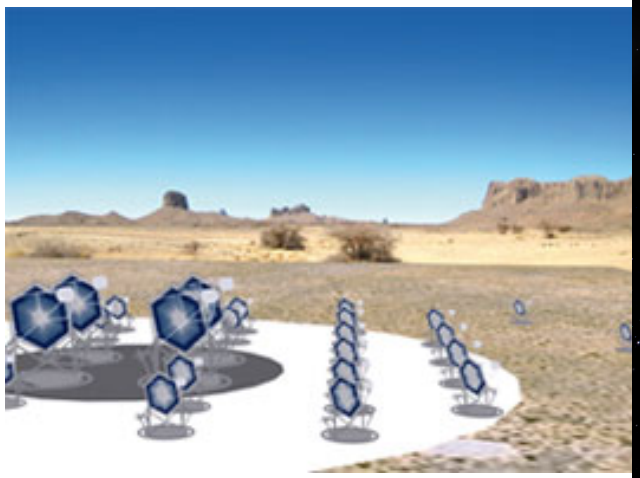
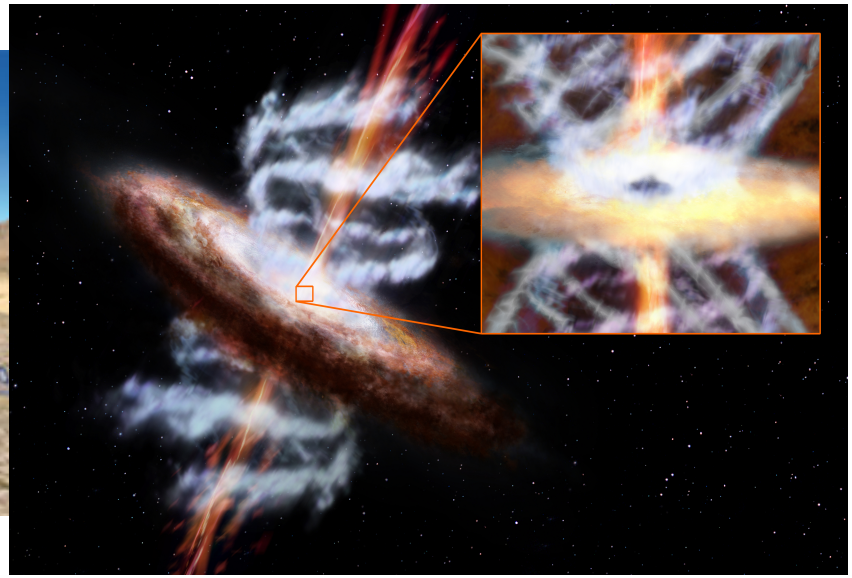
活動銀河ジェット・ウィンドからの ガンマ線（と超高エネルギー宇宙線）

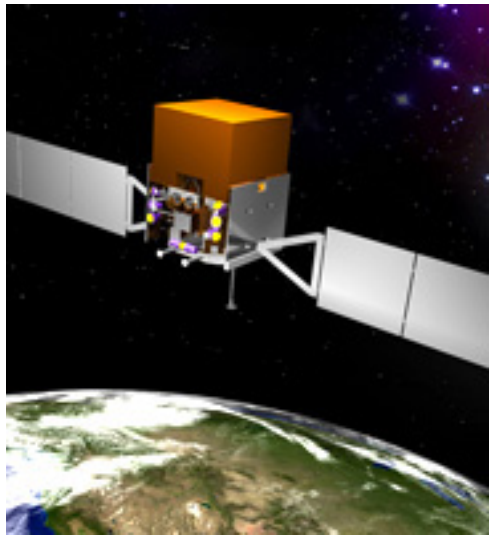
井上進 (MPI für Physik/ICRR)

1. hadronic interpretation for UHE-frequency-peaked BL Lacs (extreme blazars)
with Matteo Cerruti, Andreas Zech, Catherine Boisson

2. gamma-rays (+UHECRs?) from ultra-fast outflows (AGN winds) with Ruoyu Liu





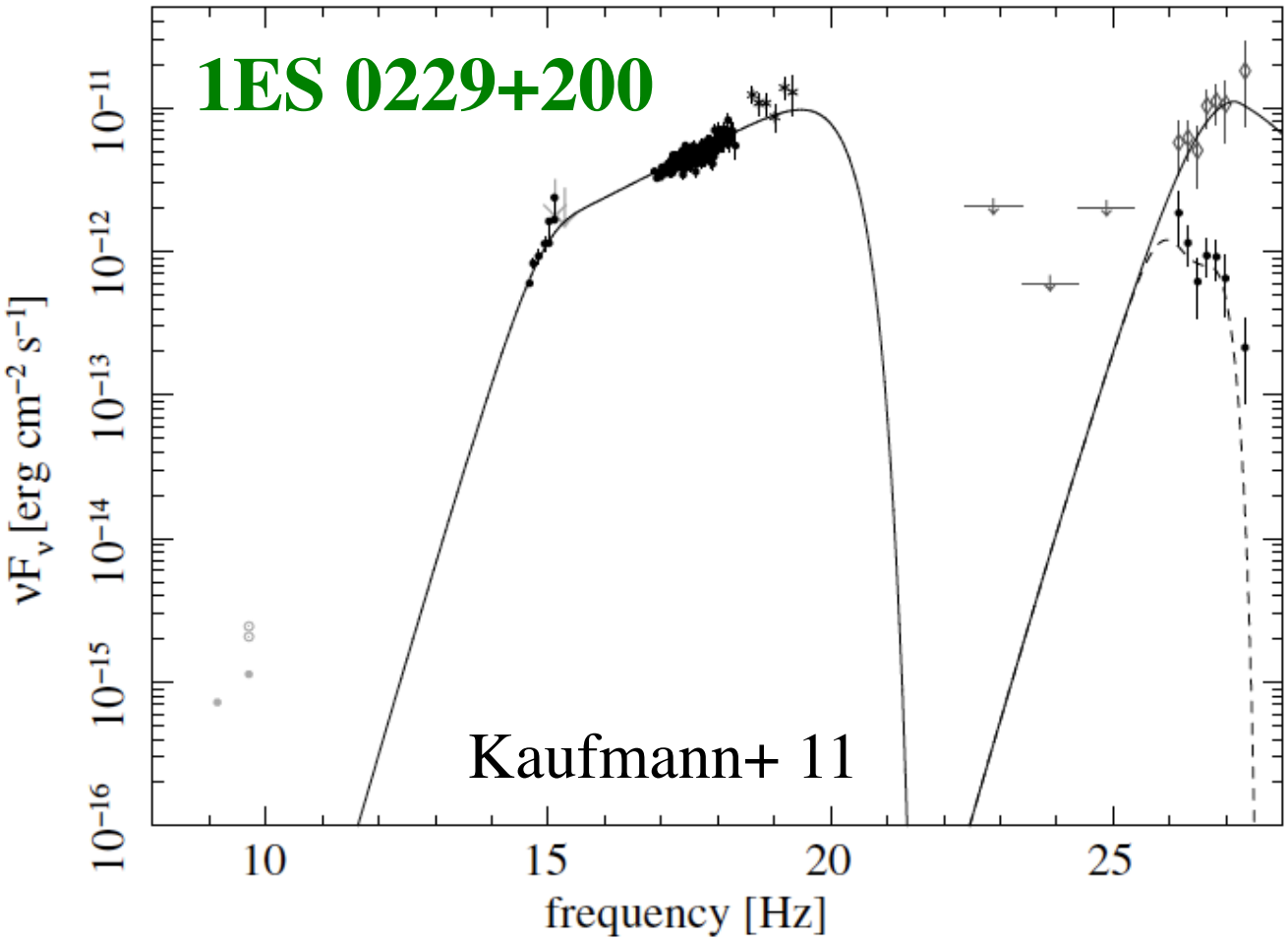


hadronic interpretation for UHE-frequency-peaked BL Lacs (extreme blazars)

Matteo Cerruti, Andreas Zech, Catherine Boisson, SI

MNRAS, submitted

UHF-peaked BL Lacs (extreme blazars)



- hard TeV spectra E_{peak}>~TeV
- limited evidence of variability

SSC interpretation requires:
high γ_{min}~10^4-10^5
<-> normally γ_{min}~<10^3
high δ>~50
<-> normally δ~10-30

stochastic electron acceleration?
Lefa+ 11, Tramacere+ 11, Asano+ 14…

intergalactic CR-induced cascades
Essey & Kusenko 12, Murase+ 12, Tavecchio 14…

proton-induced emission in blazars

Mannheim 93
Aharonian 00
Mücke+ 02,03….

$e^- + B \rightarrow e^- + \gamma_{LE}$

$p + \gamma_{LE} \rightarrow N + \pi^0, \pi^{+-}$ $E_{p,max} \sim 10^{17}\text{-}10^{19}$ eV

$\pi^0 \rightarrow 2\gamma$ $\pi^{+-} \rightarrow \mu^{+-}\nu \rightarrow e^{+-} + 3\nu$

$\mu^{+-} + B \rightarrow \mu^{+-} + \gamma$ muon synchrotron

also p-p π^0
if dense enough
Romero+

$\gamma + \gamma_{LE} \rightarrow e^+e^-$

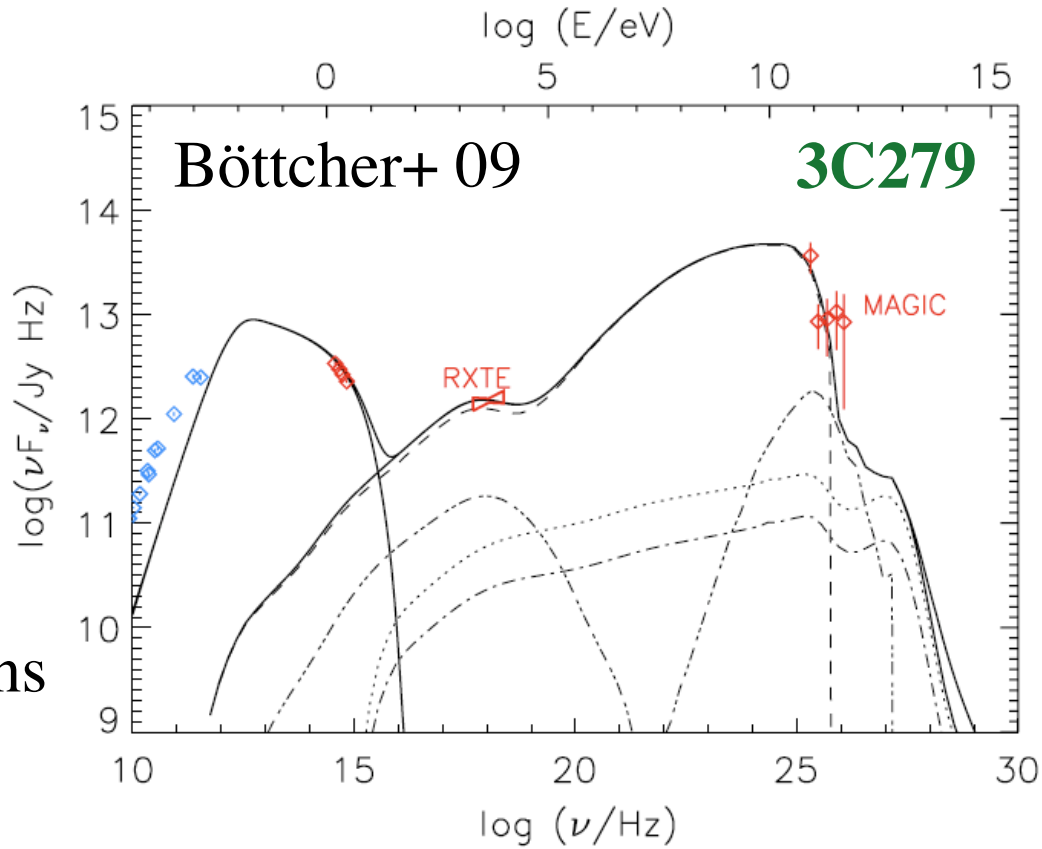
$e^+e^- + B \rightarrow e^+e^- + \gamma$

electron-positron sync. cascade

$p + B \rightarrow p + \gamma$ proton synchrotron

potential issues

1. low radiative efficiency
   generally high L_{kin} required
2. poor fit to broadband spectra?
3. $t_{p\gamma}$, t_{pB} too long to explain
   <day timescale X-TeV correlations
   in HBLs



leptonic+hadronic emission model

Cerruti, Zech, Boisson, SI, MNRAS submitted; see also arXiv:1111.0557

leptonic processes: updated version of Katarzynski+ 01
- one zone synchrotron+SSC
- electron spectrum: power-law injection $K_e\gamma_e^{-\alpha e}$ ($\gamma_{e,min}<\gamma_e<\gamma_{e,max}$)
  + break via syn.+SSC losses
- internal $\gamma\gamma$ pair production

