Relativistic Fluids around Compact Objects --
CAMK, Warsaw, Poland -- 05.v.25

Do we understand pair cascade in AGN (and BH binary) jets?

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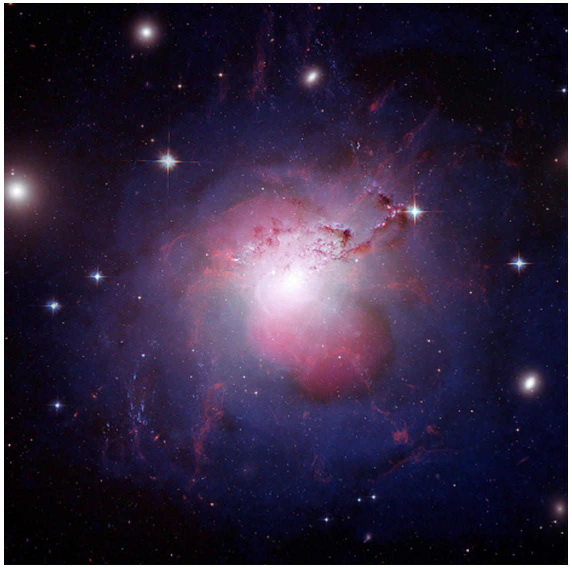
Papers: Ford, Keenan, MM - PRD (2018)
Sitarz, Fiord, MM - ApJ (2024)

Supported by the NSF grants PHY-2010109, PHY-2409249.

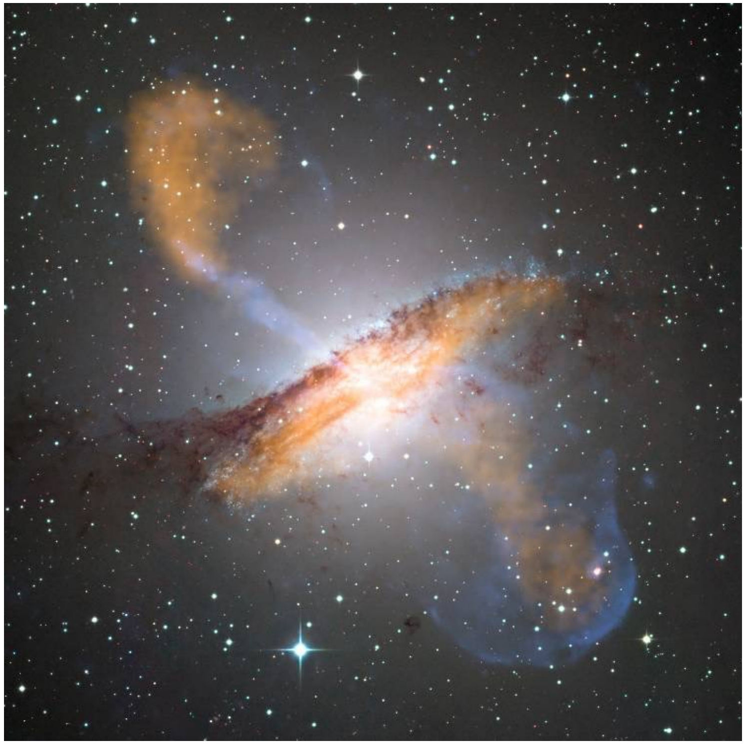
Motivation. AGN with jets/no-jets

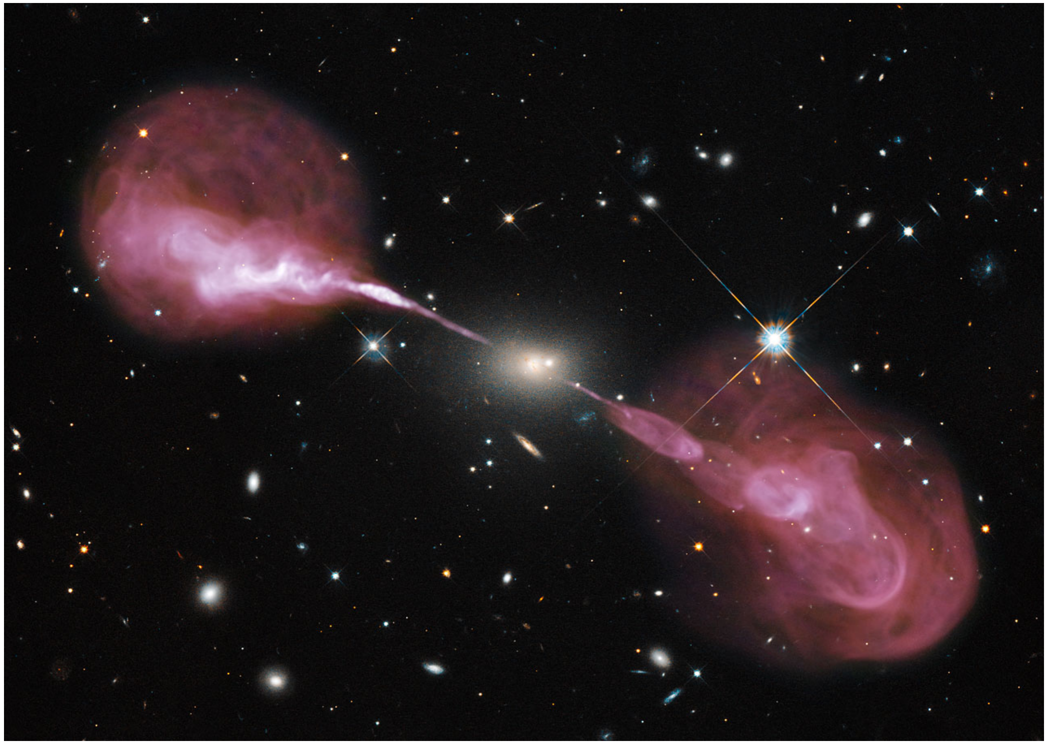


no jets

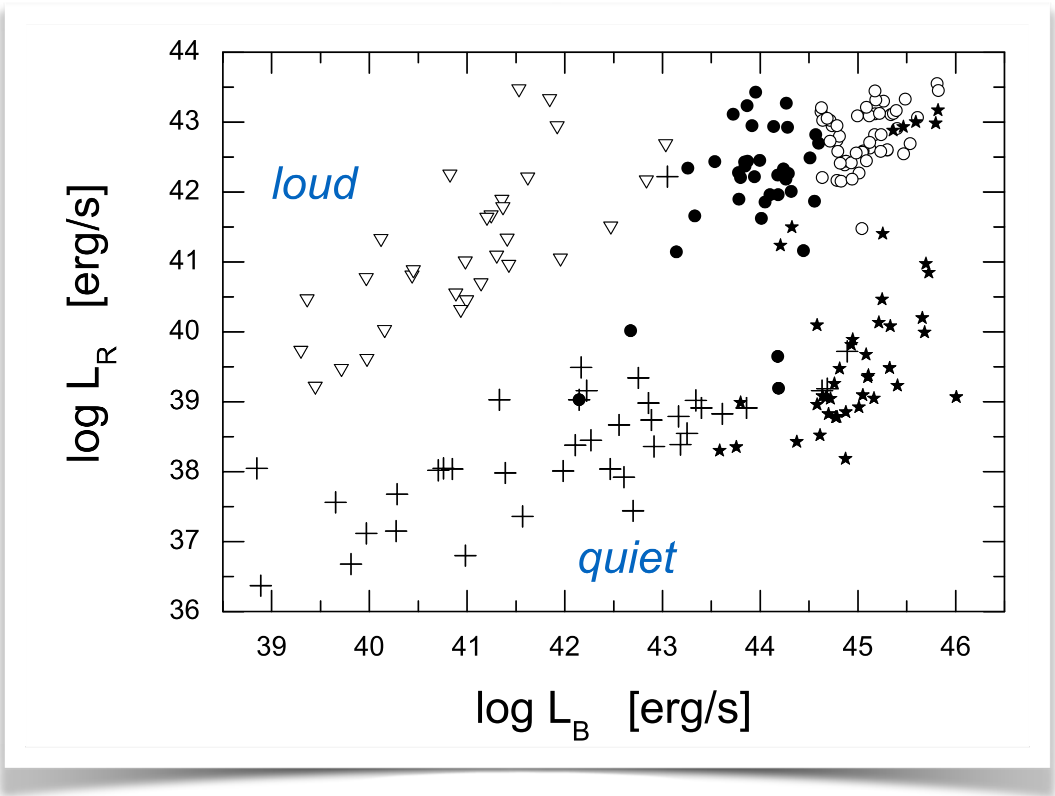
Some but not all AGN have jets —
— Why?

with jets

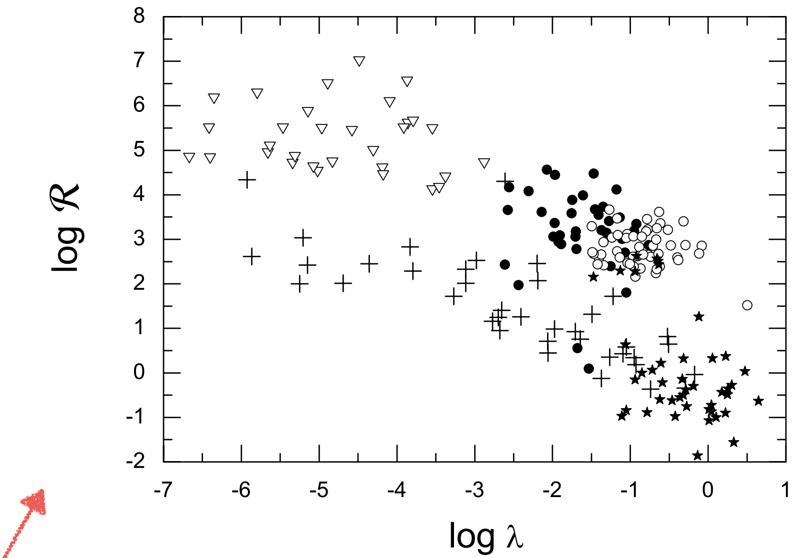


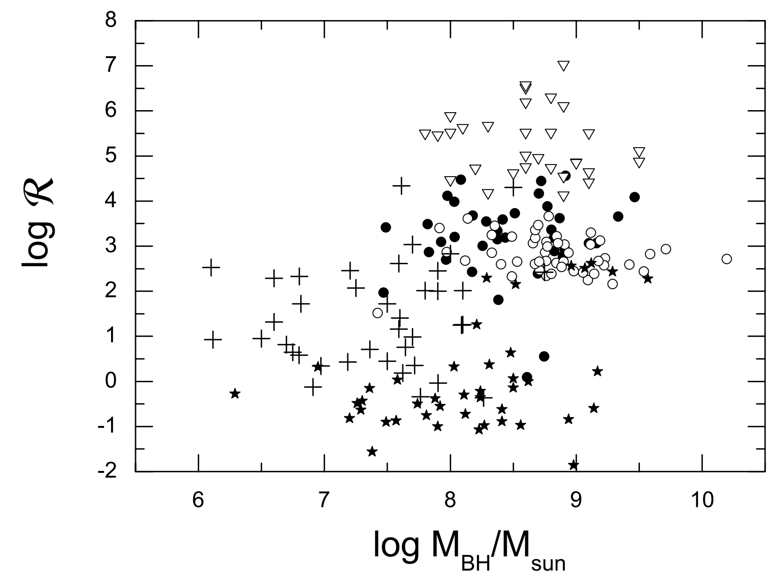


Radio loud/quiet dichotomy



Radio loudness vs Eddington ratio and BH mass

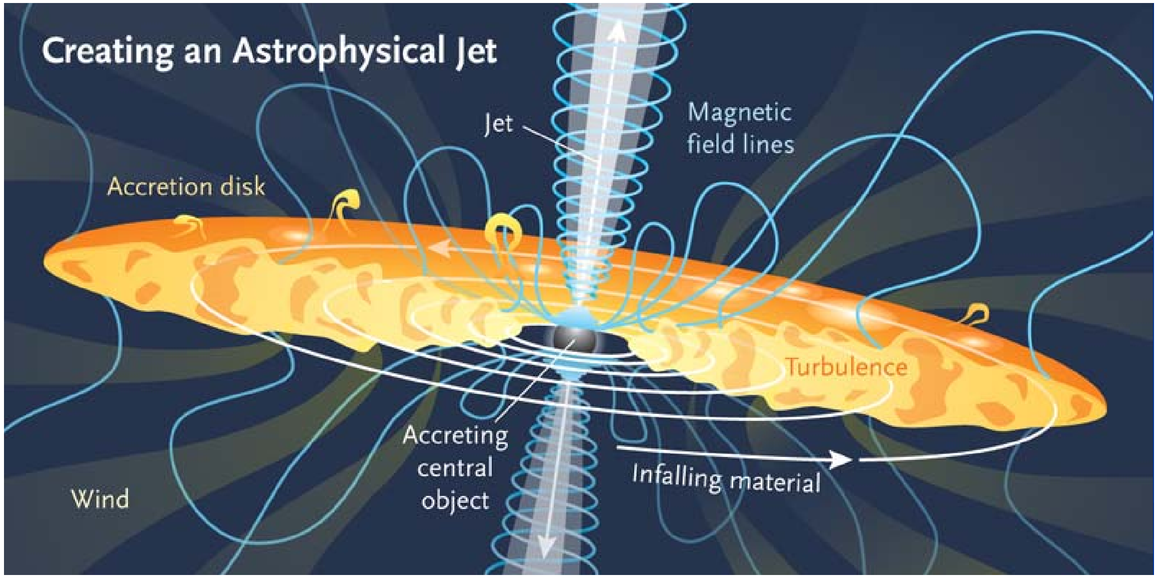




Not *entirely* due to total luminosity or BH mass!

