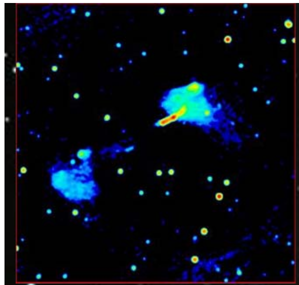
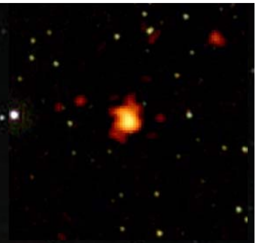


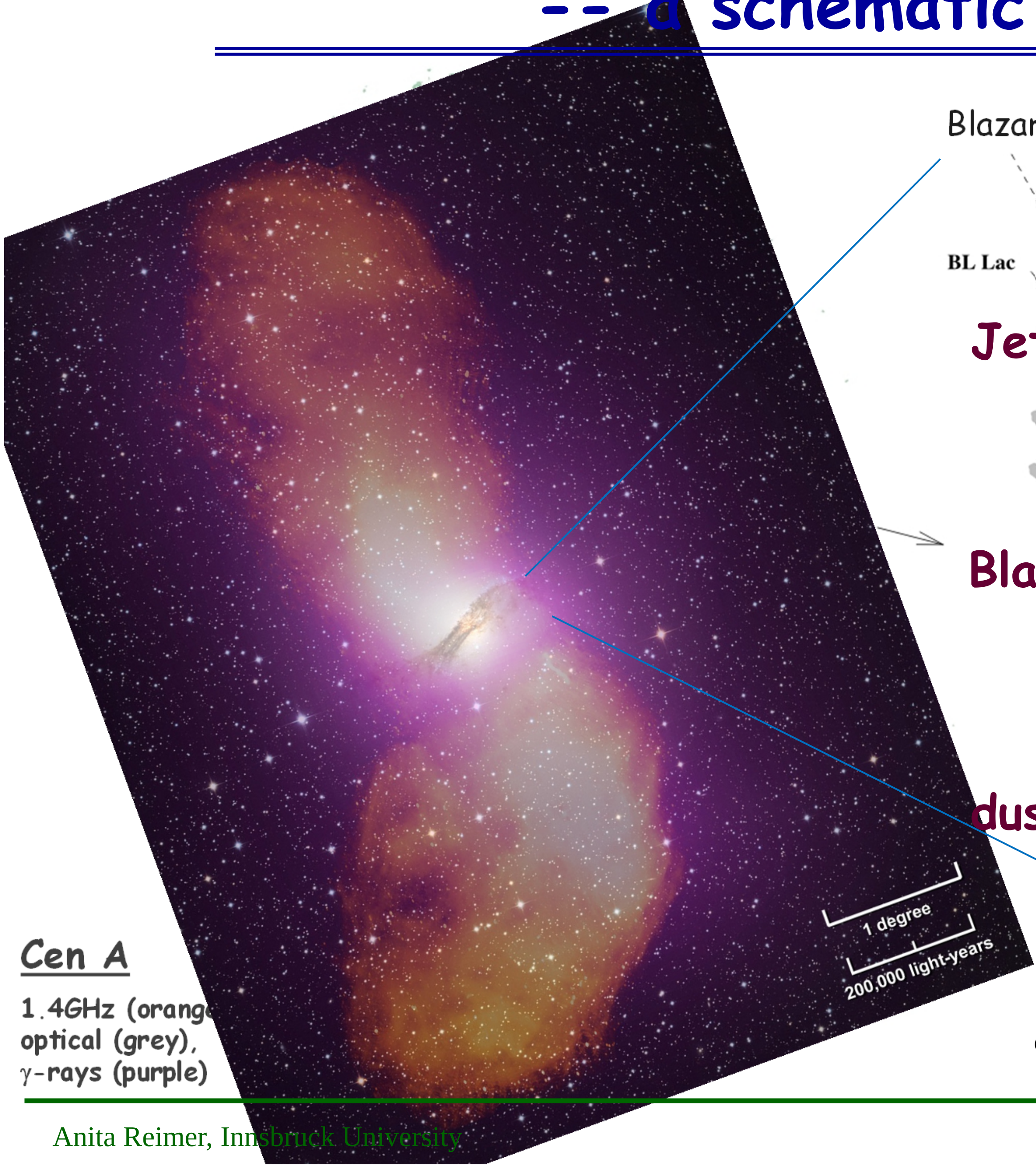


On the Physics of Gamma-ray Emitting AGN in the Fermi Era

Anita Reimer (Innsbruck University)

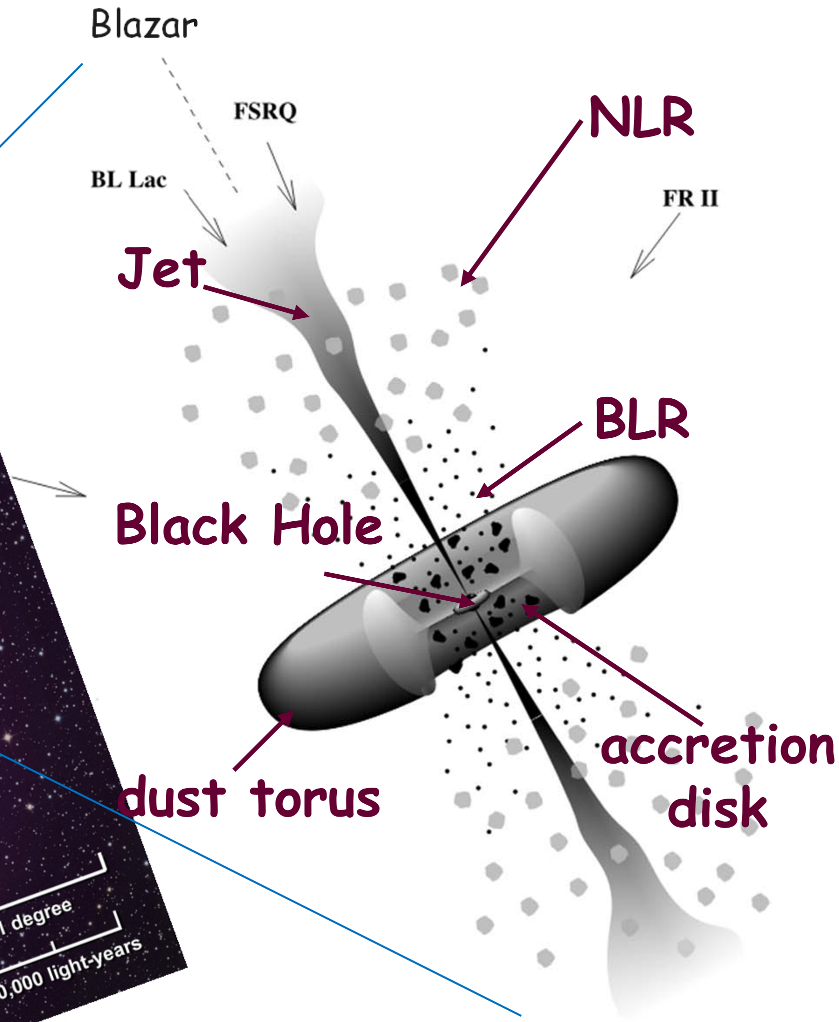
5th Fermi Symposium, Nagoya, October 2014

Active Galactic Nuclei (AGN)
-- a schematic view --



Cen A

1.4GHz (orang
optical (grey),
γ-rays (purple)



cartoon of a radio-loud AGN

Three corner marks

A. AGN AS A POPULATION AND THE BLAZAR PHENOMENON

Won't address here; see talks by Yoshiyuki Inoue, Markus Ackermann, Marco Ajello, Elisabetta Cavazzuti, Benoit Lott,…

B. THE PHYSICS OF GAMMA-RAY EMITTING AGN

Won't address misaligned AGN (see talks by Y. Fukuzawa, I. Edahiro, E. Meyer, K. Hada, J. Sitarek) or NLSy1 (see posters by F. D'Ammando, H. Shirakawa)

C. AGN AS A TOOL

Won't address here; see poster by Alberto Dominguez on EBL

Outline

I Introduction

II Models & diagnostics adressing open questions

1. ‘Crisis‘ on the location of the HE emission zone
2. On the jet composition
3. Diagnosing particle injection

III Conclusions

Jets of Active Galactic Nuclei: open questions

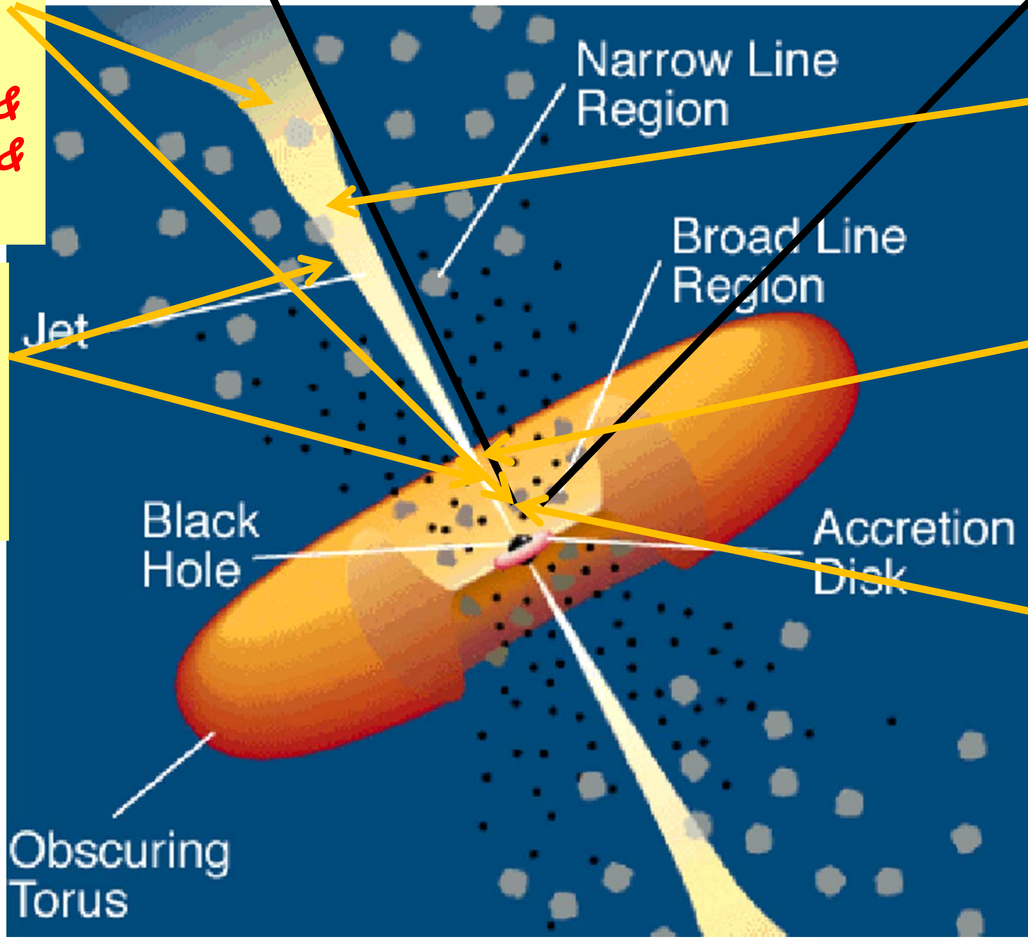
Blazar

Radio galaxy

Jet composition?

