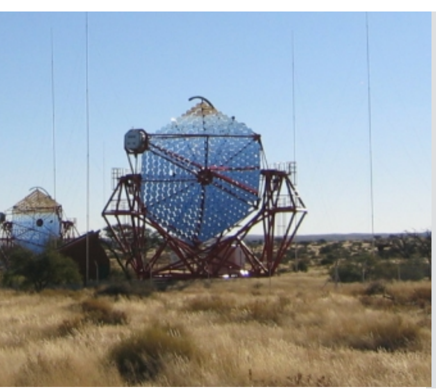
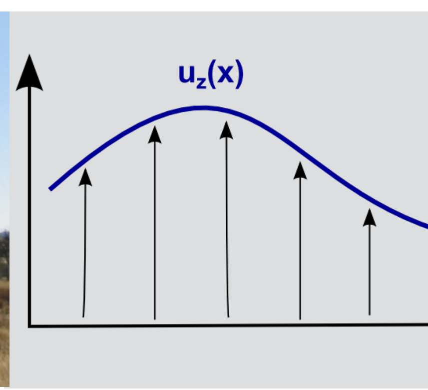
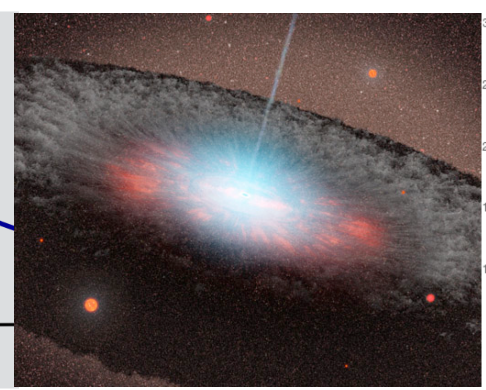
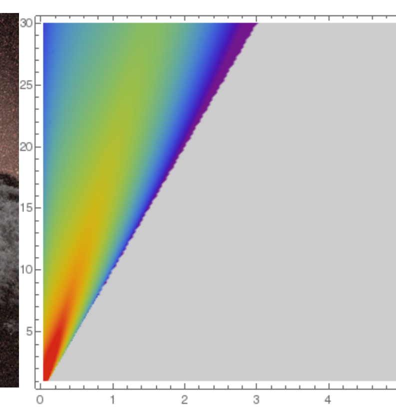
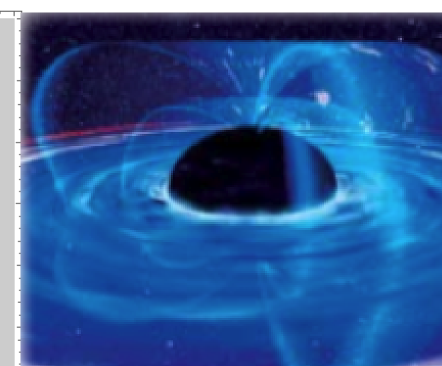
Theory of Gamma-ray loud AGN

Frank M. Rieger

7th International Symposium on High-Energy Gamma-Ray Astronomy

Barcelona, July 4, 2022

ITP Univ. Heidelberg

Max Planck Institut für Kernphysik
Heidelberg, Germany

Real pleasure to see Gamma2022 taking place in Barcelona….

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Excuses & Disclaimer

Not going to talk about:

- AGN multiwavelength radiation & related issues…

  ⇒ *Paolo Padovani*

- multi-messenger, neutrino & UHECR connection…

  ⇒ *Teresa Montaruli, Elisa Resconi & Angela Olinto*

- fundamental physics, GW & dark matter searches…

  ⇒ *Javier Rico, Marica Branchesi…*

- reconnection…

  ⇒ *Lorenzo Sironi…*

What I am going to talk about (Outline)

- Gamma-Ray Loud AGN
  - *Extragalactic HE-VHE (Short Status Summary)*
- On Challenges & Progress in (jetted) AGN Physics
- Selected Theoretical Advances:
  - *Magnetospheric Processes in AGN (conceptual)*
  - *Modelling Parsec-Scale Jet Emission in Blazars (physics)*
  - *Understanding large-scale jet emission (conceptual & methodological)*

Gamma-Ray Loud AGN

Extragalactic HE-VHE (Short Status Summary)

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

Radio-loud ***Active Galaxy***

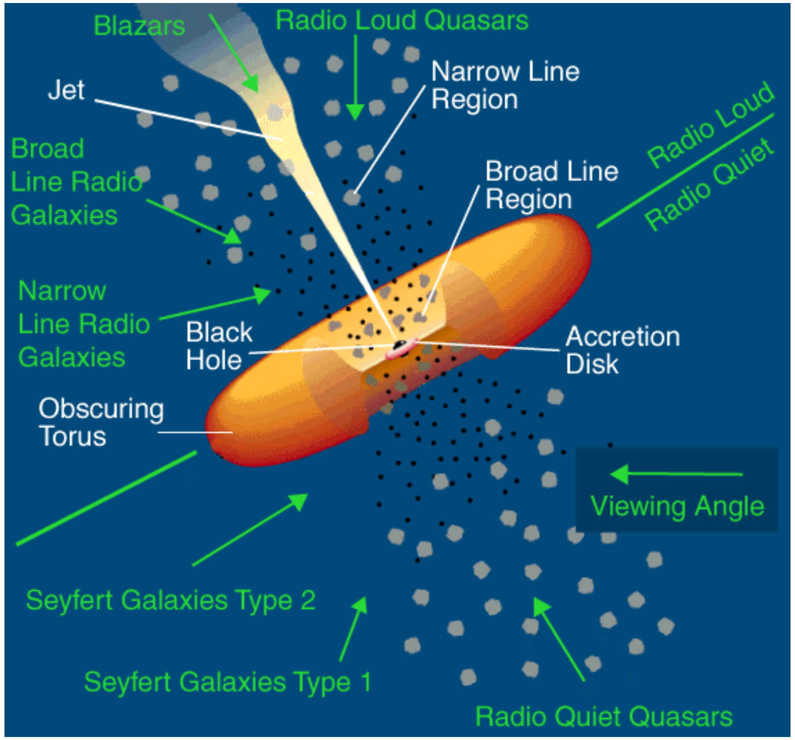
"jetted AGN"

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

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

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

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



Central engine in AGN & unification (Urry & Padovani)

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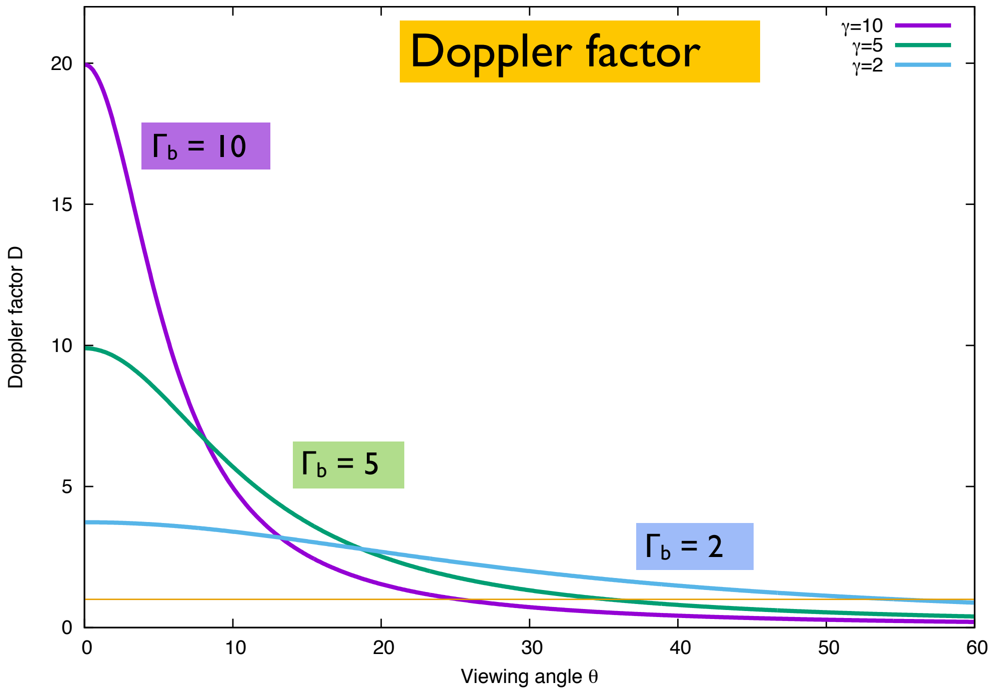
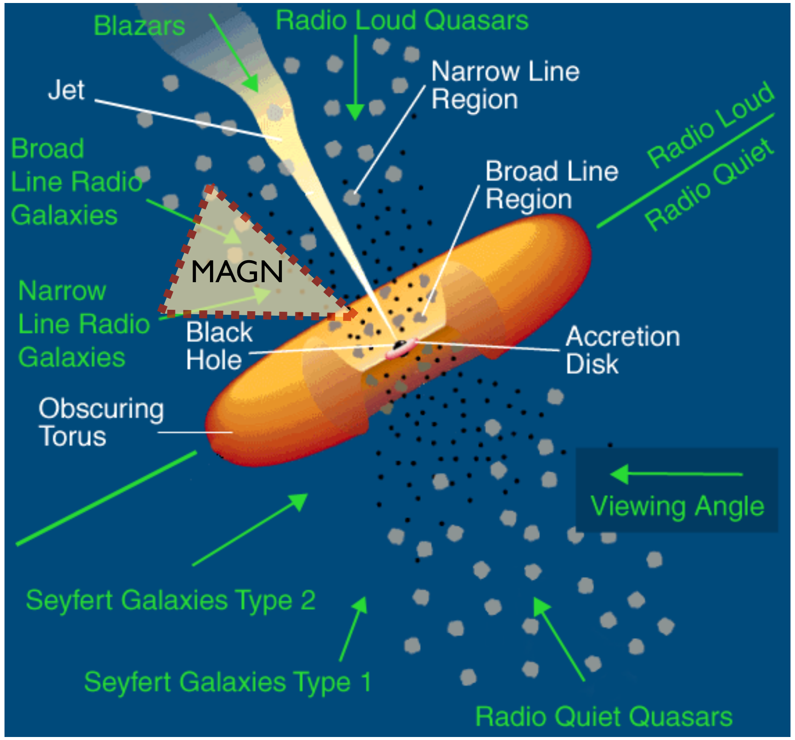
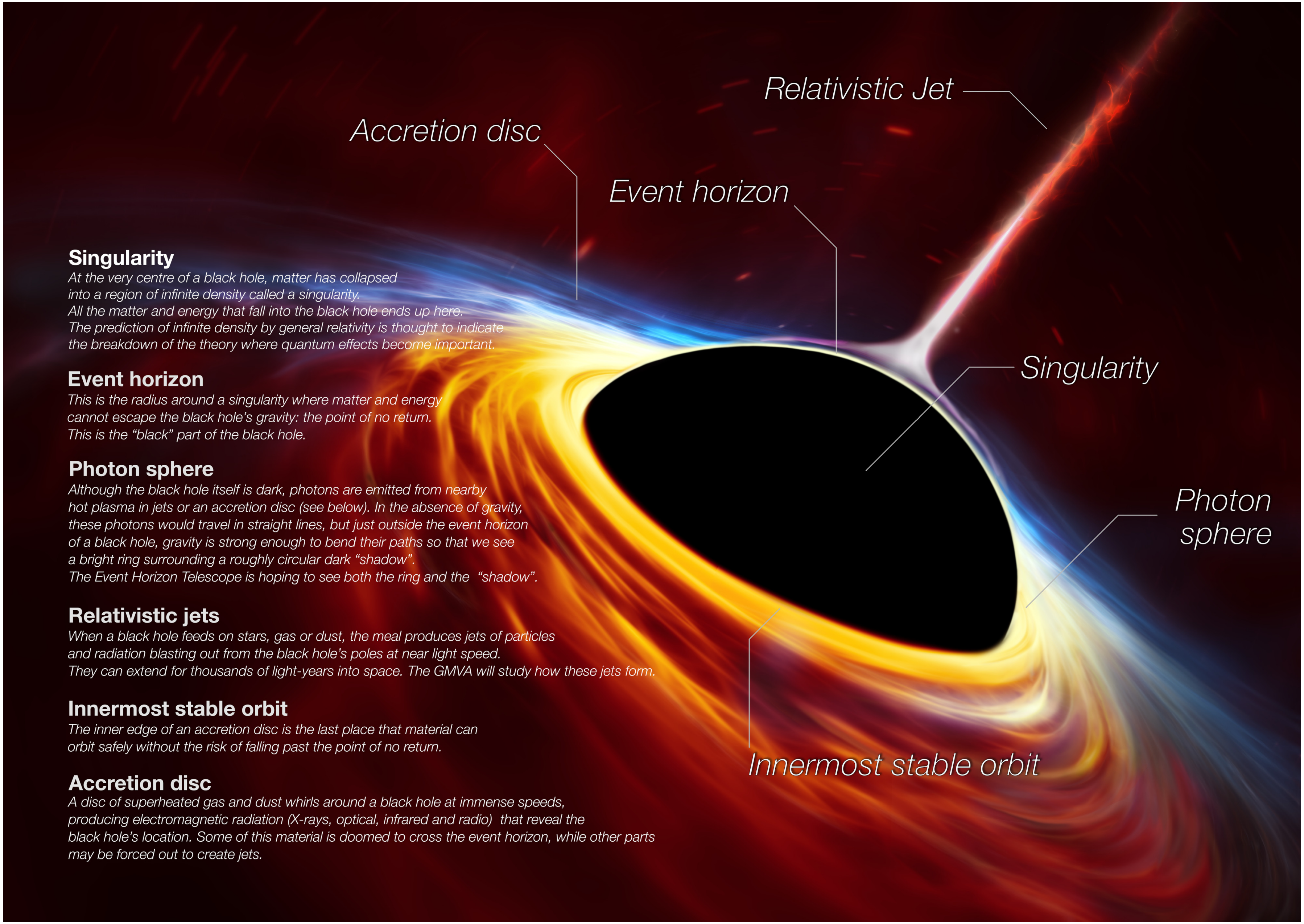




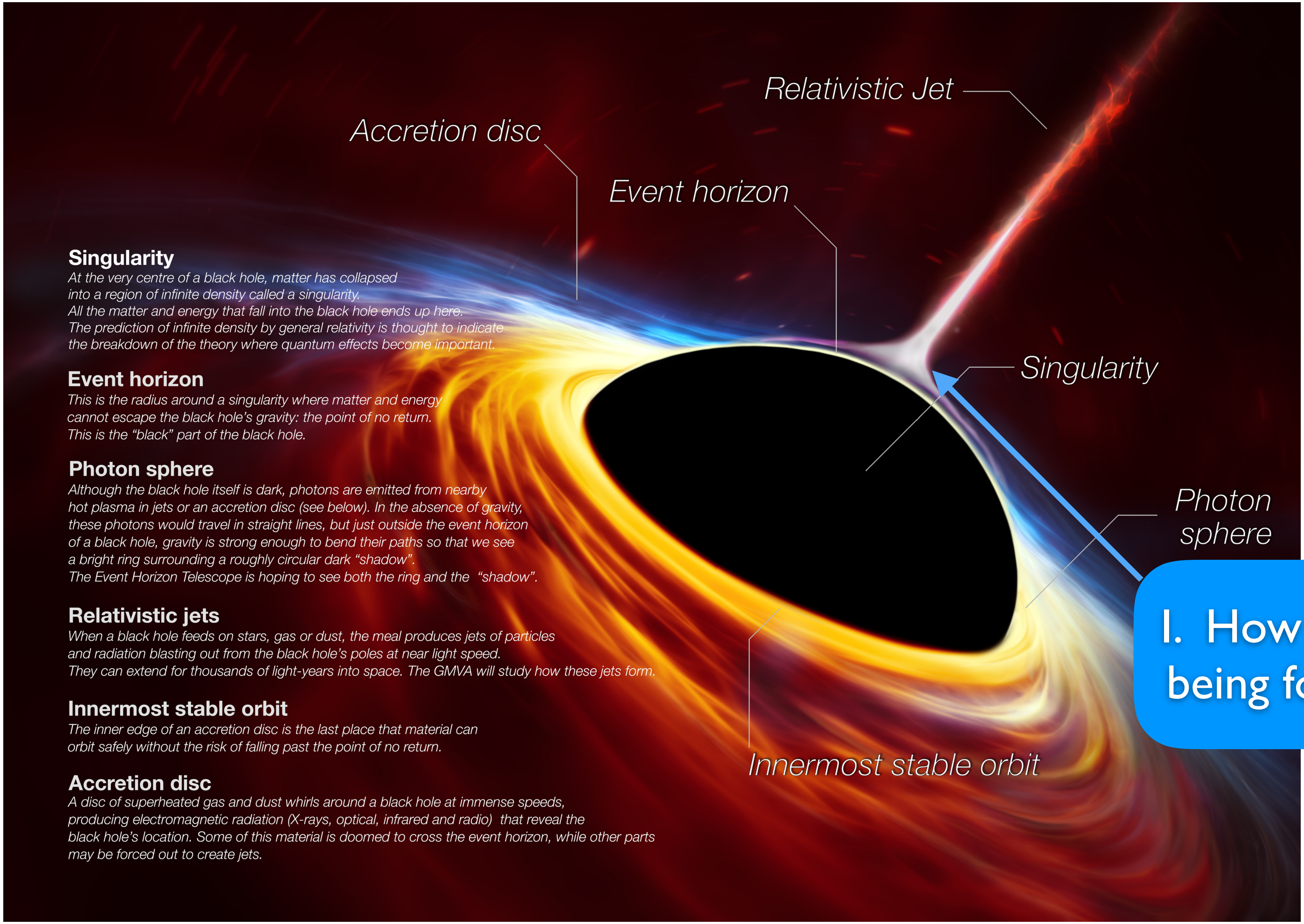
Central engine in AGN & unification
(Urry & Padovani)

Some Key Questions in AGN Physics



Credit: ESO

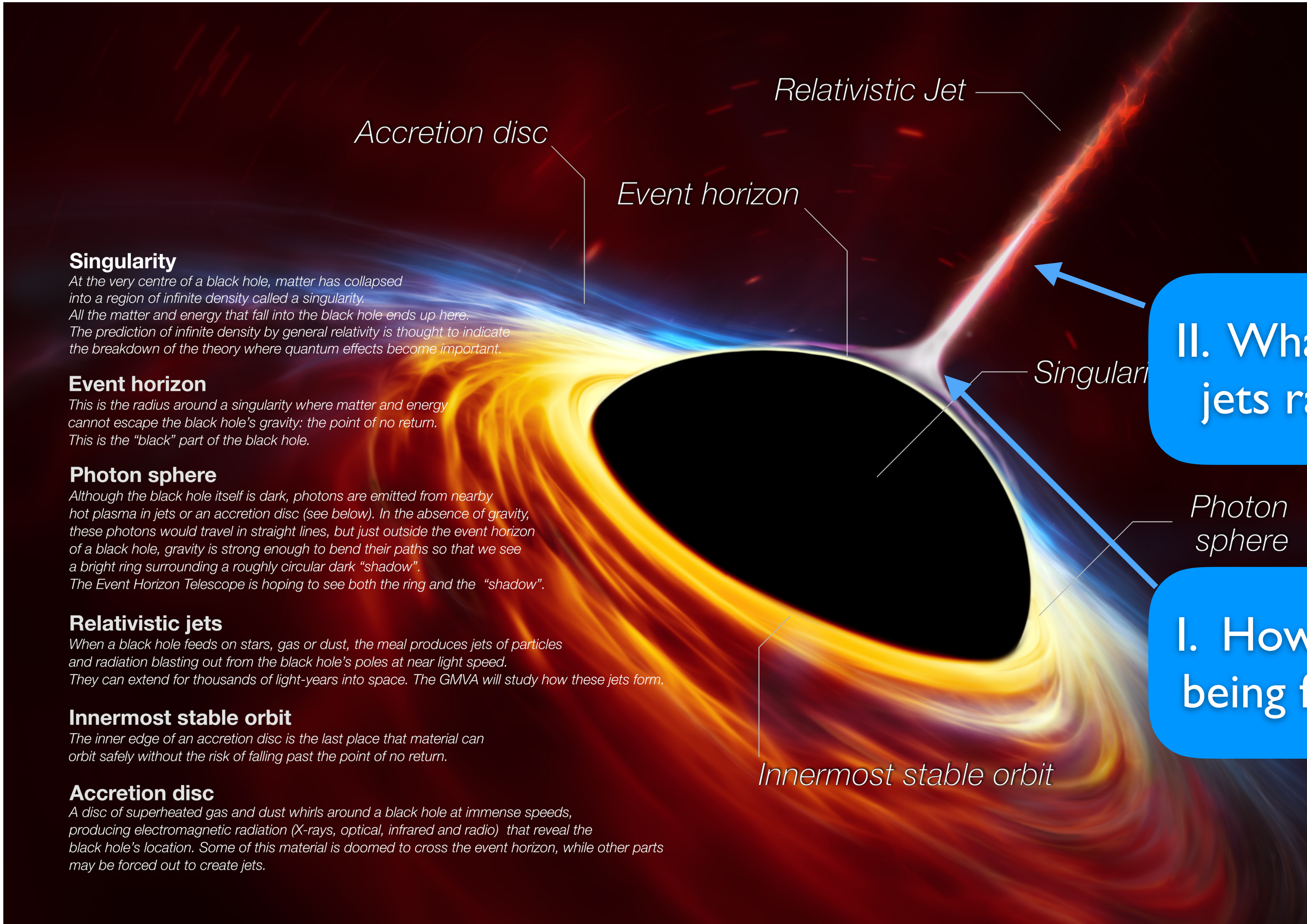
Some Key Questions in AGN Physics



1. How are jets being formed ?

Credit: ESO

Some Key Questions in AGN Physics

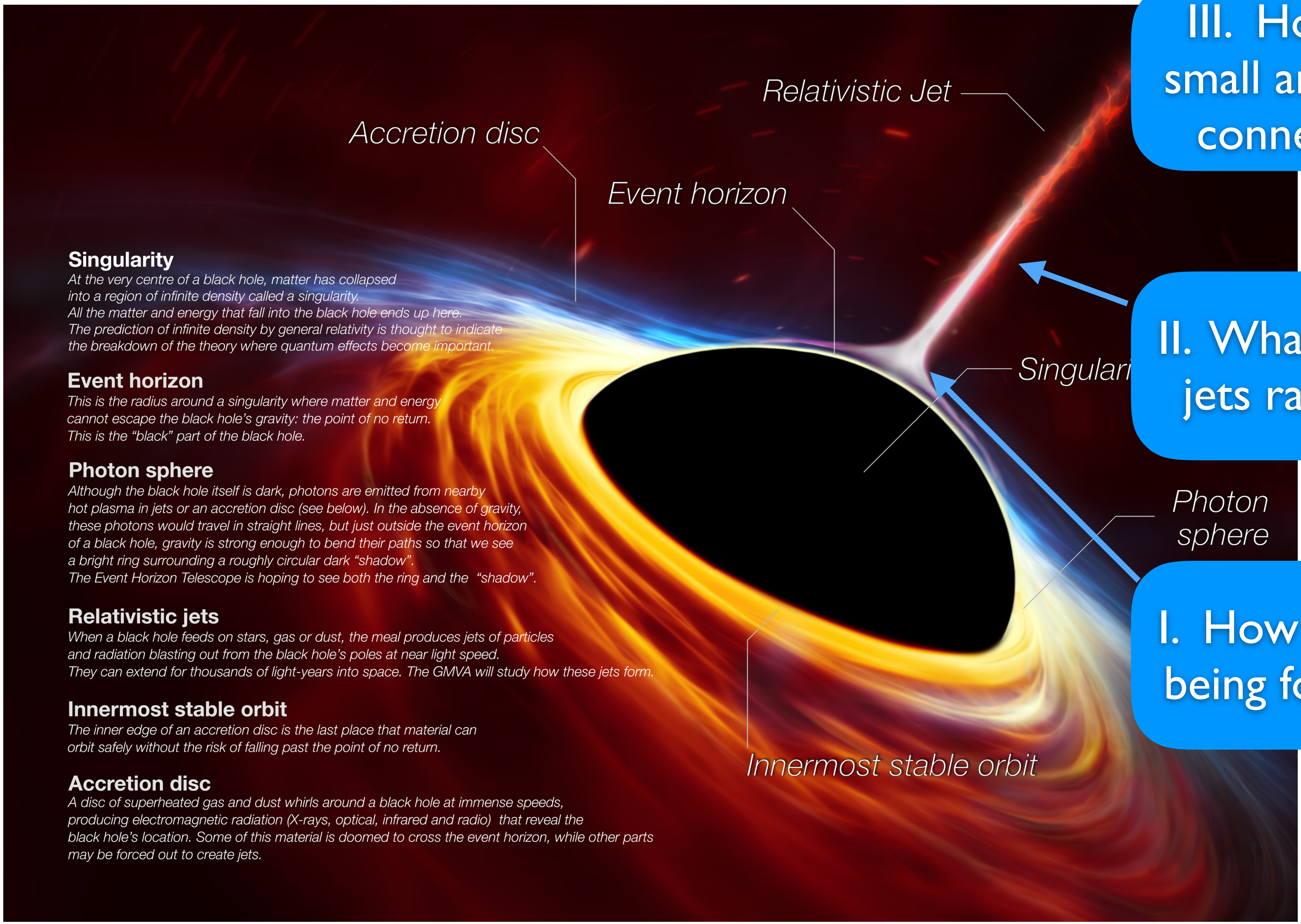


II. What makes jets radiate ?

I. How are jets being formed ?

Credit: ESO

Some Key Questions in AGN Physics



III. How are small and large connected?

II. What makes jets radiate ?

I. How are jets being formed ?

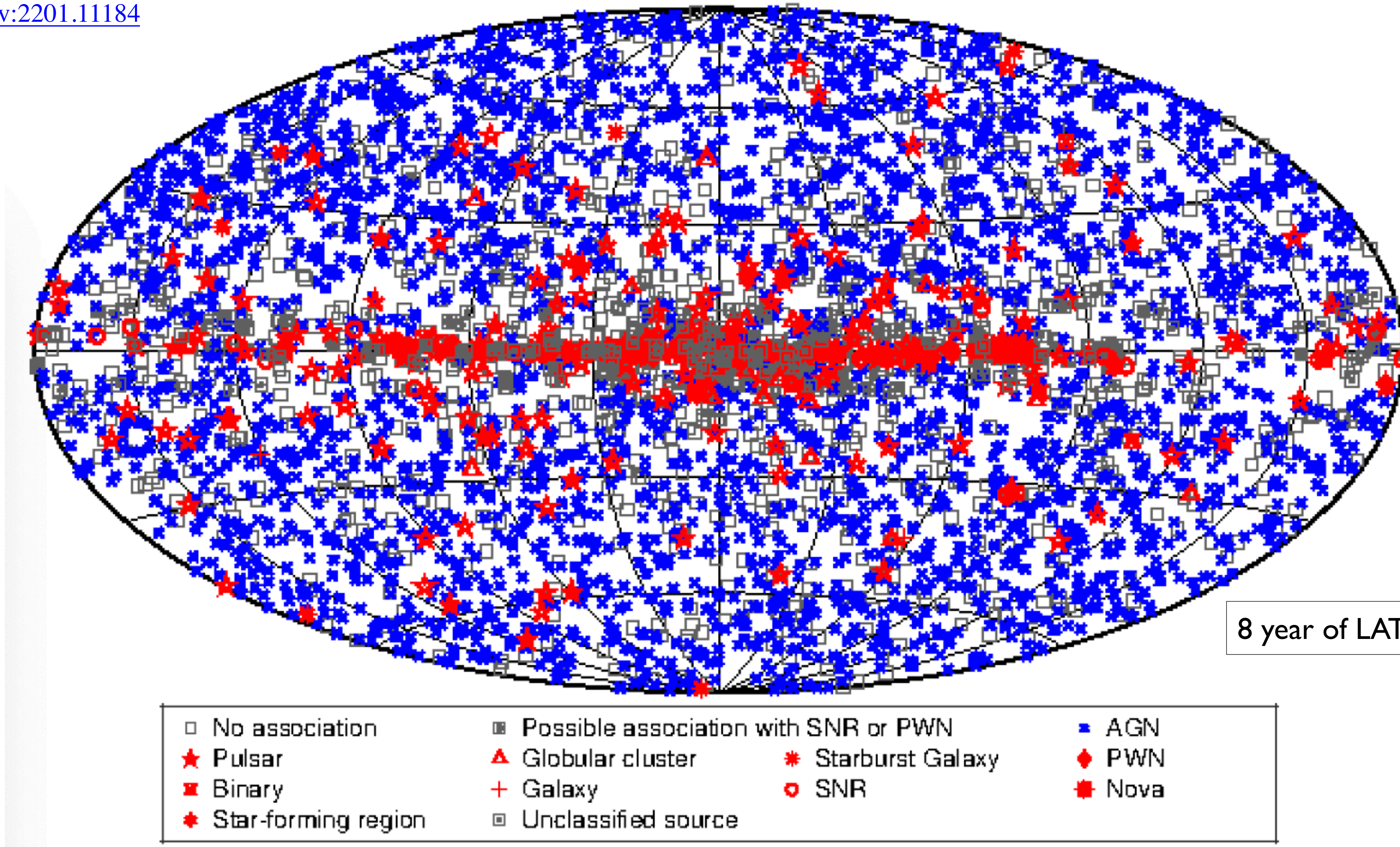
Credit: ESO

The Extragalactic HE Sky (Status)

