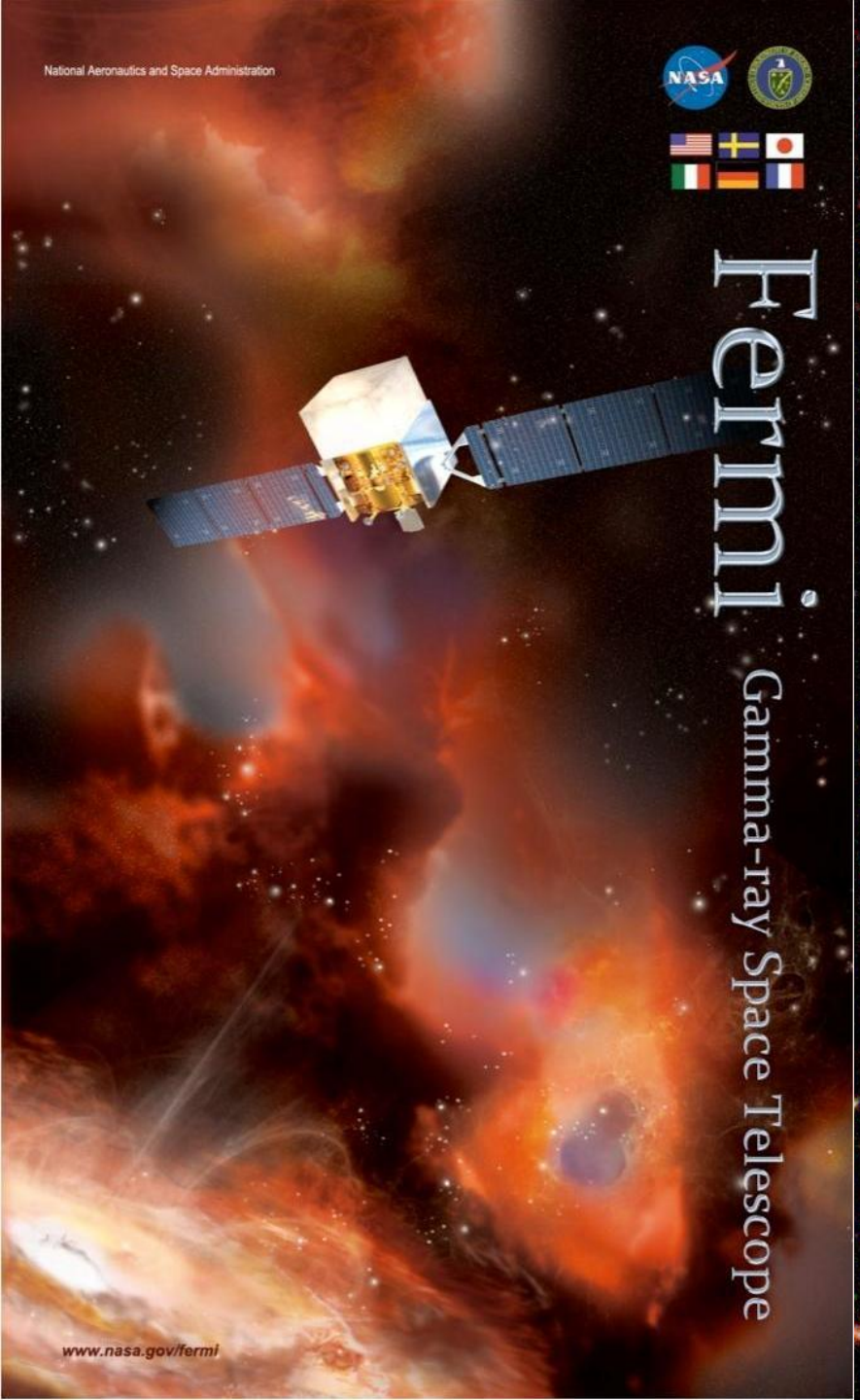


EBL & γ-ray emitting non-blazar AGN

Anita Reimer

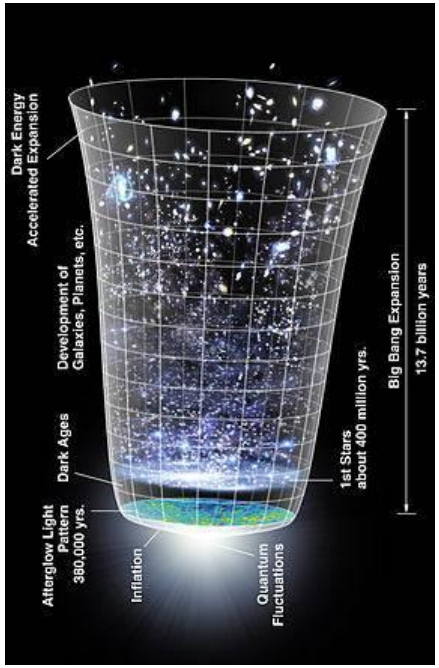
Leopold-Franzens-Universität Innsbruck

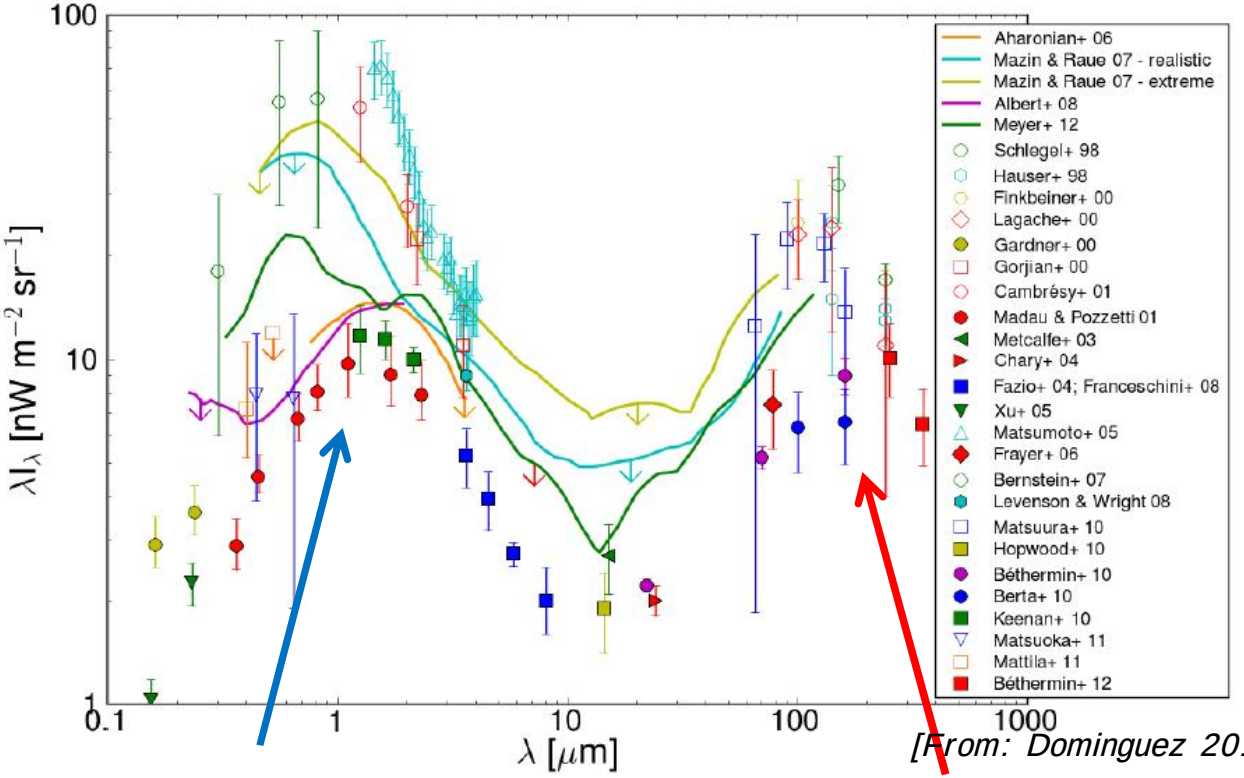
on behalf of the Fermi-LAT collaboration

EWASS 2013:
„The γ-ray sky in the era of Fermi & Cherenkov telescopes“

Turku, July 2013

What is the Extragalactic Background Light (EBL)?





[From: Dominguez 2012]

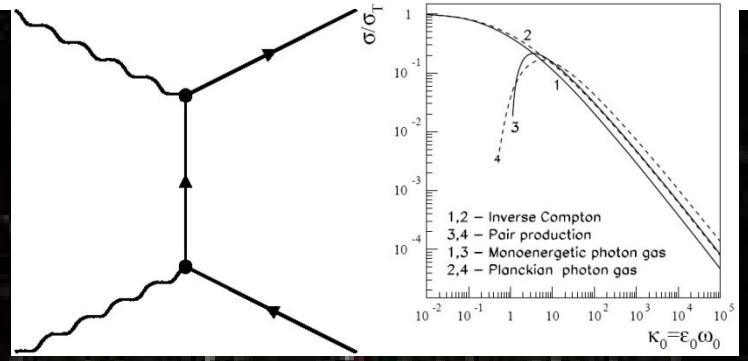
Light emitted by star light & from AGN

Reprocessed star light/AGN radiation

-> constraints on galaxy evolution, star formation activity, dust-extinction processes, etc

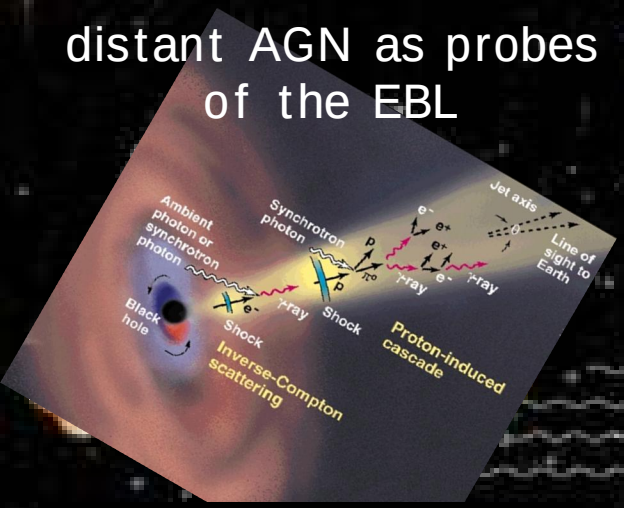
-> understanding cosmic structure formation & evolution

