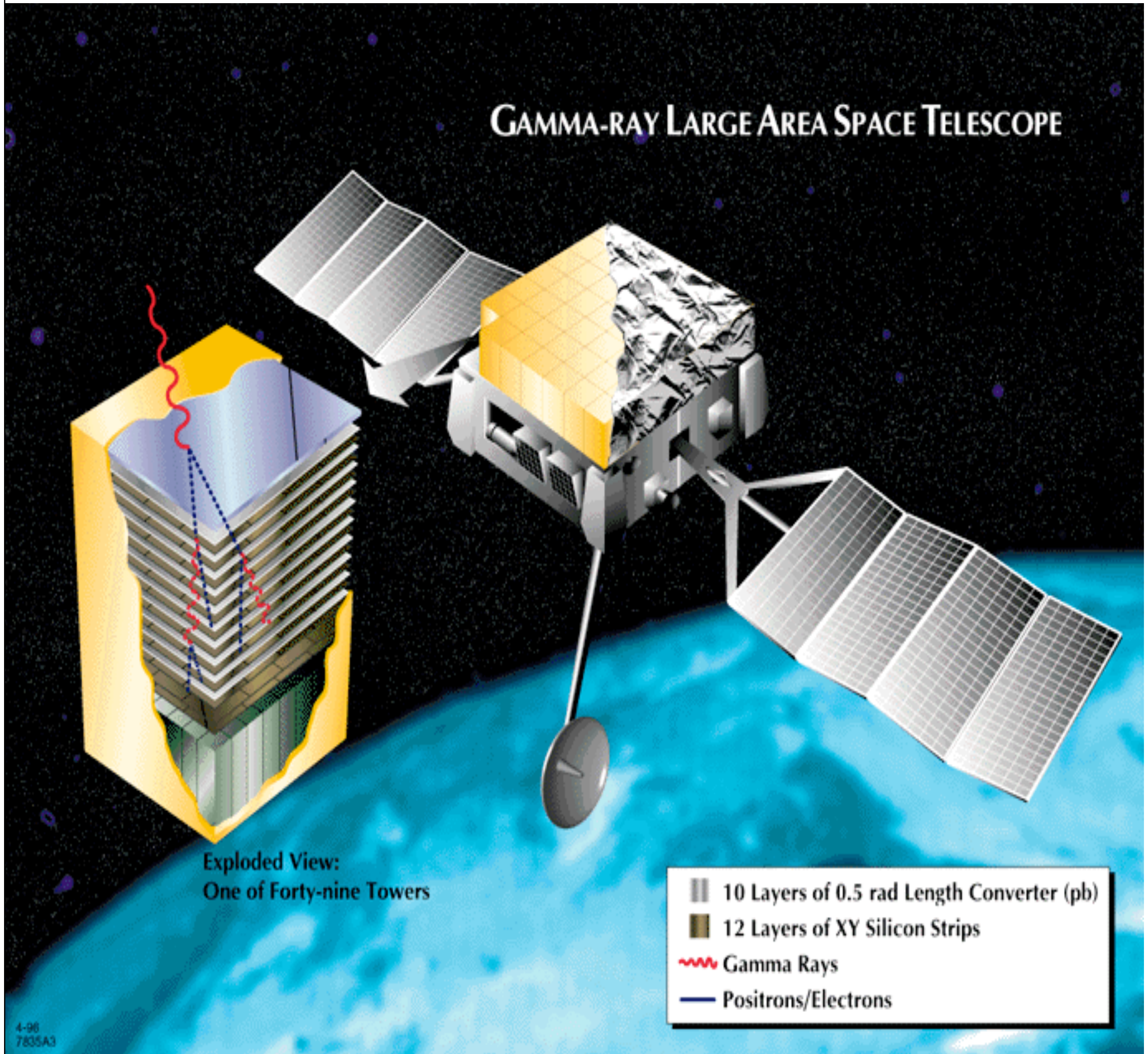
Gamma-Ray Bursts:

Recent results & connections to

VHE Cosmic Rays & Neutrinos

Peter Mészáros,
Pennsylvania State University

PASCOS, Merida, June 2012



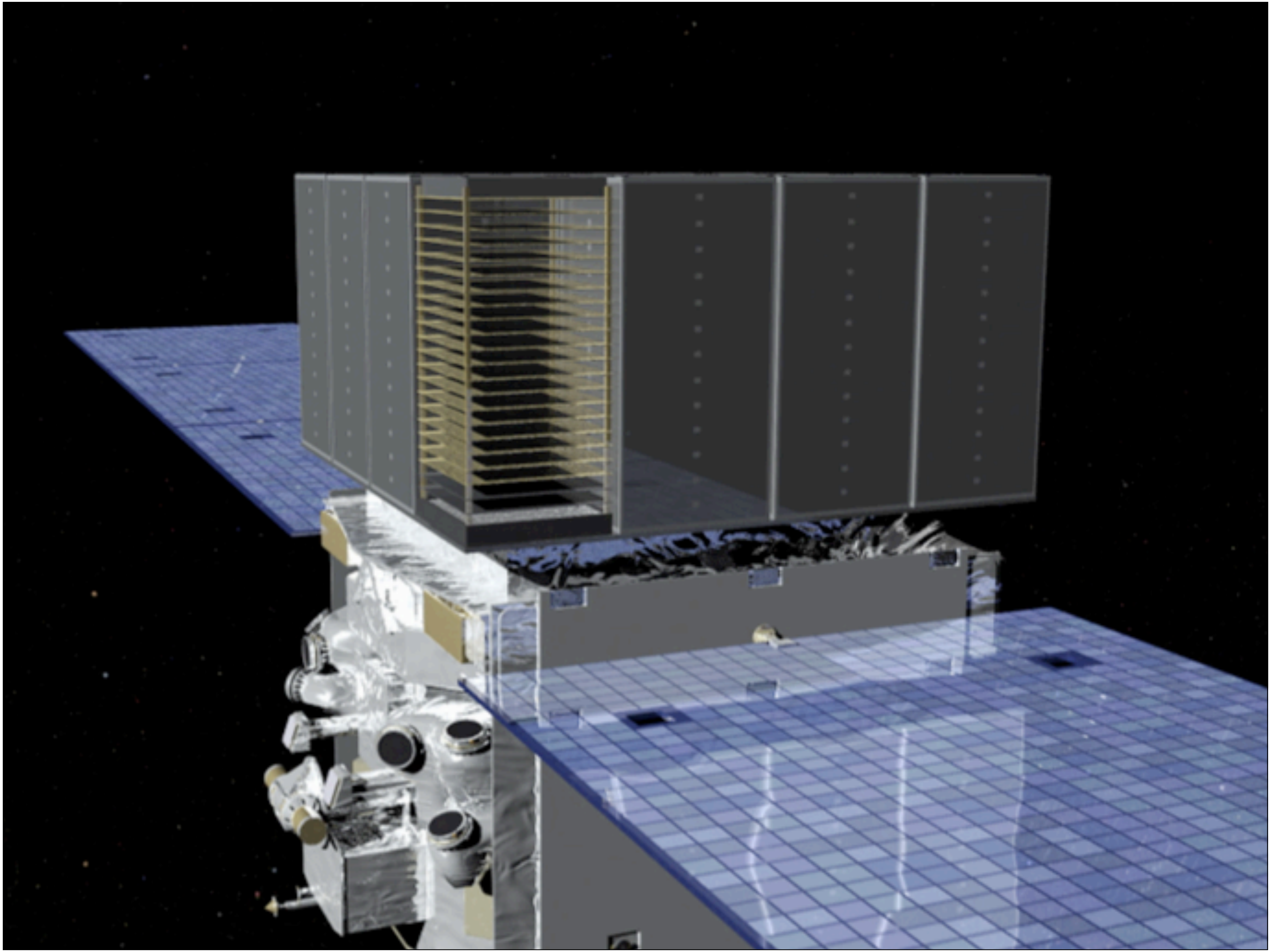
Wide FOV trigger : **GBM** (~BATSE range) ;
12 NaI: 10keV-3 MeV; 2 BGO: 150 keV-30 MeV

Fermi

- Launched June 11 2008
- **LAT**: Pair-conv.modules + calorimeter
- ***20 MeV-300 GeV,***

  $\Delta E/E \sim 10\%$@1 GeV
- FoV = 2.5 sr (2xEgret), ang.res. $\theta \sim 30''-5'$ (10GeV)
- Sensit. $\sim 2.10^{-9}$ph/cm^2/s

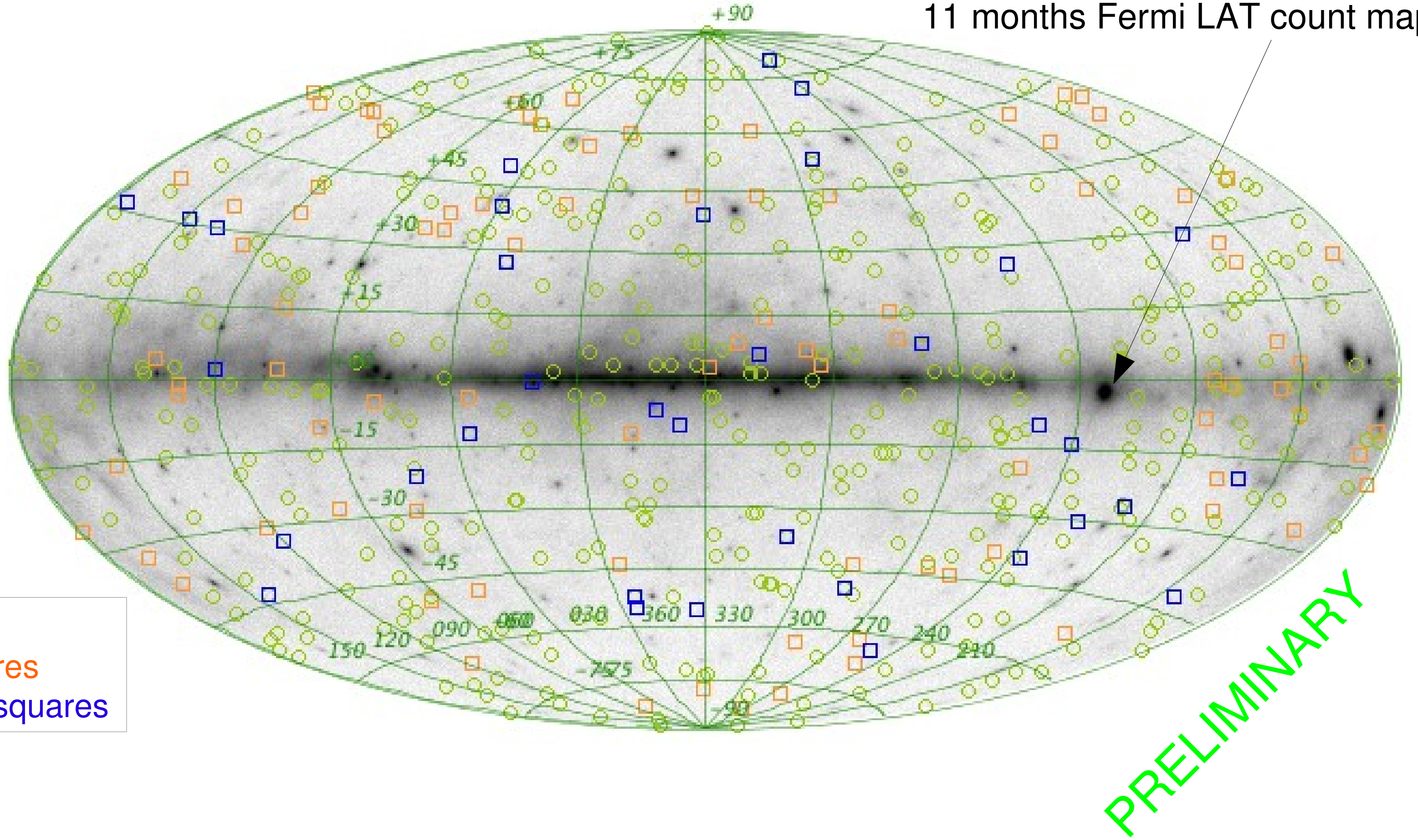
  (2 yr; > 50xEgret)
- **GBM:** NaI, BGO scintill.
- ***10 keV - 30 MeV***
- FoV= 4π , 2.5 ton , 518 W
- det ~300 GRB/yr (GBM); simult. w. Swift : 30/yr; LAT: ~1/month



Fermi GRB detection statistics

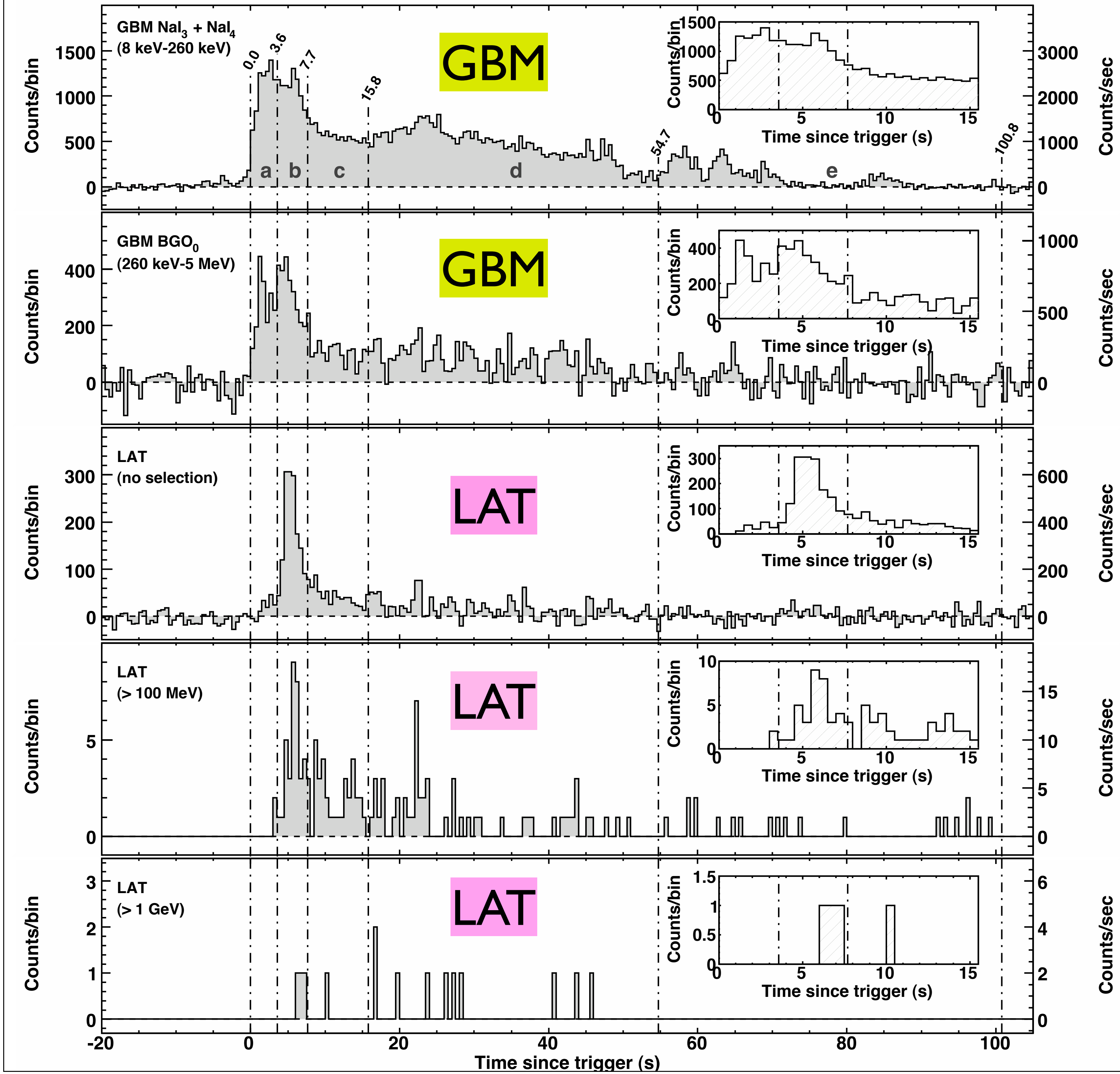
GBM 2-year catalog
LAT 3-year catalog

11 months Fermi LAT count map



GBM LGRB: green circles
GBM SGRB: orange squares
LAT detections (35): blue squares

- The GBM detects ~250 GRBs / year, ~half in the LAT FoV
- The LAT detected 35 GRBs in 3 years (30 long, 5 short), including 7 “LLE-only” GRBs
  - ~Half with more accurate follow-up localisations by Swift and ground-based observatories (GROND, Gemini-S, Gemini-N, VLT)
  - 9 redshift measurements, from z=0.74 (GRB 090328) to z=4.35 (GRB 080916C)



GRB 080916c

Light-curve E↓

Abdo, A. and Fermi coll., 09, Sci. 323:1688

Note :

GeV photons ←"lag" behind MeV!

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Fermi is able to say *something* about ***Quantum Gravity (or LIV)***

(regardless of additional astrophysical effects!)

- 'Effective theory' formulation (i.e. low energy series expansion approximation) of presumed full theory suggests an energy-dependent dispersion of boson and fermion signals
- Can visualize as space-time fluctuations inducing an energy dependent refractive index, → wave dispersion : $v_{ph}(E) \neq c$

$$c^2 p_{ph}^2 = E_{ph}^2 \left[1 + \frac{E_{ph}}{M_{QG,1}c^2} + \left(\frac{E_{ph}}{M_{QG,2}c^2} \right)^2 + \ldots \right] \quad , \quad v_{ph} = \frac{\partial E_{ph}}{\partial p_{ph}} \approx c \left[1 - \frac{1+n}{2} \left(\frac{E_{ph}}{M_{QG,n}c^2} \right)^n \right]$$

$$\Rightarrow \quad \Delta t = \frac{(1+n)}{2H_0} \frac{E_h^n - E_l^n}{(M_{QG,n}c^2)^n} \int_0^z \frac{(1+z')^n}{\sqrt{\Omega_m (1+z')^3 + \Omega_\Lambda}} dz'$$

~

QG-LIV limits from GRB

from Fermi/LAT/GRB obs.

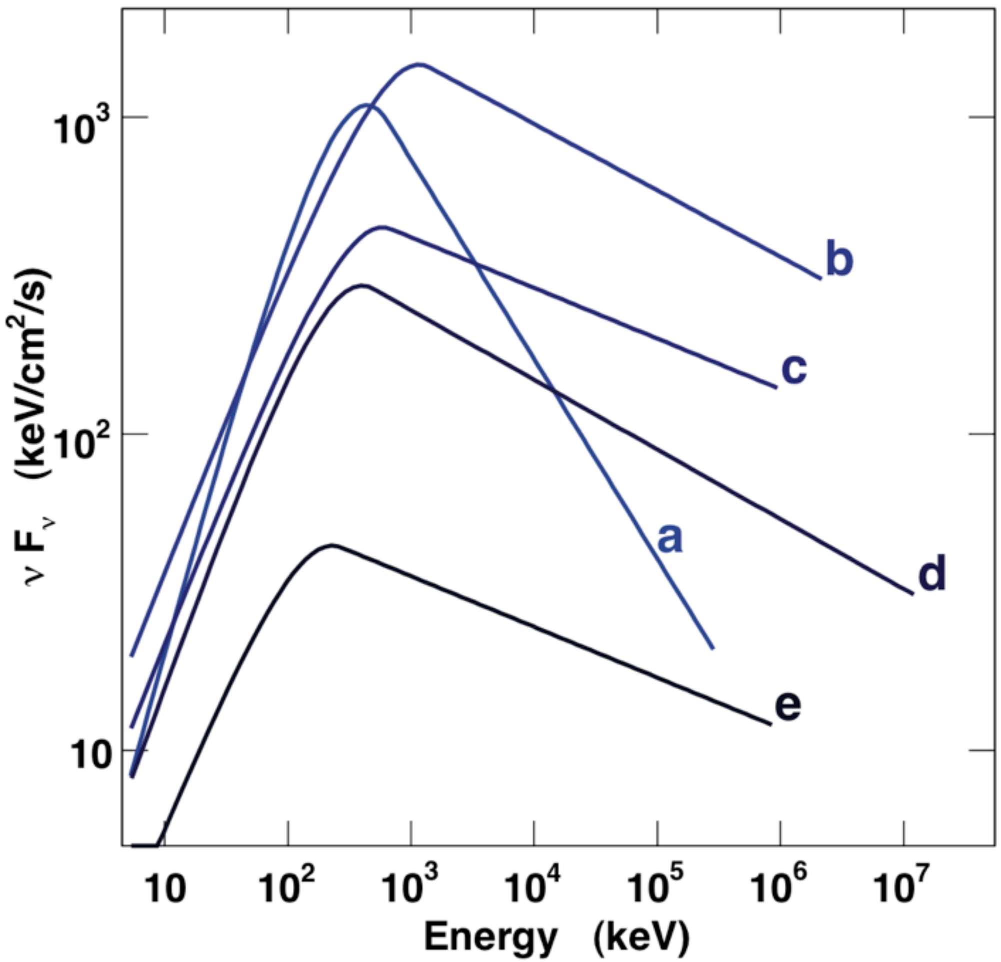
- ***GRB 080916C*** (long burst - E_{ph} >10 GeV)
  → conservative lower limit for
  $M_{QG}(n=1) \geq$ ***(1.50 ±0.20)x10¹⁸ GeV/c²***
- ***GRB 090510*** (short burst- E_{ph} >31 GeV)
  →conservative lower limit for
  $M_{QG}(n=1) \geq$ ***few x10¹⁹ GeV/c² ~ M_Planck***

→ can rule out n=1 term!

Sci. 323:1688 (2009) ; Nat. 462:331 (2009)

GRB 080916C

Spectrum : up to ~***10 GeV*** (obs.)



- "***Band***" (broken power-law) fits, joint GBM/LAT, in ***all*** time intervals
- "Soft-to-hard" spectral time evolution
- ***Long***-lived (10^3 s) GeV afterglow
- ***No*** evidence for ***2nd*** spectr. comp. (in ***some*** cases)

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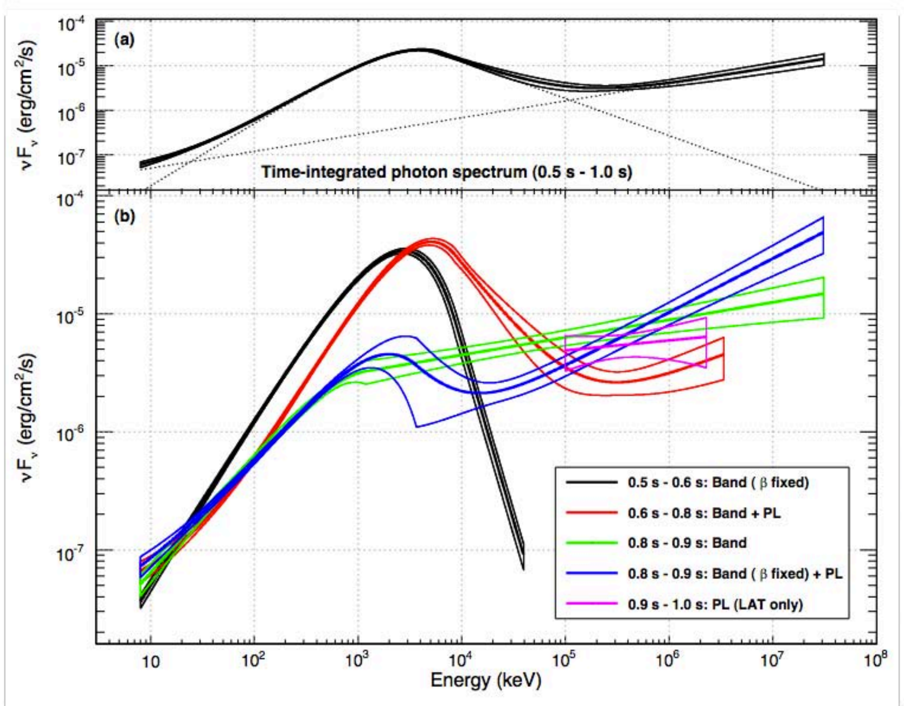
But: *in other bursts,*

Evidence of the "extra components" (in some cases)