Fermi-LAT Collab. 2020 & 22

arXiv:1902.10045
arXiv:2201.11184

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



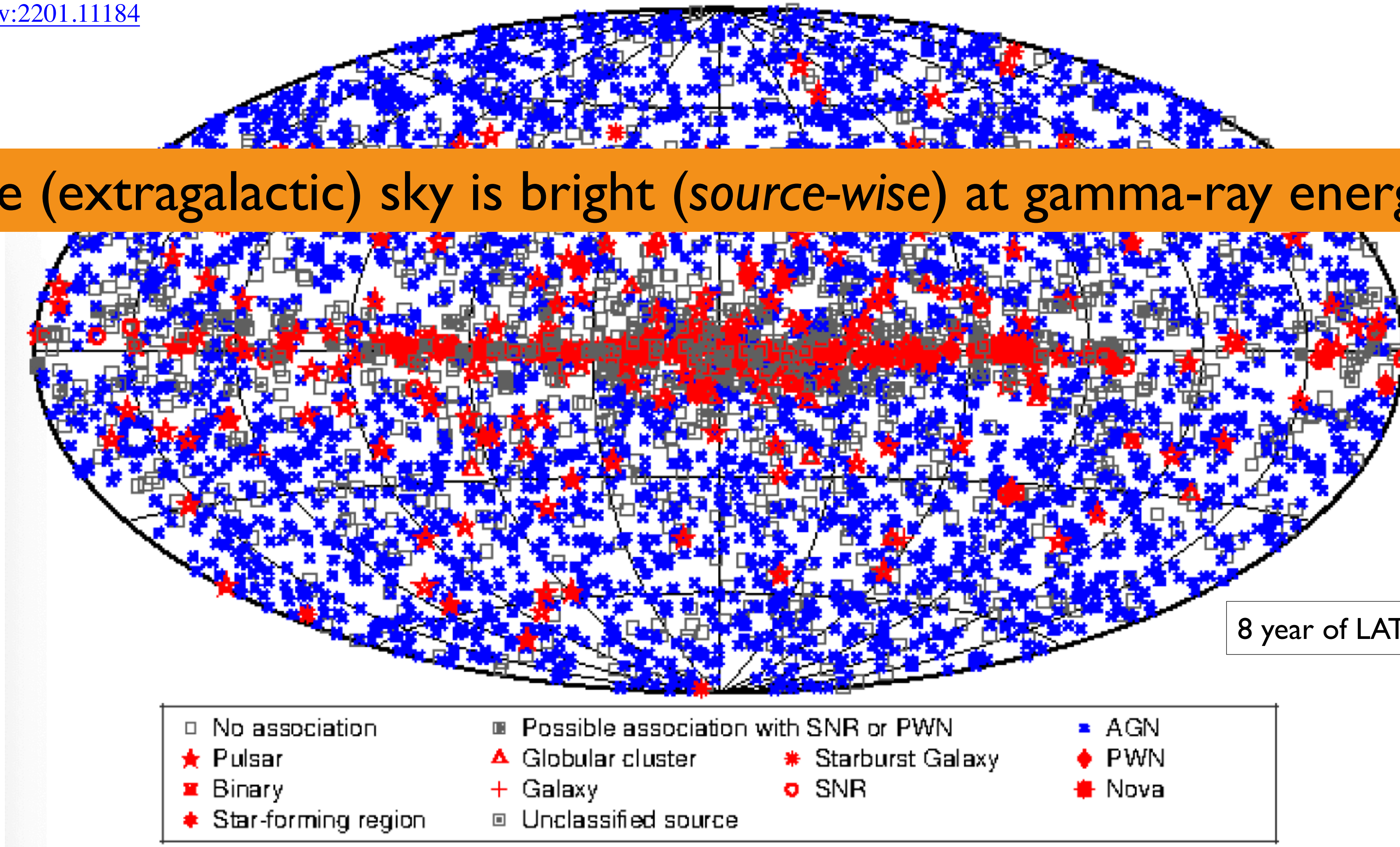
8 year of LAT data

The Extragalactic HE Sky (Status)

Fermi-LAT Collab. 2020 & 22
arXiv:1902.10045
arXiv:2201.11184

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

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



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…

The Extragalactic VHE Sky (Status)

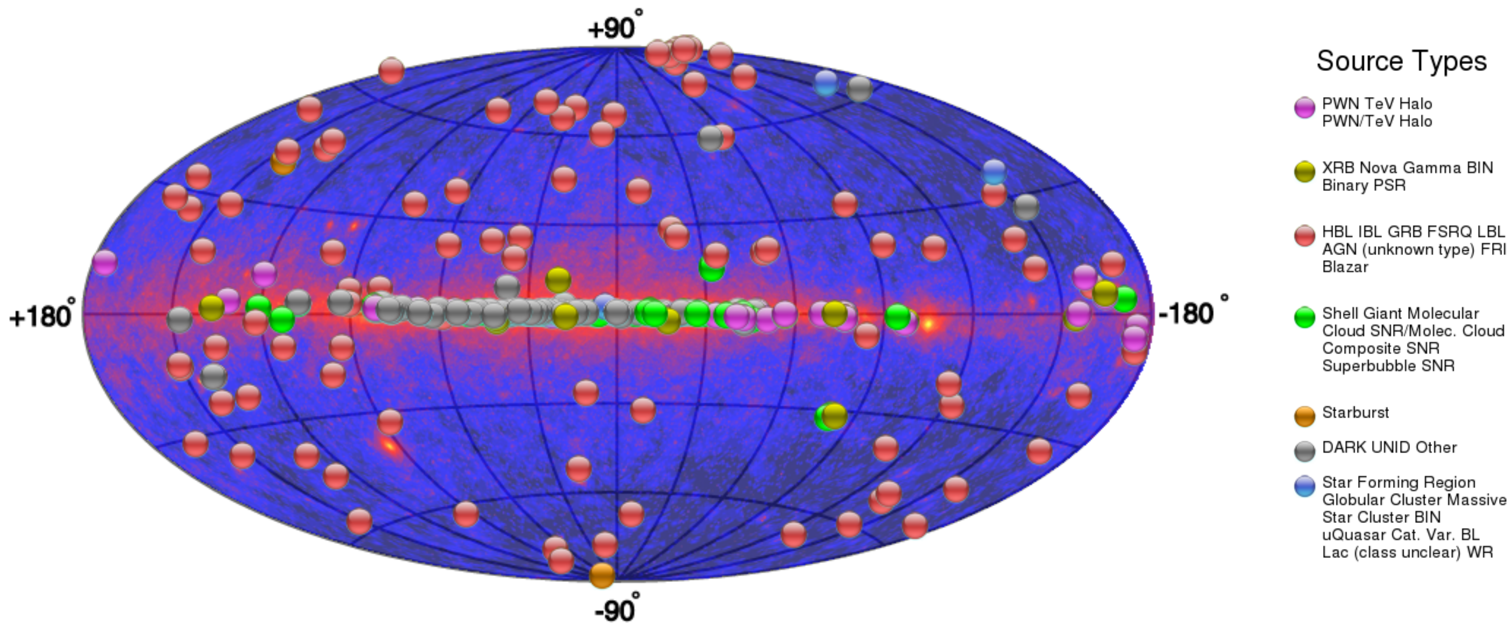
TeVCat (2022):

>250 sources

~ 85 AGN

mostly BL Lacs

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



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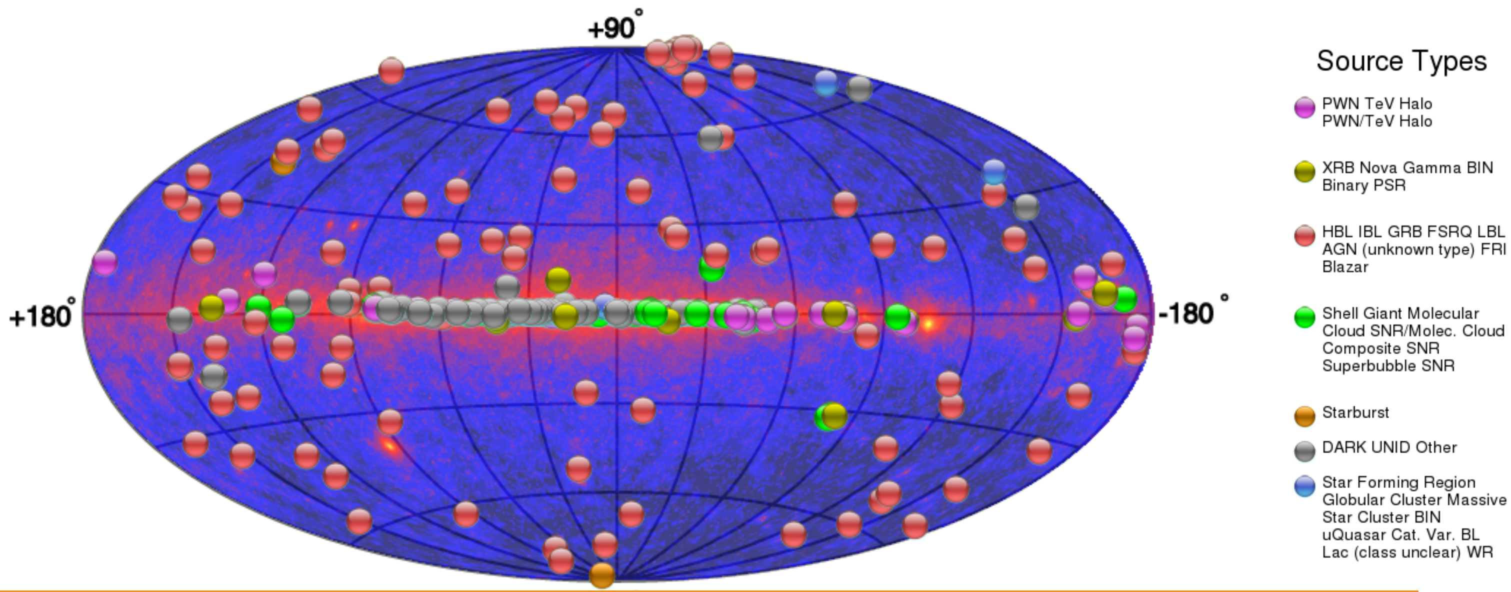
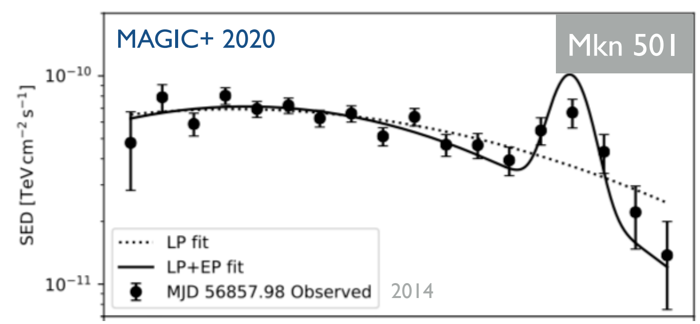


From "simple" source detection to the physics of sources

Spectral (photon) distribution

smoothness, curvature, breaks, extension, precision….

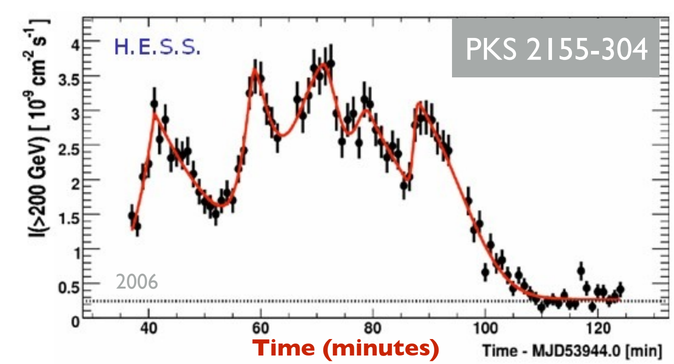
➪ maximum particle energy, emission process…



Timing capabilities (light curves)

Variability, outbursts/active states, regularities….

➪ timescales, physical triggers, location, geometry…



Non-Blazar Objects / MAGN as seen by Fermi-LAT (Status)

for the physics case, see e.g. FR & Levinson 2019 [review]

name	flux 1 100 gev [photon/cm^2/s]	detection significance [sigma]	spectrum type	assoc name	pl index	tevcat assoc	source type
4FGL J1324.0-4330e	3.7002e-09	35.1073	LogParabola	Cen A Lobes	2.5172		RDG
4FGL J1325.5-4300	3.5857e-09	73.5350	PowerLaw	Cen A	2.5911	Centaurus A	RDG
4FGL J0433.0+0522	7.7690e-10	24.5960	LogParabola	3C 120	2.7625		RDG
4FGL J0316.8+4120	2.5167e-10	9.2602	PowerLaw	IC 310	1.8478	IC 310	RDG
4FGL J0322.6-3712e	5.5896e-10	18.4001	PowerLaw	Fornax A	2.0537		RDG
4FGL J0319.8+4130	3.3759e-08	245.4858	LogParabola	NGC 1275	2.1136	NGC 1275	RDG
4FGL J0627.0-3529	1.2646e-09	39.4164	PowerLaw	PKS 0625-35	1.9114	PKS 0625-35	rdg
4FGL J0009.7-3217	2.0176e-10	9.0697	PowerLaw	IC 1531	2.2399		rdg
4FGL J2227.9-3031	1.1062e-10	6.3087	PowerLaw	PKS 2225-308	1.8003		rdg
4FGL J2341.8-2917	1.7410e-10	7.4609	PowerLaw	PKS 2338-295	2.2444		rdg
4FGL J0958.3-2656	1.6787e-10	6.8136	PowerLaw	NGC 3078	2.1579		rdg
4FGL J1306.7-2148	5.2204e-10	14.3777	LogParabola	PKS 1304-215	2.1266		rdg
4FGL J2329.7-2118	4.0031e-10	12.4182	PowerLaw	PKS 2327-215	2.4532		rdg
4FGL J2302.8-1841	2.0032e-10	8.8755	PowerLaw	PKS 2300-18	2.2577		rdg
4FGL J0038.7-0204	1.7722e-10	9.4753	PowerLaw	3C 17	2.8397		rdg
4FGL J2326.9-0201	2.2694e-10	8.4645	PowerLaw	PKS 2324-02	2.5875		rdg
4FGL J1516.5+0015	3.0255e-10	9.9088	PowerLaw	PKS 1514+00	2.5078		rdg
4FGL J0237.7+0206	1.3551e-10	5.8586	PowerLaw	PKS 0235+017	2.1045		rdg
4FGL J0308.4+0407	8.4397e-10	24.7727	PowerLaw	NGC 1218	2.0020		rdg
4FGL J1521.1+0421	1.2635e-10	4.4093	PowerLaw	PKS B1518+045	2.0383		rdg

45 radio galaxies in Fermi-LAT 12-year Point Source Catalog (4FGL-DR3)

4FGL (+DR3)

3743 blazars

~70 non-blazar AGN

45 radio galaxies

(in DR3)

among them

22 FR I

14 FR II

2 SSRQ

8 NLSy1

2 Seyfert

5 CSS

9 others

(cf. also Rulten 2022)

Expectation: SSC jet models for radio galaxies - Reminder

The BL Lac heart of Centaurus A L35

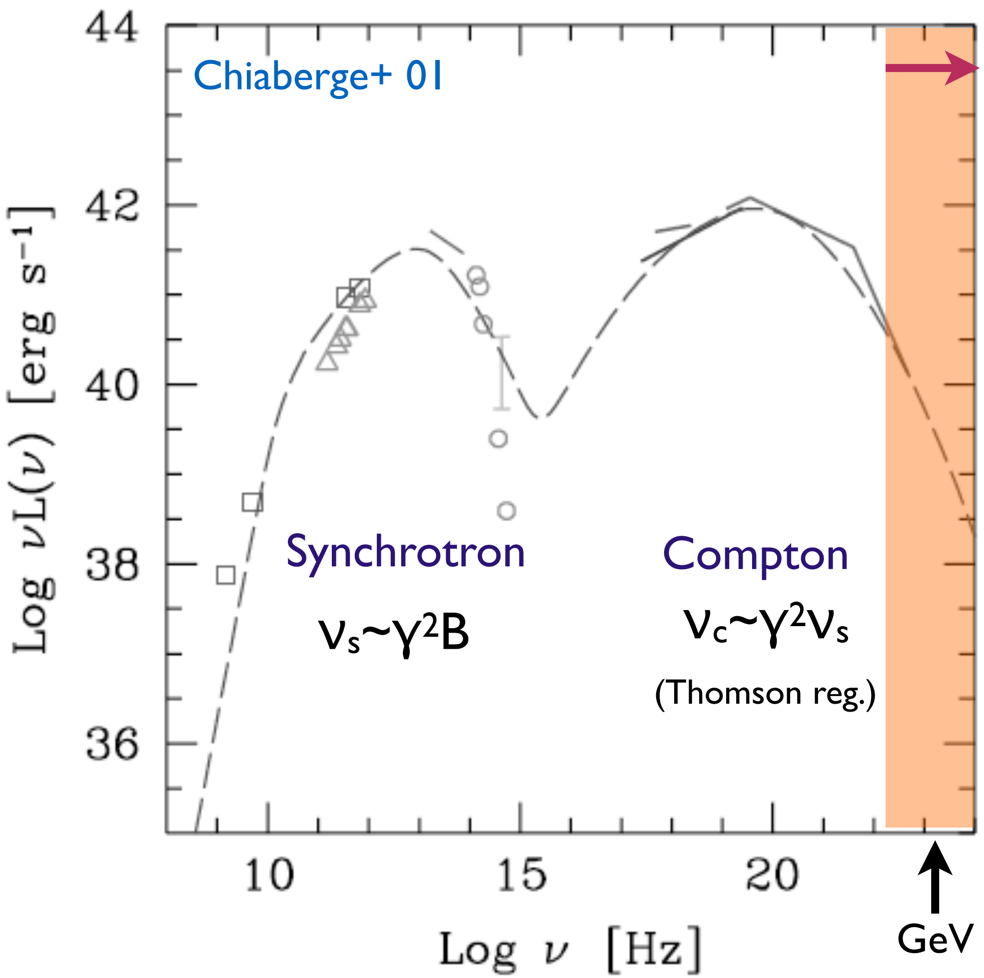


Figure 2. The nuclear SED of Centaurus A. The empty circles represent the optical and near-infrared luminosities dereddened with $A_V = 8$. The dashed line is the prediction of the SSC model described in the text. The large error bar represents the optical luminosity predicted using the radio–optical core flux correlation for FR I found by Chiaberge et al. (1999).

Table 1. Model parameters for the SED of Centaurus A.

R	1.2×10^{16} cm	p	3.0
B	0.5 G	γ_{min}	2×10^3
δ	1.2	γ_{max}	1×10^4
L_{inj}	2.7×10^{42} erg s^{-1}	t_{esc}	$10 \times Rc$

L_{inj} is the injected power (in particles of energy equal to $\gamma m_e c^2$).

if non-thermal emission in radio galaxy is SSC-jet type (misaligned BL Lac) then we may expect to see some of them at high energies with FERMI, but not much in TeV

VHE detection of misaligned AGN / RG (Status)

Out of ~45 HE radio galaxies (3743 Fermi-blazar) only 6 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	50	✔	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	✔	
PKS 0943-76		FR 2	1360 Mpc			
......						

(e.g., FR & Levinson 2019, Rulten 2022)

On the potential theory-relevance of gamma-ray emitting NL Sy1

cf. D'Ammando 2019 [review]

Narrow Line Seyfert I:

- high-Eddington sources, small BH masses (~10^{6-8} $M_\odot$), spiral galaxy host ?

HE-emitting (radio-loud) NL Sy I as jetted AGN

- evidence for the presence of one-sided jets, superluminal motion, strong variability

➡ "blazar-like" properties

➡ ***origin & formation of jets ?***

- BH mass limit, accretion state, spin-merger history

But note:

- BH masses in radio-loud NLSy 1 on average larger;
- emerging evidence for HE emitting, radio-loud NLSy 1 hosted by ellipticals?

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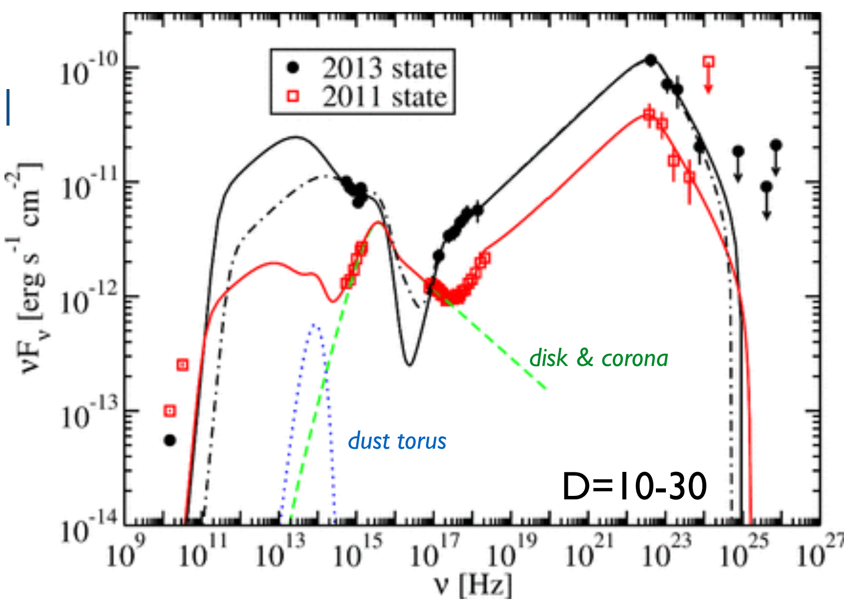
PMN J0948+0022 (z=0.584) D'Ammando+ '15



- no VHE emission yet seen from NL Sy1
  - double-humped shaped SED (synchrotron-IC)
  - HE due to external Compton (BLR, dust torus)
  - no VHE due to EBL or BLR absorption?

On Challenges & Progress in (jetted) AGN Physics

On Challenges & Progress in (jetted) AGN Physics

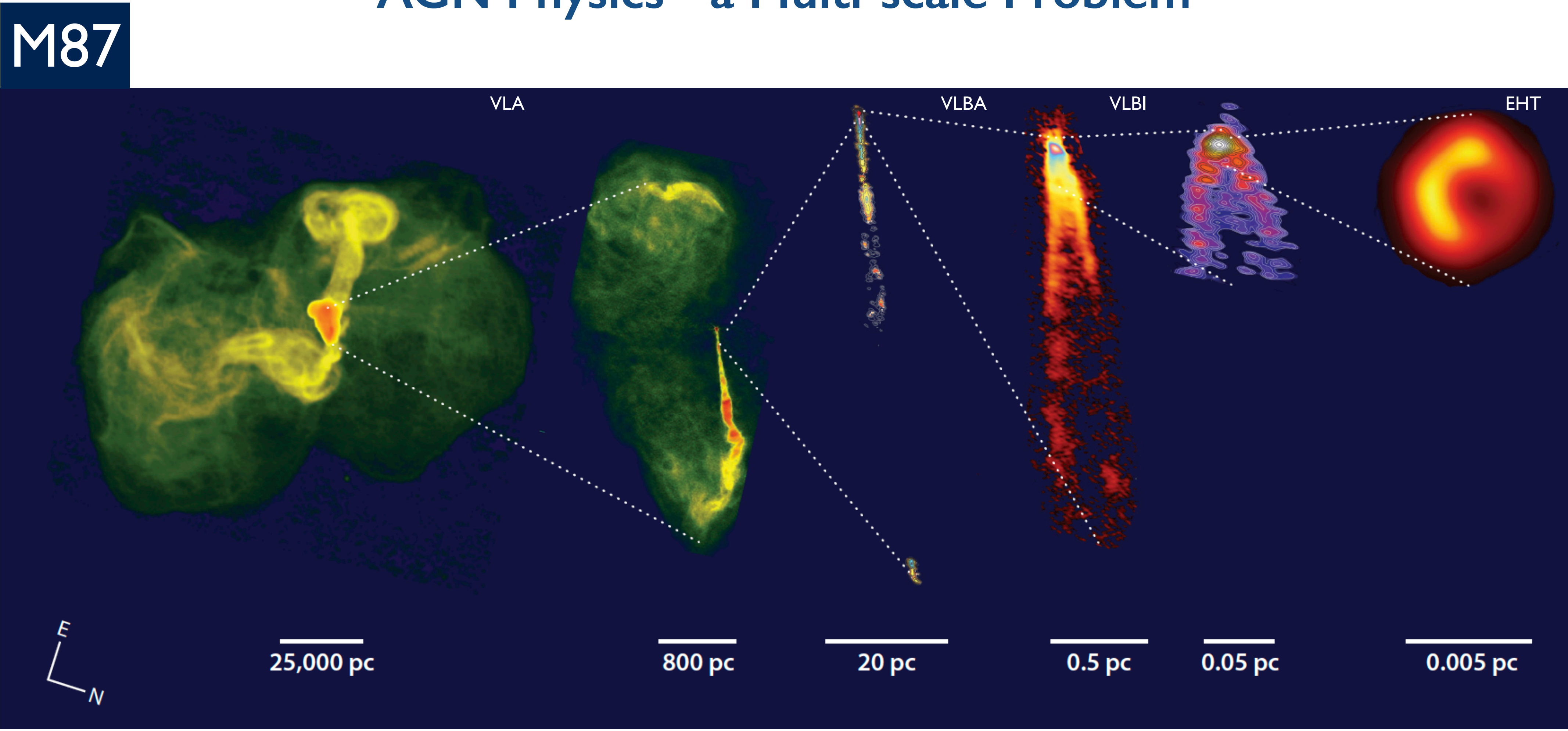
- a not (so) unbiased view…

I apologize in case I may miss to mention your work,

but I hope that I can set the scene for it….

