

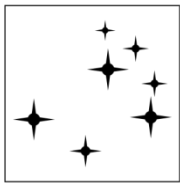
**Κέντρο Ερευνών Αστρονομίας
και Εφαρμοσμένων Μαθηματικών**
της Ακαδημίας Αθηνών

A Cosmic Battery in accretion flows around astrophysical black holes

Ioannis Contopoulos

Research Center for Astronomy and Applied
Mathematics, Academy of Athens

Purdue, Tuesday, May 8, 2018



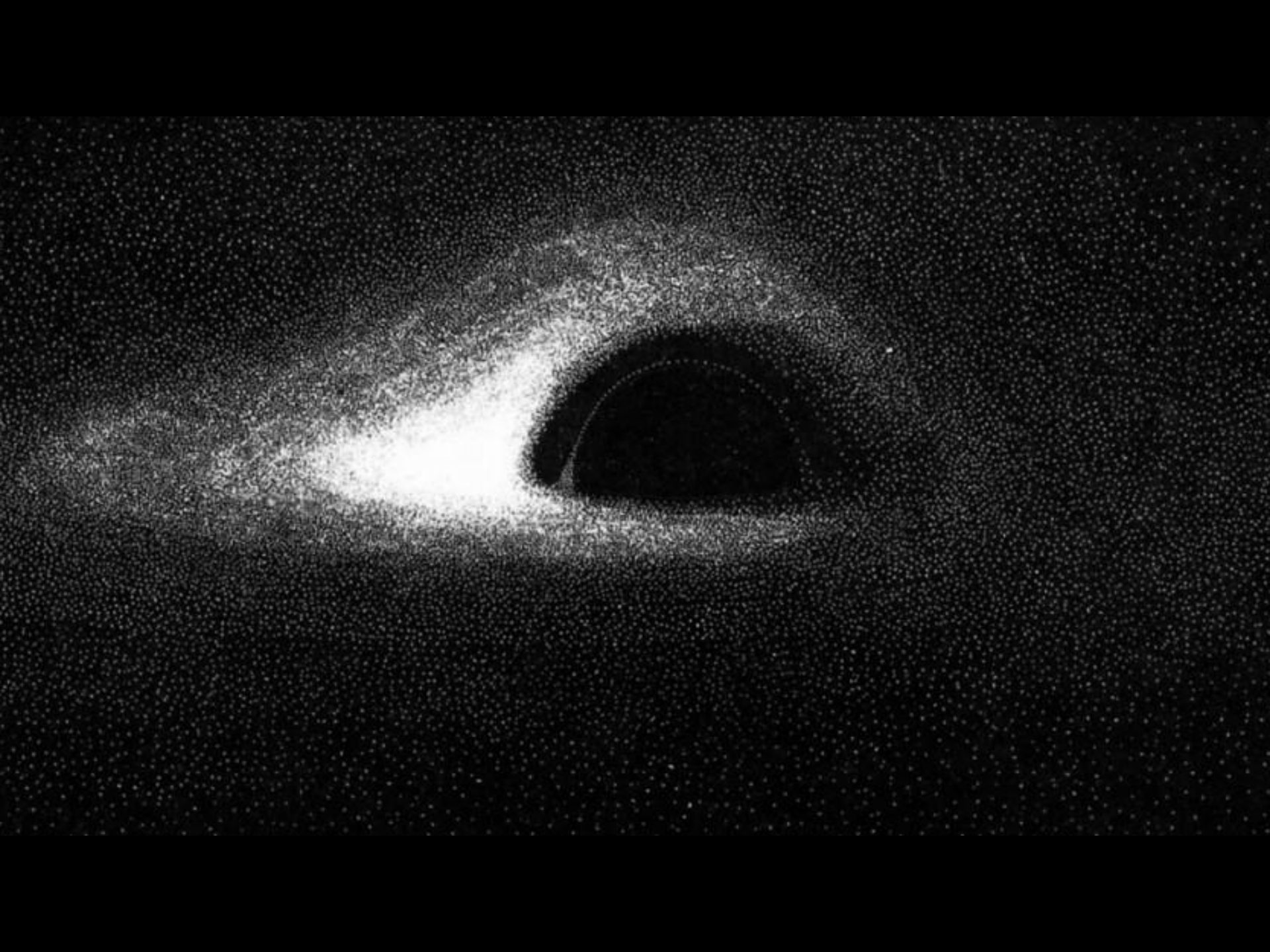
Κέντρο Ερευνών Αστρονομίας
και Εφαρμοσμένων Μαθηματικών
της Ακαδημίας Αθηνών

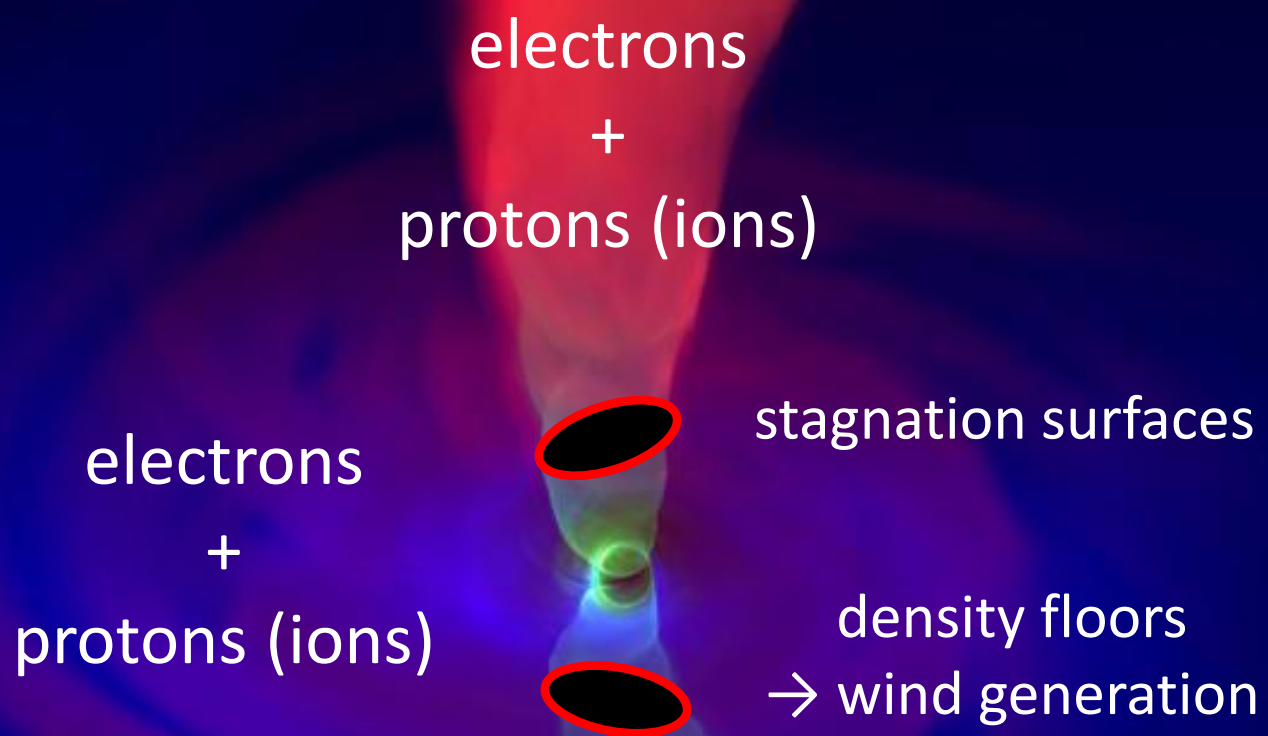
«Extra Physics» in accretion flows around astrophysical black holes

Ioannis Contopoulos

Research Center for Astronomy and Applied
Mathematics, Academy of Athens

Purdue, Tuesday, May 8, 2018





Black hole jet: electron-positron

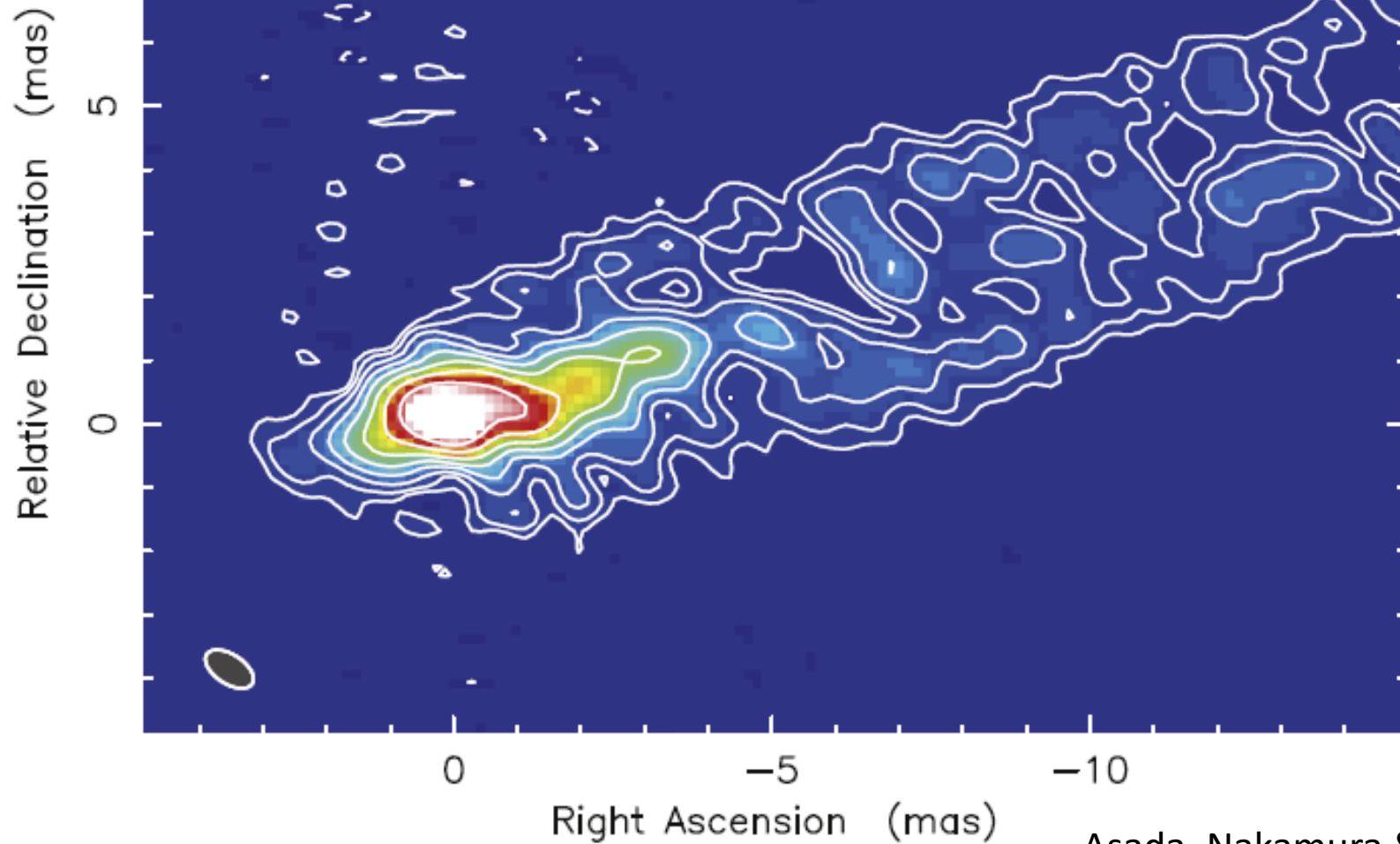
+ electron-proton
disk wind

electrostatic gaps

EHT: Ozel et al. 2017
Levinson/Chen/Medvedev et al.
Fukumura, Kazanas, Contopoulos et al.

J1230+12 at 4.866 GHz 2000 Mar 23

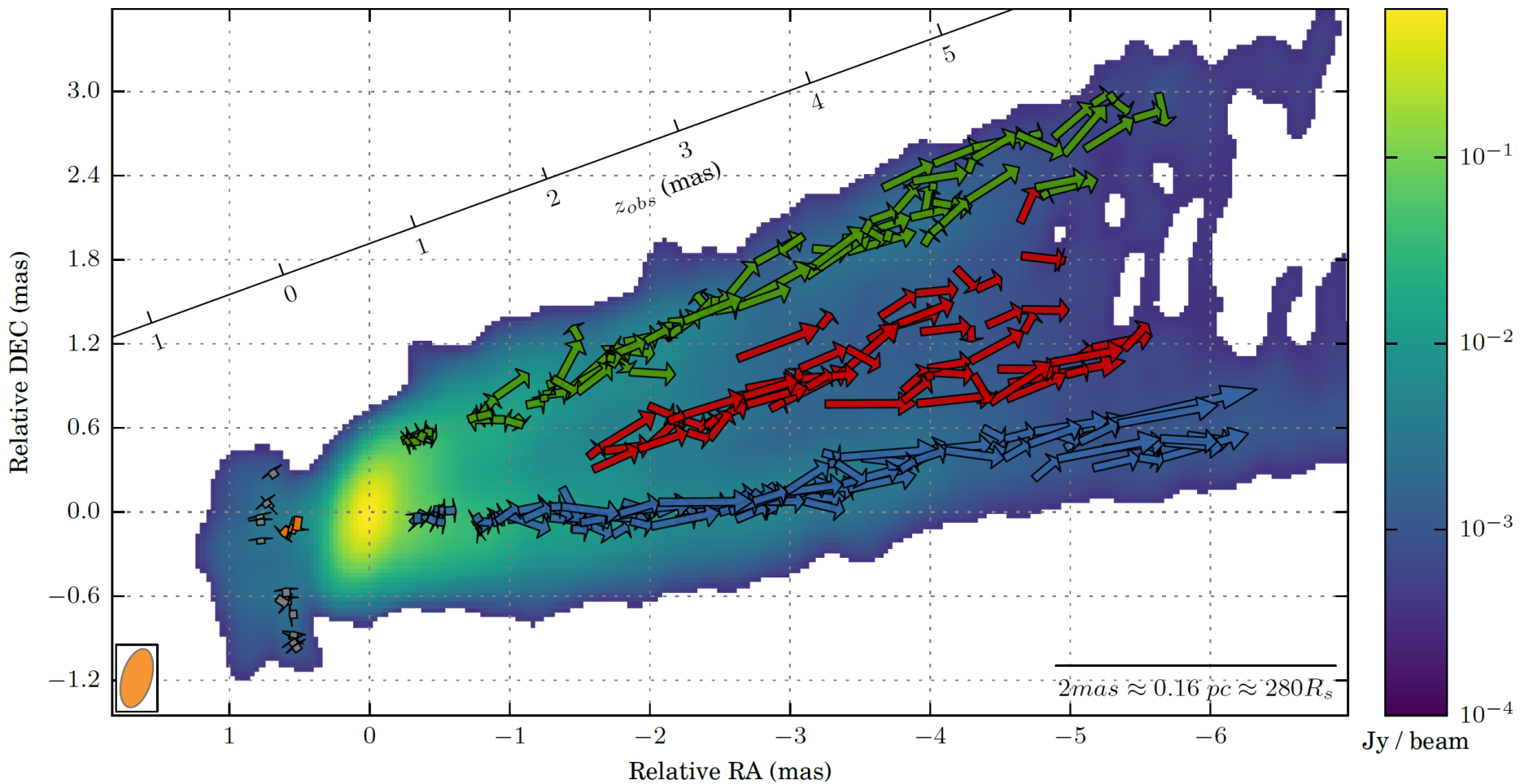
M87 «spine» jet!