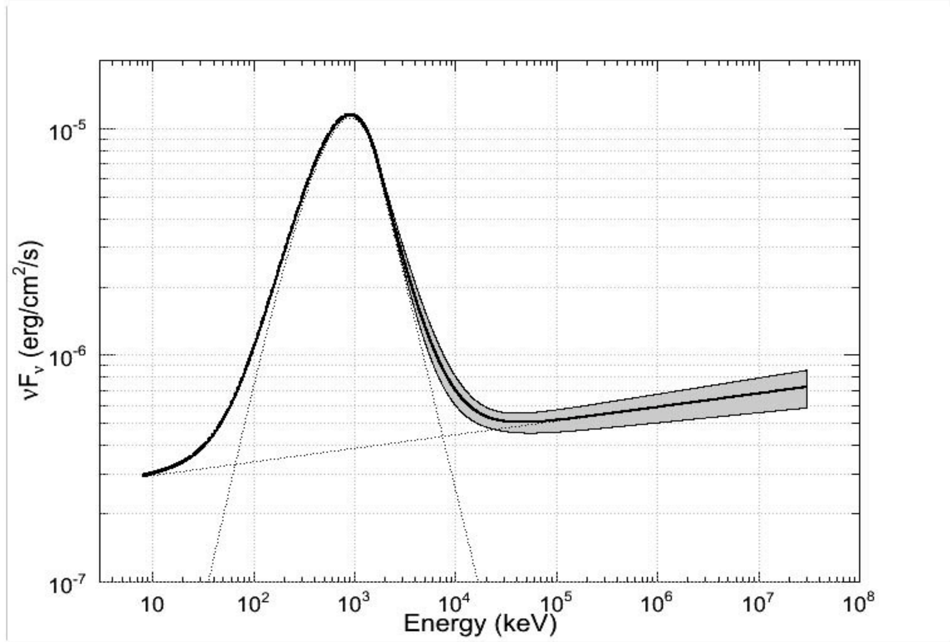
Fermi Gamma-ray Space Telescope

GRB 090510
Ackermann, et al. 2010, ApJ, 716, 1178



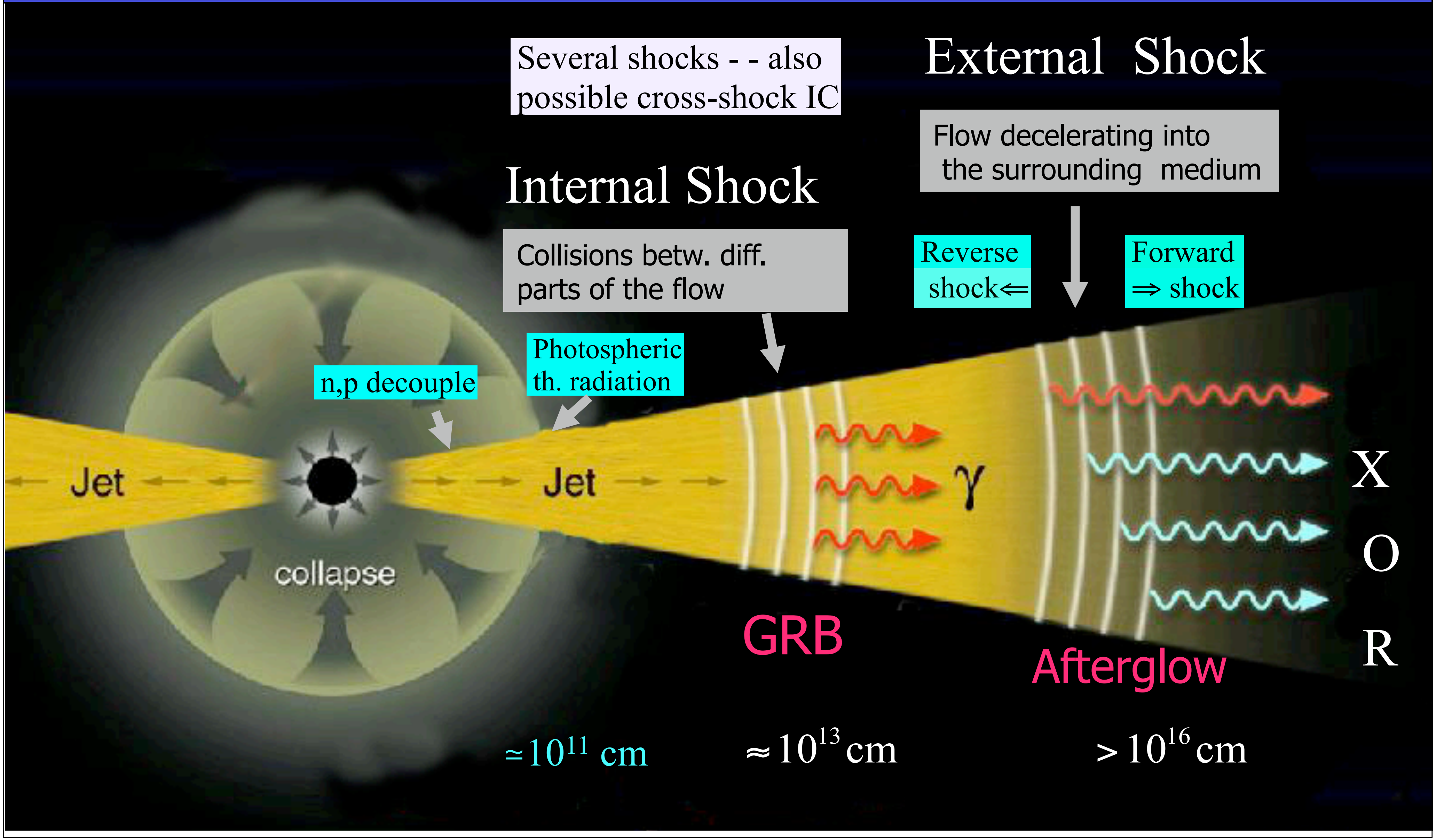
Joint spectral fit (of binned data) :
GBM<40MeV
standard LAT data>100MeV

GRB 090902B
Abdo et al. 2009,ApJ, 706L, 138A

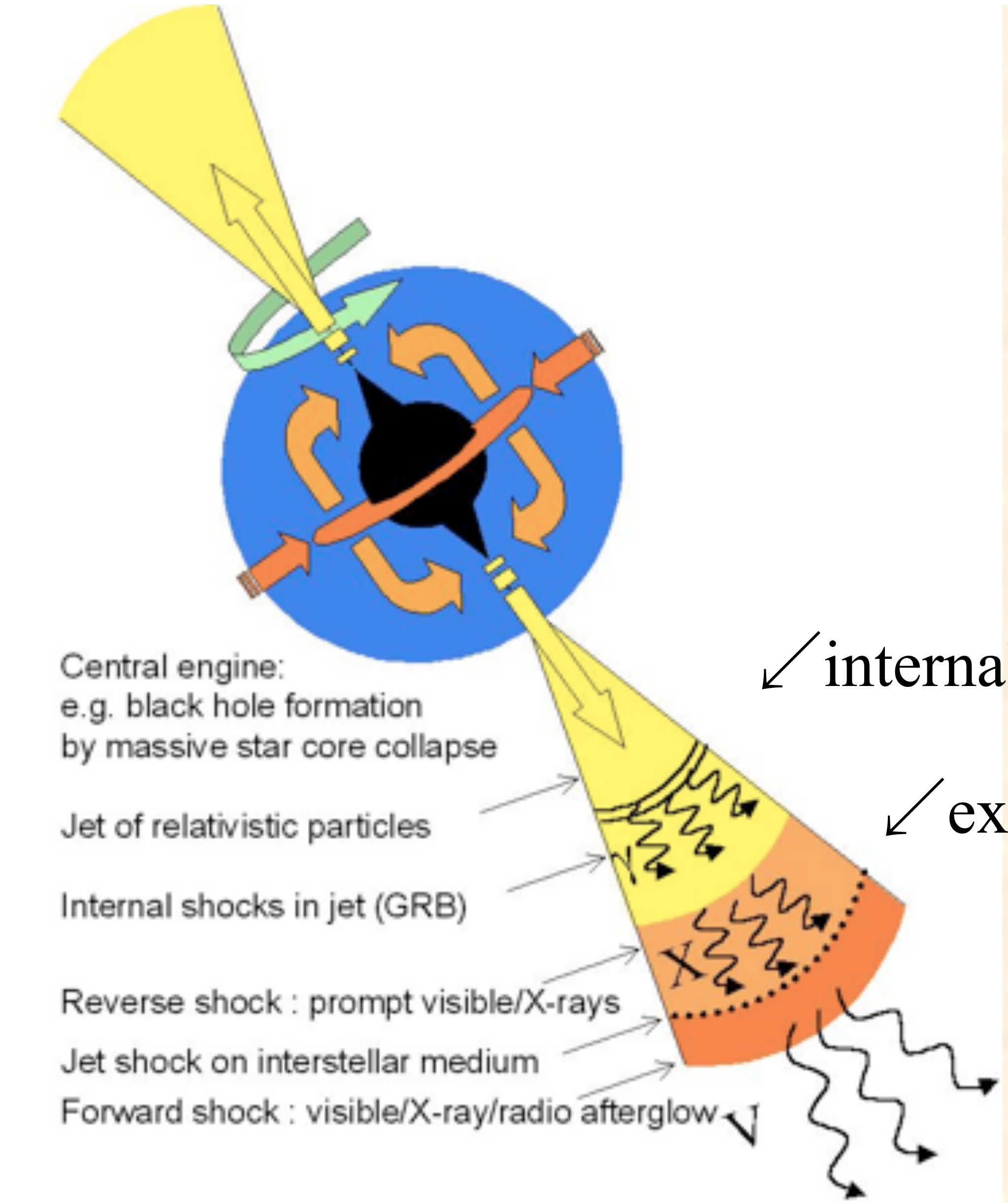


- Constrains main keV-MeV component
- Spectral evolution during prompt phase
- **Additional PL component seen at high and low energies**

Fireball *Shock* Model of GRBs



Jets in GRBs → int. & ext. shocks



↙internal shocks

↙external shock

Int. & ext. shocks,
accelerate electrons
e,B →γ (***leptonic***);
and

accel. protons too (?)
pγ→ν, γ (***hadronic***)

Internal & external shocks:

- Note: they are *Collisionless* shocks (rarefied gas)
- (1) *"Internal"* shock waves: due to modulated outflow; two gas shells ejected with bulk Lorentz factor differences $\Delta\Gamma = \Gamma_1 - \Gamma_2 \sim \Gamma$, starting at time intervals $\Delta t \sim t_v$ collide at r_{is} ,

$$r_{is} \sim 2\, c\, \Delta t\, \Gamma^2 \sim 2\, c\, t_v\, \Gamma^2 \sim 10^{12}\, t_{-3}\, \Gamma_2^{\,2}\ \mathrm{cm}$$

(internal shock)

- (2) *"External"* shock: merged ejected shells coast out to r_{es}, where they have swept up enough enough external matter to slow down: $E \sim (4\pi/3)\, r^3\, n_{ext}\, m_p\, c^2\, \Gamma^2$, forms at:

$$r_{es} \sim (3E/4\pi n_{ext} m_p c^2)^{1/3}\, \Gamma^{-2/3} \sim 3.10^{16} (E_{51}/n_O)^{1/3}\, \Gamma_2^{-2/3}\ \mathrm{cm}$$

(external shock)

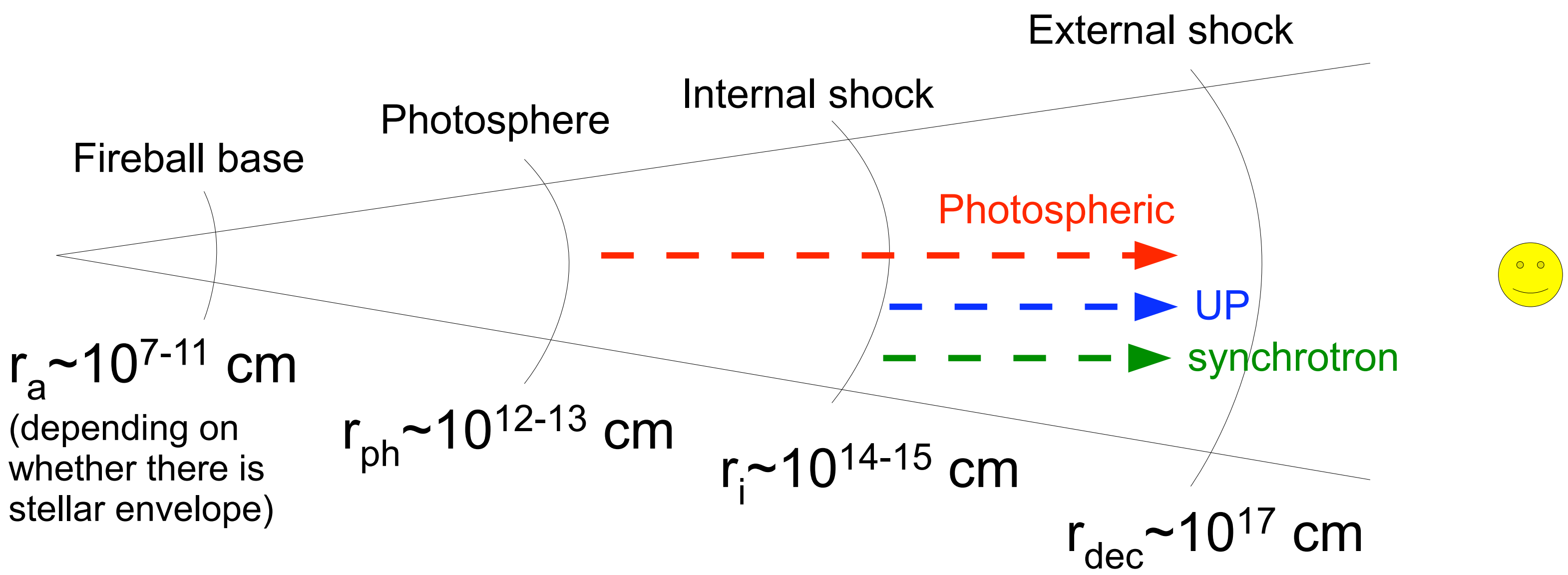
Theoretical Issues:

- Is single component spectrum at GeV due to ***internal*** or ***external*** shocks - or ***other***?
- Are photons of purely ***leptonic*** or ***hadronic*** origin, or mixed?
- Besides delay providing QG upper limits (based on zero intra-source GeV-MeV delay): what are the ***astrophysical*** causes of delay?
- Is ***2nd*** component a ≠ rad.mech. from ***1st***? are we forced beyond one-zone models?

A "leptonic" model:

Toma, Wu, Mészáros, 2011, MN 415:1663

Photosphere and internal shock of the GRB jet

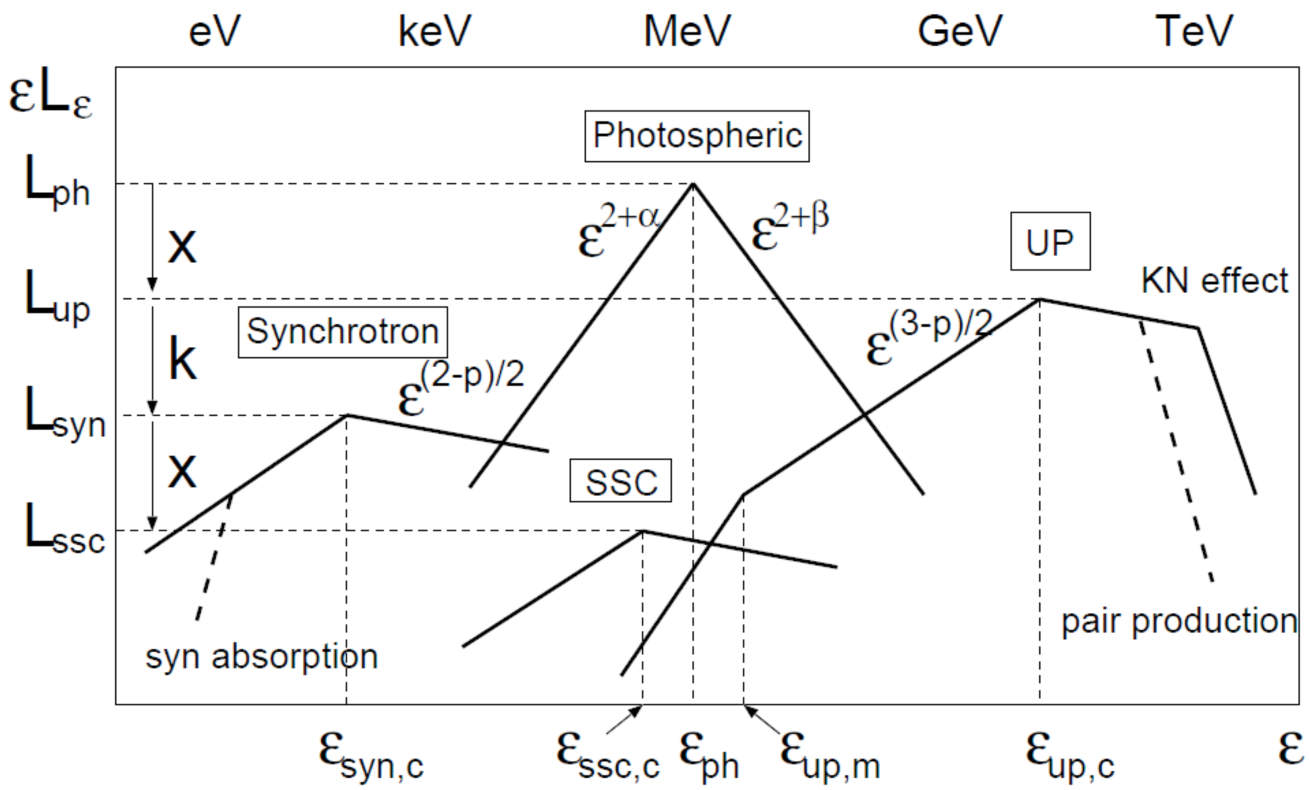


The photospheric emission can naturally provide a high γ-ray efficiency and the typical photon energy of the Band spectrum, ~ 1 MeV (Paczynski 86; Goodman 86).

The dissipation below the photosphere could cause the emission to be non-thermal (Meszaros & Rees 00; Rees & Meszaros 05; Pe'er et al. 05; Ioka et al. 07; Beloborodov 09)

We discuss the general properties of the photospheric emission and upscattered photospheric (UP) emission off the internal shock electrons.

Photosphere + Internal Shock model, cont.



$$x \simeq \frac{\epsilon_d \epsilon_e}{(\eta/\eta_*)^{8/3}} \left(\frac{\gamma_c}{\gamma_m}\right)^{2-p}.$$

$$k \equiv \frac{L_{\rm syn}}{L_{\rm up}} = \frac{U'_B}{U'_{\rm ph}} = \frac{\epsilon_d \epsilon_B}{(\eta/\eta_*)^{8/3}},$$

$$L_{\rm up} = L \epsilon_d \epsilon_e \left(\frac{\gamma_c}{\gamma_m}\right)^{2-p}$$

$$\varepsilon_{{\rm up},c} = \varepsilon_{\rm ph} \gamma_c^2$$

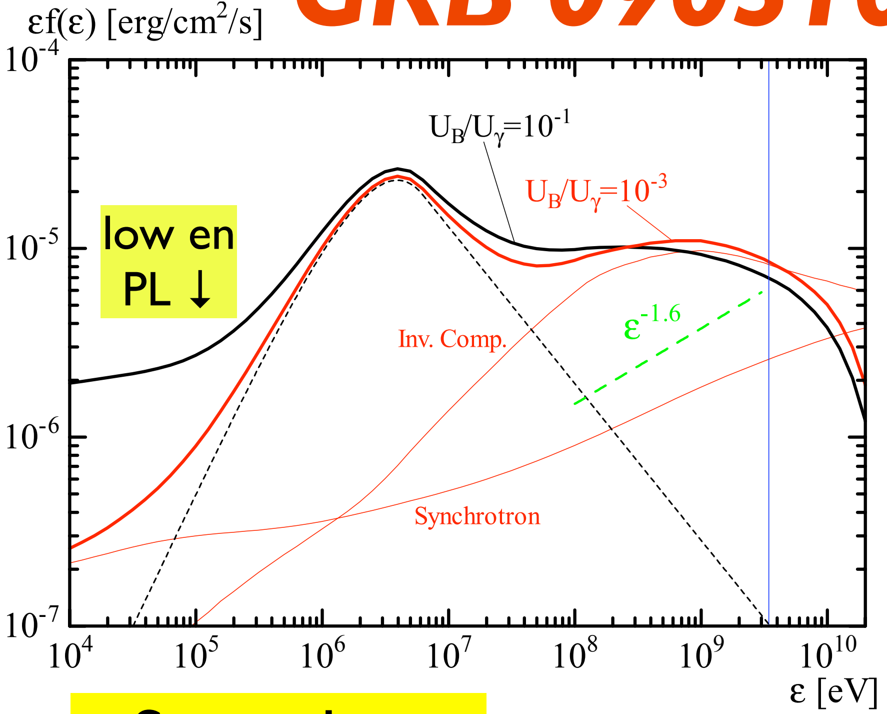
Generic shape comparable to Fermi observations ✔

but, alternatively:

Hadronic model of extra comp:

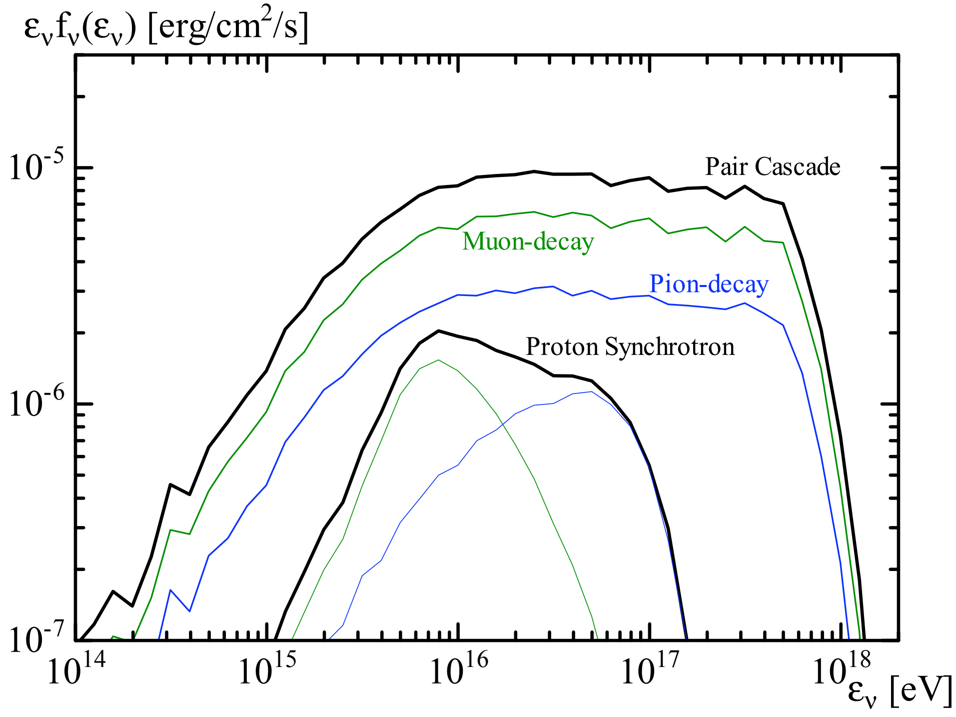
GRB 090510

Asano, Guierec, Mészáros, 09
ApJL, 705:L191



Secondaries from photomeson cascades ✔

(but: need $L_{p,iso}$~10^{55} erg/s !)



Secondary photons ↑

Secondary neutrinos →

(not detectable for this burst)

Generic photon spectrum: comparable to Fermi observations: ✔

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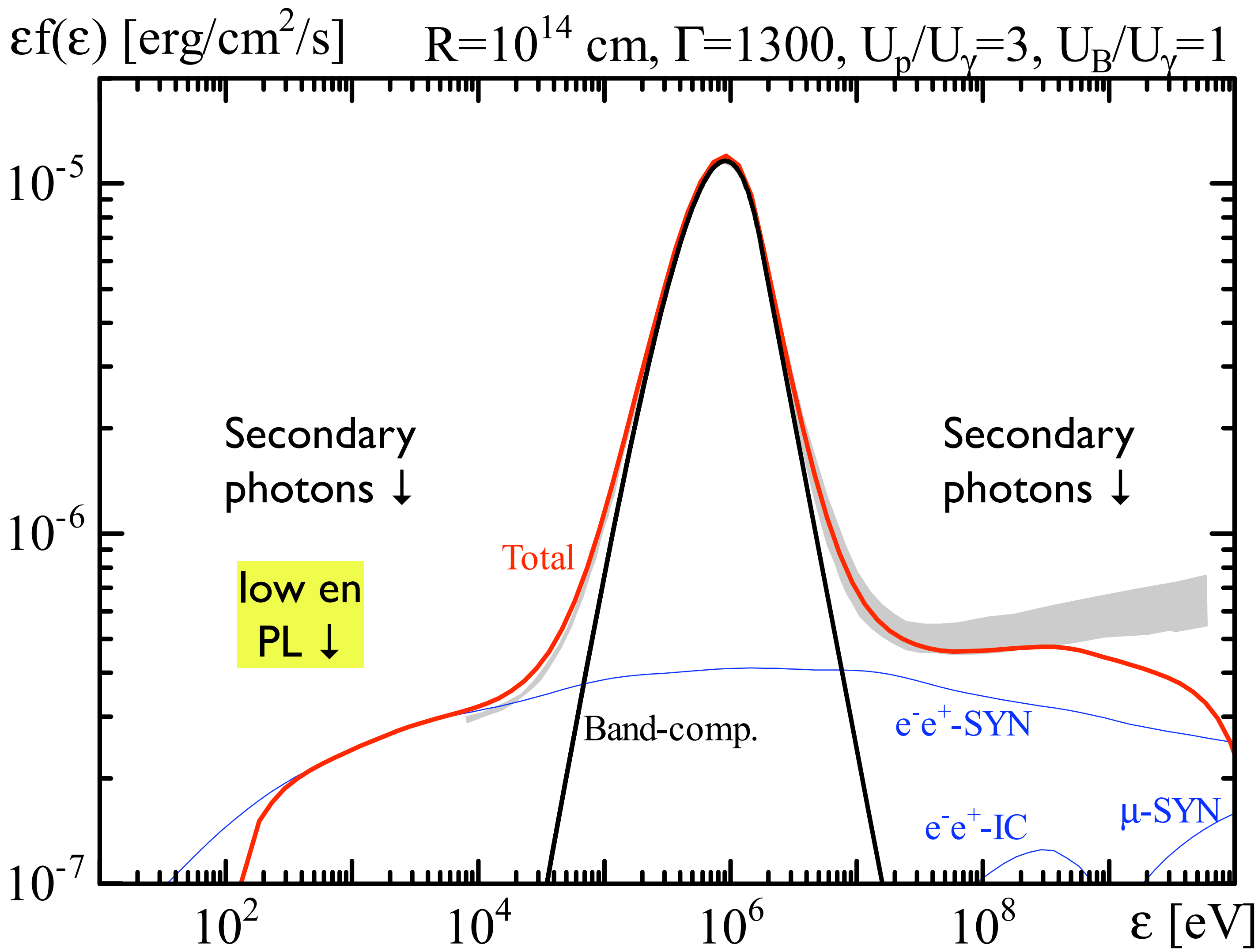
Hadronic model: 090902B



Also explain presence of low energy power law spectral component

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

Can make *(retro)prediction:*

Hadronic retro-model: ***080319B***

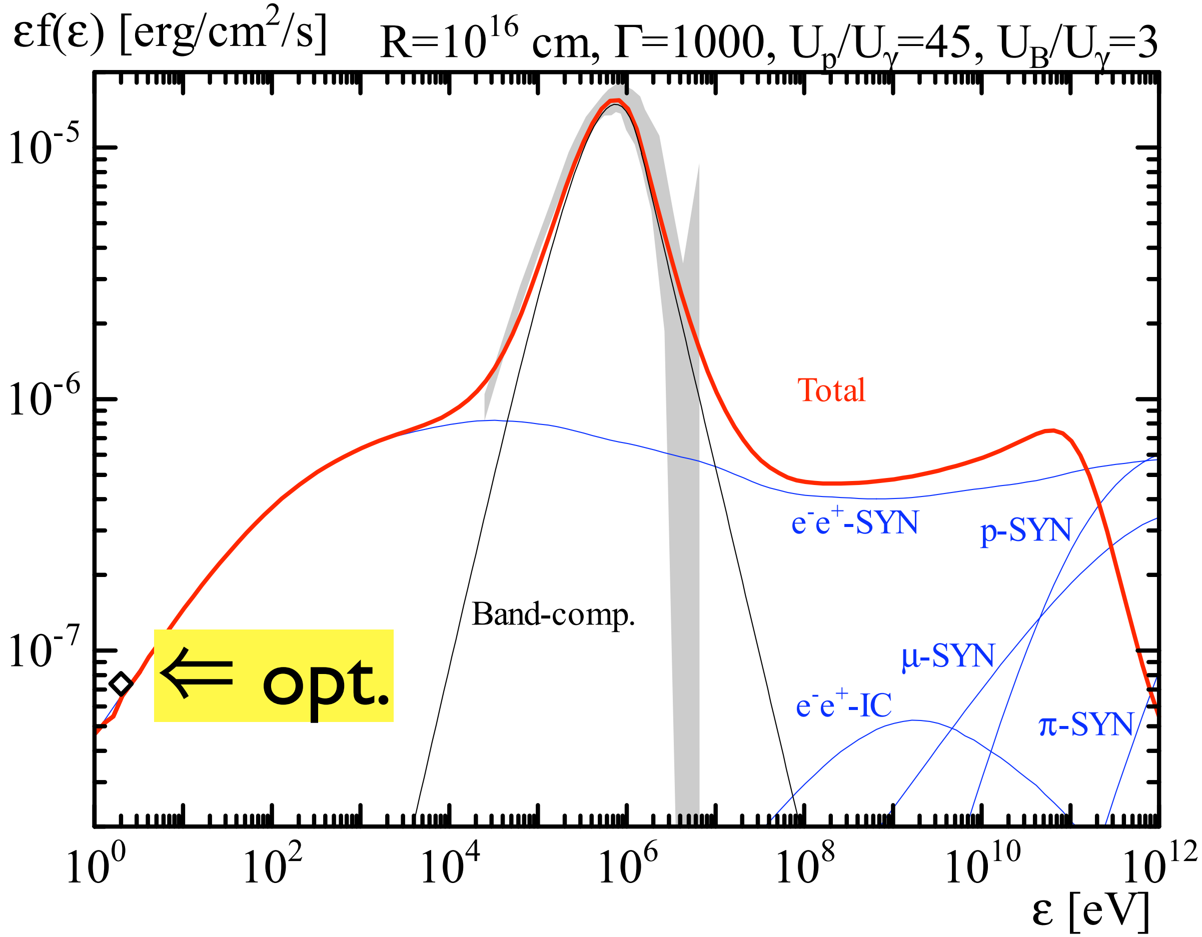


Fig. 2.— Model spectrum for parameters listed at the top as thick red curve compared with observations of GRB 080319B, for which the gray shaded area represents the spectrum measured between T_0+12 s and T_0+22s by Swift/BAT and Konus-Wind. The contemporaneous optical flux observed by "Pi of the Sky" 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.

