The extragalactic sky with CTA

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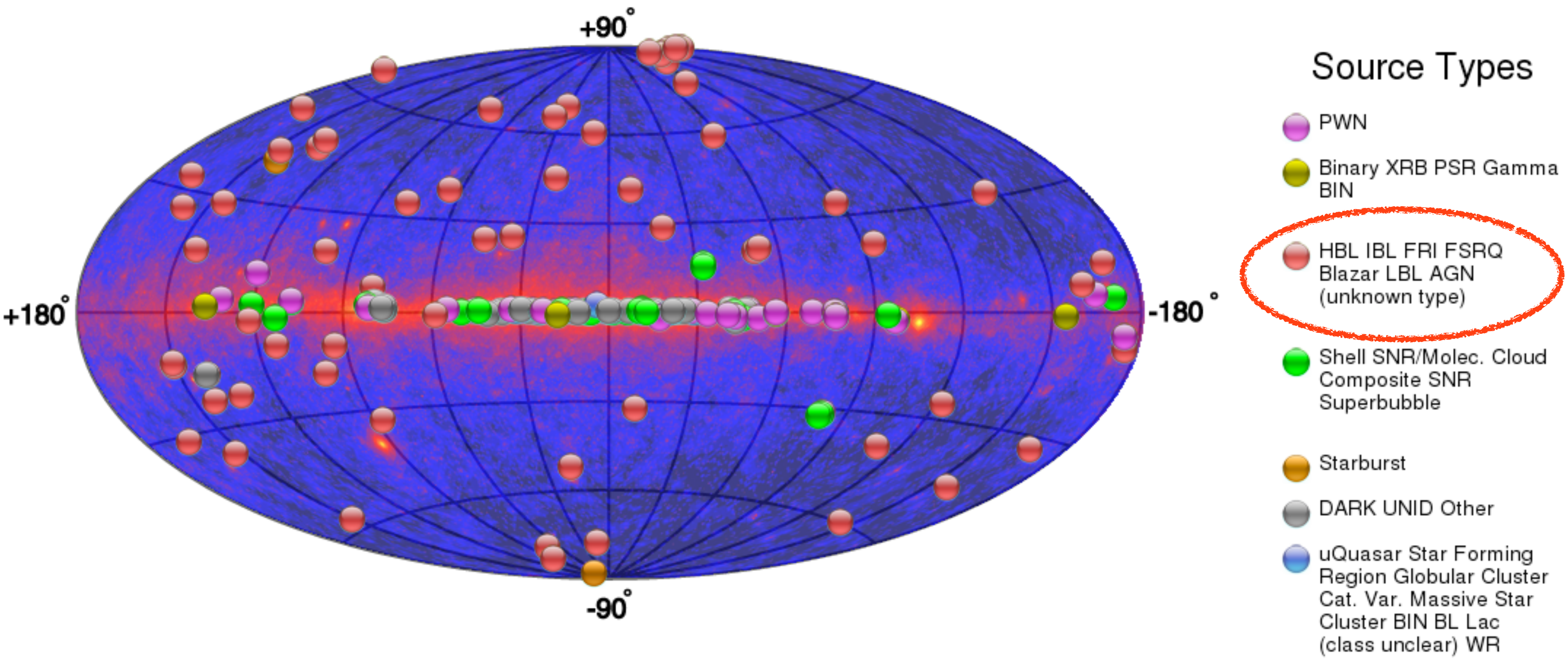
INAF-OA Brera

Introduction: relativistic jets & blazars

1) Jet physics

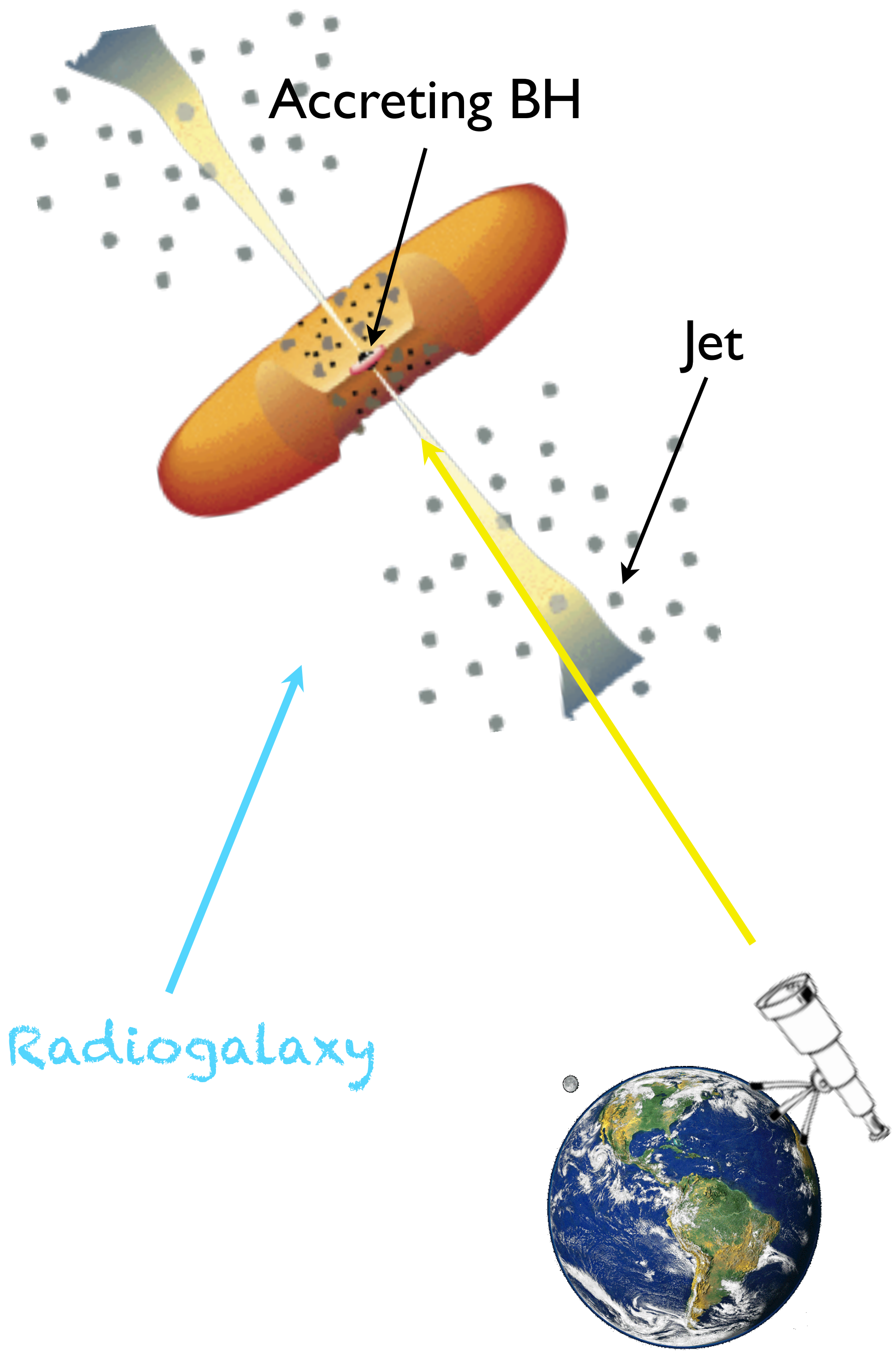
2) Propagation effects

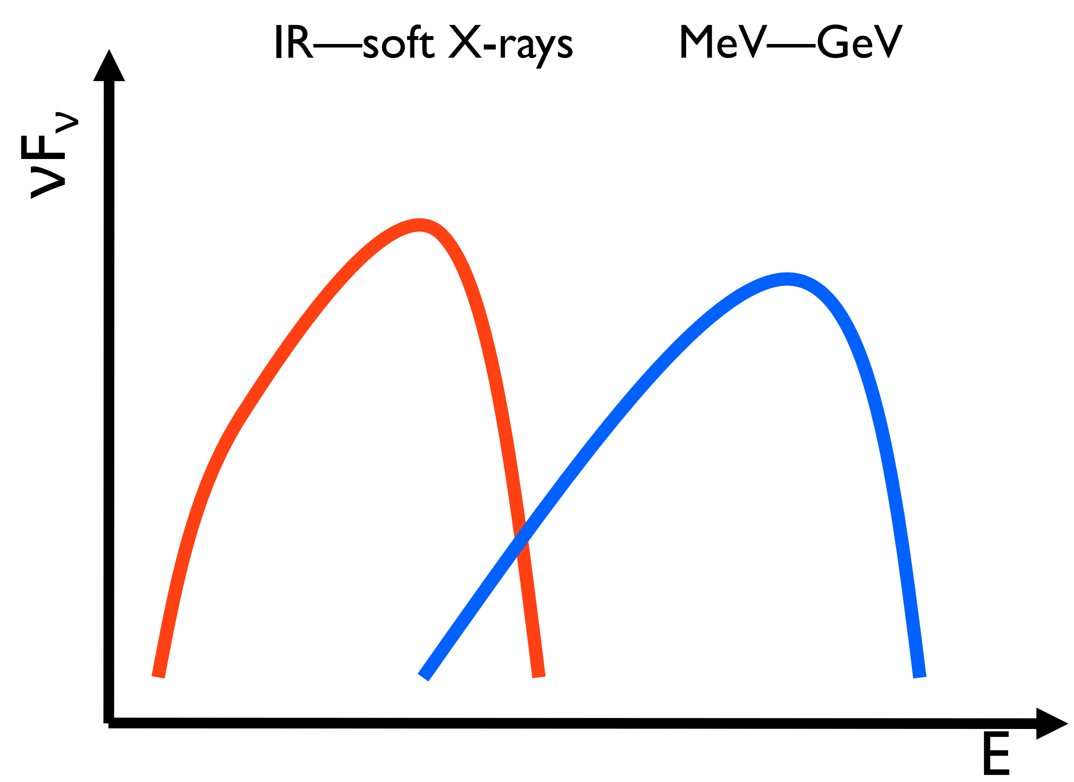
The extragalactic gamma-ray sky: the BLAZAR realm



66 Blazars (all types)

Jets pointing at us: BLAZARS



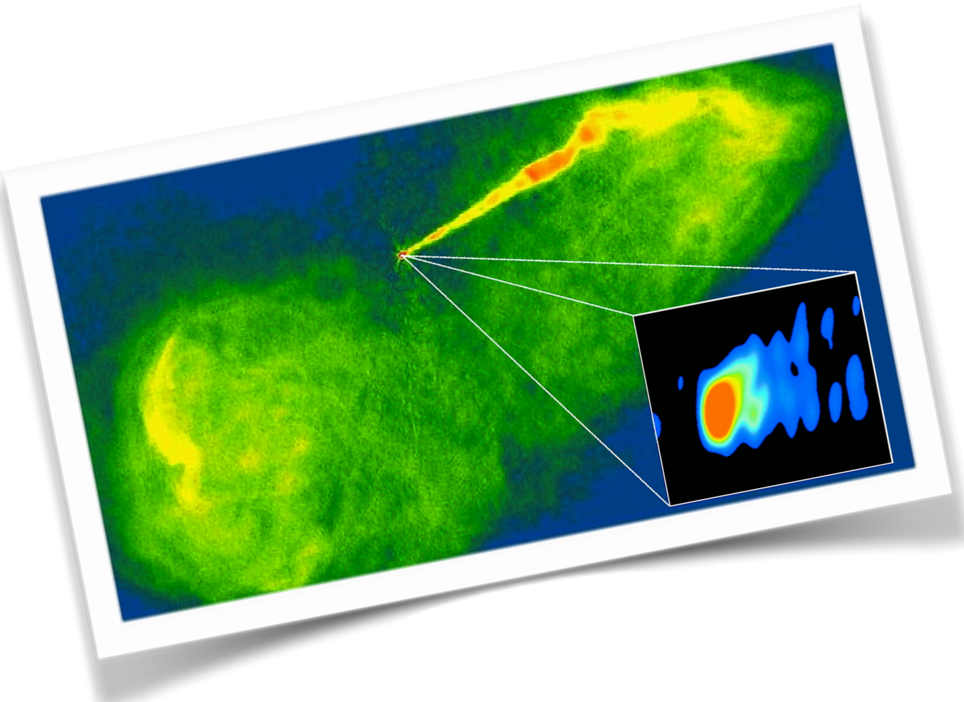


SED dominated by the relativistically boosted non-thermal continuum emission of the jet.

Synchrotron and IC in leptonic models.

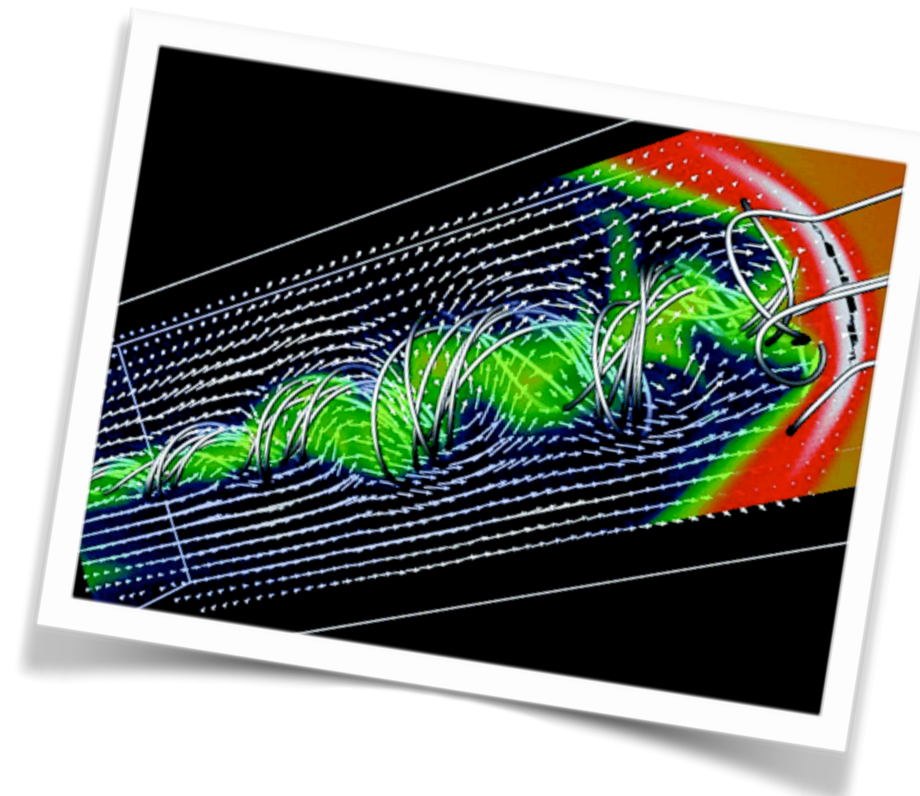
Also **hadronic** scenarios
(proton synchrotron or photo-meson reactions)

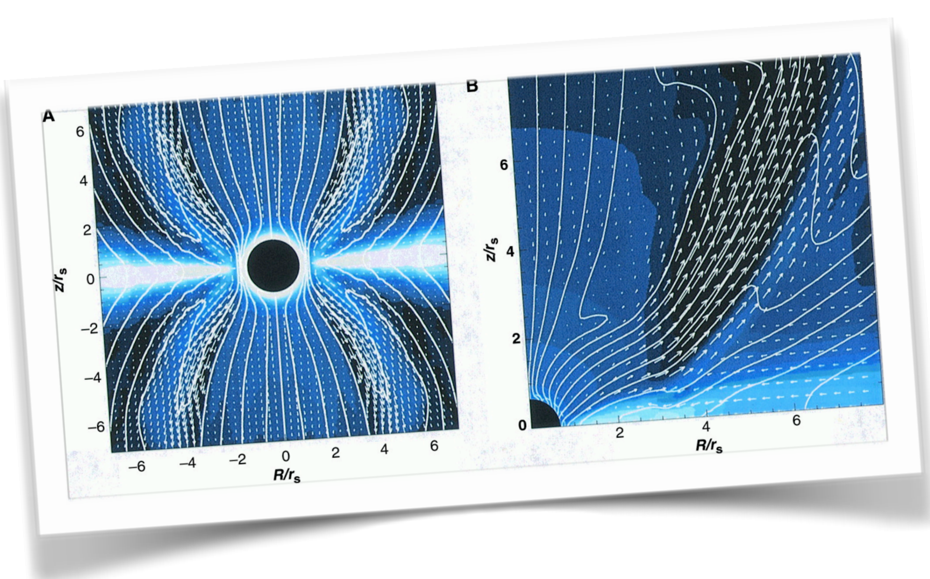
Astrophysical Labs



Jet speed,
composition,
power

Magnetic fields,
particle acceleration
emission mechanisms





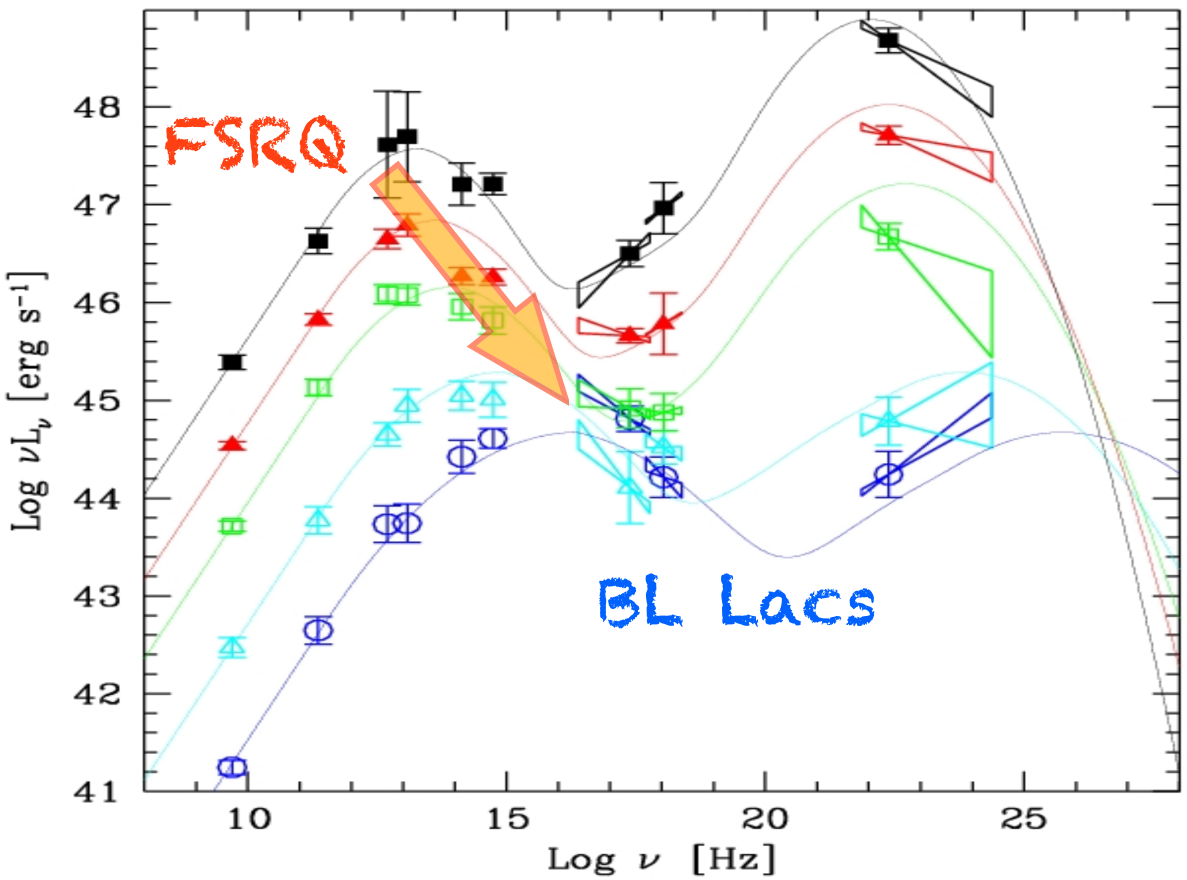
Formation, collimation,
acceleration

Blazars: basic phenomenology

Blazars occur in two flavors:

FSRQ: high power, thermal optical components

BL Lacs: low power, lack of important thermal comp.



