Radiation from Supermassive Black Hole Binaries Approaching Merger

Eduardo M. Gutiérrez

(IGC Postdoctoral Fellow,

Penn State Univ.)

PennState

Institute for Gravitation and the Cosmos
Department of Physics

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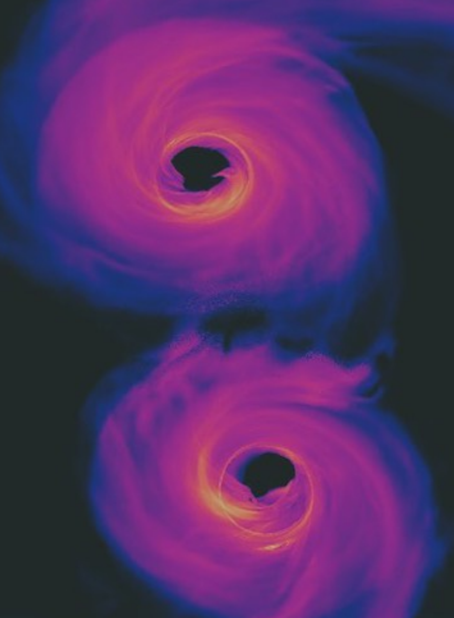
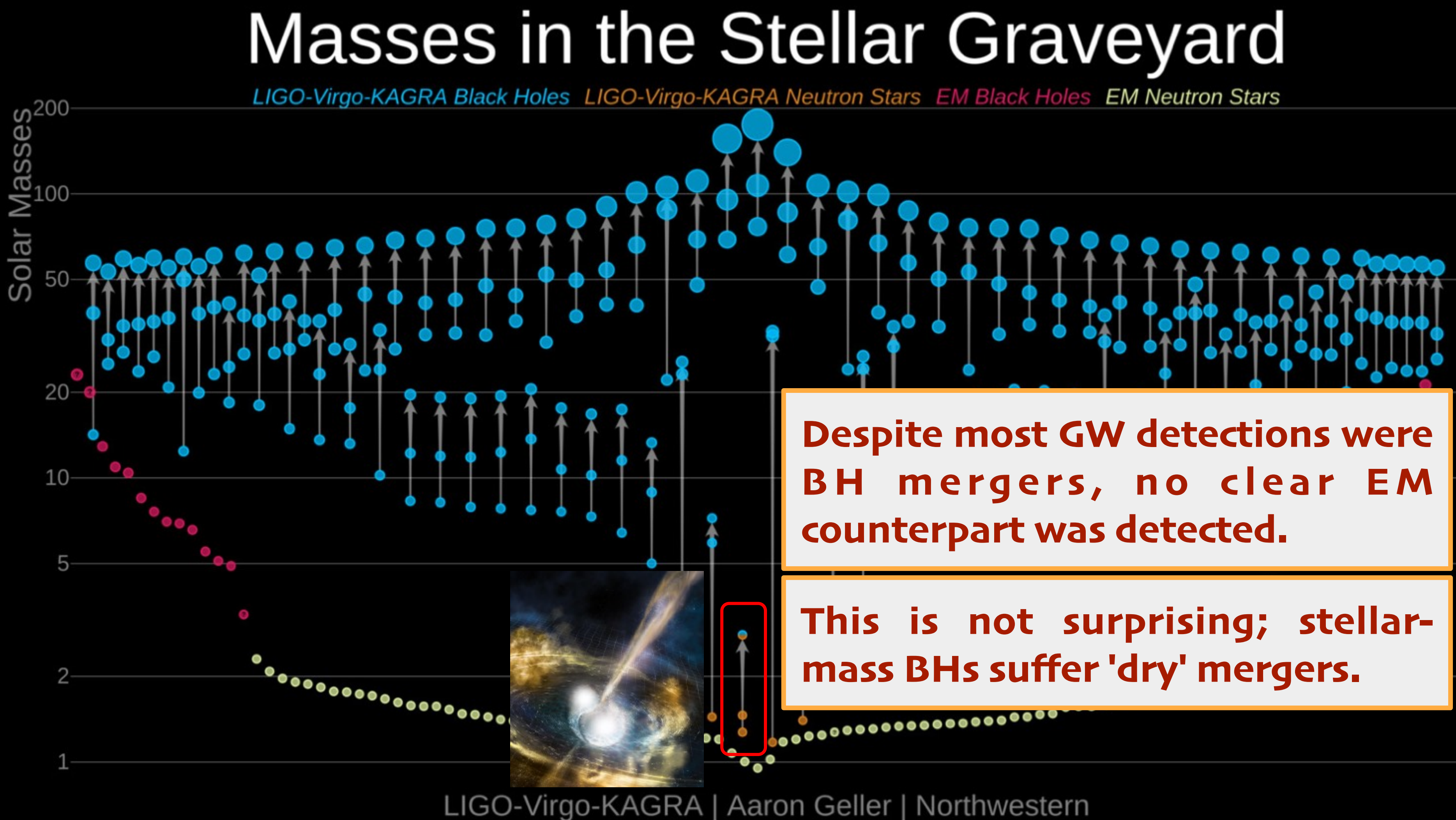


Coll: L. Combi (PI, UoG, CITA), S. Noble (NASA/GSFC), M. Campanelli (RIT), J. Krolik (John Hopkins Univ.), G. Romero (IAR), F. García (IAR), K. Porter (RIT), J. Pelle (FAMAF)

Credit Image: NASA's GSFC, Scott Noble; simulation data, d'Ascoli et al. 2018



Despite most GW detections were BH mergers, no clear EM counterpart was detected.

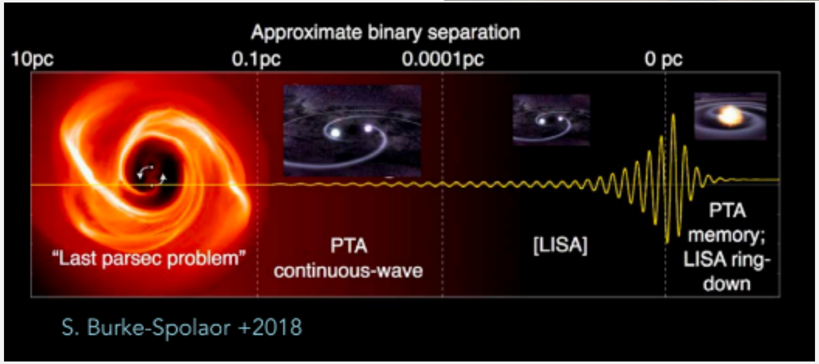
This is not surprising; stellar-mass BHs suffer 'dry' mergers.

And what about binary systems of Supermassive Black Holes?

How do supermassive black hole binaries form and evolve?

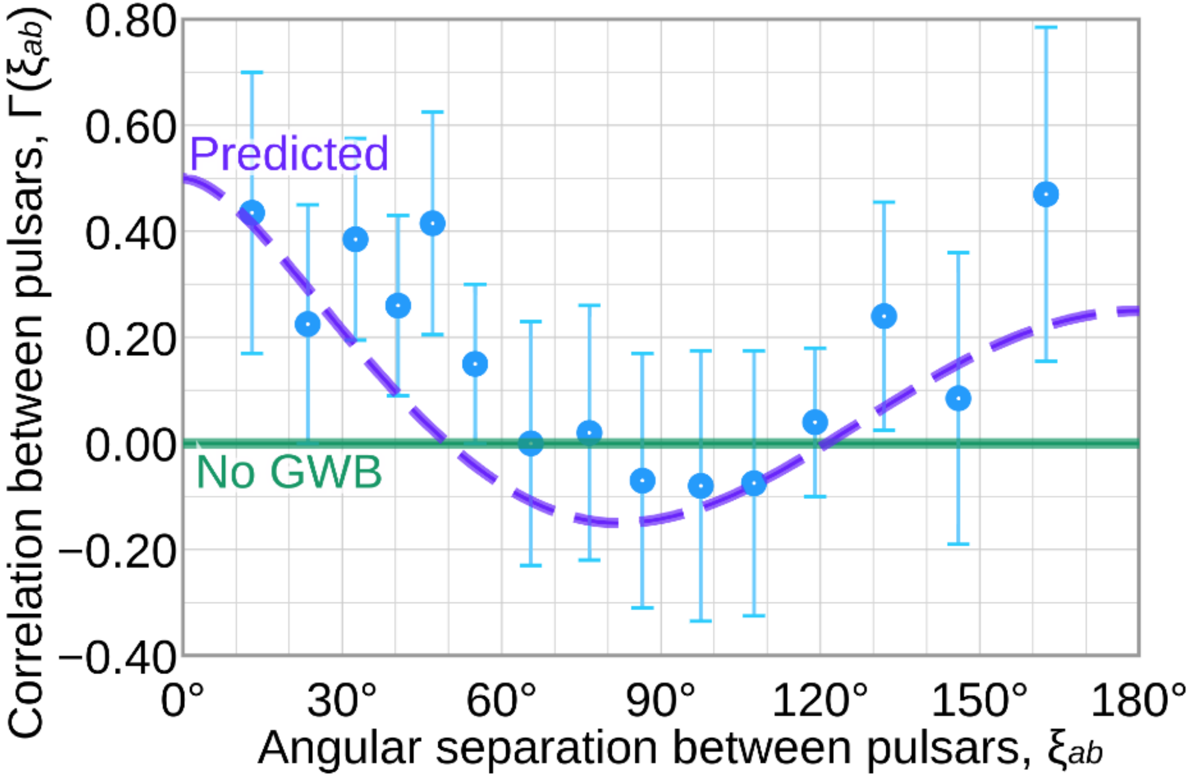
kpc	Galaxy Mergers. Relaxation
pc	Lose angular momentum
sub-pc	Inspiralling (GW emission)
r_g	BH merger

The study of SMBBHs is fundamental to understand the formation and accretion history of SMBHs across cosmic ages.



Adapted from L. Combi's slides

The NANOGrav 15 yr Data Set: Evidence for a Gravitational-wave Background



Hellings–Downs curve

Consistent with astrophysical expectations for a signal from a population of supermassive black hole binaries!