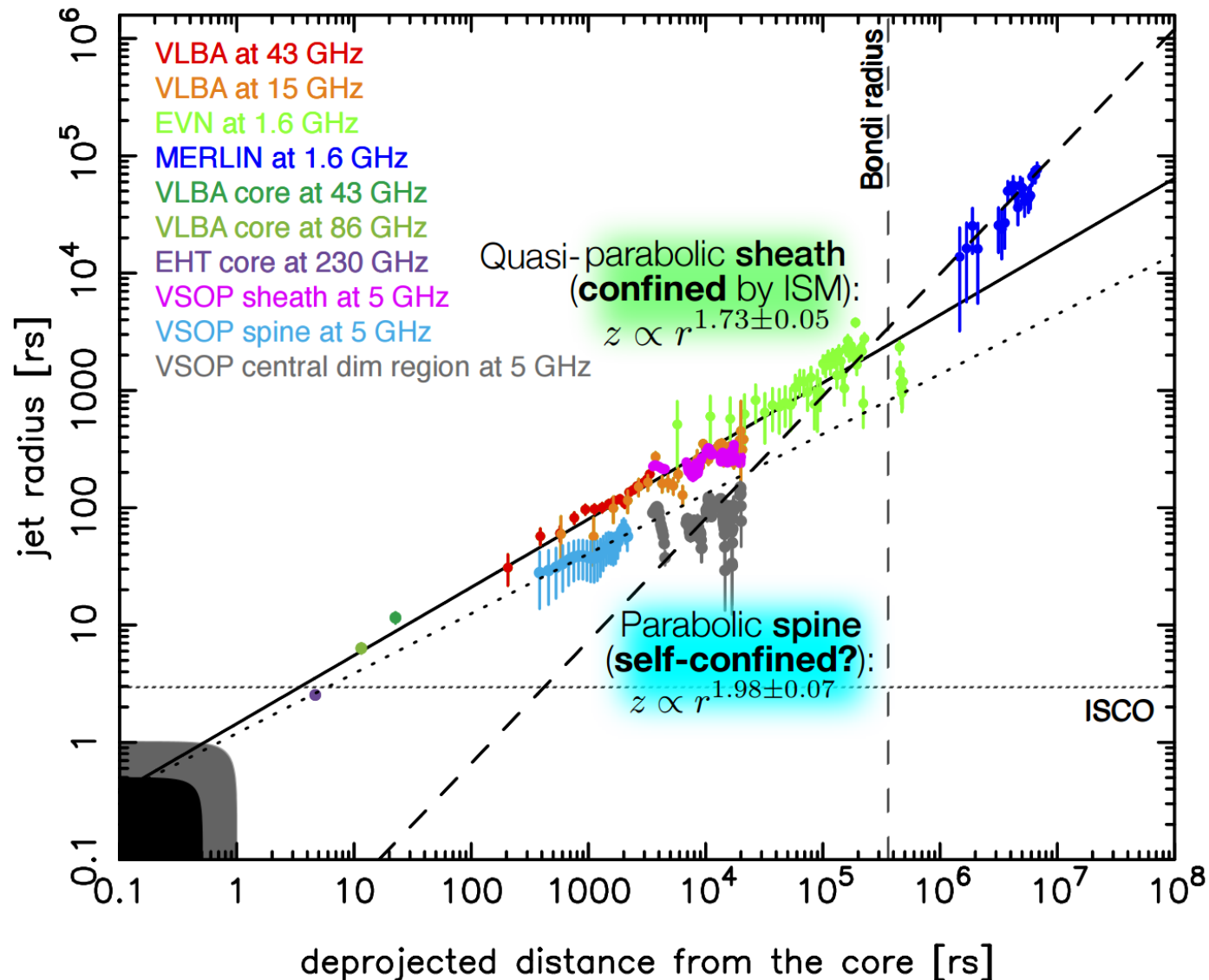
Asada, Nakamura & Pu 2016

Mertens et al. 2016

M87 «spine» jet!

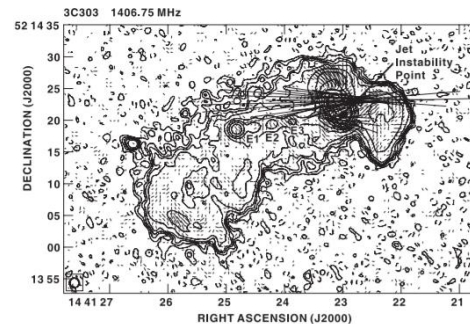
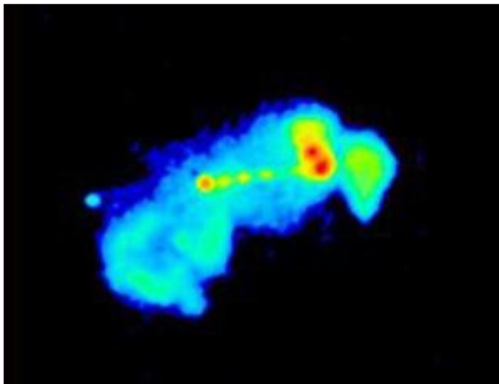


M87 «spine» jet!



IN BRIEF 15 June 2011

Universe's highest electric current found



A COSMIC jet 2 billion light years away is carrying the highest electric current ever seen: 10^{18} amps, equivalent to a trillion bolts of lightning.

[Philipp Kronberg](#) of the University of Toronto in Canada and colleagues measured the alignment of radio waves around a galaxy called 3C303, which has a giant jet of matter shooting from its core. They saw a sudden change in the waves' alignment coinciding with the jet. "This is an unambiguous signature of a current," says Kronberg.

The team thinks magnetic fields from a colossal black hole at the galaxy's core are generating the current, which is powerful enough to light up the jet and drive it through interstellar gases out to a distance of about 150,000 light years (arxiv.org/abs/1106.1397).

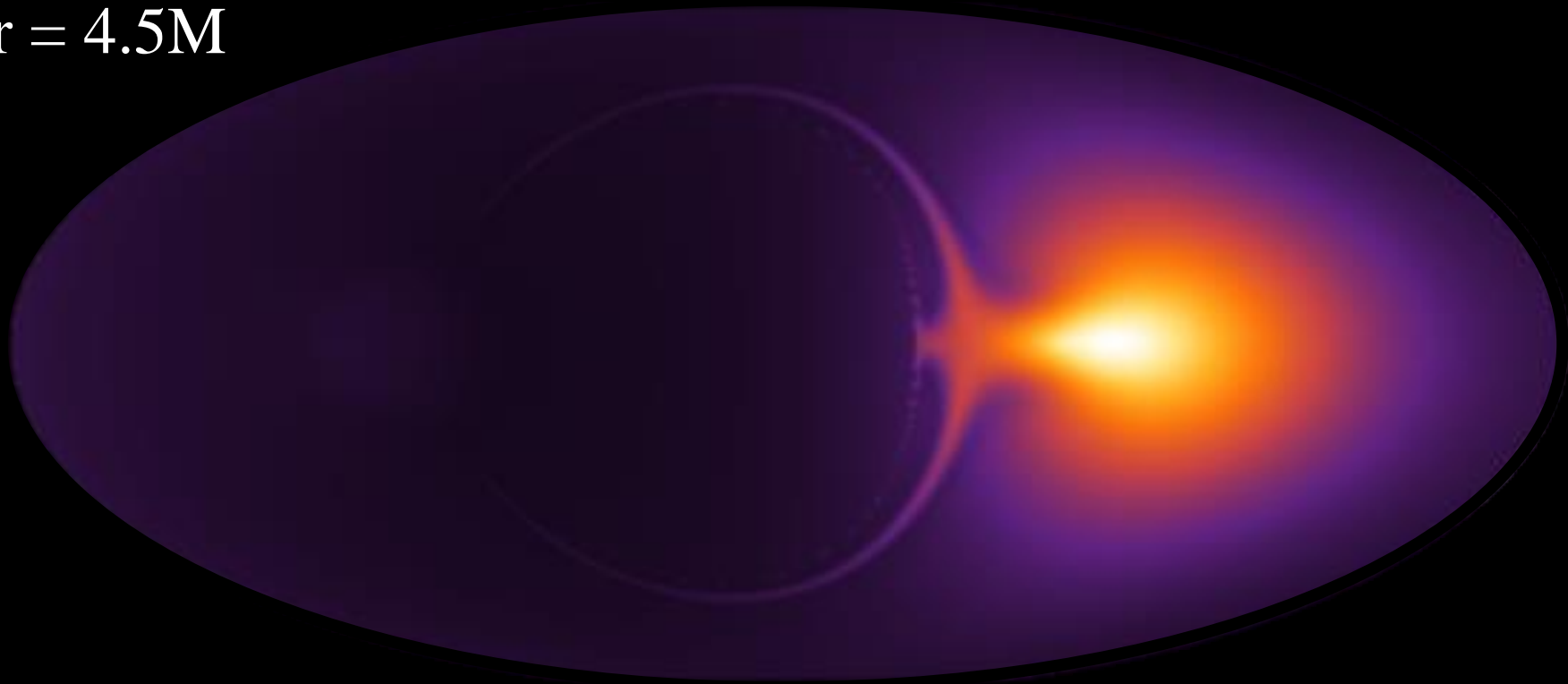
The kpc-scale jet **is not**
the electron-positron BH jet

The kpc-scale jet is the
electron-proton disk wind!

