Towards multi-messenger observations of accreting binary black holes

Raphaël Mignon-Risse
Postdoctoral Researcher – LOVE-NEST Team (PI: M. Linares)
raphael.mignon-risse@ntnu.no

Collaborators: P. Varniere, F. Casse, A. Coleiro
F. Dodu, L. Arthur, P.-A. Duverne (APC, Paris), M. González (AIM, Saclay)

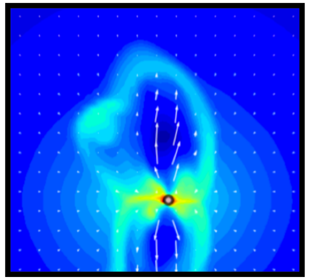
NTNU

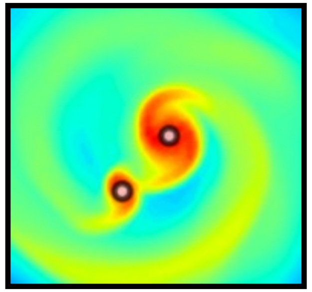
My scientific path

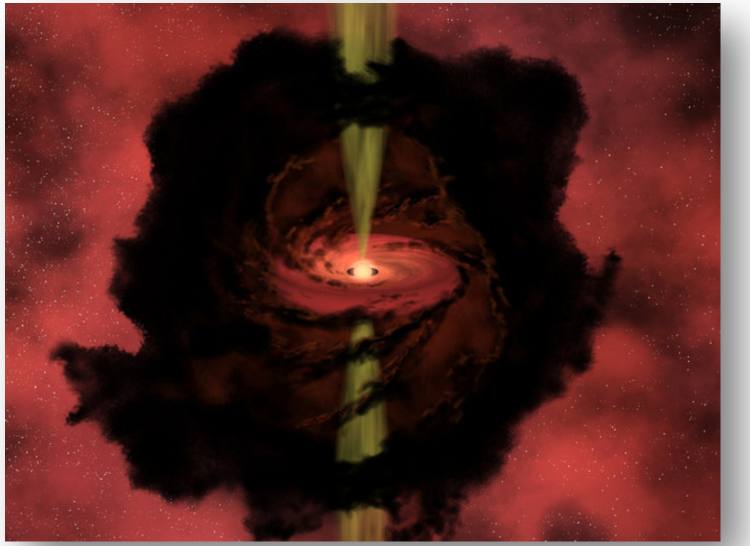
Black hole accretion disks

Internship, AstroParticule & Cosmology, Paris

- X-ray data reduction + phenomenological model





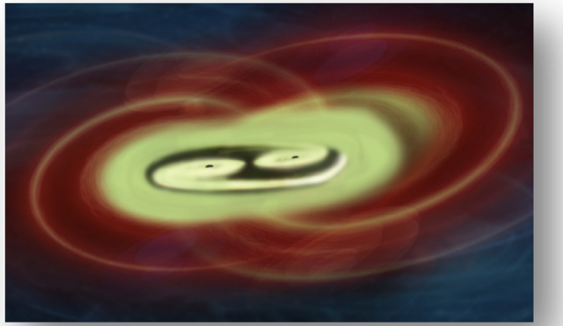


Massive star formation

Ph.D., AIM (CEA Saclay, France)

- Accretion/ejection processes
  radiative+magneto-centrifugal+
  magnetic-pressure-driven outflows
- Origin/properties of multiple systems

RADIATIVE TRANSFER MODULE (PI) | 3D Radiative MHD | Binaries



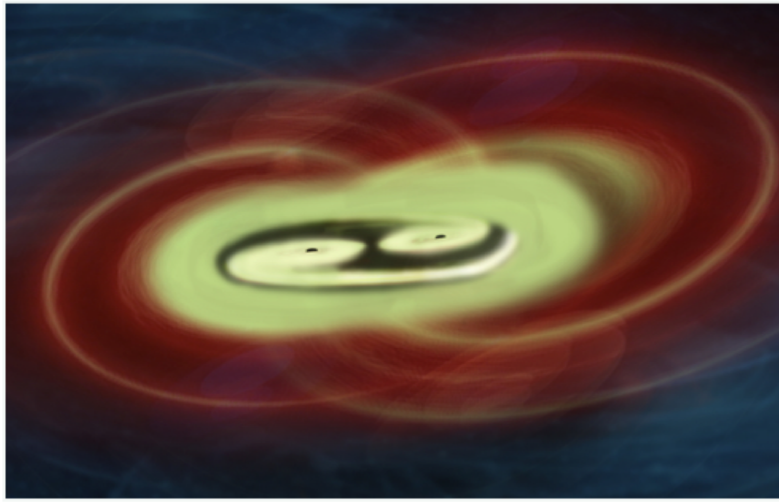
Pre-merger binary black holes (BBHs)

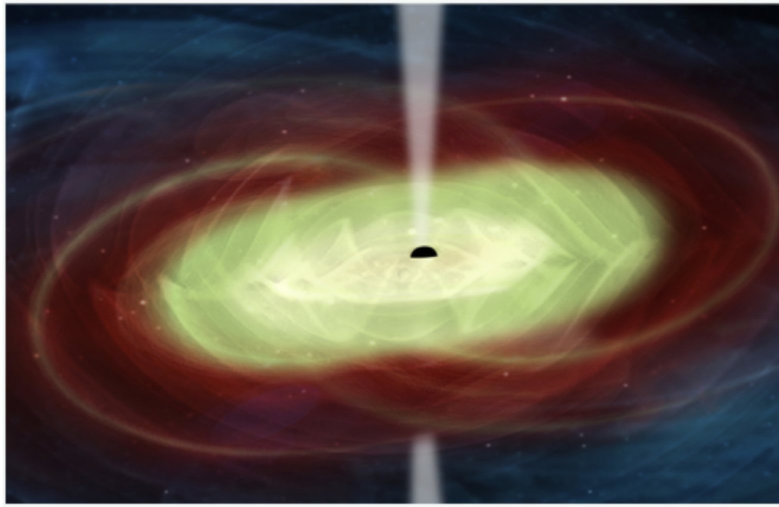
Research & Teaching Assistant → CNES Fellow, APC, Paris

