Title: "Solar Flares From Black Holes: Electromagnetic Signals From Merging Supermassive Binaries"

Speakers: Sean Ressler

Collection/Series: Strong Gravity

Subject: Strong Gravity

Date: May 15, 2025 - 1:00 PM

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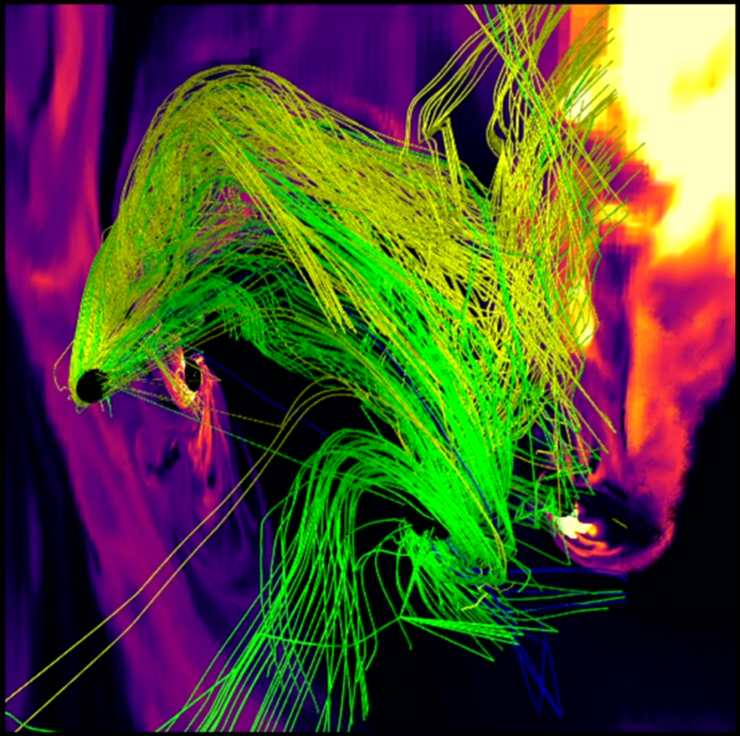
Abstract:

The recent detection of a low frequency gravitational wave background by pulsar timing arrays provides solid evidence that the observable universe contains a population of in-spiralling supermassive black hole binaries. Such binaries likely form as a result of collisions between galaxies and can offer clues as to how black holes and galaxies grow over time. Moreover, since galactic centers are often densely populated by gas and stars, these systems are much more likely to be actively accreting and radiating compared to stellar mass-sized black hole binaries. This makes them promising candidates for multi-messenger detection (combining electromagnetic and gravitational wave information), particularly when LISA comes online or as pulsar timing arrays improve their sensitivity. In order to facilitate this goal, it is important that, in addition to predictions for the possible gravitational wave signals from numerical relativity, we also develop predictions for electromagnetic signals from simulations of black hole binary accretion. In this talk I will present some of our recent results from 3D general relativistic magnetohydrodynamic simulations that utilize a strong-field approximation to the in-spiralling spacetime metric. Specifically, I will showcase several possible distinctive electromagnetic signals from black hole binaries, including quasi-periodic emission, jet precession, and two processes analogous to flaring activity frequently observed in the outer layer of the Sun.

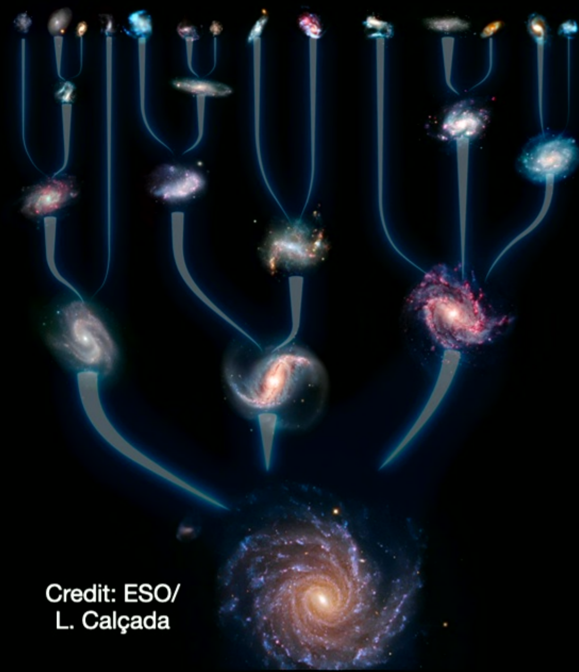
Solar Flares From Black Holes: Electromagnetic Signals From Merging Supermassive Binaries



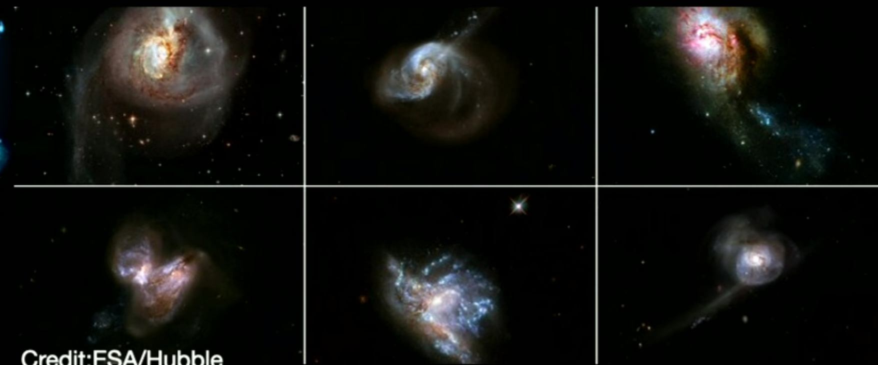
Sean Ressler (CITA)

Luciano Combi (Perimeter Institute/CITA/ University of Guelph)
Bart Ripperda (CITA/University of Toronto)
Elias Most (Caltech)
Xinyu Li (Tsinghua University
Huan Yang (Perimeter Institute/University of Guelph/Tsinghua University)

Galaxies Grow By Merging



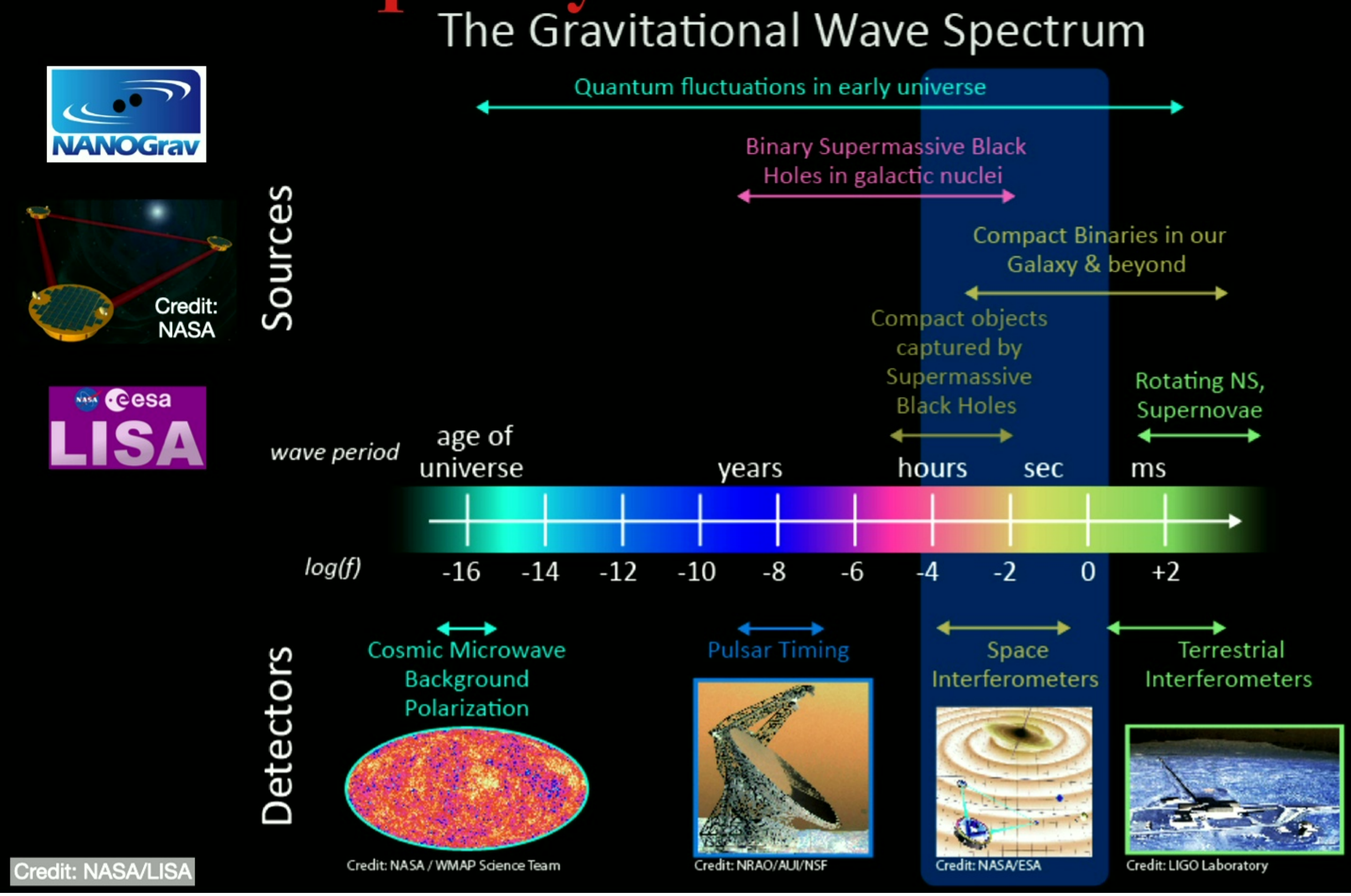
Credit: ESO/
L. Calçada



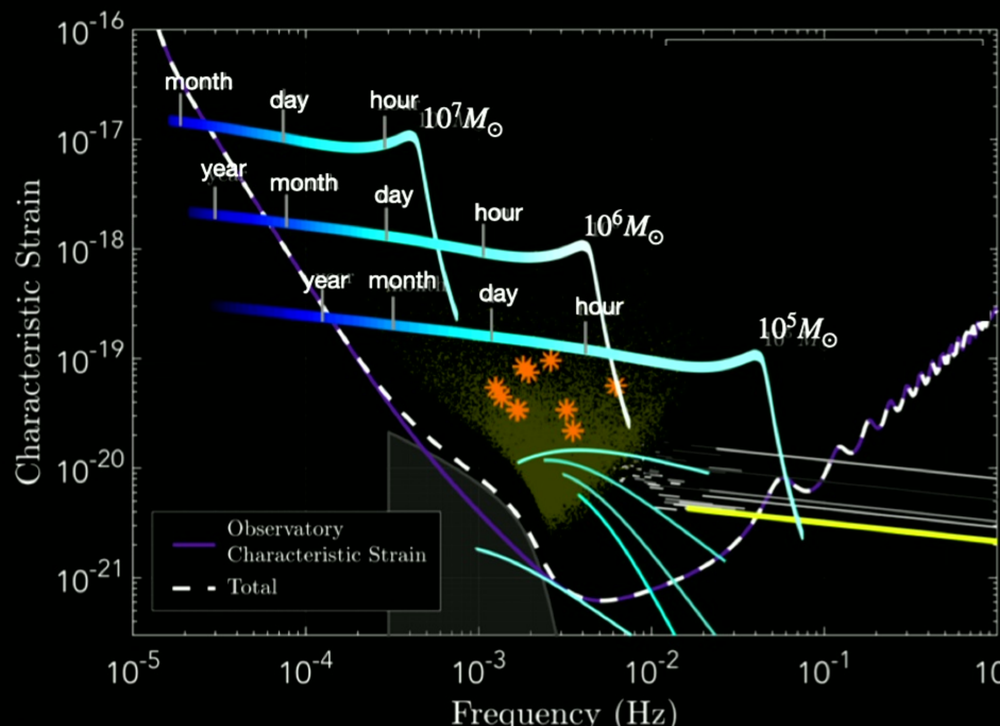
Credit:ESA/Hubble

Credit: Spitzer, NASA/JPL-Caltech/STScI/Vassar

Low Frequency Gravitational Waves



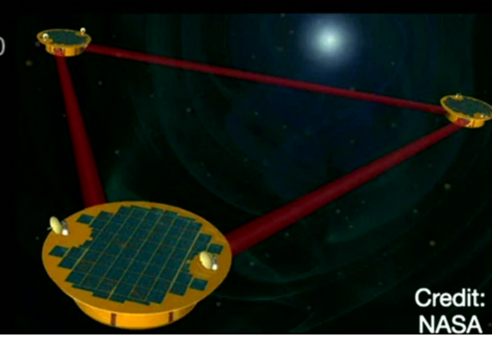
Laser Interferometer Space Antenna (LISA)