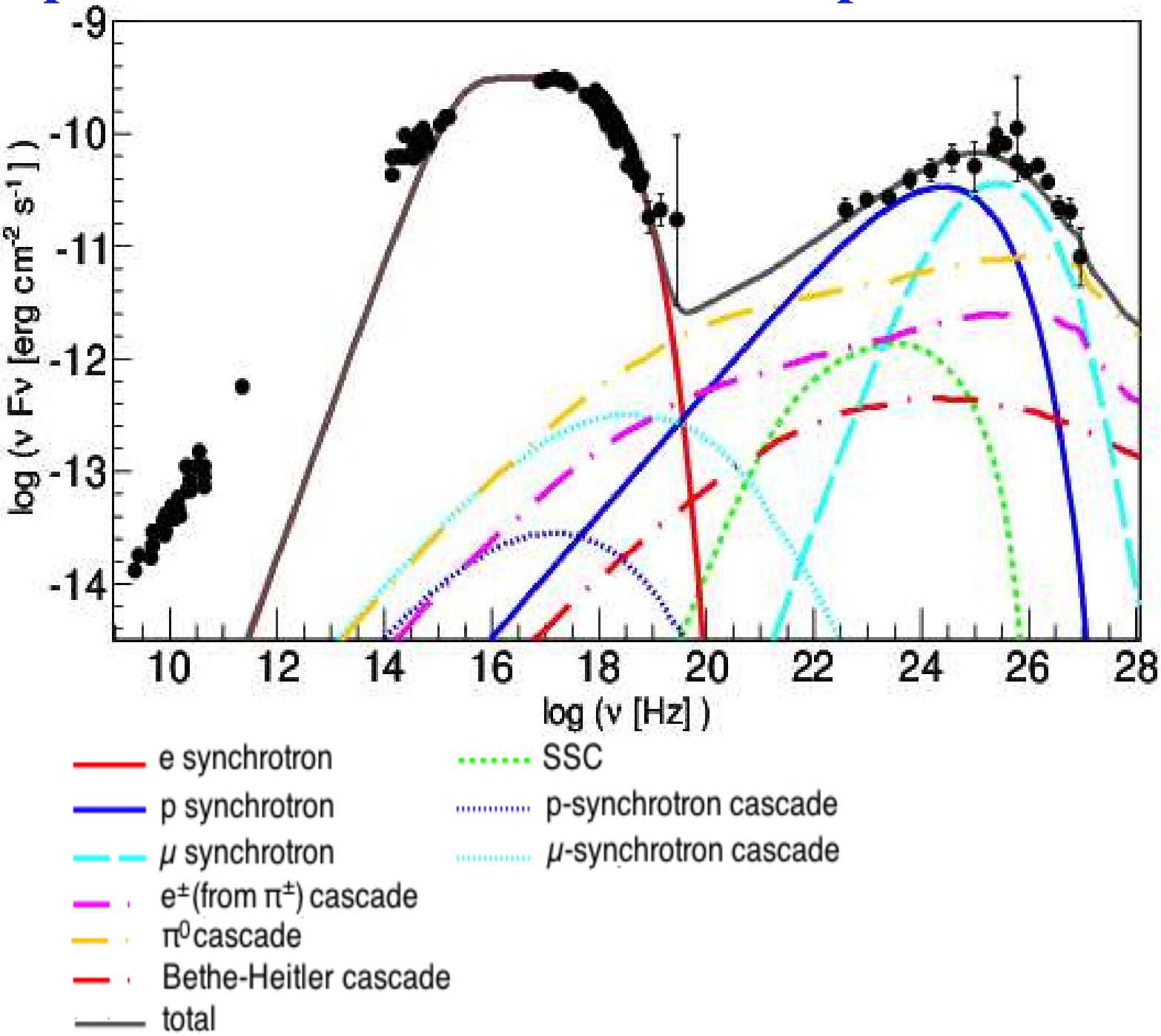
hadronic processes
- proton synchrotron
- photomeson interactions (SOPHIA)
- sync.+IC emission by all secondary pairs ($p\gamma + \gamma\gamma$)
- muon synchrotron
- Bethe-Heitler pair production

- proton spectrum: power-law injection $K_p\gamma_p^{-\alpha p}$ ($1<\gamma_p<\gamma_{p,max}$), $\alpha_p=\alpha_e$
  break via syn. losses
  max via accel vs radiative/adiabatic losses

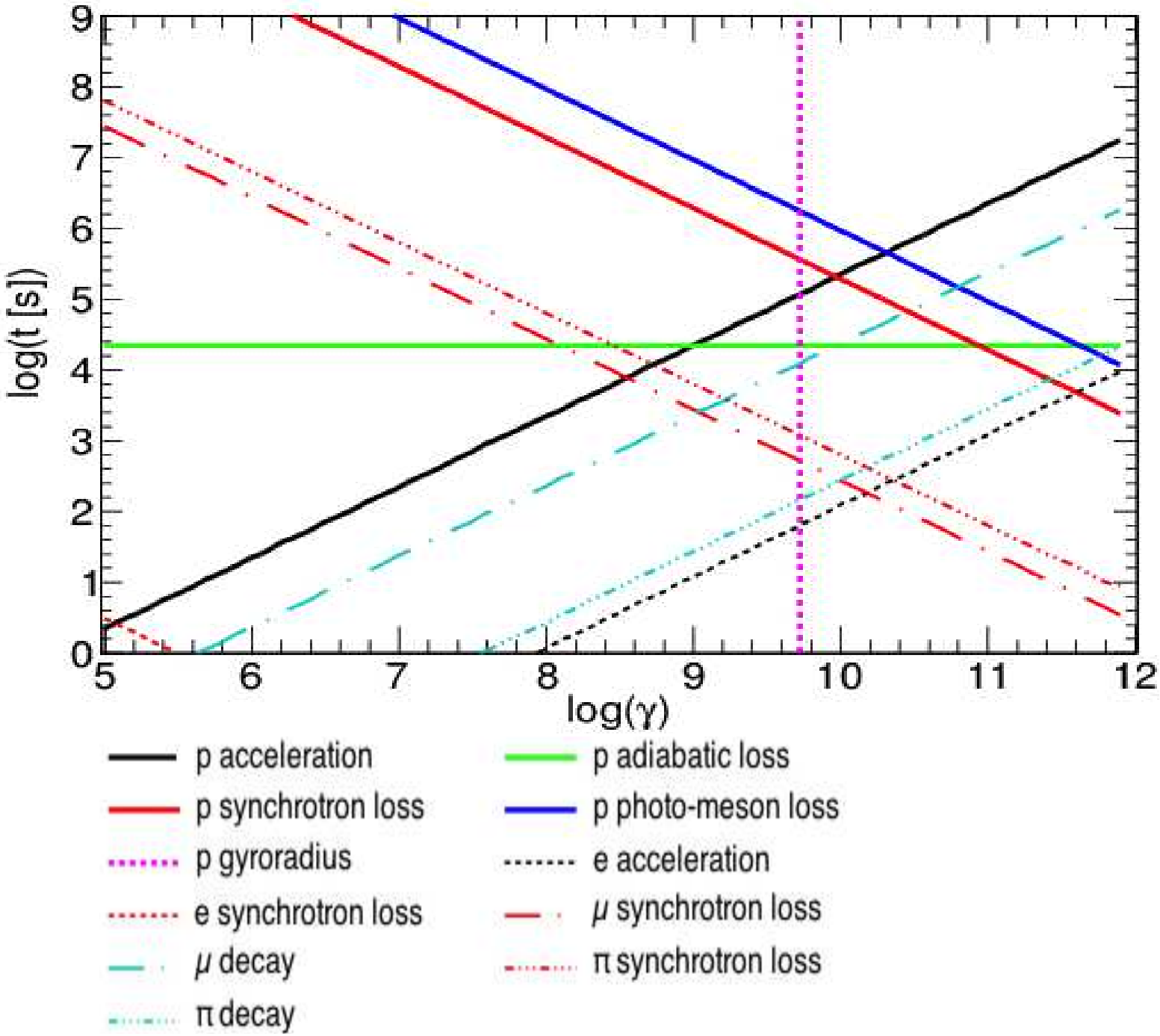
parameters: δ, R, B, $\alpha_e=\alpha_p$, $\gamma_{e,min}$, $\gamma_{e,max}$, K_e, K_p

