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The last electromagnetic breath of binary black holes

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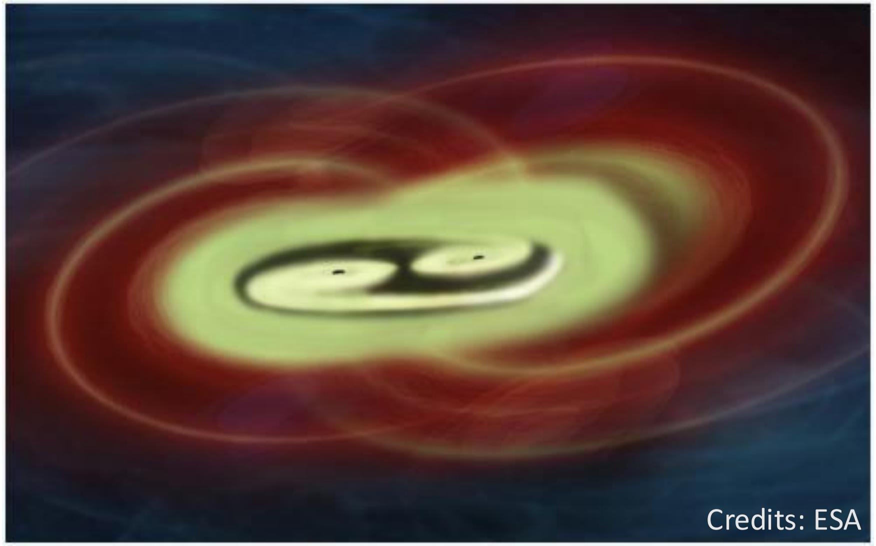
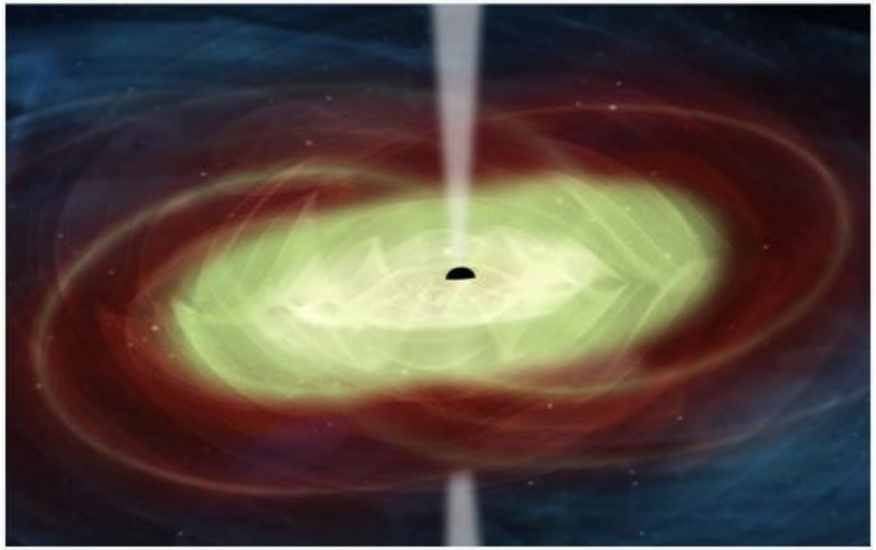
Universidad de Valladolid

Electromagnetic counterpart to binary black hole merger

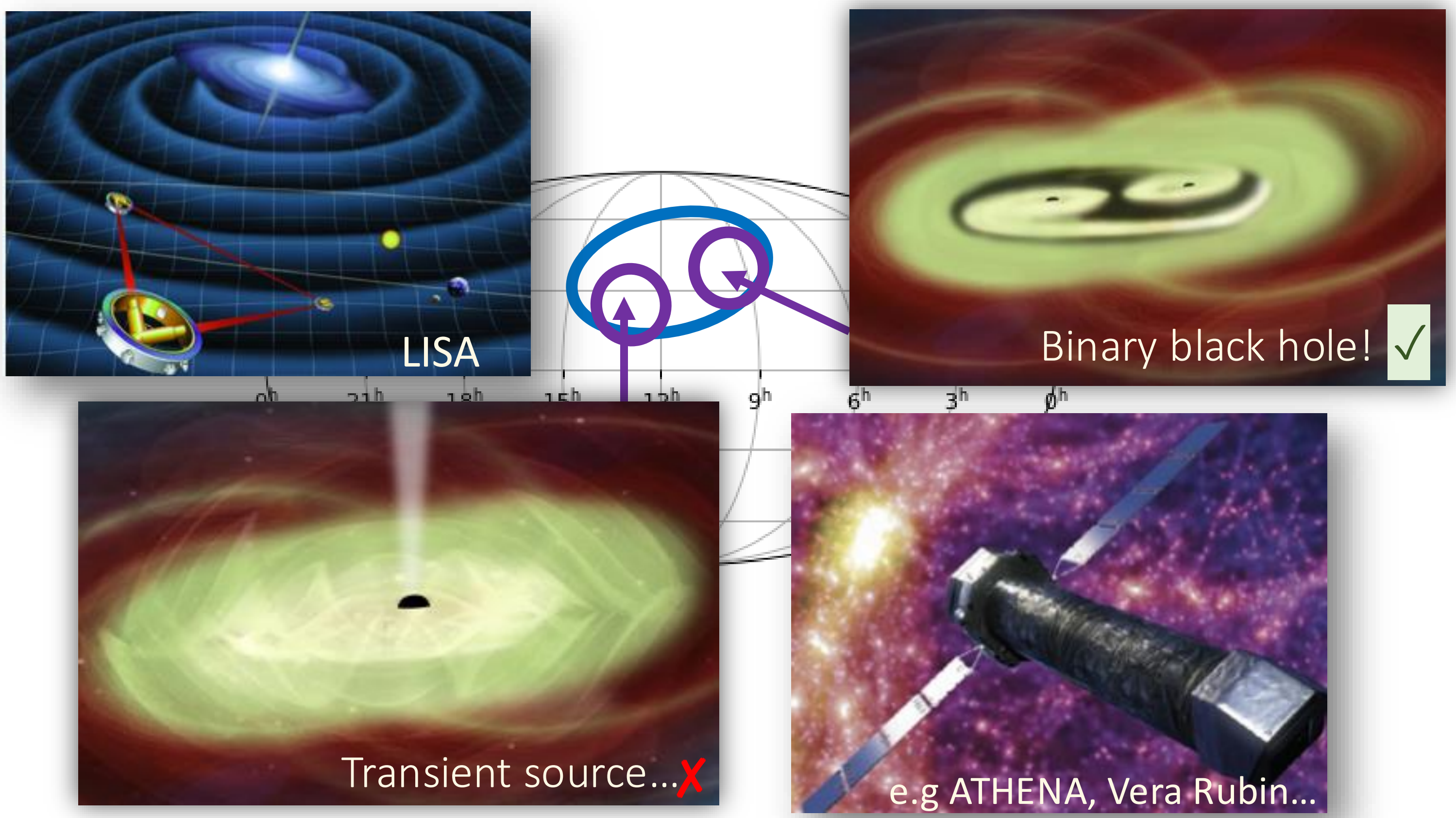
Need a gas-rich environment:
e.g. galaxy merger
or AGN disk (Graham+20,+22)





- Binary black holes and their coalescence
  - Galaxy + black hole growth
  - Cosmology: Hubble constant
  - Fondamental physics: speed of gravity
  - Formation of active galactic nuclei?

Identification of BBHs before/after GW detection



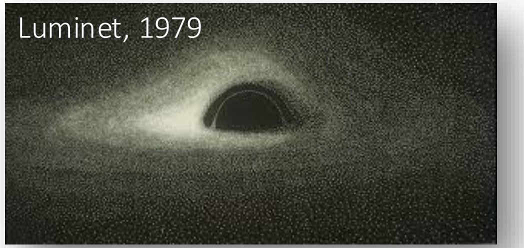
- LISA: space-based gravitational wave detector
  0.1-100 mHz band
  - BBHs $10^{4-7} M_\odot$: ~10 days before merger

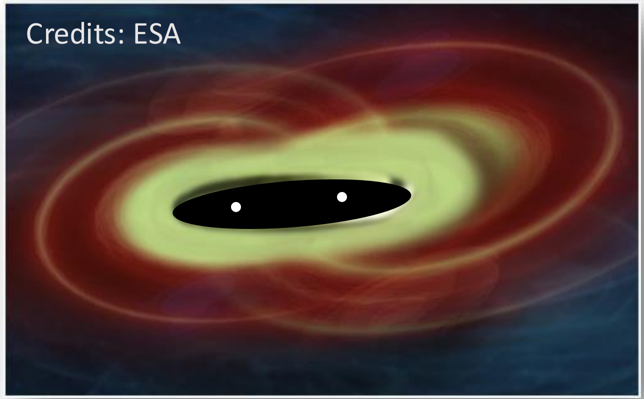
- PTA: Pulsar Timing Arrays
  1nHz-100nHz band
  - Close individual BBHs $10^{7-10} M_\odot$ mergers

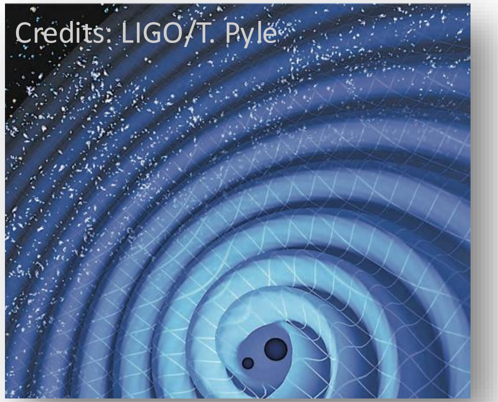
How to distinguish binary black holes from other (transient) sources ?

Modelling a BBH and its circumbinary disk

- **GR-AMRVAC** code (Keppens+12, GR: Casse+17)
- How does the fluid know about the binary black hole?
  - ➢ Newtonian gravity ? (e.g. D'Orazio+13)
  - ➢ Solving the Einstein's equations ? (e.g. Einstein Toolkit, Löffler+12)







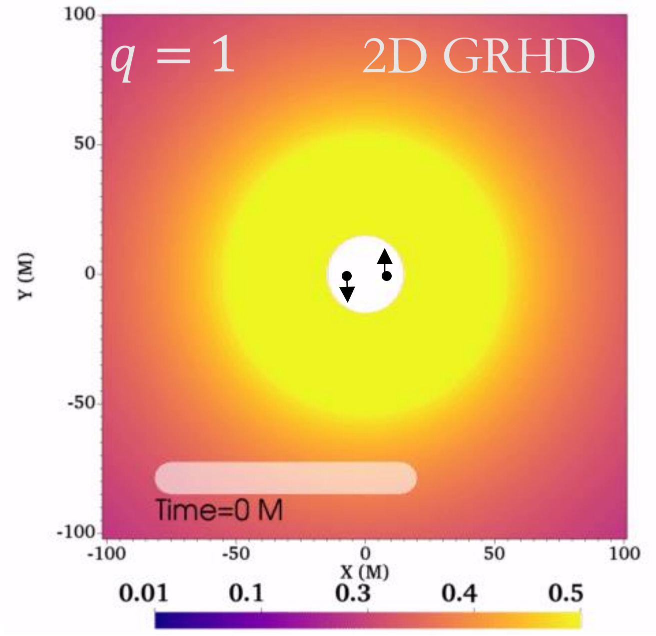
- ➢ Extend GR-AMRVAC to dynamical spacetimes + implement approximate analytical BBH metric valid in the circumbinary region (Mignon-Risse et al. 2022, MNRAS)

➢ Still, a computationally-heavy, and conceptually more complex, construction (see e.g. Ireland+16):

$$g_{00} + 1 = \frac{2m_1}{r} + \frac{m_1}{r}\left\{v_1^2 - \frac{m_2}{b} + 2\left(\vec{v}_1 \cdot \hat{n}\right)^2 - \frac{2m}{r} + 6\frac{\left(\vec{x}_1 \cdot \hat{n}\right)}{r}\left(\vec{v}_1 \cdot \hat{n}\right) - \frac{x_1^2}{r^2} + \frac{\left(\vec{x}_1 \cdot \hat{n}\right)^2}{r^2}\left(3 - 2r^2\omega^2\right)\right\}$$
$$+ (1 \leftrightarrow 2) + O(v^5),$$

