The environment of pre-merger binary black holes

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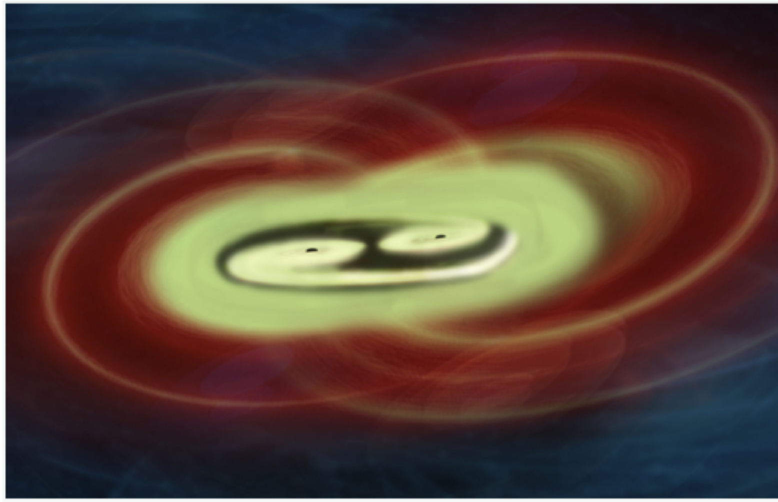
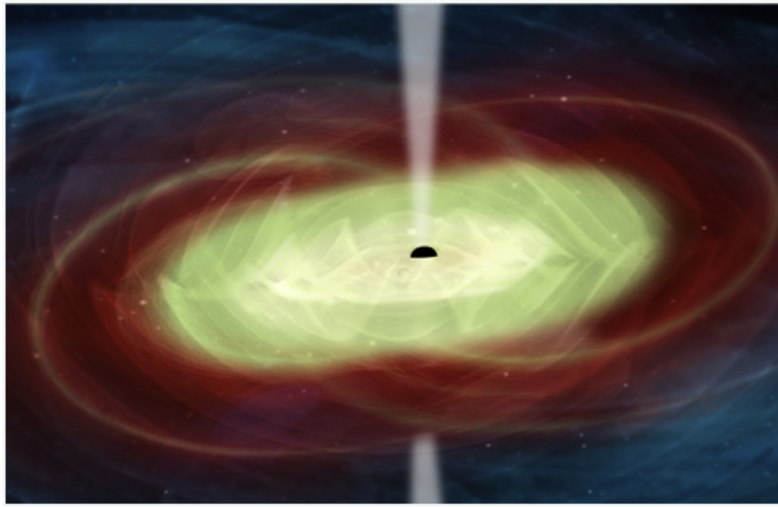
Electromagnetic counterpart to BBH fusion

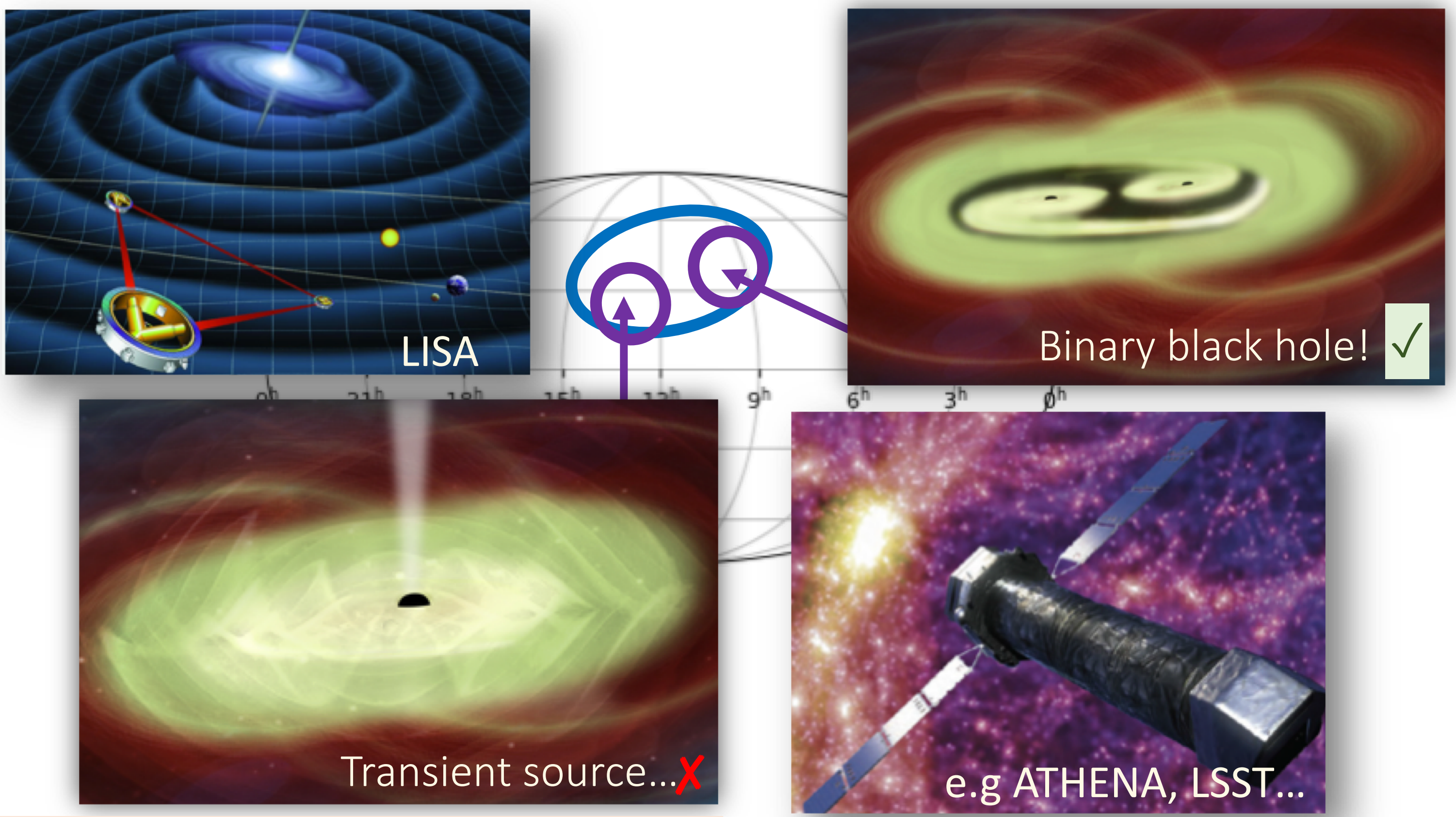
Need a gas-rich environment:
e.g. galaxy merger,
tidal disruption event or « fallback disk »
following supernova explosion





- 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 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

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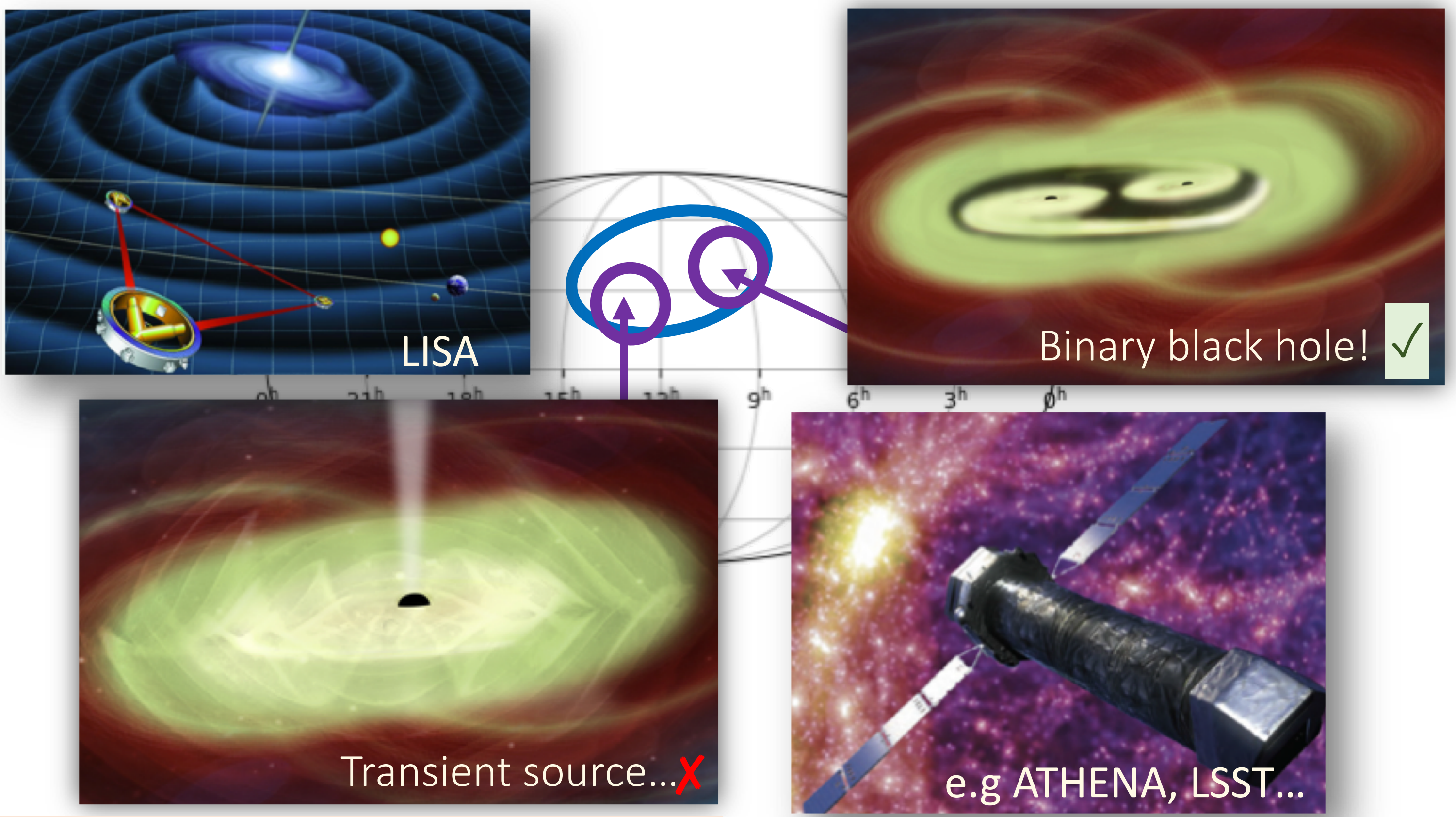

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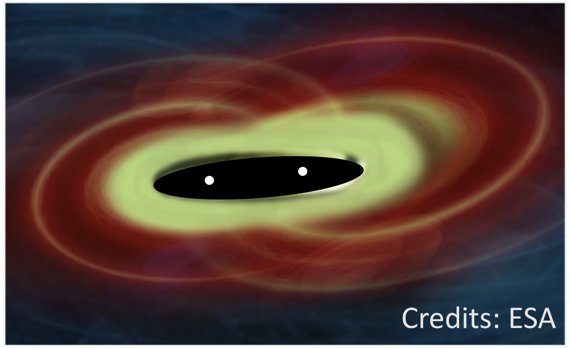
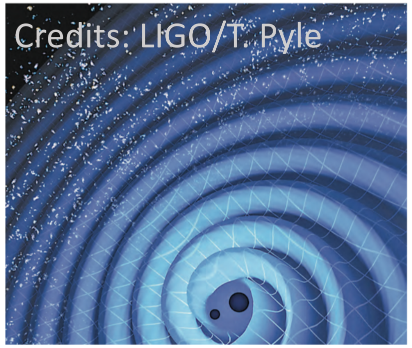
How to distinguish binary black holes from other (transient) sources ?