[rel./cold leptons & hadrons, B-fields & their properties]

γ-ray production: *Where? How?*



Energy transport?

Energy conversion?

Jet formation?

[from: Urry & Padovani 1995]

Blazar γ-ray emission is beamed

Opacity ($\gamma\gamma$ -> e^+e^-) argument:

- *broad* band high energy radiation with
- high luminosity L
- from a compact region $R \leq cT_{var}$

→ $\gamma\gamma$ -pair production opacity $\tau_{\gamma\gamma} = n\,\sigma_{\gamma\gamma} R \approx n\,\sigma_T R$ with $n \approx L / (4\pi c R^2 E)$
photon density

→ $\tau_{\gamma\gamma} \approx \sigma_T L / (4\pi c^2 E\, T_{var})$ with $E \cdot E_\gamma > (m_e c^2)^2$ threshold condition

Transparency requires $\tau_{\gamma\gamma} \ll 1$.

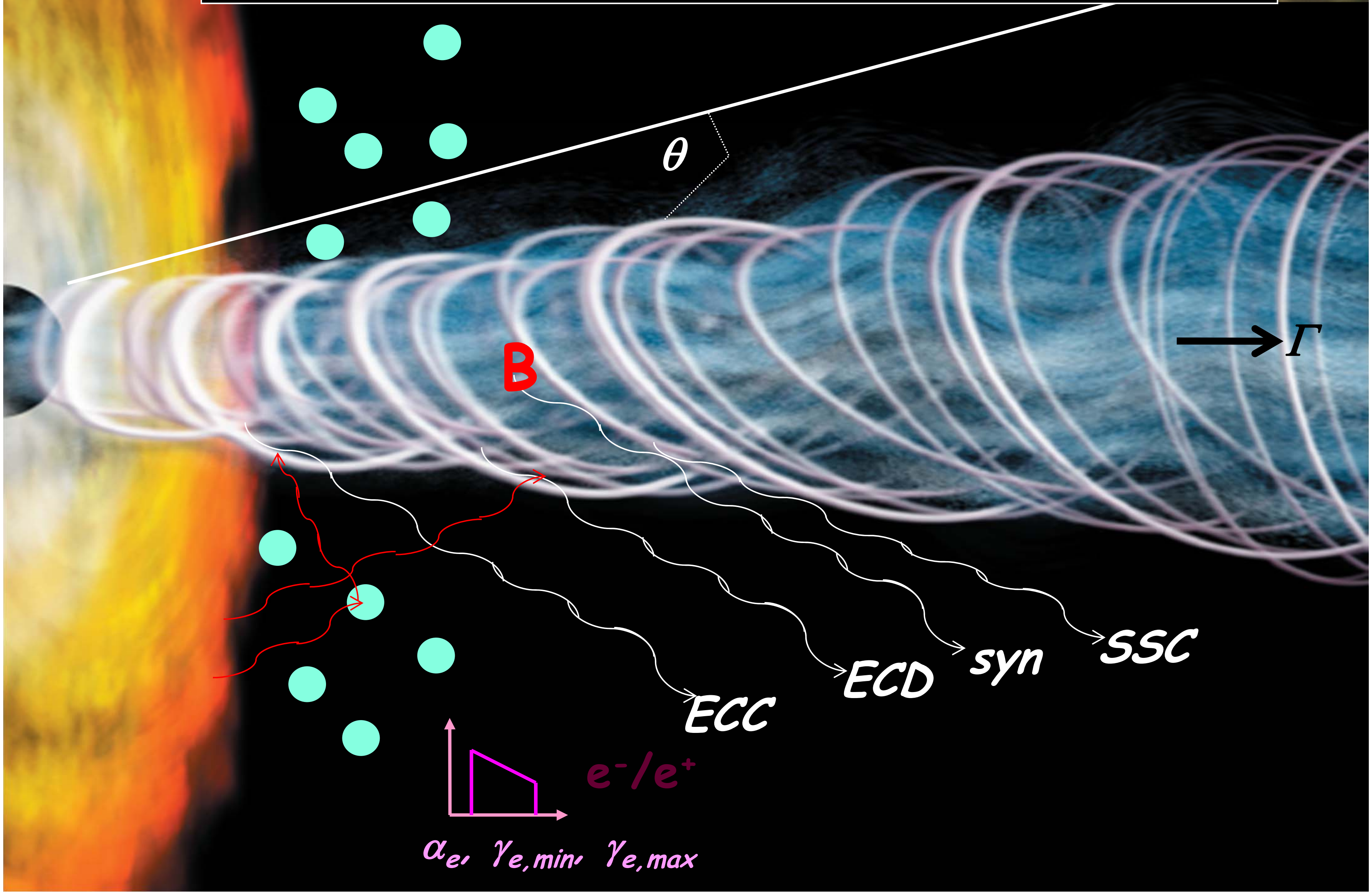
BUT: for many blazars one finds:

$$\tau_{\gamma\gamma} \approx 100\, L_{46} E^{-1}_{MeV} T^{-1}_{1hr} \gg 1$$

Solution *[Rees 1966]:* *γ-ray emission from jet, beamed!*

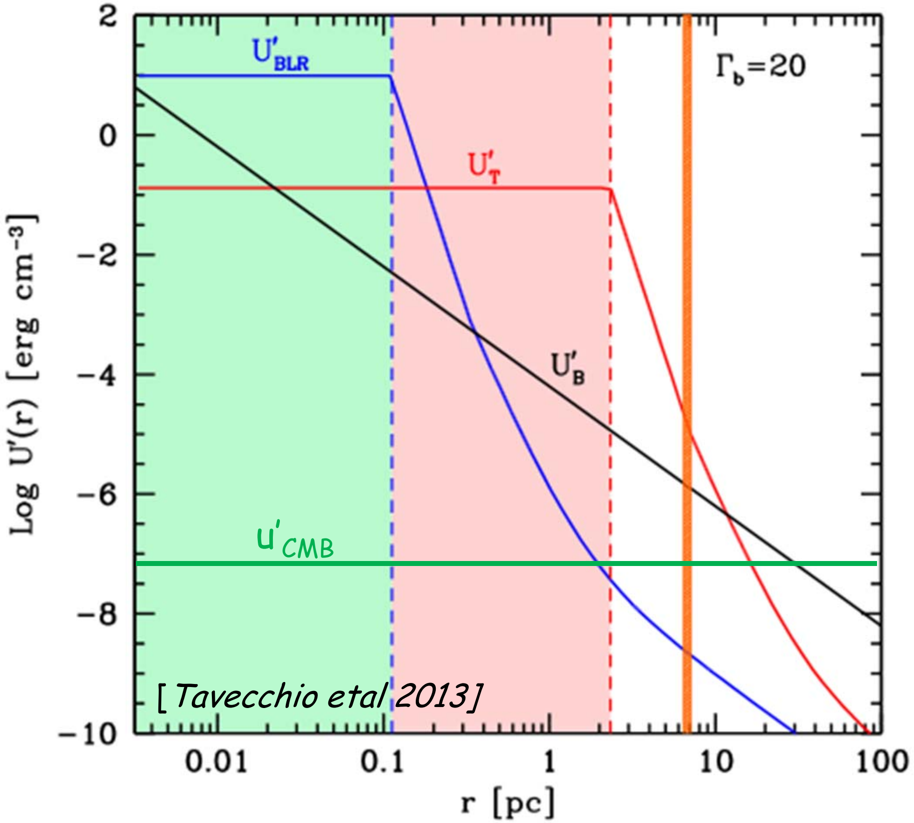
e.g., for blob geometry: $L \approx D^4 \cdot L' \approx 4\pi c^3 D^6 \cdot u' \cdot T^2_{var}$

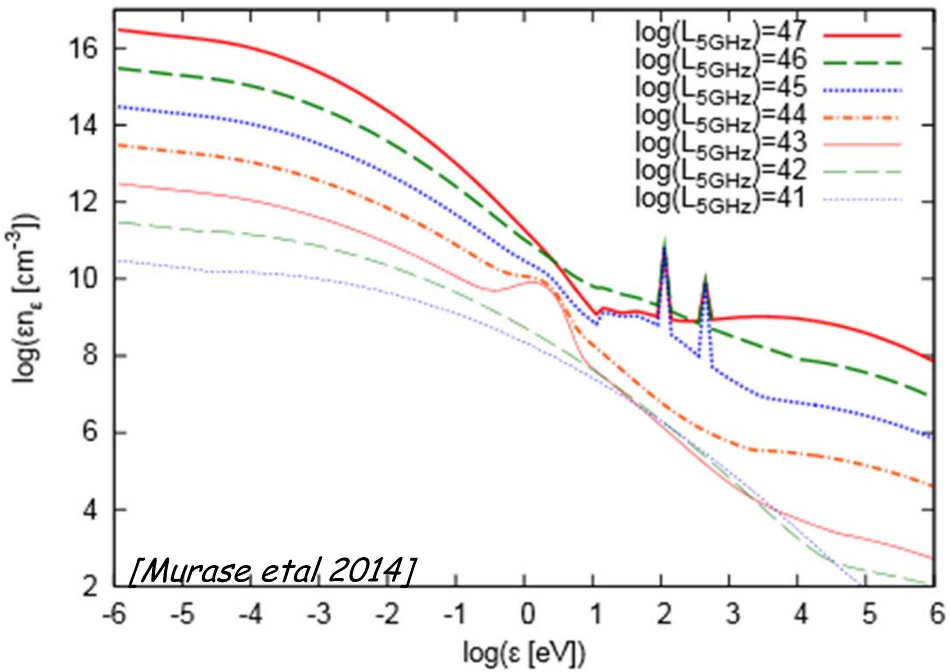
Non-thermal Emission Processes in AGN Jets: Leptons



Location of the γ-ray emitting region

-> implications for dominating target photon field for particle-photon interactions





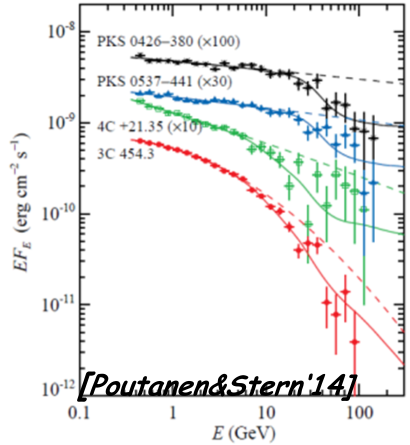
Jet-frame densities of blazar target photon fields along the 'blazar sequence'

=> Nature (& frequency) of dominating external target photon field in jet frame depends on distance from the central engine

γ-ray emitting region inside the BLR?