Gaudi & Parc Güell @ Barcelona

AGN Physics - a Multi-scale Problem



Blandford+2019

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

The general challenge

*translates into **physics & modelling challenge…***

(Credits: Amir Levinson)

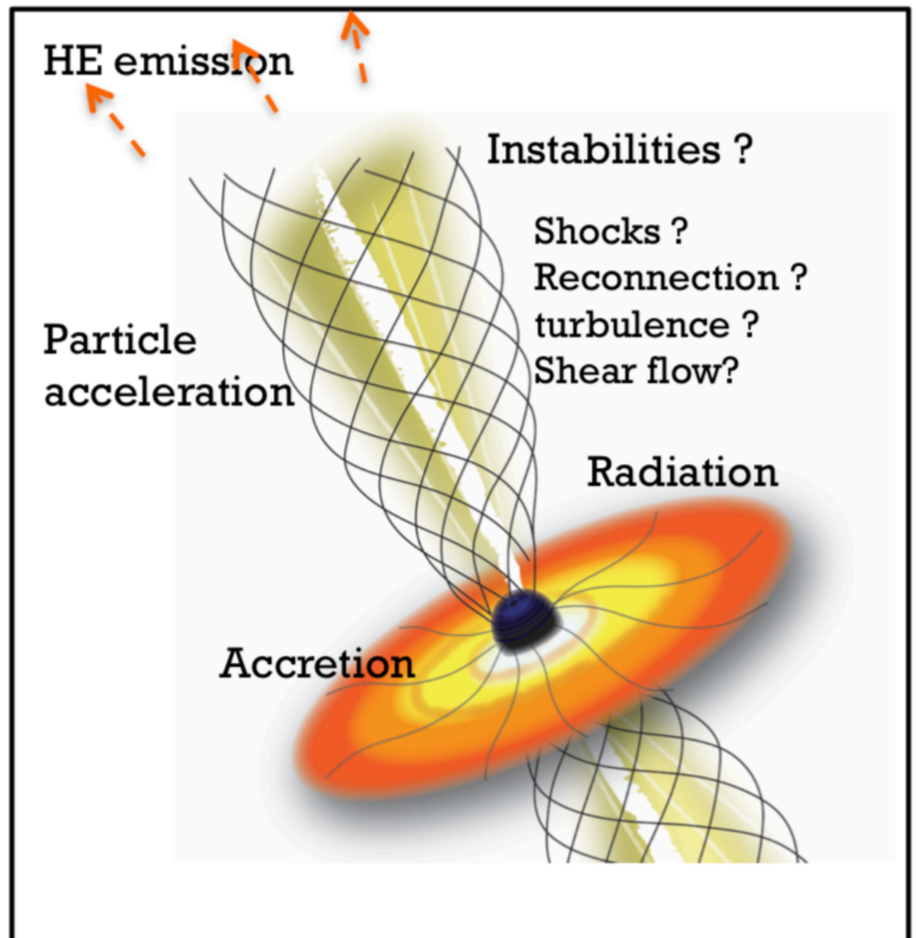
BH magnetosphere and jet are multi-scale systems

Global scales
formation and dynamics

Radiation scales
Sync, IC, pp

Dissipation scales
shocks, reconnection, turbulence

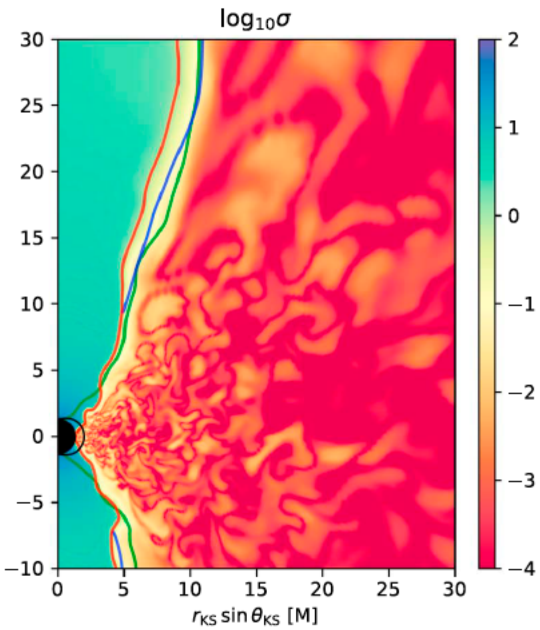
How are they connected?



and methodological (computational) challenge…

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?…)
- radiative processes (e^- - distribution in non-ideal regions?)



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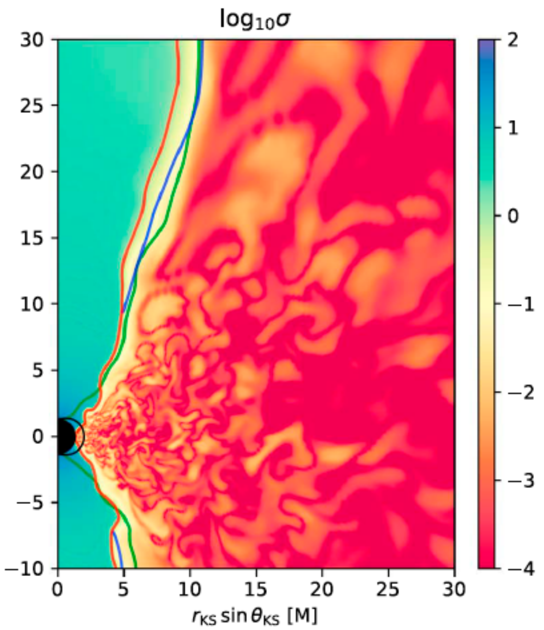
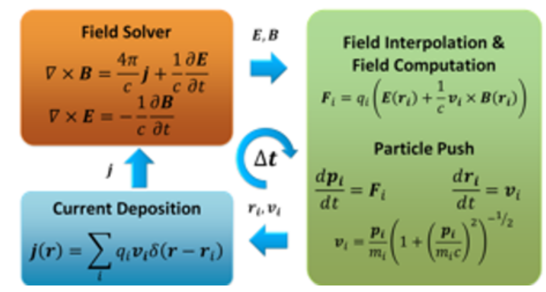


PIC:

- idealized setups (e.g., 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])



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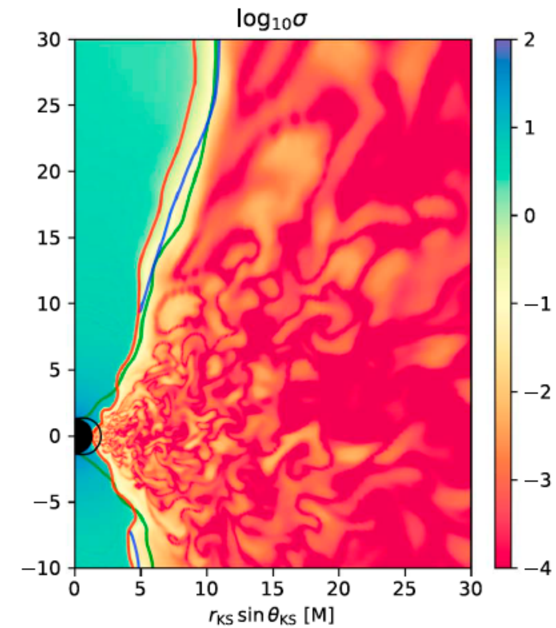

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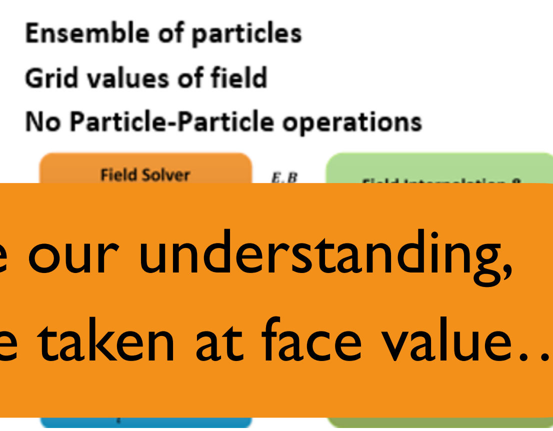

Essential to inform & advance our understanding,
but should probably not (yet) be taken at face value…

On Progress in our Understanding of (jetted) AGN Physics

- addressing the Felix' (CDY) question

CDY = Columbia & DIAS & Yale Initiative
https://cdy-institute.ie/index.php/events/

On progress in AGN research I

- **supermassive black holes at center of AGN** *(2020 Nobel prize, EHT)*

Roger Penrose
University of Oxford, UK

"for the discovery that black hole formation is a robust prediction of the general theory of relativity"

and the other half jointly to

Reinhard Genzel
Max Planck Institute for Extraterrestrial Physics, Garching, Germany and University of California, Berkeley, USA

and

Andrea Ghez
University of California, Los Angeles, USA

"for the discovery of a supermassive compact object at the centre of our galaxy"

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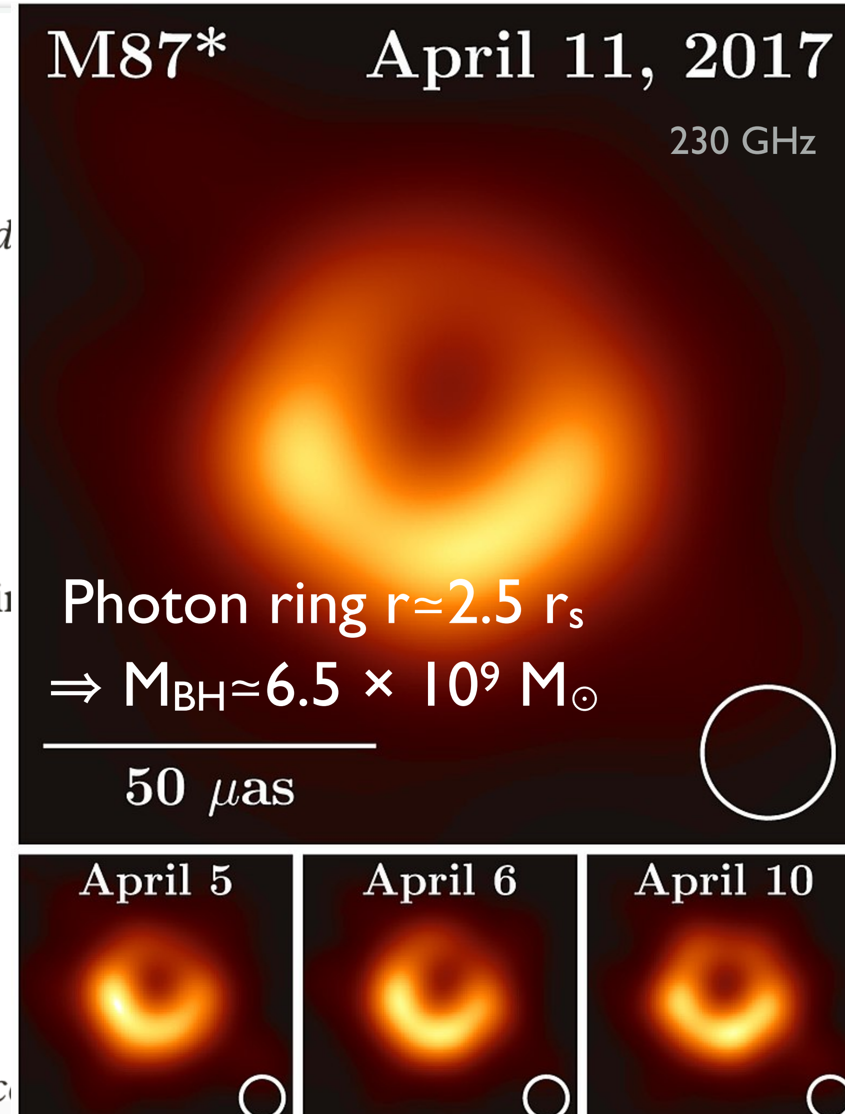
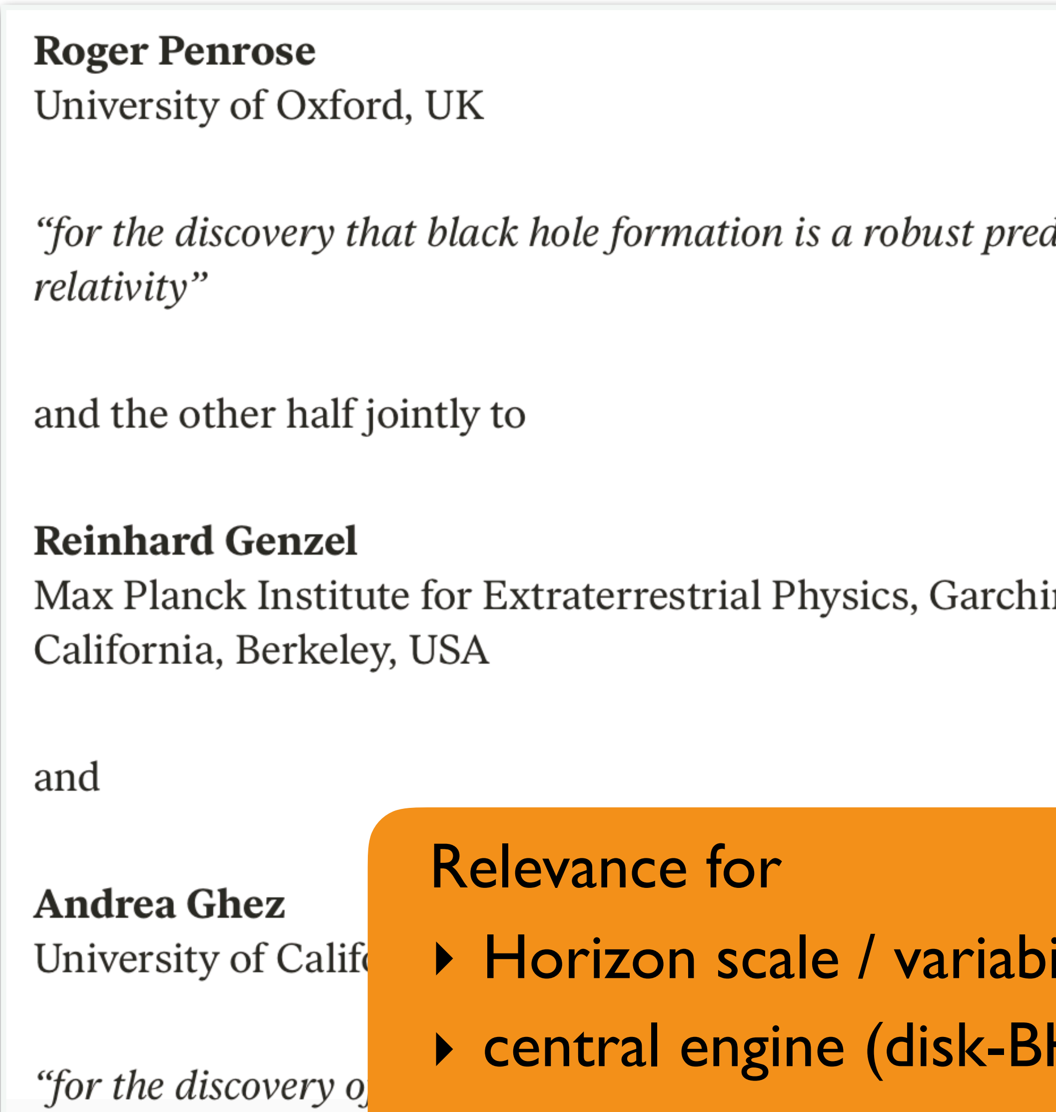


(EHTC 2019)

- **supermassive black holes at center of AGN** *(2020 Nobel prize, EHT)*



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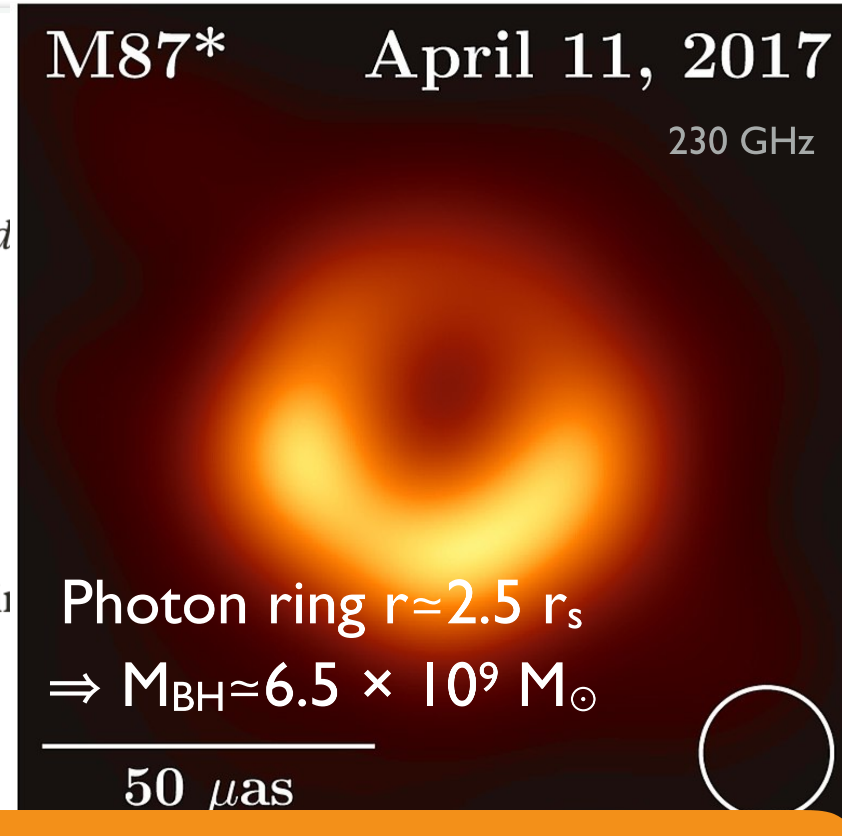


Photon ring $r \simeq 2.5\, r_s$
$\Rightarrow M_{BH} \simeq 6.5 \times 10^9\, M_\odot$

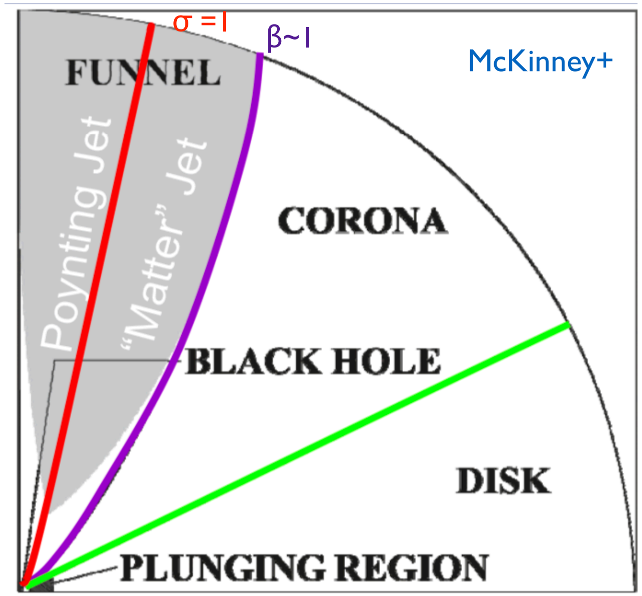
Relevance for
- Horizon scale / variability constraint ($t_H = 0.38$d)…
- central engine (disk-BH-jet) dynamics & connection…
- current jet power (e.g., spin)….

On progress in AGN research II

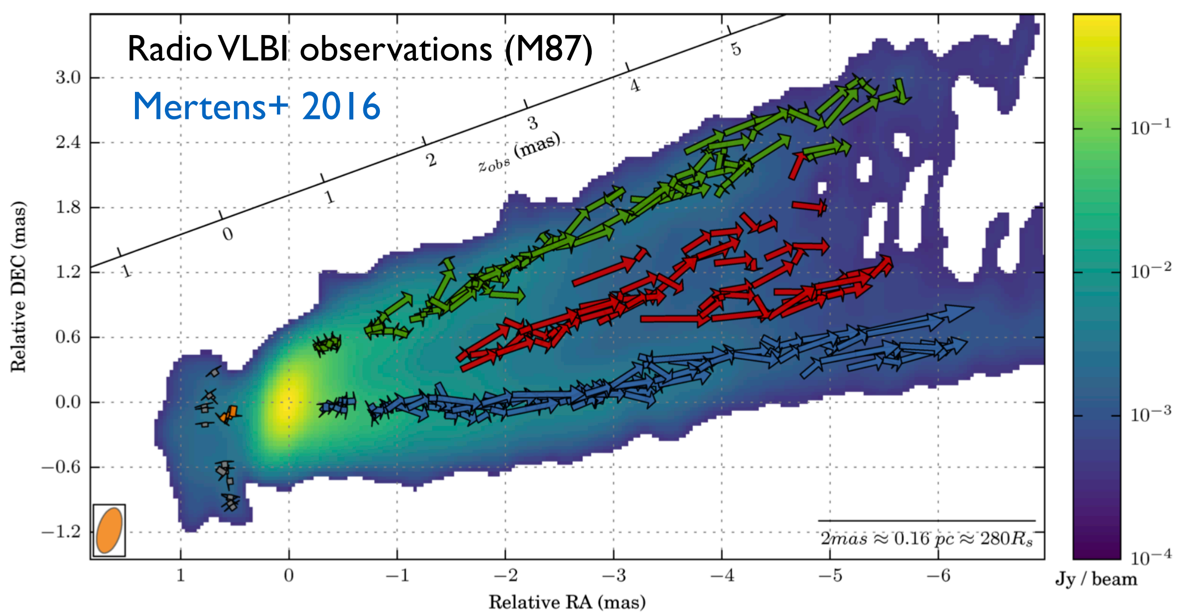
- **convergence of theoretical, numerical & observational evidence for jet stratification**
  - BH-driven (BZ) jet & disk-driven (BP) outflow…
  - two-flow & spine-sheath models (Sol+ 1989; Ghisellini, Tavecchio & Chiaberge 2005….)
  - *Emission:* limb-brightening & polarisation signatures…(Kim+ 2018…)
  - 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)



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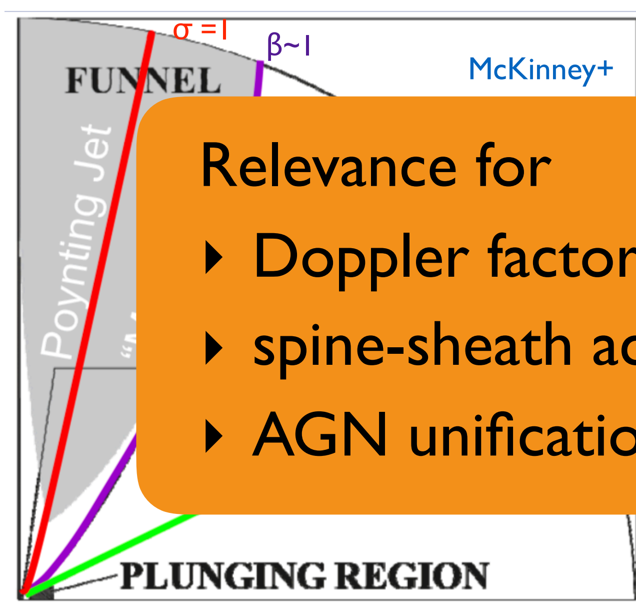
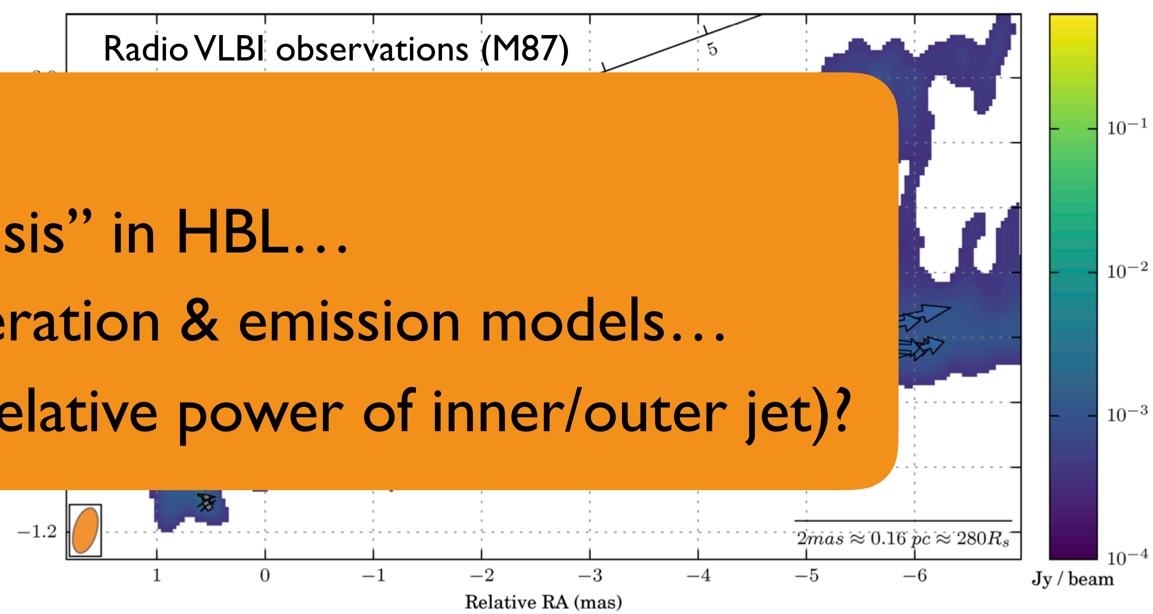
  - two-flow & spine-sheath models (Sol+ 1989; Ghisellini, Tavecchio & Chiaberge 2005….)
  - *Emission:* limb-brightening & polarisation signatures…(Kim+ 2018…)
  - M87: significant structural patterns on sub-pc scales ⇒ presence of both slow (~0.5c) and fast (~0.92c) components….

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

GRMHD simulations - Flow Structure



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



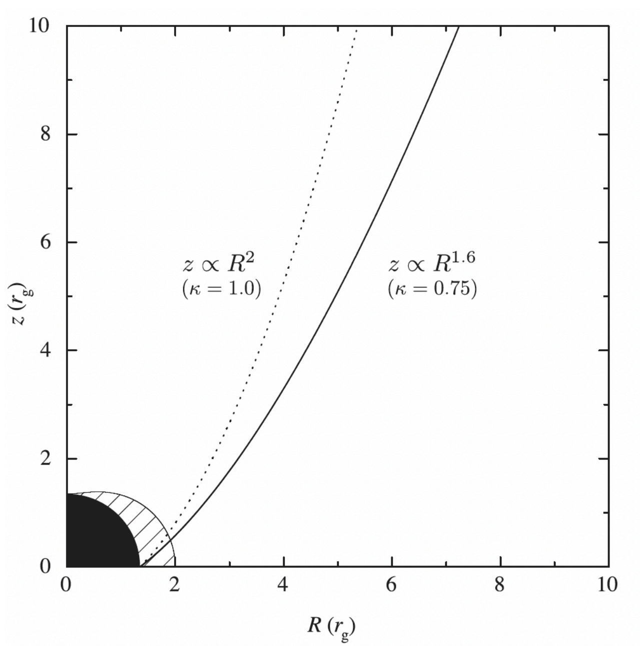
Relevance for

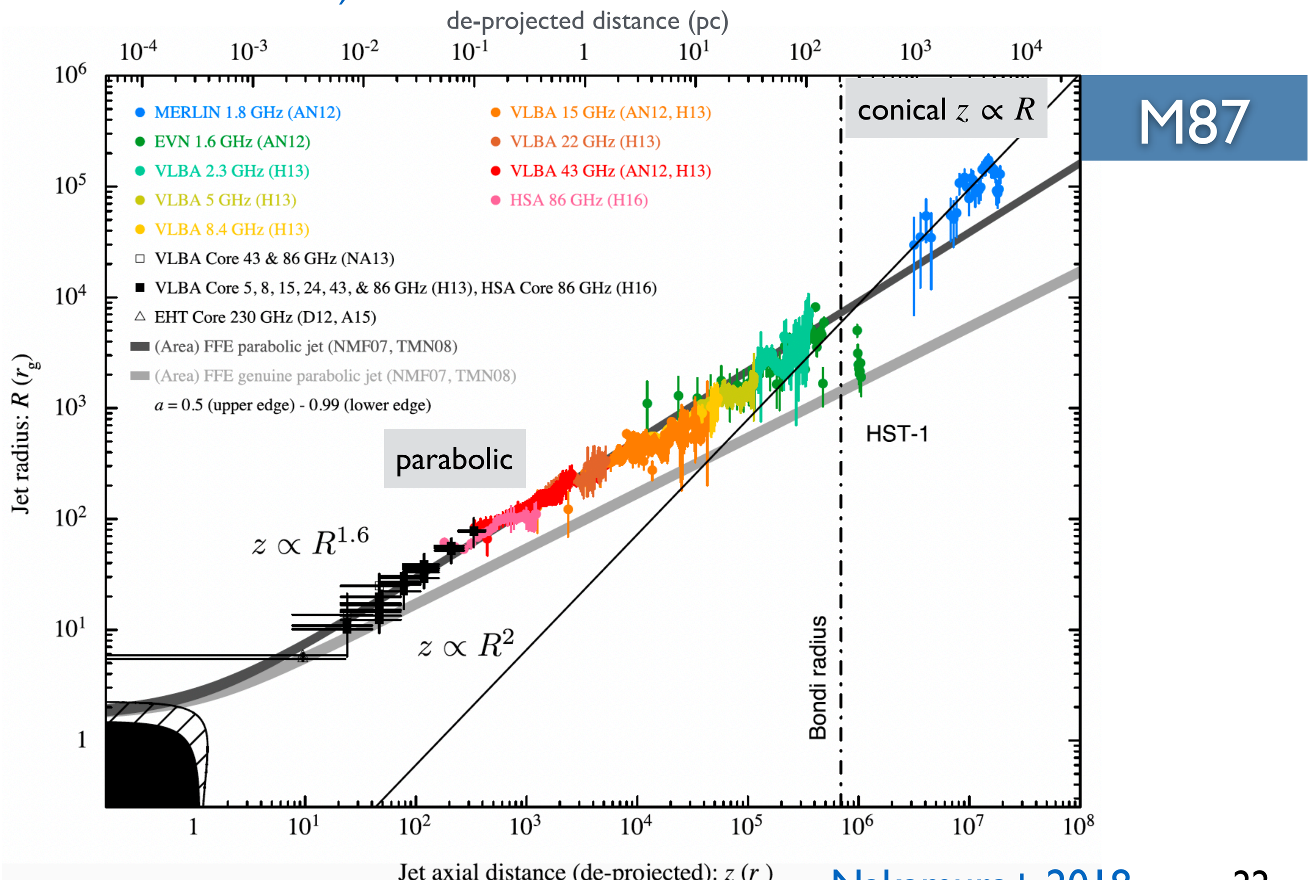
- Doppler factor “crisis” in HBL…
- spine-sheath acceleration & emission models…
- AGN unification (relative power of inner/outer jet)?

