

Particle acceleration in the vacuum gaps in black hole magnetospheres

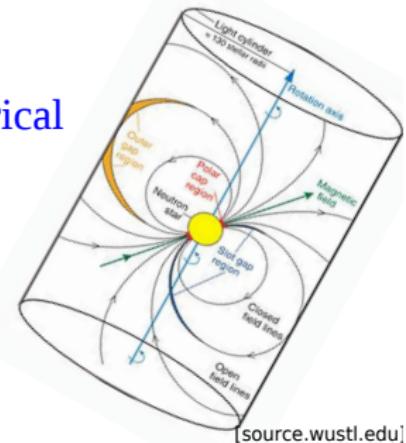
Ksenia Ptitsyna¹, Andrii Neronov²

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2016

Outline

- Subject: Gaps in the magnetospheres of SMBH
- Wanted: To test the model, to find observational signatures
- Method: Analytical estimates, numerical Monte-Carlo simulations



arXiv:1510:04023v2, Astronomy&Astrophysics

The gap: Why?

Motivation:

- observations: fast variability of VHE γ -radiation

causality

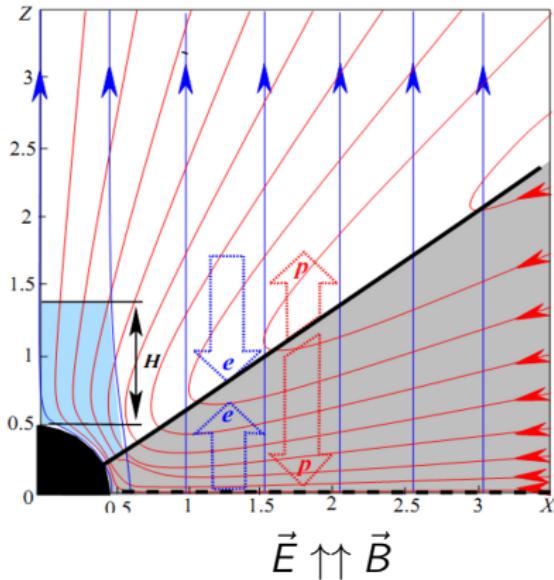
size of the source is $\sim R_h$ ($M_{BH} \sim 10^9 M_\odot$)

source - BH ? gap?

- AGN activity - gap?
- UHECR sources - gap? (HE neutrino)

MODELS

VACUUM



$$\mathcal{E}_p \sim 10^{20} \frac{A}{Z^{1/4}} \left(\frac{M}{10^9 M_\odot} \right)^{1/2} \left(\frac{B}{10^4 G} \right)^{1/4} \text{eV}$$

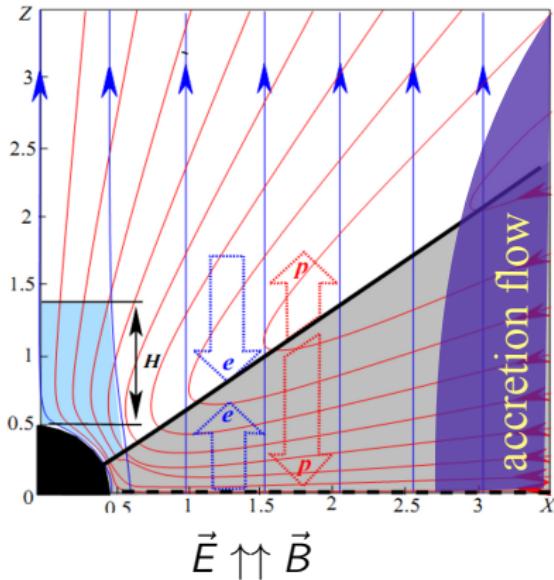
[Neronov, Semikoz, Tkachev, 2007]

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MODELS

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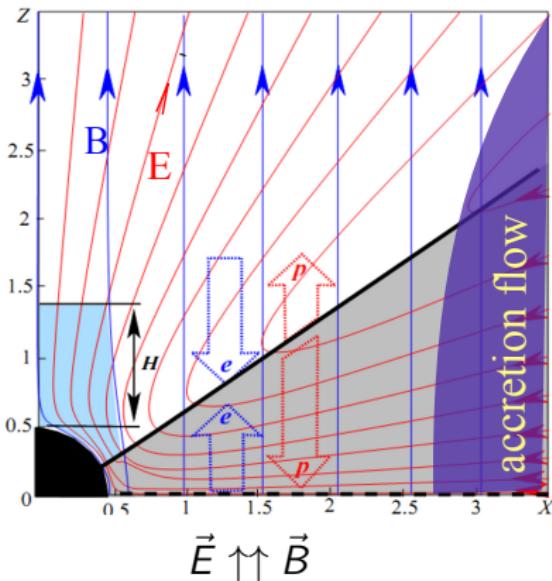


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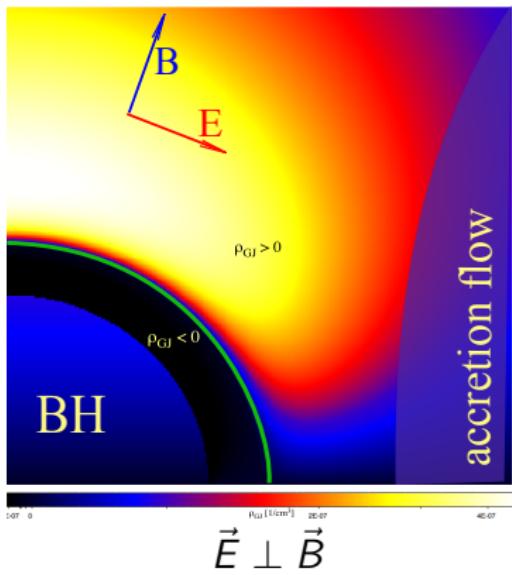
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MODELS

VACUUM



FORCE-FREE

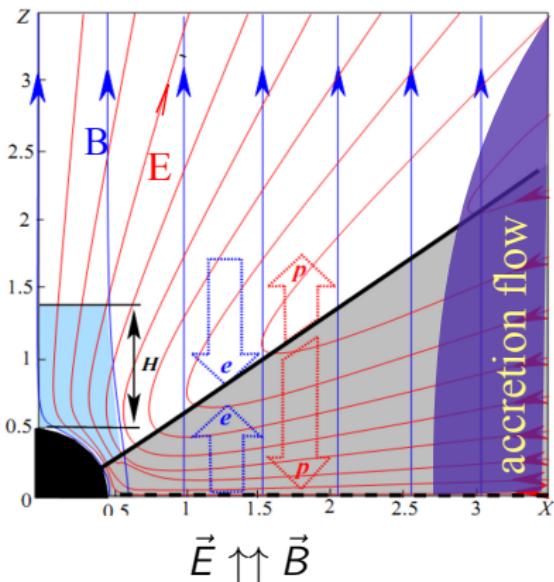


$$\mathcal{E}_p \sim 10^{20} \left(\frac{M}{10^9 M_\odot} \right)^{1/2} \left(\frac{B}{10^4 \text{G}} \right)^{1/4} \text{eV} \quad \rho \vec{E} + [\vec{j} \cdot \vec{B}] = 0$$

