Black hole energy extraction and spin in polarized EHT images

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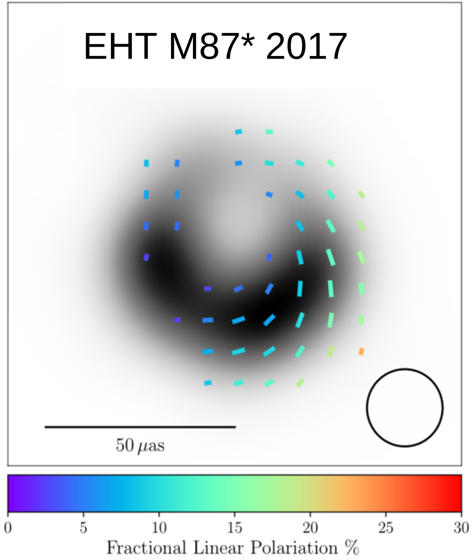
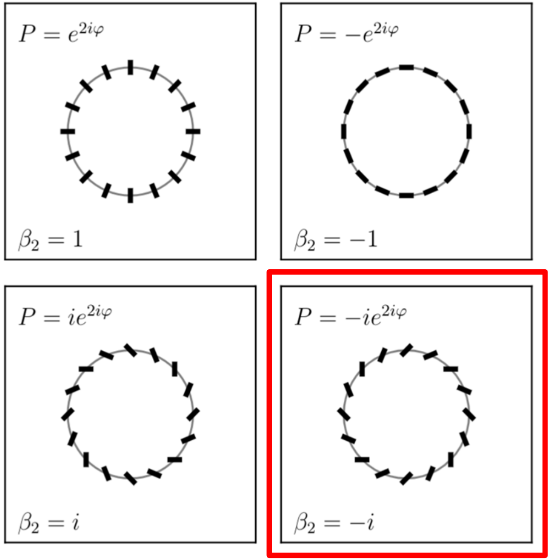
Polarized Images of the M87 Supermassive Black Hole

