Magnetized black holes:

the role of rotation, boost and accretion in

twisting the field lines and accelerating particles

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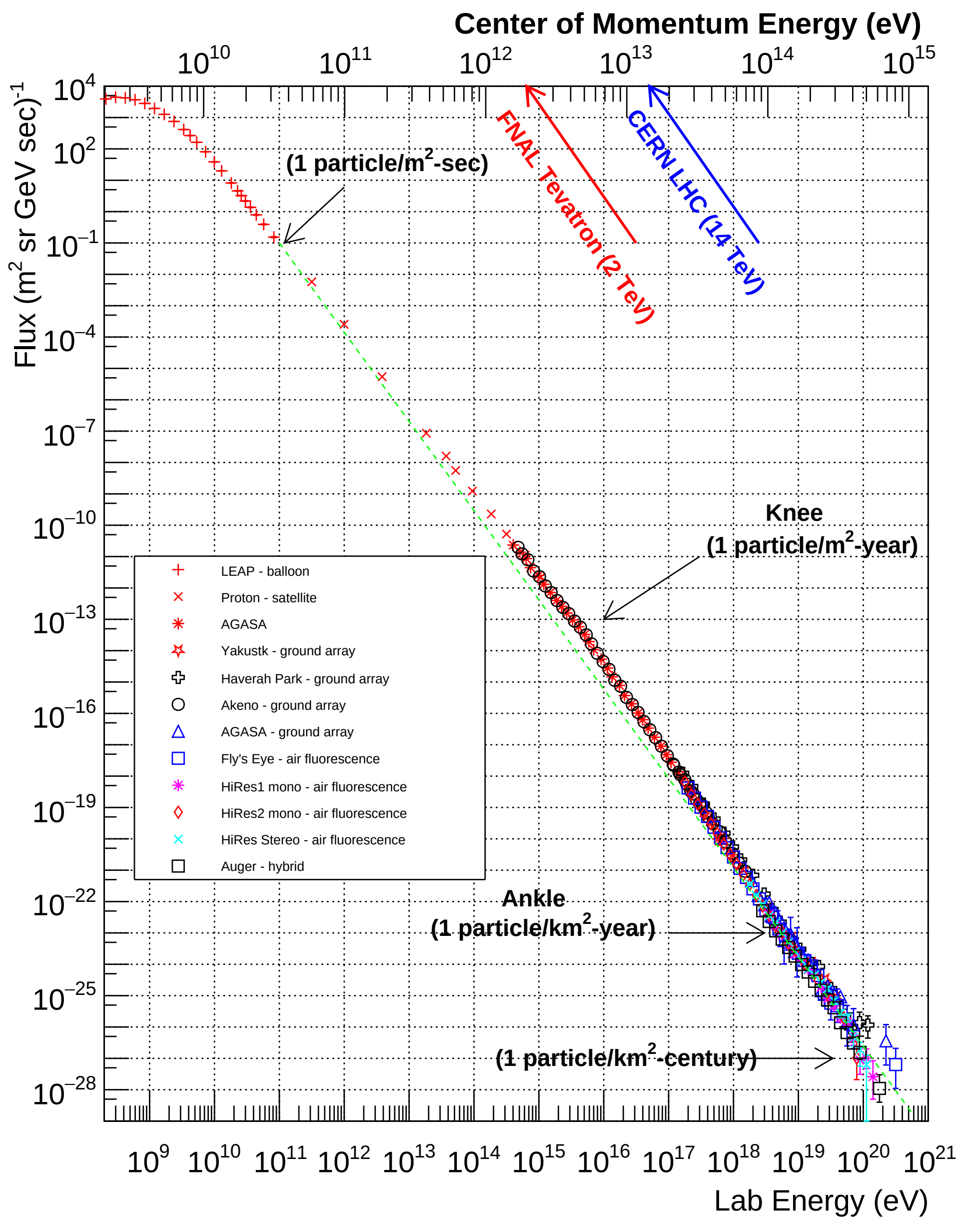
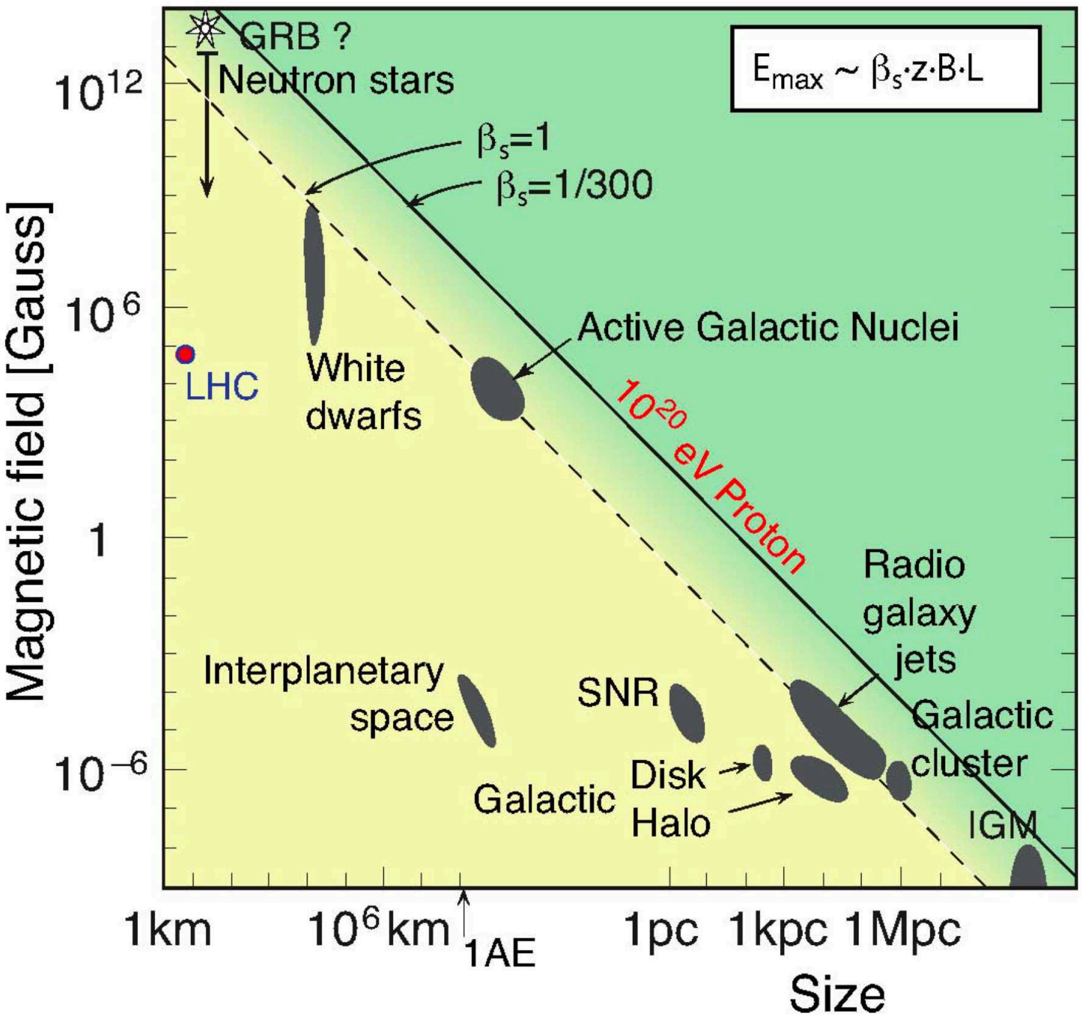
Motivation: Spectrum of cosmic ray particles