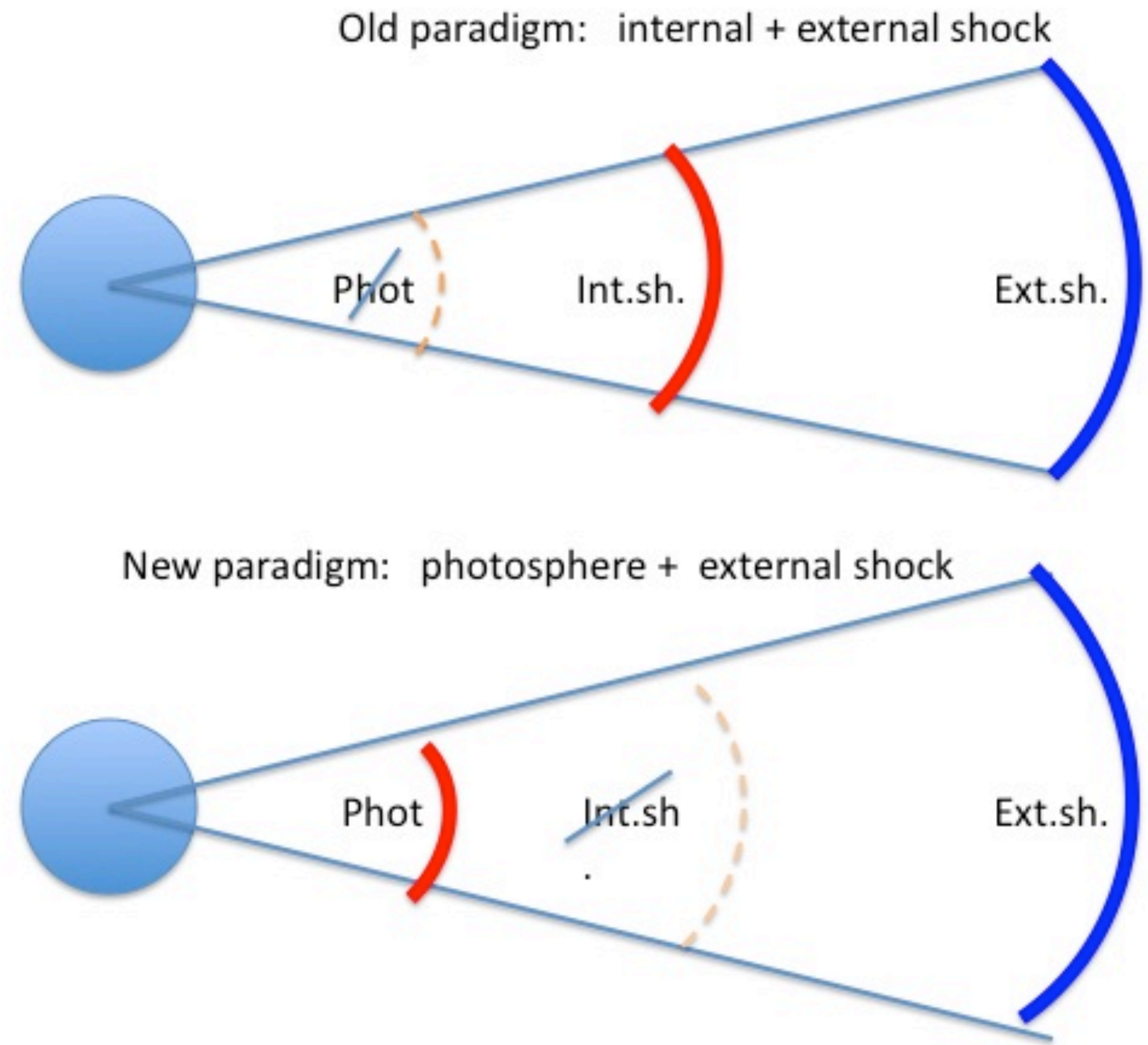
This is how the ***"naked-eye "*** burst ***might*** have looked, had Fermi been looking: could explain prompt ***5th mag.*** optical flash seen by the Pi-in-the-Sky!

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

But

- Why sometimes a single broken PL peaking at MeV, which ***does not*** show up at GeV?
- Why sometimes a single broken PL peaking at MeV ***and*** extending into GeV?
- Why other times one broken PL peaking at MeV, plus a ***second, much harder*** component, extending into GeV?

Fireball paradigms:



$\lesssim$ 2005

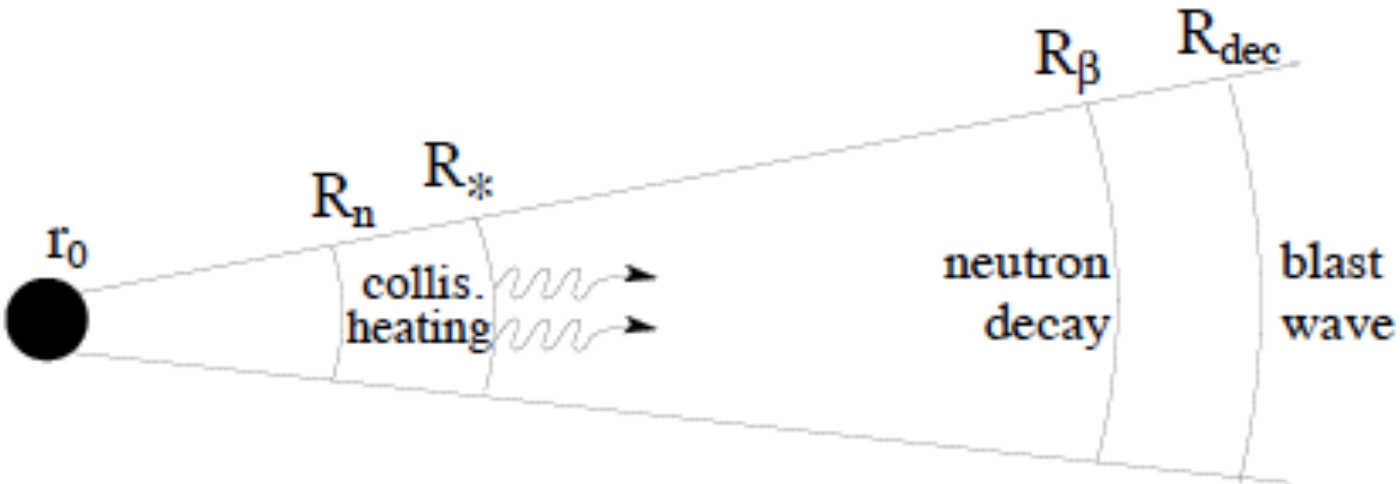
$\gtrsim$2005

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. + external shock*** (weak int.sh.)
- Photosphere: if dissipative, **good** *rad. efficiency*
- (Internal shock: if magnetic, may be absent)
- External shock: most of GeV and soft afterglow

A hadronic “thermal” MeV broken PL spectrum?

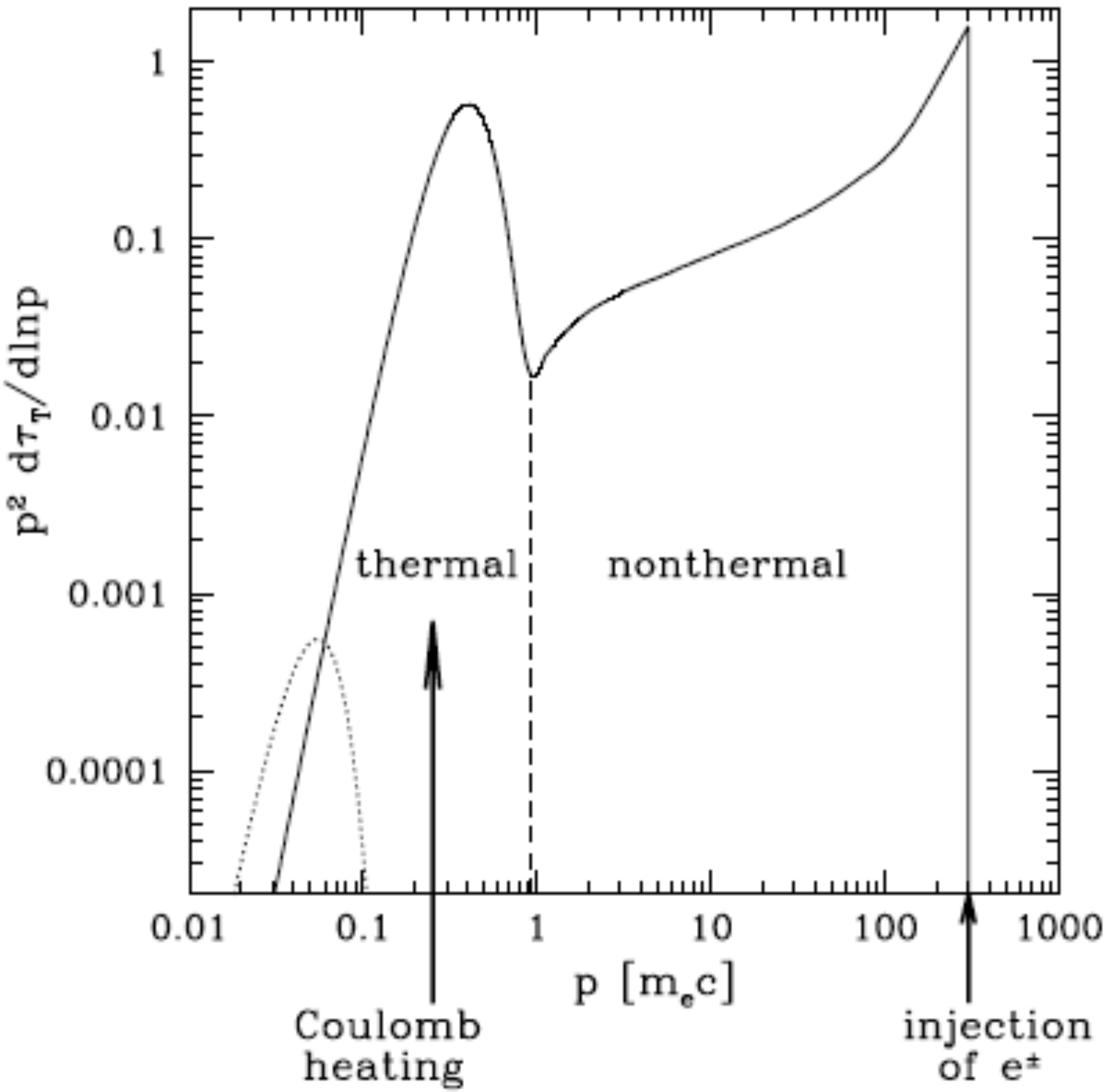
p-n collisional dissipation



Beloborodov, ’10, MN 407:1033

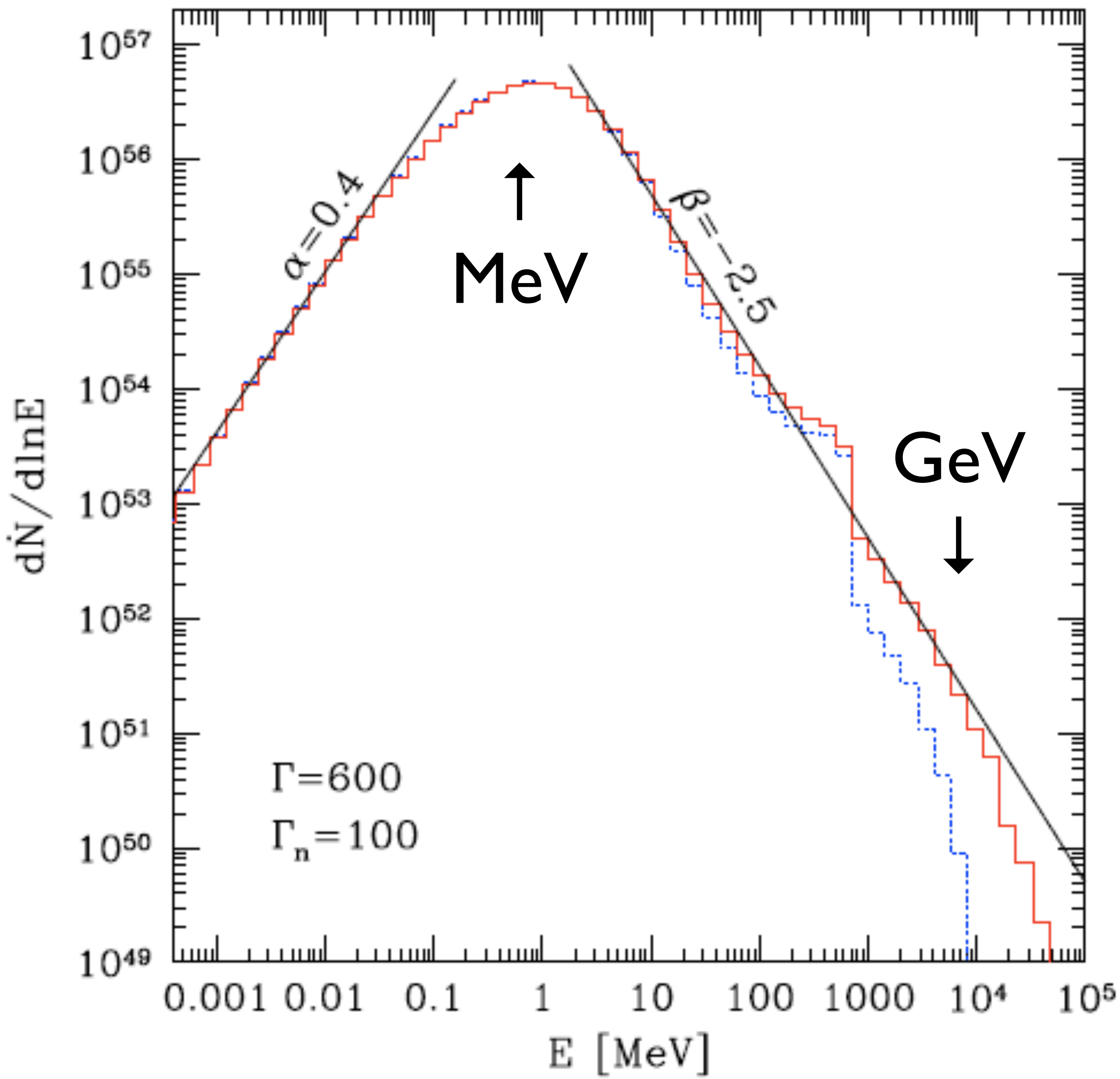
- Long history: Derishev-Kocharovsky 89, Bahcall-Meszaros 00, Rossi et al 04, etc
- Either p-n decoupling or internal colls. → relative p-n streaming, inelastic colls.
- Highly effective dissipation (involves baryons directly)- can get >50% efficiency
- Sub-photospheric dissipation can give strong photospheric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

p-n coll. → $e^{\pm}$ p-distr.



- n-p collision lead to $\pi^{\pm}$, π^0, leading to $e^{\pm}$ and γs
- The $e^{\pm}$ and γs quickly thermalize to produce an observer frame photospheric peak at ~ 0.2-0.5 MeV
- Some of the $e^{\pm}$ are Coulomb heated by protons into a higher energy non-thermal distribution

p-n coll. →e± → γ-spectrum



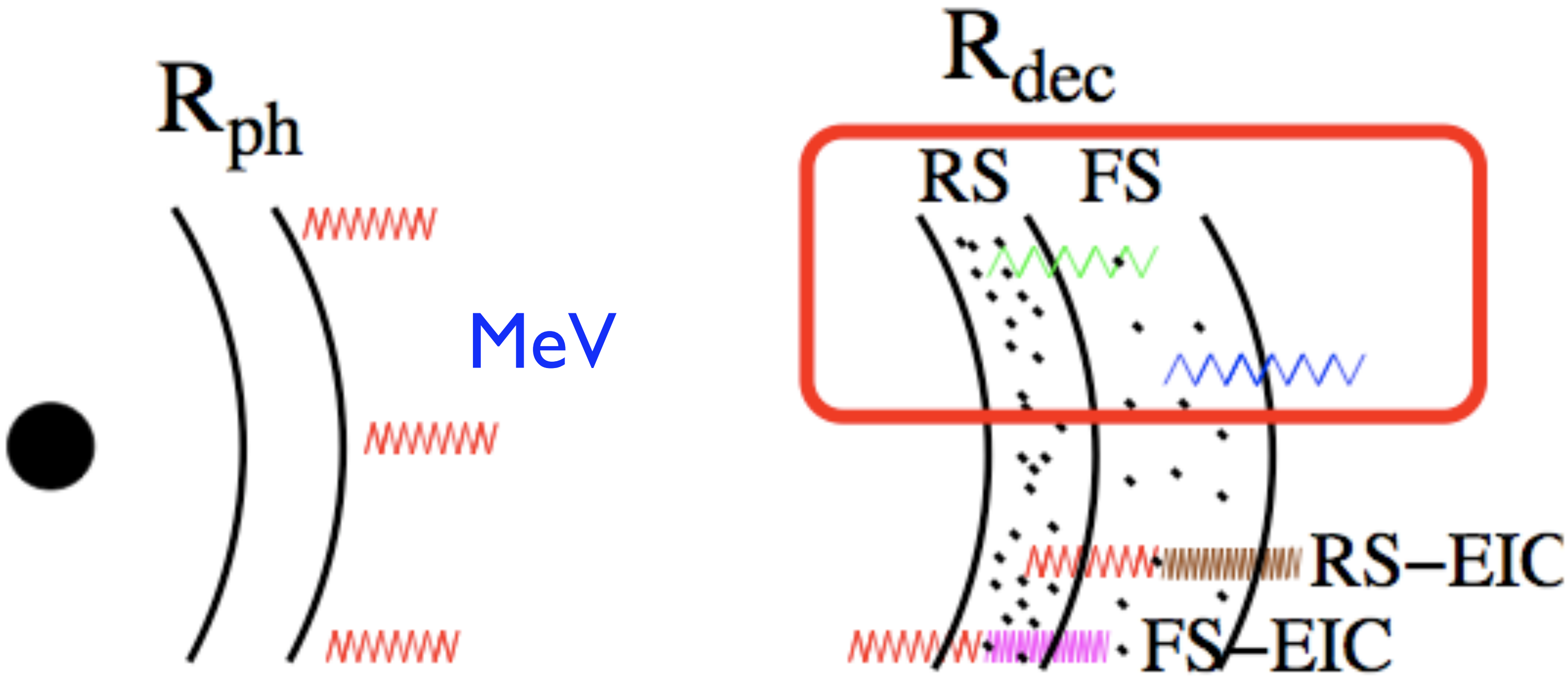
- The result is a thermal peak at the ~MeV Band peak, plus
- a high energy tail due to the non-thermal $e^{\pm}$, whose slope is comparable to that of the observed Fermi bursts with a "single Band" spectrum
- The "second" higher energy component (when observed) must be explained with something else

Magnetic-dominated GRB jets

- Dynamics of expansion $\Gamma \sim r^{1/3} \rightarrow \Gamma \sim$ const
- Dissipative (mag.) scattering photosphere → results in broken PL MeV spectrum
- No internal shocks expected
- Magnetiz. param. σ drops to ~ o(1) at r_{decel}
- External shock present (forward; +reverse?) →both shocks up-scatter photospheric MeV →to GeV -TeV range

Veres & Mészáros, ApJ in press, arXiv:1202.2821

Photosphere + external shock (leptonic) upscattering model

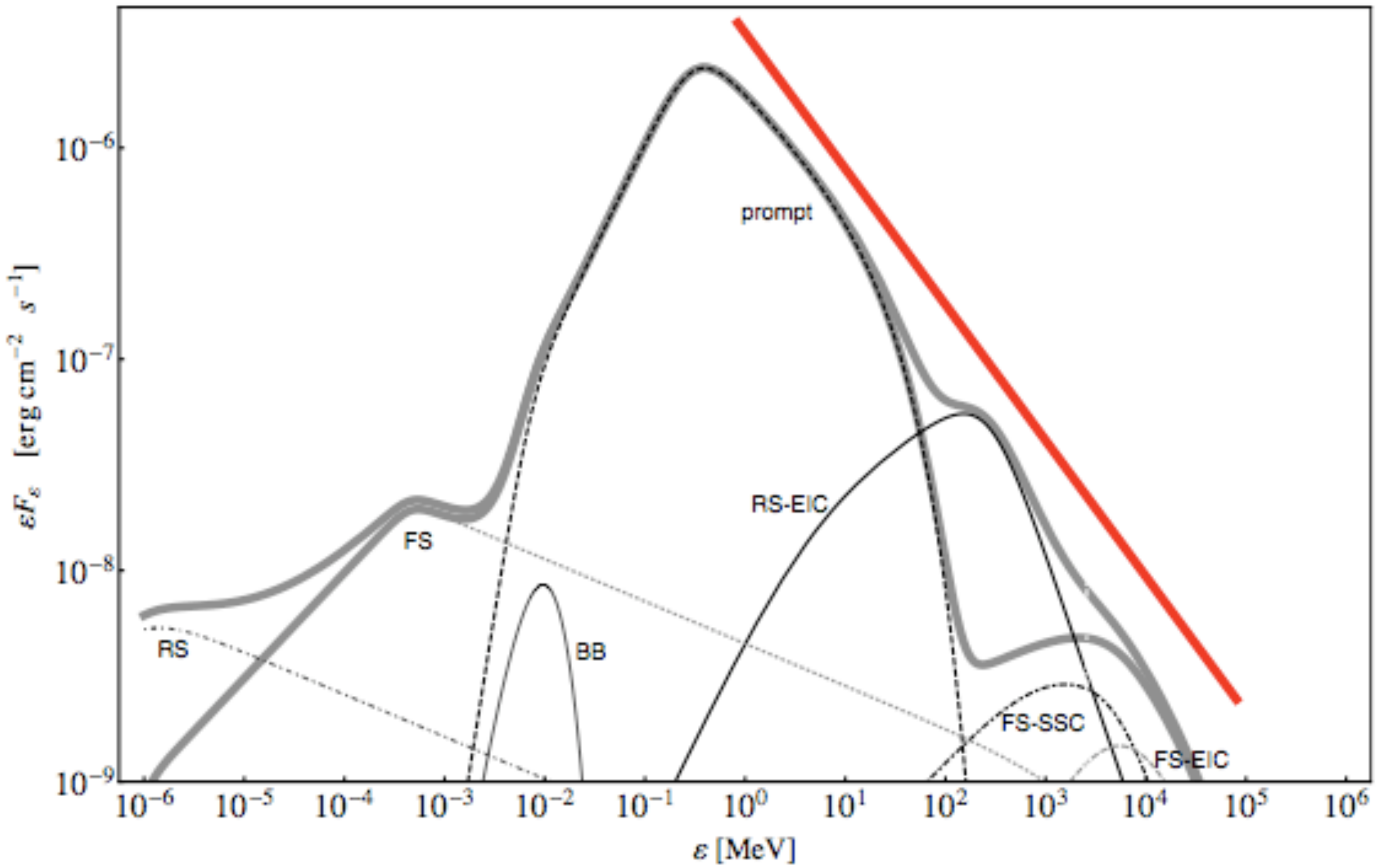


- Leptonic photosph. spectrum extend to $\Gamma_{ph}\, m_e$ ~50-100 MeV
- Ext. shock upscattering spectrum extend to $\Gamma_{es}\, \gamma_{e,KN}\, m_e \rightarrow$ TeV