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)





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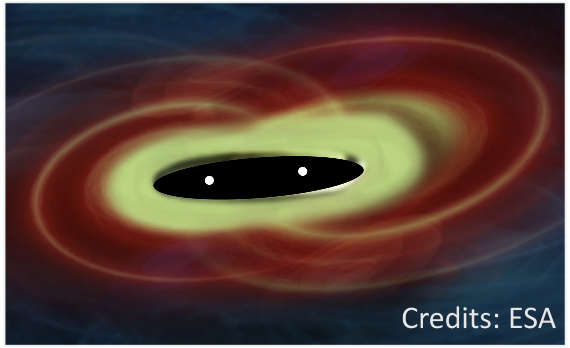

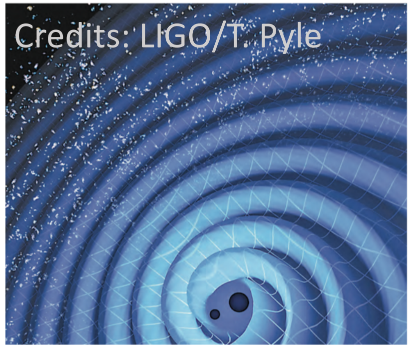

➢ Implement an approximate, analytical BBH spacetime
+ solve post-Newtonian equation of motion for GW-driven inspiral (Mignon-Risse et al. 2022, MNRAS)

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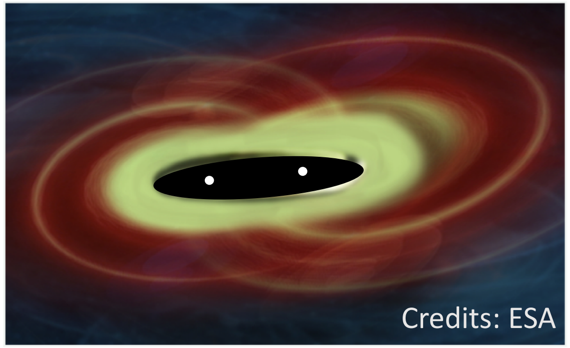
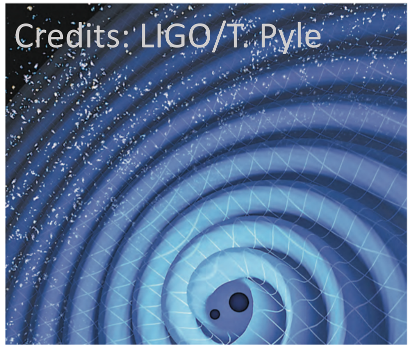




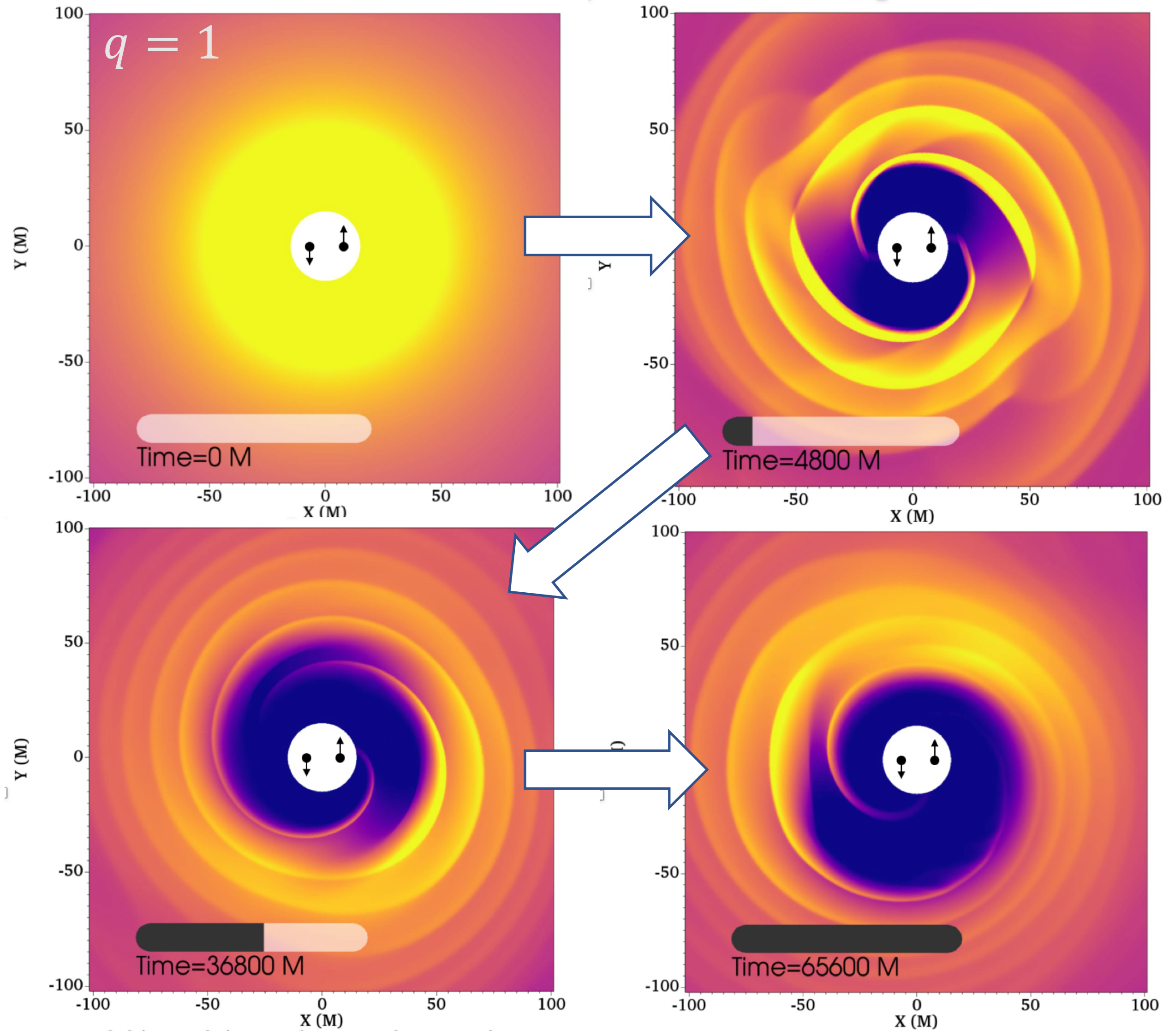
➢ Implement an approximate, analytical BBH spacetime
+ solve post-Newtonian equation of motion for GW-driven inspiral (Mignon-Risse et al. 2022, MNRAS)

➢ 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

Results: Accretion structures



Surface density

In circular orbit, 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. 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…)

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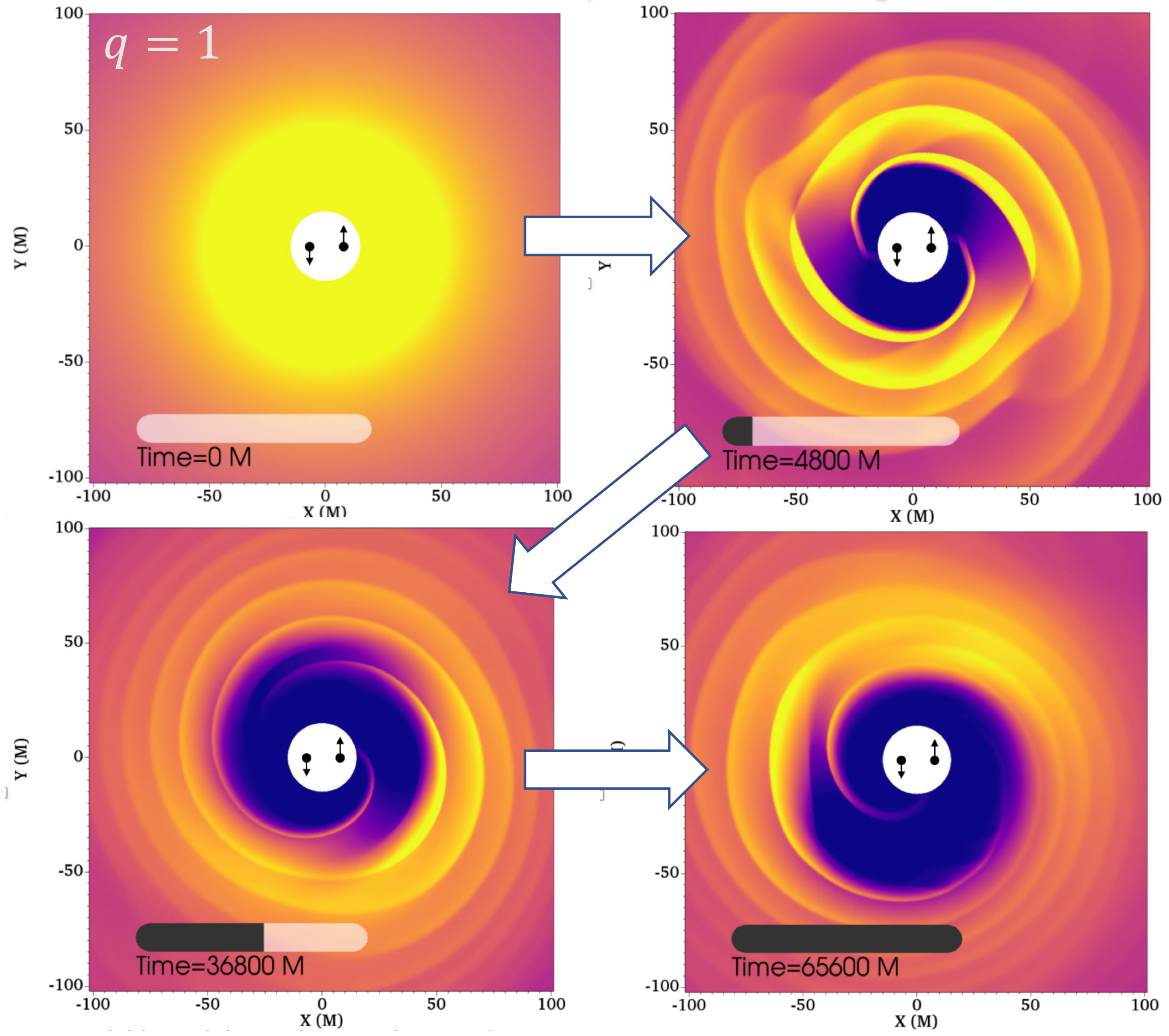

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Pre-merger electromagnetic features ?

