Gamma-Ray Bursts: A Theoretical Framework

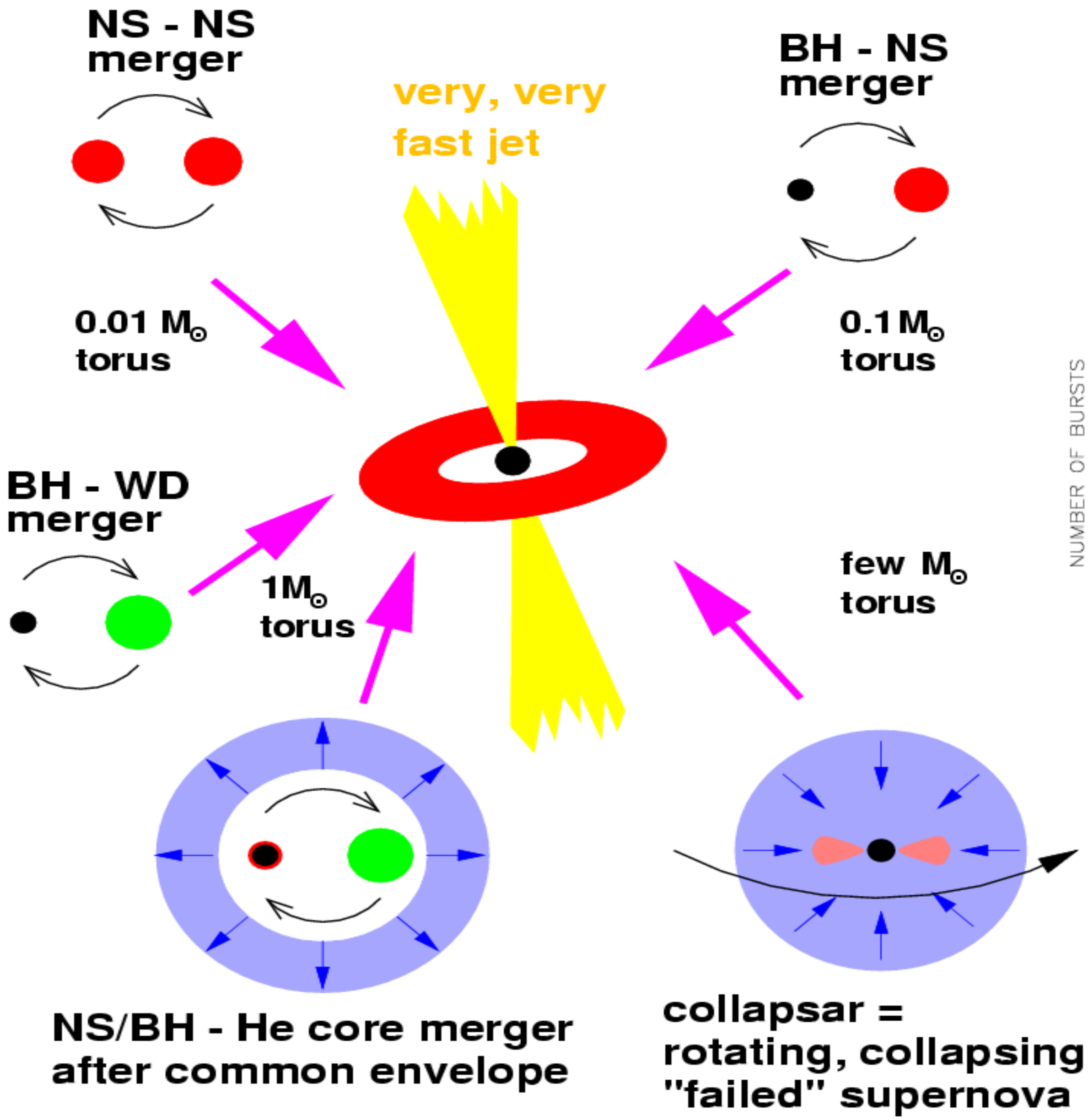
Péter Mészáros

Pennsylvania State University

@ 12th INTEGRAL, Geneva CH, Feb. 2019

GRB: standard paradigm

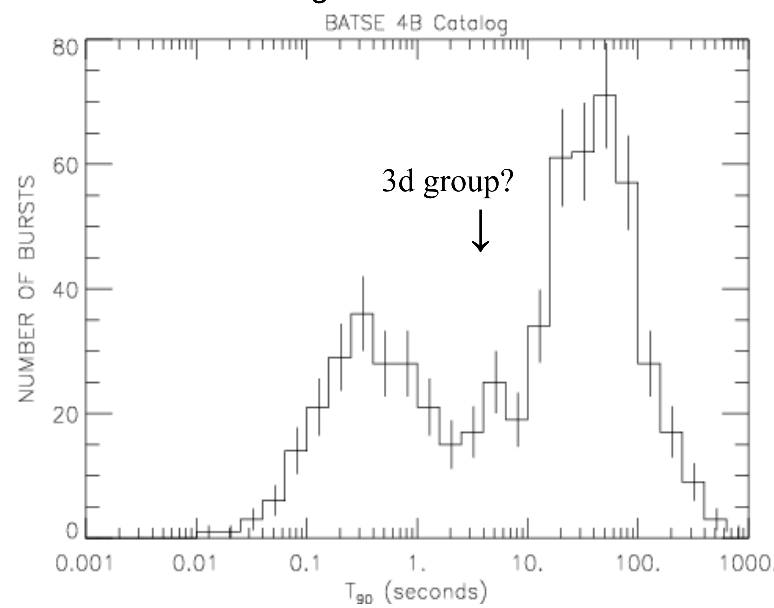
Has held up for >25 years!



M. Ruffert, H.-Th. Janka, 1998

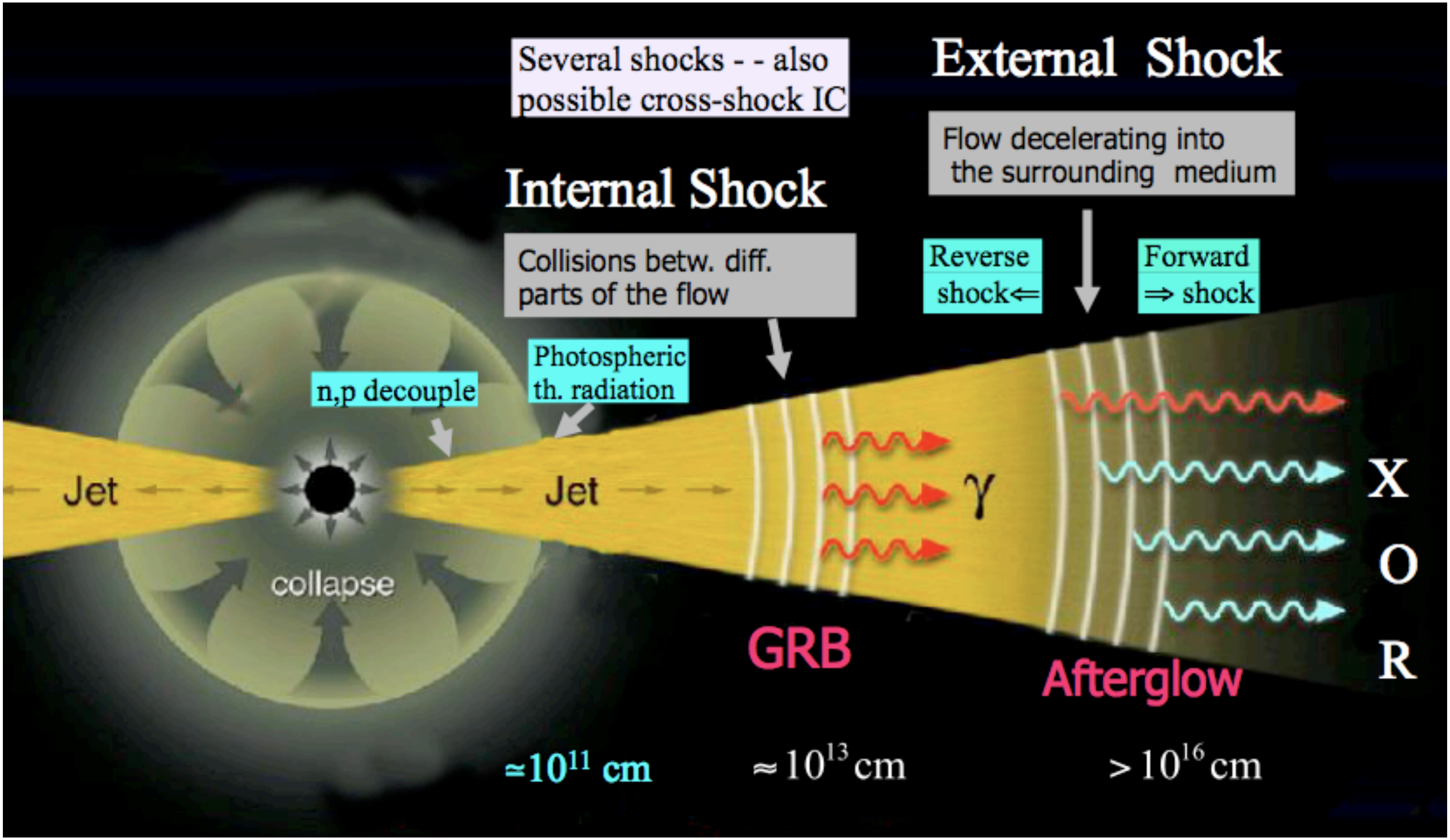
Bimodal distribution of t_γ duration

←↓**Short** (t_g< 2 s)



→↑**Long** (t_g >2 s)

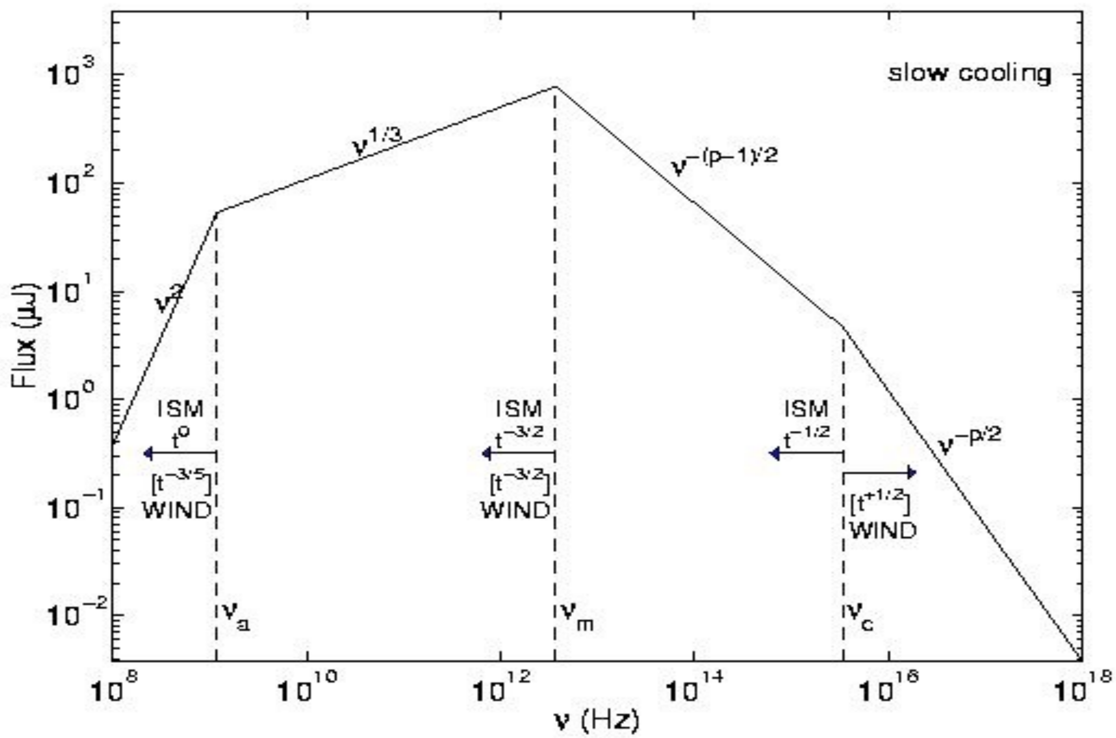
GRB “Standard” Model



- E.g. M. Rees & PM, 1992, ,.. . . .1997, others ..

Synchrotron shock simplest paradigm:

Snapshot (leptonic) Afterglow Fits



Sari, Piran, Narayan '98 ApJ(Let) 497:L17)

Break frequency decreases in time (at rate dep. on whether ext medium homog. or wind (e.g. $n \propto r^{-2}$)

- Simplest case: $t_{cool}(\gamma_m) > t_{exp}$, where $N(\gamma) \propto \gamma^{-p}$ for $\gamma > \gamma_m$ (i.e. $\gamma_{c(ool)} > \gamma_m$)
- 3 breaks: $\nu_{a(bs)}$, ν_m, ν_c
- $F_\nu \propto \nu^2$ $(\nu^{5/2})$; $\nu < \nu_a$;

  $\propto \nu^{1/3}$; $\nu_a < \nu < \nu_m$;

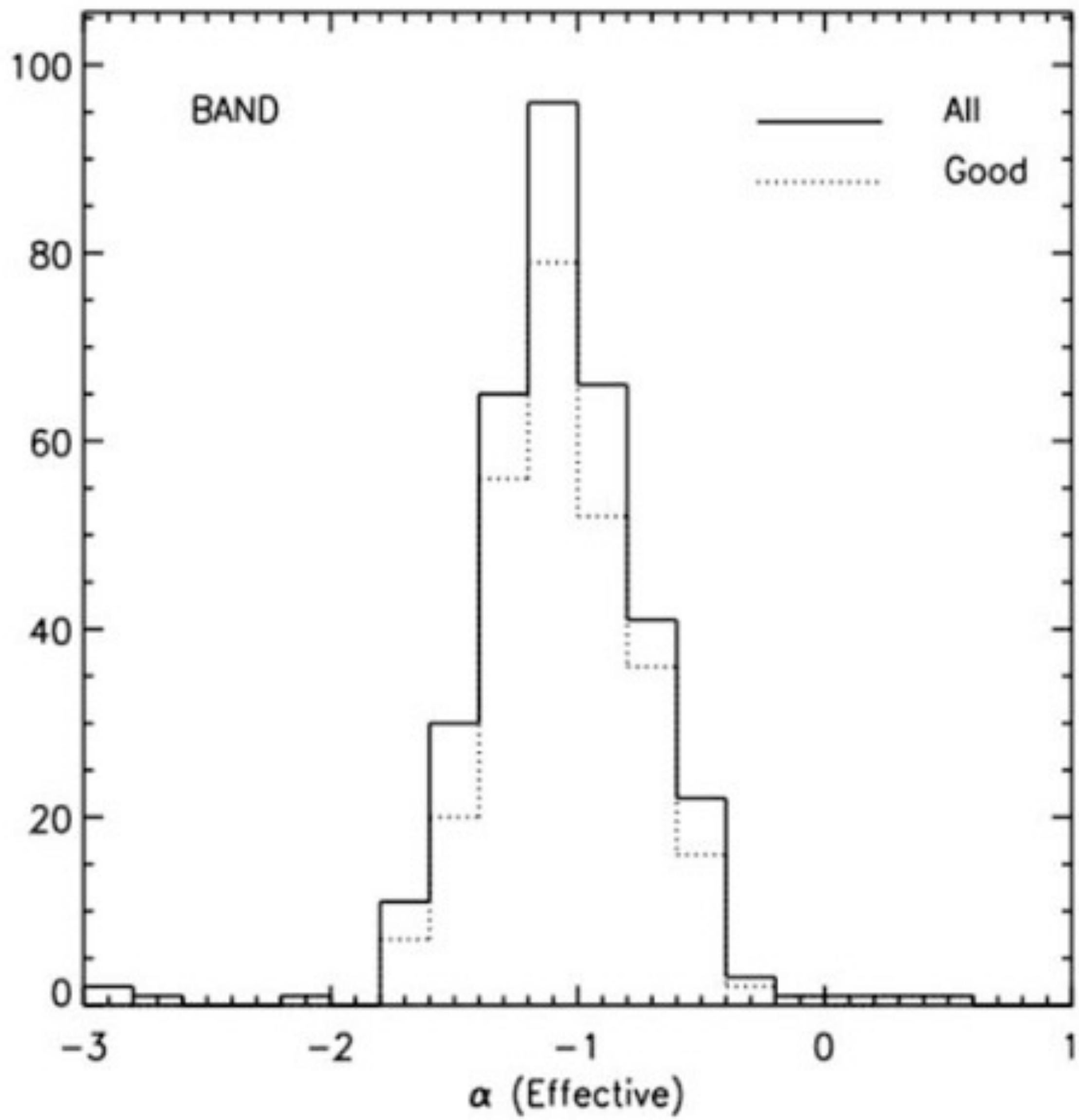
  $\propto \nu^{-(p-1)/2}$; $\nu_m < \nu < \nu_c$

  $\propto \nu^{-p/2}$; $\nu > \nu_c$

(Mészáros, Rees & Wijers '98 ApJ 499:301)

BUT: for $\boxed{\textbf{\textit{prompt emission:}}}$

Synchrotron Deathline ?



Single particle limit of synchrotron spectrum

$$dN/dE \sim E^{-2/3}$$

(below peak)

With cooling

$$dN/dE \sim E^{-3/2}$$

(but: not to worry - easy to see ways how slopes steeper than -2/3 or -3/2 could arise)

Kaneko et al 2006

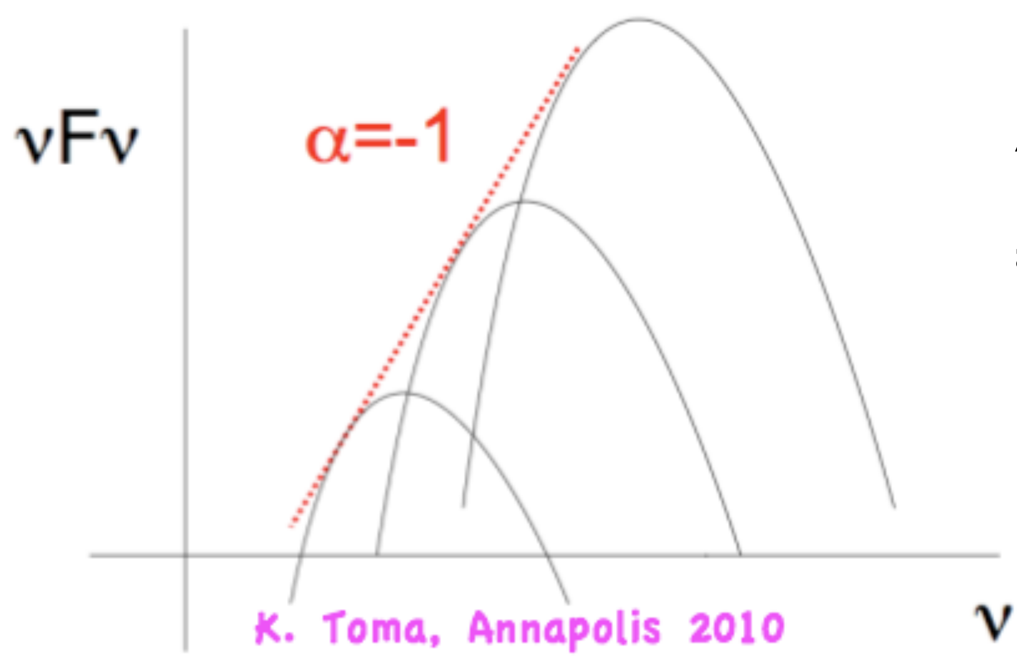
$$\alpha_{\rm eff} = \alpha - \frac{25\ \rm keV}{E_{\rm peak}}(2+\alpha) = \alpha - \frac{25\ \rm keV}{E_0}$$

Possible Solution: E.g., a $\boxed{\text{photospheric}}$

Origin of steep spectrum?

