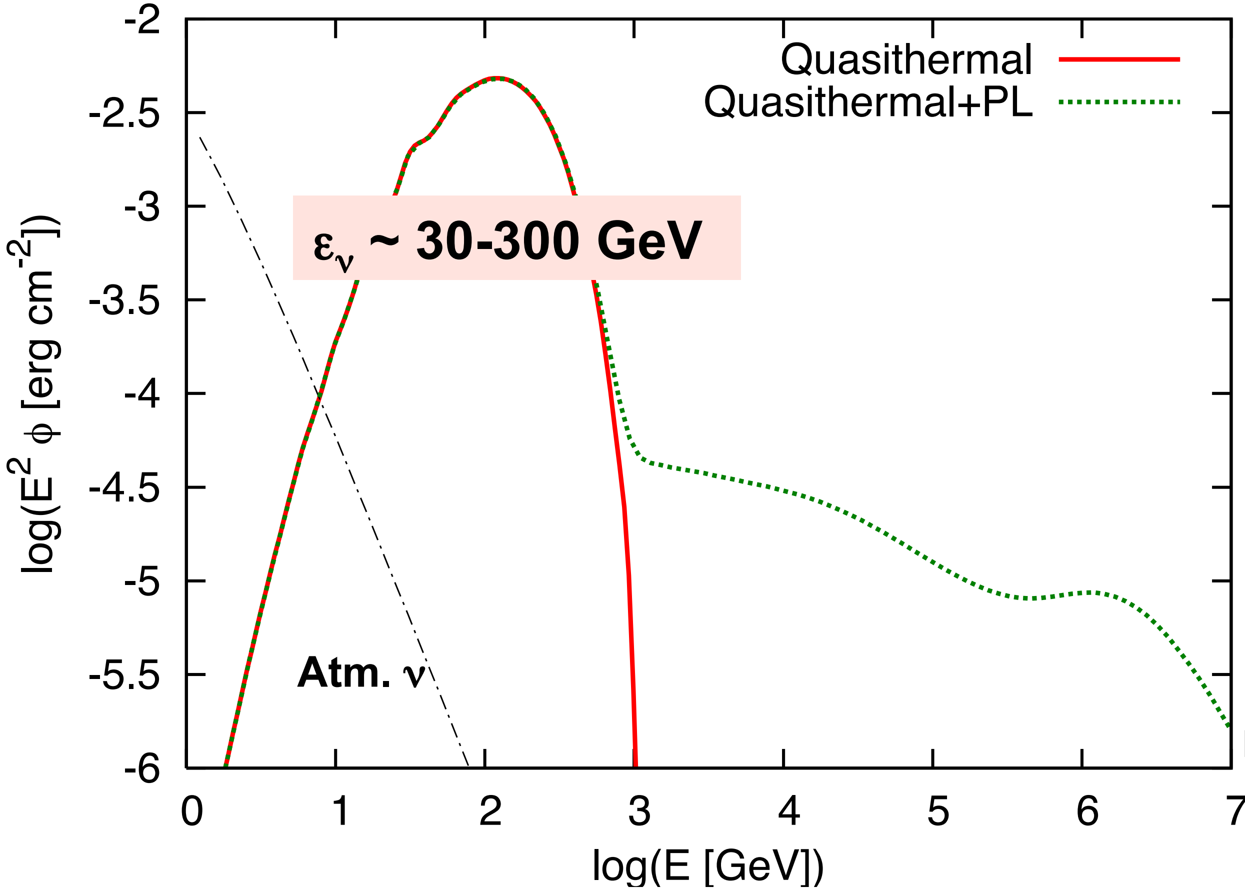
Collision w. compound flow (ex. Meszaros & Rees 00)



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



Quasi-Thermal Neutrinos from pn Collisions



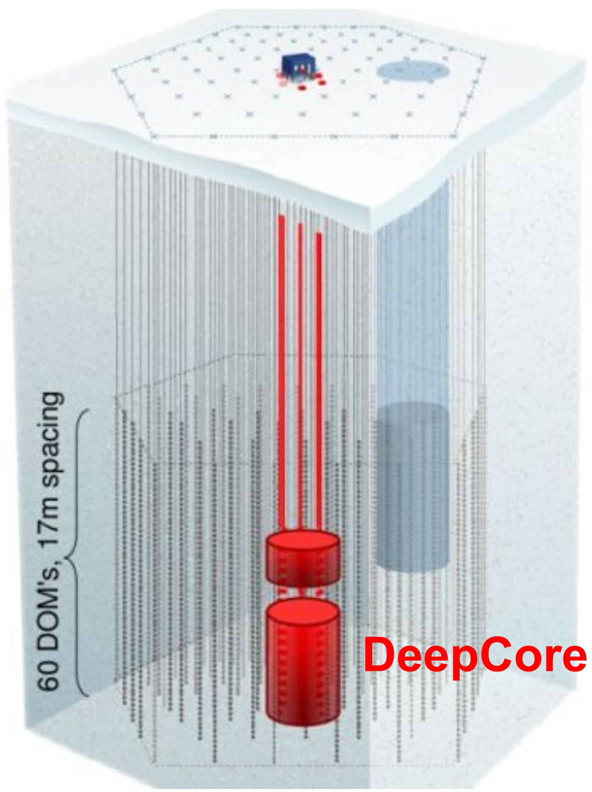
$E_k^{iso}/E_\gamma^{iso}=4$
$E_\gamma^{iso}=10^{53.5}$ erg
$\Gamma=600$, z=0.1

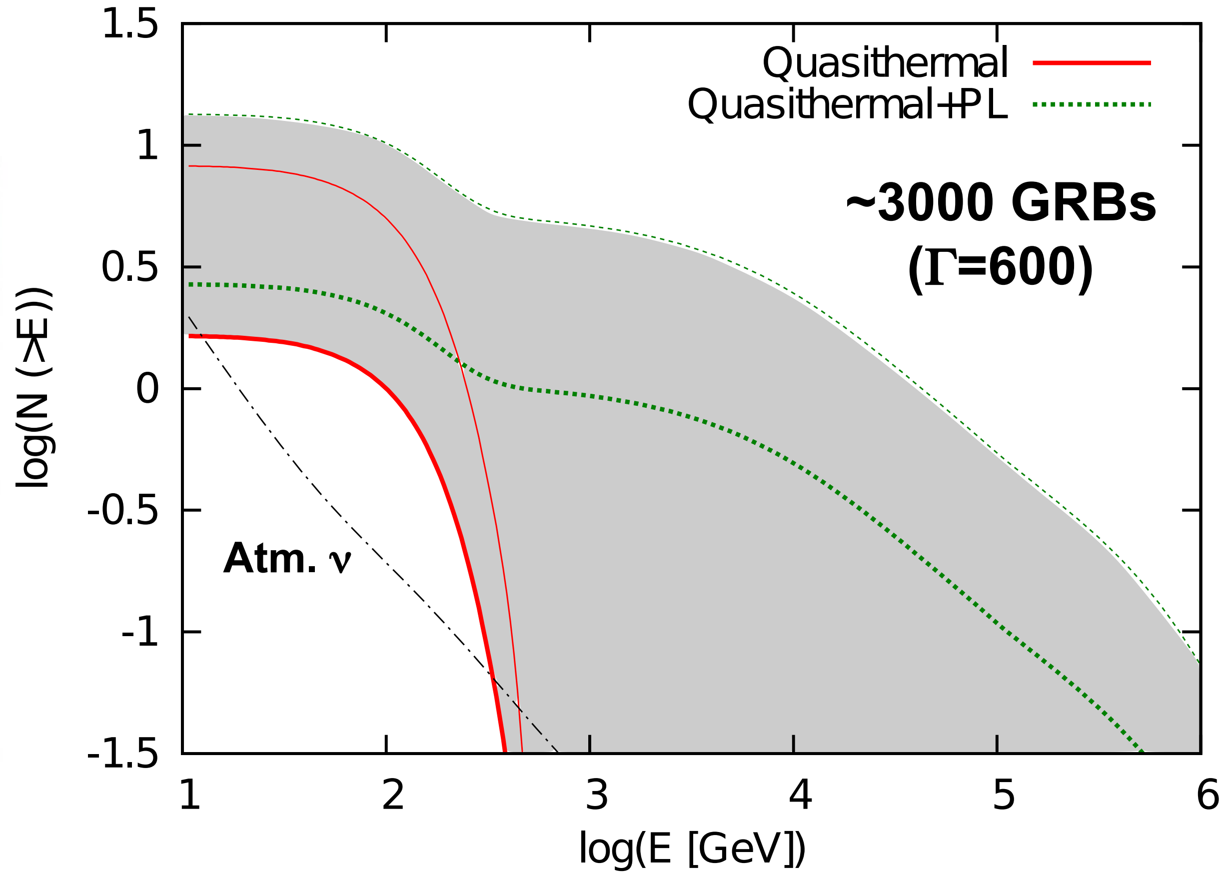
KM, Kashiyama & Meszaros 13 PRL

- Quasithermal ν w. $\varepsilon_\nu \sim 0.1\Gamma\Gamma_{rel} m_p c^2$: fairly robust
- Strong consequence of the inelastic collision model: $\varepsilon_\nu^2\phi_\nu \sim \varepsilon_\gamma^2\phi_\gamma$=prompt emission fluence (less uncertainty)

Prospects for DeepCore+IceCube

- Including DeepCore is important at ~10-100 GeV
- Reducing atm. bkg. is essential (select bright GRBs w. $>10^{-6}$ erg cm^{-2}
- Quasithermal νs are detectable in ~10 yrs or sooner w. nonthermal p





KM+ 13 PRL (see also Bartos+ 13 PRL)

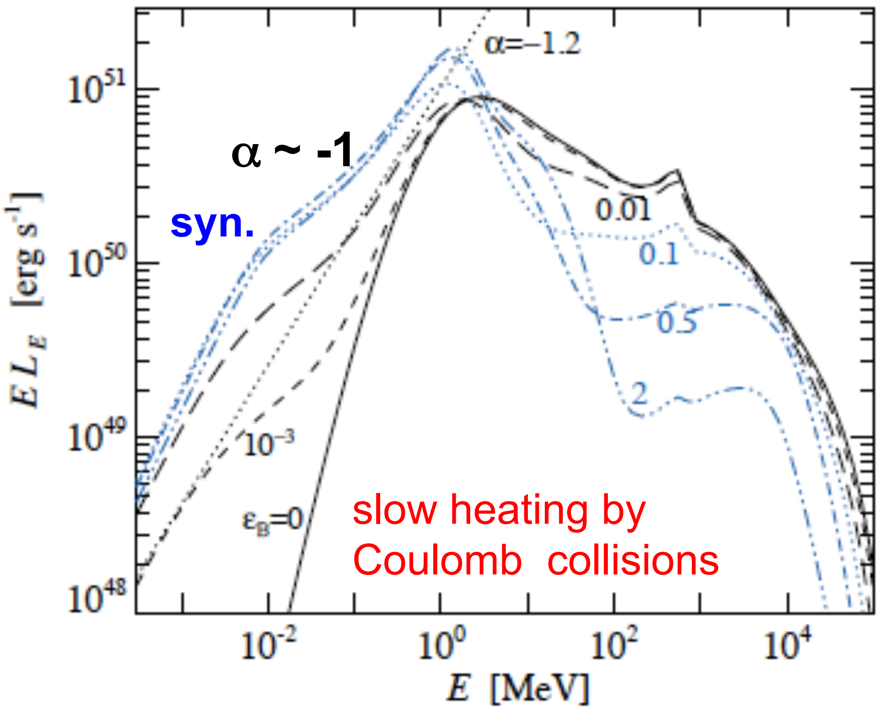
γ Rays?: Pair Injection via Proton-Induced Cascades

see also Petropoulou's talk

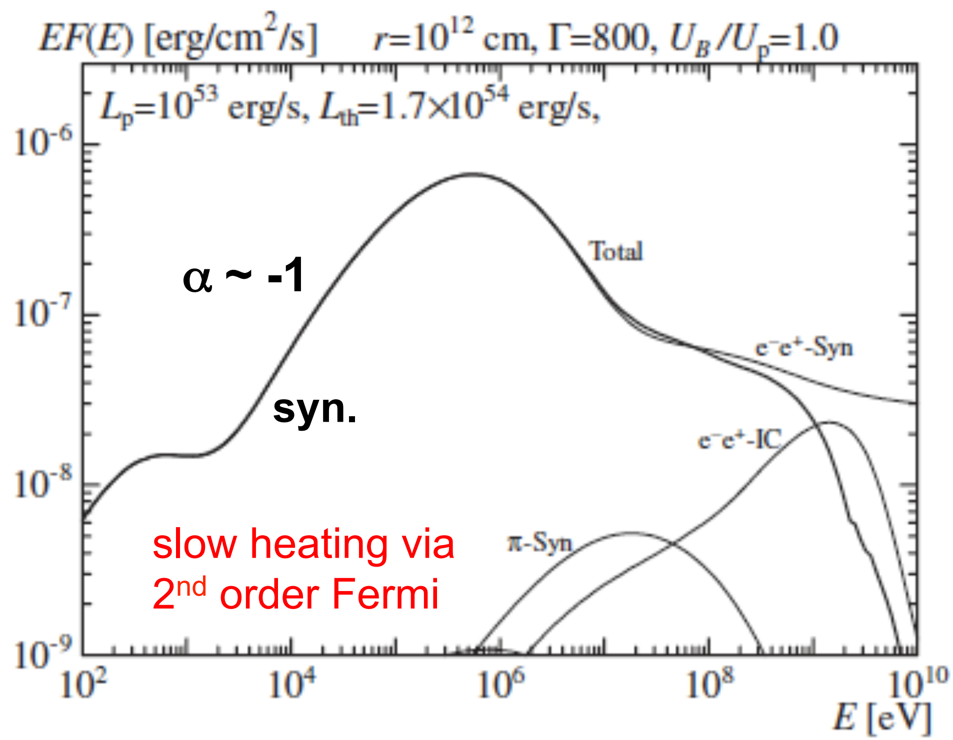
$$\pi^{\pm} \rightarrow \nu_{\mu} + \bar{\nu}_{\mu} + \nu_e(\bar{\nu}_e) + e^{\pm}$$
$$\pi^0 \rightarrow \gamma + \gamma \qquad \text{etc.}$$

$$\gamma + \gamma \rightarrow e^+ + e^- \quad e + B \rightarrow e + \gamma\ (\text{syn})$$
$$e + \gamma \rightarrow e + \gamma\ (\text{IC})$$