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)

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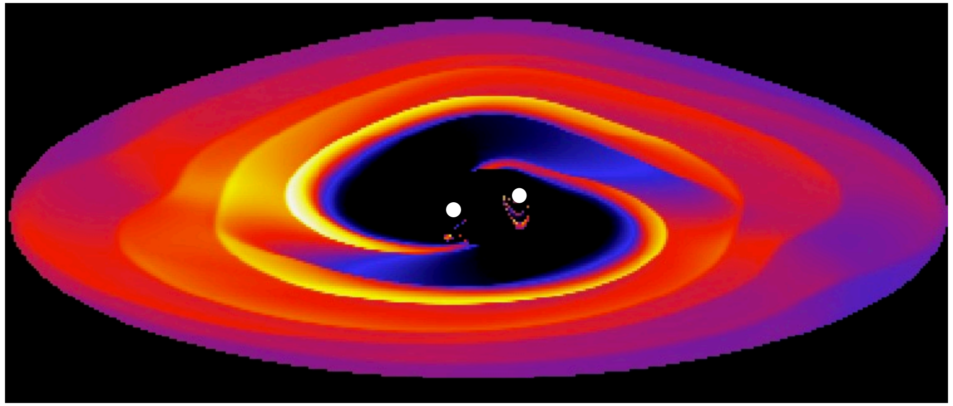
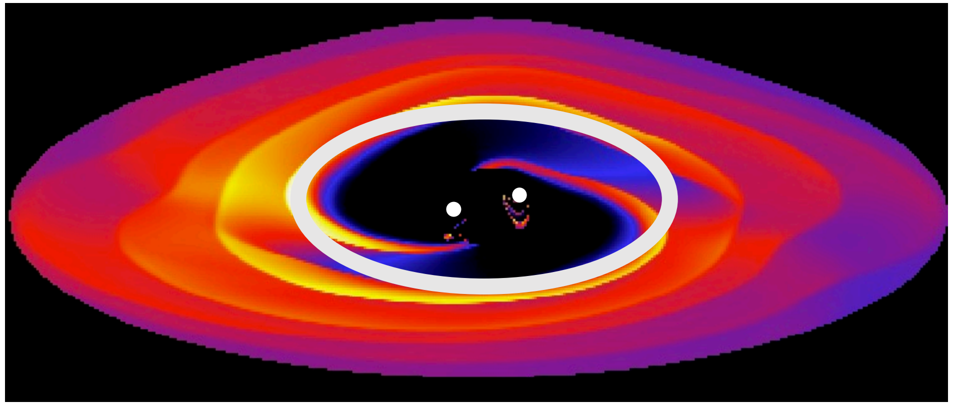
- Thermal emission, thin disk approximation (Shakura & Sunyaev, 1973)

- 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





Impact of the cavity

Cavity: high-energy deficit in the SED

- Circumbinary disk edge settles around $\sim 2\, r_{12}$ in BBHs, e.g. $\sim 30\ \mathrm{r_g}$ here
  - Deficit at high energy (e.g. Roedig+14, Shi & Krolik 2016, Tang+18; but Farris+15, D'Ascoli+18)

- In single BHs: disk inner edge set at the innermost stable circular orbit (ISCO) in single BHs
  - Highest-energy contribution to the spectrum at $6\ \mathrm{r_g}$

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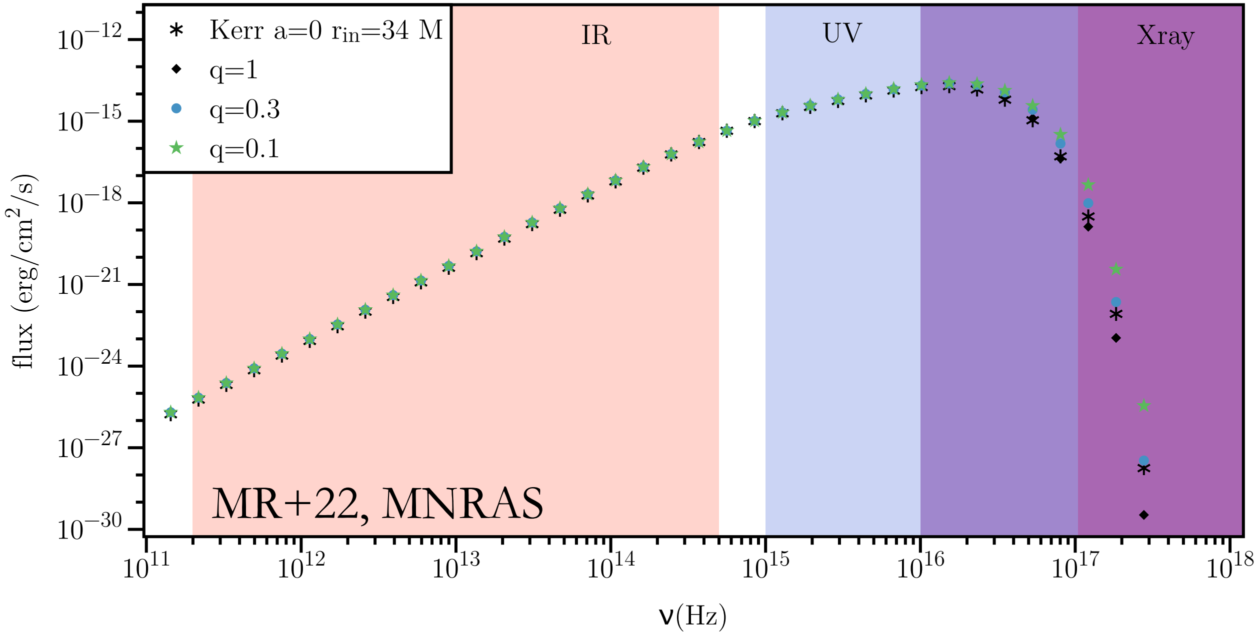
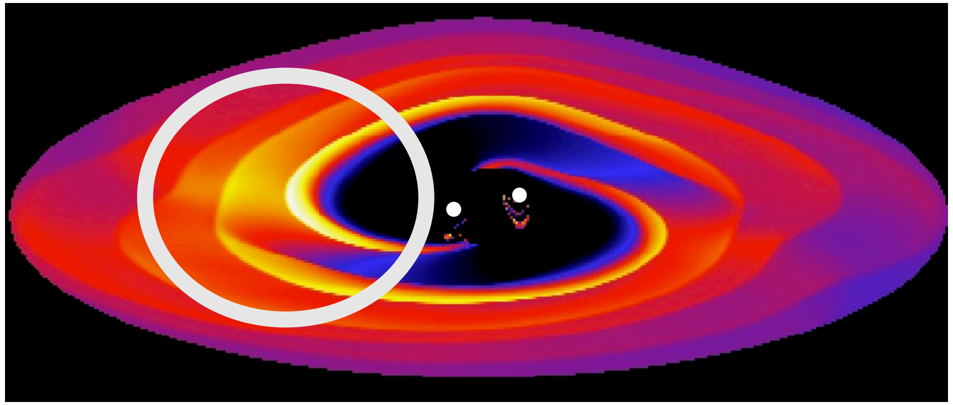


see also Varniere+in prep.

A BBH can be hidden behind a BH source whose disk inner edge is away from its ISCO

(B)BH mass measurement needed !!

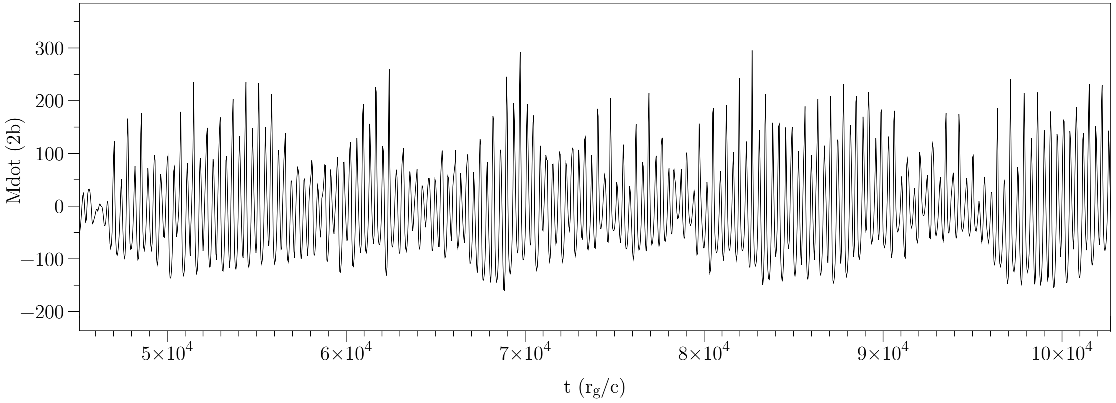


Impact of the lump & spiral arms

Timing features

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

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



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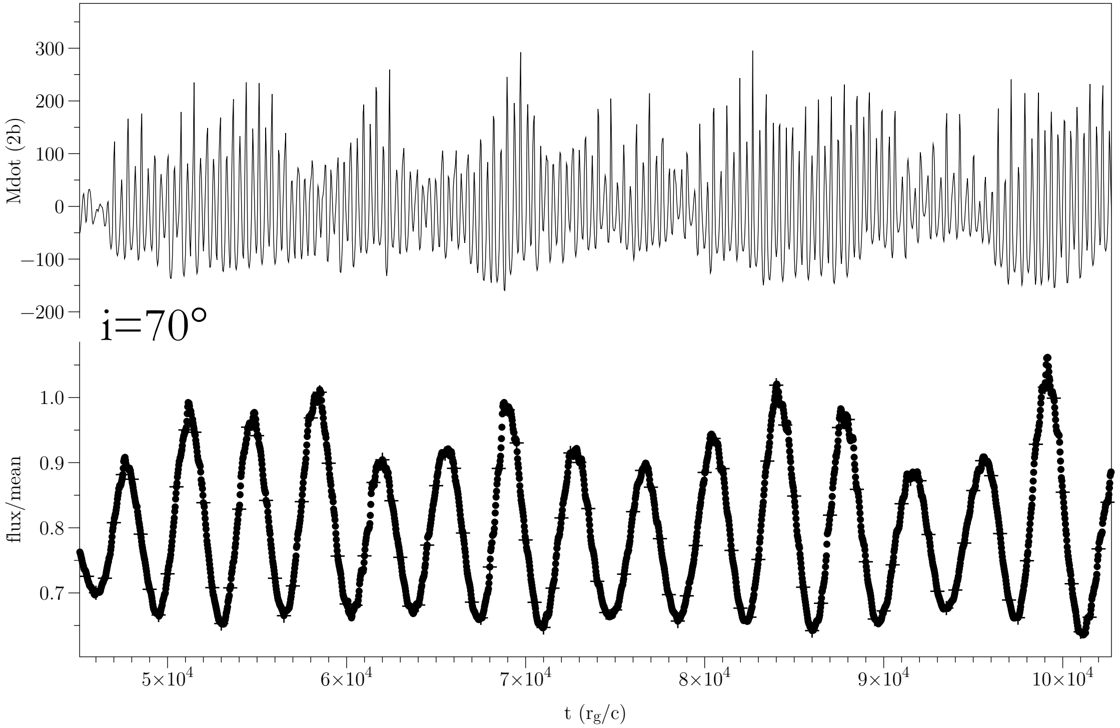

- Flux is normalized by the mean value ⇒ mass-independent lightcurve
- The main modulation of the lightcurve is produced by the lump
- Relativistic beaming of non-axisymmetric structures