NANOGrav coll. (2023)

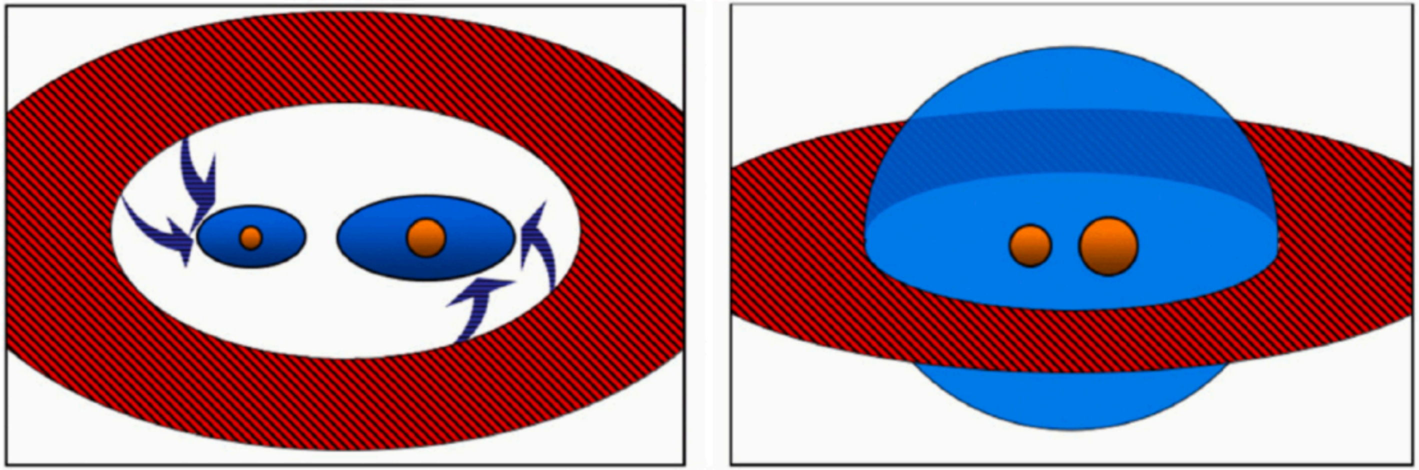
Contrary to stellar-mass BH binaries, supermassive black hole binaries would be located in **gas-rich environments**

$$L \sim \dot{M}_B \propto M_{BH}^2$$

EM emission?

Accretion structure may be quite different from what we know of single BH accretion disks

$a_{cav} \sim 2r_{12}$



THE PROBLEM: Identifying SMBHBs before/during/after merger -> theoretical and observational problem

- How is the accretion system? How much matter falls into the cavity and forms a disk?

- How much matter is close to the black holes at the merger? When does the decoupling occur? -> EM bright merger?

- Do SMBHBs produce dual Jets? EM signatures associated?

- Post-merger -> Kicks? Reborn accretion disk and rebrighting?

- Other messengers? Neutrinos or CRs?

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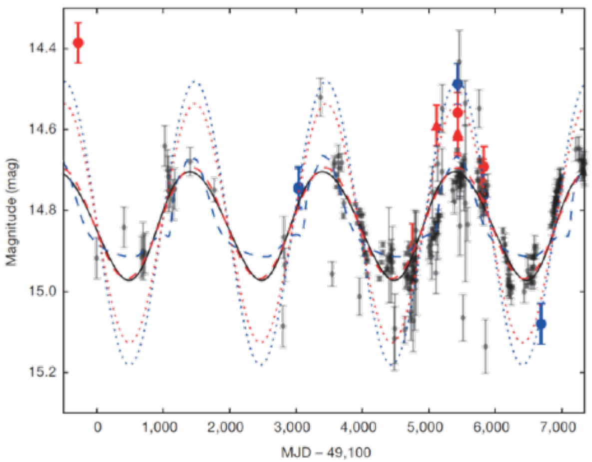
Adapted from S. Noble's slides

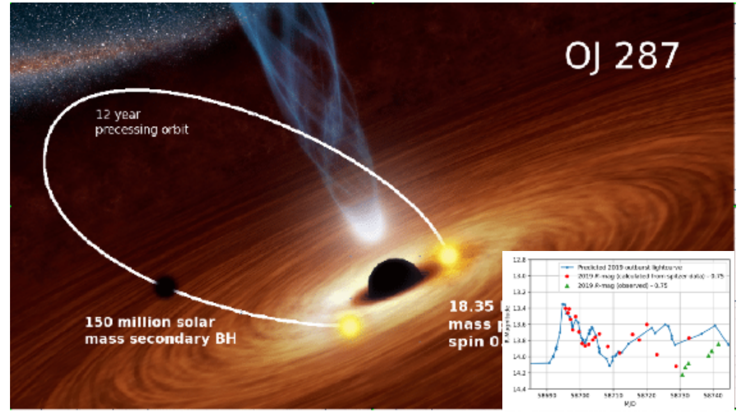
Proposed EM signatures:

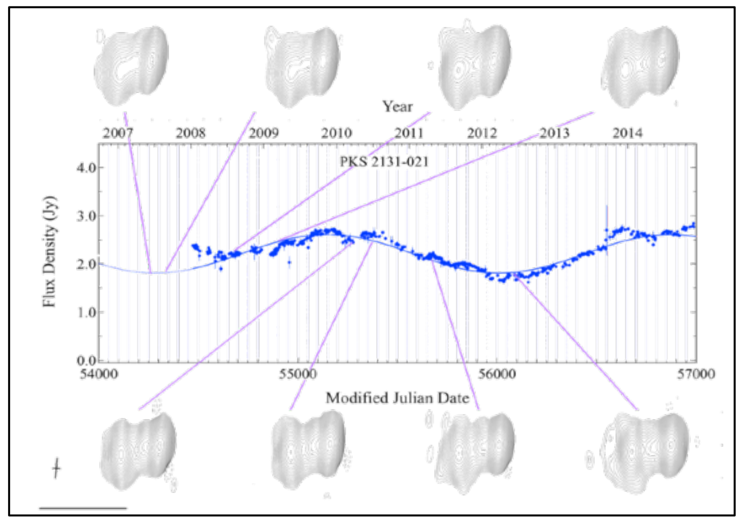
PG 1302-102

(Graham+ 2015, D'Orazio+ 2015, Jun+2015)



Not confirmed. It could be statistical red-noise. Need many cycles.

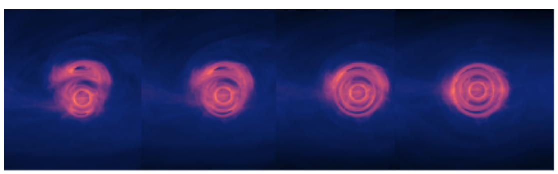


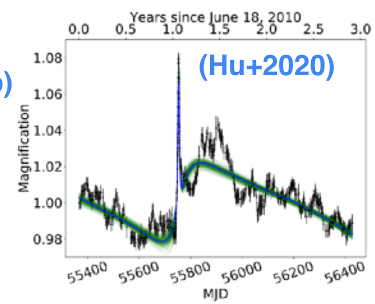


PKS 2131−021

(O'Neill+ 2021)

Self-lensing? (D'Orazio+ 2017, Ingram+ 2021, Davelaar+ 2022, Gutierrez+ in prep)

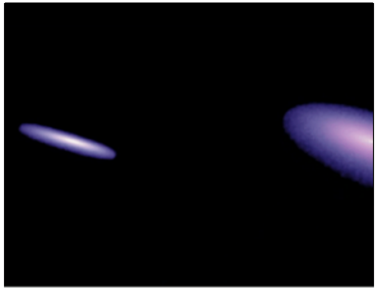




Simulating SMBHB is a multi-scale and highly non-linear problem

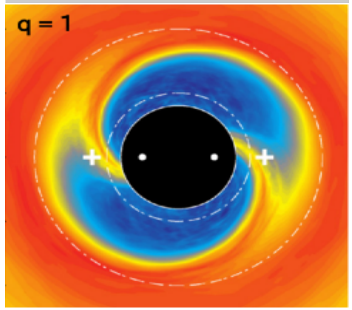
Different numerical strategies and techniques are applied!

Matter + Gravity



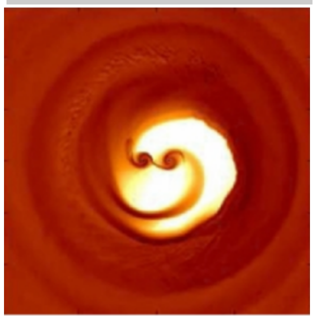
Hopkins, Hernquist,
Di Matteo, Springel++

MHD + Newtonian



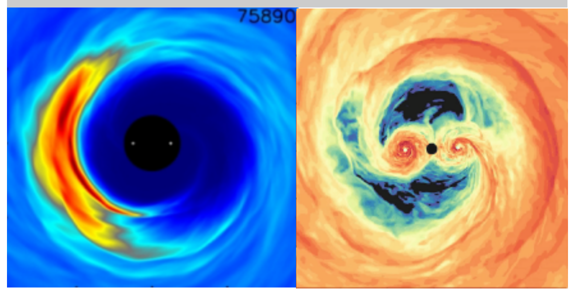
Shi & Krolik
(2014-2016)

Viscous Hydro. + Newtonian



Farris++2014, d'Orazio++2015-, Munoz, Miranda, Lai (2017-2019), Moody++(2019), Tang++(2017-2019)

