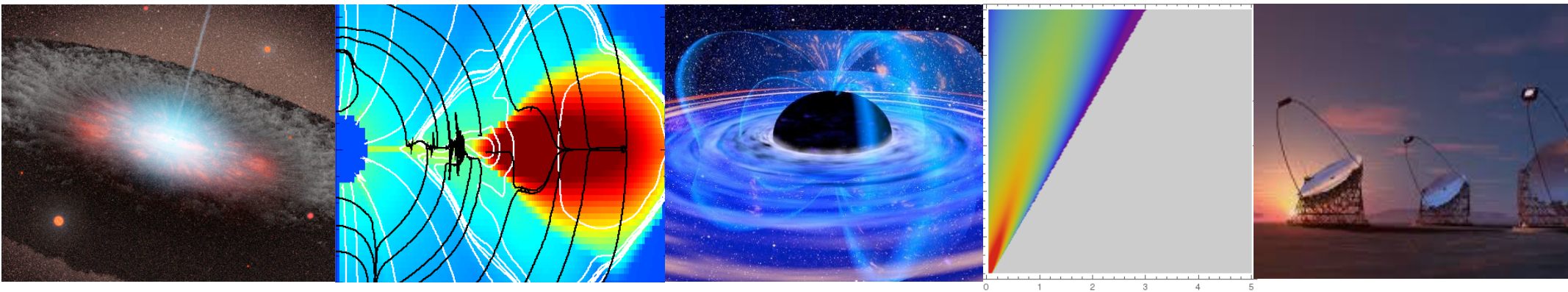
Magnetospheric Gamma-Ray Emission in Active Galactic Nuclei (AGN)

Frank M. Rieger

June 11, 2019

Workshop on Magnetospheres of Neutron Stars and Black Holes (GSFC)



Institute of Theoretical Astrophysics
Heidelberg University

Max Planck Institut für Kernphysik
Heidelberg, Germany

Outline

- *Context & Motivation*
- *Candidate Sources: Cen A, IC 310, M87*
- *The Occurrence and Relevance of gaps*
  - *The power of (steady) gaps*
  - *On "unsteady" gaps*
- *Conclusions & Perspectives*

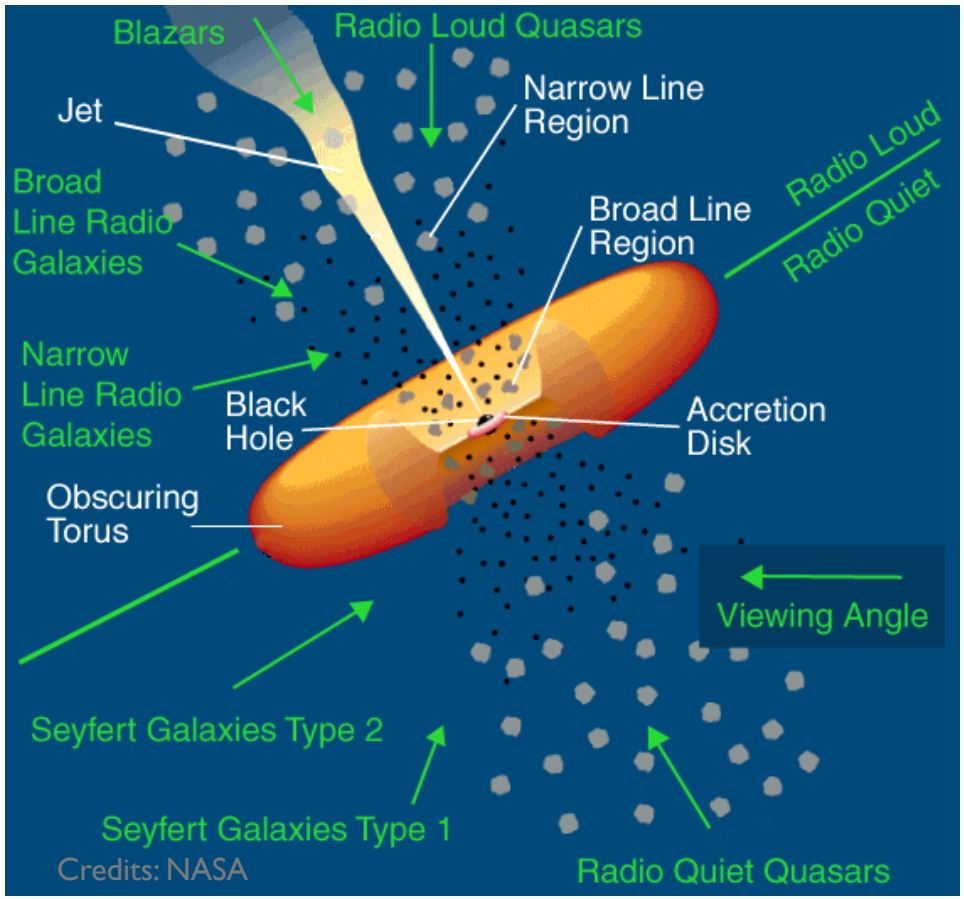
Context of Sources

Non-blazar radio-loud ***AGN*:**

- **misaligned jets (MAGN)**
- **modest Doppler boosting** $D = 1/[\gamma(1-\beta \cos i)]$
- **Radio Galaxies** as prototypes

Radio Galaxy **Centaurus A** (Cen A), core region, nearest ***Active Galaxy*** (d ~ 4 Mpc)

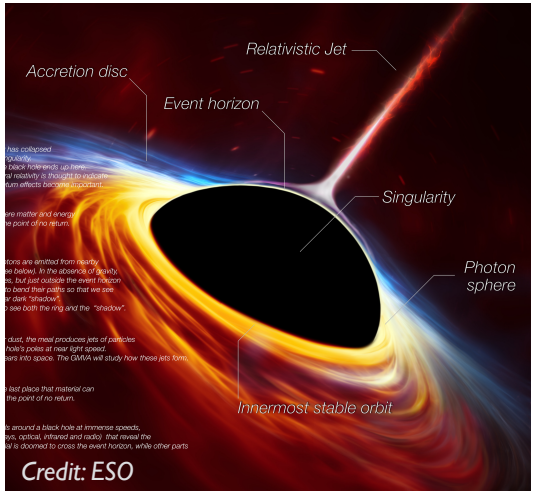
X-rays (Chandra/blue), radio (orange) & optical



Central engine in AGN & unification

Phenomenological Motivation

"Energetic processes in BH magneto-sphere can lead to gamma-ray emission showing up in the HE-VHE band"



Observation of ***rapid VHE variability*** *and/or* ***spectral hardening*** *(additional component beyond one-zone SSC jet expectation) as possible signatures in "misaligned" AGN:*

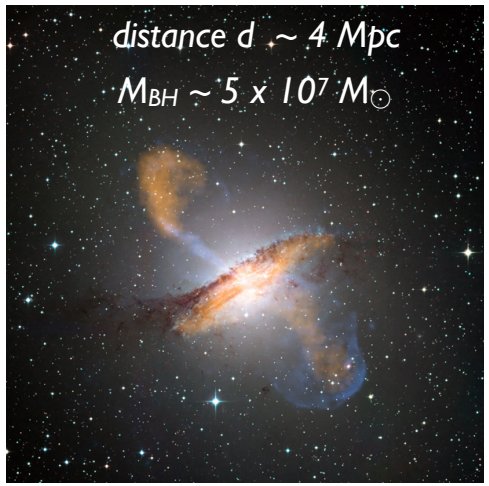
- ***Cen A*** *- unusual spectral HE hardening*
- ***IC 310*** *- extreme VHE variability*
- ***M87*** *- rapid VHE variability, radio-link, γ-ray excess emission*