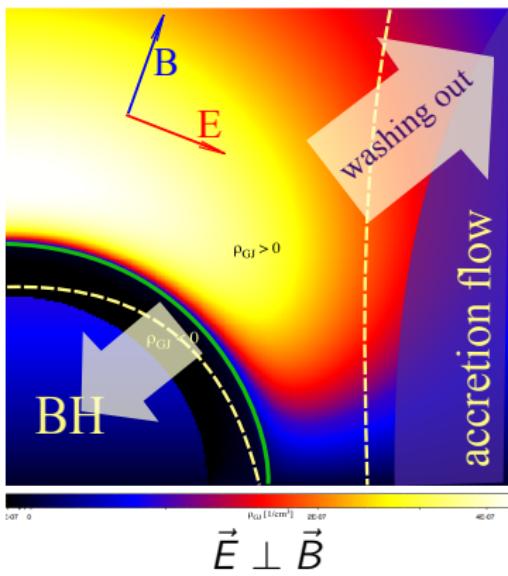
[Neronov, Semikoz, Tkachev, 2007]

MODELS

VACUUM



FORCE-FREE

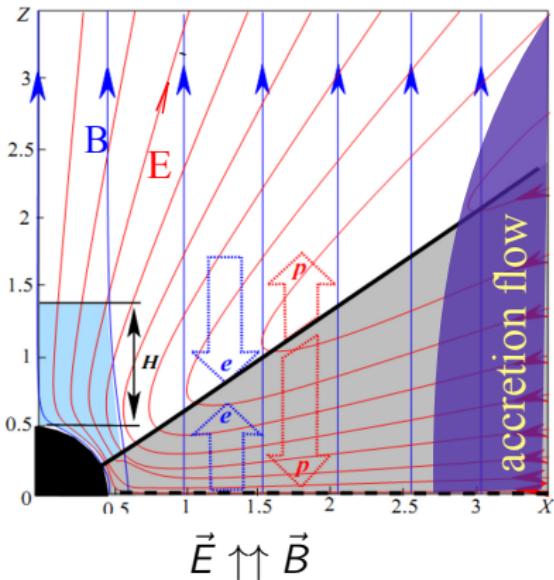


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[Neronov, Semikoz, Tkachev, 2007]

MODELS

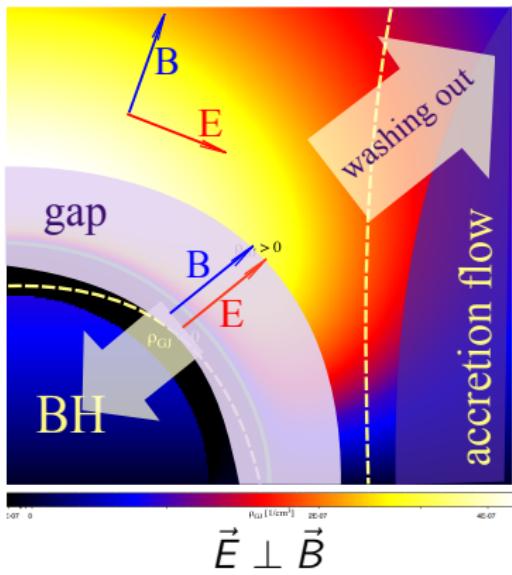
VACUUM



$$\mathcal{E}_p \sim 10^{20} \left(\frac{M}{10^9 M_\odot} \right)^{1/2} \left(\frac{B}{10^4 \text{G}} \right)^{1/4} \text{eV} \quad \text{in the gap : } \vec{E} \uparrow\uparrow \vec{B}$$

[Neronov, Semikoz, Tkachev, 2007]

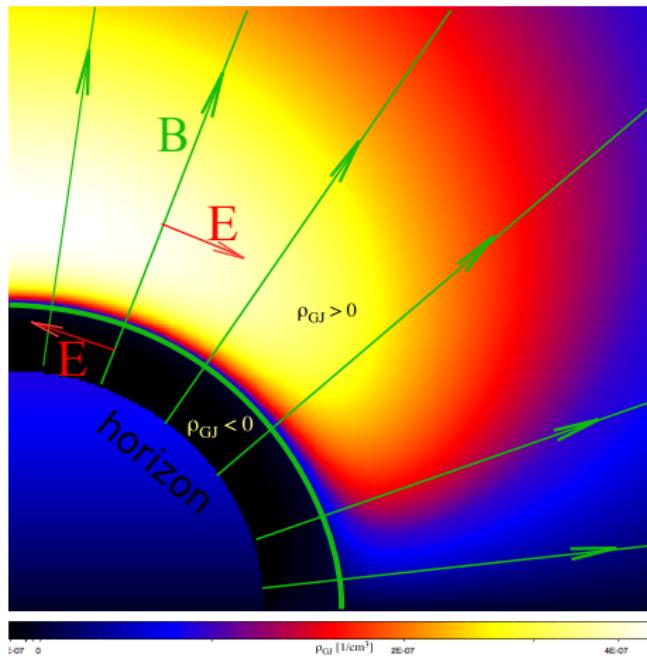
FORCE-FREE



[Beskin et al., 1992], [Hirotani, Okamoto, 1998]

[Levinson, Rieger, 2011]

Gap model: force-free magnetosphere $\rho \vec{E} + [\vec{j} \cdot \vec{B}] = 0$



Goldreich – Julian density :