Radiation

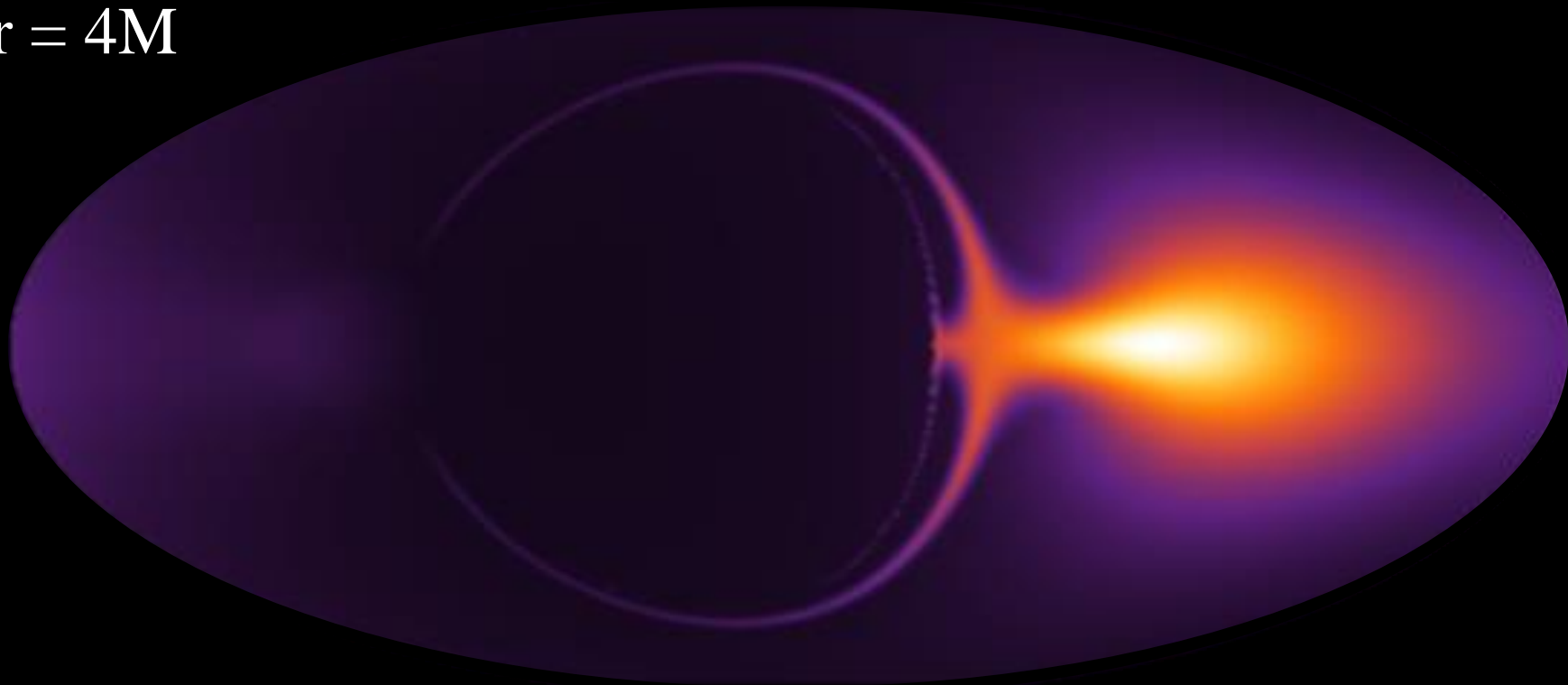
$\alpha = 0.9M$

$r = 4.5M$

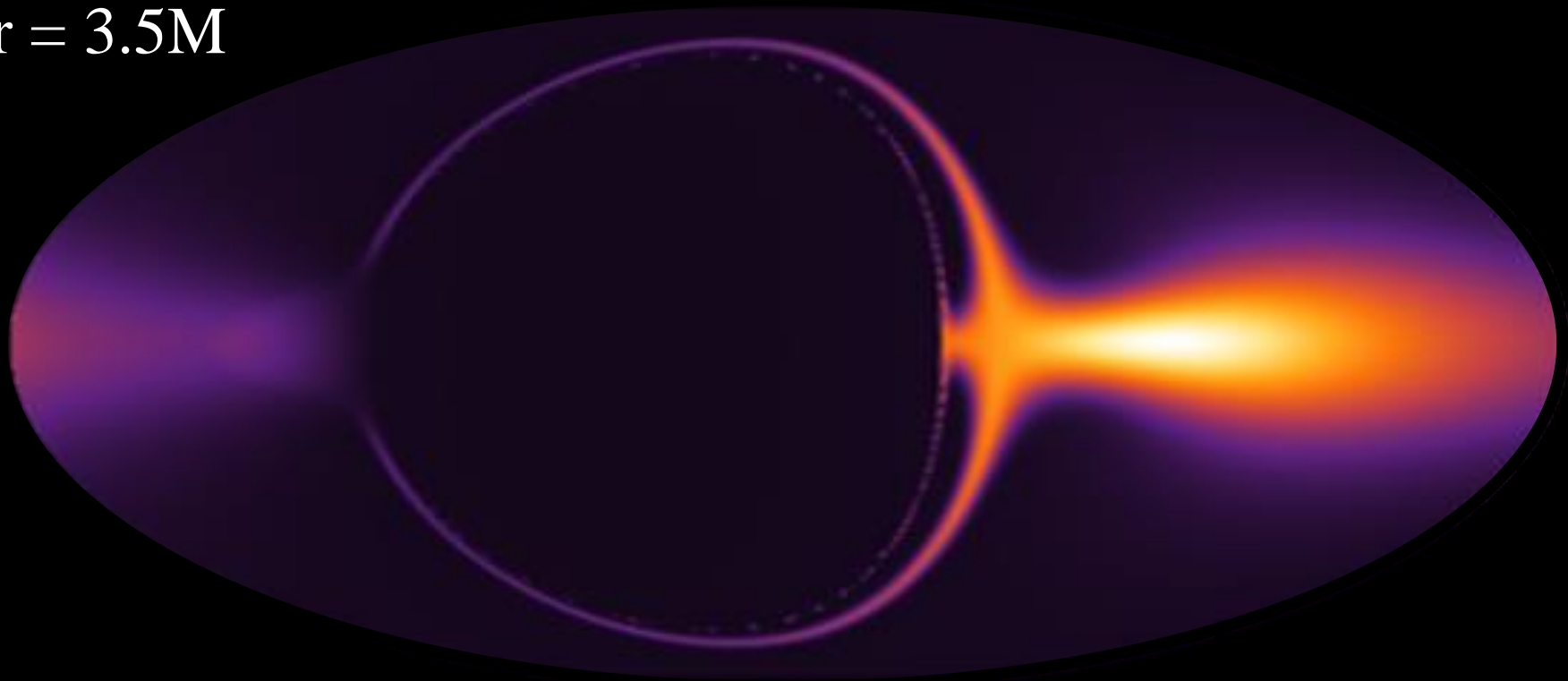


$\alpha = 0.9M$

$r = 4M$

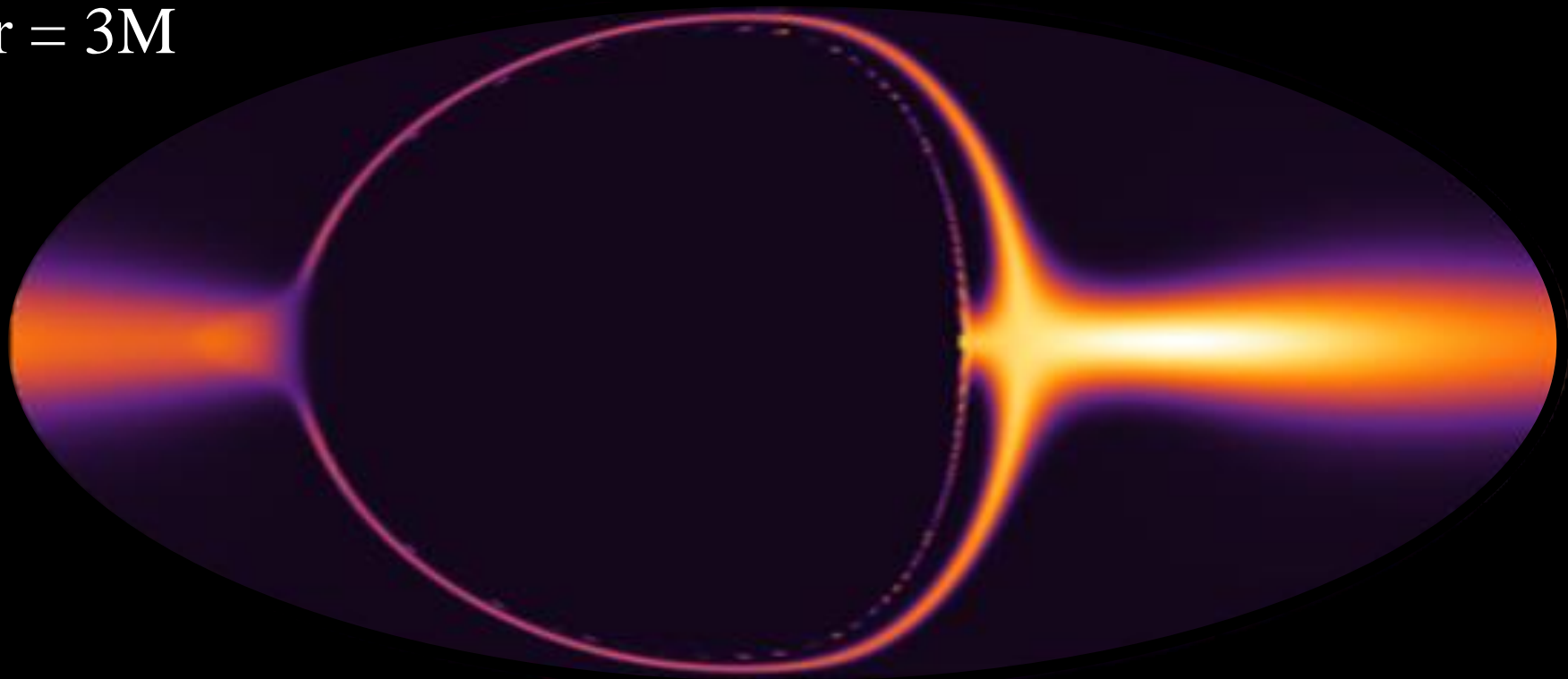


$\alpha = 0.9M$
 $r = 3.5M$

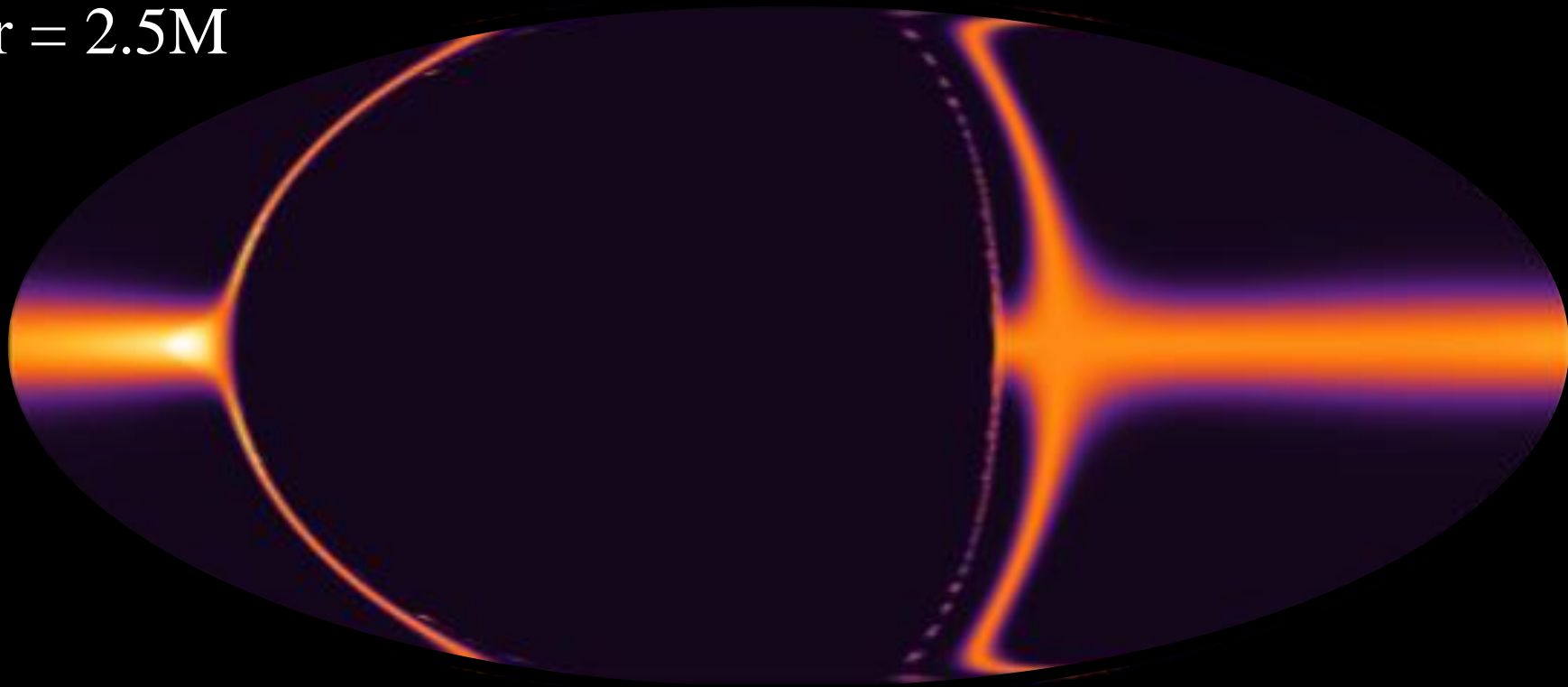


$\alpha = 0.9M$

$r = 3M$

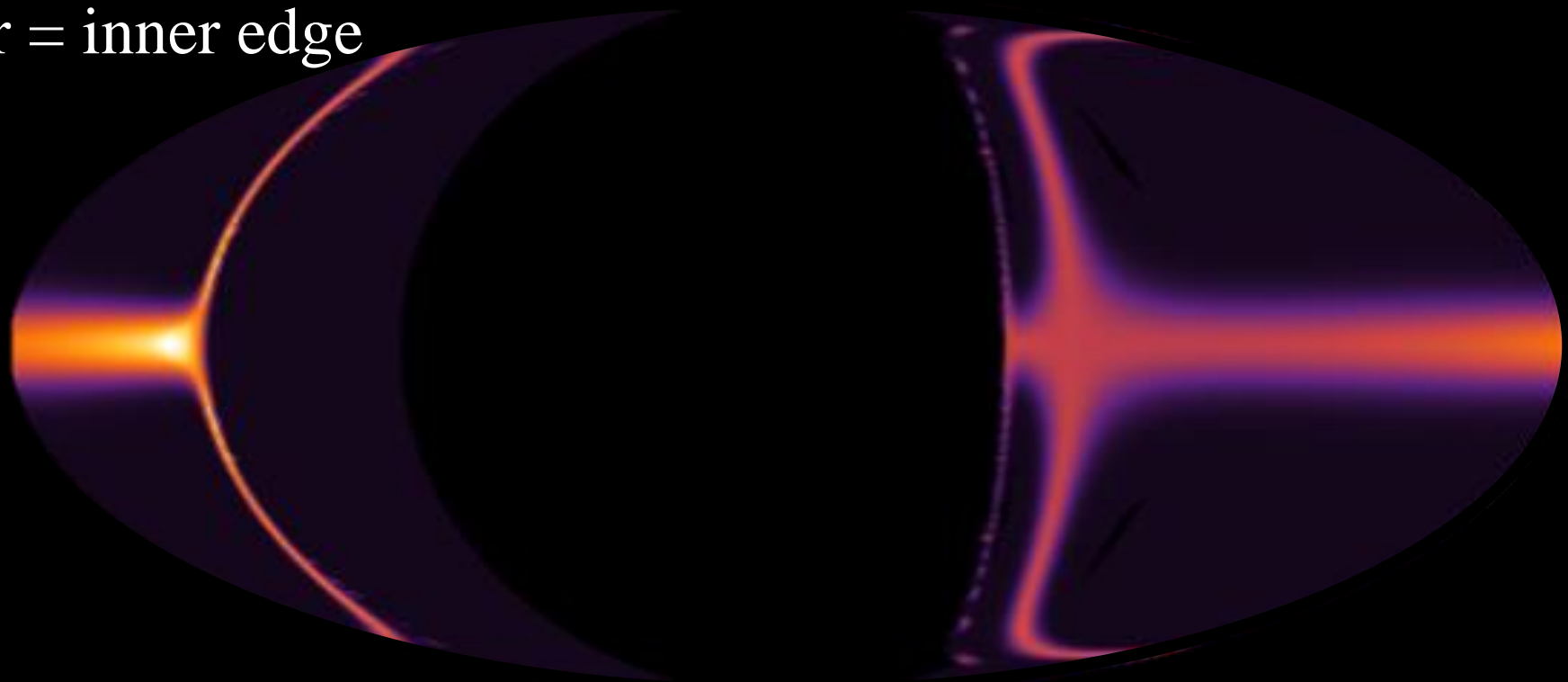


$\alpha = 0.9M$
 $r = 2.5M$



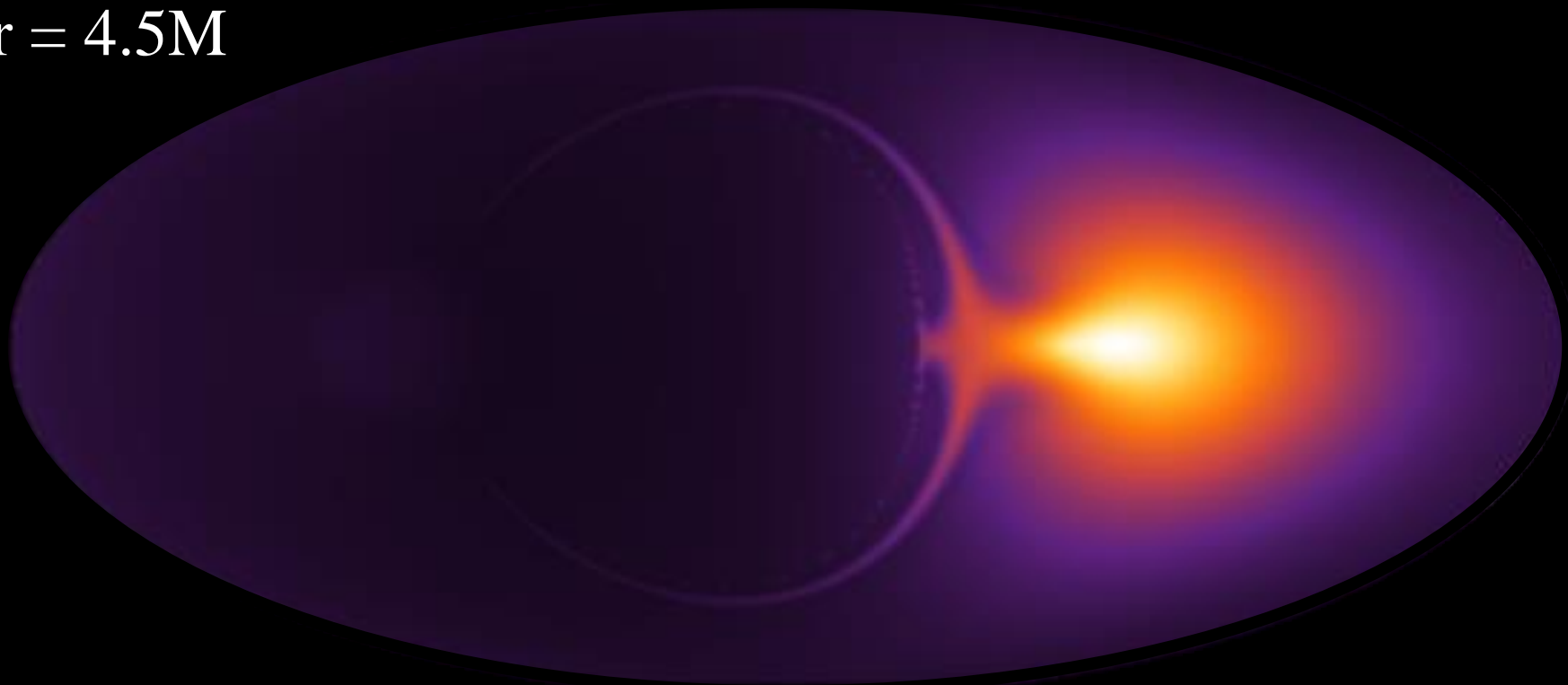
$\alpha = 0.9M$

$r = \text{inner edge}$



$$\alpha = 0.9M$$

$$r = 4.5M$$



$$\mathbf{f}_{\text{rad}} = -\frac{L\sigma_{\text{T}}}{4\pi r^2 c} \frac{\mathbf{v}}{c}$$

$$m_p \frac{d\mathbf{v}_p}{dt} = \mathbf{f}_{\text{rad}} + \dots$$

$$m_e \frac{d\mathbf{v}_e}{dt} = \mathbf{f}_{\text{rad}} + \dots$$

«Extra Physics»

$$m_e \frac{d\mathbf{v}_e}{dt} = \mathbf{f}_{\text{rad}} - e\mathbf{E} + \dots \approx 0$$

