Leptonic & Hadronic Photon Emission Models of High-Energy Sources

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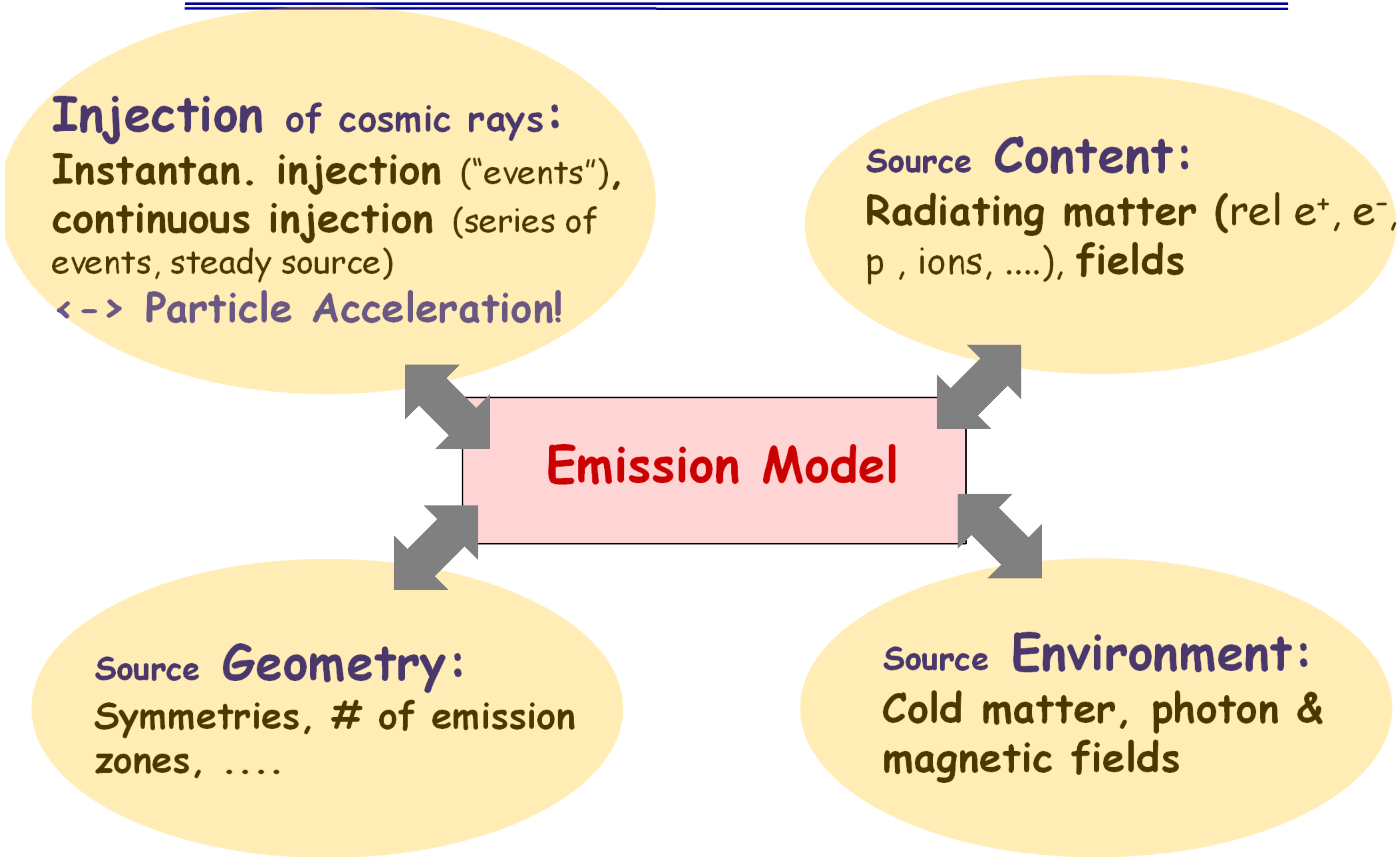
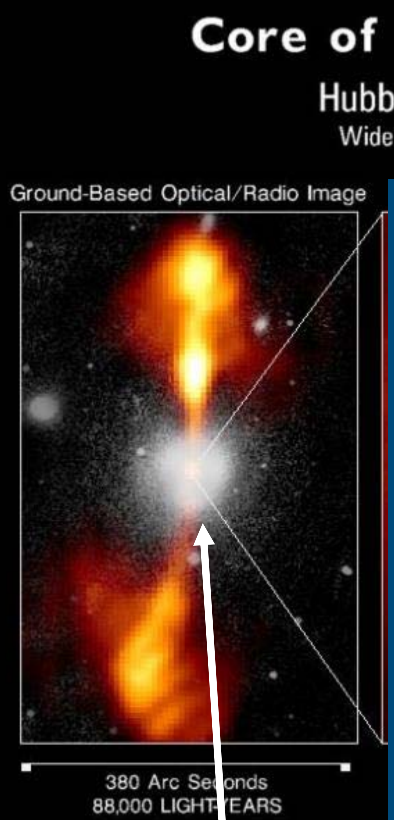
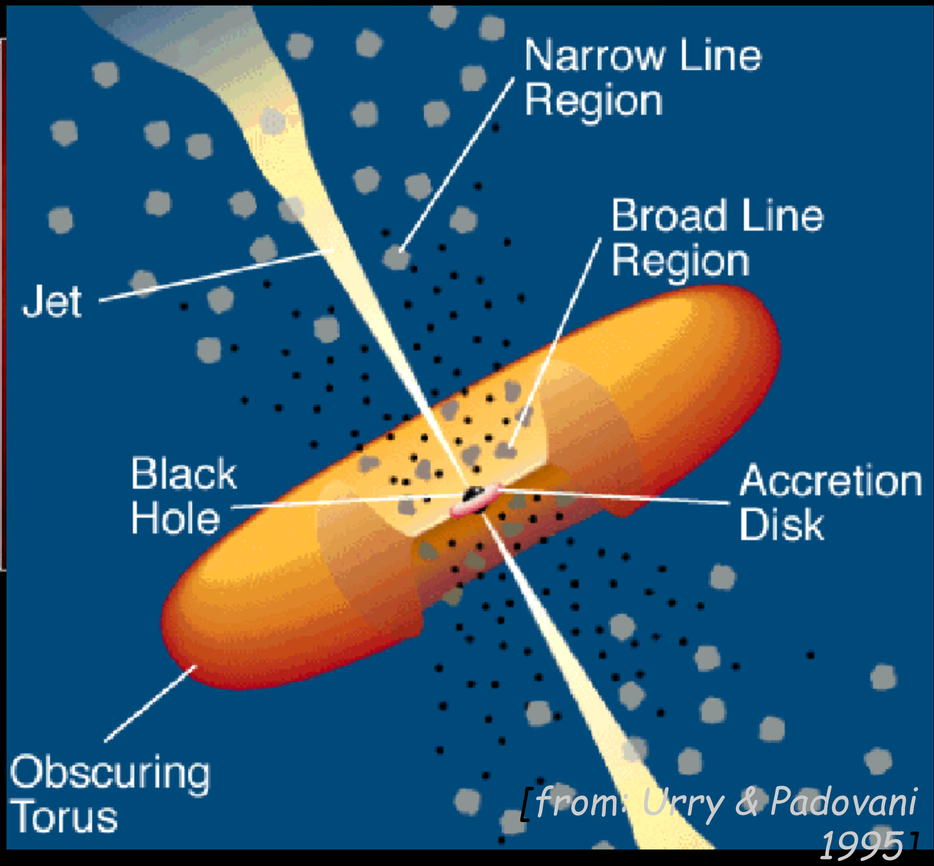
Workshop, "PASTO – Particle Acceleration in Astrophysical Objects",
Astron. Observatory of Rome, Sept 5, 2022

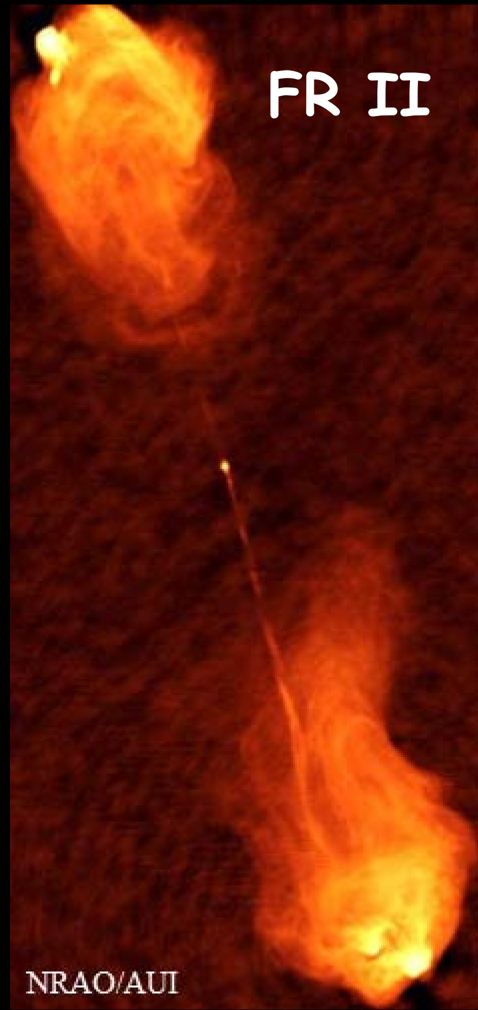
Model Building in HE Astrophysics



Environment of Jetted Active Galactic Nuclei (AGN)

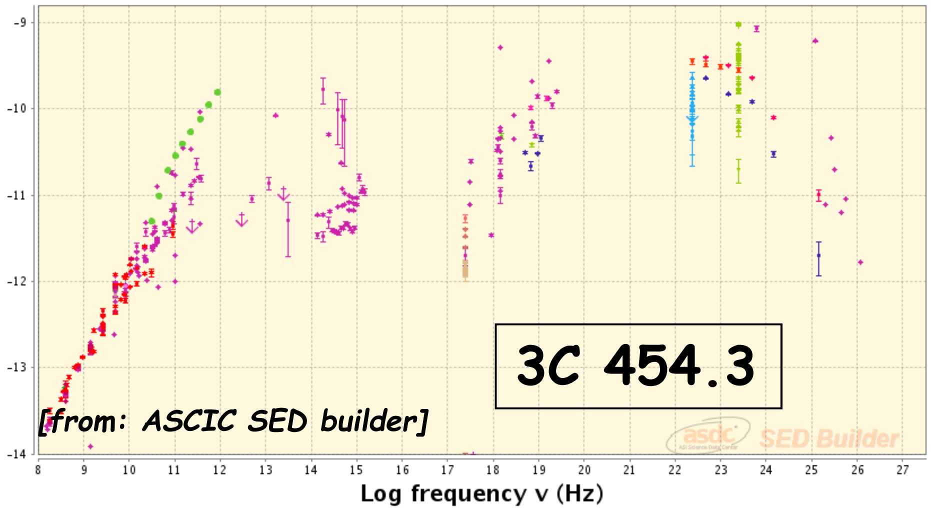




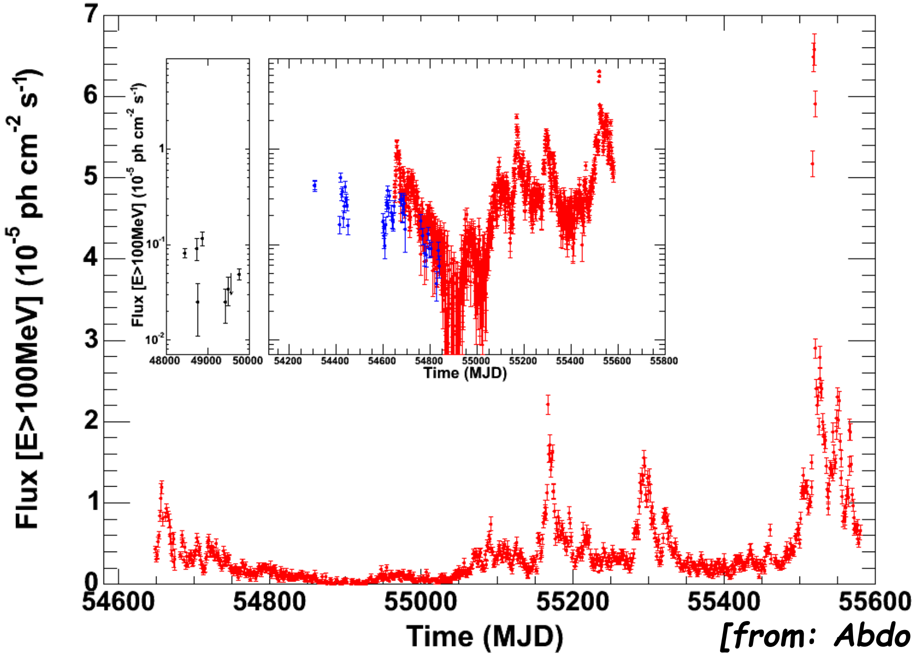


host galaxy

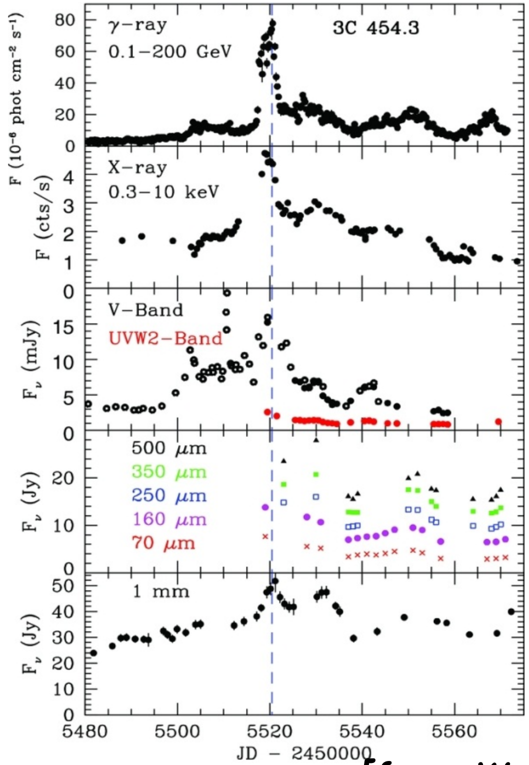
Radiative Properties of the Non-thermal AGN