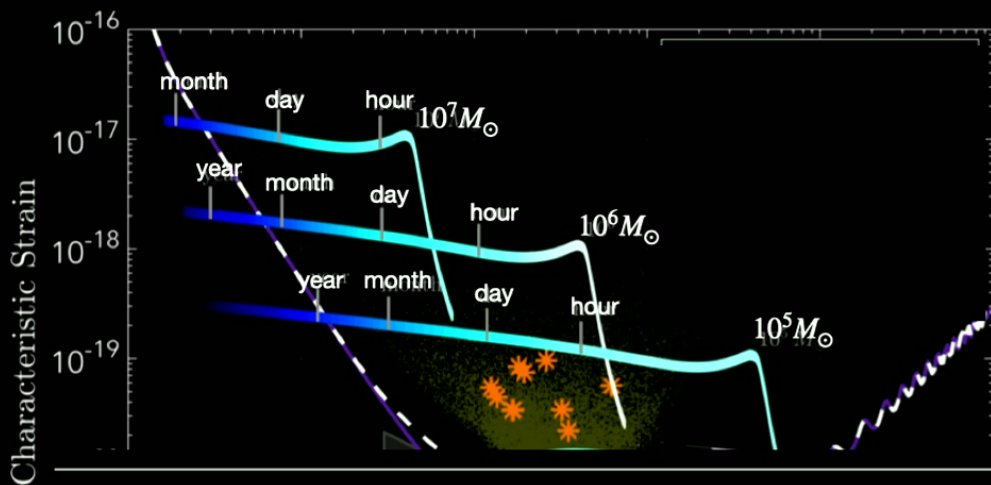
Credit:Amaro-Seoane+ 2017

Masses: $10^5 - 10^8 M_\odot$

Mission Lifetime:
4 yr + 6 yr



Laser Interferometer Space Antenna (LISA)



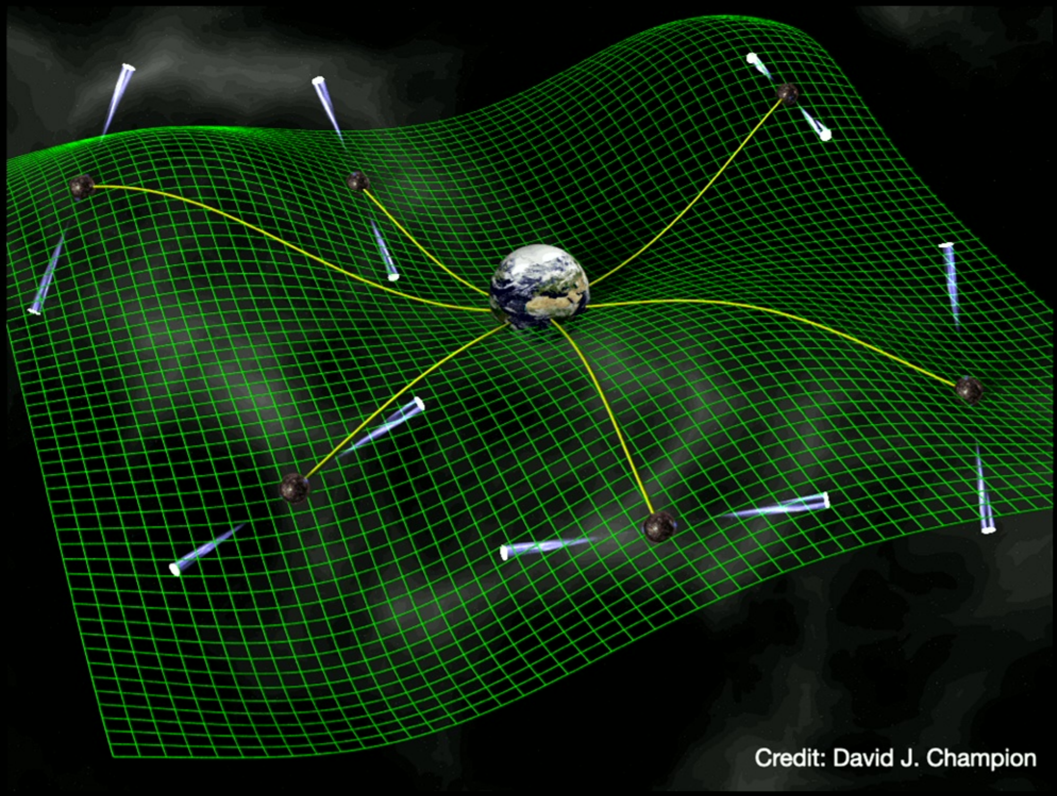
Masses: $10^5 - 10^8 M_\odot$

Mission Lifetime:
4 yr + 6 yr

Reference	Base population	MBHB evolution prescription	Merger rate (yr^{-1})
Arun et al. (2009)	SAM	None	~22
Sesana et al. (2011)	SAM	None	~25
Klein et al. (2016)	SAM	DF, LC, VD, GW, Tri	~8
Berti et al. (2016)[a]	SAM	DF, LC, VD, GW, Tri	~8
Salcido et al. (2016)	Hydrodynamic	Constant[b]	~2
Bonetti et al. (2019)	SAM	DF, LC, VD, GW, Tri	~23
This paper	Hydrodynamic	DF, LC, VD, GW	~0.5–1

