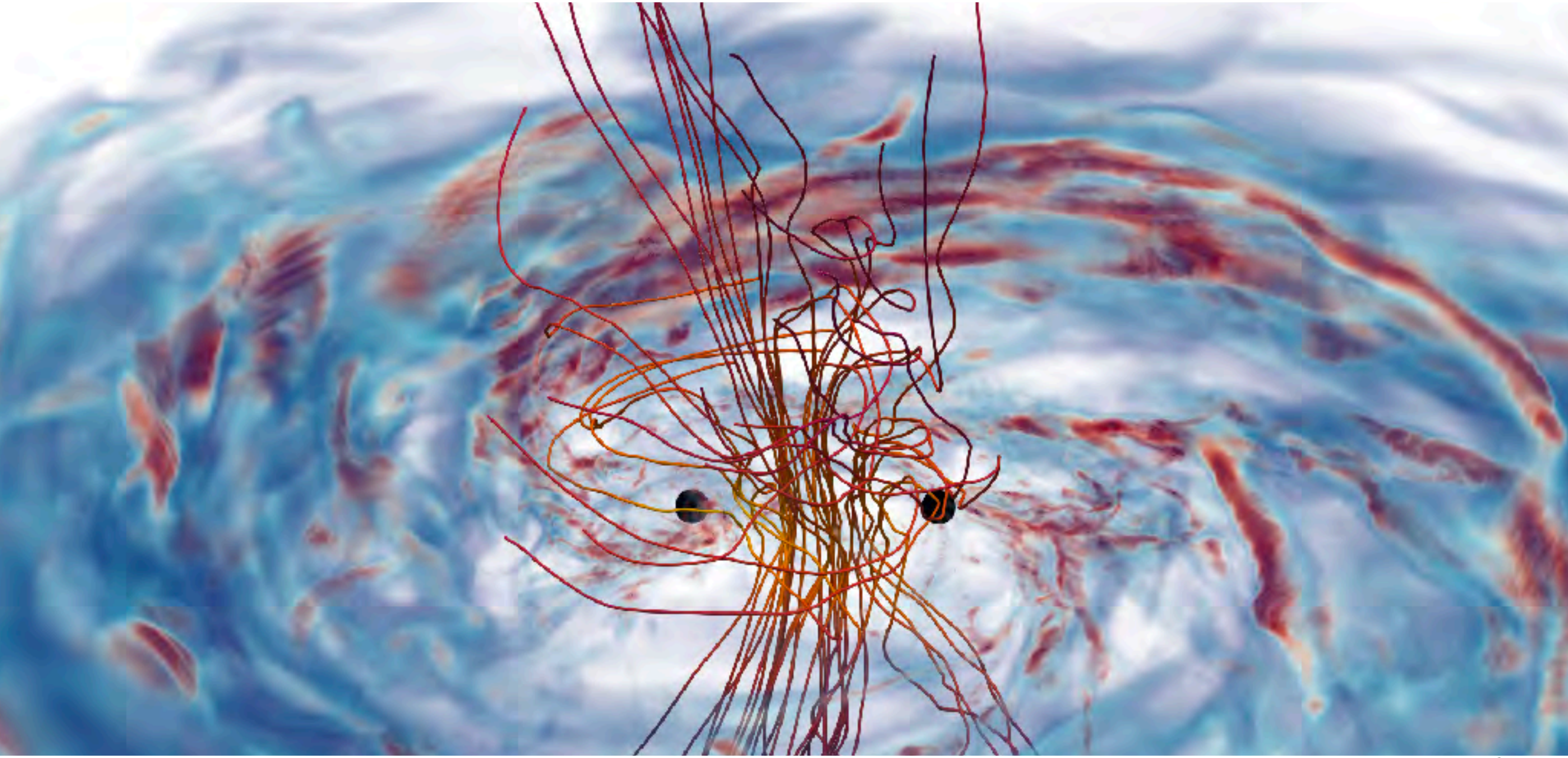
Computational Relativistic Astrophysics

Elias Roland Most



Caltech | Computational Relativistic Astrophysics
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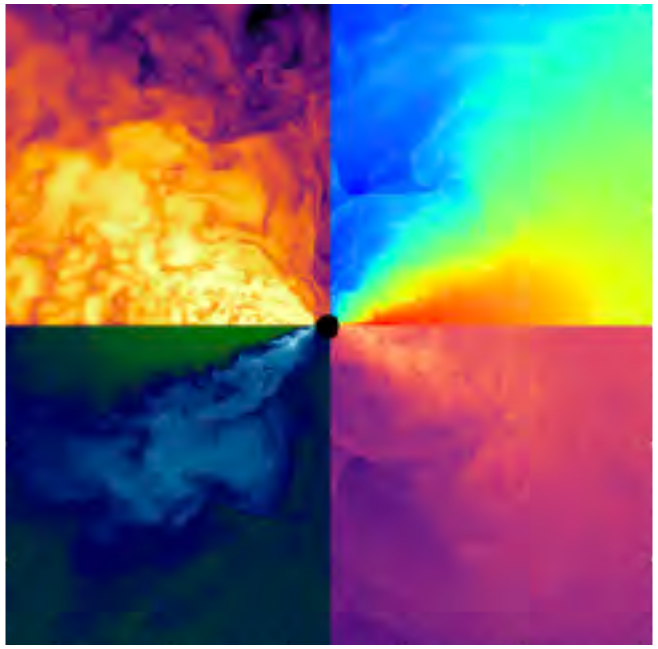
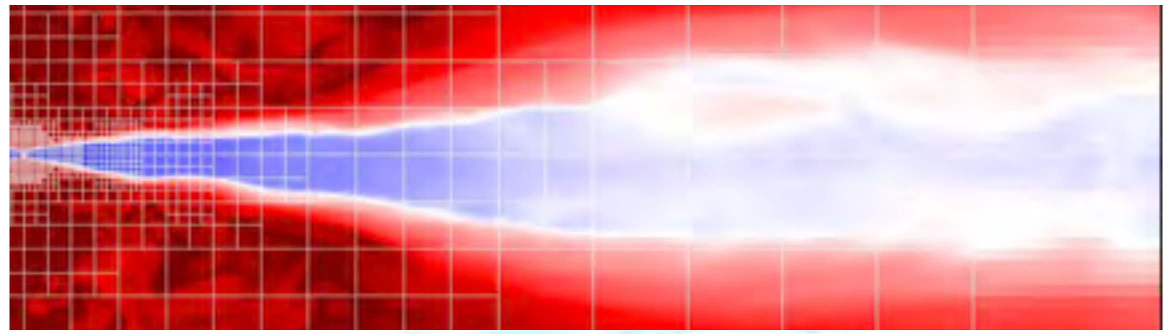
NSF NASA TAPIR

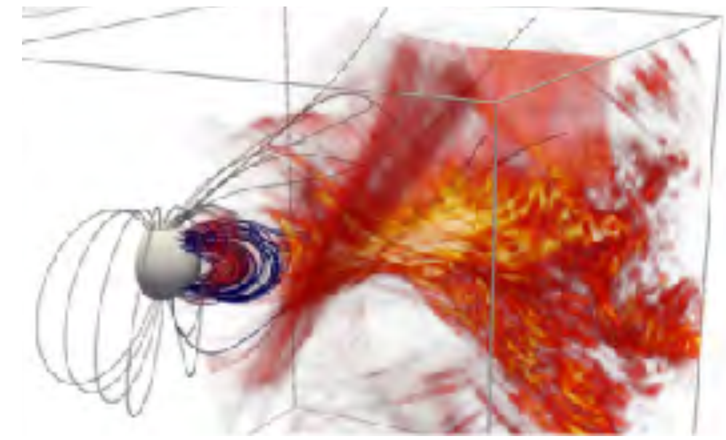
Simulating the Relativistic Universe!

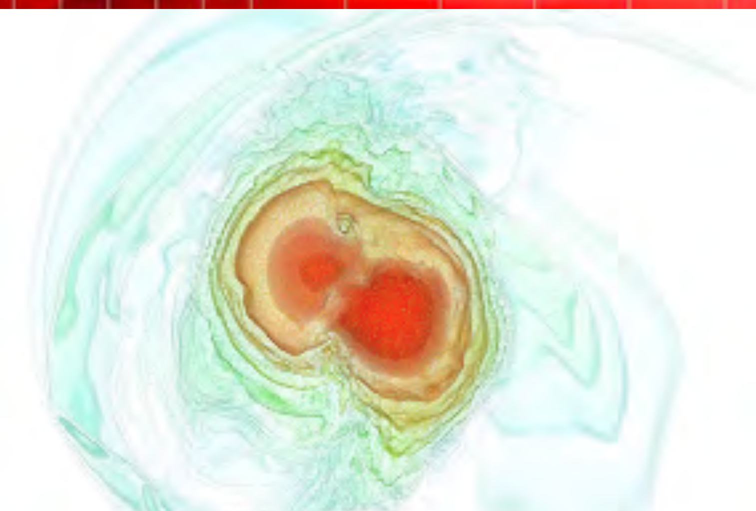
Black holes



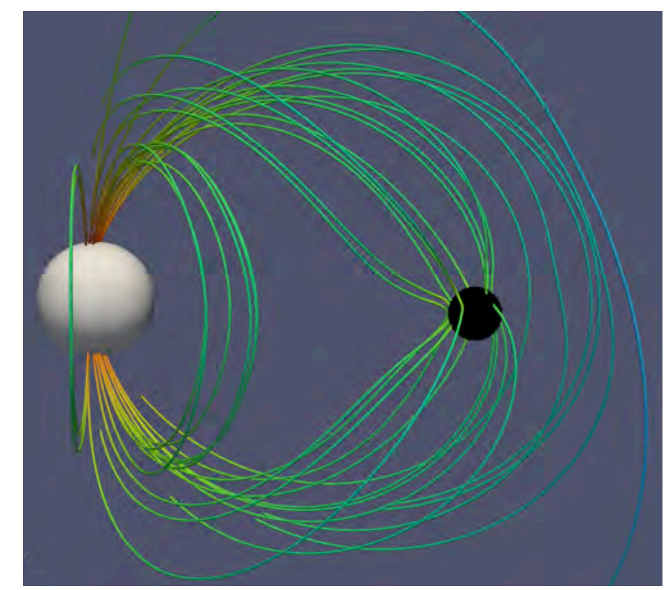
Relativistic jets

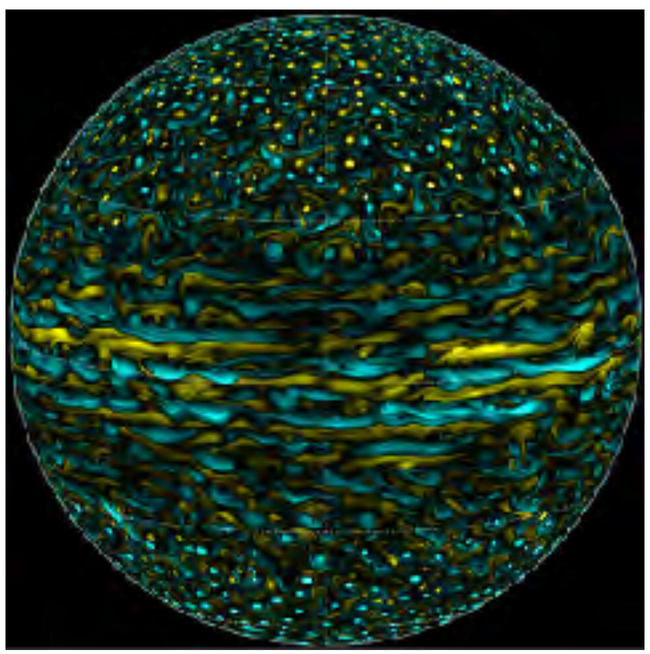




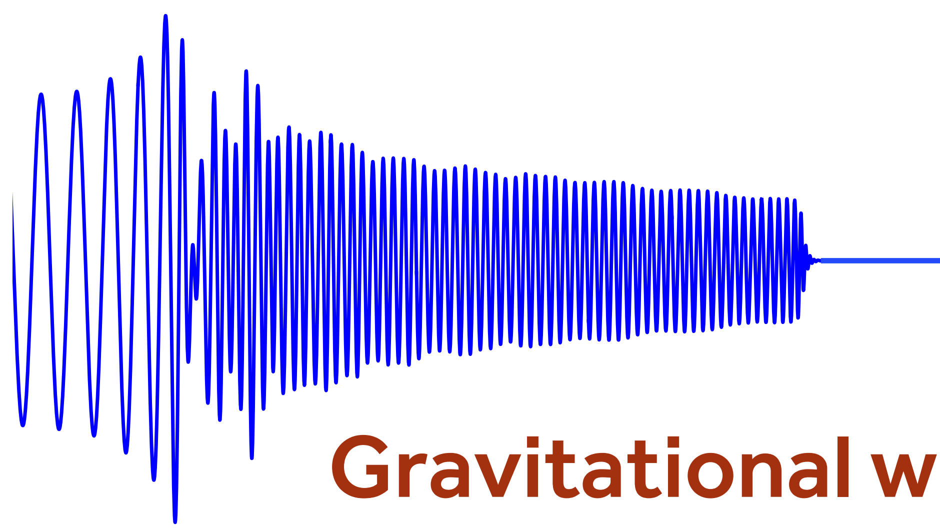


Relativistic transients

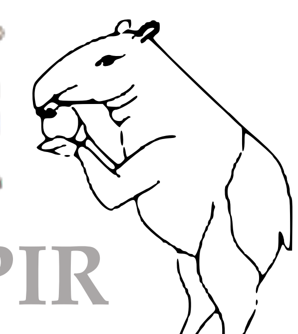




Neutron stars



Gravitational waves



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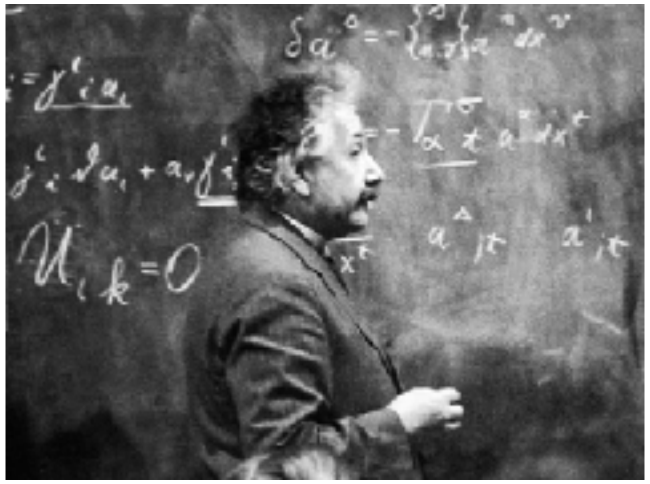
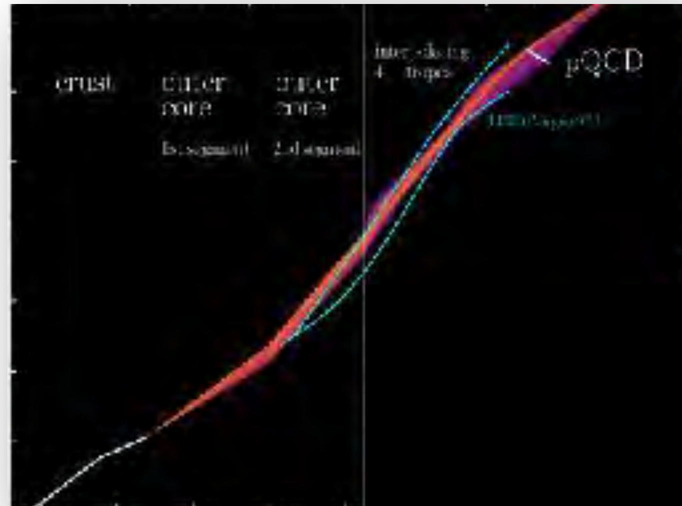
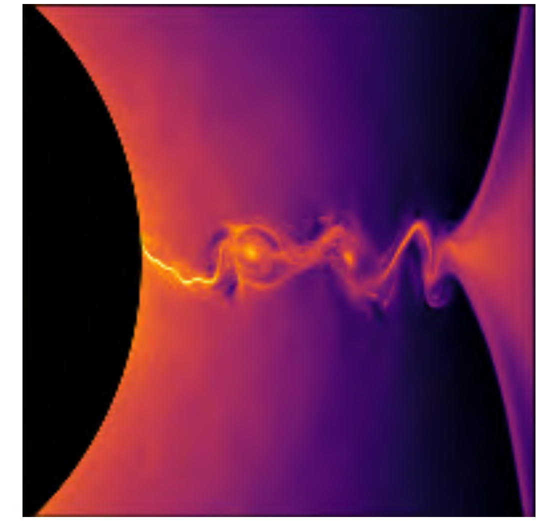
Computational Relativistic Astrophysics



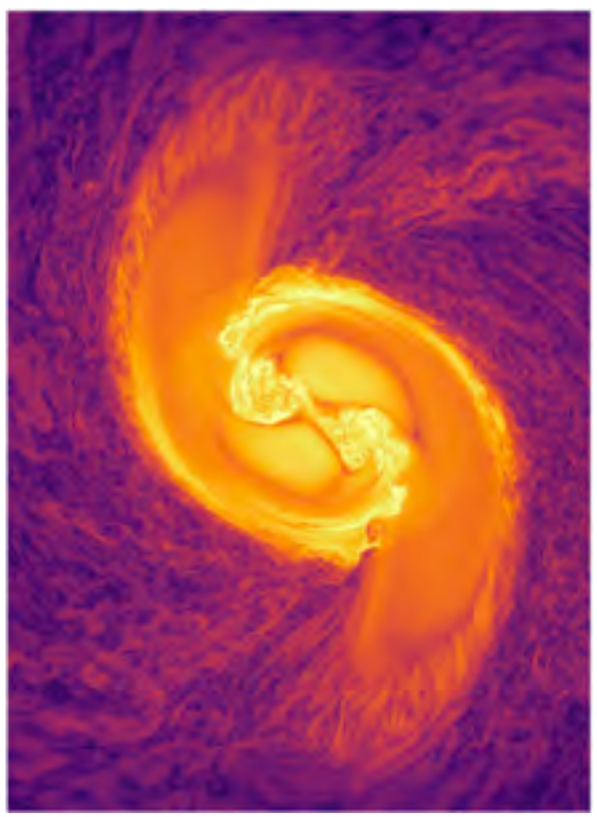
General relativity



Nuclear physics



Plasma physics



Exascale computing with GPUs!

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NASA NSF TAPIR

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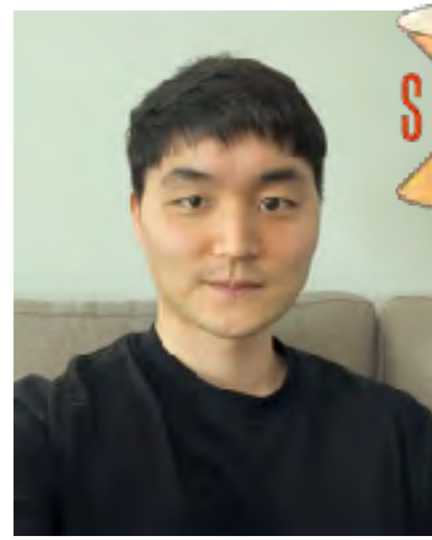
Team CompRelAstro @ Caltech

Holly Krynicki

Yuan Feng



Yoonsoo Kim

now PCTS/Princeton

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Elias R. Most

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now CITA/Toronto

Sam Dunham

Yici Zhong

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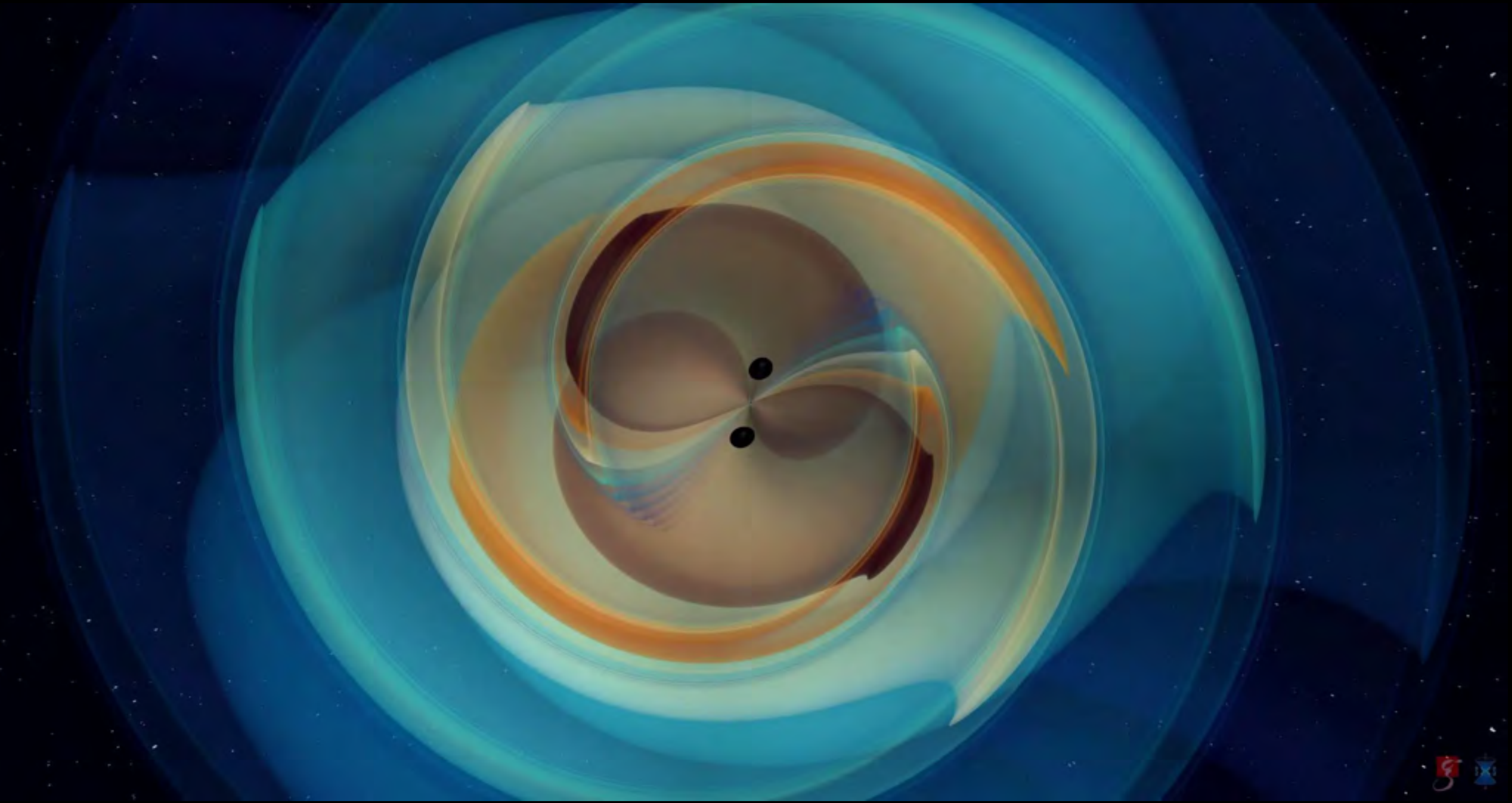
Numerical Relativity

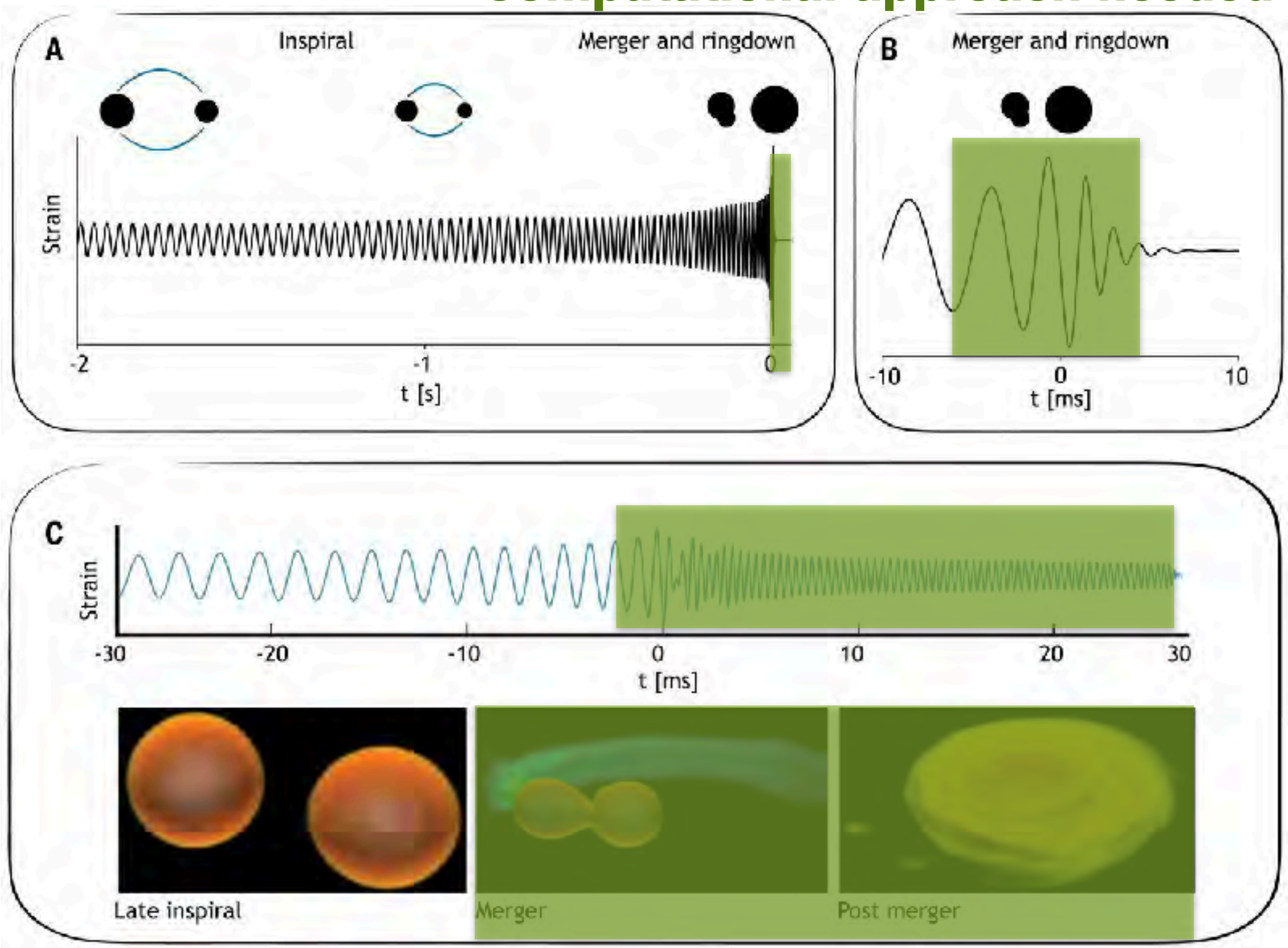


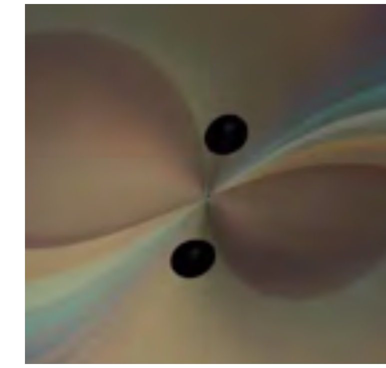
SIMULATING eXTREME SPACETIMES

Black holes, neutron stars, and beyond...

Why a computational approach?

Computational approach needed





Spacetime dynamics

Data-driven need for accuracy!

Image credit: Vitale+2021

Computational challenges

Non-linear interplay of physics at different scales!

Non-linear dynamics

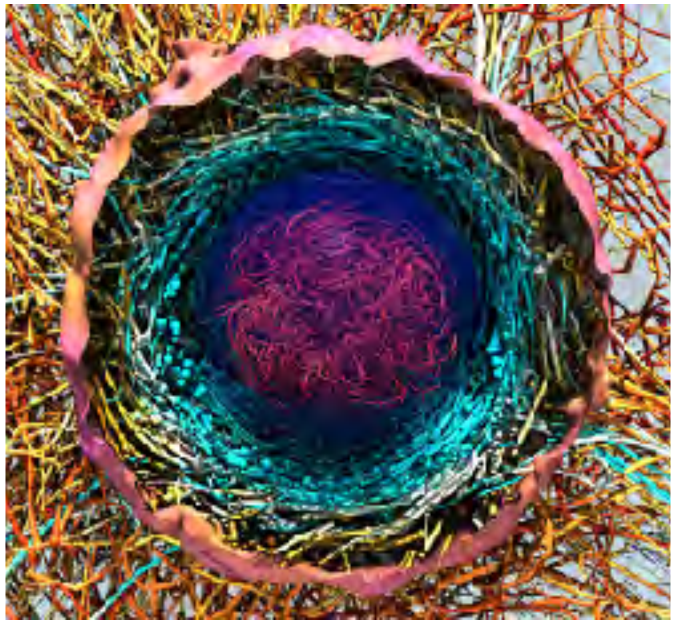


Image credit: Burrows

Complex equations

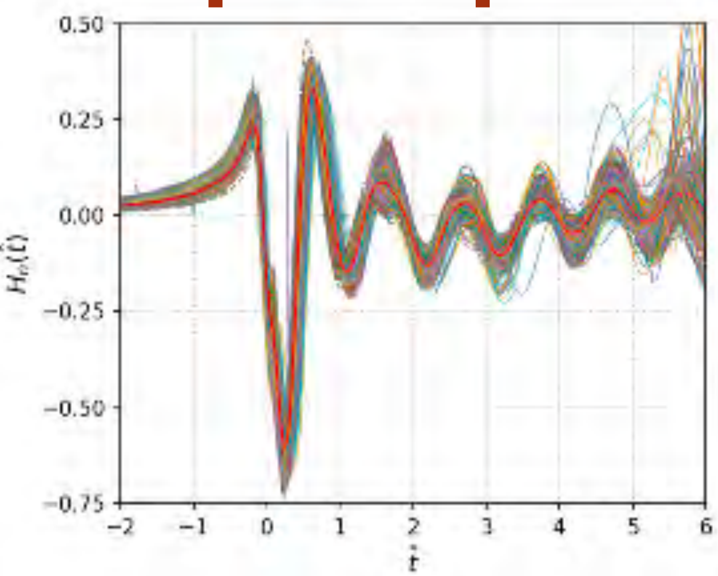


Image credit: Pastor-Marcos+23

No symmetries

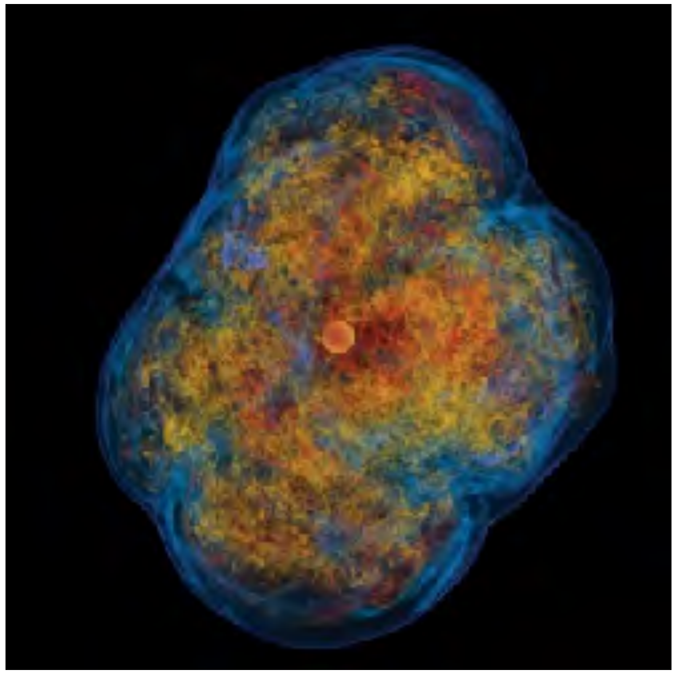


Image credit: Nordhaus

Multi physics

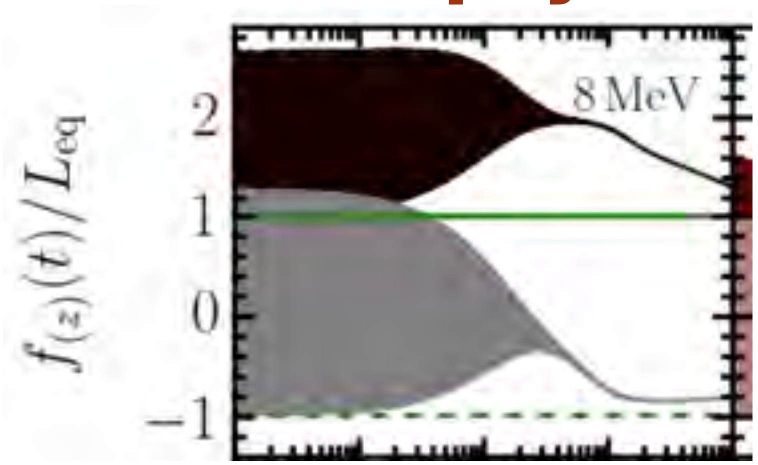


Image credit: Richers

Choosing the right approach

Black hole accretion for collisionless plasma

$$p^\mu \partial_\mu f + \left(\mathfrak{q} F^\alpha_\mu + \Gamma^\alpha_{\mu\nu} p^\nu \right) p^\mu \partial_{p^\alpha} f = \mathscr{C} \left[f \right]$$

Six dimensional phase space!
Can't possibly solve this directly?