- **Broad-band emission** (radio …. γ)
- **Highly variable at all energies** (min – months)



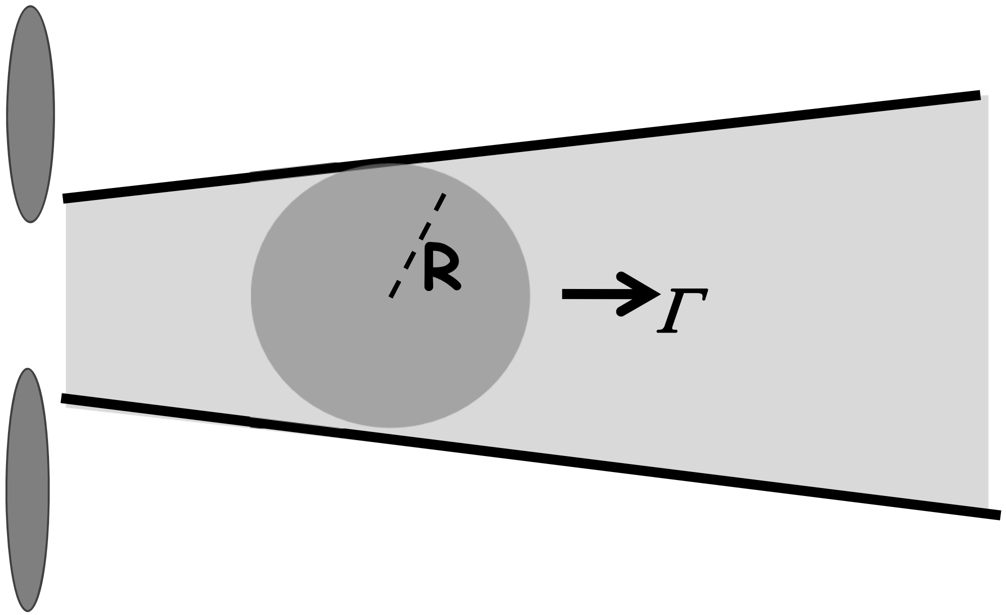
[from: Abdo et al '11]



[from: Wehrle et al '12]

-> T_{var} ~ R_{emi}: **HE-flare radiation from a well localized region**

Homogeneous one-zone emission region

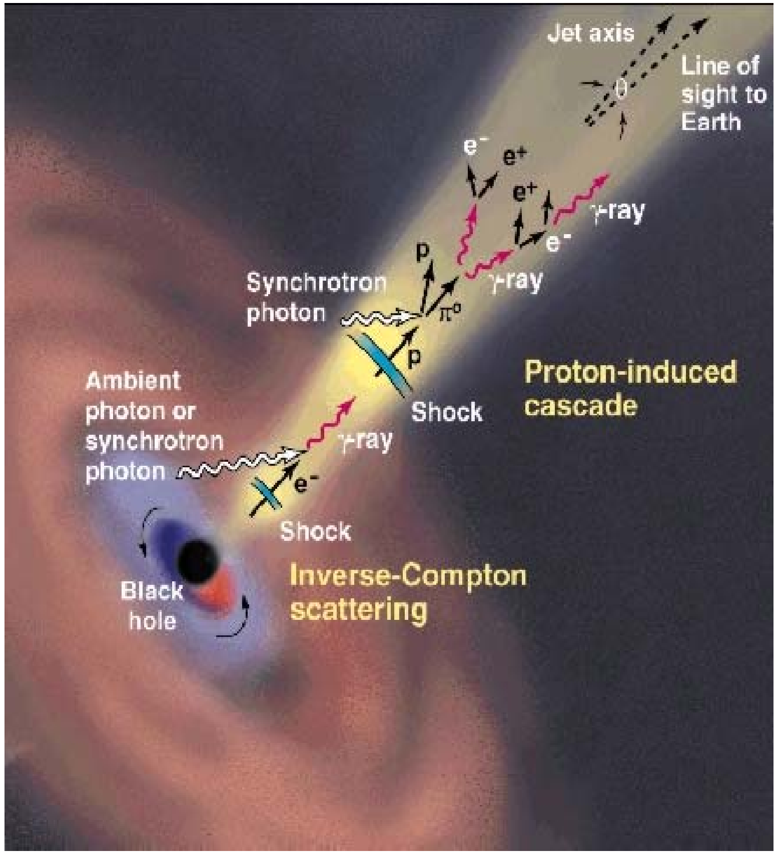


Particle & Photon Transport Equation:

$$\partial_t F_N + \cancel{\partial_x(\kappa\partial_x F_N)} + \cancel{u\partial_x F_N} - \frac{p}{3}\cancel{\partial_x u}\partial_p F_N + \frac{1}{p^2}\partial_p[p^2(\dot{p}_{loss} F_N) - p^2 \cancel{A\partial_p F_N}] + \dot{F}_N^{cat} = Q_N^{inj}$$

with $F_N = F_N(\cancel{x}, p, t)$ **the phase-space density of CRs**

Emission Models of AGN Jets



- **"Leptonic" models:**

Jet material: rel e^+e^- + cold e,p

HE emission e^+e^--initiated

- **"Hadronic" models:**

Jet material: rel e^+e^-p + cold e,p

HE emission dominantly p-initiated

- **"Lepto-hadronic" models:**

Jet material: rel e^+e^-p + cold e,p

HE emission dominantly e^+e^--initiated

Cosmic-ray Sources as Complex Systems

$$\partial_t F_N + \dot{F}_N^{esc} + \frac{1}{p^2}\partial_p[p^2(\dot{p}_{loss}F_N)] + \dot{F}_N^{cat} = Q_N^{inj}$$

Nucleons

$\vdots$

$$\partial_t F_{\mu,\pi} + \dot{F}_{\mu,\pi}^{esc} + \frac{1}{p^2}\partial_p[p^2(\dot{p}_{loss}F_{\mu,\pi})] + \dot{F}_{\mu,\pi}^{cat} = \dot{F}_{\mu,\pi}^{p\gamma;h}$$

Unstable secondaries

$\vdots$

$$\partial_t F_e + \dot{F}_e^{esc} + \frac{1}{p^2}\partial_p[p^2(\dot{p}_{loss}F_e)] = Q_e^{inj} + \dot{F}_e^{\gamma\gamma} + \dot{F}_e^{p\gamma}$$

e+/e-

$$\partial_t F_\gamma + \dot{F}_\gamma^{esc} + \dot{F}_\gamma^{\gamma\gamma} = \dot{F}_\gamma^{em} + \dot{F}_\gamma^{p\gamma;h}$$

Photons

wi $F_X = F_X(p, t)$, $F_\gamma = F_\gamma(\epsilon, t)$ the PS density of type X particles/photons

and $\dot{F}_{\mu,\pi}^{p\gamma;h} = \dot{F}_{\mu,\pi}^{p\gamma;h}(F_\gamma(\epsilon,t); p, t)$

$\dot{F}_e^{p\gamma} = \dot{F}_e^{p\gamma}(F_\gamma(\epsilon,t); p, t)$

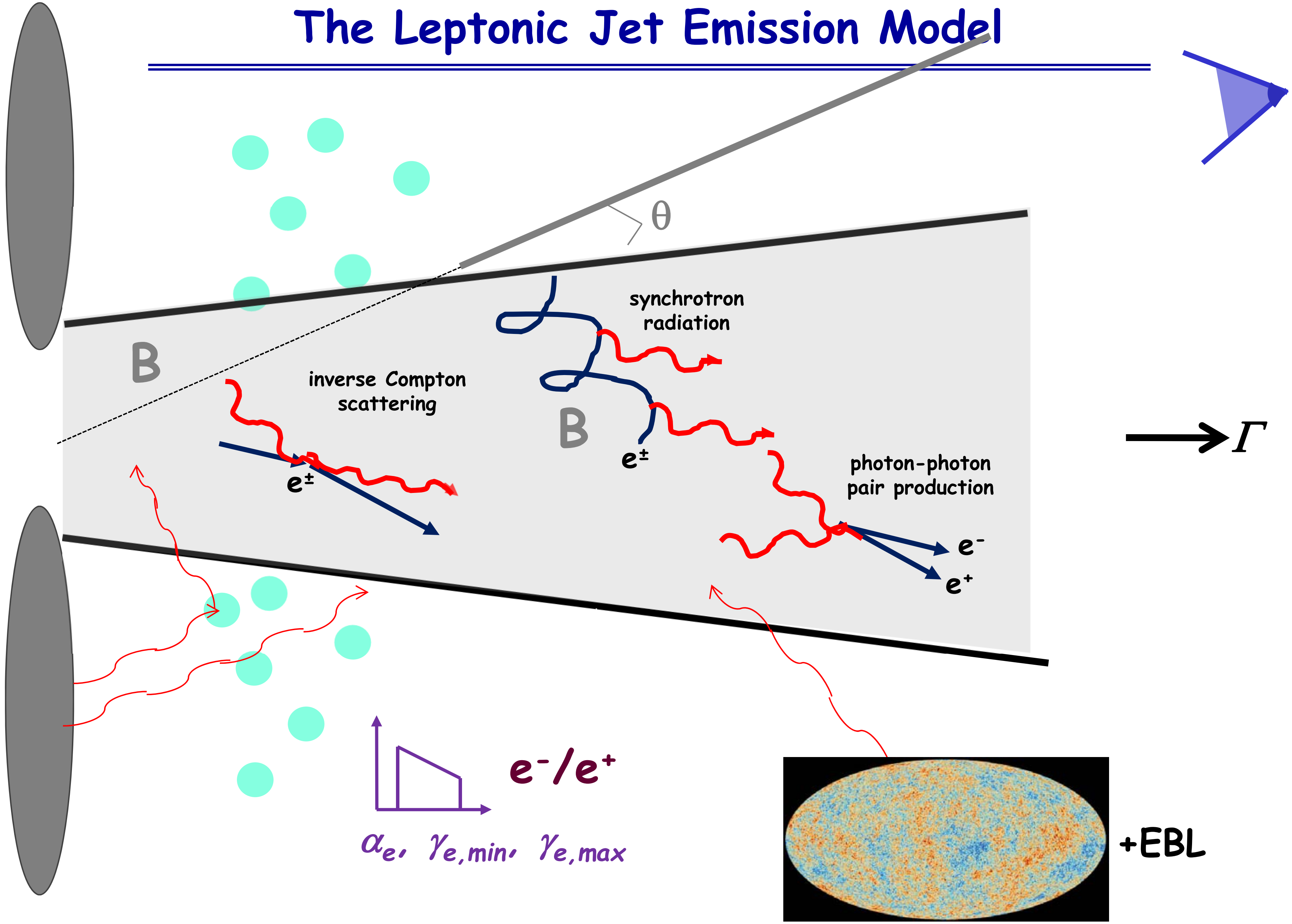
$\dot{F}_\gamma^{\gamma\gamma} = \dot{F}_\gamma^{\gamma\gamma}(F_\gamma(\epsilon,t); \epsilon, t)$

$\dot{F}_e^{\gamma\gamma} = \dot{F}_e^{\gamma\gamma}(F_\gamma(\epsilon,t); p, t)$

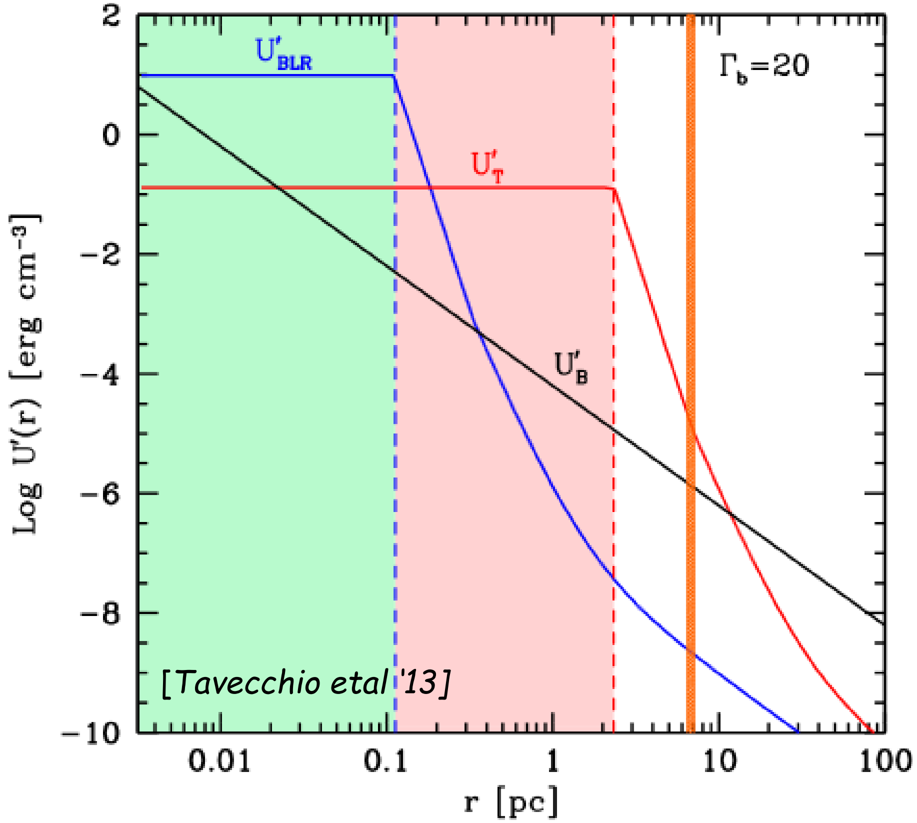
& losses: $\dot{p}_{loss} = \dot{p}_{loss}(F_\gamma(\epsilon,t), B(t); p, t)$

Photomeson production, Bethe-Heitler pair production, decay of unstable particles, γγ-pair production, synchrotron radiation, inverse Compton scattering, adiabatic losses, particle escape

The Leptonic Jet Emission Model



Interaction Targets



=> Nature (& frequency) of dominating external target photon field depends on distance from the central engine

Target photons for IC scattering are ...

