Lepto-hadronic emission models for BL Lac objects seen at TeV

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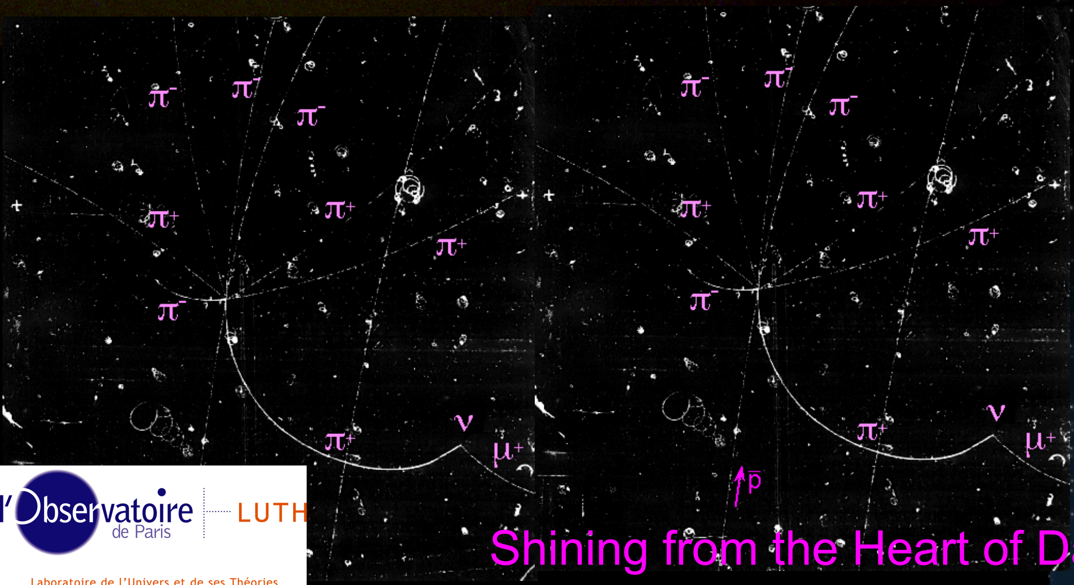

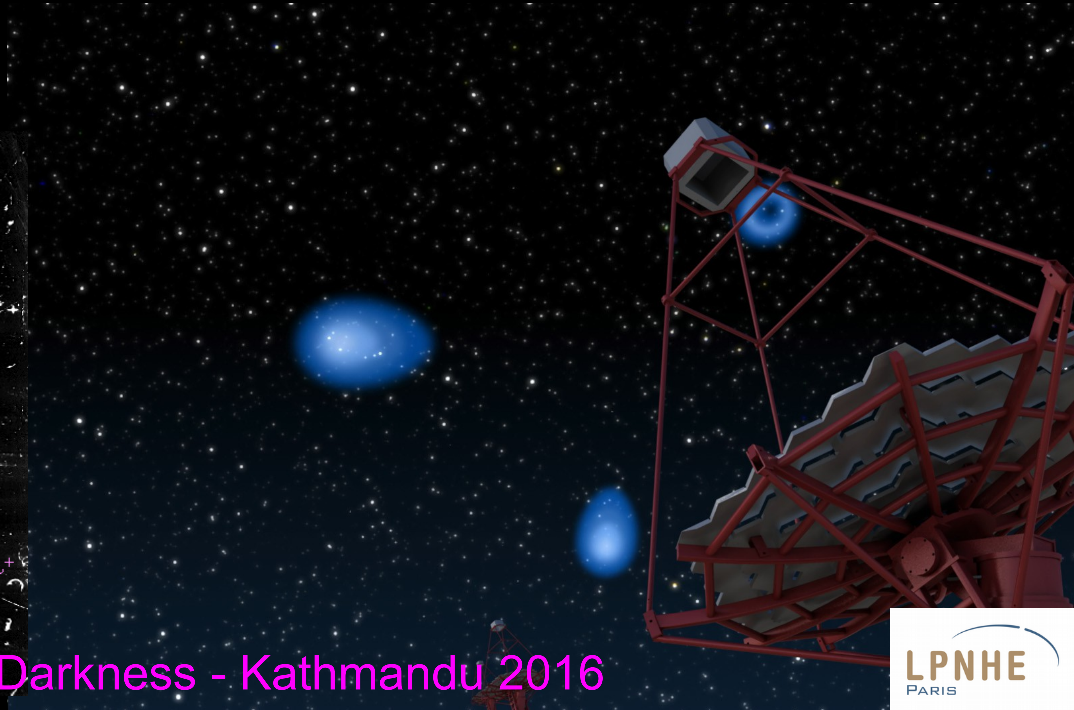

l'Observatoire de Paris — LUTH
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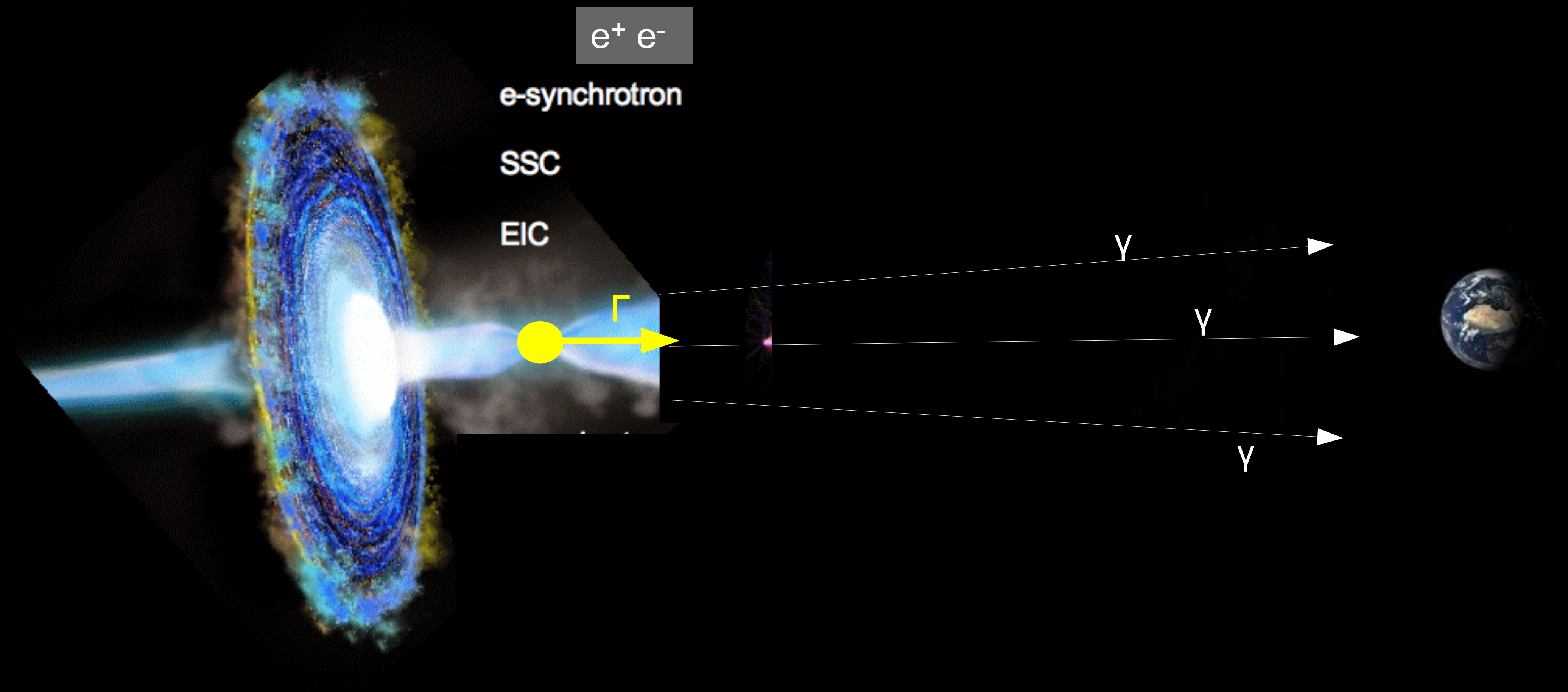
Shining from the Heart of Darkness - Kathmandu 2016

