Electromagnetic cascades in Kerr black hole magnetospheres

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GReCO Seminar, IAP

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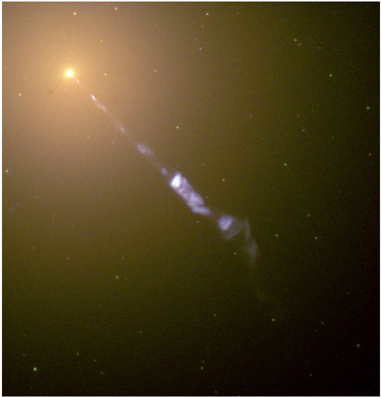
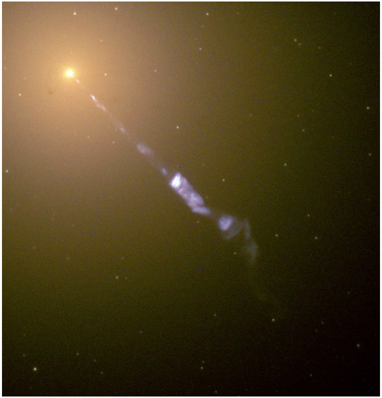


Hubble photo of the jet ejected from M87



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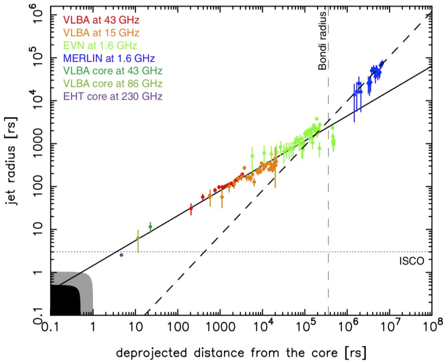
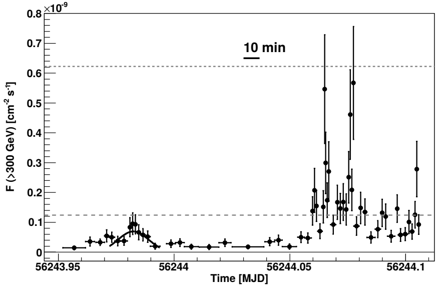


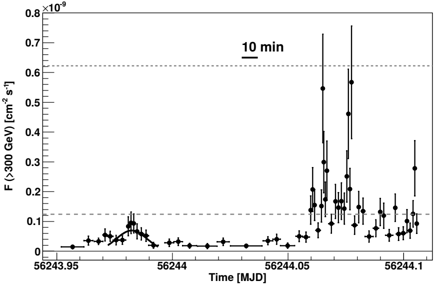
M87 radio jet (Blandford et al., 2018)

Jets are launched very close to the event horizon!



Gamma-ray lightcurve of the AGN IC 310 (Aleksic et al., 2014)

- For IC 310: horizon crossing time $\Delta t = r_g/c = GM/c^3 \approx 23$ min
- Very high-energy radiation from AGN (up to TeV)
- Extremely variable flares



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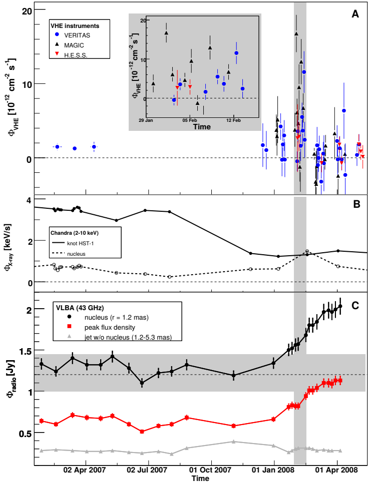
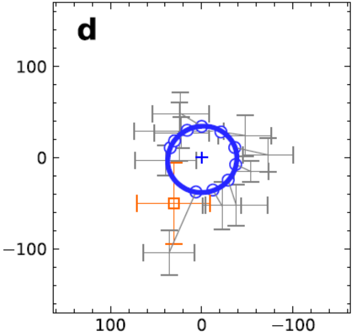
- For IC 310: horizon crossing time $\Delta t = r_g/c = GM/c^3 \approx 23$ min
- Very high-energy radiation from AGN (up to TeV)
- Extremely variable flares