EBL: Franceschini+ 08

leptonic+hadronic emission: example Mrk 421

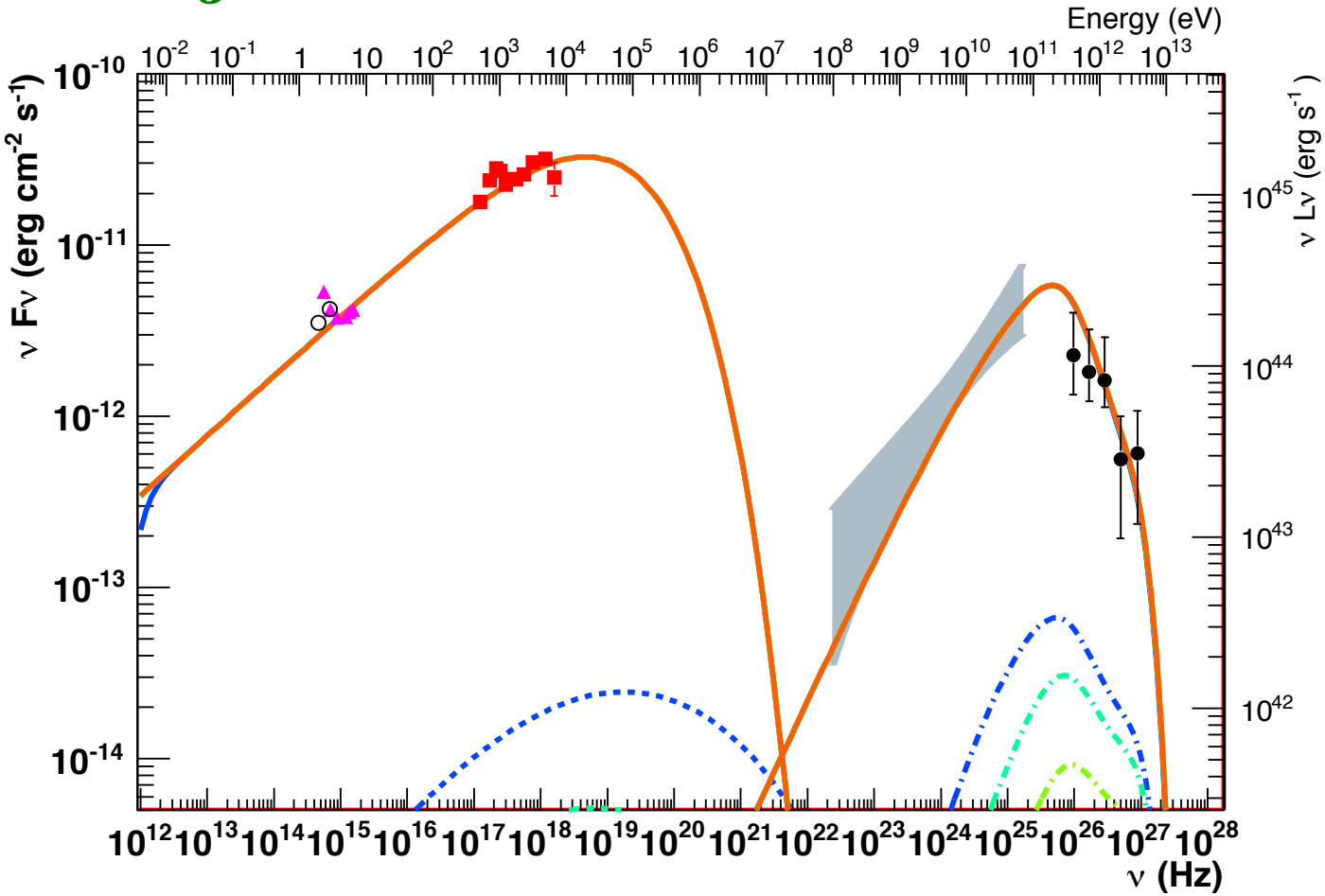


leptonic+hadronic emission: example Mrk 421



UHF BLL: proton synchrotron

RGB J0710+591 simul. Fermi+VERITAS



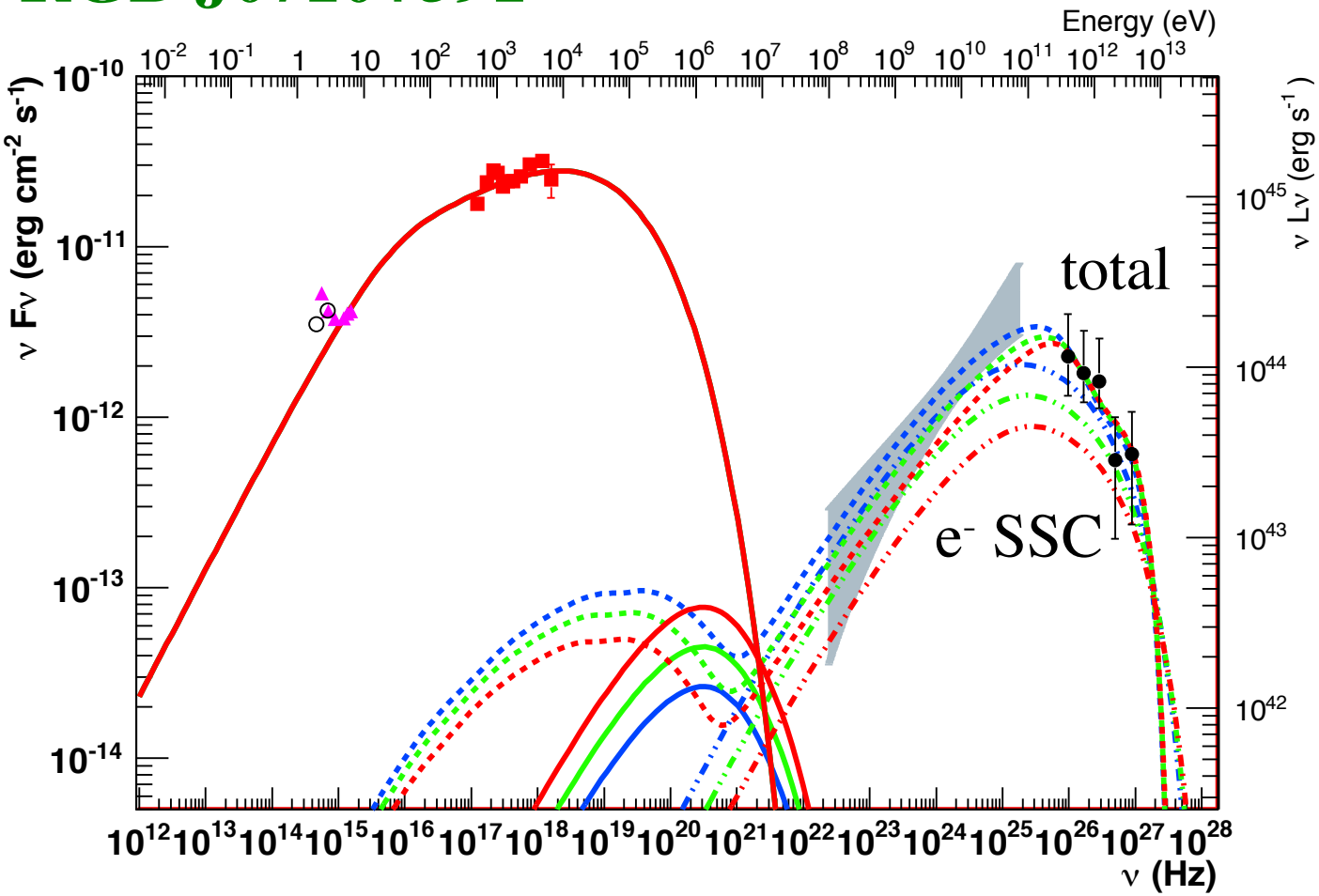
δ=30 B=70, 24, 8, 3G

$\alpha_p=\alpha_e=1.35$

z	0.125
δ	30
R_{src} [10^{16} cm]	0.1 – 67
B [G]	1.0 – 90
$^\star u_B$ [erg cm^{-3}]	0.04 – 320
$\gamma_{e,min}$ [10^2]	0.01
$\gamma_{e,break}$ [10^3]	0.001 – 0.03
$\gamma_{e,max}$ [10^5]	0.4 – 3.7
$\alpha_{e,1} = \alpha_{p,1}$	1.35
$\alpha_{e,2} = \alpha_{p,2}$	2.35
K_e [cm^{-3}]	7.3×10^{-5} – 130
$^\star u_e$ [erg cm^{-3}]	1.6×10^{-9} – 6.4×10^{-4}
$\gamma_{p,min}$	1
$\gamma_{p,break}$[10^9]	3.9 – 47
$\gamma_{p,max}$[10^9]	3.9 – 47
η	$(1.0 - 7.2) \times 10^{-7}$
$^\star u_p$ [erg cm^{-3}]	3.0×10^{-7} – 0.2
$^\star u_p/u_B$[10^{-5}]	0.3 – 200
$^\star L$ [10^{45} erg s^{-1}]	3.2 – 460

UHF BLL: pγ cascade+SSC

RGB J0710+591 simul. Fermi+VERITAS



δ=30, B=0.6, 0.4, 0.3G

$\alpha_p=\alpha_e=1.35$

z	0.125
δ	30
R_{src} [10^{16} cm]	0.1 – 67
B [G]	1.0 – 90
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η	$(1.0 - 7.2) \times 10^{-7}$
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$^\star u_p/u_B$[10^{-5}]	0.3 – 200
$^\star L$ [10^{45} erg s^{-1}]	3.2 – 460

