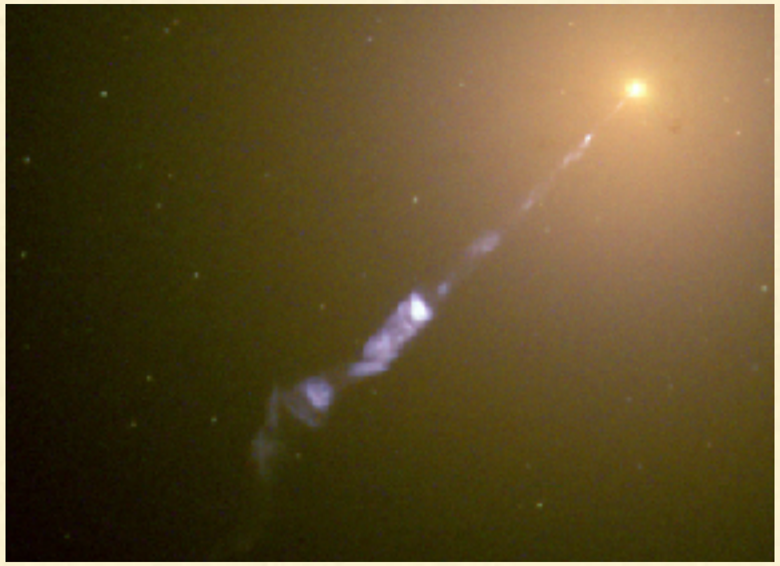


AGN at very high energies - a possible link with astro-neutrinos ?

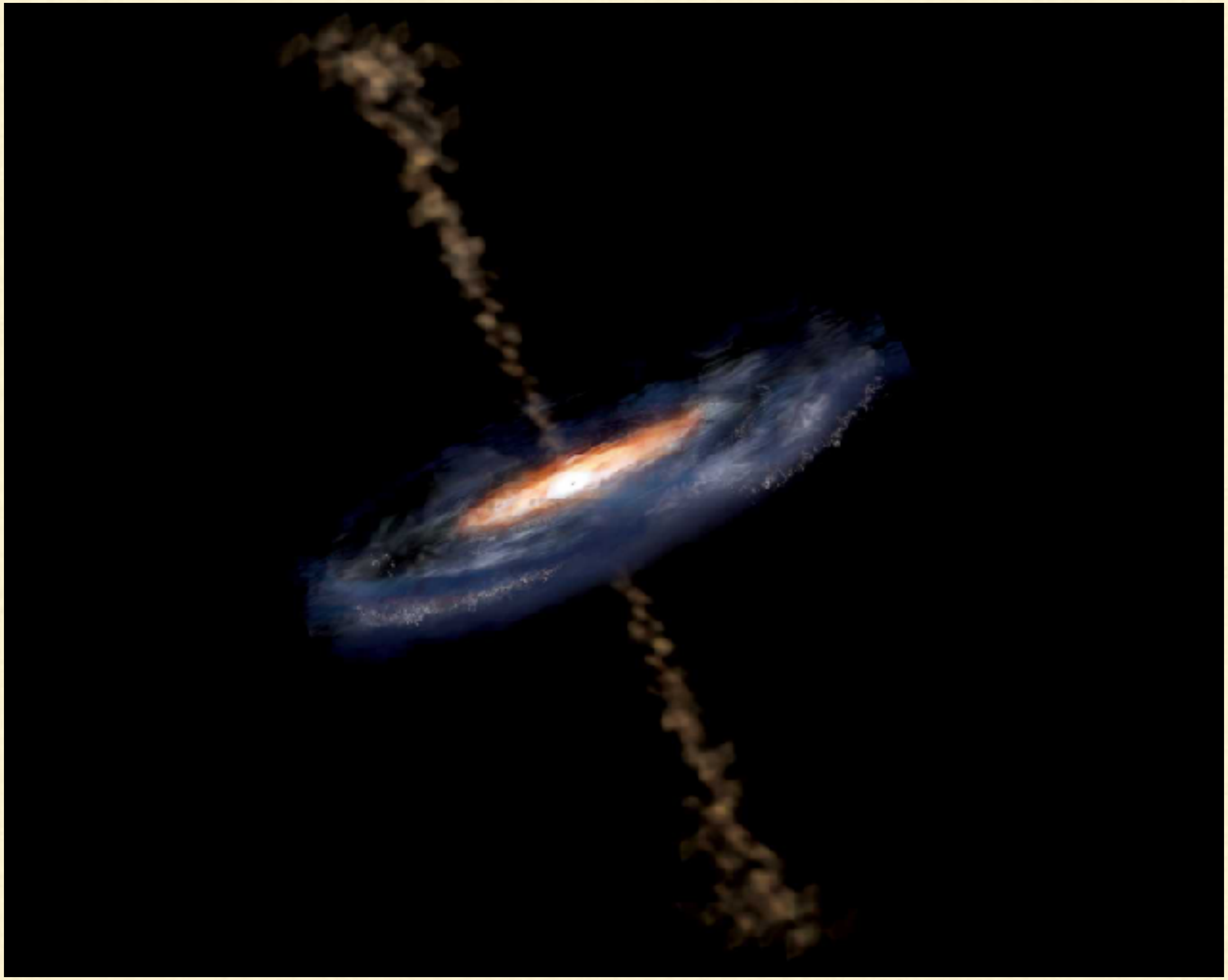
Andreas Zech (LUTH, OBSPM)

Seminar at the CPPM 05.03.2018

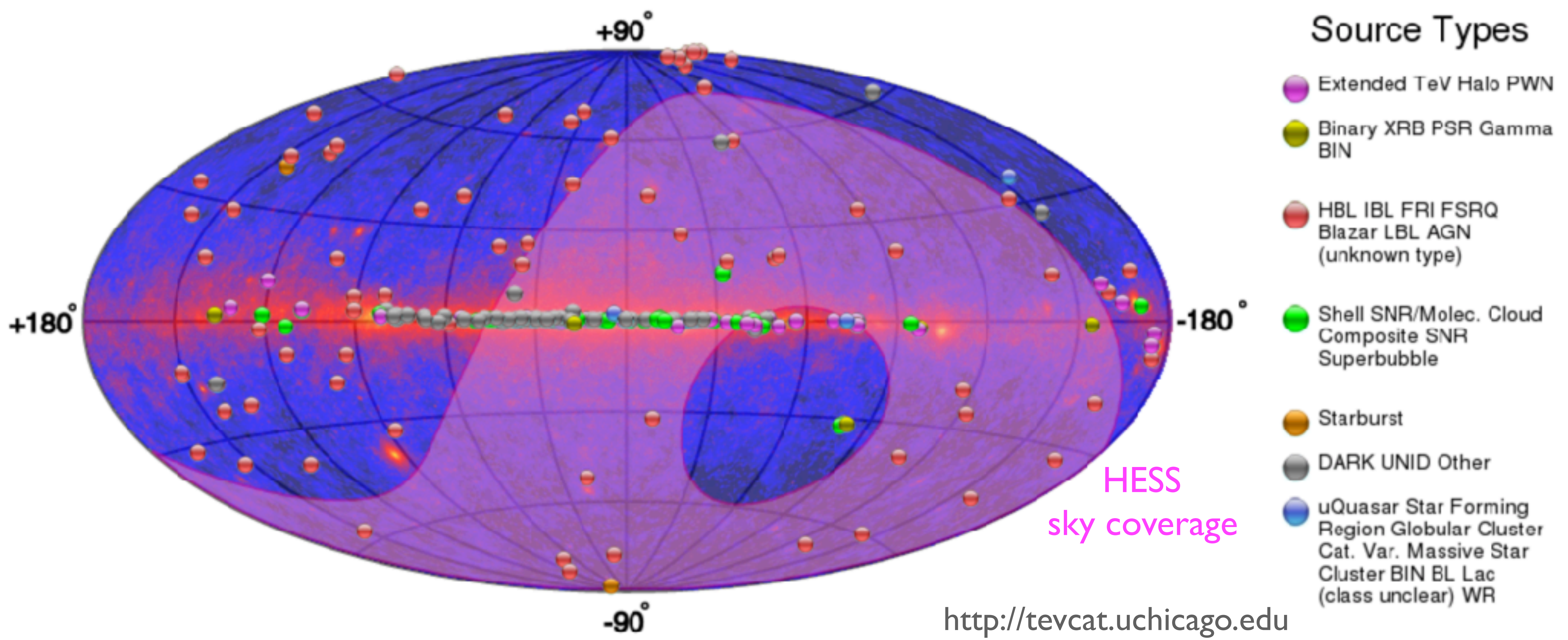
Outline

1. The population of very-high-energy AGN
2. Two recent results from H.E.S.S.
3. Leptonic emission models
4. Hadronic emission models
5. Predicting neutrino fluxes for blazars
6. What to expect from CTA ?

1. The population of very-high-energy AGN



The very-high-energy sky

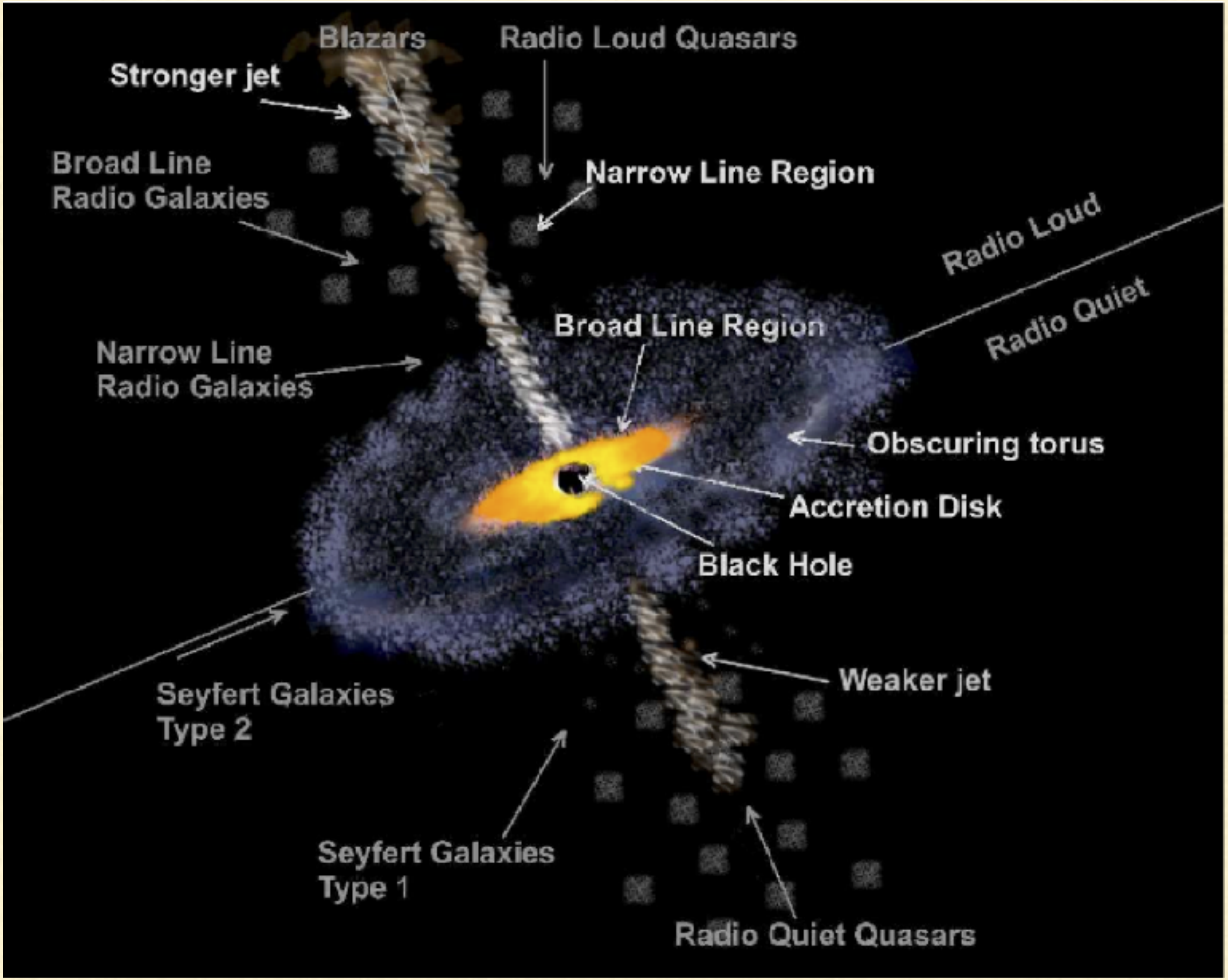


208 very-high-energy (~TeV) sources in total (as of February 2018)

extragalactic sources at TeV : 73 AGN (69 blazars, 4 FRI) , 2 starburst galaxies

(compare to Fermi LAT 3LAC (MeV / GeV) : 1591 AGN, 98% blazars)