(Sikora, Stawarz & Lasota 2007)

Motivation...



PROBLEMS:

- jet composition — leptons/baryons — is unknown
- what *switches* jets *on* is unclear
- CR acceleration is discussed

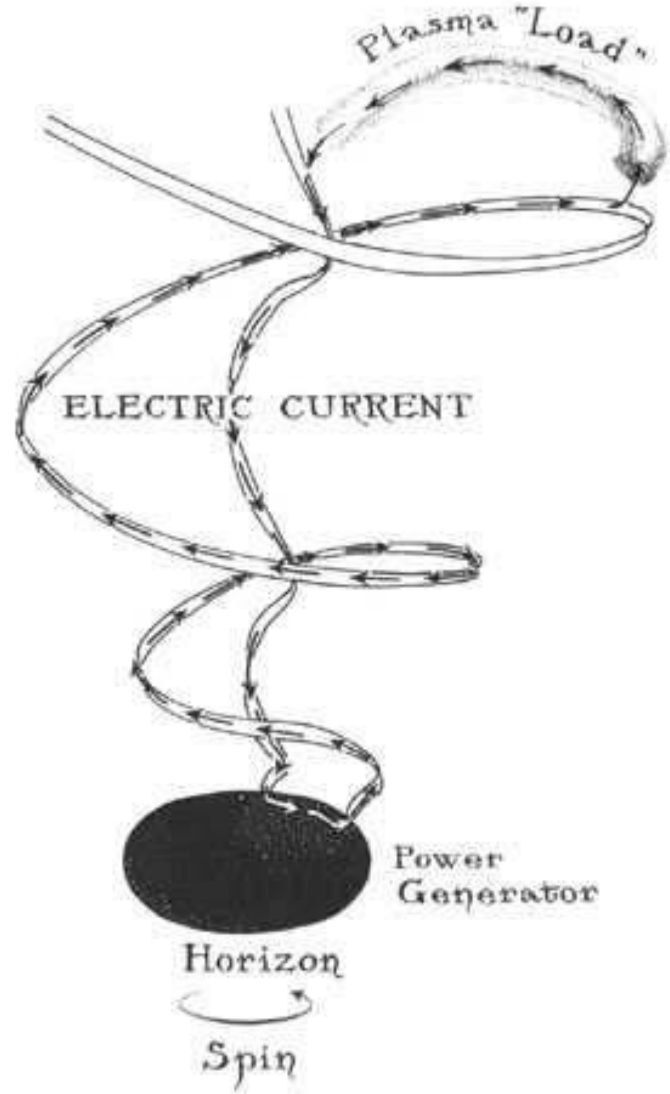
and also debated:

- jet launching mechanism
- jet collimation mechanism
- role of accretion
- role of spin of a SMBH
- role & structure of magnetic field

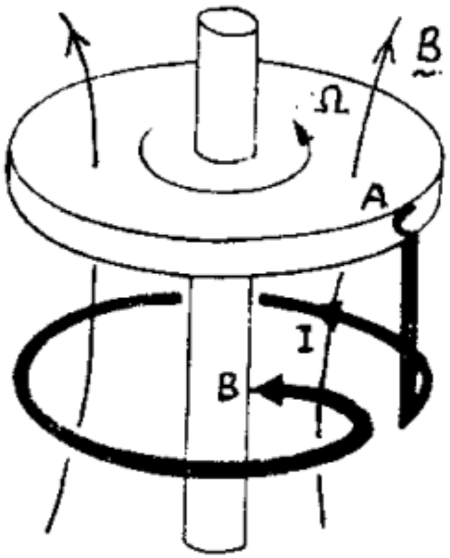
What powers a jet?

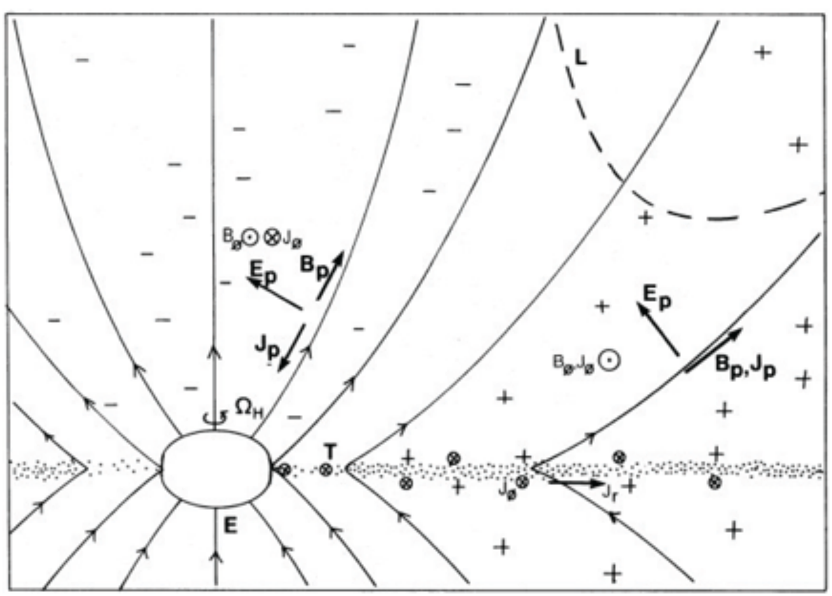
Energy source of a jet — rotational energy of a BH

Energy extraction mechanism — Blandford-Znajek — *a la* unipolar inductor



Blandford-Znajek (1977)





spinning BH — poor conductor (r~377 Ohm)
— in an external B-field → unipolar inductor

Magnetic flux

$$\Phi \sim B\, R_{BH}^2 \quad (R_{BH} \sim GM/c^2)$$

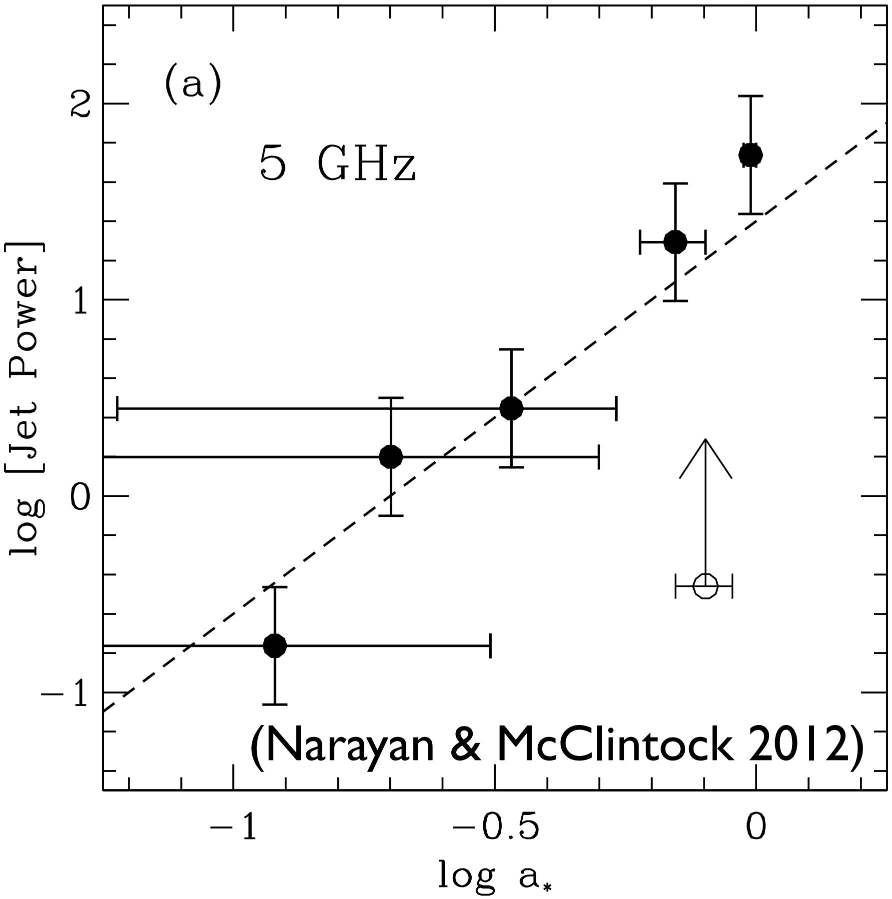
Electromotive force

$$U \sim d(flux)/dt \;\sim B\, R_{BH}^2\, \Omega_{BH}$$

Power

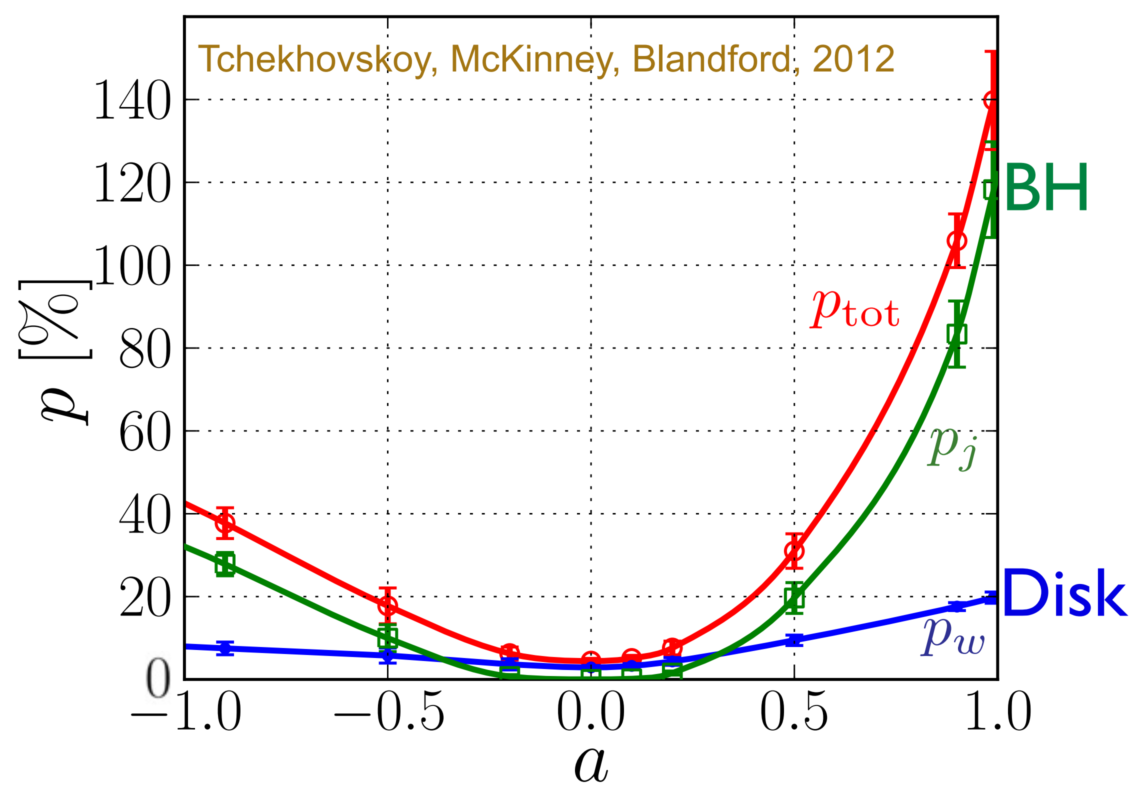
$$P \sim U^2/r \sim B^2\, R_{BH}^4\, \Omega_{BH}^2 \sim B^2\, M^2\, (spin)^2$$