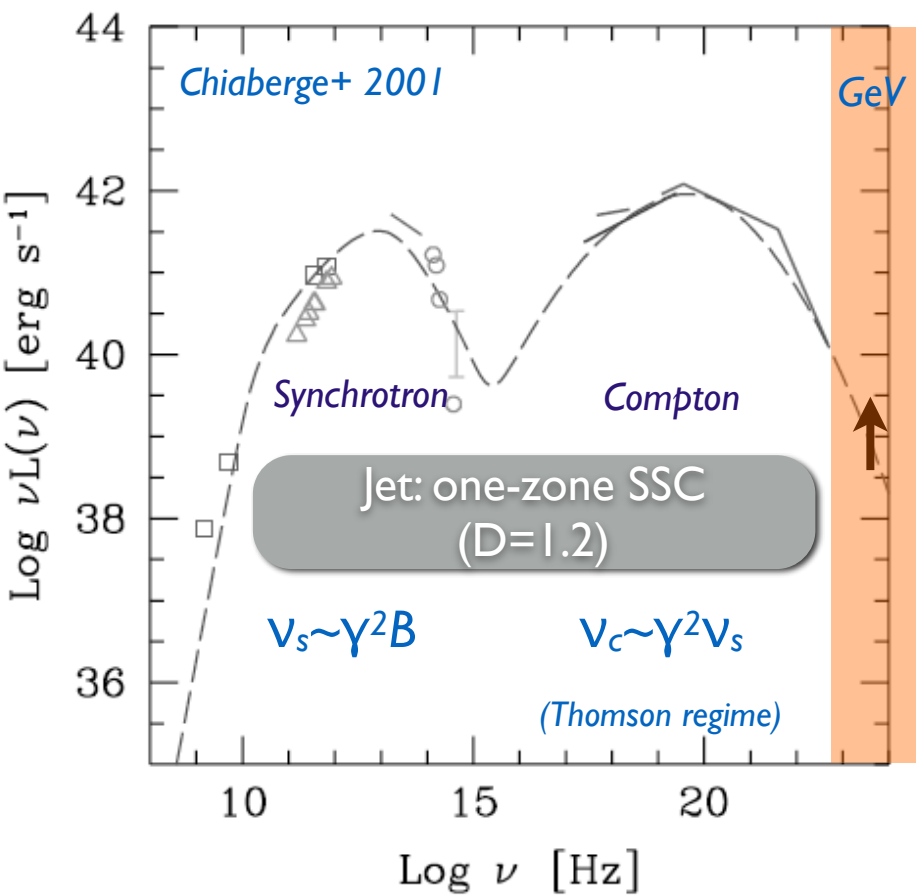
FR & Levinson 2018 (review)

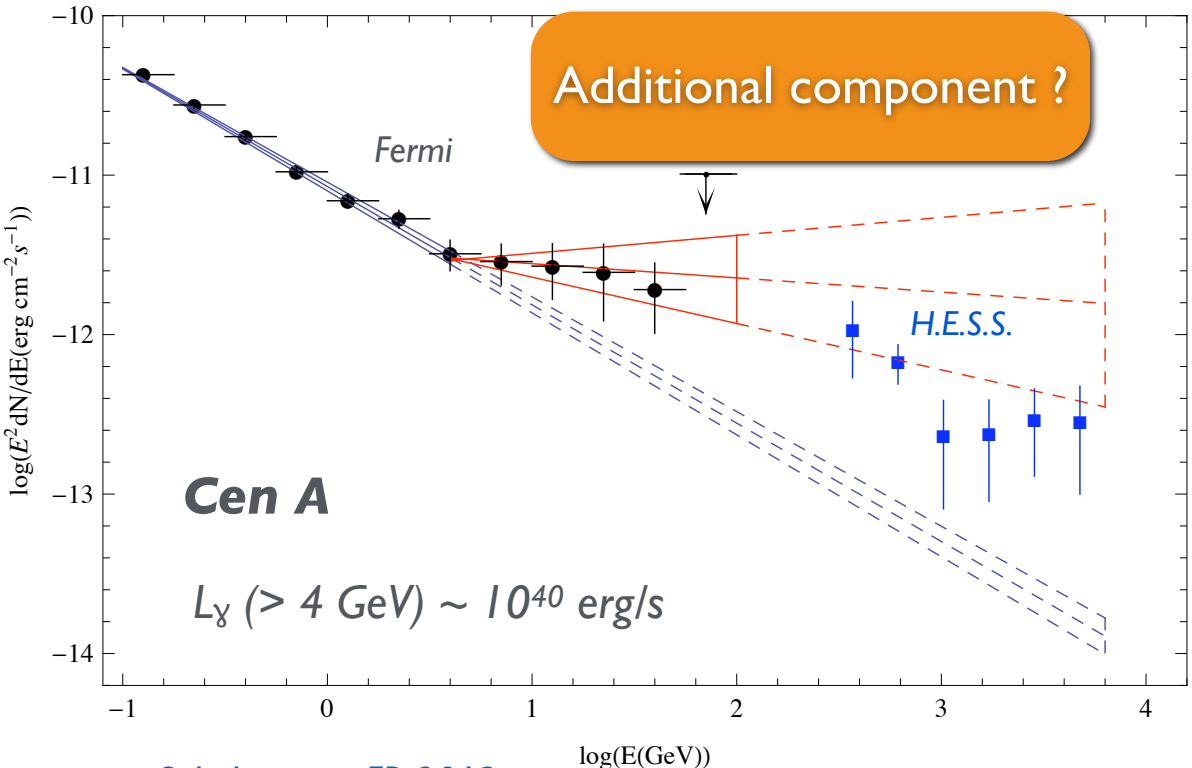
Cen A - spectral hardening at HE beyond 1-zone SSC

*Unusual **spectral hardening** @ E_{break}~4 GeV (-2.7 → -2.2):*

- beyond jet emission (SSC) for misaligned source (D ~ 1)
- *additional emission component that allows to connect to VHE*
- caveat: no significant variability detected ⇒ a number of possible origins...







Sahakyan, ..+ FR 2013

for update: Brown+ 2017; H.E.S.S. + 2018

IC 310 - extreme VHE variability

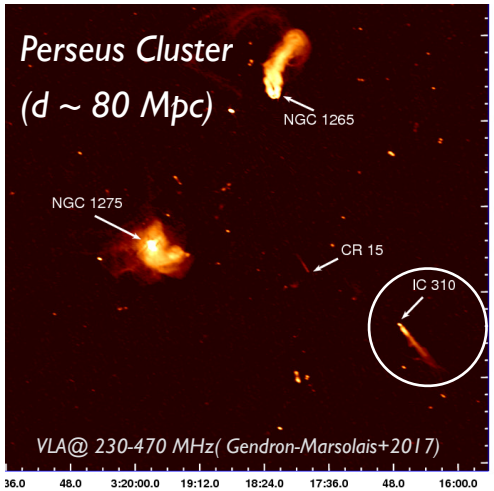
VHE flare in 2012 (MAGIC):

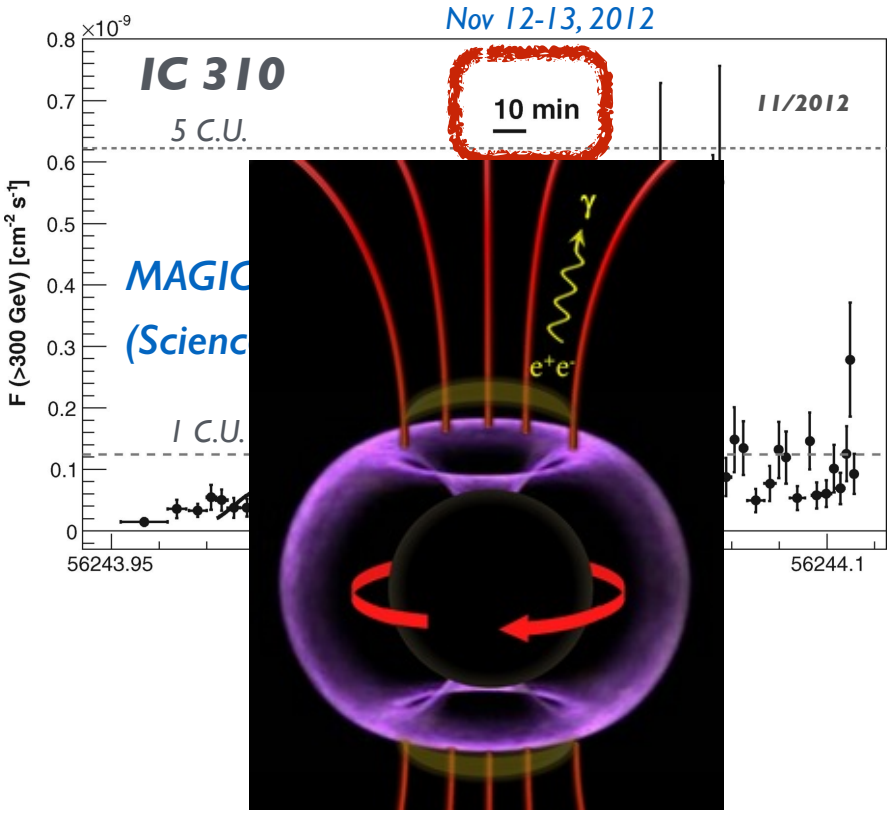
Extreme **short-term VHE variability**

- bright outburst $L_\gamma \sim 2 \times 10^{44}$ erg/s
- doubling time ~ 5 min
- BH mass = $3 \times 10^8\, M_\odot$ ($3\times10^7\, M_\odot$??)
- BH crossing time $r_g(3\times10^8 M_o)/c$ = 25 min
- **sub-horizon "gap-type" particle acceleration (?)**
  - gap height h ~ 0.2 r_g