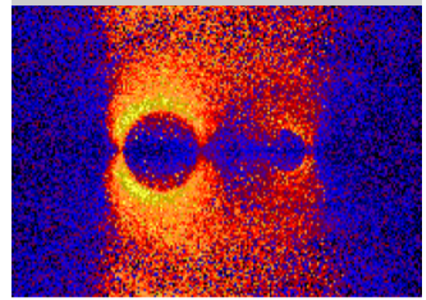
GR-MHD + Post-Newtonian



Noble++2012-
López Armengol++
2021

Bowen++2018
Combi++ 2022,
Avara++ 2023

GR-MHD + Numerical Relativity

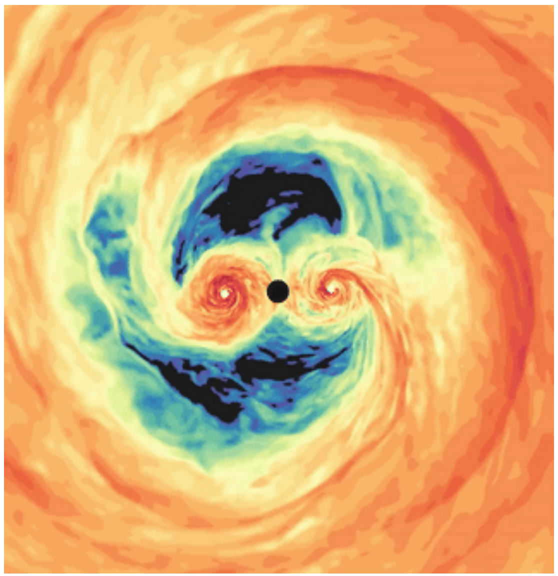


Kelly++2017
Gold++2014,
Paschalidis++2021

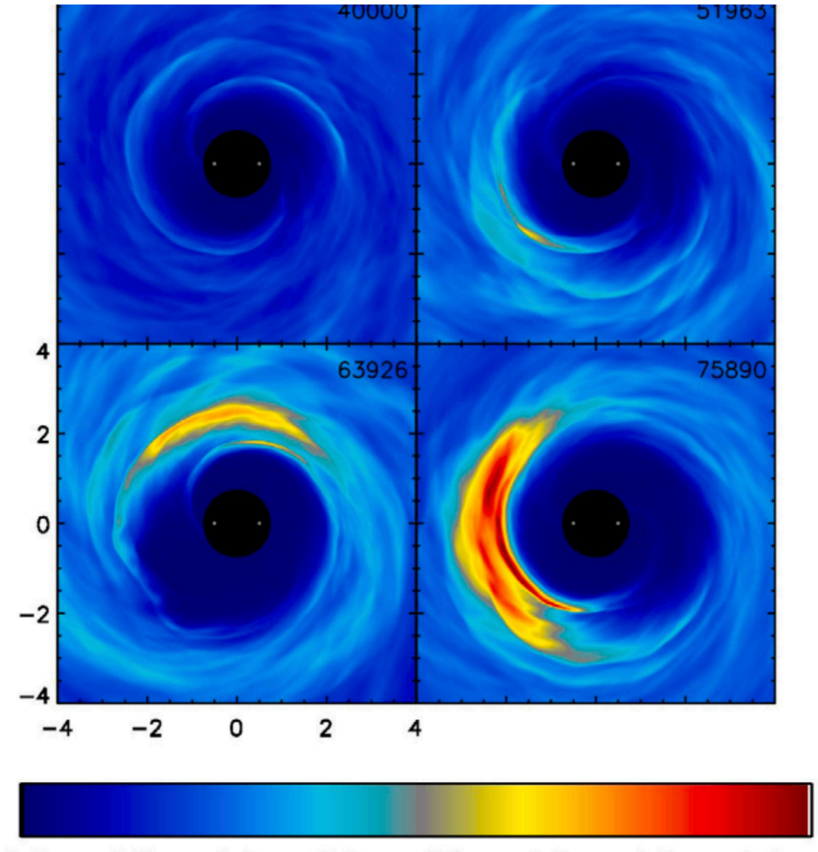
Adapted from S. Noble's slides

GRMHD simulations of SMBBHs approaching merger

- For cold disks and q ~ 1, the accretion system has an overdensit at the inner cavity, called the **‘lump’**
- Formation of minidisks

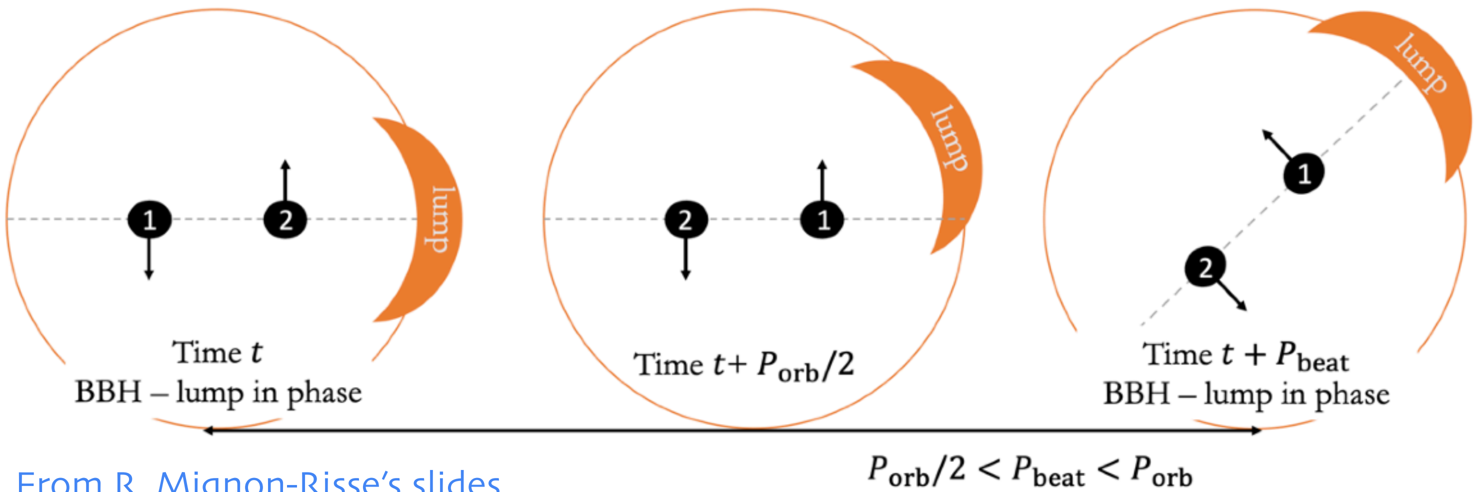


(Bowen+ 2018, 2019, Combi+ 2022)



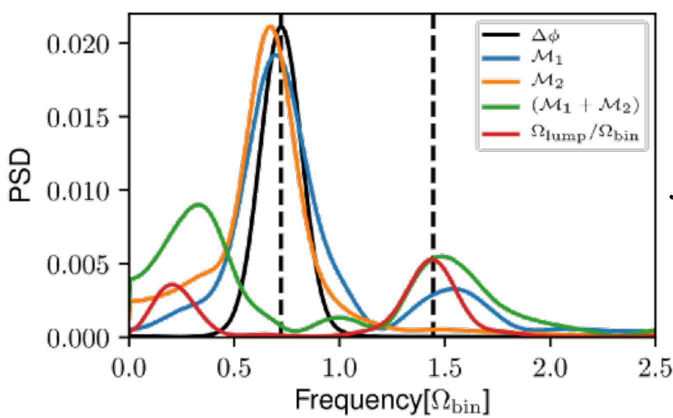
(Noble+2012, Noble+2021, López-Armengol+ 2021)

Modulated accretion onto cavity at the **beat frequency** between the lump and the disks



From R. Mignon-Risse's slides

Consistently found in several simulations (hydro 2D -> 3DGRMHD)



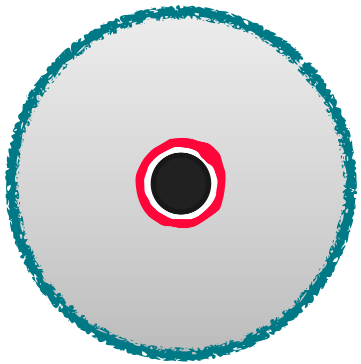
$$f_{\mathrm{lump}} \sim 0.28 f_{\mathrm{bin}}$$

$$f_{\mathrm{beat}} \sim f_{\mathrm{bin}} - f_{\mathrm{lump}} \sim 0.72 f_{\mathrm{bin}}$$

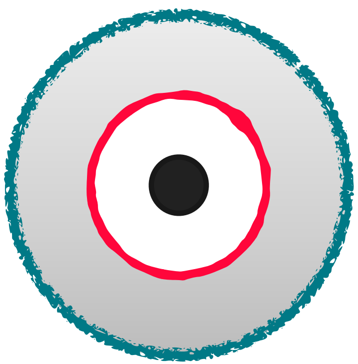
(Bowen+ 2019)

How massive are minidisks?