➢ Construction valid until the BBH motion becomes relativistic

Circular orbits: accretion structures and EM variability

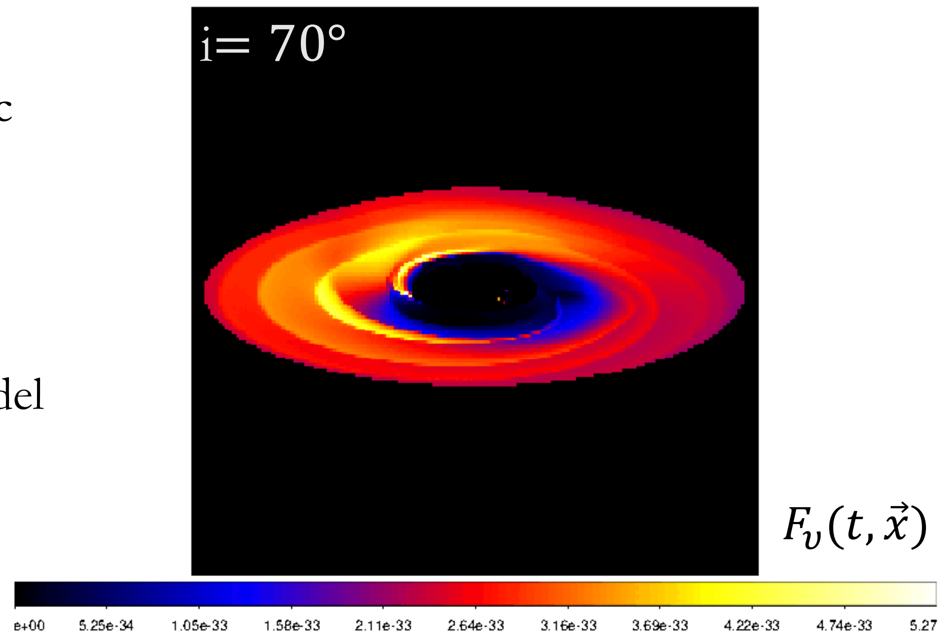


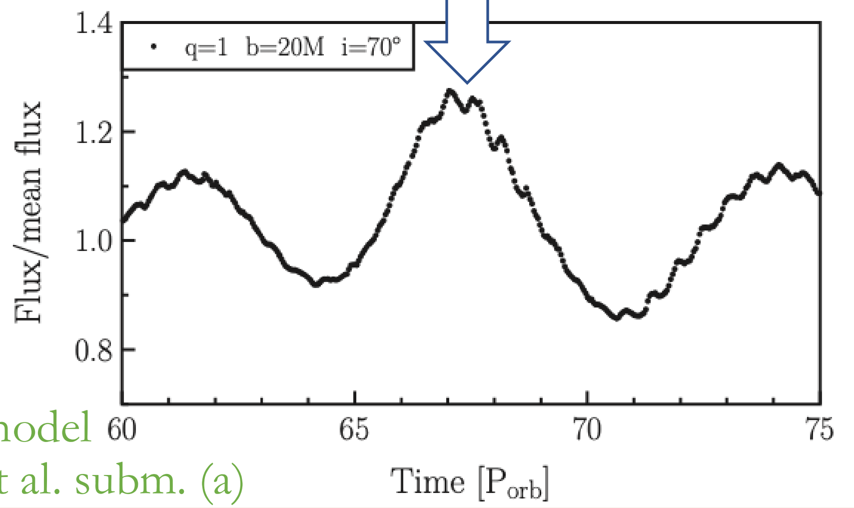
Surface density

-NOVAs

- GR ray-tracing in BBH metric
  with GYOTO (Vincent+11)
  no fast-light approximation

- Simple thermodynamical model
  $T \sim \Sigma^{\gamma - 1}, \gamma = 5/3$



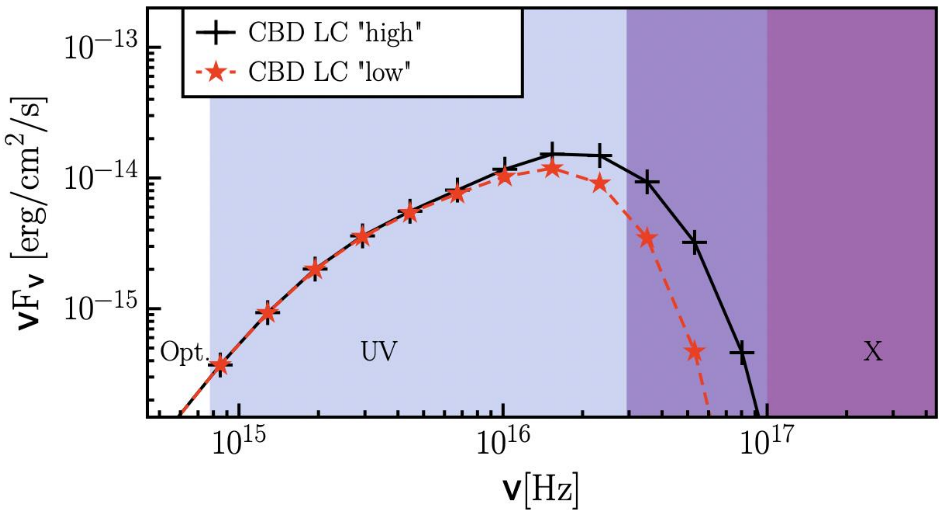


1. Cavity at ~2x separation
   (Artymowicz+94)
2. Streams (Artymowicz+96) & spiral arms
3. An overdensity, or « lump »
   (e.g. MacFadyen+08, Shi+12, Noble+12, Mignon-Risse+23…)

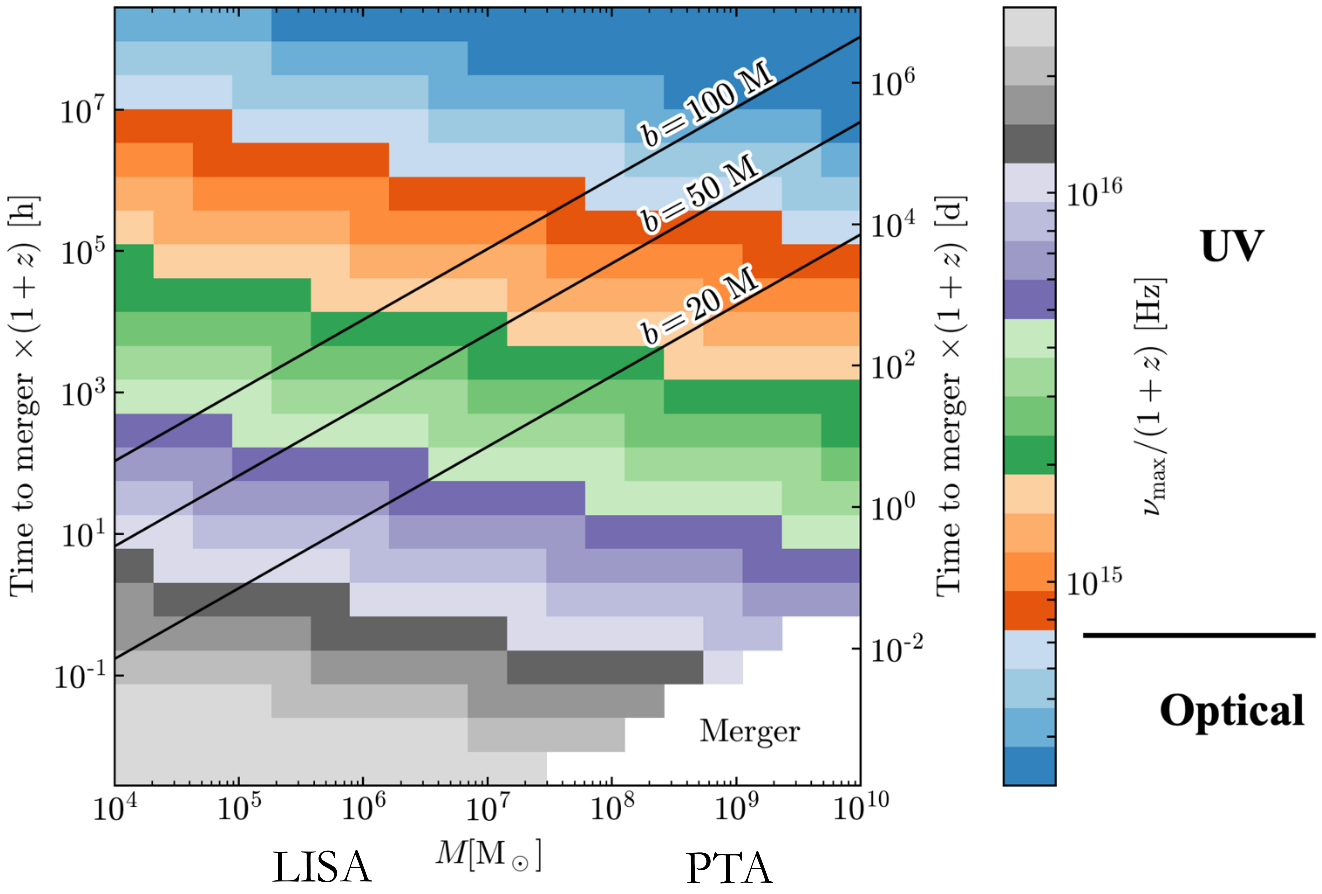
Variability toy model
Mignon-Risse et al. subm. (a)

Which frequency band to observe this modulation?

$M = 10^5 M_\odot$

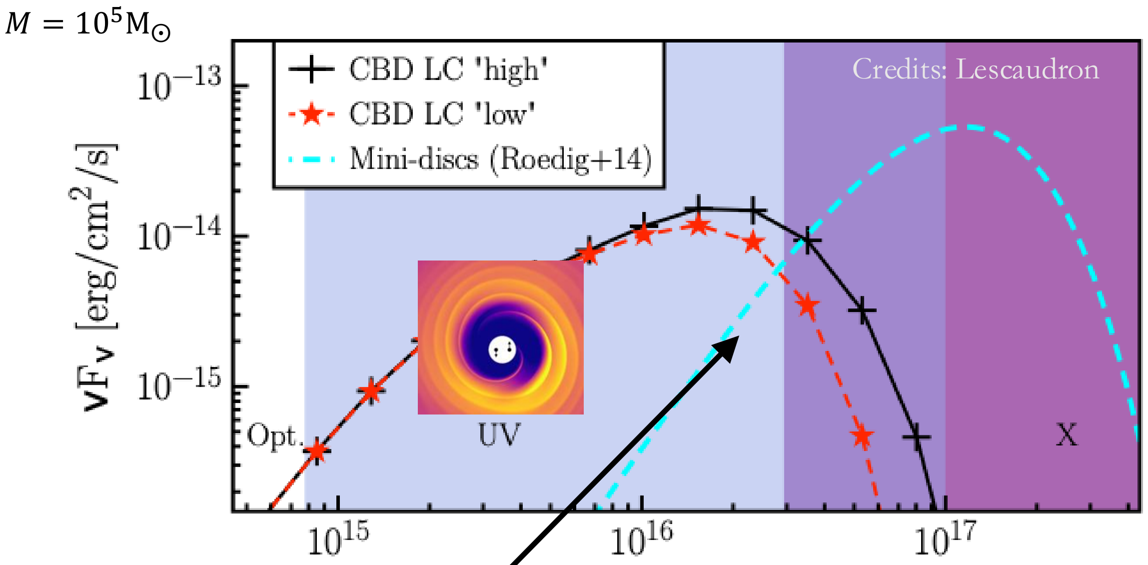


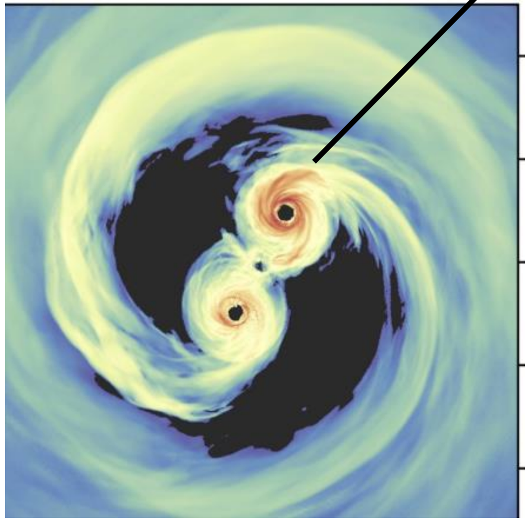
For $q = 1$, $\dot{M} = 0.5\,\dot{M}_{Edd}$
Time-to-merger estimated analytically (Peters 1964)

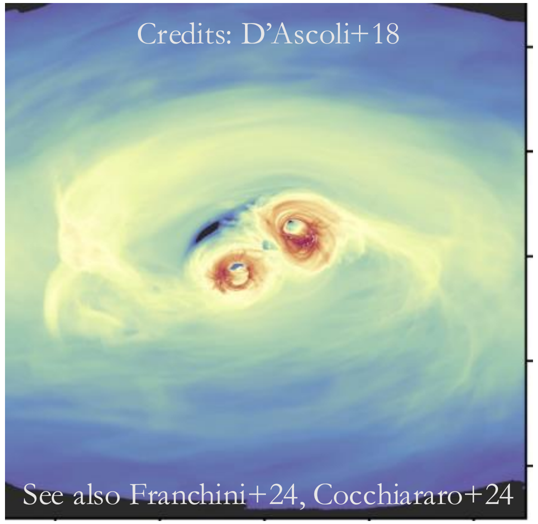


→ UV/optical for most LISA/PTA sources

Higher-frequency EM signatures from individual disks but…



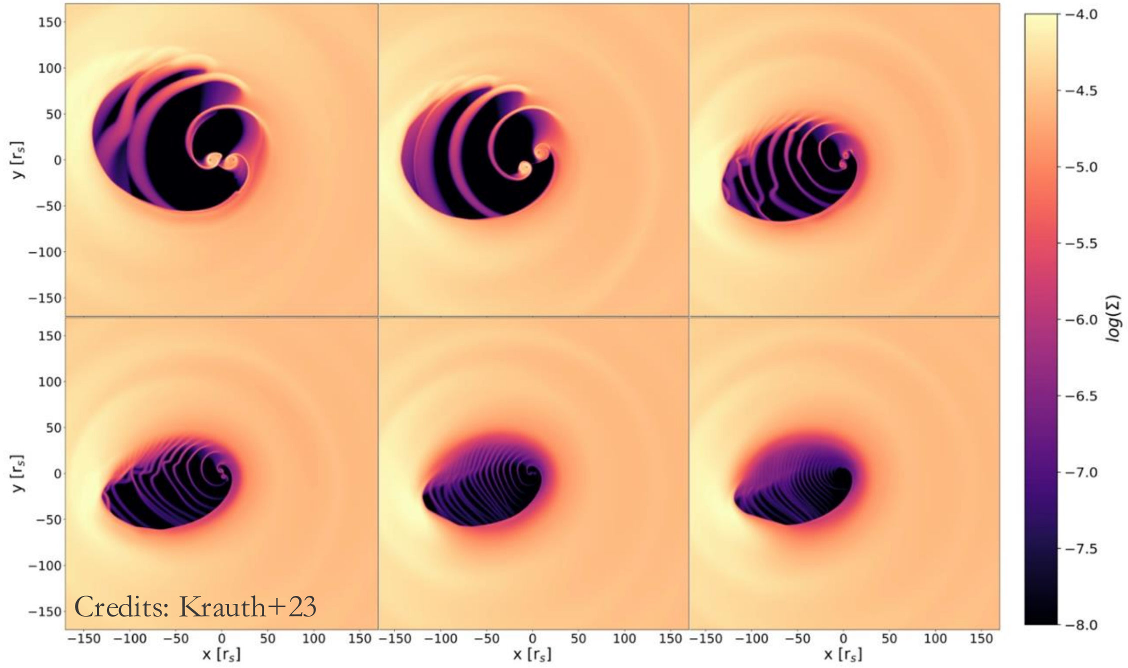




- Expected X-ray emission from « mini-disks »

but…

- Gas plunges → weak radiative efficiency (Gutiérrez+22)
- Between (inner) last stable orbit and (outer) tidal truncation
  → mini-disk disappearance (no GR: Krauth+23+25, Franchini+24)