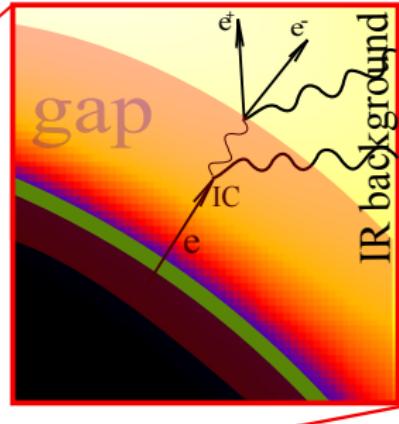
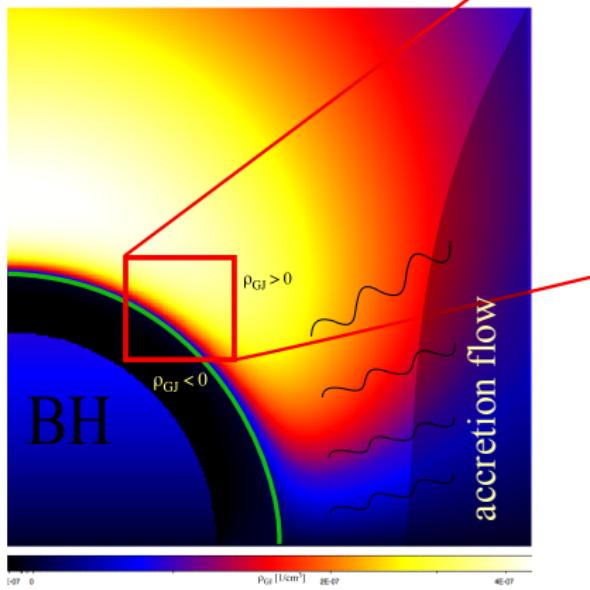
$$\rho_{GJ} = -\frac{1}{4\pi} \vec{\nabla} \cdot \left(\frac{\Omega_F - \omega}{2\pi\alpha} \vec{\nabla} \Psi \right)$$

Gap model: Radiatively Inefficient Accretion Flow (RIAF)

The height of the **gap** is limited by the onset of the **electron-positron pair production**

Threshold energy:

$$E_{\gamma, th} = \frac{m_e^2}{\epsilon_{ir}} \simeq 3 \left[\frac{\epsilon_{ir}}{0.1 \text{ eV}} \right]^{-1} \text{ TeV}$$



- **synchrotron:**
 $E_\gamma \sim 10^7 \left[\frac{B_\perp}{1 \text{ G}} \right] \left[\frac{\mathcal{E}}{10^{13} \text{ eV}} \right]^2 \text{ eV}$
- **curvature:**
 $E_\gamma \sim 10^9 \left[\frac{\mathcal{E}}{10^{15} \text{ eV}} \right]^3 \left[\frac{M}{10^9 M_\odot} \right]^{-1} \text{ eV}$
- **IC:**
$$E_\gamma \simeq \begin{cases} \mathcal{E}^2 / (\epsilon_{ir} m_e^2), & \mathcal{E} \ll E_{\gamma, thr} \\ \mathcal{E}, & \mathcal{E} \gtrsim E_{\gamma, thr} \end{cases}$$

Gap model: e^+/e^- in the gap - defines the gap height

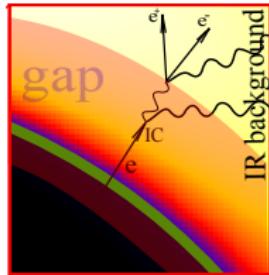
- acceleration length

$$h \gtrsim h_{*,acc} \sim \left(\frac{m_e^2}{e\epsilon_{ir}BR_H} \right)^{1/3}$$

$$h \gtrsim h_{*,ic} \sim \left(\frac{\sigma_T L m_e^2}{4\pi e\epsilon_{ir}^2 BR_{ir}^2} \right)^{1/2}$$

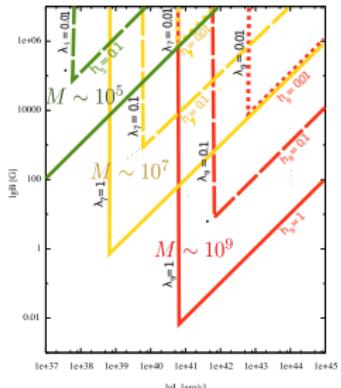
- γ -ray mean free path

$$\lambda_{\gamma\gamma} = \frac{1}{\sigma_{\gamma\gamma} n_{ph}} = \frac{4\pi R_{ir}^2 \epsilon_{ir}}{\sigma_{\gamma\gamma} L}$$



gap height

$$h \simeq \min(h_{*,acc}, h_{*,ic}) + \lambda_{\gamma\gamma}$$



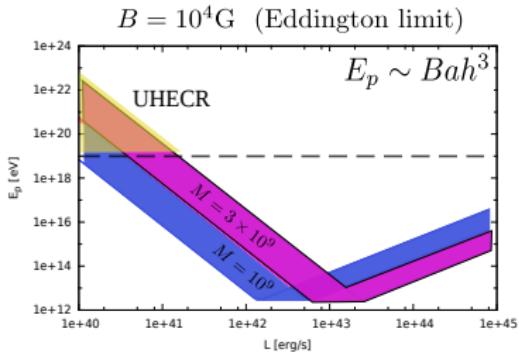
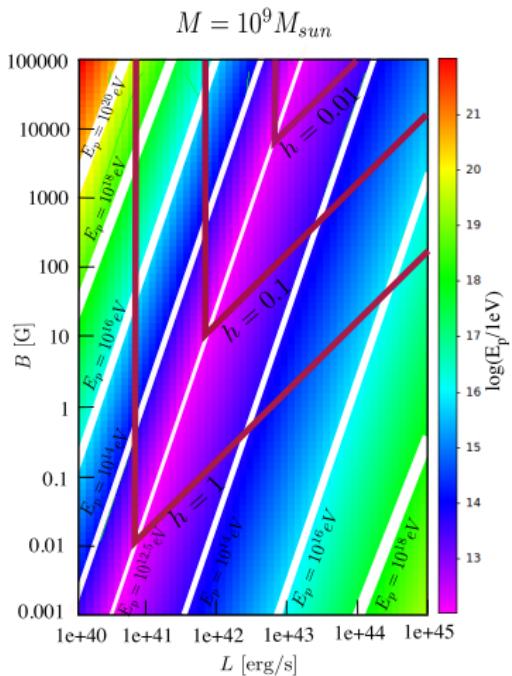
- low-luminosity

$$\lambda_{\gamma\gamma} \gg \min(h_{*,acc}, h_{*,ic}), \\ h \simeq \lambda_{\gamma\gamma}$$

