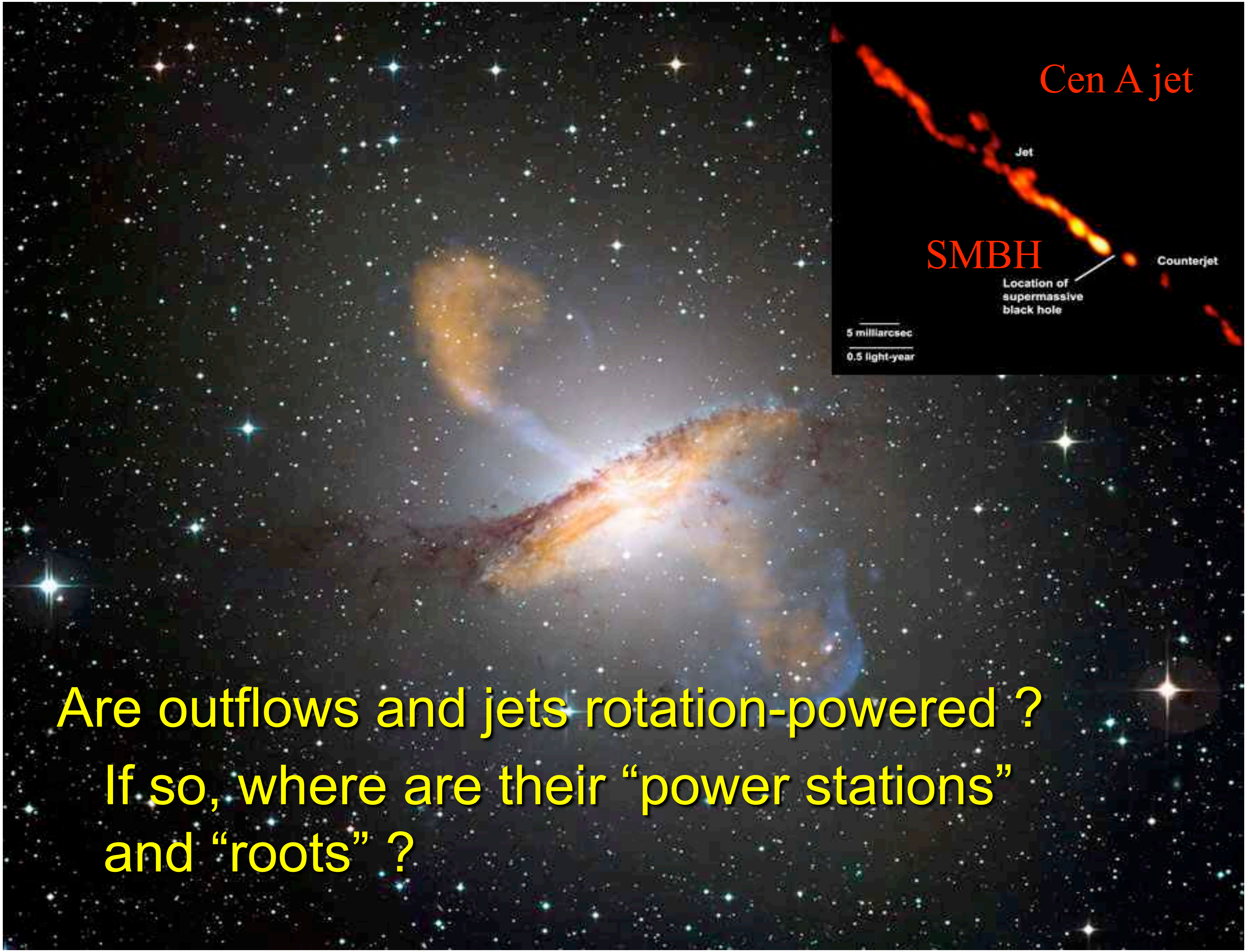
Cen A jet
Jet
SMBH
Counterjet
Location of supermassive black hole
5 milliarcsec
0.5 light-year
Are outflows and jets rotation-powered ?
If so, where are their "power stations"
and "roots" ?

“28th Texas Symposium on Relativistic Astrophysics”
(Geneva, Switzerland, 2015, December 13 – 18)

Frame dragging, Unipolar induction and Jets in Kerr black hole magnetospheres

Toward Constructing “Power Station” for Outflows and Jets

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- 4.3 Interface S_N between two domains
- 5. Double Circuits with Magnetized Gap
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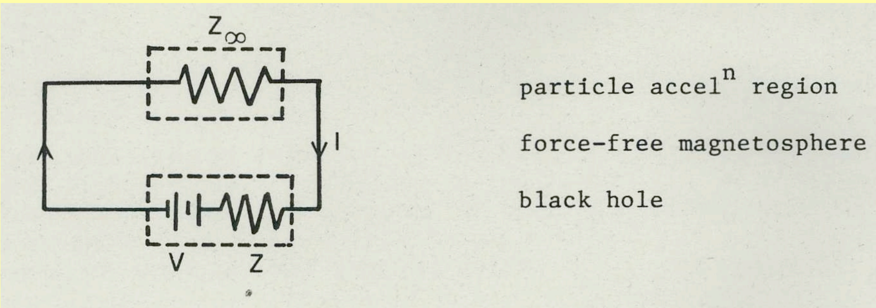
Acknowledgement
References

1. Introduction
1.1 Scenario in the 1980s

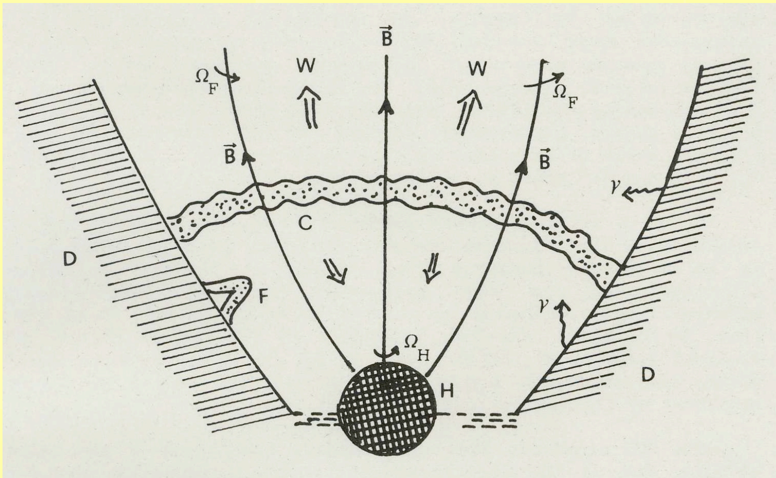
- Extraction of hole's spin energy: Blandford-Znajek process (1977), Phinney's jet model (1982), Macdonald & Thorne' s "3+1" formalism (82), Thorne et al.'s "The Membrane Paradigm" (86). Invited a criticism of causality violation.
- Existence of a battery in the horizon of a magnetized Kerr hole.
- By no-hair theorem, we can draw out no information from under the Kerr hole's horizon, except mass M and angular momentum J.