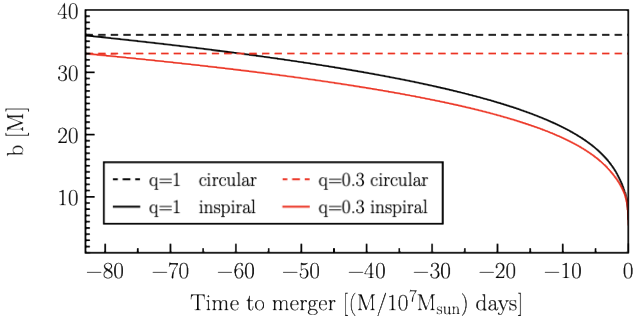
- Only the circumbinary disk remains
- but BBH inspirals faster: binary-disk « decoupling »
  e.g. Armitage & Natarayan 2002

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

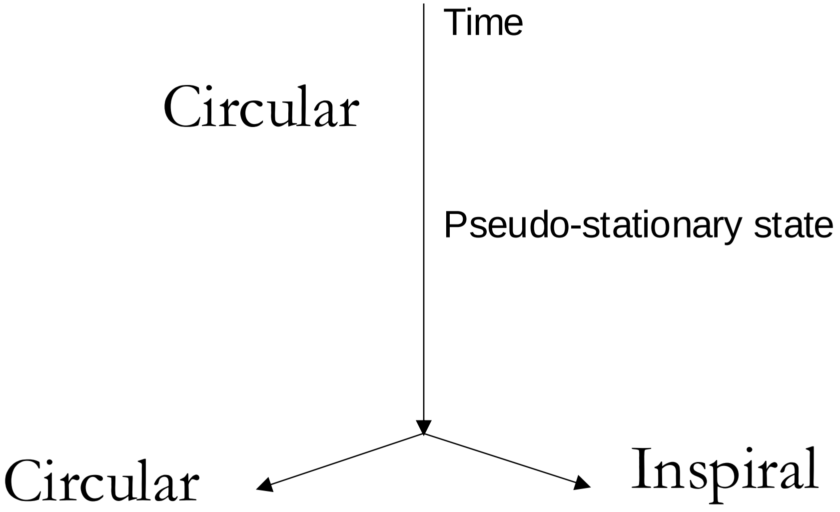
Modelling the inspiral

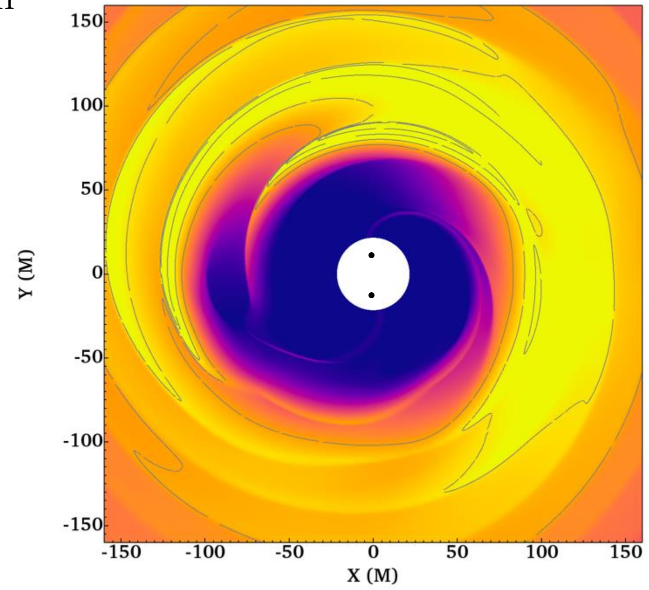
$q \in [0.3, 1]$

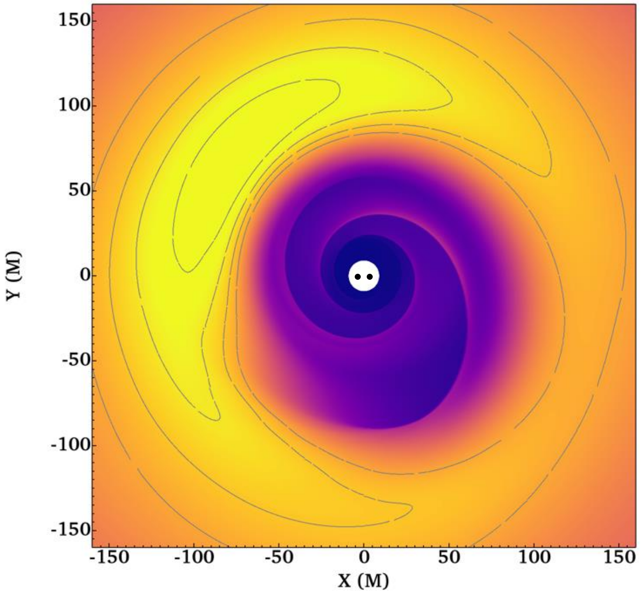
Time to merger : $80 \frac{M}{10^7 M_\odot}$ days



3.5 PN equation of motion







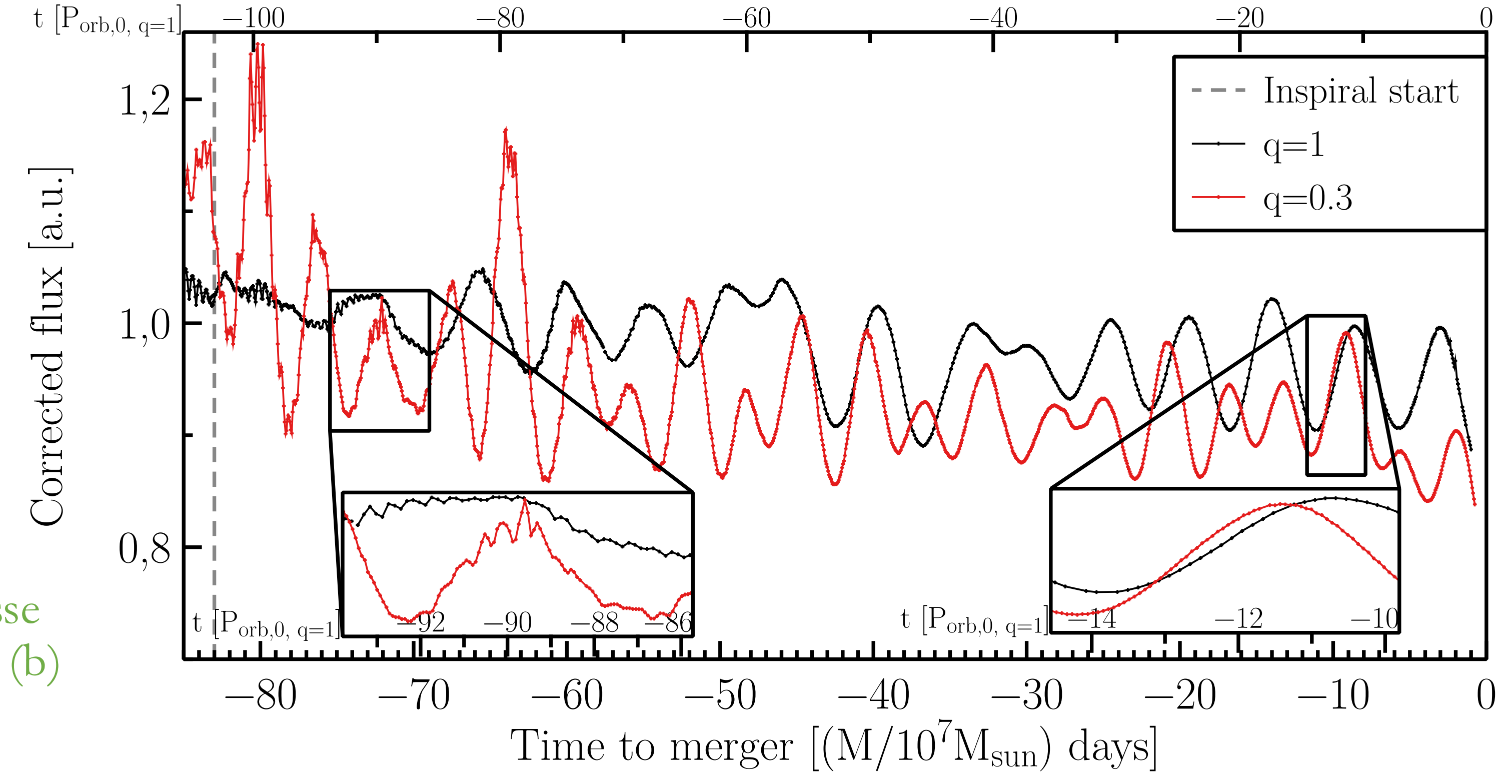
Numerical challenges :

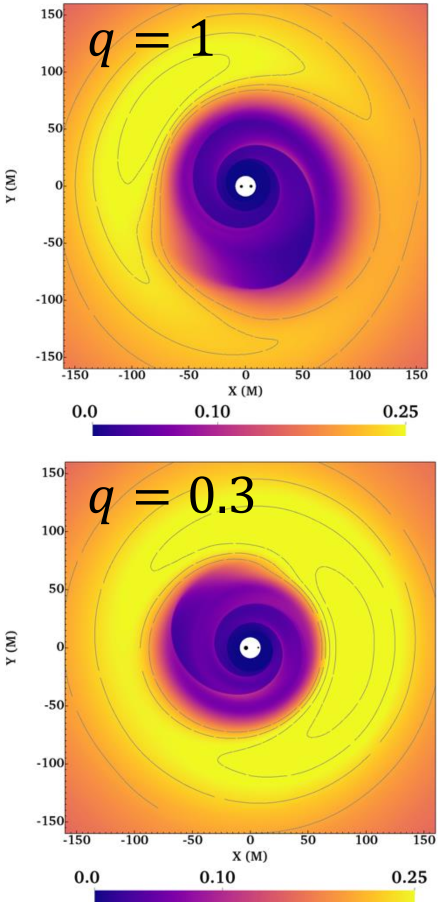
- Moving inner boundary
- Spatial resolution disk edge
- Inspiral time $\propto r_{12}^4$
- Inspiral time $\propto (1+q)^2/4q$

Electromagnetic signatures post-decoupling

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

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



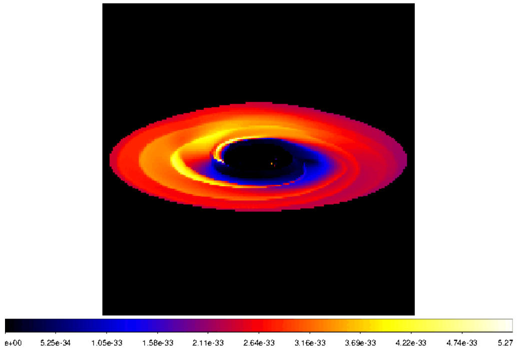


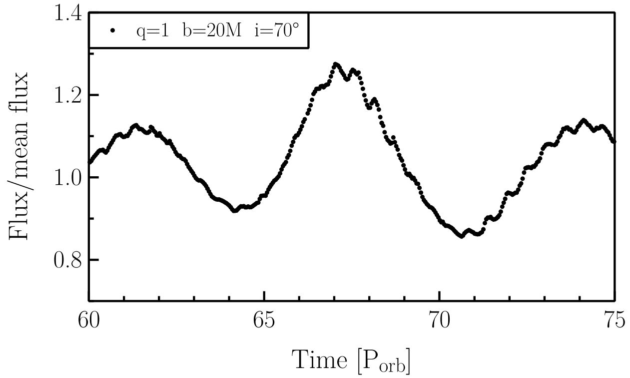
Mignon-Risse et al. subm. (b)

The lump and its modulation survive post-decoupling

Conclusions: EM appearance of pre-merger BBHs

- EM variability in the circular-orbit case

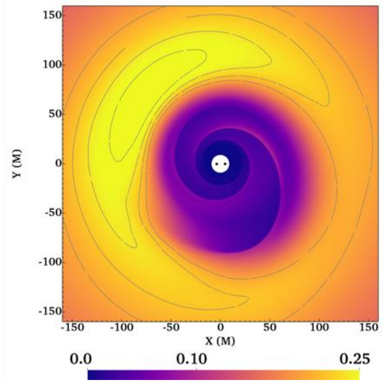


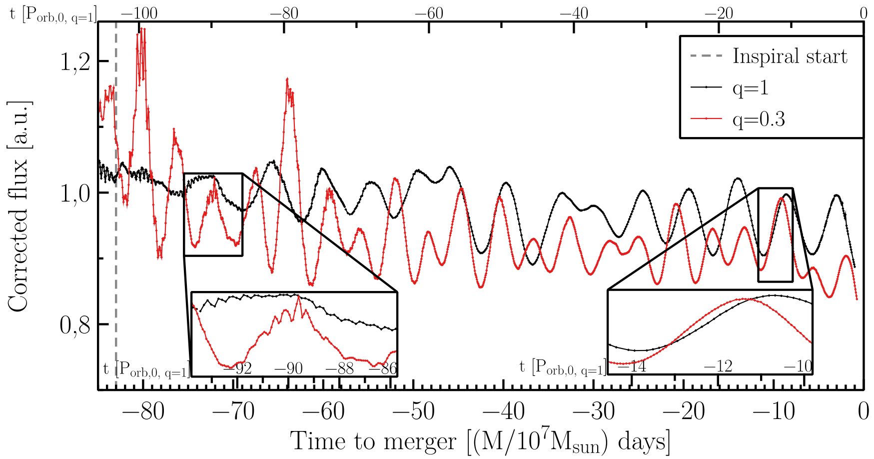


$q \in \{0.1, 0.3, 1\}$

MR+subm. (a)

