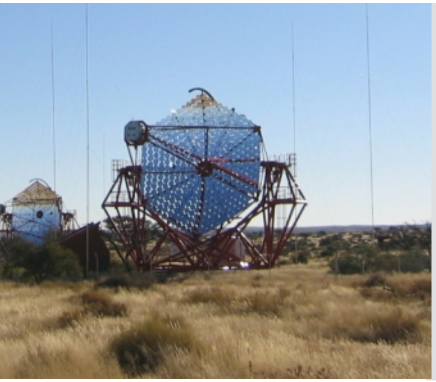
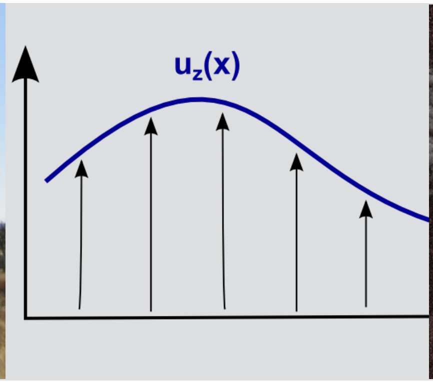
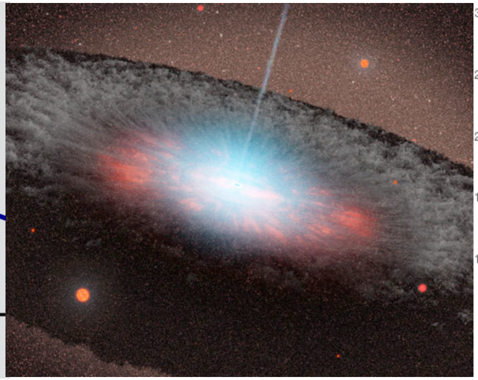
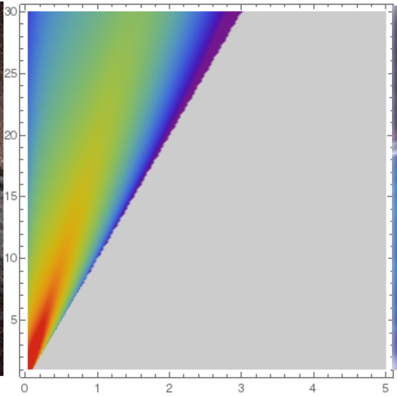
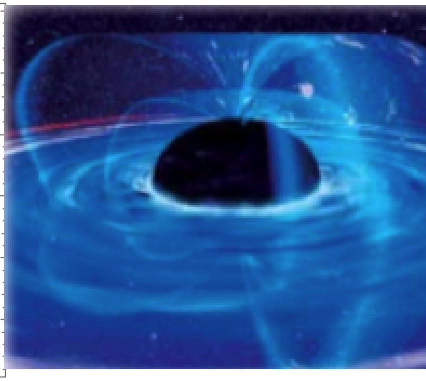
Supermassive Black Holes as Cosmic Particle Accelerators

Frank M. Rieger

IAP Paris

December 6, 2022

ITP Univ. Heidelberg

Max Planck Institut für Kernphysik
Heidelberg, Germany

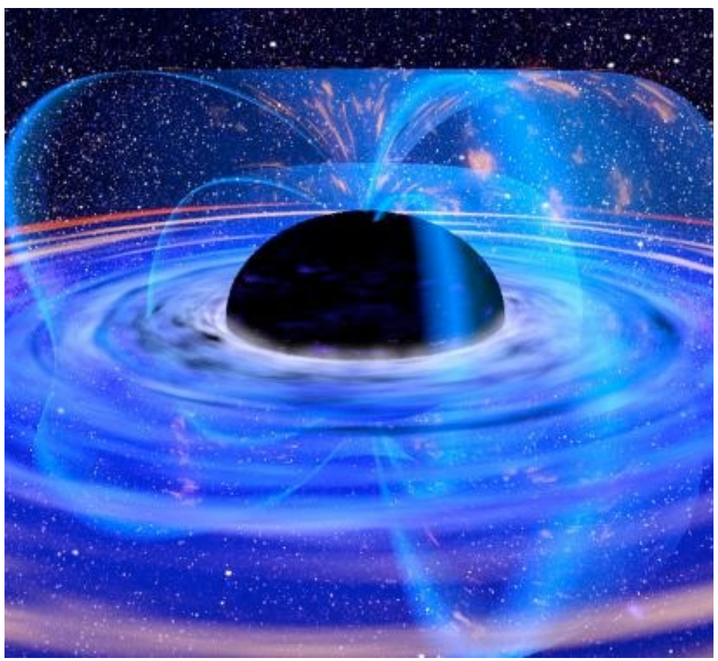
Outline

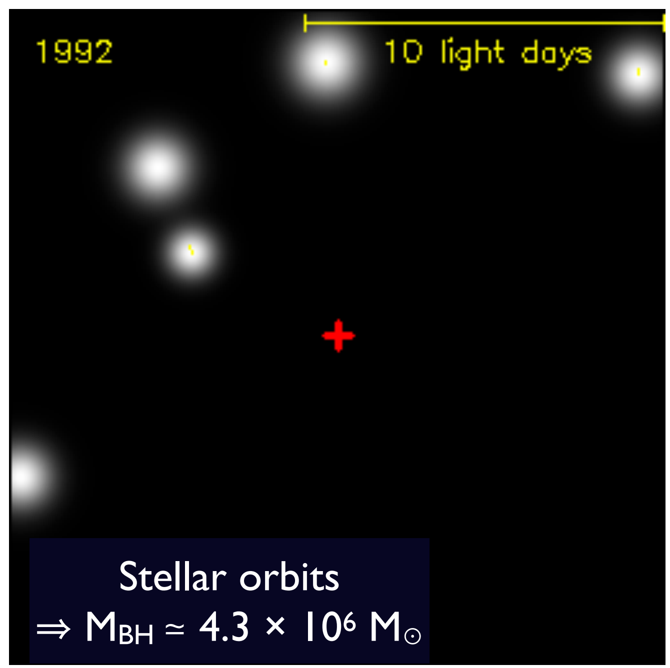
- **Supermassive Black Holes (SMBHs) in the Universe**
  - Astrophysical Context & Background
  - High Energy Diagnostics of AGN
- **Cosmic Particle Acceleration**
  - Gap-Type Particle Acceleration in the Magnetosphere of SMBHs
  - Shear Acceleration in the Relativistic Jets of AGNs

Context - I

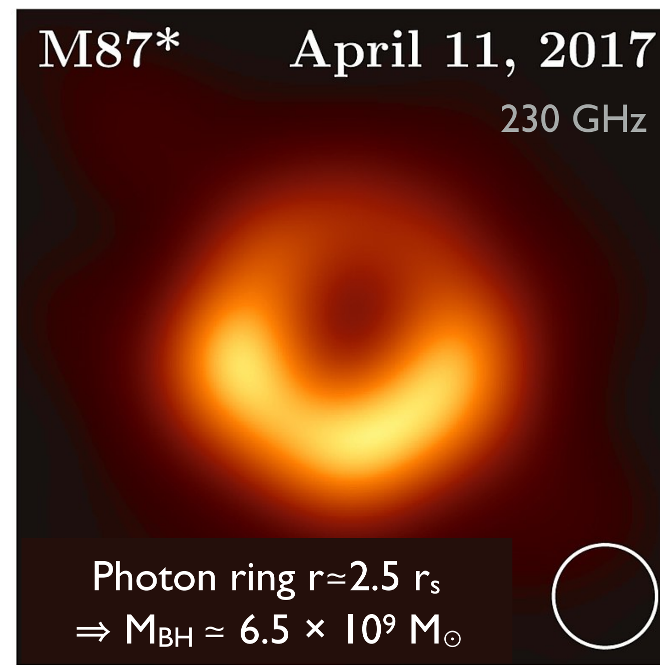
Supermassive Black Holes (SMBHs)

- *masses ~(10^6-10^{10}) $M_\odot$*
- *not isolated (accretion disk etc)*
- *residing in the center of galaxies*
- *best example: Sgr A*, M87*





Galactic Center Black Hole: Sgr A [MPE]*



Photon Ring in M87 [EHTC 2019]

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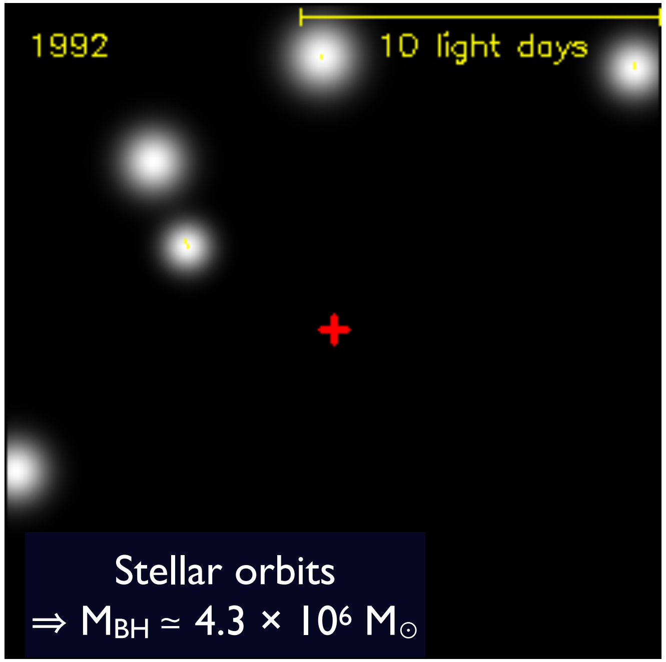

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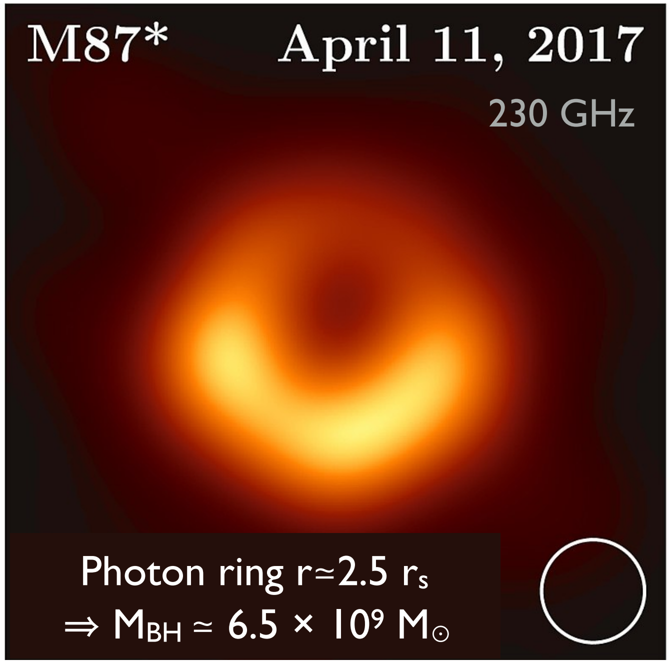


Photon Ring in M87 [EHTC 2019]

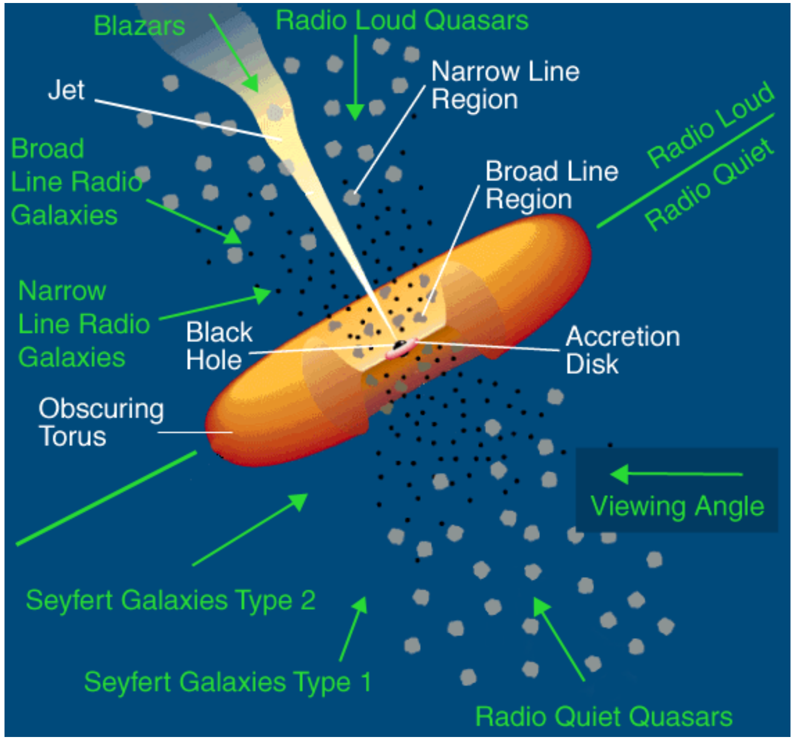
Radio-loud ***Active Galaxy***

"jetted AGN"

- SMBH + accretion disk + jet…
- *radiation across the whole elm spectrum*
- blazars → radio galaxies:
  - reduced beaming / Doppler boosting:

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

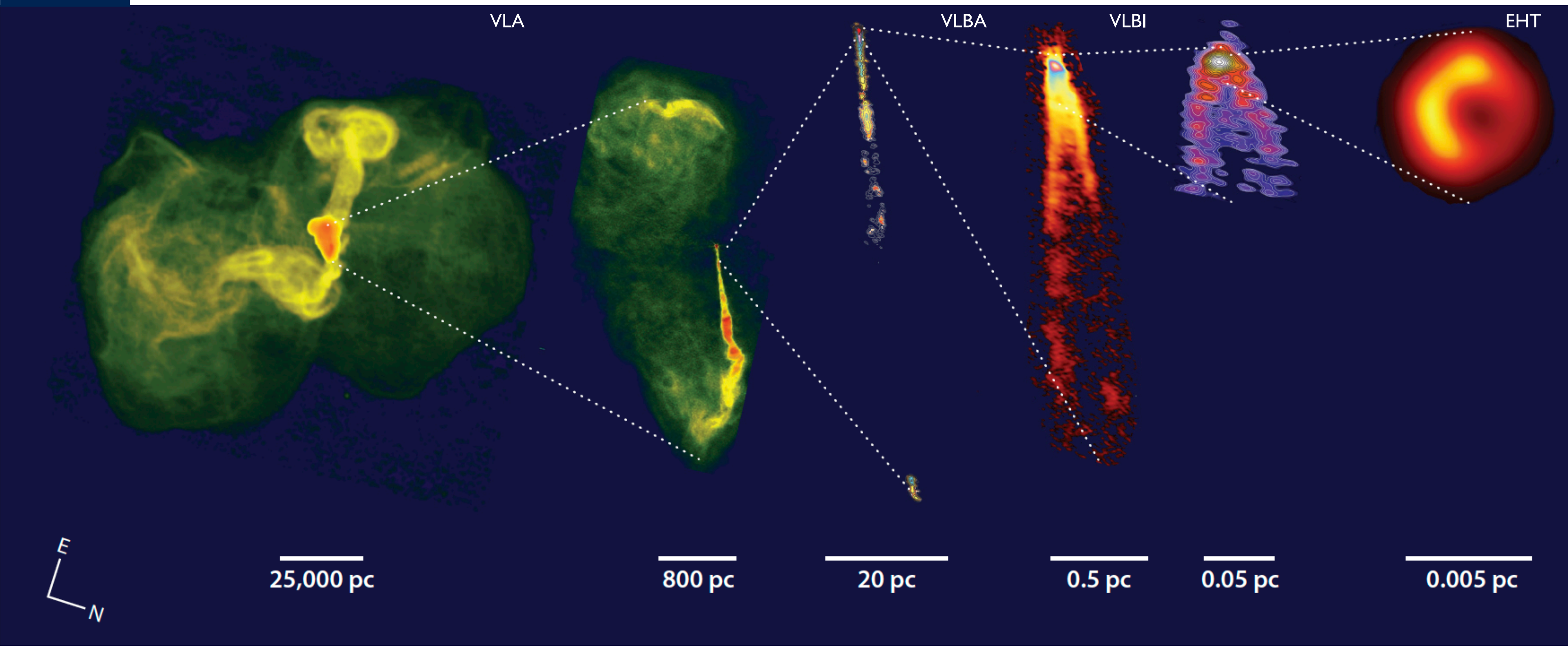
X-rays (Chandra/blue), radio (orange) & optical…[Credit: ESO/NASA]



Central engine in AGN & unification (Urry & Padovani)

AGN Physics - a Multi-scale Problem

M87

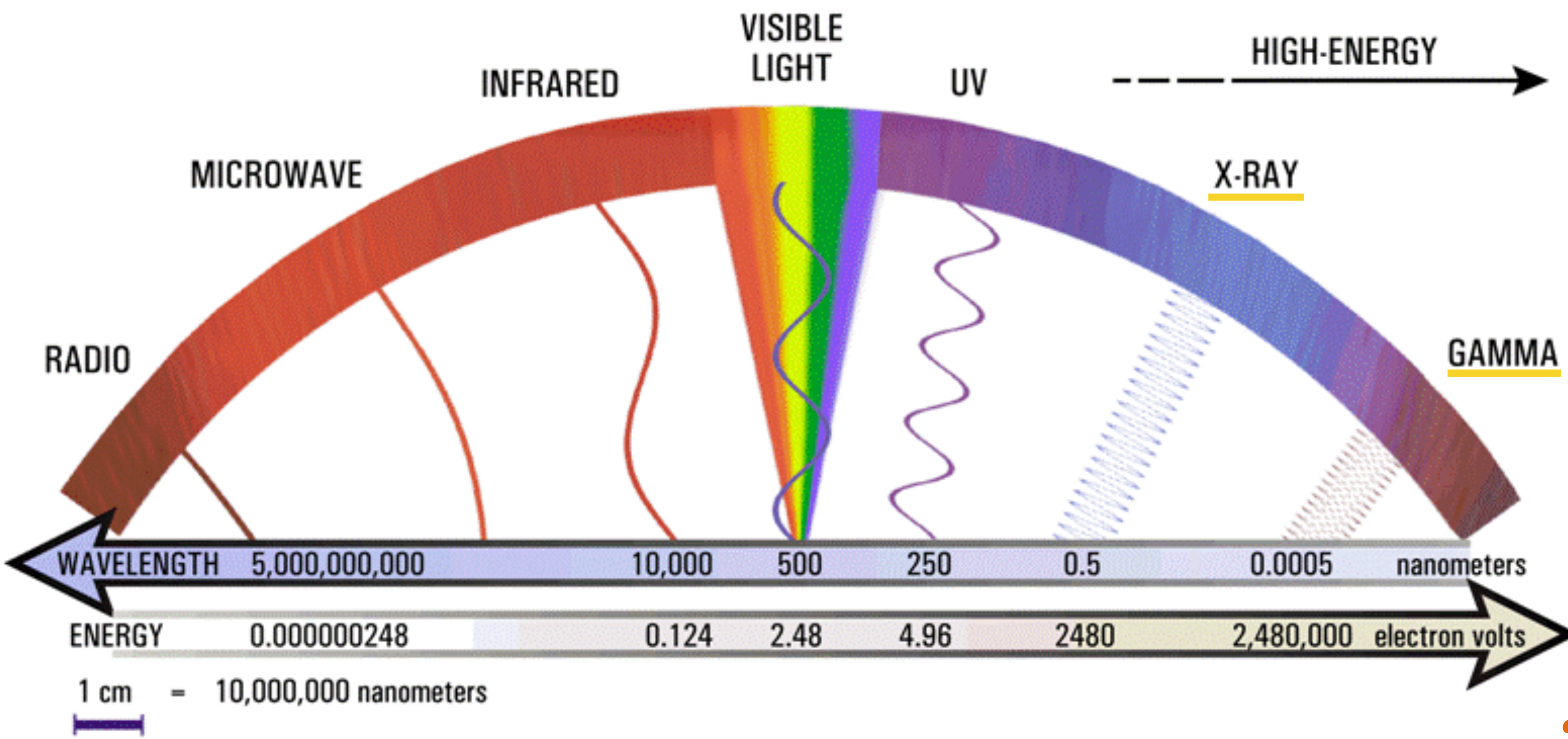


[1 pc = 3.26 ly = 3.09×10^{18} cm]