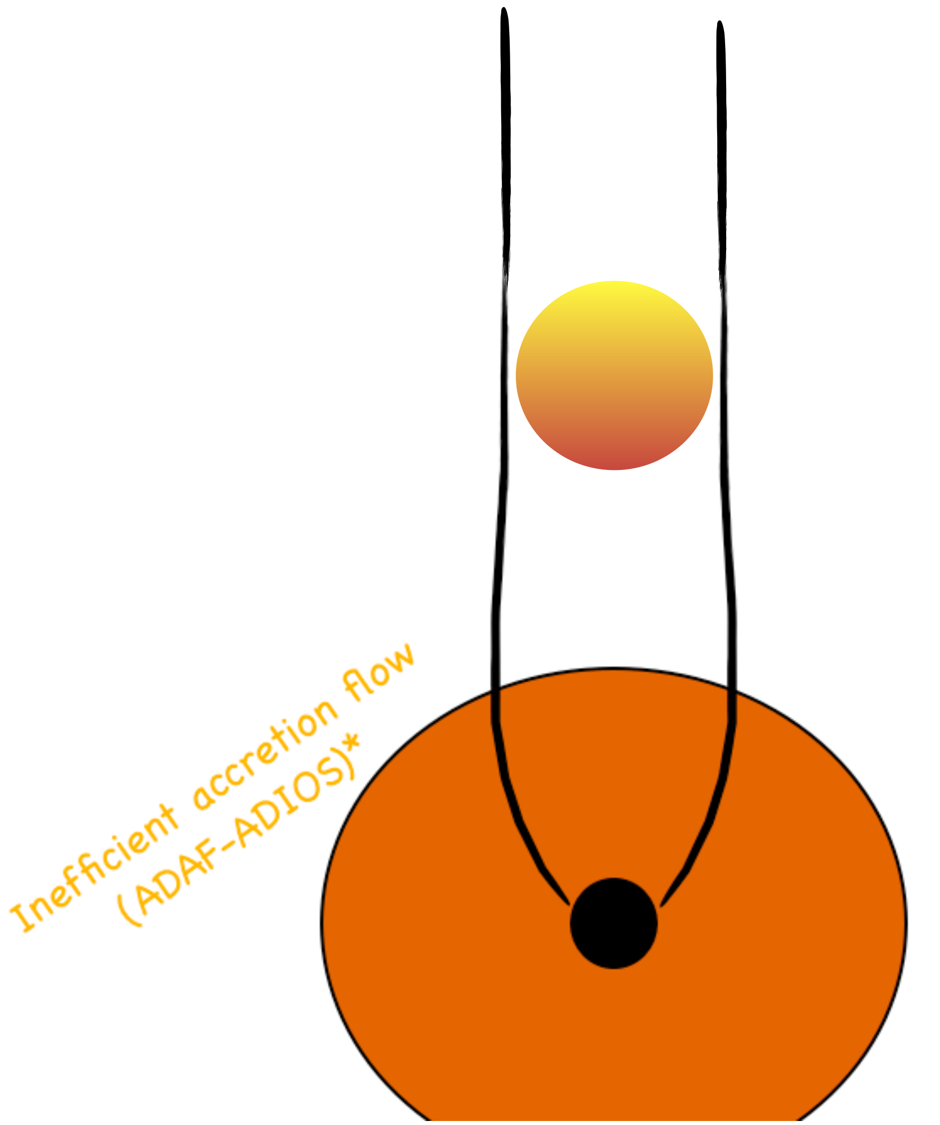
The "blazar sequence"

Fossati et al. 1998

Ghisellini et al. 2017

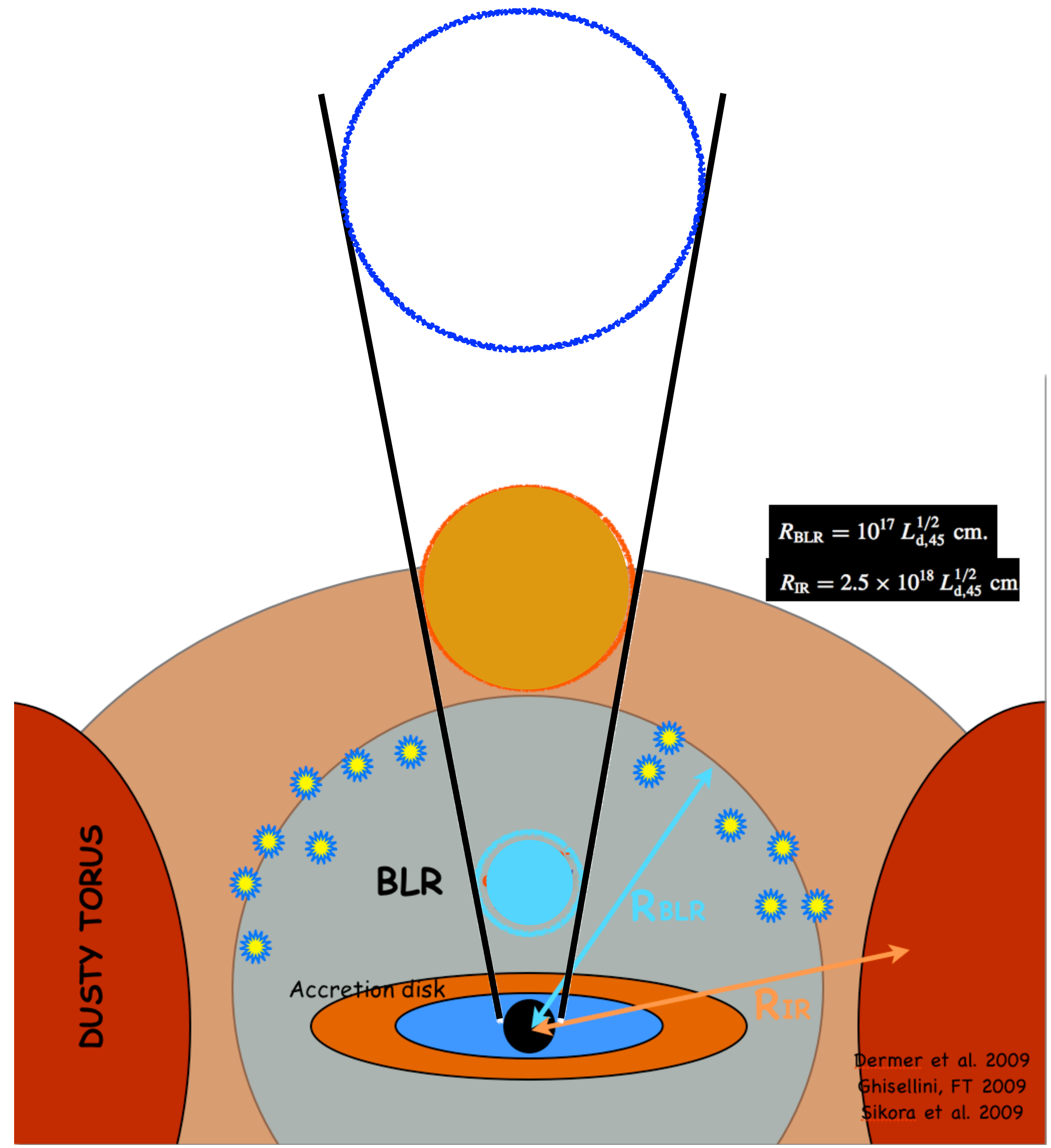
Blazars: basic phenomenology

BL Lacs: "naked" jets



Large majority of
TeV-detected blazars

FSRQ: "dressed" jets



VHE Flat spectrum radio quasars

FSRQ are powerful blazars.

Nuclear environment similar to QSOs, very different from BL Lacs (lines)

⇨ Absorption of gamma-rays ($\gamma\gamma \rightarrow e^{\pm}$)

Still a small fraction of blazars VHE population: 6/66

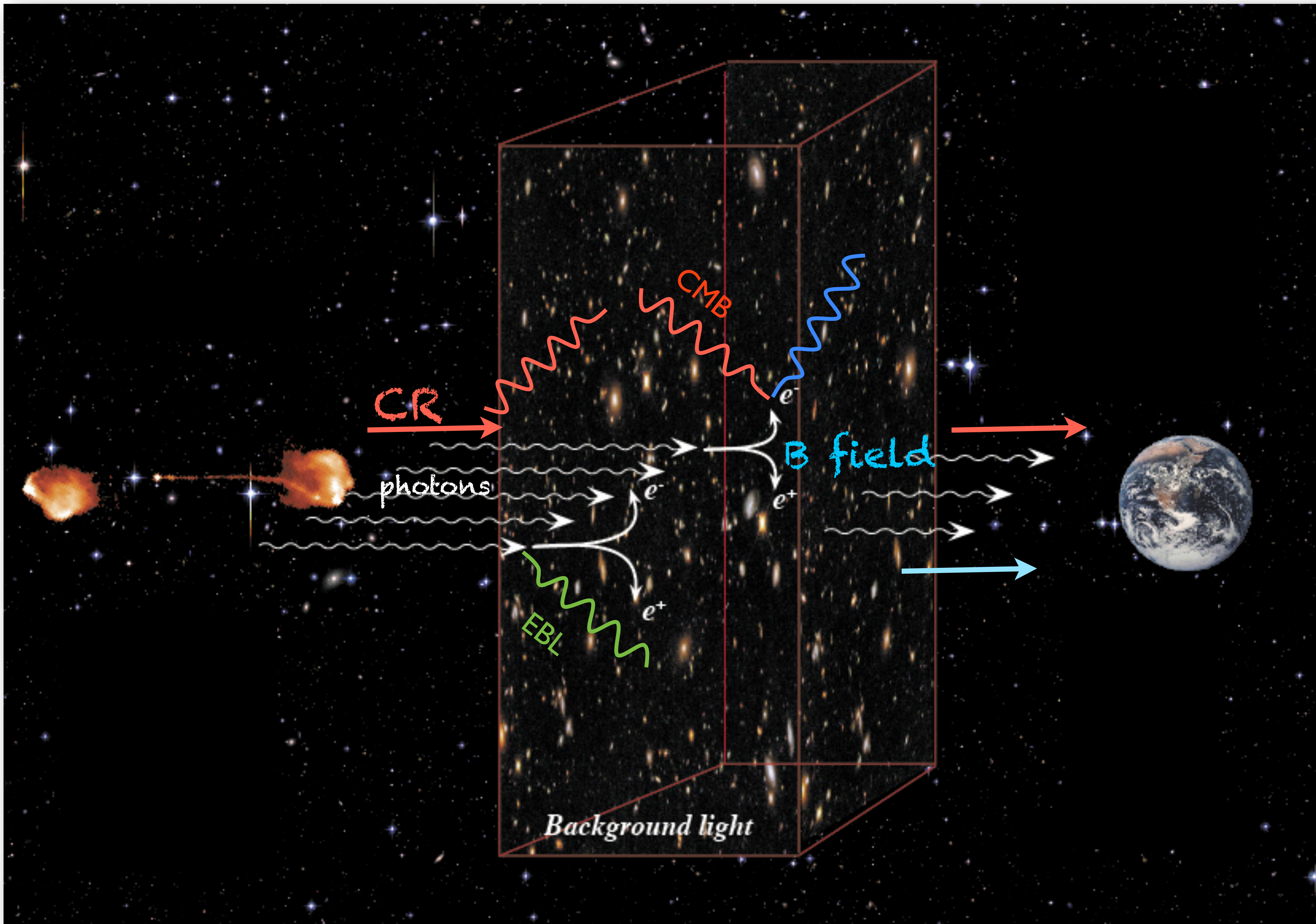
Large redshift (up to z~1!): EBL probes

Quite soft spectra (intrinsic+EBL)

Name	z
PKS 1510-089	0.361
PKS 1222+216	0.432
3C279	0.536
PKS 1441+25	0.939
B0218+367	0.944
PKS 0736+017	0.189

Low energy threshold

Cosmic particle beams/propagation effects

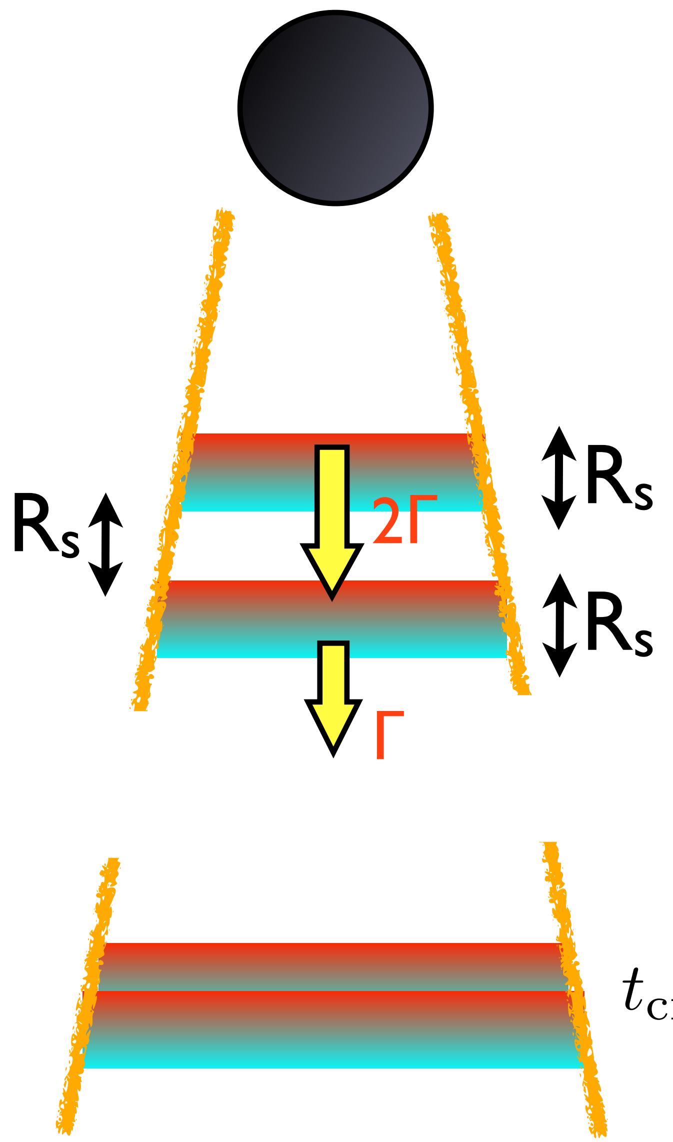


1) Jet physics

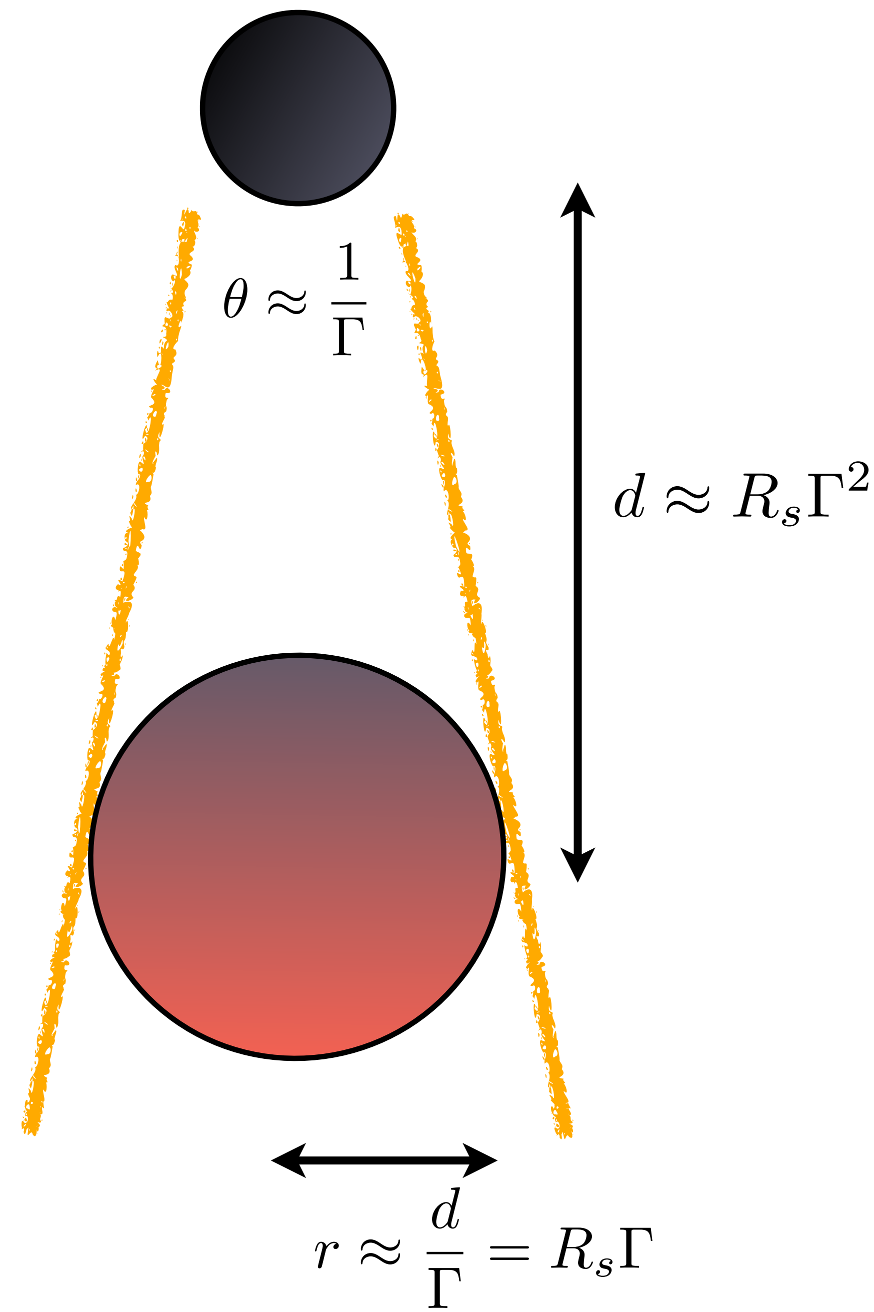
- ➤ Minimum variability timescale
- ➤ Hadronic vs leptonic emission
- ➤ Radiogalaxies

2) Propagation effects

Minimum variability timescale



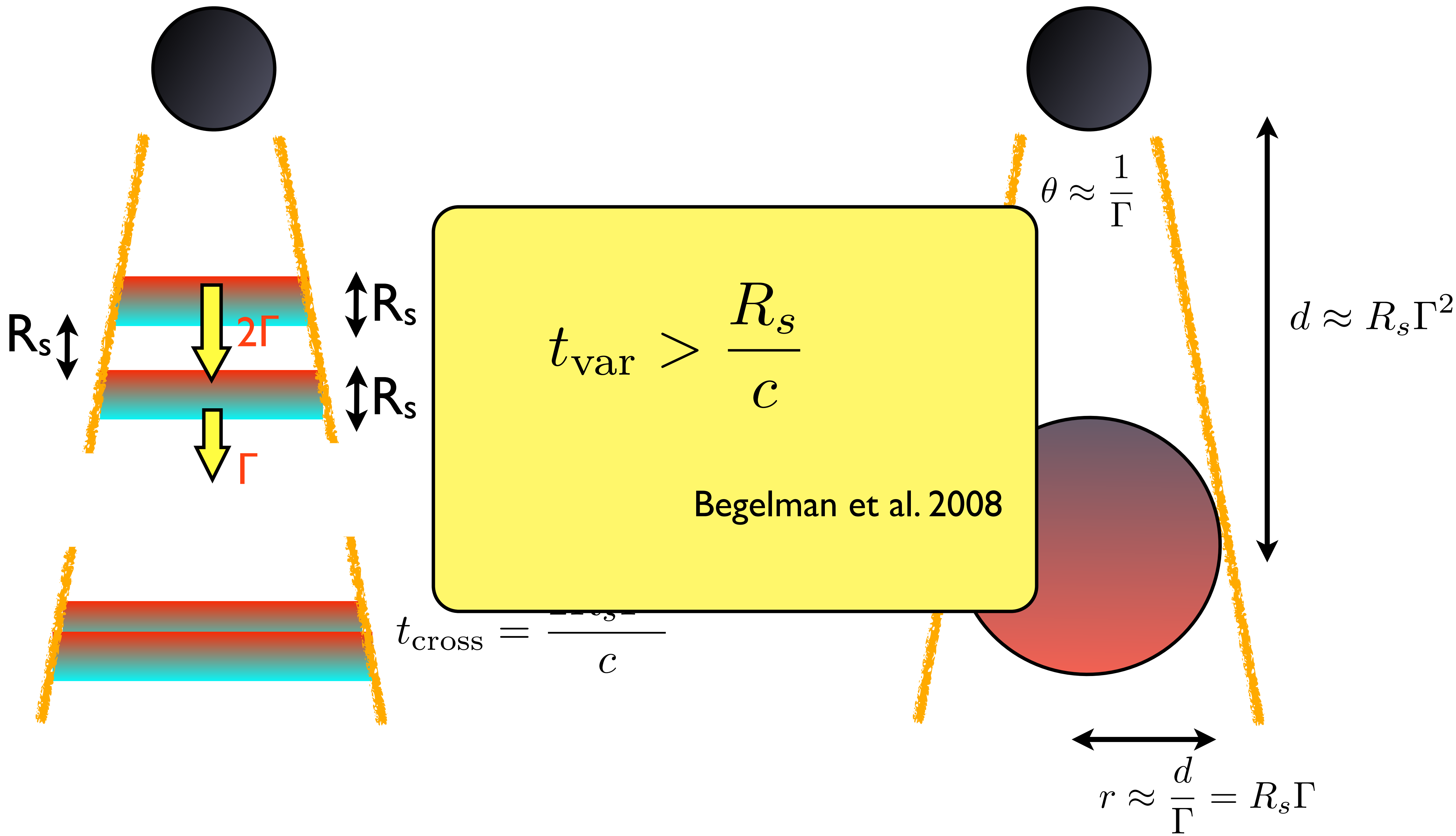
$$t_{\rm cross} = \frac{2 R_s \Gamma^2}{c}$$



$$t_{\rm obs} = \frac{t_{\rm cross}}{2\Gamma^2} = \frac{R_s}{c}$$

$$t_{\rm obs} = \frac{r}{c\,\delta} = \frac{R_s \Gamma}{c\,\delta} \simeq \frac{R_s}{c}$$

