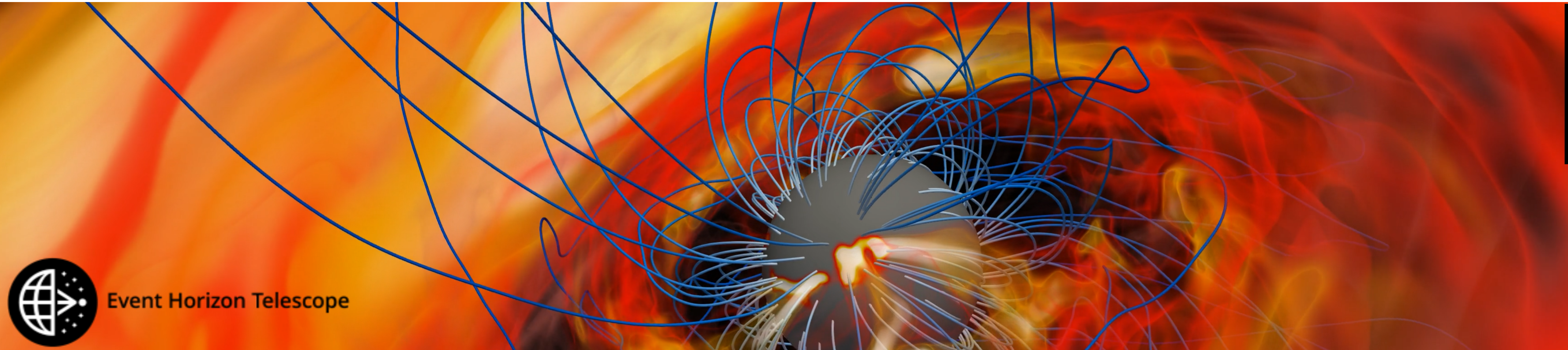
Magnetospheres, jets and pulsed emission from compact objects

CAMK 2025 -- Oliver Porth

University of Amsterdam



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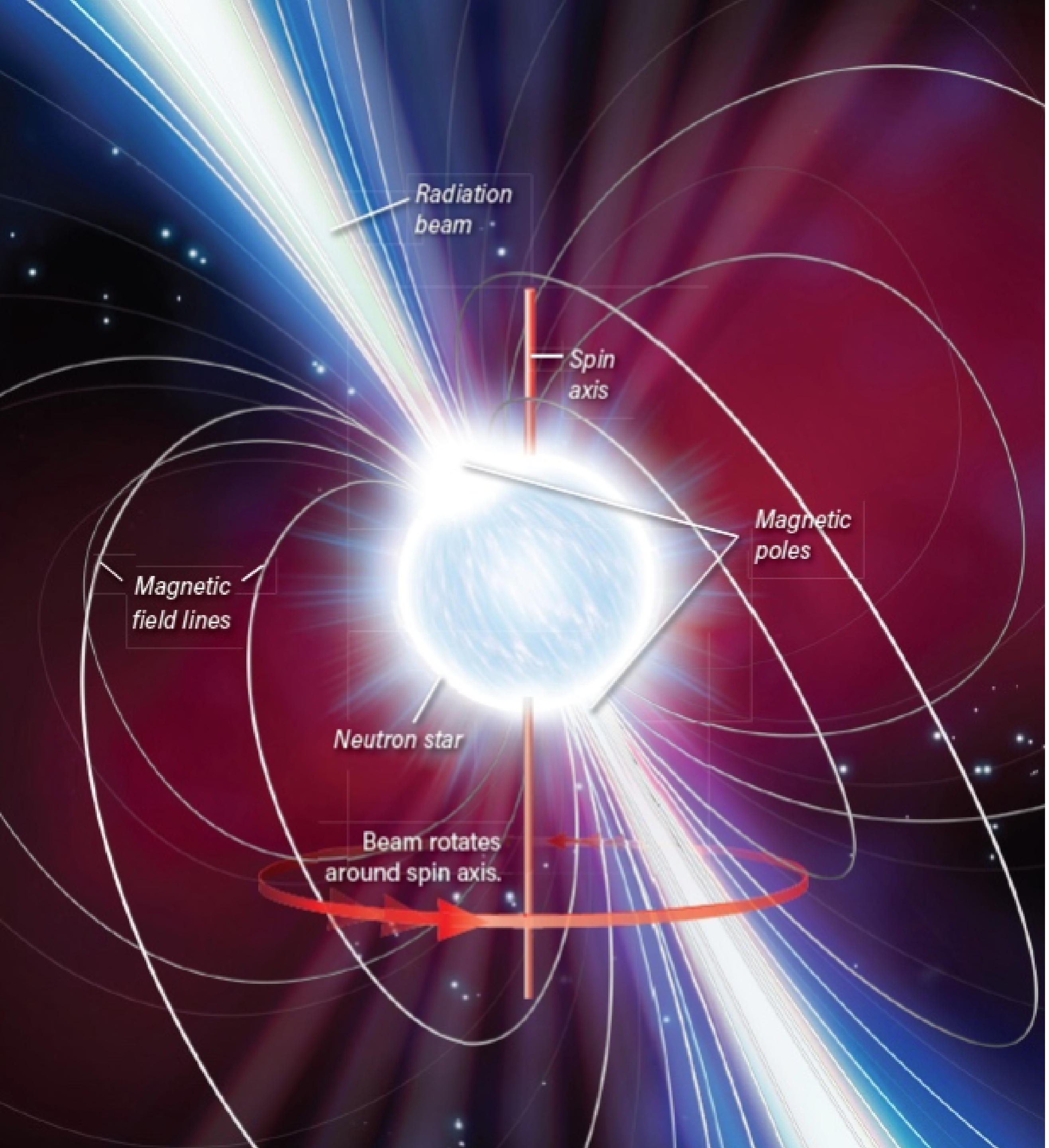
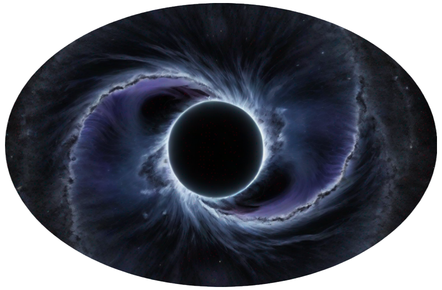
What do we know?



We know a lot about the Pulsar magnetosphere (just not how it emits radio signals :)

- vacuum solution (Deutsch 1955)
- force free models (Contopoulos et al. 1999, Spitkovsky 2006, Gralla et al. 2016/17)
- Full oblique MHD models (Tchekhovskoy 2013)
- Ab-initio PIC models (in GR) (Philippov&Spitkovsky 2014/18, Philippov 2015, Kalapotharakos et al. 2018)
- Reconnection and particle acceleration (Sironi&Spitkovsky 2011, Cerutti&Philippov 2017-21, Werner et al. 2016, Petropolou et al. 2018)
- Modeling of multi-wavelength lightcurves (e.g. Bai&Spitkovsky 2010, Cerutti et al. 2016, Chen et al. 2020, Kalapotharakos et al. 2021)

How much of this carries over to:



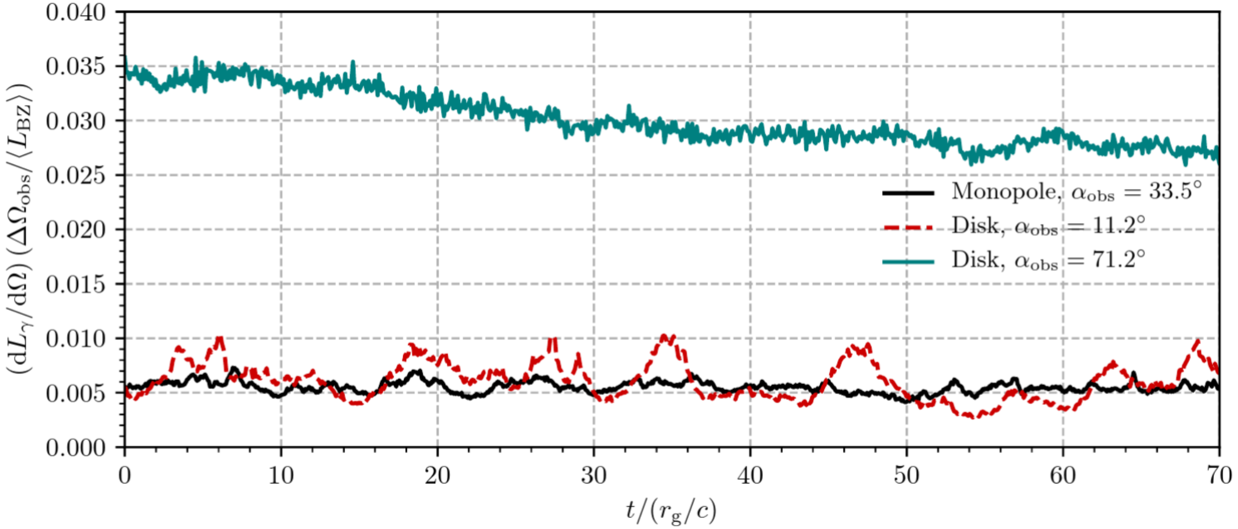
The (isolated) black hole magnetosphere

Does it even exist?