- high-luminosity

$$\lambda_{\gamma\gamma} \ll \min(h_{*,acc}, h_{*,ic}), \\ h \simeq h_{*,ic}$$

Gap model: proton acceleration

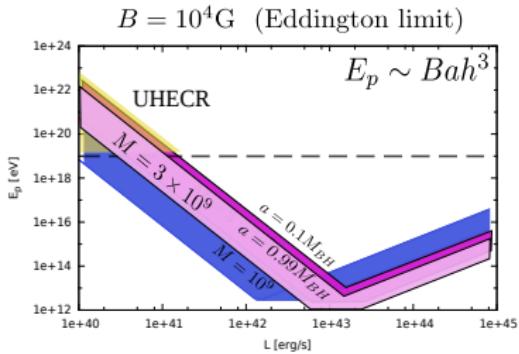
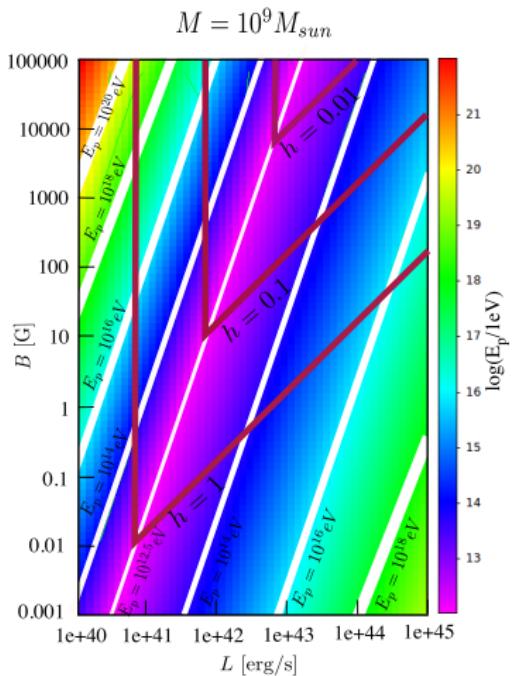


- Low-luminosity regime: $h \sim \lambda_{\gamma\gamma}$
- High-luminosity regime: $h \sim h_{acc}$

$$E_p \sim 6 \cdot 10^{20} \text{ eV} \left(\frac{L}{10^{40} \text{ erg/s}} \right)^{-3} \left(\frac{M}{3 \cdot 10^9 M_{sun}} \right)^4 \left(\frac{B}{10^4 \text{ G}} \right)$$

$$E_p \sim 2 \cdot 10^{14} \text{ eV} \left(\frac{L}{10^{44} \text{ erg/s}} \right)^{3/2} \left(\frac{M}{3 \cdot 10^9 M_{sun}} \right)^{-2} \left(\frac{B}{10^4 \text{ G}} \right)^{-1/2}$$

Gap model: proton acceleration



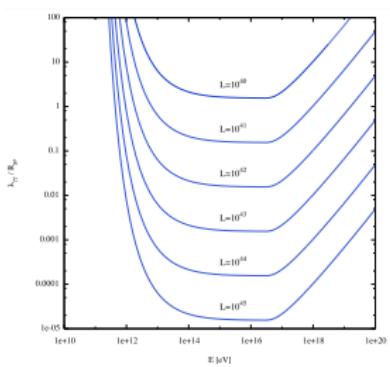
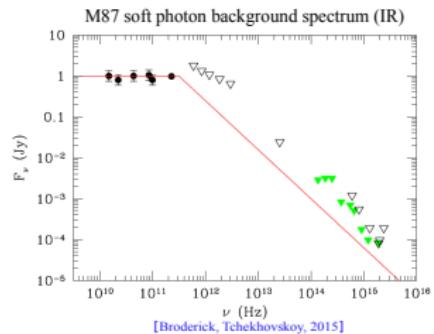
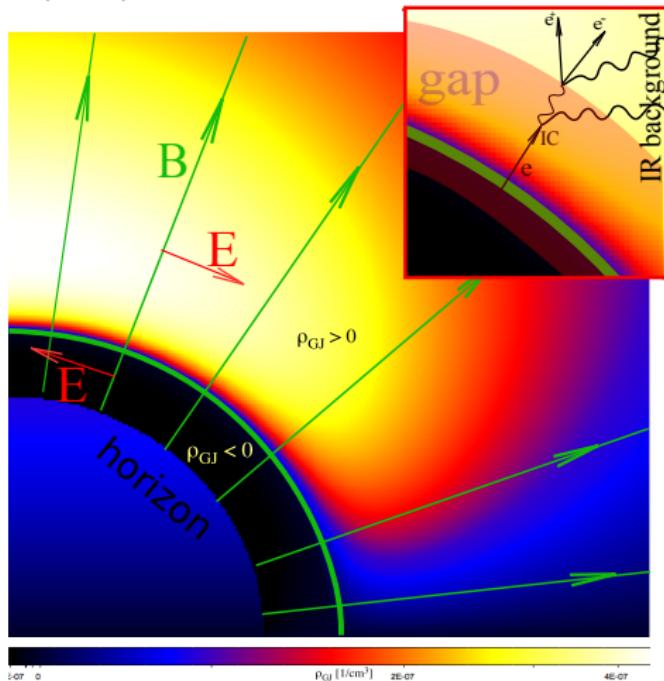
- Low-luminosity regime: $h \sim \lambda_{\gamma\gamma}$
- High-luminosity regime: $h \sim h_{acc}$

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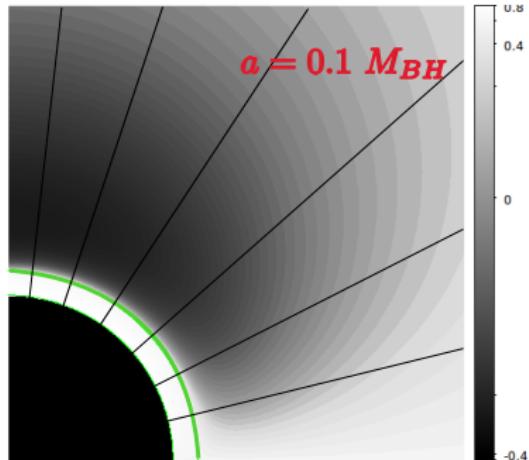
Gap model: numerical approach.

To verify the qualitative arguments we perform Monte-Carlo simulations of $e^+ / e^- / p$ in the split-monopole BH magnetosphere



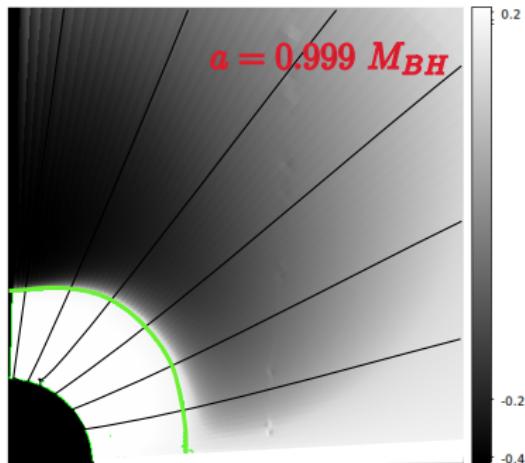
Gap model: numerical approach

slow rotation



[Blandford & Znajek, 1977]