Minimum variability timescale



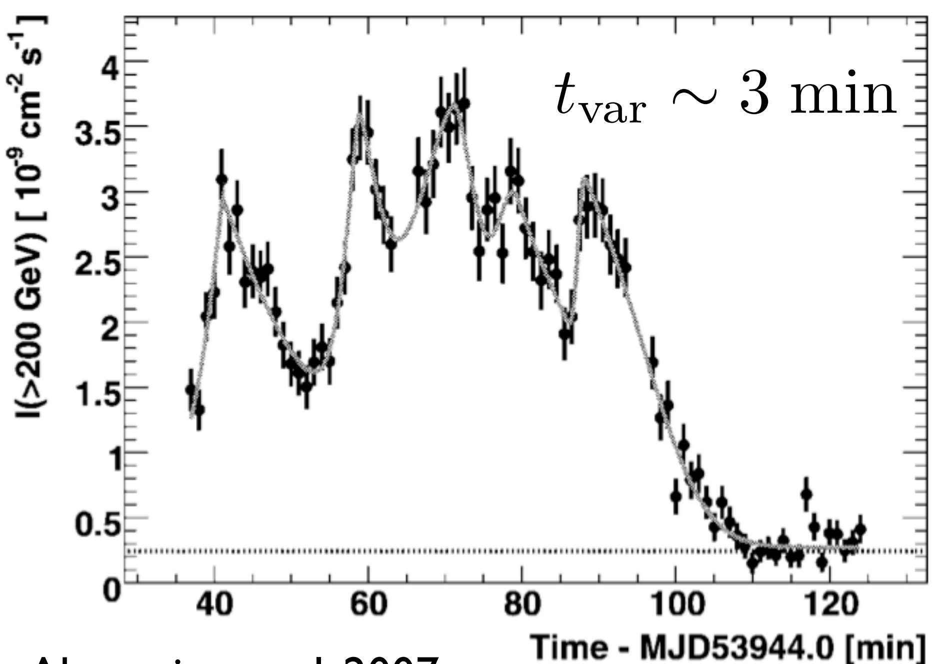
$$t_{\rm obs} = \frac{t_{\rm cross}}{2\Gamma^2} = \frac{R_s}{c}$$

$$t_{\rm obs} = \frac{r}{c\,\delta} = \frac{R_s\Gamma}{c\,\delta} \simeq \frac{R_s}{c}$$

Ultra-rapid variability

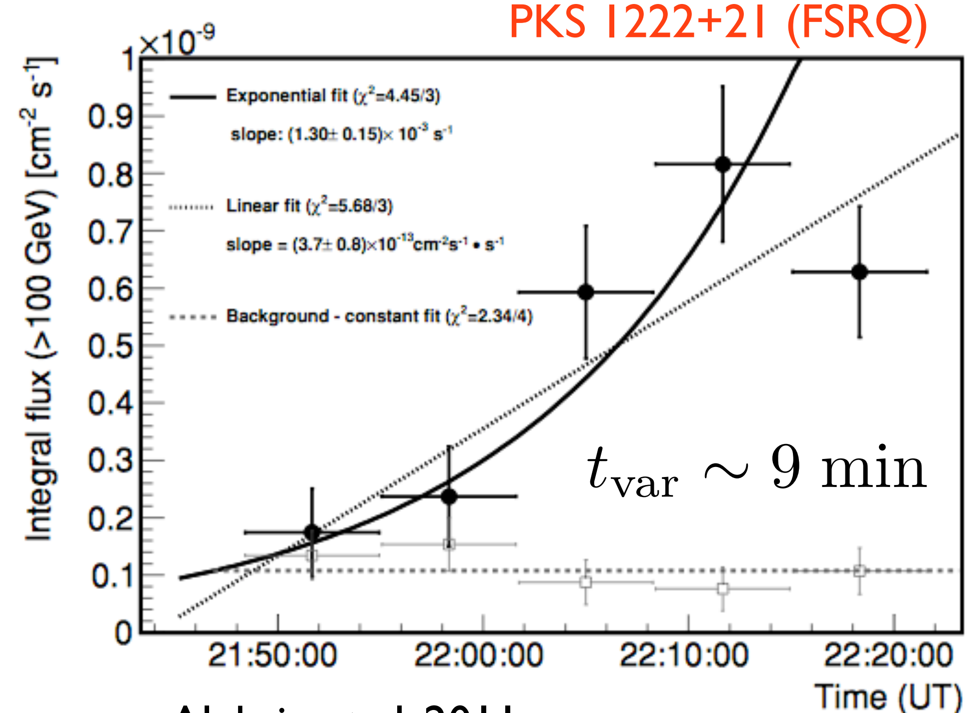
IACTs

PKS 2155-304 (BL Lac)



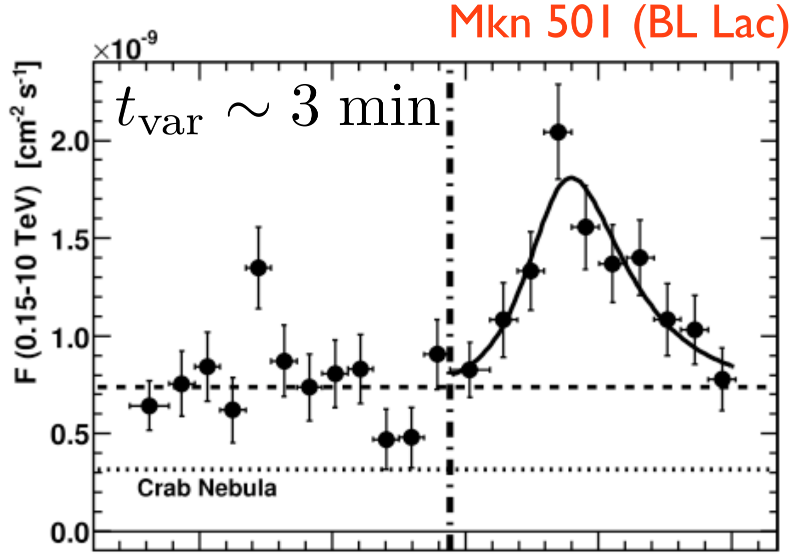
Aharonian et al. 2007

PKS 1222+21 (FSRQ)



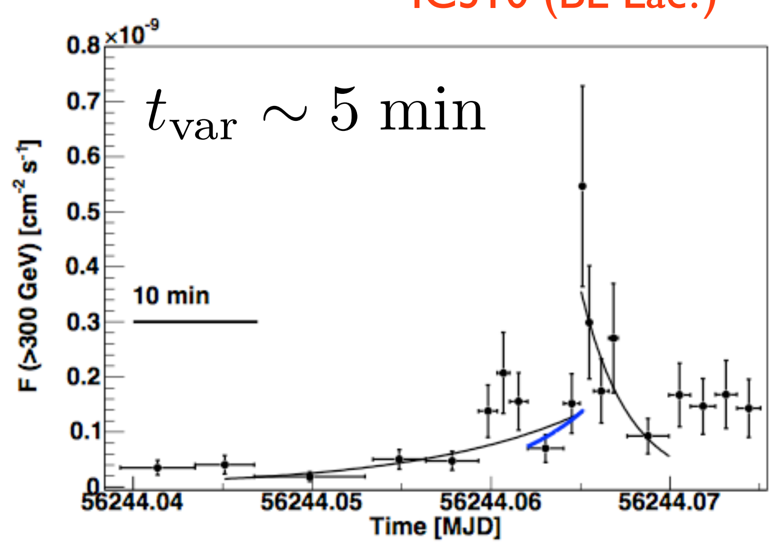
Aleksic et al. 2011

Mkn 501 (BL Lac)



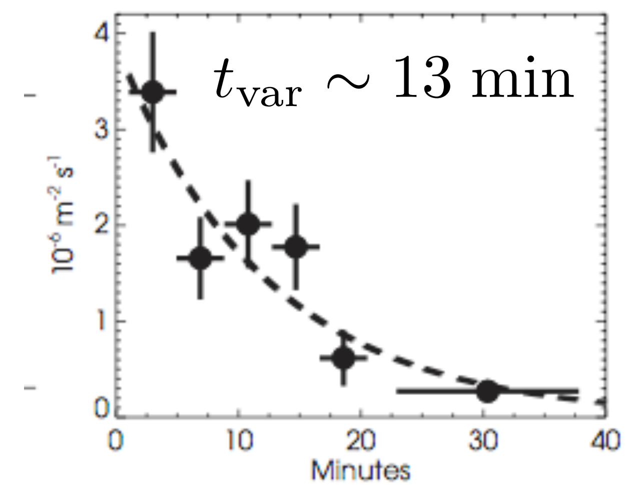
Albert et al. 2007

IC310 (BL Lac?)