$$m_p \frac{d\mathbf{v}_p}{dt} = +e\mathbf{E} + \dots$$

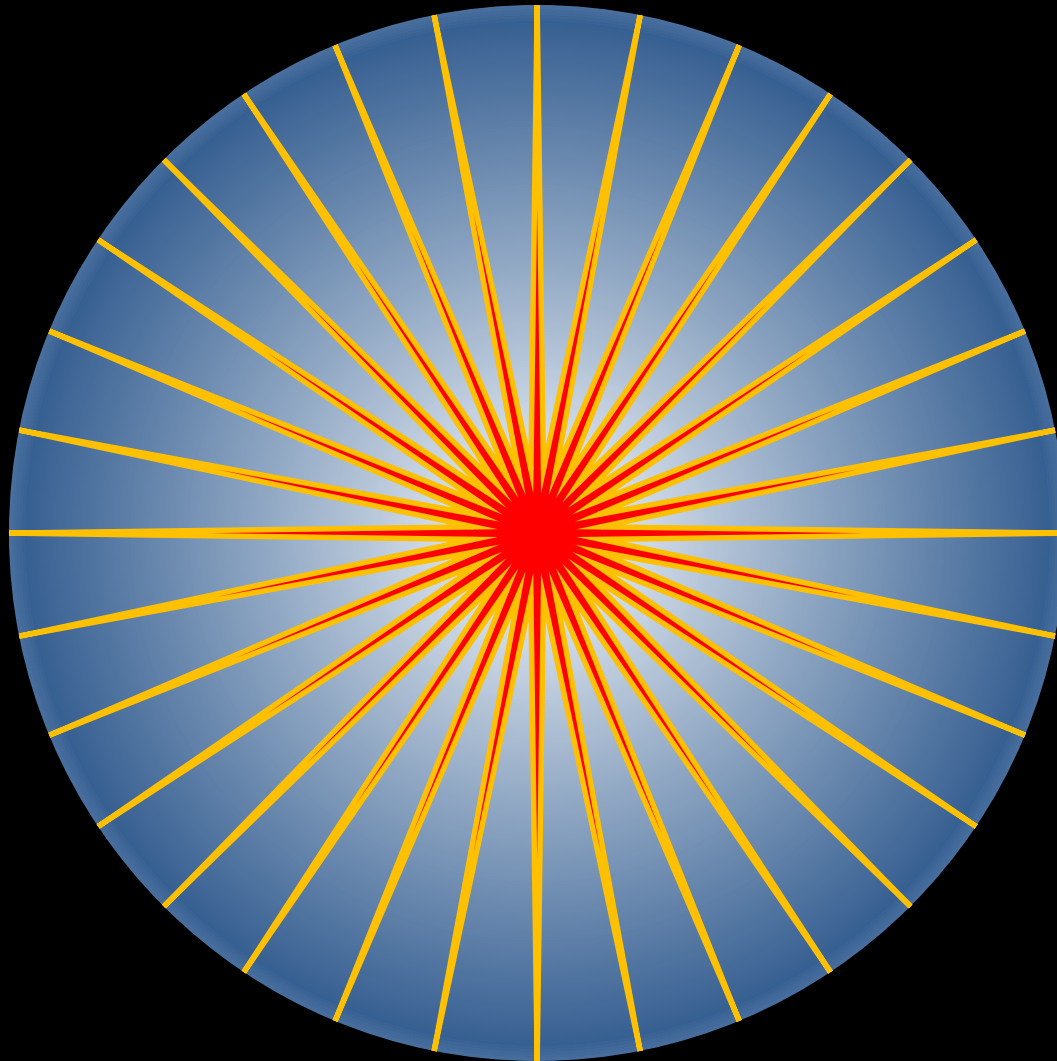
$$\mathbf{E} = \frac{\mathbf{f}_{\text{rad}}}{e}$$

«Extra Physics»

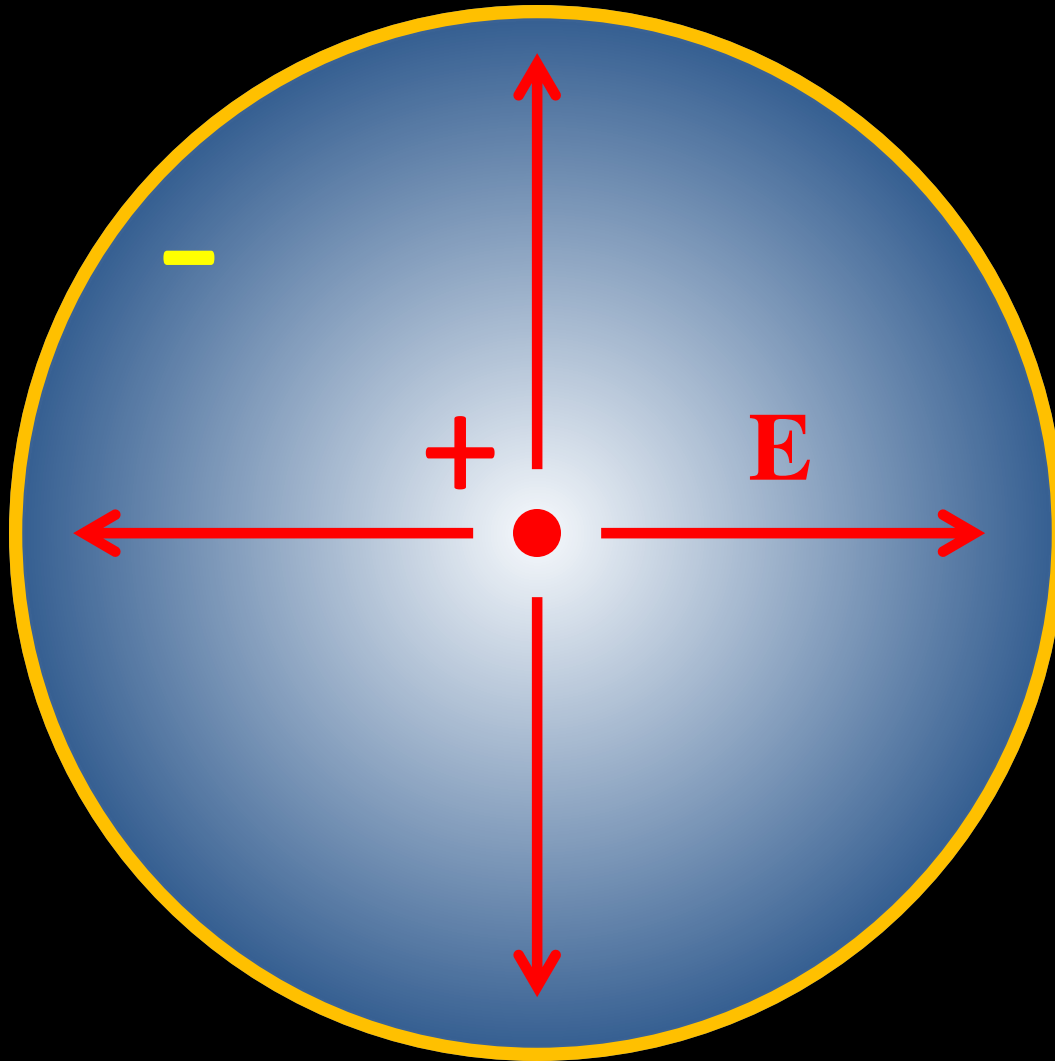
- Electrons and protons (ions)
 - **NOT** electrons and positrons
- Particles:
 - **NOT** continuous negative and positive fluids
 - Ions (positive nucleus + bound electrons)
 - Debye spheres (positive ions + electron cloud)



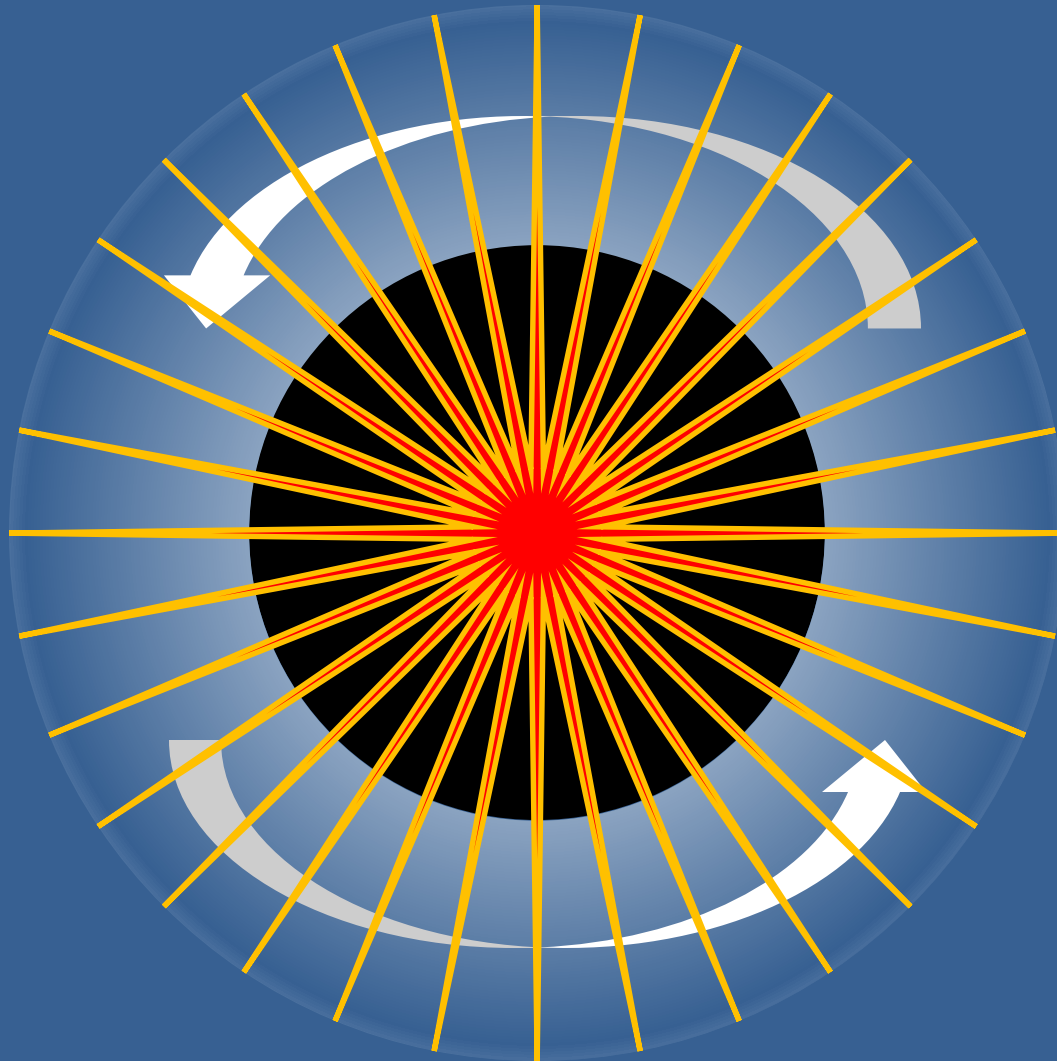
«Extra Physics»



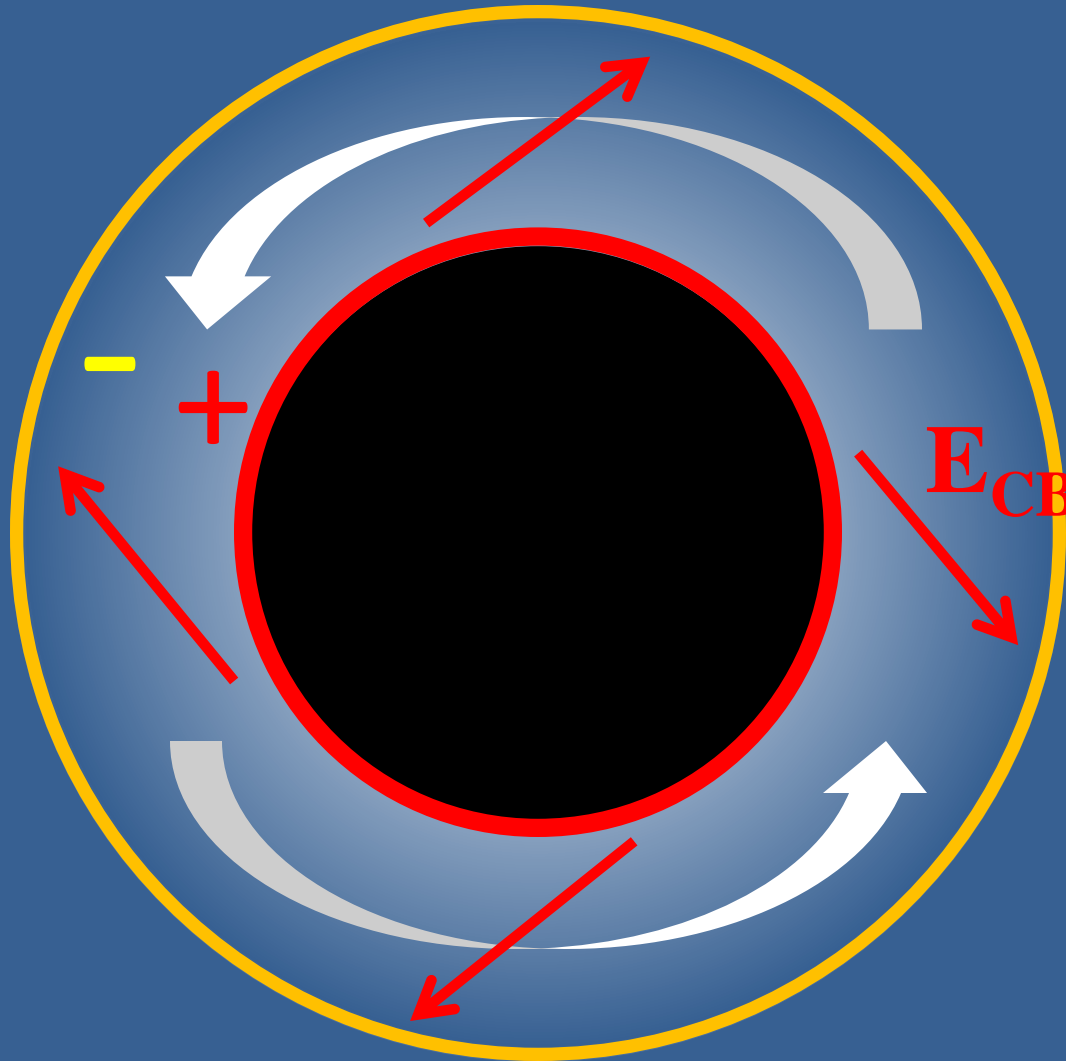
«Extra Physics»



«Extra Physics»



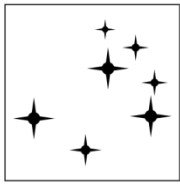
«Extra Physics»



«Extra Physics»

- \mathbf{E}_{CB} does not generate \mathbf{J}
 - It is **curl** \mathbf{E}_{CB} that generates \mathbf{B}

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times (-\mathbf{v} \times \mathbf{B} + \eta \nabla \times \mathbf{B} + \mathbf{E}_{\text{CB}})$$