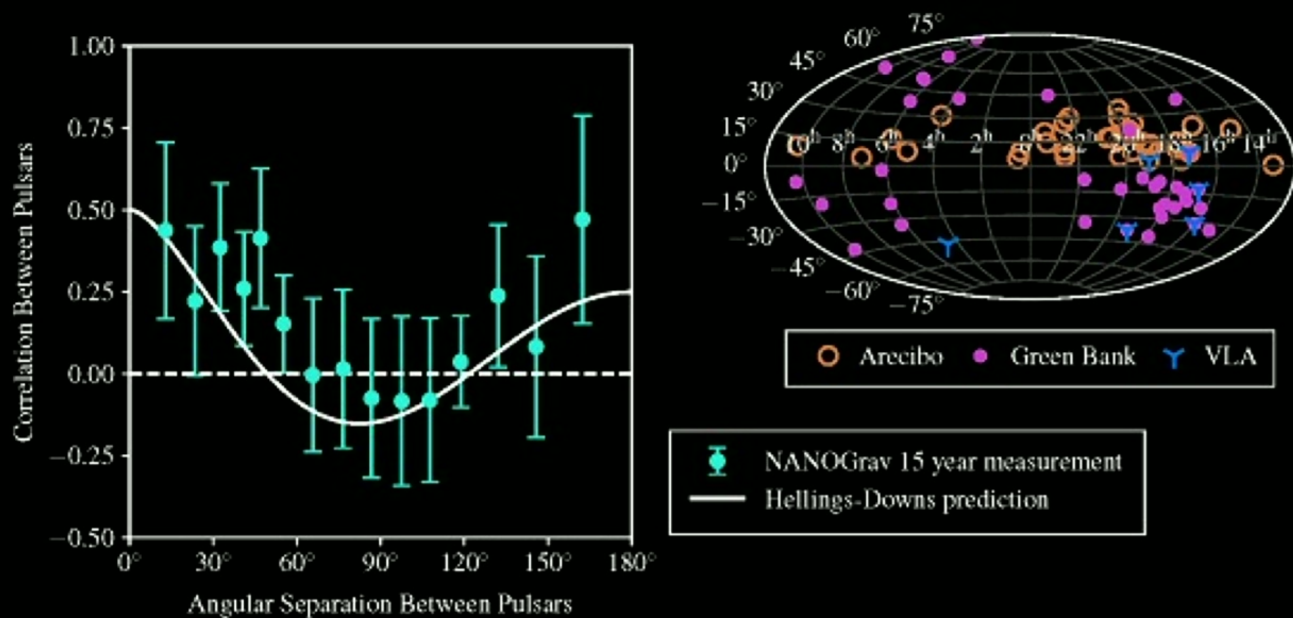
Credit: NASA

Pulsar Timing Arrays



Masses: $10^8 - 10^{10} M_\odot$ Mission Lifetime: Indefinitely

Pulsar Timing Arrays: GW Background



Credit: NanoGrav 2023

EM Counterparts to Low-Frequency GW Sources: Time-Domain Astronomy

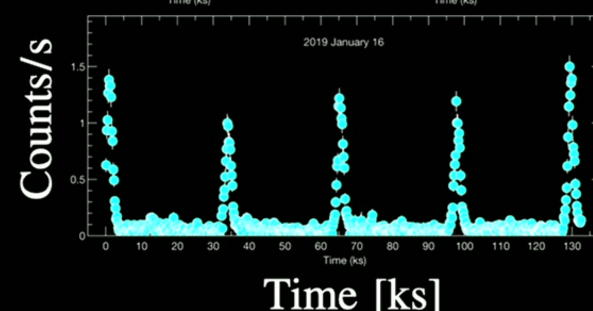
VERA C. RUBIN OBSERVATORY

AKA

Large Synoptic Survey Telescope

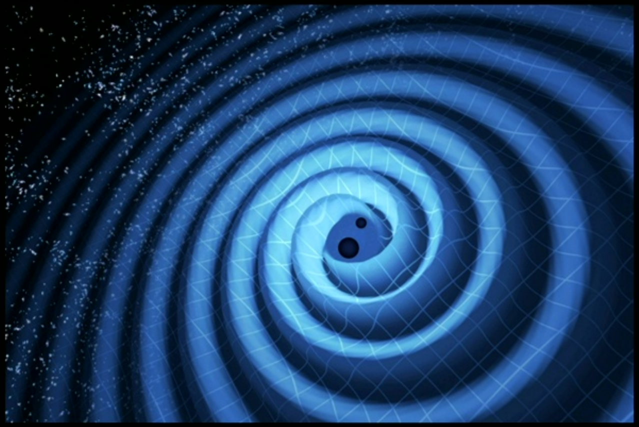
Credit: Rubin Obs/NSF/AURA

Credit: Miniutti+ 2019



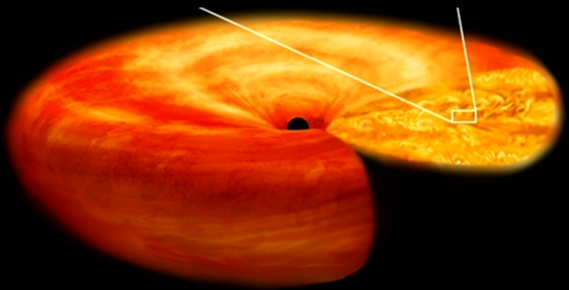
Predicting EM Signals

1. Evolution of Spacetime



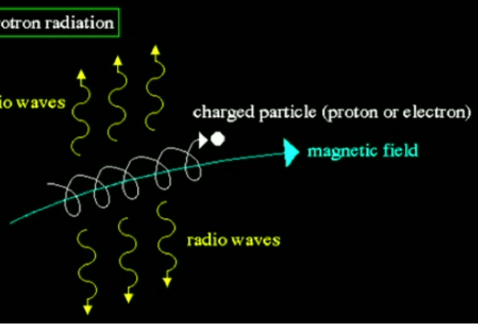
Credit: T. Pyle/LIGO

2. Evolution of Surrounding Plasma

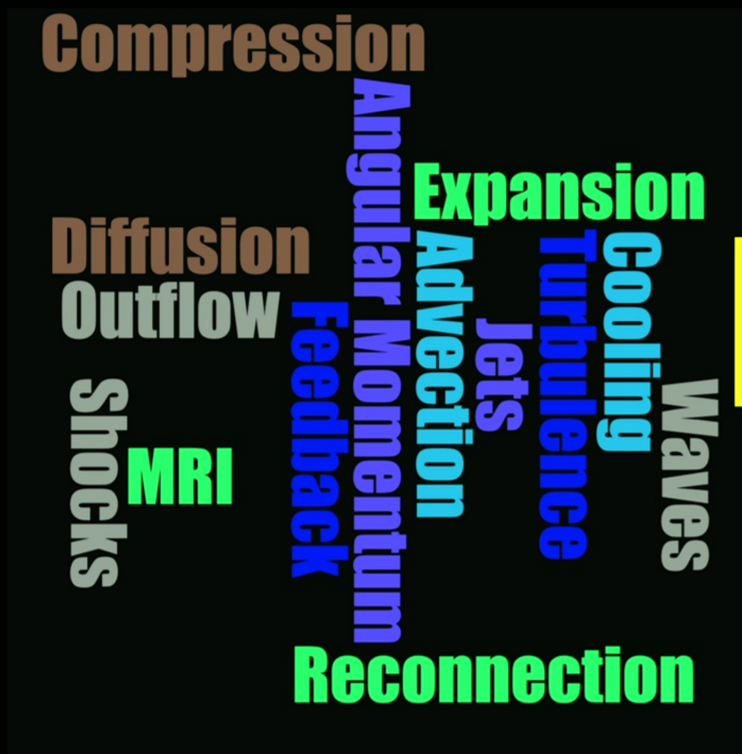


Credit: Yohei Kawazura

3. General Relativistic Radiation Transport

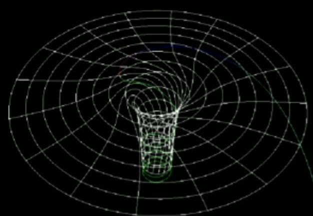


Accretion is Complex, Nonlinear, and Time-Variable



Numerical Simulations

Spacetime

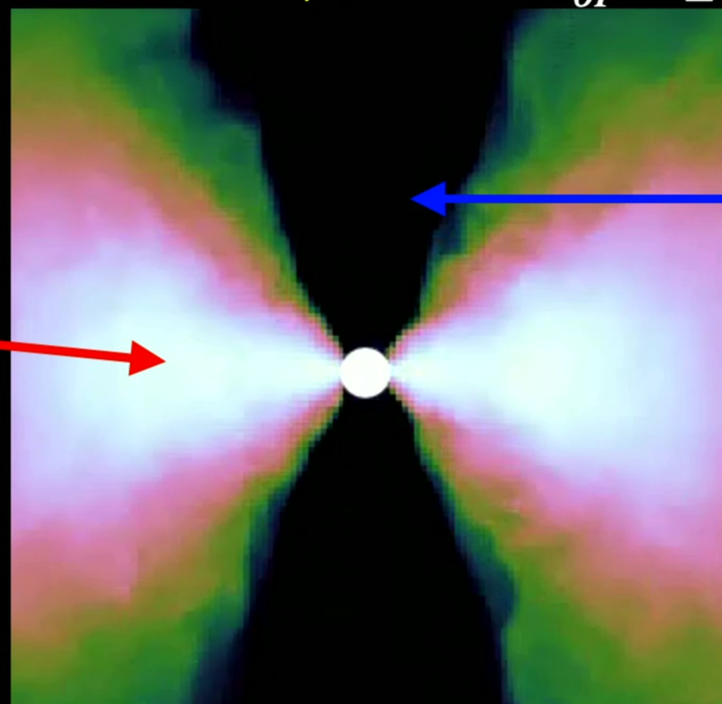


+ Conservation of Mass $\nabla_\mu\left(\rho u^\mu\right) = 0$

Conservation of Energy/Momentum $\nabla_\mu T^\mu_\nu = 0$

Maxwell's Equations $\partial F^{*\mu\nu} = 0$

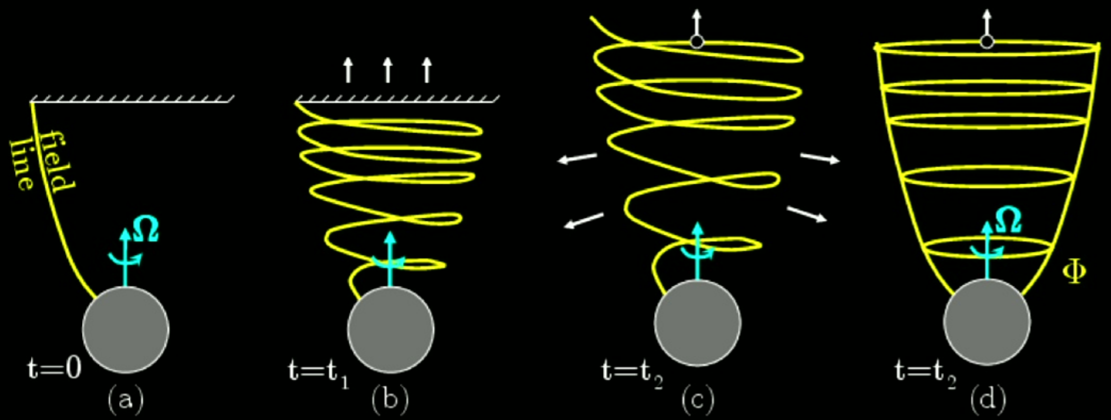
Assuming:
Ionized Gas (high T)
Collisional
Highly Conducting
$(E \sim v \times B)$



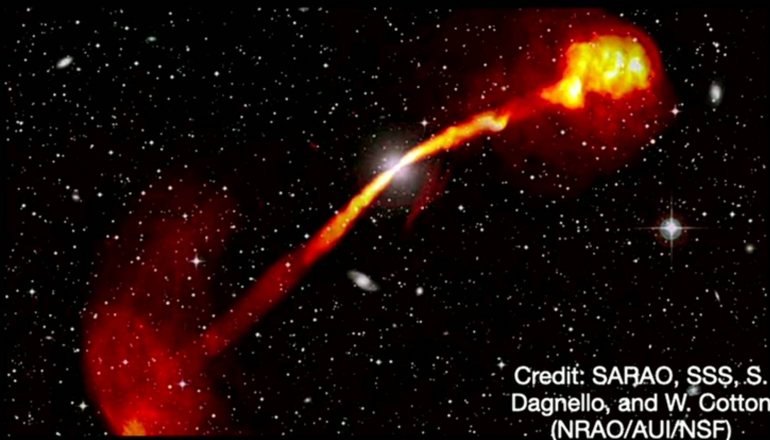
Disk: Turbulent, magnetized inflow

Jet: highly magnetized, relativistic outflow

Electromagnetic Jets



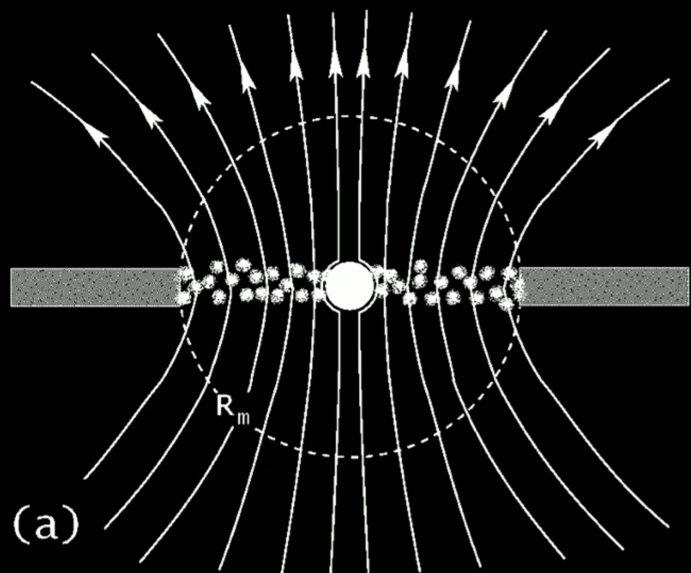
Credit: Davis & Tchekovskoy 2021



Credit: SARAO, SSS, S. Dagnello, and W. Cotton (NRAO/AUI/NSF)

Magnetically Arrested Disks (MADs)

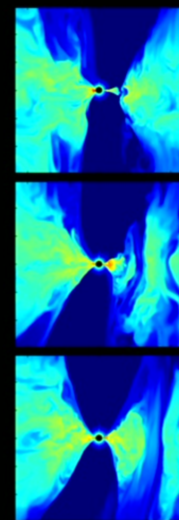
Flux Accumulation



Narayan+ 2003

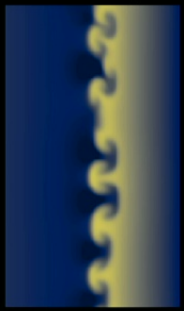
Flux Saturation

Chatterjee &
Narayan 2022



Flux
Eruption

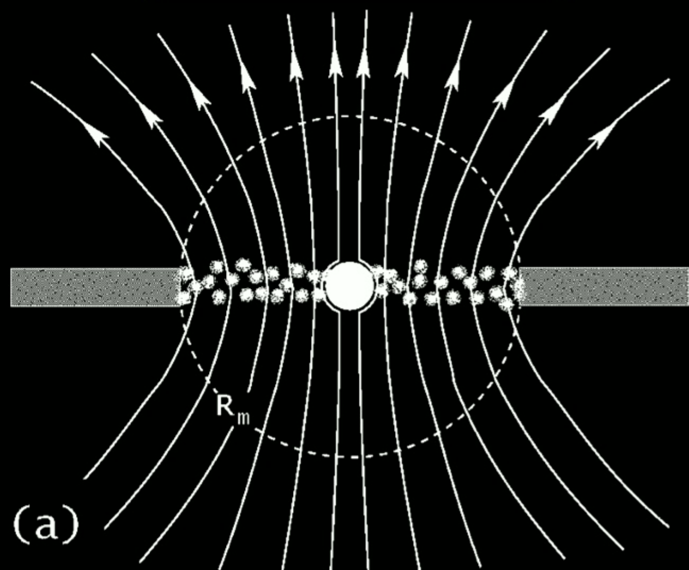
Matin Shams
(TU Delft
Undergraduate
Student)



$$\frac{\Phi_{\rm BH}}{\sqrt{\dot{M} r_{\rm g}^2 c}} \approx 50 - 70$$

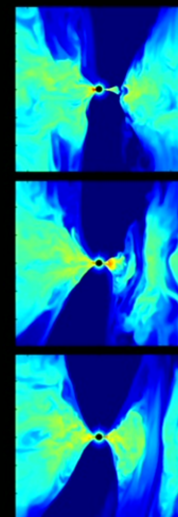
Magnetically Arrested Disks (MADs)

Flux Accumulation



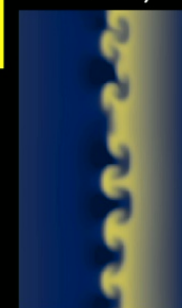
Narayan+ 2003

Chatterjee & Narayan 2022



Flux Eruption

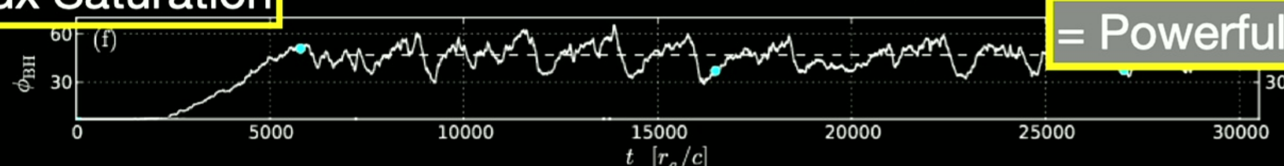
Matin Shams (TU Delft Undergraduate Student)



