

EXTRAGALACTIC GAMMA-RAY SOURCES

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Amsterdam, TeVPA 2014

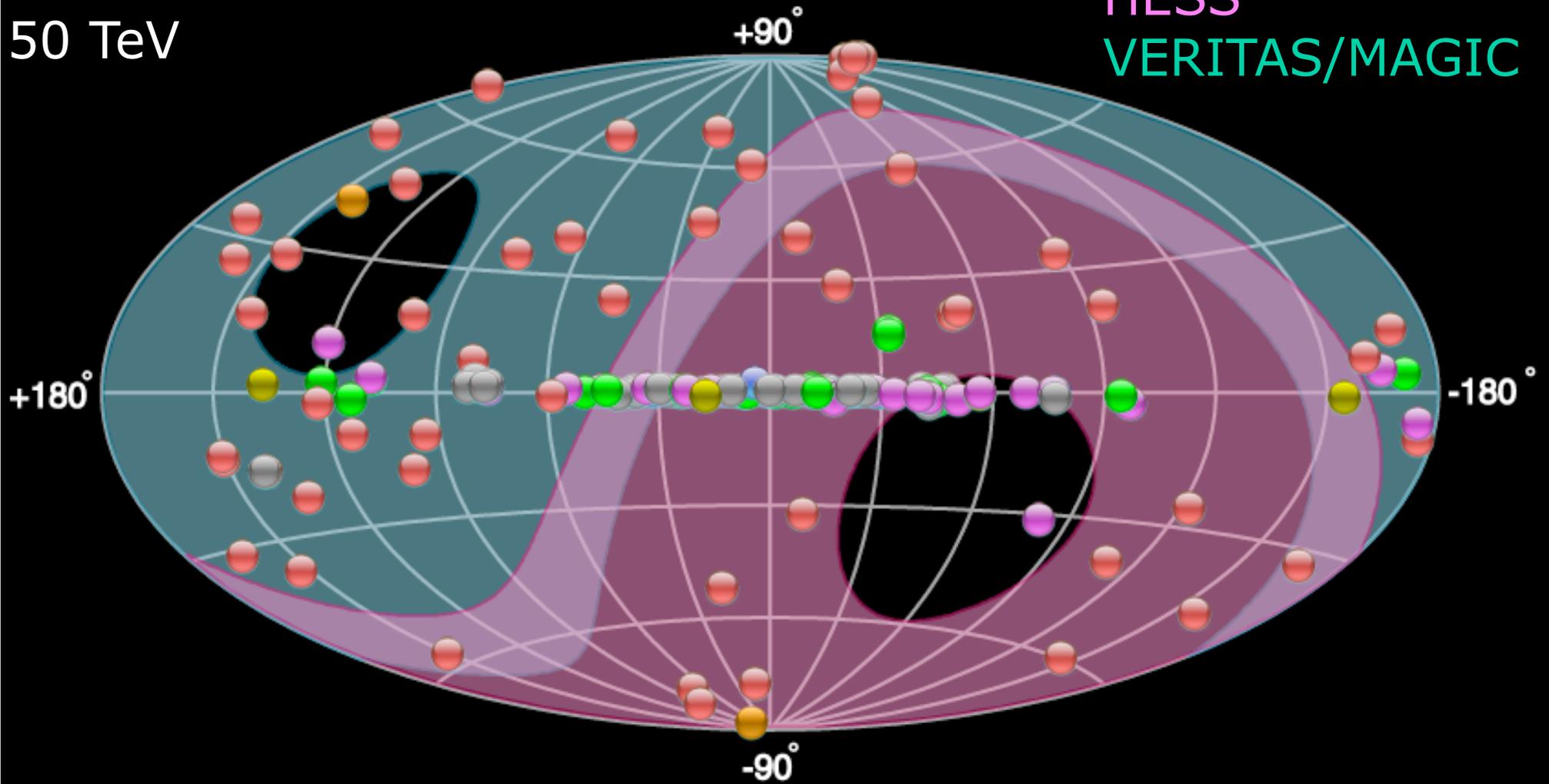
In particular...

- AGNs
- GRBs
- SFGs, SBGs (star-forming or starburst gals)
- GMSs, GSs (galactic merger or gal. shocks)
- IGB, INB (intergal. gamma or neutrino bkg)

100 GeV to
50 TeV

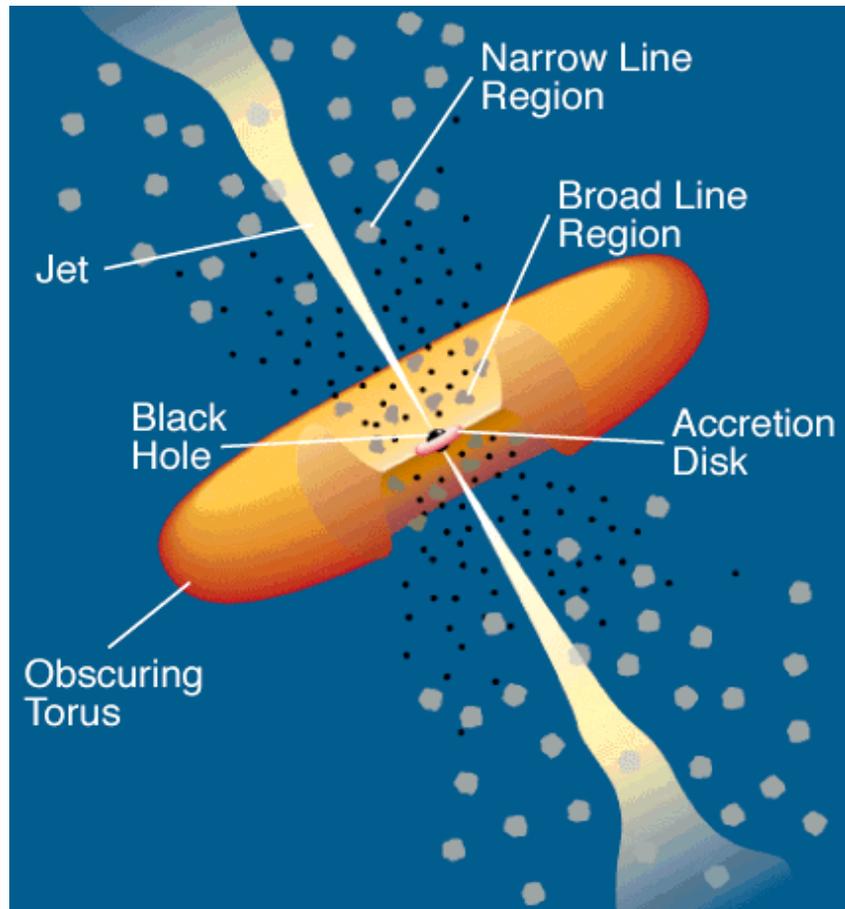
Credit TeVCat

HESS
VERITAS/MAGIC



The **extragalactic** TeV sky is dominated by blazars (mainly BL Lacs)

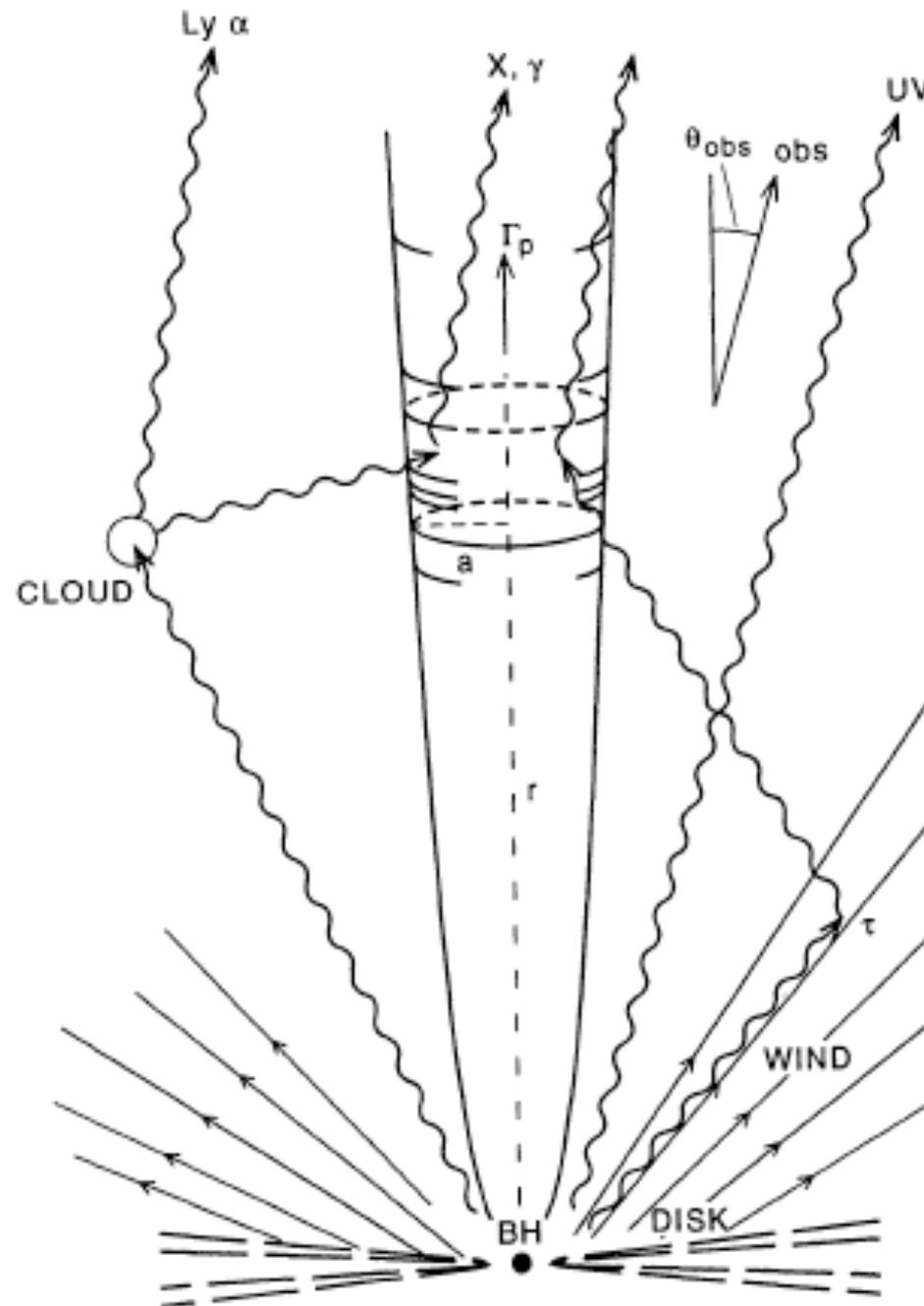
AGN as UHE γ sources



- Massive BH (10^7 - $10^8 M_{\text{sun}}$) fed by accretion disk \rightarrow jet
- Lorentz factor $\Gamma_{j,agn} \sim 10$ -30
- UV target photons from (1) accr. disk, (2) BLR line clouds
- Typical (“leptonic”) model: e^{\pm} accel. in jet shocks, and SSC (sync-self-compton); SEC(sync-exterior.compton)
- Typical hadronic model: p accel, in jet shocks, $p\gamma$ photomeson interactions, \rightarrow EM cascades

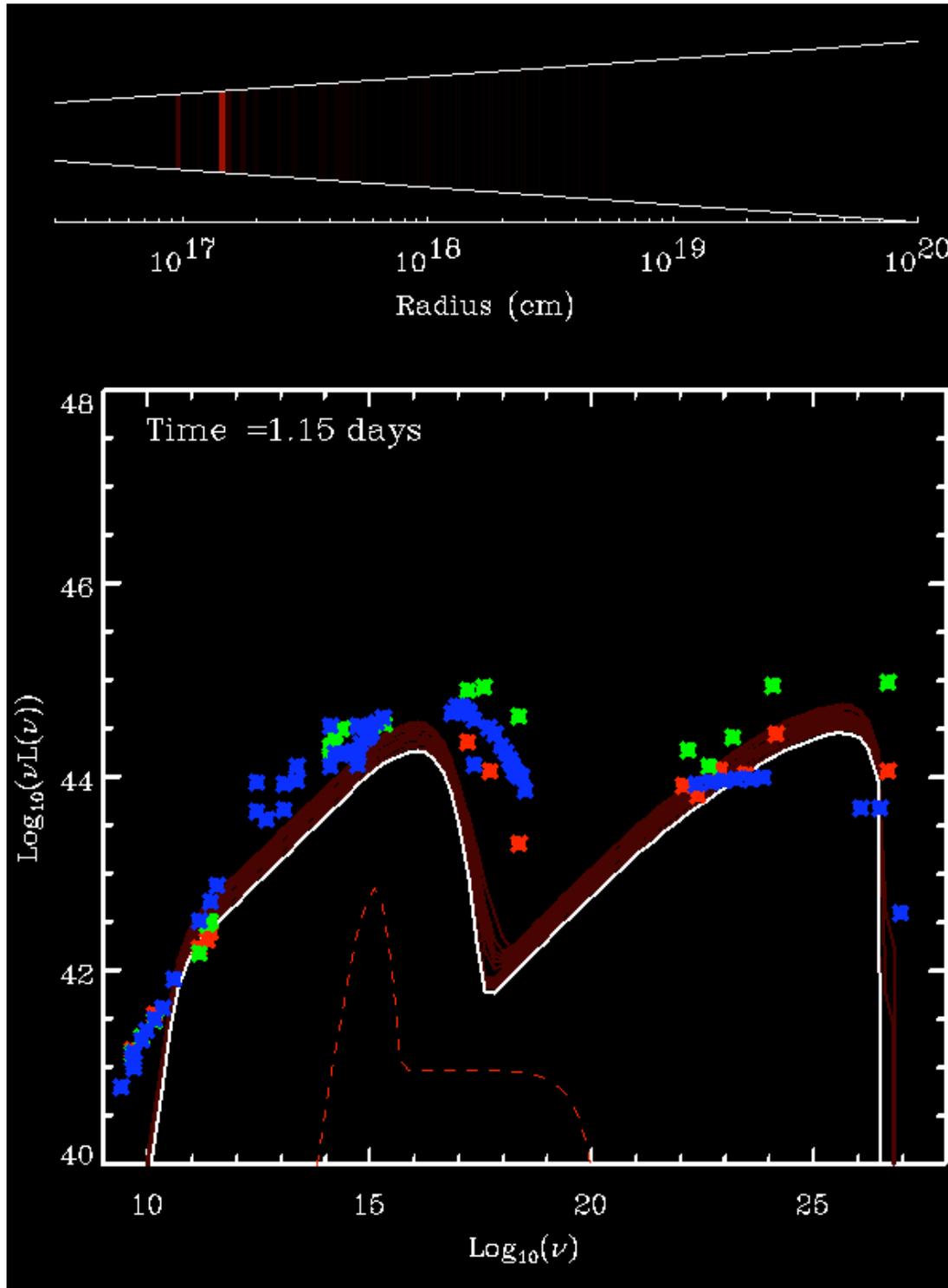
AGN Jet lepto-model

e.g., Sikora, Begelman & Rees
'94, ApJ 421:153



- Archetypal model of the AGN VHE γ -ray emission, from:
- (a) upscattering of synchrotron photons by same emitting e^\pm (SSC),
- (b) upscattering of external (disk, cloud) target photons (EIC)
- Many previous and subsequent authors & versions