- **Interplay between ISCO and Hill Sphere**



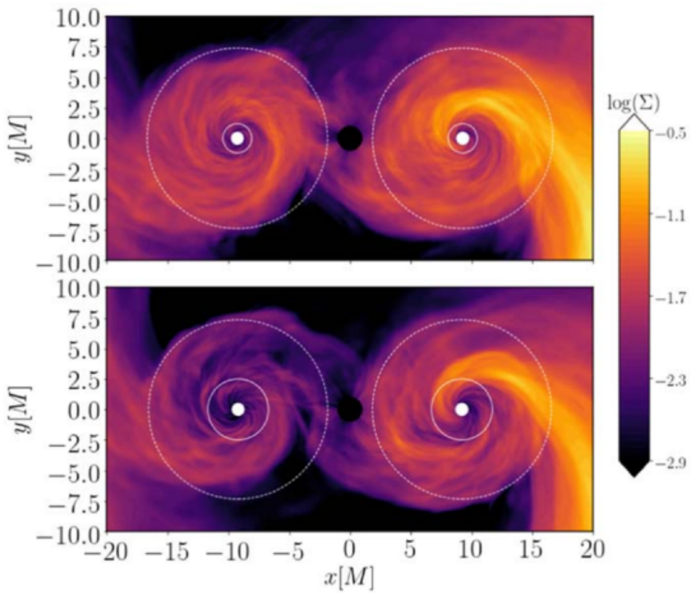
High spin

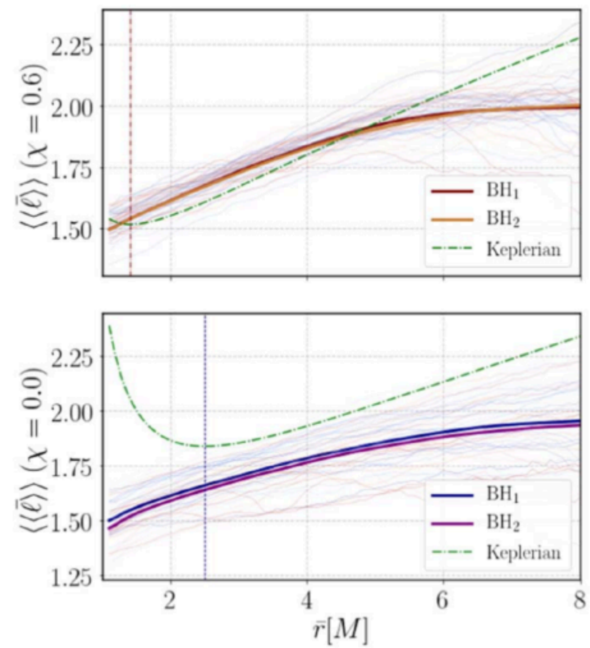


Low spin

- Hill sphere increases with separation
- ISCO decreases with spin

$$r_{\rm tr} \sim 0.35 r_{12}(t)$$

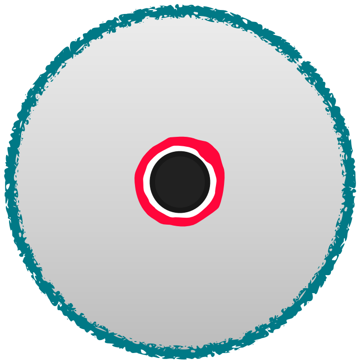




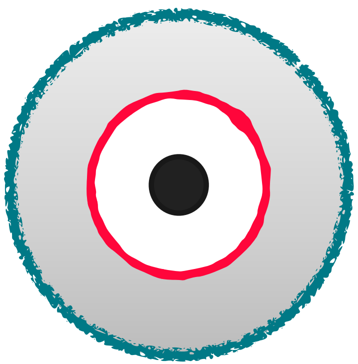
(Combi+ 2022)

How massive are minidisks?

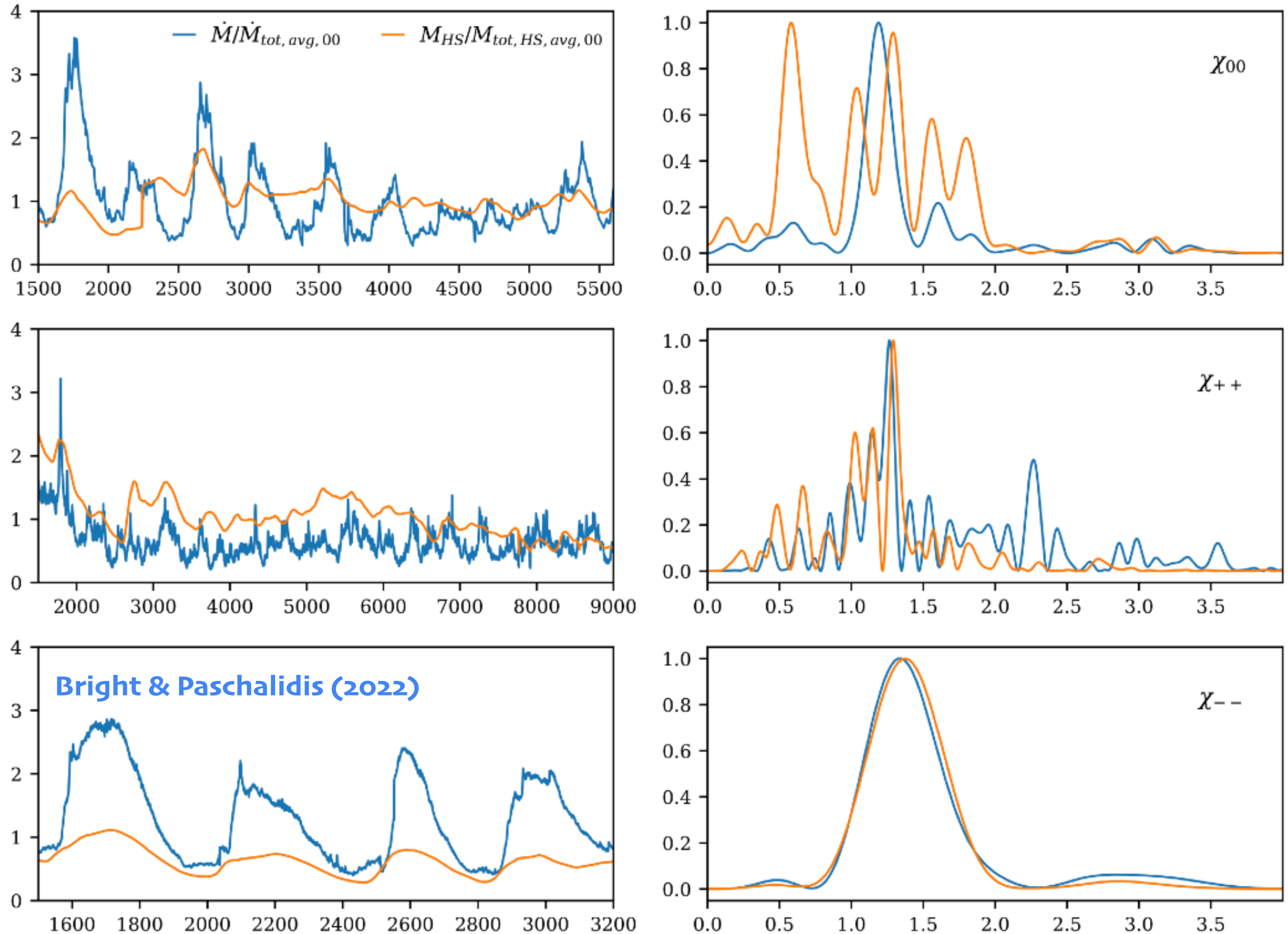
- **Interplay between ISCO and Hill Sphere**



High spin



Low spin



Calculation of EM emission

(Noble+ 2007, dAscoli+ 2018, Gutierrez+ 2022)

Camera-to-source approach

$$\frac{d^2x^\mu}{d\lambda^2} + \Gamma^\mu_{\alpha\beta}\frac{dx^\alpha}{d\lambda}\frac{dx^\beta}{d\lambda} = 0$$

