e-NOVAs:
extended Numerical Observatory for Violent Accreting systems

NTNU

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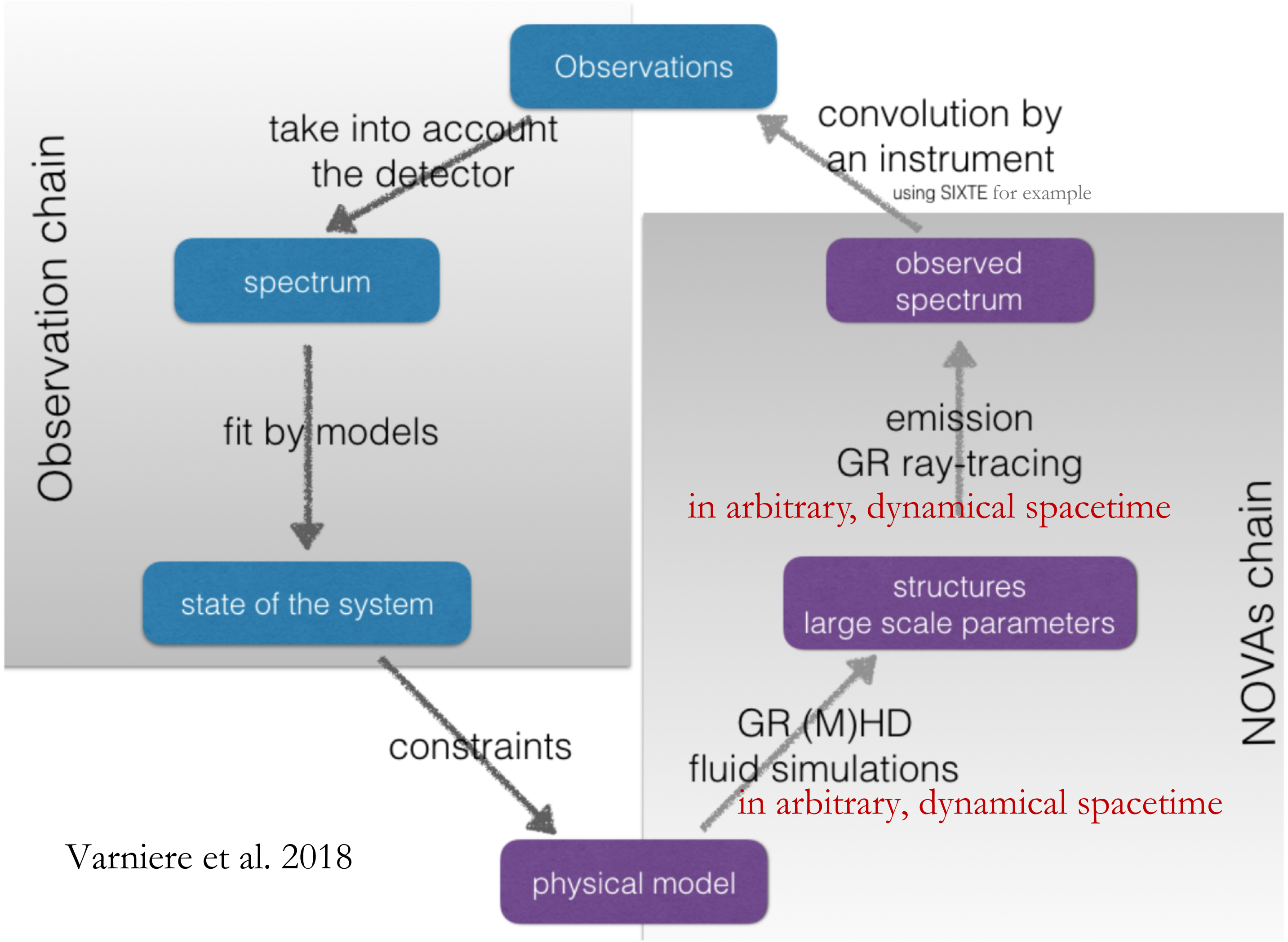
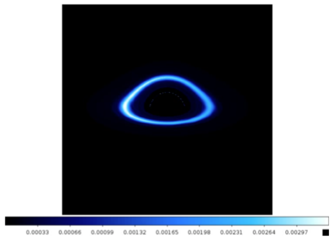
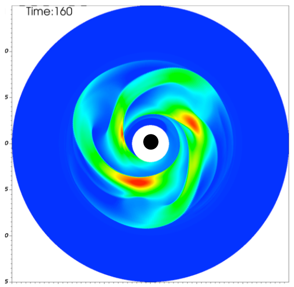
extended Numerical Observatory for Violent Accreting systems (e-NOVAs)