Blandford+2019

Observed scale separation ~ 10^8 - 10^{10} *(Cen A)*

Focusing on high-energy part of electromagnetic spectrum



HIGH & VERY HIGH ENERGY *GAMMA-RAYS*

- 10^{12} eV= 1 TeV

Electromagnetic Spectrum - Photon Energies

"Non-thermal Universe"

1 eV = 2.4×10^{14} h Hz
1 GeV = 2.4×10^{23} h Hz
1 TeV = 2.4×10^{26} h Hz

*High energy (**HE**) ɣ-rays > 100 MeV*

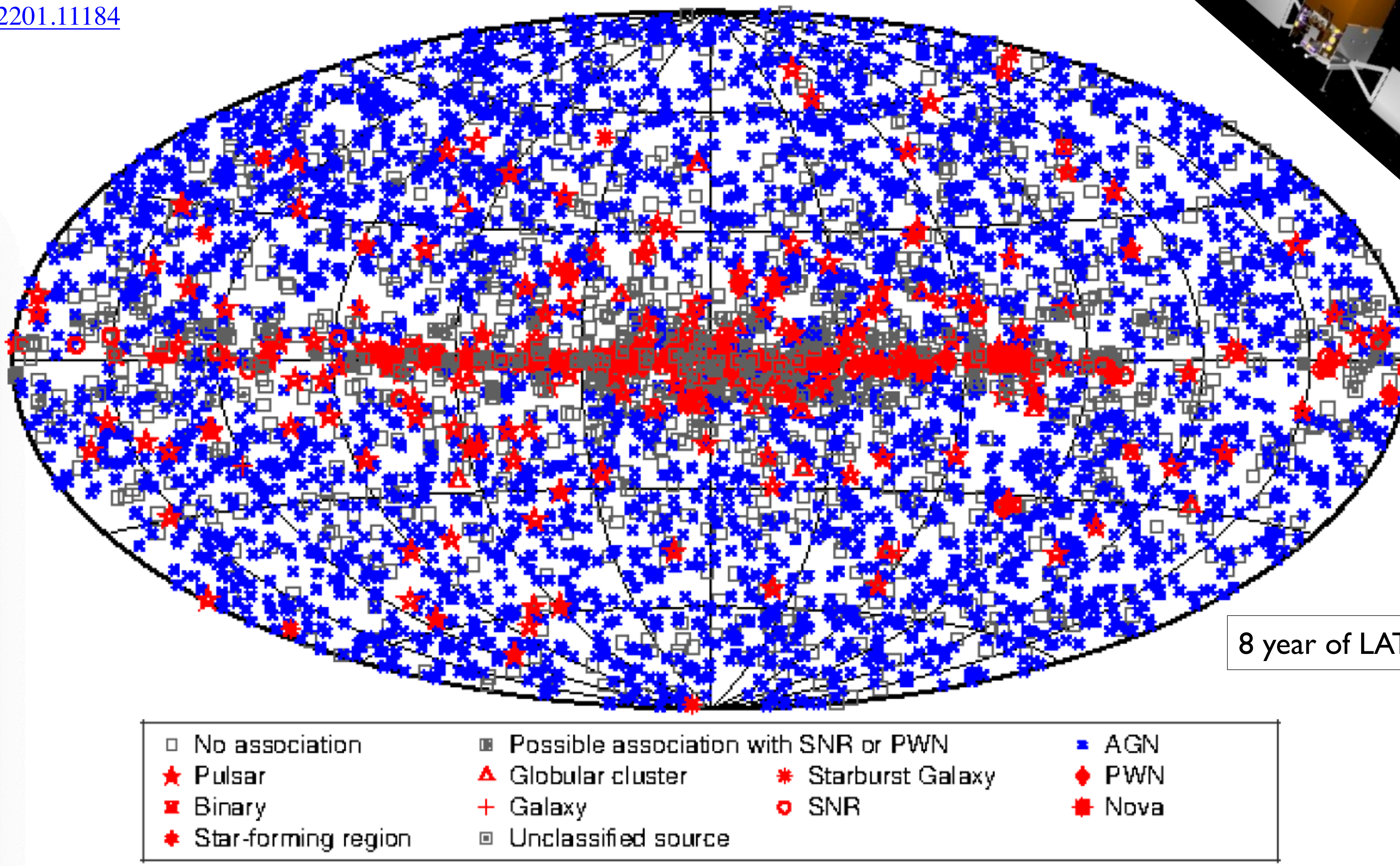
*Very High Energy (**VHE**) ɣ-rays > 100 GeV*

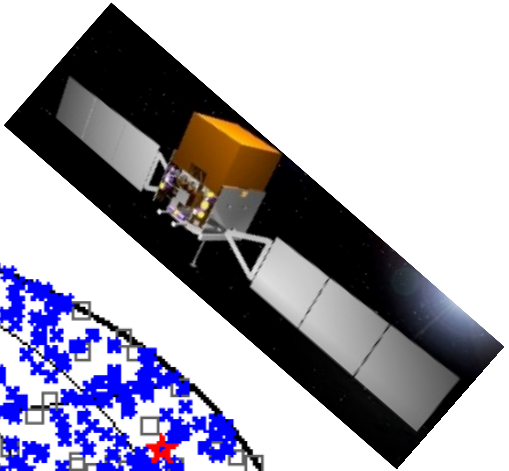
The Extragalactic HE Sky (Example)

Fermi-LAT Collab. 2020 & 22

arXiv:1902.10045
arXiv:2201.11184

4th Fermi LAT catalog (4FGL) > 50 MeV





8 year of LAT data

4FGL-DR3 (12 yr of data): 6658 sources out of which

> 3740 'identified' as AGN / blazars, 257 as pulsars, 43 SNR…

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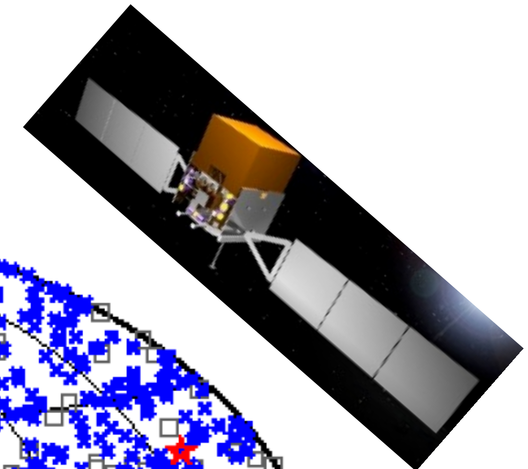

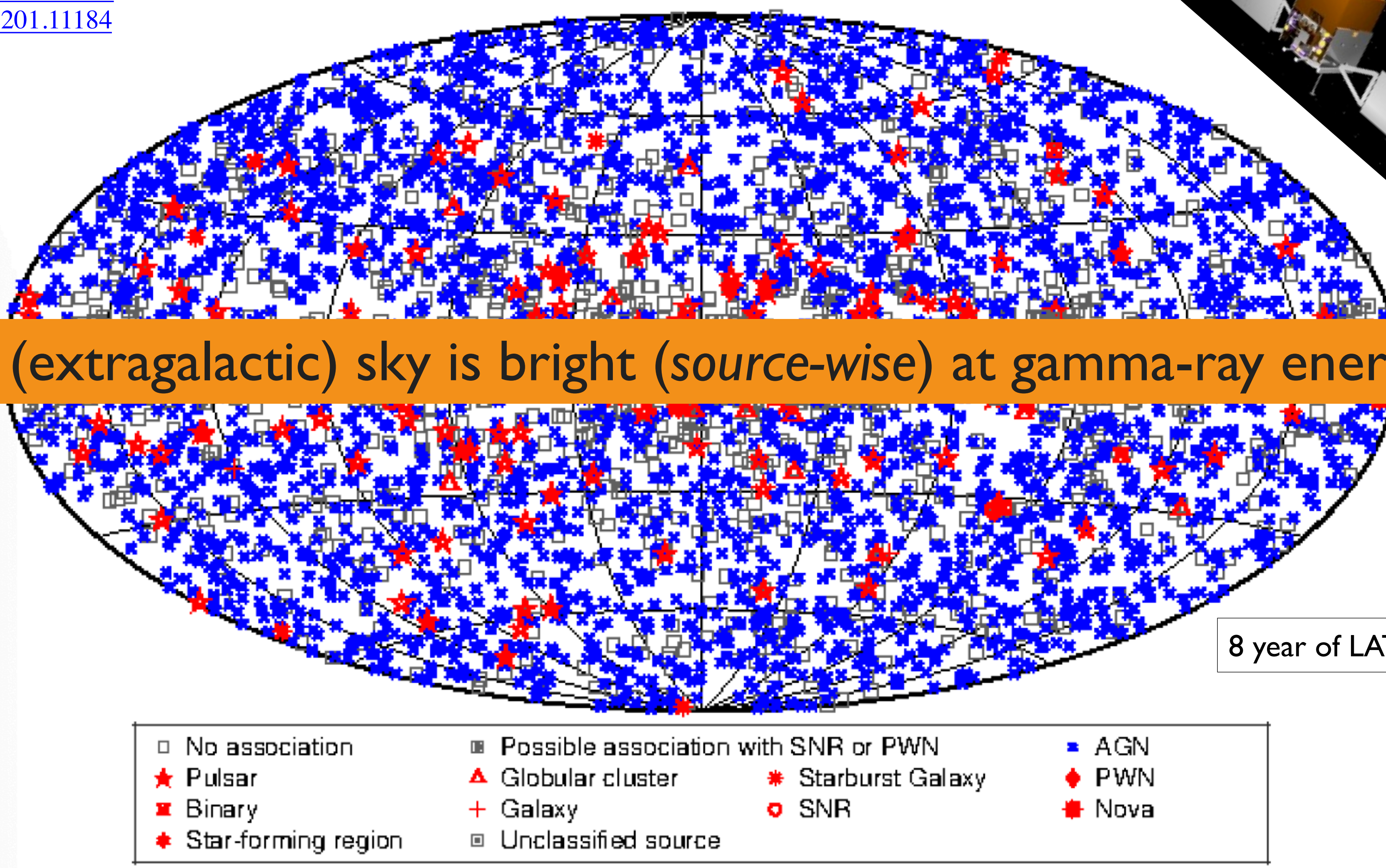

The (extragalactic) sky is bright (*source-wise*) at gamma-ray energies

8 year of LAT data

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The Extragalactic VHE Sky (>100 GeV ~ 10^{25} Hz)

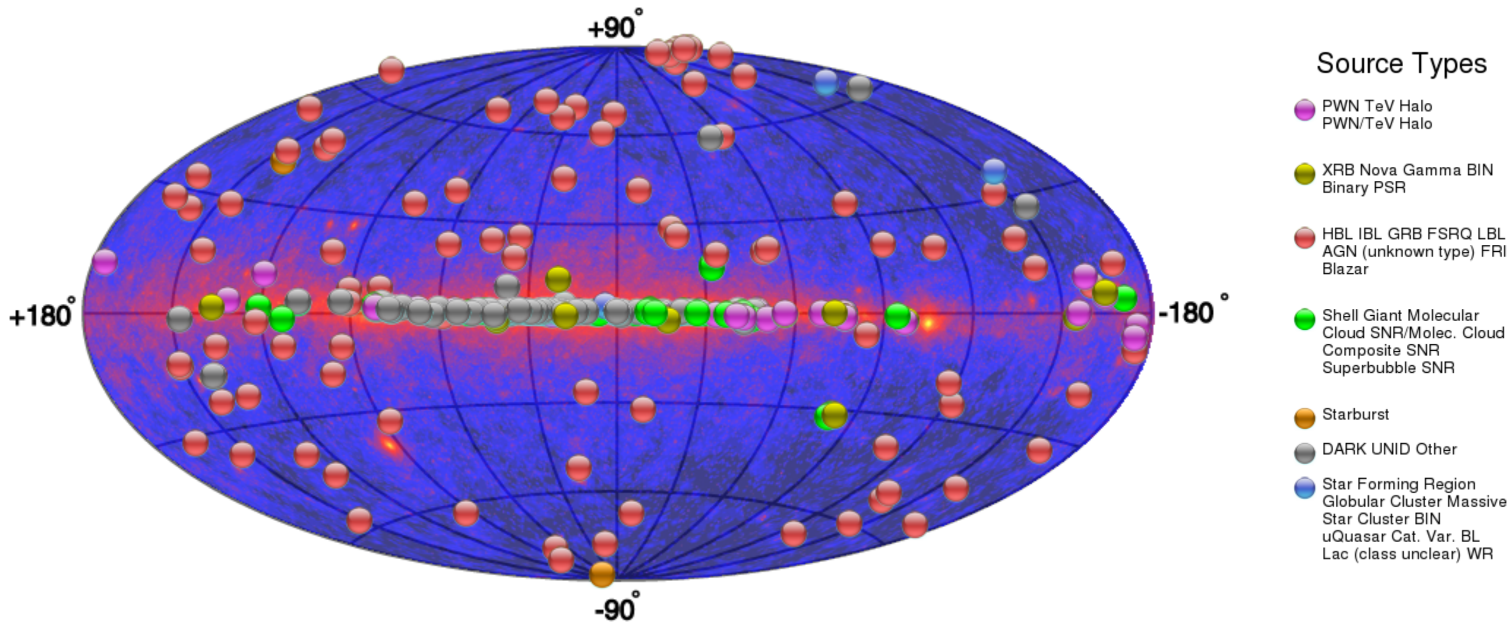
TevCat (2022):

>250 sources

~ 85 AGN

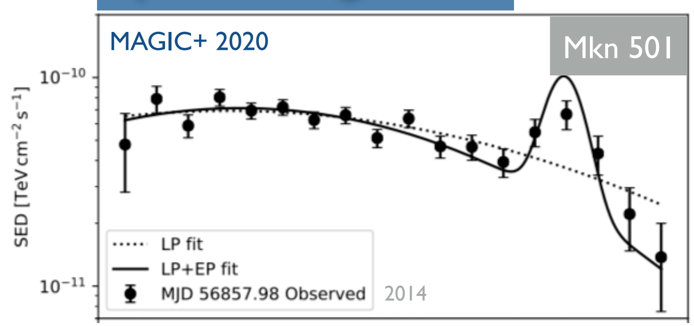
mostly BL Lacs

55 HBL
10 IBL
2 LBL
9 FSRQ
4 (6) RG
2 StarburstG.

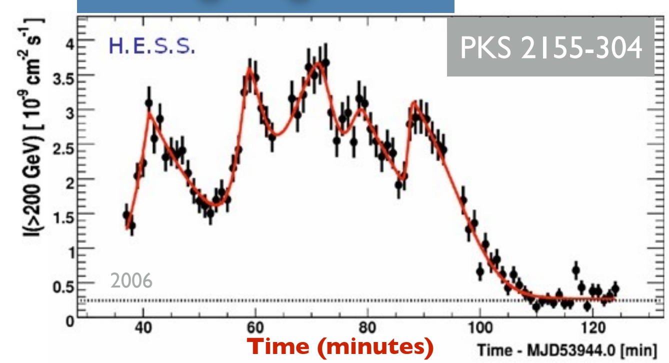


From "simple" source detection to the physics of sources

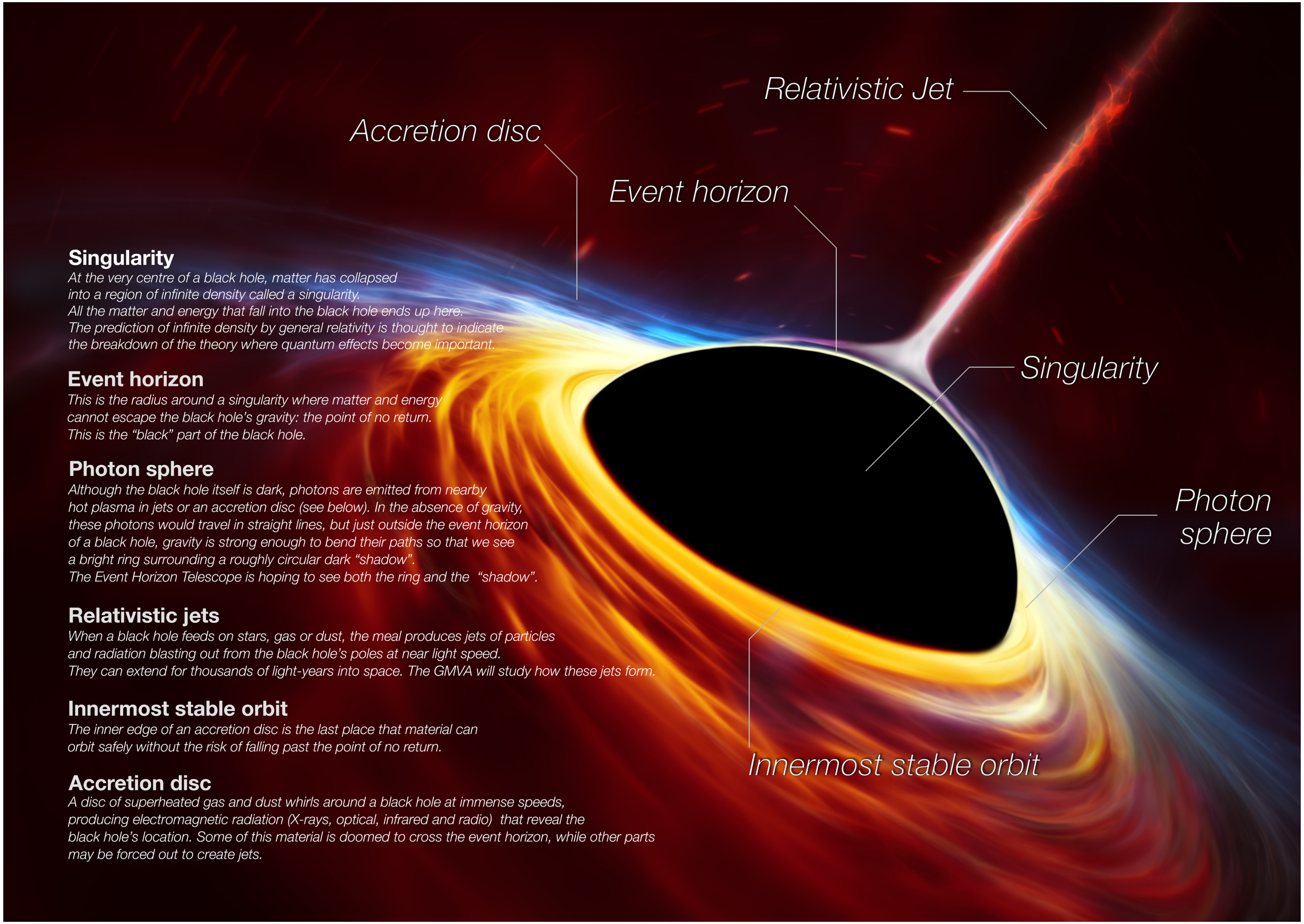
Spectral diagnostics



Timing diagnostics



Some Key Questions in AGN Physics



Credit: ESO

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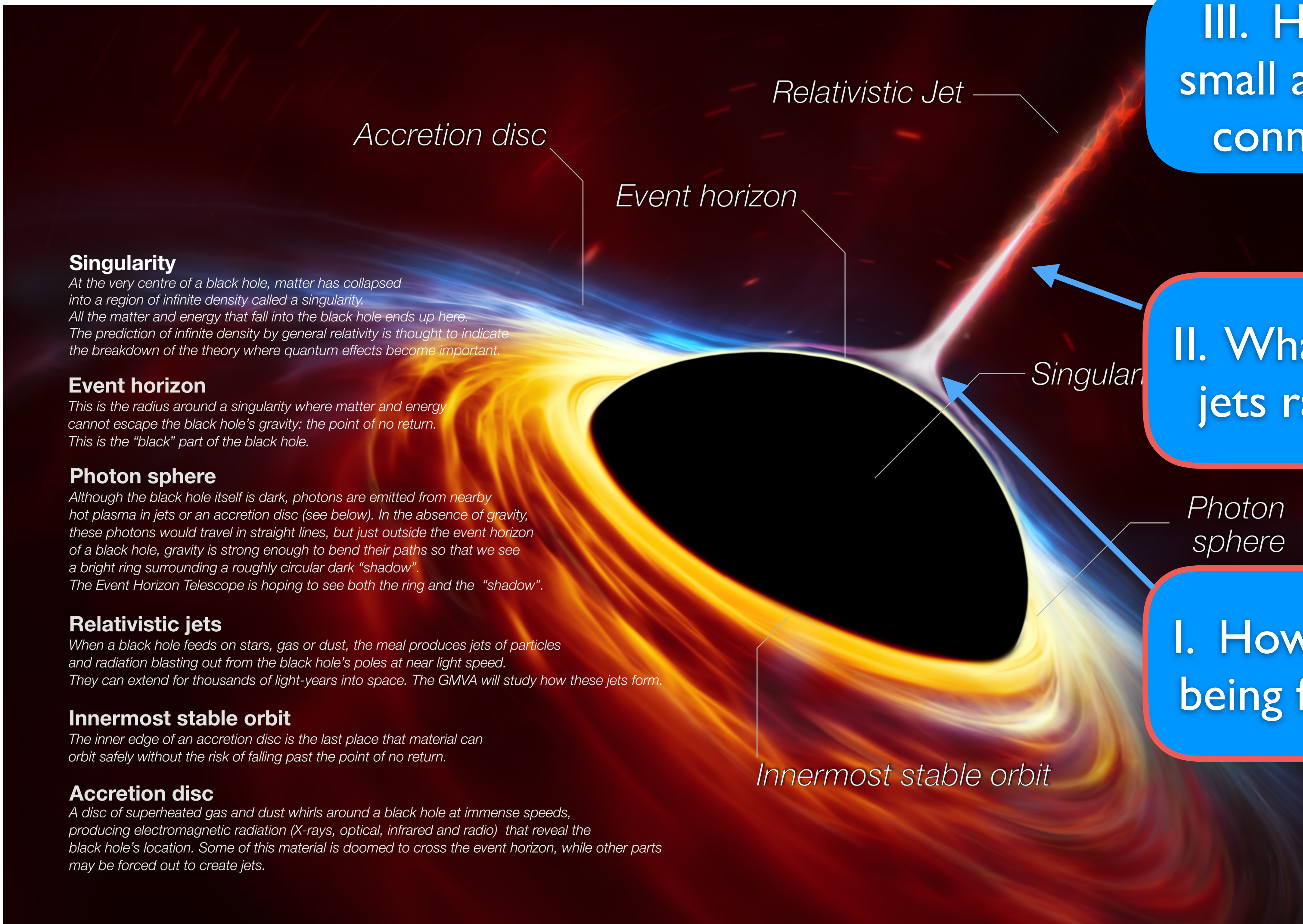