Jets powered by BH spin



radio power (observed)

power (MHD simulations)



Jets need plasma

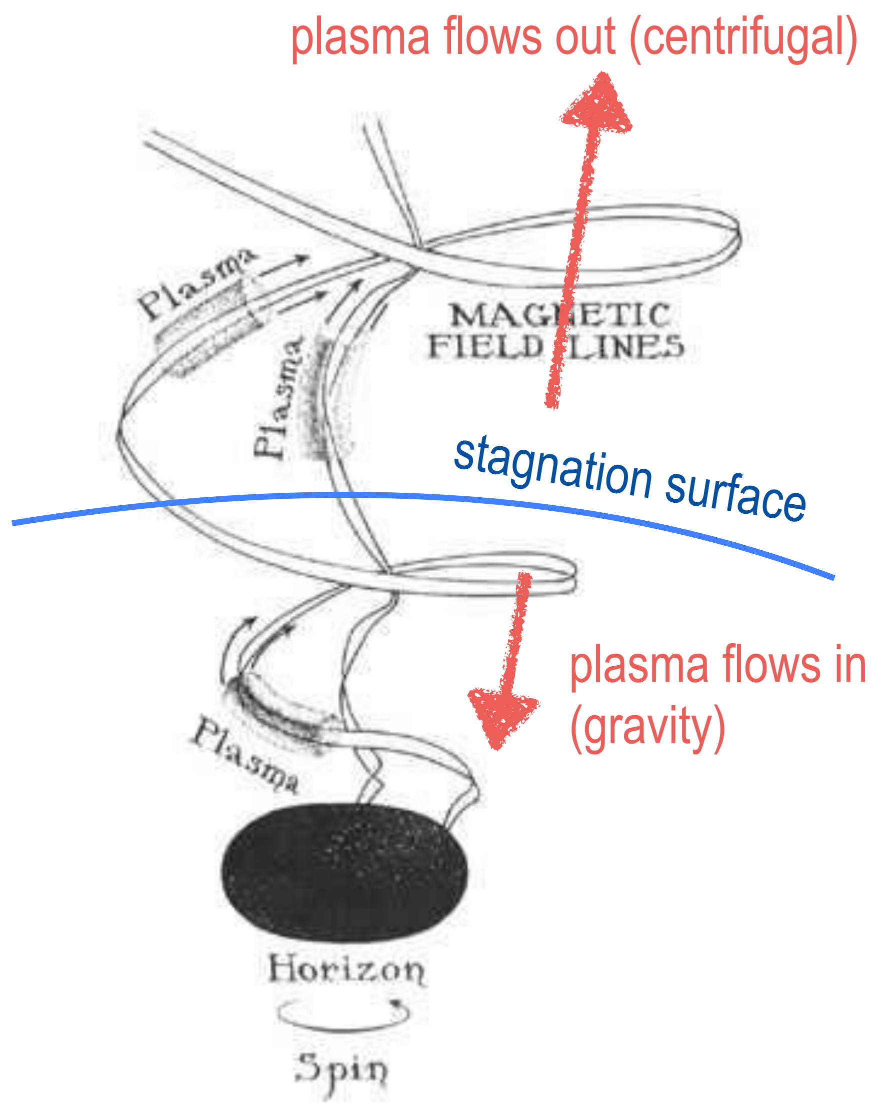
Energy source of a jet — rotational energy of a BH

Energy extraction mechanism — Blandford-Znajek — *a la* unipolar inductor

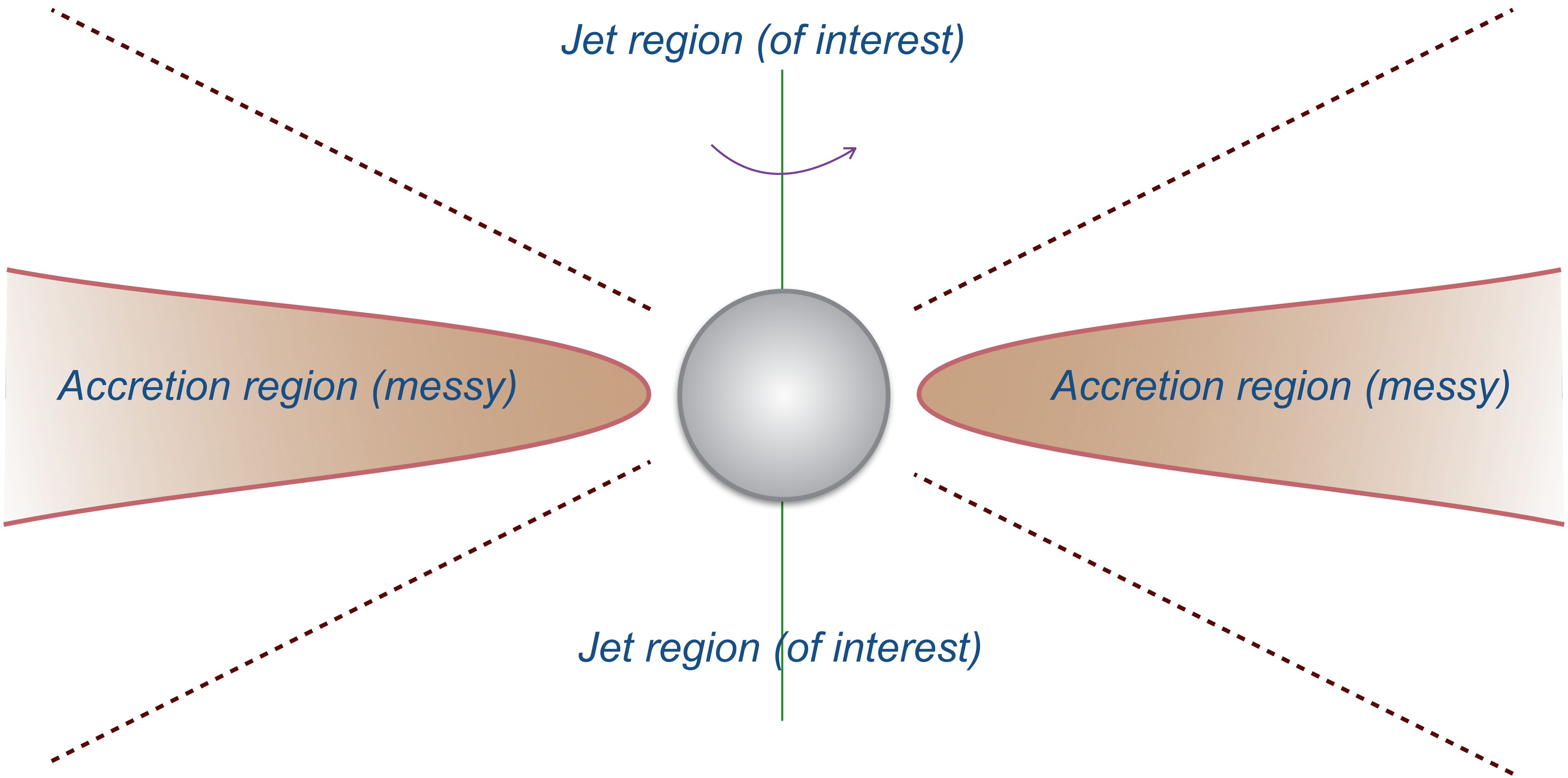
Need plasma on field lines to conduct current

No plasma => no power => no visible jet

Plasma escapes from the system. Need to produce plasma in situ. How?



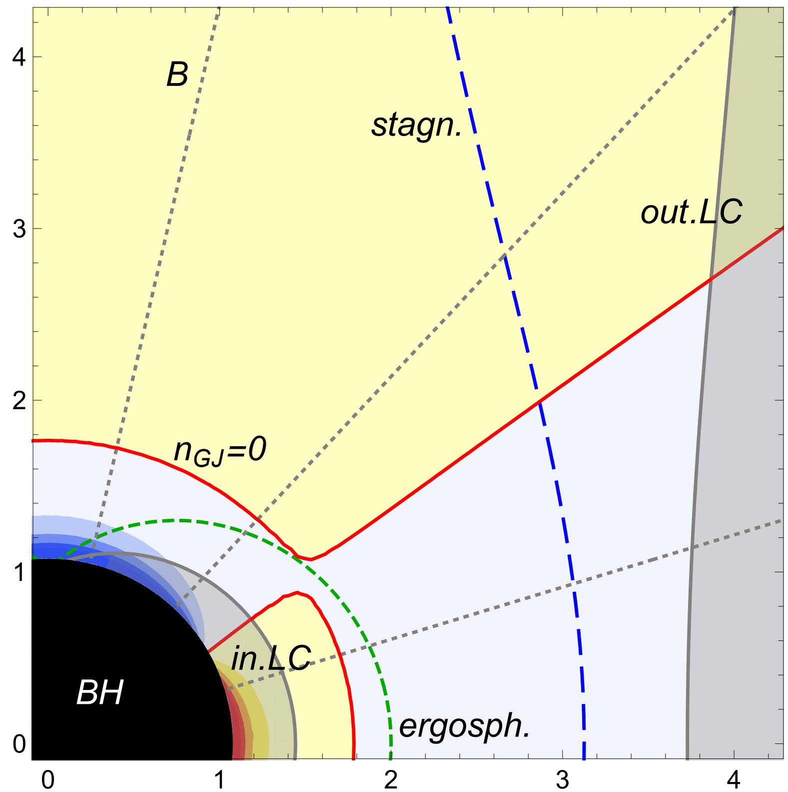
Basic setup



Choose the B to be double-split-monopole
(to exclude near-equatorial region)

$$\Psi(\theta) = \Psi_M(1 - cos(\theta))$$

Plasma production: Where?



Poisson's eq. in Kerr geometry

$$\nabla \cdot \boldsymbol{E}_{\parallel} = 4\pi(\rho_e - \rho_{\mathrm{GJ}})$$

Goldreich-Julian density

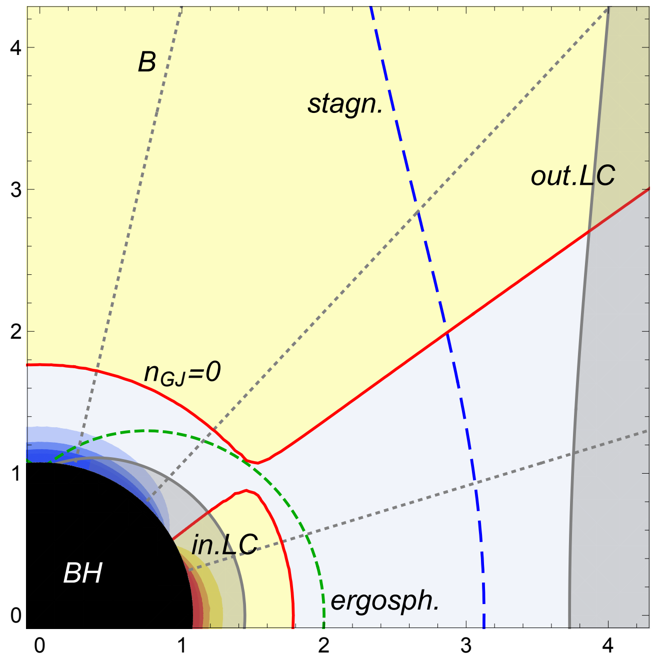
B-field line velocity frame dragging magnetic flux

$$\rho_{GJ} = \frac{1}{4\pi}\nabla \cdot E_p = -\frac{1}{4\pi}\nabla \cdot \left(\frac{\Omega_F - \omega}{2\pi\alpha c}\nabla\Psi\right)$$

Null surface $\rho_{GJ} = 0$ *is charge-deficient*
=> strongest sustained E-field || to B-field