GYOTO
Vincent+11

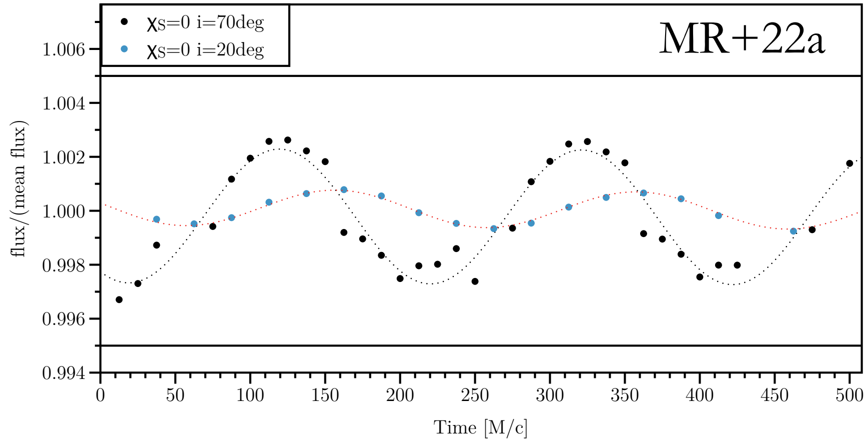


GR-AMRVAC
Keppens+12, Casse+17

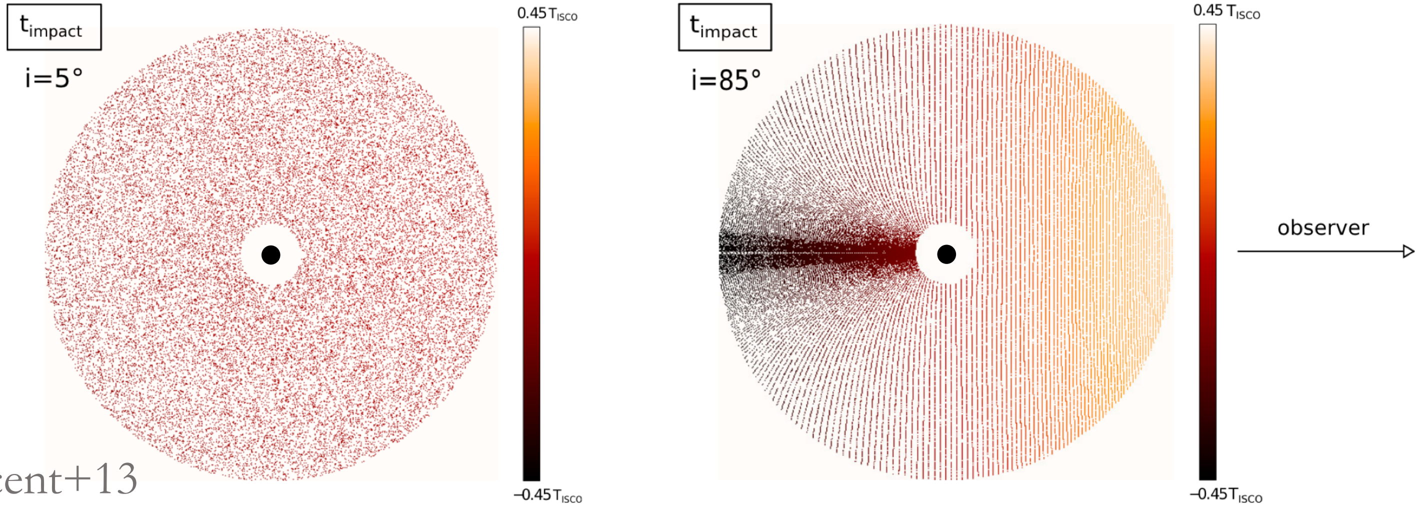
Extension of NOVAs to arbitrary, dynamical spacetimes (see MR+22, MNRAS)

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:
  same GR metric as the fluid code

- No fast-light approximation in Gyoto

Capabilities already included in eNOVAs for BBHs

Mass ratio q

Stellar-mass BBH mergers
Results scalable for any BBH mass:
temporal and spatial scales proportional to M
But 1) no gas-rich environment expected, and
2) short timescales $\sim 1(M/40M_\odot)$ seconds
In an AGN disk: OK in Pseudo-Newtonian

Post-merger phase: single BH
Initial conditions ?
A single BH with a kick or equivalently, in a moving medium

merger

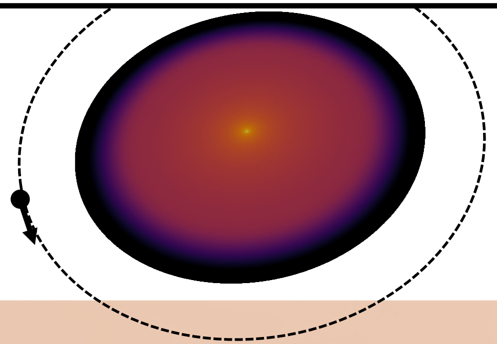
Time

Pre-circumbinary phase
Pseudo-Newtonian approximation
F. Casse, P. Varniere, L. Arthur, F. Dodu (APC)

Extreme mass-ratio inspiral (EMRIs)
BBH approximate metric valid for EMRIs
Limitation: disk self-gravity
or Pseudo-Newtonian approx.