Image credit: EHT

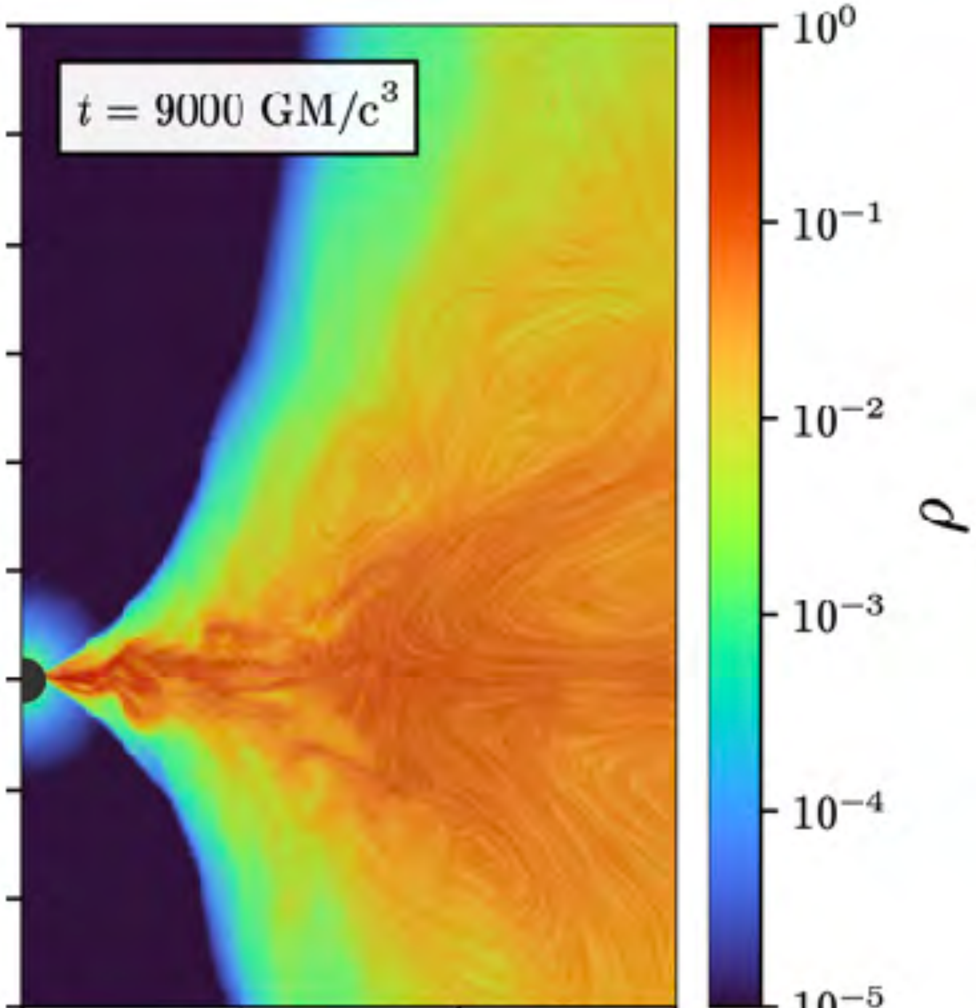


Image credit: Wong

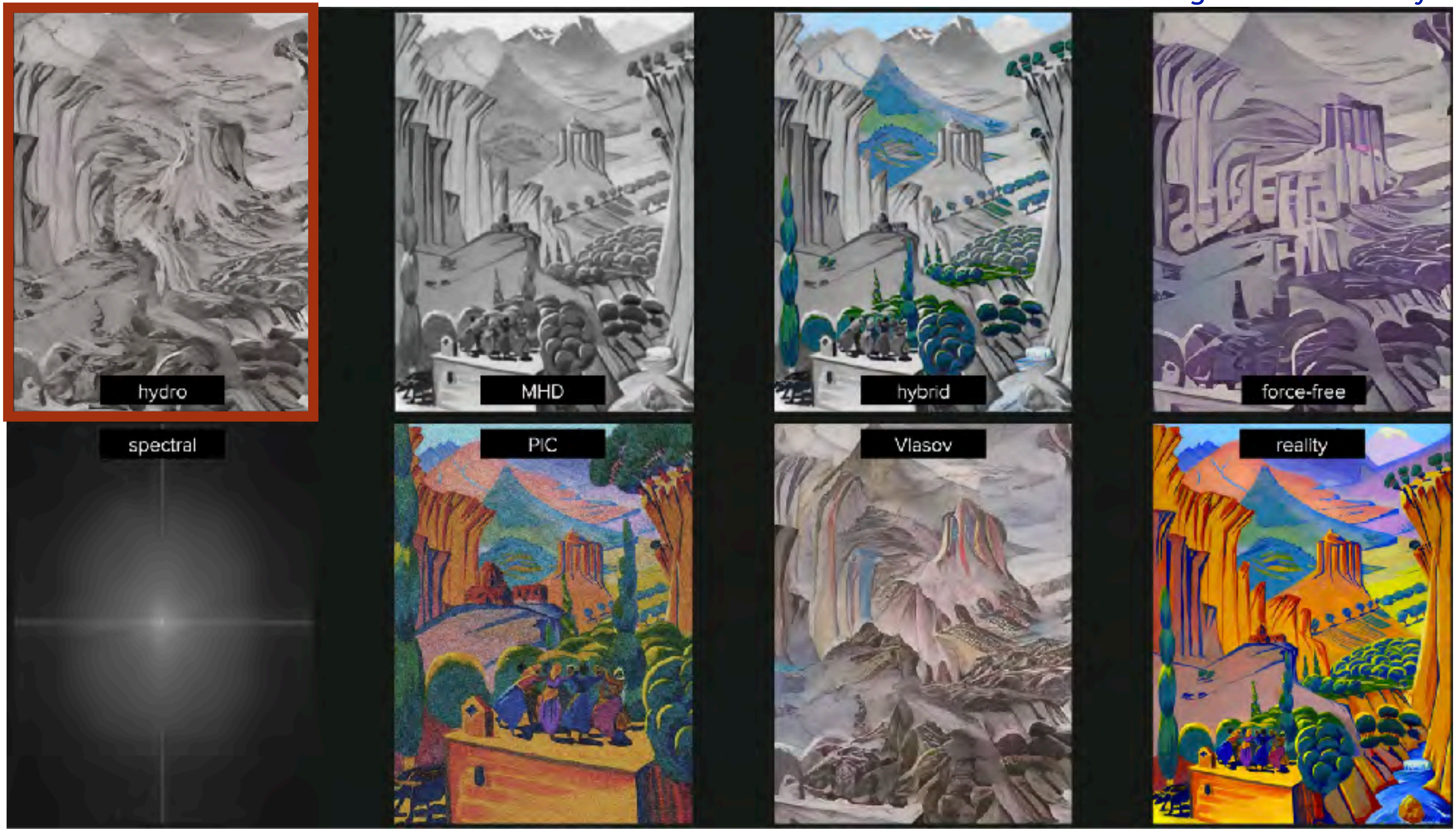
Event Horizon Telescope image sourced by gas dynamics

- Different accretion regimes?
- Precise history of gas???
- Plasma scales???
- Imprints of space time can be highly degenerate!

A simulation based viewpoint!

Choosing the right approximation

Image credit: Hakobyan

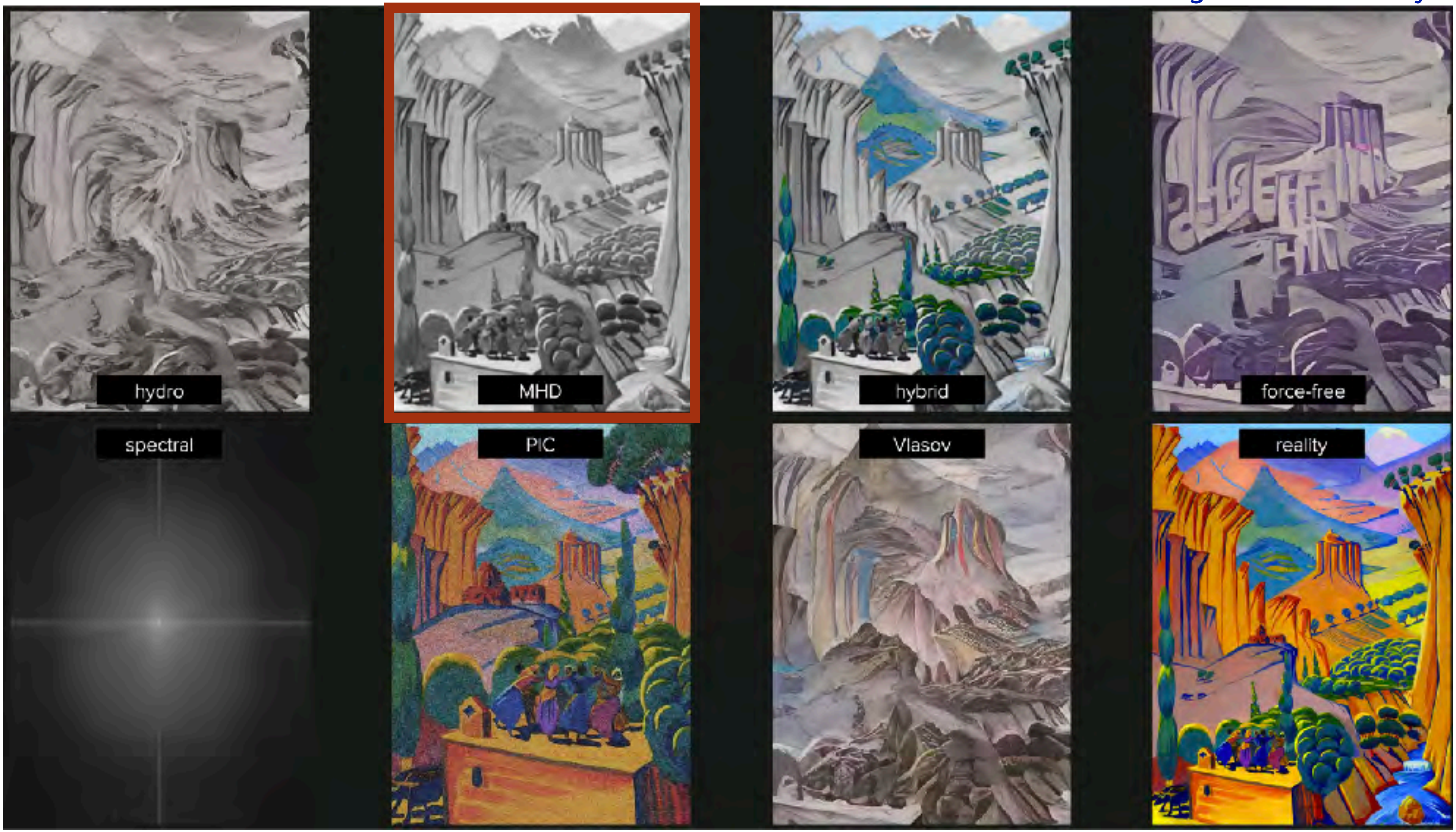


Hydrodynamics:

Inexpensive, no magnetic fields, global features wrong

Choosing the right approximation

Image credit: Hakobyan



Magnetohydrodynamics:

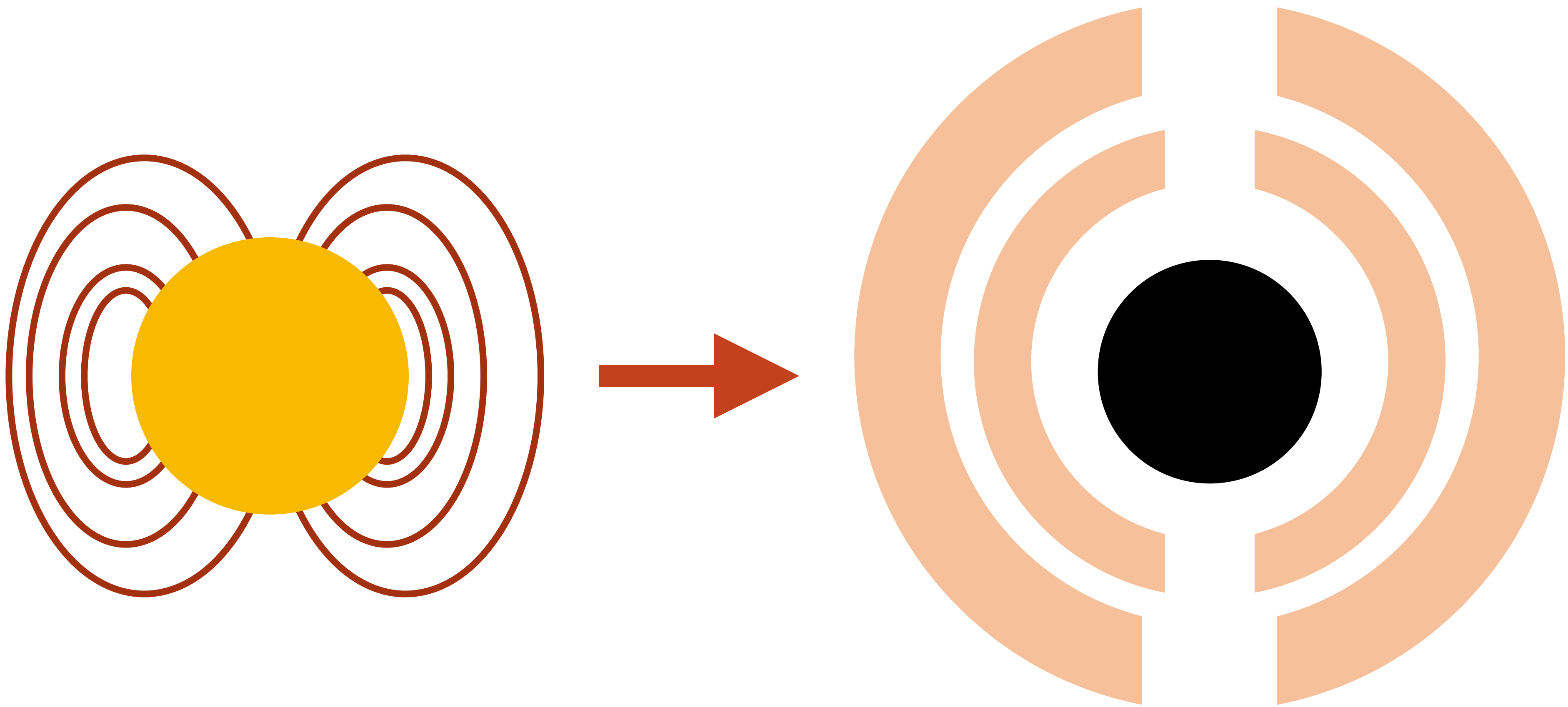
Inexpensive, global features about right. Emission features?

Why approximations matter!

Hypermassive neutron stars formed in mergers eventually collapse to black holes

Lifetime can be up to ~ 1 day

Ravi & Lasky 2014

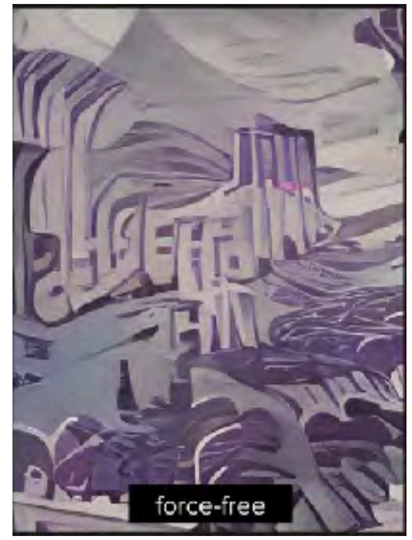


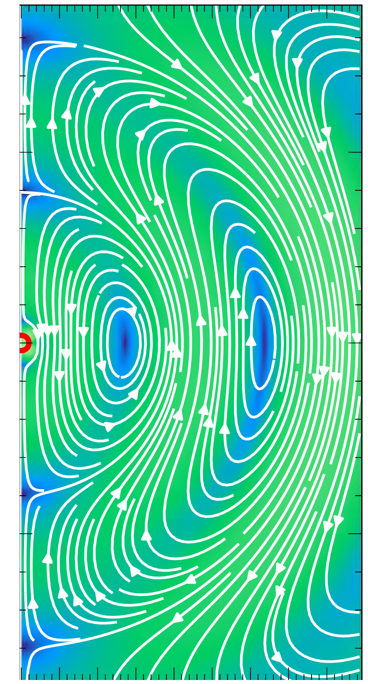
Thorne (1971), Price (1972), Baumgarte & Shapiro (2003),Lehner+ (2012), Palenzuela+(2013), ERM+(2018)

See also Stark & Piran (1986) for hydro case

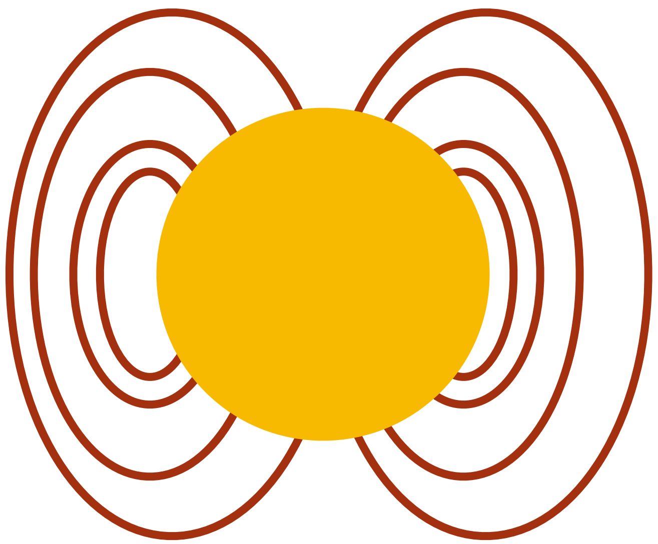
The right approximation?

Numerical relativity +

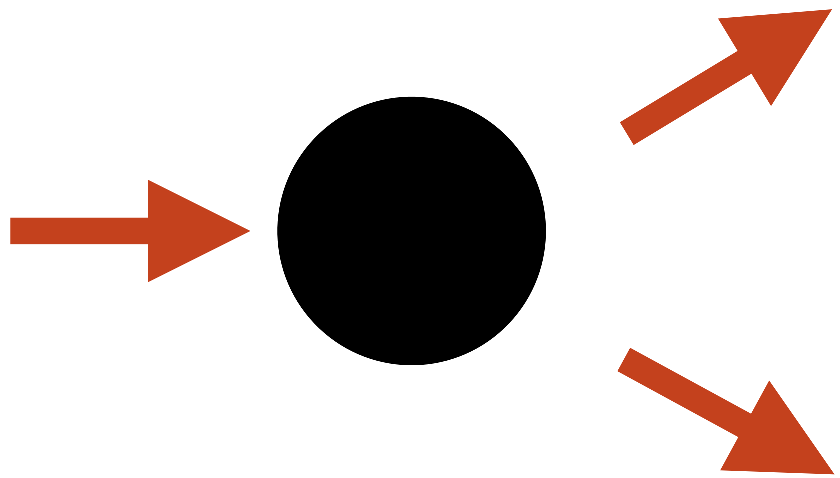


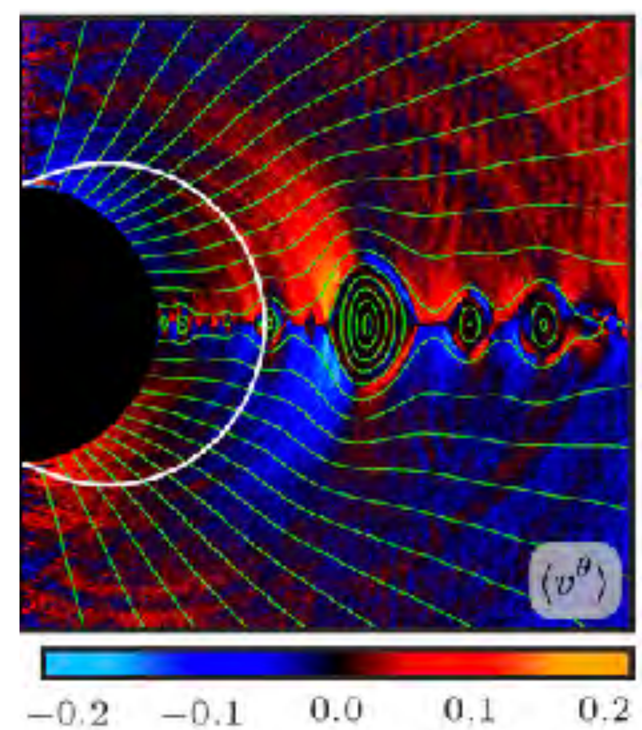


Radio?



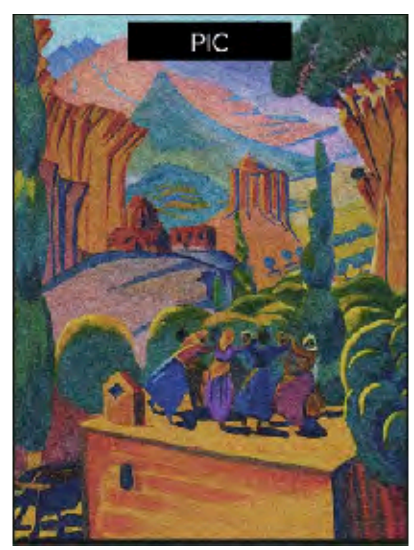
Neutron star





X-Ray?

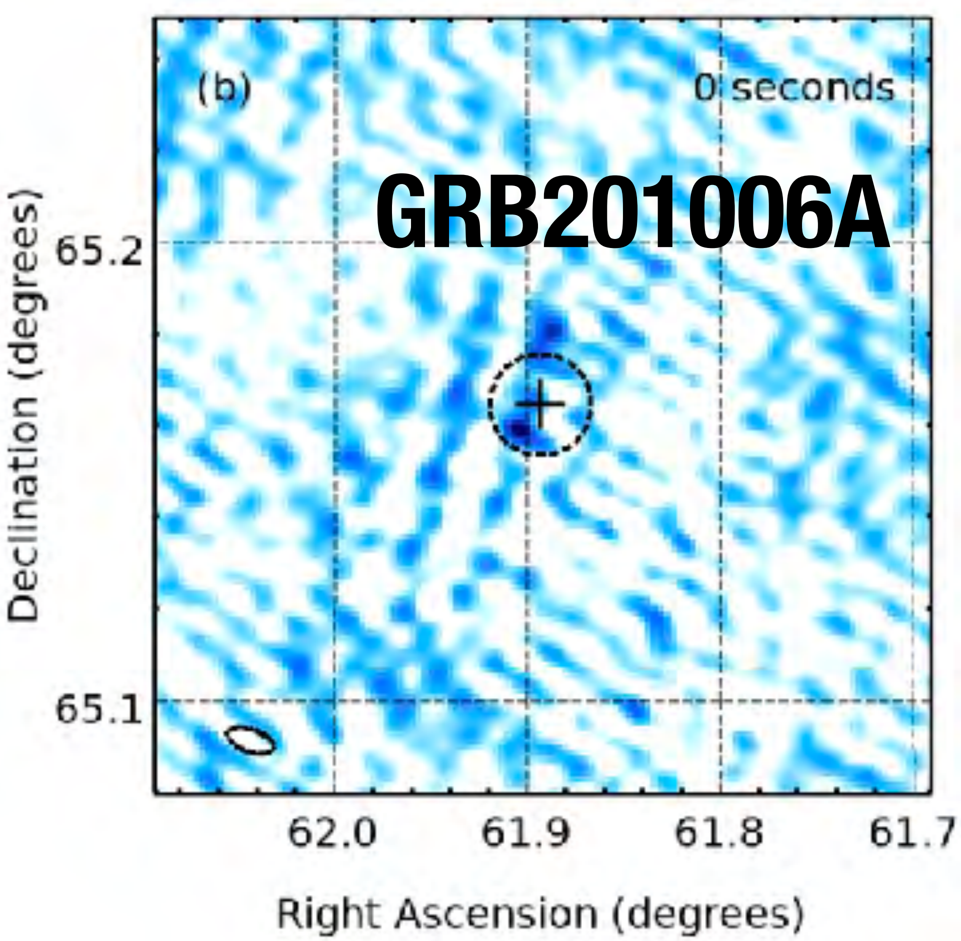
Toy model +



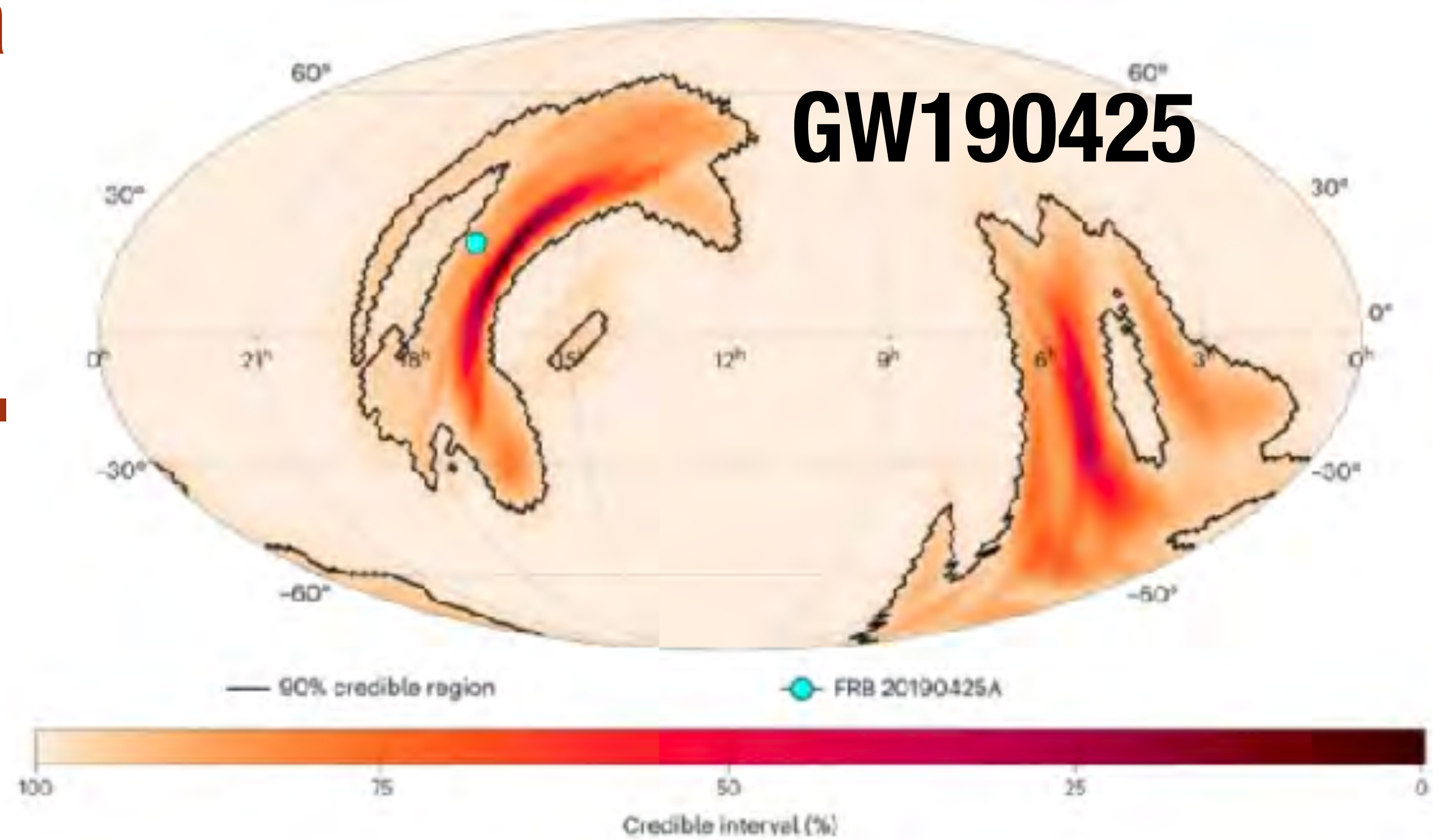
Radio bursts after merger?

Recent interest due to claimed association of radio bursts with neutron star mergers Moroianu+(2023); Rowlinson+(2023)

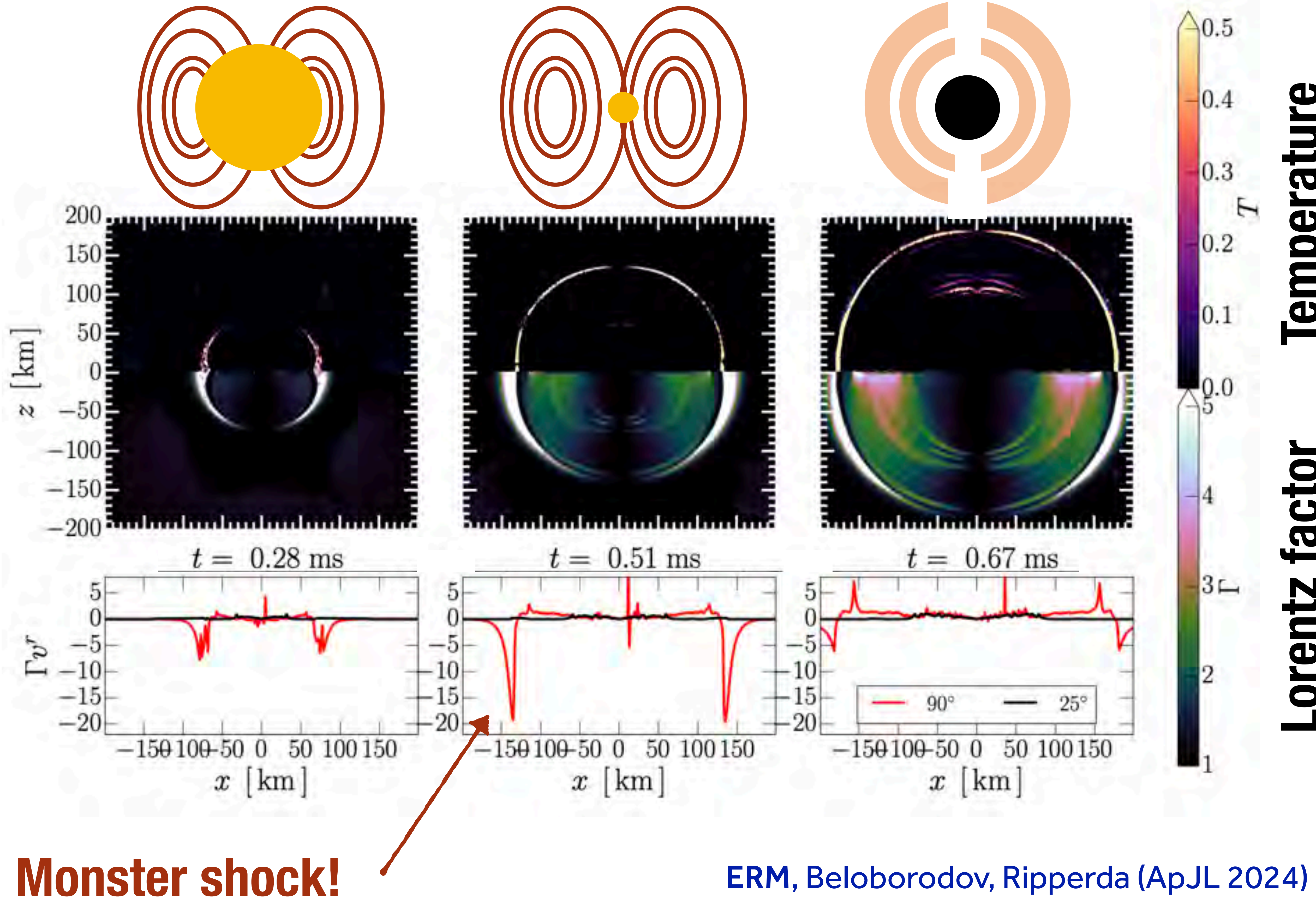
Radio? Rowlinson+ (2023)



Moroianu+(2023)

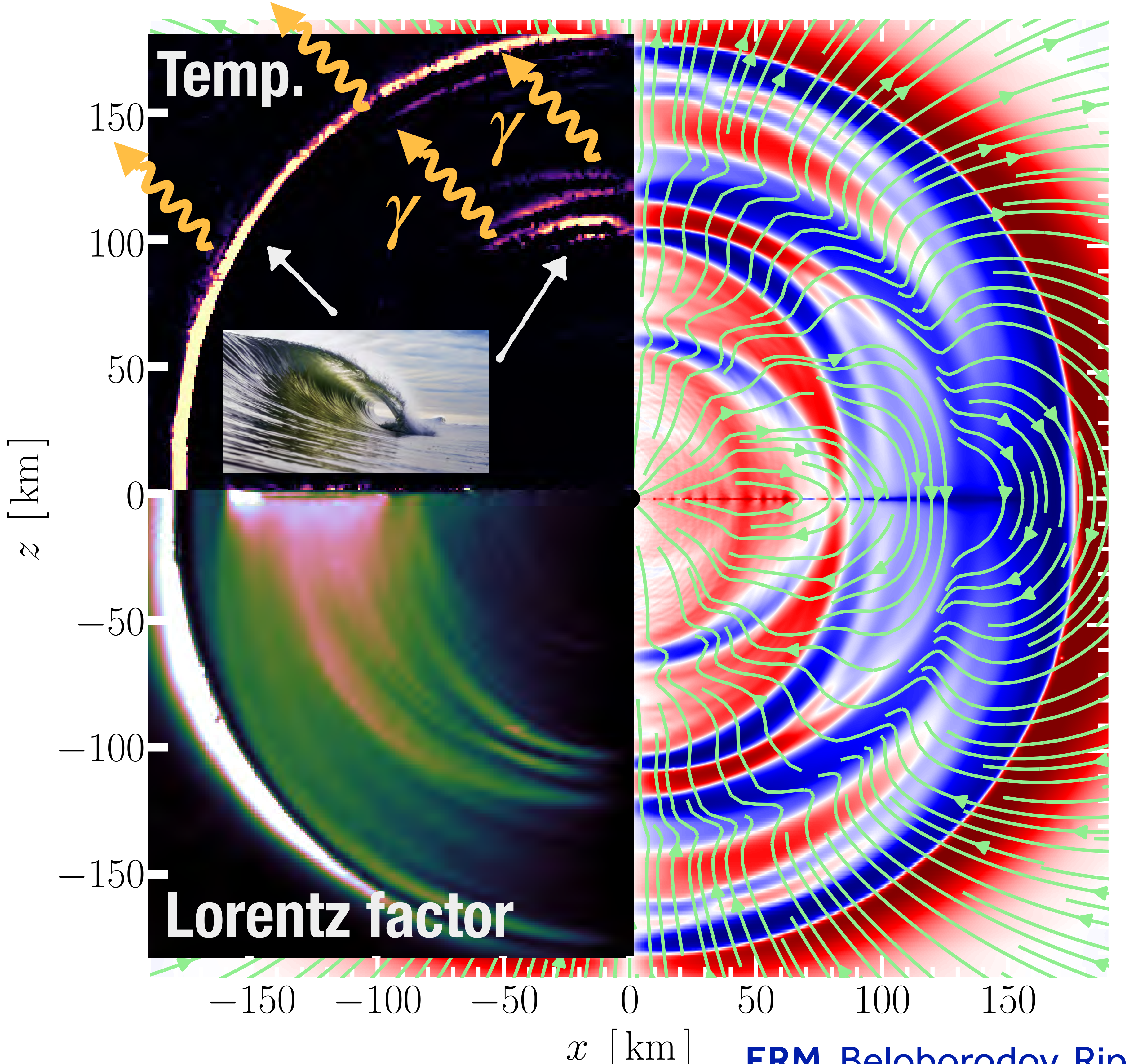


Shock formation during collapse!