III. How are small and large connected?

II. What makes jets radiate ?

I. How are jets being formed ?

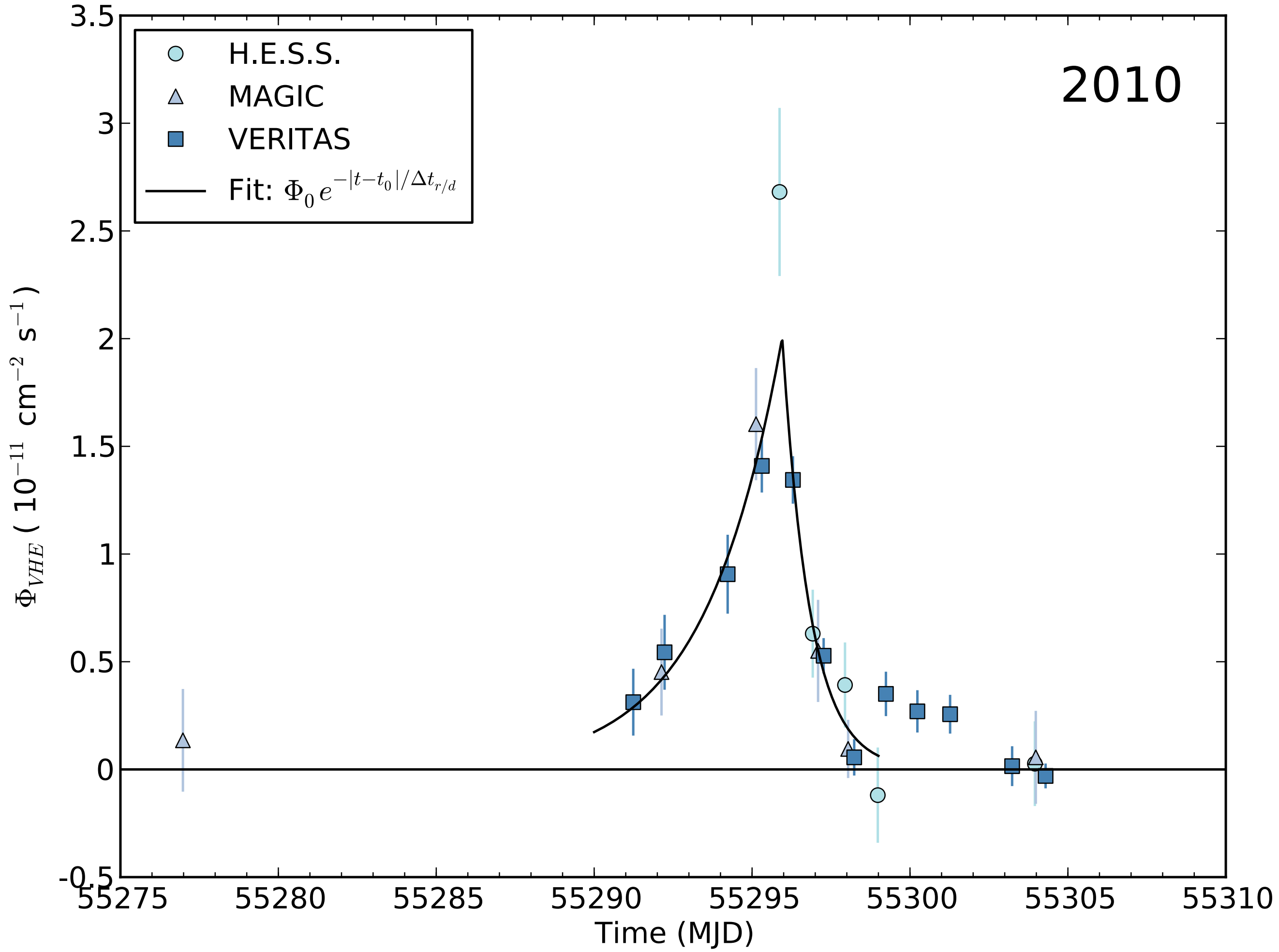
Credit: ESO

Particle Acceleration and Gamma-Ray Emission in the Magnetospheres of Supermassive Black Holes

Motivated by observation of rapid TeV variability in radio galaxies….

variability timescales of order 'light travel time across BH horizon'

Example: **M87** during VHE flare in April 2010: best-defined rise and decline



Abramowski+ 2012

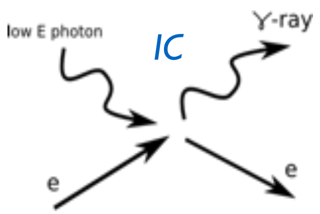
Fastest variability ever seen at any wavelength!

$$t_{\rm var} \sim r_g/c = GM/c^3 \simeq 0.4 \text{ days}$$

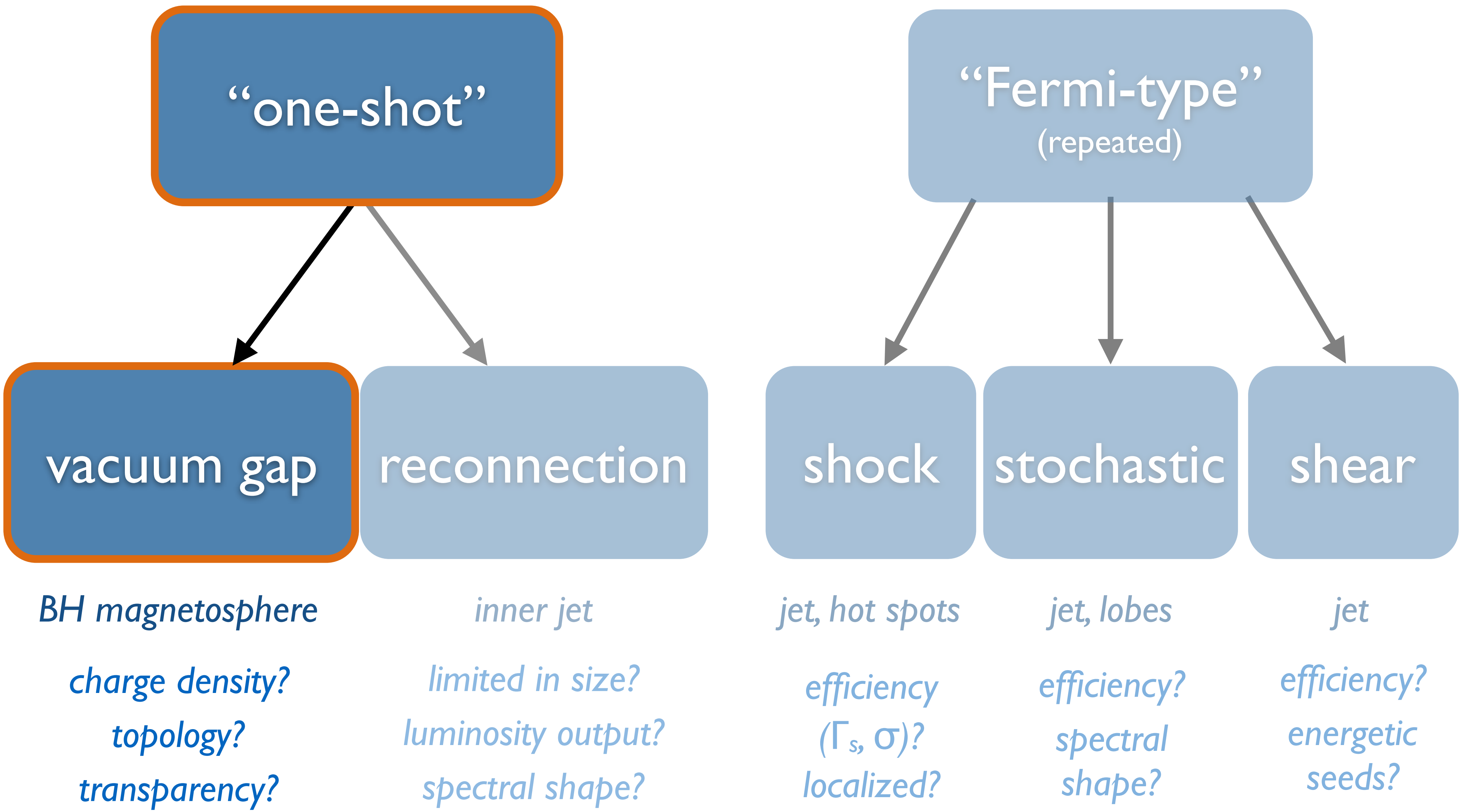
if due to upscattering of ambient photons:

$$(\epsilon_{\rm VHE} \sim \gamma_e m_e c^2)$$

$$\Rightarrow \gamma_e > 10^6$$

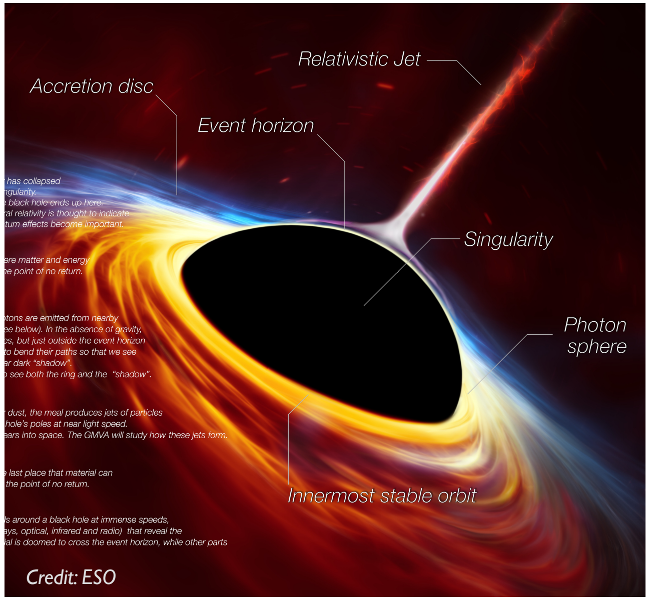


How to achieve high particle energies close to black holes…



The Occurrence of Gaps around rotating Black Holes

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



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

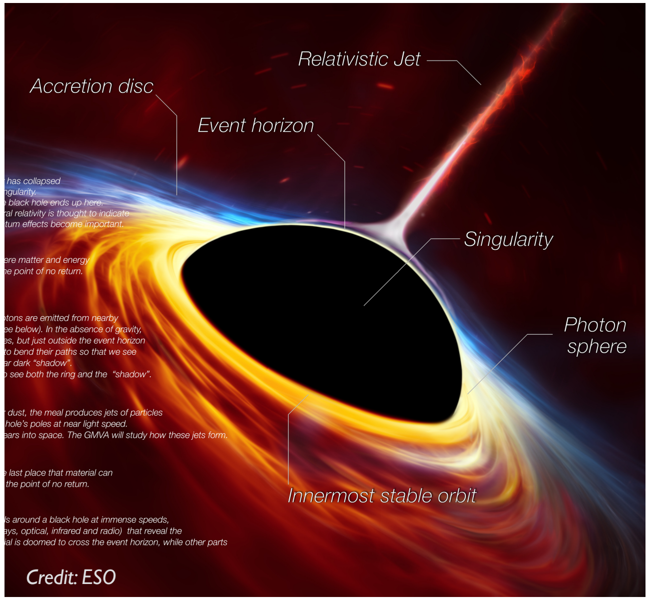
Beskin et al. 1992; Hirotani & Okamoto 1998…

The Occurrence of Gaps around rotating Black Holes

"Parallel electric field occurrence

⇒ not enough charges to screen the field

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



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- ***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*
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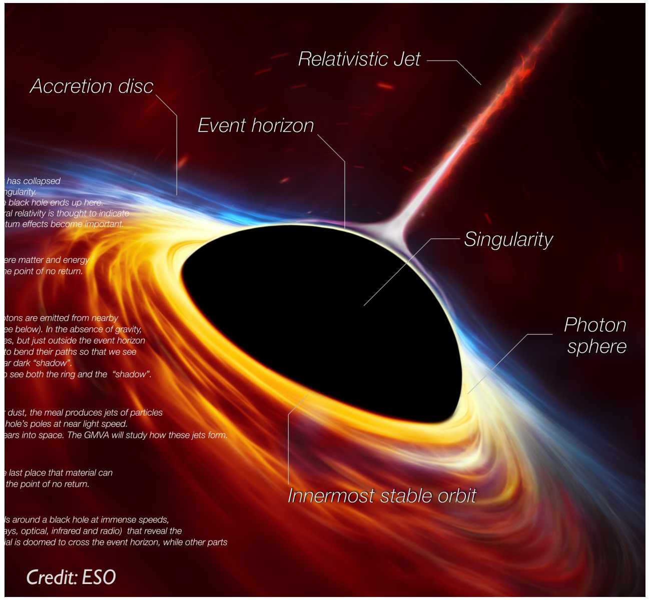
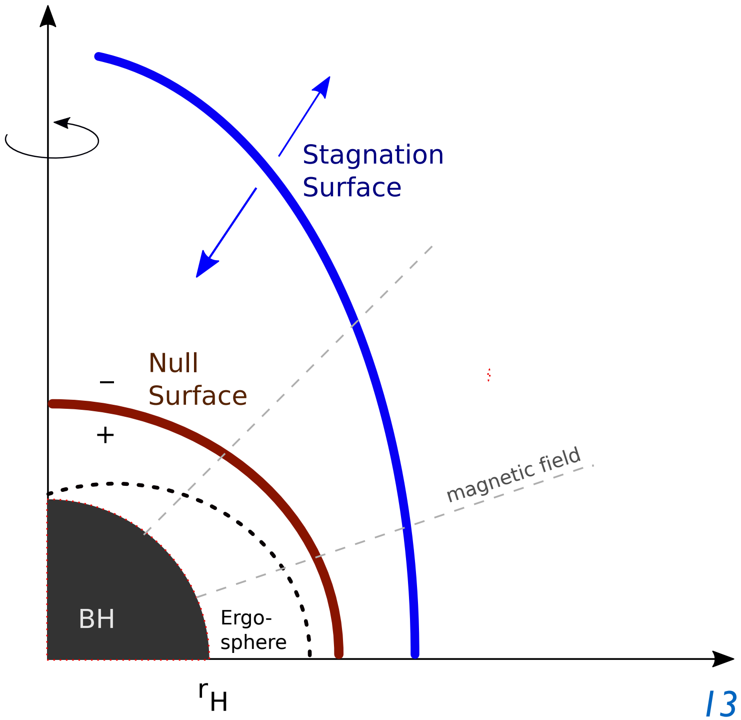
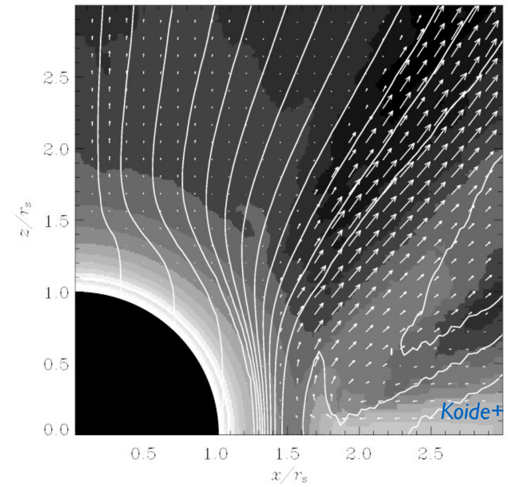




Linking Jet Formation and High Energy Emission

- for BH-driven jets *(Blandford-Znajek)*
  - *self-consistency: continuous plasma injection needed to activate BZ outflows (force-free MHD)*



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

The Conceptual Relevance of BH Gaps

Linking Jet Formation and High Energy Emission

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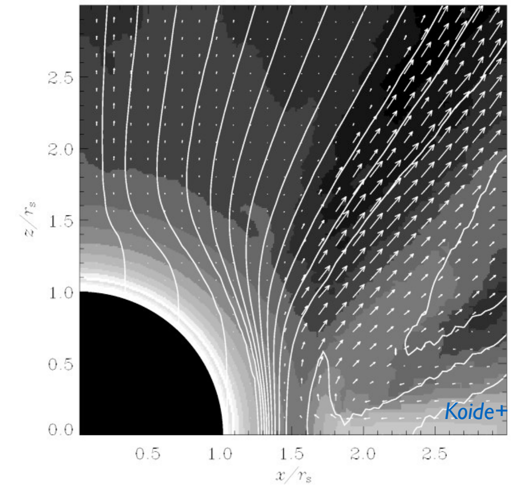
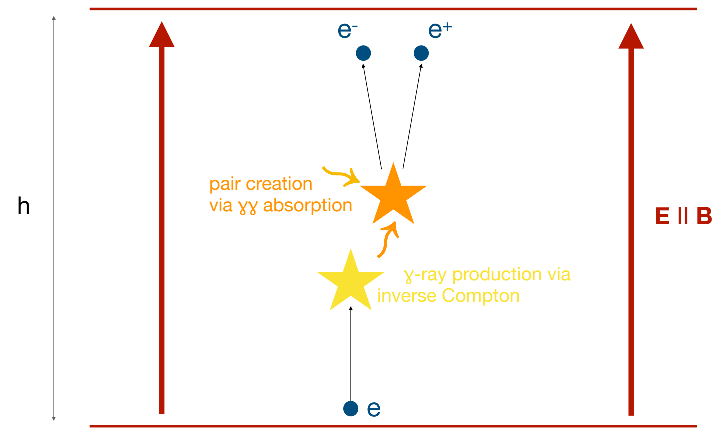
- *if BH regions becomes evacuated…*
  - *efficient (direct) acceleration of electrons & positrons in emergent $E_{||}$-field*
  - *accelerated e^-, e^+ produce γ-rays via inverse Compton*
  - *γγ-absorption triggers pair cascade…*

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

  ⇒ ensuring electric field screening (closure)





