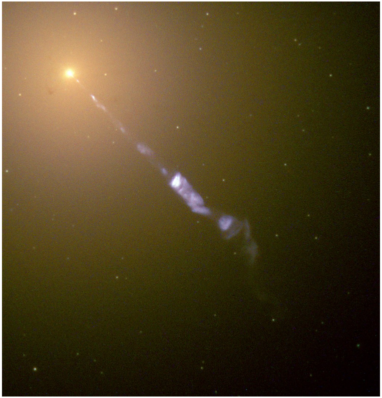
Electromagnetic cascades in Kerr black hole magnetospheres

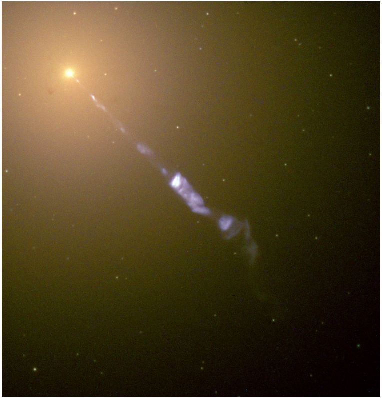
Benjamin Crinquand

Simulating the evolution and emission of relativistic outflows

28 November, 2019



Hubble photo of the jet ejected from M87



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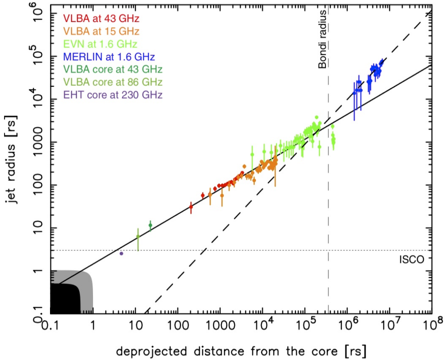
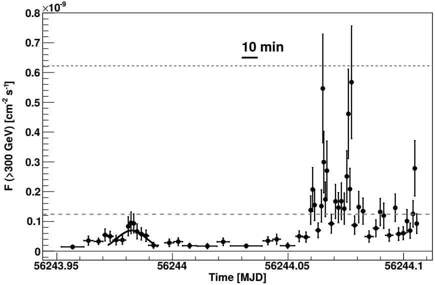


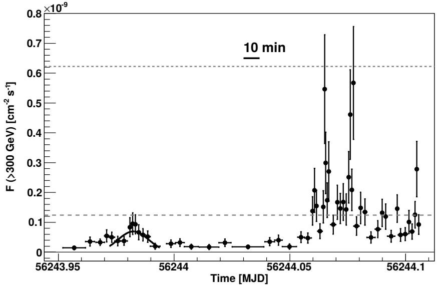
M87 radio jet width as a function of the distance to the black hole

Jets are launched very close to the event horizon!



Gamma-ray luminosity of the AGN IC 310

- For IC 310: horizon crossing time $\Delta t = r_g/c = GM/c^3 \approx 23$ min
- Extremely variable gamma-ray flares observed
- Brightening of the radio core during flares



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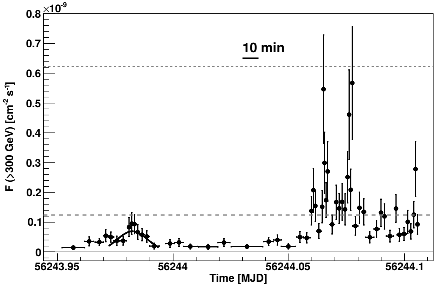

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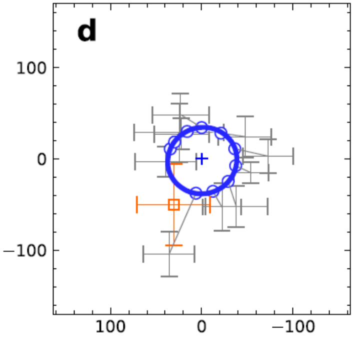
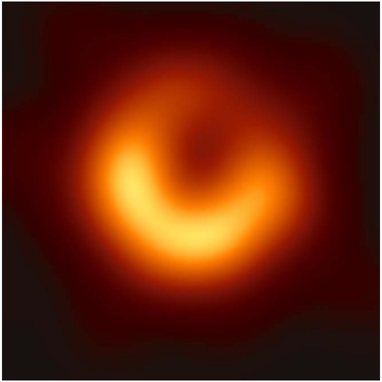
$\Rightarrow$ ***Connection between particle acceleration and jet formation***



Motion of the flare centroid

- Observation of a hot spot orbiting *Sgr A** by GRAVITY
- Polarization measurements suggest ***large scale poloidal magnetic field***