Possible probe of BH vicinity

caveat: low angular resolution of IACTs





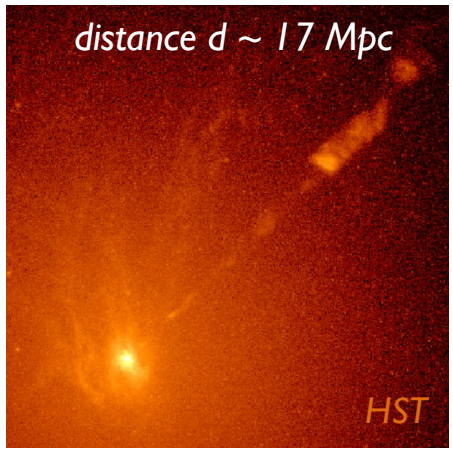
(Aleksic+ 2014; Hirotani & Pu 2016)

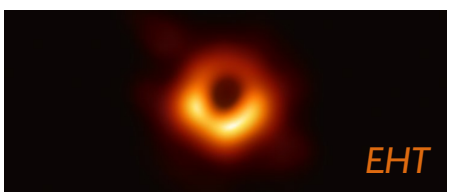
M87 - rapid VHE variability, radio link & γ-ray excess

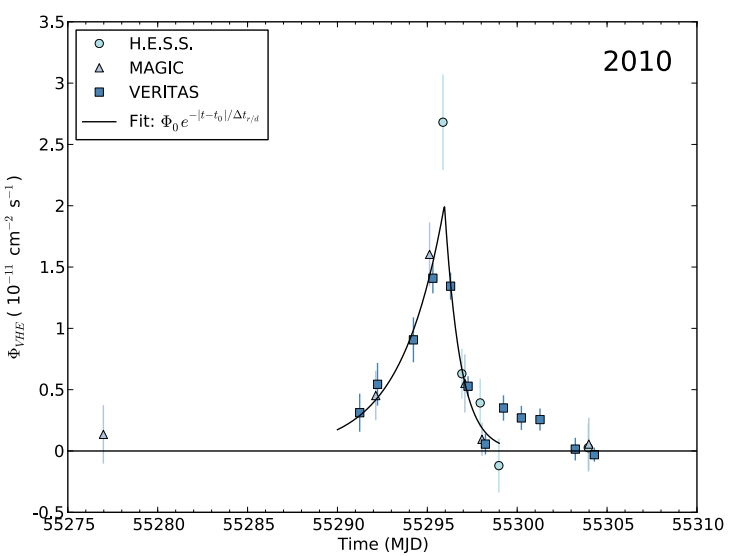
- rapid VHE variability 2005, 2008, 2010
  - *BH mass 6.5x10⁹ $M_\odot$ ⇒ r_g/c = 0.38 d (day-scale = horizon-scale)*
  - *$L_{VHE,high}$ ~ 5 x 10^{41} erg/s*
- radio-VHE correlation *(increase)* *+2008, ±2010,+2012*
- HE spectral inflection (additional component?)

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

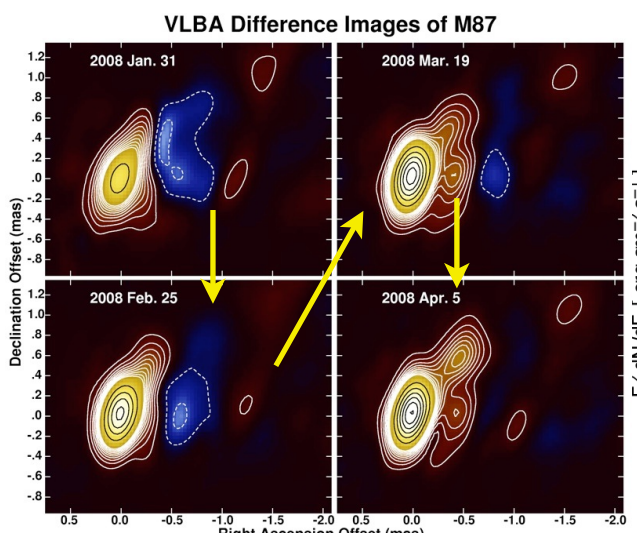
➡ ***Magnetospheric Gamma-Ray Emission*** *?* *(Levinson & FR 2011)*





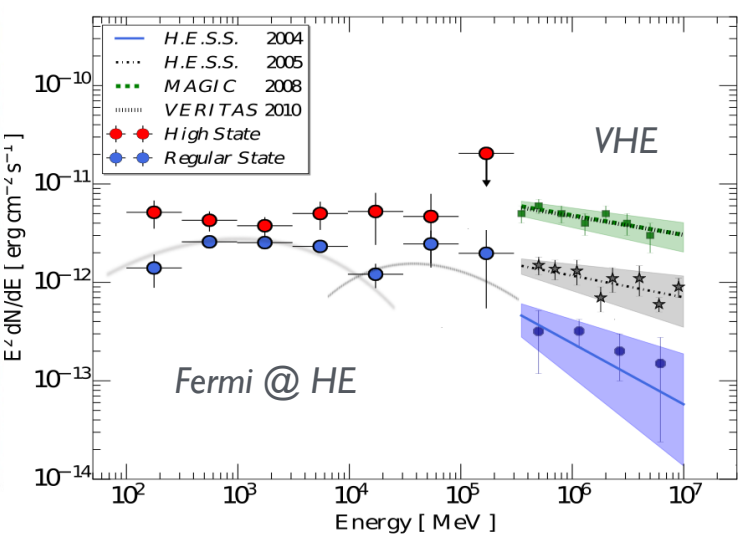


Abramowski+ 2012



VLBA (43 GHz), 1 mas = 0.08 pc

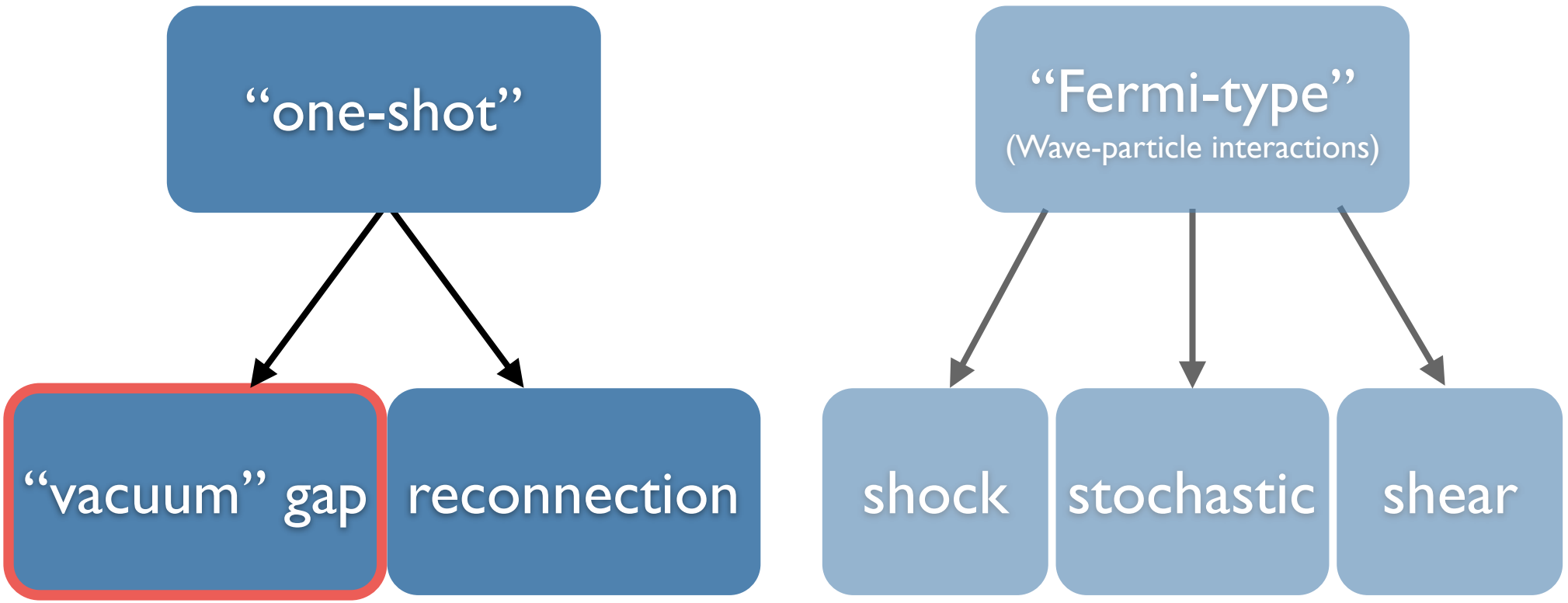
Acciari+ 2009 (Science)



Benkhali, Chakraborty & FR 2019

Orientation: How to produce relativistic particles ?