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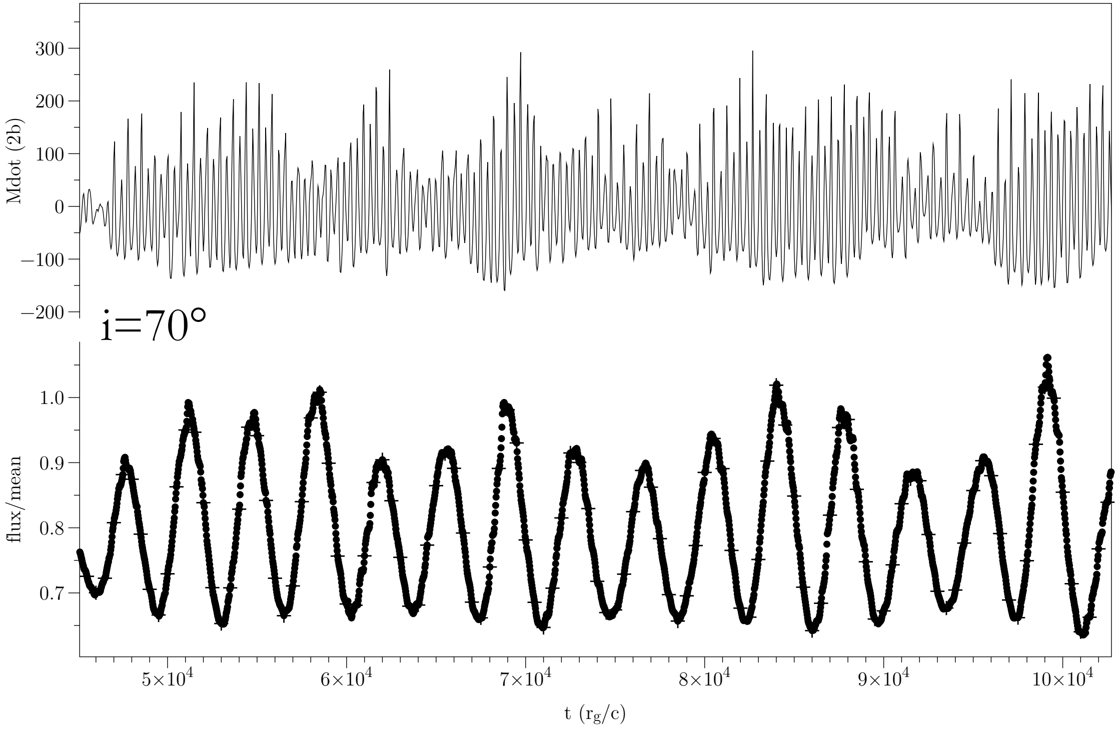
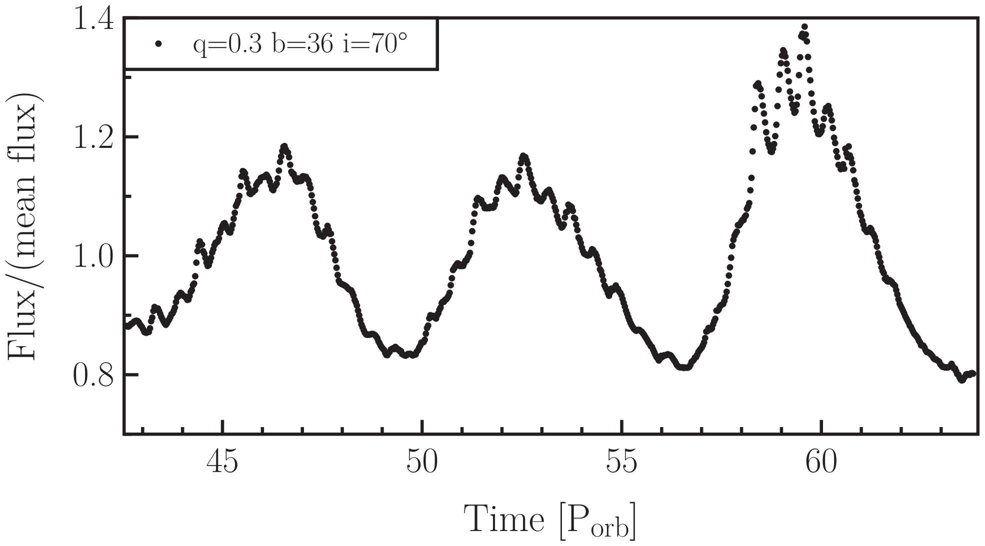


$q = 0.3;\ r_{12} = 36\mathrm{r_g}$



- Additional modulation at the semi-orbital period

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

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

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- The main modulation of the lightcurve is produced by the lump
- Relativistic beaming of non-axisymmetric structures

A two-timescale modulation : the signature of circumbinary disks around BBHs? (MR+in prep)

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
  - ➢ Accretion rate is <u>not</u> a good proxy for the luminosity

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➢ Unicity of these signatures ? see Varniere+in prep.

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

➢ Other messengers (non-thermal particles, neutrinos…)?

To be continued…

Inspiralling BBHs (preliminary)

$q = 1$

$r_{12}(t = 0) = 20M$

Time

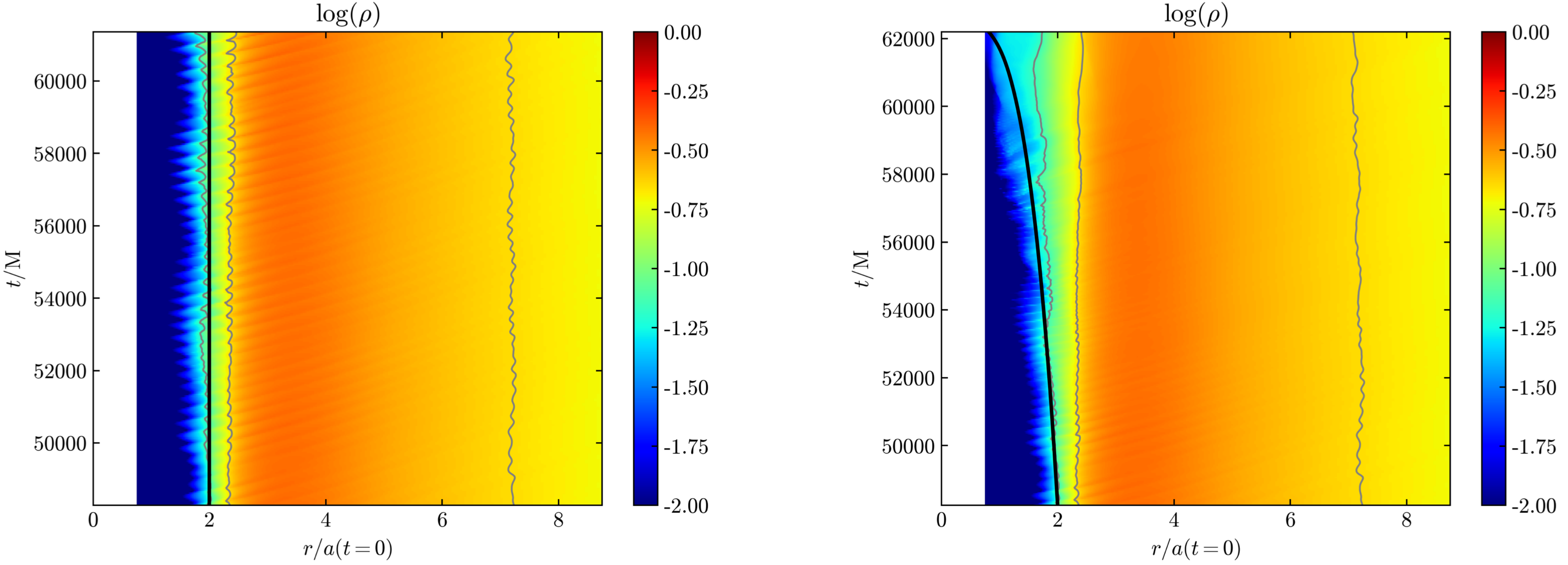
Circular

Pseudo-stationary state

Circular → Inspiral

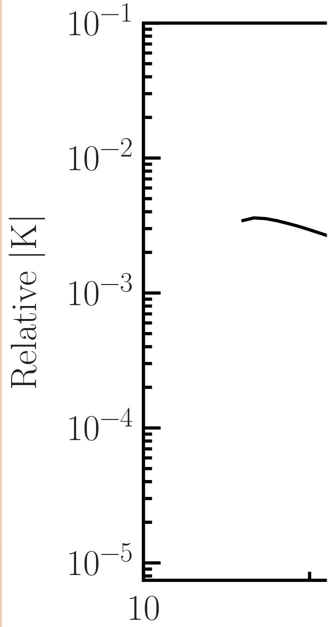
Numerical challenges :

- Cell activation
- Spatial resolution disk edge
- Inspiral time $\propto r_{12}^4$



Metric validation

- Correct ap… view
  as d…



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

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

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

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

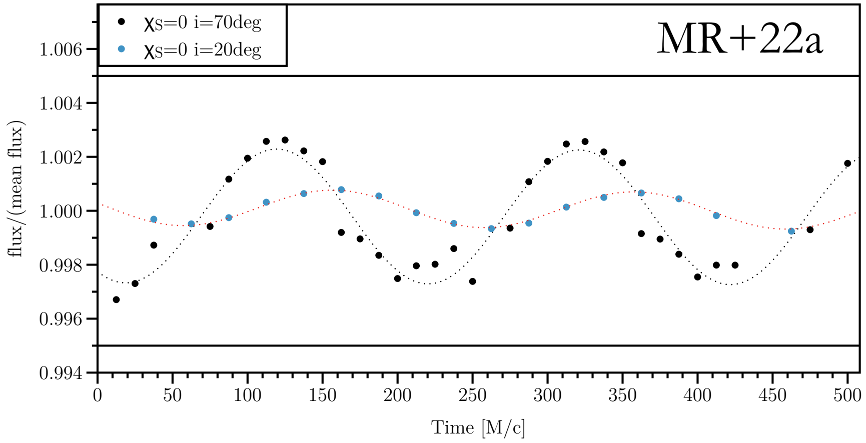
$$+\frac{240000000000\left(\frac{x\cos\left(\frac{389}{200000}\sqrt{\frac{1}{2}}\left(t-\sqrt{x^2+y^2+z^2}\right)\right)}{\sqrt{x^2+y^2+z^2}}+\frac{y\sin\left(\frac{389}{200000}\sqrt{\frac{1}{2}}\left(t-\sqrt{x^2+y^2+z^2}\right)\right)}{\sqrt{x^2+y^2+z^2}}\right)^2}{x^2+y^2+z^2}+\frac{3200000000\left(\frac{x\cos\left(\frac{389}{200000}\sqrt{\frac{1}{2}}\left(t-\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

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

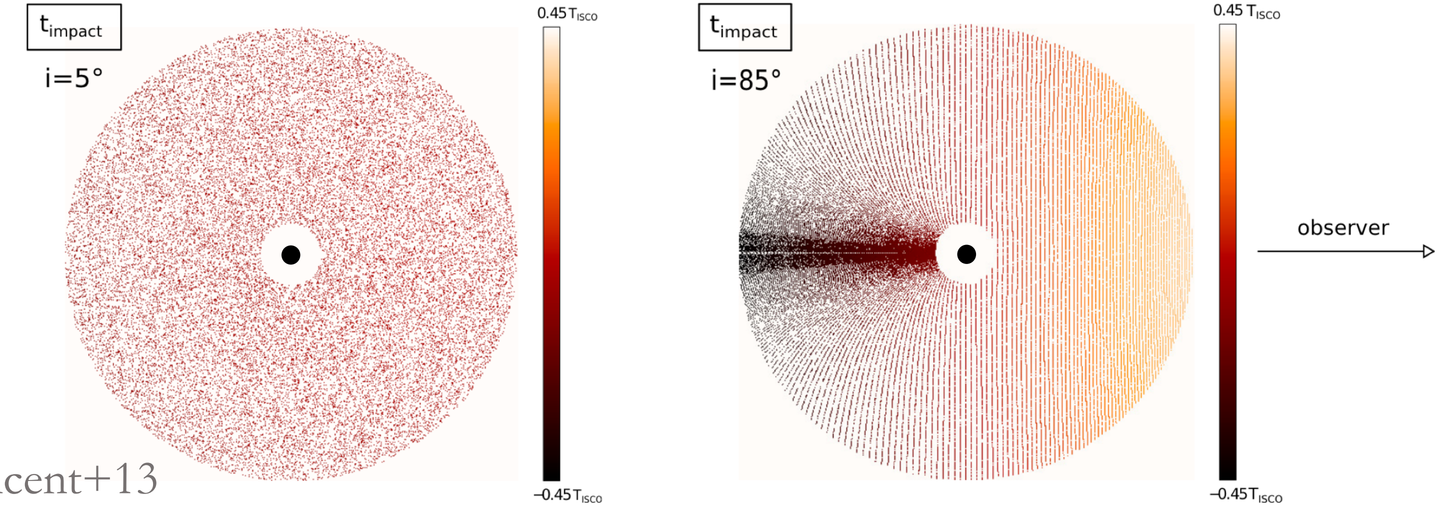
…ubm.