The image in the 1980s

Single circuit



Double structure



Phinney (1982): "Black hole-driven hydrodynamic flows"
In "Astrophysical Jets", eds. A. Ferrari & A.G. Pacholszyk,

1.2 Unipolar Induction battery for pulsars

Landau & Lifshitz "Course of Theoretical Physics", Vol. 8
"Electrodynamics of Continuous Media", p. 220-1

static magnetic field **B** due to a fixed magnet. We neglect the distortion of the field by the wire itself. According to formula (63.3), the e.m.f. between the ends of the wire is

$$\mathscr{E} = \frac{1}{c}\int_{ACB} \mathbf{v}\times\mathbf{B}\cdot d\mathbf{l} = \frac{1}{c}\int_{ACB} \mathbf{B}\times(\mathbf{r}\times\mathbf{\Omega})\cdot d\mathbf{l}, \qquad (63.9)$$

taken along the wire. This is the required solution.

A perfectly conducting sphere, rotating with Ω about the direction of magnetization M

EMF = $B_0\Omega a^3/2c = \Omega M/ca$

M = $B_0 a^3/2$

= total magnetic moment

$$\mathcal{E} = -\frac{1}{2\pi c}\int_{\Psi_1}^{\Psi_2} \Omega_F \, d\Psi$$

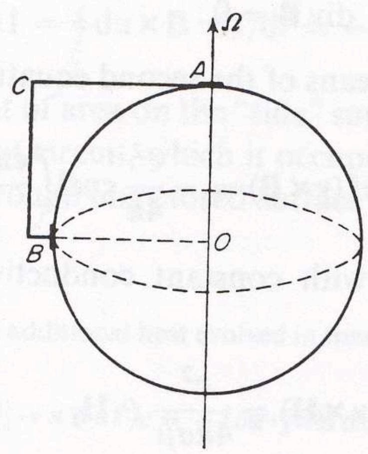


FIG. 39

OACBO=0

ACB=AOB

=OB,

OA=0

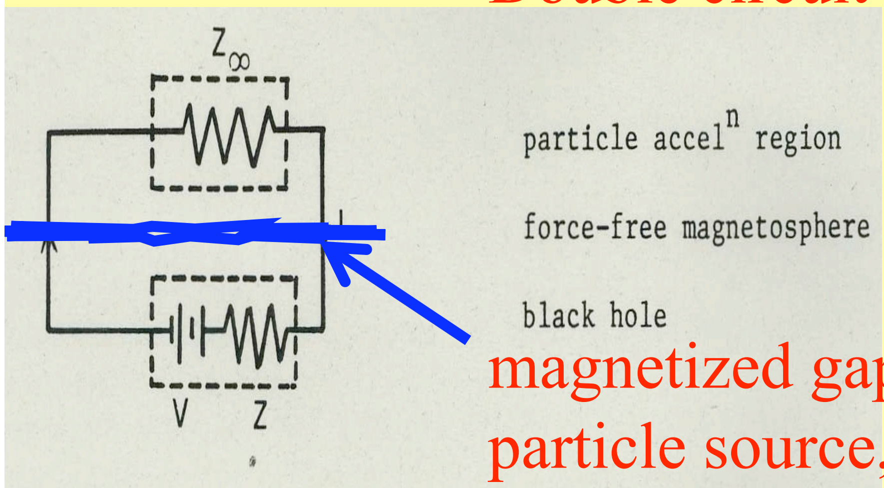
between two field lines ψ_1 and ψ_2 pinned down at the neutron star

It is Ω_F that relates unipolar induction to EMF.

1.3 Purpose

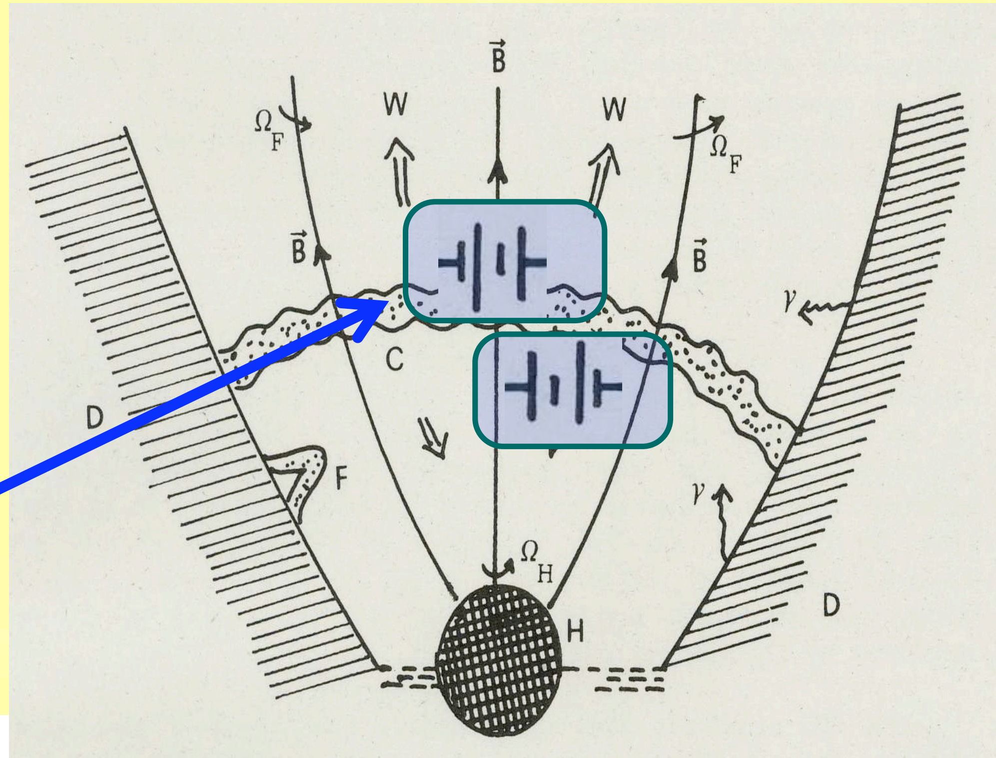
- Purpose: By coupling frame dragging effect with unipolar induction in flat space, construct a strong power station consisting of not only a pair of batteries for driving currents but strong voltage drop in-between for particle creation in a non-acausal location.
- Revive the BZ process, Phinney's jet model, and the Membrane Paradigm.