Acceleration processes & sites in AGN (not exhaustive)



The Occurrence of Gaps around rotating Black Holes

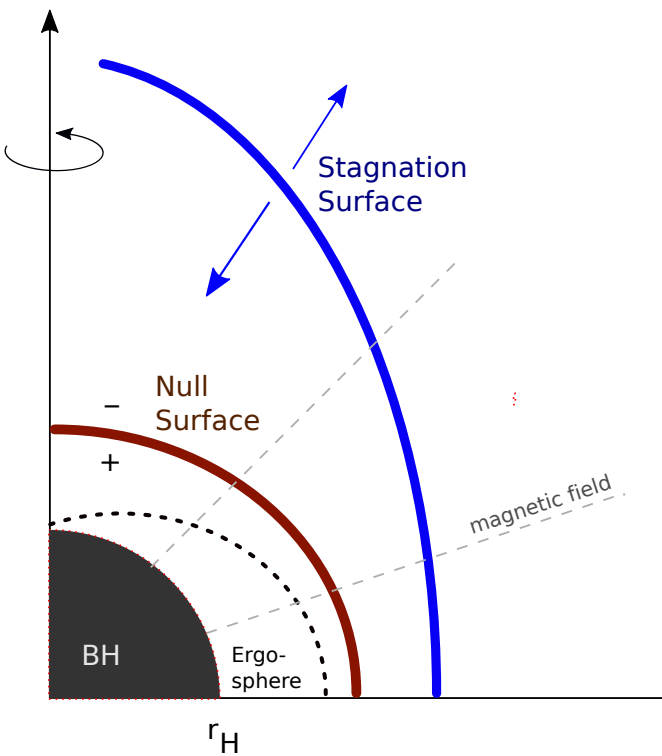
"Parallel electric field occurrence in under-dense charge regions"

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

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

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

  Inward flow of plasma below due to gravitational field, outward motion above $\Rightarrow$ *need to replenish charges*



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

Beskin et al. 1992; Hirotani & Okamoto 1998…

The Conceptual Relevance of Gaps

- ***BH-driven jets (Blandford-Znajek)***

  Self-consistency: Continuous plasma injection needed to activate BZ outflows (force-free MHD)

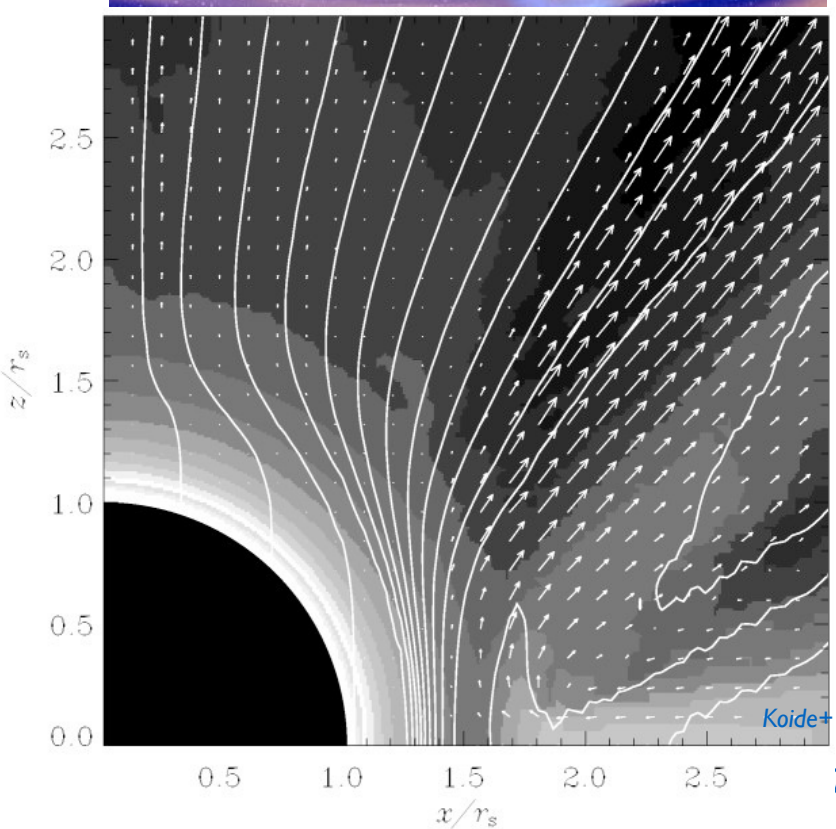
- ***Non-thermal Particle Acceleration***

  Implication: efficient (direct) acceleration of electrons & positrons

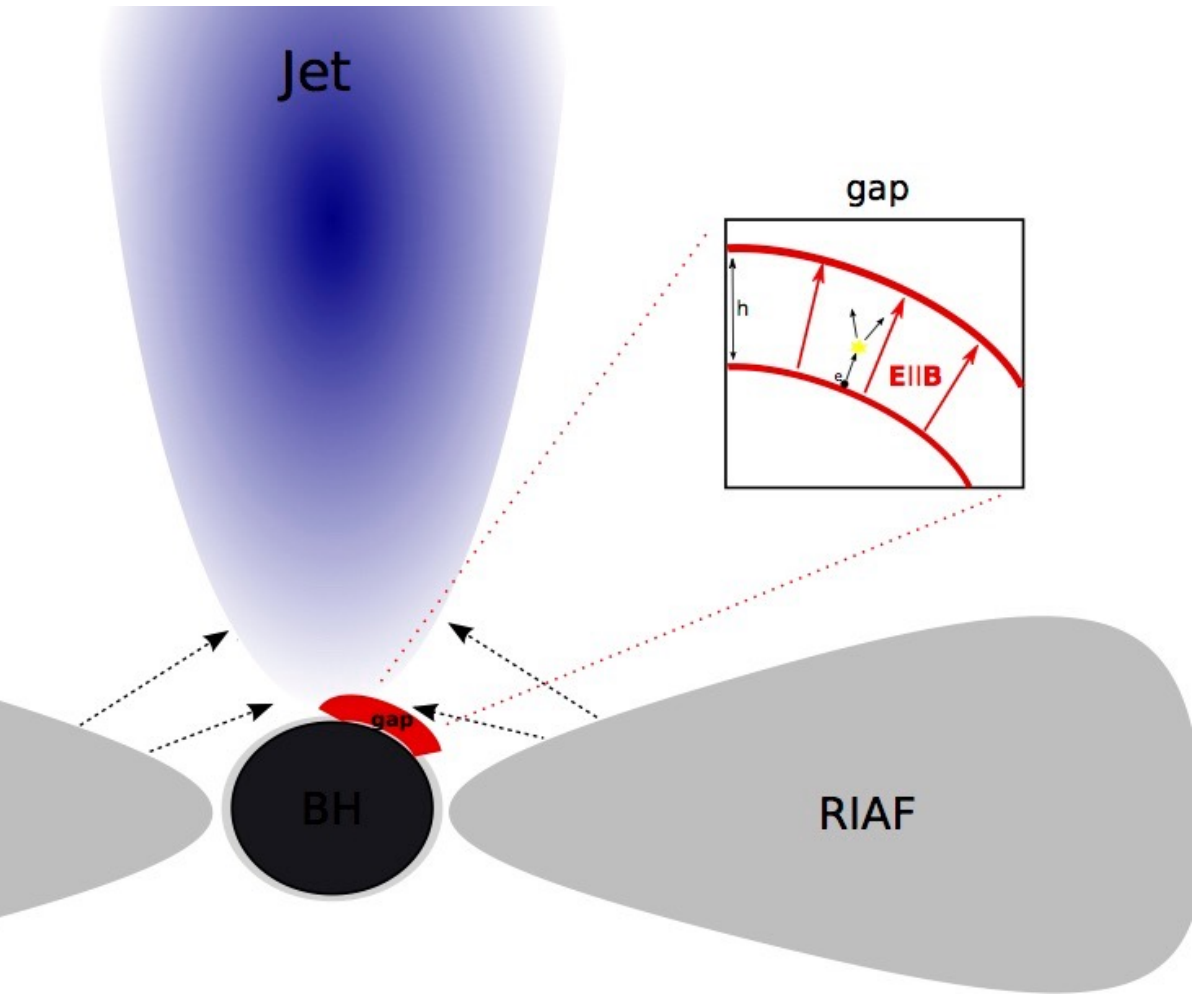
- ***Radiation & Pair Cascade…..***

  Features: expect γ-ray production, γγ-absorption triggers pair cascade generating charge multiplicity (e^+e^-) ensuring electric field screening (closure)

  (e.g., Levinson & Rieger 2011)



Gamma-Ray Emission from AGN Magnetospheres



Gamma-Ray Production:

- *HE γ-rays via curvature:*

  $\nu \sim (0.2c)\,(\gamma^3/R_c)$

- *VHE γ-rays via IC:*

  $h\nu \lesssim \gamma\, m_e\, c^2$

- *Need under-luminous (RIAF) environment to avoid absorption!*

➡ ***detectable in misaligned AGN with weakly Doppler-boosted jet emission*** *(radio galaxies)*

e.g., Levinson 2000; Neronov & Aharonian 2007; Rieger & Aharonian 2009; Acciari+ 2009; Levinson & Rieger 2011; Rieger 2011; Aleksic+ 2014; Broderick & Tchekhovskoy 2015; Vincent 2015; Ptitsyna & Neronov 2015; Hirotani & Pu 2016; Hirotani+ 2016; Hirotani+ 2017; Rieger 2017; Levinson & Segev 2017; Punsly+ 2018; Katsoulakos & Rieger 2018; Chen+ 2018; Levinson & Cerutti 2018…

What to expect for "steady" 1D gaps ?