Attenuation of γ-ray source spectra by EBL

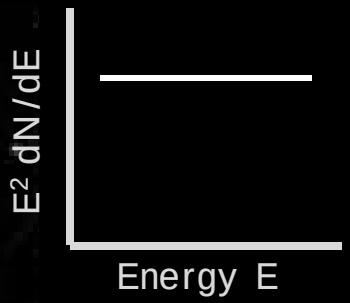


$\varepsilon \sim 0.8$ eV/ $[(1+z)\ E_{\gamma,\mathrm{TeV}}]$

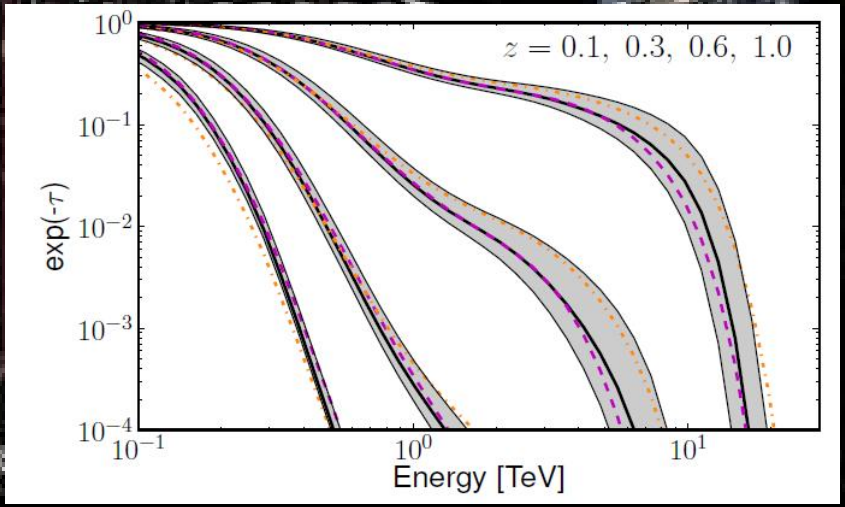
distant AGN as probes of the EBL



Emitted spectrum

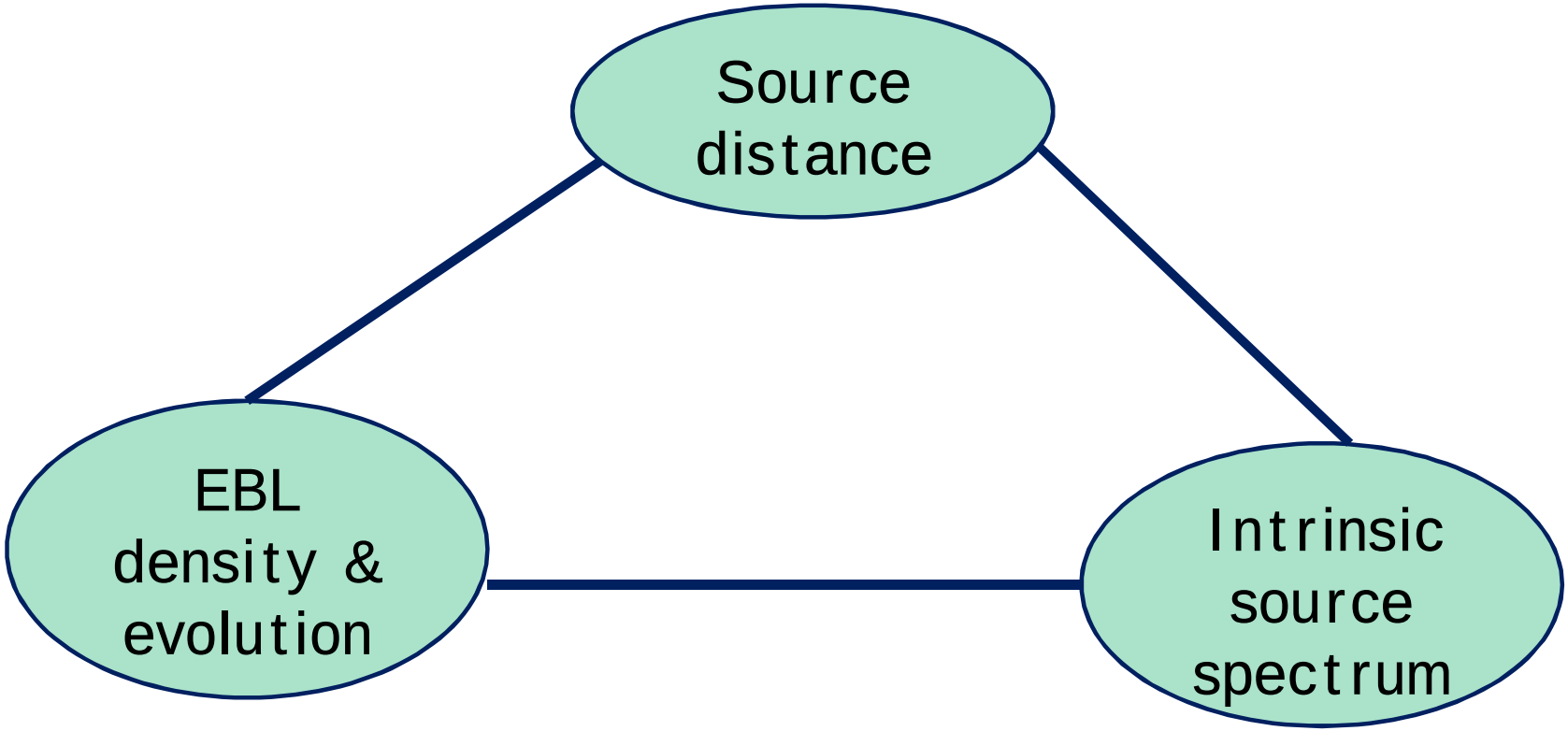


EBL



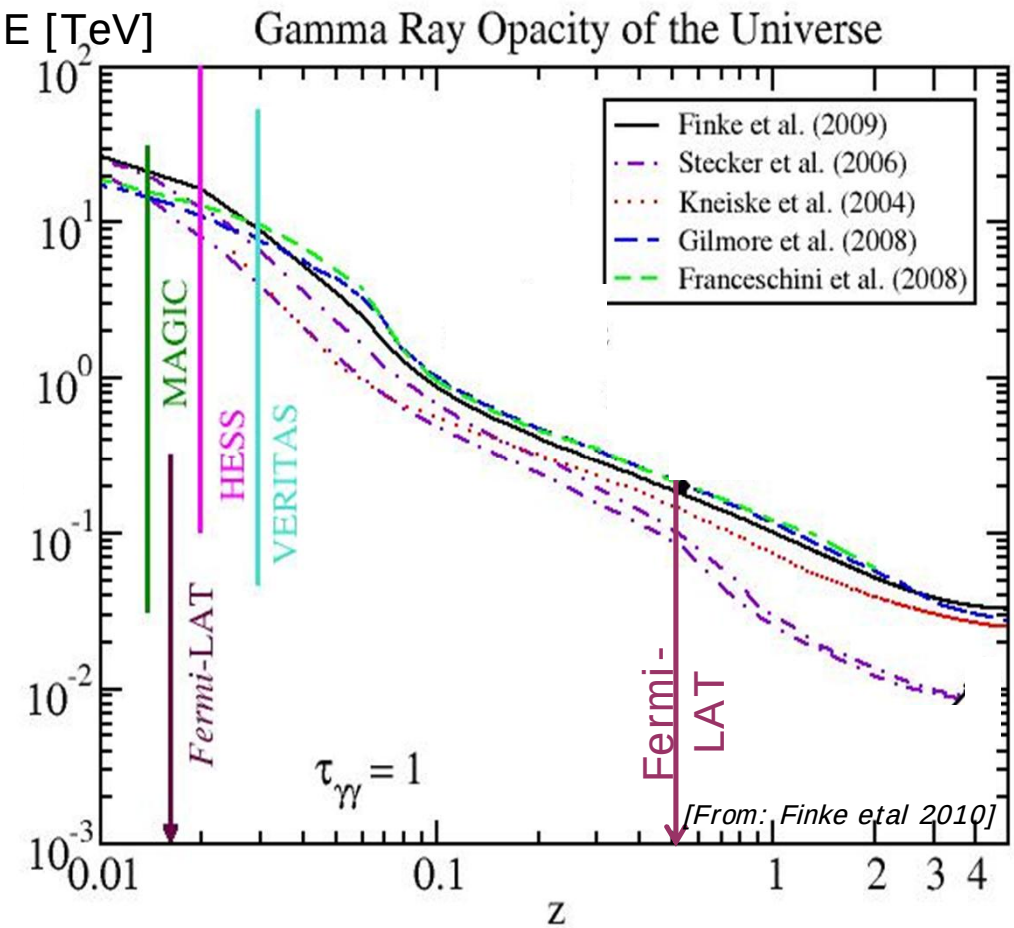
$F_0(E;z=0) \times e^{-\tau(E,z)} = F(E;z=0)$

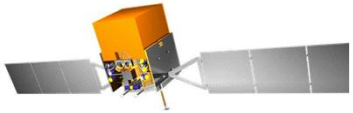
Under-determined System



[Adapted from: Costamante 2013]

The Gamma-Ray Horizon





- probe *IR/opt range* of EBL
- probe *today's* EBL
- require assumptions on *intrinsic source spectrum* & *UV/NIR EBL* flux ratio

- probes *opt/UV range* of EBL
- probes *evolution* of EBL
- adds *information on unabsorbed* part of source spectrum; lever arm!

constrain IR/opt.-EBL, z<0.5

$\varepsilon \sim 0.8\ \mathrm{eV} / [(1+z)\ E_{\gamma,\mathrm{TeV}}]$

constrains opt./UV-EBL, z>0.5

Different methods to infer intrinsic source spectrum

- *Extrapolation of LAT-spectrum to high energies*

LAT-data only

... using simple power law -> *[Abdo etal. '10]*

... using LogParabola -> *[Ackermann etal. '12]*

LAT- & IACT data

... requiring softening of VHE-spectrum -> *[Georganopoulos etal '10]*

MWL data

... using one-zone SSC modelling -> *[e.g., Mankuzhiyil etal 2010, Dominguez etal. '13]*

- *Application of plausibility arguments on source spectra*

IACT-data only

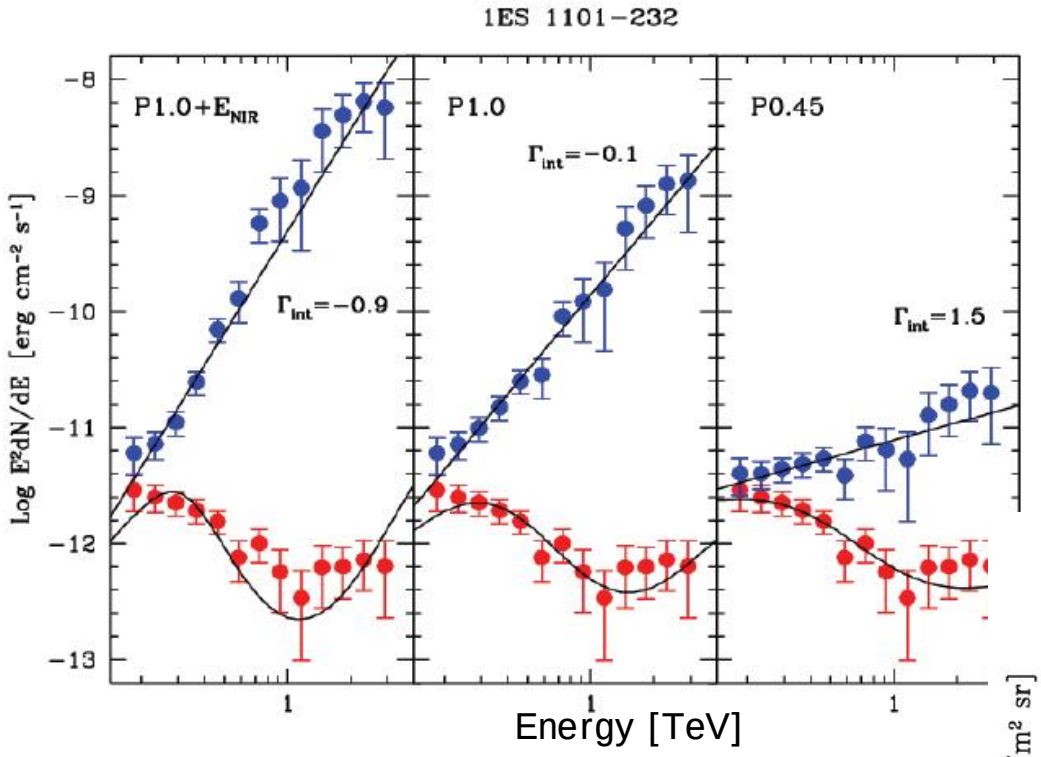
hardness limit, smooth spectral shape, no up-turns/pile-ups,
-> *[Aharonian etal. '06, Mazin & Raue '07, Abramowski etal '13, Meyer etal '12, ...]*

LAT- & IACT data

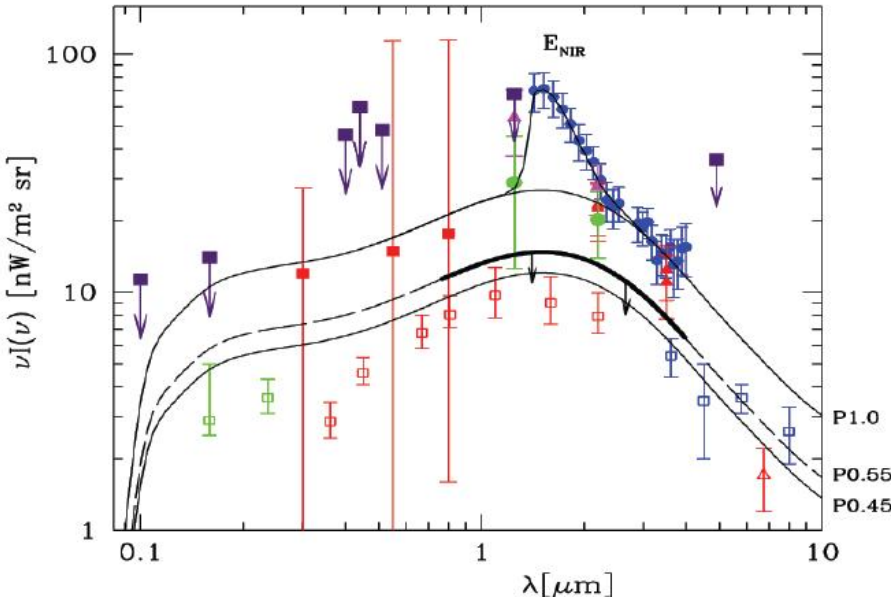
- *.....*

Hardness constraints on source spectra

[Aharonian et al 2006]