- Electromagnetic signatures
- Properties of circumbinary accretion

Electromagnetic counterpart to BBH fusion

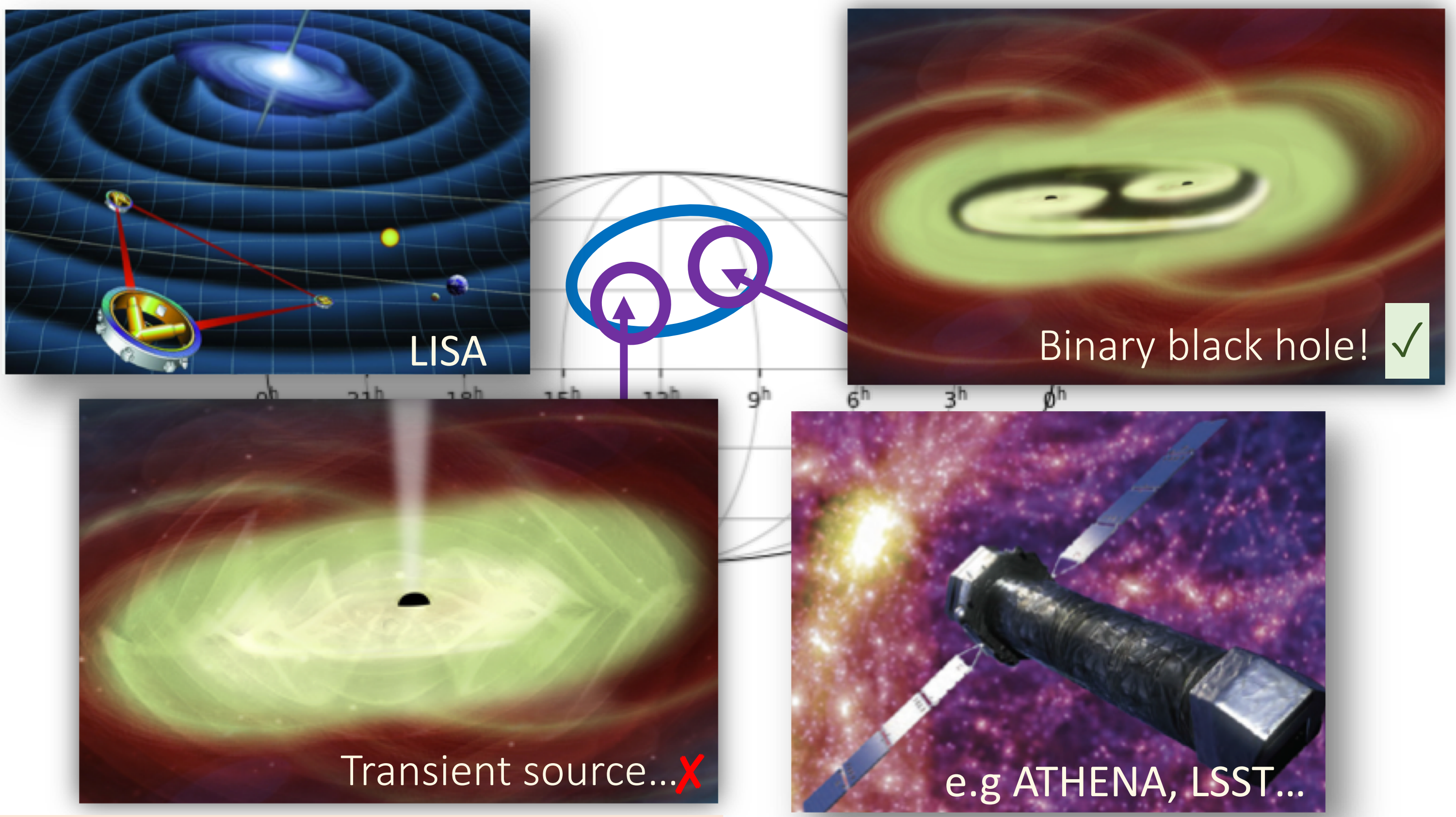
Need a gas-rich environment:
e.g. galaxy merger,
tidal disruption event or « fallback disk »
following supernova explosion





- 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 (before?) a GW detection

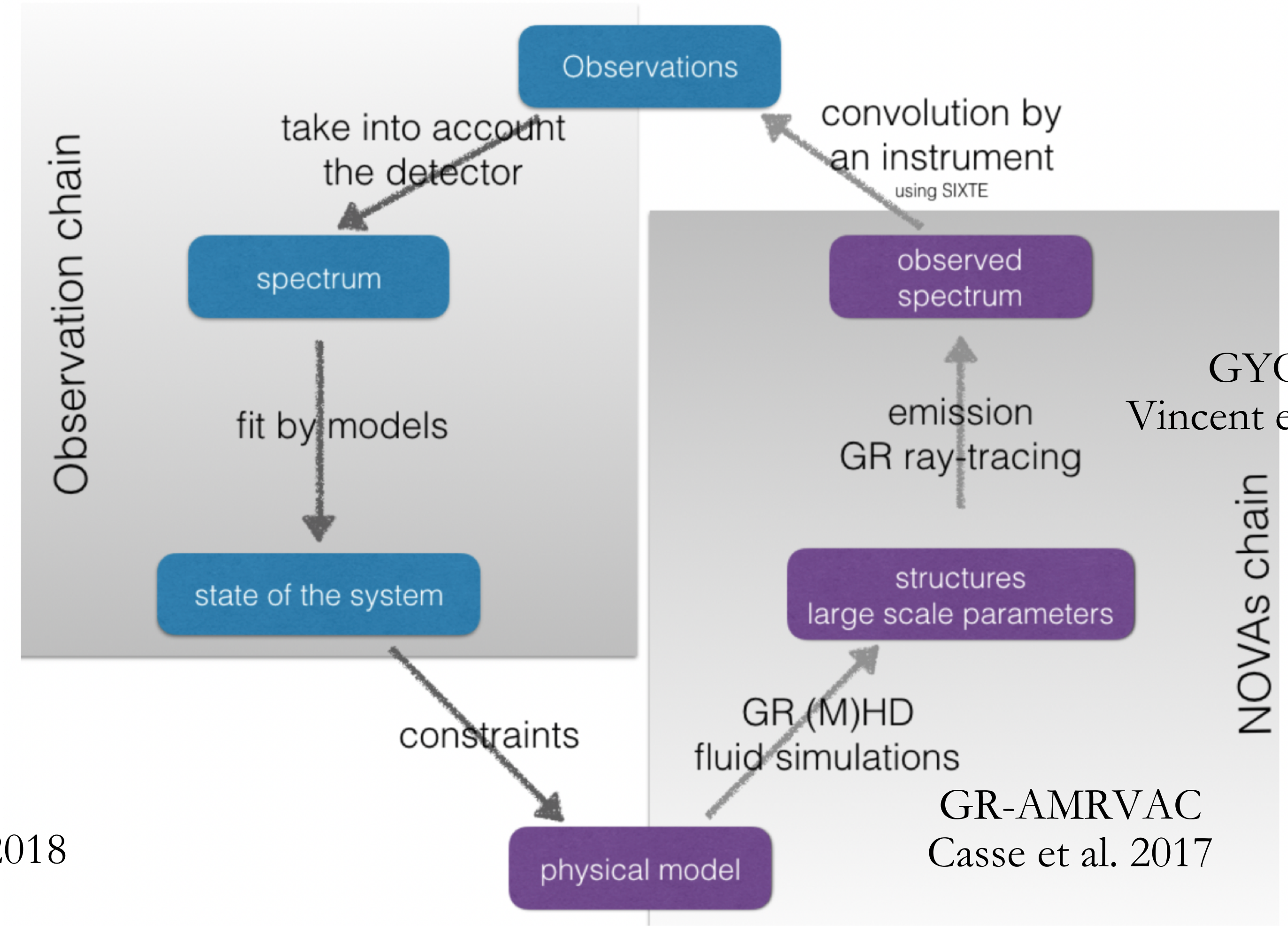


- LISA: space-based gravitational wave detector
  0.1mHz-100mHz band
  - SMBBH up to merger
  - Stellar-mass BH in early pre-merger stage only

- PTA: Pulsar Timing Arrays
  1nHz-100nHz band
  - Close individual SMBBH mergers