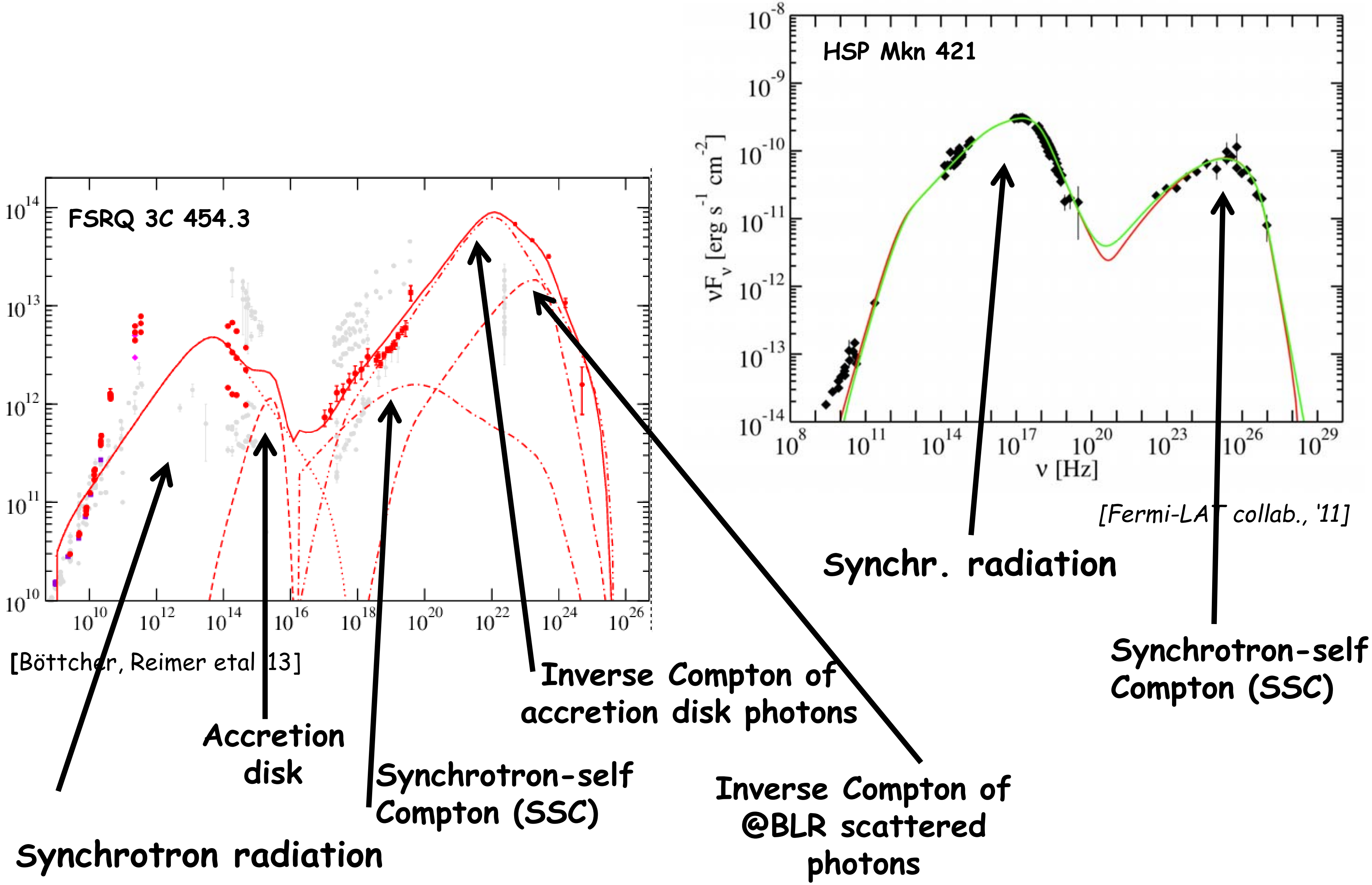
- **internal photon fields:**

  i.e. synchrotron radiation of the same relat. e^- : SSC

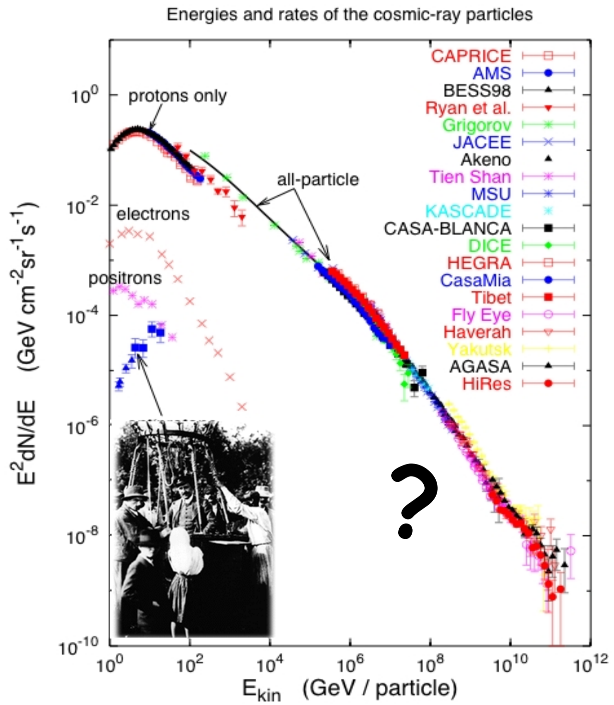
- **external photon fields:**

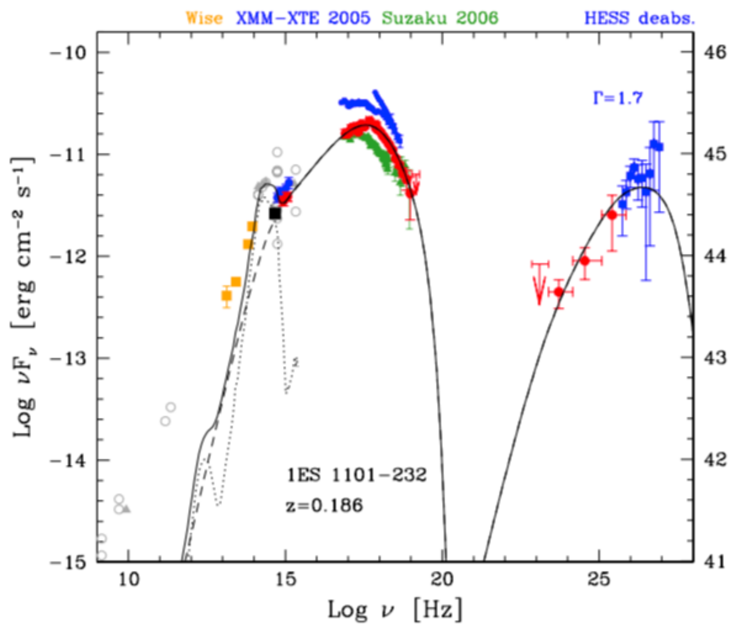
- accretion disk: EC-AC
- reproc. disk radiat. (via BLR): EC-BLR
- IR radiation from dust torus: EC-DT
- Optical radiation from host galaxy
- CMB, EBL

Modeling blazars with one-zone „leptonic models"

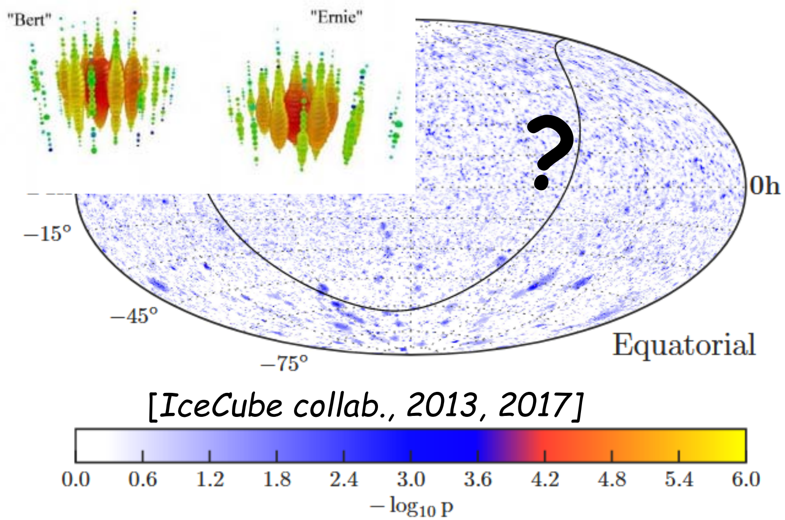


CR Hadrons in AGN Jets?





[from: Costamante etal '18]

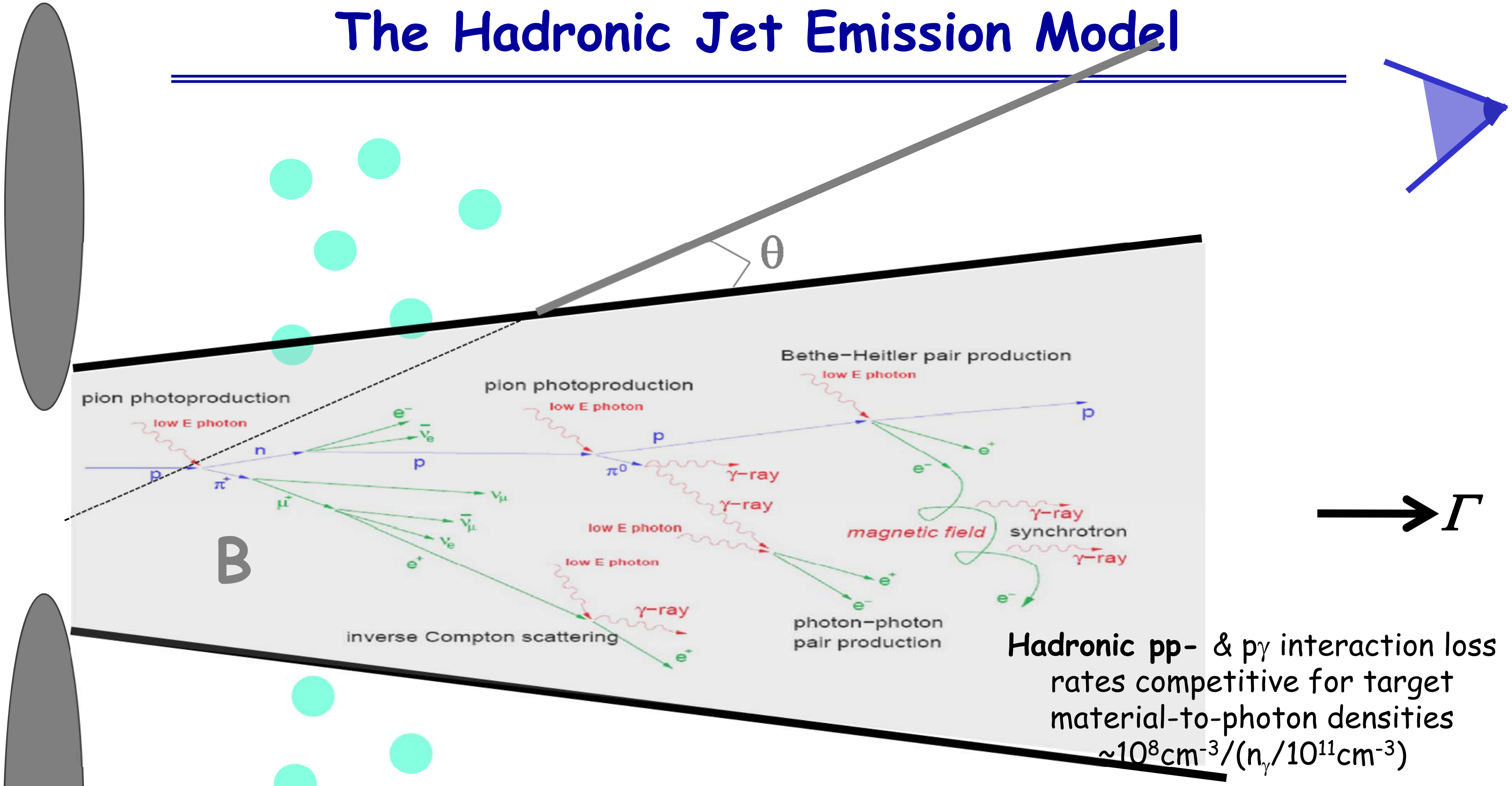


[IceCube collab., 2013, 2017]

One-zone SSC models for

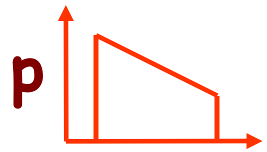
extreme HSP BL Lacs problematic!