MRK 421: leptonic



Ghisellini et al, Spada et al,
leptonic IS model, 2004

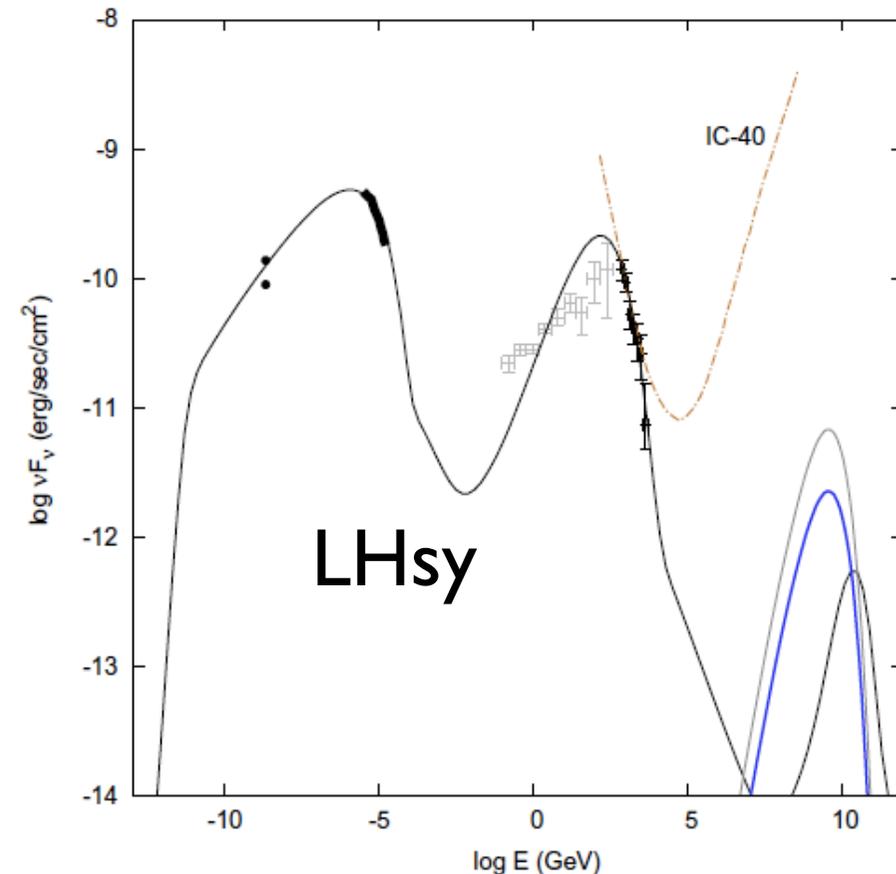
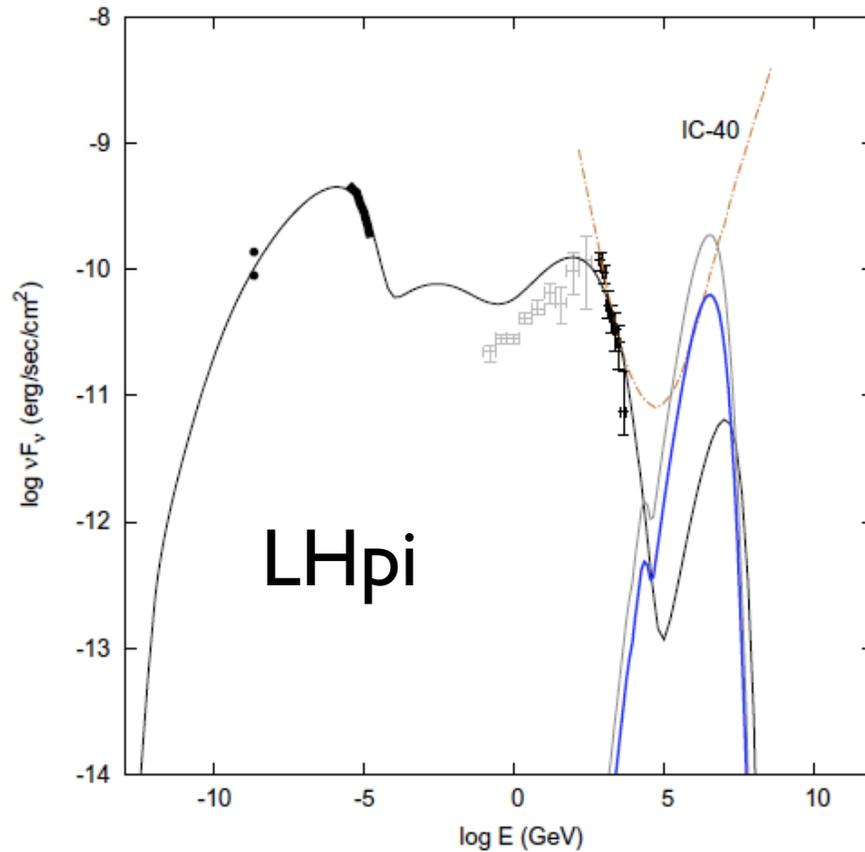
- Random intermittently ejected shells of variable bulk Lorentz factor → “internal” shocks
- Leptons accelerated to PL distribution via Fermi in these internal shocks
- Emit synchrotron and upscatter self- or external photons

Mrk 421

leptohadronic:

Dimitrakoudis, Petropoulou,
Mastichiadis '14 ApPh 54:61

Same shocks also accelerate protons



- Two models: LHpi (γ from pi-decay) and LHsy (γ from p-sync.)
- Use kinetic eqs. for primaries & second'y, SOPHIA code for p, γ
- Fit requires very flat $\Gamma_p, \Gamma_e \sim 1.2, 1.5$ (e.g. Niemec-Ostrowski)

Black pts: March 22/23 2001
Grey pts: Fermi (non-simult.)
Thin dark line: photon fit
Grey line: nu fit (all flavors)
Blue thick line: muon nu fit

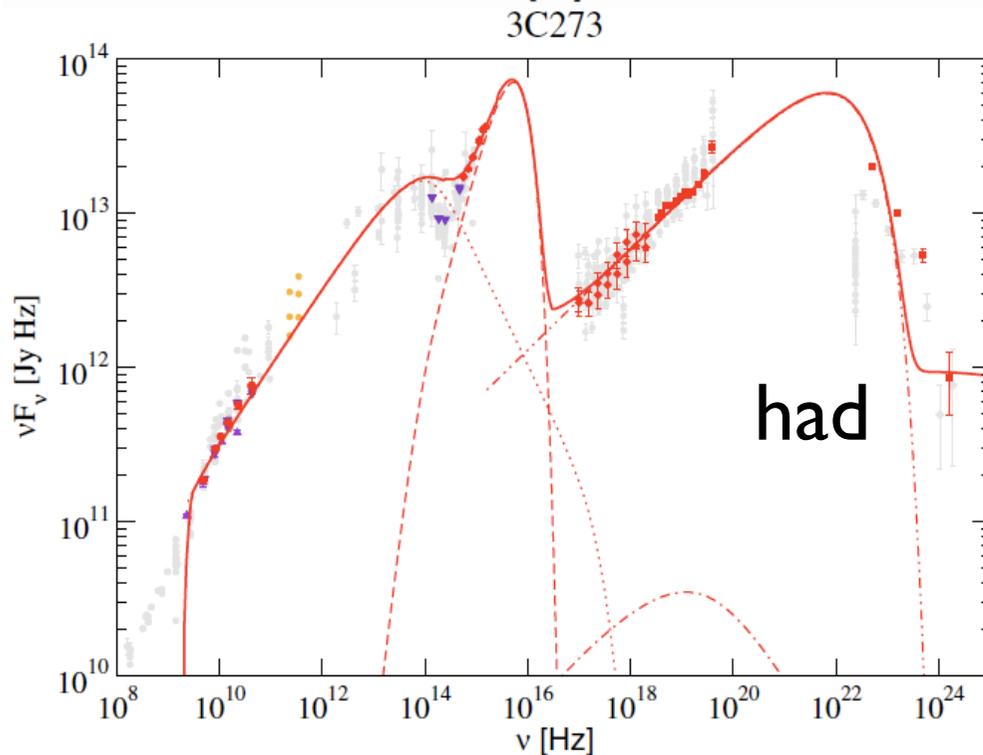
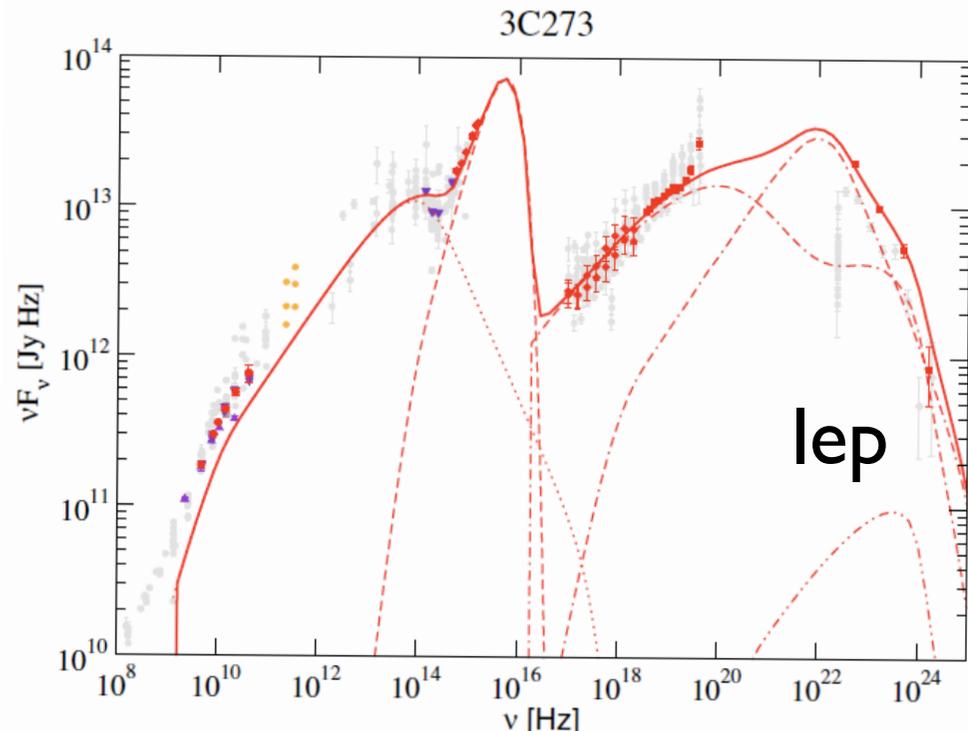
FSRQ 3C273

Leptonic vs. leptohadronic multi-band photon fits

Boettcher, Reimer, Sweeney,
Prakash '14, apj 768:54

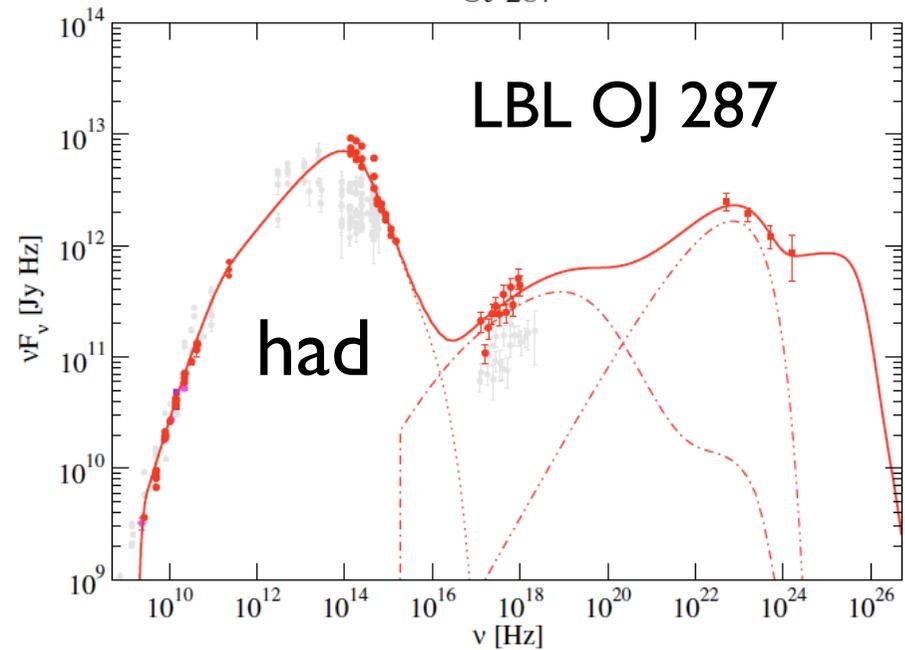
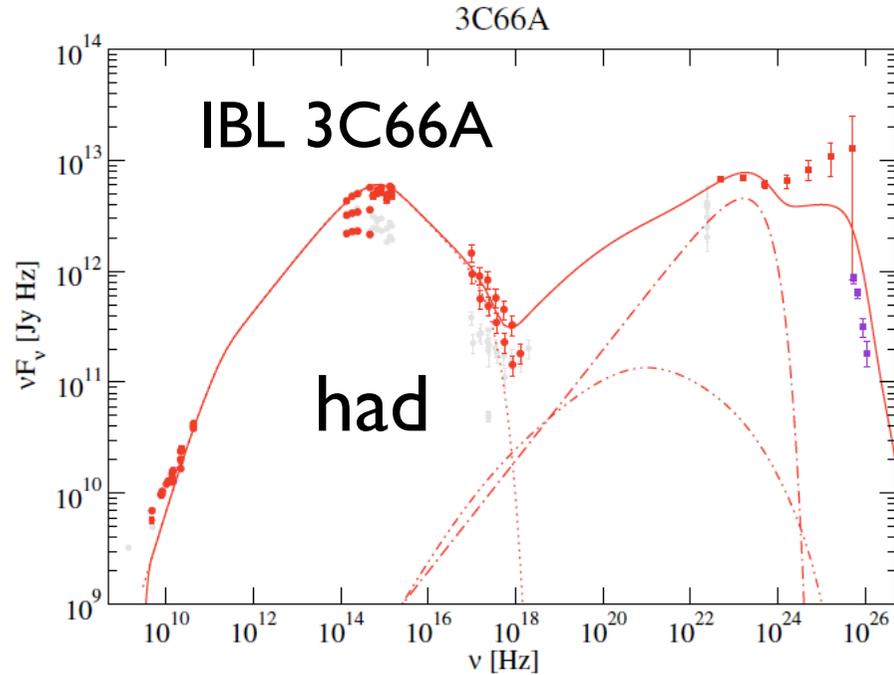
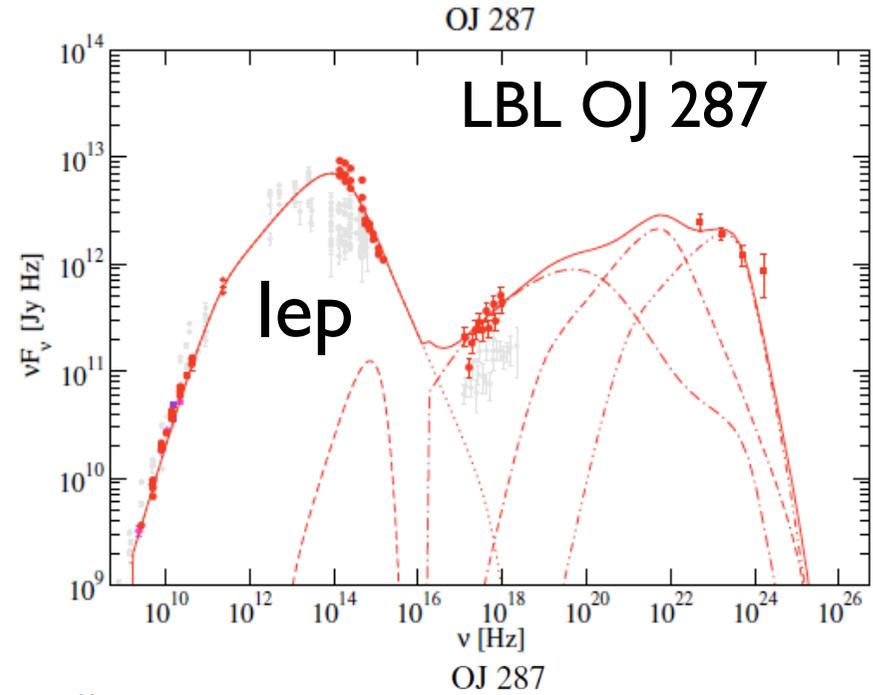
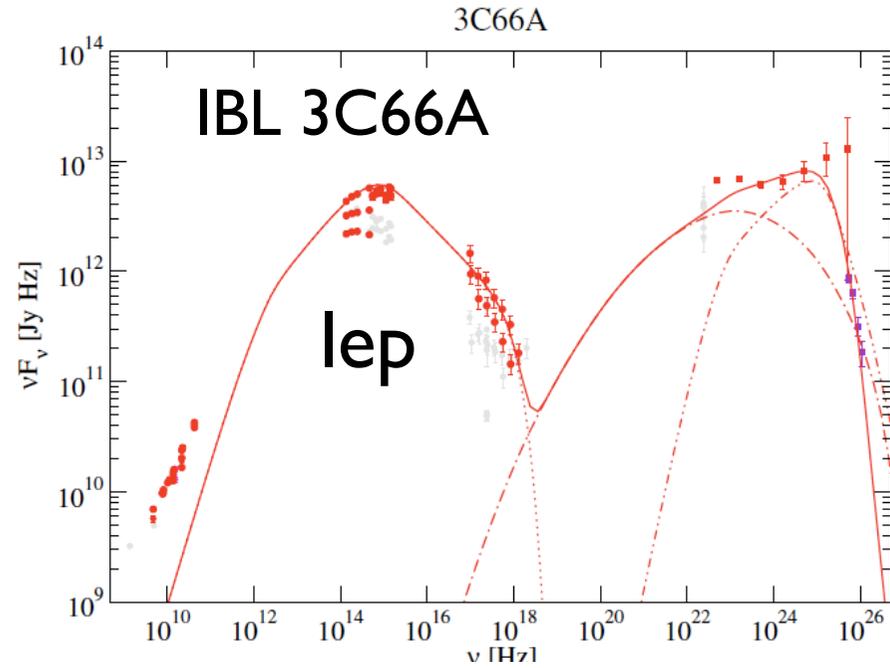
- Compare **two** models :
- (1) **leptonic** SSC, EC
- (2) **lepto-hadronic** w. semi-analyt. cascades)
- Photon targets from accr. disk, BLR clouds
- Fit 6 FSRQ, 4 LBL, 2 IBL

dotted: sync / dashed: accr. disk / dot-dash: SSC / dot-dash-dash: EC(disk) / dot-dot-dash: EC (BLR)