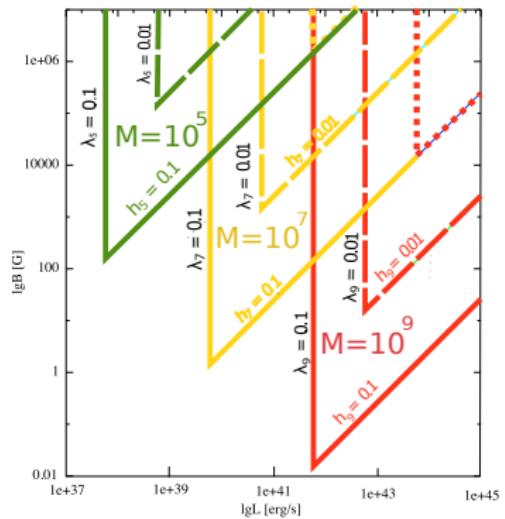
fast rotation



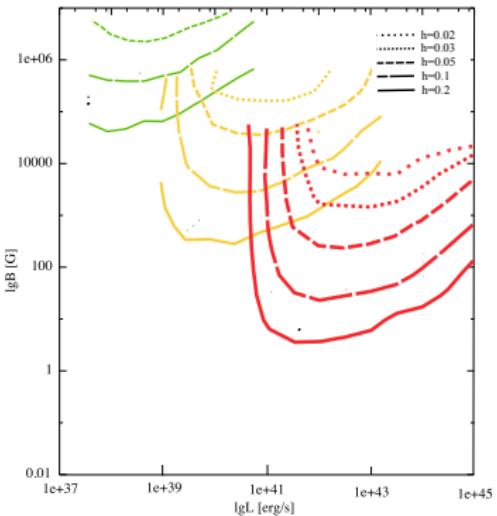
[Contopoulos & Nathanai, 2014]

Results: gap height. Slow rotation $a = 0.1 M_{BH}$

analytical

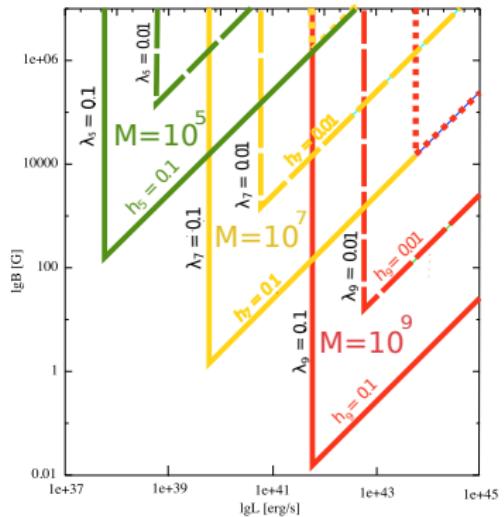


numerical



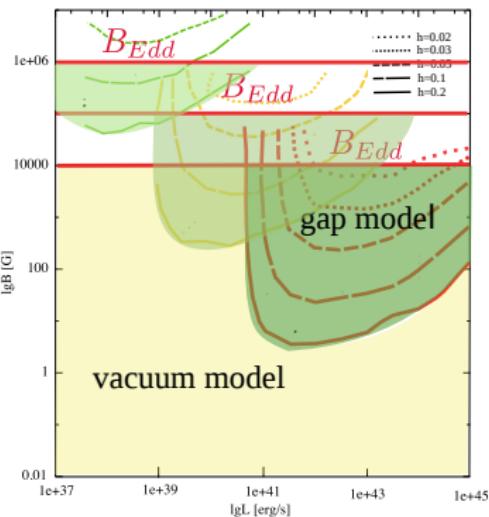
Results: gap height - Eddington limit

analytical

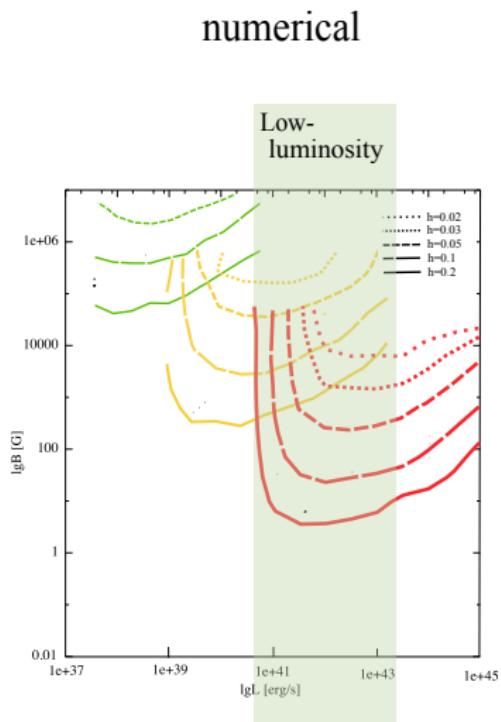
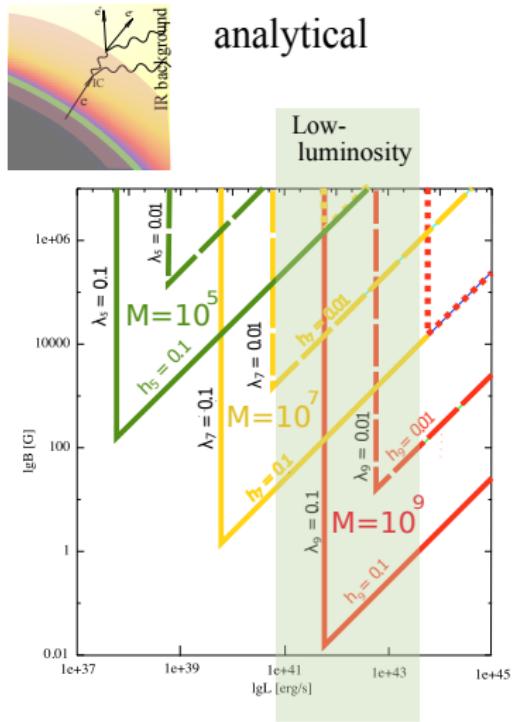