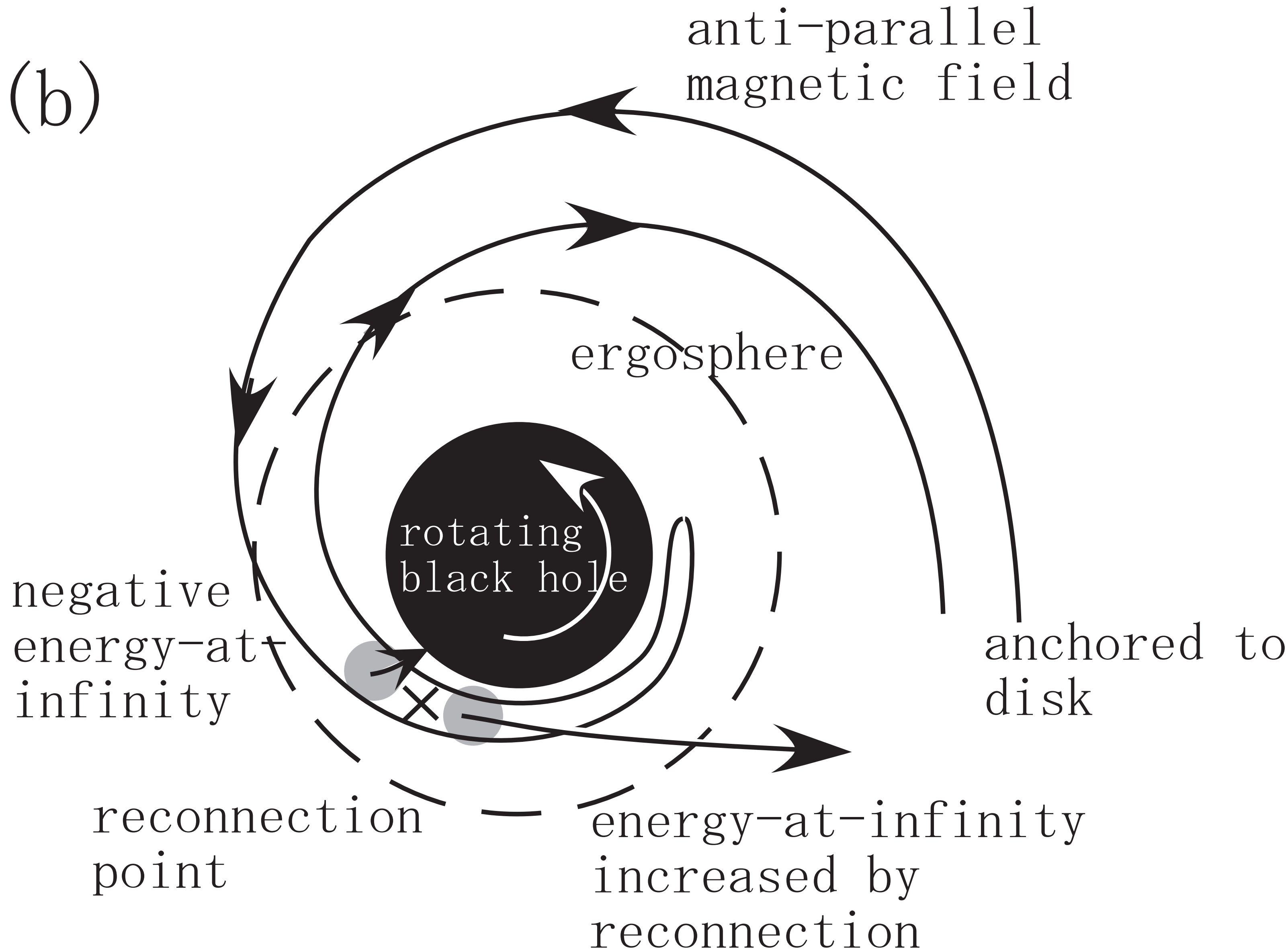
Different constituents are plotted against several limits of particle accelerator experiments (figure from Hanlon 2021).

Motivation: Hillas diagram



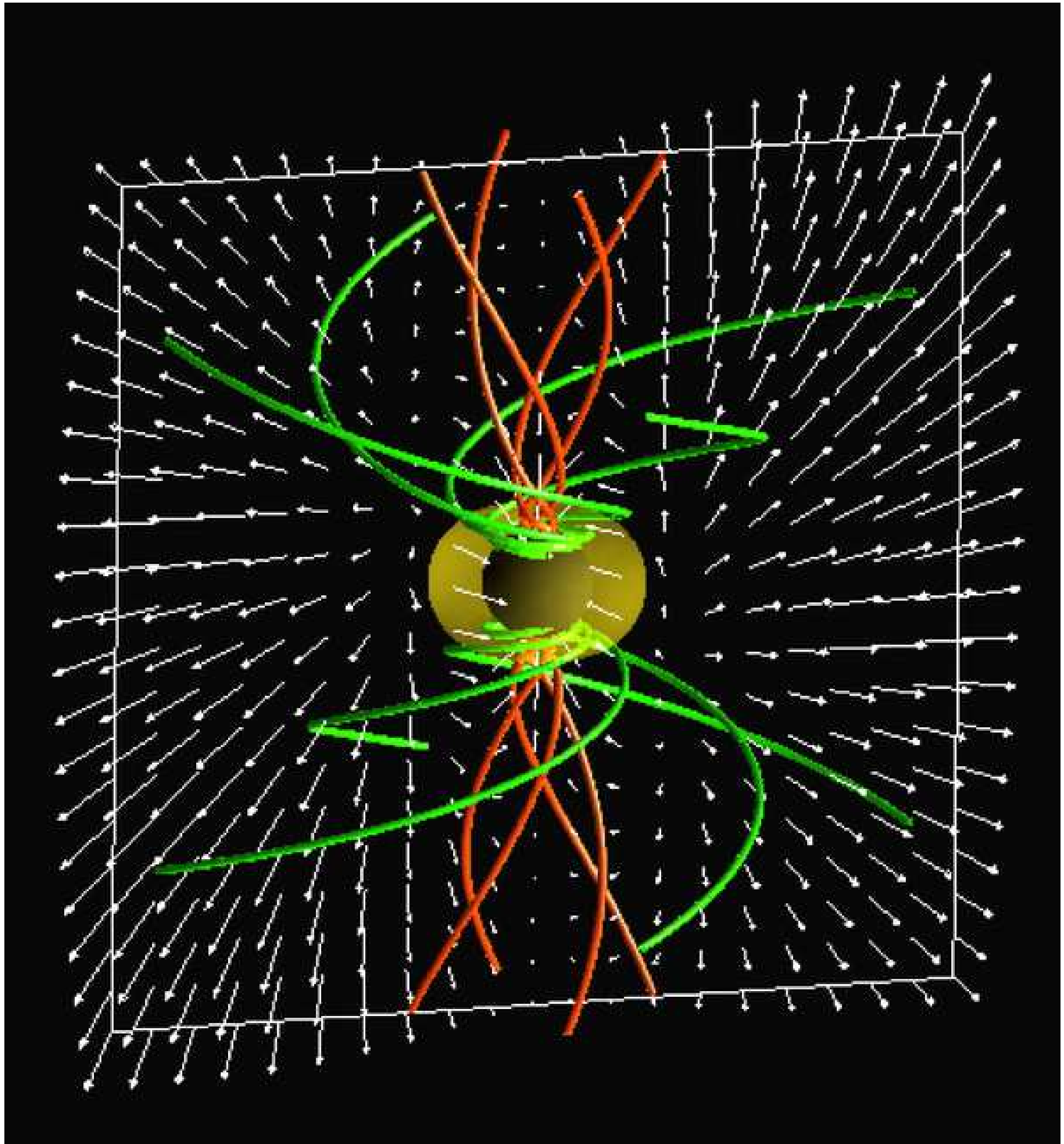
Sites of cosmic rays depending on the size of the source and the magnetic field intensity. Objects located below the diagonal line are unable to accelerate cosmic rays to the given energy of 10^{20} eV. Position of the ground based Large Hadronic Collider (LHC) is also shown. Various cosmic sources can produce cosmic rays above the limits of what laboratory accelerators achieve (De Angelis et al. 2015).

Magnetic reconnection in ergosphere



Koide & Arai (ApJ, 2008); Lyutikov (PRD, 2011); Morozova et al. (2014)

Relativistic particles from BH ergosphere?



