VHE Flares in Blazars and Radio Galaxies

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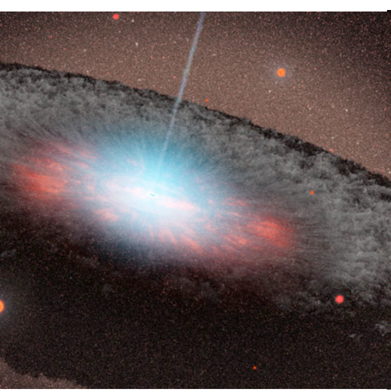
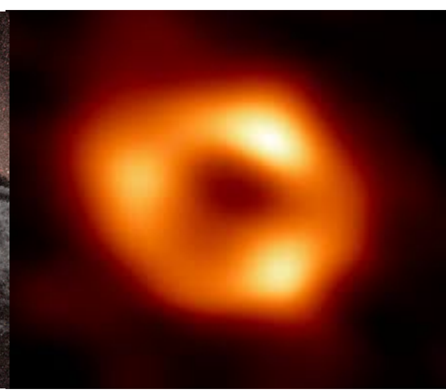
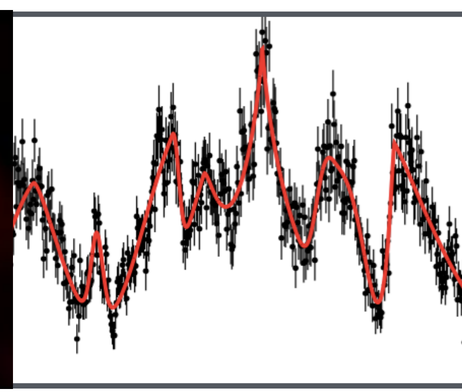
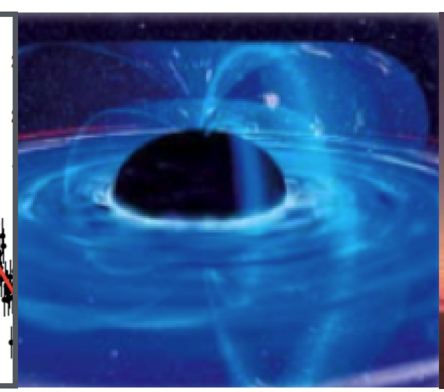
CDY Workshop on BH Flares

Nov 14, 2023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Outline

- **Rapid VHE variability in blazars and radio galaxies**
  - exemplary illustration (*minimum variability*)
- **On fast VHE variability scenarios**
  - ‘some’ overview (mini-jet to jet-star interaction)
  - magnetospheric models (BH gap)
- **Beyond minimum variability considerations**
  - variability characteristics (log-normality & PSD)

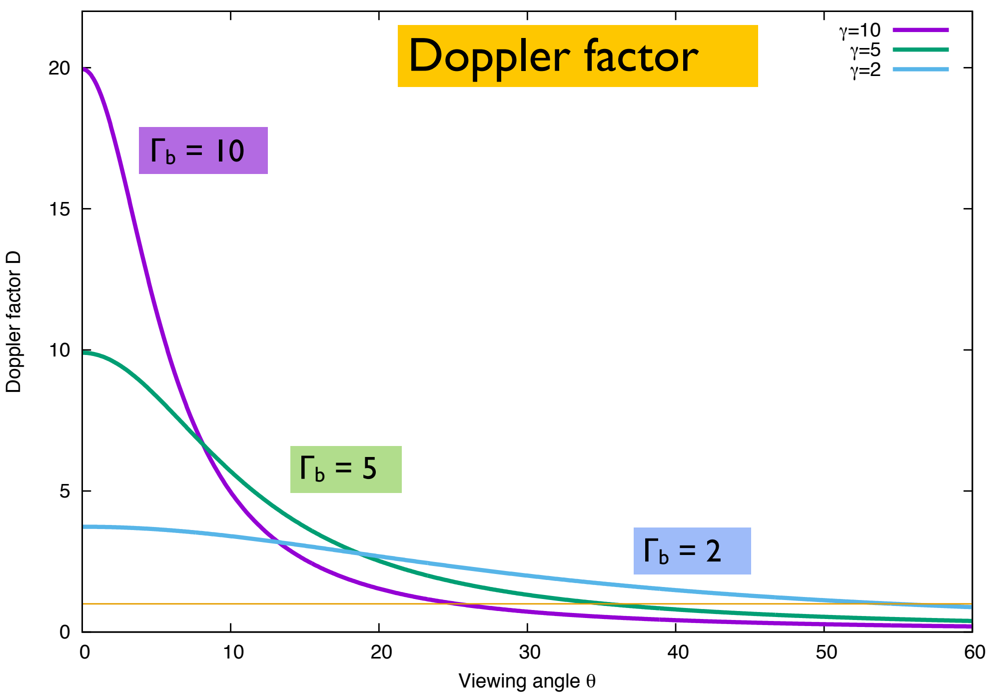
On aligned @ misaligned (jetted) AGN (= MAGN)

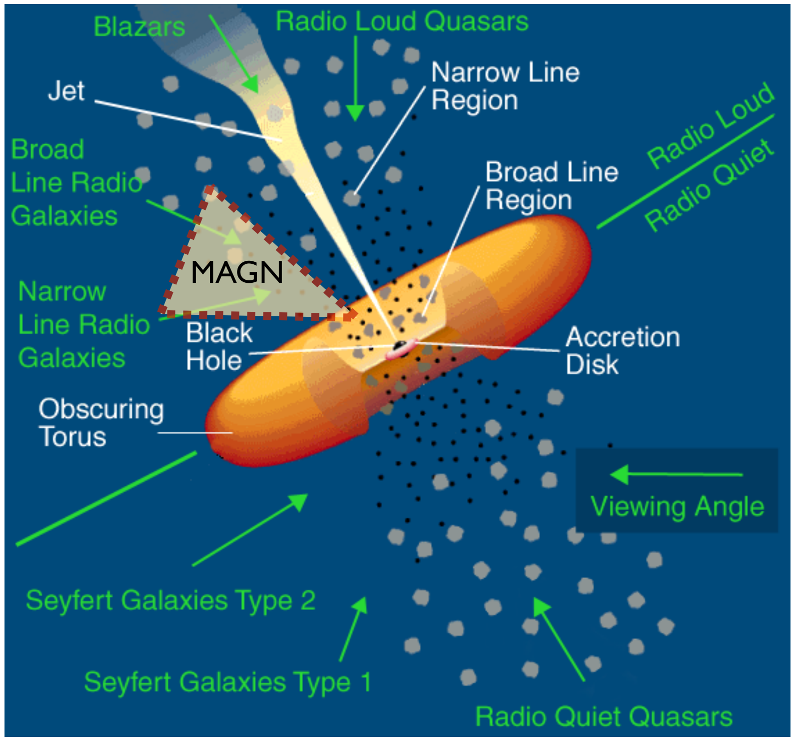
Radio-loud ***Active Galaxy***

"jetted AGN"

- blazars → radio galaxies
- reduced beaming / Doppler boosting:

$$D = \frac{1}{\Gamma_b(1 - \beta_b \cos\theta)}$$





Central engine in AGN & unification

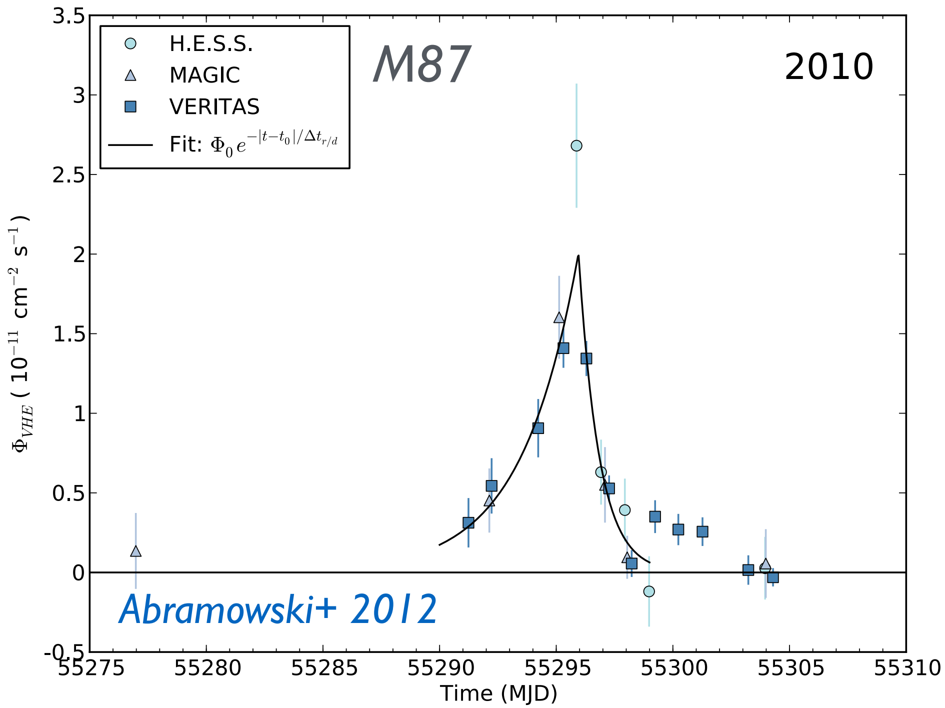
(Urry & Padovani)

Gamma-Ray Astronomy entering the Time Domain Area

1. Rapid VHE flux variability (minimum timescale)

- down to minutes in bazars, e.g., **Mkn 501** (5 min), **PKS 2155-304** (3 min)
- intra-day or less in radio galaxies, e.g. **M87** (day), **IC 310** (5 min)…

(e.g., Aharonian+ 2006 [M87]; Albert+ 2007 [Mkn 501]; Aharonian+ 2007 [PKS 2155]; Aleksic+ 2014 [IC 310])



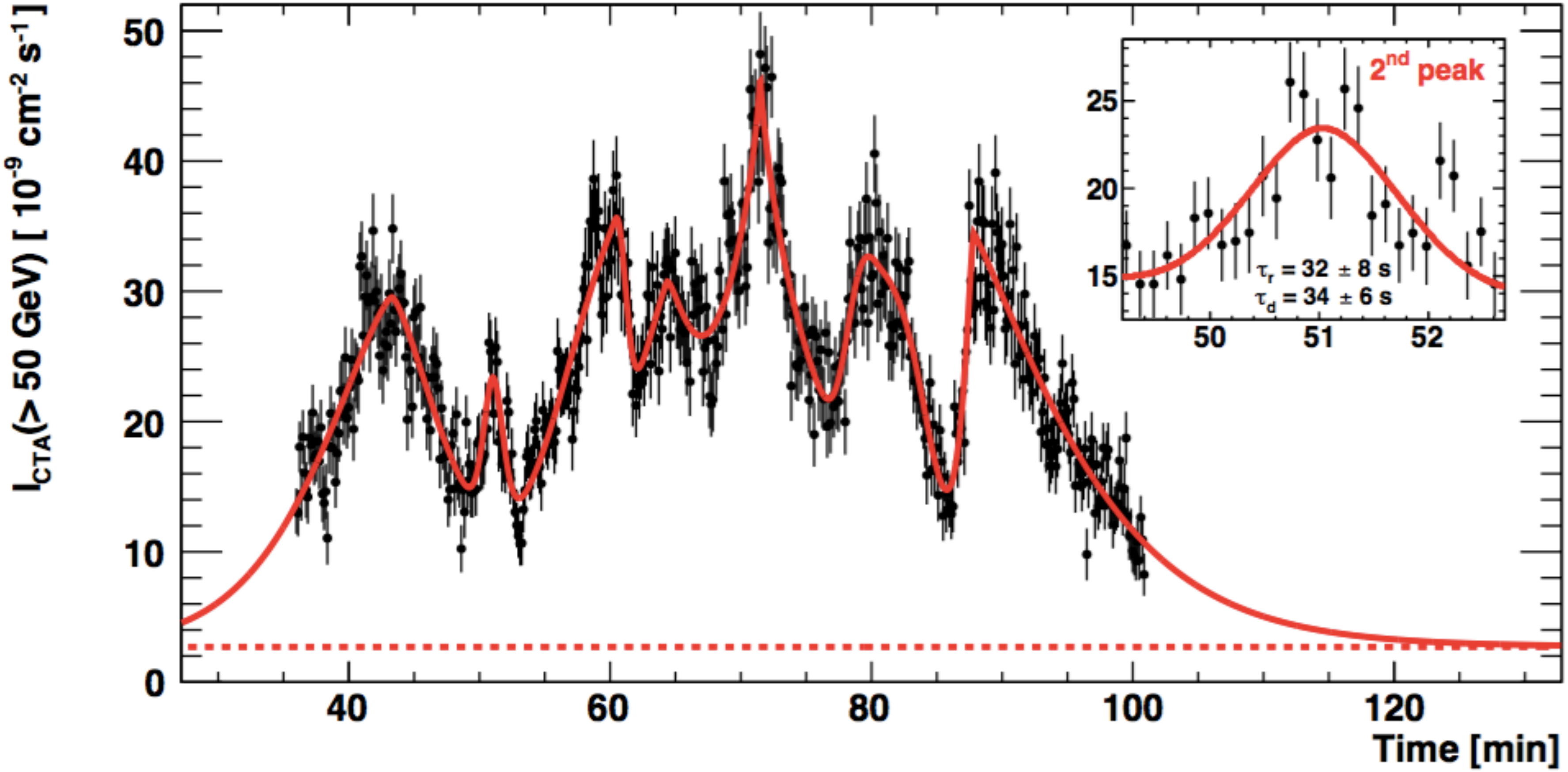
Fastest variability ever seen at any wavelength!