LPNHE PARIS

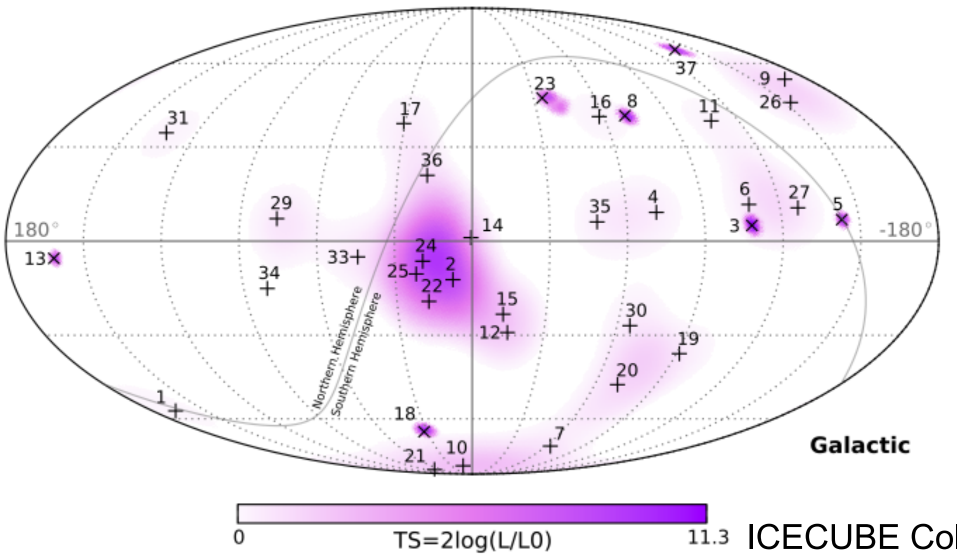
Introduction

The "standard": Synchrotron Self Compton models



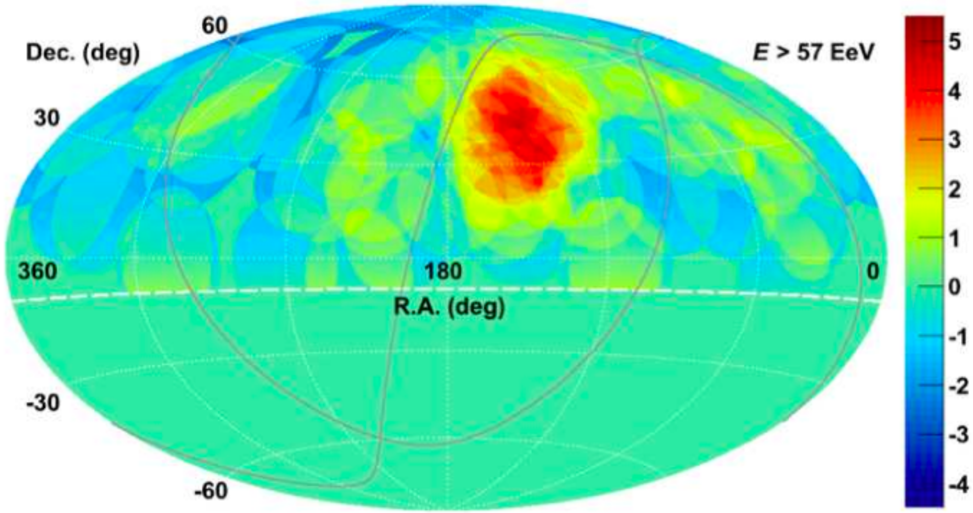
Motivation for lepto-hadronic models

neutrino observations



ICECUBE Collab., PRL 113, 101101 (2014)

UHECR observations



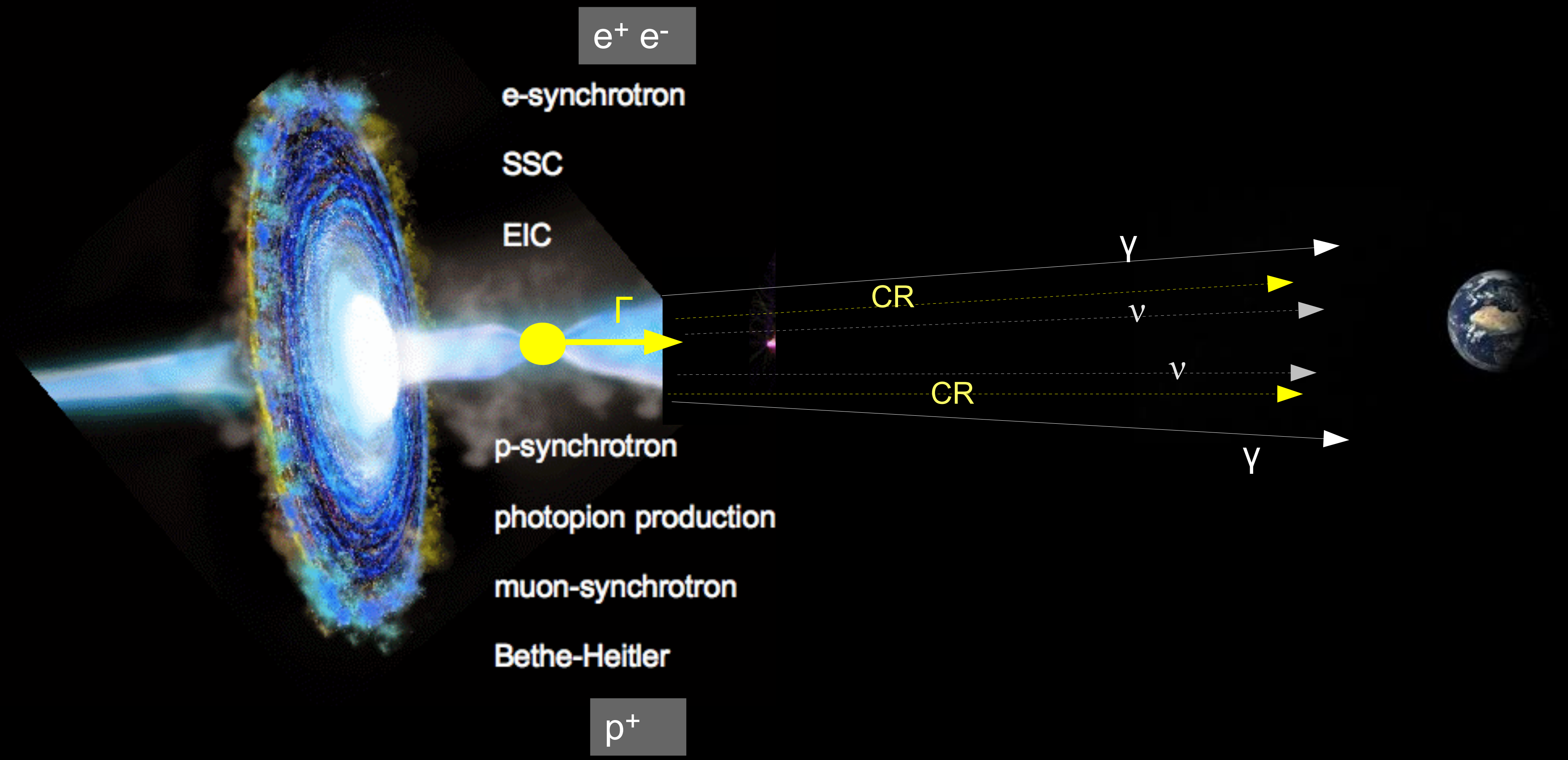
Telescope Array Collab. ApJ 790 L21 (2014)

γ-ray / TeV observations

- **"orphan" flares from blazars** *e.g. 1ES 1959+650 flare 2002, Mrk 421 flare 2012*
  VHE / γ flares without X-ray counterpart
- **extreme blazars** *e.g. 1ES 0229+200, 1ES 0347-121, RGB J0710+591, 1ES 1101-232 , 1ES 1218+304*
  require extreme parameters for SSC
- **radio-galaxies**
  e.g. M87, CenA : unbeamed high-energy emission difficult to explain
  e.g. Fornax A radio-lobes : hadronic interpretation preferred (p-p collision) (*McKinley+ 2014*)

=> often choice between simple hadronic models vs. complex leptonic models

Lepto-hadronic models



the code LEHA

→ fast, stationary one-zone "blob-in-jet" radiative model for BL Lac objects

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

- **inputs:**

  - stationary spectra for primary p^+ et e^-
  - source parameters: redshift z, size R, magnetic field B, bulk Doppler factor δ

- **processes:**

leptonic: e^- synch., SSC, external Inverse Compton,
internal & external (EBL) γγ absorption, pair production

hadronic: p+ synch., photopion production (using the SOPHIA MC code),
muon-synchrotron, synchrotron-pair cascades, Bethe Heitler pair production

secondary particles are cooled & evolved into a stationary distribution

- **constraints:**

  - co-acceleration of protons and electrons -> assume same spectral index before cooling
  - spectral breaks and max. proton energy from acceleration and cooling time scales

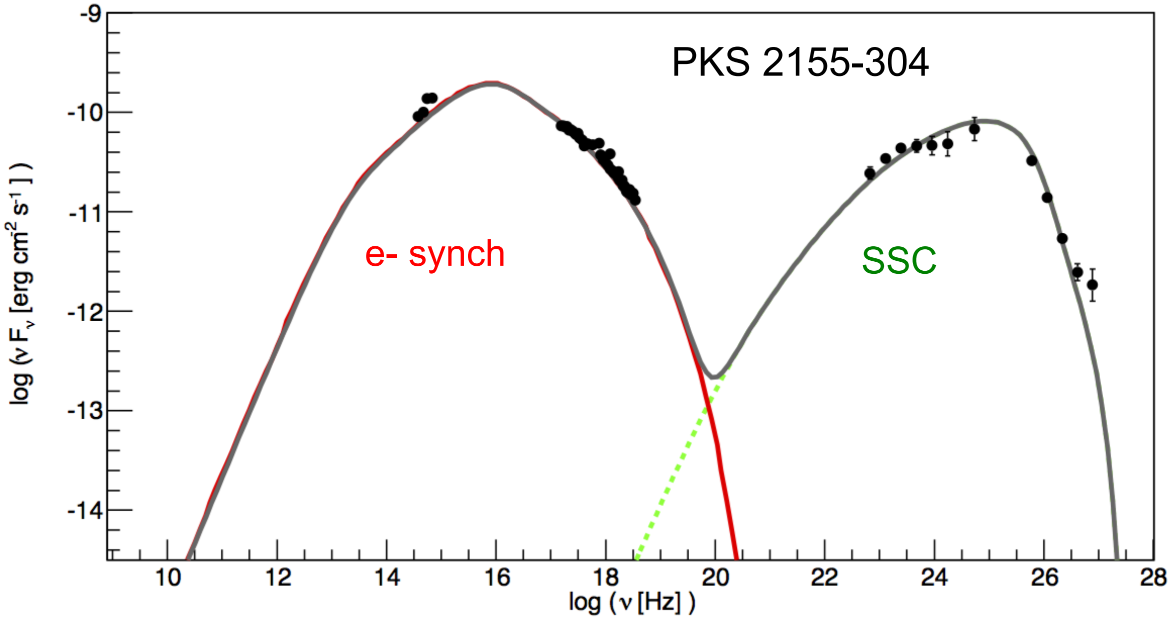
  -> only 8 free parameters

- **outputs:**

SED seen by observer , ν spectra, (n^0 spectrum retrievable from SOPHIA)