extragalactic sources : AGN



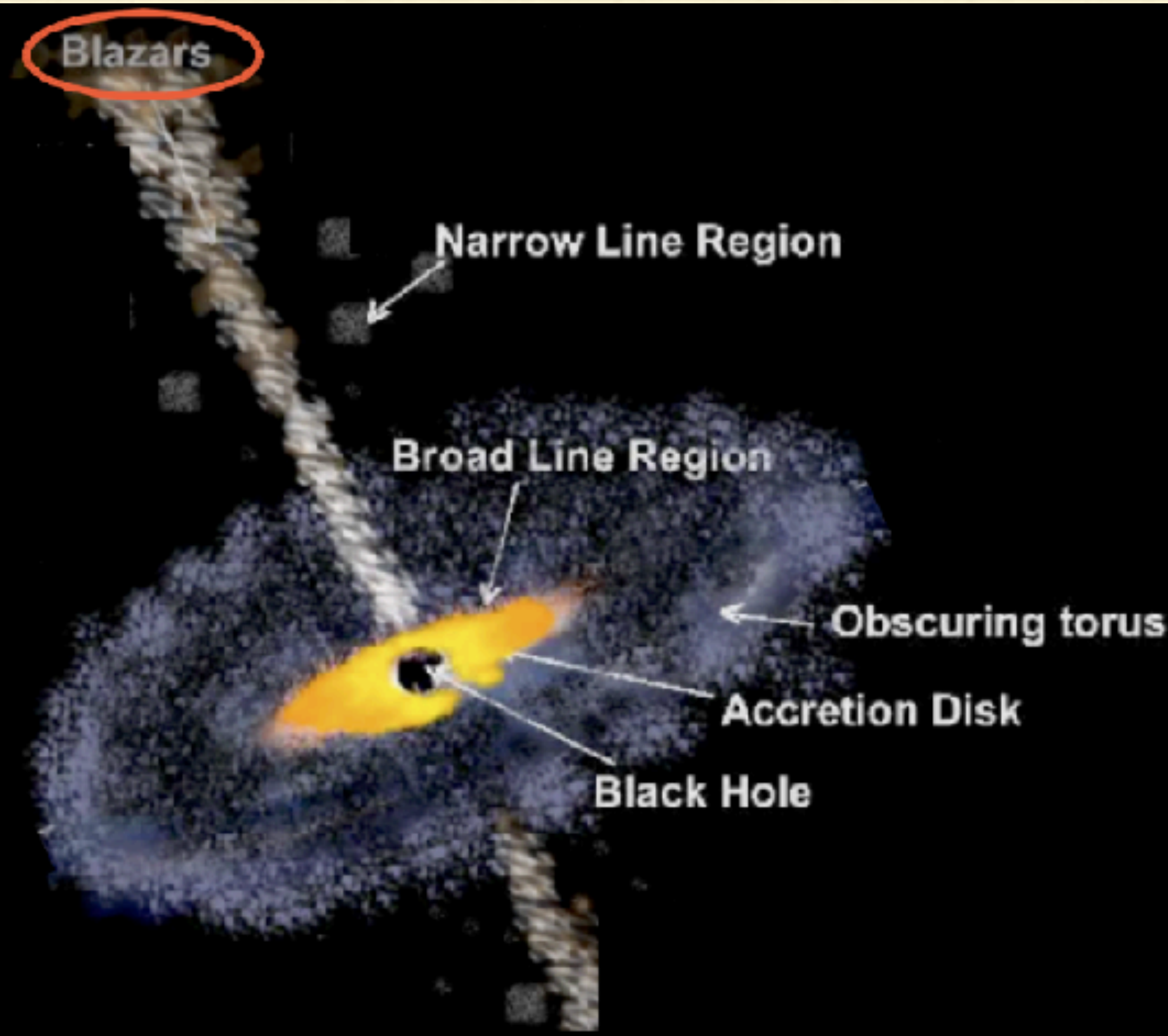
extragalactic sources : blazars

relativistic beaming

$$I_\upsilon(\upsilon) = \delta^3 I'_\upsilon(\upsilon')$$

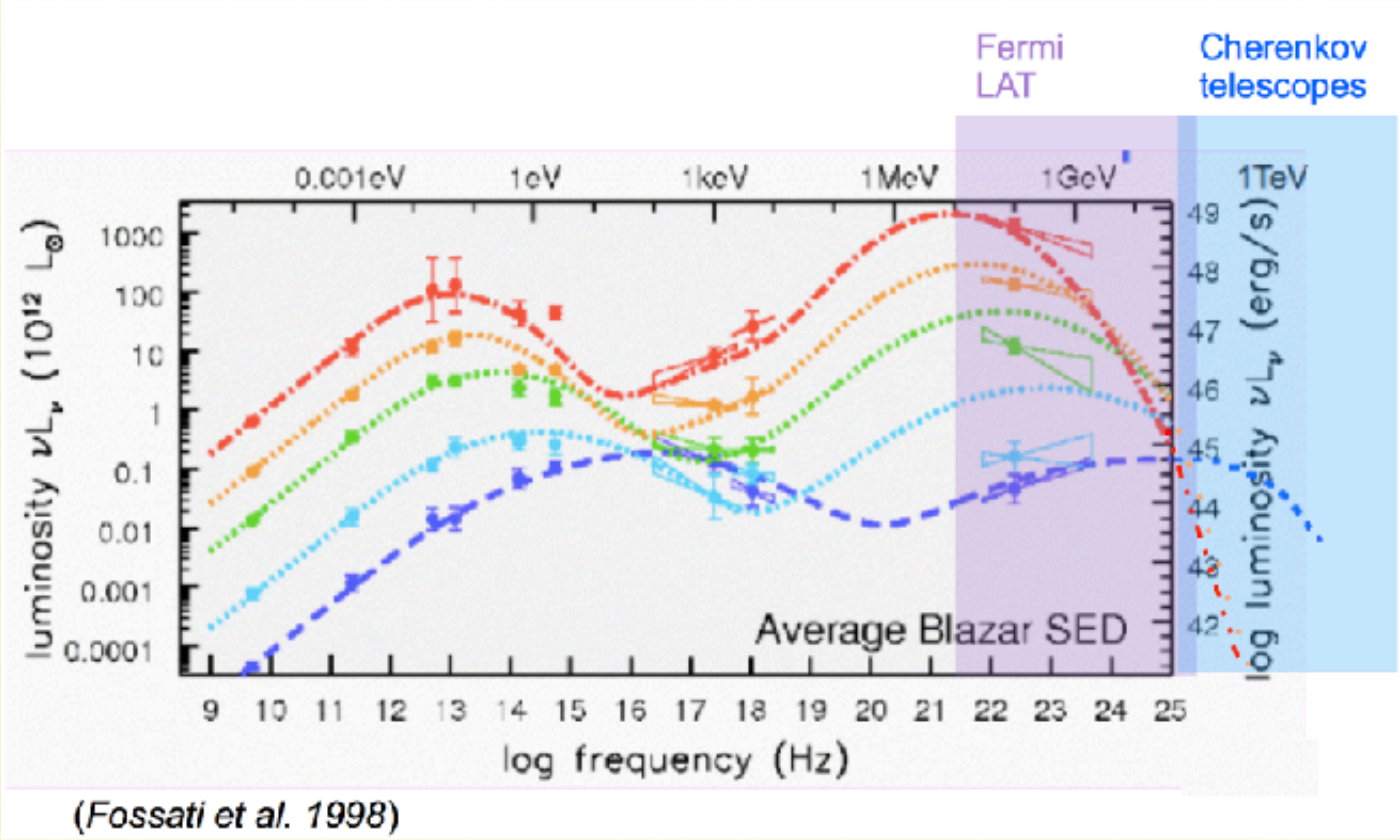
$$\Delta t = \Delta t' / \delta$$

$$\delta = \frac{1}{\Gamma(1-\beta\cos\theta)}$$



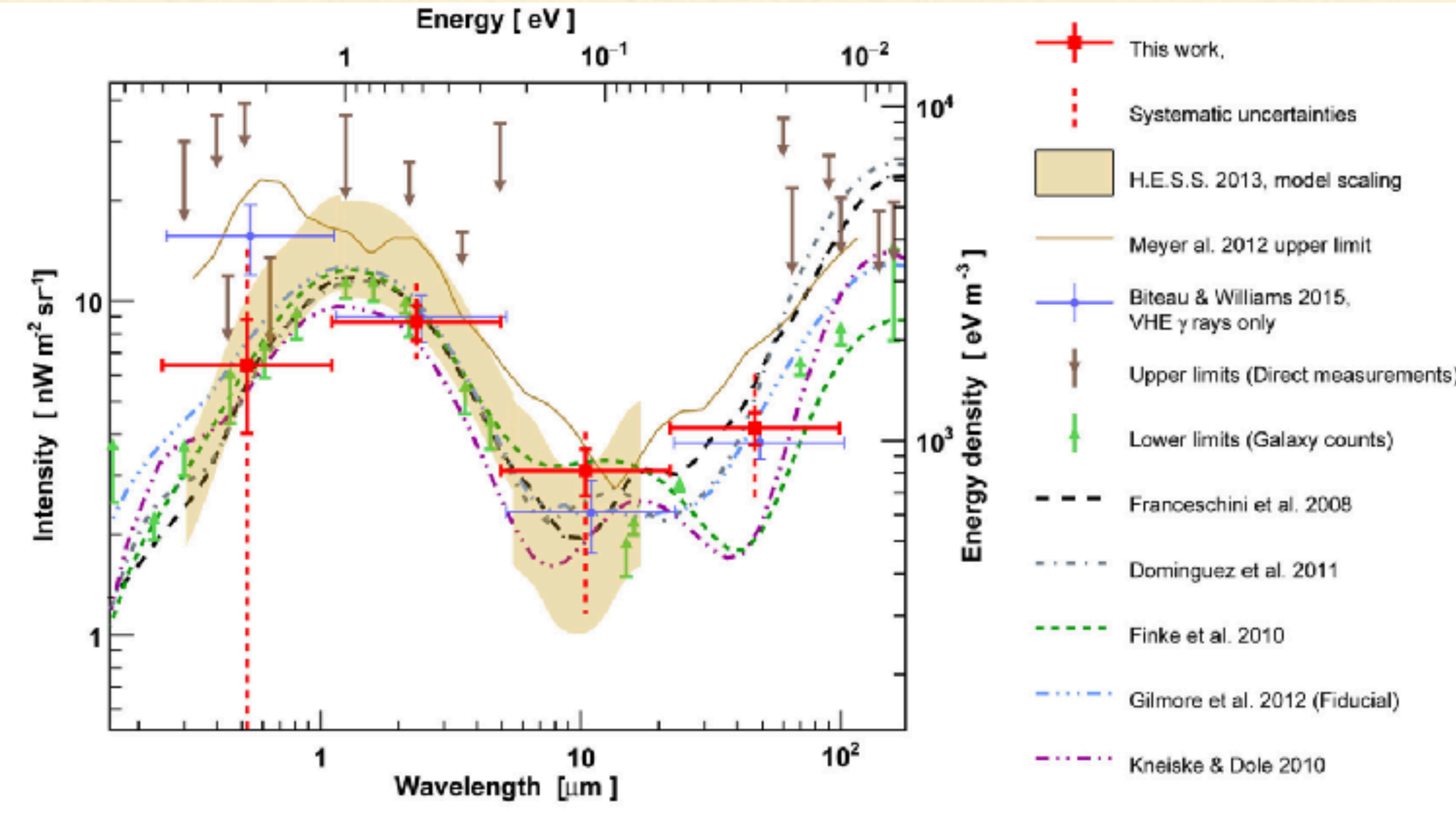
the "blazar sequence"

FSRQs (flat-spectrum radio quasars)
- strong broad emission lines in the optical
- high disk luminosity -> strong photon fields (disk, corona, torus, BLR)
- high jet luminosity & low peak frequencies



BL Lac objects (LBLs, IBLs, HBLs, UHBLs)
- emission lines weak or absent
- low disk luminosity -> low photon fields
- low jet luminosity & high peak frequencies

Extragalactic Background Light



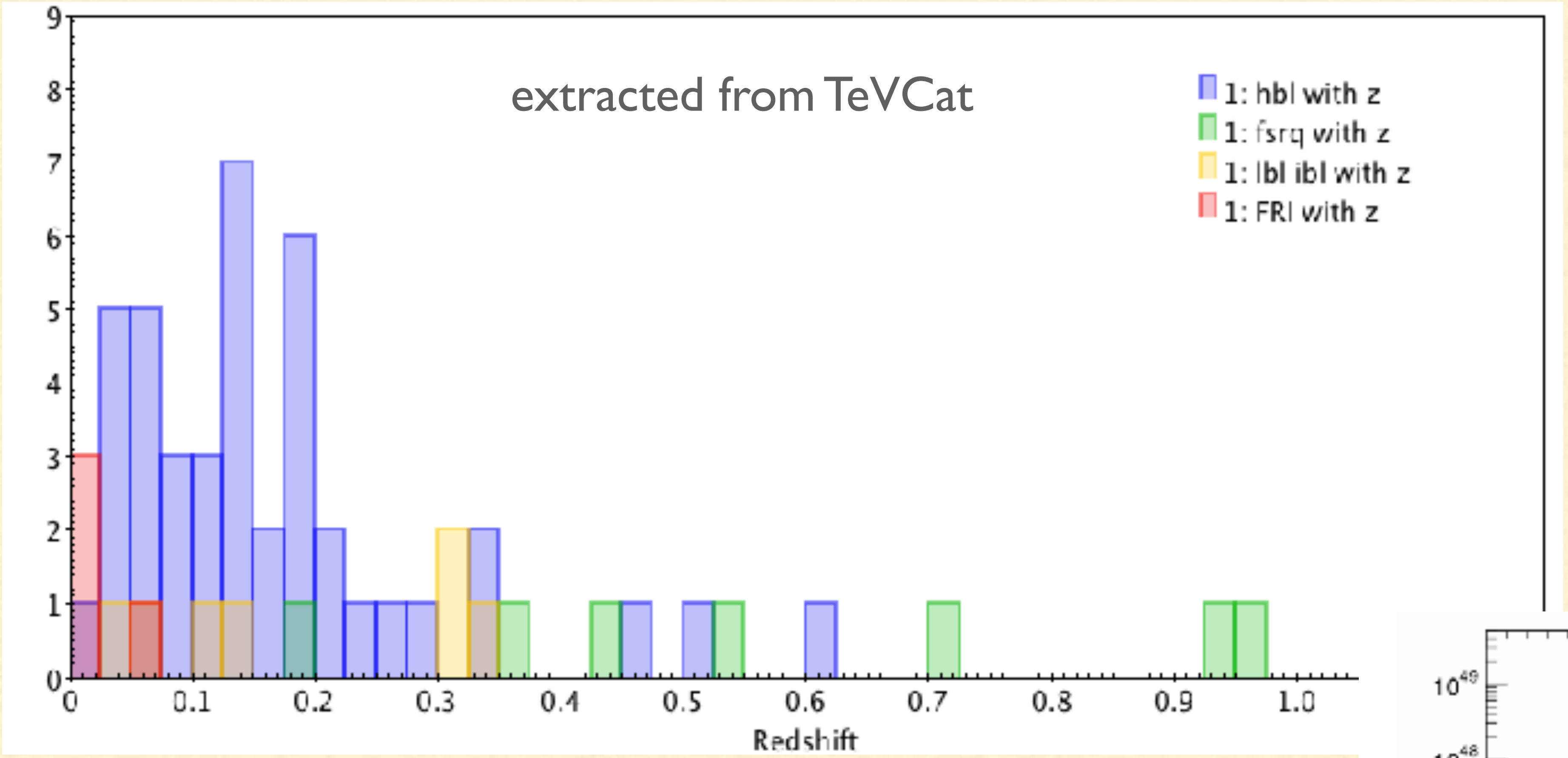
H.E.S.S. measurement of the extragalactic background light
(H.E.S.S. Collaboration, 2017, A&A, 606, A59)

peak in pair-prod. cross-section :

$$\varepsilon_1 \cdot \varepsilon_2 \approx 2(m_e c^2)^2 \approx 0.5 \cdot TeV \cdot eV$$

The diffuse EBL is the sum of light emitted during star formation and reprocessed by the interstellar medium over cosmic history. TeV photons are absorbed on infrared photons of the EBL through e+e- pair production.

redshift distribution of very-high-energy AGN



Fermi-LAT

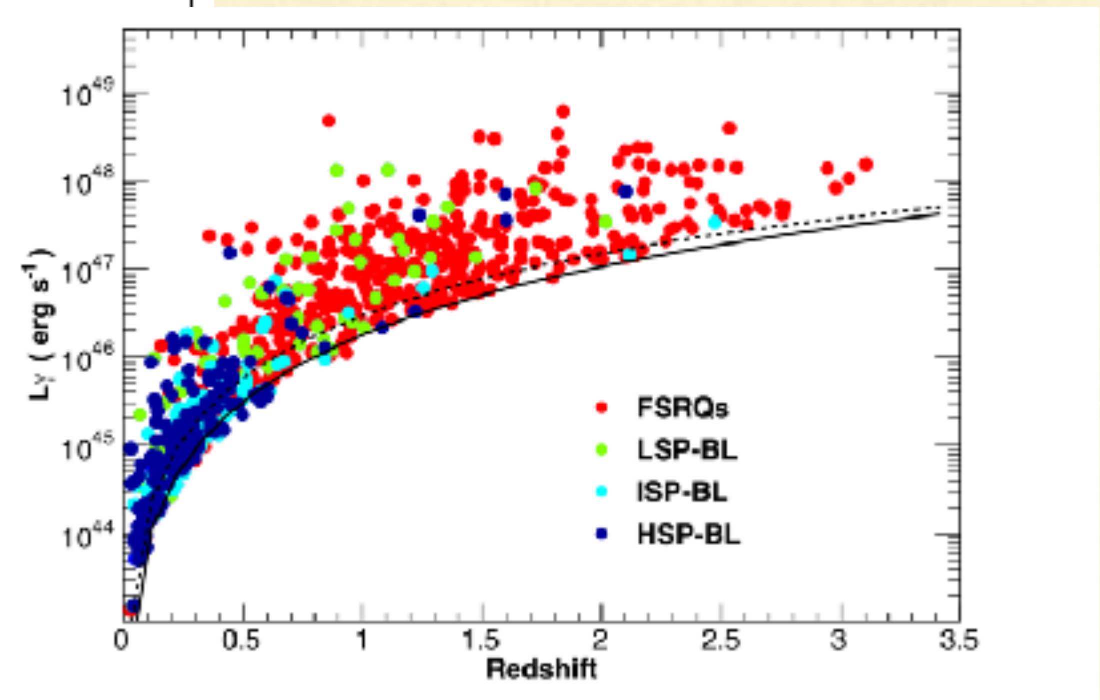


Fig. 13.— Gamma-ray luminosity versus redshift. Red: FSRQs, green: LSP-BL Lacs, light blue: ISP-BL Lacs, dark blue: HSP-BL Lacs. The solid (dashed) curve represents the approximate detection limit for Γ=1.8 (Γ=2.2). Ackermann et al. (2015) (Fermi 3LAC catalog)

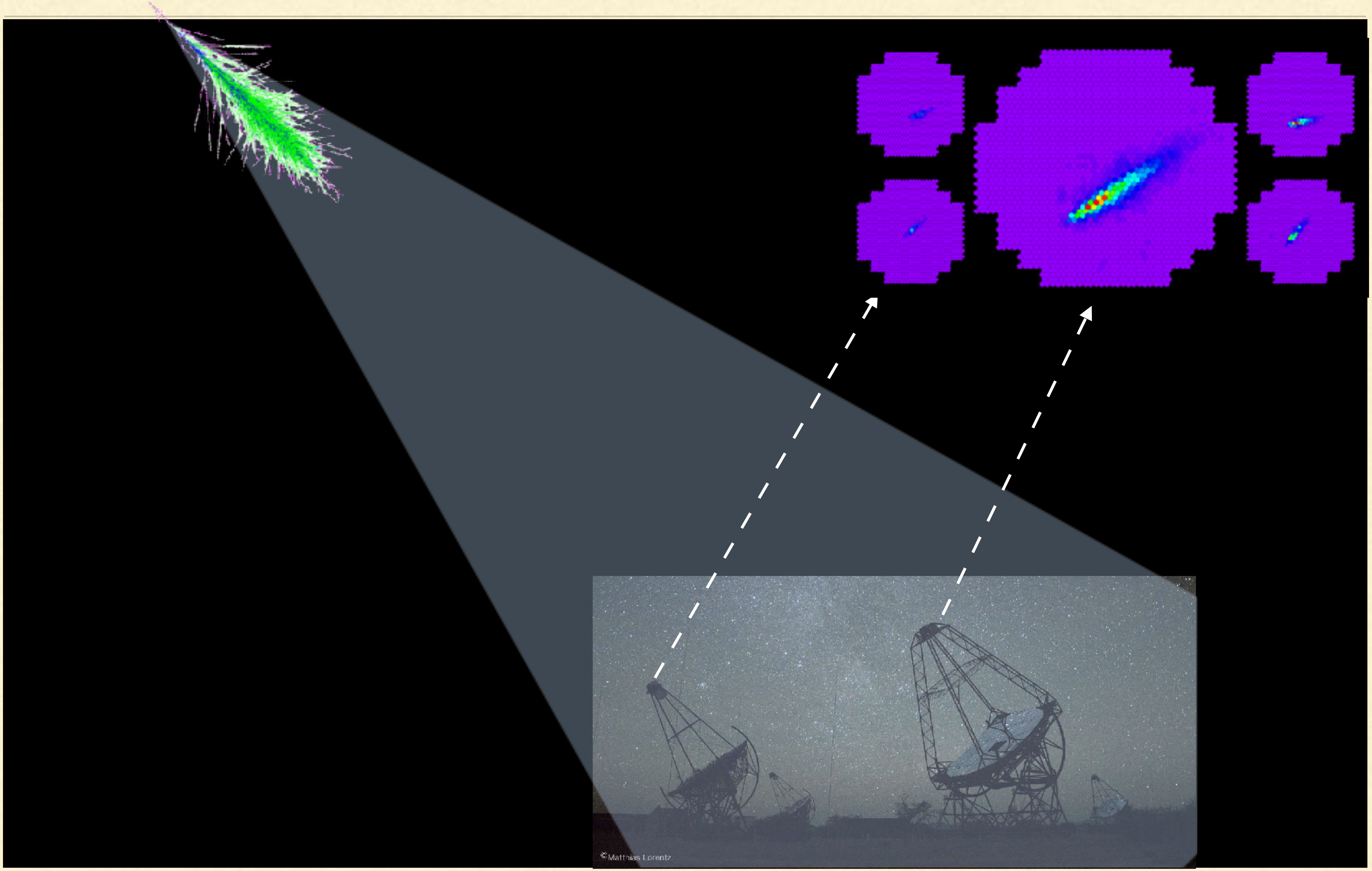
Redshift reach in the TeV range is very limited compared to Fermi-LAT for two reasons :

- absorption on the EBL
- intrinsic spectral cutoffs (especially FSRQs, LBLs)