Veres & Mészáros, arXiv:1202.2821

Ph+ES Single (Band) PL

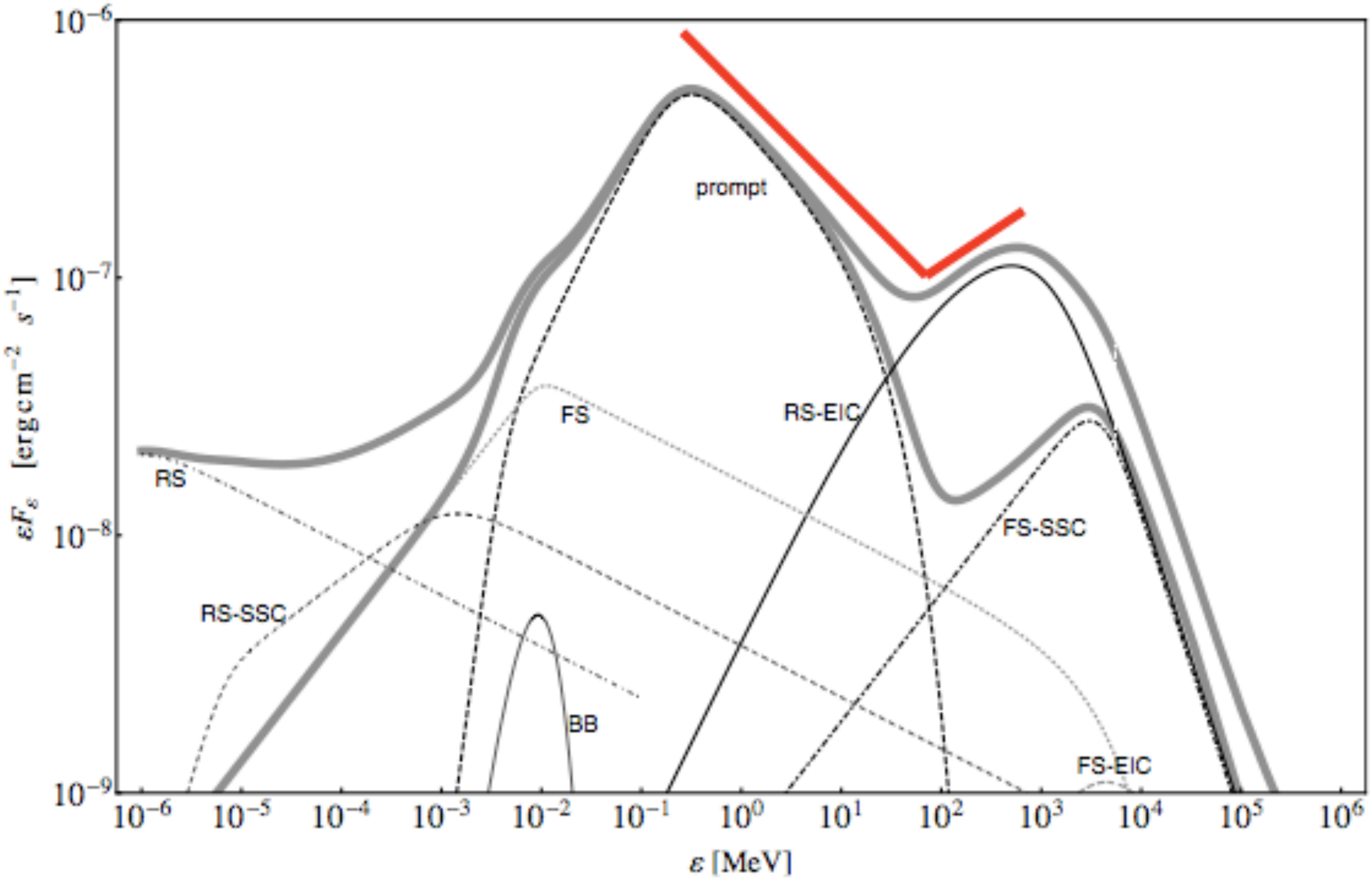
Veres & Mészáros, arXiv:1202.2821



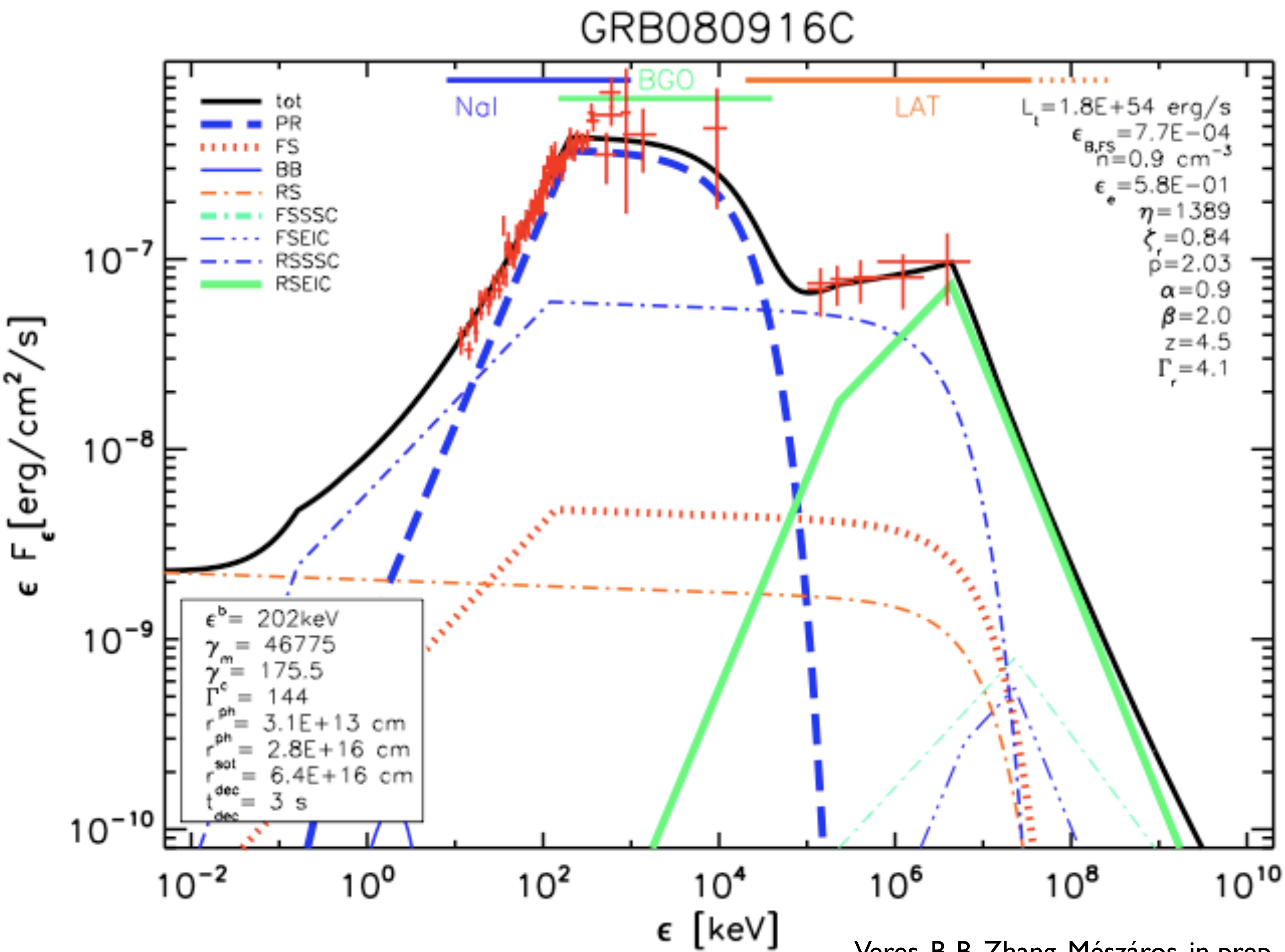
$L_t = 10^{53}$ erg/s, $\zeta_r = 0.5$, $n = 30$ cm^{-3}, $\eta = 400$, $\epsilon_{B,pr} = 1$, $\epsilon_{B,FS} = \epsilon_{B,RS} = 2 \times 10^{-2}$, $\epsilon_{e,FS} = \epsilon_{e,RS} = 5 \times 10^{-3}$, $r_0 = 10^7$ cm, $z = 1$, $\beta = 2.5$, $p = 2.4$

Ph+ES Band + 2nd comp.

Veres & Mészáros, 1202.2821

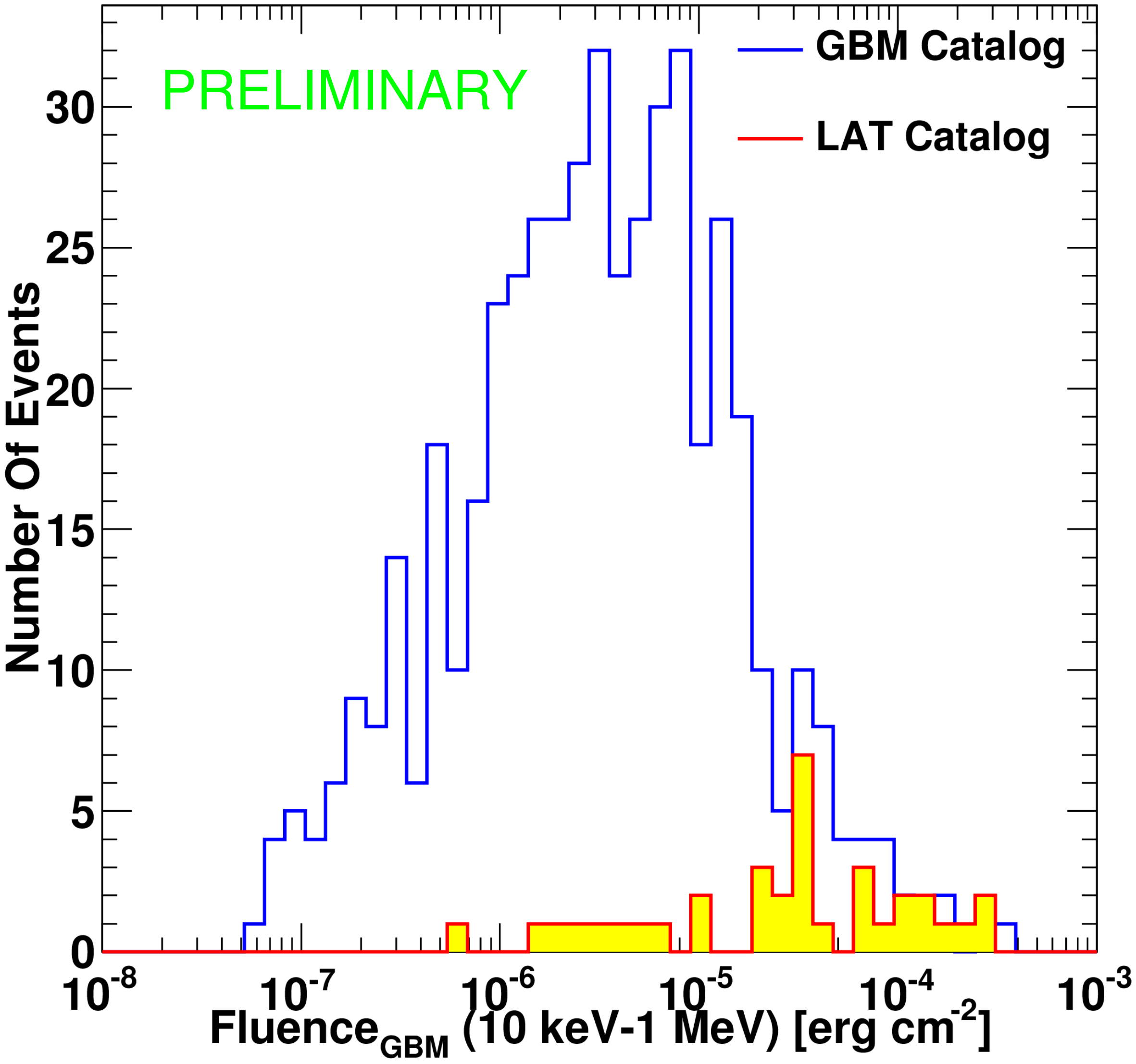


$L_t = 5 \times 10^{52}$ erg/s, $\zeta_r = 0.6$, $n = 10^2$ cm^{-3}, $\eta = 400$, $\epsilon_{B,pr} = 0.9$, $\epsilon_{B,FS} = 10^{-2}$, $\epsilon_{e,FS} = 2 \times 10^{-2}$, $r_0 = 10^7$ cm, $z = 1$, $\beta = 2.4$, $p = 2.4$



Veres, B-B. Zhang, Mészáros, in prep.

GBM Fluence of LAT GRBs

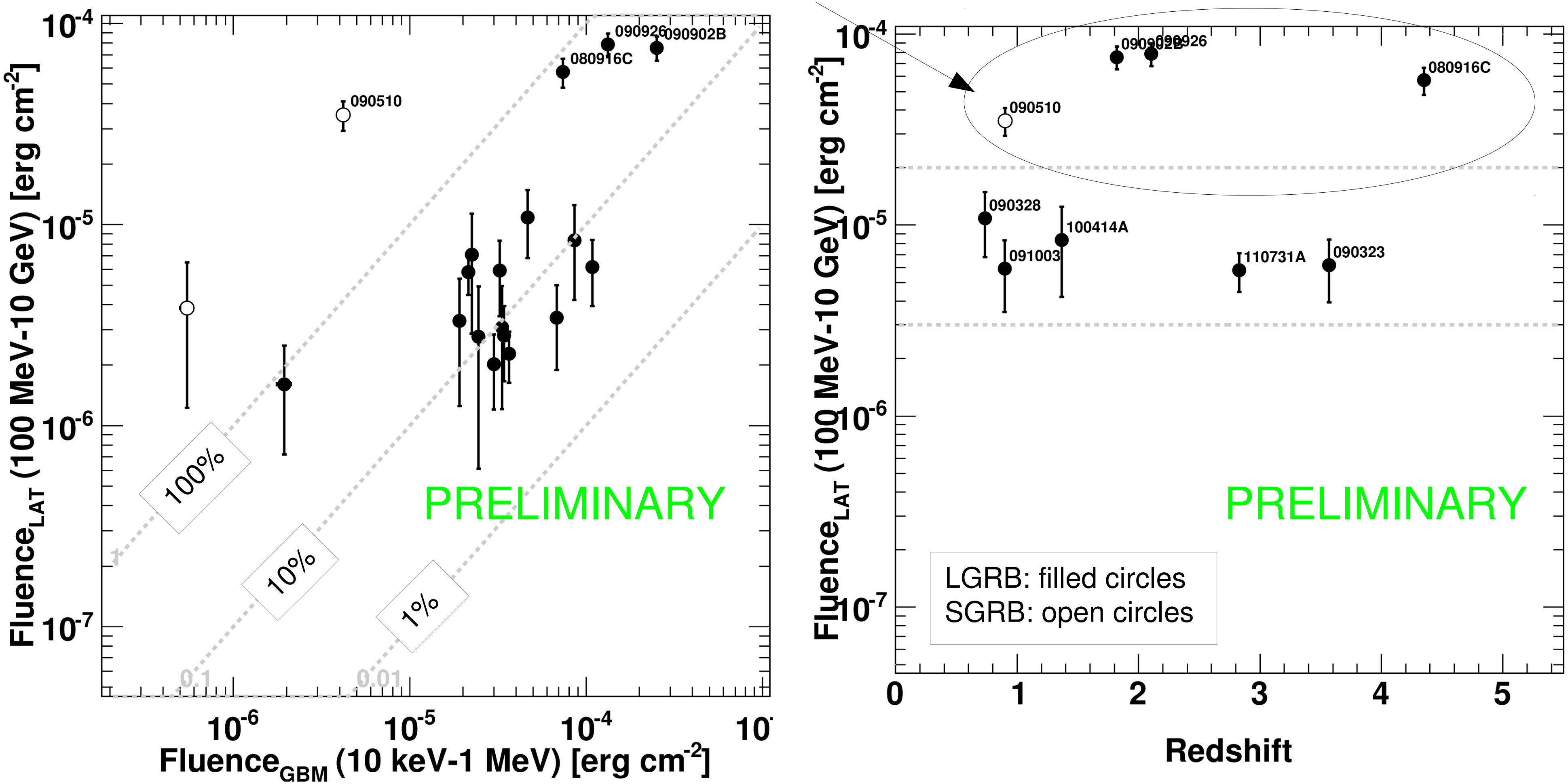


- Fluence in GBM energy range and "GBM" time window
  - LAT GRBs vs. entire sample in GBM spectral catalog (Goldstein et al. 2012)

- Not surprisingly, the LAT GRBs are among the brightest GRBs detected by the GBM
  - Selection effects (ARRs) should be investigated though

GBM vs. LAT fluences

- GBM and LAT fluences computed in "GBM" and "LAT" time windows, respectively
  - Long GRBs: LAT fluence ~10% of GBM fluence
  - Short GRBs: LAT fluence > GBM fluence
- Evidence of a hyper-energetic class: 080916C, 090510, 090902B, 090926A are exceptionally bright
  - They do not appear bright because they are systematically closer to us



Some observed photon energies and redshifts

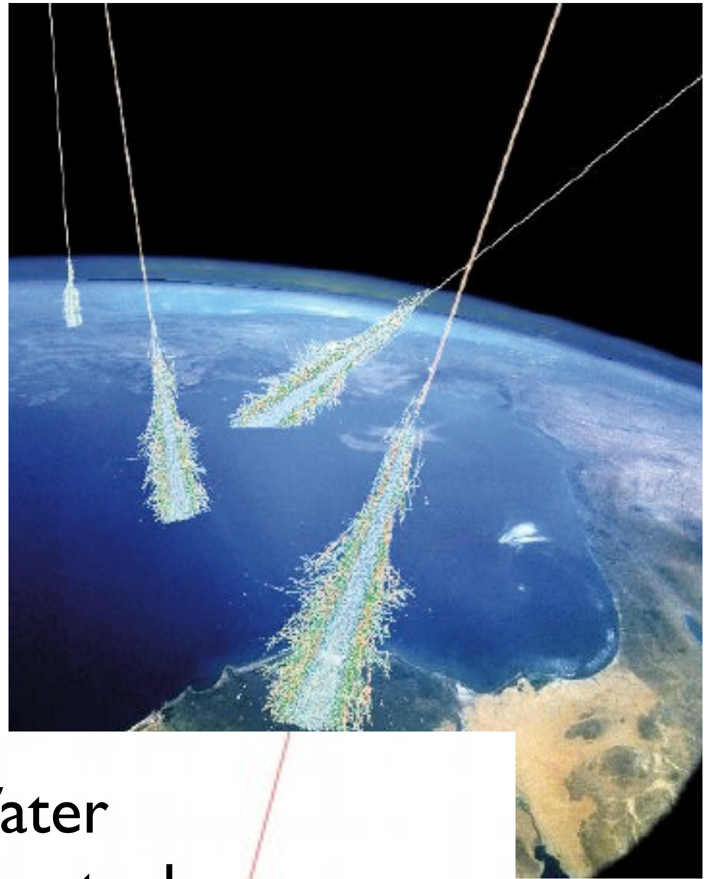
E_{obs}(GeV)	z
13.2	4.35
7.5	3.57
5.3	0.74
31.3	0.90
33.4	1.82
19.6	2.10
2.8	0.897
4.3	1.37

- Even z>4 bursts result in E_{obs}~10 GeV photons
- Some z~1 bursts produce E_{obs}≥30 GeV photons (130 GeV in rest frame!)

- ⇒ ***encouraging***

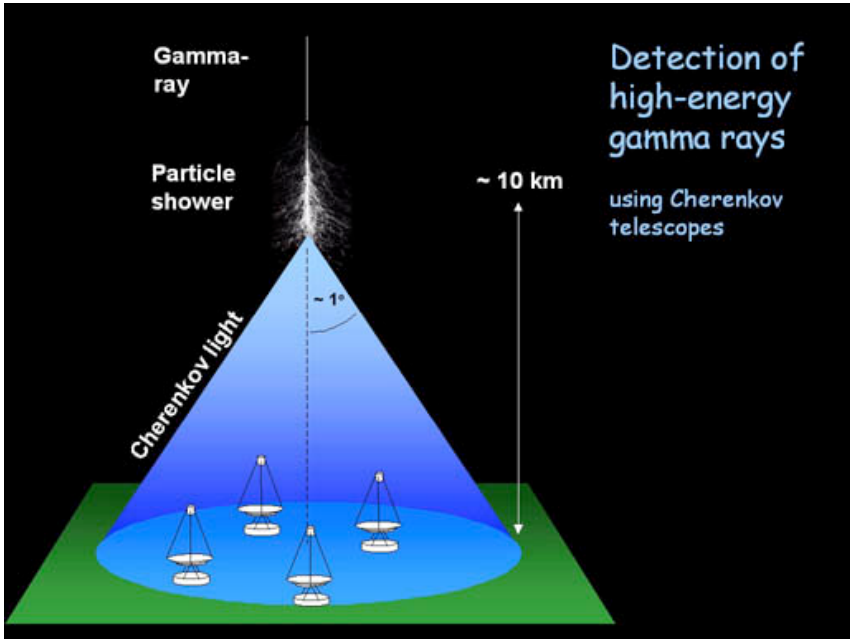
for low E_{th} ACTs: HAWC, CTA...

TeV gamma → EM showers

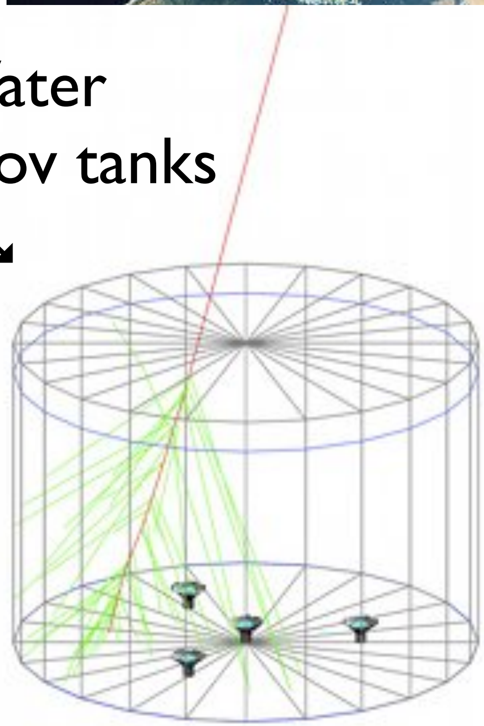


Detection techniques:

i) Air Cherenkov Telescopes ↓

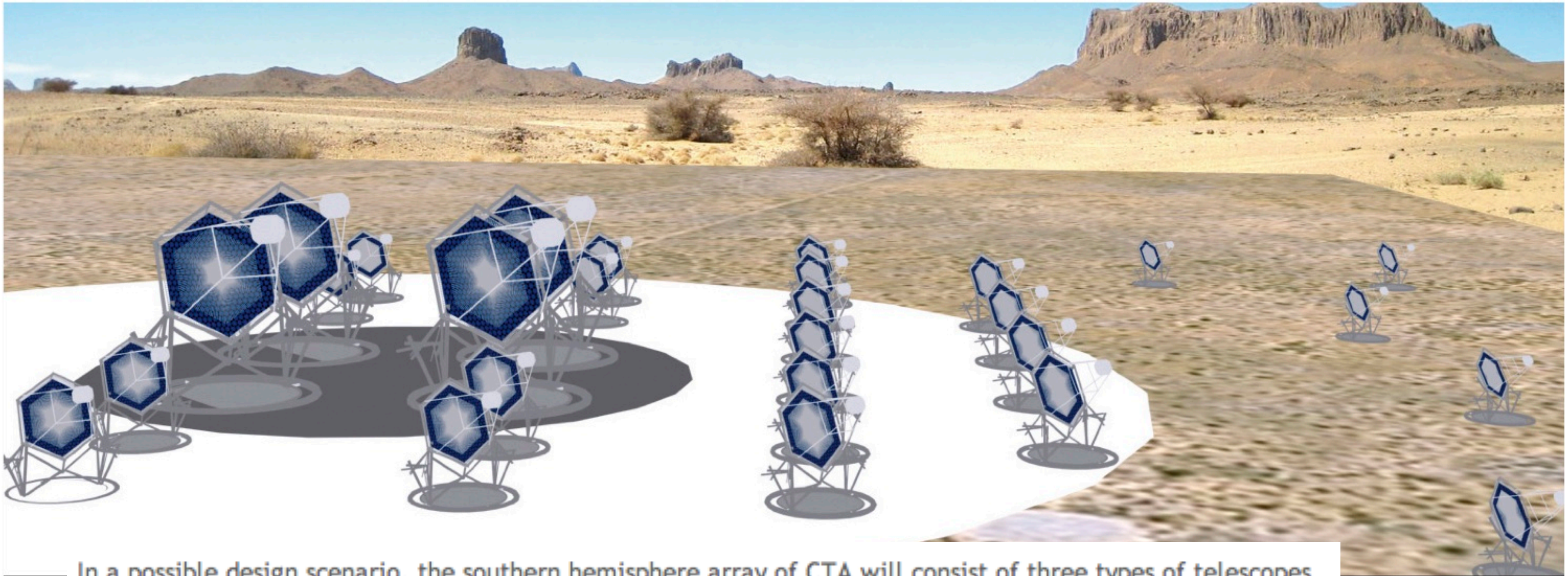


ii) Water Cherenkov tanks ↘



CTA

Cherenkov Telescope Array (air)



In a possible design scenario, the southern hemisphere array of CTA will consist of three types of telescopes with different mirror sizes in order to cover the full energy range. The northern hemisphere array would consist of the two larger telescope types.

- The low energy instrumentation will consist of a few 24 metre-class telescopes with a moderate field of view (FoV) of the order of 4-5 deg.
- The medium energy range, from around 100 GeV to 1 TeV, will be covered by telescopes of the 10-12 metre class with a FoV of 6-8 degrees.
- The high energy instruments, operating above 10 TeV, will consist of a large number of small (4-6 metre diameter) telescopes with a FoV of around 10 degrees

.

