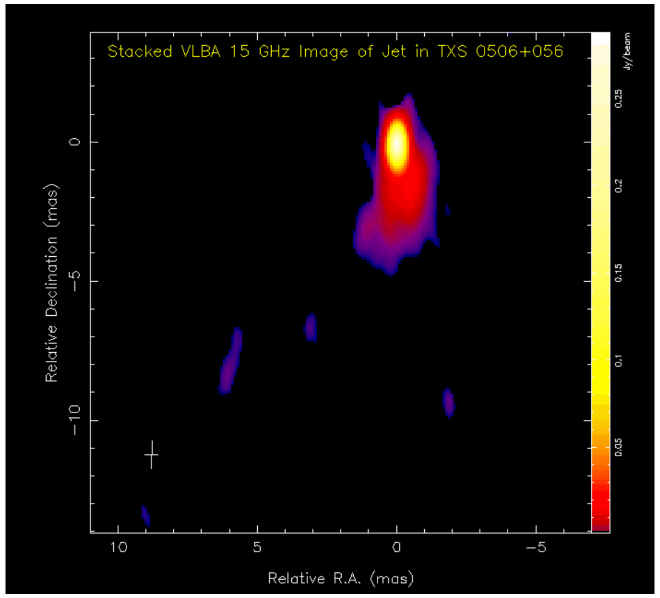
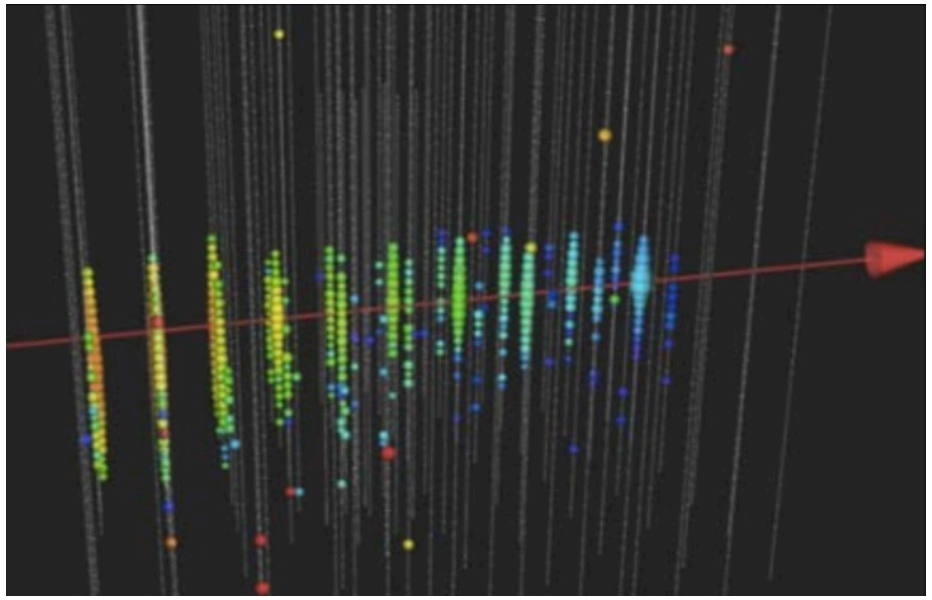
Modelling the electromagnetic and neutrino flux for the IceCube candidate source TXS 0506+056





Andreas Zech (LUTH, Observatoire de Paris)
& M. Cerruti[1], G. Emery[1], S. Inoue [3], J.P. Lenain[1] and C. Boisson[2]

1 Sorbonne Université, Université Paris Diderot, Sorbonne Paris Cité, CNRS/IN2P3, LPNHE, Paris, France
2 LUTH, Observatoire de Paris, PSL Research University, CNRS, Université Paris Diderot, Meudon, France
3 RIKEN Institute, Tokyo, Japan

Half a Century of Blazars and Beyond
Torino, Italy, June 2018

l'Observatoire de Paris — LUTH
Laboratoire de l'Univers et de ses Théories
LPNHE Paris
RIKEN

Outline

- TXS 0506+056 - the first high-energy neutrino source ?
- LEHA - a lepto-hadronic one-zone emission model
- Proton-synchrotron solutions for TXS 0506+056
- Mixed lepto-hadronic solutions for TXS 0506+056
- Conclusions

TXS 0506+056 - the first high-energy neutrino source ?

TXS 0506+056 - first high-energy neutrino source ?

TITLE: GCN CIRCULAR
NUMBER: 21916
SUBJECT: IceCube-170922A - IceCube observation of a high-energy neutrino candidate event
DATE: 17/09/23 01:09:26 GMT
FROM: Erik Blaufuss at U. Maryland/IceCube <blaufuss@icecube.umd.edu>

Claudio Kopper (University of Alberta) and Erik Blaufuss (University of Maryland) report on behalf of the IceCube Collaboration (http://icecube.wisc.edu/).

On 22 Sep, 2017 IceCube detected a track-like, very-high-energy event with a high probability of being of astrophysical origin. The event was identified by the Extremely High Energy (EHE) track event selection. The IceCube detector was in a normal operating state. EHE events typically have a neutrino interaction vertex that is outside the detector, produce a muon that traverses the detector volume, and have a high light level (a proxy for energy).

After the initial automated alert (https://gcn.gsfc.nasa.gov/notices_amon/50579430_130033.amon), more sophisticated reconstruction algorithms have been applied offline, with the direction refined to:

Date: 22 Sep, 2017
Time: 20:54:30.43 UTC
RA: 77.43 deg (-0.80 deg/+1.30 deg 90% PSF containment) J2000
Dec: 5.72 deg (-0.40 deg/+0.70 deg 90% PSF containment) J2000

We encourage follow-up by ground and space-based instruments to help identify a possible astrophysical source for the candidate neutrino.

The IceCube Neutrino Observatory is a cubic-kilometer neutrino detector operating at the geographic South Pole, Antarctica. The IceCube realtime alert point of contact can be reached at roc@icecube.wisc.edu

TXS 0506+056 - first high-energy neutrino source ?

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H.E.S.S. follow-up of IceCube-170922A

ATel #10787; ***Mathieu de Naurois for the H. E.S. S. collaboration***
on ***27 Sep 2017; 14:33 UT***
Credential Certification: Fabian SchÃÂ¼ssler (fabian.schussler@cea.fr)

Subjects: VHE, Neutrinos

Referred to by ATel #: 10799, 10817, 10830, 10833, 10844

Tweet Recommend 2

The H.E.S.S. array of imaging atmospheric Cherenkov telescopes was used to carry out follow-up observations of a high-energy neutrino detected by IceCube on 22 September 2017 at 20:54:30.43 UTC. H.E.S.S. observed the region around the IceCube best fit position (RA=77.43 deg, Dec=5.72 deg; GCN circular #21916) in two consecutive nights for about 1h each. First observations started 23 September 2017 at 01:05 UTC (about 4h after the neutrino detection). A second set of observations were obtained the following night (24 September 2017 at 03:10 UTC). A preliminary on-site calibration and analysis searching for a point-like gamma-ray source from within the 90% uncertainty region of the neutrino event IceCube-170922A revealed no significant detection. H.E.S.S. is an array of five imaging atmospheric Cherenkov telescopes for the detection of very-high-energy gamma-ray sources and is located in the Khomas Highlands in Namibia. It was constructed and is operated by researchers from Armenia, Australia, Austria, the Czech Republic, France, Germany, Ireland, Netherlands, Japan, Poland, South Africa, Sweden, UK, and the host country, Namibia.

TXS 0506+056 - first high-energy neutrino source ?

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Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.

ATel #10791; *Yasuyuki T. Tanaka (Hiroshima University), Sara Buson (NASA/GSFC), Daniel Kocevski (NASA/MSFC) on behalf of the Fermi-LAT collaboration*
on 28 Sep 2017; 10:10 UT
Credential Certification: David J. Thompson (David.J.Thompson@nasa.gov)

Subjects: Gamma Ray, Neutrinos, AGN

Referred to by ATel #: 10792, 10794, 10799, 10801, 10817, 10830, 10831, 10833, 10838, 10840, 10844, 10845, 10861, 10890, 10942

Tweet Recommend 3

We searched for Fermi-LAT sources inside the extremely high-energy (EHE) IceCube-170922A neutrino event error region (https://gcn.gsfc.nasa.gov/gcn3/21916.gcn3, see also ATels 10773, 10787) with all-sky survey data from the Large Area Telescope (LAT), on board the Fermi Gamma-ray Space Telescope. We found that one Fermi-LAT source, TXS 0506+056 (3FGL J0509.4+0541 and also included in the 3FHL catalog, Ajello et al., arXiv:1702.00664, as 3FHL J0509.4+0542), is located inside the IceCube error region. The FAVA (Fermi All-sky Variability Analysis) light curve at energies above 800 MeV shows a flaring state recently (https://fermi.gsfc.nasa.gov/ssc/data/access/lat/FAVA/SourceReport.php?week=477&flare=27). Indeed, the LAT 0.1--300 GeV flux during 2018 September 15 to 27 was (3.6+/-0.5)E-7 photons

TXS 0506+056 - first high-energy neutrino source ?

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10794, 10799, 10801, 10817, 10830, 10831, 10833, 10838, 10840, 0942

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First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A

ATel #10817; ***Razmik Mirzoyan for the MAGIC Collaboration***
on 4 Oct 2017; 17:17 UT
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

Subjects: Optical, Gamma Ray, >GeV, TeV, VHE, UHE, Neutrinos, AGN, Blazar

Referred to by ATel #: 10830, 10833, 10838, 10840, 10844, 10845, 10942

Tweet   Recommend 448

After the IceCube neutrino event EHE 170922A detected on 22/09/2017 (GCN circular #21916), Fermi-LAT measured enhanced gamma-ray emission from the blazar TXS 0506+056 (05 09 25.96370, +05 41 35.3279 (J2000), [Lani et al., Astron. J., 139, 1695-1712 (2010)]), located 6 arcmin from the EHE 170922A estimated direction (ATel #10791). MAGIC observed this source under good weather conditions and a 5 sigma detection above 100 GeV was achieved after 12 h of observations from September 28th till October 3rd. This is the first time that VHE gamma rays

TXS 0506+056 - first high-energy neutrino source ?

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on 27 Sep 2017; 14:33 UT
Credential Certification: Fabian SchÃÂ¼ssler (fabian.s

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ATel #10817; *Razmik Mirzoyan for the MAGIC Co*
on 4 Oct 2017; 17:17 UT

AGILE confirmation of gamma-ray activity from the IceCube-170922A error region

ATel #10801; *F. Lucarelli (SSDC/ASI and INAF/OAR), G. Piano (INAF/IAPS), C. Pittori, F. Verrecchia (SSDC/ASI and INAF/OAR), M. Tavani (INAF/IAPS, and Univ. Roma Tor Vergata), A. Bulgarelli (INAF/IASF-Bo), P. Munar-Adrover, G. Minervini,*

VERITAS follow-up observations of Ice(event 170922A

ATel #10833; *Reshmi Mukherje*
on 9 Oct 2017; 22:32 UT
Credential Certification: Reshmi Mukherjee (muk@c

Joint Swift XRT and NuSTAR Observations of TXS 0506+056

ATel #10845; *D. B. Fox (PSU), J. J. DeLaunay (PSU), A. Keivani (PSU), P. A. Evans (U. Leicester), C. F. Turley (PSU), J. A. Kennea (PSU), D. F. Cowen (PSU), J. P. Osborne (U. Leicester), M. Santander (UA) & F. E. Marshall (GSFC)*
on 12 Oct 2017; 16:54 UT
Credential Certification: Derek B. Fox (dfox@astro.psu.edu)