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

NOVAs: Numerical Observatory for Violent Accreting systems



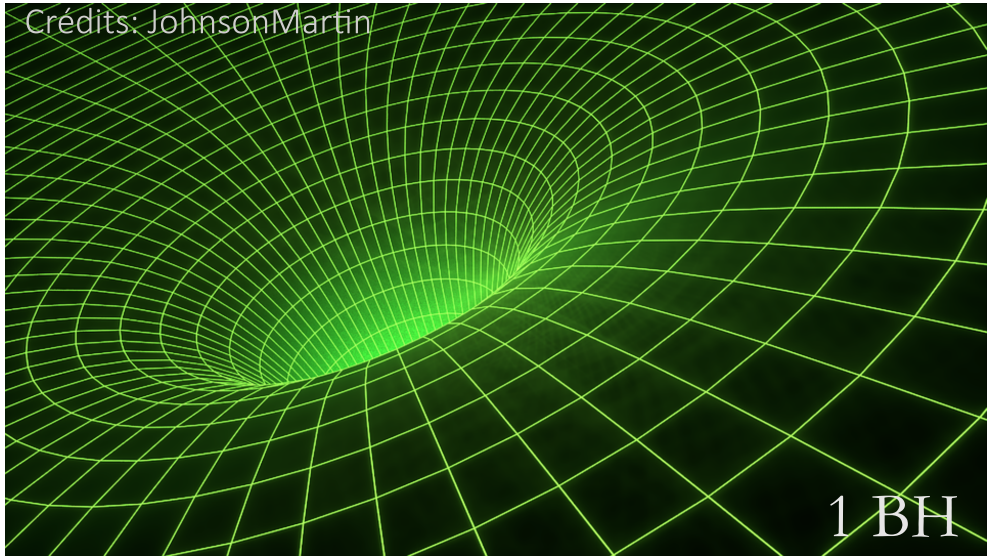
GYOTO
Vincent et al. 2011

GR-AMRVAC
Casse et al. 2017

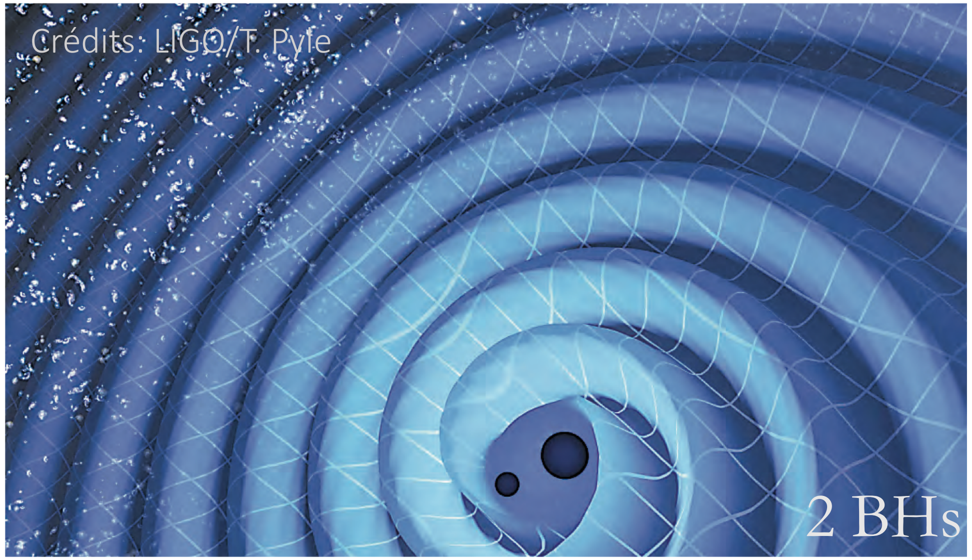
Varniere et al. 2018

And for binary black holes ?

From single to binary black holes



→

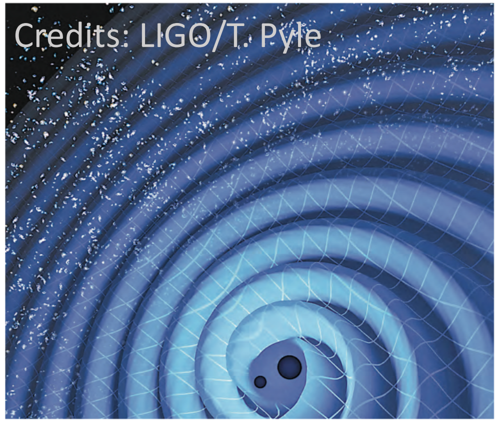


~~Stationarity~~
→ Delayed gravity
~~Axisymmetry~~

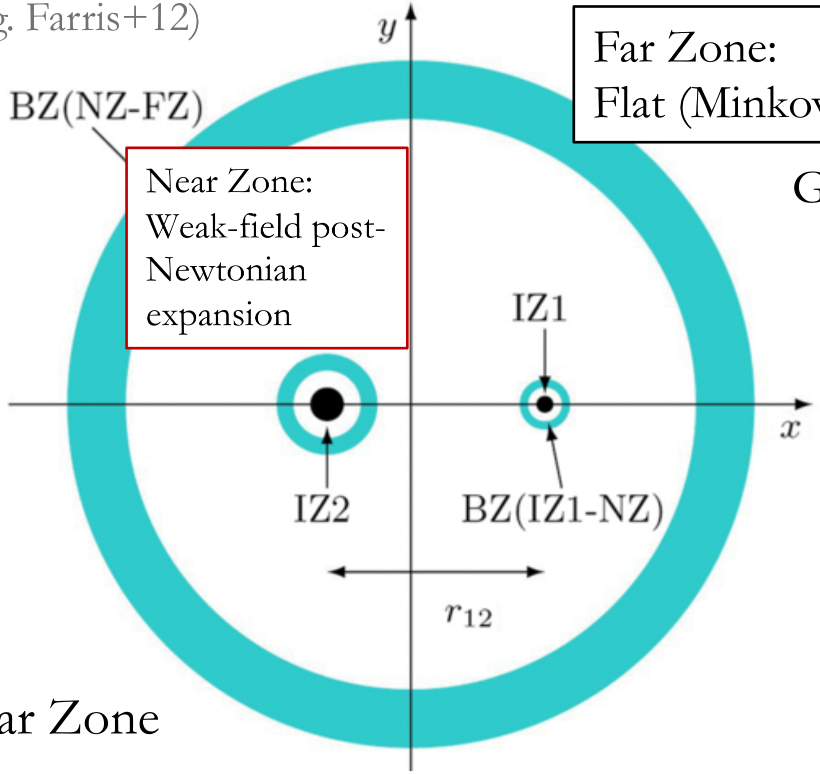
- NOVAs extended to any type of spacetime : e-NOVAS (Mignon-Risse et al. 2022, MNRAS)
  e-NOVAs is a numerical observatory for the multi-messenger era

An approximate binary black hole spacetime

- Why not using Newtonian gravity ? (e.g. D'Orazio+13)
  Focus on the pre-merger BBH vicinity + ray-tracing
- Why not solving the Einstein's equations ?
  Too expensive for >10 orbits simulations (e.g. Farris+12)



(Johnson-Mcdaniel+09)



Ireland+16

Far Zone:
Flat (Minkowski) + outgoing GWs

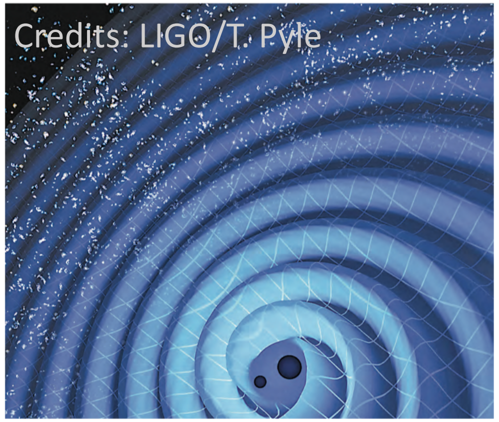
GWs ⇝ accretion disk ?
MR+22, MNRAS
MR+23, A.N.