$\Rightarrow$ ***Particles are accelerated on very small spatial scales***



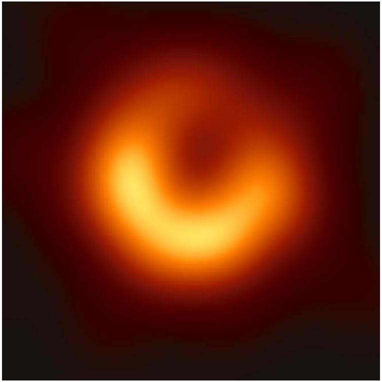
(Acciari et al., 2009)

- Correlation between radio, X-ray and gamma-ray flares
- Brightening of the radio core during flares
- Connection between particle acceleration and jet formation



(GRAVITY Collaboration et al., 2018)

- 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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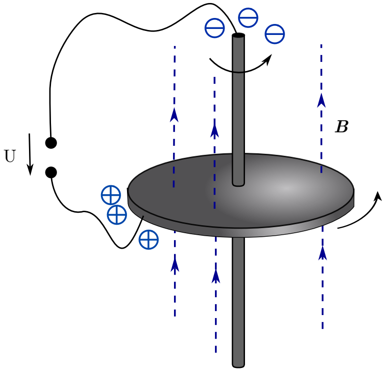
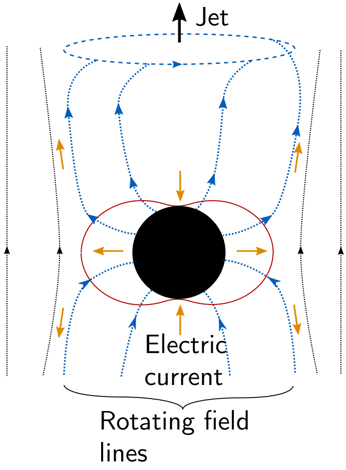
Key questions:

- 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?

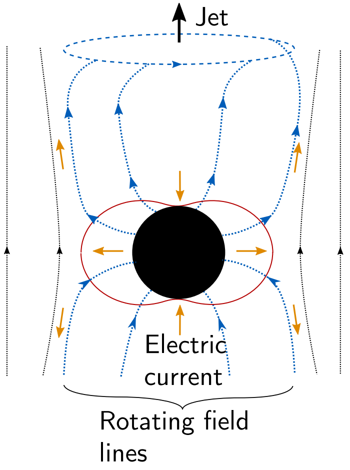


- Faraday disk rotates in a uniform magnetic fields
- Develops a potential difference between the axis and the edge
- Electric field rises from charge separation

For a spinning black hole, the electric field is **gravitationally induced**



- Current carried by plasma, which extracts energy and angular momentum from the BH
- Requires a force-free magnetosphere to be activated
- Power carried by a Poynting flux



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- Requires a force-free magnetosphere to be activated
- Power carried by a Poynting flux
- 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

MHD fluid simulations

1. Artificial loading of the jet (density floors)
2. No particle acceleration
3. Thermal particles only

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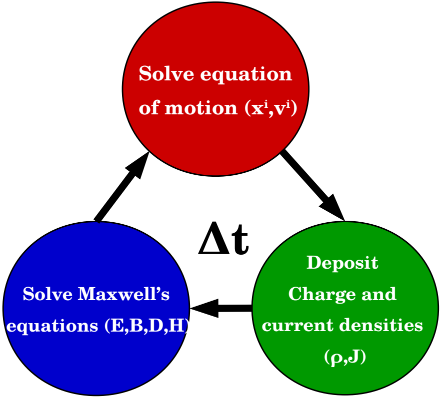
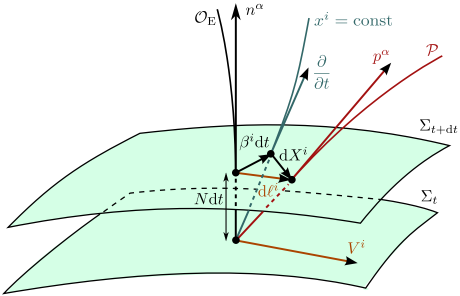
Kinetic PIC simulations