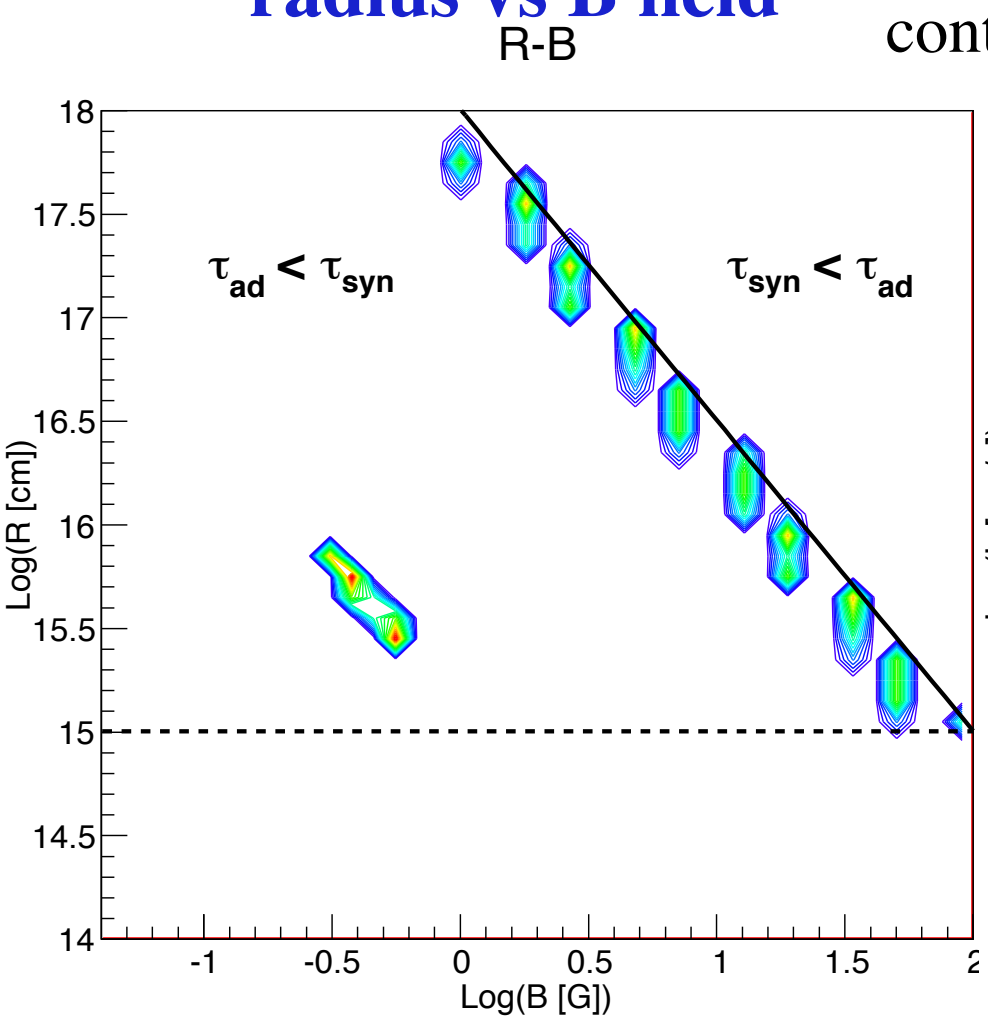
UHF BLL: parameters

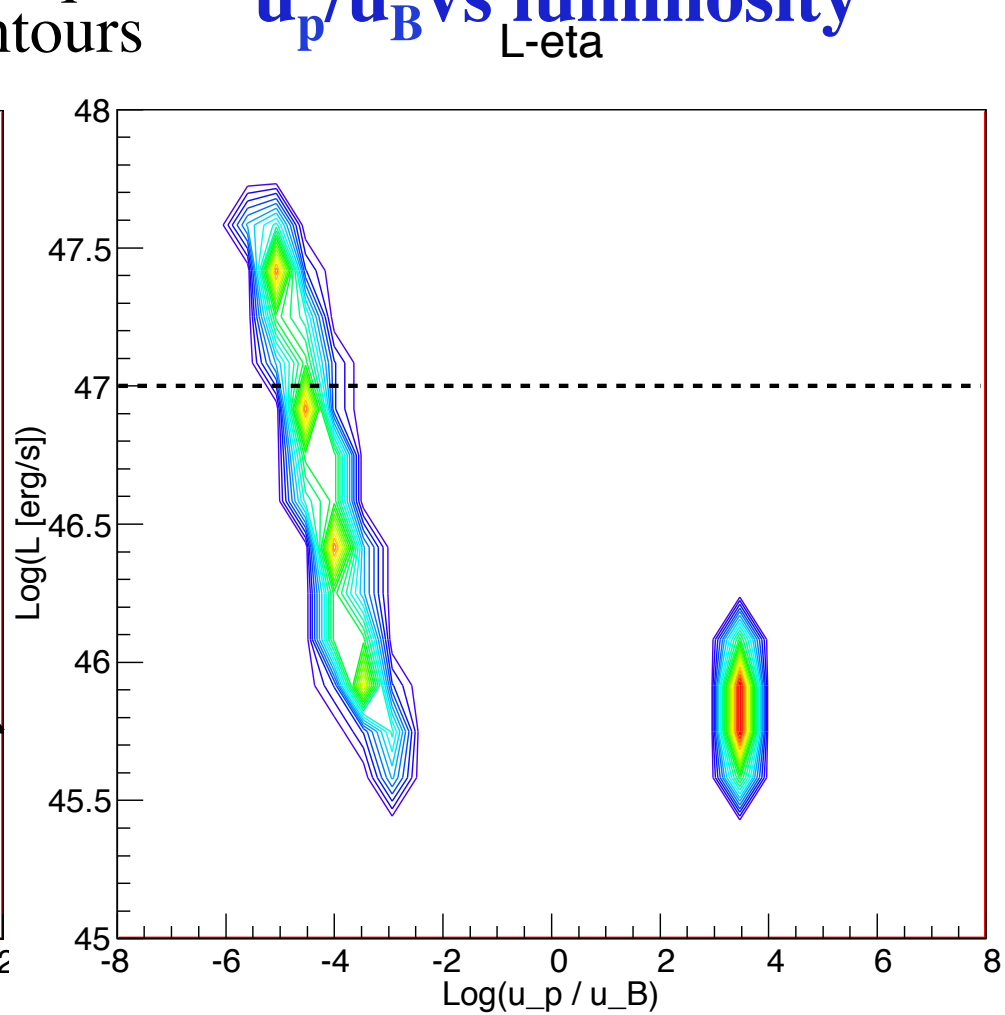
RGB J0710+591

radius vs B field

chi-square contours

u_p/u_B vs luminosity



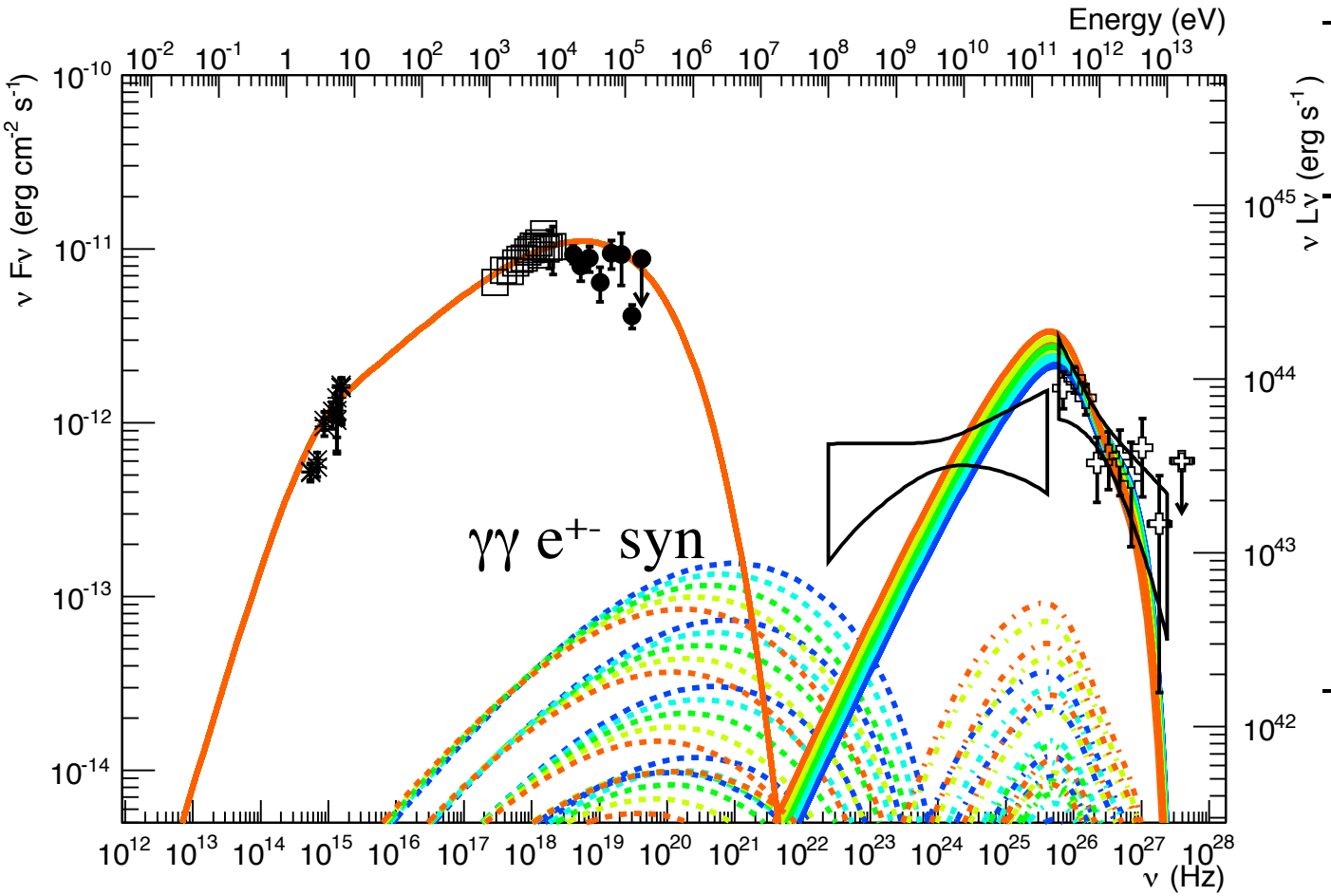


$$L = \pi R^2 c \Gamma_{bulk}^2 (u_B + u_e + u_p) \quad \Gamma_{bulk} = 2\delta.$$

interpretation possible with plausible range of jet luminosities

UHF BLL: proton synchrotron

1ES 0229+200 nonsimul. Fermi+VERITAS



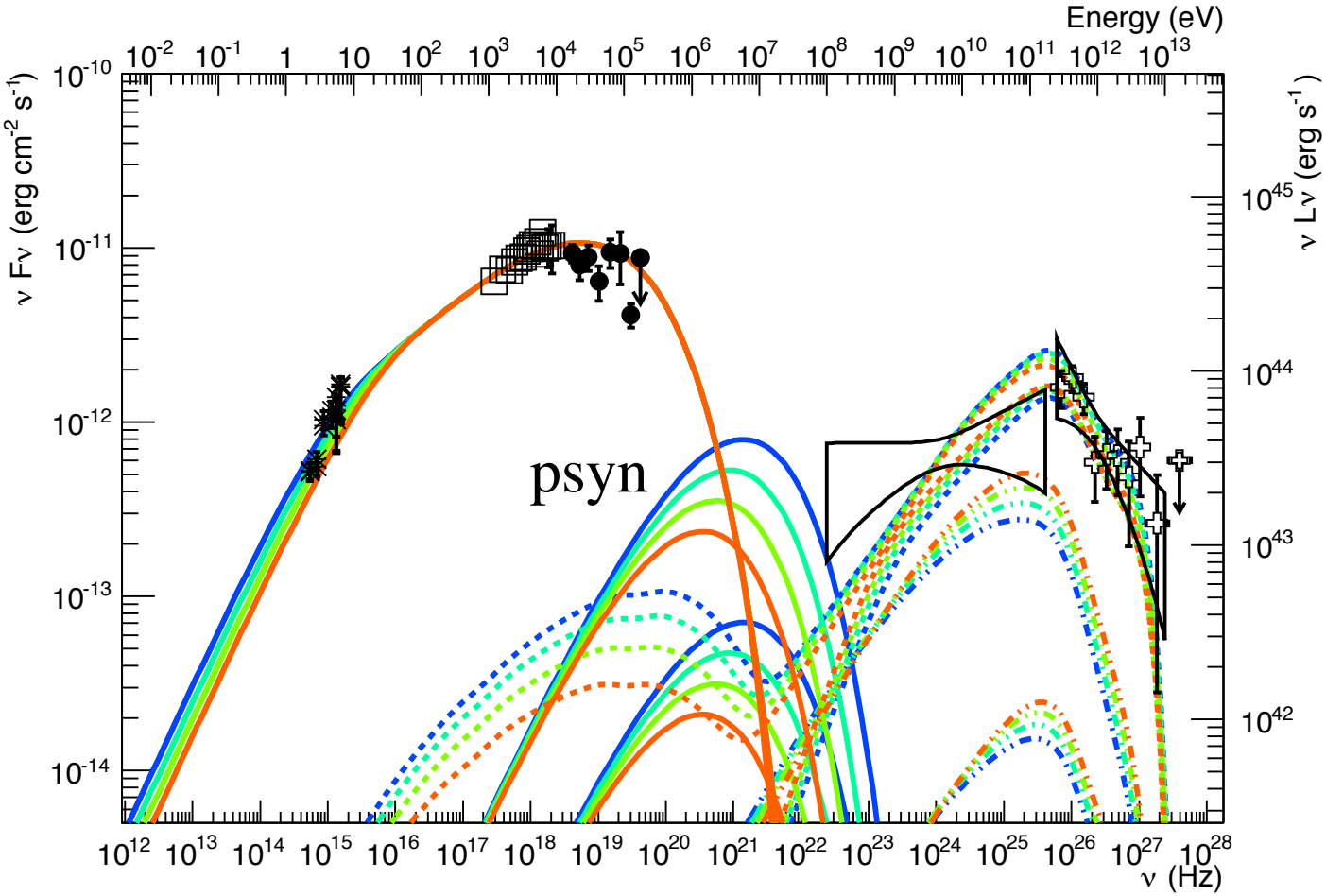
δ=30 B=160-1 G

$\alpha_p=\alpha_e=1.3$

z	0.140
δ	30
R_{src} [10^{16} cm]	0.1 – 68
B [G]	1.0 – 160
$^\star u_B$ [erg cm^{-3}]	0.04 – 1017
$\gamma_{e,min}$ [10^2]	1.6 – 20
$\gamma_{e,break}$ [10^3]	$= \gamma_{e,min}$
$\gamma_{e,max}$ [10^5]	0.3 – 4.1
$\alpha_{e,1} = \alpha_{p,1}$	1.3
$\alpha_{e,2} = \alpha_{p,2}$	2.3
K_e [cm^{-3}]	7.0×10^{-8} – 0.36
$^\star u_e$ [erg cm^{-3}]	2.2×10^{-11} – 3.2×10^{-5}
$\gamma_{p,min}$	1
$\gamma_{p,break}$[10^9]	2.6 – 57
$\gamma_{p,max}$[10^9]	4.8 – 57
η	$(9.7 - 19) \times 10^{-6}$
$^\star u_p$ [erg cm^{-3}]	6.1×10^{-8} – 0.08
$^\star u_p/u_B$[10^{-5}]	0.04 – 36
$^\star L$ [10^{45} erg s^{-1}]	4.6 – 1670

UHF BLL: pγ cascade+SSC

1ES 0229+200 nonsimul. Fermi+VERITAS



δ=30, B=1.4-0.1G

$\alpha_p=\alpha_e=1.3$

z	0.140
δ	30
R_{src} [10^{16} cm]	0.1 – 3.2
B [G]	0.1 – 1.4
$^\star u_B$ [erg cm^{-3}]	3.0×10^{-4} – 0.08
$\gamma_{e,min}$ [10^2]	0.01
$\gamma_{e,break}$ [10^3]	3.9 – 31
$\gamma_{e,max}$ [10^5]	3.4 – 14
$\alpha_{e,1} = \alpha_{p,1}$	1.3
$\alpha_{e,2} = \alpha_{p,2}$	2.3
K_e [cm^{-3}]	5.6×10^{-3} – 1.5
$^\star u_e$ [erg cm^{-3}]	1.4×10^{-5} – 2.2×10^{-2}
$\gamma_{p,min}$	1
$\gamma_{p,break}$[10^9]	$= \gamma_{p,max}$
$\gamma_{p,max}$[10^9]	0.06 – 0.3
η	0.1 – 0.8
$^\star u_p$ [erg cm^{-3}]	2.3 – 238
$^\star u_p/u_B$[10^{-5}]	2.6 – 8.7
$^\star L$ [10^{45} erg s^{-1}]	4 – 57