Koide (ApJ, 2004)

Wald's axisymmetric field

$$\boxed{F = \tfrac{1}{2} B_0 \left(\mathrm{d}\tilde{\xi} + \tfrac{2J}{M}\, \mathrm{d}\xi \right)}$$

Magnetic flux surfaces (magnetic field lines lie in these surfaces):

$$4\pi \Phi_{\mathcal{M}} = \int_{\mathcal{S}} \boldsymbol{F} \;=\; \text{const.}$$

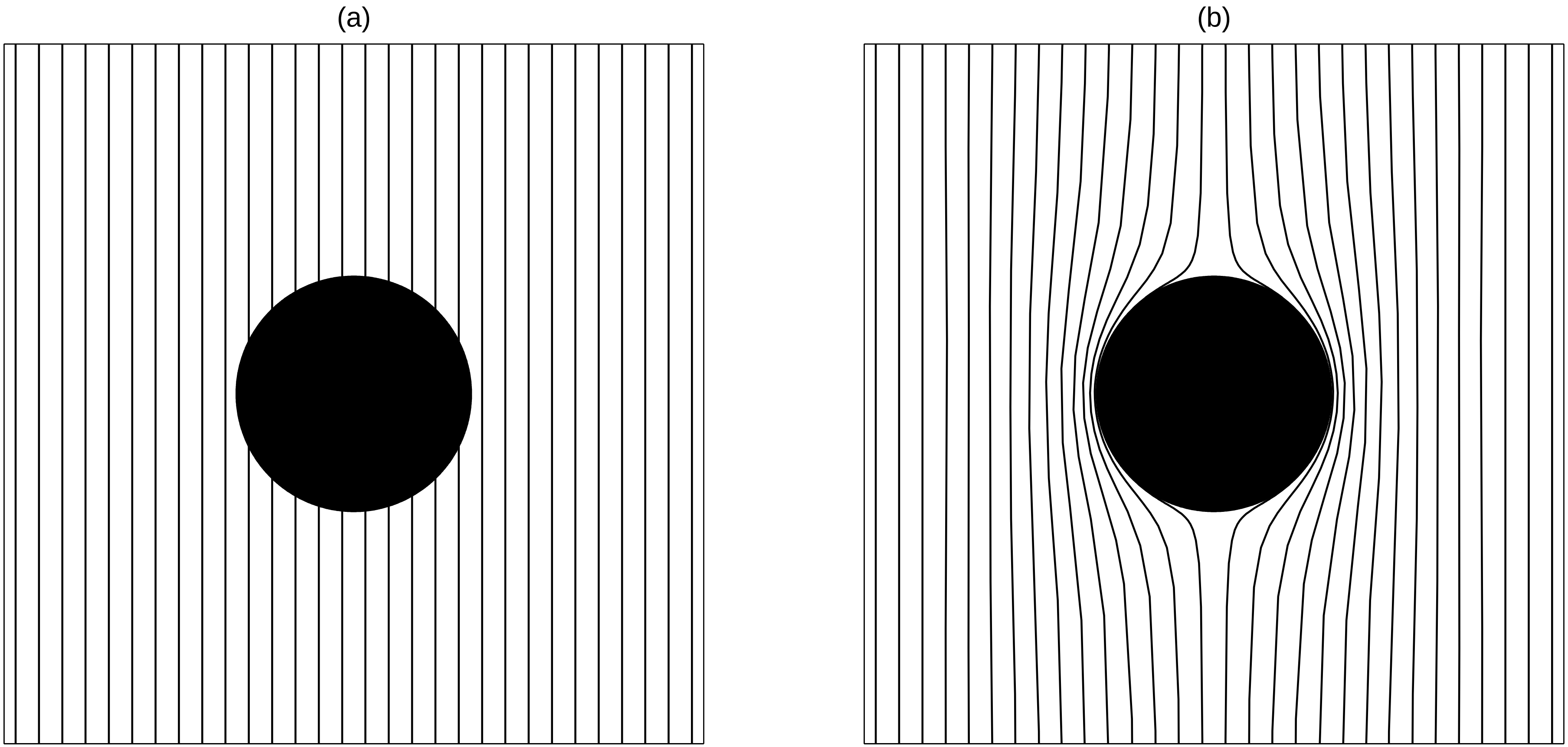
Magnetic/electric Lorentz force:

$$m\dot{\boldsymbol{u}} = q_{\mathrm{m}} {}^{\star}\boldsymbol{F}.\boldsymbol{u}, \qquad m\dot{\boldsymbol{u}} = q_{\mathrm{e}} \boldsymbol{F}.\boldsymbol{u}.$$

Magnetic field lines (aligned case):

$$\frac{\mathrm{d}r}{\mathrm{d}\theta} = \frac{B_r}{B_\theta},$$

Rotating black hole in vacuum, aligned magnetic field



An axisymmetric case: (a) $a = 0$; a non-rotating (Schwarzschild) black hole;

(b) $a = M$ a maximally rotating Kerr black hole – Meissner effect.

Magnetic/electric lines of force

Magnetic lines:

$$\frac{\mathrm{d}r}{\mathrm{d}\theta} = -\frac{F_{\theta\phi}}{F_{r\phi}}, \qquad \frac{\mathrm{d}r}{\mathrm{d}\phi} = \frac{F_{\theta\phi}}{F_{r\theta}}.$$

Magnetic flux (axially symmetric case):

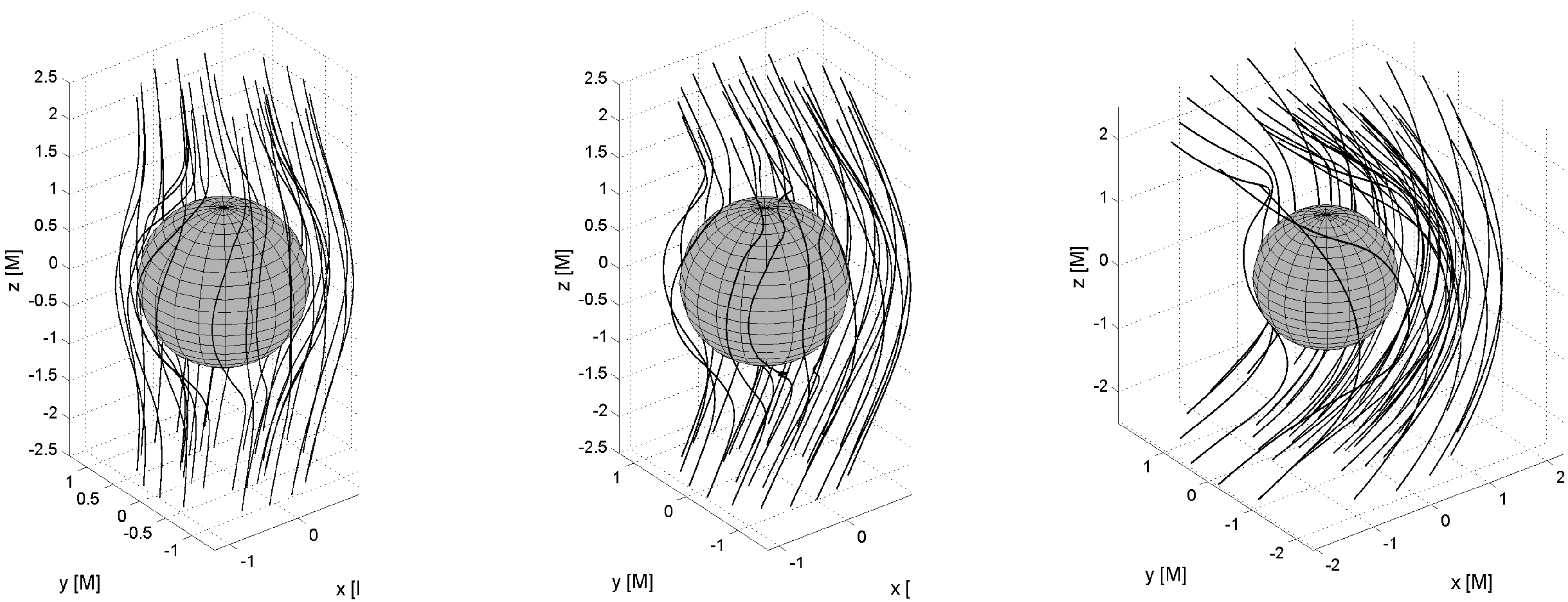
$$\Phi_{\mathrm{m}} = \pi B_0 \left[r^2 - 2Mr + a^2 + \frac{2Mr}{r^2 + a^2\,\cos^2\theta} \left(r^2 - a^2 \right) \right] \sin^2\theta$$

Expulsion of magnetic flux out of fast rotating black hole:

$\Phi_{\mathrm{m}} = 0$ on hemisphere $r = r_+$, $a = M$ (“Meissner effect”).