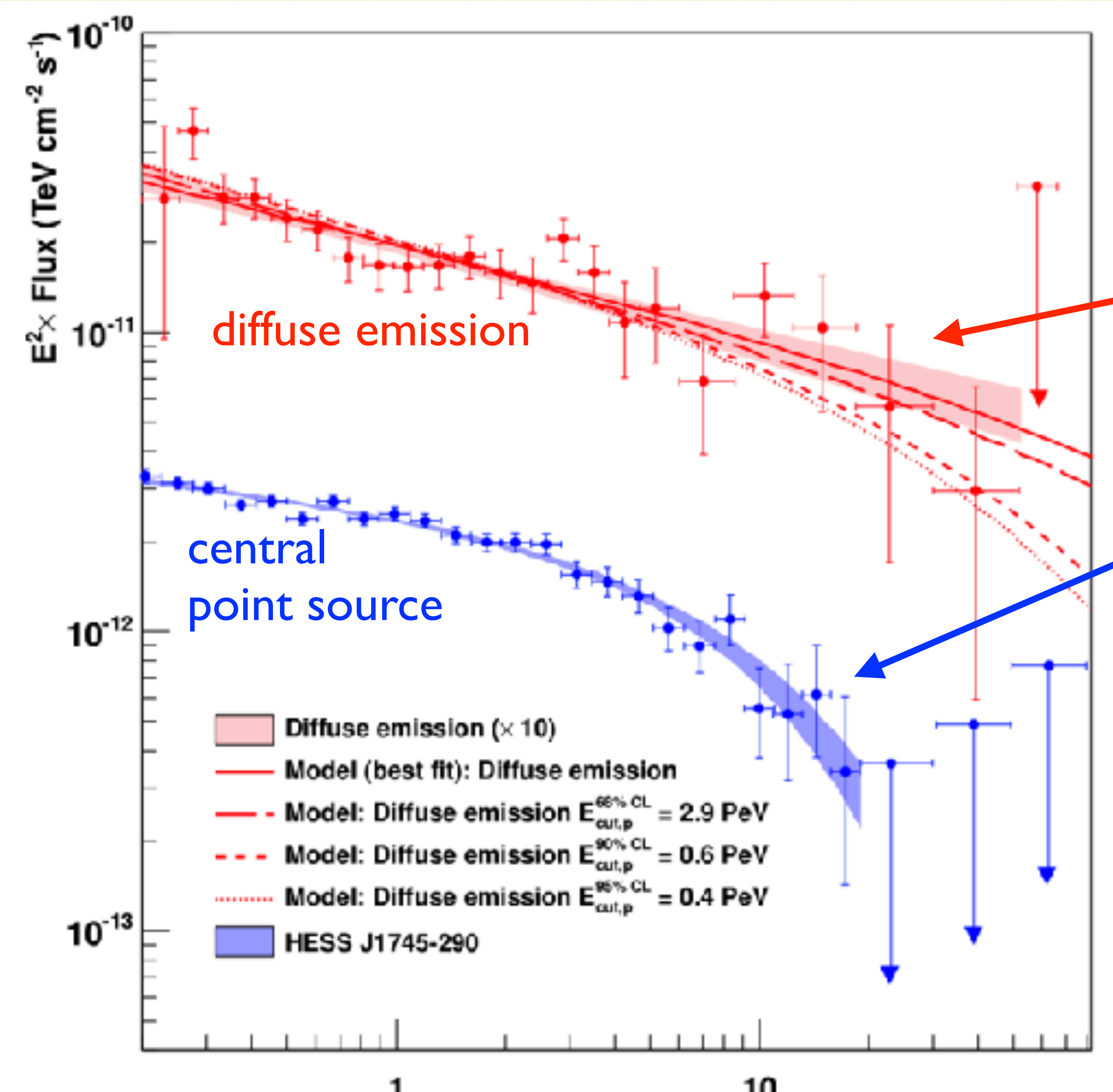
-> higher redshifts attainable with a lowering of the energy threshold (HESS-I ~ 100 GeV, HESS-II ~ 30 GeV)

2. Two recent results from H.E.S.S.

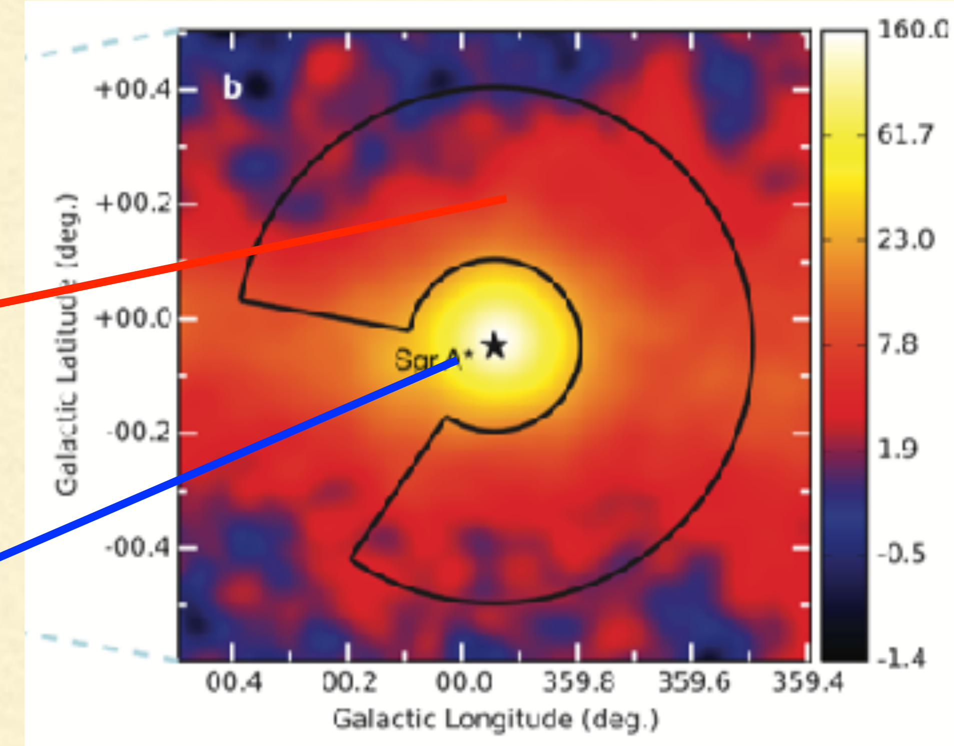
The H.E.S.S. Cherenkov telescope array



Sgr A* - a PeVatron ?



A.Abramowski et al. , Science 2016

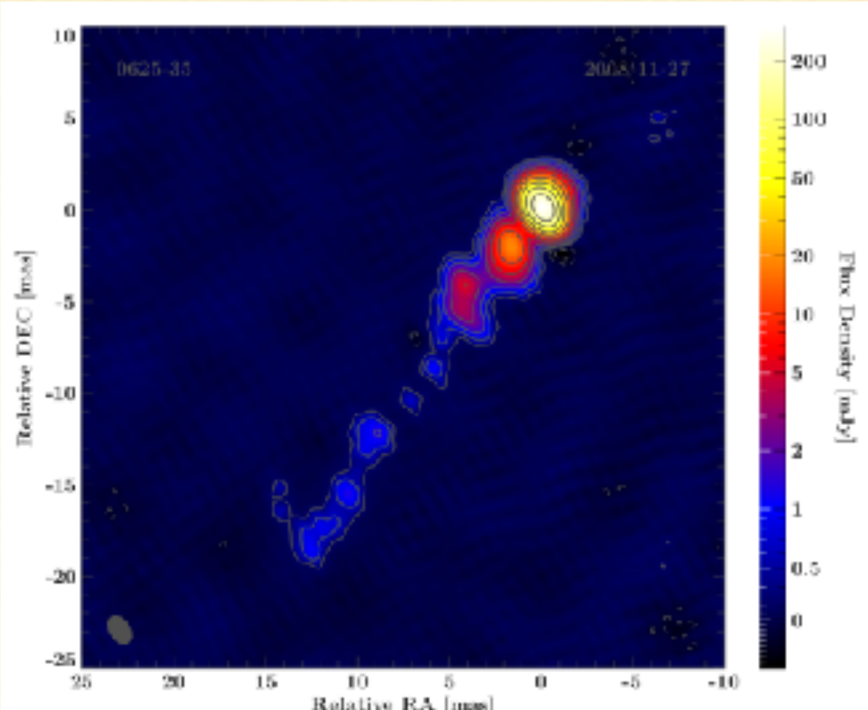


The point-like TeV source “HESS J1745-290” coincides with the position of Sgr A* in the Galactic Center.

In addition there is a more diffuse emission component that is traced back to PeV cosmic rays.

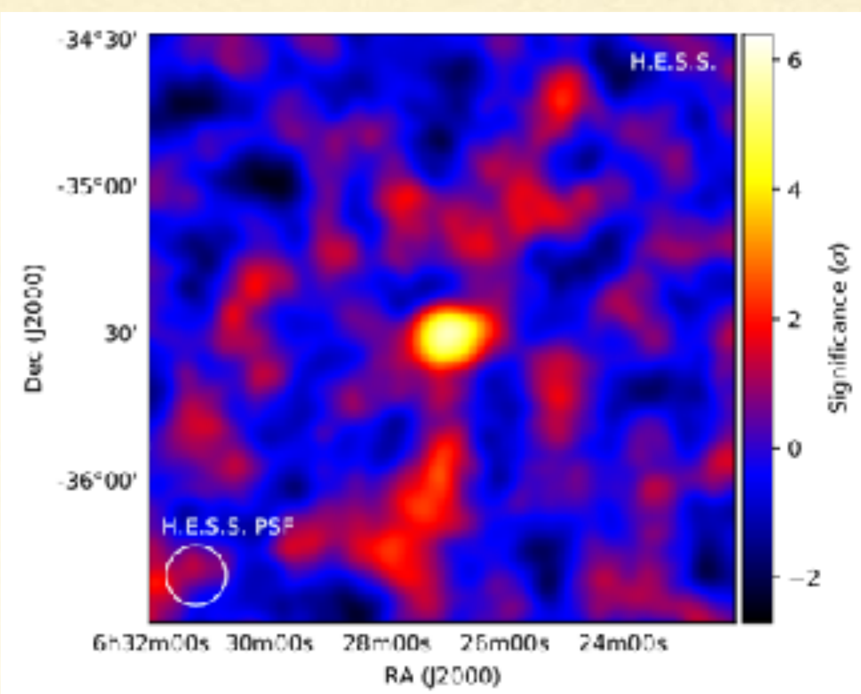
-> First direct detection of a PeV cosmic ray accelerator !

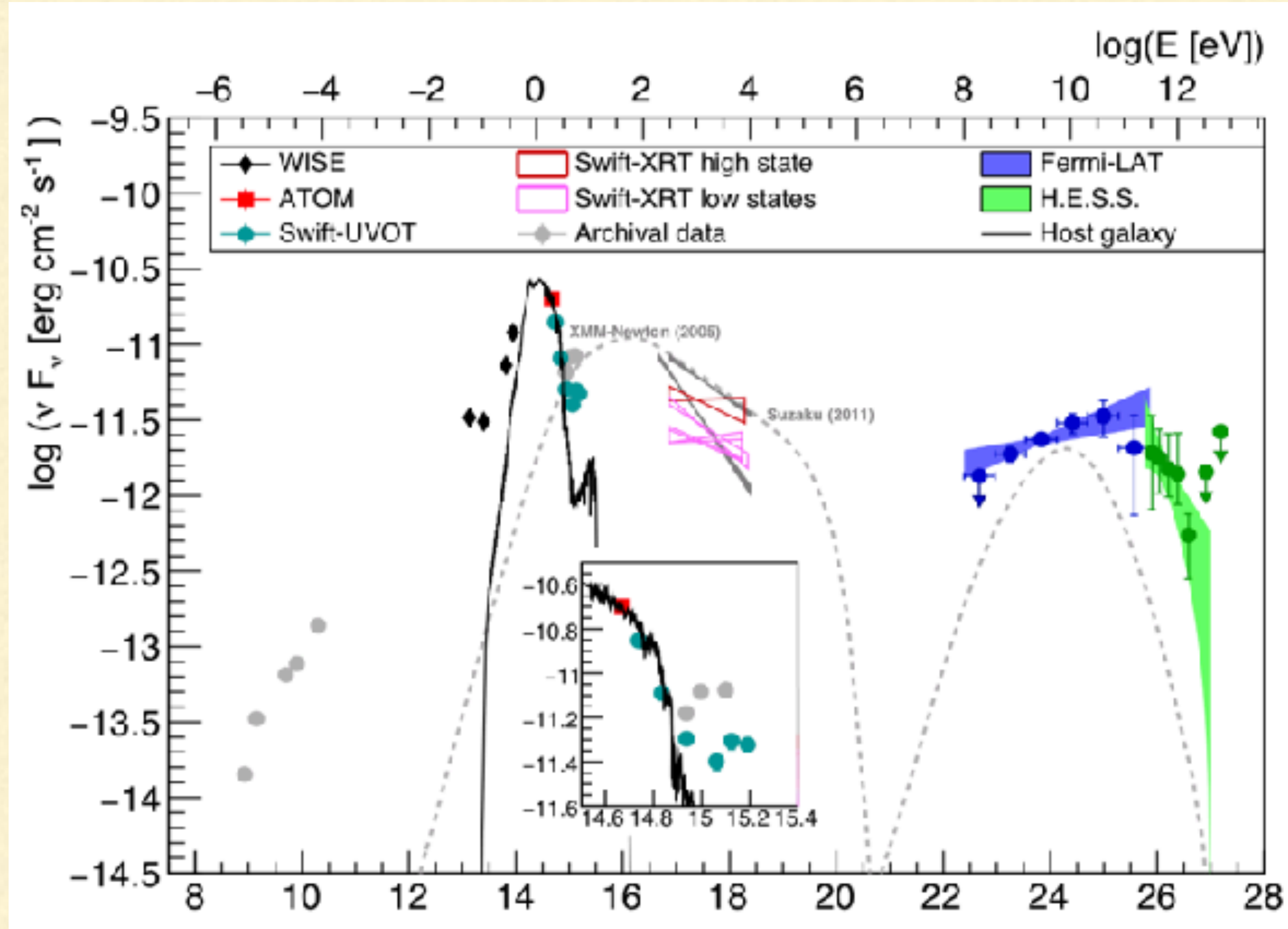
PKS 0625-354 - radio-galaxy or blazar ?



C. Müller et al. (2013)

One-sided jet with strong central core seen in VLBI (TANAMI, 8 GHz). Point-like emission seen with H.E.S.S.

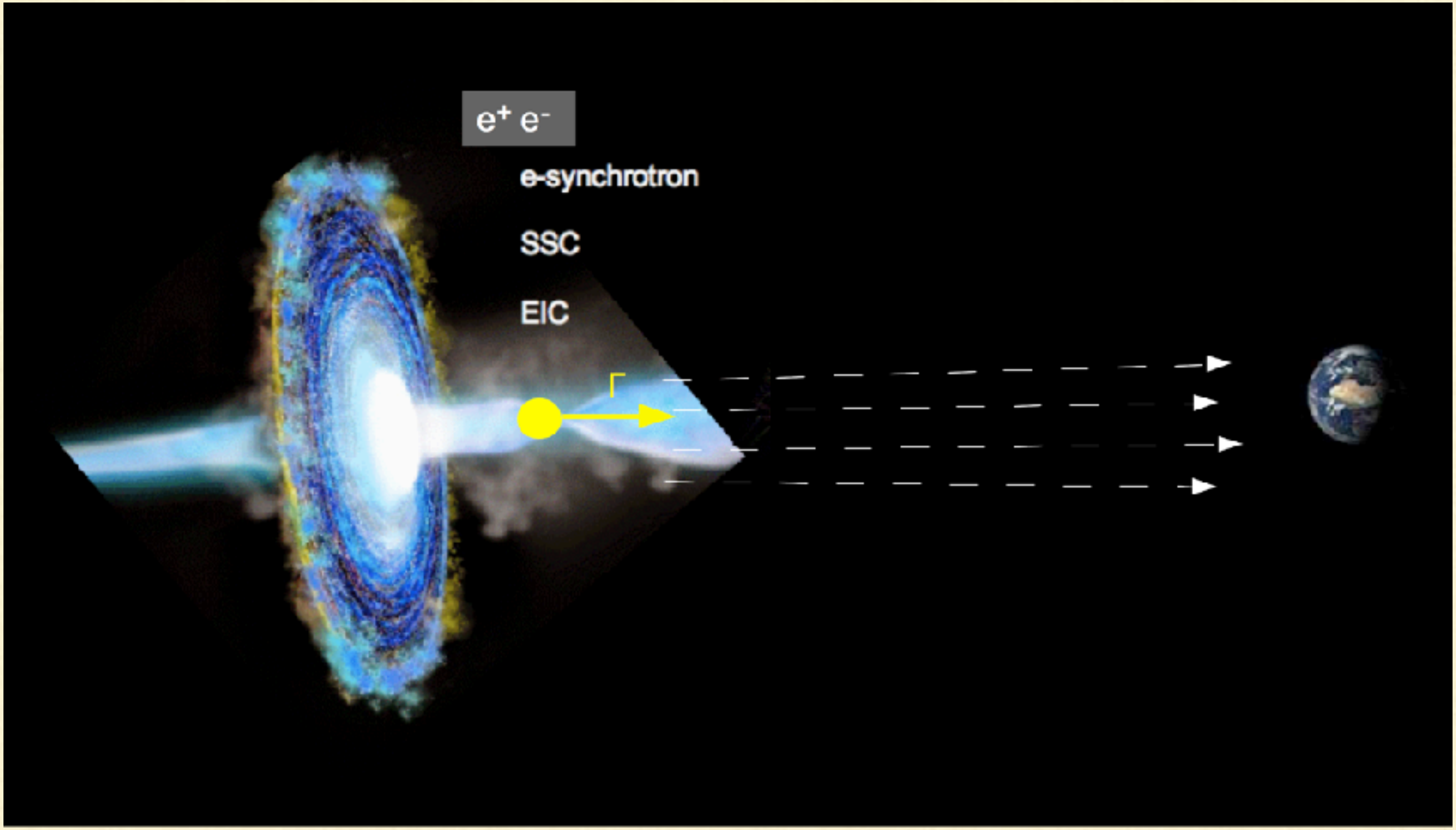




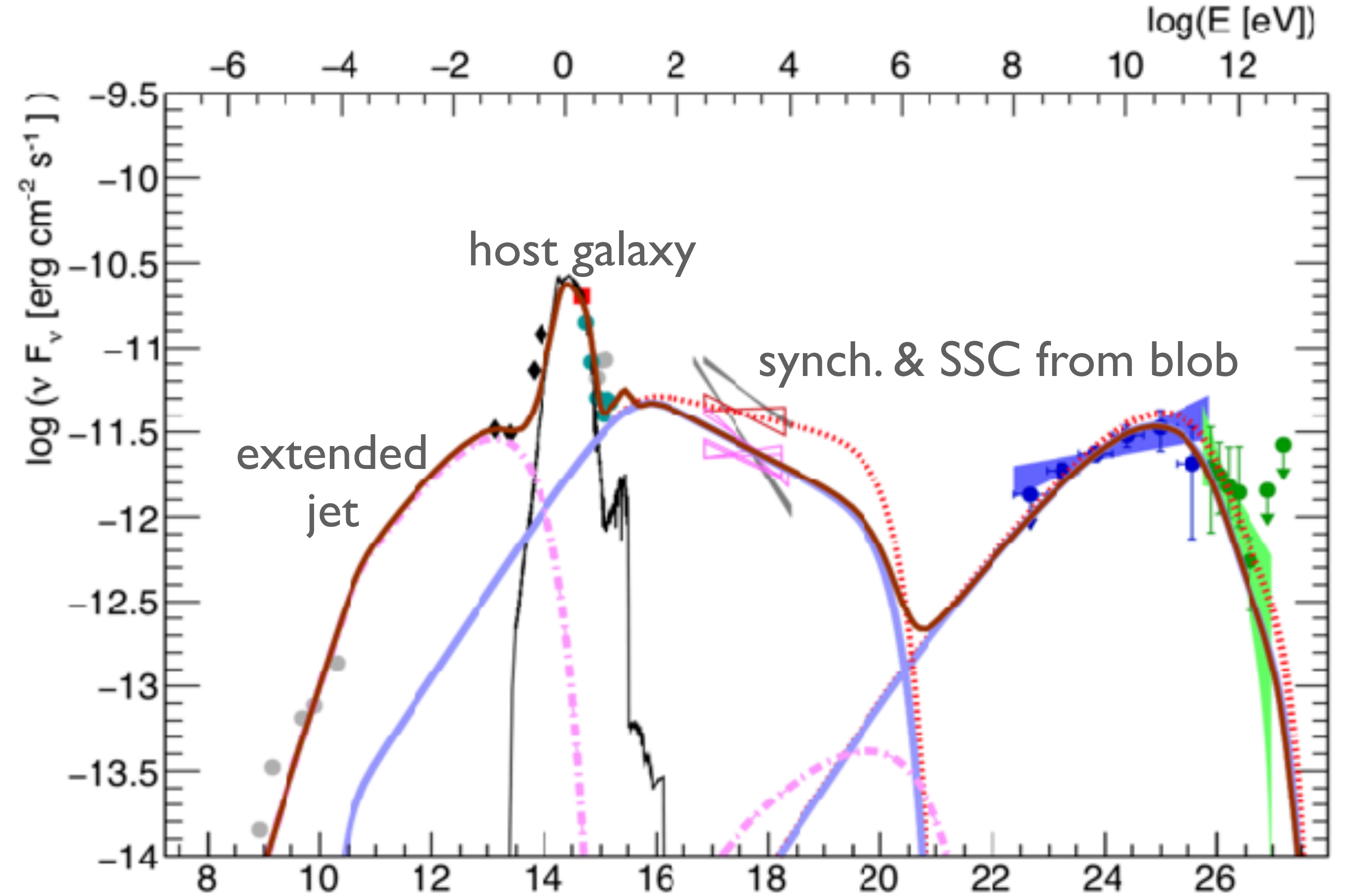
Abdalla, H. et al. (HESS), accepted for pub. in MNRAS

spectral distribution with a model for host galaxy and an emission model based on a previous data set -> ressembles the emission from BL Lacs.