Double circuit



magnetized gap
particle source,
two batteries

Double Structure



2.1 Black Hole Electrodynamics

- We use "3+1" formalism in Boyer-Lindquist coordinates. GR effects are condensed in

  α: lapse function and $0 \leq \alpha \leq 1$

  ω: frame-dragging angular velocity. $\Omega_{\rm H} \geq \omega \geq 0$
- FIDucial Observer FIDOs, resident in absolute space circulating with ω.
- FIDO-measured FLAV: $\Omega_{\rm F\omega} = \Omega_{\rm F} - \omega$

  Key quantity embodying the coupling of frame dragging with unipolar induction.
- Assume presence of copious particles threaded by large-scale magnetic field lines with the angular velocity Ω_F constant from S_H to S_∞.

- The freezing-in, force-free conditions

$$\boldsymbol{E} = -(\boldsymbol{v}/c) \times \boldsymbol{B}, \qquad \varrho_{\rm e}\boldsymbol{E} + (\boldsymbol{j}/c) \times \boldsymbol{B} = 0$$

- where

$$\boldsymbol{E} \cdot \boldsymbol{B} = \boldsymbol{j} \cdot \boldsymbol{E} = 0, \qquad \boldsymbol{j}_{\rm p} = \varrho_{\rm e}\boldsymbol{v}_{\rm p} = -\frac{1}{\alpha}\frac{dI}{d\Psi}\boldsymbol{B}_{\rm p}$$

$$\boldsymbol{B}_{\rm p} = -\frac{1}{2\pi\varpi}(\boldsymbol{t} \times \nabla\Psi), \qquad B_{\rm t} = -\frac{2I}{\varpi\alpha c},$$

where Ψ = constant ⇒ "field-streamline"

I = constant ⇒ "current line"

$$\boldsymbol{E}_{\rm p} = -\frac{\Omega_{\rm F\omega}}{2\pi\alpha c}\nabla\Psi, \quad \boldsymbol{S}_{\rm EM} = \frac{\alpha c}{4\pi}(\boldsymbol{E} \times \boldsymbol{B}) = \frac{\Omega_{\rm F\omega}I(\Psi)}{2\pi\alpha c}\boldsymbol{B}_{\rm p}$$

- No MHD-acceleration. Current-field-streamlines are equipotentials in the force-free domains.
- Charge-separated plasma. $\varrho_{\rm e} = -en^{(\ \ )}$ or $= +en^{(+)}$

3.1 Eigenvalue Problem due to Criticality-Boundary Conditions

- Two integral functions of Ψ
  $\Omega_F(\psi)$: field line angular velocity/potential gradient
  $I(\psi)$: current function/field angular momentum flux
- $S_{ff\infty}$ and S_{ffH}: two membranes terminating "force-free" domains. The "criticality condition" from wind theory fixes $I_{out}(\psi)$ and $I_{in}(\psi)$ for outflow, inflow.
- S_N: the interface between the two, outer and inner force-free domains. The "boundary condition" for continuity of angular momentum flux to be continuous across S_N, i.e. $I_{out}(\psi)=I_{in}(\psi)$, fixes $\Omega_F(\Psi)$.

3.2 Eigenvalues $I_{out}(\Psi)$, $I_{in}(\Psi)$ and $\Omega_F(\Psi)$

Criticality condition for ingoing/outgoing winds

$$I(\Psi) = \begin{cases} \frac{1}{2}(\Omega_{\rm H} - \Omega_{\rm F})(B_{\rm p}\varpi^2)_{\rm ffH} \equiv I_{\rm in}, & \text{at } {\rm S_{iF}} \approx {\rm S_{ffH}}, \quad \omega \approx \Omega_{\rm H}, \\ \frac{1}{2}\Omega_{\rm F}(B_{\rm p}\varpi^2)_{\rm ff\infty} \equiv I_{\rm out}, & \text{at } {\rm S_{oF}} \approx {\rm S_{ff\infty}}, \quad \omega \approx 0. \end{cases}$$

Equivalent to Ohm's law on resistive membranes S_{ffH} and $S_{ff\infty}$

Boundary condition $I_{\rm in} = I_{\rm out}$ at $\mathbf{S}_{\rm N}$, $\omega = \Omega_{\rm F}$

$$\Omega_{\rm F} = \frac{\Omega_{\rm H}}{1+\zeta}, \quad \zeta \equiv \frac{(B_{\rm p}\varpi^2)_{\rm ff\infty}}{(B_{\rm p}\varpi^2)_{\rm ffH}}.$$

"Continuity of angular momentum flux at S_N"

No source of angular momentum and rotational energy at S_N

3.3 FIDO-measured field line angular velocity and gravito-electric potential

$$A^{(4)} = (A_{0\omega}, 0, 0, A_\phi) :$$ Kerr space 4-potential

$$A_{0\omega} = A_0 + V :$$ Kerr space scalar potential

$$A_0 :$$ Flat-space scalar potential

$$V :$$ Gravito-electric potential

$$A_\phi = \Psi/2\pi :$$ Magnetic potential

$$\Omega_{\mathrm{F}} = -2\pi c(dA_0/d\Psi) :$$

$$\omega = 2\pi c(dV/d\Psi)_\ell :$$

$$\Omega_{\mathrm{F}\omega} = -2\pi c(dA_{0\omega}/d\Psi)_\ell = \Omega_{\mathrm{F}} - \omega :$$

4.1 Angular Momentum and Energy Fluxes

- S_J : Angular momentum flux, extracted from the hole by the surface torque.
- S_{SD} : Spin-down energy flux form the hole due to the frame dragging effect, related to S_J.
- S_{EM} : Poynting ElectroMagnetic energy flux
- S_E : Total energy flux

$$\boldsymbol{S}_{\rm J} = \frac{I(\Psi)}{2\pi\alpha c}\boldsymbol{B}_{\rm p}, \;\; \boldsymbol{S}_{\rm SD} = \omega \boldsymbol{S}_{\rm J}, \;\; \boldsymbol{S}_{\rm EM} = \Omega_{\rm F\omega}\boldsymbol{S}_{\rm J},$$

$$\boldsymbol{S}_{\rm E} = \boldsymbol{S}_{\rm SD} + \boldsymbol{S}_{\rm EM} = \Omega_{\rm F}\boldsymbol{S}_{\rm J}$$

$$\Leftrightarrow \;\; \omega + (\Omega_{\rm F} - \omega) = \Omega_{\rm F}$$

4.2 Frame-dragging spin-down energy fluxes S_{SD}

Angular momentum loss of the hole by the surface torque to S_{ffH}

$$\frac{dJ}{dt} = -\oint (\alpha \boldsymbol{\mathcal{I}}_{\mathbf{ffH}}/c \times \boldsymbol{B}_{\mathbf{p}}) \cdot \varpi \boldsymbol{t}) dA$$

surface current

$$= -\frac{1}{2\pi c}\oint I(\Psi) d\Psi = -\oint \alpha \boldsymbol{S}_{\mathbf{J}} \cdot d\boldsymbol{A}$$