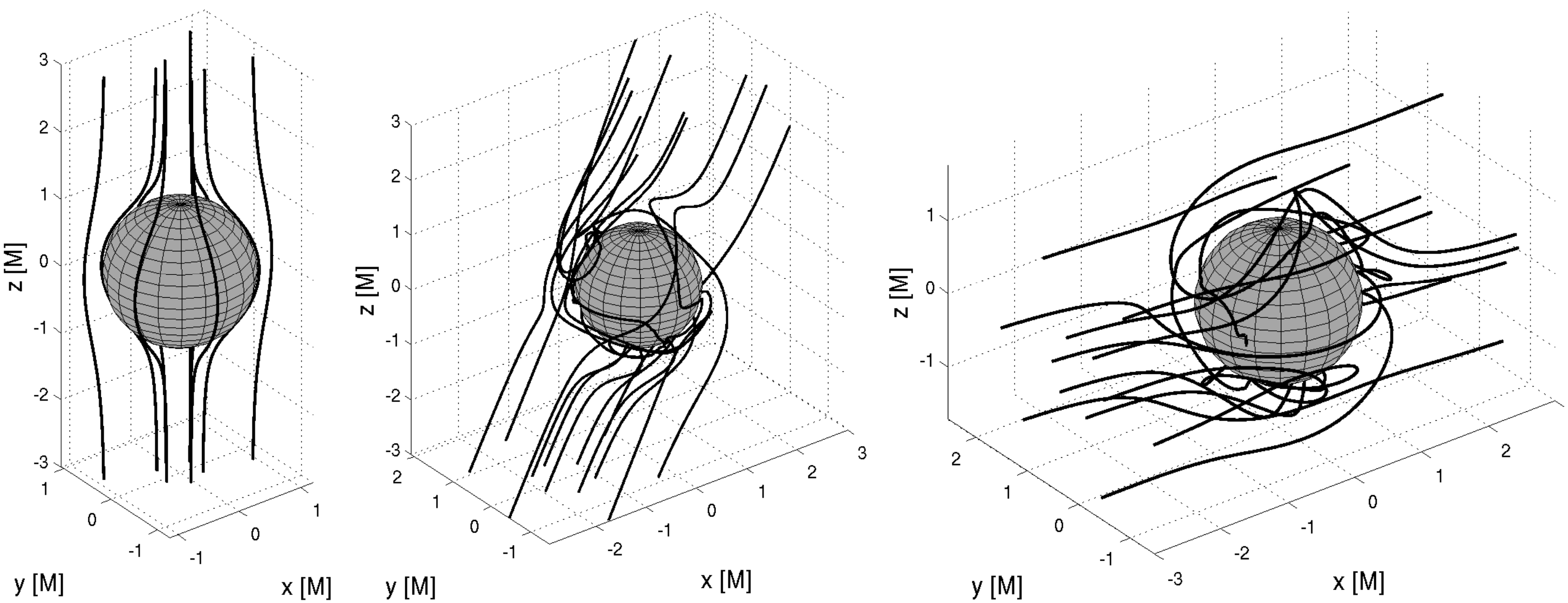
Rotating black hole + linear boost

$v = 0.1$ $v = 0.3$ $v = 0.7$



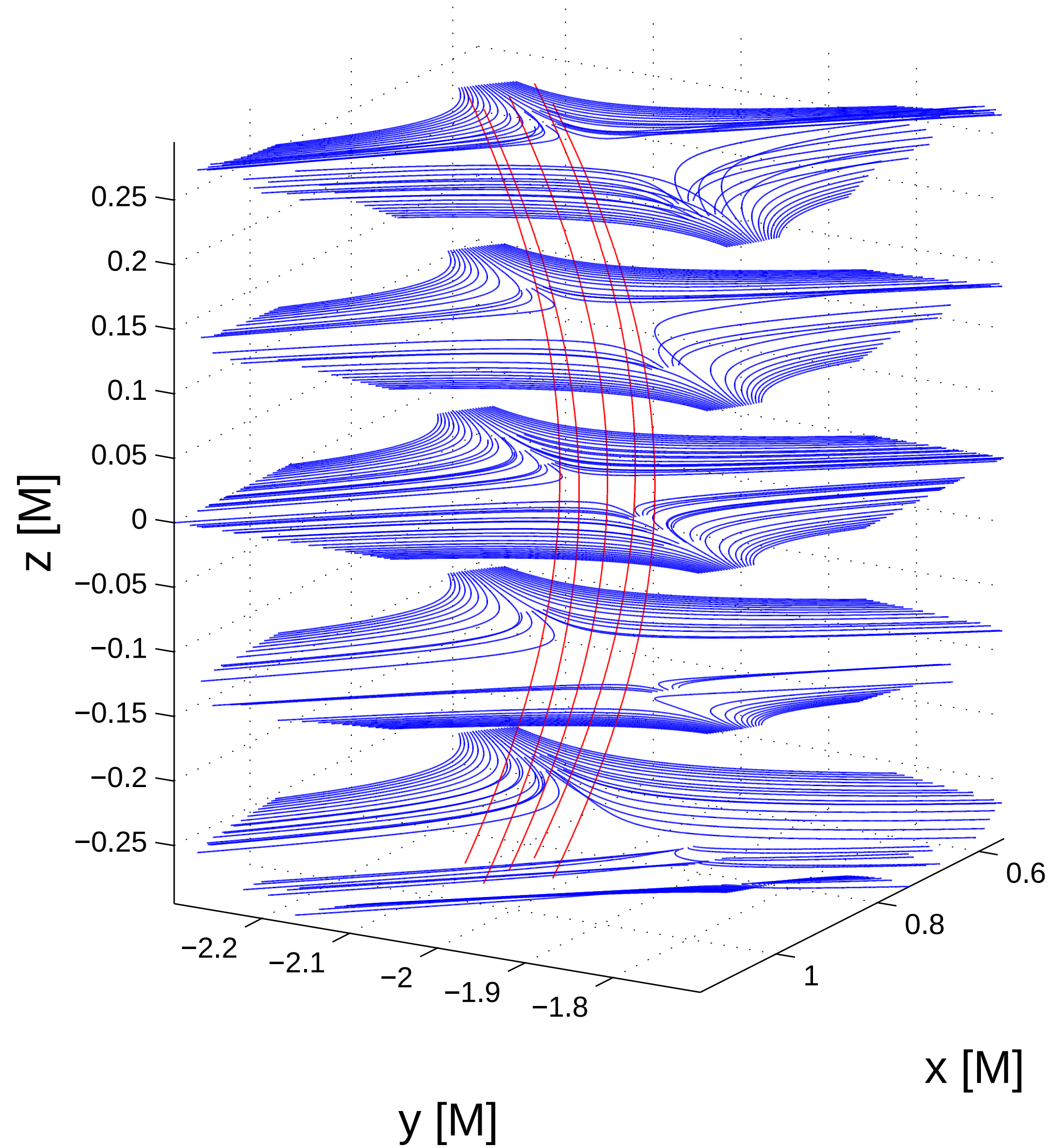
Effect of translatory motion (linear boost).

Rotating black hole in vacuum, oblique magnetic field



Effect of misalignement.

Magnetic (blue) and electric (red) field lines



Magnetic dipole in Rindler approximation

BIG BLACK HOLE, LITTLE NEUTRON STAR: MAGNETIC … PHYSICAL REVIEW D **88,** 064059 (2013)