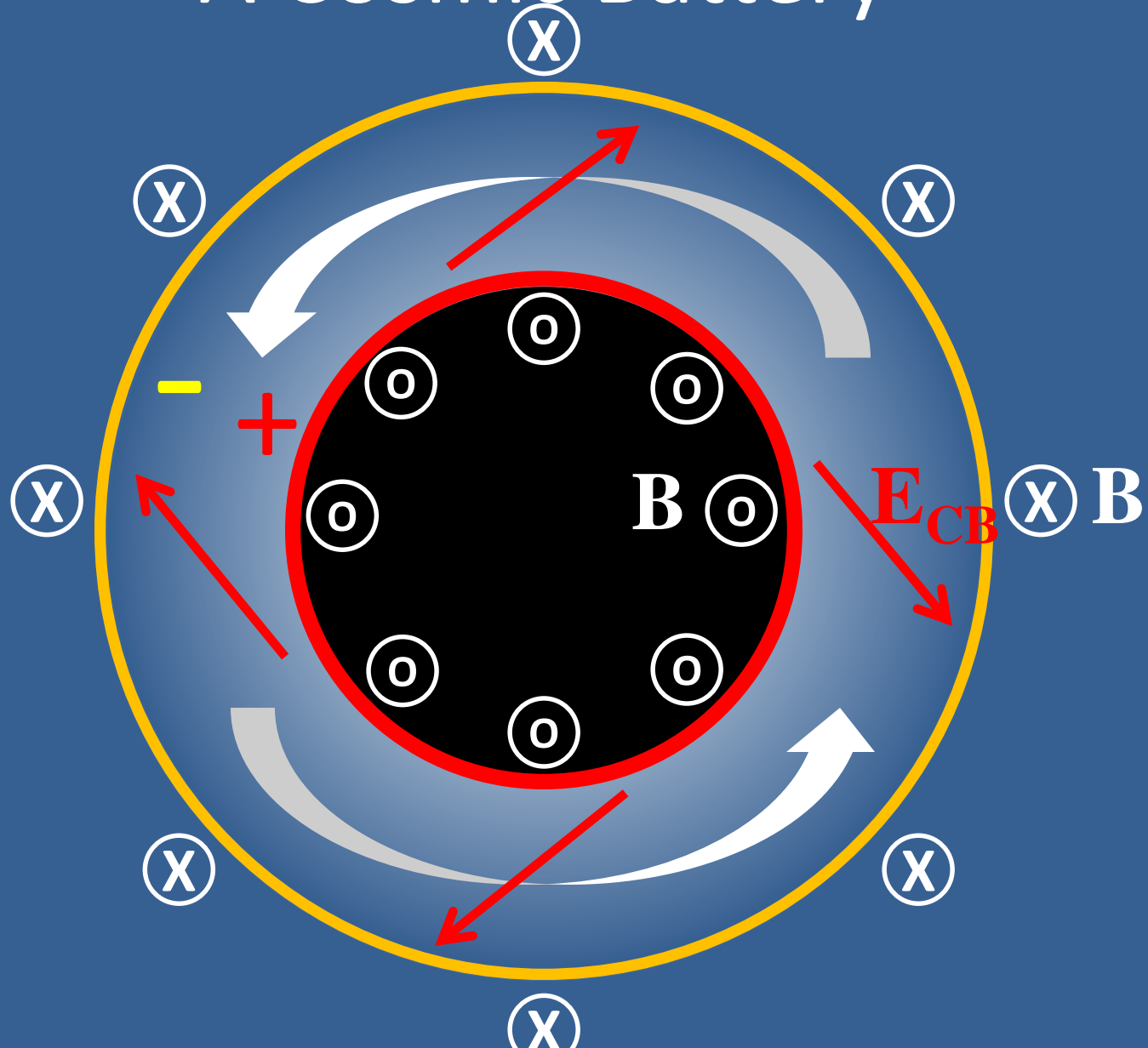


Κέντρο Ερευνών Αστρονομίας
και Εφαρμοσμένων Μαθηματικών
της Ακαδημίας Αθηνών

A Cosmic Battery in accretion flows around astrophysical black holes

Contopoulos, Kazanas, Kylafis, Christodoulou,
Gabuzda, Koutsantoniou, Nathanail 1998-2018

A Cosmic Battery



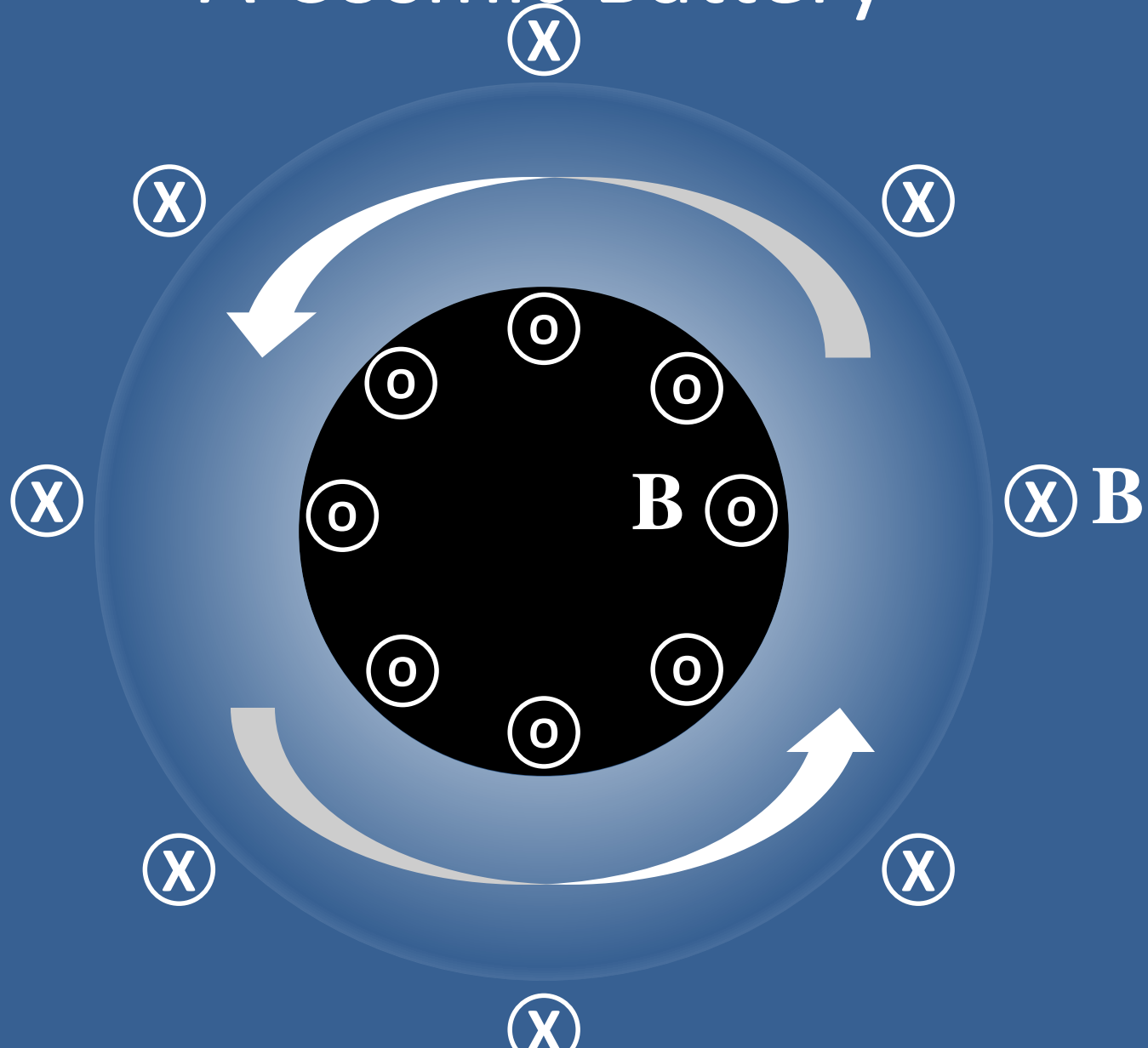
A Cosmic Battery

- \mathbf{E}_{CB} does not generate \mathbf{J}
 - It is **curl \mathbf{E}_{CB}** that generates \mathbf{B}

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times (-\mathbf{v} \times \mathbf{B} + \eta \nabla \times \mathbf{B} + \mathbf{E}_{\text{CB}})$$

- All the terms in the induction eq. are important:
 - **Inward advection** of one MF polarity
 - **Outward diffusion** of reverse MF polarity through disk
 - Magnetic Prandtl number $Pr_m = Re_m / Re = v / \eta$ in the disk ≤ 1

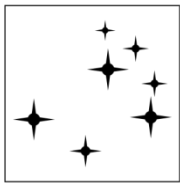
A Cosmic Battery



B along Ω in the black hole

B opposite Ω in the disk

Distinction between
perfectly conducting inner
accretion disk
and
diffusing outer disk



Κέντρο Ερευνών Αστρονομίας
και Εφαρμοσμένων Μαθηματικών
της Ακαδημίας Αθηνών

2D GR R MHD

numerical simulations of the Cosmic Battery

Contopoulos, Nathanail, Sadowski, Kazanas, Narayan 2018

(non GR: 1D: Contopoulos, Kazanas 1998;

2D: Contopoulos, Christodoulou, Kazanas 2006, 08;

Contopoulos, Nathanail, Katsanikas 2015)

Numerical simulations of the Cosmic Battery in accretion flows around astrophysical black holes

I. Contopoulos^{1,2*}, A. Nathanail^{3,4}, A. Sądowski^{5,6,7}, D. Kazanas⁸, R. Narayan⁹

¹ *Research Center for Astronomy and Applied Mathematics, Academy of Athens, Athens 11527, Greece*

² *National Research Nuclear University (MEPhI), Moscow 115409, Russia*

³ *Institute for Theoretical Physics, D-60438 Frankfurt, Germany*

⁴ *Humboldt Fellow*

⁵ *MIT Kavli Institute for Astrophysics and Space Research, 77 Massachusetts Ave, Cambridge, MA 02139, USA*

⁶ *Einstein Fellow*

⁷ *Present address: Akuna Capital, 585 Massachusetts Ave., MA 02139, USA*

⁸ *Astrophysics Science Division, NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA*

⁹ *Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA*

30 May 2017

The conservation laws for gas density, energy and momentum, radiation energy and momentum, and photon number can be written in covariant form,

$$(\rho u^\mu)_{;\mu} = 0, \quad (7)$$

$$(T^\mu_\nu)_{;\mu} = G_\nu, \quad (8)$$

$$(R^\mu_\nu)_{;\mu} = -G_\nu, \quad (9)$$

$$(n u^\mu)_{;\mu} = \dot{n}, \quad (10)$$

where ρ is the gas density in the comoving fluid frame, u^μ is the gas four-velocity, T^μ_ν is the MHD stress-energy tensor,

$$T^\mu_\nu = (\rho + u_{\text{int}} + p + b^2)u^\mu u_\nu + (p + \frac{1}{2}b^2)\delta^\mu_\nu - b^\mu b_\nu, \quad (11)$$

with u_{int} and $p = (\gamma_{\text{int}} - 1)u_{\text{int}}$ representing the internal energy density and pressure of the gas in the comoving frame with adiabatic index, γ_{int} , and b^μ - the magnetic field 4-vector (Gammie et al. 2003). R^μ_ν stands for the radiative stress-energy tensor and n for the photon number density.

where $h^\mu_\nu = \delta^\mu_\nu + u^\mu u_\nu$ is the projection tensor, and u^μ is the gas four-velocity. The new components of the dual electromagnetic field tensor, therefore, are

$$F^{*\mu\nu}_{\text{CB}} = -\epsilon^{\mu\nu\alpha\beta}(E_{\text{CB}})_\alpha u_\beta = -\epsilon^{\mu\nu\alpha\beta}h_{\alpha\gamma}G^\gamma u_\beta \frac{m_p}{\rho c}, \quad (18)$$

which leads to the **modified induction equation**

$$\begin{aligned} \partial_t(\sqrt{-g}B^i) &= -\partial_j(\sqrt{-g}(b^j u^i - b^i u^j) + \sqrt{-g}\epsilon^{ij\alpha\beta}(E_{\text{CB}})_\alpha u_\beta) \\ &= -\partial_j\left(\sqrt{-g}(b^j u^i - b^i u^j) + \epsilon^{ij\alpha\beta}h_{\alpha\gamma}G^\gamma u_\beta \frac{m_p}{\rho c}\right). \end{aligned} \quad (19)$$

It is interesting that the CB term involves the radiation four-force density G^μ which is already calculated in the numerical code, and does not require the calculation of extra quantities. Therefore, its inclusion has no extra computational cost for an MHD+radiation simulation.

This is the first time that the extra CB term appears in the general relativistic form of the induction equation. Our goal in the

Problem:

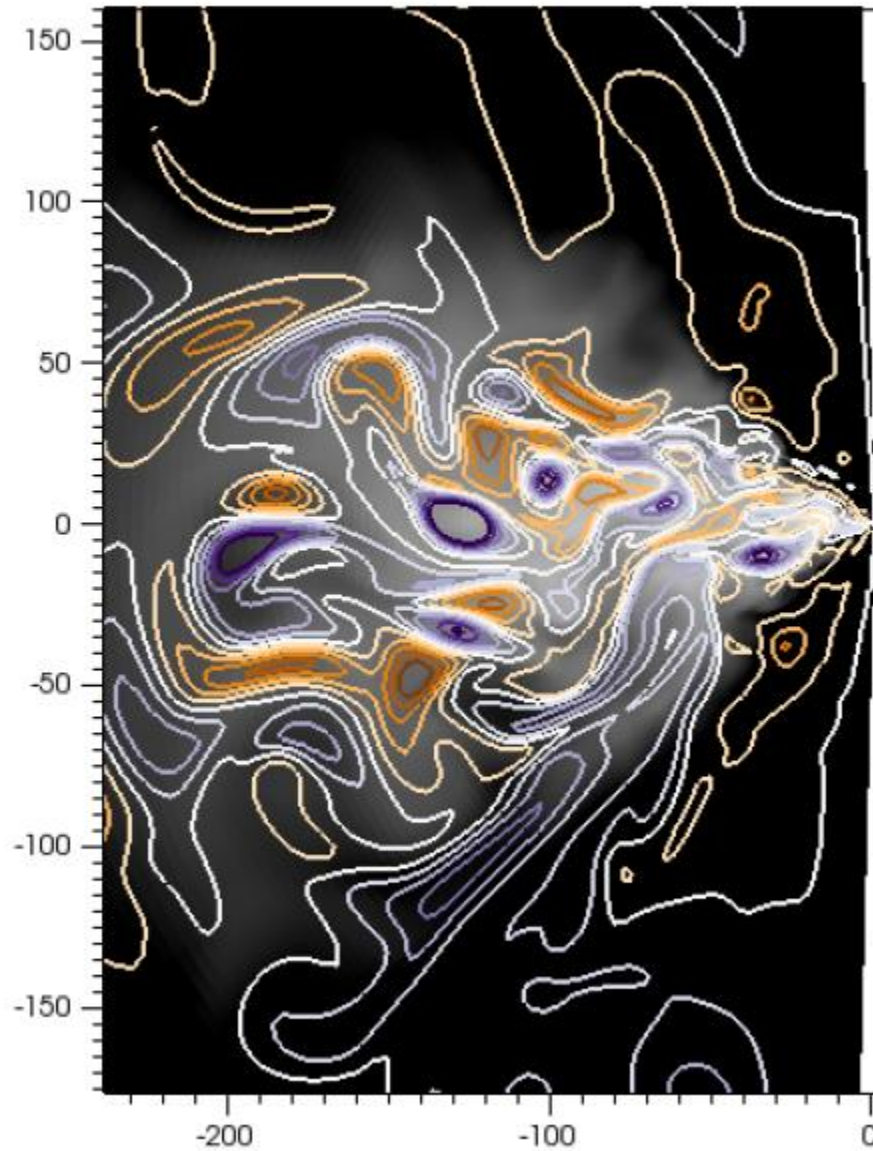
$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times (-\mathbf{v} \times \mathbf{B} + \eta \nabla \times \mathbf{B} + \mathbf{E}_{\text{CB}})$$

- Continuous (secular) effect
- The Cosmic Battery is «slow»:

$$\tau_{\text{CB}} \sim \frac{B_{\text{eq}}}{E_{\text{CB}}} \frac{r}{c} \sim 10^8 - 10^9 \left(\frac{L}{L_{\text{Edd}}} \right)^{-\frac{1}{2}} t_{\text{g}}$$

