Some results on Sgr A* from Silesia

- Alternative GR theories and observed flares from Sgr A*
- Magnetosphere of Sgr A* & charged particle acceleration

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Section 1

Alternative GR theories and observed flares from Sgr A*

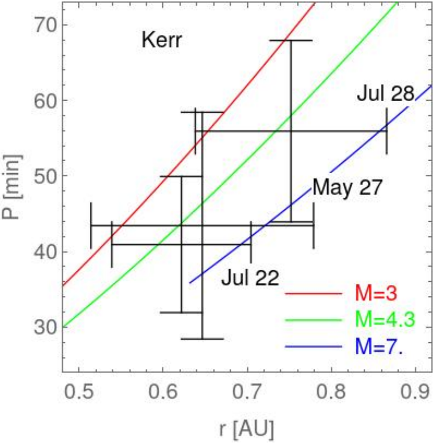
Three flares from Sgr A* (2018)

- hot-spot on geodesic orbit around BH
- distance and orbital periods known - fit!
- test effects of non-GR theories
  we used all stationary, axisymmetric, and asymp. flat BH metric we can found

$$\Omega_\phi(r) = \frac{-g_{t\phi,r} \pm \sqrt{(g_{t\phi,r})^2 - g_{tt,r}\ g_{\phi\phi,r}}}{g_{\phi\phi,r}}$$

hot-spot orbital frequency is given by $g_{\alpha\beta}$ only

$$P = \left(\frac{2\pi}{60}\right)\left(\frac{GM}{c^3}\right)\frac{1}{\Omega_\phi}$$



Kerr metric is OK and well ... more data / decrease error?
Restrictions on parameters of nonGR metric

• M Shahzadi, M Kološ, Z Stuchlík, Y Habib: Testing alternative theories of gravity by fitting the hot-spot data of Sgr A*, The European Physical Journal C, 82, 407 (2022)

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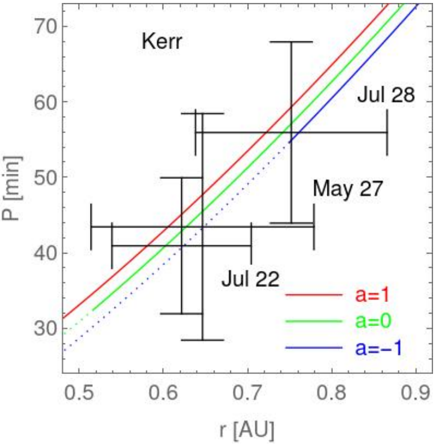

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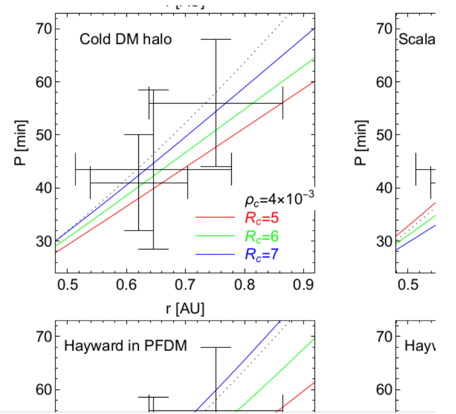

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Spacetime	Parameter
KN	$\tilde{Q} \in (0, 1.70]$
Braneworld	$\tilde{\beta} \in [-8.30, 2.90]$
Dyonic	$Q_e \in (0, 1.64]$ $Q_m \in (0, 1.64]$
Kerr-Taub-Nut	$n \in (0, 2.35]$
KN-Taub-Nut	$Q_n \in (0, 1.95]$, $\tilde{n} \in (0, 2.45]$
Dirty	$r_s \in (0, 24]$, $\Delta r_s \in (0, \infty)$, $\Delta M \in (0, 18]$
BH in PFDM	$k \in [-1.50, 0.29]$
Cold DM halo	$R_c \in [3.50, \infty)$, $\rho_c \in [0.002, 0.02]$
Scalar field DM halo	$R_s \in [2, 25]$, $\rho_s \in (0, 0.0004]$
Hayward in PFDM	$\tilde{k} \in [-1.50, 0.28]$, $Q_h \in (0, 2.90]$
BH in DM spike	$\rho_d \in (0, 0.05]$
Deformed BH in DM	$\tilde{\alpha} \in (0, 2.65]$
BH in quintessence	$\tilde{c} \in (0, 0.007]$, $\tilde{\omega} \in [-0.84, -0.32]$
Regular Bardeen	$q_2 \in (0, 2.30]$
Regular ABG	$Q \in (0, 1.44]$
Regular Hayward	$g \in (0, 3.24]$