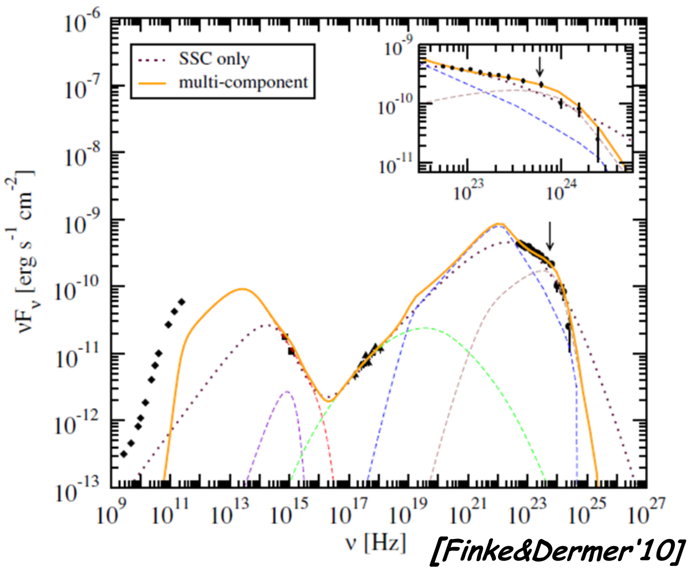
***-> explanation of spectral features** (e.g.,'GeV-break' measured in bright LSPs):*

- **γγ-absorption on H and HeII Ly continuum as possible explanation of 'GeV-break'**
  [Poutanen&Stern'10, Stern&Poutanen'11, '14]



- **'GeV-break' as superposition of Compton-scattered accretion disk and BLR target radiation fields**
  [Finke & Dermer 2010, Hunger & Reimer 2014]

- **EC off BLR photons by curved e^-distribution**
  [Cerruti etal 2013, Hunger & Reimer 2014]



-> rapid variability points to a location at small distances to the central engine

γ-ray emitting region outside the BLR?

- $\gamma\gamma$-opacity arguments for >10GeV photon detections of luminous FSRQs
  (e.g., PKS 1222+216 *[Nalewajko etal 2012]*, PKS B1424-418 *[Tavecchio etal 2013];*
  BUT: [Lei & Wang 2013]

- Change of optical polarization correlated with γ-ray flare
  (e.g., 3C 279 *[Abdo etal 2010]*, PKS 1510-089 *[Marscher etal 2010]*, PMNJ0948+0022
  [Itoh etal 2013], ...)
  ->event duration constrains location of emission region:
  $R_{diss} \sim 2\Gamma^2 ct_{var}/(1+z)$

- Within one-zone leptonic scenario large ν_{HE}/ν_{LE} + large CD [Tavecchio etal 2013, Pacciani etal 2014]

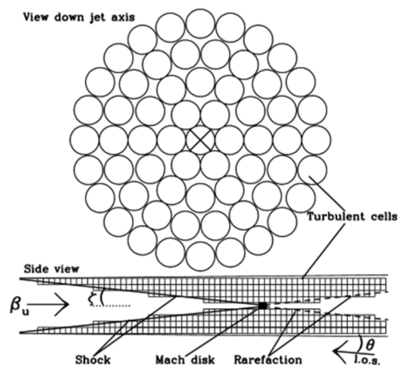
- Proposed location of the γ-ray emitting region in HSP-FSRQs?
  [Ghisellini etal 2013]

$\Rightarrow$ **Problem**: *How to explain rapid (min scale!) variability in these sources?*

Transitioning from homogeneous regions to sub-structure

-> Basic idea:

Superposition of many small fluctuatingly radiating entities within larger structure



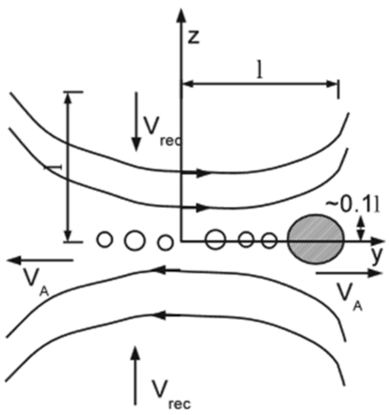
[Marscher 2014]

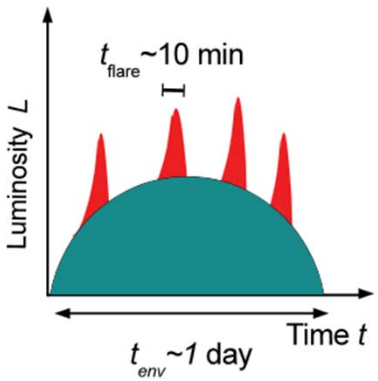
E.g.,

- **Turbulence cells passing through standing shock** *[Marscher 2014]; Turbulence in flow [Narayan & Piran2012]*
- **Red giant fragmentation upon crossing jet**

[See talk by M. Barkov]

- **Jet-within-jet models**
- **Fragmentation of magnetic reconnection layer; ‚monster' plasmoids radiate on top of ‚envelope-flare structure'** [Giannios 2013]
- ....





[Giannios 2013]

Are we starting to observe

sub-structure(s)

of the γ-ray emitting region?

[Moon phases, from: Sidereus Nuncius, Galileo Galilei]

[From:news.nationalgeographic.com/news/2009/08/photogalleries]

Synergies to lower frequency instruments

Basic idea:

γ-ray correlation studies using frequency ranges where high-precision localization measurements exist as reference system

E.g.,:

- **γ-ray correlation studies with radio band**
  [e.g., too many, Max-Moerbeck etal 2014]

[See also talk by S.Larsson]

- **γ-ray correlation studies with polarization changes**
  [e.g., Abdo etal 2010 (3C279), Marscher etal 2010 (PKS1510), Itoh etal 2013]

[See talks by M.Hayashida, D. Paneque]

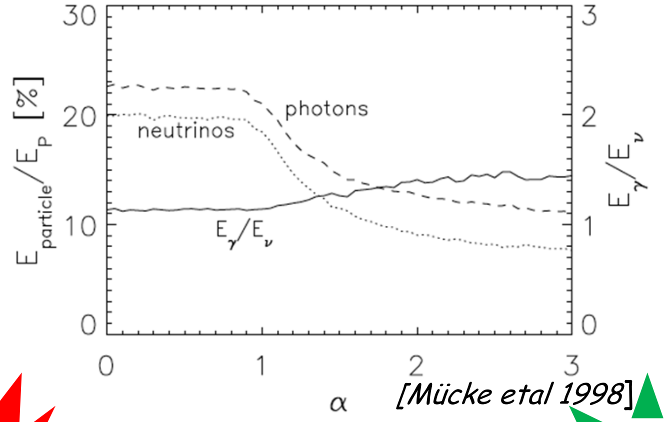
- **Looking for imprint of emission lines in γ-ray spectra**

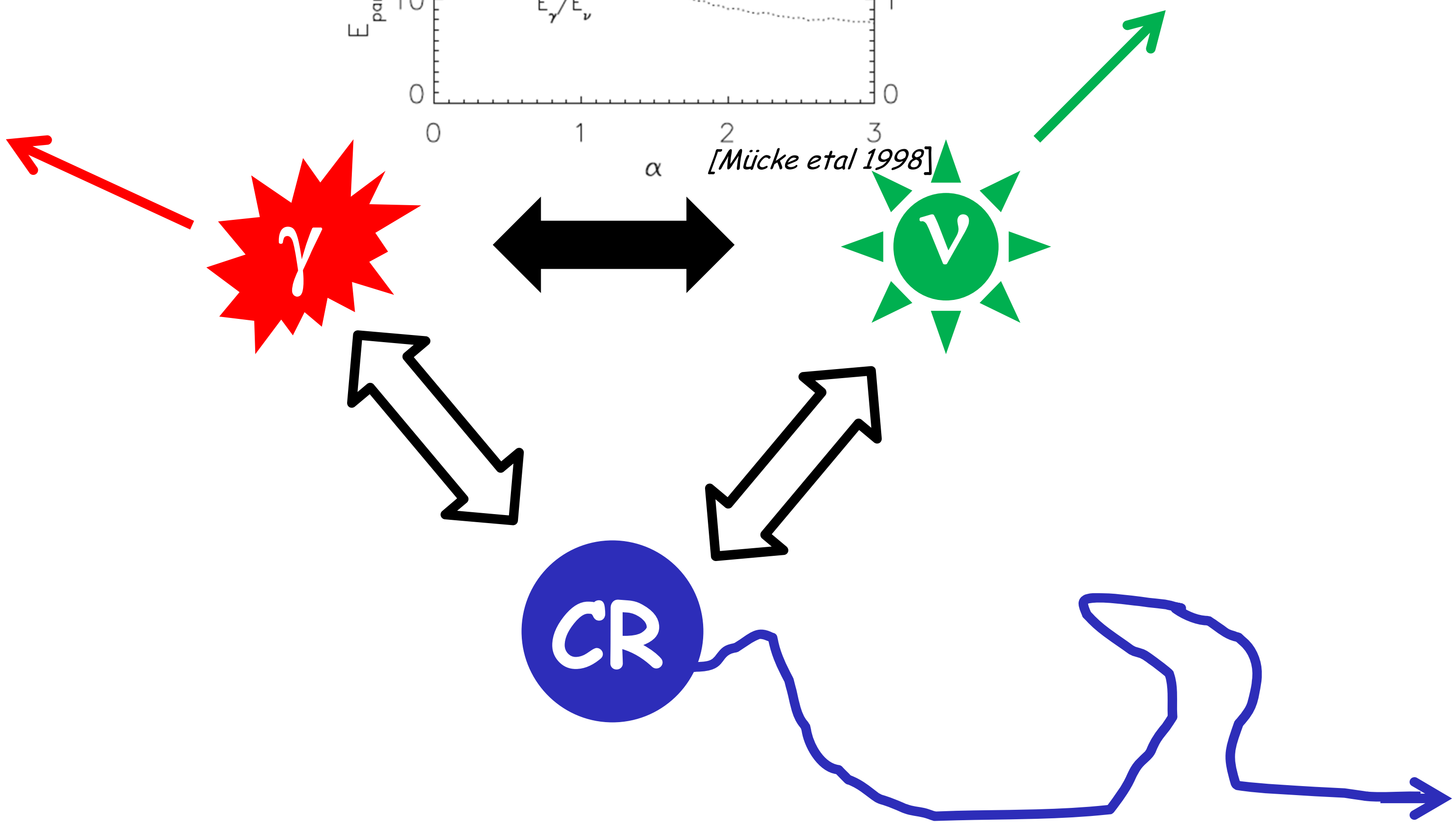
[See talk by R.Britto]

- **Gravitational lensing at γ-rays**
  [e.g., Barnacka etal 2014]

[See also poster by S.Buson; talk by D. Mazin]