Idea: pairs are naturally furnished by cascades and then heated

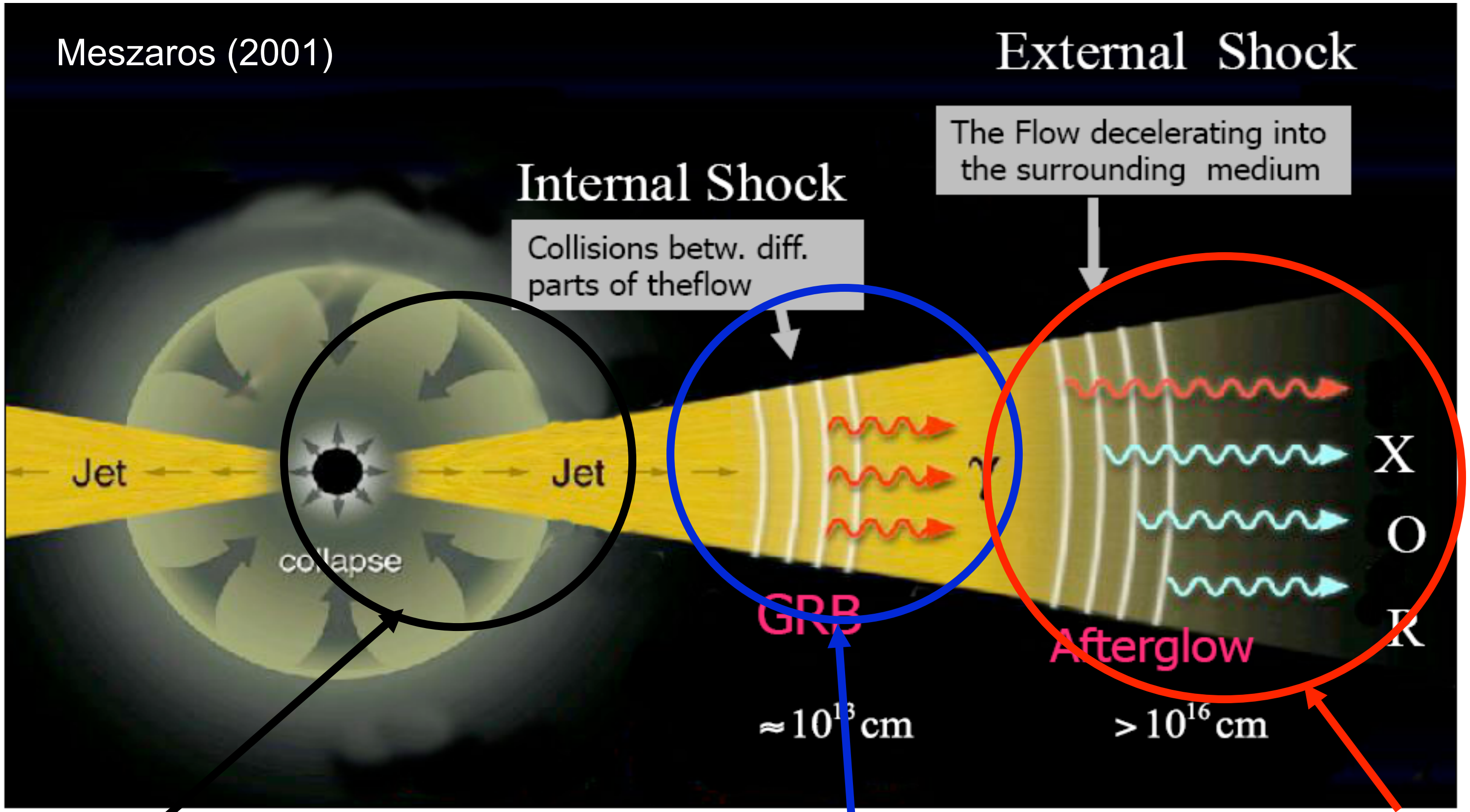


Vurm, Beloborodov & Poutanen 11 ApJ



KM, Asano, Terasawa & Meszaros 12 ApJ

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

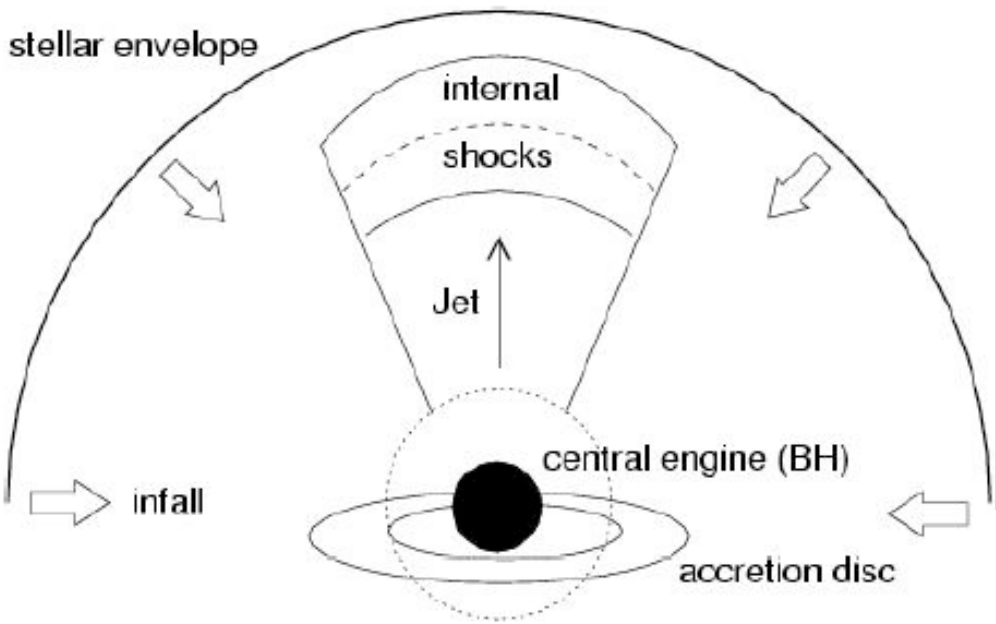
Afterglow
$r \sim 10^{14}$-10^{17} cm $B \sim 0.1$-100 G
EeV ν, GeV-TeV γ

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>

- Clues to GRB-SN connection and progenitors
- Jet acceleration and jet composition (hydrodynamic or magnetic)
- Neutrino mixing including matter effects etc.



Meszaros & Waxman 01 PRL
Razzaque et al. 04 PRL
Ando & Beacom 05 PRL

"Hidden" neutrino sources

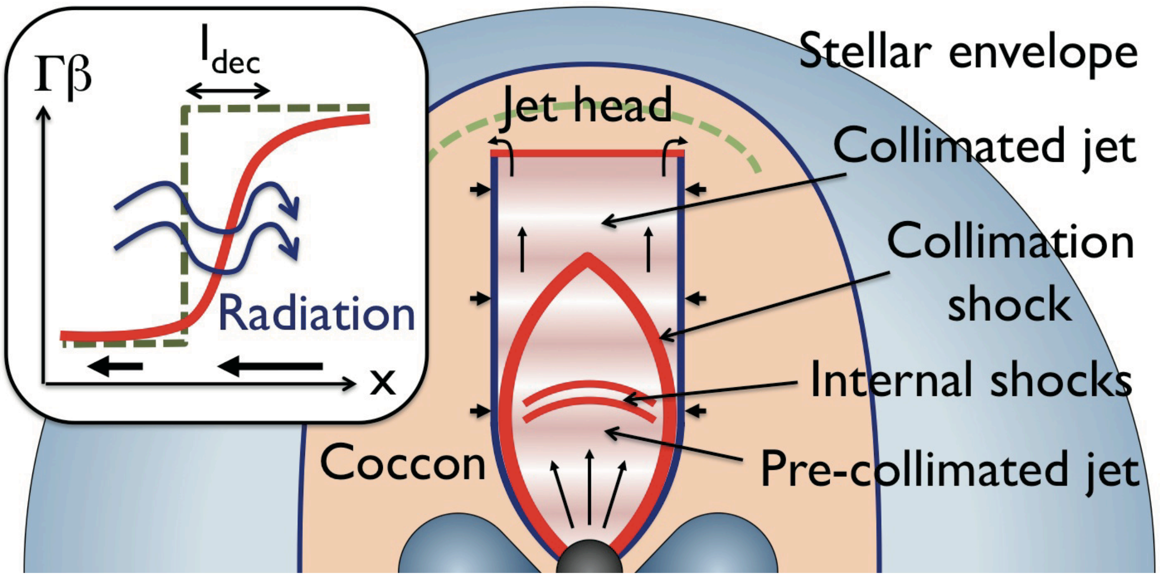
- **Jets before GRB emission "precursor neutrinos"**
- **Choked jets (failed GRBs) "orphan neutrinos"**

high density → $f_{p\gamma} >> 1$
all CRs are damped

If CRs carry E_{CR}^{iso}~0.5×10^{53} erg
→ # of νs: ~30 for a GRB/SN@10Mpc
but *no detections so far, why?*

More Realistic Picture

Two pieces of important physics were not considered

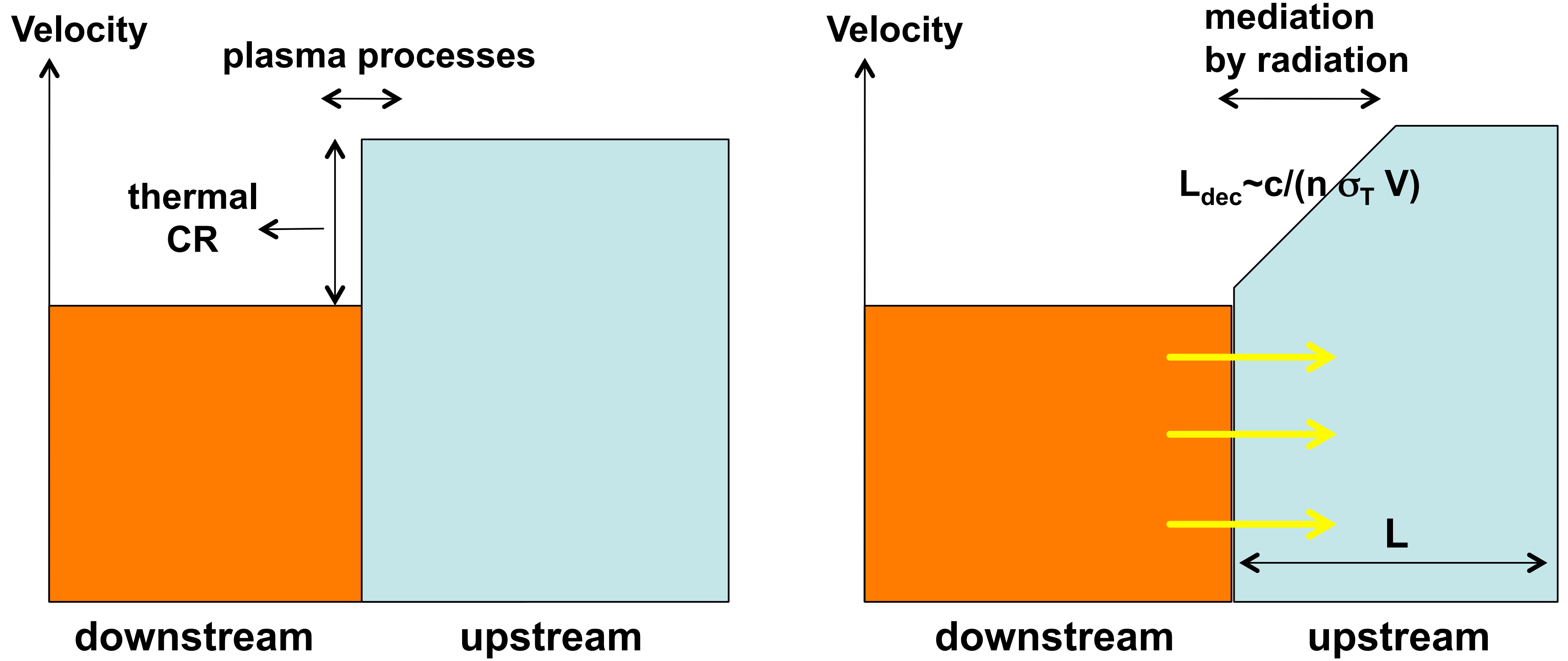


hydrodynamic jet assumed

1. Ballistic jets inside stars ❌
   → collimation shock & collimated jet (Bromberg's talk)
2. CR acceleration is naively assumed ❌
   → inefficient at radiation-mediated shocks

Limitation of Conventional Shock Acceleration

Collisionless shock (plasma-mediated) **Radiation-mediated shock**

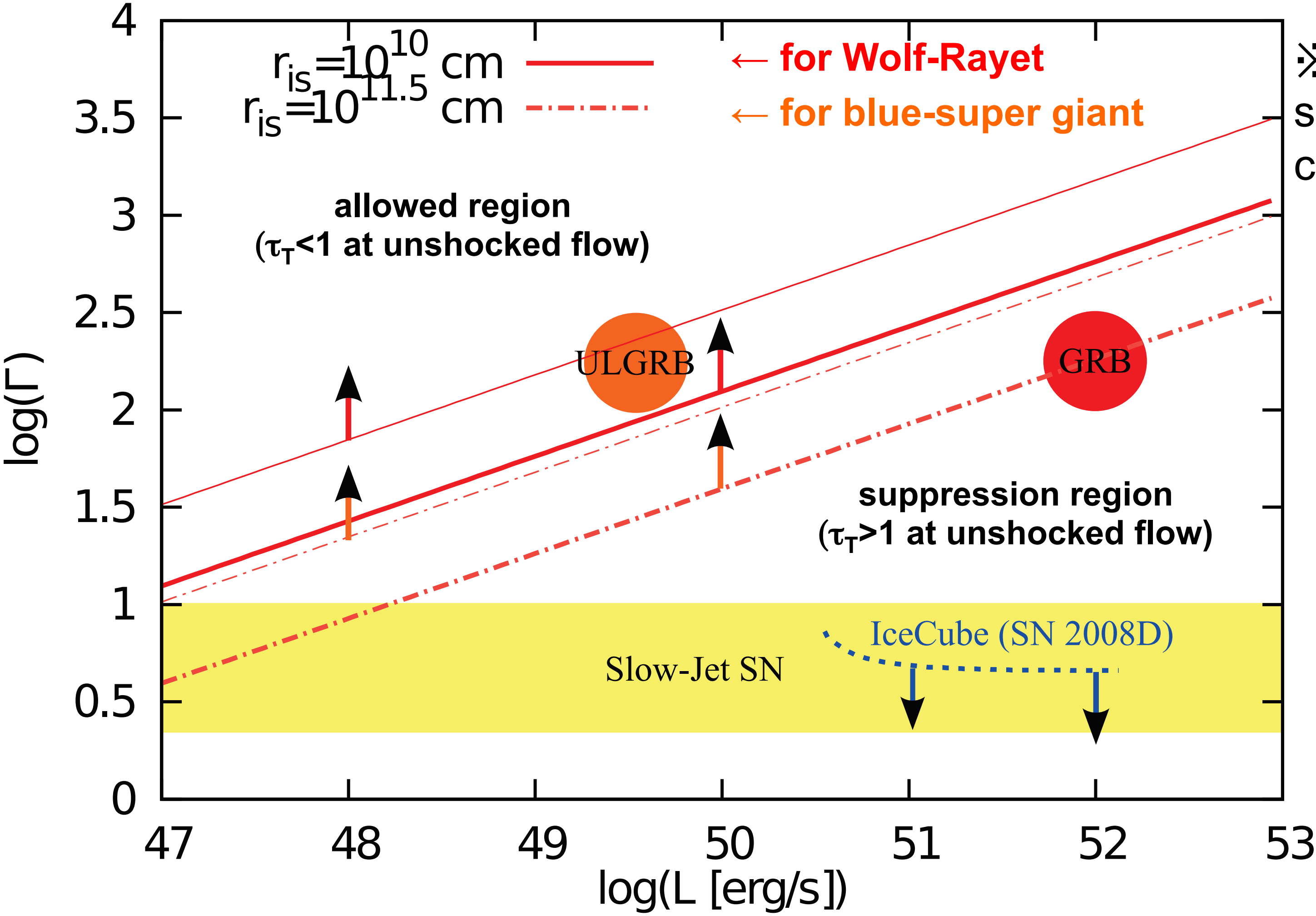


(p Larmor radius) ~> (shock width) **(p Larmor radius) << (shock width)**

$L \sim L_{dec}$ ⇔ $\tau_T \sim c/V$: after photons escape, CR acceleration may start

