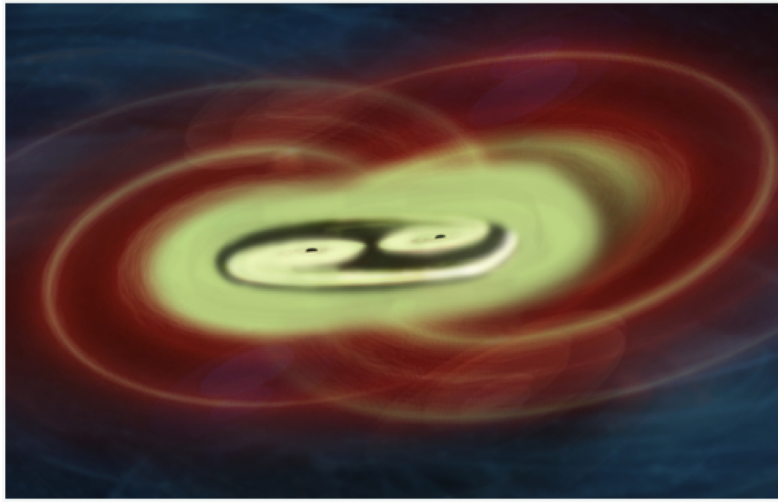
Predicting the electromagnetic signatures of pre-merger binary black holes

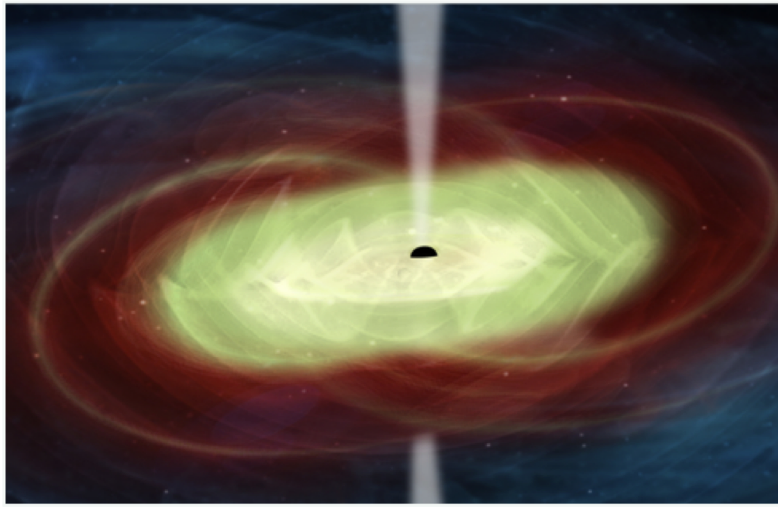
Raphaël Mignon-Risse[1]
CNES Fellow
Raphael.mignon-risse@apc.in2p3.fr
[1]**AstroParticule and Cosmologie, Université de Paris**

Collaborators: P. Varniere, F. Casse, A. Coleiro (APC, Paris)

Electromagnetic counterpart to BBH fusion

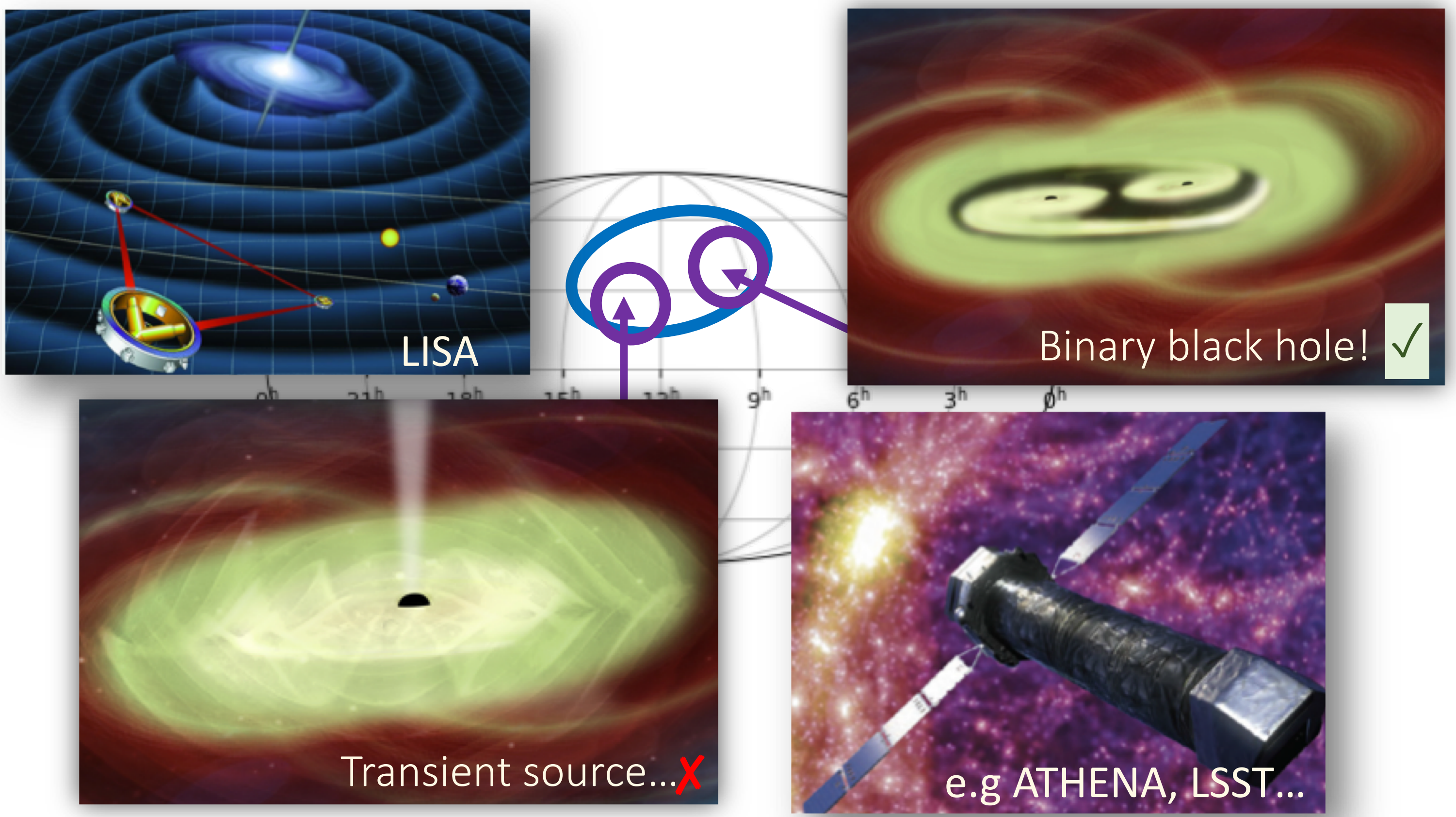
Need a gas-rich environment:
e.g. galaxy merger,
tidal disruption event or « fallback disk »
following supernova explosion





- Binary black holes and their coalescence
  - Galaxy growth vs black hole growth
  - Speed of gravity
  - Hubble tension
  - Formation of active galactic nuclei?