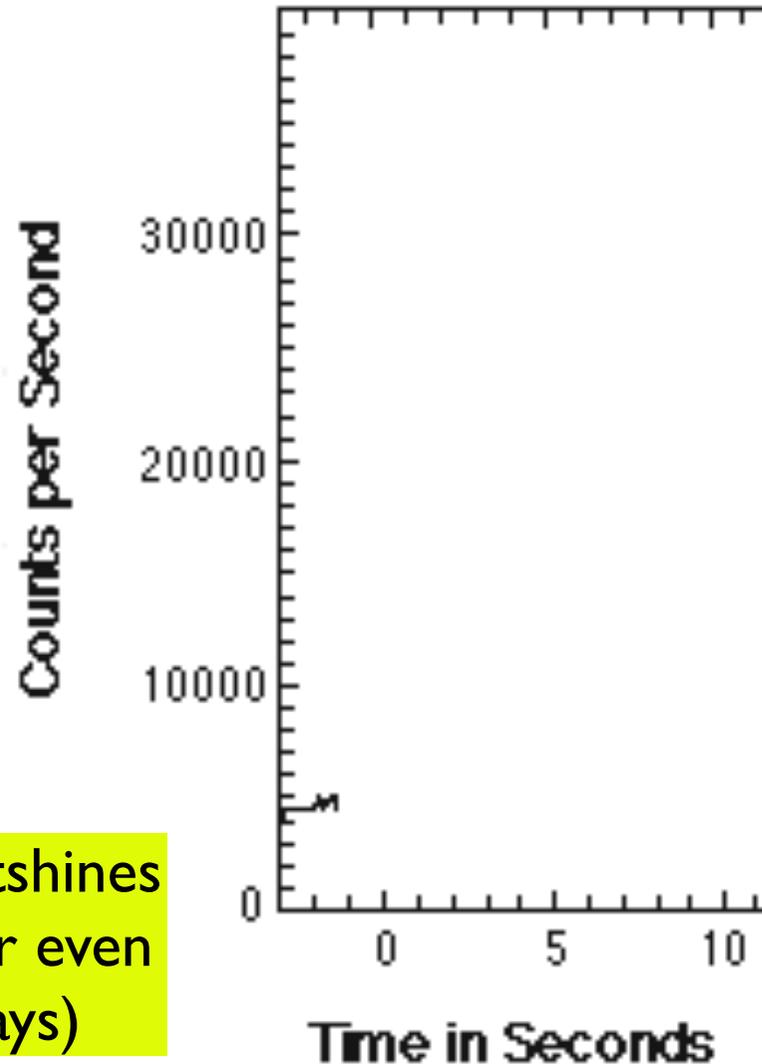
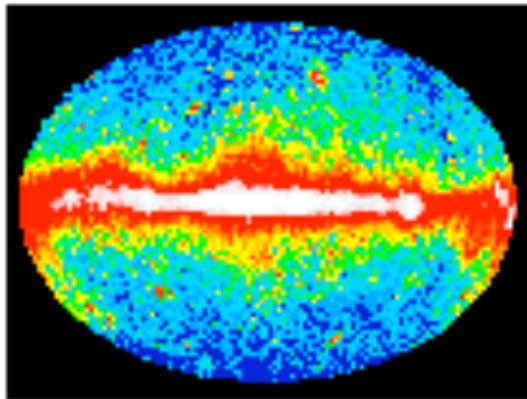


Blazars (IBL, LBL) fits

Boettcher et al'14, apj 768:54



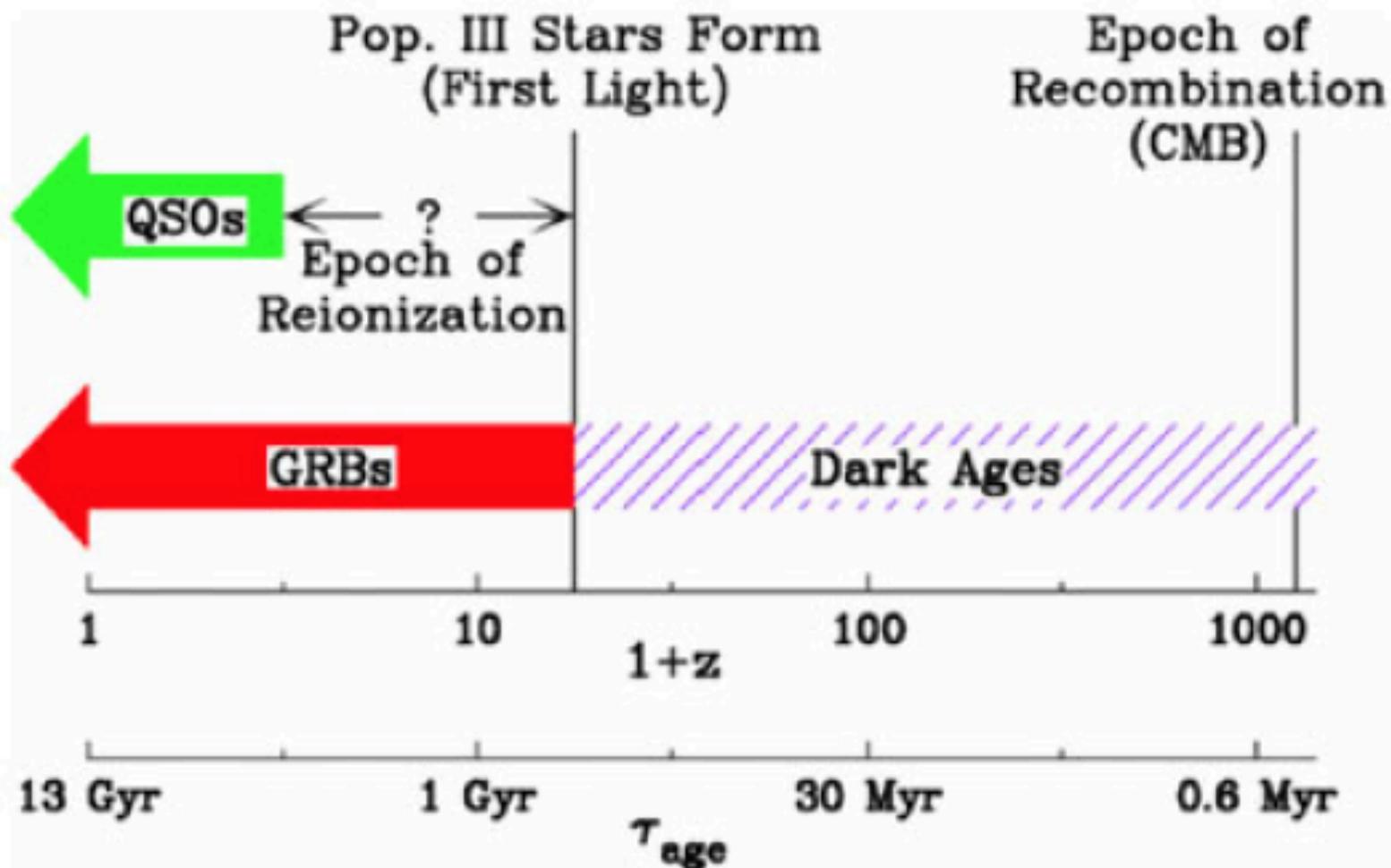
GRBs: flood the gamma-ray sky



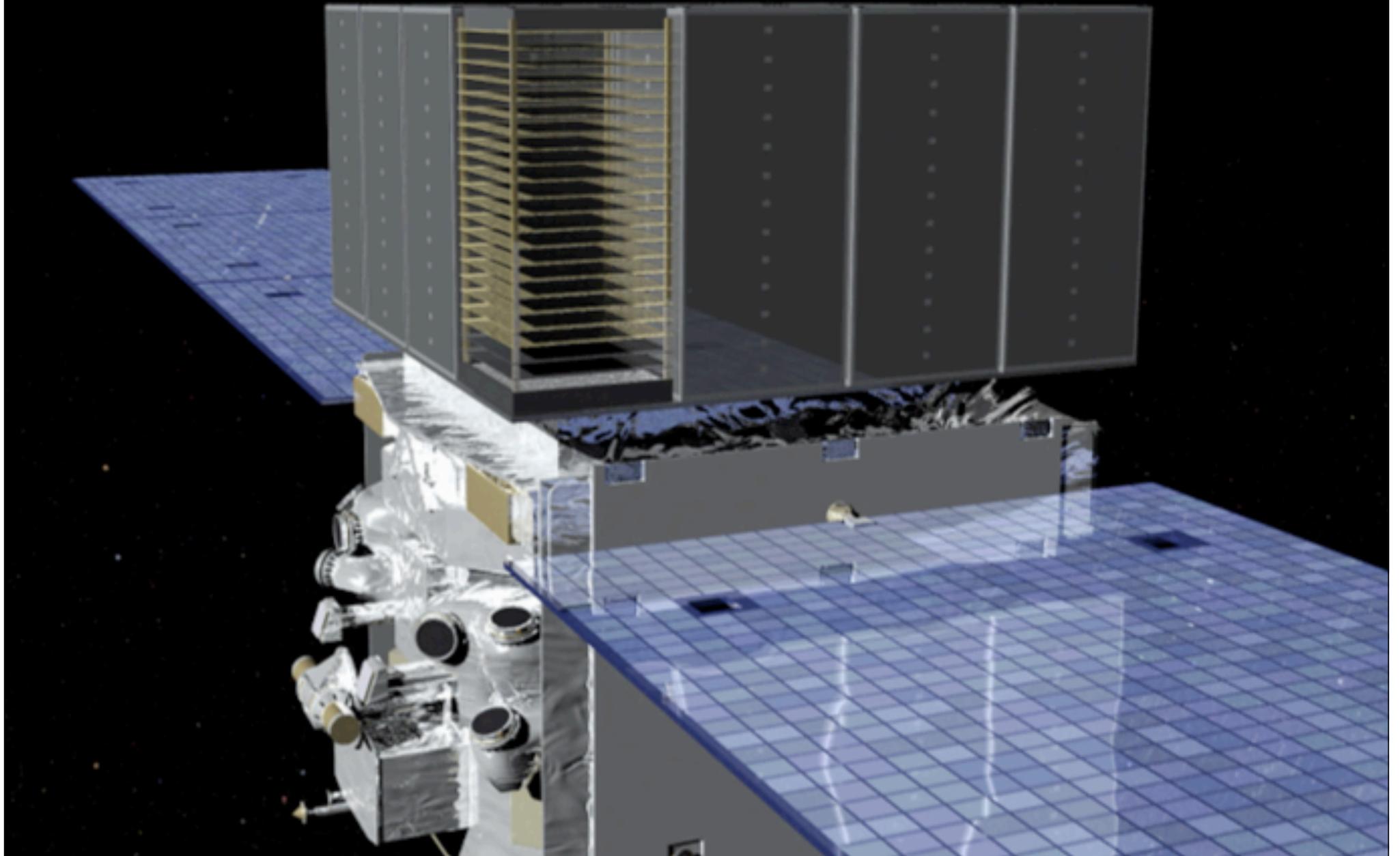
When “ON”, a GRB outshines blazars by up to 10^5 - or even the Sun (in gamma-rays)

- Cataclysmic stellar event (stellar core collapse, or compact bin. merger)
- \approx smaller, turbocharged AGNs
- $M_{\text{bh}} \sim 3-15 M_{\odot}$, LF $\Gamma \sim 10^2-10^3$

GRBs in Cosmological Context

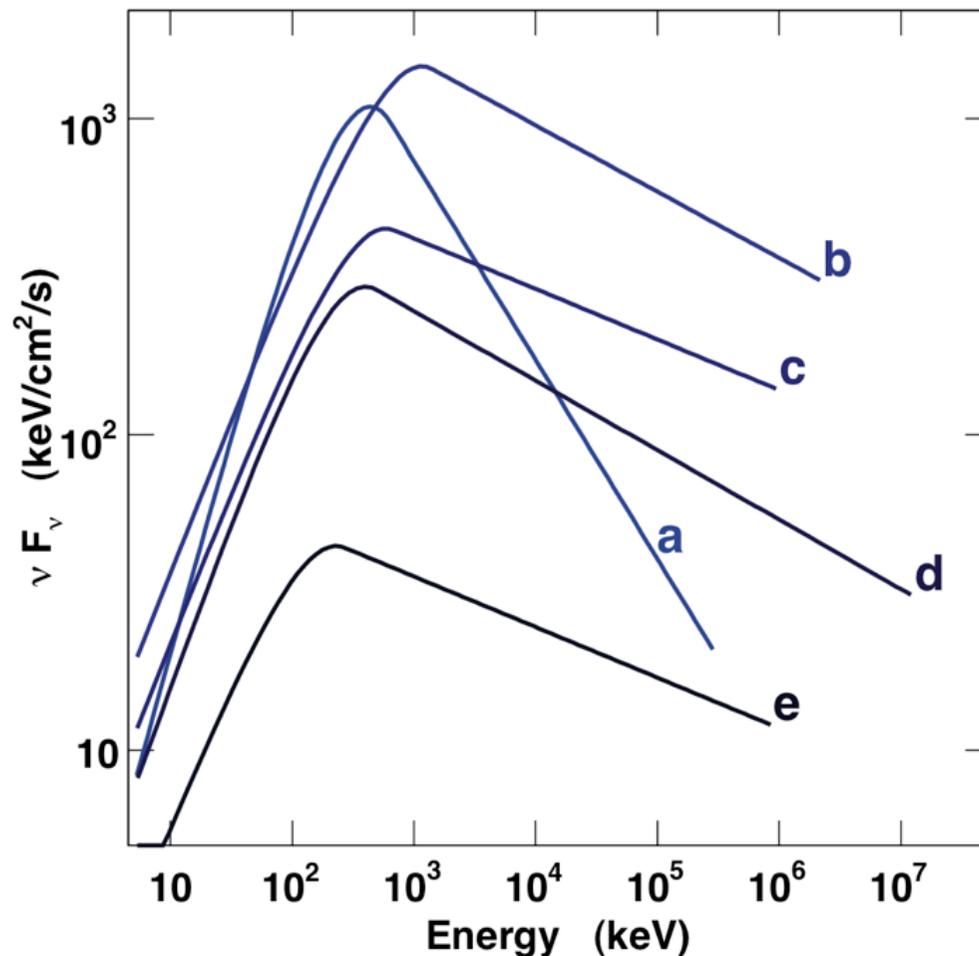


Fermi



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** (10³ s) GeV afterglow
- **Little** evidence for **2nd** spectr. comp. (in **some** cases)

But: in other bursts, **Evidence of the “extra components”** ($>3-5\sigma$)