- Lump modulation survival post-decoupling and until $< 1 \frac{M}{10^7 M_\odot}$ day before merger





MR+subm. (b)

while mini-disks will have disappeared already

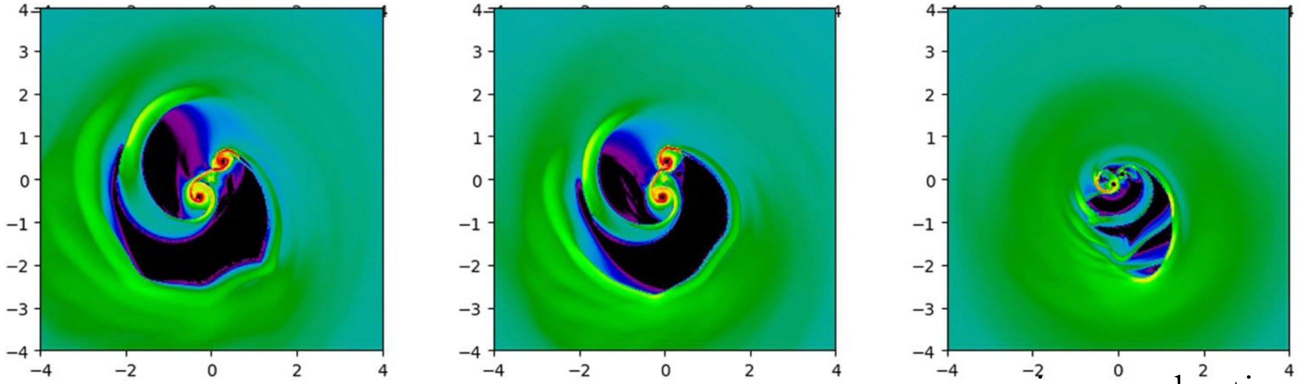
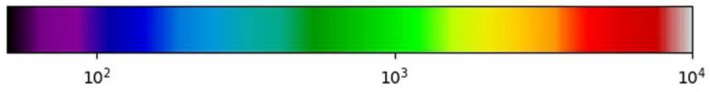
The last electromagnetic breath of binary black holes

Viscous-like heating follows the lump's orbit

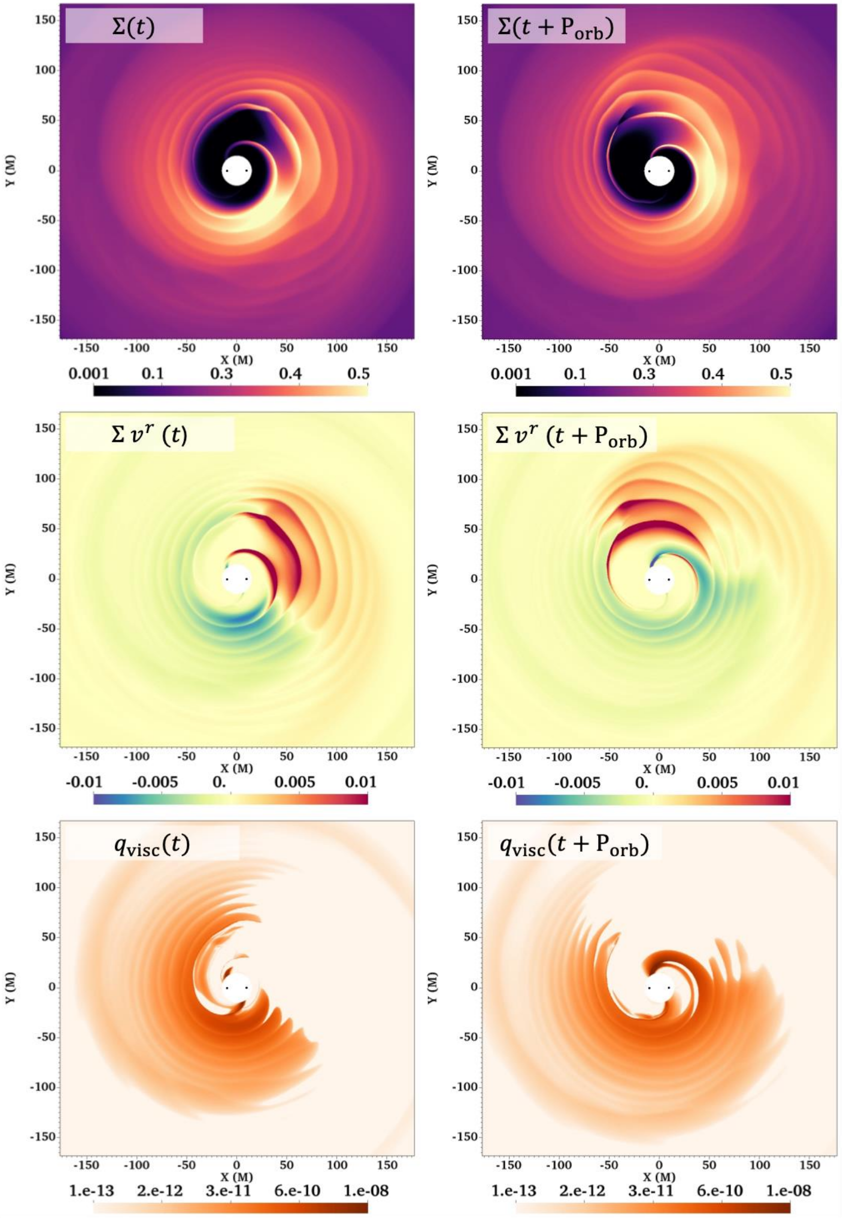
4.6 Viscous torques

From our discussion of the last section we see that an accretion disc can be an efficient 'machine' for slowly lowering material in the gravitational potential of an accreting object and extracting the energy as radiation. A vital part of this machinery is the process which converts the orbital kinetic energy into heat. The main unsolved problem of disc structure is the precise nature of this: it is surprising (and fortunate) that despite this lack of knowledge considerable progress has been achieved in some areas. Recent progress is beginning to illuminate the nature of viscosity in accretion discs and place some constraints on its magnitude and functional form.

The Accretion Power in Astrophysics
Frank, King & Raine 2003

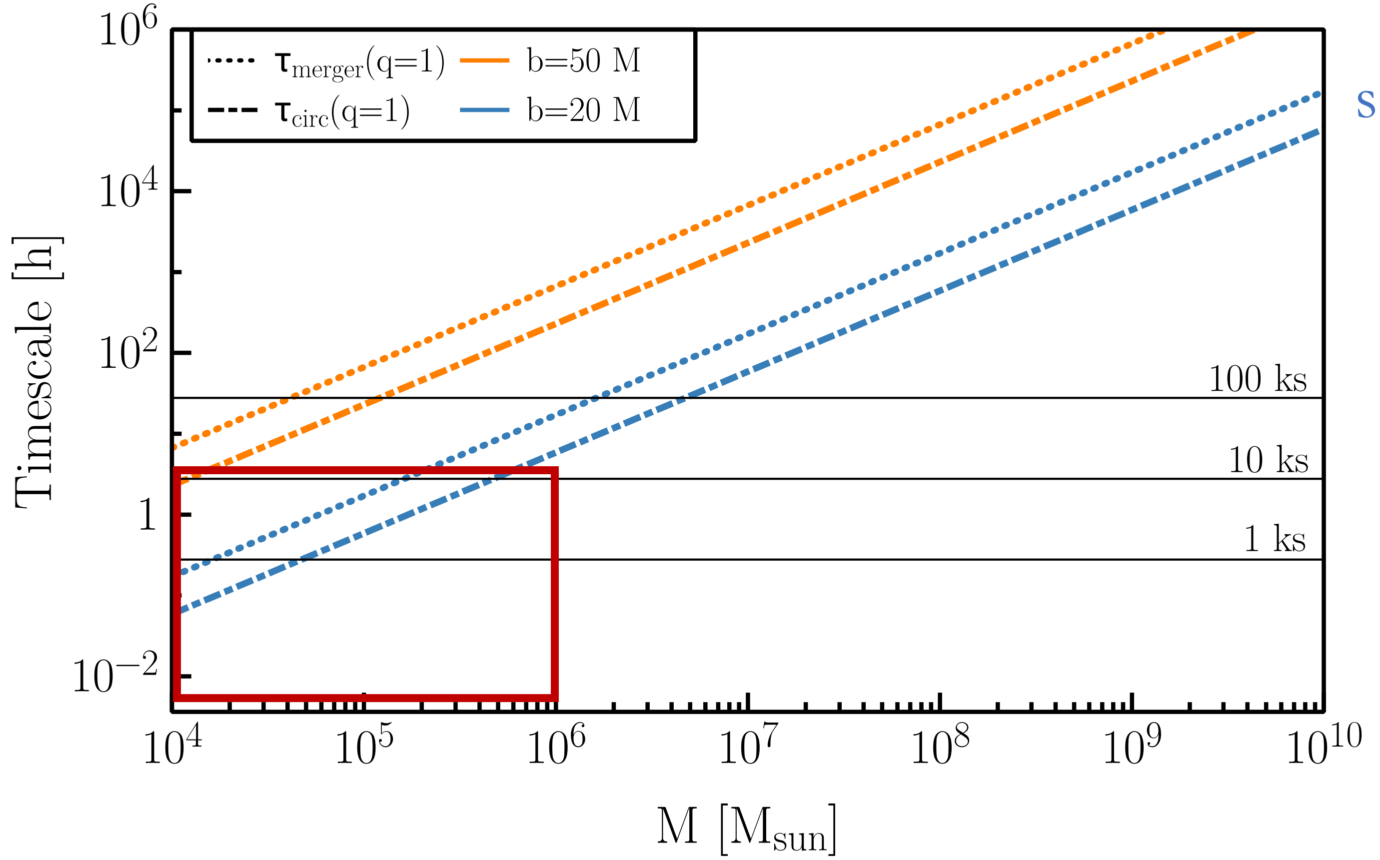
« viscous » heating
+ shock heating +
« radiative » cooling
Tang+18



Impact of inspiral on the EM variability

Q: Is the circular-orbit approximation valid for astrophysical sources ?

- Define $\tau_{\rm circ}$ as the time it takes for the separation to decrease by 10% : circular-orbit OK for $\Delta t < \tau_{\rm circ}$
- Compare $\tau_{\rm circ}$ to typical integration times of observations



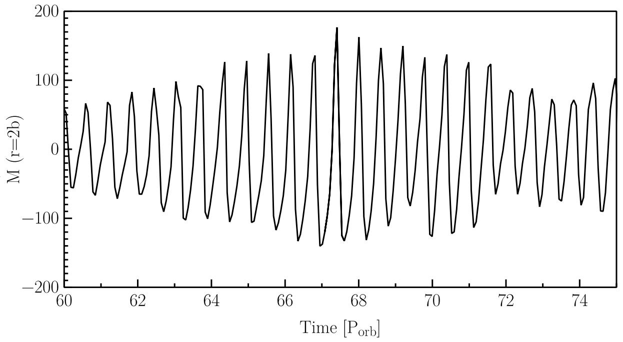
standard setup

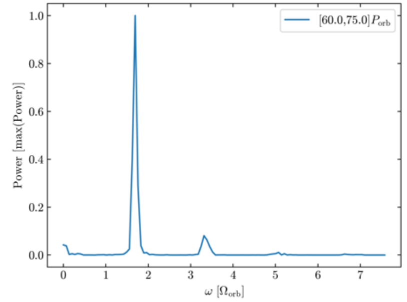
- Inspiral too short for $10^5 M_\odot$
- but slowed down if $q < 1$

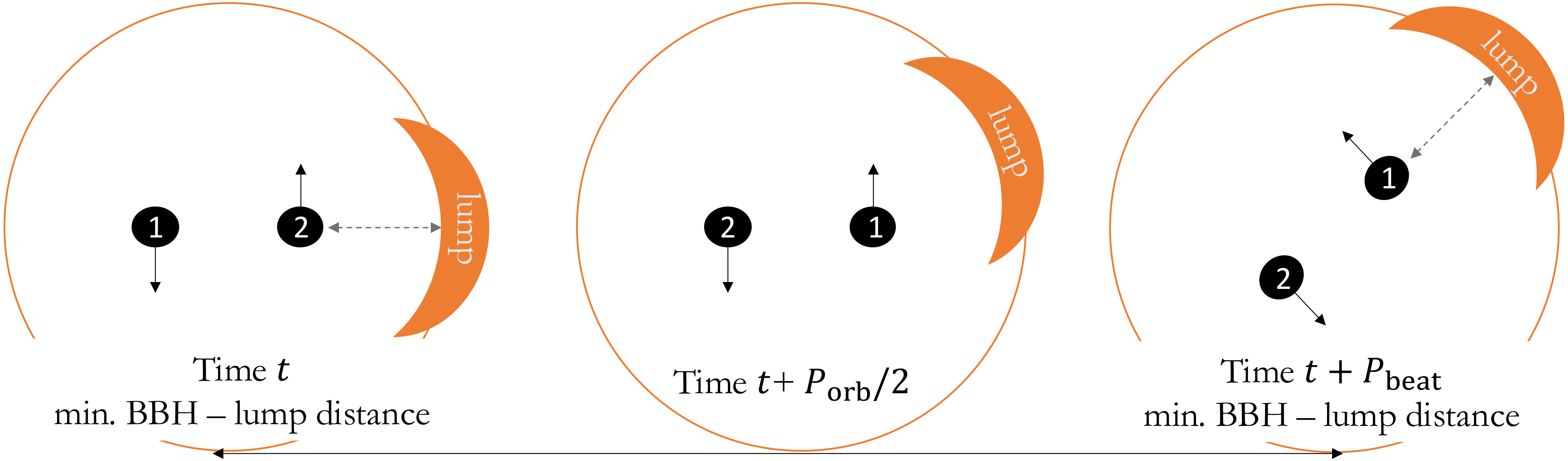
Need to consider inspiral motion

Fluid simulations: variability

- Accretion rate at $r = 2\,b \approx$ cavity radius
  (same variability at the domain innermost boundary)
  - variability at twice the binary-lump beat frequency
    $2\Omega_{\rm beat} = 2(\Omega_{\rm orb} - \Omega_{\rm lump}) \sim 1.7\Omega_{\rm orb}$