Subjects: X-ray, Gamma Ray, >GeV, TeV, Neutrinos, AGN, Blazar, Quasar

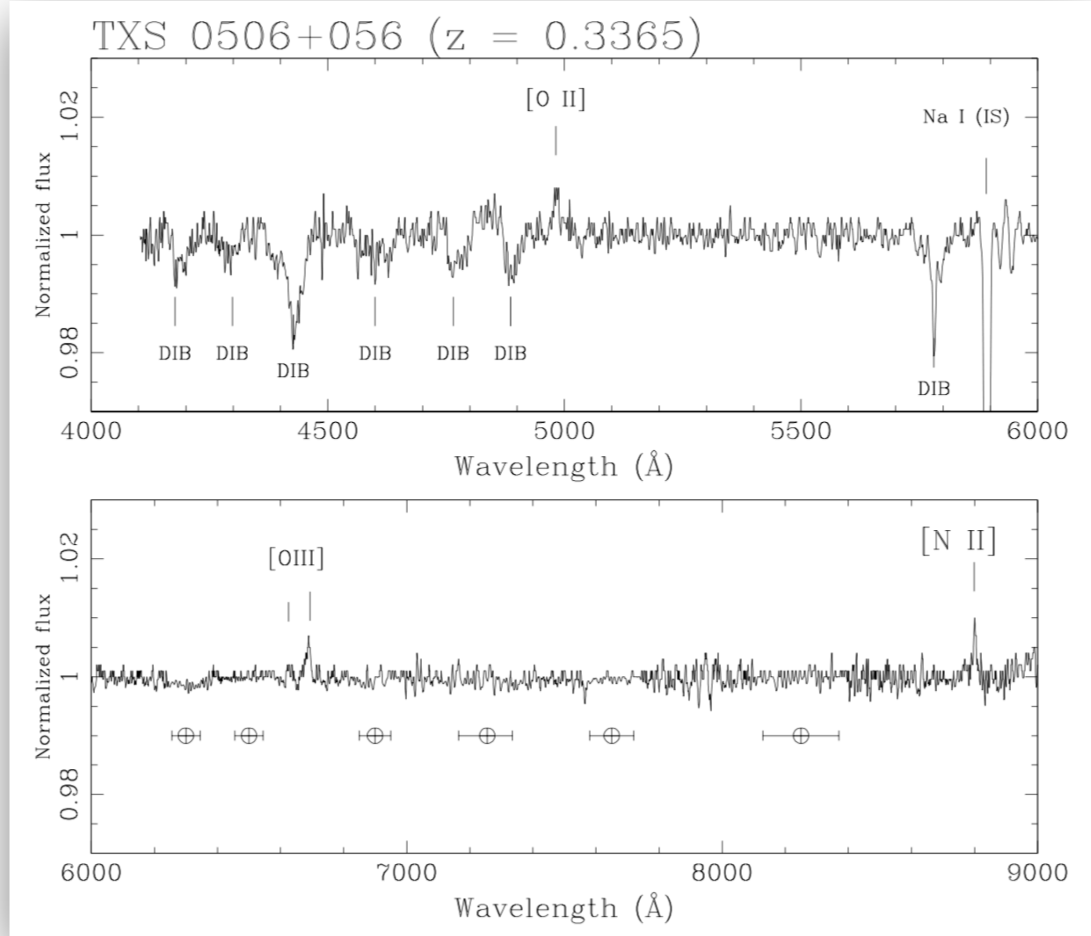
Referred to by ATel #: 10861

HAWC gamma ray data prior to Ice

ATel #10802; *Israel Martinez, Ignacio Taboada, Michelle the HAWC collaboration*
on 30 Sep 2017; 02:10 UT
Credential Certification: Ignacio Taboada (itaboa

TXS 0506+056 - first high-energy neutrino source ?

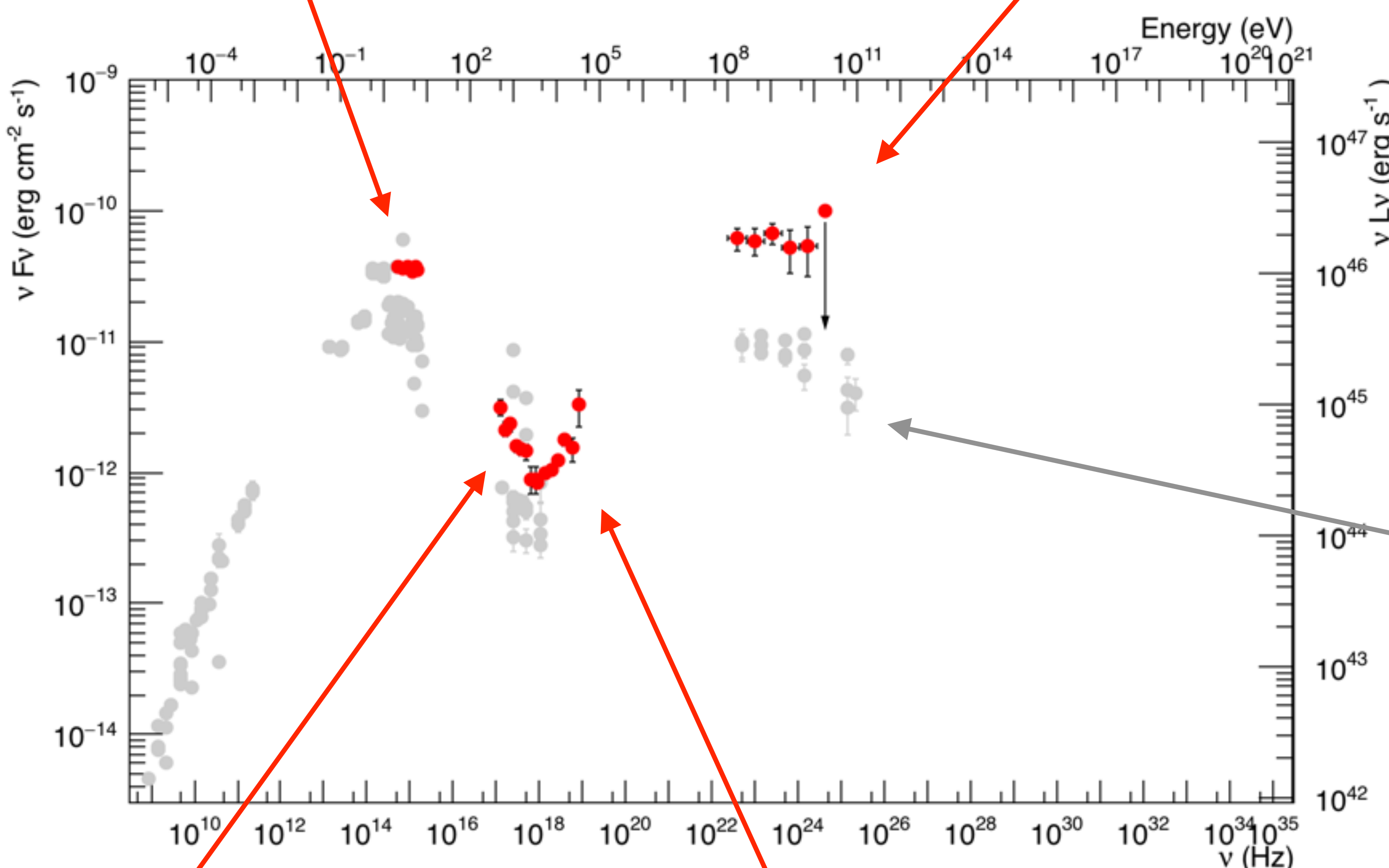
- IceCube alert for track-like VHE event (EHE sample) - most likely astrophysical muon neutrino, E > 100 TeV - on 22 sept. 2017
- arrival direction < 0.1 deg from the position of the BL Lac object TXS 0506+056 (constrained in about 1 deg^2)
- TXS 0506+056 was in a high state (flux up to 6 times that of low state seen with Fermi-LAT) from April - October 2017; detected also with AGILE
- First detection of VHE emission with MAGIC from 28 sept. to 4 oct. ; detected also with VERITAS
- recent redshift measurement z = 0.3365 +- 0.0010 (*Paiano et al. 2018* -> poster !)
- no determination of the black hole mass



Available data

SWIFT UVOT : V/U/B/W1/M2/W2 - flat spectrum (27/9/2017)

Fermi-LAT : 2.06 +- 0.08 (15 - 27/9/2017)



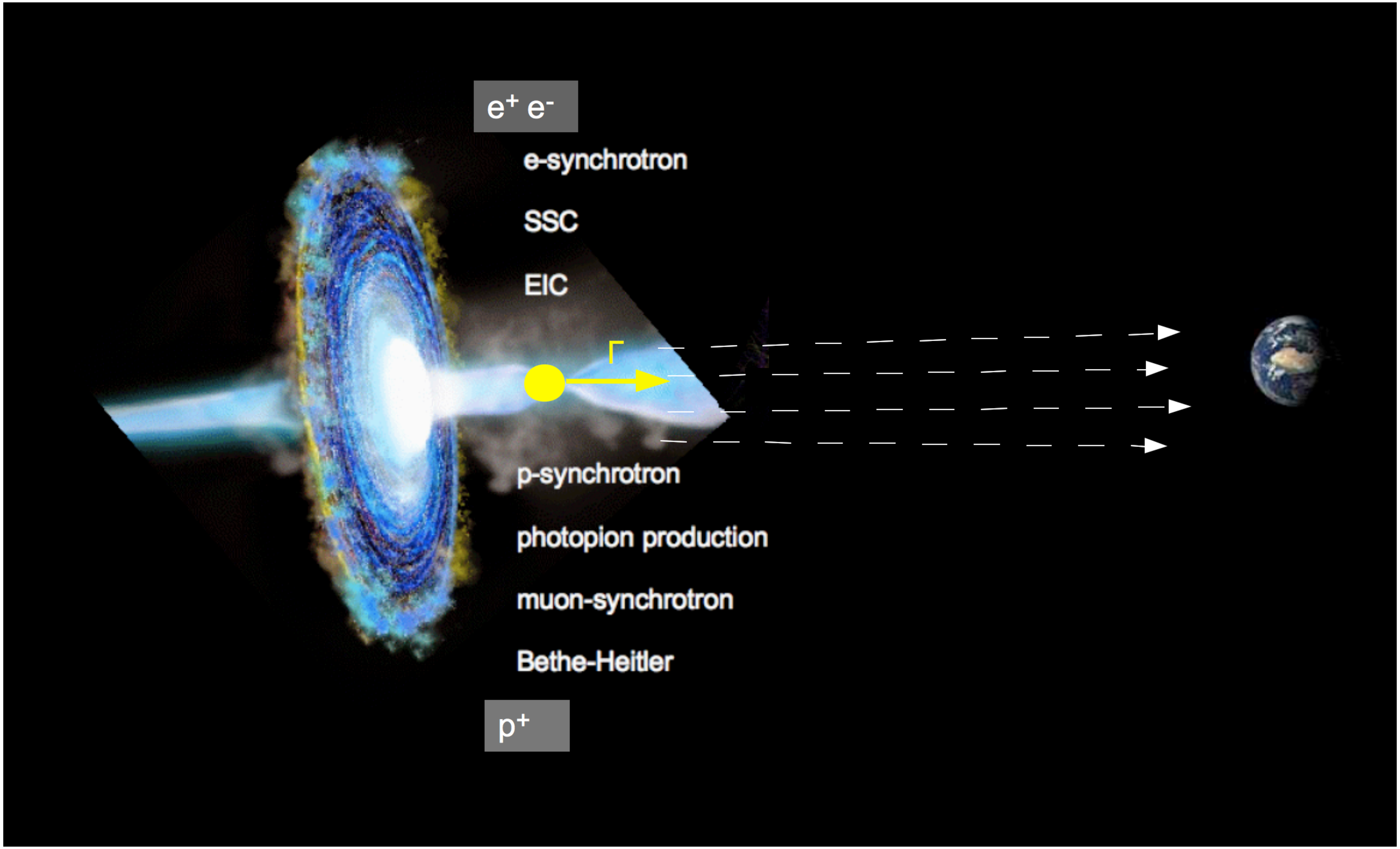
archival data (SSDC)

