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Particle Acceleration in a Black Hole Vacuum Magnetosphere with a Thin Disk

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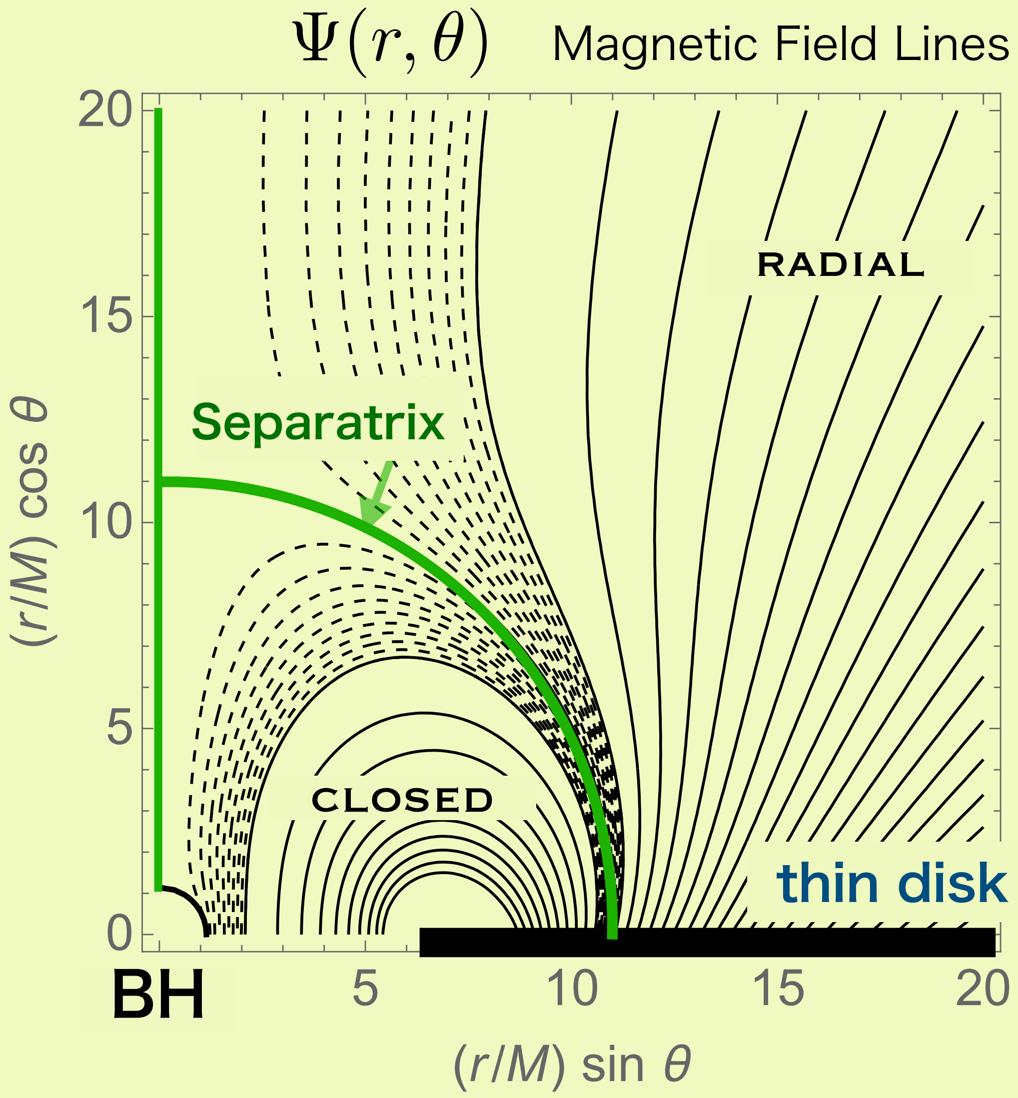

Particle Acceleration in a Black Hole Magnetosphere with a Thin Disk

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We discuss the motion of charged particles in a **vacuum** magnetosphere around a rotating black hole with a geometrically **thin disk**. The magnetic field is created by a disk's toroidal current, and the *electric field is generated by the spacetime dragging effect*. We discuss the effective potential for a charged particle, and find the *negative potential regions* above the disk surface. Hence, we show the possibility of ''***Magnetic Penrose Process***''. For a supermassive black of mass 10^9 M_sun and magnetic field strength 1 T, it is possible to explain ultrahigh-energy cosmic rays of energy > 10^20 eV.