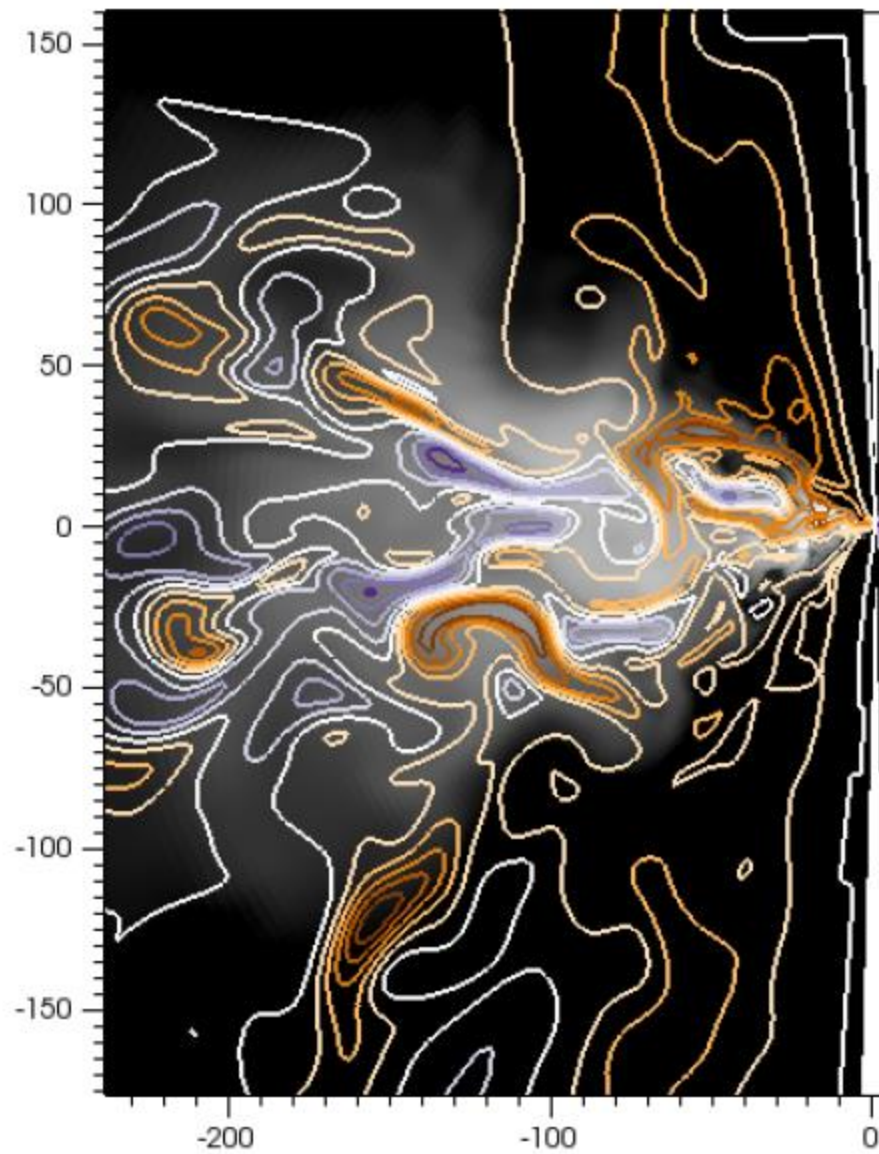
- Prohibitively long simulations
 - Artificially enhanced CB term
 - Sequence of «slow» and «fast» simulations