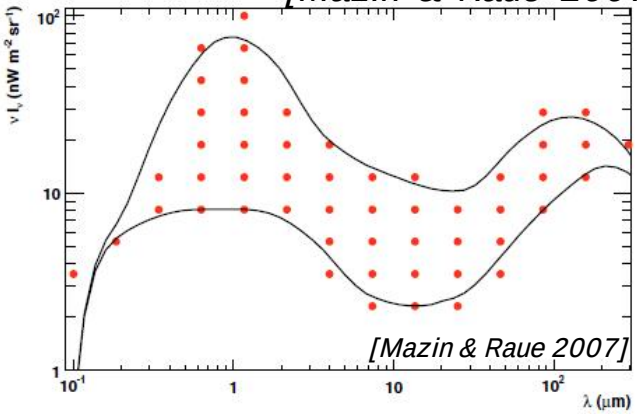
- energy-dependent attenuation feature in 2 high-z blazar (1ES1101-232: z=0.186, H2356-309: z=0.165)
- Γ=1.5 hardness limit applied



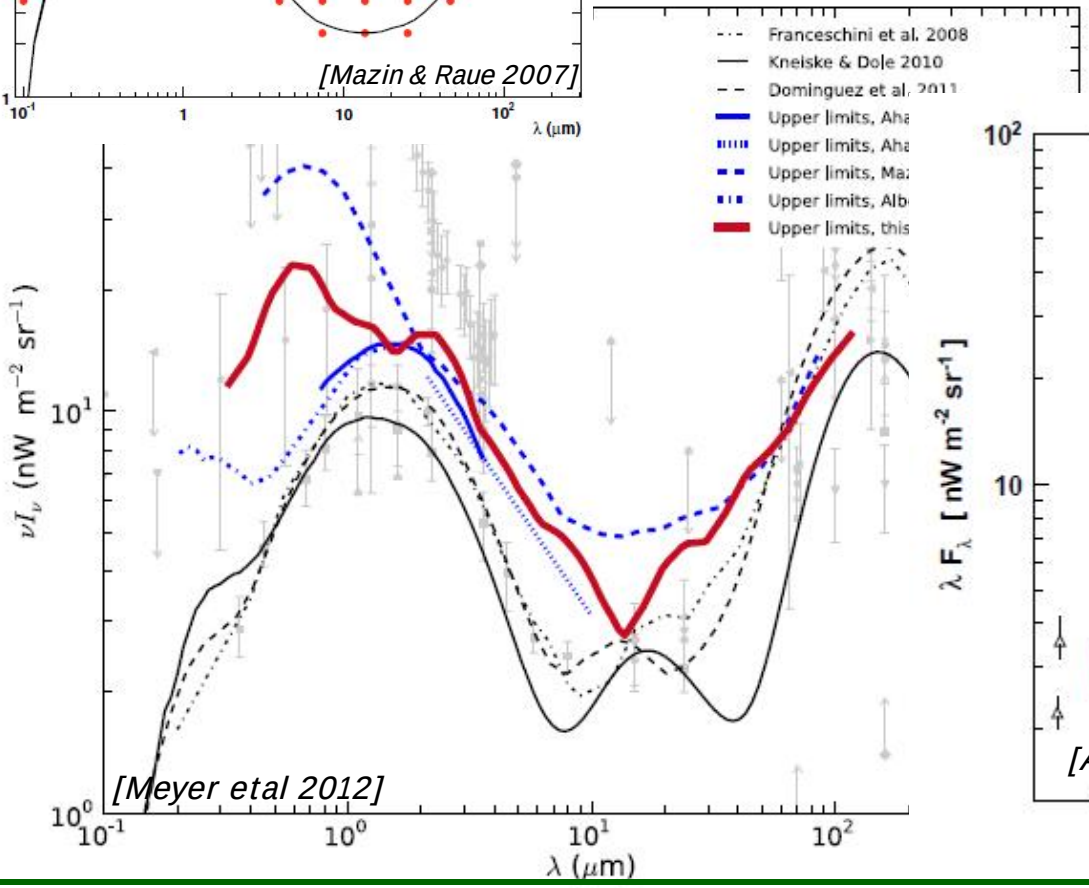
-> Gamma-ray horizon larger than previously estimated

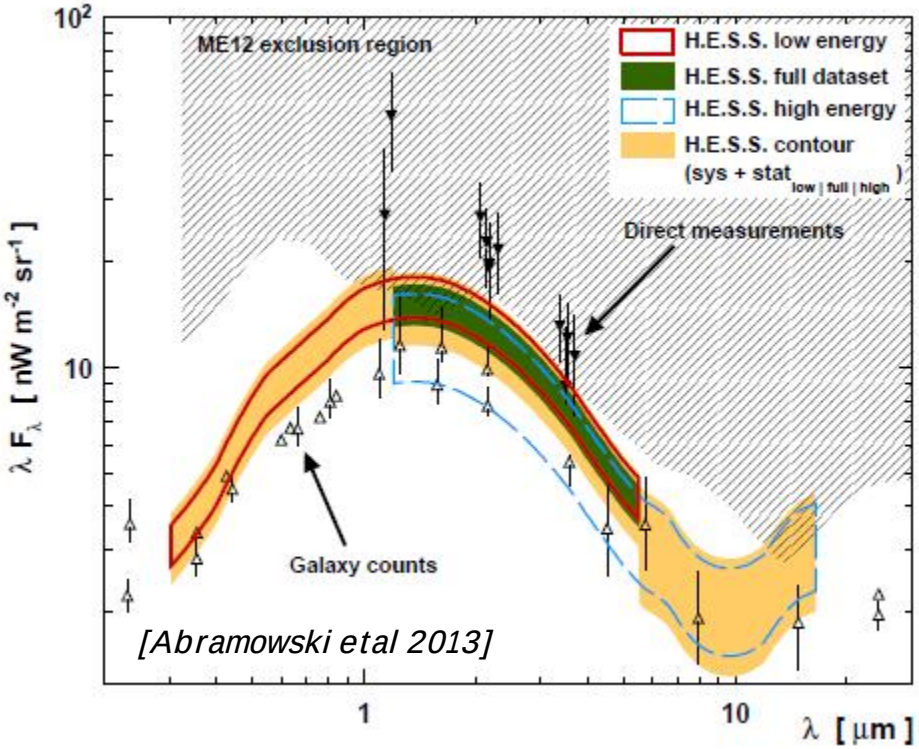
Shape constraints on source spectra

[Mazin & Raue 2007, Meyer et al 2012, Abramowski etal 2012]



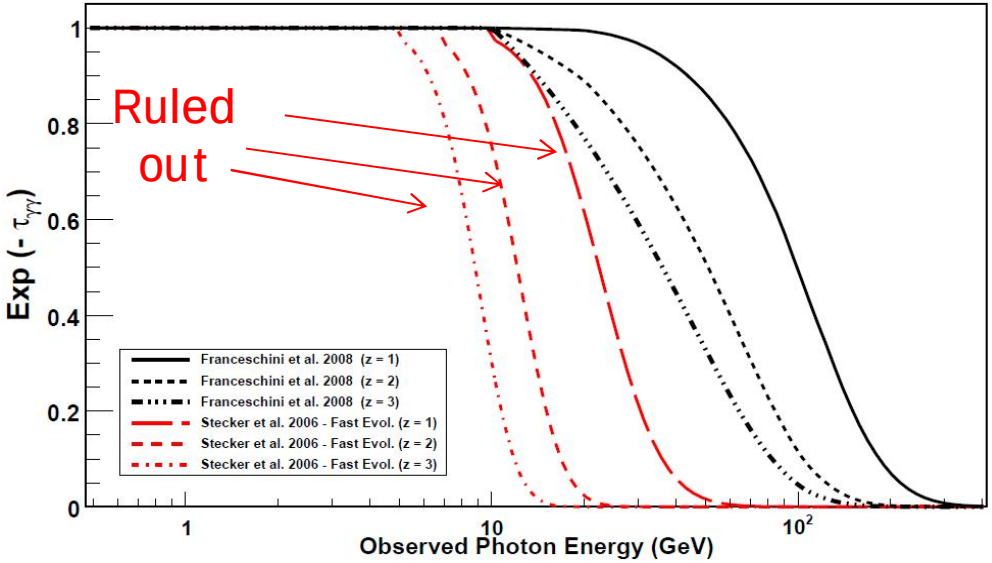
- *VHE / HE+VHE shape constraints:*
  smooth functions, no pile-ups, $\Gamma \geq 1.5$, (2/3)
  [Mazin&Raue'07, Meyer etal'12, Abramowski etal '13],
  VHE-HE index/concavity [Meyer etal'12]





The EBL @ opt/UV after 1 year LAT operation

[Abdo et al, 2010, ApJ, 723, 1082]



First Year of Fermi data:

reject with high significance [HEP:>8.9σ, LRT: >11.4σ]

EBL models that predict large opacities in the 20-50 GeV energy range for distant sources (z~1...4).

EBL absorption negligible at <15 GeV for z≲2

…. with (robust) upper limits in the range:

Source	z	E_{max}	$\tau_{UL}(z, E_{max})$
J1147-3812	1.05	73.7	1.33
J1504+1029	1.84	48.9	1.82
J0808-0751	1.84	46.8	2.03
J1016+0513	1.71	43.3	0.83
J0229-3643	2.11	31.9	0.97
J1012+2439	1.81	27.6	2.41

The EBL @ opt/UV after 46 months of LAT operation

[Ackermann et al 2012, Science, 338, 1190]

- 46-months of 1-500 GeV data
- "best" (>3σ @3-10 GeV) 150 BL Lacs from 2LAC ('non-variable' in 2LAC)
  - sub-divided into 3 redshift bins (50 sources each):

z = 0 …. 0.2,	0.2 …..0.5,	0.5 …… 1.6
35 HSPs, 10 ISPs, 5 LSPs	27 HSPs, 18 ISPs, 5 LSPs	10 HSPs, 19 ISP, 21 LSPs

- Goal: *Disentangling intrinsic curvature from EBL-caused absorption*

LAT energy range helps: negligible absorption in the EBL

- for < 15 GeV for sources @ any z<2
- for < 100 GeV for z<0.2 sources

$E_{crit} \sim 170\ (1+z)^{-2.4}$ GeV

-> observational access to intrinsic source spectrum *(parametrized as LogParabola)* @ gamma rays

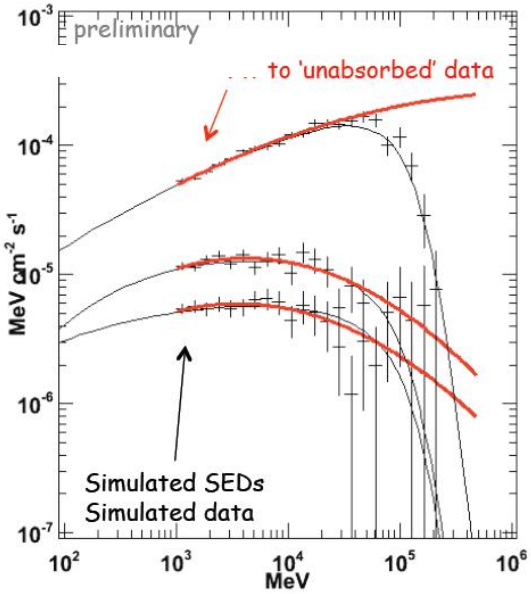
The Composite-Likelihood Method

Goal: *collective deviation of observed spectrum from its intrinsic one*

Assumption: intrinsic spectrum represented by LogParabola within LAT E-range

Procedure: *in each redshift bin…*

- fit spectra of all sources independently
- LogParabola-fit in [1GeV, E_{crit}] -> intrinsic spectrum & extrapolation to high energies
- Spectra of all sources modified by *common term* $\exp[-b\ \tau(E,z)]$ [combine likelihoods]



[From: Ajello etal 2012]

$$F(E)_{obs} = F(E)_{intr} \exp[-b \cdot \tau(E,z)_{model}]$$

Test:

(1) No EBL:

Null Hypothesis b=0

(2) Model prediction correct:

Null hypothesis b=1

TS=2 [Log L(b) – Log L(b=0/1)]