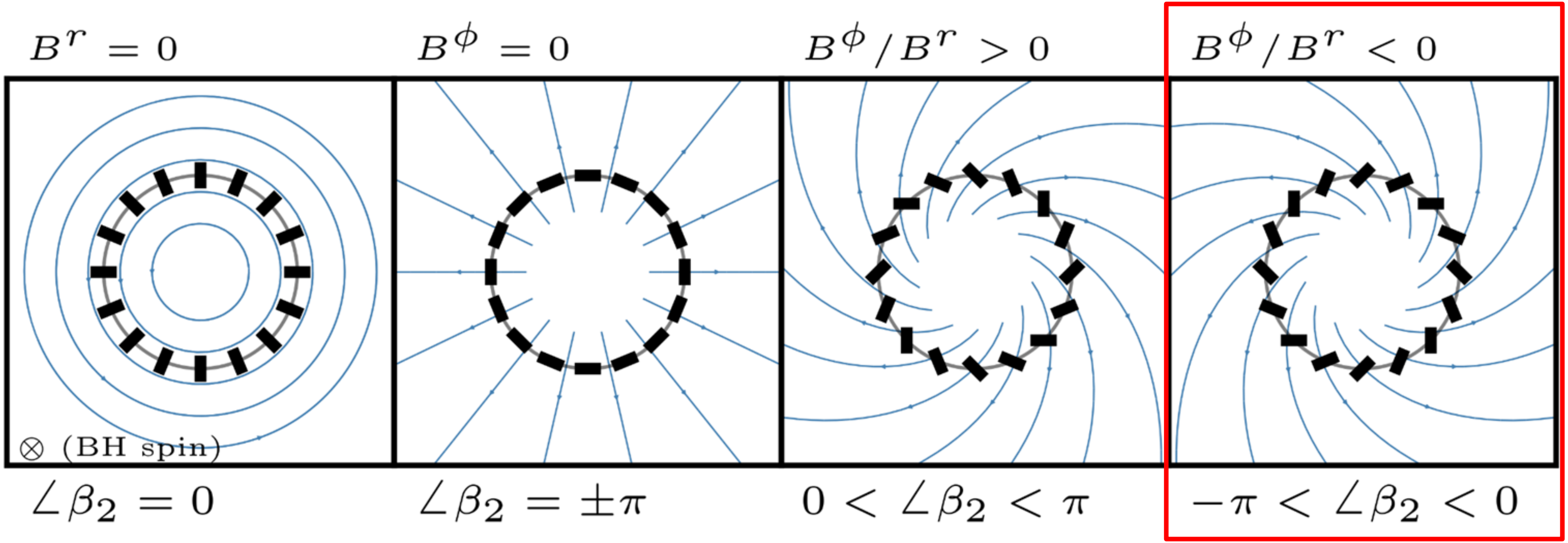




M87 Paper VIII (EHTC+ 2021: 2105.01173)

- The polarized image of M87* is consistent with GRMHD simulations of **Magnetically Arrested Accretion**
- The polarization's 2nd Fourier mode ($\boldsymbol{\beta_2}$: Palumbo+ 2020, 2004.01751) is the **most constraining** observed feature

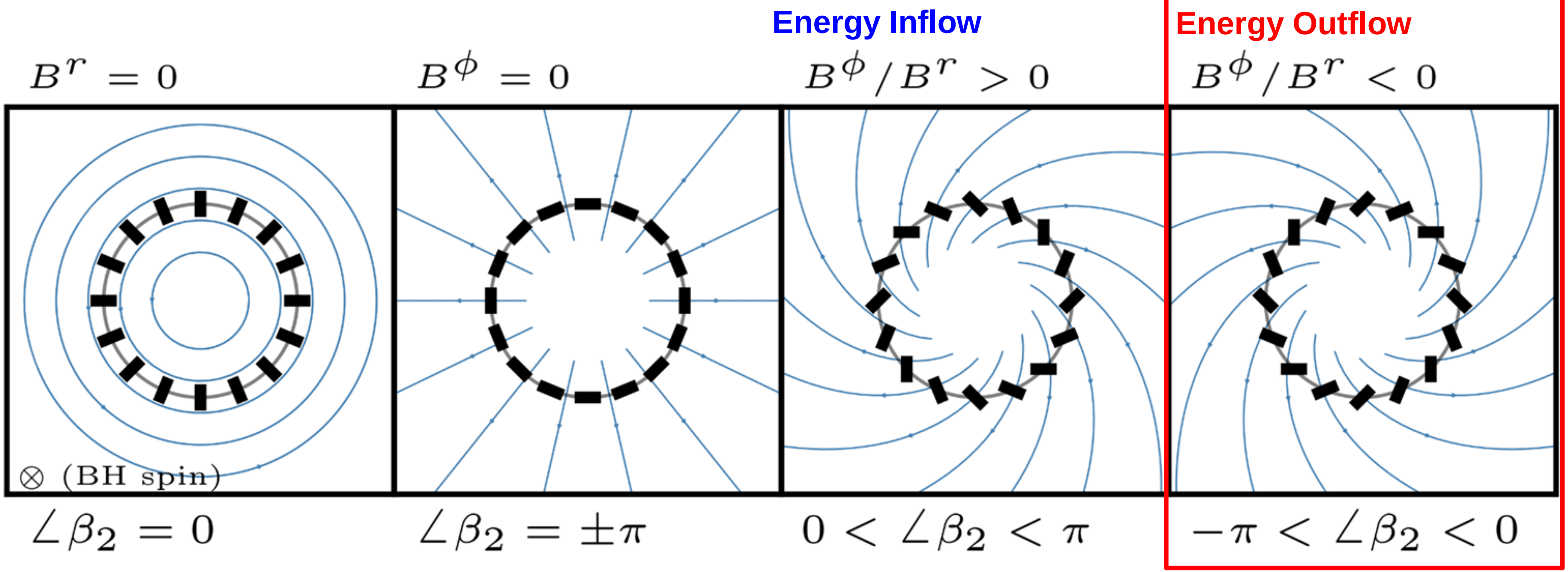
arg(β_2) is connected to the ratio B^ϕ / B^r