(ex. Waxman & Loeb 01, Levinson & Bromberg 08, KM & Ioka 13)

“Radiation Constraints” on Non-thermal Neutrino Production



※ A bit different but similar derivation for collimation shock

KM & Ioka 13 PRL

Thomson optical depth

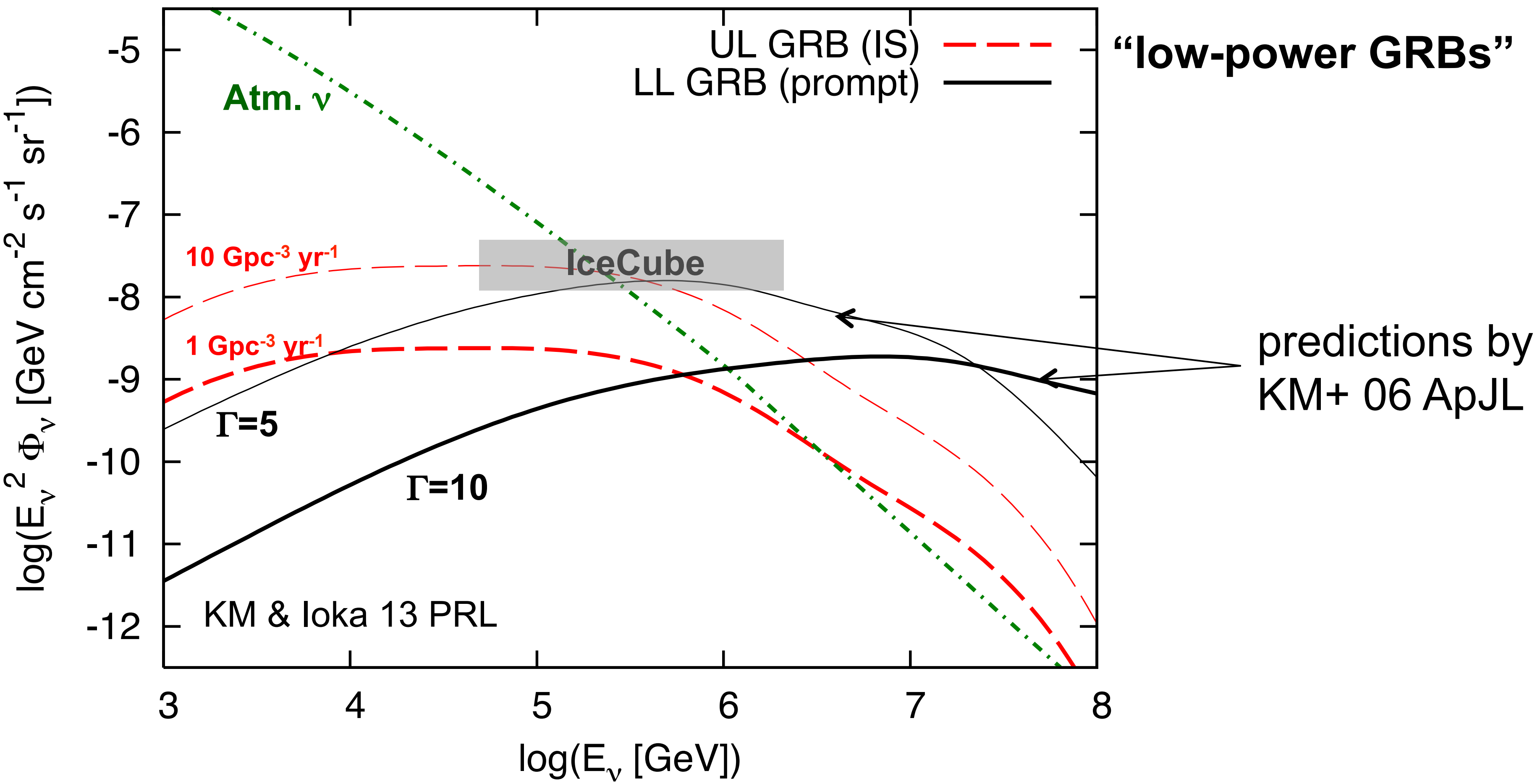
$$\tau_T = n_e \sigma_T \Delta \propto L\Gamma^{-2}$$

L: kinetic luminosity

Γ: Jet Lorentz factor

TeV-PeV Neutrinos from Low-Power GRBs?

They can give significant contributions to the diffuse neutrino flux



Low-power GRBs and their choked jets may be largely missed
→ Need better wide-field sky monitors (Lobster, WF-MAXI etc.)

High-Energy Neutrinos from Jets inside Stars?

The radiation constraint implies

- **Lower-power is better**
- **Bigger progenitor is better**

Implications

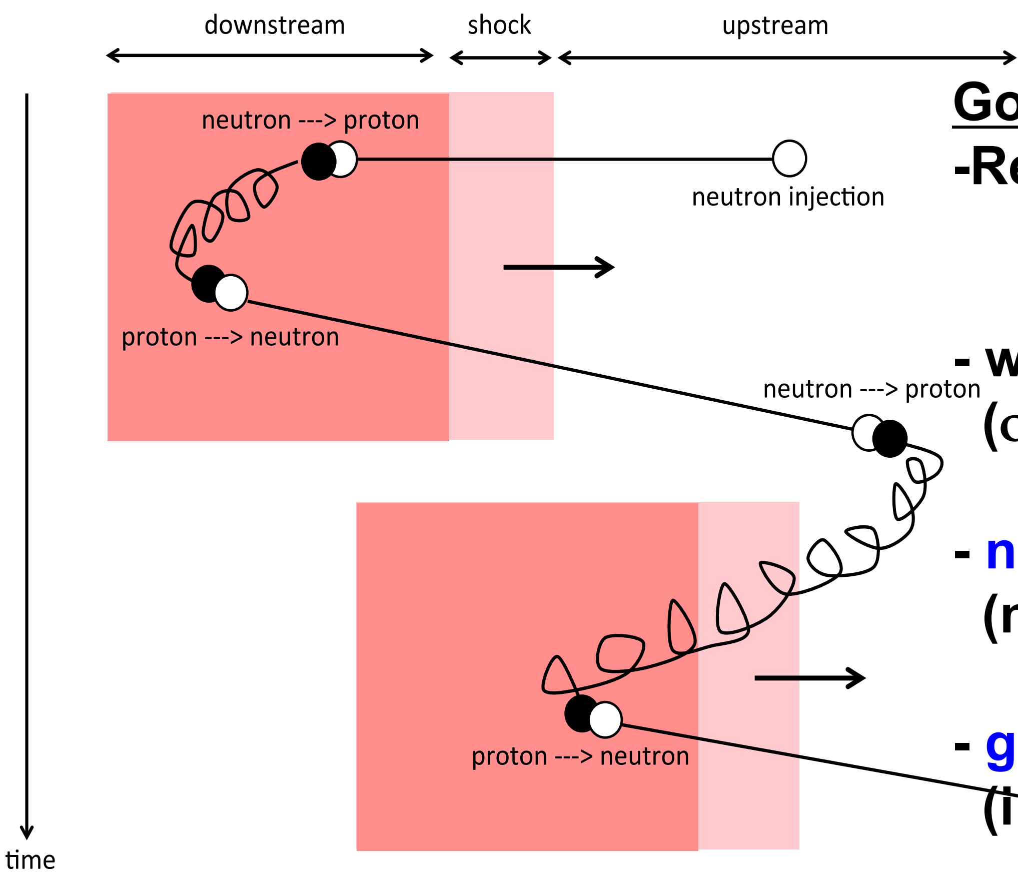
- suppressed in powerful GRBs/slow-jet SNe (consistent w. obs.)
- low-power jets (maybe low-luminosity & ultralong GRBs)
- choked jets are favorable (due to difficulty of jet penetration)

It may be disappointing… However, their is a promising mechanism can work in powerful jets

Novel Acceleration Process in Neutron-Loaded Jets

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

another Fermi acceleration mechanism without diffusion



inelastic collisions allow p ⇔ n

<u>Good points</u>

-Relevance in GRB jets inside stars
(KM+13 PRL)

- works even if radiation mediated ($\sigma_{np} < \sigma_T$)

- naturally injected (neutron m.f.p. > shock width)

- guaranteed for n-loaded flows (insensitive to plasma physics)

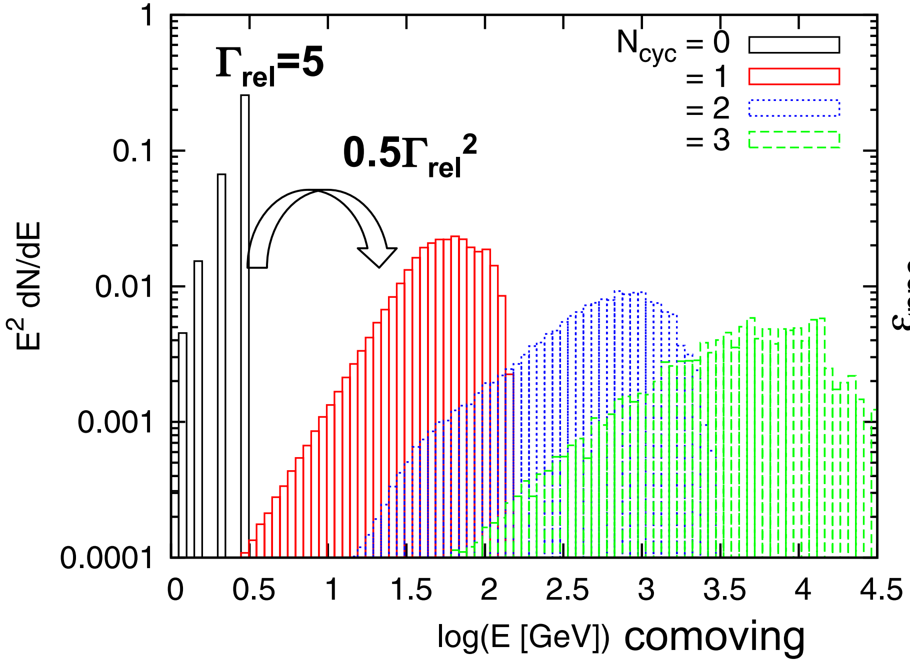
- slow process → TeV ν (not PeV ν)

NPC Acceleration: Spectra & Efficiency

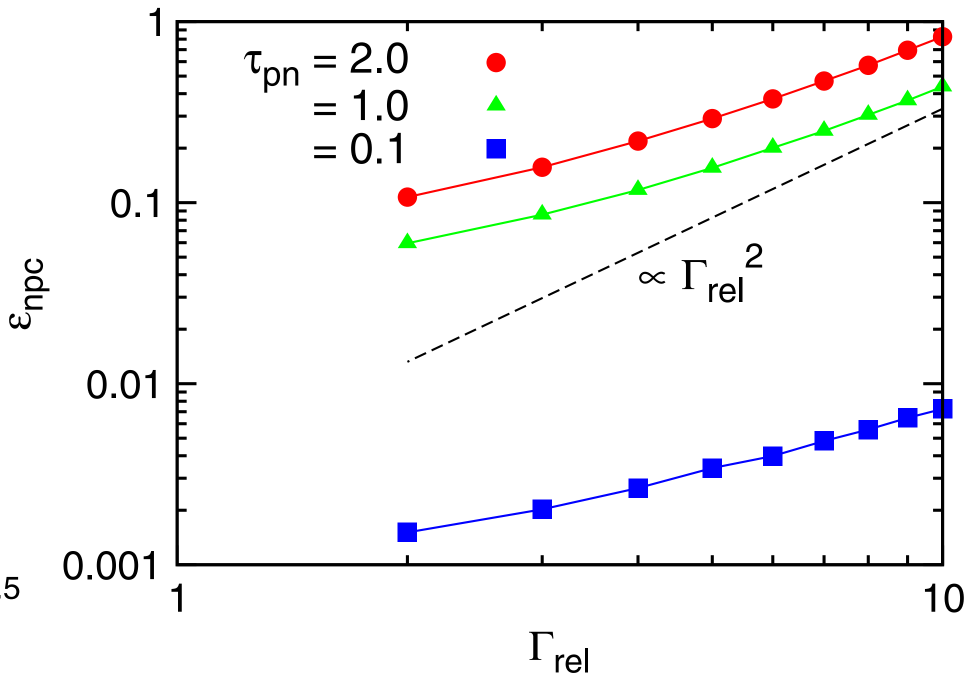
We first performed Monte Carlo simulations for test particles