- *extreme jet conditions:* very compact (r < D c Δt) & luminous emitting region, close to BH? multiple (interacting) zones?

(e.g., Begelman+ 2008; Aharonian+ 2017; FR 2019)

Potential will increase with CTA:

Simulated CTA light curve based on extrapolation of the power spectrum for the strong 2006 flare of PKS 2155-304 - *probing sub-min timescales*



CTA Consortium 2017

VHE variability of misaligned AGN / RG (Overview)

Out of ~45 HE radio galaxies (3743 Fermi-blazar/4FGL-DR3) only a few are detected at VHE (~13%):

Name	Cross-ID	Type	Distance	BH mass [$10^8 M_\odot$]	**VHE**	Variability
Cen A	NGC 5128	FR I	3.7 Mpc	0.5-1	✔	None @VHE
M 87	NGC 4486	FR I	16 Mpc	65	✔	day-type VHE
Fornax A		FR I	18 Mpc			
Cen B		FR I	56 Mpc			
NGC 1275	3C84, Perseus A	FR I	75 Mpc	3-4	✔	day-type VHE
IC 310	B0313+411	*FR I / BL Lac?*	80 Mpc	3 [0.3?]	✔	sub-hour VHE
3C 264	NGC 3862	FR I	95 Mpc	4-5	✔	monthly VHE
NGC 6251		FR I	106 Mpc			
3C 78	NGC 1218	FR I	124 Mpc			
3C 120		FR I	142 Mpc			
3C 111		FR 2	213 Mpc			
PKS 0625-35	OH 342	*FR I / BL Lac?*	220 Mpc	~10	✔	day-type VHE (?)
PKS 0943-76		FR 2	1360 Mpc			
......						

(e.g., FR & Levinson 2018, Rulten 2022)

On extreme VHE variability in IC 310

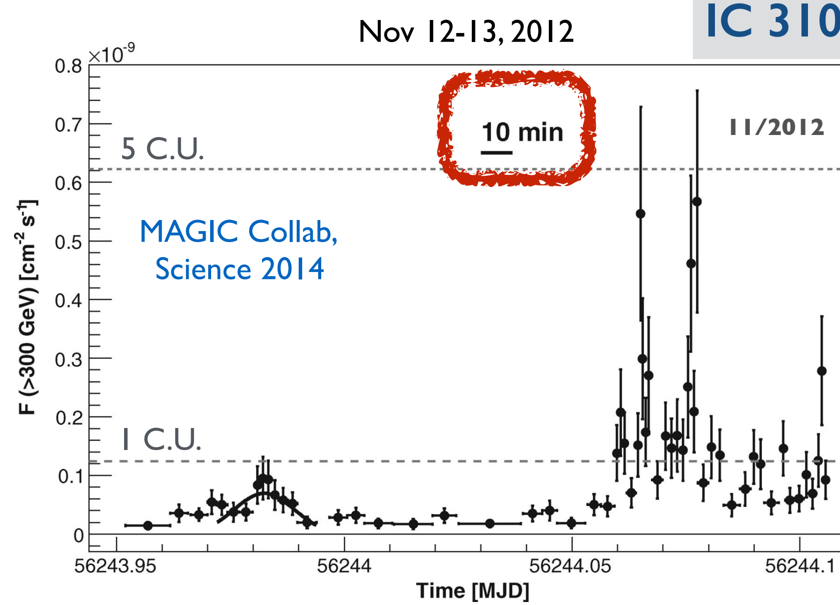
VHE flare in 2012 (MAGIC):

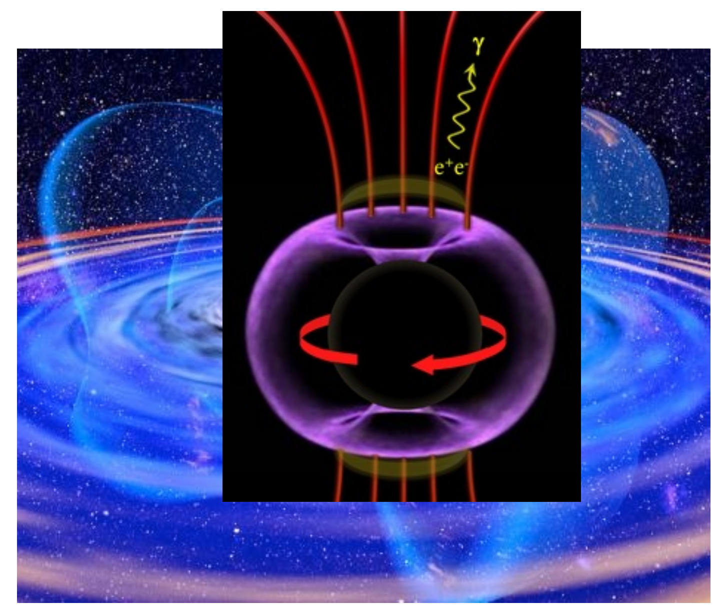
- very hard VHE spectrum up to ~10 TeV
  - Γ < 2 (EBL-corrected), no evidence for break
- extreme short-term VHE variability
  - doubling time ~ 5 min
  - BH timescale $r_g(3 \times 10^8 M_\odot)/c = 25$ min
  - ***sub-horizon "gap-type" particle acceleration (?)***
    - gap height h~0.2 r_g
- ***possible probe of near-BH environment***

Possible Caveats:

- too luminous for gap ($L_{VHE} \sim 10^{44}$ erg/s ~ L_{jet}) ?
- hard spectrum without evidence for any absorption ($\gamma + \gamma \rightarrow e^- + e^+$)
- BL Lac core ?

IC 310





Hirotani & Pu 2016;
cf. also Katsoulakos & FR 2018

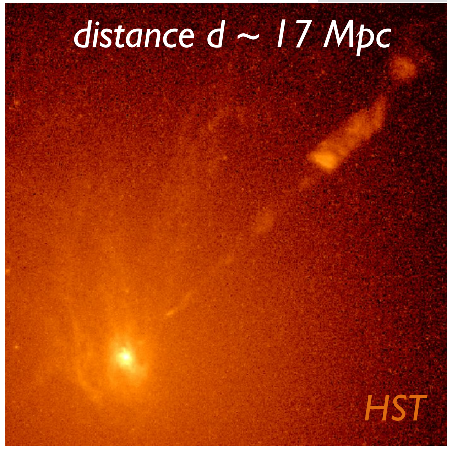
M87 - rapid VHE variability, radio link & ɣ-ray excess

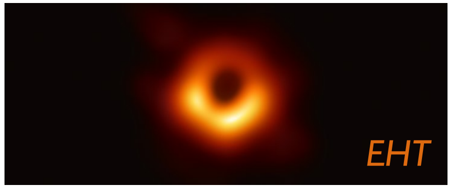
- rapidly variable VHE emission 2005, 2008, 2010, 2018 (?)
  - BH mass 6.5 x 10^9 $M_\odot$ ⇒ r_g/c = 0.38 d (day-scale = horizon-scale)
  - $L_{VHE,high}$ ~ 5 x 10^{41} erg/s
- radio-VHE correlation *(increase)* *+2008, ±2010, +2012*
- spectral inflection at HE gamma-rays (additional component?)

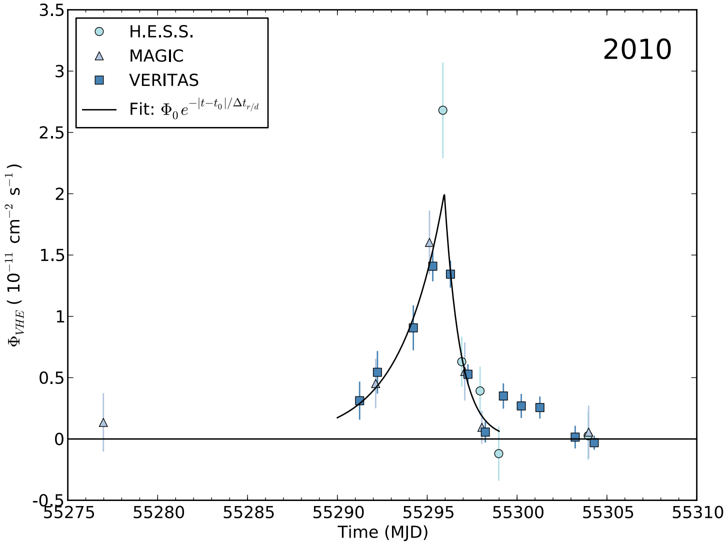
➡ *additional emission component, compact & close to black hole*

➡ *candidate for* ***magnetospheric origin*** *(Levinson & FR 2011)*

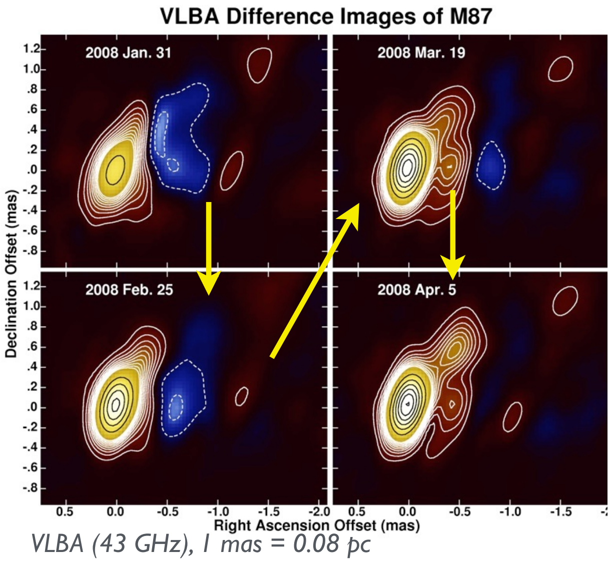
M 87





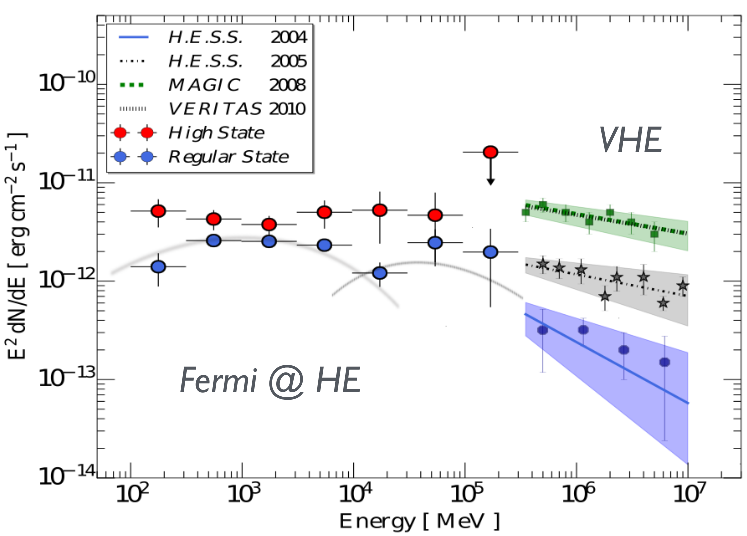


Abramowski+ 2012 IACT resolution ~0.1° =30 kpc



VLBA (43 GHz), 1 mas = 0.08 pc

Acciari+ 2009 (Science)