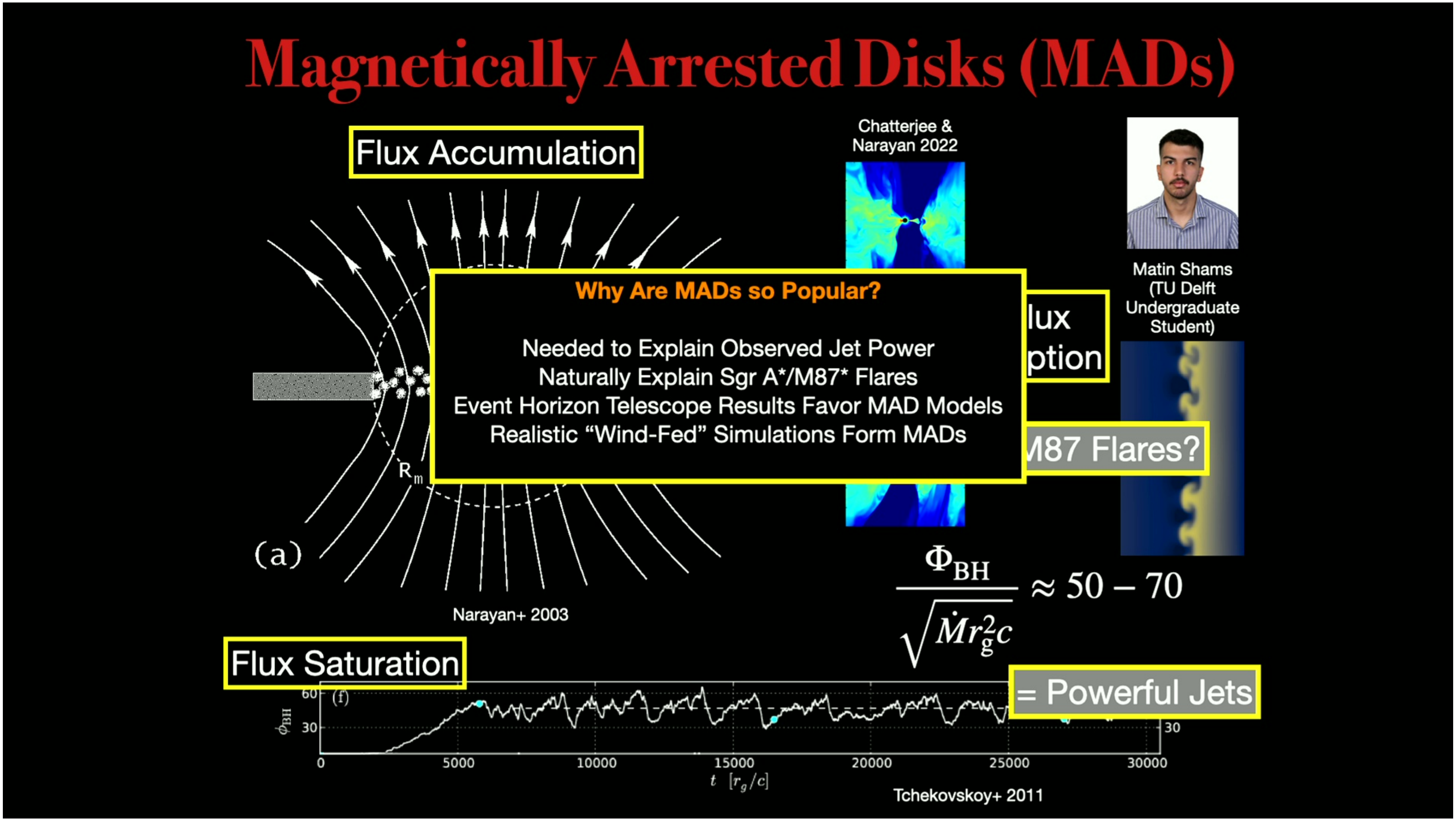
$$\frac{\Phi_{\rm BH}}{\sqrt{\dot{M} r_g^2 c}} \approx 50 - 70$$

Flux Saturation

= Powerful Jets



Tchekovskoy+ 2011


Magnetically Arrested Disks (MADs)
Flux Accumulation
Chatterjee & Narayan 2022
Matin Shams (TU Delft Undergraduate Student)
Why Are MADs so Popular?
Needed to Explain Observed Jet Power
Naturally Explain Sgr A*/M87* Flares
Event Horizon Telescope Results Favor MAD Models
Realistic "Wind-Fed" Simulations Form MADs
lux
ption
187 Flares?
R_m
(a)
Narayan+ 2003
$$\frac{\Phi_{BH}}{\sqrt{\dot{M}r_g^2c}} \approx 50-70$$
Flux Saturation
= Powerful Jets
(f)
ϕ_{BH}
60
30
0
5000
10000
15000
20000
25000
30000
$t\ [r_g/c]$
Tchekovskoy+ 2011

Simulating Binary Black Hole Accretion

Numerical Relativity + MHD

Expensive

Accurate Everywhere

Short separations + runtimes

All GR effects included

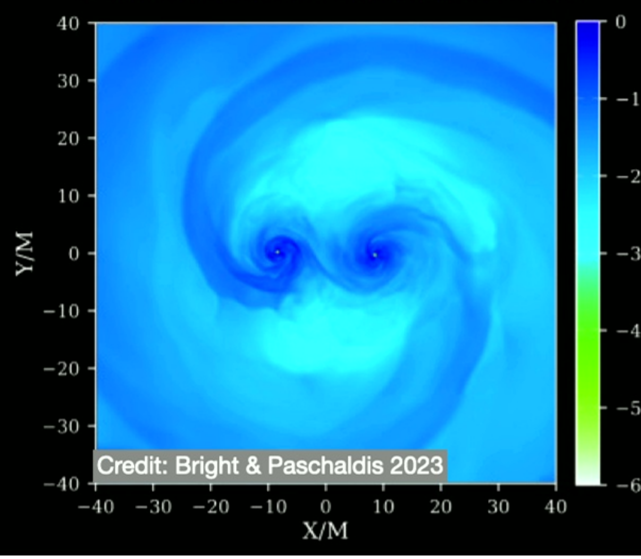
Post-Newtonian (M)HD

Cheap

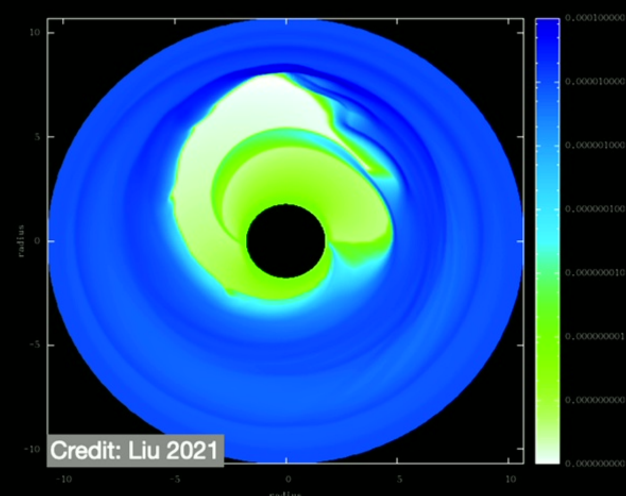
Inaccurate Near BHs

Large separations + runtimes

Limited GR effects



Credit: Bright & Paschaldis 2023

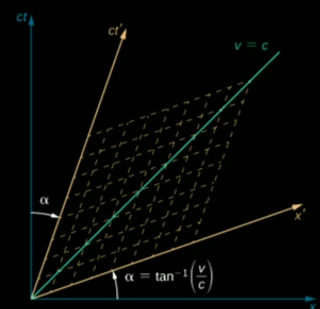

Credit: Liu 2021

Hybrid Approach: Time-Dependent GRMHD

Combi+ 2021
Combi & Ressler 2024

$$g_{\mu\nu} = \underbrace{\eta_{\mu\nu}}_{\text{Background Flat Spacetime}} + \underbrace{f}_{\sim 2\frac{GM}{r}}\ \underbrace{l_\mu l_\nu}_{\sim \hat{r}\hat{r}}$$

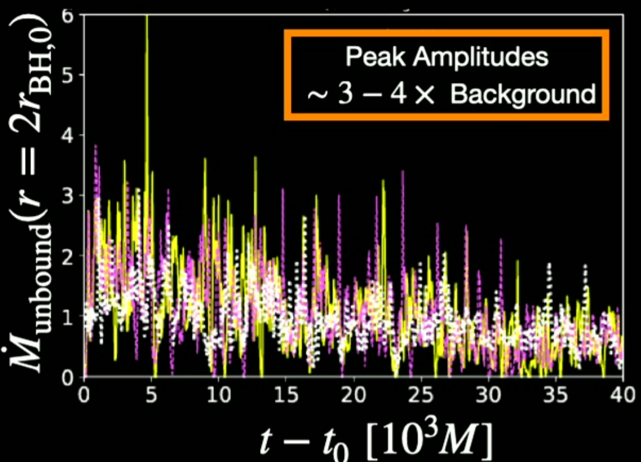
$$g_{\mu\nu} = \eta_{\mu\nu} + f\ \Lambda^{\alpha}_{\mu} l_{\alpha}\ \underbrace{\Lambda^{\beta}_{\nu} l_{\beta}}_{\sim \hat{r}'\hat{r}'}$$

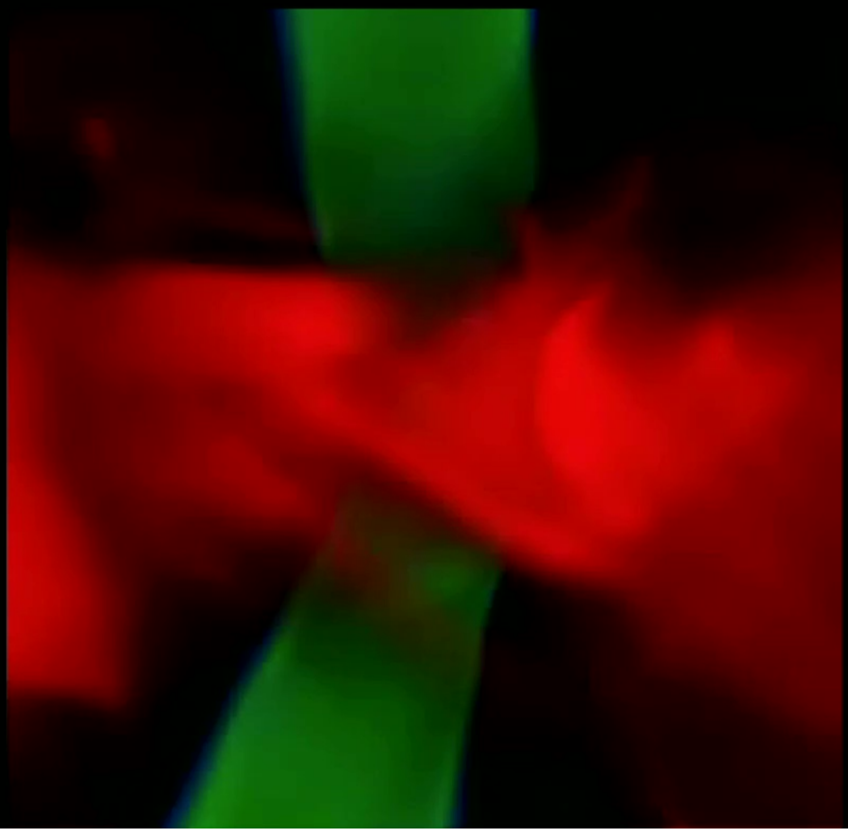


$$g_{\mu\nu} = \eta_{\mu\nu} + \left[f\Lambda^{\alpha}_{\mu} l_{\alpha} \Lambda^{\beta}_{\nu} l_{\beta}\right]_1 + \cancel{\frac{f_1 f_2}{f_1 + f_2}[\ldots]} + \left[f\Lambda^{\alpha}_{\mu} l_{\alpha} \Lambda^{\beta}_{\nu} l_{\beta}\right]_2$$

Case 1: Small Mass Ratio

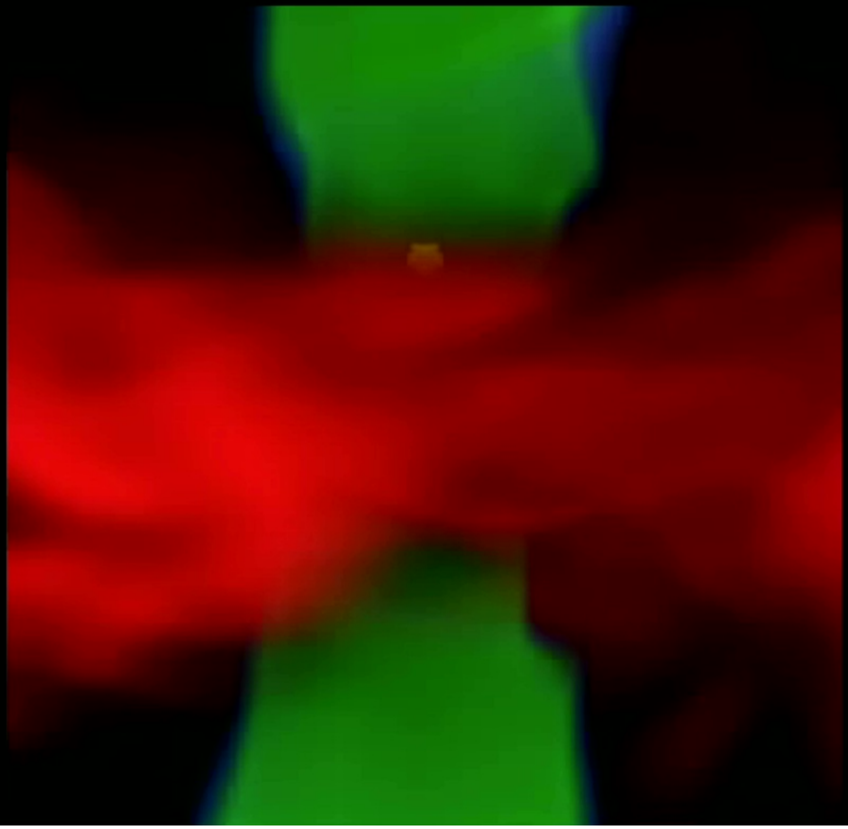
Jet Precession and Quasi-Periodic Emission For Small Mass Ratios