SWIFT XRT : power-law with index 2.58 +- 0.09 (27/9/2017)
PRELIMINARY

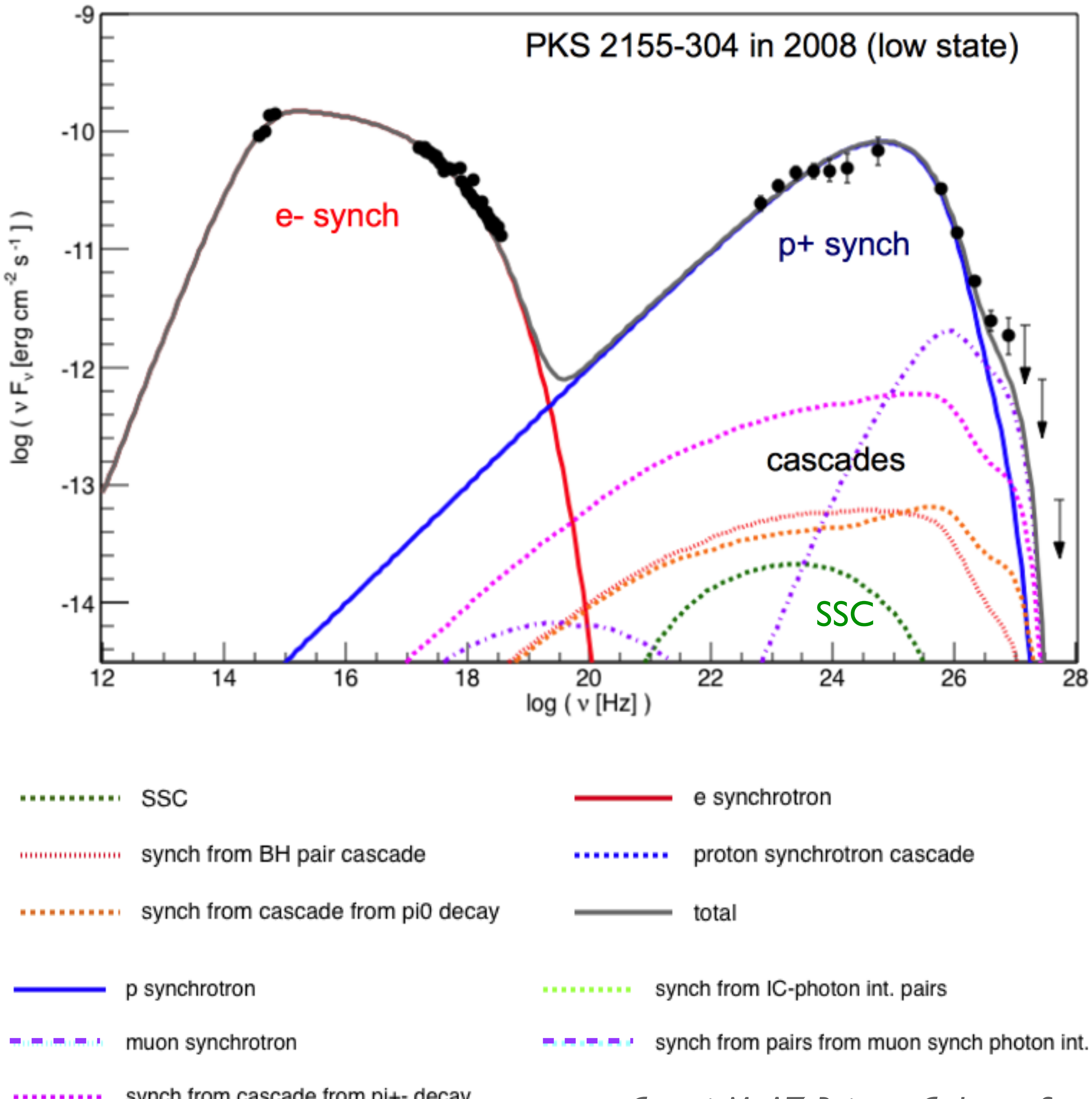
NuStar : power-law with index 1.59 +- 0.08 (29/9/2017)
PRELIMINARY (FPMA)

LEHA - a lepto-hadronic one-zone emission model

LEHA - a lepto-hadronic one-zone emission model



the "LEHA" code



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

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

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

- we usually impose **physical constraints:**

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

-- spectral breaks from synchrotron cooling.

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

-> 7 free parameters

-- verify variability time scale constraint:

$$R / \delta \leq c \, \Delta t_{obs} / (1+z)$$

-- verify jet power requirements

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

proton-photon interactions

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

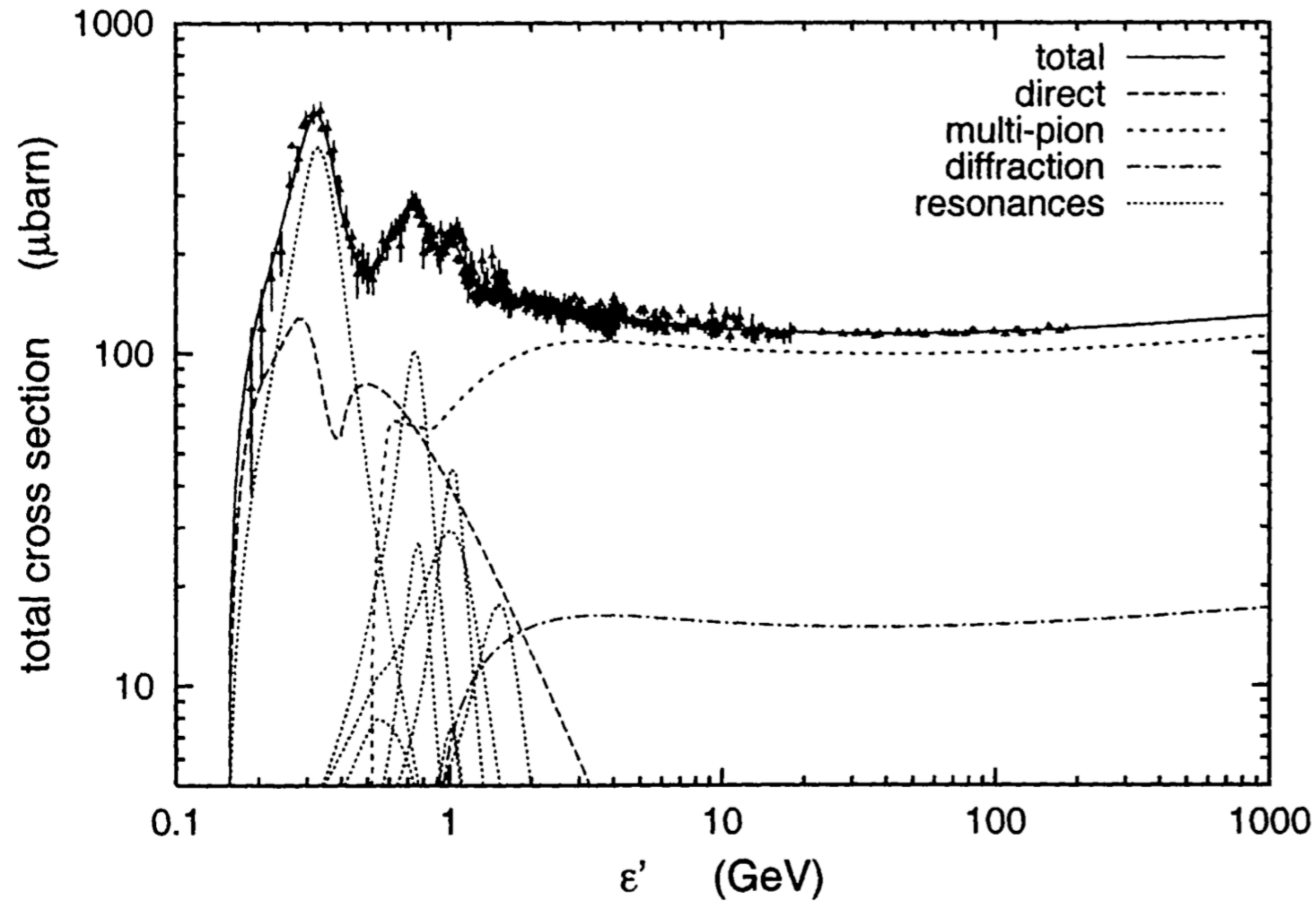
- treatment of all photopion production channels with resulting particle spectra (including ν spectra…)

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

Bethe-Heitler pair production (analytical) :
Kelner & Aharonian (2009)
+ cross-section *Blumenthal (1970).*

Leptons and gammas from proton-photon interactions have very high energies

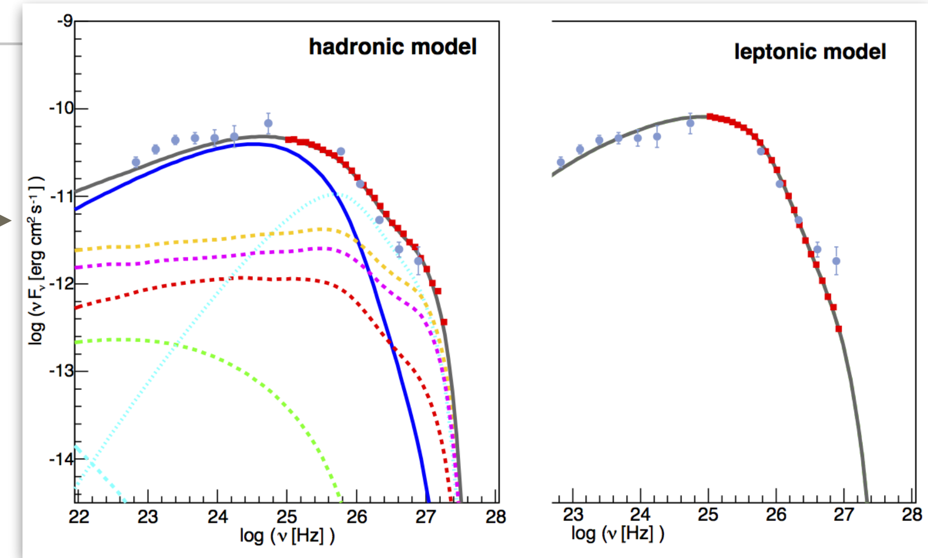
-> generate **synchrotron-pair cascades** through interactions with photon field

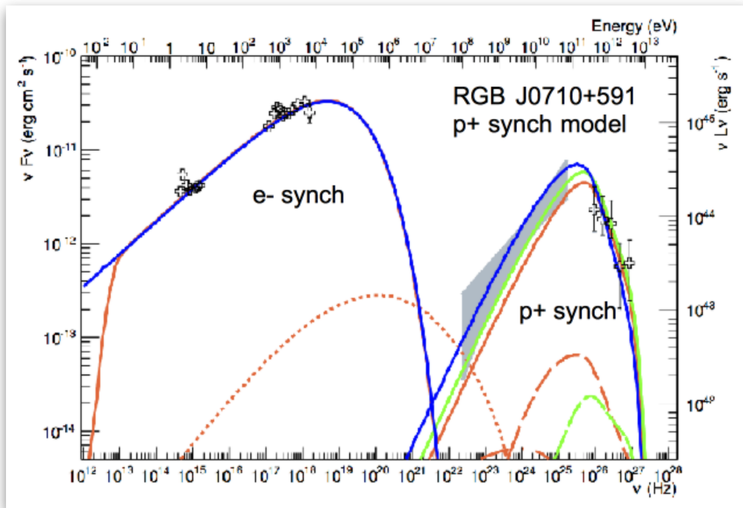


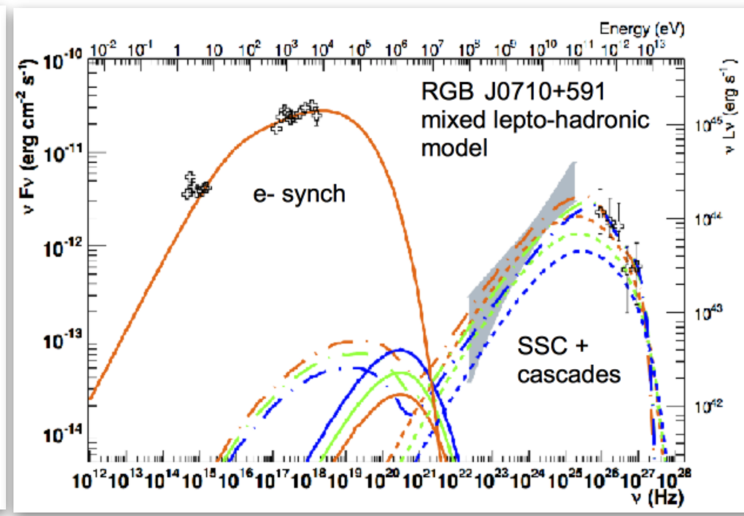
Mücke et al. 2000

Some applications of LEHA

Systematic exploration of hadronic solutions for PKS 2155-304 and Mrk 421 during low states & predictions for the CTA
AZ, Cerruti, Mazin, A&A 602 (2017) 25