2nd part of this talk: pre-merger, circumbinary accretion

BBH total mass



Credits:
P. Varniere

Ask us if you are interested in any of these

And more generally…

GR-AMRVAC d.o.f.
(hydro/MHD, non-/relativistic…
spe. relativistic PIC-MHD)

×

GYOTO d.o.f., including emission process:
thermal (e.g. Varniere+20 for BH disks)
synchrotron (e.g. MR+21 proc. SF2A for Sgr A* flares)
polarization
…

But you may be interested in …

- Binary neutron stars ?
- Boson stars ?
- Other exotic compact object ?
- Any system with a pre-determined metric, be it exact or approximate, analytical or numerical

Signatures of circumbinary disks around pre-merger binary black holes

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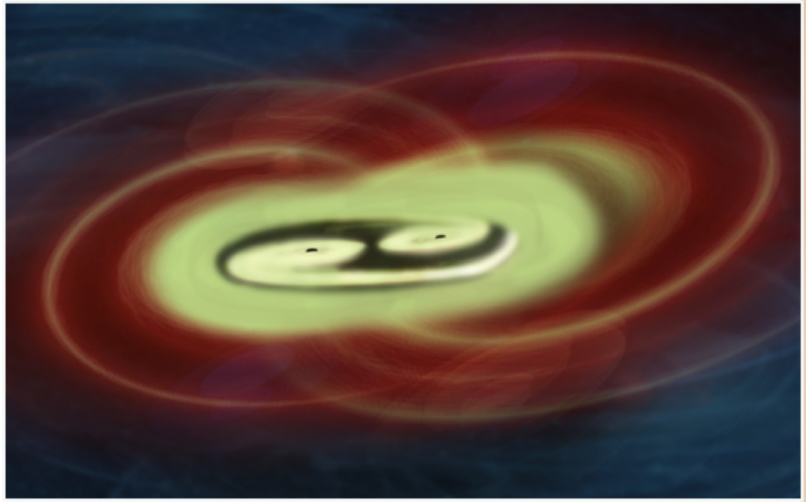
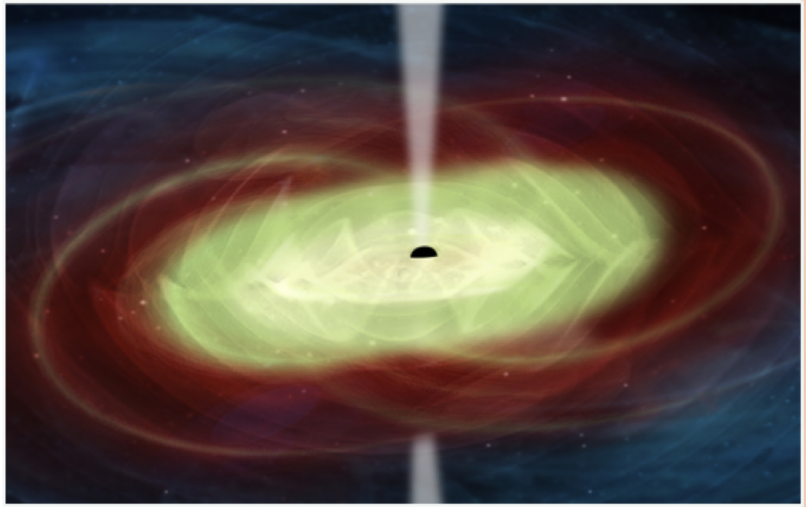
Electromagnetic counterpart to BBH fusion

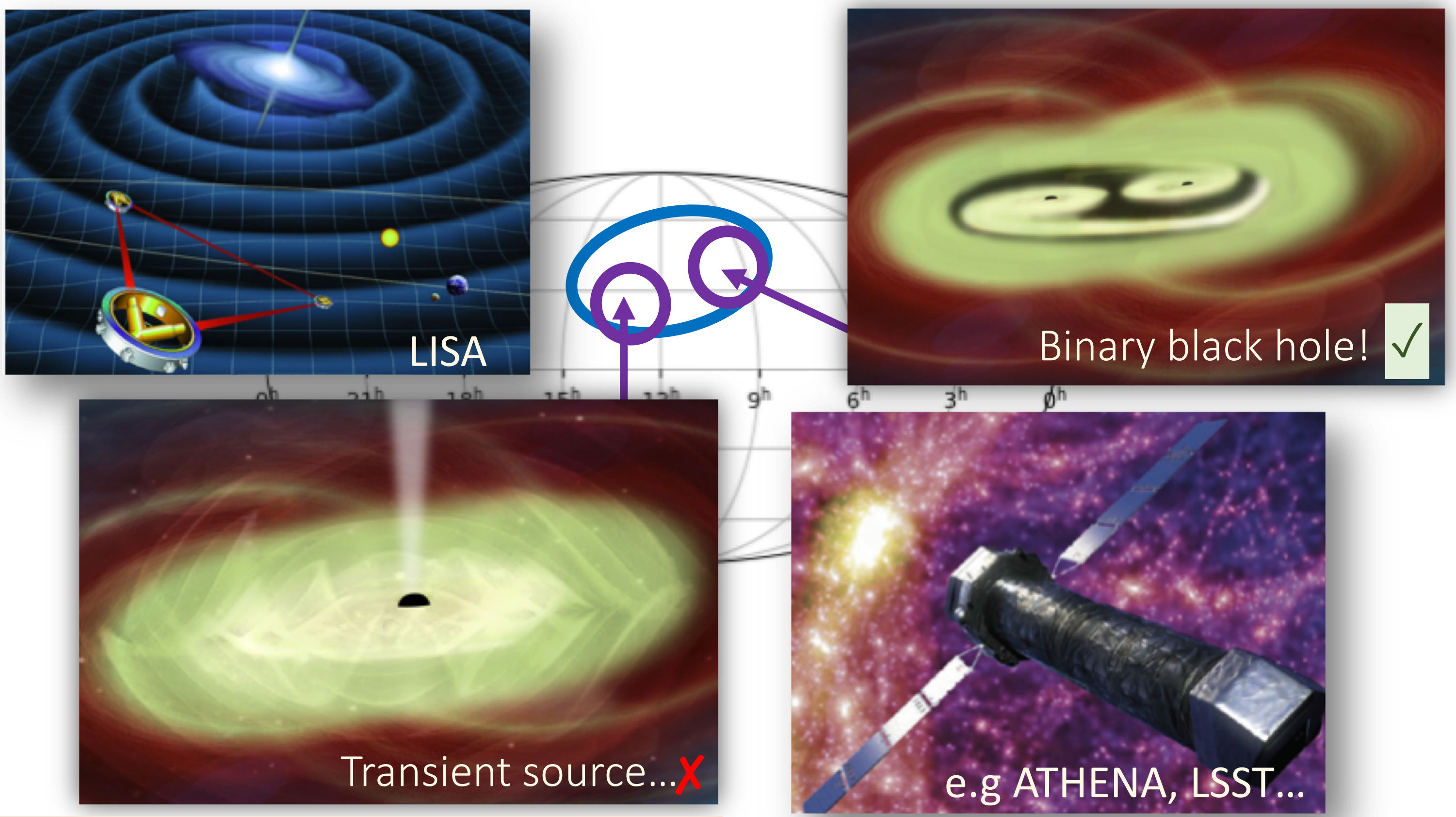
Need a gas-rich environment:
e.g. galaxy merger,
tidal disruption event or « fallback disk »
following supernova explosion