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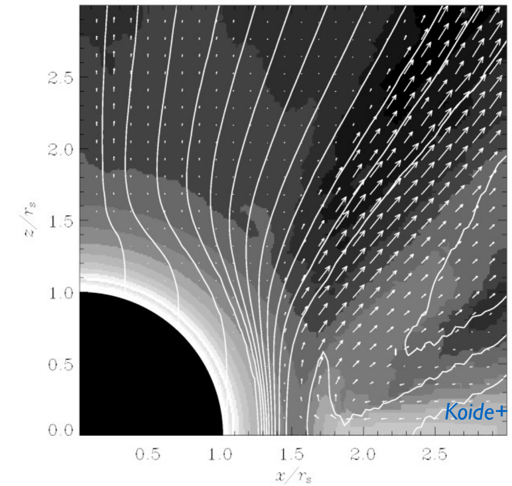
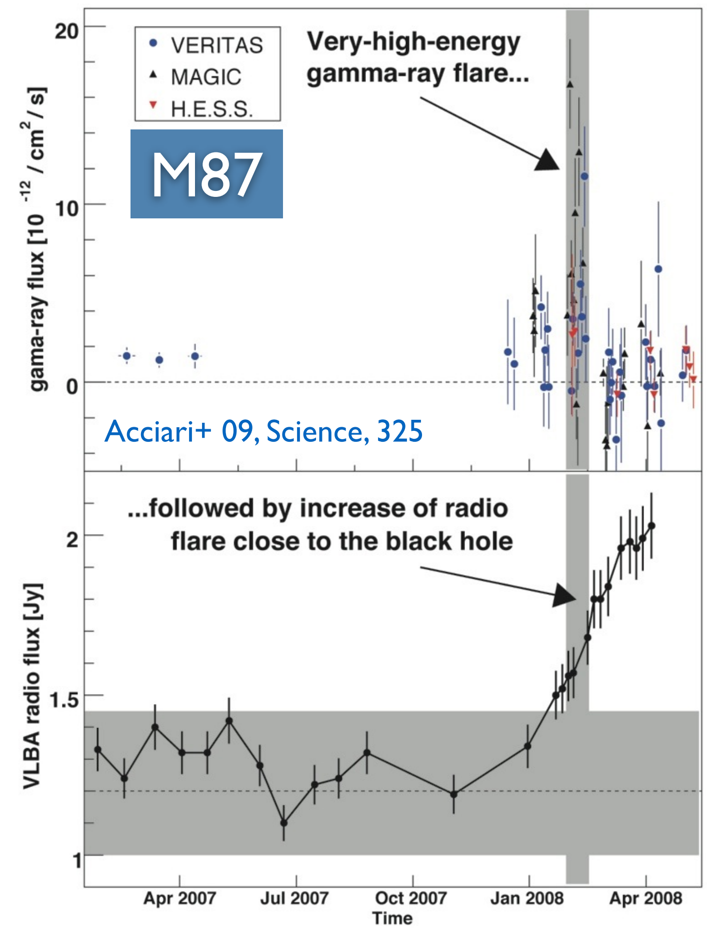
- observable in MAGN/radio galaxies (e.g., M87)

  ⇒ *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 on different boundaries

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

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e.g., *highly under-dense, $\rho \ll \rho_{GJ}$*

- *Boundaries:*

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

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

  with $L_{BZ} \sim a_s^2 c r_H^2 B_\perp^2/16$

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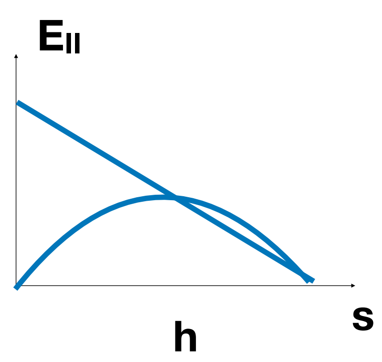

weakly under-dense: $\rho_e \sim \rho_{GJ}$

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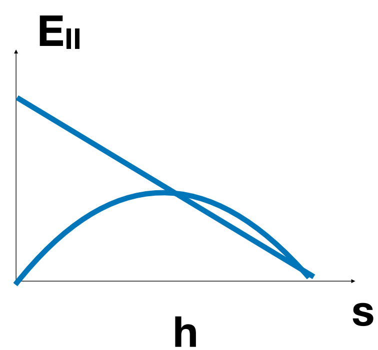

Small gap sizes '$h \ll r_g$' give small gamma-ray (VHE) power L_{gap}

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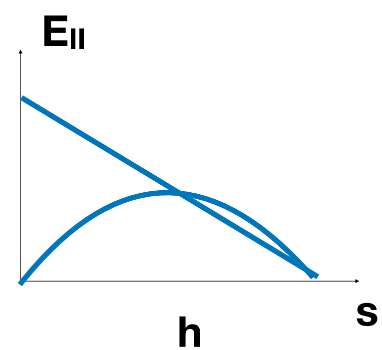

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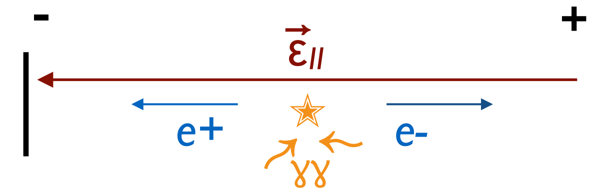
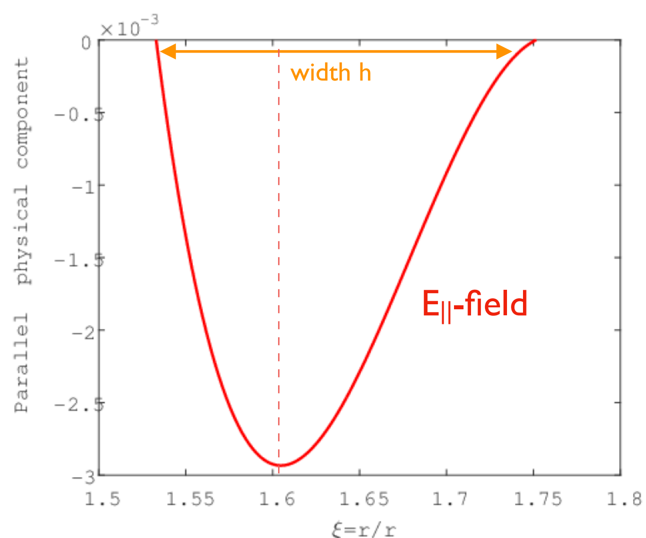
Taking variability as proxy for gap size

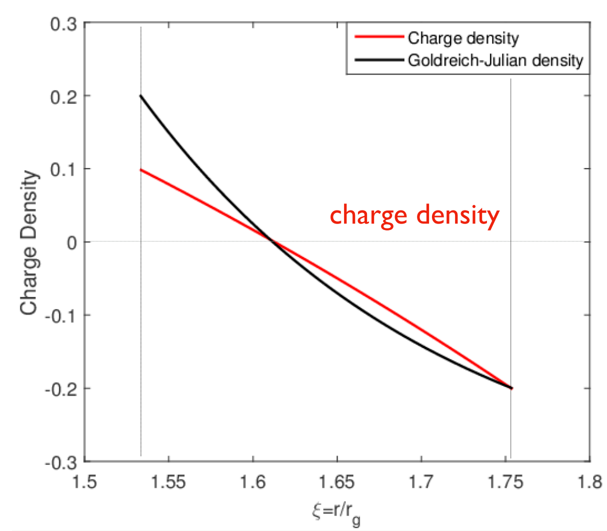
➪ Jet power constraints become relevant for rapidly varying sources *e,g., Beskin+ 1992; Hirotani & Okamoto 1998; Hirotani+ 2016; Levinson & Segev 2017; Katsoulakos & FR 2020*



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

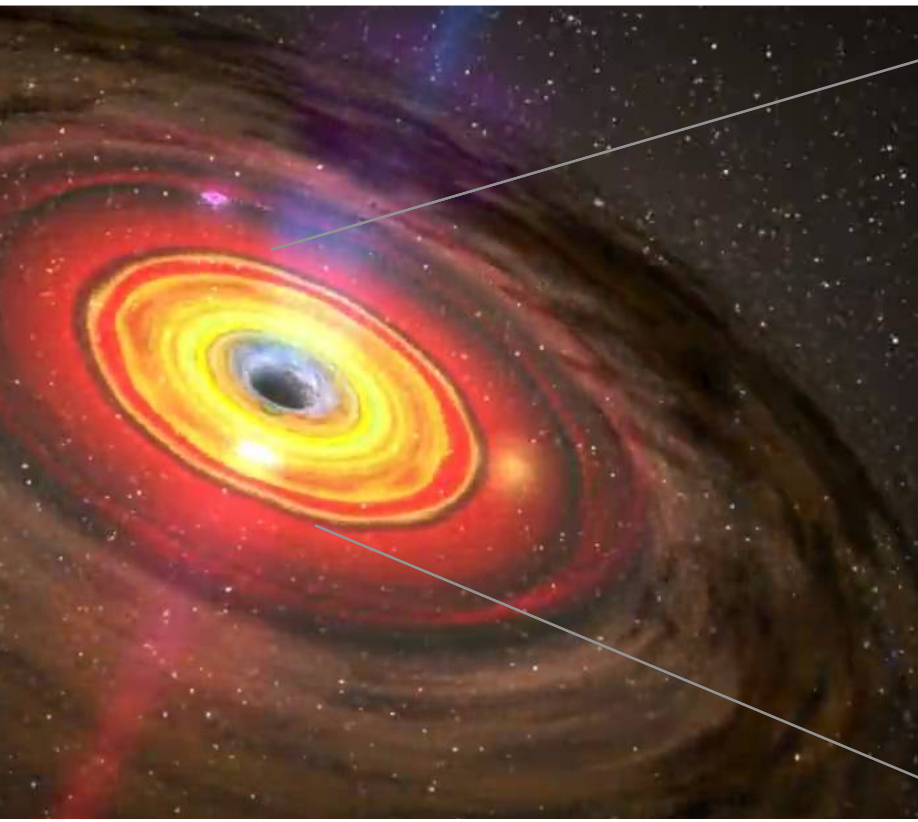
$\varrho \leq \varrho_{GJ}$ in boundaries

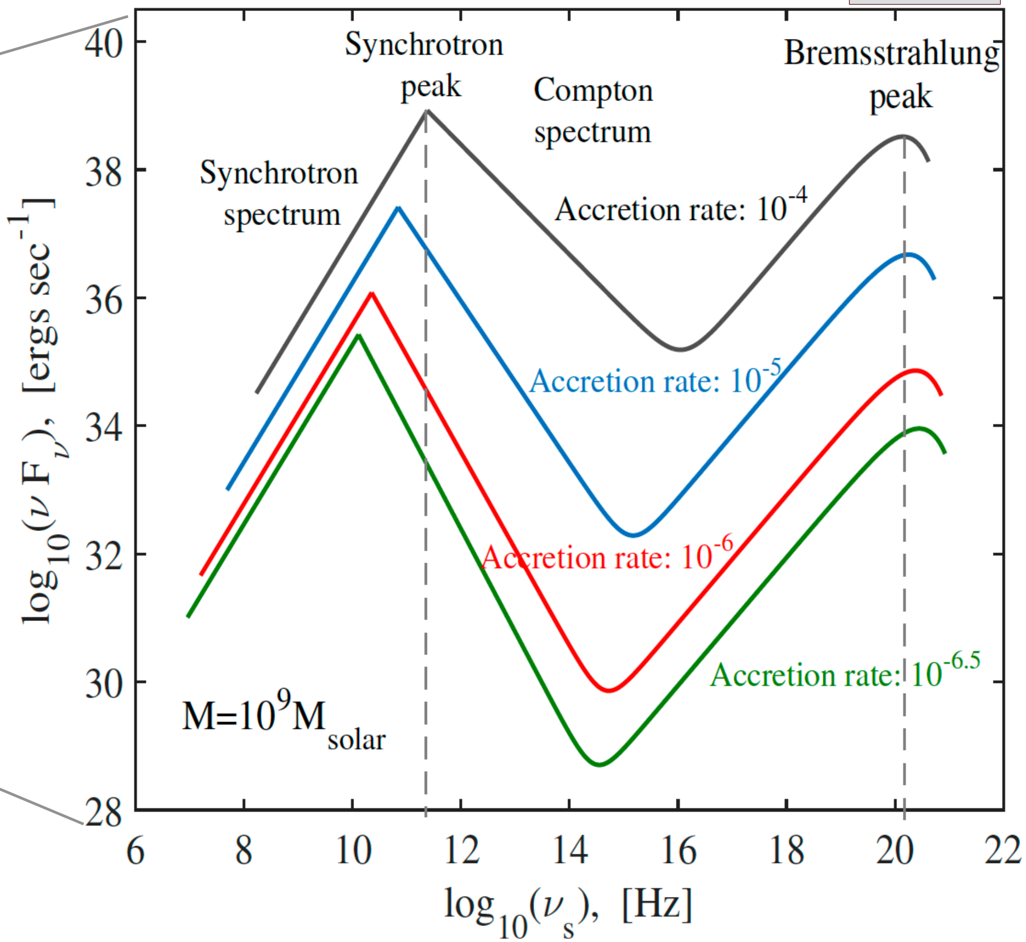
 # ADAF soft photon field

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

➡ *determines efficiency of pair cascade ($\gamma_{\rm VHE}\,\gamma_{\rm soft} \rightarrow e^+e^-$)...*

ADAF-type

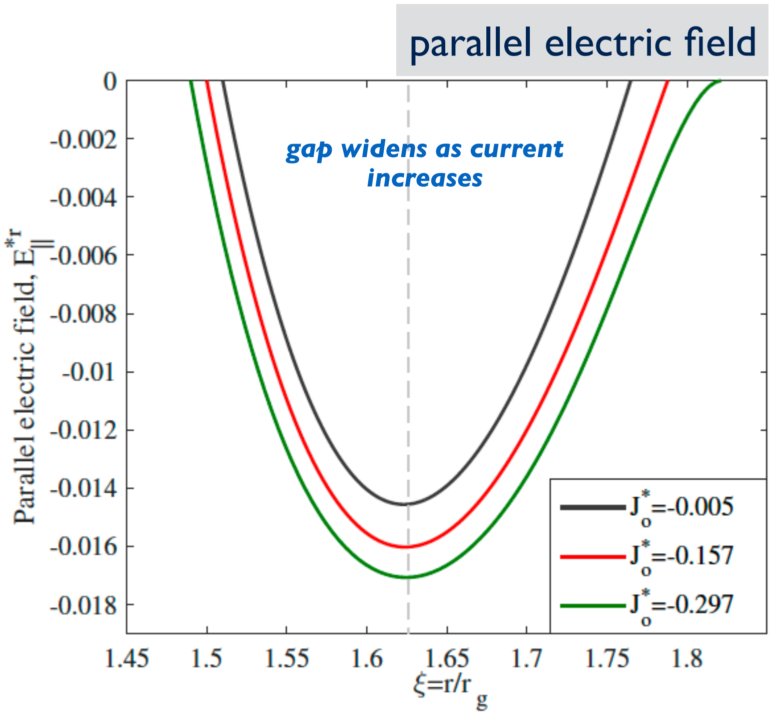




for $B_H \sim 10^5\,\dot{m}^{1/2}\,M_9^{-1/2}$ G

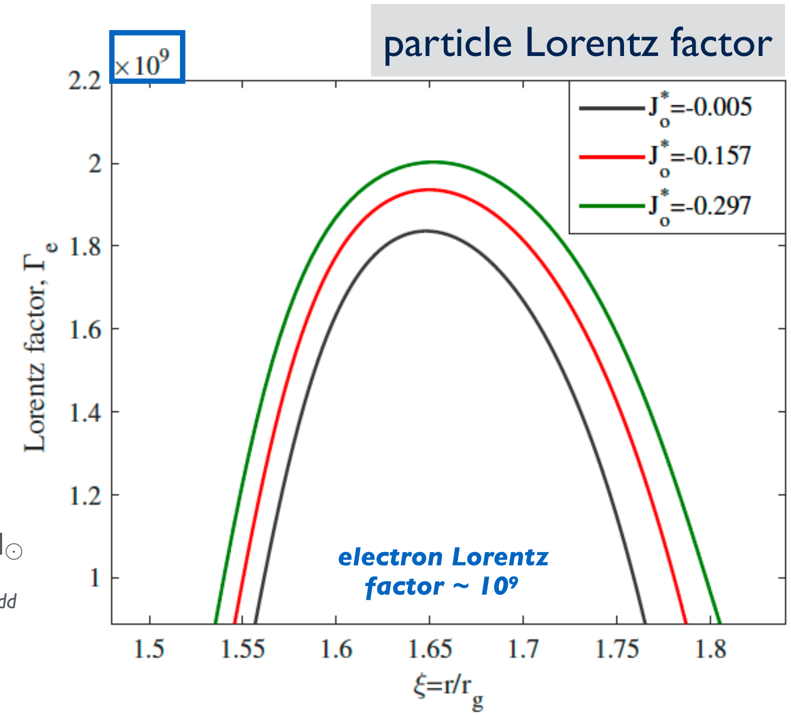
Example: Self-consistent steady (1D) gap solutions III - M87

Katsoulakos & FR 2020

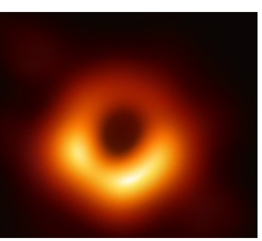


Parameters:
$M_{BH} = 10^9 M_\odot$
$\dot{m} = 10^{-5}\dot{m}_{Edd}$

$J_0^* = J_0/(\rho_c c)$
with $\rho_c = \Omega^F B/(2\pi c)$



M87:



[EHTC 2019]

Global Current $J_o^* = J_o/c\,\rho_c$ (1)	Gap Size h/r_g (2)	Voltage Drop $\times 10^{17}$ Volts (3)	Gap Power $\times 10^{41}\, erg\, s^{-1}$ (4)
−0.4	0.80	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 $L_{BZ} = 2 \times 10^{43}$ erg/s)

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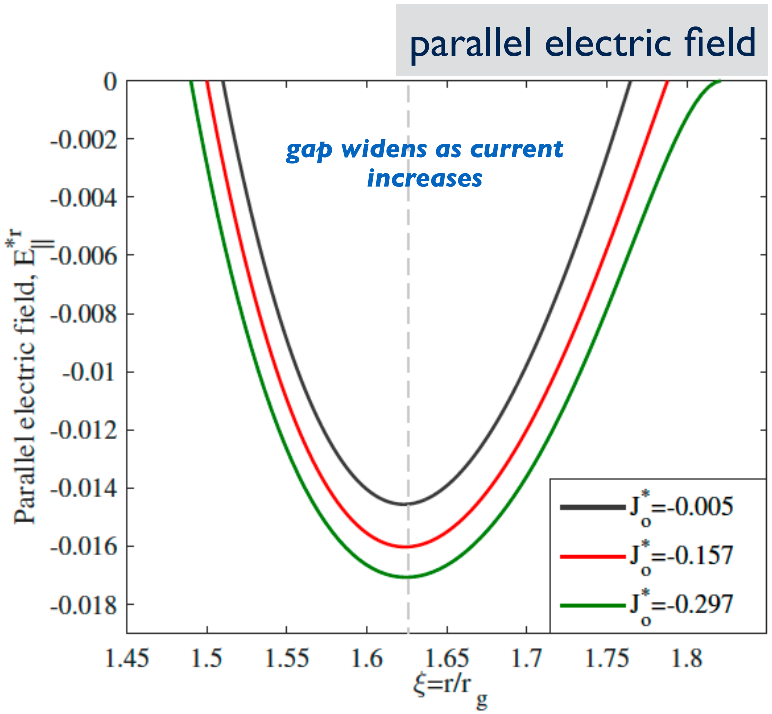