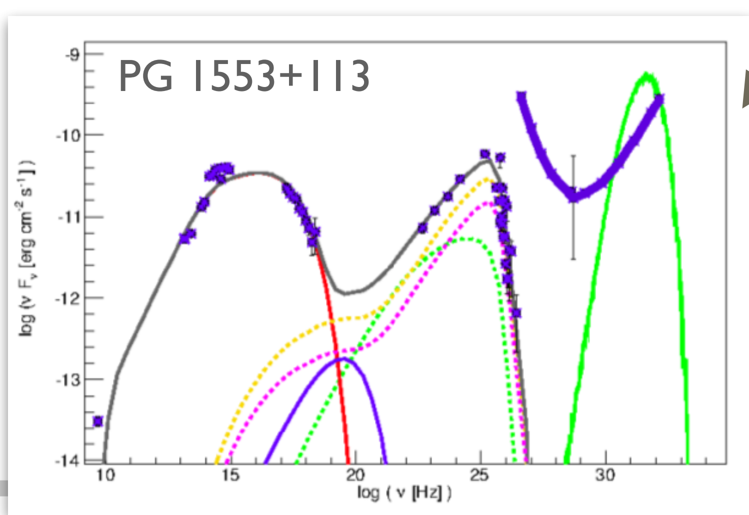




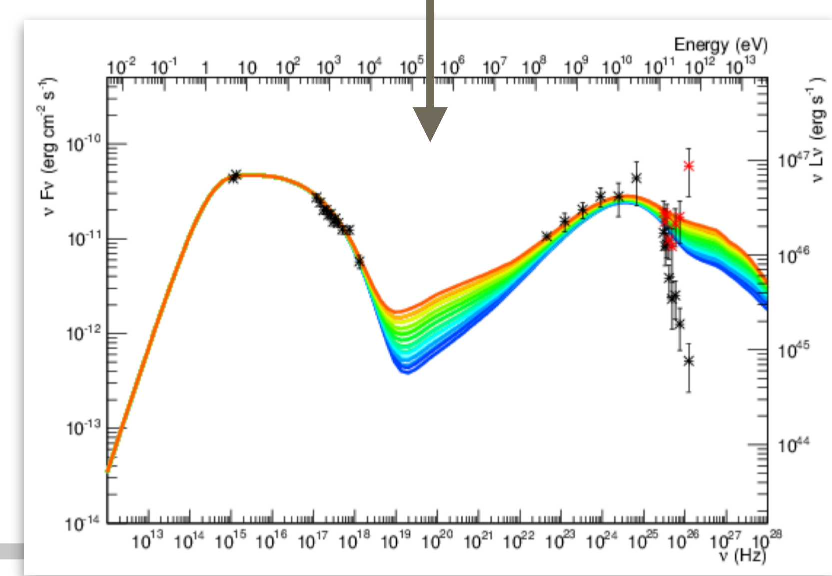


Proton-synchrotron and mixed lepto-hadronic solutions for extreme blazars
Cerruti, AZ, Boisson, Inoue, MNRAS 448 (2015) 910

Exploration of neutrino spectra for Centaurus A, PG 1553+113, PKS 2155-304
Cerruti, AZ, Emery, Guarin, Proc. of Gamma 2016 (astro-ph 1610.00255)

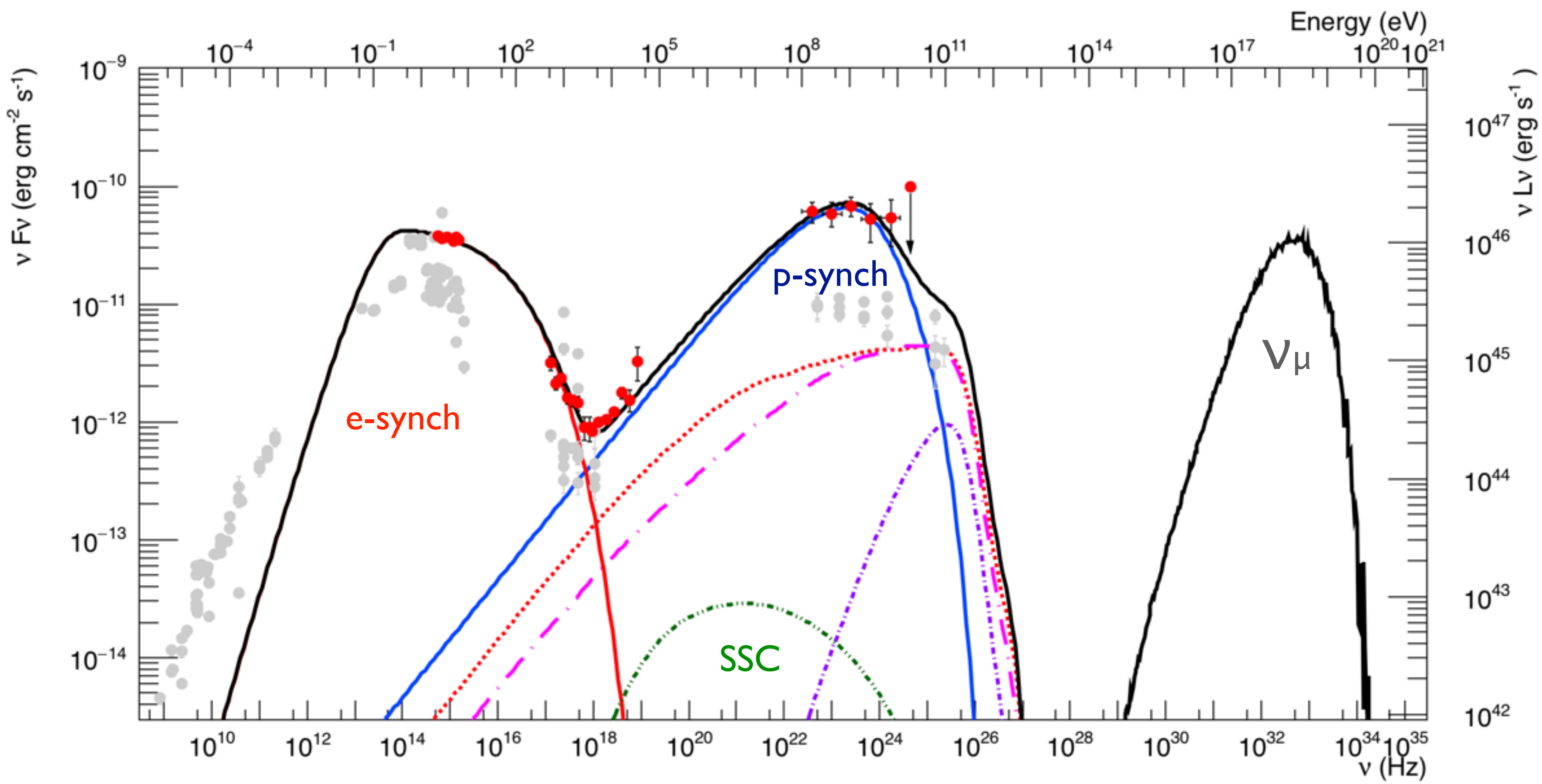


Lepto-hadronic models for the high-redshift BL Lac object PKS 1424+240
Cerruti, Benbow, Chen, et al. A&A 606 (2017) 68



Proton-synchrotron solutions for TXS 0506+056

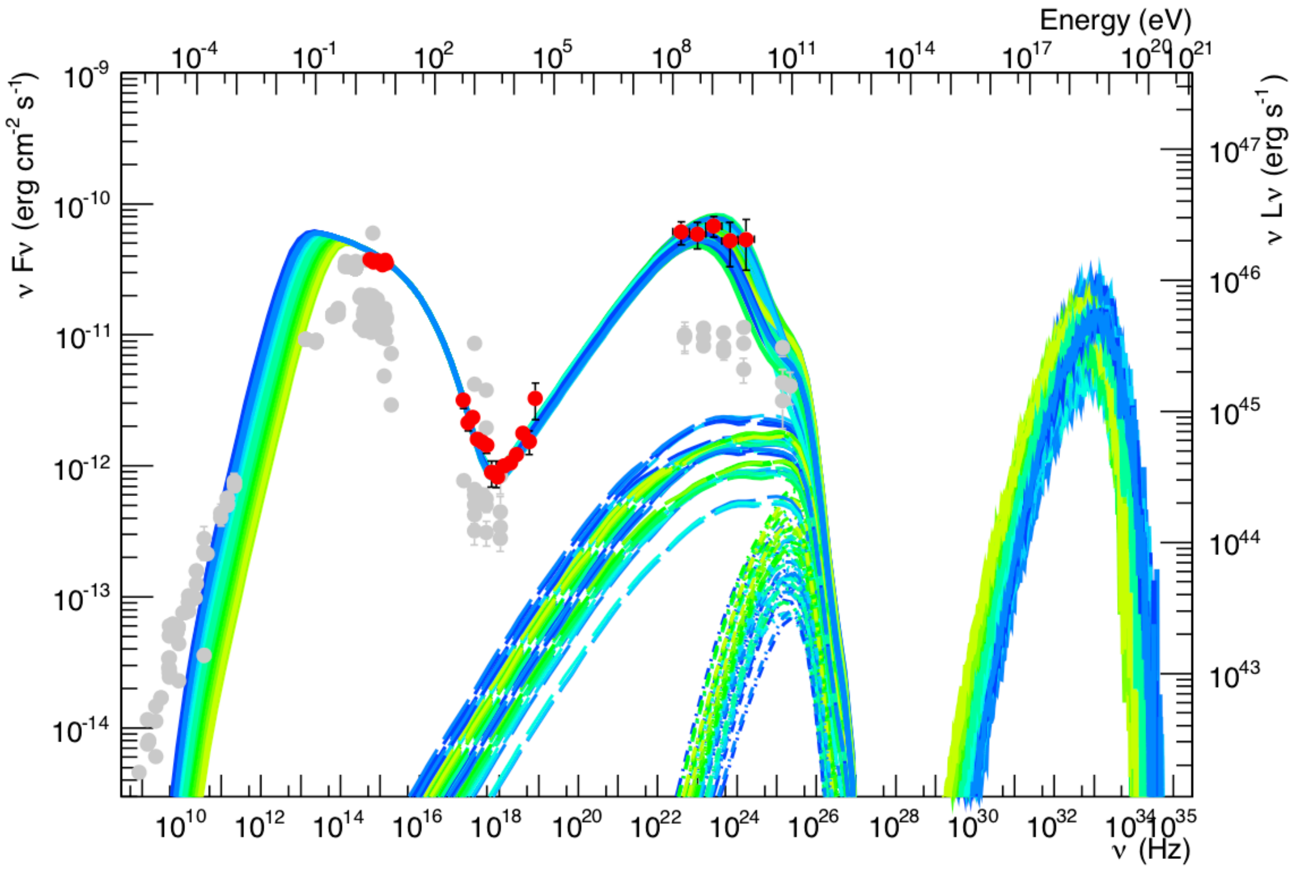
a hadronic (proton-synchrotron) interpretation for TXS 0506+056



δ = 30, R = 4.2e16 cm , B = 3 G , $\gamma_{p,max}$ = 1.7e9 , L_{jet} = 2.9e47 erg/s

Number of IceCube μ-neutrinos expected for 6 month high state : ~0.03
Poisson probability for detection of 1 muon-neutrino : ~3%

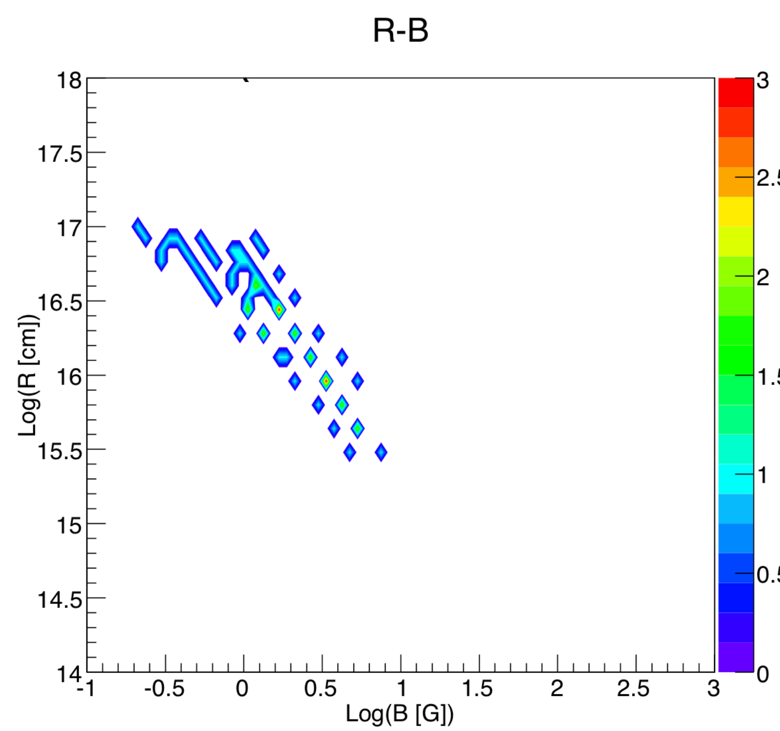
systematic exploration of proton-synchrotron solutions



z	0.3365
δ	30 – 50
R_src [1e16 cm]	0.3 – 9.7
τ_var [days]	0.03 – 1
B[G]	0.2 – 7.1
γ_e_min	200
α_e,1 = α_p,1	2
α_e,2 = α_p,2	3
γ_p_min	1
γ_p_max	2.3e+08 – 1.7e+09
*u_p/u_B	10 – 1038
L_jet [1e46 erg s^−1]	4 – 170

Scan of $\nu_{p,syn}$ in log-steps of 0.1 and Doppler factor in steps of 5.