- 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



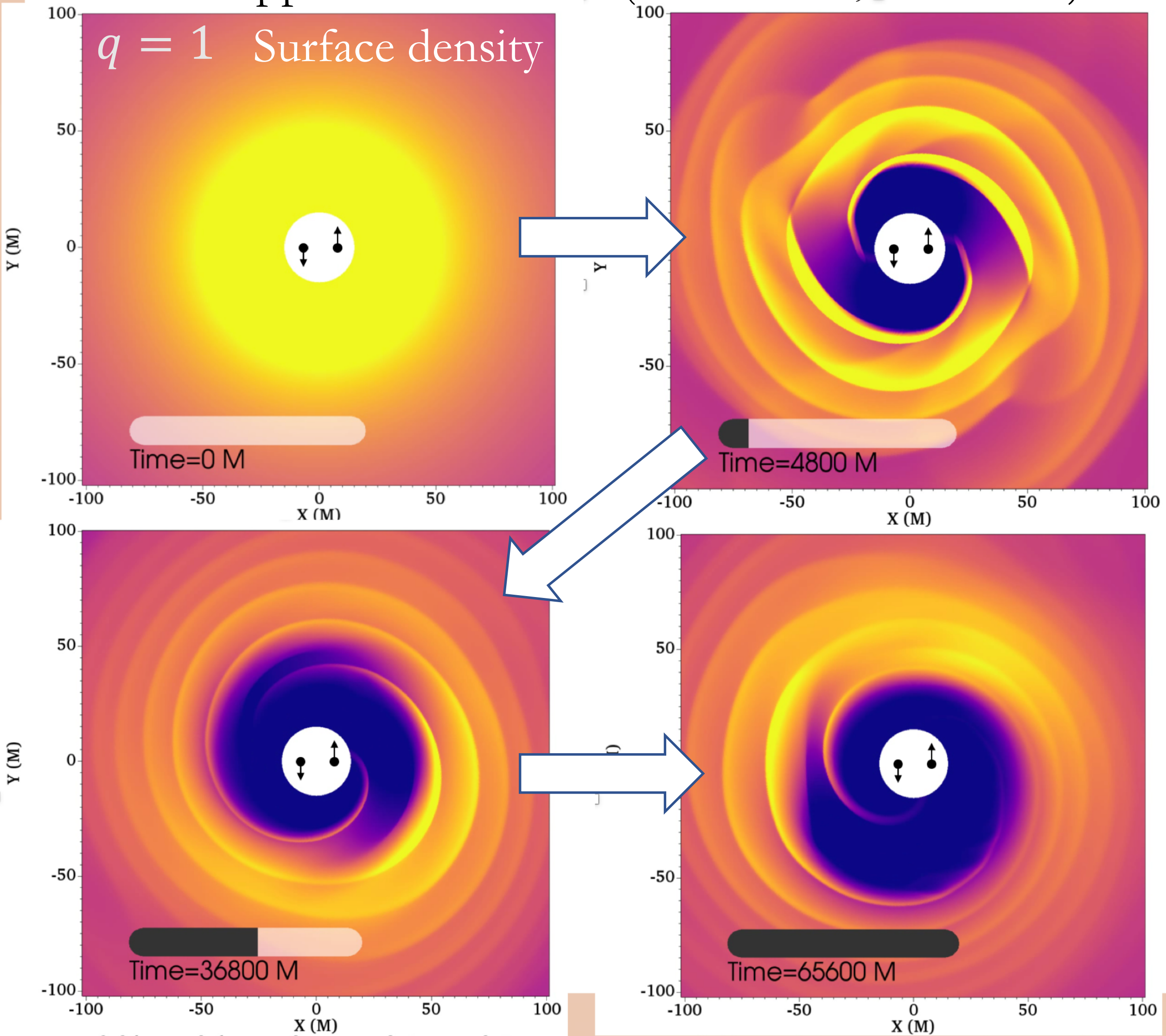
- LISA: space-based gravitational wave detector
  0.1mHz-100mHz band
  - SMBBH up to merger
  - Stellar-mass BH in early pre-merger stage only