Angular momentum flux $\boldsymbol{S}_{\mathbf{J}} = \dfrac{I(\Psi)}{2\pi\alpha c}\boldsymbol{B}_{\mathbf{p}}$

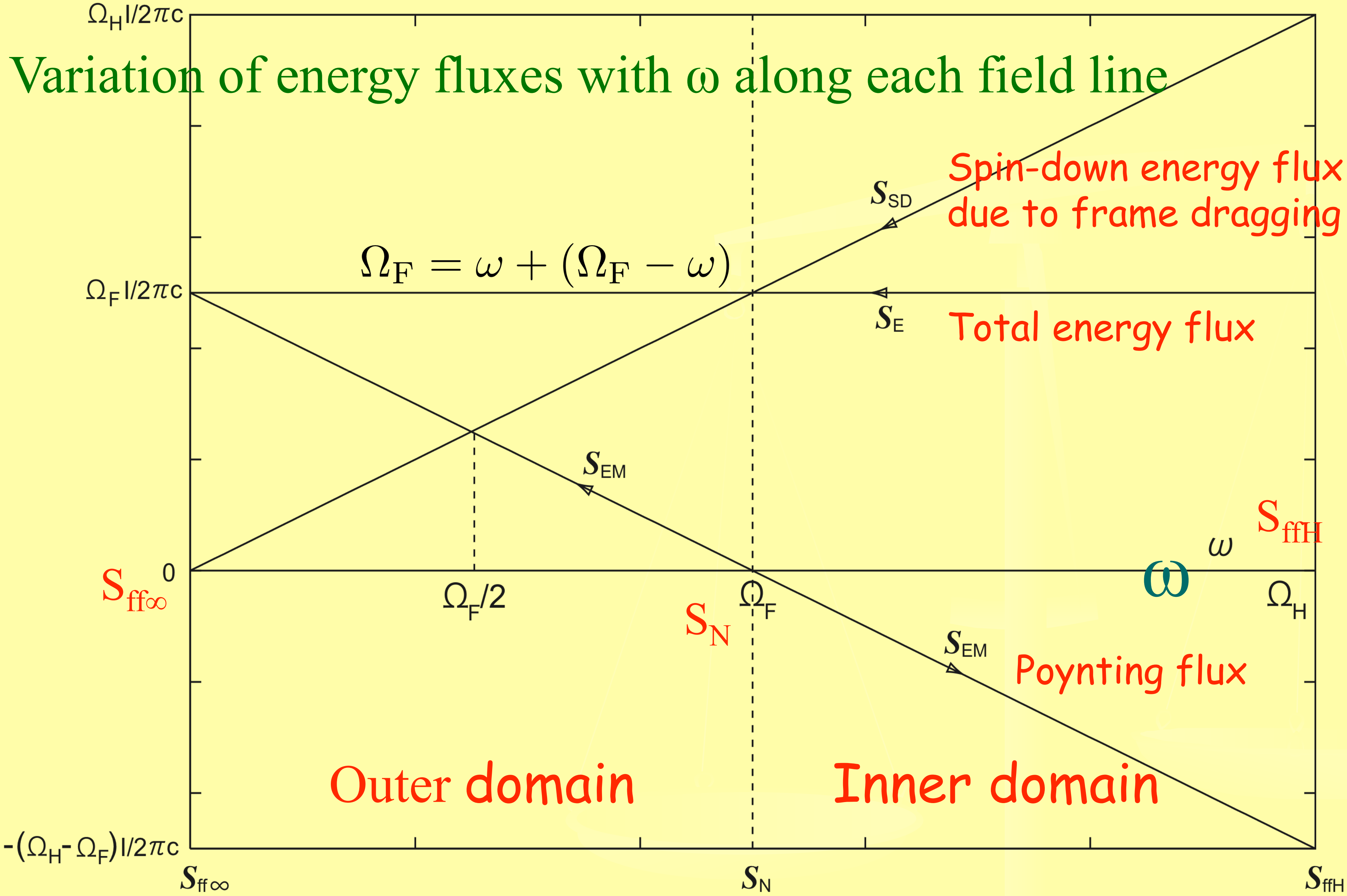
Spin-down energy flux due to the frame dragging effect

$$\boldsymbol{S}_{\mathbf{SD}} = \omega \boldsymbol{S}_{\mathbf{J}} = \frac{\omega I}{2\pi\alpha c}\boldsymbol{B}_{\mathbf{p}}$$

Loss of the hole's rotational energy

$$\oint \alpha \boldsymbol{S}_{\mathbf{SD}} \cdot d\boldsymbol{A}\Big|_{\mathrm{ffH}} = \frac{\Omega_{\mathrm{H}}}{2\pi c}\oint I(\Psi) d\Psi = -\Omega_{\mathrm{H}}\frac{dJ}{dt}$$

4.3 Three modes of energy fluxes



4.4 Interface S_N between two domains

- Outer domain : outgoing pulsar-type wind, $\Omega_{F\omega} > 0$

$$\boldsymbol{E}_{\rm p} < 0, \quad \boldsymbol{v}_{\rm p} = \boldsymbol{j}_{\rm p}/\varrho_{\rm e} > 0$$

- Inner domain : ingoing anti-pulsar-type wind with $\Omega_{F\omega} < 0$, i.e. turned-outside-in toward the hole

$$\boldsymbol{E}_{\rm p} > 0, \quad \boldsymbol{v}_{\rm p} = \boldsymbol{j}_{\rm p}/\varrho_{\rm e} < 0$$

- At S_N : $\omega = \Omega_F$ $\quad \boldsymbol{E}_{\rm p} \lesseqgtr 0, \quad \text{for } \omega \lesseqgtr \Omega_{\rm F}$

$$\varrho_{\rm e} \to 0, \quad \boldsymbol{v}_{\rm p} = \boldsymbol{j}_{\rm p}/\varrho_{\rm e} \to \pm\infty \quad \text{for } \omega \to \Omega_{\rm F}$$