This is the "spark gap" region

Plasma production: How? -- Cascade



E-field accelerates charges in the gap region

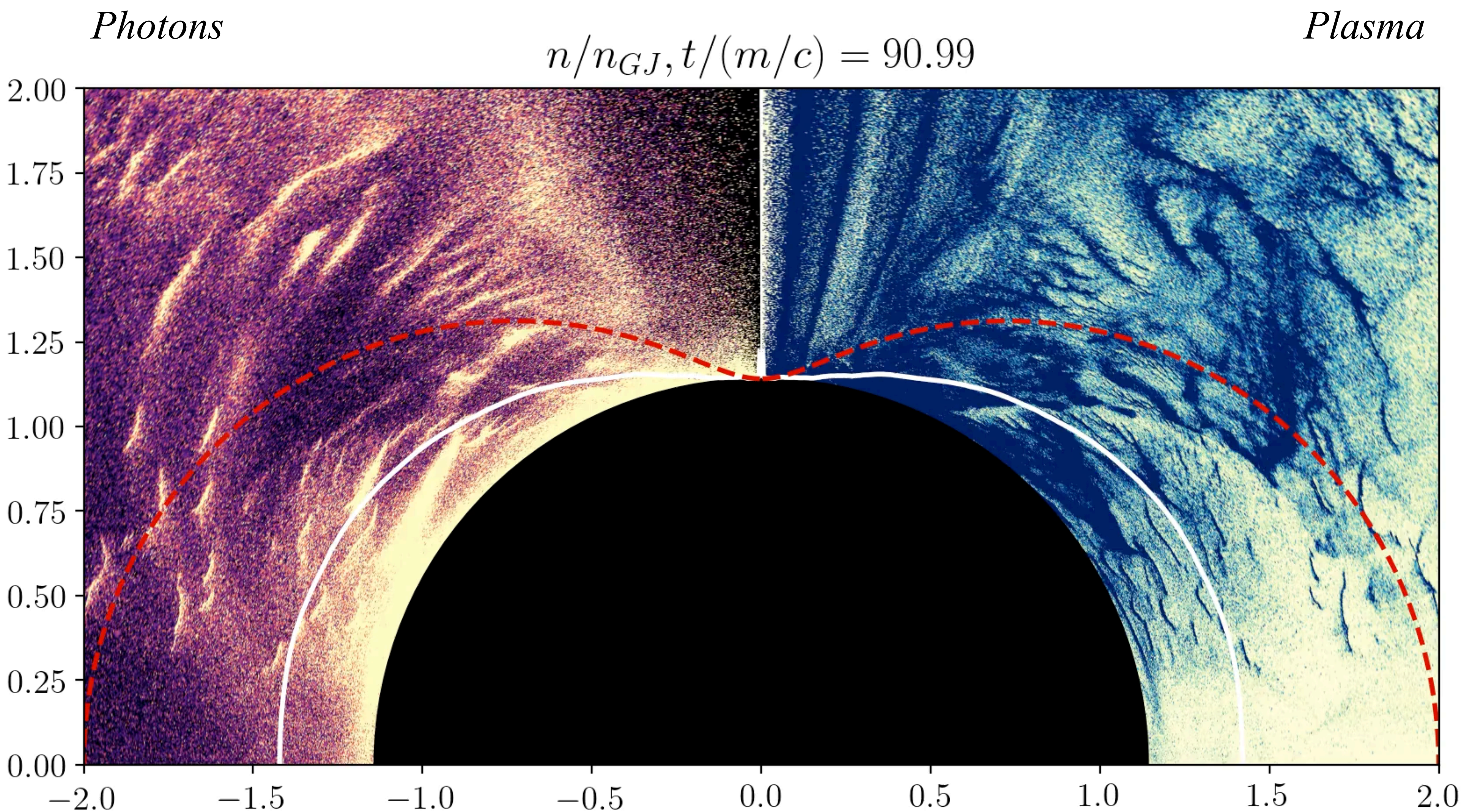
Compton up-scattering of background photons into gamma-rays

gamma-rays + background photons produce e^+e^- pairs

Mechanism:

Beskin, Istomin, Par'ev, 1992
Hirotani, Okamoto, 1998
Ptitcina, Neronov, 2015

Cascade in Particle-in-Cell simulations



(Crinquand B., Cerutti B., Philippov A., Parfrey K., Dubus G., 2020, PhRvL, 124, 145101)

Electrodynamics

Electric field

$$E_{\|} \sim \beta_F B_{BH} \xi$$

$$\beta_F = (v_F/c), \quad \xi = H_{gap}/R_{BH}$$

Eq. of motion

$$m_e c^2 \frac{d\Gamma}{dx} = eE_{\|} - (\Gamma^2 - 1)\sigma_T U_b$$

Compton drag in the radiation field of soft background photons

vanishes in steady state

Terminal Lorentz factor

$$\Gamma^2 \sim \frac{eB_{BH}}{\sigma_T U_b} \sim 10^{10} \frac{B_4 M_8 \beta_F \xi r^2}{\epsilon_b}$$

$$U_b = \epsilon_b U_{Edd} \quad U_{Edd} = \frac{L_{Edd}}{R^2 c} = \frac{4\pi G M m_p c}{\sigma_T (r^2 R_{BH}^2 c)}$$

energy density in background photons

distance to the gap region

$$R_{BH} = \frac{GM}{c^2} \sim 10^{13} M_8 \text{ cm}$$

Crude estimate of a cascade

$$e + \gamma_b \rightarrow e + \gamma_\Gamma$$
$$\gamma_b + \gamma_\Gamma \rightarrow e^+ e^-$$

Threshold: $\nu_b \nu_\Gamma \geq (2 m_e c^2)^2$

Multiplicity: $N_{tot} = N_\Gamma N_\pm > 1$

threshold multiplicity

Photons, which can yield cascade:

$$10^{-9} \left(\frac{\epsilon_{-8}}{B_4 M_8 \beta_F r^2 \xi} \right)^{1/2} \lesssim \frac{\nu_b}{m_e c^2} \lesssim 10^{-7} \left(\frac{\epsilon^3_{-8}}{B_4 M_8 \beta_F r^6} \right)^{1/4}$$

infrared - microwave

there is critical radiation luminosity fraction, epsilon_b below which the cascade does not exist

Crude estimate of a cascade

$$e + \gamma_b \to e + \gamma_\Gamma$$
$$\gamma_b + \gamma_\Gamma \to e^+ e^-$$

Threshold: $\nu_b \nu_\Gamma$

Multiplicity: N_{tot}

Note, for a stellar mass BH, the pair-producing photons are narrow-band:

$$\nu_b \sim 10^{-5} m_e c^2 \sim \text{a few eV}$$

Photons, which can yield cascade:

threshold multiplicity

$$\overset{10^{-5}}{\cancel{10^{-9}}} \left(\frac{\epsilon_{-8}}{B_4 \underset{1}{\cancel{M_8}} \beta_F r^2 \xi} \right)^{1/2} \lesssim \frac{\nu_b}{m_e c^2} \lesssim \overset{10^{-5}}{\cancel{10^{-7}}} \left(\frac{\epsilon^3_{-8}}{B_4 \underset{1}{\cancel{M_8}} \beta_F r^6} \right)^{1/4}$$

infrared - microwave

there is critical radiation luminosity fraction, epsilon_b below which the cascade does not exist

Lepton and photon fluxes

Gamma-ray production

$$\pm \frac{\partial}{\partial x} F^{\pm}(x, \epsilon_\gamma) = \eta_c(\epsilon_\gamma, \Gamma(x)) n^{\pm}(x) \sqrt{1 + \frac{1}{\Gamma^2(x)}} - \eta_p(\epsilon_\gamma) F^{\pm}(x, \epsilon_\gamma)$$

Compton redistribution function

angle-averaged pair production function

$$\eta_c \equiv \int_{\epsilon_{\min}}^{\epsilon_{\max}} d\epsilon_s \frac{dN_s}{d\epsilon_s} \sigma_{\mathrm{KN}}(\epsilon_s \Gamma) \delta(\epsilon_\gamma - \Gamma^2 \epsilon_s)$$

$$\eta_p(\epsilon_\gamma) \equiv \frac{1}{2} \int_{-1}^{1} d\mu \int_{2/[(1-\mu)\epsilon_\gamma]}^{\epsilon_{\max}} d\epsilon_s \frac{dN_s}{d\epsilon_s} \sigma_P$$

Compton scattering cross-section with Klein-Nishina

$$\sigma_{\mathrm{KN}}(z) \equiv \frac{3}{4} \sigma_{\mathrm{T}} \left\{ \frac{1+z}{z^3} \left[\frac{2z(1+z)}{1+2z} - \ln(1+2z) \right] + \frac{\ln(1+2z)}{2z} - \frac{1+3z}{(1+2z)^2} \right\},$$

pair production cross-section

$$\sigma_P \equiv \frac{3}{16} \sigma_{\mathrm{T}}(1 - v^2) \left[(3 - v^4) \ln \frac{1+v}{1-v} - 2v(2 - v^2) \right]$$

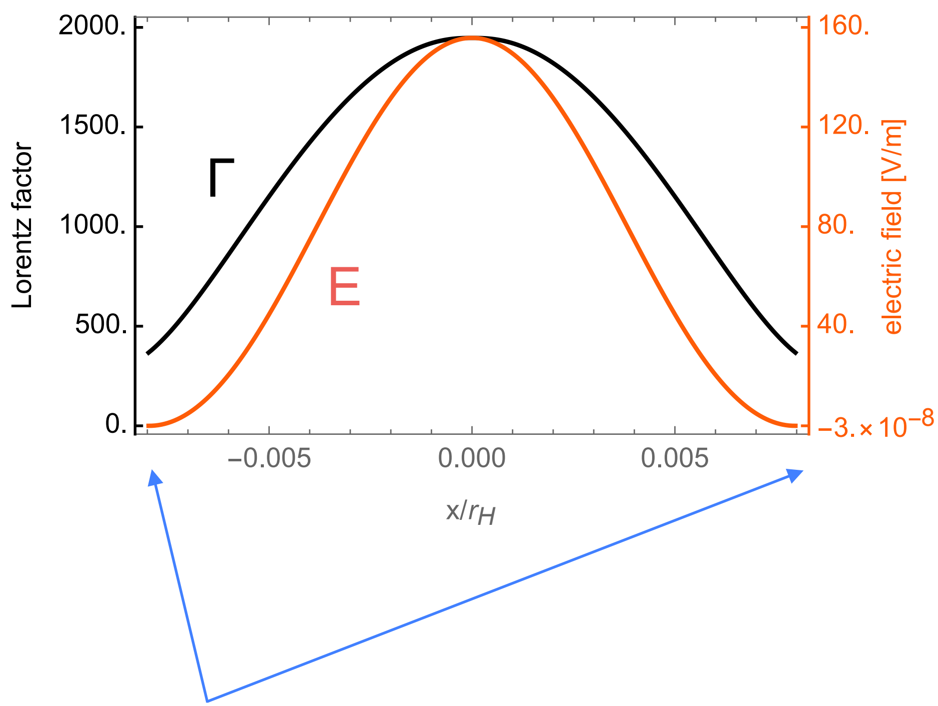
$$v(\mu, \epsilon_\gamma, \epsilon_s) \equiv \sqrt{1 - \frac{2}{1-\mu} \frac{1}{\epsilon_\gamma \epsilon_s}}$$

Pair production

$$\pm \frac{d}{dx} \left[n^{\pm}(x) \sqrt{1 - \frac{1}{\Gamma^2(x)}} \right] = \int_0^{\infty} \eta_p(\epsilon_\gamma) \left[F^+(x, \epsilon_\gamma) + F^-(x, \epsilon_\gamma) \right] d\epsilon_\gamma$$

Results:

EM structure of the gap



E-field vanishes at the gap boundaries

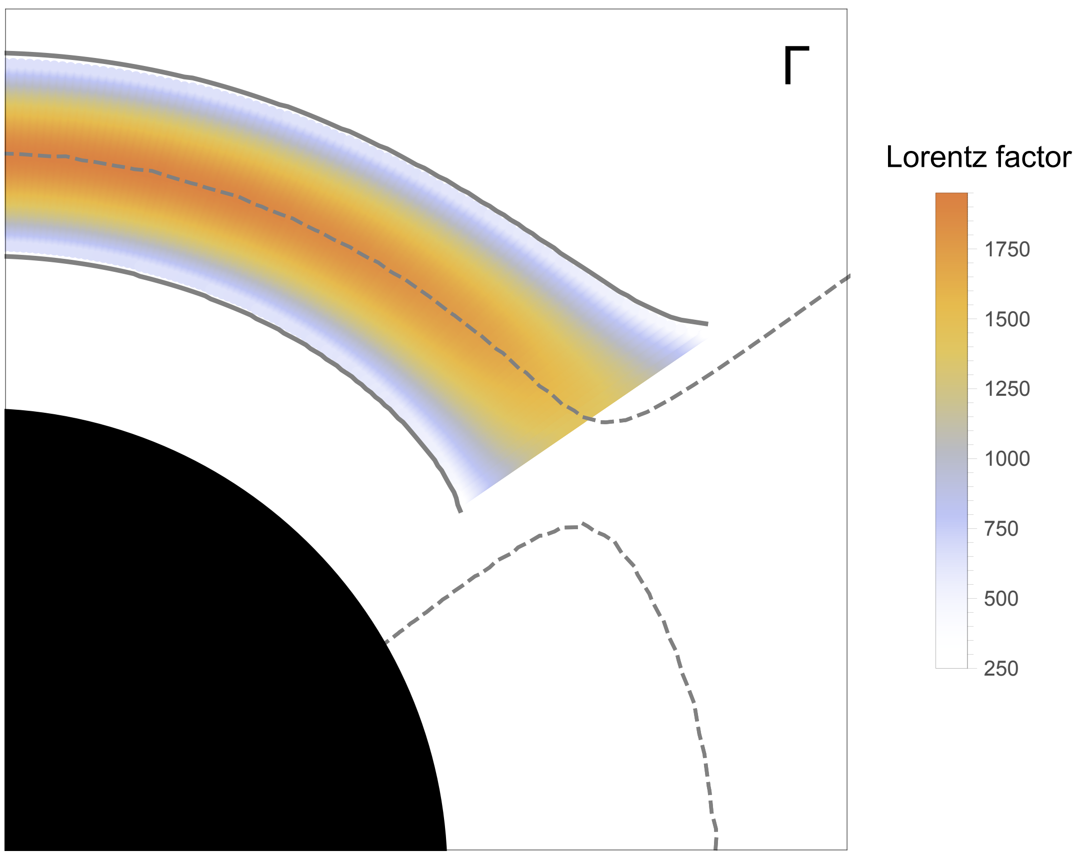
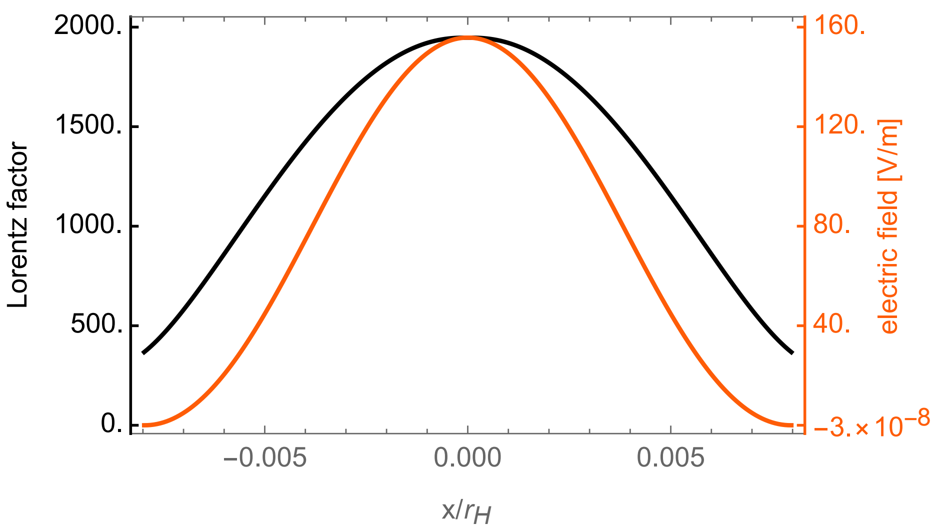
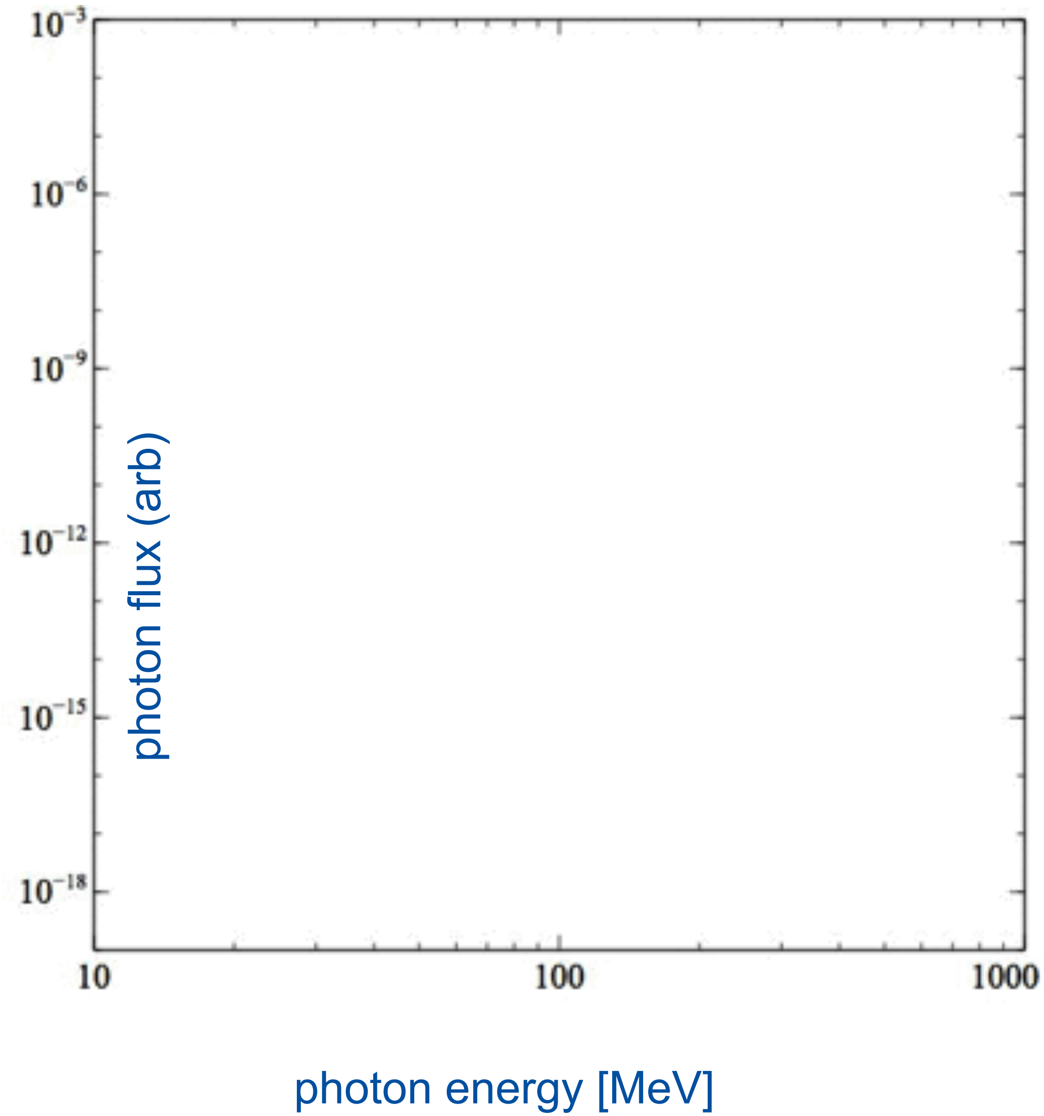