Electromagnetic follow-up after a LISA detection



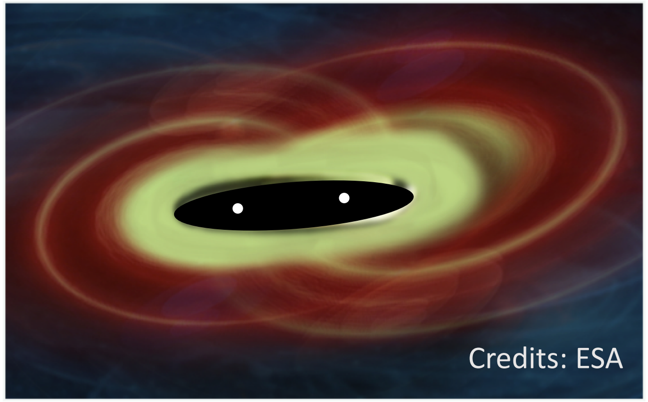
- LISA: space-based gravitational wave detector
  0.1mHz-1Hz band
  - SMBBH up to merger
  - Stellar-mass BH in early pre-merger stage only

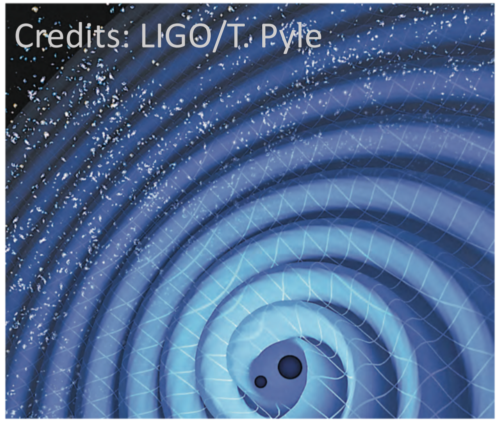
How to distinguish binary black holes from other (transient) sources ?

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)





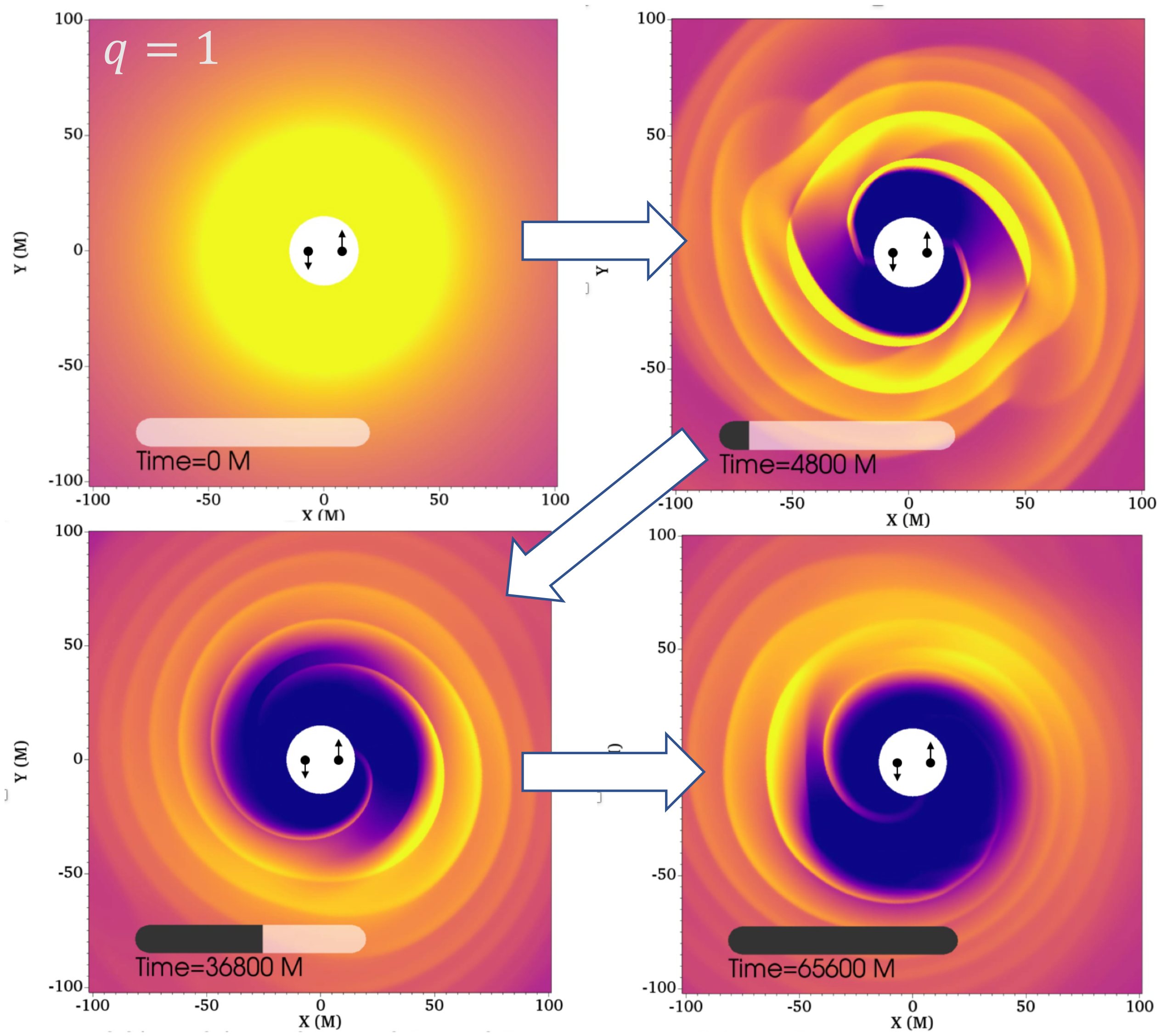
  - ➢ Implement an approximate, analytical BBH spacetime (Mignon-Risse et al. 2022, MNRAS)

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

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

➢ Construction valid until the BBH motion becomes relativistic

Results: Accretion structures



Surface density

For $q \geq 0.1$

1. A cavity at ~2x orbital separation r_{12} (Artymowicz+94)
2. Streams (Artymowicz+96) & spiral arms

and further in time…

3. An overdensity, or « lump » (e.g. Shi+12, Noble+12)

Pre-merger electromagnetic features ?