Benkhali, Chakraborty & FR 2019

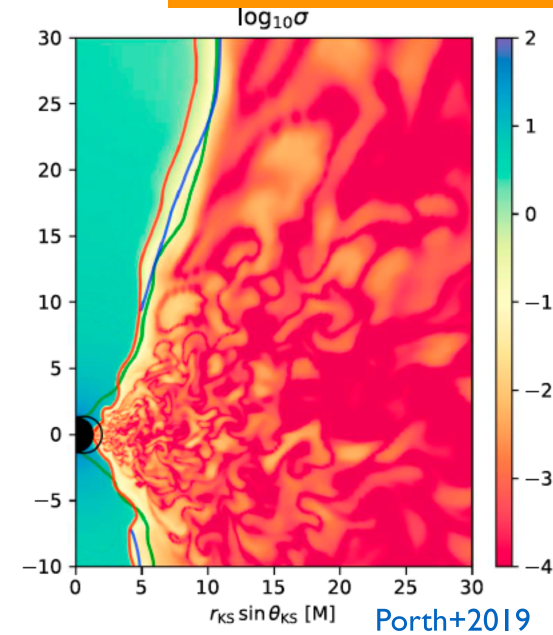
On fast VHE variability scenarios

On methodological challenges for a plasma physics perspective…

cf. also talk by Dmitri Uzdensky's

GR/RMHD:

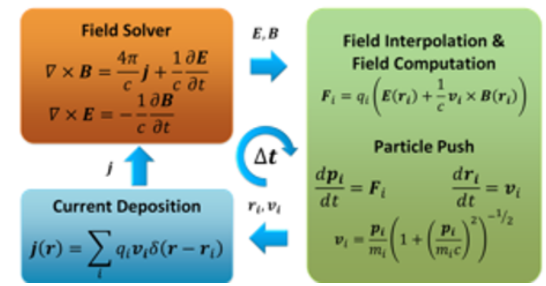
- dependency on numerical floor model (cf. jet formation)…
- no physical understanding of reconnection (in ideal MHD!)
- single fluid description (but collisionless plasma; electron temperature in accretion flow?…)
- non-thermal processes (radiation? particle acceleration ? back-reaction of accelerated particles?)



Porth+2019

PIC:

- idealized setups (e.g., reduced dimensionality, monopole m.f., no accretion disk, simplified ambient photon field, radiation reaction…)
- scale separation for AGN (system size/plasma skin depth ~ r /l_p ~10^{6-8} (Ji & Daugthon 2011; Levinson 2022 [CDY])



Essential to inform & advance our understanding, but…

Phenomenological scenarios for (variable) VHE in M87 & challenges

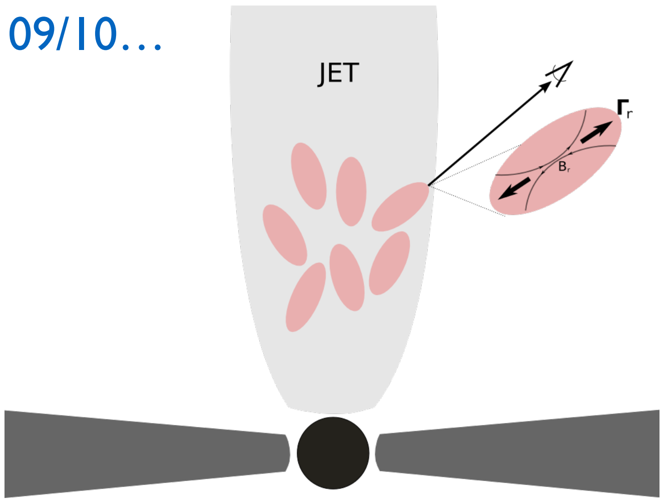
cf. also see Hayk's talk for additional alternative

HST-1		EC starlight photons (e.g. Stawarz+06)	⟺ *(too) high VHE power ?*
inner jet (sub-parsec)	leptonic	decelerating flow (e.g. Georganopoulos+05)	⟺ *(flow gradient) timescale ?*
		spine-shear (e.g. Tavecchio+08)	⟺ *internal absorption ?*
		mini/multi-blobs (e.g. Lenain+08)	⟺ *(strongly) out of equipartition ?*
		reconnection (e.g. Giannios+10)	⟺ *power-law shape & range ?*
	hadronic	proton synchrotron & p-γ (e.g. Reimer+04)	⟺ *max. energy constraints ?*
		jet-star interactions / pp (e.g. Barkov+12)	⟺ *(too) high jet power ?*
		combined lepto-hadronic (e.g. Reynoso+11)	⟺ *jet power constraints ?*
Magneto-sphere		rotational acceleration & IC (e.g. FR & Aharonian 08)	⟺ *external absorption ?*
		gap-type particle acceleration & IC (e.g. Levinson & FR 11)	⟺ *external absorption ?*

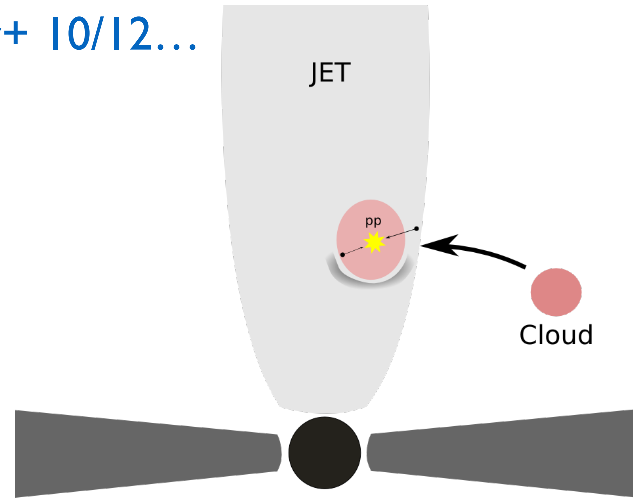
for extended discussion see, e.g. FR & Aharonian' 12, MPLA (review)

On fast variability scenarios: *magnetic reconnection & jet interactions*

Giannios+ 09/10…



Barkov+ 10/12…



Jets-in-Jet / Mini-jets / plasmoids:

- highly magnetized e^--p - jet (σ~100)
- relativistic (Petschek-type) reconnection
- additional relativistic velocity ($\Gamma_c \approx \sqrt{\sigma}$) wrt mean flow
- *differential (strong) Doppler beaming possible*
- leptonic VHE: EC by accelerated electrons…

Potential challenges ?

- lower magnetization for e^--p AGN jets ($\sigma \lesssim 10$)?
- non-negligible guide field / weak dissipation only?
- power-law e^--acceleration & shape beyond 10^2-10^3 thermal Lorentz factor $\sqrt{\sigma}\, m_p/2m_e$?
- strong synchrotron in rest (un-reconnected) B?

Jet-star / cloud interactions:

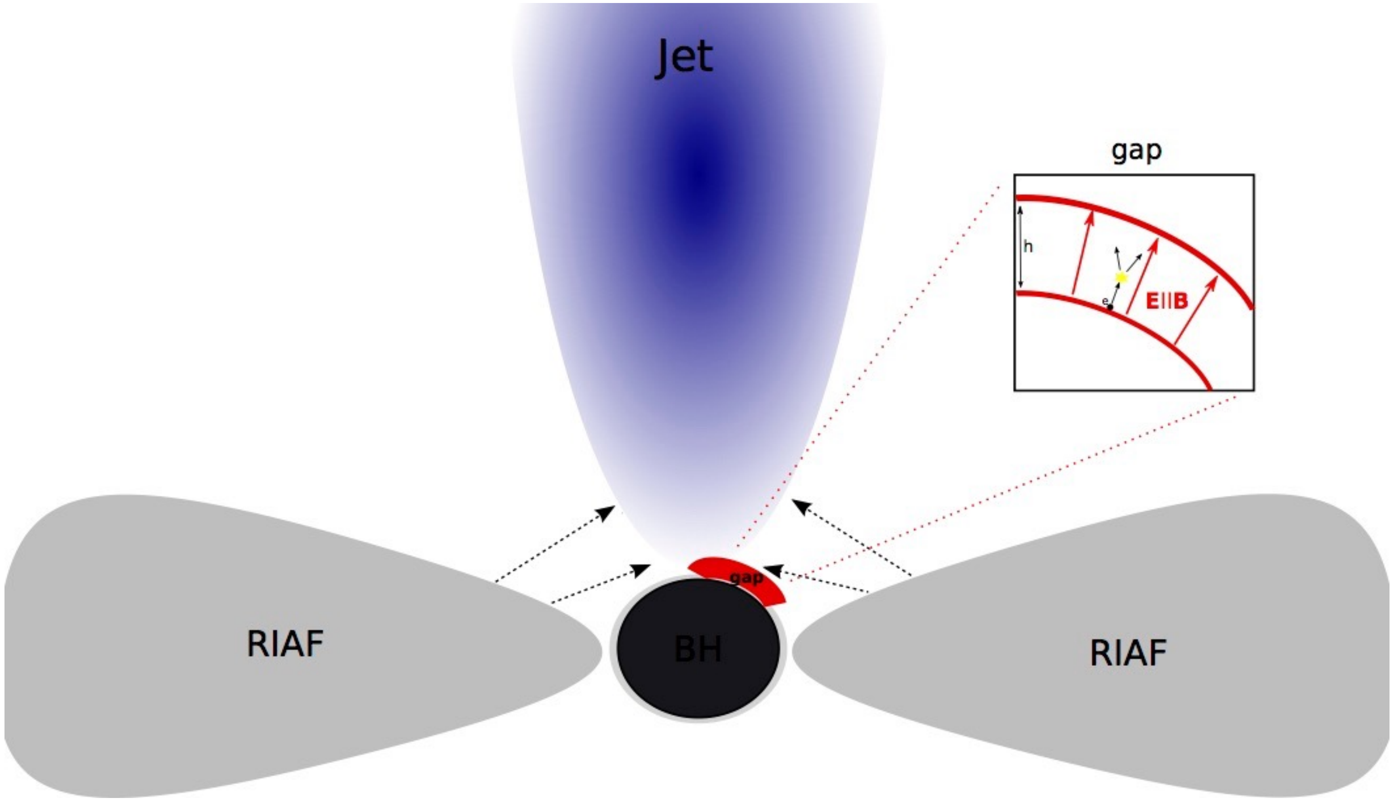
- VHE due to hadronic/pp-interactions
- high target density introduced by star/cloud
- assume efficient (shock-type) acceleration
- "modelling" of light curve & spectrum

Potential challenges ?

- wide observed radio jet opening angle, very large jet power required $L_j \sim L_{VHE} \times (r_j / r_c)^2$?
- frequency of interaction ?
- weak forward shock only (ram pressure of obstacle > jet to penetrate it), weak particle acceleration ?

(cf. also Aharonian+ 2017; FR & Levinson 2018 [review])

On fast variability scenarios: *BH magnetospheric origin*



Magnetospheric Models :

- gap-type ($E_{||}$) electron acceleration
- IC up-scattering of ambient disk photons
- pair cascade triggered by γγ absorption
- gap closure and MHD jet formation

Potential challenges ?