Johannsen-Psaltis	$\epsilon \in [-70, 20]$
Hartle-Thorne	$q_1 \in [-5.25, 27]$
Kerr-Q	$q_0 \in [-2, 1]$
Quasi-Kerr	$\tilde{\epsilon} \in [-35, 150]$
Accelerating-rotating	$\tilde{b} \in [-0.03, 0.03]$
Kerr-Sen	$Q_K \in (0, 1.25]$
Born-Infeld	$Q_B \in (0, 1.30]$, $\beta \in (0, \infty)$
Kalb-Ramond	$s \in (0, 1.65]$, $\Gamma \in (0, 4.05]$
Gauss-Bonnet	$\alpha \in [-0.7, 0.47]$
KRZ BH	$\eta \in [-12, 55]$
Kerr-MOG	$\alpha_2 \in (0, \infty)$
Kaluza-Klein	$\gamma \in [1.25, 7.95]$, $b \in [1.25, 7.50]$
Weyl corrections	$\tilde{\alpha} \in (-\infty, \infty)$, $\tilde{q} \in (0, 1.73]$
Rastall	$N_s \in (0, 0.10]$, $\psi \in (0, 0.12]$
Charged-Weyl	$Q_w \in [5, 8.80]$
Conformal	$Q_c \in (0, 1.20]$, $\lambda_0 \in (0, \infty)$
Einstein-Yang-Mills	$\tilde{Q} \in (0, 1.7]$, $\tilde{\lambda} \in (0, 70]$
Hairy	$\alpha_0 \in (0, 1.90]$, $\alpha_1 \in (0, 50]$

Section 2

Magnetosphere of Sgr A* & charged particle acceleration

Multimessenger era: Sgr A* black hole as PeVatron source

Observations of γ-ray photons from the Galactic Centre region showing acceleration of PeV particles: High Energy Stereoscopic System (H.E.S.S.) collaboration: Acceleration of PeV protons in the Galactic Centre, Nature 531, 476 (2016)

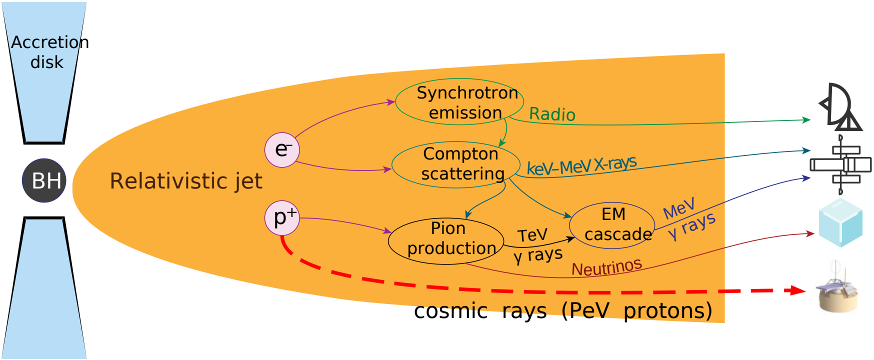
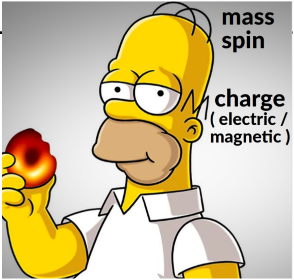


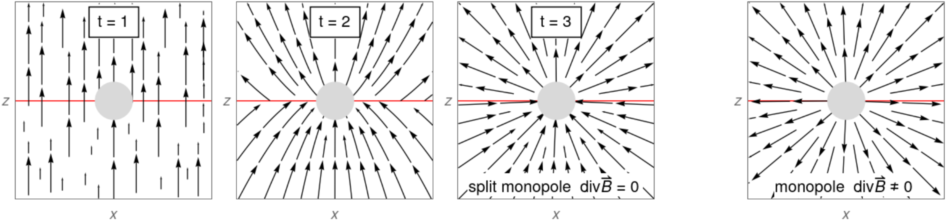
figure from: A.V.Plavin et al., The Astrophysical Journal, Volume 908, Issue 2, id.157 (2021) + my small update

Black hole magnetosphere



A) Black hole alone - BH own EM field

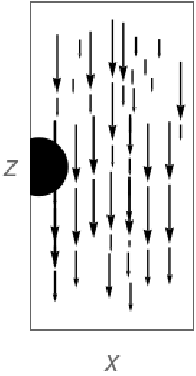
- no-hair theorem - black hole have only three hairs:
  mass, spin, **charge** (electric / magnetic)
  $\Longrightarrow$ monopole character of EM filed around BH
- $\nexists$ of magnetic monopole, but plasma accretion
  $\Longrightarrow$ BH will have **split monopole** magnetic field