Applications to TeV blazars

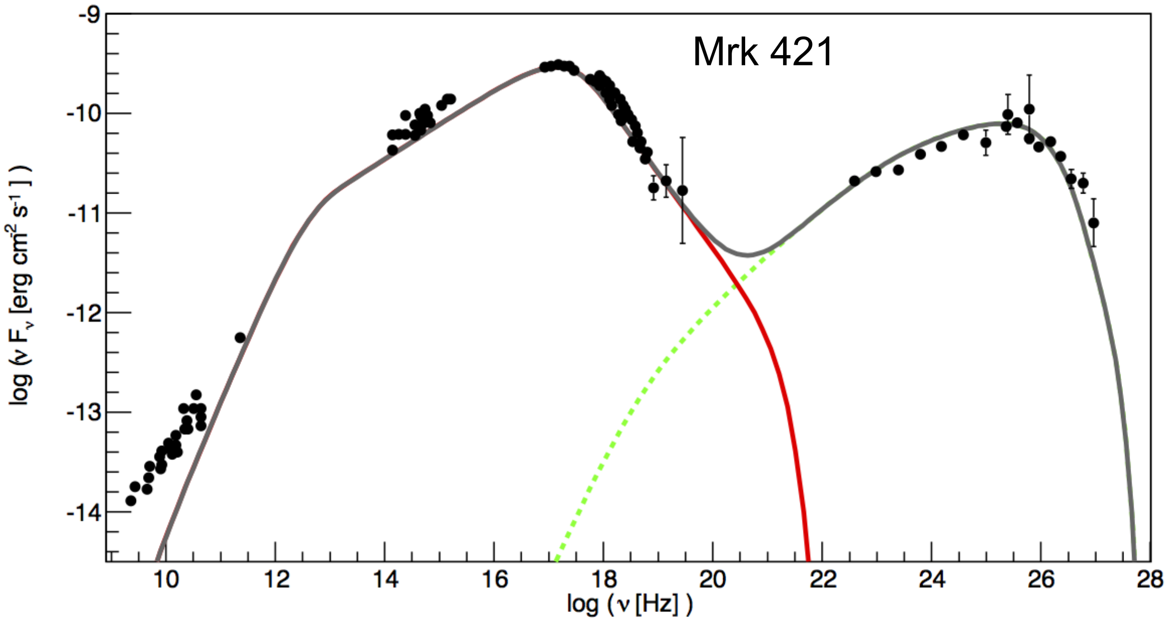
1.) Mrk 421 & PKS 2155-304 - leptonic models



- brightest HBL in Southern sky (z=0.116)
- data from 2008 MWL campaign
  Aharonian et al. (2009)
- SSC model works

  δ = 30, B = 0.04 G, R = 10^16.8 cm

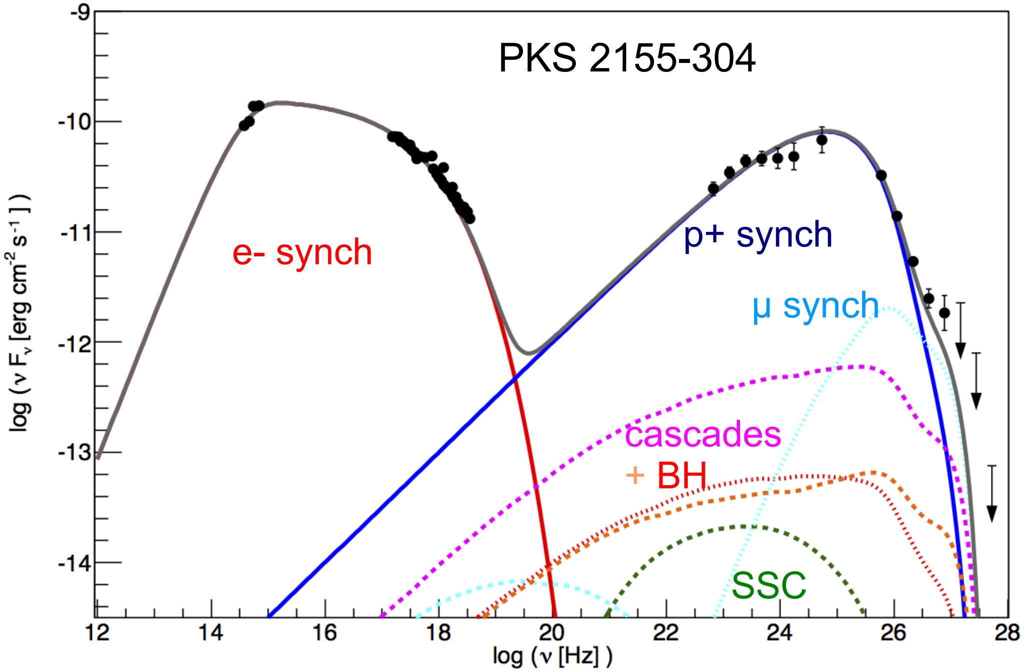
Both sources show frequent flares, but here we are interested in the steady emission.



- very bright Northern HBL (z=0.031)
- data from 2009 MWL campaign
  Abdo et al. (2011)
- SSC model gives good description

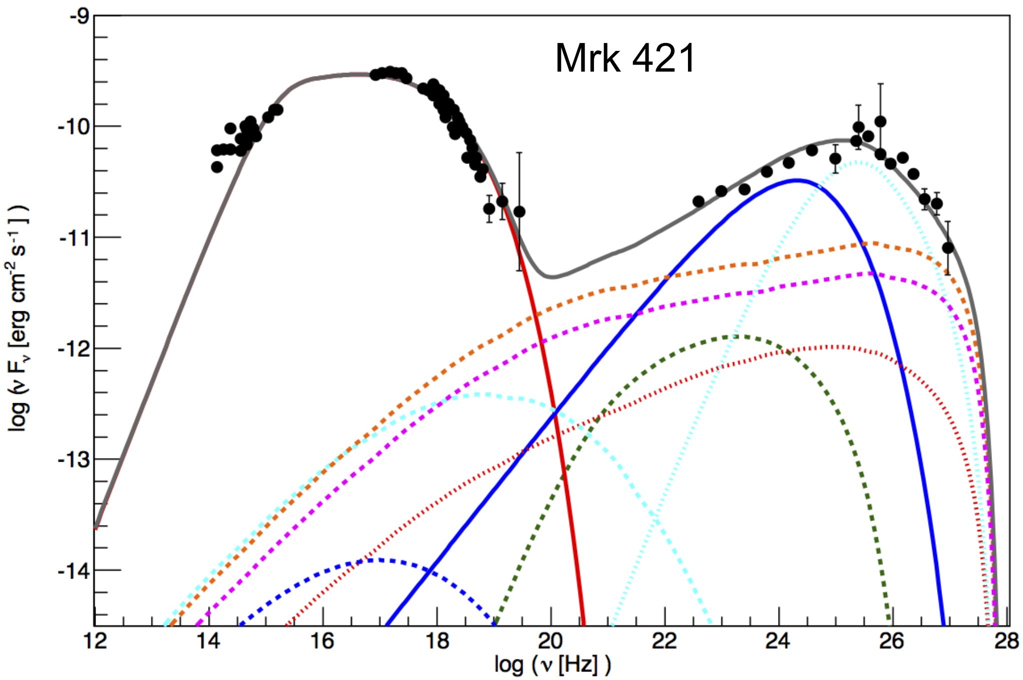
  δ = 30, B = 0.08 G, R = 10^16 cm

1.) Mrk 421 & PKS 2155-304 - hadronic models (examples)



high-energy bump :
combination of **proton-synchrotron** & **muon-synchrotron** emission
(plus cascades)