Thermal emission provides an attractive solution

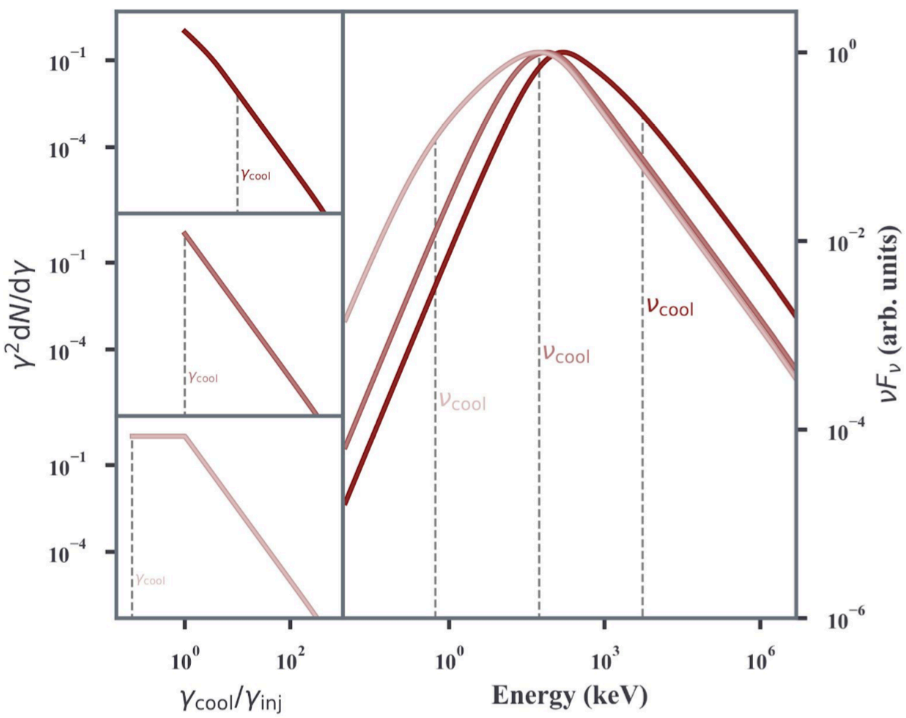
Needs to dominate the ~MeV bump



Any realistic temperature or γ_{min} distribution can reproduce almost any slope steeper than -2/3 in N_ν (flatter than 4/3 in νF_ν)

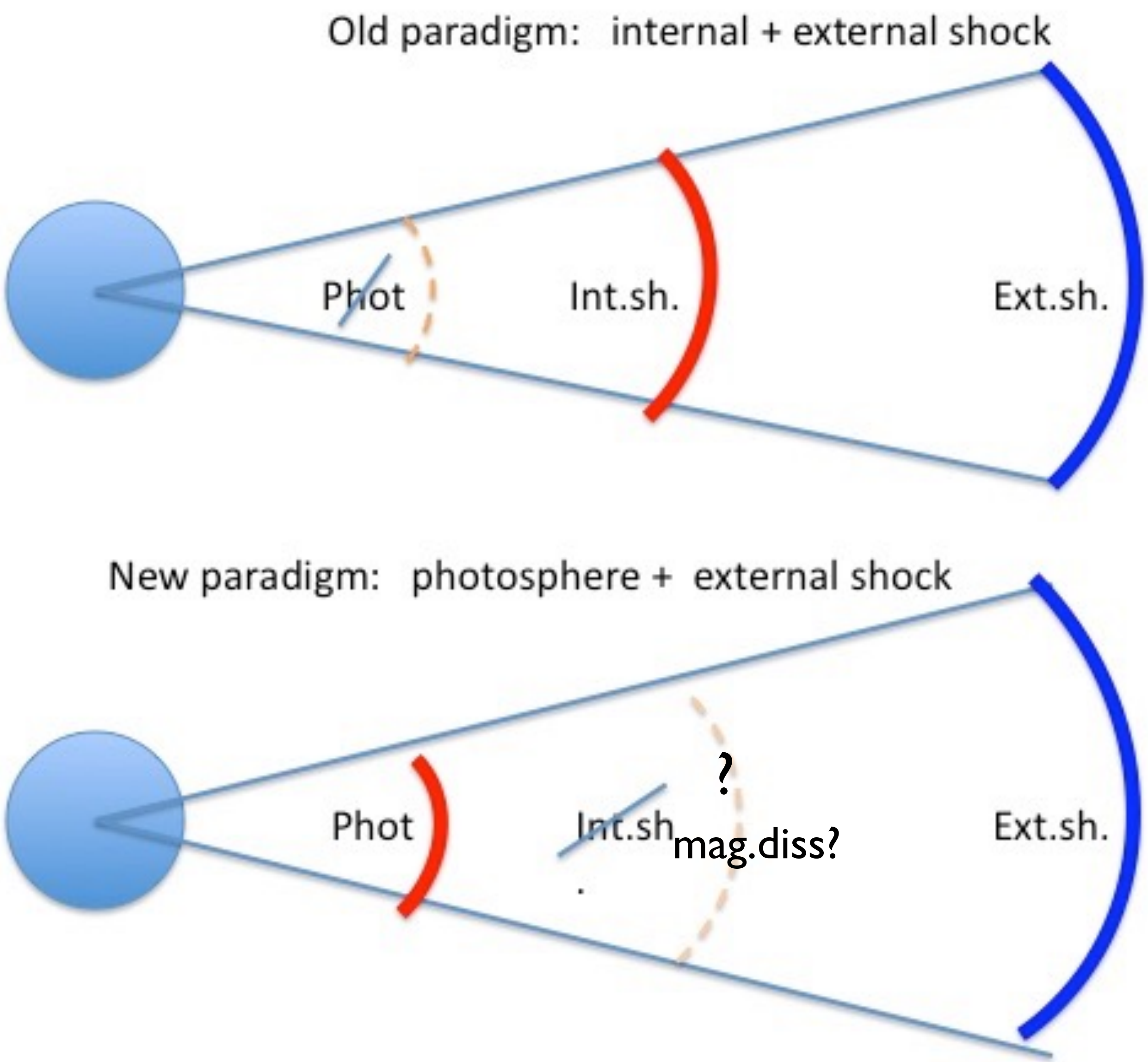
Alternatively

Figure 1: Relation between electrons and emission spectrum.
A schematic of the electron cooling and emitted photon spectra from our radiative code. Three regimes are displayed from dark red to pink: slow-cooling, moderate cooling and fast cooling. In the slow-cooling regime, the so-called cooling break is slight and barely noticable. Note that the peak energy does not always correspond to the cooling break, in contrast with usual assumptions[26].



- Usual synchrotron model may be OK in 95% cases
- But if track the electron cooling during emission process in time-dep. manner
- Burgess et al. arXiv:1810.06965
- (earlier work: LLoyd-Roning, Petrosian '00, etc)

Evolving γ-Fireball paradigm, I



$\leq$ 2005

$\geq$2005

e.g. PM & Rees, 2000, 2005, etc….

Mészáros

Paradigm shift

- ***OLD:*** ***internal + external shock*** (weak phot.)
- Photosphere: low rad. effic., wrong spectrum
- Internal sh.: good for variability, *easy to model* ; but ***poor*** *radiative efficiency (?)*
- External sh.: was, and is, *favored for afterglow model*

- ***NEW***: ***phot. + (int.sh? mag.diss?)+ext. shock***
- Photosphere: if dissipative, → ***good*** *rad. efficiency*
- **Int. sh**: if magnetic, may be absent; but ***mag. dissip***?
- ***External*** shock: most of GeV and soft afterglow

Mészáros

To be efficient, dissipation must occur in photosphere

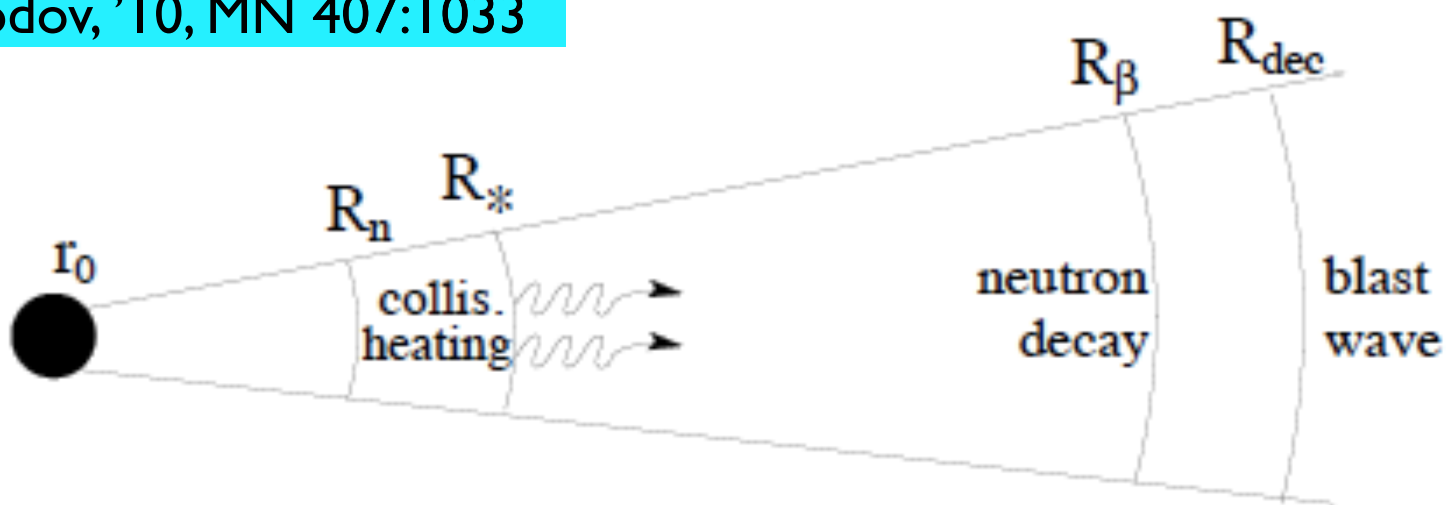
What can be the Photospheric Dissipation Mechanisms ?

- MHD reconnection, accel. $\rightarrow$ rel. $e^{\pm}$, γ
- Shocks @ photosphere (& below, above) $\rightarrow$ same
- p-n decoupling ($\perp$, $||$) $\rightarrow$ relativistic $e^{\pm}$, γ
- Or else, hadronic interactions @ internal shocks
- ....

A hadronic "thermal" photosphere PL spectrum?

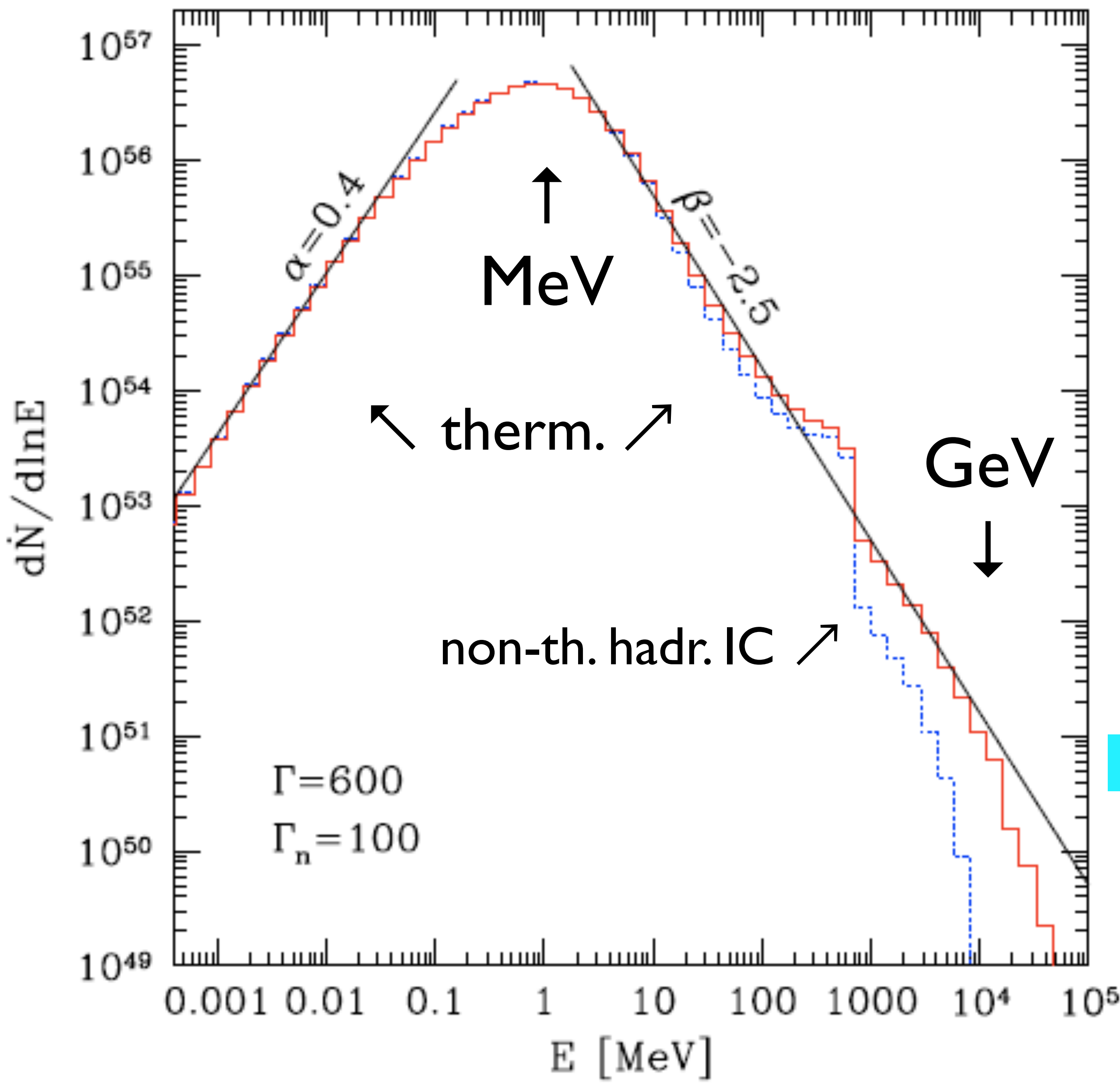
p-n collisions in sub-photosphere

Beloborodov, '10, MN 407:1033



- Long history: Derishev-Kocharovsky 89, Bahcall-Meszaros 00, Rossi et al 04, etc
- Either p-n decoupling or internal colls. → relative p-n streaming, inelastic colls.
- Highly ***effective dissipation*** (involves baryons directly)- can get >50% effic'y
- Sub-photospheric dissipation can give strong photospheric component

p-n coll. → e± → *photosphere γ-spectrum*



- The result is a thermal peak at the ~MeV Band peak, plus
- a high energy tail due to the non-thermal e± , whose slope is comparable to that of the observed Fermi bursts with a "single Band" spectrum
- The "second" higher energy component (when observed) must be explained with something else

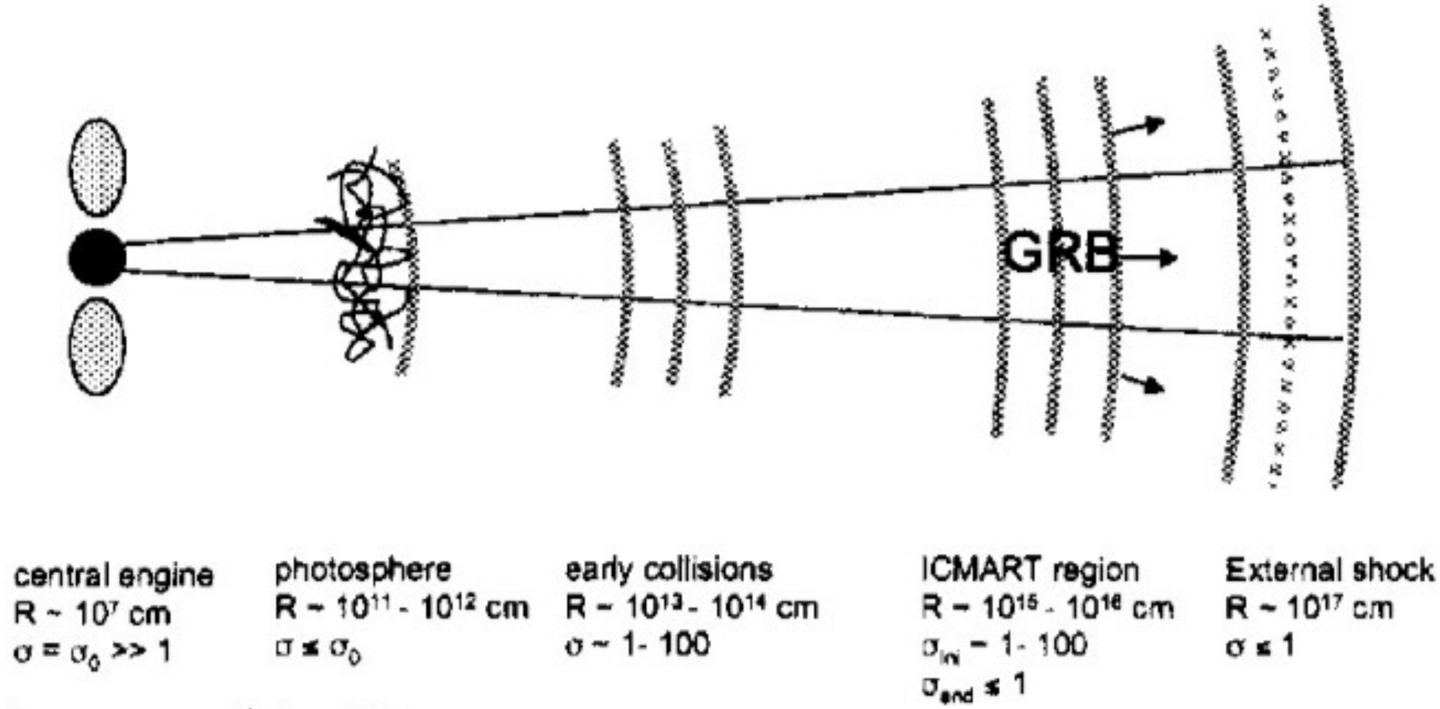
Beloborodov, 2010, MN 407:1033

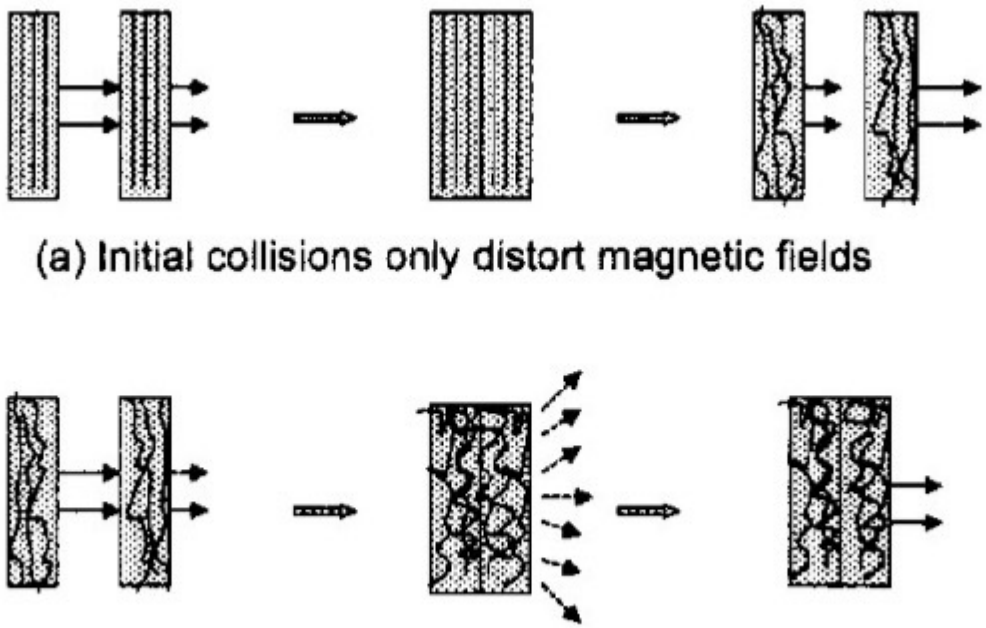
(Other phot. dissipation mechs: shocks,, Rees & PM, 2005, ApJ, etc.)