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
  …

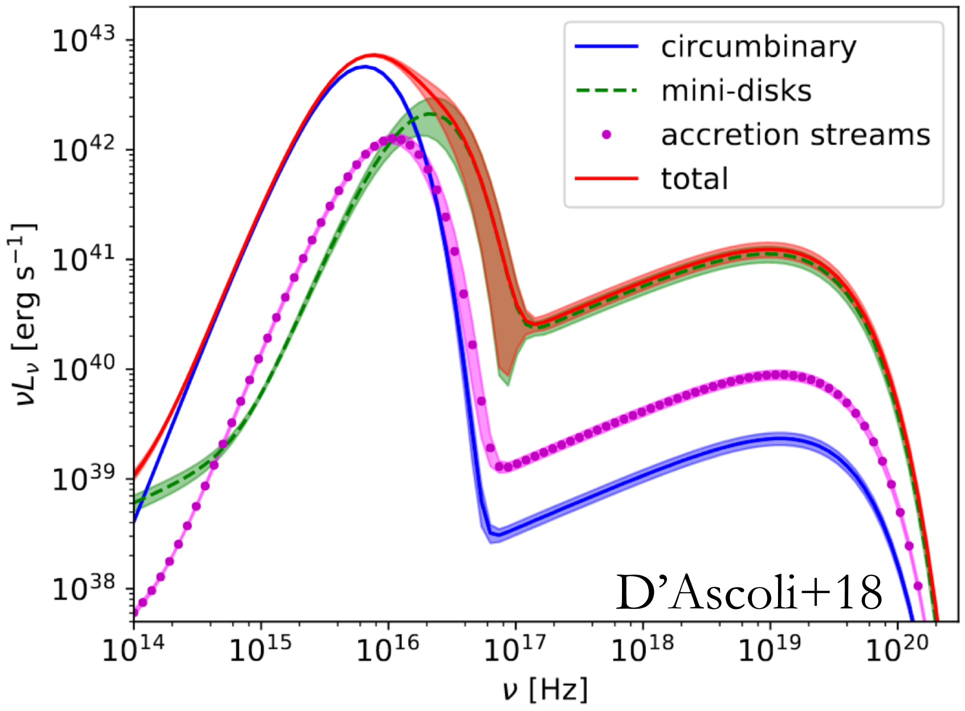


- Self-consistency:
  Incorporates the same BBH metric as the fluid code

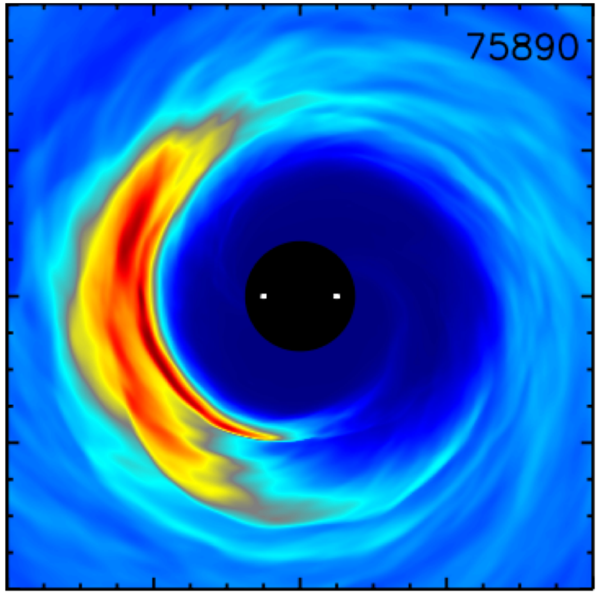
Excising the innermost region?

The flux from possible individual disks

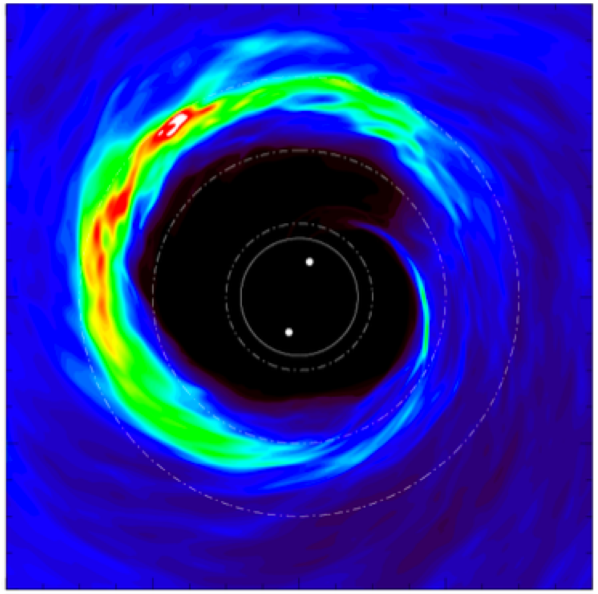
- may not dominate the integrated flux
  depends on their surface density, temperature, the BBH orbital separation…
- peak in a higher-energy band
- varies on binary orbital timescales, much shorter than the « lump's » period



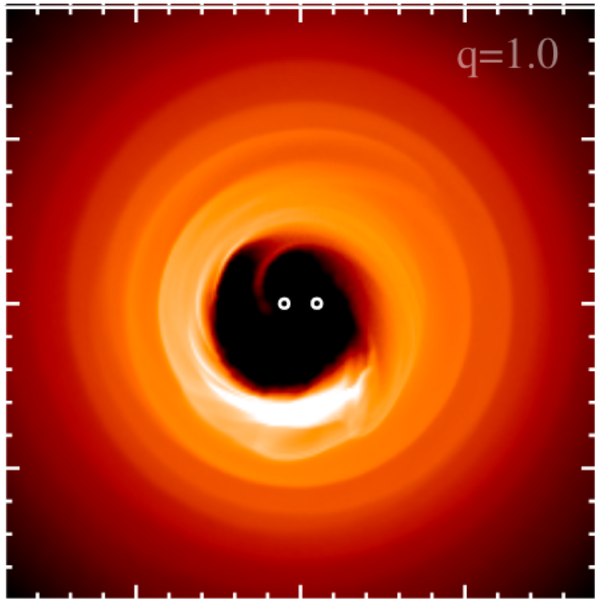
The « lump » presence in the literature



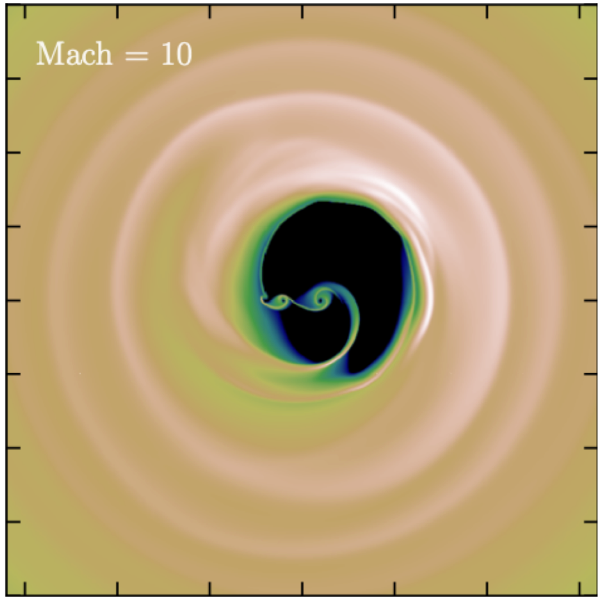
Noble+12, 3D GRMHD



Shi+12, 3D MHD

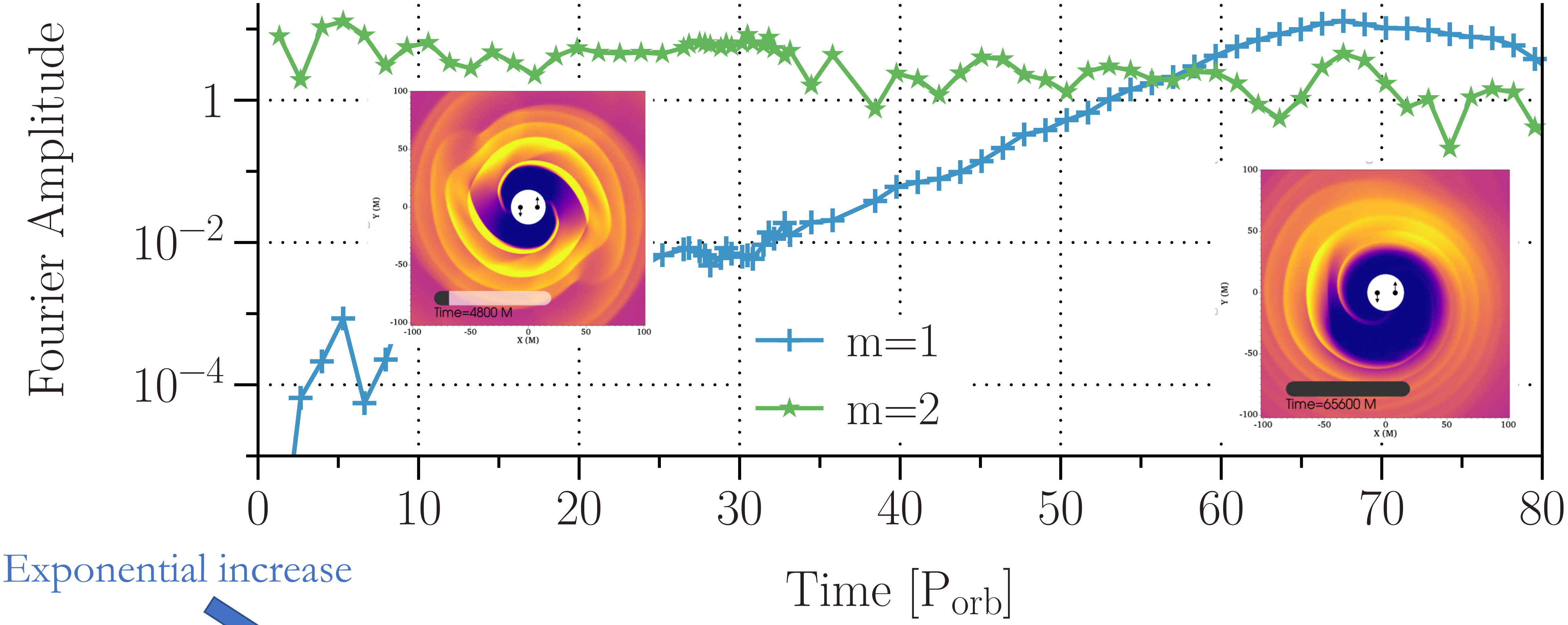


Ragusa+20, 3D SPH



Tiede+20, 2D Hydro

Lump: an instability origin ?