First principles modeling of black hole magnetospheres

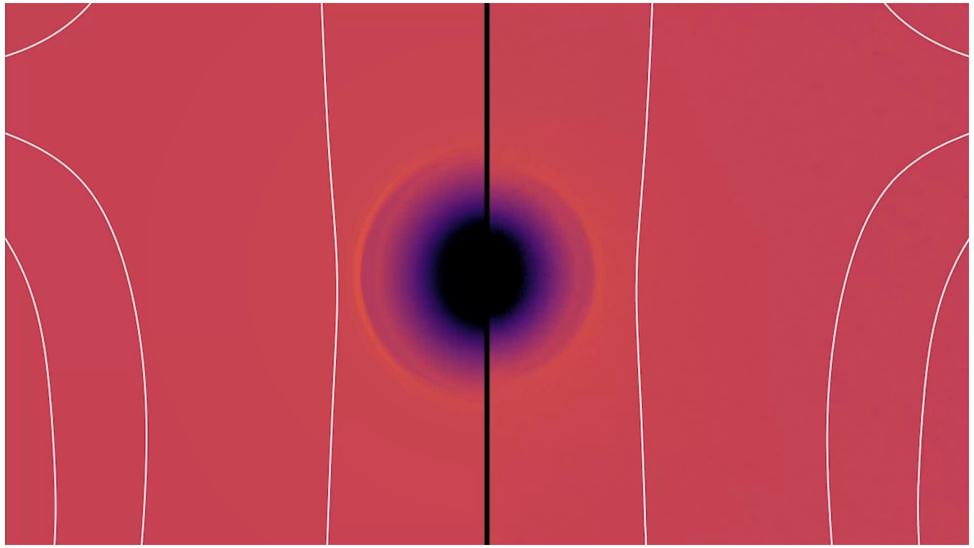
Towards (radiative) PIC and emission

Levinson & Cerutti 2018
Parfrey et al. 2019
Crinquand et al. 2020



Synthetic lightcurves (Crinquand et al. 2020)

GRMHD (left) and GRPIC (right) comparison, Galishnikova et al. 2023

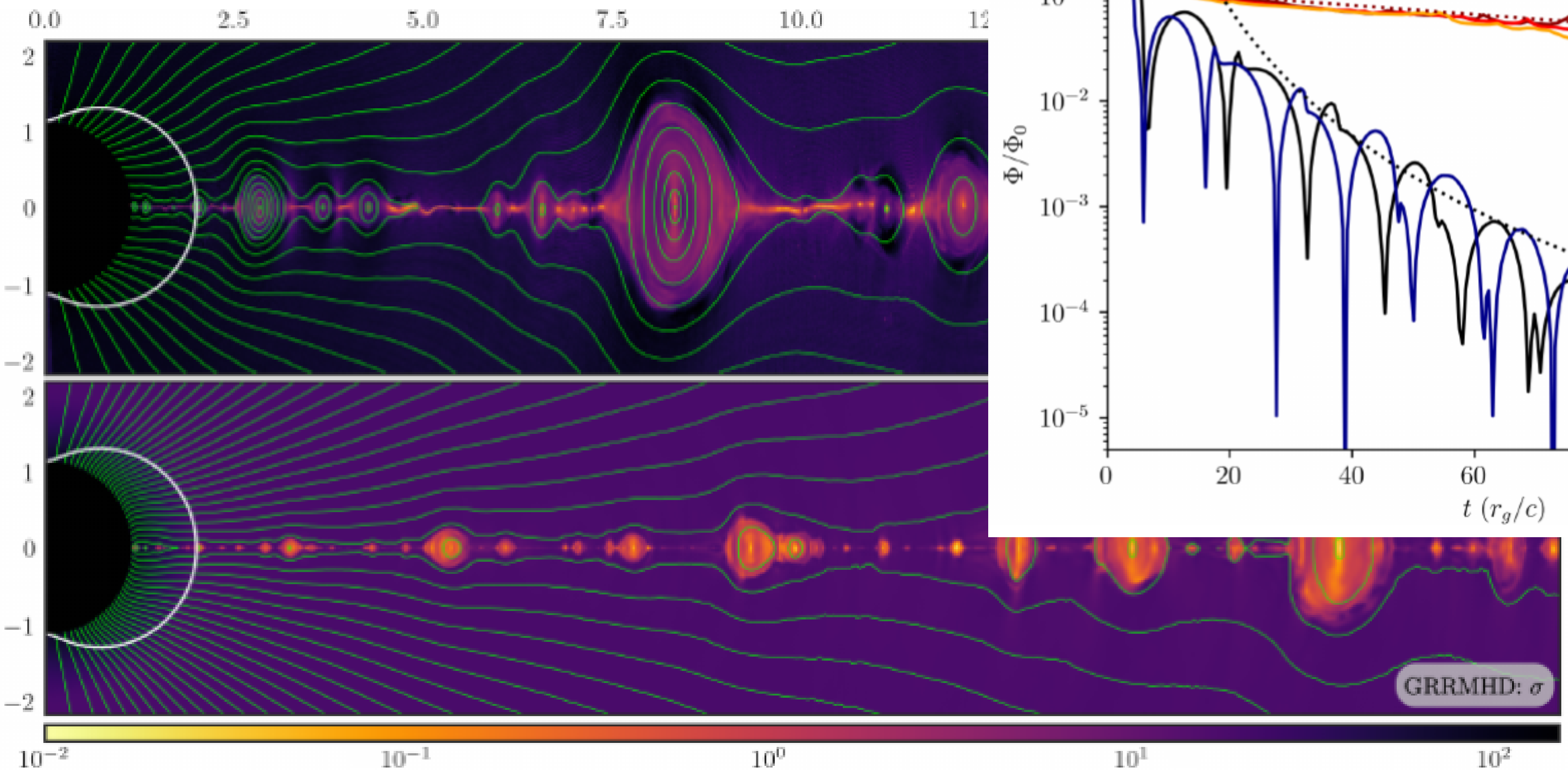


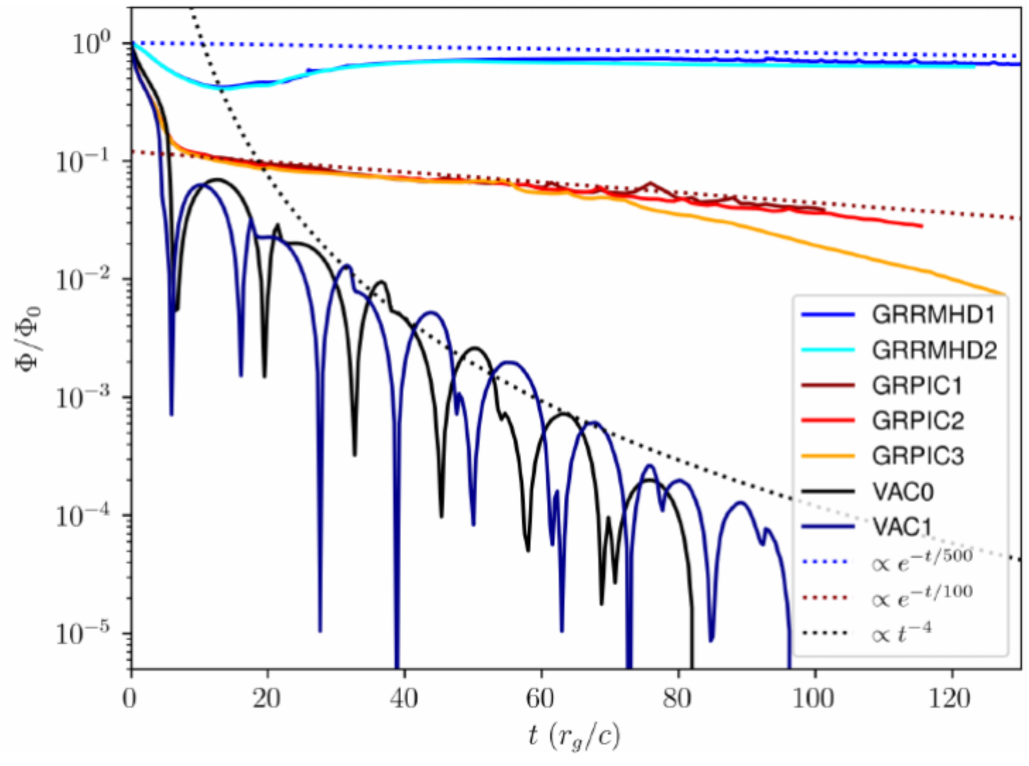
Including the accretion flow and Ions

El Mellah et al. 2022
Galishnikova et al. 2023
Vos et al. 2024
Mehlhaff et al. 2025

Isolated black hole magnetosphere

How does a black hole loose its magnetic hair?

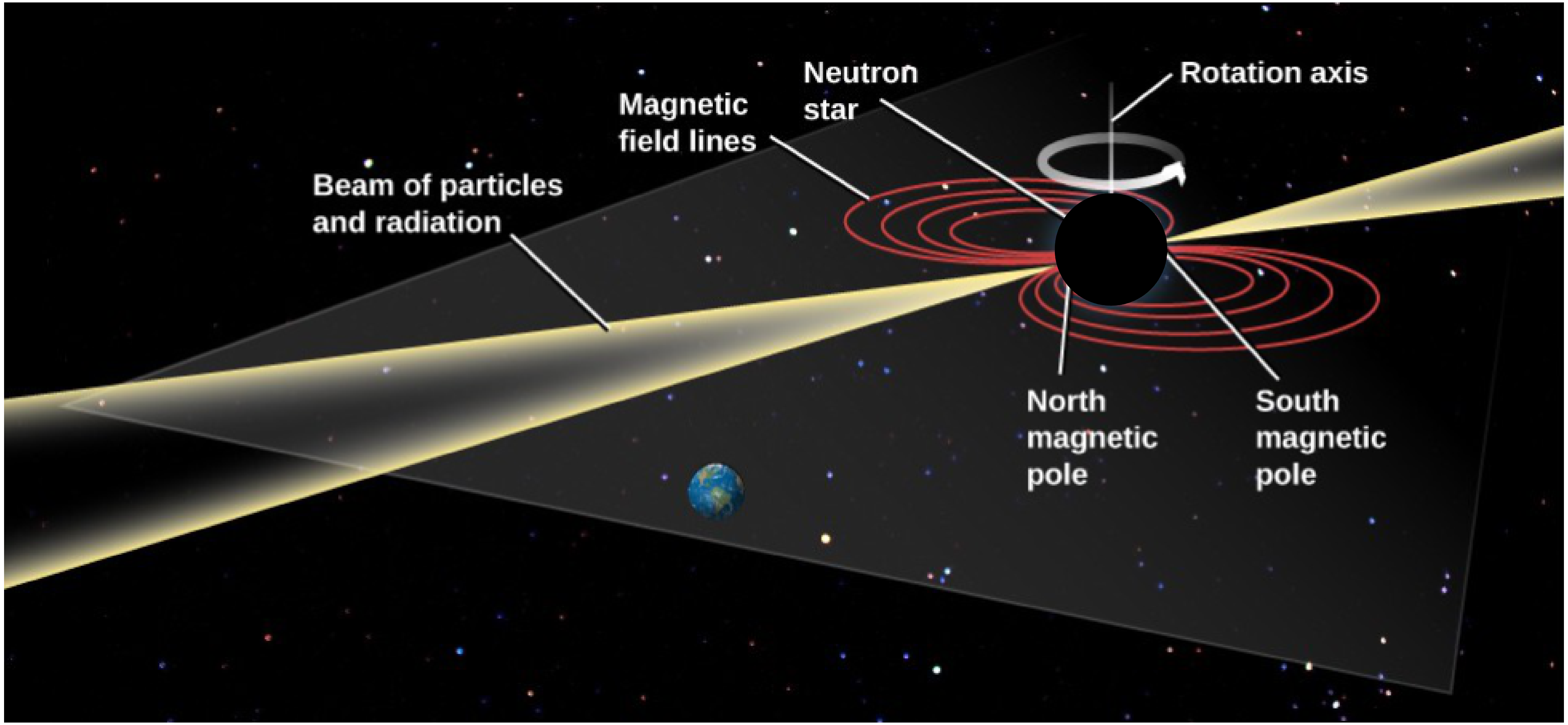




Even if there is conducting plasma around, the magnetic flux on the horizon decays exponentially through an equatorial **current sheet**

Bransgrove et al. 2021, Lyutikov & McKinney 2011

If magnetic field threads BH horizon (for a while), can we build a black hole pulsar?