numerical

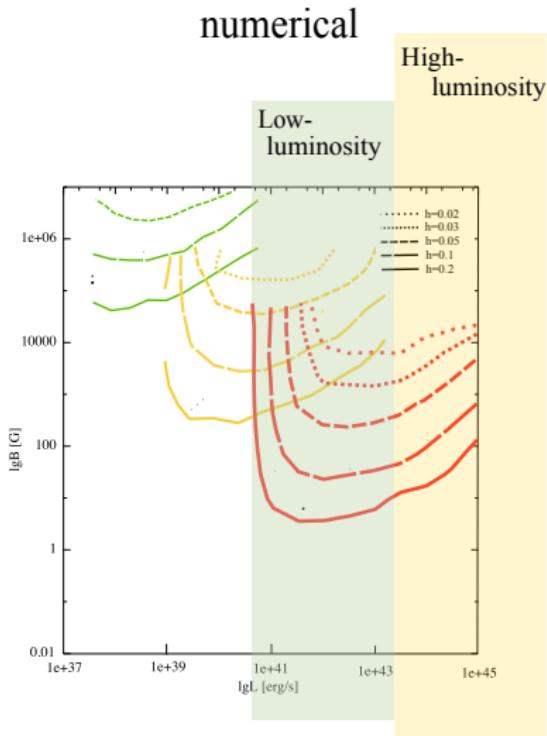
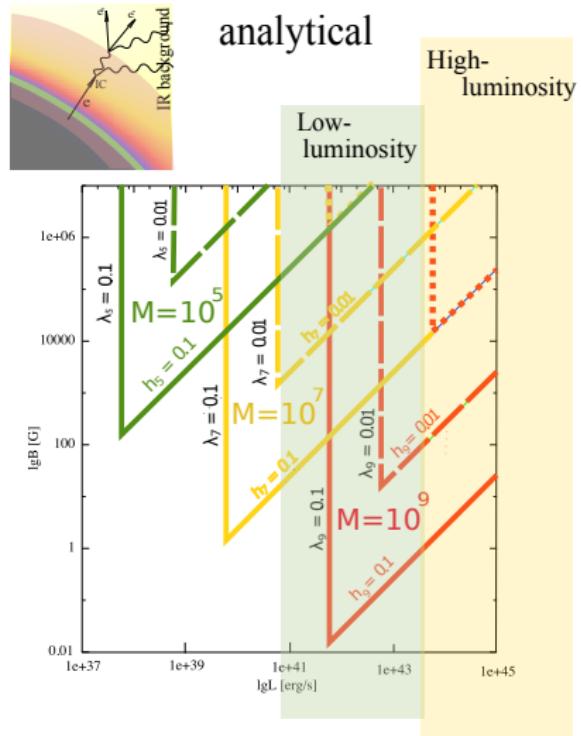
$$B_{Edd} = 10^4 \left(\frac{M}{10^9 M_\odot} \right)^{-1/2} G$$



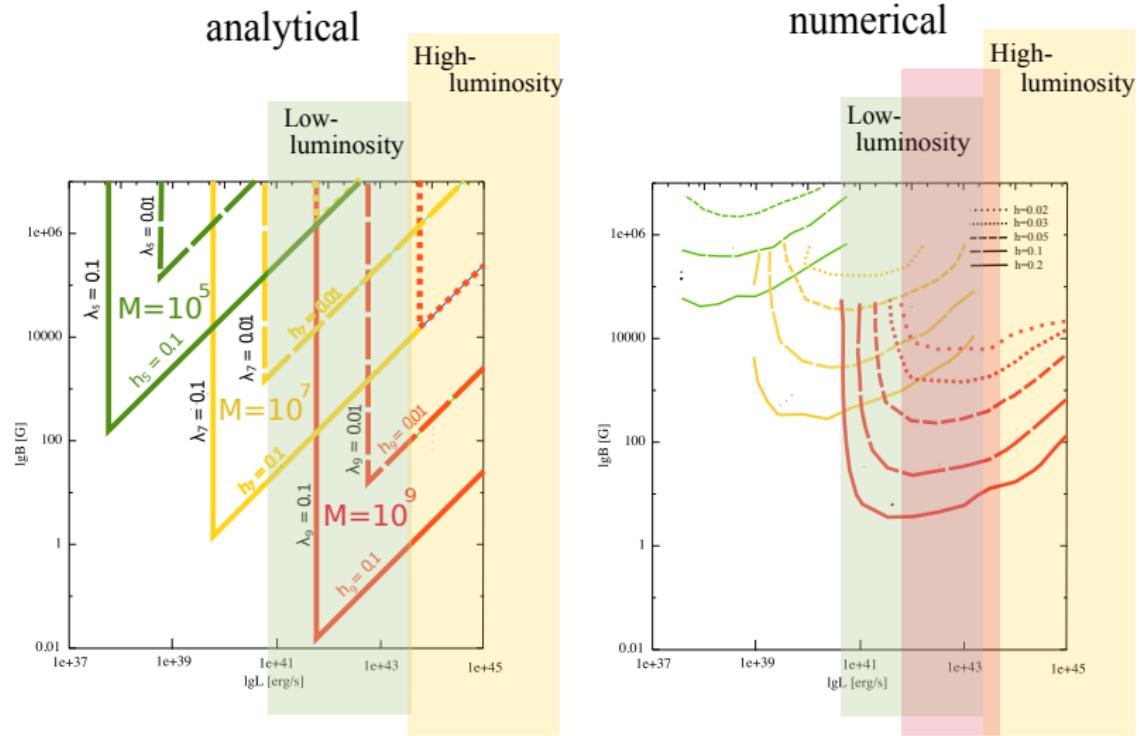
Results: gap height, acceleration regimes



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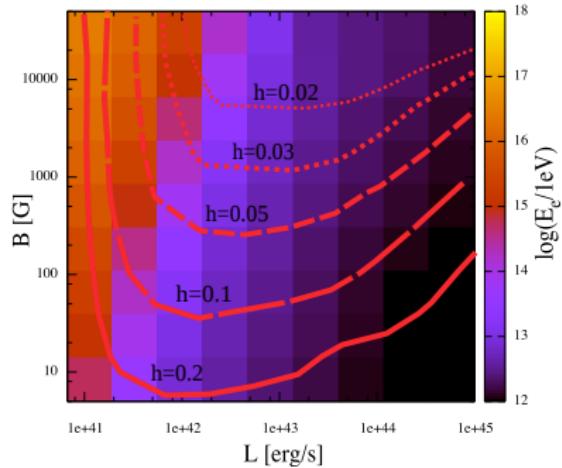


Results: gap height, acceleration regimes

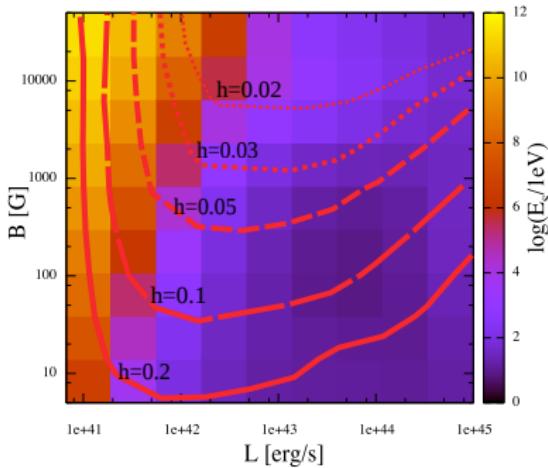


Results: $M_{BH} = 10^9 M_{\odot}$ electrons

e^+/e^- energy in the gap
(IC losses dominated)