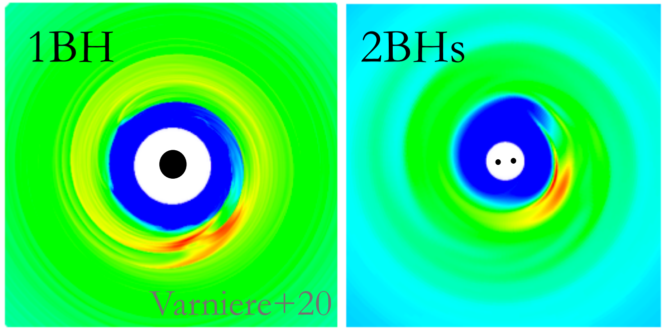


Exponential increase

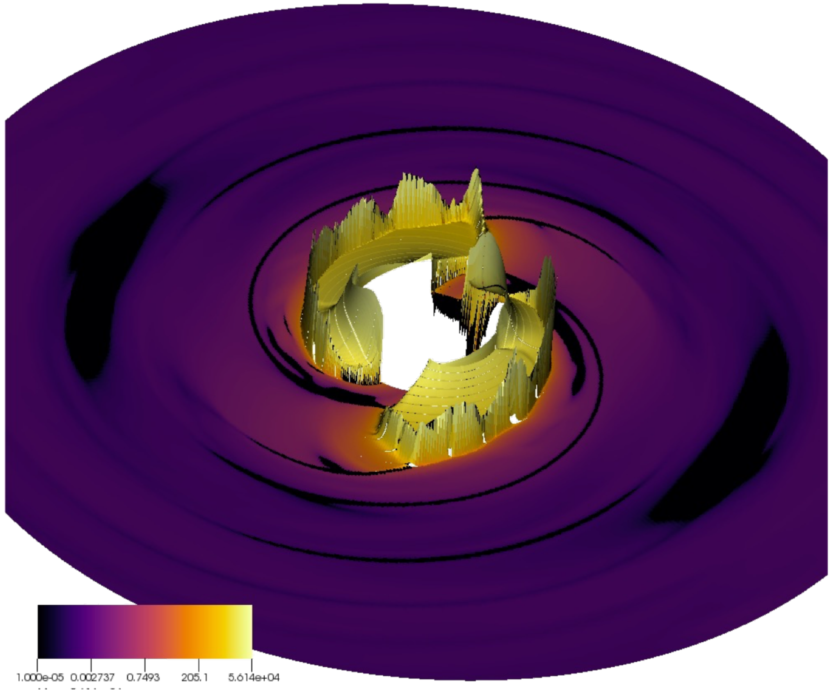
The Rossby Wave Instability as a possible origin for the « lump » (MR+23, MNRAS)

Lump: an instability origin ?

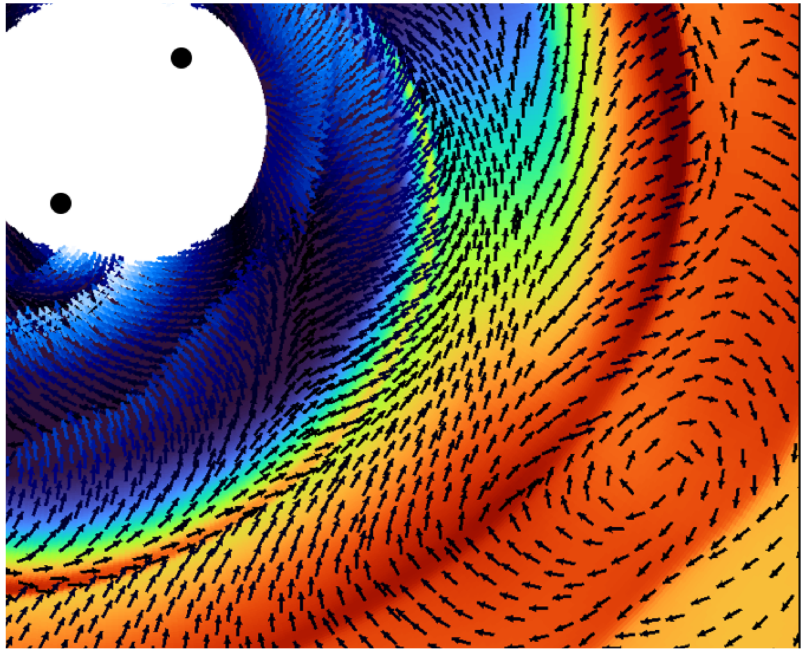
Similar to the Rossby Wave Instability (RWI) around single BH disks?



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; see also Cimerman & Rafikov 2023)

Pioneer studies

- $r_i \gg r_{g,i}$ for the i^{th} BH : Newtonian gravity is sufficiently accurate to compute the gas dynamics
  - ➢ pioneer studies from binary star simulations

Artmowicz and Lubow (1994):

- Methods: 3D, SPH, ~~self-gravity~~, fixing the binary orbit, coplanar disk
  isothermal equation of state
  varying $q = M_2/M_1$, e, α-disk viscosity (Shakura & Sunyaev 1973)

- Cavity cleared at $2 - 3\ a$, with a the semi-major axis
  balance between gravitational torques and viscous torques

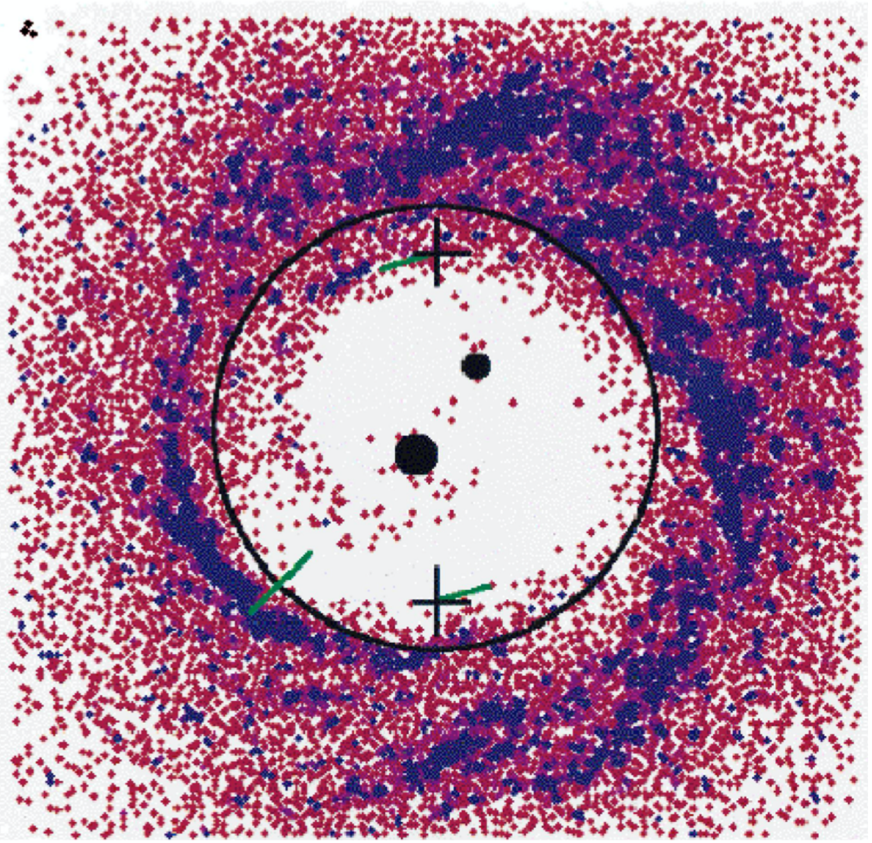
- Mass flux dramatically reduced at circumbinary disk (CBD) edge

Artmowicz and Lubow (1996):

- Accretion streams cross the gap ($\alpha > 0.01$, $H/r \gtrsim 0.05$)
  (see also Gunther & Kley 2002, hybrid grid)

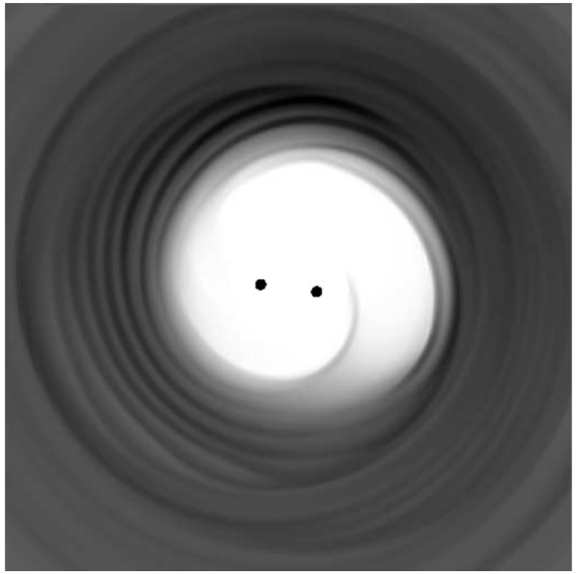
Bate (1997), Bate & Bonnell (1997), SPH:

- CBD formation if sufficiently high-angular momentum gas



Artmowicz and Lubow (1996)

Circumbinary flow morphology



Asymmetric, eccentric cavity

MacFadyen & Milosavljevic 2008

2D viscous hydro, $q = 1, e = 0$

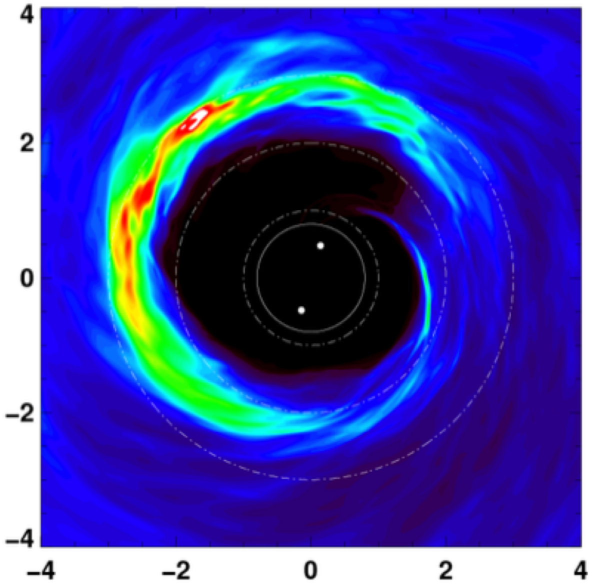
central ($r < a$) region excised

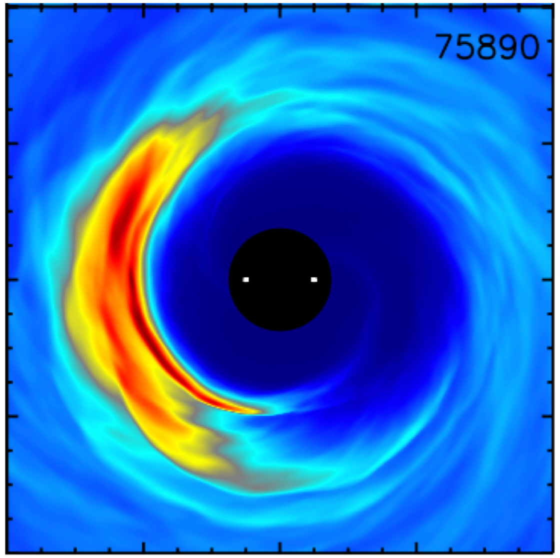
Asymmetry → « lump », orbits at $5P_{orb}$

Shi et al. 2012

3D MHD, $q = 1, e = 0$

central region excised





« lump » properties confirmed in GR

Noble et al. 2012

3D GRMHD, $q = 1, e = 0$

(+GW inspiral)