Planned : southern hemisphere

HAWC

High Altitude Water Cherenkov

(under construction)

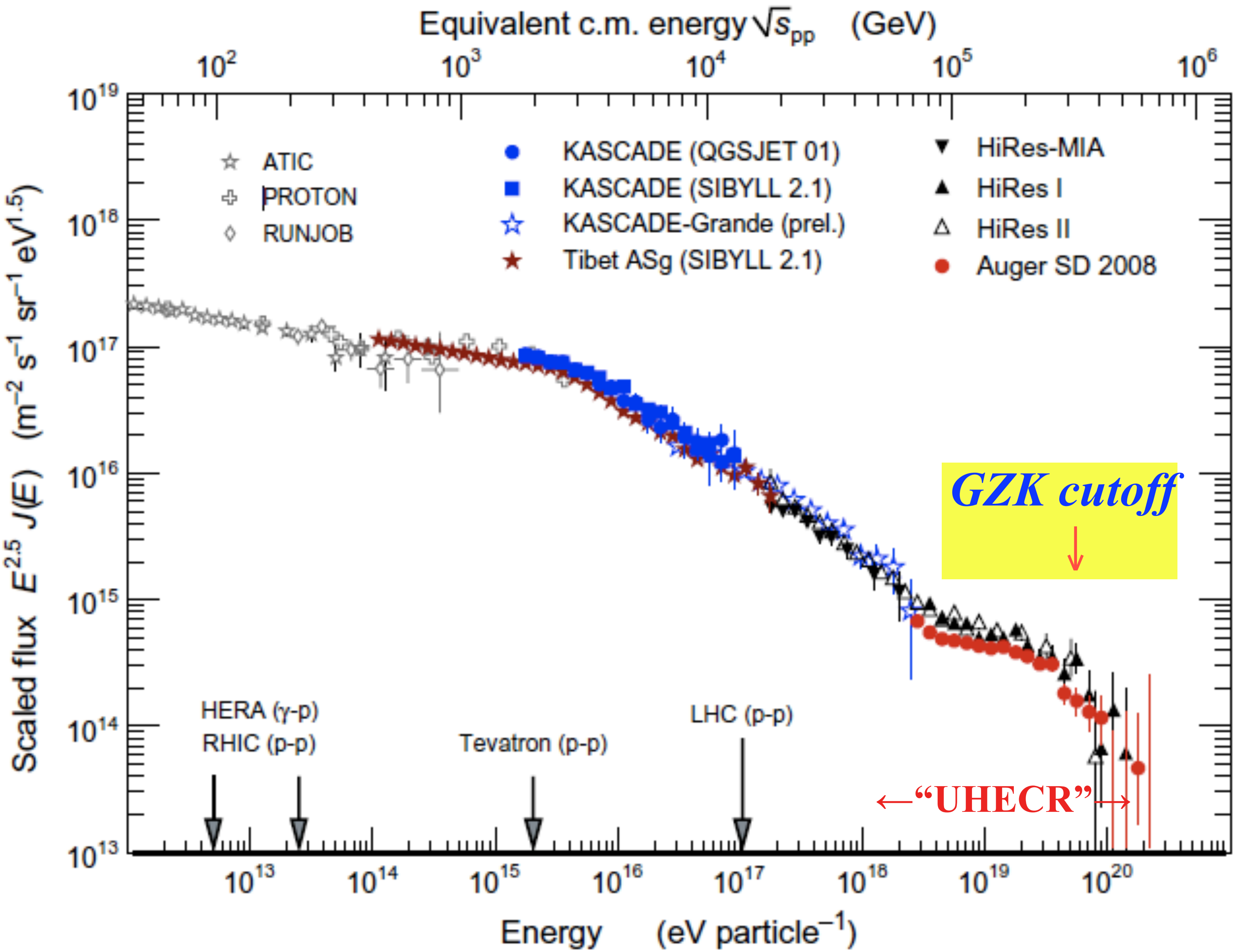
- Move Milagro PMTs and front-end electronics to 4100 meter site at Sierra Negra, Mexico
- Existing infrastructure for Large Millimeter Telescope
- 2500 square meter area.
- 300 water tanks. 3 PMTs per tank.
  - 7.5 meter diameter
  - 4.0 meter water above PMTs
- Overall 15x sensitivity improvement over Milagro.
- See sources 225x faster.
  - See 1 Crab every day.

credit: Pretz, 2011

What about CRs?

- Shocks present in HE non-thermal γ-ray sources (or else: magnetic reconnection).
- Electrons are definitely accelerated
- γ-rays usually attributable to leptonic mechanisms (synchrotron, inv. Compton)
- But: UHECR ***must be*** accelerated somewhere; likely (?) in the same shocks of one of these HE γ-ray sources- but which?

Cosmic ray spectrum (2012)

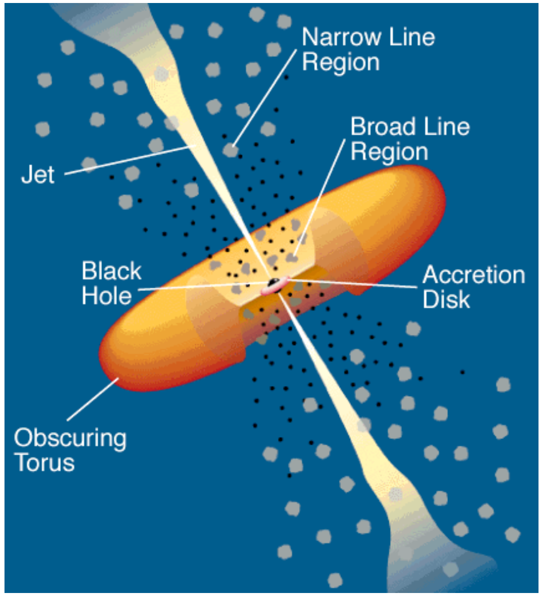


Auger ←data

Who is responsible for this?

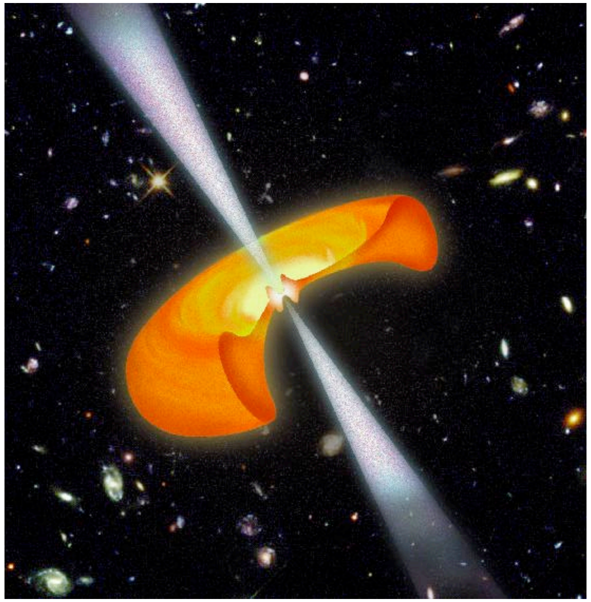
- It is ***no***t "exotic physics" - photon component too low for any plausible annihilation or decay model
- Astrophysical candidates: only a few that can qualify

Astrophys. UHECR/NU Candidates



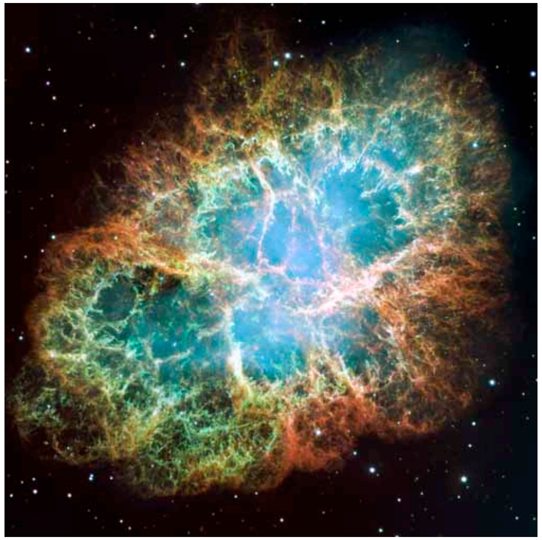
AGN

Active
Galactic
Nucleus



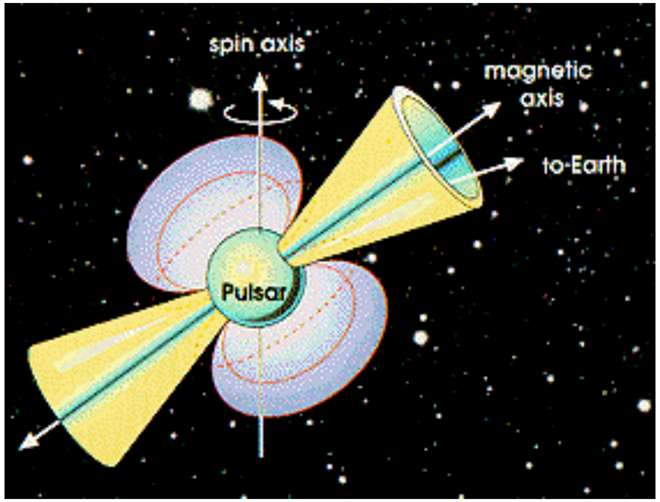
GRB

Gamma
Ray
Burst



HN

Hypernova



MGR

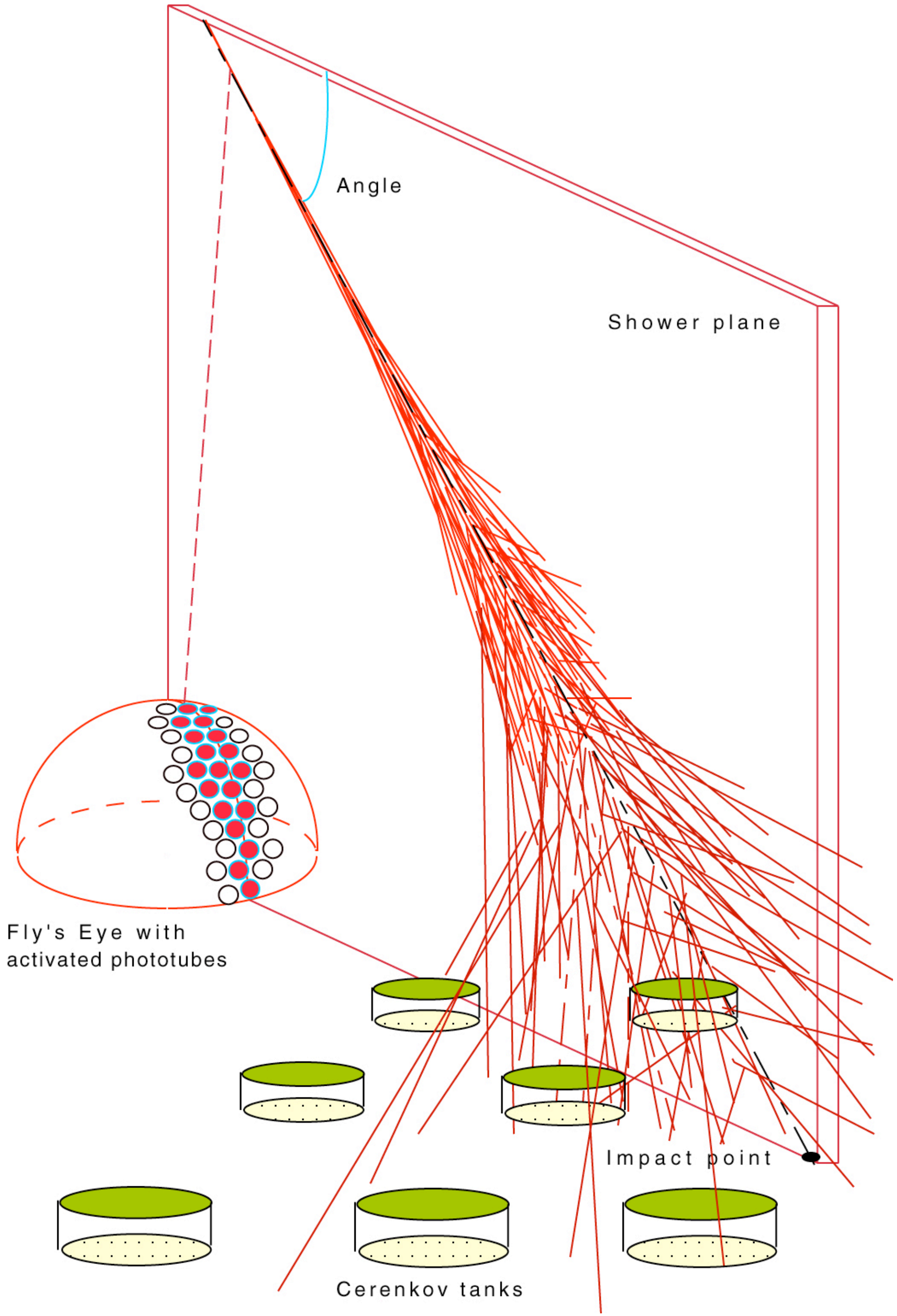
Magnetar

Pierre Auger Observatory

Uses two techniques for detecting CR shower:

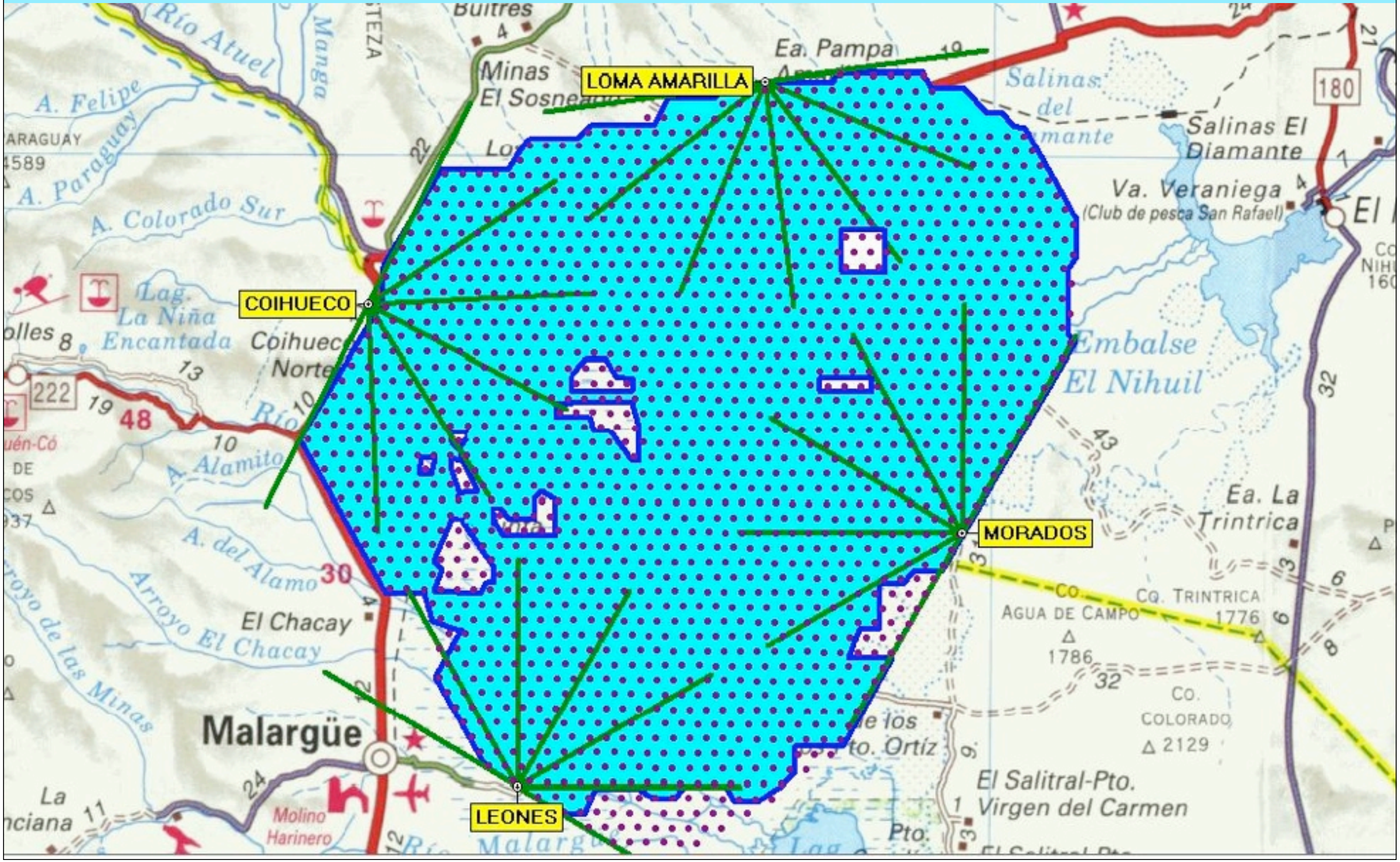
- **detect air fluorescence produced by shower particles (FD)**

- **detect shower particles on the surface (SD)**



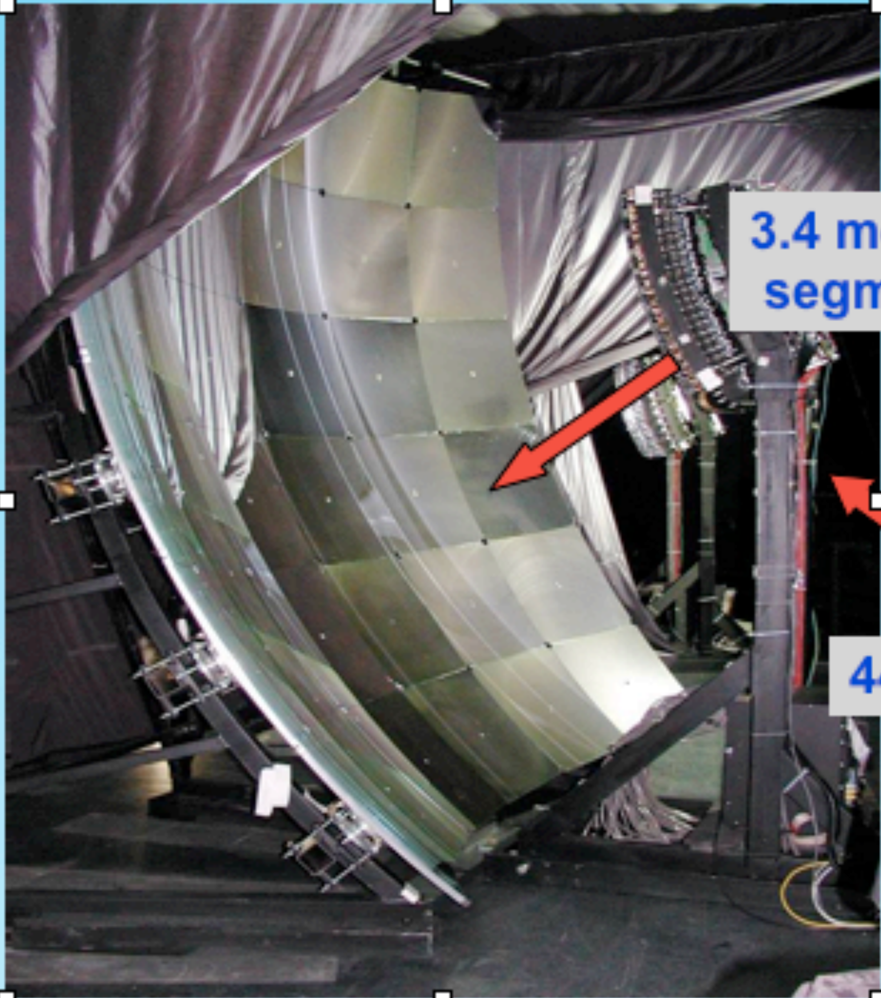
Auger Obs. - 3000 km^2 uhecr detector

Mendoza, Argentina

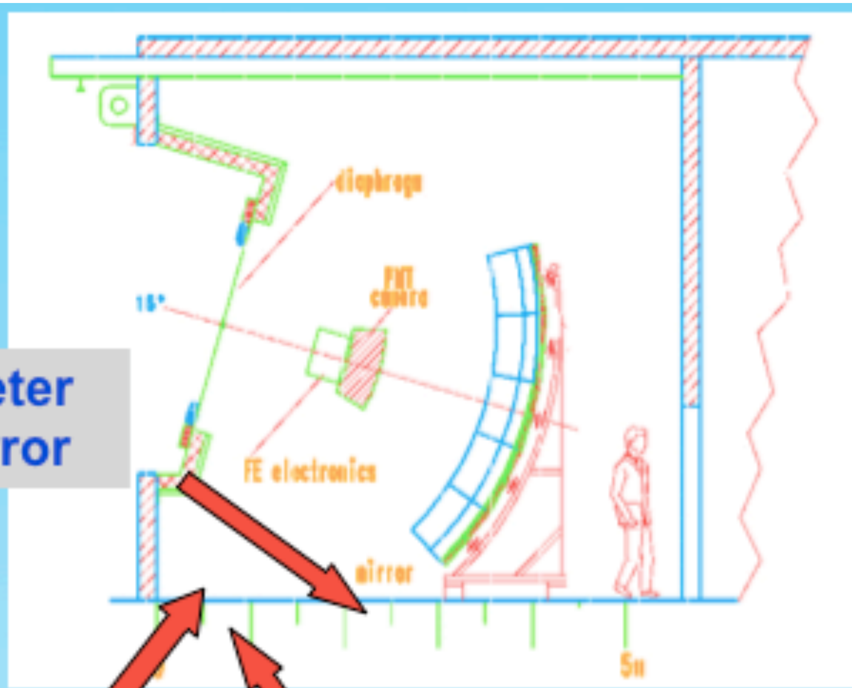


Pierre Auger Observatory: Malargue, Mendoza, Argentina: $E \sim 10^{17} - 10^{21}$ eV
-1600 surface detectors: water Cherenkov tanks, 11 kliters ea., 1.5 km apart
-32 air fluorescesnce telescopes, 4x8 arrays of 30x30 deg. sky coverage
-Also: tau-nu (horiz.l shower capability: Earth-skimming & through Andes)

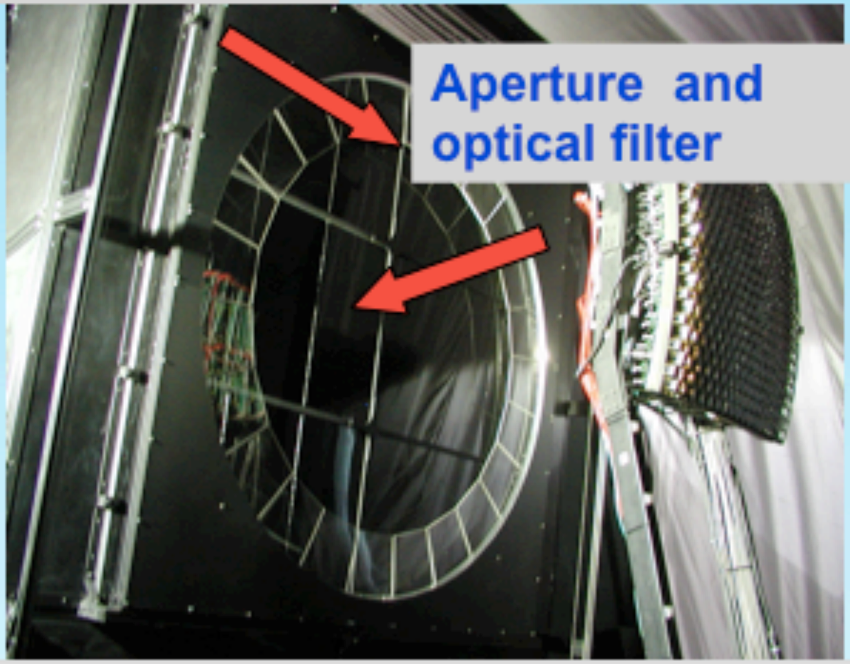
The Fluorescence Detector



3.4 meter diameter segmented mirror



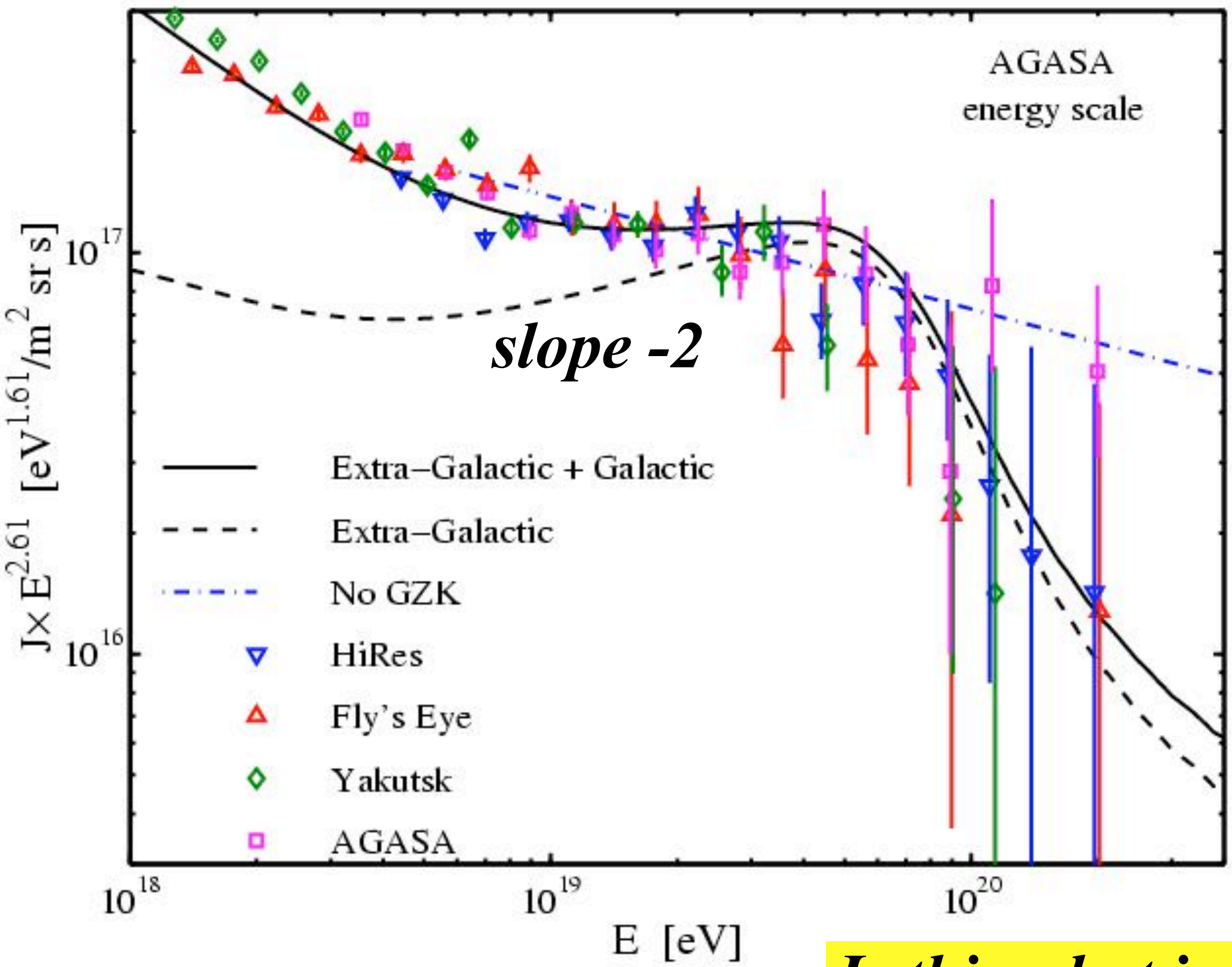
440 pixel camera



Aperture and optical filter

BONUS! Recent ***Auger-PRAM*** detection of **GRB 060117** prompt bright (**m_V** ~**10** !) optical flash; Jelinek et al, astro-ph/06060004

UHECRs *can* be Fermi-accelerated in int/ext *GRB* shocks to $E_{obs} \sim 10^{20}$ eV



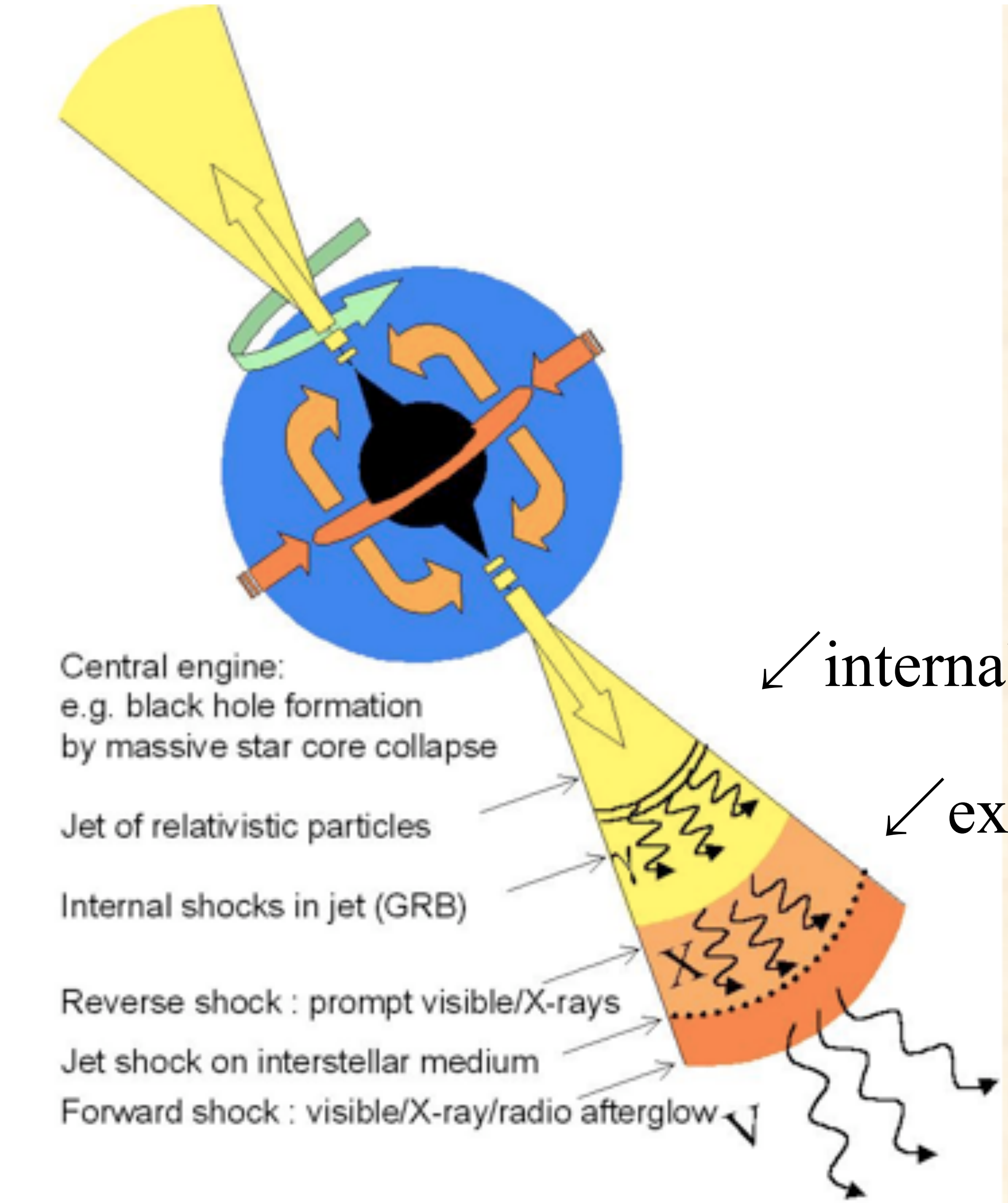
Waxman 06

Is this what is happening?