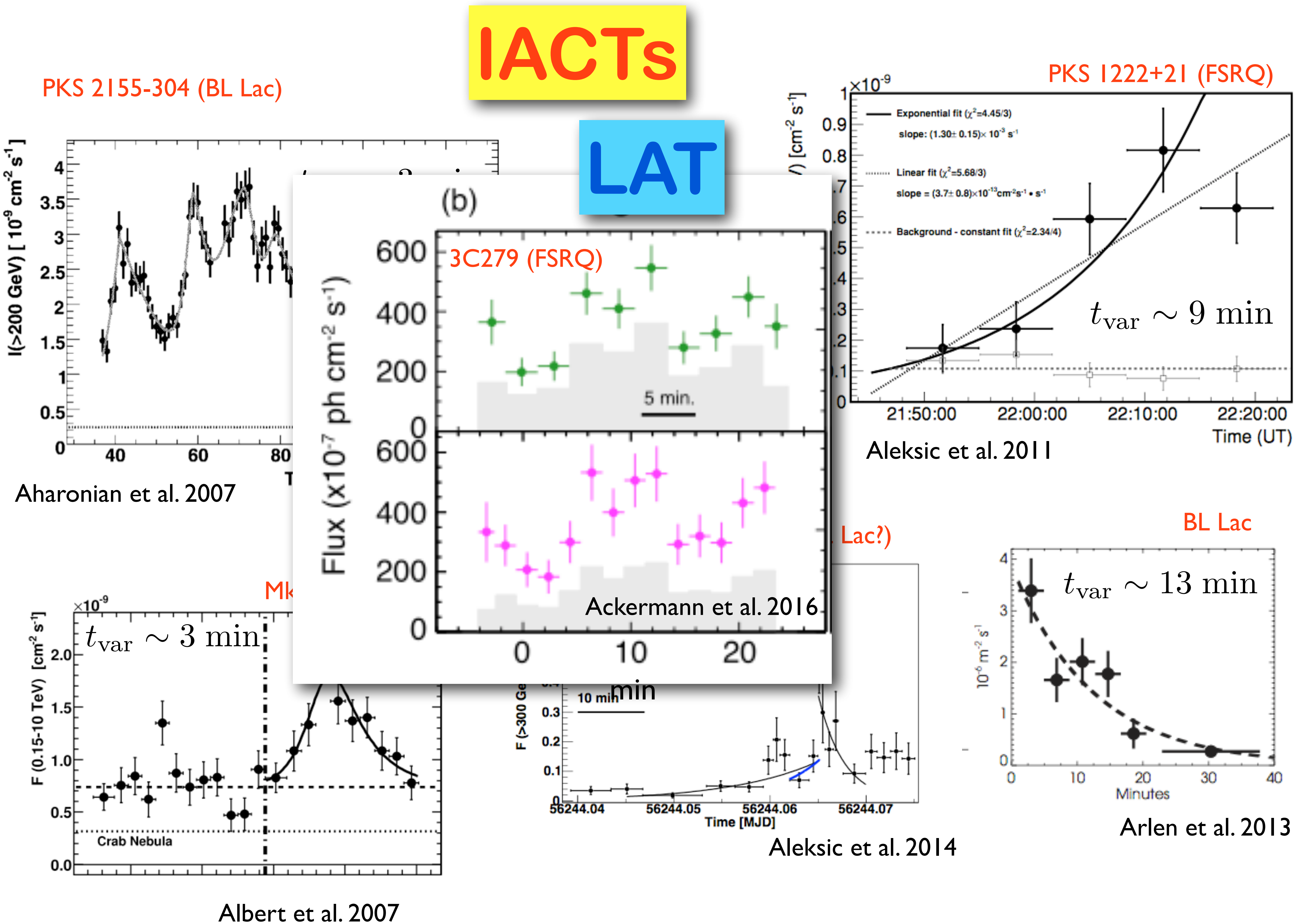
Aleksic et al. 2014

BL Lac

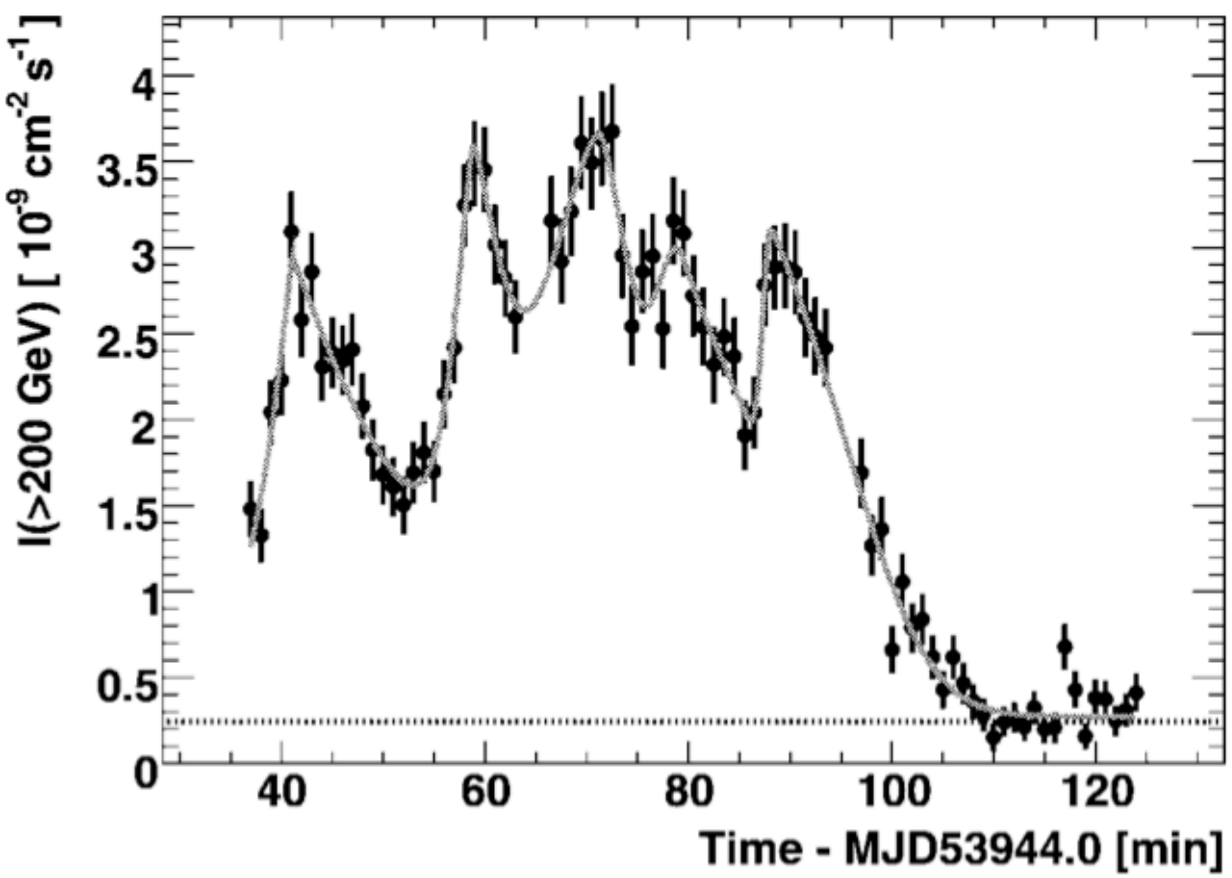


Arlen et al. 2013

Ultra-rapid variability



Ultra-rapid variability

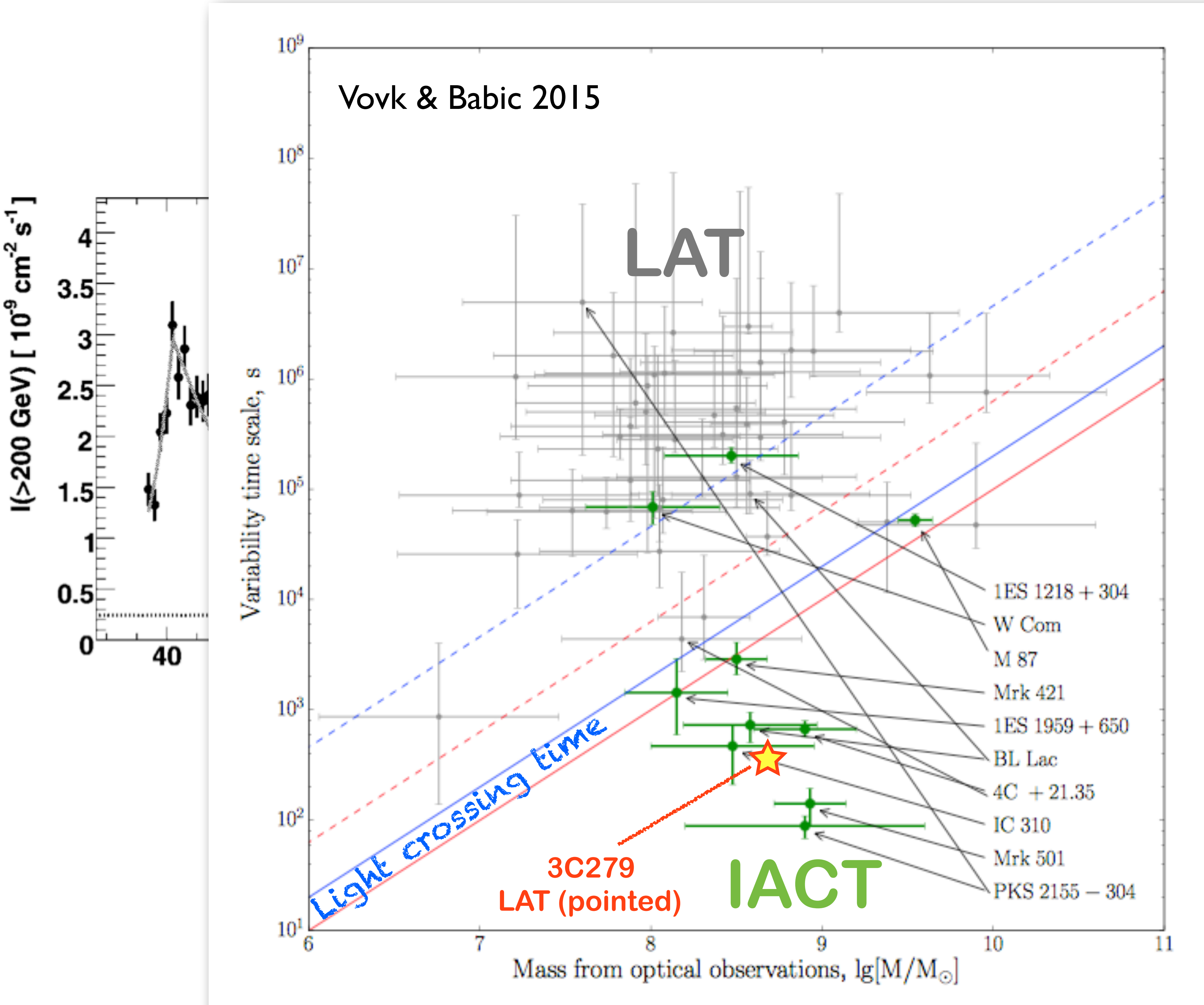


$$t_{\rm var} \sim 3 \text{ min}$$

$$\Delta t_{\rm BH} = \frac{r_g}{c} = \frac{GM}{c^3} = 8.3 M_8 \text{ min}$$

$$t_{\rm var} < \Delta t_{\rm BH}$$

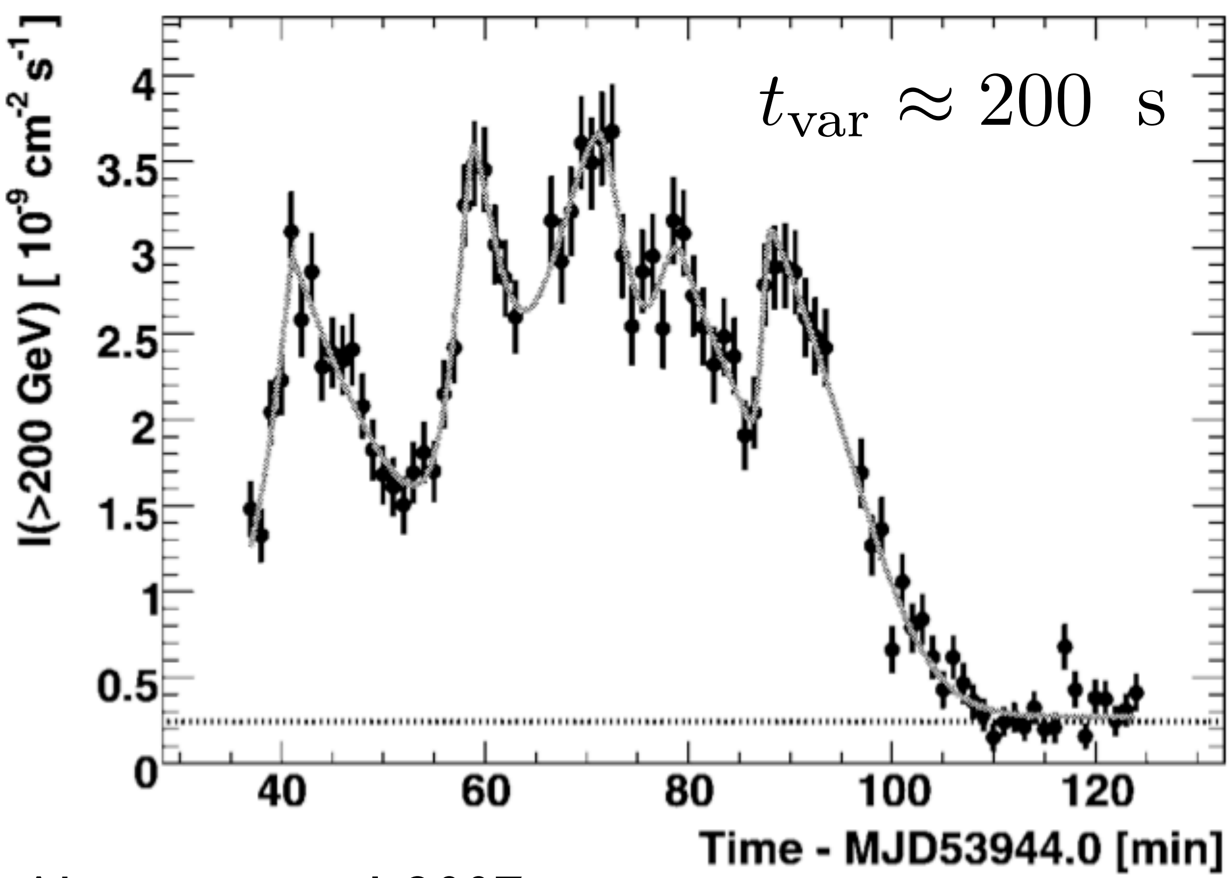
Ultra-rapid variability



$= 8.3 M_8$ min

Ultra-rapid variability

PKS 2155-304@TeV



Aharonian et al. 2007

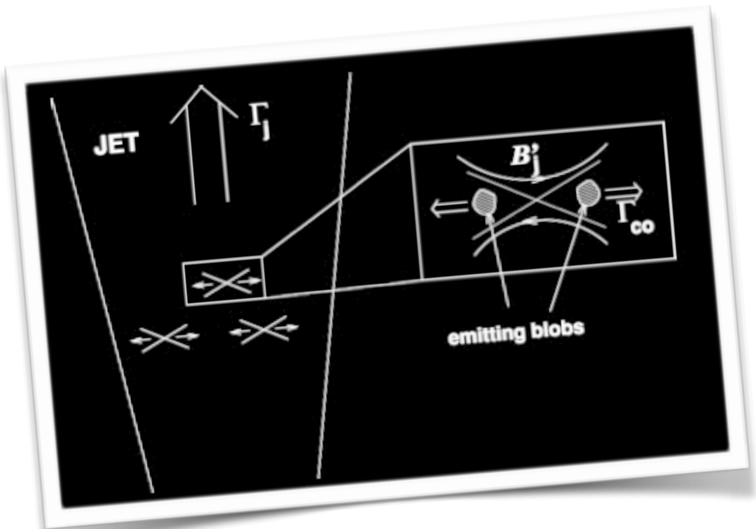
$$\Delta t_{\rm BH} = \frac{r_g}{c} = \frac{GM}{c^3} = 8.3 M_8 \text{ min}$$

$$t_{\rm var} < \Delta t_{\rm BH}$$

Emission from (small) sub-regions

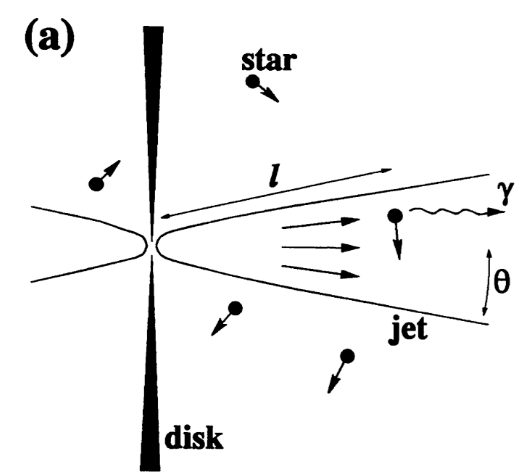
Begelman et al. 2008
Ghisellini & FT 2008
Giannios et al. 2009

Scenarios on the market:

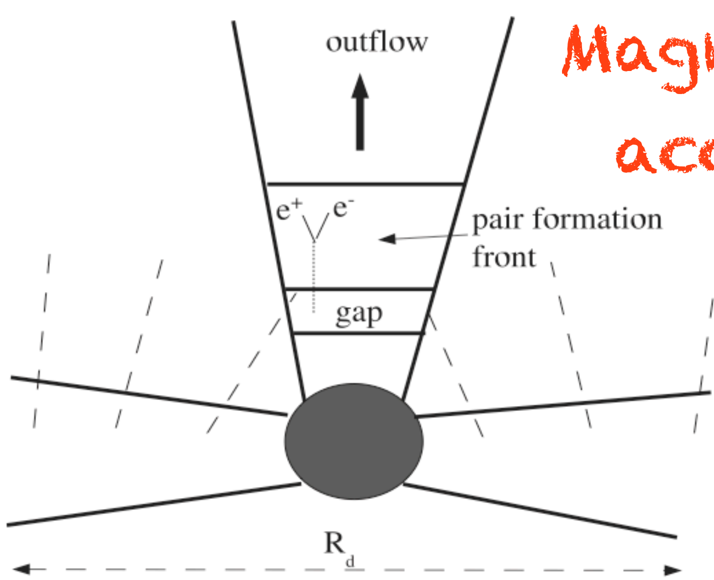


Magnetic reconnection
Giannios et al 2009, 2013

Star-jet interaction

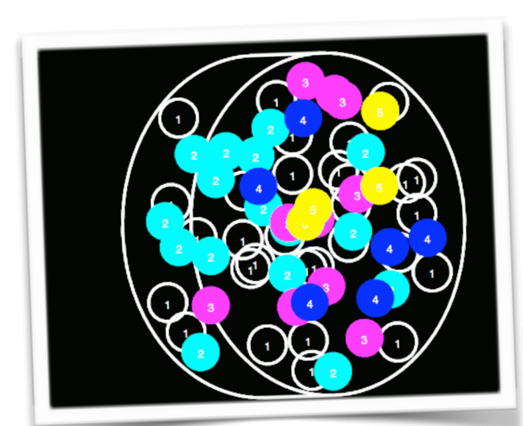


Bednarek et al. 1997
Barkov et al. 2010,2012



Magnetospheric acceleration

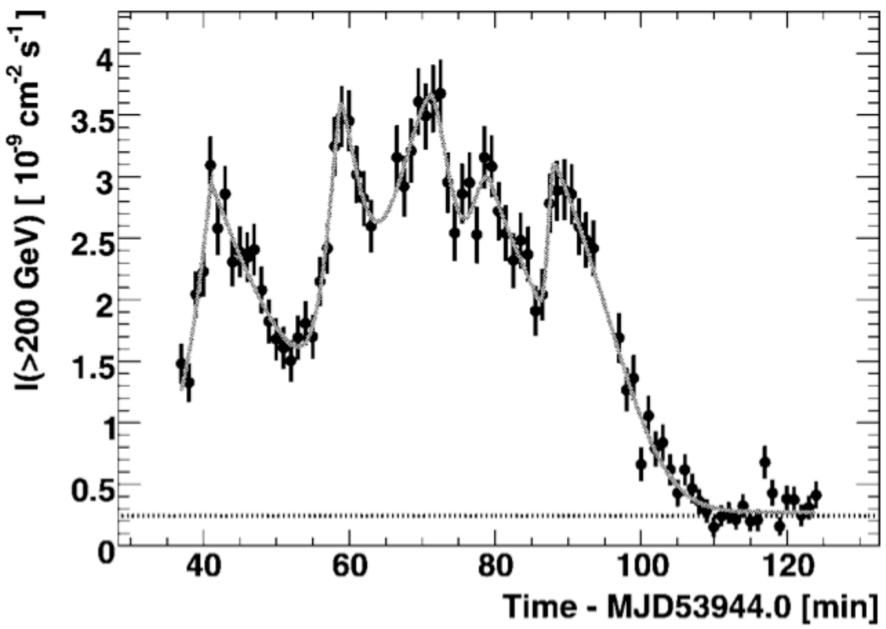
Levinson & Rieger 2011
also Neronov & Aharonian 2007
MAGIC Coll. 2015



Turbulence

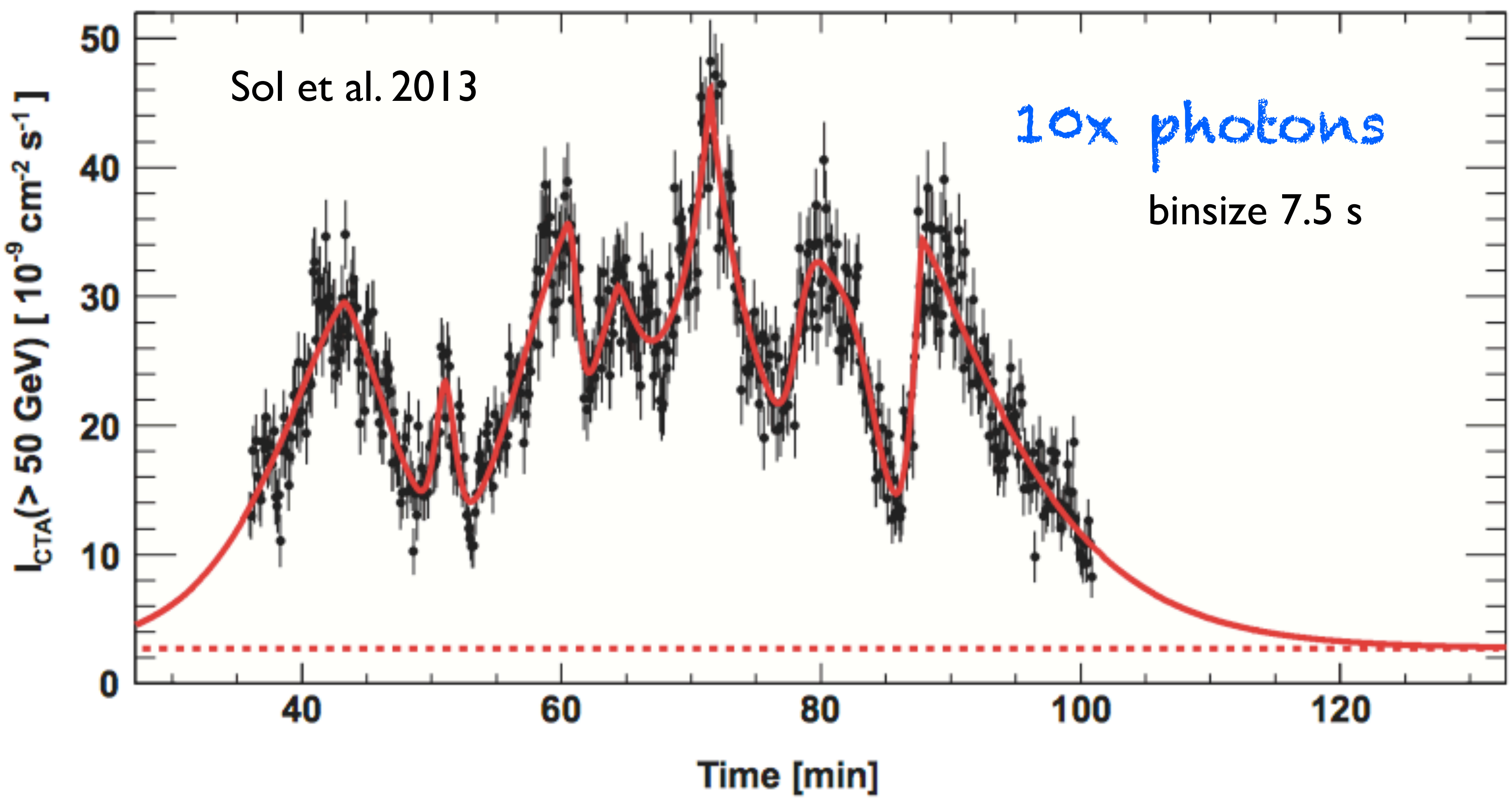
Marscher 2010, 2014
Narayan & Piran 2012

Prospects for CTA



t_{var} of 25 s could be detectable!

$$R \sim 7 \times 10^{11} \delta \text{ cm}$$



Leptons or hadrons?

Sources of UHECR?

Sources of HE neutrinos?

Jets provide a natural environment for hadron acceleration.

Expected electromagnetic signatures

e.g. Mannheim 1992, 1993

Leptons or hadrons?

$$p + \gamma \rightarrow n + \pi^+ \qquad \pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \bar{\nu_e} + \bar{\nu_\mu} + \nu_\mu$$

$$p + \gamma \rightarrow p + \pi^0 \qquad \pi^0 \rightarrow 2\gamma$$

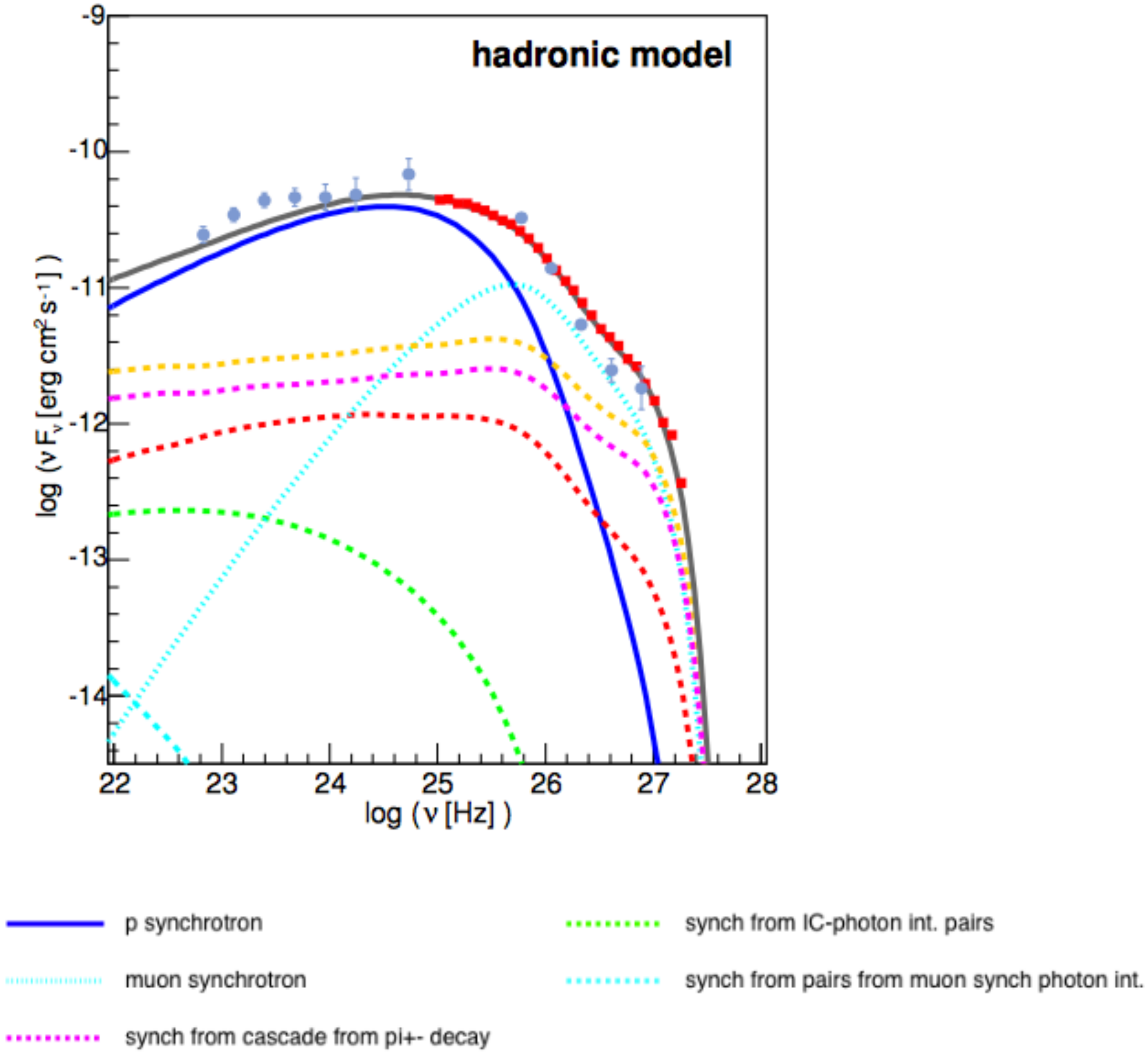
→ Cascade

Variable (<day) emission probably LEPTONIC

Hadronic baseline?

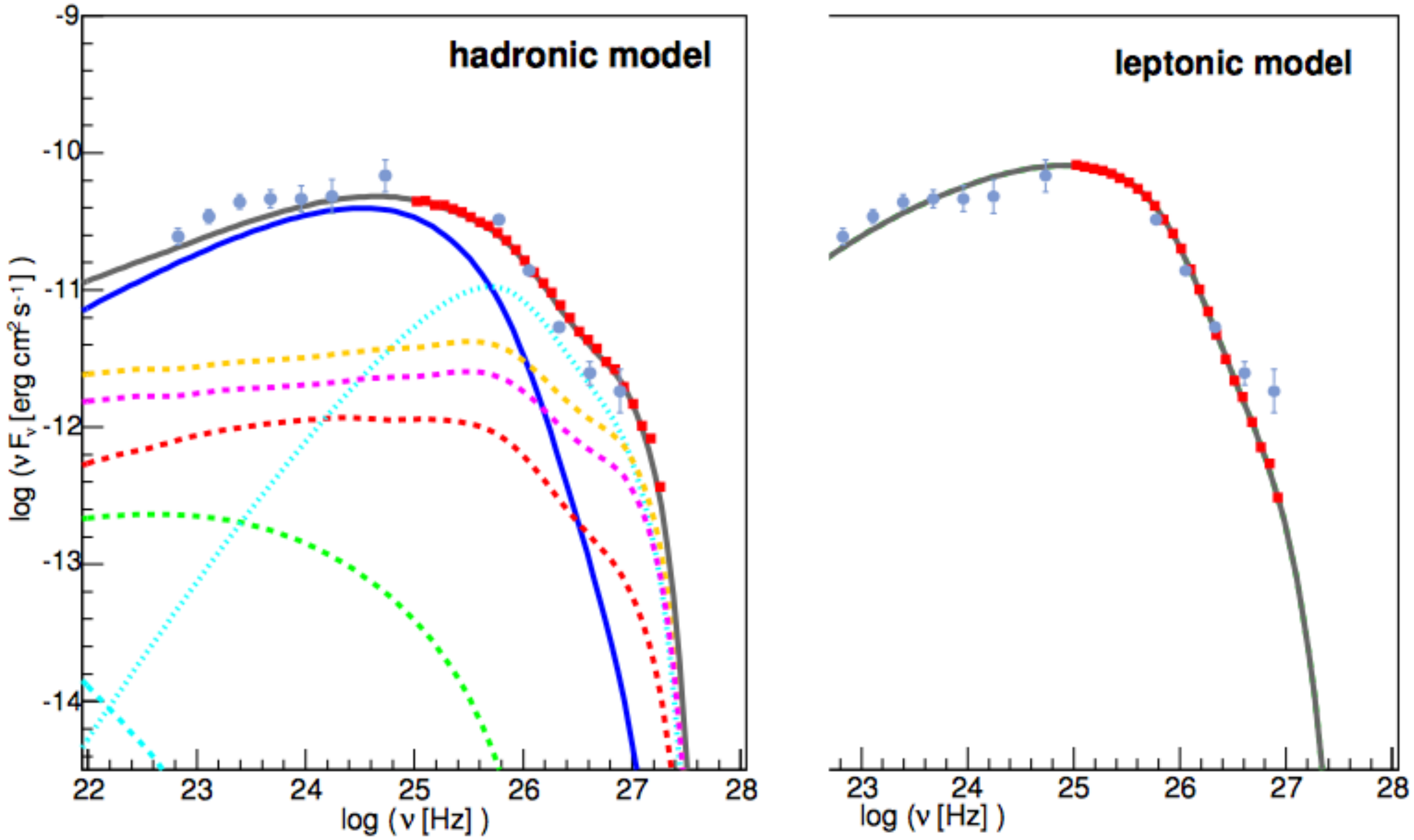
More likely in FSRQ (intense photon field)?