Results

Many EBL models tested:

no EBL

model prediction correct

Model[a]	Significance of b=0 Rejection[b]	b[c]	Significance of b=1 Rejection[d]
Stecker et al. (2006) – fast evolution	4.6	0.10±0.02	17.1
Stecker et al. (2006) – baseline	4.6	0.12±0.03	15.1
Kneiske et al. (2004) – high UV	5.1	0.37±0.08	5.9
Kneiske et al. (2004) – best fit	5.8	0.53±0.12	3.2
Gilmore et al. (2012) – fiducial	5.6	0.67±0.14	1.9
Primack et al. (2005)	5.5	0.77±0.15	1.2
Dominguez et al. (2011)	5.9	1.02±0.23	1.1
Finke et al. (2010) – model C	5.8	0.86±0.23	1.0
Franceschini et al. (2008)	5.9	1.02±0.23	0.9
Gilmore et al. (2012) – fixed	5.8	1.02±0.22	0.7
Kneiske & Dole (2010)	5.7	0.90±0.19	0.6
Gilmore et al. (2009) – fiducial	5.8	0.99±0.22	0.6

rejection >3σ

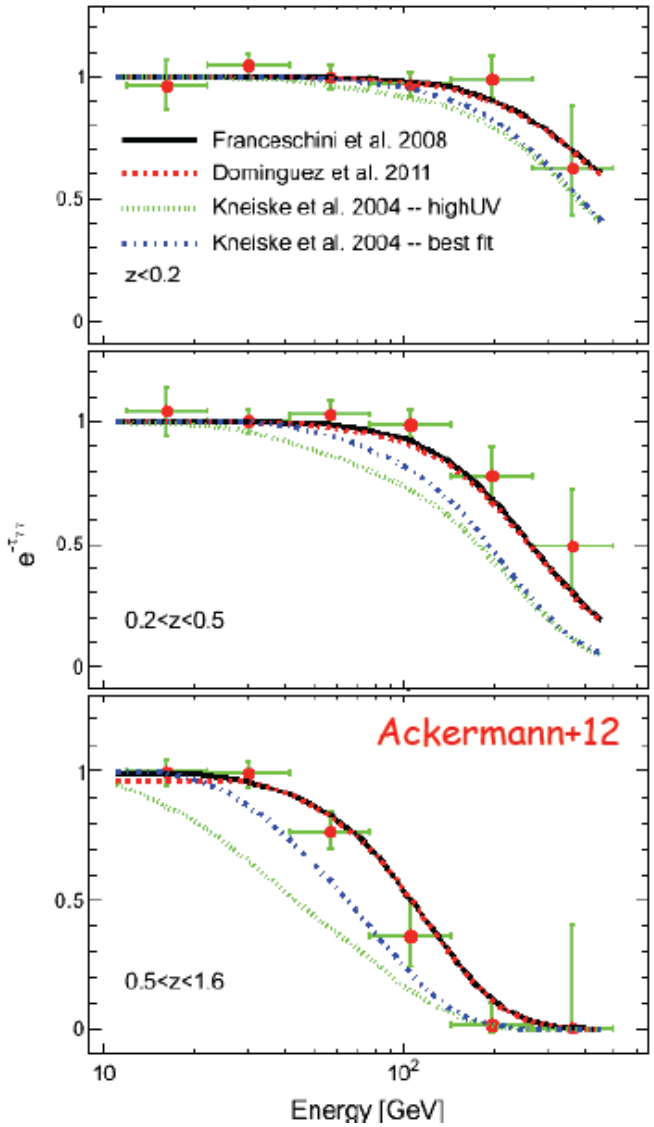
- Chance probability of no EBL: ~ 6 σ

  -> significant steepening in blazar spectra for z≥0.5

- Data compatible with low-opacity models

  (i.e., EBL @ galaxy counts level)

Collective imprint of EBL absorption in γ-spectra



In each redshift bin:

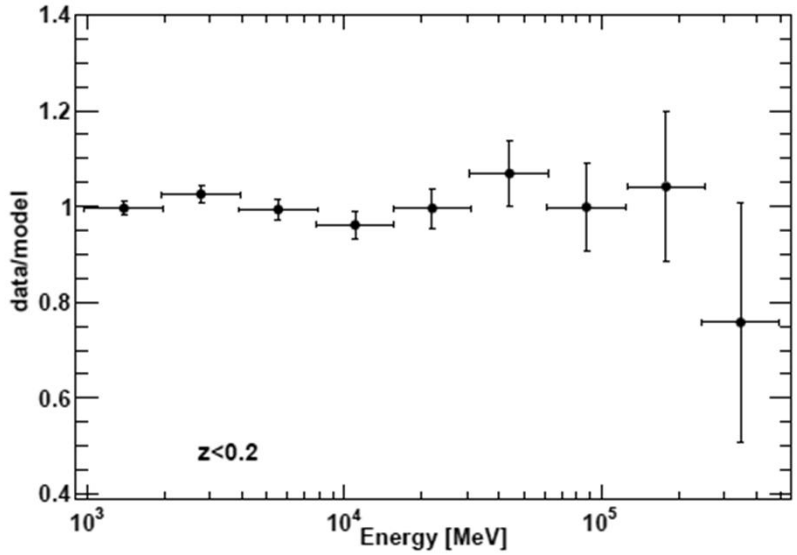
- Composite likelihood in small energy bins

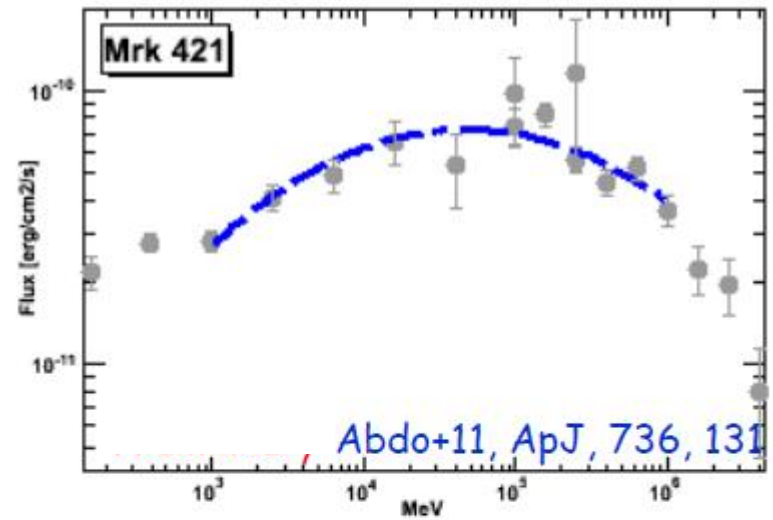
-> no spectral softening in blazar spectra $z \lesssim 0.2$ below ~150 GeV

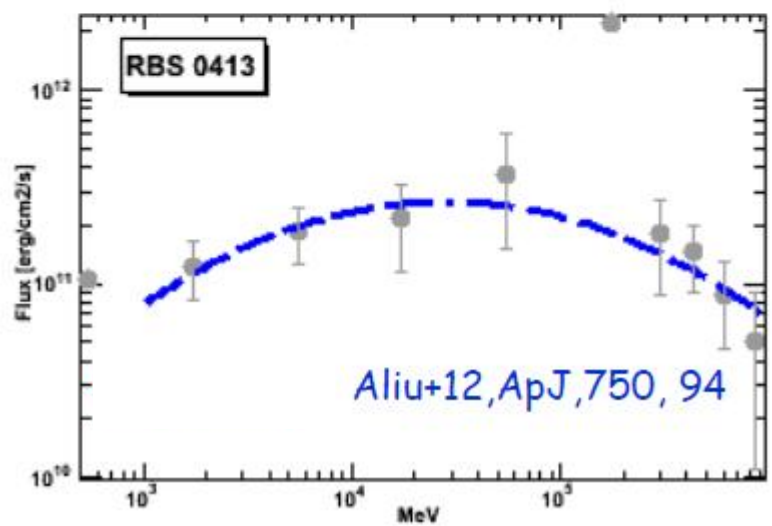
-> cutoff moves in redshift & energy as expected for low-opacity EBL absorption

-> spectral softening due to absorption in the EBL if BL Lac properties do not change significantly across z~0.2 barrier ("cosmic conspiracy")

The LogParabola assumption as intrinsic spectrum







- EBL-caused absorption in the near Universe ($z \lesssim 0.2$) negligible for E<150GeV
- GeV-to-TeV fit to LogParabola suitable

[From: Ajello etal 2012]

On disentangling intrinsic from EBL-caused absorption

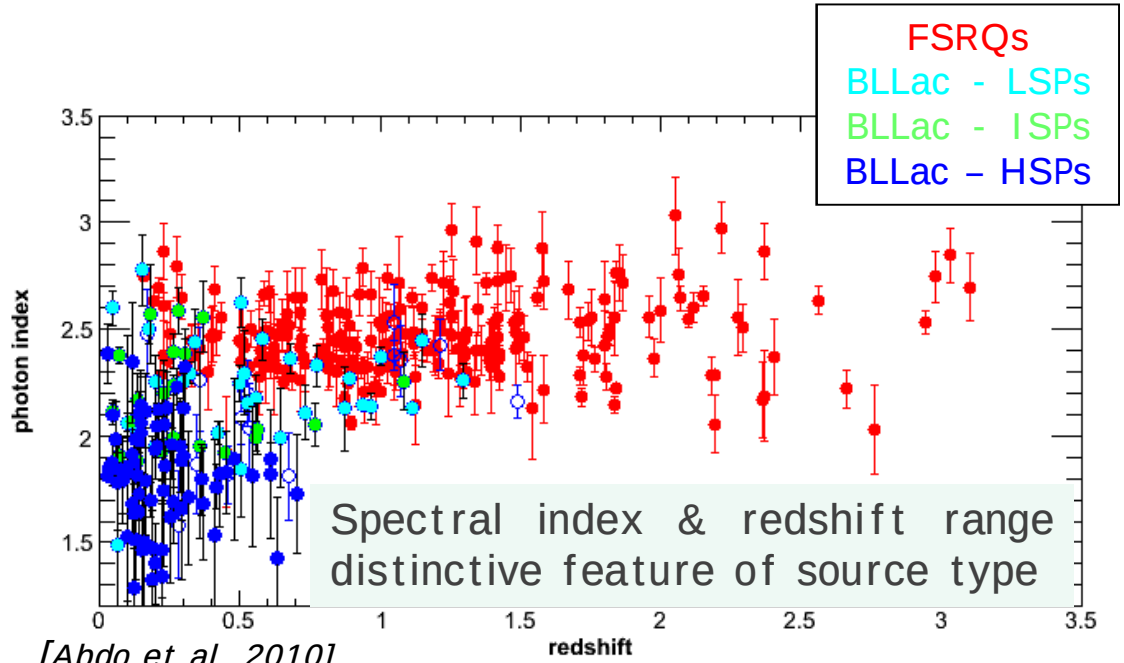
BUT: - intrinsic absorption possible *[Reimer 2007]*

-> source selection: BL Lac objects

- softening of BL Lac spectra along sequence HSP – ISP – LSP

[e.g. Abdo etal.2010, Ackermann etal.2011]

-> test EBL signal in each blazar sub-type sample separately:



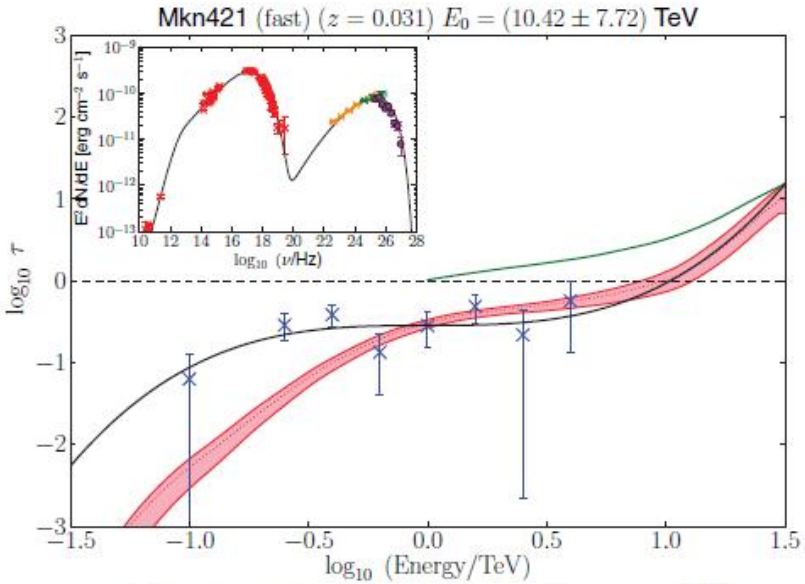
[Abdo et al, 2010]

z<0.2: no EBL softening detected
(41 HSPs, 10 ISPs, 5 LSPs)

z≥0.2:
HSPs (50) : $b=1.04^{+0.32}_{-0.28}$, TS~24
ISPs (30) : $b=2.13^{+1.11}_{-0.98}$, TS~9
LSPs (23) : $b=0.43^{+0.67}_{-0.71}$, TS~1
-> weighted average: $b=1.04^{+0.27}_{-0.24}$
TS~38