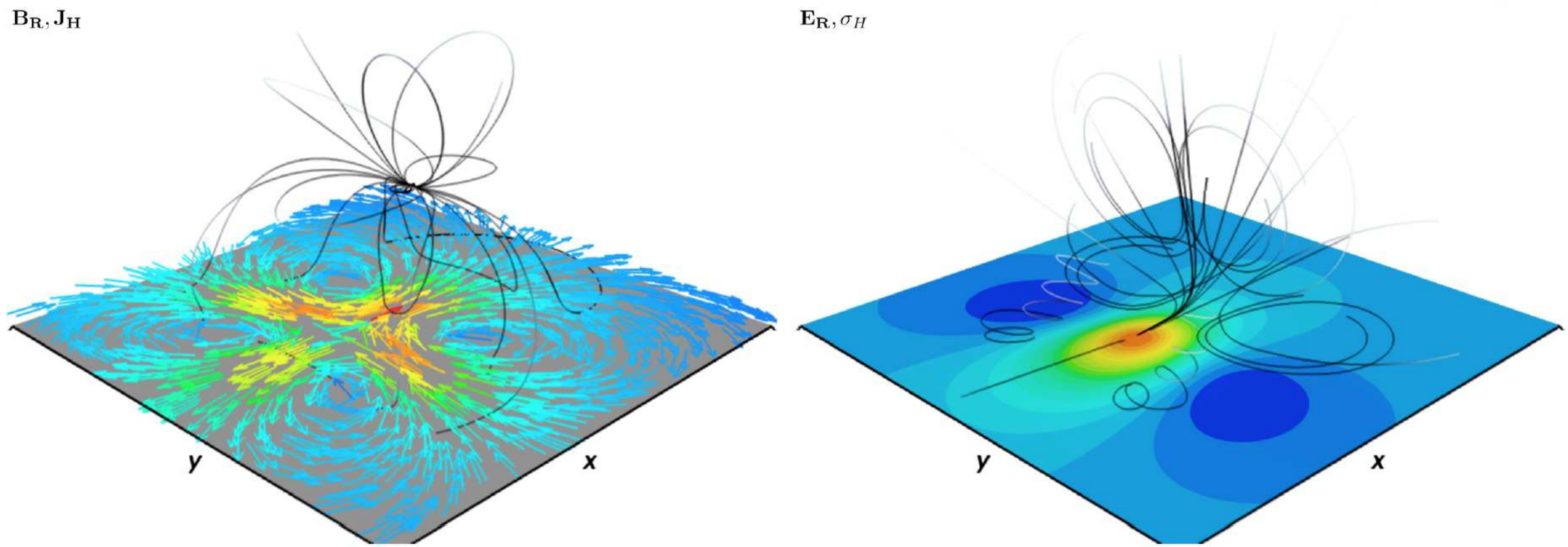


FIG. 14 (color online). A 3D visualization of the magnetic fields lines and corresponding horizon currents $\mathbf{J}_{\mathcal{H}}$ (left) and electric field lines with the corresponding horizon charges $\sigma_{\mathcal{H}}$ (right) for the boosted Rindler dipole. The case shown is for $v_{S,x} = 0.2$.

D’Orazio & Levin (Phys. Rev. D, 2013)

Magnetic dipole in Rindler approximation

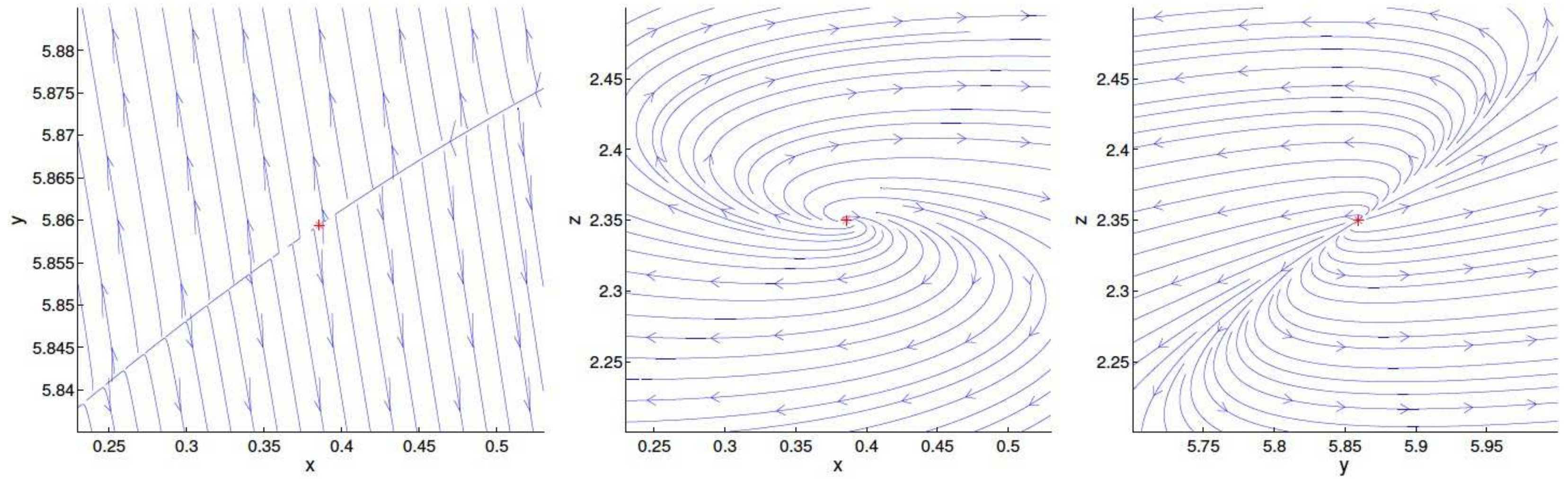


Figure 5. Two-dimensional sections of the magnetic field lines in the vicinity of the null point (red mark) located at $x_0 = 0.39$, $y_0 = 5.86$ and $z_0 = 2.35$. Same values of parameters as in Fig. 4 are used.

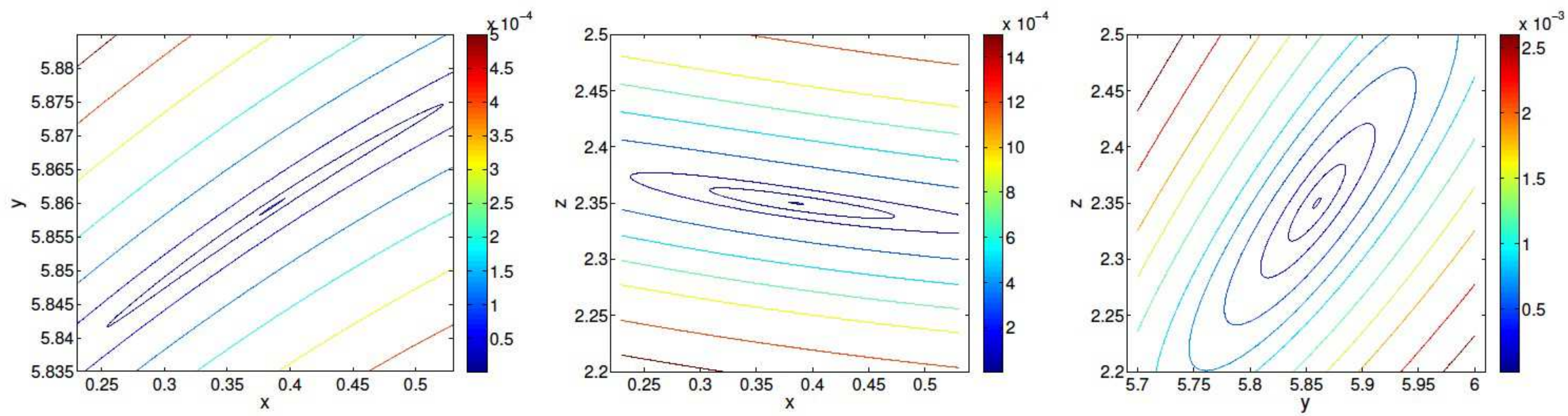
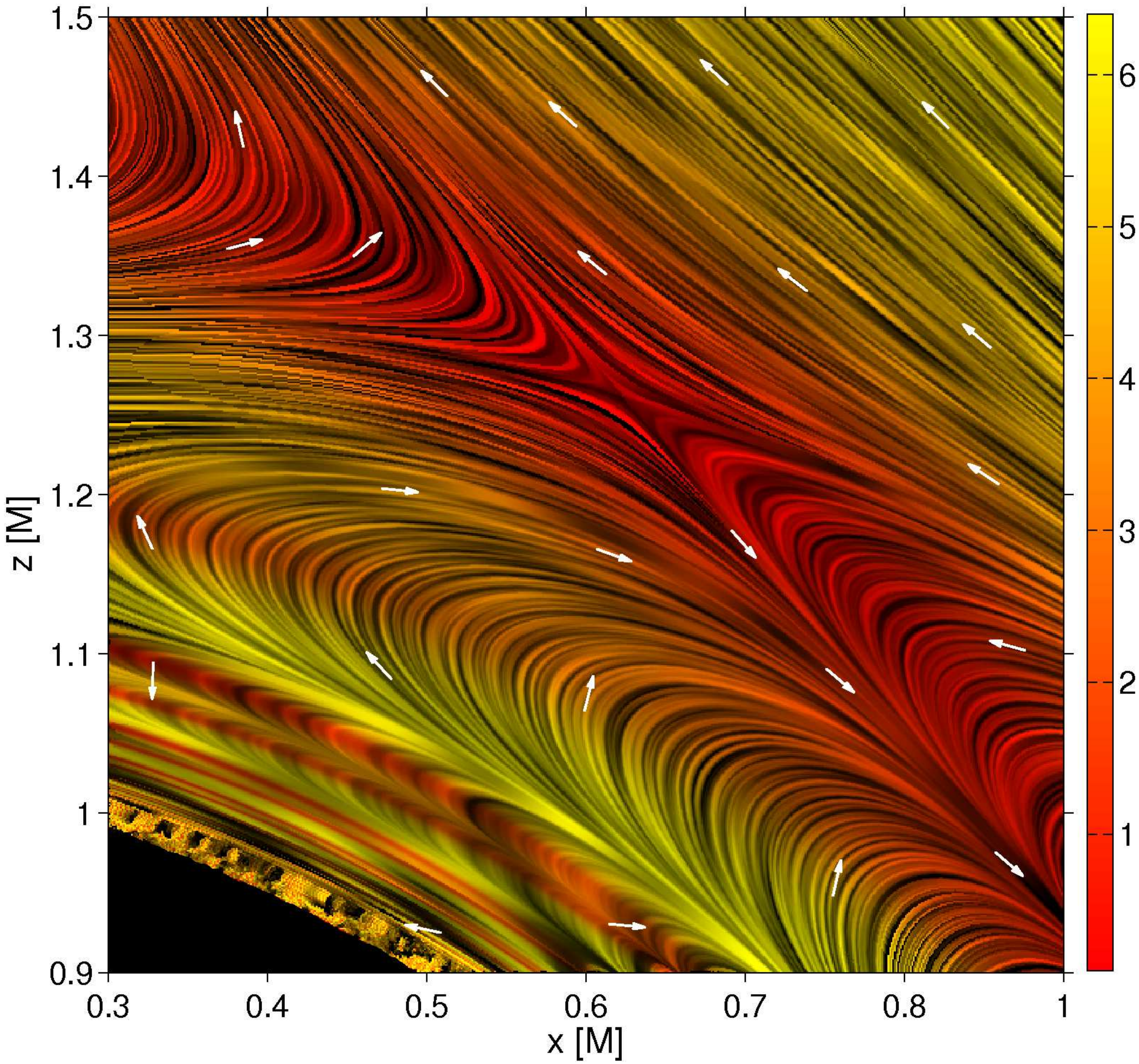