ERM, Beloborodov, Ripperda (ApJL 2024)

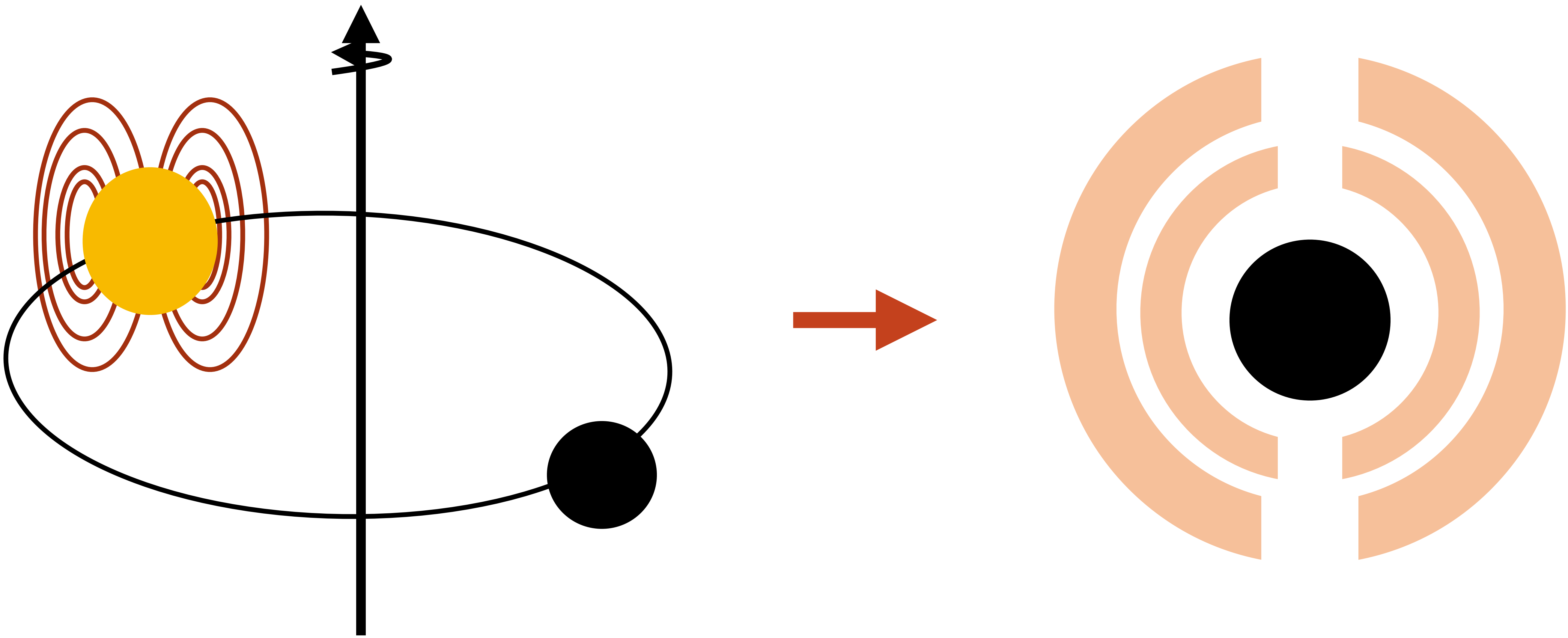
A novel gamma-ray burst scenario



First consistent simulation of collapsing neutron star magnetosphere

ERM, Beloborodov, Ripperda (ApJL 2024)

What about merging neutron stars?



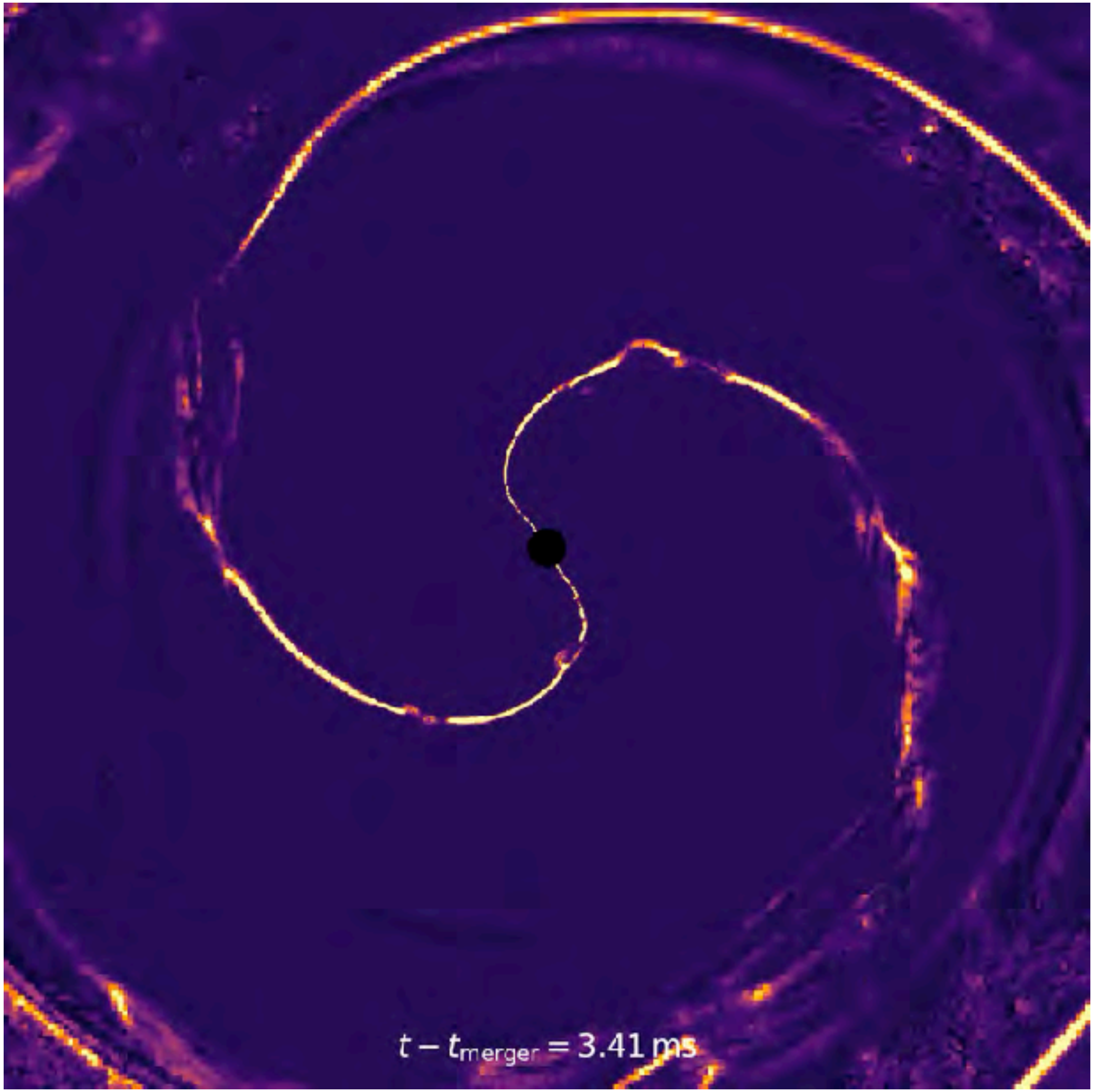
For black hole masses $M_{\rm BH} \gg 5\, M_\odot$, neutron star is swallowed whole.

➡ Monster shock ?!

Black Hole Pulsar!

Yoonsoo Kim
(Caltech =>
PCTS/Princeton)

Kim, **ERM**, Beloborodov, Ripperda (ApJL 2025)



First demonstration of <u>black hole pulsar</u> formation

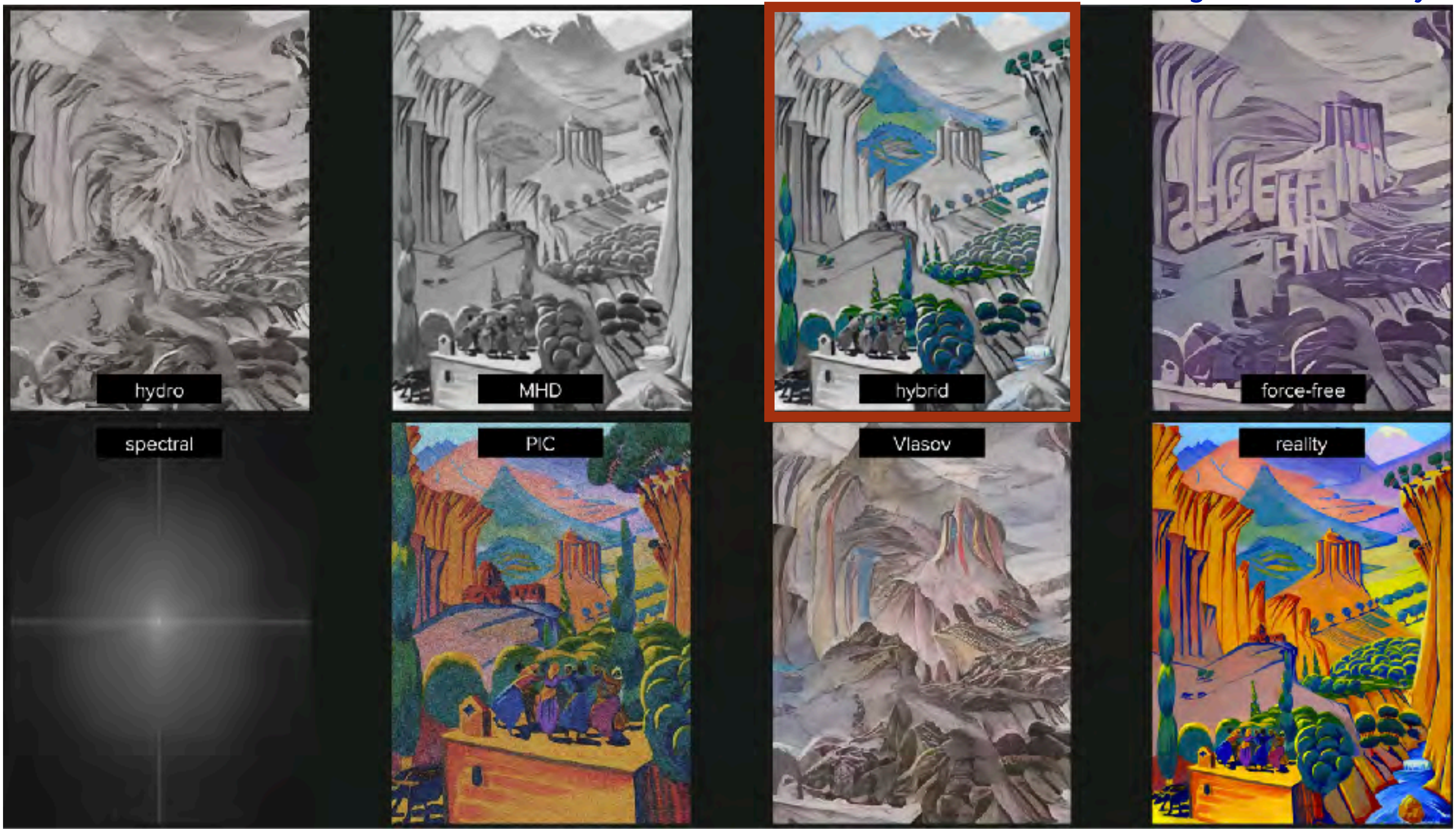
(Black hole no-hair theorem still holds, pulsar state is transient)

Levin+ (2018), Selvi+ (2024)

Striped wind (gamma/ X-ray transient)

Choosing the right approximation

Image credit: Hakobyan

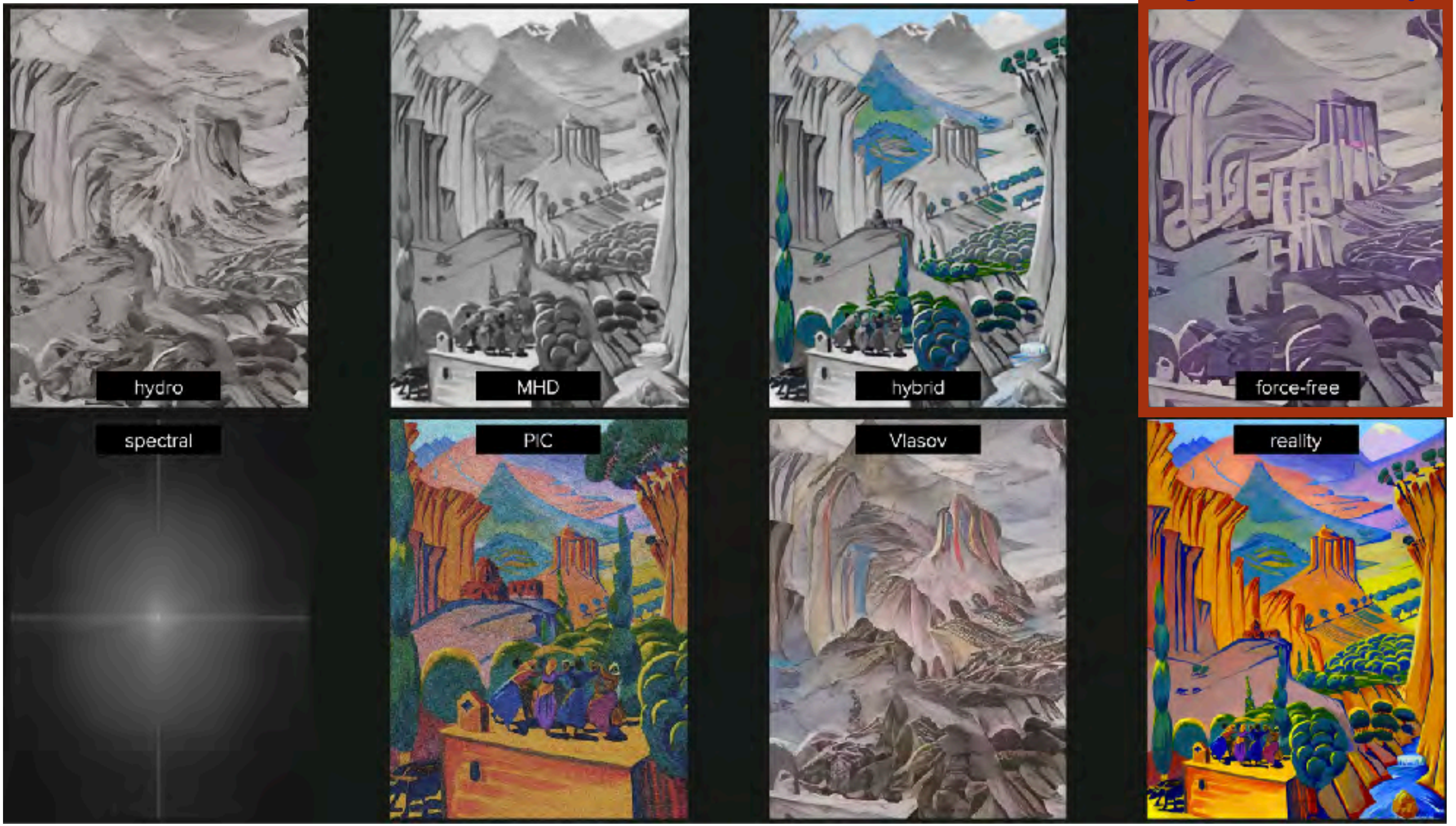


Hybrid particle-in-cell:

Expensive, global features about right, electron fluid; relativity?!

Choosing the right approximation

Image credit: Hakobyan

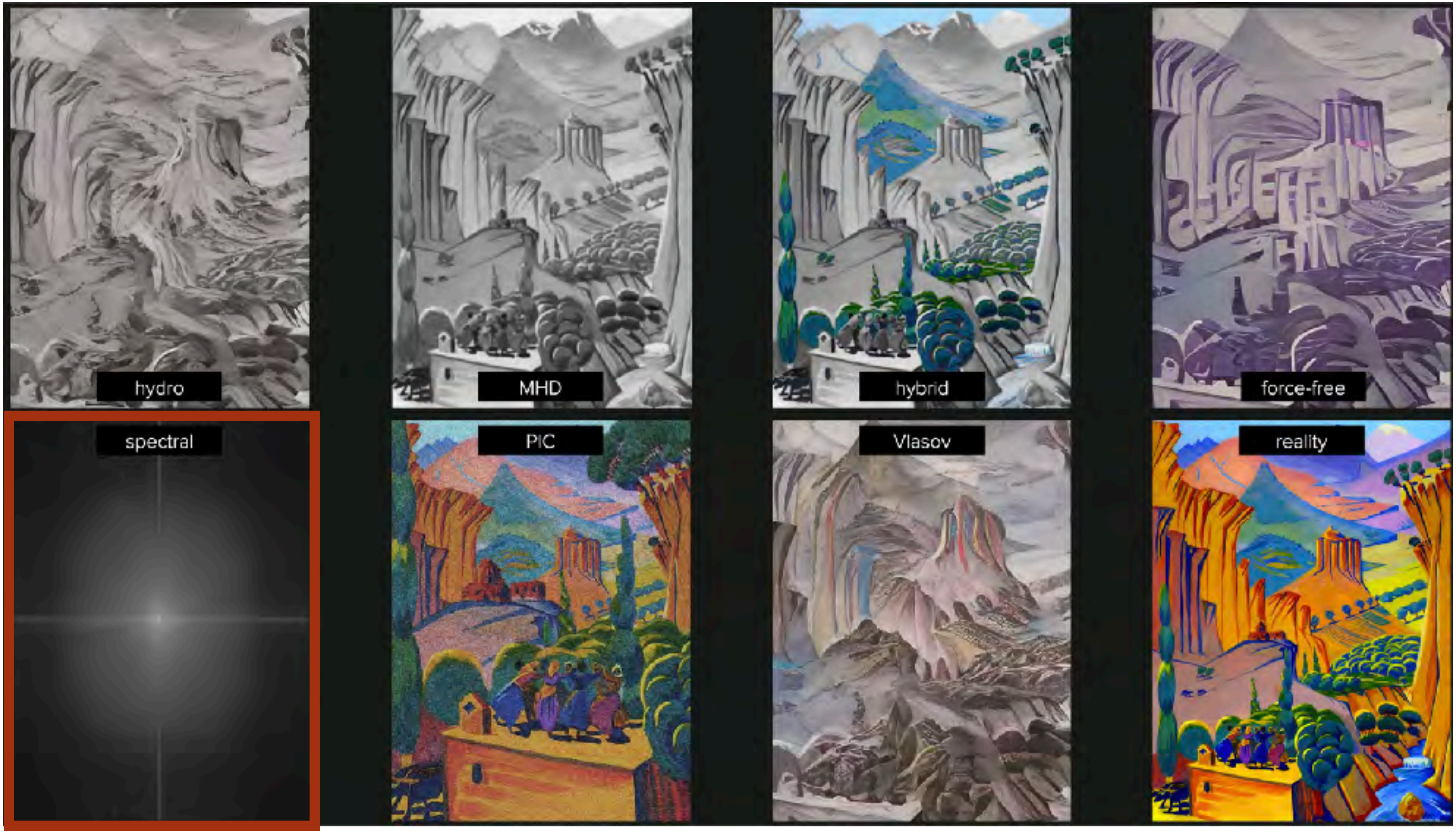


Force-free electrodynamics:

Cheap, gets global dynamics of the jet ok, no disk accretion

Choosing the right approximation

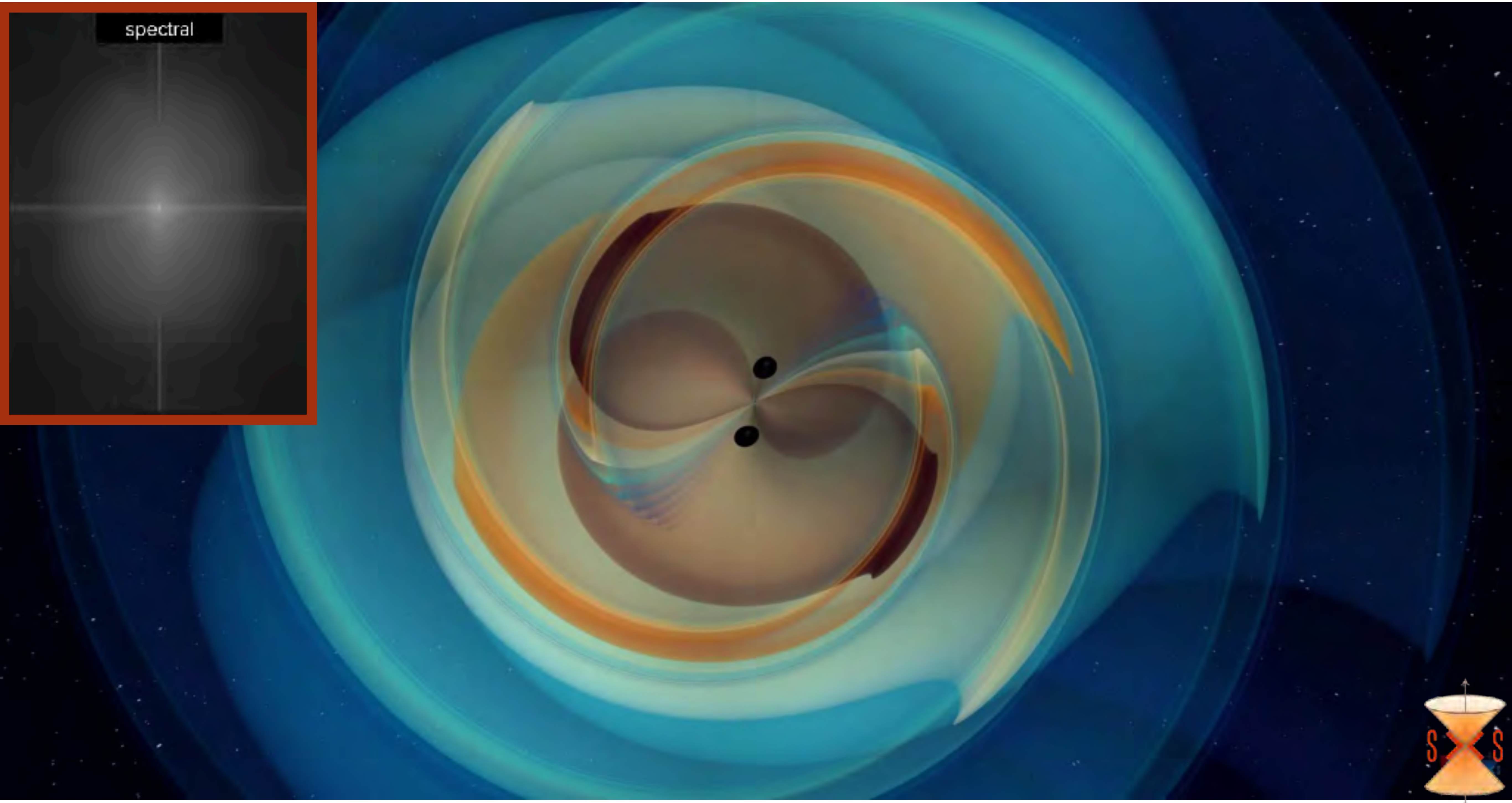
Image credit: Hakobyan



Spectral methods:

Complicated! Very hard to do for fluid problems/shocks. BUT...

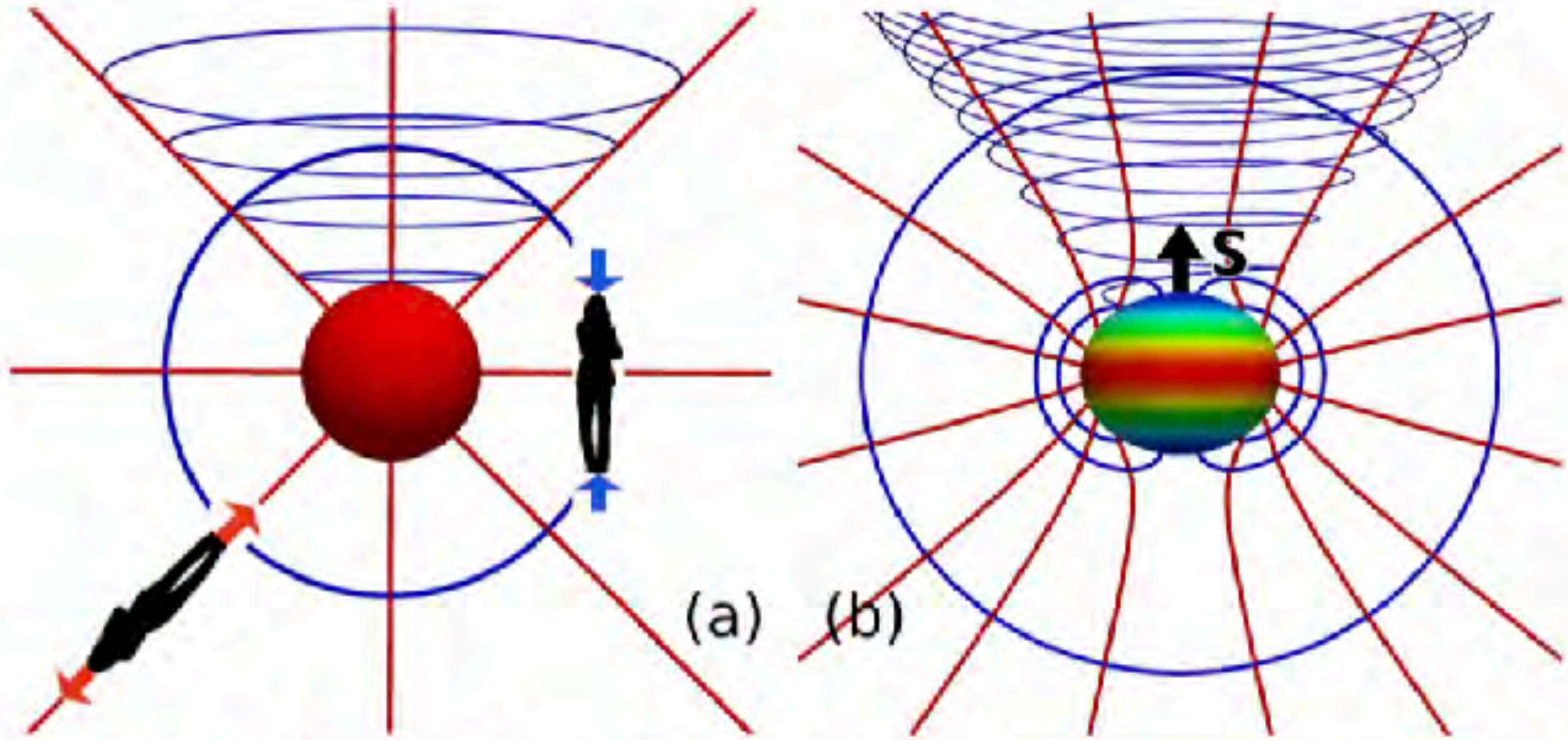
Choosing the right approximation

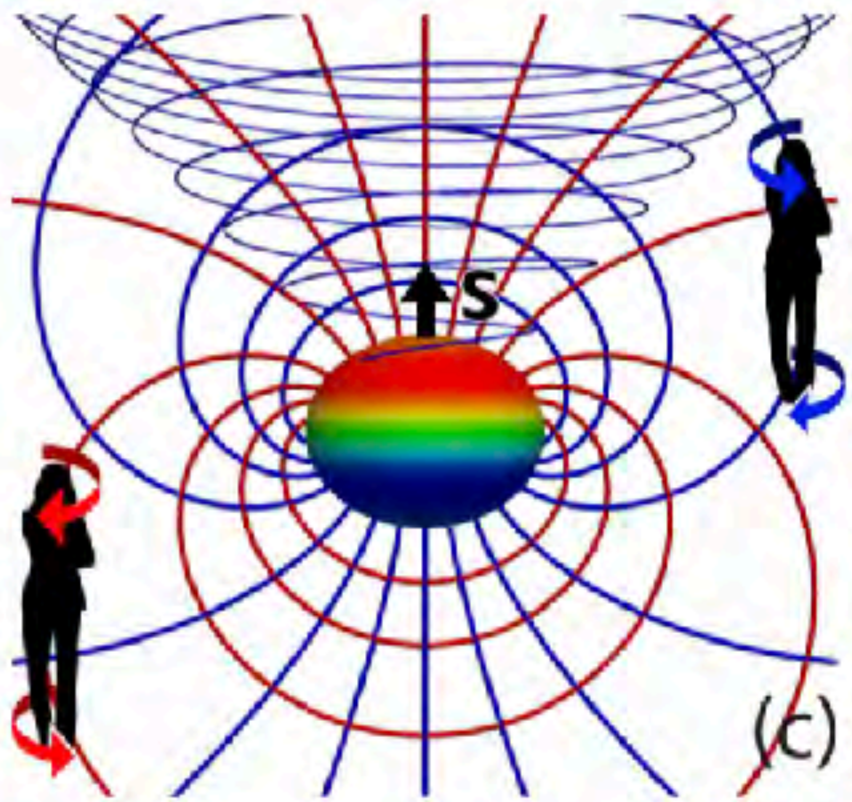


Spectral methods:

Work extremely well for black holes and gravitational waves!

Gravitometrodynamics



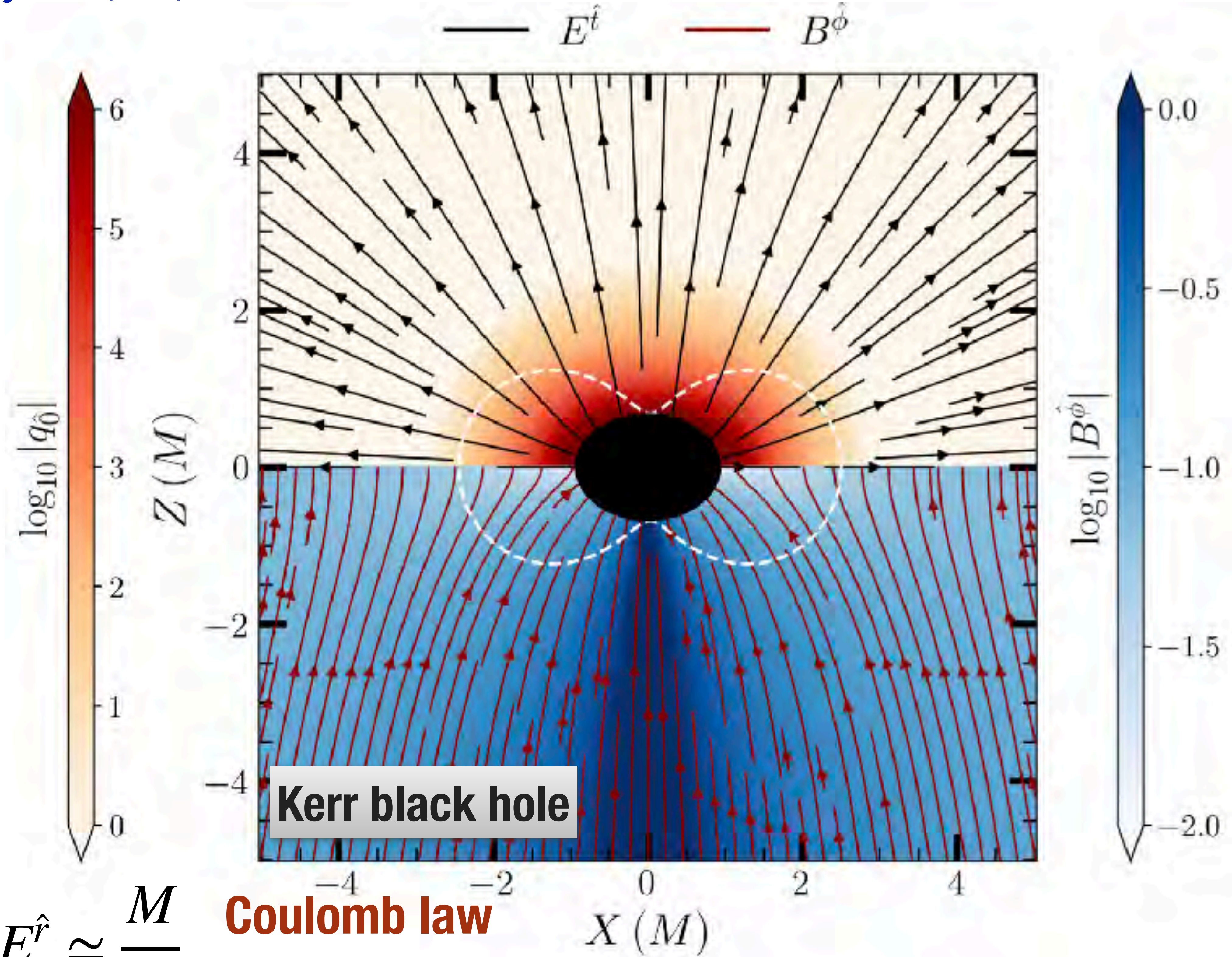


Owen et al. (2011)

Halloran & Thorne (2024)

Black Hole Electrostatics

Boyeneni, Wu, ERM (PRL 2025)



Siddharth Boyeneni (Caltech =>Columbia)

Jiaxi Wu (Caltech)

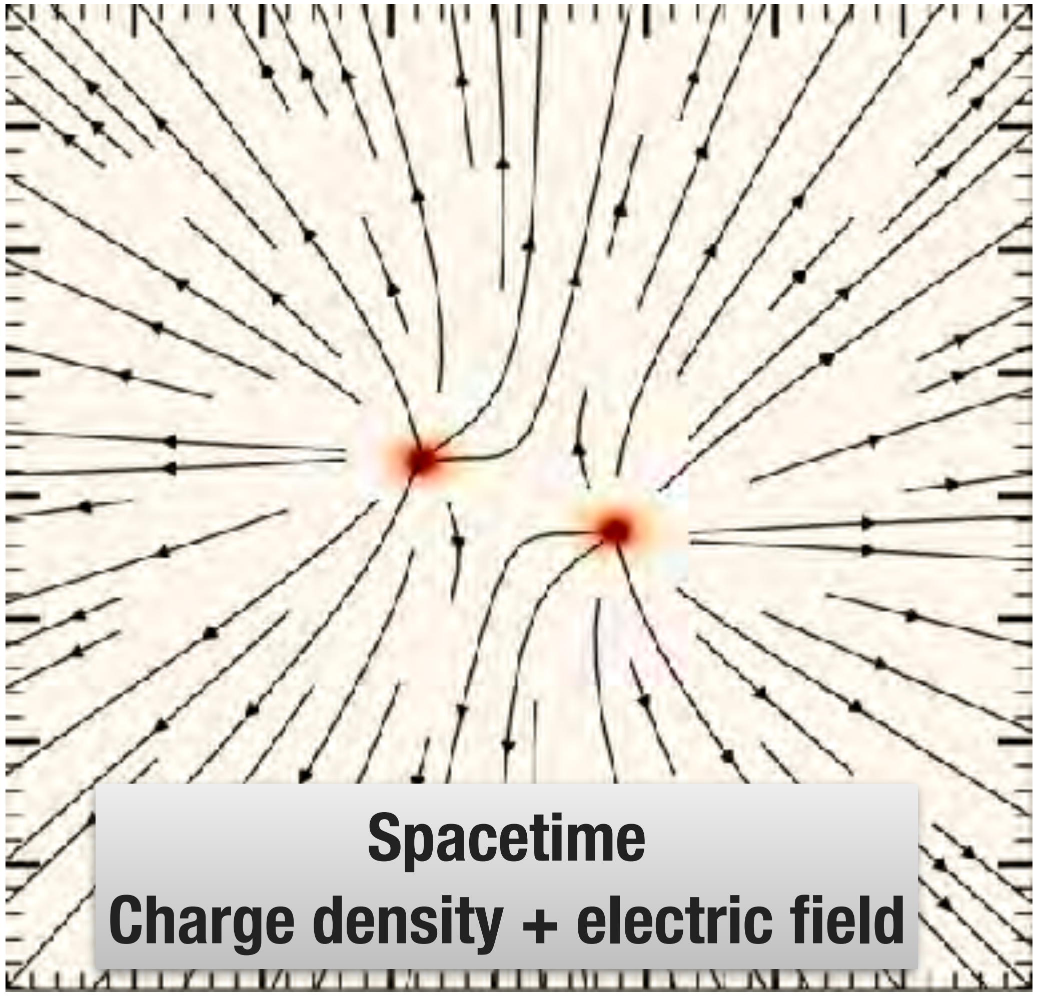
$$E^{\hat{r}} \simeq \frac{M}{r^2}$$

Coulomb law (exact!)