The Hadronic Jet Emission Model



Hadronic pp- & pγ interaction loss rates competitive for target material-to-photon densities ~$10^8 cm^{-3}/(n_\gamma/10^{11} cm^{-3})$

$\alpha_e, \gamma_{e,min}, \gamma_{e,max}$



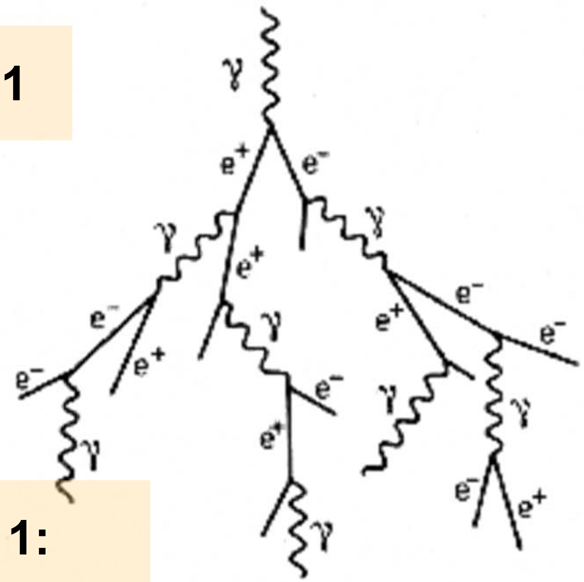
$\alpha_p = \alpha_e, \gamma_{p,min} = 1,$
$\gamma_{p,max}$, e/p

Internal Pair Cascades

Secondary pairs + photons initiate em pair cascades (Compton/synchrotron-supported) with a "strength" that is linked to the meson-production rate:

$\tau_{\gamma\gamma,thr} \sim 300\ \tau_{p\gamma,thr}$

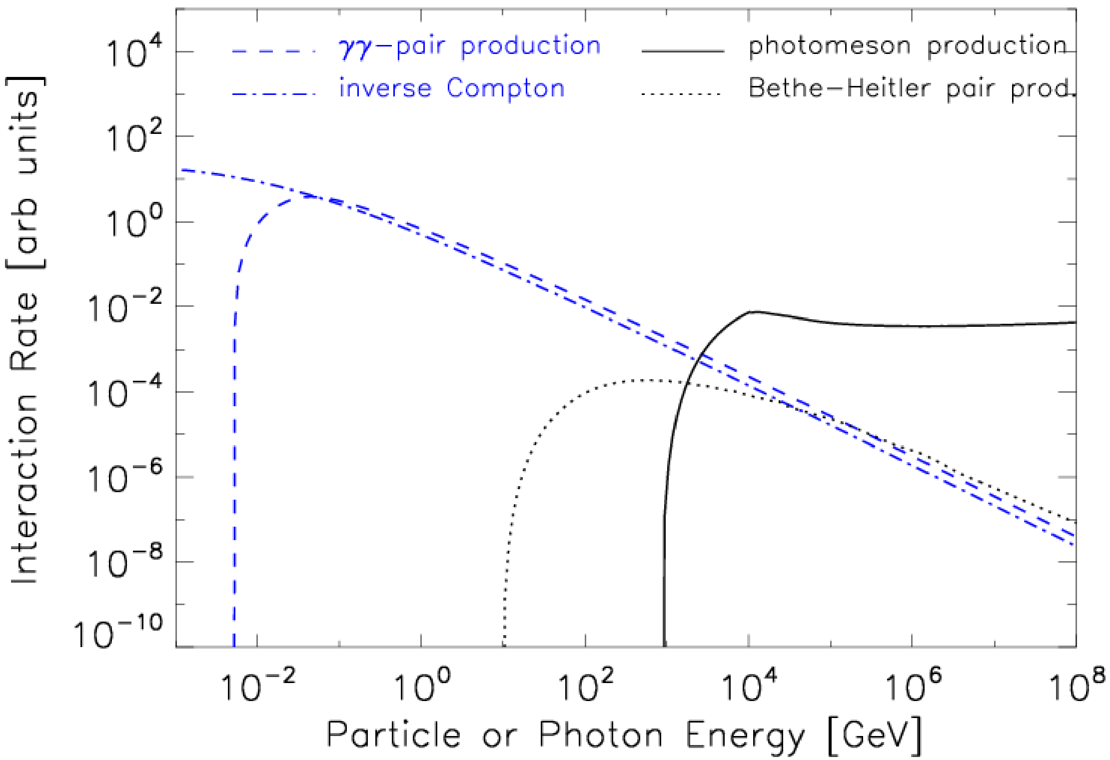
$\tau_{\gamma\gamma} \gg 1$



$\tau_{\gamma\gamma} < 1$:

photons escape

(on t_{dyn})



A Pair Cascade Classification Scheme(*)

$l_s > 10$

Type-I: completely linear cascade

KN $e^{\pm}$-/γ-production mainly on non-cascade photons $l_i < 10$ (**)

Type-II: partly non-linear cascade

$e^{\pm}$-/γ-production partly on cascade photons $l_i > 10$ (**) & $L_i/L_s < 1$ (***)

Type-III: completely non-linear cascade

TH $e^{\pm}$-/γ-production mainly on cascade photons $l_i > 10$ (**) & $L_i/L_s > 1$ (***)

(***) $0.1 < L_i/L_s < 10$: higher order Compton scattering possible

(*) [following Svennson 1987]

(**) particle compactness parameter $l_i = L_i \sigma_T/(Rmc^3)$

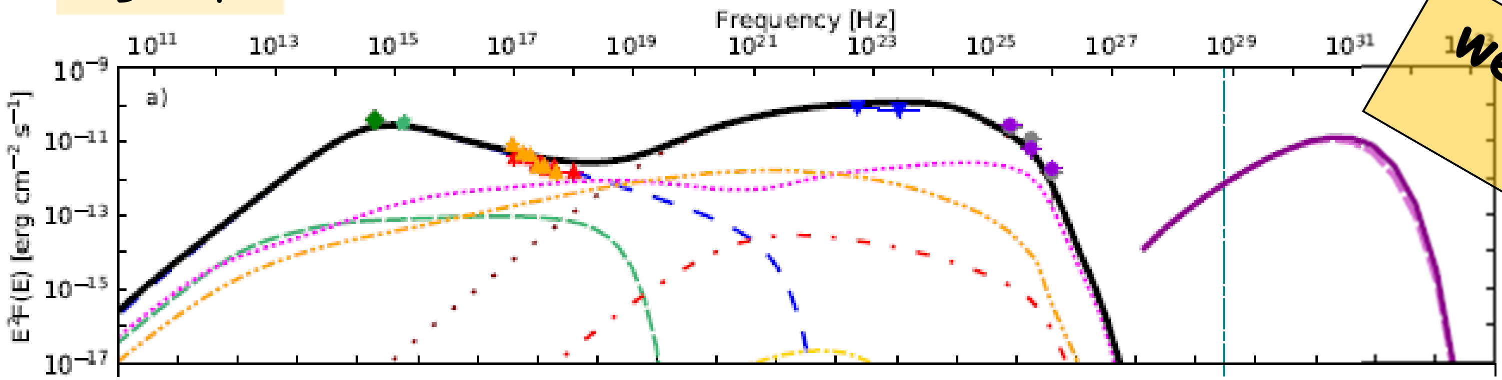
compactness parameter of the non-cascade photon field $l_s = L_s \sigma_T/(Rmc^3)$

Lepto-hadronic models of γ-loud AGN

- $\tau_{\gamma\gamma} \ll 1$, lin cascade setup: add-on classical "leptonic model" to proton-interaction weak hadronic model

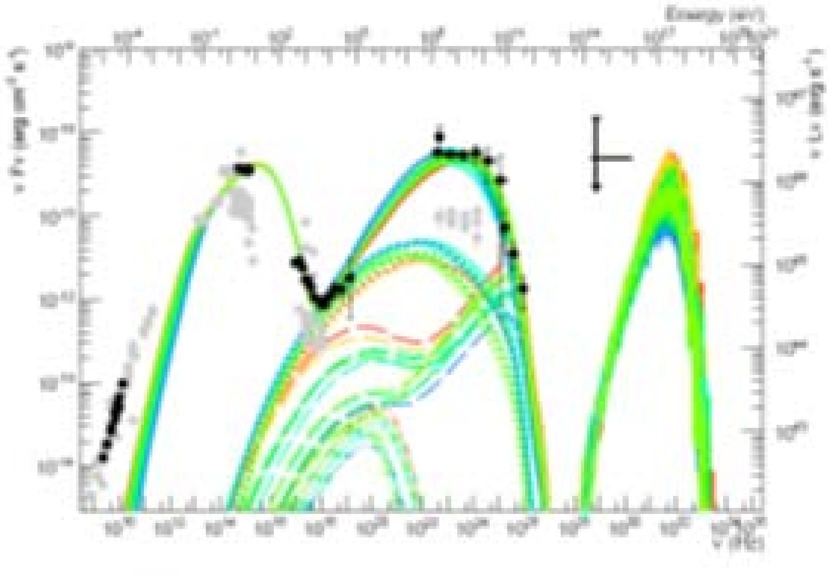
$u'_B \ll u'_t$

weak magnetic fields



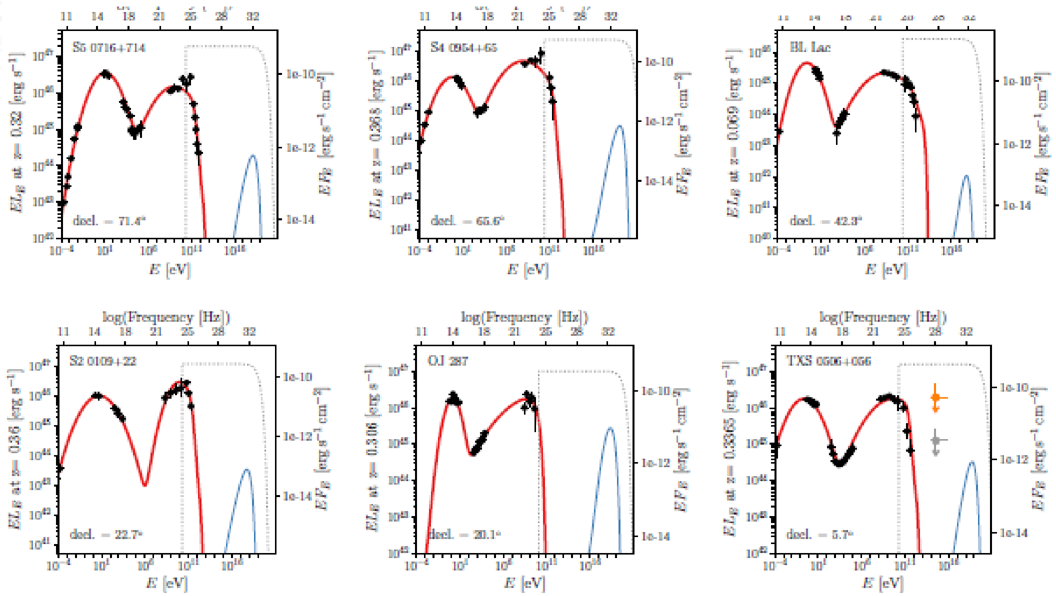
[MAGIC coll., '18]

[Oikonomou etal '19]



(b) Lepto-hadronic modeling of TXS 0506+056

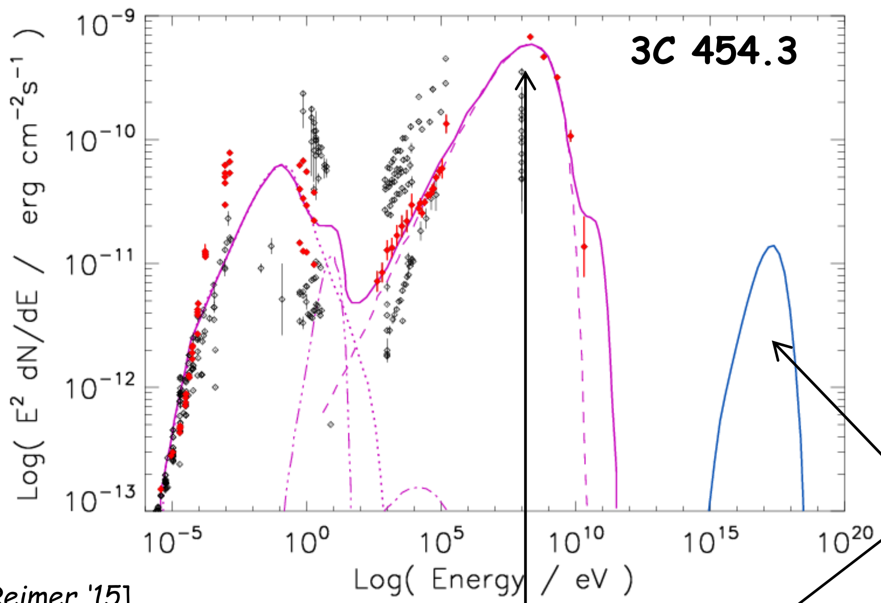
[Cerutti etal '18]



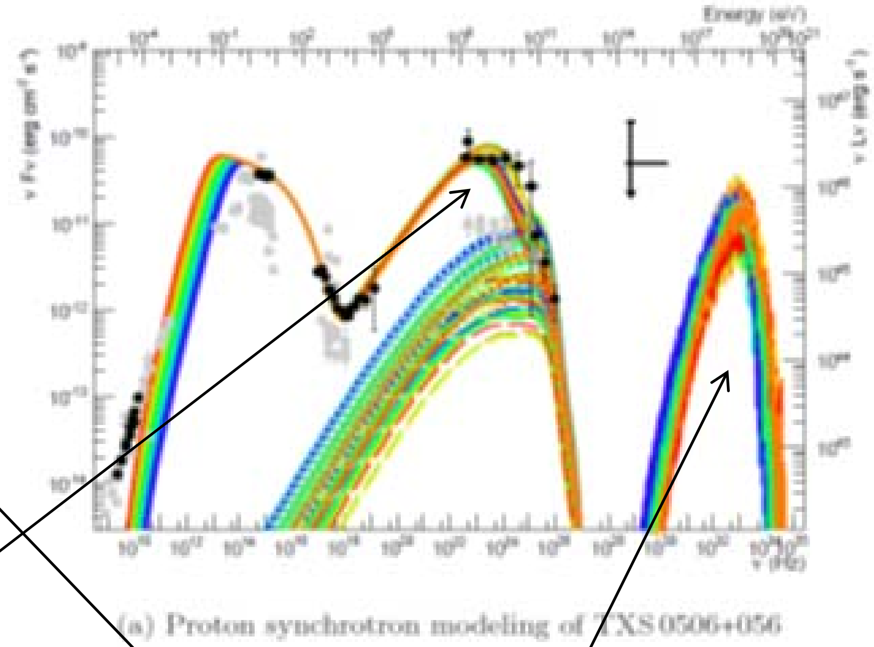
Lepto-hadronic models of γ-loud AGN

- $\tau_{\gamma\gamma} < 1$, lin cascade setup:

$u'_B \gg u'_t$



[Reimer '15]



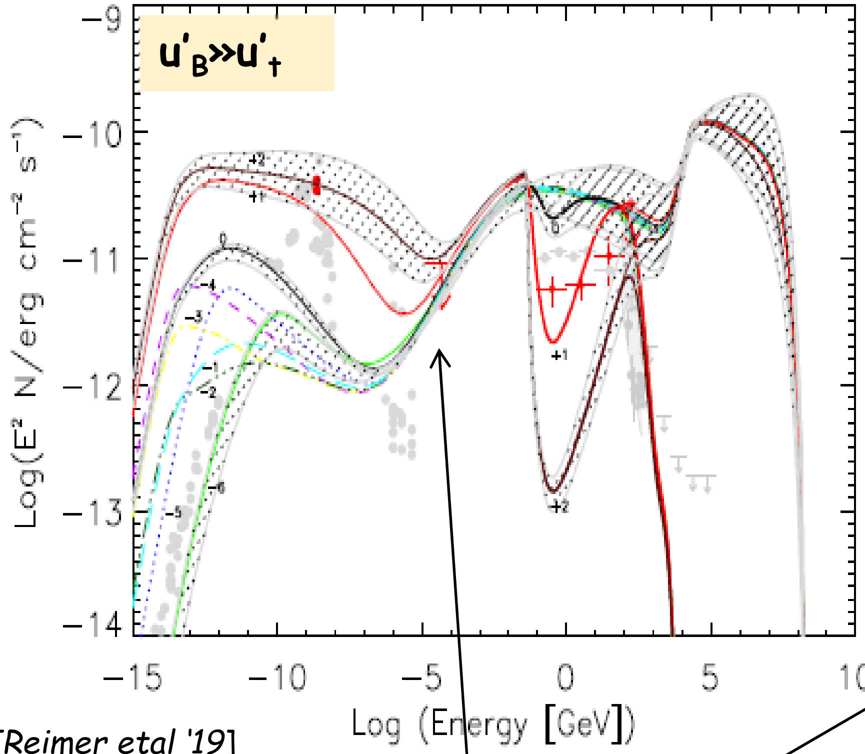
[Cerutti etal '18]