Y. Endo, H. Ishihara, and M. Takahashi, Phys. Rev. D 111, 123025 (2025).

BH-Disk Magnetosphere

$F^{\mu\nu}{}_{;\nu} = 4\pi J^{\mu} = 0$ **Maxwell equations**

$F_{\mu\nu} = A_{\nu,\mu} - A_{\mu,\nu}$

Magnetic flux function → Poloidal **Magnetic field**

$\Psi(r,\theta) \equiv A_{\phi}(r,\theta)$

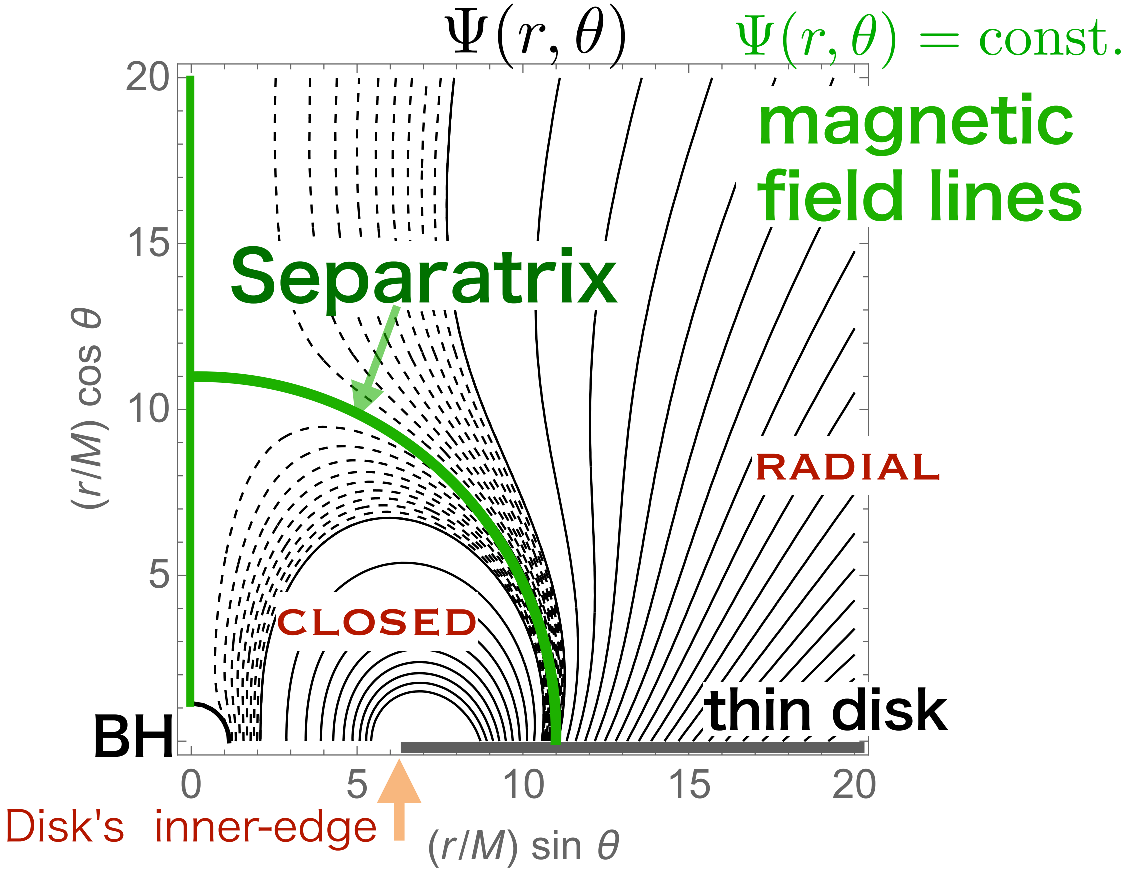
Electrostatic potential → Poloidal **Electric field**