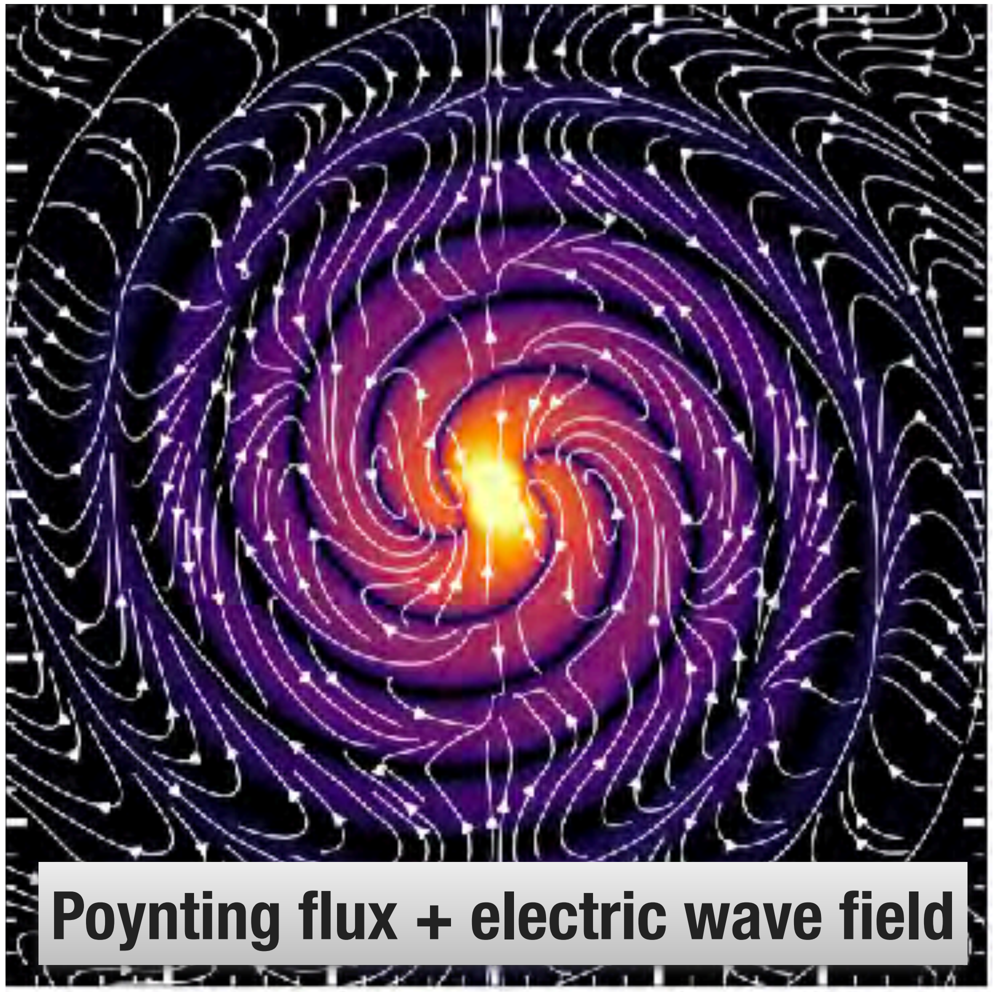
Binary Black Hole Electrodynamics

Binary black hole inspiral has static and dynamical fields!

Gravity = Lorentz force



Grav. Waves = Poynting flux



Siddharth Boyeneni (Caltech)

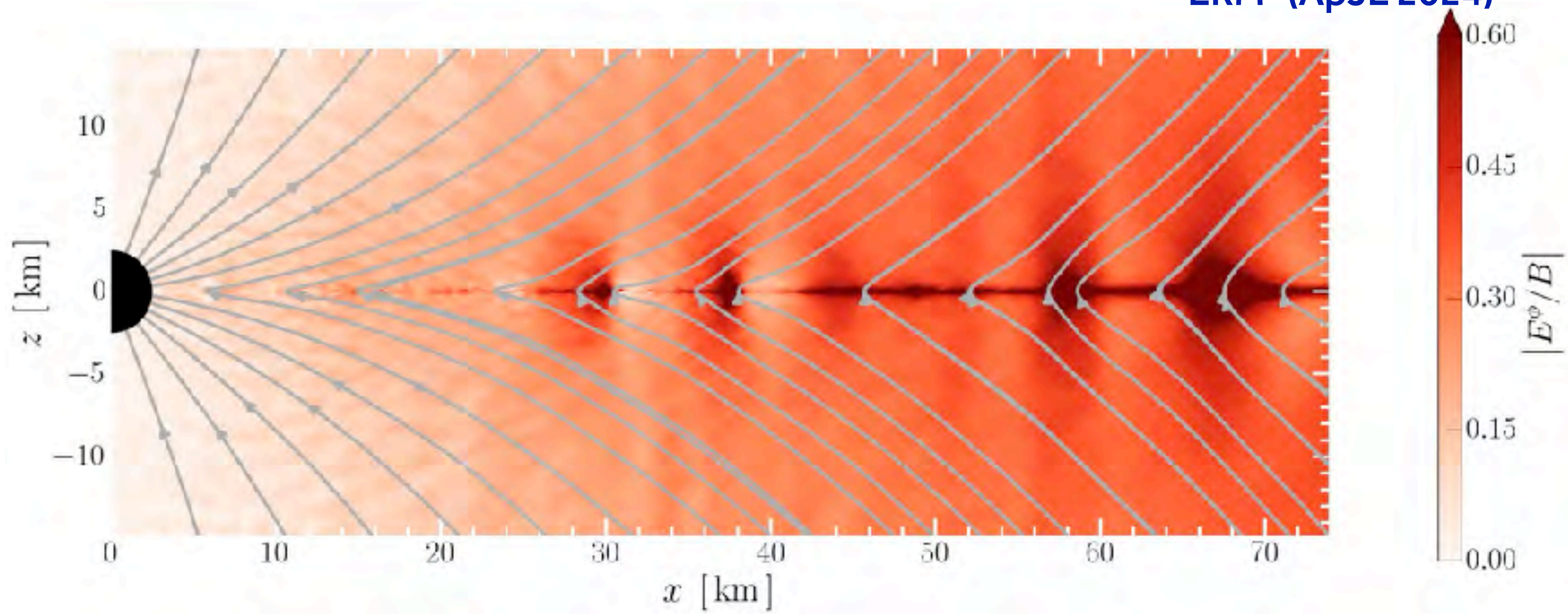
Jiaxi Wu (Caltech)

Boyeneni, Wu, **ERM** (PRL 2025)

Ringdown = Balding!

ERM+(ApJL 2024)

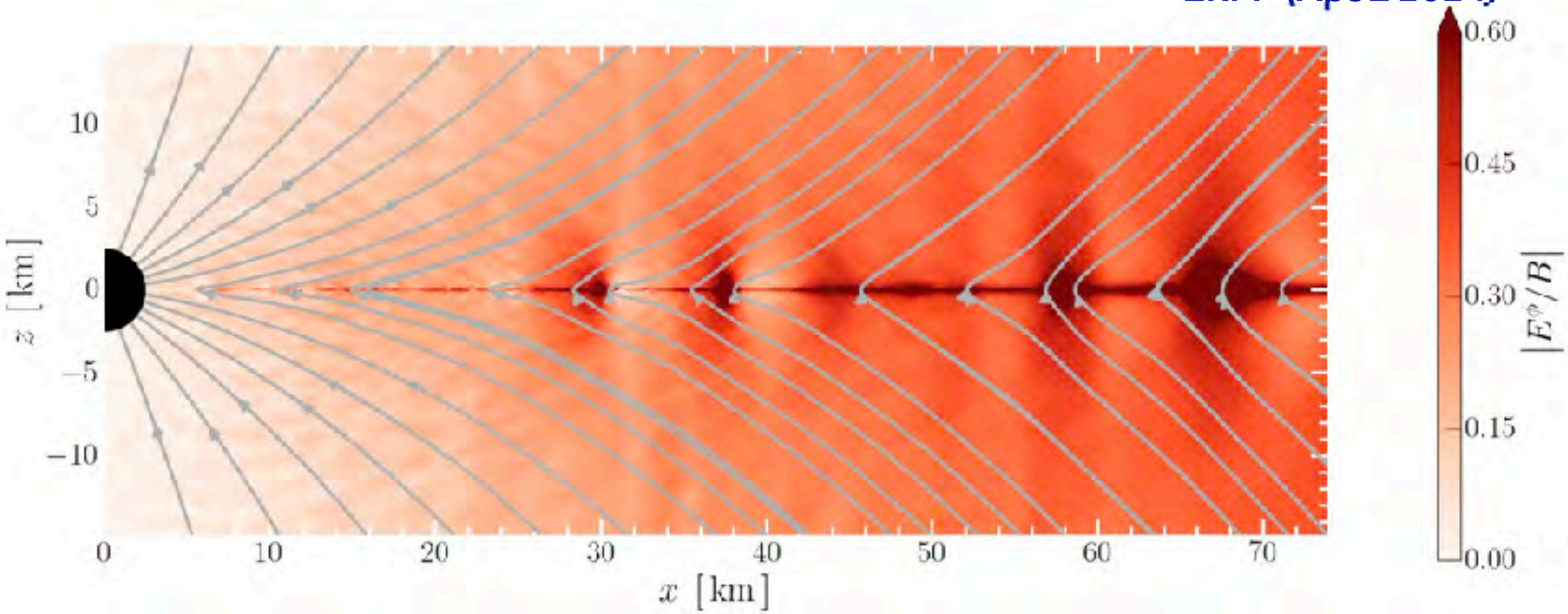
E&M



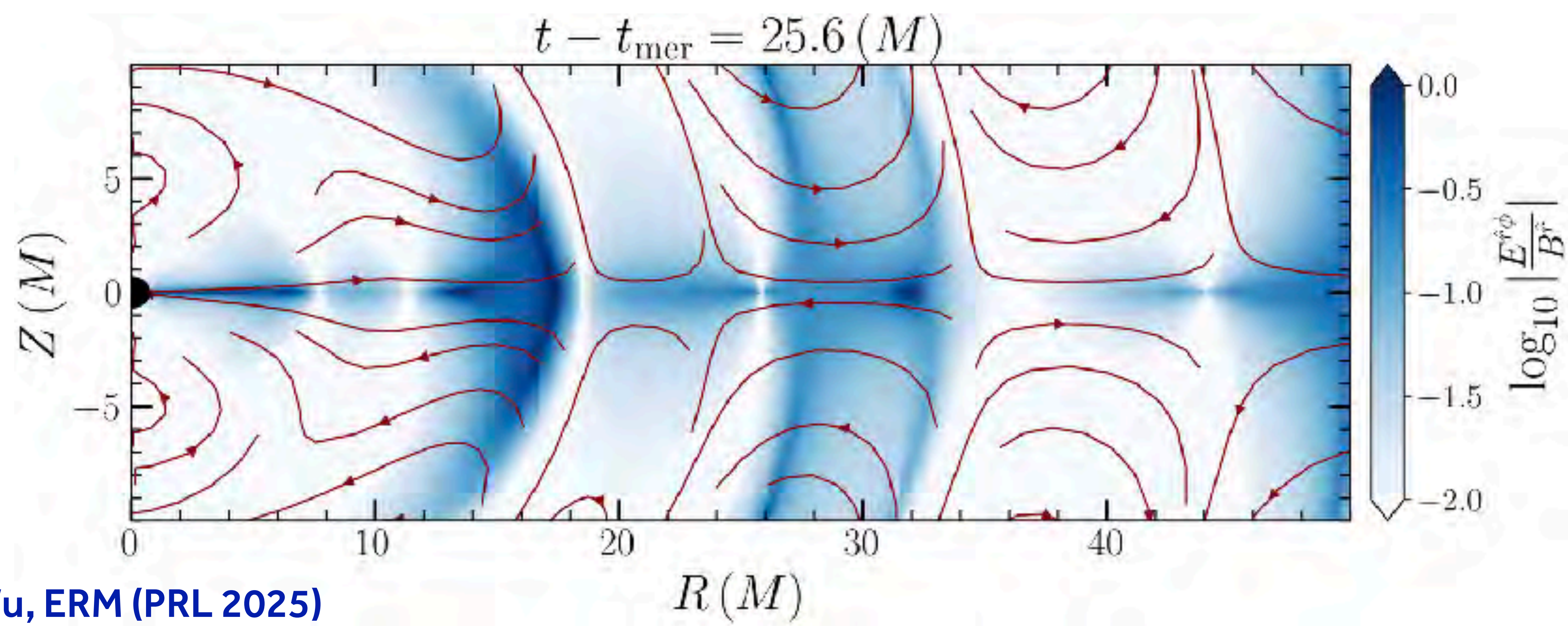
Ringdown = Balding!

ERM+(ApJL 2024)

E&M



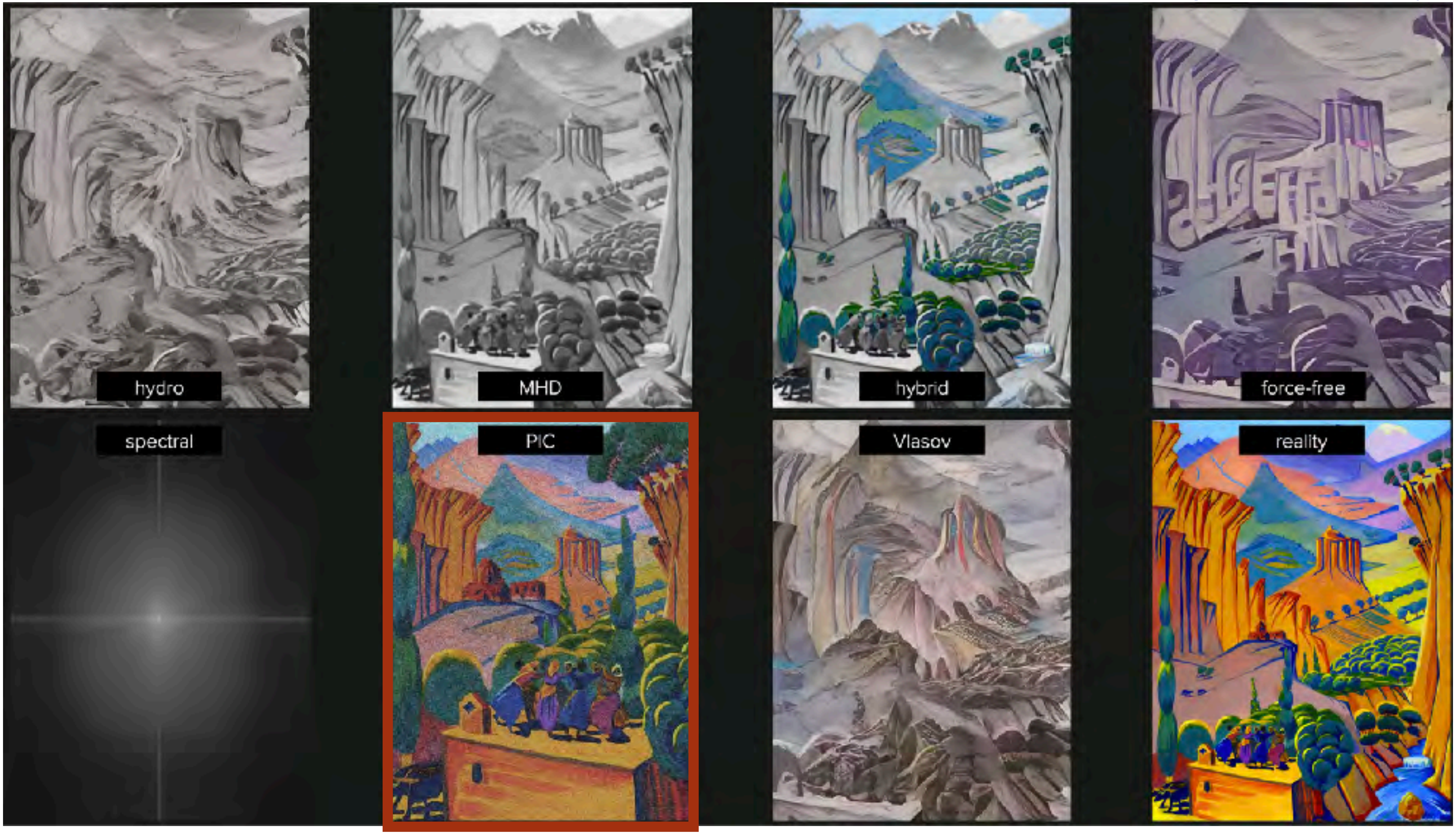
Gravity



Boyeneni, Wu, ERM (PRL 2025)

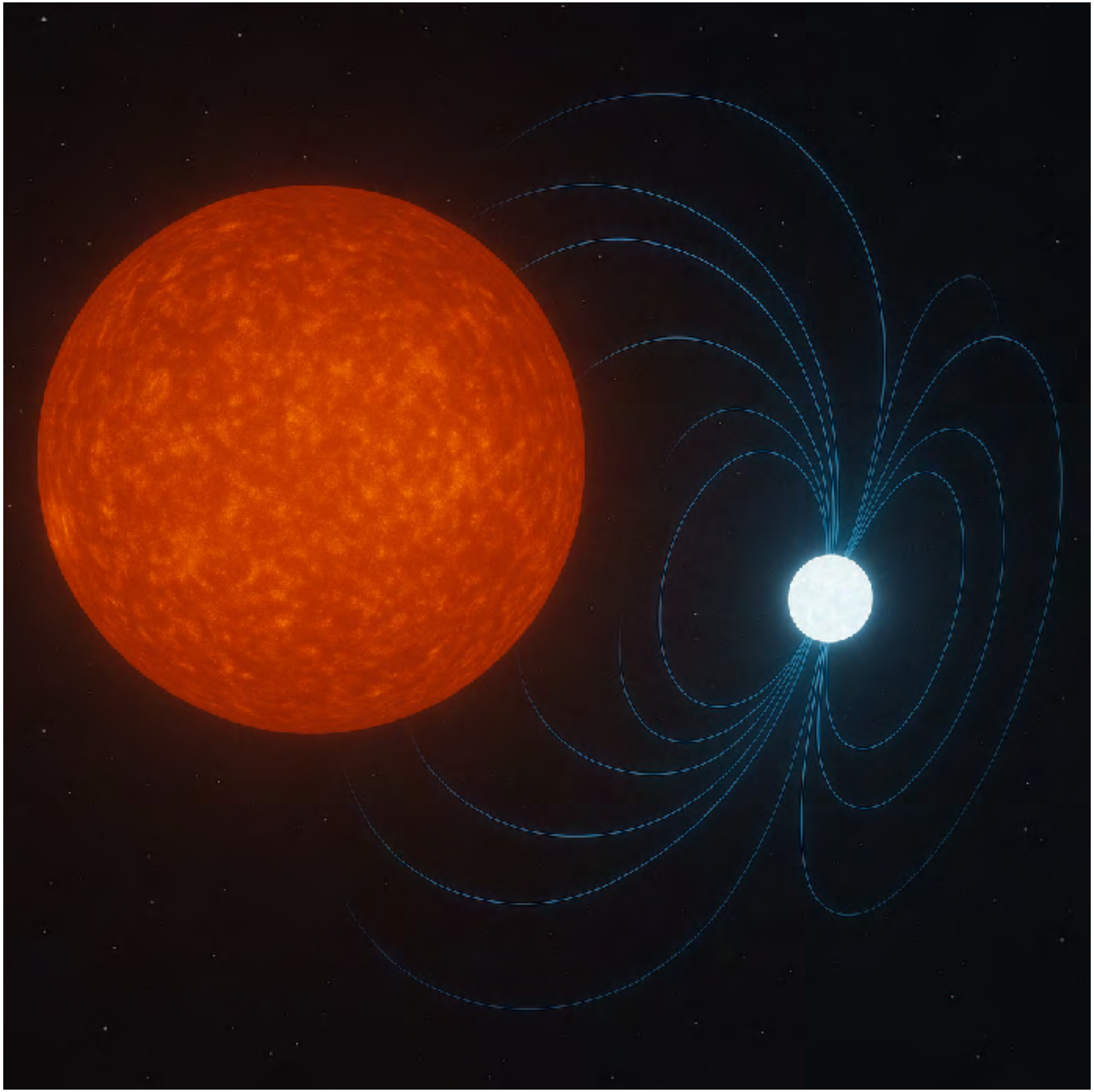
Choosing the right approximation

Image credit: Hakobyan



Particle-in-cell **(Monte-Carlo-type sampling approach):**

Extremely expensive! Includes all the physics. Scale separation...?



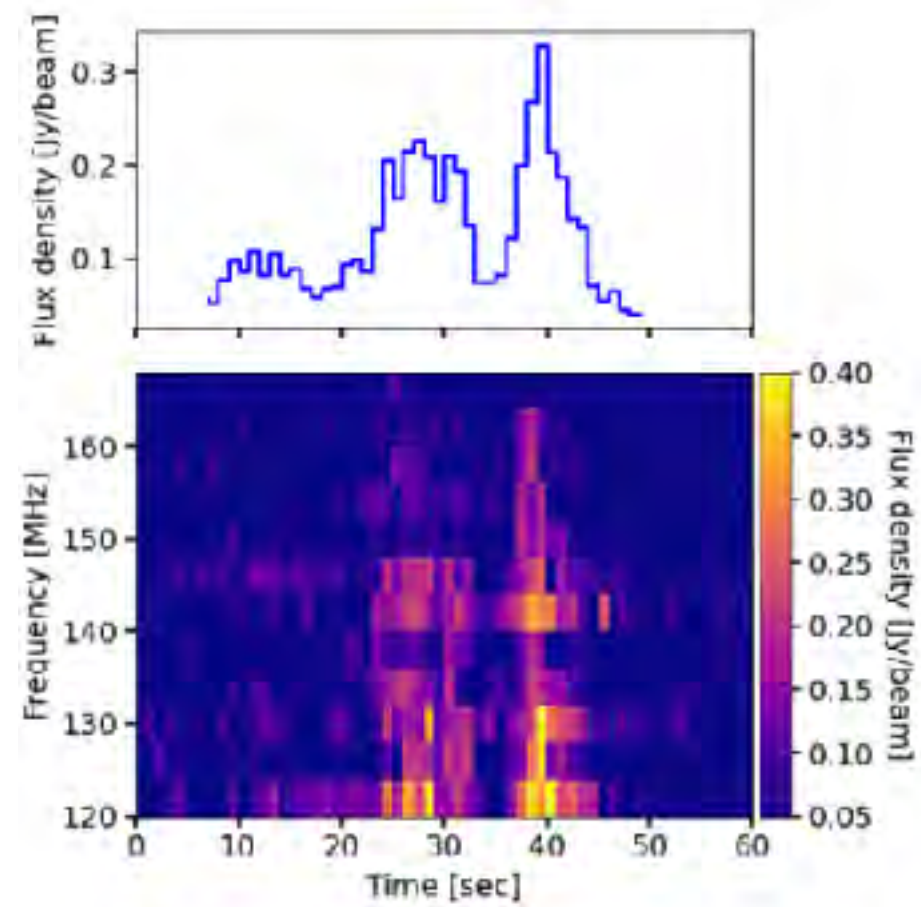
Interacting White Dwarf binaries

Recently reported discovery of short radio pulses (<1min) in galactic white-dwarf — M-dwarf binaries with LOFAR. De Ruiter+ (2025)

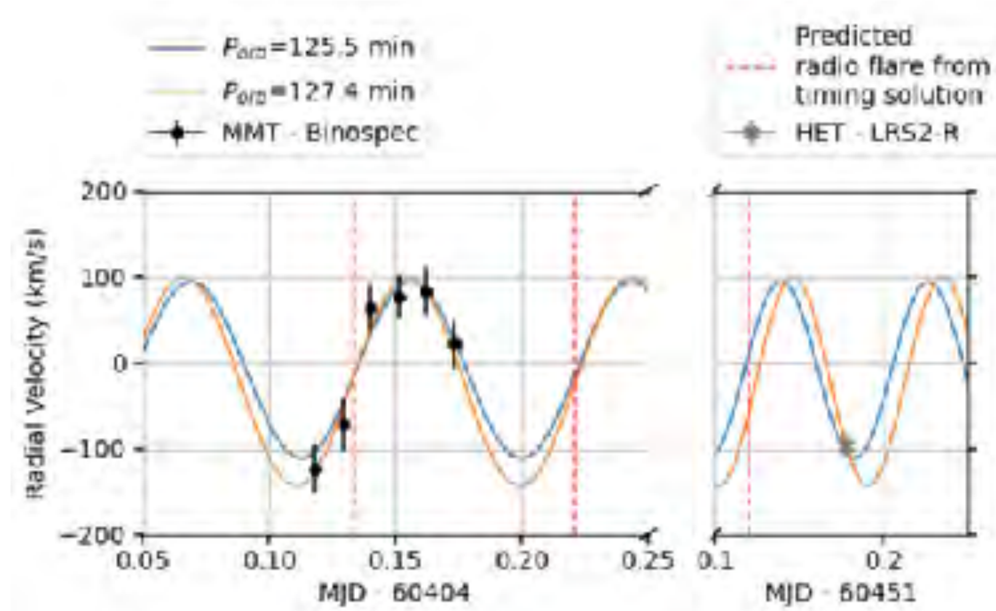
Similar system also found with MeerKAT Hurley-Walker+ (2025)

Radio emission potentially magnetospheric (luminosity, polarization)

Some similarities to proposed neutron star binary precursors



De Ruiter+ (2025)

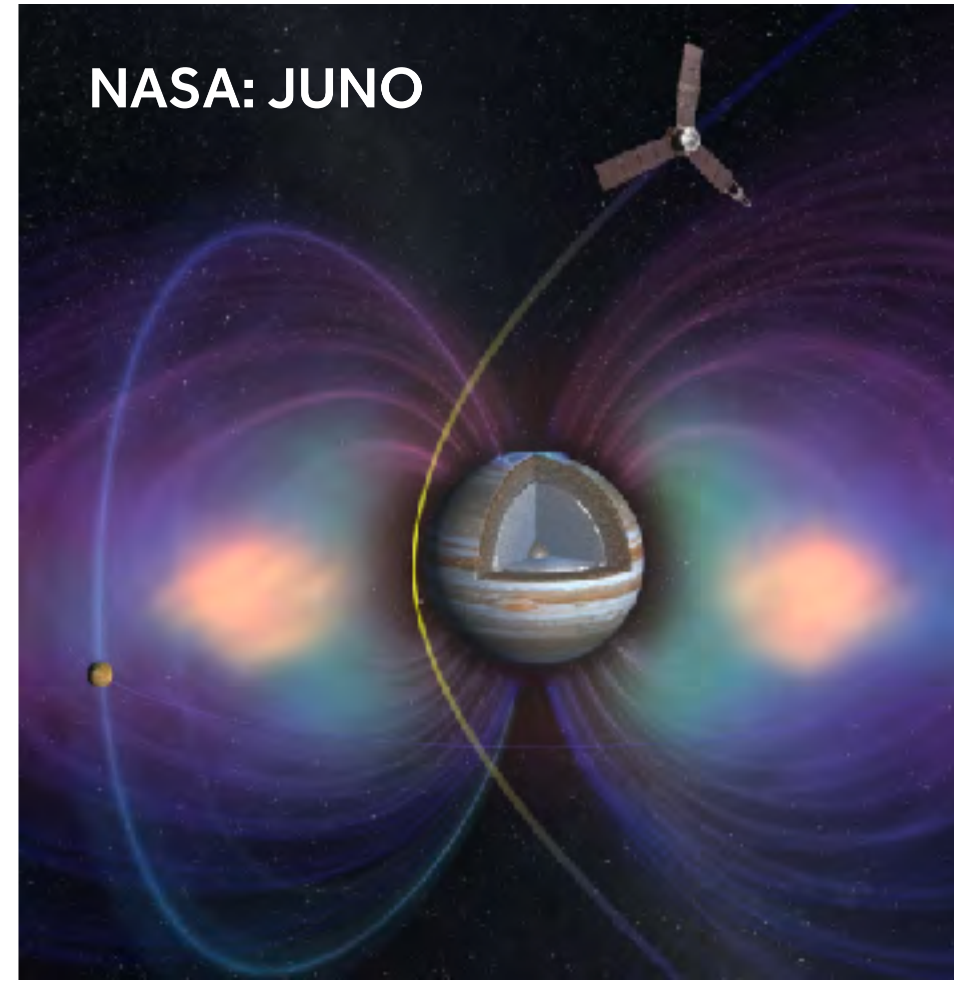


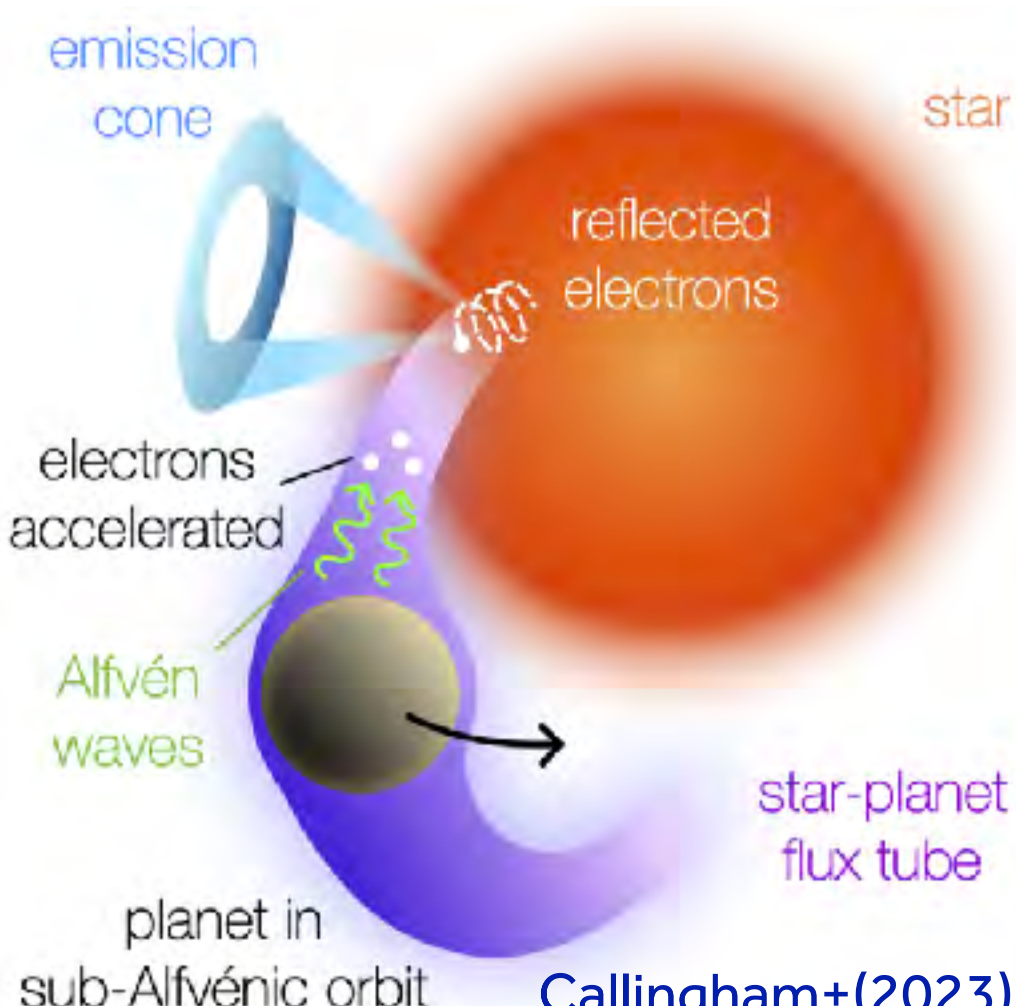
Radio emission from white dwarfs??