On progress in AGN research III

- **acceleration and collimation of relativistic jets…**
  - ***jet width profile***: initial parabolic & transition (at ~Bondi radius) to conical shape
  - ‘evidence’ for gradual flow acceleration with distance, up to $\Gamma\beta \sim 5$ (e.g., Park+ 2019)
    - *conversion of magnetic to kinetic energy while collimated by ambient medium….*

      (e.g., Komissarov+ 2007; Beskin & Nokhrina 2006…)





Nakamura+ 2018

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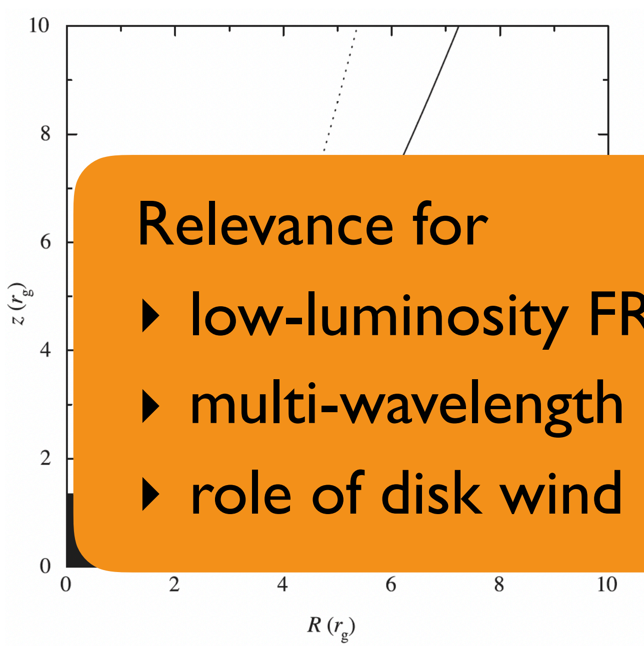
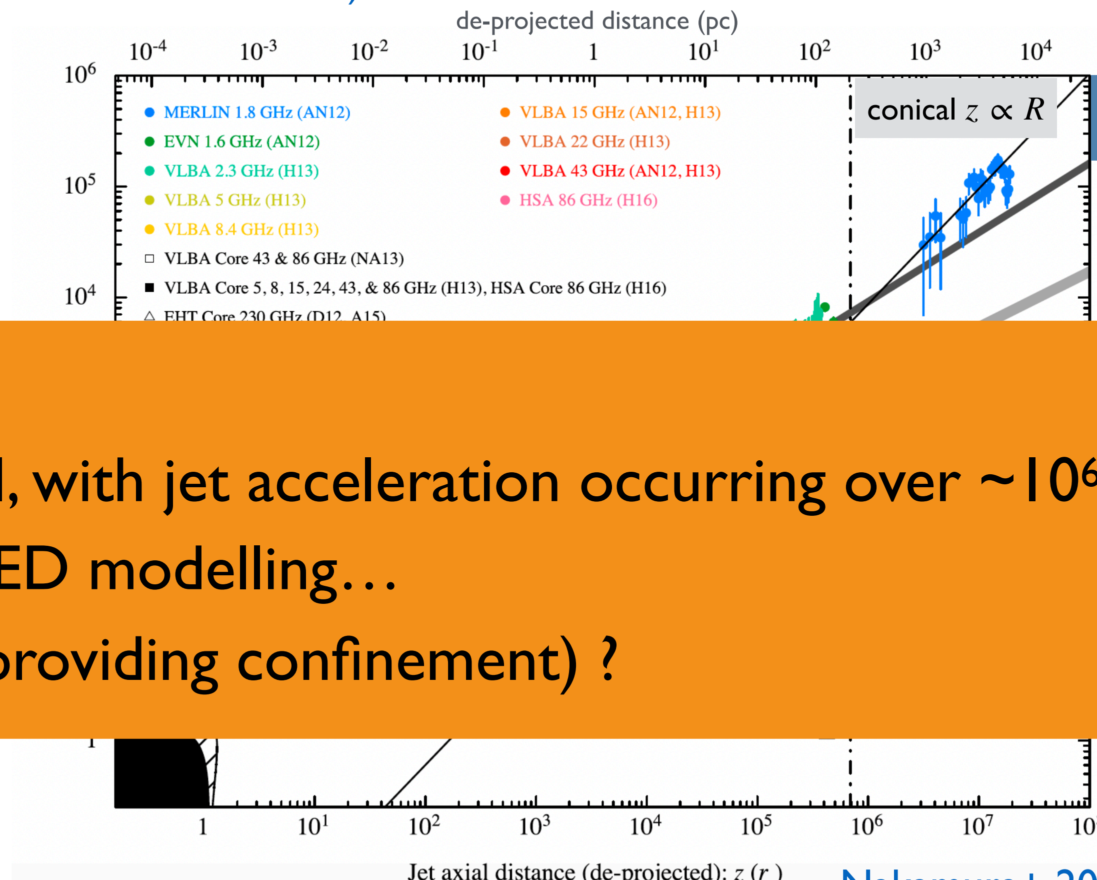




M87

Relevance for

- low-luminosity FR I, with jet acceleration occurring over ~10^6 r_g
- multi-wavelength SED modelling…
- role of disk wind (providing confinement) ?

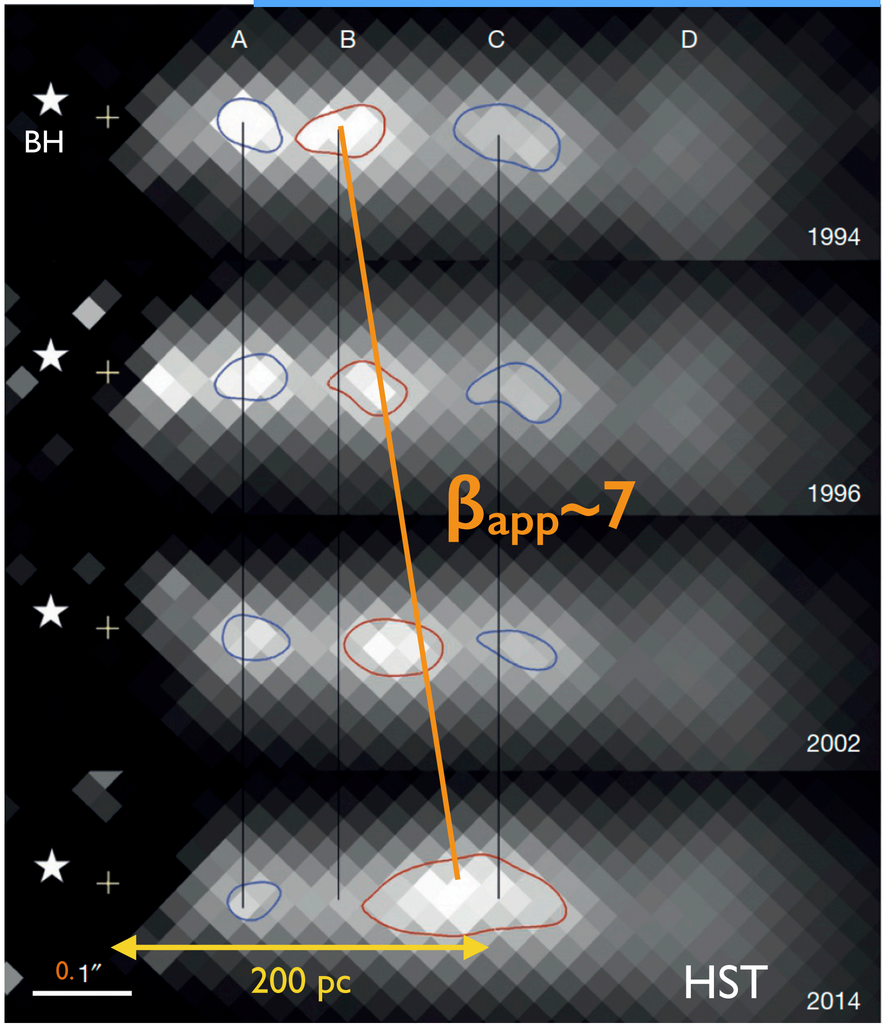
Nakamura+ 2018

On progress in AGN research IV

- **convergent evidence for relativistic motion in large-scale AGN jets**

  - jets 'can remain' relativistic even in FR I type sources on (projected!) hundreds of pc's: Γ~7, D~7 (θ~8°) for 3C 264
    - jet power $L_j \sim 5 \times 10^{43}$ erg/s (Meyer+2011)
  - collision of knots - internal shocks….

3C 264 (FR I @ d~95 Mpc)



~ 45 pc

Meyer+ 2015 (Nature)

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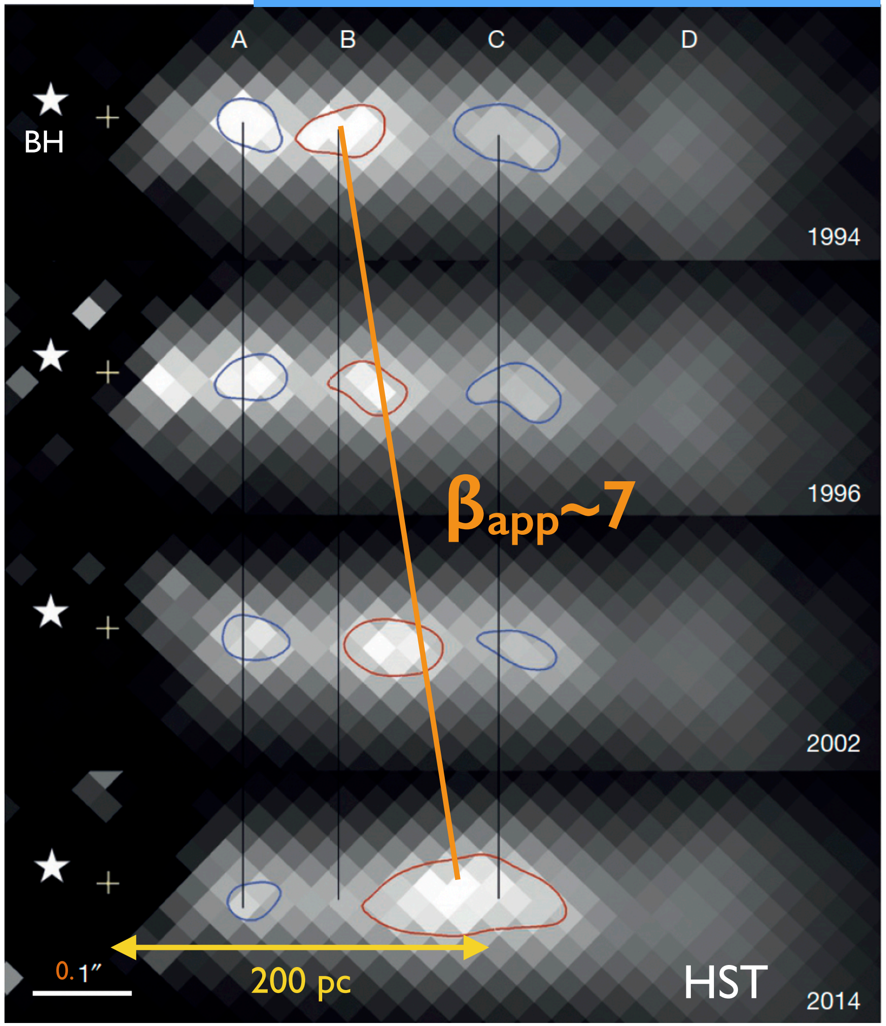
Relevance for

- 3C 264 as detected VHE emitter….
- particle acceleration @ shocks…
- VHE emission from large-scale jets…
- UHECR acceleration….

3C 264 (FR I @ d~95 Mpc)

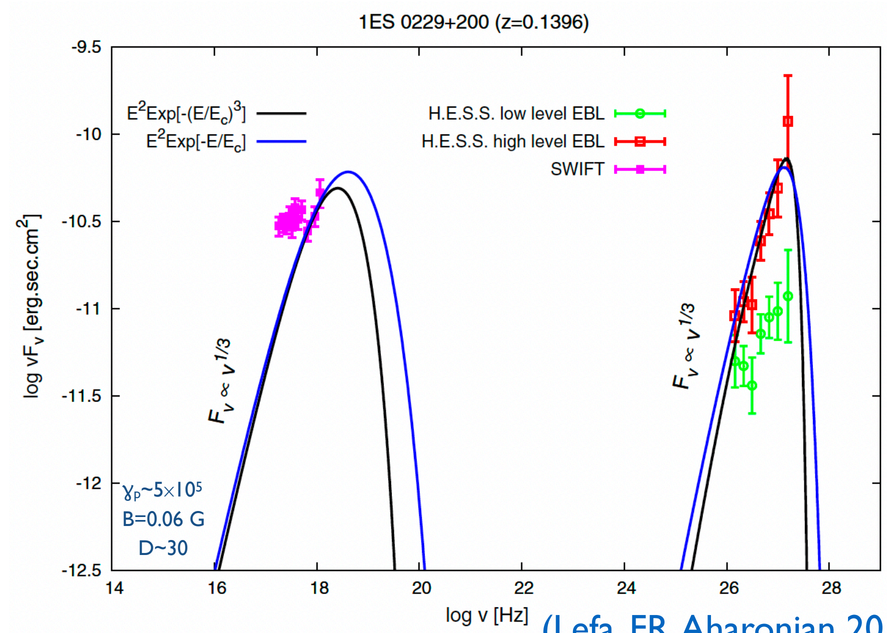


~ 45 pc

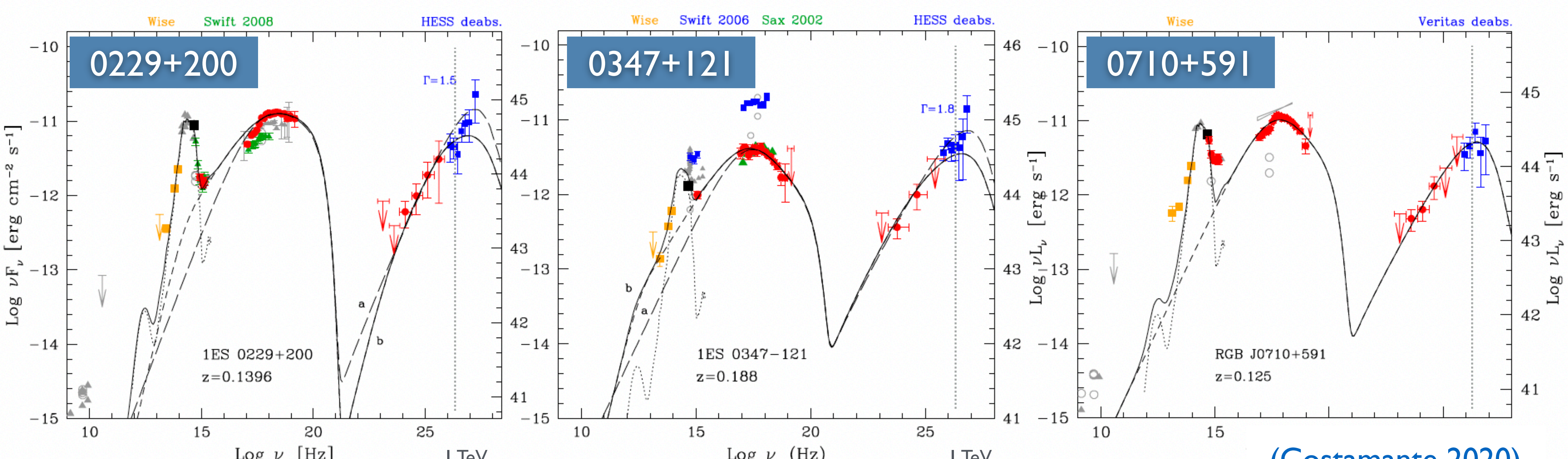
Meyer+ 2015 (Nature)

On progress in AGN research V

- **extreme TeV blazars…**
  - BL Lacs with hard intrinsic VHE spectra (photon index $\Gamma_{VHE} \lesssim 1.5$-1.9)
  - SED peak above 1 TeV
  - additional component(s), one with high $\gamma_{min} \gtrsim 10^5$, or relativistic Maxwellian-type ?
  - cf. narrow pile-up feature @ 3 TeV in Mkn 501 on July 19, 2014 (MAGIC 2020);



(Lefa, FR, Aharonian 2011)



(Costamante 2020)

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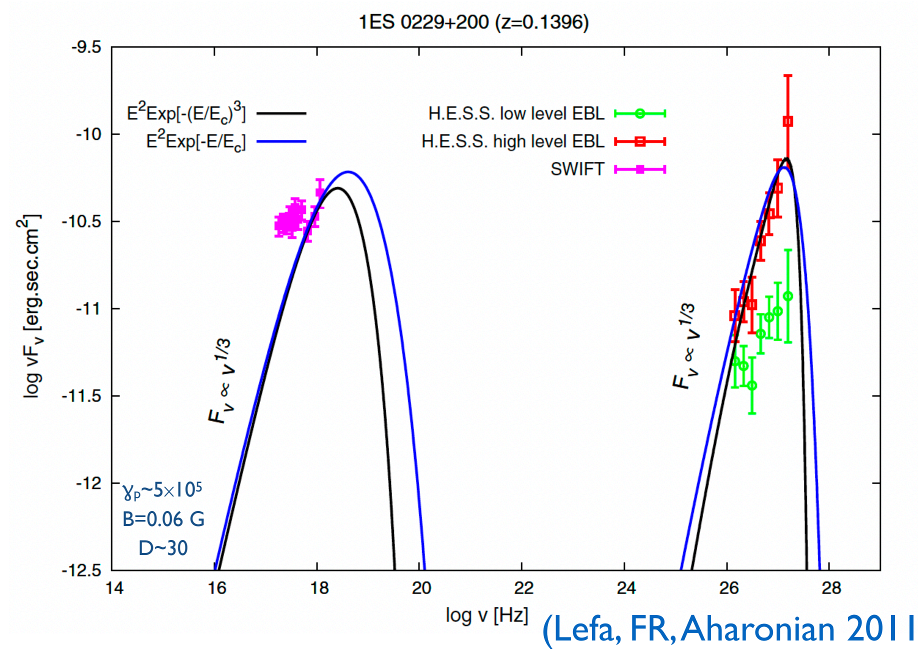
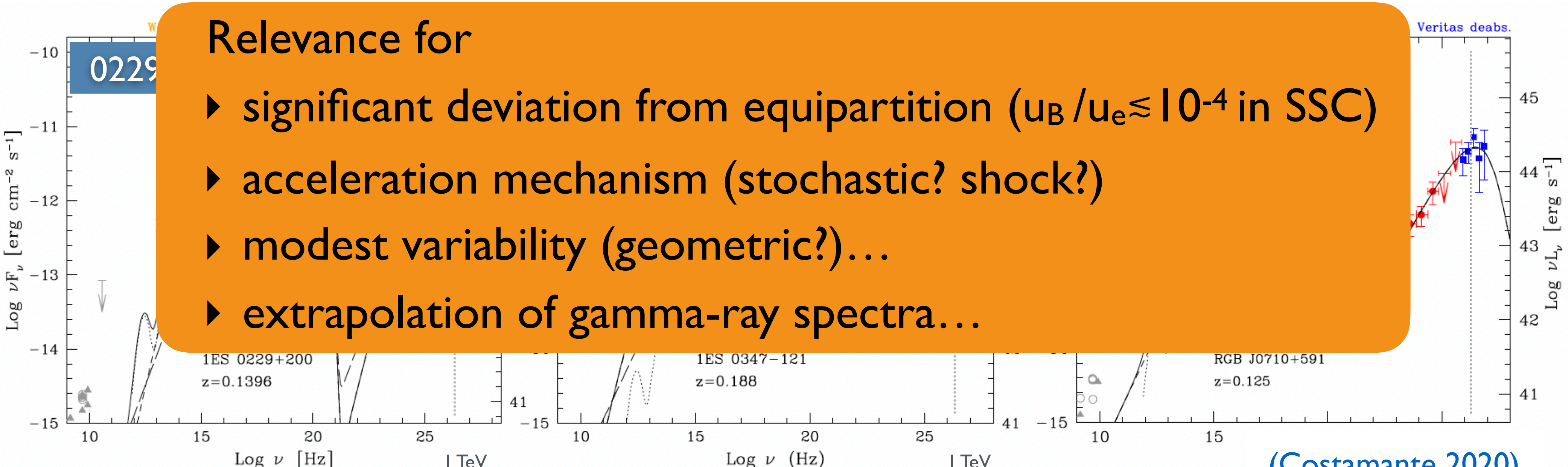


(Lefa, FR, Aharonian 2011)

Relevance for
- significant deviation from equipartition ($u_B/u_e \lesssim 10^{-4}$ in SSC)
- acceleration mechanism (stochastic? shock?)
- modest variability (geometric?)…
- extrapolation of gamma-ray spectra…

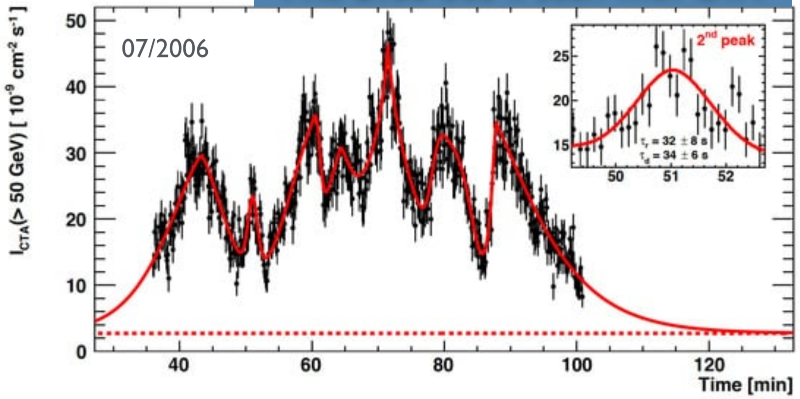


(Costamante 2020)

On progress in AGN research VI

- **gamma-ray astrophysics in the time domain**
  - ultra-fast variability (down to few minutes)…
    (e.g., Aharonian+2017)
  - evidence for year-type QPOs…
  - power-law noise behaviour & log-normality

PKS 2155-305 if seen with CTA



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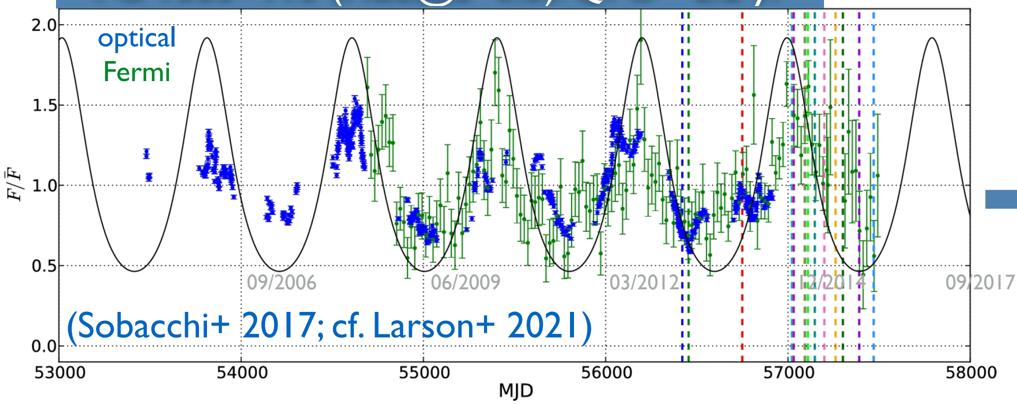
PG 1553+113 (HBL@z~0.5): QPO ~2.2 yr



?

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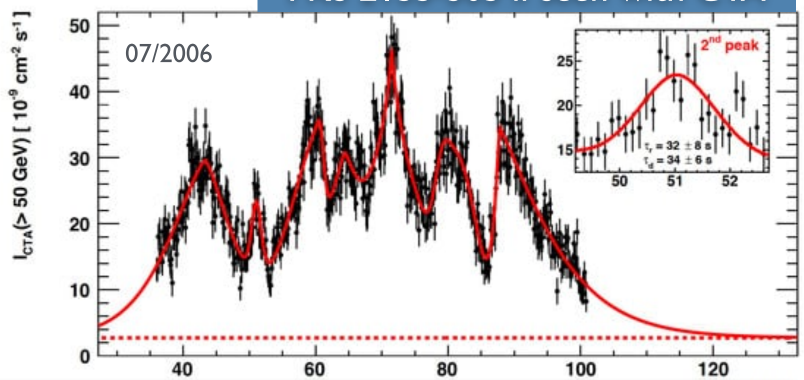

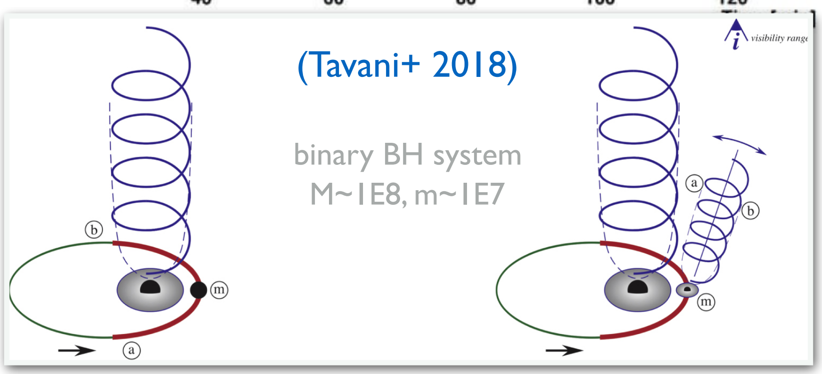

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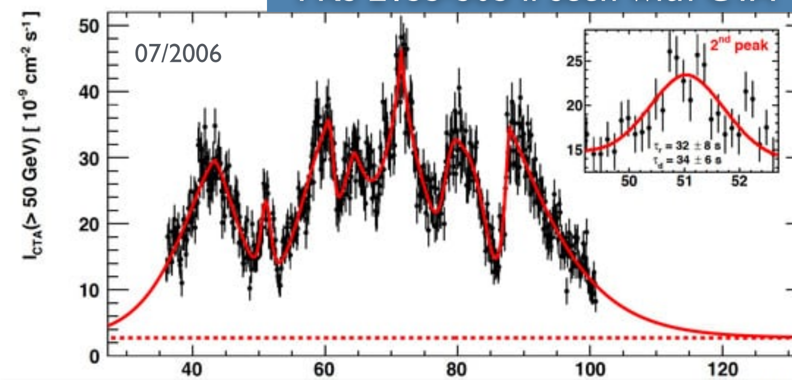

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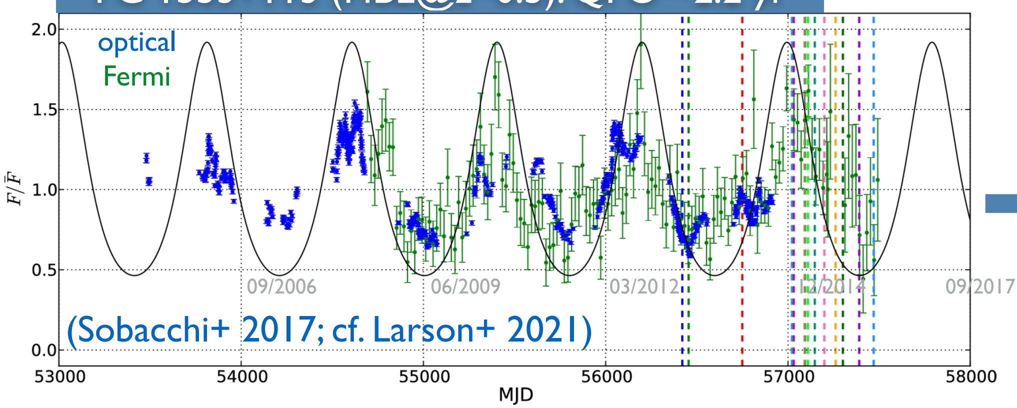
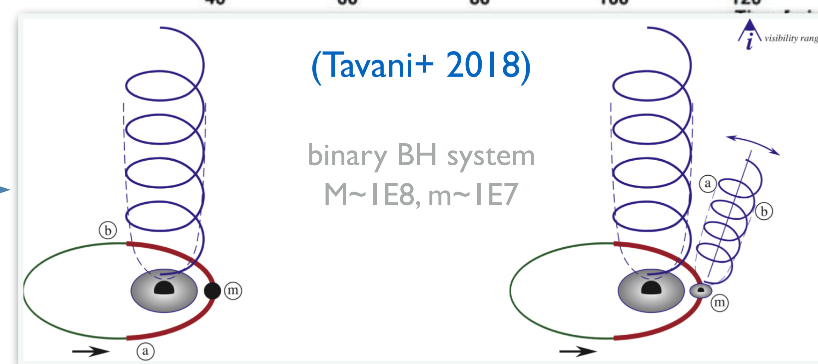


(Sobacchi+ 2017; cf. Larson+ 2021)

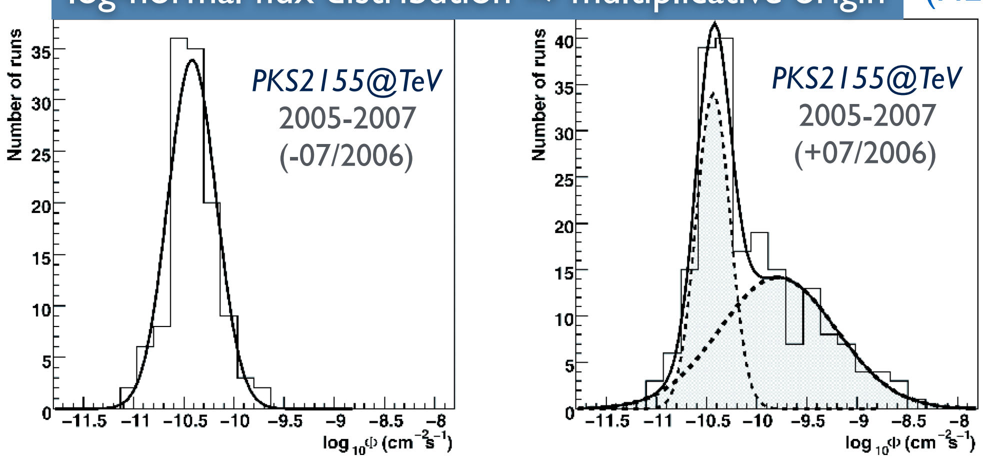
?