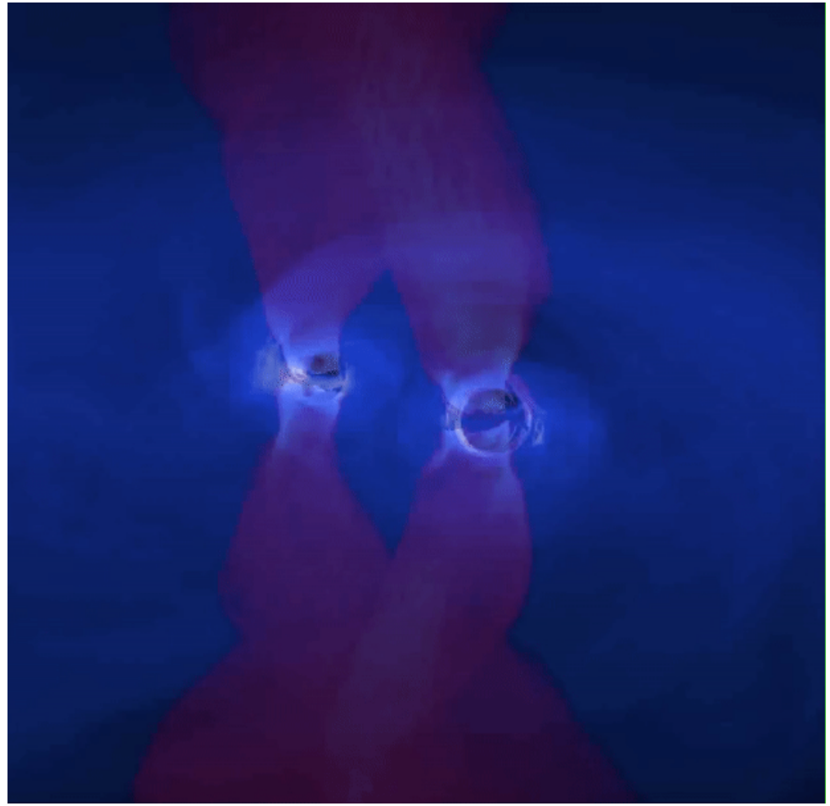
Geodesic equation

$$\frac{\partial I}{\partial \lambda} = j - \alpha I$$

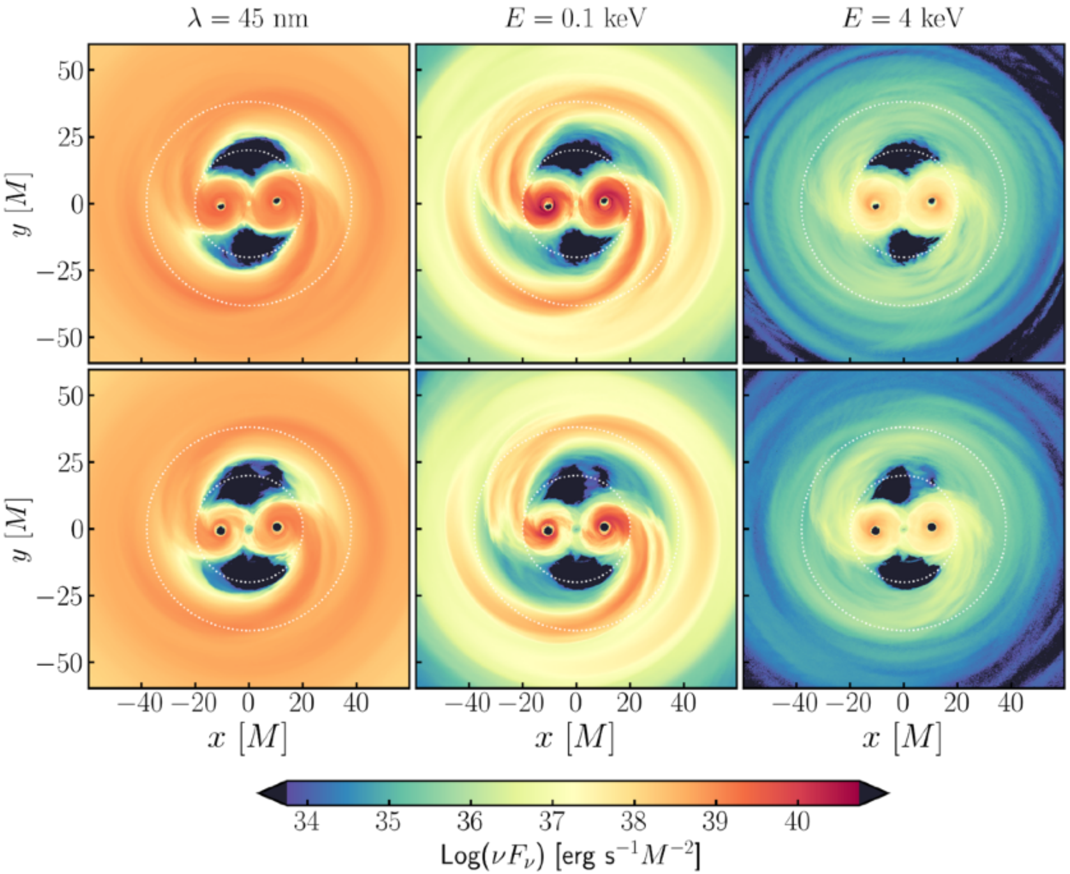
Radiative transport equation

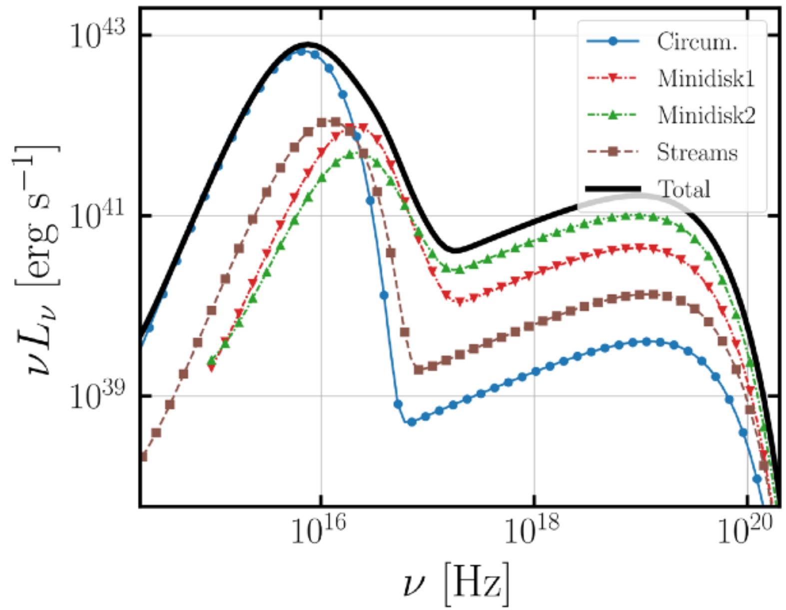
High-accretion rate systems **(Opt. thick)**

Low-accretion rate systems **(Opt. thin)**



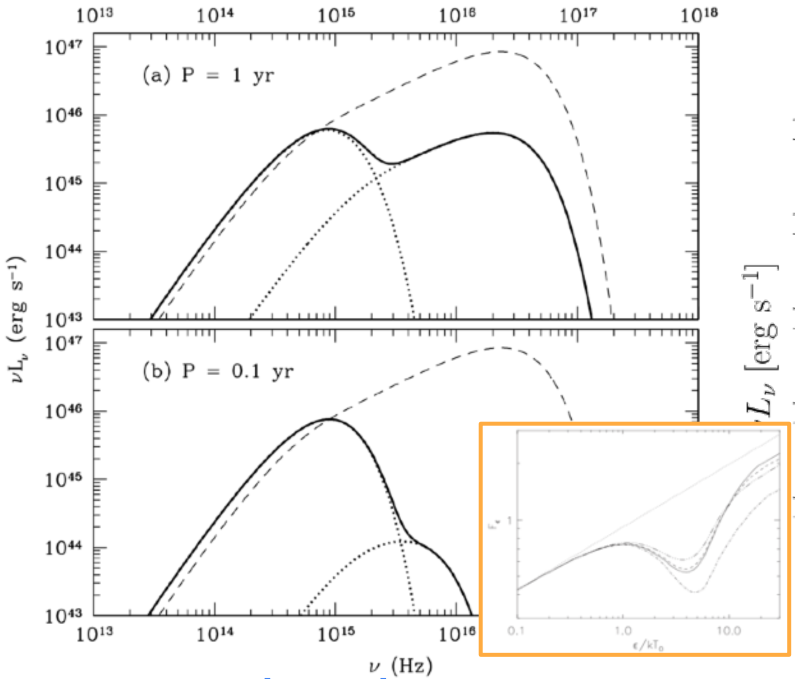
Different components dominant at different frequencies



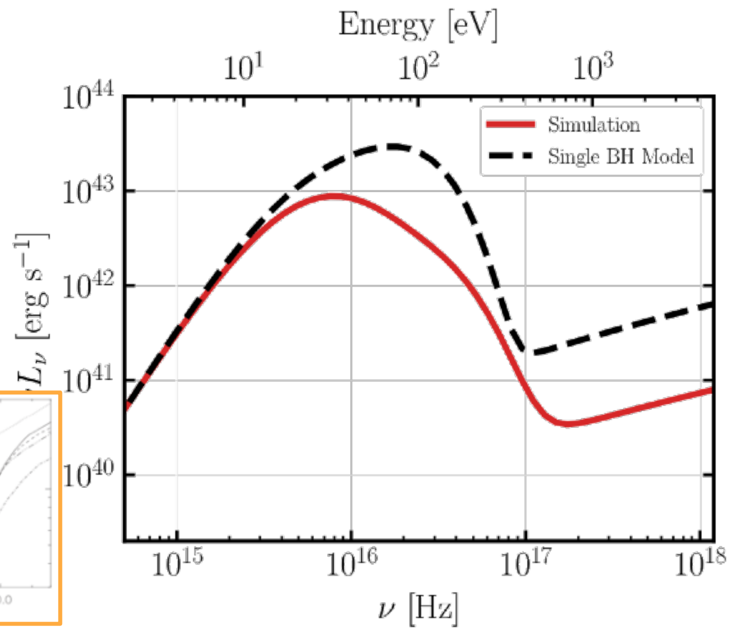


(Gutiérrez et al. 2022)

How do circumbinary disks and mini-disks compare with standard single black hole accretion disks? A `**notch**`?



Tanaka et al. (2012, ApJ)



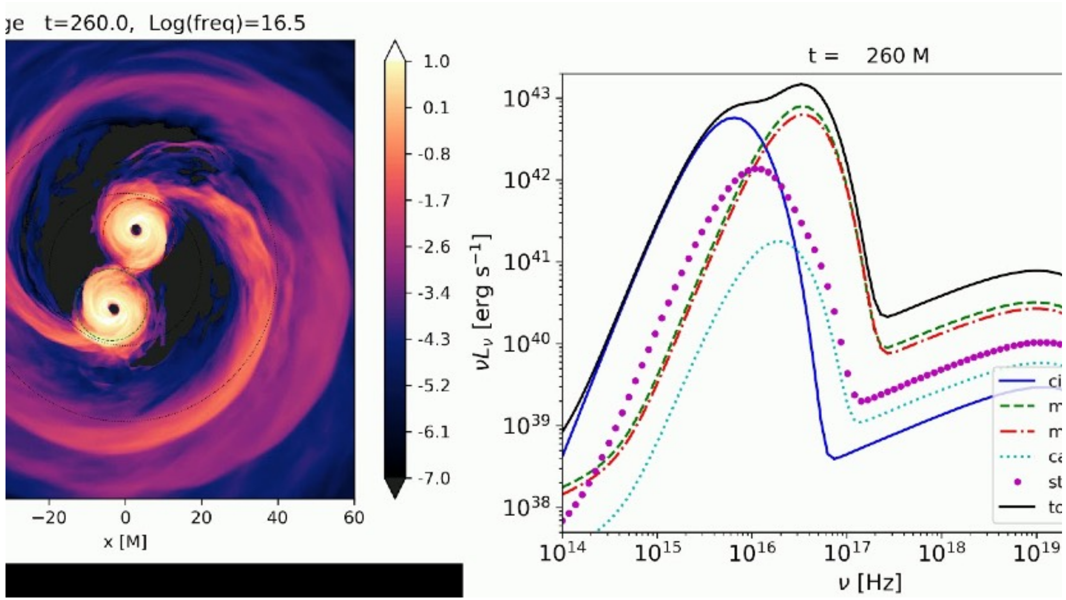
Roedig+ (201

Gutiérrez et al. (2022, ApJ)