Magnetic dissipation ICMART model

in shocks

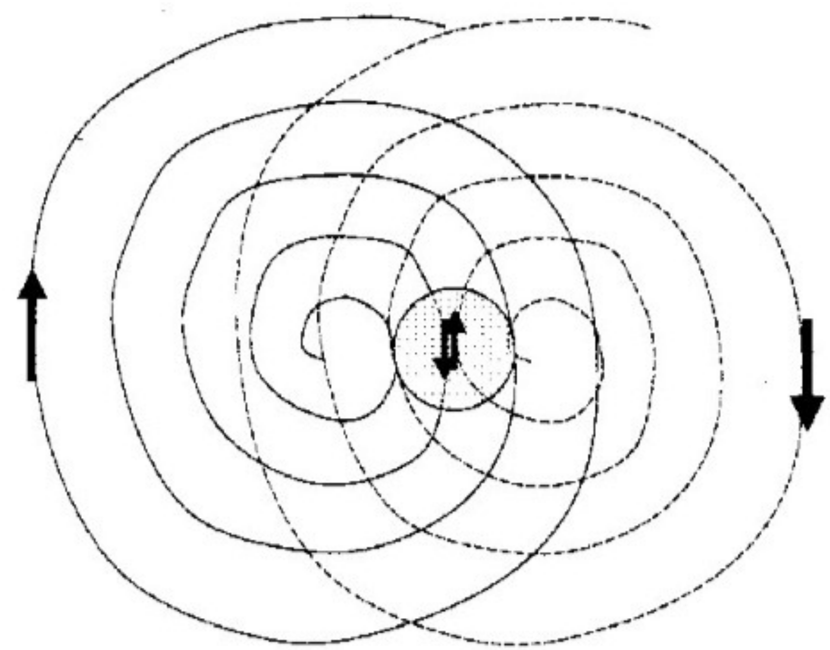
B. Zhang & H. Yan '11, ApJ, 726:90





(a) Initial collisions only distort magnetic fields

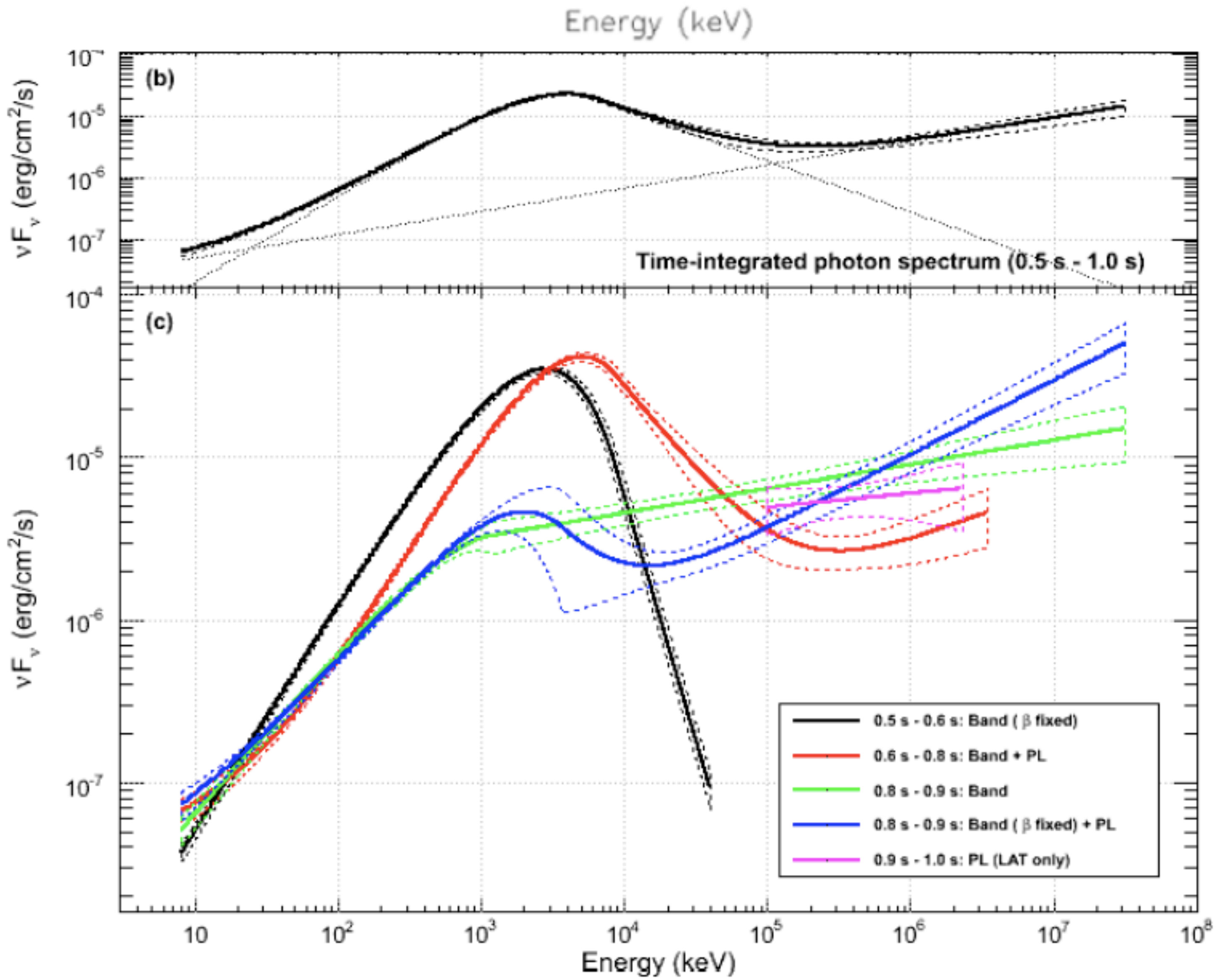
(b) Finally a collision results in an ICMART event



also:

GRB 090510

and others:



Spectrum: ***clear*** 2nd comp (>5σ)

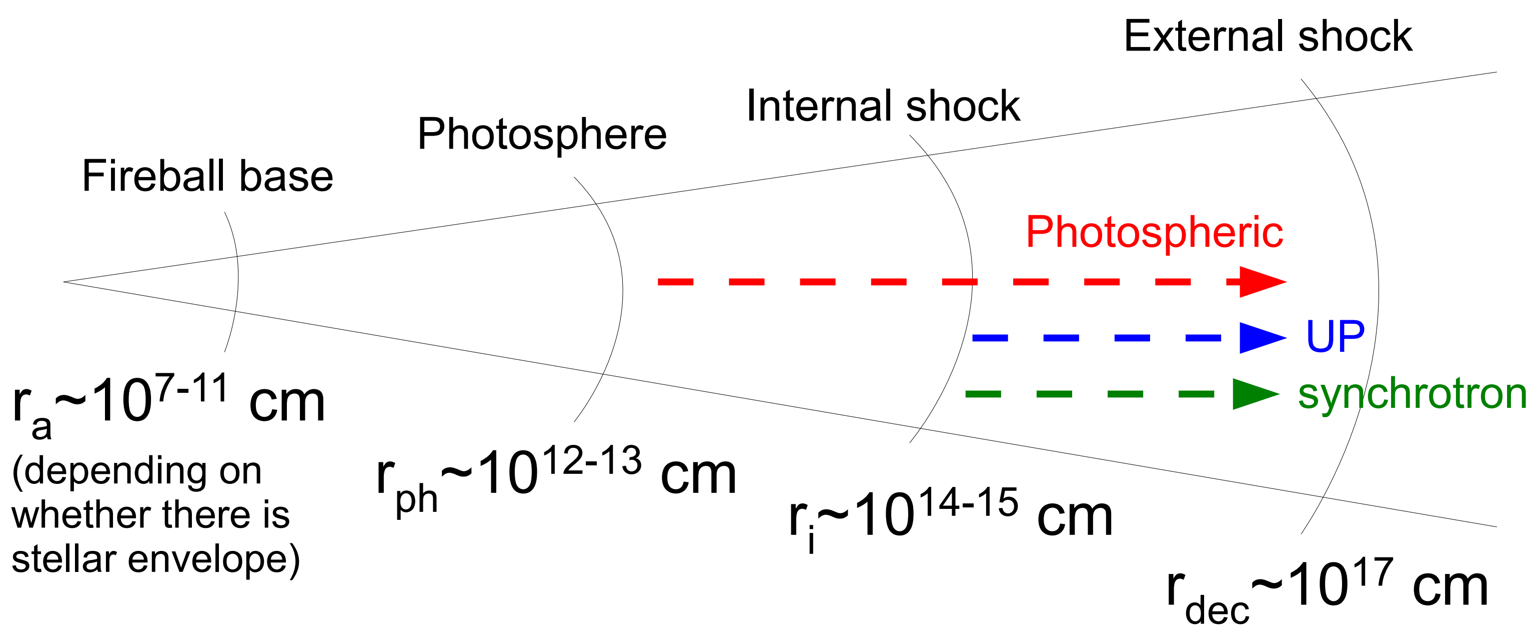
(unlike in 0809916C & some others. which show pure Band)

Abdo, et al. 09 (LAT/GBM coll.) Nature, 462:331

High energy 2nd component: Leptonic?

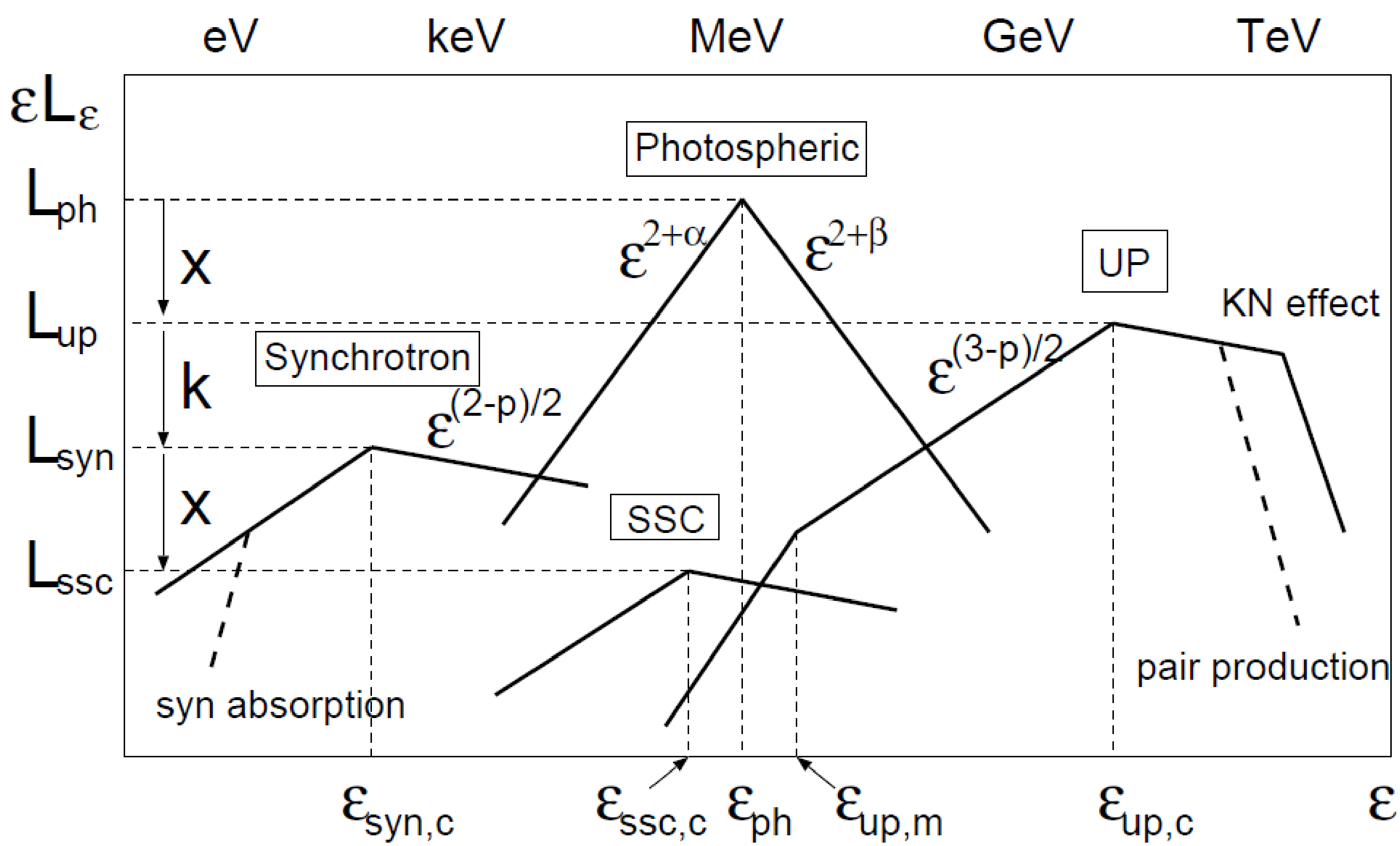
Photosphere + IS model

Toma, Wu, Mészáros, 2011, MN 415:1663



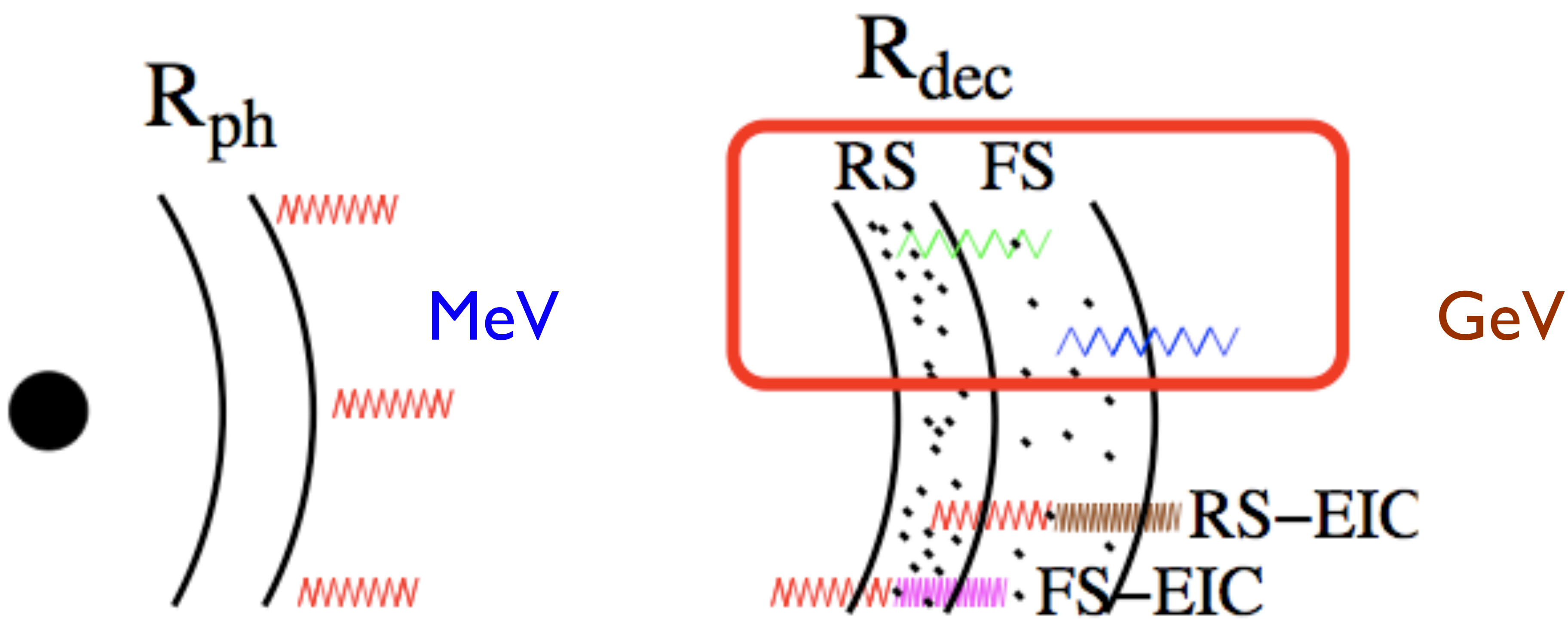
- Photosphere: prompt, variable MeV
- IS occur at $r \gtrsim 10^{15}$ cm (high Γ) : Sy=XR, IC(UP)=GeV

Photosphere-IS model, cont.



This can also produce an MeV Band function + a 2nd high energy (GeV) component; but, dep. on params., could show up as single Band

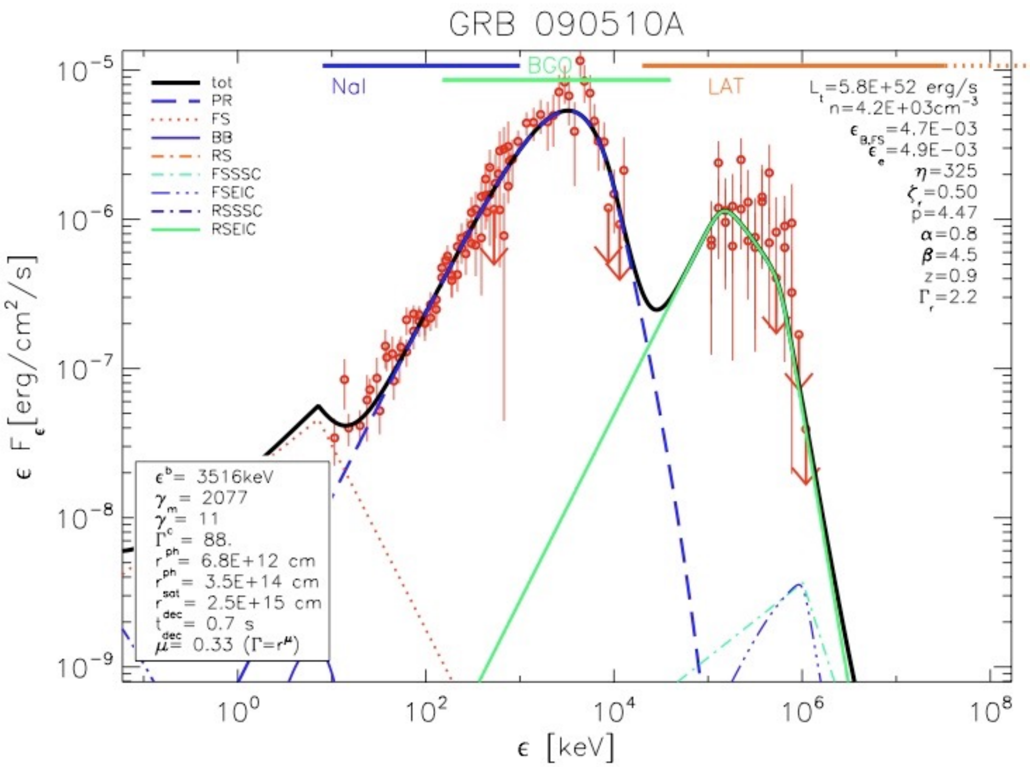
Leptonic magnetic & baryonic photosphere + external shock model