Cartoon picture:

- face on fields, no Faraday rotation, no optical depth, no relativistic redshift/abberation
- The BH spin is axis **into the screen** (EHT Paper V, 2019)

$\arg(\beta_2)$ is connected to the sign of radial energy flux



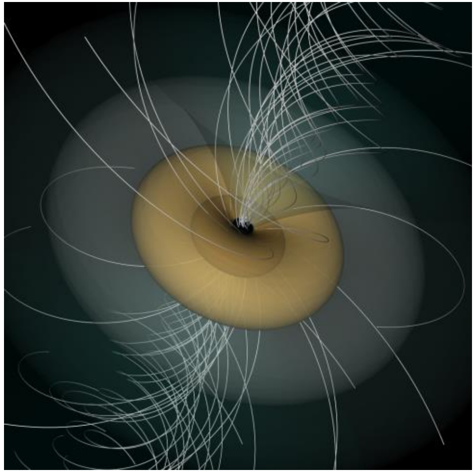
Poynting flux in Boyer-Lindquist Coordinates:

$$F_E = -T^r_{t\ \mathrm{EM}} = -\omega B^r B^\phi \Delta \sin^2\theta$$

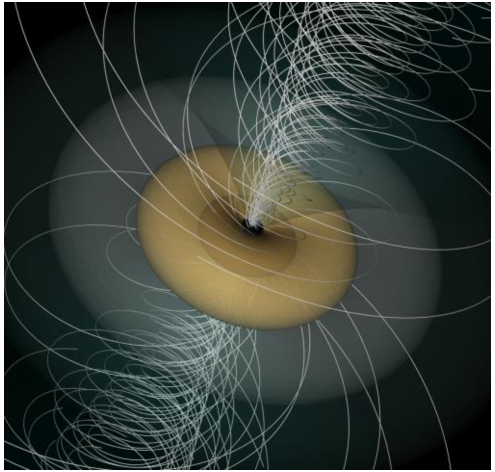
Field line angular speed

Blandford-Znajek Monopole Model

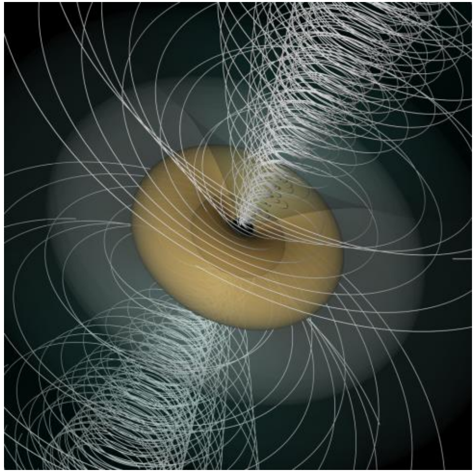
a = 0.25



a = 0.5



a = 0.9375



- BH **spin winds up initially radial fields**, so that $B^{\phi}/B^{r} < 0$
- The field winding **increases with spin**
- Increased field winding will

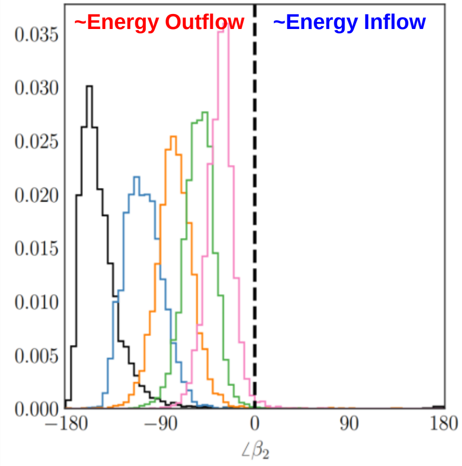
  → increase the Poynting flux (BZ jet power)