- transparency & escape of VHE (RIAF) ?
- rapid variability & possible luminosity output

  $L_{gap} \sim L_{jet}\,(h/r_g)^{2\text{-}4}$, $h \sim c\,\Delta t$

Levinson & FR 2011; Hirotani & Pu 2016; Katsoulakos & FR 2018…

Interlude

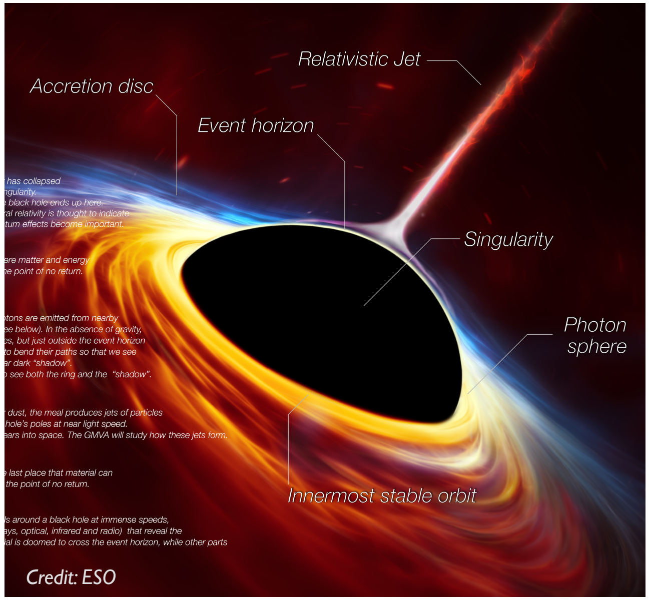
Magnetospheric (BH gap) acceleration

& VHE emission

"Parallel electric field occurrence

⇒ not enough charges to screen the field

$$n_{\rm GJ} = \frac{\Omega B}{2\pi e c} \simeq 10^{-2}\, B_4 M_9^{-1}\ {\rm cm}^{-3}$$

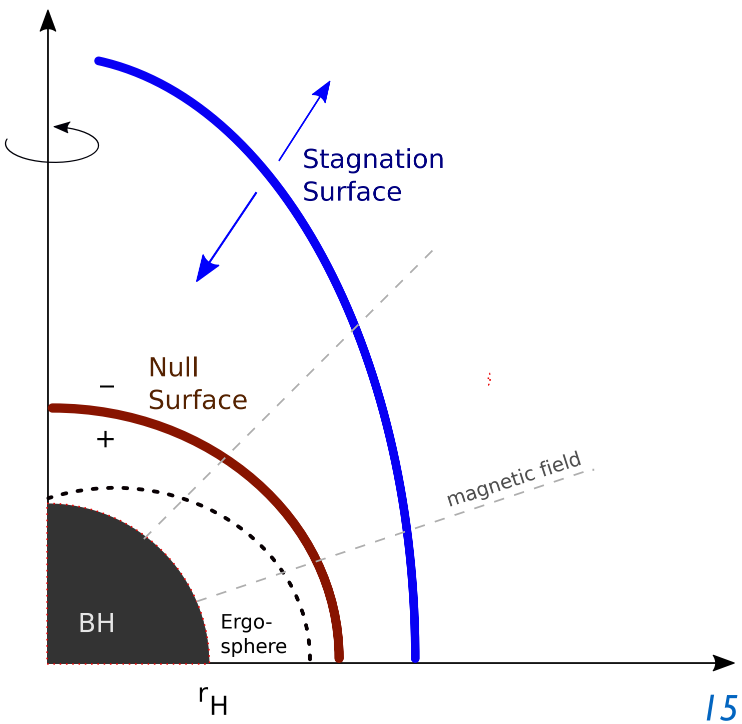


- ***Null surface*** **in Kerr Geometry ($r \sim r_g \equiv GM/c^2$)**

  for force-free magnetosphere, vanishing of poloidal electric field $\mathbf{E}_p \propto (\Omega^F - \omega)\, \nabla\Psi = 0$, *ω=Lense-Thirring*

- ***Stagnation surface*** **($r \sim$ several r_g)**

  Inward flow of plasma below due to gravitational field, outward motion above ⇒ need to replenish charges



e.g., *Blandford & Znajek 1977; Thorne, Price & Macdonald 1986*

Beskin et al. 1992; Hirotani & Okamoto 1998…

The Conceptual Relevance of BH Gaps

Physical framework for jet formation:

- for BH-driven jets *(Blandford-Znajek)*
  - *self-consistency: continuous plasma injection needed to activate BZ outflows (force-free MHD)*
- *if BH regions becomes evacuated…*
  - *efficient acceleration of e+ and e- in emergent $E_{\parallel}$ -field*
  - *accelerated e^-, e^+ produce γ-rays via inverse Compton*
  - *γγ-absorption triggers pair cascade…*

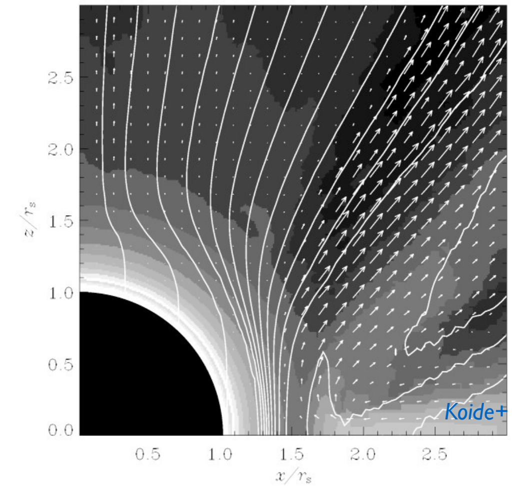
    ⇒ generating charge multiplicity (e^+e^-) = plasma

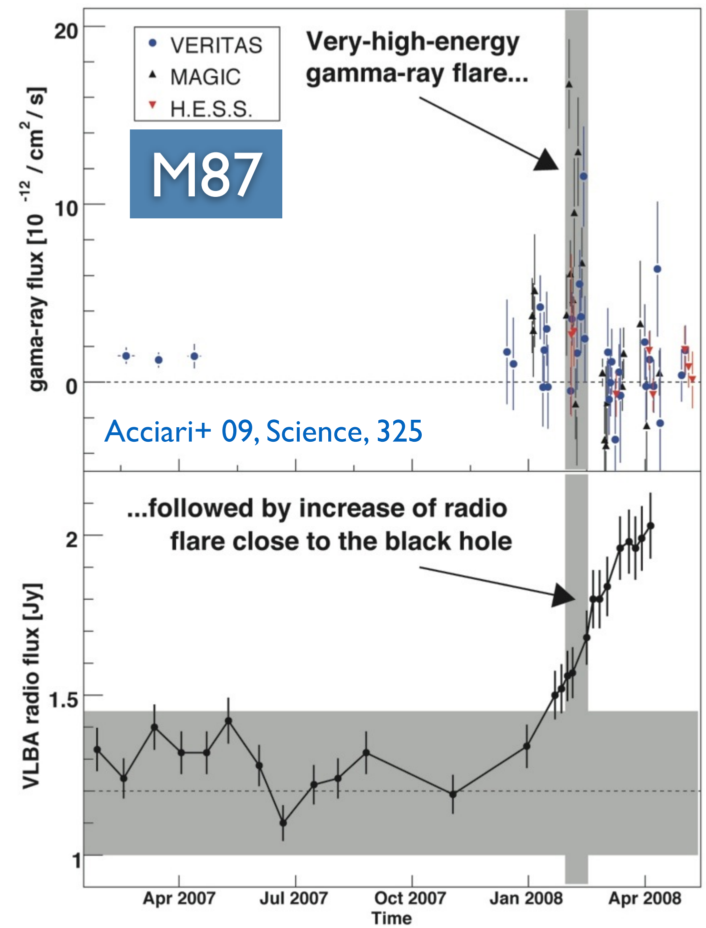
    ⇒ facilitating electric field screening (closure)

    ⇒ *limiting extractable gap potential…*
- observable in MAGN / radio galaxies (e.g., M87)

  ⇒ *γ-ray variations as signature of jet formation*

(Levinson & FR 2011, FR & Levinson 2018 [review])





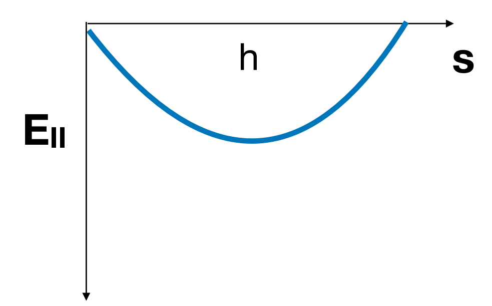
What to expect for “steady” 1D gaps ?

Solving Gauss’ laws depending for null-surface-type boundaries

$$\frac{dE_{||}}{ds} = 4\pi\,(\rho - \rho_{GJ}) \qquad [\rho_{\rm GJ} = n_{\rm GJ}\cdot e]$$

solve for $E_{||}$ ⇒ calculate potential $\phi = -\int E_{||}\, ds$ ⇒ determine power $L \sim \phi \cdot I$

- *Boundaries:* $E_{||}(s=0)=0,\ E_{||}(s=h)=0$
- *Gap potential:* $\Delta\phi_{gap} \sim a\, r_g\, B\, (\mathbf{h/r_g})^{3}$
- *Gap - Jet power:* $L_{gap} \sim L_{BZ}\, (\mathbf{h/r_g})^{4}$ …

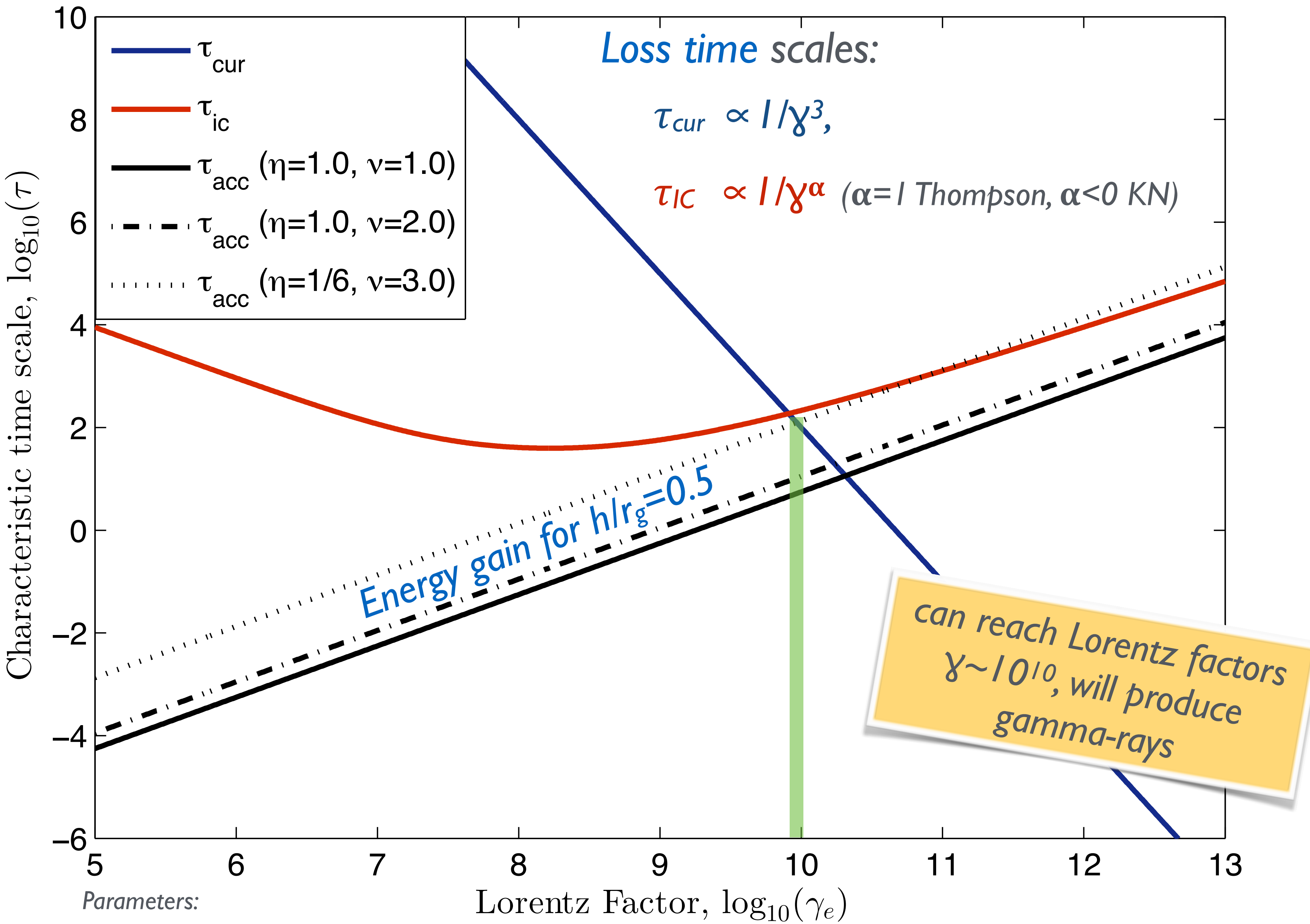


Taking variability as proxy for gap size

➩ Jet power constraints become relevant for rapidly varying sources

(e.g., Hirotani & Pu 2016; Katsoulakos & FR 2018)