- Inevitable breakdown of force-freeness
- Stationary particles / currents sources needed in-between
- We show existence of a pair of unipolar induction batteries and voltage drop ΔV

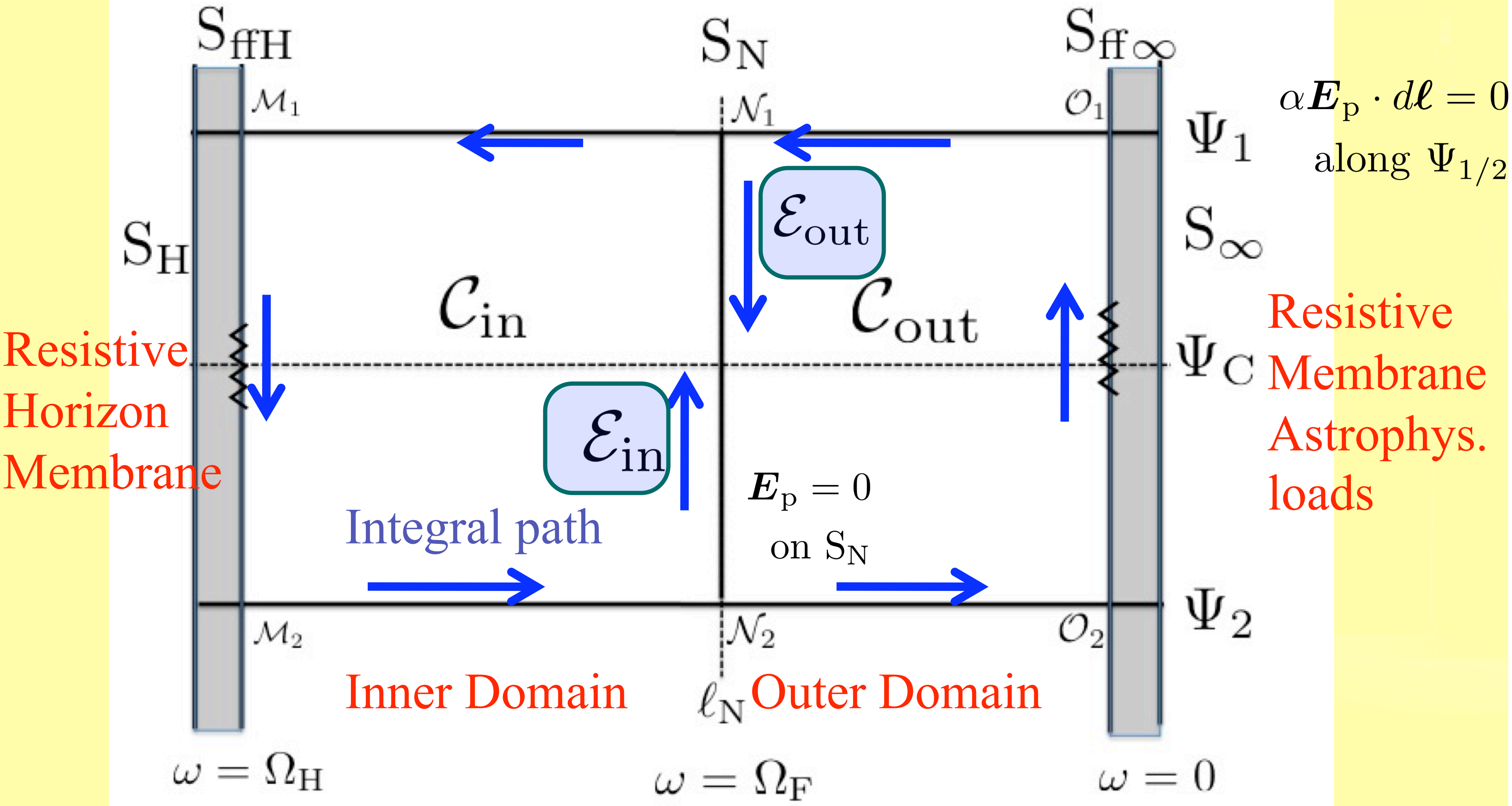
$$\Delta V = \mathcal{E}_{\rm out} - \mathcal{E}_{\rm in} = -\frac{\Omega_{\rm H}}{2\pi c}\Delta\Psi$$

5.1 Double Circuits with Magnetized Gap in-between

- DC double circuit
- = EMF
- + volume-current lines in Force-Free domains
- + Impedances on the Resistive Membranes, $S_{ff\infty}$ and S_{ffH}, dissipating Surface-Currents
- + Surface Lorenz torque extracting the hole's AM and rotational energy through S_{ffH} and transferring them to particles on $S_{ff\infty}$.
- One can describe the wind domains by superposition of infinite number of nested circuits.

5.2 Faraday integral along circuits

$$\mathcal{E}_{\mathcal{C}} = \oint_{\mathcal{C}} \alpha \boldsymbol{E}_{\rm p} \cdot d\boldsymbol{\ell} = -\oint_{\mathcal{C}} \Omega_{\rm F\omega} \boldsymbol{\nabla}\Psi \cdot d\boldsymbol{\ell} \longleftarrow \boldsymbol{E}_{\rm p} = -\frac{\Omega_{\rm F\omega}}{2\pi\alpha c}\nabla\Psi$$



5.3 EMF's for a pair of circuits, and Voltage Drop hidden under S_N

$$\mathcal{E}_{\rm out} = -\frac{1}{2\pi c}\int_{\Psi_1}^{\Psi_2} \Omega_{\rm F}(\Psi) d\Psi,$$

$$\mathcal{E}_{\rm in} = +\frac{1}{2\pi c}\int_{\Psi_1}^{\Psi_2} [\Omega_{\rm H} - \Omega_{\rm F}(\Psi)] d\Psi,$$

$$\mathcal{E}_{\rm out} - \mathcal{E}_{\rm in} = \Delta V = -\frac{\Omega_{\rm H}}{2\pi c}\Delta\Psi$$

equivalent

Note that

$$\Delta\Omega_{\rm F\omega} \equiv (\Omega_{\rm F\omega})_\infty - (\Omega_{\rm F\omega})_{\rm H}$$
$$= \Omega_{\rm F} - [-(\Omega_{\rm H} - \Omega_{\rm F})]$$
$$= \Omega_{\rm H}$$