Detecting binary black holes thanks to these accretion structures ?

- Synthetic observations through GR ray-tracing

Synthetic observations of pre-merger BBHs

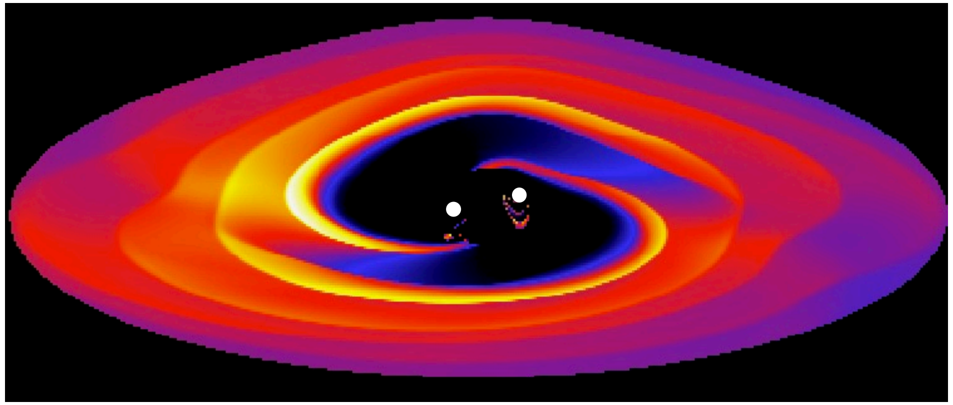
- **GYOTO** code (Vincent+11) incorporating the **BBH approximate metric** (Ireland+16)

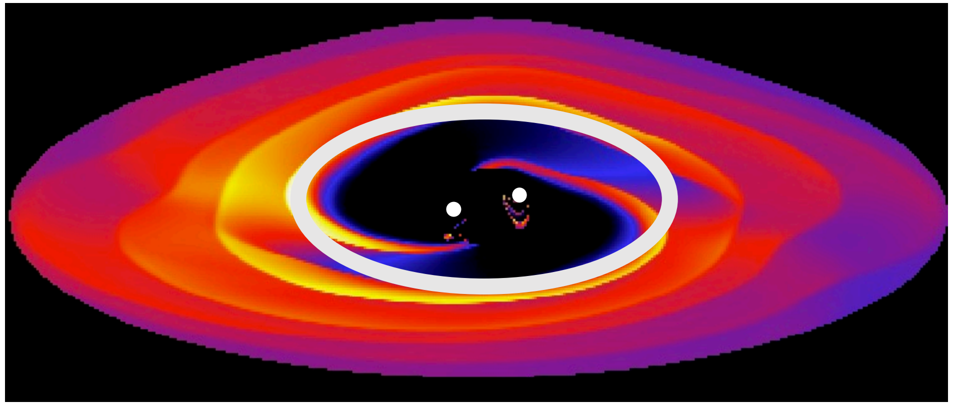
- This pipeline forms eNOVAs: **extended Numerical Observatory for Violent Accreting systems**
  The first European pipeline of its kind, second worldwide (see D'Ascoli+18)

- Thermal emission, thin disk approximation (Shakura & Sunyaev, 1973)

- Mass scaling using Lin+13 ($\mathrm{M} = 10^5 \mathrm{M}_{\odot}$; $T_{\mathrm{in}} = 0.1$ keV) as reference