- Allows us to simulate microphysics from first principles
- Non-thermal particles
- Unrealistic separation of scales



Particle (e^+, e^- and photons) motion and EM fields are self-consistently evolved **in curved space-time**

Downside: particle noise due to finite sampling of phase space



(Vincent et al., 2012)

$3 + 1$ formulation of general relativity

- Introduces a universal coordinate time $t \rightarrow$ convenient for numerical simulations
- Allows to keep a usual PIC code architecture
- More intuition to discuss 3-dimensional quantities

$3+1$ foliation of spacetime

$$\mathrm{d}s^2 = -\alpha^2 \mathrm{d}t^2 + \gamma_{ij}(\mathrm{d}x^i + \beta^i \mathrm{d}t)(\mathrm{d}x^j + \beta^j \mathrm{d}t)$$

Naturally introduces "Fiducial Observers" (FIDOs), with 4-velocity $n^\mu = (1/\alpha, -\boldsymbol{\beta}/\alpha)$

- t: coordinate time, reduces to proper time of an observer at infinity
- α: "lapse function", so the proper time of the FIDO is $\mathrm{d}\tau_{\mathrm{FIDO}} = \alpha\, \mathrm{d}t$
- β^i: "shift vector", 3-velocity of the FIDO with respect to the coordinate grid
- FIDOs have zero angular momentum: at rest with respect to absolute space

- Kerr metric in spherical Kerr-Schild coordinates (t, r, θ, φ)
- Although in curved spacetime, we solve the usual Maxwell's equations

$$\begin{aligned} \partial_t \boldsymbol{B} &= -\boldsymbol{\nabla} \times \boldsymbol{E} \\ \partial_t \boldsymbol{D} &= \boldsymbol{\nabla} \times \boldsymbol{H} - 4\pi \boldsymbol{J}, \end{aligned}$$

where $\boldsymbol{E}$ and $\boldsymbol{H}$ are given by

$$\begin{aligned} \boldsymbol{H} &= \alpha \boldsymbol{B} - \boldsymbol{\beta} \times \boldsymbol{D} \\ \boldsymbol{E} &= \alpha \boldsymbol{D} + \boldsymbol{\beta} \times \boldsymbol{B}. \end{aligned}$$

- $\boldsymbol{B}$ and $\boldsymbol{D}$ are the magnetic and electric fields in the FIDO frame $\rightarrow$ physical intuition from electrodynamics
- Spacetime acts as an active medium (constitutive relations)

Test of electromagnetic solver: check analytical solution for a magnetic monopole in Kerr spacetime

$$A_\varphi = B_0 r_g \frac{r^2 + a^2}{r^2 + a^2 \cos^2(\theta)} \cos(\theta)$$

Equations of motion in $3+1$ form:

$$\begin{aligned}\frac{\mathrm{d}x^i}{\mathrm{d}t} &= v_i = \frac{\alpha}{\Gamma}\gamma^{ij}u_j - \beta^i \\ \frac{\mathrm{d}u_i}{\mathrm{d}t} &= -\Gamma\partial_i\alpha + u_j\partial_i\beta^j - \frac{\alpha}{2\Gamma}u_j u_k \partial_i\gamma^{jk} + \epsilon\frac{\alpha}{m}F_i,\end{aligned}$$

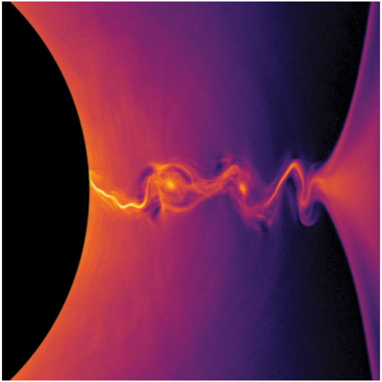
where $\boldsymbol{F}$ is the Lorentz force, A_μ is the electromagnetic 4-potential, $\Gamma = \sqrt{\epsilon + \gamma^{jk}u_j u_k}$ is the FIDO-measured Lorentz factor

($\epsilon = +1$ for a massive particle, $\epsilon = 0$ for a photon)

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

$\rightarrow$ Reconnection and particle acceleration at the equatorial current sheet