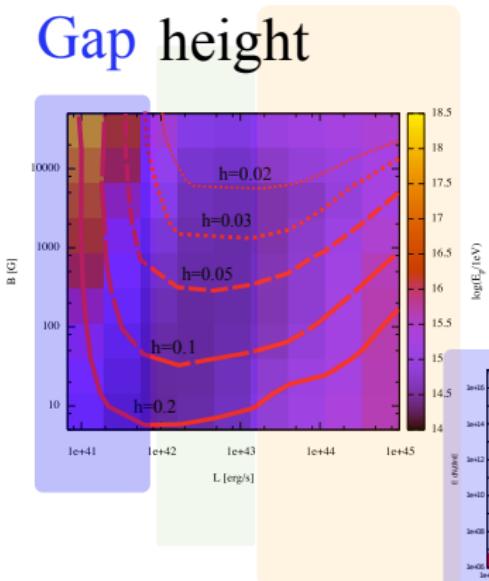


synchrotron radiation
peak energy

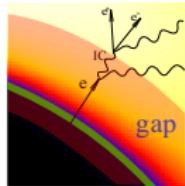
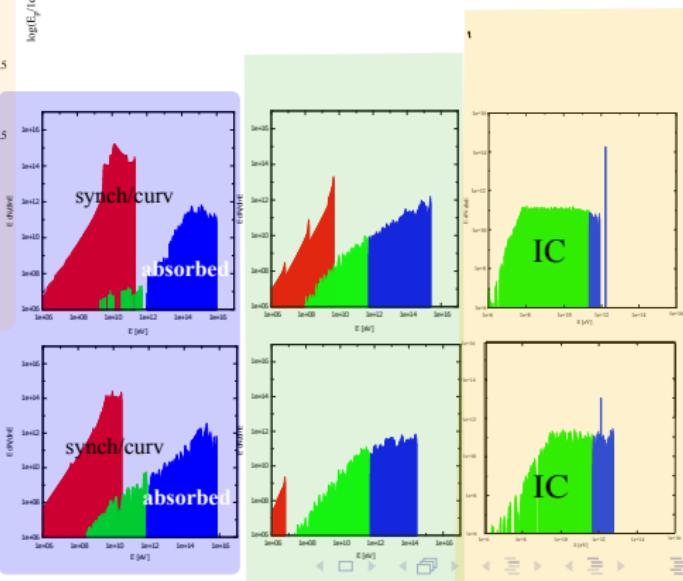


Results: $M_{BH} = 10^9 M_{\odot}$ electrons

Gap height

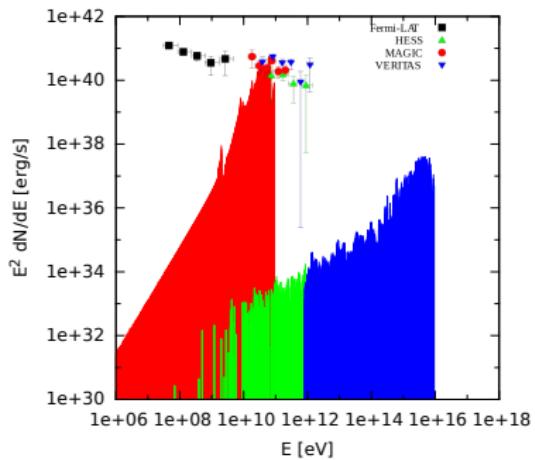


Spectra of emission
from electrons in the gap

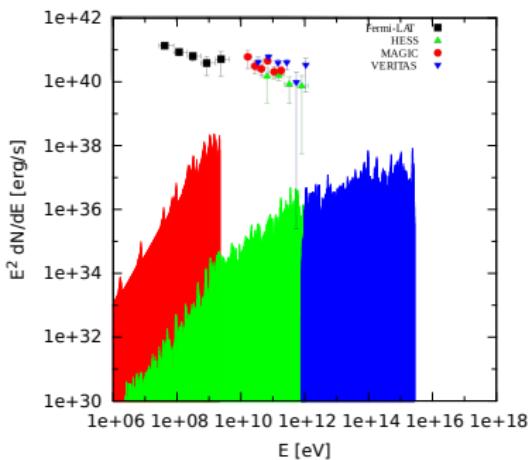


Results: radiation. M87 γ -observations.

$$L = 10^{41} \text{ erg/s}, \quad B = 10^4 G$$

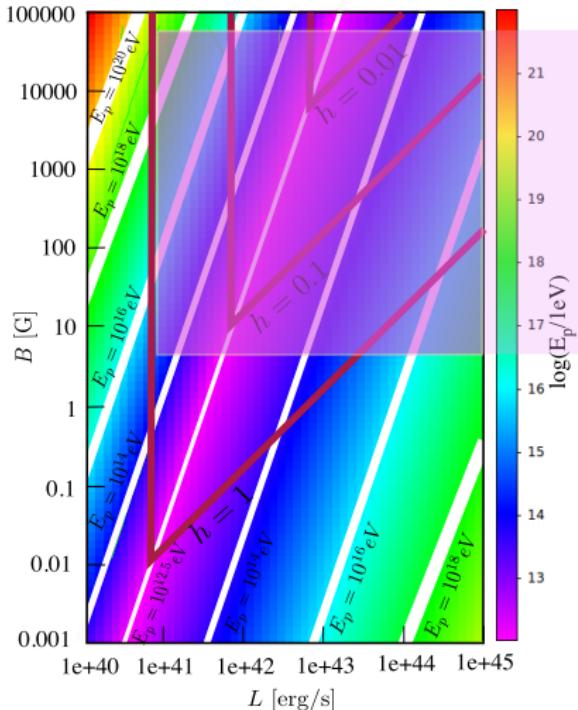


$$L = 10^{41} \text{ erg/s}, \quad B = 10^2 G$$

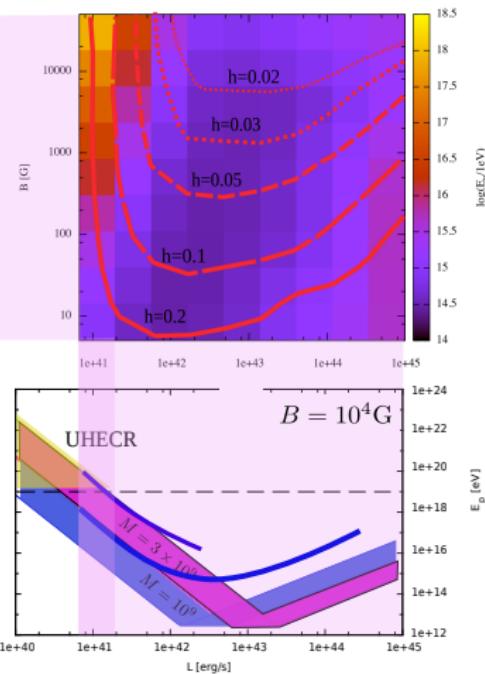


Results: proton energy ($M_{BH} = 10^9 M_\odot$)