$P_{\rm orb}/2 < P_{\rm beat} < P_{\rm orb}$

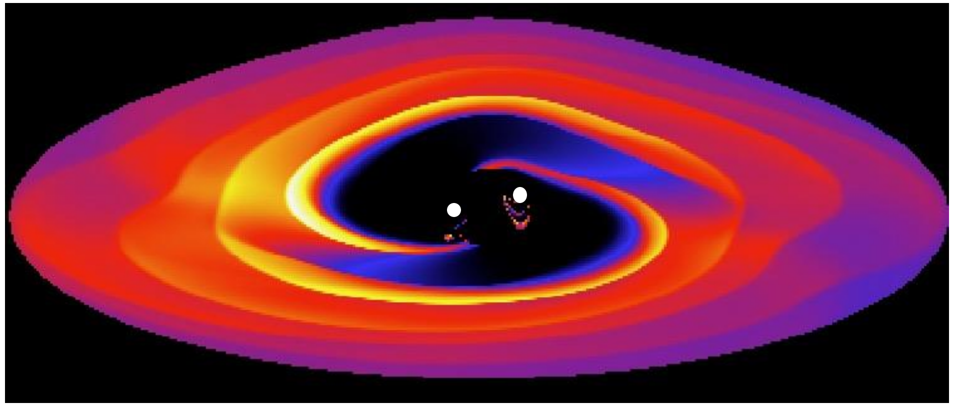
MR+subm. to MNRAS

- **Accretion rate variability → Electromagnetic variability ?**

Synthetic observations of pre-merger BBHs

- **GYOTO** code (Vincent+11) incorporating the **BBH approximate metric** (Ireland+16)
- Thermal emission, thin disk approximation (Shakura & Sunyaev, 1973)
- Putting physical units back: mass scaling from Lin+13 ($M = 10^5 M_\odot$; $T_{in} = 0.1$ keV) as reference

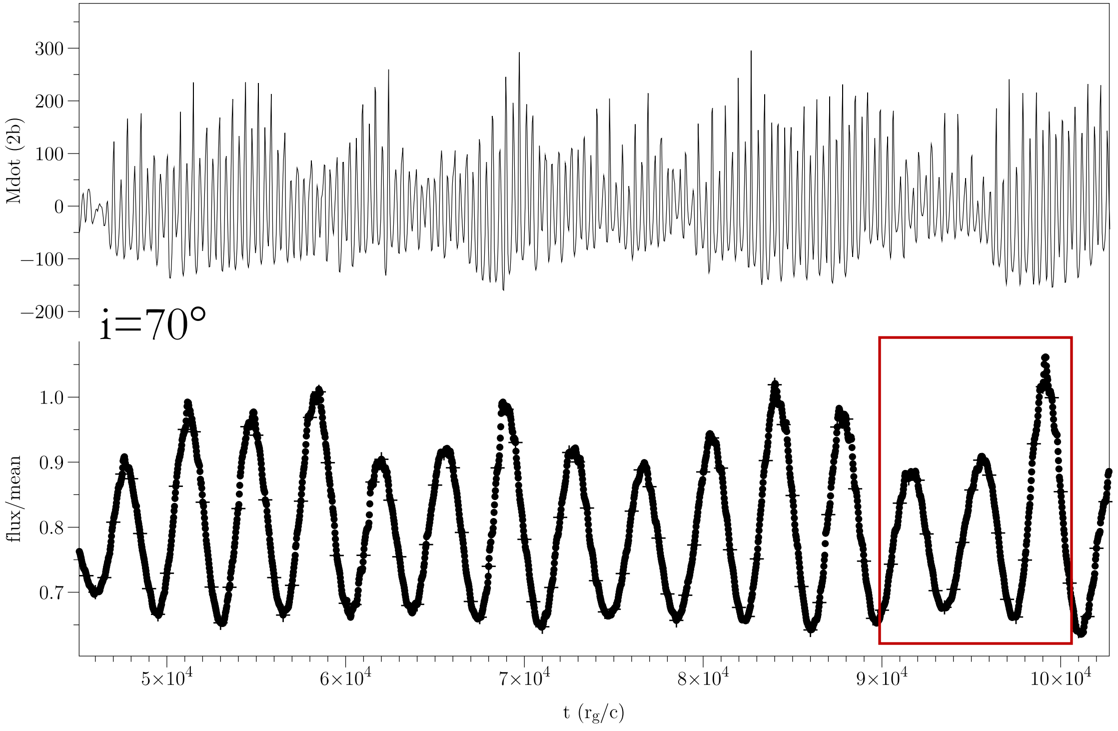
➢ Obtain the multi-wavelength emission map
  - ➢ The metric evolves as photons propagate
  - ➢ Emission map composed of photons of different time-origin (hence, fluid outputs!)



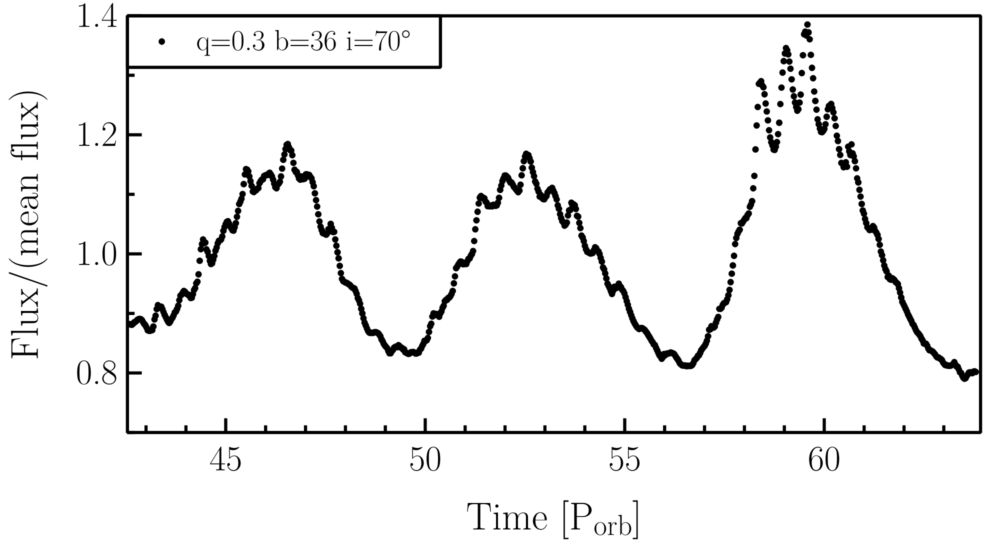
Timing features

- Accretion rate: proxy for the luminosity? (e.g. Krauth+23)

$q = 0.1;\ b = 20\mathrm{r_g}$



$q = 0.3;\ b = 36\mathrm{r_g}$



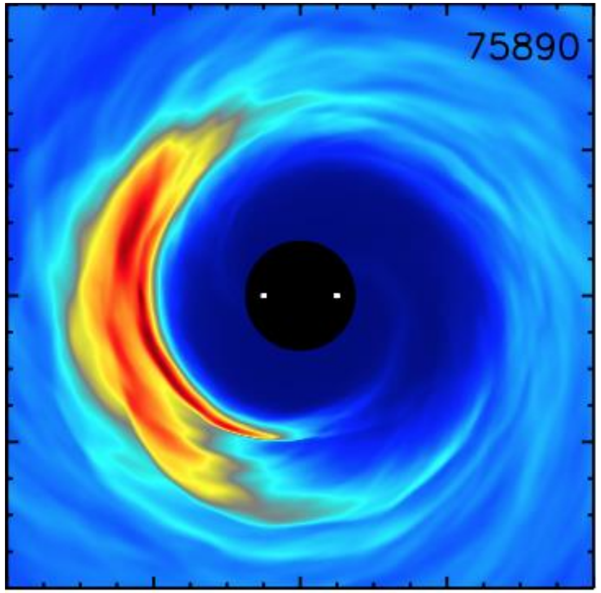
- Additional modulation at the semi-orbital period

$$P_{\mathrm{orb}} = 0.3\frac{M}{10^6 M_\odot}\ \mathrm{ks}$$

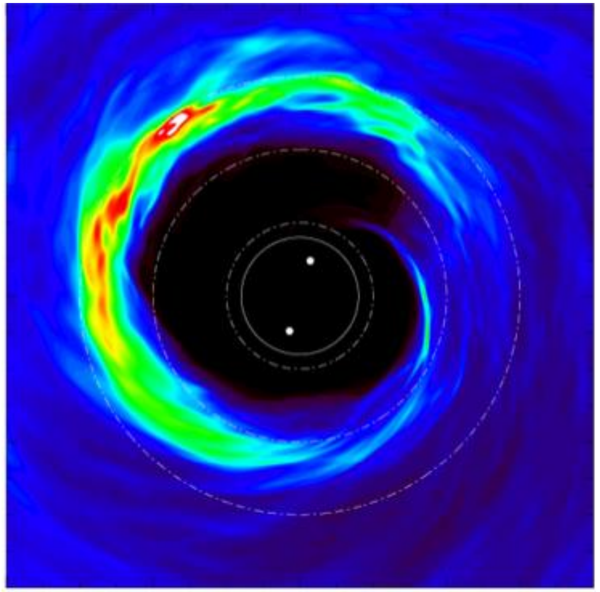
$$P_{\mathrm{lump}} \sim 1.5\frac{M}{10^6 M_\odot}\ \mathrm{ks}$$

Double EM variability: the signature of circumbinary disks around BBHs? (MR+subm.)

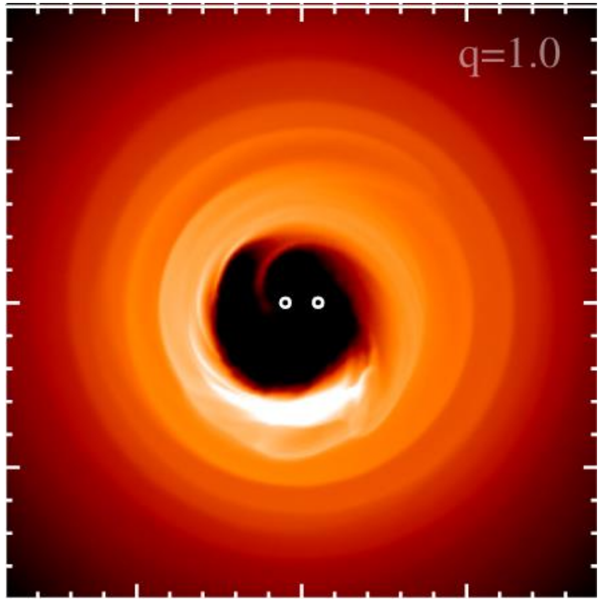
A robust prediction?



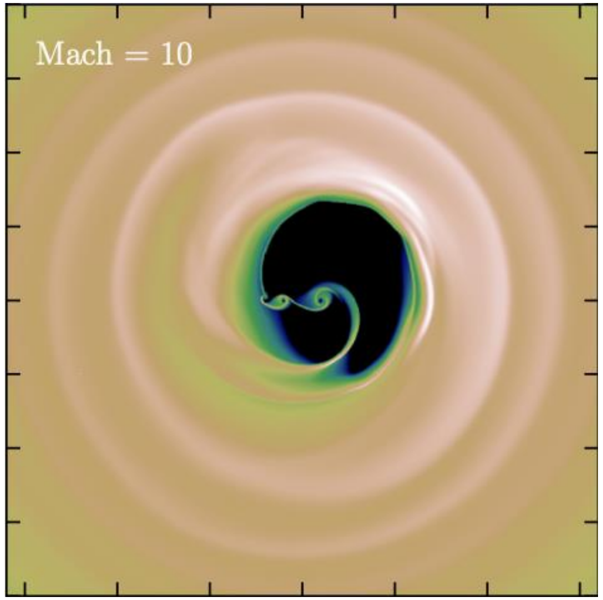
Noble+12, 3D GRMHD



Shi+12, 3D MHD



Ragusa+20, 3D SPH

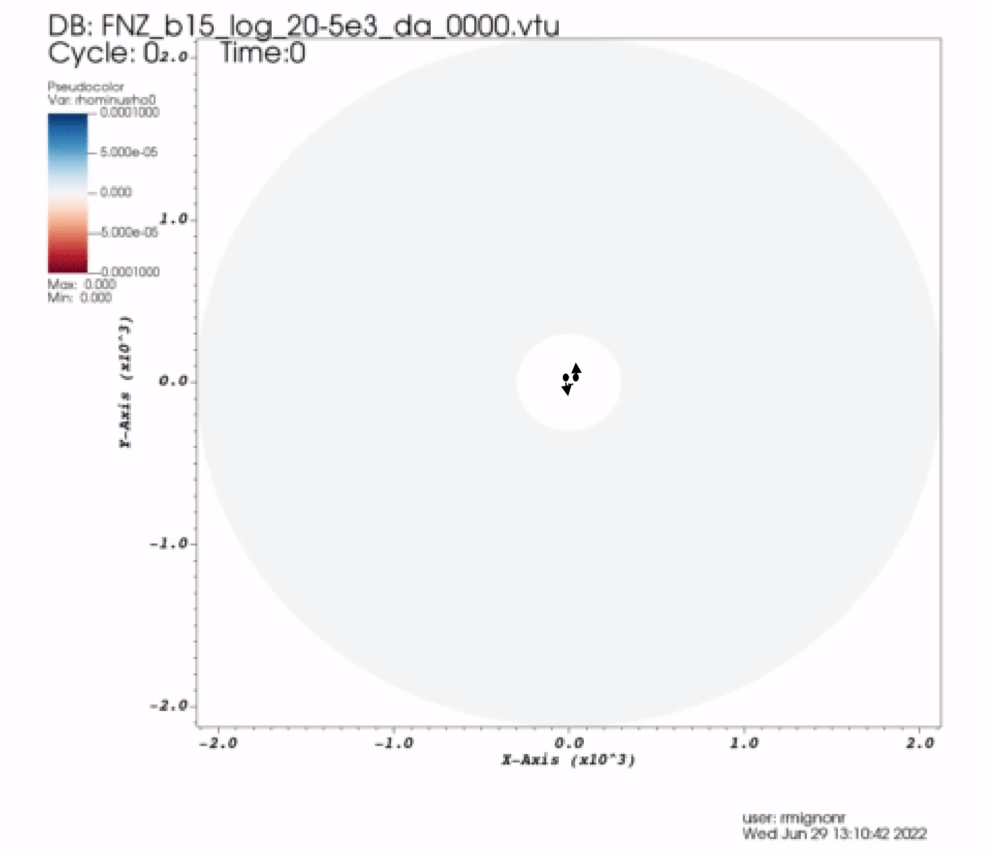


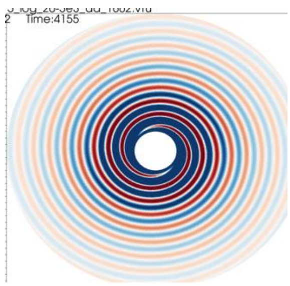
Tiede+20, 2D Hydro

Impact of GWs on the outer disk

Retardation effects?