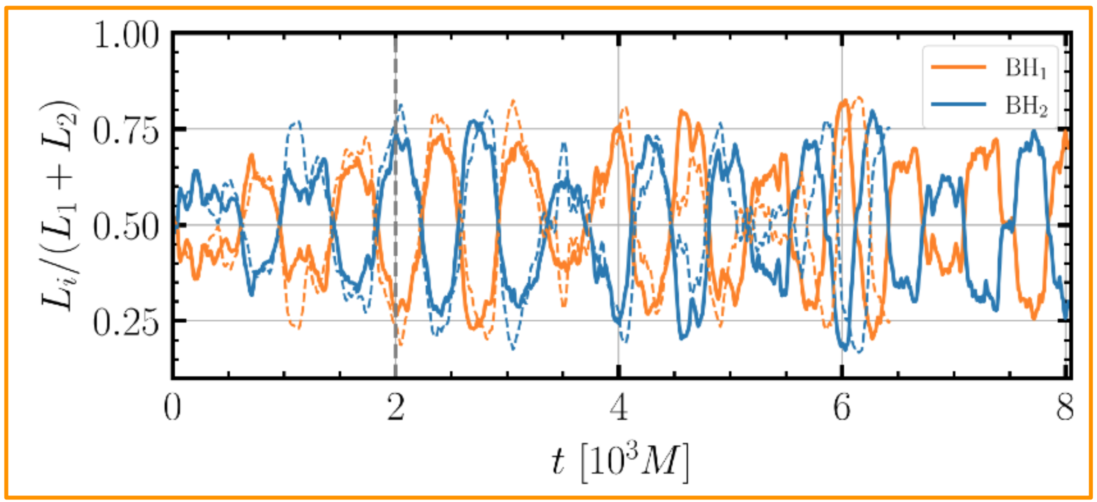
- Circumbinary disk very similar to a truncated Shakura-Sunyaev disk.
- Mini-disks are less bright due to low radiative efficiency. Most of the matter falls into the hole directly.
- 'Notch' absent due to
  - Less bright minidisks
  - Stream emission

Spinning
(a=0.6)

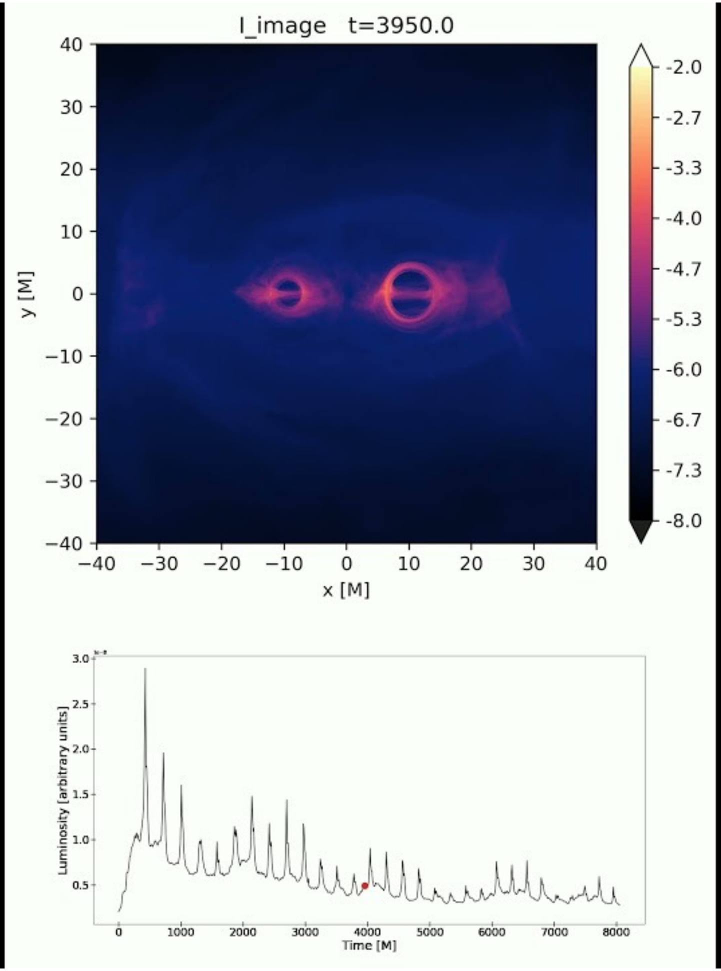
Data from
Combi+(2022)



Gutiérrez et al. (2022, ApJ)

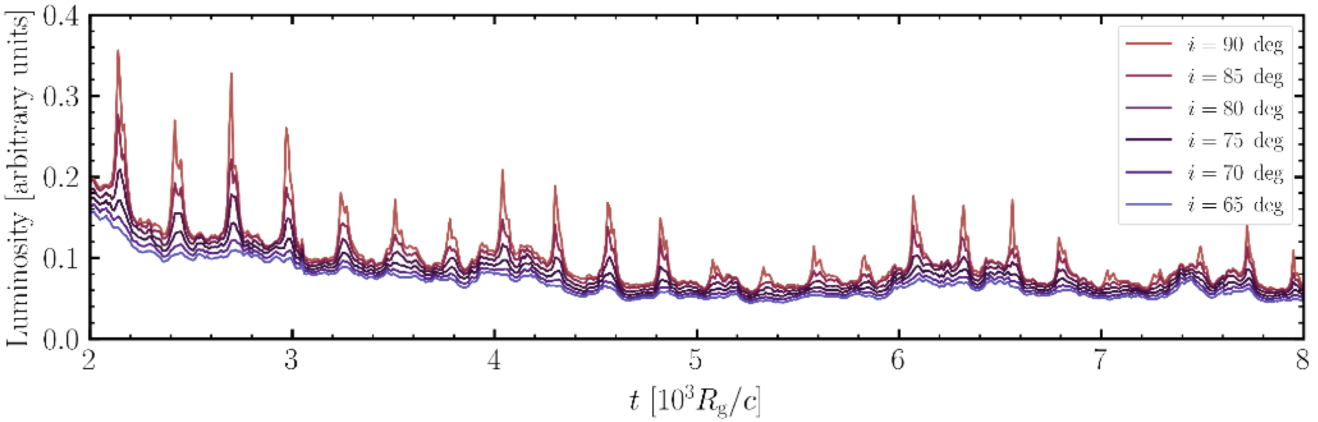


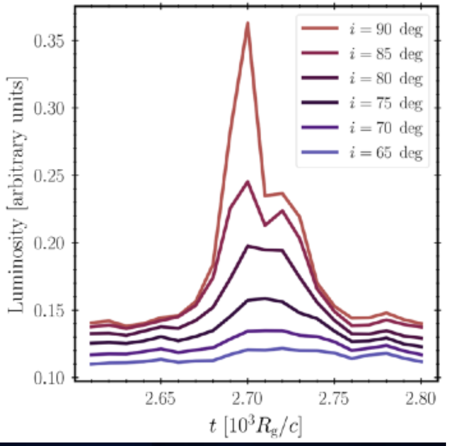
Optically thin plasma: Kinematic effects are important; Self-lensing produce strong flares!

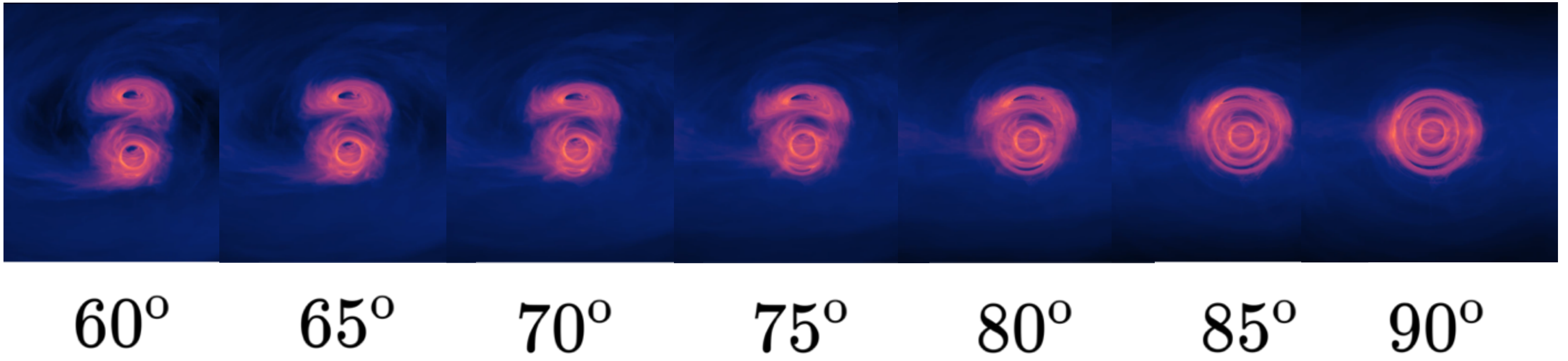


Gutiérrez et al. (2023b, in prep.)

Highly dependent on the line-of-sight inclination







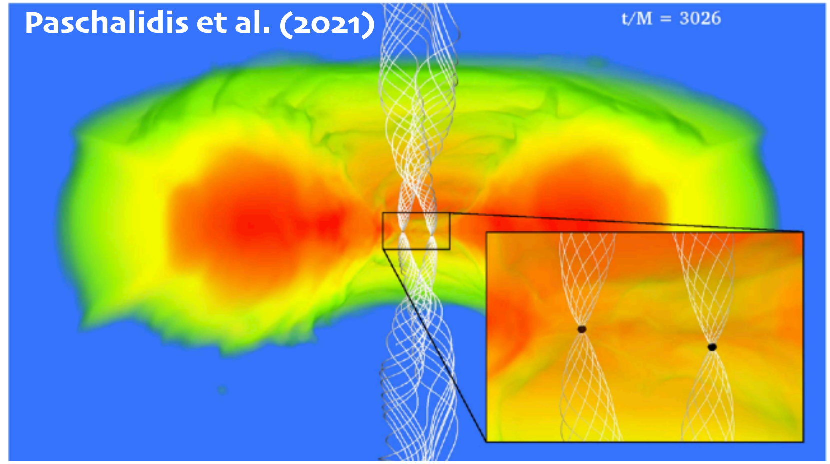
Gutiérrez et al. (2023b, in prep.)