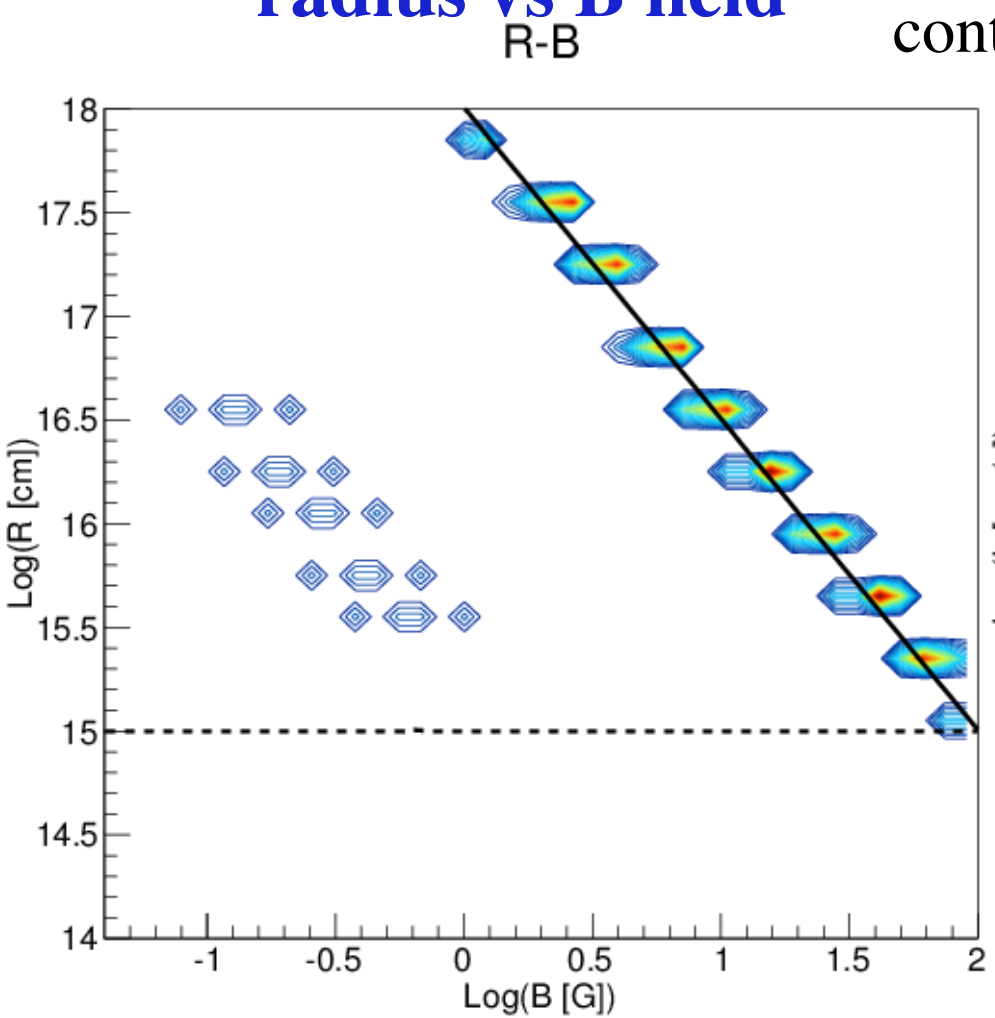
UHF BLL: parameters

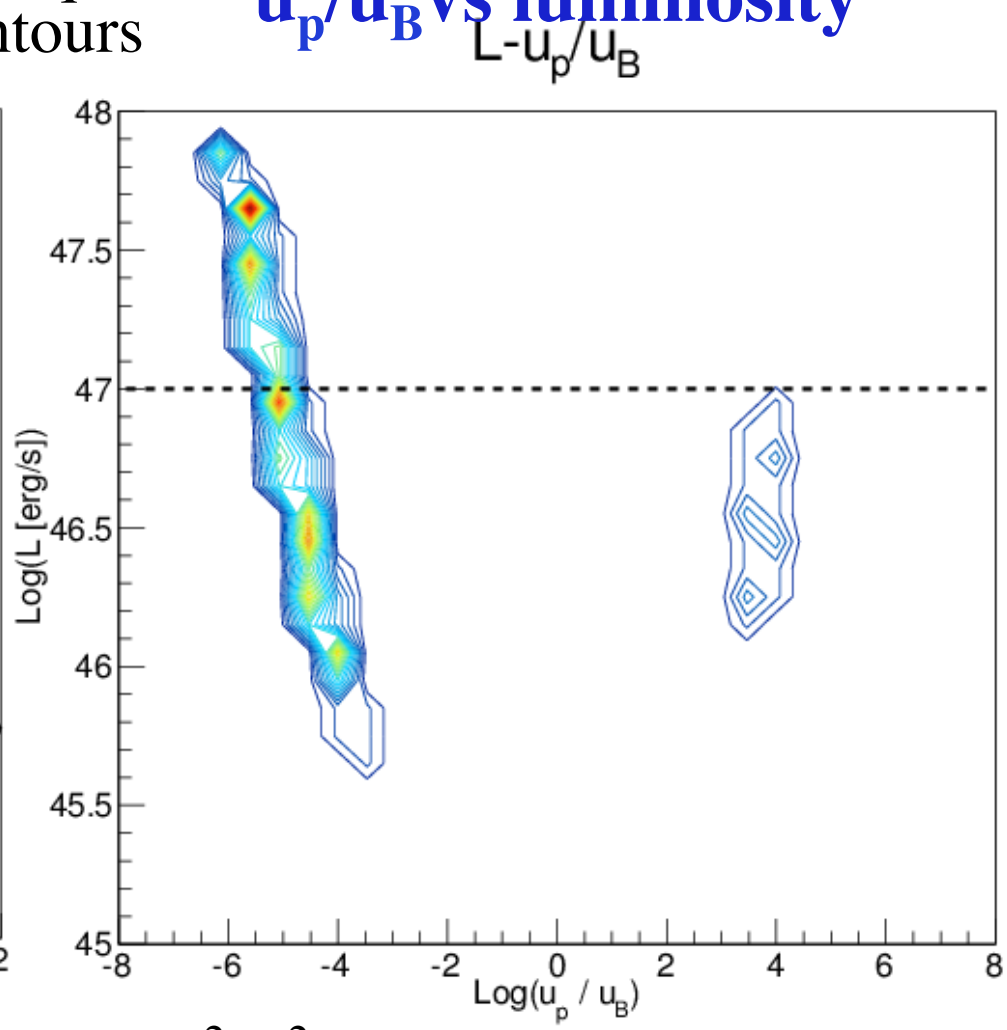
1ES 0229+220

radius vs B field

chi-square contours

u_p/u_B vs luminosity





$$L = \pi R^2 c \Gamma_{bulk}^2 (u_B + u_e + u_p) \quad \Gamma_{bulk} = 2\delta.$$

interpretation possible with plausible range of jet luminosities

UHF BLL: model parameters

	1ES 0229+200	1ES 0347-121	RGB J0710+591	1ES 1101-232	1ES 1218+304
proton synchrotron					
$\gamma_{e,min}$ $[10^2]$	1.6 – 20	3.2 – 38	0.01	4.3 – 50	3.4 – 27
$\alpha_{e,1} = \alpha_{p,1}$	1.3	1.7	1.35	1.7	1.7
$\gamma_{p,max}[10^9]$	4.8 – 57	4.8 – 56	3.9 – 47	4.8 – 56	3.5 – 26
pγ cascade+SSC					
$\gamma_{e,min}$ $[10^2]$	0.01	47 – 108	0.01	100 – 150	37 – 103
$\alpha_{e,1} = \alpha_{p,1}$	1.3	1.7	1.5	1.7	1.7
$\gamma_{p,max}[10^9]$	0.06 – 0.3	0.15 – 0.45	0.1 – 0.15	0.6 – 1.0	0.08 – 0.4

interpretation possible with plausible γ_{min}, jet power
BUT hard proton spectra required $\alpha_p<2$
-> CR-modified shock? Reconnection?
What distinguishes UHF BLLs?

$E_{p,max}<\sim10^{17}$ eV, insufficient for highest E UHECRs

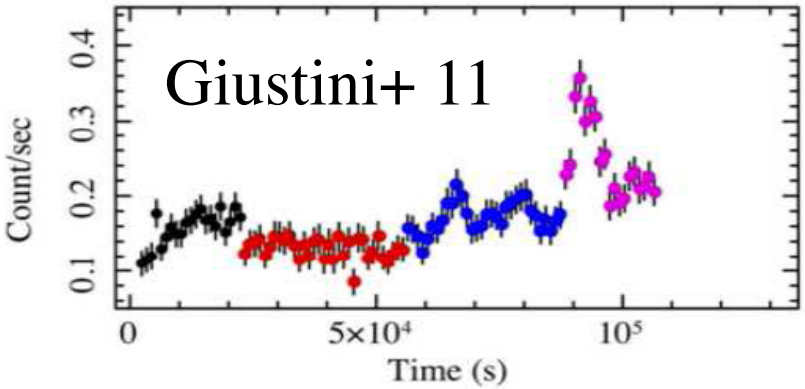
gamma-rays (+UHECRs) from ultra-fast-outflows (UFOs ~ AGN winds)

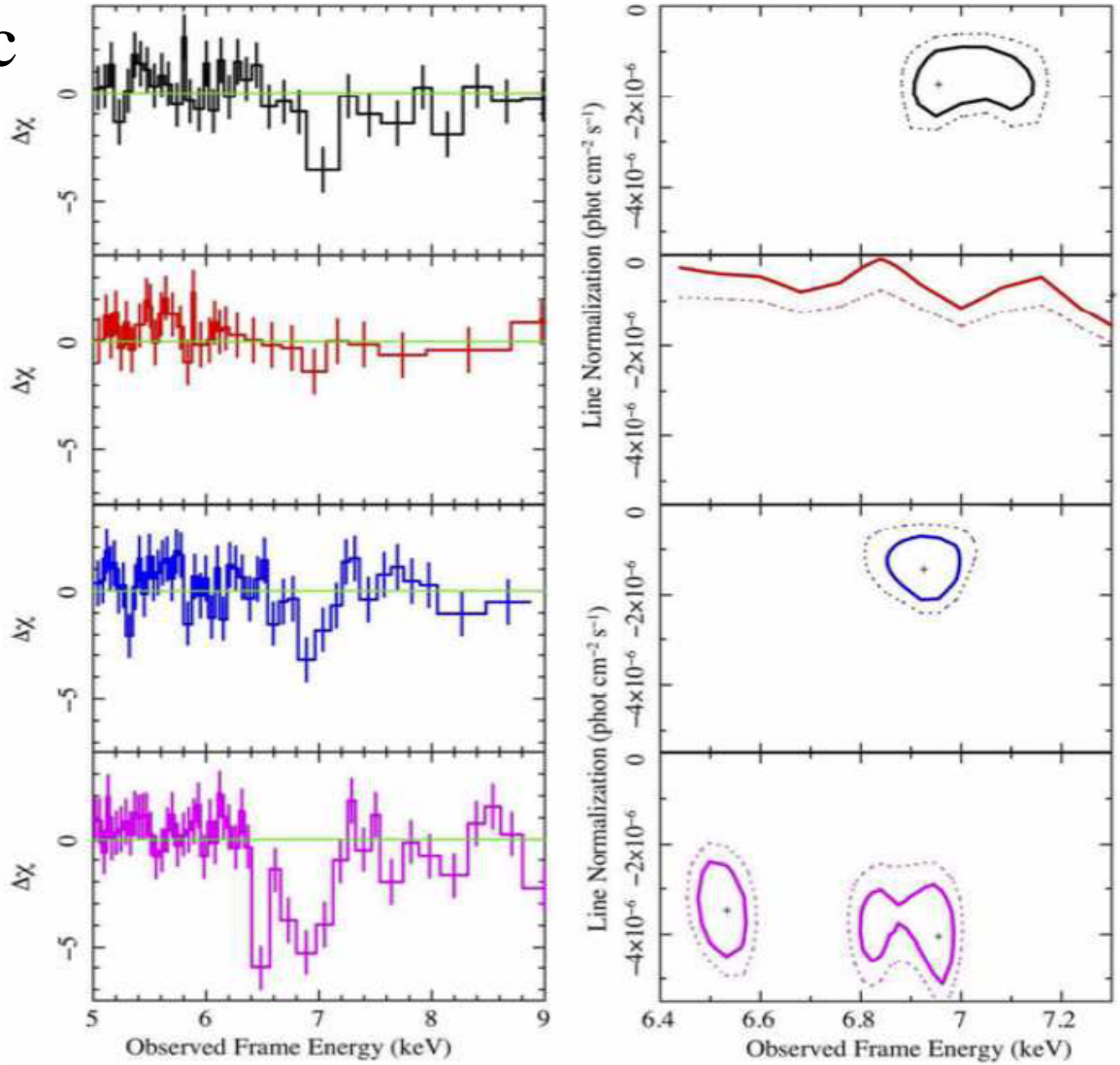
Ruo-Yu Liu, SI, in prep.

ultra-fast outflows (UFOs) in AGN

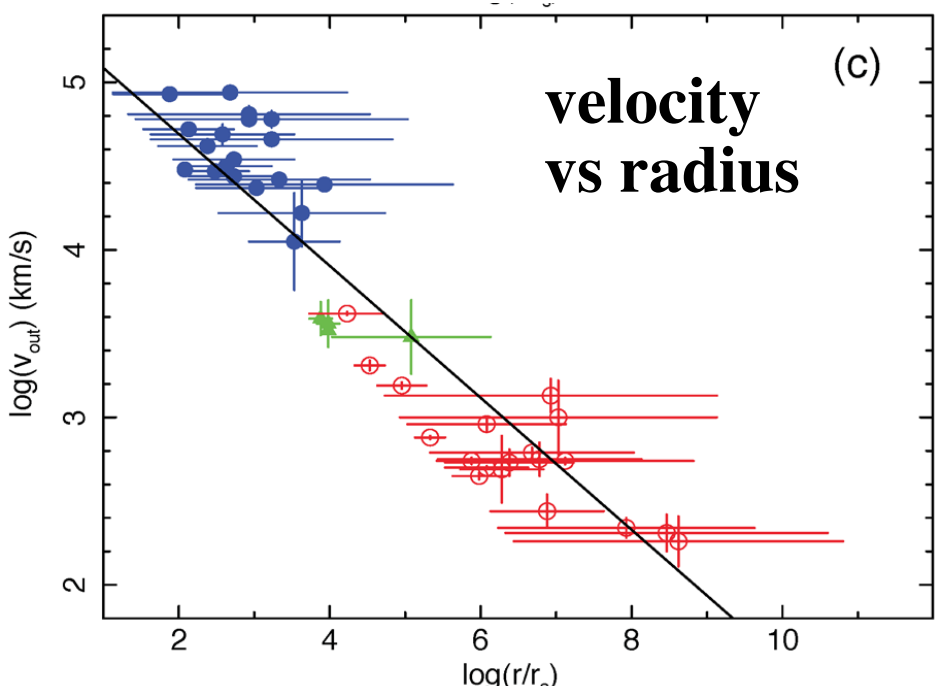
blue-shifted X-ray absorption lines

- ~40 % of all AGNs
  both radio-quiet/radio-loud
- fast outflow: v~0.05-0.3c
- highly ionized:
  Fe XXV/XXVI
  $\xi_i \sim 10^3$-10^6 erg s^{-1} cm
- high column density:
  $N_H \sim 10^{22}$-10^{24} cm^{-2}
- variable: t_{var}>~ks