Example: Acceleration versus Losses - Timescales



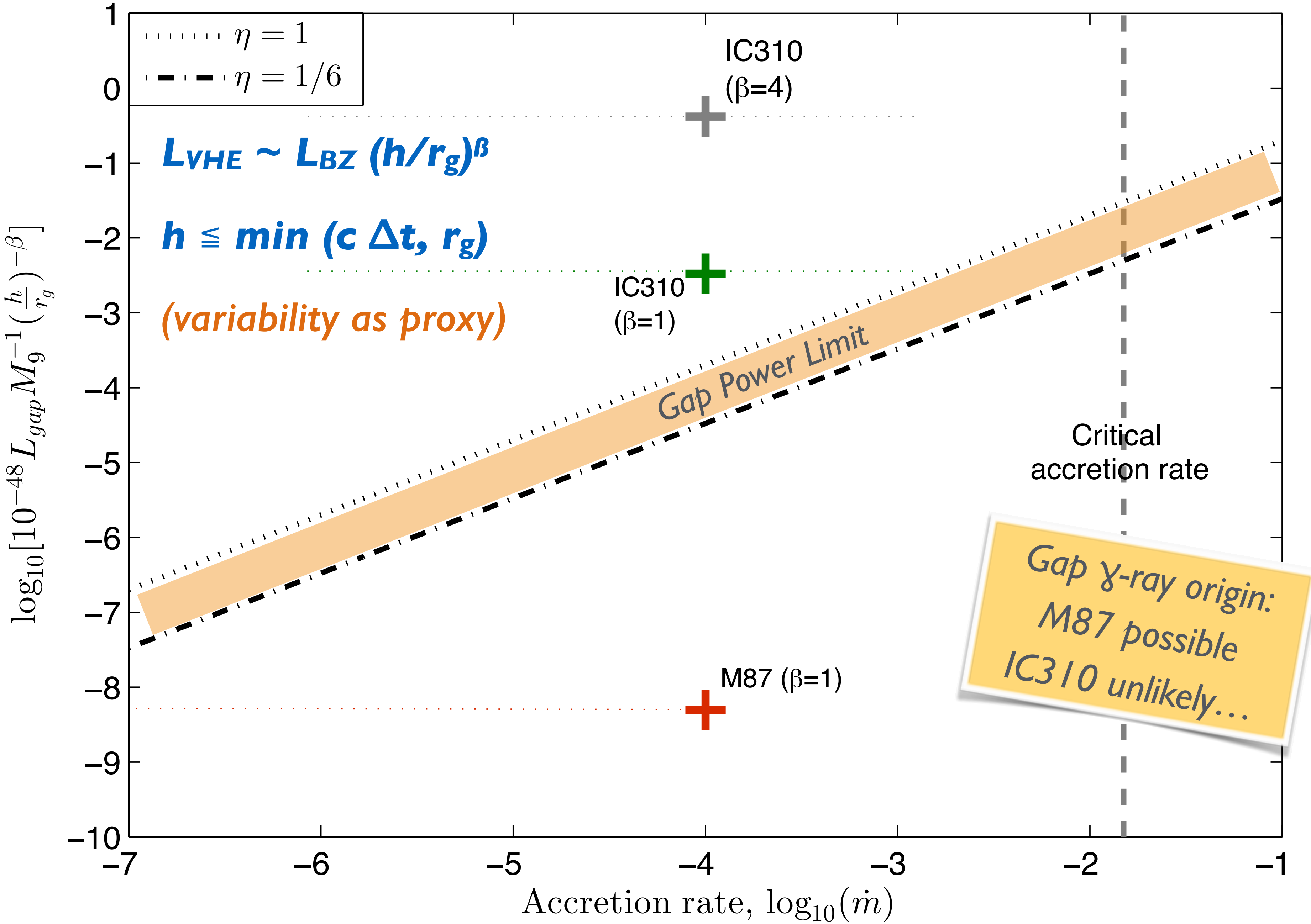
Parameters:

M_9=5, $\dot{m}=10^{-4}$ (ADAF)

$\epsilon_{s,peak} \sim 5\times10^{-3}$ eV, h/r_g=0.5

Katsoulakos & FR 2018

Maximum power constraints for quasi steady gaps

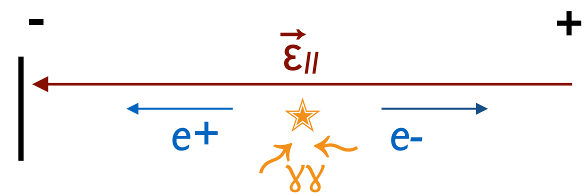


$L_{BZ} = \Omega_F (\Omega_F - \Omega_H) B_H^2 r_H^4/c \sim 10^{48} \dot{m} M_9 B_H^2$

Katsoulakos & FR 2018

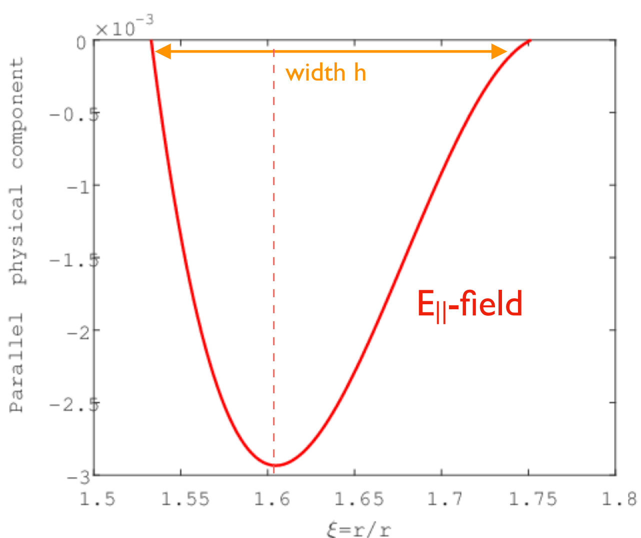
What sizes etc to expect ? - Self-consistent steady (1D) gap solutions I

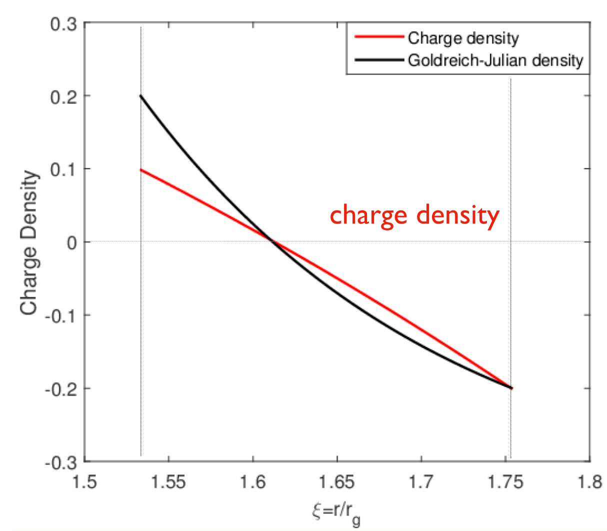
e,g., Beskin+ 1992; Hirotani & Okamoto 1998; Hirotani+ 2016; Levinson & Segev 2017; Katsoulakos & FR 2020



Solve system of relevant PDEs in 1D around null surface, assuming some soft photon description & treat current as input parameter:

- GR Gauss' law ($E_{||}$) $$\nabla \cdot \left(\frac{\mathcal{E}_{||}}{\alpha_l}\right) = 4\pi(\rho_e - \rho_{GJ}) \quad , \ \rho_e = \rho^+ + \rho^- = n^+ e - n^- e$$
- e^+, e^- equation of motion (*radiation reaction*) $$m_e c^2 \frac{d\Gamma_e}{dr} = -e\mathcal{E}^r_{||} - \frac{P_{IC}}{c} - \frac{P_{cur}}{c}$$
- e^+, e^- continuity equation (*pair production*) e.g. $$J_0 = (\rho^- - \rho^+)c\left(1 - \frac{1}{\Gamma_e^2}\right)^{\frac{1}{2}} = \text{constant}.$$
- Boltzmann equation for photons (*IC, curvature, pair production*) $$\frac{dP_\gamma^+}{dr} = \ldots \text{ etc}$$





 # Boundary Conditions:

Zero electric field at boundaries

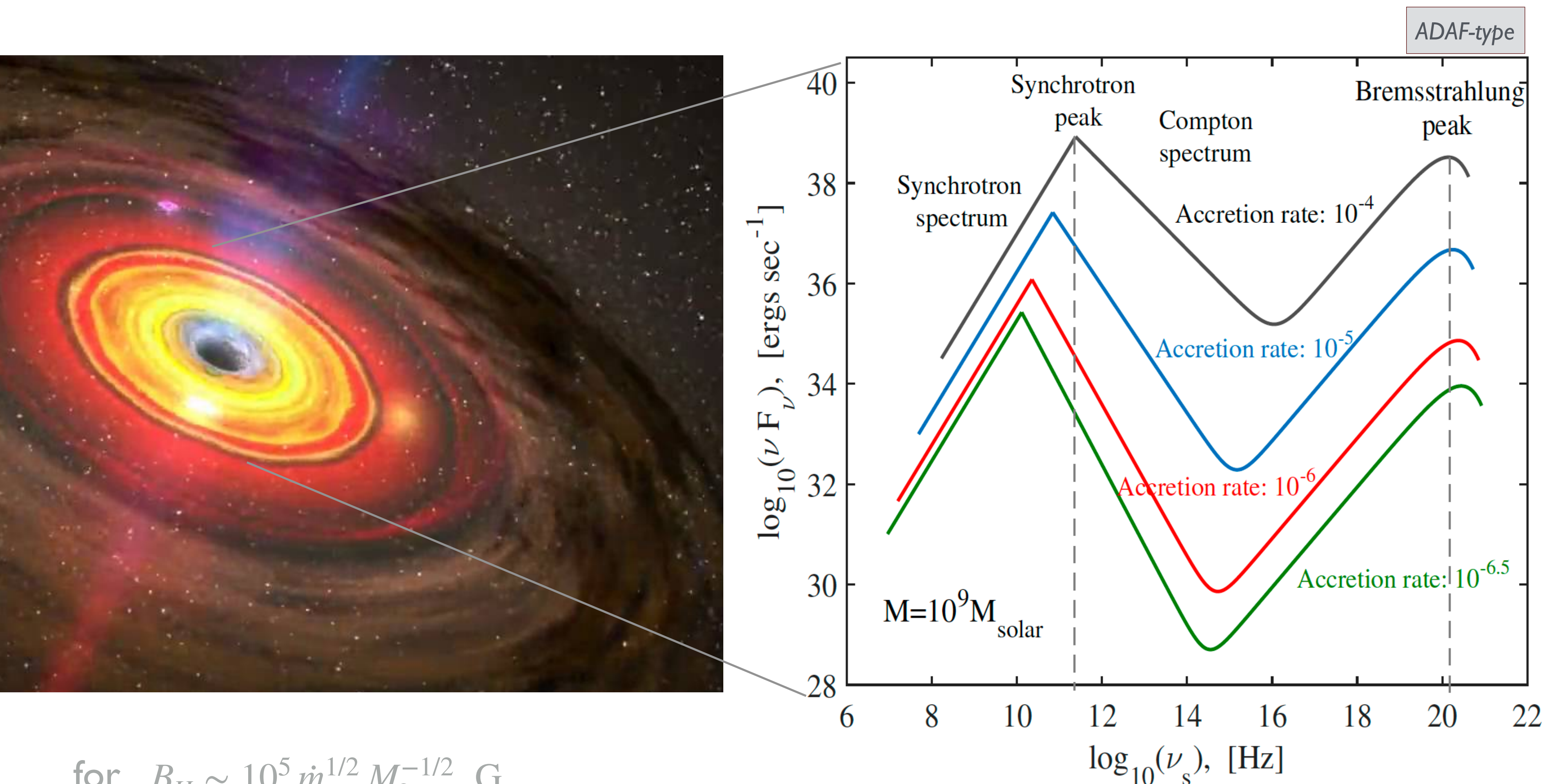
$\varrho \leq \varrho_{GJ}$ in boundaries

 # ADAF soft photon field

Self-consistent steady (1D) gap solutions II

Adequate description of ambient soft photon field turns out to be of high relevance