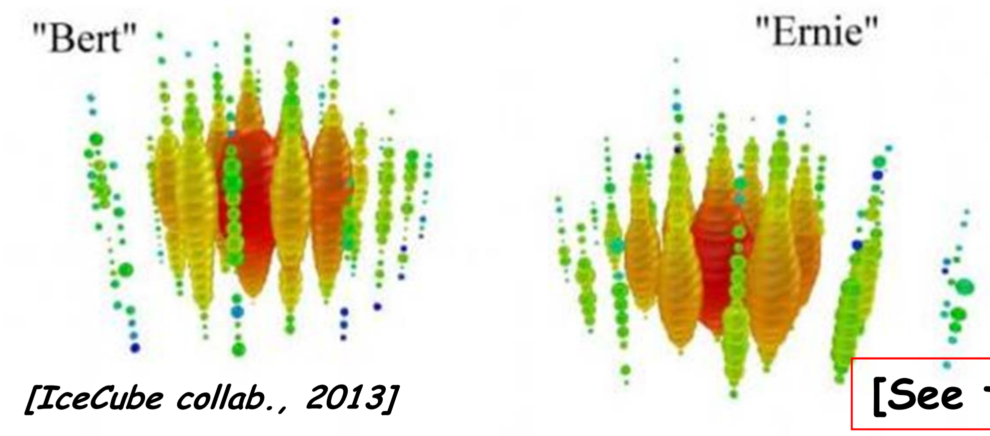
On the jet composition





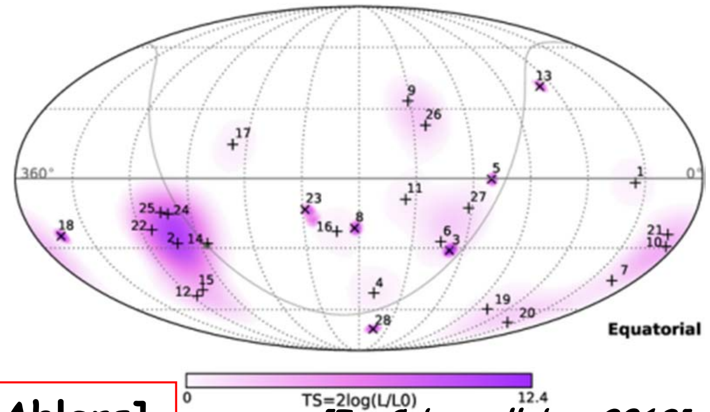
-> Multi-messenger approach

On the jet composition



[IceCube collab., 2013]

[See talk by M.Ahlers]



[IceCube collab., 2013]

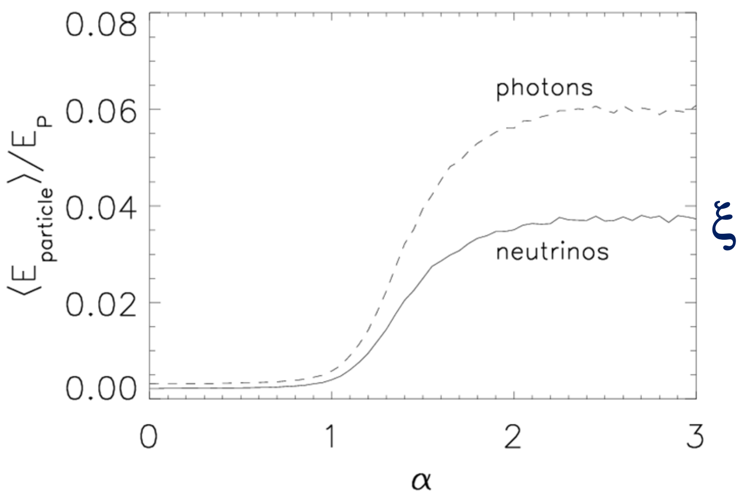
- *IceCube detects extraterrestrial (~5.7σ) neutrinos:*
  3-yrs data: 28 shower-like, 9 track-like, fully contained events [IceCube coll. 2014]
- *reconstructed energies ~30 TeV – ~2 PeV*
- *compatible with isotropic source distribution & ~$E^{-2.5}$ spectrum with cutoff above PeV energies*
- *all-sky integrated flux ~10^{-8}GeV $cm^{-2}s^{-1}sr^{-1}$(60-3000TeV) per flavor for E^{-2} spect*
- *compatible with neutrino flavor ratio ν_e:ν_μ:ν_τ = 1:1:1*

=> Evidence for hadronic (pp, pγ) interactions in cosmic sources

Requirements on jetted neutrino sources

- **Targets for hadronic interactions:**
  photons -> radiative jets
  material -> heavy jets   [See talk by M.Barkov]

- **Hadron energy in photohadronic interactions:**



Required nucleon energy:

$$E'_p \leq 20\ (E_{\nu,10PeV} / D_{10}\xi_{0.05})\ \mathrm{PeV}$$

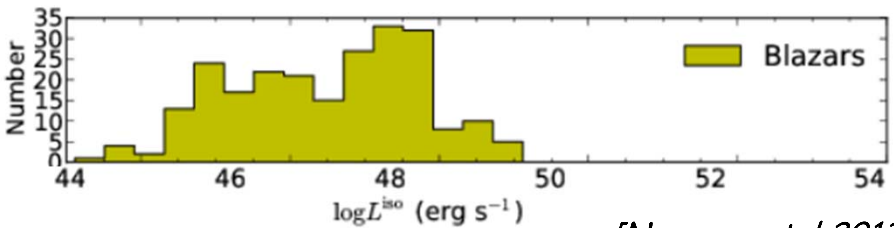
Threshold condition: $\varepsilon' \cdot E'_p \geq 0.07\mathrm{GeV}^2$

Suitable target photons of energy
$\varepsilon' \geq 3\ (E_{\nu,10PeV} / D_{10}\xi_{0.05})^{-1}$ eV

Hillas criterium *[Hillas 1984]*:

$$E'_p \leq \Gamma \cdot e \cdot Z \cdot B' \cdot R'$$

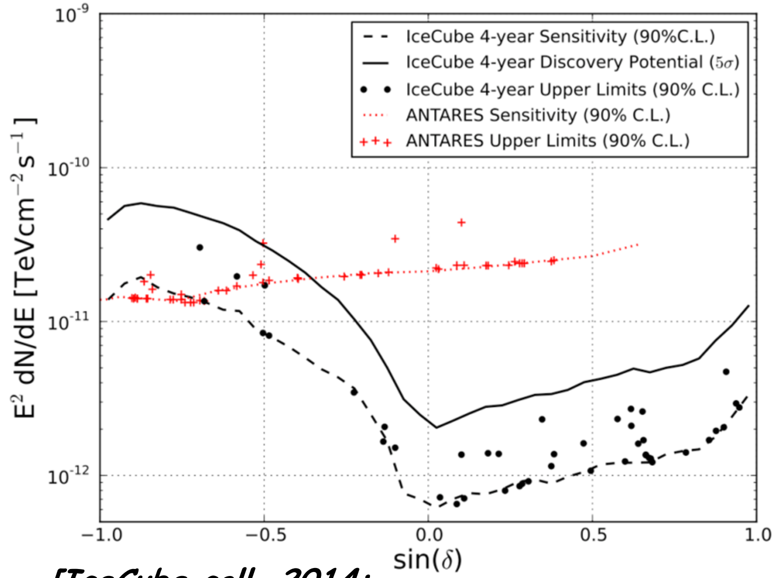
- **Source energetics:**
  $P_{jet} > 10^{43}\ \Gamma_{30}^{2} \beta^{-1} (E_{\nu,10PeV} / \xi_{0.05})^2$ erg/s
  [Waxman 2004]



[Nemmen etal 2013]

Requirements on jetted neutrino sources

- **comply with observations!**

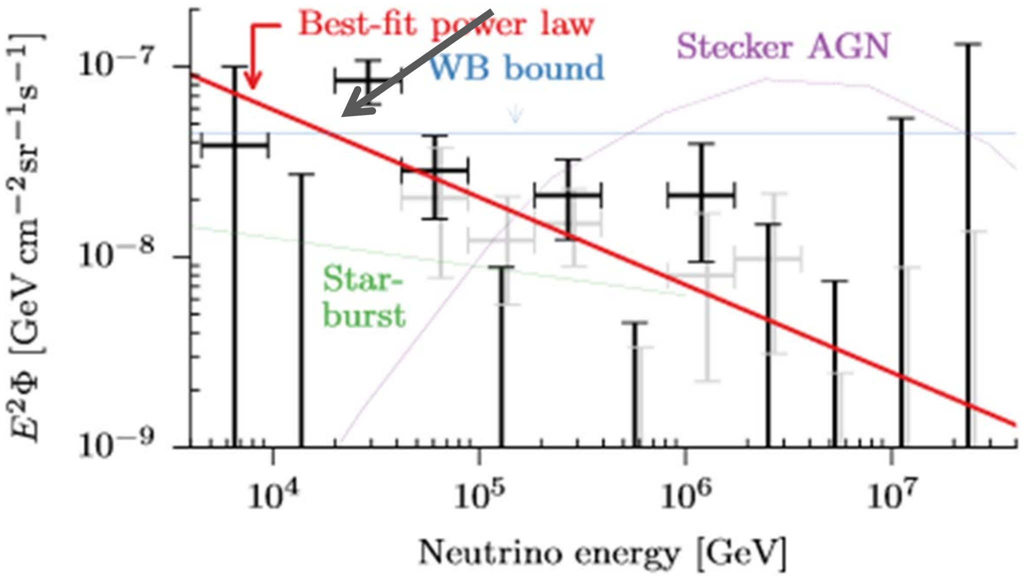


[IceCube coll. 2014: arXiv:1406.6757]