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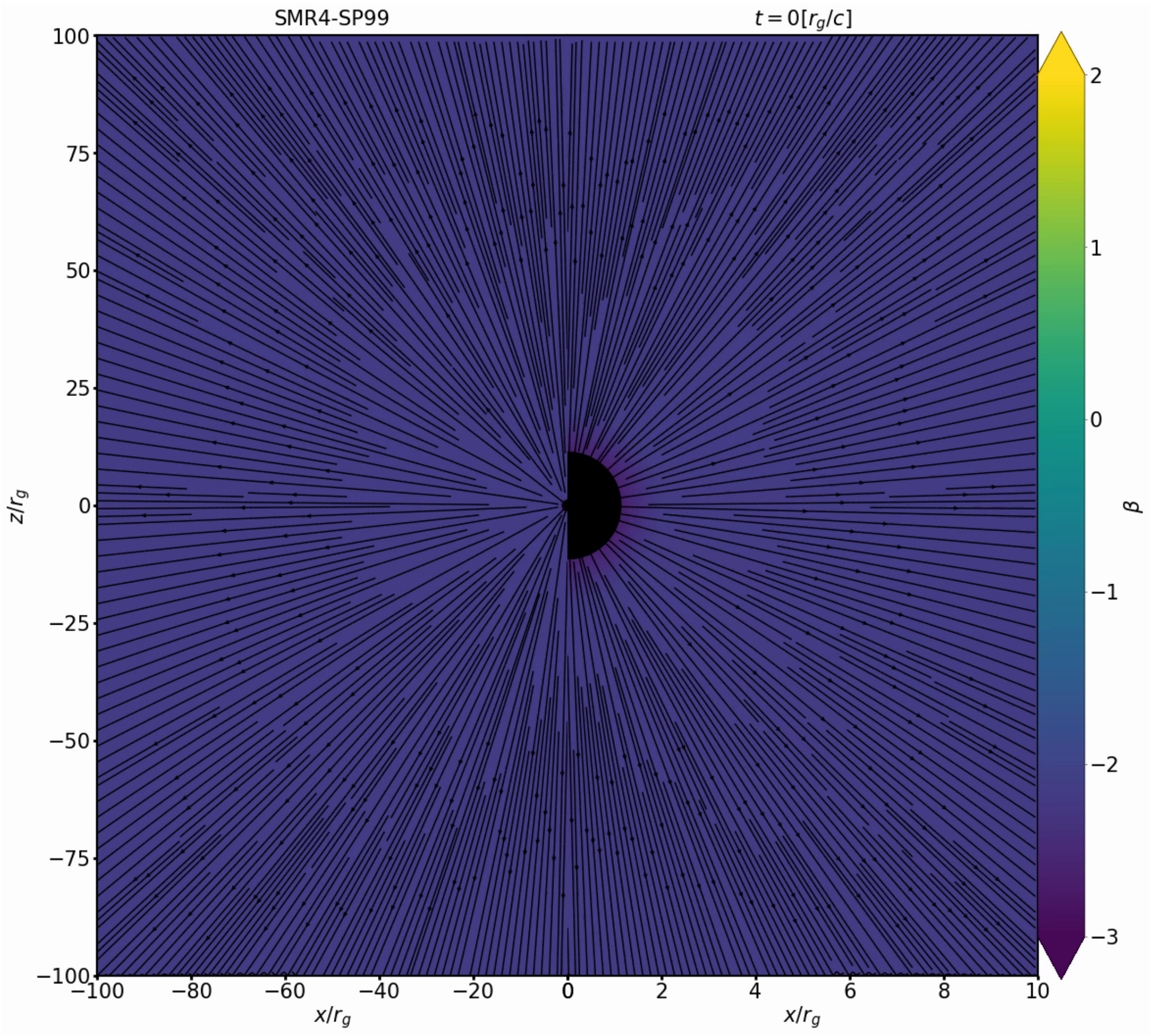
https://doi.org/10.3847/2041-8213/ad4a5b

Current Sheet Alignment in Oblique Black Hole Magnetospheres: A Black Hole Pulsar?

S. Selvi[1], O. Porth[1], B. Ripperda[2,3,4,5,6], and L. Sironi[6,7]

Sebastiaan Selvi, (phd 2024)

If magnetic field threads BH horizon, can we build a black hole pulsar?