Can *neutrinos* be used as a smoking gun test of *protons*?

- *If* have protons in jet $\rightarrow$ p^+ Fermi accelerated
- ***Whether*** to GZK energies or not: are they detectable?
- **p,**$\gamma \rightarrow \pi^{\pm} \rightarrow \mu^{\pm}, \nu_\mu \rightarrow e^{\pm}, \nu_e, \nu_\mu$
- Δ-resonance: $E_p E_\gamma \sim 0.3\ \mathrm{GeV}^2$ in jet frame
- Depending on target photon energy, the typical observer frame neutrino energies in the ***$E_\nu \sim$ GeV- EeV*** range
- Potentially, can detect with **ICECUBE, KM3NeT**
- Also: **p,**$\gamma \rightarrow \pi^0 \rightarrow 2\gamma \rightarrow \gamma\gamma$ cascade **: Fermi , ACTs..**
- Test content of jets (are they pure MHD/$e^{\pm}$, or baryonic …?)

Jets in GRBs → int. & ext. shocks



↙internal shocks

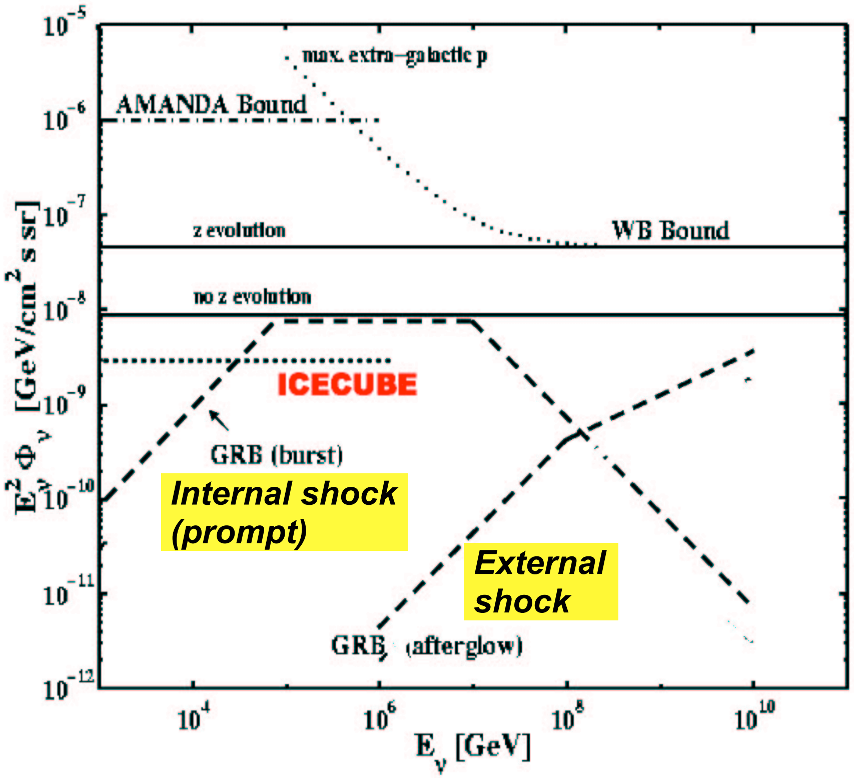
↙external shock

Int. & ext. shocks,
accelerate electrons
e,B →γ (***leptonic***);

and ***if***
accel protons too,
pγ→ν (***hadronic***)

νs from pγ from int. & ext. shocks

(NOTE: internal shock → old paradigm)



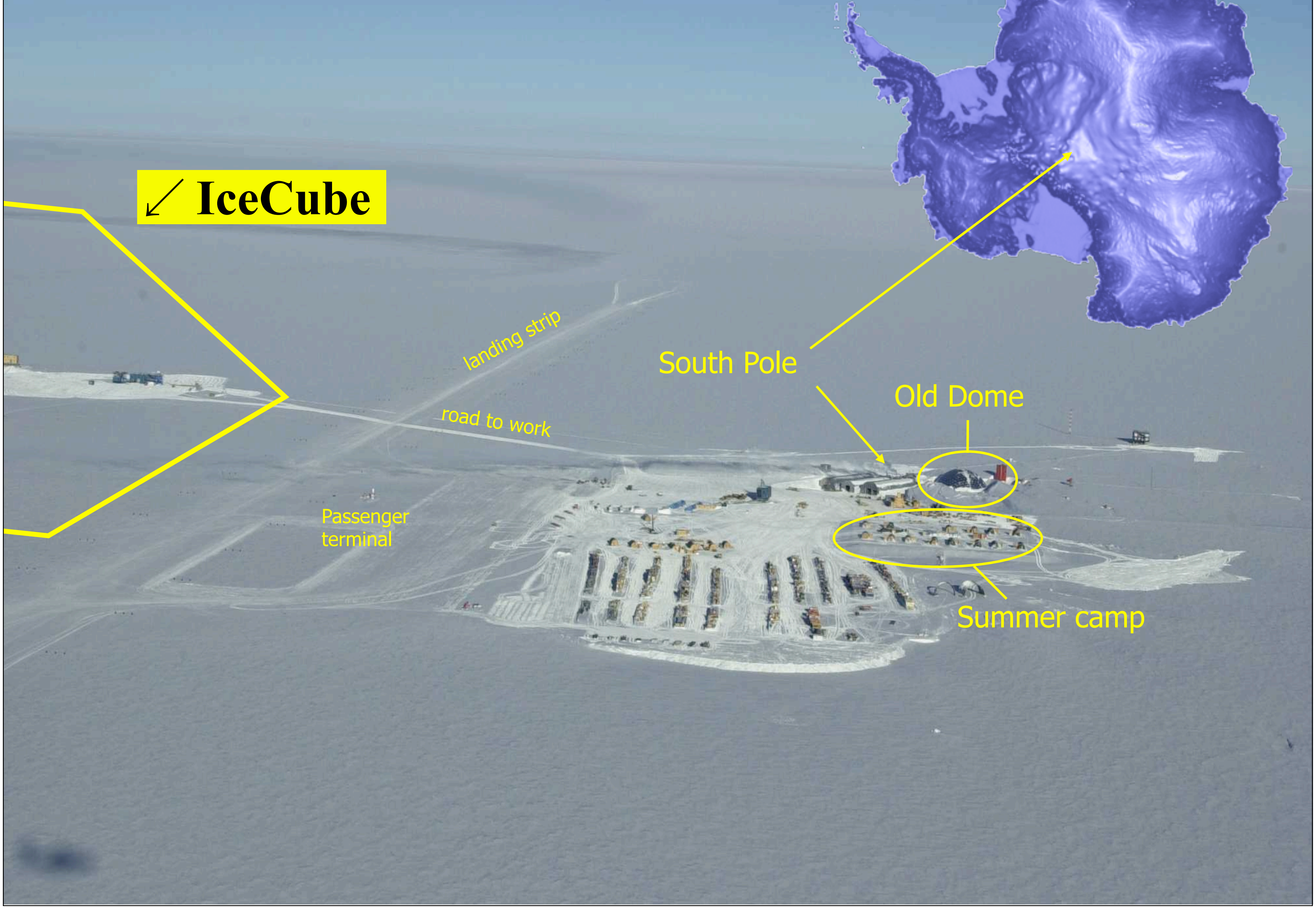
Waxman, Bahcall 97 & 99 PRL

- **Δ**-res.: $E'_p E'_\gamma \sim 0.3 \mathrm{GeV}^2$ in comoving frame, in lab:

  → $E_p \geq 3 \times 10^6\ \Gamma_2^2$ GeV

  → $E_\nu \geq 1.5 \times 10^2\ \Gamma_2^2$ TeV
- Internal shock pγ_{MeV} → ~100 TeV ν s
- (External shock pγ_{UV} → ~ 0.1-1 EeV ν s)
- Diffuse flux: det. w. km^3

Amundsen-Scott South Pole station



IceCube (2012)

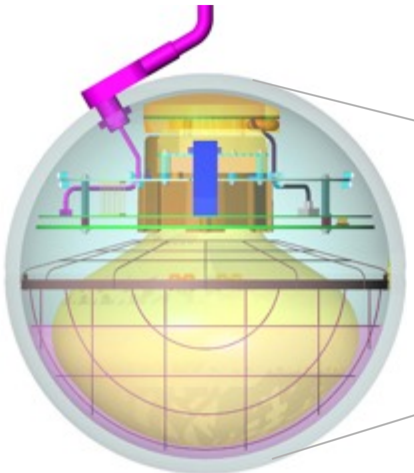
5160 DOMs on 86 strings

160 tank ice-Cherenkov surface air shower array (IceTop) – see talk by T. Gaisser

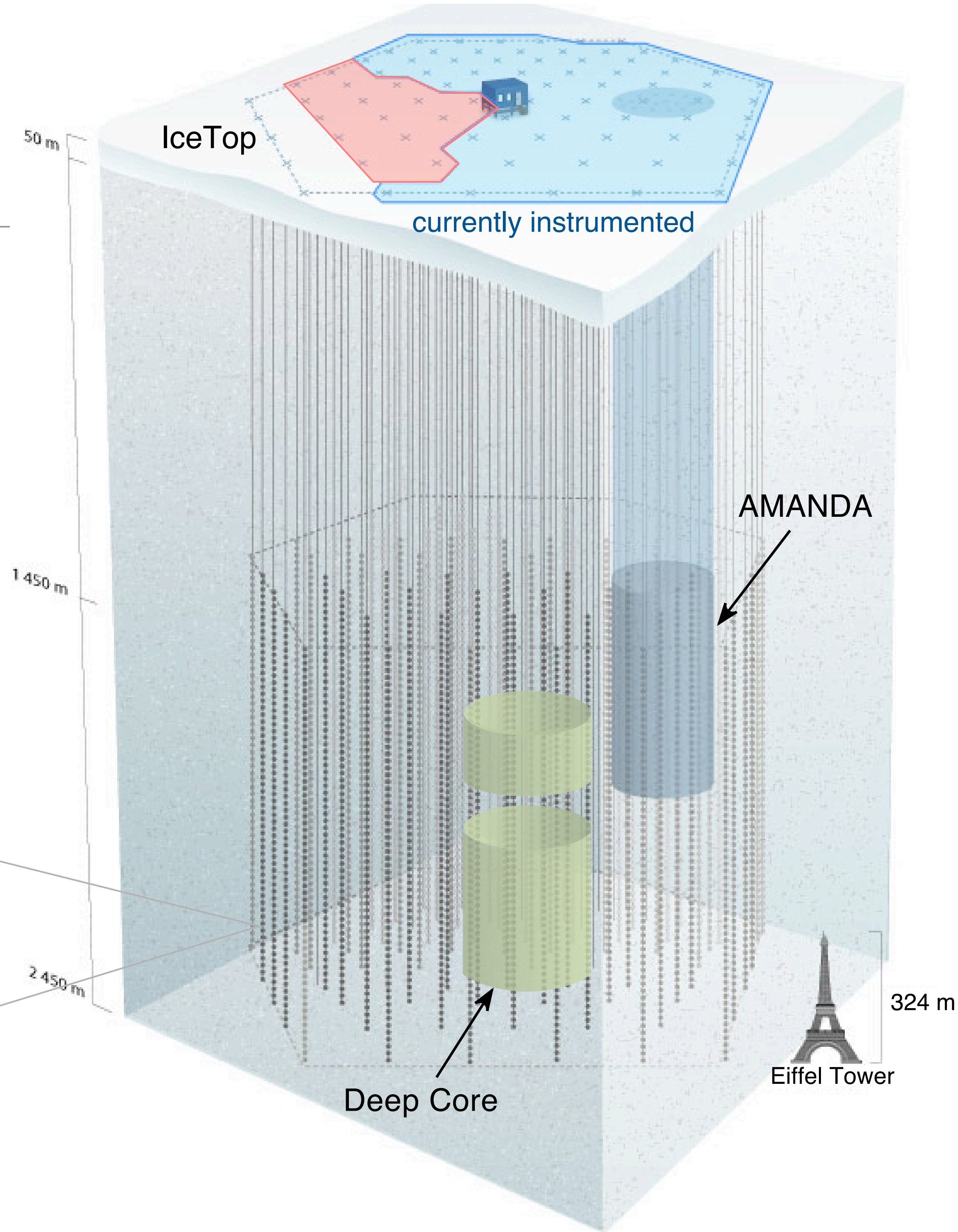
Includes DeepCore infill array (sensitivity to lower energies)

86
~~79~~ strings deployed to date in 6 construction seasons

(2011: complete)

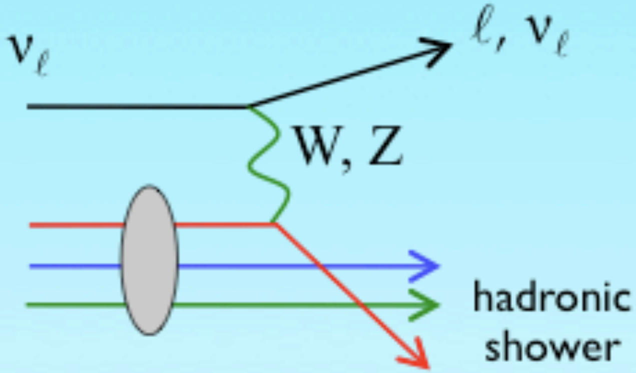


Digital Optical Module (DOM)

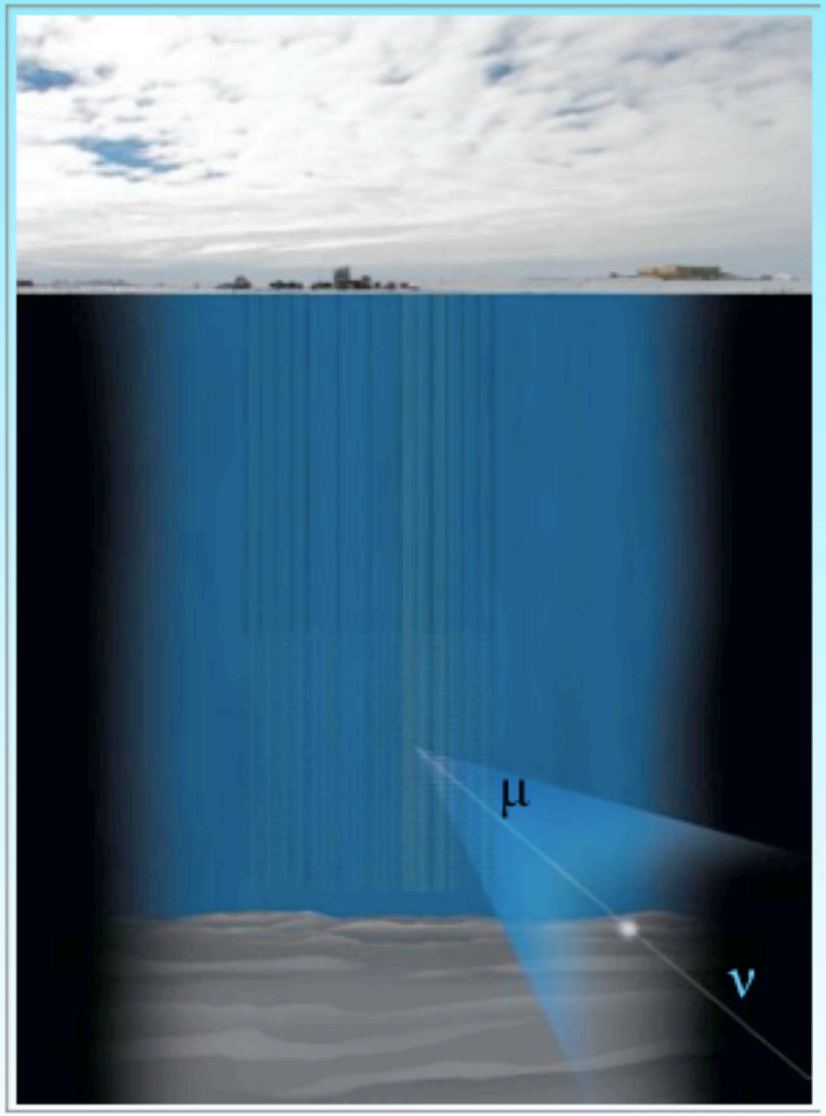


Neutrino Telescopes

- Neutrinos interact in or near the detector



  - $\mathcal{O}$(km) muons from ν_μ (CC)
  - $\mathcal{O}$(10 m) particle cascades from ν_e, low energy ν_τ, and NC interactions
  - Cherenkov radiation detected by optical sensors

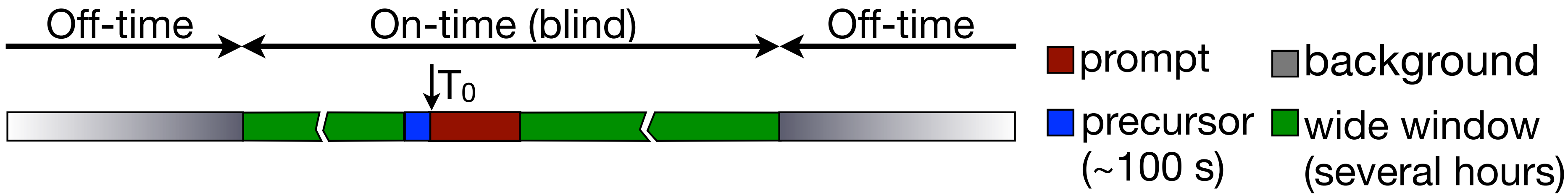


GRBs with IceCube

(Kappes et al, NUSKY, June 2011)

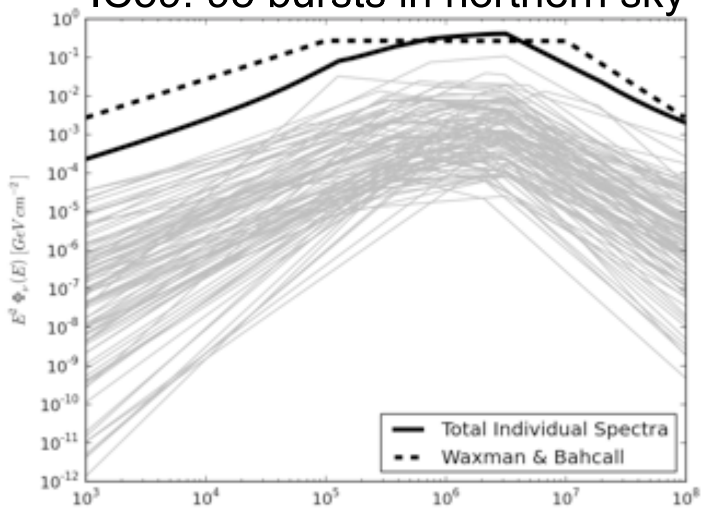
Being tested here : ***internal shock*** prompt ν-burst (WB97 simplified)

- GCN-satellite triggered searches



very low background → 1 event can be significant !

IC59: 98 bursts in northern sky

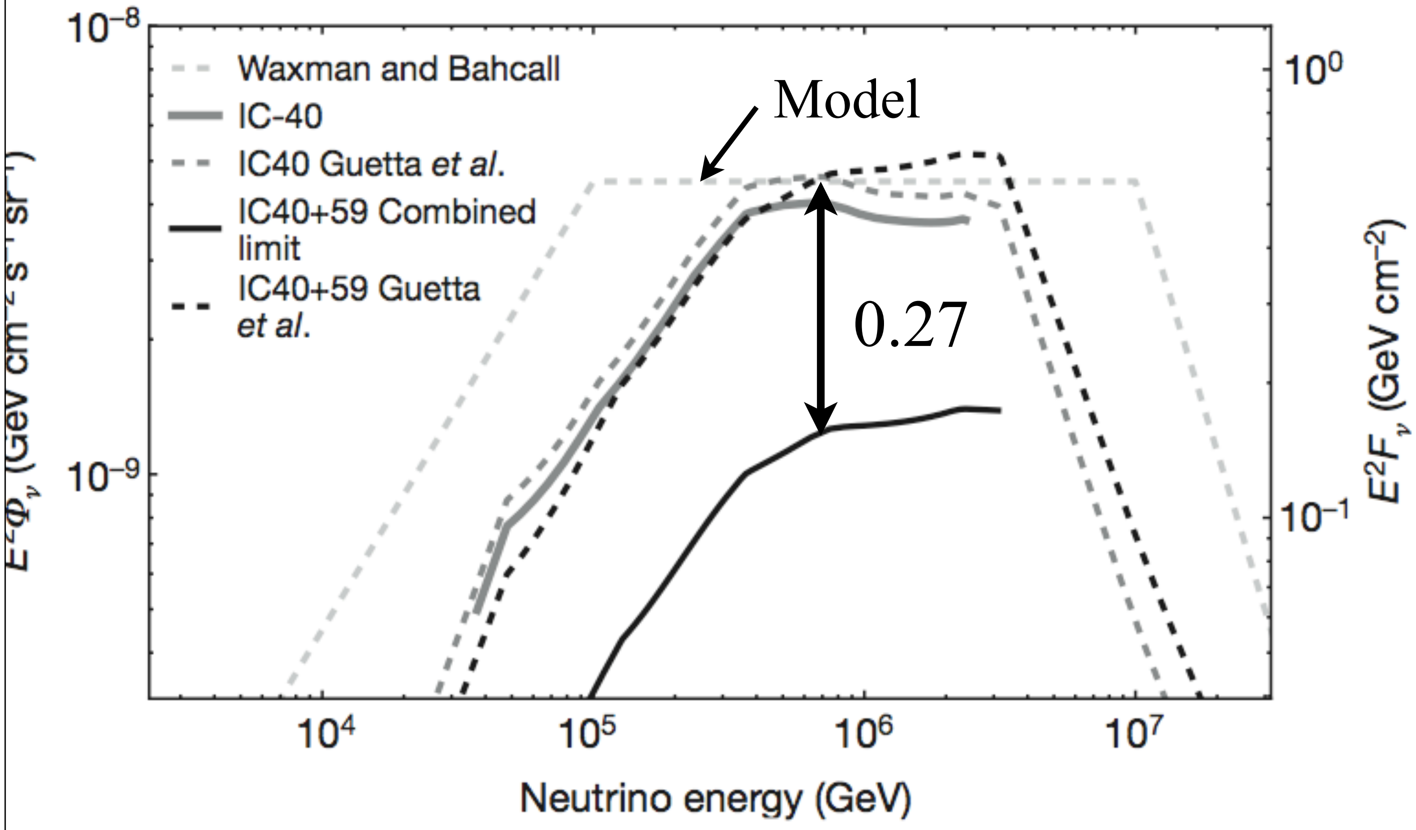


- Individual modeling of neutrino fluxes (fireball model)
- Measured parameters: γ spectrum, (redshift)
- Average parameters: Γ_{jet} (316), t_{var} (10 (1) ms), L_{iso} ($10^{52\ (51)}$ erg), ε_B *(0.1)*, ε_e *(0.1)*, $f_{e/p}$ (0.1)

IC40+59 search for VHE nus from 190 GRB (105 northern)

Nature 484:351 (2012), the Icecube collab.; Abbasi and 242 others (incl. P.M.)

