# Supermassive binary black holes: accretion ⇨ electromagnetic signatures

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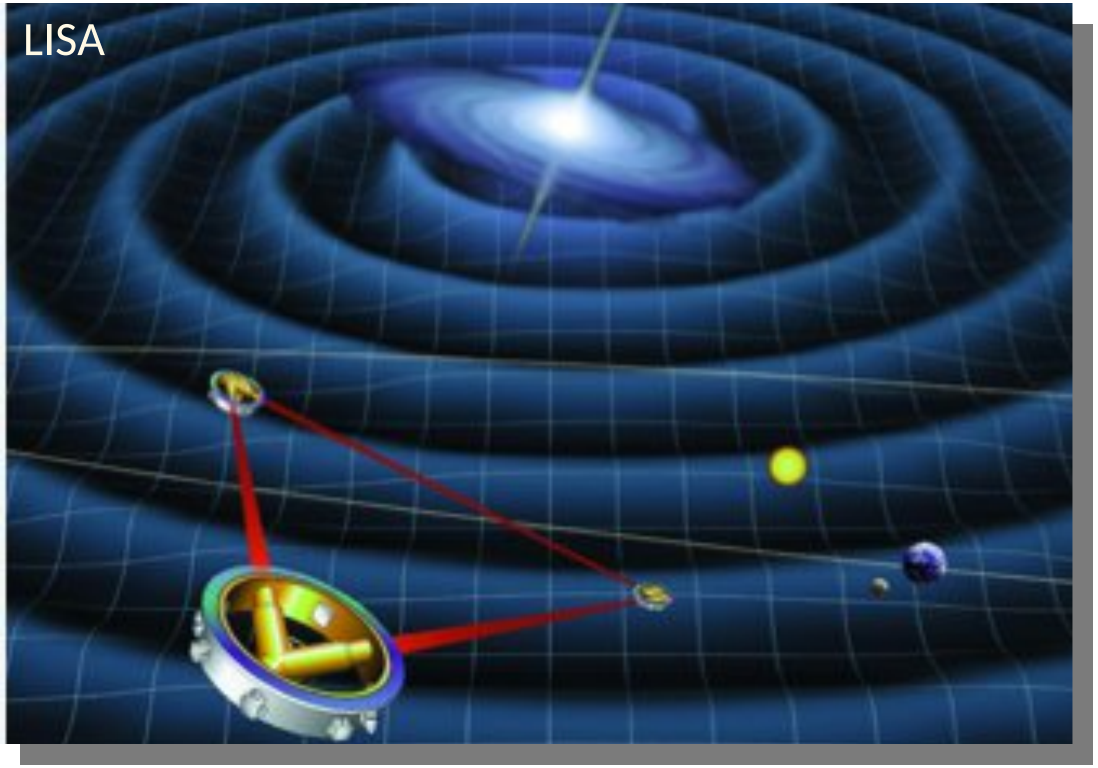
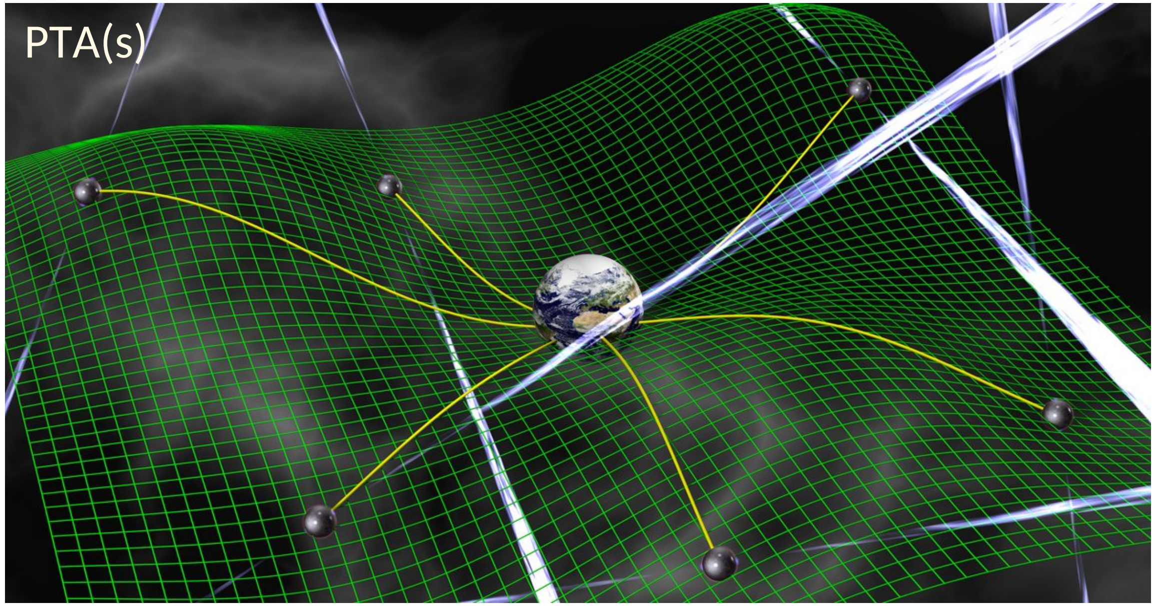
# The detection of low-frequency gravitational wave (GWs)



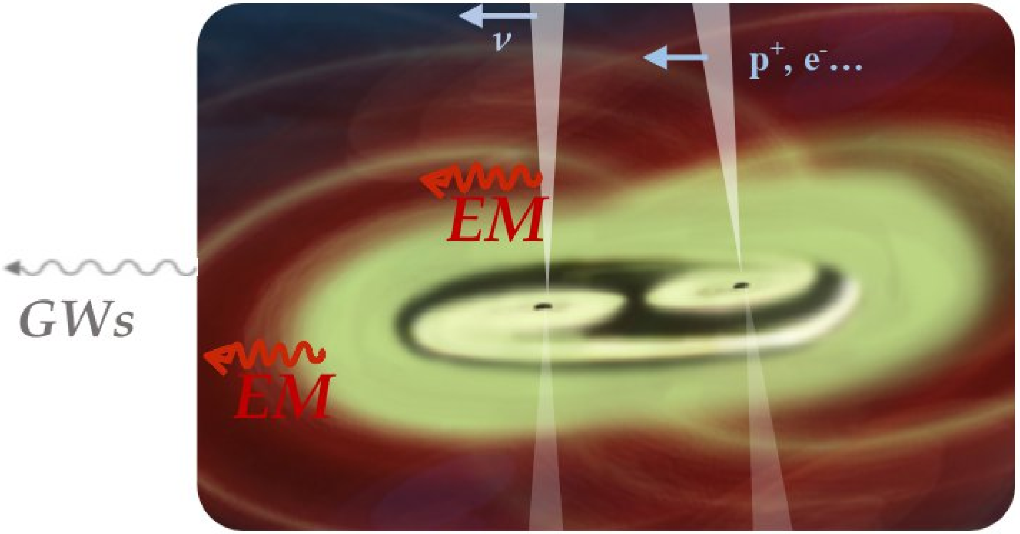

- LISA: space-based gravitational wave detector
  0.1-100 mHz band
  - **Binary black holes** $10^{4-7}M_{\odot}$
    ~10 days before merger
  - up to z~20 (e.g. Amaro-Seoane+17)
  - planned : ~2037 [4 years]

- PTAs: Pulsar Timing Arrays
  1nHz-100nHz band
  - **Binary black holes** $10^{7-10}M_{\odot}$
    mergers
  - low z
  - detection of individual sources ?

**Focus on supermassive binary black holes (SMBBHs)**

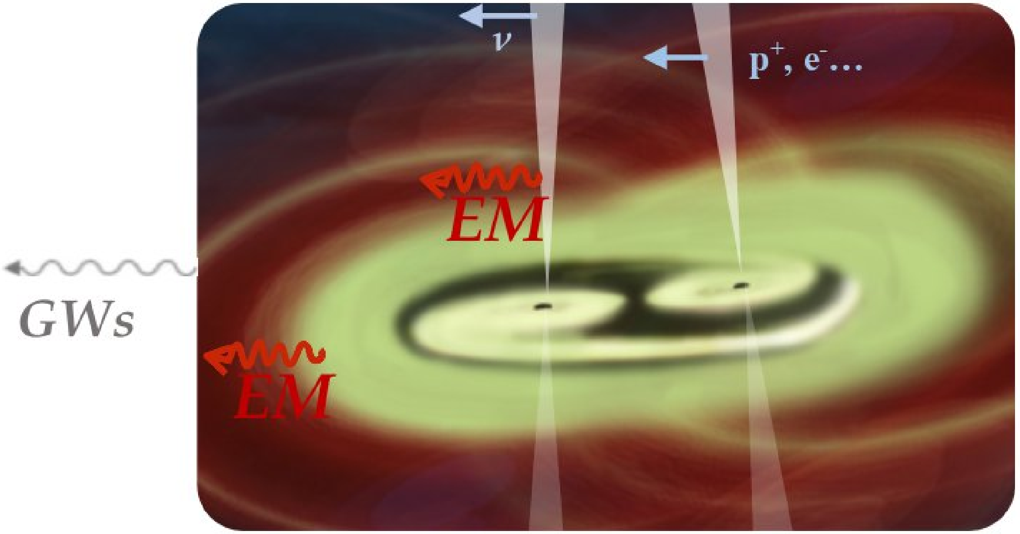
# Supermassive binary black holes (SMBBHs) as multi-messenger sources

Need a gas-rich environment:
e.g. galaxy merger



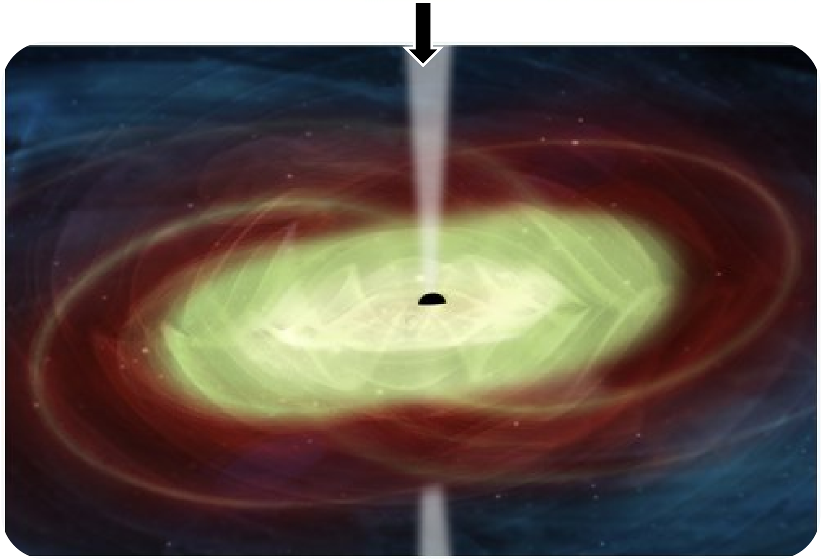
# Supermassive binary black holes (SMBBHs) as multi-messenger sources

Need a gas-rich environment:
e.g. galaxy merger
or AGN disk (Graham+20,+22)




- GW + electromagnetic (EM) counterpart
  - Galaxy + black hole growth
  - Fondamental physics: speed of gravity
  - Formation of active galactic nuclei?
  - Cosmology: Hubble constant (see next)