Ressler+ 2024

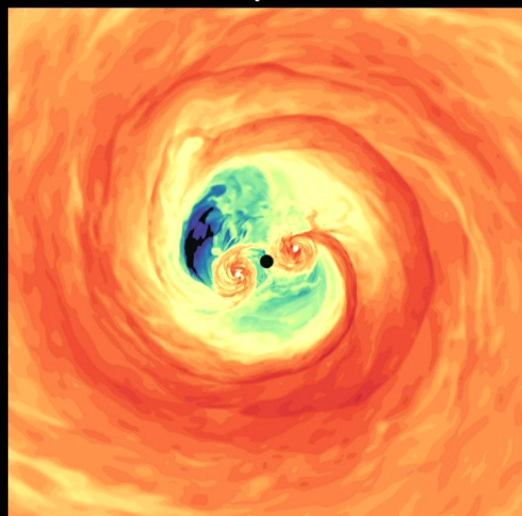
Jet Precession and Quasi-Periodic Emission For Small Mass Ratios



Summary of Previous GRMHD Simulations

Circumbinary Disk

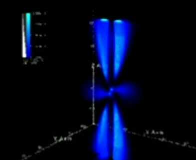
ρ



Credit: Combi+ 2021

See also: Farris+ 2012, Paschalidis+ 2021, Lopez Armegol+ 2021, Avara+ 2023

"Force-Free"

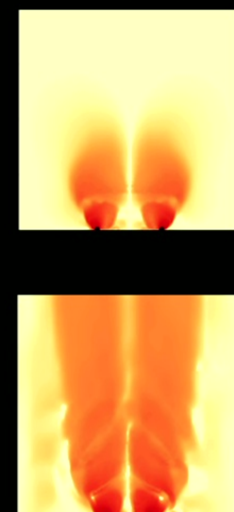


Credit: Palenzuela+ 2010a

See also: Palenzuela+ 2009, 2010b, Moesta+ 2012, Alic+ 2012

Uniform/Low Angular Momentum Gas

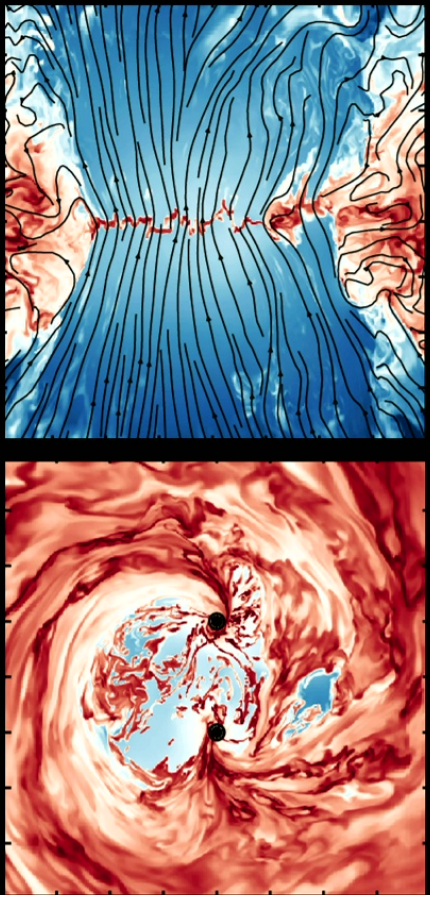
L_{Poynting}

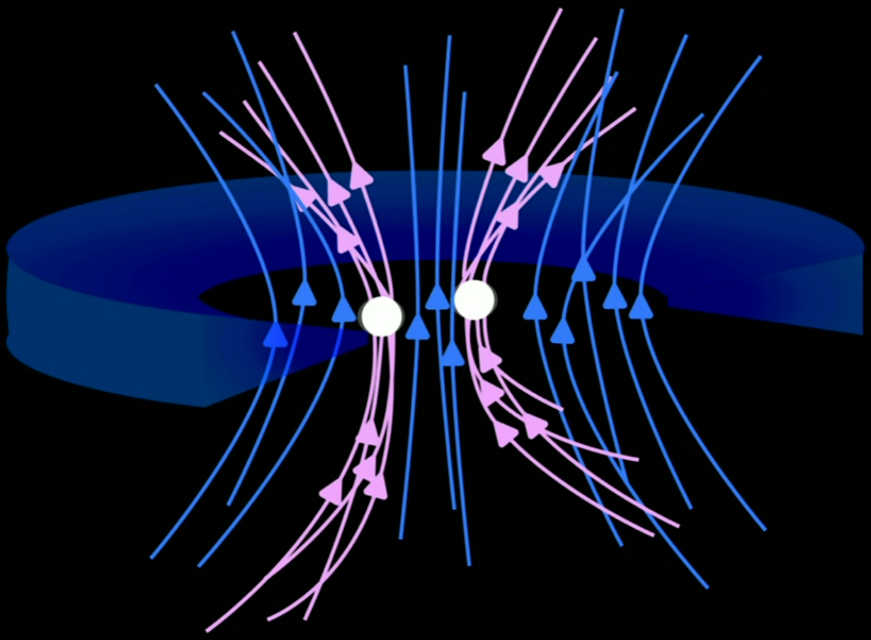


Credit: Cattorini + 2021

See also: Giacomazzo+ 2012, Kelly+ 2017, Fedrigo+ 2024

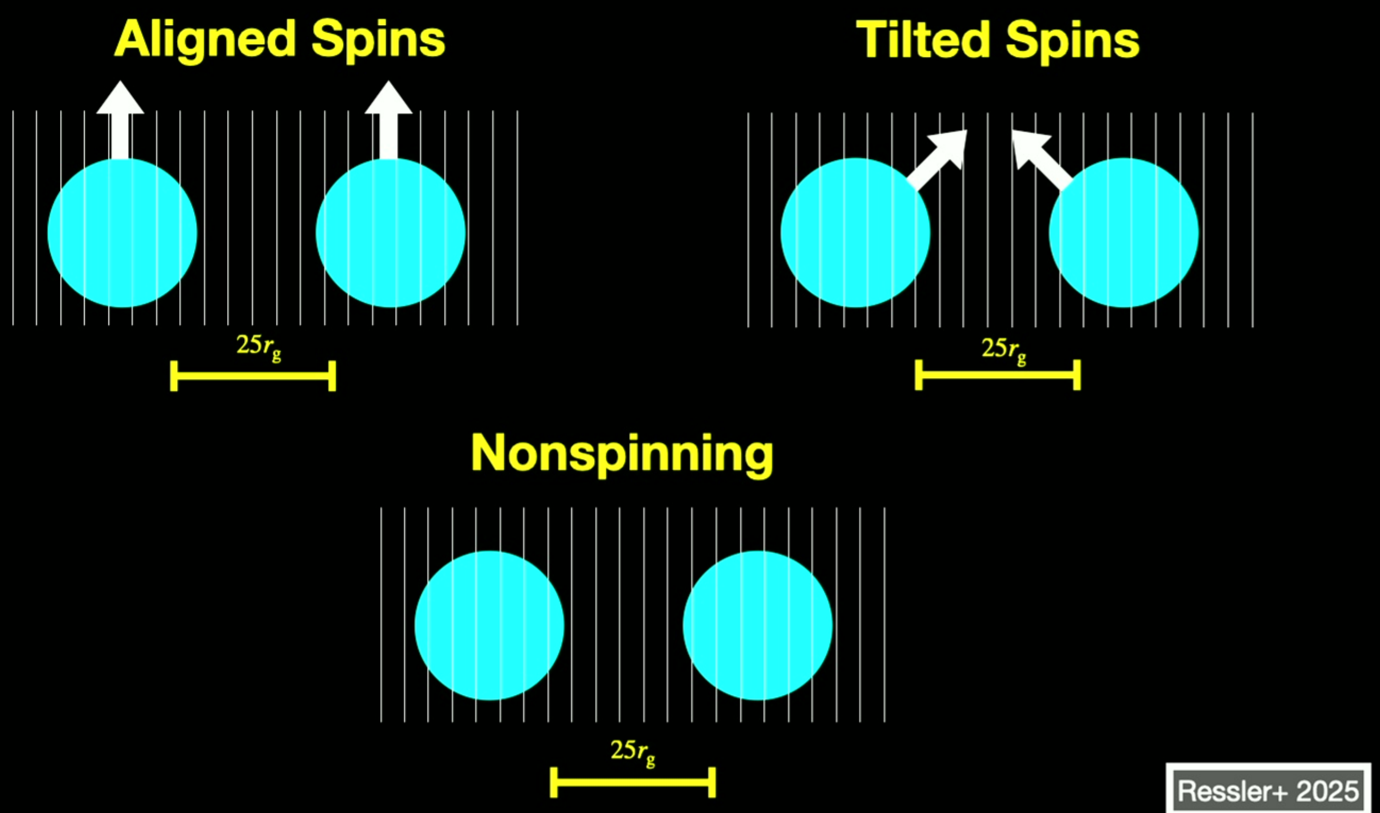
Low Angular Momentum Magnetically Arrested Accretion





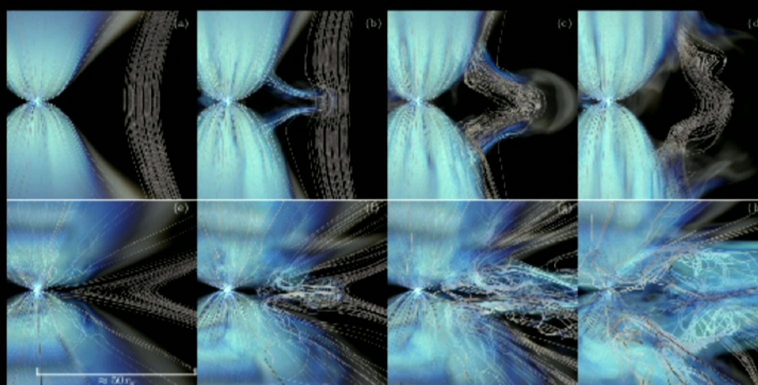
Credit: Most & Wang 2024a,b

Equal Mass Ratio Parameter Survey



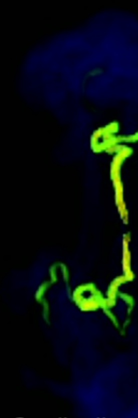
Low Angular Momentum Accretion: Not So Simple