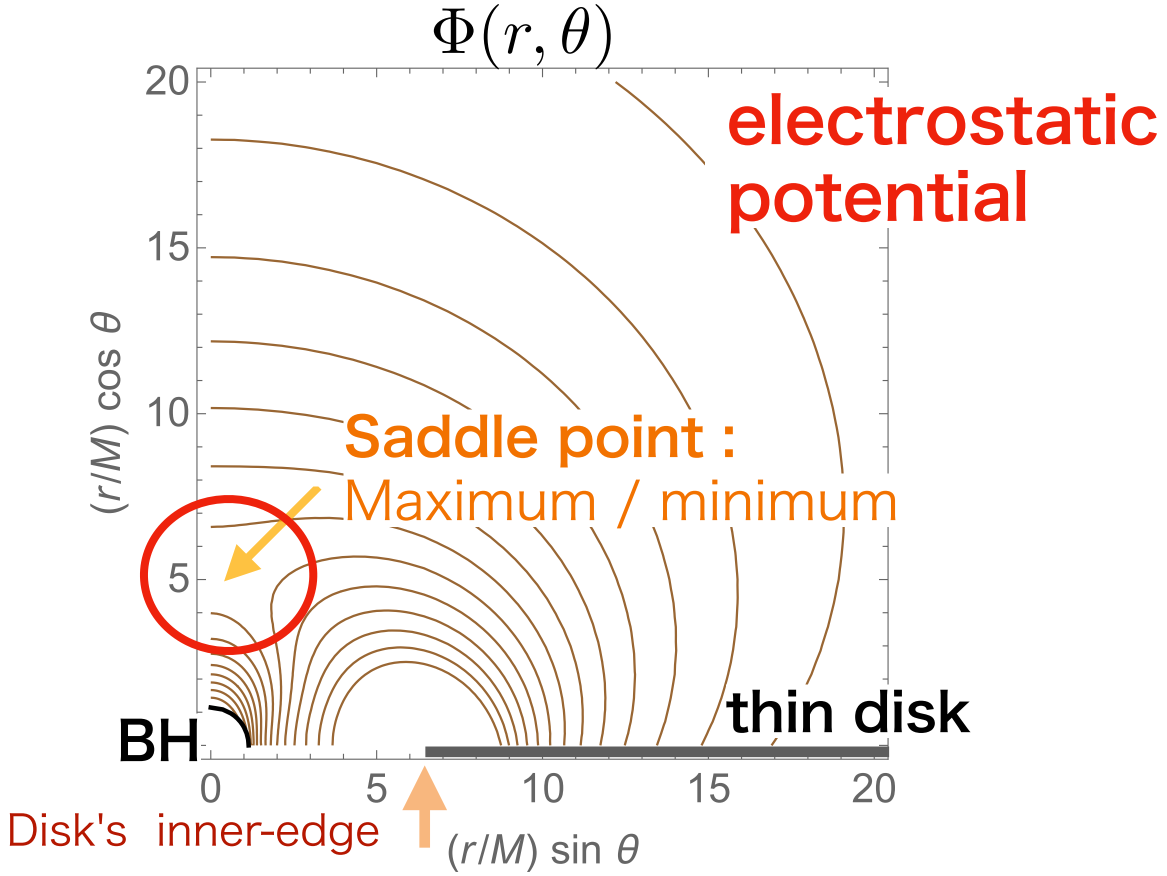
$\Phi(r,\theta) \equiv -A_{t}(r,\theta)$

★ Magnetospheric solutions with **separatrix**

★ **Electric field** is generated by **BH spin !**

★ Disk is polarized, where total charge is zero.





$a = 0.99M$

- **Separatrix** —> Inner/Outer BH Magnetosphere
- An **electric field** is generated in the magnetosphere **due to the BH spin**.
  It behaves as if **charge separation** occurs on the event horizon and thin disk.