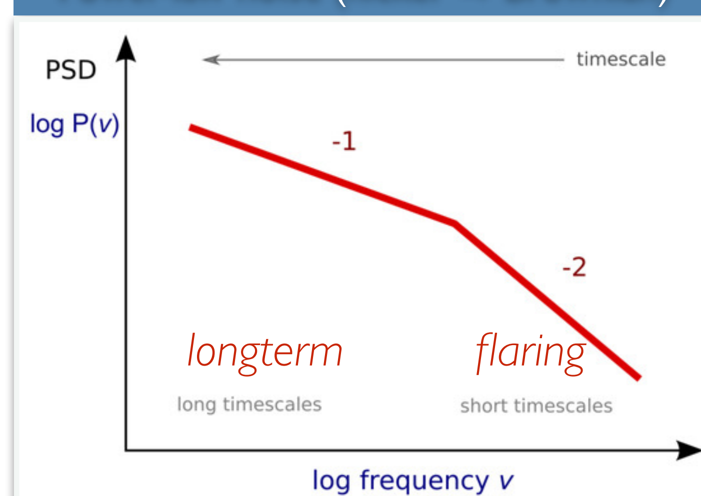
(Tavani+ 2018)

log-normal flux distribution ⇒ multiplicative origin

(HESS+2017 etc)



Power-law noise (flicker ⇒ Brownian)



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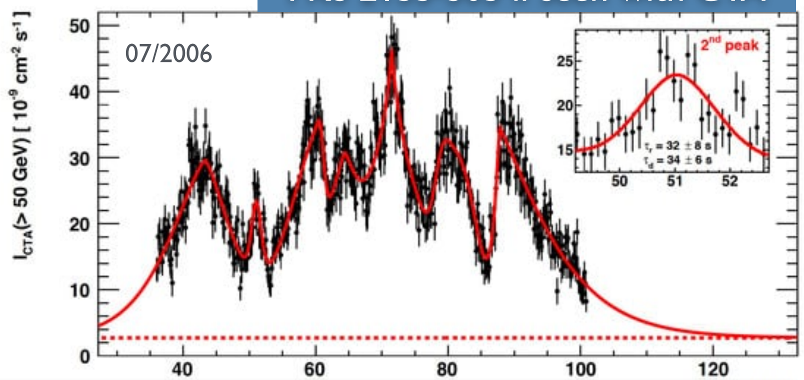

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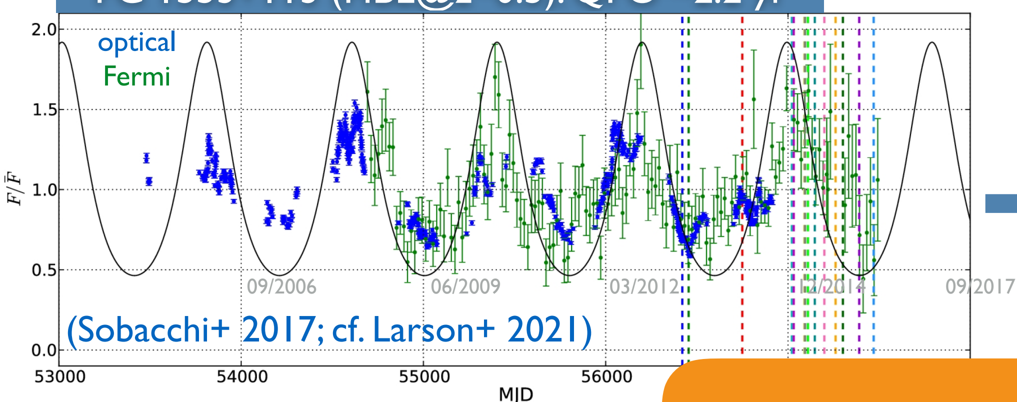
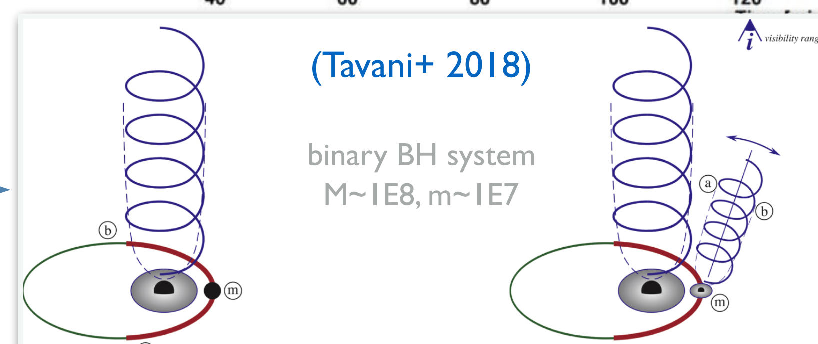
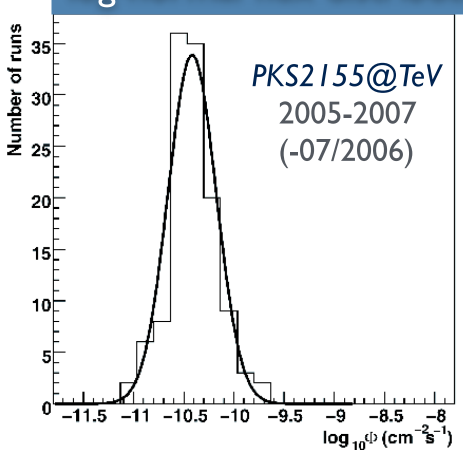


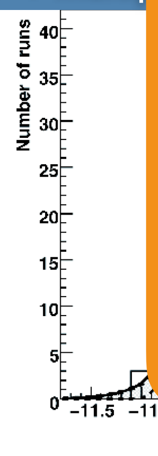
(Sobacchi+ 2017; cf. Larson+ 2021)

?



log-normal flux distribution ⇒ multip





Relevance for

- origin of emission (location, process)…
- source dynamics & evolution…
- *theoretical efforts slowly gaining momentum….*
  (e.g., Finke+2014/15; Sinha+2018; Polkas+2021; Thiersen+ 2021; Dmytrieev+2021… cf. also FR 2019 [review])

On progress in AGN research (selected reviews & references)

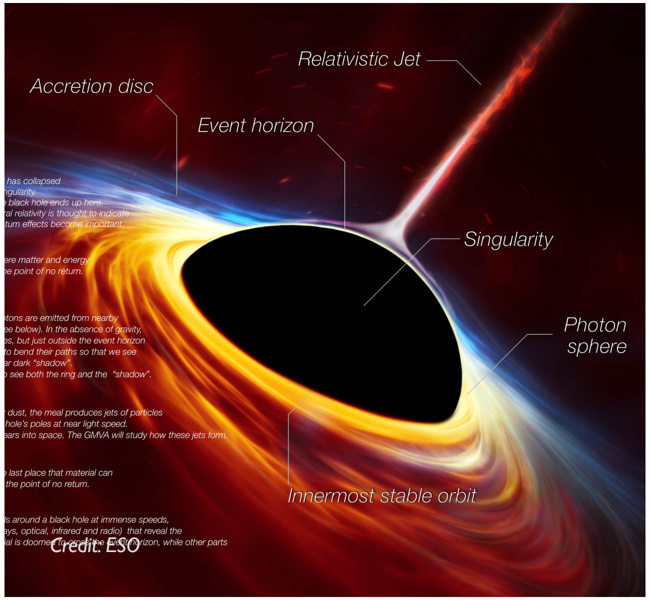
- **Biteau J. et al. 2020:** *Progress in unveiling extreme particle acceleration in persistent astrophysical jets*, NatAs 4, 124
- **Blandford R., Meier D., Readhead A. 2019:** *Relativistic Jets from Active Galactic Nuclei,* ARA&A 57, 467
- **Cerruti, M. 2020:** *Leptonic and Hadronic Radiative Processes in SMBH Jets* (Review), Galaxies 8, 72.
- **Costamante, L. 2020:** *Blazars: an updated review,* POS(MULTIF2019), 035
- **Hada, K. 2020:** *Relativistic Jets from AGN viewed at Highest Angular Resolution* (Review), Galaxies 8, 1
- **Marcowith, A. et al. 2020:** *Multi-scale simulations of particle acceleration in astrophysical systems* (Review), LRCA 6, 1
- **Mizuno, Y. 2022:** *GRHMD simulations and Modeling for Jet Formation and Acceleration Region in AGN* (Review), Universe 8, 85
- **Rieger, F. 2019:** *Gamma-ray Astrophysics in the Time Domain* (Review), Galaxies 7, 28
- **Romero, G. 2021:** *The content of astrophysical jets* (Review), ASNA 342, 727

Selected Theoretical Advances:

- *Magnetospheric Processes (conceptual)*

The Occurrence of Gaps around rotating Black Holes

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



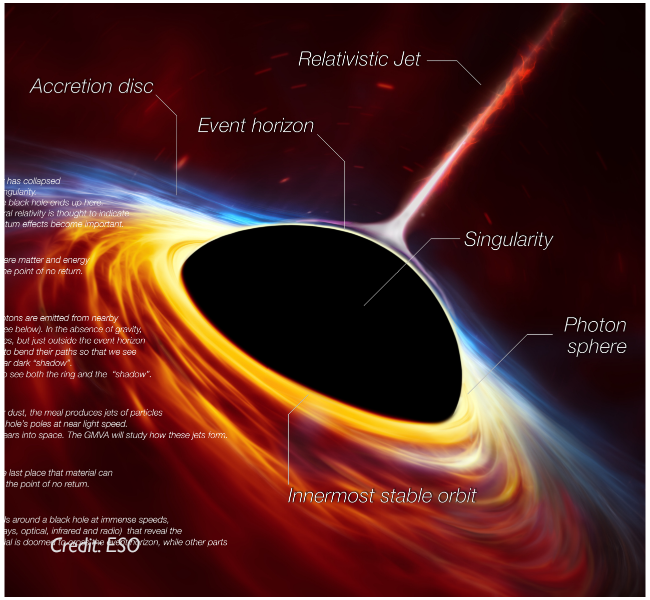
e.g., Blandford & Znajek 1977; Thorne, Price & Macdonald 1986
Beskin et al. 1992; Hirotani & Okamoto 1998…

The Occurrence of Gaps around rotating Black Holes

"Parallel electric field occurrence

⇒ not enough charges to screen the field

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



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

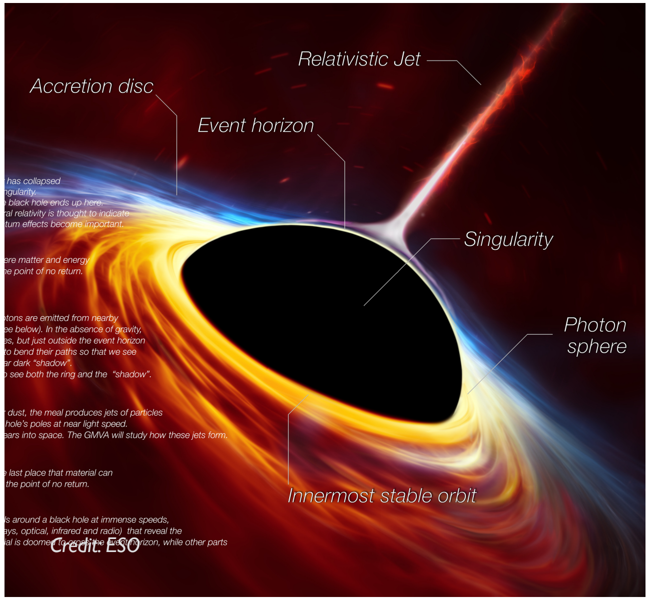
  for force-free magnetosphere, vanishing of poloidal electric field $\mathbf{E}_p \propto (\Omega^F - \omega)\, \nabla\Psi = 0$, *ω=Lense-Thirring*

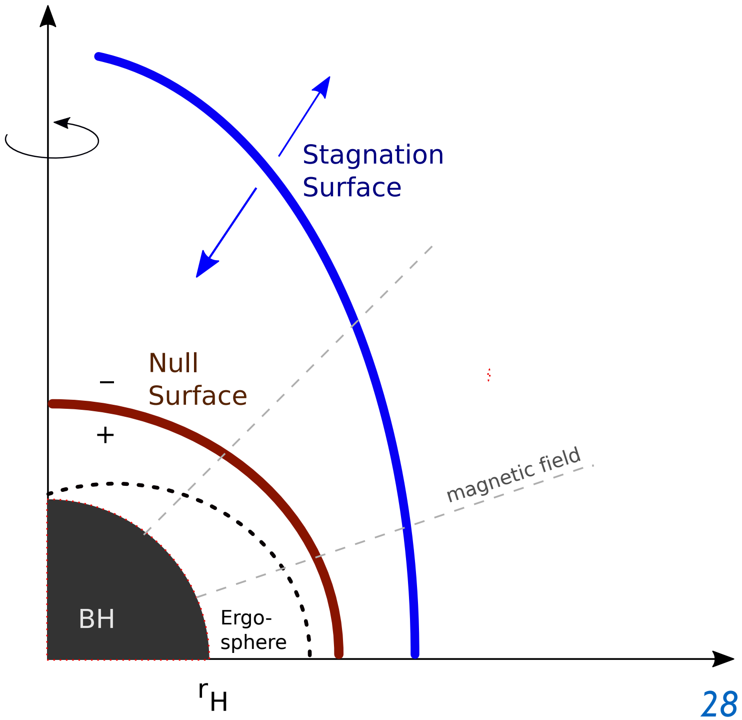
- ***Stagnation surface*** *(r ~ several* r_g*)*

  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…

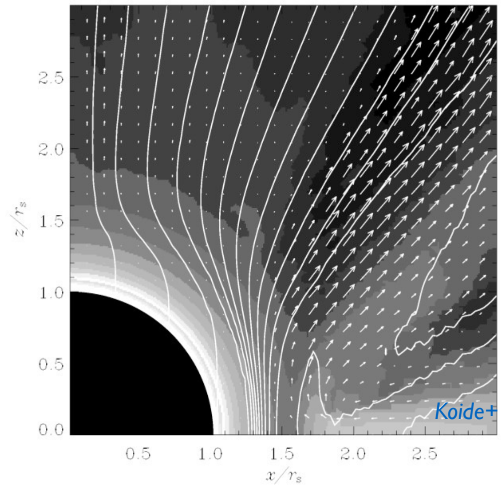




The Conceptual Relevance of BH Gaps

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])*

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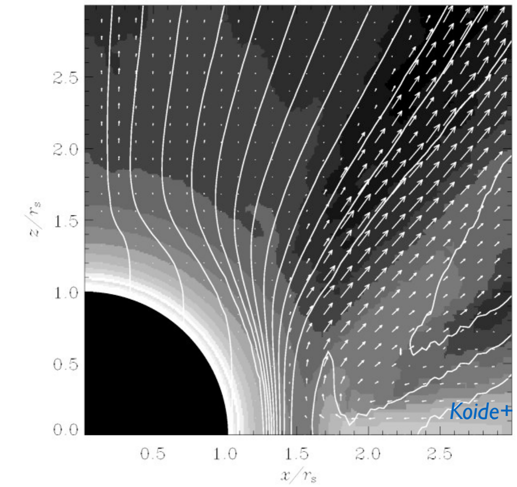
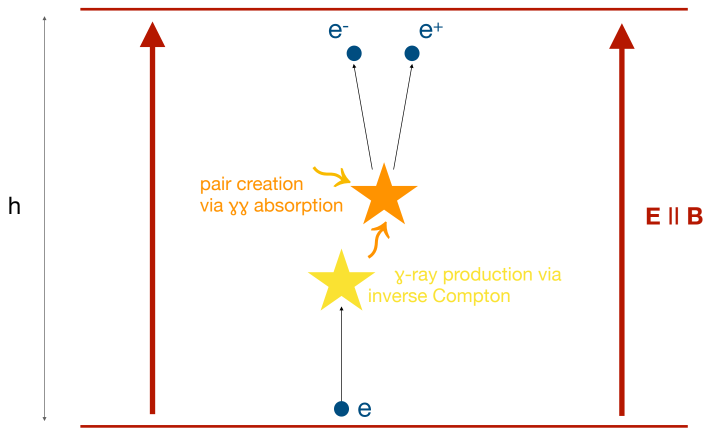


- *if BH regions becomes evacuated…*
  - *efficient (direct) acceleration of electrons & positrons in emergent $E_{\parallel}$-field*
  - *accelerated e^-, e^+ produce γ-rays via inverse Compton*
  - *γγ-absorption triggers pair cascade…*

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

  ⇒ ensuring electric field screening (closure)



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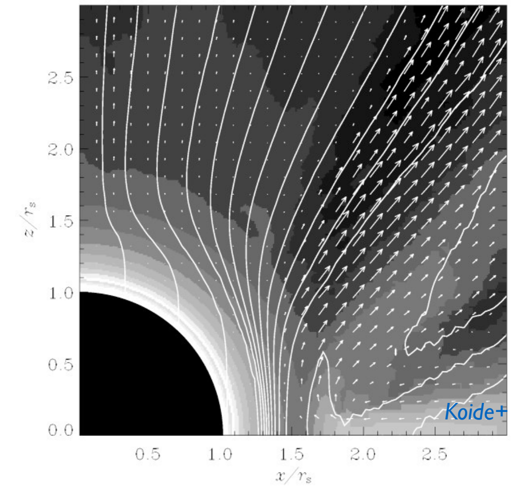
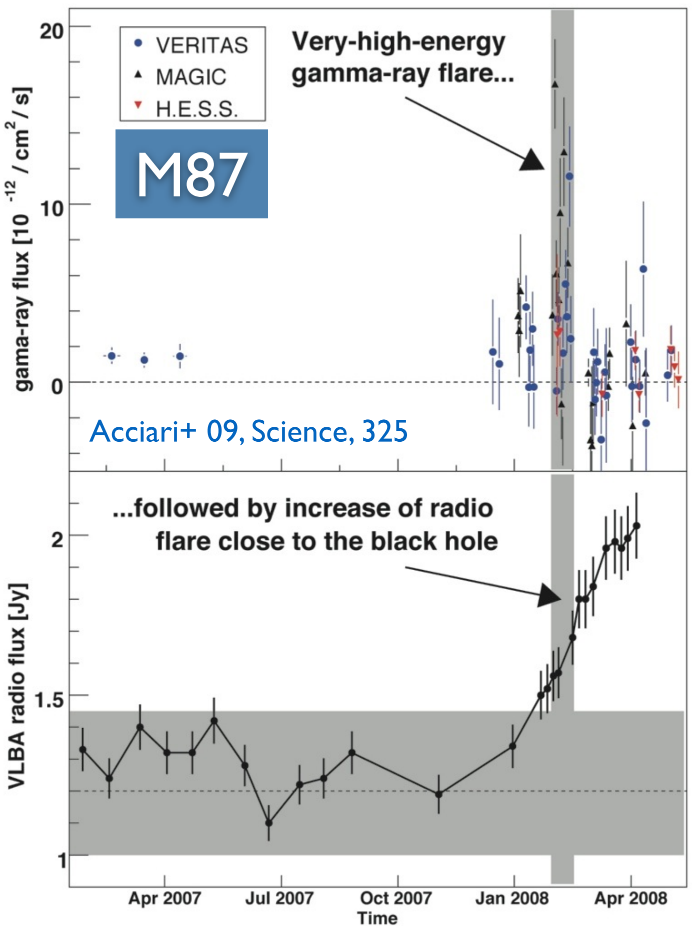
    ⇒ generating charge multiplicity (e^+e^-) = plasma

    ⇒ ensuring electric field screening (closure)
- 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

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

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

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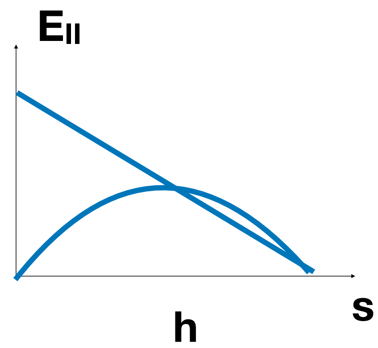
e.g., highly under-dense, $\rho \ll \rho_{GJ}$

- *Boundaries:*

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

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

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



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

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- *Gap - Jet power:*
  - $L_{gap} \sim L_{BZ}\, (h/r_g)^4$ …

with $j \propto c\,(d\rho/dr)\, h$

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

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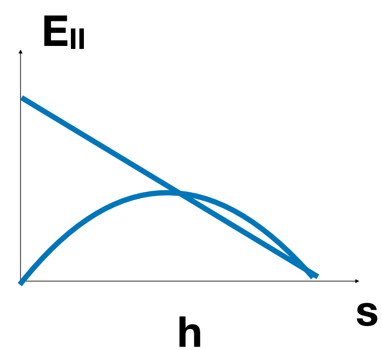

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  with $j \propto c\,(d\rho/dr)\, h$

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

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

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

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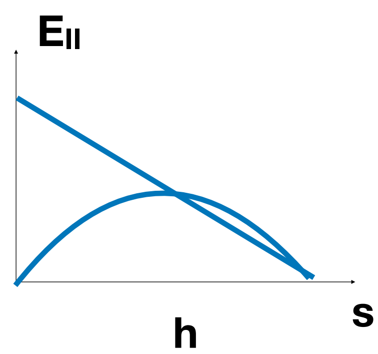
- *Gap - Jet power:*
  - $L_{gap} \sim L_{BZ}\, (h/r_g)^2$ …

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



Taking variability as proxy for gap size

⇨ Jet power constraints become relevant for rapidly varying sources

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

- *Boundaries:*

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

- *Gap potential:*
  - $\Delta\phi_{gap} \sim a\, r_g\, B\, (h/r_g)^3$

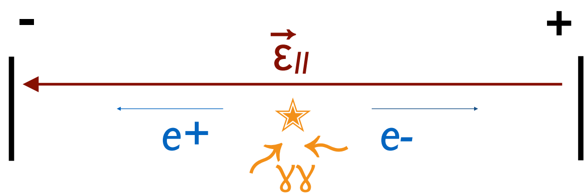
- *Gap - Jet power:*
  - $L_{gap} \sim L_{BZ}\, (h/r_g)^4$ …

with $j \propto c\, (d\rho/dr)\, h$

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

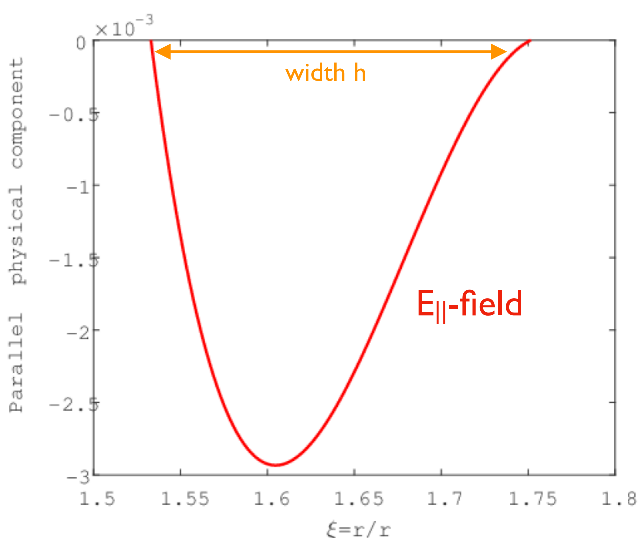
What sizes etc to expect ? - Self-consistent steady (1D) gap solutions I

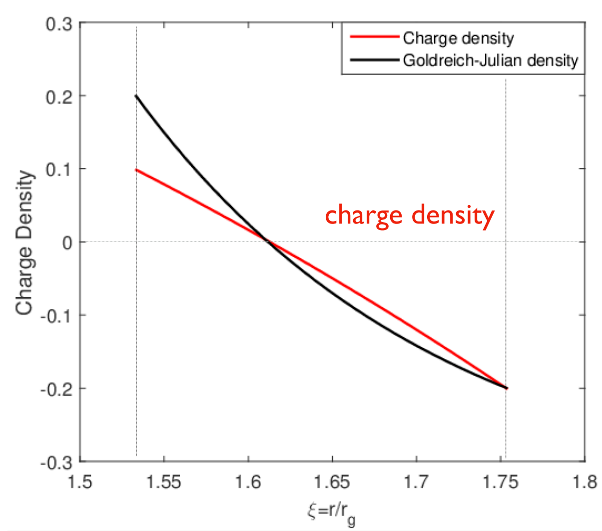
e,g., Beskin+ 1992; Hirotani & Okamoto 1998; Hirotani+ 2016; Levinson & Segev 2017; Katsoulakos & FR 2020