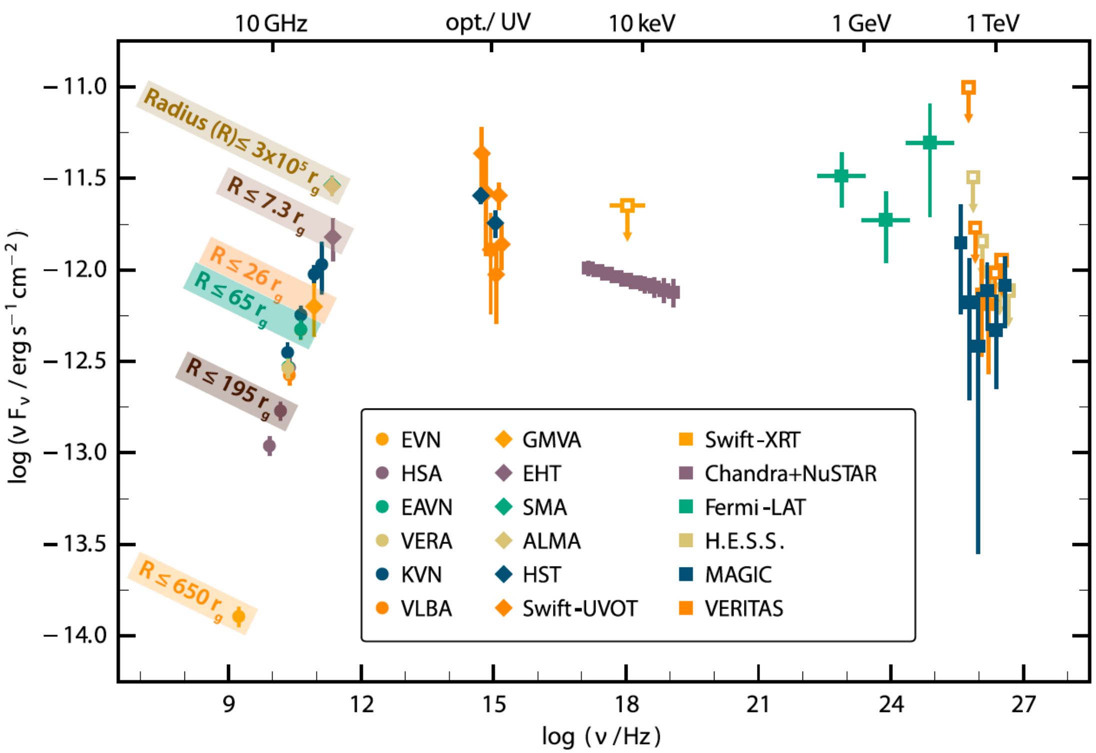
➡ *determines efficiency of pair cascade…*



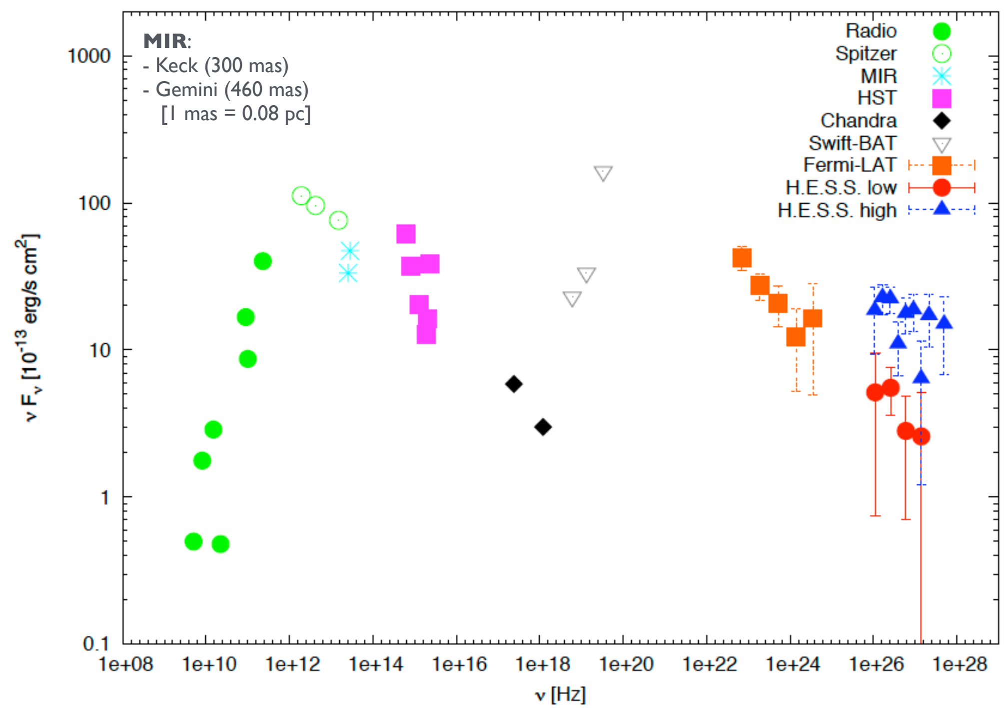
for $B_H \sim 10^5 \, \dot{m}^{1/2} \, M_9^{-1/2}$ G

Self-consistent steady (1D) gap solutions II

On the nuclear SED of M87 …



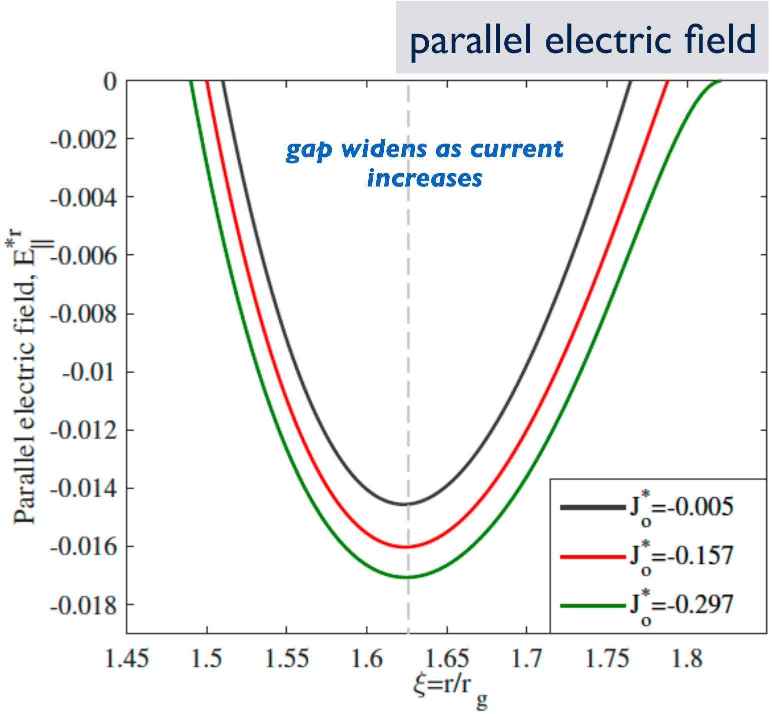
EHT+2021



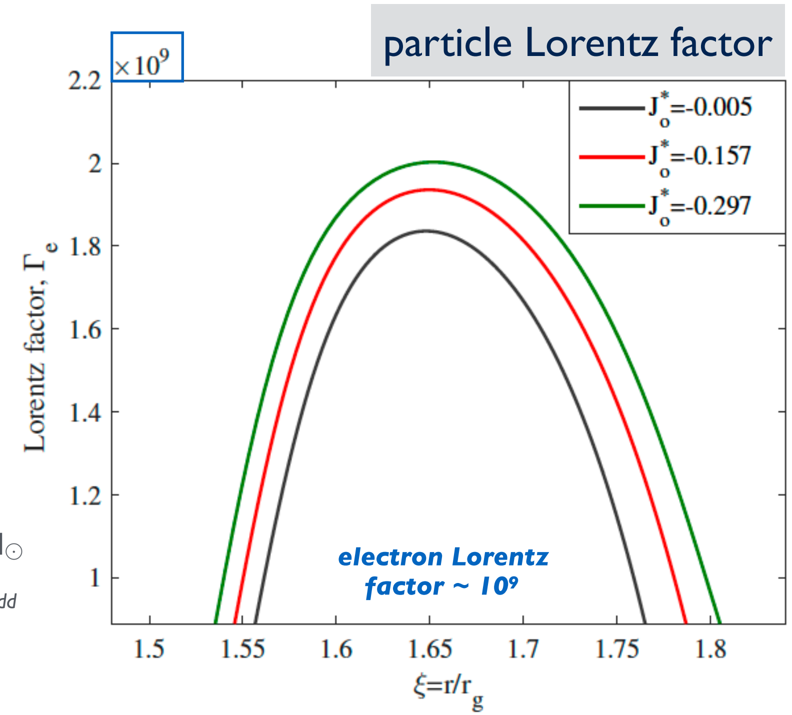
FR 2012

Example: Self-consistent steady (1D) gap solutions III - M87

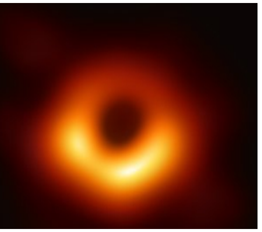
Katsoulakos & FR 2020



Parameters:
M_{BH} = 10^9 $M_\odot$
$\dot{m}$ = 10^{-5} $\dot{m}_{Edd}$



M87:



[EHTC 2019]

Global Current	Gap Size	Voltage Drop	Gap Power
$J_o^* = J_o/c\,\rho_c$	h/r_g	$\times 10^{17}$ Volts	$\times 10^{41}\, erg\, s^{-1}$
(1)	(2)	(3)	(4)
−0.4	0.8076	9.8	4.9

NOTE—Results for the gap extension, the associated voltage drop and total gap power for a global current $J_0^* = -0.4$, assuming $M_9 = 6.5$, and $\dot{m} = 10^{-5.75}$.

(using spin parameter a_s^*=1; max L_{BZ} = 2 x 10^{43} erg/s)

Consistent solutions possible for M87 max. voltage drop ~10^{18} eV

TeV gamma-ray emission, but no strong UHECR acceleration close to BH

- *expect gaps to be intermittent* $\Longrightarrow$ *need time-dependent studies (PIC simulations)*
  (Levinson & Cerutti 2018; Chen+ 2018; Crinquand+ 2020, 21; Chen & Yuan 2020; Kisaka+ 2020, 21; Hirotani+ 2021…)
  - different complexity employed (e.g., SR/GR, resolution, 1d/2d, radiation reaction, ambient soft field)
  - outcome generally highly sensitive to assumed ambient photon field (ε_{min}, PL index)
  - indications for periodic (timescale ~ r_g/c) opening of macroscopic (h ~ 0.1-1 r_g) gaps….

Model: Start with plasma-filled condition, where E=0 and $\rho=\rho_{GJ}$, no curvature radiation …

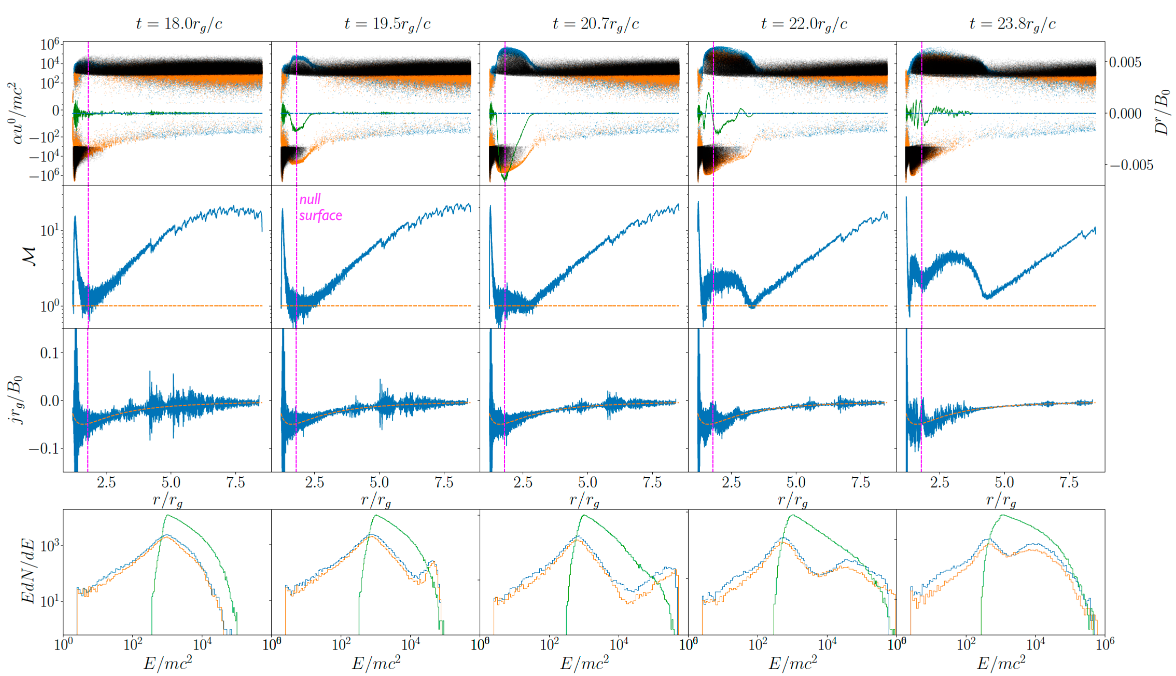
phase space plot (e+, e-, photons); electric field