- Characteristic spectra: bumps rather than a power law
- High acc. efficiency: >10% of incoming neutron energy

nucleon spectra w.o. cooling

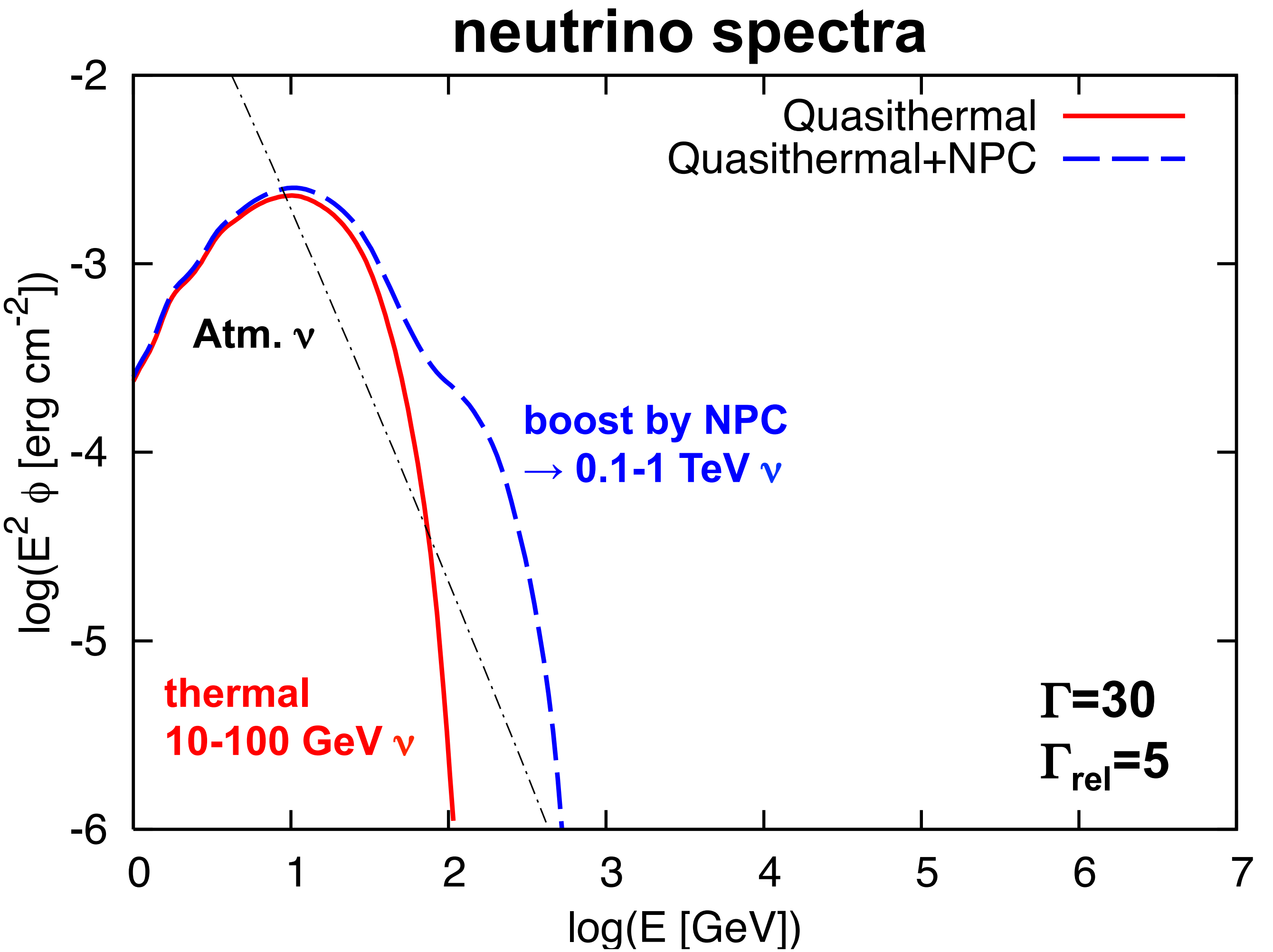


acceleration efficiency



Kashiyama, KM & Meszaros 13 PRL

NPC Acceleration: Application to GRB Jets



KM+13 PRL

- Higher-energies are better: atm. ν bkg. & (effective area)$\propto E^2$
- NPC acc. enhances the detectability of GeV-TeV νs

Summary: Multimessenger Approaches are Crucial

<u>GRB as the UHECR origin? → allowed at present</u>

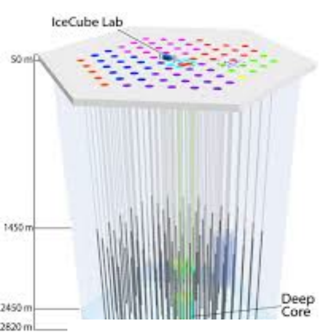
- Classical: most parameter space will be covered in ~10 yrs if UHEp
- Hard to exclude the UHE heavy-nuclei scenario or afterglow scenario

<u>HE neutrinos from dissipative photospheres? → more promising</u>

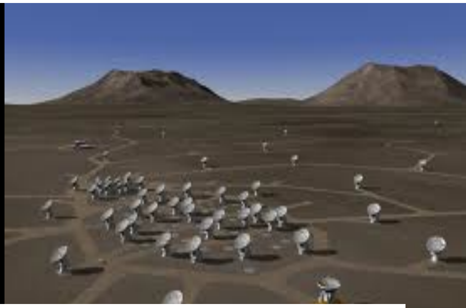
- GeV-TeV neutrinos from pp/pn interactions (→ DeepCore, PINGU etc.)
- Quasithermal νs from n-loaded outflows can be detected in ~10 yrs

<u>HE neutrinos from jets inside stars? → unique probe of hidden jets</u>

- TeV-PeV ν production is possible only for low-power GRB jets
- For powerful jets, NPC acc. enhances detectability of TeV neutrinos



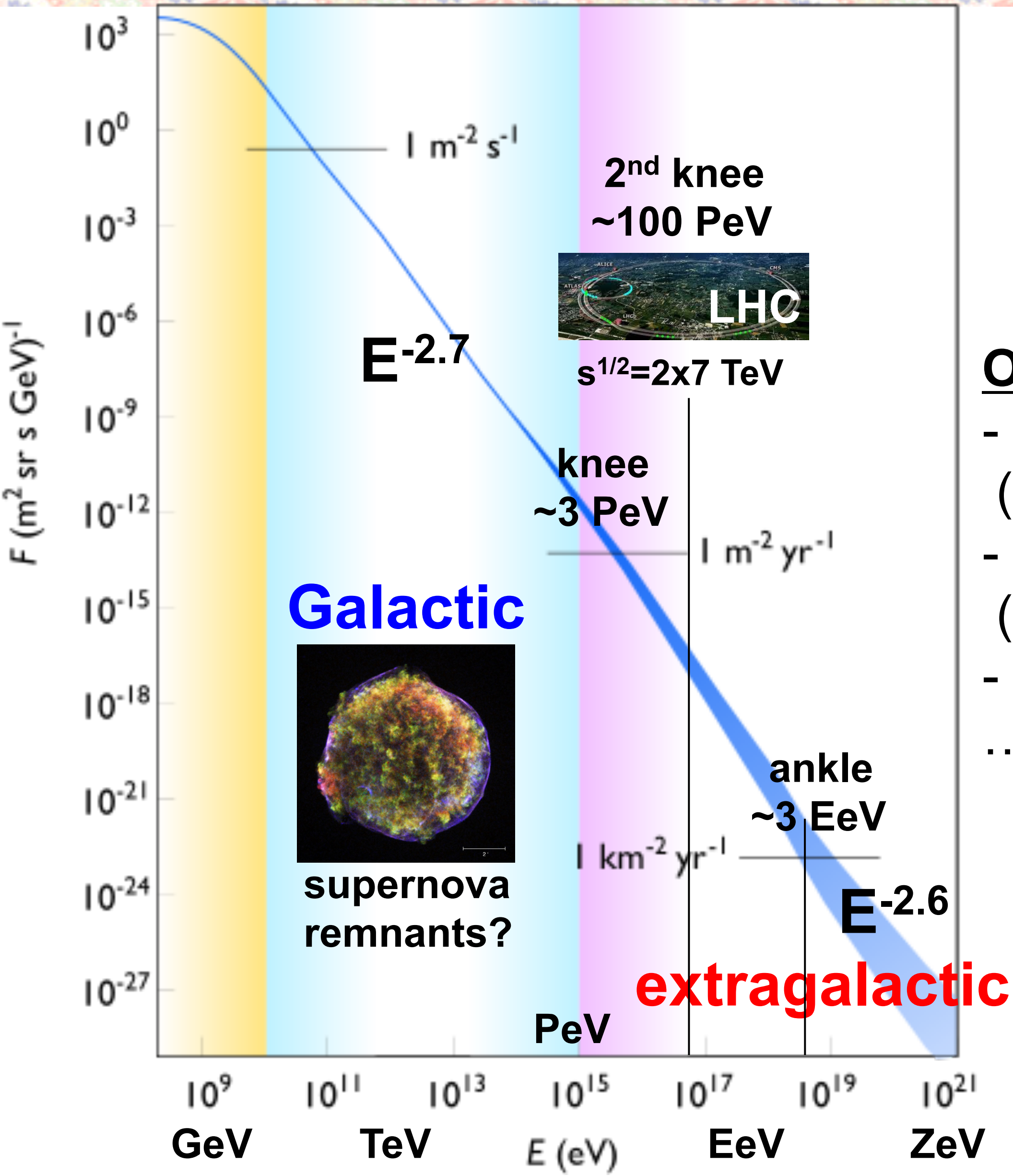


Need more GRB/SN data w. rapid followups/surveys in opt., X and γ rays

Backup Slides

Motivation I: Cosmic Rays – A Century Old Puzzle



$$\frac{dN_{\mathrm{CR}}}{dE} \propto E^{-s_{\mathrm{CR}}}$$

Open problems

- How is the spectrum formed?
 (ex. transition to extragalactic)
- How are CRs accelerated?
 (ex. Fermi mechanism: s_{CR}~2)
- How do CRs propagate?

…

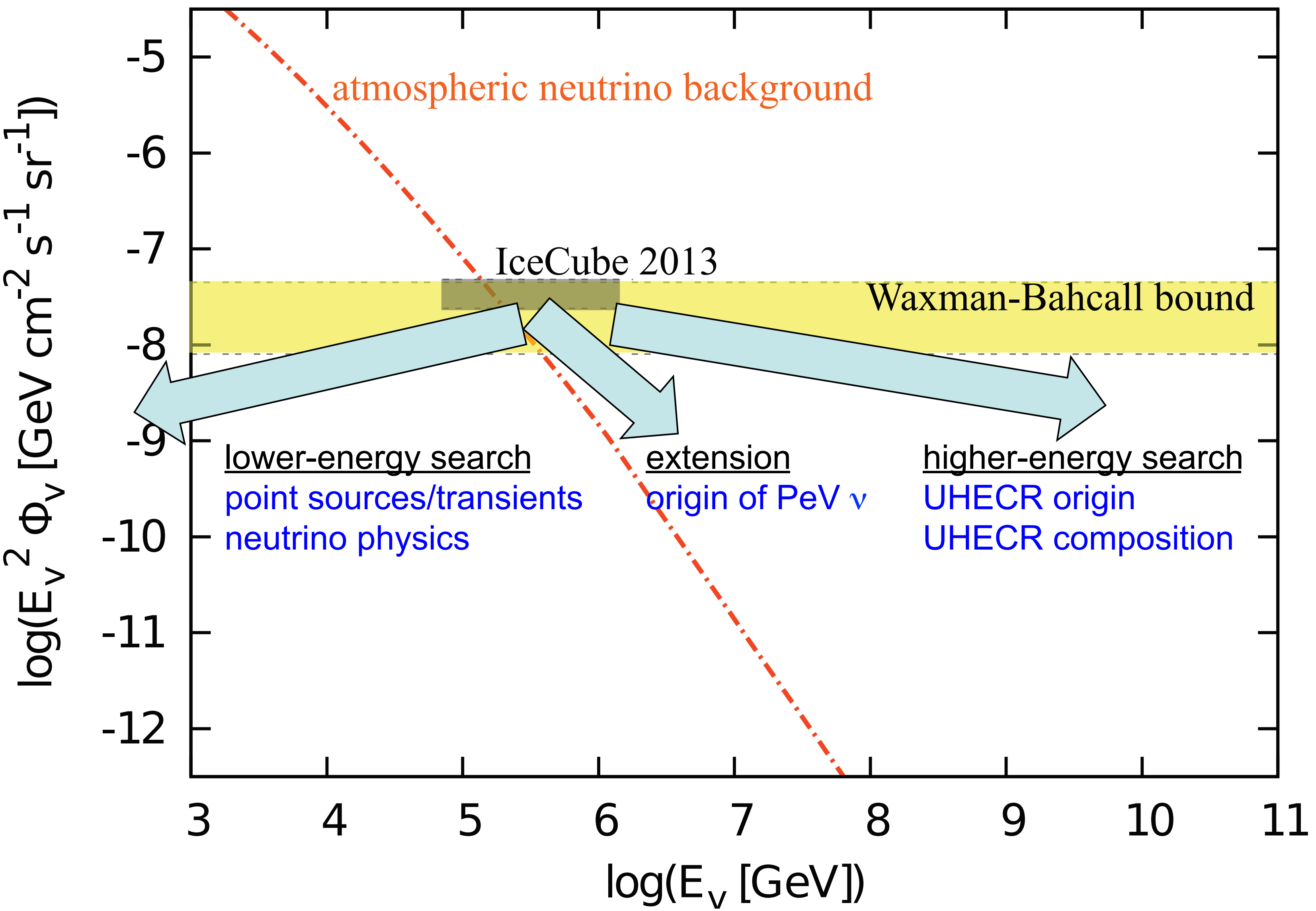
The key question

"What is the origin?"

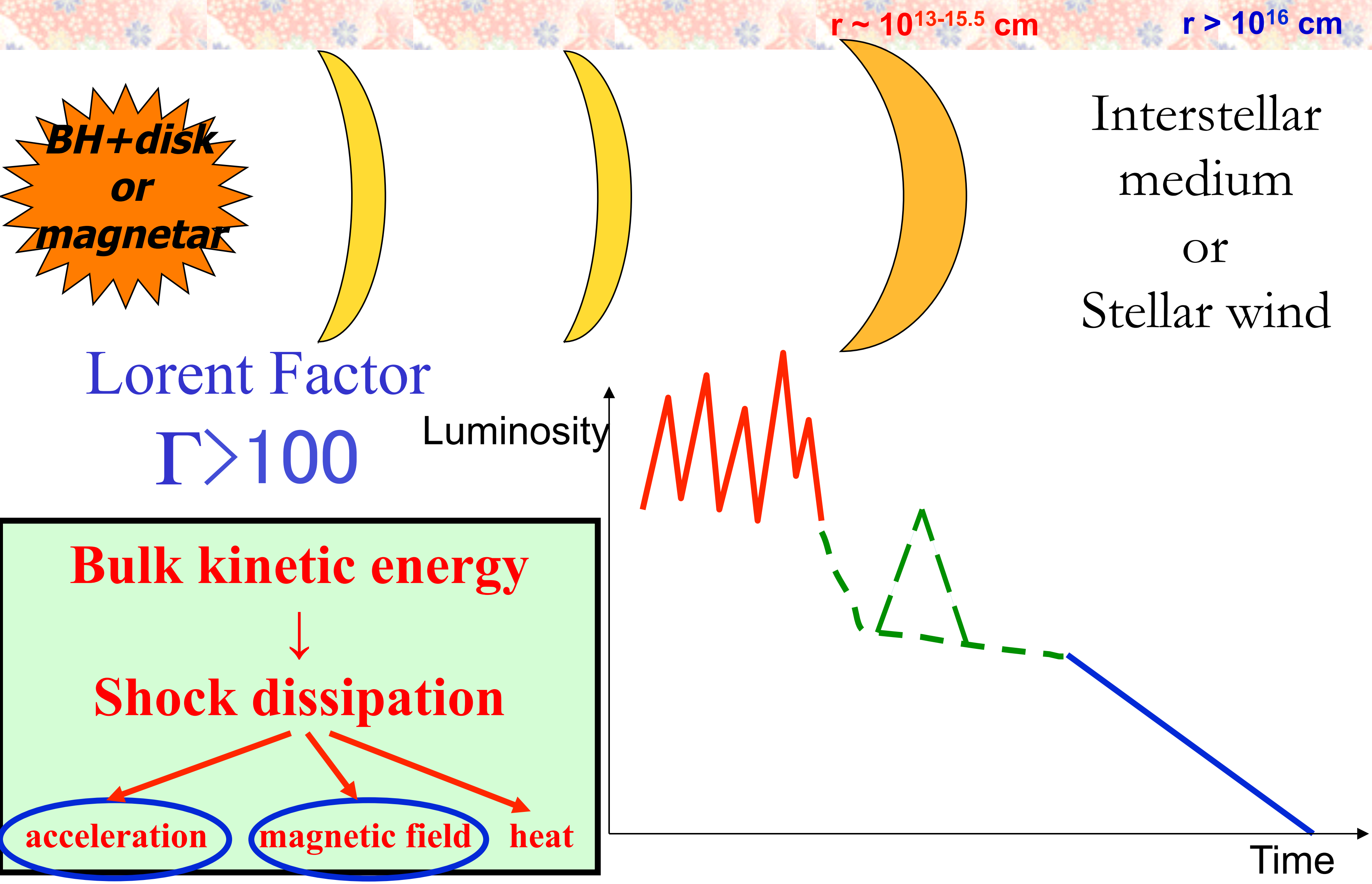
extreme energy (EeV-ZeV)

→ extreme sources

Next Strategies?