Equation of Motion for a charged particle

e.g., *Gravitation* (1973), Takahashi & Koyama (2009)

Hamiltonian of the system

$$H(r,\theta) \equiv \frac{1}{2} g^{\mu\nu}(\pi_\mu - qA_\mu)(\pi_\nu - qA_\nu)$$

canonical momentum

four-vector potential of EM

Four-momentum of a charged particle

$$p^\mu \equiv \frac{dx^\mu}{d\lambda} = g^{\mu\nu}(\pi_\nu - qA_\nu)$$

$$\lambda = \tau/m$$

Hamilton's equation (eq. of motion)

$$\frac{dx^\mu}{d\lambda} = \frac{\partial H}{\partial \pi_\mu}, \qquad \frac{d\pi_\mu}{d\lambda} = -\frac{\partial H}{\partial x^\mu}$$

↔ The covariant equation of motion

$$\frac{\mathrm{D}p_\mu}{\mathrm{D}\tau} = qF_{\mu\nu}u^\nu,$$

Lorentz force

Constants of motion

Energy of a charged particle

$$-E \equiv \pi_t = p_t + qA_t$$

electrostatic potential

Angular momentum

$$L \equiv \pi_\phi = p_\phi + qA_\phi$$

magnetic flux function

particle's rest mass

$$m^2 = g^{\mu\nu} p_\mu p_\nu$$

at the disk's inner edge

Physical parameters :

$$a, \quad \tilde{L}, \quad \hat{q}\Psi_{\mathrm{D}}, \quad \tilde{q}Q^*$$

where $\tilde{L} \equiv L/m, \quad \tilde{q} \equiv q/m, \quad Q^* \equiv Q/M$

$$|\hat{q}\Psi_{\mathrm{D}}|/M \approx 10^8 (M/M_\odot)(B_{\mathrm{D}}/1T)$$

Effective Potential *for a charged particle*

$$\tilde{V}_{\mathrm{eff}}(r,\theta) \equiv \tilde{E}_{\mathrm{min}} = \overset{\text{1st term}}{\tilde{q}\Phi} + \overset{\text{2nd term}}{\frac{g^{t\phi}}{g^{tt}}\left(\tilde{L}-\tilde{q}\Psi\right)} - \frac{1}{g^{tt}}\left[\frac{1}{\Delta\sin^2\theta}\left(\tilde{L}-\tilde{q}\Psi\right)^2 - g^{tt}\right]^{1/2}$$

Minimum near the separatist surface

only Kerr case

electrostatic potential

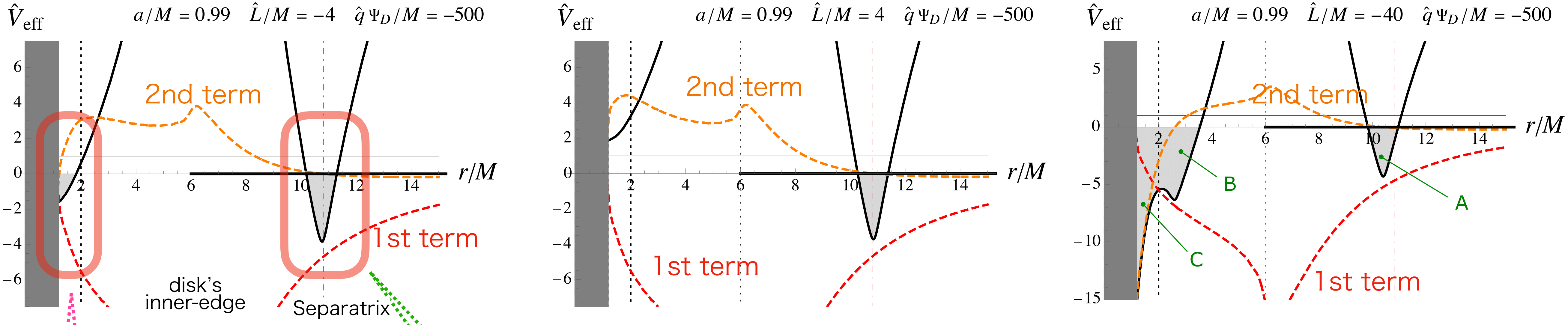
$\propto \omega(r,\theta)$ spacetime dragging

★ Evaluate the contribution of each term at the equatorial plane:

Negative angular momentum
Negative charge

Positive angular momentum
Negative charge

Larger angular momentum
Negative charge



due to spacetime **dragging**

The 2nd term is only prominent in the **ergosphere**

due to **electrostatic potential**

The third term is minimal.
→ The first term dominates.
→ Negative potential

[C]
Restrictions on
relative velocity
at fragmentation

$$|\boldsymbol{v}| > v_* \sim \frac{1}{2}c$$

[A][B]
No restrictions

$$|\boldsymbol{v}| < v_* \sim \frac{1}{2}c$$

Electrostatic energy extraction

Magnetic Penrose Process (MPP)

Depends on magnetic field strength and angular momentum

★ A **neutral particle** near the disk surface splits into positive and negative charged particles.