B) Black hole in plasma
electromagnetic field around BH generated by accretion disk

0) Vacuum Maxwell Equations

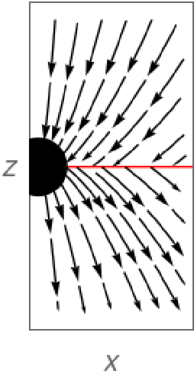
vacuum $J^\mu = 0$



Wald (1974)

1) Force Free Electrodynamics

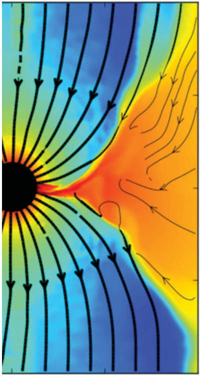
$B^2 \gg \rho c^2$



Blandford-Znajek (1977)

2) Magneto-hydrodynamics

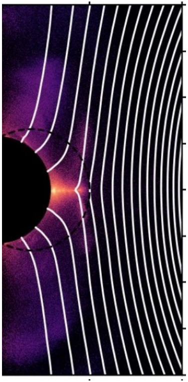
fluid description



Gammie+(2003) HARM code

3) Particle-In-Cell

charged particles



Crinquand+(2020) Hirotani+(2021)

difficulty level $\Longrightarrow$

Charged particle acceleration - magnetic Penrose process

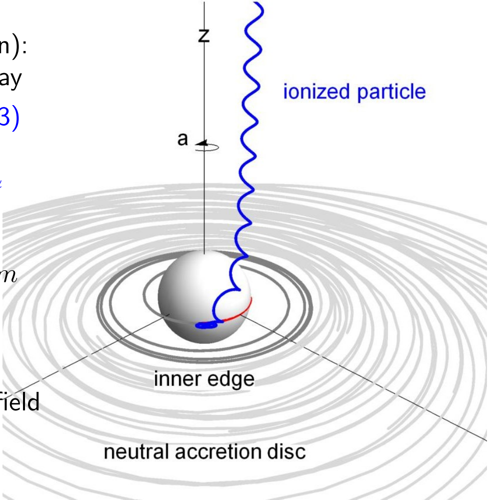
- How to populate BH magnetosphere with charged particles (particle injection): neutral particle split - ionization or decay
- neutral particle (1) $\rightarrow$ charged (2) + (3)

$$p_{\alpha(1)} = p_{\alpha(2)} + qA_\alpha + p_{\alpha(3)} - qA_\alpha$$

- axial symmetry $A_\alpha = (A_t, 0, 0, A_\phi)$
- A_t can change particle energy $\mathcal{E} = E/m$

$$\boxed{\mathcal{E} = -g_{t\alpha}u^\alpha + (q/m)A_t}$$

- BH rotation $g_{t\phi}$: electric $\leftrightarrow$ magnetic field



selective accretion
$\rightarrow$ BH with Wald charge $Q_\mathrm{W} = 2aMB$

• M. Zajaček, A. Tursunov, A. Eckart, S. Britzen: *On the charge of the Galactic centre black hole*, MNRAS, 480, 4, 4408–4423 (2018) [arXiv:1808.07327]

Testing Sgr A* black hole as PeVatron source (10^{15}eV p)

- available energy (BH rotation) ✓
- total flux ($\sim$ accretion rate) ✓
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  proton and $M_{\mathrm{SgrA}} = 4.3\times10^6\,\mathrm{M}_\odot$

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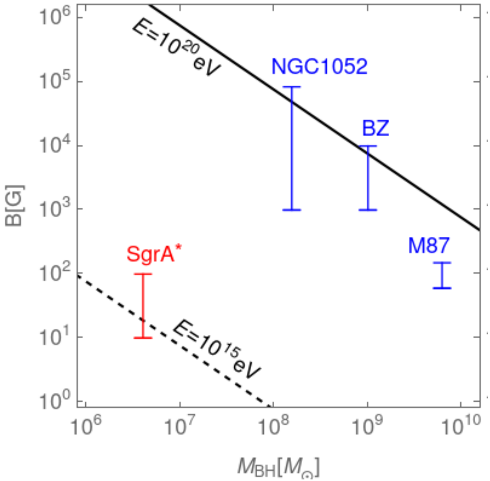