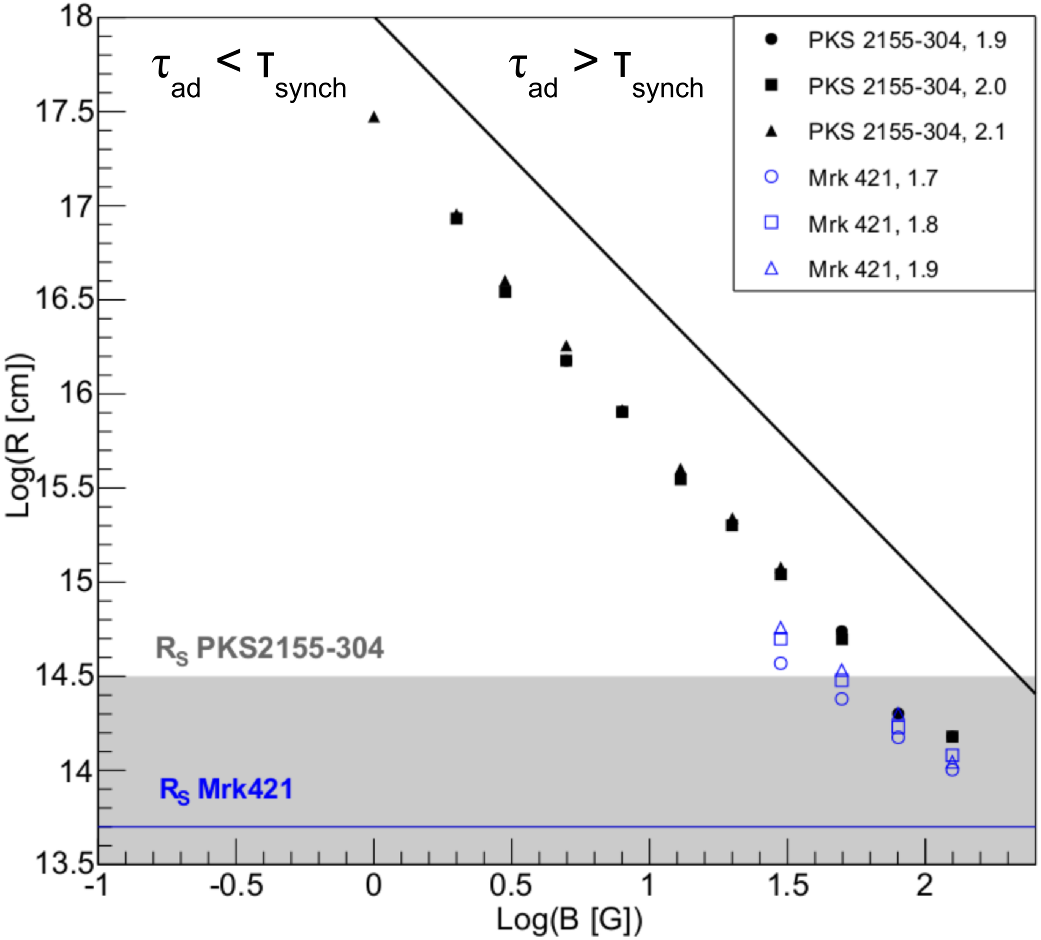
δ = 30, B = 2 G, R = 9 e16 cm

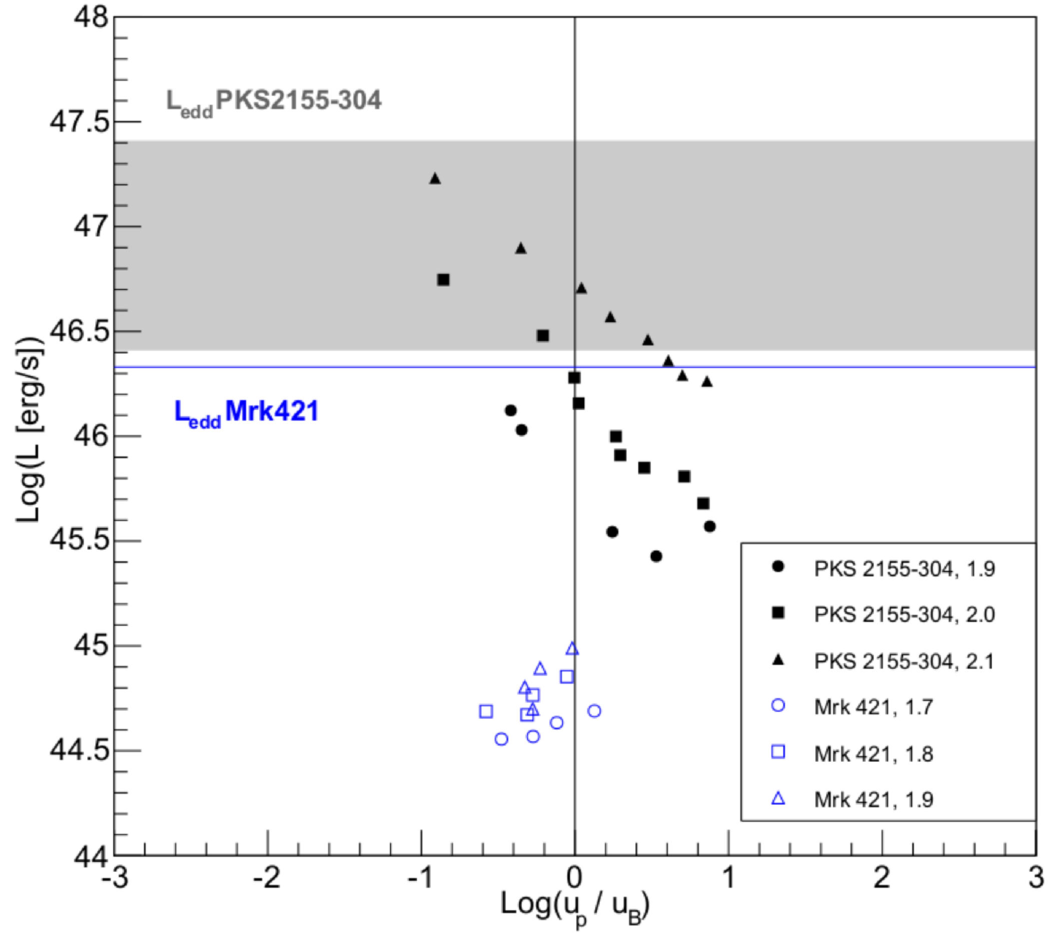


high-energy bump :
- **proton-synchrotron** dominates Fermi range
- **muon-synchrotron** dominates VHE range
(plus cascades)

δ = 30, B = 80 G, R = 1.5 e14 cm

1.) parameter space for the two HBLs





- PKS 2155-304 : solutions over a large range in R vs. B in adiabatic cooling dominated regime

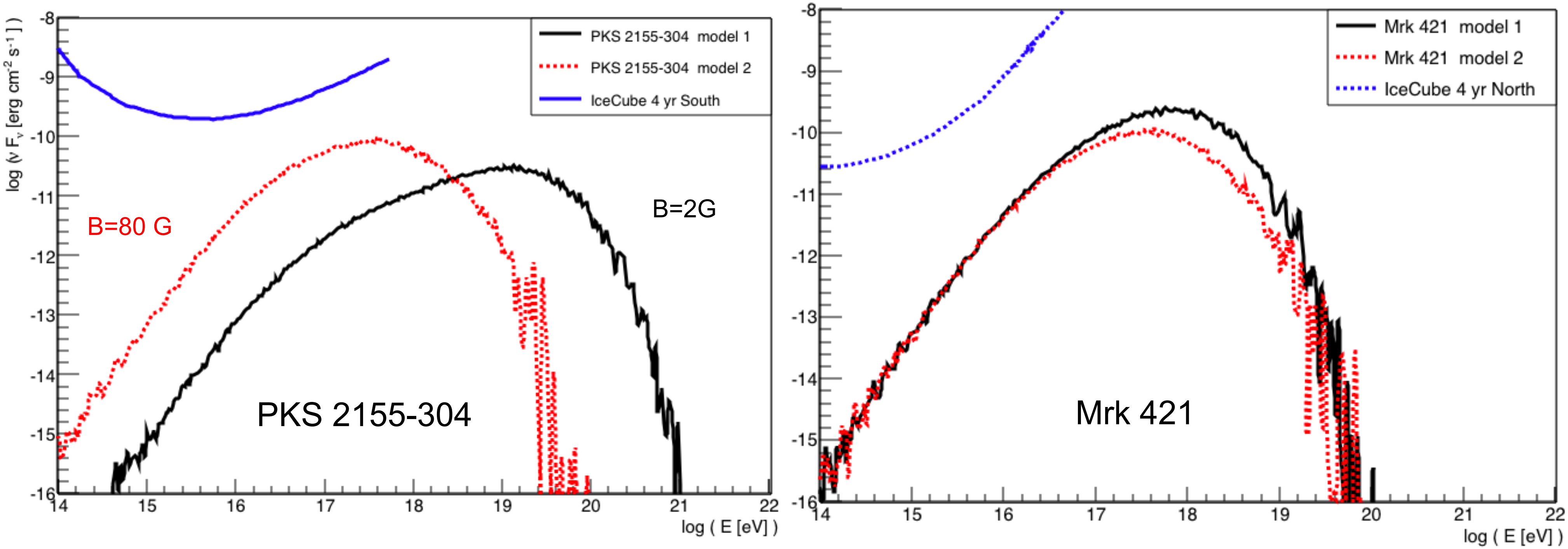
- Mrk 421 : range more resctricted, R close to Rs

solutions exist with P_{jet} << P_{edd} and close to equipartition

(with $P_{jet} \approx 2\pi R^2 \beta c \Gamma^2 (u_B + u_p)$)

for Mrk 421, based on BLR data:
$P_{jet} / L_{disk} < 100$

1.) neutrinos from HBLs ?



large range of neutrino distributions
for different solutions for PKS 2155-304

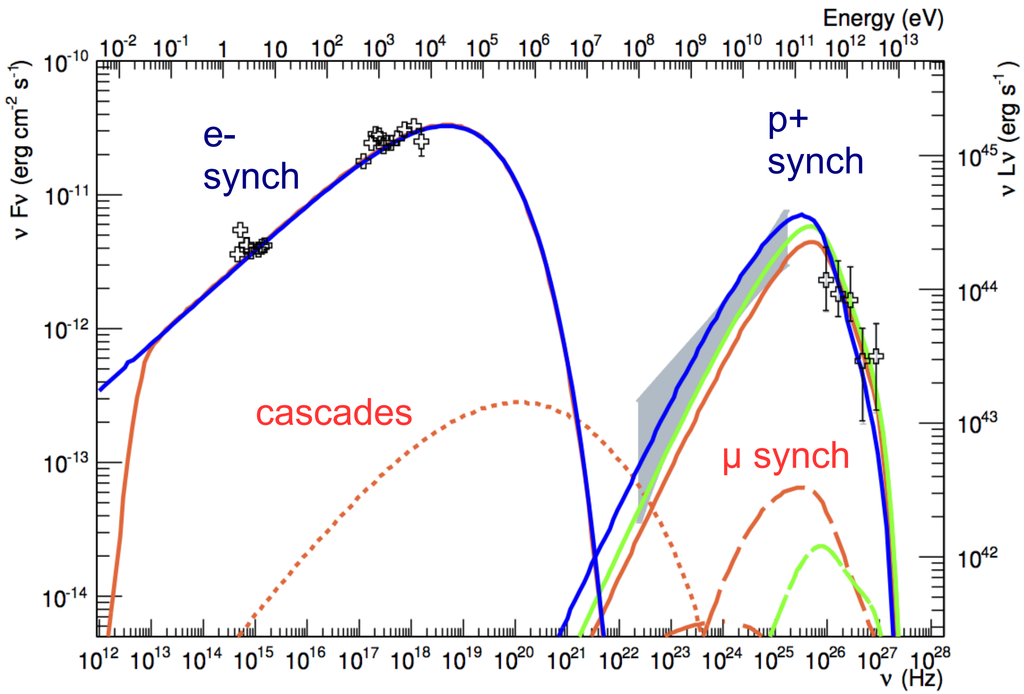
smaller range for Mrk 421

Neutrino flux depends on compactness of source -> photo-pion contribution

Very-high-energy neutrino flux with peak around 10^{17}- 10^{19} eV.
-> Out of reach for IceCube. Need to evaluate detectability with ARA, GRAND, ...