Leptons or hadrons?



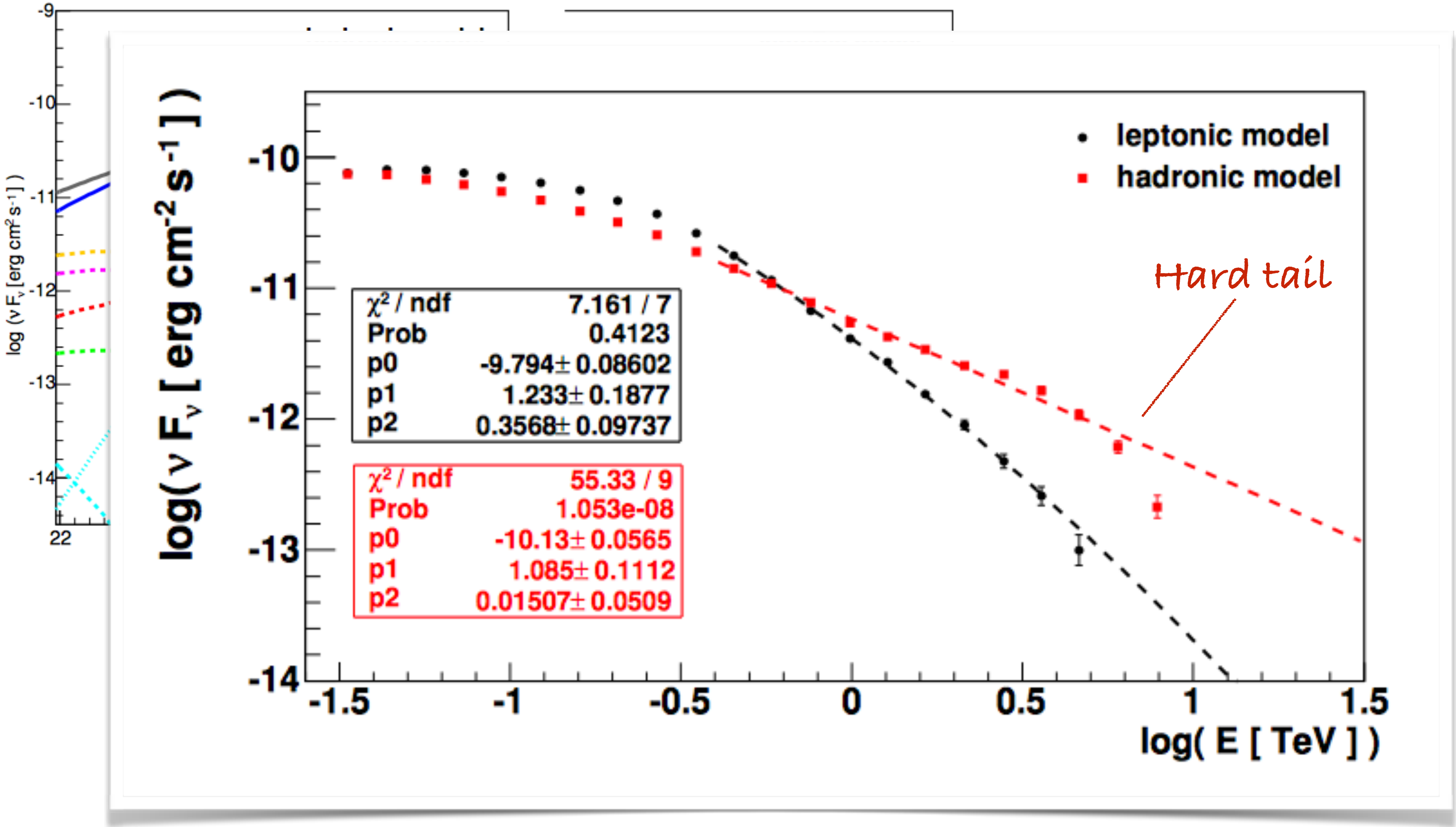
Zech et al. 2017

Leptons or hadrons?



Zech et al. 2017

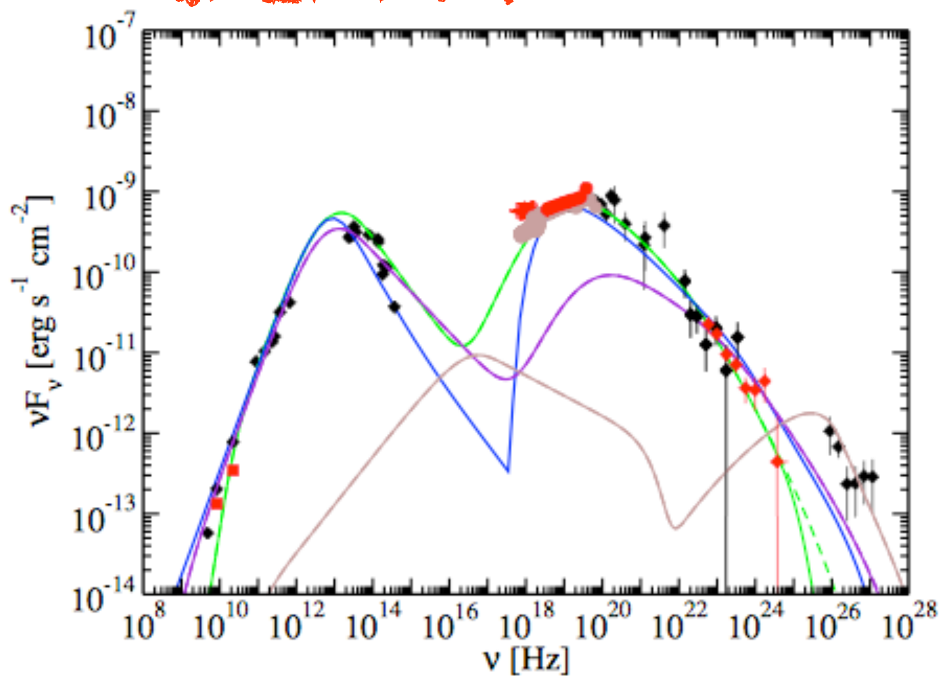
Leptons or hadrons?



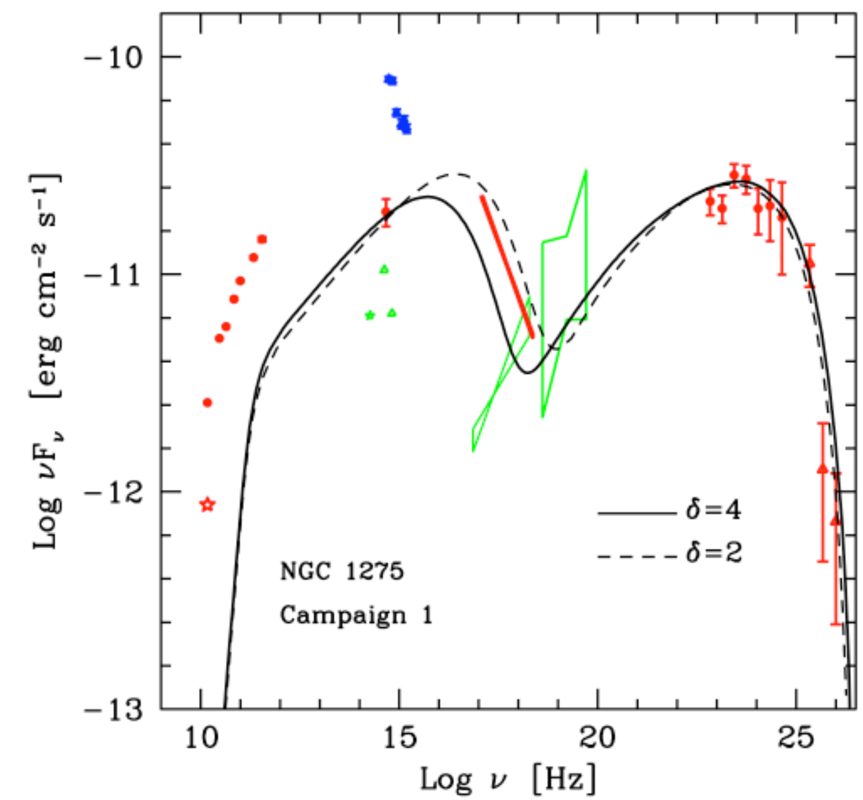
Zech et al. 2017

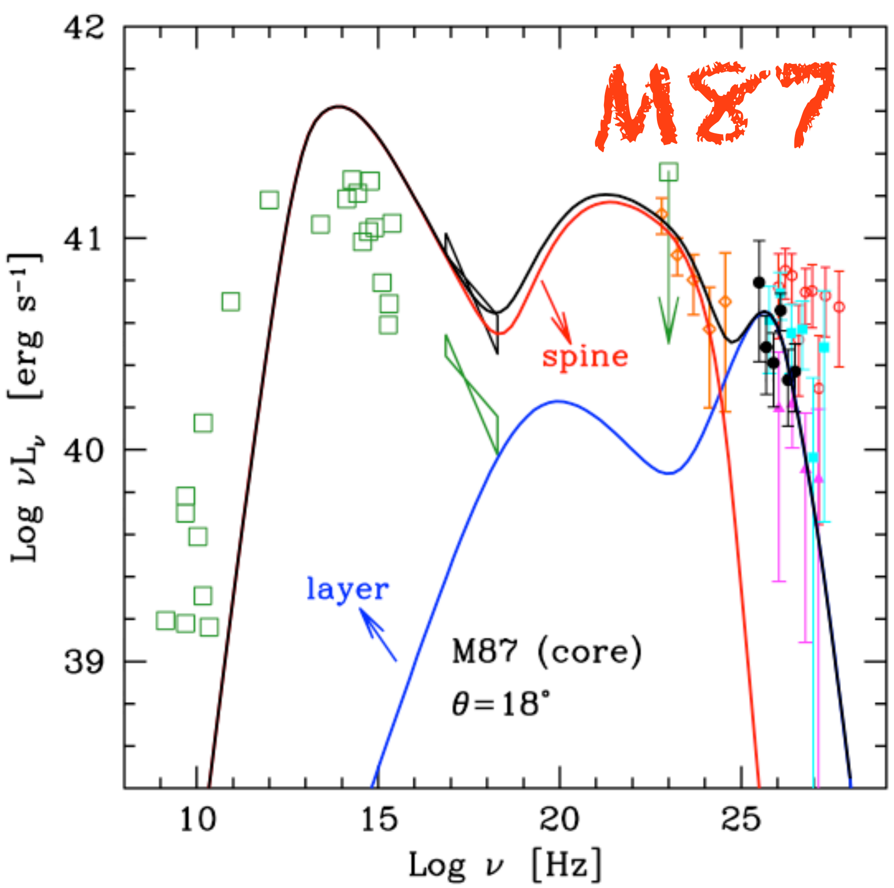
The radiogalaxy zoo

Cen A



NGC 1275





In all cases the angle is intermediate, $\theta<20^{o}$

Origin?

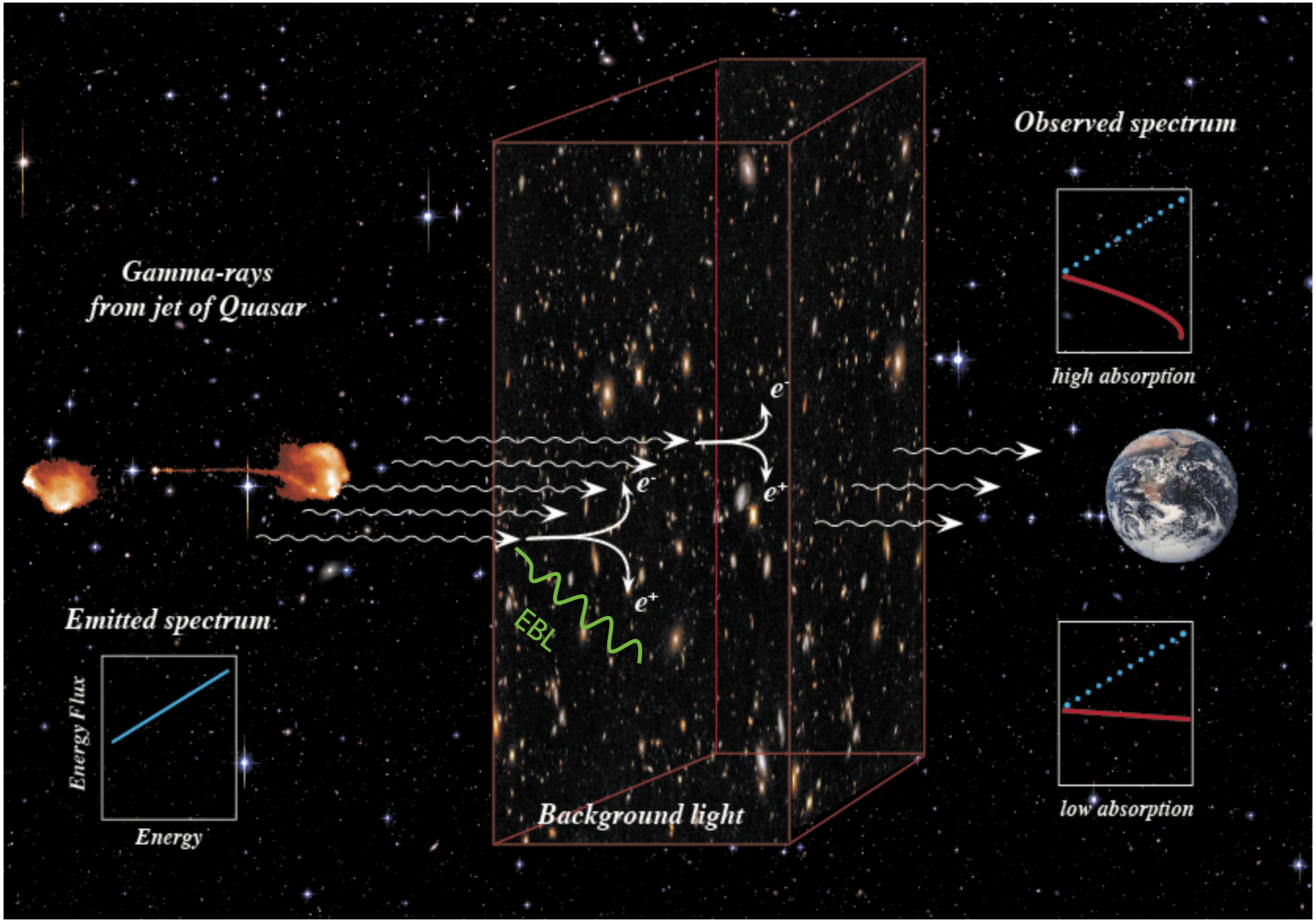
Two-flow jet (spine-layer)	Huge absorption at large θ
Magnetospheric emission	Huge absorption at E>10 TeV
Reconnection mini-jets	Huge absorption at large θ
Stars/clouds in jet	Absorption
Hadronic emission	Absorption? Too steep spectra?

1) Jet physics

2) Propagation effects

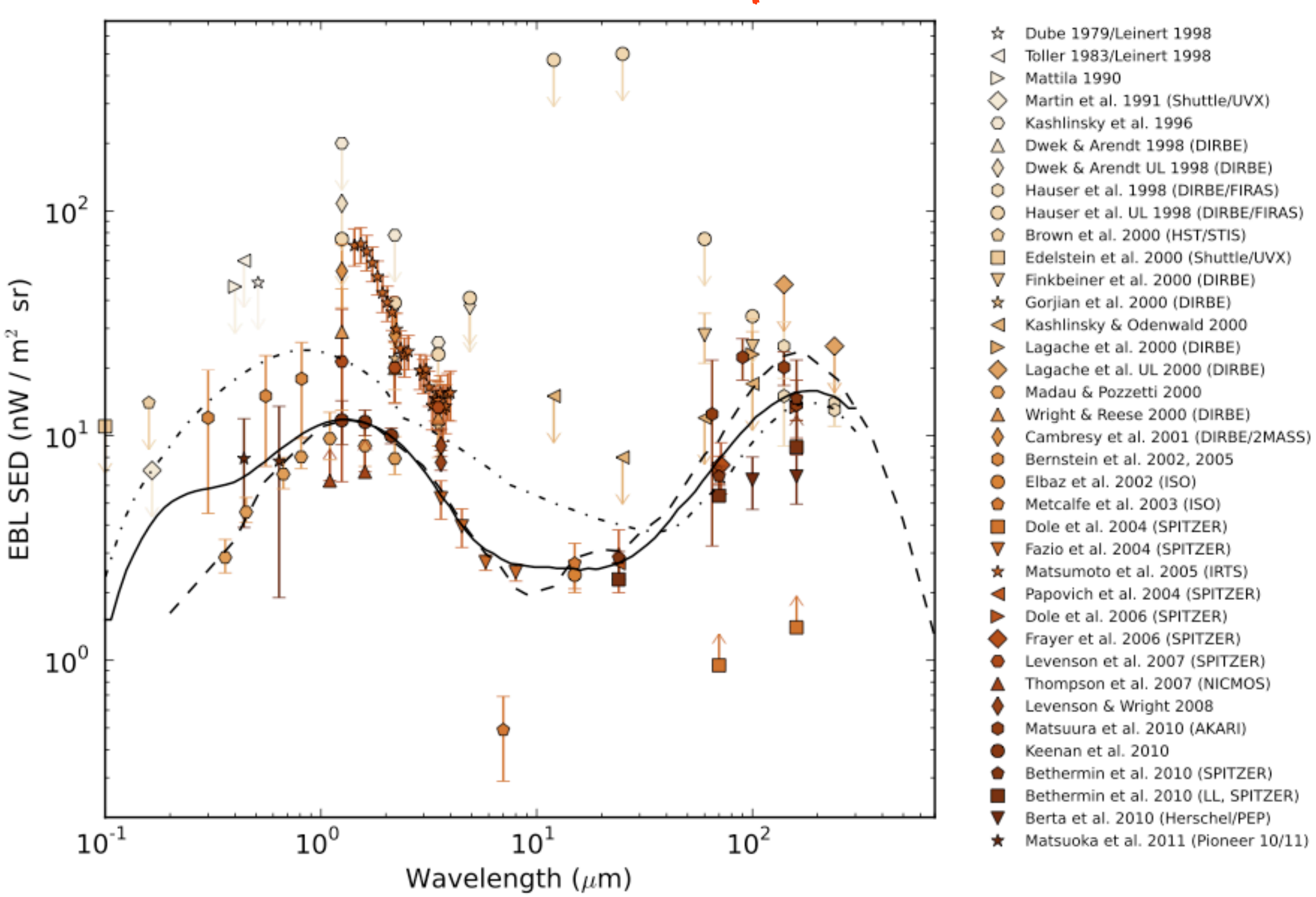
- ➤ EBL
- ➤ Intergalactic magnetic field
- ➤ Hadronic beams