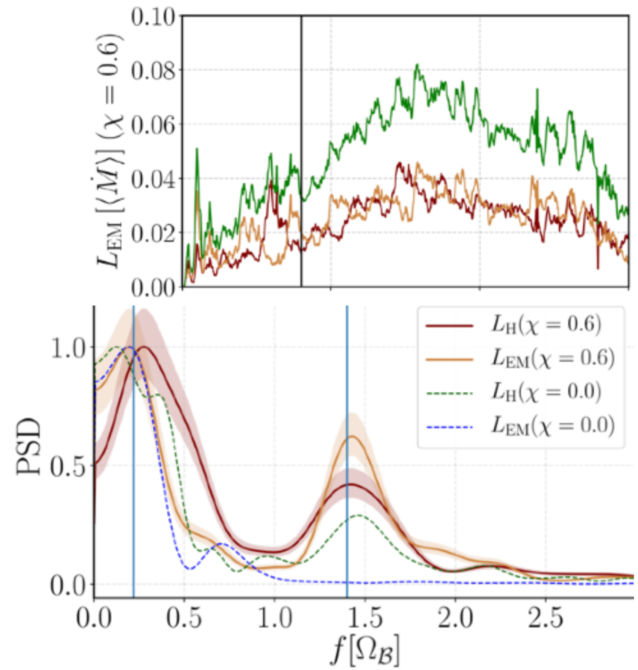
What about jets?

- Possibility of **dual** jets -> EM signatures?
- Important questions: how do they compare with single AGN jets? Are they equally bright? How do the emission change during merger? -> MM merger

- Individual jets? Unique jet?
- Simulations show a jet efficiency of ~ 10 % for spinning black holes
- Dual jet interaction?

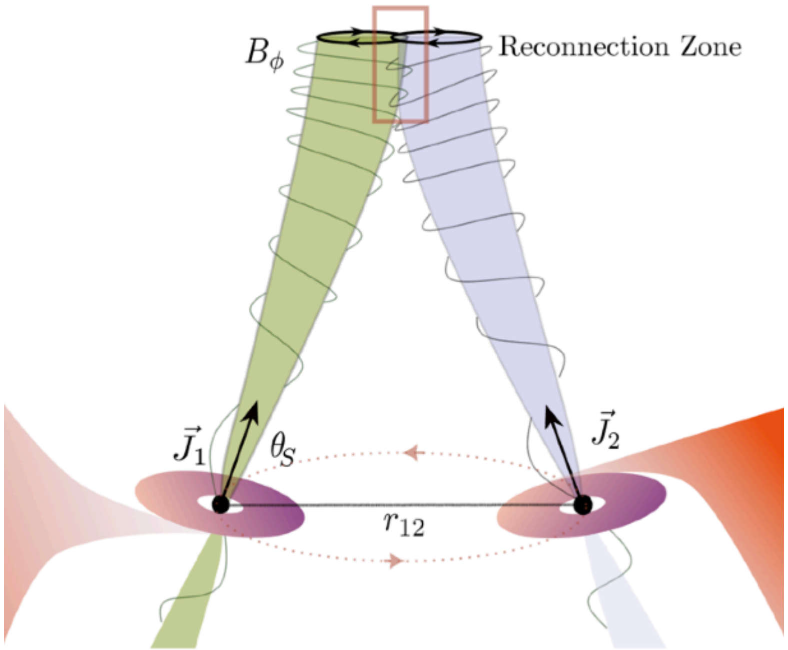
$$L_j \sim \eta_{\rm eff} \dot{M} c^2$$

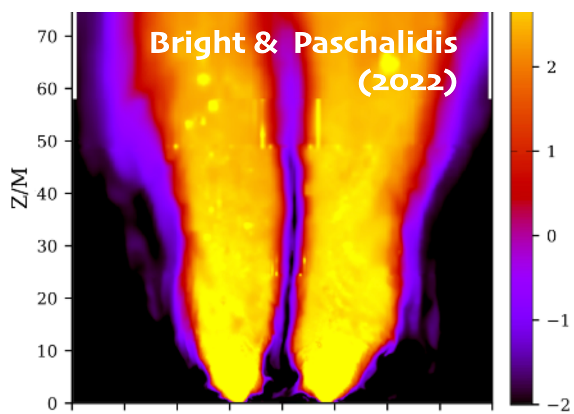


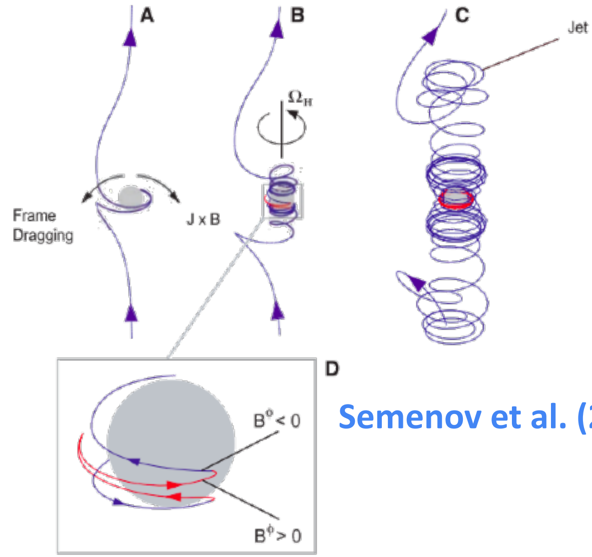


Combi et al. (2022)

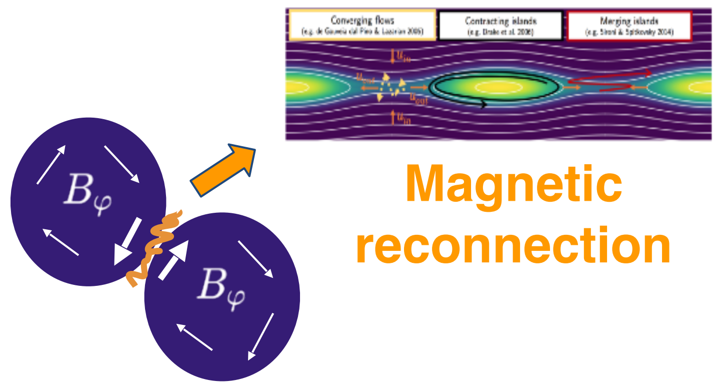
Jet-jet interaction*: non thermal radiation?*







Semenov et al. (2004)



Magnetic reconnection

Gutierrez et al. (2023, submitted)

Radiation from dual jet interaction

Dissipation at a height

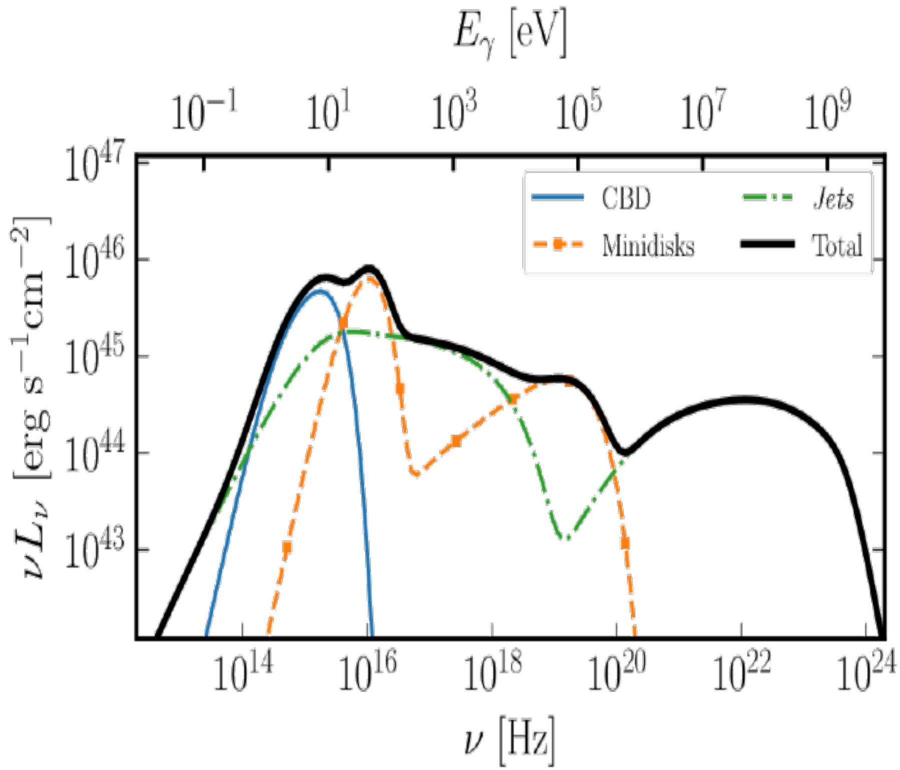
$$z_{\rm diss} \sim (r_{12}/2)/\theta$$

$$B' \approx 1.5\times10^{3}\eta_{-1}{}^{1/2}\dot{m}^{1/2}M_7^{-1/2}\left(\frac{\Gamma_{\rm j}}{3}\right)^{-1}\left(\frac{r_{12}}{30R_{\rm g}}\right)^{-1}\ {\rm G}$$

Particle acceleration

$$\frac{d}{d\gamma''}\left[\dot{\gamma}''|_{\rm loss}N''(\gamma'';\xi)\right]+\frac{N''(\gamma'';\xi)}{t'_{\rm esc}}=Q''(\gamma'';\xi),$$

$$\nu_{\rm obs}F_{\nu_{\rm obs}}(t_{\rm obs})=\left(\frac{3u(\tau'')}{\tau''}\right)\frac{\mathcal{D}_{\rm p}^4V''}{d_L^2}\nu''j''_{\nu''}(t_{\rm em})$$

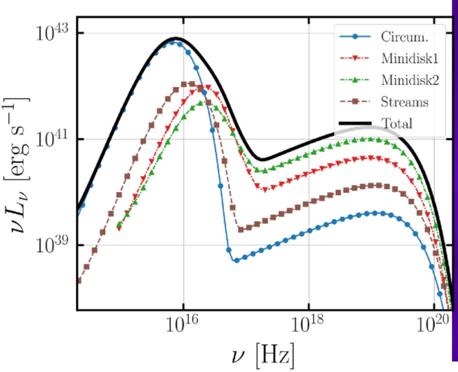


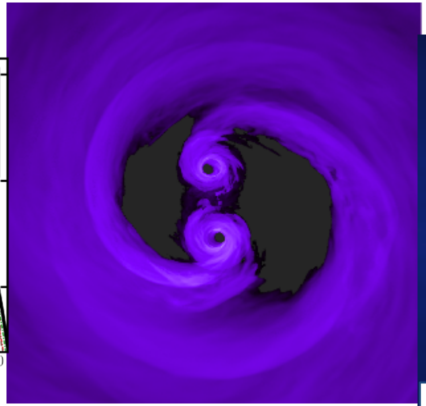
Periodicities? Flaring behavior?