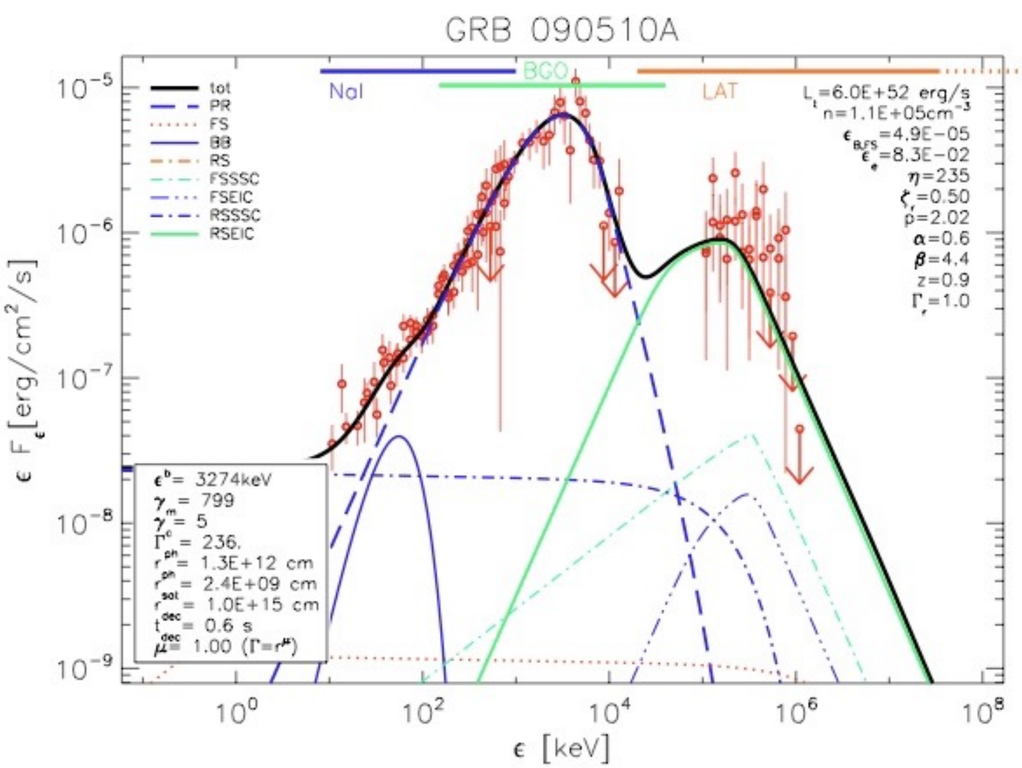
- Leptonic photosph. spectrum extend to $\Gamma_{ph}\, m_e$ ~50-100 MeV
- Ext. shock upscattering spectrum extend to $\Gamma_{es}\, \gamma_{e,KN}\, m_e \rightarrow$ TeV

Veres & Mészáros '12, ApJ 755:12

Photosphere + Extern. shock IC Leptonic model



090510A
←magphot



090510A
←barphot

Veres, BB Zhang & Mészáros ’12, ApJ 764:94

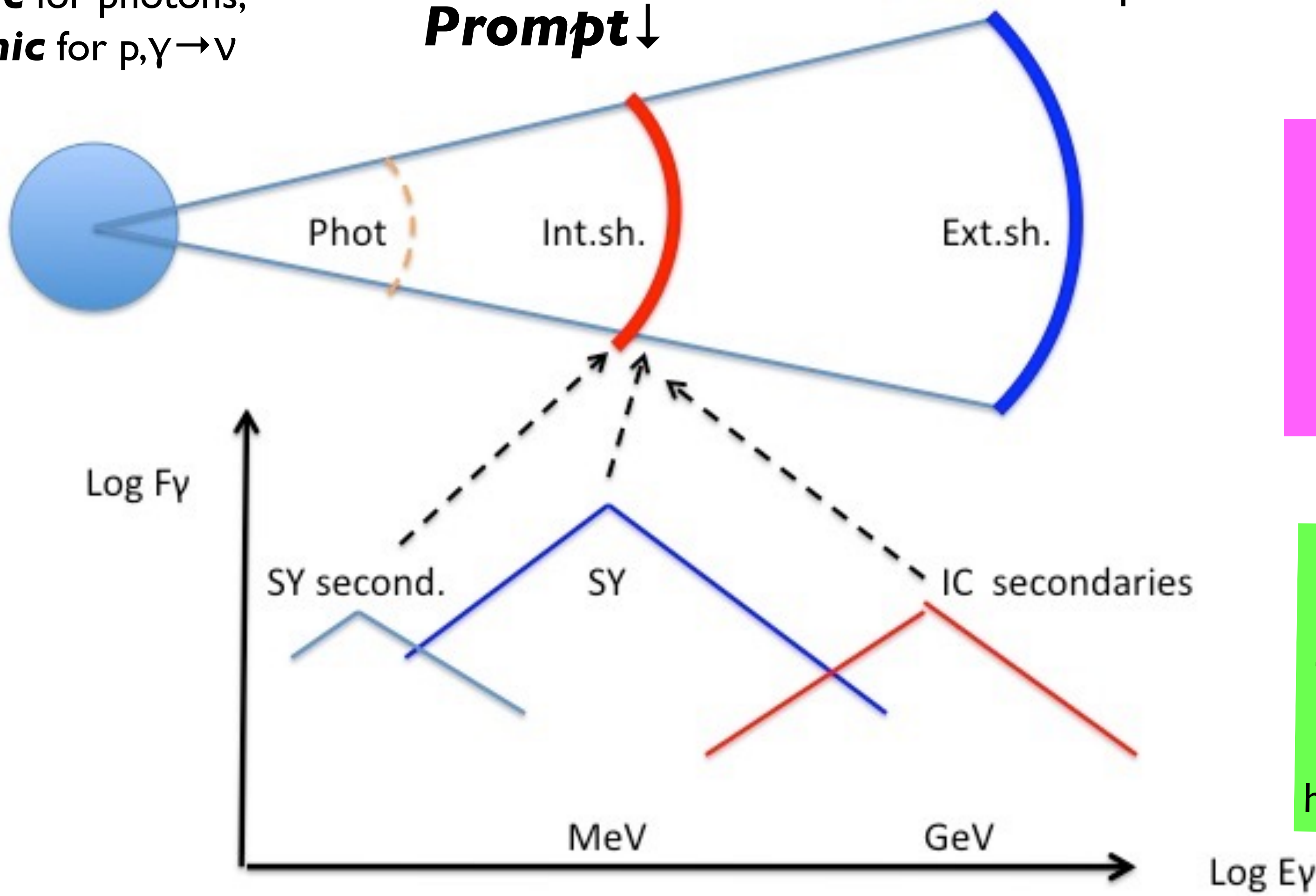
Self-consistent hadronic int. shock

Calculate ***self-consistent*** CR proton, photon & neutrino spectra

• Originally: Waxman & Bahcall '97 consider standard int. shock as ***leptonic*** for photons, ***hadronic*** for p,γ→ν

Prompt↓

↙ ***Afterglow***
FS: X-ray, etc.;
RS: Opt. flash



New Feature:

Hadron accel. + photomeson →
"dissipation"
→inject copious ***relativistic sec'y leptons***

•↙ Asano & PM, 09-12 on, calculate second'y ***photons*** & second'y ***neutrinos*** from both original & hadronic sec'y leptons

also: Murase et al, 2012, ApJ 746:164

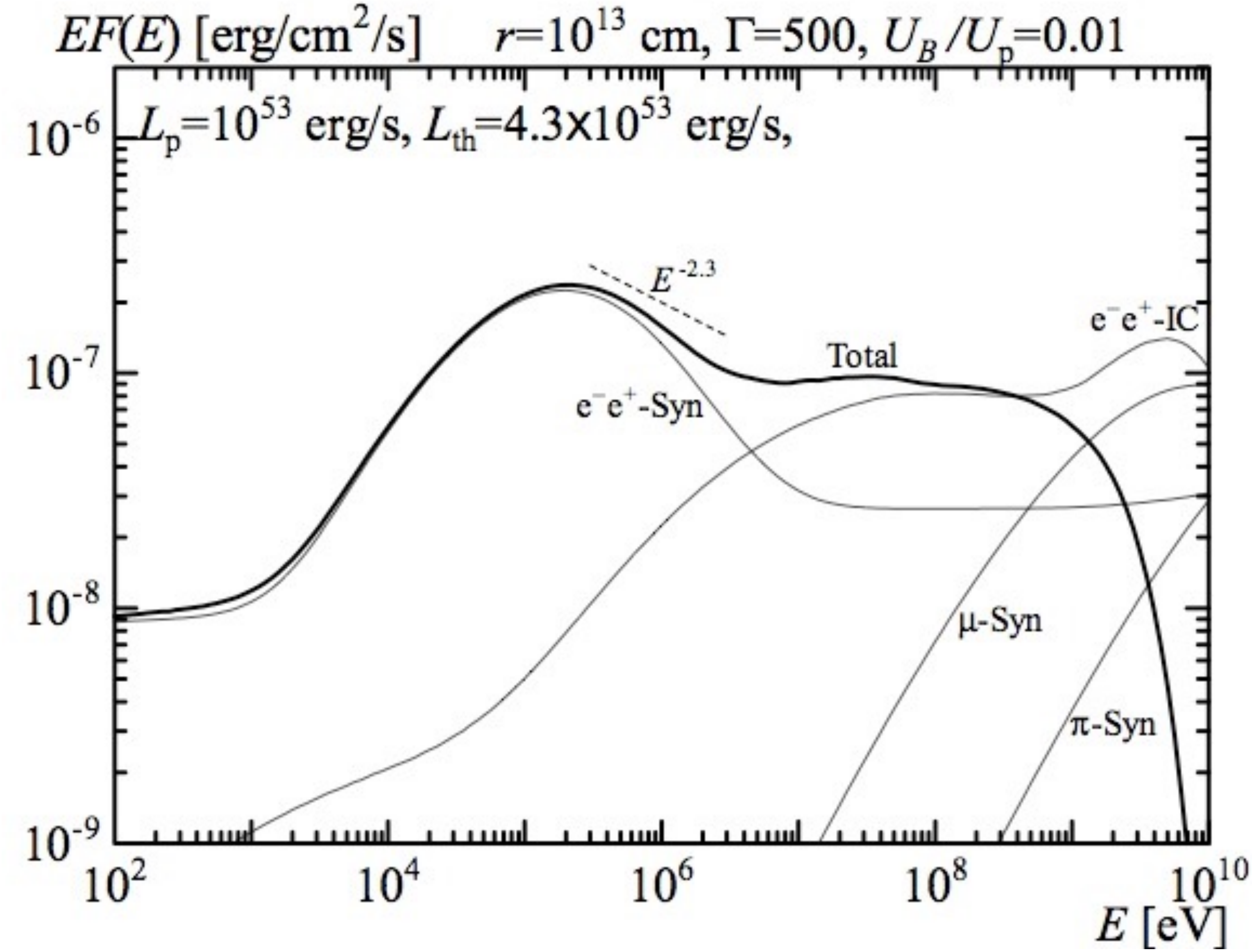
IS w. hadronic cascades

Murase, Asano, Terasawa & PM'12, ApJ746:164

- Assume dissipation region at R_0 (photosphere, IS, etc.)
- Inject Fermi (1st ord) accelerated e^-, p^+ , spectrum~E^{-2}
- Allow cool, subject to ***Sy, IC, pair-form., photomeson***
- Secondary leptons are ***reaccelerated*** by scattering on turbulence/MHD waves behind shocks
- Modulo some plausible assumptions about mag. field growth, turbulence, etc, reaccelerated lepton spectrum leads to a ***self-consistent*** "Band" photon spectrum plus a ***2nd hard*** high en. power law, ~ similar to Fermi LAT.
- ***Good radiative*** efficiency for γ; but below IceCube ν limit

IS w. hadronic cascades II

Murase, Asano, Terasawa & Mészáros, 2012, ApJ746:164



Then, very recently:

GRB190114C: MAGIC

First time detection of a GRB at sub-TeV energies; MAGIC detects the GRB 190114C

ATel #12390; ***Razmik Mirzoyan on behalf of the MAGIC Collaboration***
on ***15 Jan 2019; 01:03 UT***
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

Subjects: Gamma Ray, >GeV, TeV, VHE, Request for Observations, Gamma-Ray Burst

Referred to by ATel #: 12395

Tweet

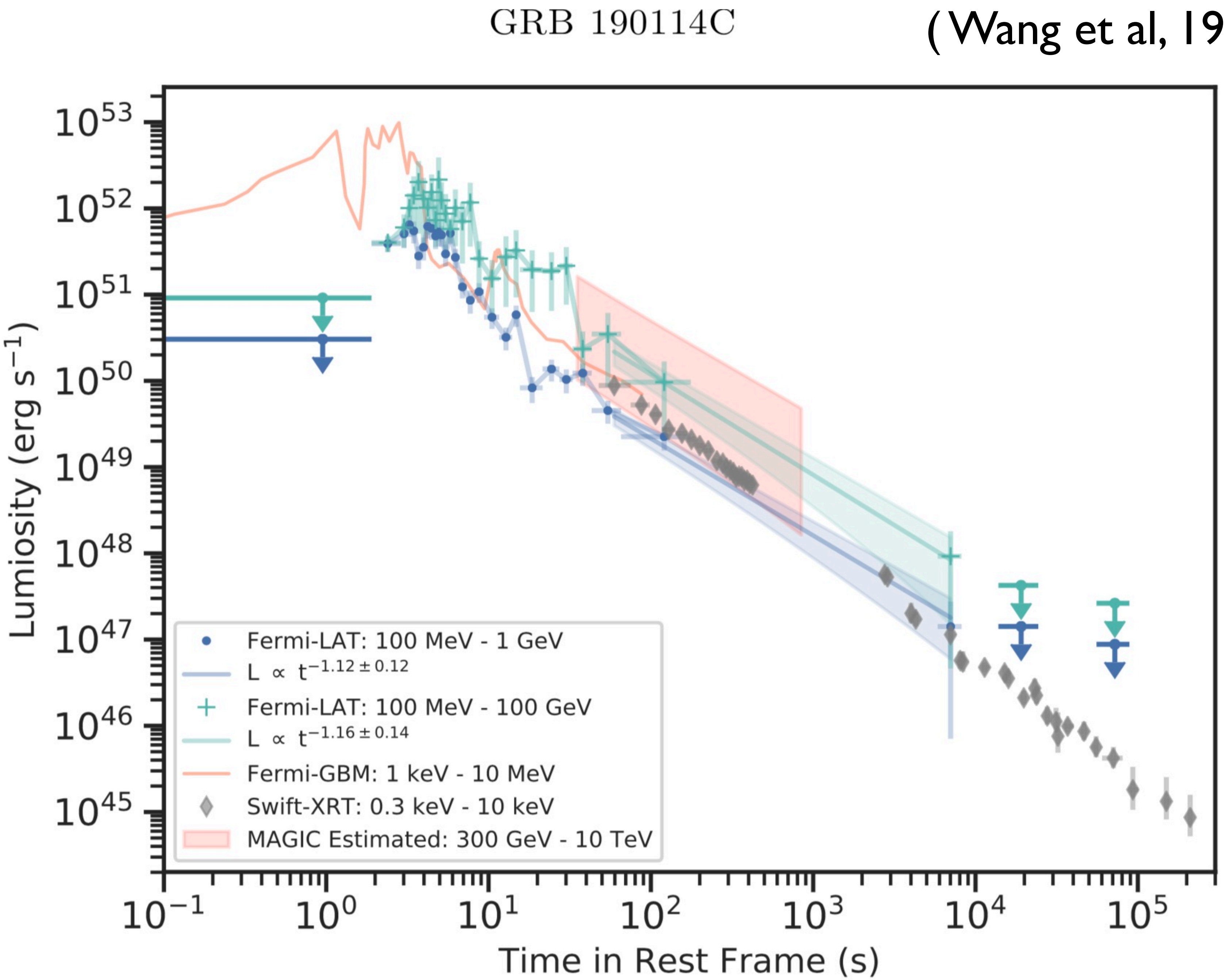
The MAGIC telescopes performed a rapid follow-up observation of GRB 190114C (Gropp et al., GCN 23688; Tyurina et al., GCN 23690, de Ugarte Postigo et al., GCN 23692, Lipunov et al. GCN 23693, Selsing et al. GCN 23695). This observation was triggered by the Swift-BAT alert; we started observing at about 50s after Swift T0: 20:57:03.19. The MAGIC real-time analysis shows a significance >20 sigma in the first 20 min of observations (starting at T0+50s) for energies >300GeV. The relatively high detection threshold is due to the large zenith angle of observations (>60 degrees) and the presence of partial Moon. Given the brightness of the event, MAGIC will continue the observation of GRB 190114C until it is observable tonight and also in the next days. We strongly encourage follow-up observations by other instruments. The MAGIC contact persons for these observations are R. Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de) and K. Noda (nodak@icrr.u-tokyo.ac.jp). MAGIC is a system of two 17m-diameter Imaging Atmospheric Cherenkov Telescopes located at the Observatory Roque de los Muchachos on the Canary island La Palma, Spain, and designed to perform gamma-ray astronomy in the energy range from 50 GeV to greater than 50 TeV.

GRB 190114C

- Bright optical, XR, radio, etc
- z=-04245
- And: $\boxed{\text{MAGIC} \quad E_\gamma > 300 \text{ GeV !}}$ *ATel # 12390*
- $\boxed{\text{A 2nd. Flatter (-1) spec. comp.}}$ above Band
- EBL cutoff? Intrinsic continues to…TeV?
- How far? $\boxed{\text{Leptonic? Hadronic?}}$

GRB 190114C light curve

(Wang et al, 1901.07505)



- (Caveat: not Fermi/Swift analysis)
- Similarity to GRB090902B, GRB130427A
- Substantial thermal comp. kT~150 keV
- $E_{\gamma,iso}$ ~ 2.5x10^{53} erg

GRB 190114C spectrum

(Ravasio et al, 1902.01861)

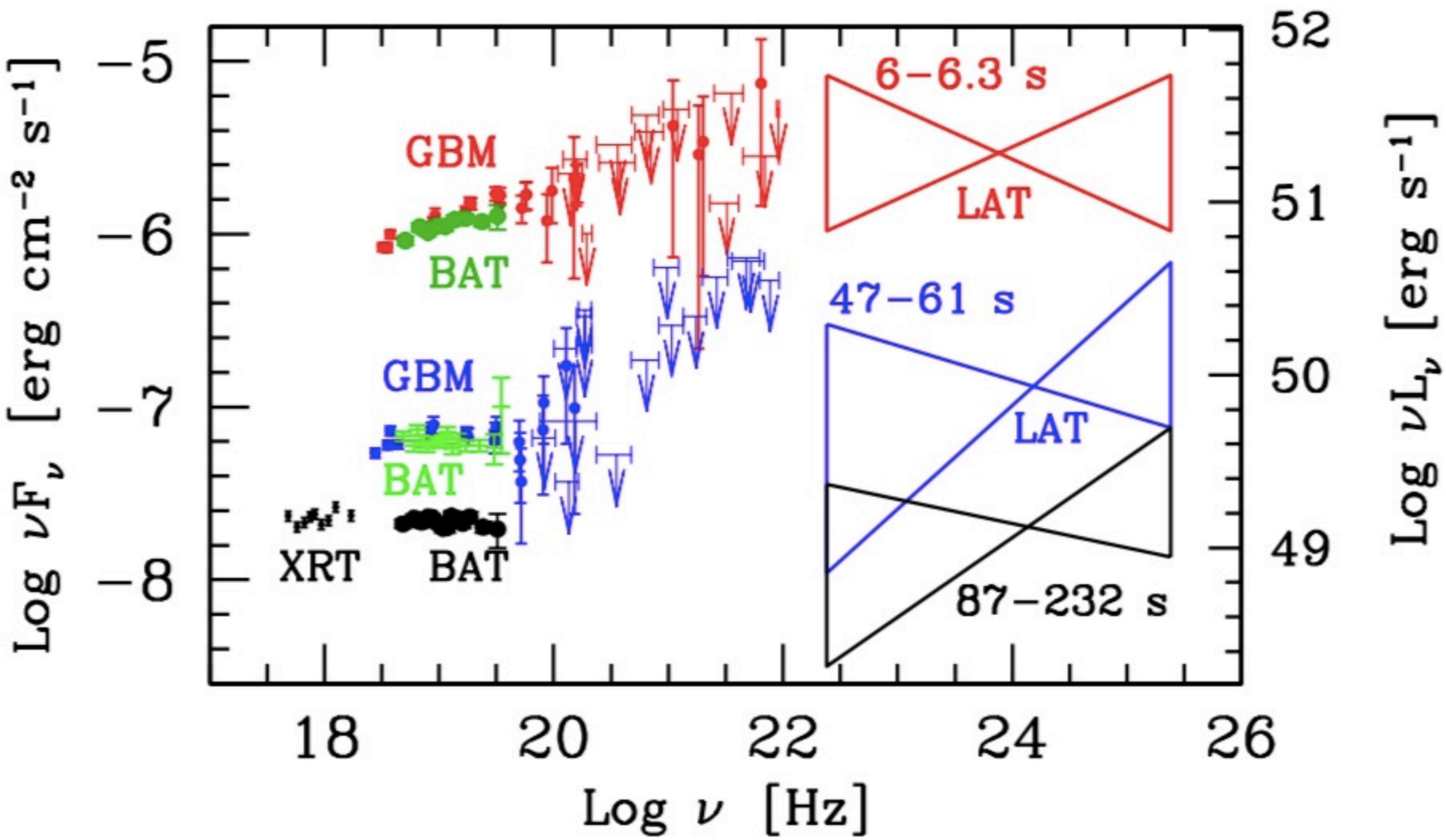


Fig. 2. The X–ray to GeV SED of GRB 190114C at three specific times: at 6-6.3 s, when the power law component has its peak in the GBM data (see panel (B) of Fig.1, blue symbols), at 47–61 s and at 87–232 s (as labelled). We show the GBM, BAT and XRT data (the latter de-absorbed as described in the text). Errors and upper limits on the data points represent 1σ.