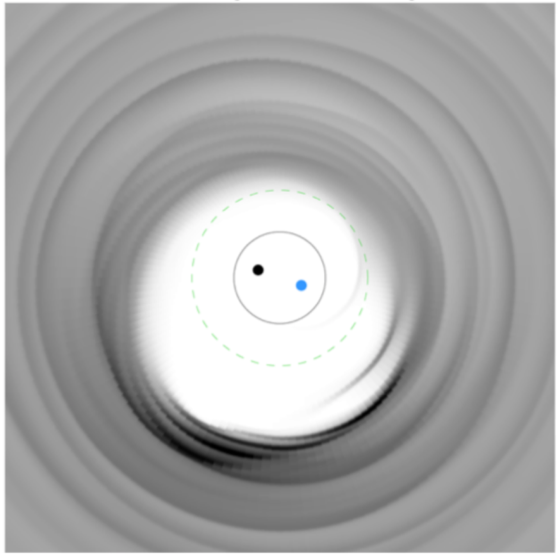
central region excised

Eccentric cavity; « lump » for $q > 0.1$

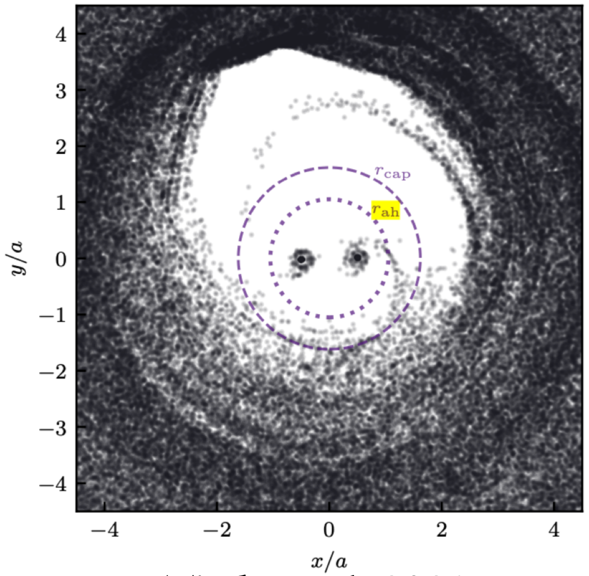
D'Orazio et al. 2013

2D viscous hydro, $q > 0.003, e = 0$

central region excised



Accretion flow morphology: mini-disks



Tiede et al. 2021

Cavity = no stable orbit

e.g. D'Orazio et al. 2016 for $q > 0.04$

« accretion horizon » at $r \sim a$

Tiede et al. 2021

2D viscous hydro+tracer particles

locally isothermal, $H/r = 0.1$

$q = 1, e = 0$

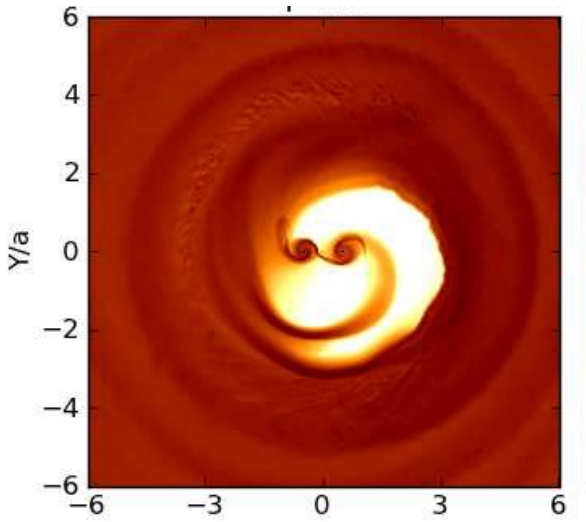
Mini-disks form

Farris et al. 2014

2D viscous hydro

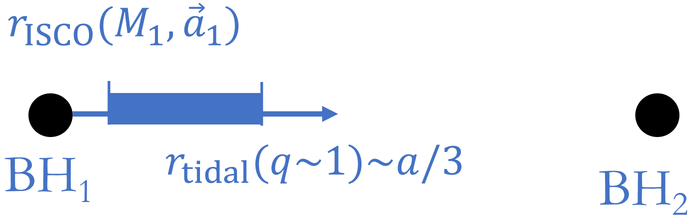
locally isothermal

$q > 0.026, e = 0$



Farris et al. 2014

Mini-disk existence region:



Papaloizou & Pringle 1977

Paczynski 1977

survival during inspiral?

(see Bowen et al. 2017, Tang et al. 2018, Krauth et al. 2023…)

Confirmed in GR

+ enhanced « sloshing »

Bowen et al. 2017

2D GRHD

adiabatic+local cooling

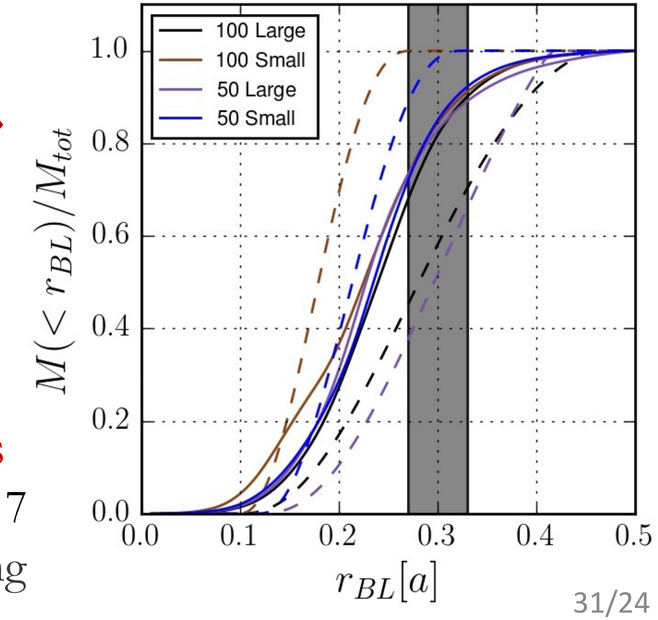
$q = 1, e = 0$

(+ GW inspiral)

m=2 spiral shock waves

e.g. Ryan & MacFadyen 2017

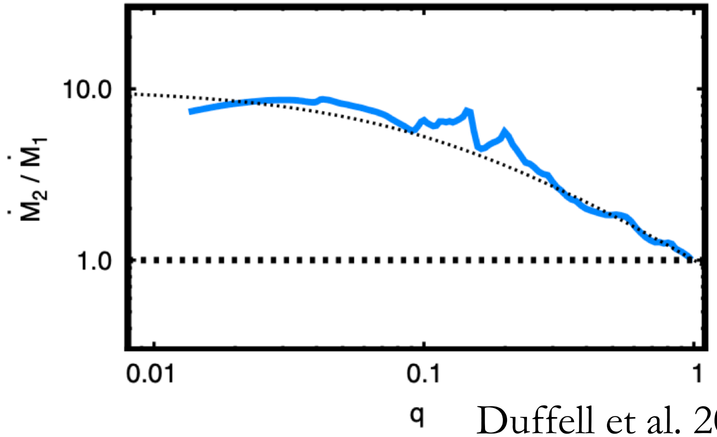
2D GRHD, radiative cooling



Accretion properties

- Preferential accretion onto secondary for $e = 0$:

e.g. Bate 2000, Farris et al. 2014, Duffell et al. 2020, Muñoz et al. 2020



Duffell et al. 2020
2D viscous hydro

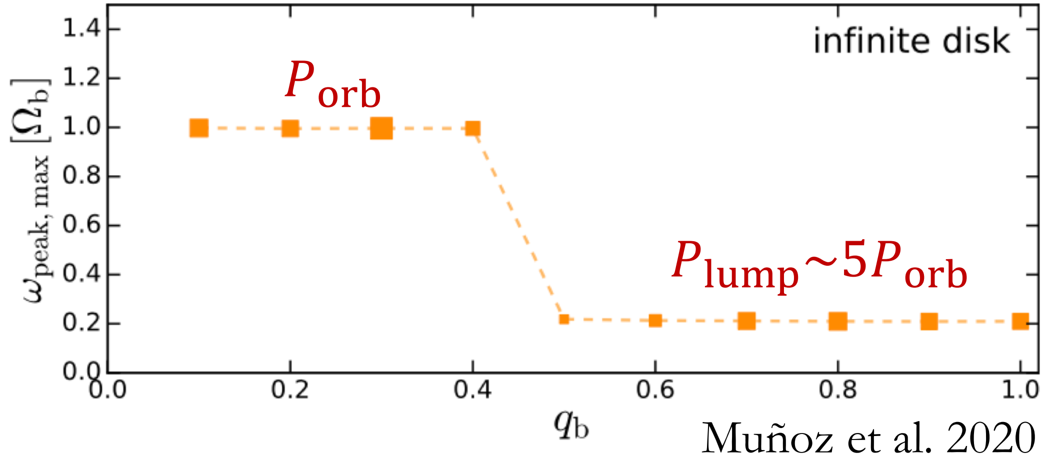
- Accretion rate shows periodicities for $e = 0$:

$P_{\rm orb}$ for $q \gtrsim 0.075$,
$+ P_{\rm orb}/2$ for $q \gtrsim 0.25$,
$+ P_{\rm lump} \sim 5 P_{\rm orb}$ for $q \rightarrow 1$

MacFadyen & Milosavljevic 2008, D'Orazio et al. 2013
2D hydro, central region excised
locally isothermal, $\alpha = 0.01$, $H/r = 0.1$
Farris et al. 2014, Muñoz et al. 2016, no excision
Shi et al. 2012, 3D MHD

- $e \geq 0.05 \rightarrow$ reduce/suppress lump and related periodicity

$+$ accretion rate asymmetric switching every $\sim 200\ P_{\rm orb}$
Muñoz & Lai 2016, Miranda et al. 2017, 2D hydro, $\alpha = 0.1$



Muñoz et al. 2020
2D viscous hydro, $q \geq 0.1$, $e = 0$,
$\alpha = 0.1$, locally isothermal

- $e \geq 0.4 \rightarrow$ suppress preferential accretion

Siwek et al. 2022, 2D hydro, $\alpha = 0.1$

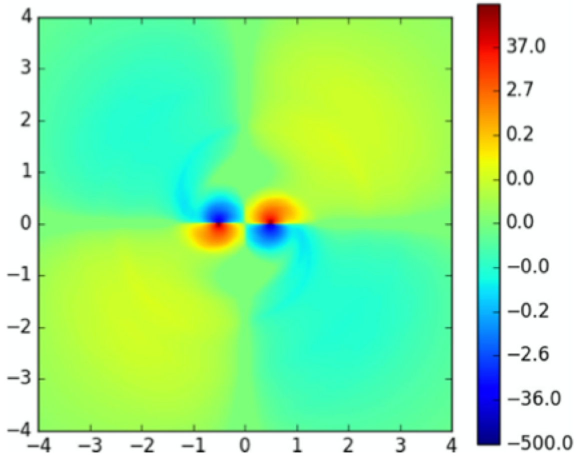
Orbital evolution for non-eccentric binaries

- Torques: gravitational + « accretional »

- Theoretical prediction (Newton 3rd law):
  positive torque binary/CBD ⇔ negative torque CBD/binary

- Orbital evolution dominated by mini-disk gravitational torque

Sink rate ↗ : inspiral → outspiral, Tang et al. 2017



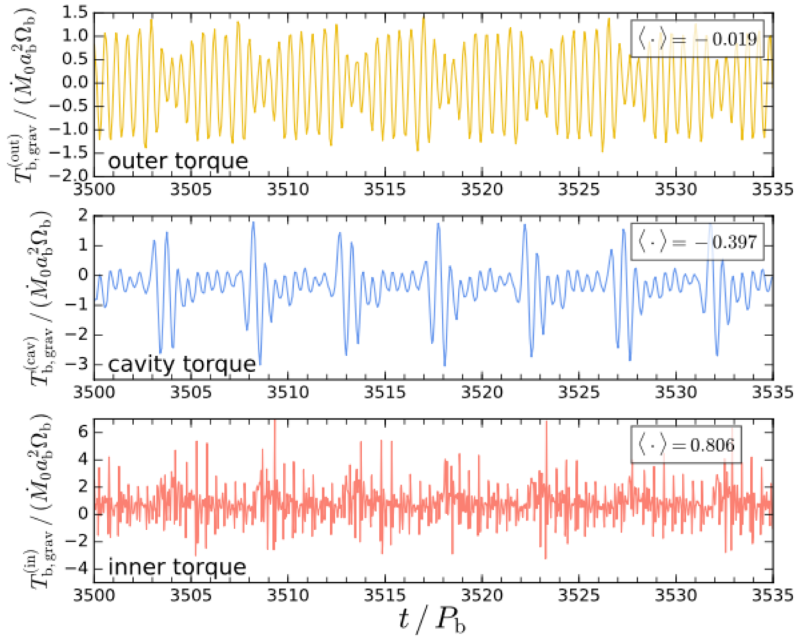
Tang et al. 2017

- For $H/r = 0.1$ outspiral, inner torques dominate

Miranda et al. 2017, Muñoz et al. 2019, Moody et al. 2019 (3D),
Muñoz et al. 2020, Tiede et al. 2020