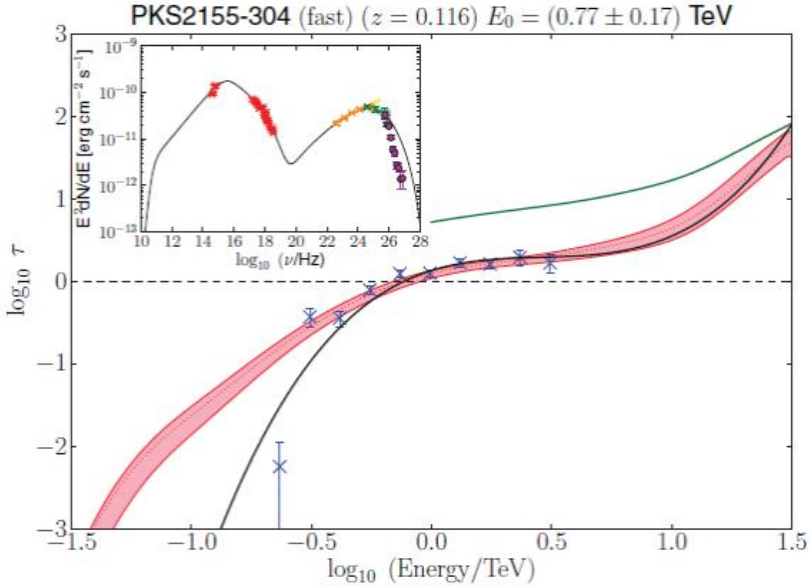
Extension of LAT-spectrum by SSC-modelling

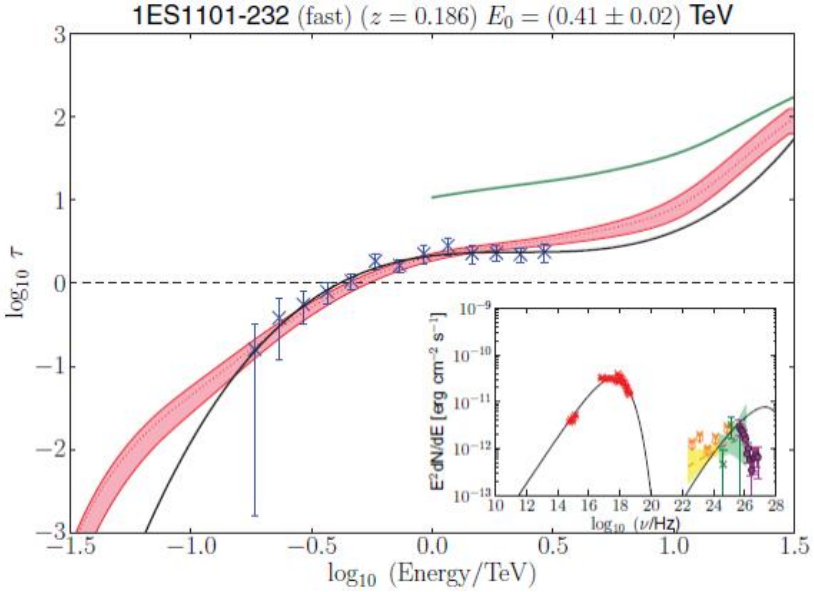
[Dominguez et al 2013]



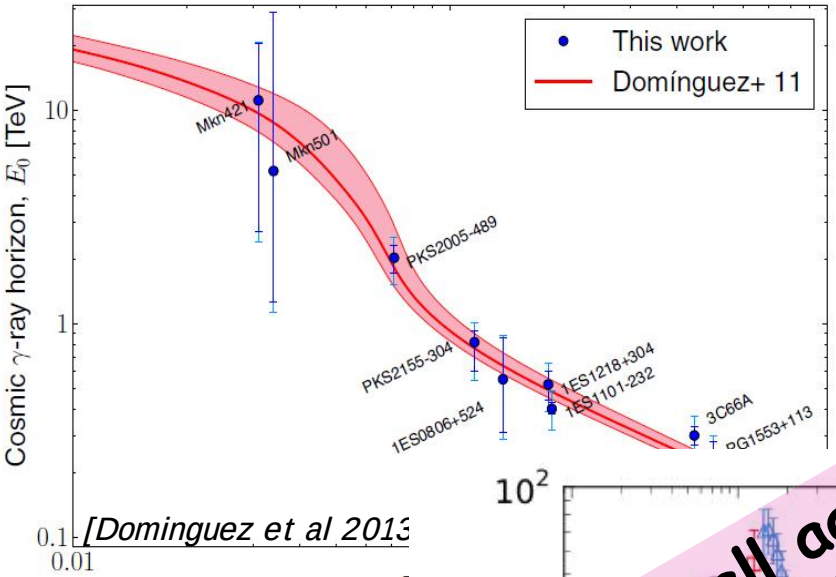
- (hom. one-zone) SSC-modeling of 15 TeV BL Lacs with quasi-sim MWL (IR-GeV)-data to describe intrinsic spectrum

- comparison to observed IACT spectrum & maximum likelihood polynomial fitting of log τ(log E) under some assumptions for τ(E)

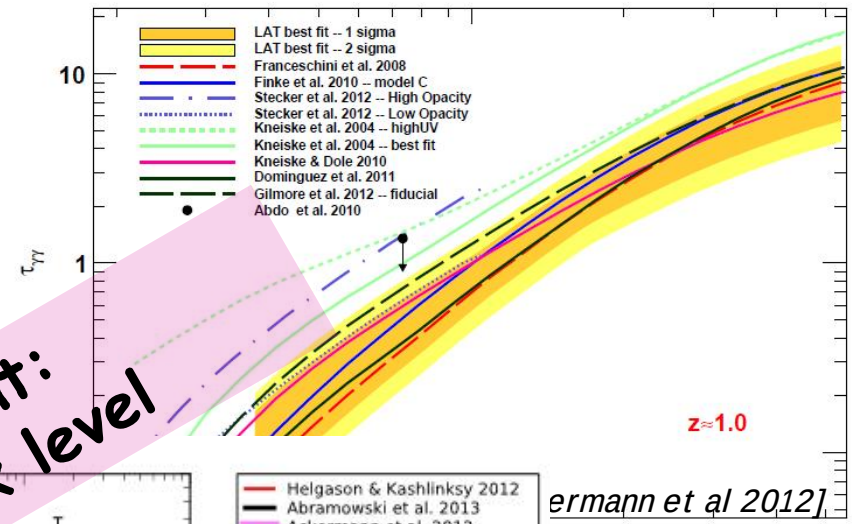




EBL summary



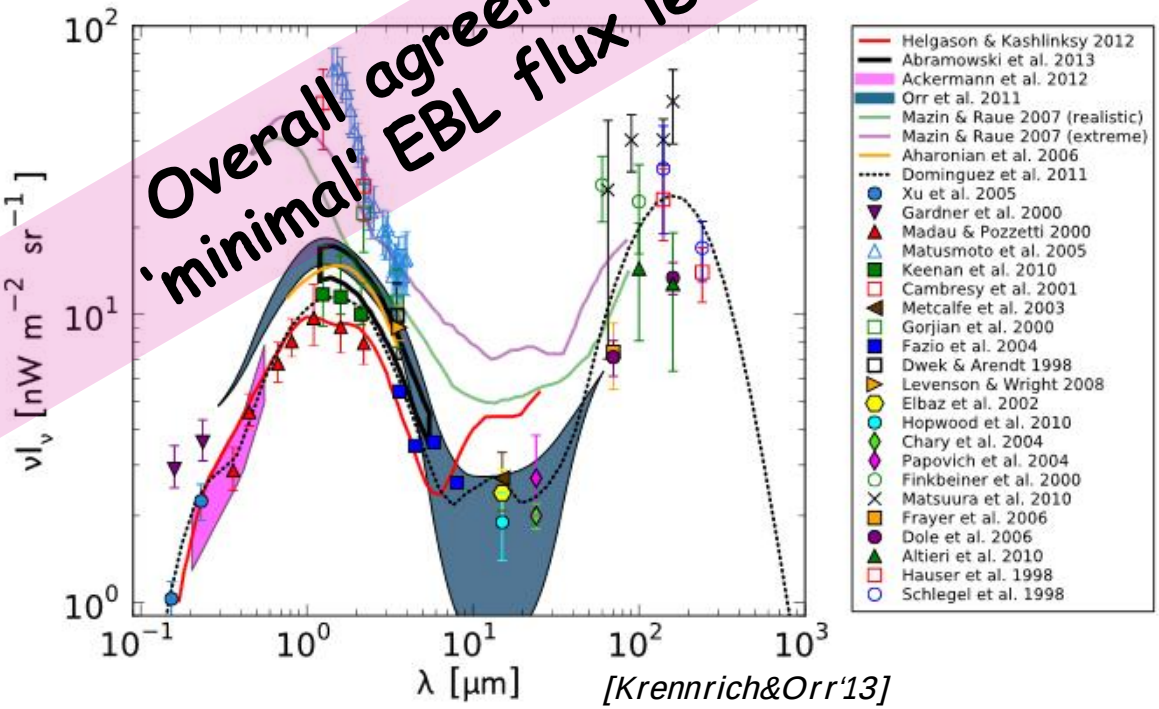
[Dominguez et al 2013



ermann et al 2012],

gy [GeV]

Overall agreement: 'minimal' EBL flux level



[Krennrich&Orr'13]

EBL Conclusions & Implications

- Stellar peak of the EBL SED (~0.4-10μm) in agreement with "minimum EBL flux" from galaxy counts

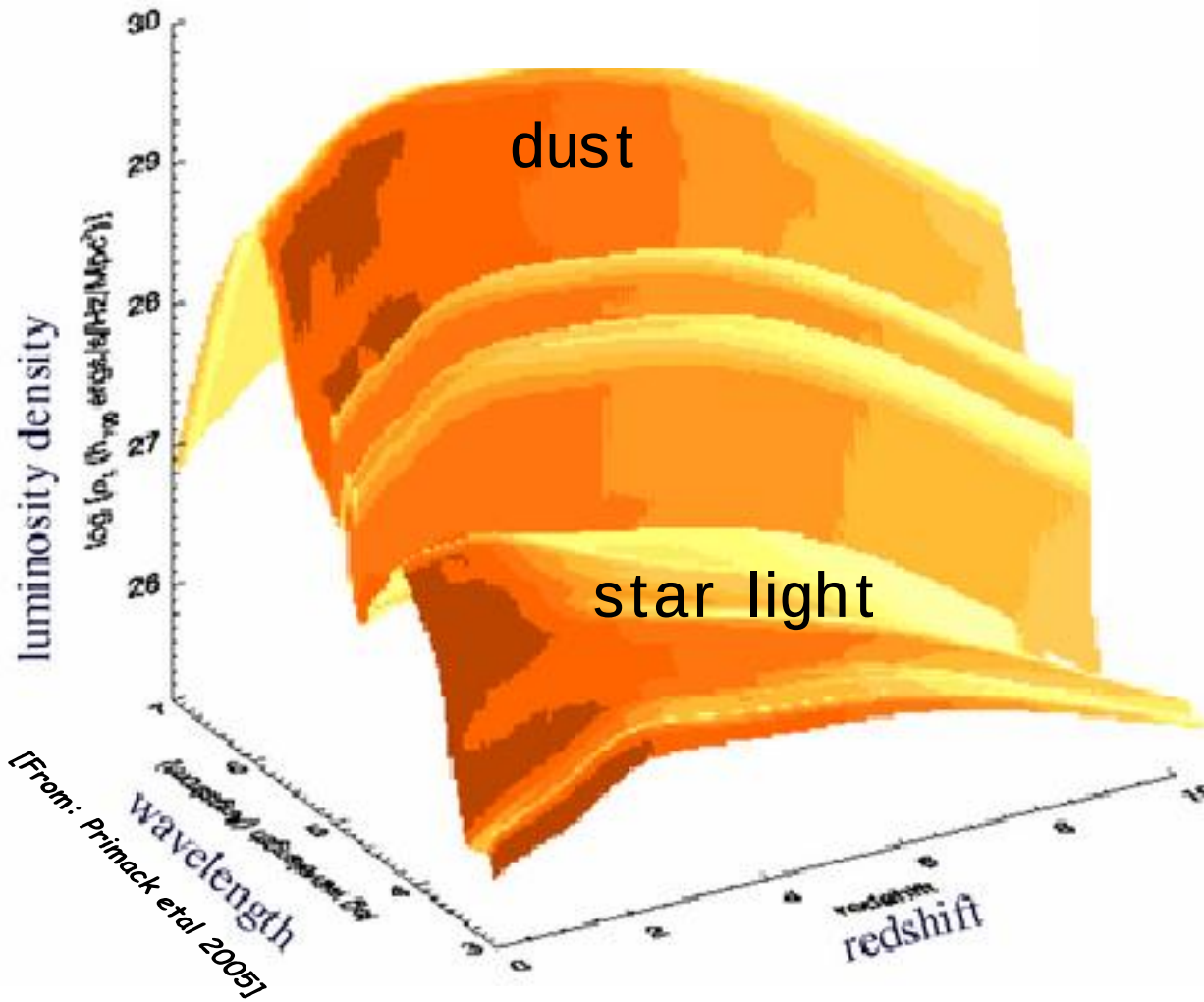
- excess contribution (above galaxy counts EBL level) from Pop III stars disfavored from constraints @VHEs *[Aharonian etal 06, Mazin&Raue'07]*

- From LAT EBL analysis:
  UV component of EBL ~ 3 nW $m^{-2}sr^{-1}$ @ z~1
  HST galaxy counts: 2.9-3.9 nW $m^{-2}sr^{-1}$ *[Gardner etal 2000]*
  -> residual diffuse UV background small

- massive star SFR peak <0.5 $M_{sun}yr^{-1}Mpc^{-3}$ & @ z>10

- *BUT some challenges:*
  - the strange case of PKS1424+24 (see A. Furniss Talk)
  - unusual hard VHE spectra of some high-z blazars

The *evolving* extragalactic photon density



[From: Primack etal 2005]

Wish list for CTA:

Ideally, one would like to probe the energy- & redshift resolved extragalactic photon density.