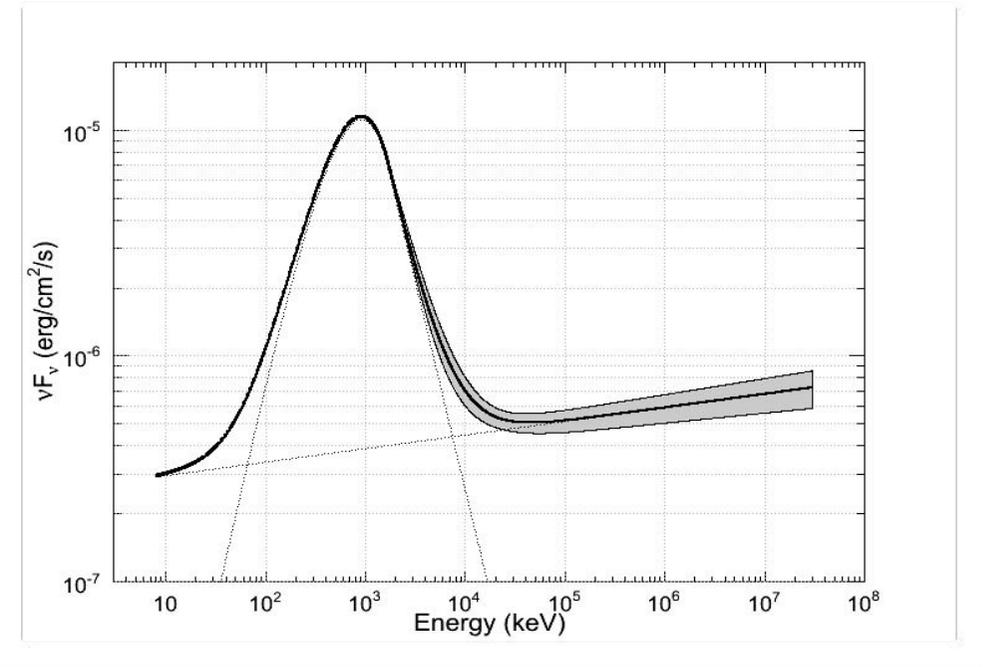
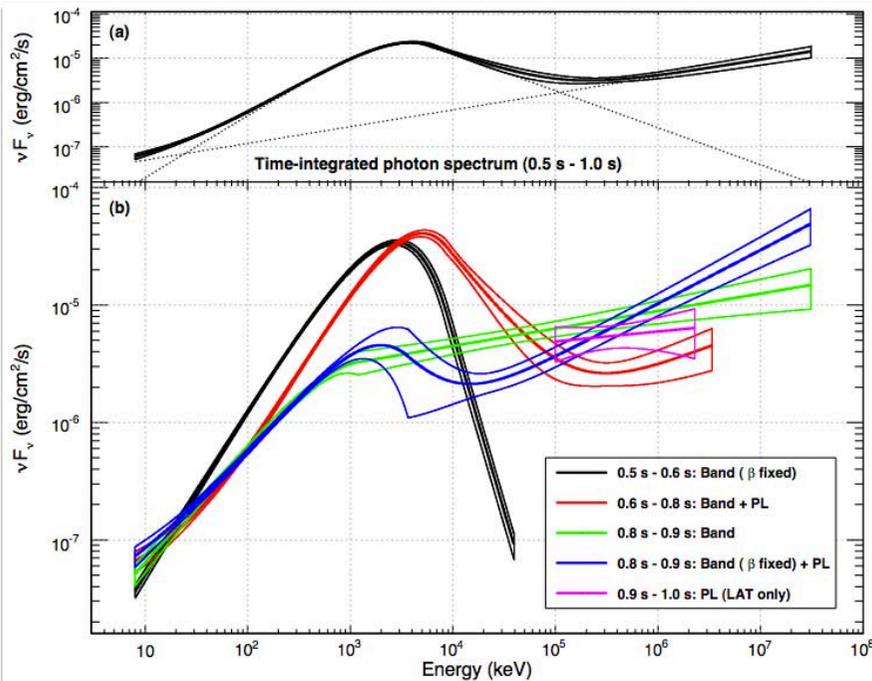


GRB 090510

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

GRB 090902B

Abdo et al. 2009, ApJ, 706L, 138A



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

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

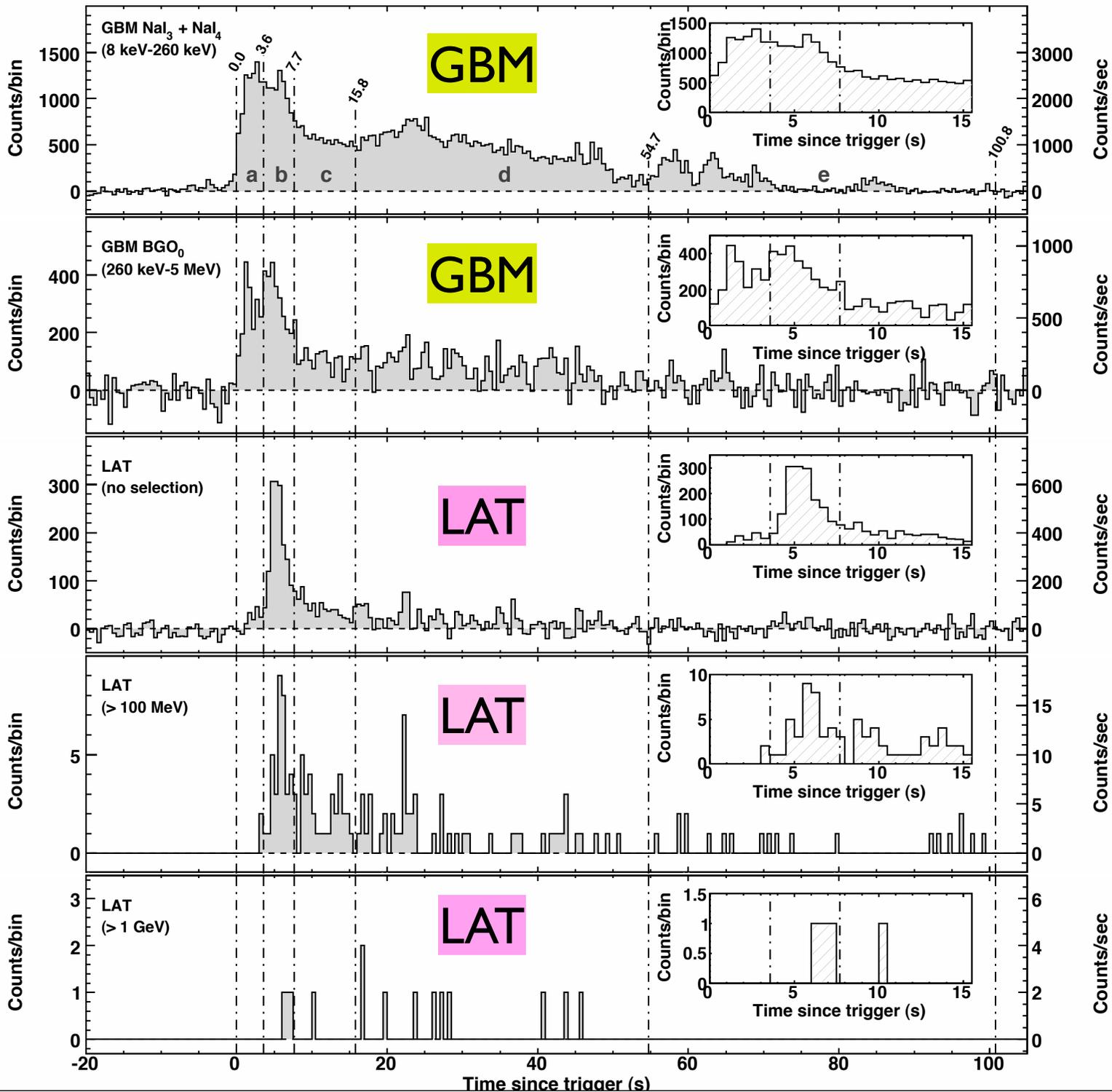
Some observed photon energies and redshifts

$E_{\text{obs}}(\text{GeV})$	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 $E_{\text{obs}} \sim 10 \text{ GeV}$ photons
- Some $z \sim 1$ bursts produce $E_{\text{obs}} \geq 30 \text{ GeV}$ photons (130 GeV in rest frame!)

• \Rightarrow *encouraging*
for low E_{th} ACTs:
HAWC, CTA...

GRB 080916c

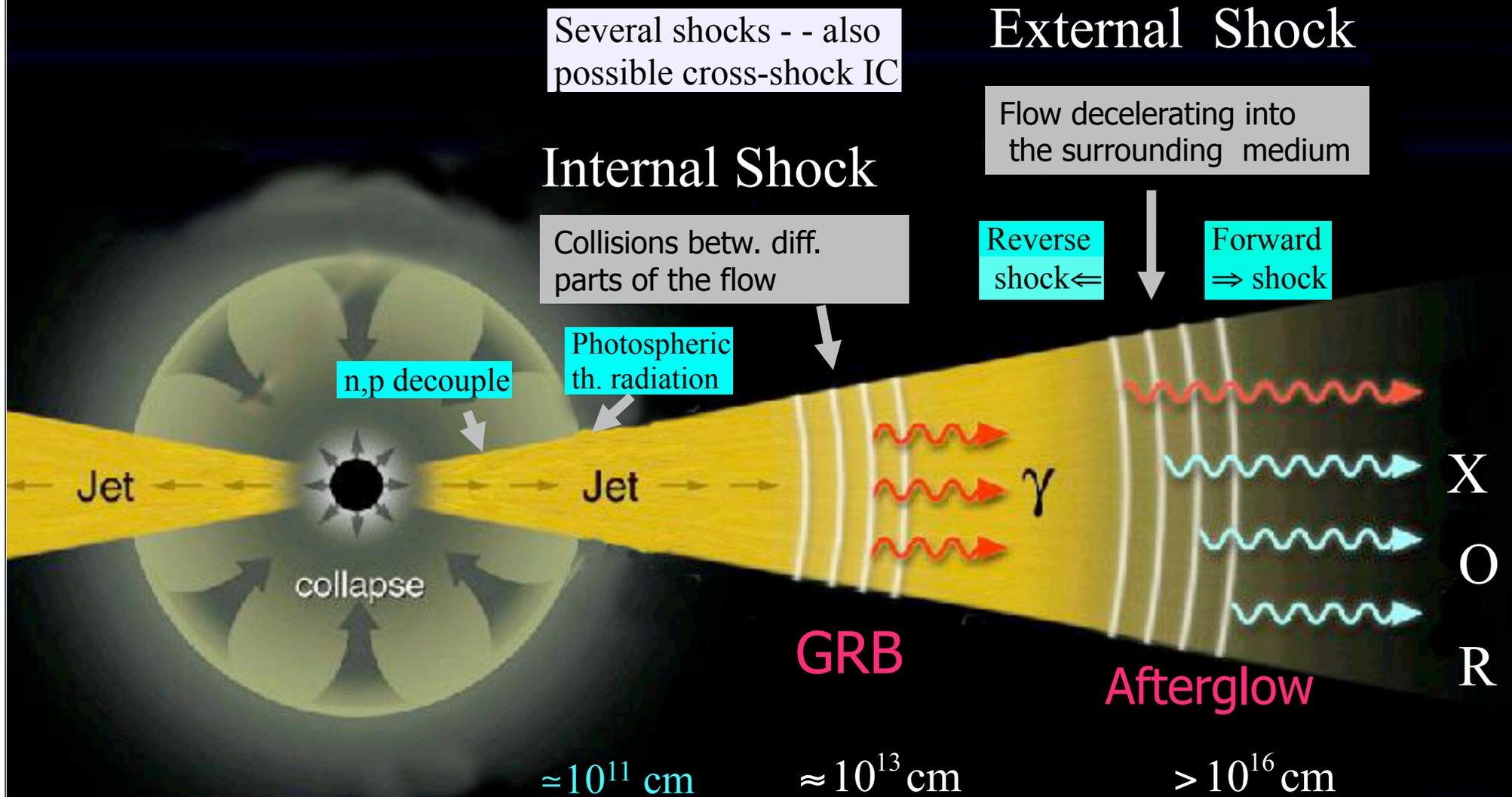


Light-curve
 $E \downarrow$

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

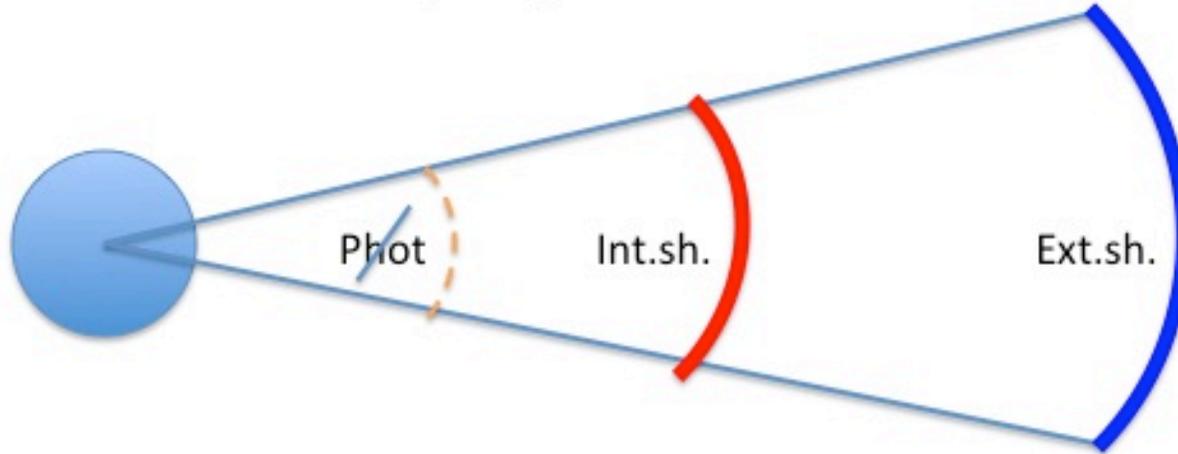
Note :
GeV photons
← “lag”
behind MeV!

Fireball Shock Model of GRBs



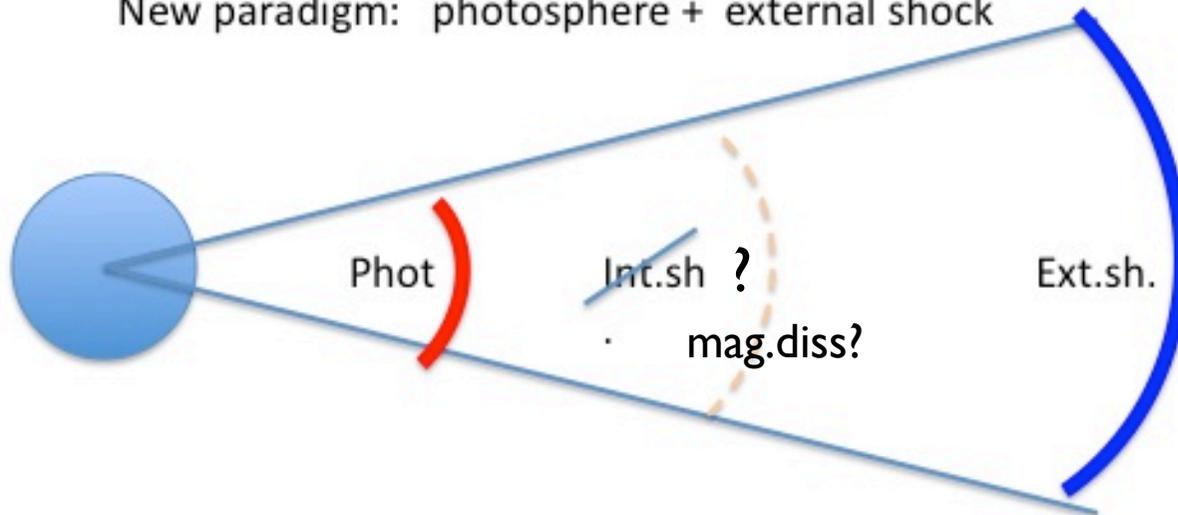
(A) Evolving Fireball paradigm:

Old paradigm: internal + external shock



≤ 2005

New paradigm: photosphere + external shock

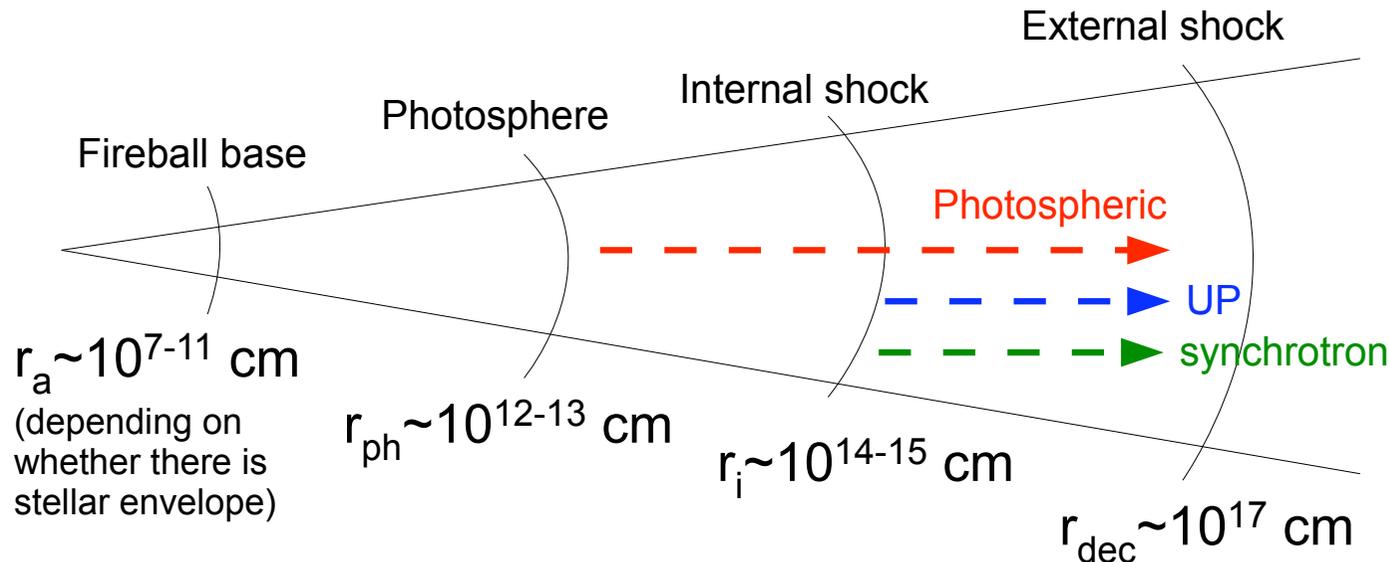


≥ 2005

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 (Mészáros & Rees 00; Rees & Mészáros 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.