First kinetic simulations of relativistic electron-cyclotron maser under WDMD conditions supports a Jupiter-Io-like emission scenario

Zhong & **ERM** (arXiv 2025)

Also Goldreich&Lynden-Bell (1968)
Qu & Zhang (2025)





Callingham+(2023)

$$\mathcal{L}_{\rm radio} \simeq \xi \dot{E}_{\rm diss}\,,$$
$$\simeq 6.0\times 10^{27} {\rm erg\ s^{-1}}\,\zeta_\phi \left(\frac{\Delta\Omega}{\Omega}\right)\left(\frac{P}{100\,{\rm min}}\right)^{-13/3} \left(\frac{\xi}{10^{-2}}\right)\left(\frac{\mu}{10^{34}\,{\rm G\,cm^3}}\right)^2\left(\frac{M_\star+M_c}{0.8\,M_\odot}\right)^{-5/3} \left(\frac{R_{\rm MD}}{0.217R_\odot}\right)^2 .$$

Zhong & **ERM** (arXiv 2025)

Radio emission from white dwarfs??

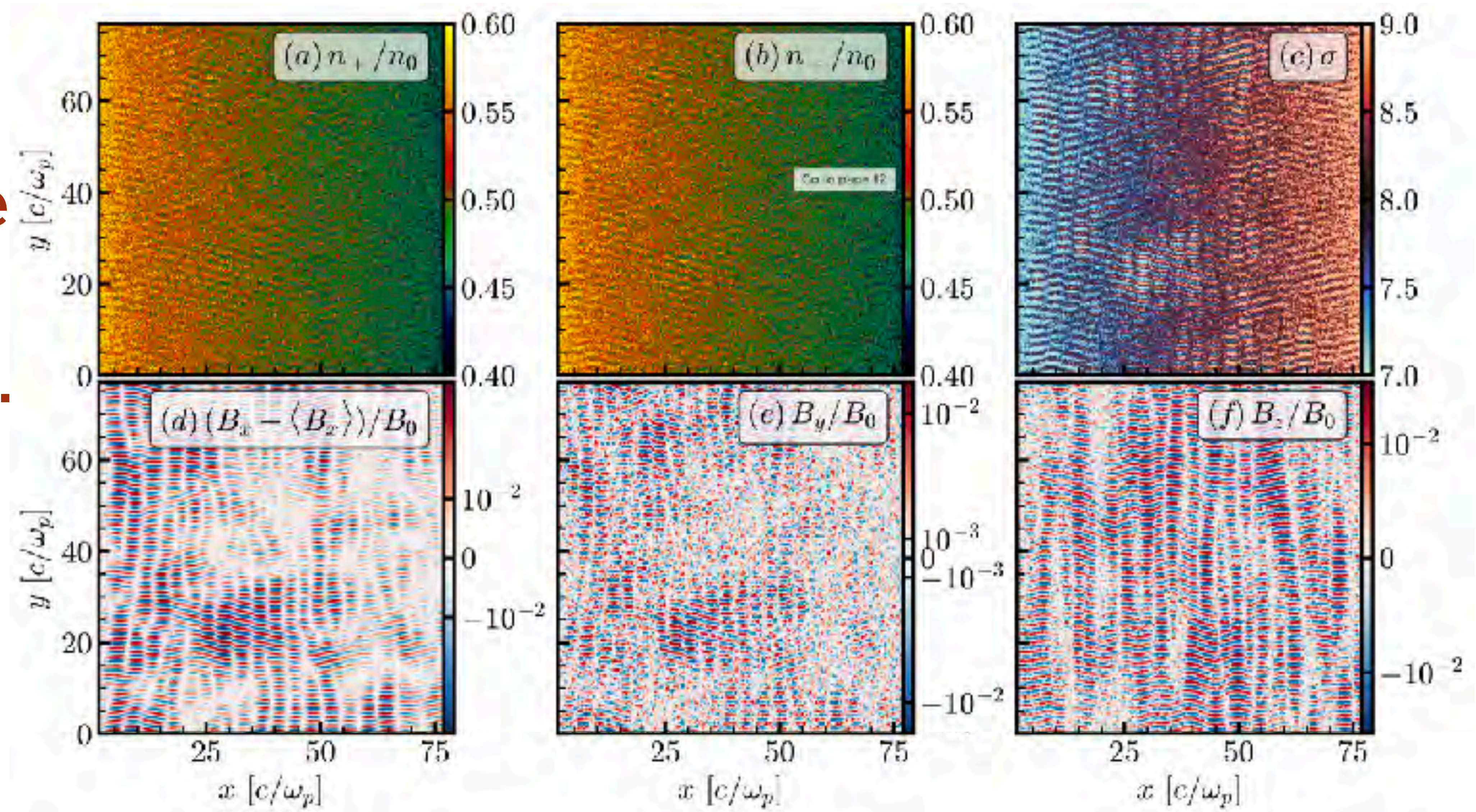
First kinetic simulations of relativistic electron-cyclotron maser under WDMD conditions supports a Jupiter-Io-like emission scenario

Yici Zhong (Caltech)

Zhong & **ERM** (arXiv 2025)

Nonlinear maser regime up to 10x more efficient for radio emission.

Polarization matches (with caveats)



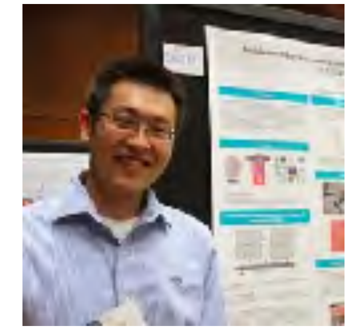
Machine learning Jupiter's radiation belts

Jet Propulsion Laboratory
California Institute of Technology

New collaboration between Caltech (CMS & TAPIR) and JPL

Franca Hoffmann

Houman Owhadi



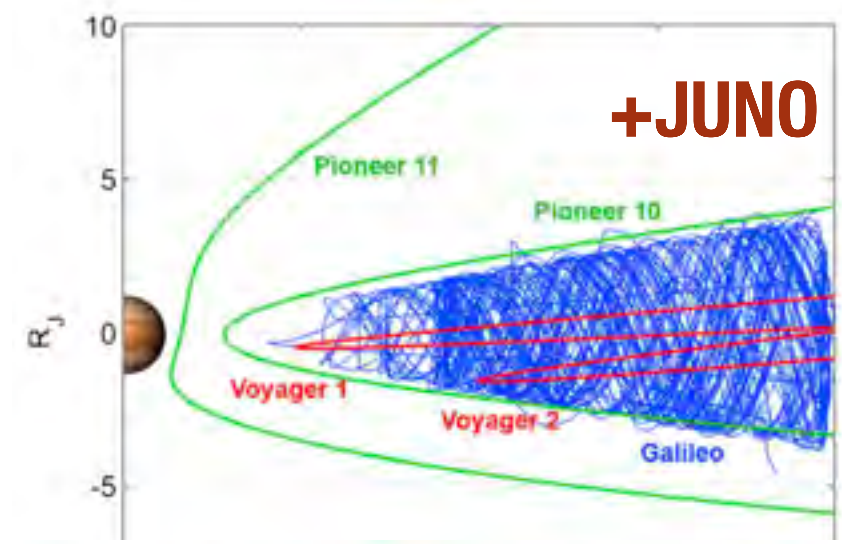
Brian X. Zhu

Insoo Jun

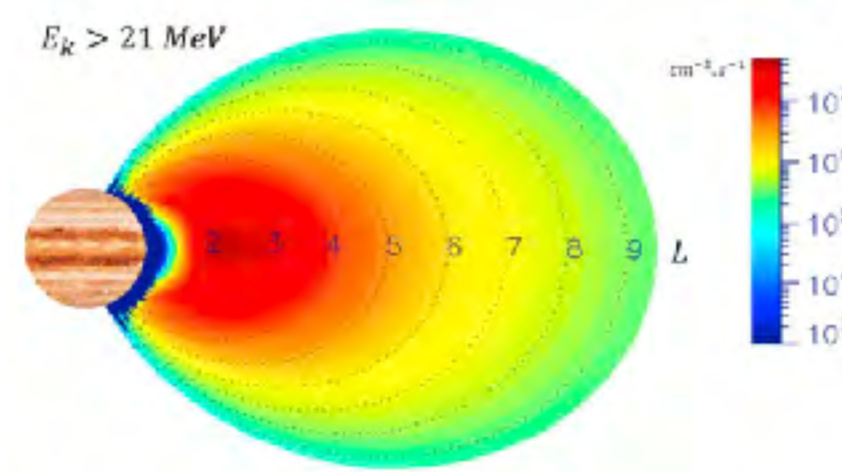
Trapped electron fluxes f inside the magnetosphere

(solar wind interaction, moon sweeping etc.)

De Soria-Santacruz+2016



Can we use modern machine learning algorithms to learn electron diffusion along sparsely sampled orbits?

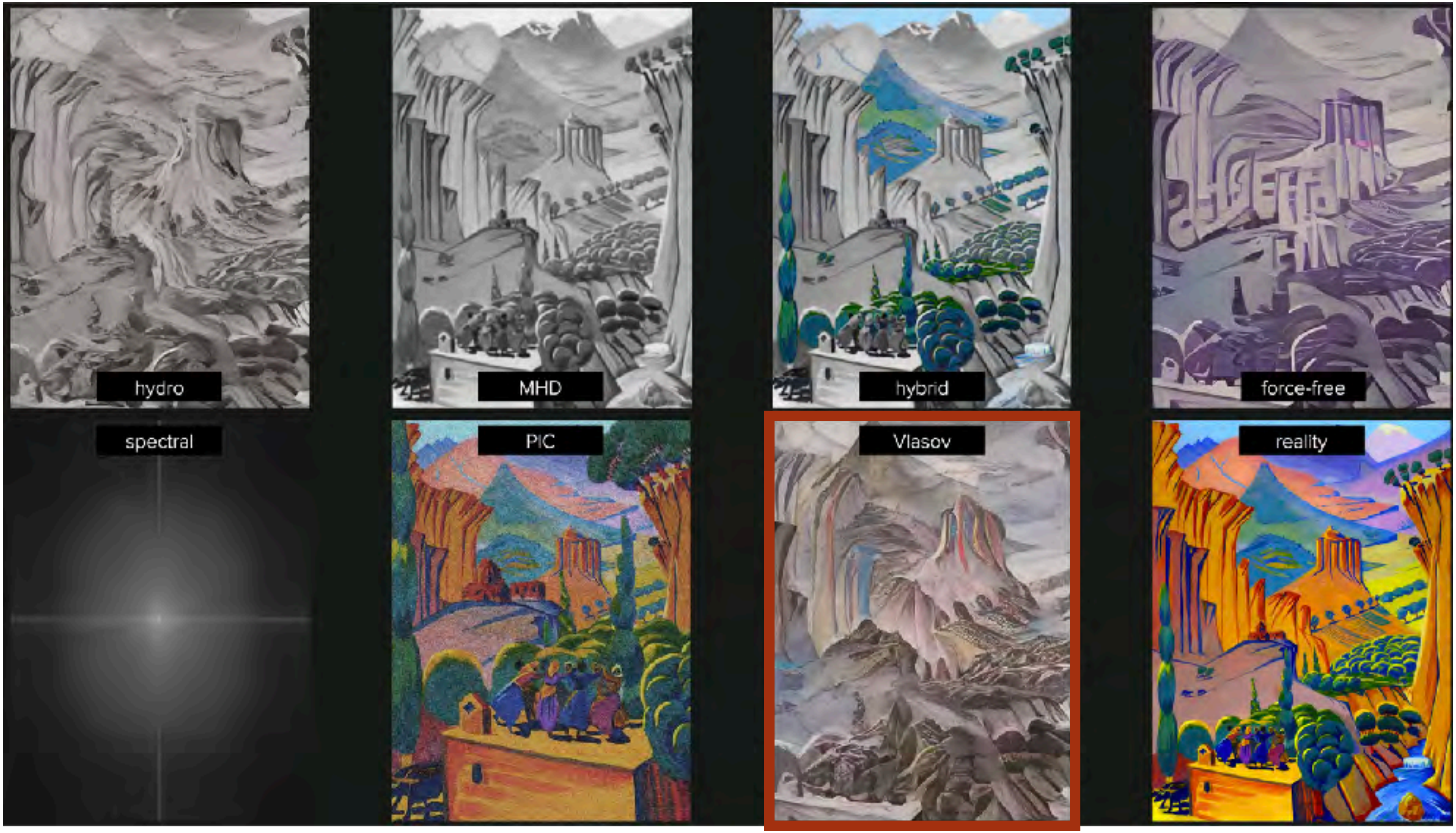


Nenon+2017

$$\frac{\mathrm{d}}{\mathrm{d}t} f = -\frac{1}{\tau_{\mathrm{moon}}} f + L^2 \frac{\partial}{\partial L}\left[\frac{1}{L^2} D_{\mathrm{LL,wind}} \frac{\partial f}{\partial L}\right] + \dots$$

Choosing the right approximation

Image credit: Hakobyan

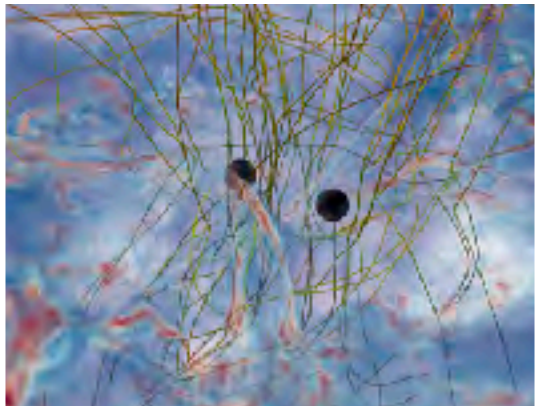


Vlasov Solver **(Brute force 6D phase space):**

Extremely expensive! Does it really work for global problems?

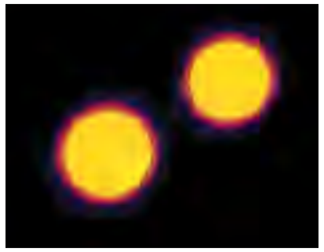
Challenge when studying magnetic fields

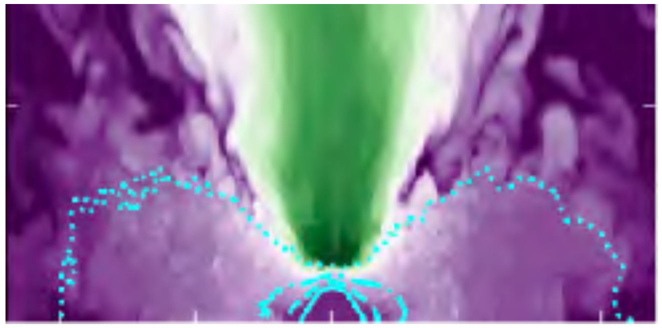
- Natural ordering parameter for how dynamically important magnetic fields are

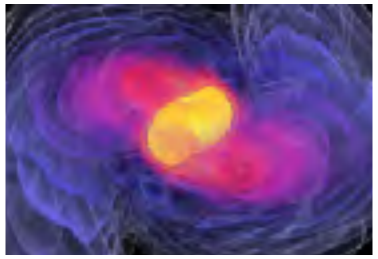


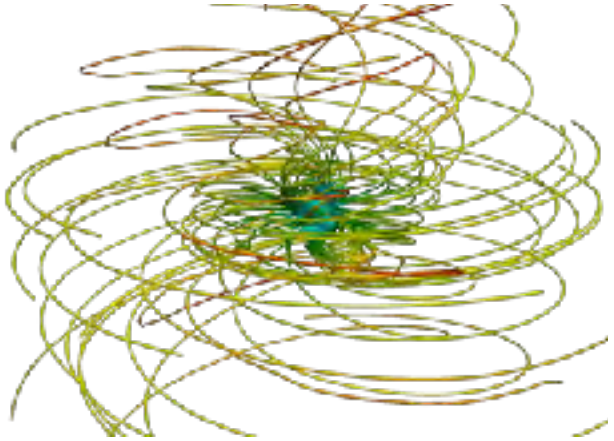
10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3}

b^2/ρ









Challenge when studying magnetic fields

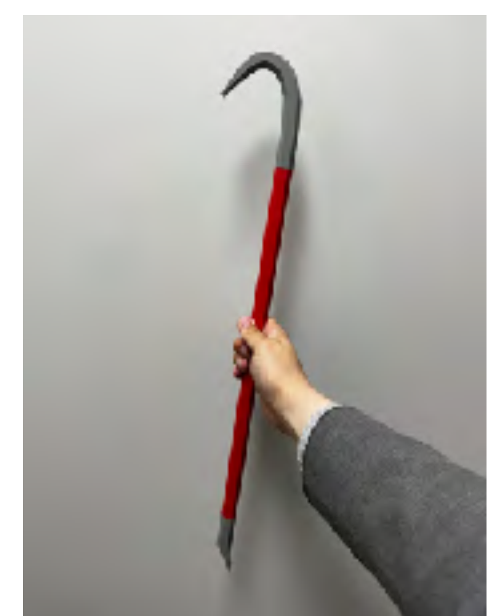
- Natural ordering parameter for how dynamically important magnetic fields are

b^2/ρ

10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3}

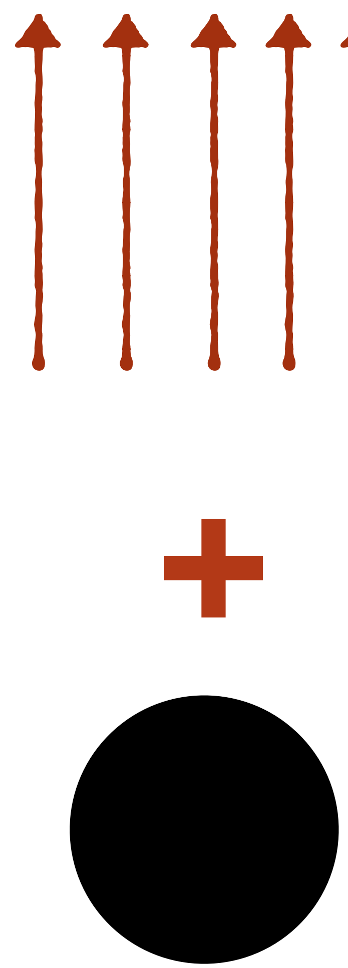
Flow dynamics dominated **B-field dynamics dominated**





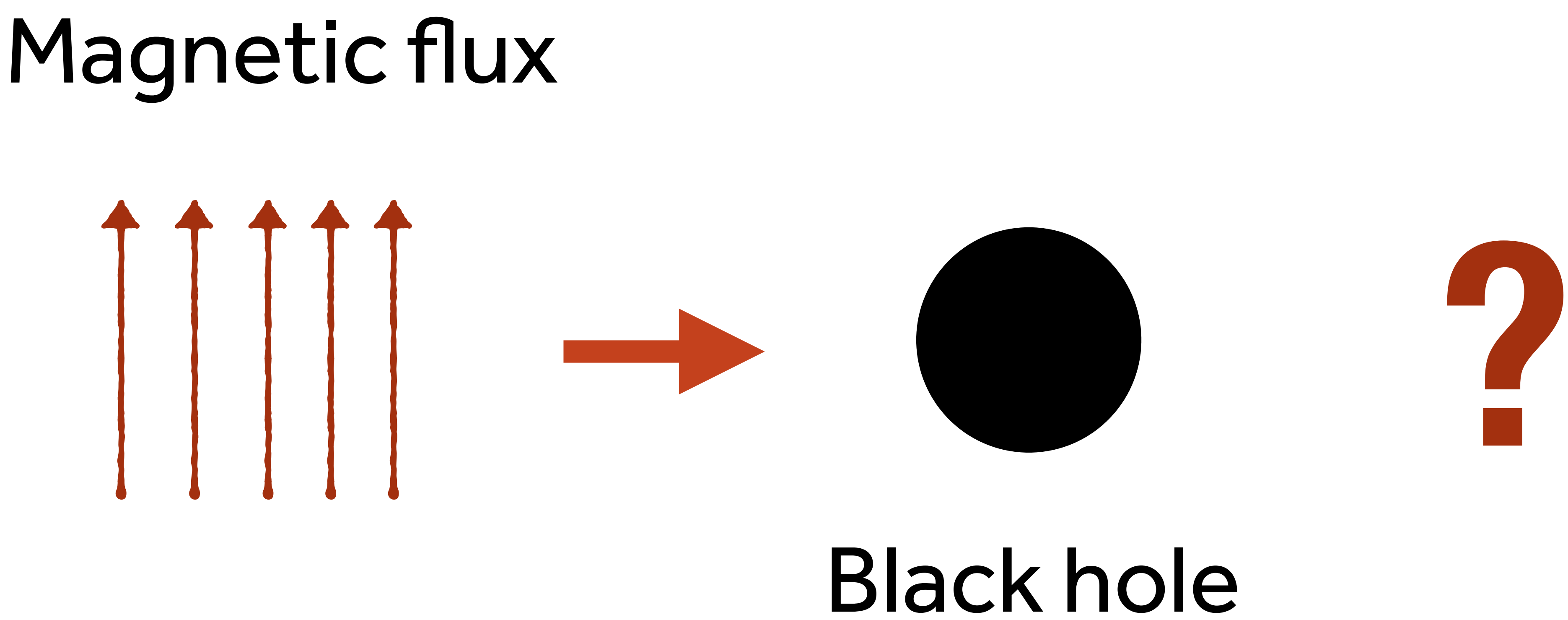
What happens next?

Magnetic flux



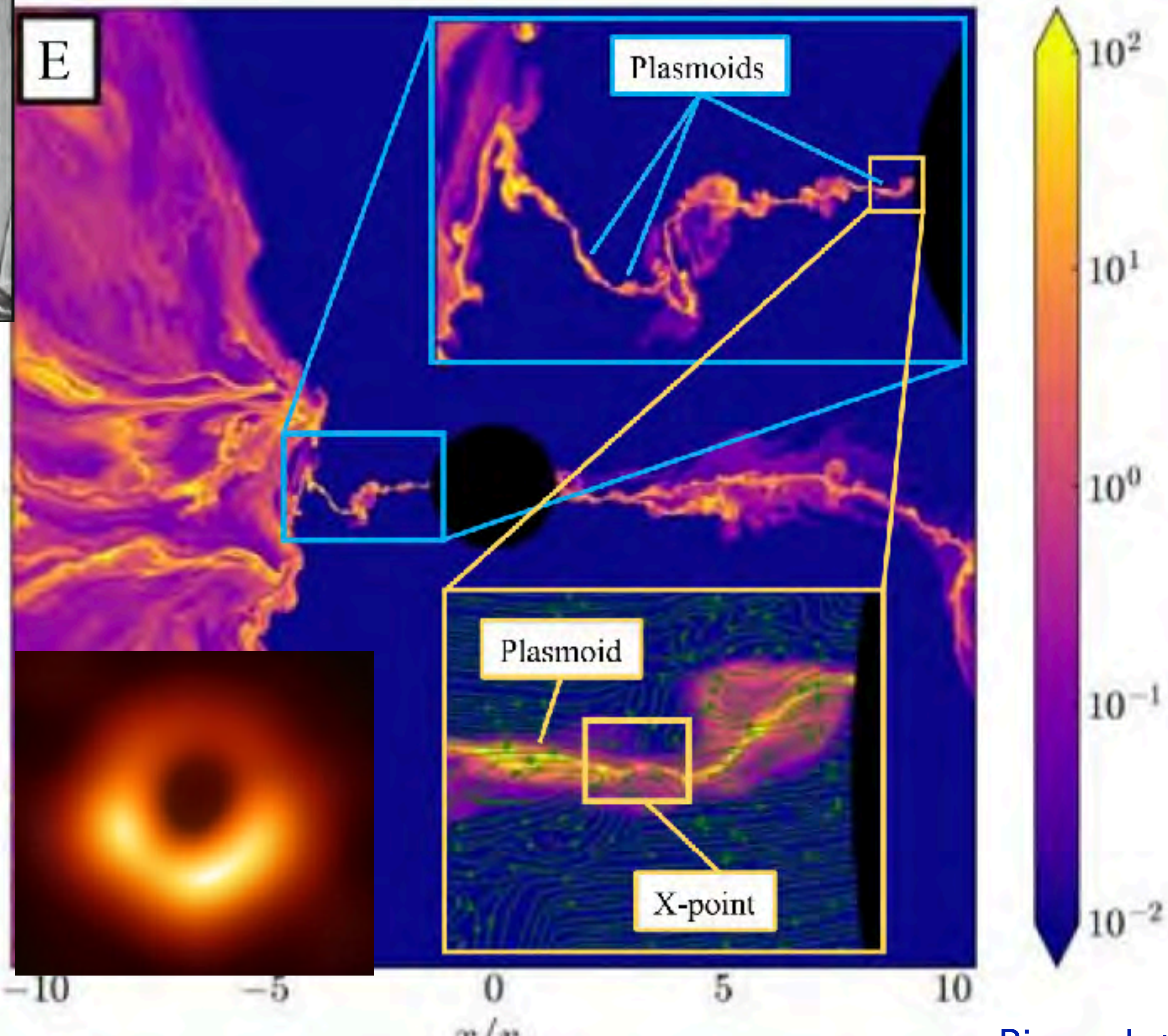
Black hole

Choosing what is feasible!



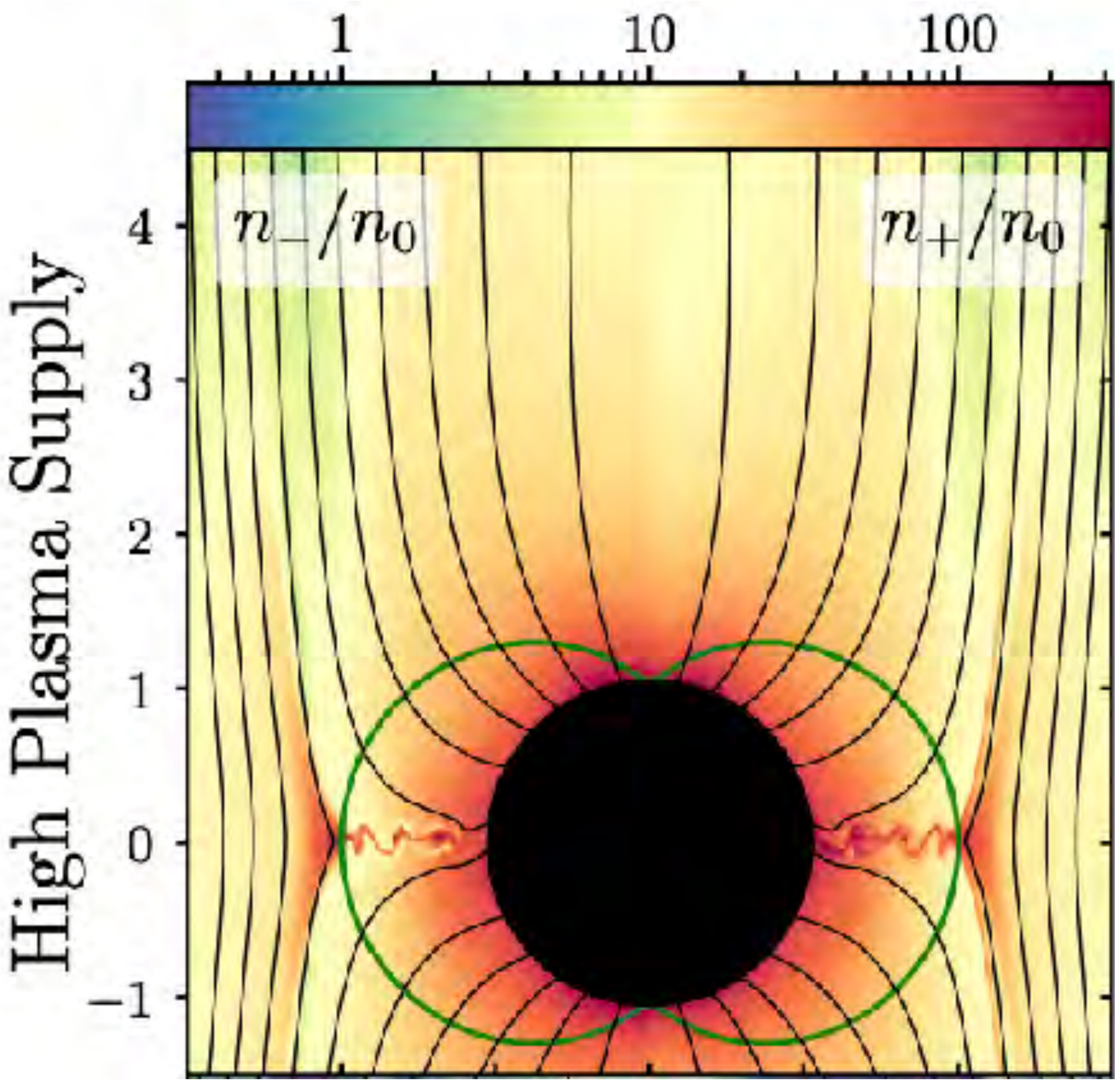
For conducting background

Black hole accretion



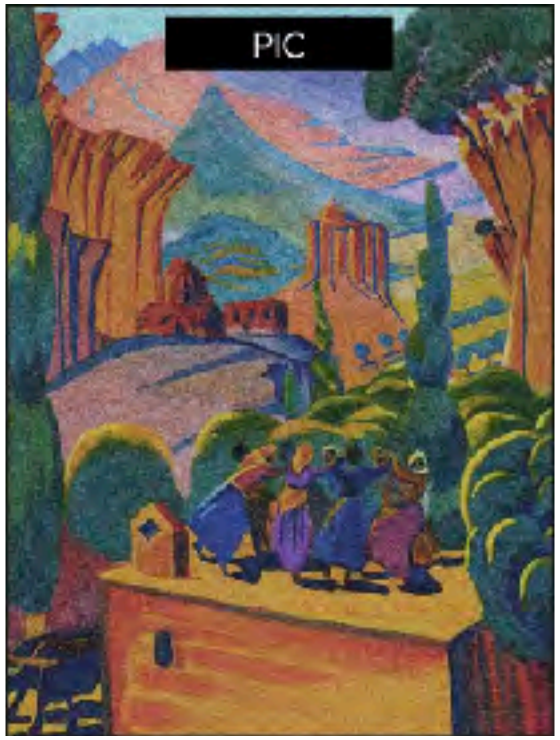
Ripperda+(2021)

Black hole accretion

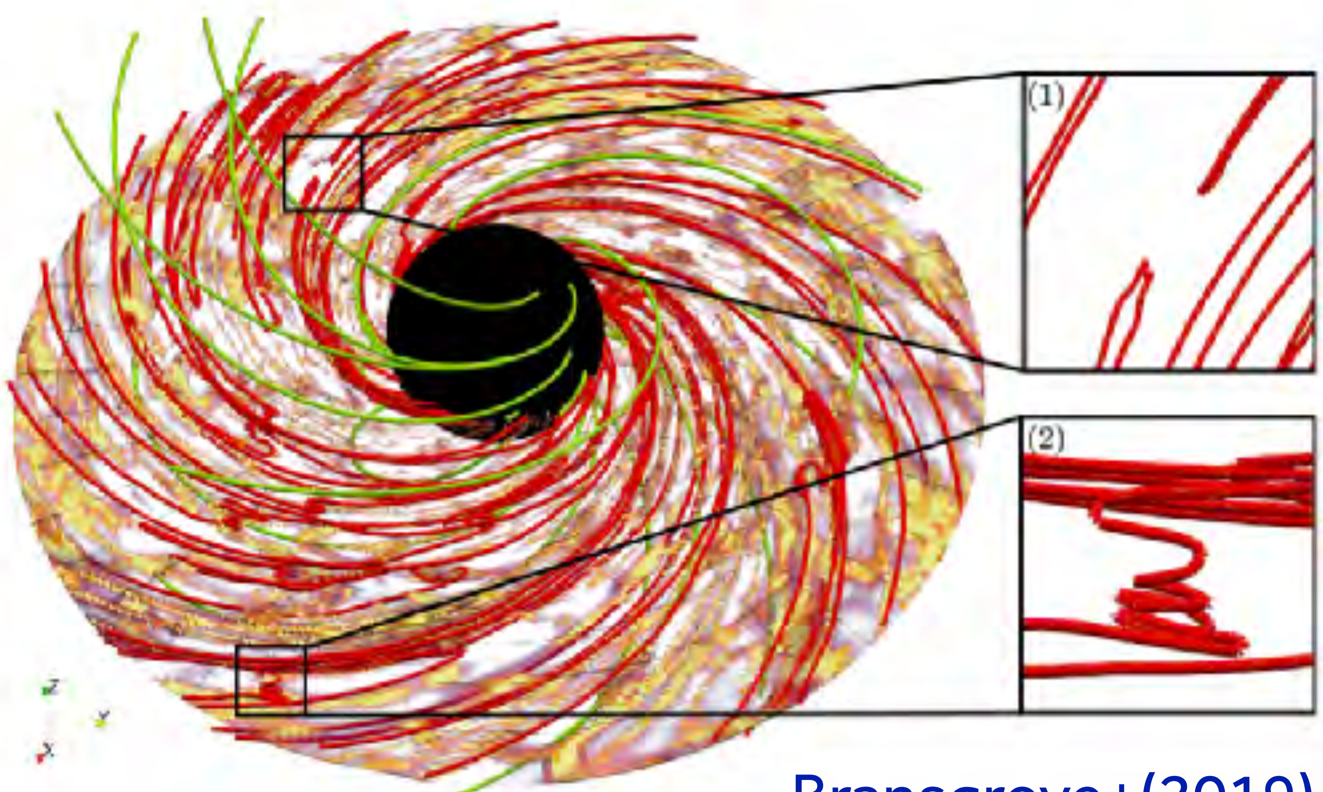


Parfrey+(2019)

Develop current sheet within ergosphere.