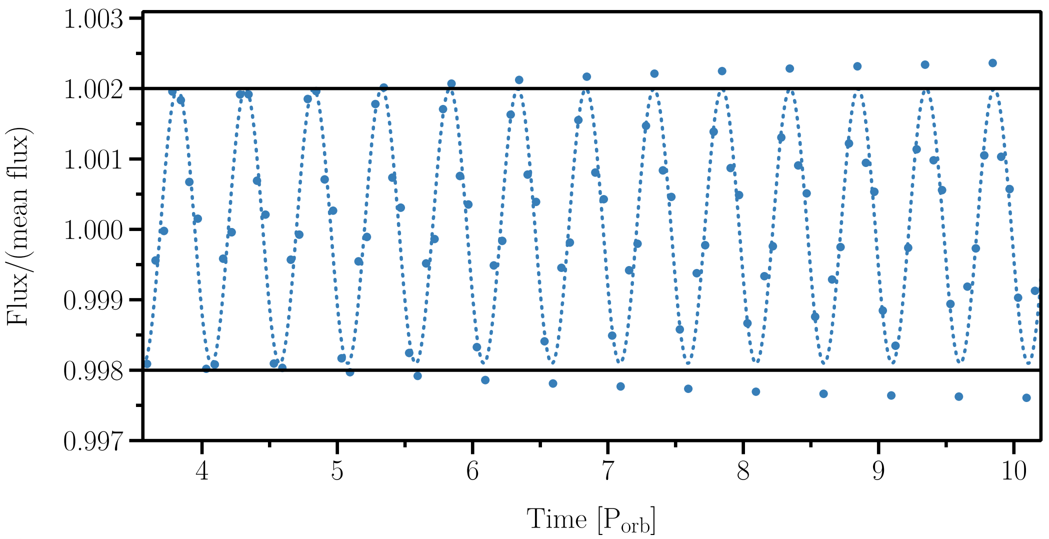
- Disk radius ~2000M = $2000r_g$
- Orbital period ~600M = $600r_g/c$





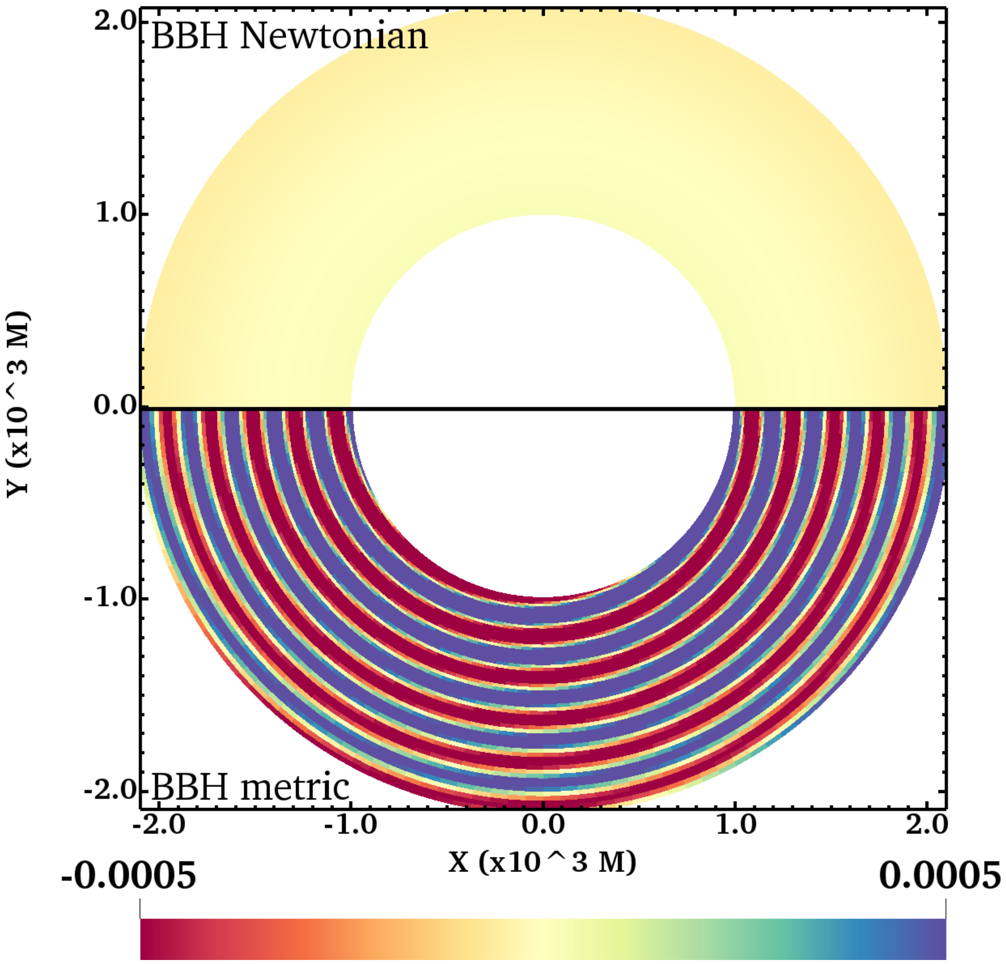
Weak (<1%) but increasing modulation of the EM flux

Mignon-Risse et al. 2023, Astronomical Notes

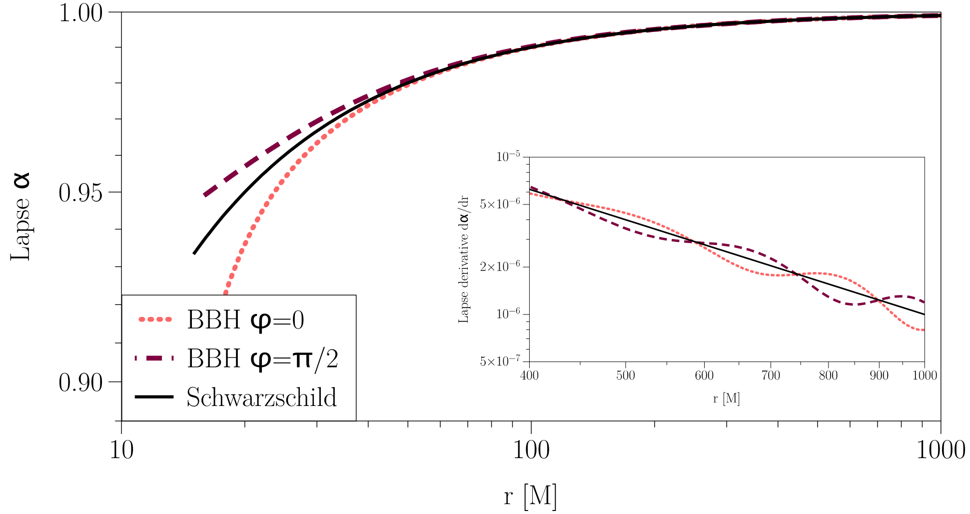


Impact of GWs on the outer disk

1. Not a 2-armed spiral as in Newtonian gravity

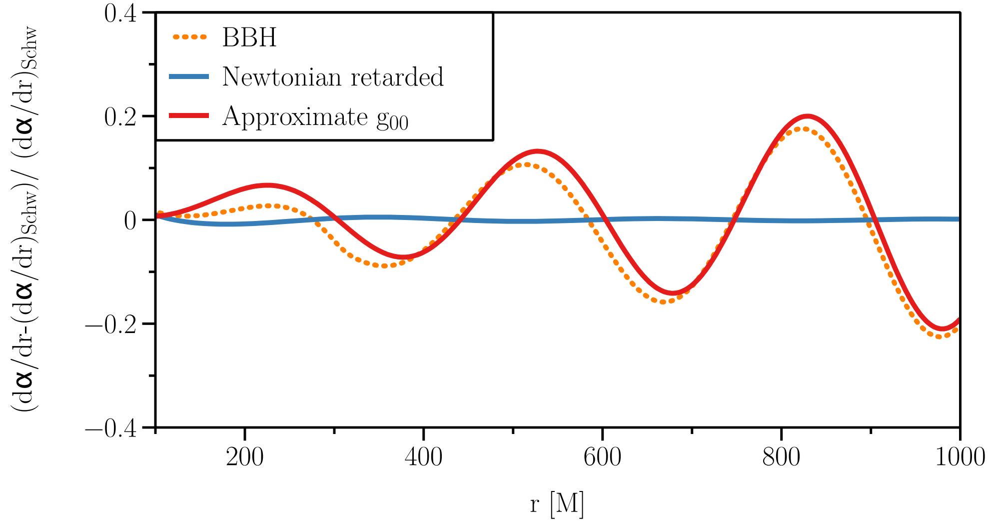


2. Oscillating lapse function: retardation effects → GWs



3. Not reproducible with retarded Newtonian potential

4. Diagonal terms of the source stress-energy tensor



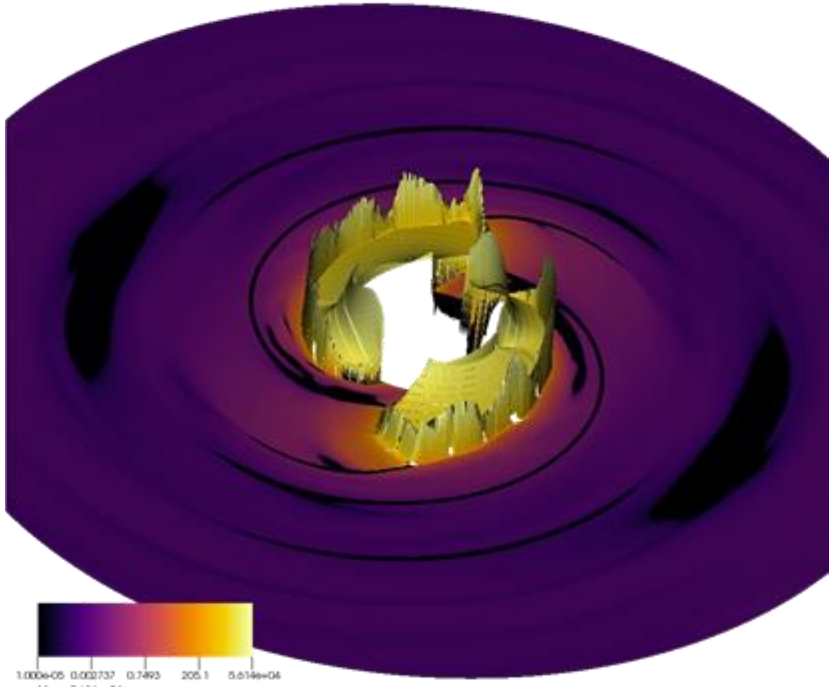
A possible instability origin for the lump

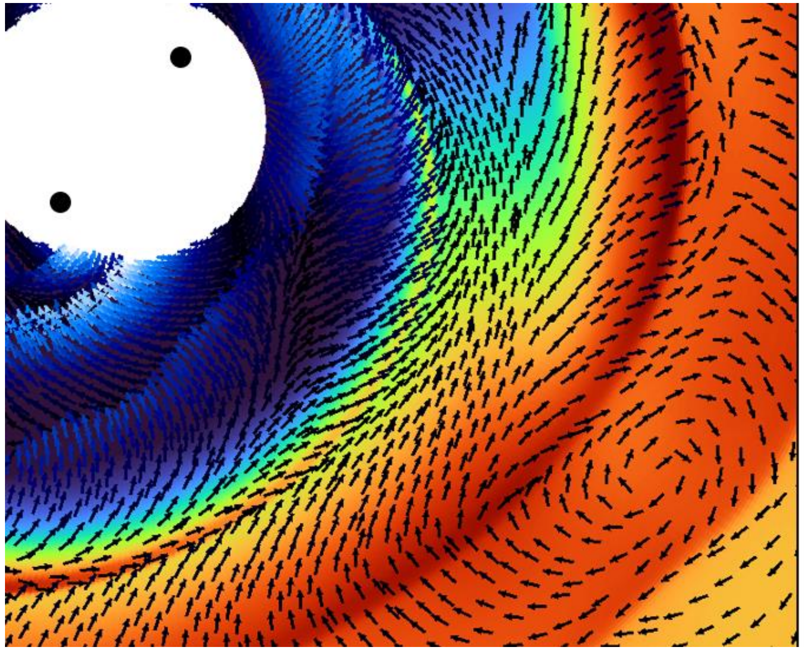
i. Why do we care ?

- Lump is claimed to be a distinct (observational?) feature of accreting BBHs

ii. Is Rossby Wave Instability a good candidate ?