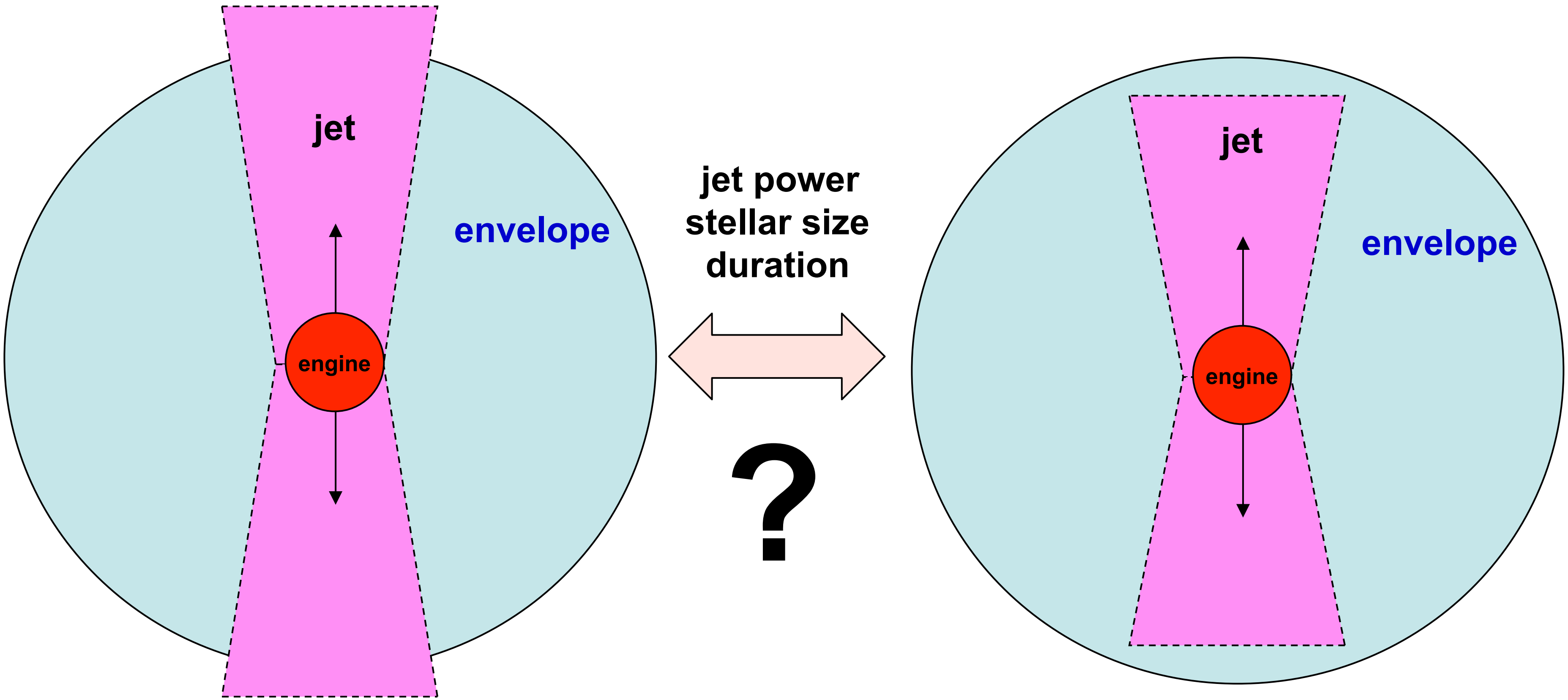


Gamma-Ray Bursts: “Classical” Pictures



Jets May Be the Key to GRB-SN Connection

“Successful” Jet | **“Choked” Jet**



Long GRB

GRB before breakout
Failed GRB or jet-driven SN
(Trans-relativistic SN? hypernova?)

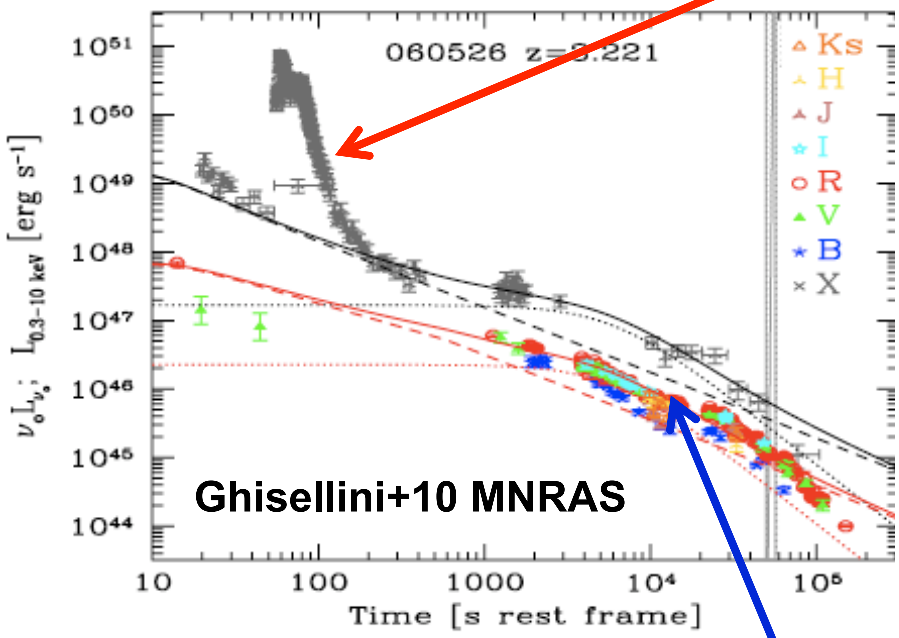
direct counterparts in e,g., γ rays

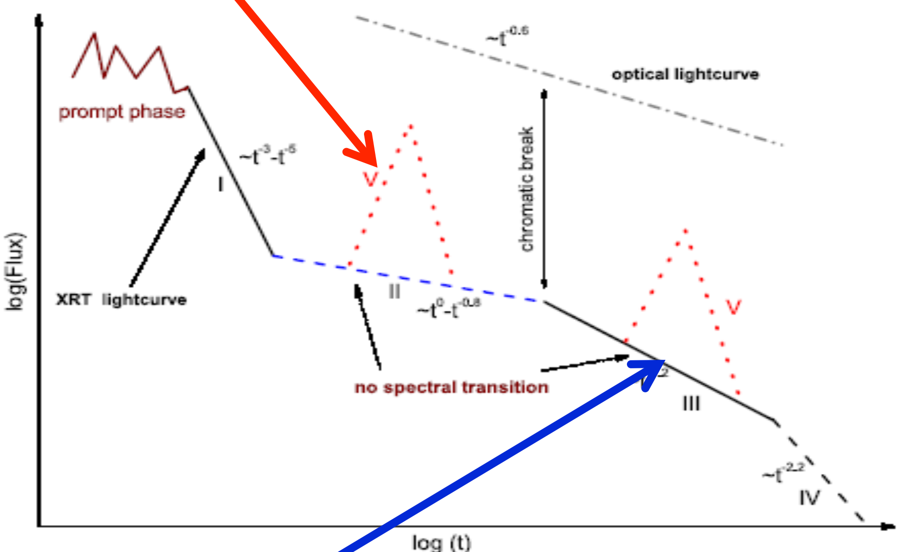
indirect counterparts in e,g., opt, X rays

Afterglows

GRB Afterglow Emission

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



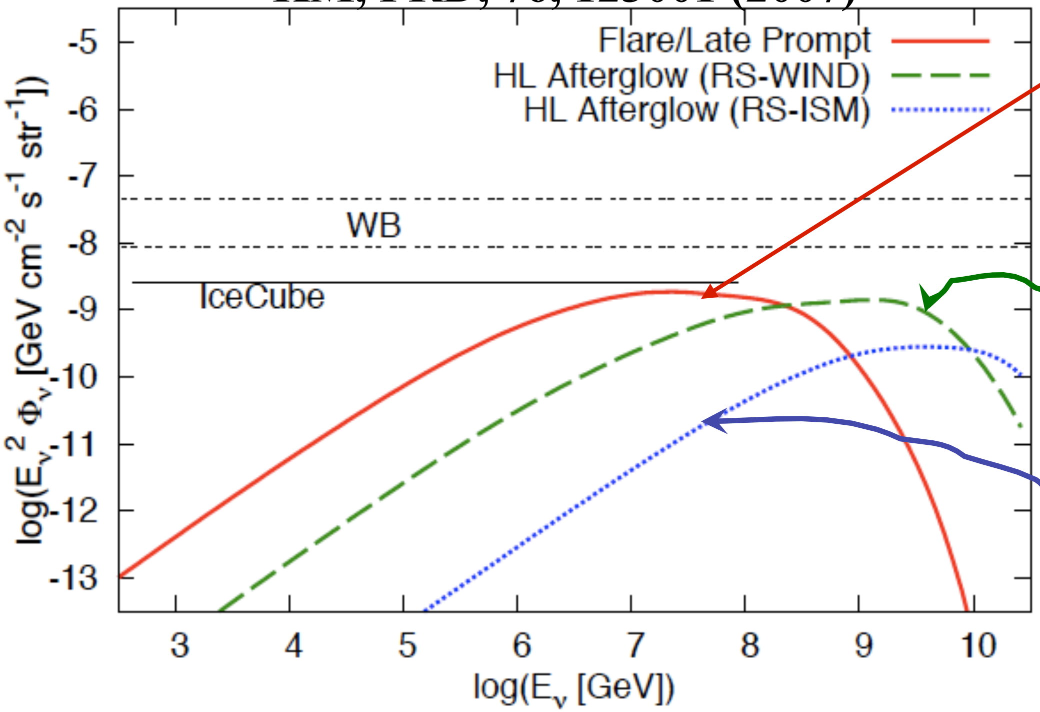


Afterglow: syn. emission from electrons accelerated at ext. shock

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)

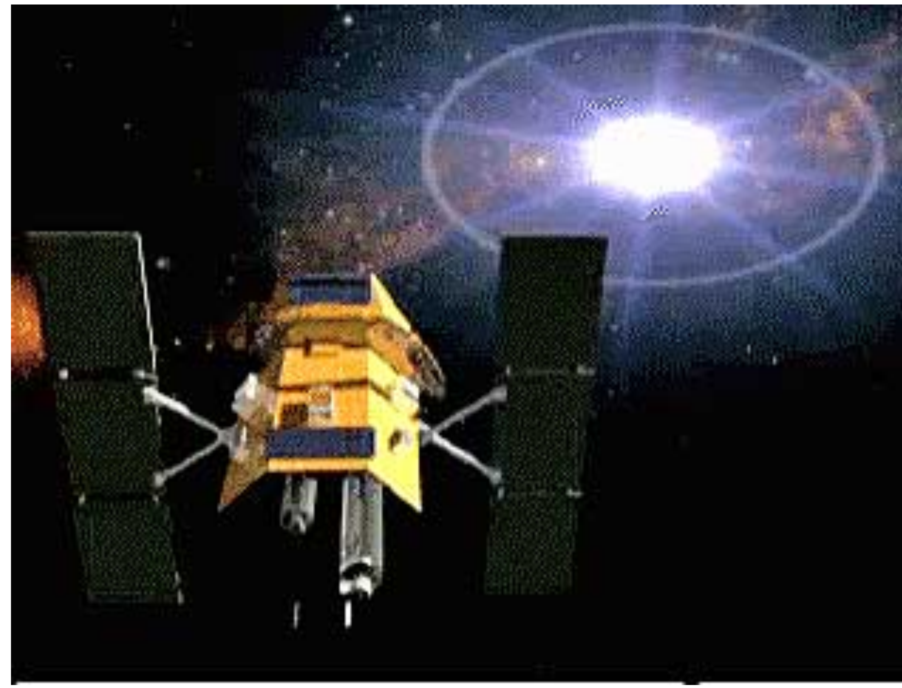
ES protons + ES opt-x rays
stellar wind medium
(normalized by UHECR budget)