-> satisfactory solutions for B-field values 0.5 G < B < 10 G



-> minimum jet power 4e46 erg/s

-> accommodates variability down to below day-scale

proton-synchrotron solutions : expected neutrino rate

- minimum and maximum expected rates for IceCube :

  0.003 − 0.053 μ-neutrinos / year

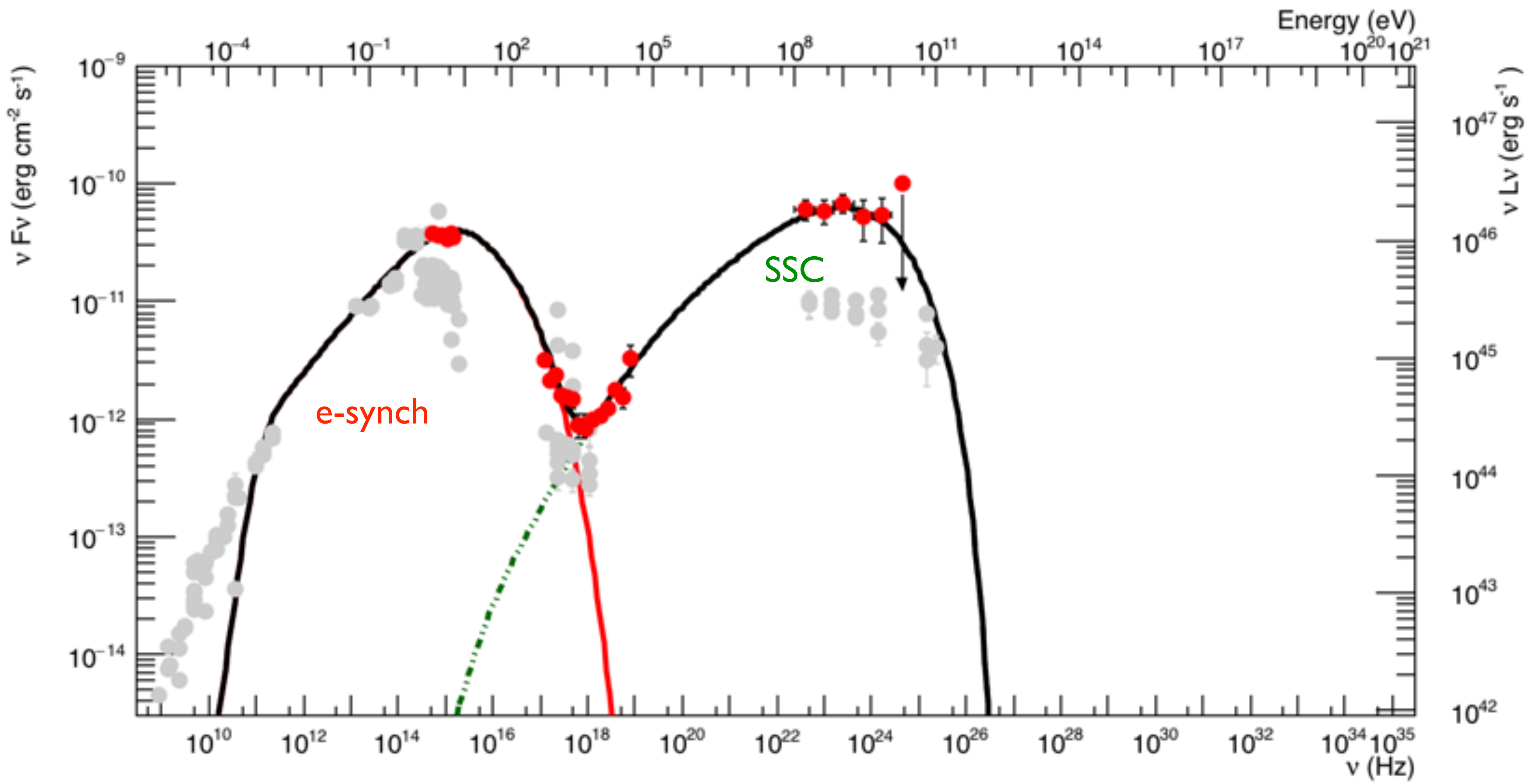
- Poisson probabilities for finding 1 μ-neutrino / 6 months given the flux estimations from the model:

  0.1% - 2.6%

-> Proton-synchrotron solutions are not favorable for a direct link with the IceCube event.

Mixed lepto-hadronic solutions for TXS 0506+056

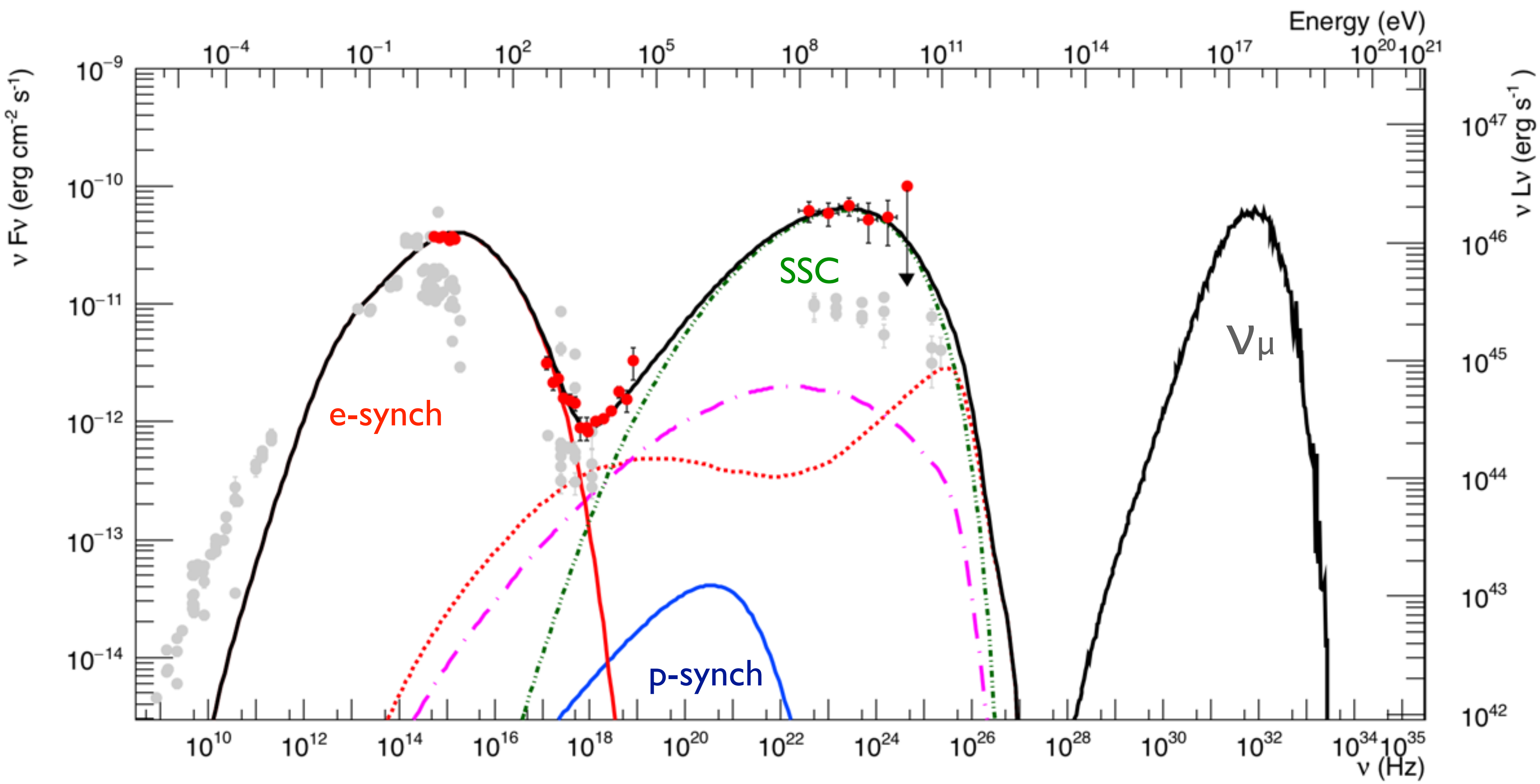
starting with a pure SSC interpretation



δ = 20 , R = 2.7e16 cm , B = 0.2 G , Np=0 , L_{jet} = 2e43 erg/s

Start from this solution, increase $\gamma_{min,e}$ (here =100), and add a hadronic component that is limited by the NuStar spectrum -> maximum hadronic contribution

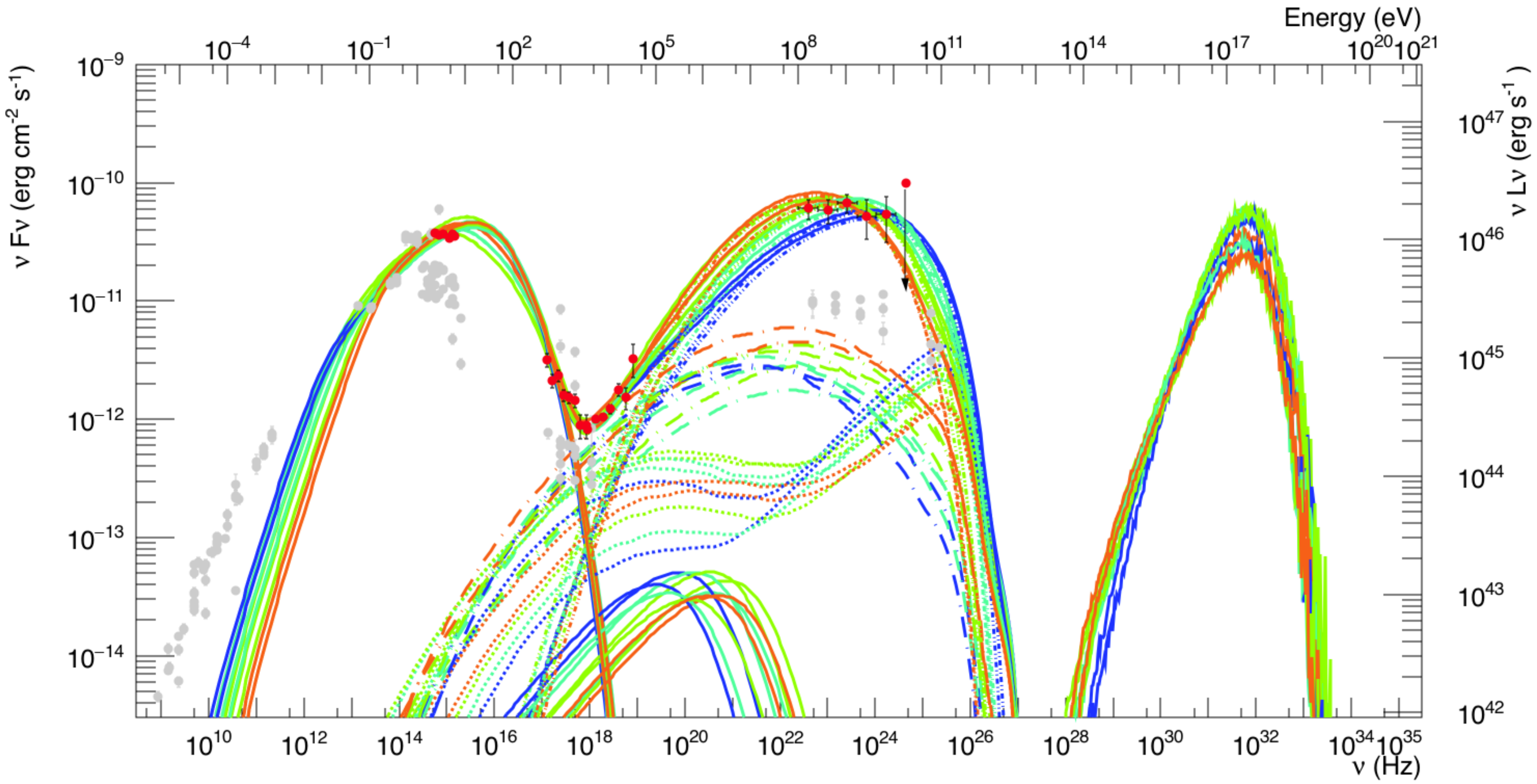
a lepto-hadronic interpretation for TXS 0506+056