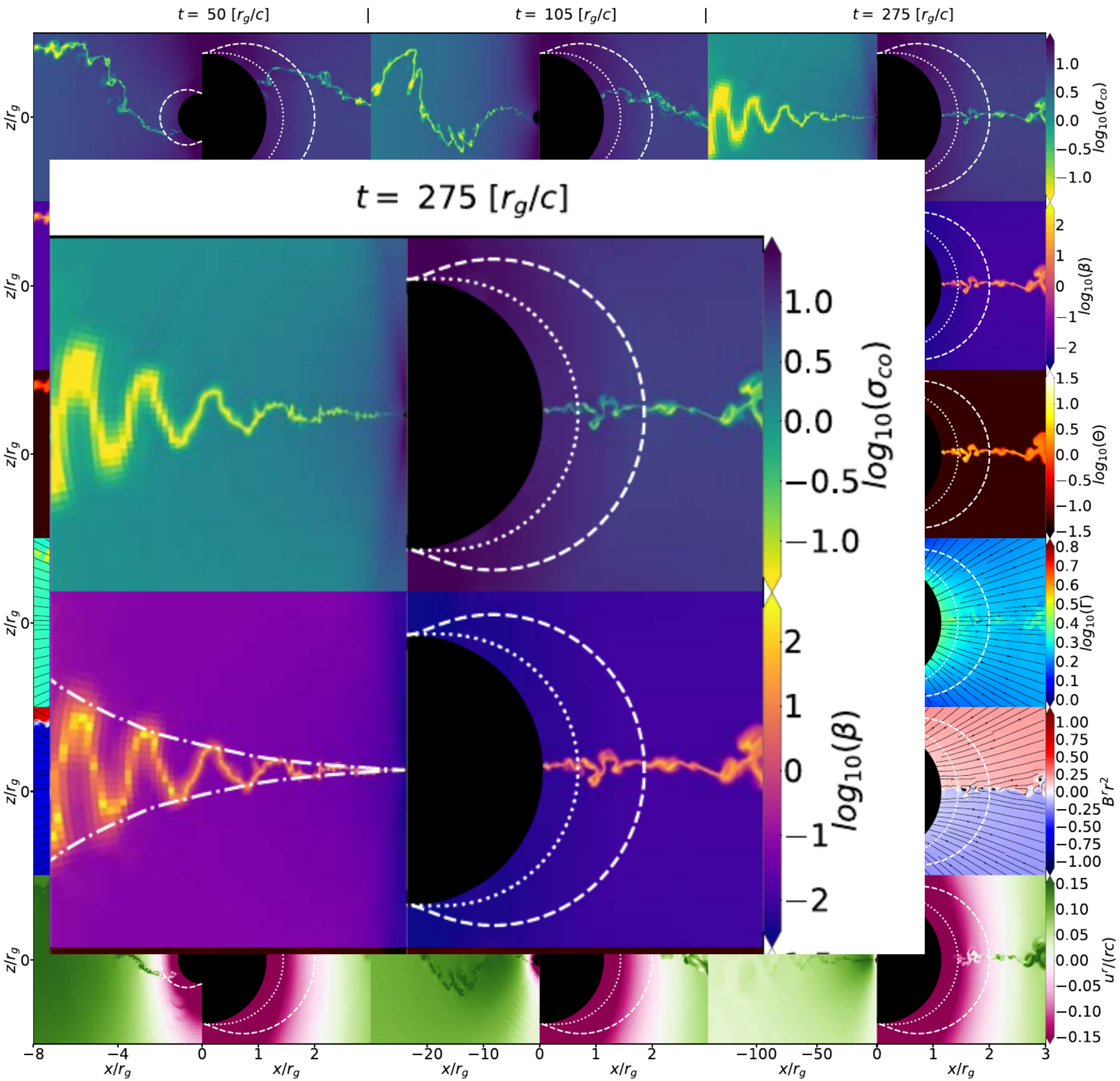
Plasma-β and velocity streamlines

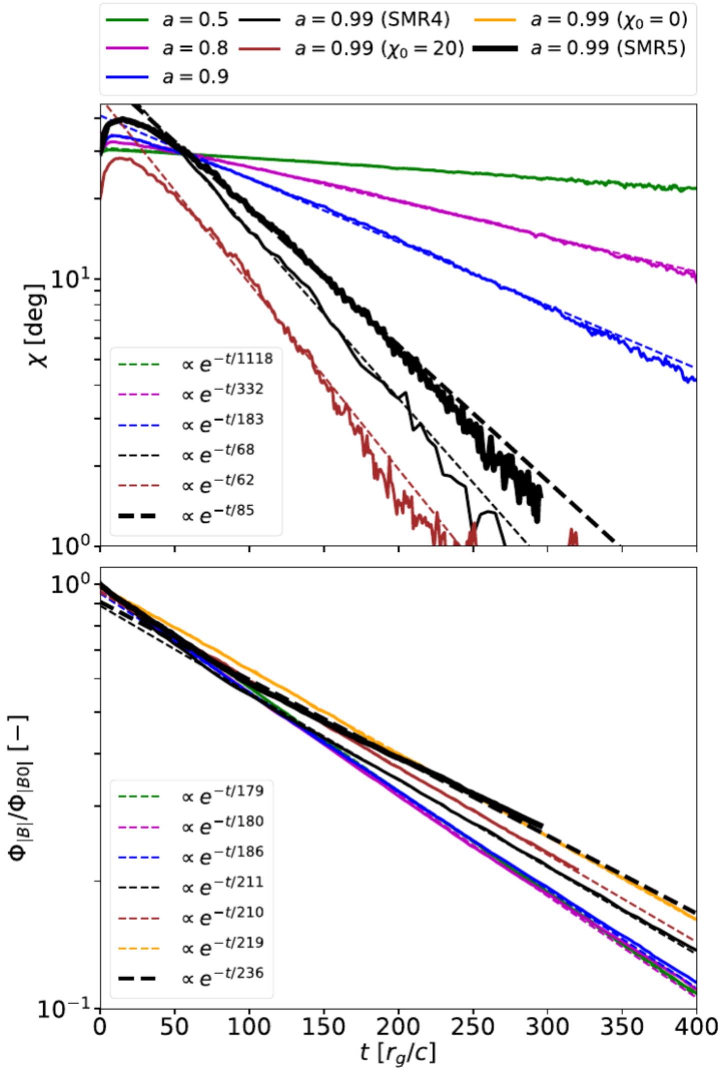
Initial condition:

- Split monopole magnetic field
- Inclined wrt. spin χ_0=30deg
- Spin a=0.5-0.99
- Highly magnetized σ_{co}>10
- Up to 2048x1024x2048 eff. cells (r,θ,φ)

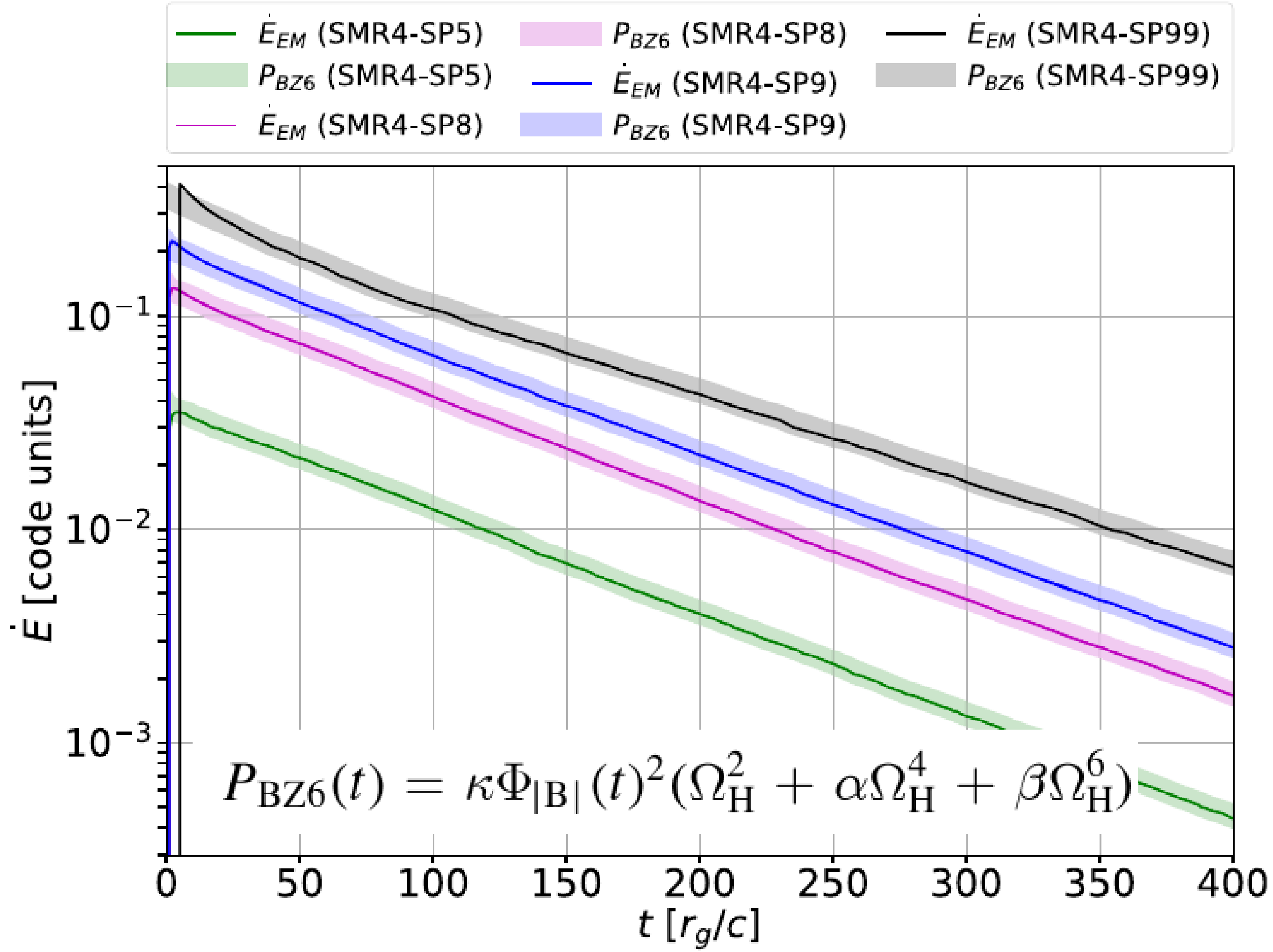
http://ww.bhac.science

If magnetic field threads BH horizon, can we build a black hole pulsar?





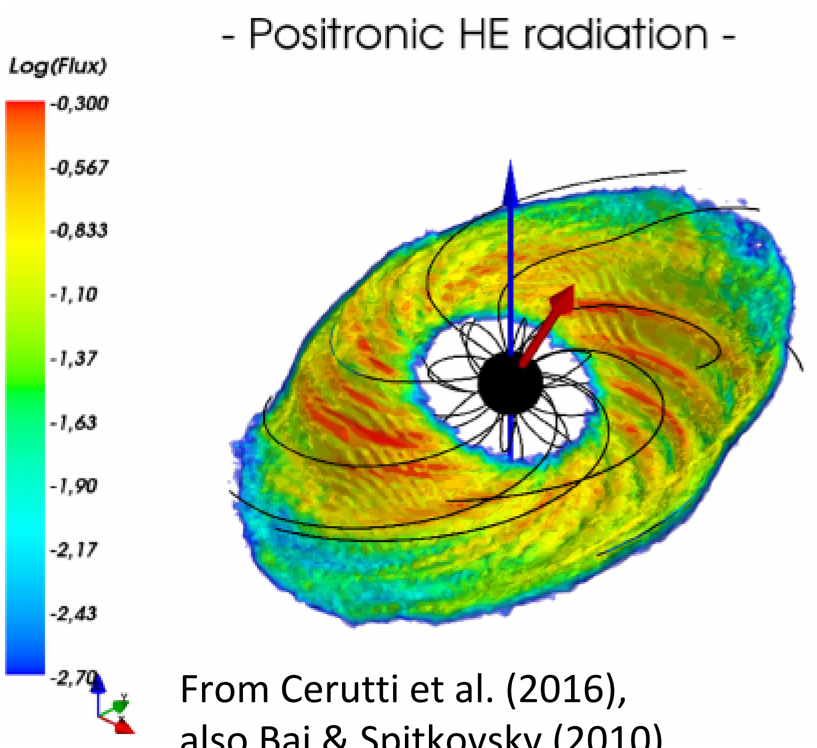
Extracted Power



At all times, the power is **well predicted by the BZ process** for a monopolar magnetosphere

Blandford & Znajek (1977), Tchekhovskoy et al. (2010)

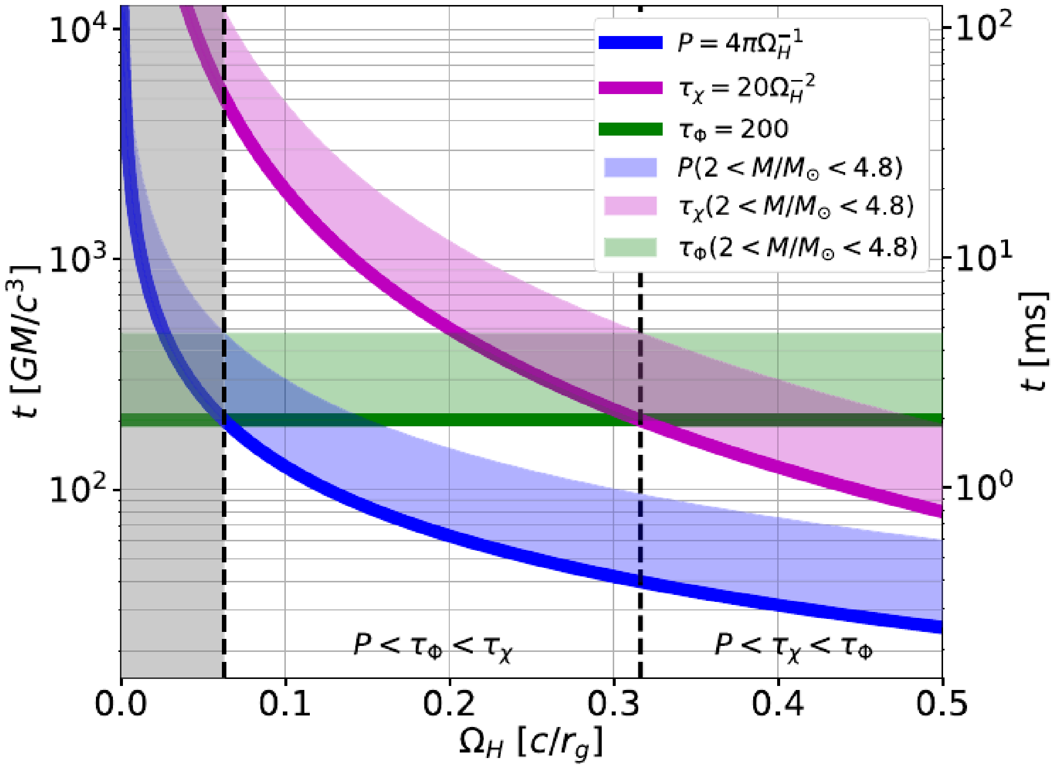
Emission from the current-sheet



From Cerutti et al. (2016), also Bai & Spitkovsky (2010)