- A computationally-heavy construction: example Far Zone

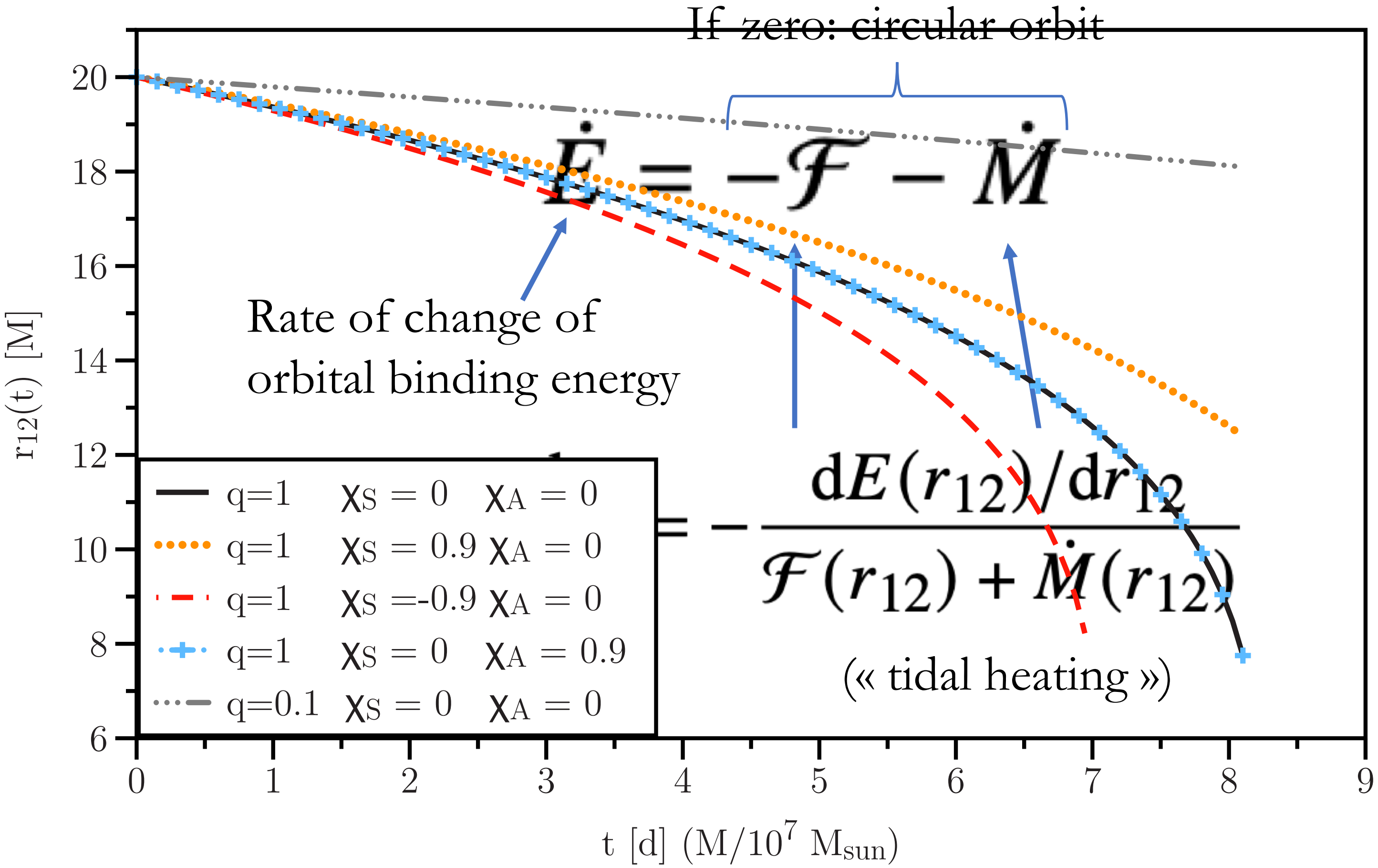
$$g_{00} + 1 = \frac{2m_1}{r} + \frac{m_1}{r}\left\{v_1^2 - \frac{m_2}{b} + 2\left(\vec{v}_1 \cdot \hat{n}\right)^2 - \frac{2m}{r} + 6\frac{(\vec{x}_1 \cdot \hat{n})}{r}\left(\vec{v}_1 \cdot \hat{n}\right) - \frac{x_1^2}{r^2} + \frac{(\vec{x}_1 \cdot \hat{n})^2}{r^2}\left(3 - 2r^2\omega^2\right)\right\}$$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

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

Inspiral equation of motion



- ✓ 3.5 Post-Newtonian inspiral motion for **orb. separation and orb. frequency**
- ✓ **valid for spinning BBHs**



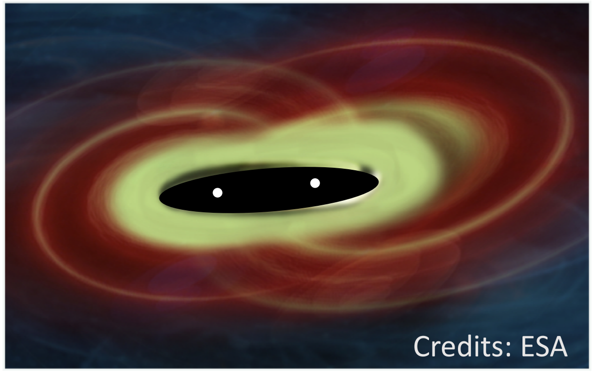
- **Recover the orbital hang-up effect**
- **Slower inspiral for *q* ↘**

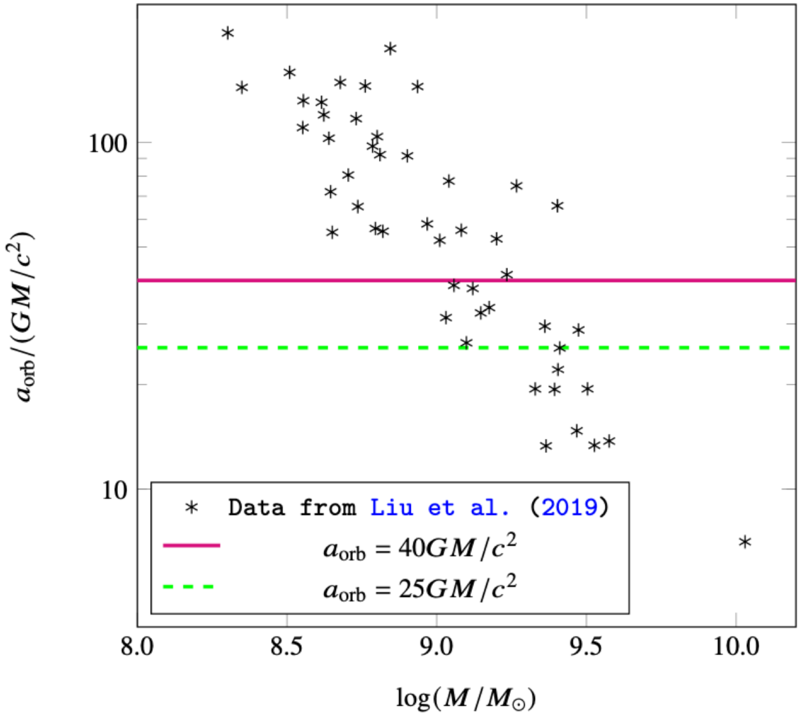
Modelling BBH and circumbinary disk

- **2D disk at equilibrium around a single BH** (resolution 784×400)