(A) Model dependent search

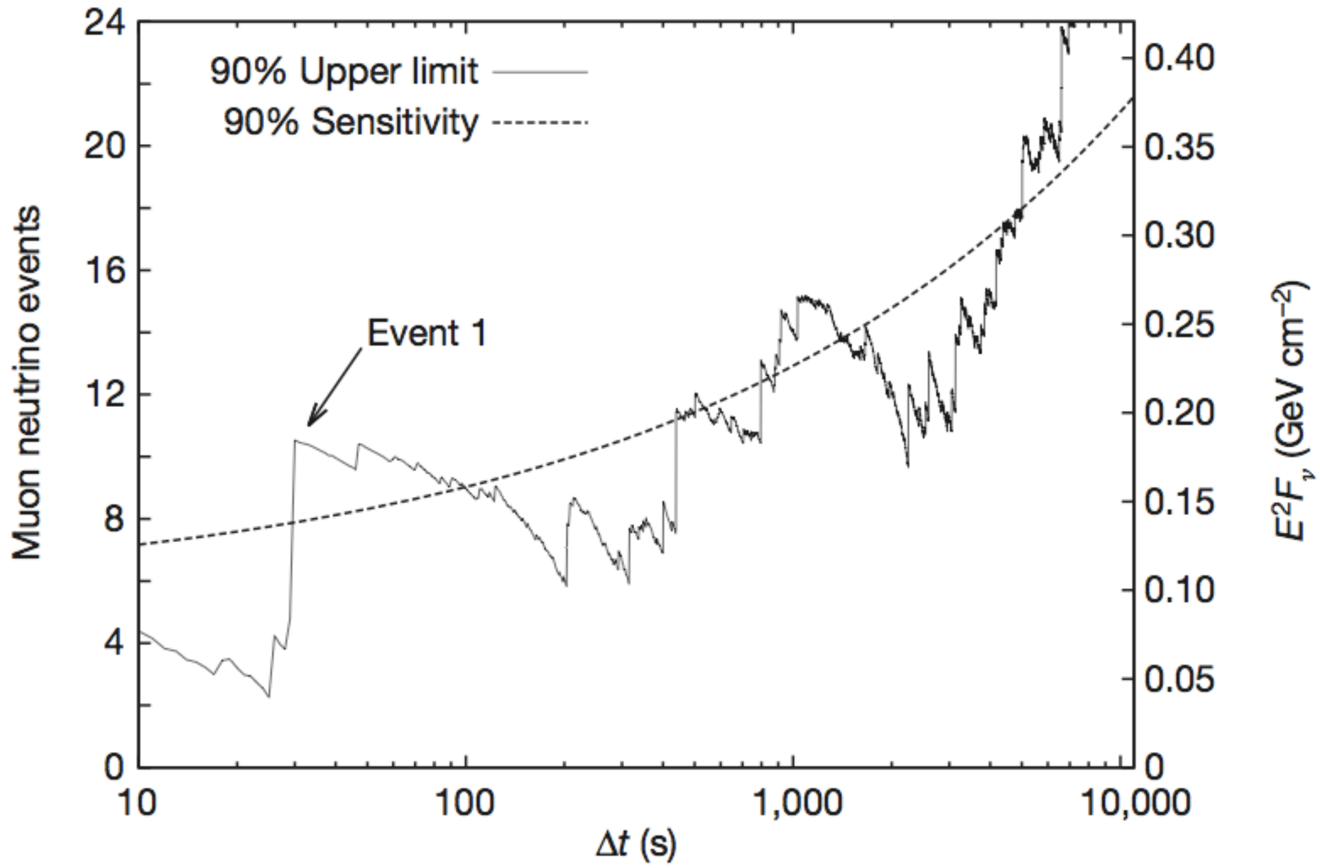


Data is factor 0.27 below model F_ν at 90% CL

- Analyze 190 GRBs localized w. γ-rays betw, T_{start} & T_{end}
- Use the WB'97 and Guetta'04 proton acceleration model in internal shocks, with E^{-2} spectr, $\varepsilon_p/\varepsilon_e$=10, and $p\gamma \rightarrow \Delta$-res $\rightarrow \nu_\mu$
- Nu-flux normalized by obs. γ-ray flux, get F_ν for 190 (right axis), and diffuse flux (all) assuming 677 yr^{-1}

IC59 model-indep. search

Nature 484:351 (2012)

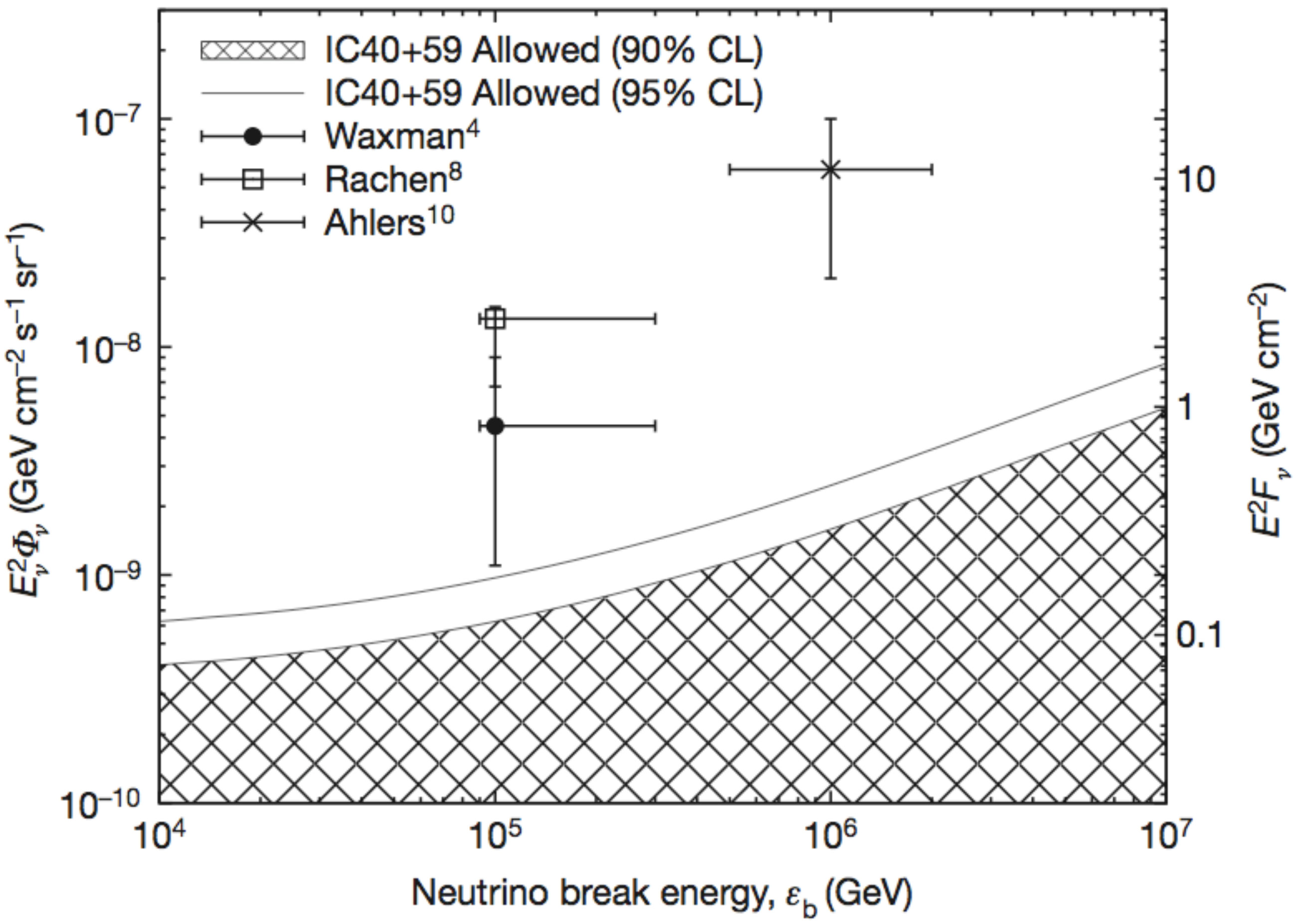


UL % CL is similar as for model dep. search

- Searched 190 GRB @ γ-trigger ± Δt window up to 1 day, also using ≠ spectra & params
- Two candidate events seen at low signif., probably due to (other) CRs
- ← Results shown are for E^{-2} spectra as function of Δt
- Right axis is data deficit below F_ν model

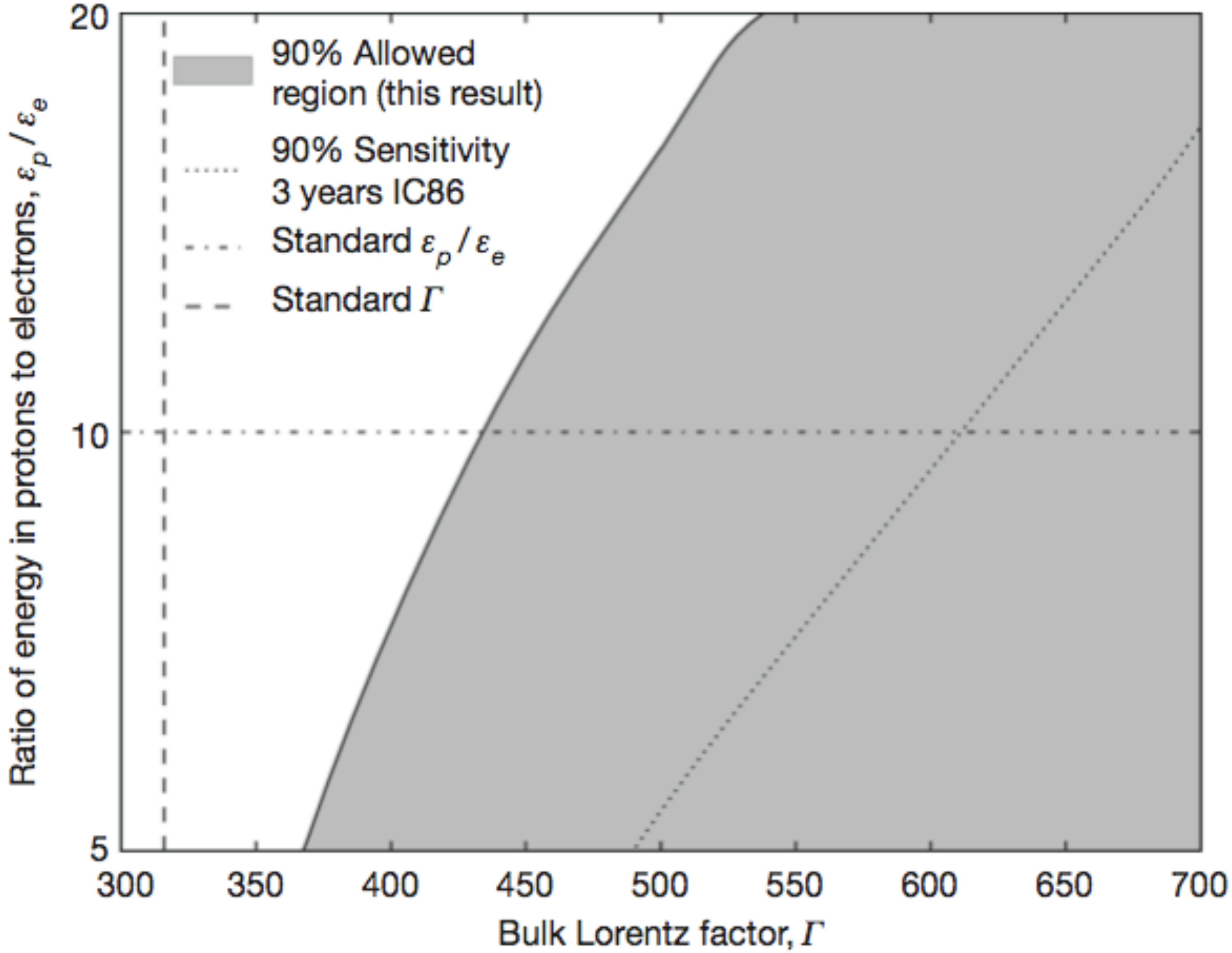
IC59 nu search assuming GRB model is source of observed GZK UHECR

Nature 484:351 (2012)



- If same proton accel. in int. shock model makes proton flux = obs. GZK UHECRm and if nu-flux is from $p\gamma \rightarrow \Delta$-res $\rightarrow \nu_\mu$
- ← then, nu-flux data as fcn. of nu-spectral break $E_{\nu b}$, shows the allowed nu-flux (hashed) is below the required value required to give the obs. UHECR flux (for three somewhat ≠ int. shock models)

IC59 constraint on standard IS



- Constrain Γ vs. $\varepsilon_p/\varepsilon_e$ (i.e. L_p/L_e), assuming some E_{iso}, $\varepsilon_B/\varepsilon_e$, t_{var}, i.e. total luminosity, magnetic efficiency and shock radii

IC59 2-year ***conclusions*** (190 GRBs)

Nature 484:351 (2012)

- The fireball (more accurately: ***internal shock***) model *overpredicts* the TeV-PeV nu-flux by a ***factor 3.7***, (asuming L_p/L_e=10, Δ-res only, Lorentz Γ~300-600)
- In the same model, the 95% CL nu-flux allowed by the data falls below ***2-3σ*** of what expected if GRBs contribute most of GZK UHECR flux.
- In these models, either ***L_p/L_e*** must be substantially below factor 3-10 assumed here, or the production ***efficiency of neutrinos*** is lower than was assumed.

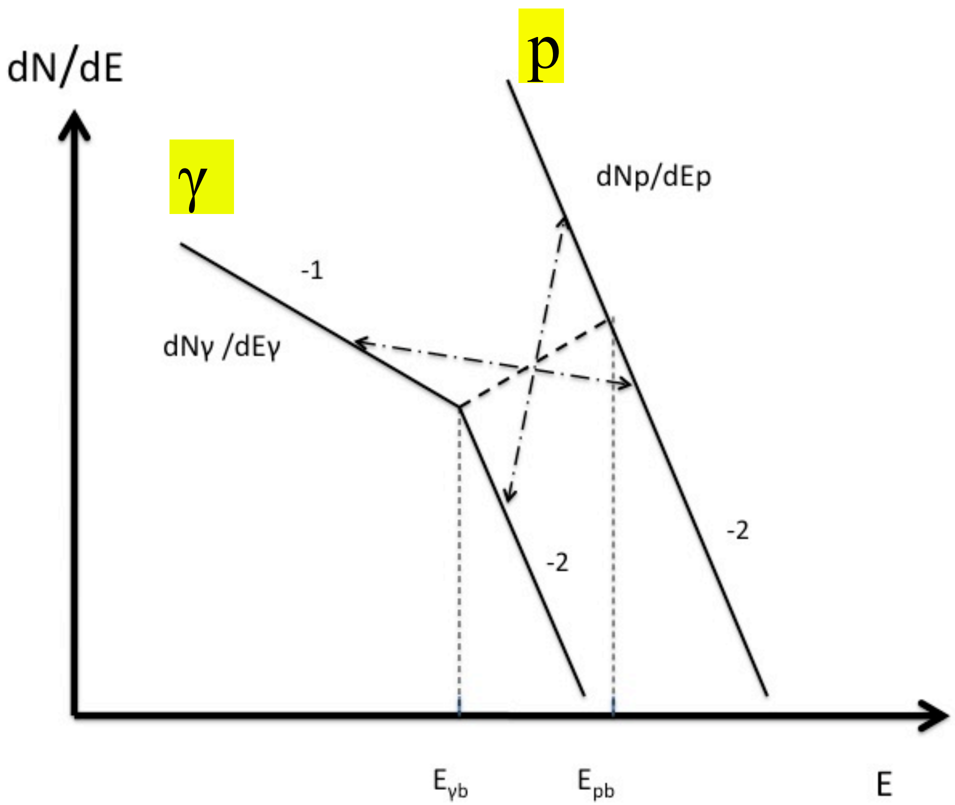
Conclusion on the conclusions:

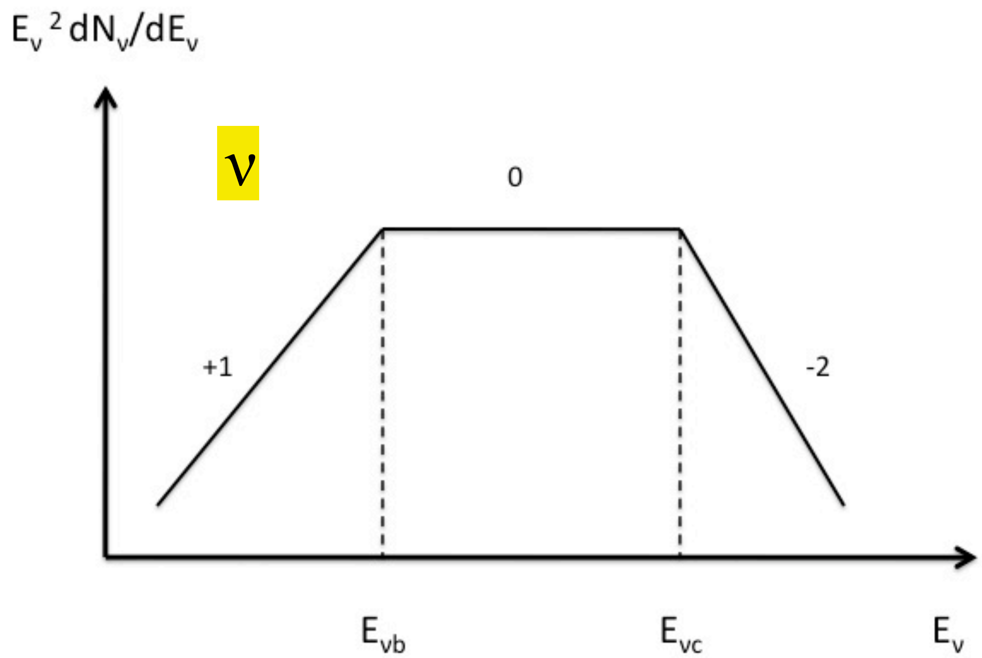
- These are ***conservatively*** stated conclusions
- The ***first time*** VHE nus have put a significant ***constraint*** on a well-calculable astrophysical UHECR-UHENU model, at ***90-95% CL***
- This is very ***valuable***
- Icecube is doing ***exciting*** astrophysics
- A significant first step towards ***GZK physics***

Some model details ....

$p\gamma \rightarrow \Delta$ interaction of a Band-γ spec. with an E^{-2} proton spec.

(WB 97)





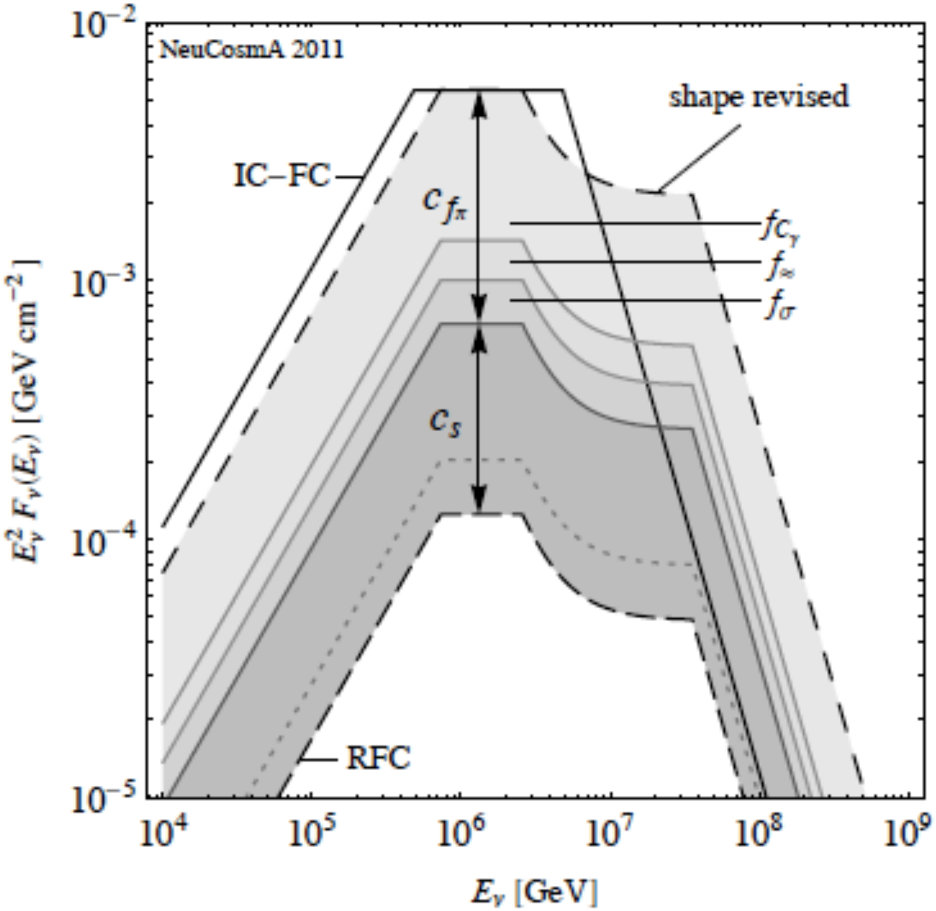
However ...

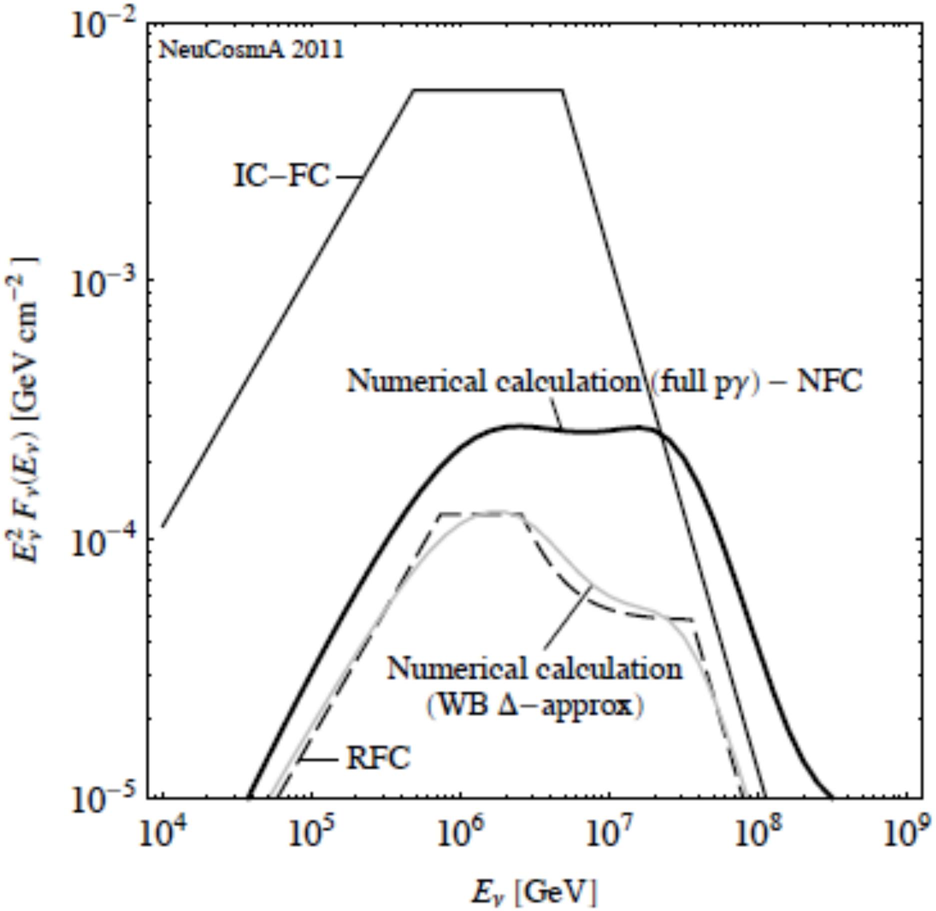
(Li, arXiv:1112.2240, PRD accepted)

- IC22-59 analysis used a ***simplified*** version of WB97 , which results in overestimated model nu-fluxes
- Assumed $F_\nu^{IC} / F_p = (1/8)\, f_{\pi,b}$, where 1/8 because 1/2 pγ lead to π^+ and each ν_μ carries 1/4 E_π, and $f_{\pi,b} = f_\pi\,(E = E_b)$
- Used $f_\pi\,(E) = f_{\pi,b}$, but this is OK only for $E_b < E < E_{\pi,cool}$;
- Also for $E < E_b$, have $f_\pi \propto E$, because of decr. # of photons
- Net result: model ν_μ flux ***overestimated*** by factor ~5

Graphically....

Even using the (old paradigm) int. shock model, the simplifications have an effect



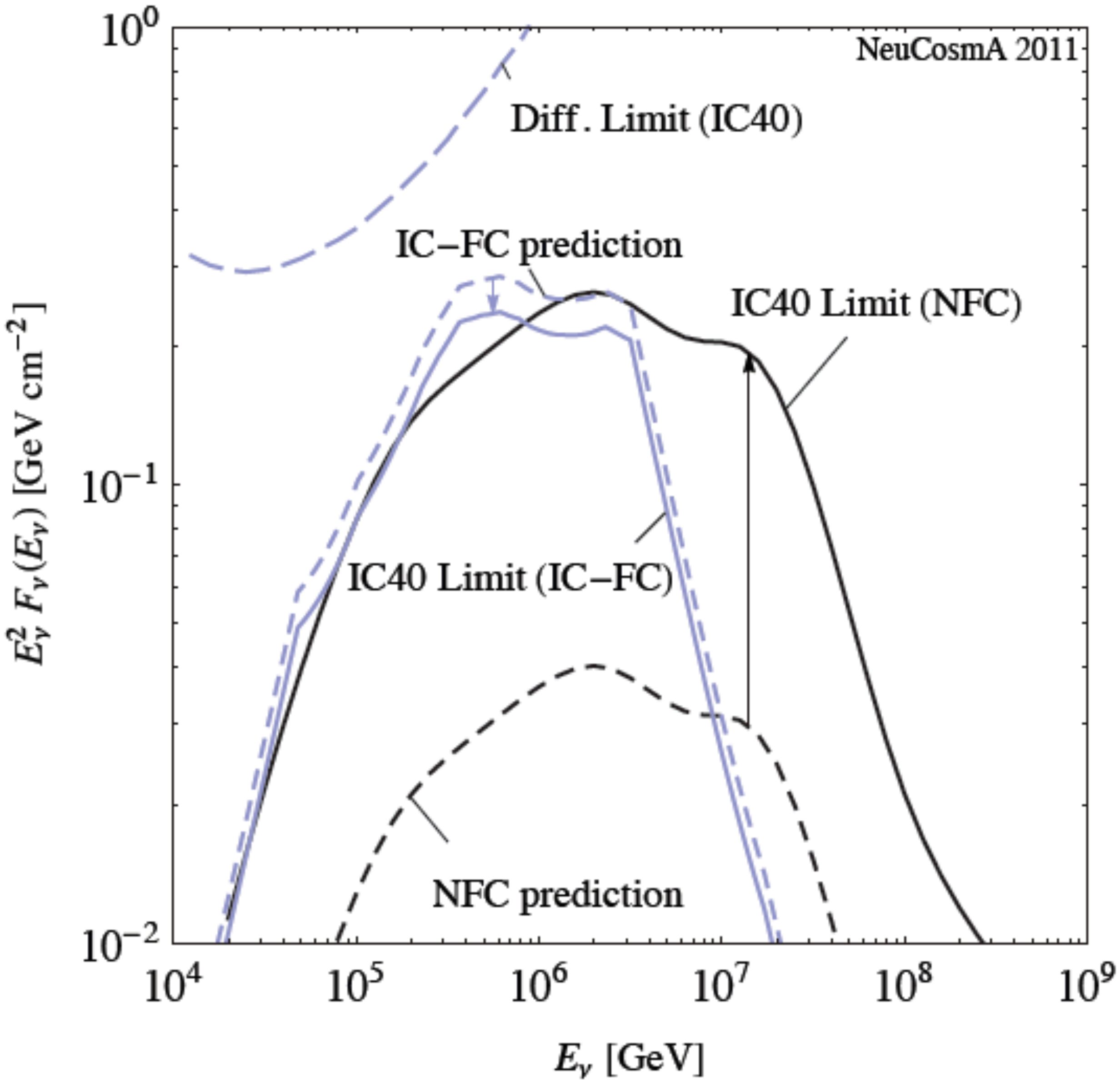


- IC-FC: IceCube Fball. Calc.
- RFC: "Revised" Fball.Calc. ⇒
- NFC: Numerical Fball.Calc.