★**Particle 1**: Negative energy orbital **bound** by negative electrostatic potential.

Particle 2: Can **escape** from the magnetosphere on an amplified energy orbit.

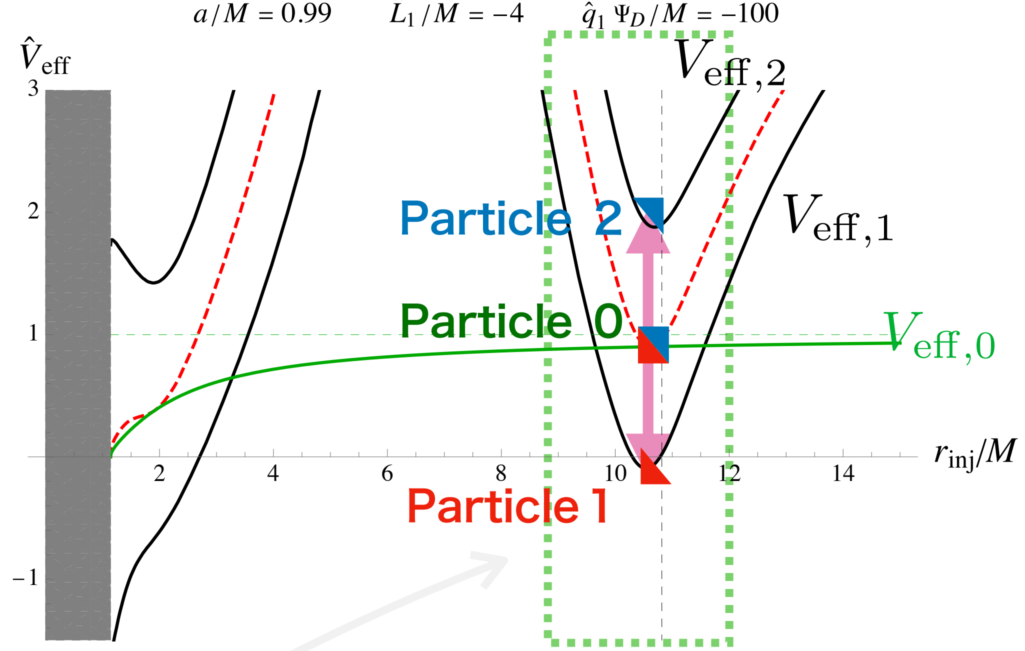
→ Origin of cosmic rays ?

= **Electrostatic energy extraction** from the BH magnetosphere.

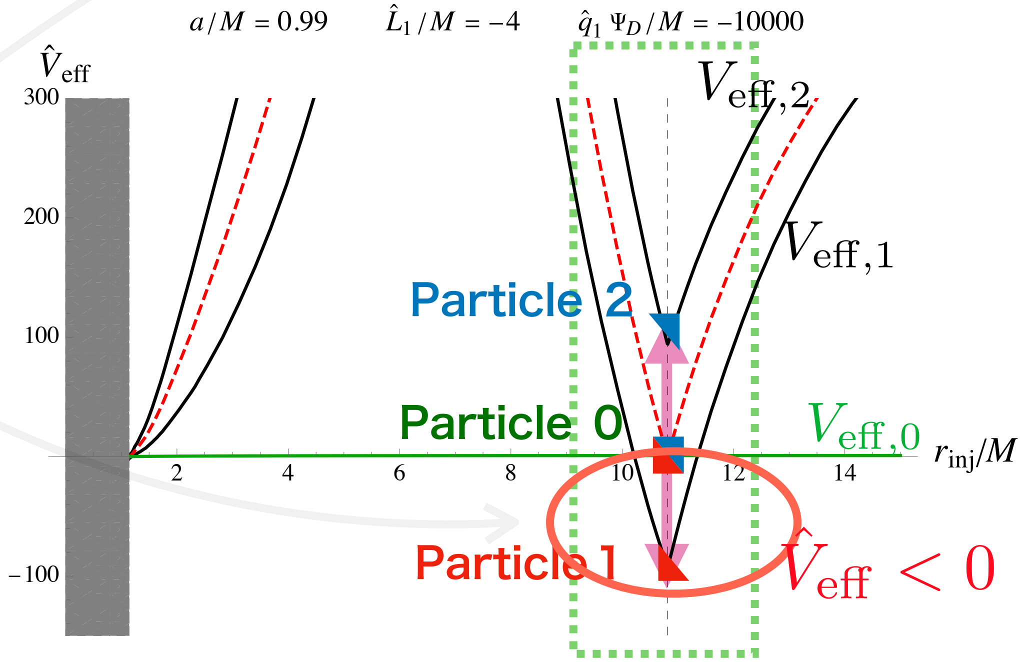
★ In the BH-Disk magnetosphere, negative orbits are possible near the separatrix (above the disk).