3. Leptonic Emission Models



Modelling a BL Lac blazar : PKS 0625-354



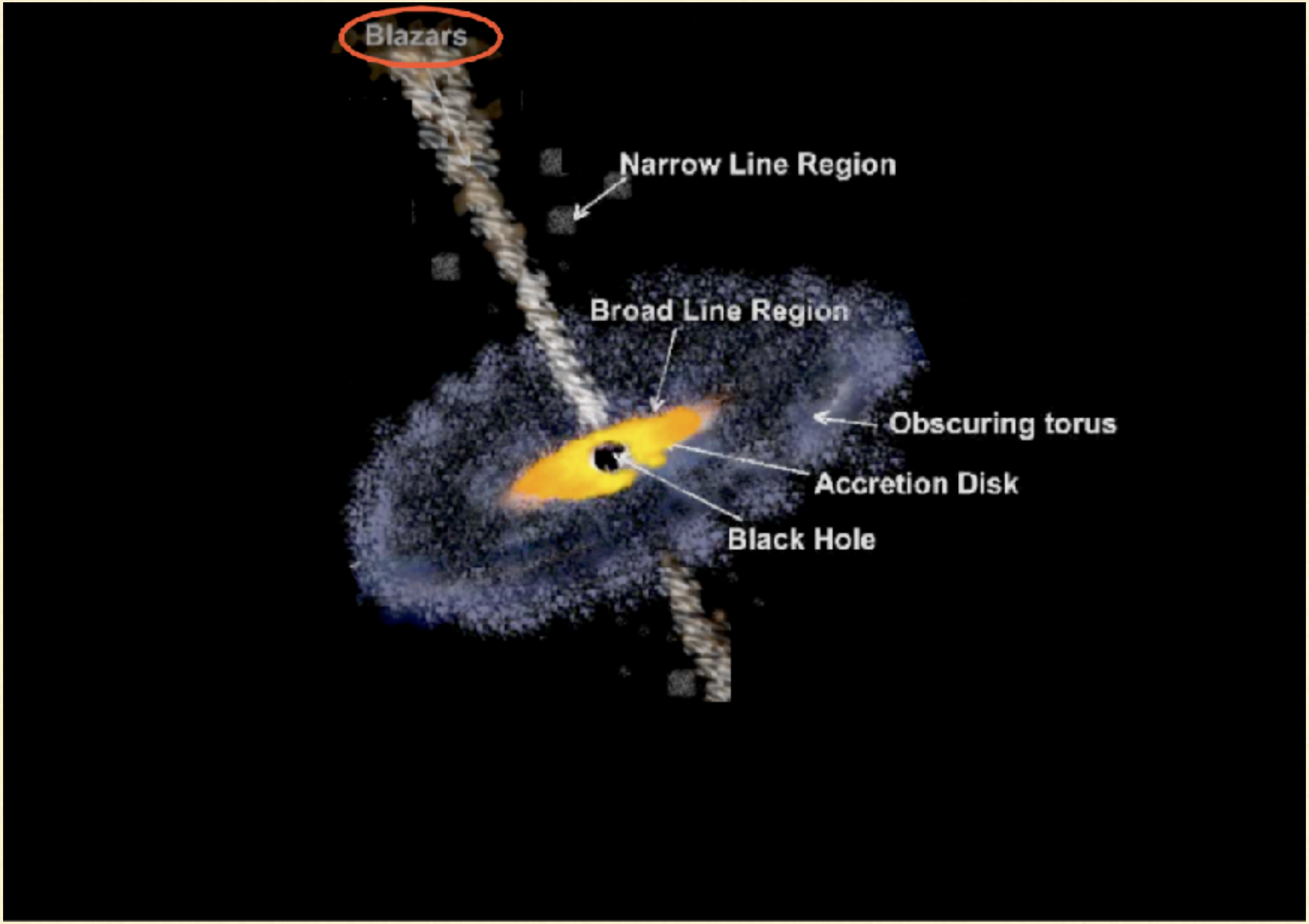
Abdalla, H. et al. (HESS), accepted for pub. in MNRAS

Parameter	Value	Unit
θ	1.0	deg
Blob		
Γ	10.4	–
K	2.3×10^3	cm^{-3}
n_1	2.0	–
n_2 (low state)	3.35	–
n_2 (high state)	3.15	–
γ_{min}	1.0	–
γ_{max}	6.0×10^6	–
γ_b	4.0×10^4	–
B	4.0×10^{-2}	G
R	9.0×10^{15}	cm
Jet		
Γ	4.1	–
K	8.5×10^2	cm^{-3}
n	2.1	–
γ_{min}	1.0	–
γ_{max}	3.2×10^3	–
B_1	3.1×10^{-1}	G
R_1	1.5×10^{16}	cm
L*	3.0×10^2	pc
$\alpha/2$*	1.0	deg

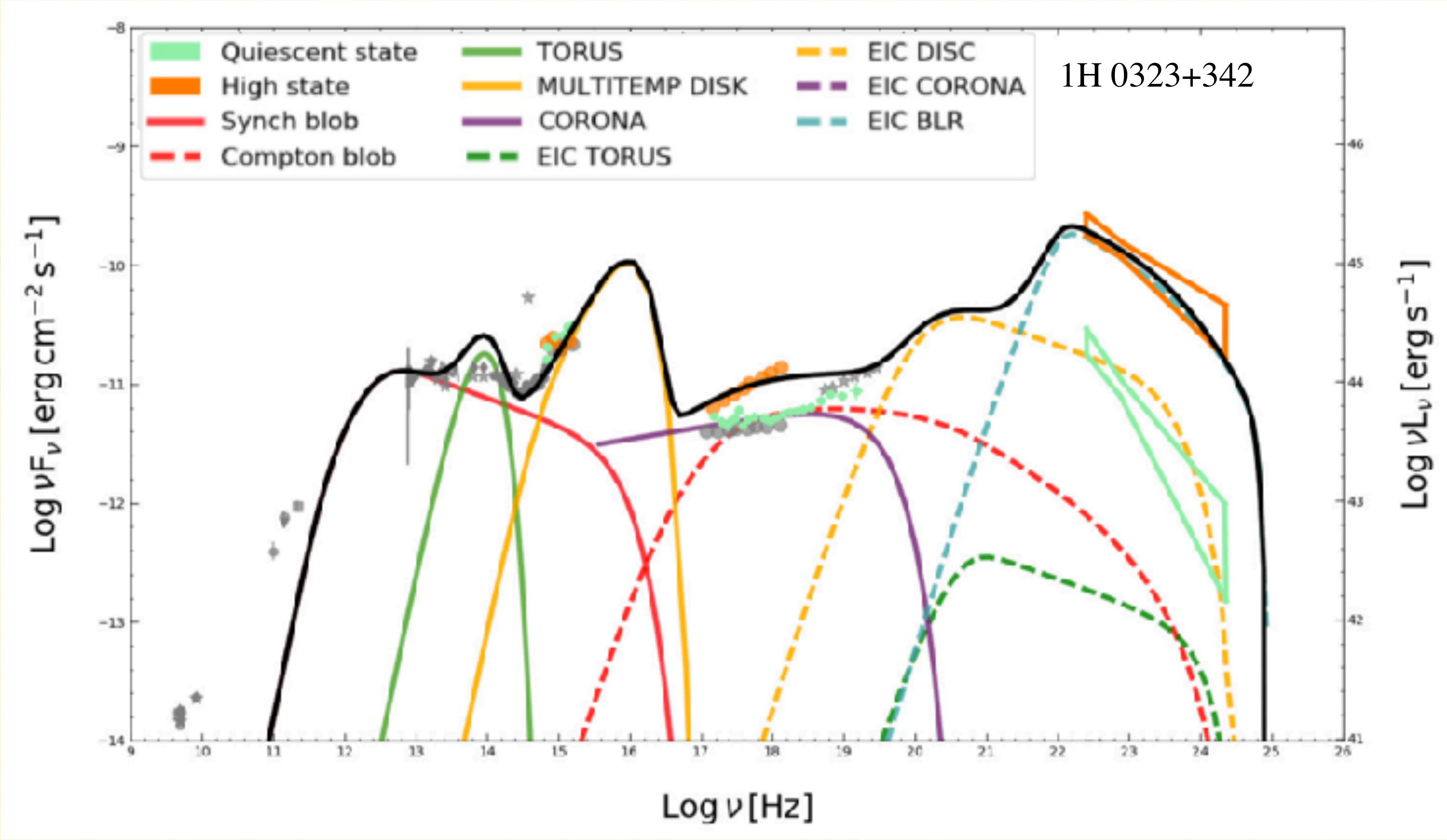
For most blazars, the radio spectrum is ascribed to an extended jet, while higher energies stem from a dense region inside the jet (plasma "blob").

Model by O. Hervet (LUTH)

high-luminosity blazars : adding external photon fields



e.g. the Narrow Line Seyfert 1 galaxy 1H0323+342

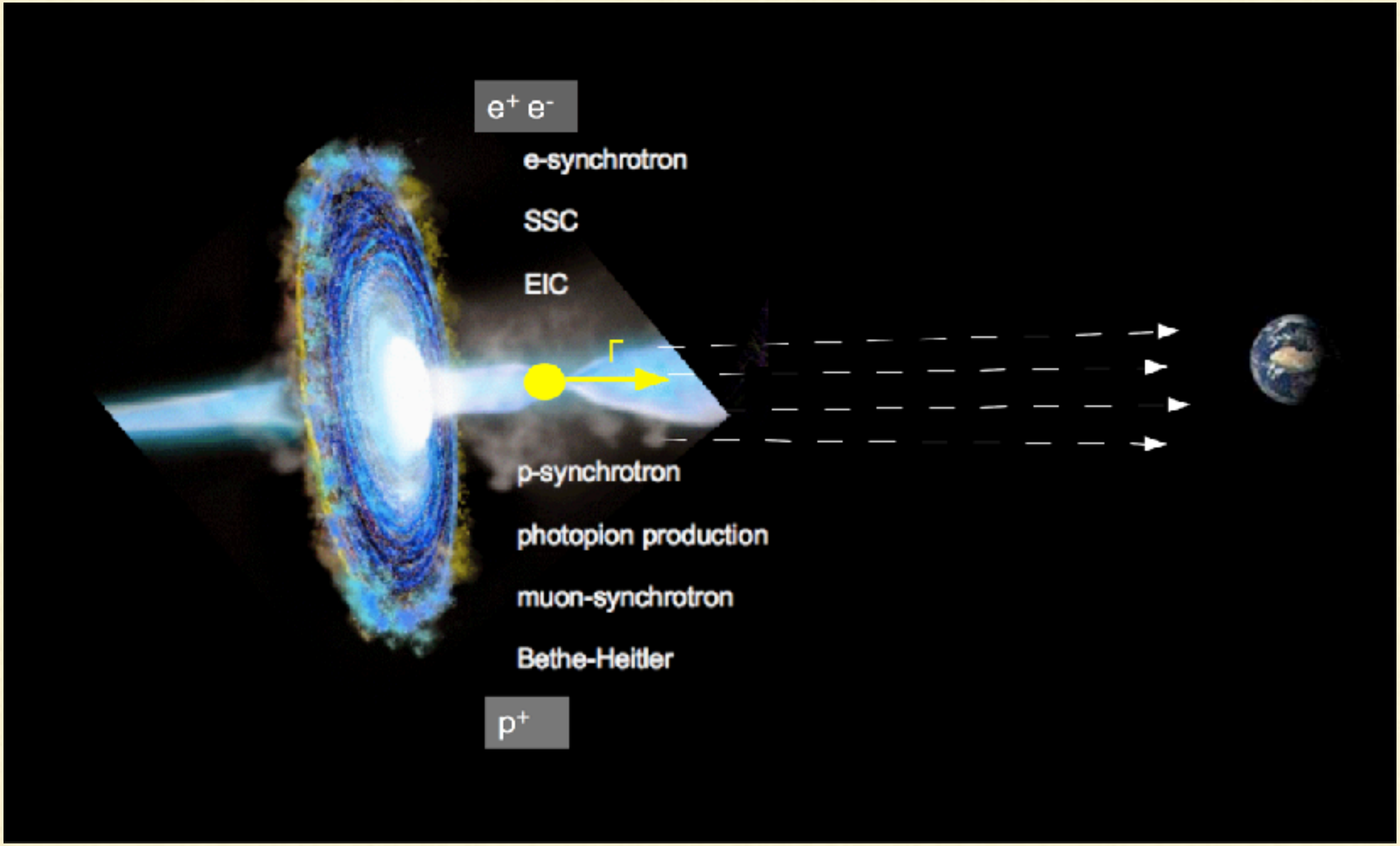


M. Arrieta-Lobo, C. Boisson, AZ, Proc. of "Quasars" workshop in Padua 2016

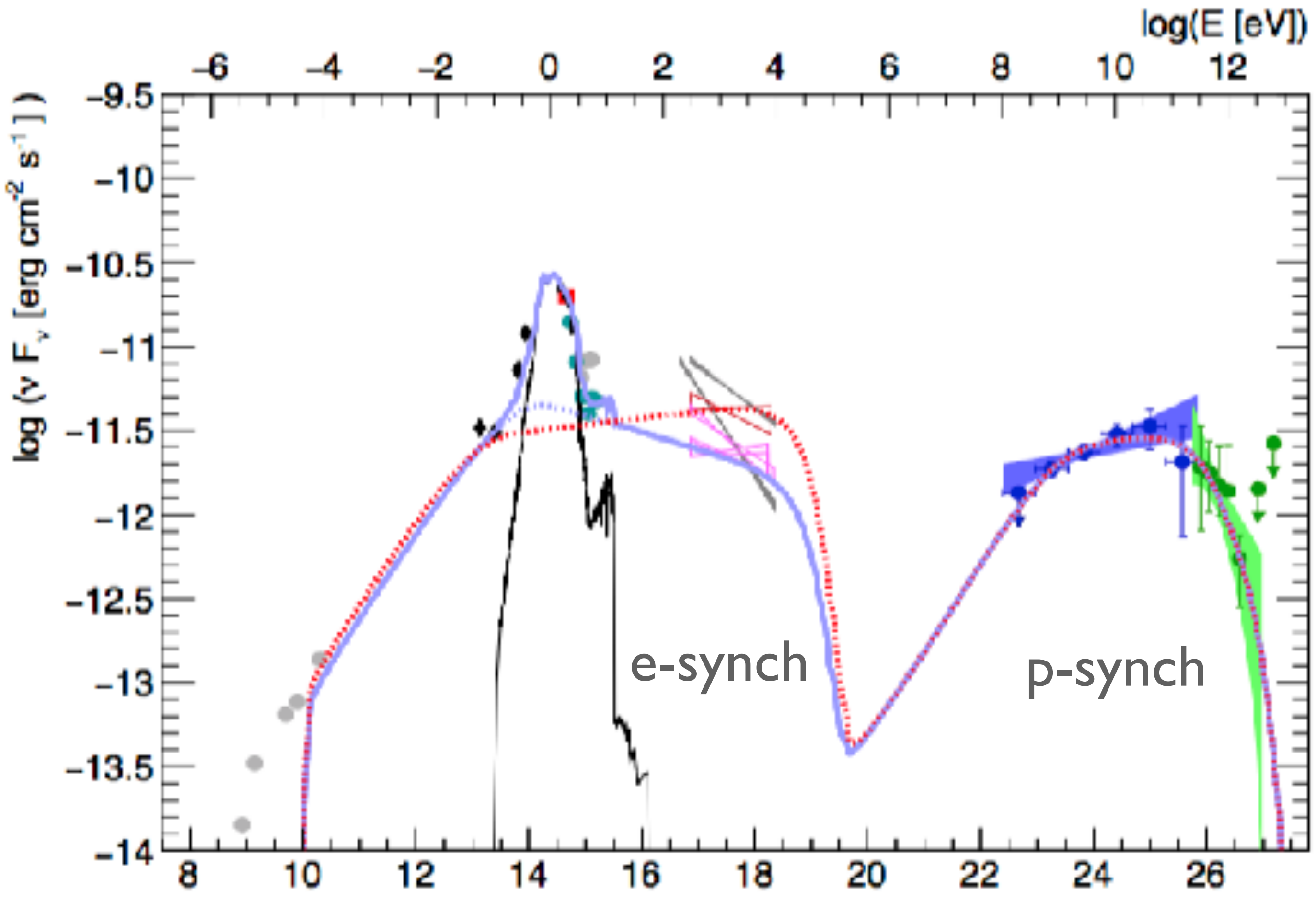
In NLSy1s, the accretion disk emission is visible in the optical/UV. High-energy emission is ascribed to a combination of External Inverse Compton on the BLR, torus and disk photon fields.