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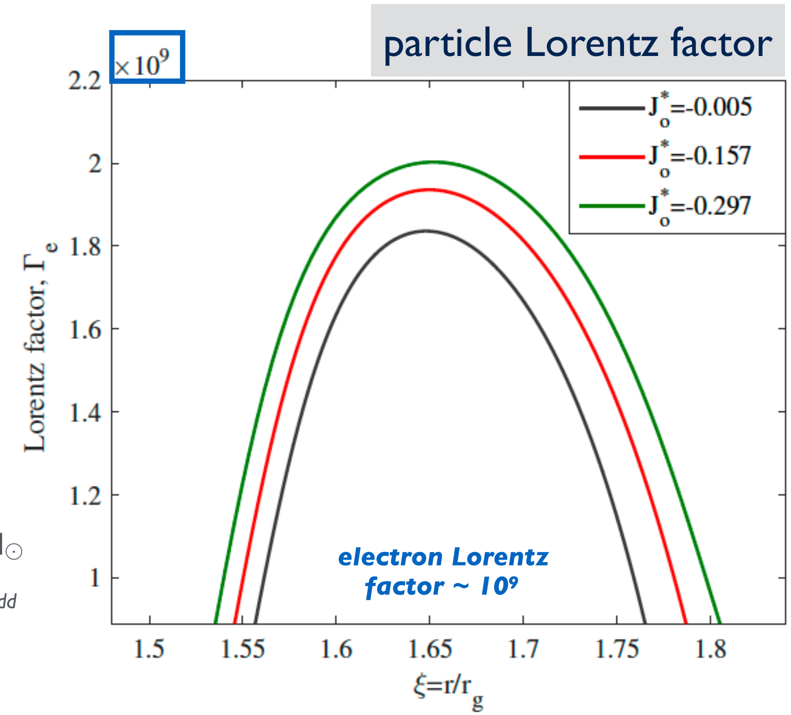

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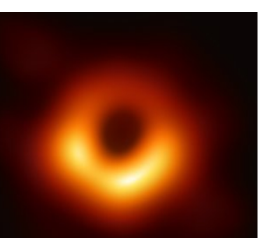

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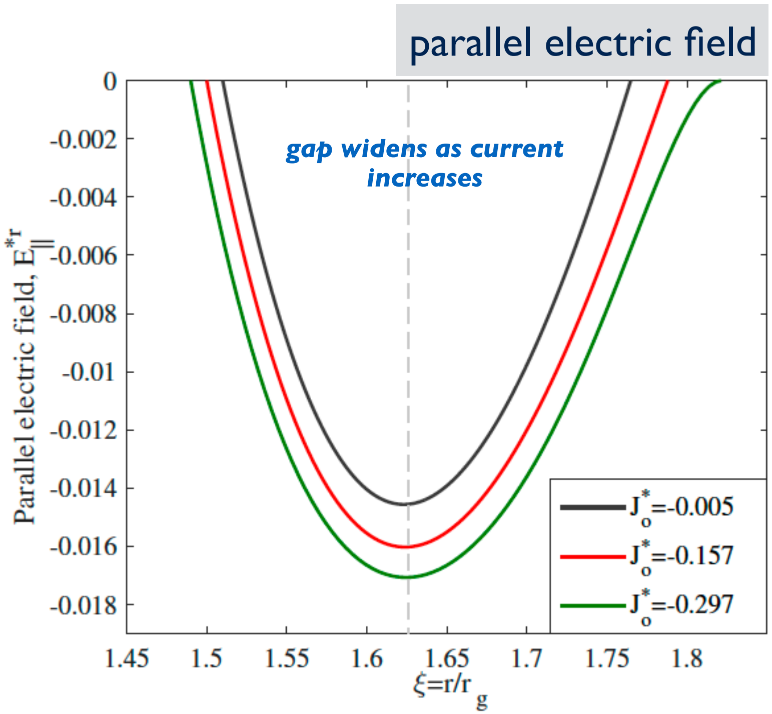
Consistent solutions possible for M87
max. voltage drop ~10^{18} eV

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

Katsoulakos & FR 2020



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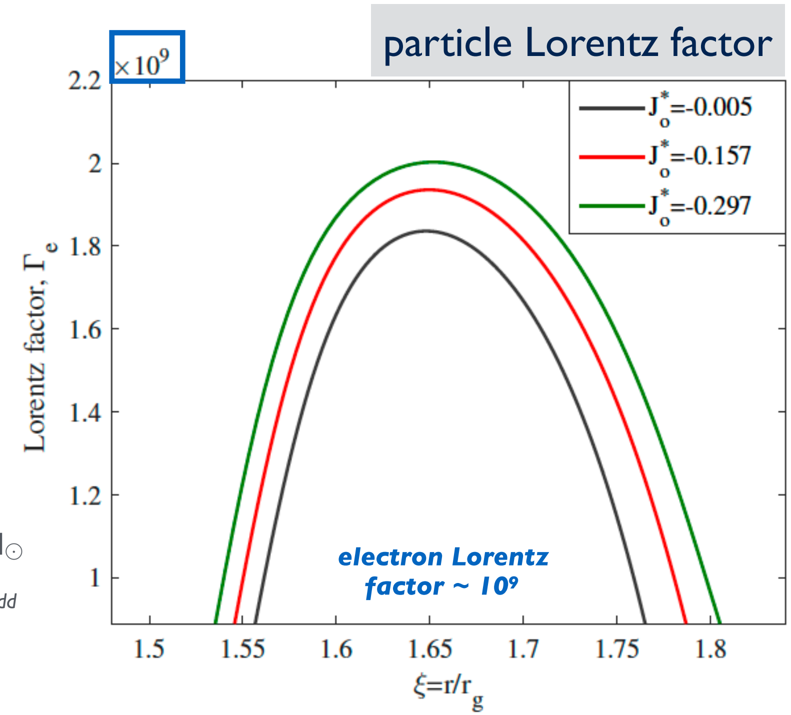

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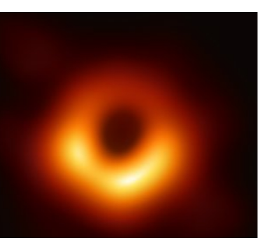

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(using spin parameter a_s*=1; max L_{BZ} = 2 x 10^{43} erg/s)

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

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

Issues & developments

- *gaps are expected 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 …

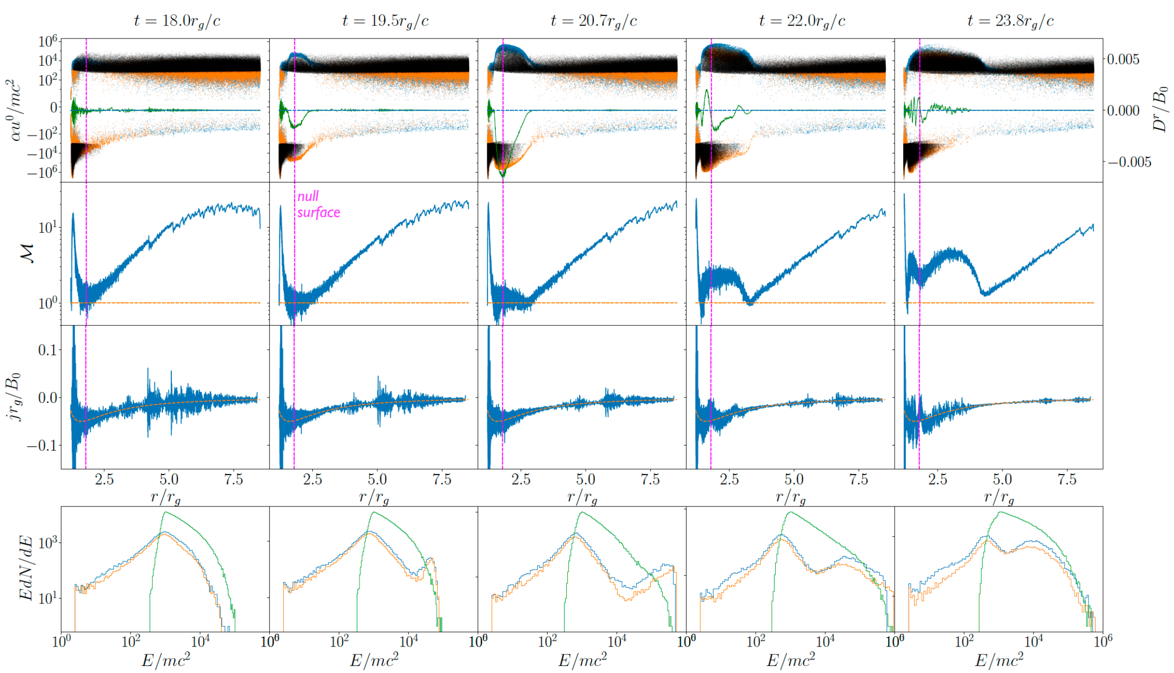
phase space plot (e+, e-, photons); electric field

Multiplicity $\mathcal{M} \sim n/\hat{n}_{GJ}$

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
$\tau_{IC} = r_g / l_{IC} = 10$
and soft photons with
ε_{min} ~ 5 eV
PL index = 2.2

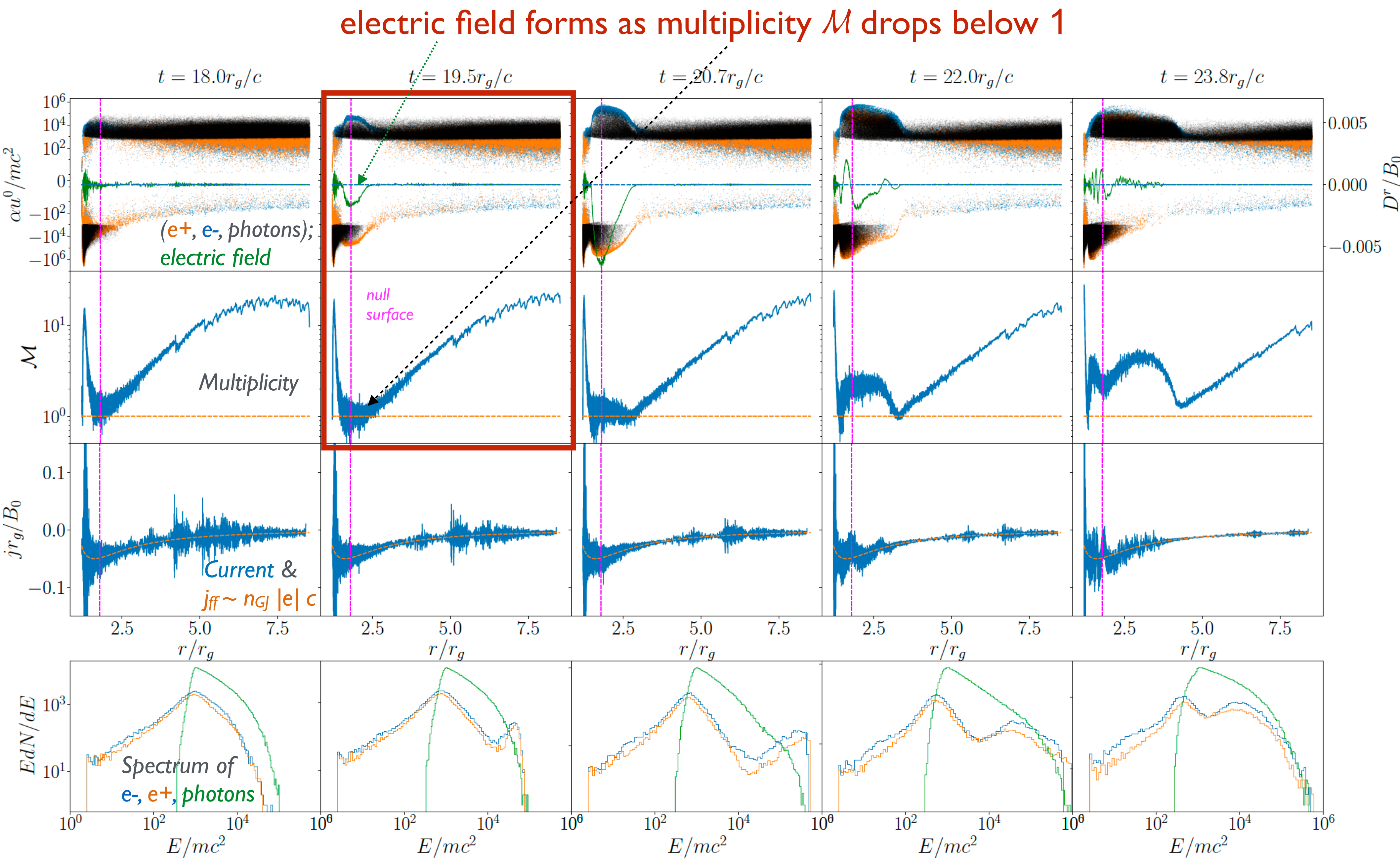
(size r_g ~ $10^4\,\lambda_p$, l_{IC} ~ $10^3\,\lambda_p$)

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



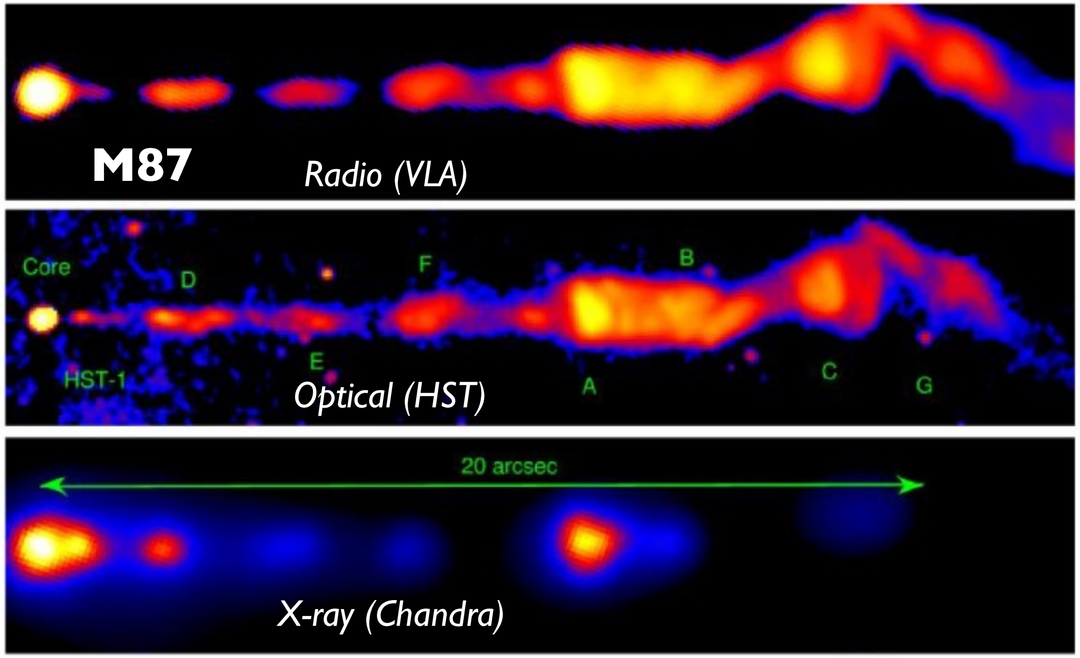
Chen & Yuan 2020

Shear Particle Acceleration in the Relativistic Jets of AGN

_Example: High-Energy Emission from large-scale jets

- extended X-ray electron synchrotron emission
- needs electron Lorentz factors $\gamma \sim 10^8$
- short cooling timescale $t_{cool} \propto 1/\gamma$; cooling length $c\, t_{cool} << $ kpc
- distributed acceleration mechanism required (Sun, Yang, FR+ 2018 for M87)

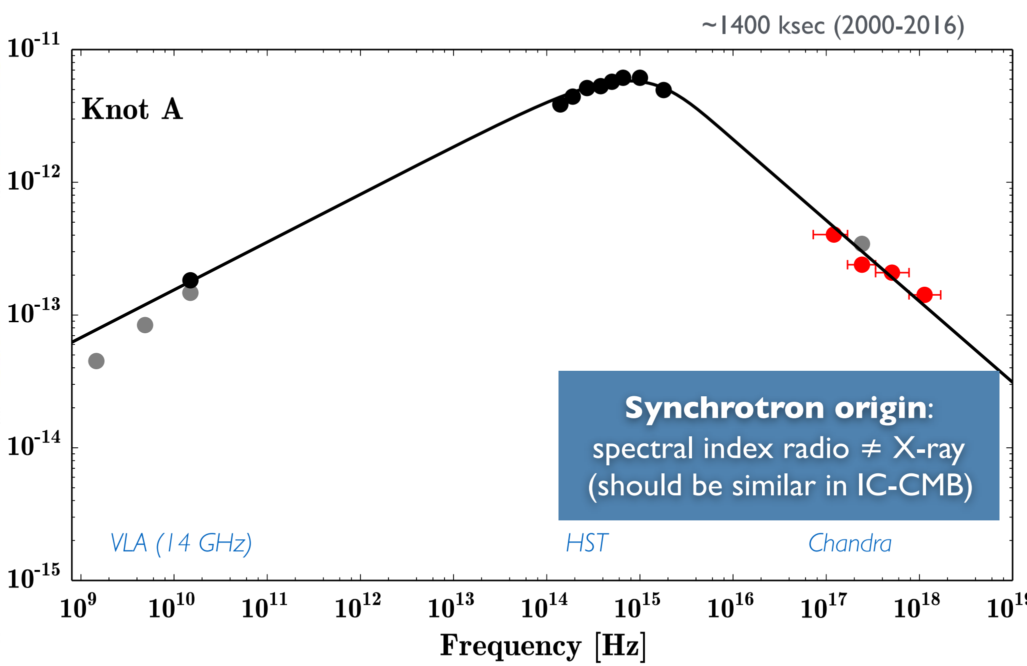
$\nu \propto \gamma^2 B$



1 arcsec ~ 0.1 kpc (0.081 kpc)

Marshall+ 2002

Relativistic particles throughout whole jet

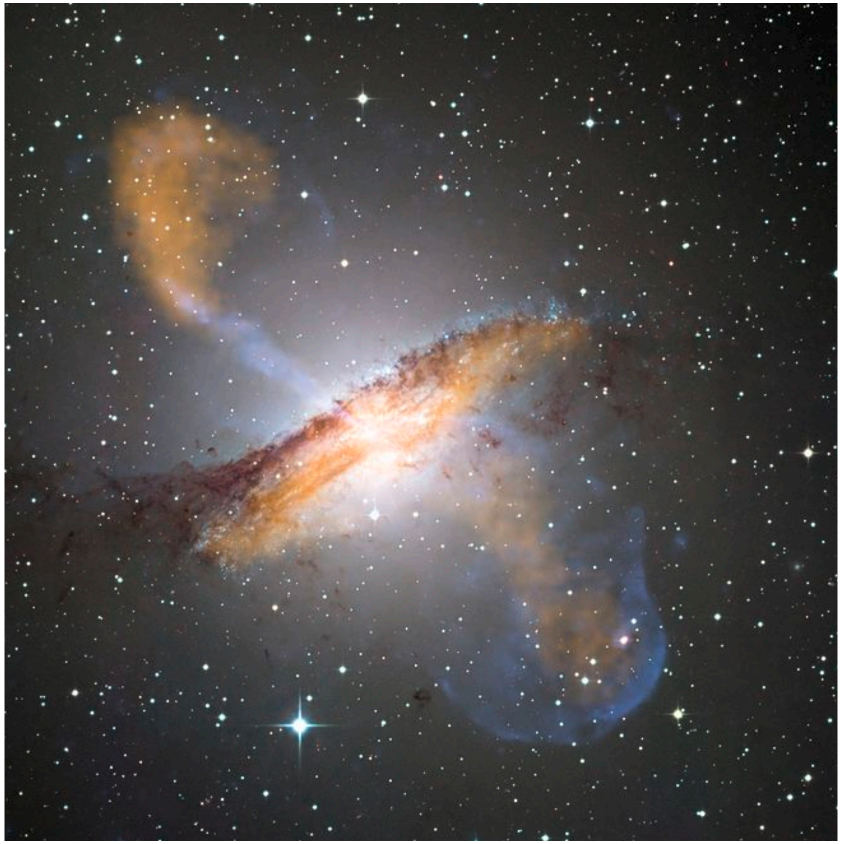


Synchrotron origin: spectral index radio ≠ X-ray (should be similar in IC-CMB)