Parfrey, Philippov & Cerutti, 2019

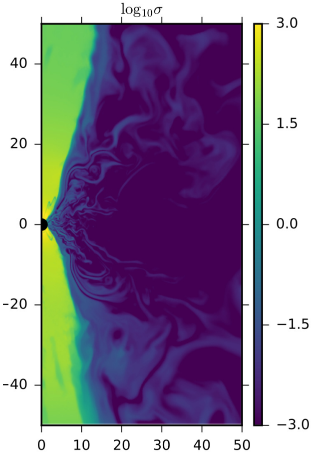


Plasma density in the current sheet

Approximate injection method

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

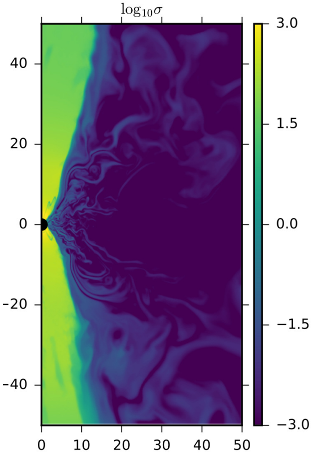
- Development of a force-free magnetosphere
- But no chance to see a gap!



Magnetization in accreting black hole GRMHD simulations (Porth et al., 2019)

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

- Unlikely that jet plasma originates from accretion disk



Magnetization in accreting black hole GRMHD simulations (Porth et al., 2019)

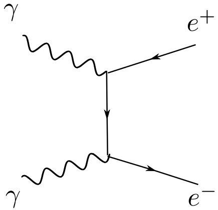
In this picture, plasma must be continuously injected in the black hole magnetosphere

- Unlikely that jet plasma originates from accretion disk
- Magnetosphere bathed in soft bakground radiation field produced by the accretion flow (ADAF)
- Plausible plasma source: pair production by $\gamma\gamma$ annihilation
- If photon density low enough, formation of electrostatic gaps $\Rightarrow$ electromagnetic cascade

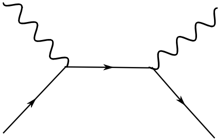
(Works for **low-luminosity AGN**, with sufficiently low accretion rates)

1. Electric fields induced

Pair creation



Compton scattering



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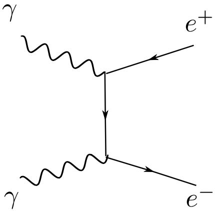

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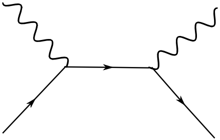
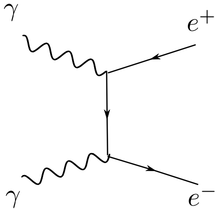


1. Electric fields induced
2. Primary particles accelerated

Radiative transfer
Pair cascade

Pair creation



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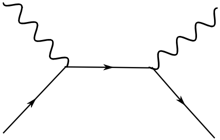

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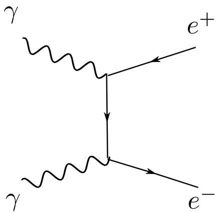
3. Upscattering of a soft photon to high energies (γ)

Pair creation



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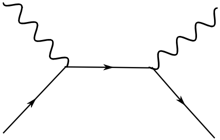

1. Electric fields induced
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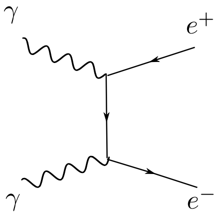
4. Annihilation between a γ and a soft photon

Pair creation



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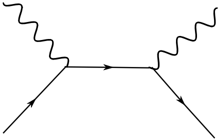

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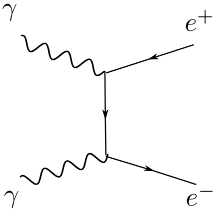
5. Creation of a pair that screens the electric field

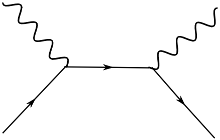
Radiative transfer

Pair cascade

Pair creation



Compton scattering



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Pair creation

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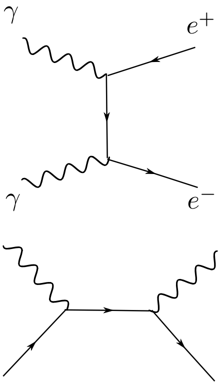