➢ Obtain the multi-wavelength emission map

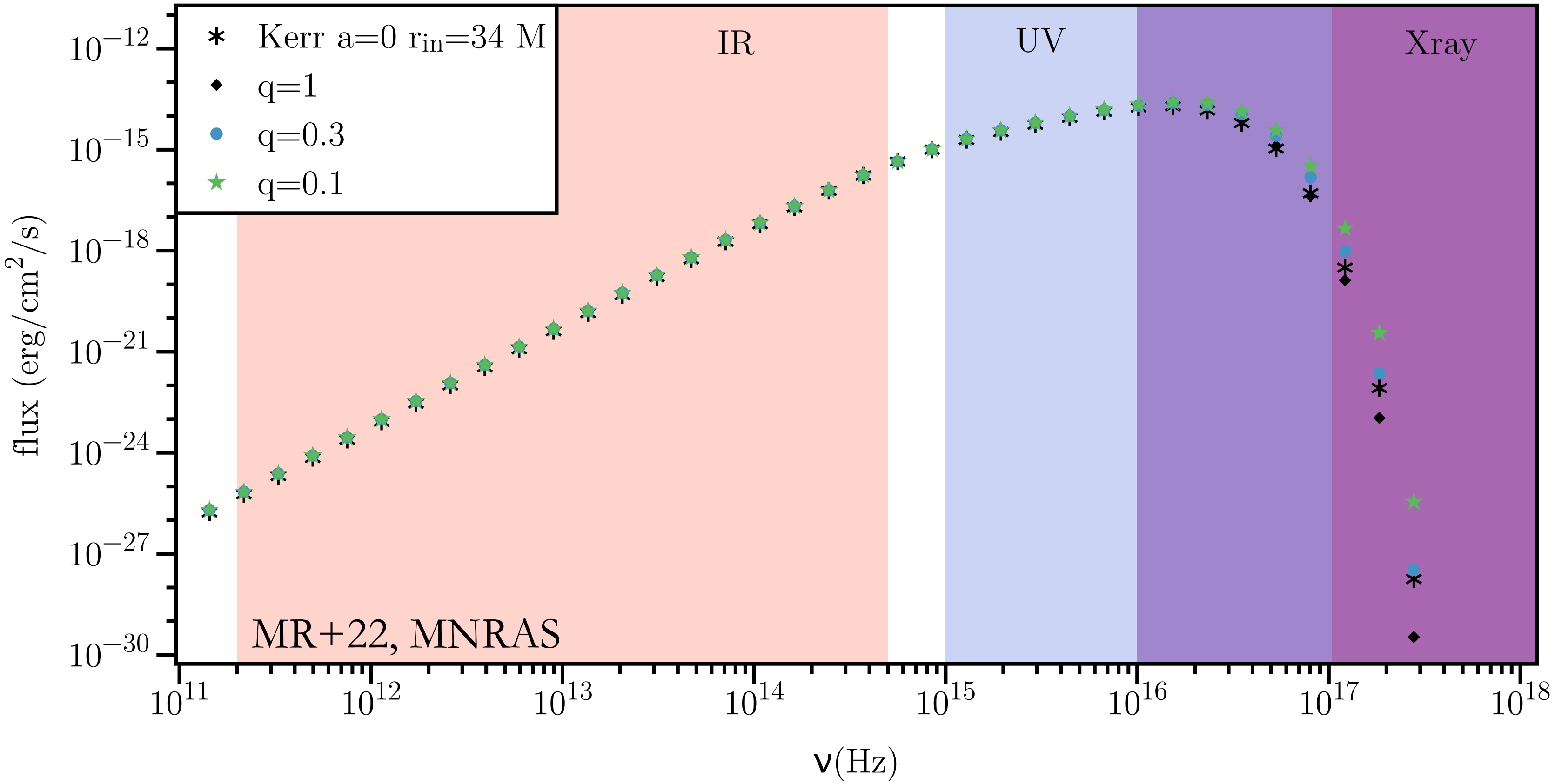




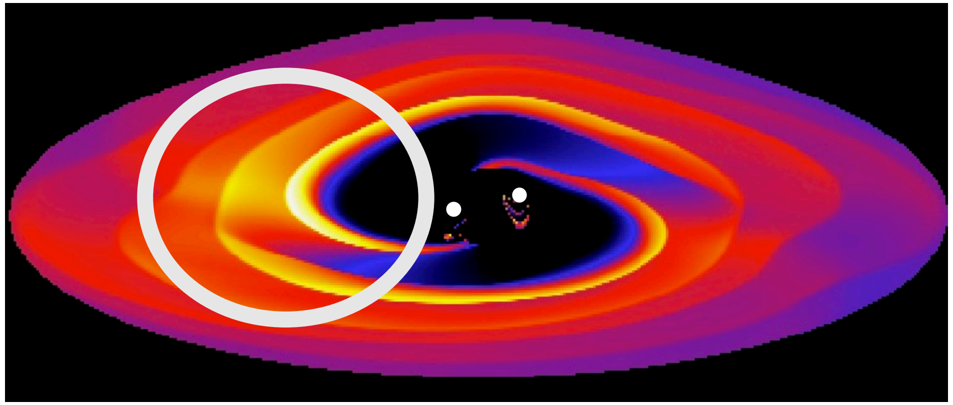
Impact of the cavity

Is a BBH hidden behind a single BH with a far away disk?

- Disk inner edge set at the innermost stable circular orbit (ISCO) in single BHs
  - ➢ Highest-energy contribution to the spectrum at 6 r_g
- Circumbinary disk edge settles around $\sim 2\, r_{12}$ in BBHs, e.g. $\sim 30\ r_g$ here



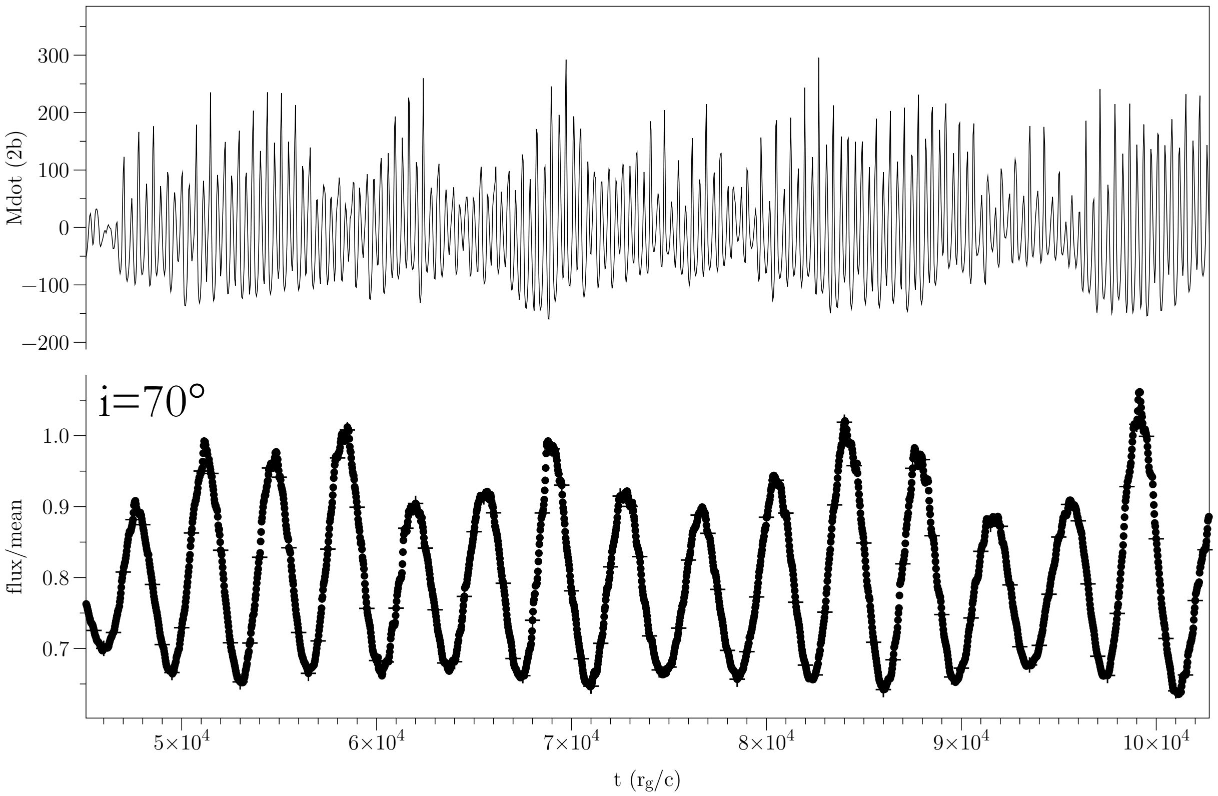
A BBH can be hidden behind a BH source whose disk inner edge is away from its ISCO
(B)BH mass measurement needed !!