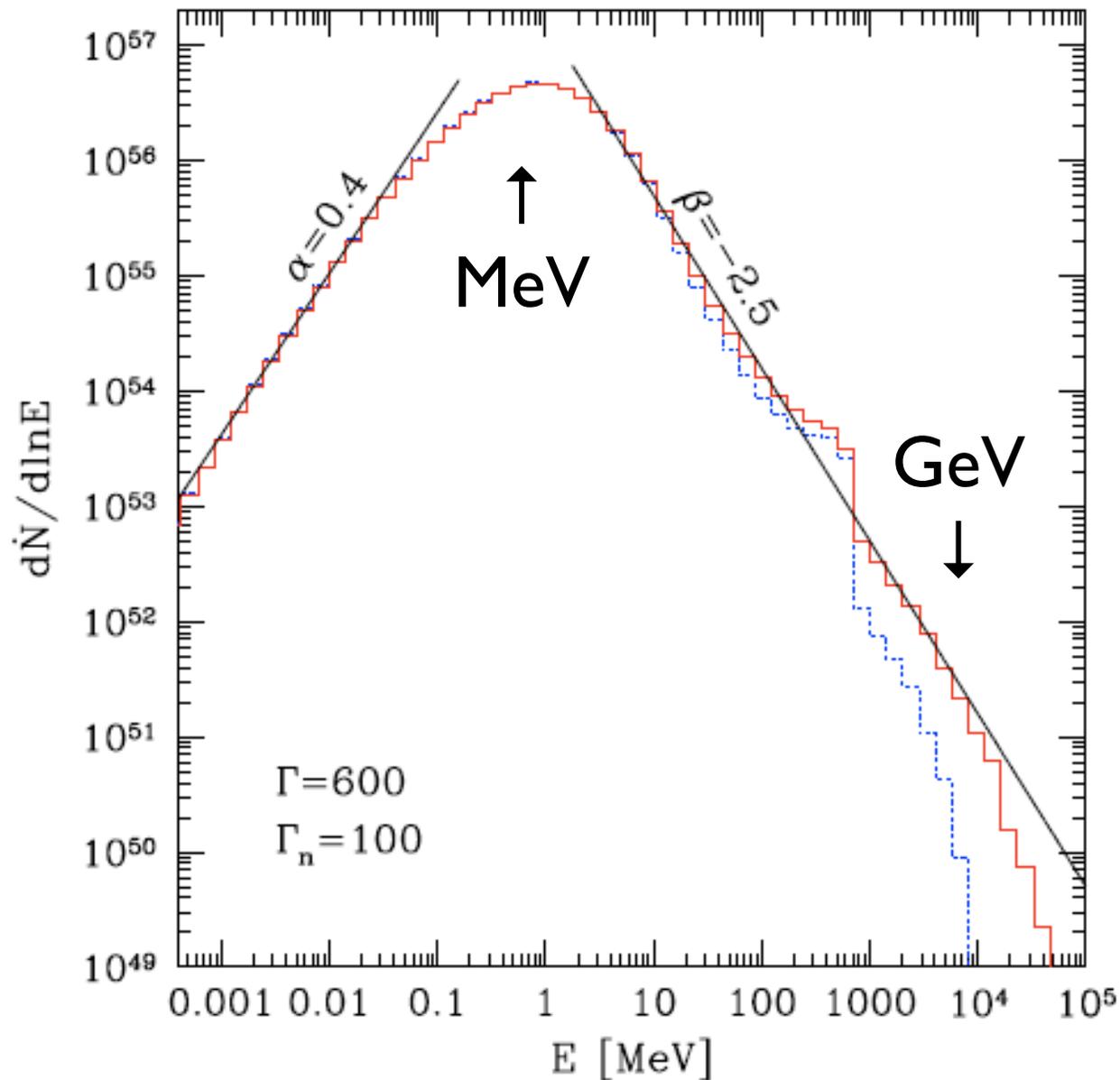
Recent thrusts in exploring the GRB prompt emission:

A) De-emphasize internal shocks (inefficient)
→ ***dissipative photospheric models***

or:

B) ***Modify*** internal shocks : ***slow heating***,
(i) turbulence behind shocks (Fermi 2nd ord),
(ii) magnetic dissipation (high rad. efficiency),
(iii) hadronic cascades (naturally slower heat'g)

p-n coll. $\rightarrow e^\pm \rightarrow \gamma$ -spectrum

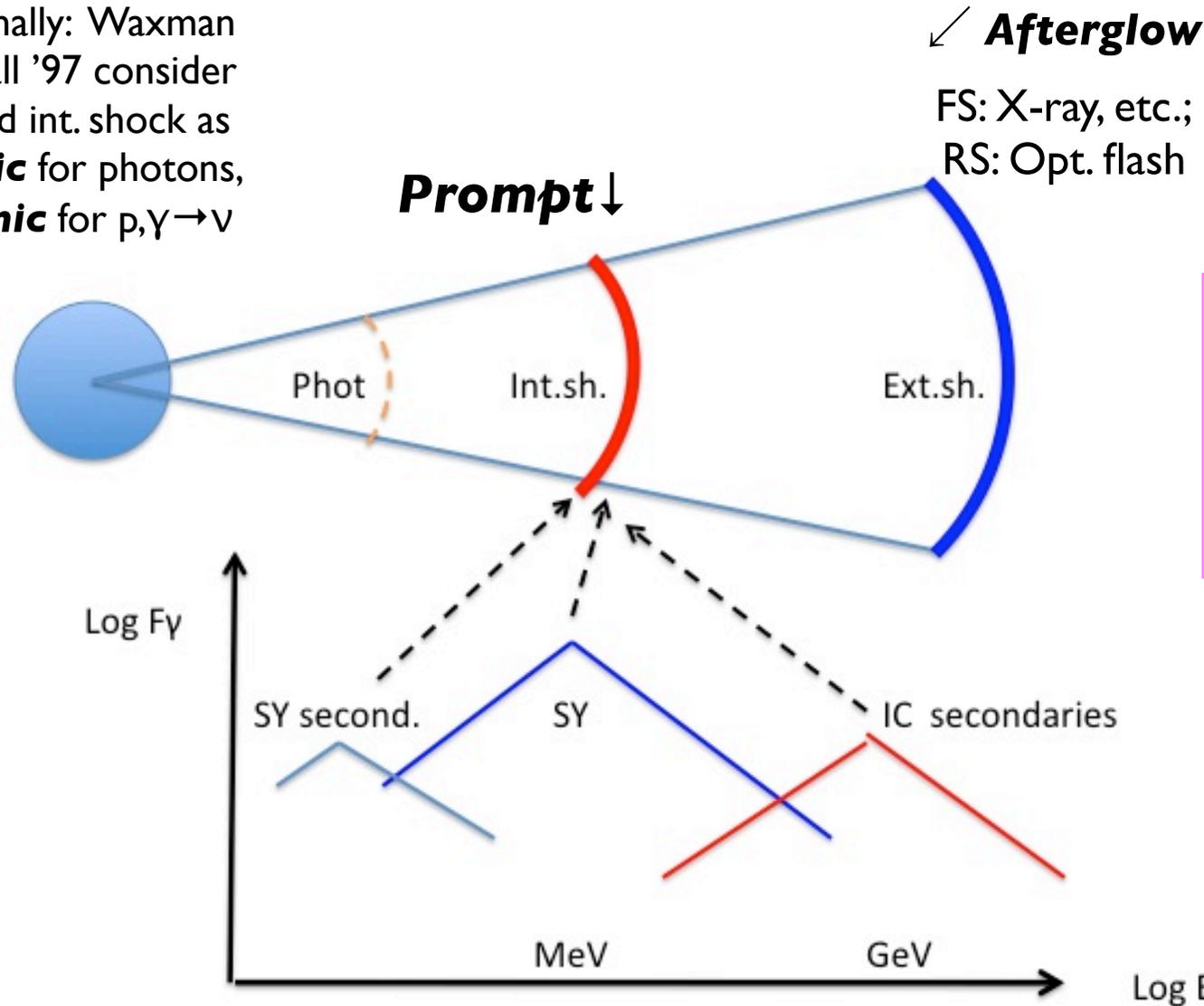


- The result is a thermal peak at the \sim MeV Band peak, plus
- a high energy tail due to the non-thermal e^\pm , whose slope is comparable to that of the observed Fermi bursts with a “single Band” spectrum
- The “second” higher energy component (when observed) must be explained with something else

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 $p, \gamma \rightarrow \nu$



New Feature:

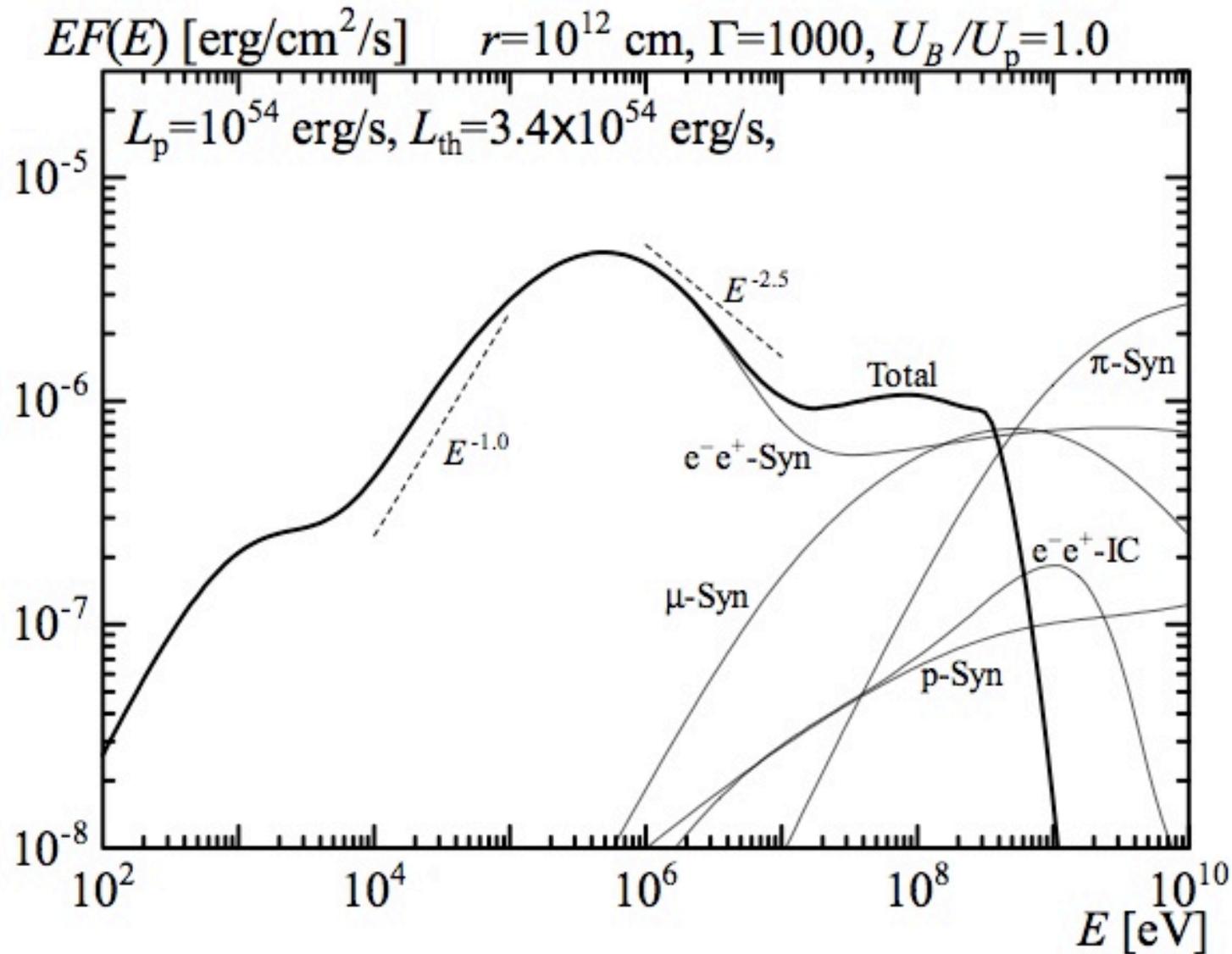
Hadron accel. + photomeson → “**dissipation**”
→ inject copious **relativistic sec’y leptons**

- 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, γ

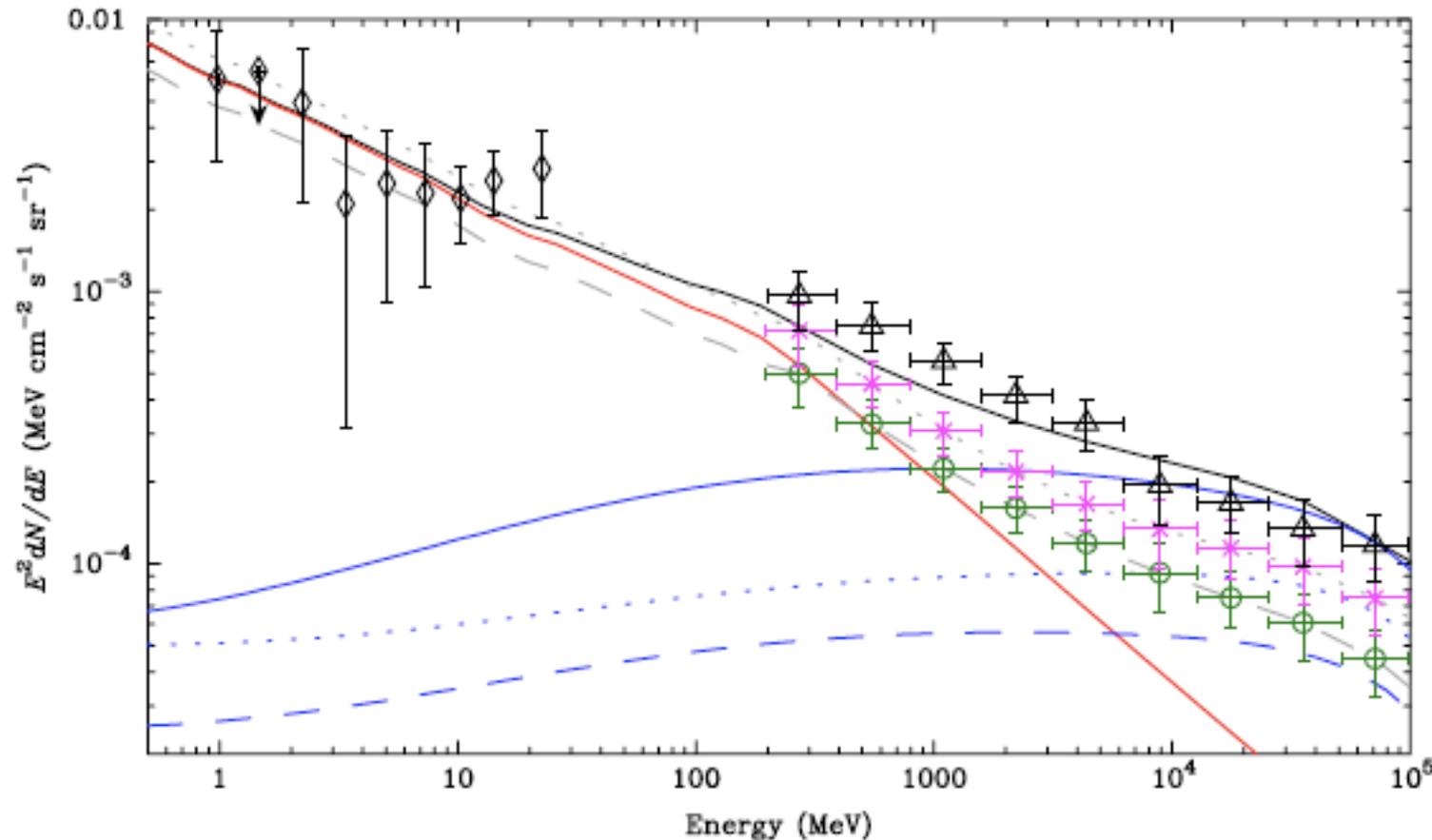
Murase, Asano, Terasawa & PM'12, ApJ746:164



The PeV **v- γ Bkg** Connection: GRBs? AGNs? SFGs? HNe? GMSs?