These sources look similar to FSRQ type blazars, but have smaller masses (10^6 -10^7 $M_\odot$)

4. Hadronic Emission Models



A hadronic model for PKS 0625-354



Abdalla, H. et al. (HESS), accepted for pub. in MNRAS

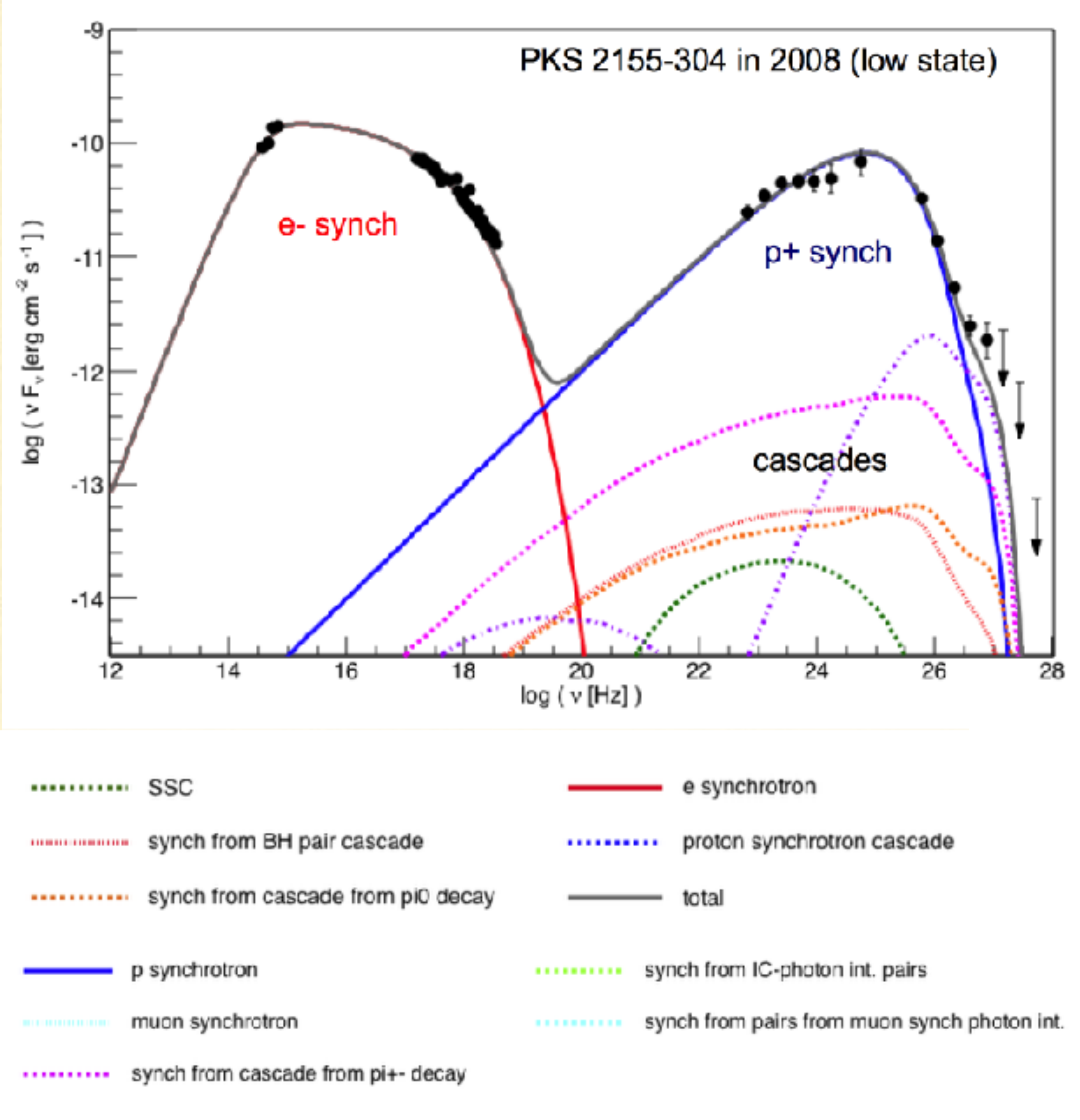
Parameter	Value	Unit
General		
Γ	10.0	–
θ	5.74	deg
B	1.0×10^2	G
R	1.0×10^{16}	cm
η_{esc}	3.0	–
Electrons		
P_e (low state)	4.28×10^{39}	erg s^{-1}
P_e (high state)	4.72×10^{39}	erg s^{-1}
n_e (low state)	2.20	–
n_e (high state)	1.92	–
$\gamma_{min,e}$(low state)	1.40×10^2	–
$\gamma_{min,e}$(high state)	6.50×10^2	–
$\gamma_{max,e}$	4.50×10^4	–
Protons		
P_p	8.75×10^{42}	erg s^{-1}
n_p	1.90	–
$\gamma_{min,p}$	1.07	–
$\gamma_{max,p}$	2.13×10^{10}	–

$P_{jet} \sim P_B \sim 4 \times 10^{47}$ erg s^{-1}

Hadronic models present a valid alternative to the "standard" SSC models.

They require (much) higher jet power, but provide a possible link to ultra-high-energy cosmic rays and astro-neutrinos.

the "LEHA" code



LEpto-HAdronic stationary one-zone model for BL Lac objects

(developped by Matteo Cerruti, during his PhD at the LUTH)

- models all emission processes due to e- and p+ interactions in the source

- we usually impose constraints:

  -- power-law input spectra with same index for p+ and e- (co-acceleration)

  -- max. p+ energy from comparison of acceleration and cooling time scales

Cerruti, M., AZ, Boisson, C., Inoue, S. MNRAS 448 (2015) 910-927.

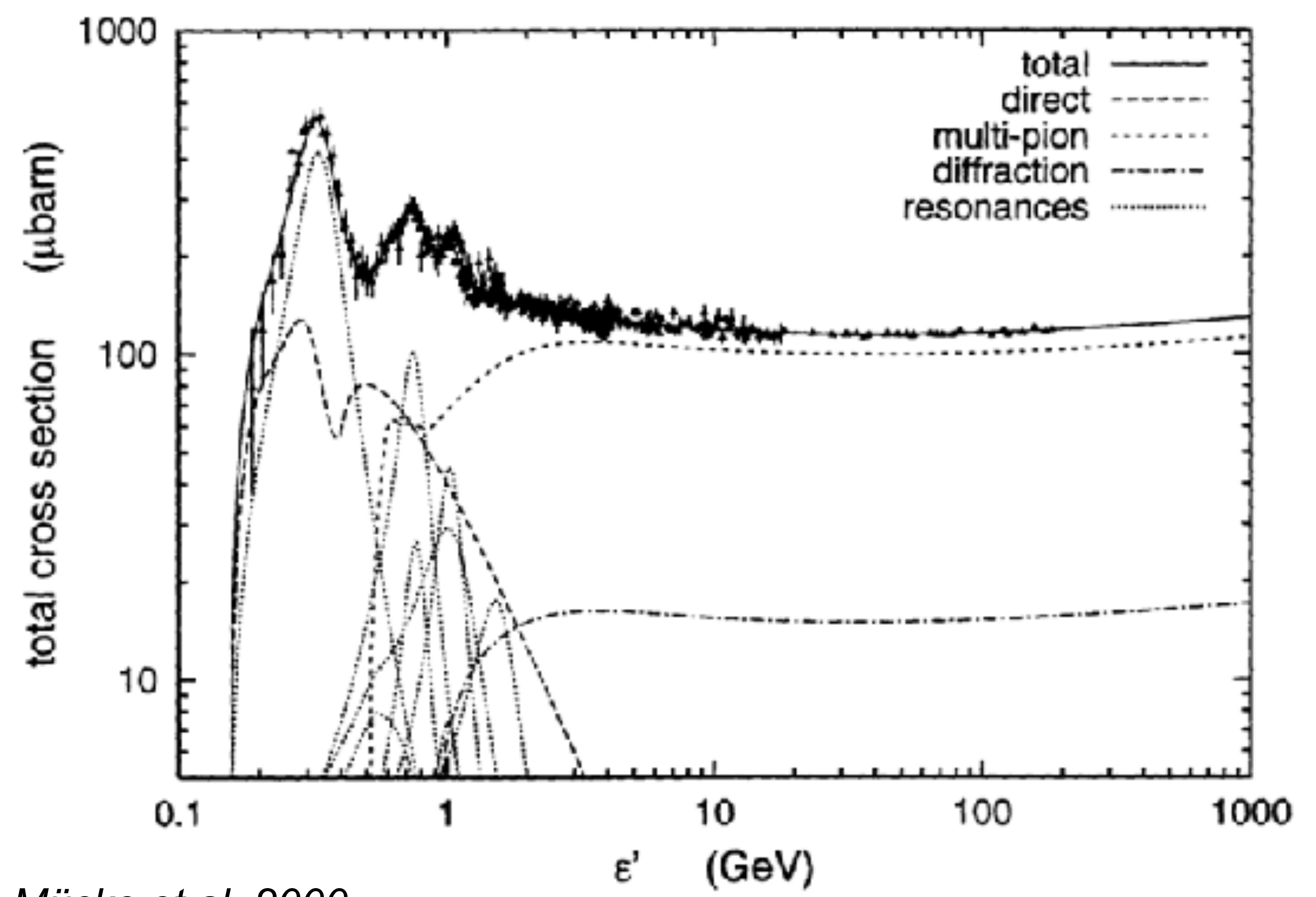
proton-photon interactions

Monte Carlo treatment of proton-photon interactions with the Sophia code (*Mücke et al. 2000*)

advantages of the Monte Carlo approach:

- treatment of all photopion production channels with all resulting particle spectra (including ν spectra…)

- allows explicit treatment of unstable particles (muons, pions, Kaons...)



Mücke et al. 2000

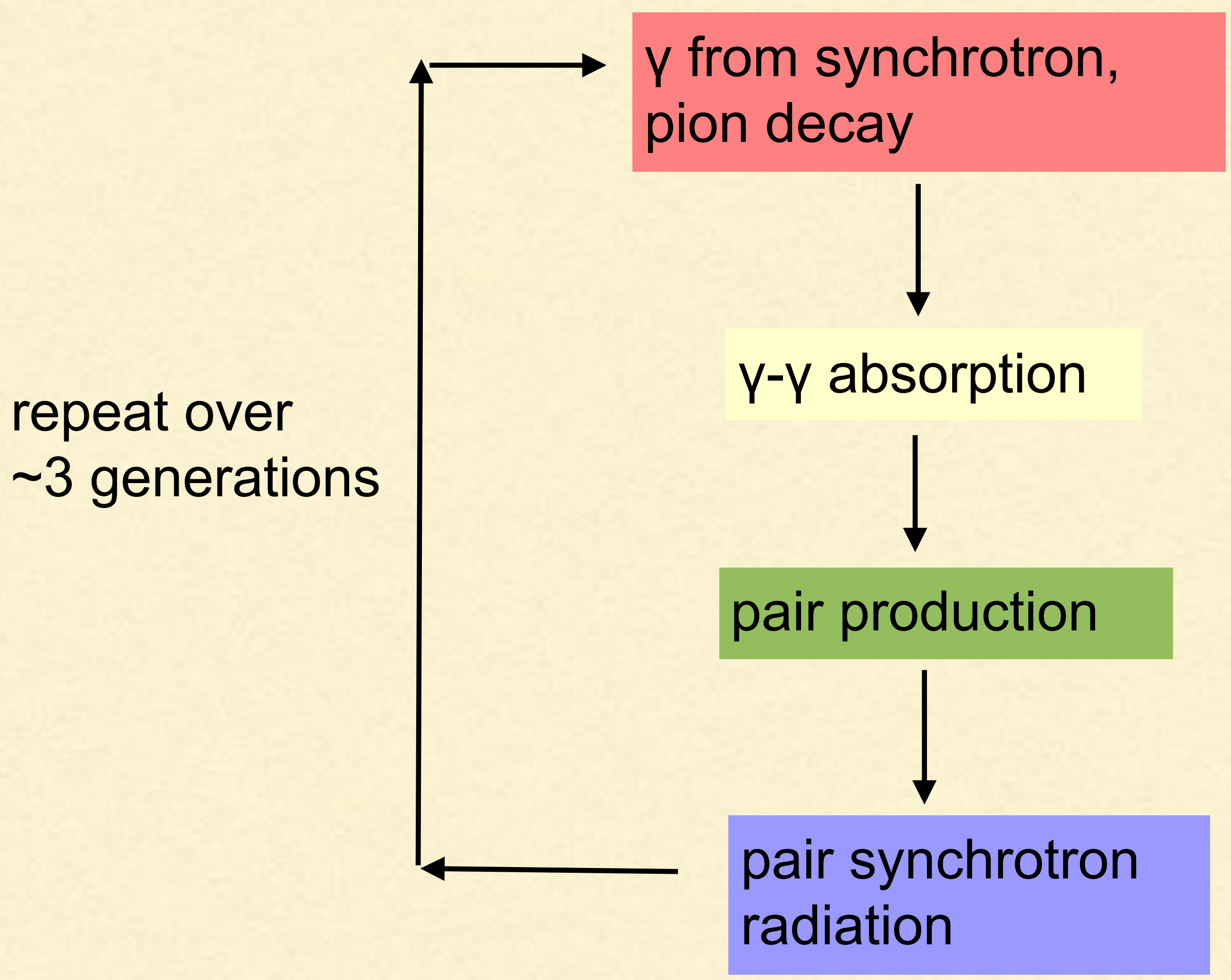
SOPHIA does not treat Bethe-Heitler pair production.
We use *Kelner & Aharonian 2009* + cross-section by *Blumenthal 1970.*

treatment of cascades

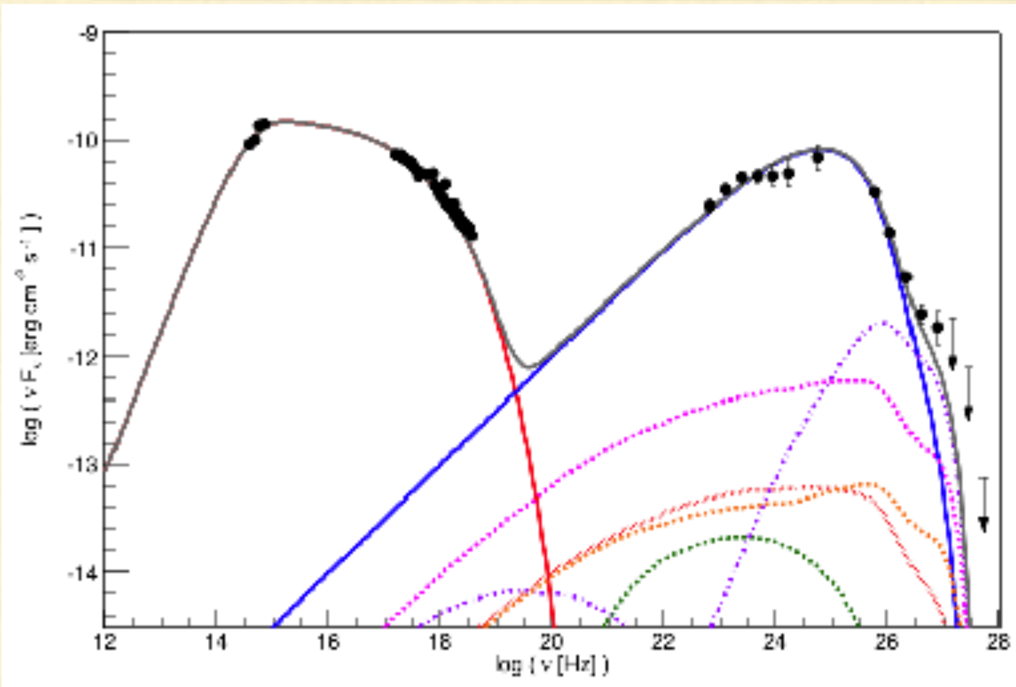
LEHA simulates **synchrotron-pair cascades** triggered by:

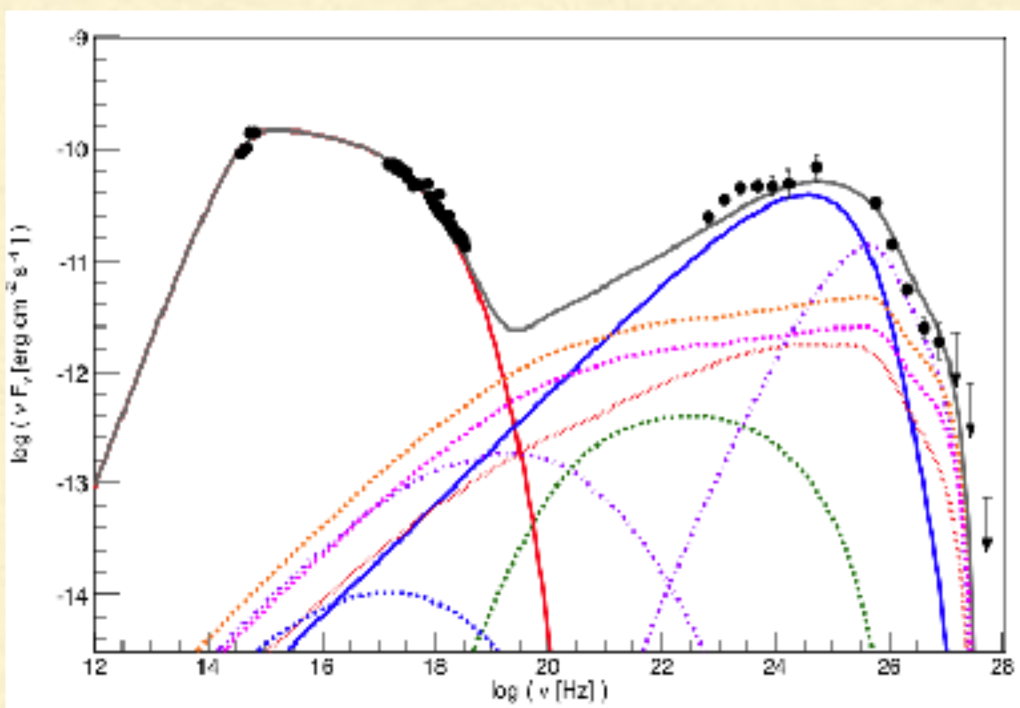
- γ-γ absorption of proton-synchrotron photons, muon synch. photons, photons from π0