Figure 6. Iso-contours of the magnetic field strength B in the vicinity of the null point located at $x_0 = 0.39$, $y_0 = 5.86$ and $z_0 = 2.35$. Same values of parameters as in Fig. 4 and same section planes as in Fig. 5 are used.

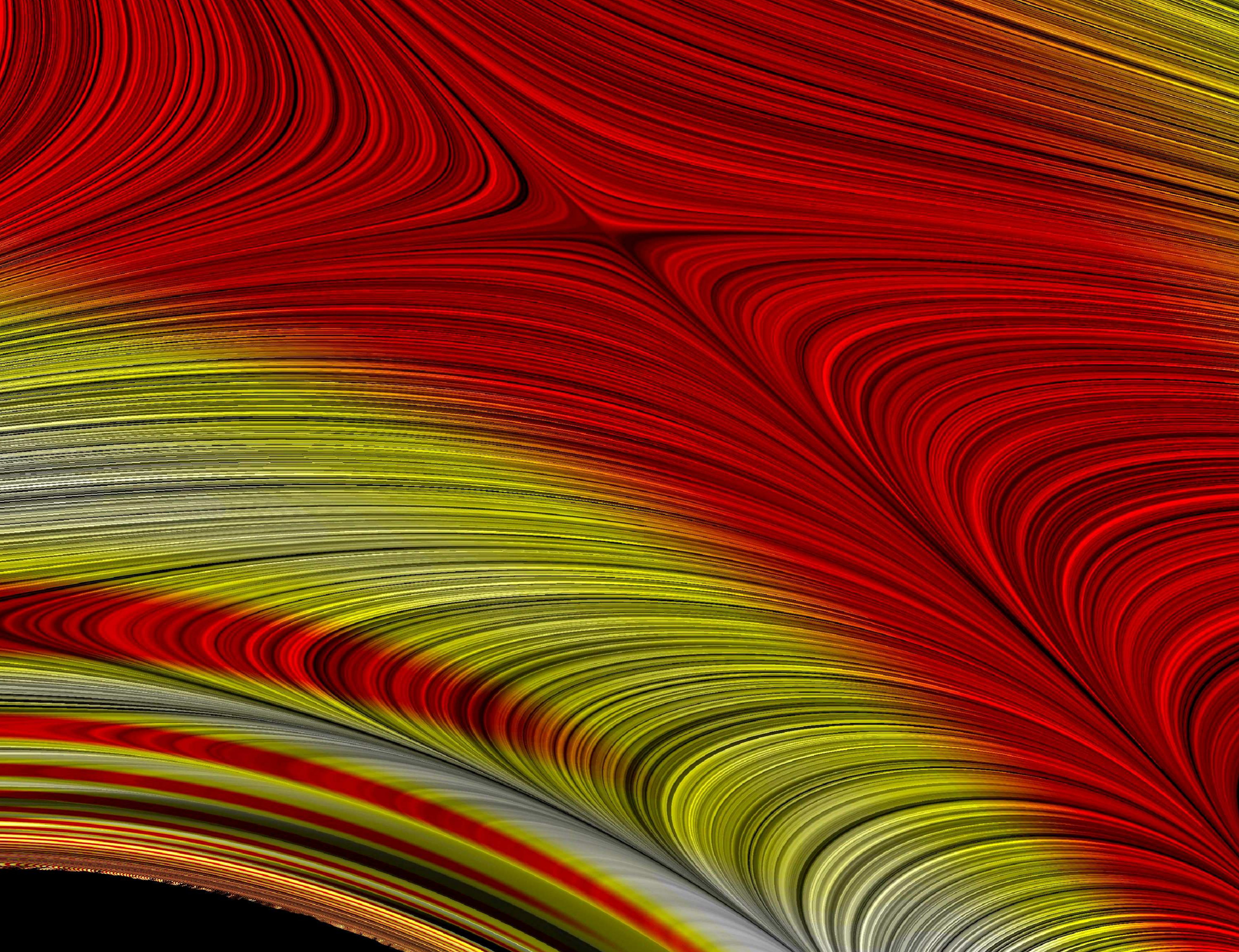
Kopáček, Tahamtan & Karas (2018)

Magnetic null points



Field lines in equatorial plane

Karas et al. (CQG, 2009, 2012)