Orbital separation r_{12} =20M ; circular orbits ; polytropic EoS

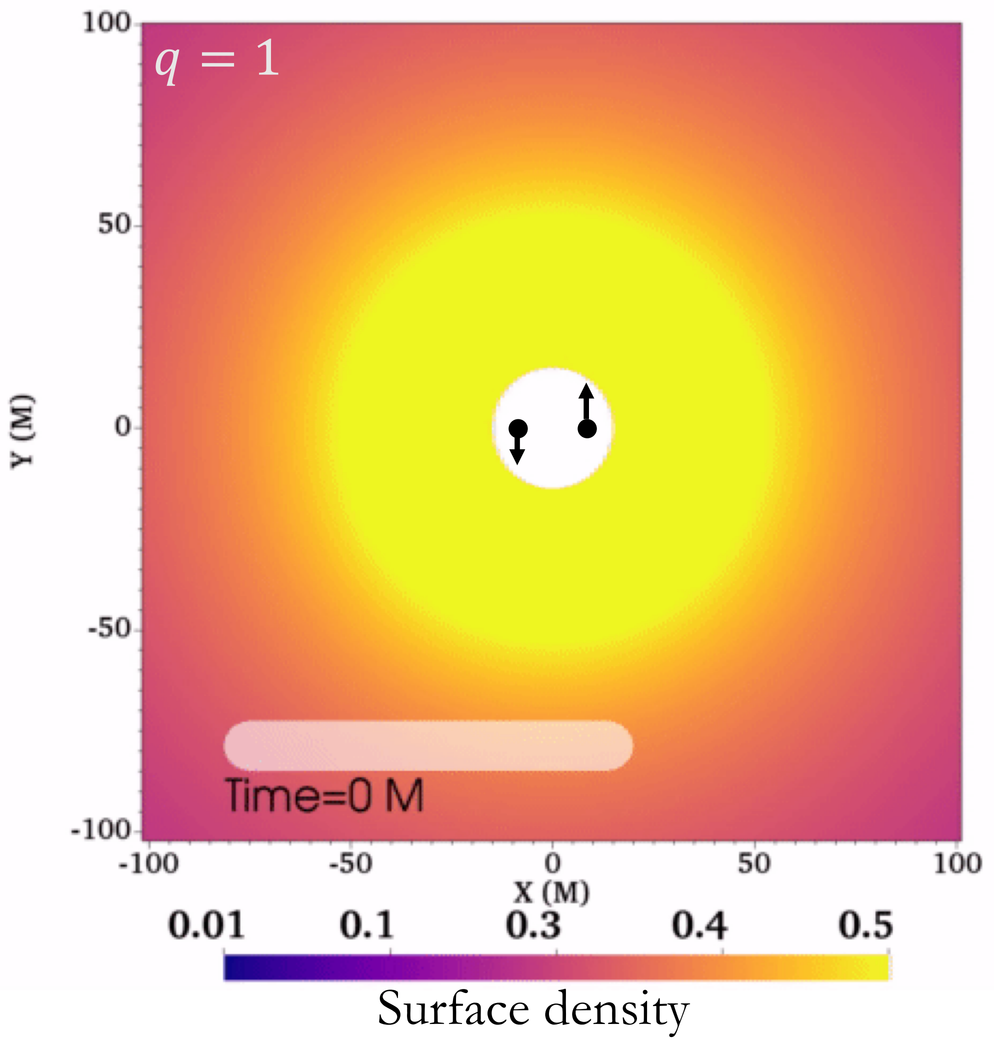
$P_{\rm orb} = 0.3 \frac{M}{10^6 M_\odot}$ ks $\qquad r_{12} = 6.5 \times 10^{-7} \frac{M}{10^6 M_\odot}$ pc





Bright & Paschalidis, 2022

Fluid simulations: accretion structures



In circular orbit, for $q \geq 0.1$:

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

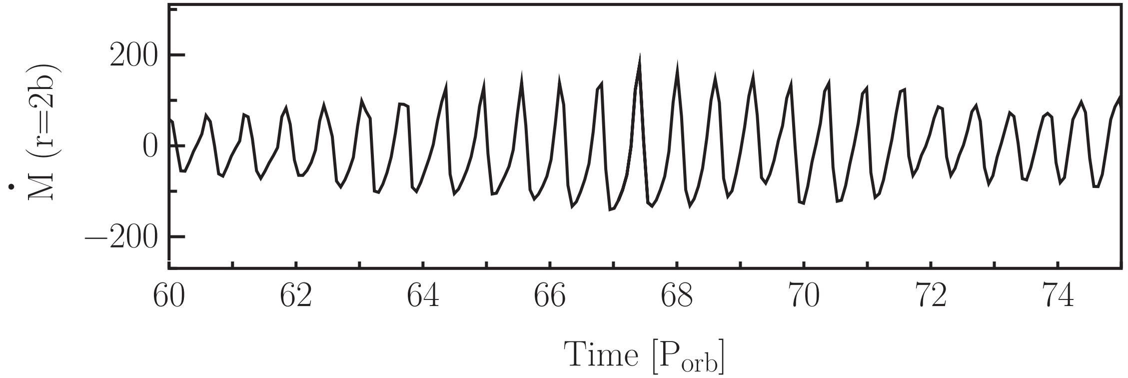
   and further in time…

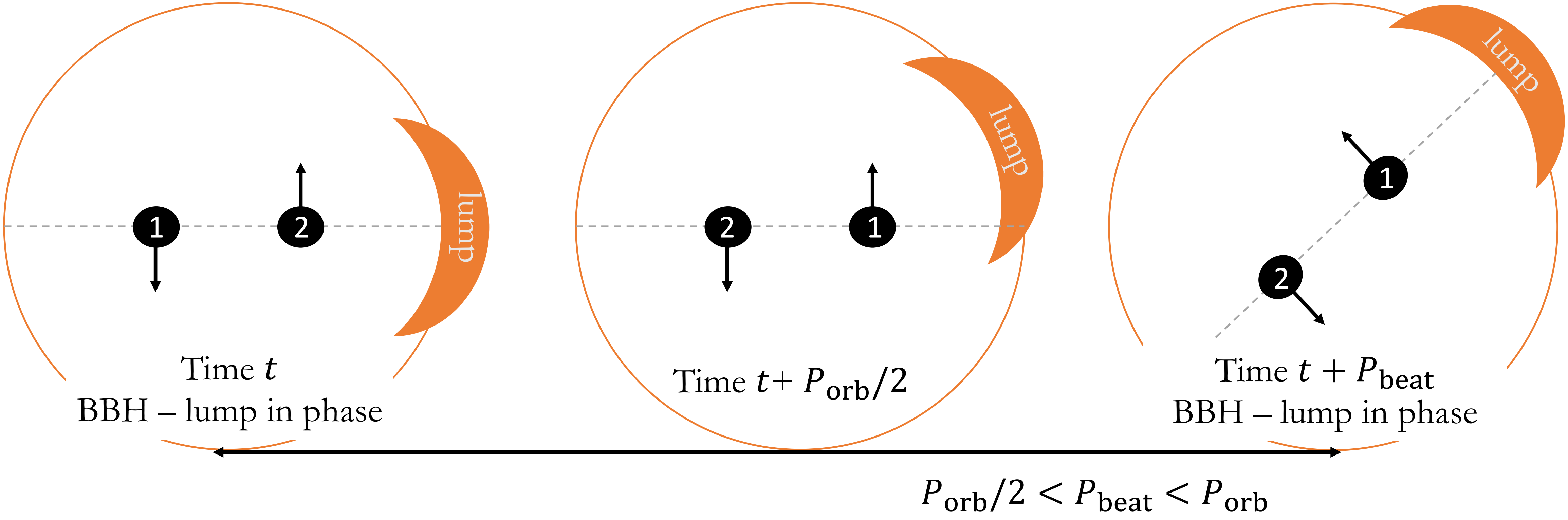
3. An overdensity, or « lump » (e.g. MacFadyen+08, Shi+12, Noble+12, D'Orazio+13, Gold+14, Farris+14, Ragusa+16, Miranda+17, Muñoz+19, Duffell+20, Armengol+21, Tiede+20+21, Liu+21, Franchini+22 (priv. com.), Siwek+22, Cimerman+23…)

Accretion structures → Observational features?

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
    $2\Omega_{\rm beat} = 2(\Omega_{\rm orb} - \Omega_{\rm lump}) \sim 1.7\Omega_{\rm orb}$





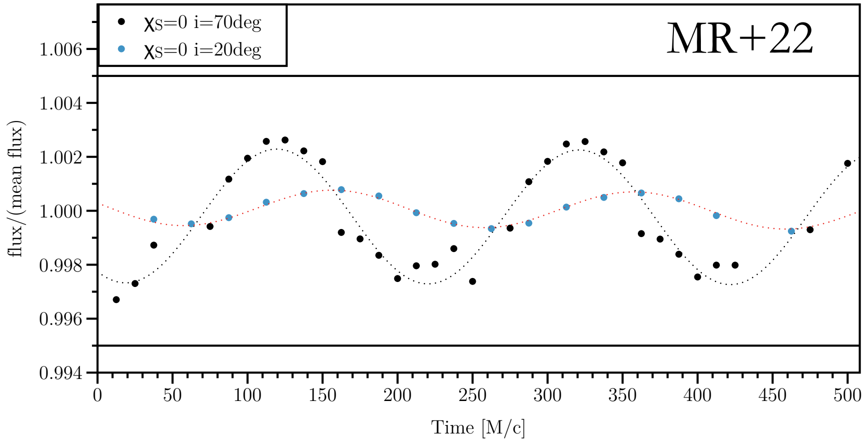
➢ **Accretion rate variability → Electromagnetic variability ?**

Detecting binary black holes thanks to these accretion structures and/or variability ?