Illustration: photon flux

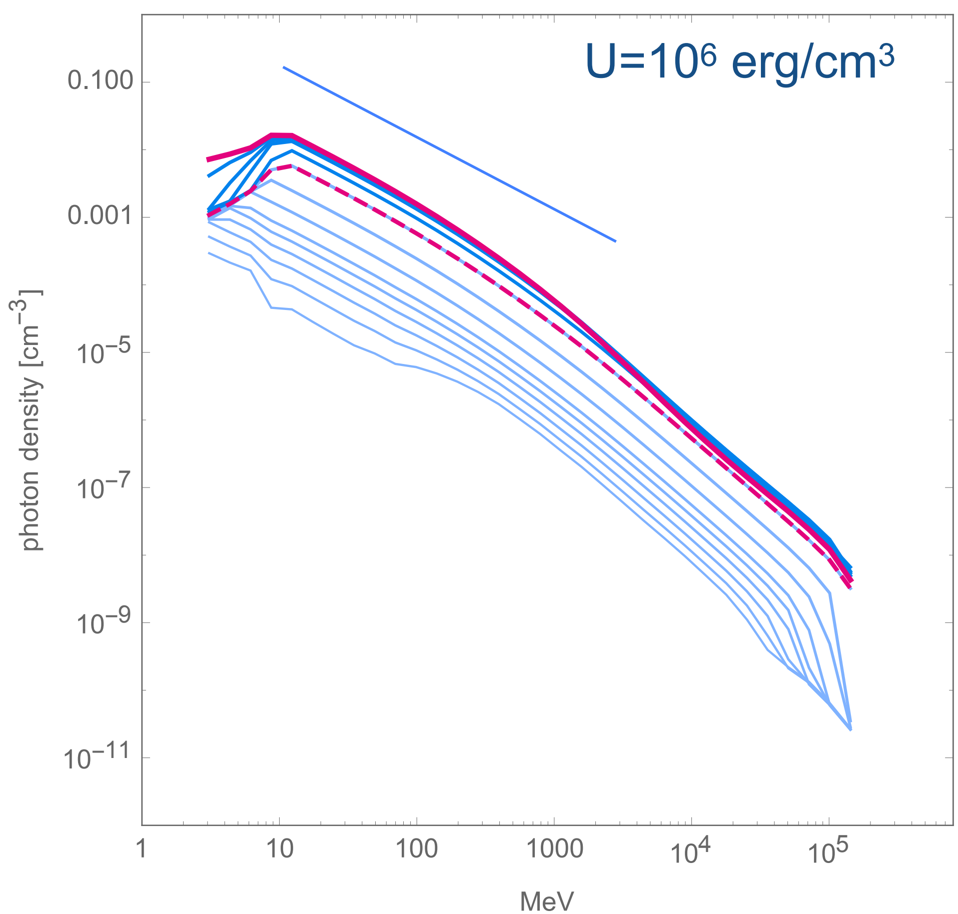
start movie

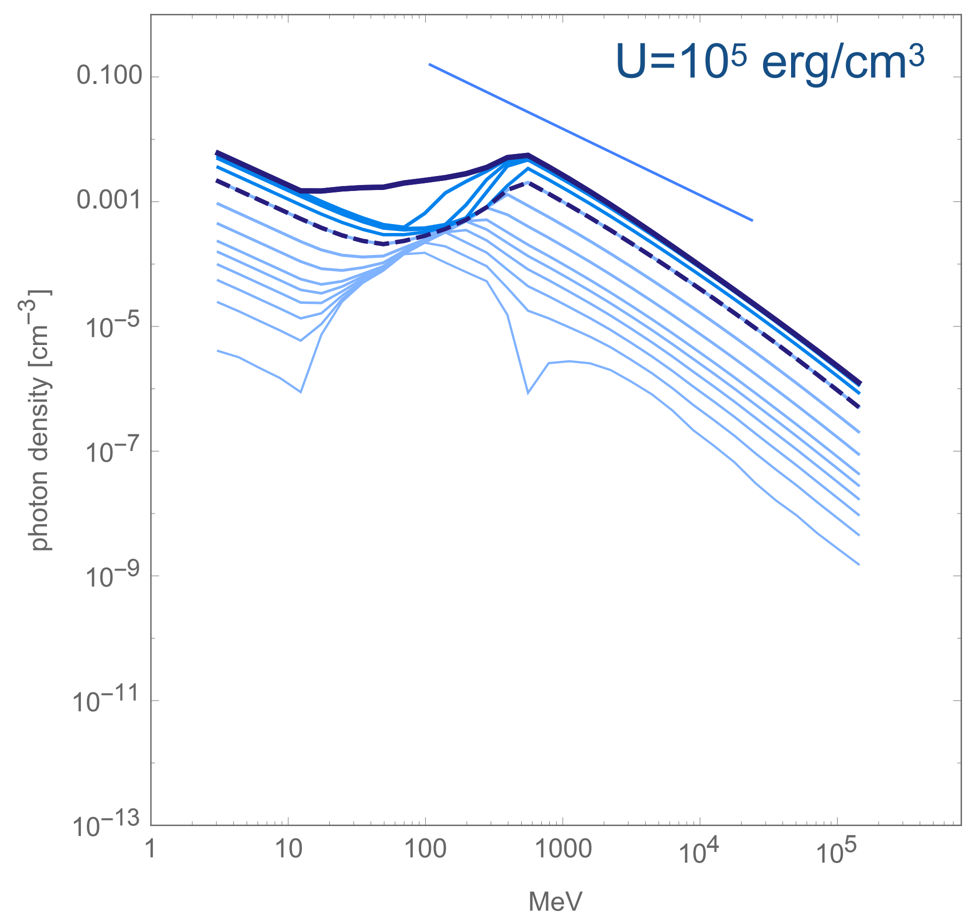
end movie





Build-up of photon fluxes





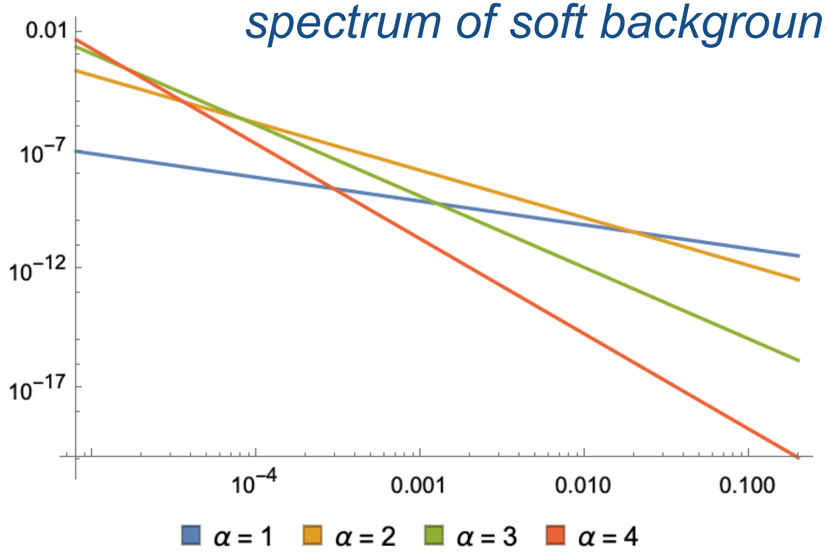
Seed photons:
index-2 power-law,
4 eV< E <100 keV