SED can be fitted by broken power-law

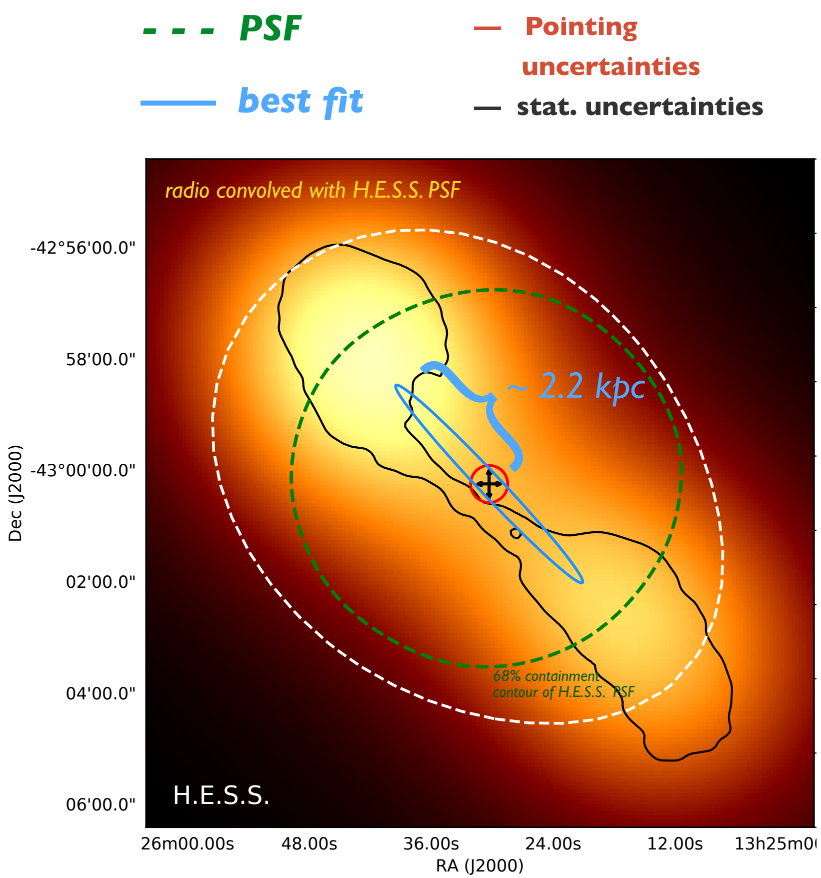
($B = 3\times10^{-4}$ G, $\gamma_b \sim 10^6$, $\gamma_{max} \sim 10^8$, $P_{jet} \sim 10^{43}$ erg/s, $\Delta\alpha \sim 2$)

On ultra-relativistic electrons in AGN Jets II



VHE emission along the kpc-jet of Cen A

- Inverse Compton up-scattering of dust by ultra-relativistic electrons with $\gamma = 10^8$
- verifies X-ray synchrotron interpretation
- continuous re-acceleration required to avoid rapid cooling



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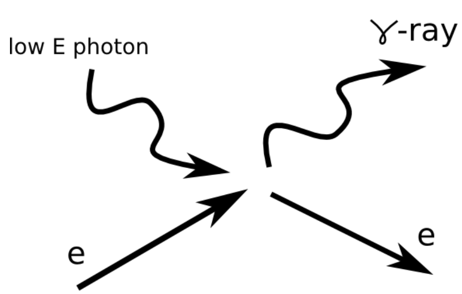
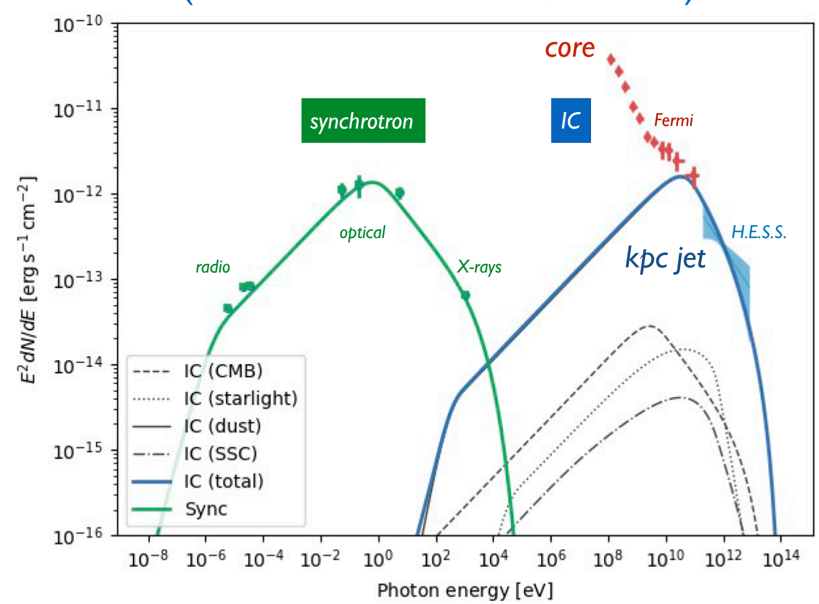
Inverse Compton emission



$$\nu_2 \propto \gamma^2 \ \nu_1$$

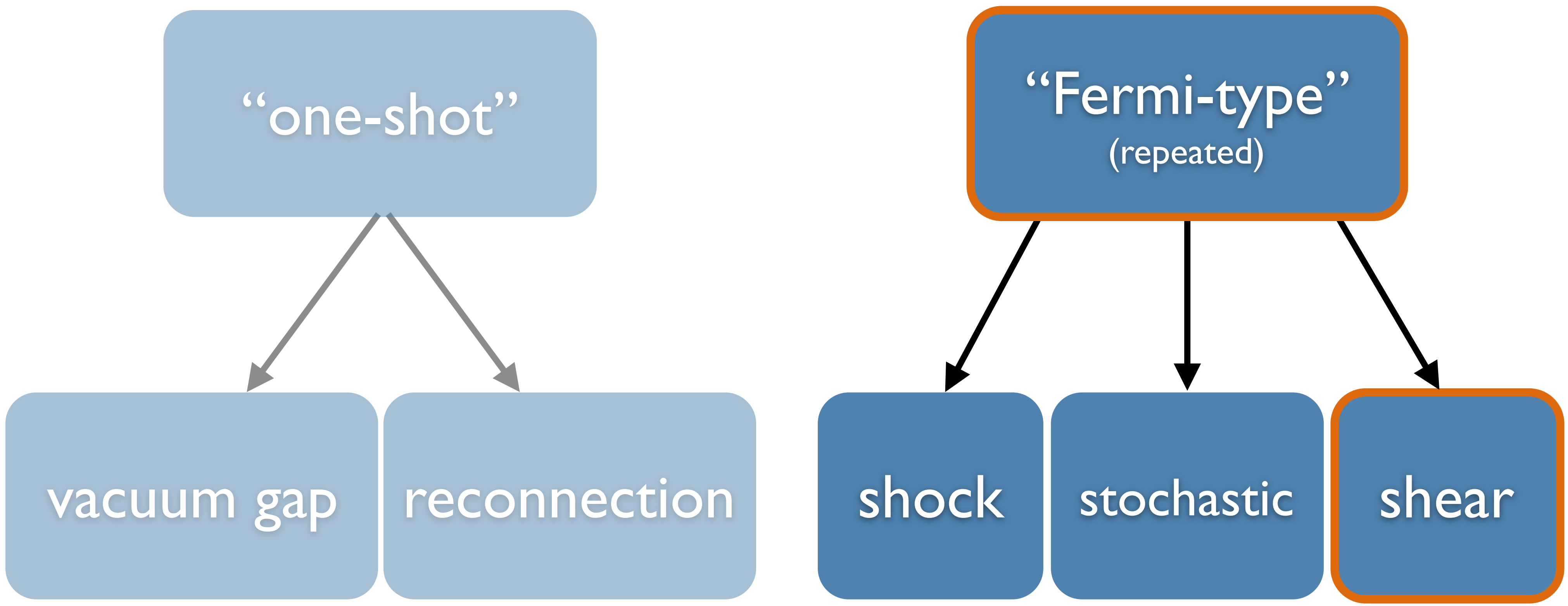
(H.E.S.S. Collab. 2020, Nature)



Parameters: ECBPL: α_1=2.30, α_2=3.85 , γ_b =1.4 x 10^6, γ_c=10^8, B=23μG, W_{tot} = 4 x 10^{53} erg

How to accelerate electrons to $\gamma \sim 10^8$ and keep them energized ?

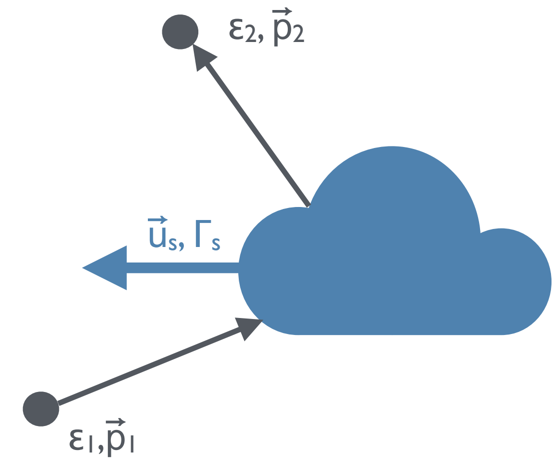
A possible scenario…



- **vacuum gap** — *BH magnetosphere*: *charge density? topology? transparency?*
- **reconnection** — *inner jet*: *limited in size? luminosity output? spectral shape?*
- **shock** — *jet, hot spots*: *efficiency (Γ_s, σ)? localized?*
- **stochastic** — *jet, lobes*: *efficiency? spectral shape?*
- **shear** — *jet*: *efficiency? energetic seeds?*

Kinematic effect resulting from *scattering off magnetic inhomogeneities*

E. Fermi, Phys. Rev. 75, 578 [1949]



_Ingredients: in frame of scattering centre

- momentum magnitude conserved
- particle direction randomised

_Characteristic energy change per scattering:

$$\Delta\epsilon = \epsilon_2 - \epsilon_1 = 2\,\Gamma_s^2\left(\epsilon_1\, u_s^2/c^2 - \vec{p_1}\cdot\vec{u_s}\right)$$

➡ *energy gain for head-on* ($\vec{p}_1 \cdot \vec{u}_s < 0$), *loss for following collision* ($\vec{p}_1 \cdot \vec{u}_s > 0$)

- I. **stochastic:** average energy gain 2nd order: $\langle\Delta\varepsilon\rangle \propto (u_s/c)^2\, \varepsilon$
- II. **shock:** spatial diffusion, head-on collisions, gain 1st order: $\langle\Delta\varepsilon\rangle \propto (u_s/c)\, \varepsilon$

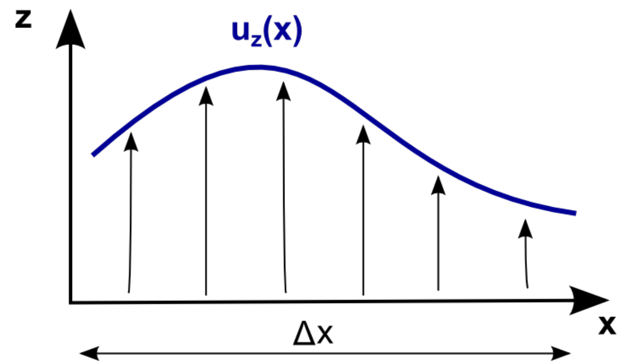
- III. ***Gradual shear flow*** with frozen-in scattering centres:

non-relativistic

$$\vec{u} = u_z(x)\ \vec{e}_z$$

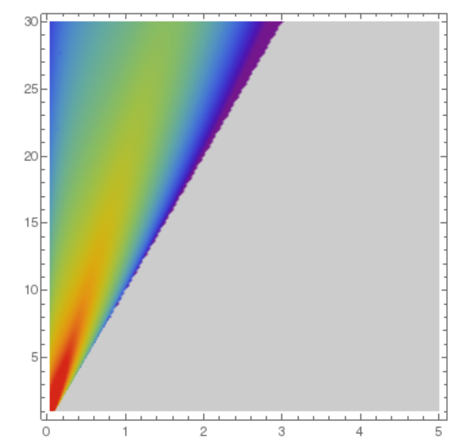
  - *like 2nd Fermi, stochastic process with average gain:*

$$\frac{<\Delta\epsilon>}{\epsilon} \propto \left(\frac{u}{c}\right)^2 = \frac{1}{c^2}\left(\frac{\partial u_z}{\partial x}\right)^2 \lambda^2$$



using *characteristic* *effective velocity:*

$$u = \left(\frac{\partial u_z}{\partial x}\right)\lambda$$, where λ = *particle mean free path*



Berezhko & Krymsky 1981; Berezhko 1982; Earl+ 1988; Webb 1989; Jokipii & Morfill 1990; Webb+ 1994; FR & Duffy 2004, 2006, 2016; Liu, FR & Aharonian 2017; Webb+ 2018, 2019; Lemoine 2019; FR & Duffy 2019, 2021….

Stochastic Shear Particle Acceleration (basic idea)

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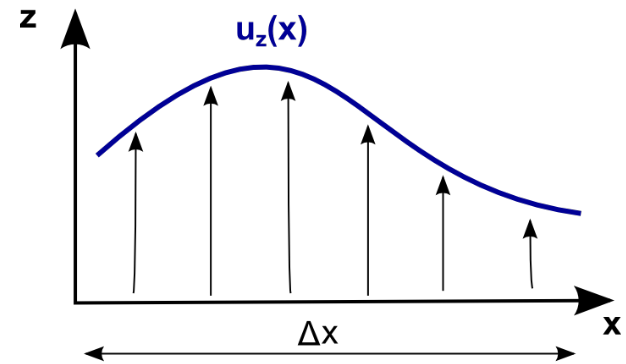
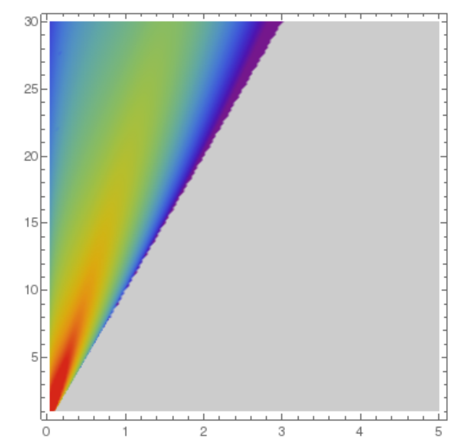


using *characteristic effective velocity:*

$$u = \left(\frac{\partial u_z}{\partial x}\right)\lambda$$, where λ = *particle mean free path*

  - leads to:

$$t_{acc} = \frac{\epsilon}{(d\epsilon/dt)} \sim \frac{\epsilon}{<\Delta\epsilon>} \times \frac{\lambda}{c} \propto \frac{1}{\lambda}$$



⇒ *seeds* from acceleration @ shock or stochastic…

⇒ easier for protons…(⇨ UHECR)

Berezhko & Krymsky 1981; Berezhko 1982; Earl+ 1988; Webb 1989; Jokipii & Morfill 1990; Webb+ 1994; FR & Duffy 2004, 2006, 2016; Liu, FR & Aharonian 2017; Webb+ 2018, 2019; Lemoine 2019; FR & Duffy 2019, 2021….

Stochastic Shear Particle Acceleration (basic idea)

Microscopic Picture for non-relativistic Shear Flows

Calculate Fokker Planck coefficients for particle travelling across shear $\mathbf{u}_z(x)$ with

$\mathbf{p}_2 = \mathbf{p}_1 + m\,\boldsymbol{\delta}\mathbf{u}$ where $\delta u = (du_z/dx)\,\delta x$ and $\delta x = v_x\,\tau$. Then for $\Delta p := p_2 - p_1$

$$\left\langle \frac{\Delta p}{\Delta t} \right\rangle \propto p \left(\frac{\partial u_z}{\partial x} \right)^2 \tau$$

$$\left\langle \frac{(\Delta p)^2}{\Delta t} \right\rangle \propto p^2 \left(\frac{\partial u_z}{\partial x} \right)^2 \tau$$

⇒ detailed balance satisfied [scattering being reversible P(p, -Δp) = P(p-Δp, Δp)]

Fokker Planck eq. reduces to momentum diffusion equation:

$$\frac{\partial f}{\partial t} = \frac{1}{p^2} \frac{\partial}{\partial p} \left(p^2 D \frac{\partial f}{\partial p} \right)$$

$$D = \frac{1}{15} \left(\frac{\partial u_z}{\partial x} \right)^2 p^{2+\alpha} \tau_0 \quad for \quad \tau = \tau_0\, p^\alpha$$

(cf. Jokipii & Morfill 1990; FR & Duffy 2006)

Simplified leaky-box model for shear acceleration

$$\frac{\partial f}{\partial t} = \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 D_p \frac{\partial f}{\partial p}\right) - \frac{f}{\tau_{\rm esc}}$$

(FR & Duffy 2019)

Momentum-diffusion: $D_p = \Gamma p^2 \tau_s \propto p^{2+\alpha}$

mean free path: $\lambda = c\,\tau_s \propto p^\alpha$

[$\alpha = 1/3$ for Kolmogorov]

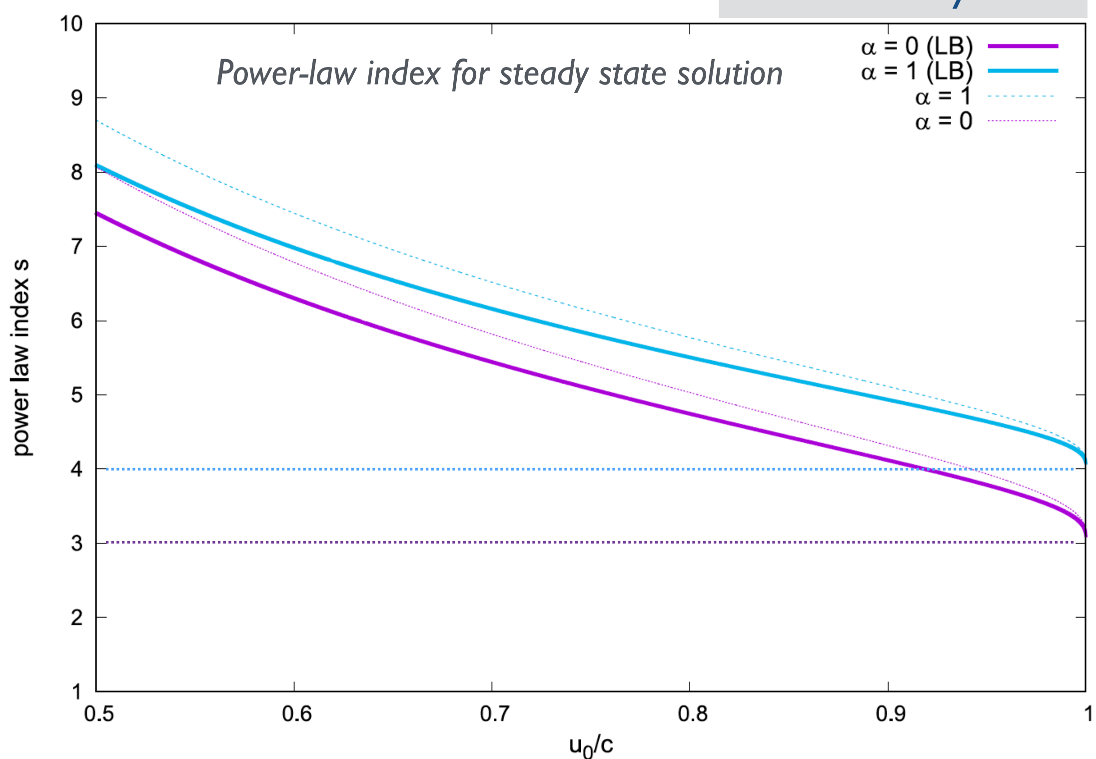
Escape time: $\tau_{\rm esc}(p) \simeq \frac{(\Delta r)^2}{2\,\kappa(p)} \propto p^{-\alpha}$

Power-law solution:

$$f(p) = f_0\, p^{-s}$$

- *PL index s sensitive to maximum flow speed*
- *only for relativistic flow speeds is classical index $s = 3 + \alpha$ obtained.*

linear velocity shear



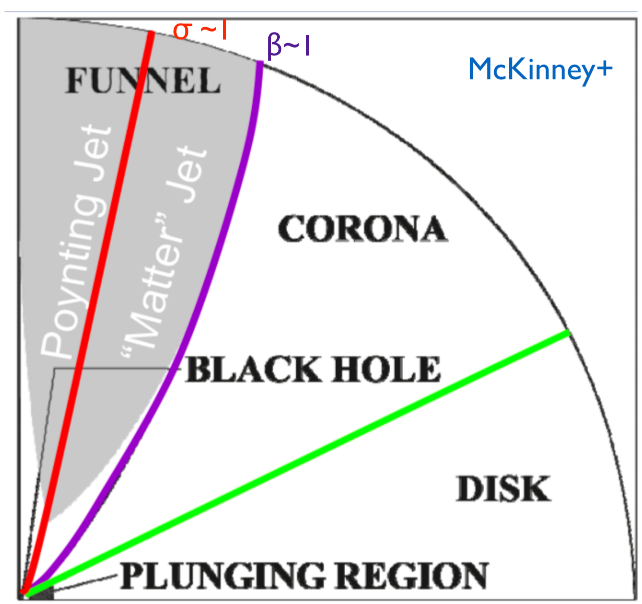
(also Webb+ 2018)