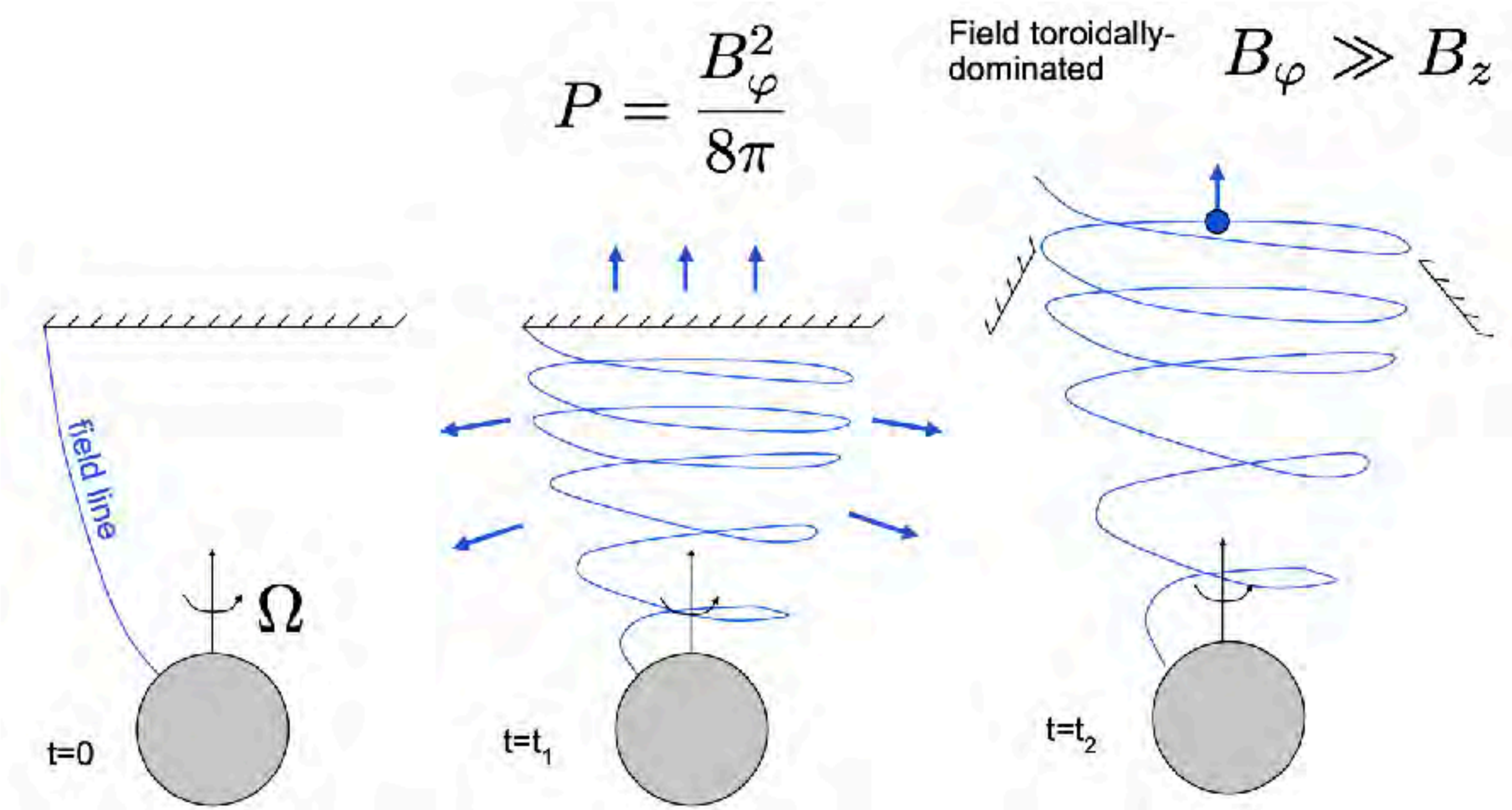
Dynamics governed by magnetic reconnection!



Bransgrove+(2019)

Observational signatures and time scales can be influenced by reconnection dynamics

What happens next?



Courtesy of A. Tchekhovskoy

MHD outflows

Conservation for magnetic fields in axisymmetry changes in two ways

$$\mathscr{B} = \left(h + \frac{b^2}{\rho} \right) u_t - \frac{b_t}{\kappa}$$

Bekenstein & Oron (1978)

Magnetically driven jets

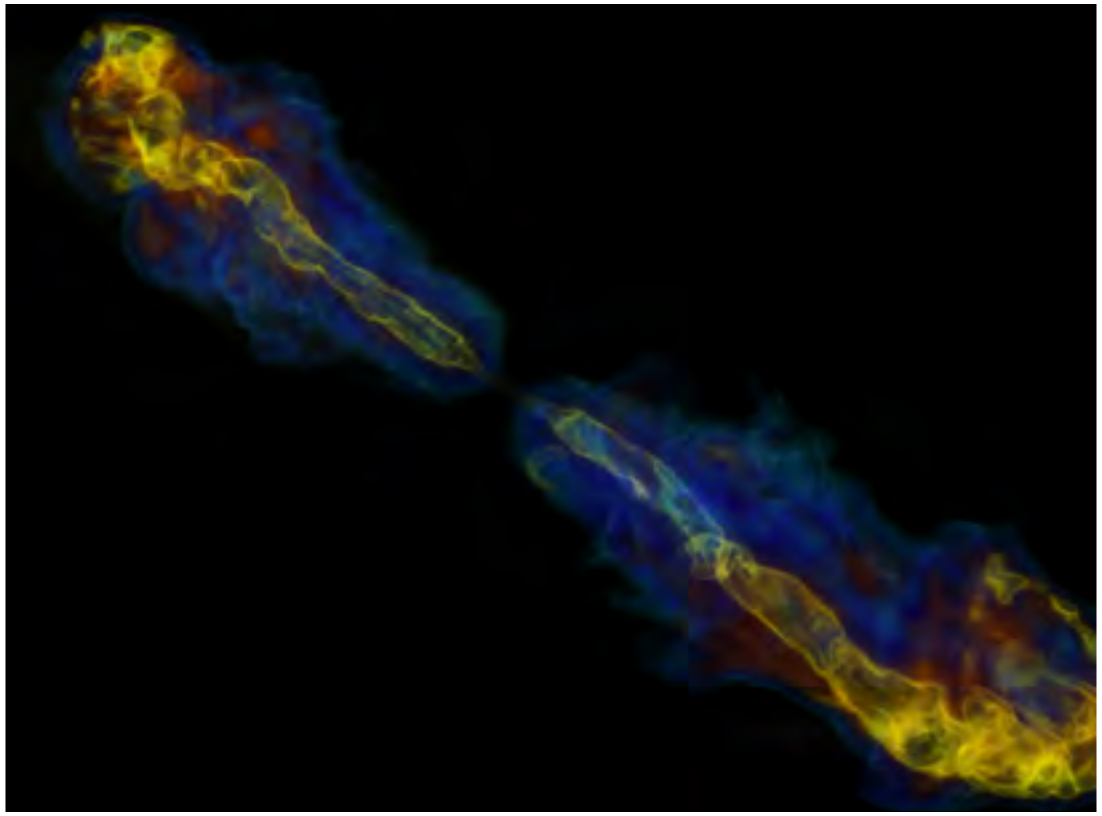


Image credit: Gottlieb

Magneto-centrifugal winds!

Blandford & Payne (1977)

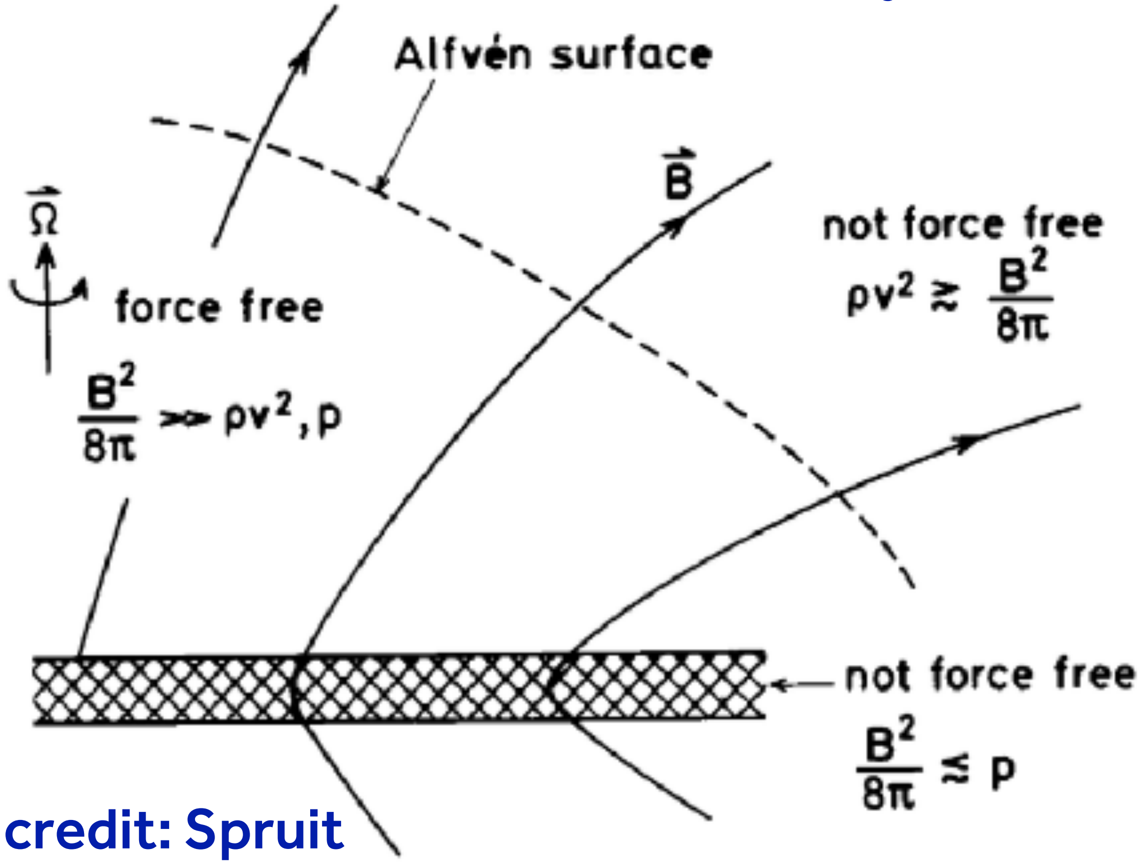
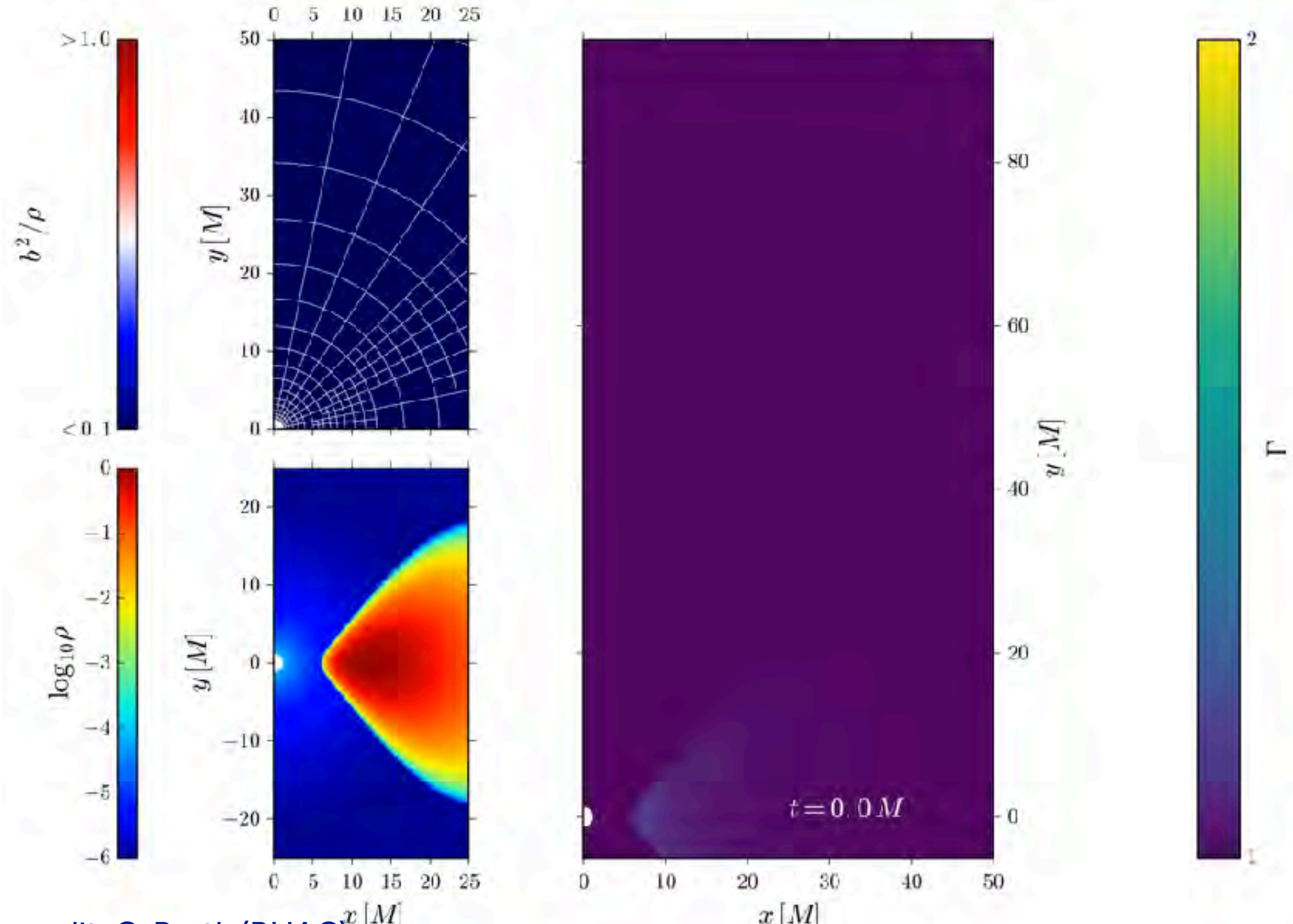


Image credit: Spruit

Example: Relativistic outflows

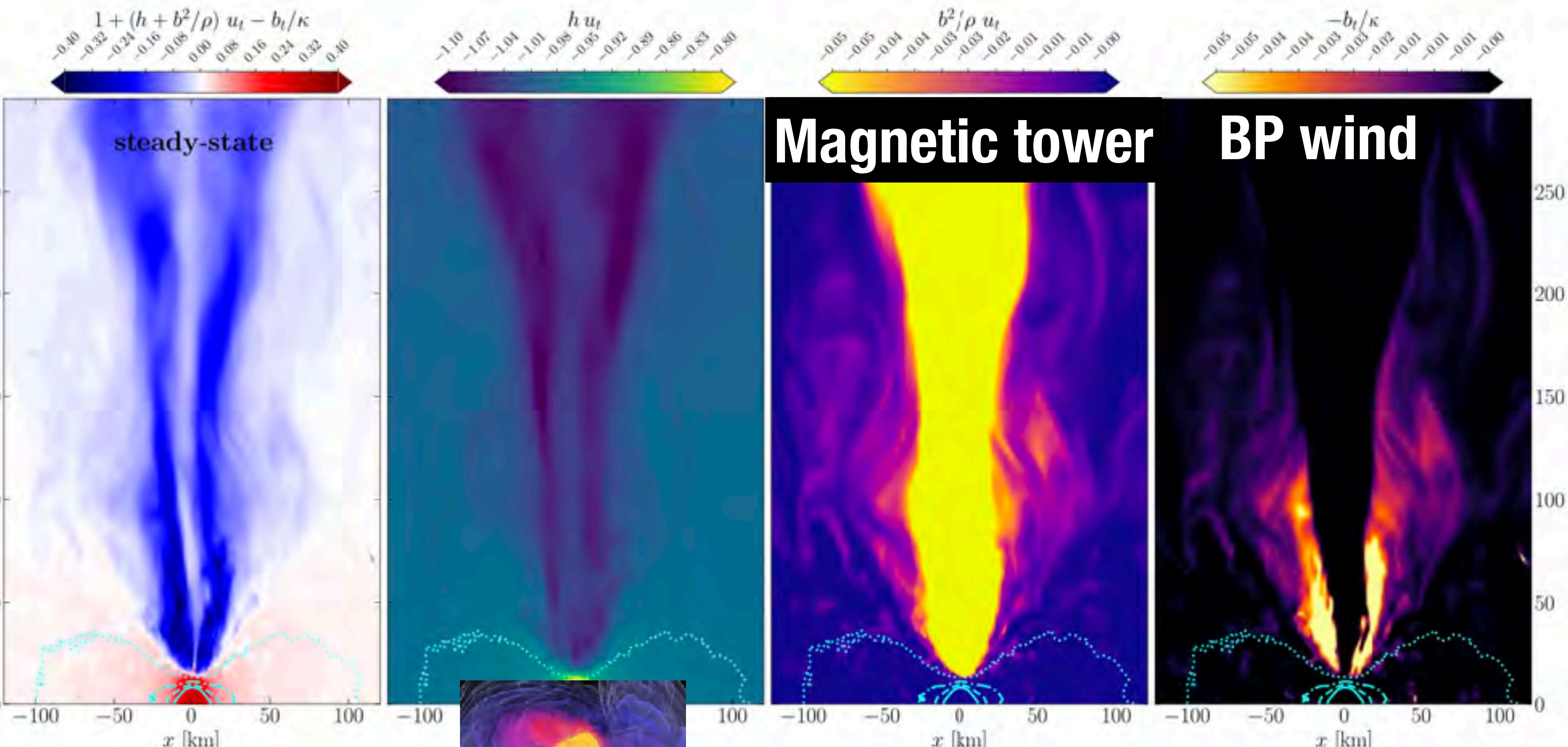


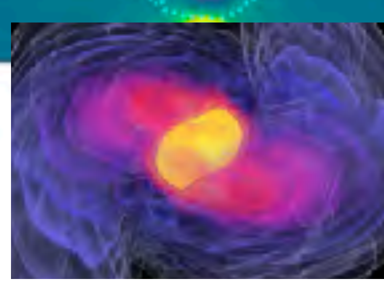
Animation credit: O. Porth (BHAC)
based on Olivares, Porth+ (incl. **ERM**, A&A 2019)

Jets and winds from neutron-star remnants

Magnetar-like remnants from in neutron star mergers can launch jets, too!

Mösta+(2019), **ERM** & Quataert (ApJL 2023) Combi & Siegel (2023), Kiuchi+(2023), **ERM** (PRD 2023)





Musolino+(incl. **ERM**, ApJL 2025)

What happens next?

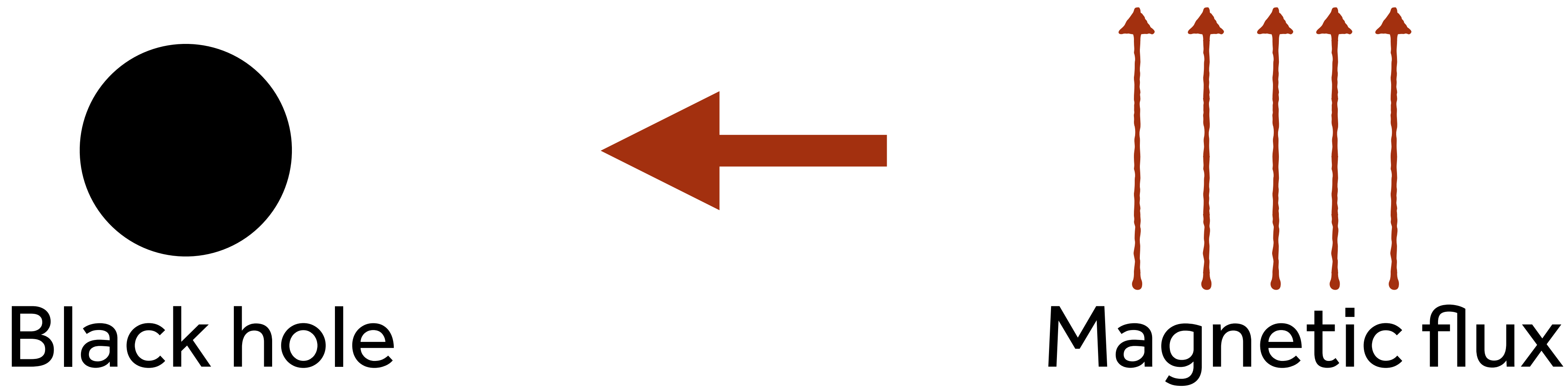


Image credit: Siemens

Bondi-Hoyle-Lyttleton Accretion

Since black hole velocities will be mainly subrelativistic, can equivalently study the accretion of a slow wind onto an accretor

$$R_a = \frac{2GM}{v_\infty^2}$$

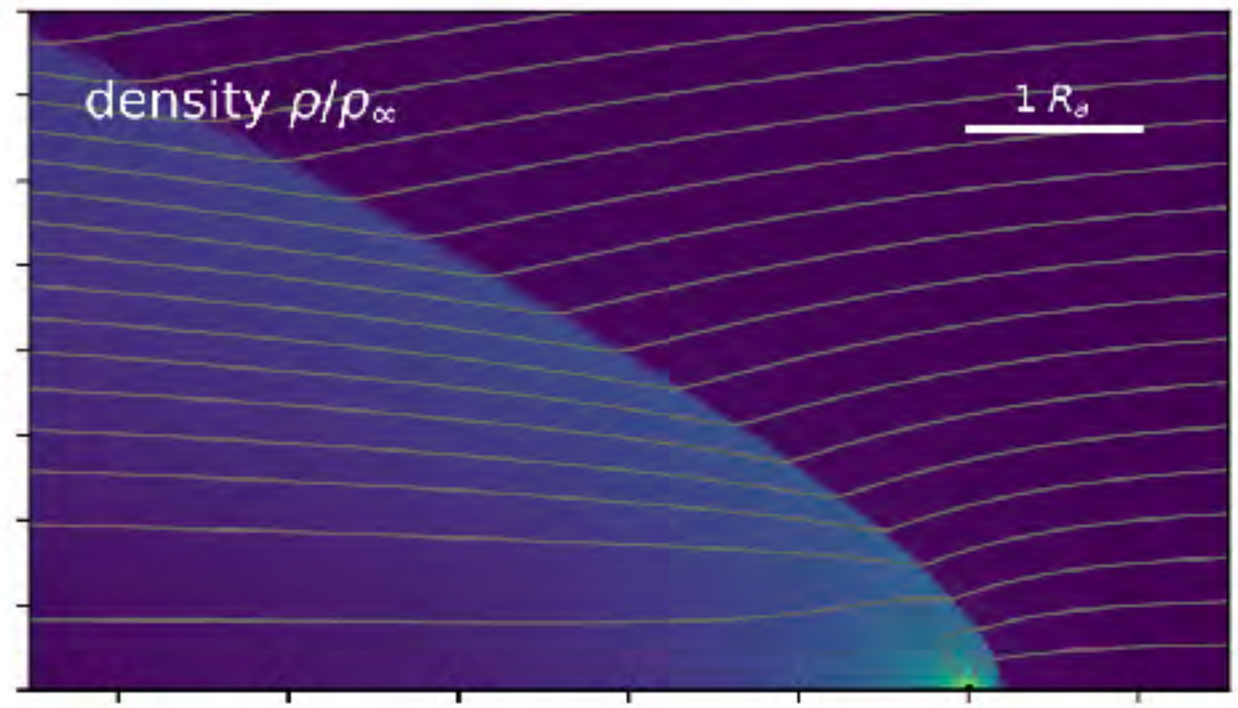
Accretion radius

$$r_g = \frac{GM}{c^2}$$

Grav. radius

$$\tau_a = \frac{2GM}{v_\infty^3}$$

Accretion time



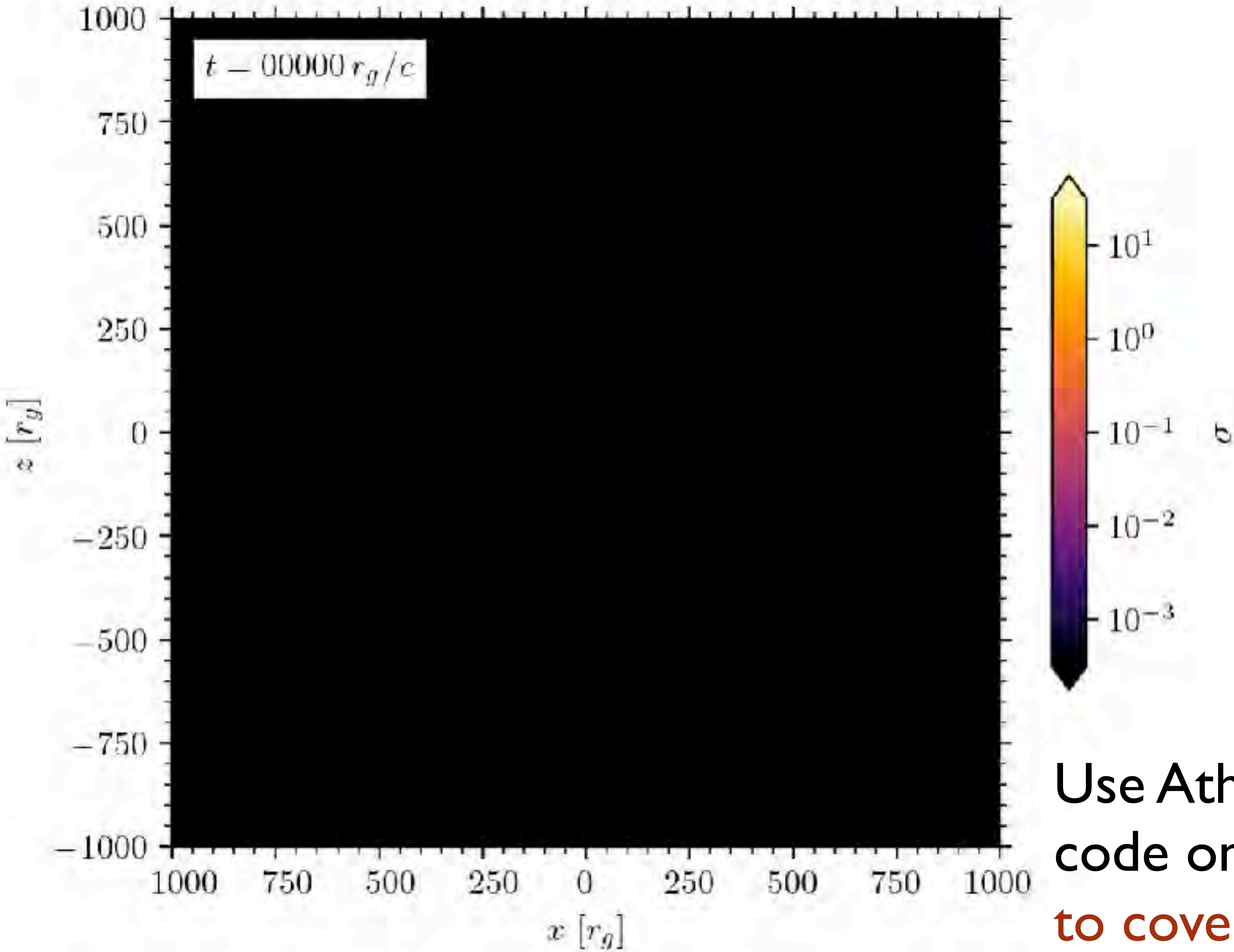
Xu & Stone (2019)

Main challenge: Realistic wind speeds need very long accretion times…

$$\frac{\tau_a}{r_g/c} \sim \left(\frac{c}{v_\infty}\right)^3$$

BHL accretion with toroidal fields

Kim & **ERM** (arXiv)



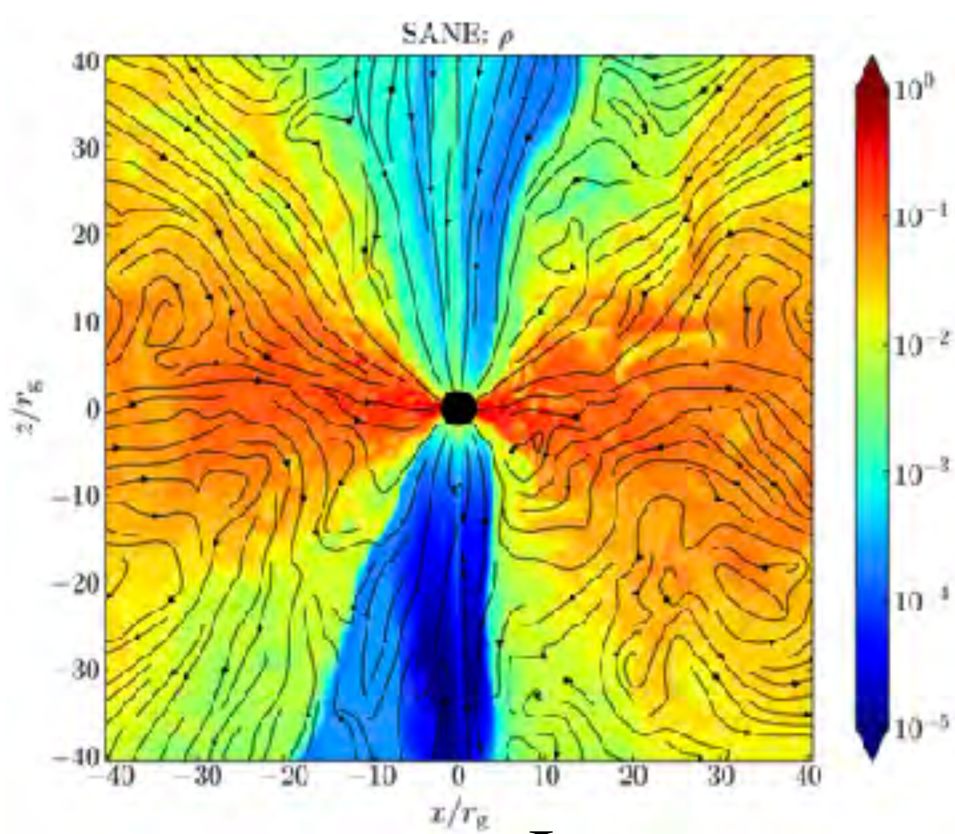
Y. Kim (Caltech)

Shi, Kremer, Hopkins (2024)

Use AthenaK GRMHD code on 800 GPUs to cover $40\,\tau_a$

Black hole accretion states 101

Standard and Normal Evolution (SANE)

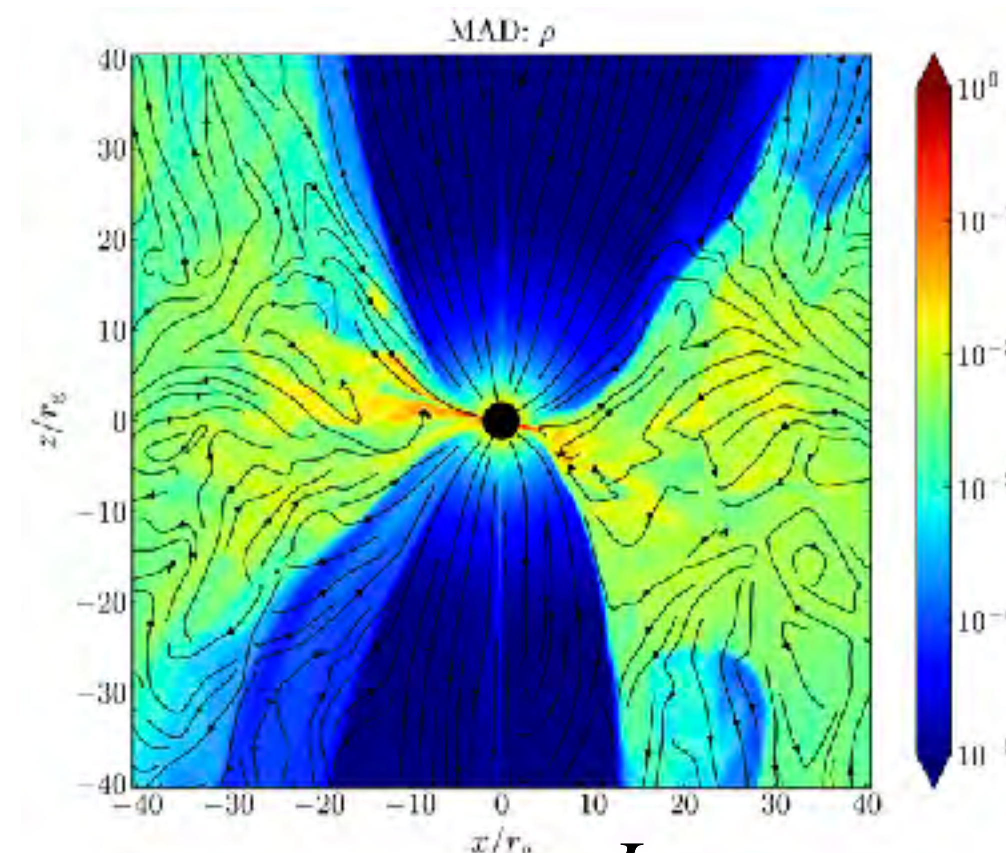


Jet efficiency: $\eta = \frac{L_{\rm jet}}{\dot{M}c^2} \ll 1$

Magnetic flux on horizon $\phi < 50$

Angular momentum transport in disk driven by magneto-rotational instability

Magnetically Arrested Disks (MAD)



Jet efficiency: $\eta = \frac{L_{\rm jet}}{\dot{M}c^2} > 1$ (BZ!)