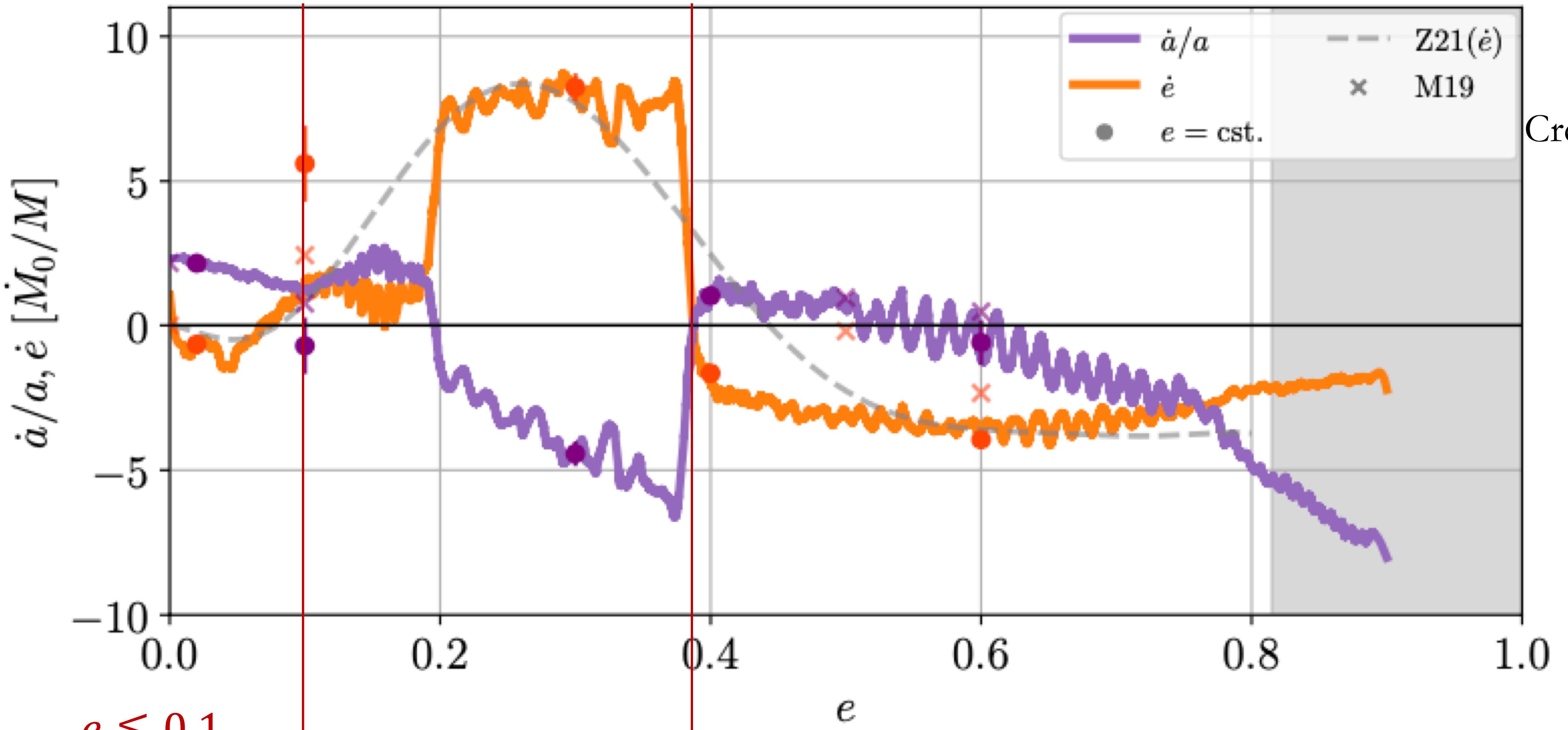
- Independent of α ?

Muñoz et al. 2020,
but see also Franchini et al. 2022, 3D meshless, self-gravity



Muñoz et al. 2019

Orbital evolution: eccentricity



$e \lesssim 0.1$
$\rightarrow \dot{e} < 0, \dot{a} > 0$
(circular outspiral)

$e \sim 0.4$
attractor

Zrake et al. 2021
Muñoz et al. 2019
Credits: D'Orazio & Duffell 2021
2D hydro, $q = 1$,
$\alpha = 0.1, \frac{H}{r} = 0.1$
locally isothermal

Heating/cooling processes

- « Radiative » cooling
  i) following thin disk model, with electron scattering constant opacity (but see Jiang & Blaes 2020), e.g. Farris et al. 2015, Tang et al. 2018:

$$q_{\rm cool} = 4\sigma/3\tau T^4$$

  ii) « beta-cooling », following a dynamical timescale, e.g. Wang et al. 2022:

$$t_{\rm cool} = \beta/\Omega_{\rm K}$$

  iii) towards target (initial) entropy, e.g. Noble et al. 2012:

$$\mathcal{L}_c = \frac{\rho\epsilon}{T_{\rm cool}}\left(\frac{\Delta S}{S_0} + \left|\frac{\Delta S}{S_0}\right|\right)$$

- Shock heating: comes from adiabatic compression for non-isothermal EoS

- Viscous heating following thin disk model, e.g. Farris et al. 2015, Tang et al. 2018 : $q_{\rm vis} = 9/8\alpha P\Omega$

Impact of heating/cooling, pressure, thermodynamics

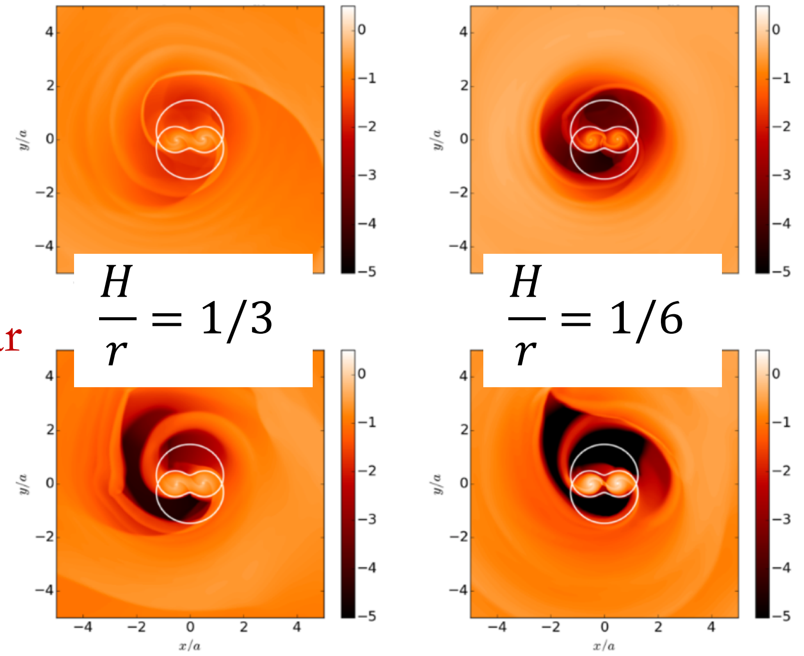
- If pressure > binary grav. barrier: no cavity for $q > 0.04$

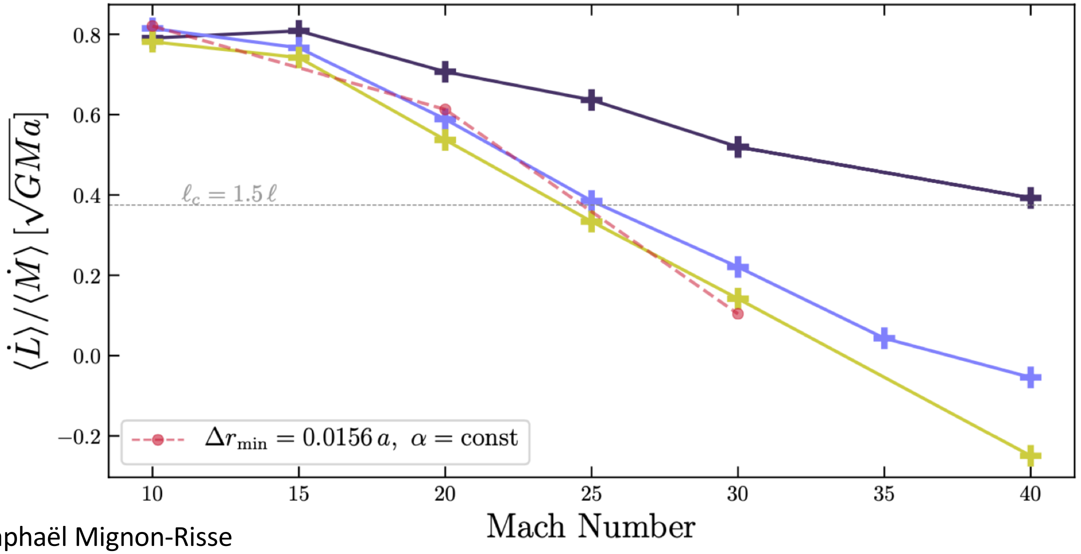
D'Orazio et al. 2016, 2D viscous hydro

- Cooling timescale ↗ $0.7 - 1\ \Omega_K$: lump+$\dot{M}$ variability disappear

  Cooling timescale $> 4\Omega_K$: steady accretion

Wang et al. 2022, 2D, viscous hydro,
beta-cooling, central region excised





- $\frac{H}{r} < 0.04$: outspiral → inspiral because negative torque from the (denser when M ↗) CBD inner edge

Tiede et al. 2020, 2D hydro, $\alpha \in [0.1, 1.6]$, locally isothermal

(some) conclusions on the state-of-the-art

- Cavity, two spiral arms+streams, « lump »
  - ➢ associated accretion variability → plausible luminosity variability (e.g. Noble et al. 2012, Tang et al. 2018, Westernacher-Schneider et al. 2022, 2023, Krauth et al. 2023…)

- Thick disks → outspiral
  thin ($H/r < 0.04$, AGN-like?) disks → inspiral (Tiede et al. 2020)

- Circular outspiral vs eccentric inspiral (e.g. Zrake et al. 2021, D'Orazio & Duffell 2021)

- Accretion flow thermal state important for accretion variability (e.g. Wang et al. 2022) and orbital evolution (Tiede et al. 2020)

Not mentioned here:

- self-gravity: e.g. Cuadra et al. 2009, Roedig et al. 2012, Franchini et al. 2021, 2022 (live binary)
- 3D: warps (e.g. Gerosa et al. 2020), misaligned disk (Moody et al. 2019)
- Outflows: MHD and/or GR needed (e.g. Combi et al. 2022)
- Missing? RHD (has to be 3D), more realistic opacities for AGN disks