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

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





 # Boundary Conditions:

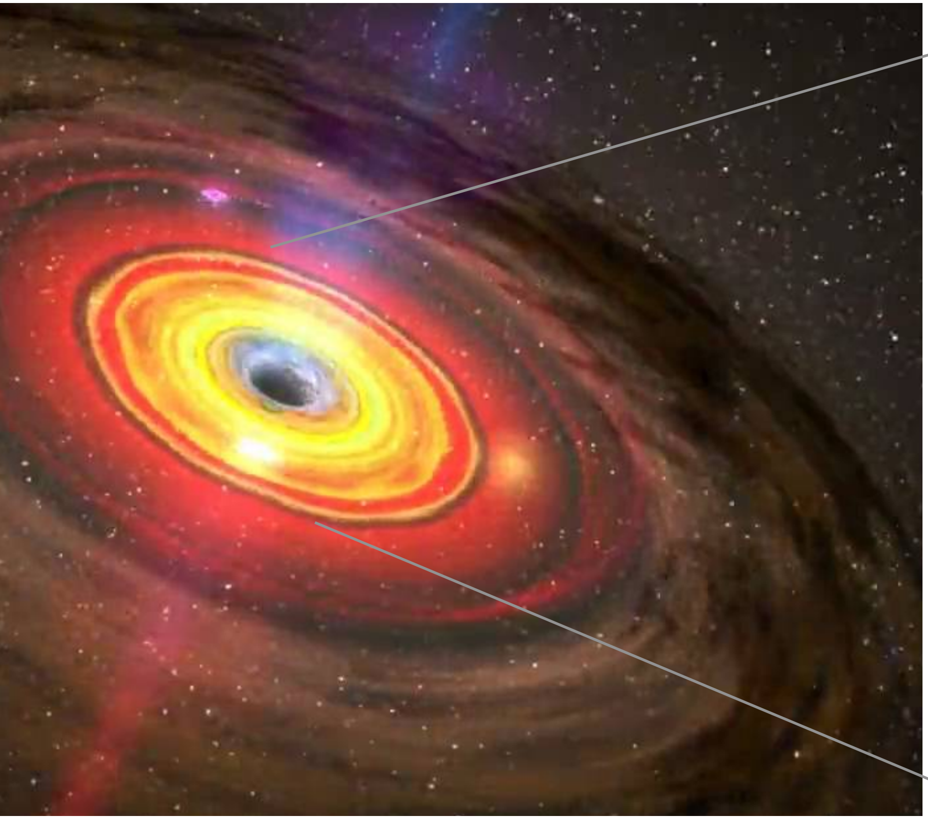
Zero electric field at boundaries

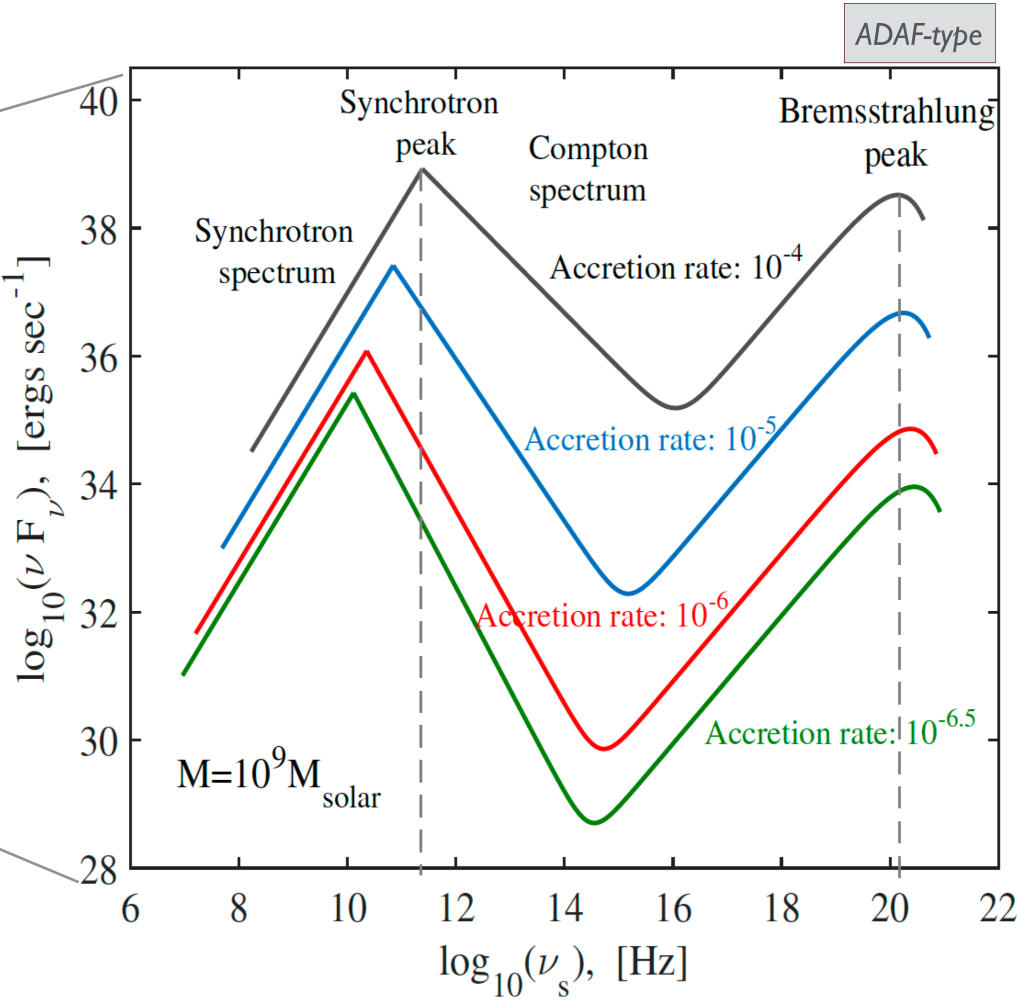
$\varrho \leq \varrho_{GJ}$ in boundaries

 # ADAF soft photon field

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

➡ *determines efficiency of pair cascade…*

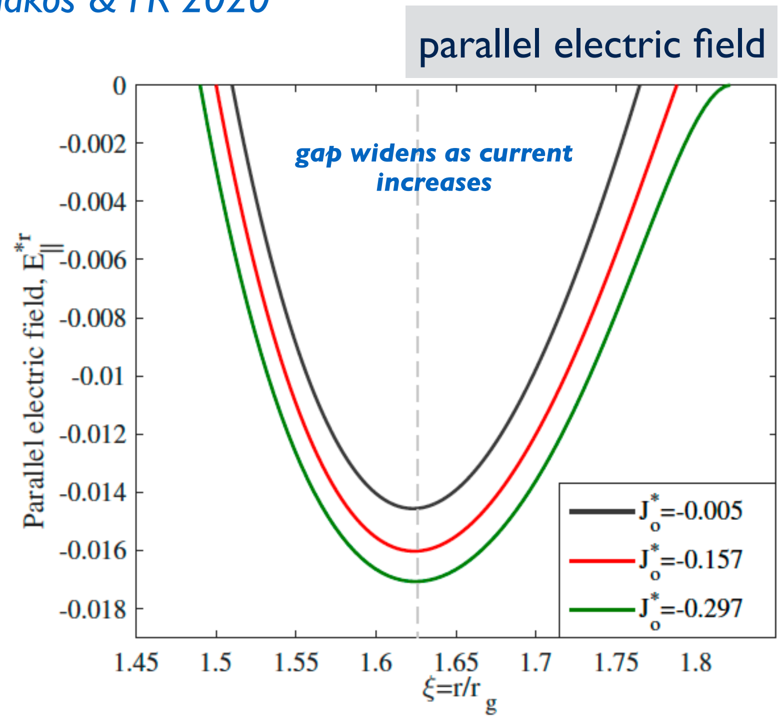




for $B_H \sim 10^5\, \dot{m}^{1/2}\, M_9^{-1/2}$ G

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

Katsoulakos & FR 2020



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

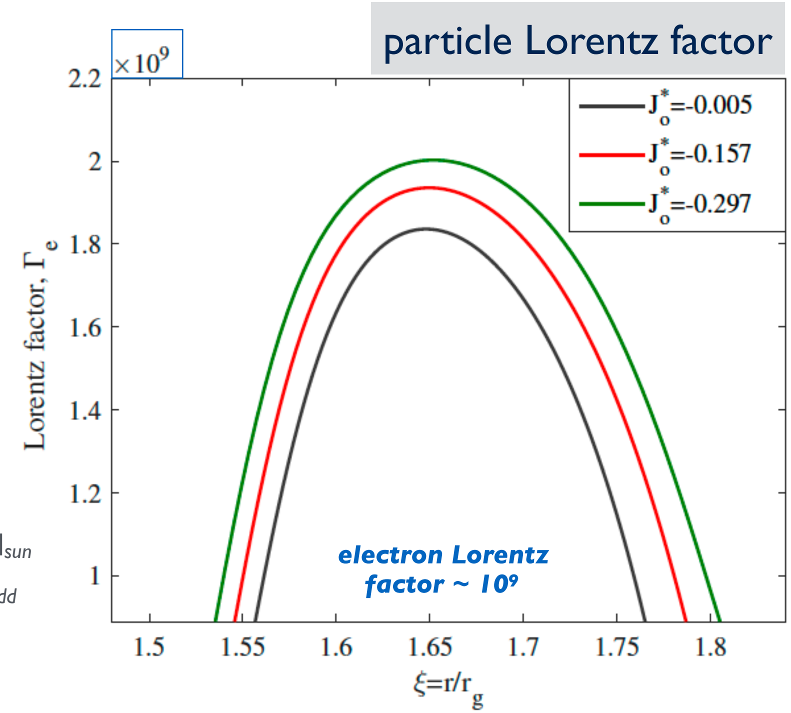
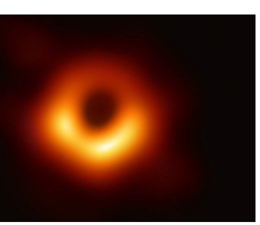


Figure 6. Left: The normalized distribution of the parallel electric field component $\mathcal{E}^{*r}_{||}$ shown for current values $J^*_o = -0.005$ (black line), $J^*_o = -0.157$ (red line) and $J^*_o = -0.297$ (green line). Right: The corresponding Lorentz factor distribution Γ_e of the particles.

M87:

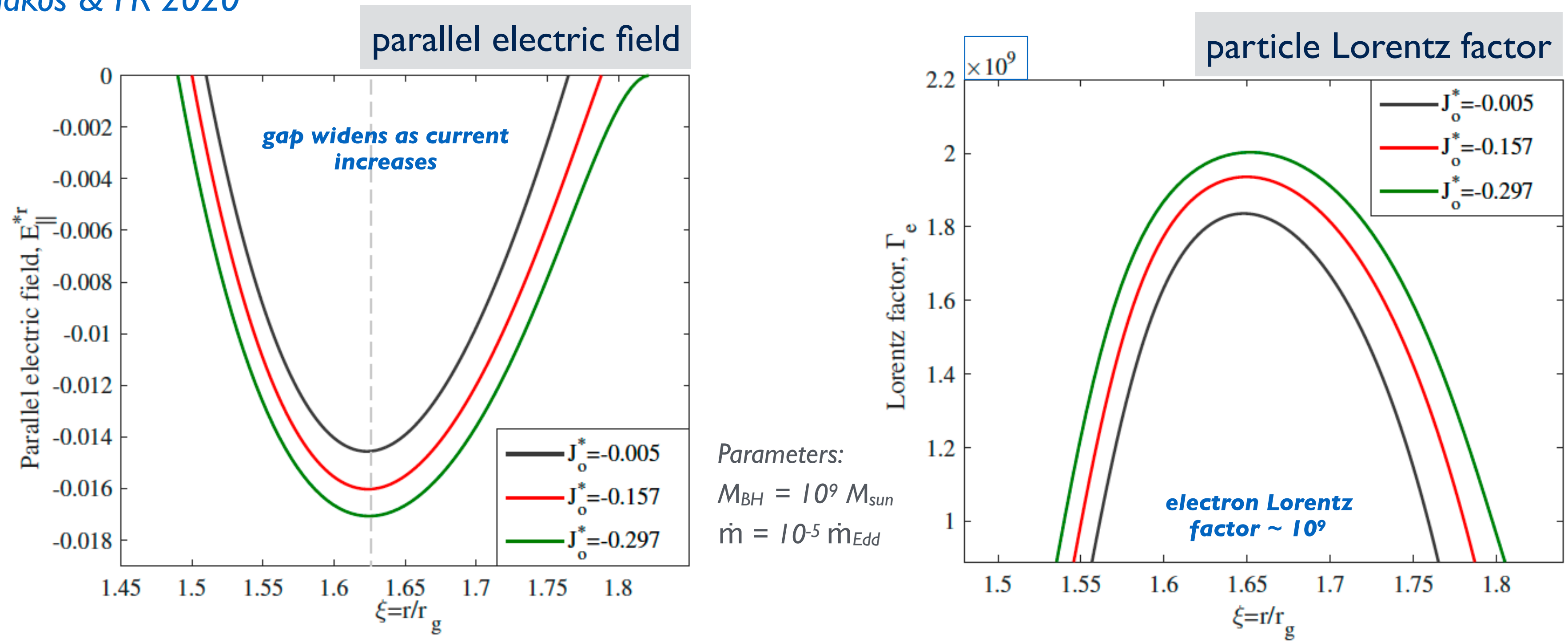


Global Current	Gap Size	Voltage Drop	Gap Power
$J^*_o = J_o/c\,\rho_c$	h/r_g	$\times 10^{17}$ Volts	$\times 10^{41}\, erg\, s^{-1}$
(1)	(2)	(3)	(4)
−0.4	0.8076	9.8	4.9

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)

Katsoulakos & FR 2020



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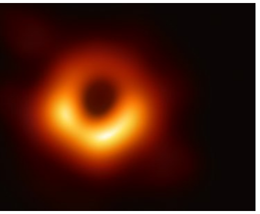

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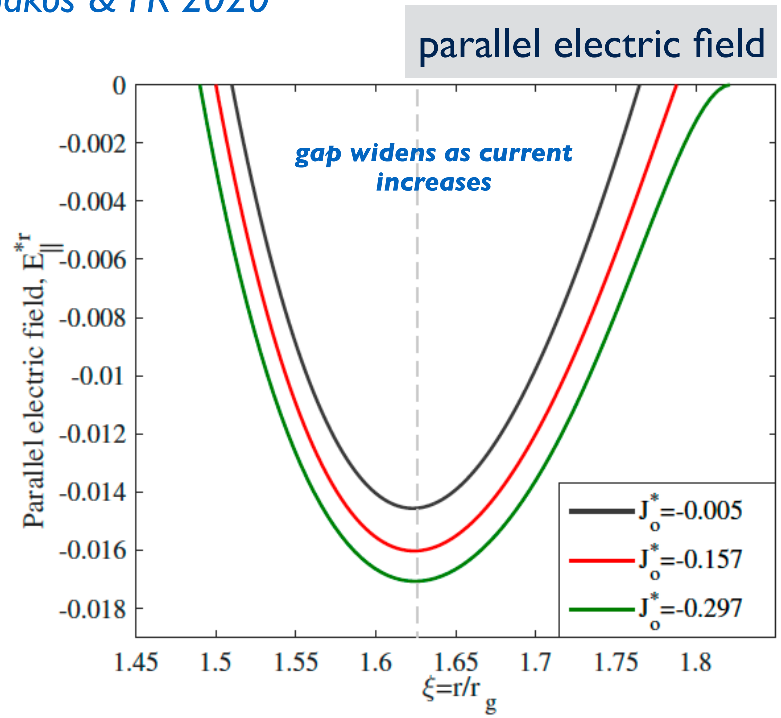
Consistent solutions possible for M87
max. voltage drop ~10^{18} eV

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

Katsoulakos & FR 2020



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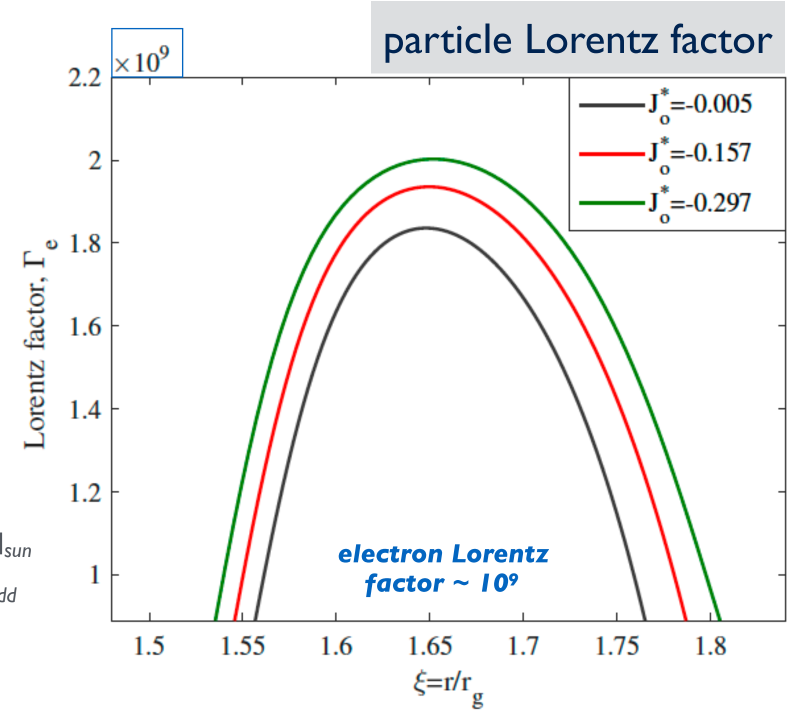

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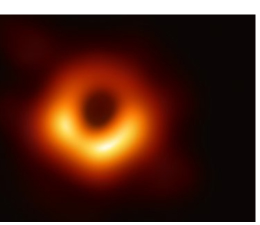

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Consistent solutions possible for M87
max. voltage drop ~10^{18} eV

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 …

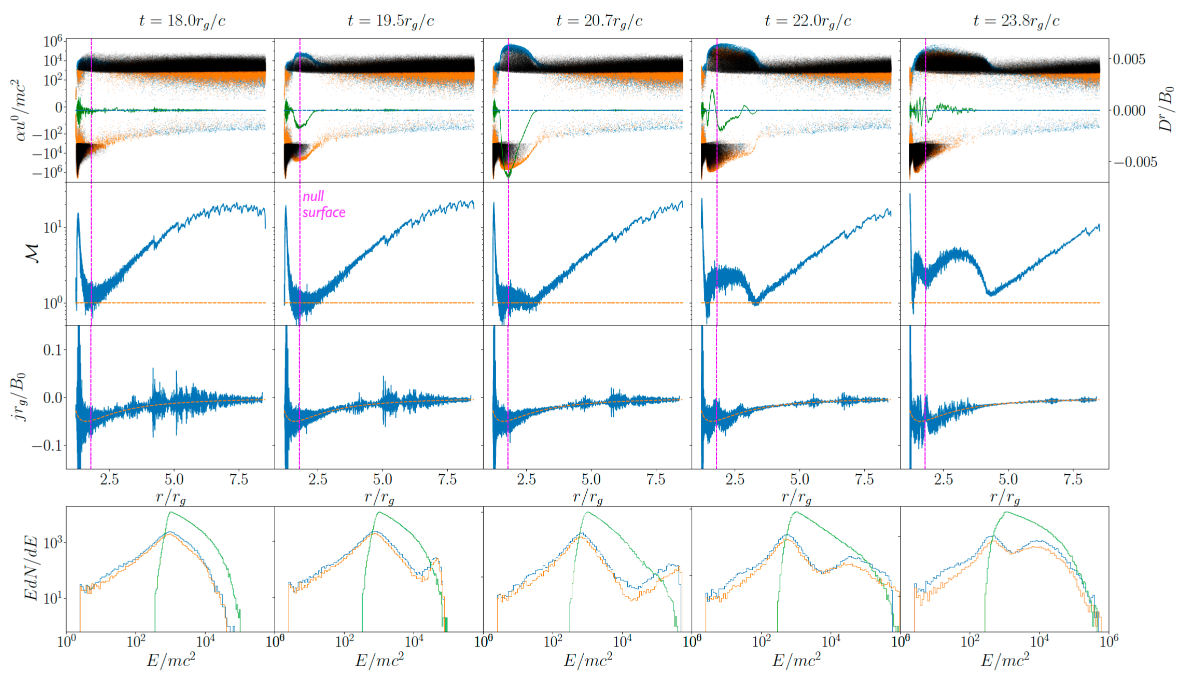
phase space plot (e+, e-, photons); electric field

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

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

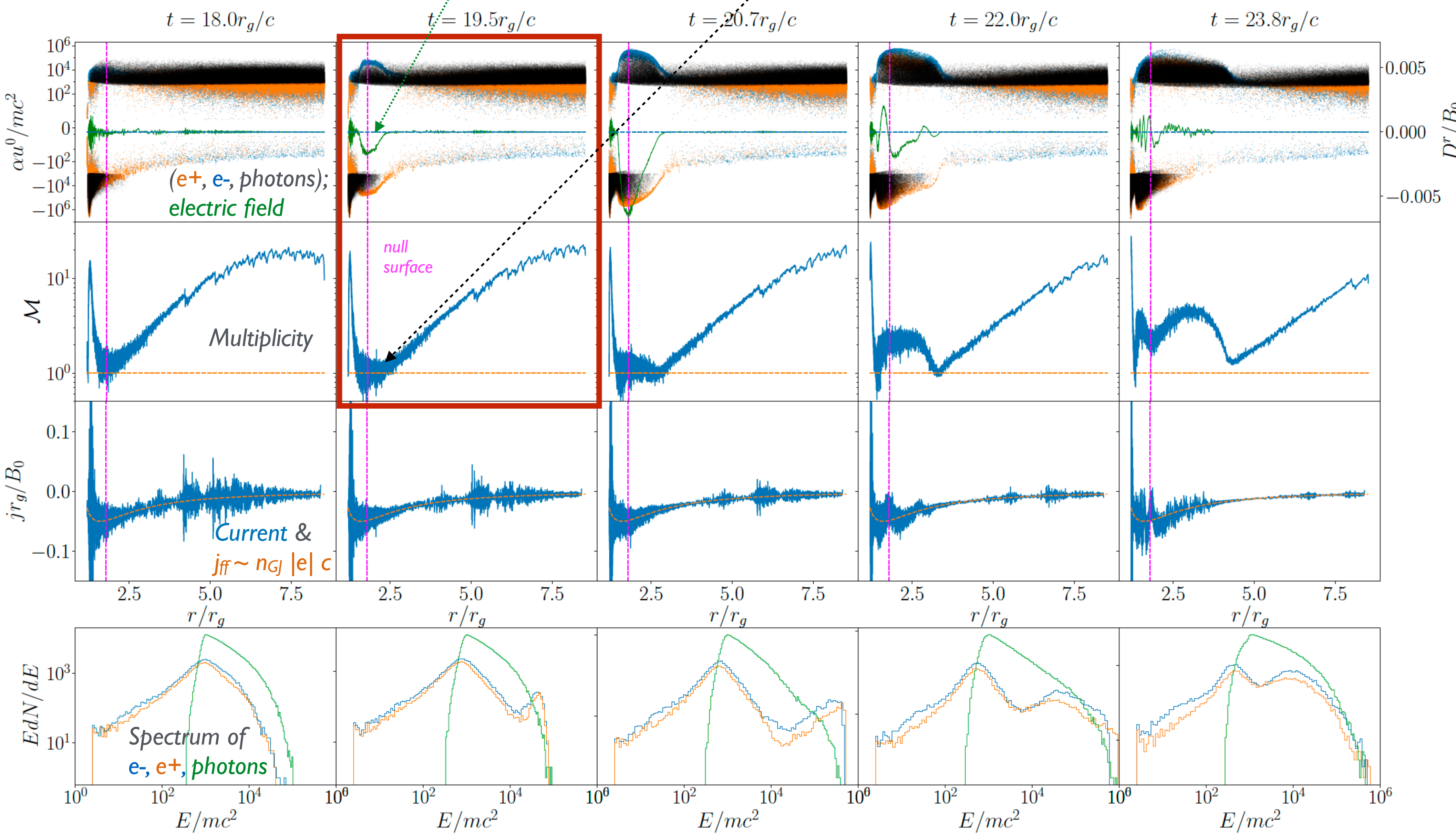
(size $r_g \sim 10^4\,\lambda_p$, $l_{IC} \sim 10^3\,\lambda_p$)

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

electric field forms as multiplicity drops below 1



Chen & Yuan 2020

Selected Theoretical Advances:

- *Modelling Parsec-Scale Jet Emission in Blazars (physics)*

On shock acceleration in extreme blazars

incorporating micro-physical insights (constraints) into SED modelling:

- requirement of **high minimum electron Lorentz factor** $\gamma_{\mathrm{min,e}} \gtrsim 10^3$ and **low magnetisation in SSC model for extreme TeV blazars…**

- **possible scenario** *(Zech & Lemoine 2021)*:
  - co-acceleration of electrons and protons @ weakly magnetised shocks in jet
  - *energy transfer from p to e⁻ in shock transition layer* (heating/thermal coupling):

    $k_B T_P \sim \Gamma_s m_p c^2$ and $T_e = \xi T_p$ **(pre-heating)**, with $\xi < 1$

    and for thermal Maxwellian $(k_B T_e / m_e c^2) \sim \gamma_{\min}$

    $$\Rightarrow \gamma_{\min} \sim \left(\frac{m_p}{m_e}\right) \Gamma_s \xi \simeq 1800\, \Gamma_s \xi$$

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$$\Rightarrow \gamma_{\rm min} \sim \left(\frac{m_p}{m_e}\right) \Gamma_s \xi \simeq 1800\, \Gamma_s \xi$$

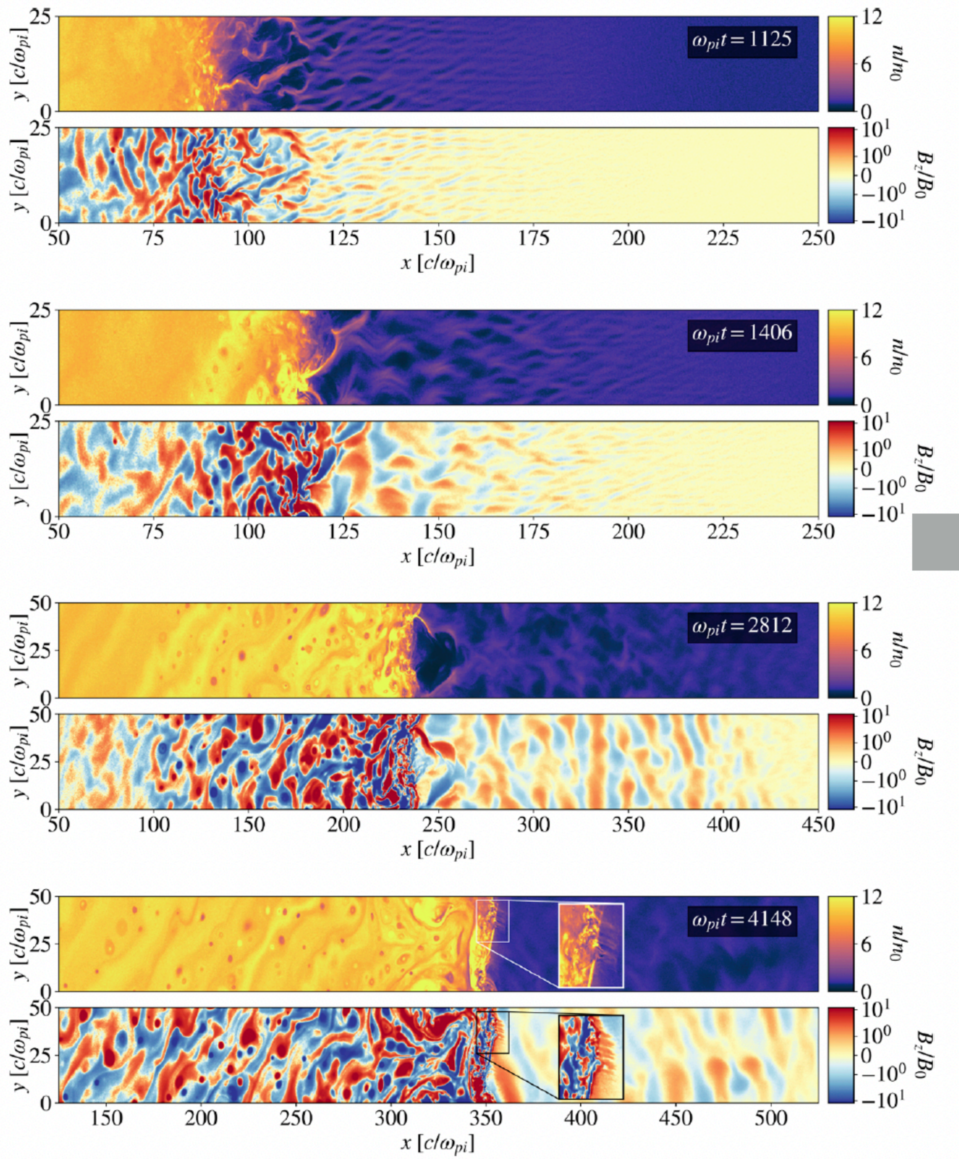
- **generation of micro-turbulence (e.g., Weibel)** $\Longrightarrow$ effective magnetization higher than initial $\sigma \lesssim 10^{-3}$, but decaying downstream with distance [magnetization $\sigma = B^2/(4\pi \langle\gamma\rangle nmc^2)$]