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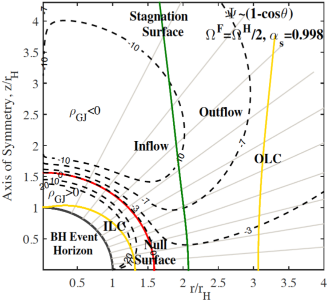
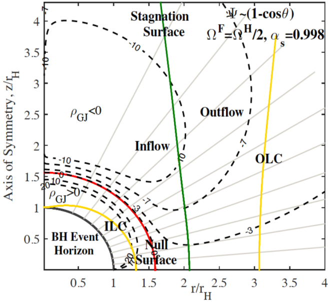
$\rightarrow$ **Electromagnetic cascade develops**
$\rightarrow$ **Self-consistent plasma injection**



(Katsoulakos & Rieger, 2020)

Aside on the relevant surfaces:

1. **Ergosphere:** no static observer exists inside the ergoregion



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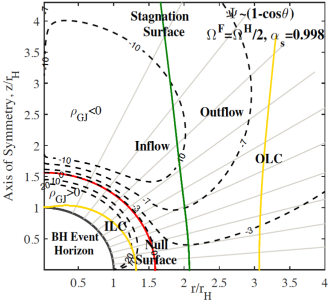

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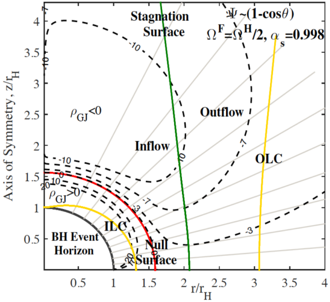

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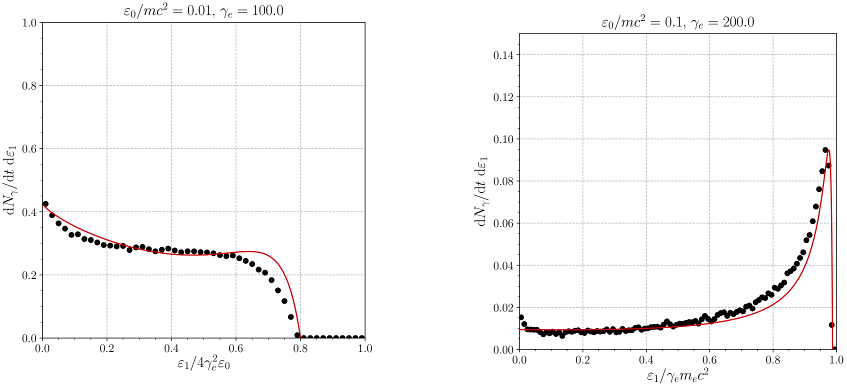
3. **Stagnation surface:** a steady MHD flow has zero velocity
4. **Outer light surface:** similar to the pulsar light cylinder, a point orbiting at angular velocity Ω goes superluminal
5. **Inner light surface:** specific to Kerr black holes, an orbiting point goes superluminal because of spacetime dragging

- Particles bathed in a soft radiation field (uniform, isotropic, **monoenergetic**)
- High-energy γ photons added as a 3^{rd} species
- γ photons can **pair produce** against soft field, $e^{\pm}$ can produce γ photons by **scattering** off soft field
- Semi-analytical to save computation time
- **Monte-Carlo** algorithm: an interaction occurs if

$$p < 1 - e^{-\delta\tau}$$

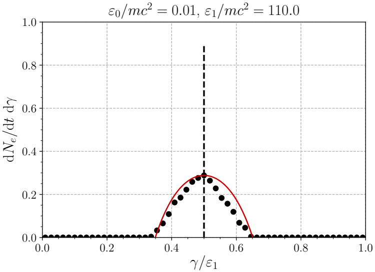
where $p \in [0, 1]$ is a random number and $\delta\tau$ is the optical depth traversed by a particle between two time steps