Requirements:

- more high-z probing sources
- improved understanding of *intrinsic source HE spectra*

On the SED of mis-aligned blazars

-> understanding intrinsic AGN spectra using mis-aligned blazars?

$$D=[\Gamma(1-\beta\cos\theta)]^{-1}$$

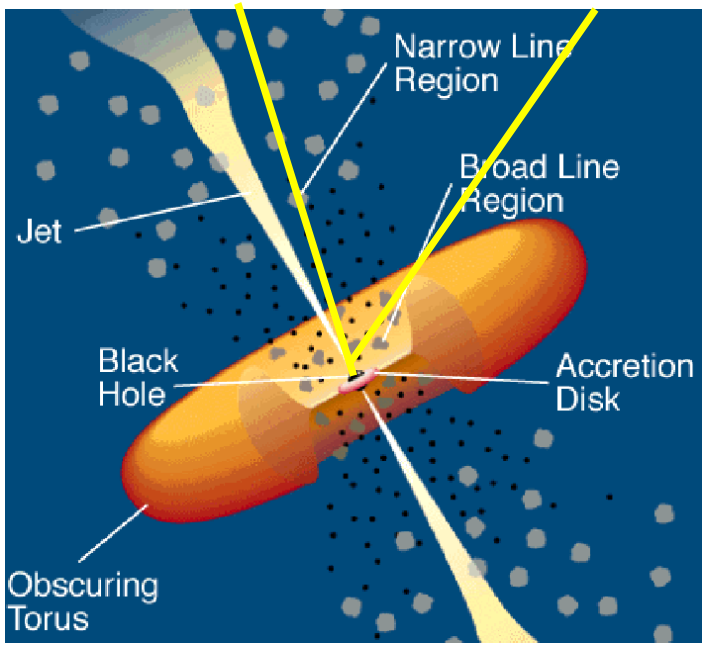
-> affects

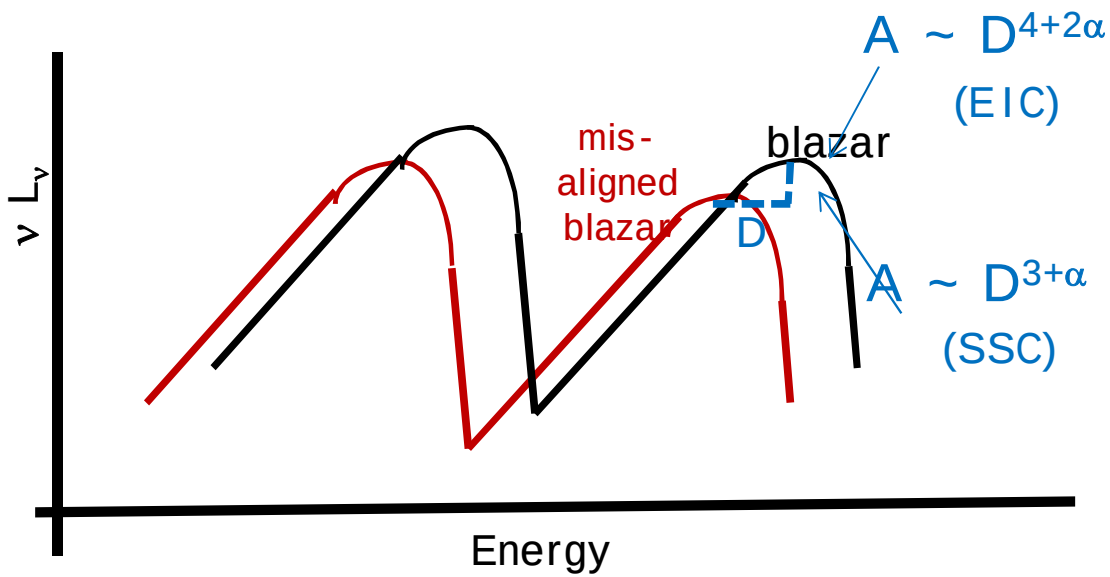
- *energy scale: E -> E'·D*
- *luminosity: L -> L' A*
- *variability: t -> t'/D*

$\Gamma\sim10$, $\langle\theta\rangle\sim1^{o}$

[Ajello etal'12]

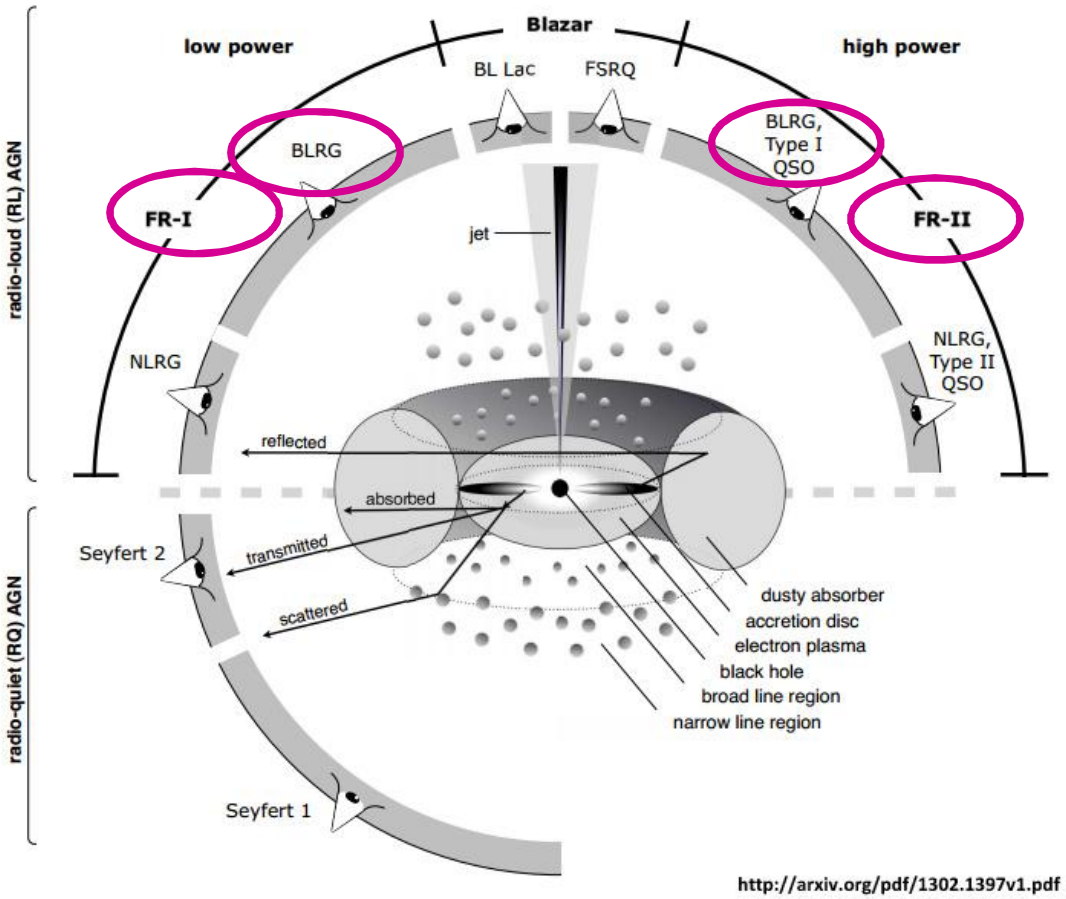
FSRQ FRII



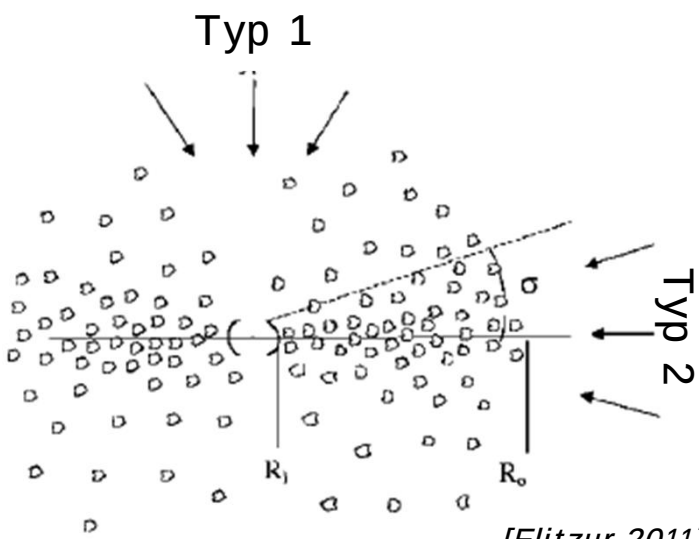


Are HE spectra of radio galaxies de-beamed *only* versions of blazar spectra?

Unifying AGN



"Minimal Unification"
[Urry & Padovani 1995]



[Elitzur 2011]

"Clumpy Unification"
[e.g., Elitzur 2011, 2012]

Further possible aspects:
Geometry of BLR, NLR (shell, sphere, toroidal,…?), corona, accretion rate, black hole mass,…

Mis-aligned AGN (MAGN) at high energies

Name	Class	z	GeV	1FHL	VHE	Γ_{LAT}	$Lg(L_{LAT})$	Variability?
NGC1218	FRI	0.029	L			~2.0	~43.0	~years
NGC1275	FRI	0.018	L	+	M	~2.0	~44.0	~week-month var.
0625-354	FRI	0.055	L	+	cand.	~1.9	~44.0	
M87	FRI	0.004	L	+	H,M,V	~2.2	~41.7	1d-TeV var.
Cen A	FRI	0.0009	L, E	+	H	~2.8	~41.1	~years
NGC6251	FRI	0.024	L, E			~2.2	~43.3	~years
IC310	FRI	0.019	L	+	M	~2.1	~42.9	1d-VHE var.
CenB	FRI	0.013	L			~2.3	~42.9	
Fornax A	FRI	0.006	L			~2.2	~41.7	~years

FRI: $L_\gamma \sim 10^{41-44}$ erg/s, $\Gamma_\gamma \sim 1.9-2.2$ (except. CenA)

[Abdo etal '10, Nolan etal. '12, Brown&Adams'12, Ackermann etal '13]

Mis-aligned AGN (MAGN) at high energies

Name	Class	z	GeV	1FHL	VHE	Γ_{LAT}	$Lg(L_{LAT})$	Variability?
3C111	FRII/BLRG	0.049	L, E			~2.5	~44.0	~months var.
3C120	FRI/BLRG	0.033	L			~2.7	~43.4	~months var.
3C207	FRII/SSRQ	0.681	L			~2.4	~46.4	
3C380	FRII/SSRQ	0.692	L			~2.3	~46.6	
0943- 76	FRII	0.27	L			~2.4	~45.4	
Pic A	FRII	0.035	L			~2.9	~43.3	

[Abdo etal '10, Nolan etal '12, Brown&Adams'12, Ackermann etal '13]