Solving Gauss' laws depending on different boundaries

$$\frac{dE_{||}}{ds} = 4\pi\,(\rho - \rho_{GJ})$$

e.g. highly under-dense, $\rho_e << \rho_{GJ}$

- *Boundaries:*

  $E_{||}(s=0) \neq 0$, $E_{||}(s=h)=0$

- *Gap potential:*
  - $\Delta\phi_{gap} \sim a\, r_g\, B\, (h/r_g)^2$
- *Gap - Jet power:*
  - $L_{VHE} \sim L_{BZ}\, (h/r_g)^2$ …

e.g., Blandford & Znajek 1977; Levinson 2000; Levinson & Rieger 2011

Taking variability as proxy for gap size

⇨ Jet power constraints becomes relevant for rapidly varying sources

weakly under-dense: $\rho_e \sim \rho_{GJ}$

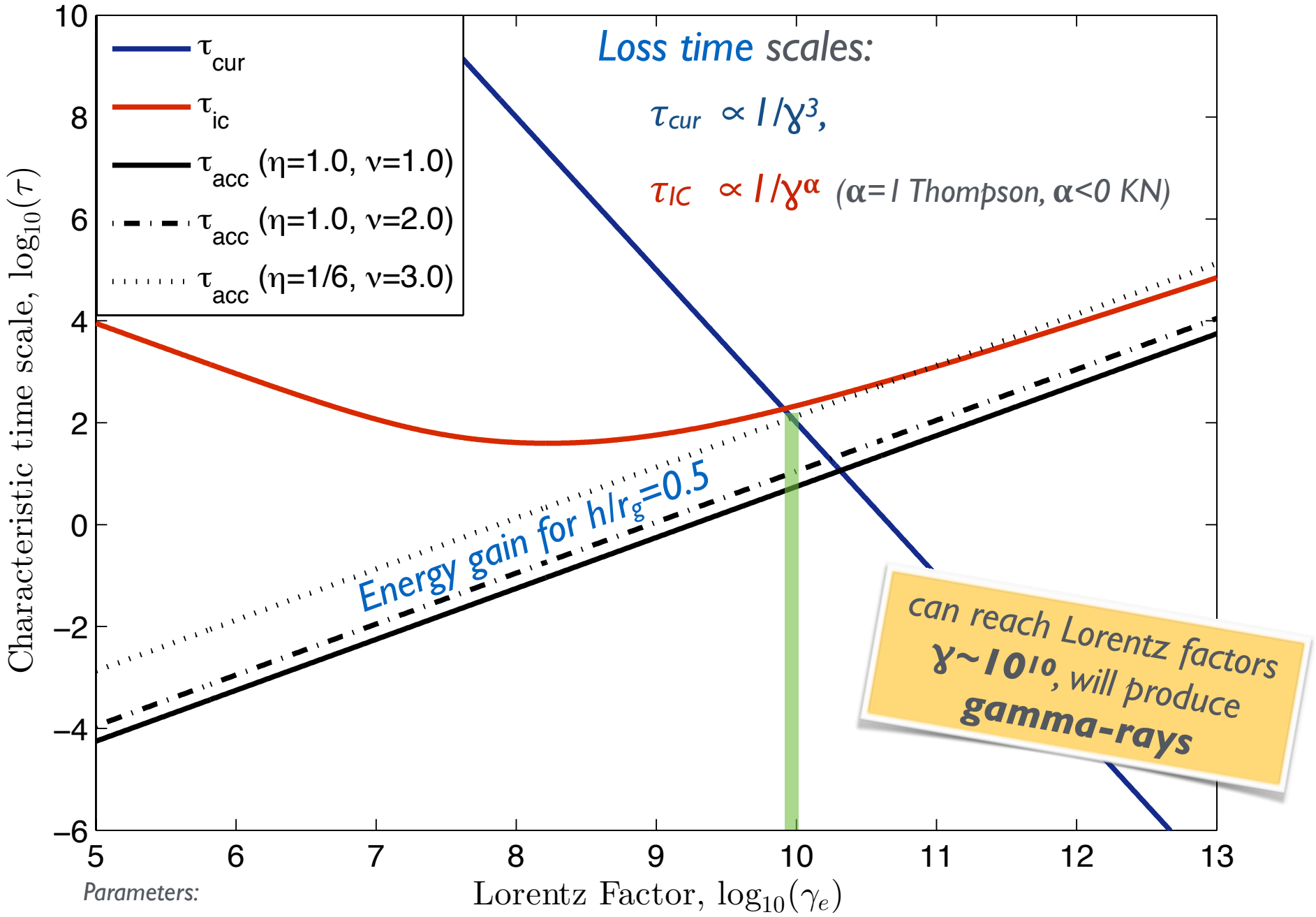
- *Boundaries:*

  $E_{||}(s=0) = 0$, $E_{||}(s=h)=0$

- *Gap potential:*
  - $\Delta\phi_{gap} \sim a\, r_g\, B\, (h/r_g)^3$
- *Gap - Jet power:*
  - $L_{VHE} \sim L_{BZ}\, (h/r_g)^4$ …

e.g., Hirotani & Pu 2016; Katsoulakos & Rieger 2018

Example: Acceleration versus Losses - Timescales



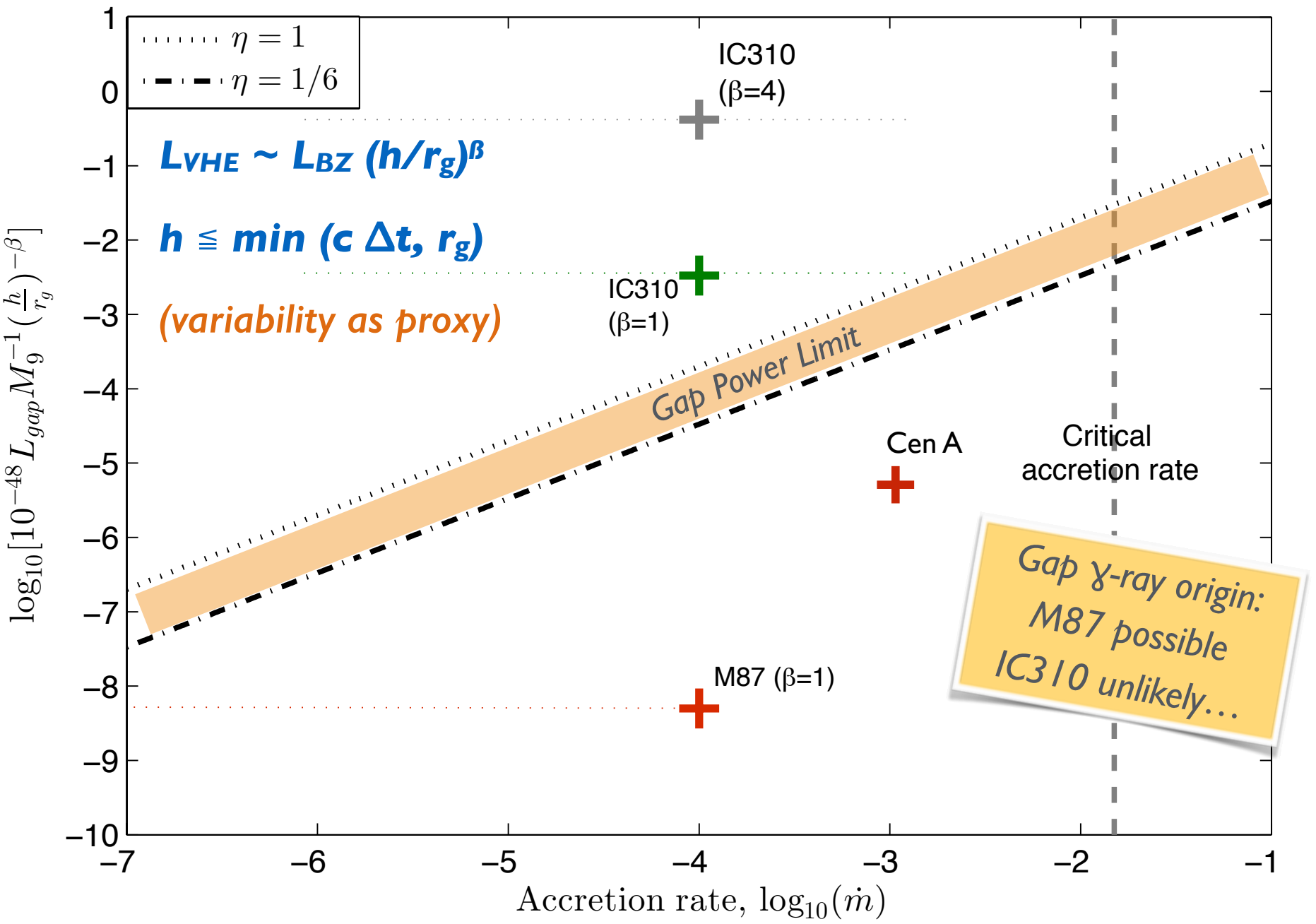
Parameters:

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

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

Katsoulakos & FR 2018

Maximum Power Constraints for steady Gaps



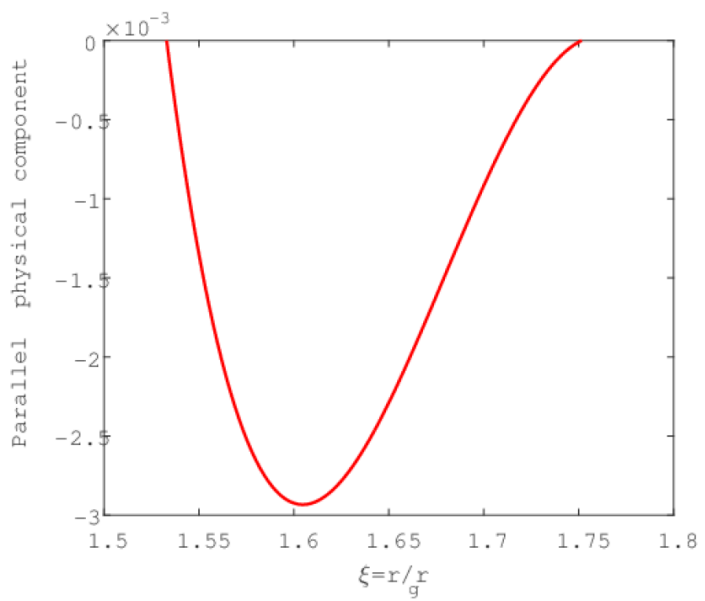
Katsoulakos & FR 2018

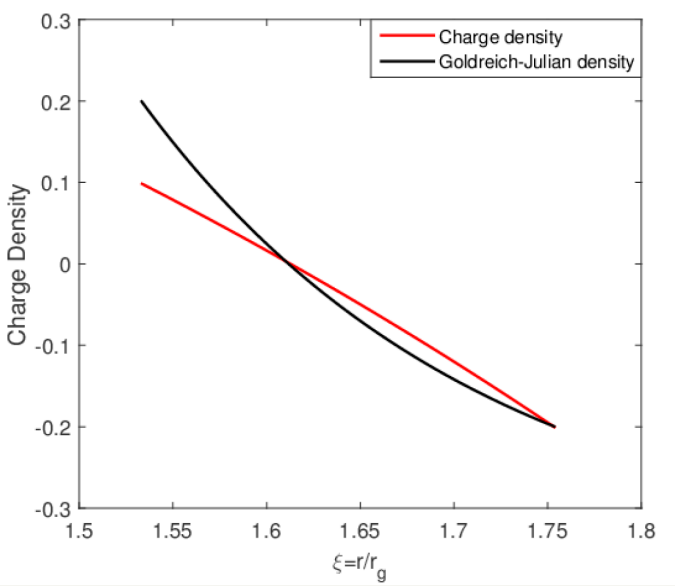
What sizes etc to expect ? - Self-consistent steady (1D) gap solutions

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

Solve system of relevant PDEs in 1D assuming some soft photon description:

- Gauss' law ($E_{||}$)
- e^+, e^- equation of motion (*radiation reaction*)
- e^+, e^- continuity equation (*pair production*)
- Boltzmann equation for photons (*IC, curvature, pair production*)





 # Boundary Conditions:
Zero electric field at boundaries
$\varrho \leq \varrho_{GJ}$ in boundaries
 # ADAF soft photon field

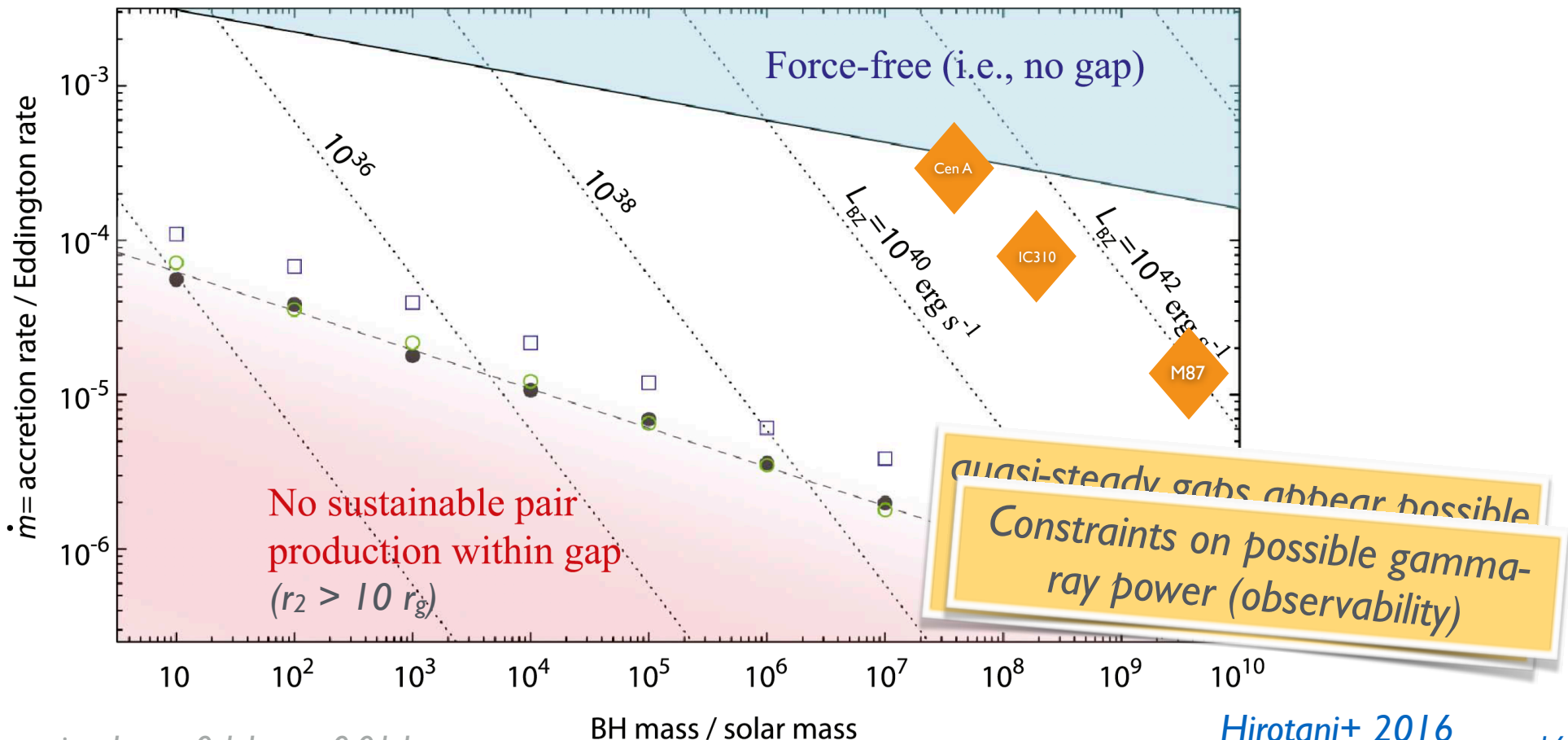
Conditions for "steady" gap formation

(1) seed injection (pair production in hot ADAF) must be low enough:

$n_{\pm} / n_{GJ} \propto \dot{m}^{7/2} M_{BH}^{1/2} < 1$ ⇒ *otherwise force-free*

(2) if $\dot{m}$ (soft photon field) becomes too low, pair creation within gap no longer efficient

⇒ *no closure*



Hirotani+ 2016

Assumption: $L_{BZ} \sim 0.1\ L_{Edd} \sim 0.01\ L_{acc}$

Can "steady" gaps (1D) be realized I ?