Less Net Flux Reaching BH



Credit: Galishnikova+ 2024

Unstable, Weaker Jets

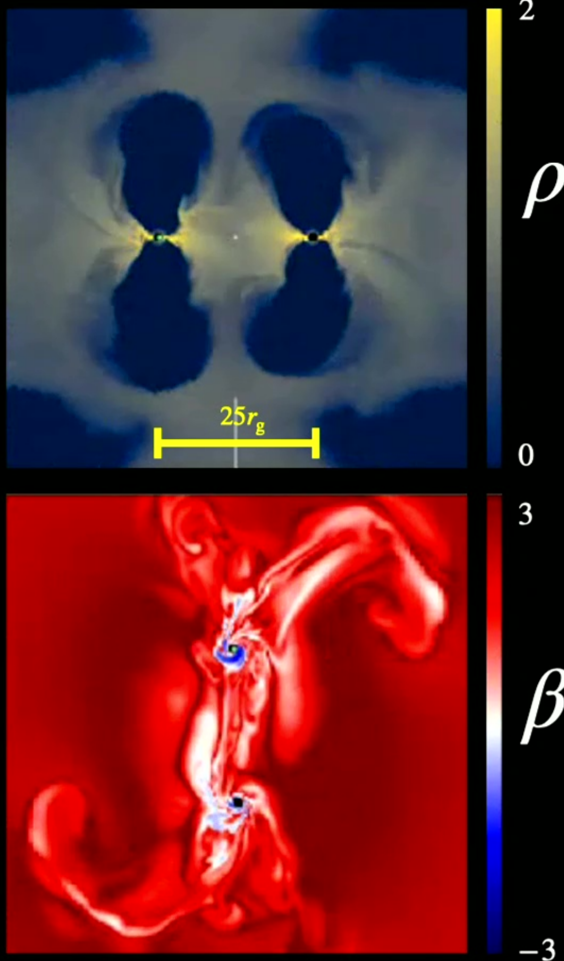


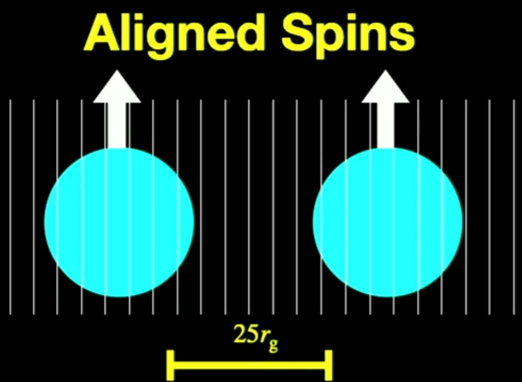
Credit: Jia+ 2022, Ressler+2021

He Jia
Princeton PhD
Student

See also: Lalakos+ 2024

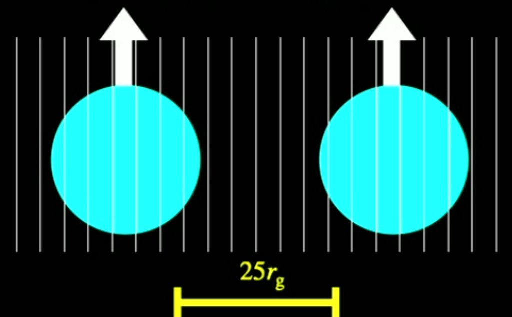
Fiducial Evolution



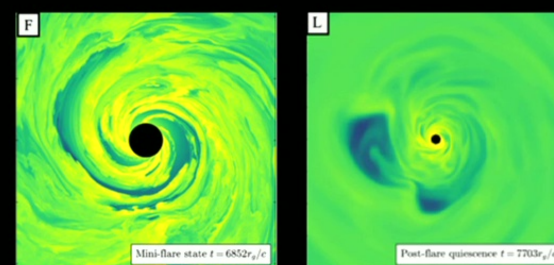


Flux Tube Ejection

Aligned Spins

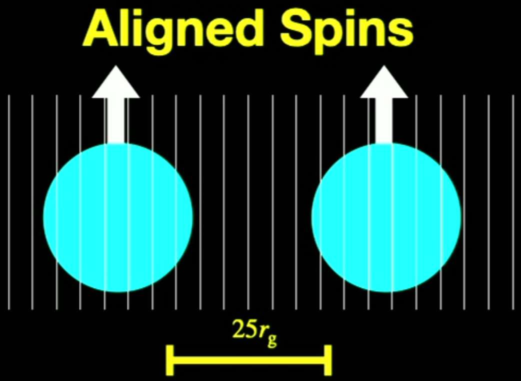


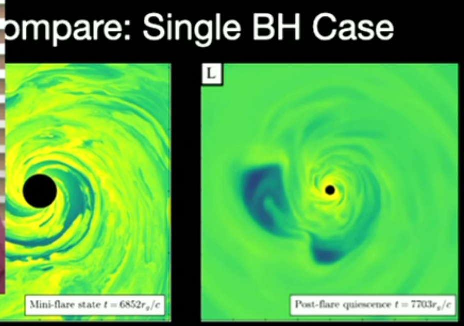
Compare: Single BH Case



Credit: Ripperda+ 2022

Flux Tube Ejection

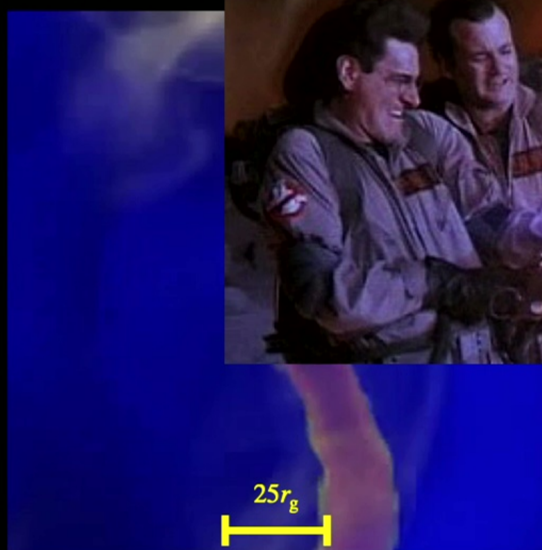




Credit: Ripperda+ 2022

Colliding Jets As “Solar Flares”

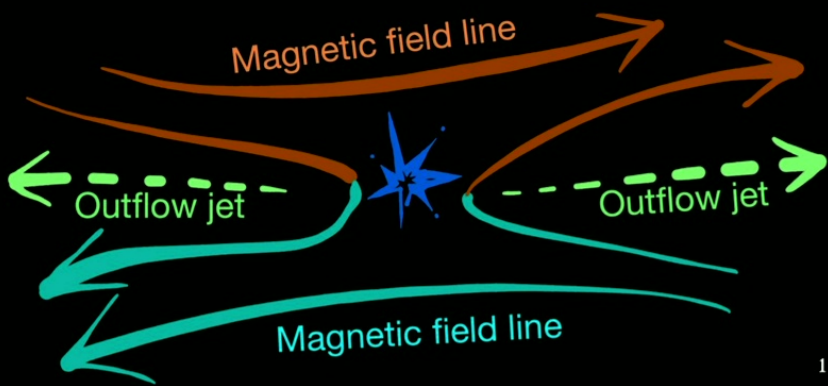
See also: Palenzuela+ 2010,
Guitierrez+ 2023



Spengler+ 1984

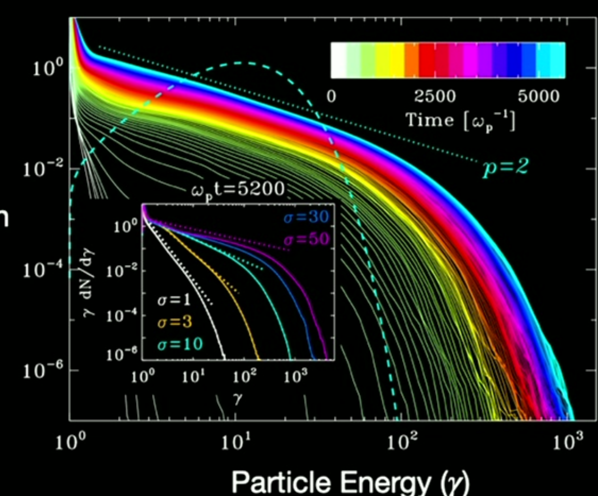
Ressler+ 2024b

Flaring Mechanism: Magnetic Reconnection

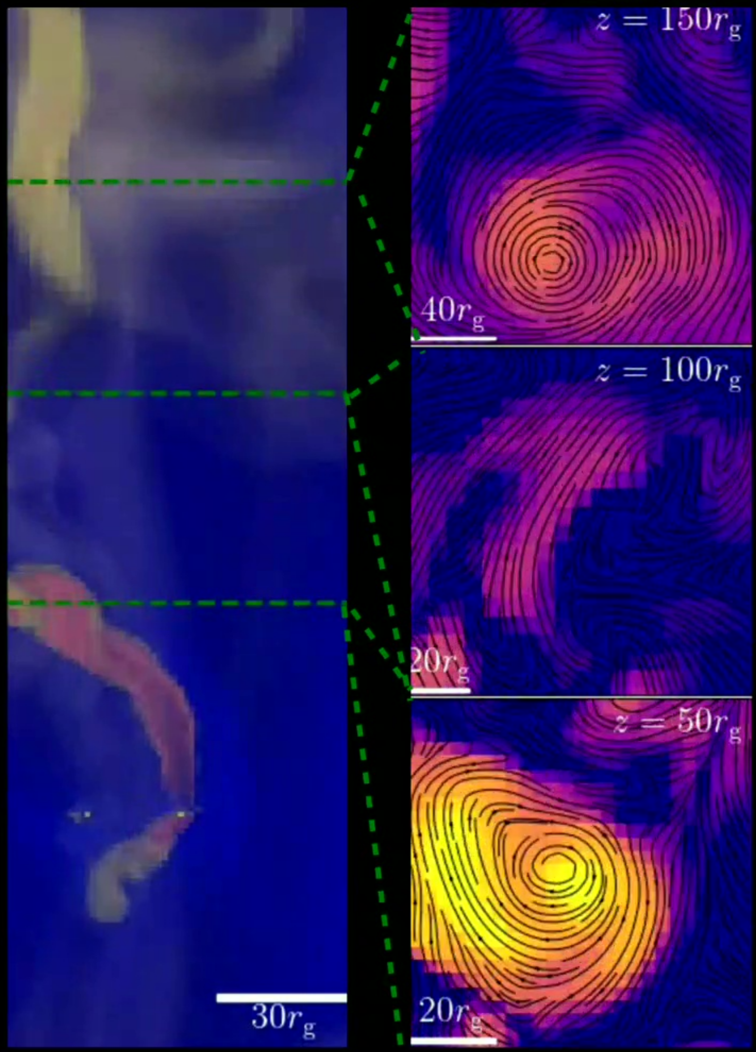


Credit: Dartmouth College, Yi-Hsin Liu

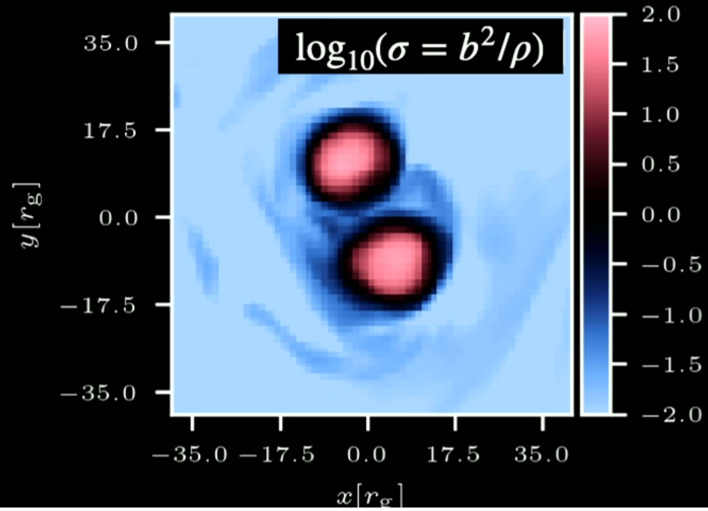
Credit: Sironi & Spitkovsky 2014



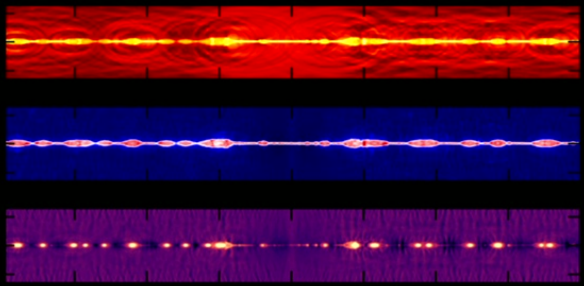
Jet Cores Reconnect and Merge



Isolating Reconnection Layer



Estimating EM Signature



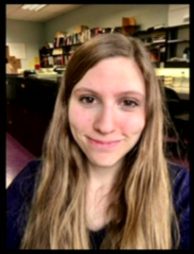


Image Credit: Alicia Savelli
(U of Toronto PhD Student)

Estimating EM Signature

Luminosity

$$L \sim \underbrace{\frac{b^2}{4\pi}}_{\text{Magnetic Energy Density}} \underbrace{l_{\rm rec}^2}_{\text{~Area of Current Sheet}} \underbrace{\beta_{\rm rec} c}_{\text{Reconnection Rate}}$$

Magnetic Energy Density

~Area of Current Sheet

Reconnection Rate

$(\beta_{\rm rec} \approx 0.1c)$

Thermal Emission

$$\boxed{\begin{aligned} L_{\rm thermal} &\sim f_{\rm Edd} L_{\rm Edd} \\ \nu_{\rm thermal} &\sim \Theta_{\rm e}^2 \omega_B \end{aligned}}$$

Synchrotron Photon Frequency

$$\nu \sim \underbrace{\Gamma^2}_{\text{Peak Electron Lorentz Factor}} \underbrace{\omega_B}_{\text{Electron Gyrofrequency}} \sim \left(\frac{b^2}{\rho_{\rm e} c^2}\right)^2 \left(\frac{eB}{m_{\rm e} c}\right)$$