Point source ν-limits

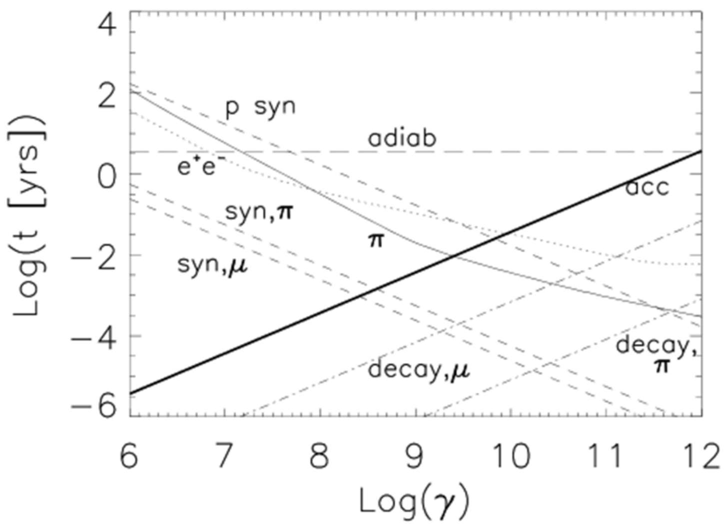
All-sky flux

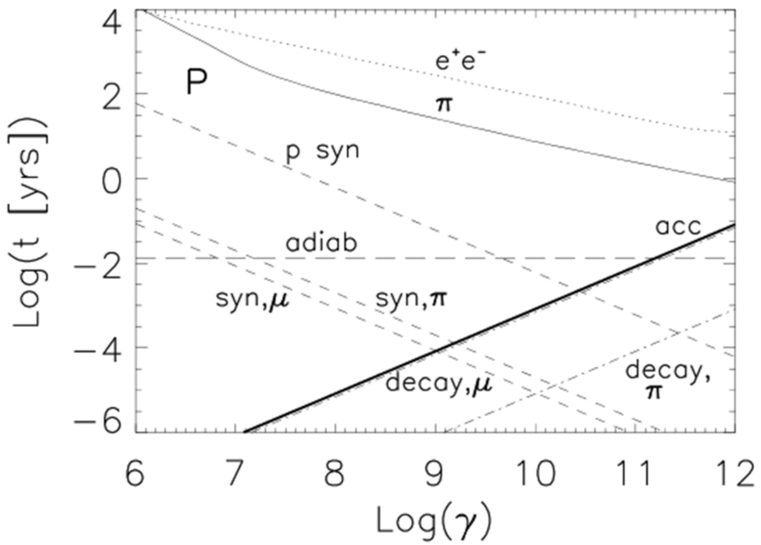
$dN/dE \sim E^{-2.5}$

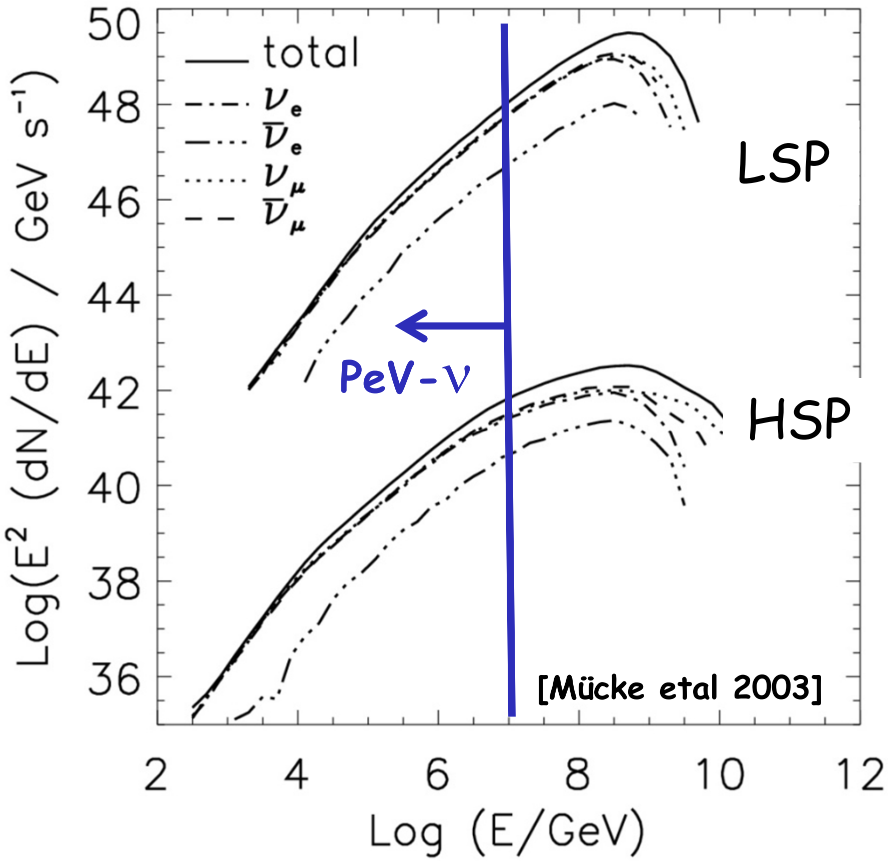


[Aartsen etal 2014]

LSPs versus HSPs as neutrino source candidates







=> Among blazars LSP-type AGN produce potentially higher neutrino luminosities than HSP-type AGN

Searches for AGN counterparts of PeV-νs

Difficult!

Various strategies (γ–ν synergy):

E.g.,

- *use localization & brightness constraint*

-> radio & γ-ray bright TANAMI blazars in localization region of 2 ν-events [Krauß etal 2014]:

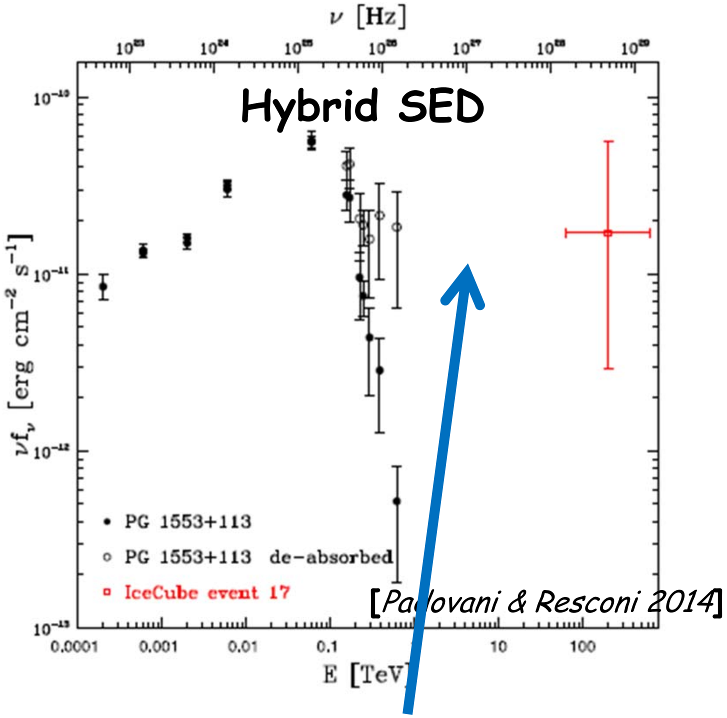
- all of FSRQ type

[See poster by Krauß etal]

- *use localization & 'energetics diagnostic'*

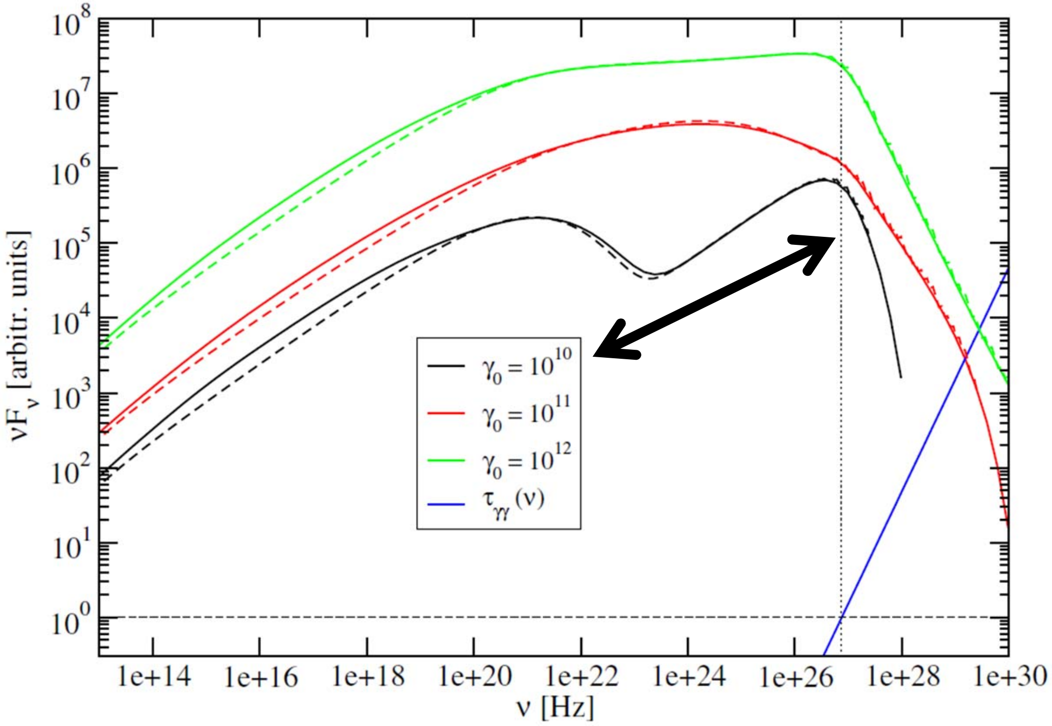
-> TeVcat+WHSP-cat+1FHL blazar counterparts for 16/18 ν-events [Padovani & Resconi 2014]:

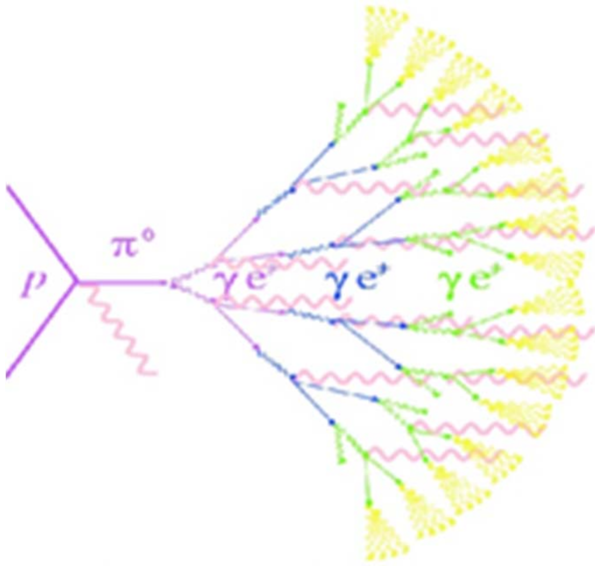
- mostly BL Lac type (VHE-emitting AGN)



How to close the 'gap' between GeV/TeV-photons and PeV-νs?

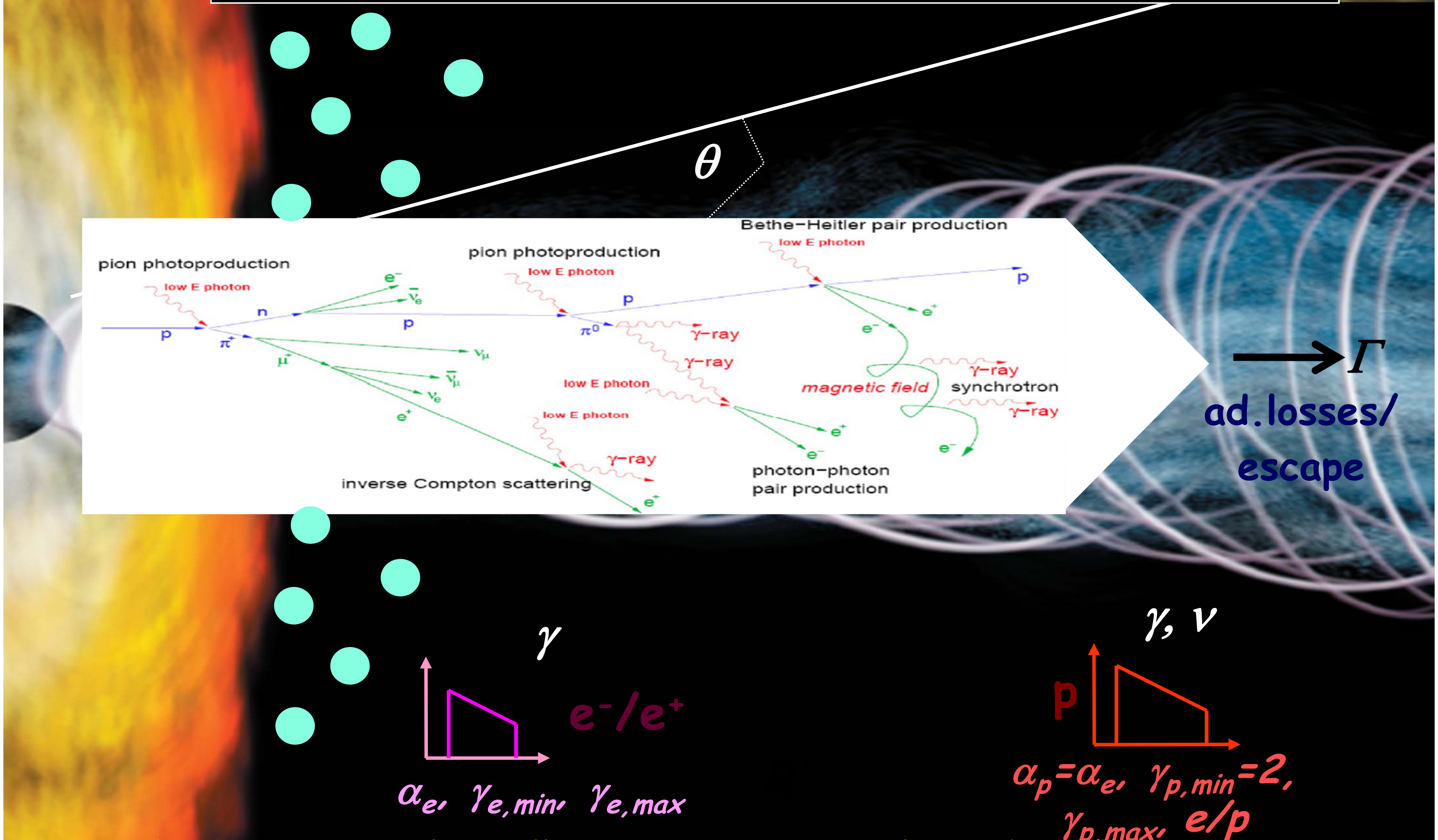
Pair cascades





[Böttcher, Reimer et al 2013]