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

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

Fluid simulations: accretion structures

- 2D General-relativistic-hydrodynamical simulations of a circumbinary disk
- with **GR-AMRVAC** (GR: Casse+17, MR+23) : incorporates any (e.g. non-stationary) metric
- BBH approximate metric (Mundim+14, Ireland+16)



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

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

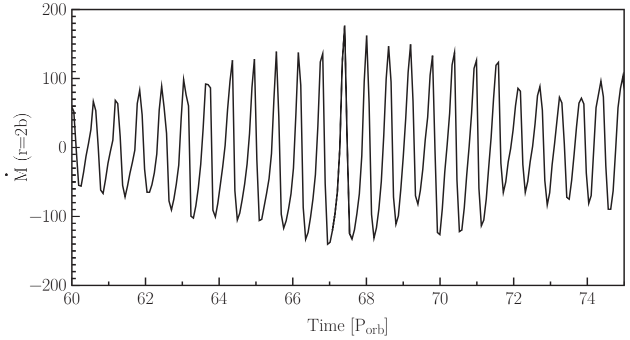
and further in time…

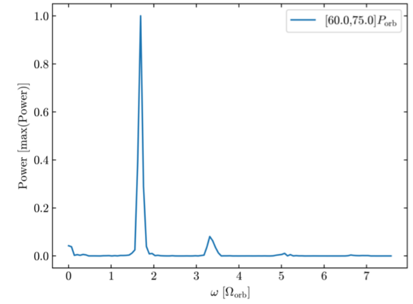
3. An overdensity, or « lump » (e.g. MacFadyen+08, Shi+12, Noble+12, D'Orazio+13, Gold+14, Farris+14, Ragusa+16, Miranda+17, Muñoz+19, Duffell+20, Armengol+21, Tiede+20+21, Liu+21, Franchini+22 (priv. com.), Siwek+22, Cimerman+23…)

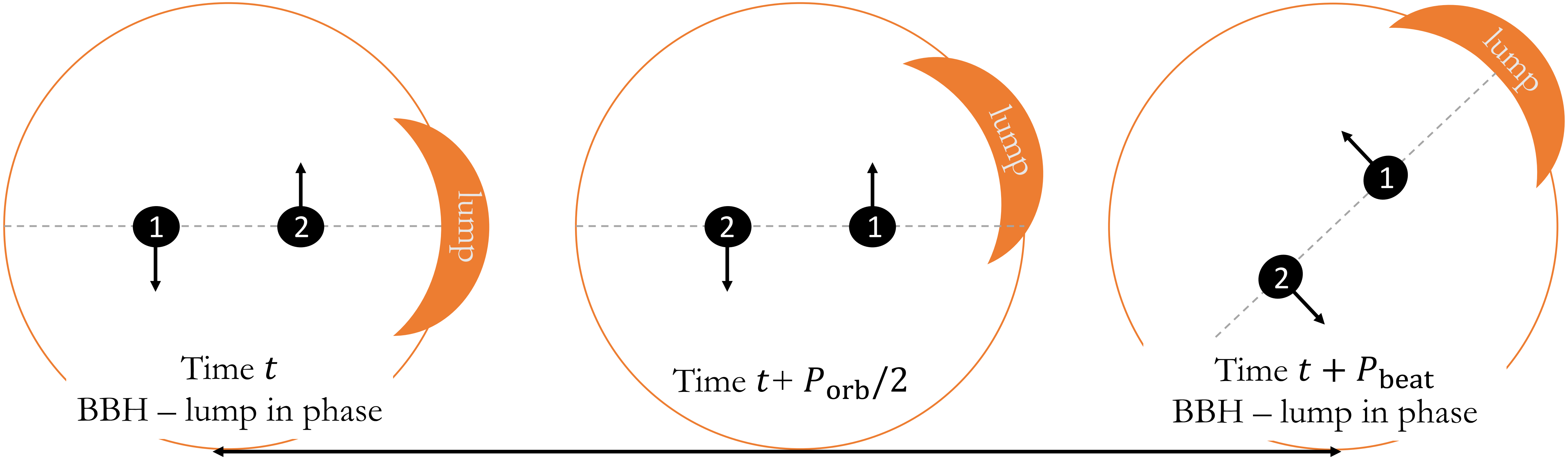
Accretion structures → Observational features?