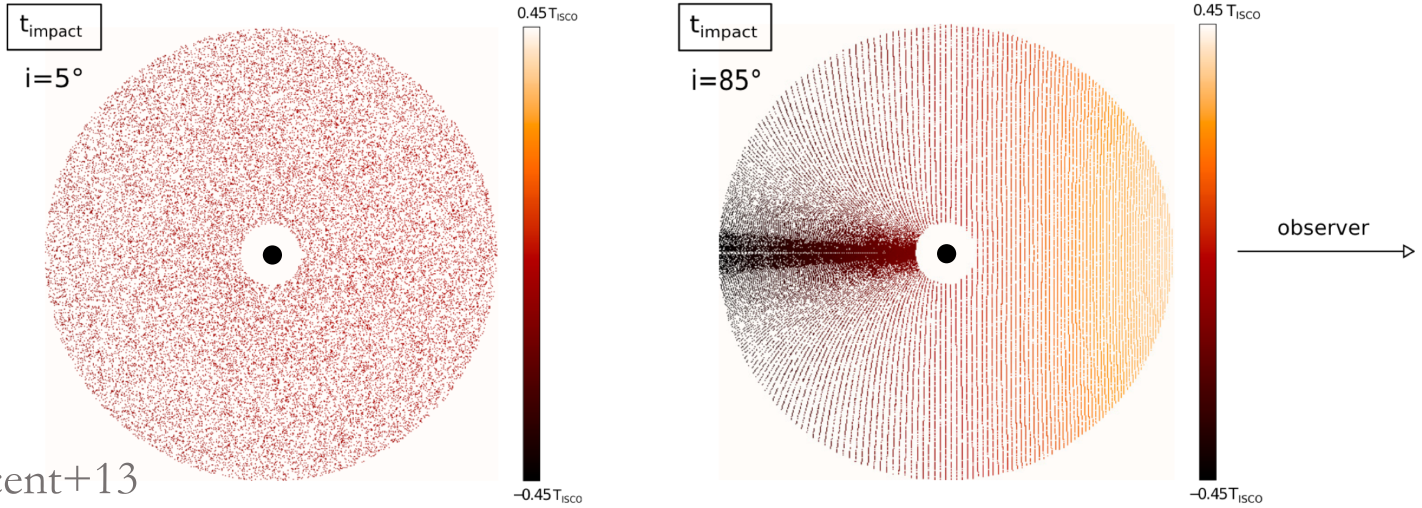
- Synthetic observations through GR ray-tracing

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
  …



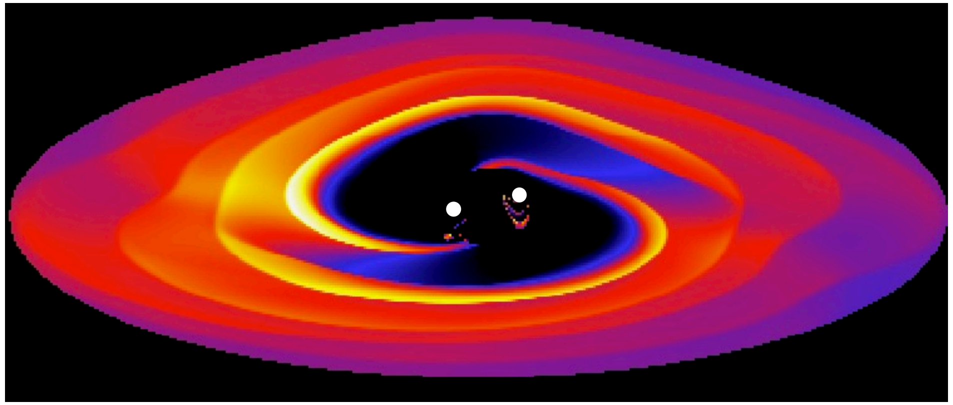
Vincent+13

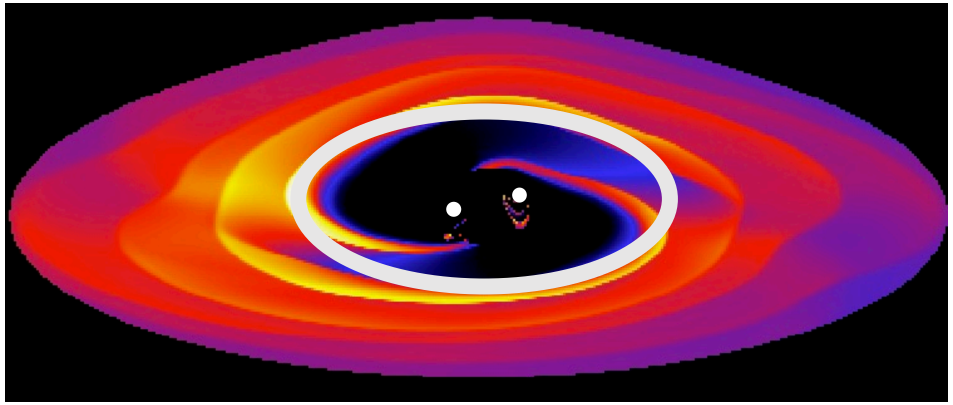
- Self-consistency:
  Incorporates the same BBH metric as the fluid code

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, Gutiérrez+22)
- 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 during photons' propagation
  - ➢ Emission map composed of photons of different time-origin (hence, fluid outputs!)