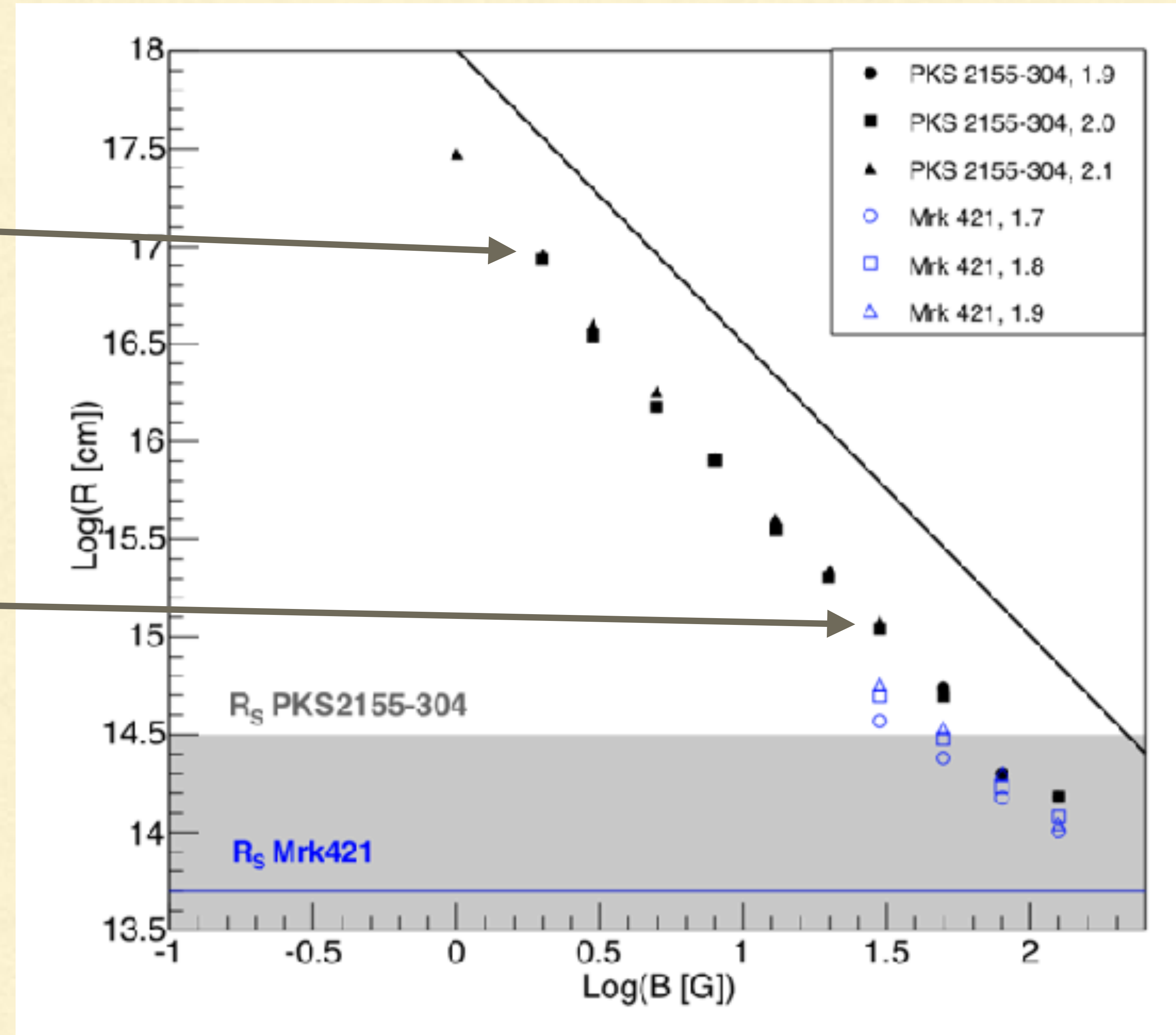
- e+ e- pairs from Bethe-Heitler, leptons from π+, π-



hadronic parameter space for HBLs



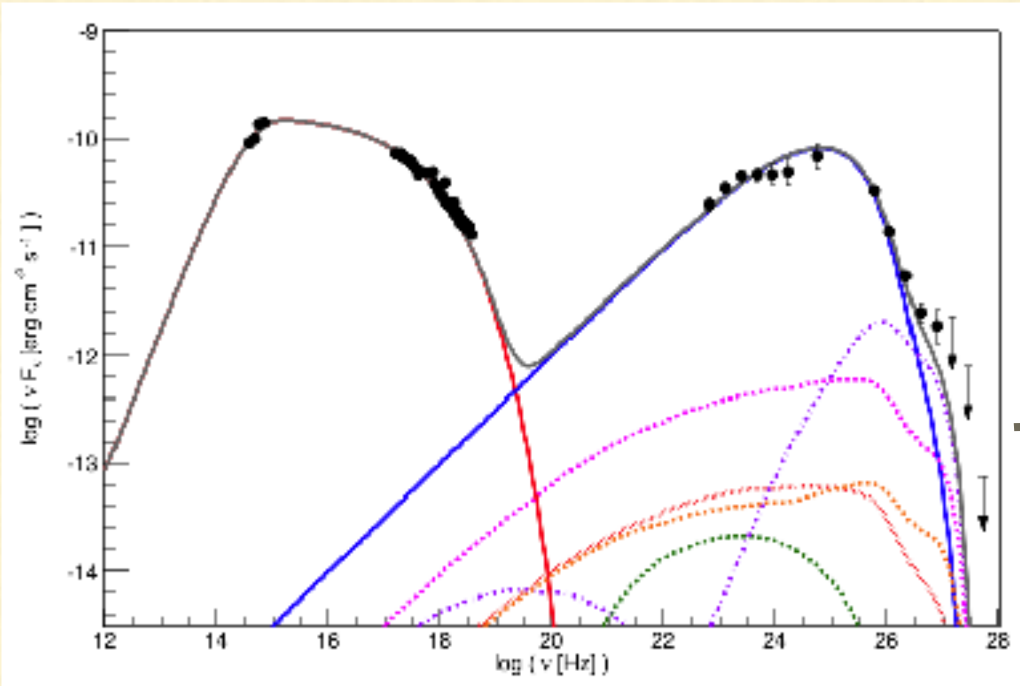


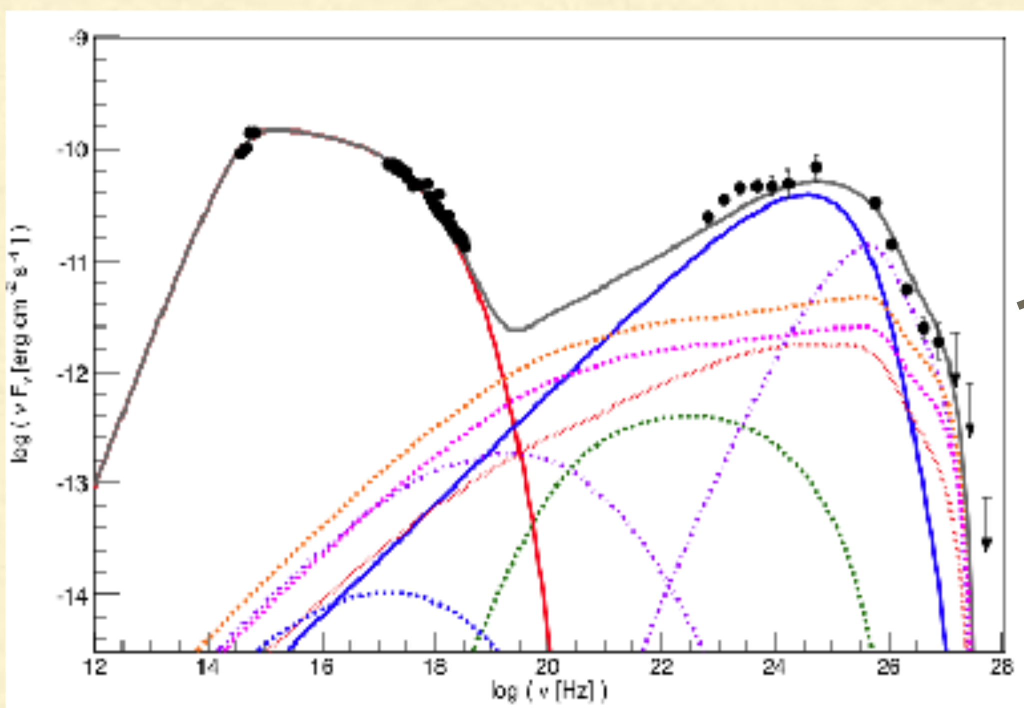


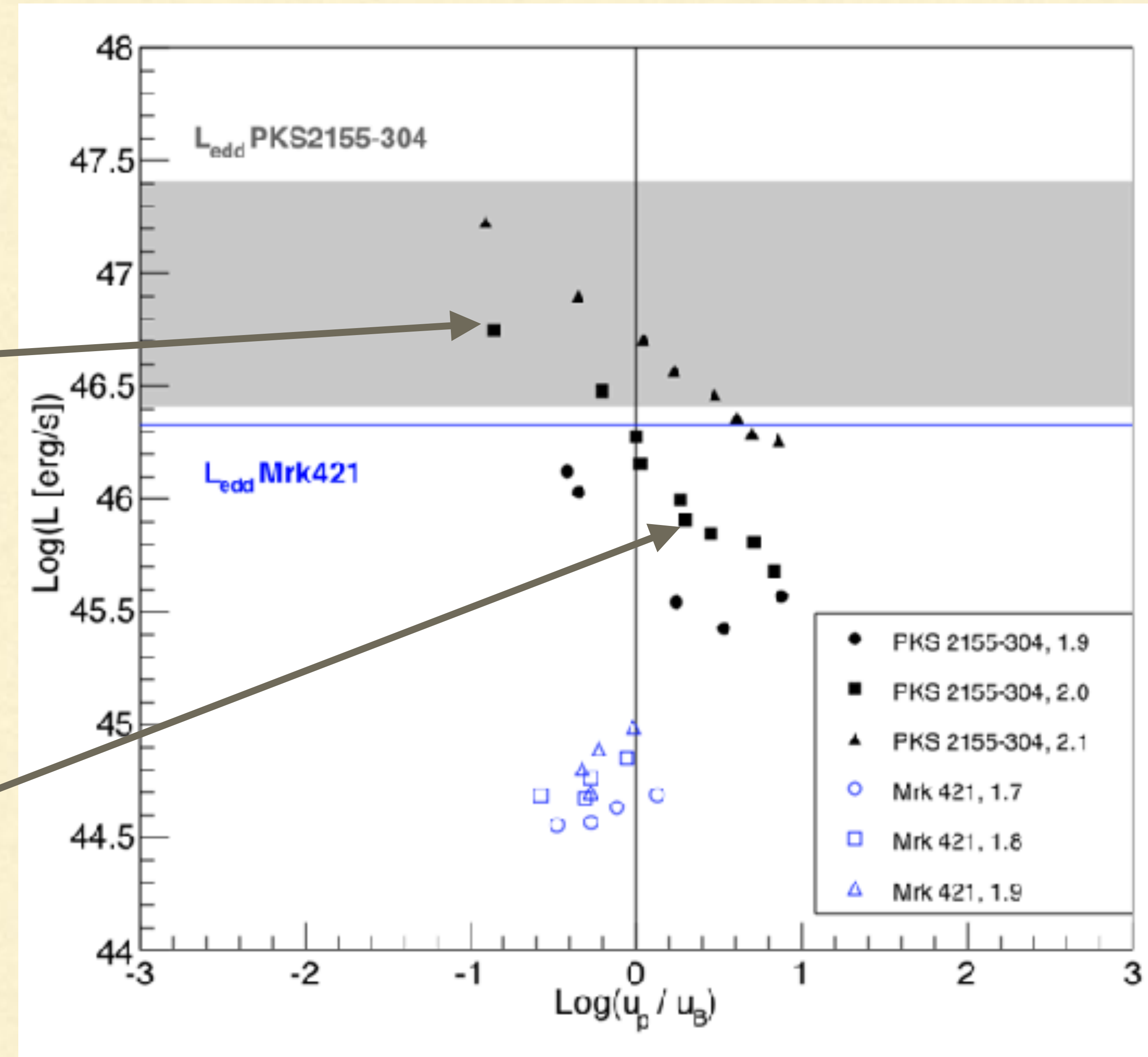
Zech, Cerruti, Mazin,
A&A 602 (2017) 25

size of emission region
vs. magnetic field

hadronic parameter space for HBLs







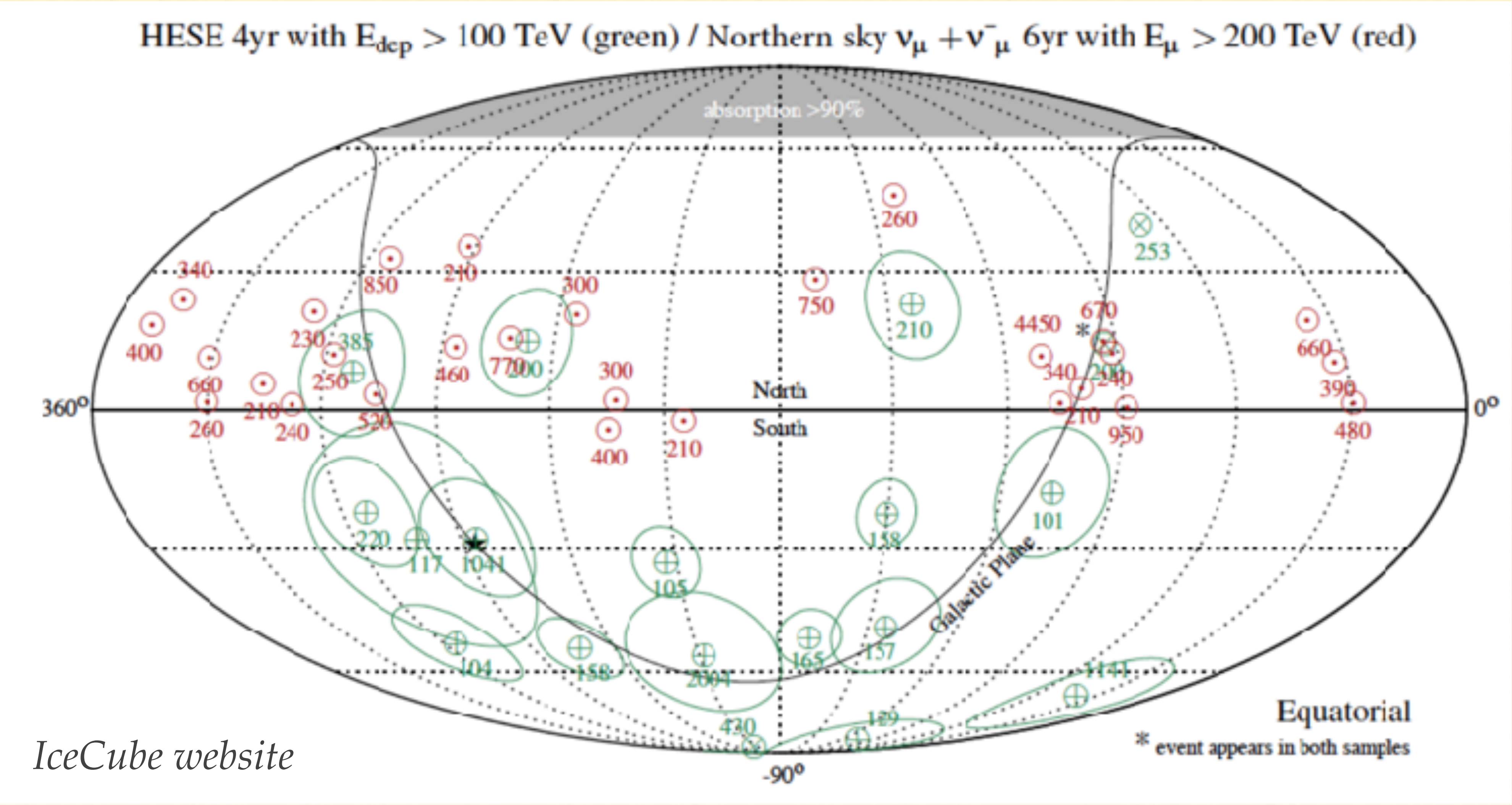
jet power vs.
equipartition ratio (p+ / B-field)

$$L_j \approx 2\pi R^2 \beta c \Gamma^2 (u_B + u_e + u_p) + 2 L_r$$

$$L_{edd} = \frac{4\pi G M m_p c}{\sigma_T}$$

Zech, Cerruti, Mazin, A&A 602 (2017) 25

4. Predicting neutrino fluxes for blazars



IceCube website

Studies on AGN - neutrino correlations

"all-sky studies", e.g. :

- *Neronov et al. (2016)* : comparing stacked Fermi AGN and IceCube upper limit
  -> exclude certain hadronic models ("PIC")

- *Padovani et al. (2016)* : correlation of IceCube neutrinos with blazar catalogs
  -> ~5 bright HBL identified as probable counterparts

- *Righi et al. (2016)* : estimate neutrino flux for Fermi BL Lacs with emission model
  -> several BL Lacs identifiable for KM3Net within a few years (less likely for IceCube)

studies of individual sources, e.g. :