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







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

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

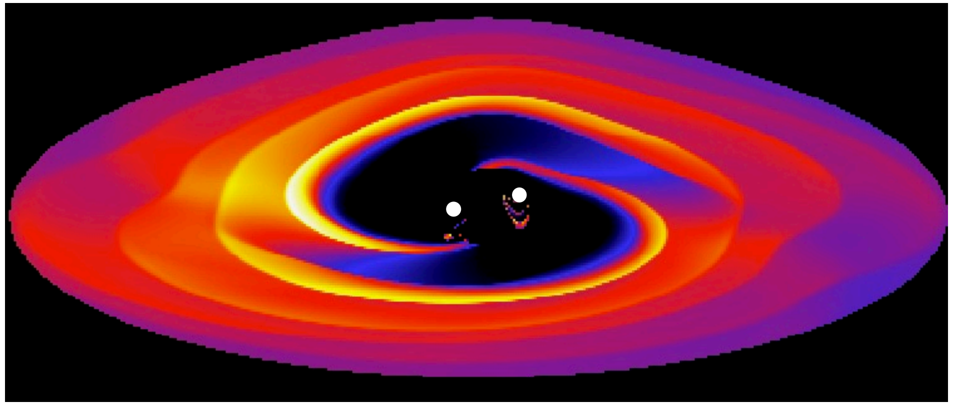
Detecting binary black holes thanks to these accretion structures and/or variability ?

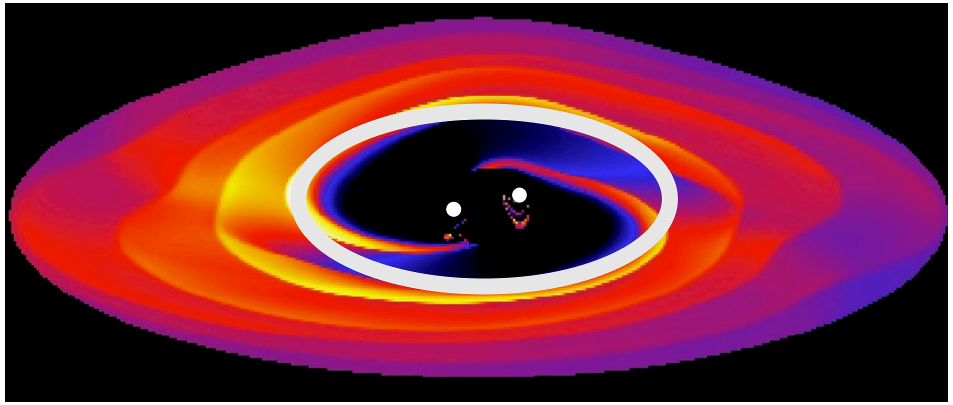
- Synthetic observations through GR ray-tracing

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**
- 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!)