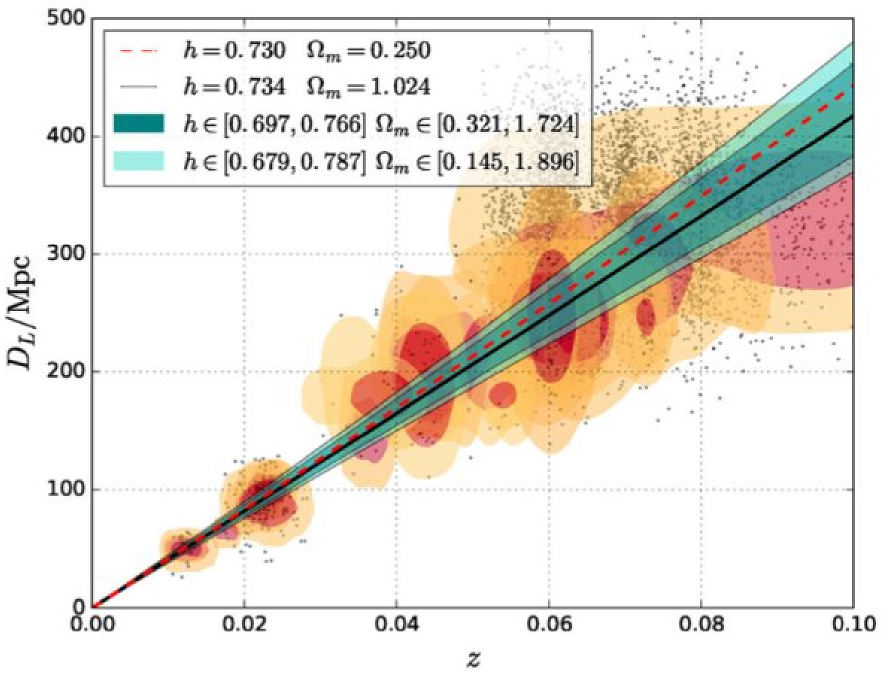
+ neutrino emission? (e.g. TXS0506, IceCube+18)



**Supermassive binary black holes: key targets in the multi-messenger era**

# SMBBHs as bright sirens

- « dark sirens » :
  e.g. stellar-mass BBHs, extreme mass ratio inspirals
  - ➢ correlation with galaxy catalogs




Cosmology with the Laser Interferometer Space Antena, 2023 arXiv:2204.05434v1

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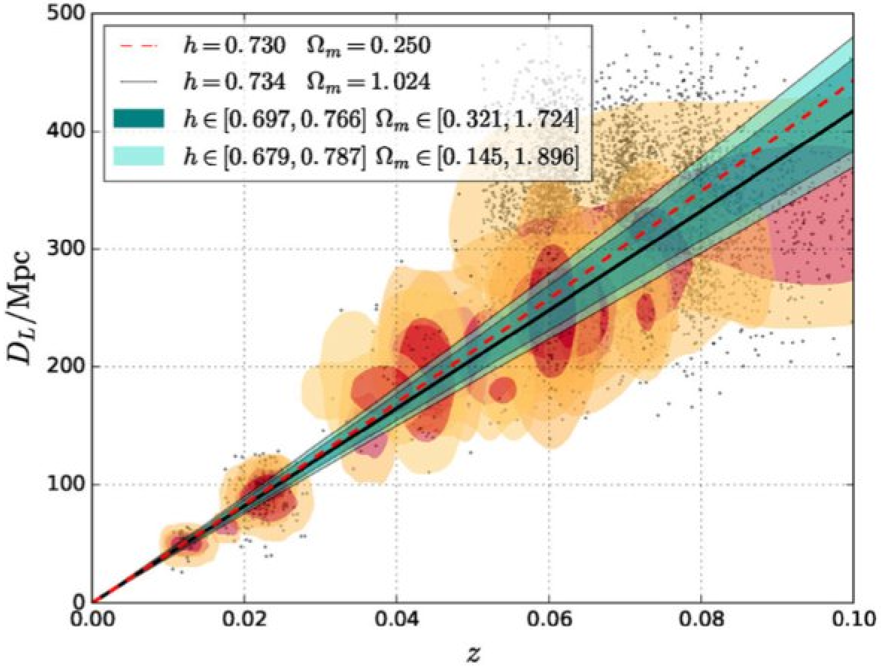
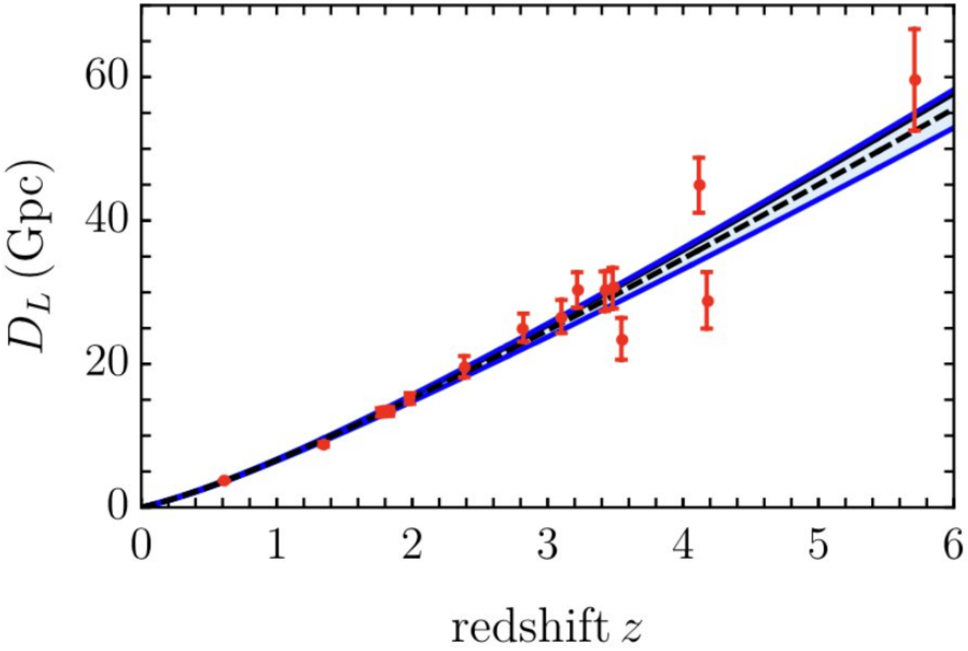



Cosmology with the Laser Interferometer Space Antena, 2023 arXiv:2204.05434v1

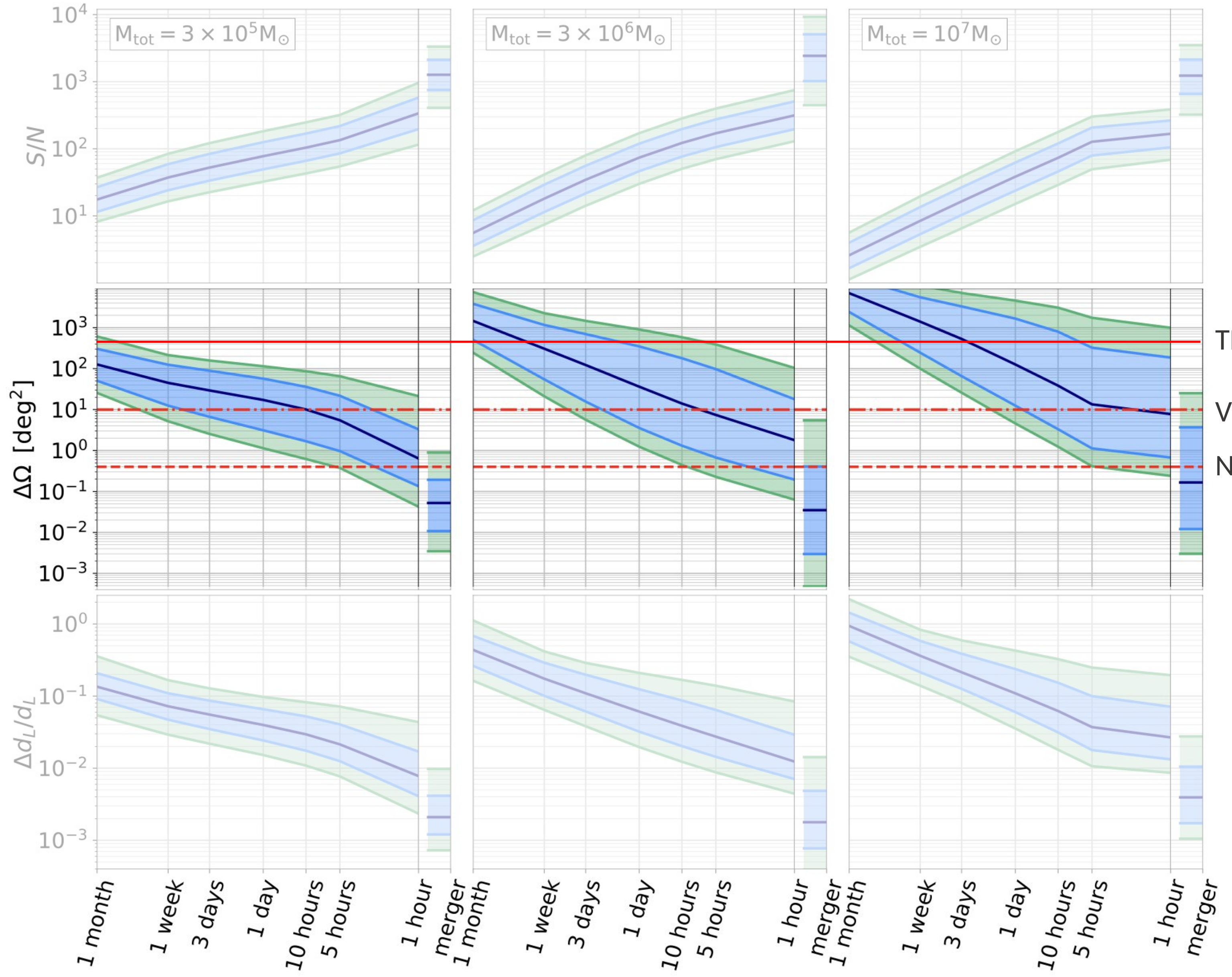
➢ "sure bet": systems currently detected by ground-based GW detectors LIGO/Virgo/Kagra