M. Cerruti, AZ, G. Emery, D. Guarin, proc. of Gamma 2016 (astro-ph 1610.00255)

2.) the extreme blazar (UHBL) RGB J0710+591

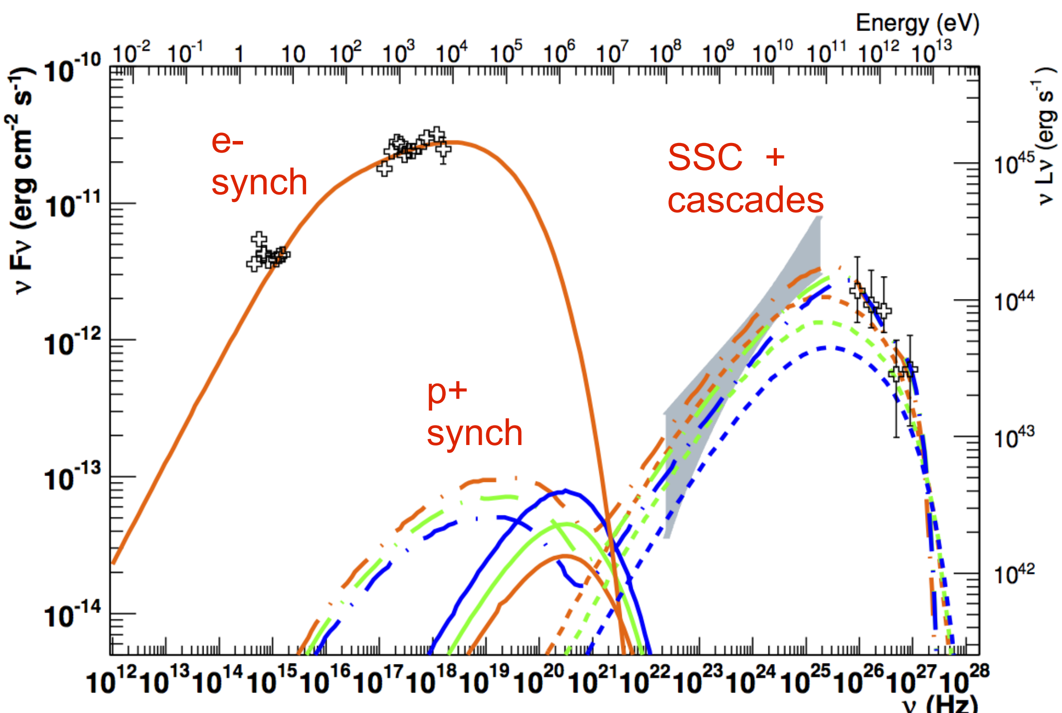


RGB J0710+591

"proton-synchrotron" solution
HE peak dominated by p^+ synch
high B field
high jet power

(*different colours show different models*)

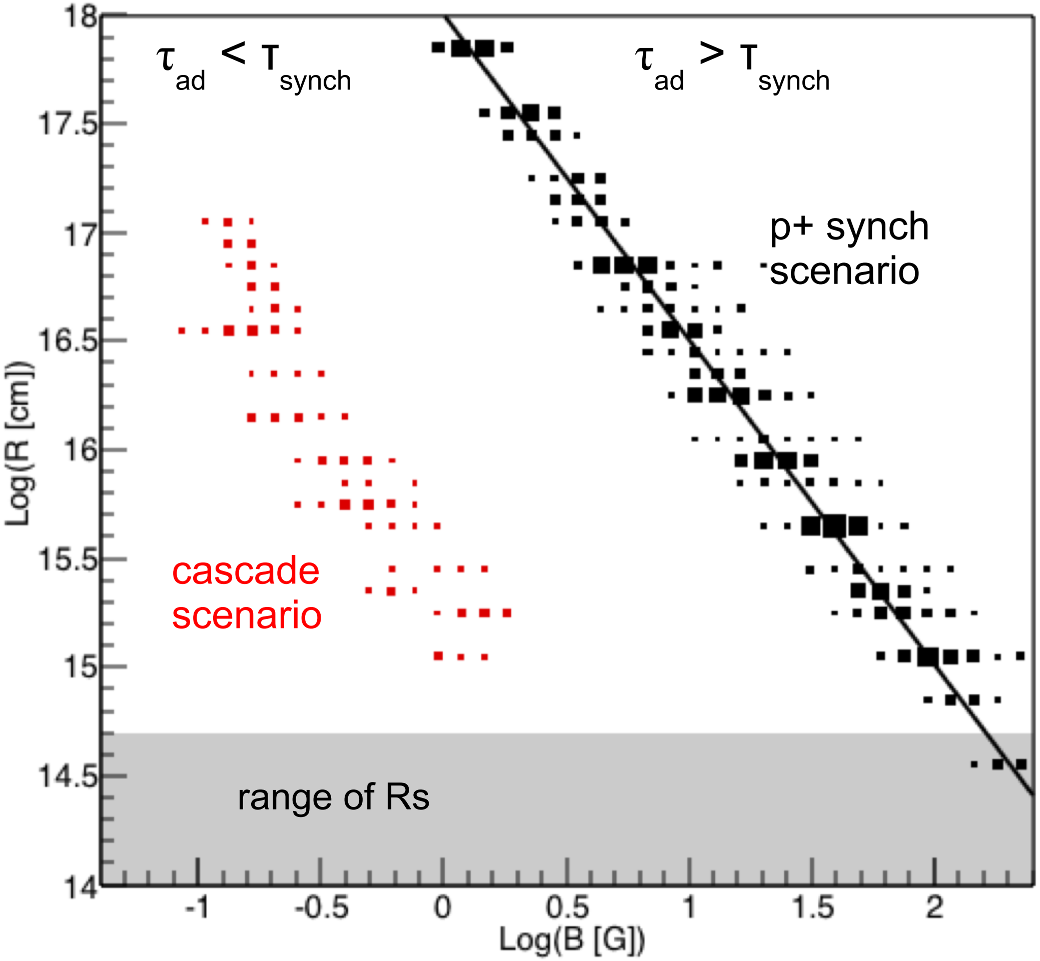
"cascade" solution
HE peak as combination of SSC
+ proton-induced cascades
lower B field
lower jet power

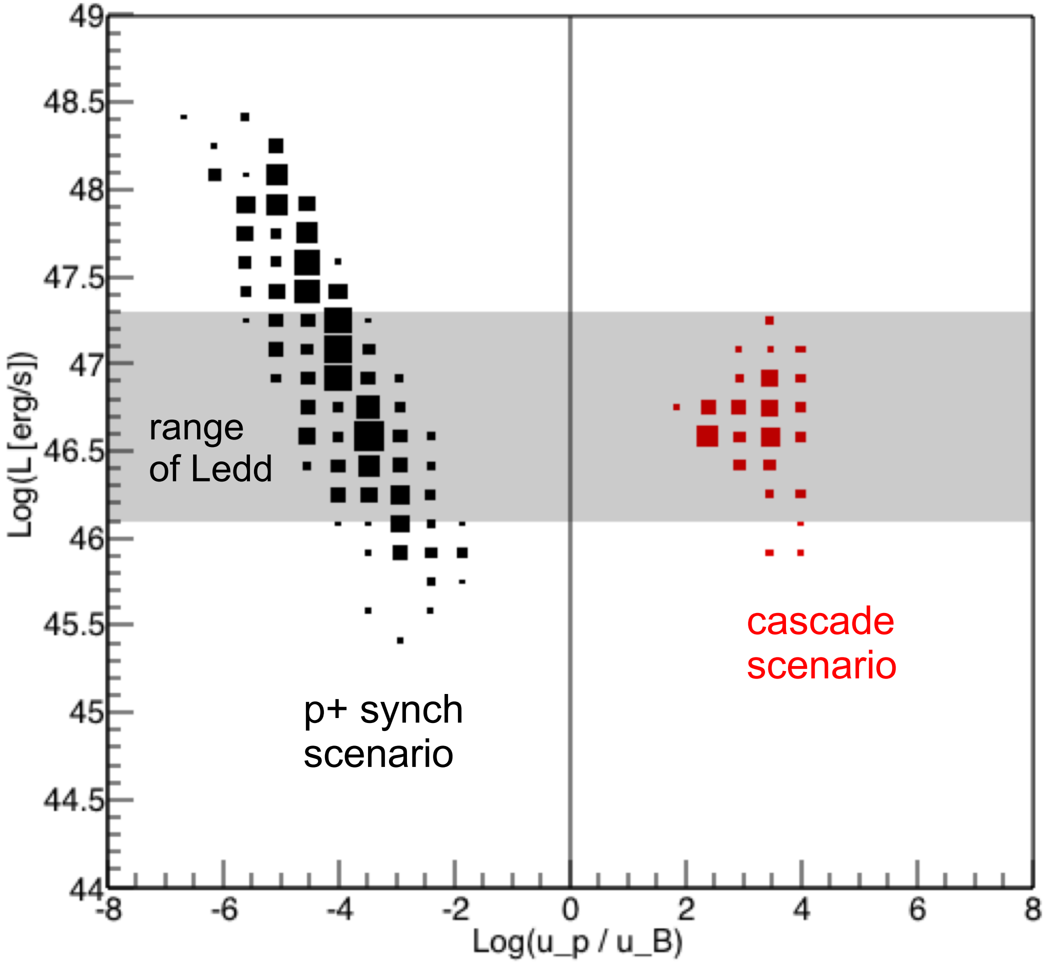


RGB J0710+591

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

2.) parameter space for five UHBLs





- the two scenarios occupy distinct regions in B-R space

- in both scenarios, solutions exist with $P_{jet} < P_{edd}$

- no solutions for equipartition between magnetic and kinetic p+ energy density

3.) Centaurus A (a mis-aligned blazar ?)