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

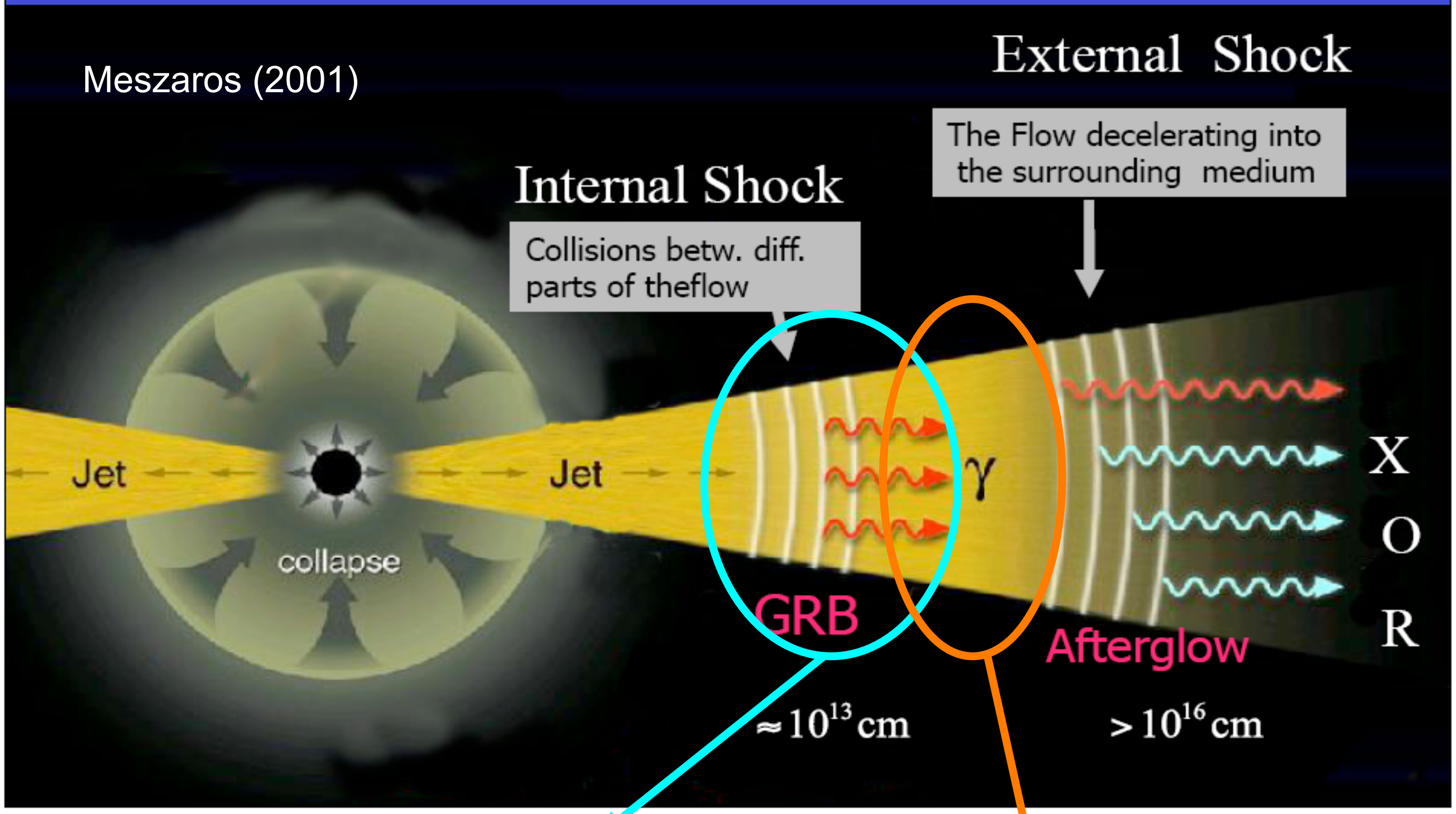


Swift brought us many novel results

↓

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)

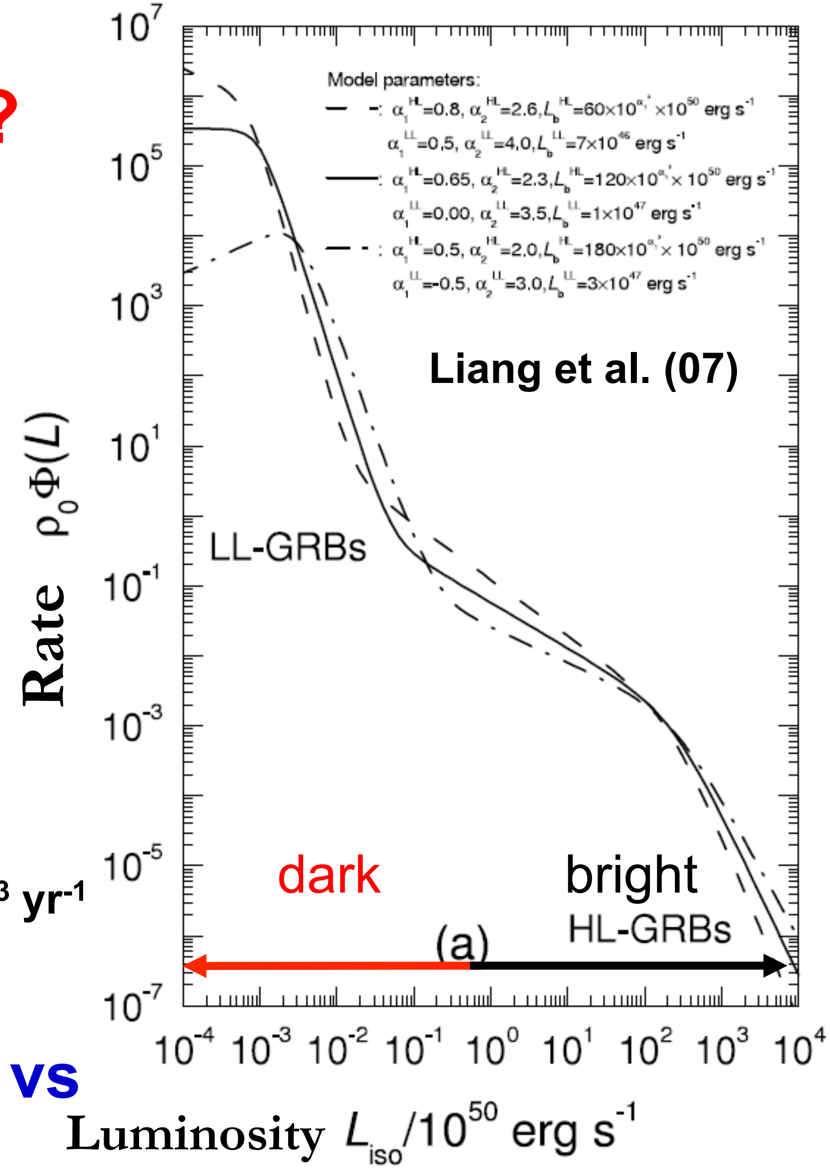
Novel Results of Swift (GRB060218)

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^{2-3} Gpc^{-3} yr^{-1} >> (0.01-1) Gpc^{-3} yr^{-1}

(Soderberg et al. 06, Liang et al. 07 etc…)



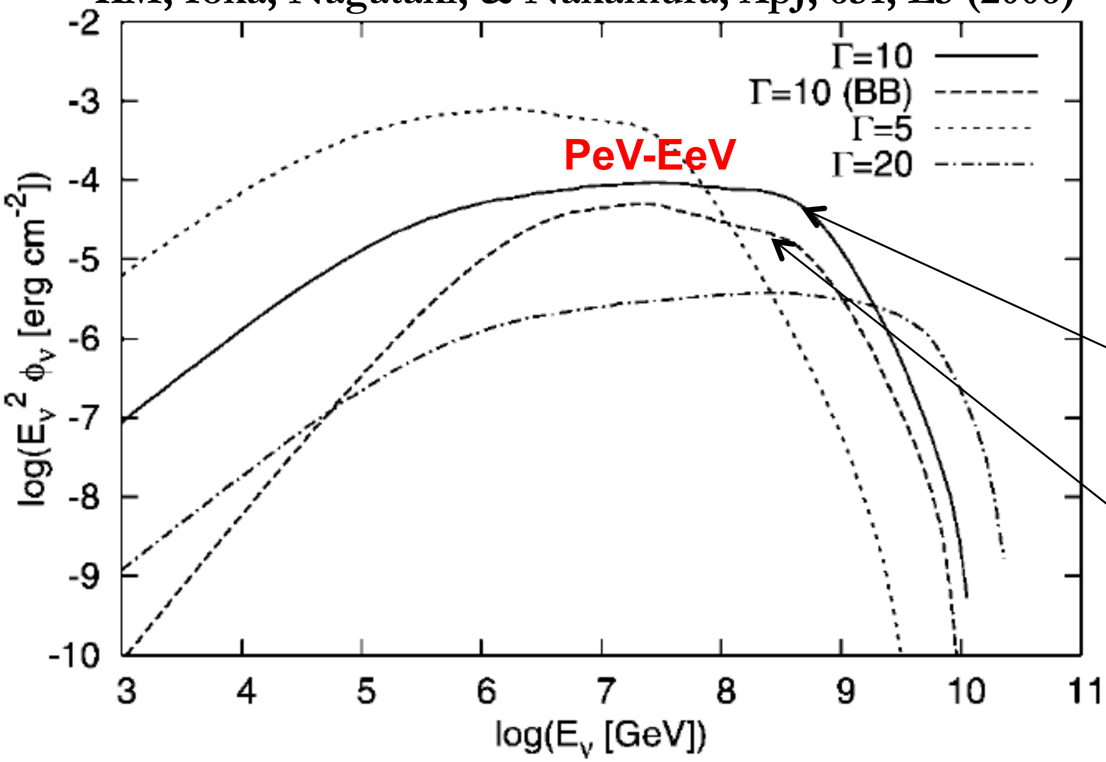
If true → contribution to HECRs & νs

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

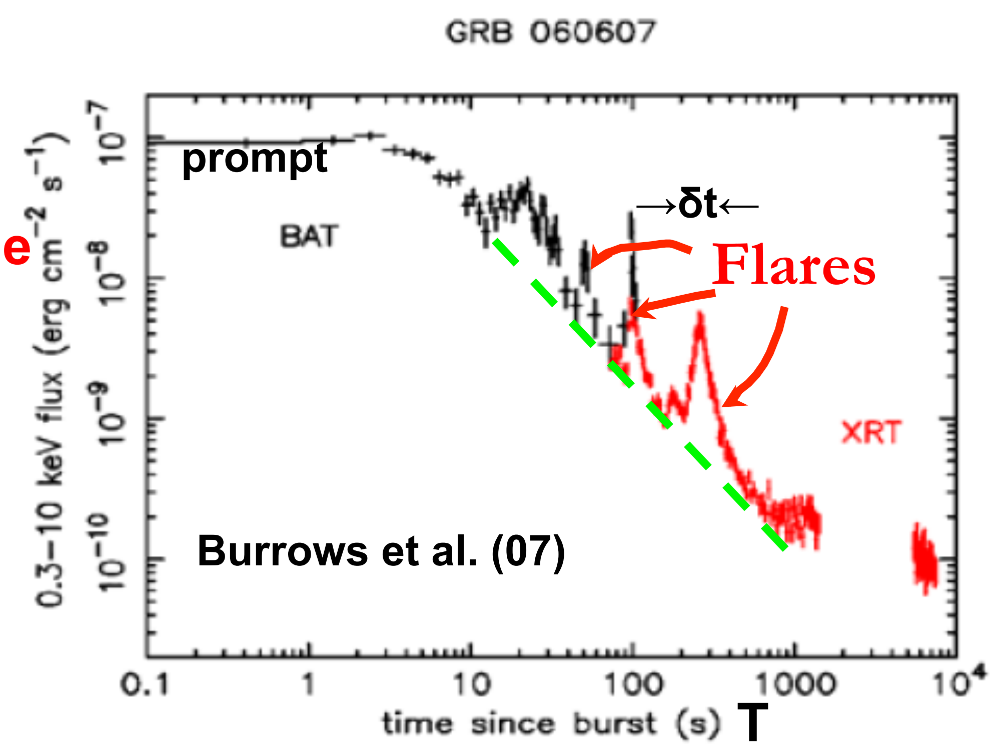
- Energetic ($E_{flare\gamma}$ ~ 0.1 $E_{GRB\gamma}$) (e.g., Falcone et al. 07)
  ($E_{flare\gamma}$ ~ $E_{GRB\gamma}$ for some flares such as GRB050502B
  potentially comparable to energy of prompt emission)

- δt >~ $10^{2\text{-}3}$ s, $\delta t/T < 1$ → internal dissipation models
  (e.g. late internal shock model
  vs
  magnetic dissipation model)

- Flaring in the far-UV/x-ray range
  ε_{pk} ~ (0.1-1) keV

- Lower Lorentz factors (likely)
  Γ ~ a few×10

- Flares are common
  (at least 1/3-1/2 of LGRBs)
  (also seen in SGRBs)



Energetics

Neutrino Energy Flux $\propto$ Rate $\times$ Photomeson ($p \to \pi$) Production Efficiency $\times$ Nonthermal Baryon Energy

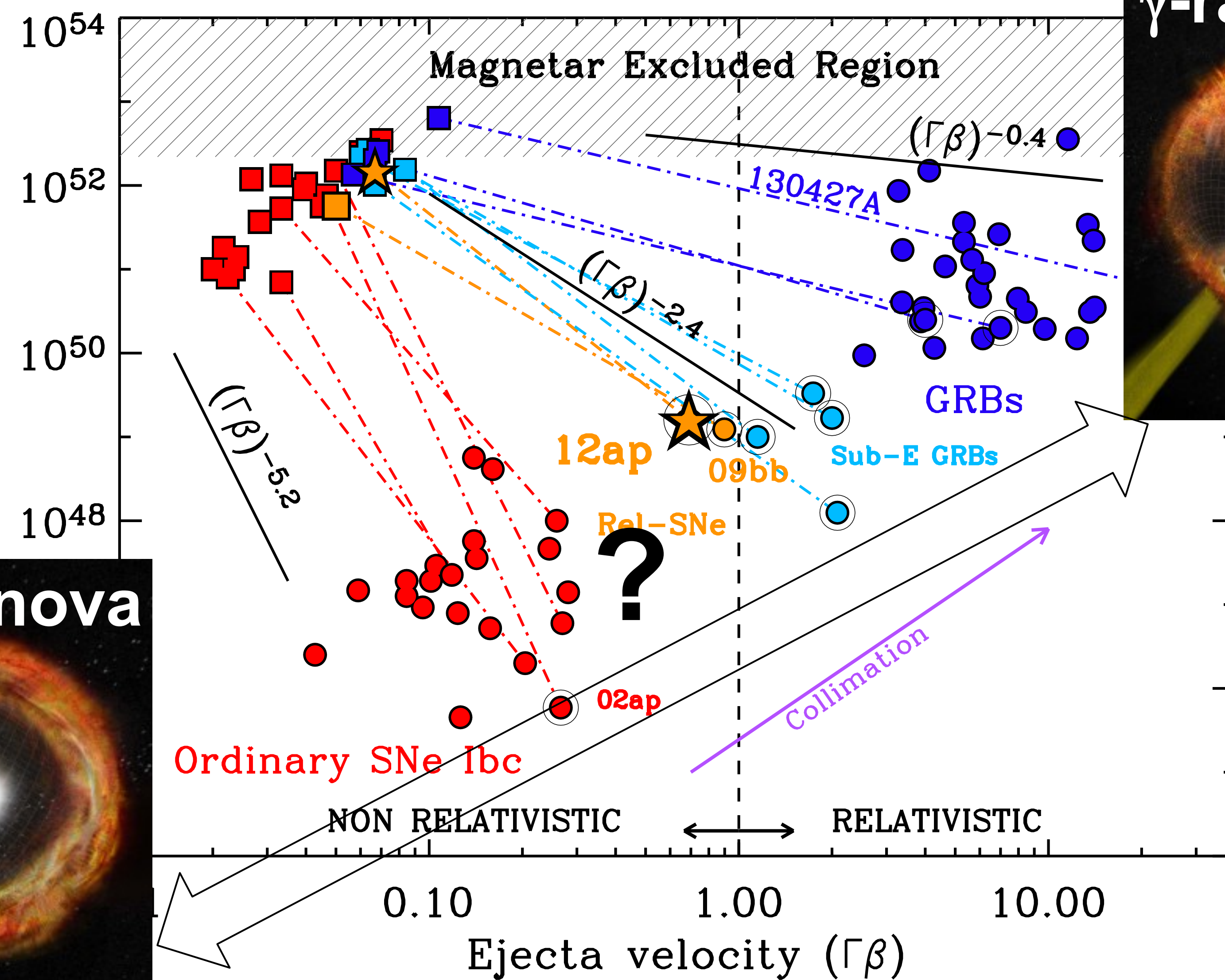
$\downarrow$ Normalizing all the typical values for HL GRBs to 1

	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!