Conclusions

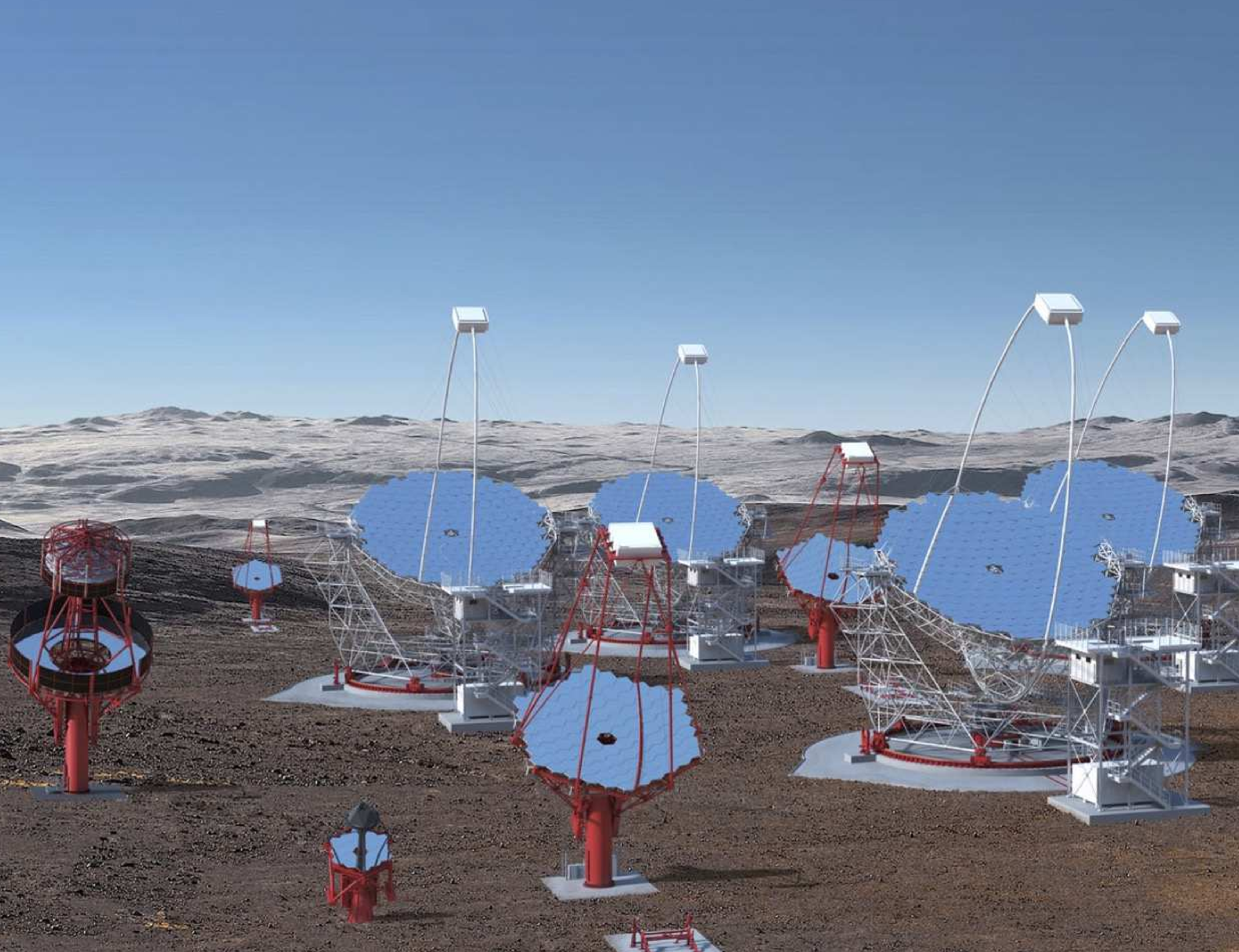
Because of the combined effect of frame dragging and boost, a rotating BH forms magnetic null points.

Charged particles can be efficiently accelerated by electric field passing through magnetic nulls.

Karas, Kopáček, & Kunneriath (2012), Classical and Quantum Gravity, 29, id. 035010

Kopáček, Tahamtan, & Karas (2018), Physical Review D, 98, id.084055

Kopáček, & Karas (2020), Astrophysical Journal, 900, id.119



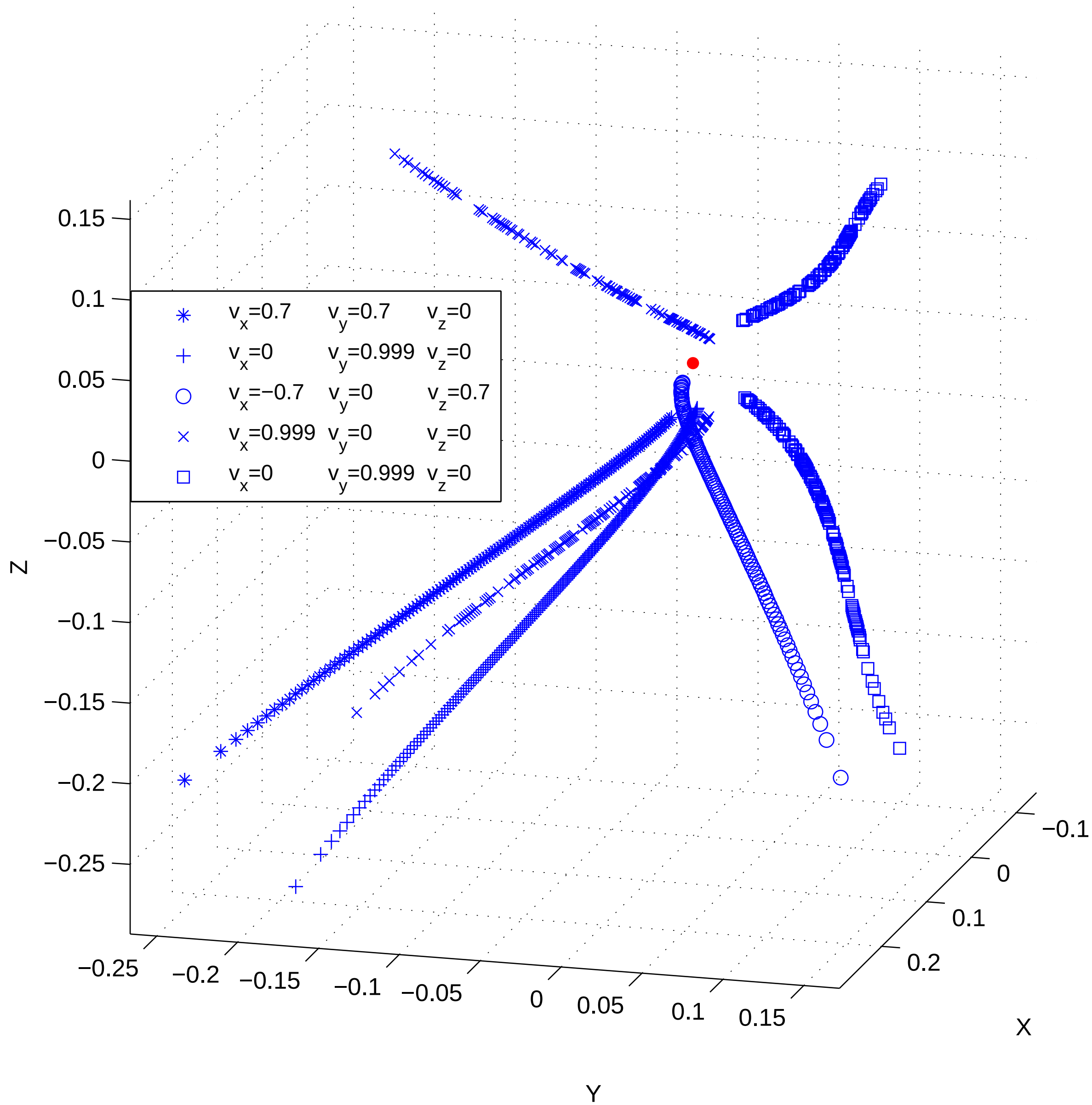
Conclusions

The Small-Sized Telescope SST-1M is a single-mirror design with a 4 m diameter reflector (focal length of 5.6 m) with hexagonal facets.