- « bright sirens » : accreting SMBBHs




➢ higher redshift : H(z)
➢ smaller uncertainty
❖ more uncertain population

# Pre-merger localization with LISA




Mangiagli+20

**Need to distinguish binary black holes from other (transient) sources**

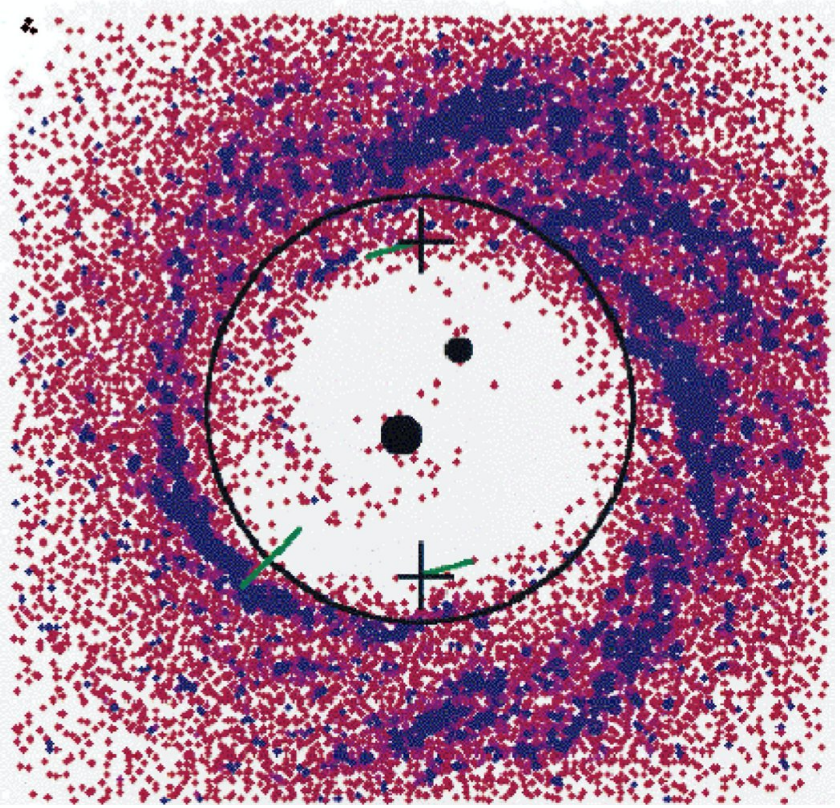
**...**

**ideally before LISA is launch**

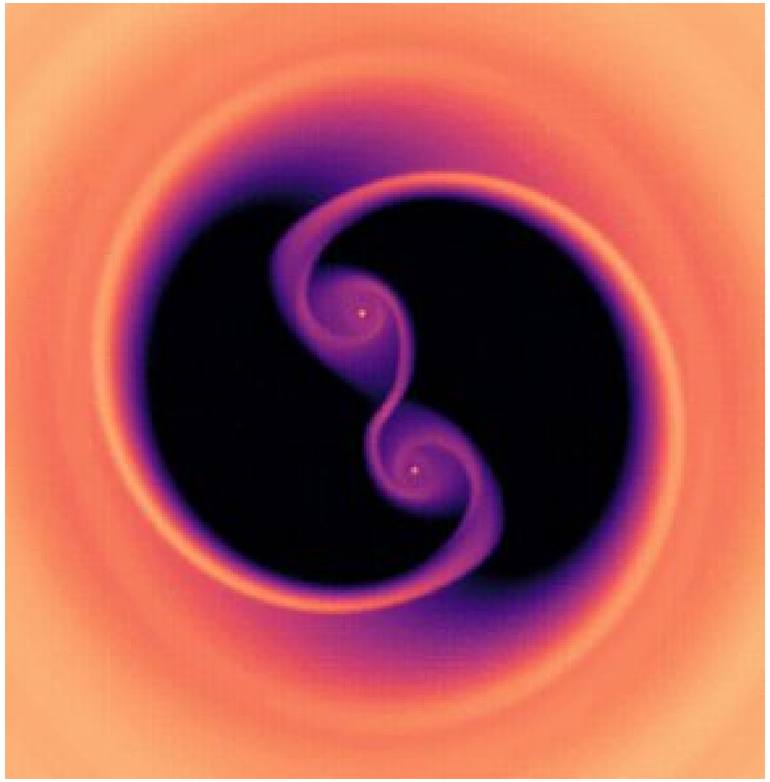
# Predicting the EM emission: the binary-disk interaction

For circular-orbit and mass ratio $q \equiv M_2/M_1 \sim 1$ :

- Pioneering works: Artymowicz & Lubow 1994, 1996



Artmowicz and Lubow (1996)
SPH

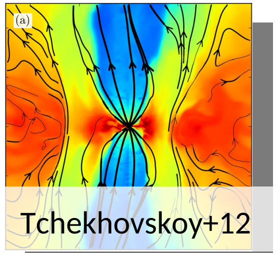


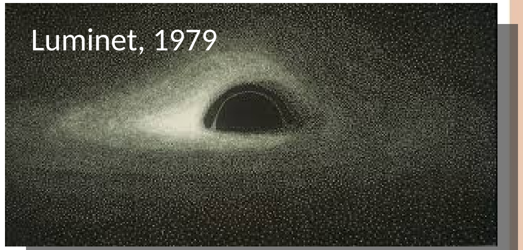
Credits: Edwin Santiago Leandro, PhD student
First binary-disk simulation with RAMSES (Teyssier+02), 2D viscous hydro

- Circumbinary disk + a cleared cavity + individual accretion structures (« mini-disks ») + streams

# Modelling a BBH and its circumbinary disk

- **Which approach for gravity ?**
  - Newtonian ? (e.g. D'Orazio+13, Franchini+21...)
  - Solving Einstein's equations ? (e.g. Einstein Toolkit, Löffler+12)


Tchekhovskoy+12


Luminet, 1979

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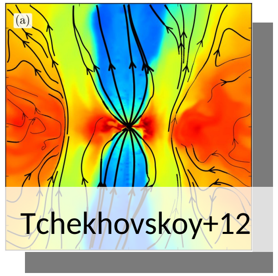
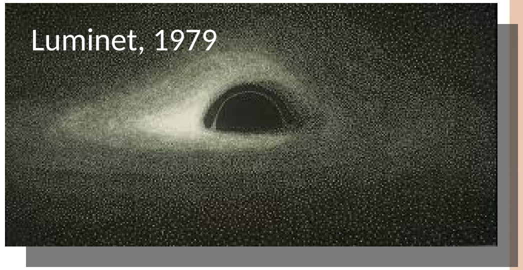
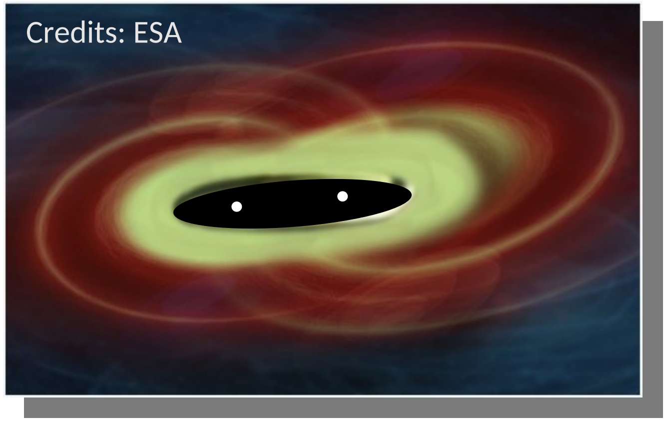



- ➢ Approximate, post-Newtonian analytical BBH metric valid in the circumbinary, « Near Zone » region (see e.g. Ireland+16)



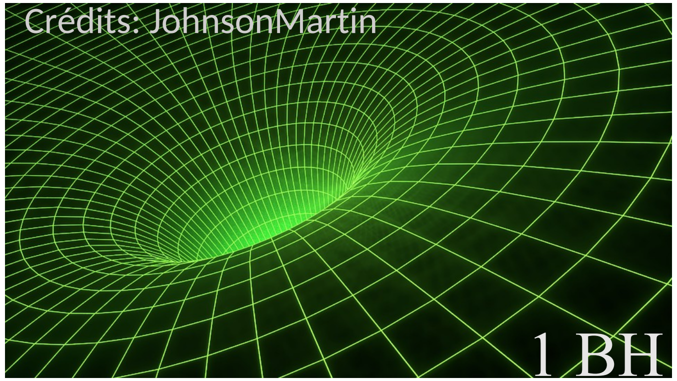

$$g_{\mu\nu}^{\rm NZ} = \eta_{\mu\nu} + h_{\mu\nu}^{\rm NZ}$$

$$\begin{aligned}
g_{00}^{\rm NZ} + 1 =& \frac{2m_1}{r_1} + \frac{m_1}{r_1}\left[4\mathbf{v}_1^2 - (\mathbf{n}_1\cdot\mathbf{v}_1)^2\right] - 2\frac{m_1^2}{r_1^2} \\
&- m_1 m_2\left[\frac{2}{r_1 r_2} + \frac{r_1}{2r_{12}^3} - \frac{r_1^2}{2r_2 r_{12}^3} + \frac{5}{2r_2 r_{12}}\right] \\
&+ \frac{4m_1 m_2}{3r_{12}^2}(\mathbf{n}_{12}\cdot\mathbf{v}_{12}) \\
&+ \frac{4}{r_1^2}\epsilon_{ijk} v_1^i s_1^j n_1^k + (1\leftrightarrow 2) + \mathcal{O}(v^6)\,, \\
g_{0i}^{\rm NZ} =& -\frac{4m_1}{r_1} v_1^i - \frac{2}{r_1^2}\epsilon_{ijk} s_1^j n_1^k + (1\leftrightarrow 2) + \mathcal{O}(v^5)\,, \\
g_{ij}^{\rm NZ} - \delta_{ij} =& \frac{2m_1}{r_1}\delta_{ij} + (1\leftrightarrow 2) + \mathcal{O}(v^4)\,,
\end{aligned} \tag{4}$$

➢ Hypotheses/approximations :

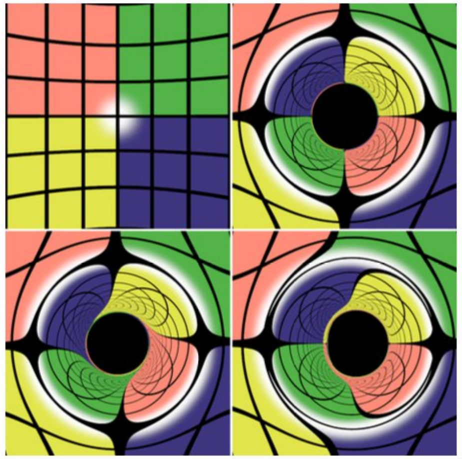
- Weak-field $GM/(rc^2) \ll 1$ « not too close to each BH »
- Slow motion $v/c \ll 1$ « not too close to merger »

# From single to binary black holes




$$g_{\mu\nu} = \begin{pmatrix} 1+\frac{2Mr}{\rho^2} & 0 & 0 & \frac{4Mar\sin^2\theta}{\rho^2} \\ 0 & -\rho^2/\Delta & 0 & 0 \\ 0 & 0 & -\rho^2 & 0 \\ \frac{4Mar\sin^2\theta}{\rho^2} & 0 & 0 & -(r^2+a^2+\frac{2Ma^2r\sin^2\theta}{\rho^2})\sin^2\theta \end{pmatrix}$$

Bohn+15



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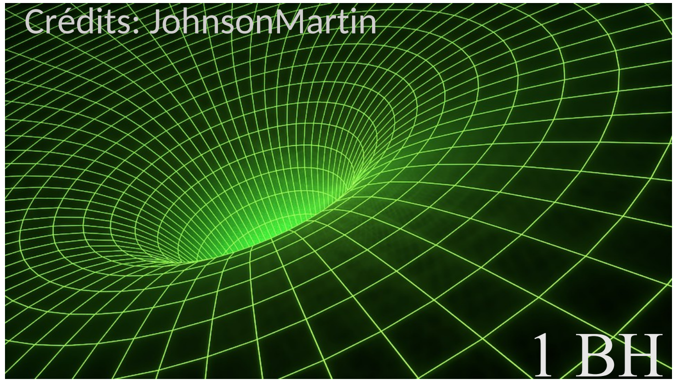