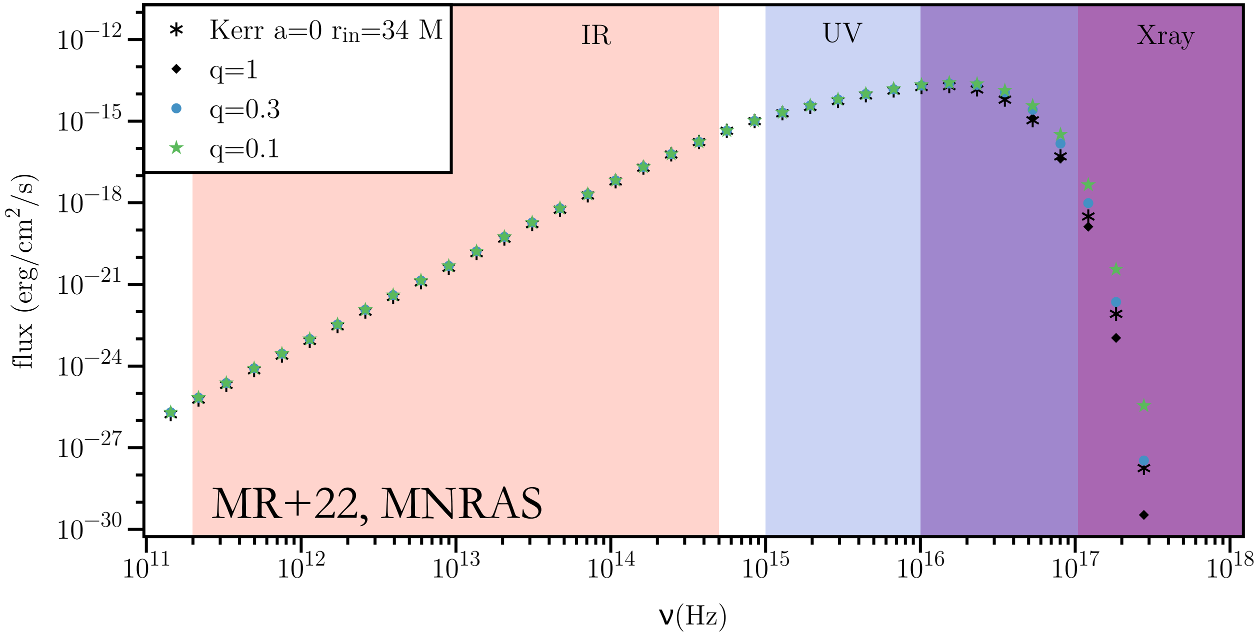




Impact of the cavity

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 $6\ r_g$



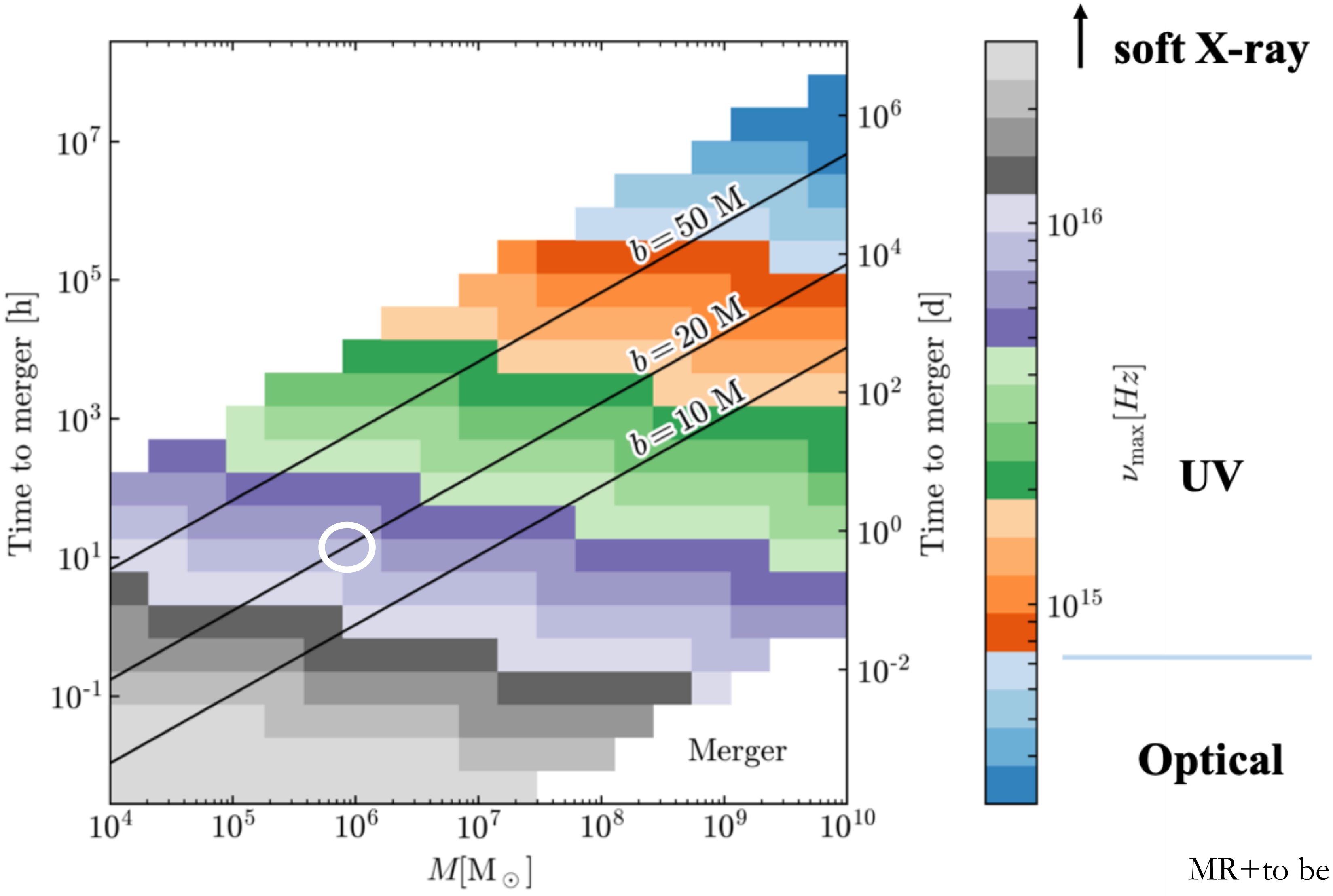
see also
Varniere, MR+to be subm.

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

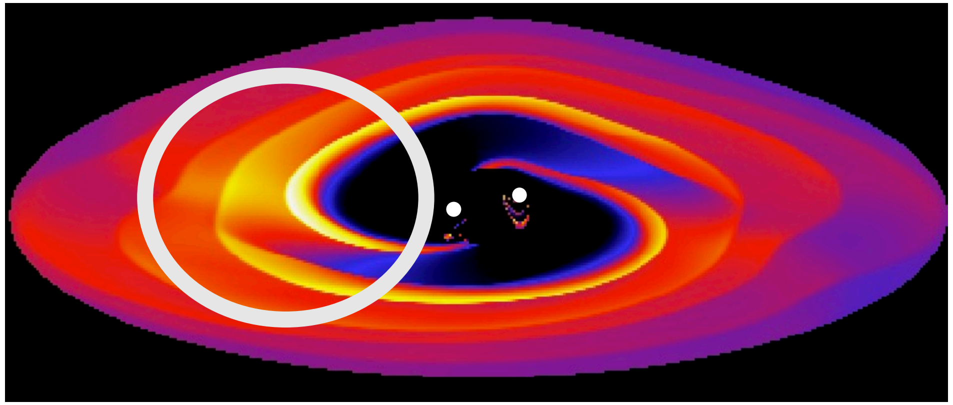
(B)BH mass measurement needed !!