The electric field cannot occur unless the BH is rotating.
The energy extraction mechanism unique to the rotating BH magnetosphere.

Weak mag. Field



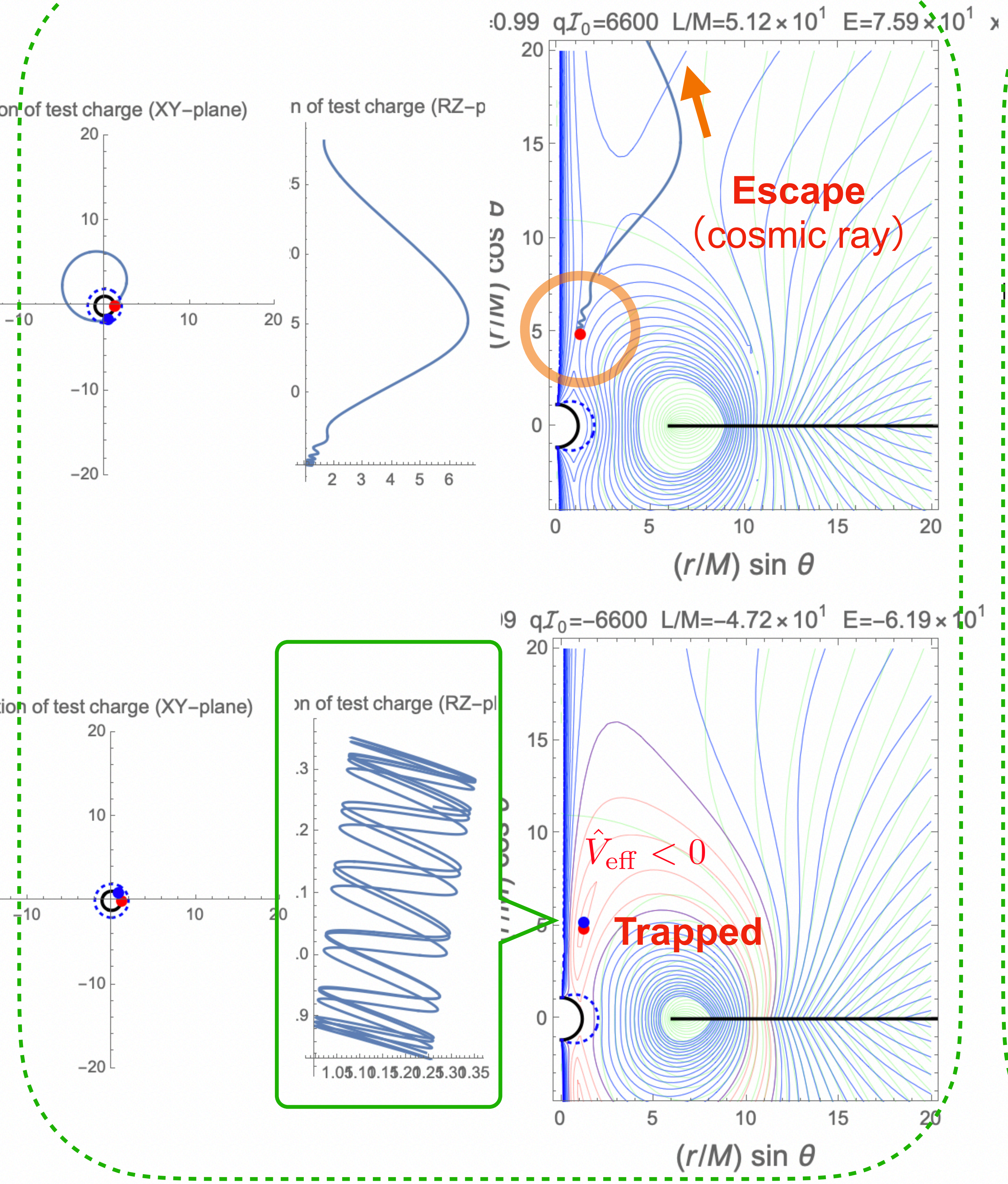
Strong mag. field



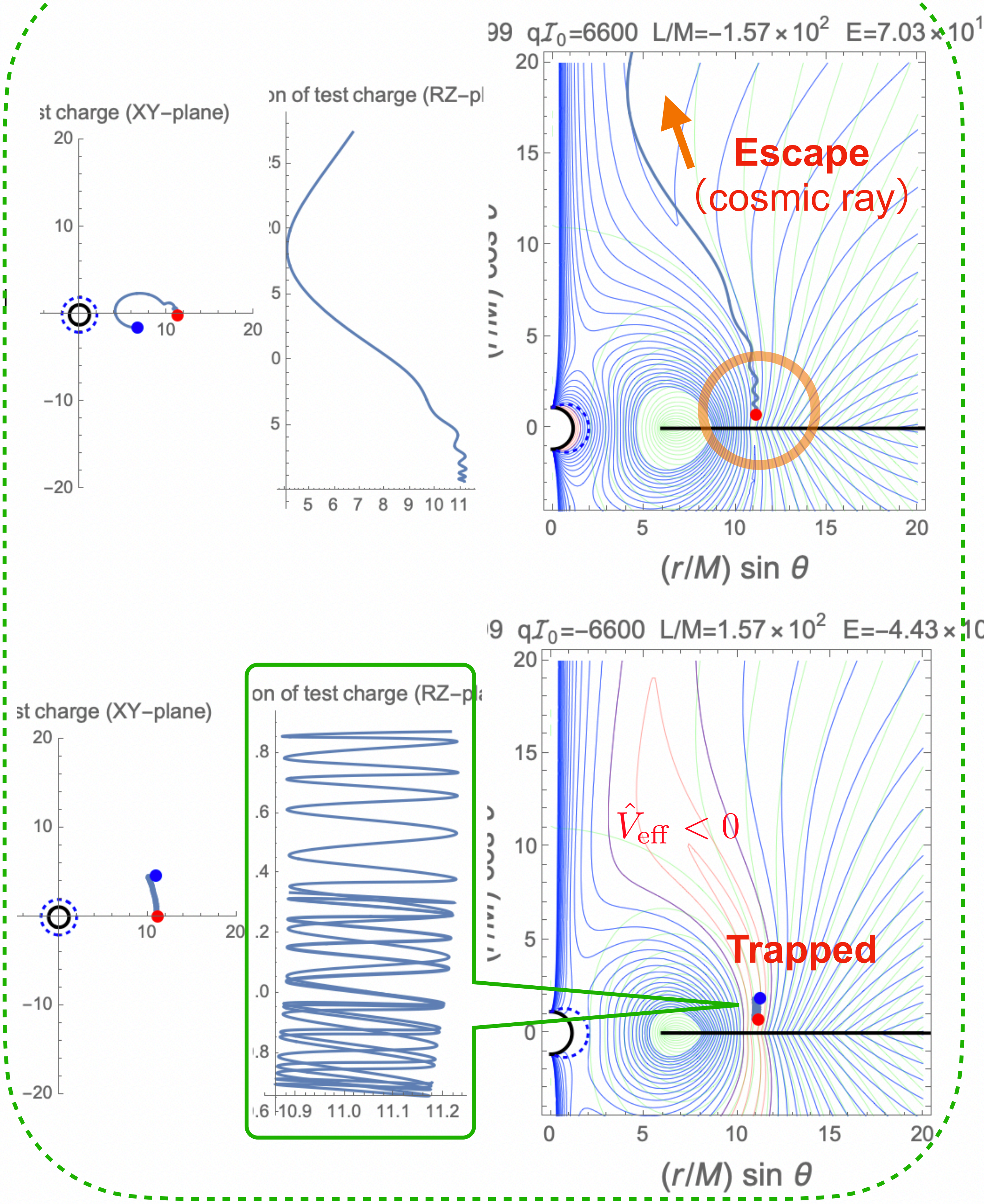
A large amount of energy can be extracted from this narrow area.