Three timescales:

- Reconnection τ_ϕ
- Alignment τ_χ
- Spin period P

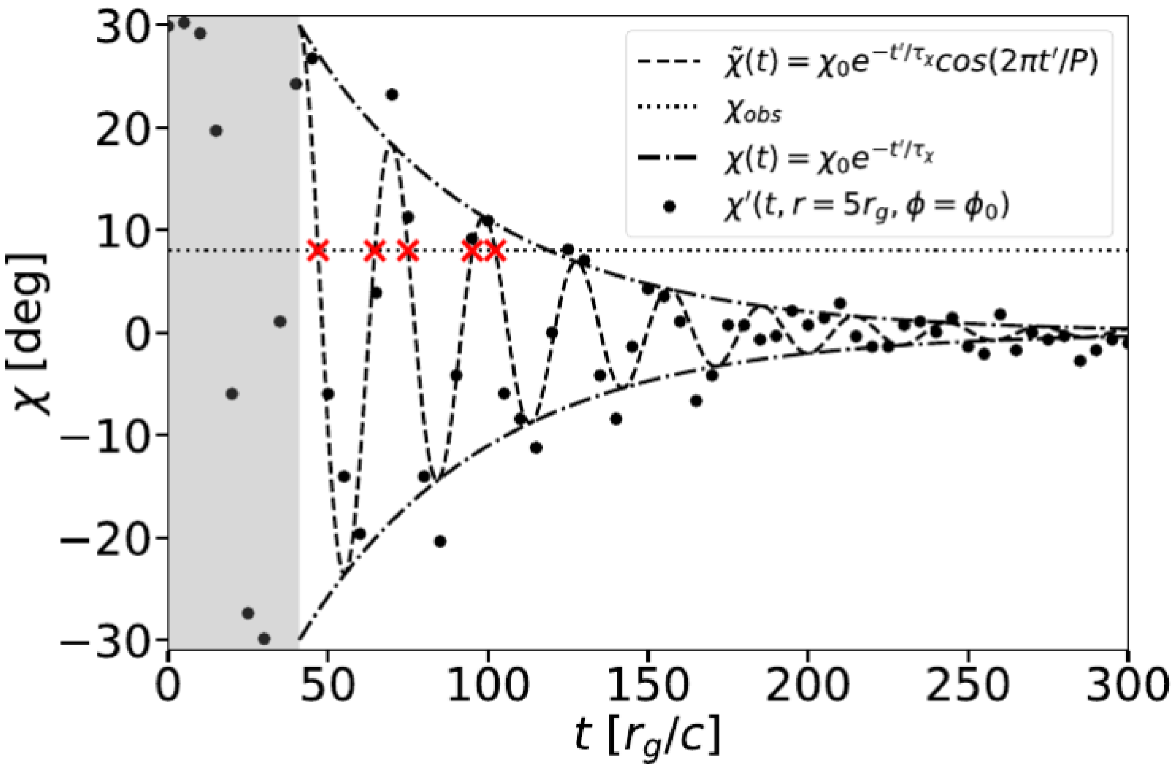


This could give rise to a **rapid** transient em signal with unique characteristic

Different story for SMBHs!

We have yet to observe it…

What to do with this?



$$\tau_\chi(\Omega_{\rm H}) \simeq 20\Omega_H^{-2}\left[\frac{GM}{c^3}\right]$$ (Empirical)

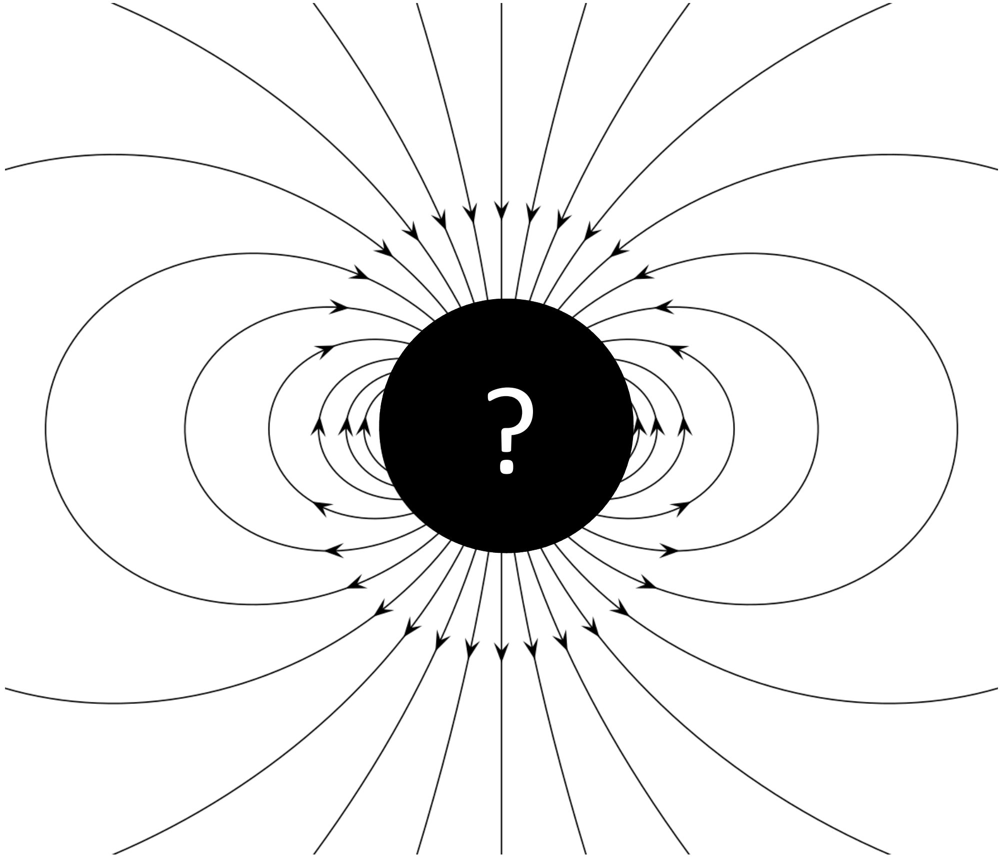
$$P(\Omega_{\rm H}) = 4\pi\Omega_H^{-1}\left[\frac{GM}{c^3}\right]$$

Extract τ_χ and P from modeling the pulsed arrival times

Obtain mass and spin!

$$M \sim 26\frac{(P\,[\mathrm{ms}])^2}{\tau_\chi[\mathrm{ms}]}M_\odot \qquad a \sim \frac{20\pi\tau_\chi P}{(100P^2 + \pi^2\tau_\chi^2)}$$

Universality of the aligned split monopole magnetosphere

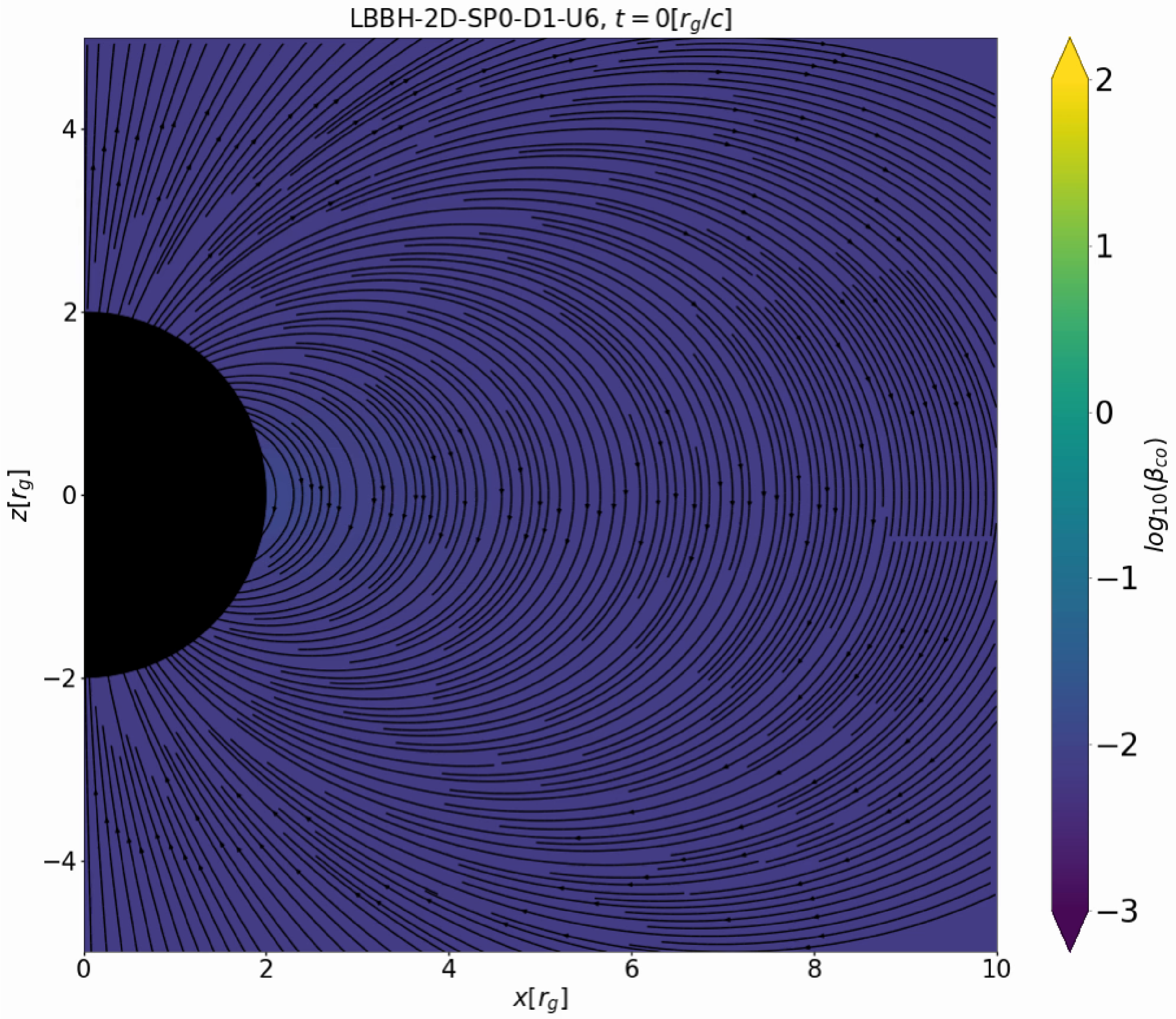


Wikipedia

Selvi et al. (submitted to ApJ)