DB: sil2200.silo
Cycle: 0 Time:22000

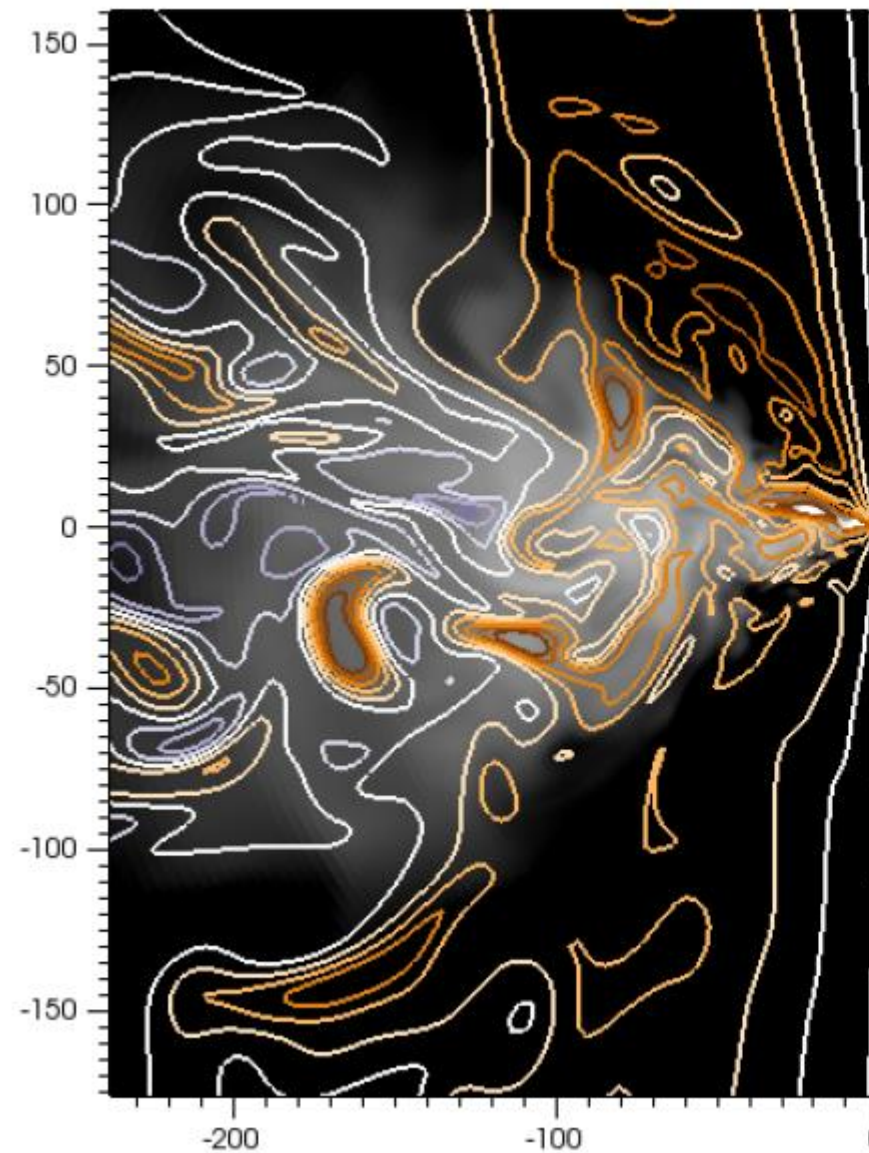


SANE: Standard and Normal Evolution

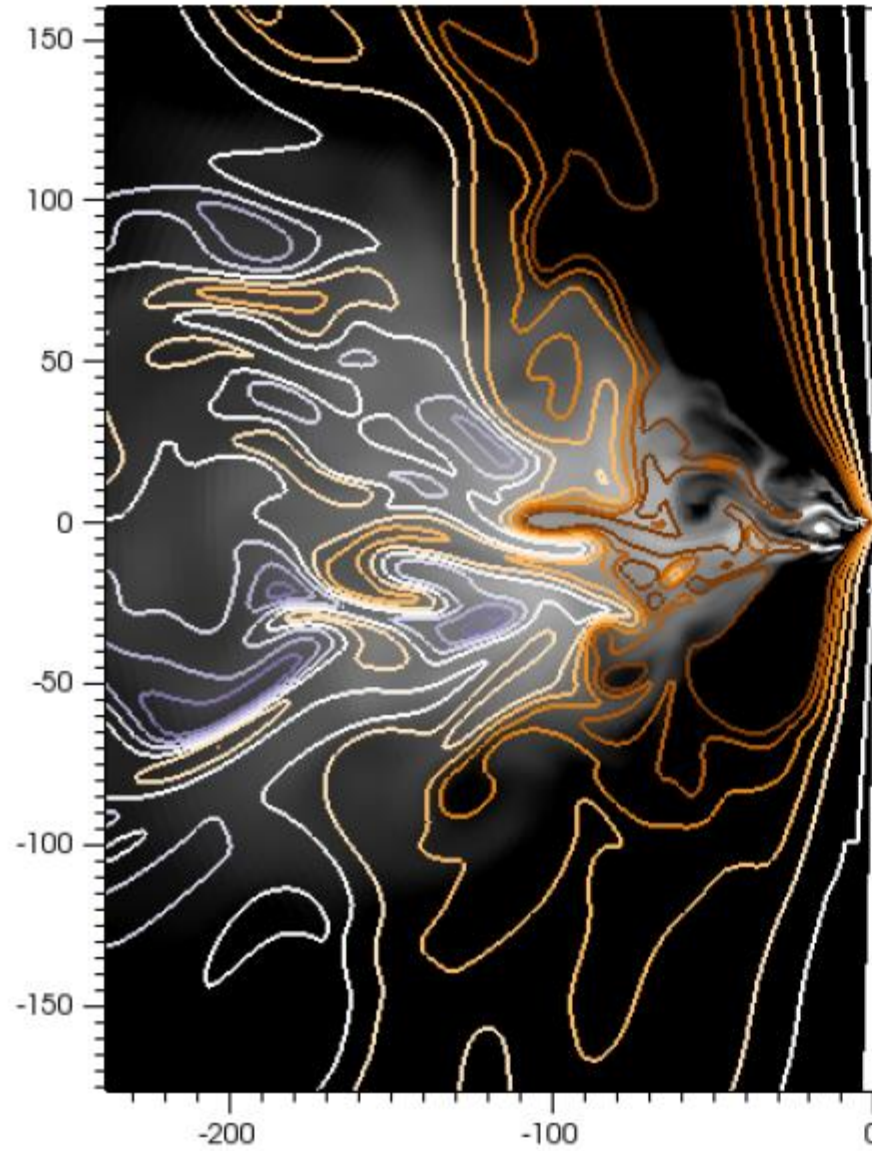
DB: sil3064.silo
Cycle: 0 Time:30640



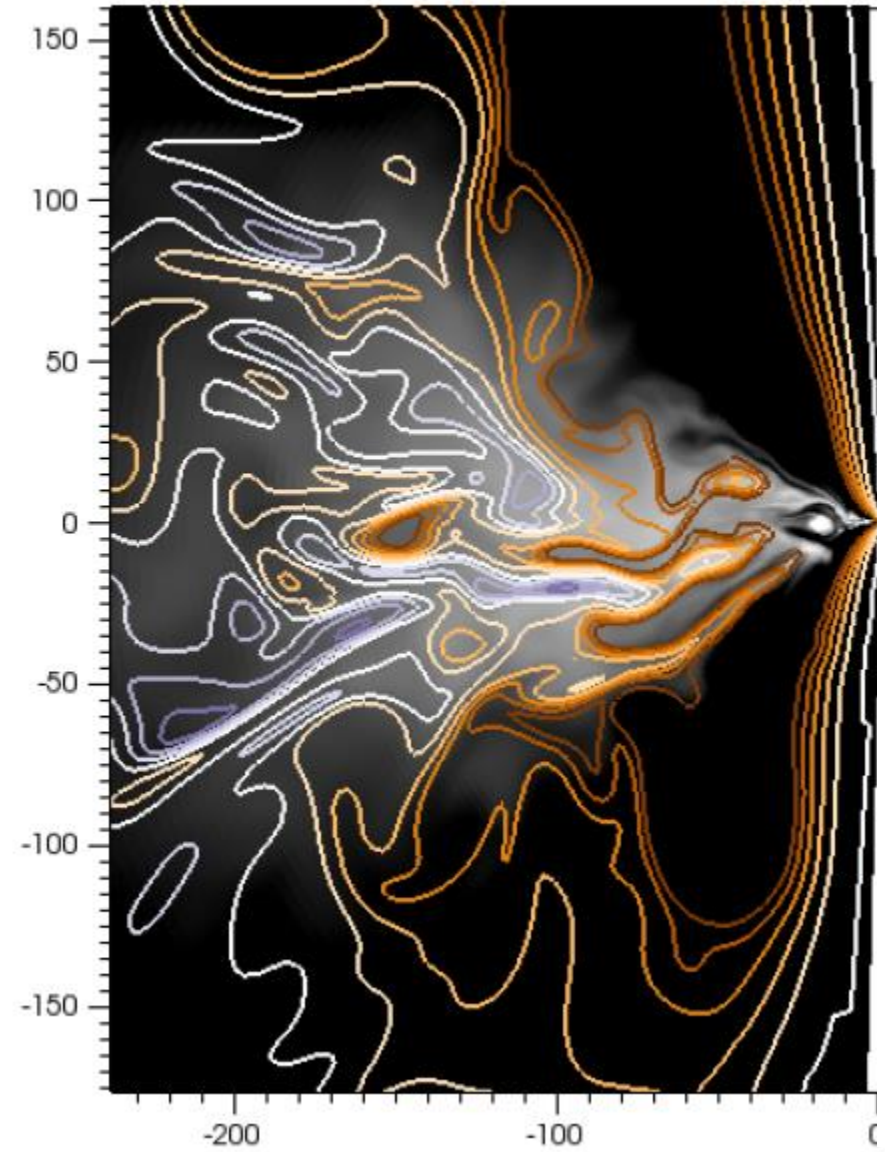
DB: sil3549.silo
Cycle: 0 Time:35490

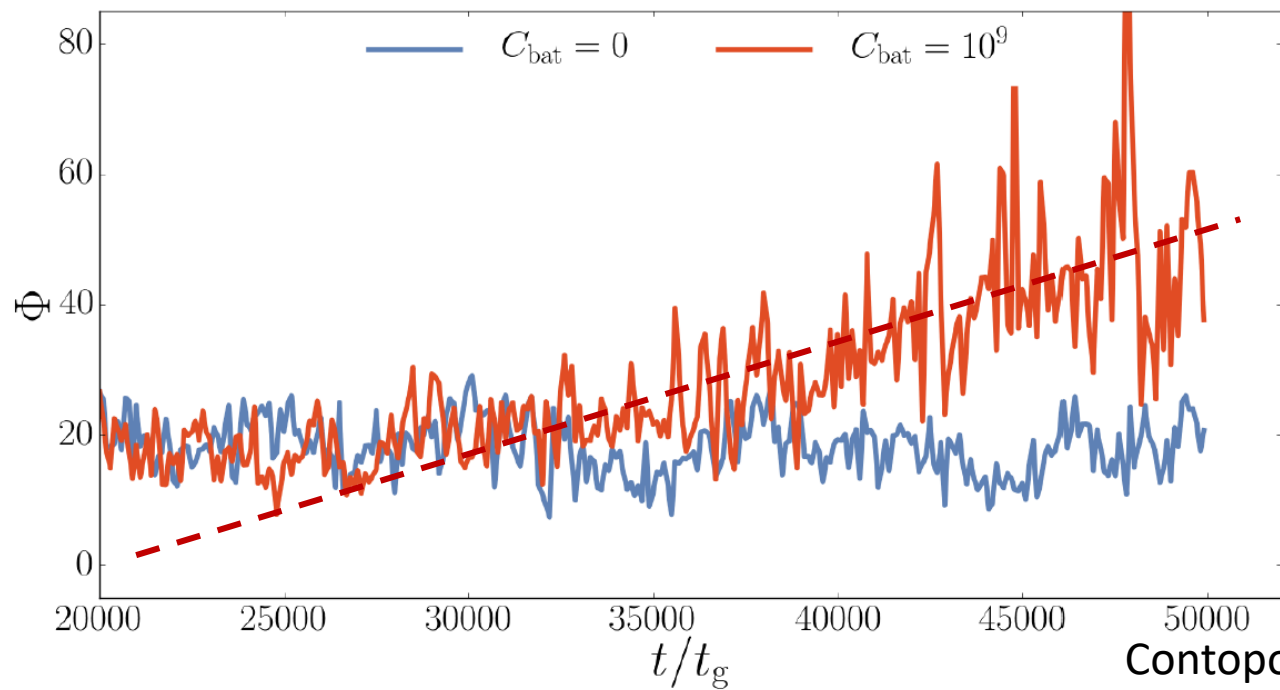
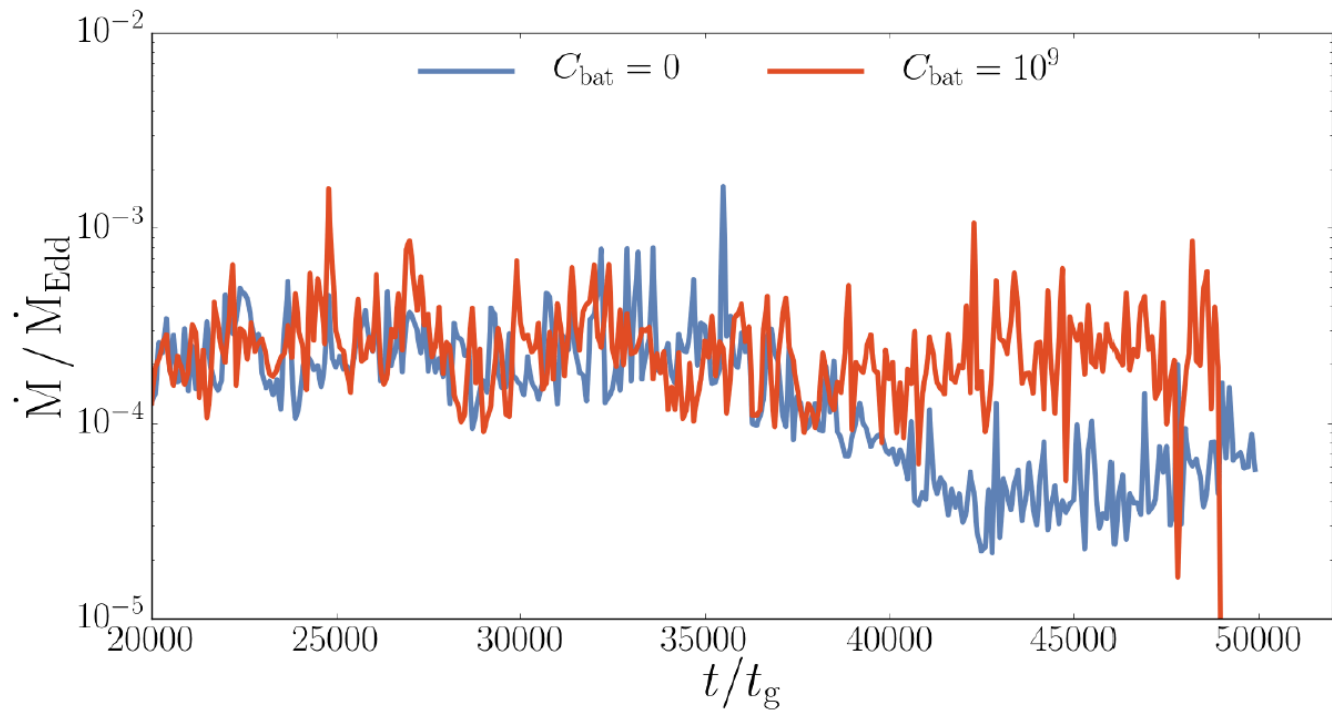


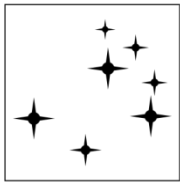
DB: sil4568.silo
Cycle: 0 Time:45680



DB: sil4800.silo
Cycle: 0 Time:48000







**Κέντρο Ερευνών Αστρονομίας
και Εφαρμοσμένων Μαθηματικών**
της Ακαδημίας Αθηνών

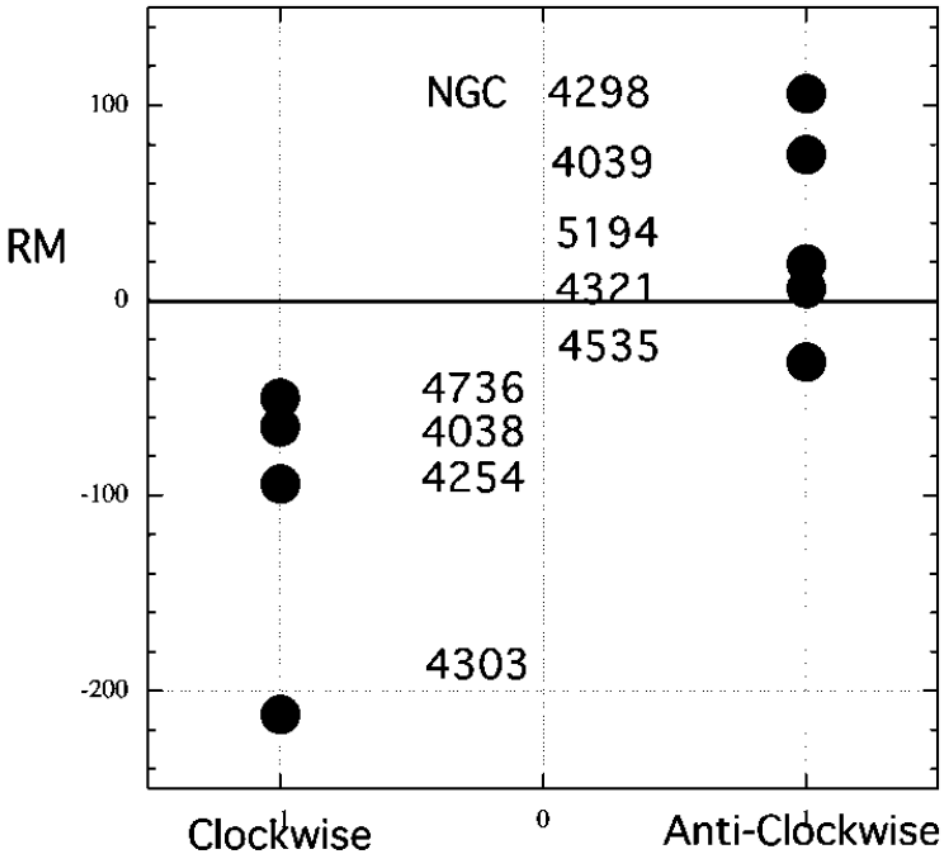
Observational confirmation of the Cosmic Battery

collaboration with Denise Gabuzda (Cork)
Jose Gomez and collaborators (Granada)

B along Ω in the black hole

B opposite Ω in the disk

Internal Faraday Rotation Measures



“Magnetism along spin”, Lynden-Bell 2013

B along Ω in the black hole

→ “ $B_\phi < 0$ ” in the bh jet

irrespective of Ω !

B opposite Ω in the disk

→ “ $B_\phi > 0$ ” in the disk wind irrespective of Ω

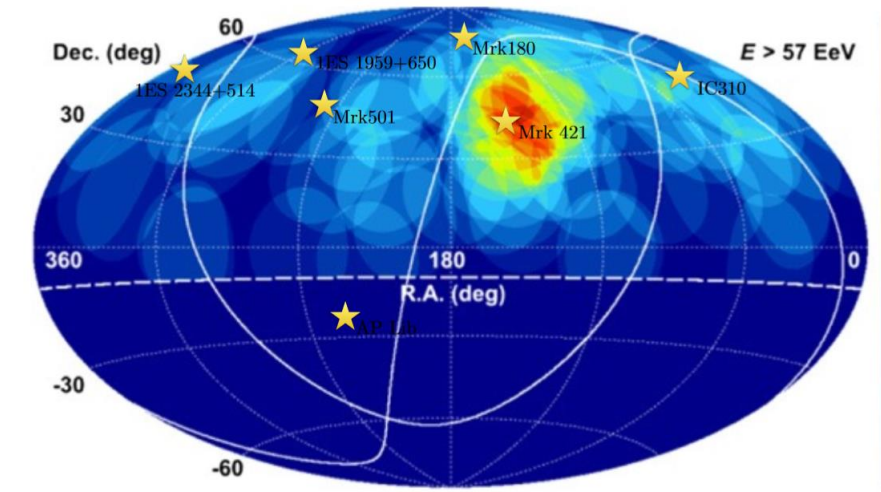
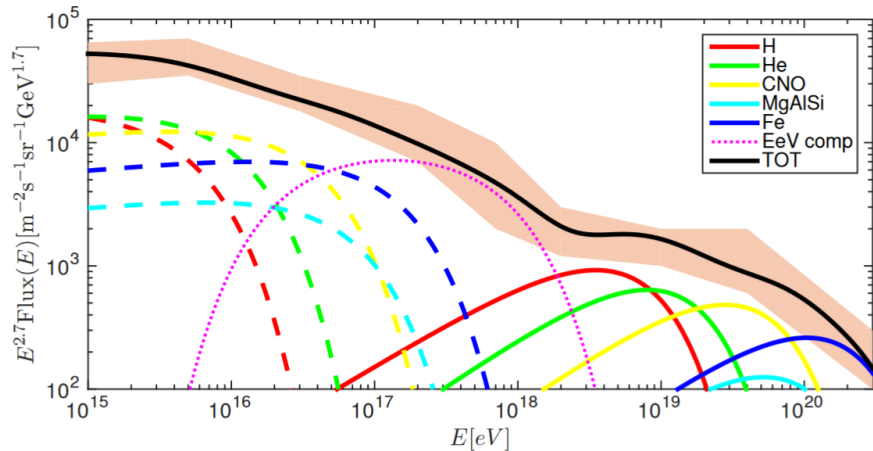
An Original Mechanism for the Acceleration of Ultra-High-Energy Cosmic Rays

Damiano Caprioli

University of Chicago, Department of Astronomy & Astrophysics, 5640 S Ellis Ave., Chicago, IL 60637, USA

Abstract

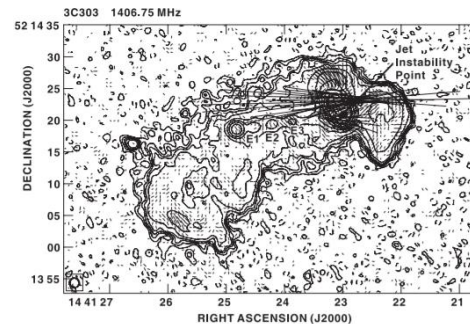
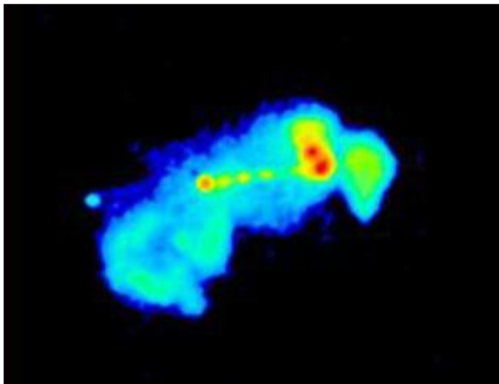
We suggest that ultra-high-energy (UHE) cosmic rays (CRs) may be accelerated in ultra-relativistic flows via a one-shot mechanism, the “espresso” acceleration, in which already-energetic particles are generally boosted by a factor of $\sim \Gamma^2$ in energy, where Γ is the flow Lorentz factor. More precisely, we consider blazar-like jets with $\Gamma \gtrsim 30$ propagating into a halo of “seed” CRs produced in supernova remnants, which can accelerate UHECRs up to 10^{20} eV. Such a re-acceleration process naturally accounts for the chemical composition measured by the Pierre Auger Collaboration, which resembles the one around and above the knee in the CR spectrum, and is consistent with the distribution of potential sources in the local universe; particularly intriguing is the coincidence of the powerful blazar Mrk 421 with the hotspot reported by the Telescope Array Collaboration.



“ $B_\phi < 0$ ” (not “ $B_\phi > 0$ ”!): clearly non-MHD

IN BRIEF 15 June 2011

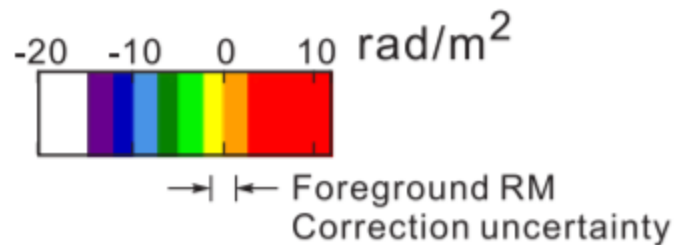
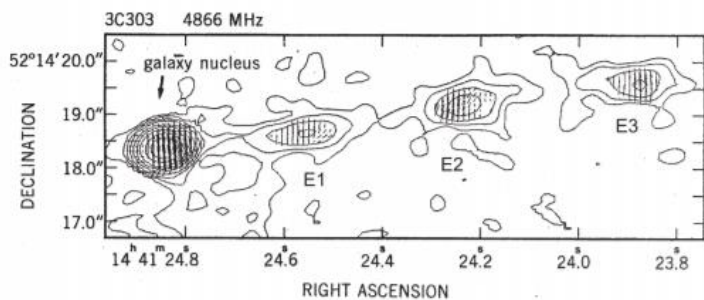
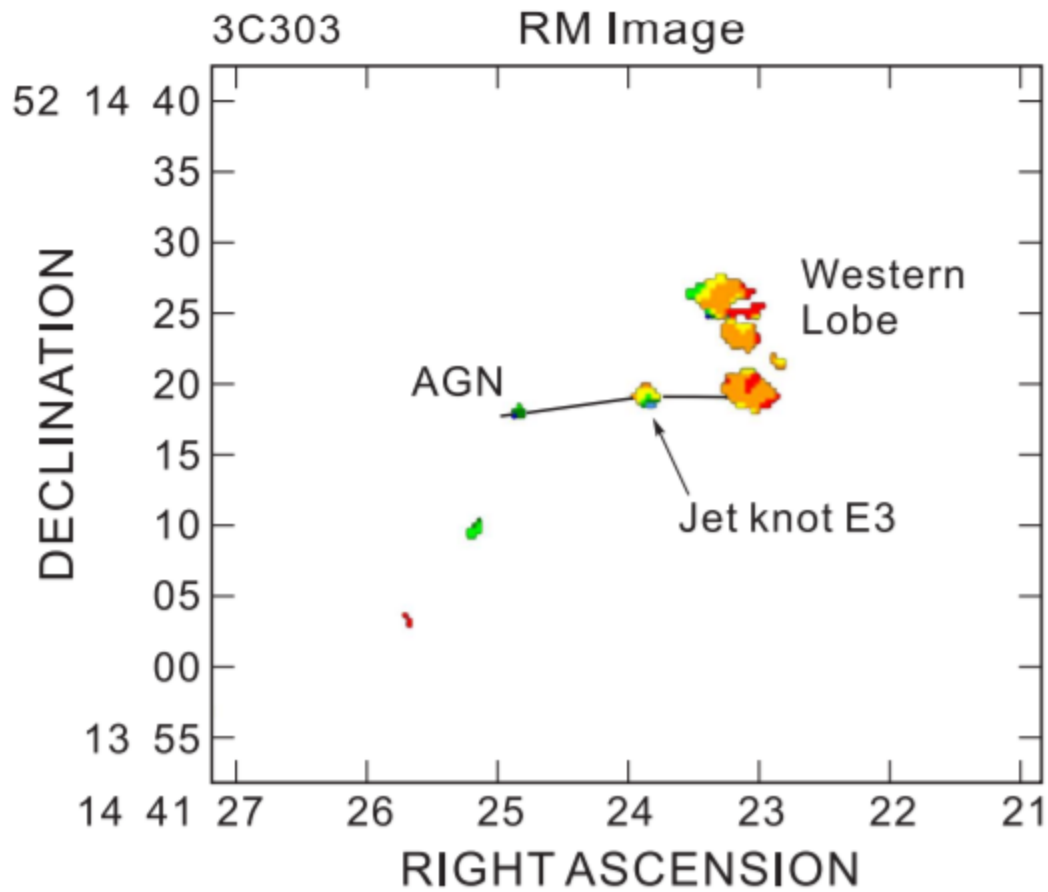
Universe's highest electric current found



A COSMIC jet 2 billion light years away is carrying the highest electric current ever seen: 10^{18} amps, equivalent to a trillion bolts of lightning.