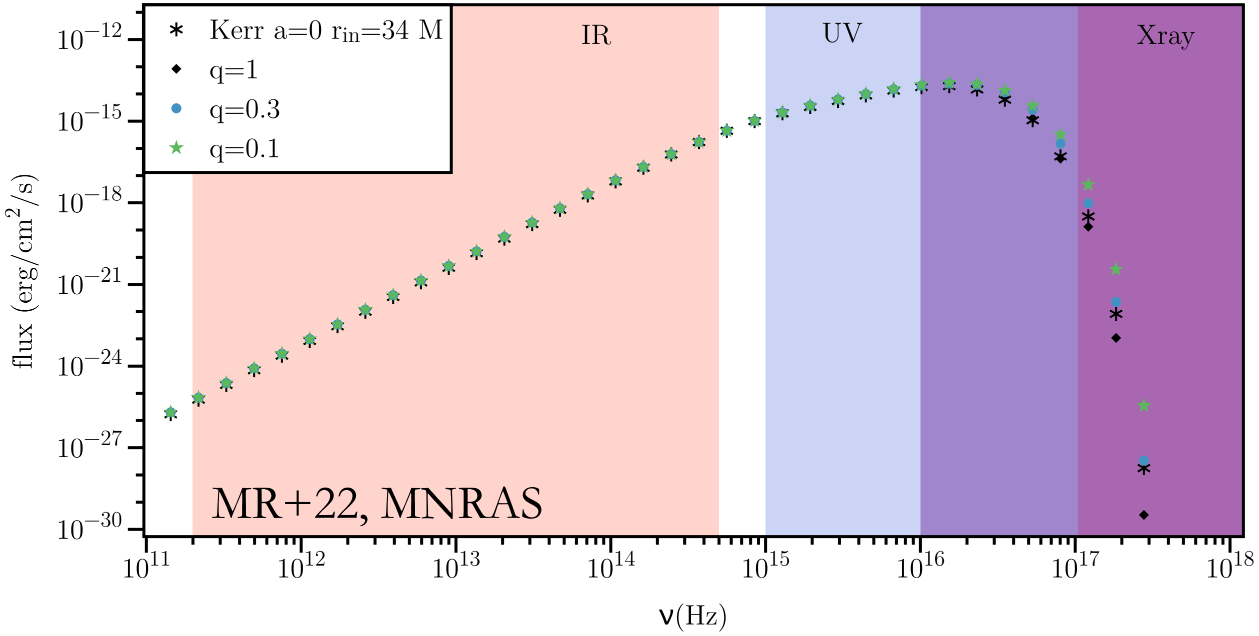




Impact of the cavity

Cavity: impact on the high-energy part of the SED

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

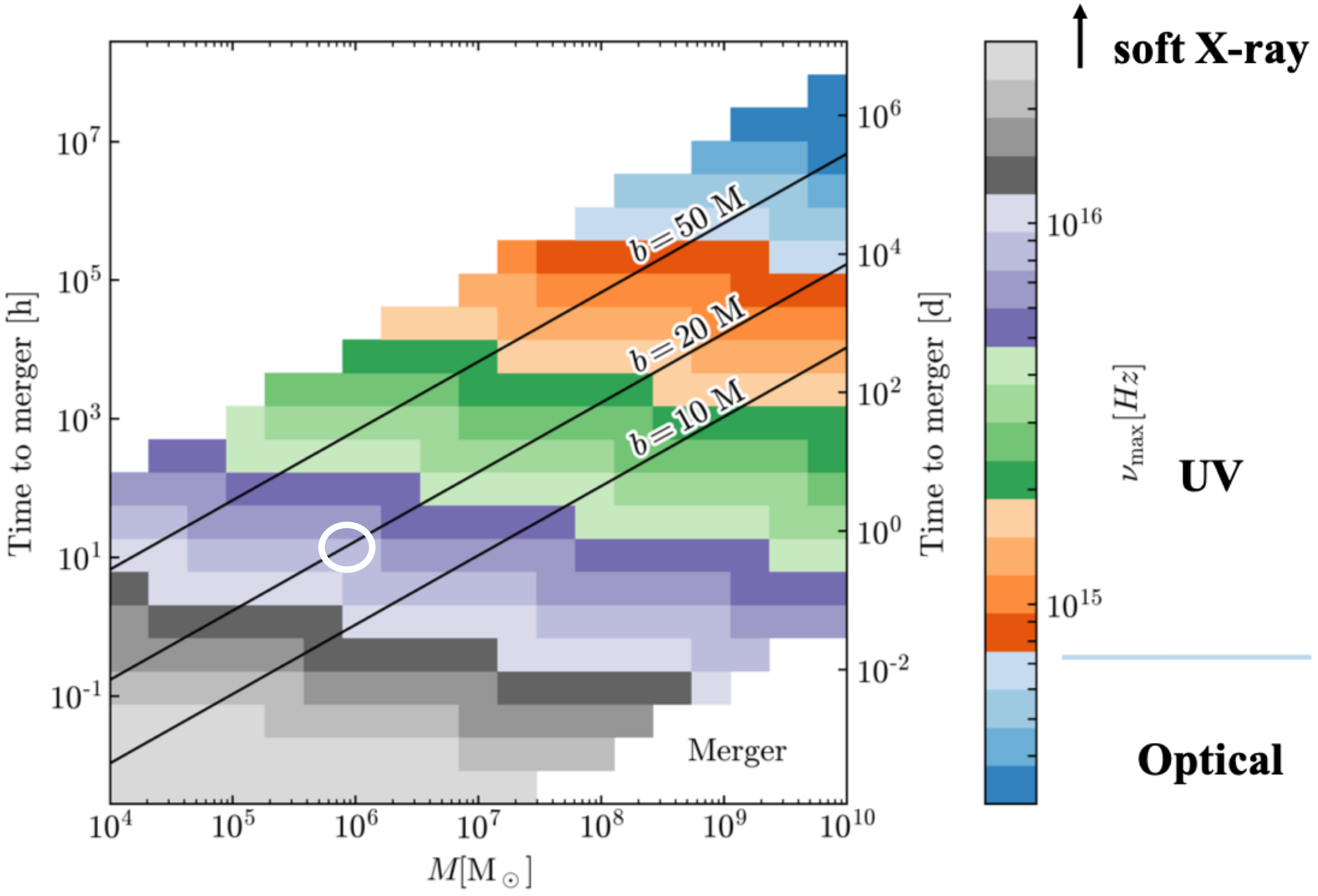


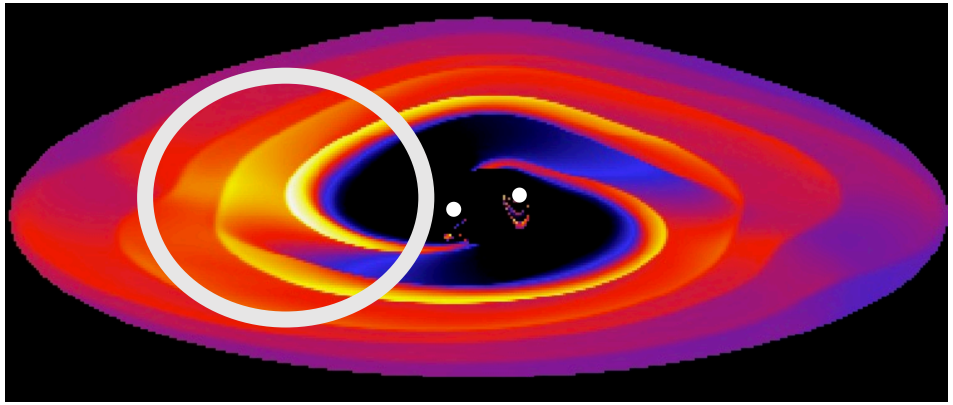
A BBH can be hidden behind a BH source with a truncated inner disk

(B)BH mass measurement needed !!

Which frequency band to observe BBH circumbinary disks?