6.1 Twin Pulsar Model

The results for EMF's are the same for $\Omega_{F\omega}$ and $\overline{\Omega_{F\omega}}$

$$\mathcal{E}_{\rm out/in} = \oint_{\mathcal{C}_{\rm out/in}} \Omega_{F\omega} \boldsymbol{\nabla}\Psi \cdot d\boldsymbol{\ell}$$

in the curved space

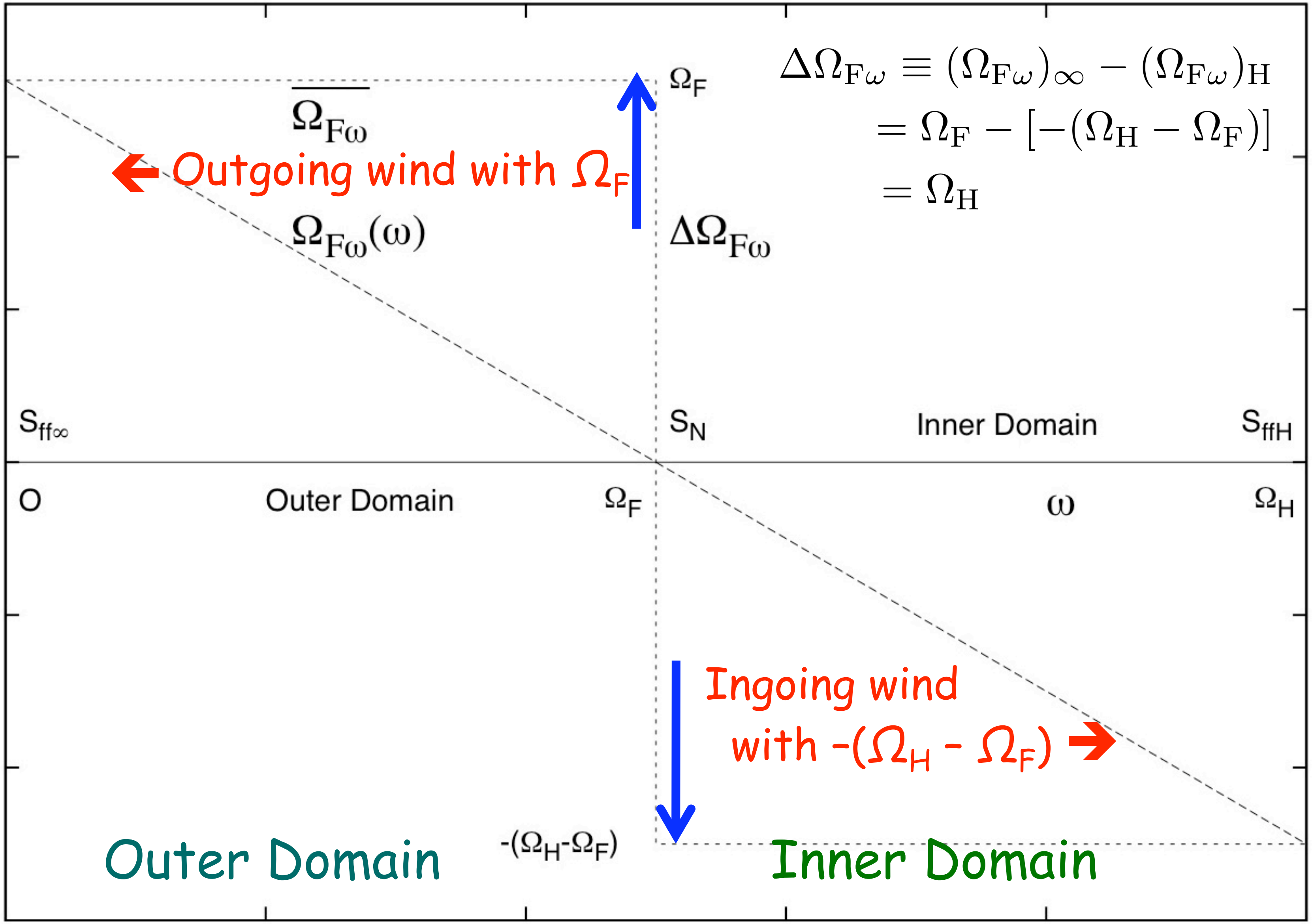
$$= \oint_{\mathcal{C}_{\rm out/in}} \overline{\Omega_{F\omega}} \boldsymbol{\nabla}\Psi \cdot d\boldsymbol{\ell}$$

in the pseudo-flat space

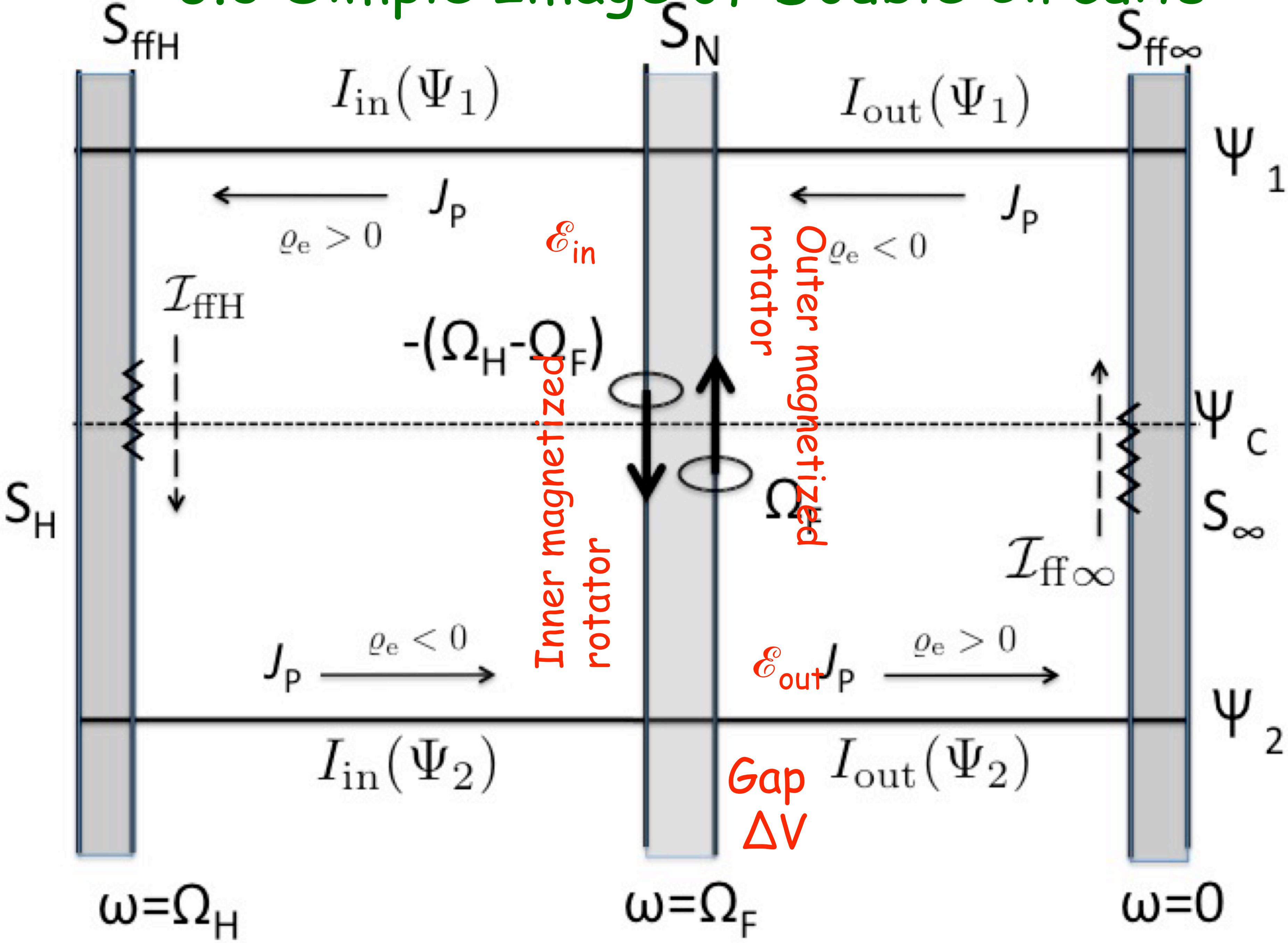
$$\overline{\Omega_{F\omega}} = \begin{cases} \Omega_F \uparrow & ; 0 \le \omega < \Omega_F \quad : \text{pulsar.type} \;\; (\omega=0) \\ 0 & ; \omega = \Omega_F \quad : \text{gap} \\ -(\Omega_H - \Omega_F) \downarrow & ; \Omega_F < \omega \le \Omega_H \quad : \text{anti.pulsar.type} \;\; (\omega=\Omega_H) \end{cases}$$