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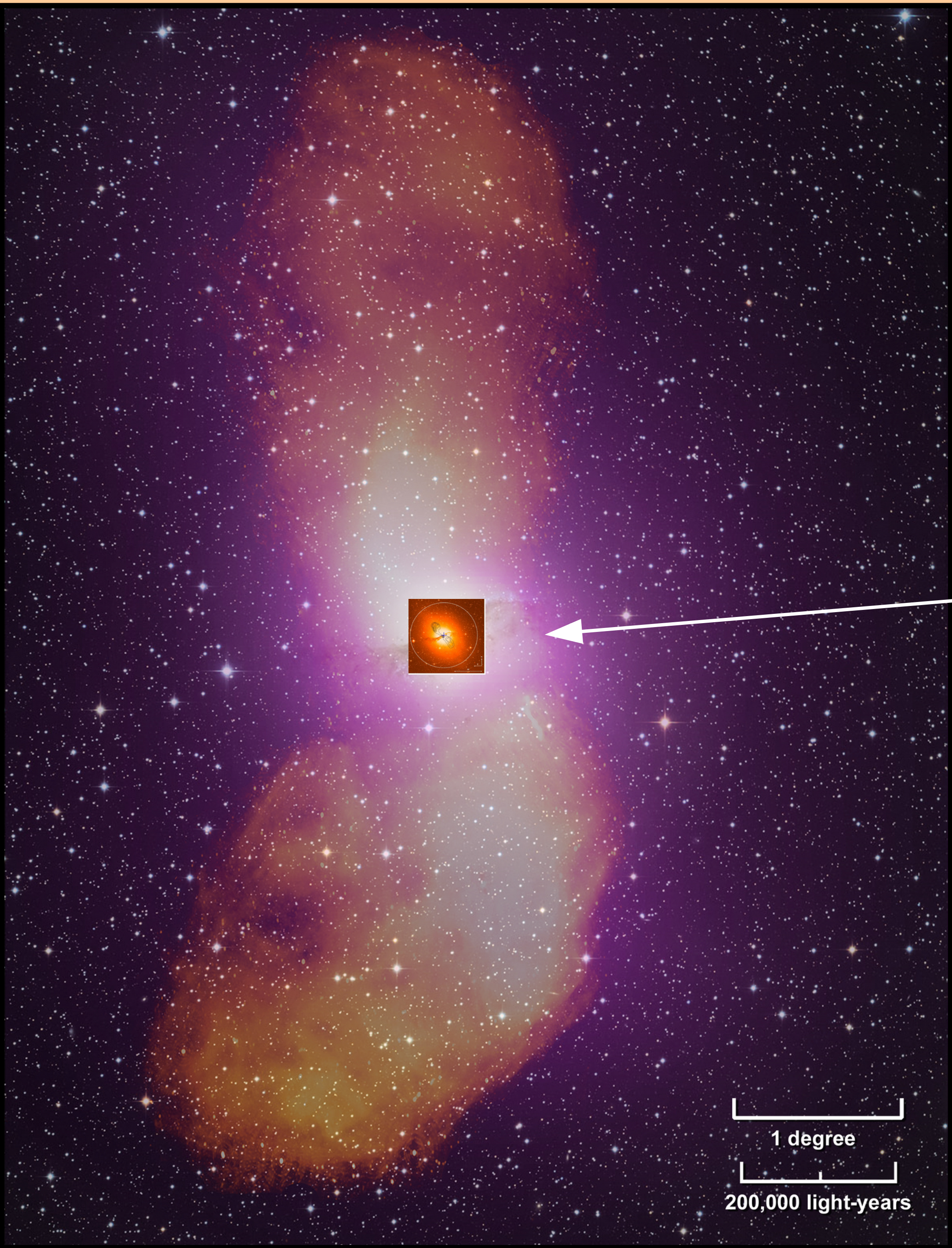
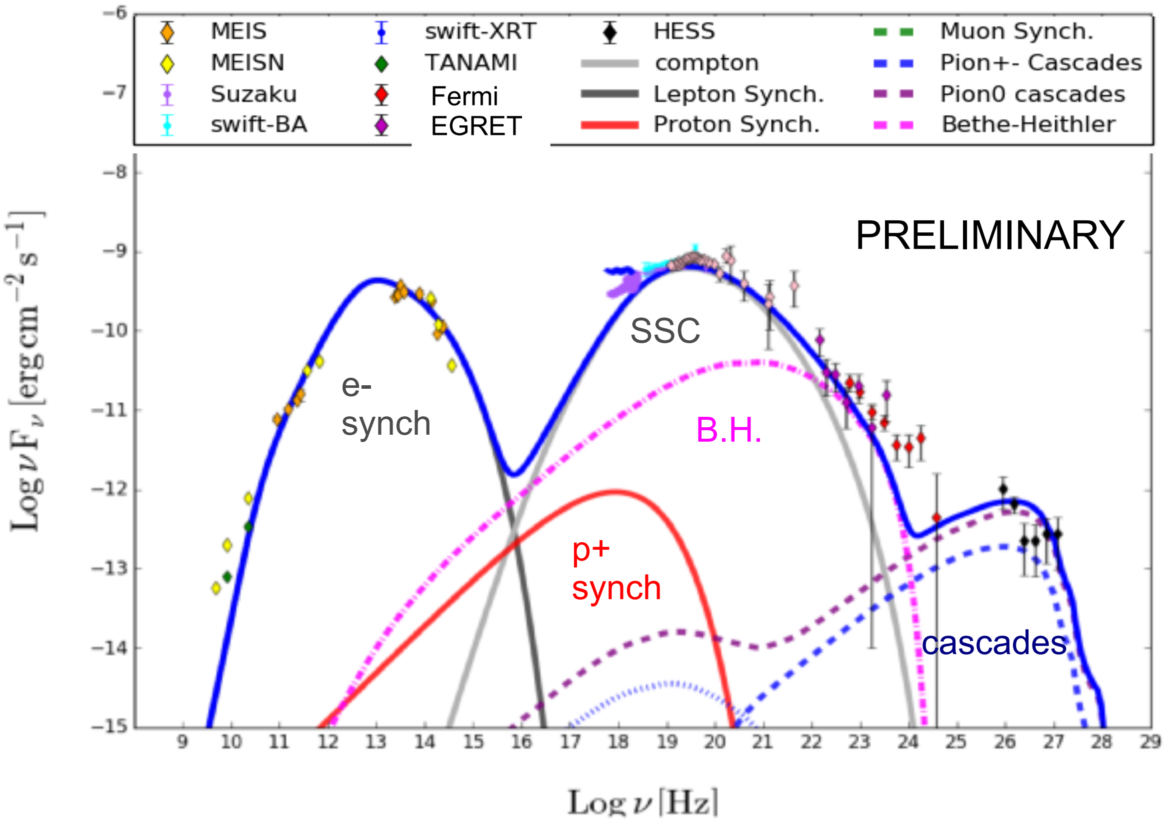
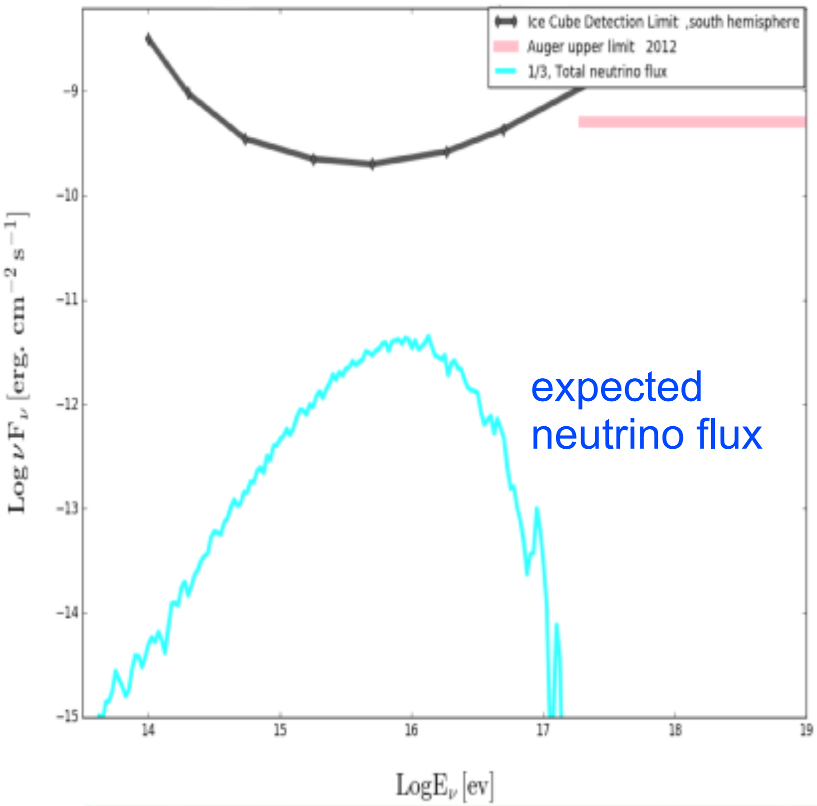


core seen with Fermi-LAT & HESS

3.) scenario 1 : SSC + cascades





- SED shows spectral hardening between Fermi-LAT and H.E.S.S. bands
  -> interpretation with single zone SSC model fails