For $q = 1$, $\dot{M} = 0.5\ \dot{M}_{\mathrm{Eddington}}$



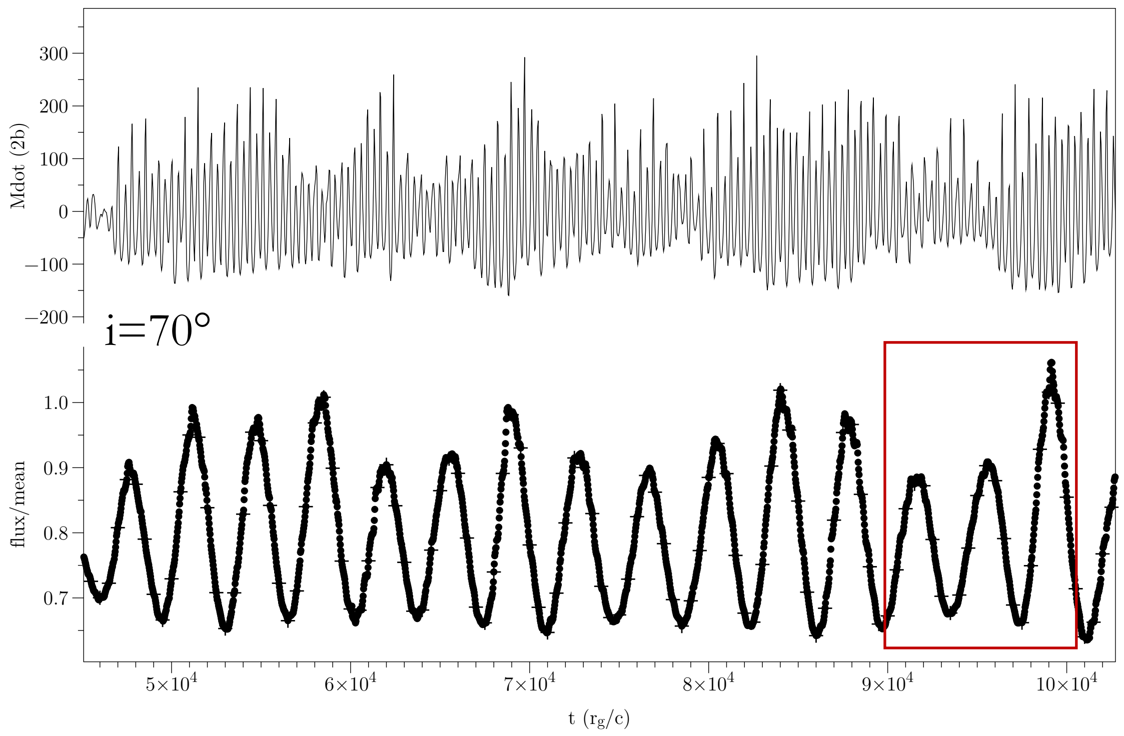


Impact of the lump & spiral arms

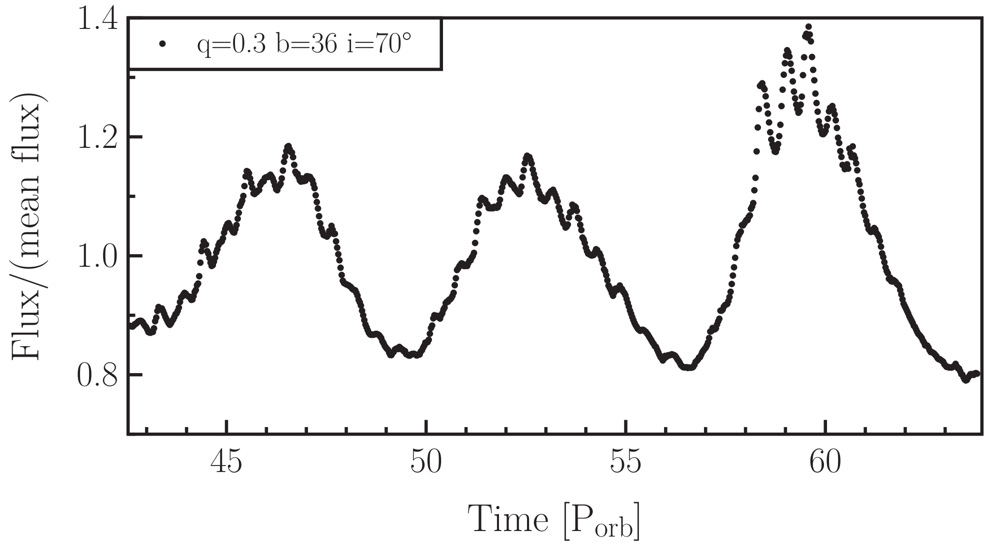
Timing features

- 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

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

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

A two-timescale modulation: the signature of circumbinary disks around BBHs? (MR+to be subm.)

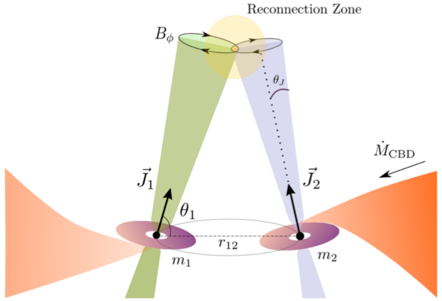
Conclusions: observational features of BBH circumbinary disks

Using eNOVAs (MR+22, MNRAS) we found:

- Accretion structures typical of BBHs: streams+spiral arms, cavity, «lump» (e.g. Noble+12, Shi+12)
  (Lump origin model: MR+23, MNRAS)
- Accretion rate variability at twice the orbital-lump beat frequency
- Thermal observational consequences:
  - ➢ Cavity causes the disk spectrum to be similar to that of a truncated single BH disk
  - ➢ Two-timescale modulation in the lightcurve, dominated by the «lump» modulation
    - ➢ Accretion rate is <u>not</u> a good proxy for the luminosity

(MR+to be subm.)

➢ Inspiral motion?
➢ Mini-disk emission?
➢ <u>Other messengers</u> (non-thermal particles, neutrinos…)? e.g. Gutiérrez+23



My project here: accretion flow interaction with pulsar wind

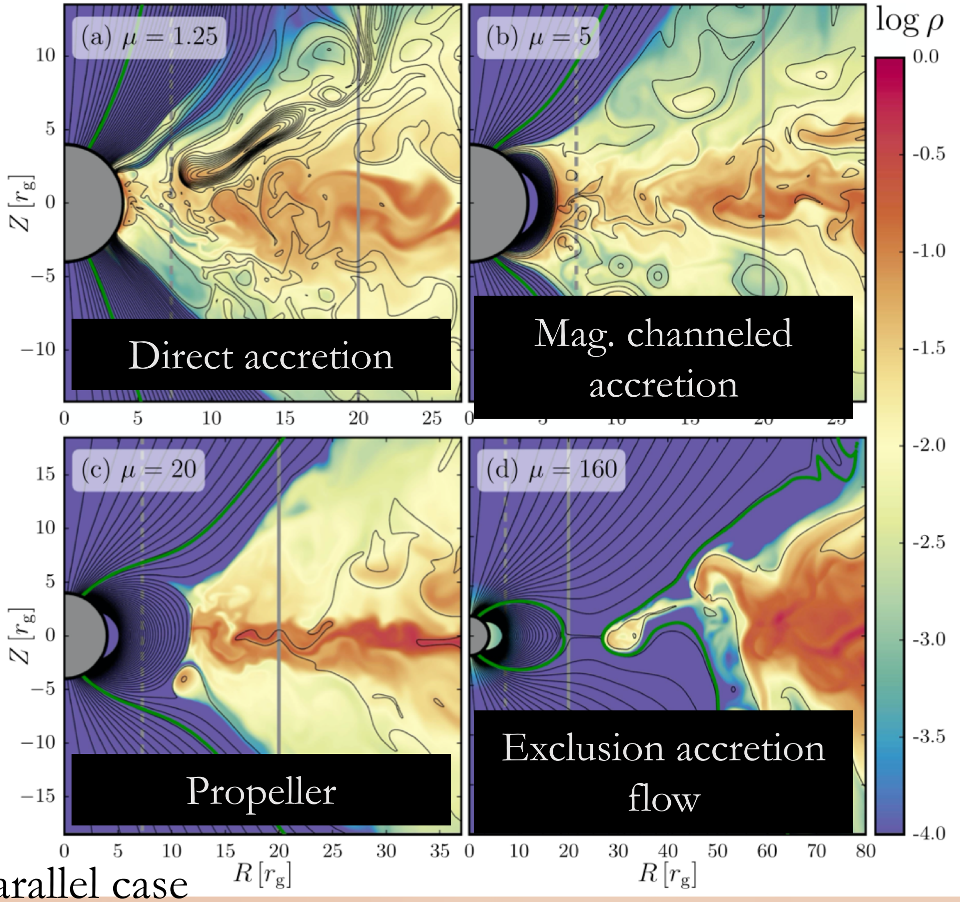
Observational constraints:

- Transitional millisecond pulsars: switch between accretion-powered (« disk ») and rotation-powered (« pulsar ») states:
  3 sources: IGR J18245-2452, XSS J12270-4859, PSR J1023+0038

- « X-ray mode switching »: L_X (0.5-10keV) changes by $5-7$ between a high (« active ») and low (« passive ») value, randomly, when in the disk state (Linares+14, MNRAS), on timescales ~seconds. Not observed in LMXBs

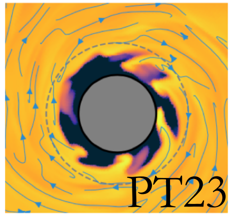
State-of-the-art of simulations:

- States reproduced, individually, in 2D axisym. GRMHD simulations:
  Stellar field – disk field parallel/anti-parallel
  Stellar magnetic moment $\mu \nearrow \Longrightarrow$ disk truncation radius $\nearrow \Longrightarrow$ 4 states
  Note: $\mu \nearrow$ equivalent to $\dot{M} \searrow$
  + one intermediate state: frequent flow expulsion from light cylinder
  (Parfrey & Tchekhovskoy, 2017)



PT17:
anti-parallel case

- Recently extended to 3D (Parfrey & Tchekhovskoy, 2023)
  - ➢ non-axisymmetries?



  - ➢ disk field evolution? (blocked in 2D)
  - ➢ stellar dipole obliquity? Das & Porth, arXiv