On the naturalness of velocity shears

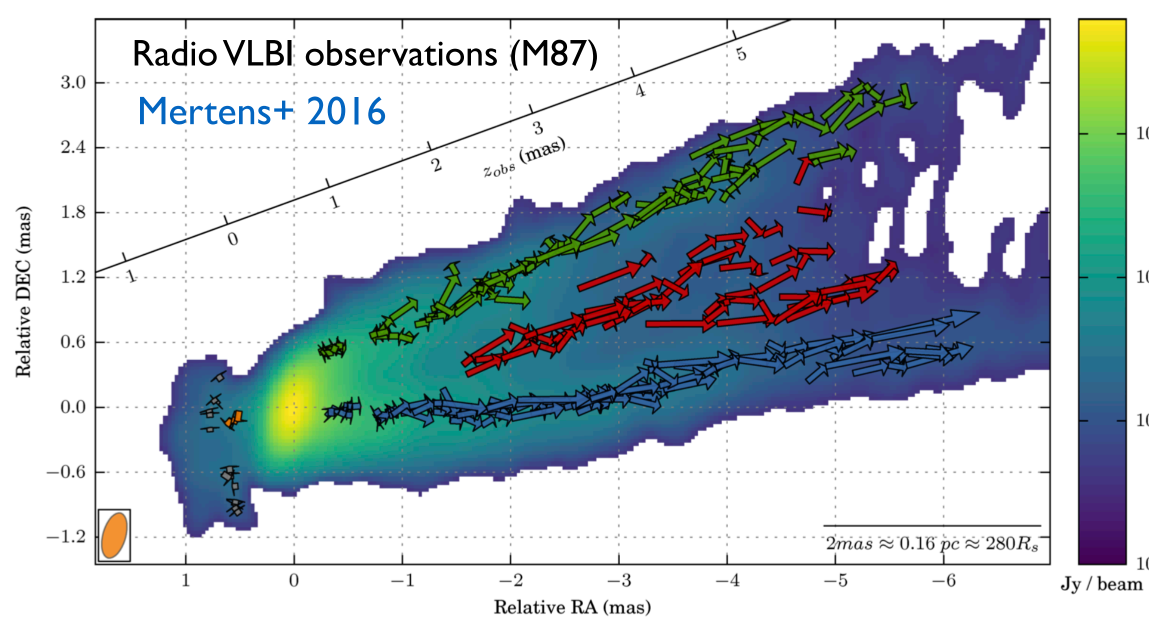
- **theoretical, numerical & observational evidence for jet stratification**
  - *Theory/GRMHD*: BH-driven (BZ) jet & disk-driven (BP) outflow…(e.g., Mizuno 2022)
  - *Modelling*: two-flow & spine-sheath models (e.g., Sol+ 1989; Ghisellini+ 2005)
  - *Jet propagation:* instabilities, mixing, layer formation… (e.g., Perucho 2019;)
  - *Observational*: limb-brightening & polarisation signatures… (e.g., Kim+ 2018)
  - M87: significant structural patterns on sub-pc scales ⇒ presence of both slow (~0.5c) and fast (~0.92c) components….

[similar indications in Cen A, cf. EHT observations in Janssen+ 2021]

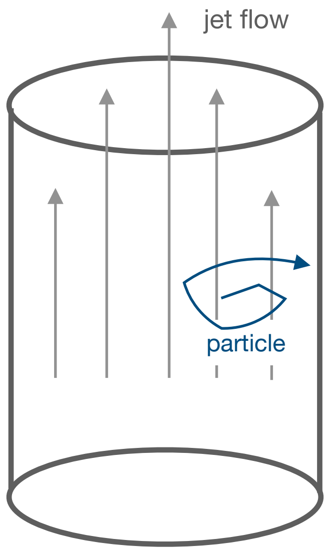
GRMHD simulations - Flow Structure



(cf. Gammie & McKinney 2004; Porth+2019)



Radiative-loss-limited electron acceleration in mildly relativistic flows



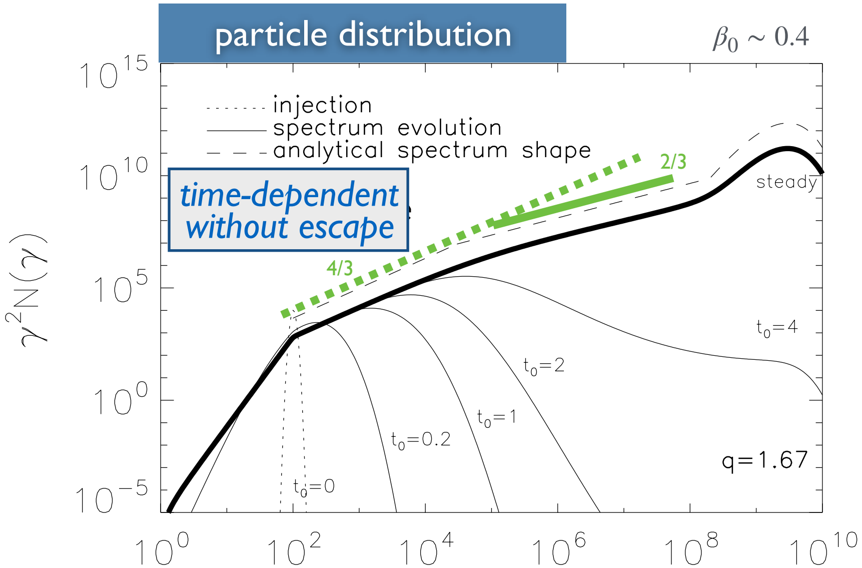
Ansatz: Fokker-Planck equation for f(t,p) incorporating acceleration by stochastic and shear, and losses due to synchrotron and escape for cylindrical jet.

Parameters I: $B = 3\mu G$, $v_{j,max} \sim 0.4c$, $r_j \sim 30$ pc, $\beta_A \sim 0.007$, $\Delta r \sim r_j/10$, mean free path $\lambda = \xi^{-1} r_L (r_L/\Lambda_{max})^{1-q} \propto \gamma^{2-q}$, $q=5/3$ (Kolmogorov), $\xi=0.1$

(cf . also FR & Duffy 2019, 2022; Tavecchio 2021)

On continuous electron acceleration in large-scale AGN jets

Radiative-loss-limited electron acceleration in mildly relativistic flows

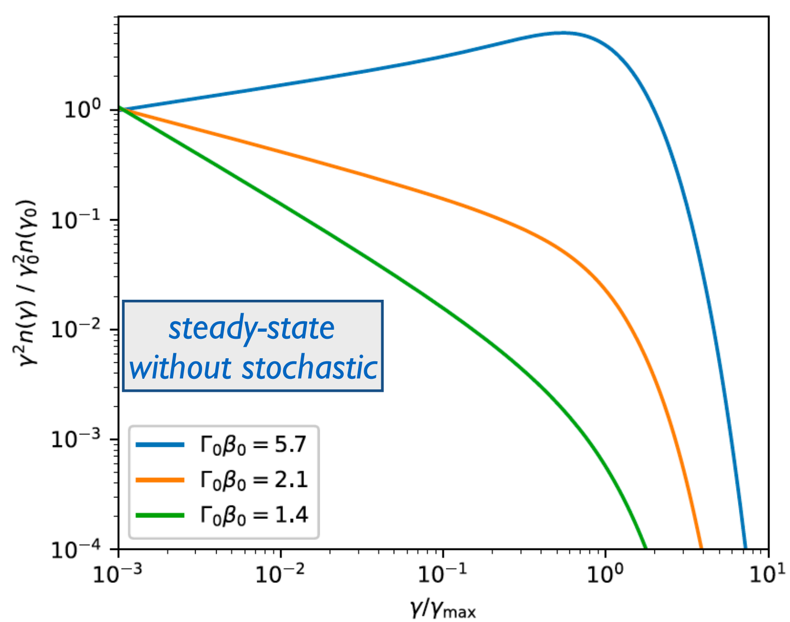


γ

(Liu, FR & Aharonian 2017)

Ansatz: Fokker-Planck equation for f(t,p) incorporating acceleration by stochastic and shear, and losses due to synchrotron and escape for cylindrical jet.

- from 2nd Fermi to shear…
- electron acceleration beyond $\gamma \sim 10^8$ possible
- formation of multi-component particle distribution
- incorporation of escape softens the spectrum



(Wang, Reville, Liu, FR & Aharonian 2021)

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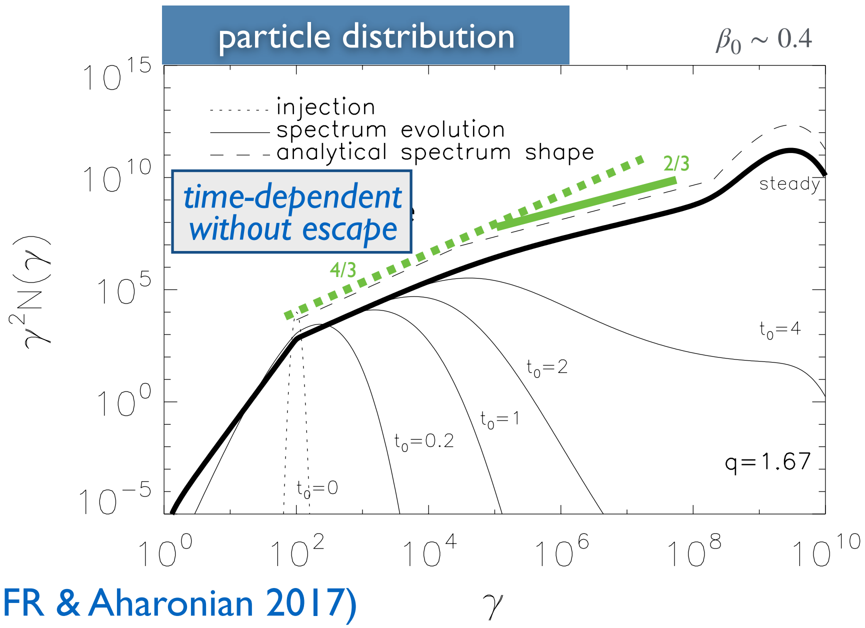
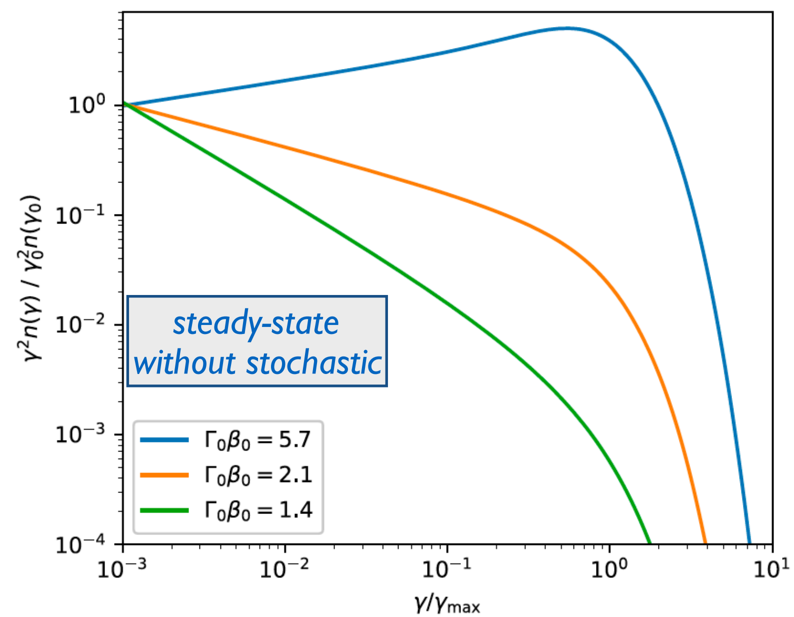


(Liu, FR & Aharonian 2017)



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Ansatz: Fokker-Planck equation for f(t,p) incorporating acceleration by stochastic and shear, and losses due to synchrotron and escape for cylindrical jet.

- from 2nd Fermi to shear…
- electron acceleration beyond $\gamma \sim 10^8$ possible
- formation of multi-component particle distribution
- incorporation of escape softens the spectrum

caveat: simplification of spatial transport; in general, high jet speeds needed.

(cf . also FR & Duffy 2019, 2022; Tavecchio 2021)

On cosmic-ray acceleration in mildly relativistic, large-scale AGN jets

(FR & Duffy 2019)

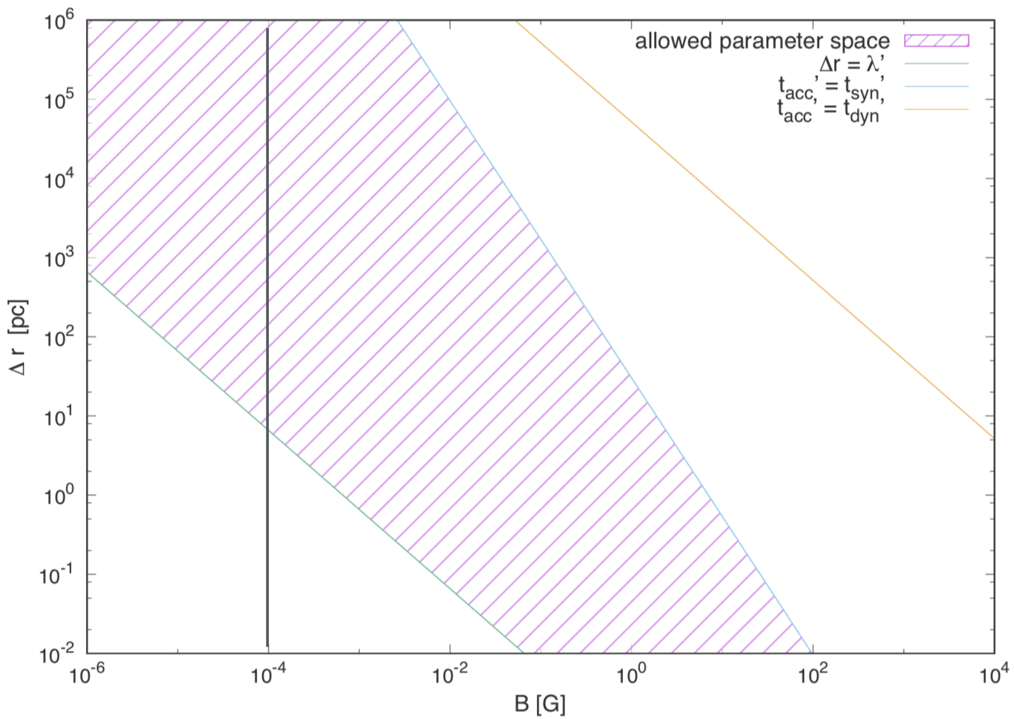

Figure 2. Allowed parameter range (shaded) for shear acceleration of CR protons to energies $E'_p = 10^{18}$ eV for a particle mean free path $\lambda' \propto p'^{\alpha}$ with $\alpha = 1/3$ (corresponding to Kolmogorov type turbulence $q = 5/3$). A flow Lorentz factor $\gamma_b(r_0) = 3$ has been assumed.

$(t_{acc,shear} \propto \gamma^{q-2})$

Potential for UHECR acceleration:

need jet widths such as to

(1) *confine particles,*

(2) *beat synchrotron losses,*

(3) *operate within system lifetime*

– expect KHI-shaped shear width $\Delta r > 0.1 r_j$ (FR & Duffy 2021)

- for protons ~10^{18} eV achievable in jets with relatively plausible parameters (i.e., lengths ~1 kpc – 100 Mpc, B ~ [1– 100] μG)
- escaping CRs may approach $N(E) \propto E^{-1}$

(cf. also Liu+ 2017, Wang+2021; Webb+ 2018, 2019)

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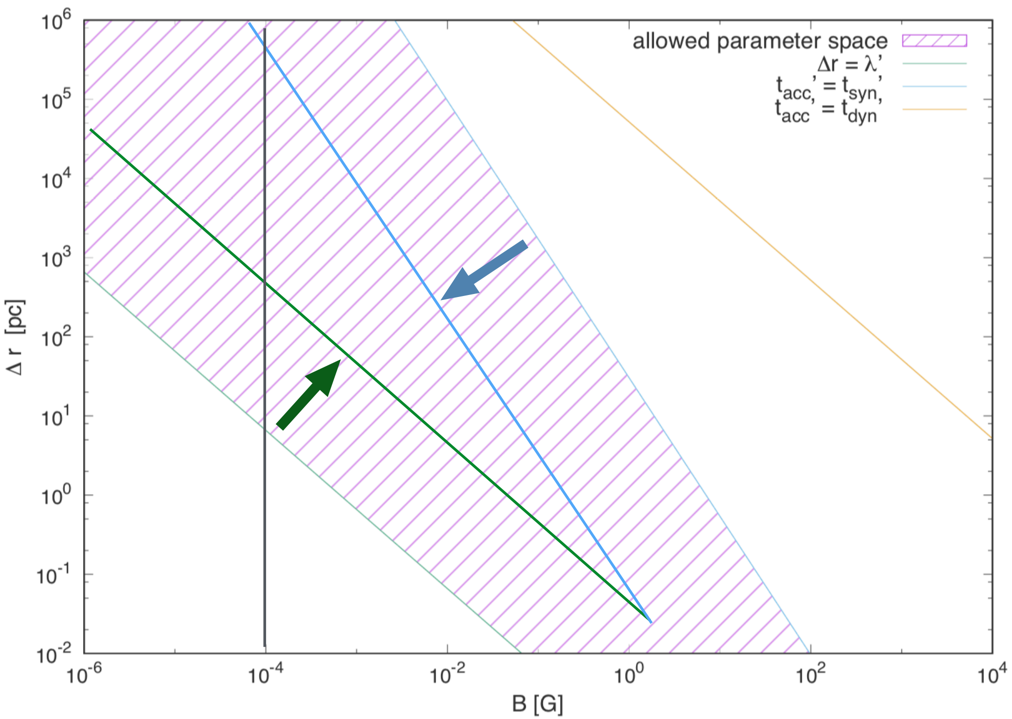

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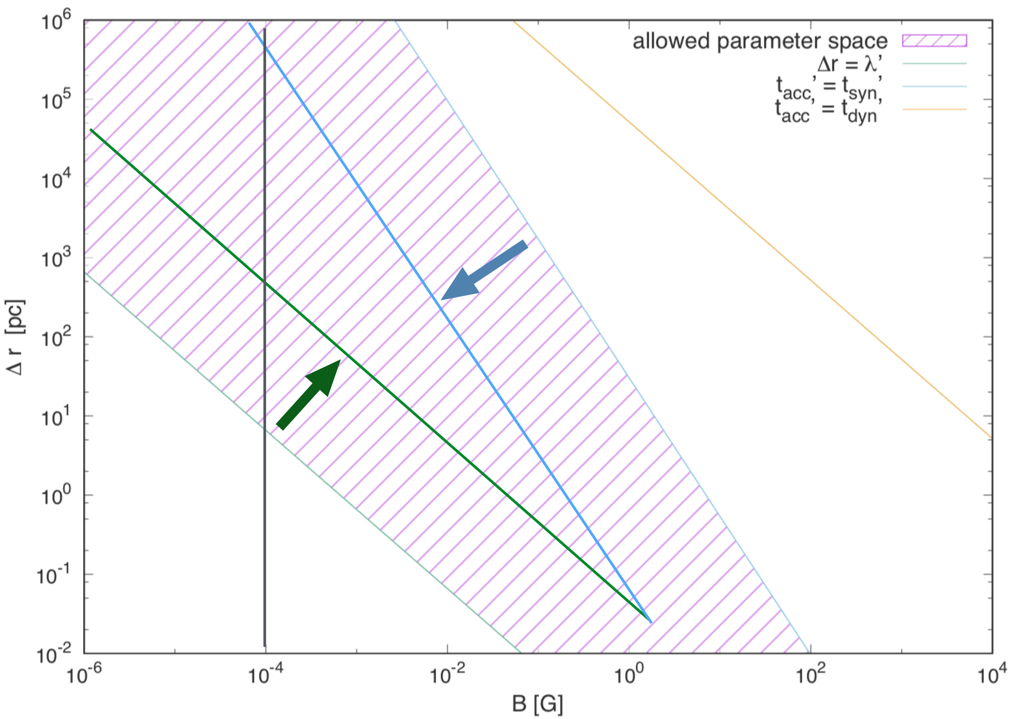