TRSNe Have the Key to the GRB-SN Connection

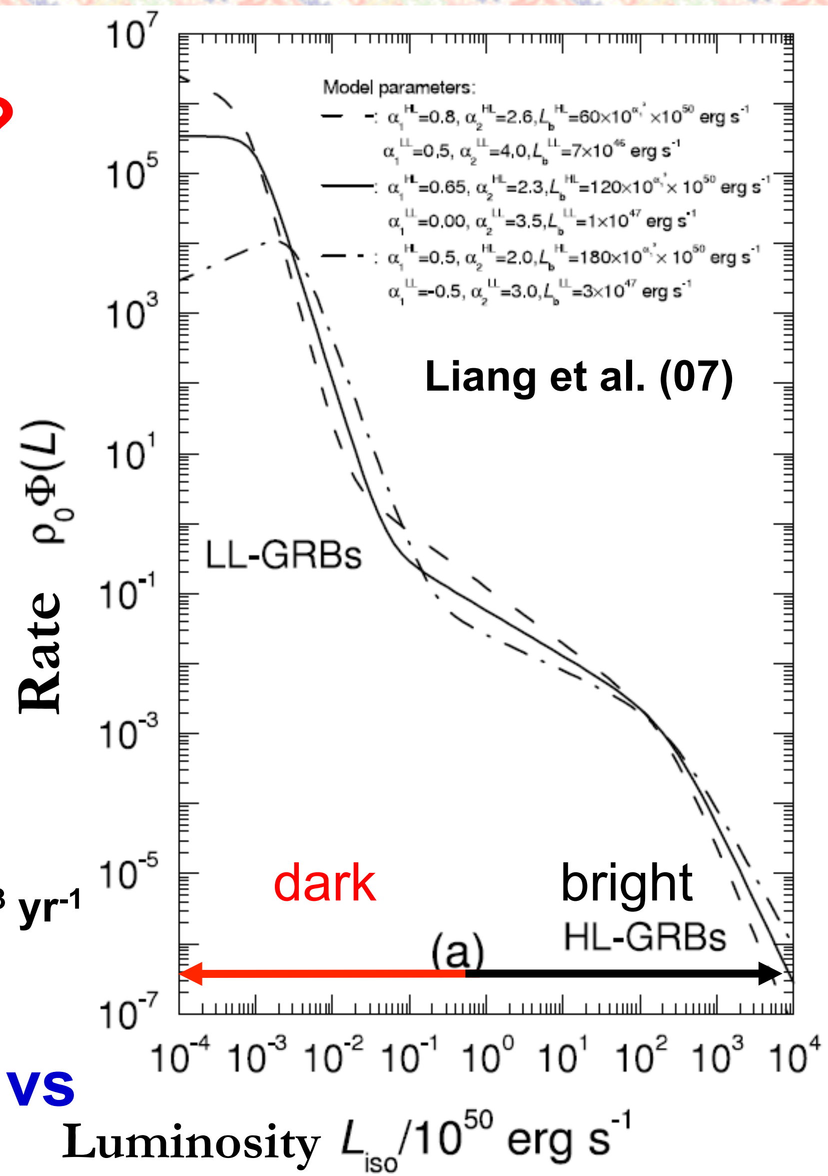
Margutti+ 14



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 ($E_{LLGRB\gamma} \sim 10^{50}$ 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…)

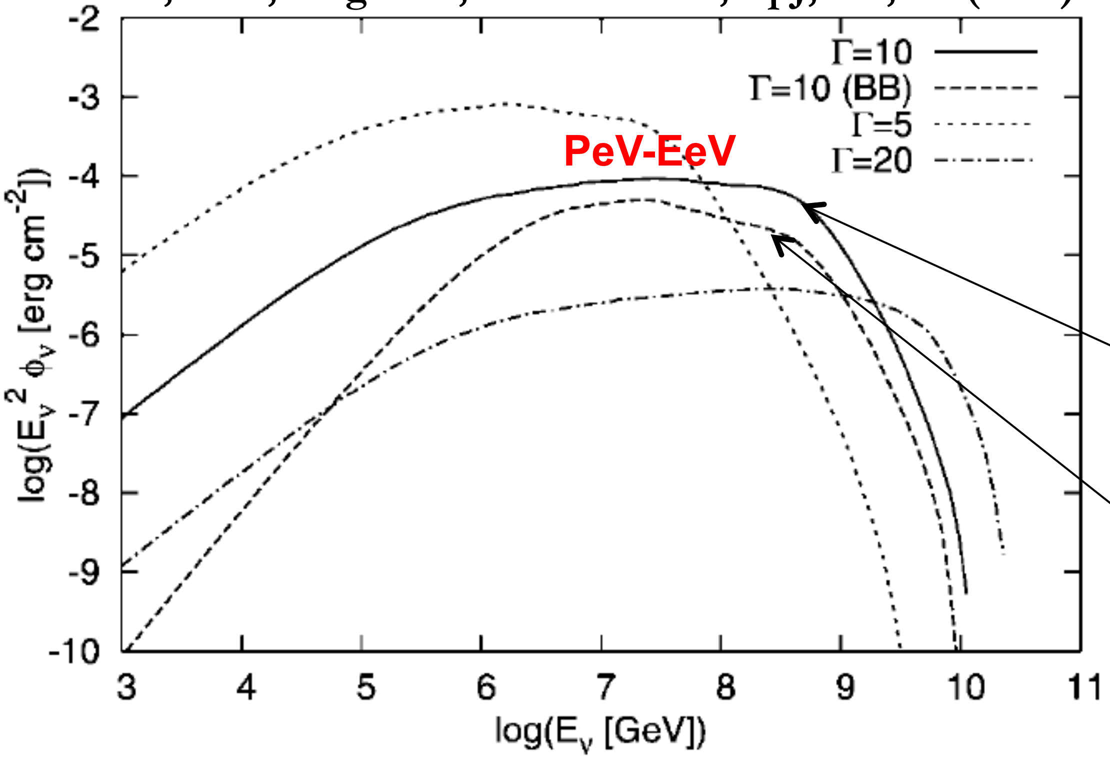
If true → contribution to HECRs & νs

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!

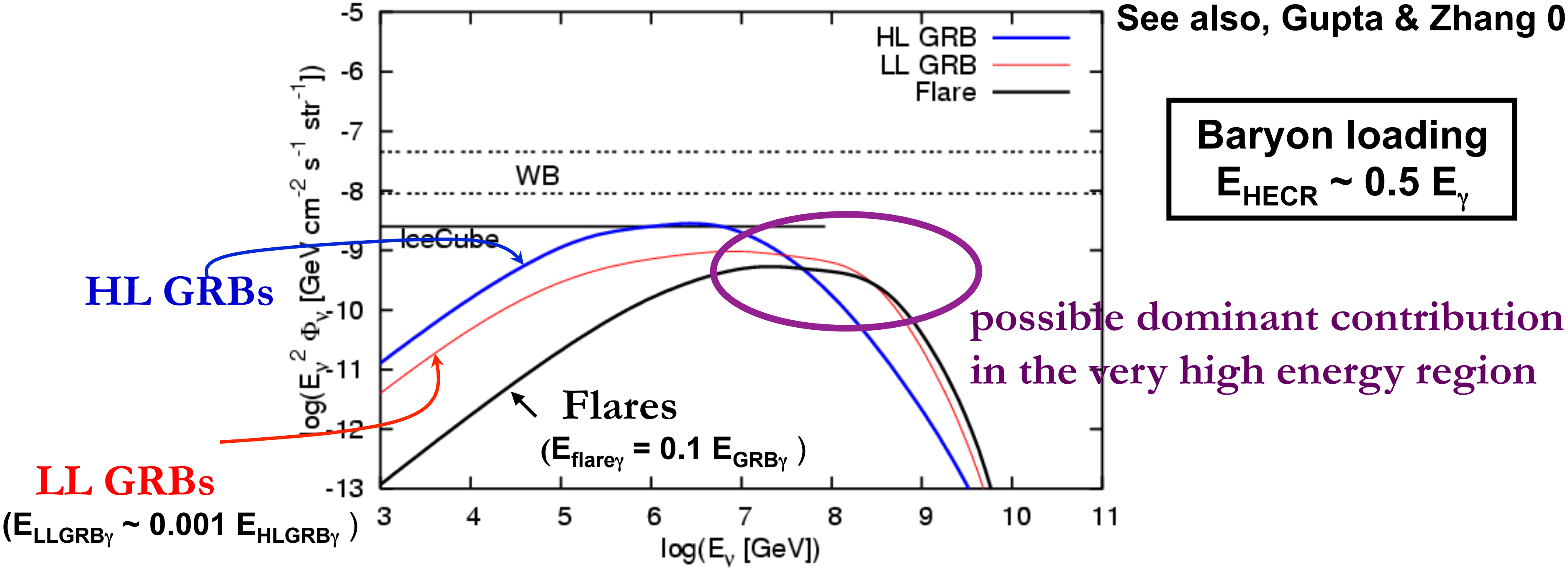
If Γ=10 w. thermal X rays
(stellar shock breakout or cocoon)
→ # of μs ~ 0.1-0.2

※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)

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

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

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

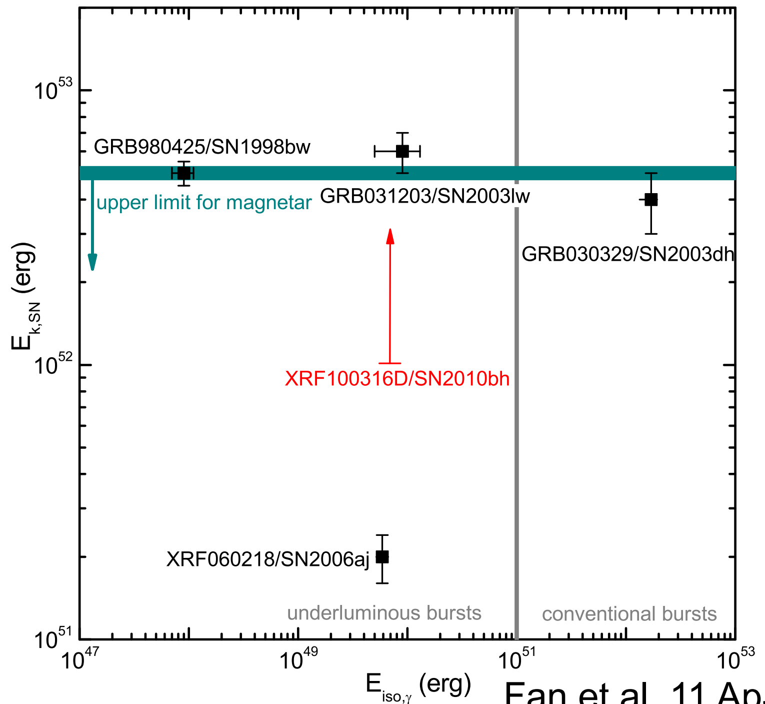
<u>Approaches to GRBs through high-energy neutrinos</u>

Flares → potentially more baryon-rich and efficient neutrino emitters

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

Neutrinos from Hidden Supernova Shocks

Low-Luminosity GRBs/Transrelativistic SNe



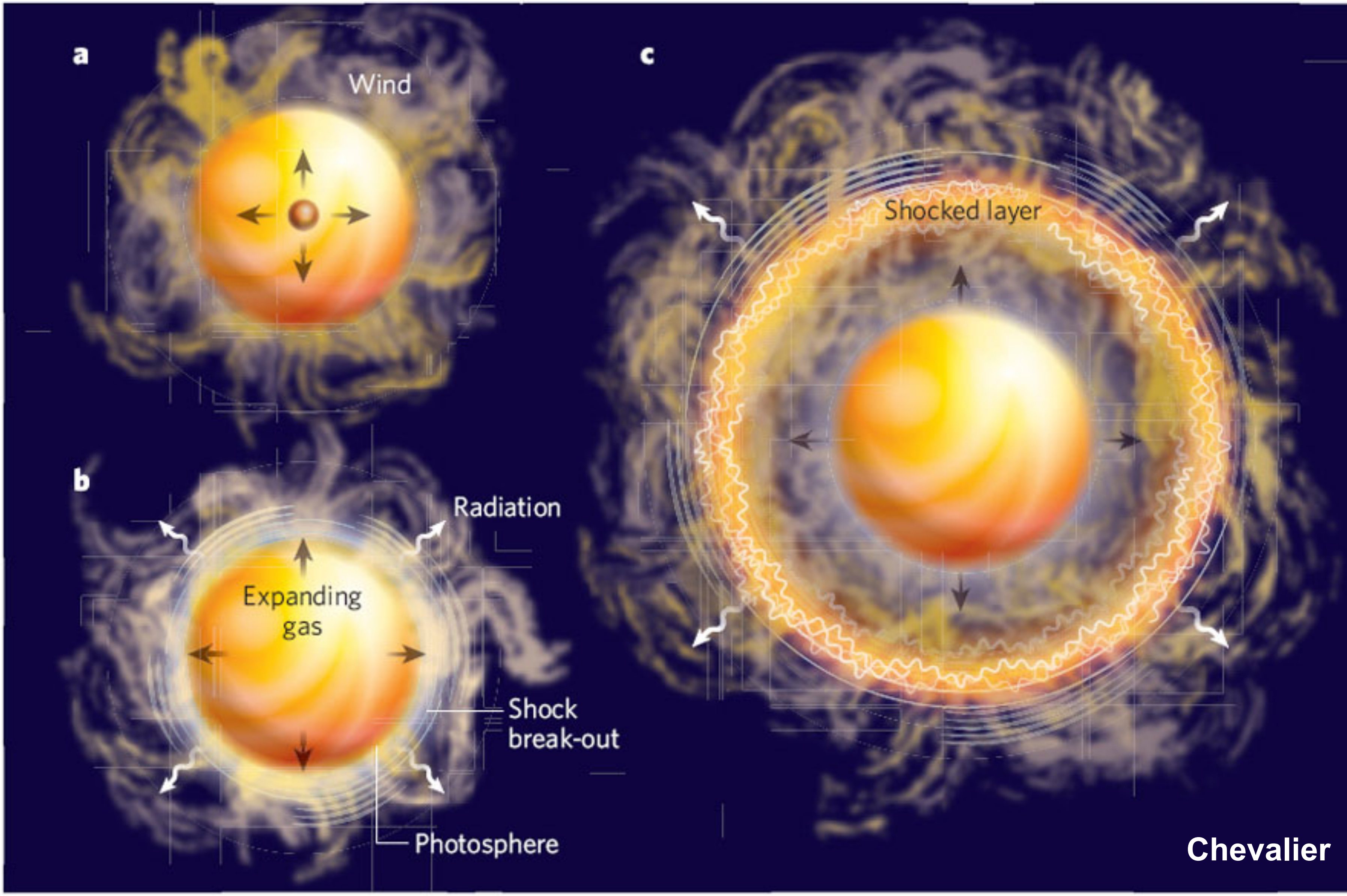
Fan et al. 11 ApJL

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^{2-3} Gpc^{-3} yr^{-1} ⇔ ρ_{GRB} ~0.05-1 Gpc^{-3} yr^{-1})
- relativistic ejecta (GRB-SNe + 2009bb, 2012ap) (Soderberg+ 10 Nature)