Which frequency band to observe BBH circumbinary disks?

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



MR+to be subm.

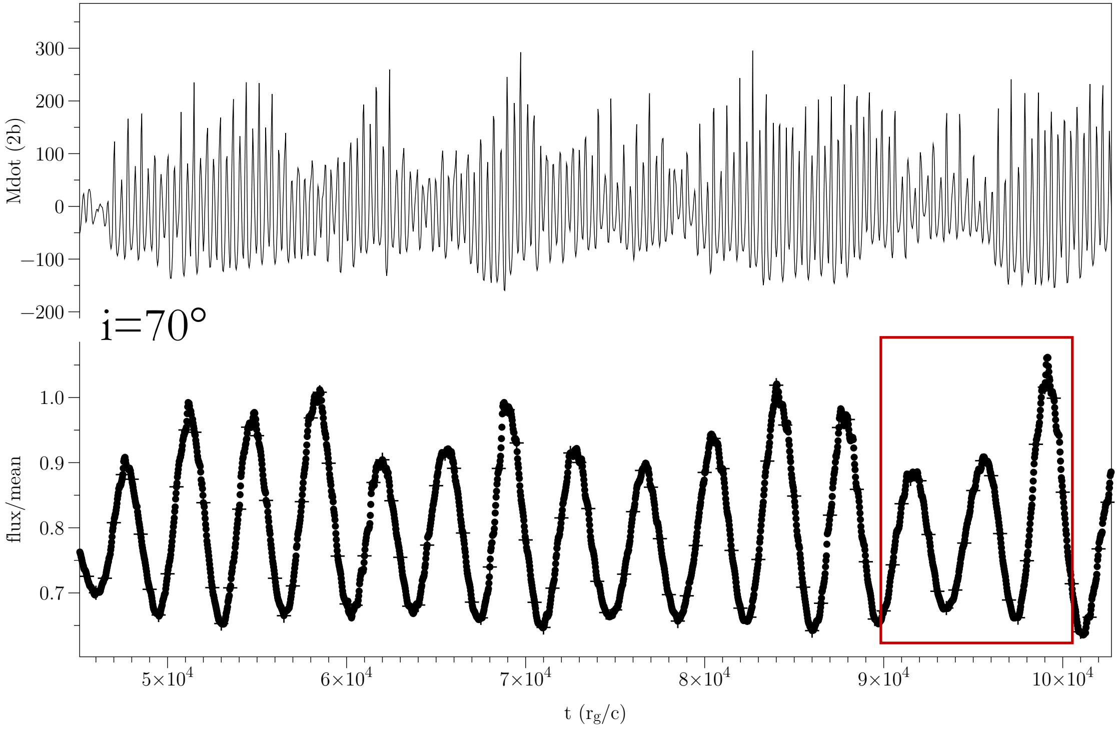


Impact of the lump & spiral arms

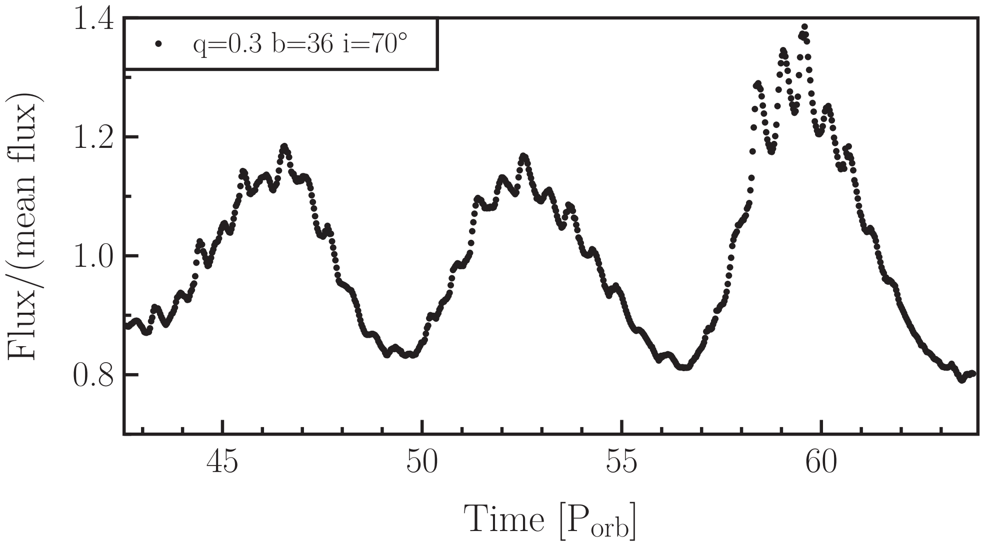
Timing features

- 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.)

- ➢ Unicity of these signatures? Varniere, MR+to be subm.
- ➢ Detecting pre-merger BBHs from now on?
- ➢ Mini-disk emission?
- ➢ Other messengers (non-thermal particles, neutrinos…)?

To be continued…