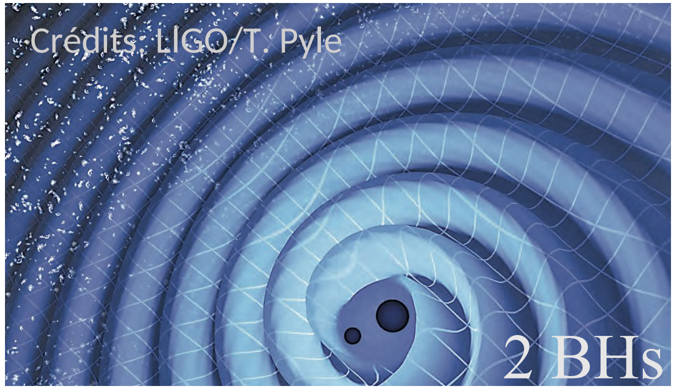


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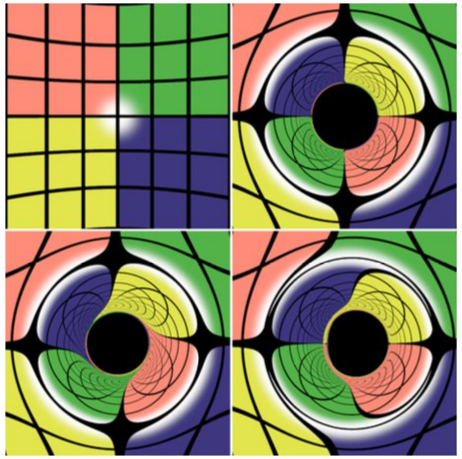
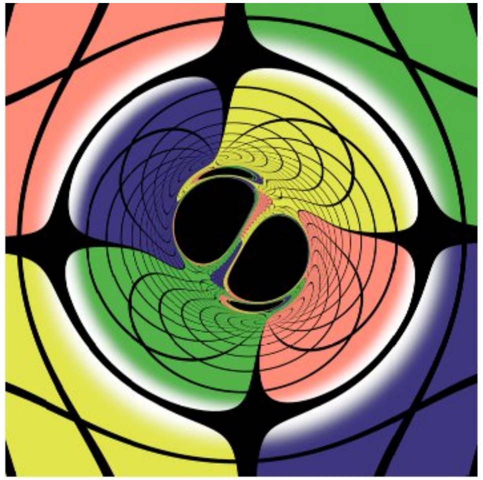
~~Stationarity~~
“Delayed gravity”
~~Axisymmetry~~
~~Diagonality of $g_{ij}$~~

$$g_{\mu\nu} = \begin{pmatrix} g_{tt} & g_{tr} & g_{t\theta} & g_{t\phi} \\ g_{rt} & g_{rr} & g_{r\theta} & g_{r\phi} \\ g_{\theta t} & g_{\theta r} & g_{\theta\theta} & g_{\theta\phi} \\ g_{\phi t} & g_{\phi r} & g_{\phi\theta} & g_{\phi\phi} \end{pmatrix}$$



Bohn+15



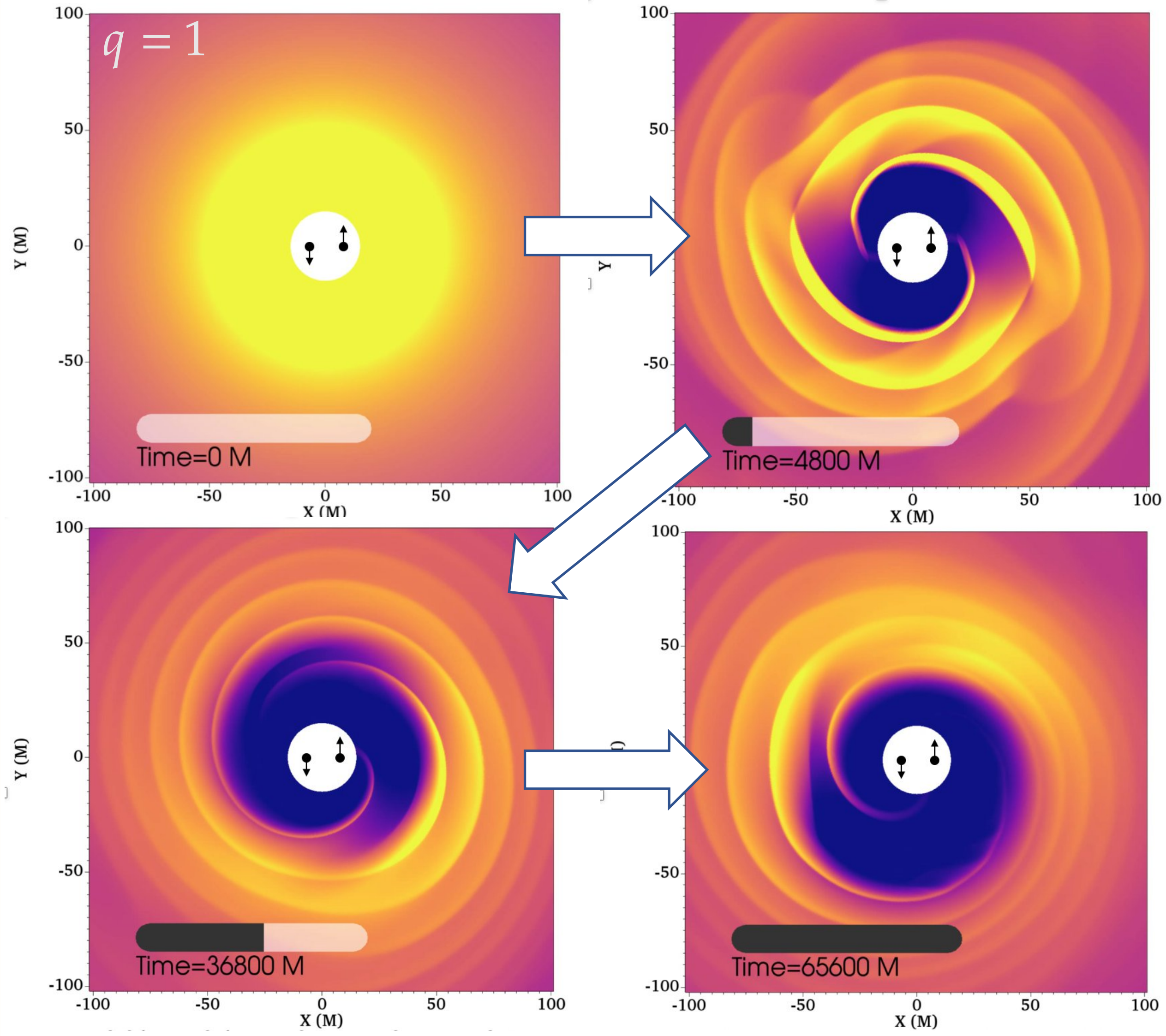
# 2D GRHD simulations: accretion structures

Solve the equations of conservation of

- baryons $\nabla_\mu(\rho u^\mu) = 0,$
- energy (entropy here) - momentum $\nabla_\mu T^{\mu\nu} = 0,$

in this metric with `GR−AMRVAC` (Casse+17 ; see MR+23a)

# 2D GRHD simulations: accretion structures




Surface density

Solve the equations of conservation of

- baryons $\nabla_\mu(\rho u^\mu) = 0,$
- energy (entropy here) - momentum $\nabla_\mu T^{\mu\nu} = 0,$

in this metric with GR−AMRVAC (Casse+17 ; see MR+23a)

Recover the standard features of binary-disk interaction:

1. A cavity at ~2x orbital separation (Artymowicz+94)
2. Streams (Artymowicz+96) & spiral arms

and further in time…

3. An overdensity, or « lump » (e.g. MacFadyen+08, Shi+12, Noble+12, D'Orazio+13, Gold+14, Farris+14, Ragusa+16, Miranda+17, Muñoz+19, Duffell+20, Armengol+21, Tiede+20+21, Liu+21, Franchini+22 (priv. com.), Siwek+22, Cimerman+23…)

possibly linked to an instability
Mignon-Risse et al. 2023b, MNRAS

**Accretion structures → Observational features?**

# Synthetic observations of pre-merger BBHs

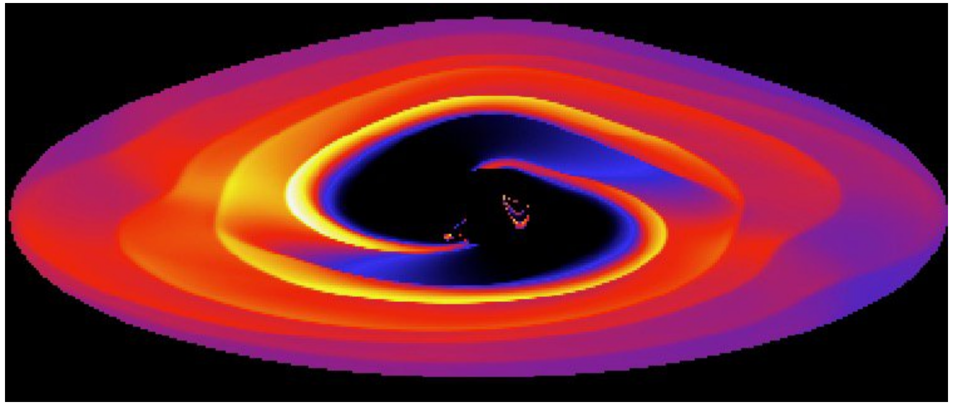
- **GYOTO** code (Vincent+11) incorporating the **BBH approximate metric** (Ireland+16)
  - ➢ **Fluid+ray-tracing pipeline = e-NOVAs**

- Thermal emission

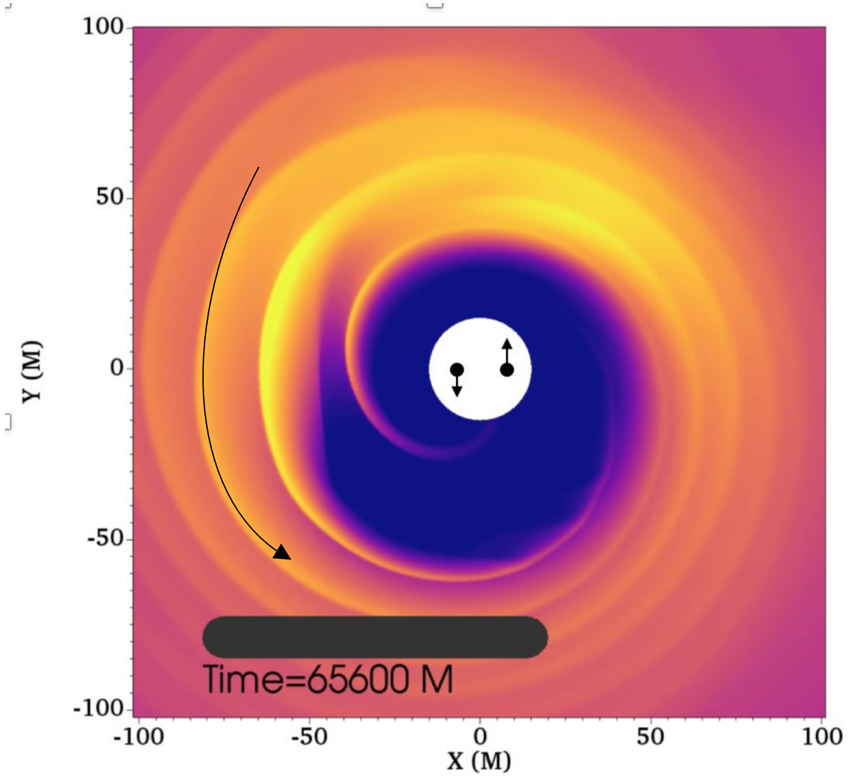
- Putting physical units: $M = 10^5 M_\odot$; $T_{in} = 0.1$ keV as reference (Lin+13), mass scaling from Shakura & Sunyaev, 1973

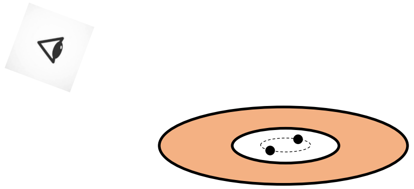
➢ Obtain the multi-wavelength emission map
  - ➢ The metric evolves as photons propagate
  - ➢ Emission map composed of photons of different time-origin (hence, fluid outputs!)