  → make the observed polarization more radial

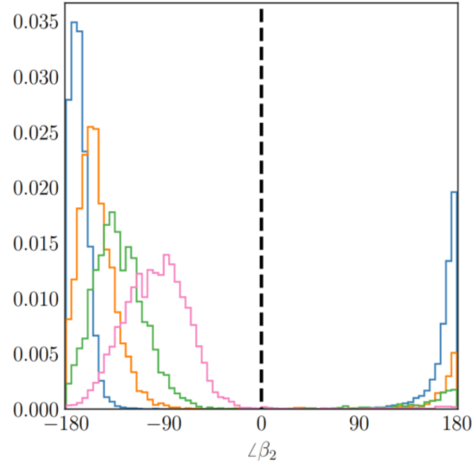
Image credit: George Wong

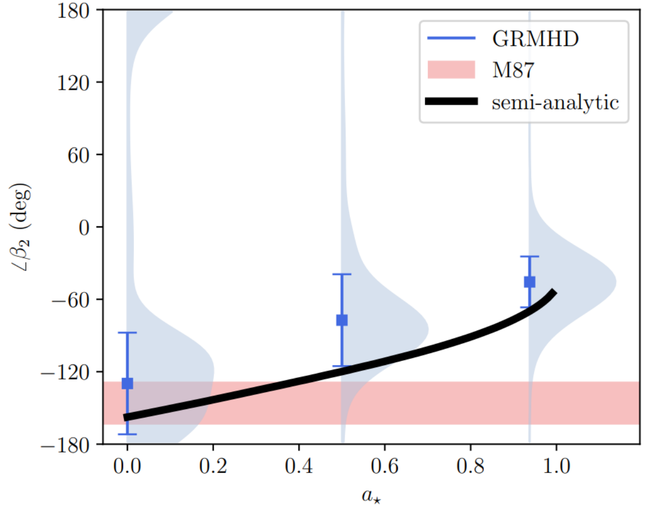
Does the relationship between β_2, spin, and energy flux persist in GRMHD simulations?