Non-thermal Emission Processes in AGN Jets: Leptons & Hadrons

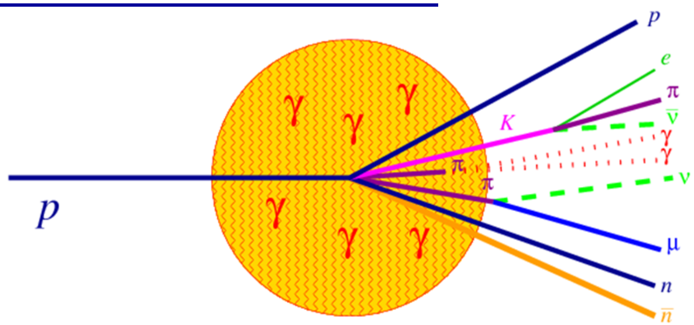


In hadronic models ν-fluxes must not scale with γ-fluxes due to competing nucleon losses!

Target photon fields

- **Internal photon fields**

  (jet synchrotron radiation; z.B. PIC, SPB
  [Mücke et al 2003, ...])



- **External photon fields:**

  e.g., - accretion disk radiation field **-> redshifted in jet frame!**

  [e.g. Protheroe 1996; Bednarek & Protheroe 1999, ...]

  - BLR lines & at BLR scattered accretion disk radiation

  [e.g. Atoyan & Dermer 2003, Dermer etal 2014, Murase etal 2014, ...]

  - IR/dust torus

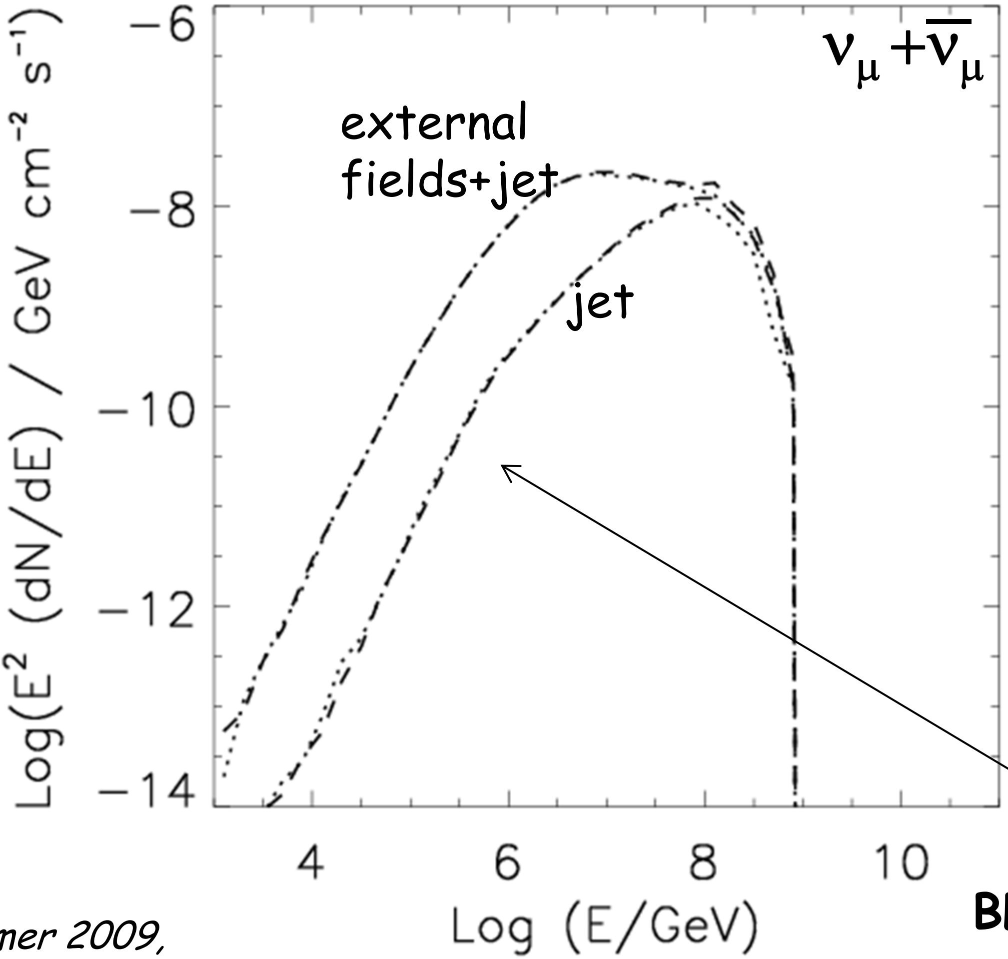
  [e.g. Murase etal 2014]

  - Spine/sheeth within structured jet model

  [e.g. Tavecchio etal 2014]

External radiation blueshifted in jet frame relaxes required γ_p for π-production

Neutrino fluxes: External versus jet target photons



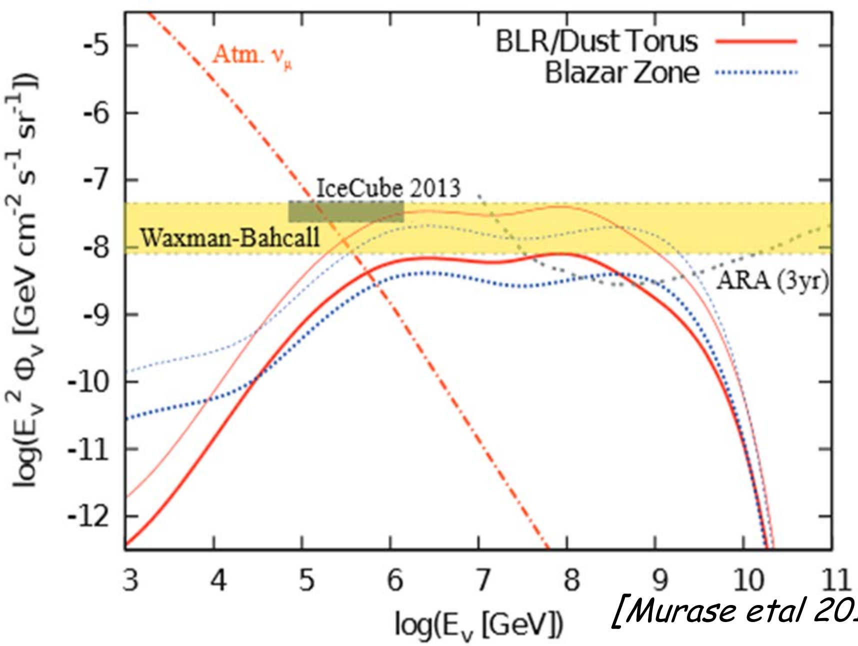
[Reimer 2009, Abbasi etal 2009]

π-production in BLR radiation field adds predominantly > PeV neutrinos

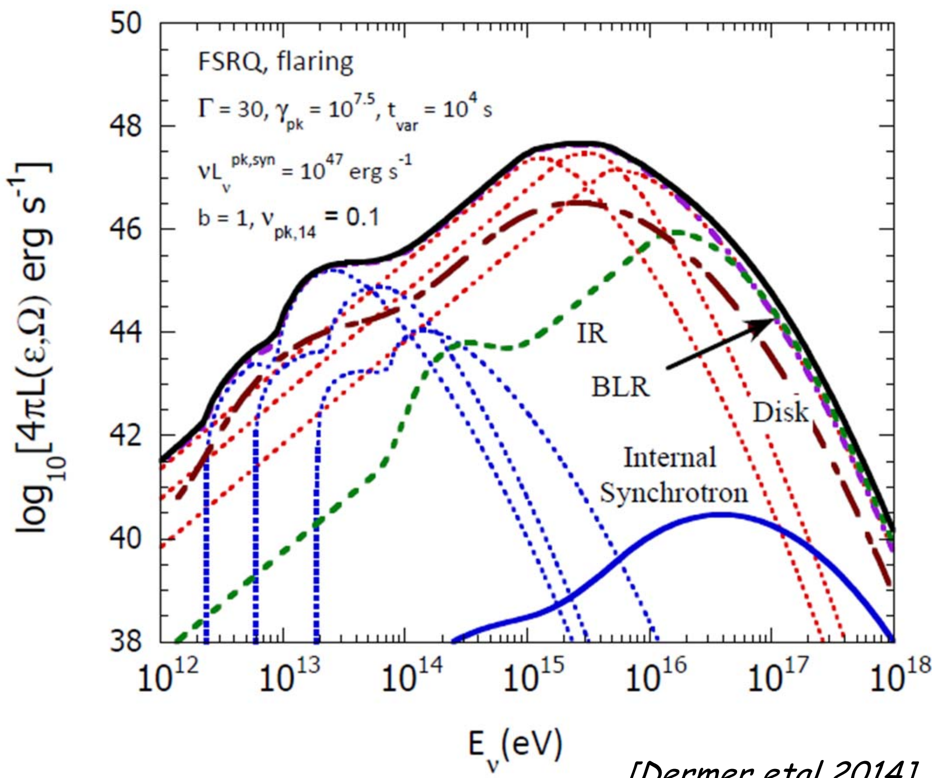
BL Lac-type blazars with highly magnetized emission regions - if sources of the HECRs – are *weak, hard-spectrum* TeV-PeV ν-emitter!

Predicted neutrino fluxes .....