γ-ray emission dominated by proton synchrotron radiation

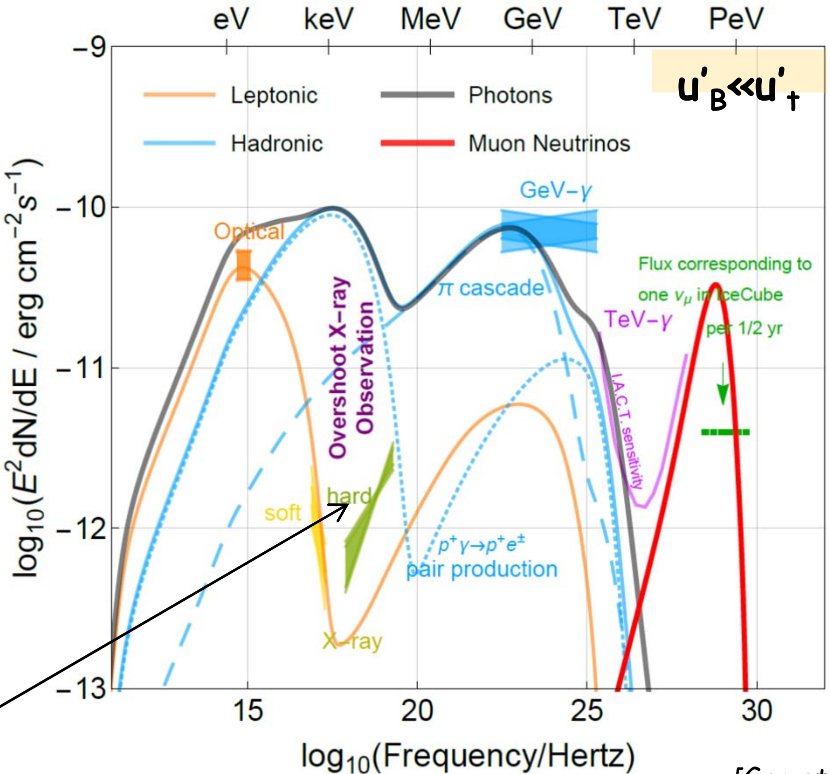
-> low neutrino fluxes

The Cascade Bound

- $\tau_{\gamma\gamma} > 1$, lin cascade setup:



[Reimer etal '19]



[Gao etal '18]

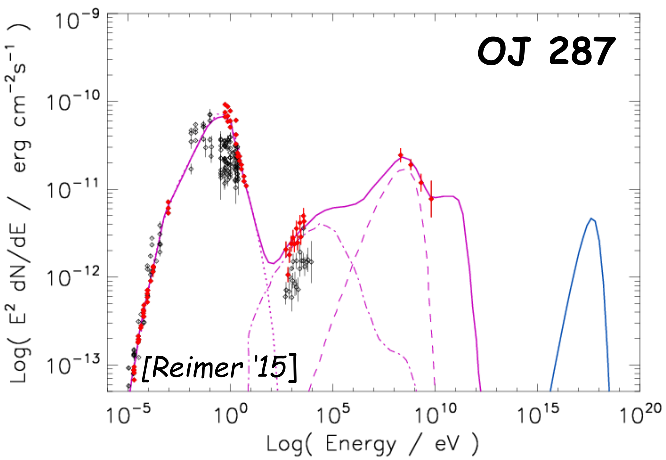
-> X-ray dip of SED constrains cascade photon flux

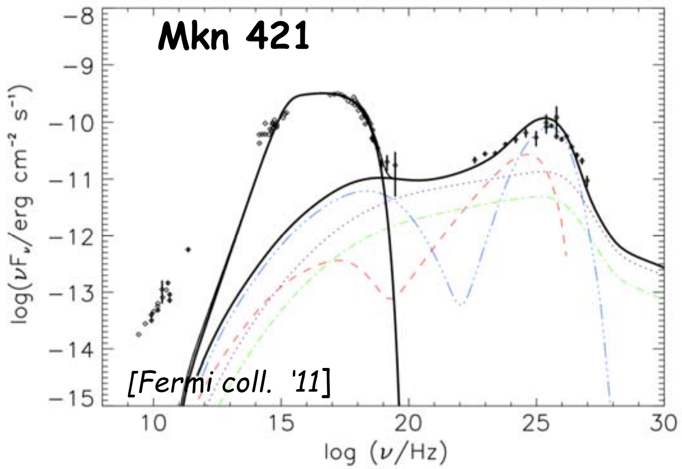
(escape @ <soft γ-/X-rays for TXS0506+056-like AGN)

Linear em Cascades: *Targets*

- **Internal (i.e., jet) target photon fields**

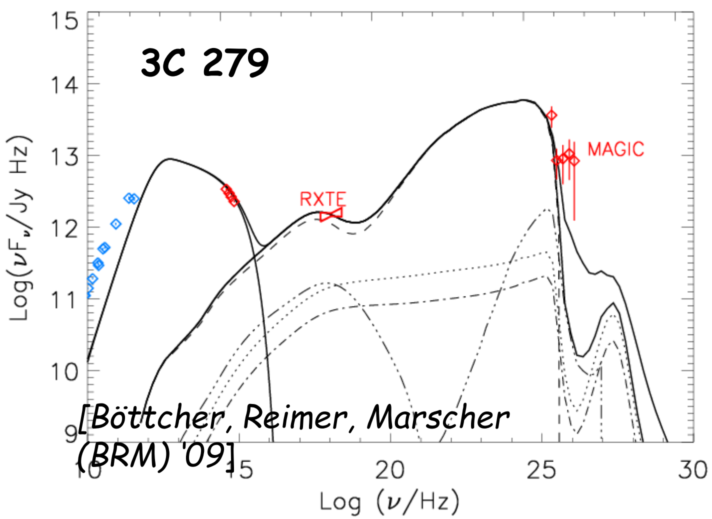
(e.g., Mannheim etal '91, '93, Mücke etal '01, '03, Dimitrakoudis etal '12, Böttcher etal'13, Weidinger etal, '15, Cerutti etal, Zech etal, Gao etal '18, Oikonomou etal '19, ...)





- **External target photon fields**

(e.g., Protheroe '96, Atoyan&Derner'03, BRM'09, Dermer etal '14, Murase etal '14, Diltz etal '15, Zacharias etal '22, ...)



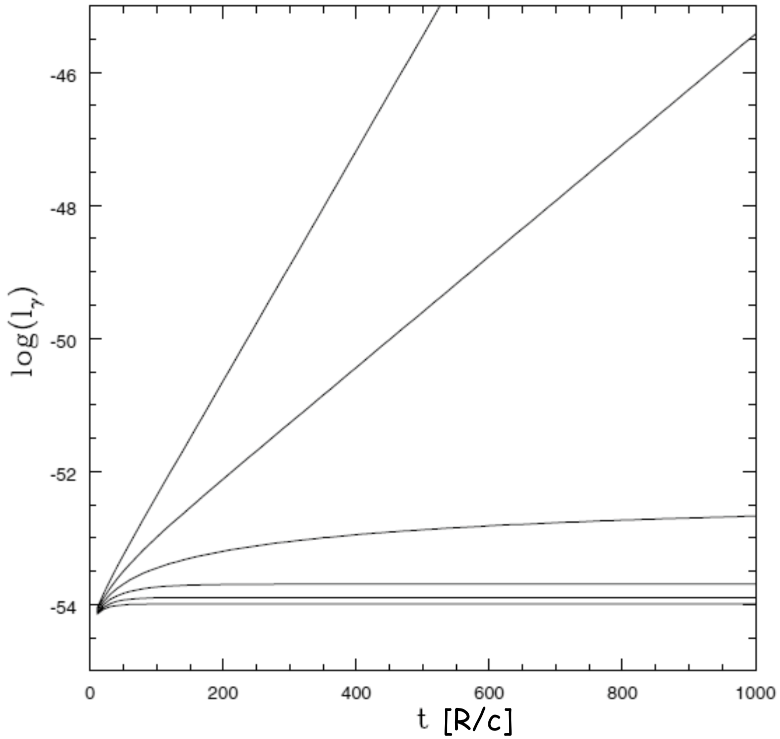
- **Hadronic models with dominantly jet target photon fields can fit average blazar SEDs; require large jet powers ~$10^{47...49}$erg/s**

- **External target fields boosted into jet frame can reduce required jet power to some extend**

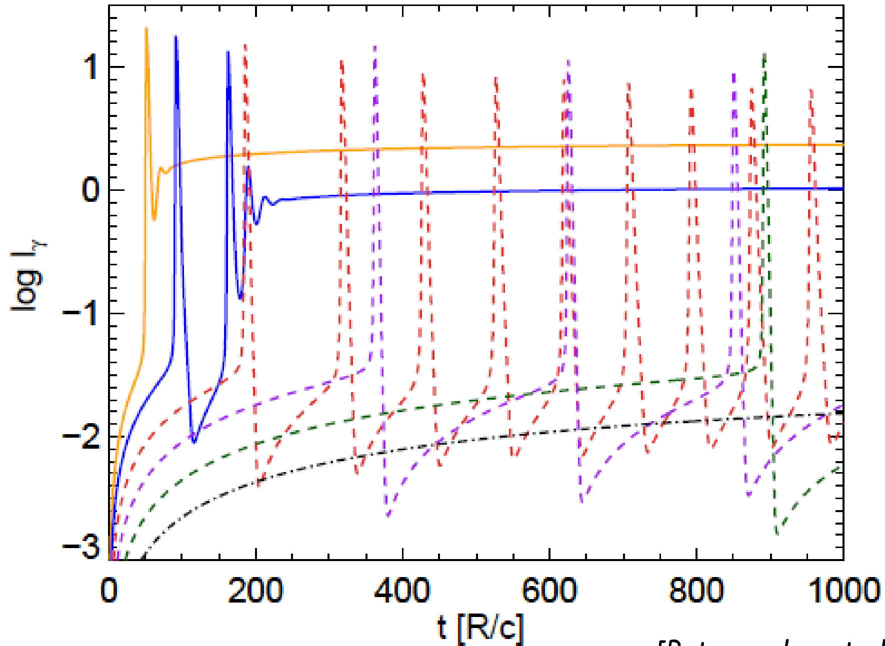
Non-linear em Cascades

- $l_p > l_{p,crit}$, $\gamma_P > \gamma_{crit} = (2B_c/B)^{1/3}$, t_{esc} large:
  -> protons become targets of their own radiation (syn-radiating $e^\pm$), radiative instabilities/feedback loops : $l_\gamma \sim e^{st}$, $s>0$

  [e.g., Stern&Svennson'91, Kirk&Mastichiadis'92, Mastichiadis etal'05, Petropoulou etal'18]

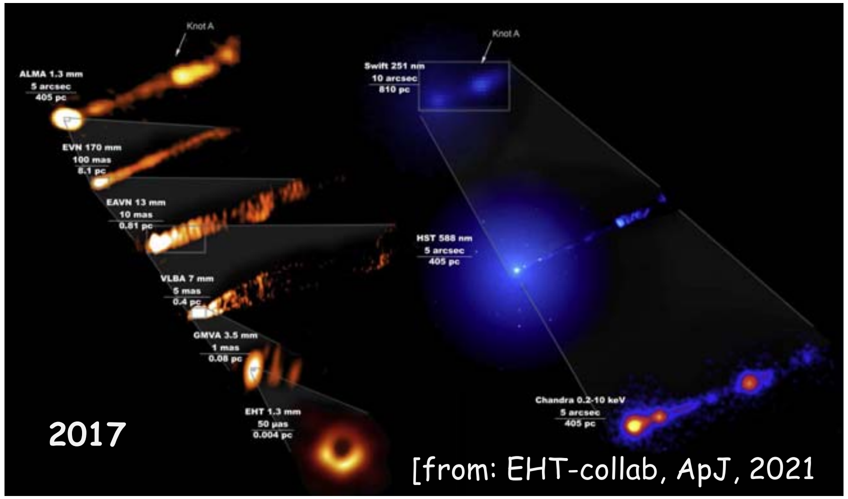


[Mastichiadis et al '05]

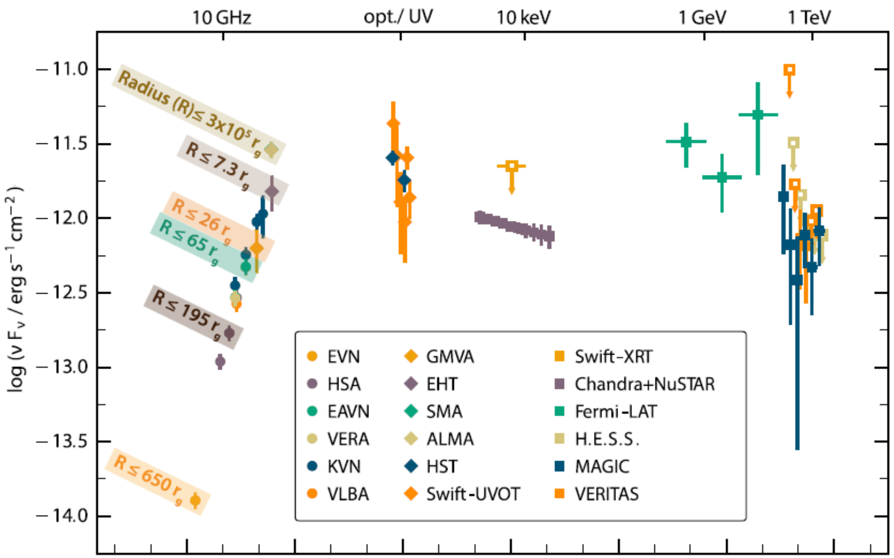


[Petropoulou et al '18]