- **PeV nu bkg (INB)** obs. by IC3 is $\sim 10^{-8}$ GeV/cm²/s/sr, but **IC3 limit** on GRB nus is factor ~ 10 below the “standard” IS or photospheric models-ICRC13) \rightarrow could be **EM dim/nu-bright GRBs?** (Liu & Wang 13,ApJ 766:73, Murase & Ioka, 13, PRL 111:121102)
- **PeV nu INB** from hadronic **low lum. AGNs ?**: scaling L_p from L_e via L_{phot} , , argue that **FRI RGs** (higher density knots) \sim reproduce via **pp** the PeV nu bkg (Julia Becker Tjus+, arXiv:1406.0506) \rightarrow **and also IGB?**
- **PeV nus** from individual **bright** radio-gamma **AGNs? (blazars** in TANAMI sample), if X- γ flux is due to **p γ** photohadronic interactions, conclude that 6 of these blazars within 1σ error box of the three PeV events could account for the **INB** (Krauss, et al, 1406.0645) \rightarrow **IGB?**
- Starburst galaxies (**SBGs**)? if responsible for PeV nu **INB** via **pp**, can contribute \sim **20%** of the gamma background (**IGB**) (Chang et al, 1406.1099)

IGB (Fermi) & resolved sources



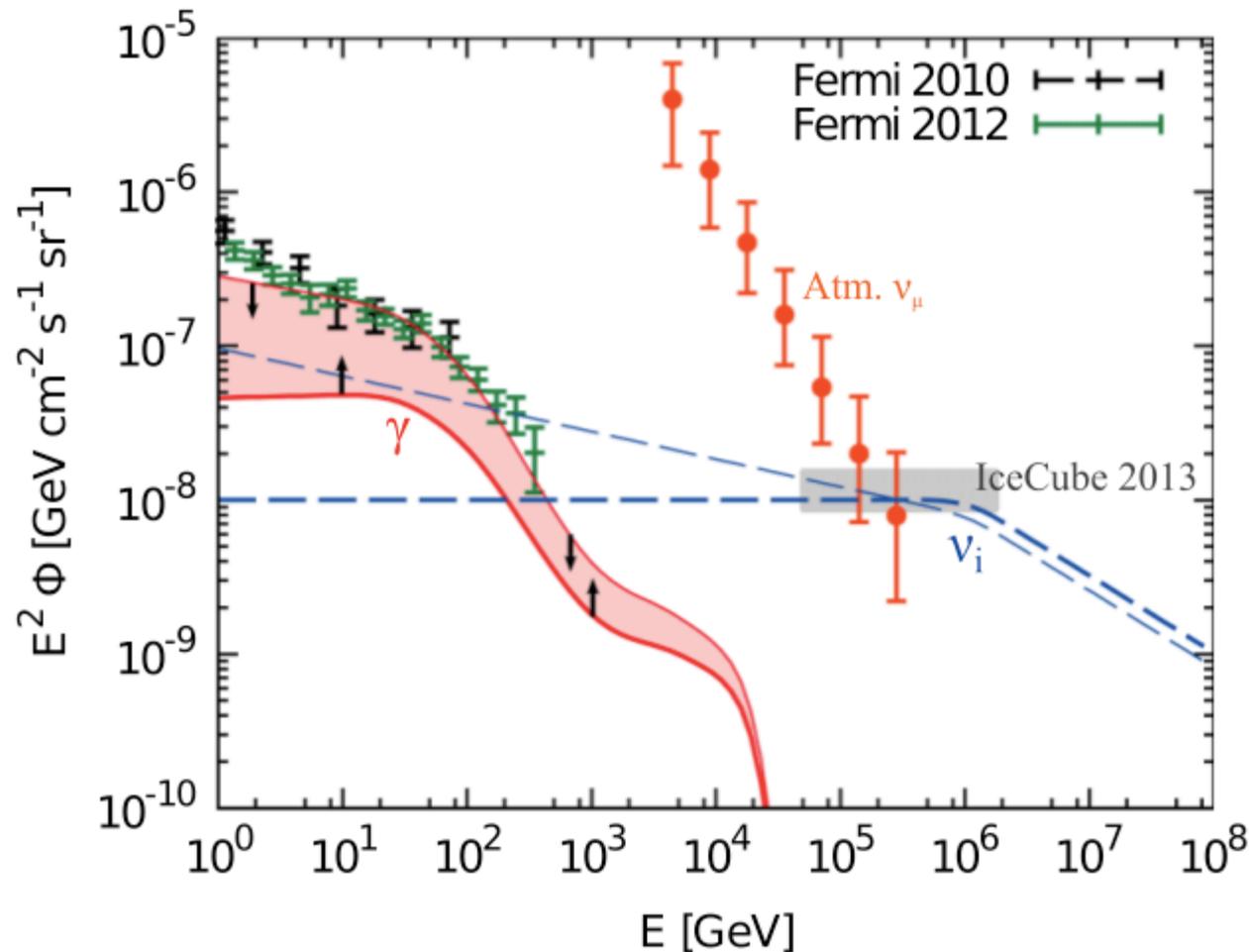
Abazajian+II,
PRD 84:103007

- Black triangles: Fermi IGB spectrum, Abdo+2010, PRL 104:101101 (see also Ackermann+2012 & his Tuesday talk)
- Red line: FSRQ contributions ; blue line: BL Lac contributions
- Magenta star/green circle: upper/lower 95% CL forecast of Fermi-LAT 95% CL 5 year sensitivity

INB & IGB from pp sources

Murase, Ahlers, Lacki 13
PRD 88, 121301

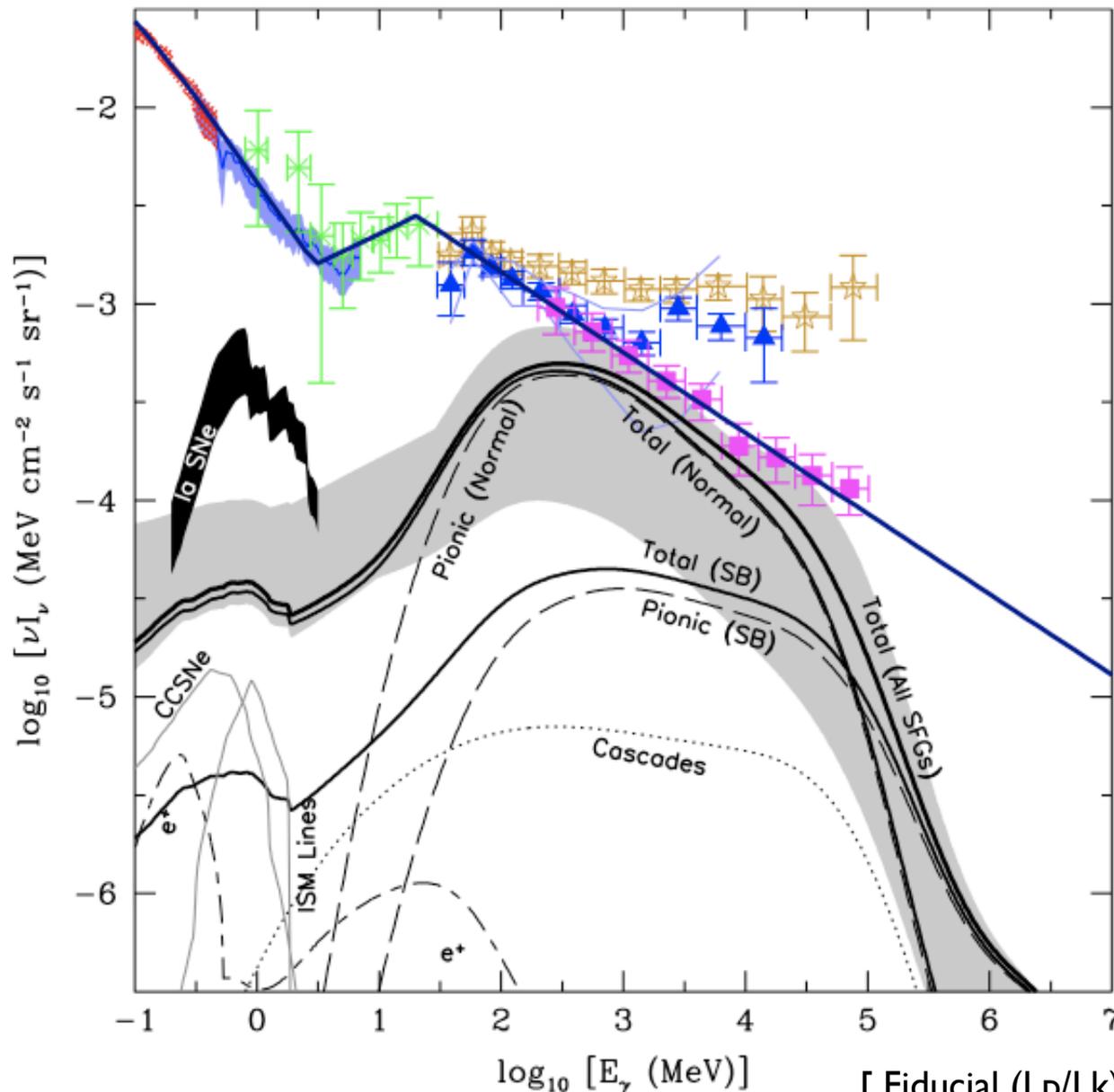
- Stress pp vs. p γ because no \gg GeV threshold
- Use IC3 det. of PeV vs, consider $\pi^\pm \rightarrow \nu$ INB & $\pi^0 \rightarrow 2\gamma$ IGB & satisfy Fermi/LAT bound, also lack of Glashow reson.
- Conclude $\Gamma_p \sim 2.0-2.18$ with cutoff $< 3-4$ GeV ✓
- Sources could be galaxy cluster shocks (IGS) or SFG/SBG - cutoff may be $t_{diff} \sim t_{inj}$ (or $t_{diff} \sim t_{pp}, t_{adv}$)



See also He+13, PRD 87:063011, Liu+14, PRD 89:083004,
Tamborra+, 1404.1189, Chang & Wang, 1406.1099,
Kashiyama & Mészáros, 1405.3262

SFG-SBG and the IGB

Lacki+14, ApJ 786:40

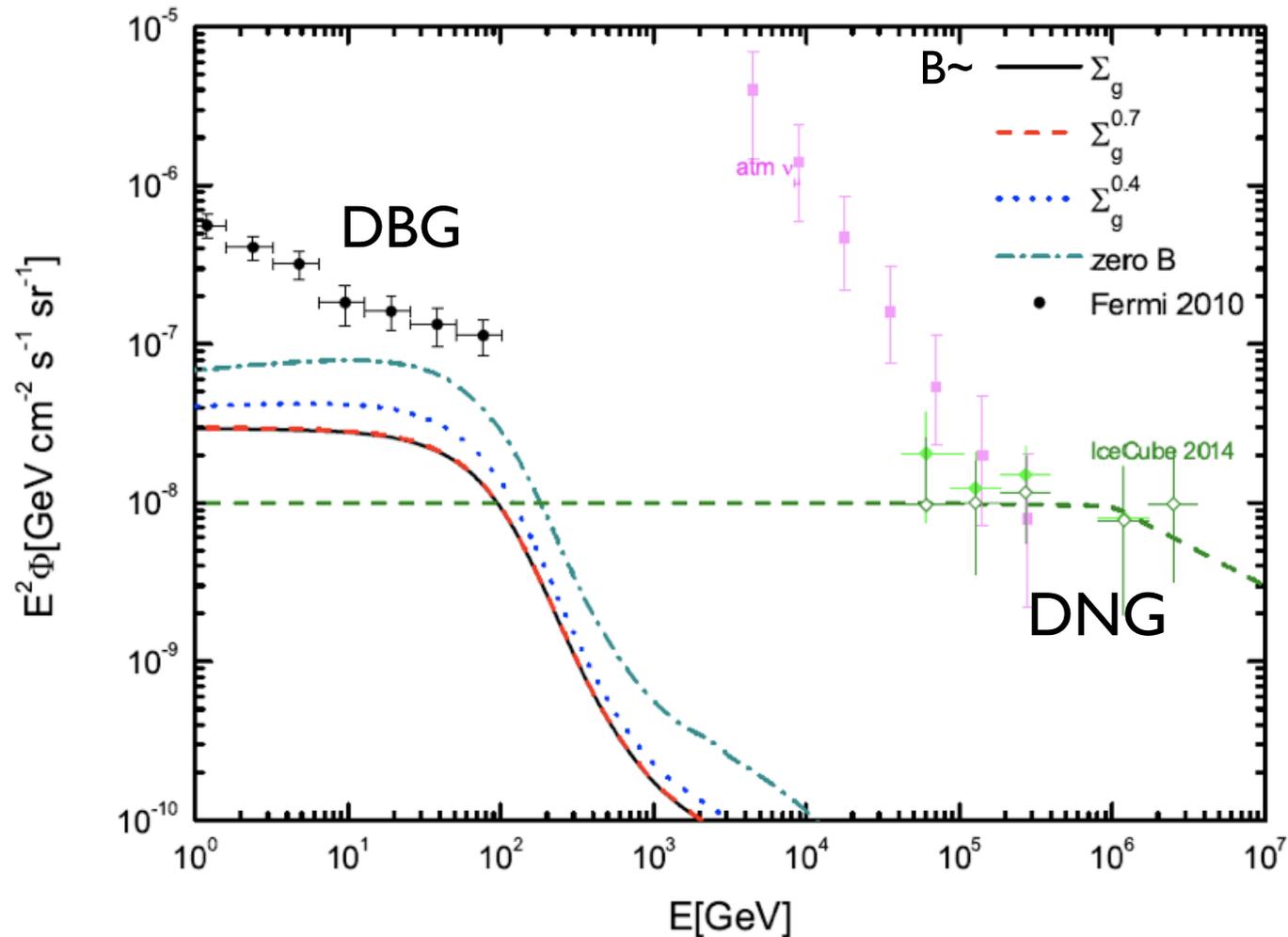


- Red: CXB; blue: SMM; green X: COMPTEL, gold star: EGRET, blue triangle: EGR error est; magenta square: Fermi
- Black line: total γ IGB (i) from SFG (normal) & (ii) from SBG (SB), inc. π^\pm (pionic bump), etc. Gray shade: uncertainty estimate of SF IGB
- One-zone leaky box CR evolution, input from SNR \propto SFR, PL injection $E_{p,\max} \sim \text{PeV}$, $E_{e,\max} \sim \text{TeV}$, w. diffusive & $\gamma\gamma$ losses, constrain by GHz radio

[Fiducial (Lp/Lk)snr=0.1, SBG/SFG=0.15 (0.8, 0.05)]