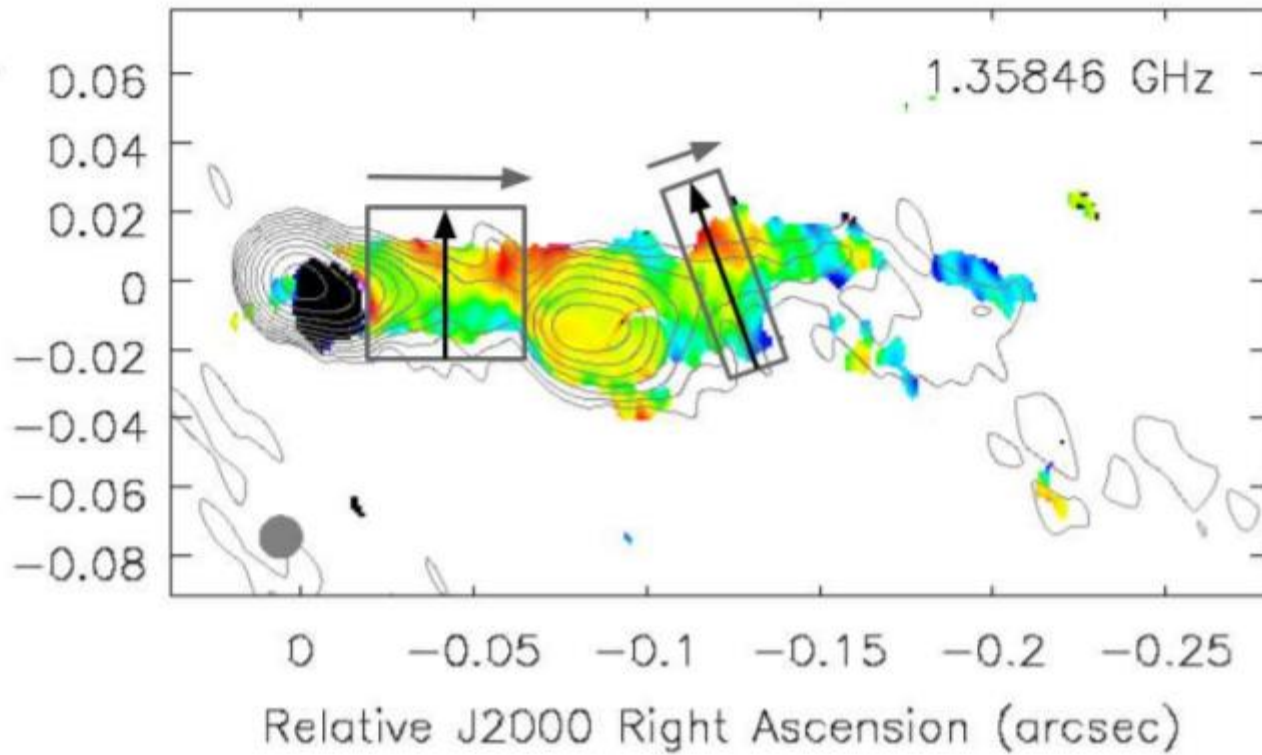
[Philipp Kronberg](#) of the University of Toronto in Canada and colleagues measured the alignment of radio waves around a galaxy called 3C303, which has a giant jet of matter shooting from its core. They saw a sudden change in the waves' alignment coinciding with the jet. "This is an unambiguous signature of a current," says Kronberg.

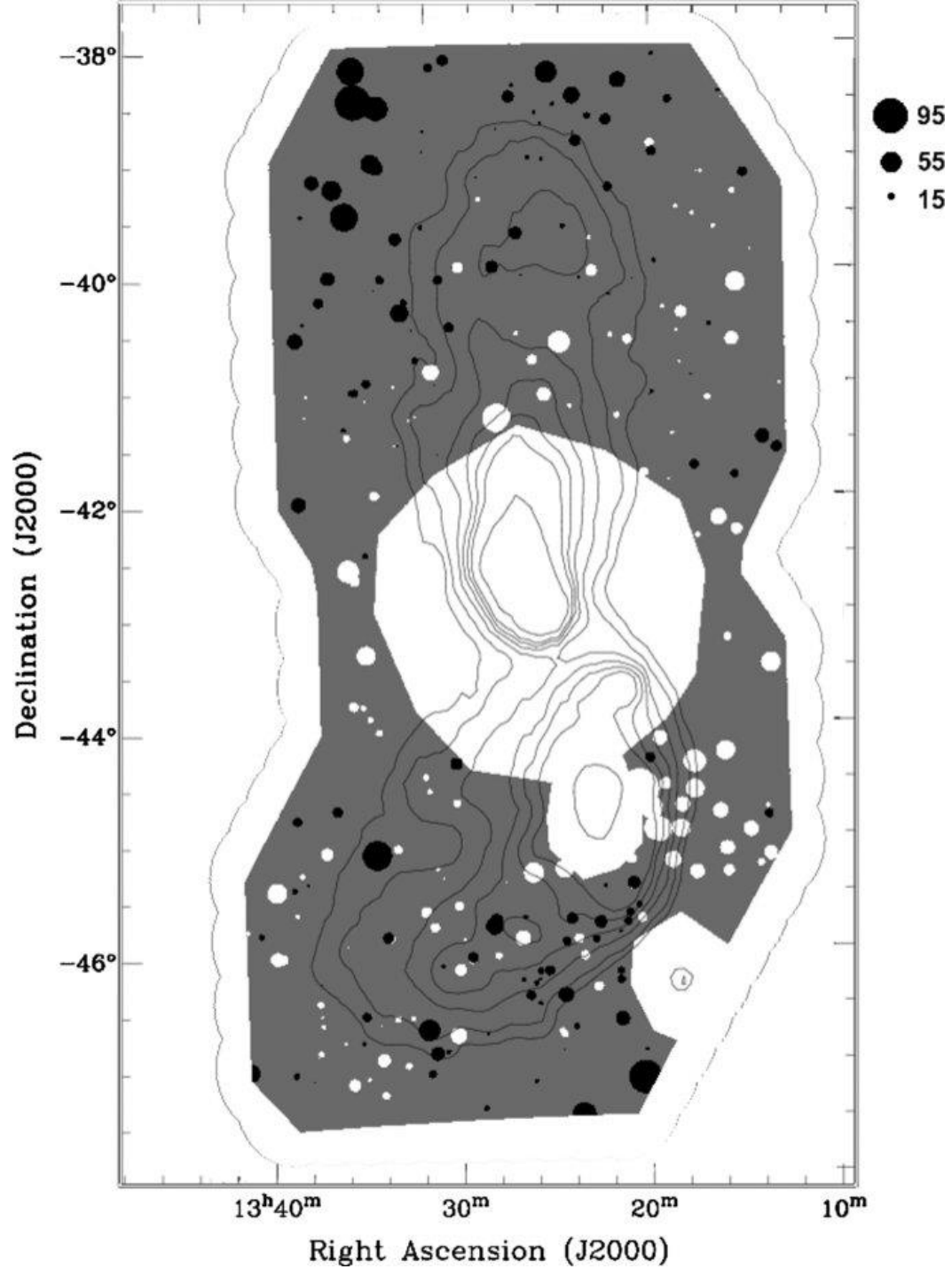
The team thinks magnetic fields from a colossal black hole at the galaxy's core are generating the current, which is powerful enough to light up the jet and drive it through interstellar gases out to a distance of about 150,000 light years (arxiv.org/abs/1106.1397).

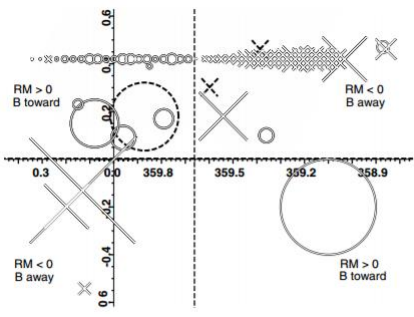
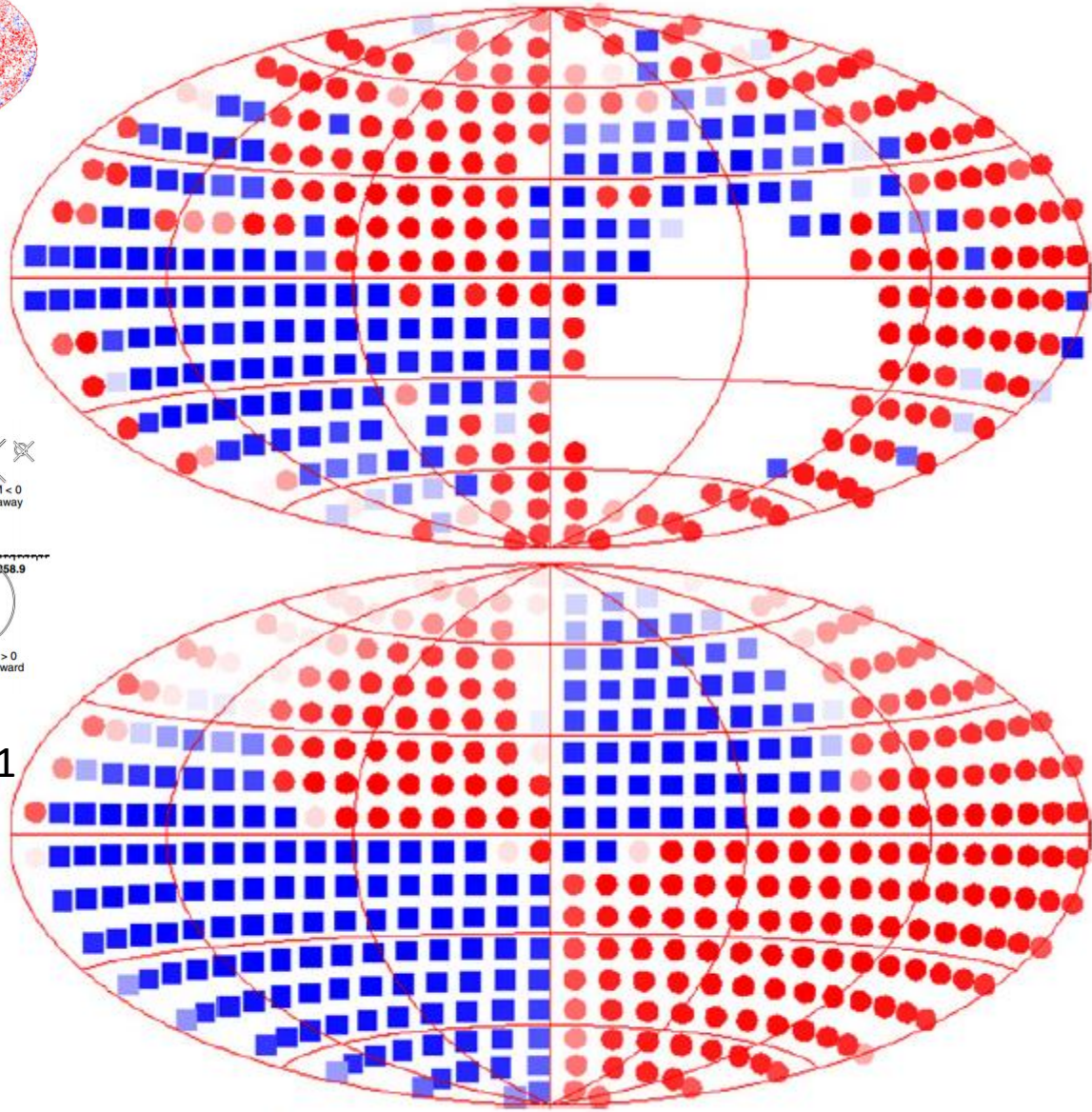
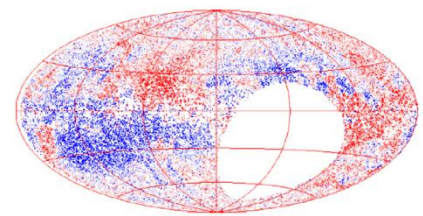


Relative J2000 Declination (arcsec)

3C120 Circular Beam







Law et al. ApJ 2011

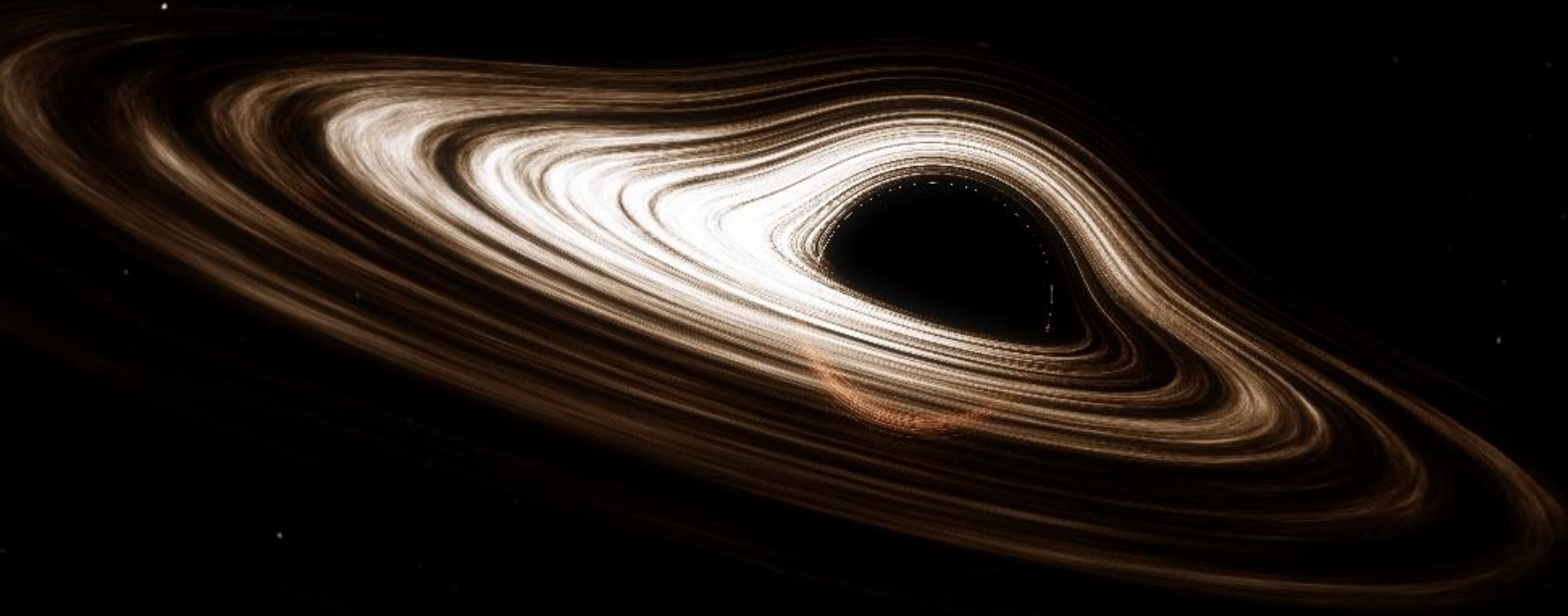
Figure 8. Average RMs in bins. Red circles (blue squares) represent positive (negative) RMs. The color intensity reflects the absolute magnitude. Top: NVSS data. Bottom: best-fit model.

Out of 89 kpc-scale jets
18 with RM gradients

Electric currents all outward.

Clearly a non-MHD effect!

The magnetic field topology
according to the Cosmic Battery:



e^-p^+
disk wind

e^-e^+
relativistic BH jet

region empty of MF

B opposite Ω
I away from BH

B along Ω