EHT image of the supermassive black hole shadow in M87

- Confirms M87* as a supermassive black hole
- Asymmetry of the ring controlled by the BH spin
- Multi-wavelength observation $\rightarrow$ black hole must be spinning

Ingredients:

- Spinning black hole
- Large scale magnetic field
- Hot and collisionless accretion flow

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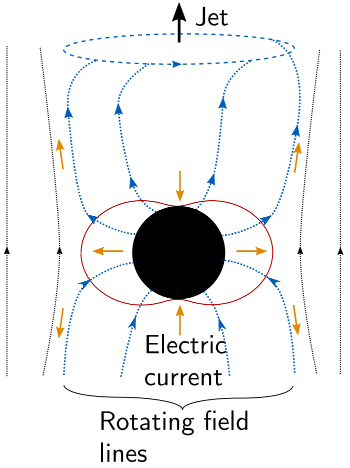
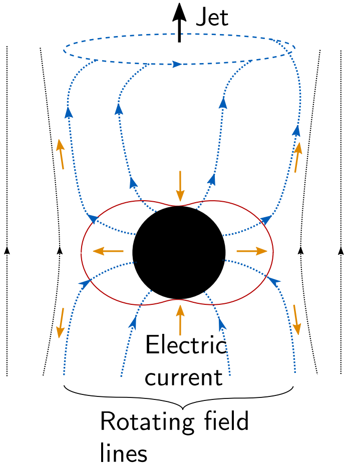
Key questions:

- How is energy extracted from the black hole? (What powers the jet?)
- How is the jet loaded with mass?
- How (and where) are particles accelerated?



- Electromotive force originates from space-time dragging by the spinning black hole
- Current carried by plasma, which extracts energy and angular momentum from the BH



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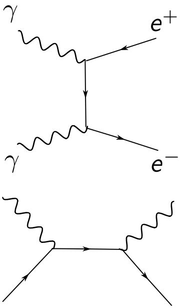
- Output power prediction:

$$L \sim 10^{46} a^2 \left(\frac{B_0}{10^4 \text{ G}} \right)^2 \left(\frac{M}{10^9 \text{ M}_\odot} \right)^2 \text{erg/s}$$

$\Rightarrow$ Can account for the observed power of AGN

Pair creation

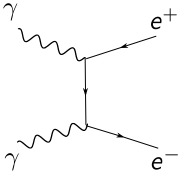
Compton scattering



In this picture, plasma must be continuously injected in the black hole magnetosphere

- Particles and photons interact with a soft bakground radiation field (produced by the accretion disk)

Pair creation



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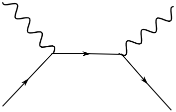

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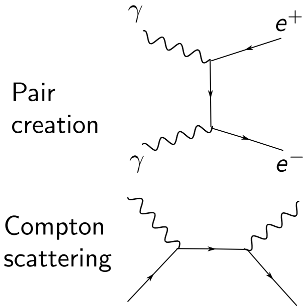

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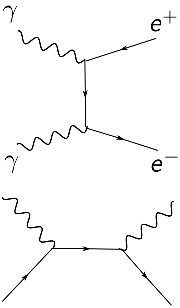

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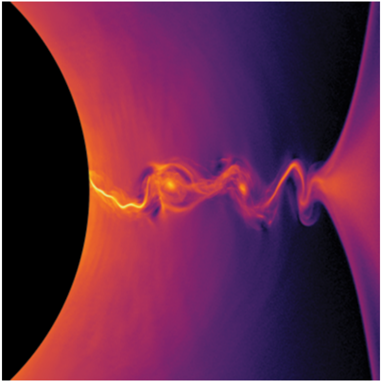
- Particle acceleration by gravitationally induced electric field
- Inverse Compton scattering of ultra-relativistic particles off soft photons $\rightarrow$ high-energy radiation
- Photon-photon annihilation $\rightarrow$ plasma injection

Particle-in-cell simulations including full GR, with vertical magnetic field

Approximate injection method

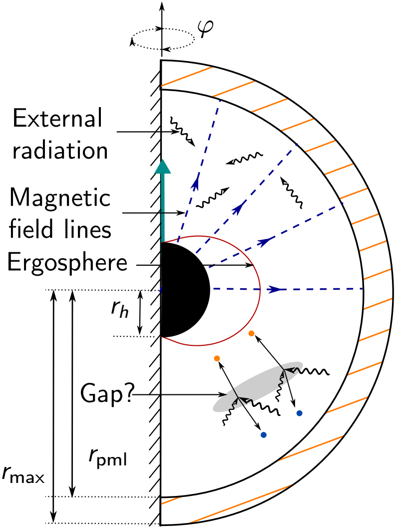
Every time step, inject density $\delta n \propto |\boldsymbol{D} \cdot \boldsymbol{B}| / B$, provided $|\boldsymbol{D} \cdot \boldsymbol{B}| / B^2 > \epsilon$