Peak Electron Lorentz Factor

Electron Gyrofrequency

$\Gamma_{\rm rec} \sim b^2/[\rho_e c^2]$

Estimating EM Signature

$$L \sim \frac{b^2}{4\pi} l_{\rm rec}^2 \beta_{\rm rec} c$$

$$l_{\rm rec} \sim 20 r_{\rm g} \qquad \beta_{\rm rec} \approx 0.1c$$

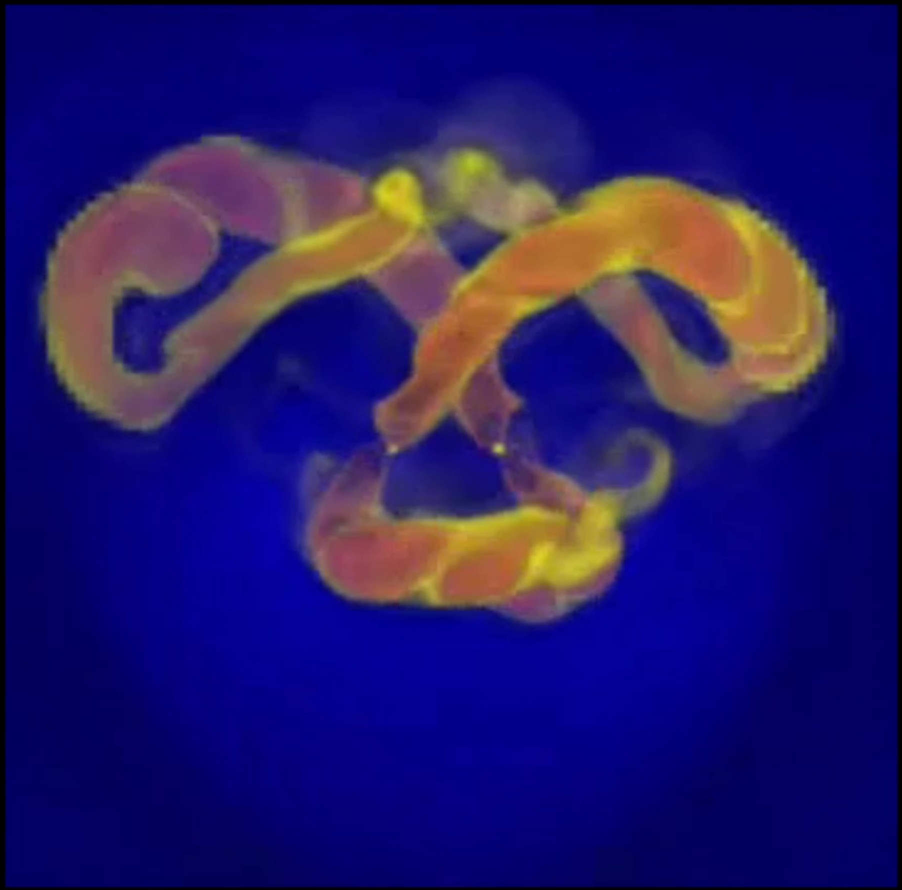
$$\frac{(L_{\rm rec})_{\rm jet}}{L_{\rm thermal}} \approx \underline{0.02} \left(\frac{u_{b,\rm rec} r_{\rm g}^2}{|\dot{M}|c} \cdot \frac{1}{5\times 10^{-5}} \right) \left(\frac{l_{\rm rec}}{20 r_{\rm g}} \right)^2$$

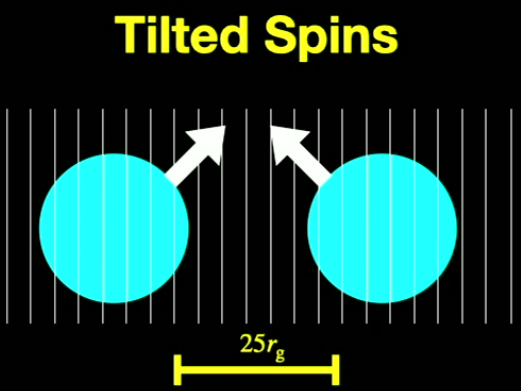
$$(L_{\rm rec})_{\rm jet} \approx \underline{3\times 10^{42}\,\frac{\rm erg}{\rm s}} \left(\frac{u_{b,\rm rec} r_{\rm g}^2}{|\dot{M}|c} \cdot \frac{1}{5\times 10^{-5}} \right) \left(\frac{l_{\rm rec}}{20 r_{\rm g}} \right)^2 f_{\rm Edd} \left(\frac{M}{10^6 M_\odot} \right) \left(\frac{\eta_{\rm rad}}{0.1} \right)^{-1}$$

$$\nu \sim \Gamma^2 \omega_B \sim \underbrace{\left(\frac{b^2}{\rho_{\rm e} c^2} \right)}_{\text{Floor}}{}^2 \left(\frac{eB}{m_{\rm e} c} \right) \qquad \underline{\nu \approx 2.5\times 10^{22}\,{\rm Hz}}$$

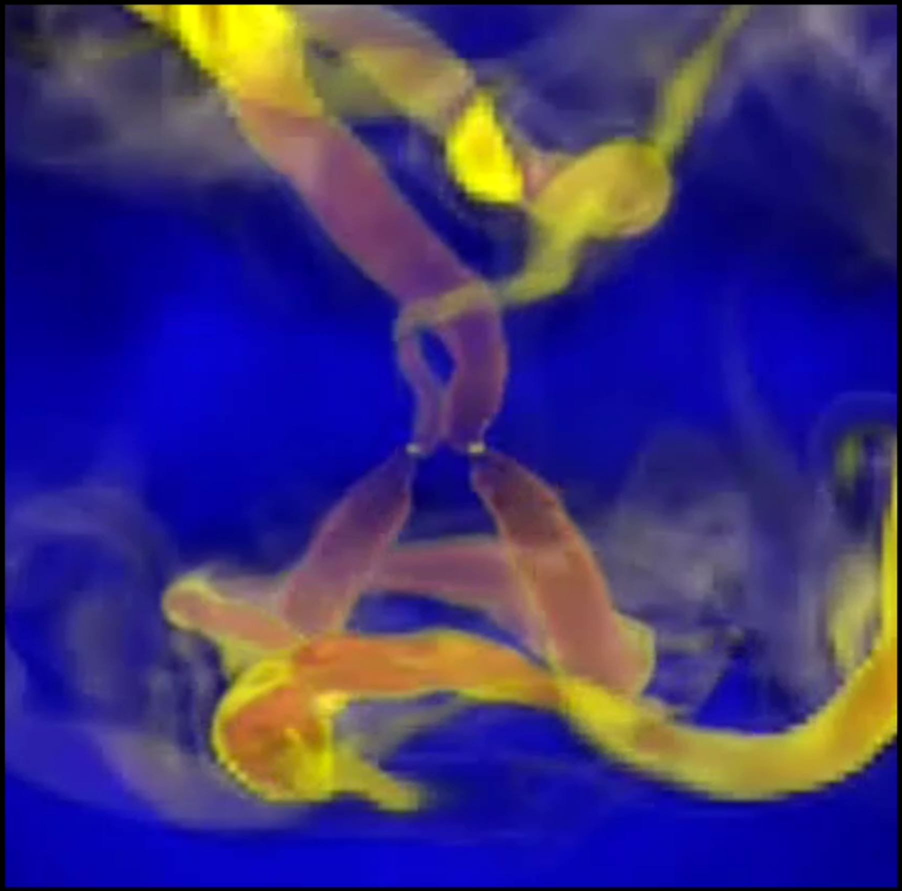
$$\frac{\nu_{\rm jet}}{\nu_{\rm thermal}} \approx \underline{10^5} \left(\frac{\Theta_{\rm e}}{200} \right)^{-2} \left(\frac{u_b r_{\rm g}^2}{|\dot{M}|c} \Big/ 0.075 \right)^{-1/2} \times f_{\rm Edd}^{-1/2} \left(\frac{M}{10^6 M_\odot} \right)^{1/2} \left(\frac{\eta_{\rm rad}}{0.1} \right)^{1/2}$$

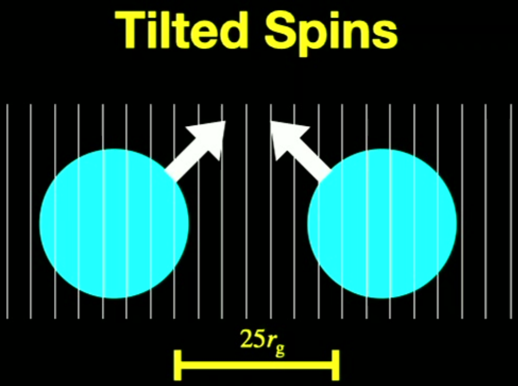
But Jets Can Be Suppressed





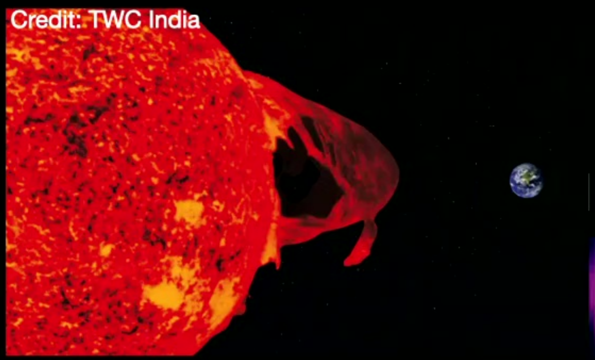
But Jets Can Be Suppressed

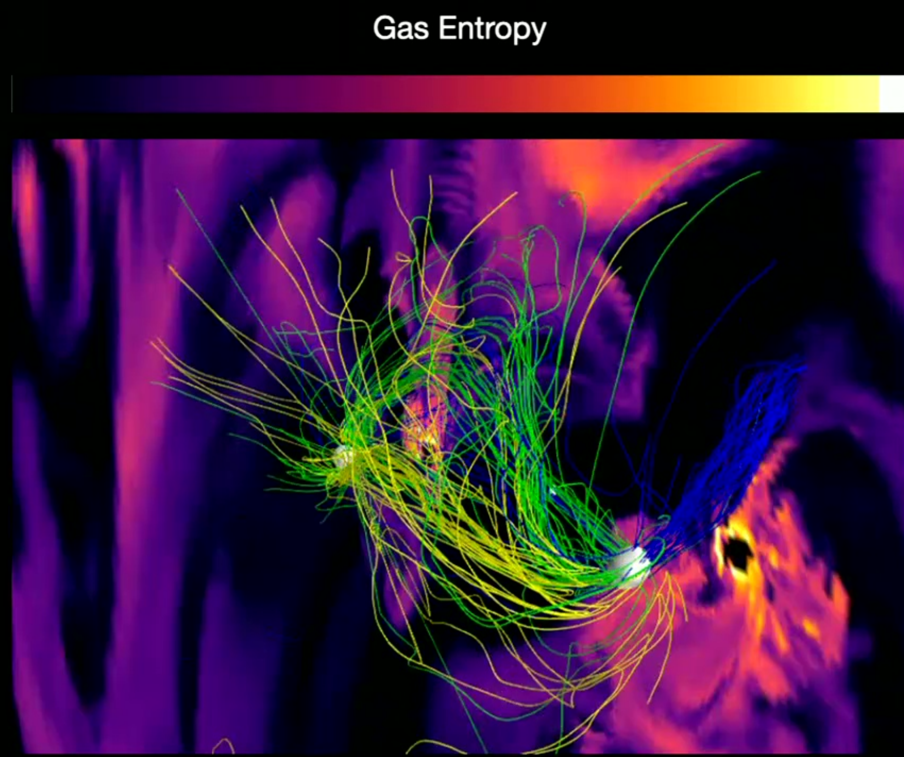




“Coronal Mass Ejections”

BNS and NS/NS Mergers:
Most & Philippov 2020, 2022





Field Line Legend:

Connected to BH on left

Connected to BH on right

Connected to both BHs

Quantifying EM Signature

$$L \sim \frac{b^2}{4\pi} l_{\rm rec}^2 \beta_{\rm rec} c$$

$$l_{\rm rec} \sim 20 r_{\rm g} \qquad \beta_{\rm rec} \approx 0.1c$$

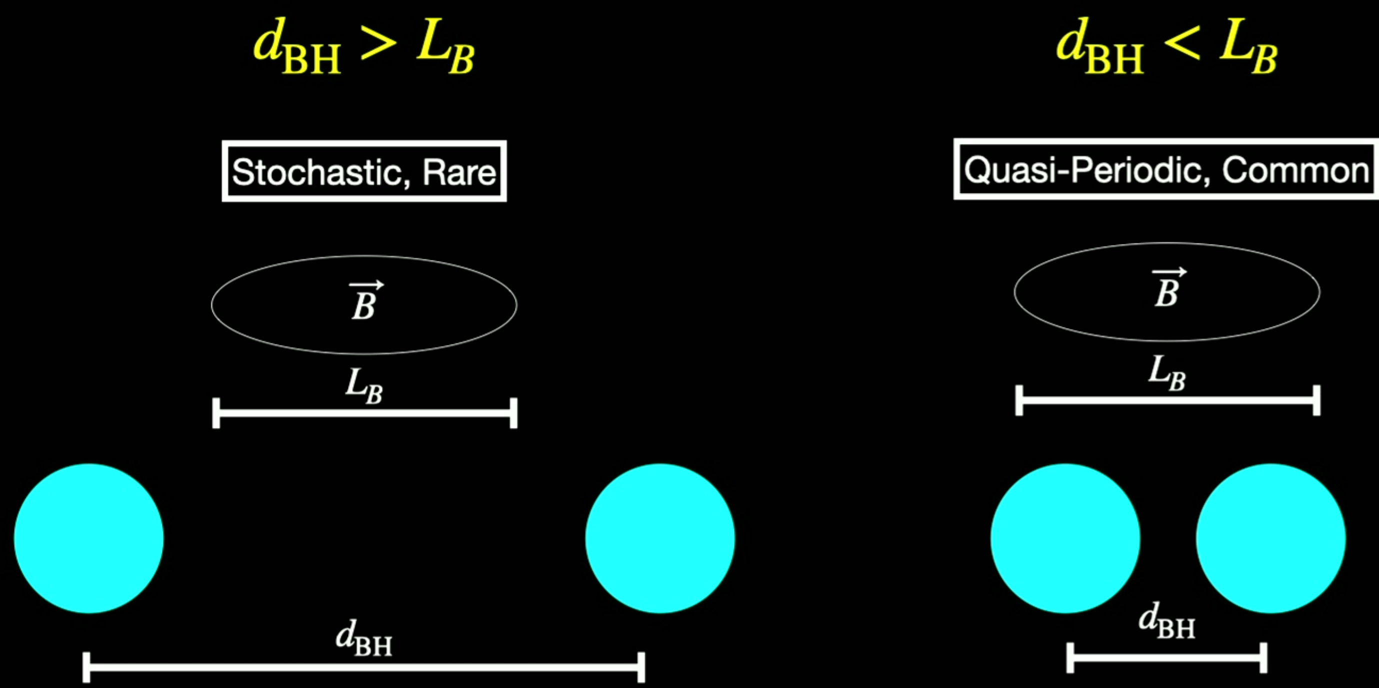
$$\frac{(L_{\rm rec})_{\rm bridge}}{L_{\rm thermal}} \approx 0.08 \left(\frac{u_{b,{\rm rec}} r_{\rm g}^2}{|\dot{M}|c} \cdot \frac{1}{0.075} \right)_{r=r_{\rm H}} \left(\frac{r_{\rm H}}{0.67 r_{\rm g}} \right)^2 \left[\frac{\log\,(l_{\rm rec}/r_{\rm H})}{2.7} \right]$$

$$(L_{\rm rec})_{\rm bridge} \approx 10^{43}\,\frac{\rm erg}{\rm s} \left(\frac{u_{b,{\rm rec}} r_{\rm g}^2}{|\dot{M}|c} \cdot \frac{1}{0.075} \right)_{r=r_{\rm H}} \left(\frac{r_{\rm H}}{0.67 r_{\rm g}} \right)^2 \left[\frac{\log\,(l_{\rm rec}/r_{\rm H})}{2.7} \right] f_{\rm Edd} \left(\frac{M}{10^6 M_\odot} \right) \left(\frac{\eta_{\rm rad}}{0.1} \right)^{-1}$$

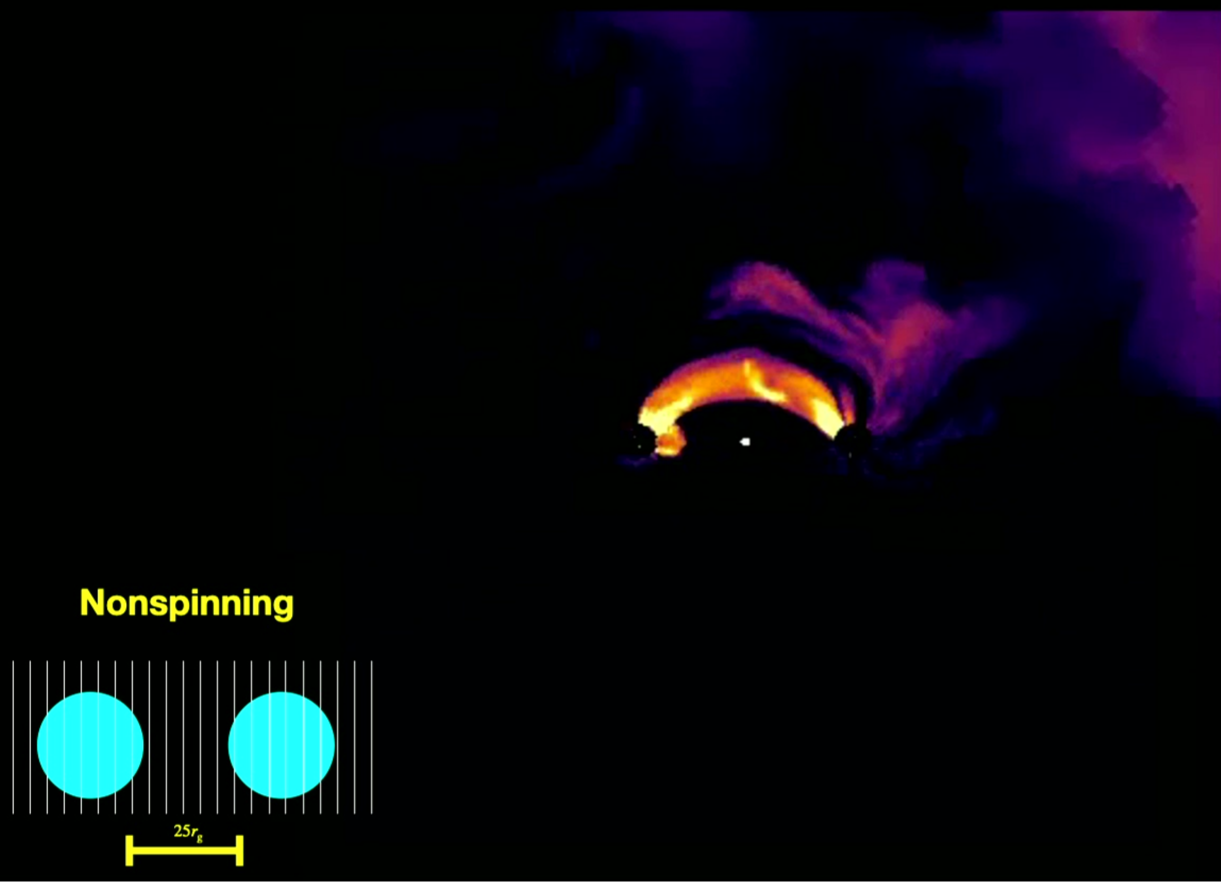
$$\nu \sim \Gamma^2 \omega_B \sim \left(\frac{b^2}{\rho_{\rm e} c^2} \right)^2 \left(\frac{eB}{m_{\rm e} c} \right)$$

$$\nu \approx (\nu_{\rm synch})_{\rm bridge} \approx 3 \times 10^{20}\,{\rm Hz} \left(\frac{\sigma_{\rm bridge}}{4} \right)^2 \left(\frac{u_{b,{\rm rec}} r_{\rm g}^2}{|\dot{M}|c} \cdot \frac{1}{0.075} \right)^{1/2} f_{\rm Edd}^{1/2} \left(\frac{M}{10^6 M_\odot} \right)^{-1/2} \left(\frac{\eta_{\rm rad}}{0.1} \right)^{-1/2}$$

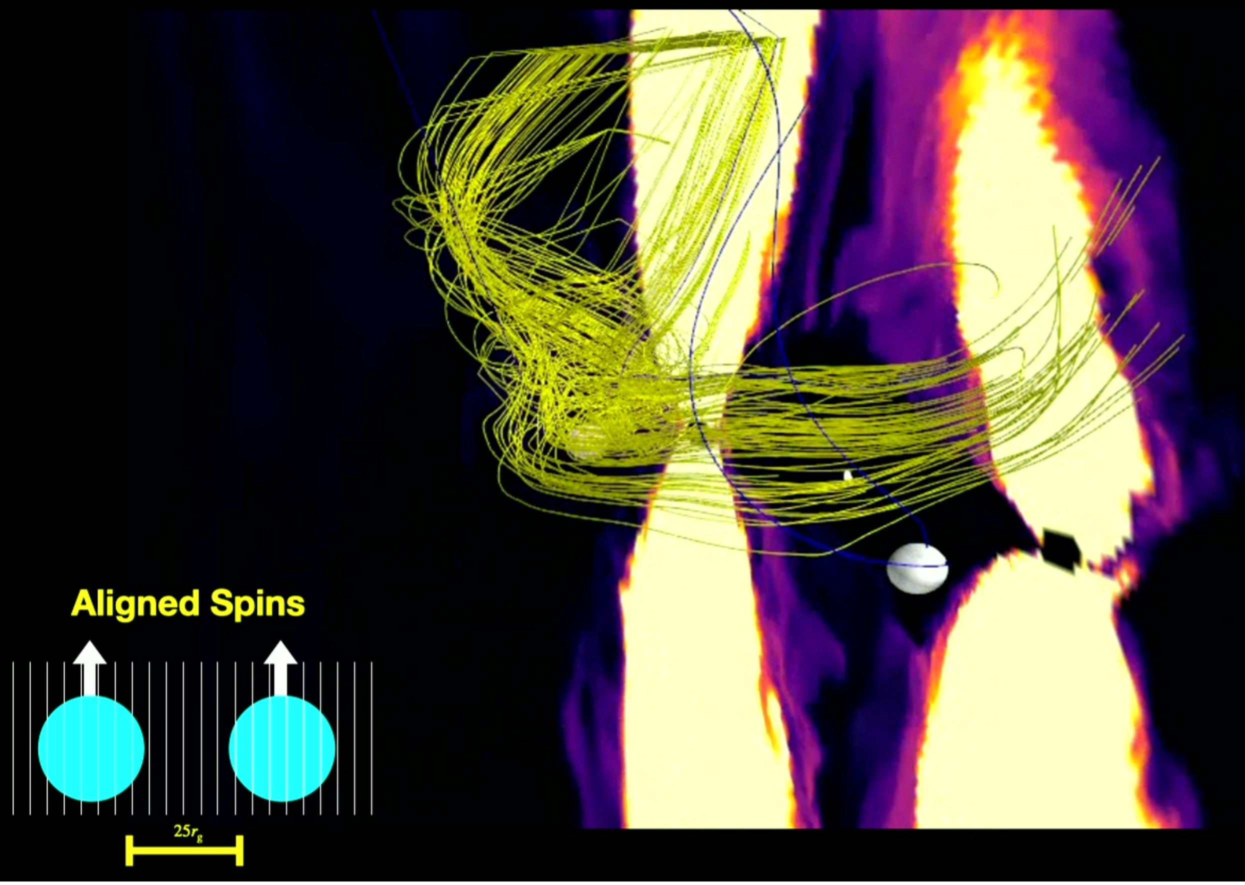
How Often Do Flares Happen?



Frequent Flares Approaching Merger?

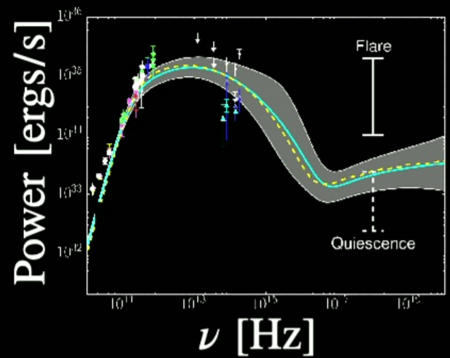


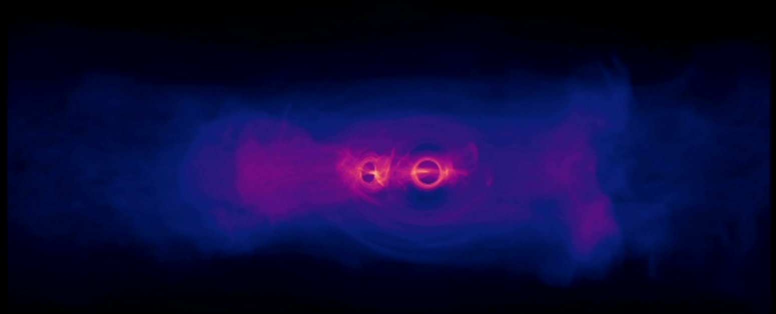
Flares Don't Happen When Jets Are Present



Next Steps

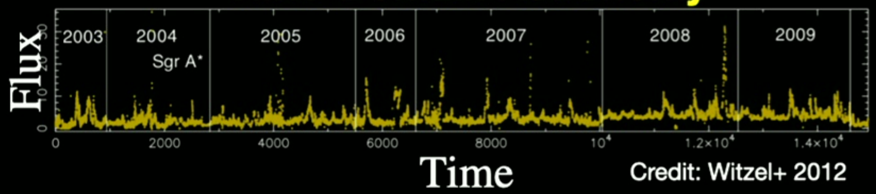
Unique Spectral Features





Credit: NASA Goddard, Scott Noble, d'Ascoli et al. 2018

Time-Domain Astronomy



Credit: Witzel+ 2012

Summary