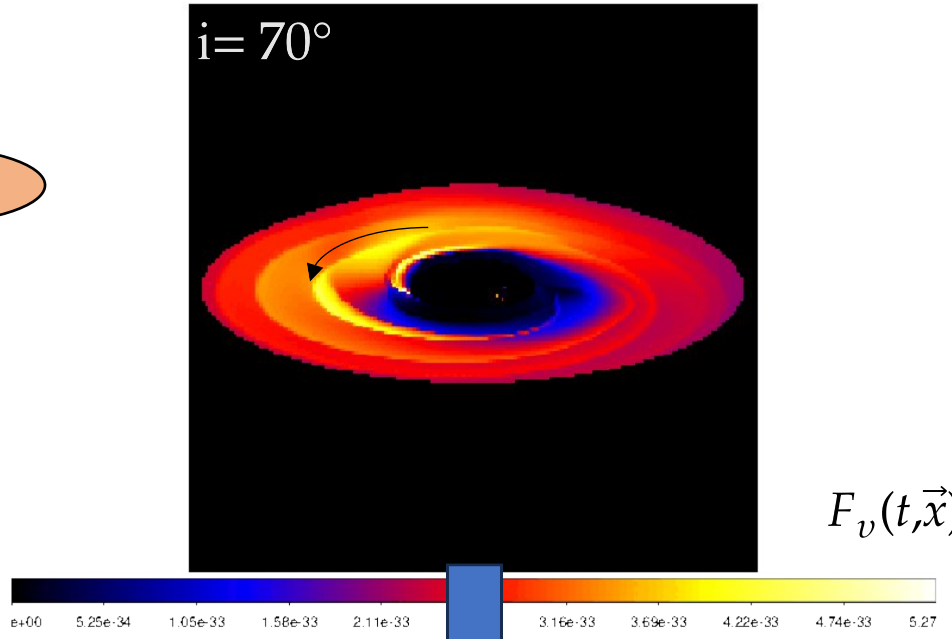
    ≠ fast-light approximation (e.g. D'Ascoli+18, Gutierrez+22)



# Accretion structures → EM variability

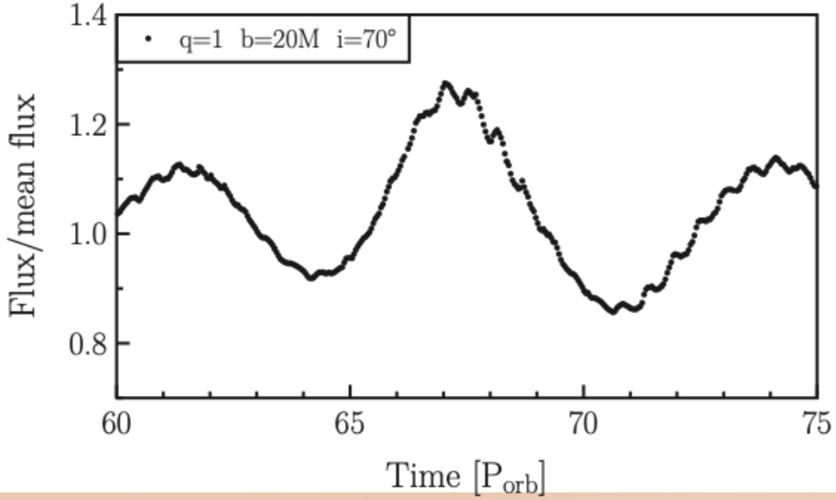





$F_\nu(t,\vec{x})$

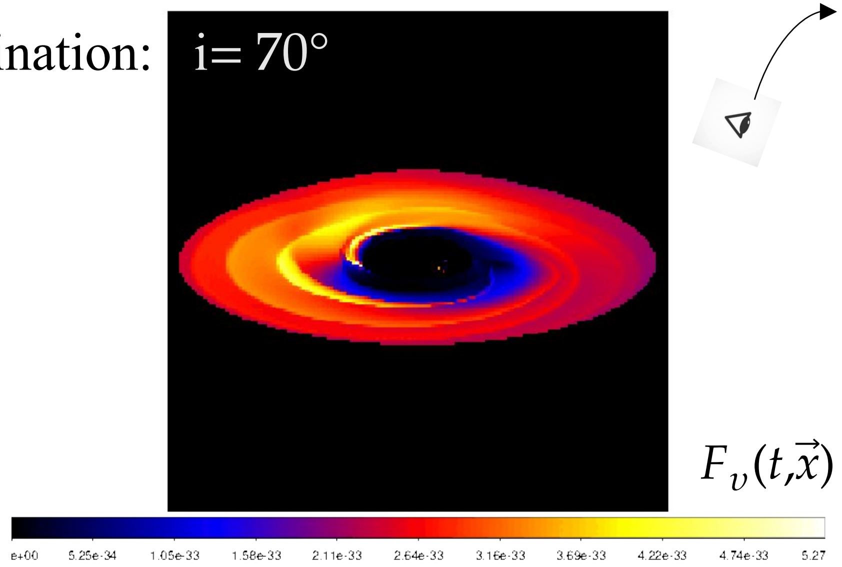
If not spatially resolved: $F_\nu(t)$

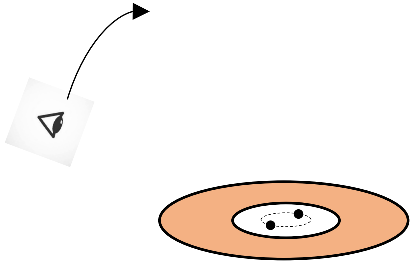


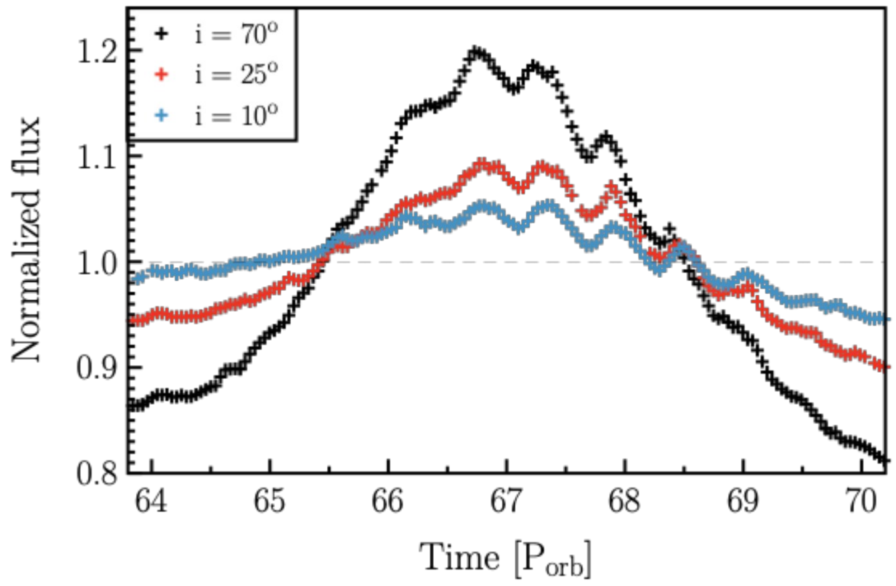

- Relativistic (Doppler) beaming effect onto the lump's emission

# Characterization of the modulation

- Vary inclination:






➢ Relativistic (Doppler) beaming effect optimal for edge-on views

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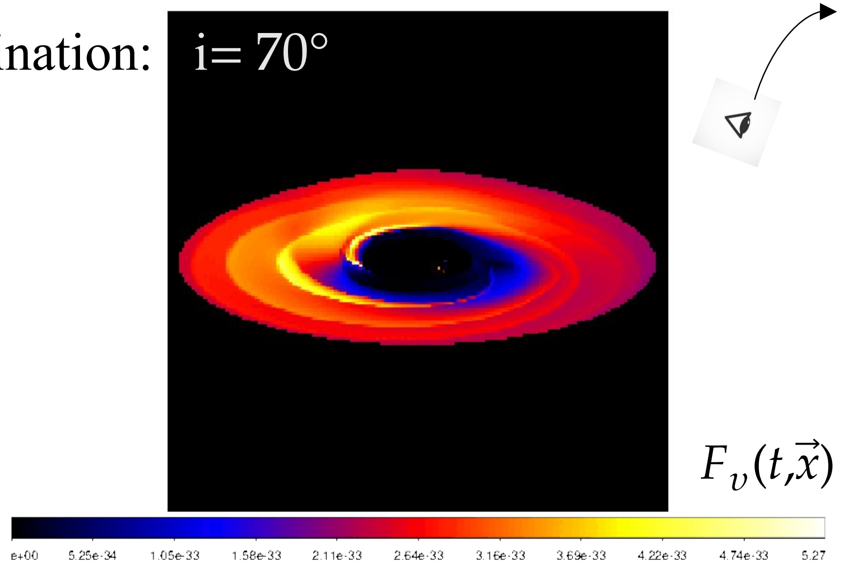
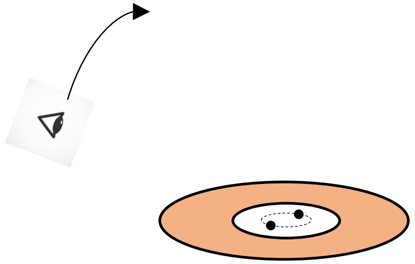
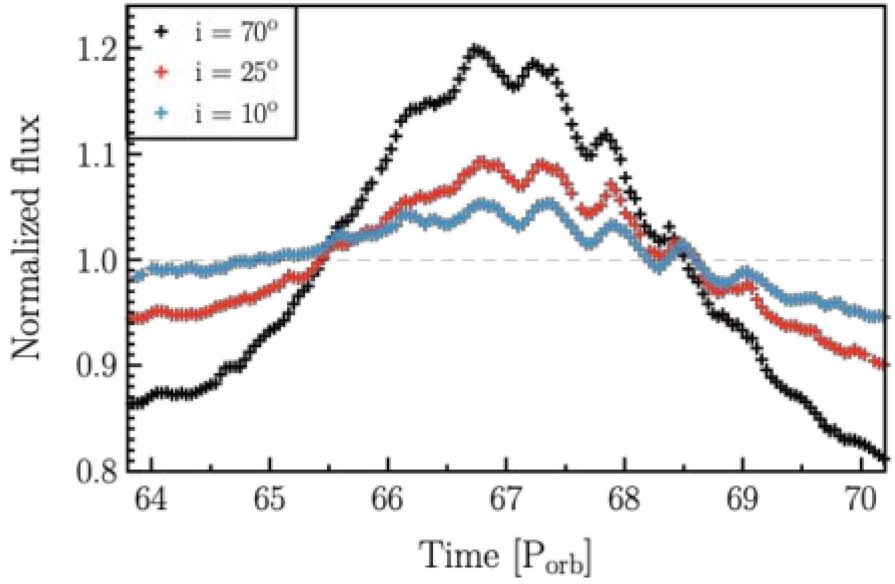