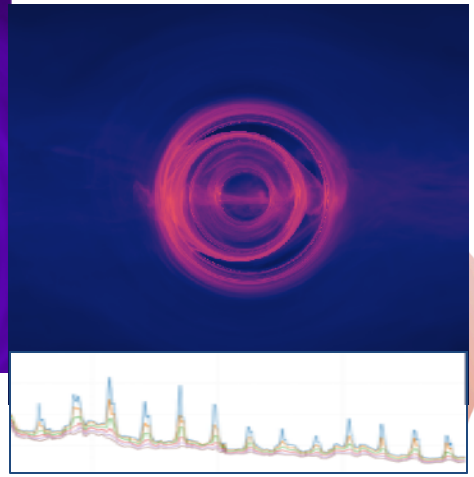
Takeaways

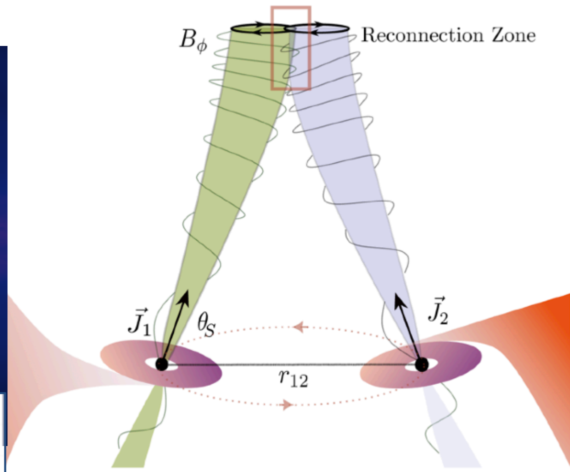
SMBH binaries are very likely **multimessenger** sources, we need **good -precise- predictions** to identify them:

- **before**, during, and after merger
- **very hard problem** (need complex and expensive simulations)
- possible signatures: periodic modulations (Doppler boosting, **variable accretion rate**, BL shifting, jet precession), **periodic flares (self-lensing, jet-jet interaction?), unique SED features?**



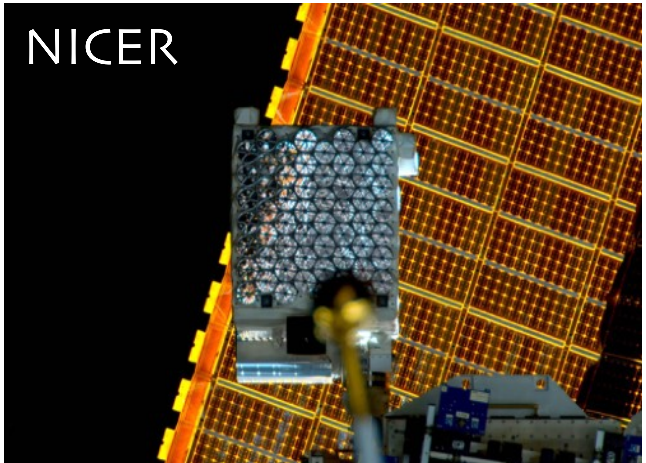


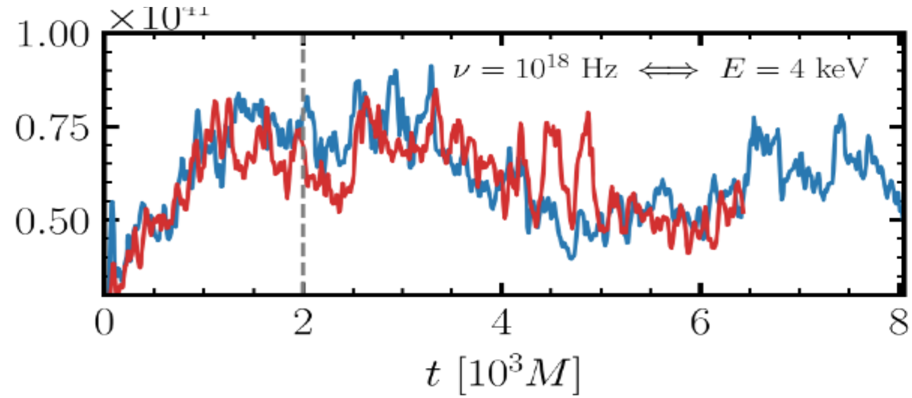


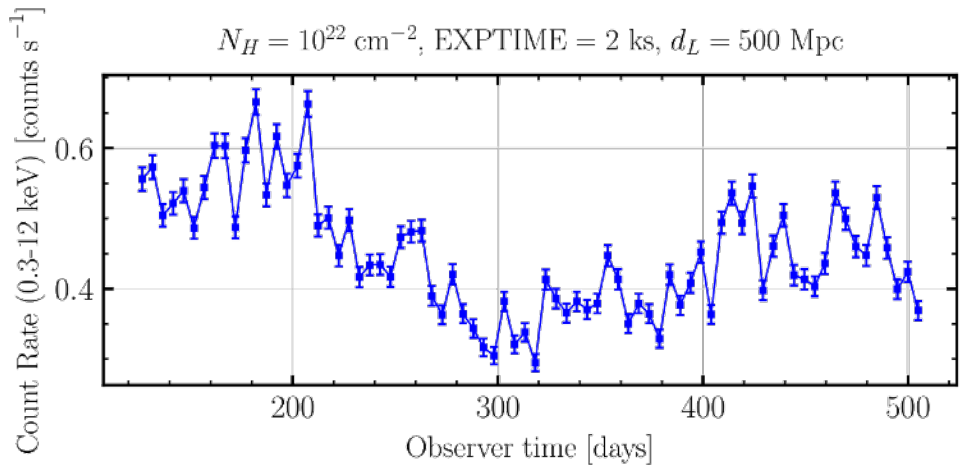


Background slides

Different observational strategies needed for different systems: masses, separations, mass ratios



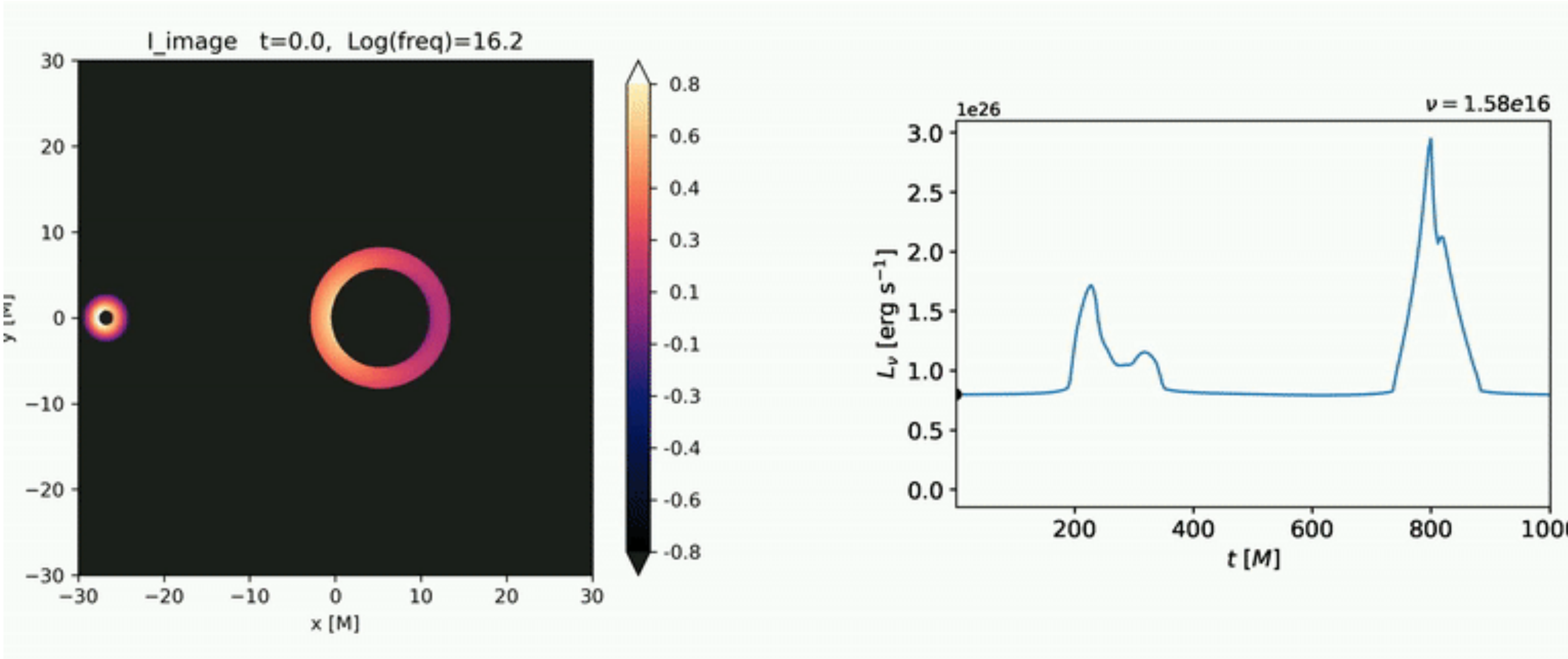




For a SMBHB of $M = 10^9 M_\odot$ short observations every ~ 5 days and catch the variabilities.

Gutiérrez et al. (2022, ApJ)

Self-lensing for q=0.1



Porter, EG,+ in prep.