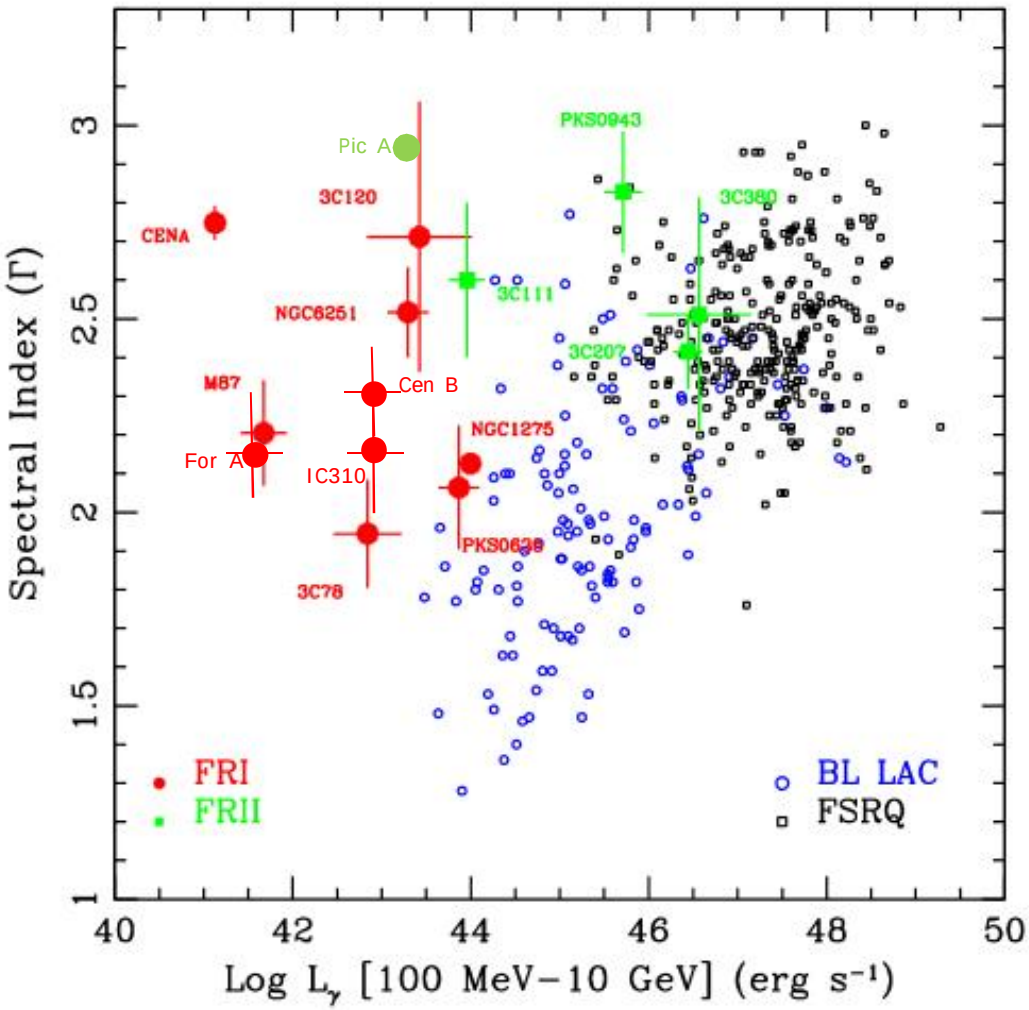
BLRG: $L_\gamma \sim 10^{43-44}$ erg/s, $\Gamma_\gamma \sim 2.5-2.7$

FRII&SSRQ: $L_\gamma \sim 10^{43-46}$ erg/s, $\Gamma_\gamma \sim 2.3-2.9$

=> No FRII, BLRGs yet detected at VHEs

HE properties of mis-aligned blazars

FRI/FRII luminosity puzzle



[adapted from Abdo etal 2010]

- FRII &FSRQs tend to be more luminous than FRI &BL Lacs
- FRI &BL Lacs span larger luminosity range than FRII &FSRQs
- FRI tend to be more separated from blazar range than FRII

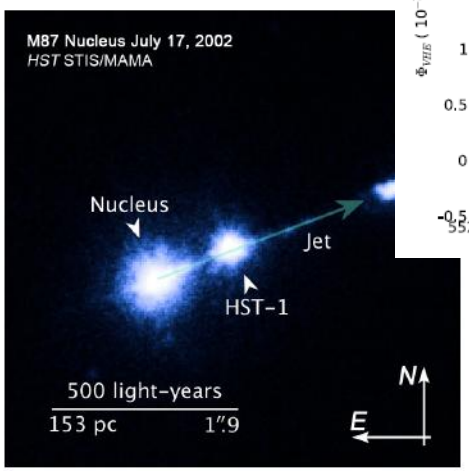
-> different beaming patterns, jet structure (inner fast spine&external slow layer),…?

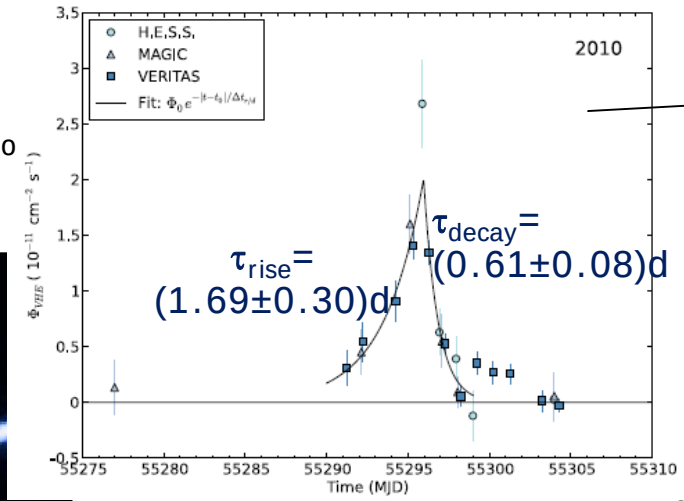
- FRI &BL Lacs tend to possess harder spectra than FRII &FSRQs

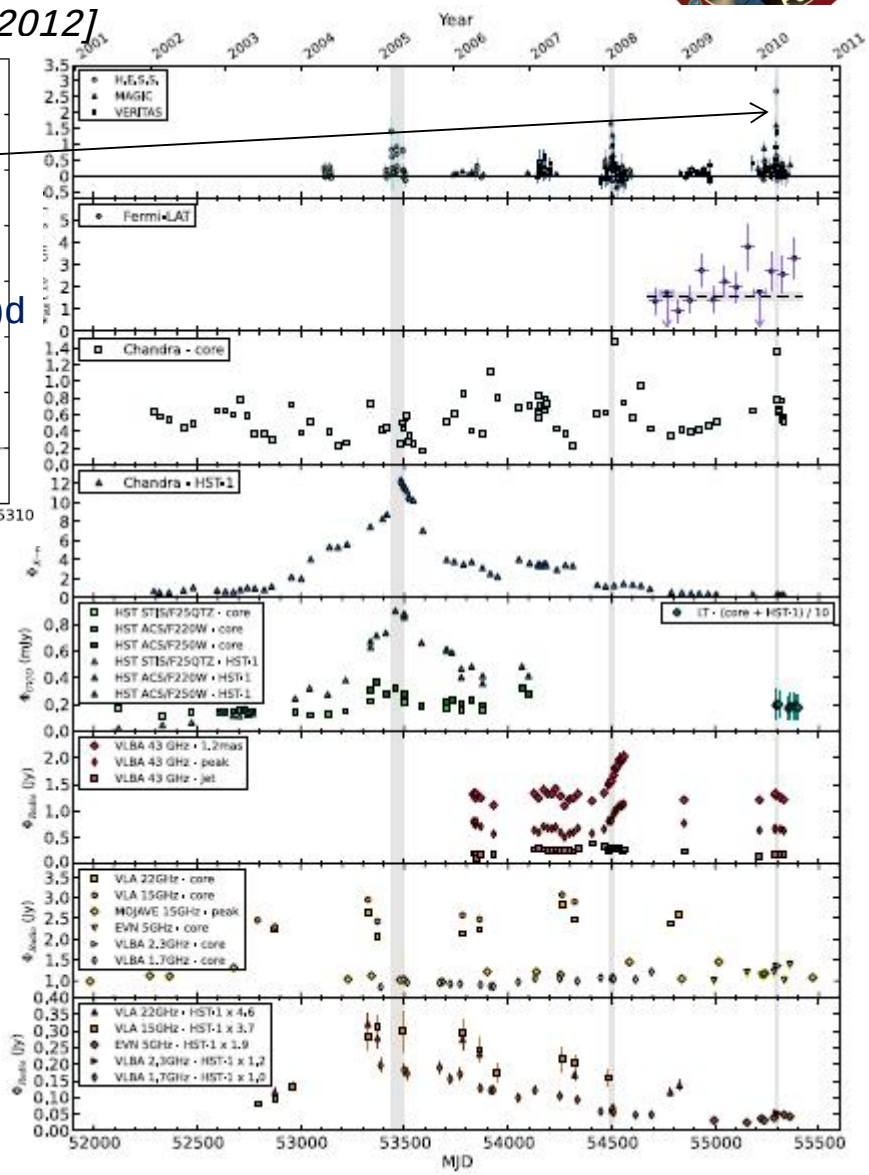
Case study: *FRI M87 @ high energies*

[Abramowski et al 2012]

- M_{BH}~(2-6) $10^9 M_o$
- Θ ~ 15-25°







- rapid day-scale VHE variability, no significant HE variability

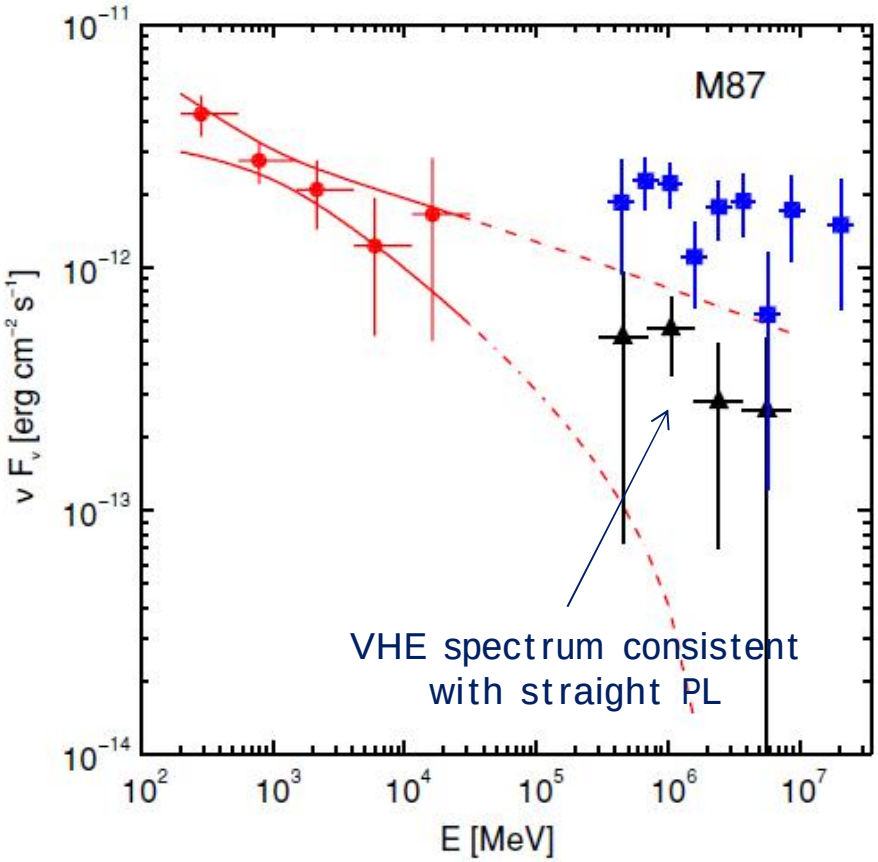
-> compact emitting region of size comparable to Schwarzschild radius ~10^{15}cm

Case study: *FRI M87 @ high energies*

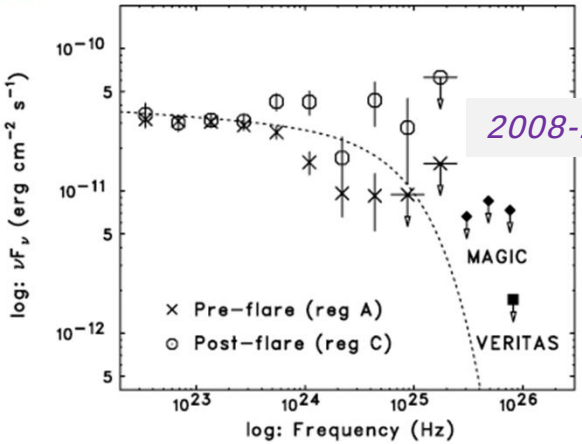
[Abdo et al 2009]

- VHE:
hard spectrum (Γ~2.2) extending up beyond ~10 TeV

- HE:
PL photon index comparable to VHE (Γ~2.2), extension underpredicts high-state TeV emission component