Impact of the lump & spiral arms

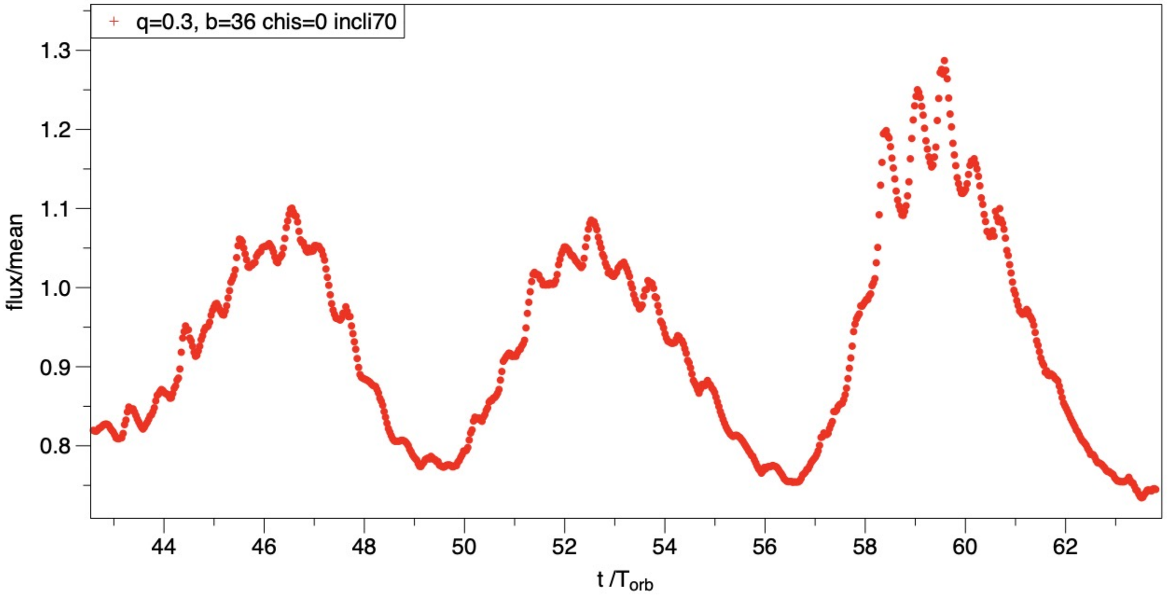
Timing features

$q = 0.1;\ r_{12} = 20\mathrm{r_g}$



$q = 0.3;\ r_{12} = 36\mathrm{r_g}$

MR+2023, in prep.



- Additional modulation at half the orbital period

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

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

- Accretion rate through the cavity modulated at the orbital period
- Flux is normalized by the mean value ⇒ mass-independent lightcurve
- The main modulation of the lightcurve is produced by the lump

Conclusions: observational features of BBHs

- Development of eNOVAs:
  - ➢ First European pipeline from fluid simulations to synthetic obs. in dynamical spacetimes

(Mignon-Risse et al. 2022, MNRAS)

- Accretion structures typical of BBHs: streams, cavity, overdensity/«lump» (e.g. Noble+12, Shi+12)

(Lump origin model: Mignon-Risse et al. 2023, MNRAS)

- Periodic behaviour at i) the semi-orbital period and ii) at the «lump» period (e.g. D'Orazio+13)
  - ➢ Two-timescale modulation, dominated by the «lump» modulation

(MR+23, in prep.)

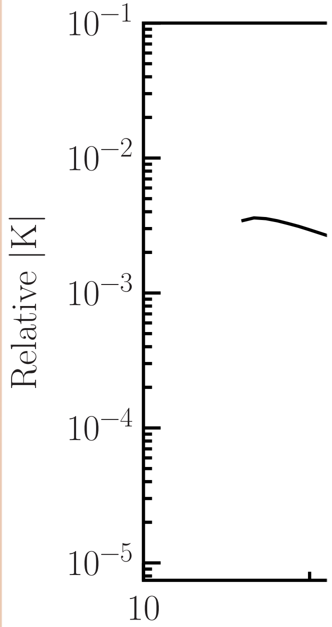
- In any case, knowing the (B)BH mass is <u>crucial</u>

➢ What remains of these EM signatures when the BBH inspirals towards merger?

To be continued…

Metric validation

- Correct ap… view as d…



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

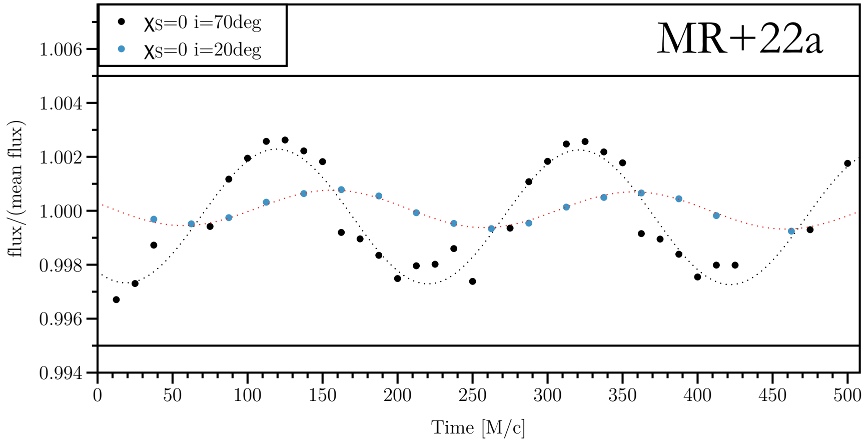
$$389\sqrt{\frac{1}{2}}\Bigg(2421136\left(\frac{\sqrt{\frac{1}{2}}\,y\cos\left(\frac{389}{200000}\sqrt{\frac{1}{2}}\left(t-\sqrt{x^2+y^2+z^2}\right)\right)}{\sqrt{x^2+y^2+z^2}}-\frac{\sqrt{\frac{1}{2}}\,x\sin\left(\frac{389}{200000}\sqrt{\frac{1}{2}}\left(t-\sqrt{x^2+y^2+z^2}\right)\right)}{\sqrt{x^2+y^2+z^2}}\right)^2-453963\left(\frac{x\cos\left(\frac{389}{200000}\sqrt{\frac{1}{2}}\left(t-\sqrt{x^2+y^2+z^2}\right)\right)}{\sqrt{x^2+y^2+z^2}}+\frac{y\sin\left(\frac{389}{200000}\sqrt{\frac{1}{2}}\left(t-\sqrt{x^2+y^2+z^2}\right)\right)}{\sqrt{x^2+y^2+z^2}}\right)^2 \cdots$$
$$+\frac{6224000\sqrt{\frac{1}{2}}\,y\cos\left(\frac{389}{200000}\sqrt{\frac{1}{2}}\left(t-\sqrt{x^2+y^2+z^2}\right)\right)}{\sqrt{x^2+y^2+z^2}}-\frac{6224000\sqrt{\frac{1}{2}}\,x\sin\left(\frac{389}{200000}\sqrt{\frac{1}{2}}\left(t-\sqrt{x^2+y^2+z^2}\right)\right)}{\sqrt{x^2+y^2+z^2}}$$
$$+\frac{933600000\left(\frac{\sqrt{\frac{1}{2}}\,y\cos\left(\frac{389}{200000}\sqrt{\frac{1}{2}}\left(t-\sqrt{x^2+y^2+z^2}\right)\right)}{\sqrt{x^2+y^2+z^2}}-\frac{\sqrt{\frac{1}{2}}\,x\sin\left(\frac{389}{200000}\sqrt{\frac{1}{2}}\left(t-\sqrt{x^2+y^2+z^2}\right)\right)}{\sqrt{x^2+y^2+z^2}}\right)\left(\frac{x\cos\left(\frac{389}{200000}\sqrt{\frac{1}{2}}\left(t-\sqrt{x^2+y^2+z^2}\right)\right)}{\sqrt{x^2+y^2+z^2}}+\frac{y\sin\left(\frac{389}{200000}\sqrt{\frac{1}{2}}\left(t-\sqrt{x^2+y^2+z^2}\right)\right)}{\sqrt{x^2+y^2+z^2}}\right)}{\sqrt{x^2+y^2+z^2}}$$
$$+\frac{240000000000\left(\frac{x\cos\left(\frac{389}{200000}\sqrt{\frac{1}{2}}\left(t-\sqrt{x^2+y^2+z^2}\right)\right)}{\sqrt{x^2+y^2+z^2}}+\frac{y\sin\left(\frac{389}{200000}\sqrt{\frac{1}{2}}\left(t-\sqrt{x^2+y^2+z^2}\right)\right)}{\sqrt{x^2+y^2+z^2}}\right)^2}{x^2+y^2+z^2}+\frac{3200000000\left(\frac{x\cos\left(\frac{389}{200000}\sqrt{\frac{1}{2}}\left(t-\sqrt{x^2+y^2+z^2}\right)\right)}{\sqrt{x^2+y^2+z^2}}+\frac{y\sin\left(\frac{389}{200000}\sqrt{\frac{1}{2}}\left(t-\sqrt{x^2+y^2+z^2}\right)\right)}{\sqrt{x^2+y^2+z^2}}\right)}{\sqrt{x^2+y^2+z^2}}$$
$$80000000000\left(\cos\left(\frac{389}{200000}\sqrt{\frac{1}{2}}\left(t-\sqrt{x^2+y^2+z^2}\right)\right)^2+\sin\left(\frac{389}{200000}\sqrt{\frac{1}{2}}\left(t-\sqrt{x^2+y^2+z^2}\right)\right)^2\right) \cdots$$