$\delta = 20$, $R = 2.7e16$ cm , $B = 0.2$ G , $\gamma_{e,min} = 500$, $\gamma_{p,max} = 3.4e8$, $L_{jet} = 6.0e47$ erg/s

Number of IceCube μ-neutrinos expected for 6 month high state : ~0.18
Poisson probability for detection of 1 muon-neutrino : ~15%

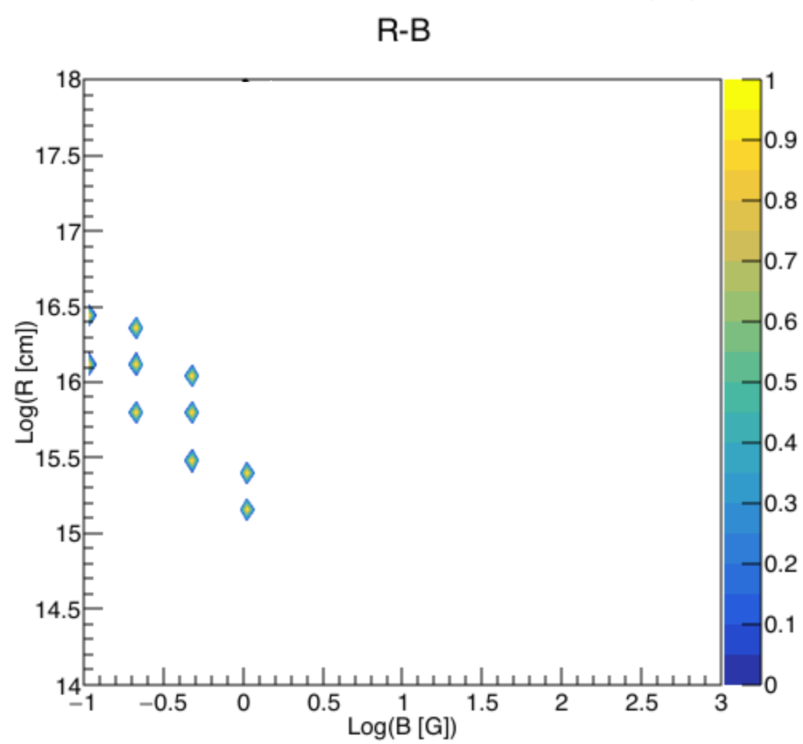
systematic exploration of mixed lepto-hadronic solutions



z	0.3365
δ	20 – 40
R_src [1e16 cm]	0.15 – 2.85
τ_var [days]	0.02 – 0.6
B[G]	0.1 – 1
γ_e_min	500
α_e,1 = α_p,1	2
α_e,2 = α_p,2	3
γ_p_min	1
γ_p_max	8.2e+07 – 3.3e+08
*u_p/u_B	1.7e4 – 6.3e5
L_jet [1e46 erg s^-1]	20 – 386

Tested four values for B-field and 3 values for Doppler factor.

-> satisfactory solutions for B-field values 0.1 G < B < 1 G



-> minimum jet power 2e47 erg/s

-> accommodates variability down to below day-scale

-> far out of equipartition

mixed lepto-hadronic solutions : expected neutrino rate

- minimum and maximum expected rates for IceCube :

  0.19 - 1.23 μ-neutrinos / year

- Poisson probabilities for finding 1 μ-neutrino / 6 months given the flux estimations from the model:

  9% - 33%

- Keep in mind that the lepto-hadronic scenario, the hadronic contribution and neutrino flux can be arbitrarily low, depending on $\gamma_{e,min}$

Conclusions

- The SED of TXS 0506+056 is rather well constrained (especially in X-rays).
- Proton-synchrotron scenario : good solutions for broad-band SED, but difficult to account for IceCube event.
- Mixed lepto-hadronic scenario : good solutions for broad-band SED; accounts well for Ice Cube event.
- Waiting for more details on Ice Cube events and on VHE data…

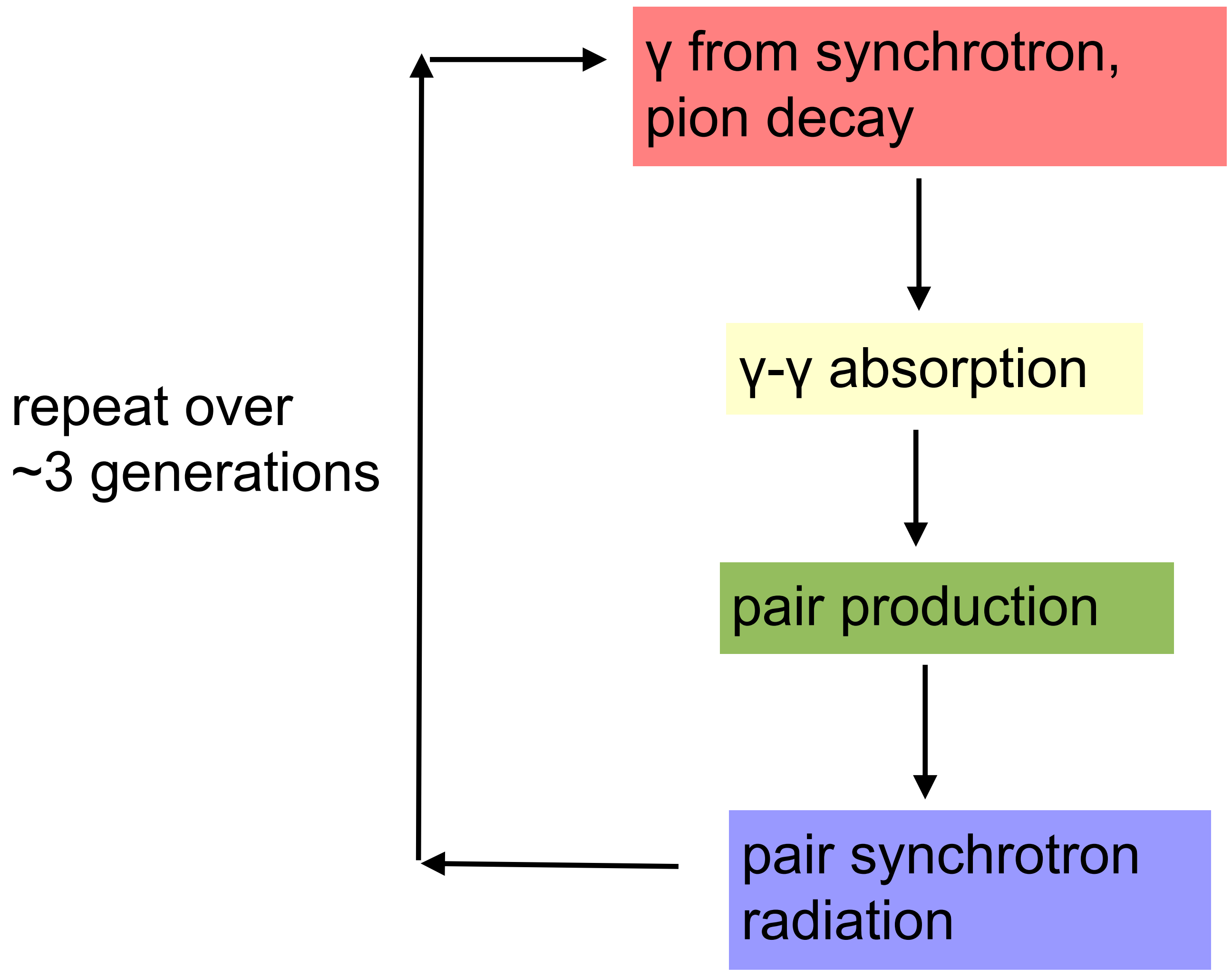
Thank You !

treatment of cascades

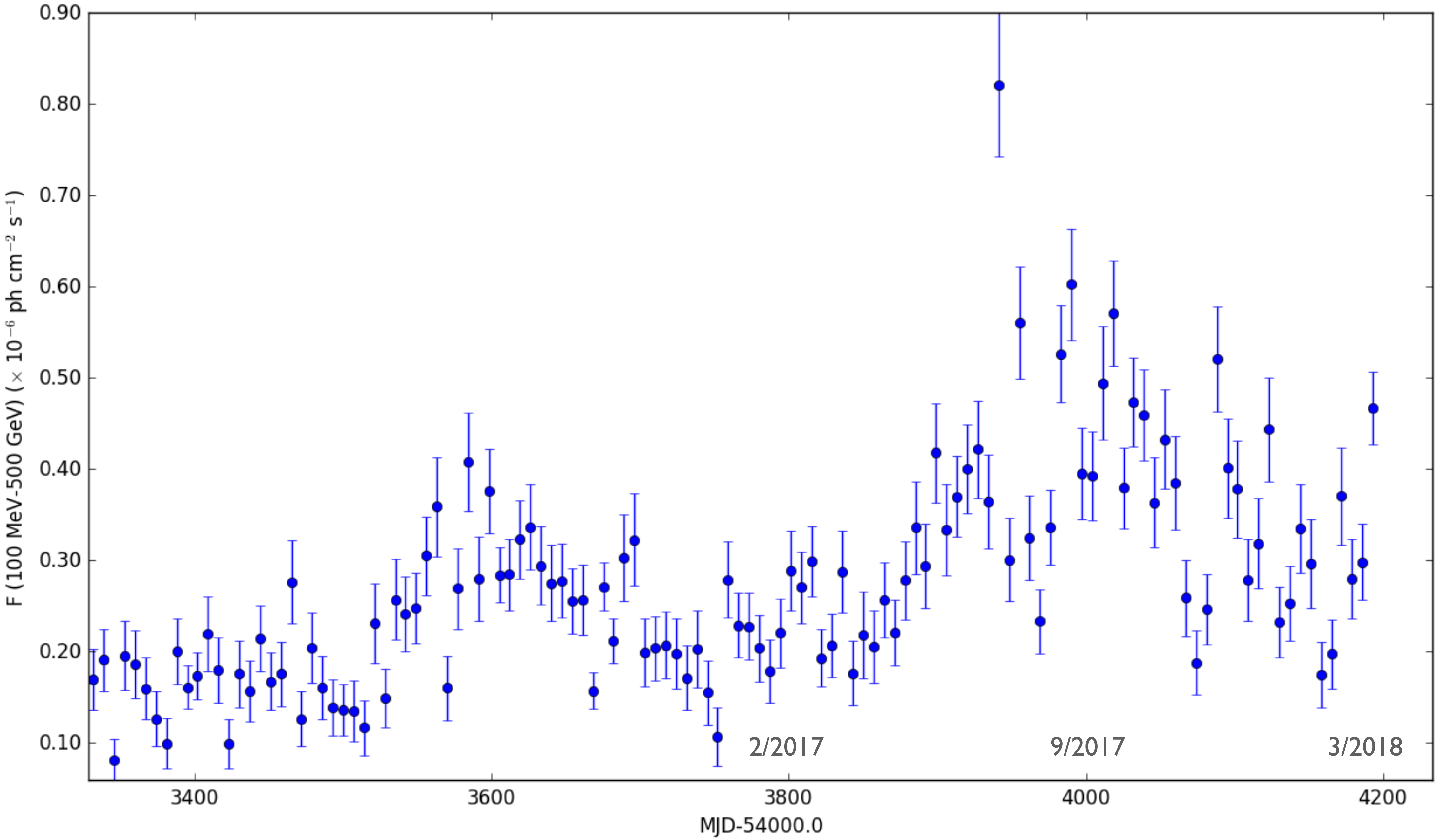
LEHA simulates **synchrotron-pair cascades** triggered by:

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

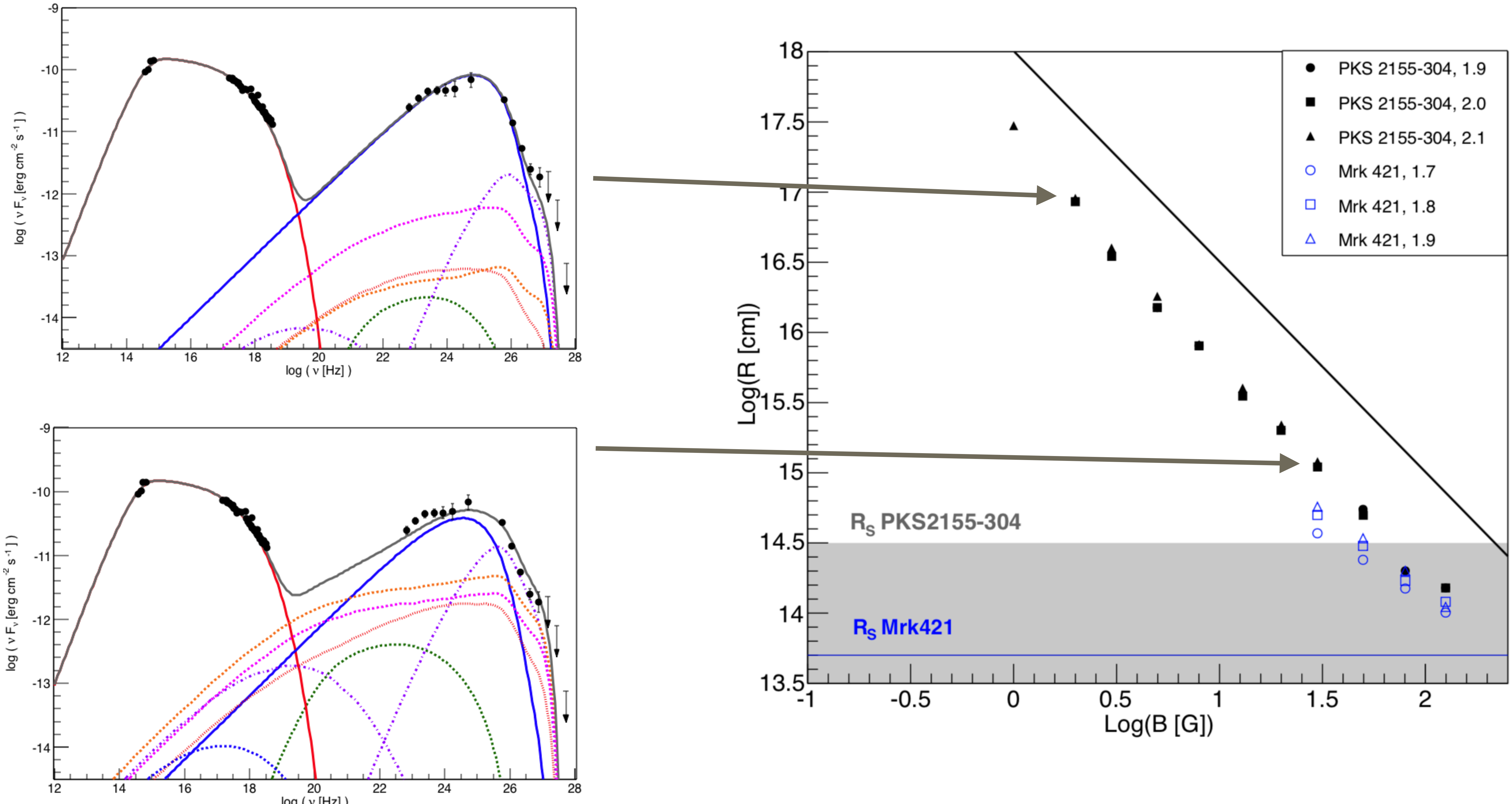
- e+ e- pairs from Bethe-Heitler, leptons from π+, π-



Fermi light curve



hadronic parameter space for HBLs



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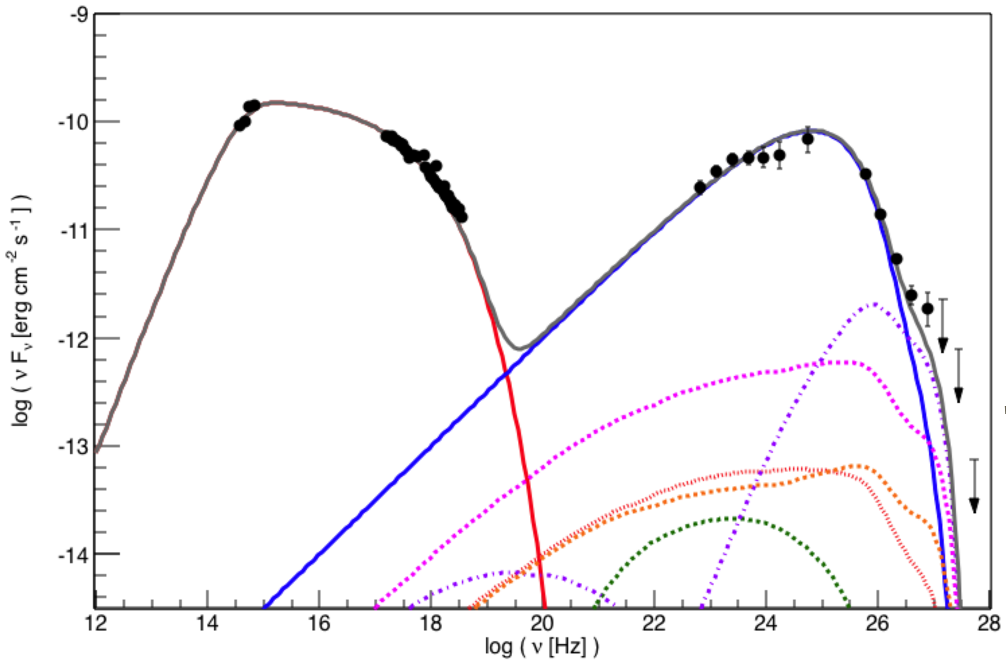
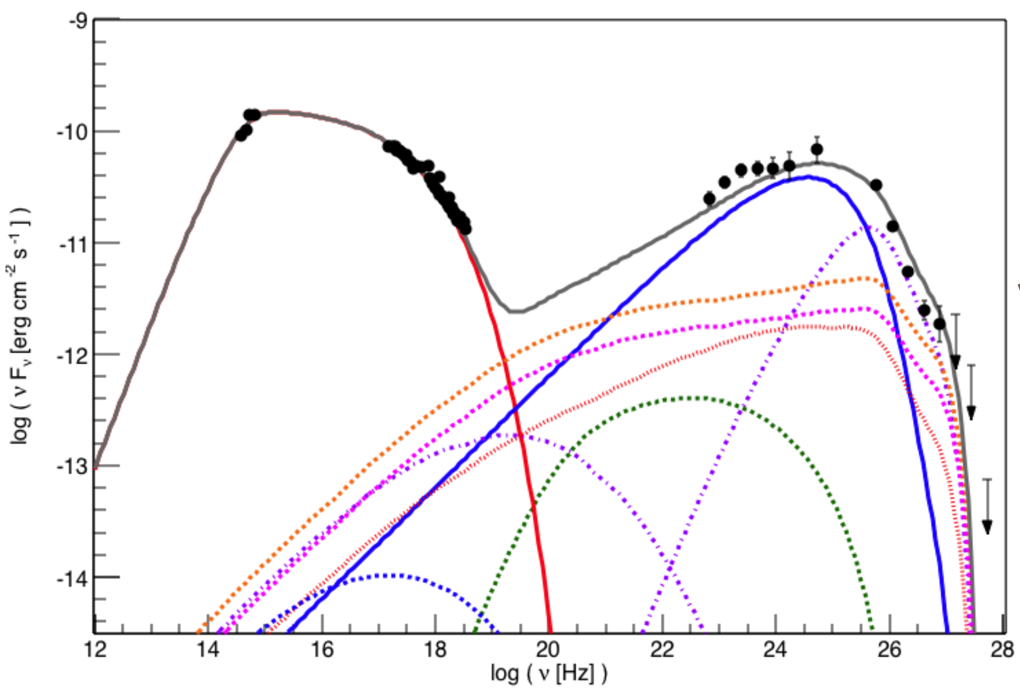
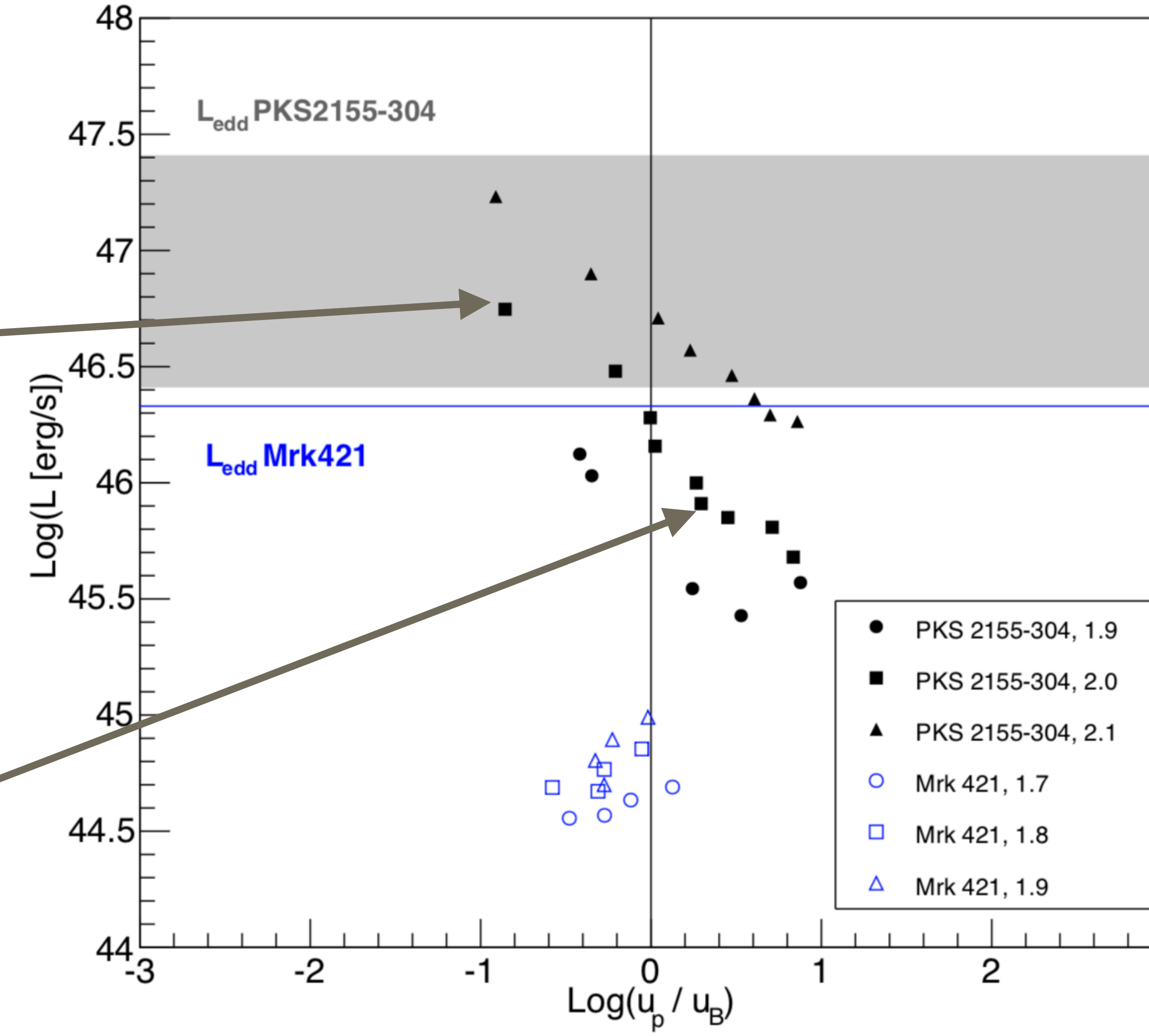
size of emission region vs. magnetic field

hadronic parameter space for HBLs







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

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

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

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hadronic model - time-scales