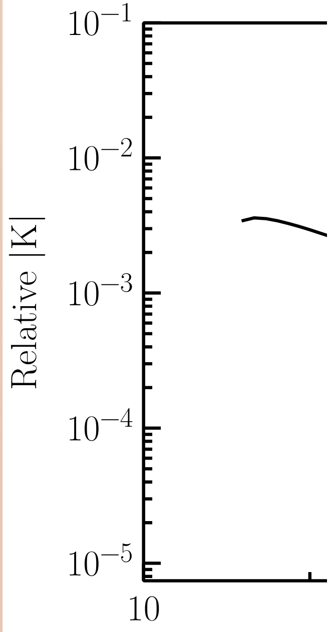
1. Exponential growth
2. Rossby Wave Instability criterion fullfilled (extremum in vortensity)
3. Presence of vortices





Metric validation

- Correct ap… view
  as d…



$$g_{tt} = \frac{605284\left(\frac{\sqrt{\frac{1}{2}}\,y\cos\left(\frac{389}{200000}\sqrt{\frac{1}{2}}\left(t-\sqrt{x^2+y^2+z^2}\right)\right)}{\sqrt{x^2+y^2+z^2}}-\frac{\sqrt{\frac{1}{2}}\,x\sin\left(\frac{389}{200000}\sqrt{\frac{1}{2}}\left(t-\sqrt{x^2+y^2+z^2}\right)\right)}{\sqrt{x^2+y^2+z^2}}\right)^2-\frac{2\left(151321x^2+151321y^2+151321z^2-120000000000\right)\left(\frac{x\cos\left(\frac{389}{200000}\sqrt{\frac{1}{2}}\left(t-\sqrt{x^2+y^2+z^2}\right)\right)}{\sqrt{x^2+y^2+z^2}}+\frac{y\sin\left(\frac{389}{200000}\sqrt{\frac{1}{2}}\left(t-\sqrt{x^2+y^2+z^2}\right)\right)}{\sqrt{x^2+y^2+z^2}}\right.}{x^2+y^2+z^2}+151321\cos\left(\frac{389}{200000}\sqrt{\frac{1}{2}}\left(t-\sqrt{x^2+y^2+z^2}\right)\right)^2+151321\sin\left(\frac{389}{200000}\sqrt{\frac{1}{2}}\left(t-\sqrt{x^2+y^2+z^2}\right)\right)^2+\frac{933600000\left(\frac{\sqrt{\frac{1}{2}}\,y\cos\left(\frac{389}{200000}\sqrt{\frac{1}{2}}\left(t-\sqrt{x^2+y^2+z^2}\right)\right)}{\sqrt{x^2+y^2+z^2}}-\frac{\sqrt{\frac{1}{2}}\,x\sin\left(\frac{389}{200000}\sqrt{\frac{1}{2}}\left(t-\sqrt{x^2+y^2+z^2}\right)\right)}{\sqrt{x^2+y^2+z^2}}\right)\left(\frac{x\cos\left(\frac{389}{200000}\sqrt{\frac{1}{2}}\left(t-\sqrt{x^2+y^2+z^2}\right)\right)}{\sqrt{x^2+y^2+z^2}}+\frac{y\sin\left(\frac{389}{200000}\sqrt{\frac{1}{2}}\left(t-\sqrt{x^2+y^2+z^2}\right)\right)}{\sqrt{x^2+y^2+z^2}}\right)}{\sqrt{x^2+y^2+z^2}}-\frac{80000000000\left(\cos\left(\frac{389}{200000}\sqrt{\frac{1}{2}}\left(t-\sqrt{x^2+y^2+z^2}\right)\right)^2+\sin\left(\frac{389}{200000}\sqrt{\frac{1}{2}}\left(t-\sqrt{x^2+y^2+z^2}\right)\right)^2\right)}{x^2+y^2+z^2}-\frac{128000000}{\sqrt{x^2+y^2+z^2}}-320000}{16000000\sqrt{x^2+y^2+z^2}}+\frac{4}{\sqrt{x^2+y^2+z^2}}-1$$

$$389\sqrt{\frac{1}{2}}\left(2421136\left(\frac{\sqrt{\frac{1}{2}}\,y\cos\left(\frac{389}{200000}\sqrt{\frac{1}{2}}\left(t-\sqrt{x^2+y^2+z^2}\right)\right)}{\sqrt{x^2+y^2+z^2}}-\frac{\sqrt{\frac{1}{2}}\,x\sin\left(\frac{389}{200000}\sqrt{\frac{1}{2}}\left(t-\sqrt{x^2+y^2+z^2}\right)\right)}{\sqrt{x^2+y^2+z^2}}\right)^2-453963\left(\frac{x\cos\left(\frac{389}{200000}\sqrt{\frac{1}{2}}\left(t-\sqrt{x^2+y^2+z^2}\right)\right)}{\sqrt{x^2+y^2+z^2}}+\frac{y\sin\left(\frac{389}{200000}\sqrt{\frac{1}{2}}\left(t-\sqrt{x^2+y^2+z^2}\right)\right)}{\sqrt{x^2+y^2+z^2}}\right)^2\right.$$

$$+\frac{6224000\sqrt{\frac{1}{2}}\,y\cos\left(\frac{389}{200000}\sqrt{\frac{1}{2}}\left(t-\sqrt{x^2+y^2+z^2}\right)\right)}{\sqrt{x^2+y^2+z^2}}-\frac{6224000\sqrt{\frac{1}{2}}\,x\sin\left(\frac{389}{200000}\sqrt{\frac{1}{2}}\left(t-\sqrt{x^2+y^2+z^2}\right)\right)}{\sqrt{x^2+y^2+z^2}}$$

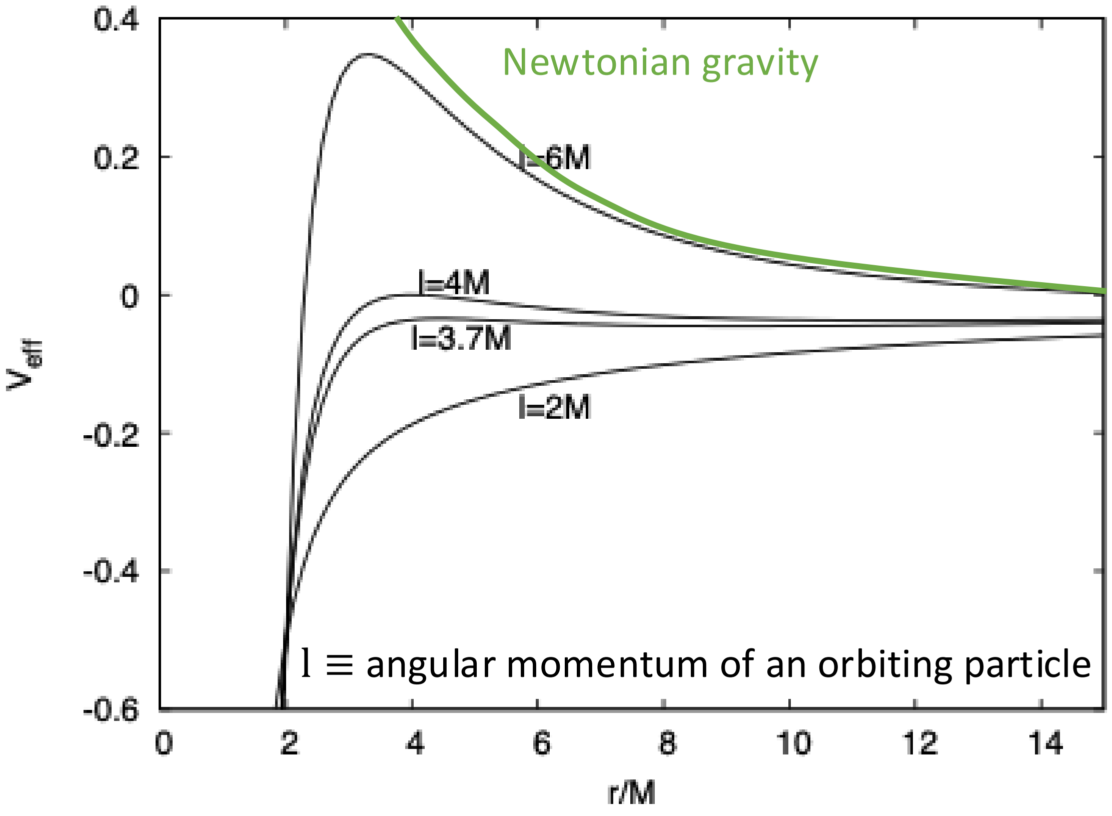
$$+\frac{933600000\left(\frac{\sqrt{\frac{1}{2}}\,y\cos\left(\frac{389}{200000}\sqrt{\frac{1}{2}}\left(t-\sqrt{x^2+y^2+z^2}\right)\right)}{\sqrt{x^2+y^2+z^2}}-\frac{\sqrt{\frac{1}{2}}\,x\sin\left(\frac{389}{200000}\sqrt{\frac{1}{2}}\left(t-\sqrt{x^2+y^2+z^2}\right)\right)}{\sqrt{x^2+y^2+z^2}}\right)\left(\frac{x\cos\left(\frac{389}{200000}\sqrt{\frac{1}{2}}\left(t-\sqrt{x^2+y^2+z^2}\right)\right)}{\sqrt{x^2+y^2+z^2}}+\frac{y\sin\left(\frac{389}{200000}\sqrt{\frac{1}{2}}\left(t-\sqrt{x^2+y^2+z^2}\right)\right)}{\sqrt{x^2+y^2+z^2}}\right)}{\sqrt{x^2+y^2+z^2}}$$

$$+\frac{240000000000\left(\frac{x\cos\left(\frac{389}{200000}\sqrt{\frac{1}{2}}\left(t-\sqrt{x^2+y^2+z^2}\right)\right)}{\sqrt{x^2+y^2+z^2}}+\frac{y\sin\left(\frac{389}{200000}\sqrt{\frac{1}{2}}\left(t-\sqrt{x^2+y^2+z^2}\right)\right)}{\sqrt{x^2+y^2+z^2}}\right)^2}{x^2+y^2+z^2}+\frac{3200000000\left(\frac{x\cos\left(\frac{389}{200000}\sqrt{\frac{1}{2}}\left(t-\sqrt{x^2+y^2+z^2}\right)\right)}{\sqrt{x^2+y^2+z^2}}+\frac{y\sin\left(\frac{389}{200000}\sqrt{\frac{1}{2}}\left(t-\sqrt{x^2+y^2+z^2}\right)\right)}{\sqrt{x^2+y^2+z^2}}\right)}{\sqrt{x^2+y^2+z^2}}$$

$$80000000000\left(\cos\left(\frac{389}{200000}\sqrt{\frac{1}{2}}\left(t-\sqrt{x^2+y^2+z^2}\right)\right)^2+\sin\left(\frac{389}{200000}\sqrt{\frac{1}{2}}\left(t-\sqrt{x^2+y^2+z^2}\right)\right)^2\right)$$

Example of a direct effect from GR

- Around a Schwarzschild black hole exists a so-called « innermost stable circular orbit » (ISCO) – Fig. 4.1 of your lecture notes



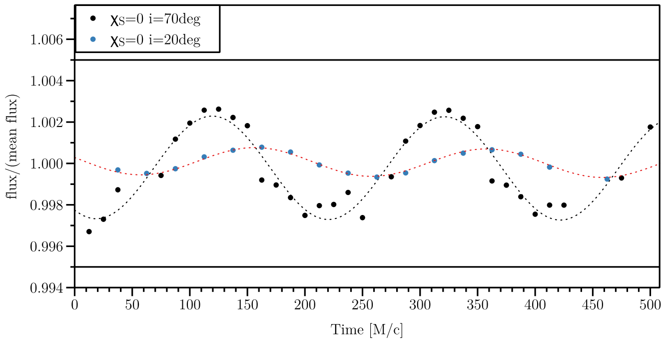
l ↗ ⇒ centrifugal force (outward) ↗

- ➢ An accretion disk should be truncated at this ISCO

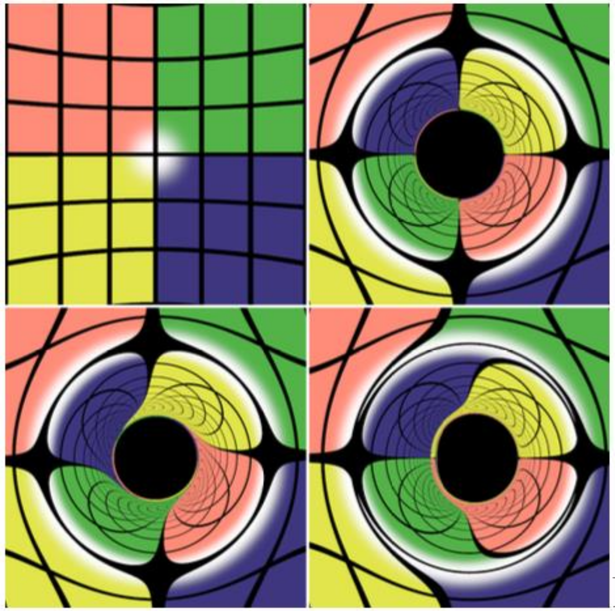
Why using a GR ray-tracing code ?