- (Caveat: not Fermi/Swift analysis)
- LAT emiss. and GBM nonthermal PL belong to same component (afterglow)
- Conclude Lorentz factor ~500

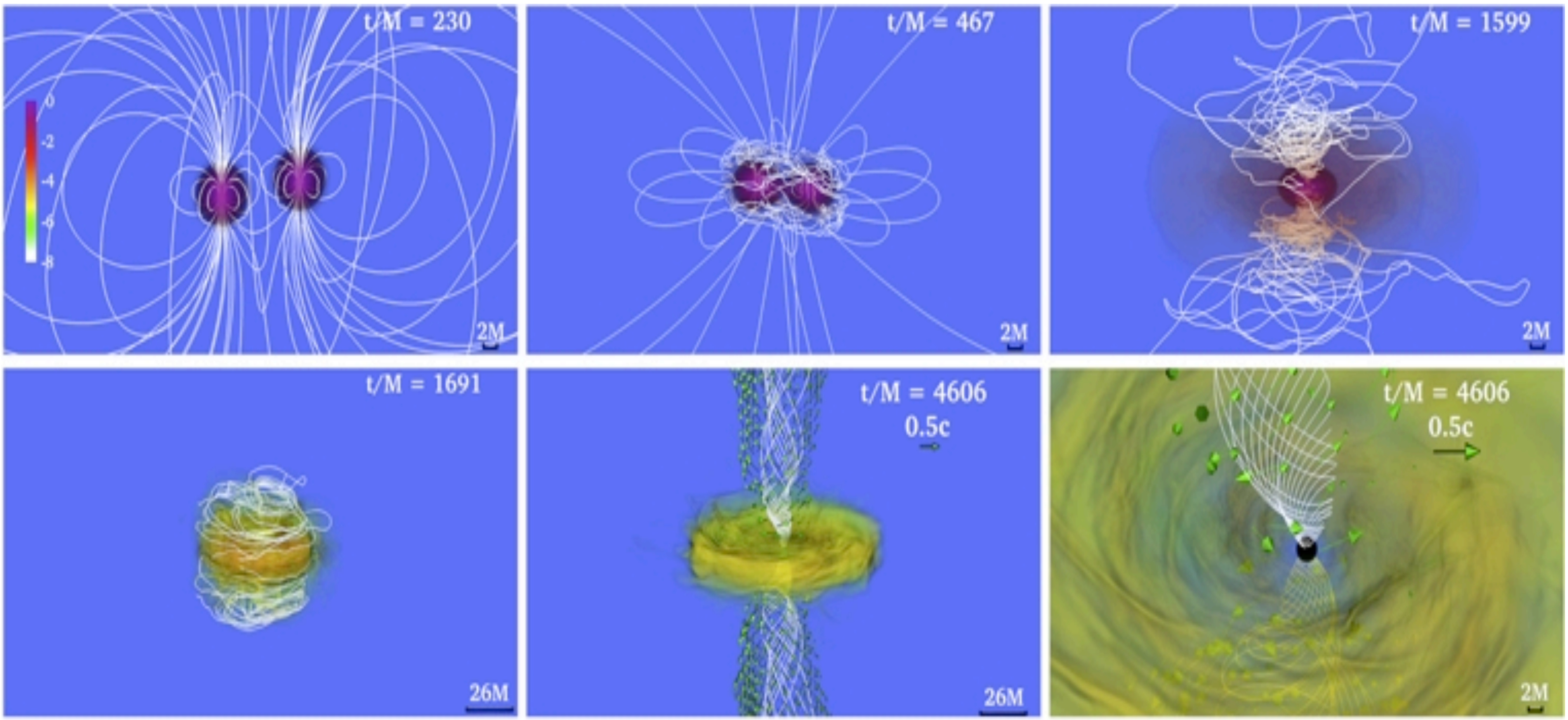
Short GRBs

The dream of Multimessenger
Astrophysics fulfilled ...

GRMHD simuations :

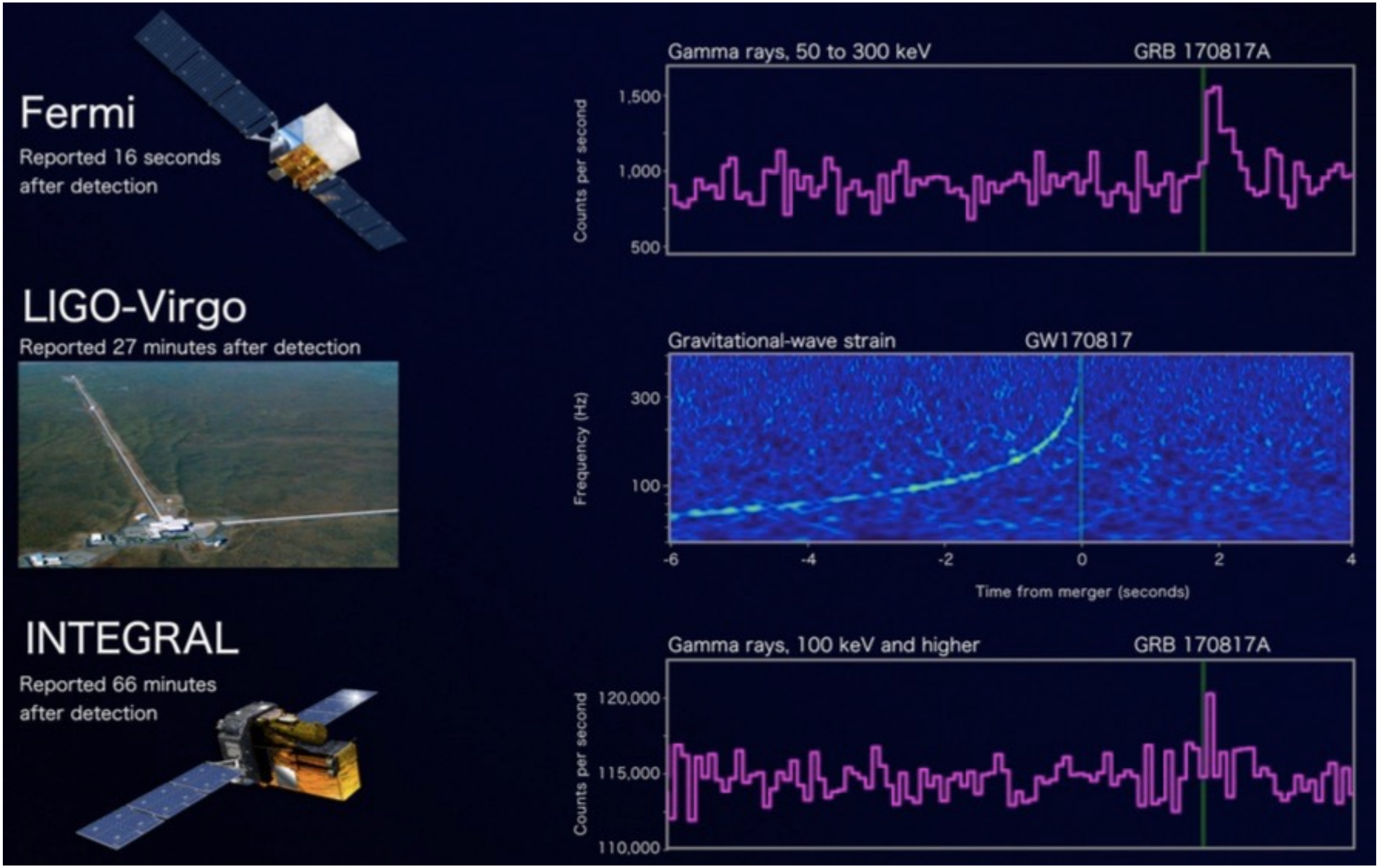
BNS merger→HMNS→jet, ✓

e.g., M. Ruiz+16 ApJL 824:L6



(also: Rezzolla, Kouveliotou et al '11, ApJ 732:L6,) Observational proof :

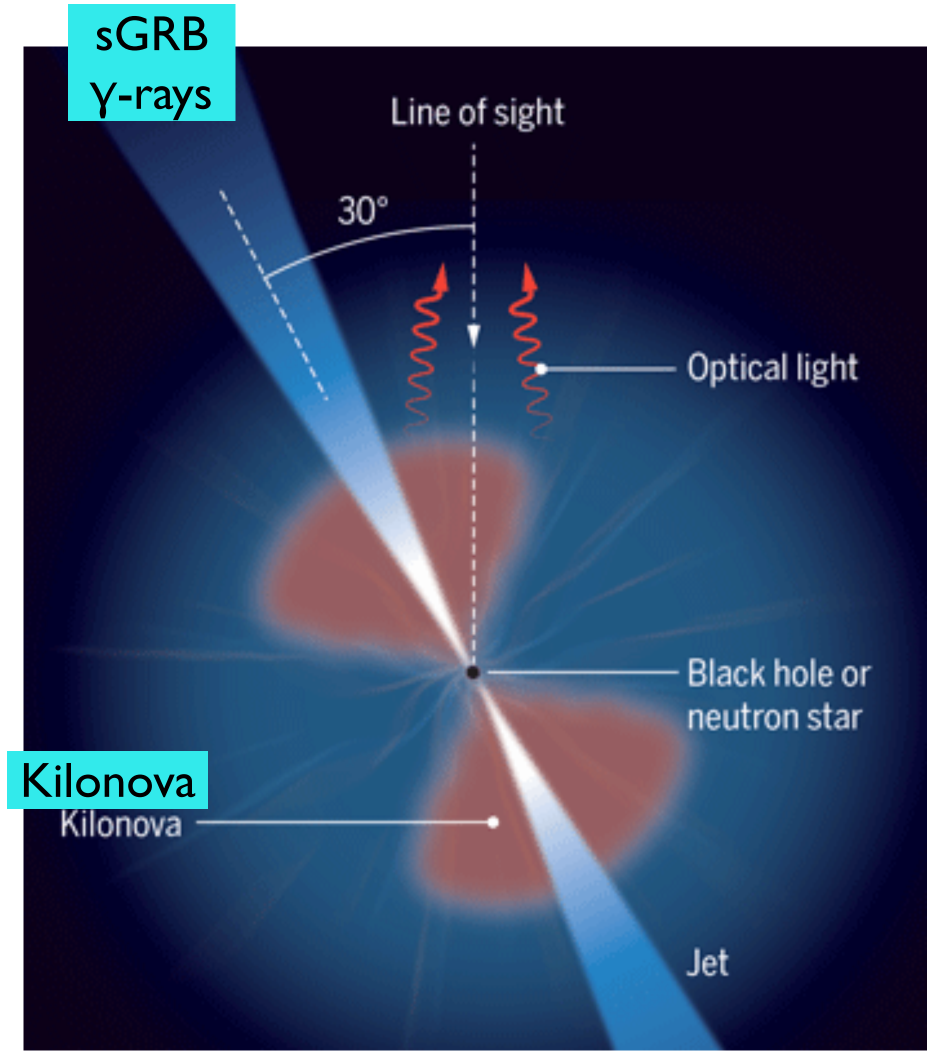
GRB/GW 170817



i.e.

BNS→[GW, sGRB, KN]

- Along and off-axis of structured jet (or cocoon), see the ***SGRB*** γ-rays
- at large angles, see ***kilonova*** caused by slower neutron-rich outflow where rapid neutron-capture ***r-process*** →very heavy elements, whose opacity and slow decay → **optical/IR**
- at all angles, see **GWs**



so, with

SGRB/GW 170817

re-confirmed that:

- SGRBs are indeed BNS mergers
- and BNS/SGRBs are also GW sources
- Multi-messenger astronomy now takes off in earnest (beyond SN1987a 1/100 yr events)
- A long awaited development !

Are there arguments for relativistic hadronic ***secondaries*** in the GRB γ-emisslon?

• *YES*

- Hadrons ***solve*** the radiative efficiency and the gamma-spectrum issues in ***photospheres***
- They also solve this for ***internal shocks***
- And of course, if electrons are accelerated, why would hadrons ***not*** be accelerated?

BUT: no conclusive proof yet

As a test, can we detect

UHECRs and/or Neutrinos ?

from ***both*** or ***either*** standard
IS and **photospheric** models ***?***

pp or pγ neutrino production

$$p + p/\gamma \to N + \pi^{\pm} + \pi^0 + \ldots$$

$$\begin{aligned} \pi^+ &\to \mu^+ + \nu_\mu \ , \\ & \quad\ \mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu \end{aligned}$$

$$\begin{aligned} \pi^- &\to \mu^- + \bar{\nu}_\mu \ , \\ & \quad\ \mu^- \to e^- + \bar{\nu}_e + \nu_\mu \end{aligned}$$

$$K^+ \to \mu^+ + \nu_\mu$$

$$n \to p + e^- + \bar{\nu}_e$$

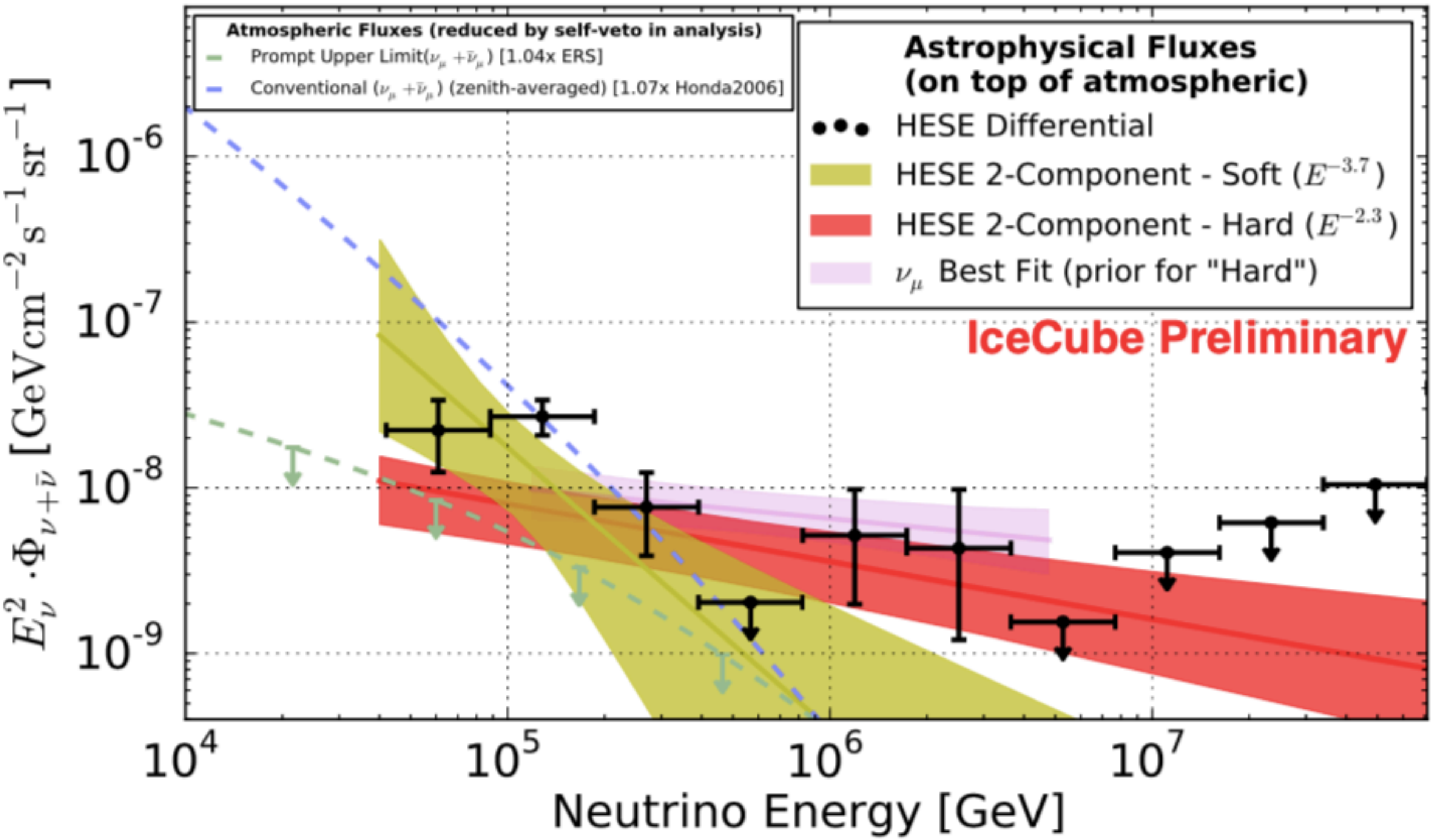
$$\pi^0 \to \gamma + \gamma$$

- Both ν_e and ν_μ are produced by charged pion decay,
- γ-ray photons are produced by neutral pion decay

Confront with observations:

IceCube data on astrophysical VHE νs

IC3 HE ν-bkg

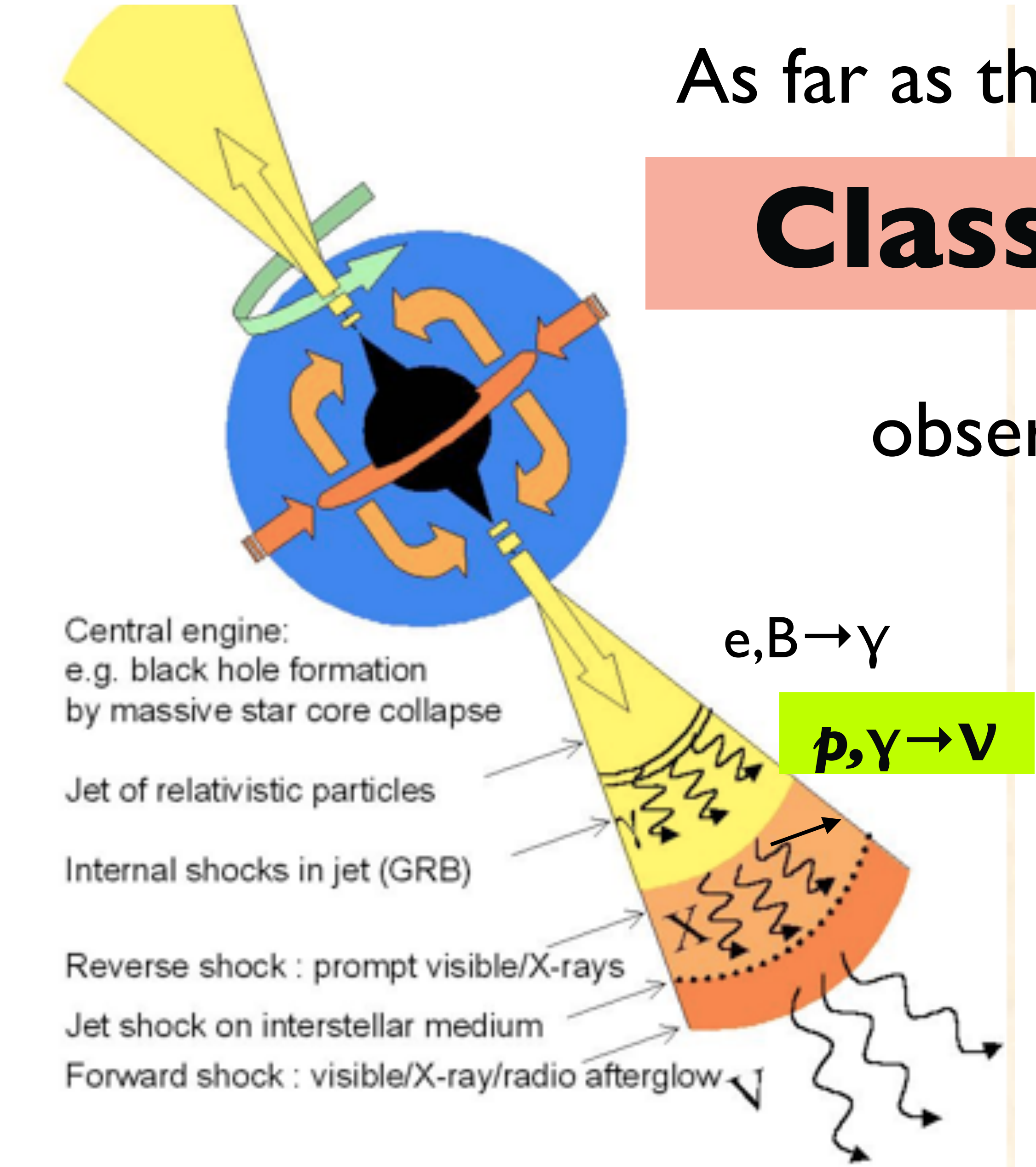


Ahlers&Halzen, 1805.11112

As far as the

Classical GRBs:

observational tests made:



- If $L_p/L_\gamma \sim 10$, expect that $L_\nu/L_\gamma \sim 1$,
- ***but*** IC3 + Swift : **≲1% of νs** can come from standard intern. shock model GRBs where γ, ν are produced in the same shocks,

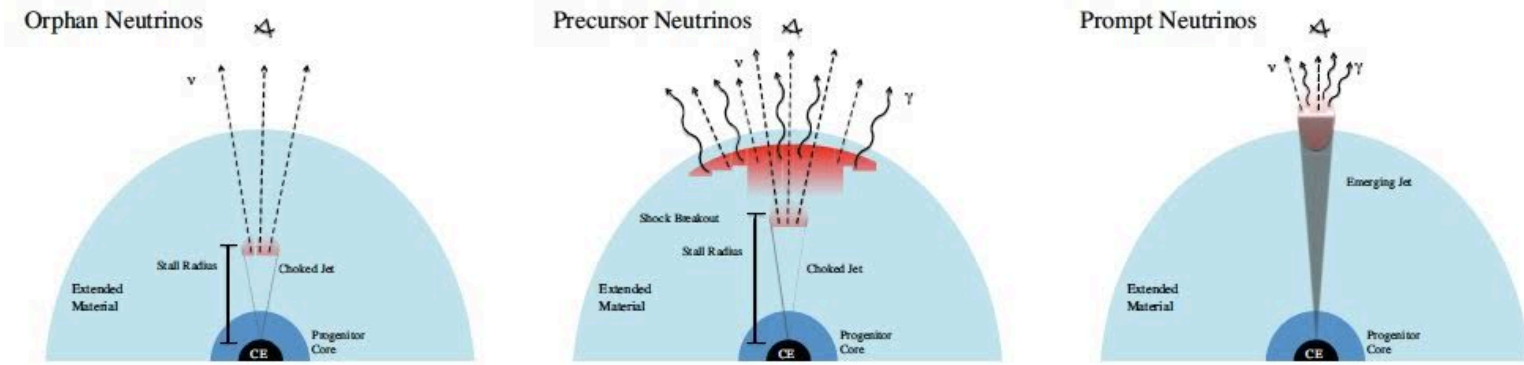
(IC3 team, 2015, ApJL, 805: L5)

Model dependent constraint: γ↔ν

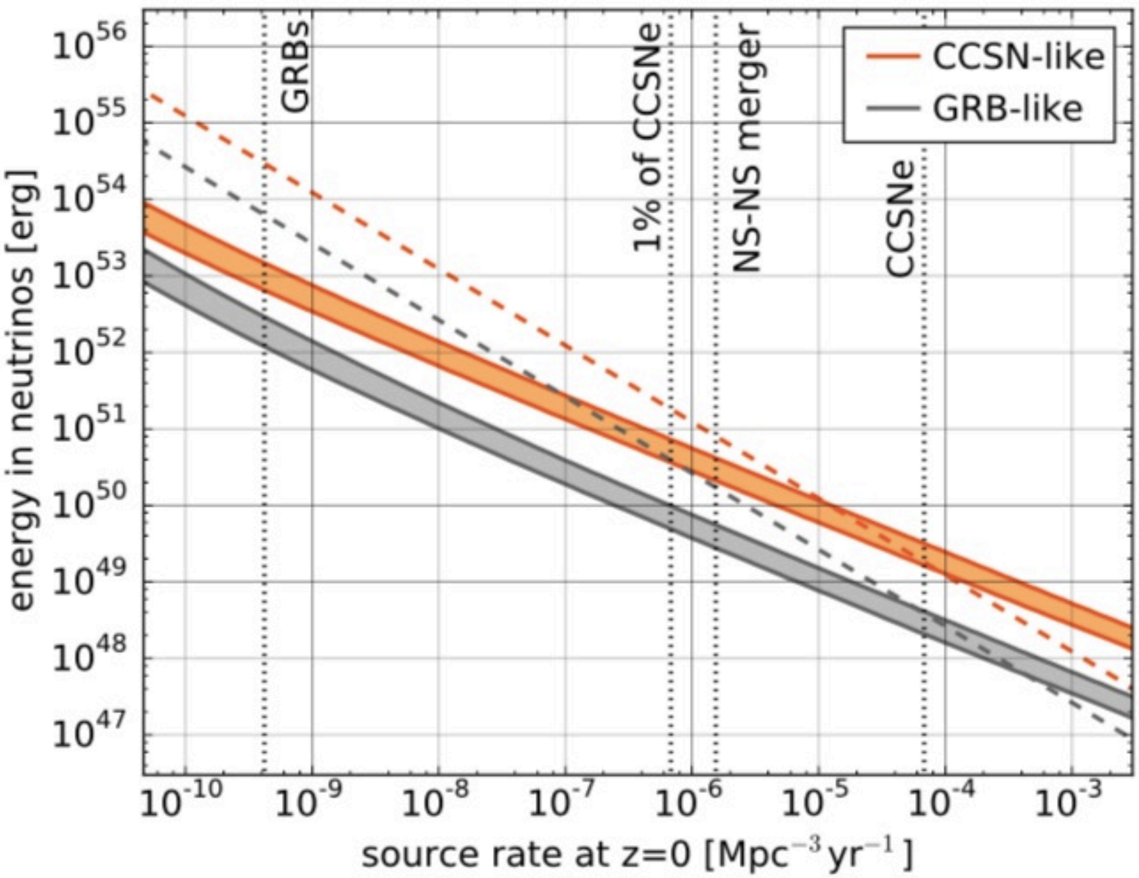
Low optical depth →no hiding!

Another possibility:

Choked GRB - Shock Breakout - LLGRB



↑Senno, Murase, Mészáros, (2016) PRD, 93, 083003



- ← IceCube 1807.11492, model-independent constraints on transients
- For ***GRB***-like (orange) upper limit: ≲ 5-30% for spectrum s=2.13 (s=2.50)
- For **ccSN**-like (gray), i.e. **choked** jet, could provide much or all of diffuse flux

(see also Ismaili+18, 1809.09610)

Thanks!

Caption for fig. IC3 limit GRB/ccSNe

- Define doublets and multiplest as 2 more νs within 100 s and 3.5 deg
- Very low rate of multiplet alerts allow to define limits on a transient source population with durations up 100 s
- Use typical distributions of GRBs and ccSNe @z<8, assume GRB peak L_ν propto peak L_γ , fluctuating
- Region above red (ccSN/choked GRB) or gray (GRB) is ruled out, for 2.5 (upper) and 2.5 (lower) spectrum
- Dashed line: where ccSNe or GRB provide 100% of ν background, for 2.5 spectrum (lower by 13 for 2.13)

A different question:

Can we expect any νs from short GRBs (SGRBs)?

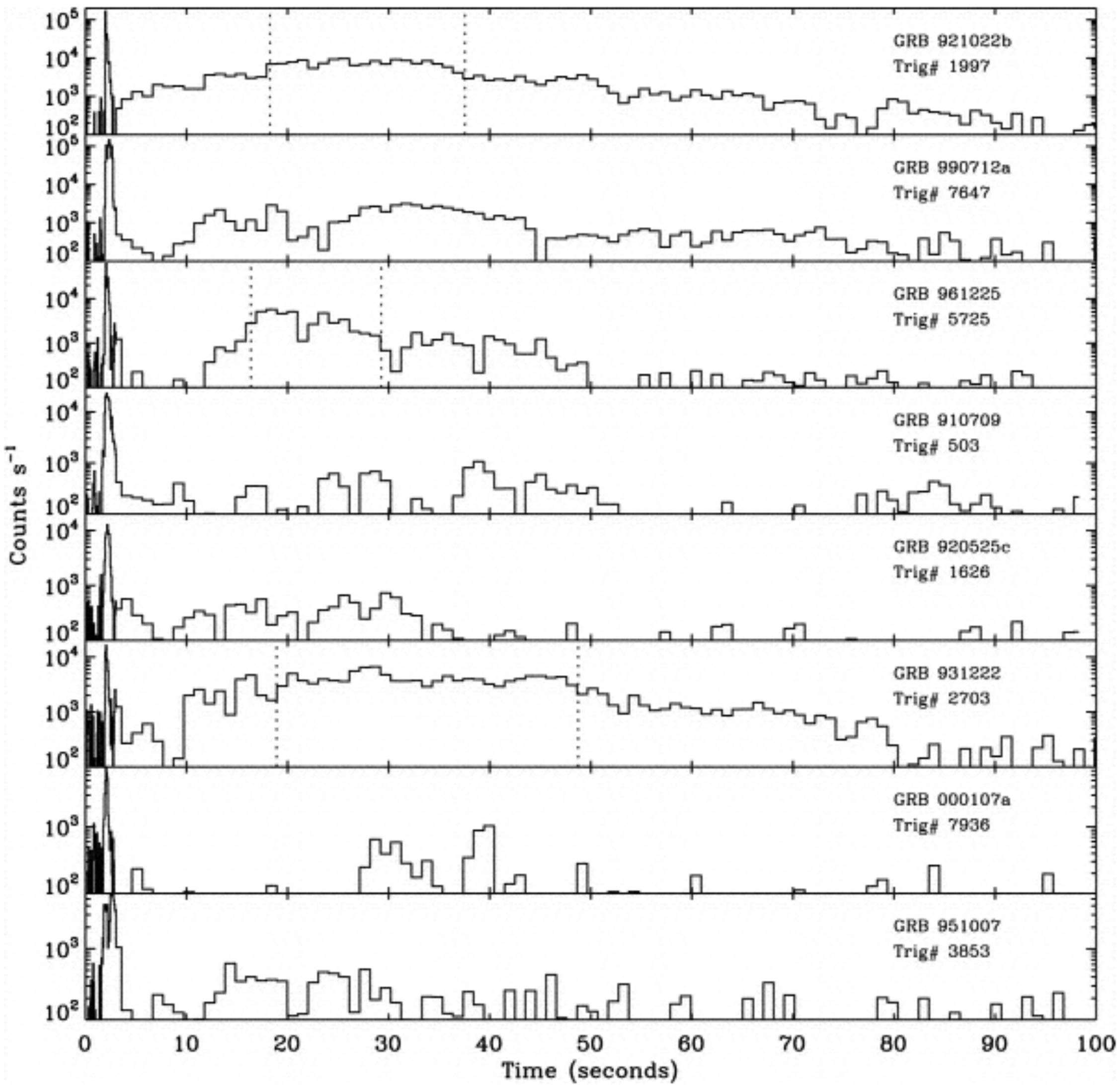
Highly relevant,
in view of GW/GRB170817,
a confirmed multimessenger source !

Of course, previously:

- IceCube found that <1% of the EM-observed "classical" GRBs can be contributing to this observed neutrino flux (or <5-30% in model-indep. analysis)
- And these are mostly **long GRBs** from ccSNe; and **short GRB**s (BNS) are much **fainter;** so would assume SGRBs are even less likely sources;
- ***But*** these were tests for neutrinos in close time / direction coincidence w. ***prompt*** (main) jet MeV γs

However:

SGRB are ***not*** always "**short**"!



in 30-50% of cases:

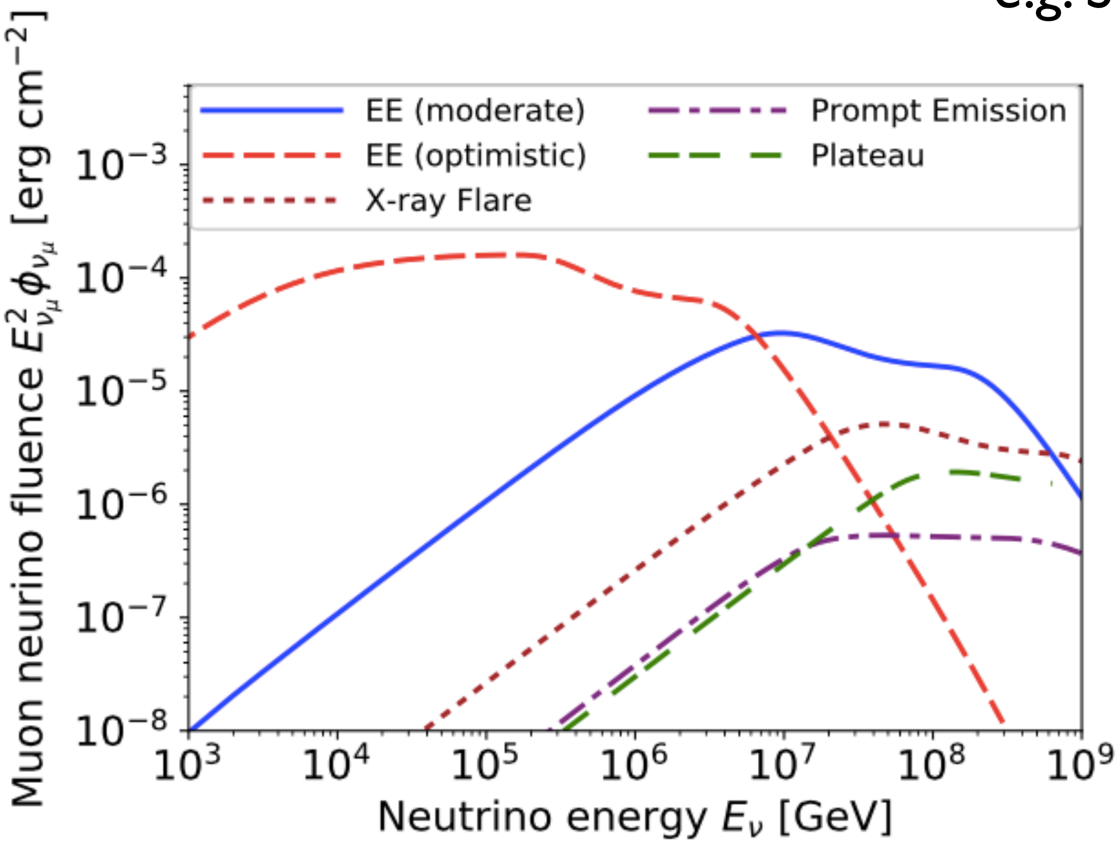
- ***Extended*** emission (EE) in 30-50% cases
- EE spectrum is ***softer*** than that of the "prompt"
- Prompt: E~1-3 MeV
- Ext'd: E~ 30-60 KeV
- $\Delta t_{EE} \sim\leq 10^2$ s

Norris+06, ApJ 643:266

When one calculates BNS Merger ***Neutrino light curves***

including also ***delayed*** components

e.g. SGRB extended emission (EE), etc



Neutrino fluence from *on-axis* SGRB for EE-mod, EE-opt, prompt, flare & plateau component @ d_L=200 Mpc (e.g. aLIGO)

Kimura, Murase, Mészáros & Kiuchi, 2017, ApJL, 848:L4

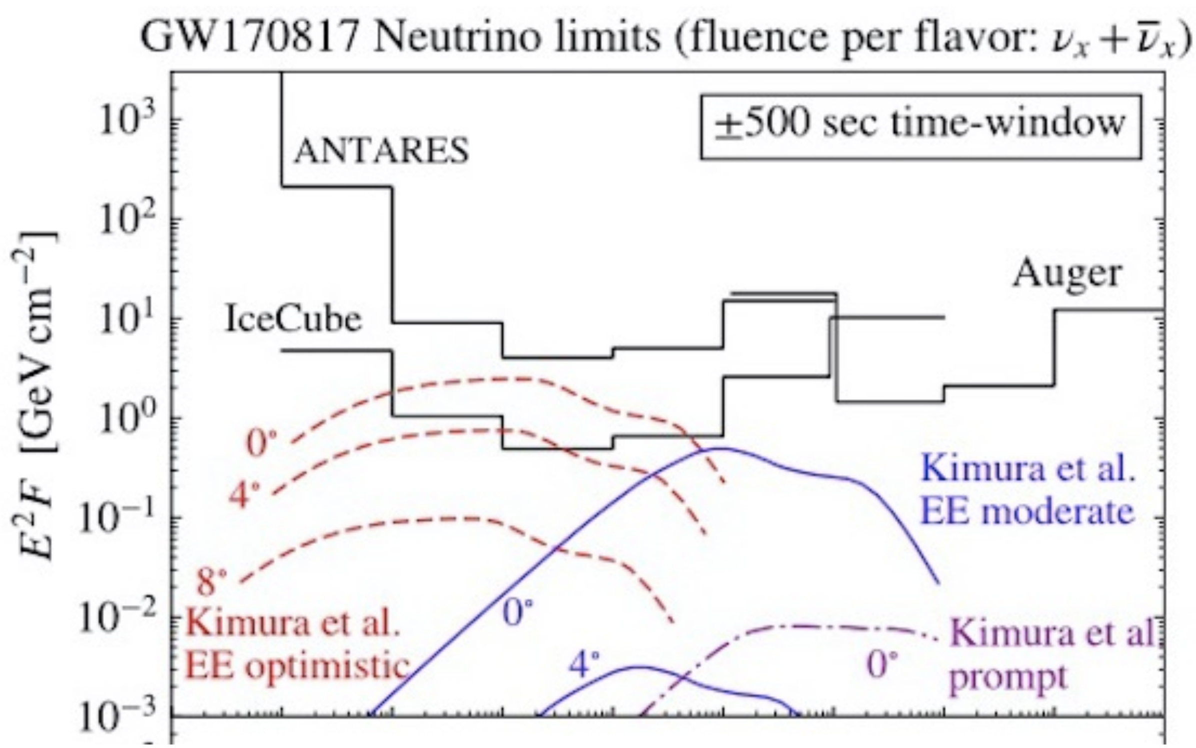
Find a

ν-dominance of BNS EE:

- Caused by ***lower*** Γ, ***higher baryon*** load
- ⇒ ***higher photon*** density and ***shorter*** $t_{p\gamma}$
- →***higher B***-field, stronger ***pion cooling***
- →***lower*** pion cooling break, TeV-PeV spectra
- ***Still***, fluence ***low*** for IC3, unless ***very*** nearby

And observationally,

IceCube, Antares, Auger test ν-limits on GW170817:



- GW indicates off-axis jet, $\theta_{obs} \in [0°, 36°]$,
- Kimura et al. models for Doppler factor at various θ_{obs}-θ_j offset
- No detection (OK, ✔)

Antares, IceCube, Auger, LIGO-Virgo coll, 2017, ApJ 850:L35

Det. Prob.($\geq$k events)

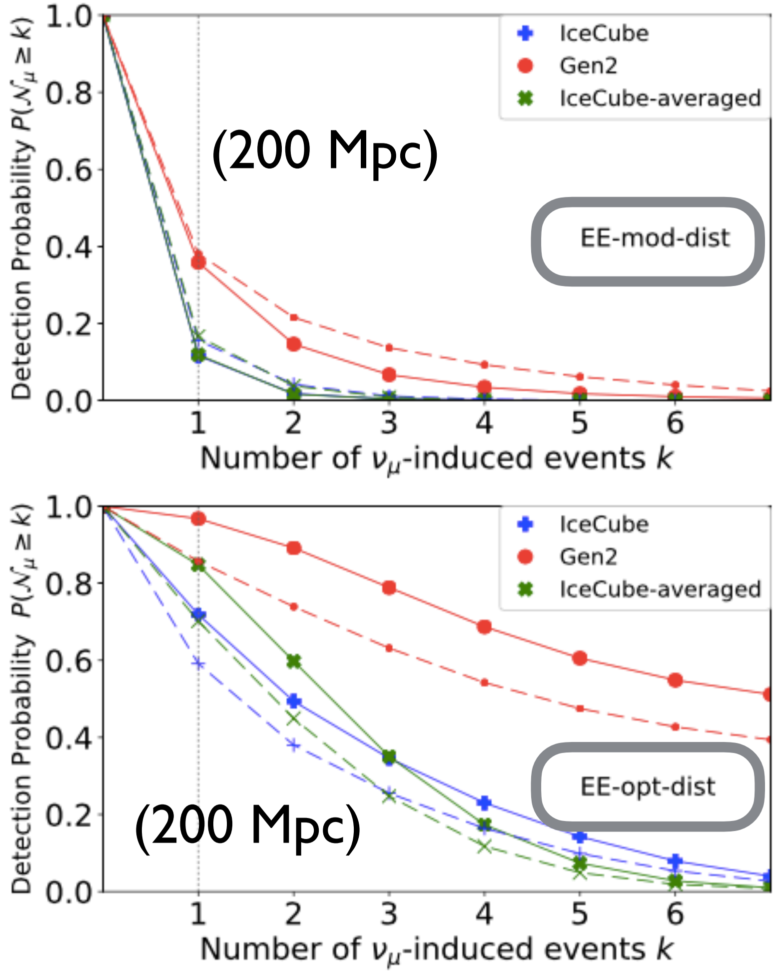


Figure 2. The detection probability $P(\mathcal{N}_\mu \geq k)$ for d_L = 200 Mpc. The upper and lower panels are for EE-mod-dist and EE-opt-dist, respectively. The solid and dashed lines are for the cases with $\sigma_\Gamma = 2$ and $\sigma_\Gamma = 4$, respectively. The vertical thin-dotted line shows $\mathcal{N}_\mu = 1$.

(IceCube-averaged includes down-going events)

Det.Prob($\geq$1 event) vs. d_L

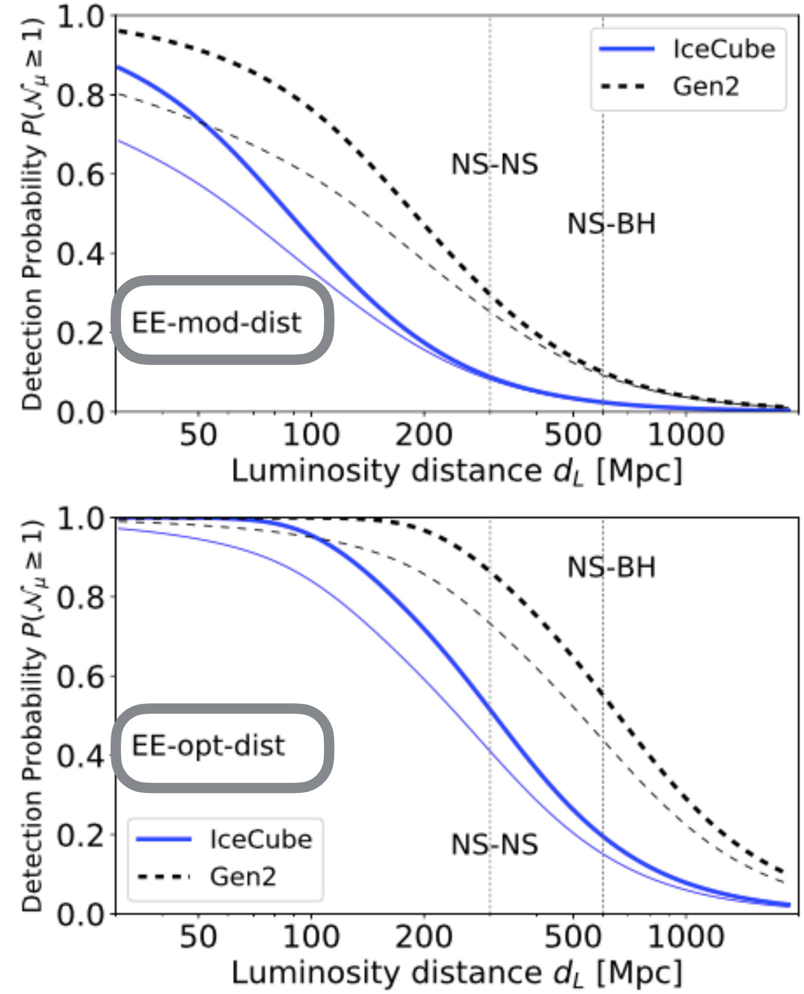


Figure 3. The detection probability $P(\mathcal{N}_\mu \geq 1)$ as a function of luminosity distance d_L. The upper and lower panels are for EE-mod-dist and EE-opt-dist, respectively. The thick and thin lines are for the cases with $\sigma_\Gamma = 2$ and $\sigma_\Gamma = 4$, respectively. The vertical thin-dotted lines show d_L = 300 Mpc and d_L = 600 Mpc.

i.e., IC3: maybe - Gen-2: likely

Kimura, Murase, Mészáros & Kiuchi, 2017, ApJL, 848:L4

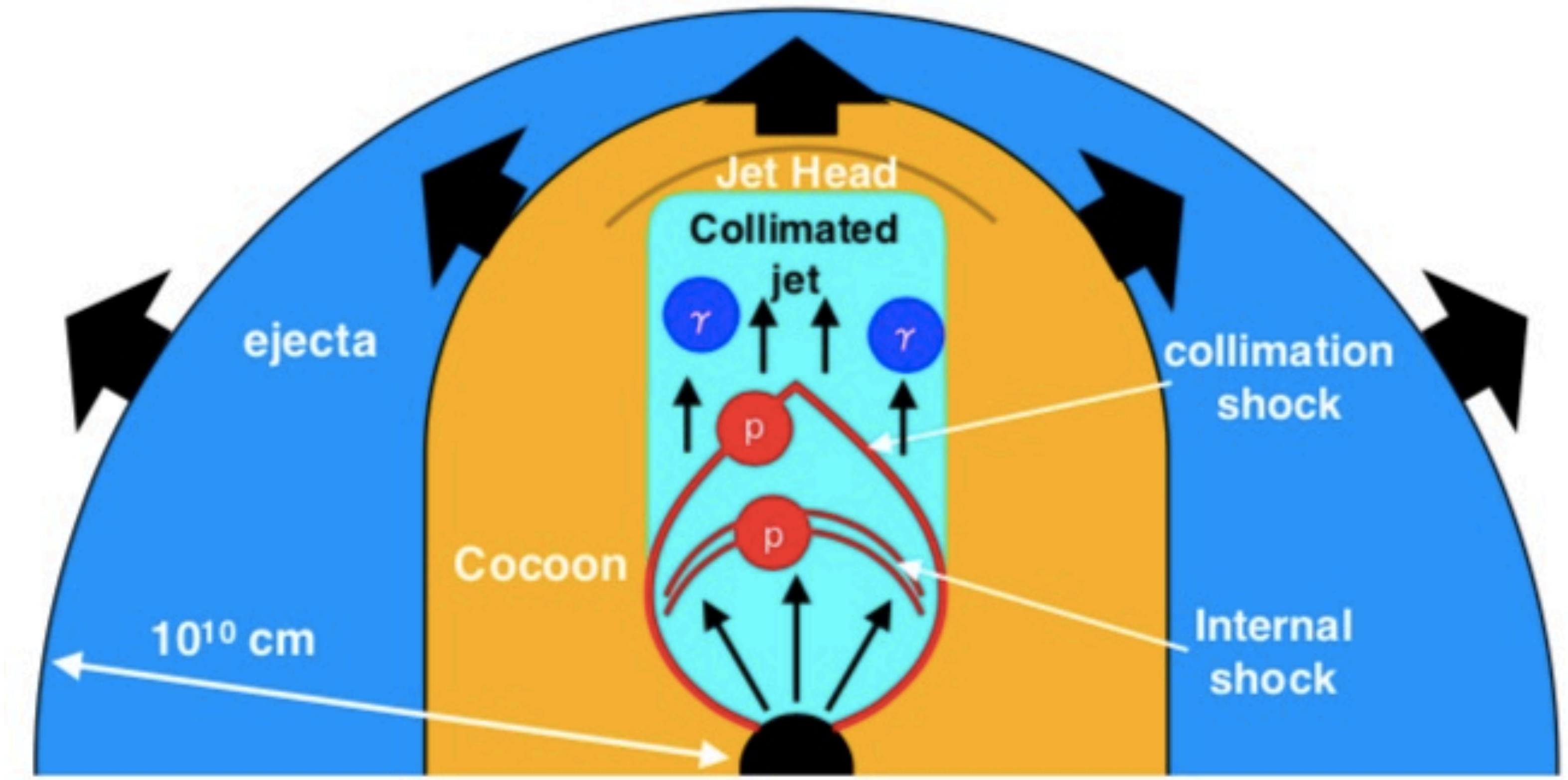
Another possible HENU mechanism for SGRB :

Jet choked in the merger dynamical ejecta

↓

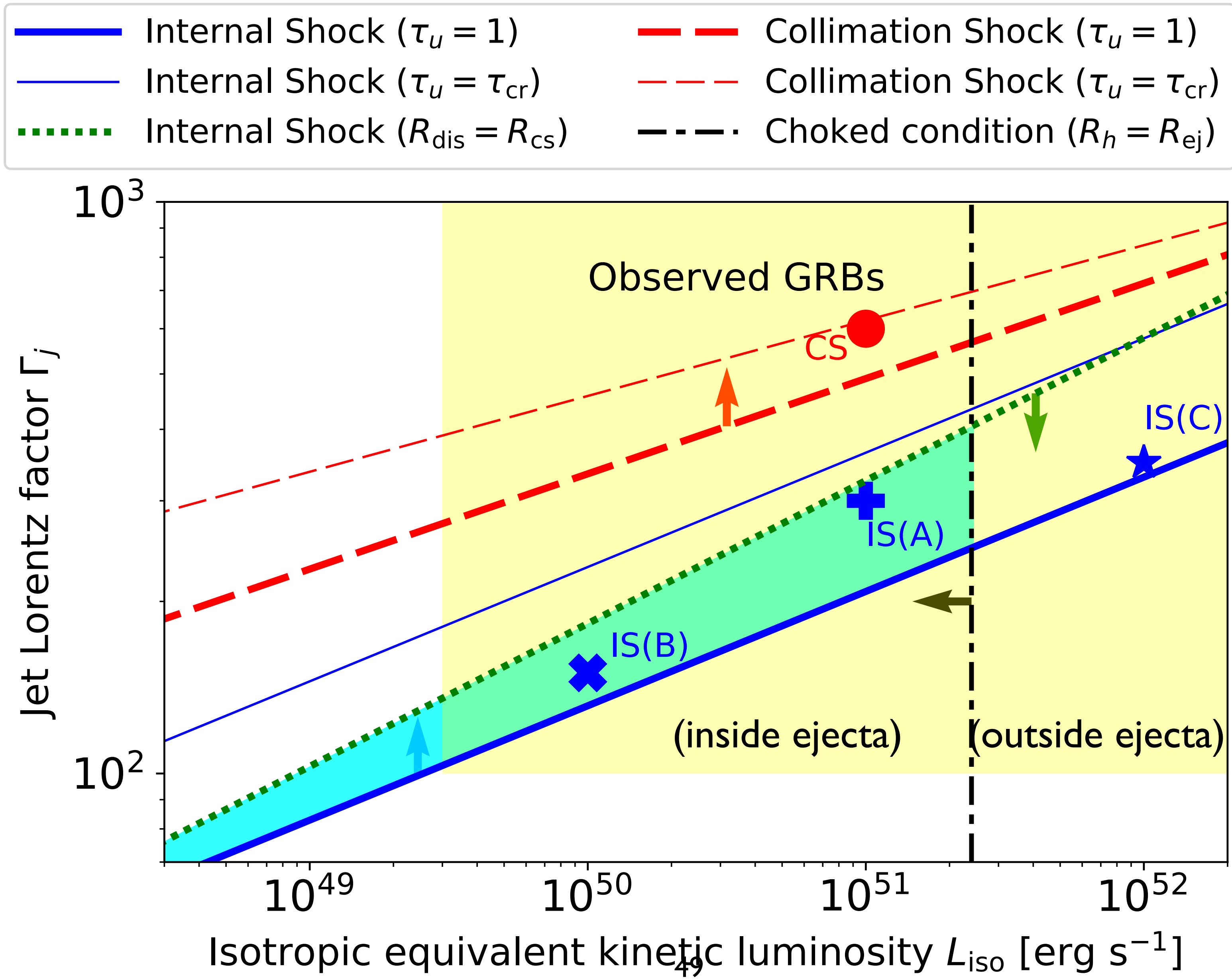
Trans-Ejecta HE Neutrinos

Internal and collimation shocks in BNS jet-cocoons within the dynamical ejecta

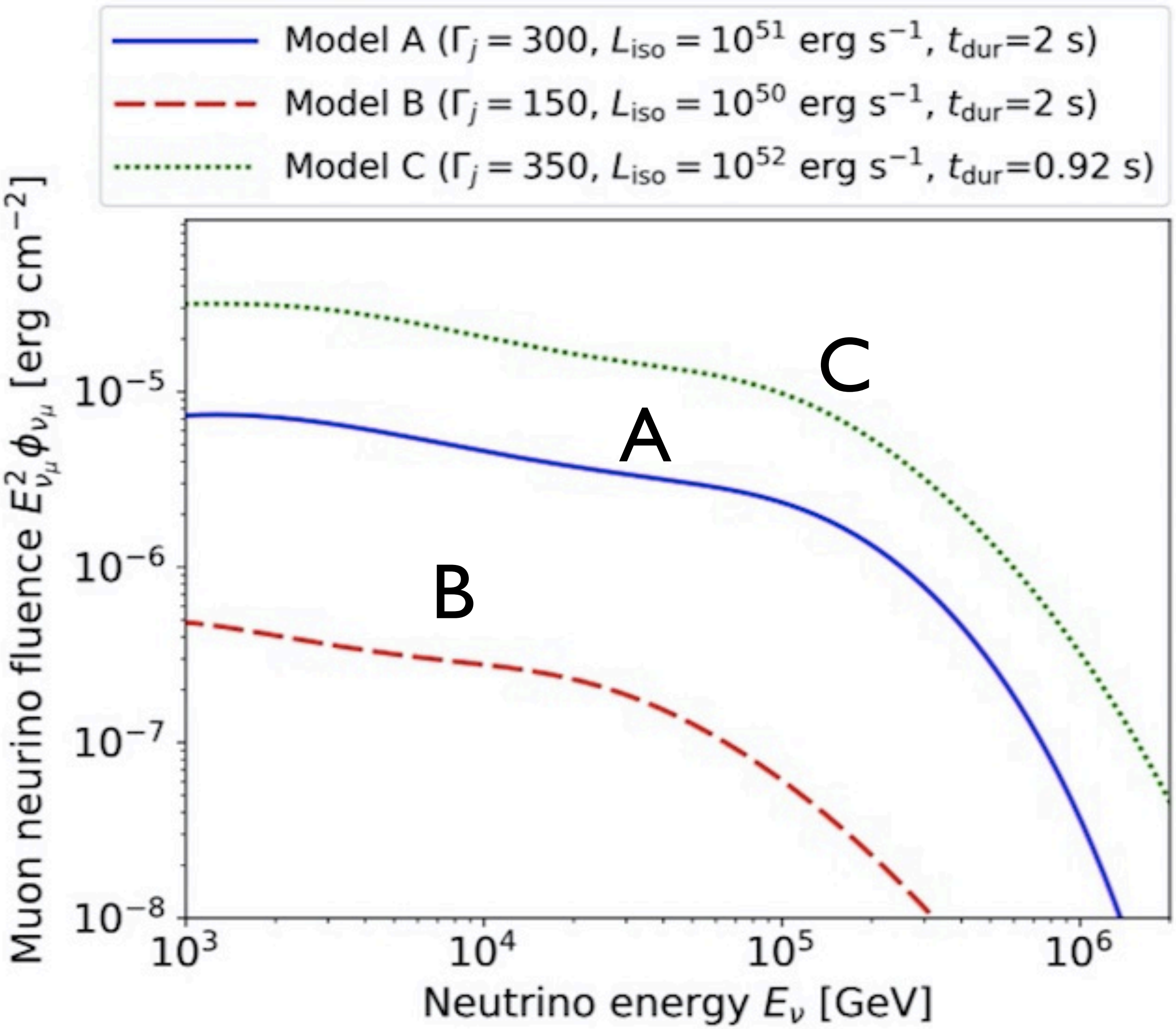


Kimura, Murase, Bartos, Ioka, Heng, Mészáros+18, PRD 98:043029

Allowed parameters for Fermi acceleration by internal & collimation shocks inside ejecta



Spectral nu-flux @ 300 Mpc



Note: Due to strong pion cooling, the initial flavor ratio at source is (0,1,0). After oscillations, using the tri-bimaximal matrix for propagation, the flavor ratio at Earth is (4,7,7), so nue/numu ~1/2. Also, the IceCube eff. area for cascades is lower than for tracks at this energy, so here we neglected nue fluence

Detection probability

TABLE II. Detection probability of neutrinos by IceCube and IceCube-Gen2

Number of detected neutrinos from single event at $\boxed{40\,\mathrm{Mpc}}$			
model	IceCube (up+hor)	IceCube (down)	Gen2 (up+hor)
A	6.6	0.55	29
B	0.36	0.023	1.5

Number of detected neutrinos from single event at $\boxed{300\,\mathrm{Mpc}}$			
model	IceCube (up+hor)	IceCube (down)	Gen2 (up+hor)
A	0.12	9.7×10^{-3}	0.52
B	6.2×10^{-3}	4.2×10^{-4}	0.027

GW+neutrino detection rate [yr^{-1}]		
model	IceCube (up+hor+down)	Gen2 (up+hor)
A	$\boxed{1.1}$	2.6
B	$\boxed{0.076}$	0.28

possible ↗ (?)