- *Time-dependent 1D PIC simulations of gaps in BH magnetospheres (Chen+ 2018)*
  - ➡ solutions are highly time-dependent, quasi-periodic opening (timescale ~ r_g/c); gap can develop "everywhere" & extend several 10% of r_g; no steady gap seen…

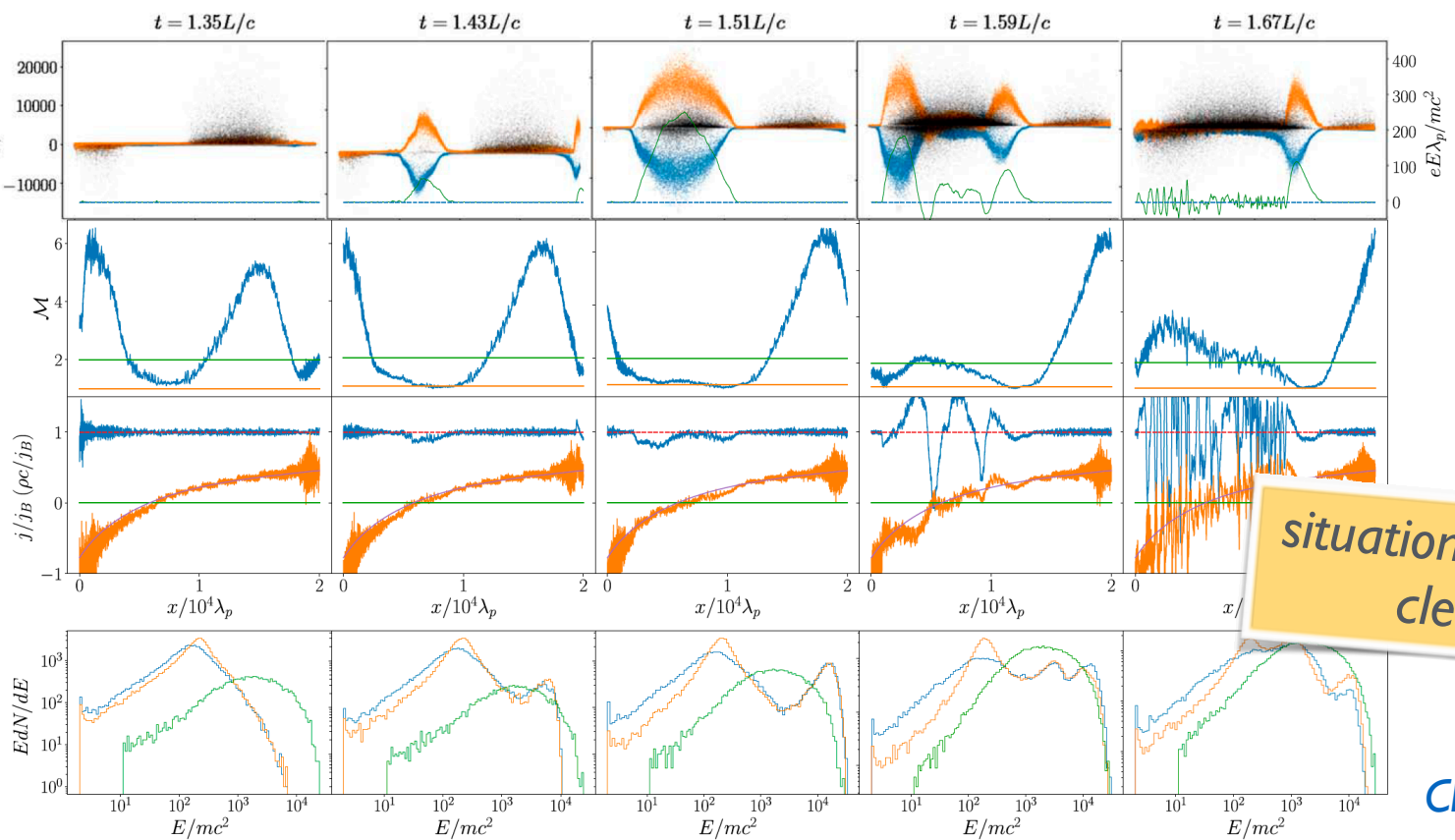
- Concerns - *conceptually & astrophysical:*
  - *mirror setup: toroidal field reversal, current sheet?; scale-separation: re-scaling; no curvature; 'unusually' high ε_{min} for soft photons; quickly in KN & $l_{\gamma\gamma} \sim r_g$ ….*

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

Multiplicity

Current & charge density

Spectrum of e-, e+, photons



gap cycle assuming soft photons with ε_{min} ~0.5 eV

($r_g \sim 10^4\ \lambda_p$, $l_{IC} \sim 10\ \lambda_p$)

situation not yet clear

Chen+ 2018

Can "steady" gaps (1D) be realized II ?

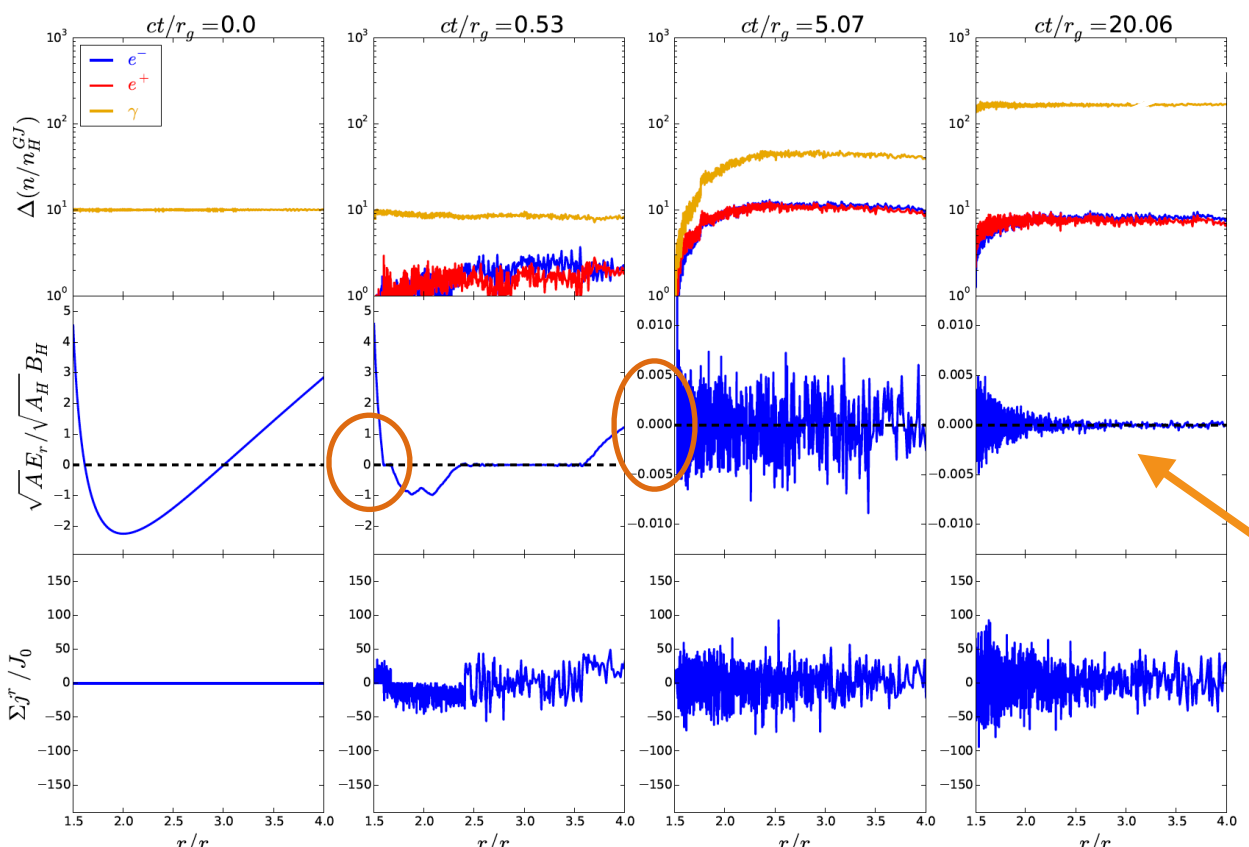
- *Time-dependent 1D GR-PIC simulations of BH gaps in (Levinson & Cerutti 2018)*
  - *with IC & γγ in a Monte Carlo treatment, and including curvature feedback; current as input*