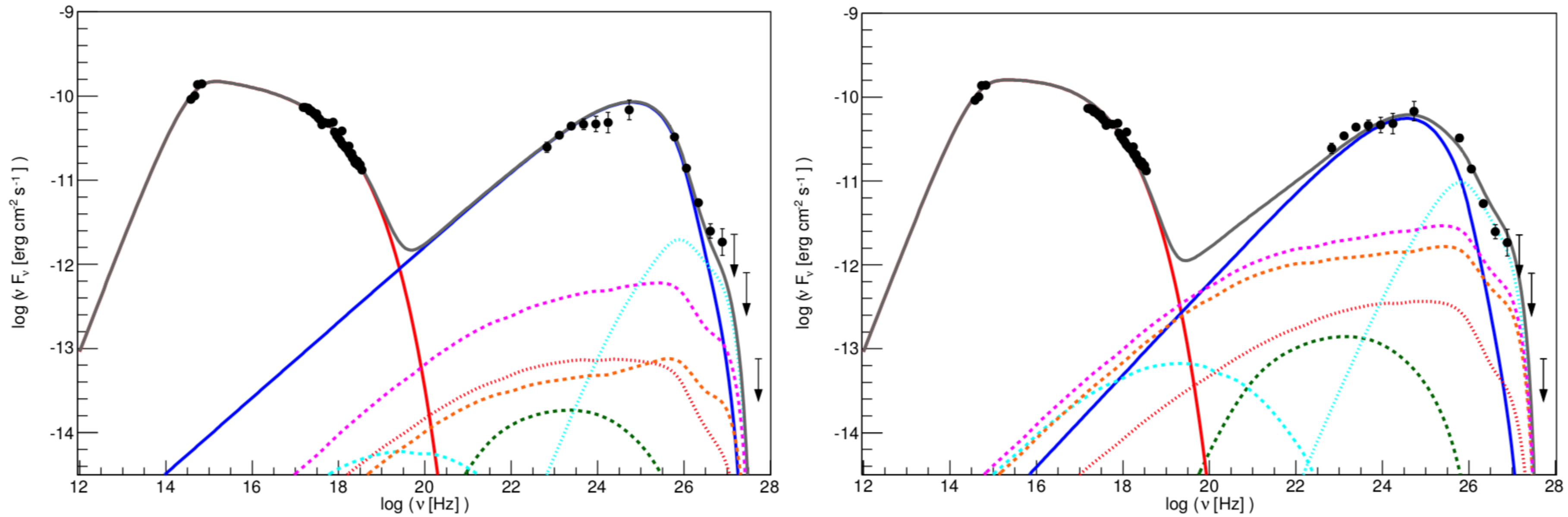
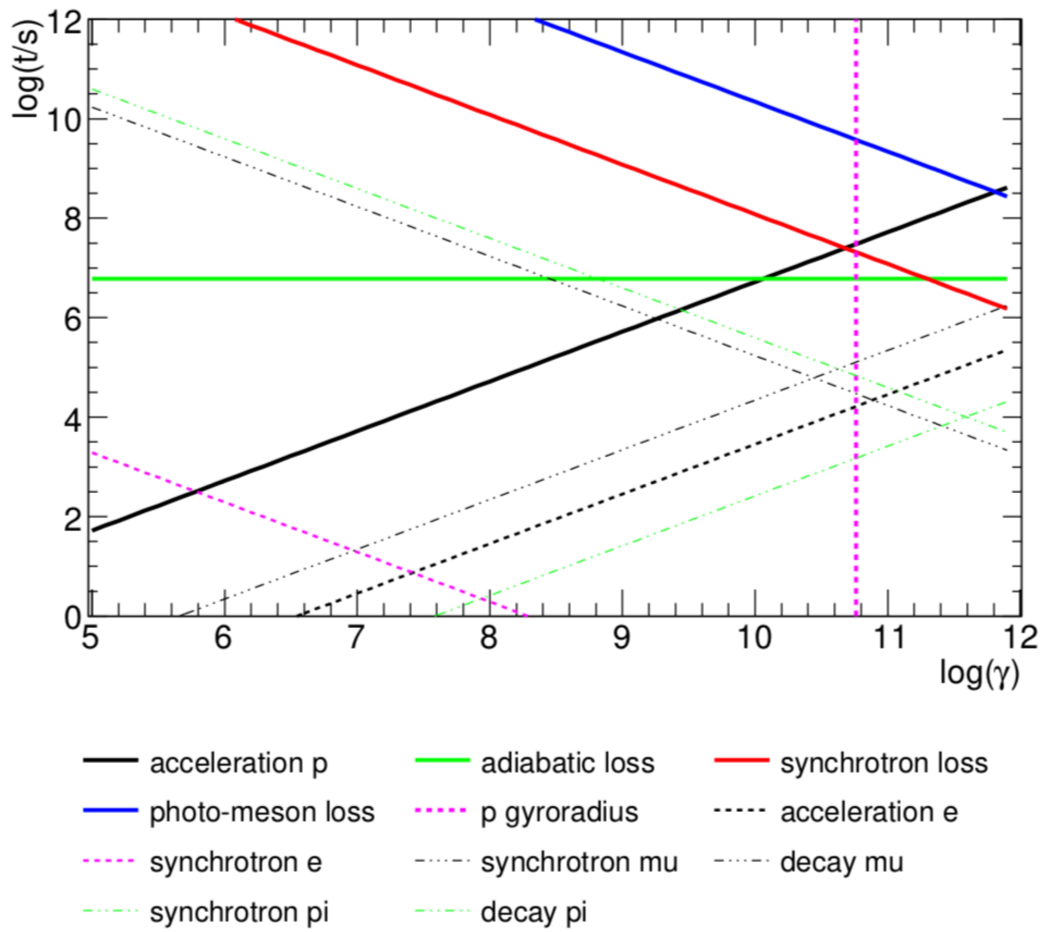
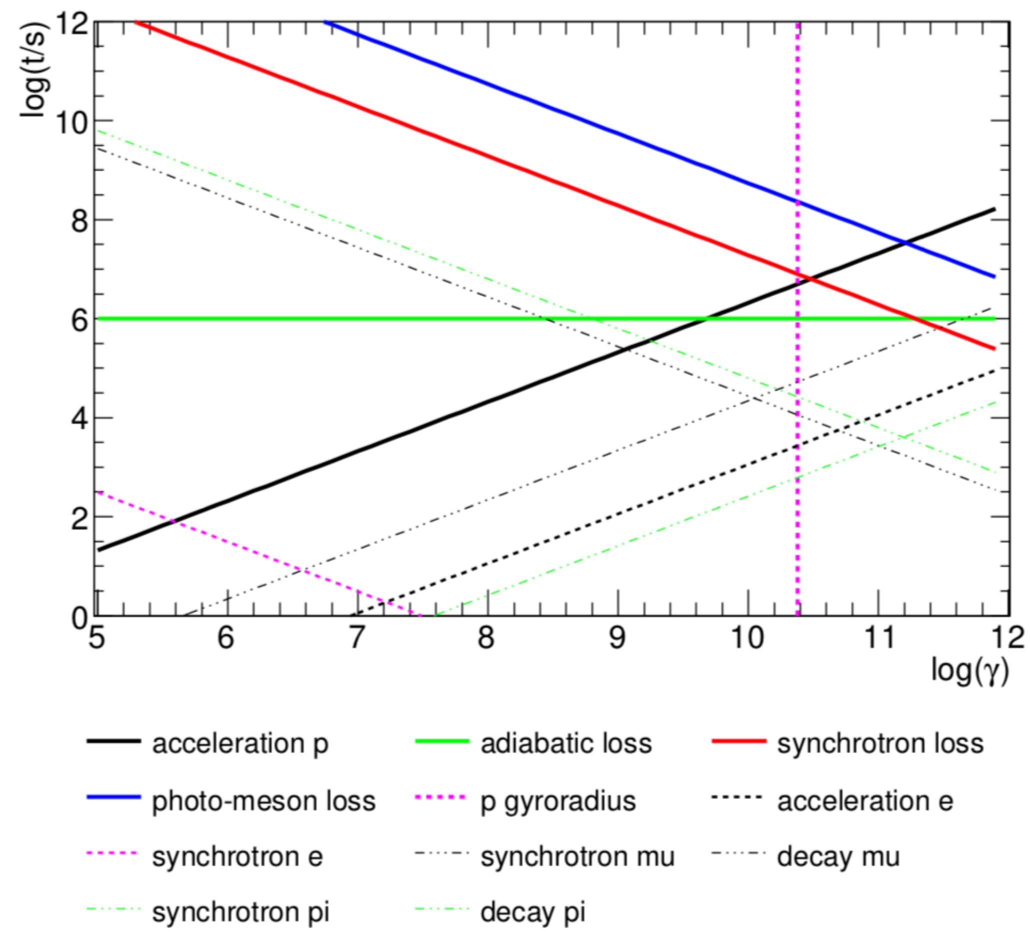


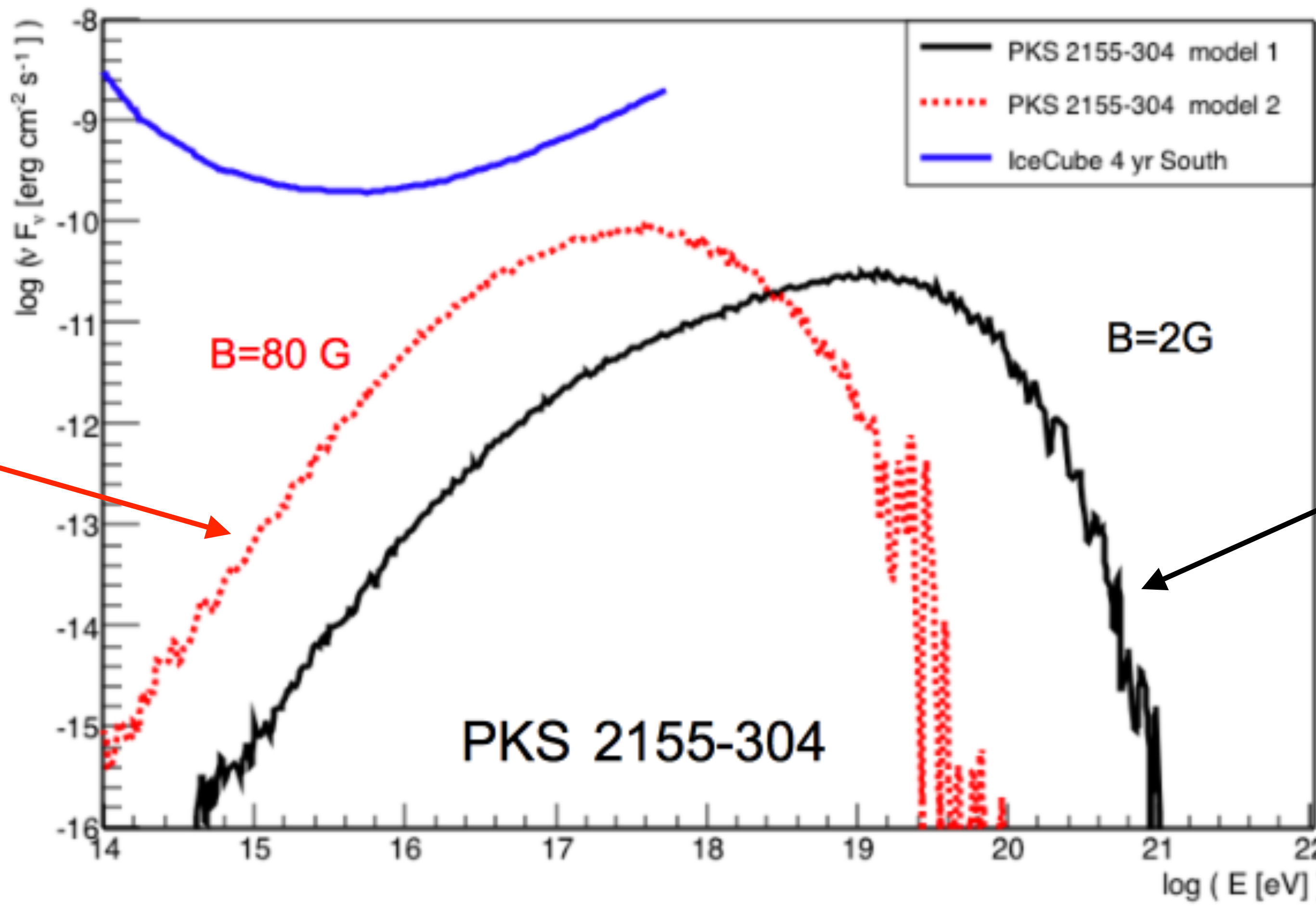
Fig. 6. SEDs for PKS 2155-304 with two hadronic models where proton synchrotron emission (*left figure*) or muon-synchrotron emission (*right figure*) dominates the TeV spectrum. These solutions correspond to a spectral index of $n_1 = 2.1$ and 1.9, a magnetic field with $\log B[\mathrm{G}] = 0.3$ and 0.7, and an emission region of size $\log R[\mathrm{cm}] = 9 \times 10^{16}$ and 1.5×10^{16}, respectively. See Fig. 2 for a description of the different curves. The dataset is described in the text.





high-energy neutrinos from PKS 2155-304 ?

emitting region dense, cascades important



emitting region less dense, cascades less important

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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 GRAND, etc. …