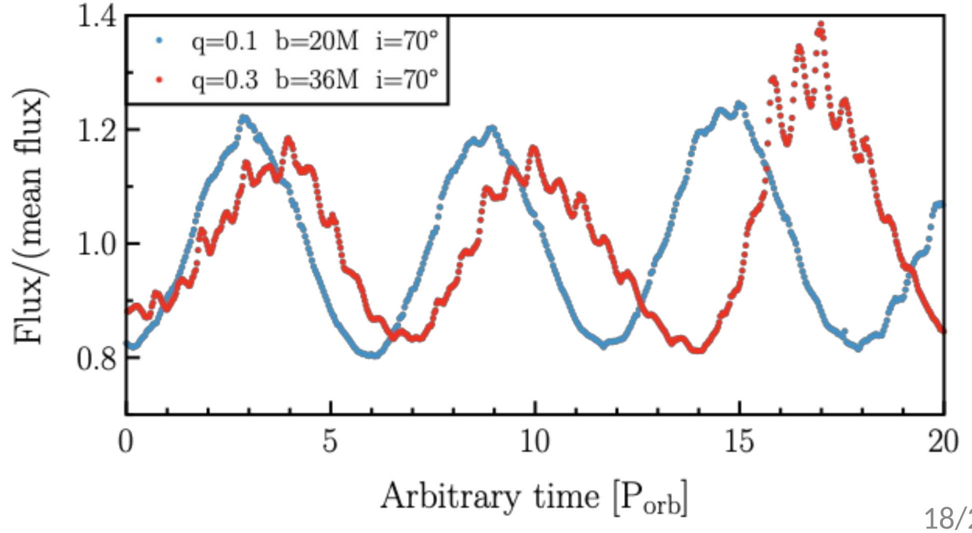



➢ Relativistic (Doppler) beaming effect optimal for edge-on views

- Vary the mass ratio $q$ and separation $b$

➢ Modulations present for $q \in [0.1, 1]$

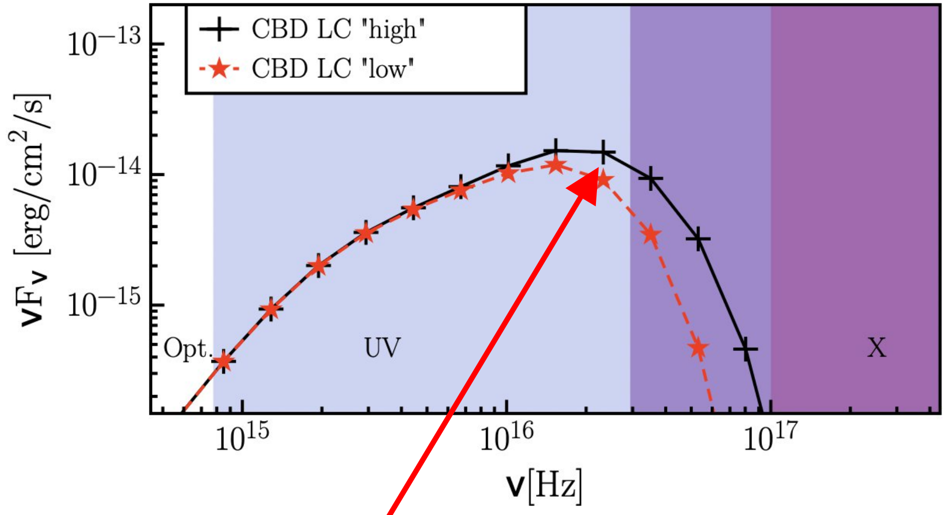
➢ Relativistic effects increase as $b$ ↘

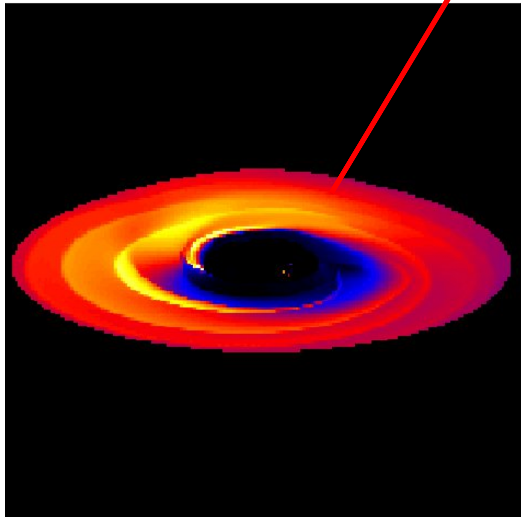



➢ Toy model reproducing the lightcurve (MR+25a, A&A)

# Which frequency band to observe the lump modulation?

For $q = 1$, $\dot{M} = 0.5\ \dot{M}_{Edd}$, $M = 10^5 M_\odot$



→ UV for most LISA

→ optical for most PTA sources

(ZTF, V. Rubin Obs. (ex-LSST), Habitable Worlds Observatory...)

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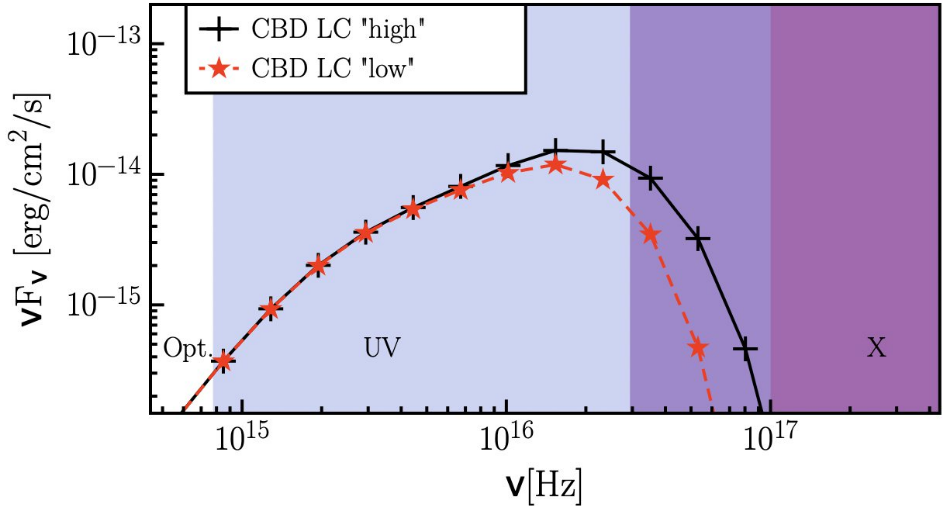


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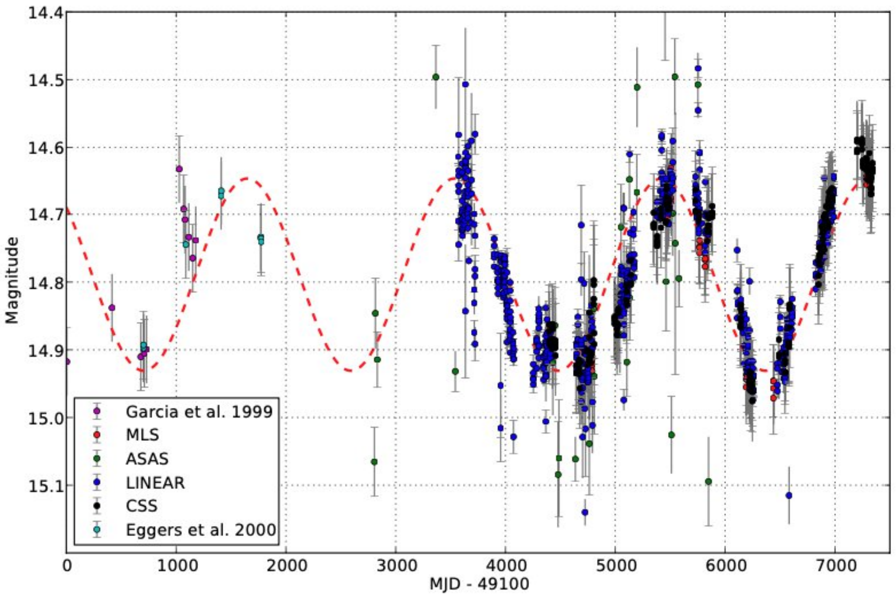


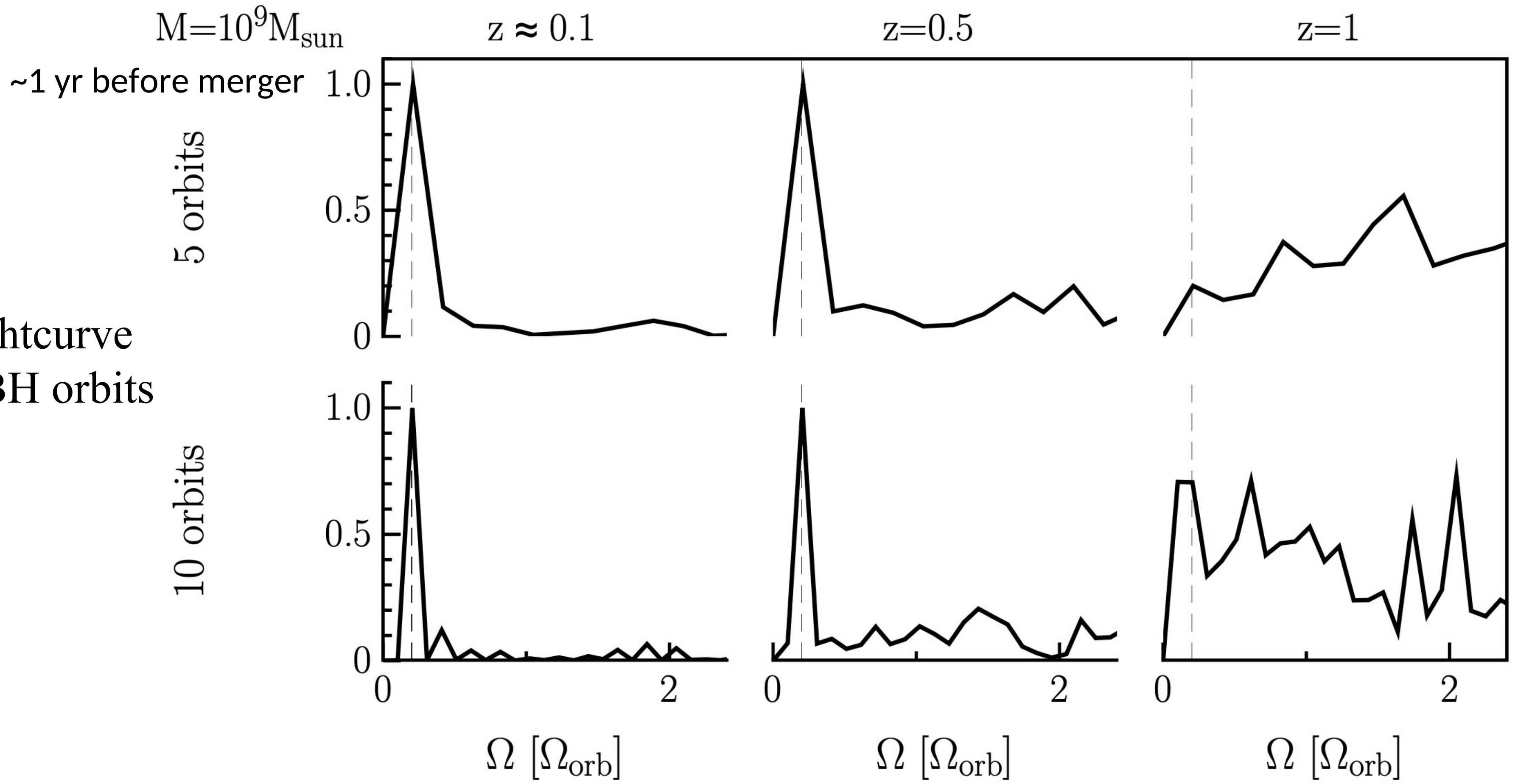

Graham+15:
111 BBH candidates
Optical follow-up : Foustoul, Webb, MR et al. 2025

An imprint from the lump ?