because current-field-streamlines are equipotentials, and $\boldsymbol{E}_p=0$ on S_N. This allows us to present the hole's magnetosphere with a pair of a pulsar and an anti-symmetric pulsar (the outside-turned-in version).

6.2 Two "Virtual" Magnetized Rotators



6.3 Simple Image of Double Circuits



7.1 New Gap Physics ?

(1) Two oppositely directed UPI batteries due to two oppositely directed magnetized rotators seem to be existent back-to-back under S_N.

(2) Voltage drop ΔV between inner and outer circuits is stationary, stable, strong enough to pair-create particles.

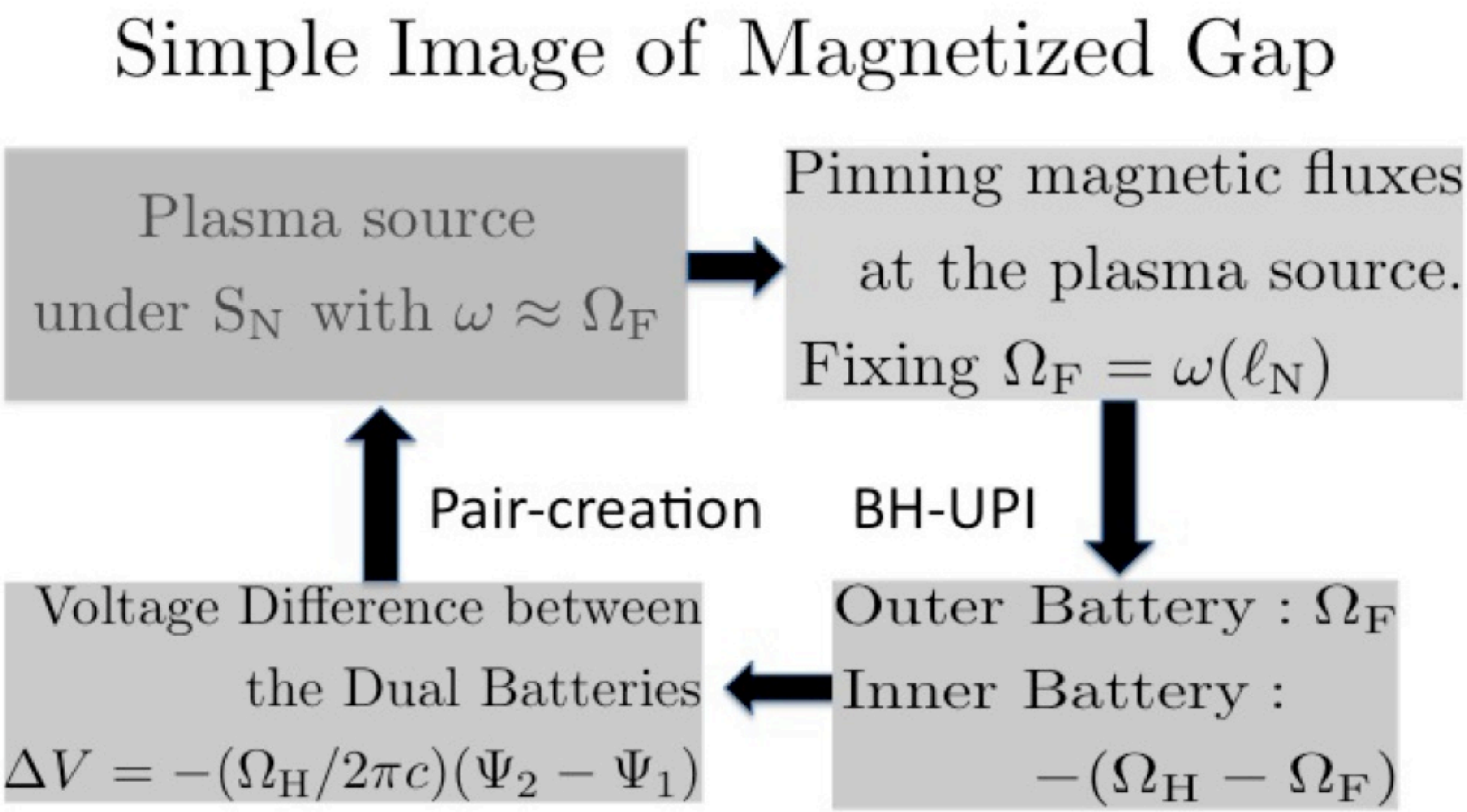
$$\Delta V = \mathcal{E}_{\rm out} - \mathcal{E}_{\rm in} = -\frac{\Omega_{\rm H}}{2\pi c}\Delta\Psi$$

(3) How large should the particle density be, to pin down magnetic field lines and to fix Ω_F by the local value ω_N ?