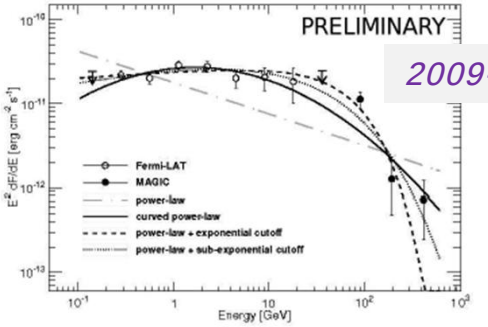


Case study: *FRI NGC 1275 @ high energies*

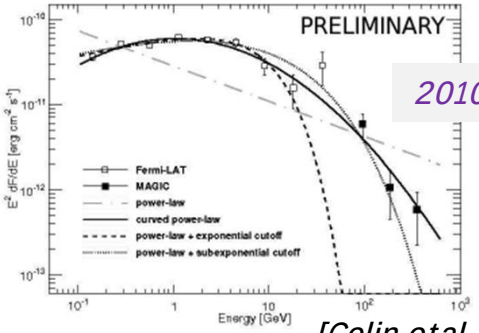


- M_{BH}~3 $10^8 M_o$
- $\Theta > 30^o$

Flux
(weeks … months) &
spectral variability

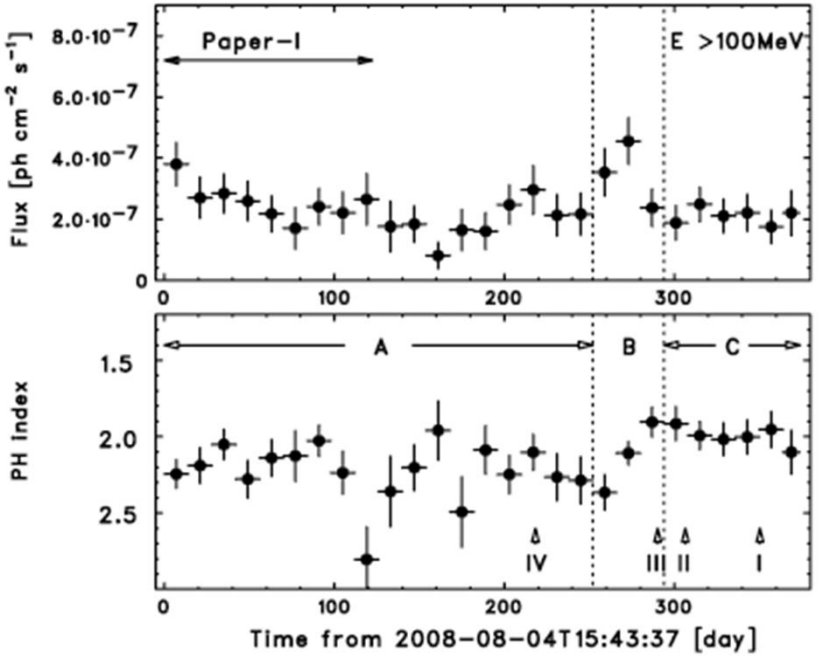


- Curved spectrum, cutoff @tens of GeV



[Colin etal 2013]

Flux & spectral variability



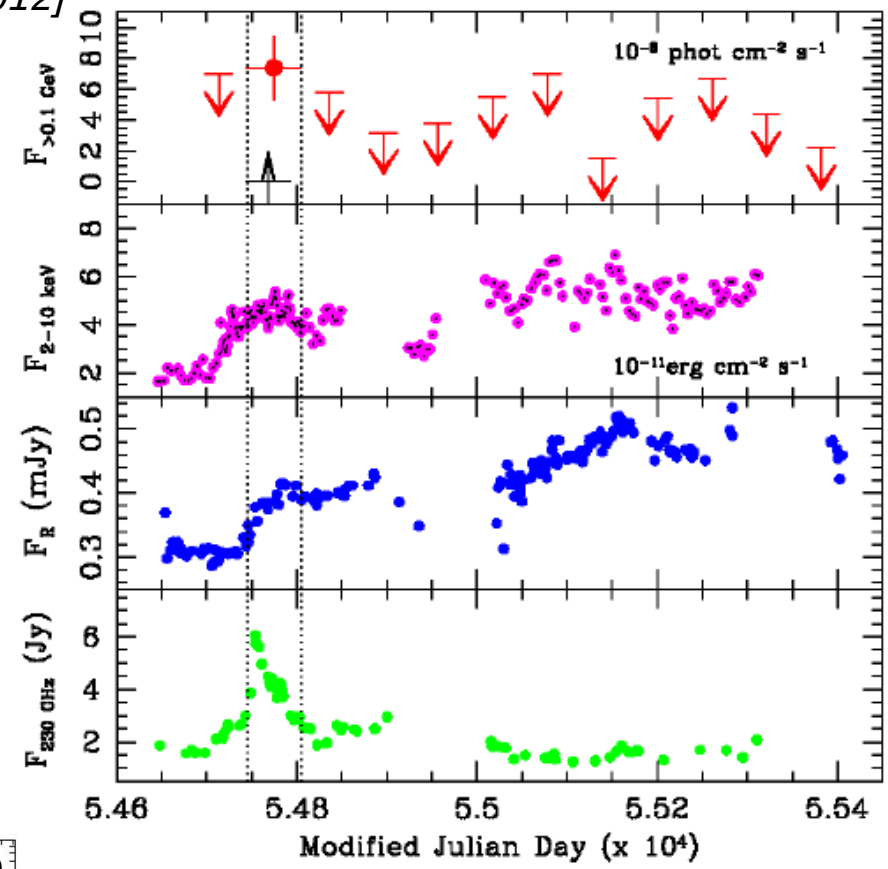
[Kataoka etal 2010]

- MWL picture: see K. Dutson's Talk

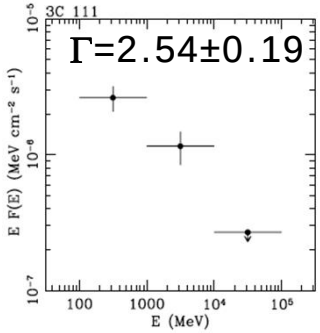
Case study: *FRII/BLRG 3C111 @ high energies*

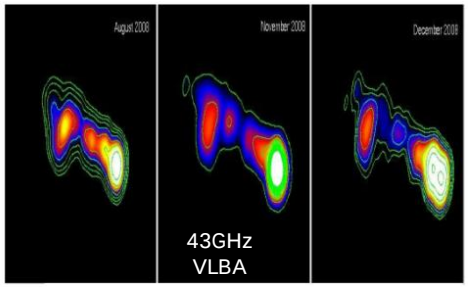
[Grandi et al 2012]

- M_{BH}~(2-3) $10^8 M_o$
- Θ ~ 18°
- Jet-disk connection *[Chatterjee etal'11]*



- Connection between γ-ray flare (Oct/Nov'08) & ejection of new radio knot
- γ-ray flare during increasing mm-X flux (Oct/Nov'08) & ejection of new radio knot
- implied radio-γ co-spatiality suggests compact γ-ray emission region <0.1pc within ~0.3pc distance from black hole
- Not listed in 1FHL as likely VHE candidate source





[BU group]

Radio-quiet AGN as gamma ray emitter?

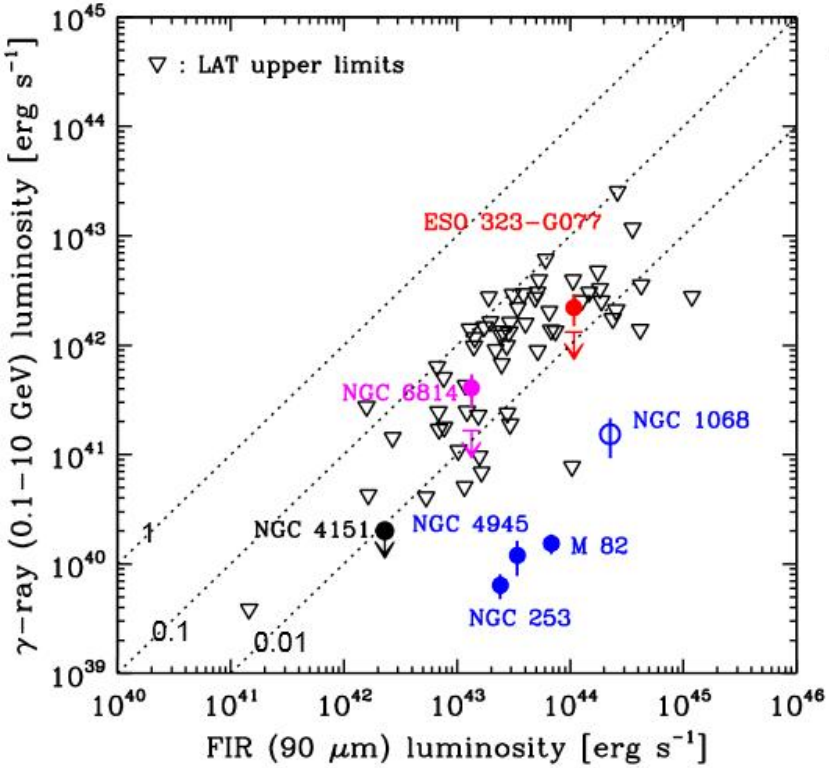
[Ackermann et al 2012]

- 120 hard X-ray selected Sy with $F_{14-195keV}$>2.5 10^{-11}erg $cm^{-2}s^{-1}$ & radio-loudness parameter R_{rX}<10^{-4} from 58months BAT catalog

-> Upper limit (>0.1GeV,95% conf.limit) @ few 10^{-9}ph $cm^{-2}s^{-1}$

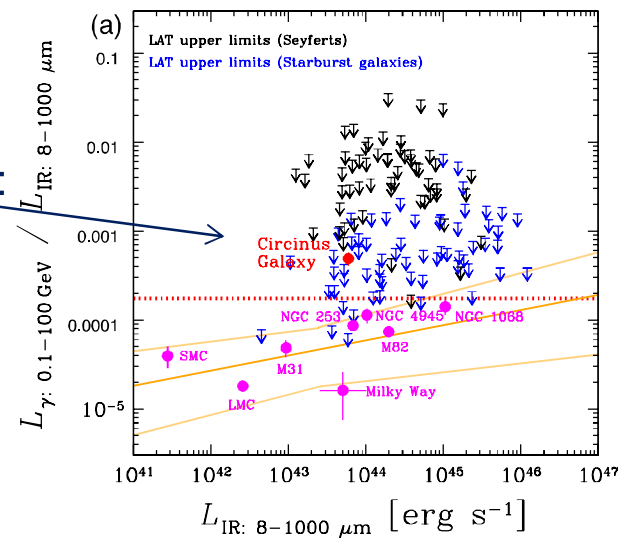
… corresponding to L_γ/L_X < 0.01…0.1

=> LAT upper limits on GeV luminosity probe ~1% of L_{bol}



- detection of Sys' ISM emission @GeVs require ~factor 10 sensitivity improvement

exception: *Circinus*



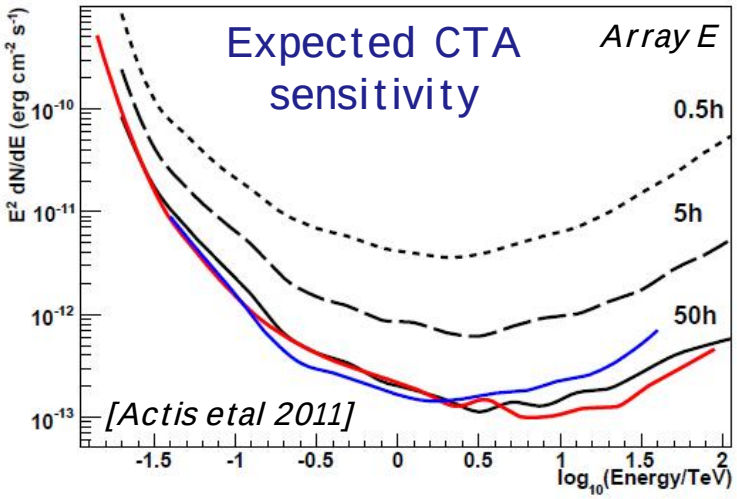
[Hayashida etal 2013]

- NLSy1: see F. D'Ammando's Talk

Conclusions & expectations for CTA

- Optical peak of today's EBL at galaxy counts level assuming *'reasonable' shapes* for blazars SEDs
  -> justified?

- LAT has detected imprint of EBL absorption in 3 redshift bins up to z~1.6
  -> *goal for CTA:* probe energy & redshift resolved extragalactic photon density



- HE radio galaxies: -> γ-ray emission from jet
  - compact emission region (core) -> blazars physics @ large viewing angle
  - lobes (e.g. CenA) -> energy transport along jet

  FRI: HE @ VHE sources
  FRII: not (yet?) detected above tens of GeV

- Radio-quiet Sy: - no jet emission detected @ HE from Sy galaxies
  - Sy's ISM emission detectable in CTA energy range?