# Detectability with the Vera Rubin Observatory

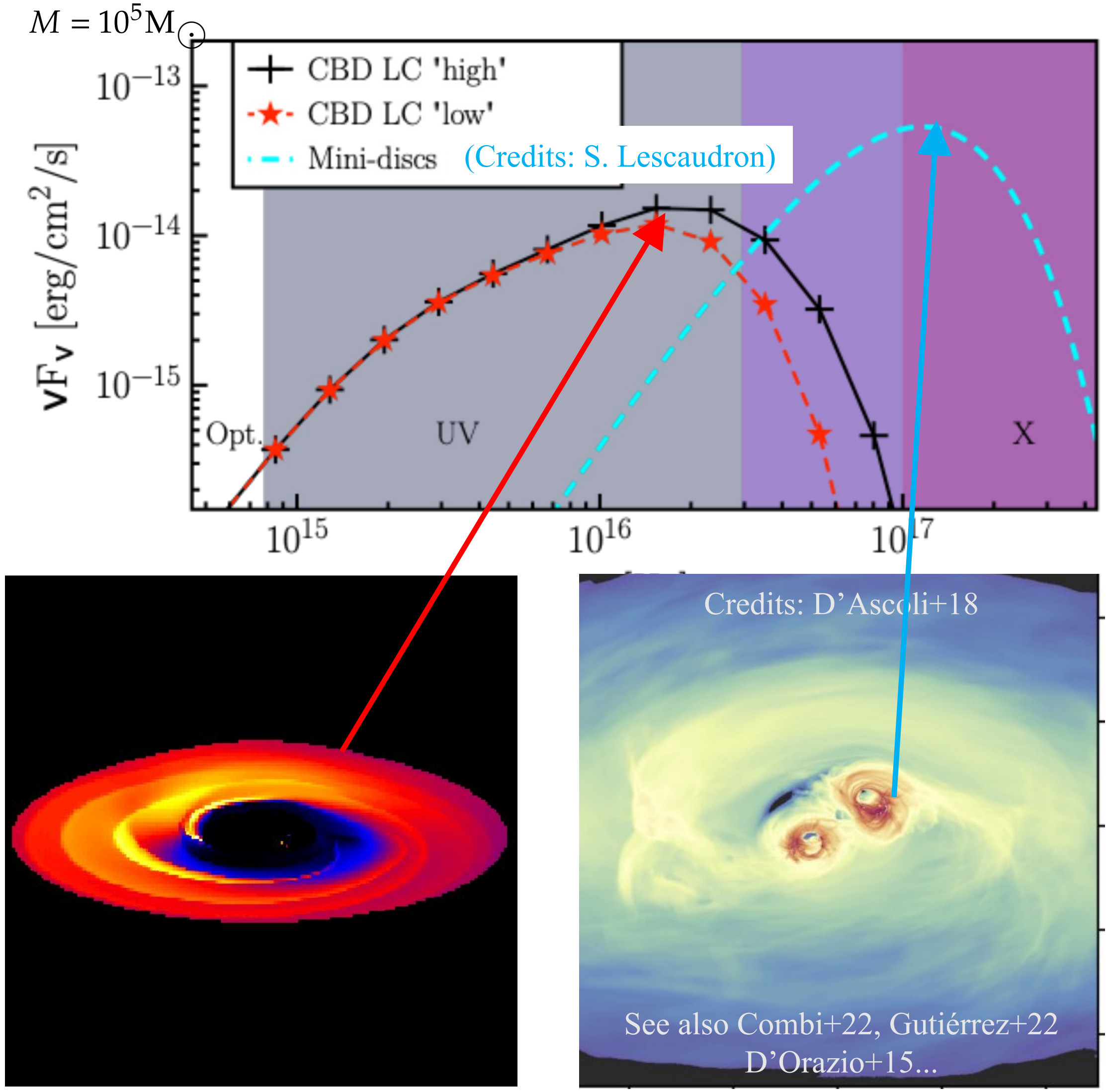
- Optical band
- Survey the entire sky every 3 days
- Exposure time ~30s

1. Add noise to synthetic lightcurve
2. Perform FFTs on 5/10 BBH orbits



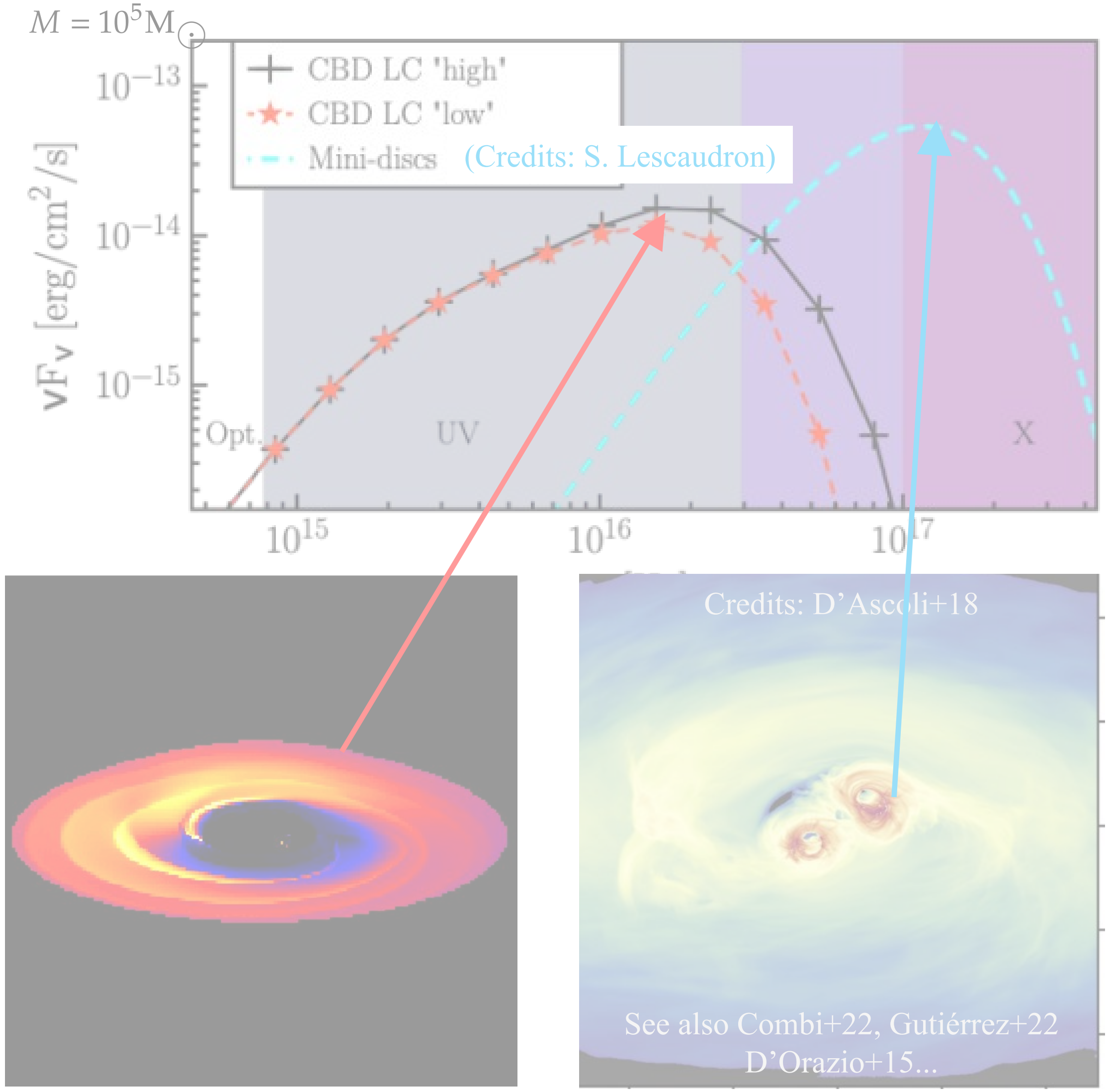

➢ **Lump modulation detectable up to z = 0.5**

# Higher-frequency EM signatures from individual disks




- Expected X-ray emission from « mini-disks »
  - ➢ Importance for NewATHENA, THESEUS

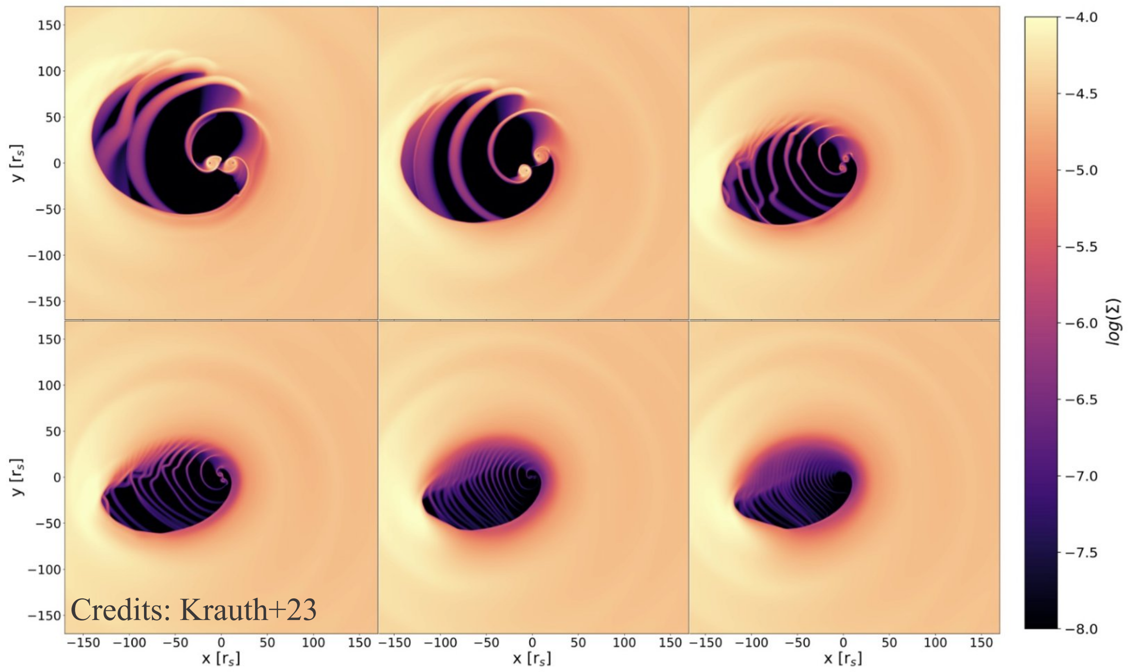
# Higher-frequency EM signatures from individual disks but...




- Expected X-ray emission from « mini-disks »
  - Importance for NewATHENA, THESEUS

but...

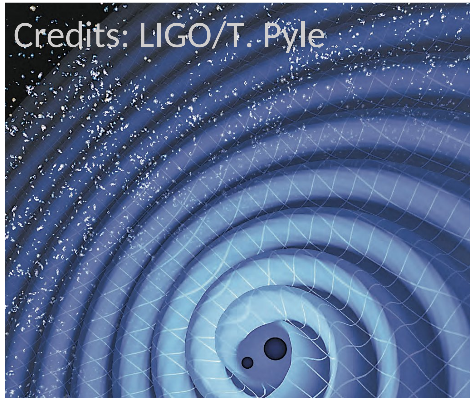
- Gas plunges → weak radiative efficiency (Gutiérrez+22)
- Between (inner) last stable orbit and (outer) tidal truncation → mini-disk disappearance (e.g. Krauth+23, Franchini+24)




- Only the circumbinary disk remains
- but BBH inspirals faster: binary-disk « decoupling »
  e.g. Armitage & Natarayan 2002, Dittmann+23

→Survival of EM lump modulation « post-decoupling »?