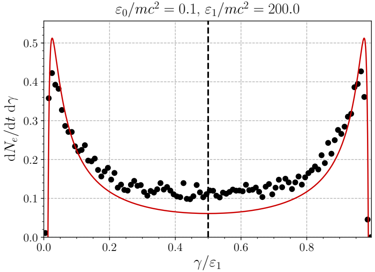
Test: isotropic initial distribution of monoenergetic particles with Lorentz factor γ_e in a monoenergetic radiation field with energy ε_0



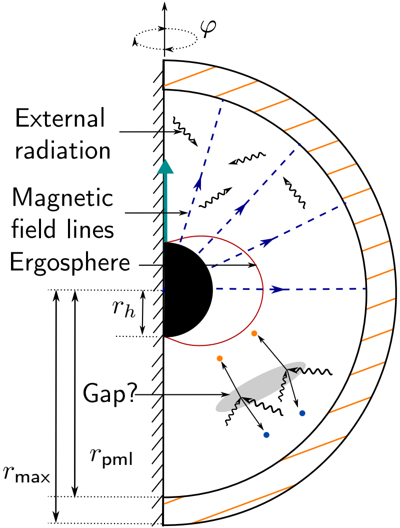
$\Rightarrow$ Fits well the analytic prediction in the Thomson ($\varepsilon_0^{'} \ll m_e c^2$) and Klein-Nishina ($\varepsilon_0^{'} \gg m_e c^2$) regimes

- $e^{\pm}$ pairs can only be created if the photons have sufficient energy : $\varepsilon_1\varepsilon_0 \gtrsim (m_e c^2)^2$
- Pair production cross section peaks at the threshold $\varepsilon_1\varepsilon_0 \simeq (m_e c^2)^2$





$\Rightarrow$ Fits well the analytic prediction close to, and far from the pair creation threshold



- 2D axisymmetric simulation
- Initial magnetic monopole configuration
- Maximally spinning black hole: $a = 0.99$
- Start with a monoenergetic, isotropic, uniform distribution of photons

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

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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

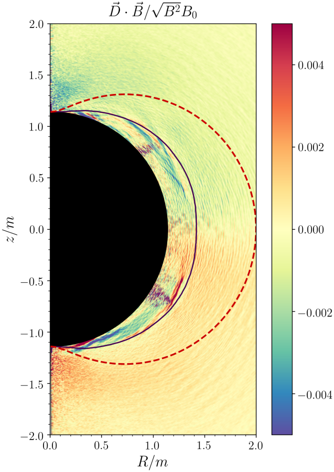
$$1 \ll \gamma_s \ll a\tilde{B}_0,$$

where $\gamma_s = 1/\tilde{\varepsilon}_0$ is the Lorentz factor of the bulk of the particles

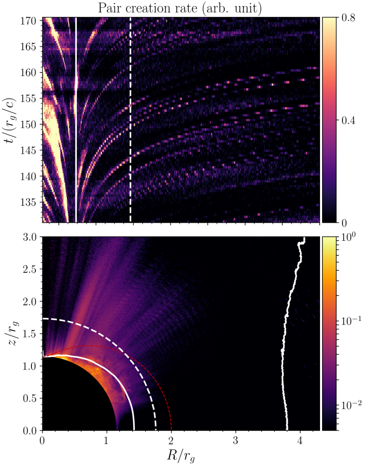
We kept $\tilde{\varepsilon}_0 = 0.005$, $\tilde{B}_0 = 5 \times 10^5$ fixed