SBG & IGB - host sy losses

Chang & Wang, 1406.1988

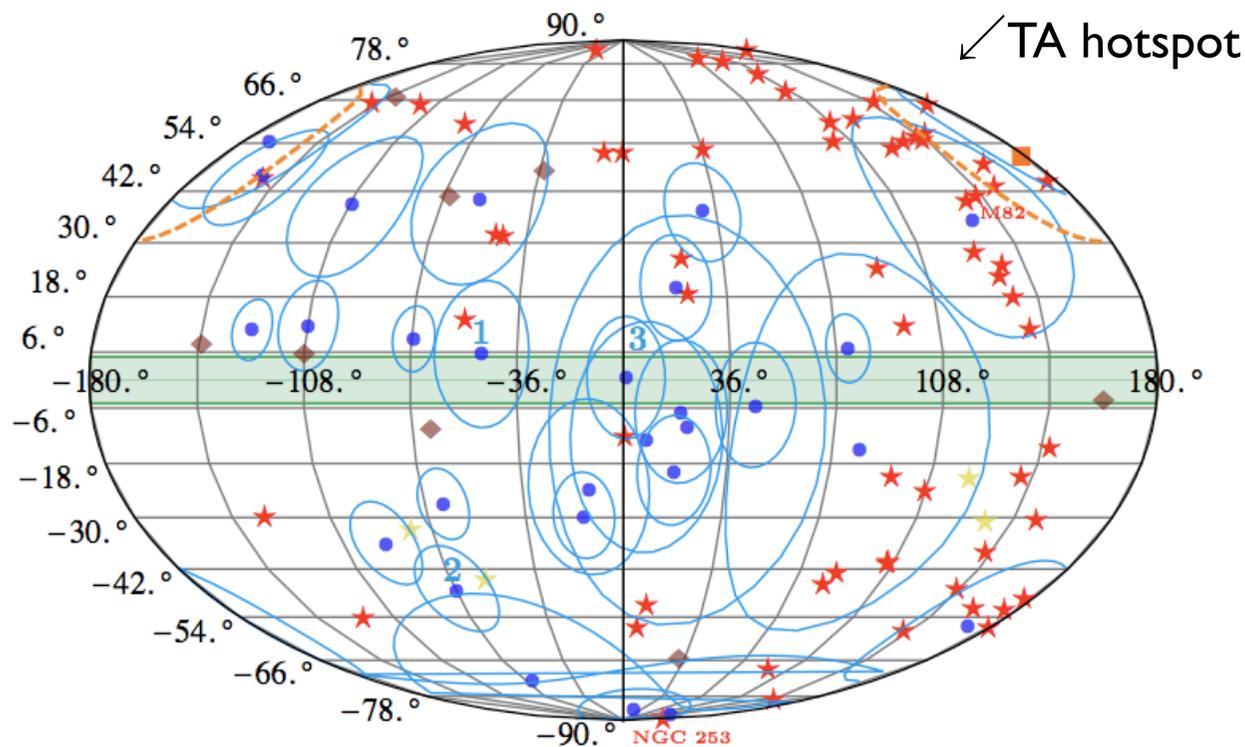
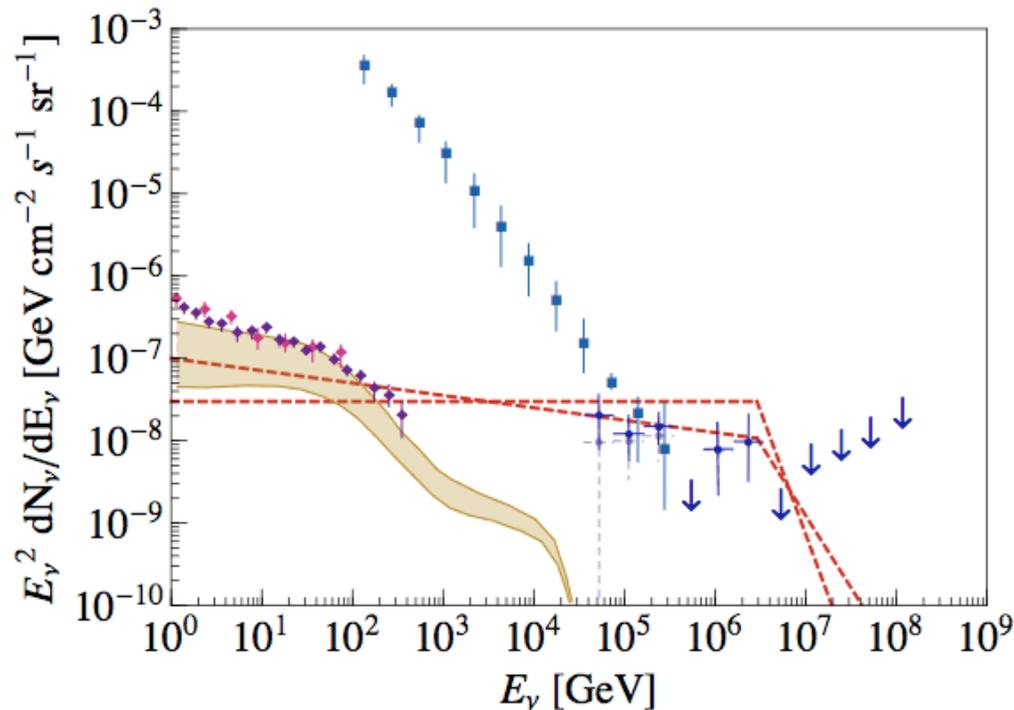


- Calibrate $\pi^0 \rightarrow 2\gamma$ flux using IC3 PeV nu obs. flux,
- Assume due to SBG
- Inside host galaxy, consider $\gamma\gamma$ casc. of primary π^0 & π^\pm IC upscatt. photons.
- If **no** sync. losses, $\Phi_{\gamma, \text{casc}} \sim 0.5 \Phi_{\gamma, \text{IGB}}$
- If incl. sync. losses inside host SBG ($B_{\text{ISM}} \sim \text{mG}$) then $\Phi_{\gamma, \text{casc}} \sim \mathbf{0.2} \Phi_{\gamma, \text{IGB}}$

However: if IGB & INB arise in less excited galaxies (e.g. SFGs), B_{ISM} may be smaller \rightarrow the sy losses are smaller, and $\Phi_{\gamma, \text{casc}}$ larger

INB, IGB & SFGs

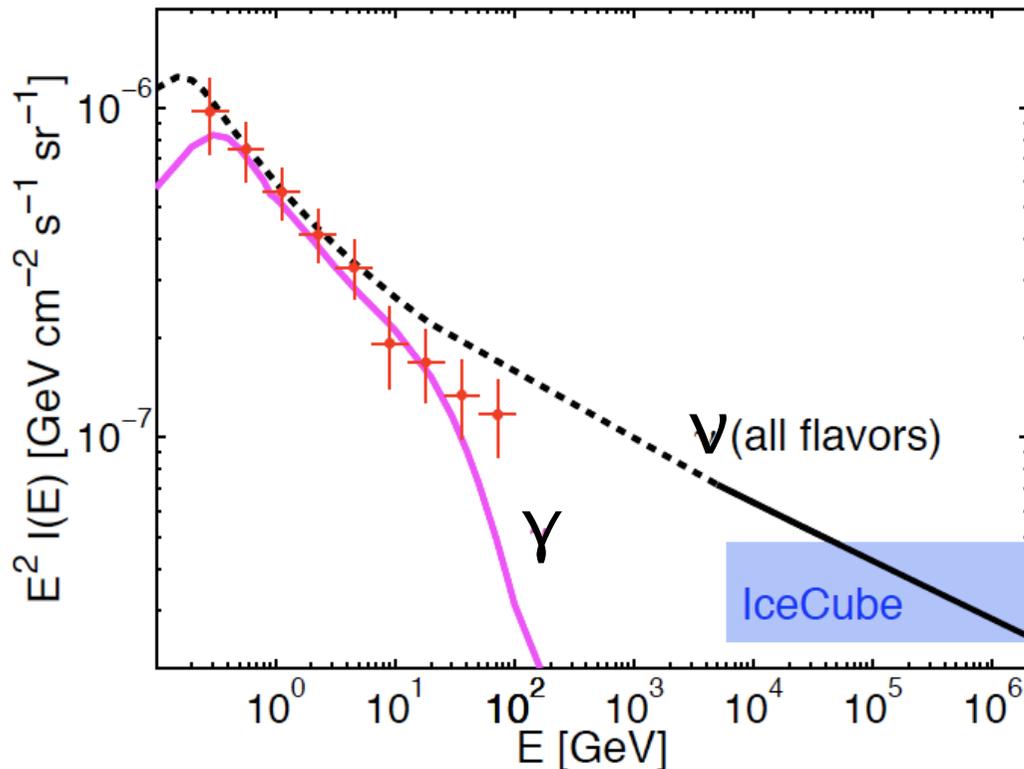
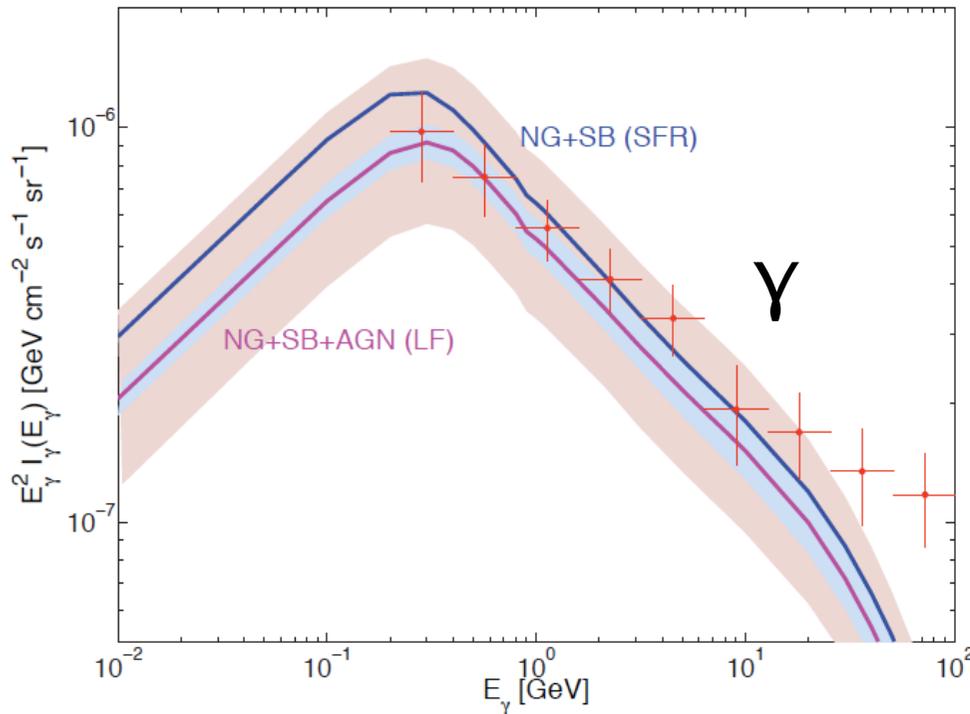
Anchordoqui+14, 1405.7648



- Consider $\pi^\pm \rightarrow \nu$ ING & $\pi^0 \rightarrow 2\gamma$ IGB, so that spectrum does not violate Glashow ✓
- Check location of showers (blue circles) and tracks (◆) versus known SFGs
- M82, NGC253, NGC4945, SMC, IRAS18293 “corr” w. showers - but no track corr.
- Will need 10 yrs w. IC3, or a next gen. detector, to detect >5 track events which corr. with SFGs at > 99% CL

IGB, INB & SFG, SBGs

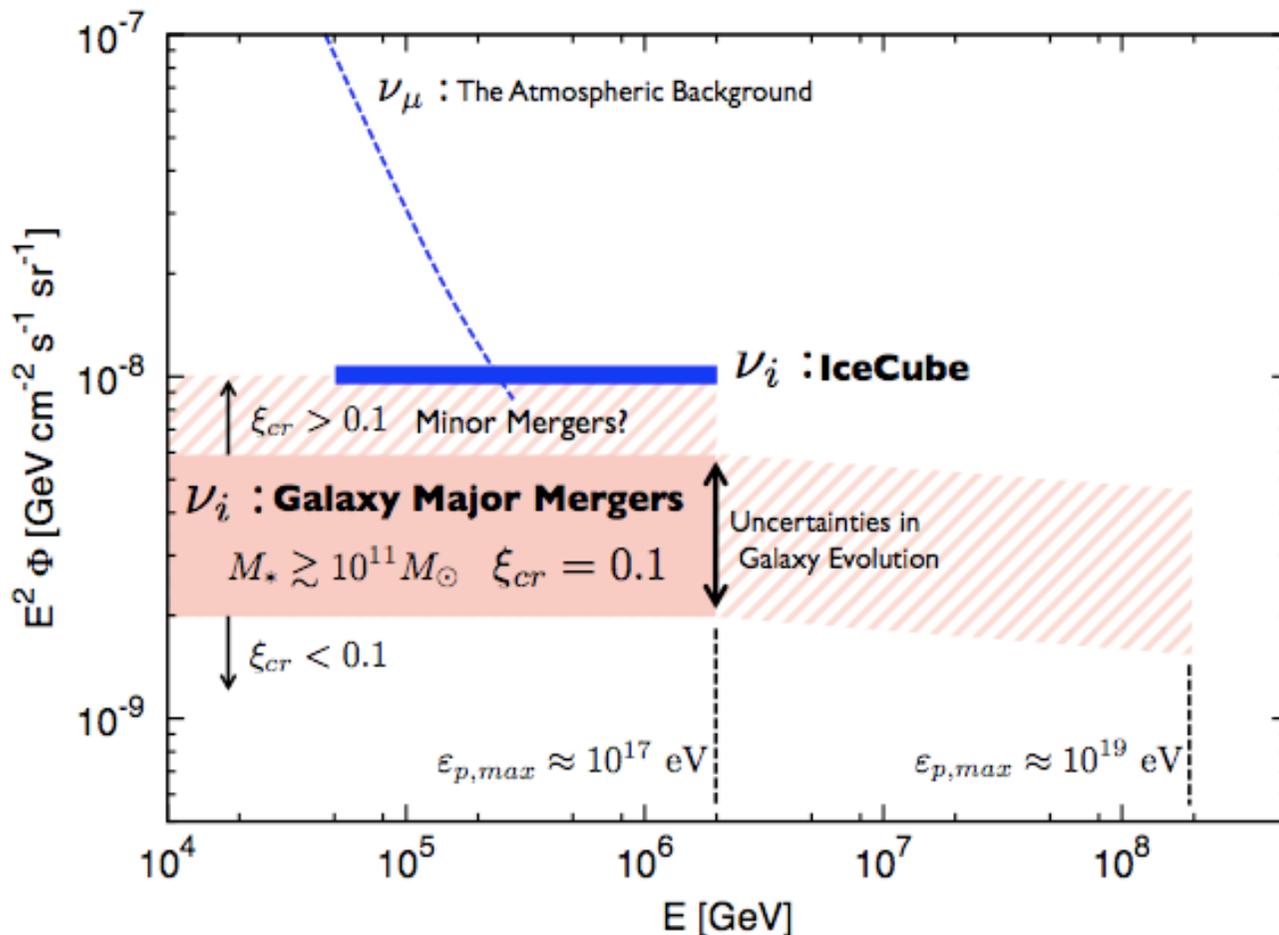
Tamborra, Ando & Murase
1404.1189



- Use Herschel PEP/herMES Lum.Fcn of FIR bright gals
- From this deduce distribution of SFG, SBG up to $z \sim 4$
- Use this and the Fermi correl $L_Y \sim L_{\text{FIR}}^{1.17}$ to deduce an IGB \nearrow which fits Fermi obs. IGB
- Under same assumptions, find also that if 100 PeV CRs can be confined in host galaxies, \leftarrow can fit also IC3 PeV INB

Galaxy mergers, INB & IGB

Kashiyama & Mészáros, 1405.3262



- **Every galaxy** merged at least **once** in the last **Hubble time**
- **Major mergers** \rightarrow
 $E_{\text{gms}} \sim 10^{58.5} \text{ erg}$,
 $R \sim 10^{-4} \text{ Mpc}^{-3} \text{ Gyr}^{-1}$
 $v_s \sim 10^{7.7} \text{ cm/s}$
 $Q_{\text{cr,gms}} \sim 3 \times 10^{44} \text{ erg Mpc}^{-3} \text{ yr}^{-1}$
 $\xi_{\text{cr,max}} \sim 10^{18.5} \text{ Z eV}$
- **pp** \rightarrow PeV vs, 100 GeV γ s
- **v**: Indiv. GMS: 0.01 μ/yr ,
INB: **20-60%** IC3 obs.flux
- **γ** : Individual GMS flux:
 $\sim 3 \cdot 10^{-13} \text{ erg/cm}^2/\text{s} \rightarrow \text{CTA?}$
IGB $\sim 10^{-8} \text{ GeV/cm}^2/\text{s/sr}$,
 about **10-30%** Fermi IGB
- Minor mergers: uncertain,
 could add up to 70-100%

Outlook & Issues

- *Both in AGNs and GRBs, major question is whether basic emission is leptonic or hadronic - contribution to the observed CRs/UHECRs and PeV nus?*
- *Location of the GeV(TeV) emission region (inner/outer jet, photosphere?) Role of (which?) target photon sources*
- *Role of pair cascades in VHE spectrum formation*
- *Do galaxy/cluster shocks and/or galaxy merger shocks contribute much (all?) of SFG/SBG VHE radiation?*
- *Relative contribution of AGNs, SFG/SBG/GMS to the IGB and/or the INB? is pp, py or leptonic dominant in γ ?*



EXTRA SLIDES

SFR & SFGs, SBGs detected

- SFR of SFG (75% local rate): 0 - few M_{\odot}/yr
- SFR of SB (25% local rate): (i) SBG: few M_{\odot}/yr
(ii) LIRG: 50 M_{\odot}/yr ; (iii) ULIRG: 10^2 - 10^3 M_{\odot}/yr
- Detected SFGs: MW, LMC, SMC, M31
- Detected SBGs: M82, NGC253 (Fermi, Veritas),
SB Sy NGC4945, NGC1068, Circinus (Fermi)

Boettcher'14 lep params

Table 2
Parameters for the Leptonic SED Fits Shown in Figures 4–6

Object	$\gamma_{e,1}$	$\gamma_{e,2}$	q_e	B [G]	D	f_{BLR}^a	L_e^b	L_p^b	L_B^b	ϵ_{Be}	$t_{\text{var,min}}^c$
3C 273	1×10^3	5×10^4	3.5	2.0	13	5.4×10^{-5}	6.0	130	0.63	0.11	4.1
3C 279	1×10^3	1×10^5	3.0	0.7	17	1.7×10^{-2}	5.8	29	5.4	0.94	29
3C 454.3	800	5×10^4	3.0	2.1	15	8.0×10^{-2}	22	870	75	3.5	52
PKS 1510–089	1×10^3	2×10^5	3.1	0.8	20	4.1×10^{-3}	2.1	41	2.1	1.0	9.4
PKS 0420–01	1.4×10^3	5×10^4	3.4	2.5	8.0	1.0×10^{-1}	6.9	670	38	5.4	110
PKS 0528+134	700	1×10^4	3.0	3.0	19	9.1×10^{-3}	9.4	600	110	11	45
BL Lacertae	1.1×10^3	1×10^5	3.2	2.5	15	1.3×10^{-1}	0.44	4.6	0.41	0.94	1.8
AO 0235+164	700	5×10^4	3.7	1.3	25	1.1	12	87	33	2.8	21
S5 0716+714	1.9×10^3	5.5×10^4	3.8	3.8	20	... ^d	1.3	6.7	14	10	4.9
OJ 287	800	5×10^4	3.8	3.5	15	1.5×10^{-1}	1.8	16	15	8.2	9.7
W Comae	1×10^3	8×10^4	2.4	1.5	30	2.8×10^{-2}	0.30	1.52	0.30	1.0	0.68
3C 66A	9×10^3	3×10^5	2.8	0.065	40	... ^d	13	8.2	0.45	0.034	13

Notes.