# Inspiral equation of motion




zero ⇔ circular orbit

$$\dot{E} = -\mathcal{F} - \dot{M}$$

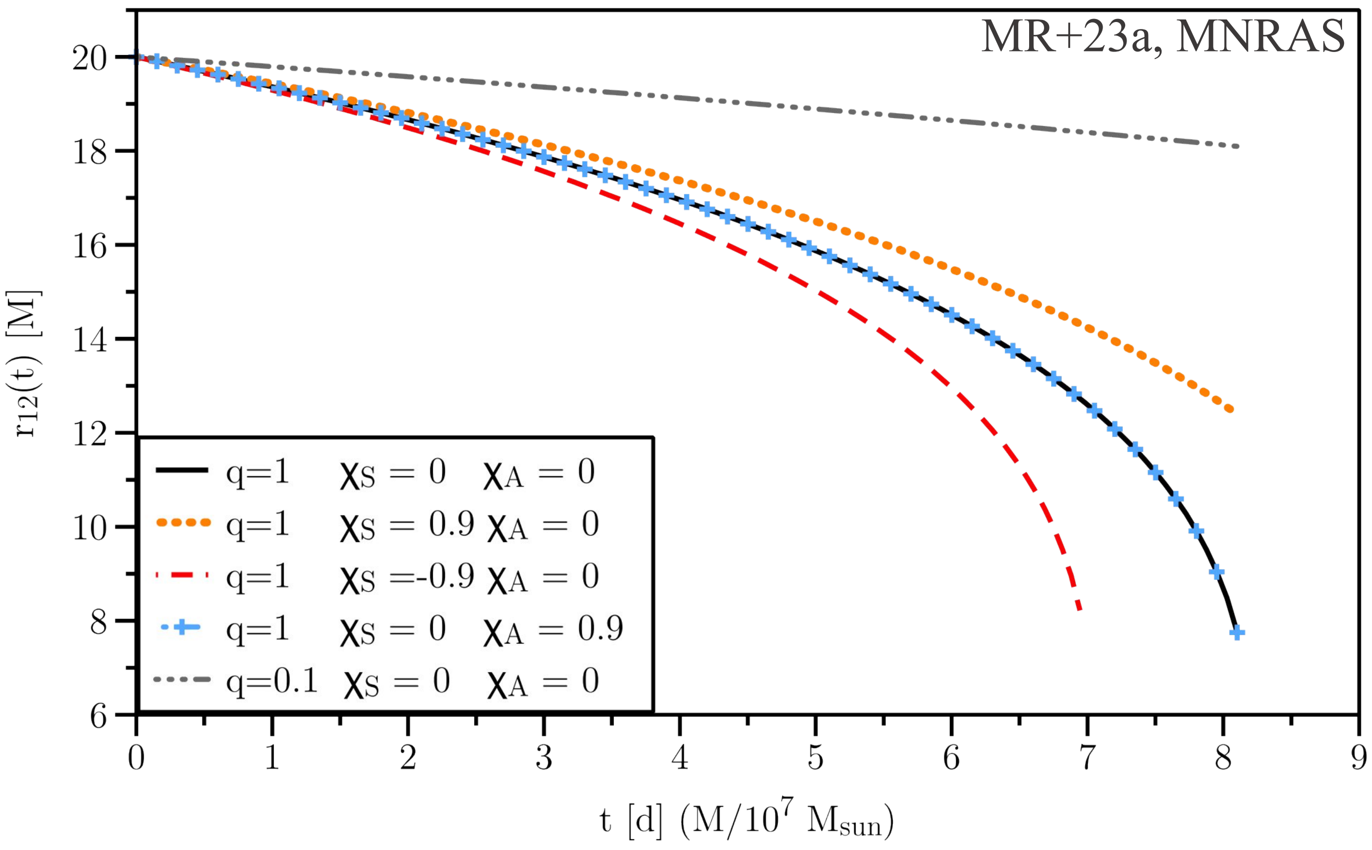
Rate of change of orbital binding energy

$$\frac{\mathrm{d}t}{\mathrm{d}r_{12}} = -\frac{\mathrm{d}E(r_{12})/\mathrm{d}r_{12}}{\mathcal{F}(r_{12}) + \dot{M}(r_{12})}$$

Change in mass (« tidal heating »)

Post-Newtonian terms from Ajith+12

# Inspiral equation of motion

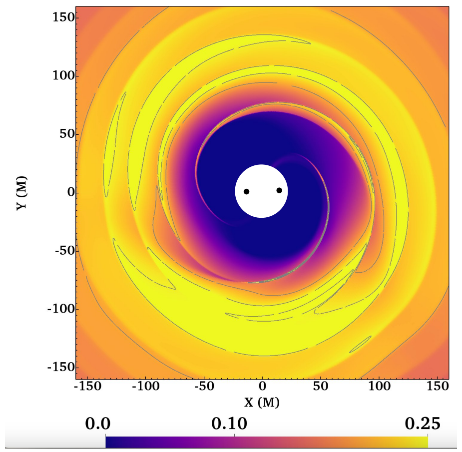


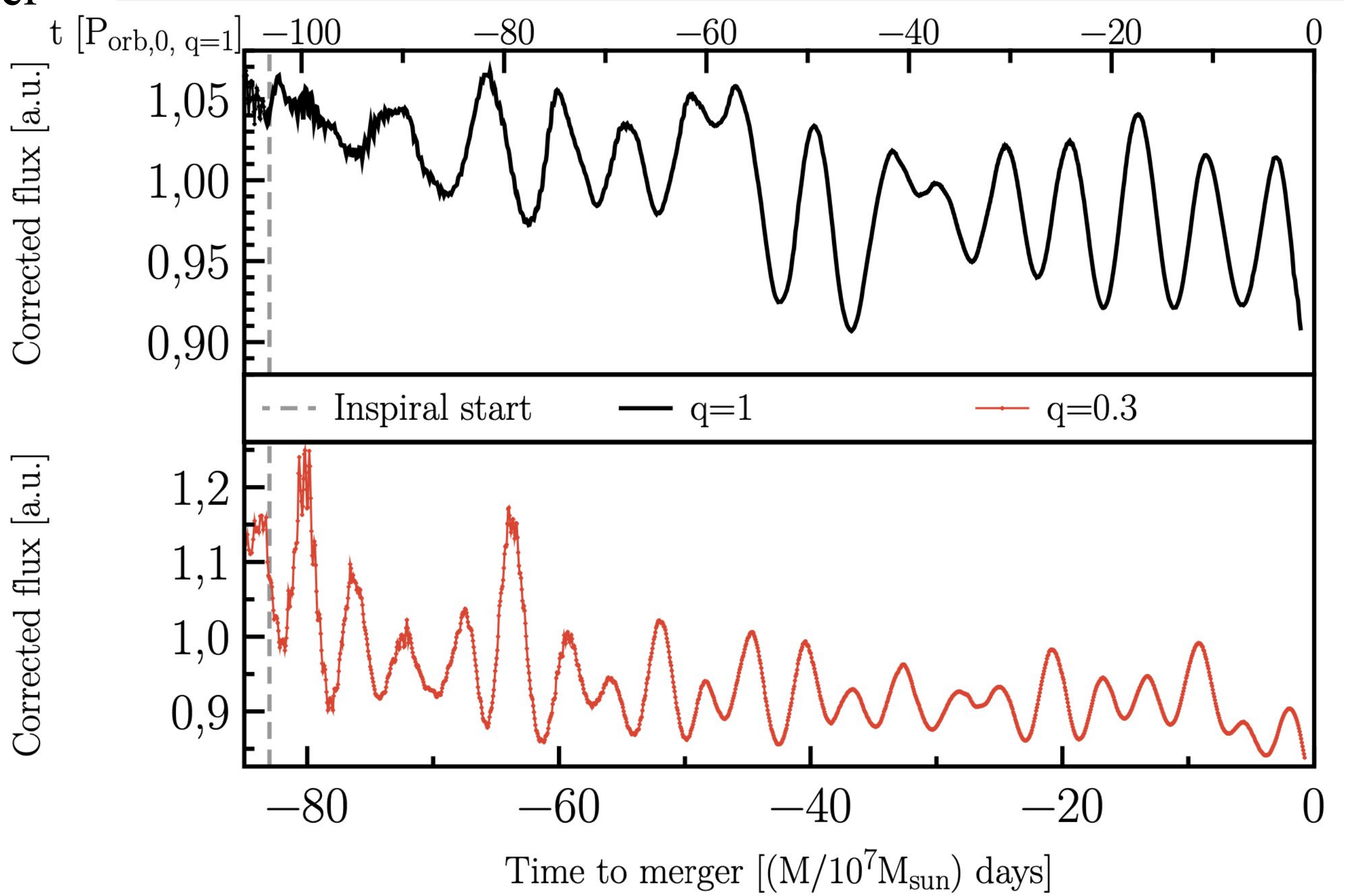

- Post-Newtonian equation of motion
- **Slower inspiral for *q* ↘ or prograde spin**
  (“orbital hang-up” effect, Campanelli+06)

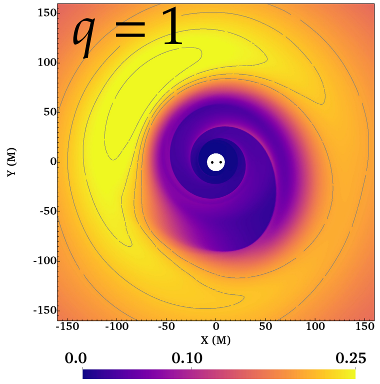
# Electromagnetic signatures post-decoupling

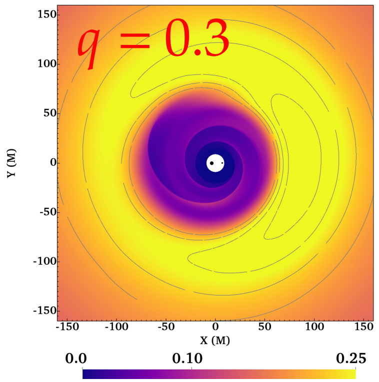
$80 \frac{M}{10^7 M_\odot}$ days before merger

$< 1 \frac{M}{10^7 M_\odot}$ day before merger





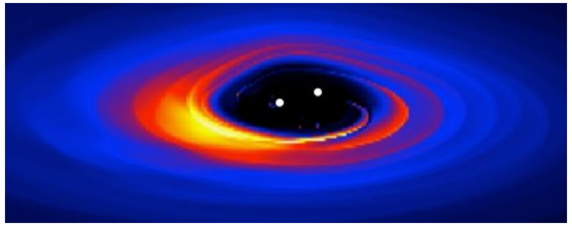




The lump and its modulation survive post-decoupling

MR+25b
MNRAS

# Conclusions

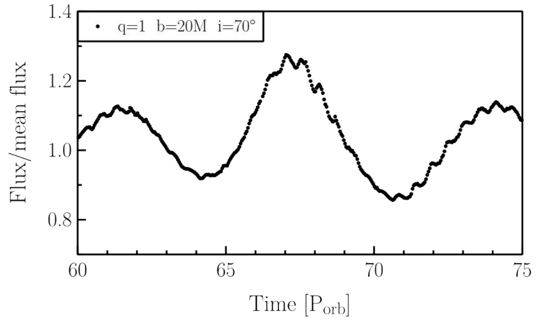
- Supermassive binary black holes are likely the next multi-messenger sources



- Binary-disk interaction is key in predicting their electromagnetic appearance

UV/optical emission → circumbinary disk + lump's modulation

MR+25a, A&A

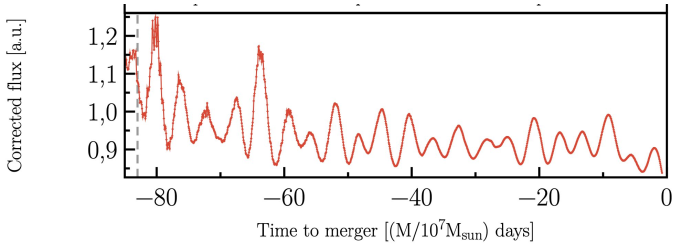



X-ray emission → mini-disk + disappearance close to merger

e.g. Tang+18, Krauth+23, Franchini+24...

while the lump-related modulation survives

MR+25b, MNRAS




❖ Unicity of the circumbinary disk EM variability? /!\ BH disk instabilities

Varniere, MR, Casse, 2025, MNRAS

❖ Poor source localization + short time for EM follow-up

→ need multi-wavelength campaigns