Phase space plot of the freshly created pairs

Time averaged parallel electric field

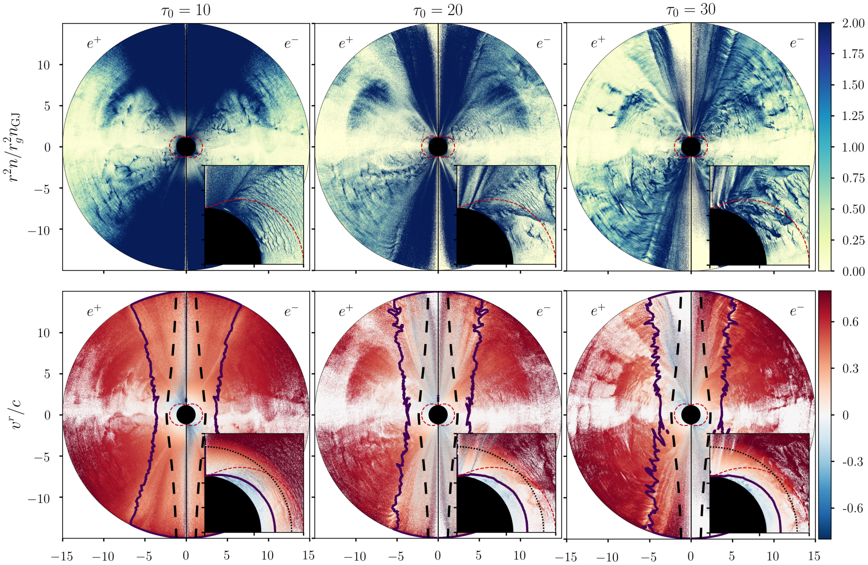


- Gap opens at the **light surface**, then moves inwards or outwards
- Conclusion holds for lower spin a
- Gap size: larger than plasma skin depth, smaller than horizon radius r_g



Crinquand et al., 2020

- Bursts of pair creation at short time scales (a fraction of r_g/c)
- Dissipated power around 3% of the total Poynting flux
- Pair creation occurs in these "flying gaps"


$\tau_0 = 10$
$\tau_0 = 20$
$\tau_0 = 30$
e^+
e^-
$r^2 n / r_g^2 n_{\rm GJ}$
v^r / c
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
0.6
0.3
0
-0.3
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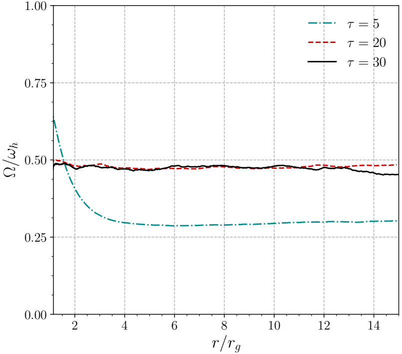
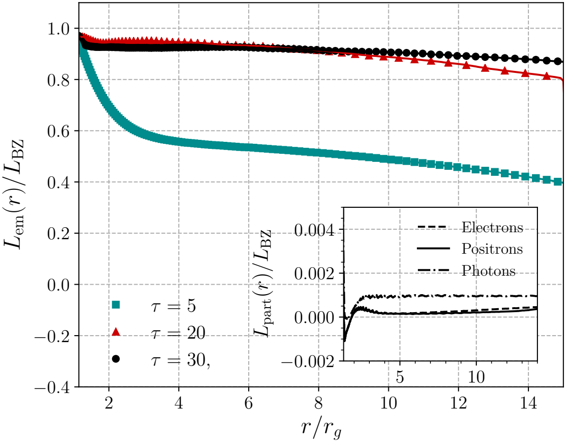
−5
−10
−15
15



- Low opacity: large gap, pair creation occurs at larger distances, more dissipation
  $\Rightarrow$ higher density achieved outside the gap
- High opacity: gap screened completely, self-regulation gives rise to pair creation bursts
- Almost force-free behaviour



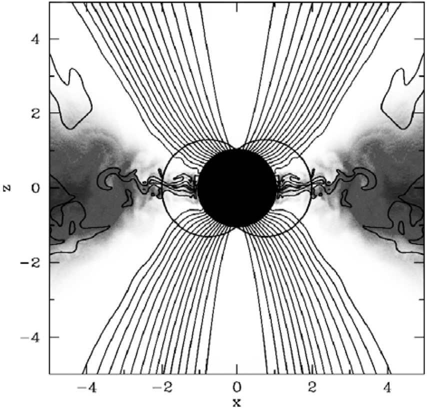
- Output power matches BZ prediction $L_{\rm BZ} = B_0^2 \omega_{\rm BH}^2 / 6$
- Dissipation goes down as opacity increases
- Most energy transferred to low-energy photons (beyond pair creation threshold)

Conclusion

Results: (see Crinquand et al. for details)

1. Blandford-Znajek process can be activated
2. Plasma supply of the jet explained
3. Time dependent gap at the inner light surface

Now we have to link with observations!