Kimura, et al+18, PRD 98:043029

Thanks!

Evolving Fireball Paradigm

Internal Shocks Redux: modified internal shocks

(address/mitigate or even solve IS problems)

Modifications currently of two main types:

- ***Magnetic dissipation*** in int.shock, R~ 10^{15} cm, allow GeV photons - but hard to calculate quantitatively details of reconnection, acceleration and spectrum, e.g. McKinney-Uzdensky '12, MN 419:573, Zhang & Yan '11, ApJ 726:90
- ***Hadronic internal shocks,*** protons are 1st order Fermi accelerated, and secondaries are subsequently re-accelerated by 2nd order Fermi ('slow heating"), e.g. Murase et al, 2012, ApJ 746:164 - more susceptible to quantitative analysis

Hadronic models: e.g. 080319B

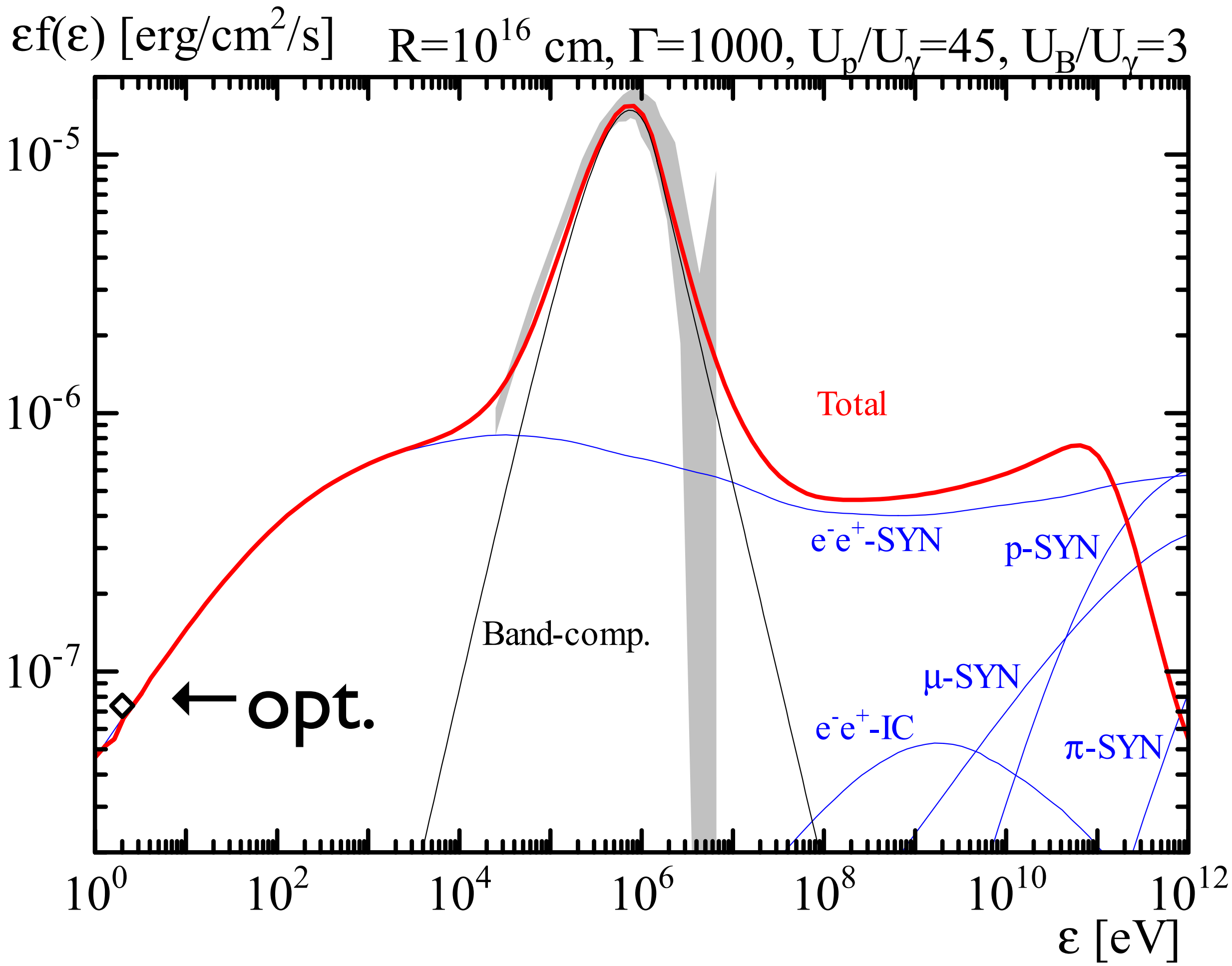


Fig. 2.— Model spectrum for parameters listed at the top as thick red curve compared with observations of GRB 080319B, for which the gray shaded area represents the spectrum measured between $T_0 + 12$ s and $T_0 + 22$s by Swift/BAT and Konus-Wind. The contemporaneous optical flux observed by "Pi of the Sky" is the black diamond. The best-fit Band component is shown separately as the thin black curve. Individual contributions of synchrotron and inverse Compton from secondary electron-positron pairs, as well as muon synchrotron and proton synchrotron are denoted by thin blue curves as labelled, not including the effects of $\gamma\gamma$ absorption or synchrotron self-absorption.

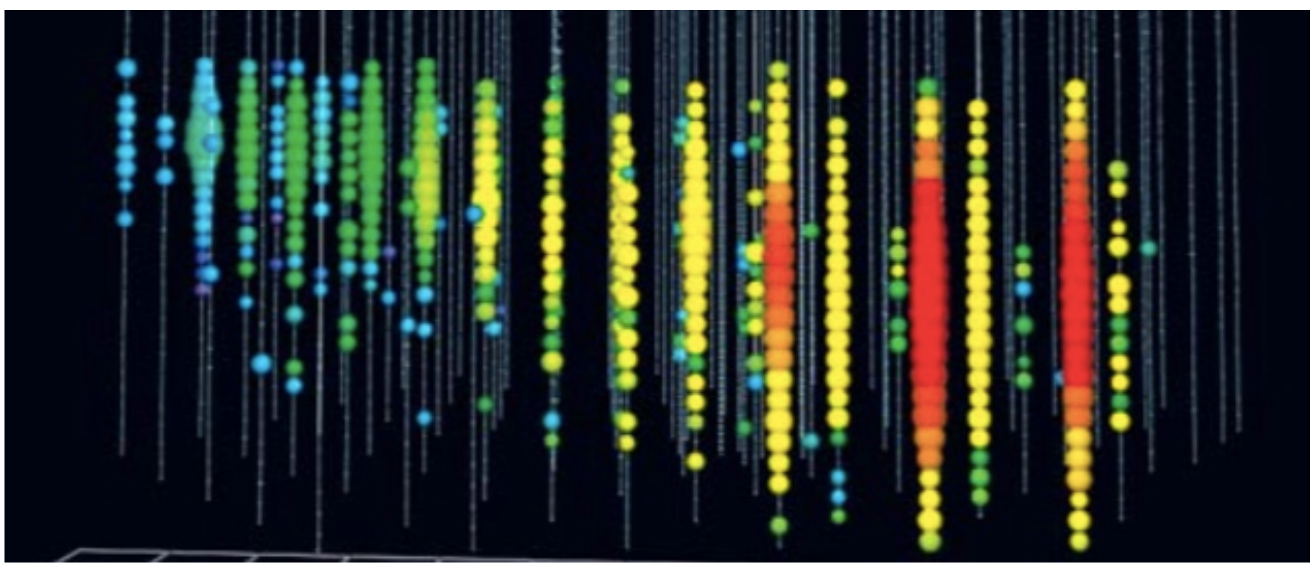
Retro-fit of "naked eye" burst

Asano, Inoue, Mészáros, 2010, ApJ, 725:L121

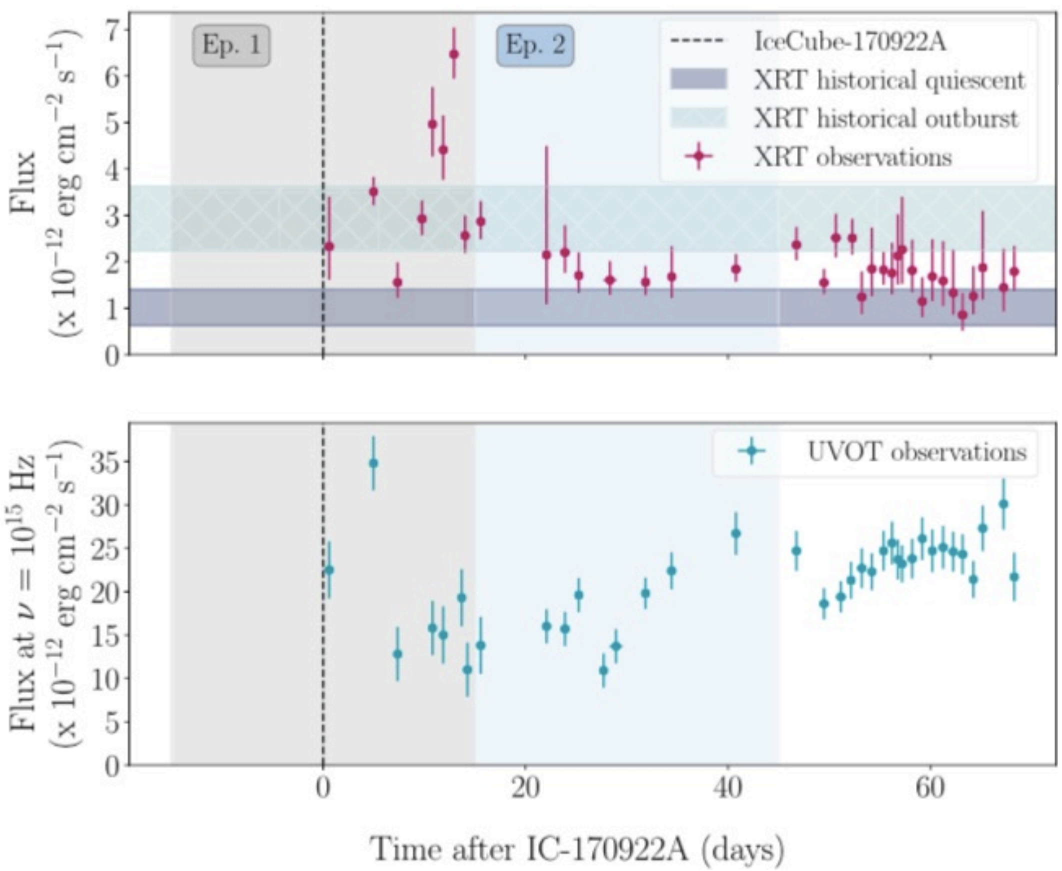
Of course, there is also

Blazar TXS 0506+056

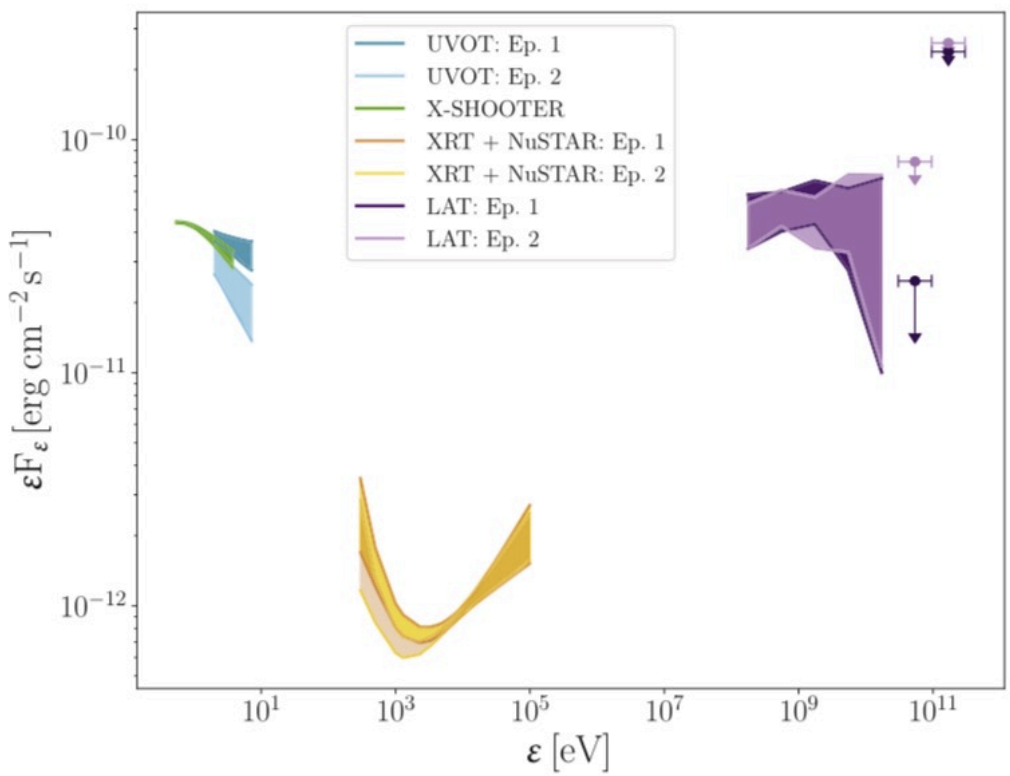
- IC3 detects an ap. 300 TeV ***EHE neutrino***
- Coincident at $\boldsymbol{3\sigma}$ level, blazar TXS 0506 is in γ***-flaring*** state (days, weeks), obs. by:
- Swift XRT/UVOT, Fermi, NuSTAR, MAGIC..



TXS 0506+056 obs.



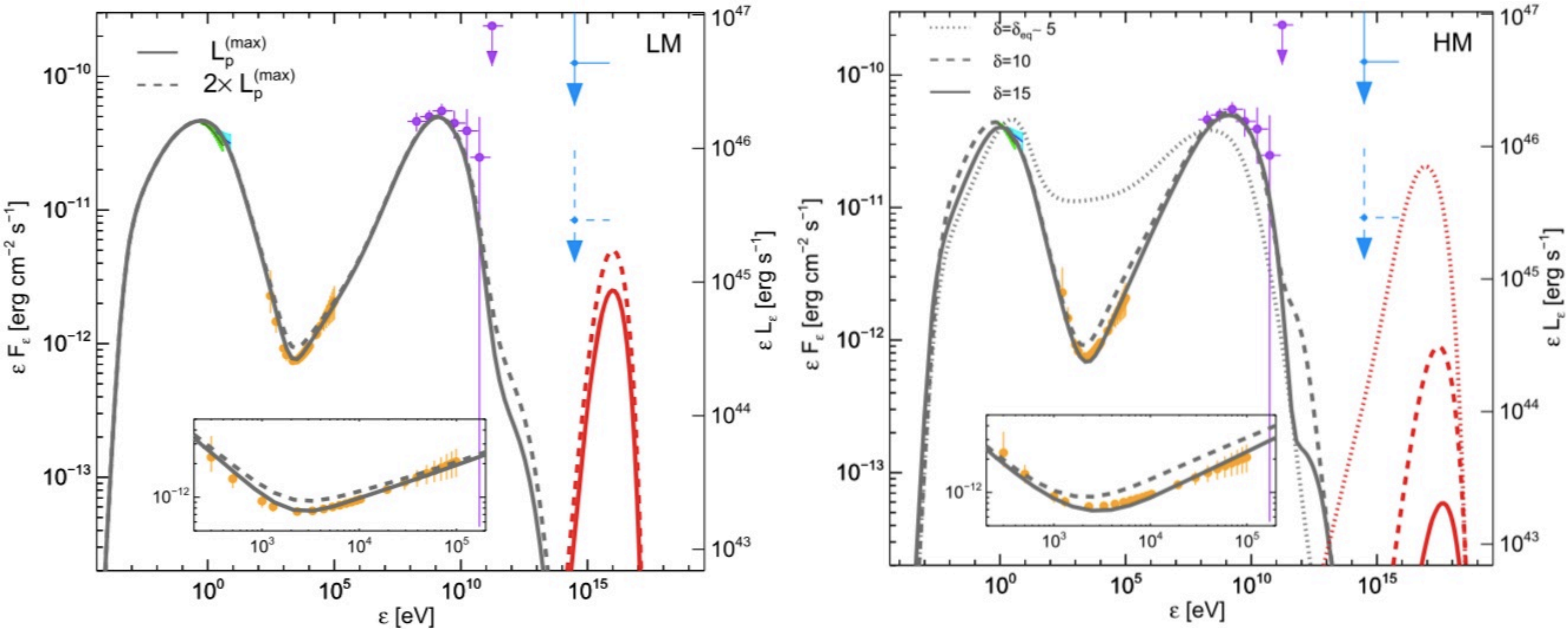
Swift XRT, UVOT



Swift + Fermi

Keivani+18, ApJ 864:84

TXS 0506 one-zone ν-γ models:

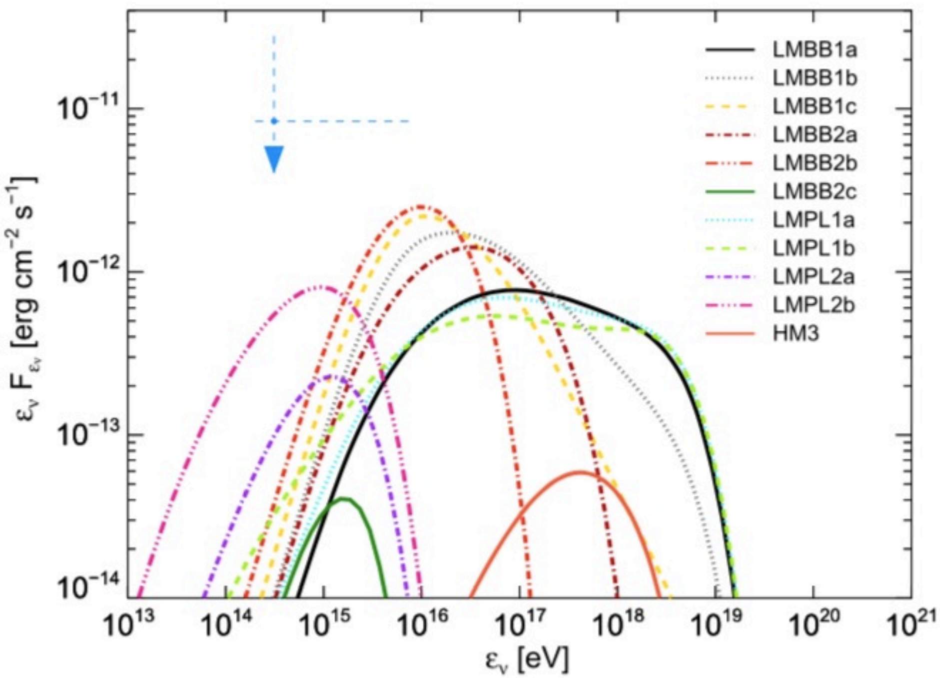


Lepto-hadronic model

Hadronic model

- Hadronic →EM cascades→ **XR**s which **fill in** the Sy and IC peak gap
- Pure hadronic one-zone model (for both ν and γ): can be **ruled out**
- Lepto-hadron. one-zone model: low by x2-3 ✔, **very constrained**

Keivani+18, ApJ 864:84



Keivani+18, ApJ 864:84

But: not as simple as one would have hoped:

TXS 0506 tentative bottom line:

- If 3σ flare coincidence is true, one-zone models severely constrained
- $E_\nu F_{E_\nu} \leq 3.6 \times 10^{-12}$ erg/cm2/s $\rightarrow$ Poisson prob.<1% one event in 6 mo.
- 2- or more zones explain it ✓(?), but w. extra uncertain parameters
- But such blazar flares may not account for >10%-30% of entire ν-bkg
- Also previous attempts at finding correlations via stacking have failed

At the very least, may need ***other sources***