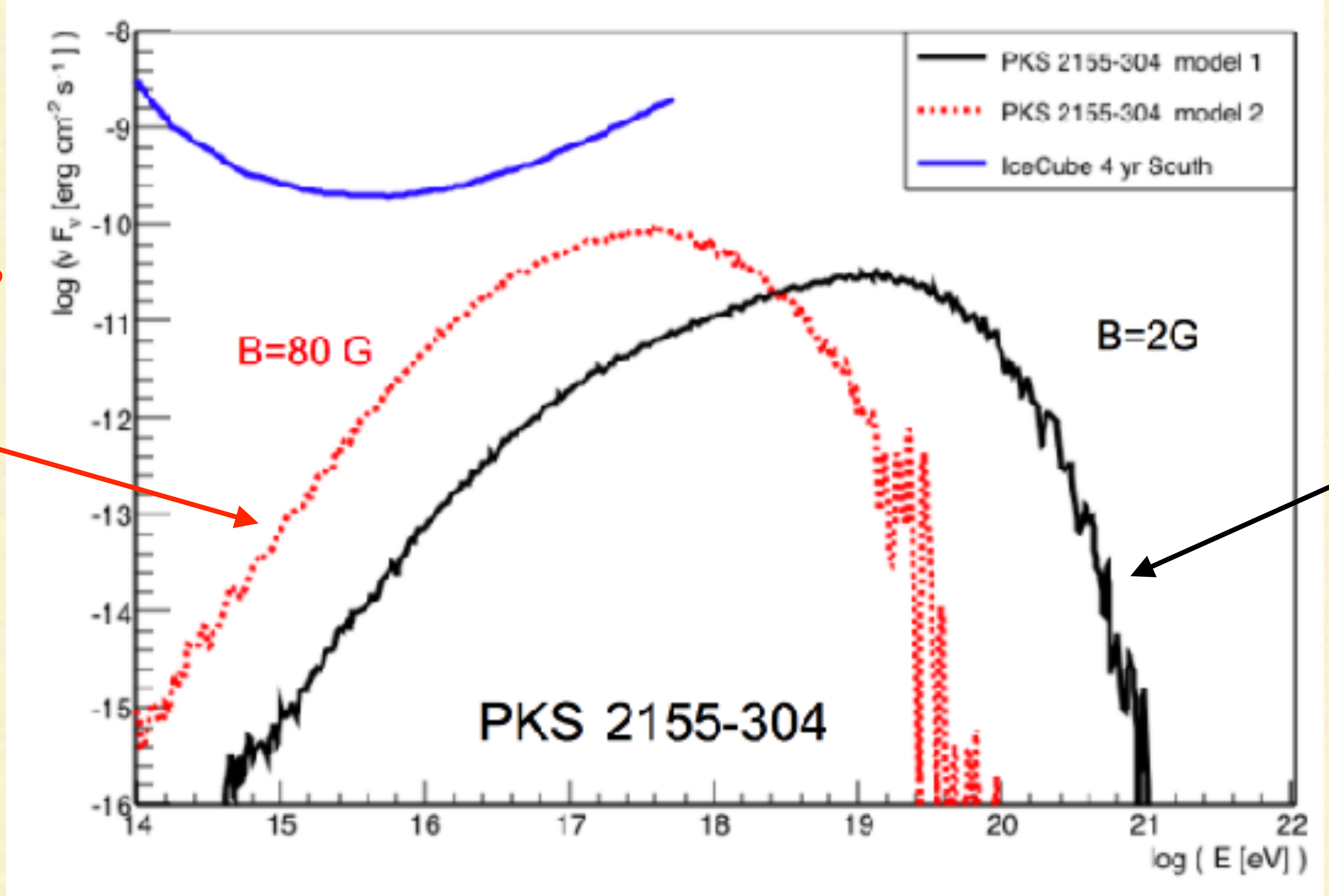
- *Petropoulou et al. (2015)*: BL Lac counterparts of IceCube neutrinos
  -> "good match" for Mrk 421 and H 1914-194, but very high jet powers

- blazar flares coincident with IceCube events :
  Kadler et al., Nature (2016): PKS B1424-418 (FSRQ) -> 5% chance prob.
  Gao et al. (2017) : PKS B1424-418 modelling -> hadronic component subdominant

  IceCube et al., Science (in prep.): TXS 0506+056 (HBL) -> correlation at 3σ

high-energy neutrinos from PKS 2155-304 ?

emitting region dense, cascades important



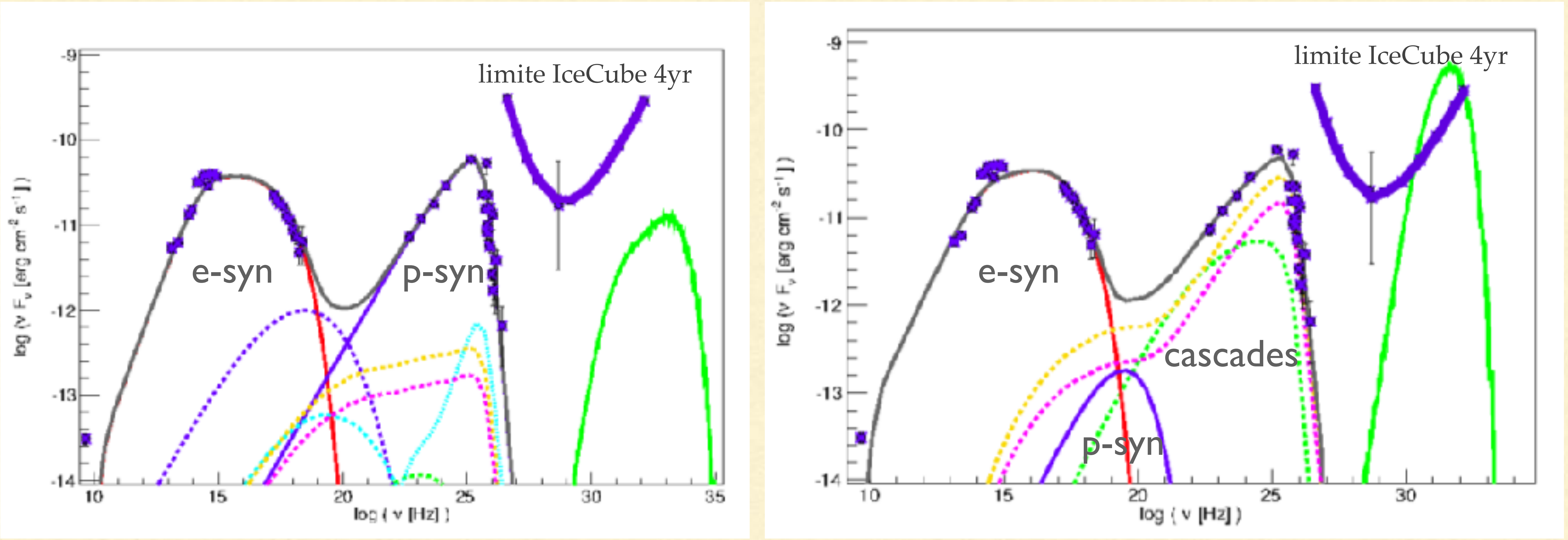
emitting region less dense, cascades less important

Zech, Cerruti, Mazin, A&A 602 (2017) 25

Hadronic models produce very-high-energy neutrino flux, peak around 10^{17}- 10^{19} eV.

-> Out of reach for IceCube / KM3Net ? Need to evaluate detectability with ARA, GRAND, ...

high-energy neutrinos from PG 1553+113 ?

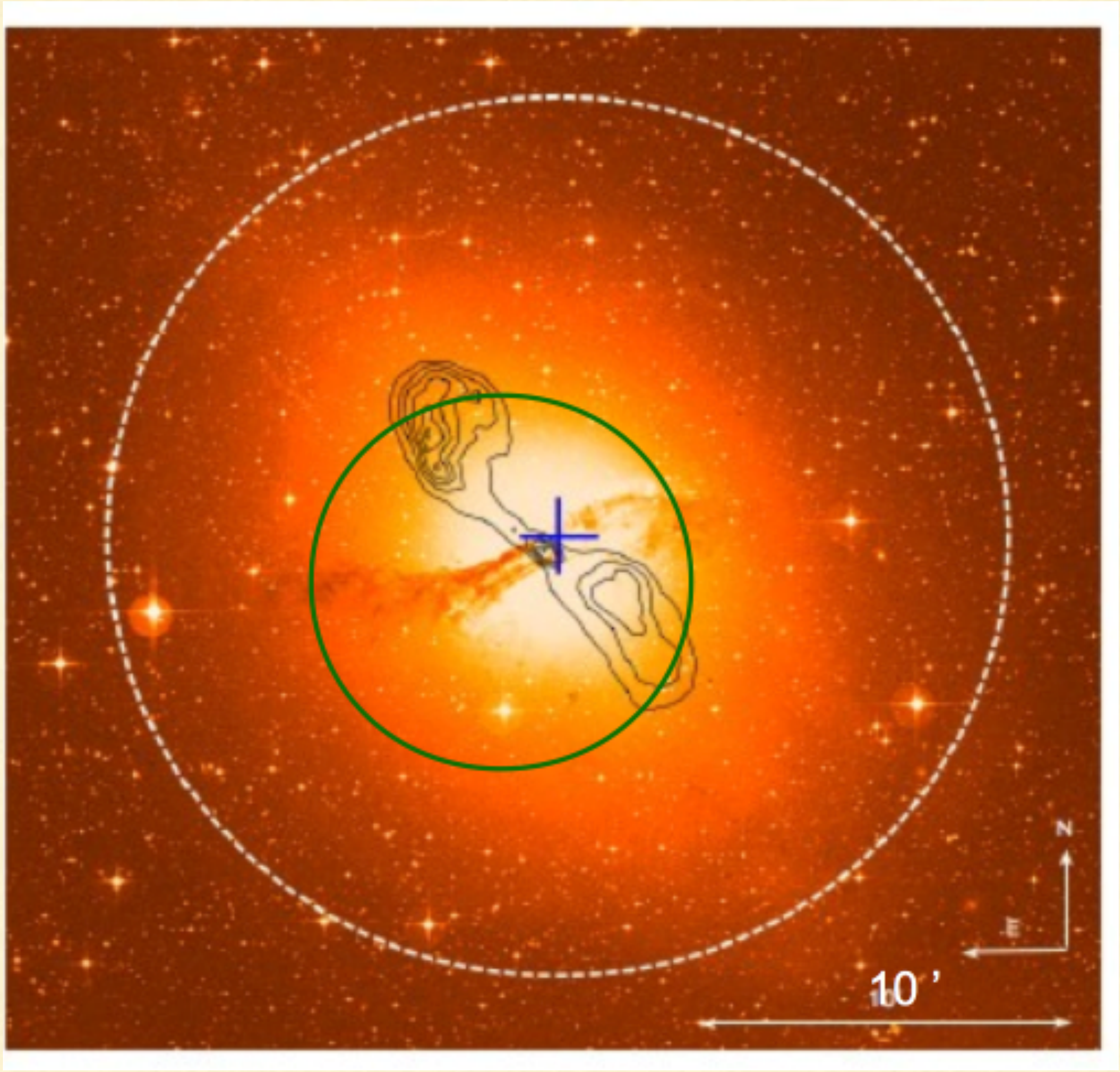


Two scenarios for the BL Lac PG 1553+113 with expected neutrino fluxes.
(IceCube event “NU-17” at a distance of 8.9 deg +/- 11.6 deg)

The “lepto-hadronic” model (right) can be excluded from neutrino limits and jet power requirements.

Cerruti, Zech, Emery, Guarin, Proc. of Gamma 2016 (astro-ph 1610.00255)

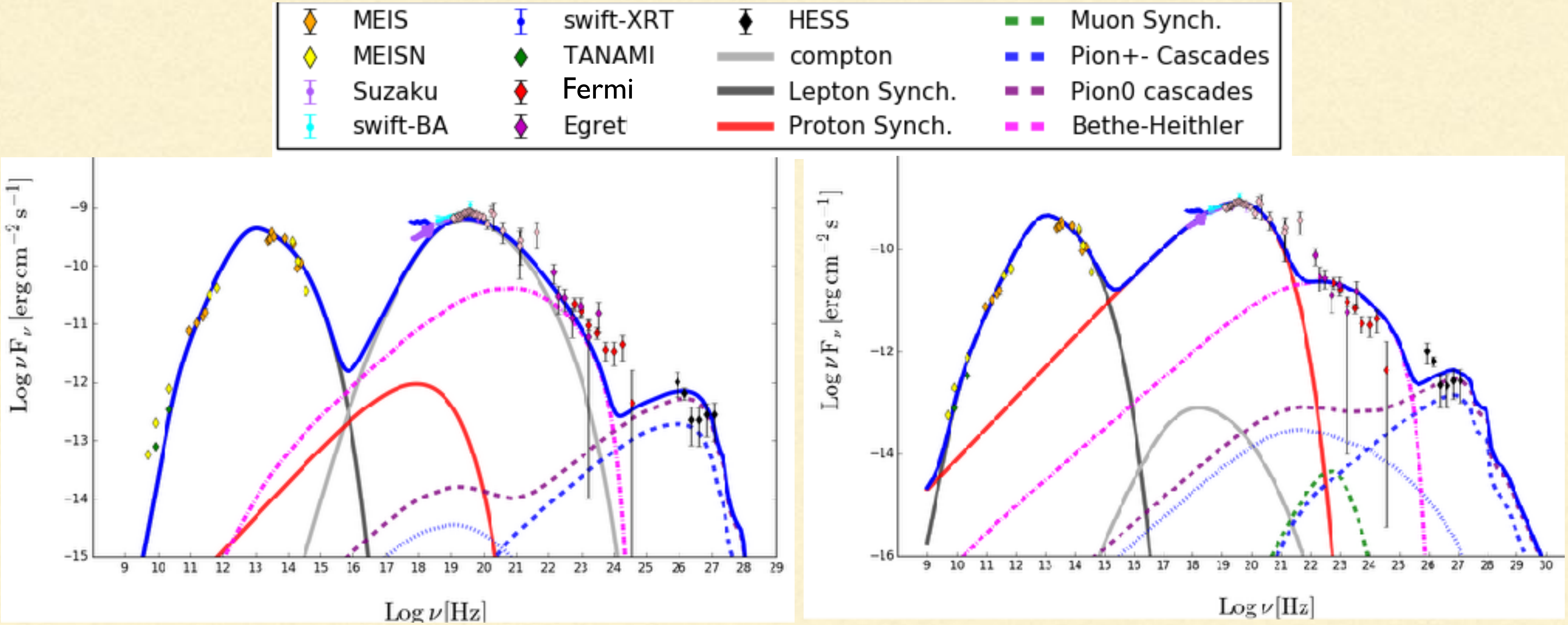
neutrinos from the radio-galaxy Centaurus A ?



γ-rays detected from the core of **Centaurus A** with Fermi-LAT (*95% containment radius :~green circle*) and H.E.S.S. (*best fit position, 1 σ : cross ; 95% containment radius : dashed line*)

Aharonian et al. (HESS) ApJ Lett. 695 (2009) L40-L44

neutrinos from the radio-galaxy Centaurus A ?



scenario 1 : lepto-hadronic model

X-rays and Fermi-LAT: SSC + Bethe Heitler

VHE: pair cascades

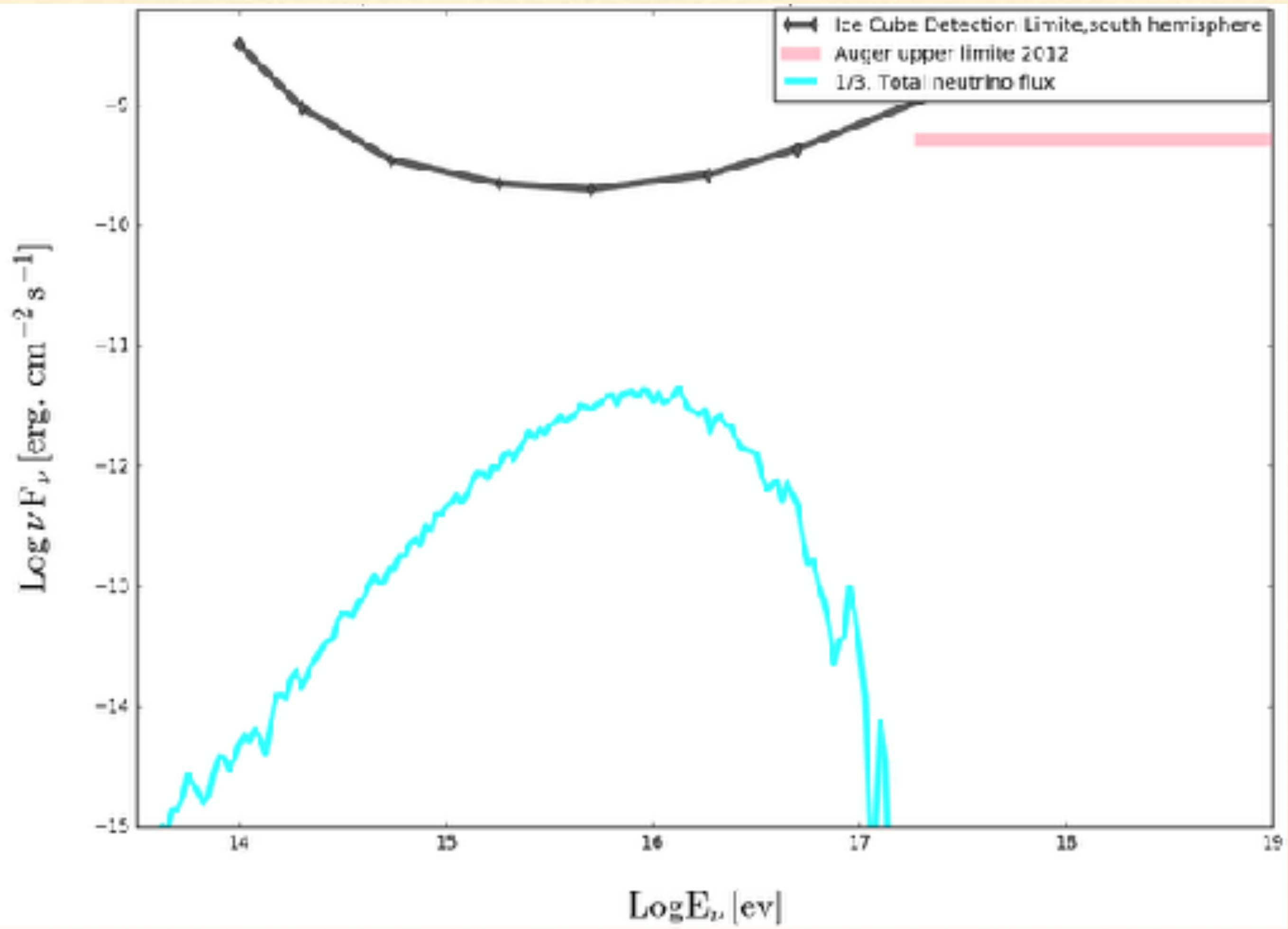
scenario 2 : hadronic model

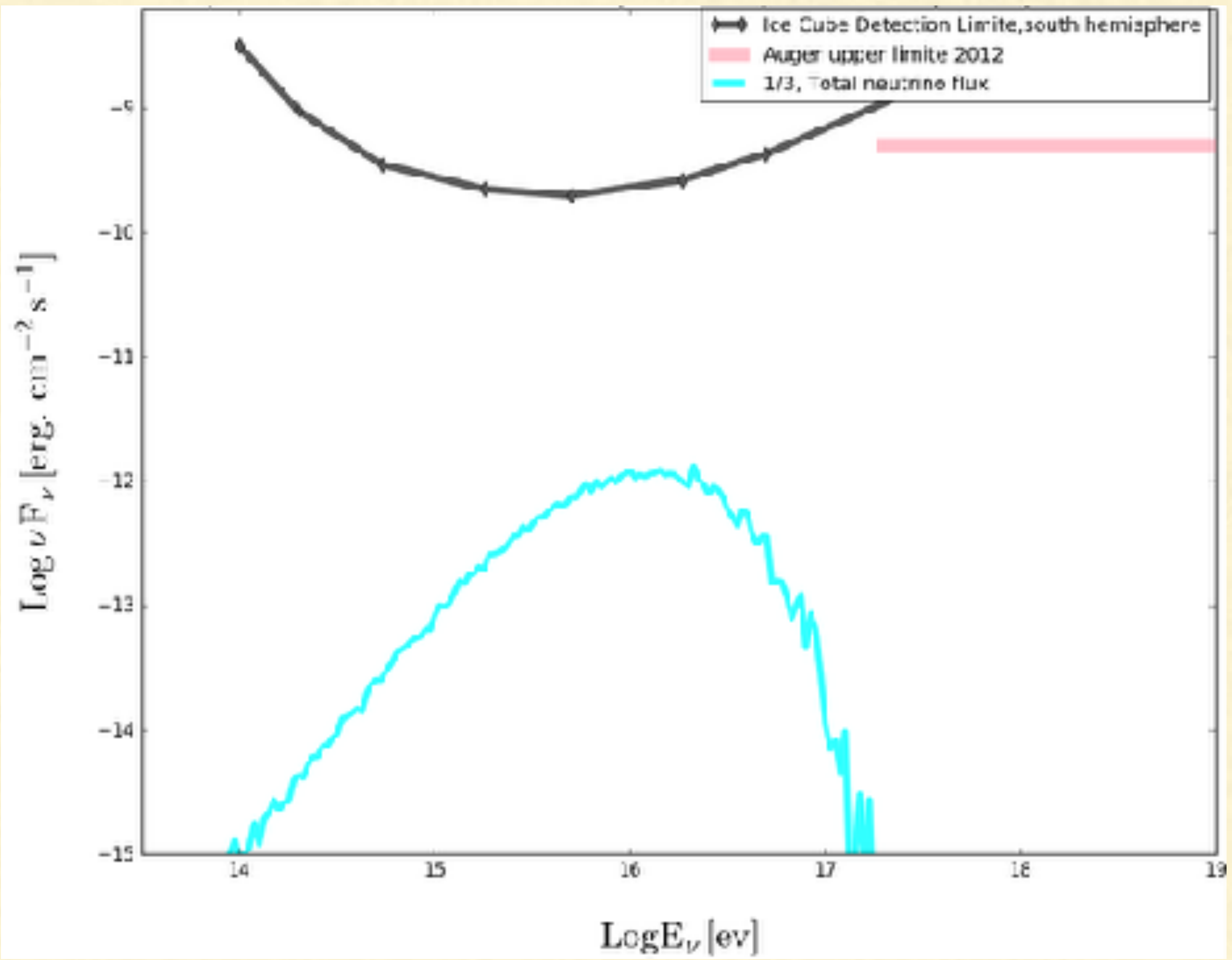
X-rays and Fermi-LAT:
proton synch + Bethe Heitler

VHE: pair cascades

Cerruti, Zech, Emery, Guarin, Proc. of Gamma 2016 (astro-ph 1610.00255)

neutrinos from the radio-galaxy Centaurus A ?