…view

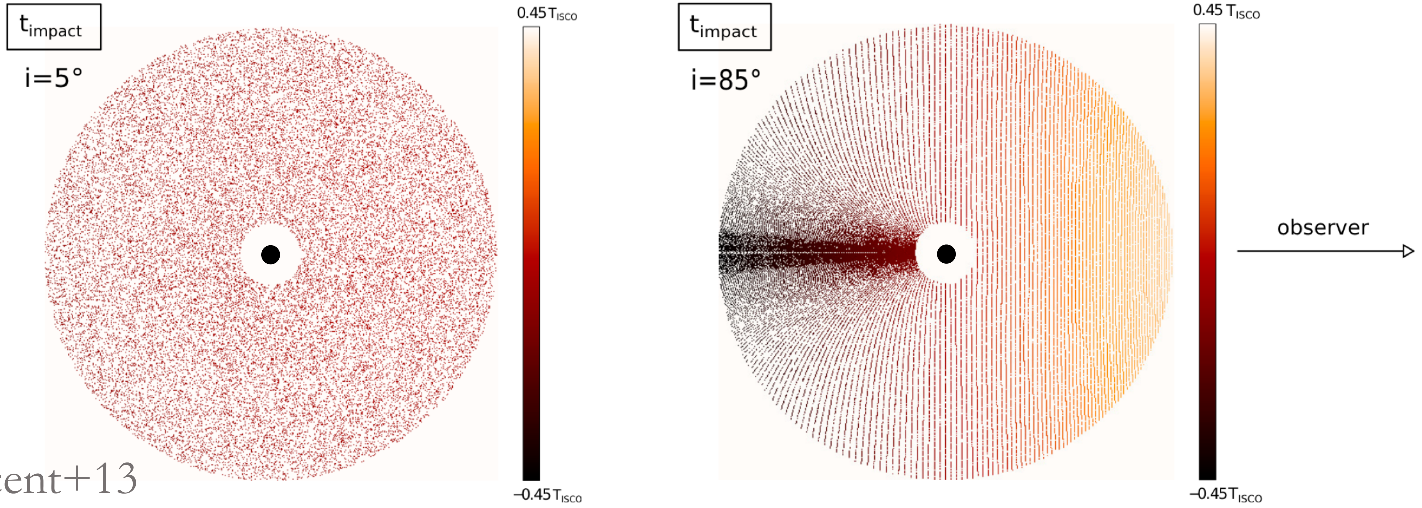
…ubm.

Why using a GR ray-tracing code ?

- **Ray-tracing:**
  Influence of source inclination on timing features associated with non-axisymmetries in the disk



- **GR** effects:
  Lensing (see e.g. Davelaar+22)
  time dilation
  …



Vincent+13

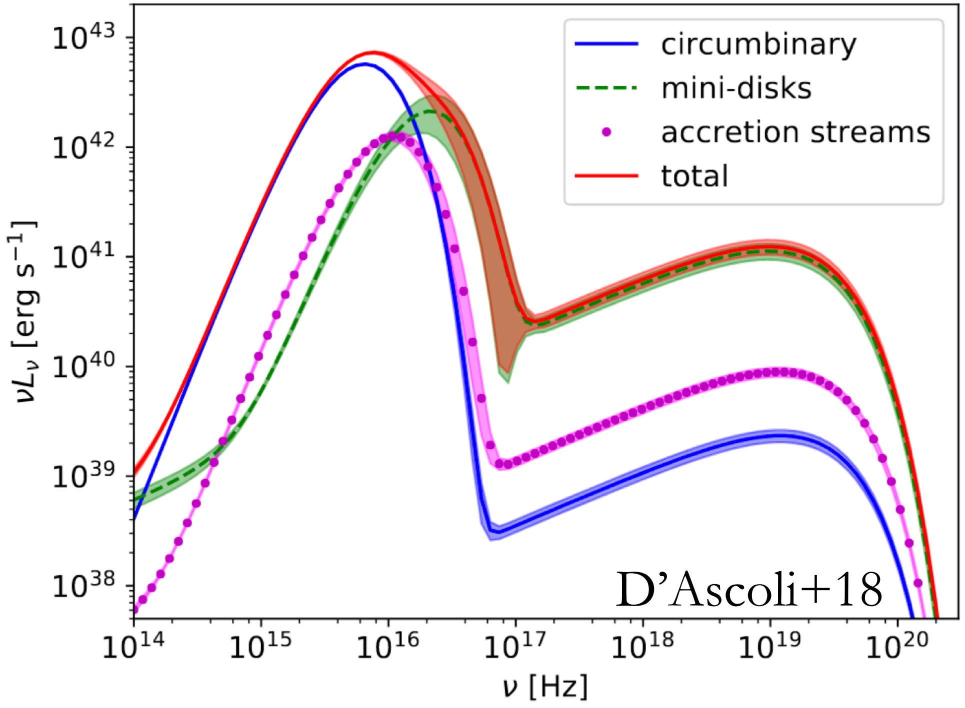
- Self-consistency:
  Incorporates the same BBH metric as the fluid code

Excising the innermost region?