- **scenario 1**: X-rays : SSC , Fermi : Bethe-Heitler,
  HESS : cascades

- $\delta = 3.8$, $B = 1$ G , $R = 2.3e15$ cm , $P_{jet} \sim 5\ L_{edd}$

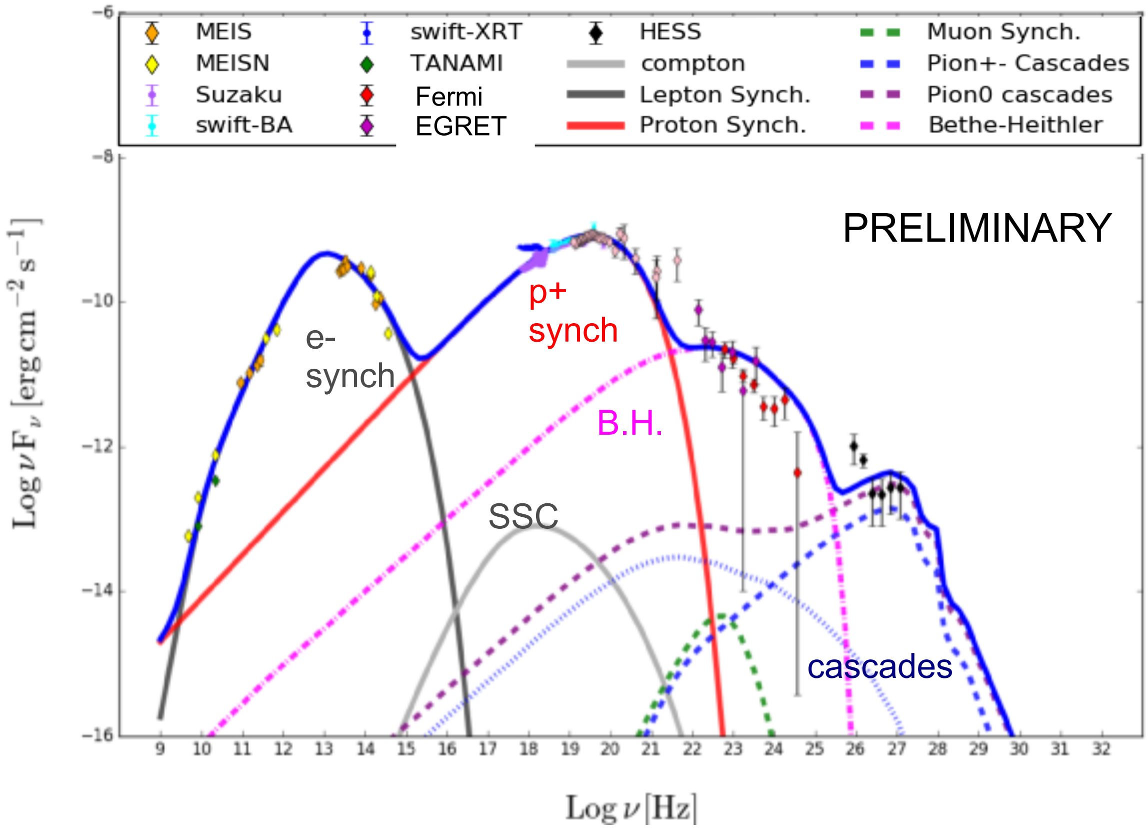
- predicted neutrino flux << IceCube limit for 4 years
  Aartsen et al. (2014)

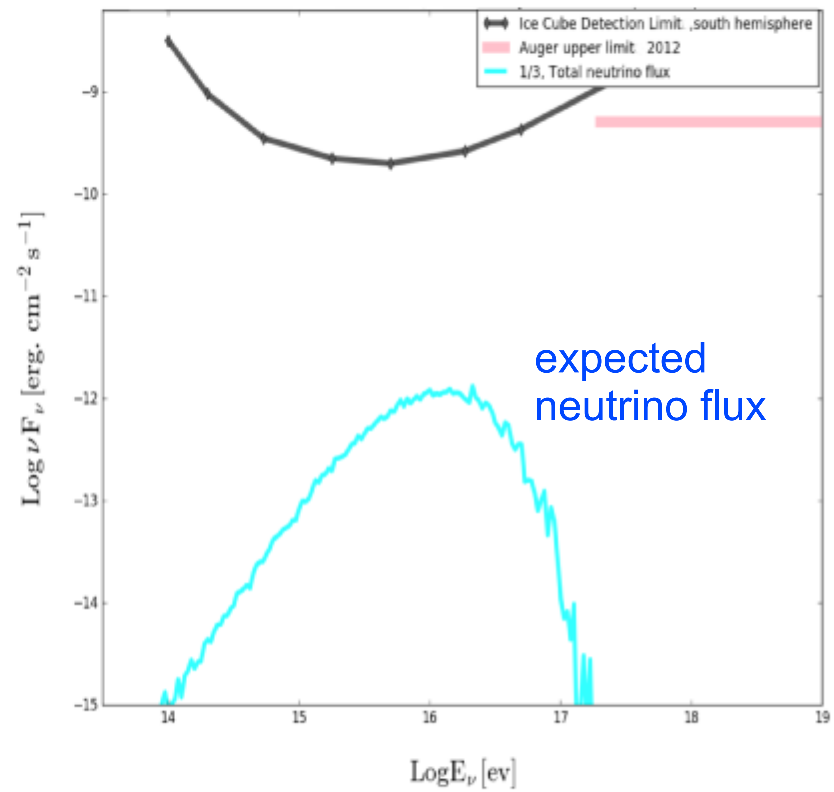
- *peak around 10^16 eV*

M. Cerruti, AZ, G. Emery, D. Guarin, proc. of Gamma 2016 (astro-ph 1610.00255)

SED from *Abdo et al. (2010)*

3.) scenario 2 : proton-synch + cascades





- **scenario 2**: X-rays : p+ synch ,
  Fermi : Bethe-Heitler,
  HESS : cascades

- δ = 3.8 , B = 18 G , R = 1.3e16 cm , $P_{jet} \sim 2\ L_{edd}$

- predicted neutrino flux << IceCube limit for 4 years
  Aartsen et al. (2014)