…. from π-production in external blazar radiation fields



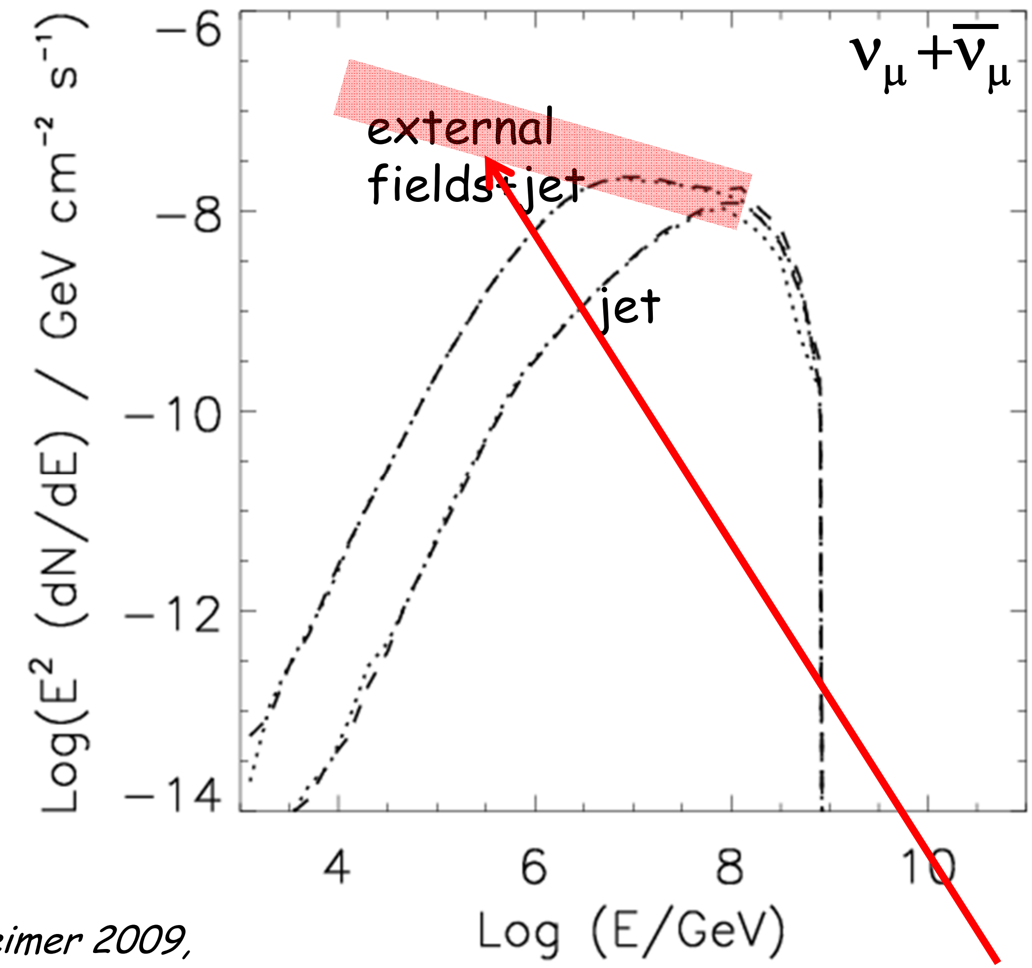
[Murase etal 2014]



[Dermer etal 2014]

predict hard ν-spectra below PeV energies

Neutrino fluxes: External versus jet target photons



[Reimer 2009, Abbasi etal 2009]

π-production in BLR radiation field adds predominantly > PeV neutrinos

Need dense x-ray target photon field!

On co-spatial GeV-photon & 10TeV ν-emission

If γ-ray & ν-emission *co-spatial*:

- Significant >GeV emission requires:

$$\tau_{\gamma\gamma} = n_{T,\gamma\gamma}\,\sigma_{\gamma\gamma}\,R \ll 1 \qquad \text{with } n_{T,\gamma\gamma} = n_x$$

- Significant >tens of TeV ν-production from pγ-interactions requires:

$$\tau_{p\gamma} = n_{T,p\gamma}\,\sigma_{p\gamma}\,R \gg 1 \qquad \text{with } n_{T,p\gamma} = n_x$$

→ Together: $1 \gg \tau_{\gamma\gamma} / \tau_{p\gamma} \approx \sigma_{\gamma\gamma} / \sigma_{p\gamma} \gg 1$

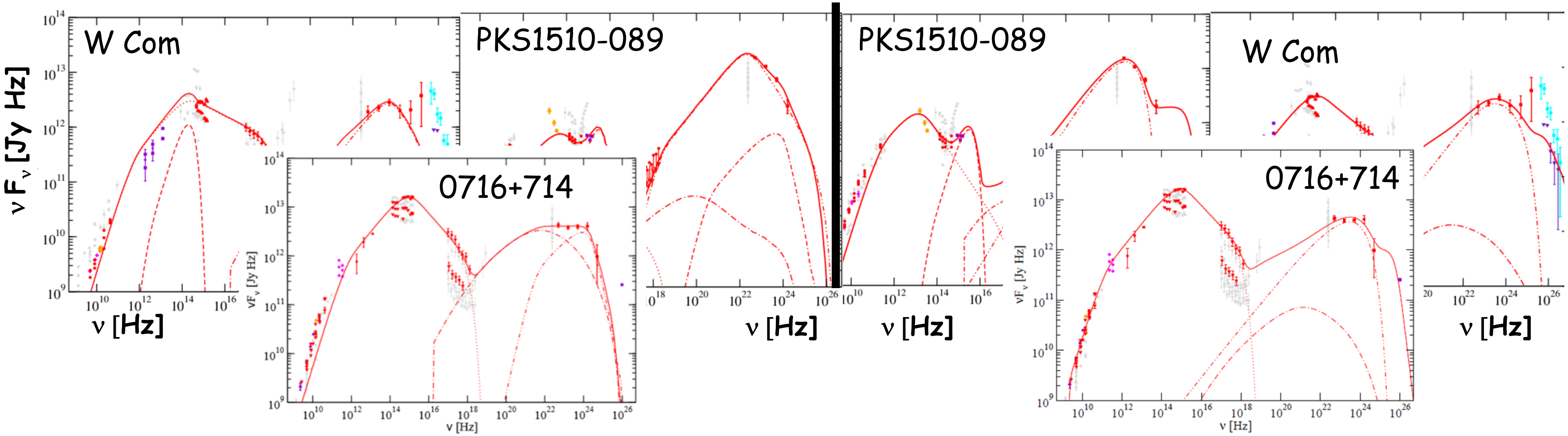
requirement

if same target photon field for γγ- & pγ-interactions

GeV-photon emission suppressed in regions where significant ~10TeV soft-spectrum ν-flux is photohadronically produced.

Multifrequency Modelling of *LAT*-detected Blazars

Leptonic Models [Böttcher, Reimer et al 2013] **Hadronic Models**



One-zone leptonic models:

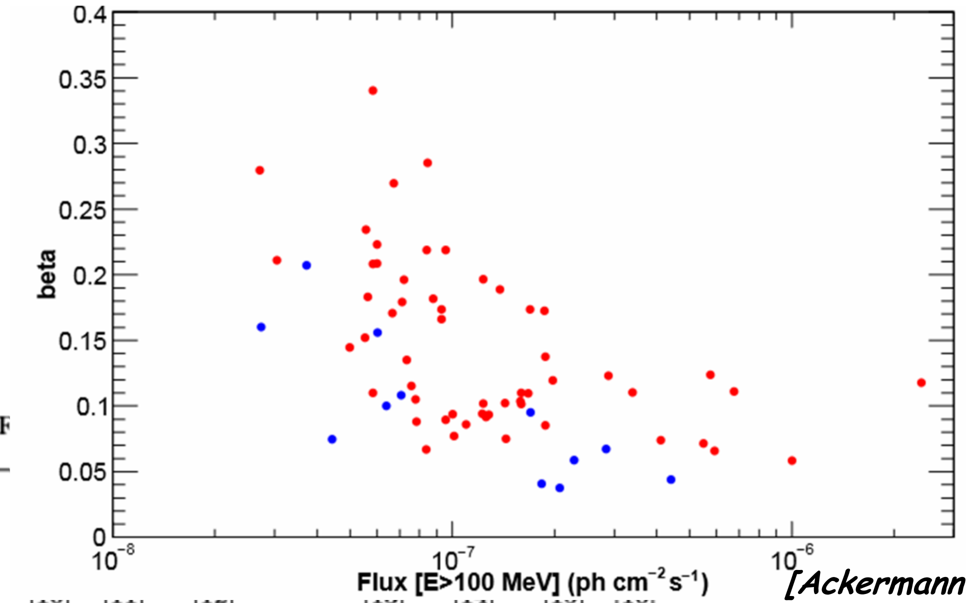
- acceptable fits to ~9/12 of all cases
- need external target photons *in all cases*

One-zone hadronic models:

- acceptable fits to ~8/12 of all cases
- proton syn. @GeVs + cascade emission @ higher energies
- require very large jet powers ~10^{47-49}erg/s
- $E_{p,max}$ ~ $10^{17...18}$eV

Ambient electron spectrum

- **Broad range of curvature in γ-ray spectra**



[Ackermann etal 2011]

Example:

High Energy flares of

source name	L_{disk} 10^{45} erg/s [1]	B 10^{-2} G [2]	γ_{min} [3]	γ_{break} 10^3 [4]	γ_{max} 10^3 [5]	n_1 [6]	n_2 [7]	K 10^3 cm^{-3} [8]	δ [9]								
PKS 0250-225	5.3	2.5	55	8	20	2.7	3.2	10	26	25	330	29	60	2.30	5.76	8	9
PKS 0454-234	3.7	3.5	350	4	20	2.7	3.2	20	26	15	110	9.5	30	1.92	4.81	8	7.6
PKS 1502+106	15	11	100	0.9	17	2	3.35	0.24	26	15	24	5.4	1	3.87	9.68	6	6
B2 1520+031	8	6.3	100	0.9	15	2	3.5	0.3	25	14	13.3	3.1	2	2.83	7.07	4	4
4C +38.41	50	26	13	0.15	6.3	2.7	2.7	16	25	17	79	1.7	1.6	7.07	17.68	4.	4.
B2 1846+32A	3.4	59	235	0.27	90	2.2	3.4	47	22	20	5.1	1.9	1.5	1.84	4.61	0.5	0.7
PMN J2345-1555	1.5	21	18	7	300	2	4.3	0.03	26	21	4.6	0.42	3	1.22	3.06	2.	2
CTA 102	41	14.3	1.7	3.3	30	2	3.55	5.6	20	14	920	8.5	20	2.03	5.09	1	1
PKS 0805-07	24	31.5	5	8	50	2.3	3.5	2.4	20	15	460	6.0	20	4.90	12.25	2.5	2.5
3C454.3	33	28	2.5	4	14	2.25	4.	4.3	24	15	294	4.6	8.8	5.7	14.4	1.5	2.3