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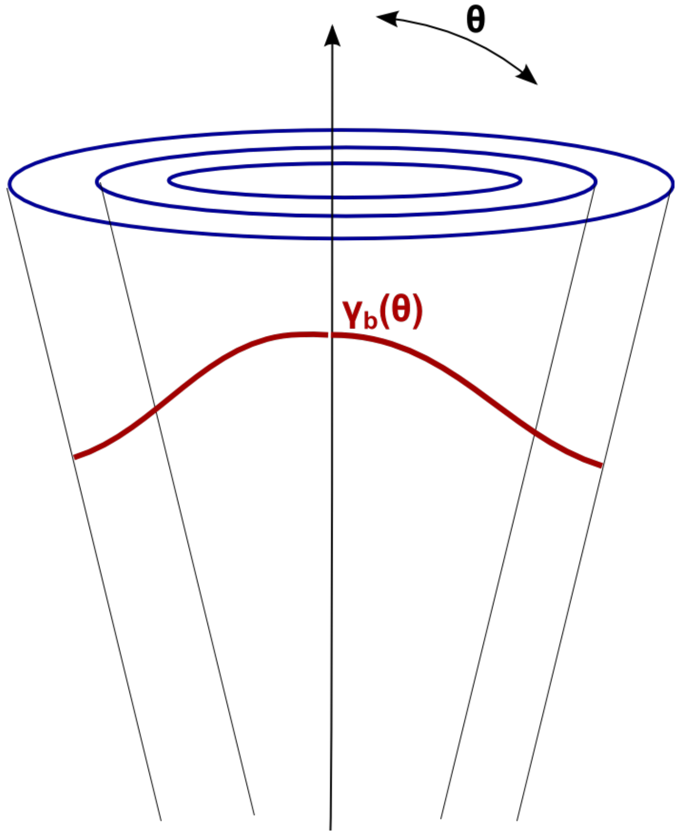
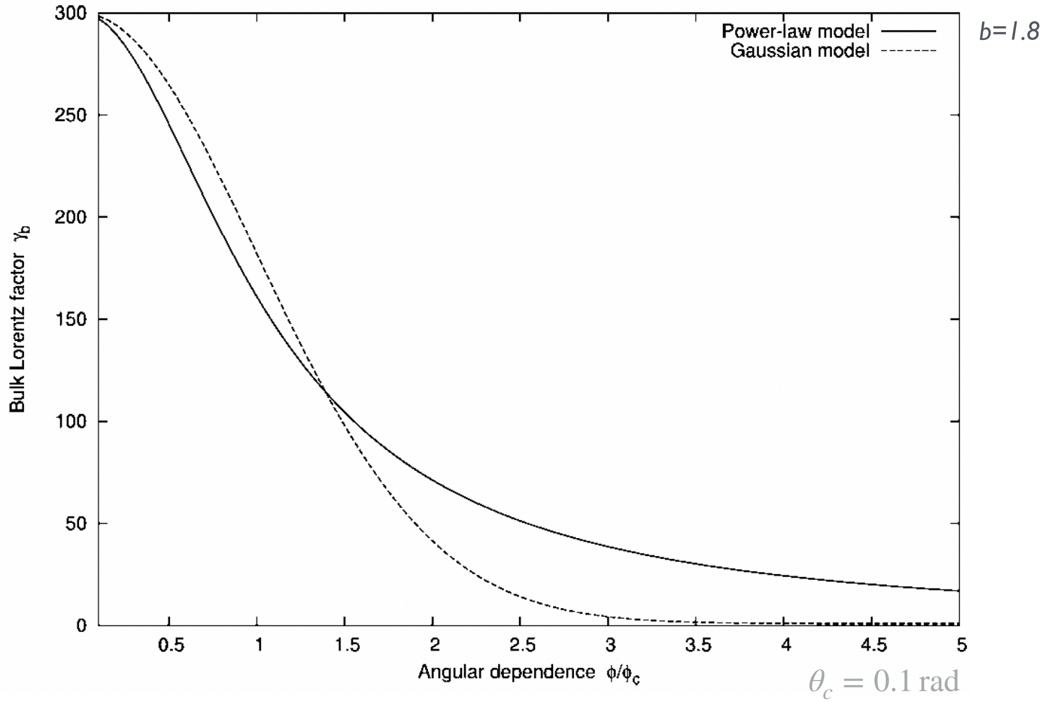
On shear particle acceleration in structured GRB flows

Shear acceleration in expanding relativistic outflows (“universal structured jet”)

- Flow profile: $u^\alpha = \gamma_b(\theta)\ (1,\ v_r(\theta)/c\ ,\ 0,\ 0)$ θ = polar angle
- power-law and Gaussian type profile for γ_b :



Example: $\gamma_0 = 300$



(FR & Duffy 2005 & 2016)

Relativistic Particle Transport Equation [incl. spatial transport]

Particle Transport Equation (PTE) - mixed frame - for isotropic distribution function $f_0(x^\alpha, p)$, with $x^\alpha = (ct,x,y,z,)$ and metric tensor $g_{\alpha\beta}$

(fluid four velocity u^α and fluid four acceleration $\mathring{u}_\alpha = u^\beta u_{\alpha;\beta}$)

$$\nabla_\alpha \left[c u^\alpha f_0 - \kappa (g^{\alpha\beta} + u^\alpha u^\beta) \left(\frac{\partial f_0}{\partial x^\beta} - \dot{u}_\beta \frac{(p^0)^2}{p} \frac{\partial f_0}{\partial p} \right) \right]$$
$$+ \frac{1}{p^2} \frac{\partial}{\partial p} \left[-\frac{p^3}{3} c u^\beta_{;\beta} f_0 + p^3 \left(\frac{p^0}{p} \right)^2 \right.$$
$$\left. \times\ \kappa \dot{u}^\beta \left(\frac{\partial f_0}{\partial x^\beta} - \dot{u}_\beta \frac{(p^0)^2}{p} \frac{\partial f_0}{\partial p} \right) - \Gamma \tau p^4 \frac{\partial f^0}{\partial p} \right] = Q.$$

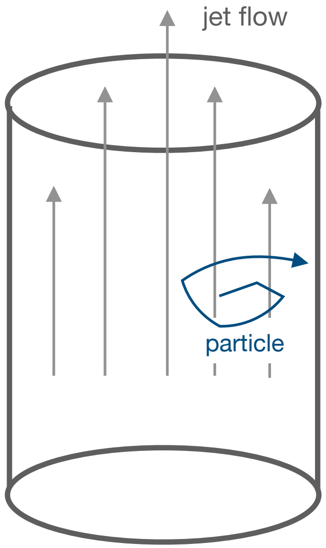
(Webb 1989; cf. also FR & Mannheim 2002; Webb+ 2018)

shear term

Γ relativistic shear coefficient

Note: for steady shear flow profile $\vec{u} = u(r)\vec{e_z}$, fluid four acceleration $\dot{u}_\beta = 0$ and divergence $\nabla_\beta u^\beta = 0$

On continuous electron acceleration in large-scale AGN jets



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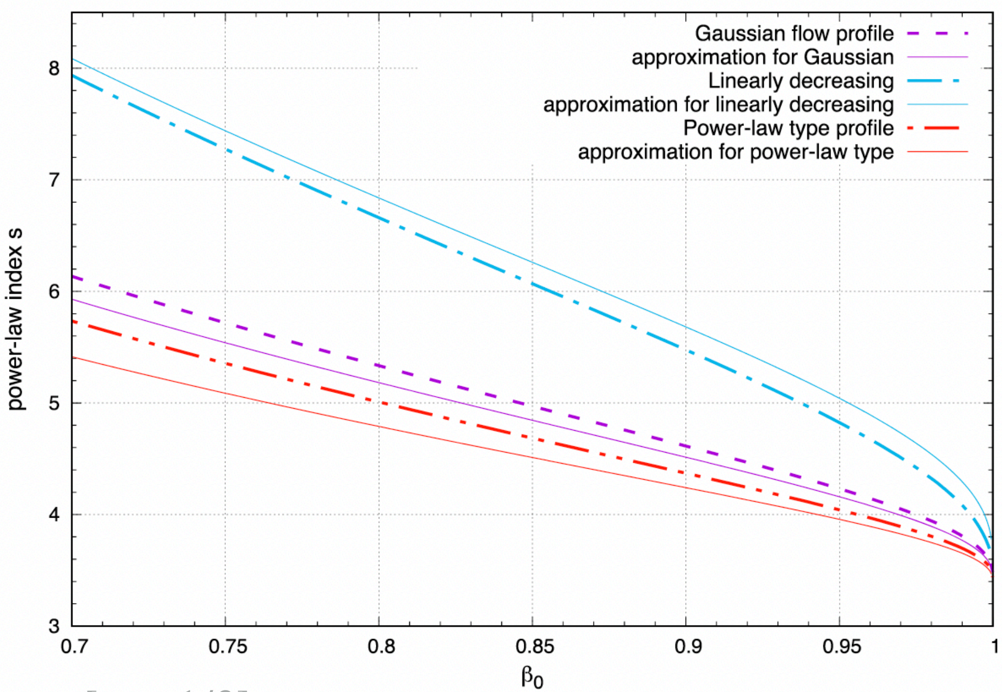

$[\alpha = 1/3]$

Solve full PTE for cylindrical shear flow without radiative losses

- at ultra-relativistic flow speeds, universal PL index recovered: $f \propto p^{-s}$ with $s \rightarrow (3+\alpha)$
- at mildly relativistic flow speeds, PL index gets softer & becomes sensitive to flow profile
- 1st-order FP-type approximation possible…

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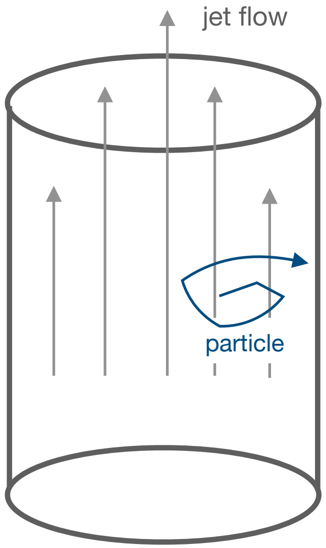

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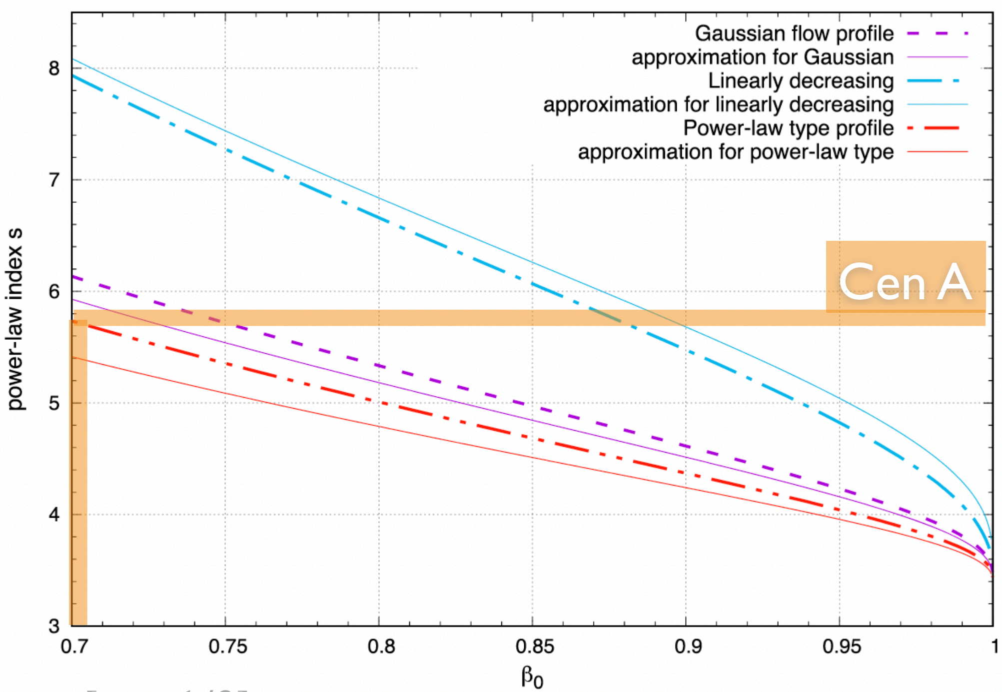

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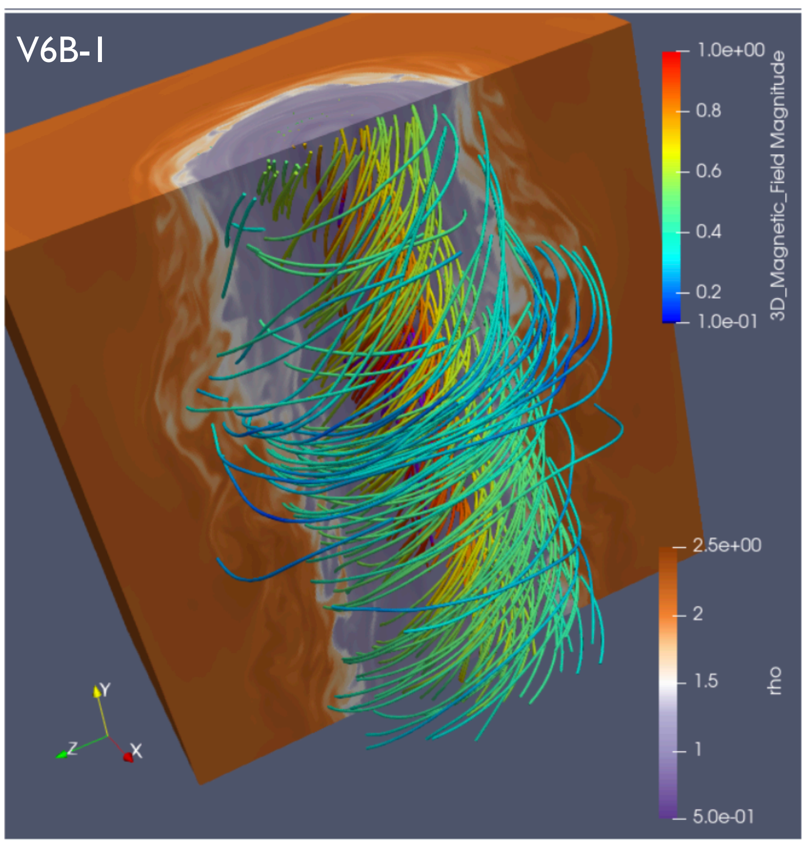
allows to constrain flow profile through observed PL index….

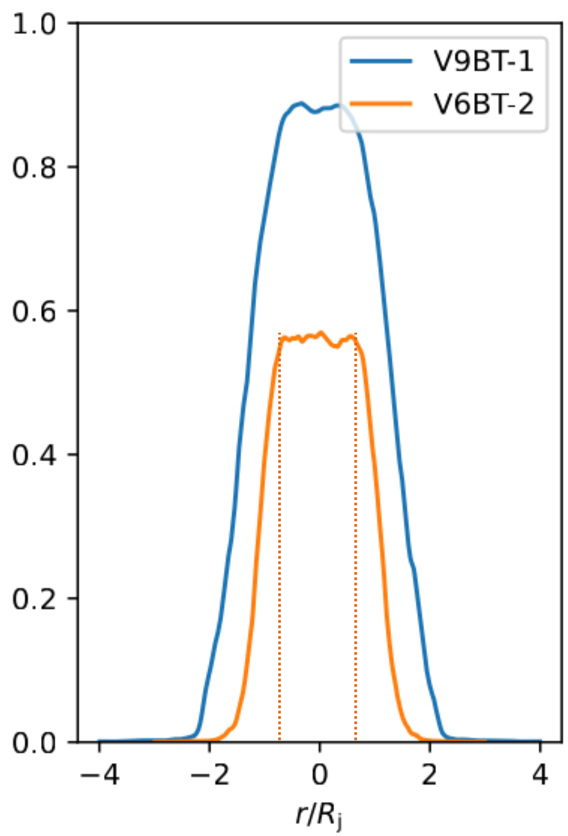
Outlook

on sheath formation in large-scale relativistic jets *(Wang,..FR..2022, MNRAS accept.)*

- employ 3D relativistic MHD jet simulations (PLUTO)
- study sheath formation in kinetically dominated jets (KHI; $\sigma<1$)
- extract shear flow profile for particle acceleration…



jet structure and KHI evolution



averaged flow velocity profiles

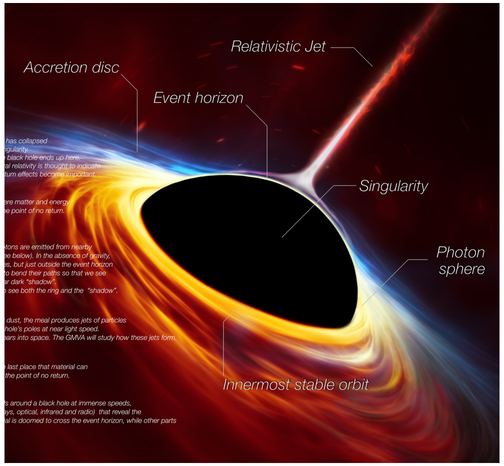
Parameters:

V9BT-1: v_j=0.9c, σ=0.2, $L_j \approx$3E46 erg/s

V6BT-2: v_j=0.6c, σ=0.02, $L_j \approx$5E43 erg/s

Summary

Supermassive Black Holes as Cosmic Particle Accelerators



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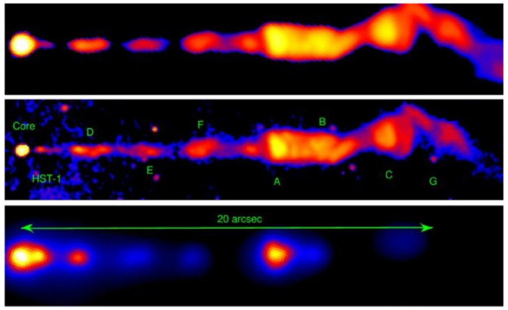
  - plasma source for driving continuous outflows (BZ)…
  - rapid VHE flaring as observable signature…



- **shear acceleration in the relativistic large-scale jet of AGNs**
  - 'natural' mechanisms providing ultra-relativistic electrons…
  - large-scale jets as possible UHE accelerators….

On bridging scale-separation…

- lots of exploration space…lots of work to do…

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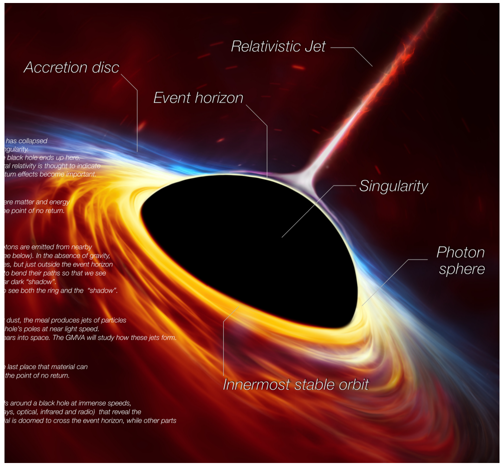

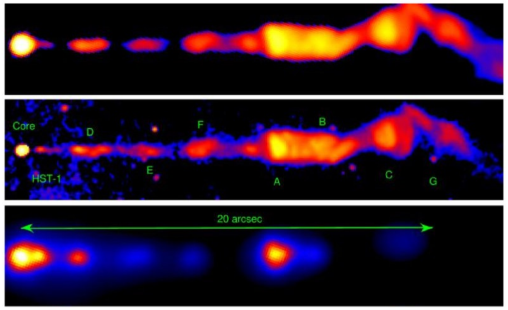

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Thank you!
&
Questions ?