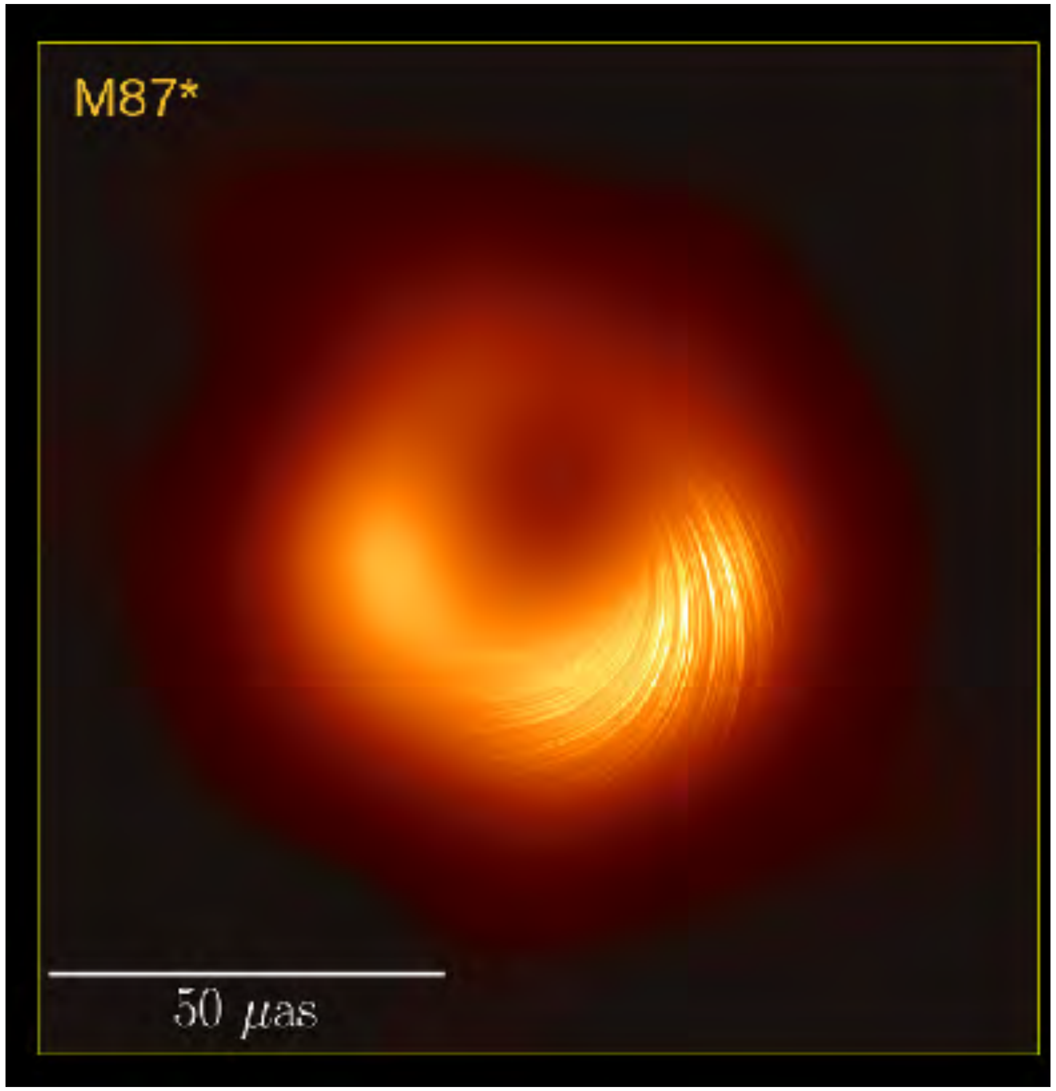
Magnetic flux on horizon $\phi > 50$

Angular momentum transport in disk driven by magnetic-flux eruptions

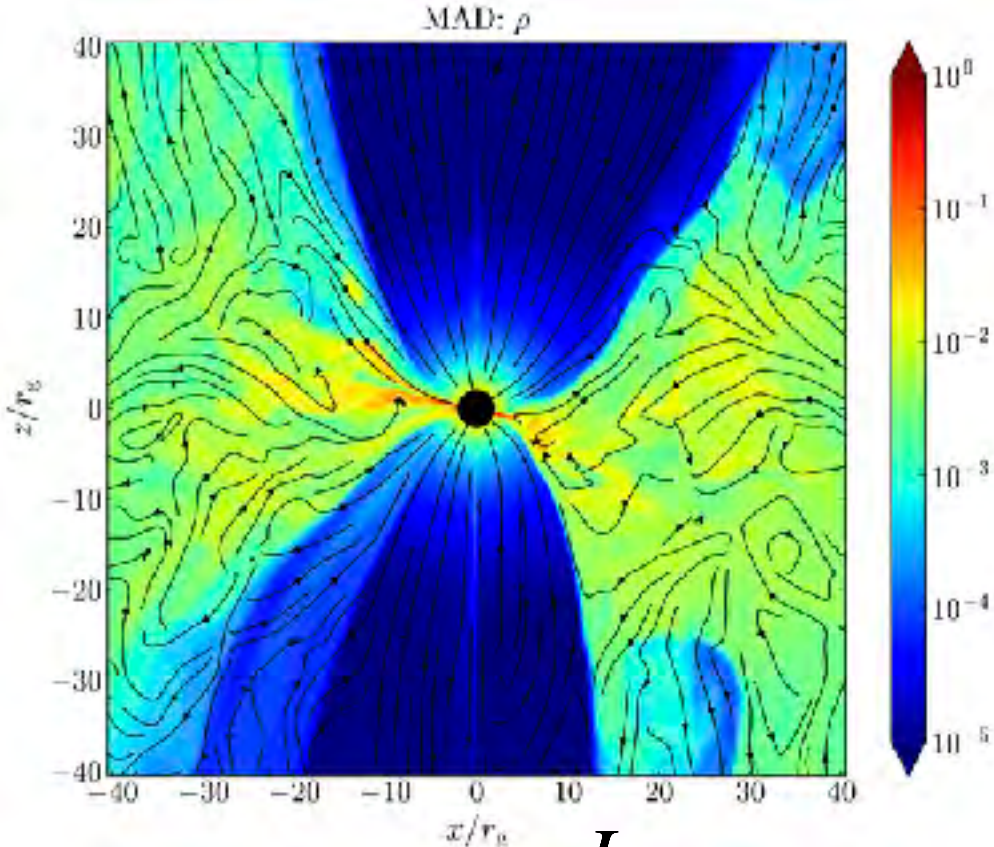
Jets can spin down the black hole!

Black hole accretion states 101

Magnetically Arrested Disks (MAD)



EHT (2021)



Jet efficiency: $\eta = \frac{L_{\rm jet}}{\dot{M} c^2} > 1$ (BZ!)

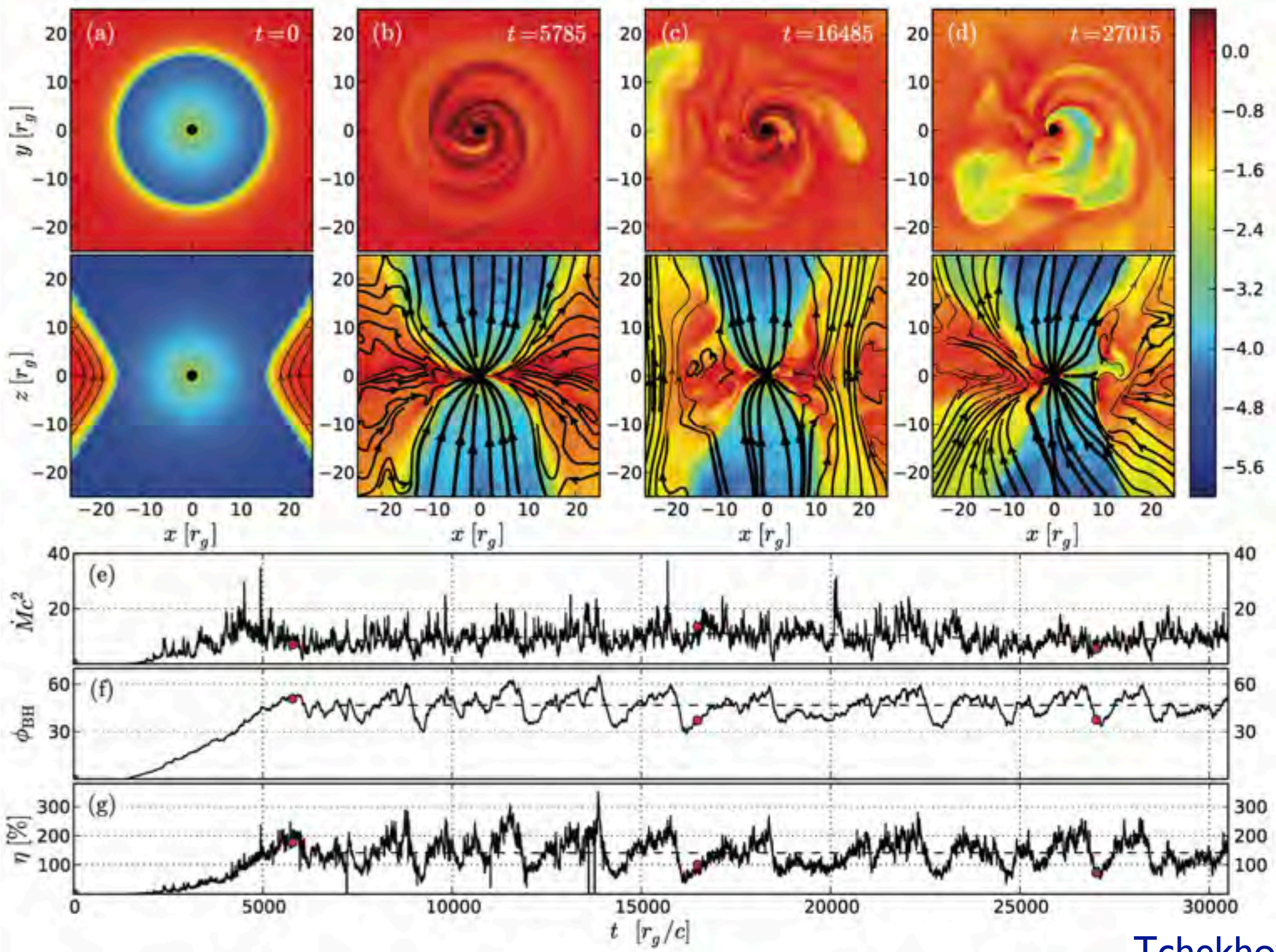
Magnetic flux on horizon $\phi > 50$

Angular momentum transport in disk driven by magnetic-flux eruptions

Jets can spin down black hole!

Magnetic flux eruptions in MAD flows

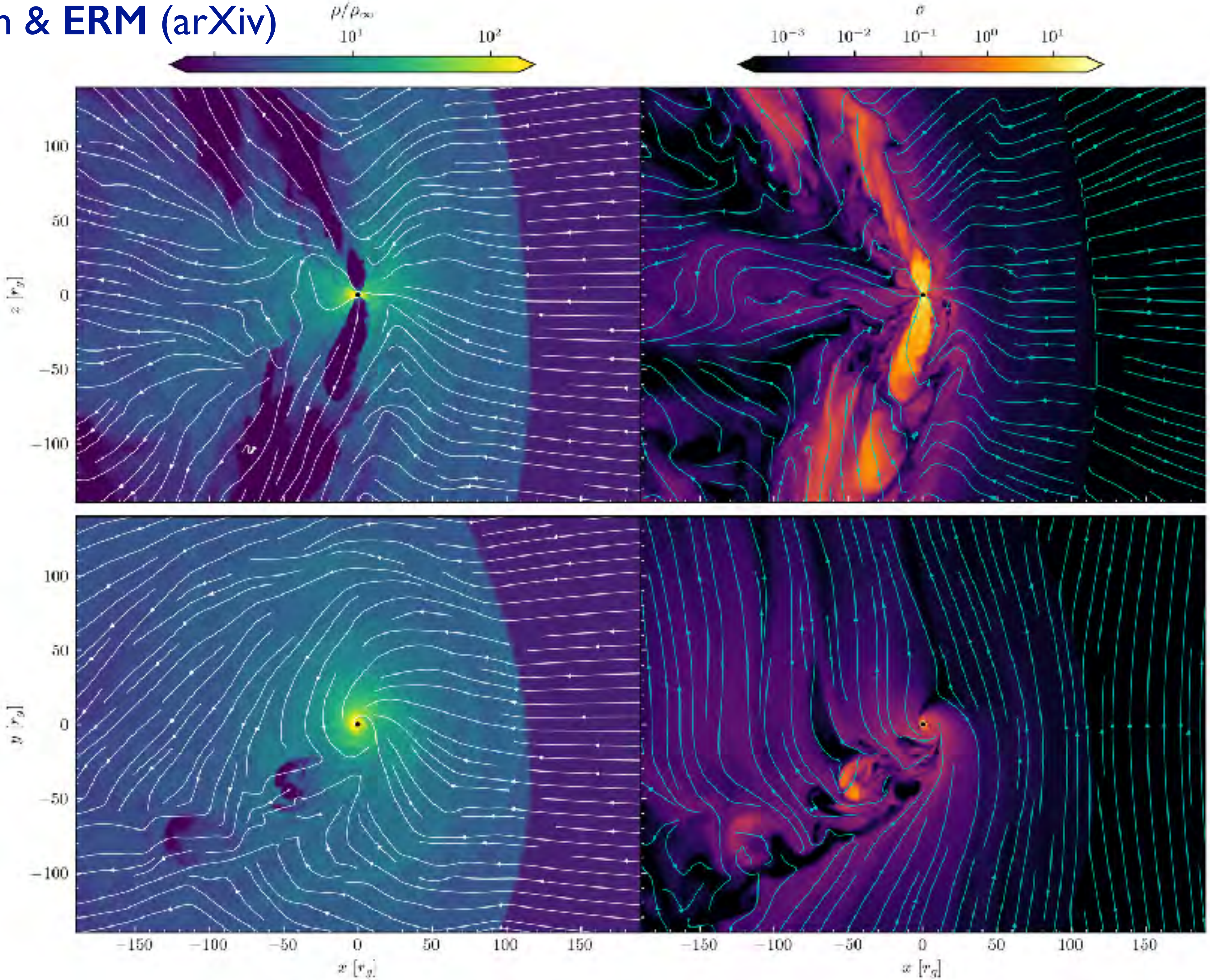
Black hole over saturates with vertical magnetic flux. This flux cannot end up in the black hole, only way is to eject it via interchange instability!



Tchekhovskoy+(2011)

BHL accretion with toroidal fields

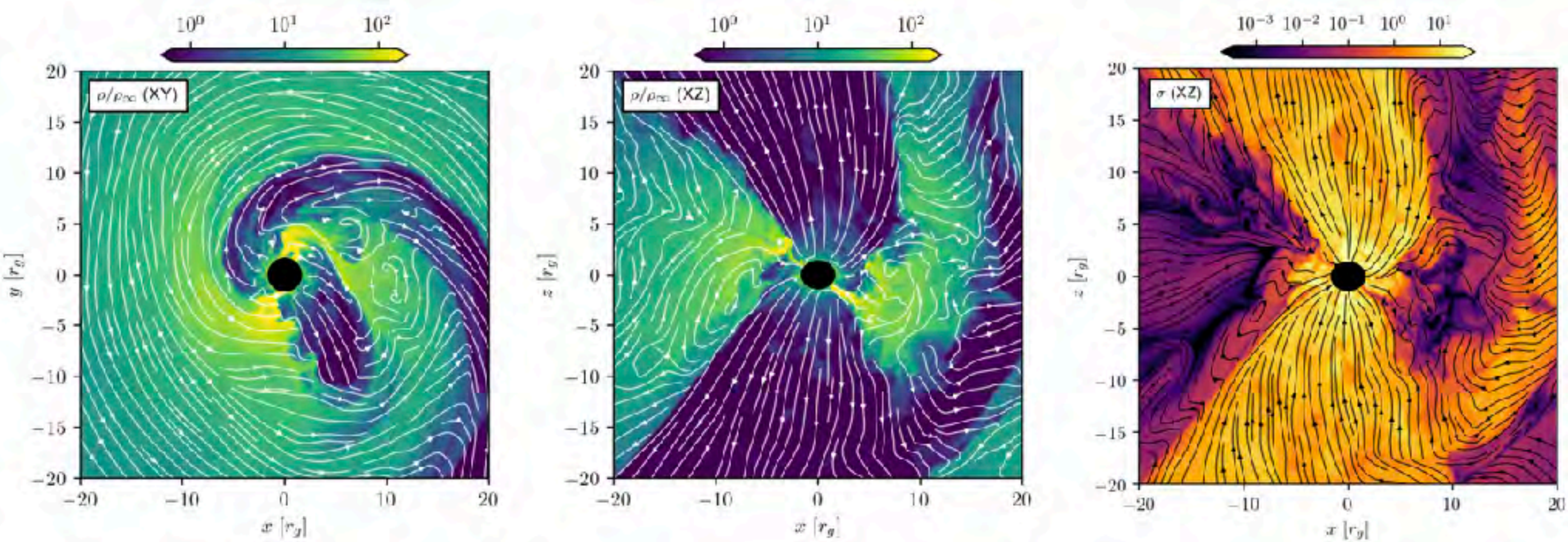
Kim & **ERM** (arXiv)



Y. Kim (Caltech)

Magnetical flux eruption in BHL

Kim & **ERM** (arXiv)



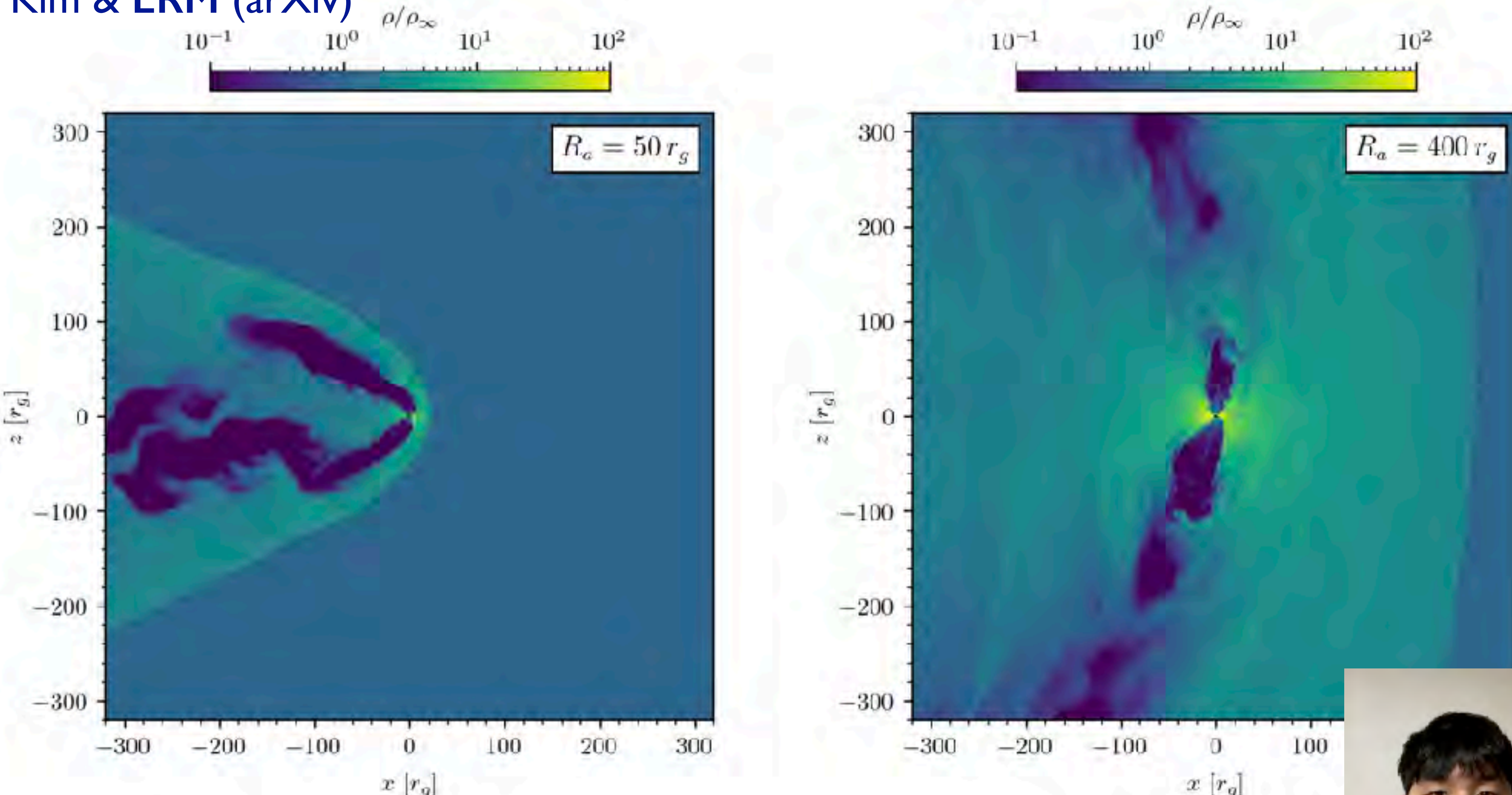
Even in the absence of net angular momentum the flow enters a semi-MAD ($\phi_{\rm BH} \sim 25$) state. Kaaz+(2022), Kwan+(2023)

Copious flux eruptions and a weak jet form, even for pure toroidal field!

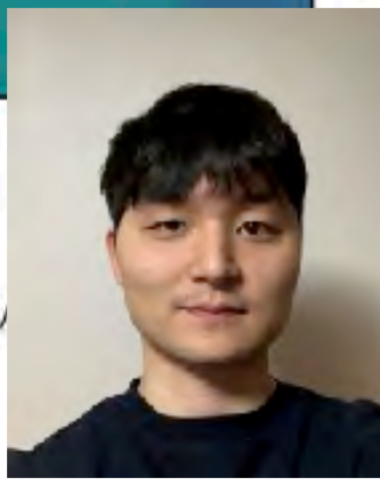
Y. Kim (Caltech)

Wind speed

Kim & **ERM** (arXiv)



(a) $R_a = 50r_g$ (at $t = 2 \times 10^4\, r_g/c$) (b) $R_a = 400r_g$ (at $t = 4 \times 10^4\, r_g$/



Jet morphology depends strongly on the wind speed.

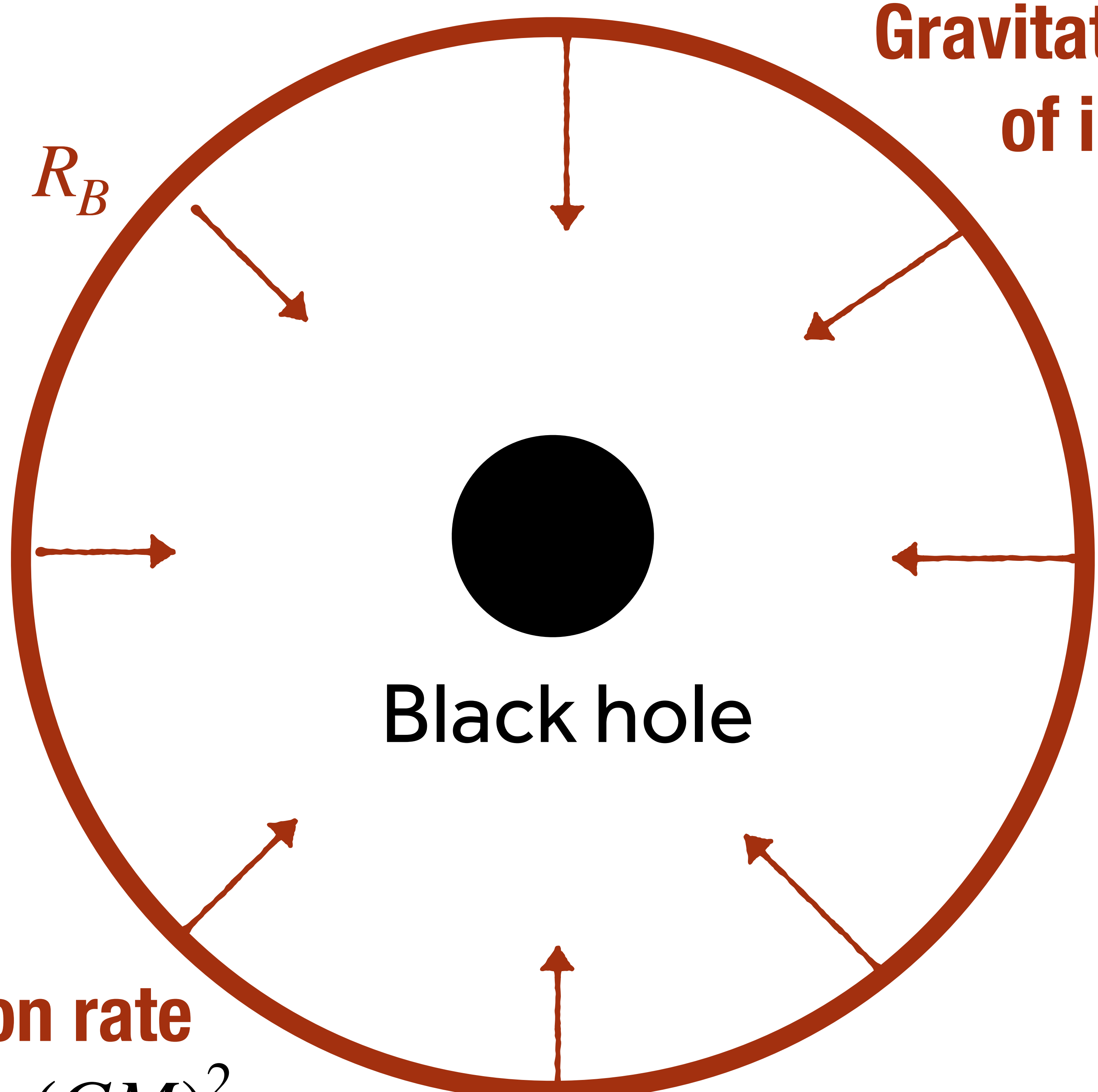
For weak jets, see strong kink instability!!

Y. Kim (Caltech)

Let's get more realistic

Bondi Radius

$$R_B = \frac{2GM}{c_s^2}$$



Mass accretion rate

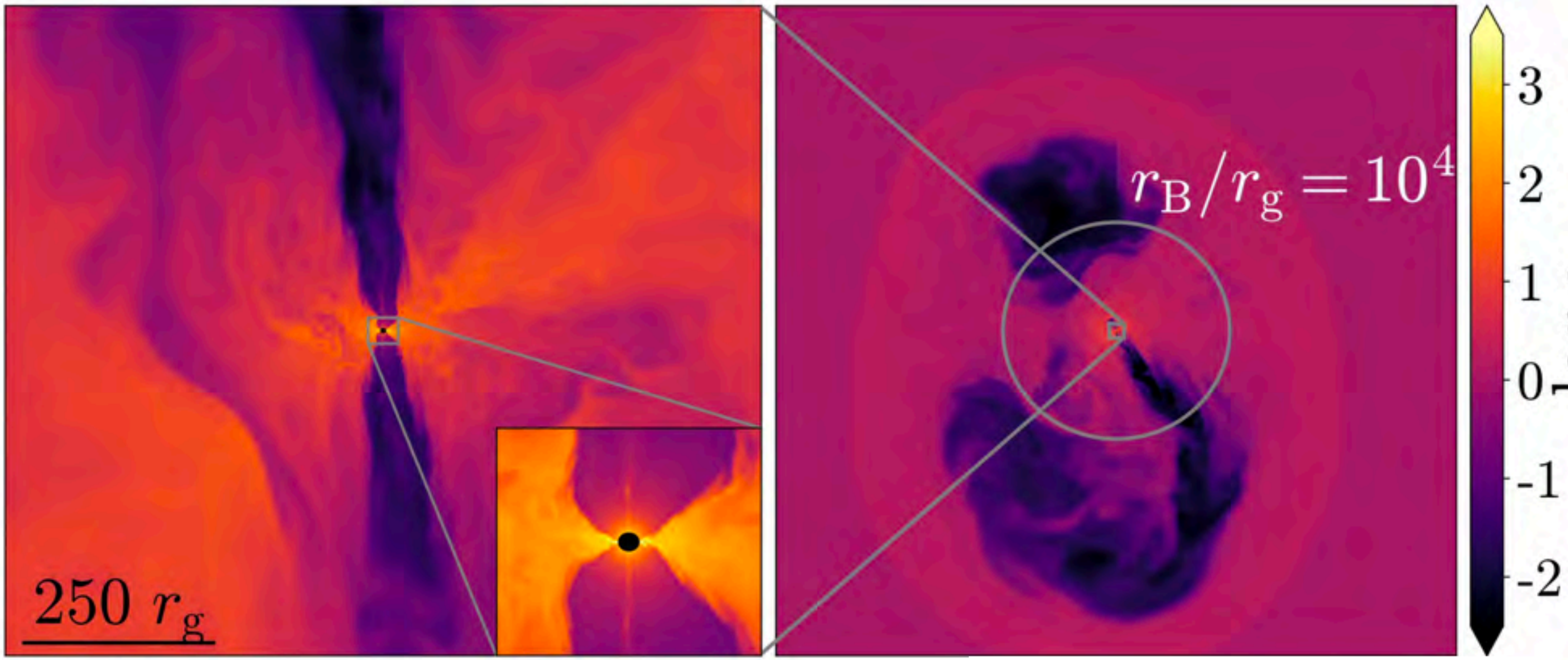
$$\dot{M}_{BH} = \dot{M}_B \sim \frac{(GM)^2}{c_s^3}\rho$$

Jet feedback

In reality, the jet (and other outflows) will feedback on the accretion flow. So for real flows, $\dot{M}_{\rm BH} \ll \dot{M}_B$

Aris Lalakos (Caltech)

Largest contiguous GRMHD Bondi accretion simulation to date!

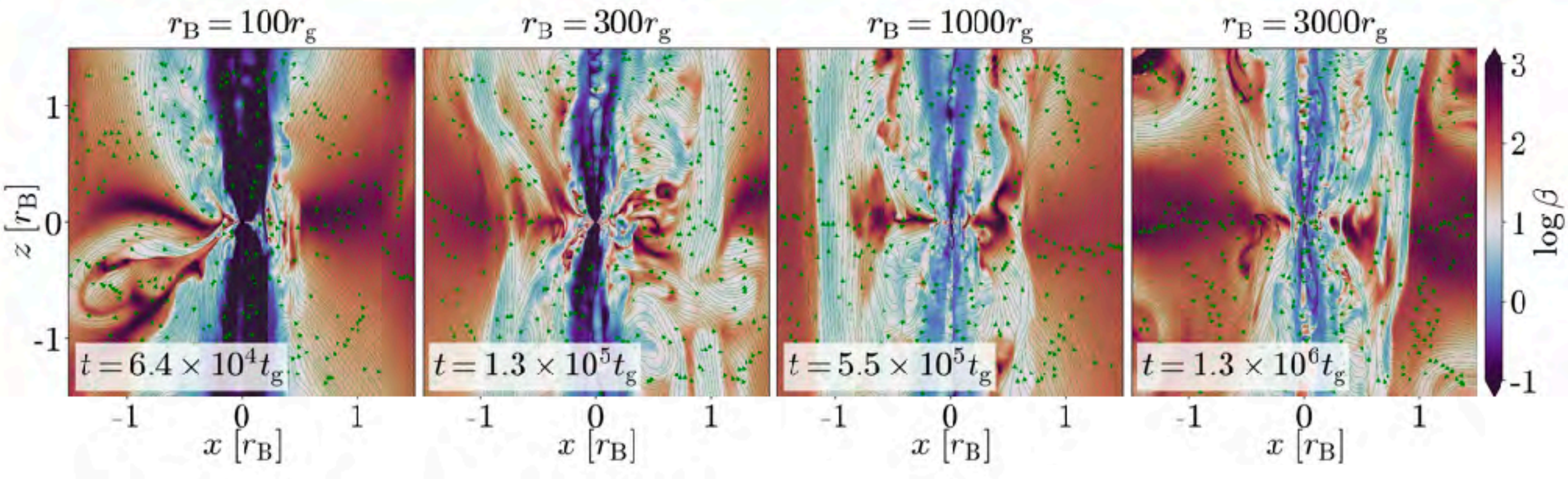


Lalakos, Tchekhovskoy, ERM+ (2025)

MAD extravaganza

Aris Lalakos
(Caltech)

Ejected magnetic flux tubes propagate all the way out to the Bondi radius!