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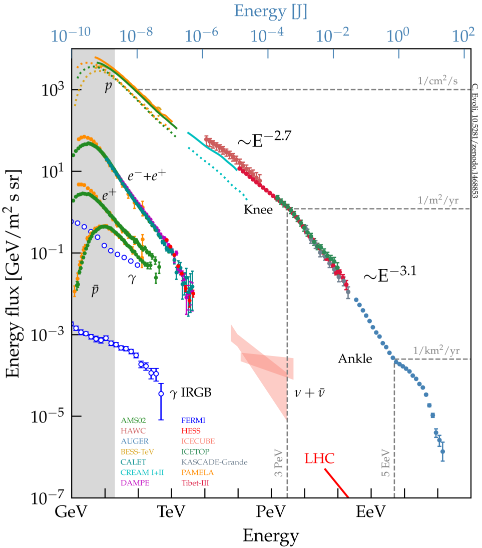
- cosmic rays energy spectrum ?
  power law with spectral index -2.7



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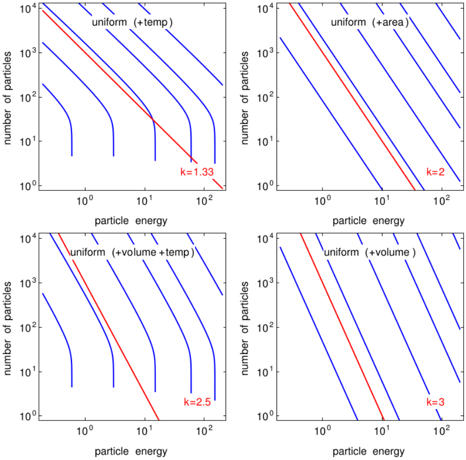
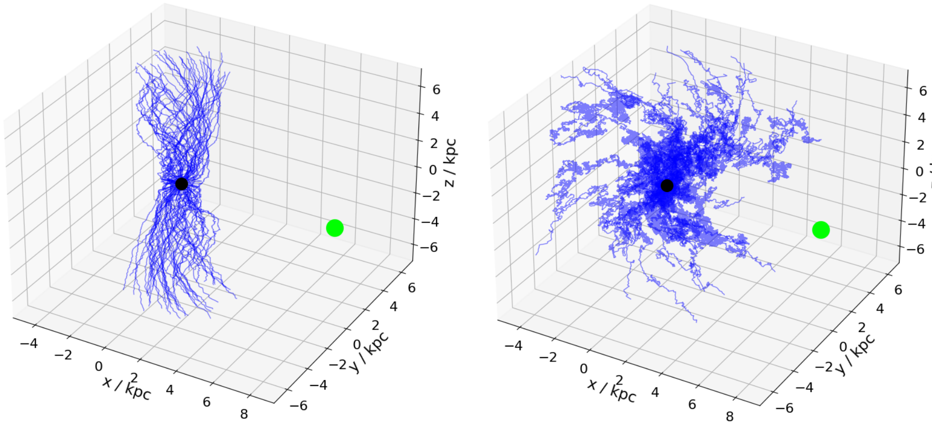
  charged particles initial distribution:
  -1.3 (accretion disk surface)
  -3 (region above disk)

preliminary theoretical models:



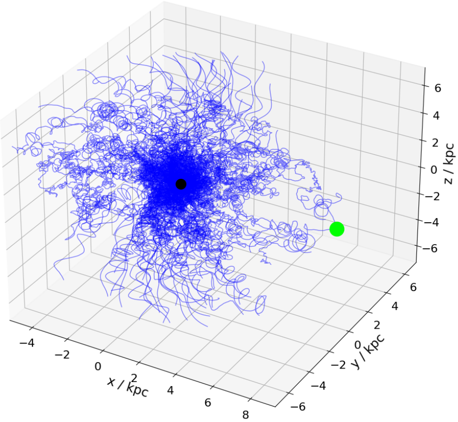
(preliminary) PeV proton propagation from Sgr A* to Earth

toy model: Sgr A* BH - isotropic source shooting protons with 50 PeV energy



(Berenika Čermáková) Study the propagation of PeV protons (ions) using CRPropa = simulation framework for charged particle propagation through an (extra)galactic environment https://crpropa.desy.de/

Summary & we are working. . .



- Sgr A* BH is PeVatron
  can accelerate protons to 10^{15} eV
  (or more if you increase mag. field)

- Propagation of PeV protons (ions)
  Sgr A* to Earth
- realistic BH magnetosphere (Sgr A*)
  & radiating charged particle dynamic

Thank you for your attention

• M. Shahzadi, M. Kološ, Z. Stuchlík, Y. Habib: *Testing alternative theories of gravity by fitting the hot-spot data of Sgr A**, EPJC, 82, 407 (2022) [arXiv:2201.04442]
• A. Tursunov, M. Kološ, Z. Stuchlík: *Constraints on Cosmic Ray Acceleration Capabilities of Black Holes in X-ray Binaries and Active Galactic Nuclei*, Symmetry 14 (3), 482 (2022)