- **Concept: solve the geodesic equation for photons back from the observer (Earth) to the source**

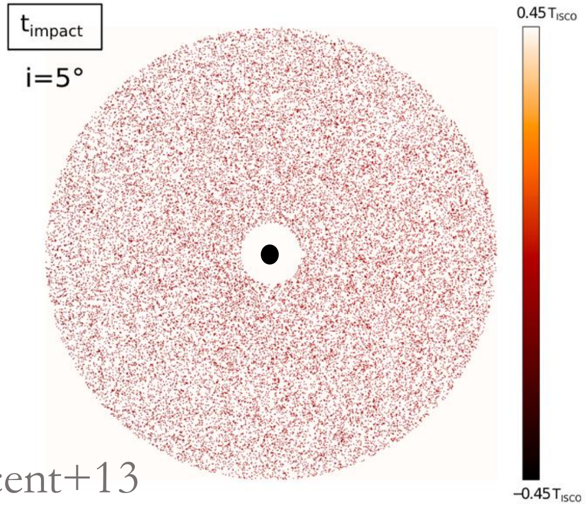
- **Relativistic ray-tracing:**
  e.g. Doppler beaming: matter approaching the observer appears brighter
  → an orbiting dense blob produces a sinusoid in the luminosity



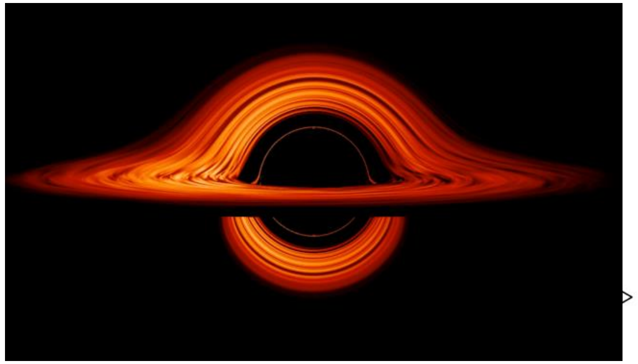
- **GR** effects:
  Light deflection (p. 57)
  « Shapiro effect »: time delay



Bohn+15



Vincent+13



Inspiral equation of motion

zero ⇔ circular orbit

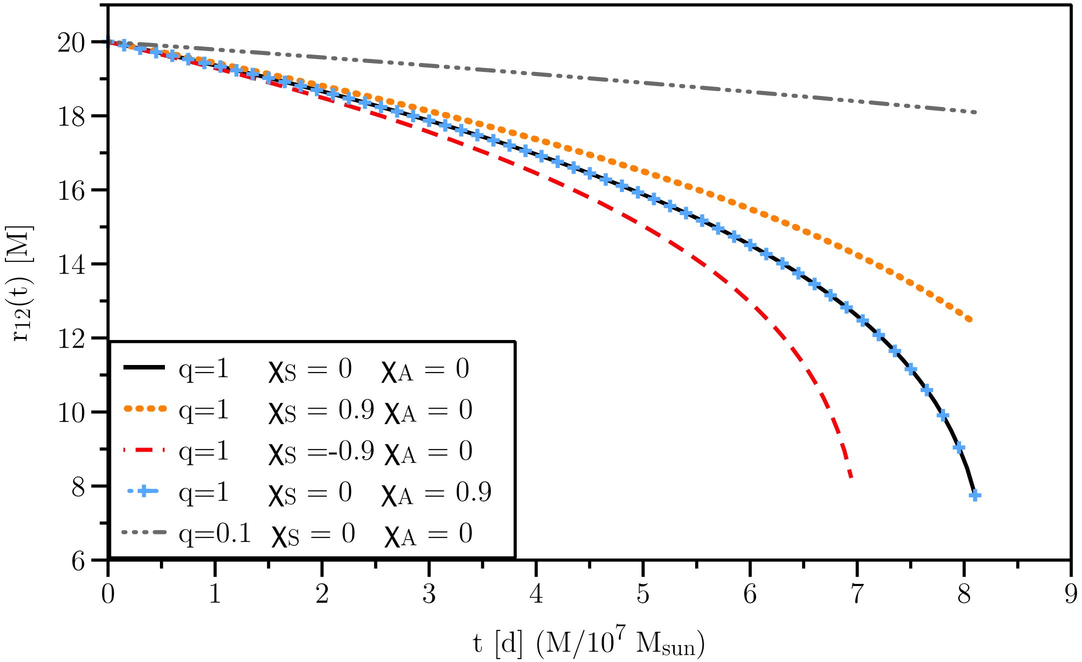
$$\dot{E} = -\mathcal{F} - \dot{M}$$

Rate of change of orbital binding energy

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

Change in mass
(« tidal heating »)

Inspiral equation of motion



zero ⇔ circular orbit

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

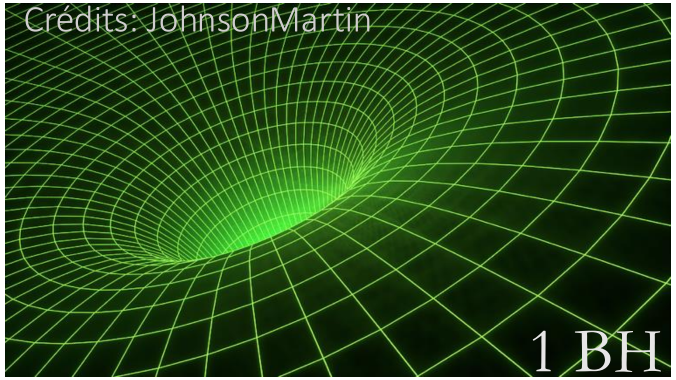
Rate of change of orbital binding energy

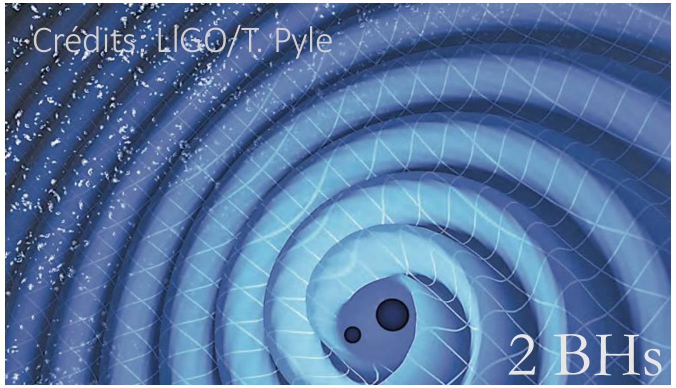
$$\Rightarrow \quad \frac{dt}{dr_{12}} = -\frac{dE(r_{12})/dr_{12}}{\mathcal{F}(r_{12}) + \dot{M}(r_{12})}$$

Change in mass (« tidal heating »)

- 3.5 Post-Newtonian equation of motion validated
- **Slower inspiral for *q* ↘**

From single to binary black holes



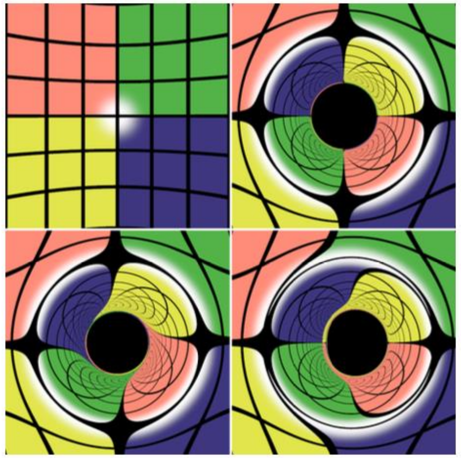


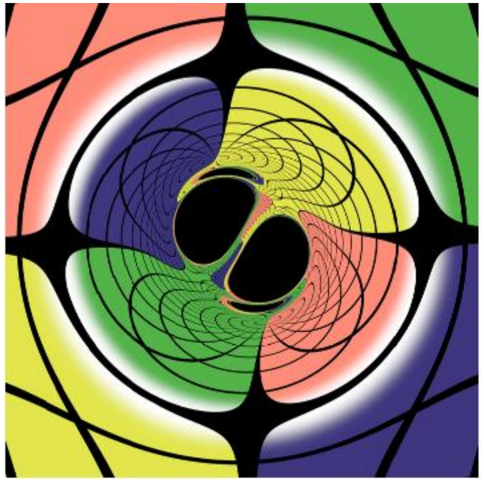
$$g_{\mu\nu} = \begin{pmatrix} 1 + \frac{2Mr}{\rho^2} & 0 & 0 & \frac{4Mar\sin^2\theta}{\rho^2} \\ 0 & -\rho^2/\Delta & 0 & 0 \\ 0 & 0 & -\rho^2 & 0 \\ \frac{4Mar\sin^2\theta}{\rho^2} & 0 & 0 & -(r^2 + a^2 + \frac{2Ma^2r\sin^2\theta}{\rho^2})\sin^2\theta \end{pmatrix}$$

~~Stationarity~~
Delayed gravity
~~Axisymmetry~~

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

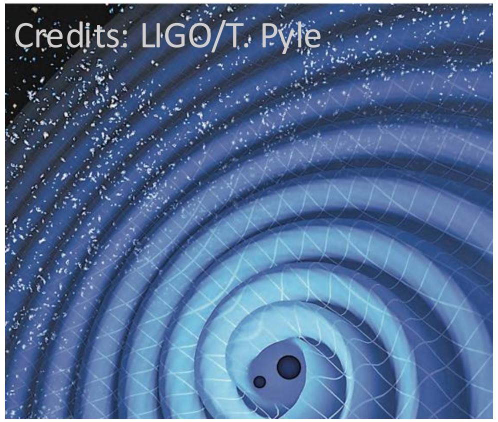
Bohn+15



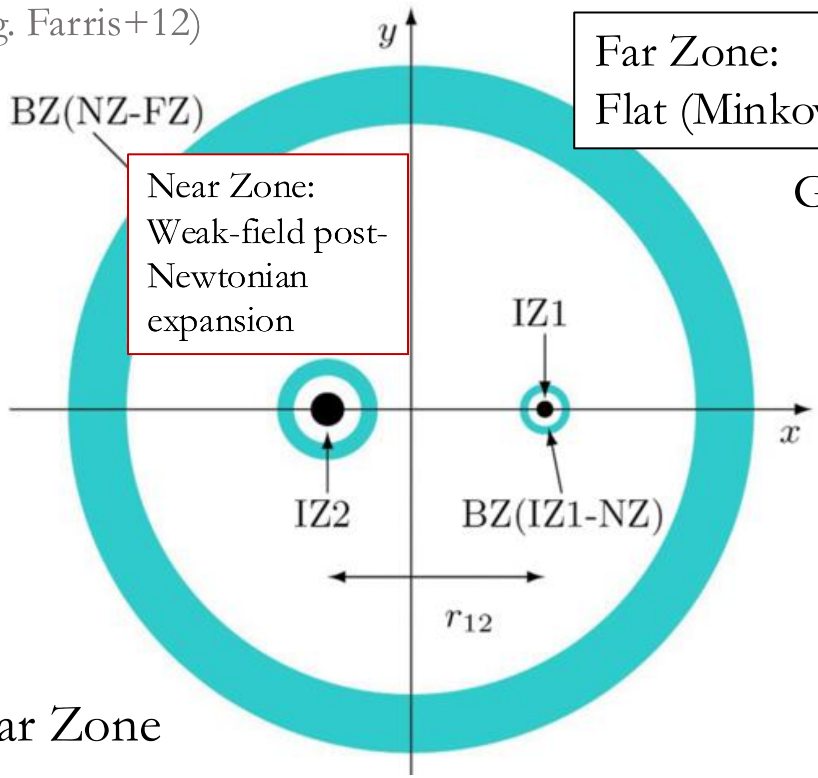


An approximate binary black hole spacetime

- Why not using Newtonian gravity ? (e.g. D'Orazio+13)
  GR IS important !!
- Why not solving the Einstein's equations ?
  Too expensive for >10 orbits simulations (e.g. Farris+12)



(Johnson-Mcdaniel+09)



Far Zone:
Flat (Minkowski) + outgoing GWs

GWs ⇝ accretion disk ?
MR+22, MNRAS
MR+23, A.N.

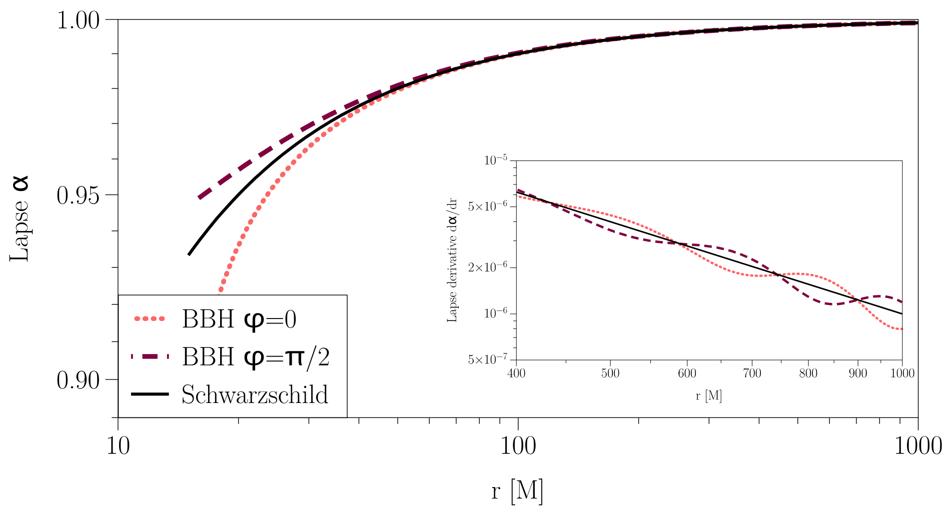
- A computationally-heavy construction: example Far Zone

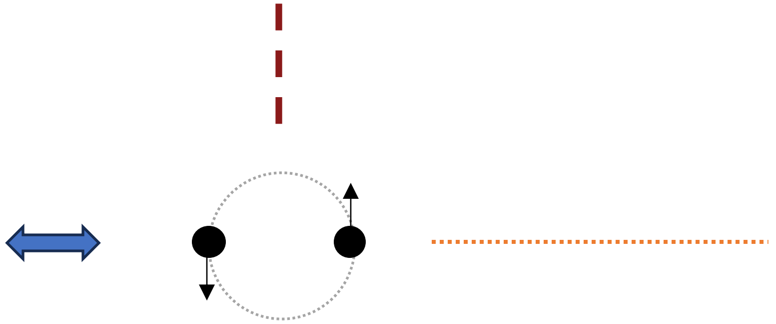
Ireland+16

$$g_{00}+1=\frac{2m_1}{r}+\frac{m_1}{r}\left\{v_1^2-\frac{m_2}{b}+2\left(\vec{v}_1\cdot\hat{n}\right)^2-\frac{2m}{r}+6\frac{\left(\vec{x}_1\cdot\hat{n}\right)}{r}\left(\vec{v}_1\cdot\hat{n}\right)-\frac{x_1^2}{r^2}+\frac{\left(\vec{x}_1\cdot\hat{n}\right)^2}{r^2}\left(3-2r^2\omega^2\right)\right\}$$
$$+\left(1\leftrightarrow 2\right)+O(v^5),$$

- Construction valid down to r_{12}~8M (because $v > 0.1$ c, slow-motion approx. for PN breaks down)

What does a binary black hole metric look like?





- Far from the binary, similar to a single BH, except for GW residual

$g_{t\phi} \neq 0 \rightarrow ?$

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

- Frame-dragging (Lense-Thirring) effect, as in the Kerr metric, but due to the orbital motion of the BBH