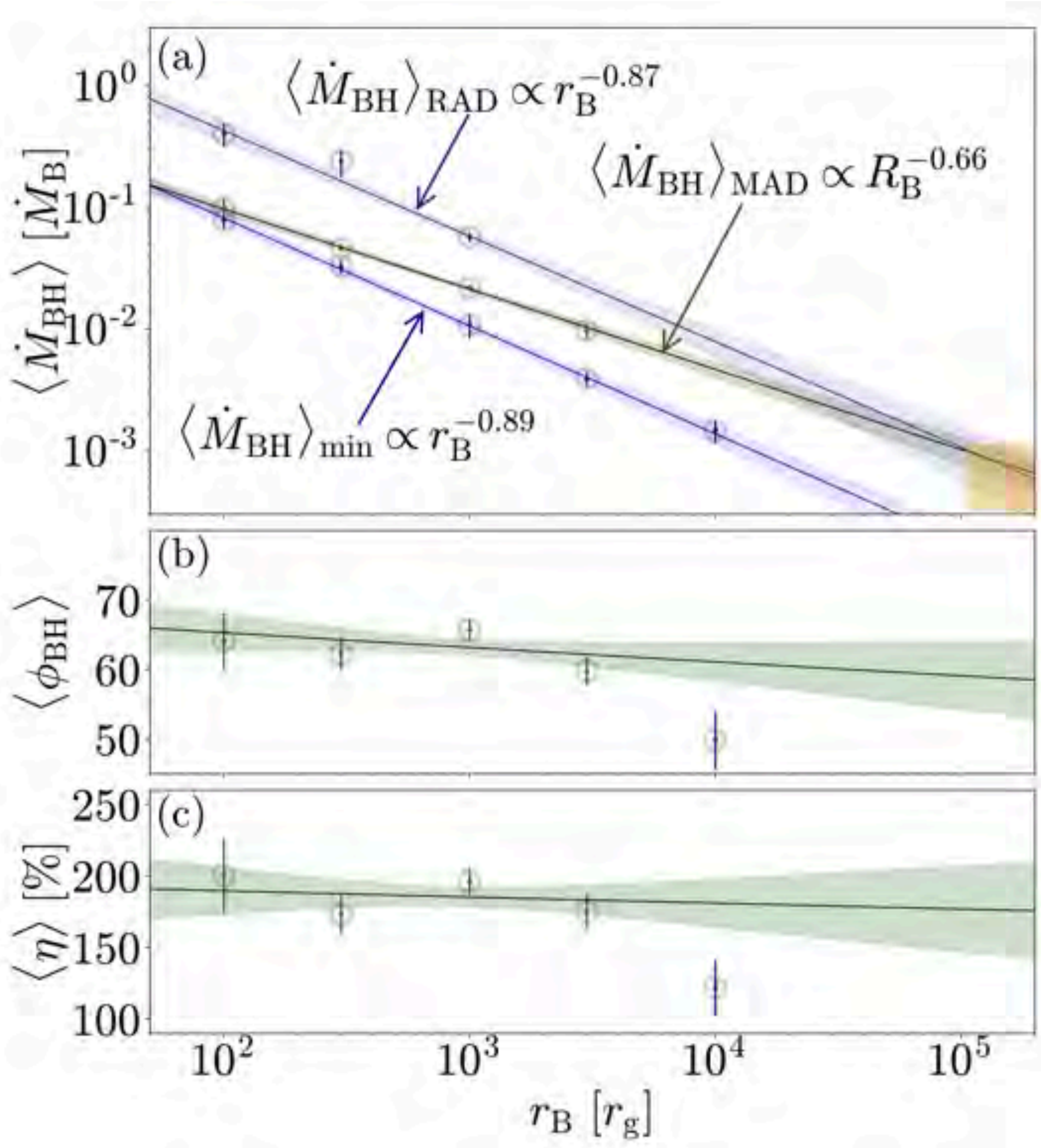
Lalakos, Tchekhovskoy, ERM+ (2025)

Universal mass accretion

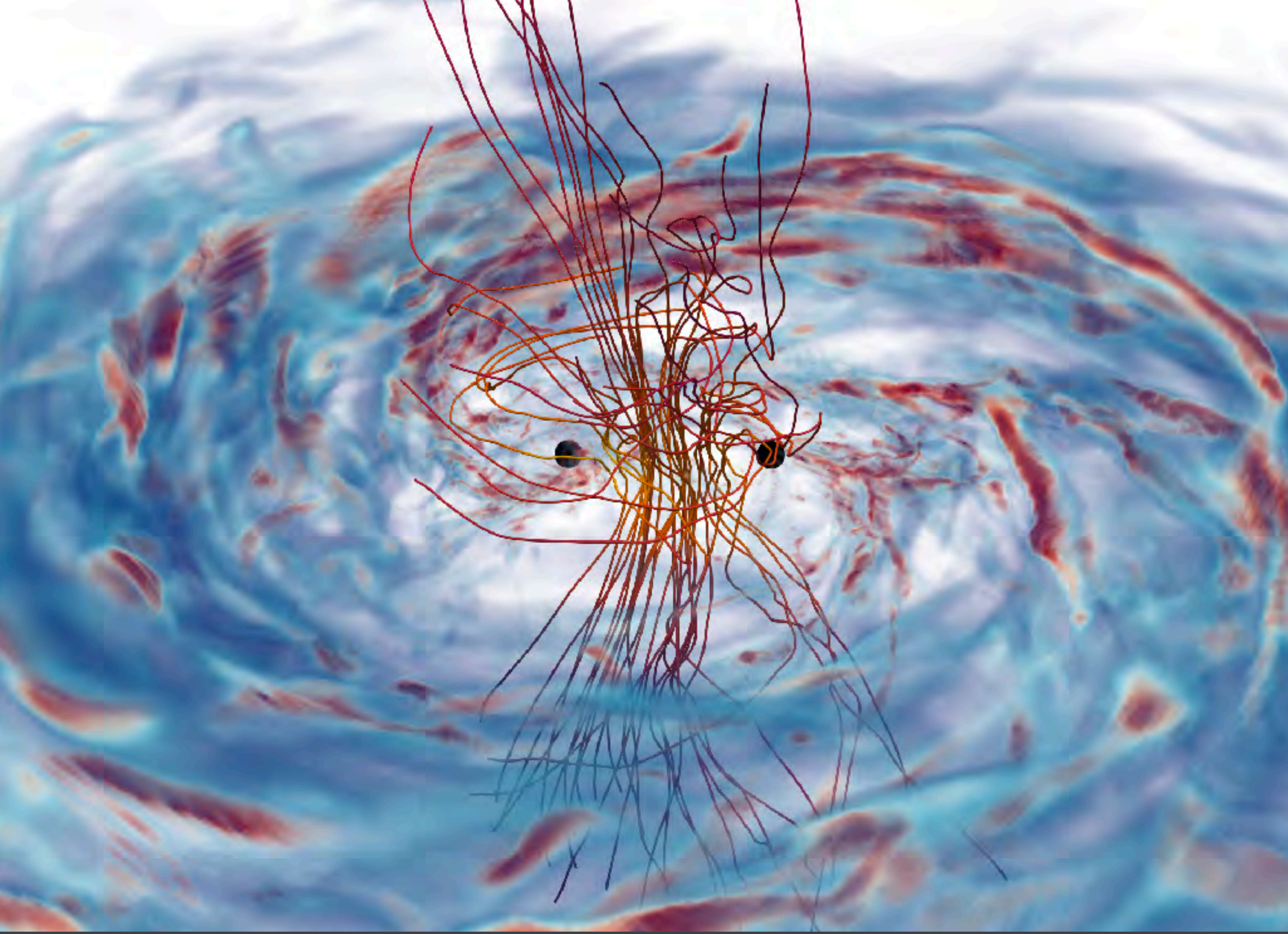
Aris Lalakos
(Caltech)

Feedback in magnetically arrested regime leads to universal accretion behavior

For realistic scale separations , e.g., in M87, only percent-level mass accretion from outer supply

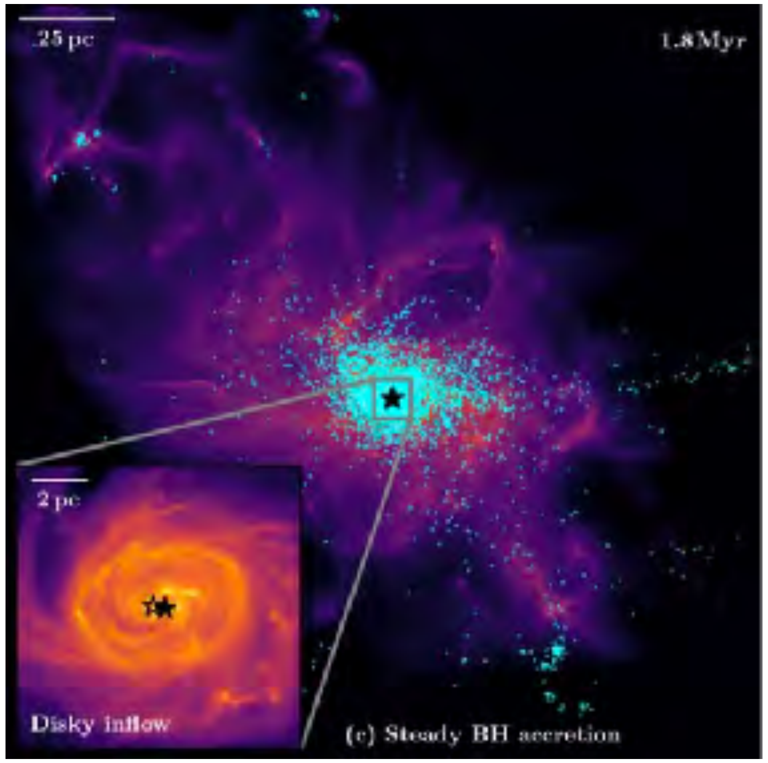


Lalakos, Tchekhovskoy, ERM+ (2025)



Circumbinary accretion disks

Circumbinary disks can form in galaxy mergers, potentially with strongly magnetized disks. e.g., Mayer+(2007), Shi+(2024)



Shi, Kremer, Hopkins (2024)

Accretion from circumbinary disk could be a possible channel for driving the binary to sub-pc separation

Begelman+(1980), Pringle (1991), Milosavljevic & Merritt (2003), Merritt & Milosavljevic (2005), Colpi (2014)

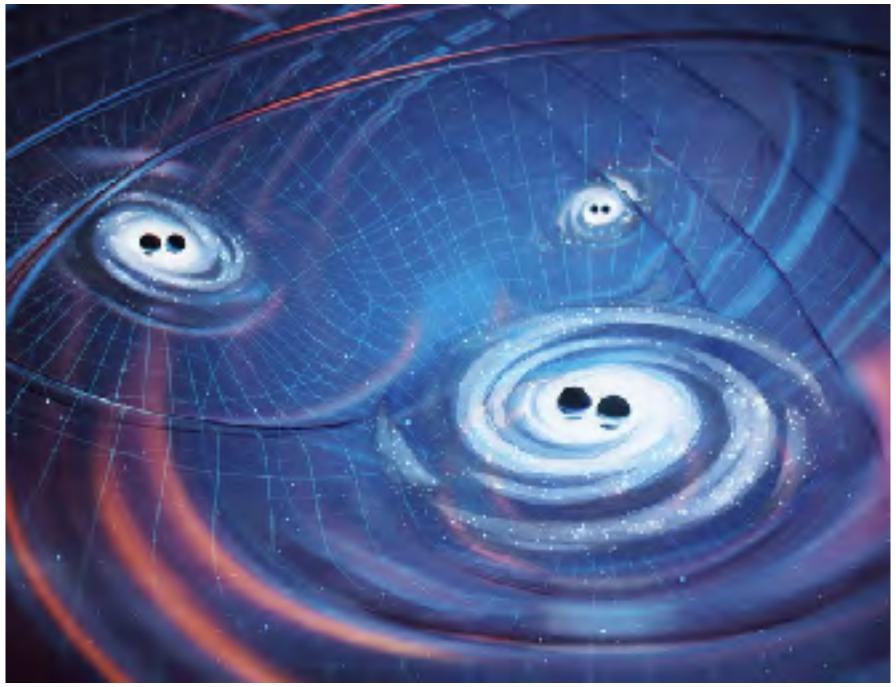


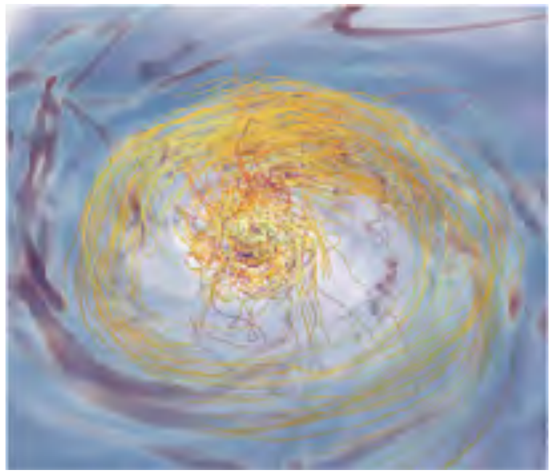
Image credit: NANOgrav

Interesting in the context of merging binary population seen with Pulsar Timing Arrays or future LISA observations

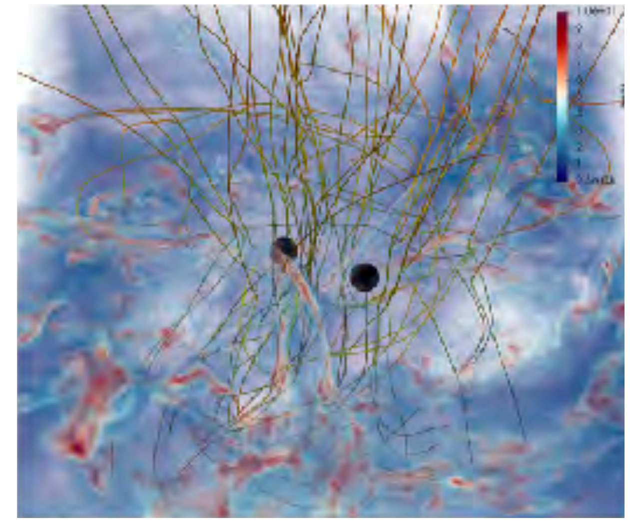
Amaro-Seoane+(2017), Agazie+(2023)

Interaction with disk may also drive electromagnetic signatures

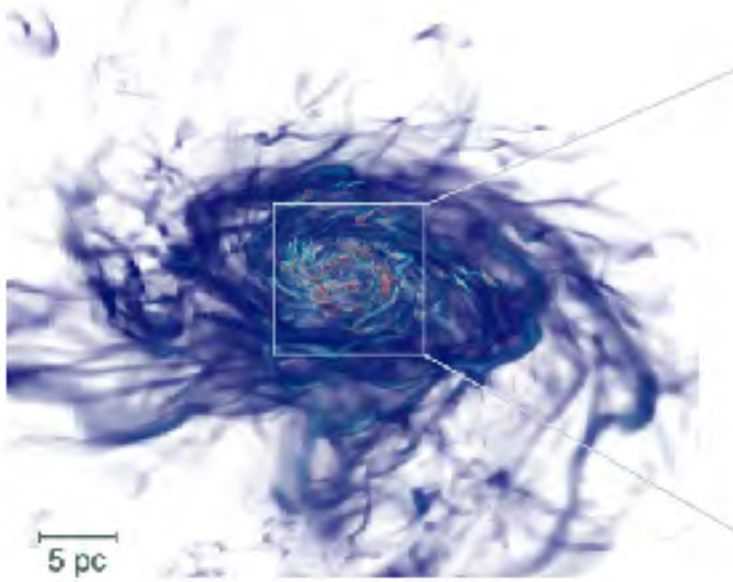
Supermassive Black Hole Coalescence

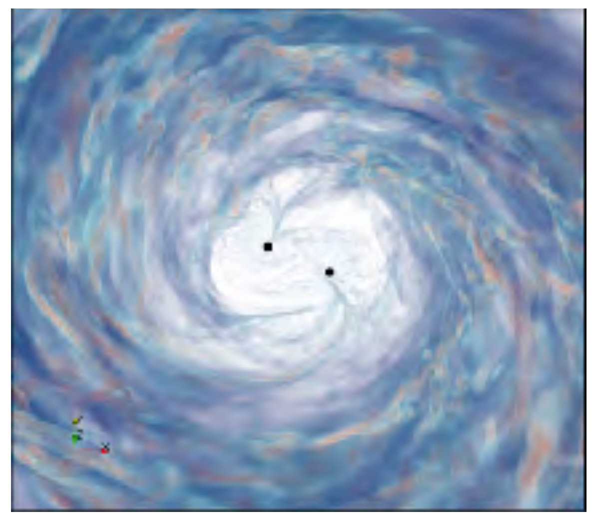


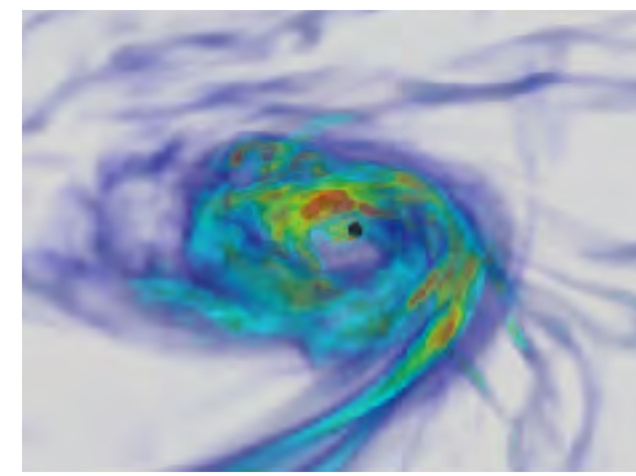
(Hyper??)-Magnetized disks



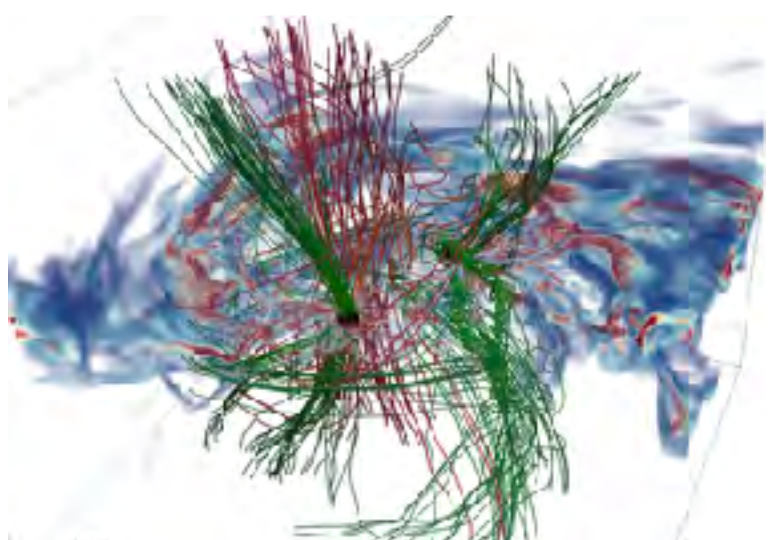
EM transients leading up to merger



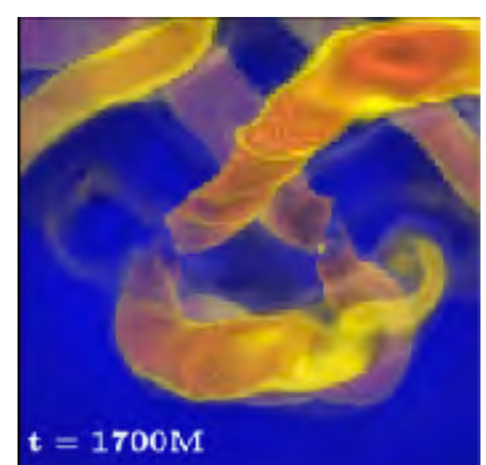




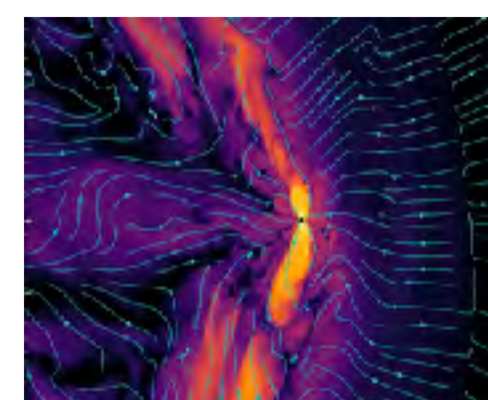
Circumbinary driven inspiral?



Jet interaction



Recoil transients?



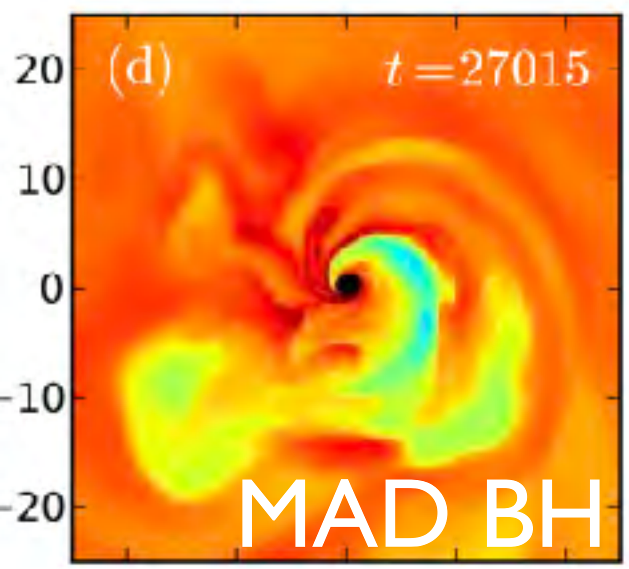
Magnetic flux eruption cycle

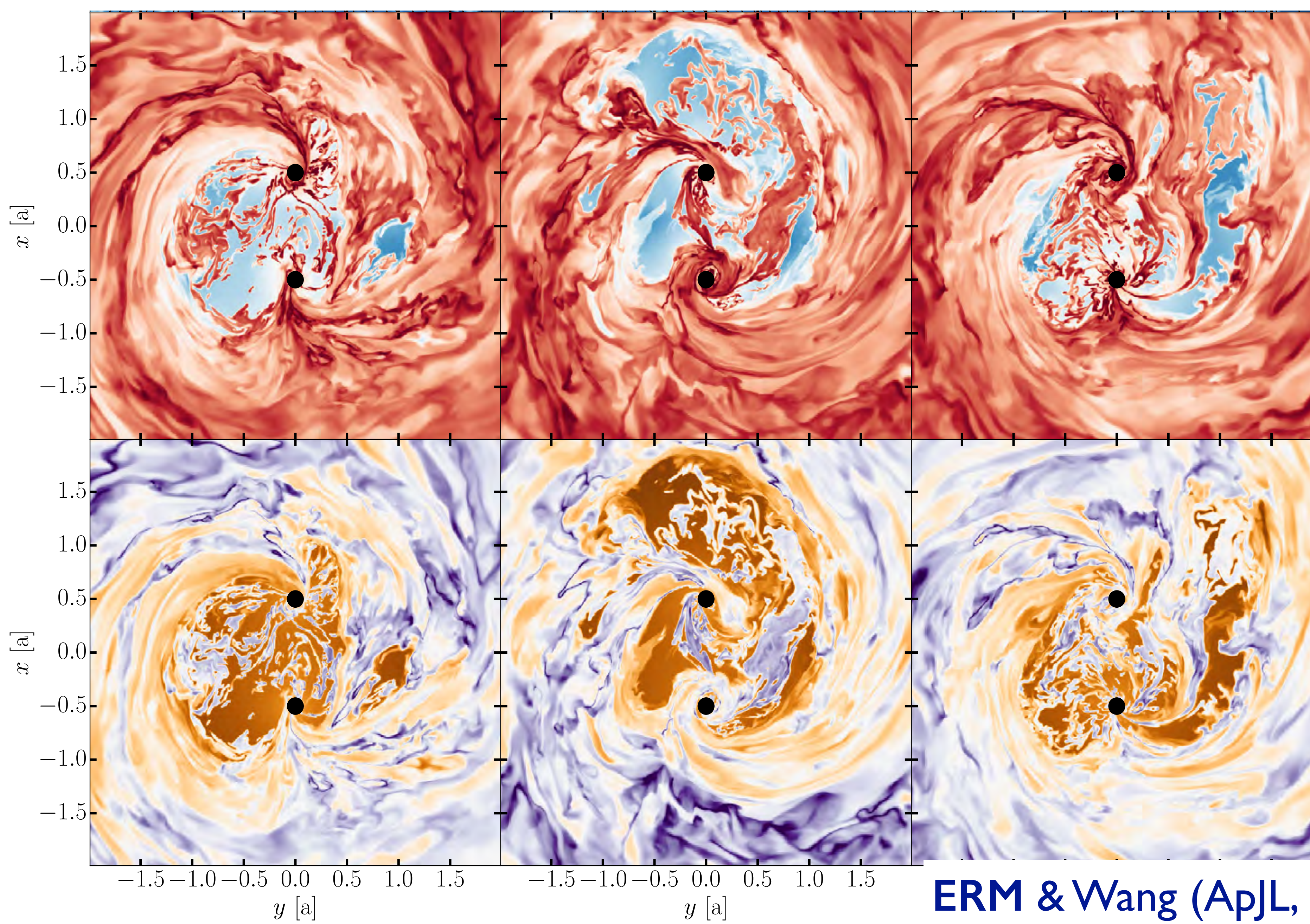
Interchange instabilities at the cavity wall trigger magnetic flux eruptions.

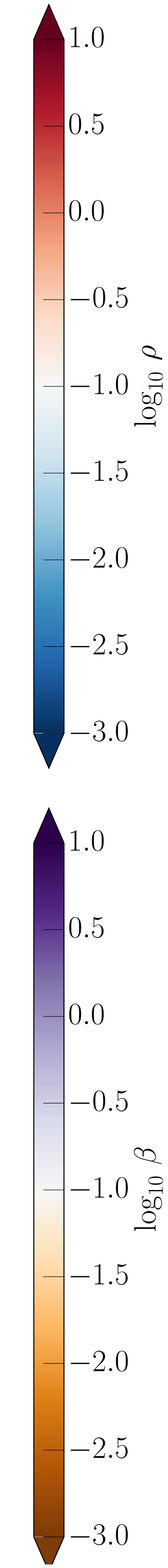
This is the analogous to a MAD state of a single black hole!

Narayan+(2003), Igumenchev+(2003), Begelmann+(2022)

Tchekhovskoy+(2011)

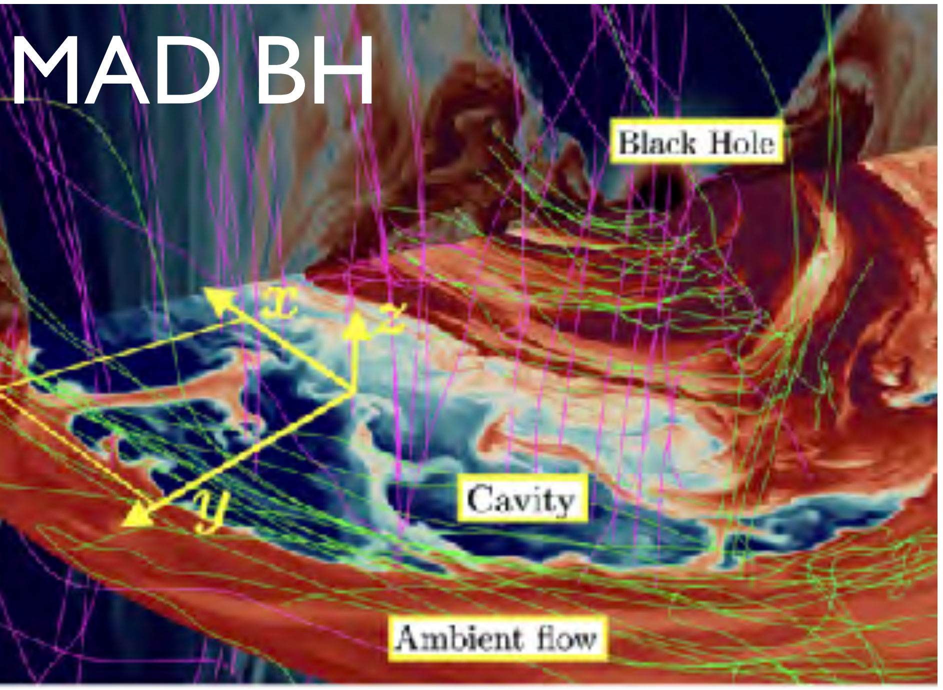




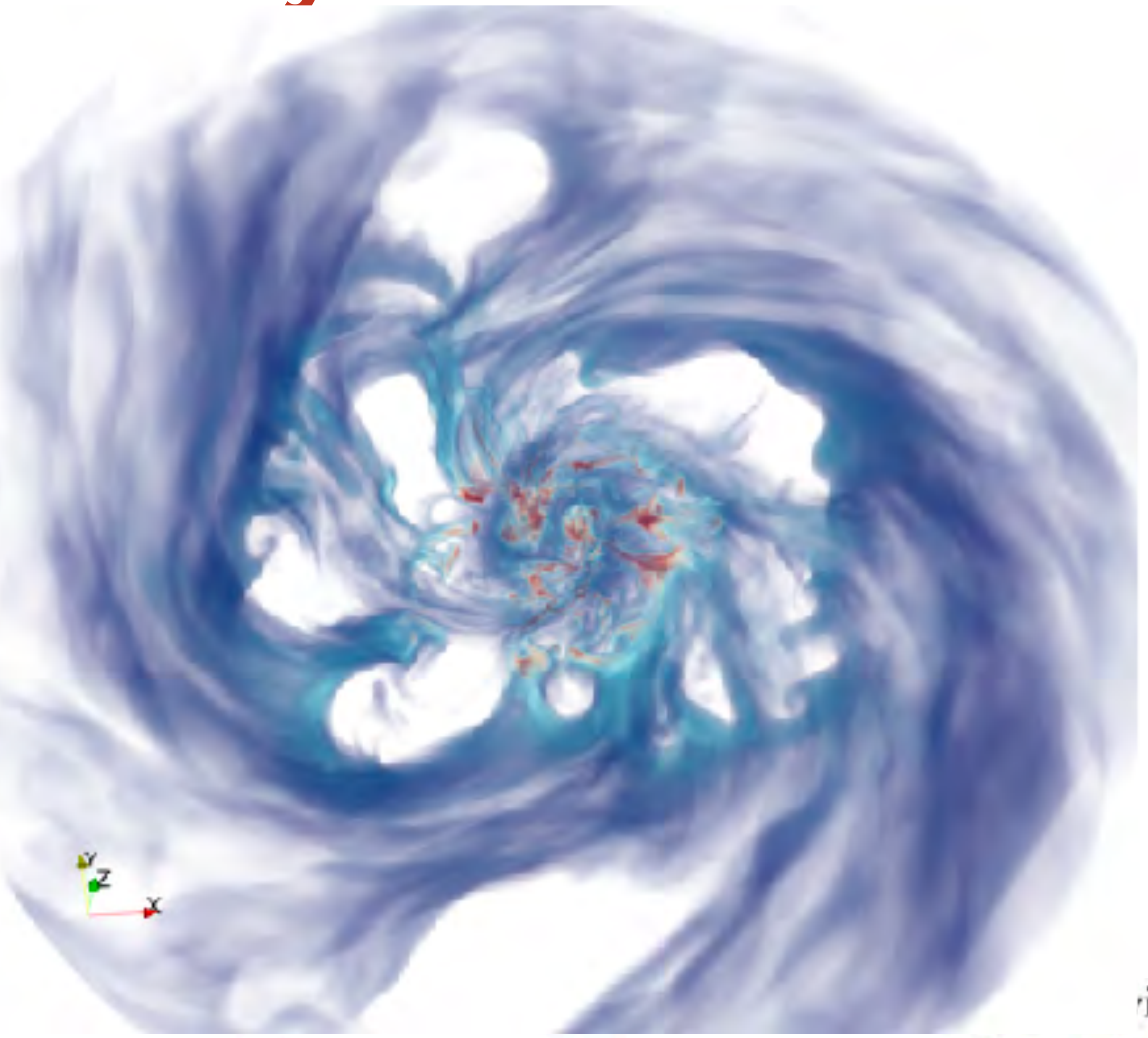


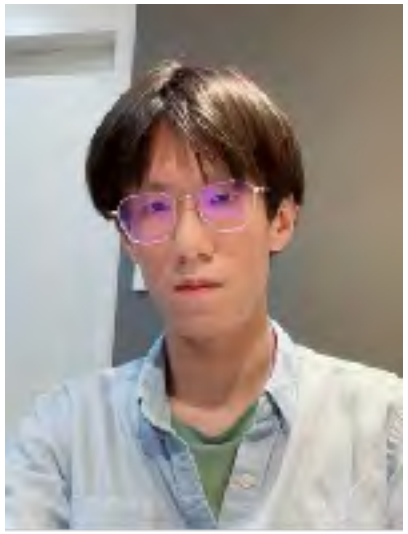
ERM & Wang (ApJL, in press)

Circumbinary accretion disks



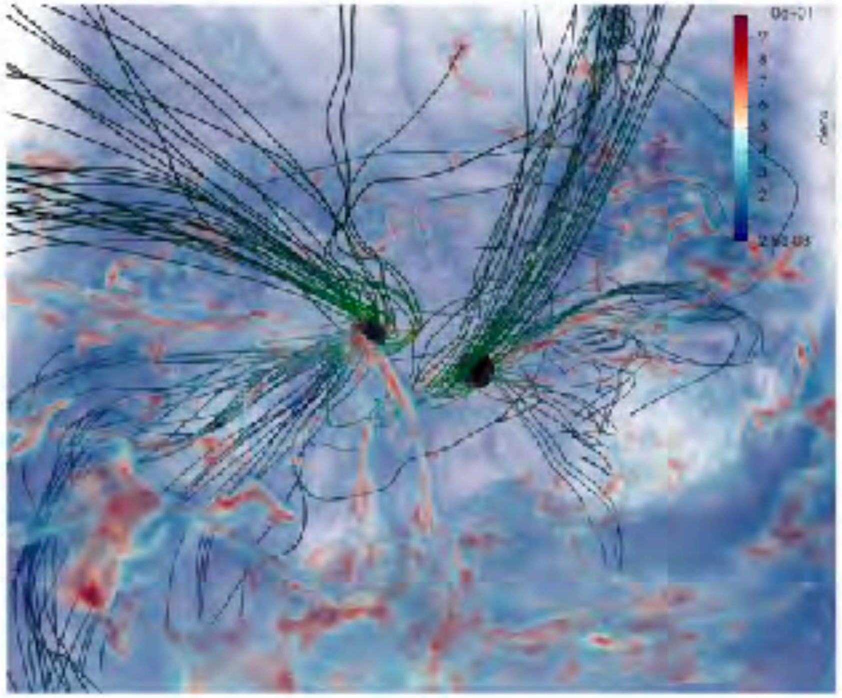
Zhdankin+(2023)

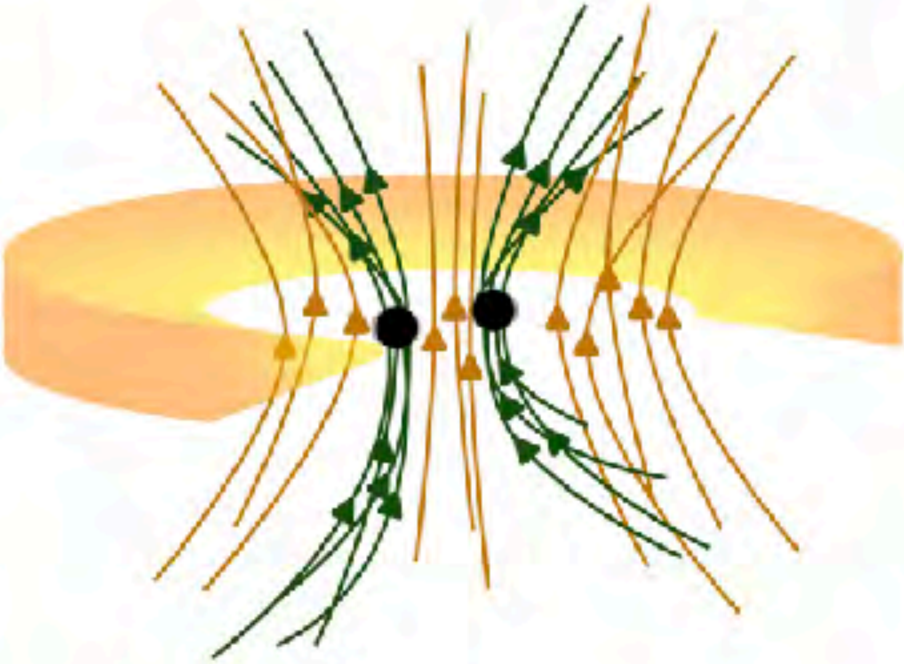




H. Wang (Caltech)

twisted dual jets





ity flux