Prograde Simulations



Retrograde Simulations



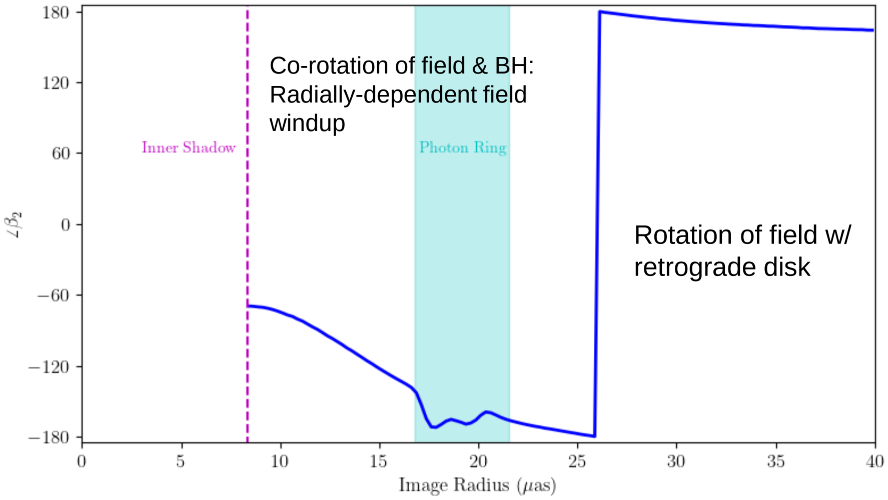


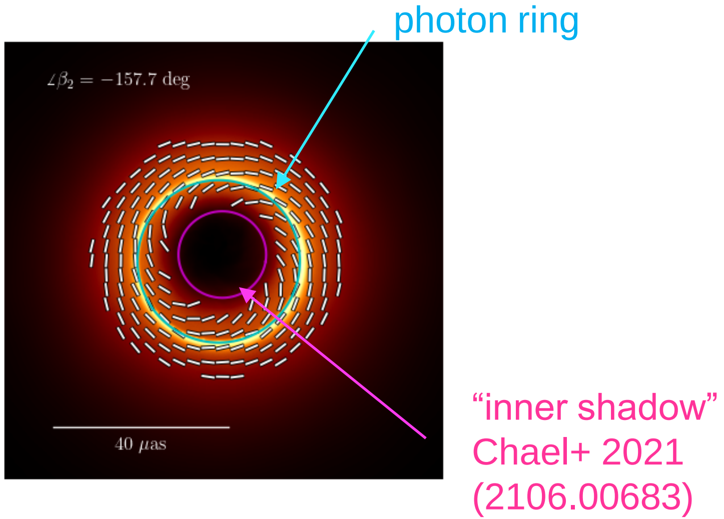
`KORAL` MAD simulations (Narayan+ 2022)
1600 snapshots covering different 6 different electron heating models

`HARM` MAD simulations (EHTC+ 2021)
1600 snapshots covering 6 different electron heating models

$\beta 2$ **evolves** with image radius

GRMHD





Same time-average retrograde GRMHD **a=-0.5** average image as in **Ricarte+ 2022** (2211.01810)
Analytic models suggest $\beta 2$ has a a **unique, spin dependent value** at the inner shadow

backup slides

Energy Flux in Kerr, Static, Axisymmetric, Degenerate fields

Poynting flux in Boyer-Lindquist Coordinates

$$F_E = -T^r_t{}_{\mathrm{EM}} = -\omega B^r B^\phi \Delta \sin^2\theta$$

For co-rotating EM fields, $B^\phi/B^r < 0$ corresponds to outward energy flow

Znajek condition: must exactly hold on the horizon

In BL, B^ϕ blows up on the horizon, but ΔB^ϕ is finite.

$$\frac{\Delta B^\phi}{B^r} = \pm 2Mr_+ \left(\omega - \Omega_+\right)$$

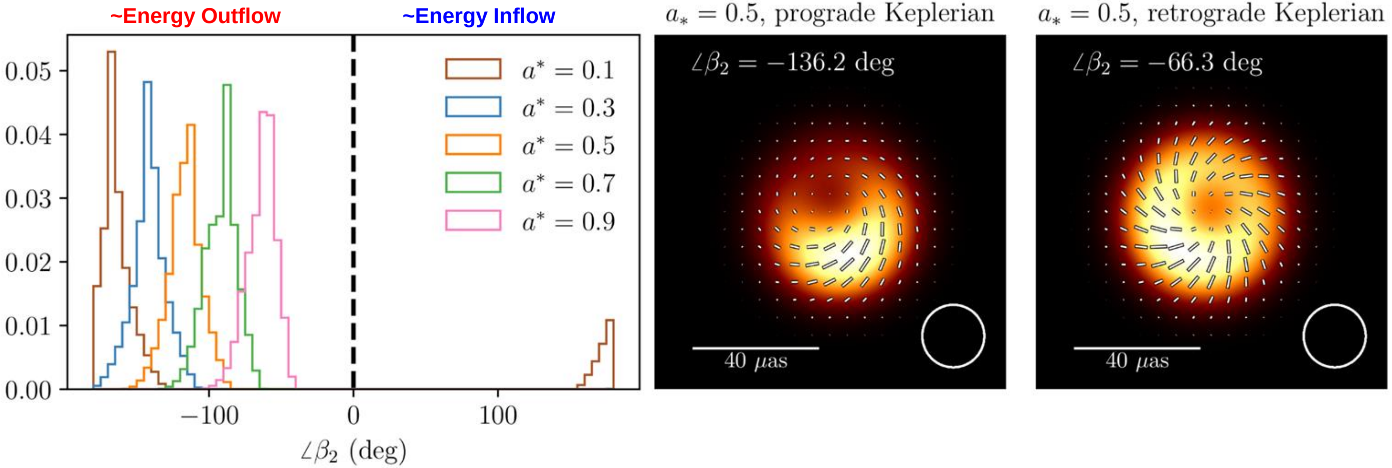
Blandford-Znajek Poynting flux on horizon

$$F_E|_{r=r_+} = \mp 2Mr_+\omega(\Omega_+ - \omega)\left(B^r \sin\theta\right)^2$$