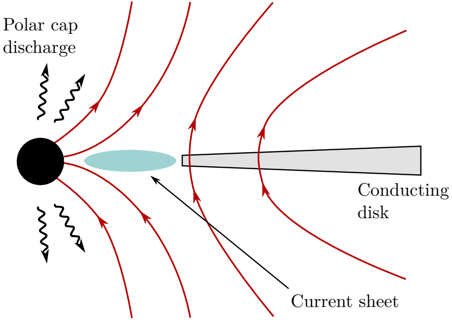
(Komissarov & McKinney, 2007)

- Need of a more realistic magnetic configuration
- Interaction with an accretion disk?
- How does magnetic reconnection at the current sheet impact pair creation at the poles?

Start with paraboloidal magnetic field $A_\varphi = \left(\frac{r + r_0}{r_h + r_0}\right)^\nu (1 - |\cos\theta|)$
$\rightarrow$ Presence of an equatorial current sheet

$\rightarrow$ Enables us to have an outflow, as both light surfaces are crossed by field lines

Problem: All magnetic flux gets dissipated



We implemented a perfectly conducting disk as boundary conditions for the fields, simulating an accretion disk, that anchors the fields lines

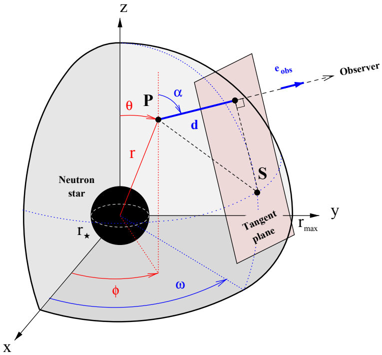
$\rightarrow$ Allows the simulation to reach a stationary state

Disk simulations
Density

- Initially, magnetic flux dissipated by reconnection at the current sheet
- Accretion of giant plasmoids provides the BH with magnetic flux
- Polar cap discharge ignited by accretion of plasmoids?
- Time-dependent behaviour

- So far, only high-energy photons above the pair creation threshold were simulated
- Background field with uniform opacity $\rightarrow$ These photons are quickly absorbed

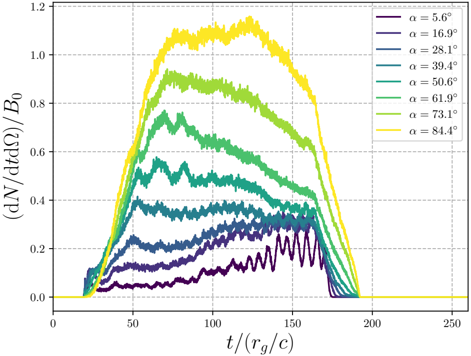
Goal: reproduce variability and explain high-energy emission from AGN
$\rightarrow$ Need to simulate photons below the pair creation threshold and reconstruct a lightcurve



(Cerutti et al., 2016)

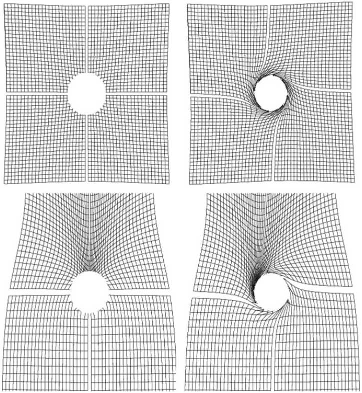
- Photons below the PP threshold no longer interact with the rest of the simulation
- Far enough from the BH, they propagate in straight lines
- Collect all photons with a fixed outgoing viewing angle
- Accounts for the propagation time delay to the observer:

$$\Delta t_{\mathrm{d}} = \frac{\mathbf{PS} \cdot e_{\mathrm{obs}}}{c}$$



Lightcurve for different viewing angles

- Enhanced variability when looking at higher latitudes (polar emission), but lower intensity
- Sub-horizon scale variability is hard to resolve
- Periodicity of a few r_g/c, visible in the movies $\rightarrow$ flares?



(Dexter & Agol, 2009)

Use of the `geokerr` code, by J. Dexter and E. Agol

- Computes photon geodesics in Kerr spacetime using semi-analytical formulation
- Allows to compute efficiently the outgoing directions and time delays of photons as soon as they are emitted

We are working on coupling it to `Zeltron`, to produce time and angle-resolved lightcurves