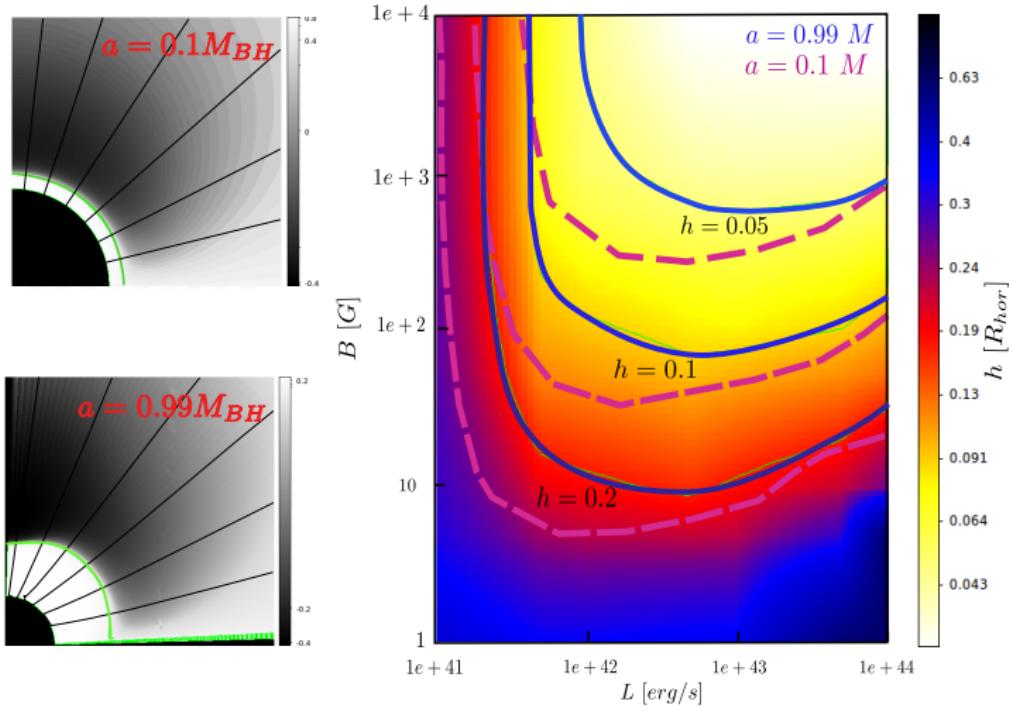
analytical



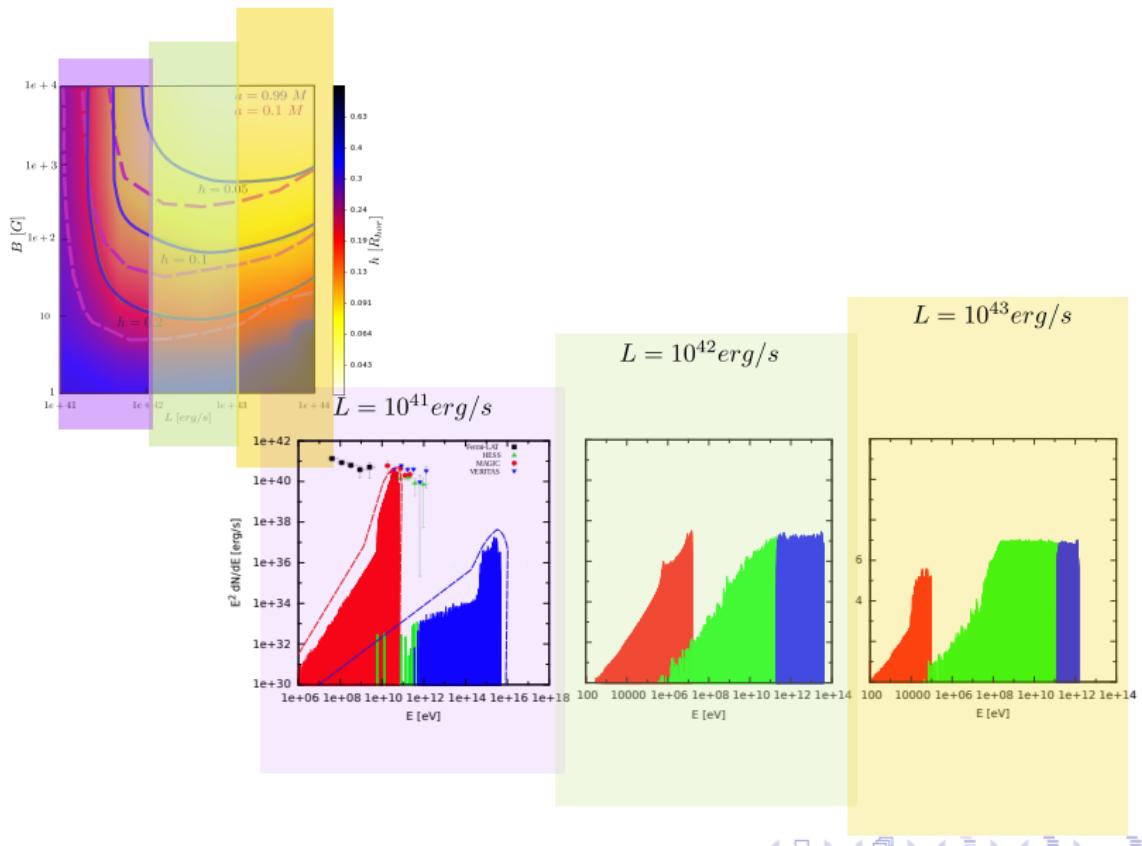
numerical



Results: fast rotating black hole $a = 0.999M_{BH}$



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Conclusions

- Found (numerically checked): range of parameters, where the gap model is valid
- UHECR only for the extreme values of the source parameters ($M \sim 10^9 M_{\odot}$, $B = B_{Edd} = 10^4$ G, $a \approx M$) .
- Observational features of the gap presence: sharp features in γ -rays