For static, axisym, degenerate fields, poynting flux is conserved along field lines

Full (perturbative) BZ solution needed to calculate B^ϕ/B^r off horizon

Rrelationship between β_2, spin, and energy flux in semi-analytic models

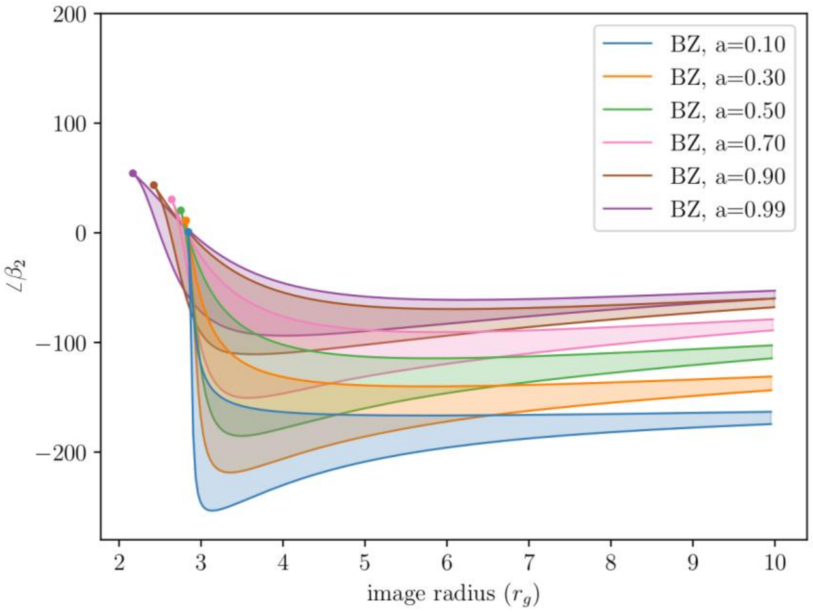


- Magnetic fields given by BZ monopole
- BH spin into page
- Equatorial emission ring at 2 r_h
- Explore uniform priors [0,1] over $(\xi, \beta_r, \beta_\phi)$