MPP positron e^+ vs. electron e^-

Near the rotation axis



Near the disk surface



Summary

High-energy phenomena in the black hole magnetosphere

★ We investigate the orbits of charged particles and effective potential for a BH magnetosphere solution with a thin disk.

★ **Negative potential region** originating from the electrostatic potential exists. The electrostatic potential is generated by the spacetime dragging effect of the BH.

★ We consider the **Magnetic Penrose process** in the negative potential region.

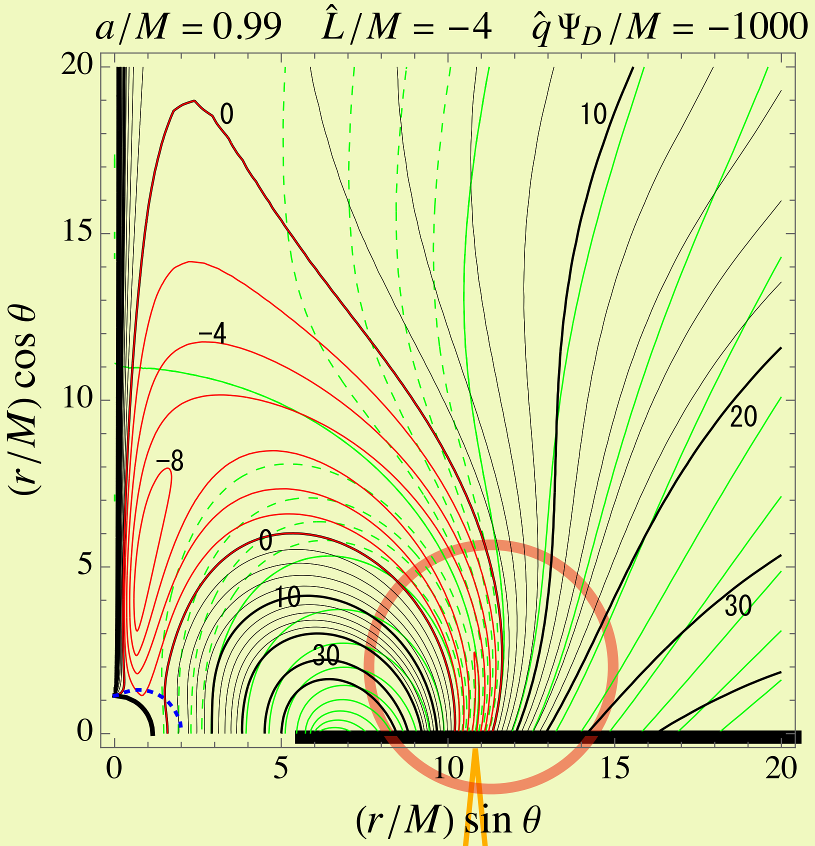
Expected as the origin of Ultrahigh-energy cosmic rays ($E > 10^{18}\,\mathrm{eV}$) !?

e.g.) $a \sim M \qquad M_{\rm BH} = 10^9 M_\odot \qquad B_0 = 10^4 \mathrm{Gauss}$

$$(\hat{V}_{\rm eff})_{\rm min} \approx \hat{q}\Phi(R_{\rm sp}, \pi/2) = -0.9 \times 10^{15} \left(\frac{m_{\rm e}}{m}\right)\left(\frac{a}{M}\right)\left(\frac{B_{\rm Disk}}{1\mathrm{T}}\right)\left(\frac{M}{10^9 M_\odot}\right) \mathrm{eV}$$

$$(V_{\rm eff})_{\rm min} \approx -0.9 \times 10^{15}\, mc^2 = \underline{-4.6 \times 10^{20}\,\mathrm{eV}}$$

This can explain UHECRs



Plasma is supplied from the disk surface.