M=10^7 M$_\odot$, a=0.9, B=10^4 G

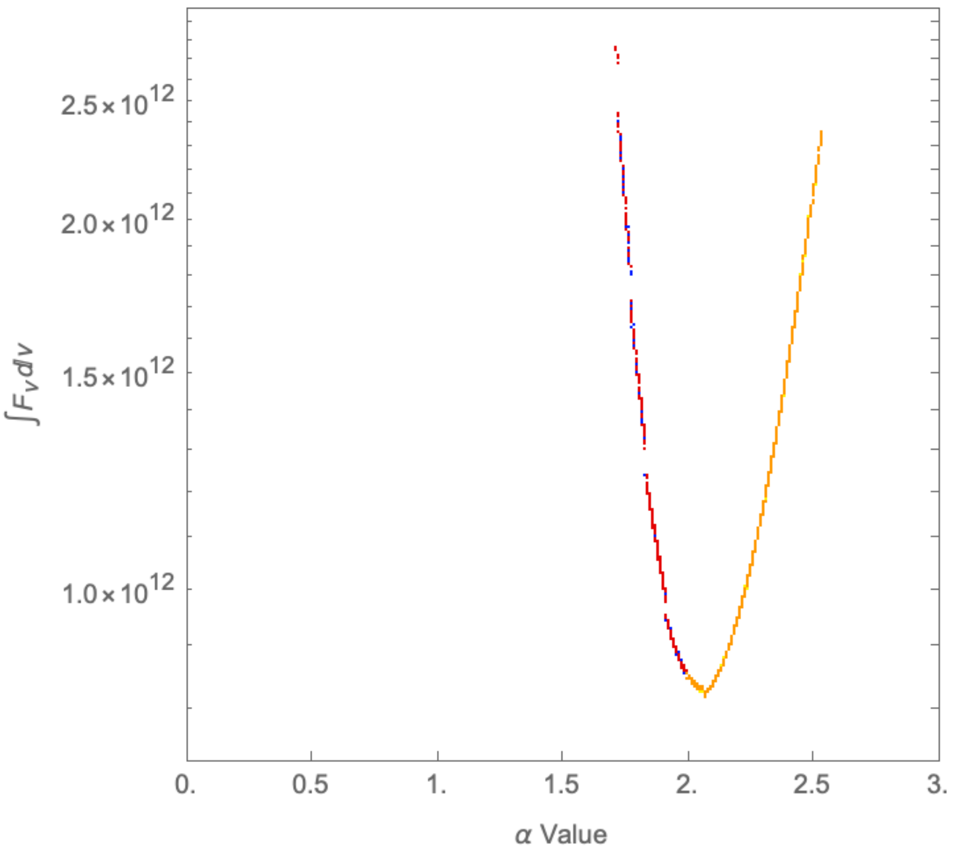
Spectral dependence

Nice similarity of quantities normalized to 1 at θ = 0

spectrum of soft background photons



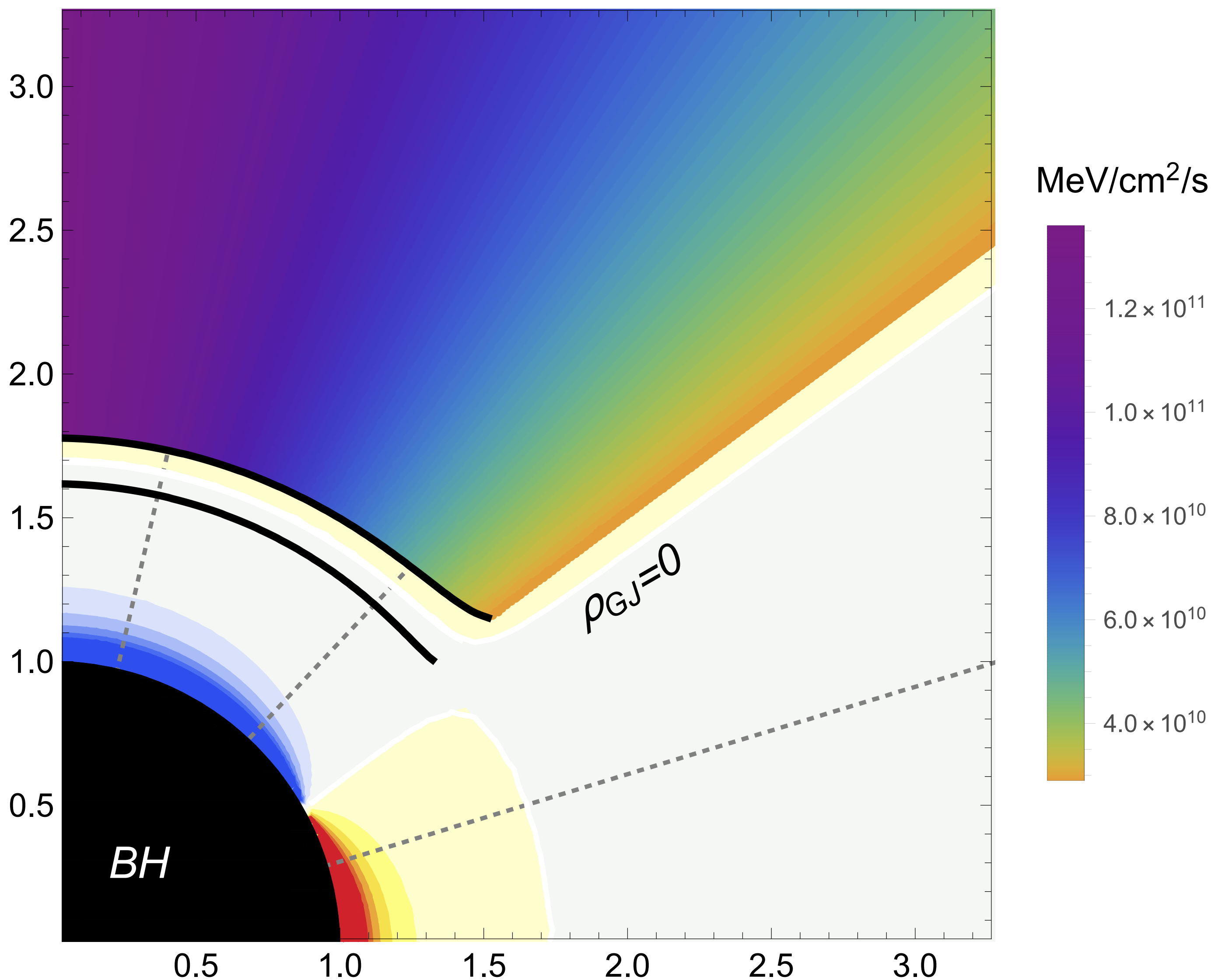
produced gamma-ray flux



gap photon energy flux

gap half-width

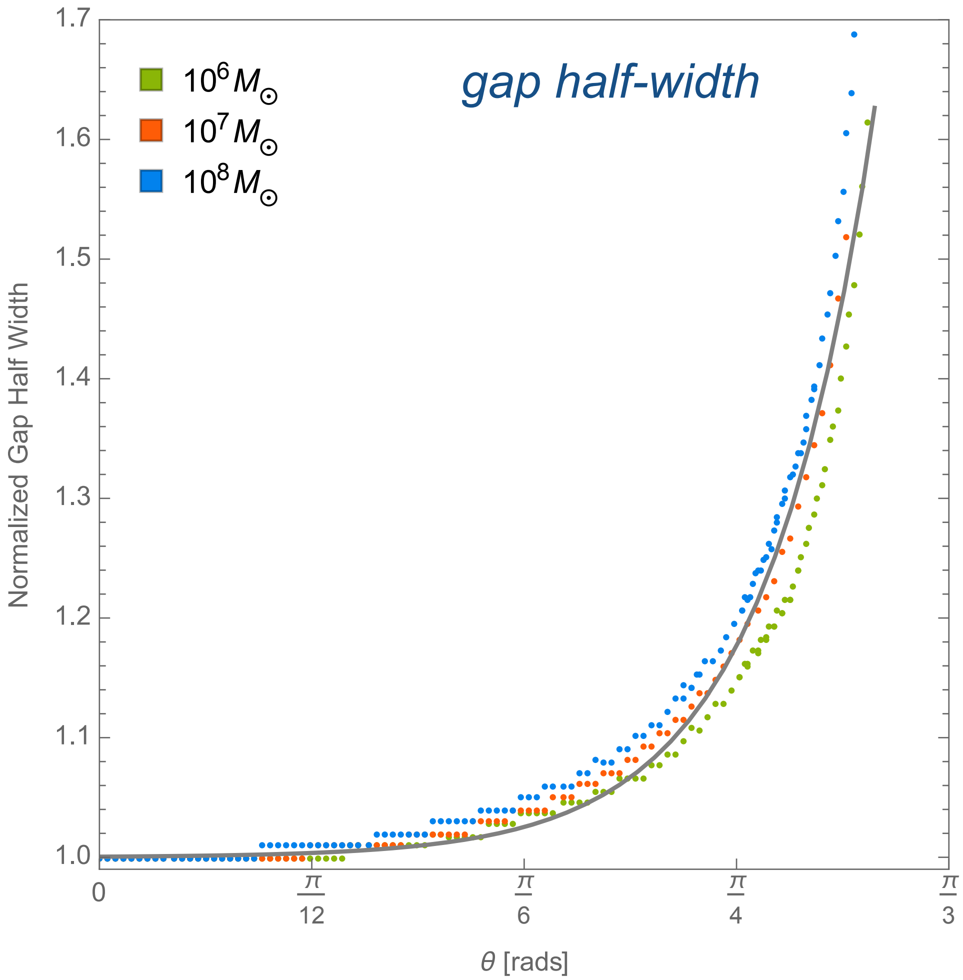
Outgoing gamma-ray flux

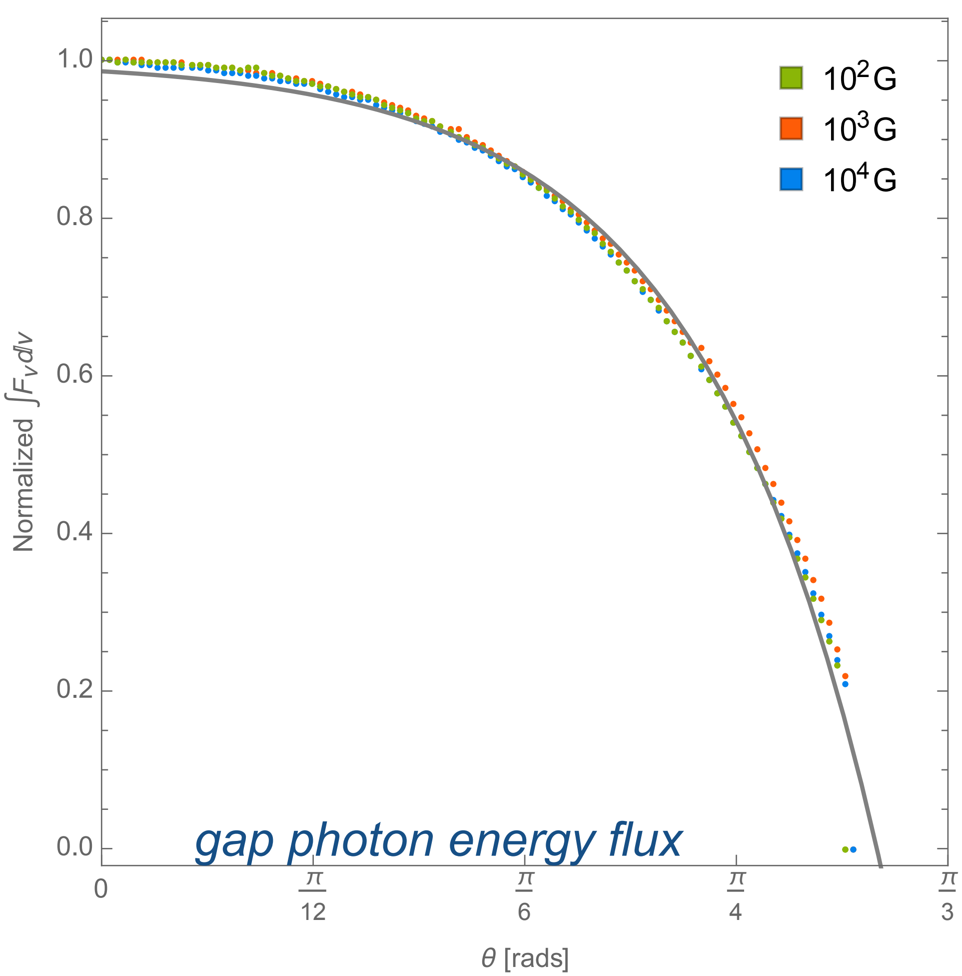


Seed photons:
index-2 power-law,
4 eV< E <100 keV

$M=10^7\ M_\odot$, $a=0.9$, $B=10^4$ G, $U=10^6$ erg/cm^3

Angular structure similarity

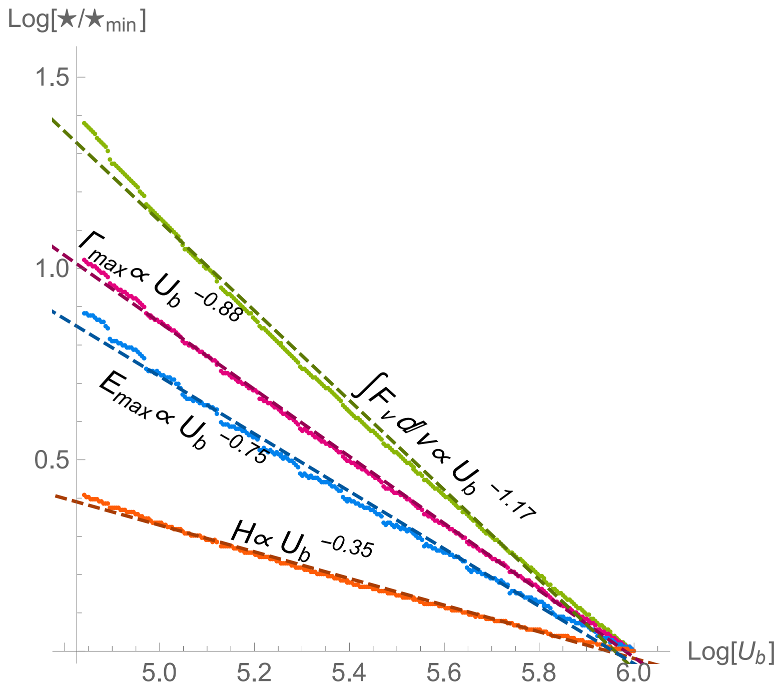


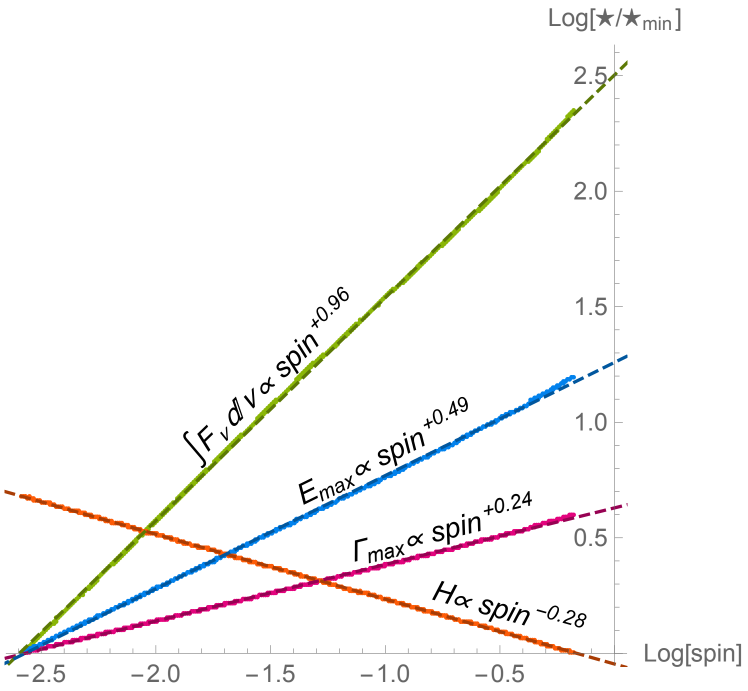


Nice similarity of quantities normalized to 1 at θ = 0

This allows to factor out other parameters -- next slide

Parameter scalings





Gap width

$$H \sim \left(10^{10}\ \mathrm{cm}\right)\ M_7^{1/2}\, a^{-1/3}\, B_4^{1/4}\, U_{b,6}^{-1/4}$$

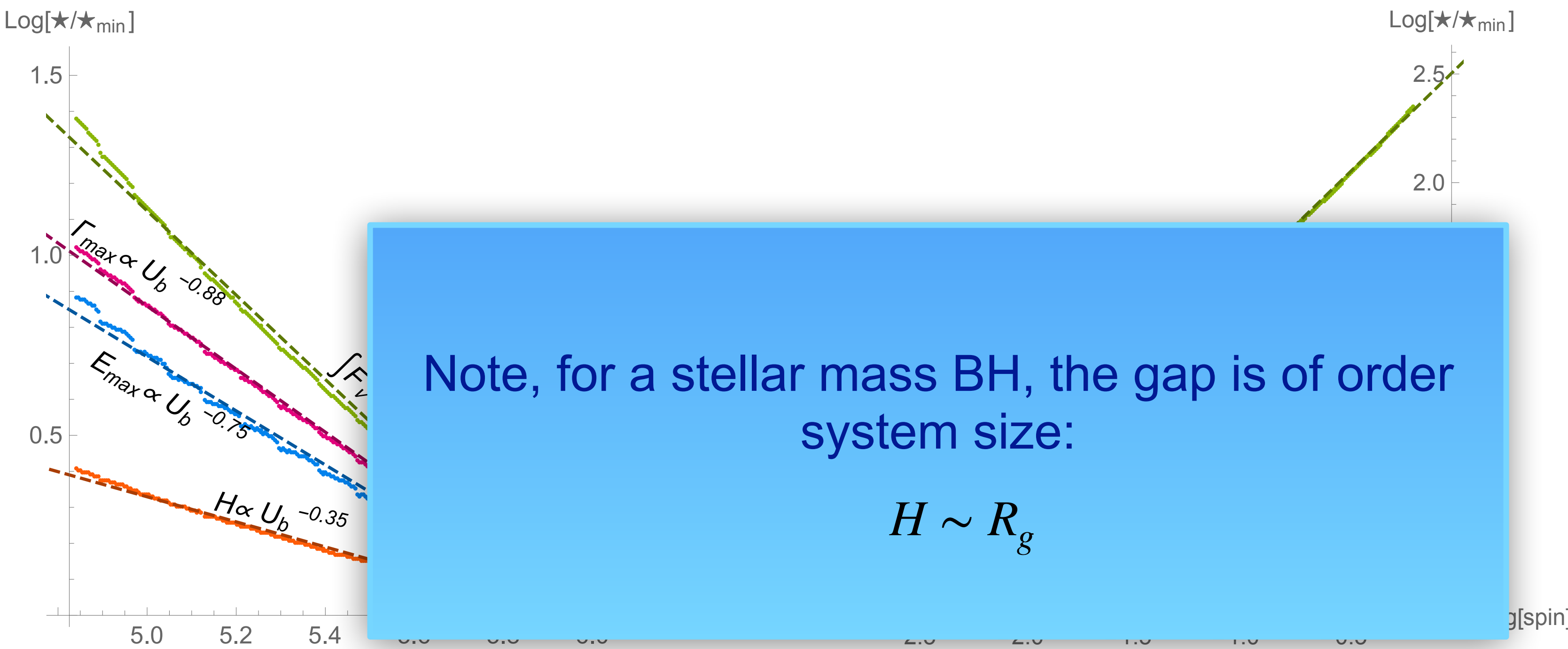
Lorentz factor

$$\Gamma_{\max} \sim 10^3\, M_7^{-1/2}\, a^{1/4}\, B_4^{1/4}\, U_{b,6}^{-9/10}$$

Gamma-ray luminosity

$$\frac{dL}{d\Omega} \sim \left(3 \times 10^{35}\ \mathrm{erg/s/sr}\right)\ M_7^{-5/2}\, a^1\, B_4^1\, U_{b,6}^{-1}$$

Parameter scalings



Note, for a stellar mass BH, the gap is of order system size:

$$H \sim R_g$$

Gap width

$$H \sim \left(\overset{3 \times 10^5\ \mathrm{cm}}{\cancel{10^{10}}\ \mathrm{cm}}\right)\ \underset{1}{M_7^{1/2}}\ a^{-1/3}\ B_4^{1/4}\ U_{b,6}^{-1/4}$$