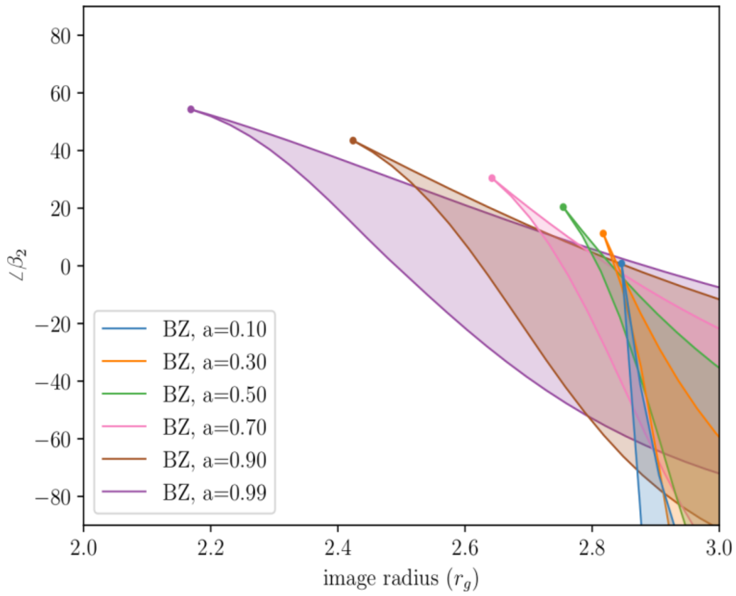
subkeplerian factor

Mixing between Keplerian and infall solutions

Evolution of β_2 in face-on equatorial BZ models

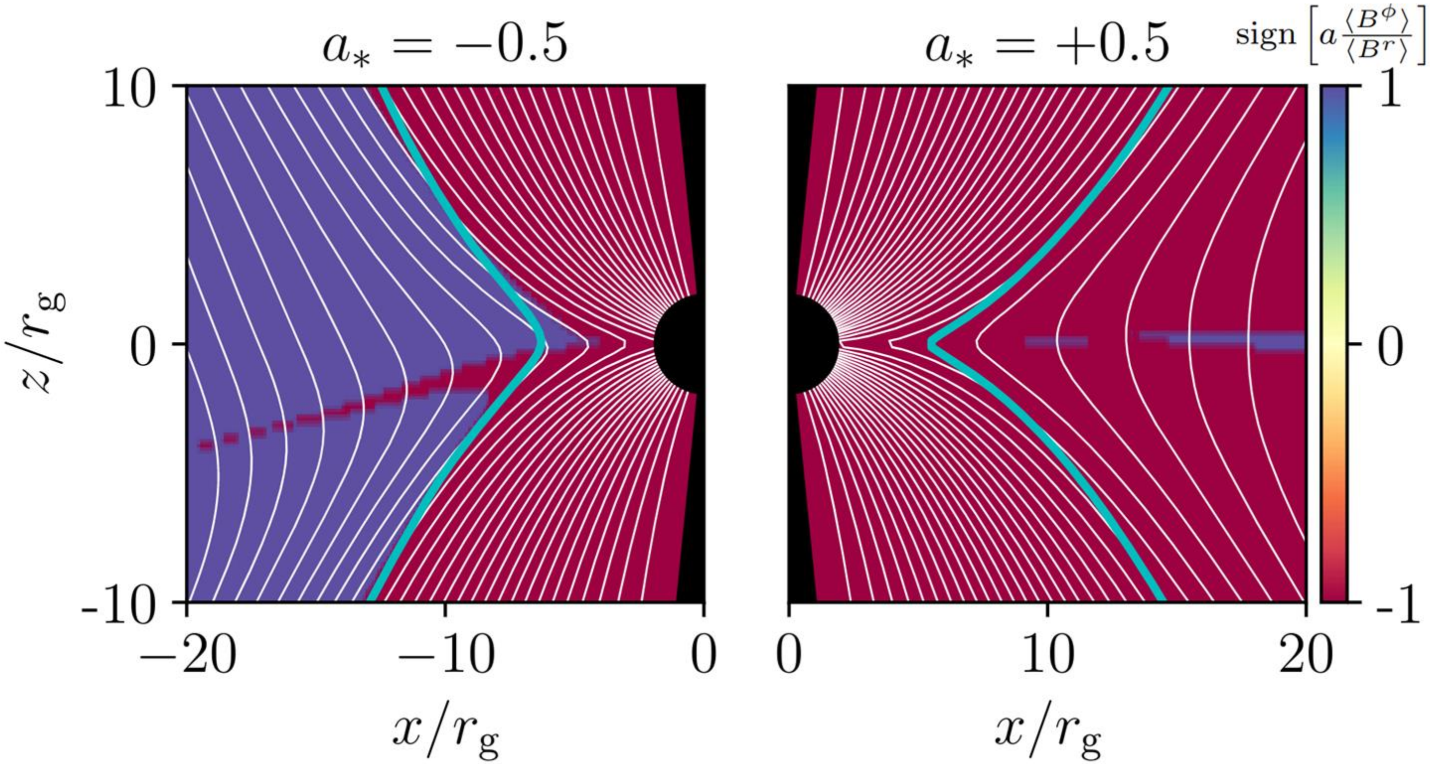


zoom in



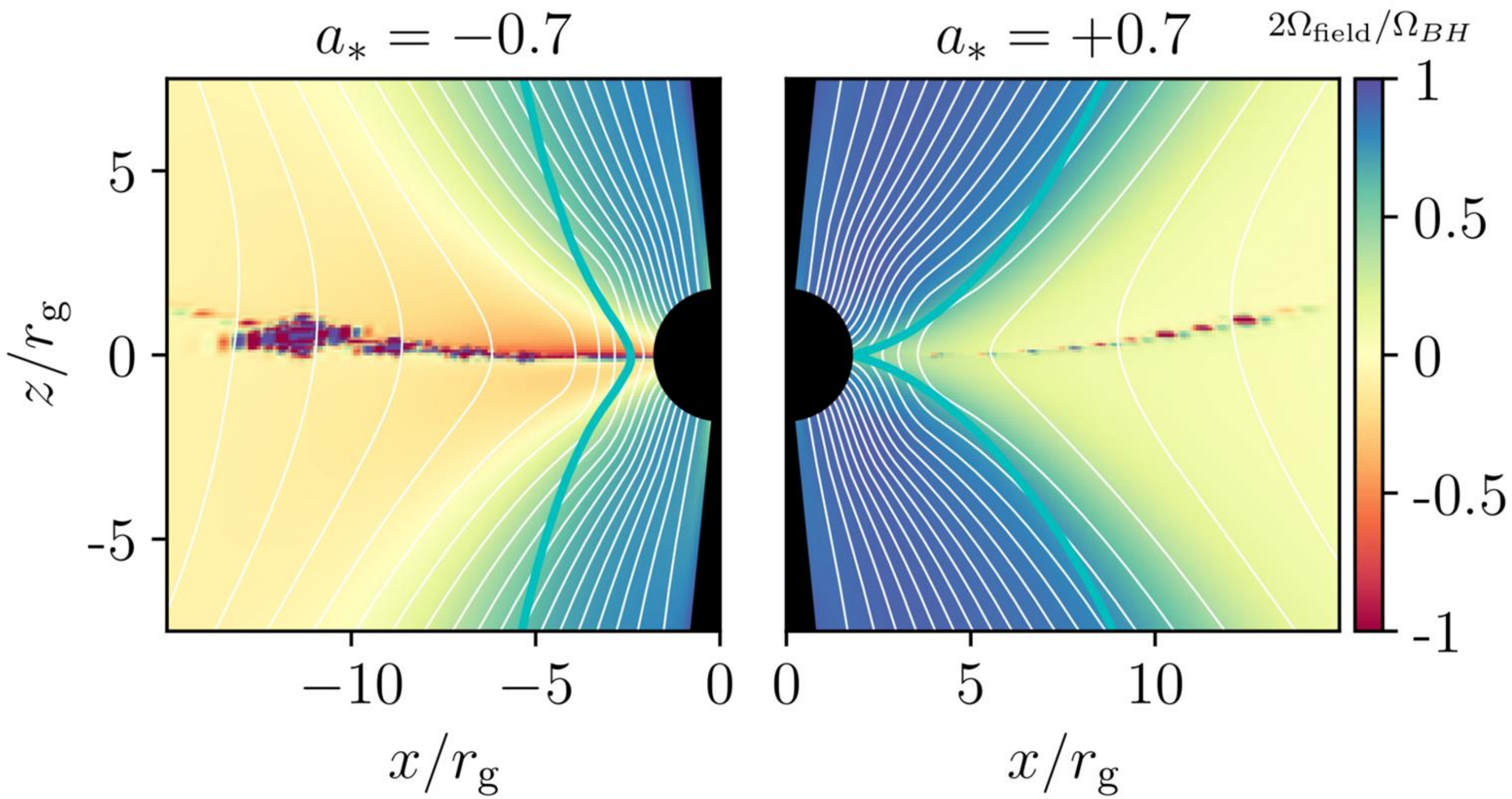
- In these models, arg(β_2) has a **value independent of the fluid velocity at the inner shadow** determined only by the Znajek condition: $\frac{\Delta B^\phi}{B^r} = \pm 2 M r_+ \, (\omega - \Omega_+)$
- How does this change with inclination/off-equatorial emission? With omega?

Sign of B^{ϕ} / B^{r}



Narayan+ 2022 simulations (averaged), see also Ricarte+ 2022

Field line angular frequency



Narayan+ 2022 simulations (avg)