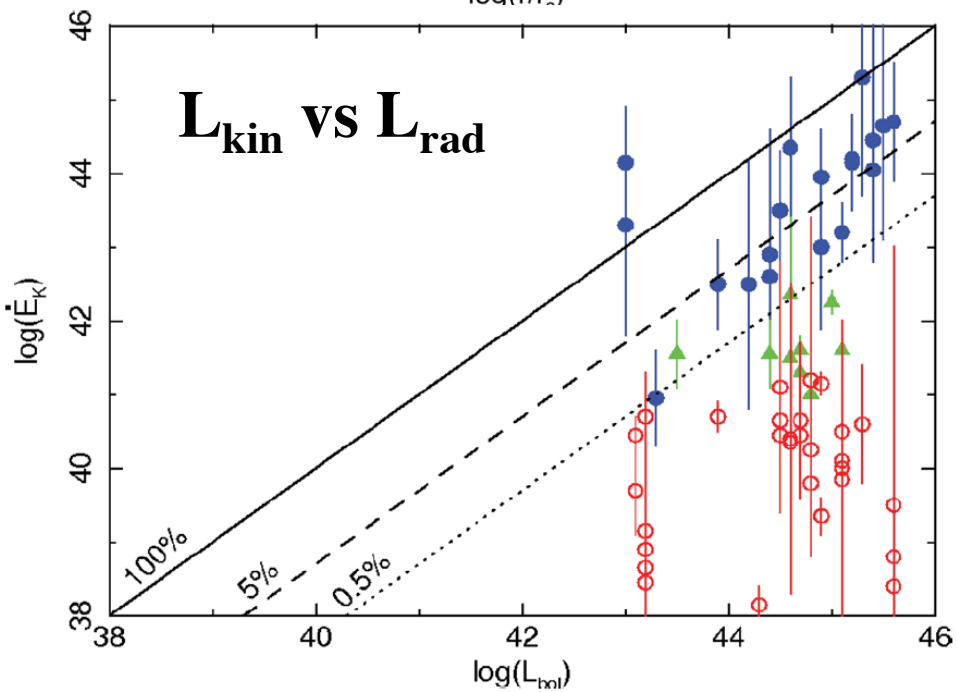




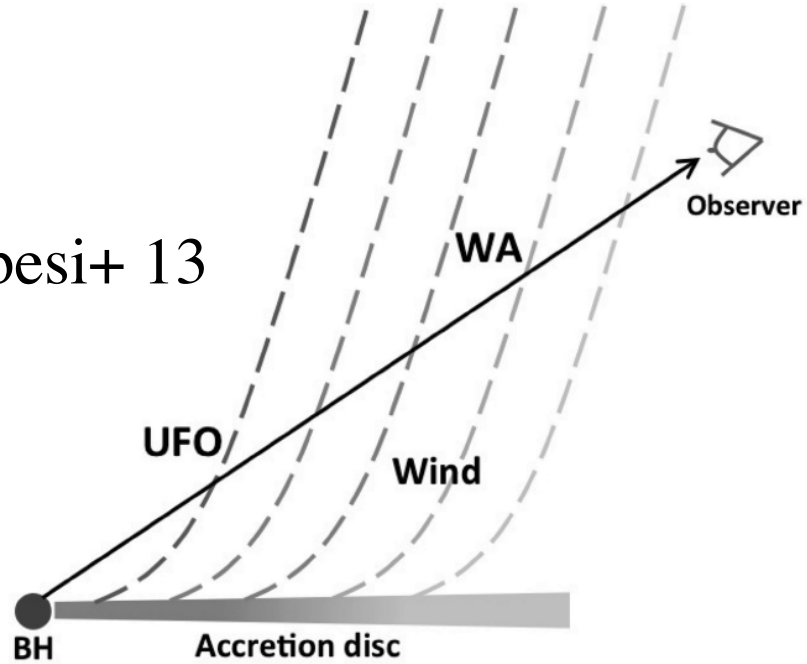
ultra-fast outflows (UFOs) in AGN



- R~0.0003-0.03 pc
  (~10^2-10^4 Rs)
- M~0.01-1 M_{sun}/yr
  L_{kin}~0.01-1 L_{edd}
- broad opening angle
  independent of relativistic jet

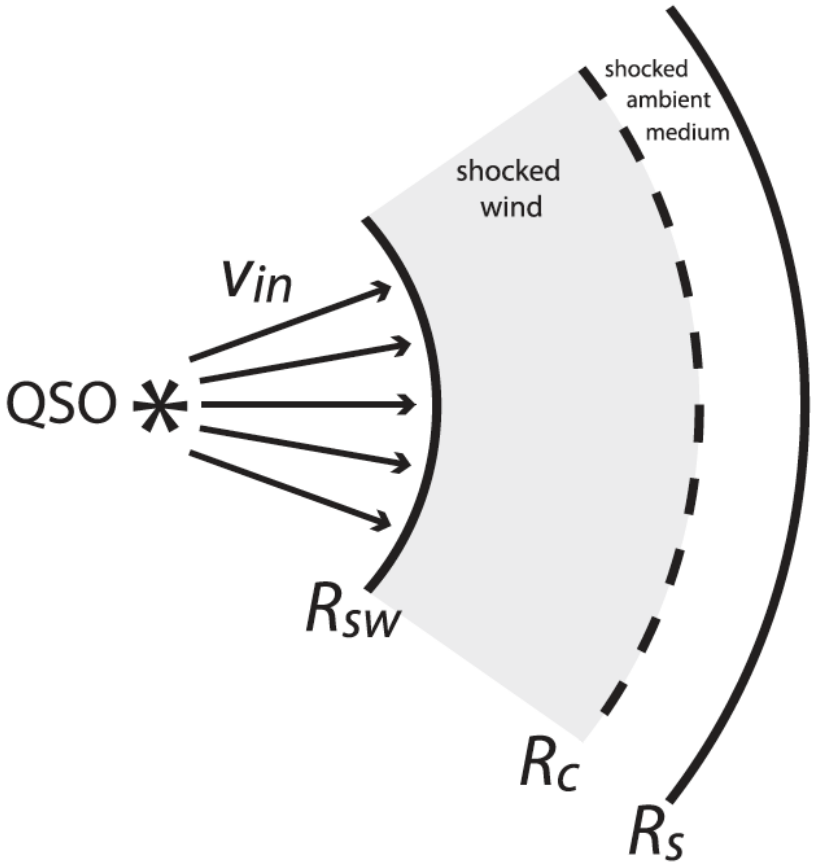


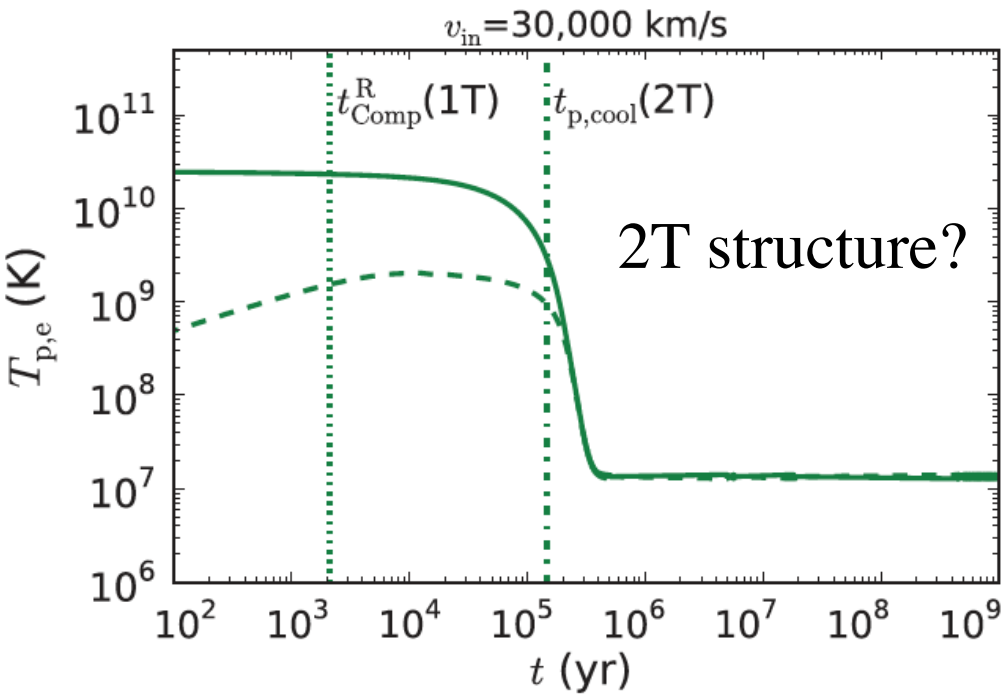
Tombesi+ 13



UFO external shock

Faucher-Giguere & Quataert 12

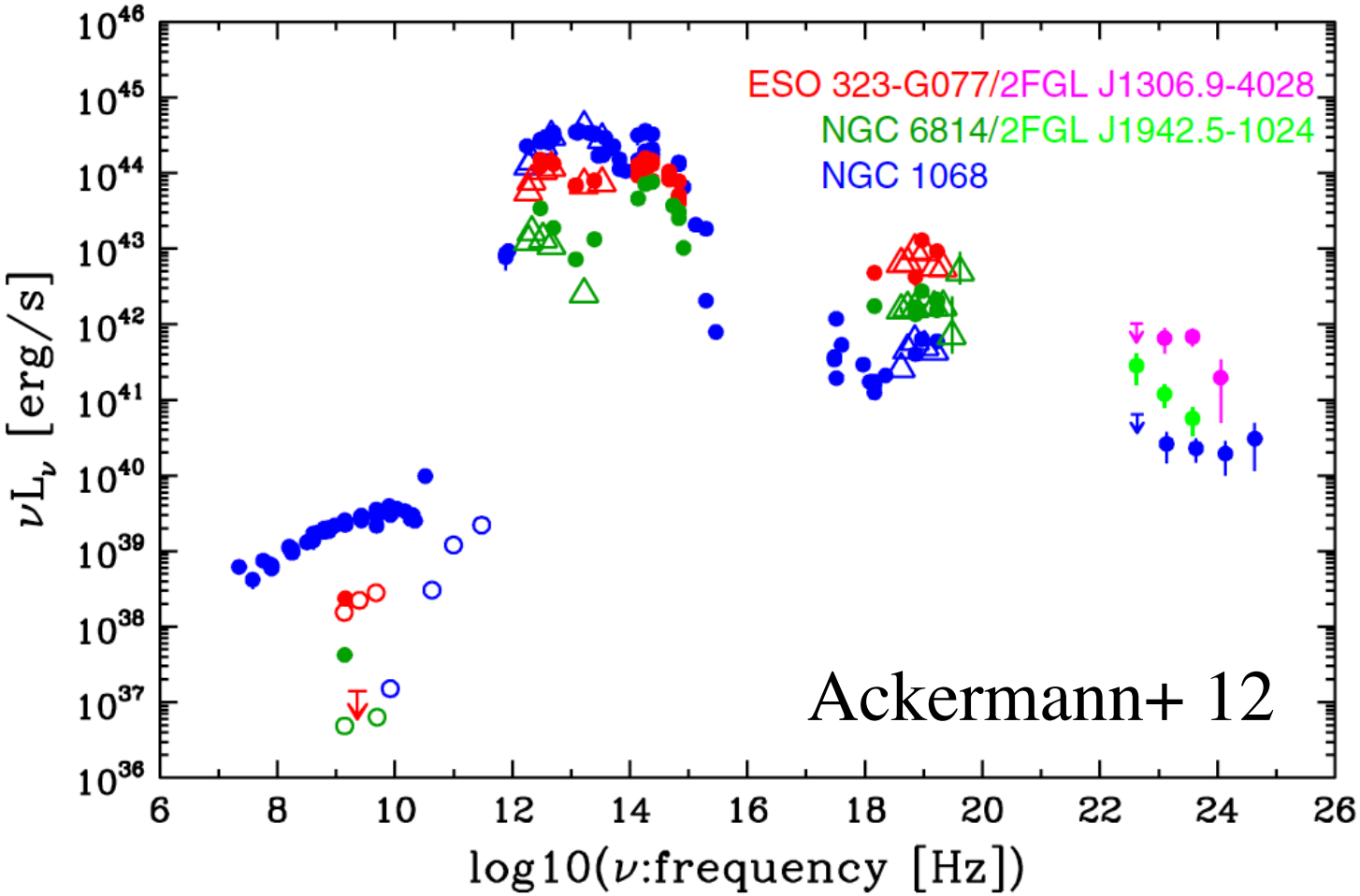




expected radii R_s~0.1-10 pc

- mechanical/thermal feedback on host galaxy gas
  -> origin of M_{BH} - σ_{bulge} correlation?
- particle acceleration and nonthermal emission?

radio-quiet AGN with UFO ESO 323-G77



2/120 Seyferts with GeV association -> chance coincidence?

correlation with Auger UHECR event Nemmen+ 10, Jiang+ 10

known (relatively slow) UFO -> UFO as UFO?

UFO shocks: electron & proton acceleration

Liu & SI
in prep.