Lorentz factor

$$\Gamma_{\rm max} \sim 10^3\ M_7^{-1/2}\ a^{1/4}\ B_4^{1/4}\ U_{b,6}^{-9/10}$$

Gamma-ray luminosity

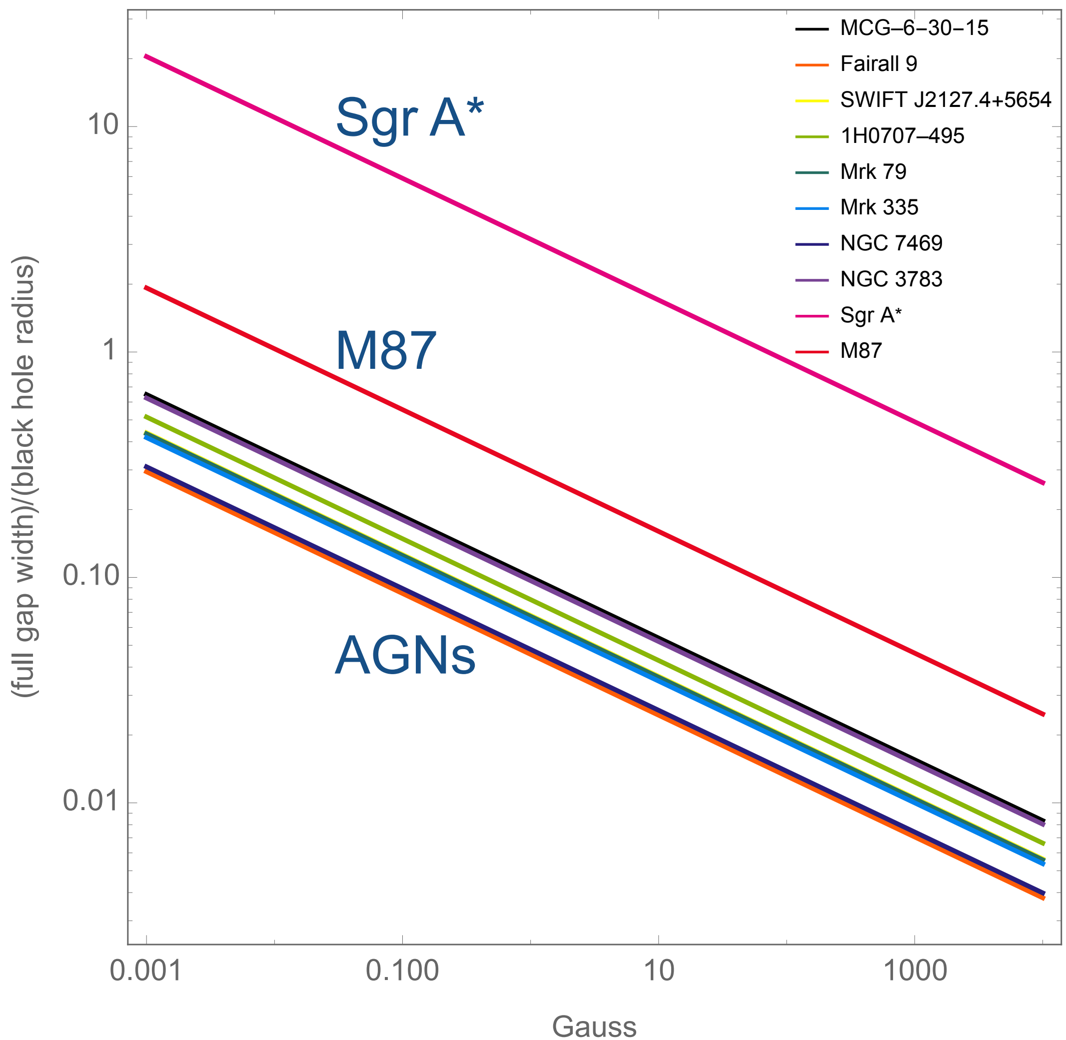
$$\frac{dL}{d\Omega} \sim \left(3 \times 10^{35}\ \mathrm{erg/s/sr}\right)\ M_7^{-5/2}\ a^1\ B_4^1\ U_{b,6}^{-1}$$

AGN: H/R_{BH} ratio

Cascade should be efficient if H/R_{BH} ≪ 1

$$\mathrm{H/R_{BH}} = 9.4\times10^{8} r_H^{-1} a^{-0.31}\times \left[\frac{M}{M_\odot}\right]^{0.54}\left[\frac{B}{\mathrm{Gauss}}\right]^{-0.27}\left[\frac{L/(4\pi c r_{\mathrm{isco}}^2)}{\mathrm{ergs/cm^3}}\right]^{-0.22}$$

AGN	Spin	Mass	Energy Density
M87	0.65	$10^{9.5}M_\odot$	0.33 $\mathrm{ergs/cm^3}$
Sgr A*	0.65	$10^{6.6}M_\odot$	2.1 $\mathrm{ergs/cm^3}$
MCG–6-30-15	0.98	$10^{6.65}M_\odot$	3.8×10^{7} $\mathrm{ergs/cm^3}$
Fairall 9	0.65	$10^{8.41}M_\odot$	8.2×10^{4} $\mathrm{ergs/cm^3}$
SWIFT J2127.4+5654	0.65	$10^{7.18}M_\odot$	5.0×10^{6} $\mathrm{ergs/cm^3}$
1H0707–495	0.98	$10^{6.7}M_\odot$	8.4×10^{7} $\mathrm{ergs/cm^3}$
Mrk 79	0.7	$10^{7.72}M_\odot$	4.0×10^{5} $\mathrm{ergs/cm^3}$
Mrk 335	0.7	$10^{7.15}M_\odot$	7.5×10^{6} $\mathrm{ergs/cm^3}$
NGC 7469	0.69	$10^{7.09}M_\odot$	3.8×10^{7} $\mathrm{ergs/cm^3}$
NGC 3783	0.98	$10^{7.47}M_\odot$	8.5×10^{4} $\mathrm{ergs/cm^3}$



Sgr A*, M87 gaps to scale

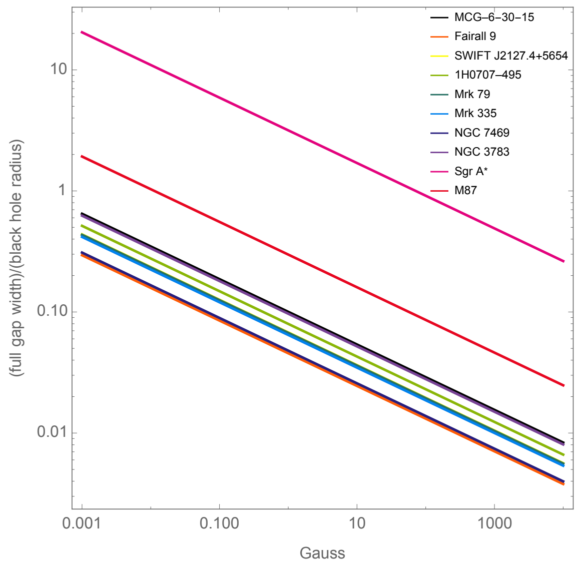
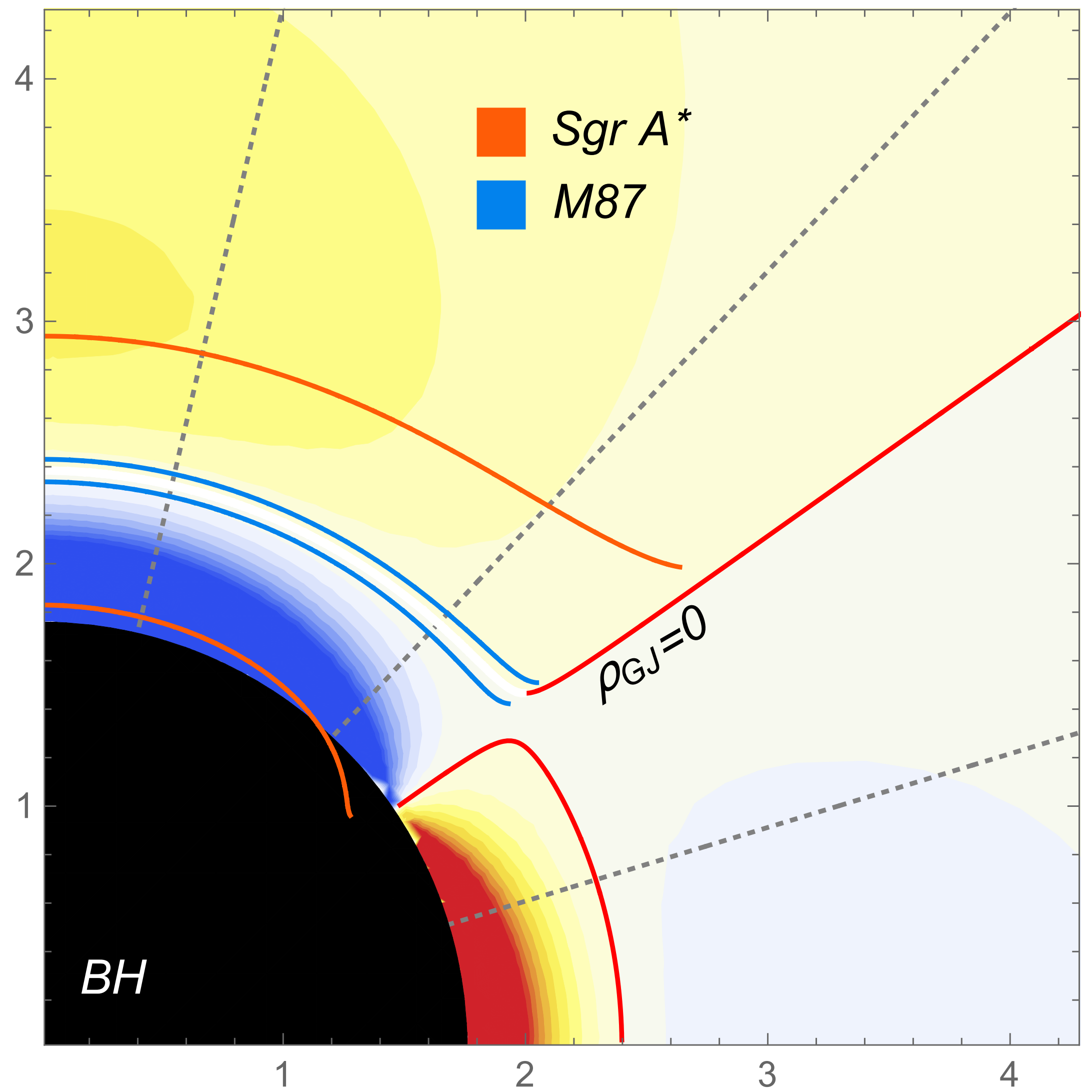


Figure 16. The BH radius of a maximumly spinning BH has been set to one and the gap widths have been left to scale. M87 has a luminosity of 2.7×10^{42} ergs/s, mass of $10^{9.5} M_{\odot}$, a spin of 0.65, and a magnetic field of 15 G. Sgr A* has a luminosity of 10^{37} ergs/s, mass of $10^{6.6} M_{\odot}$, a spin of 0.65, and a magnetic field of 30 G.



Puzzle: jet in 3C120

The Astrophysical Journal Letters, 928:L9 (6pp), 2022 March 20
https://doi.org/10.3847/2041-8213/ac5b70

The Composition and Power of the Jet of the Broad-line Radio Galaxy 3C 120

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Inferred pair production rate $2\dot{N}_+ \approx 3.9^{+6.3}_{-2.8} \times 10^{49} \left(\frac{R_{\rm hot}}{10R_{\rm g}}\right)^{-1} \left(\frac{R_{\rm jet}}{R_{\rm hot}}\right)^{2} {\rm s}^{-1}$

(1) Simulations yield $n_e \sim 10^{-3}\mathrm{cm}^{-3}$ hence $\dot{n}_e \sim n_e c R^2 \sim 10^{35}\mathrm{s}^{-1} \ll 10^{49}$

(2) Maximum estimated yield assumes that all gamma-ray flux is converted into pairs

$L_\gamma \sim 3 \times 10^{36}\mathrm{erg/s}$ is equivalent to $\dot{n}_e \sim 10^{42}\mathrm{s}^{-1} \ll 10^{49}$

Why the discrepancy?

Conclusions

- jet composition — *leptons*
- jet's "electric switch" — *cascade (photon SED, B, a)*
- gap structure — *interesting & useful scalings obtained*
- gap emission — *nsAGN are observable* ("not-so-ActiveGN")*
- Sgr A*, M87 — *near-threshold gaps --> affect jet formation*
- 3C120 — *obs. vs theor. lepton production too large?*
- beware — *1D, fixed B, fluid e+e-, approx Compt, pair prod.*

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*Fermi can see ~ 10^{39} erg/s at 1 Mpc at 100 MeV,
Can see nsAGN: M ~ 10^{6} , B ~ 10^{4}, U_b <~10 at 10 Mpc