Propagation effects: EBL



Propagation effects: EBL

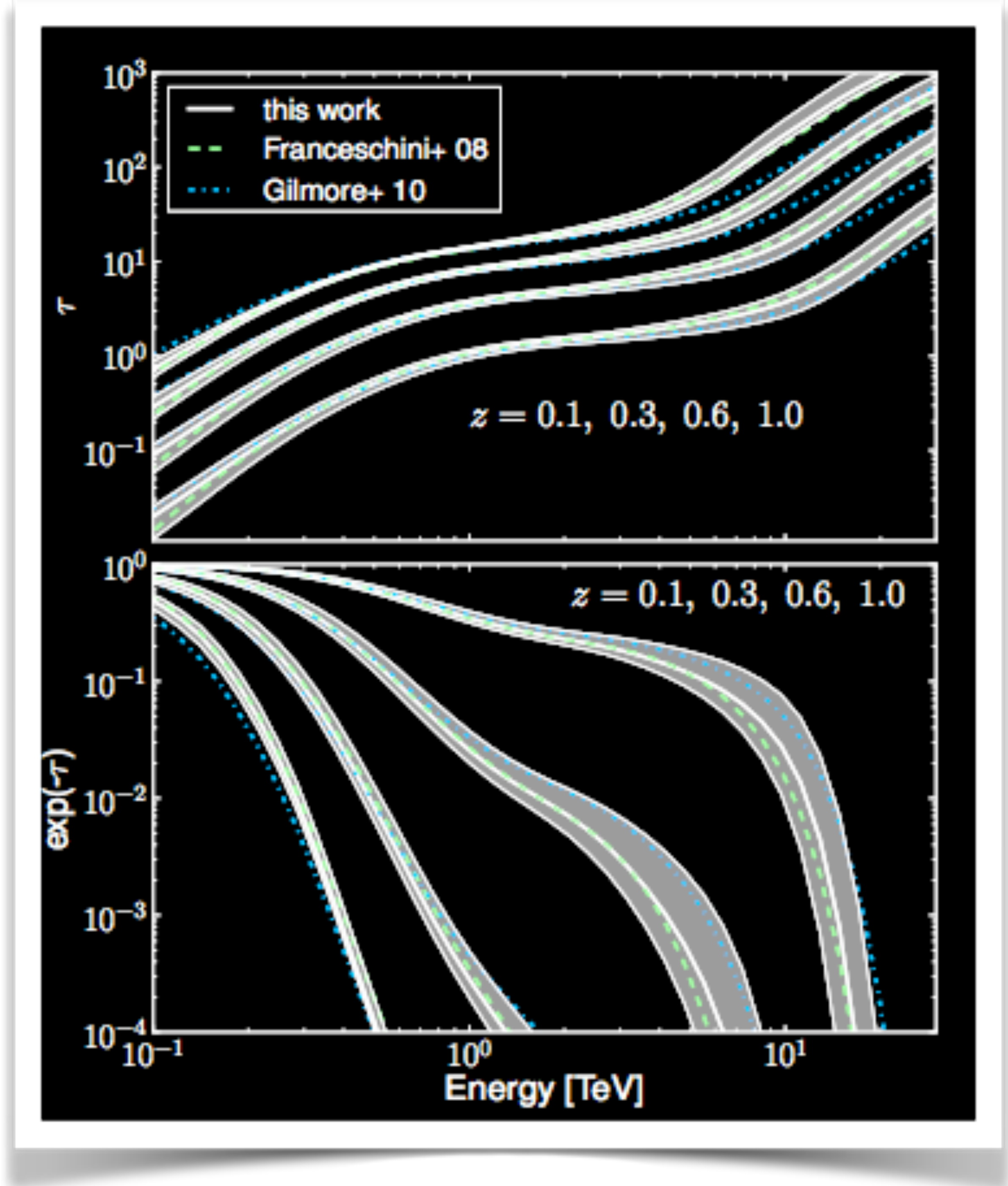
Direct Reproc.



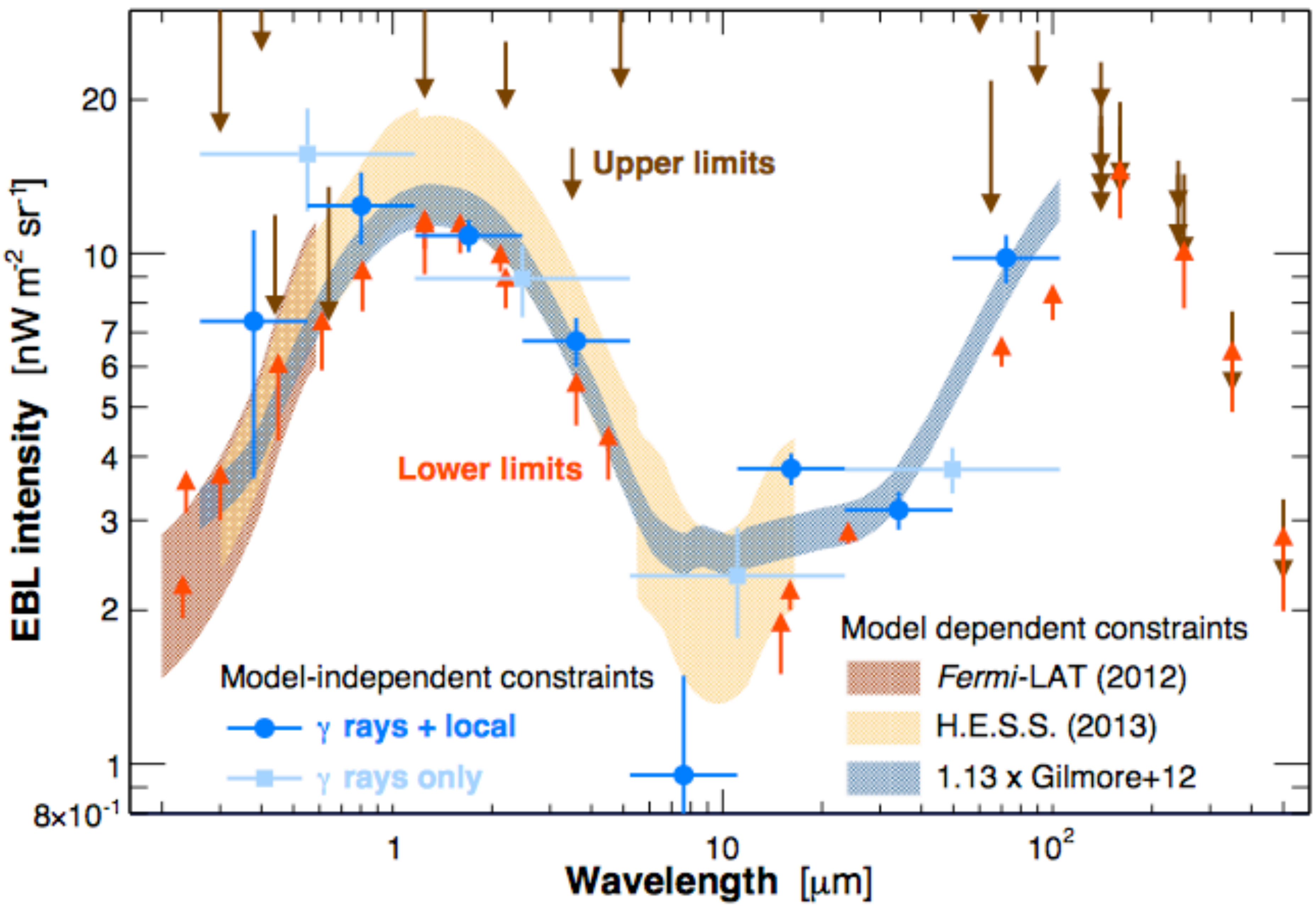
Mazin et al. 2013

$$\lambda \simeq 1.5\, E_{\rm TeV}\ \mu{\rm m}$$

Dominguez et al. 2011



The current status



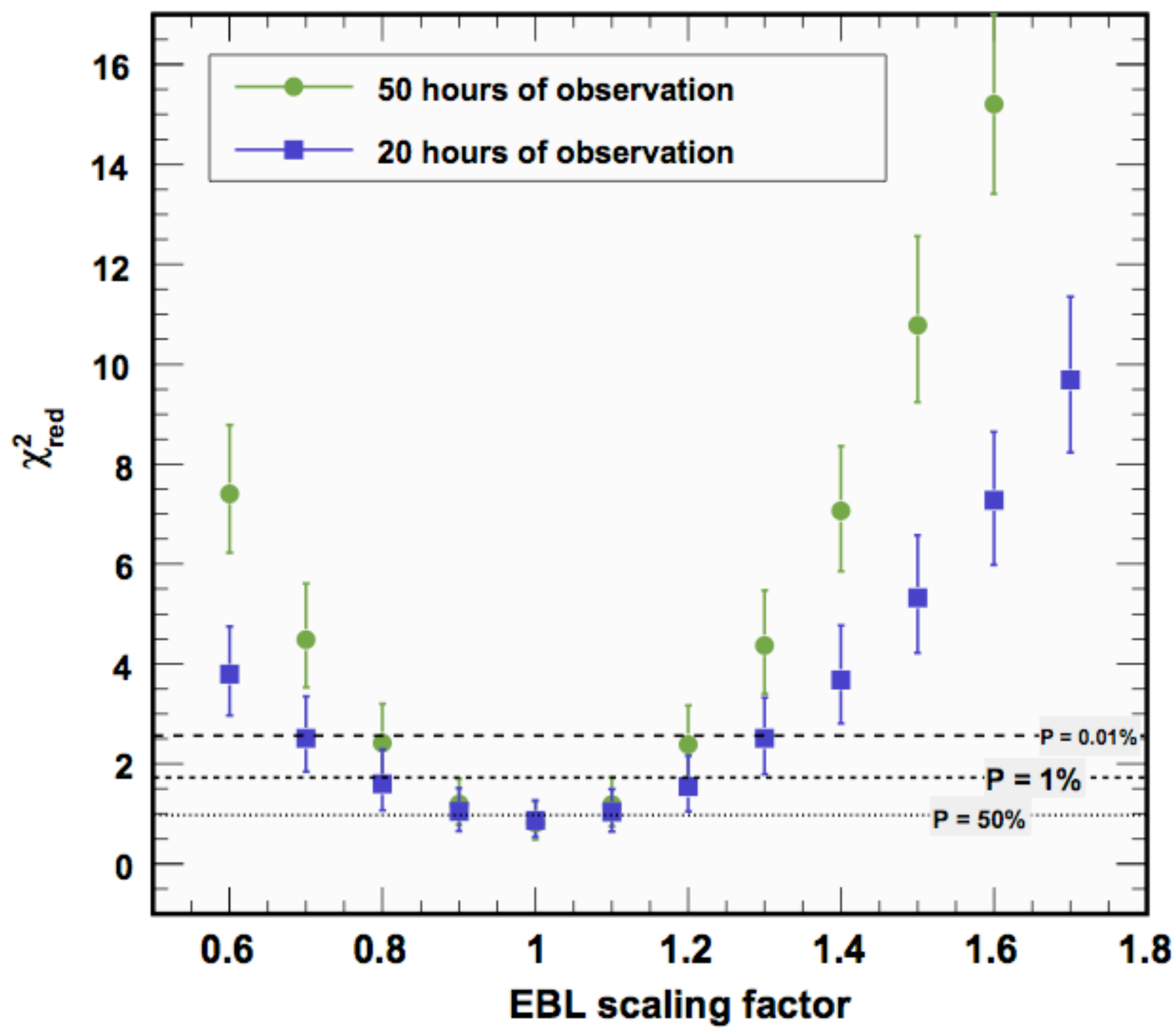
Biteau & Williams 2015

Propagation effects: EBL

Goals:

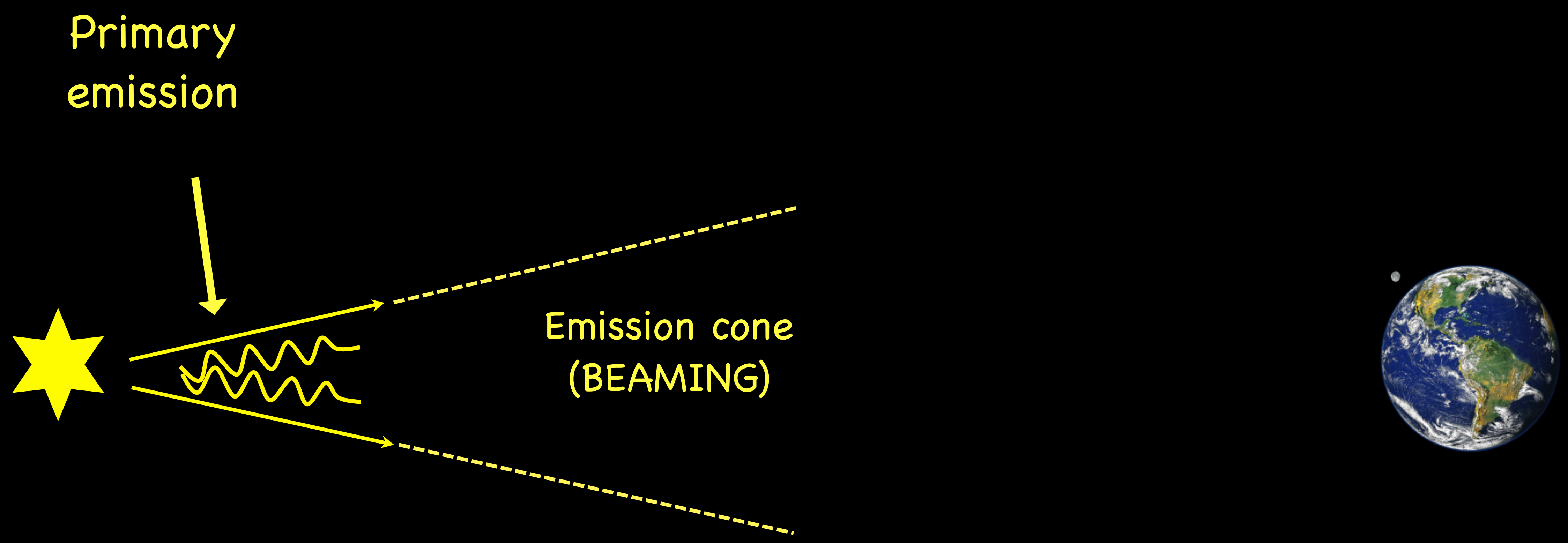
EBL z=0

Evolution with z

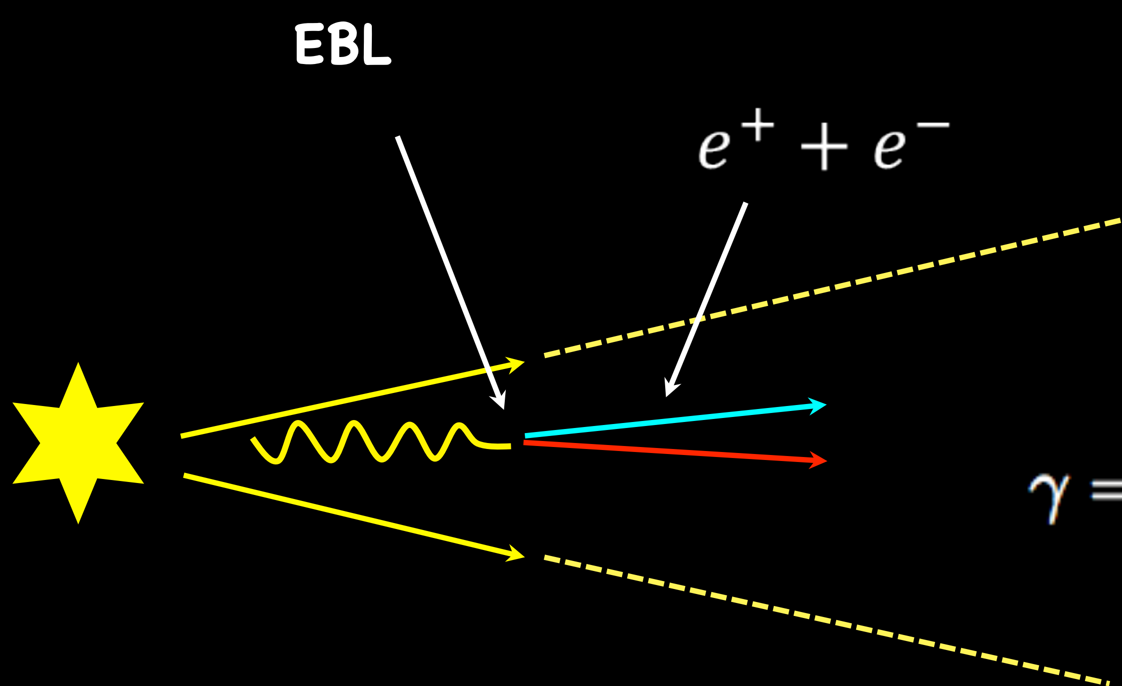


Mazin et al. 2013

Reprocessed emission



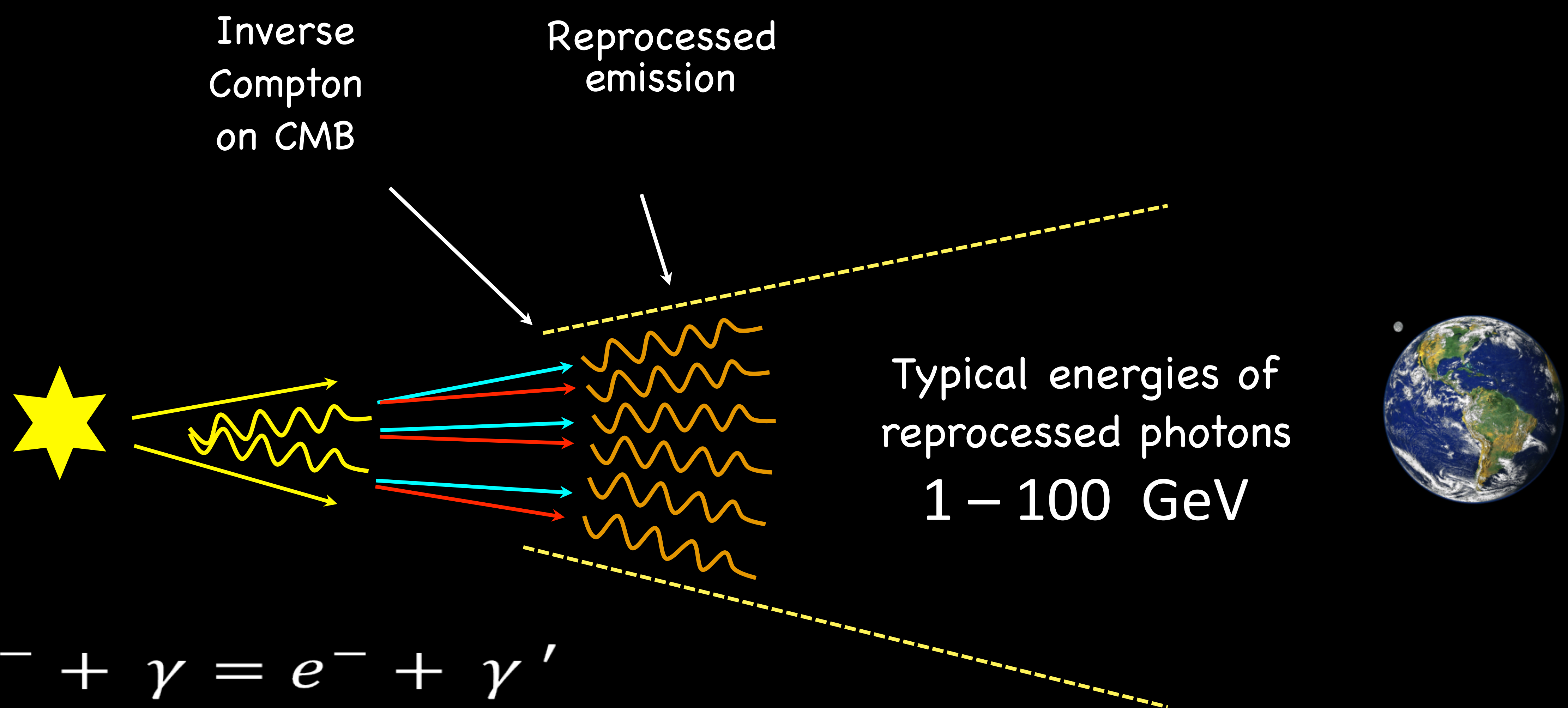
Reprocessed emission



$$\gamma = \frac{E}{2m_ec^2} \simeq 10^6 E_{\rm TeV}$$

$$\gamma_1 + \gamma_2 = e^- + e^+$$

Reprocessed emission



$$e^- + \gamma = e^- + \gamma'$$

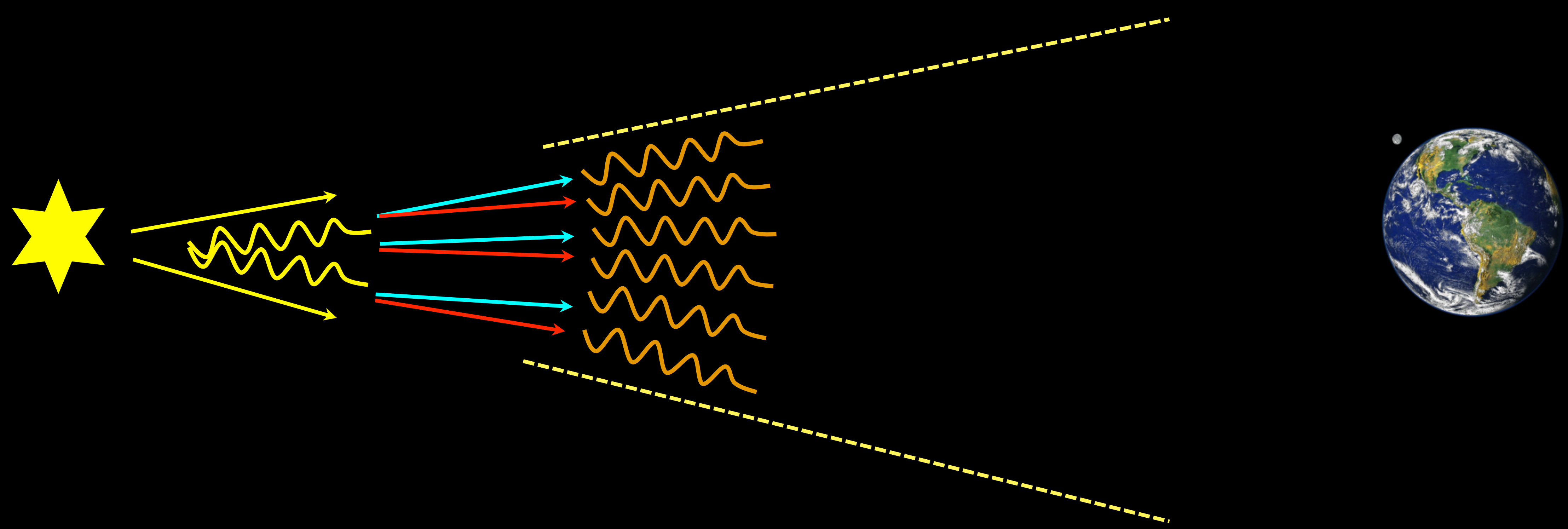
$$\epsilon = \gamma^2 h\nu_{\rm CMB} \simeq 2.8\, kT_{\rm CMB}\, \gamma^2 = 0.63\, E_{\rm TeV}^2 \ {\rm GeV}$$