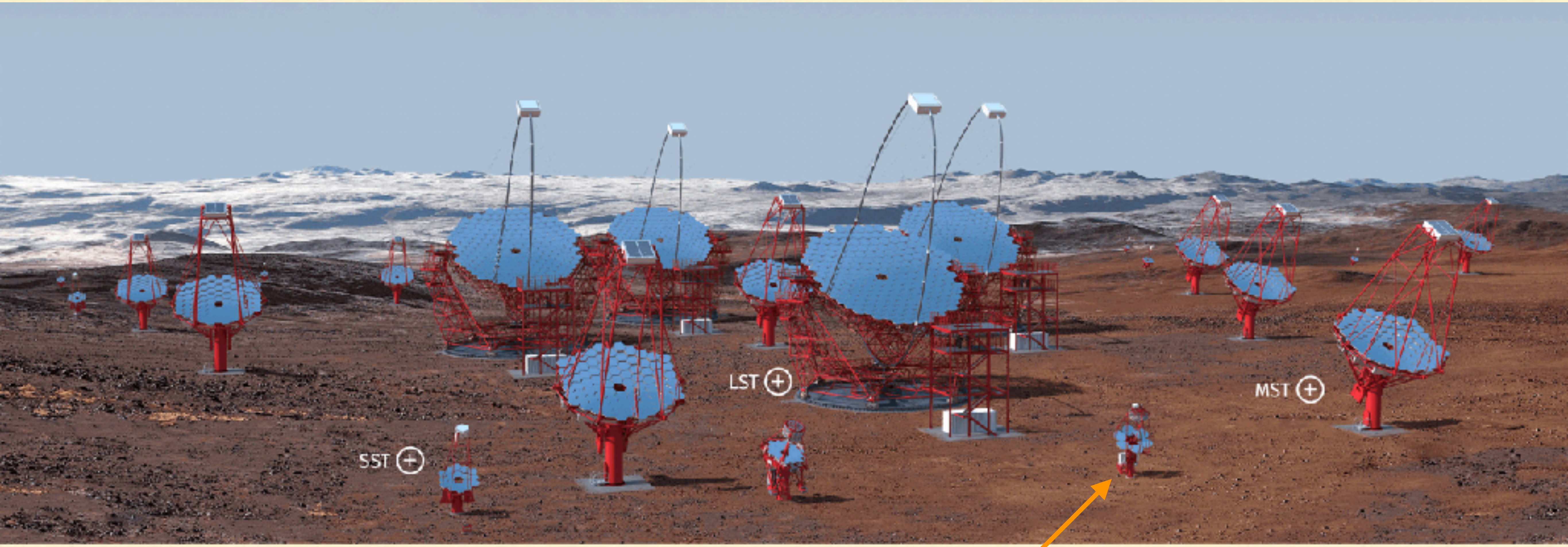


Very-high-energy neutrino flux peaks around 10^16 eV.

A factor ~10 to 100 below IceCube 4yr sensitivity curve for these scenarios.

Cerruti, Zech, Emery, Guarin, Proc. of Gamma 2016 (astro-ph 1610.00255)

What to expect from CTA ?



CTA Key Science Projects

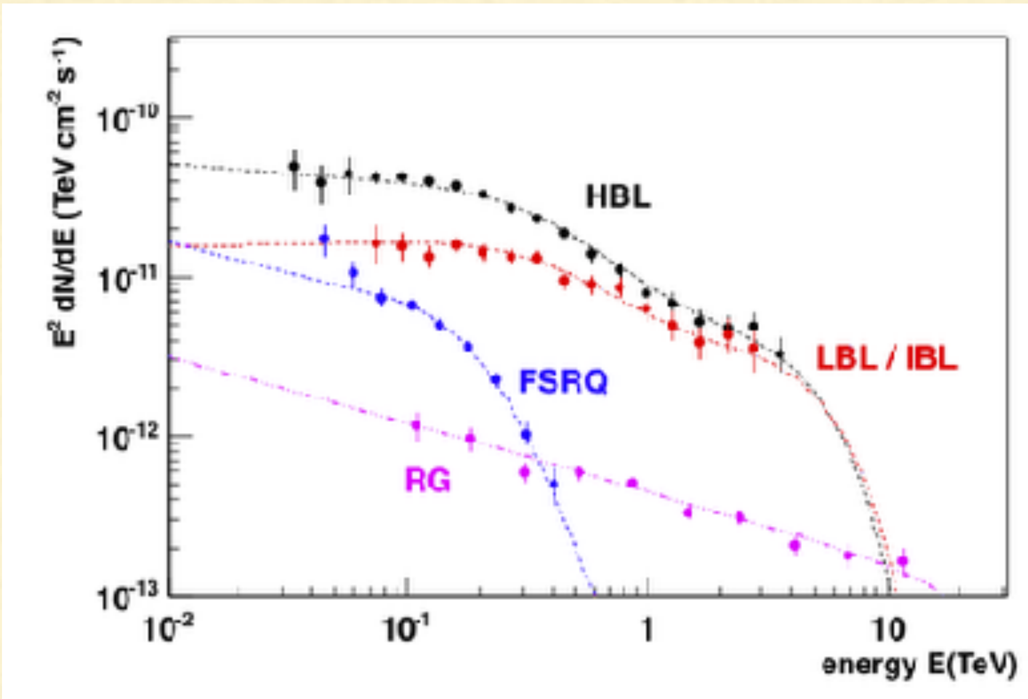
- Galactic Centre
- Galactic Plane Survey
- Cosmic Ray PeVatrons
- LMC Survey

- Extragalactic Survey
- Transients
- Active Galactic Nuclei
- Clusters of Galaxies

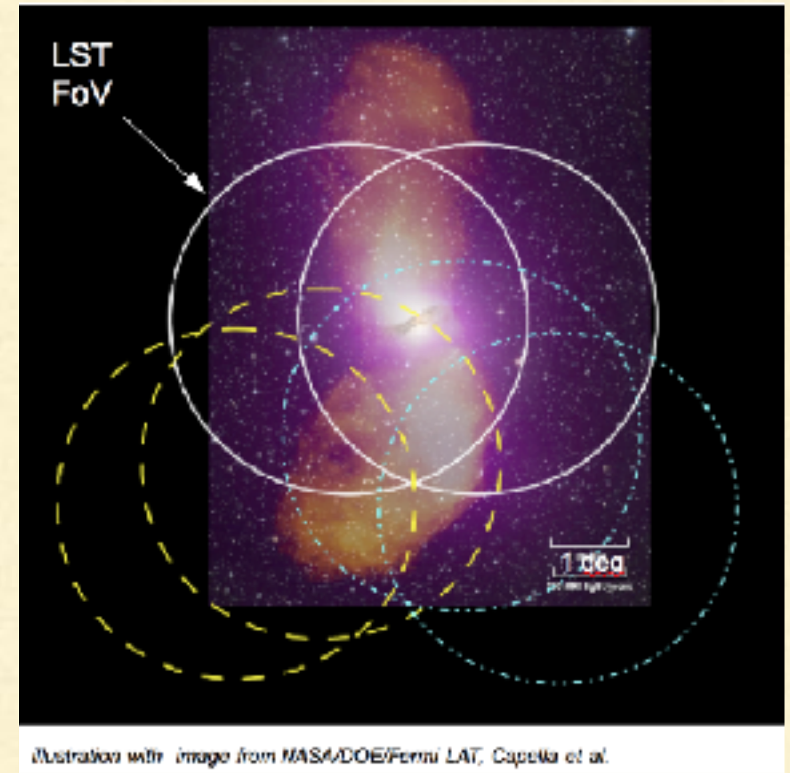
- Star Forming Systems

- Dark Matter Programme

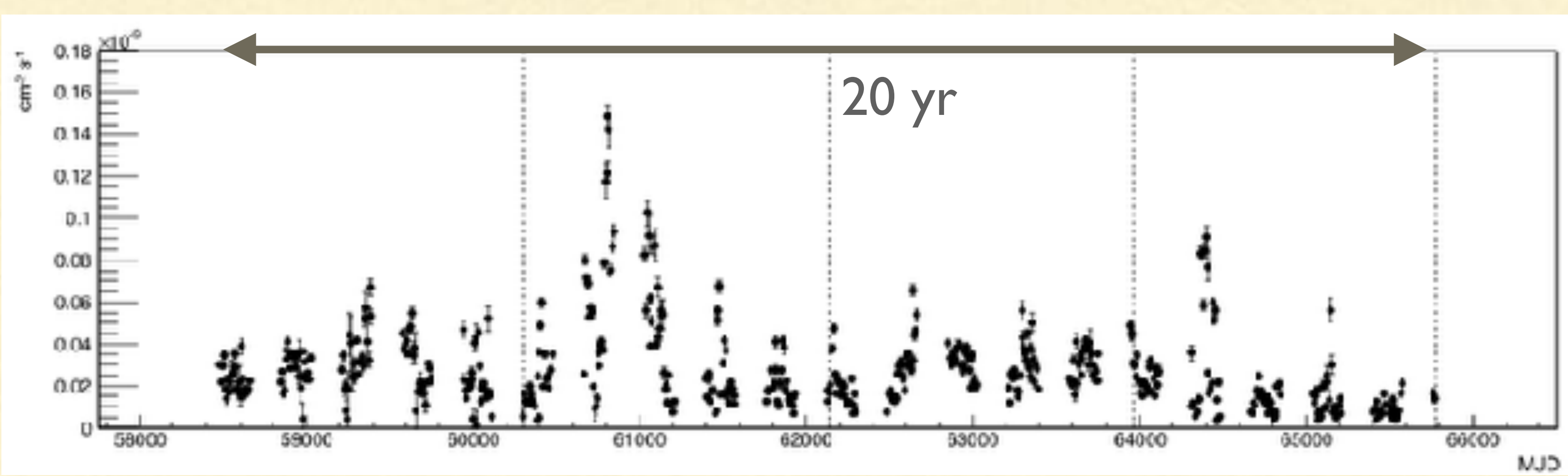
The AGN Key Science Project



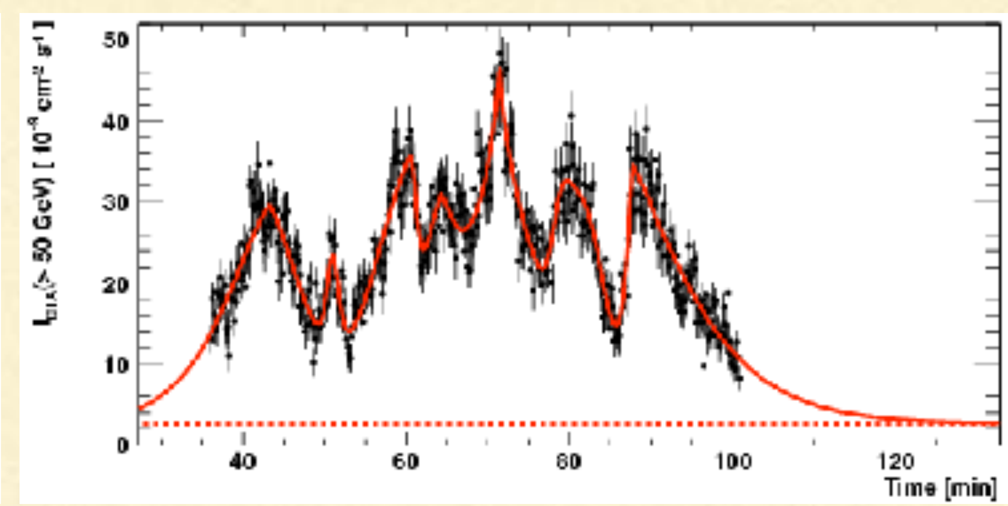
high-quality spectra (pointed observations)



radio-galaxy scan (Cen A & M 87)

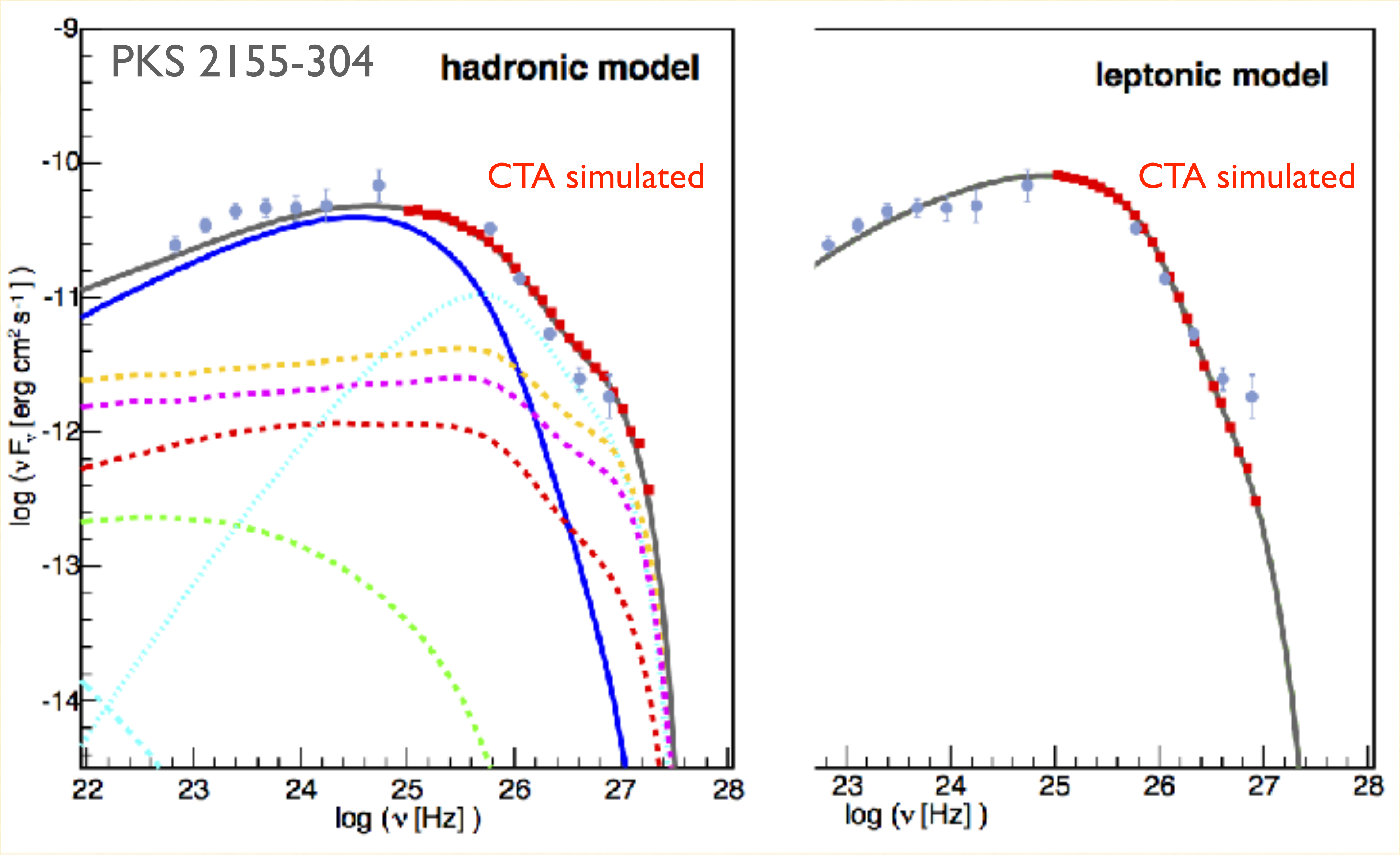


long-term monitoring



flare programme

e.g. high-quality spectra programme : spectral signatures in blazars



This specific simulation was done for 33 hr of observations.
With 50 - 100 hr of observations one should be able to distinguish hadronic vs. leptonic one-zone models over the whole acceptable parameter range.

Zech, Cerruti, Mazin, A&A 602 (2017) 25

Outlook

- Source-by-source studies with hadronic emission models allow to predict a range for the expected neutrino flux, instead of an average (often optimistic) value.
- to be done : need to include external photon fields in our model (work in progress with M. Cerruti) for application to FSRQs.
- Finding hadronic signatures in blazars (or constraining them) might be our best chance to find the origin of ultra-high energy cosmic rays and astro-neutrinos.