➡ *solutions highly time-dependent, but* ***approach to quasi-steady state at much reduced $E_{||}$-field seen*** *(self-sustained pair cascade leading to quasi-stationary pair and gamma-ray spectra)*

charge (e+, e-) and photon densities

Electric field $E_{||}$

Current density



Example:

assuming τ_0=10

with $\tau_0 = \sigma_T\, n_{ph}\, r_g$,

γγ-opacity across gap

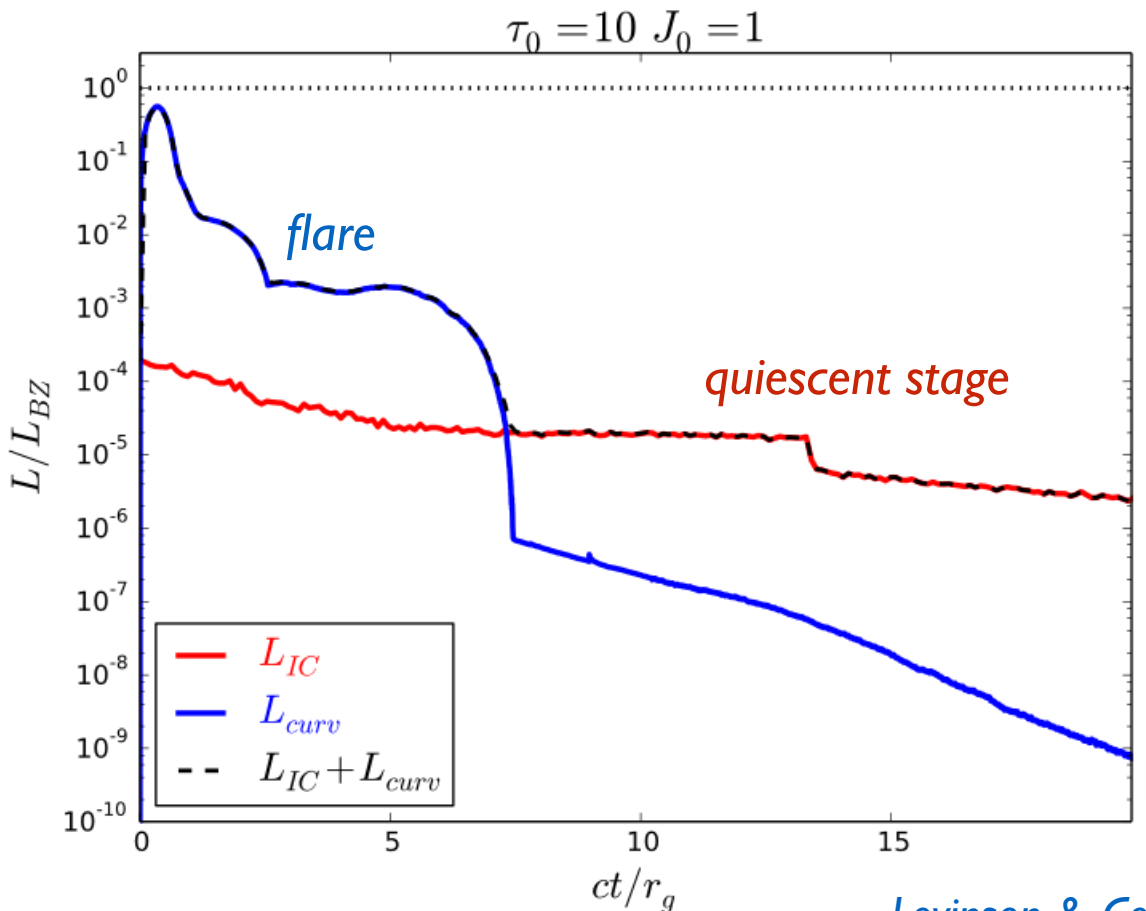
onset of quasi-steady oscillations

Levinson & Cerutti+ 2018

Can "steady" gaps (1D) be realized III ?

Light curve:

- *initial discharge on ~r_g/c - timescales (**"flare"**), curvature-dominated, with $L_{gap} \sim L_{BZ}$*
- *followed by quasi-steady low-level ($L_{gap} \sim 10^{-5}\ L_{BZ}$; with $\langle \gamma_e \rangle \sim 10^7$) gamma-ray emission ("quiescent state")*



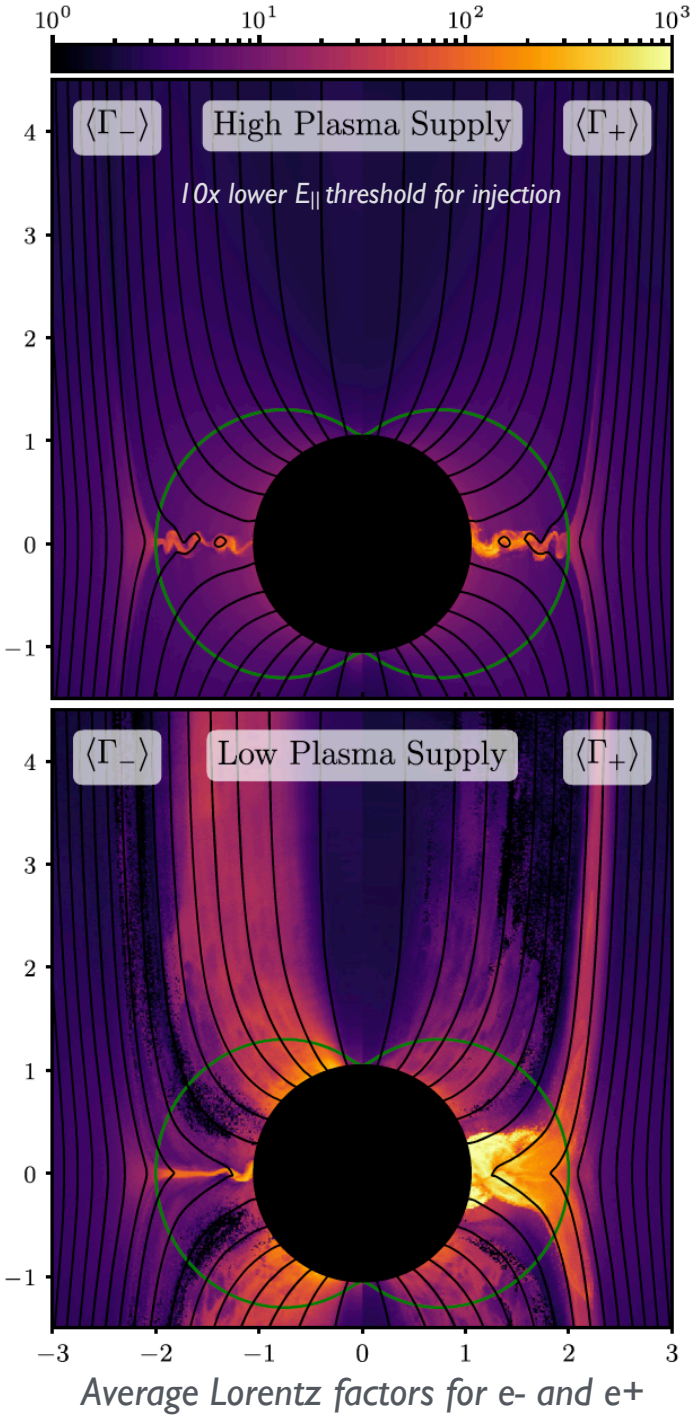
tempting to relate this to M87 light curve

Possible Caveat:
transverse modes (2D); dependence of resultant values on soft photon (PL) description (?)

Soft photons: E_{min}=0.005 eV, PL index -2

Levinson & Cerutti+ 2018

Towards 2D "gap" simulations



Global 2D GR-PIC simulations of BH jet launching (Parfrey+ 2019)

Depending on magnitude of plasma supply (low vs high) different steady states are found.

Still to overcome:

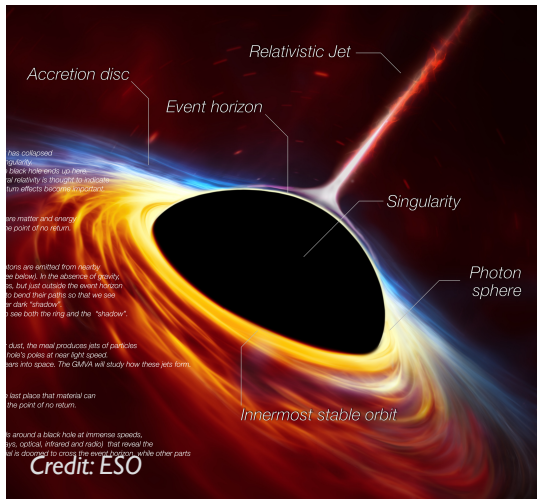
- re-scaling of system…
- artificial treatment of pair creation…

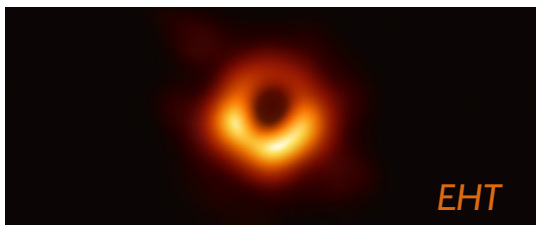
  (e+e- pair injected in each cell, at each time step within volume $r_H<r<6\ r_g$ depending on $E_{||}$ threshold)
- no accretion disk/flow…
- no radiation processes…

Parfrey+ 2019

Conclusions & Perspectives

- ***Occurrence of magnetospheric gaps 'naturally' expected for under-luminous AGN sources***
  - *null surface & stagnation surface…*
  - *ensuing pair cascade facilitates plasma supply…*
- ***Explore gap physics under "realistic" conditions***
  - *steady vs non-steady gaps ? conditions ? power ?*
  - *e.g. include appropriate soft photon field etc*
  - *time-dependent changes (boundary conditions)…*
- ***Probing gap physics with γ-ray observations***
  - *origin of VHE emission in nearby misaligned AGN*
  - *M87 most promising candidate*
- ***New observational input to be expected***
  - *@ radio with **EHT**, @ VHE with **CTA**…*





Thank you!