(4) What is magnetized matter under S_N ? (Cf. neutron stars' matter of pinning field lines down under the surface.)

(5) No need of resorting to invoking vacuum $E_{||}$ and pair-creation discharge for particle supply, as in the previous models. (cf. Hirotani & Okamoto 1998, ApJ, 497, 563)

7.2 What do we expect to take place ?



8. Estimate of Location S_N, ΔV and Power

Location of "Power Station"

$$\omega = \Omega_{\rm F} \simeq (1/2)\Omega_{\rm H},$$

$$r \simeq 1.6 r_{\rm H}$$

Voltage Drop at S_N

$$\Delta V = \frac{\Omega_{\rm H}}{2\pi c}\Delta\Psi$$

$$\simeq \frac{1}{2\pi c}\frac{a}{2Mr_{\rm H}}B_n \pi r_{\rm H}^2$$

$$\simeq (10^{20}\text{volts})\left(\frac{a}{M}\right)\left(\frac{M}{10^9 M_\odot}\right)\left(\frac{B_n}{10^4 \text{G}}\right)$$

Power

$$P_{\rm H} = \frac{1}{2\pi c}\oint \Omega_{\rm F}(\Psi) I(\Psi) d\Psi$$

$$\simeq 2 \times (10^{45}\text{erg/sec})\left(\frac{a}{M}\right)^2\left(\frac{M}{10^9 M_\odot}\right)^2\left(\frac{B_n}{10^4 \text{G}}\right)^2$$

9. Summary

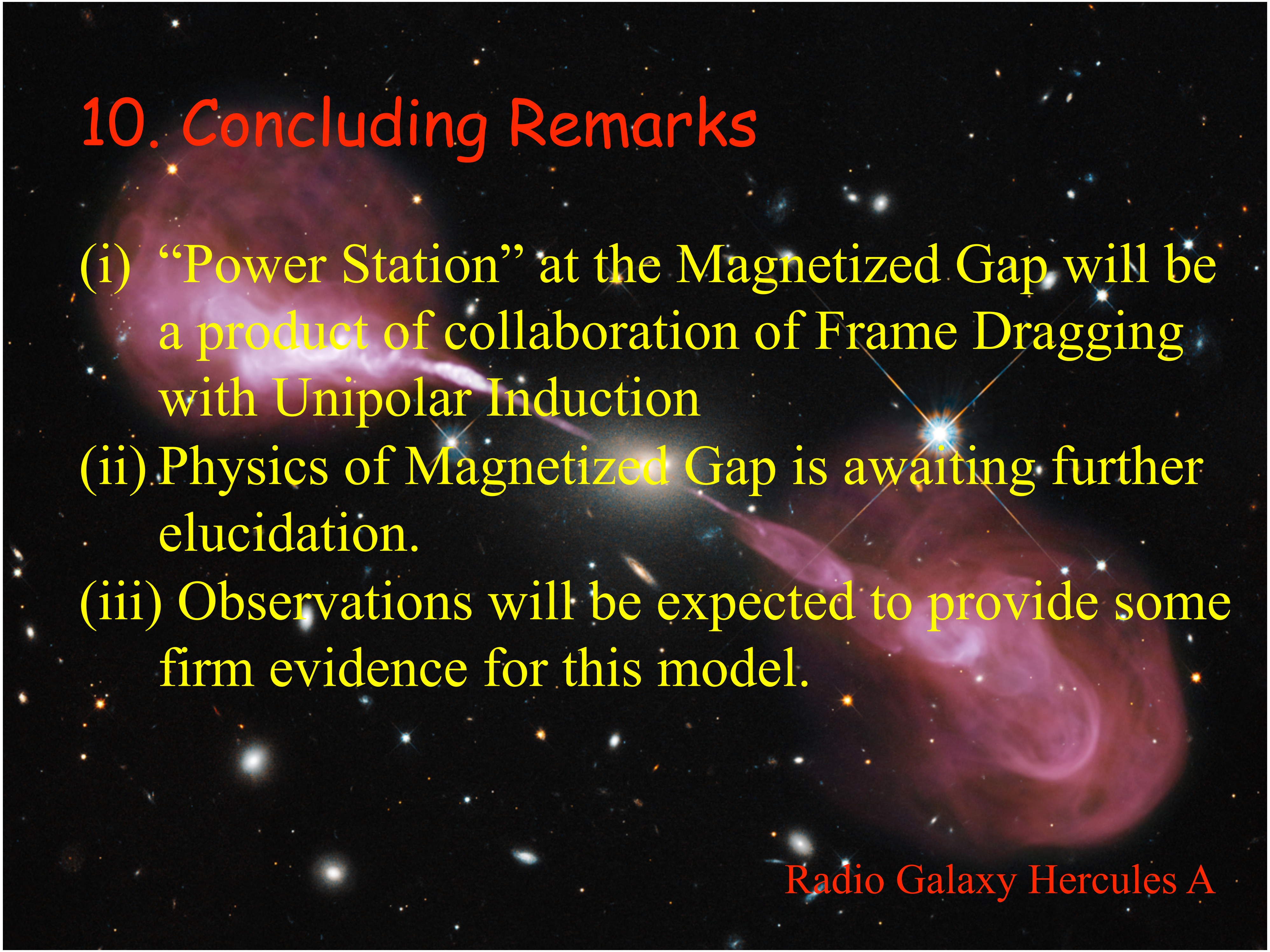
- By collaboration of frame dragging and unipolar induction, the hole's magnetosphere has a double structure, divided by interface S_N into two domains, outer S-C and inner G-R domains, with outflow and inflow. Strong magnetized gap with voltage drop is concealed under S_N, with a secret Power Station for launching outflow, which will be accelerated to a large-scale jet.
- Large-scale jets will be a manifestation of the frame-dragging effect, coupled with unipolar induction.
- The present model is an extended version of S. Phinney's jet model (1982).

10. Concluding Remarks

(i) "Power Station" at the Magnetized Gap will be a product of collaboration of Frame Dragging with Unipolar Induction

(ii) Physics of Magnetized Gap is awaiting further elucidation.

(iii) Observations will be expected to provide some firm evidence for this model.



Radio Galaxy Hercules A

Acknowledgement

I appreciate the Foundation of Promotion for Astronomy, Japan for supporting the flight expenses.

Thank you for listening.

I love Switzerland, the Alps and Matterhorn.

I. Okamoto

43 years ago.
At the summit of Matterhorn.

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