Parfrey, Philippov & Cerutti, 2019



Plasma density in the current sheet

- Development of a force-free magnetosphere
- Reconnection and particle acceleration at the equatorial current sheet
- Energy extraction by negative-energy particles (Penrose process)

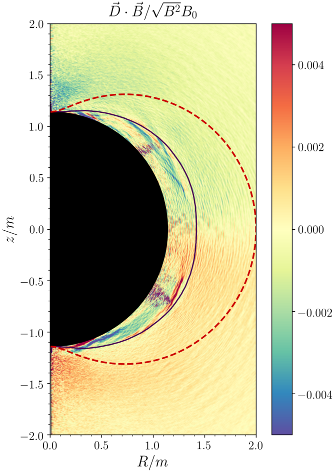


Here we include IC scattering and $\gamma\gamma$ annihilation to have **self-consistent plasma injection**

- 2D axisymmetric simulation
- Magnetic monopole
- Maximally spinning black hole: $a = 0.99$

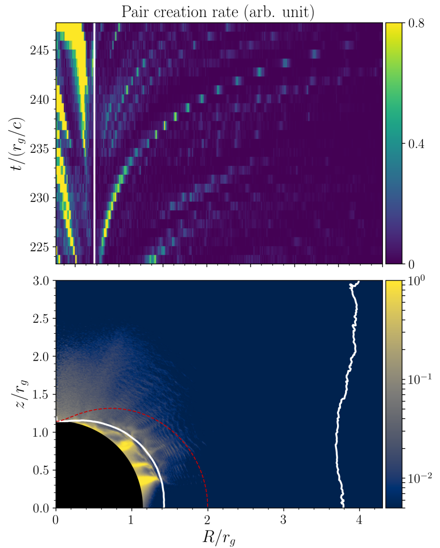
Phase space plot ($\log_{10}\gamma$ as a function of the distance to the black hole, at $\theta = \pi/4$)

Time averaged parallel electric field

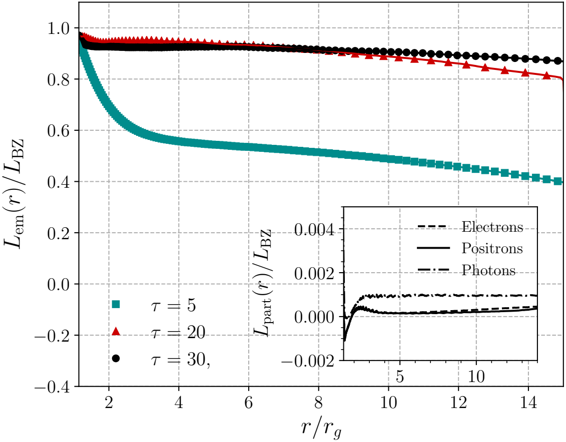


- Gap opens at the **light surface**, then moves inwards or outwards
- Conclusion holds for lower spin a
- Gap size h: larger than plasma skin depth, smaller than r_g

Phase space plot of the freshly created pairs



- Bursts of pair creation at short time scales (a fraction of r_g/c)
- Pair creation occurs in these "flying gaps"
- Dissipated power around 5% of the total Poynting flux



Time-averaged Poynting flux

- Output power matches BZ prediction $L_{\rm BZ} = B_0^2 \omega_{\rm BH}^2 / 6$
- Dissipation goes down as opacity increases
- Most energy transferred to low-energy photons (beyond pair creation threshold)

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Results:

1. Blandford-Znajek process extracts energy
2. Mass loading of the jet explained
3. Time dependent gap at the light surface

Outlooks:

- Study other magnetic configurations
- Reproduce observables (*e.g.* γ-ray lightcurve)
- Model black hole-disc interaction (GRAVITY observations)

Key parameters

- Opacity $\tau_0 = n_s \sigma_T r_g$, where n_s is the background radiation field density
- Magnitude of the magnetic field $\tilde{B}_0 = r_g e B_0 / m_e c^2$
- $\tilde{\varepsilon}_0 = \varepsilon_0 / m_e c^2$ energy of the background radiation field

In M87*, $\tilde{B}_0 \sim 10^{14}$ and $\tilde{\varepsilon}_0 \sim \tilde{1}0^{-9}$; in practice we have a smaller separation of scales, which must satisfy

$$\gamma_{\rm rad} \gg \gamma_s \gg 1,$$

where $\gamma_s = 1/\tilde{\varepsilon}_0$ is the Lorentz factor of the bulk of the particles, and $\gamma_{\rm rad}$ is the maximum Lorentz factor achievable with radiative losses

We kept $\varepsilon_0 = 0.01 m_e c^2$, $e B_0 r_g / m_e c^2 = 10^5$ fixed