  $\Longrightarrow$ **magnetization in radiation zone** $\sigma \leq \sigma_{\rm rad} \leq 0.01$

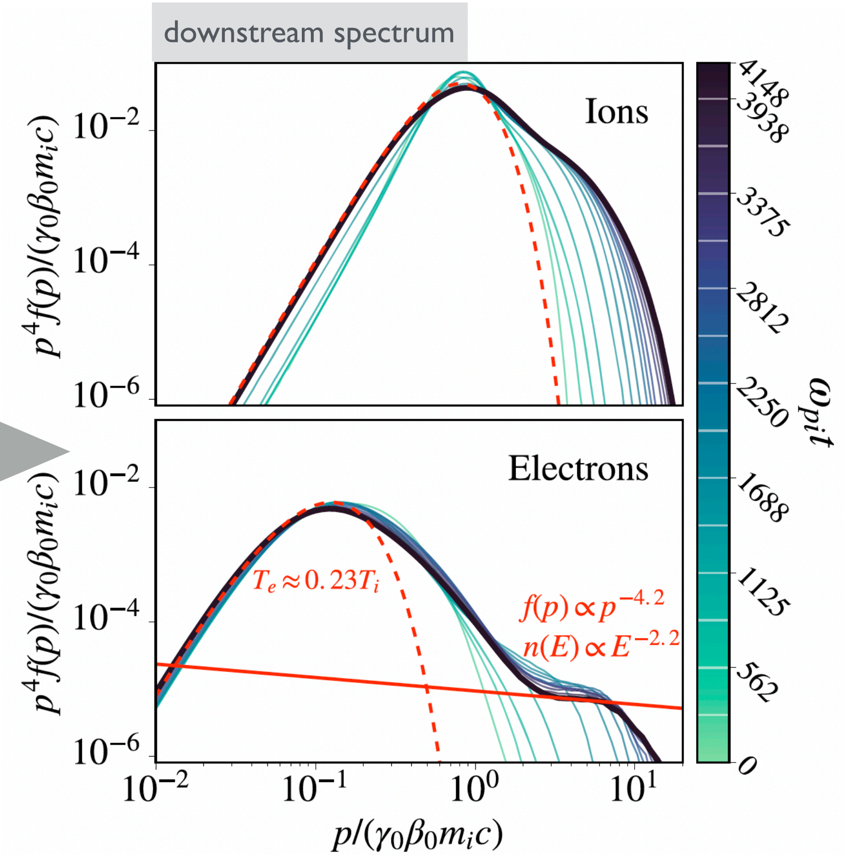
- high $\gamma_{\rm min,e}$, low $\gamma_{\rm max,p}$, B ~ O(mG) $\Longrightarrow$ emission leptonic (protonic suppressed)

On electron heating in relativistic shocks

Crumley+ 2019: 2D PIC of quasi-parallel, mildly relativistic ($\Gamma_s \simeq 1.5$), low-σ, e- p shocks



$\sigma_0 = 0.007$ (downstream), high Mach number (M=15)
at early times, shock Weibel-mediated, later Bell-mediated

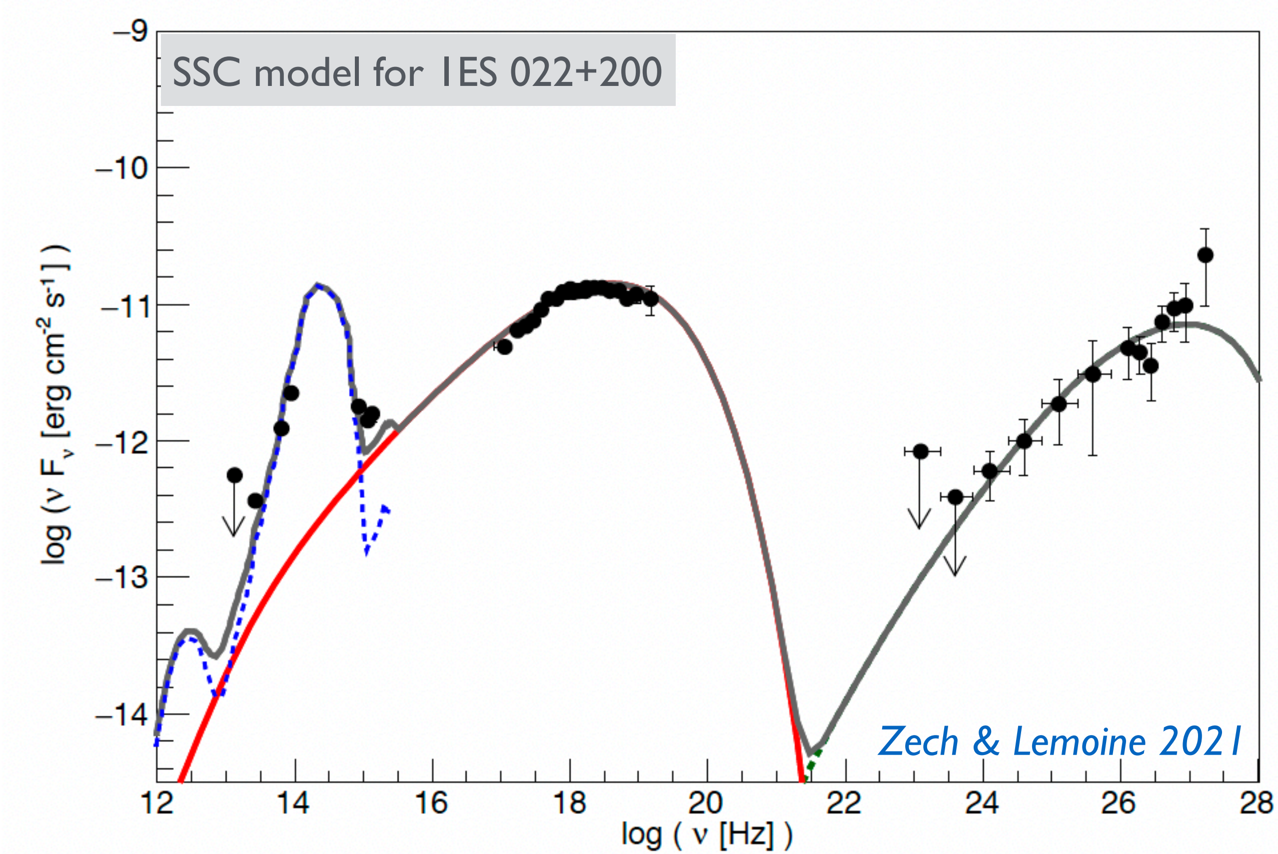


$T_e \sim 0.3\, T_p$ and $k_B T_p \sim 0.2\, m_p c^2$

- electron preheating becomes more efficient at lower magnetizations and larger shock speeds…

(e.g., Sironi+ 2013, Vanthieghem+ 2020)

On shock acceleration in extreme blazars



scenario III	
δ	50
$R_{\rm src}$ [$10^{16} cm$]	1.3
B [mG]	4.4
$\sigma_{\rm rad}$	1.0×10^{-4}
$\sigma_{\rm rad}/\sigma$	270
$\gamma_{e,\rm min}$	1.8×10^{3}
$\gamma_{e,\rm max}$	2.9×10^{6}
n_e [cm^{-3}]	0.13

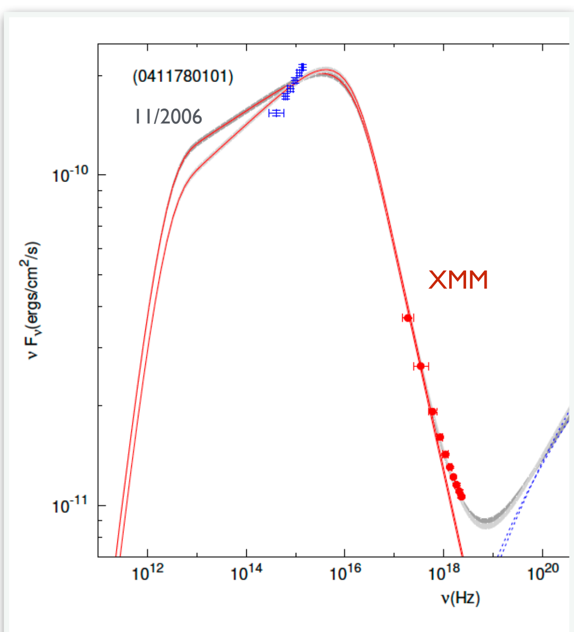
electron distribution

- re-acceleration at multiple (≥2) shocks required to produce hard particle spectra (deviating from PL) and increasing $\gamma_{\rm min,e}$
- input: for single shock spectrum, PL index s = 2.2, $< \gamma_e > = 600\,\Gamma_s$ …
- possible caveat: significantly out of equipartition, very low m.f. (cf. flux conservation)….

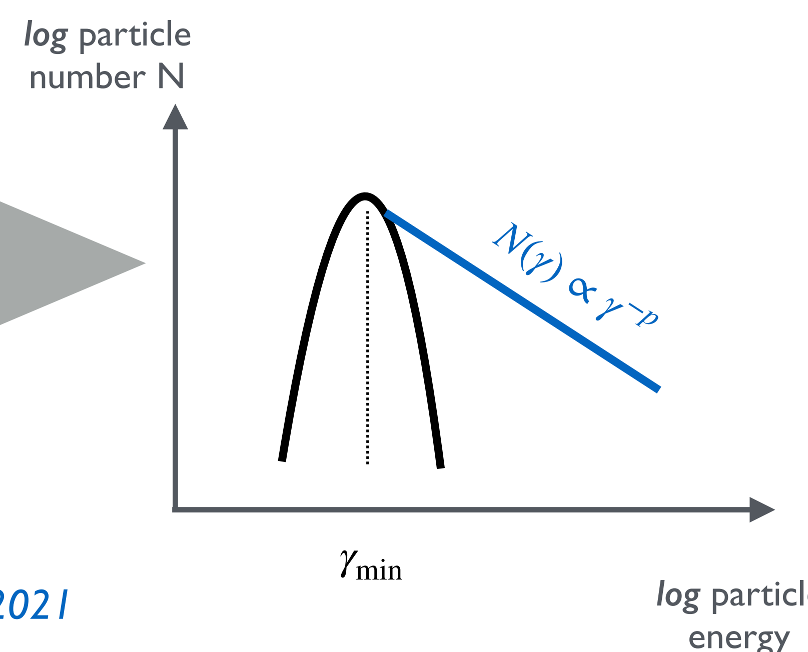
$\Longrightarrow$ ***probing model assumptions via variability….***

Convex X-ray spectrum in PKS 2155-304 indicating emergence of IC contribution

- no dilution by up-scattering of synchrotron peak photons $\Longrightarrow \gamma_{\rm min,e} \sim 300$ (best fit)
- associated with peak of shocked, thermal Maxwellian: $\gamma_{min,e} \sim \left(\frac{m_p}{m_e}\right) \Gamma_s \xi$, where $T_e = \xi T_p$ with $\xi \sim 0.1$ *(moderate thermal coupling)*
- *weakly-magnetized* $(\sigma_u \Gamma_s < 0.1)$ X-ray emission region dominated by e-p composition…



δ ~ 25
B ~ 0.2 G
p ~ 2.5
γ_{min}~60-350
semi-equipartition between emitting electrons and m.f.



Jagan,…FR…2021

cf. also Madejski+ 2016

Selected Theoretical Advances:

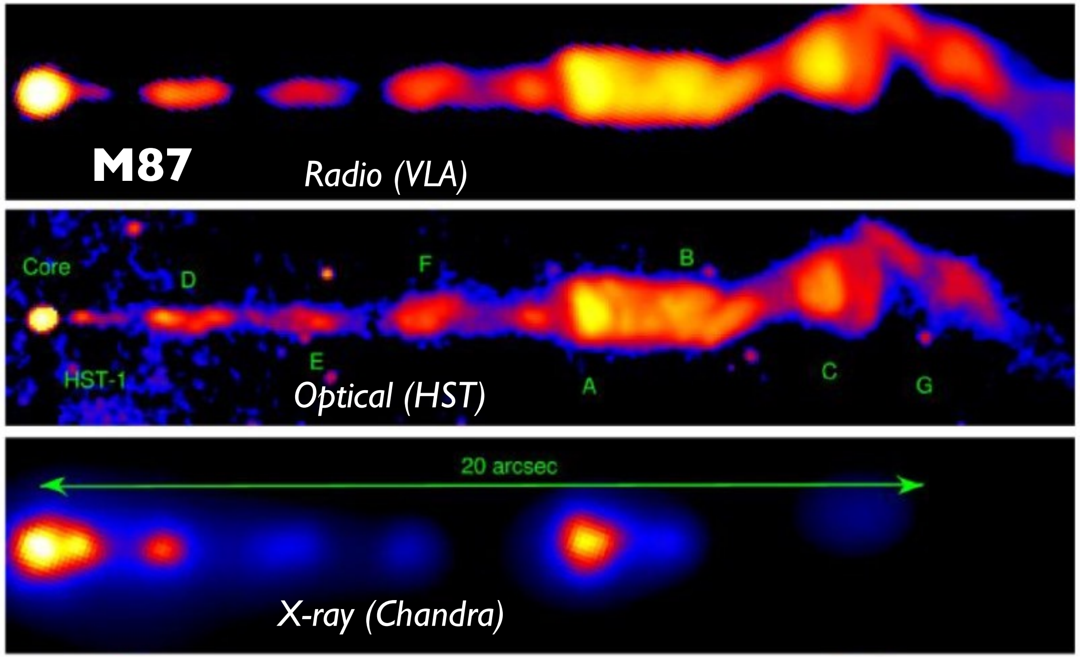
- *Understanding large-scale jet emission (conceptual & methodological)*

Progress in understanding HE emission from large-scale AGN jets I

_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)

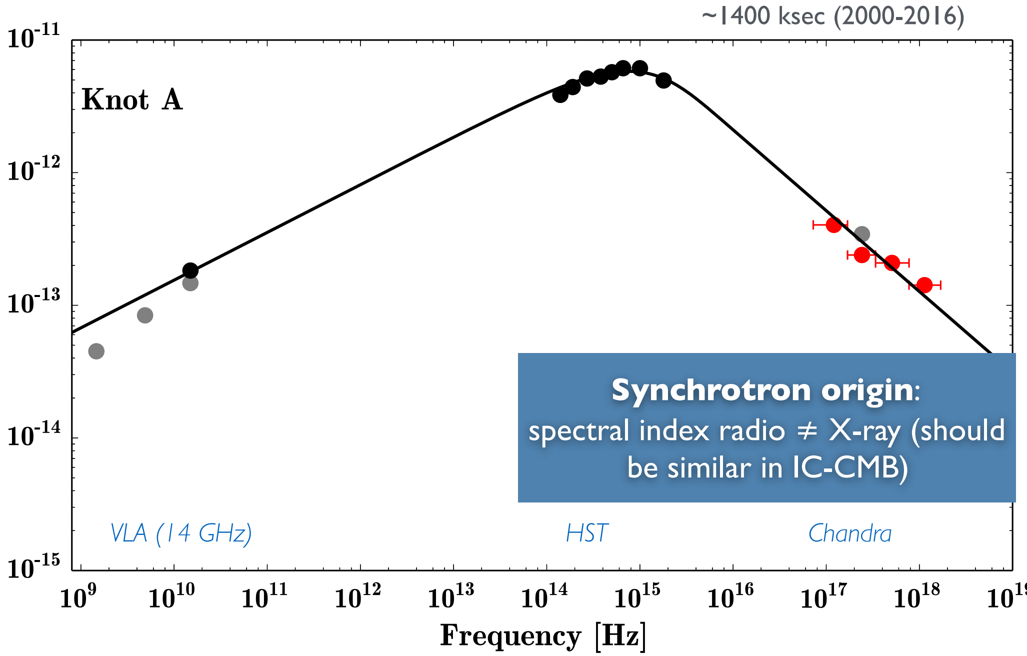
$\nu \propto \gamma^2 B$



1 arcsec ~ 0.1 kpc (0.081 kpc)

Marshall+ 2002

Relativistic particles throughout whole jet

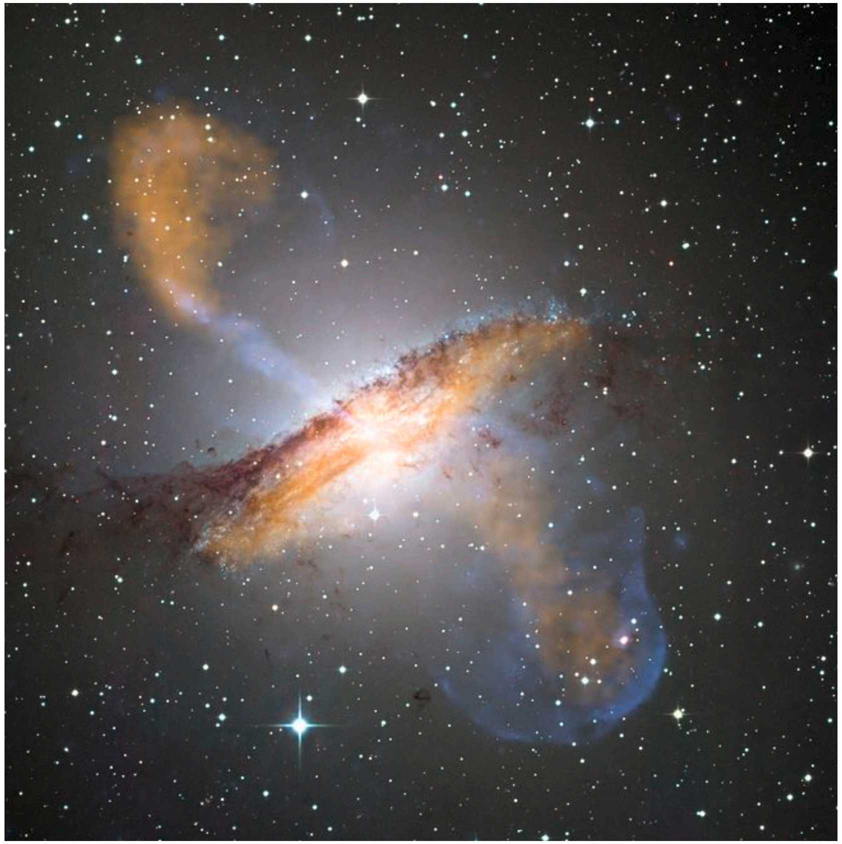


Synchrotron origin: spectral index radio ≠ X-ray (should be similar in IC-CMB)

SED can be fitted by broken power-law

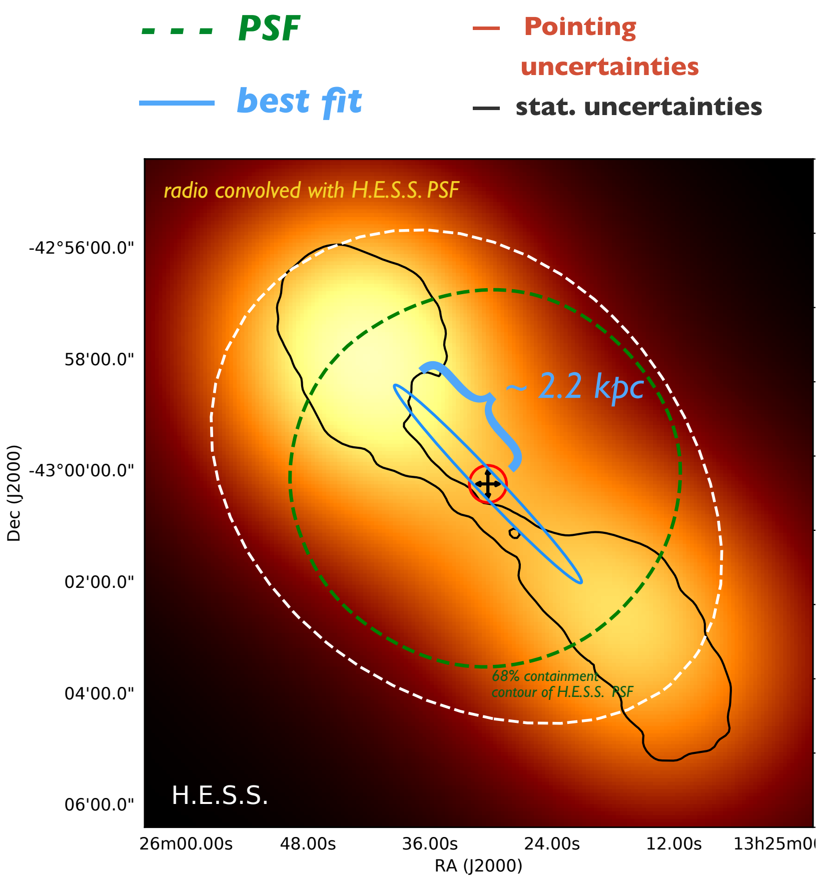
($B = 3 \times 10^{-4}$ G, $\gamma_b \sim 10^6$, $\gamma_{max} \sim 10^8$, $P_{jet} \sim 10^{43}$ erg/s, $\Delta\alpha \sim 2$)

Progress in understanding HE emission from large-scale 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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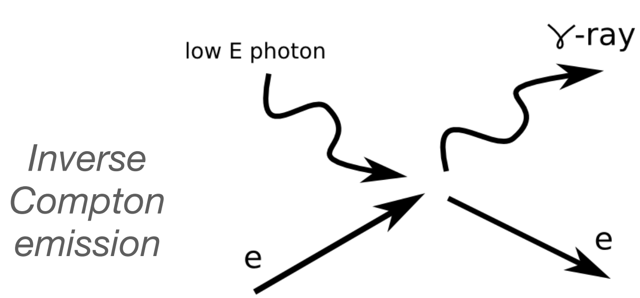
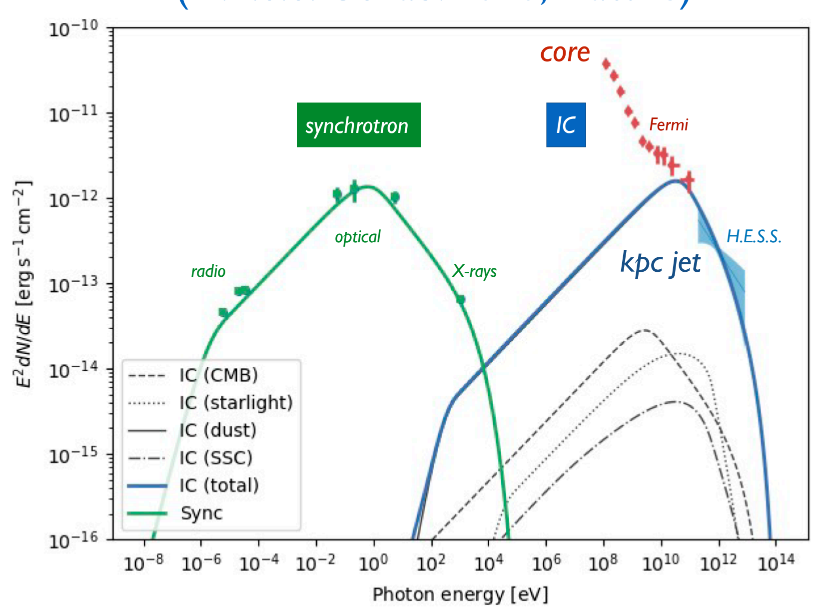


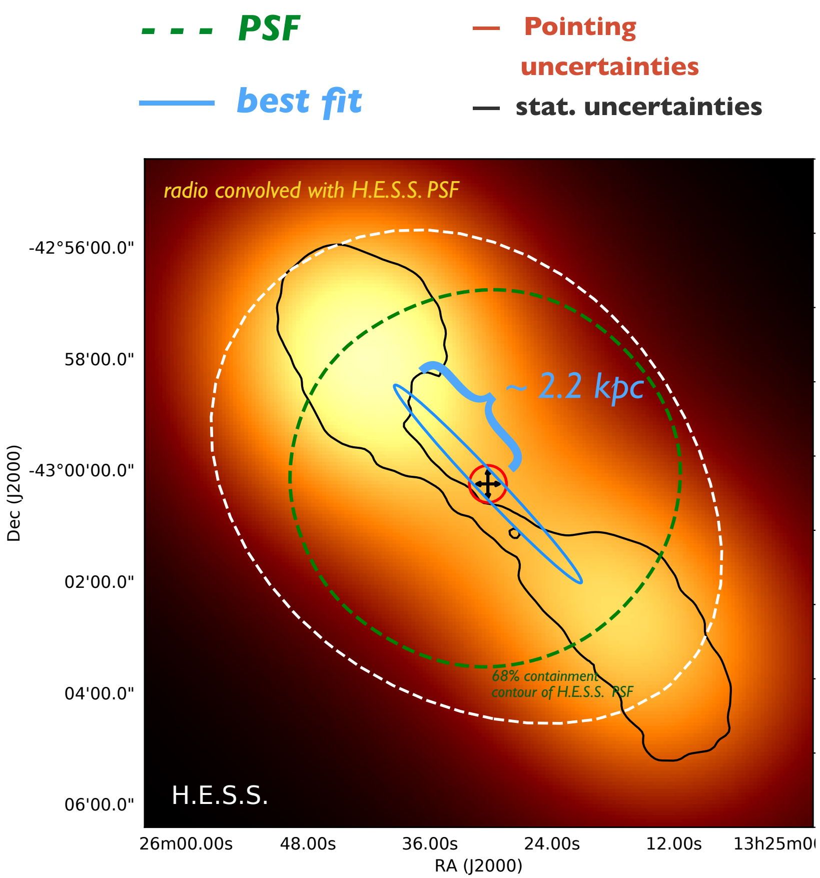
$$\nu_2 \propto \gamma^2 \nu_1$$

(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

Progress in understanding HE emission from large-scale AGN jets II



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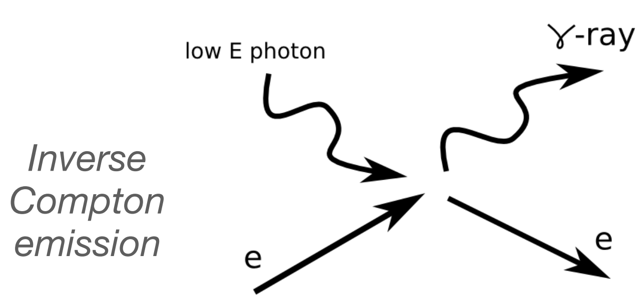