Multiplicity $\mathcal{M} = n/n_{GJ}$

Current & $j_{ff} \sim n_{GJ}\,|e|\,c$

Spectrum of e-, e+, photons

$\lambda_p = c/\omega_p \propto n_e^{-1/2}$



gap cycle assuming τ_{IC}=10 and soft photons with ***ε_{min} ~ 5 eV***

PL index = 2.2

(size r_g ~ $10^4\,\lambda_p$, l_{IC} ~ $10^3\,\lambda_p$)

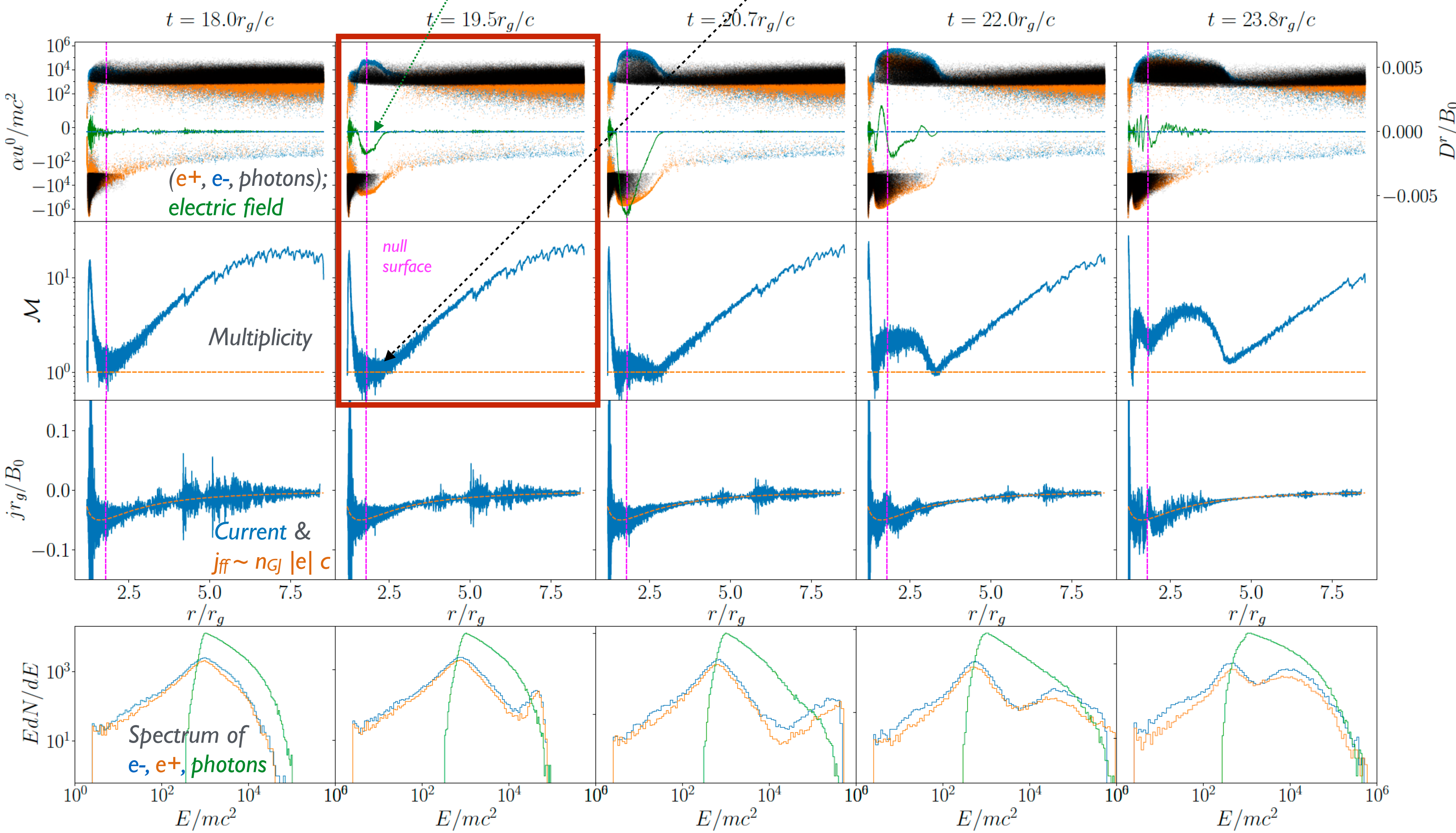
Note scale-separation $r_g / \lambda_p \sim 10^8$ (M87)

plasma skin depth = depth to which low-frequency waves can penetrate:
$\lambda_p = c/\omega_p = c/[4\pi n_{GJ} e^2/m_e]^{1/2}$

Chen & Yuan 2020

Issues & developments

electric field forms as multiplicity drops below 1



Chen & Yuan 2020

Characterizing variability beyond minimum timescales

(see also FR 2019 [review])

galaxies

MDPI

Review

Gamma-Ray Astrophysics in the Time Domain

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check for updates

Abstract: The last few years have seen gamma-ray astronomy maturing and advancing in the field of time-domain astronomy, utilizing source variability on timescales over many orders of magnitudes, from a decade down to a few minutes and shorter, depending on the source. This review focuses on some of the key science issues and conceptual developments concerning the timing characteristics of active galactic nuclei (AGN) at gamma-ray energies. It highlights the relevance of adequate statistical tools and illustrates that the developments in the gamma-ray domain bear the potential to fundamentally deepen our understanding of the nature of the emitting source and the link between accretion dynamics, black hole physics, and jet ejection.

Keywords: gamma-rays; emission: non-thermal; variability; origin: jet; origin: black hole

Characterizing VHE variability in AGN

I. Rapid VHE flux variability (minimum variability timescale)

- e.g., Mkn 501 (5 min), PKS 2155-304 (3 min)
  - *extreme jet conditions*, very compact & luminous region, multiple zones?

Beyond minimum variability considerations:

II. Evidence for log-normal distribution of fluxes

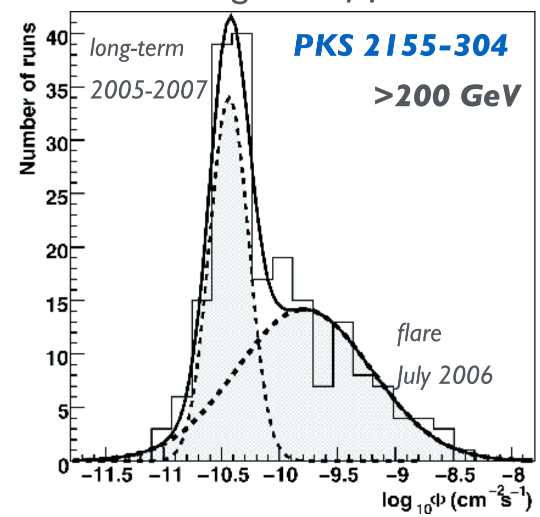
- ***Log(Flux) is Gaussian distributed***
  - for both low & high VHE source states

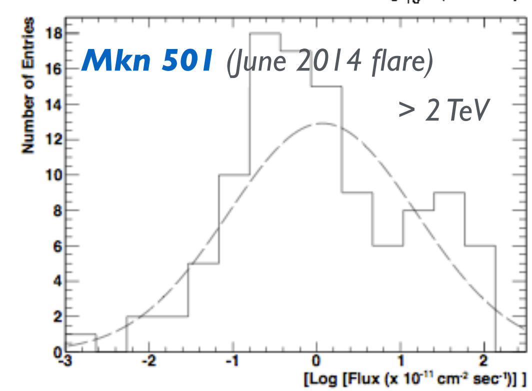
- *multiplicative* or cascade-type process

$$X = \log F_1 + \log F_2 + \ldots = \log(F_1 * F_2 \ldots)$$

  - *additive models less likely (shot-noise; mini-jets…?)*
  - hadronic cascade emission ? *(but different energy bands)*
  - cascade-type injection…

Histogram of fluxes



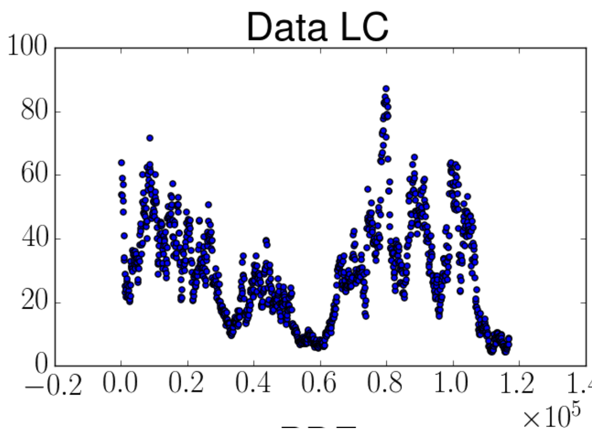


H.E.S.S. Collab., 2010 & 2015

Characterizing VHE variability in AGN

III. Power Spectral Density (PSD)

- which power at which (temporal) frequency?
  How is variability on different timescales related to each other?
- ~modulus-squared of discrete FT (frequency domain)



▸ ***"AGN vary more strongly towards longer timescales"***

  ▸ <u>power-law noise</u> ***P(ν) ~ ν*** $^{-\alpha}$

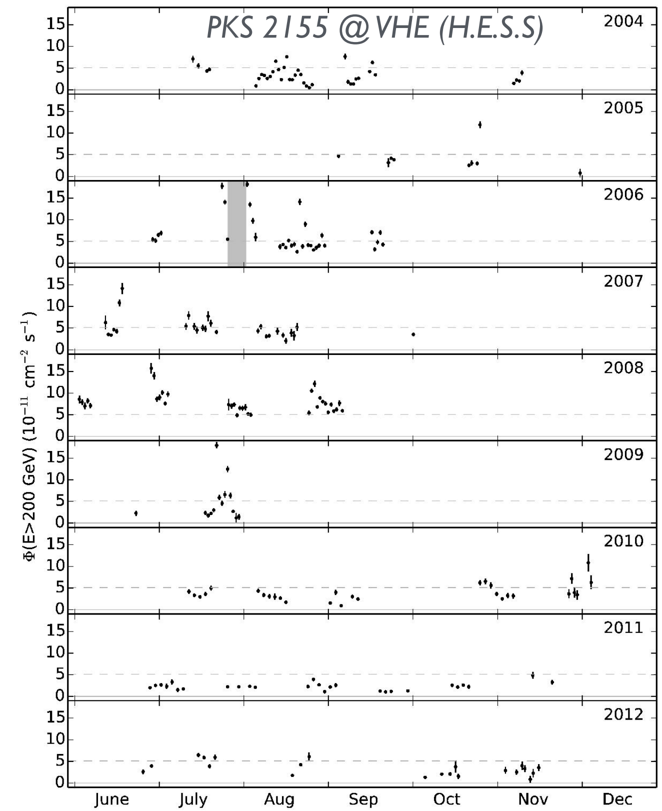
- **Example: PKS 2155-304:**

  ▸ α ~ 2 for VHE active/flare states

  ▸ α ~ 1 for 'quiescent' HE & VHE

<u>flare:</u> timescales < 3h

<u>quiescent:</u> timescales > 1d (H.E.S.S.) > 10 d (Fermi)