$M_{BH}=10^8\ M_{sun}$, $v_{out}=0.1c$, $L_{kin}=10^{45}$ erg/s ~ 0.1 L_{edd}

$B^2/8\pi=\varepsilon_B\ L_{kin}/4\pi\ R^2\ v_{out}$

dynamical $t_{dyn}=R/v_{out}$, $t_{lc}=R_s/c=500$ s

acceleration $t_{acc}\sim 10\ (v_s/c)^{-2}\ E/ceB$

electron loss

$t_{esyn}=3\ m_e^2c^3/4\sigma_T u_B E_e$

$t_{eIC}=3\ m_e^2c^3/4\sigma_T u_{ph} E_e$

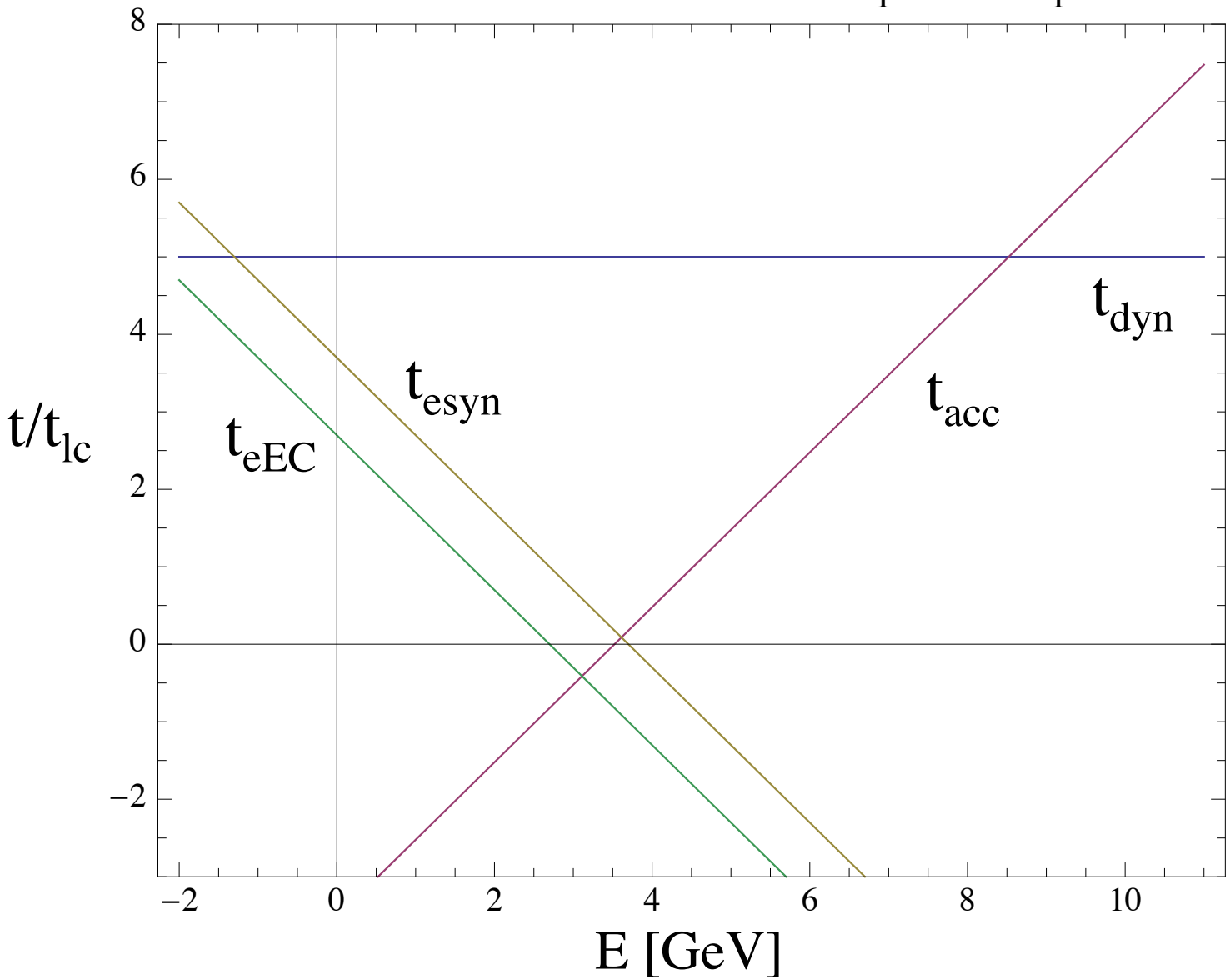
proton loss

$t_{pp}=(\kappa_{pp}\sigma_{pp}n_p c)^{-1}$

$t_{p\gamma} \propto \int \kappa_{p\gamma}(x)\sigma_{p\gamma}(x)x\ dx \int n_{ph}(x)dx)^{-1}$ $x=h\nu/m_e c^2$

UFO external shock

R=0.1 pc -> B_{eq}~3 G, n_p~5x10^3 cm^{-3}

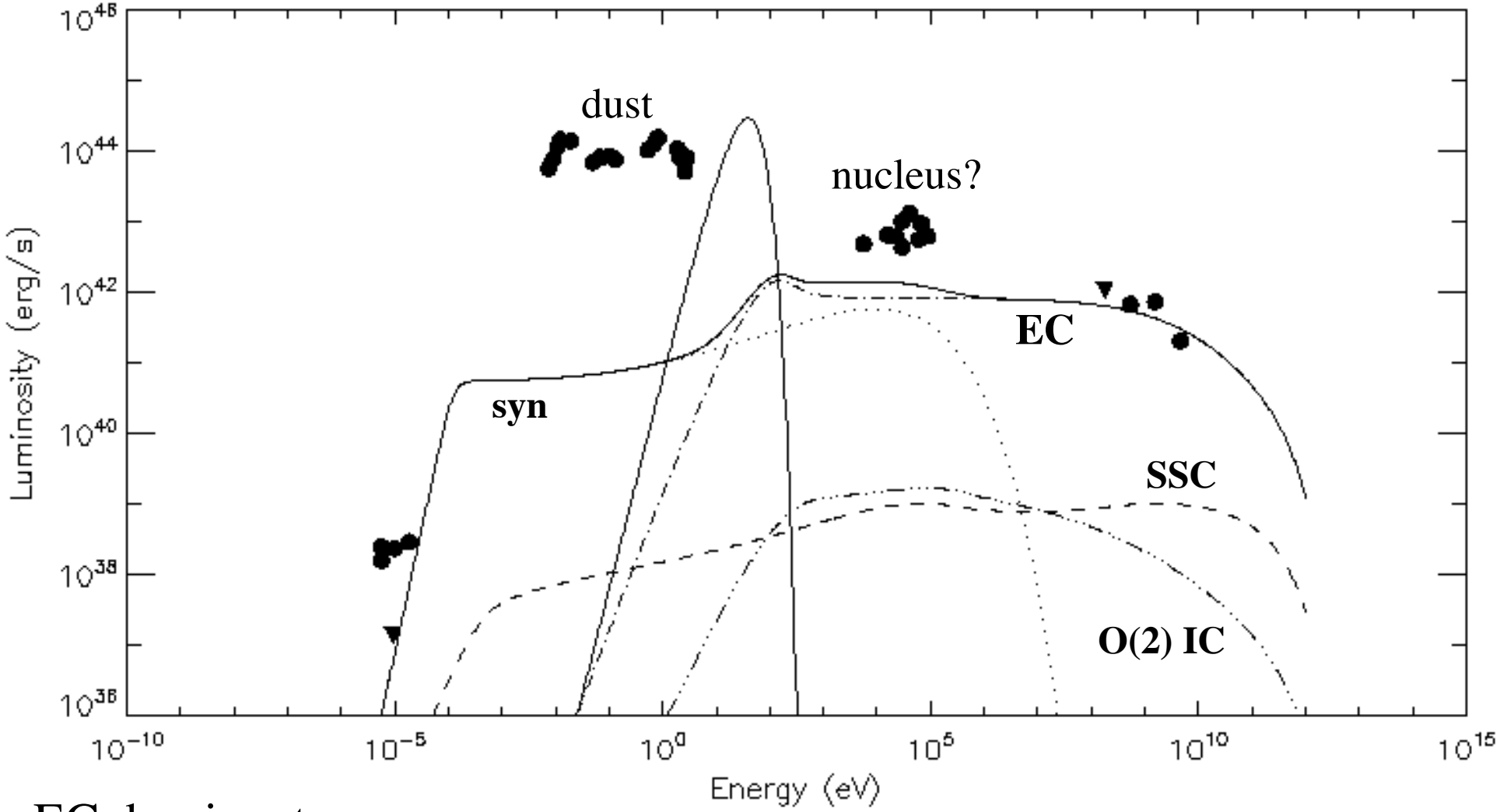


electrons up to ~1 TeV, cooling for ~<10 MeV NB: γγ

protons up to ~3x10^{18} eV (Fe up to ~10^{20} eV)

model results R=0.03pc, B=1G (ε_B~0.1) ESO 323-G77

L_e=2x10^{44} erg/s, L_{nuc}=10^{44} erg/s



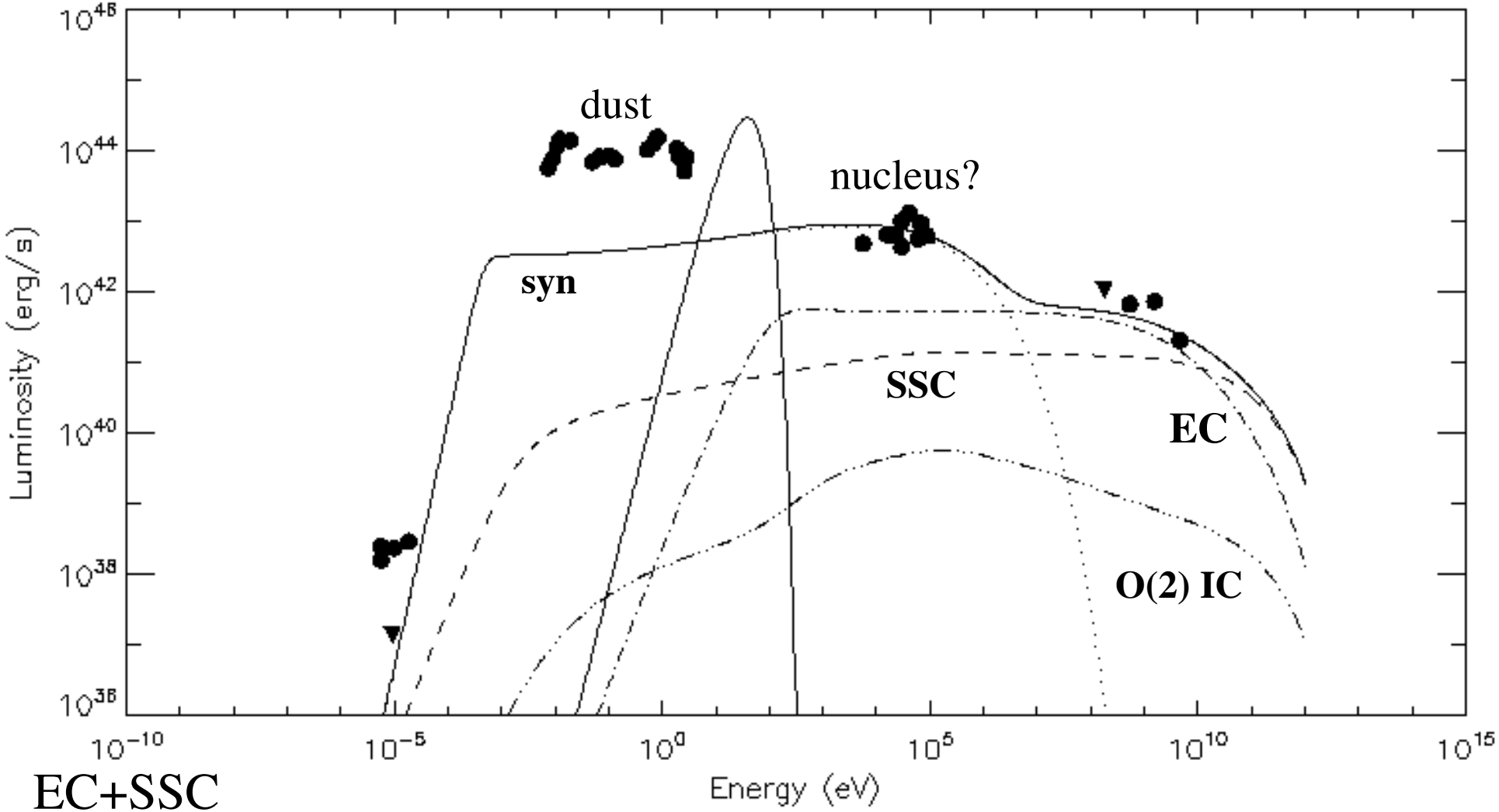
EC dominant

GeV steepening by KN effects? (possibly also γγ)

necessary L_e rather high?

model results R=0.03pc, B=3G (ε_B~1) ESO 323-G77

L_e=2x10^{44} erg/s, L_{nuc}=10^{44} erg/s



EC+SSC

X-ray nonthermal?