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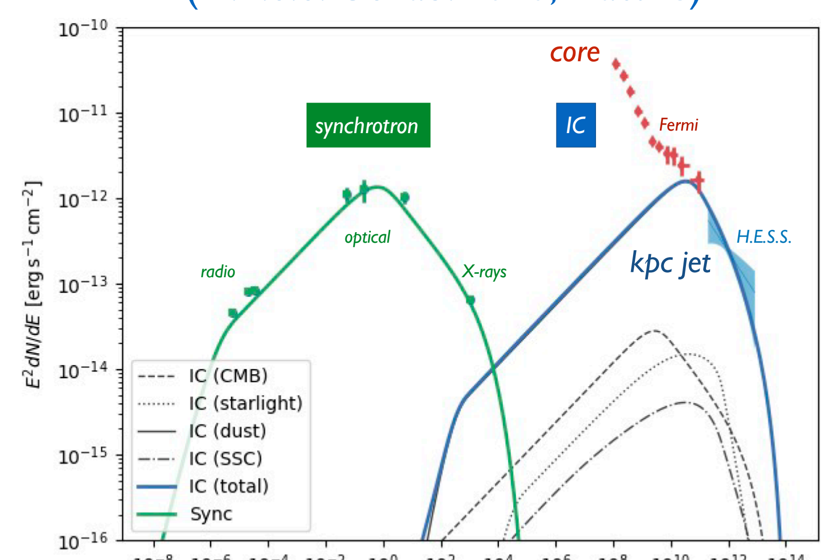
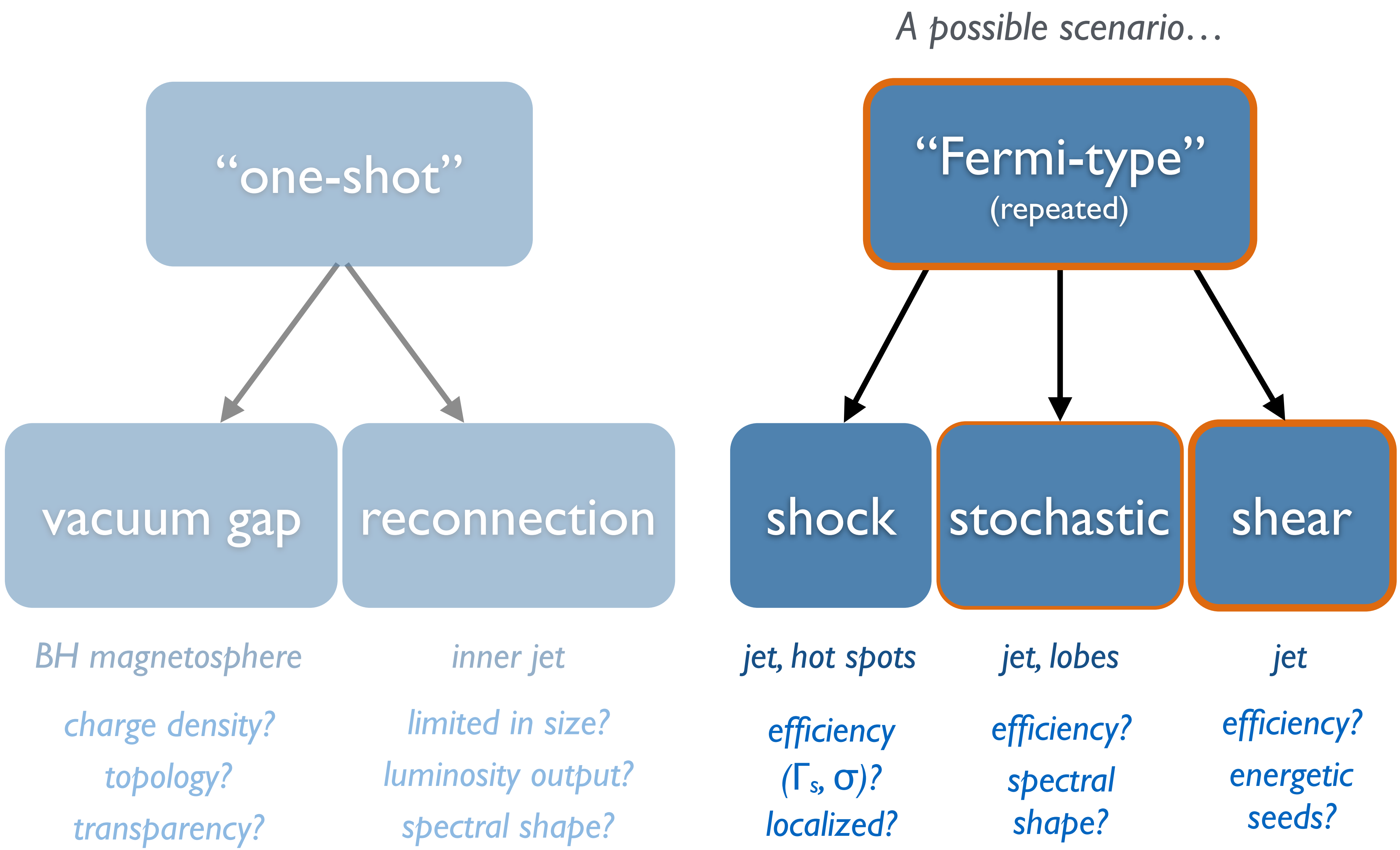


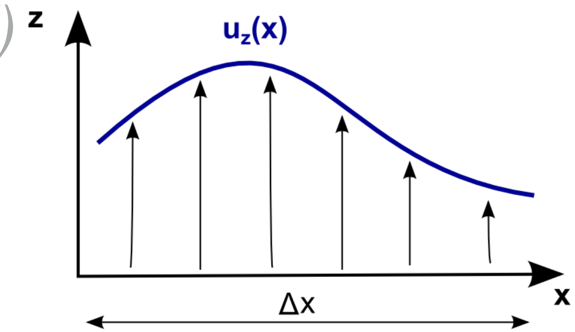
VHE variability as potential probe…

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



Basics of Shear Particle Acceleration

Gradual *shear flow*, e.g. $\vec{u} = u_z(x)\,\vec{e}_z$ *(scattering center speed)*



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

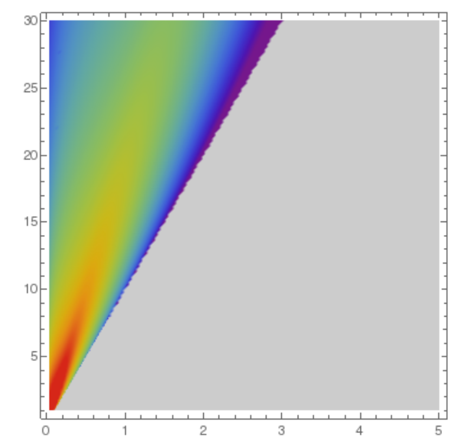
$$\frac{<\Delta\epsilon>}{\epsilon_1} \propto \left(\frac{u}{c}\right)^2 = \left(\frac{\partial u_z}{\partial x}\right)^2 \lambda^2$$

using *characteristic effective velocity:*

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

- So:

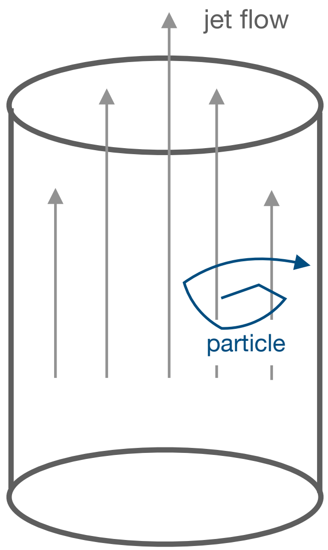
$$t_{acc} = \frac{\epsilon}{(d\epsilon/dt)} \sim \frac{\epsilon}{<\Delta\epsilon>} \times \frac{\lambda}{c} \propto \frac{1}{\lambda}$$



  - *seed from acceleration @ shock or 2nd Fermi….*
  - *easier for protons…(⇨ UHECR)*

e.g., Jokipii & Morfill 1990; FR & Duffy 2004, 2006f; Webb+ 2018f - see FR 2019 [review]

Radiative-loss-limited electron acceleration in mildly relativistic flows

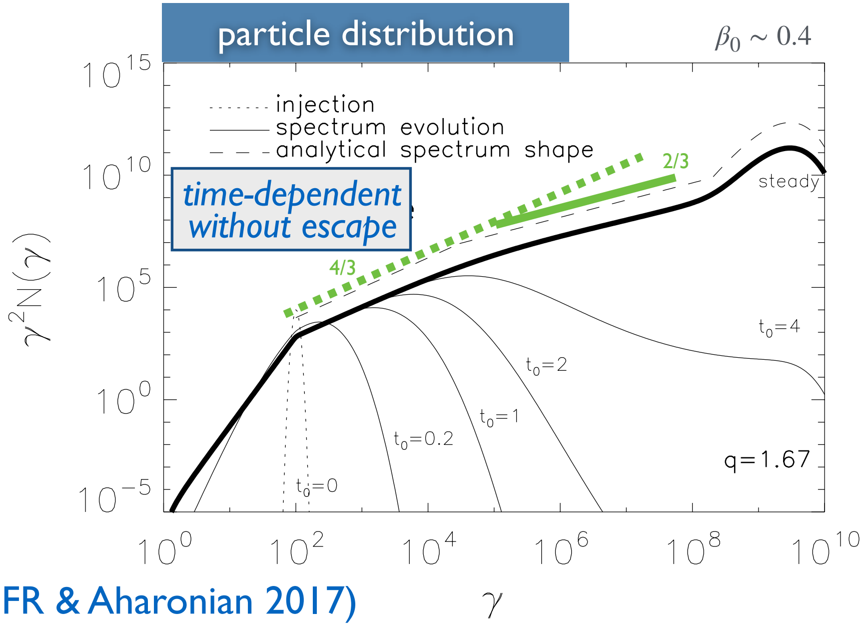


Ansatz: Fokker-Planck equation for f(t,p) incorporating acceleration by stochastic and shear, and losses due to synchrotron and escape for cylindrical jet.

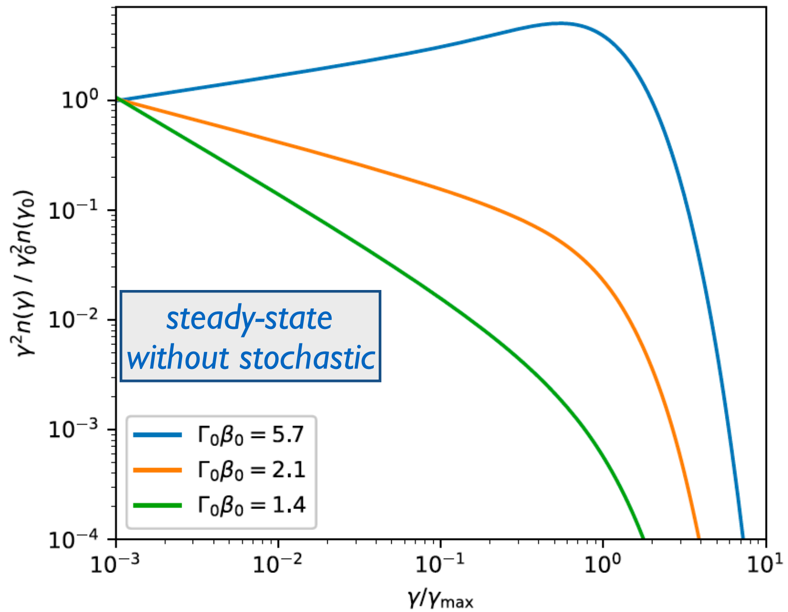
Parameters I: $B = 3\mu G$, $v_{j,max} \sim 0.4c$, $r_j \sim 30$ pc, $\beta_A \sim 0.007$, $\Delta r \sim r_j/10$,
mean free path $\lambda = \xi^{-1} r_L (r_L/\Lambda_{max})^{1-q} \propto \gamma^{2-q}$, q=5/3 (Kolmogorov), ξ=0.1

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

Radiative-loss-limited electron acceleration in mildly relativistic flows



(Liu, FR & Aharonian 2017)



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

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

Parameters I: B = 3μG, $v_{j,max} \sim 0.4c$, $r_j \sim 30$ 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), ξ=0.1

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

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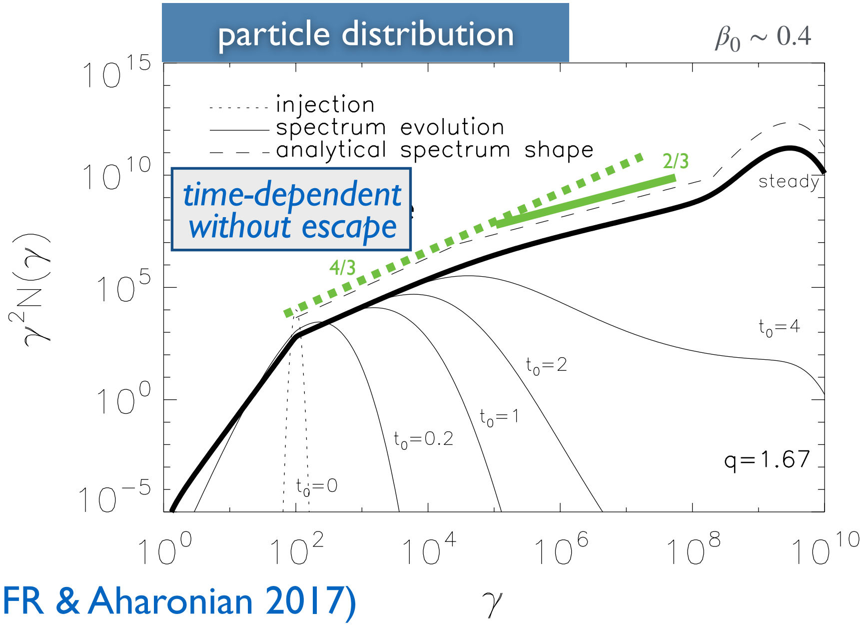

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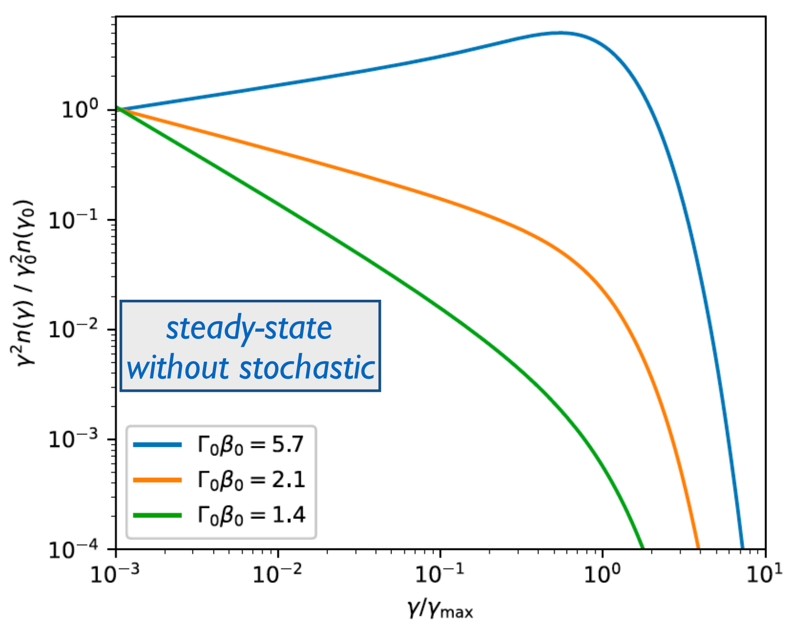

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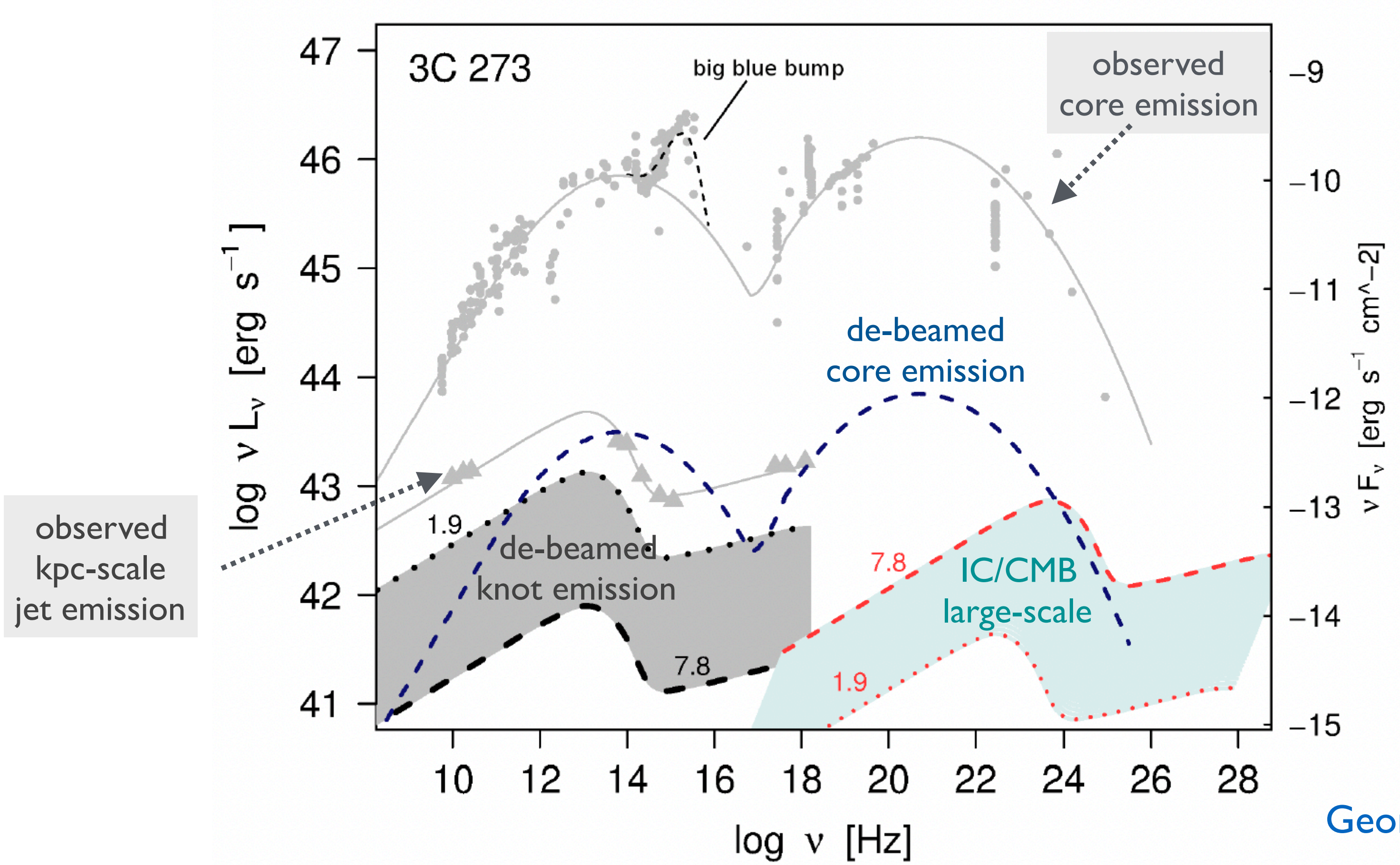
caveat: simplification of spatial transport; in general, high jet speeds needed.

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

If large-scale AGN jets would be multi-TeV accelerators…

- ***extended X-ray synchrotron requires multi-TeV electrons, as validated for Cen A***
  - synchrotron X-ray emitting electrons IC up-scatter CMB to TeV energies…
  - steady IC contribution of knots and kpc-scale jet not necessarily insignificant compared to core (cf. D^{-2} beaming-correction)

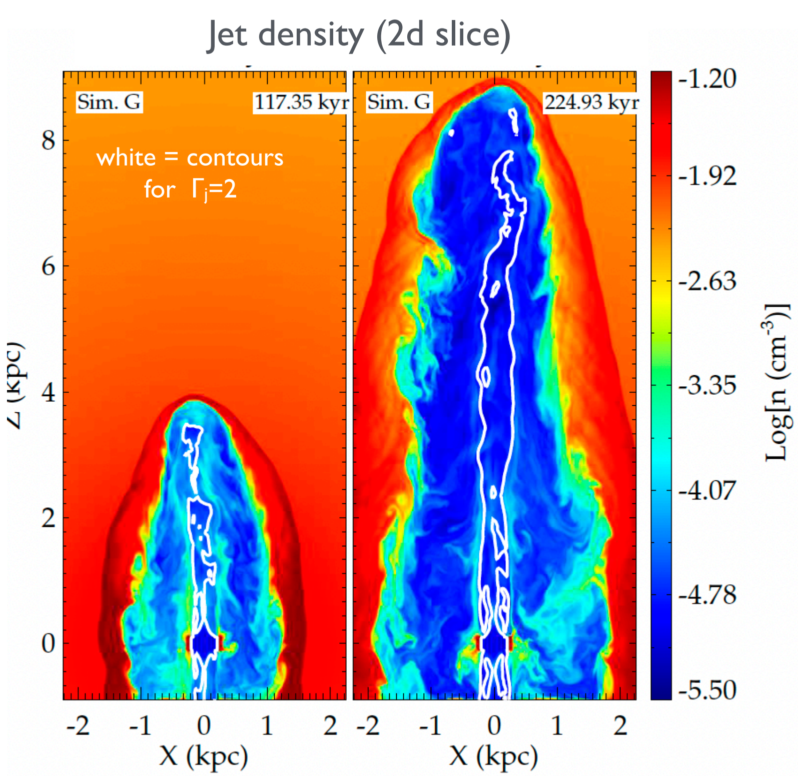
➡ *potential contribution to astrophysical TeV background (exceeding TeV blazars)*



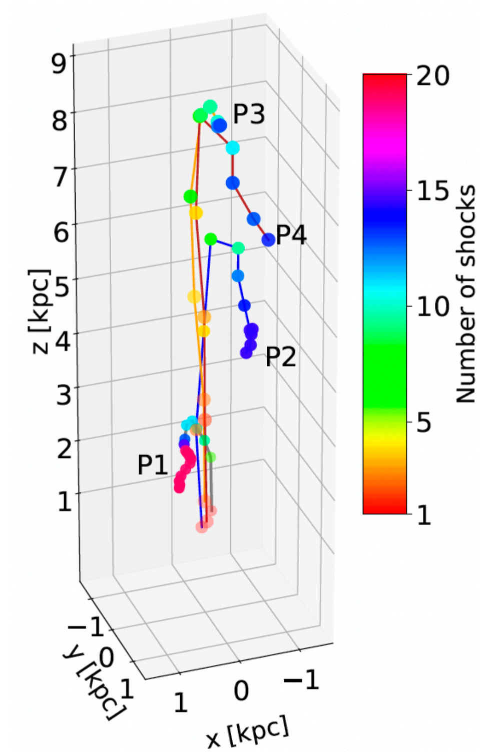
Georganopoulos+ 2016

simulating synchrotron emission from relativistic jets *(Mukherjee+ 2020, 2021)*

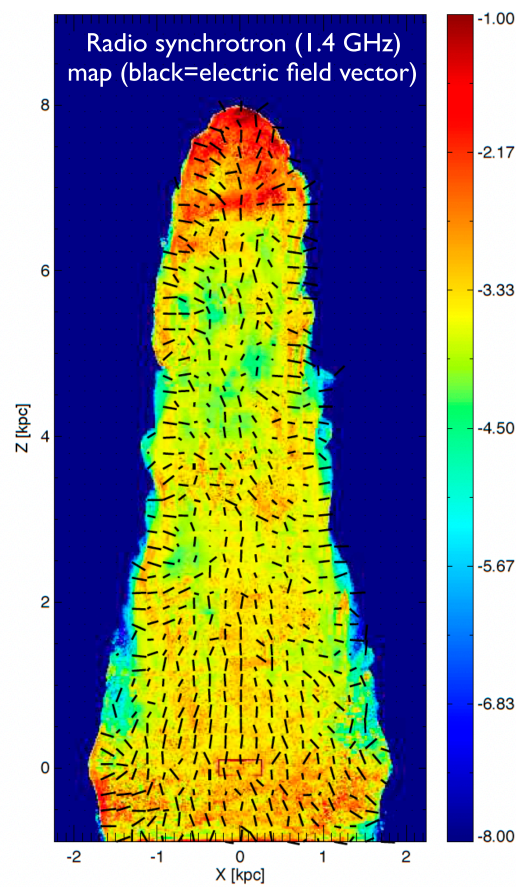
- use 3D relativistic MHD jet simulations (PLUTO)
- add Lagrangian (macro)particle module to simultaneously evolve *spatial and spectral evolution of non-thermal electrons* producing synchrotron emission (vs. post-processing)
- focus on particle acceleration via shocks (inject with $\gamma \geq 100$ & convolve with DSA)…



instabilities are not disruptive



particles encounter multiple shocks



case: high-power jet ~10^{46} erg/s

generation of longitudinal magnetic fields in cocoon

parameters:
$\Gamma_{j,i}$ =6
σ_i =0.2
$r_{j,i}$ =0.2 kpc

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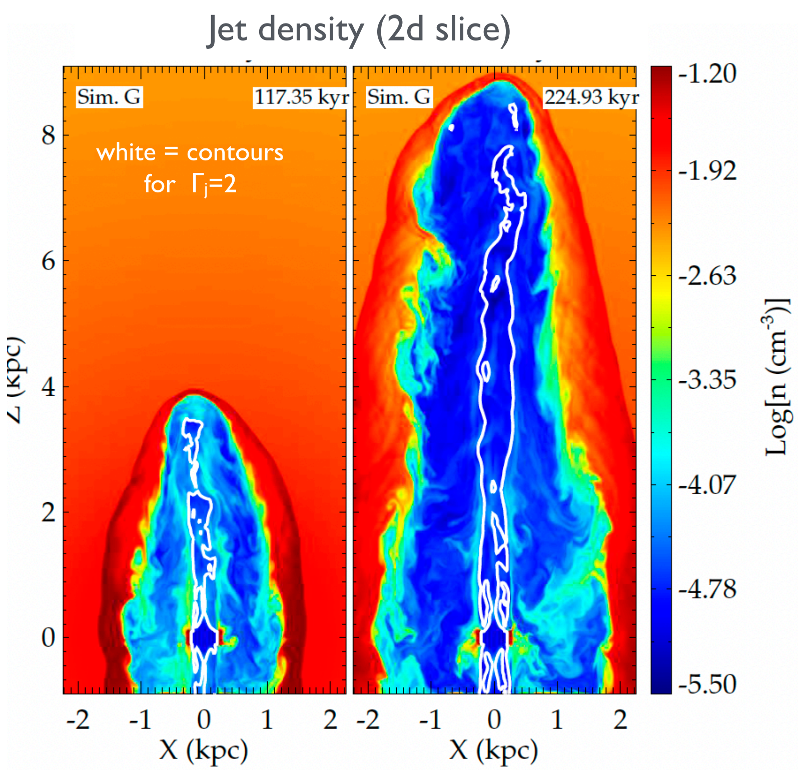

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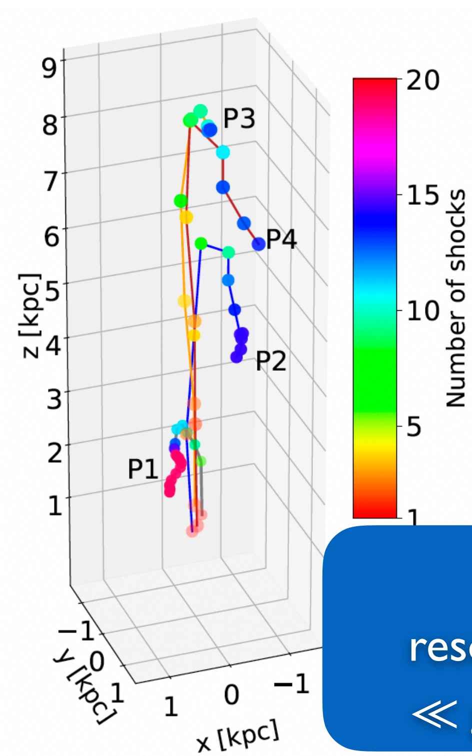

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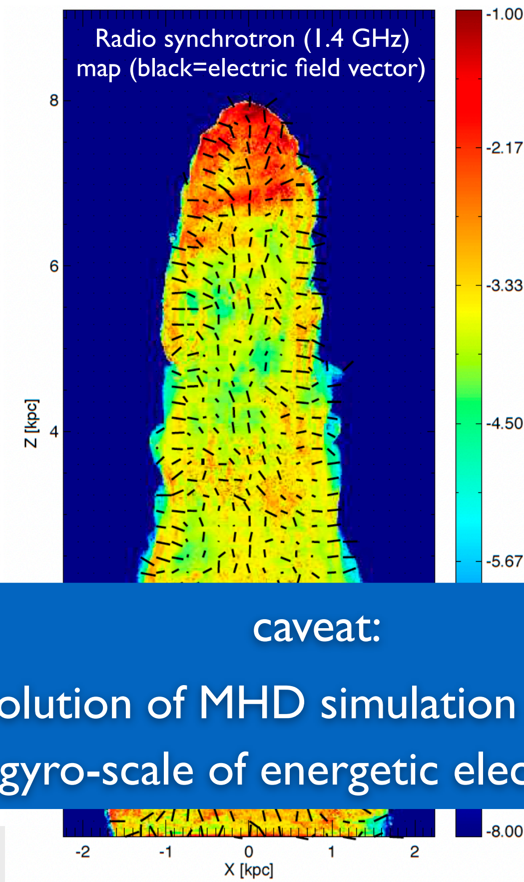

case: high-power jet ~10^{46} erg/s

generation of longitudinal magnetic fields in cocoon

caveat:

resolution of MHD simulation $\sim r_j/10$

$\ll$ gyro-scale of energetic electrons ….

Summary

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Addressing the Felix' question (progress)…

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- conceptual (BH magnetosphere)
- modelling physics (shock microphysics…)
- large-scale jet emission (PeV accelerators)

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Thank you!
&
Questions ?