- *peak around 10^16 eV*

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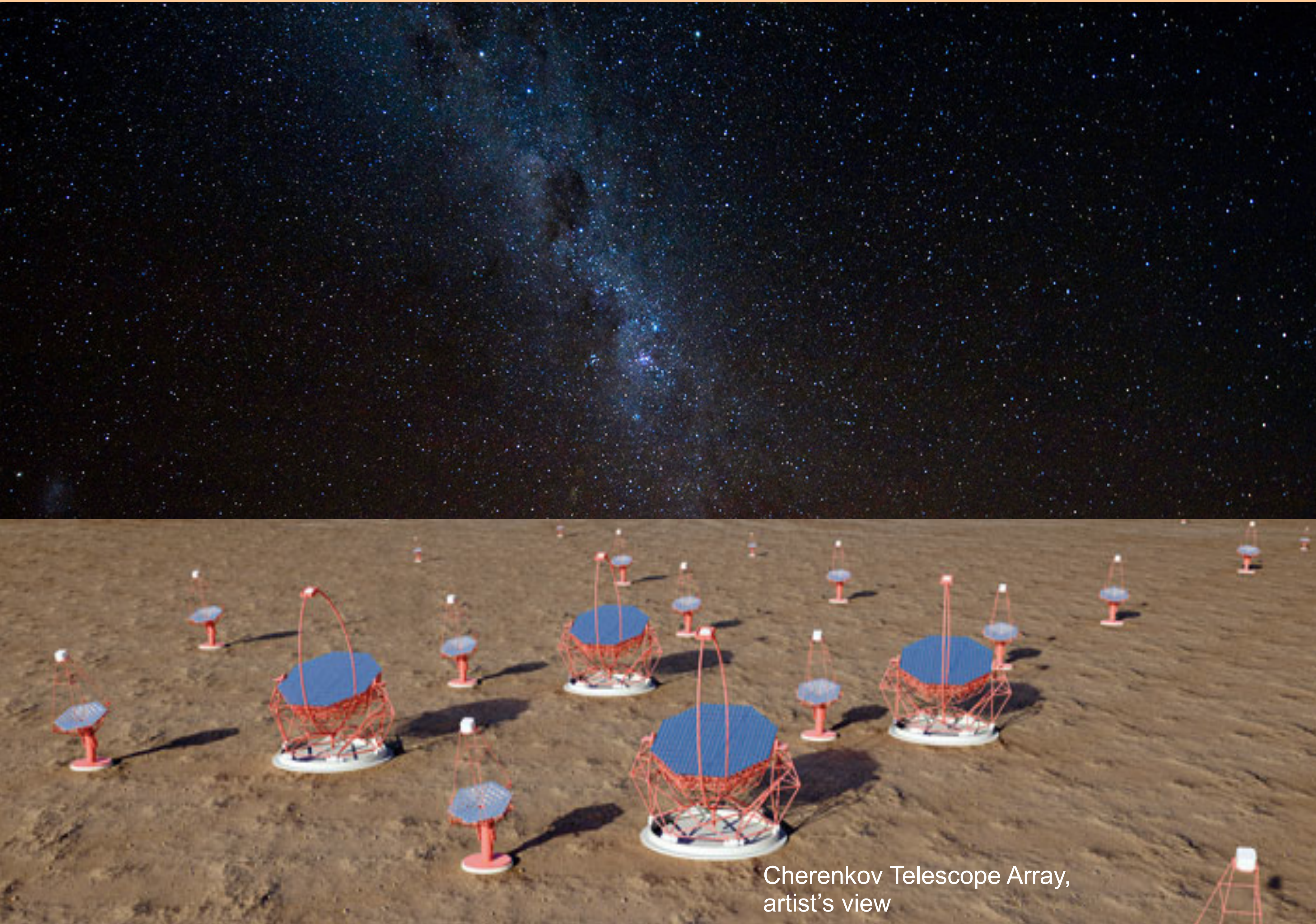
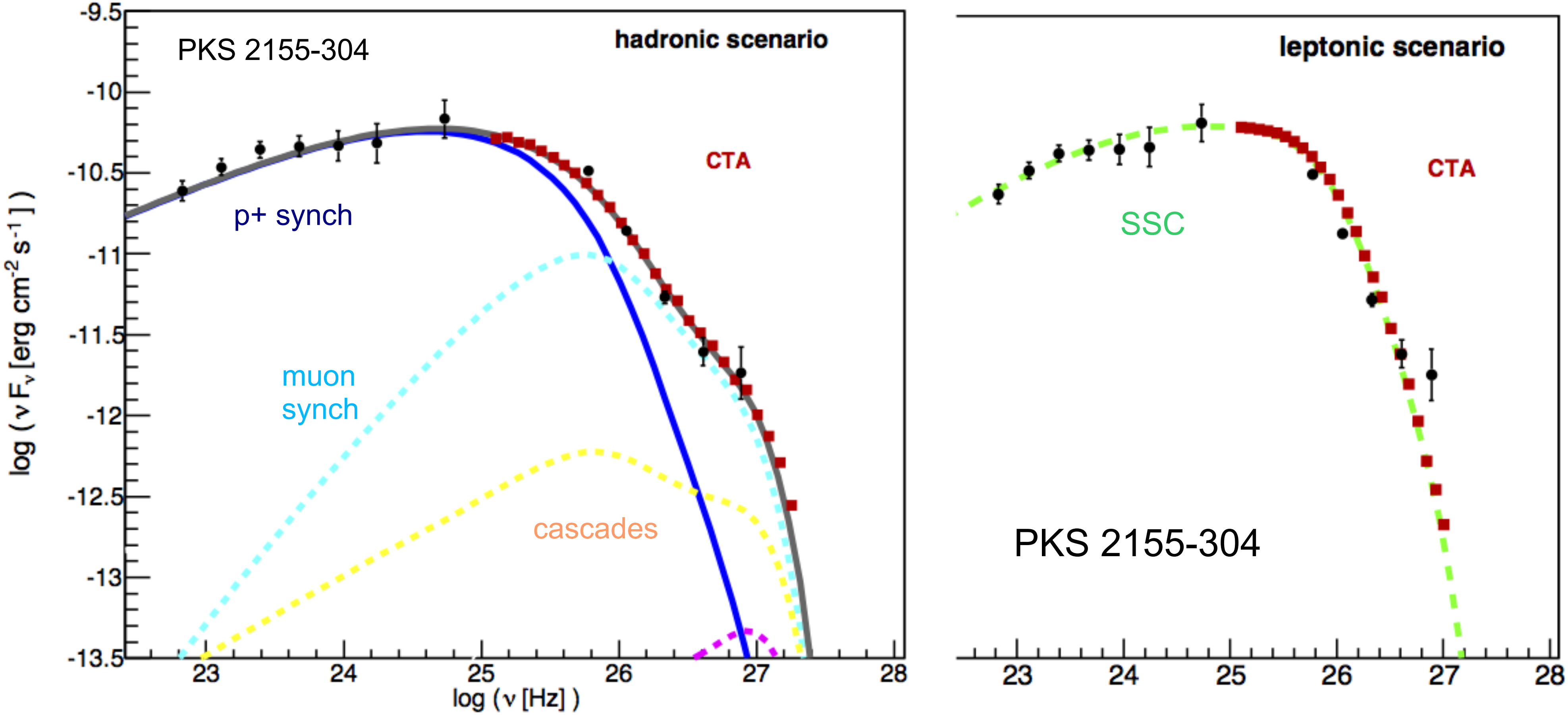
Outlook

Spectral signatures for CTA ?



What would CTA detect ?



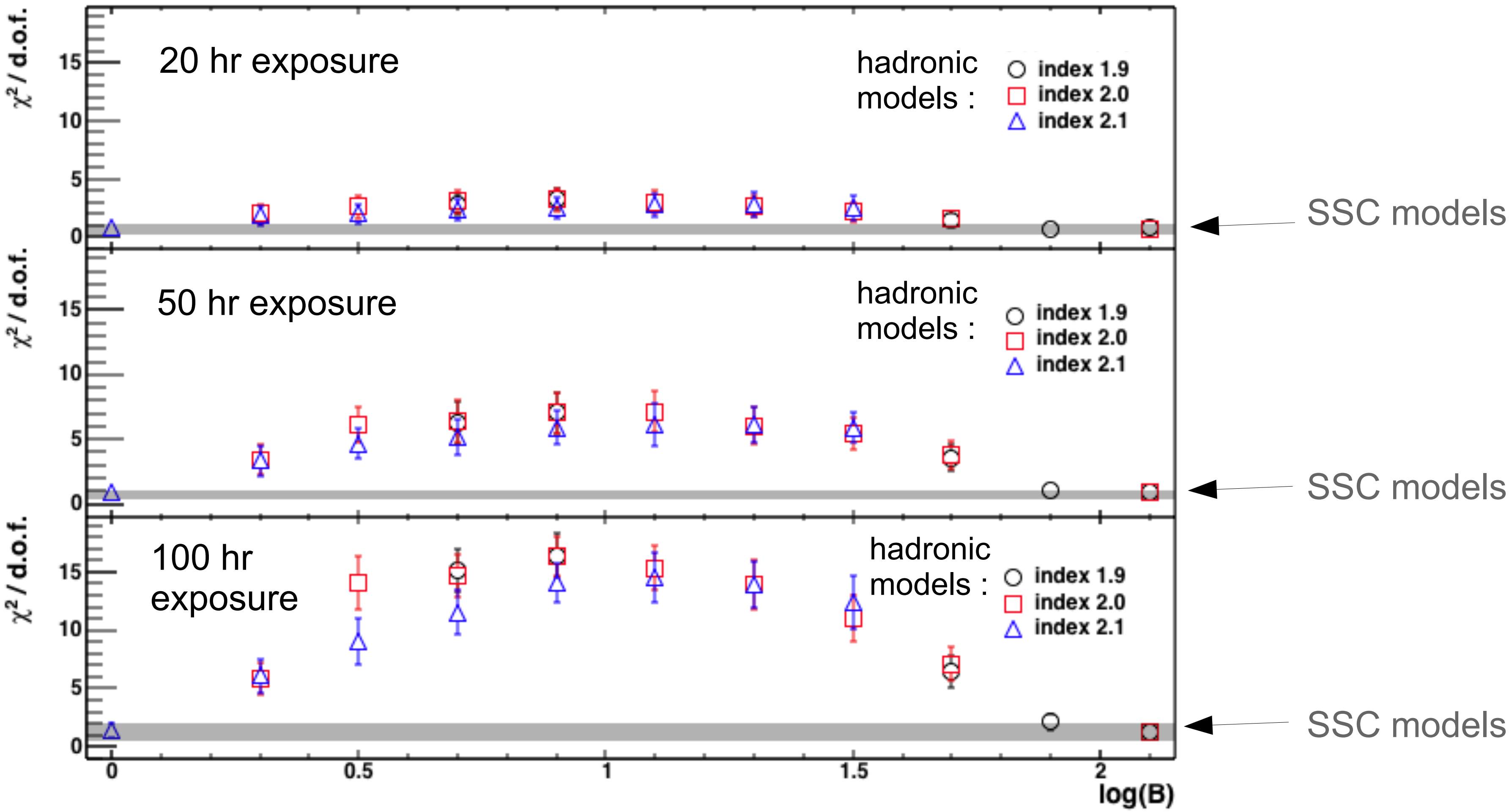
- 33 hr of observations (= exposure for HESS)
- CTA performance curves (Southern array)

-> this particular model shows clear spectral hardening due to muon synch. and cascades

What about the other hadronic models ?

CTA Technical Design Report
to be released on ArXiv

hadronic spectral signatures to look for...



- logparabola fit to SSC and to hadronic models & distinction using Chi^2 or fit probability

-> detectability for 50 - 100 hr exposure time for all the most probable hadronic models

- similar result for Mrk 421

Conclusions

	HBLs	UHBLs	Centaurus A
one-zone SSC models	work well in general	extreme parameters	insufficient
one-zone lepto-hadronic models	- range of solutions with acceptable parameters - H.E. bump = p+ synch + μ synch (+ cascades)	- range of solutions with acceptable parameters (caveat: steep input spectra of 1.3 - 1.5) - p+ synch and "cascade" scenarios	- VHE component due to cascades - H.E.: Bethe-Heitler - X-rays : SSC or p+ synch (caveat need high jet power >~ L edd)
expected neutrino flux	at very high energies	not evaluated - expected to be low	in ICE Cube energy range, but below detection level
UHECRs ?	max. p+ energies around 10^19 eV	max. p+ energies up to 10^19 eV	max. p+ energies around 10^16 eV