(Hümmer et al, arXiv:1112.1076)

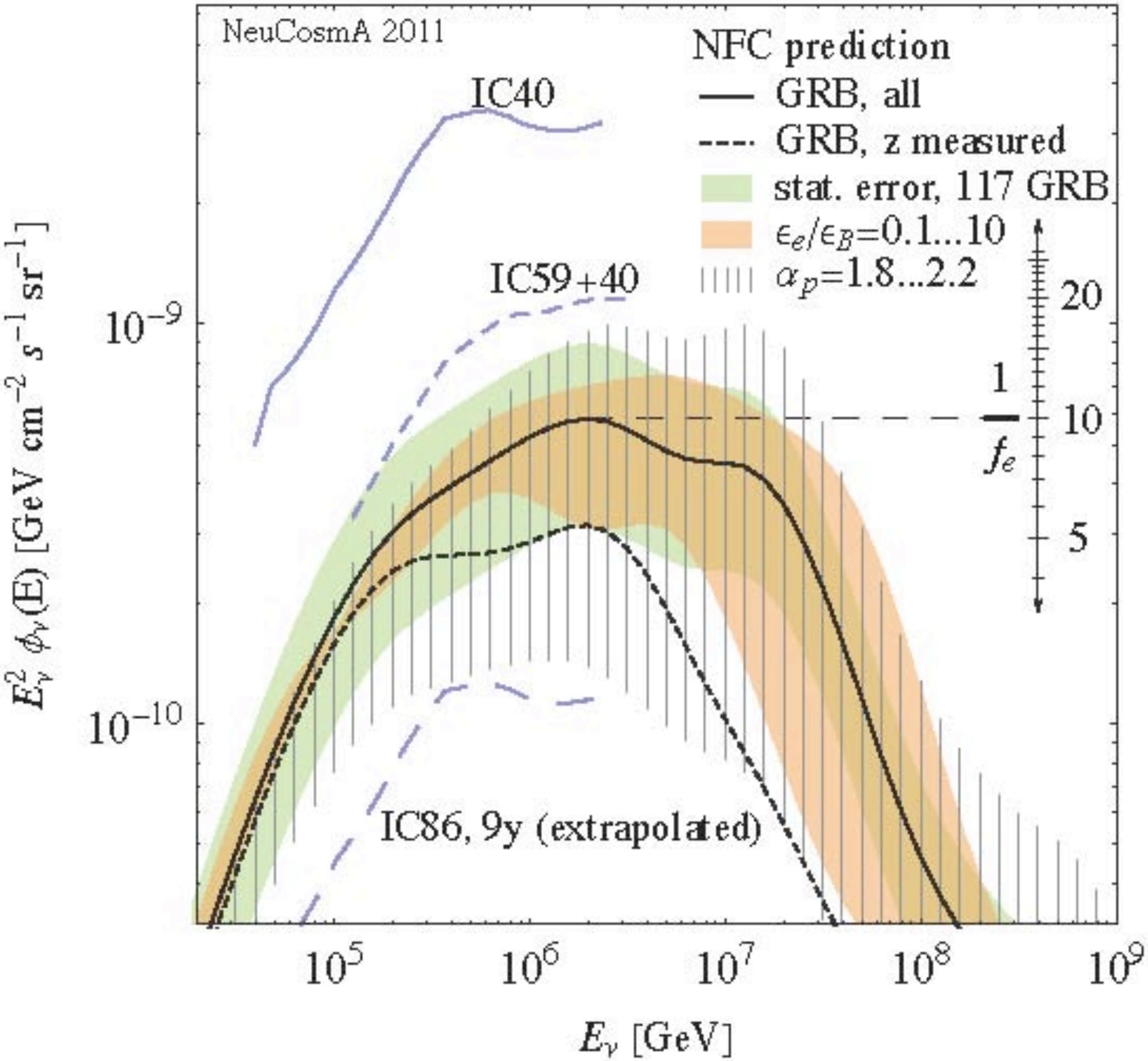
- f_C: energy of all photons approx. by break energy
- $f_\approx$: 0.7 (rounding error in one eq.)
- f_σ : 2/3(negelected width of Δ-res.)
- C_s : correct en. loss of second's & E-dep of proton mfp

Comparison using IC40 data



- IceCube 40 str. results :
  -IC-FC analyt. predict. (dash-blue)
  - IC40 Upper Limit (full-blue)
- Huemmer et al results:
  - NFC num. prediction (dash-black)
  - IC40 (NFC) Up.Limit (full-black)

In summary .... (1)



- Even when using old paradigm of ***internal shock***, but more detailed physics (incl. multi-pion and Kaon production, $\neq$ cool'g. break for π, μ, and numerical as opposed to analytical calcul.)
- ***⇒ F_ν predictions below IC40+59 !***

(Hümmer et al, arXiv:1112.1076)

(see also
Li, arXiv: 1112.2240 ;
He, et al, arXiv:1204.0857)

Also ..... (2)

- Internal shock model use is ***expedient***: best documented so far, and easy to calculate ⇒ reason why its use is widespread
- ***But*** ... int. shocks known (past 10 years) to have difficulties for gamma-ray phenomenology (efficiency, spectrum, etc)
- ***And***, acceleration rate of protons vs. electrons is unknown; are protons injected into accel. process at = or ≠ rate as electrons? Only energy restriction on model is $L_p/L_e \lesssim 10$.
- ***Alternatives to internal shock***: being investigated - but so far, are less easy to calculate. Progress, however, is being made.
- ***Even*** if GRB are not GZK sources, model indep. searches leave possibility of *lower, observable* nu-fluxes from GRB

New developments in "internal shock-like" dissipation regions

Are of two main types:

- Magnetic dissipation regions, R~ 10^{15} cm, allow GeV photons - but hard to calculate quantitatively details of reconnection, acceleration and spectrum, e.g. McKinney-Uzdensky, 2012, MNRAS 419:573
- Baryonic 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, e.g. as follows

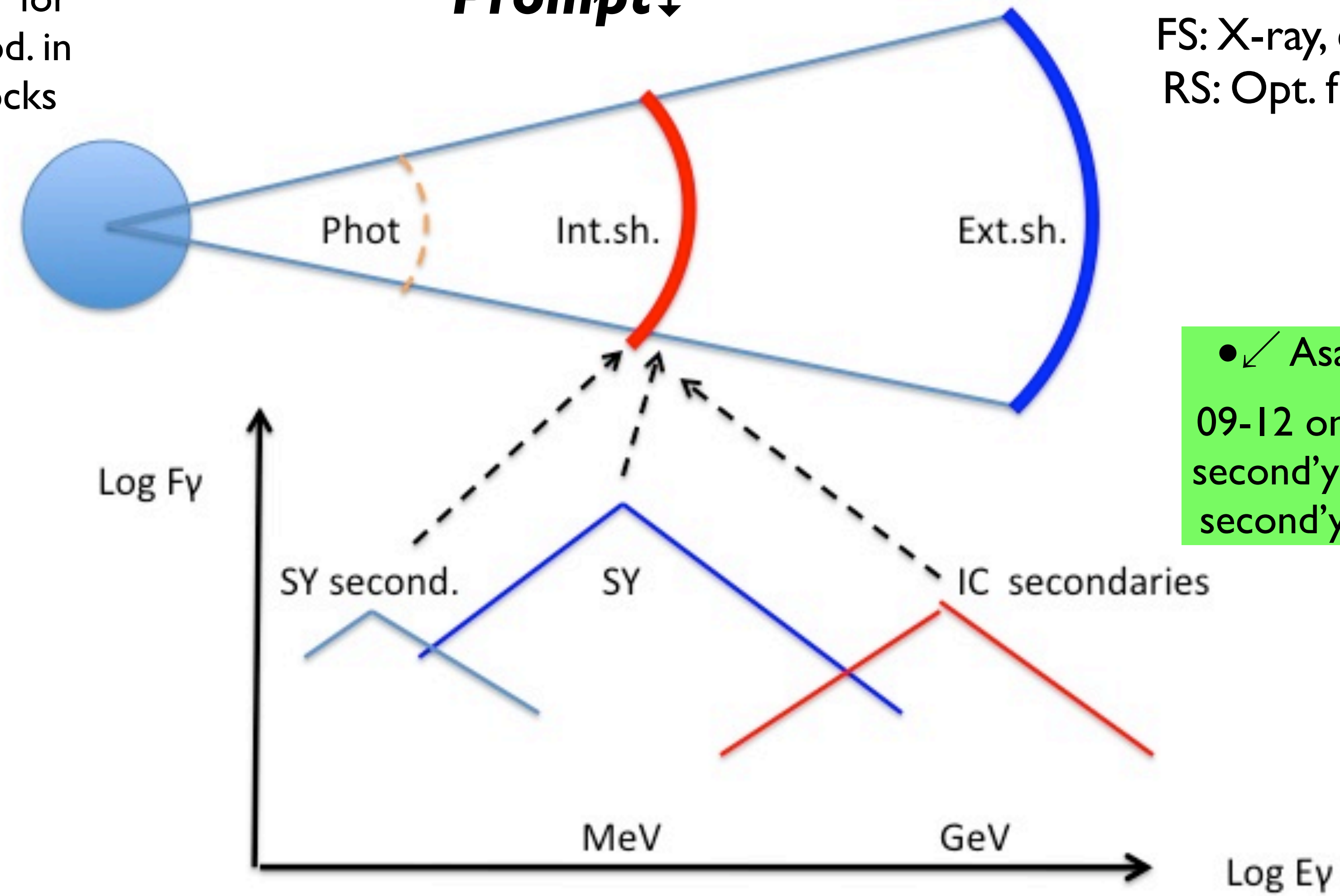
Simple hadronic: more detailed

• Orig: Waxman & Bahcall '97 for neutrino prod. in internal shocks

***Prompt*↓**

↙ ***Afterglow***

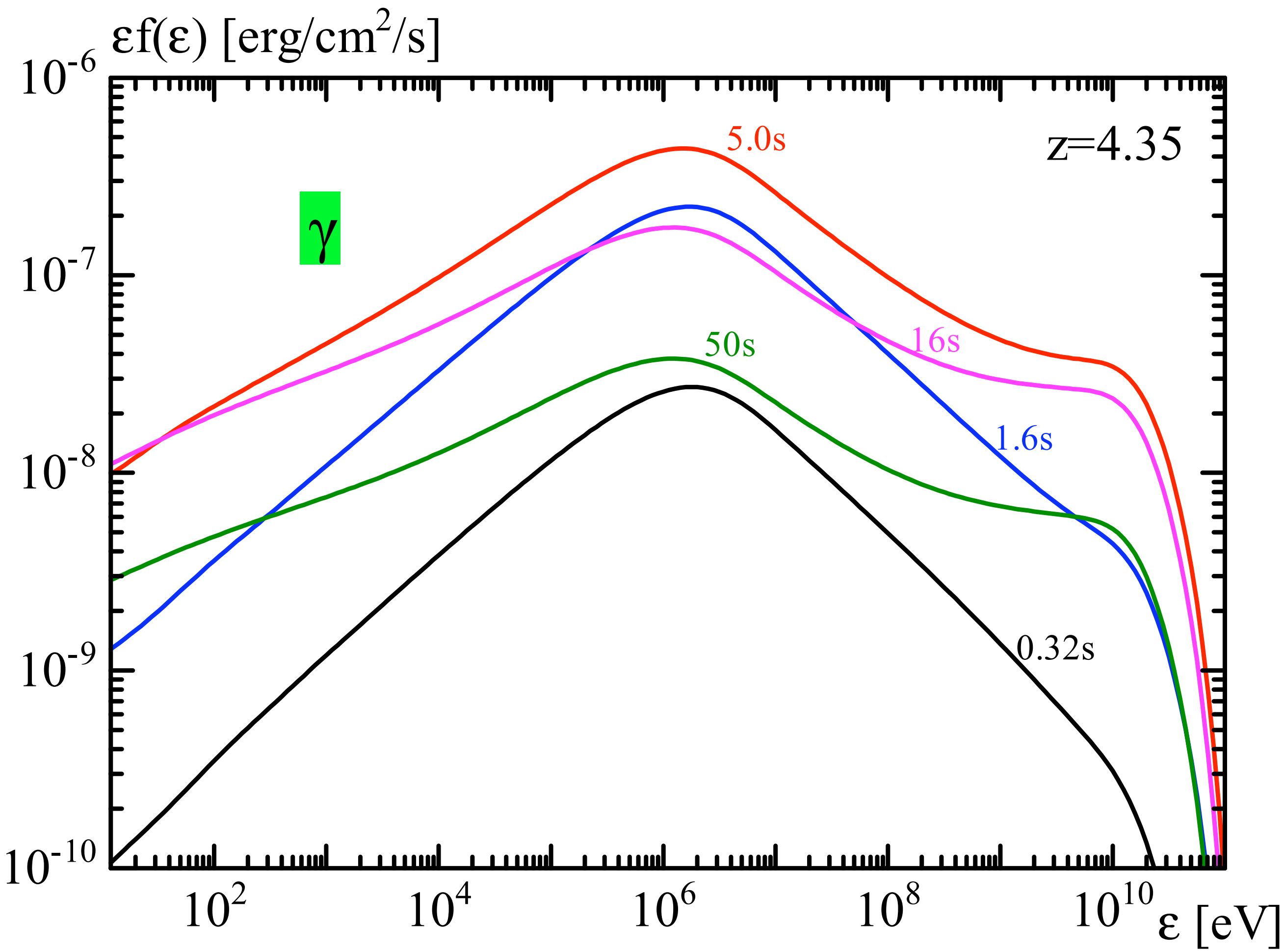
FS: X-ray, etc.;
RS: Opt. flash



•↙ Asano & PM, 09-12 on, calculate second'y photons & second'y neutrinos

Now: numerical time dependence of photon & neutrino secondaries

(Asano & PM, ApJ sub.)

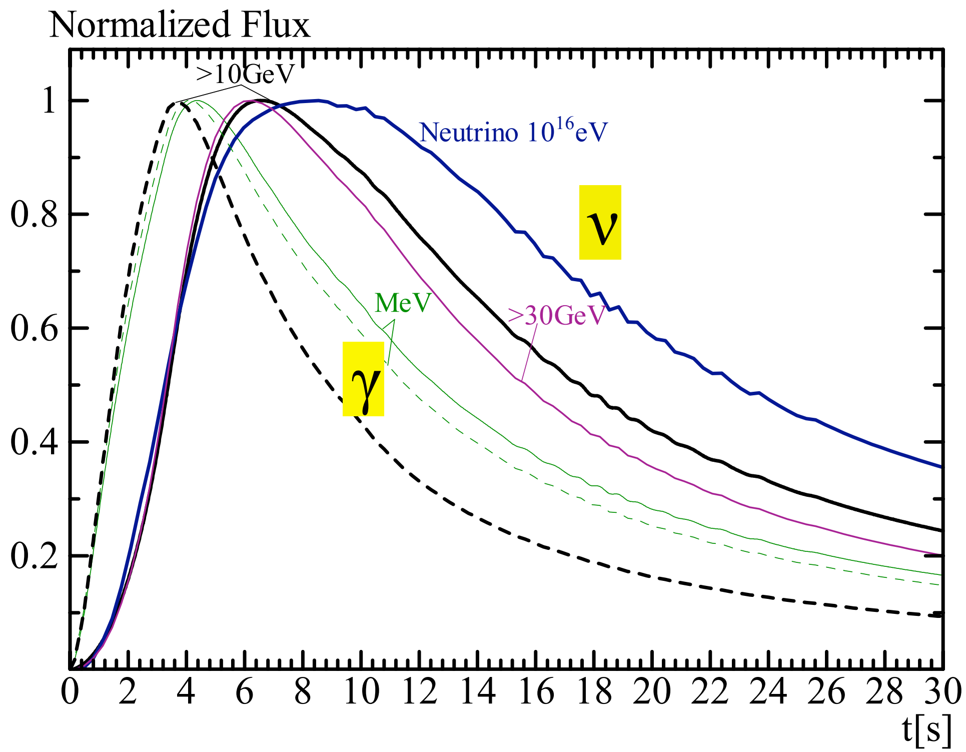


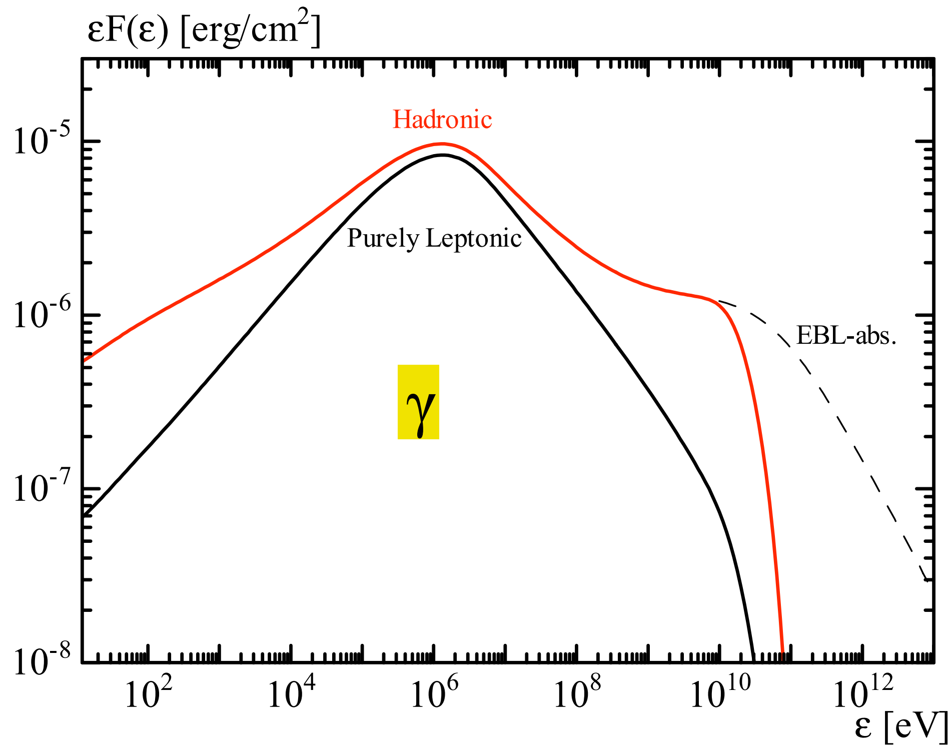
- Generic dissipation region at a radius $R \sim 10^{14}$-10^{16} cm (could be Int.Sh. or mag. diss. region, etc.)
- Numerical Monte Carlo one-zone rad. transfer model with all EM & ν physics
- ←Fermi/LAT param. $E_{\gamma iso} \sim 2.10^{54}$, $L_p/L_e=20$, $\Gamma=600$, $R \sim 10^{16}$cm, z=4.5

Fermi/LAT hadronic case

- For very bright, rare bursts (<10% of all cases)
- Get 2nd GeV γ- comp. & its delay
- Predict complying ν-flux, but on rare LAT bursts and at > 10^{16} eV
- Predict substantial nu-gamma delay

(Asano & PM, ApJ sub.)

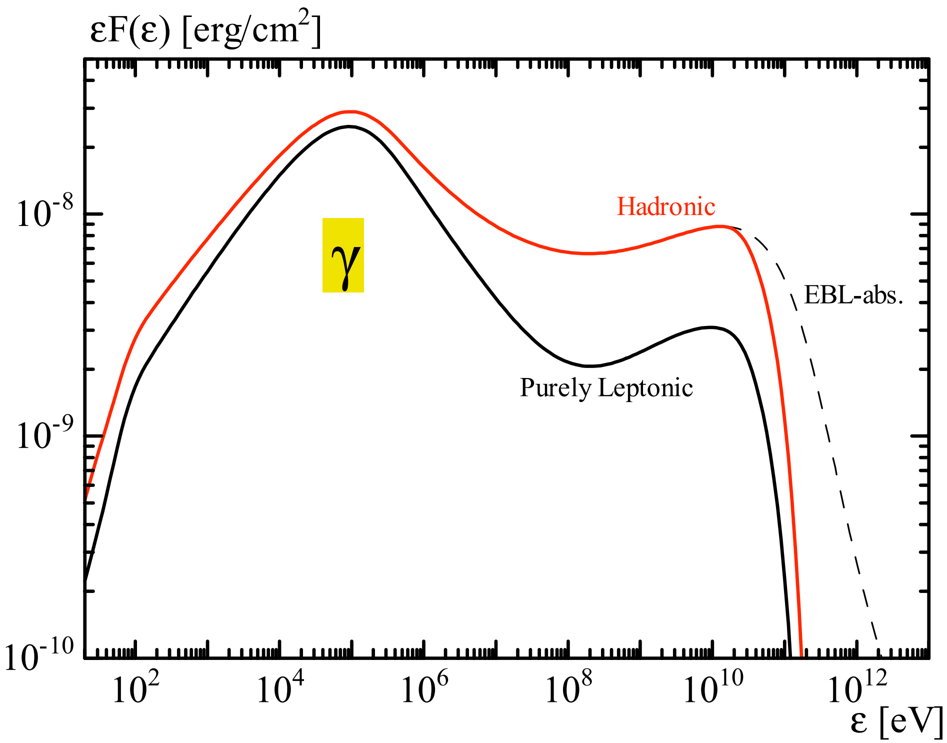


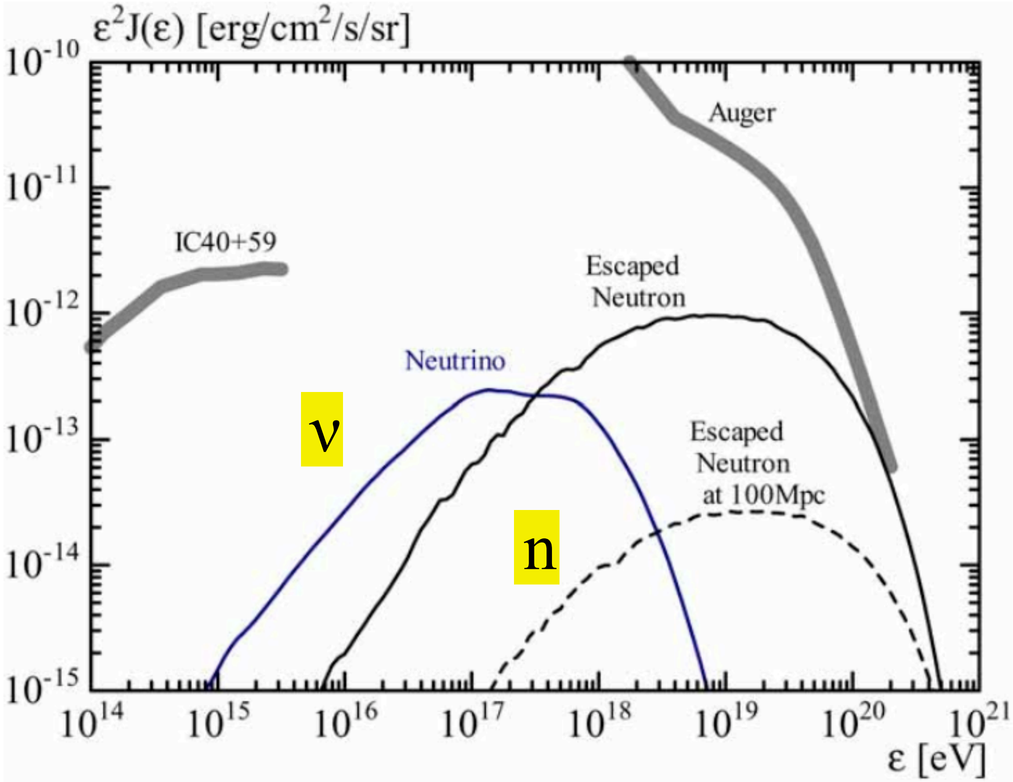


"Moderate" hadronic case

(Asano & PM, ApJ sub.)

"Typical" GRB params., $E_{\gamma iso}$~5.10^{50} erg, L_p/L_e=10, Γ=800, R~10^{14}cm





- Predict complying nu-flux, at $>10^{16}$ eV - may be detectable in future
- Predict larger 2nd photon component than does leptonic model, in all bursts and starting in the prompt phase - perhaps hard to detect if low photon stats.?
- UHECR flux from escaped neutrons: not sufficient, if L_p/L_e=10 - need more work!

Outlook

- ***Observational prospects for ground-based multi-GeV astrophysics of GRB are very encouraging - there are enough bursts that show photons there!***
- ***If GRB spectra reaching TeV are detected, this would provide new constraints on hadronic vs. leptonic GRB models - but much further theoretical work is needed to specify models***
- ***Of course, GeV-TeV neutrino observations could clinch this issue - further address GRB-GZK UHECR contrib.***
- ***Will be able to constrain particle acceleration / shock parameters, compactness of emission region (dimension, mag.field,.), etc.***