$$ct_{\rm cool} = \frac{3 m_e c^2}{4\gamma U_{\rm CMB,0}(1+z_r)^4} \simeq 2 \times 10^{24} \gamma_6^{-1} (1+z_r)^{-4} \ {\rm cm}$$

$$N(\gamma) = k\gamma^{-2}$$

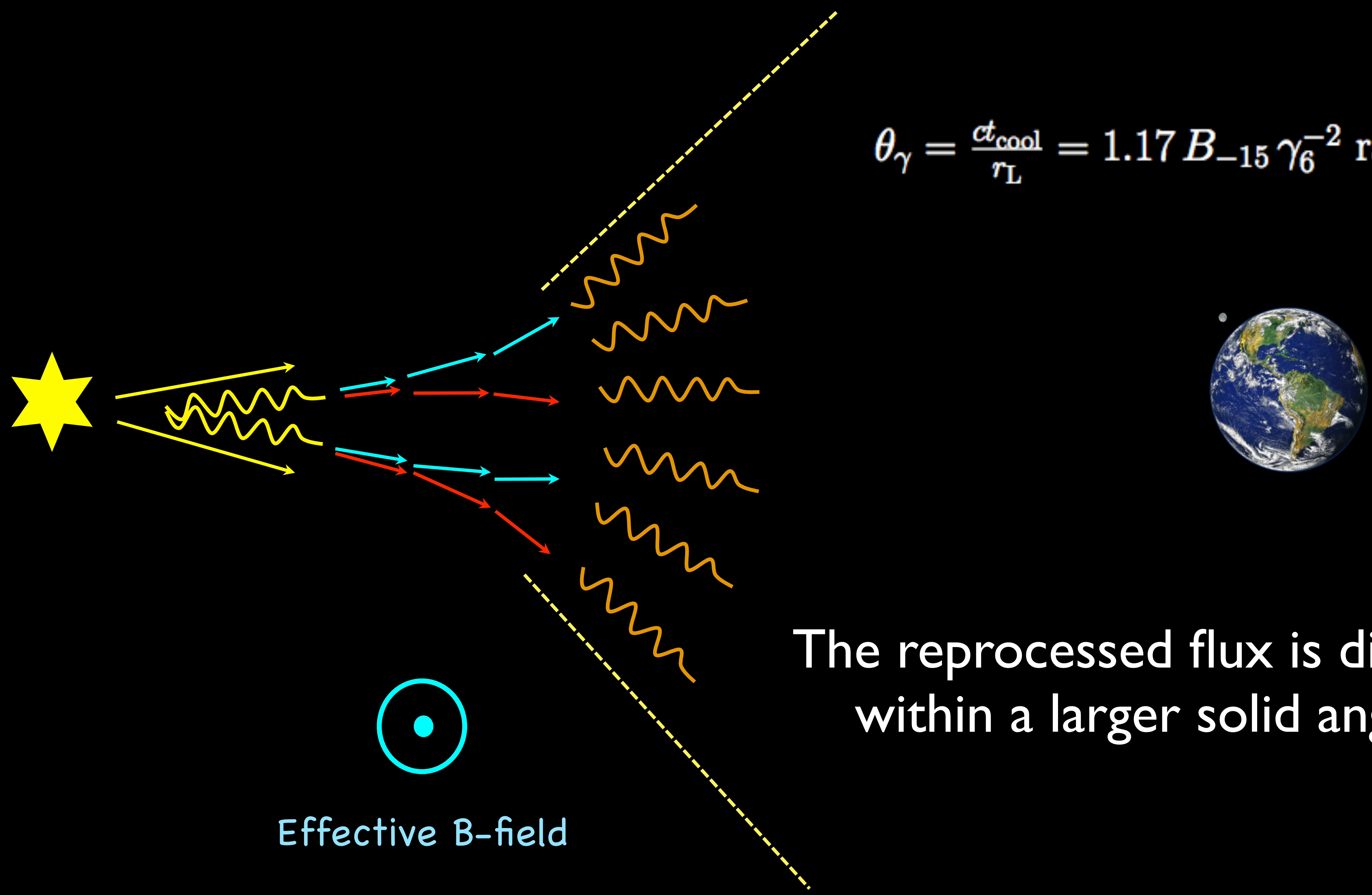
"cooled" distribution

B=0



The reprocessed emission is contained within the primary beaming cone

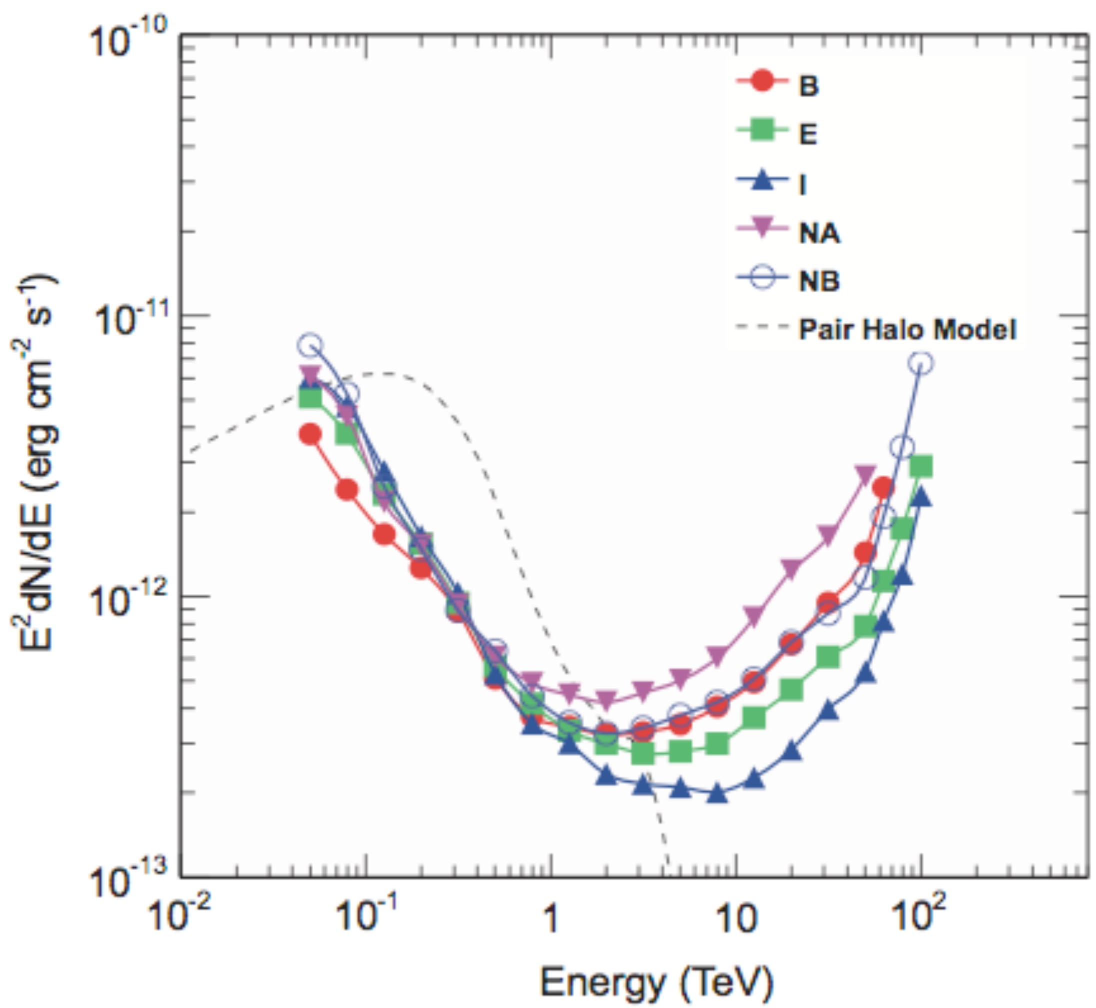
B>0

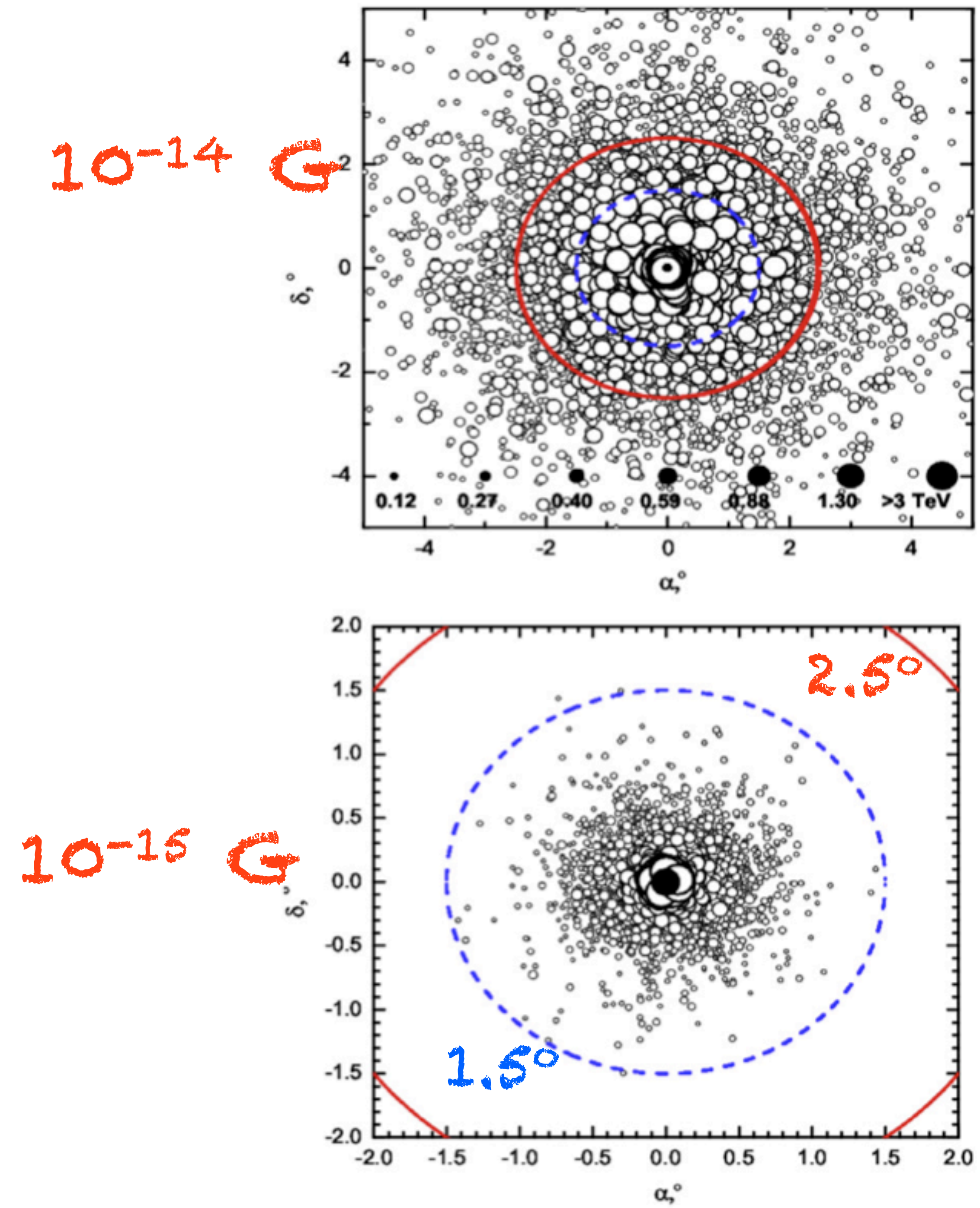


$$\theta_\gamma = \frac{c t_{\rm cool}}{r_{\rm L}} = 1.17\, B_{-15}\, \gamma_6^{-2}\ {\rm rad}$$

The reprocessed flux is diluted within a larger solid angle

CTA and IGMF

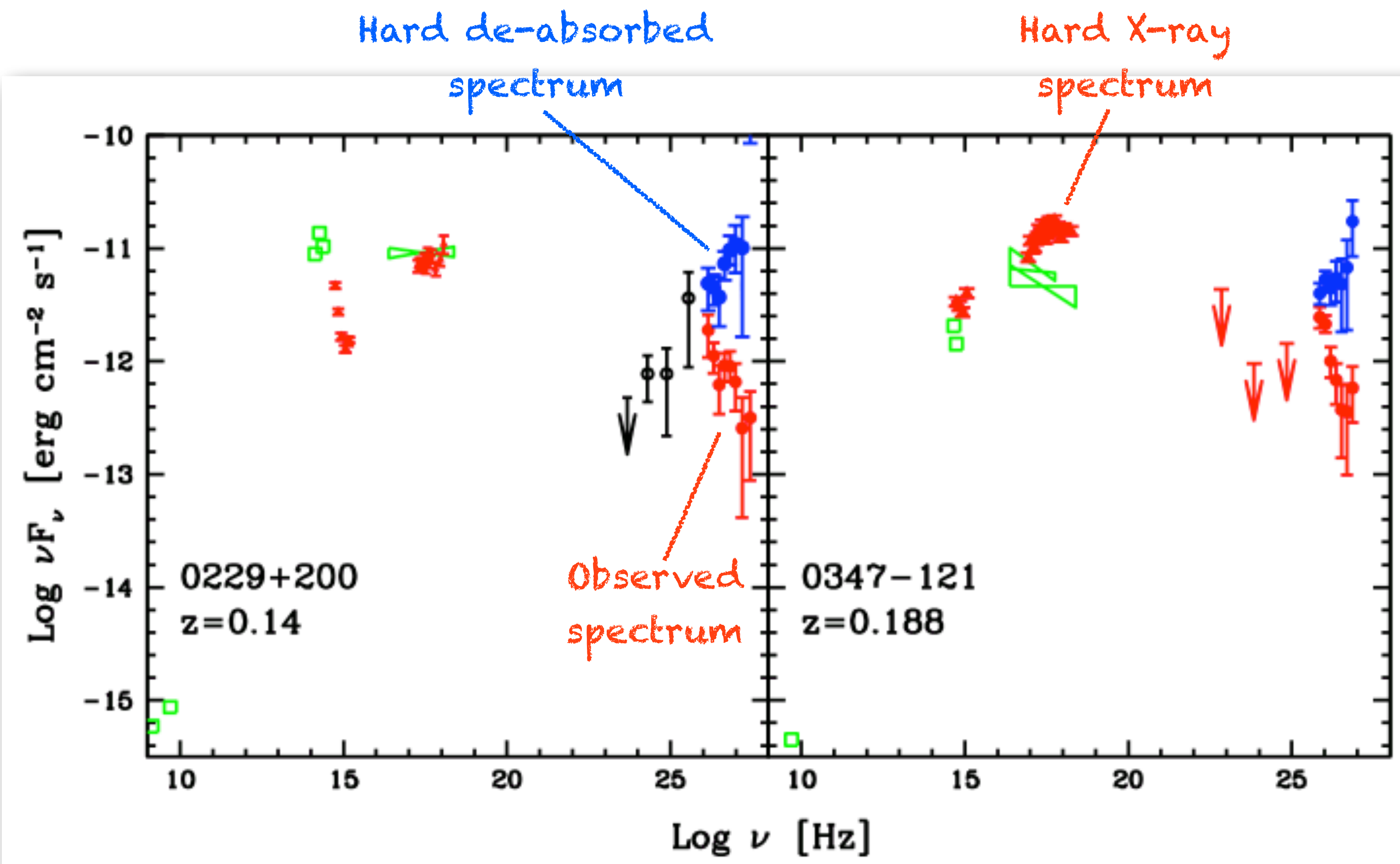




Sol et al. 2013

Extreme BL Lacs

after Costamante et al. 2001



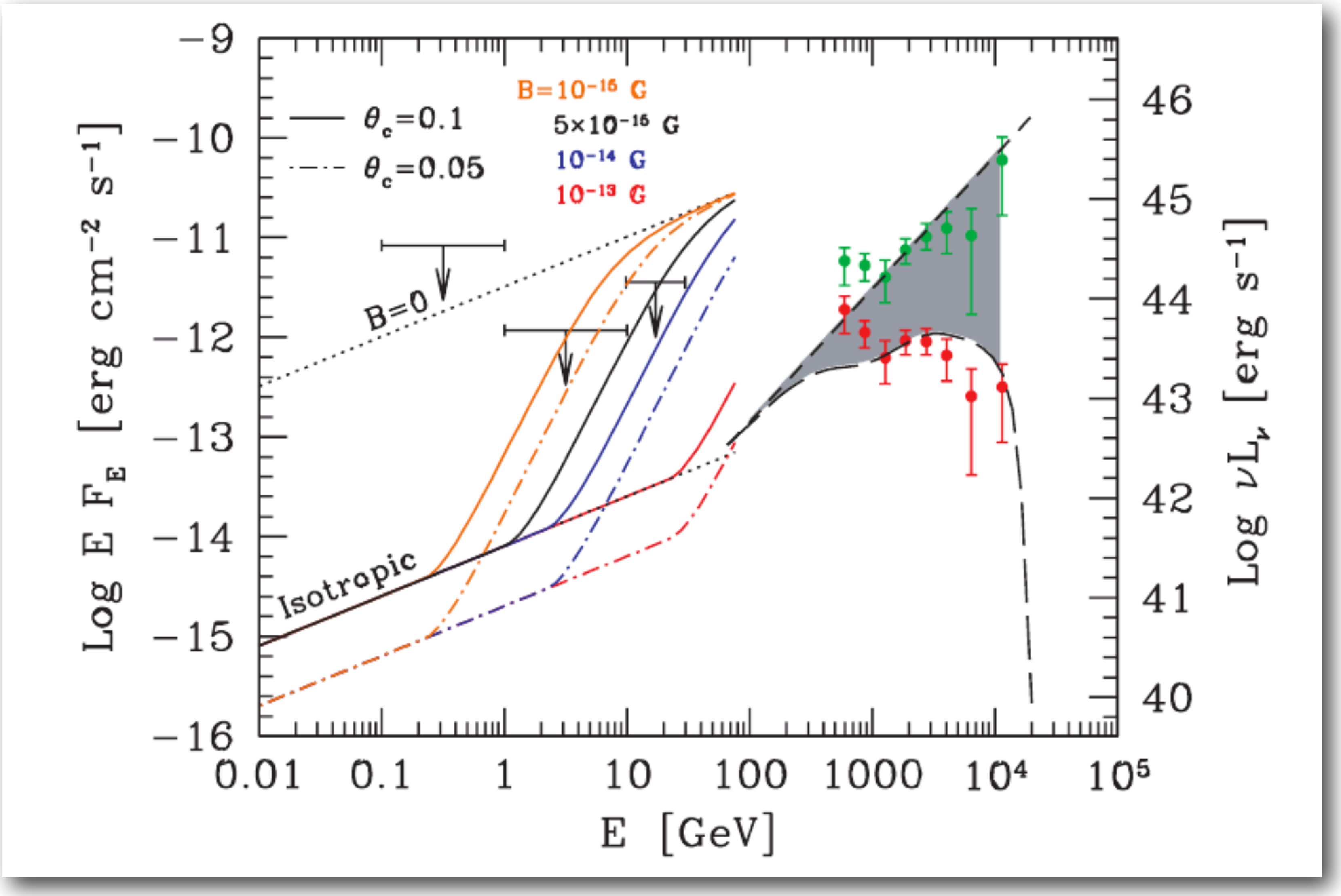
Very hard X-ray and gamma-ray (deabsorbed) spectra