^a The factor f_{BLR} , determining the energy density of the re-processed disk radiation field, is defined as $f_{\text{BLR}} \equiv \eta_{\text{BLR}}/R_{\text{BLR}}^2$; values are in pc^{-2} .

^b Powers are in units of $10^{44} \text{ erg s}^{-1}$.

^c Minimum allowed variability timescale in hours.

^d For S5 0716+714 and 3C 66A, no accretion disk luminosity has been measured/constrained; for S5 0716+714, an isotropic external radiation field with $u_{\text{ext}} = 5 \times 10^{-5} \text{ erg cm}^{-3}$ and $T_{\text{BB}} = 2 \times 10^4 \text{ K}$ has been used for the SED fit; for 3C 66A: $u_{\text{ext}} = 1.3 \times 10^{-8} \text{ erg cm}^{-3}$ and $T_{\text{BB}} = 10^3 \text{ K}$.

Boettcher'14 hadr params

Table 3
Parameters for the Hadronic SED Fits Shown in Figures 7–9

Object	$\gamma_{e,1}$	$\gamma_{e,2}$	q_e	B^a	D	$\gamma_{p,max}$	q_p	L_e^b	L_p^c	ϵ_{Be}^d	ϵ_{Bp}^d	ϵ_{ep}^d	t_{var}^e
3C 273	350	1.5×10^4	3.4	15	15	4.3×10^8	2.4	0.13	25	3300	1.7×10^{-3}	5.2×10^{-7}	11
3C 279	100	2.0×10^4	3.0	100	15	6.4×10^8	2.2	0.19	3.5	1410	7.9×10^{-3}	5.6×10^{-6}	1.7
3C 454.3	300	1.5×10^4	3.2	10	15	1.1×10^9	2.1	1.0	35	1.2×10^4	0.035	2.9×10^{-6}	138
PKS 1510–089	150	1.5×10^4	3.2	10	20	1.1×10^9	1.7	0.57	2.5	24	5.4×10^{-4}	2.3×10^{-5}	1.9
PKS 0420–01	75	1.0×10^4	3.2	100	10	4.3×10^8	1.3	0.52	0.42	2200	0.27	1.2×10^{-4}	9.7
PKS 0528+134	150	1.0×10^4	3.8	30	20	1.1×10^9	2.0	1.9	44	1020	4.4×10^{-3}	4.3×10^{-6}	17
BL Lacertae	700	1.5×10^4	3.5	10	15	1.9×10^9	2.4	0.087	9.8	39	3.4×10^{-5}	8.9×10^{-7}	1.3
0235+164	200	750	3.0	15	25	4.3×10^9	1.9	1.5	10	130	1.9×10^{-3}	1.5×10^{-5}	4.3
S5 0716+714	900	3.0×10^4	2.9	20	15	2.7×10^9	2.0	0.089	0.14	1.4×10^4	0.85	6.2×10^{-5}	15
OJ 287	350	4.0×10^4	4.1	20	15	1.0×10^9	1.6	0.53	8.3	66	0.042	6.3×10^{-4}	2.6
W Comae	800	2.1×10^4	2.6	30	15	1.9×10^9	2.0	0.014	0.021	560	0.037	6.6×10^{-5}	0.68
3C 66A	750	1.3×10^4	2.8	10	30	1.2×10^9	2.0	0.32	1.2	24	6.5×10^{-4}	2.7×10^{-5}	0.57

Notes.

^a Magnetic field in units of Gauss.

^b Kinetic luminosity in relativistic electrons in units of 10^{44} erg s⁻¹.

^c Kinetic luminosity in relativistic protons in units of 10^{48} erg s⁻¹.

^d Partition fractions defined as $\epsilon_{ij} \equiv L_i/L_j$.

^e Minimum allowed variability timescale in hours.

Table 1

Initial parameters for the two fits.

Parameter	Model LH π	Model LHs
$\gamma_{p,max}$	3.2×10^6	6.3×10^9
$\gamma_{e,max}$	8×10^4	4×10^4
p_p	1.3	1.5
p_e	1.2	1.2
ℓ_p	2×10^{-3}	1.6×10^{-7}
ℓ_e	3.2×10^{-5}	10^{-4}
R (cm)	3.2×10^{15}	3.2×10^{15}
B (G)	5	50
δ	26.5	21.5

Mrk 421

LH π , LHs

parameters

Table 2

Neutrino parameters compared to the respective ones of the parent proton distribution. The values of the proton (u_p) and magnetic field (u_B) energy densities refer to steady state; the luminosities of primary electrons, photons and neutrons are also included as is the total observed luminosity of the jet.

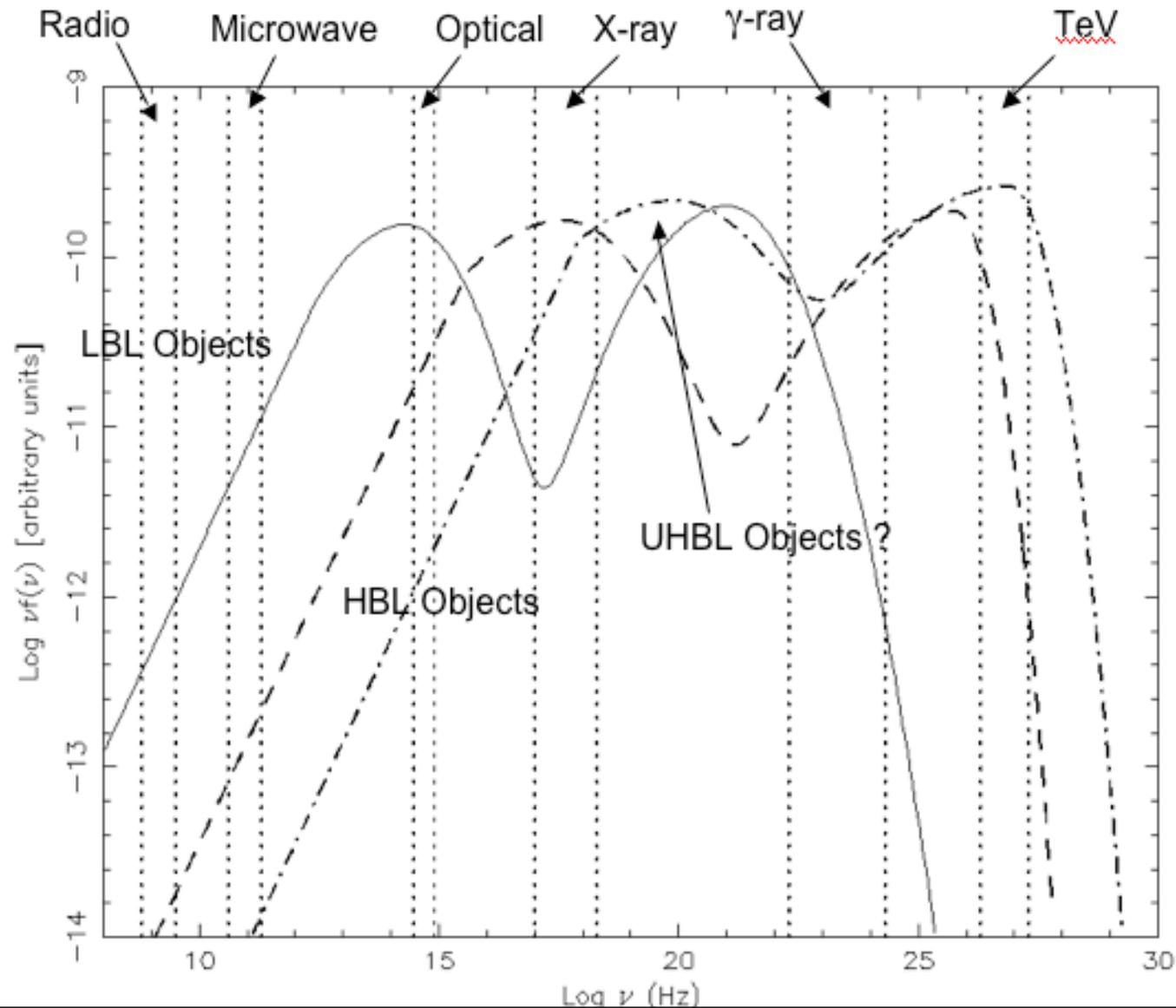
Parameter	Model LH π	Model LHs
$\gamma_{p,max}$	3.2×10^6	6.3×10^9
$E_{\nu,peak}$	1.3×10^5	1.6×10^8
p_p	1.3	1.5
p_ν	0.3	0.3
L_p (erg s $^{-1}$)	5.7×10^{45}	4.5×10^{41}
L_e^{inj} (erg s $^{-1}$)	4.6×10^{40}	1.2×10^{41}
L_γ (erg s $^{-1}$)	6.9×10^{40}	1.3×10^{41}
L_ν (erg s $^{-1}$)	7.9×10^{39}	7.4×10^{38}
L_n (erg s $^{-1}$)	3.8×10^{40}	2.6×10^{39}
u_p (erg cm $^{-3}$)	1.6×10^3	9.7×10^{-2}
u_B (erg cm $^{-3}$)	1	100
P_{jet}^{obs} (erg s $^{-1}$)	1.1×10^{48}	4.2×10^{46}

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AGN schematics

- FR2 RG : high luminosity, well collimated jets w. bright outer lobes -> parent pop. of RLQ and FSRQ (softer than BL Lacs)
- FR1 RG: lower luminosity, less collimated jets, low brightness outer lobes -> parent pop of BL Lacs (LBL, IBL, HBL) (harder than FSRQ)
- BL main sequence: for decreasing bol. lum. the frequ. peaks shift up in energy and gamma/XOR decreases - argue (lep) that decr. ext rad field leads to decr. IC upscattering or p,gamma

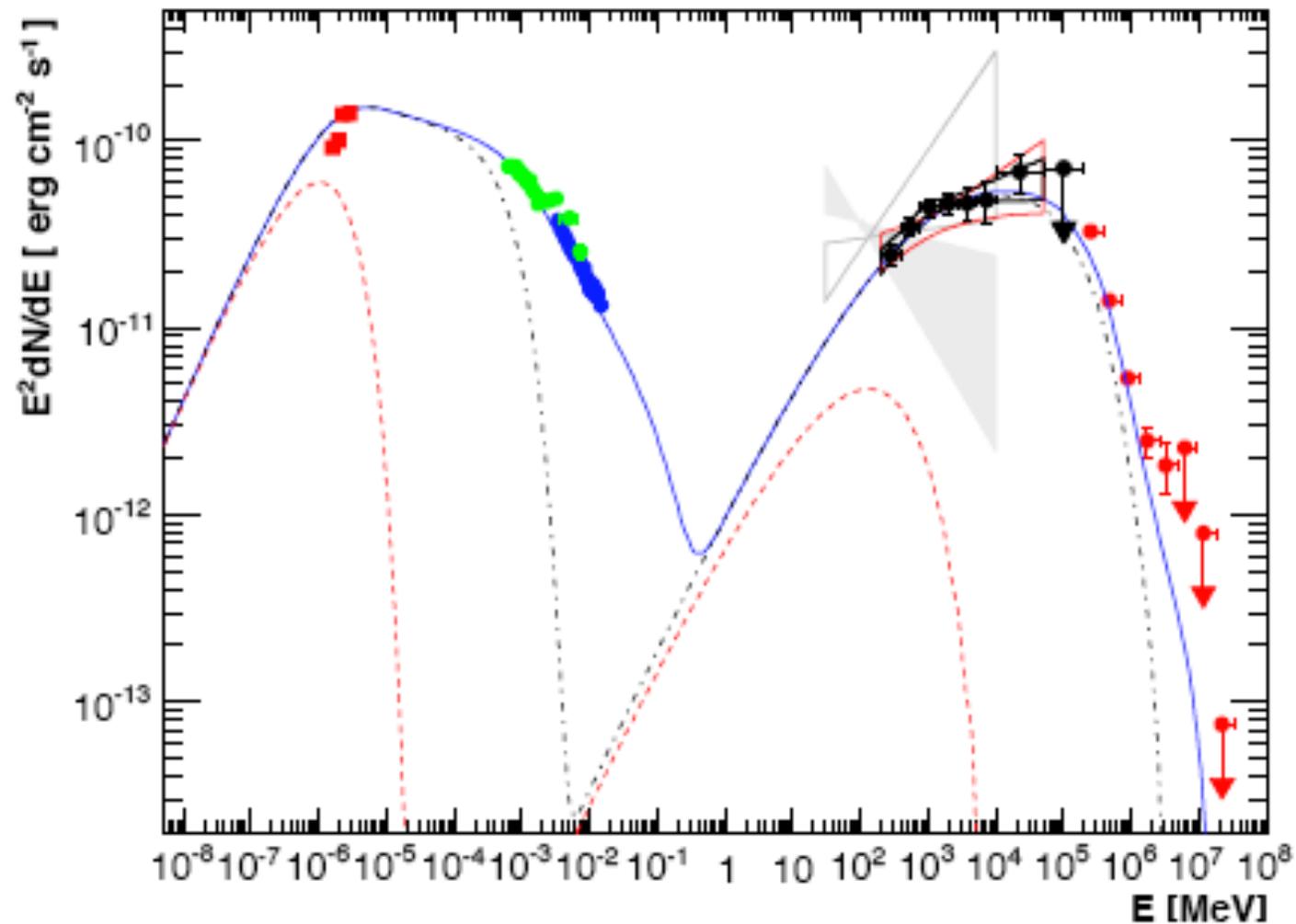
Blazar schematic spectra



Parkes 2155-304

Fermi-Hess lep-fit 2010

Aharonian et al'09, A&A 509:749



Biggest recent excitement:

GRB 130427A

(a.k.a the “Nearby Ordinary Monster”)

- Largest apparent fluence (by far): $\approx 10^{-3}$ vs $\lesssim 10^{-4}$ erg/cm²
- And/but: distance only **$z \sim 0.34$** (uncommon close)
- ***Very rare***: per Lum.Fcn., expected rate $\sim 1/50$ - $1/25$ yr⁻¹
- Yet, $E_{\text{iso}} \sim 1.4 \times 10^{54}$ erg : ***ordinary*** high-z GRB iso-output
- V. high ***photon count*** → unprecedented study opportunity