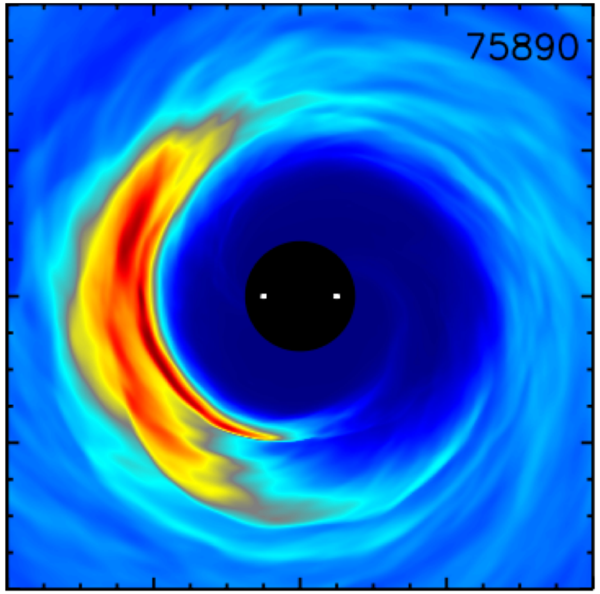
The flux from possible individual disks

- may not dominate the integrated flux

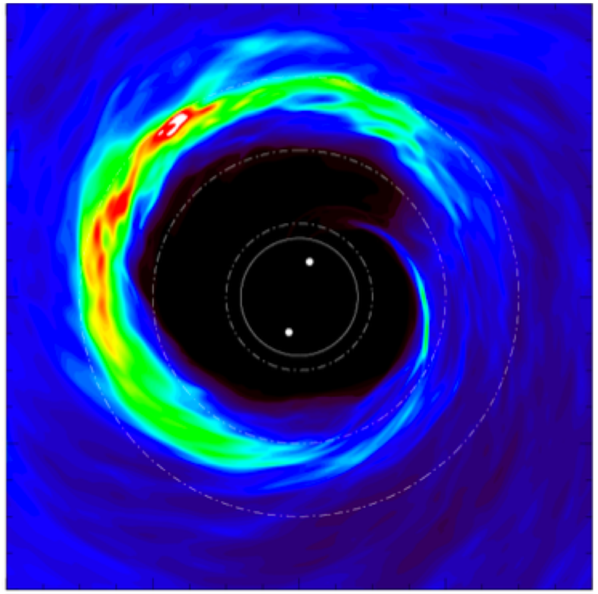
  depends on their surface density, temperature, the BBH orbital separation…
- peak in a higher-energy band
- varies on binary orbital timescales, much shorter than the « lump’s » period