Rather modest variability

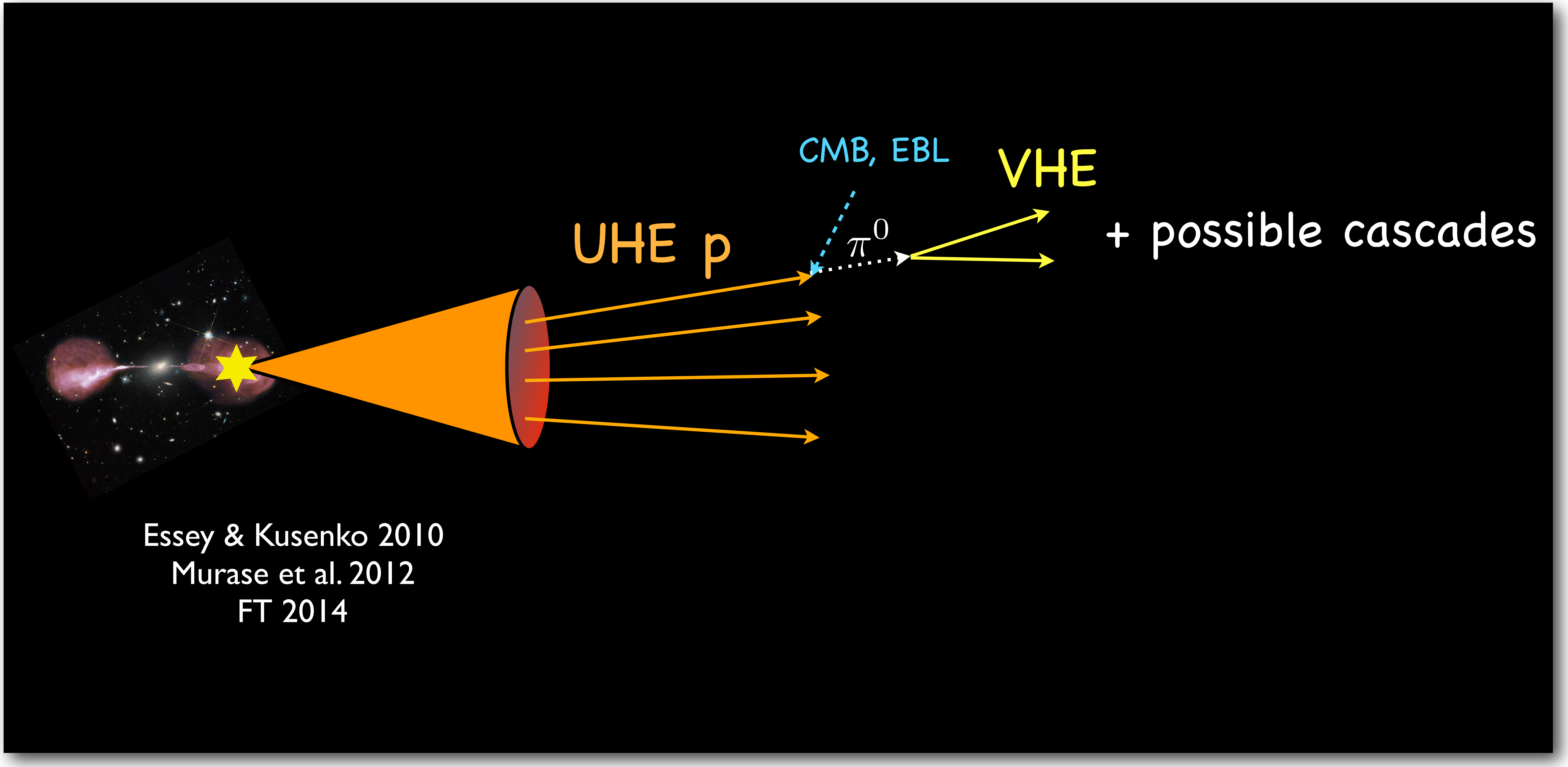
EHBL and IGMF

- large multi-TeV power to reprocess
- low GeV intrinsic (pure reprocessed)

Tavecchio et al. 2010
also Neronov & Vovk 2010

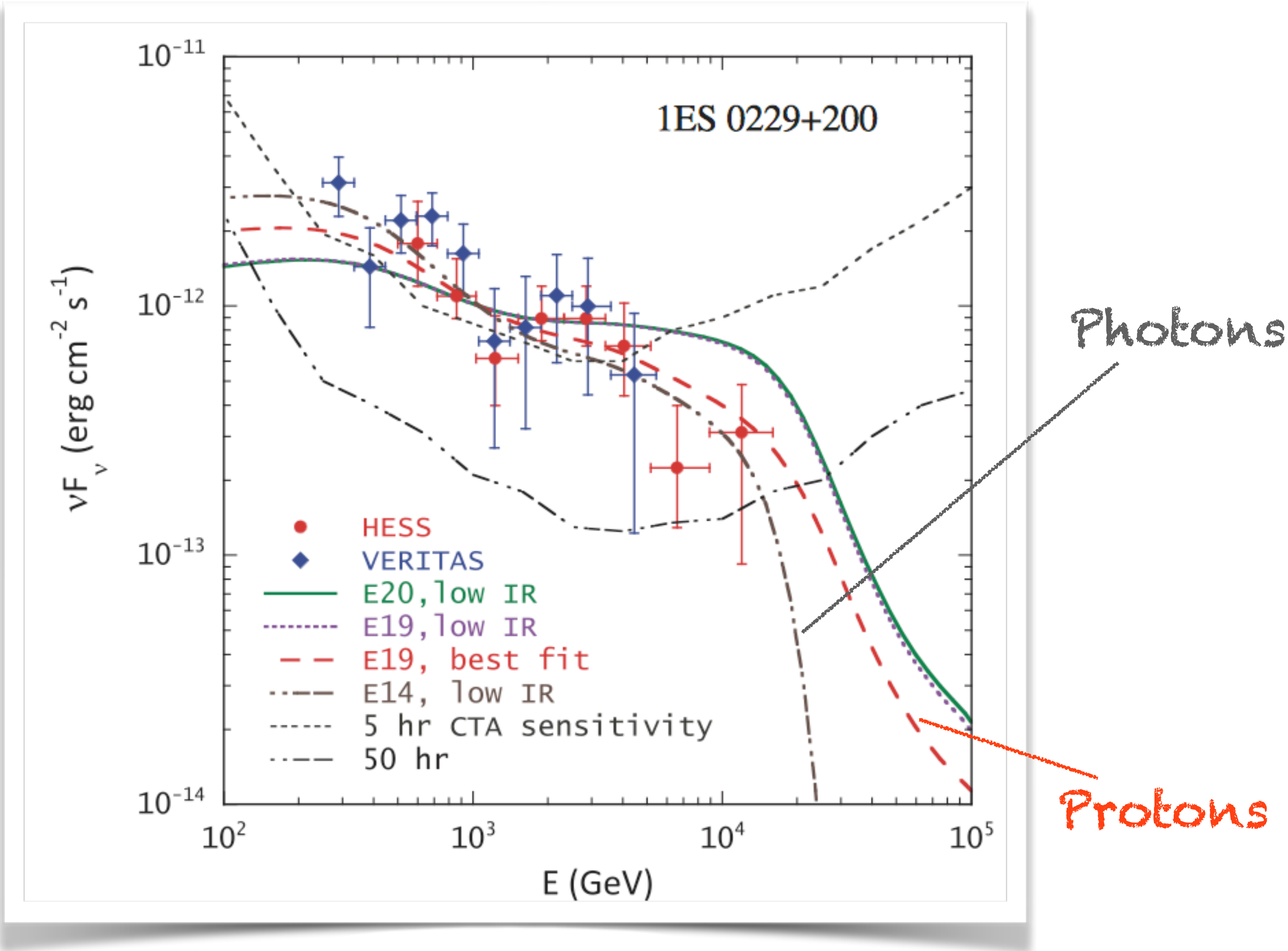


Proton beams?



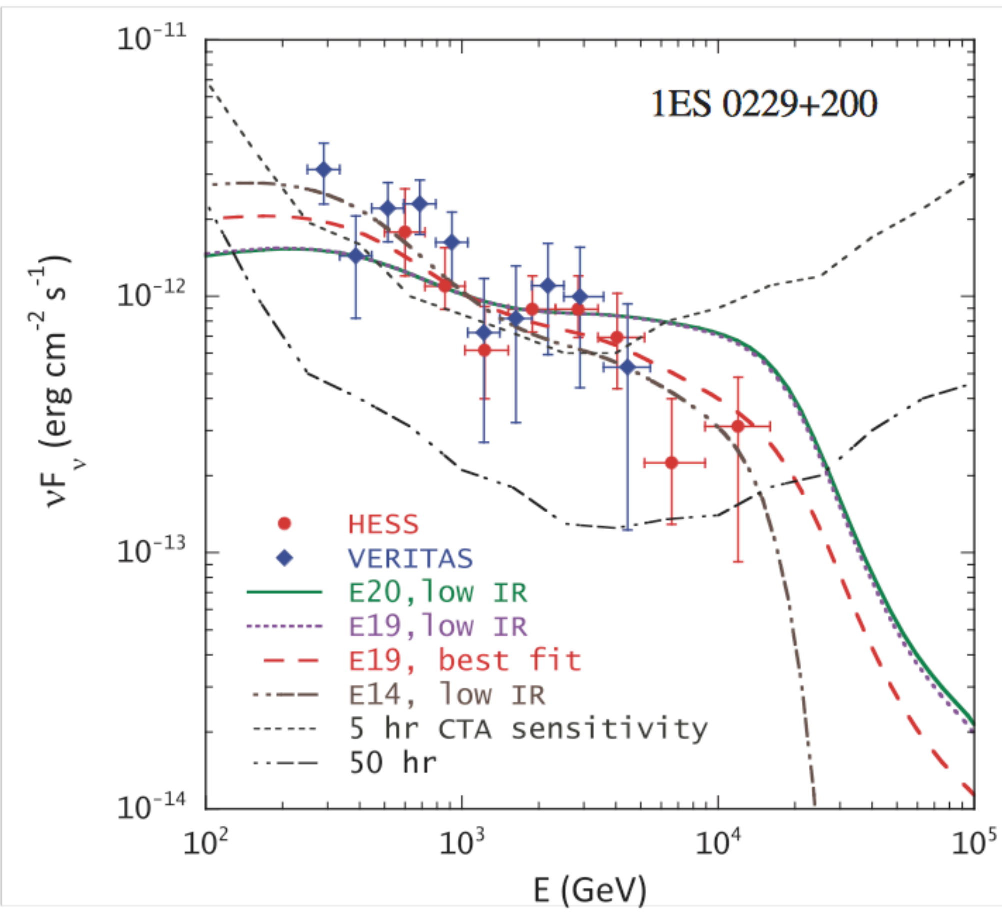
Proton beams?

Murase et al. 2012

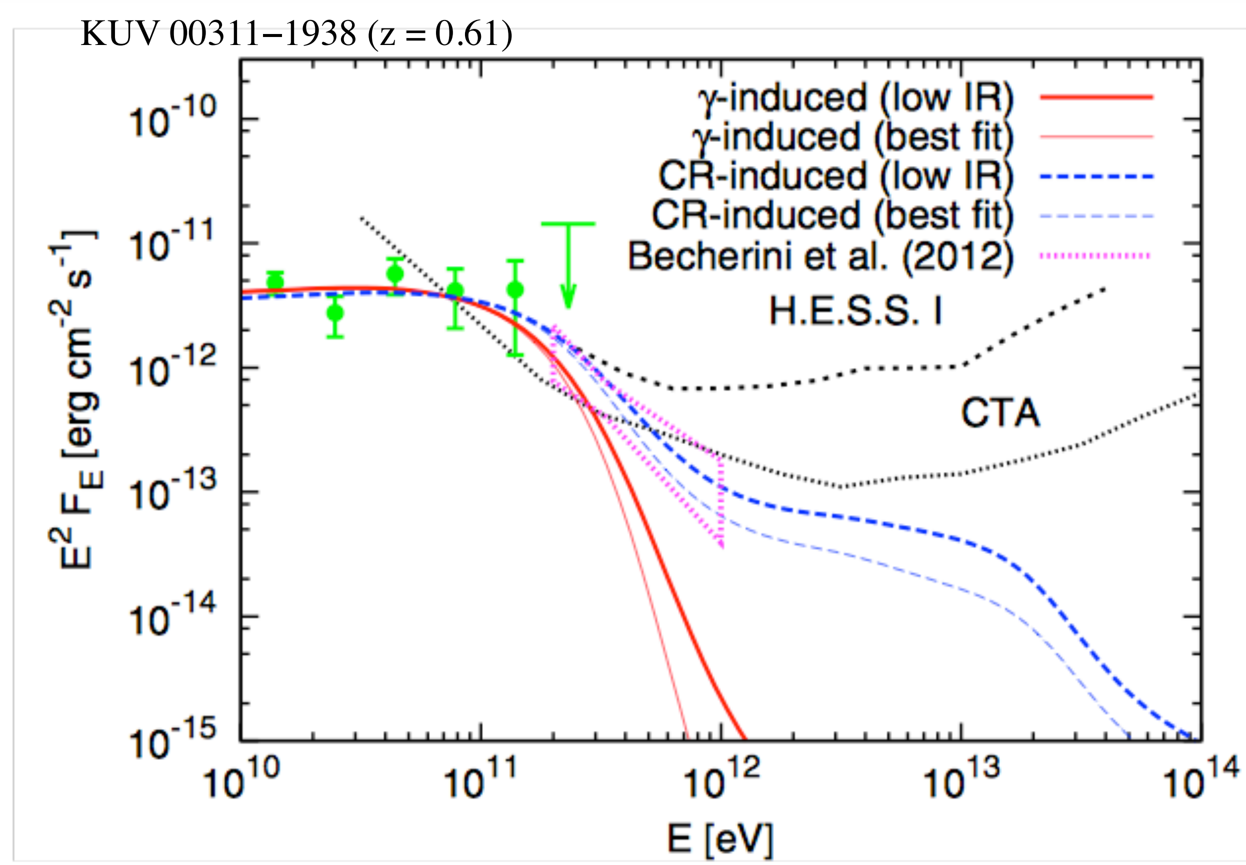


Prospects for CTA

Murase et al. 2012



Takami et al. 2013



Cosmic opacity anomaly: LIV

LIV induces an affective mass for the photon

$$\beta_\gamma = 1 - \left(\frac{E_\gamma}{M_{LVn}}\right)^n \quad ; \quad m_\gamma^2 = -\frac{E_\gamma^{2+n}}{M_{LVn}^n},$$

Modification of threshold for pair production at high E

LIV induces suppression of EBL-opacity

Jacob & Piran 2008
Fairbarn et al. 2014
Tavecchio & Bonnoli 2016

Cos… : LIV

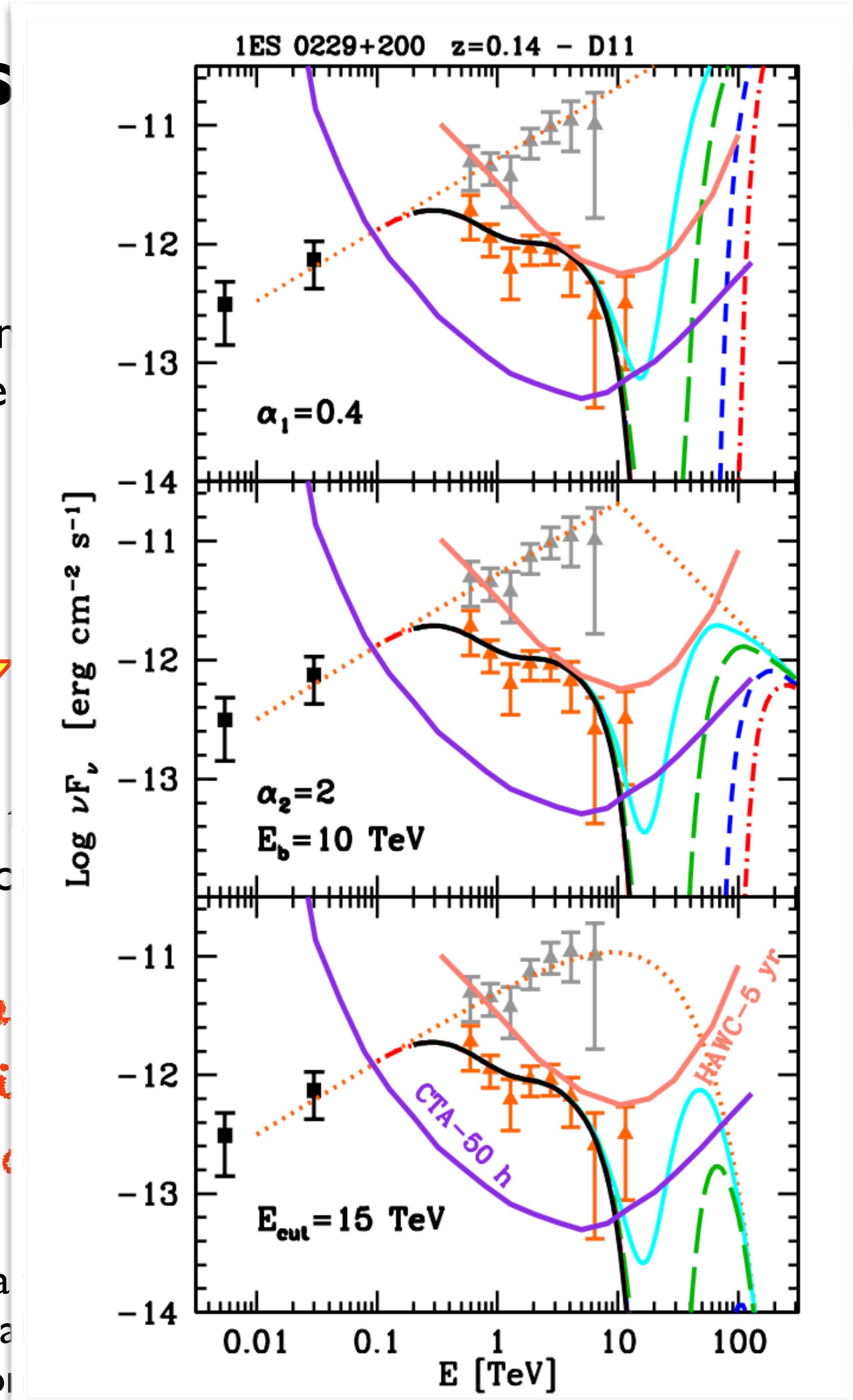
LIV induces ar…
mass for the…

$$\beta_\gamma = 1 - \left(\frac{E_\gamma}{M_{LVn}}\right)^n$$

Modification of …
for pair productio…

LIV indu…
suppressi…
of EBL-opa…

Jacob & Pira…
Fairbarn et a…
Tavecchio & Bo…



All these scientific topic will be better addressed if sources are observed in high-state/flare.

⇨ Strong efforts for monitoring (TeV and MW) and ToO - Dedicated KSP for CTA


THANK you!

Introduction: relativistic jets & blazars

1) Jet physics

- ➤ Minimum variability timescale
- ➤ Hadronic vs leptonic emission
- ➤ Radiogalaxies

2) Propagation effects

- ➤ EBL
- ➤ Intergalactic magnetic field
- ➤ Hadronic beams

3) Demography