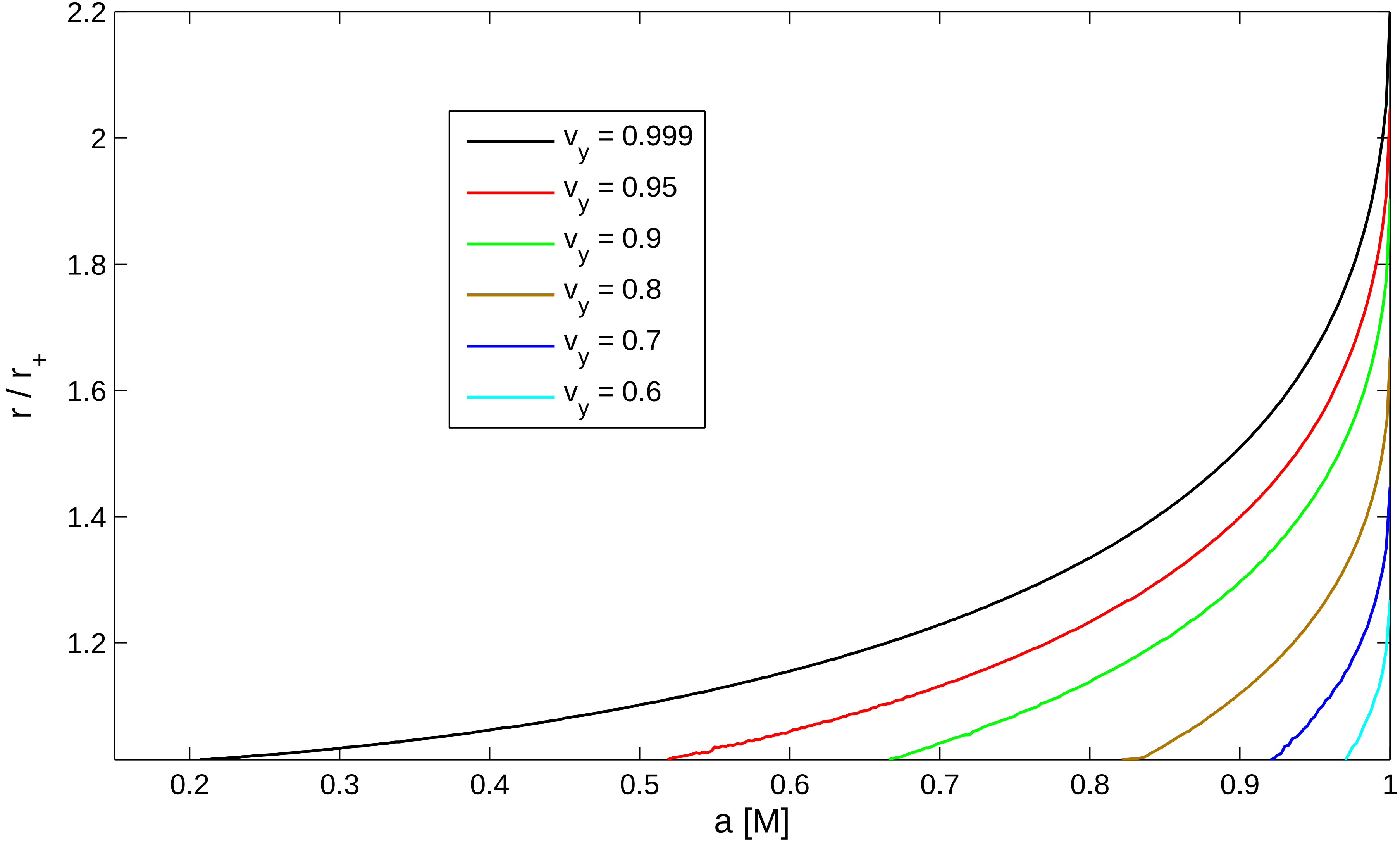
The camera uses silicon photomultipliers SiPM with $\sim 1\,300$ ultra-fast (time resolution 500 picoseconds) light-sensitive pixels to convert the light into an electrical signal that is then digitized and transmitted to record the image of the cascade shower.

The showers generated by very high-energy γ rays (between a few TeV and 300 TeV) produce Cherenkov light; it is sufficient to build small mirrors to detect the signal.

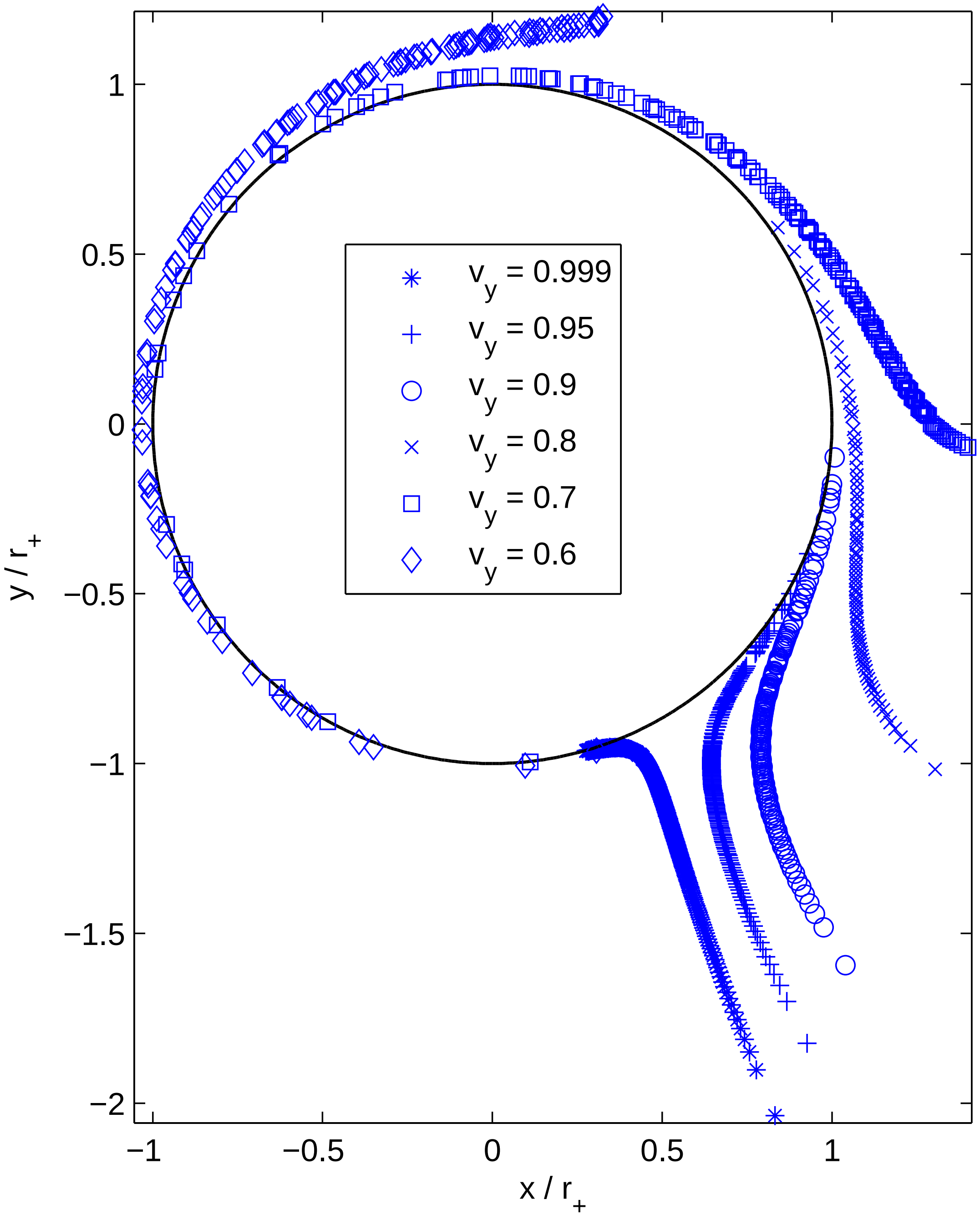
Supplementary slides – Magnetic null points



Magnetic null points – II



Magnetic null points – III



Supplementary slides – Killing vectors

in a vacuum spacetime generate a test-field solution of Maxwell equations:

$$\xi_{\mu;\nu} + \xi_{\nu;\mu} = 0$$

We *define*

$$F_{\mu\nu} = 2\xi_{\mu;\nu}.$$

Then, using the Killing equation and the definition of Riemann tensor,

$$\boxed{F^{\mu\nu}{}_{;\nu} = 0.}$$

Field invariants:

$$\boldsymbol{E}.\boldsymbol{B} = \tfrac{1}{4}\,{}^{\star}F_{\mu\nu}F^{\mu\nu}, \qquad B^2 - E^2 = \tfrac{1}{2}F_{\mu\nu}F^{\mu\nu}.$$

Two examples of non-diverging elmg. test field

1. A spherically symmetric electric field. A unique solution that is well-behaving both at $r = r_+$ and at $r \to \infty$. This term describes a weakly charged Reissner-Nordström black hole.

2. An asymptotically uniform magnetic field:

$$
\begin{aligned}
F_{\mu\nu} \quad &\rightarrow \quad B_{\|}\boldsymbol{e_z} + B_{\perp}\boldsymbol{e_x}, \\
\text{i.e.} \quad & F_{r\theta} \rightarrow -B_{\perp}\, r \sin\phi, \\
& F_{r\phi} \rightarrow B_{\|}\, r\, \sin^2\theta - B_{\perp}\, r\, \sin\theta\, \cos\theta\, \cos\phi, \\
& F_{\theta\phi} \rightarrow B_{\|}\, r^2\, \sin\theta \cos\theta + B_{\perp}\, r^2\, \sin^2\theta\, \cos\phi.
\end{aligned}
$$