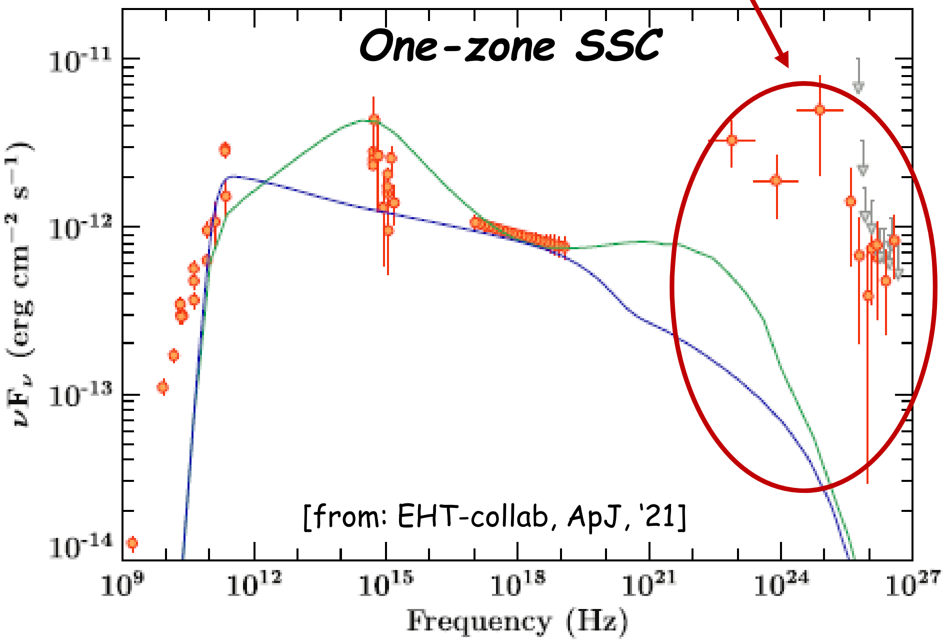
Quiescent Core Emission: The Case of M87



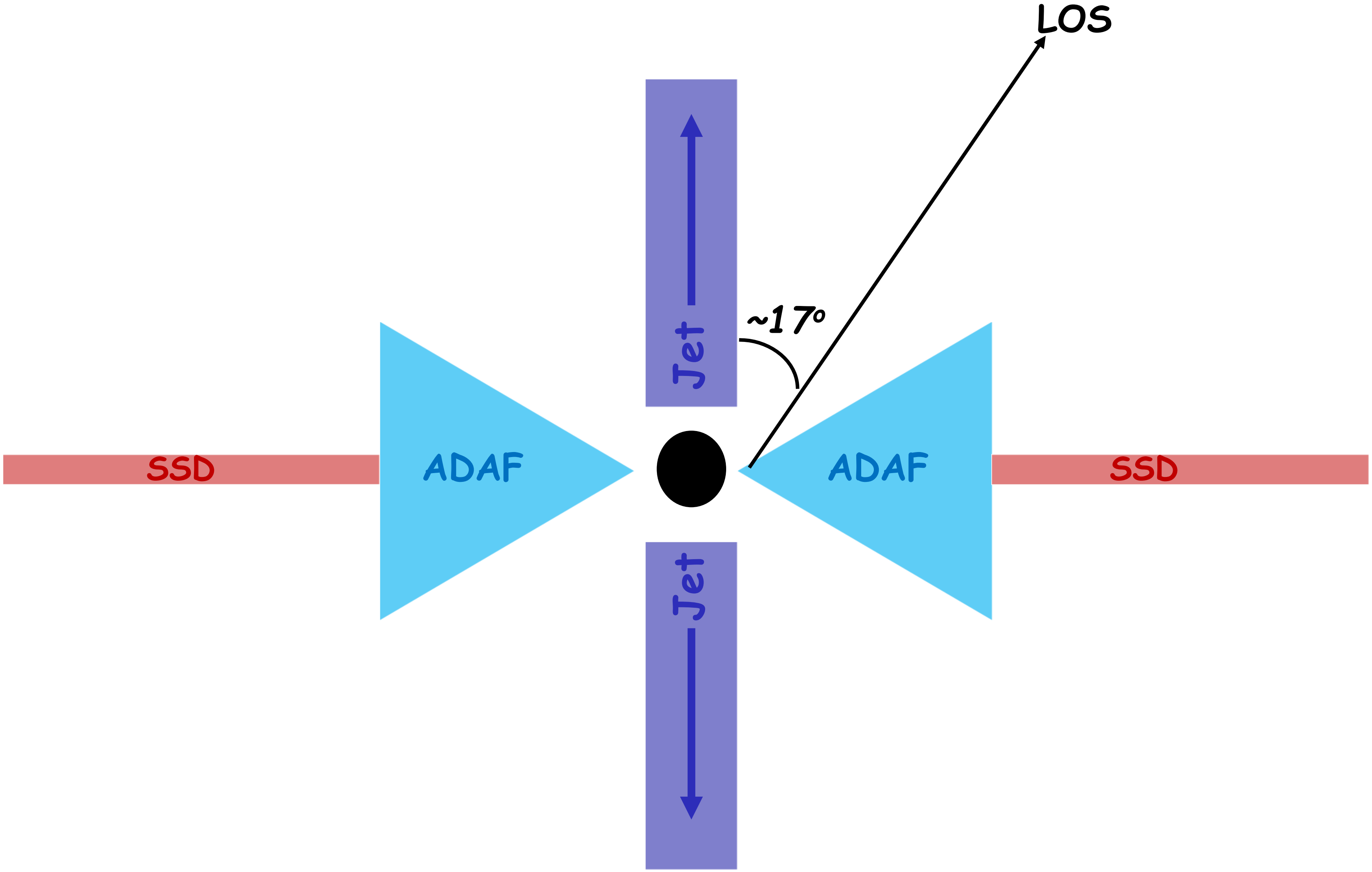
γ-ray emission not from core!
[see also Lucchini etal '19]



[from: EHT-collab, ApJ, '21]

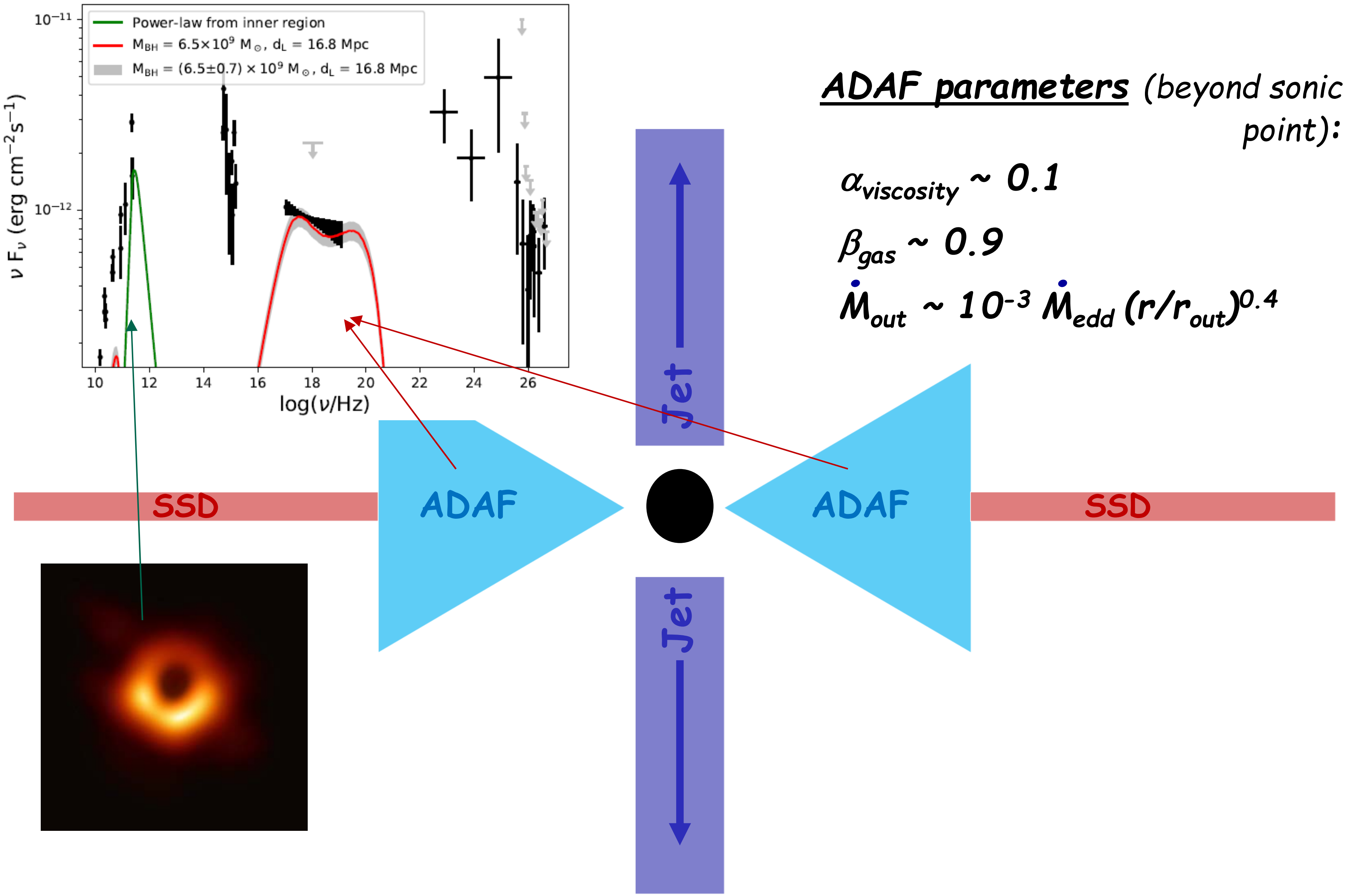


LLAGN Jet Emission Models: The Case of M87



Hadronic Jet-Disc Model for M87

[Boughelilba, Reimer, Merten, 2022, ApJ, accepted]



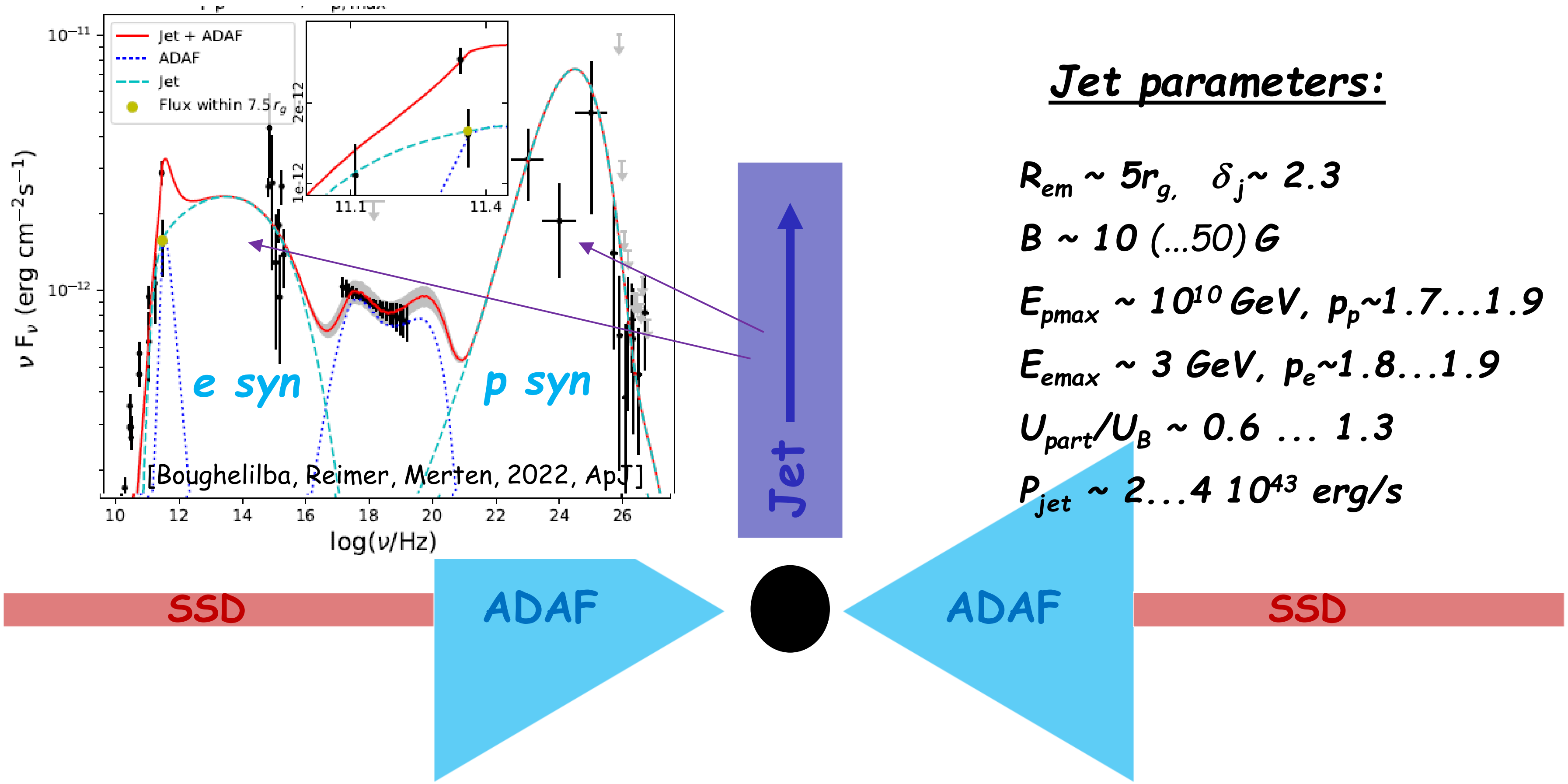
ADAF parameters (beyond sonic point):

$\alpha_{viscosity}$ ~ 0.1

β_{gas} ~ 0.9

$\dot{M}_{out}$ ~ 10^{-3} $\dot{M}_{edd}$ $(r/r_{out})^{0.4}$

Hadronic Jet-Disc Model for M87



Jet parameters:

R_{em} ~ $5r_g$, δ_j~ 2.3

B ~ 10 (...50) G

E_{pmax} ~ 10^{10} GeV, p_p~1.7...1.9

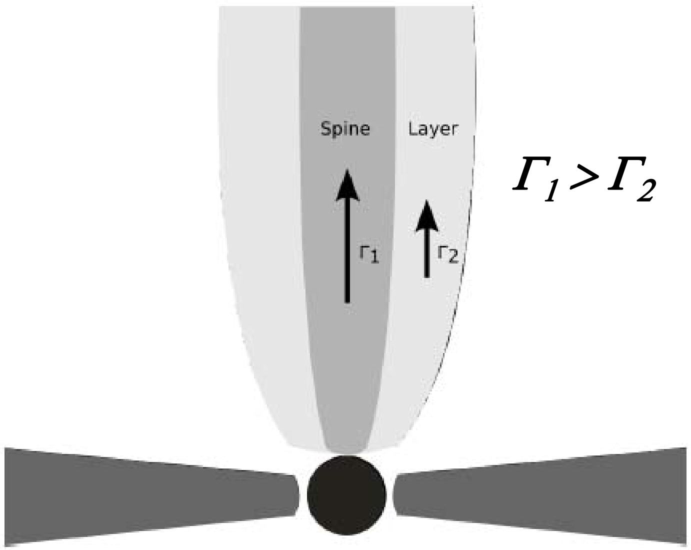
E_{emax} ~ 3 GeV, p_e~1.8...1.9

U_{part}/U_B ~ 0.6 ... 1.3

P_{jet} ~ 2...4 10^{43} erg/s

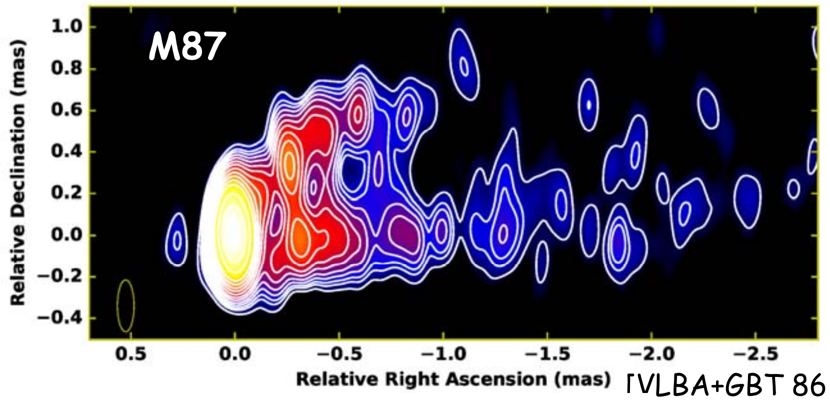
Close-to-equipartition parameters fit core-jet SED of M87

Structured Jets: Spine-Sheath Configuration

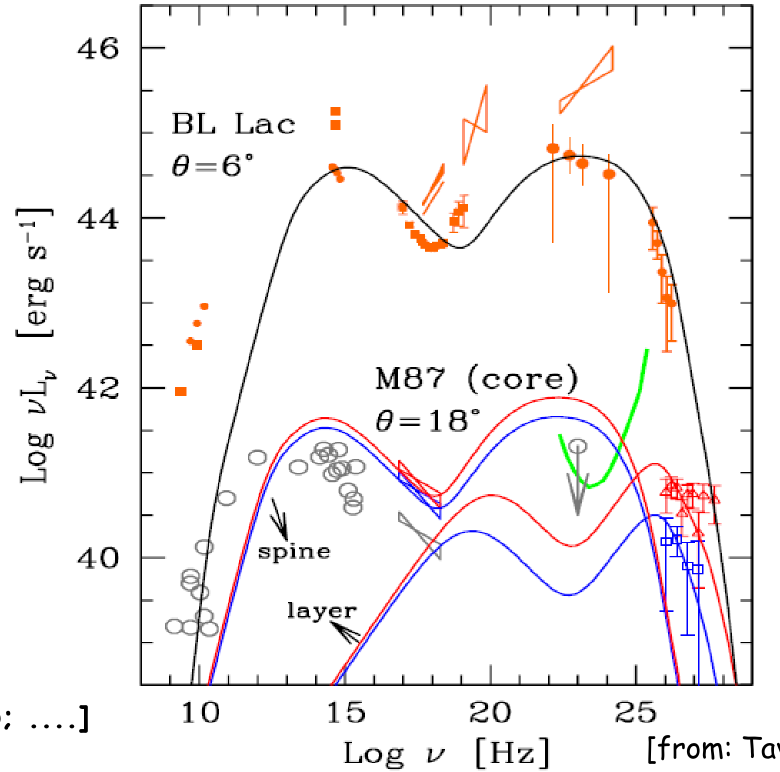


$\Gamma_1 > \Gamma_2$

[from: Rieger & Levinson '18]



[VLBA+GBT 86 GHz image; from: Hada et al '16]



[from: Tavecchio & Ghisellini '08]

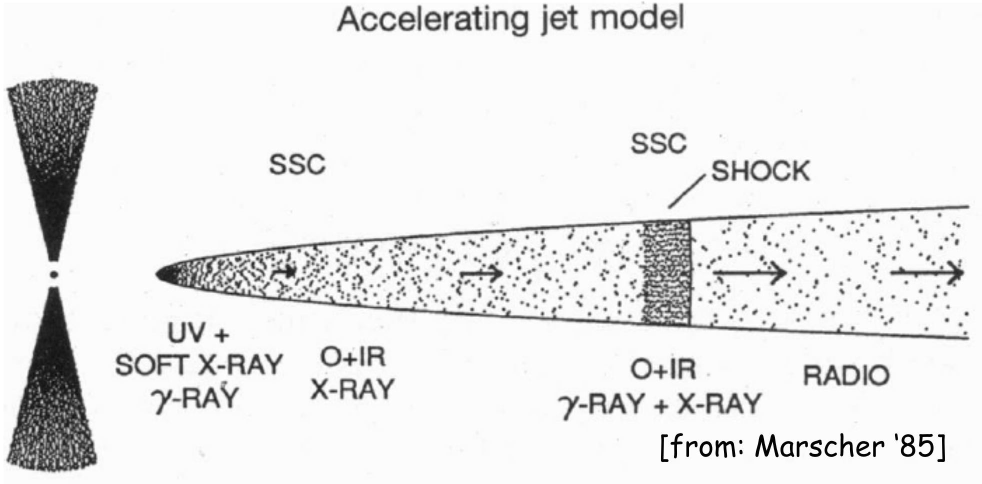
Radiation produced from spine is seen amplified by the sheath & vice versa

-> IC emission of both components enhanced

[Ghisellini etal '05, Tavecchio & Ghisellini '08,'14,'15; ....]

Structured Jets: Extended Jets

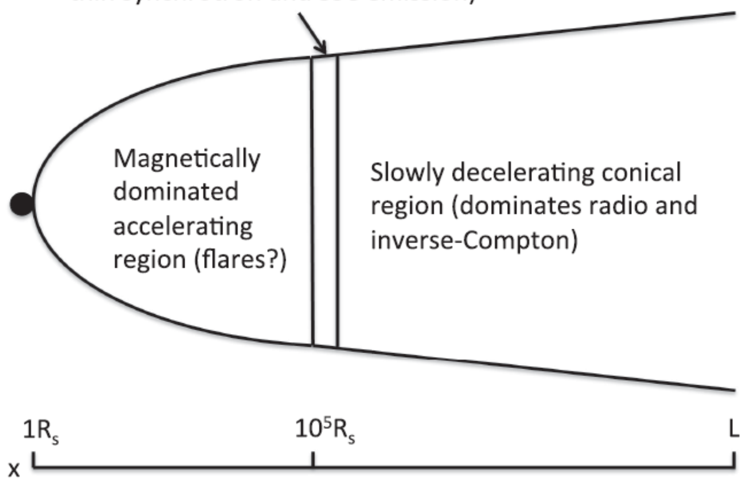
- **Early works**: *Blandford & Königl '79; Marscher etal '80,'85; Reynolds '82; Ghisellini etal '85; Markoff etal '00; Graff etal '08; Jamil etal '10; ...*



[from: Marscher '85]

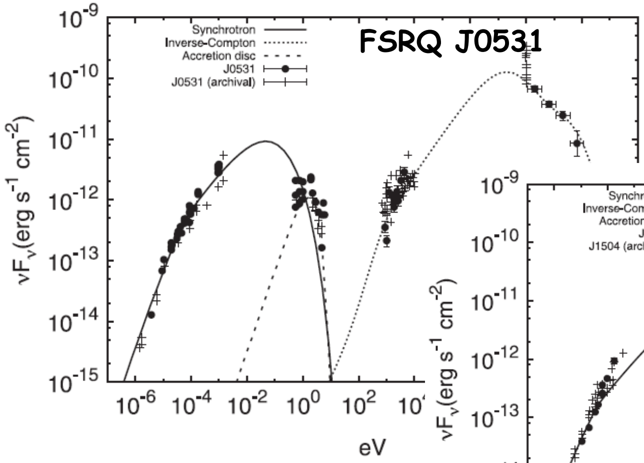
- **Accelerating/decelerating jets**: *Ghisellini & Maraschi '89; Georganopoulos '89,'03; Spada etal '01; ...*

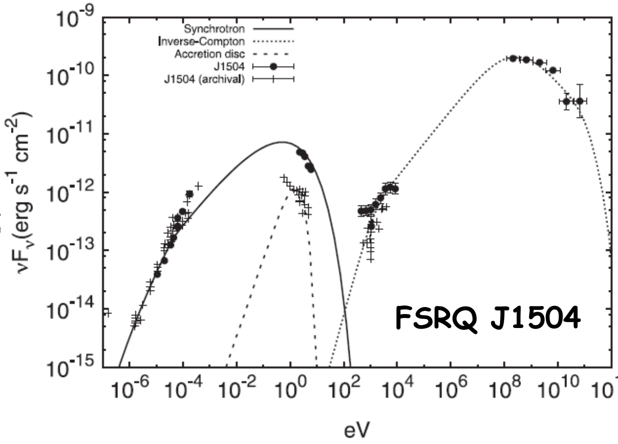
- **Accelerating parabolic base transitioning to conical jet:** *Ghisellini & Maraschi '89; Potter & Cotter '13a-c,'18; Zacharias et al '22; ....*



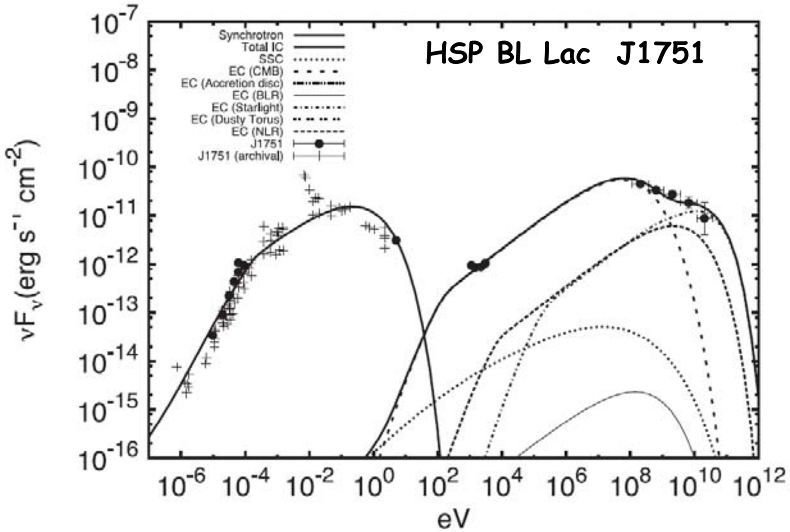
[from: Potter & Cotter '13]

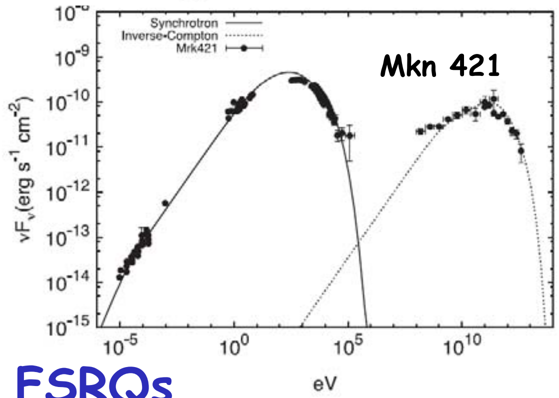
Extended Jets: Leptonic Emission Models





[from: Potter & Cotter '13]



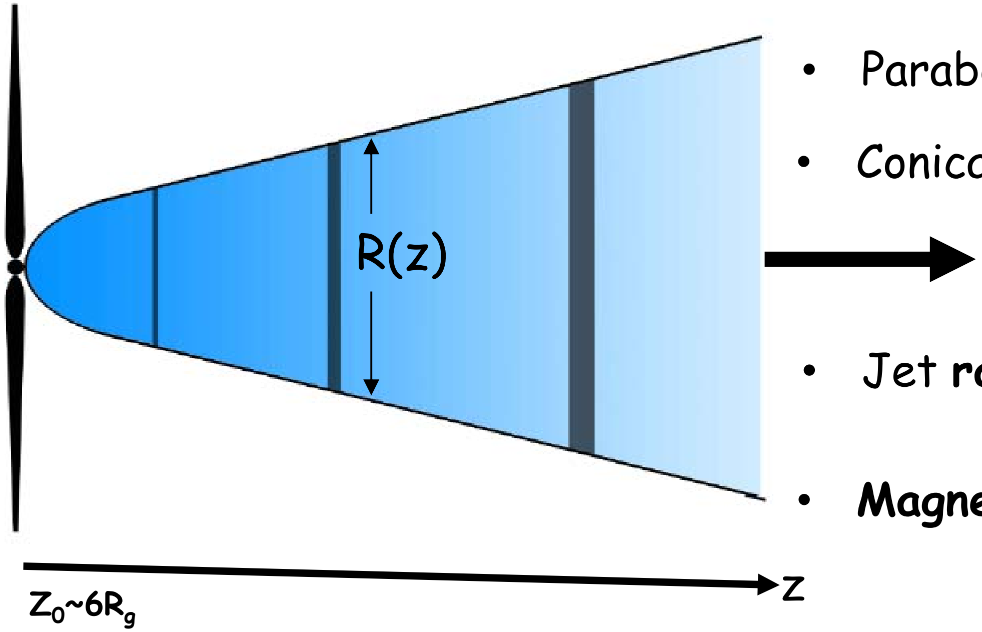


- Transition region outside BLR
- Max syn power near transition zone
- HSPs require lower jet power and bulk speeds than FSRQs
- Compton-dominance from IC off CMB beyond transition region;