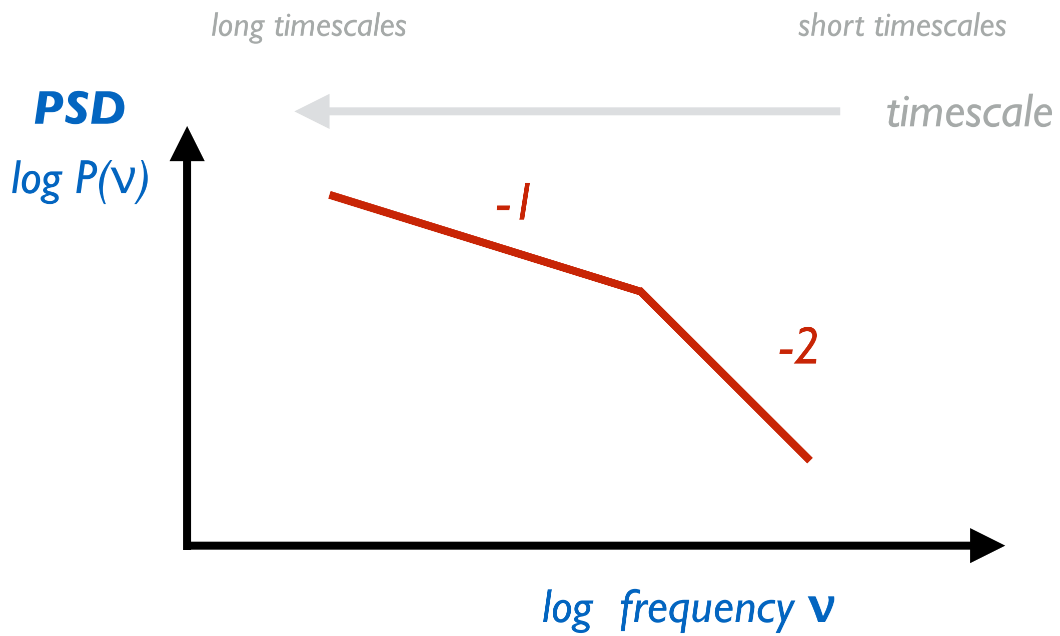


H.E.S.S. Collab., 2010, 2017

Characterizing VHE variability in AGN

- PSD break by $\Delta\alpha=1$ (around ~1 day) as in Seyfert AGN (X-ray) ?

Uttley & McHardy 2005…



- change in accretion flow conditions ? *Lyubarskii 1997…*

Note: need to be consistent (TK'95 vs Emmanoulopoulos+ '13 simulations)

On PSD-slope dependencies

Explore possible modifications of PSD-shape due to radiation

(Finke & Becker 2014, 2015)

- *start from some time-dependent particle transport equation for $N_e(\gamma,\mathbf{t})$*
- *Fourier transform equation ⇒ $\tilde{N}_e(\gamma, \mathbf{f})$*
- *inject power-law noise $\mathbb{Q}(\gamma, f) \sim \mathbf{f}^{\,-\beta}$*
- *study impact on synchrotron, EC and SSC*
  - *PSD proportional $|\mathcal{F}_{SSC}(f)|^2 \sim \mathbf{f}^{\,-(4\beta-2)}$ versus $|\mathcal{F}_{EC}(f)|^2 \sim \mathbf{f}^{\,-2\beta}$ ($\mathcal{F}$ Fourier transform of flux)*
  - *differences for FSQP (EC) and BL Lacs (SSC) ?*

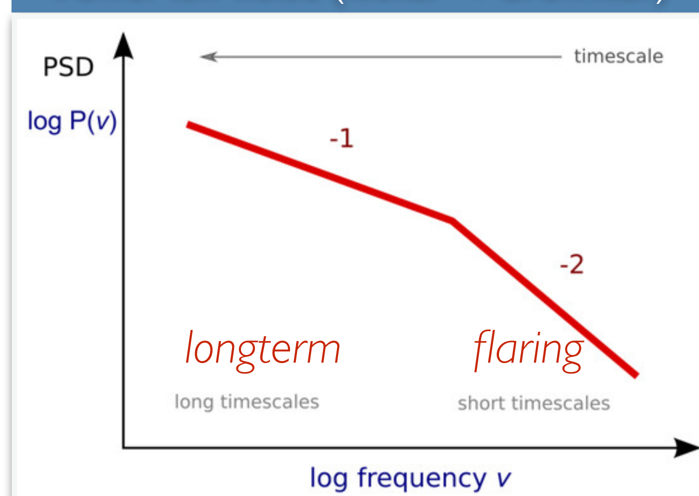
EC and SSC show different dependencies,

*i.e. **2ß** versus **(4ß-2)***

*e.g. for **PKS 2155-304** (SSC):*

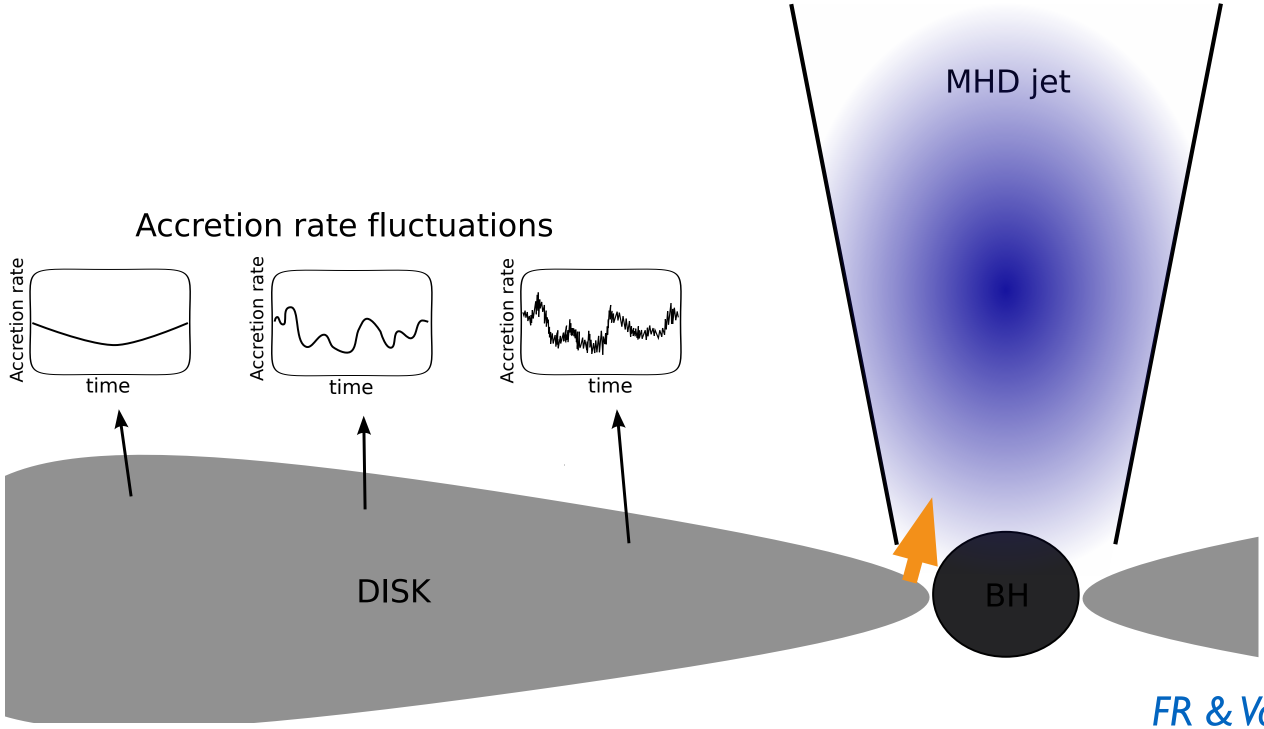
ß~1 (flare)** versus **ß ~ 0.75 (quiescent)

Power-law noise (flicker ⇒ Brownian)



Is the VHE variability driven by accretion disk fluctuations ?

- *accretion disk variations as multiplicative, power-law noise* *(Lyubarskii 1997)*
- *if efficiently transmitted to jet, power-law noise in injection for Fermi acceleration*
  - *need to study the scales on which this gets blurred by radiation etc* *(FR & Volpe 2010)*
  - *in particular, minimum VHE variability (~3 min) limits BH size*



possible disk-origin of jet

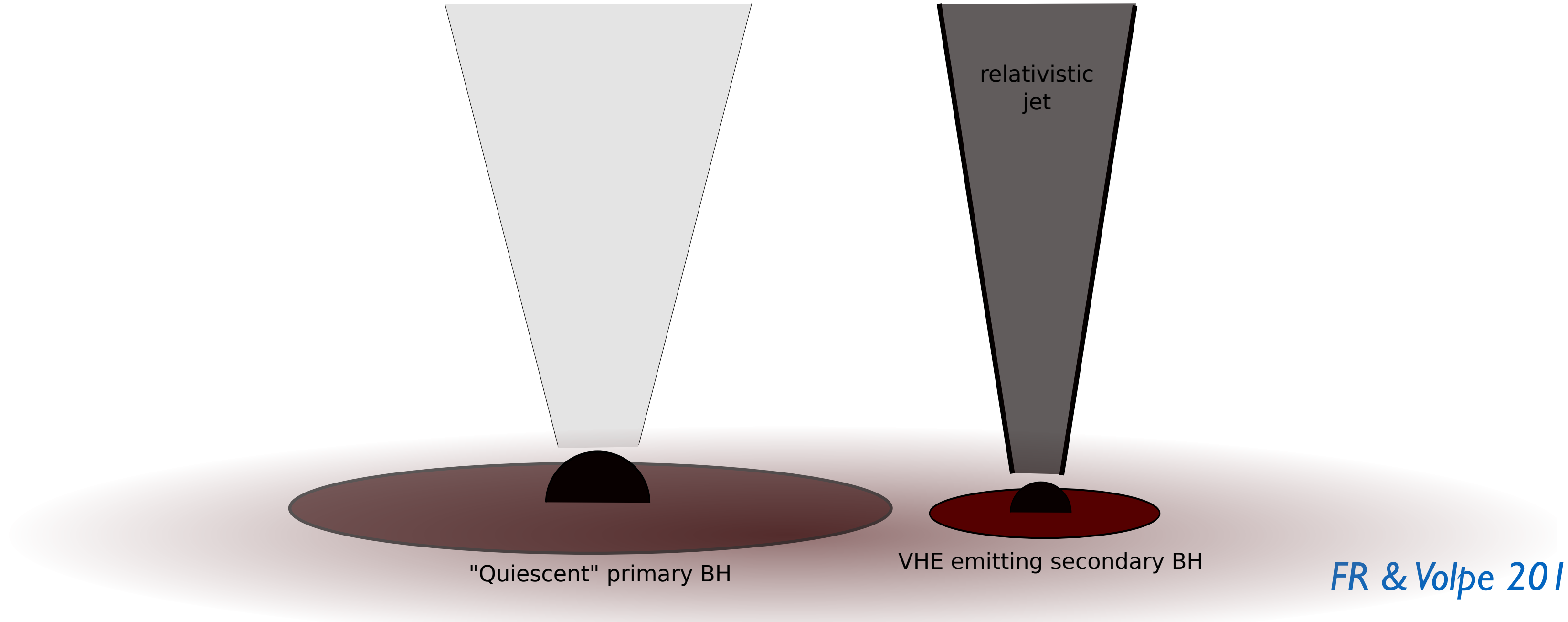
FR & Volpe 2010; Volpe & FR 2011

On the VHE characteristics of PKS 2155-304

The 'cost' for it in the case of PKS 2155-304:

- *only works for "small" black hole* ~3 x 10^7 M_{sun} < $M_{BH\ total}$ (from $M_{BH\ total}$ - L_{bulge})
  ~2 x 10^8 M_{sun}

- ***possible in a binary black hole system***
  - *elliptical galaxies as spiral merger results…*
  - *circumbinary disk-accretion preferentially feeds secondary BH* *(e.g., Artymowicz & Lubow 1996)*
  - *X-ray variability (PSD) support small BH mass* *(e.g., Czerny et al. 2001)*
  - *"evidence" for optical longterm periodicity (~7 yr)* *(Fan & Lin 2000)*



FR & Volpe 2010; Volpe & FR 2011

Conclusions

- The gamma-ray flaring / variability phenomenology may be richer than we currently anticipate (e.g., limited by statistics, shape & extension…)
- In many cases, we do not (yet?) know where the emission / variability really occurs (location / geometry)
- M87 remains best-motivated case for near-BH origin (massive, under-luminous, nearby source!)
- there may be other scenarios than reconnection-related ones…😀
- need to build "bridges" (e.g., scale separation vs real system size)…
- may need to spell out "costs" (source-specific requirements)

Thank you!