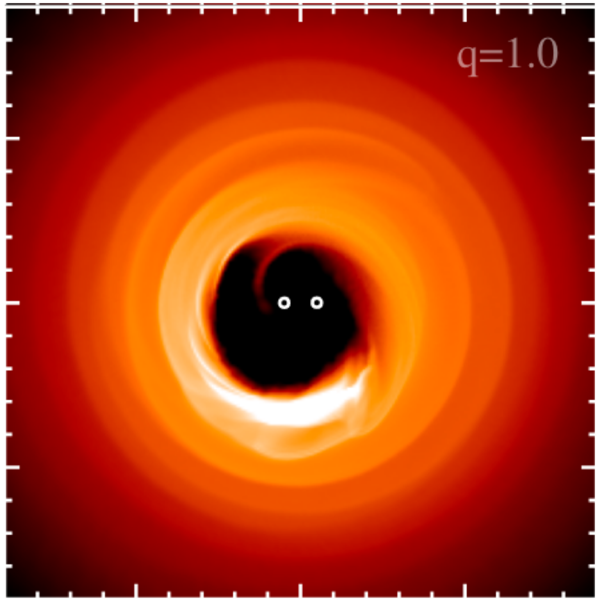
The « lump » presence in the literature



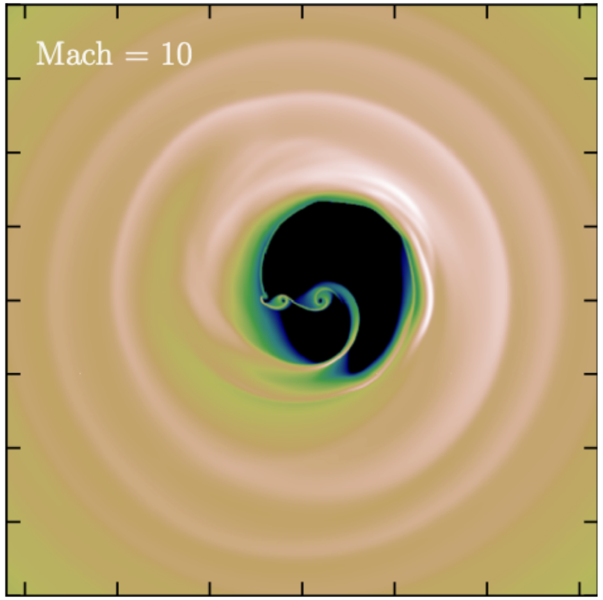
Noble+12, 3D GRMHD



Shi+12, 3D MHD

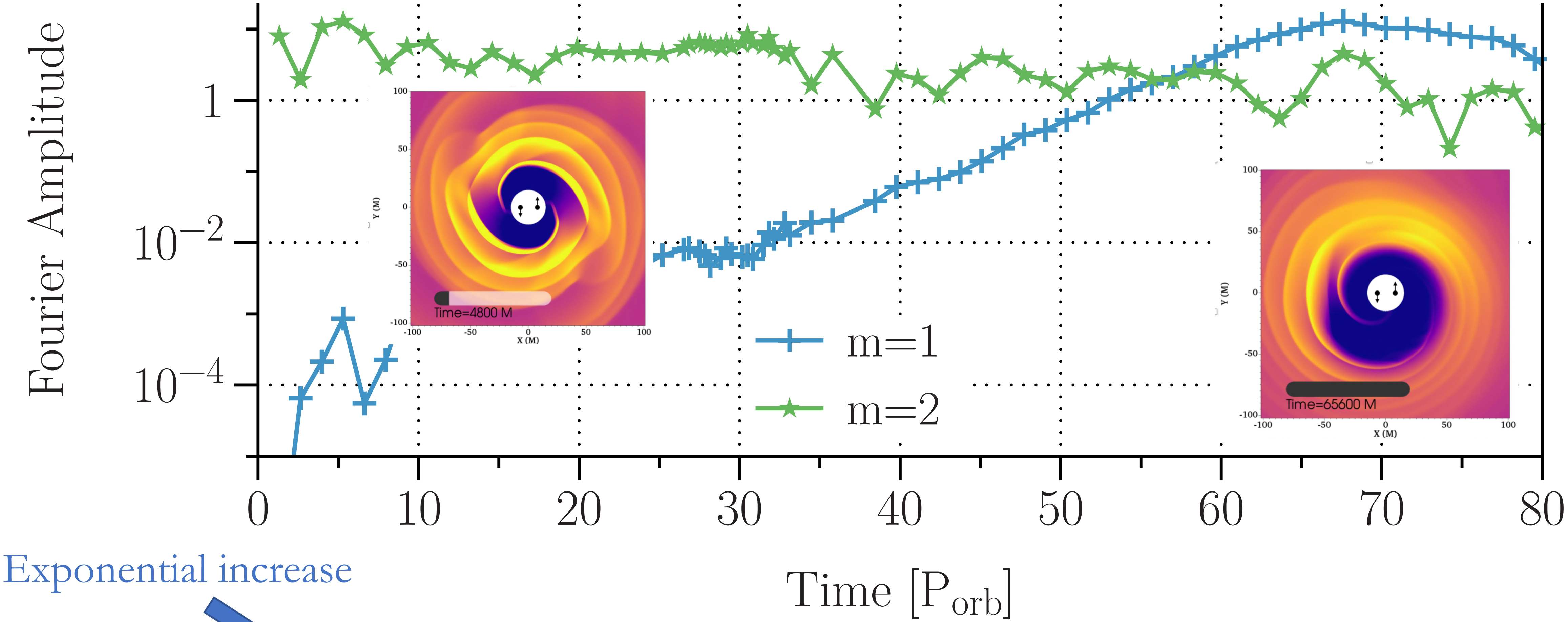


Ragusa+20, 3D SPH



Tiede+20, 2D Hydro

Lump: an instability origin ?

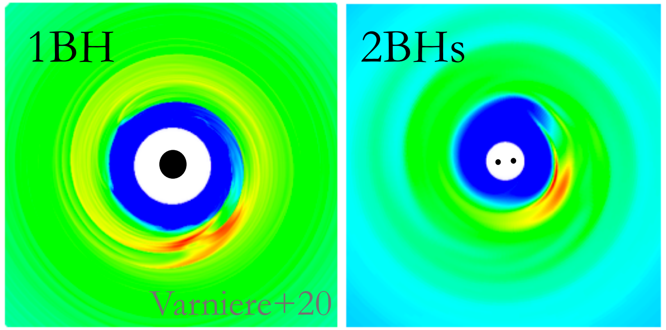


Exponential increase

The Rossby Wave Instability as a possible origin for the « lump » (MR+23, MNRAS)

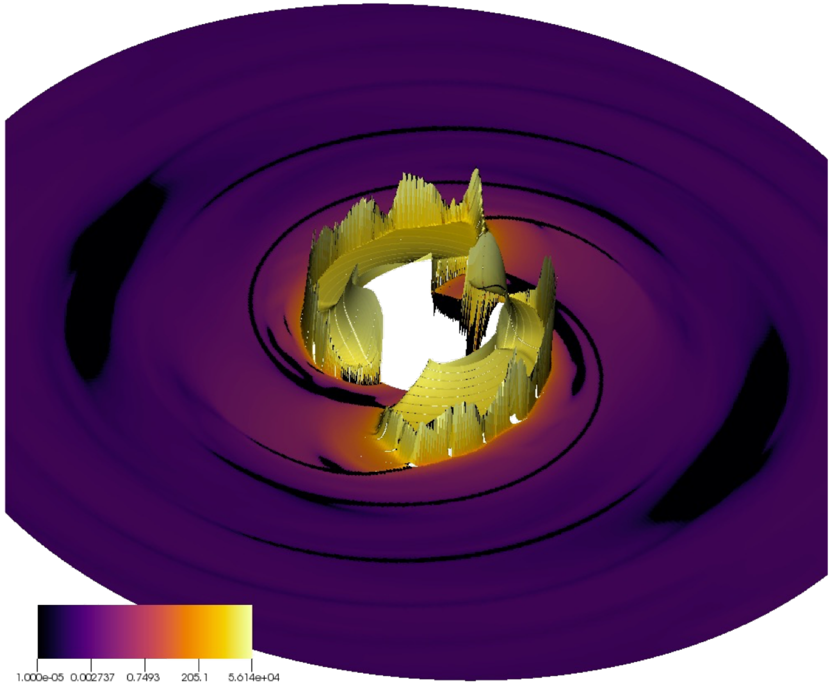
Lump: an instability origin ?

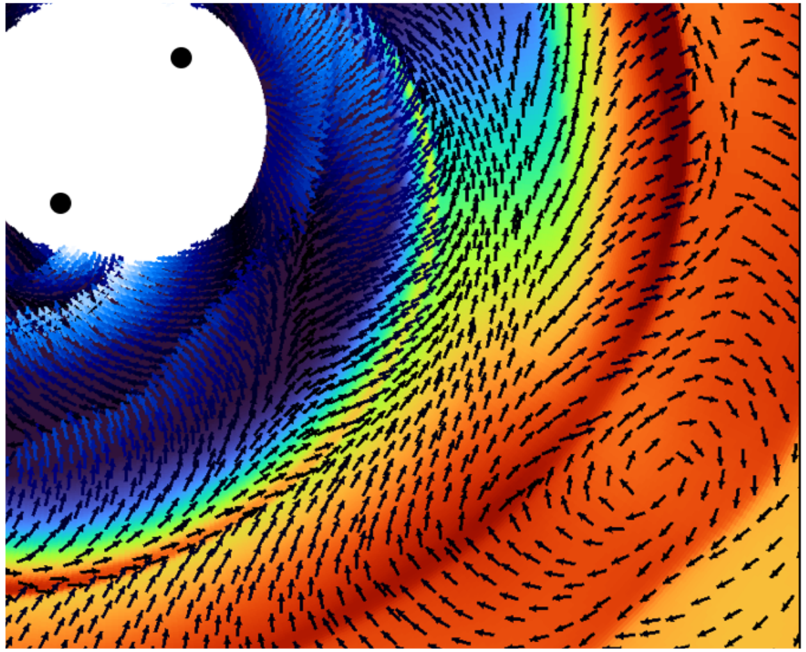
Similar to the Rossby Wave Instability (RWI) around single BH disks?



RWI criterion fullfilled: extremum in vortensity $\mathcal{L} = \frac{\nabla \times \mathbf{v}}{\Sigma}$

Presence of vortices





The Rossby Wave Instability as a possible origin for the « lump » (MR+23 MNRAS)