B=3G may allow UHECR acceleration with Fe?

NB variability possible

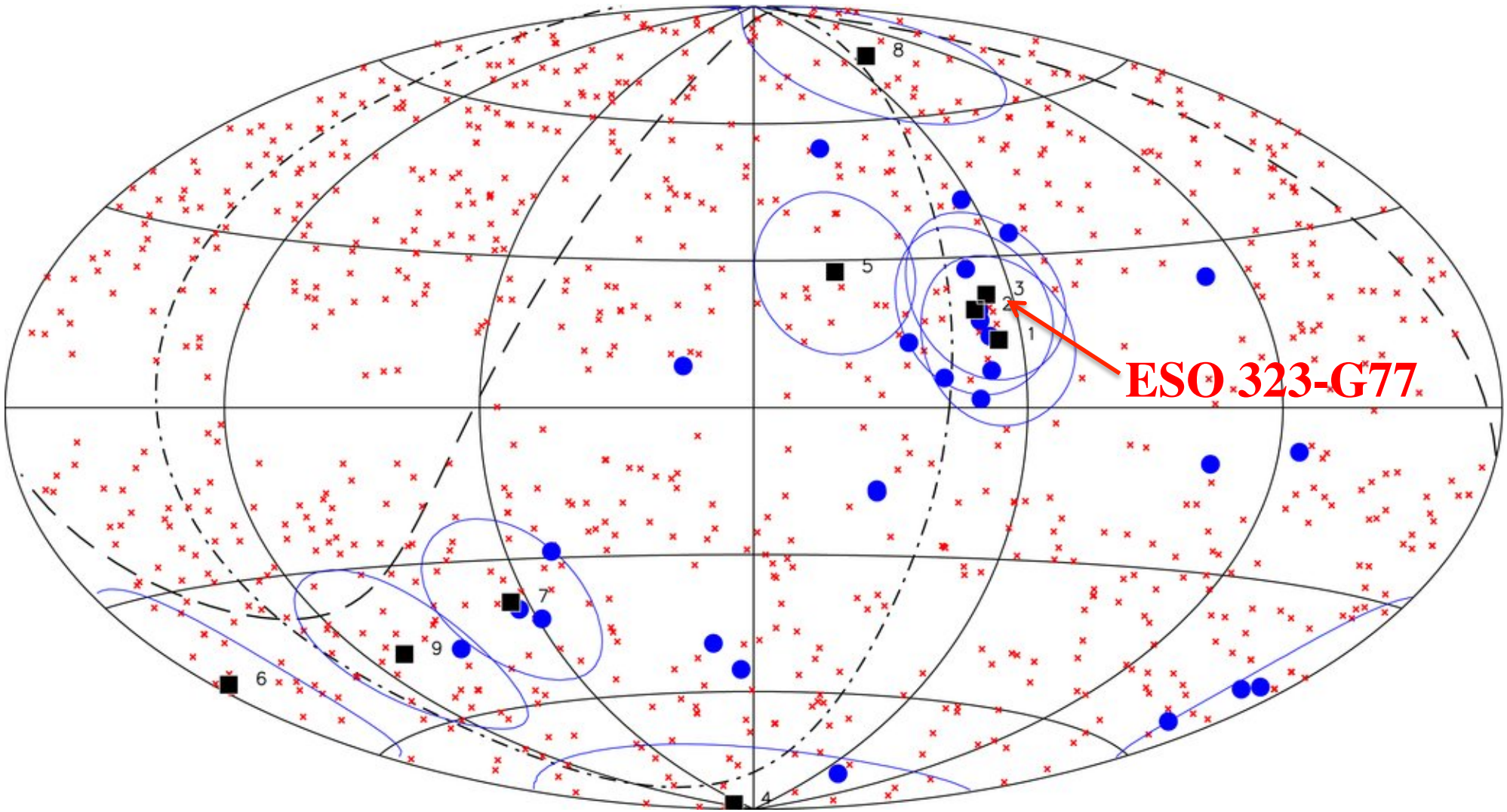
UHECR events: correlations with LAT AGN

Nemmen+ 10
also Jiang+ 10

Blue: Auger events E>57 EeV

Black: AGN with z<0.048 (GZK) in Auger FOV

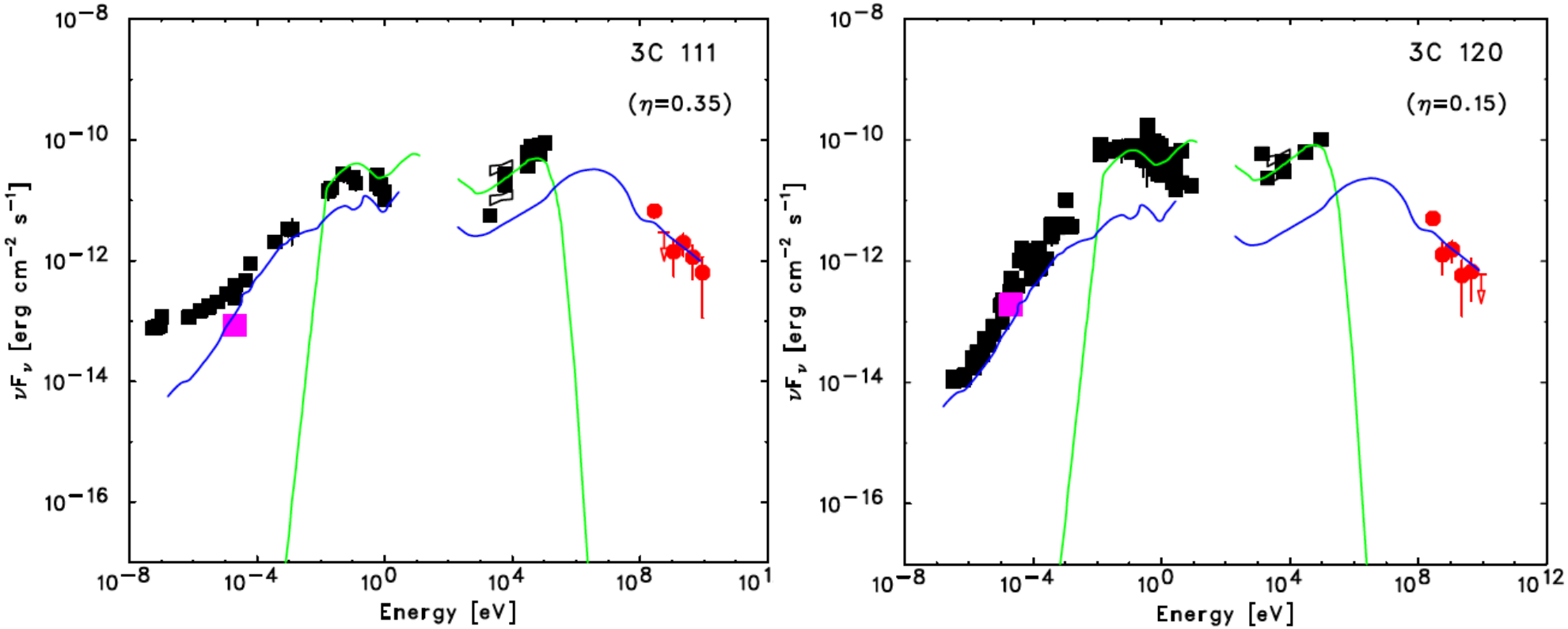
5.4σ correlation on 17deg scale



radio-loud AGNs with UFOs

Kataoka+ 11

2/18 broad-line radio galaxies detected at GeV



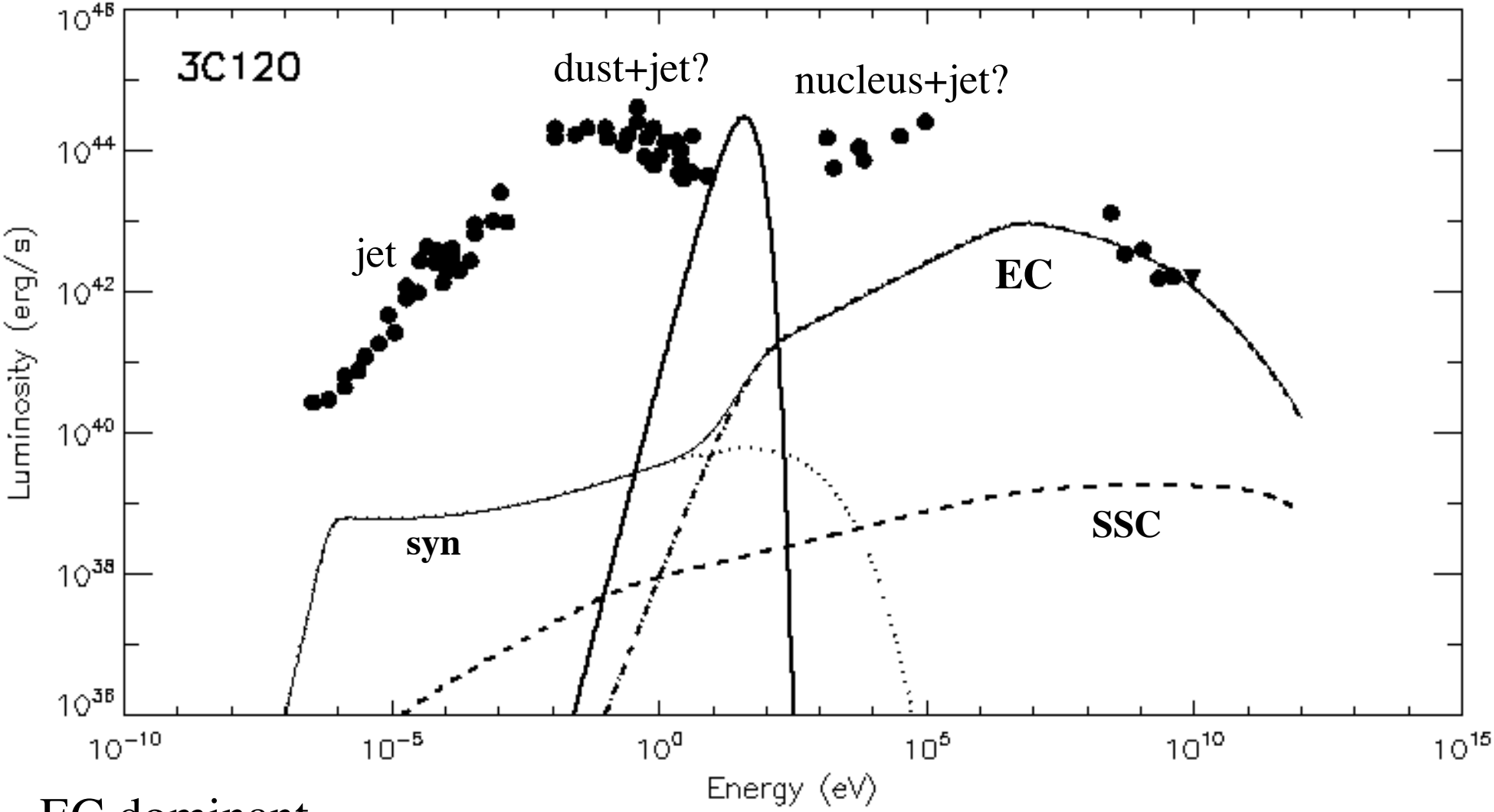
stronger than average core radio emission
-> jet emission at intermediate viewing angle?

50+-20% radio-loud galaxies found to have UFOs

Tombesi+ 14

model results R=1pc, B=10^{-4} G ($\varepsilon_B \sim 10^{-4}$) 3C120

$L_e = 3 \times 10^{45}$ erg/s, $L_{nuc} = 10^{44}$ erg/s



EC dominant

GeV steepening by KN effects? (possibly also $\gamma\gamma$)

necessary L_e rather high?

まとめ

hadronic emission from UHF-peaked BL Lacs

- SSCモデルでは異常な$\gamma_{e,min}$, δの値が必要
- proton synchrotron or pγ cascade+SSCによる説明が可能
  無理のない$\gamma_{e,min}$, LでOK
  ハードな陽子スペクトルは必要 -> 加速機構？
  UHECRは困難
- 将来的に時間分解スペクトルで識別 -> CTA

gamma-rays (+UHECRs) from ultra-fast outflows

- ジェットの有無に関わらず、AGNの多く(4割)で
  高速(光速の数割)、強力(L_{Edd}の数割)のoutflow
- 母銀河へのfeedbackと共に粒子加速・非熱的放射の可能性
- UFO伴うSeyfert ESO323-G77のGeV γ(?)説明可能
  (+UHECRとの相関?)
  UFO伴う電波銀河 3C120などのGeV γも?
  -> CTA他今後のさらなる観測に期待