  TeV emission component from IC on star light
- Hard PL e injection required

Extended Jets: Hadronic Emission Models

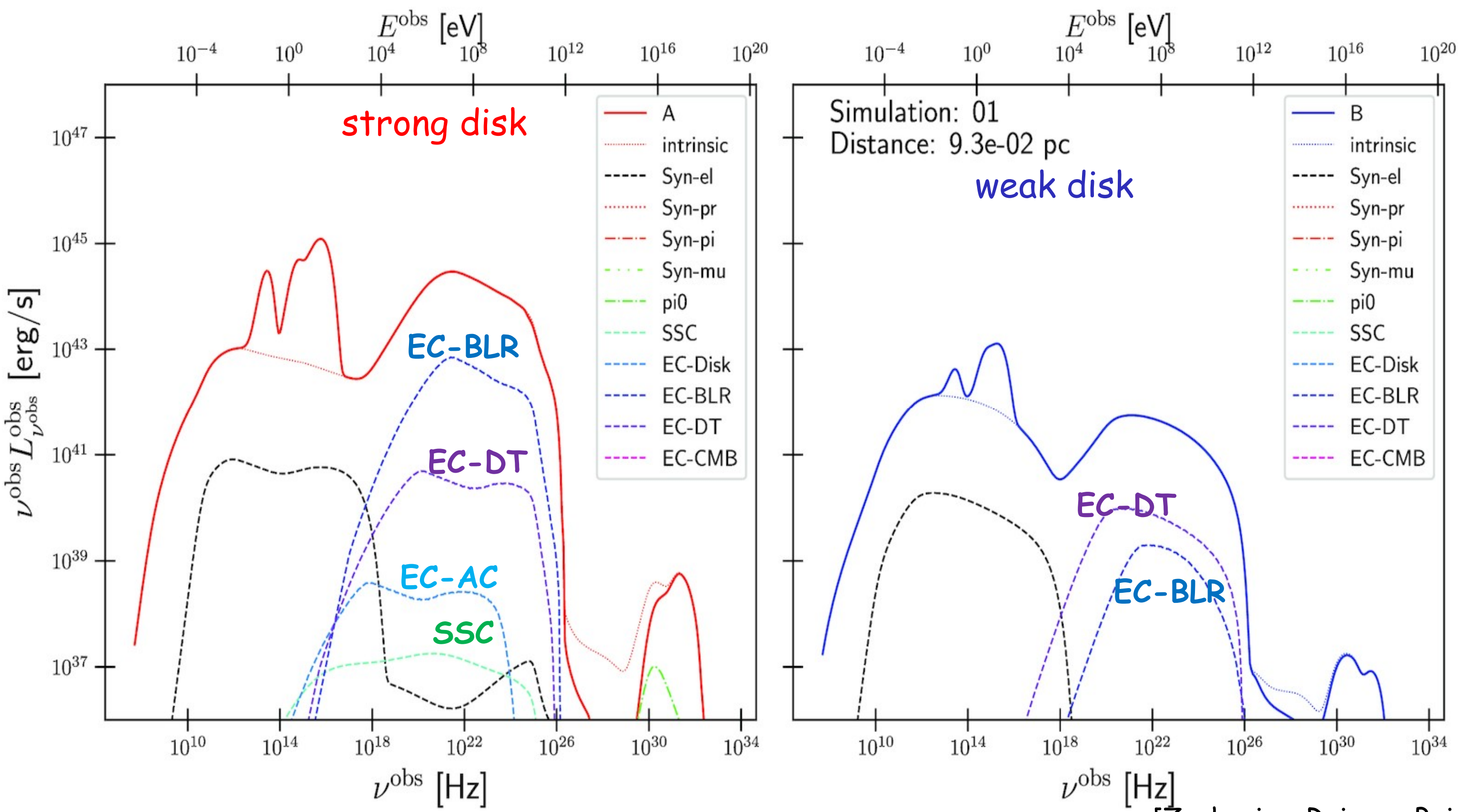
[Zacharias, Reimer, Boisson, Zech 2022, MNRAS]



- Parabolic bulk **acceleration zone**: $\Gamma_b(z) \sim \sqrt{z}$
- Conical **coasting zone**: $\Gamma_b \sim$ const
- Jet **radius R(z)** $\propto$ z tan $(0.26/\Gamma_b(z))$
  [Pushkarev et al '09, '17]
- **Magnetic field** evolution following relativistic Bernoulli eq

- **Injection of prim. p & e** PL distribut. at base with e/p-density ratio =1
- Particle (e,p) injection **from one slice to next** slice following **continuity equation**
- **Global continuity equation fulfilled only for p**
- For magnetic-to-particle enthalpy ratio $\sigma_B(z_{term})>1$ one obtains **sub-Eddington L_{jet}**
- **Particle** (e,p,π,μ) **evolution** followed in each slice until steady-state reached; all relevant **losses** (internal & external targets) & **gains** (PL particle inj. to fulfill cont. eq.) considered

Extended Jets: Hadronic Emission Models



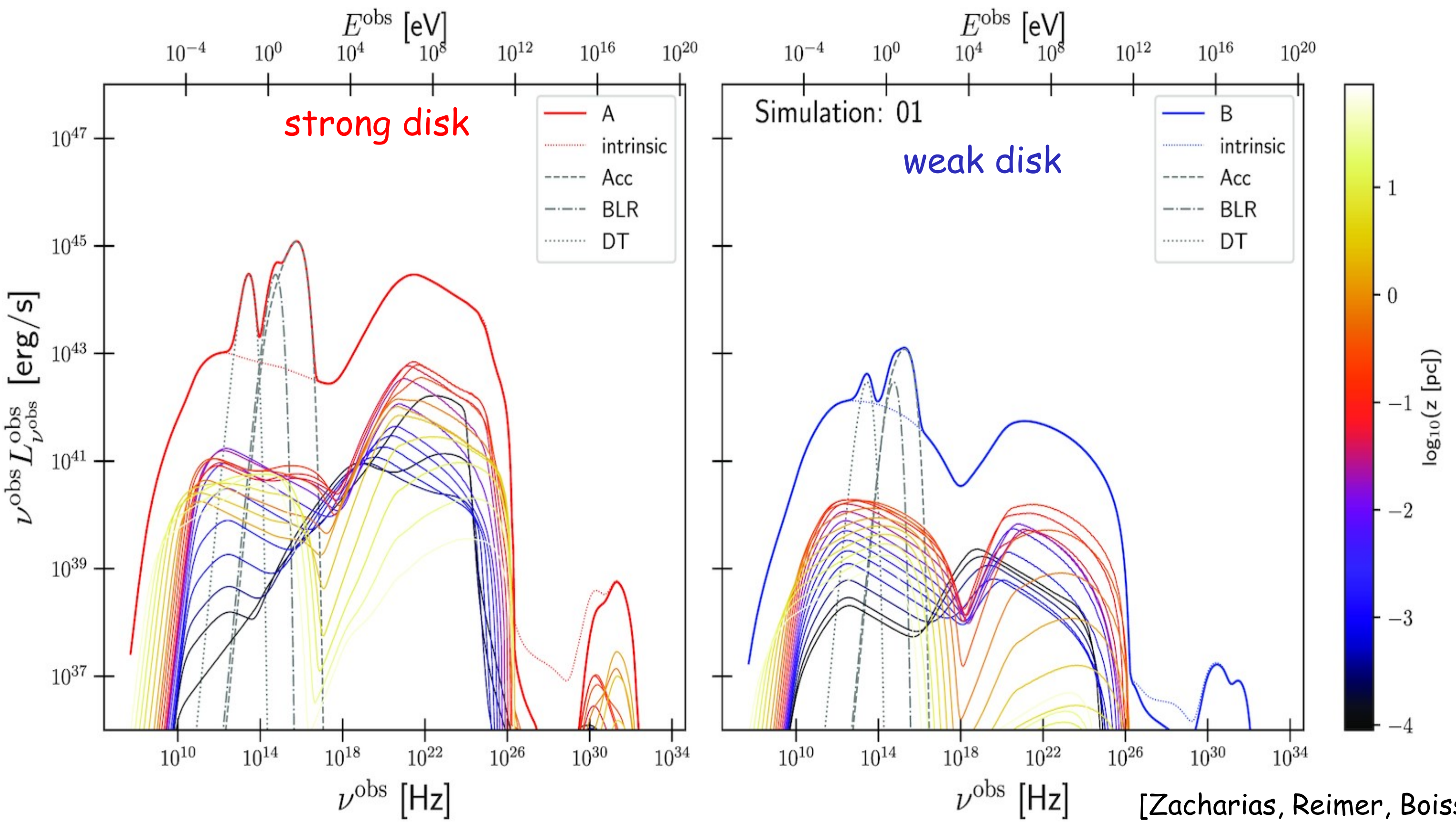
[Zacharias, Reimer, Boisson, Zech '22]

- Photon spectra dominated by **leptonic processes** **(synchr., external IC)**
- Strong impact **of external radiation fields**:

  HE-hump mainly from **external IC** on BLR & DT; "Compton dominance"

  Photomeson production & photon absorption mainly on external fields

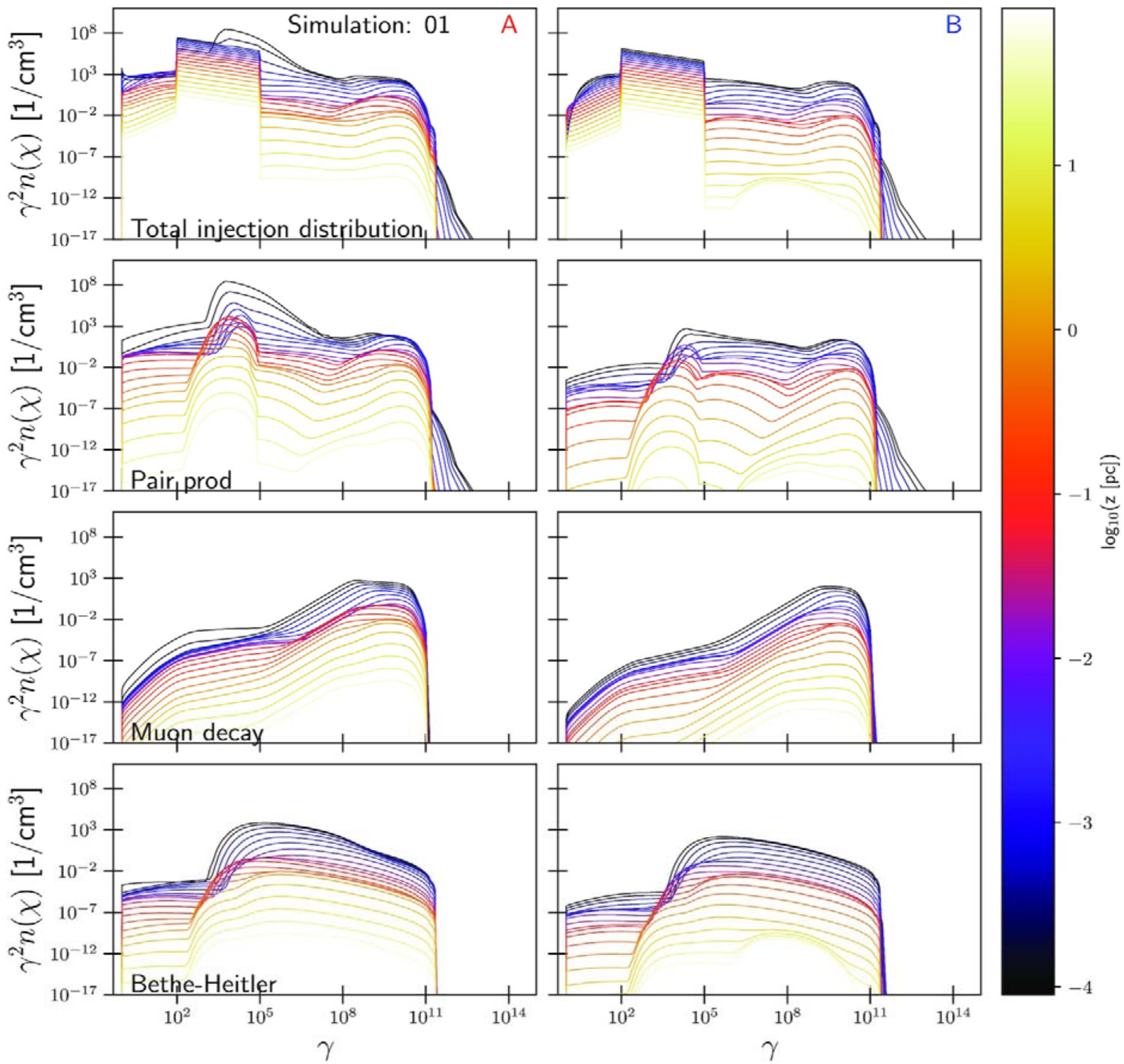
Extended Jets: Hadronic Emission Models



[Zacharias, Reimer, Boisson, Zech '22]

- **e syn flux** component: gradual increase till ~0.1pc, gradual decrease beyond ~10pc
- **IC flux** component: sequential dominance of AD -> BLR -> DT -> CMB as target with increasing z
- **γ-rays produced all along jet;** strongest IC flux contribution from ≈0.1–1 pc(z_{acc})

Extended Jets: Hadronic Emission Models



[Zacharias, Reimer, Boisson, Zech '22]

- **Leptonic &** (for the presented parameter setting) **hadronic extended jet models predict EC to dominate**

- **Notable impact of relativistic protons in extended jets: Strong secondary pair production!**

Concluding Remarks

- Presented general workings of jet photon emission models
- Source dynamics [->(GR)MHD, ..] & particle acceleration simulations enter emission models typically in parametrized form
- Progress by combining particle acceleration & source dynamics models with emission models?