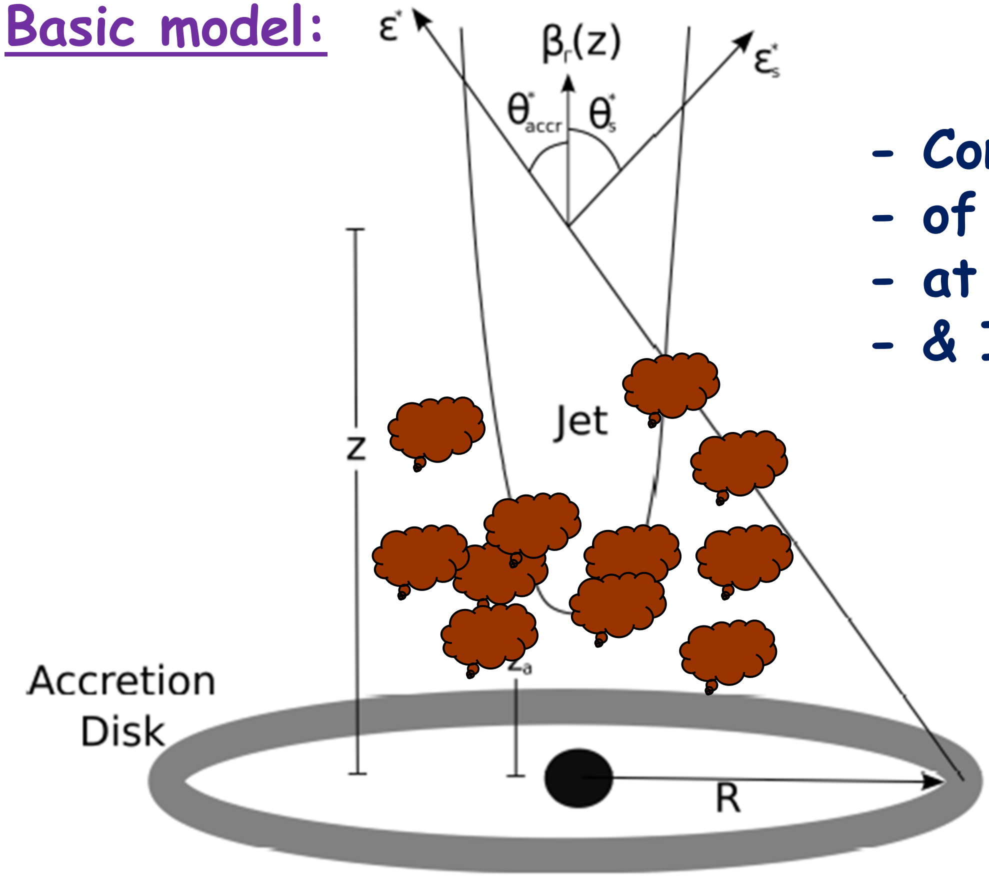
[Pacciani etal 2014]

- **Rather narrow γ_{peak}-γ_{max} range; γ_{min} , γ_{max}**
- **Breaks in ambient e spectrum often larger than expected from radiative cooling**

Explanation?

Shaping the GeV-spectrum of bright blazars

Basic model:



- Continuous **particle injection**
- of spectrum $\sim\gamma_i^{-s} H(\gamma_i-\gamma_1)\, H(\gamma_2-\gamma_i)$
- at rate $t_i^{-\alpha}$ along jet between $z_a \ldots z_b$
- & IC cooling

Motivation:

Bridging injection/acceleration with emission models using a *phenomenological model-independent* approach

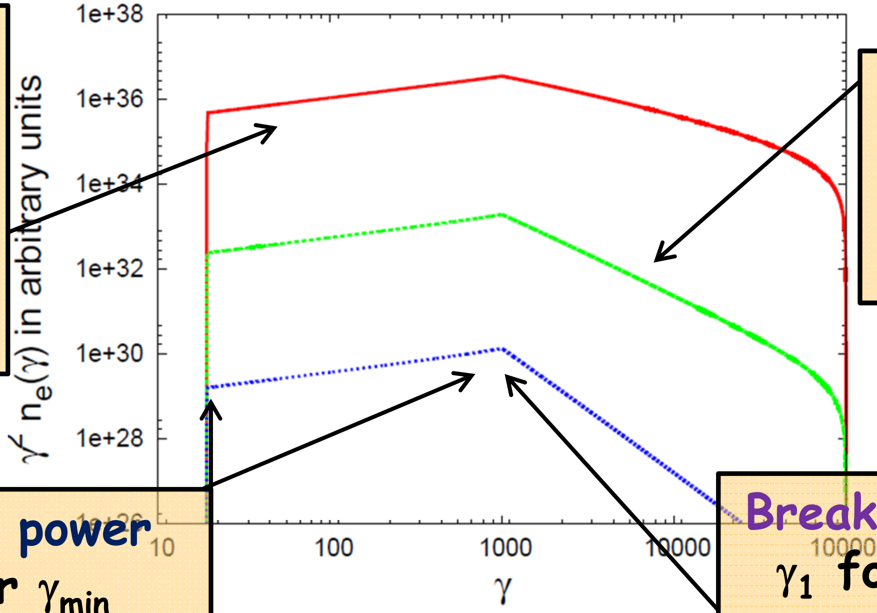
Target photon fields:

- (Shakura-Sunyaev) Accretion disk
- At BLR re-scattered accretion disk radiation

[Hunger & Reimer 2014, submitted]

Shaping the ambient e spectrum & GeV photon spectrum

pre-break spectral shape affected by α, target radiation density at blob location (l_{edd}, z_a), injection duration

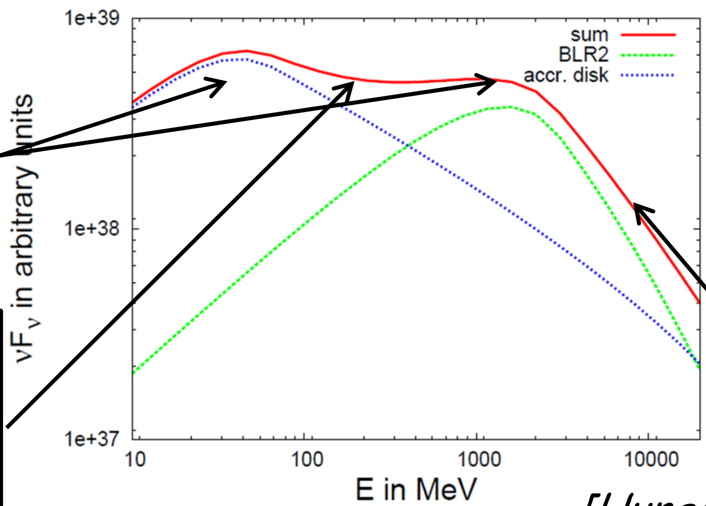


post-break spectral shape affected by s, γ_2, distance from last injection point

Peak of ambient e power spectrum @ γ_1 or γ_{min} depending on injection mode

Break energy determined by γ_1 for non-instantaneous-like injection

Peak energy determined by peak energy of ambient e spectrum

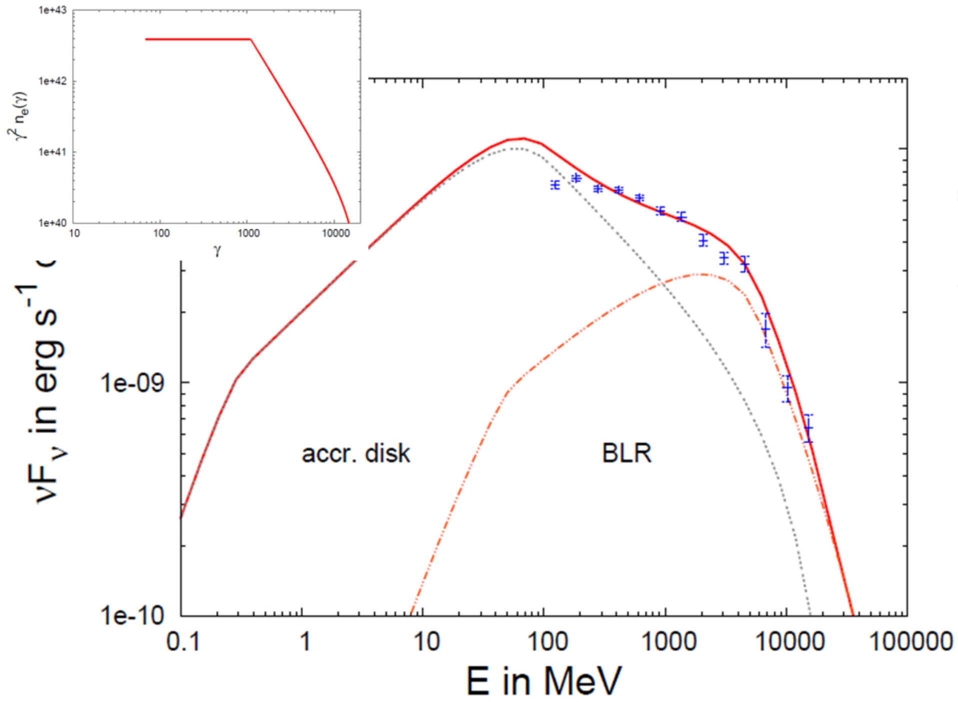


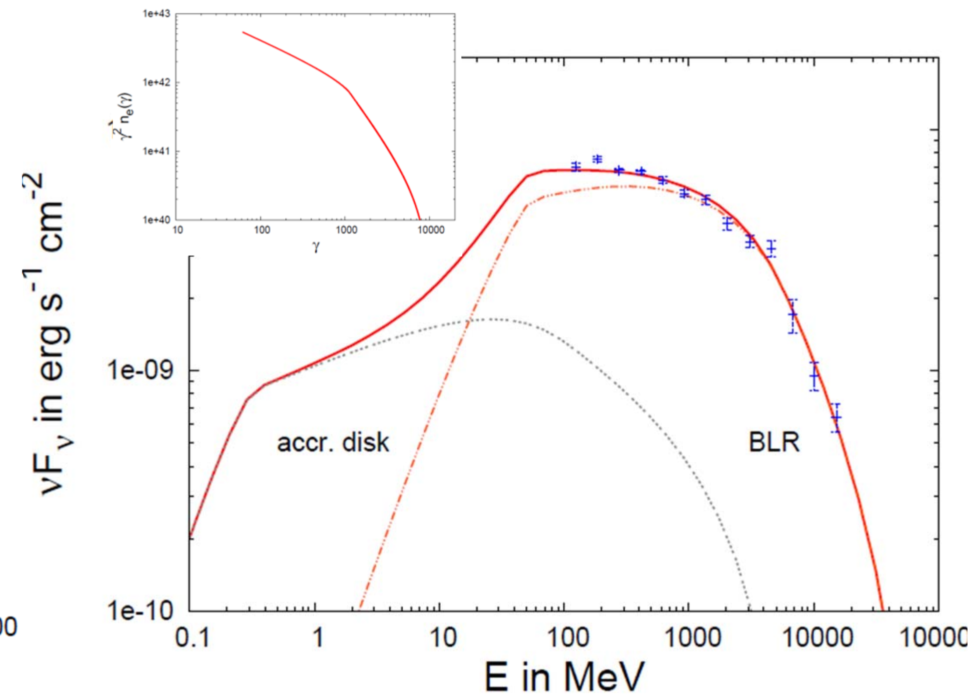
IC components merge for sufficient broad particle spectrum

Possible KN-effects

[Hunger & Reimer 2014, submitted]

3C 454.3 during the Nov 2010 flare





- GeV-break explained by either combination of Compton scattered accretion disk & BLR spectrum,
  or break in ambient electron spectrum

- Resulting particle injection parameters:
  compatible with conventional shock acceleration scenario,
  disfavor impulsive-like injection of particles

[Hunger & Reimer 2014, submitted]

Conclusions

- Where are the γ-rays produced? -

- The 'crisis' on the location of the γ-ray emitting region as a sign of sub-structure in the emission region?

- Diagnosing particle injection -

- Understanding interplay between acceleration & radiation key to understand broad variety of curvature in photon spectra.
  -> couple acceleration models with emission models
  -> phenomenological prescription to bridge AGN jet emission models with particle injection/acceleration models

- On the jet composition -

- Soft TeV-PeV ν-spectra unlikely produced photohadronically by luminous >GeV photon emitters if γ-ray & ν-emission co-spatial.