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

Supernovae in Optically-Thick Wind



Chevalier

Shock Breakout & Collisionless Shocks

Interaction between ejecta and circumstellar material

photon diffusion time: $t_{diff} \sim L^2/\kappa$ ($\kappa \sim (c/n\,\sigma_T)$)
dynamical time: $t_{dyn} \sim L/\beta c$, $\beta = V/c$

Before shock breakout: $t_{diff} > t_{dyn} \Leftrightarrow \tau_T > 1/\beta$
$\rightarrow L > L_{dec} \sim (1/n\,\sigma_T\,\beta)$: radiation-mediated
$\rightarrow$ CR acc. is (typically) inefficient

After shock breakout: $t_{diff} < t_{dyn} \Leftrightarrow \tau_T < 1/\beta$
$\rightarrow L < L_{dec} \sim (1/n\,\sigma_T\,\beta)$: radiation-unmediated
$\rightarrow$ CR acc. may occur

(Waxman & Loeb 01 PRL, KM et al. 11 PRD, Katz et al. 11, Kashiyama, KM+ 13 ApJL)

CRs Should Lead to Efficient Hadronic Interactions

particle collisions with CSM $p+p \rightarrow N\pi + X$

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

(σ_{pp}~3×10^{-26} cm^2)

$f_{pp}(r_{bo}) \sim \beta^{-2}(\kappa_{pp}\sigma_{pp}/\sigma_T) \sim 0.03\,\beta^{-2}$ at breakout: $\tau_T = 1/\beta$

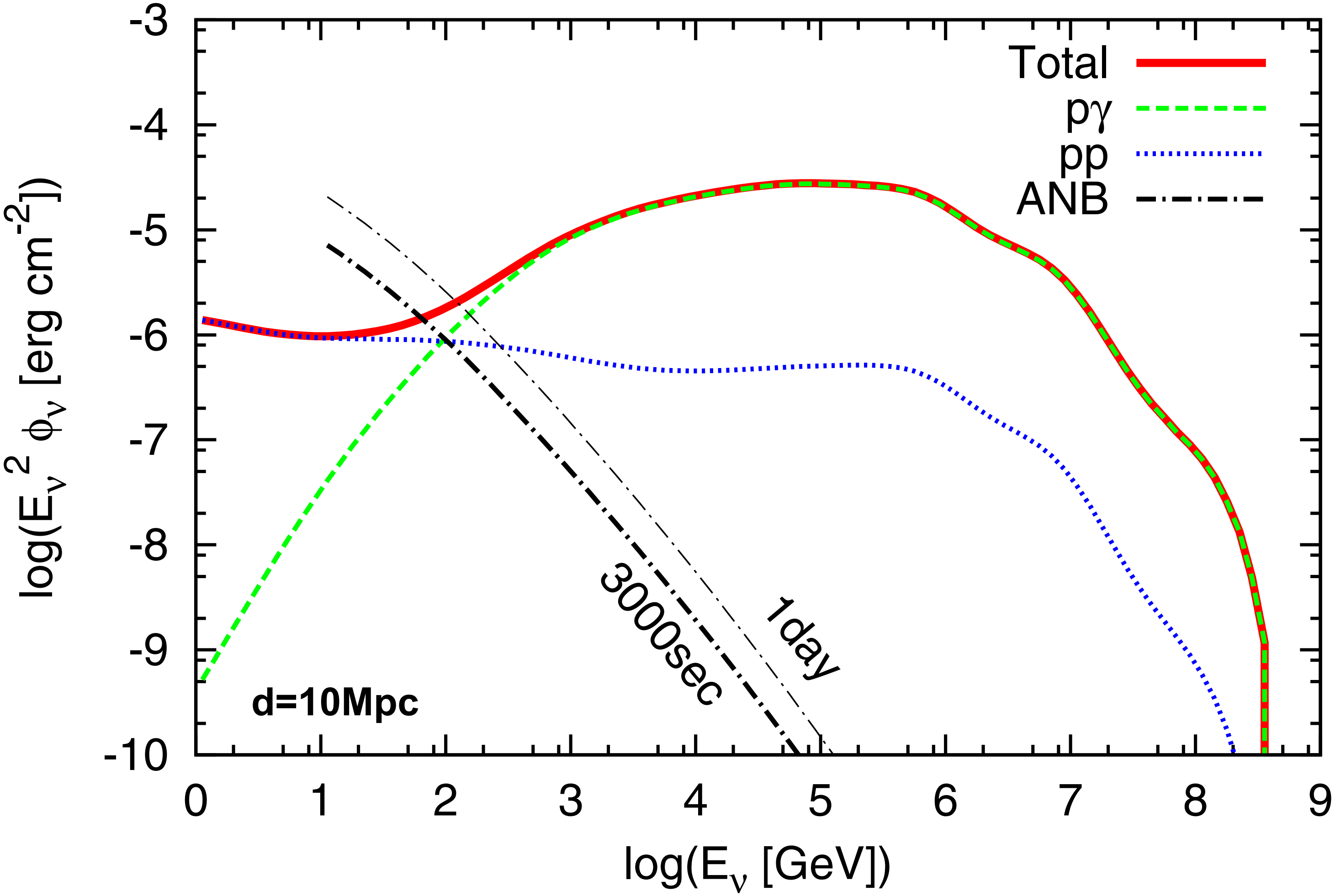
$\beta \sim 0.1\text{-}1$ ⇔ **transrelativistic SNe**
$\beta \sim 0.01\text{-}0.03$ ⇔ **nonrelativistic SNe**
most CR energy goes to pions

$$\pi^0 \rightarrow \gamma + \gamma$$
$$\pi^\pm \rightarrow \nu_\mu + \bar{\nu}_\mu + \nu_e(\bar{\nu}_e) + e^\pm$$

new probes

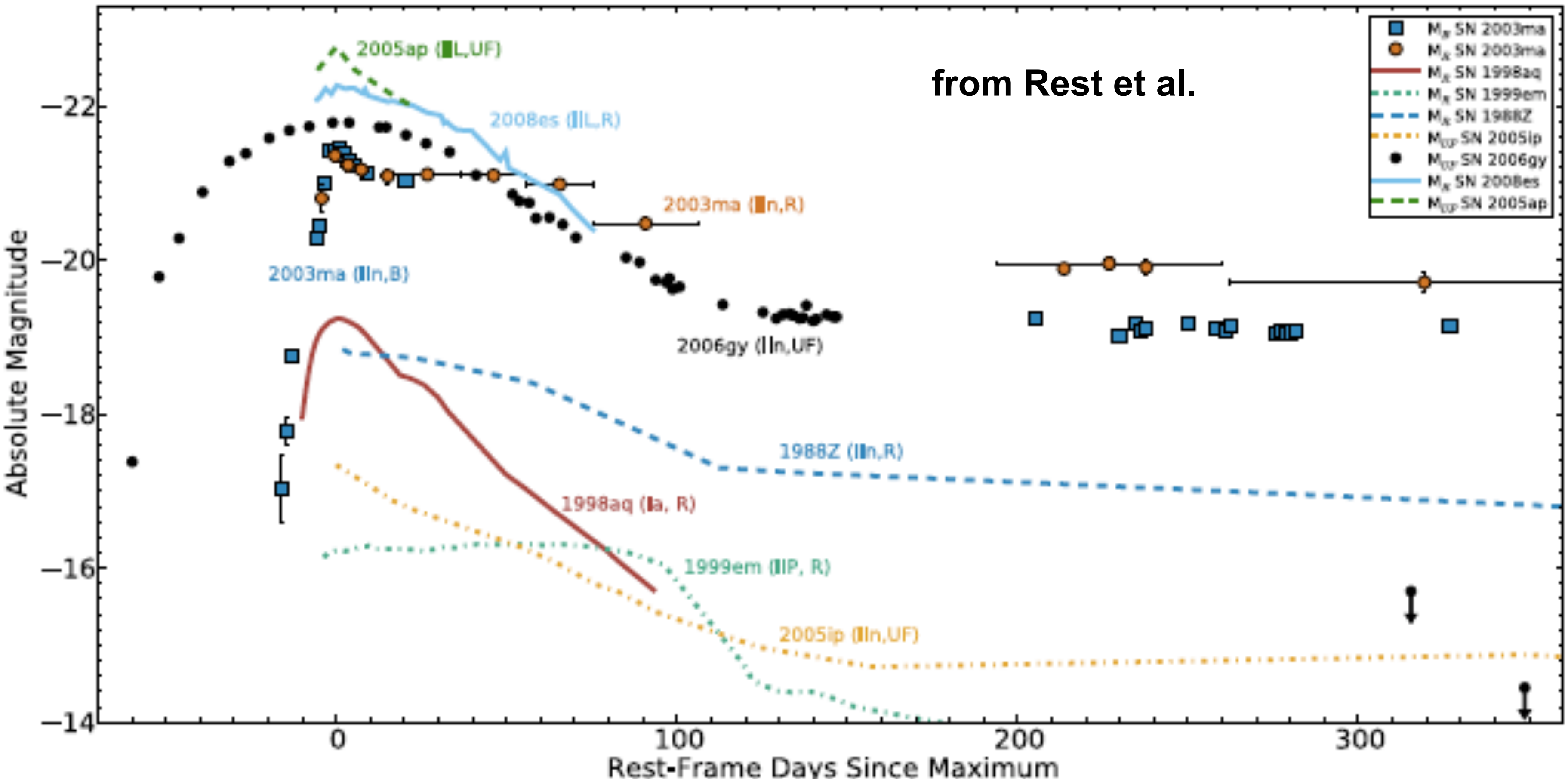
Neutrinos from Transrelativistic SNe

Kashiyama, KM+ 13 ApJL



- Detectable by IceCube up to ~10 Mpc → stacking analyses?
- TeV γ-ray follow-up obs. can detect a SN at ~100 Mpc

Super-Luminous SNe & SNe IIn (β<<1)

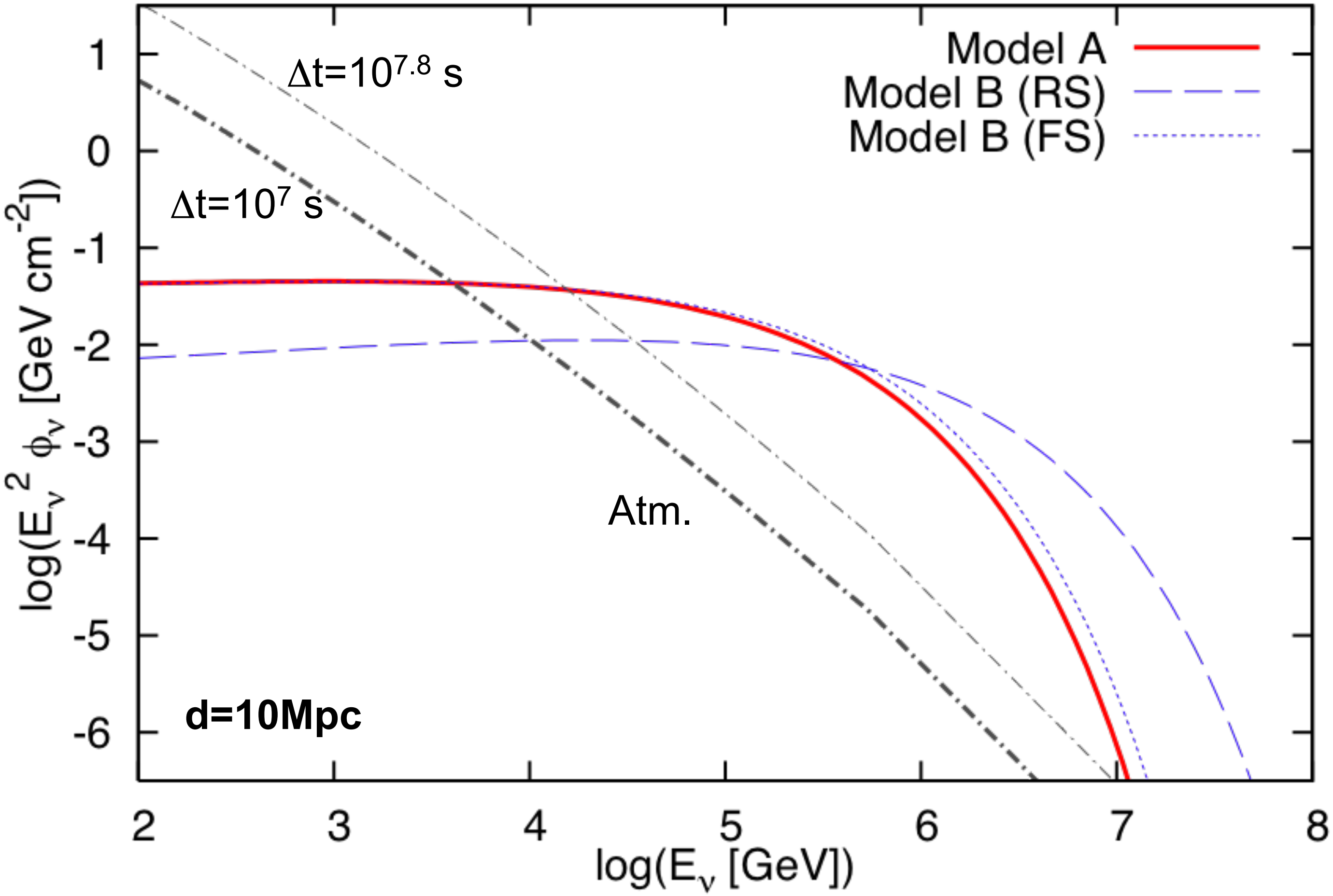


Some SNe are super-luminous and long duration

Such long duration (~ 0.1-1 yr) is common in SN IIn

Neutrinos from Interaction-Powered SNe

KM, Thompson, Lacki & Beacom 11 PRD



Model A
- optically thick collision

Model B
- optically thin collision

- If CRs carry ~10% of E_{ej} → # of μs ~a few for SN@10Mpc
- Multimessenger implications → Pizza Lunch tomorrow