Dipole …

Universality of the split monopole magnetosphere



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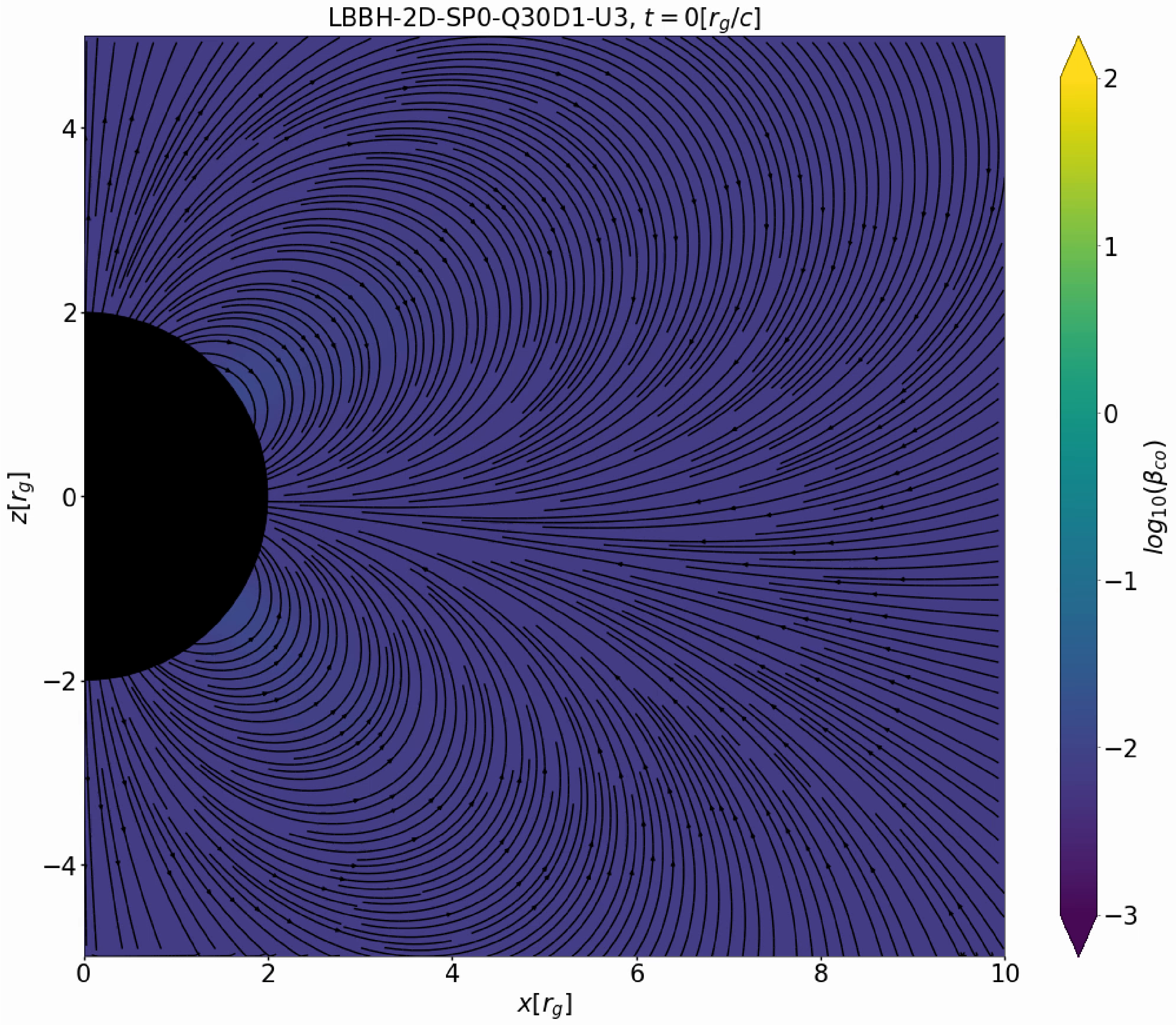
Quadru-dipole

Universality of the split monopole magnetosphere



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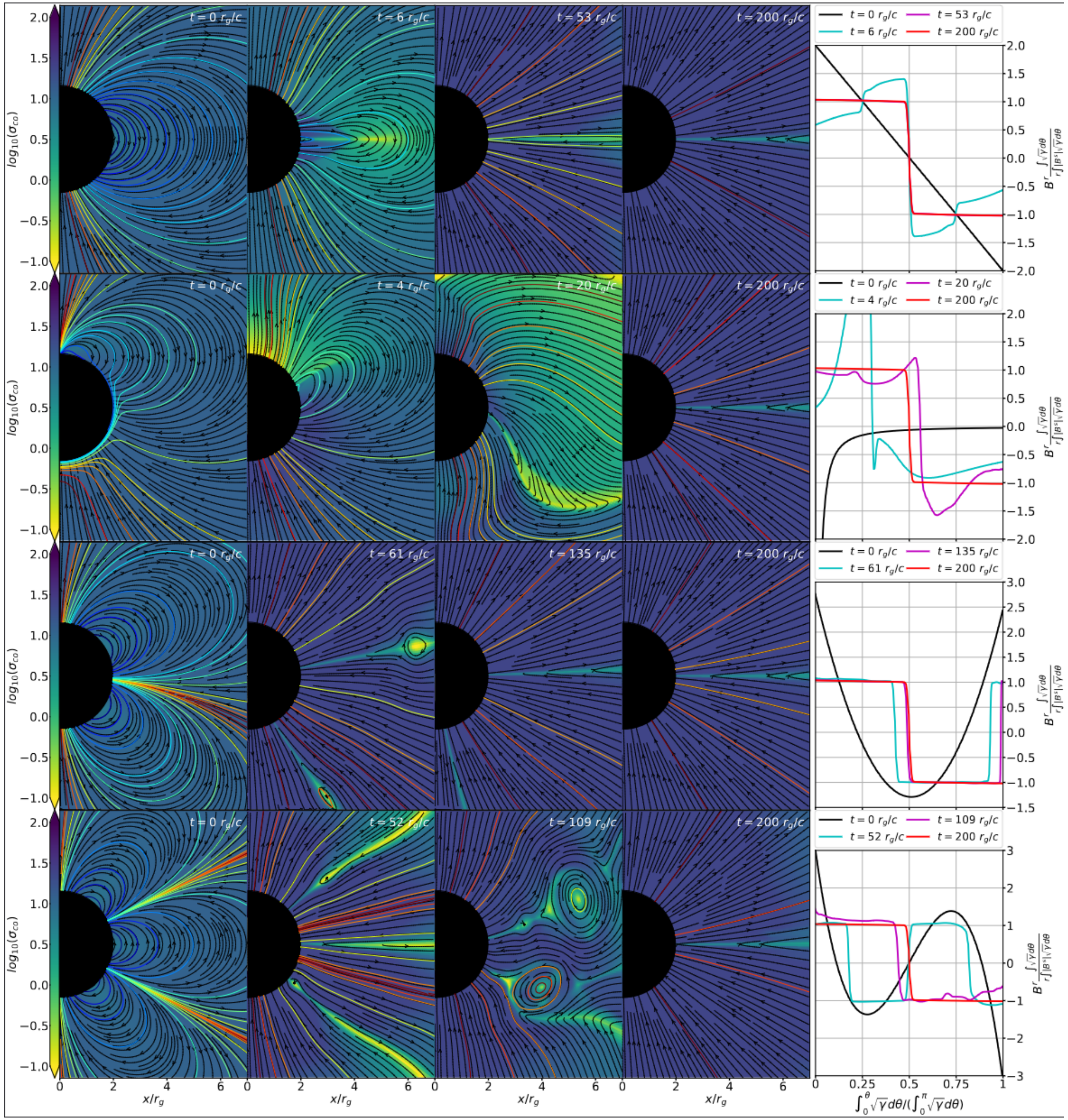


Universality of the split monopole magnetosphere

Two phases:

1. Magnetic loops are **expelled and accreted** unitil ~50GM/c^3
2. Current sheets **merge and migrate**

In phase 2:

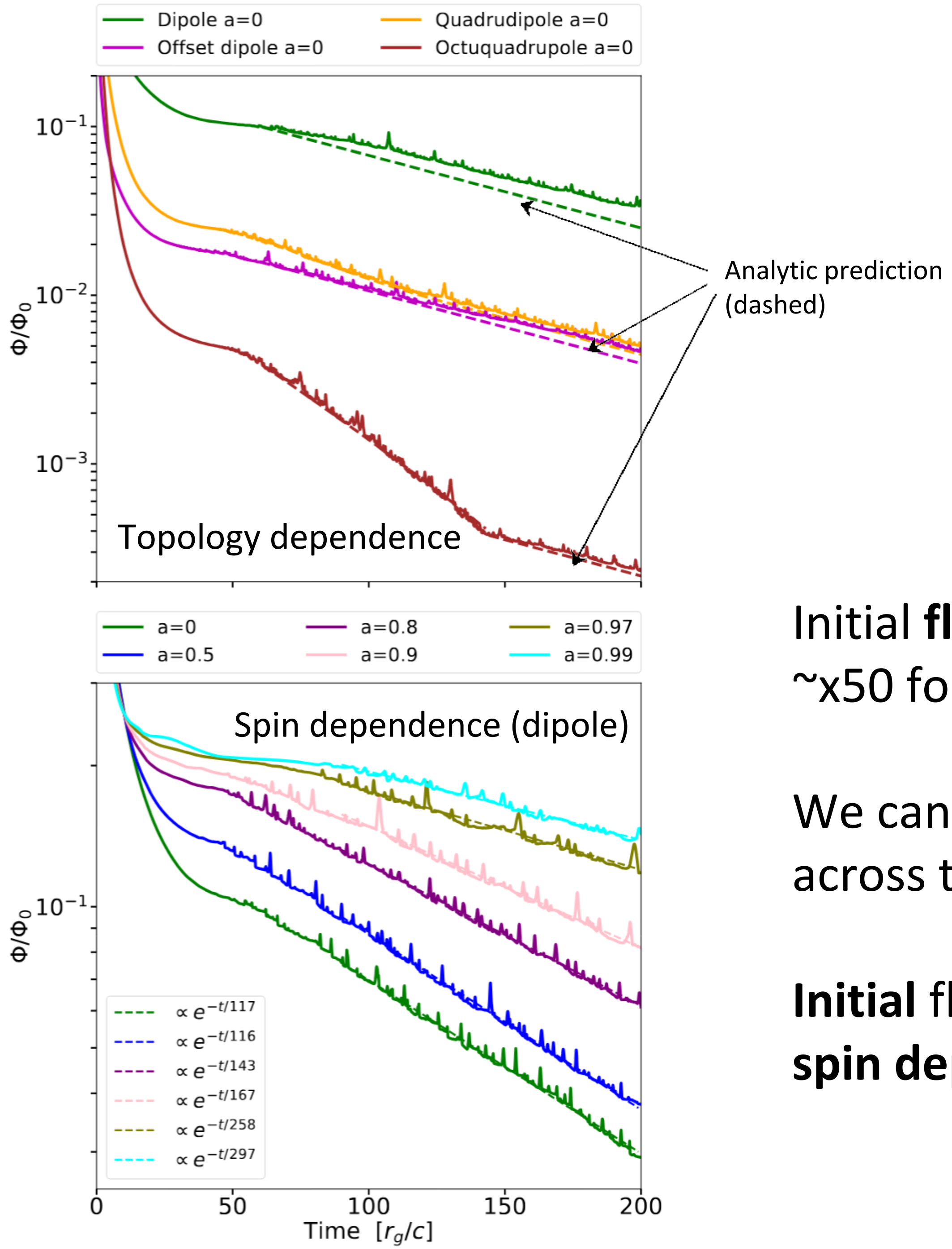
- Pressure balance redistributes flux across horizon

- Multiple current-sheets across the horizon, depending on initial topology

- Back to the split monopole after ~100 GM/c^3

Selvi et al. (submitted to ApJ)

Universality of the split monopole magnetosphere



$$\Phi_{\rm tot}(t) := \int_0^{2\pi}\int_0^{\pi} |B^s|\sqrt{\gamma}\, d\theta d\phi$$

(Magnetic flux at infinity)

Initial **flux drop depends on magnetic topology**. E.g. ~x50 for the offset dipole

We can **analytically predict** how current-sheets move across the horizon

Initial flux drop **and reconnecting** flux decay are both **spin dependent**. Smaller/Slower for larger spins.

Selvi et al. (submitted to ApJ)

Analytic model of current sheet migration

Reconnected flux in each current sheet:

$$\frac{\partial \Phi_1}{\partial t} = -\frac{\alpha v^{\widehat{\theta}}}{4 r_{\mathrm{g}}} \Phi_{\mathrm{tot}} \sin(\theta_{\mathrm{cs},1})$$

$$\frac{\partial \Phi_2}{\partial t} = -\frac{\alpha v^{\widehat{\theta}}}{4 r_{\mathrm{g}}} \Phi_{\mathrm{tot}} \left(\sin(\theta_{\mathrm{cs},1}) + \sin(\theta_{\mathrm{cs},2})\right)$$

$$\vdots$$

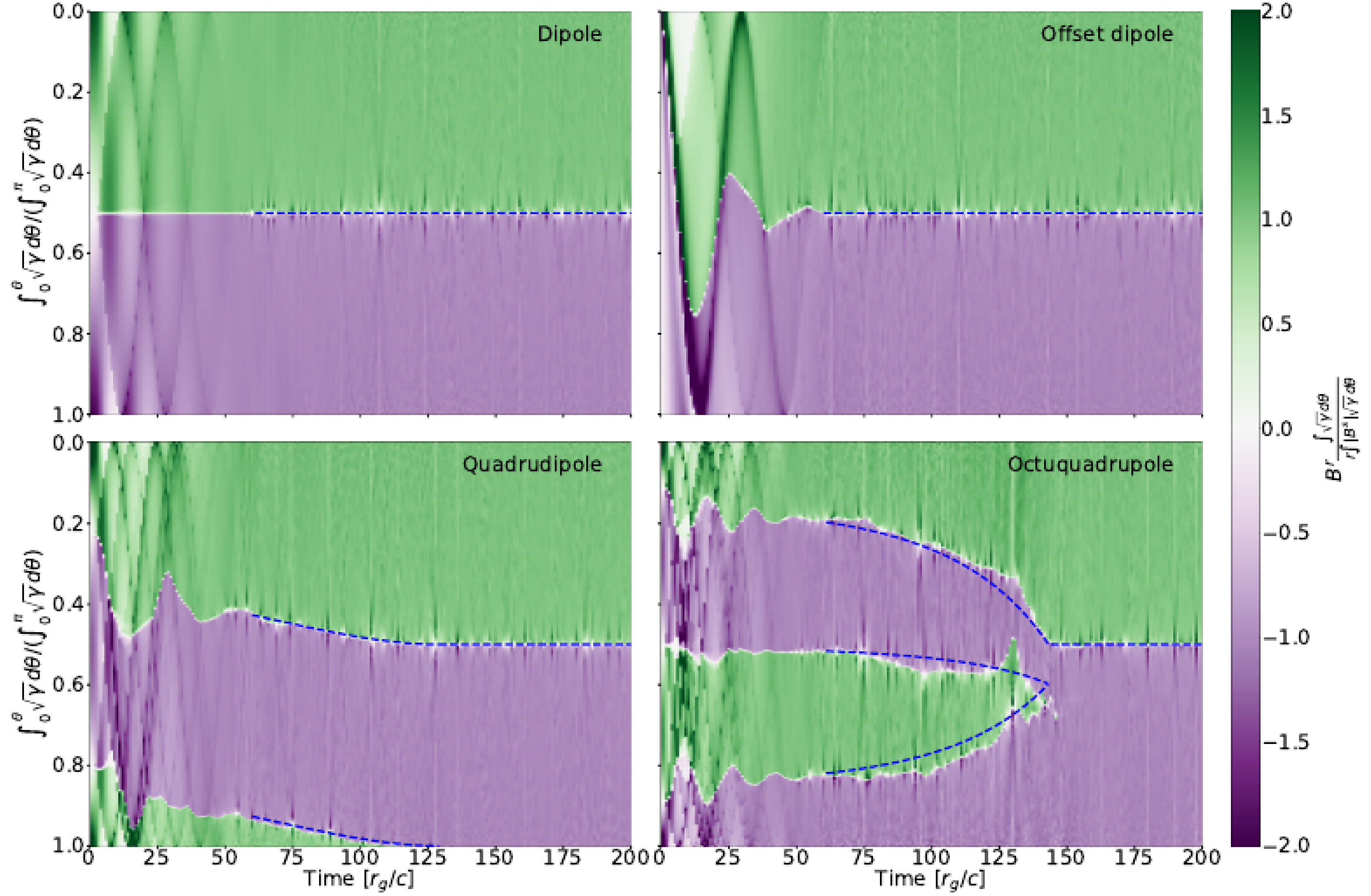
$$\frac{\partial \Phi_{N-1}}{\partial t} = -\frac{\alpha v^{\widehat{\theta}}}{4 r_{\mathrm{g}}} \Phi_{\mathrm{tot}} \left(\sin(\theta_{\mathrm{cs},N-2}) + \sin(\theta_{\mathrm{cs},N-1})\right)$$

$$\frac{\partial \Phi_N}{\partial t} = -\frac{\alpha v^{\widehat{\theta}}}{4 r_{\mathrm{g}}} \Phi_{\mathrm{tot}} \sin(\theta_{\mathrm{cs},N-1})$$

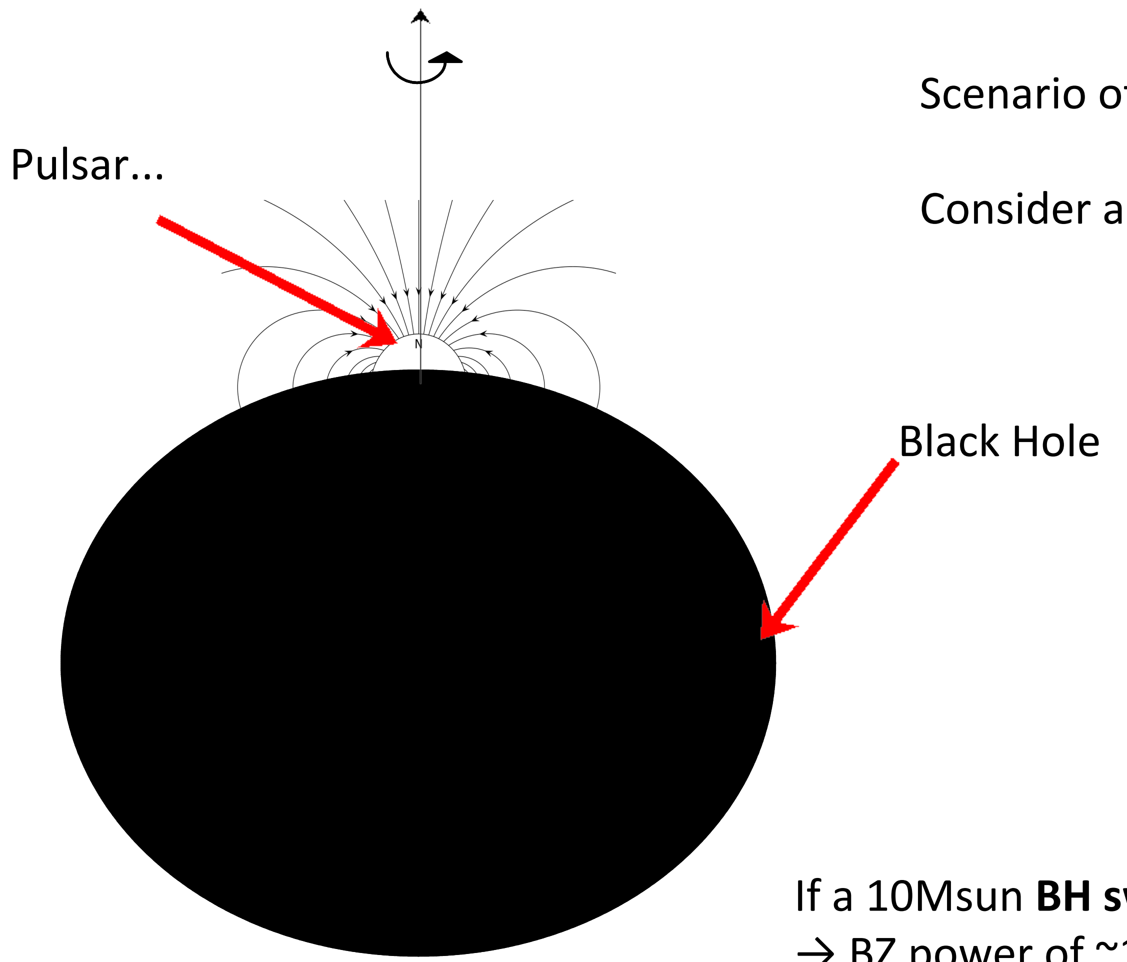
Pressure equilibrium:

$$\varsigma_{\mathrm{cs},j}(t) = \frac{\sum_{n=1}^{j} \Phi_n(t)}{\Phi_{\mathrm{tot}}(t)} \quad , j \in \{1, \ldots, N-1\}$$

$$\theta(\varsigma) = \arccos(1 - 2\varsigma)$$



What to do with this?



Scenario of a **heavily perturbed magnetosphere**:

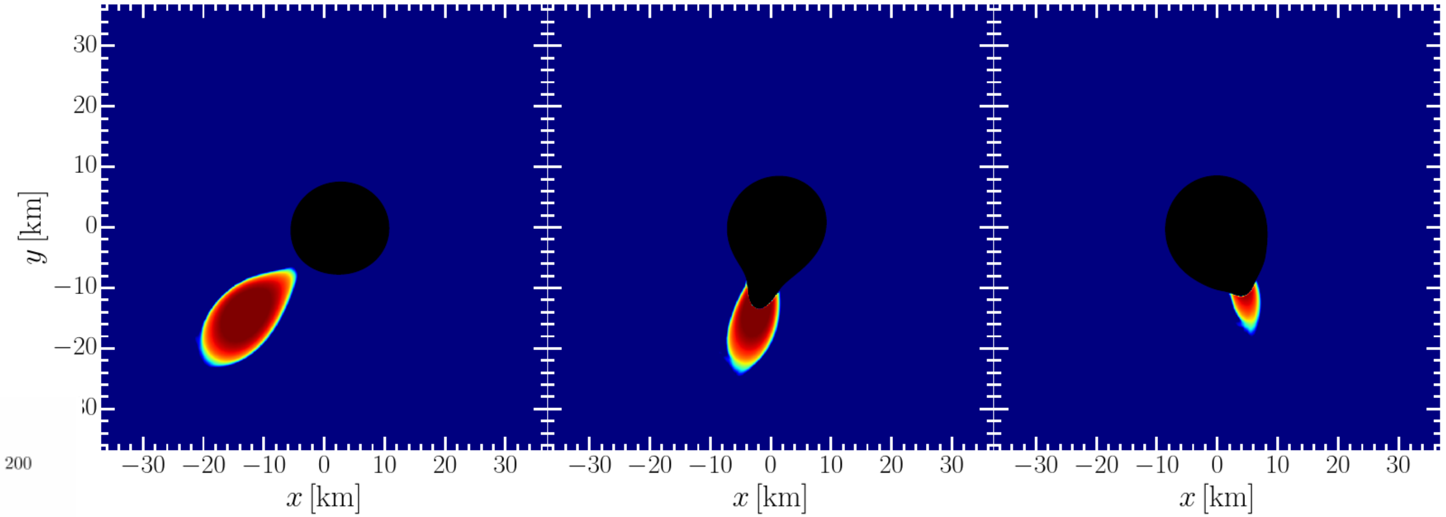
Consider a black hole swallowing a Pulsar.

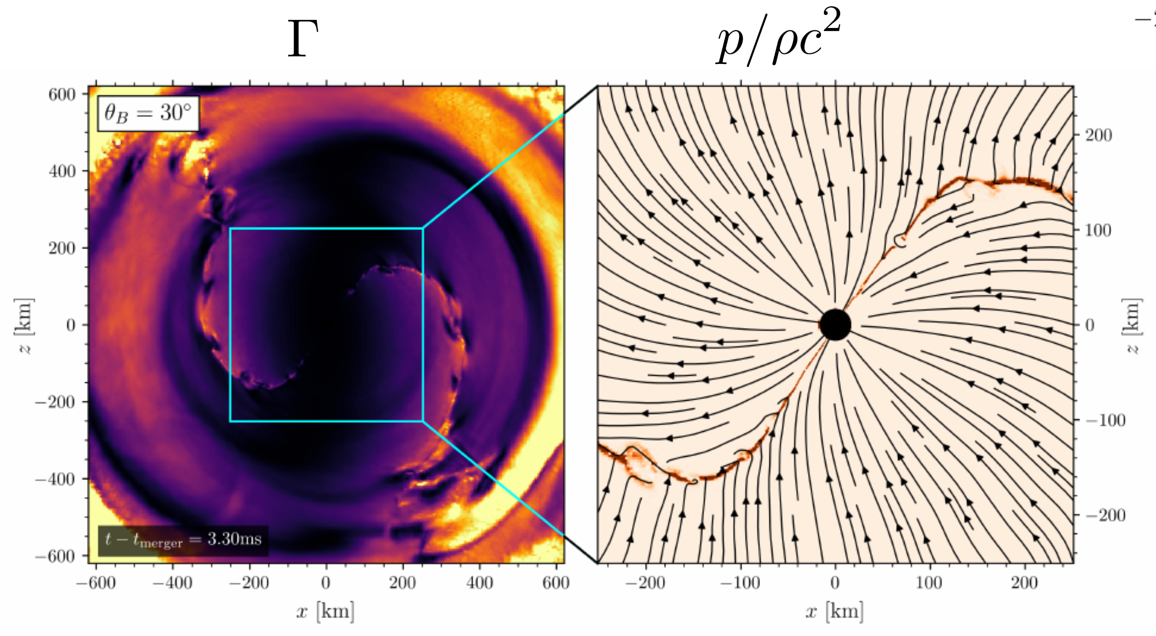
If a 10Msun **BH swallows a 10^{12} G Pulsar**
→ BZ power of ~1e43 erg/s or energy of ~1e41 erg (sufficient for most FRBs)

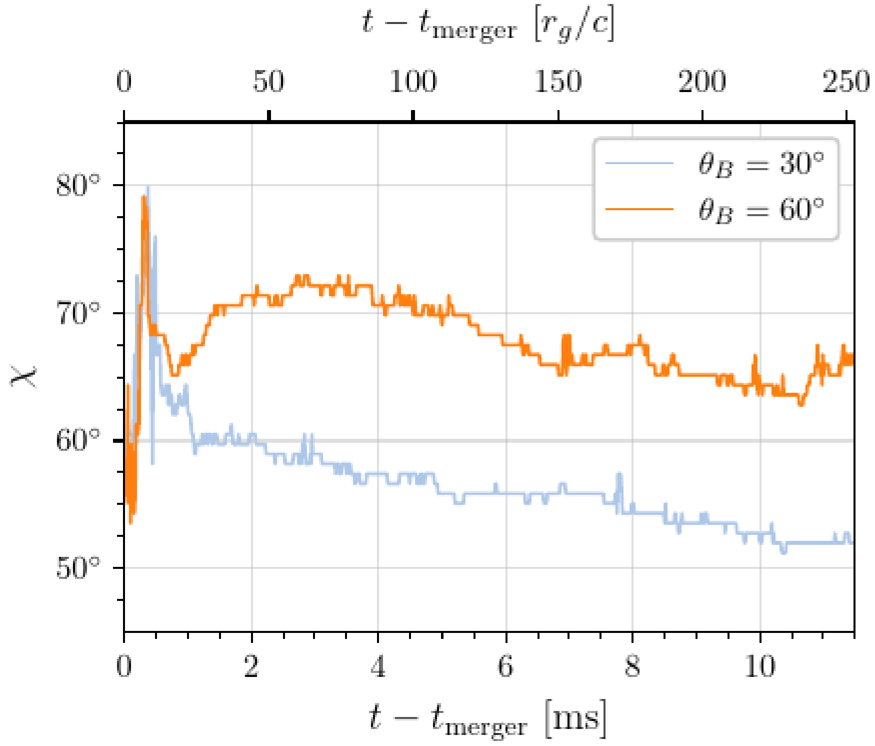
Less energetic in case of supermassive black hole.

Selvi et al. (submitted to ApJ)

Not just a toy problem







Draft version December 10, 2024
Typeset using LaTeX **twocolumn** style in AASTeX631

Black hole pulsars and monster shocks as outcomes of black hole–neutron star mergers

Yoonsoo Kim,[1,2] Elias R. Most,[1,3] Andrei M. Beloborodov,[4,5] and Bart Ripperda[6,7,8,9]

Take aways

- Black hole magnetospheres: quite simple.
  - The **aligned monopole** solution appears to be **universal**!
  - **Alignment process** is fast, *not quite understood*
  - The '**black hole pulsar**' (striped wind) lasts for only <2 ms for $a>0.6$
- Reconnection physics determines black hole balding rate and **current sheet migration**
- **Spin dependence** of flux decay!

- Will imprint on electromagnetic signal from mixed-merger and hypermassive ns collapse

- Predictions of toy model (rates, initial flux drops) consistent with full mixed-merger simulations