The Electromagnetic Chirp of a Supermassive BH Binary

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Why should we care about photons?

GWs alone from (10^4-10^7)$M_\odot$ binaries a rich source of information

but:

(1) EM counterparts: revolution for astronomy and astrophysics

— *accretion physics*: luminosity and spectrum, as functions of BH masses, spin, orbital parameters
— *quasar/galaxy (co)evolution:* long-standing problem

(2) EM counterparts: benefits for fundamental physics

— Hubble diagrams from standard sirens (Schutz 1986 + …)
— $d_L(z)$ from GWs and photons: new test of non-GR gravity (Deffayet & Menou 2007)
— delay between arrival time of photons and gravitons: extra dimensions, graviton mass ($\gamma m_0 c^2 = hf$; Kocsis et al. 2008)
— frequency-dependence in delay: test Lorentz invariance

(3) EM counterparts will also help with confidence of detection

LISA binaries should be surrounded by gas

1. **Most galaxies contain SMBHs**
   - SMBH mass correlates with galaxy size

2. **Galaxies experience several mergers**
   - typically a few major mergers per Hubble time

3. **Most galaxies contain gas**
   - $M < 10^7 M_\odot$ SMBHs are in gas-rich disk galaxies
   - $M > 10^7 M_\odot$ SMBHs are in "dry" ellipticals (still *some* gas)

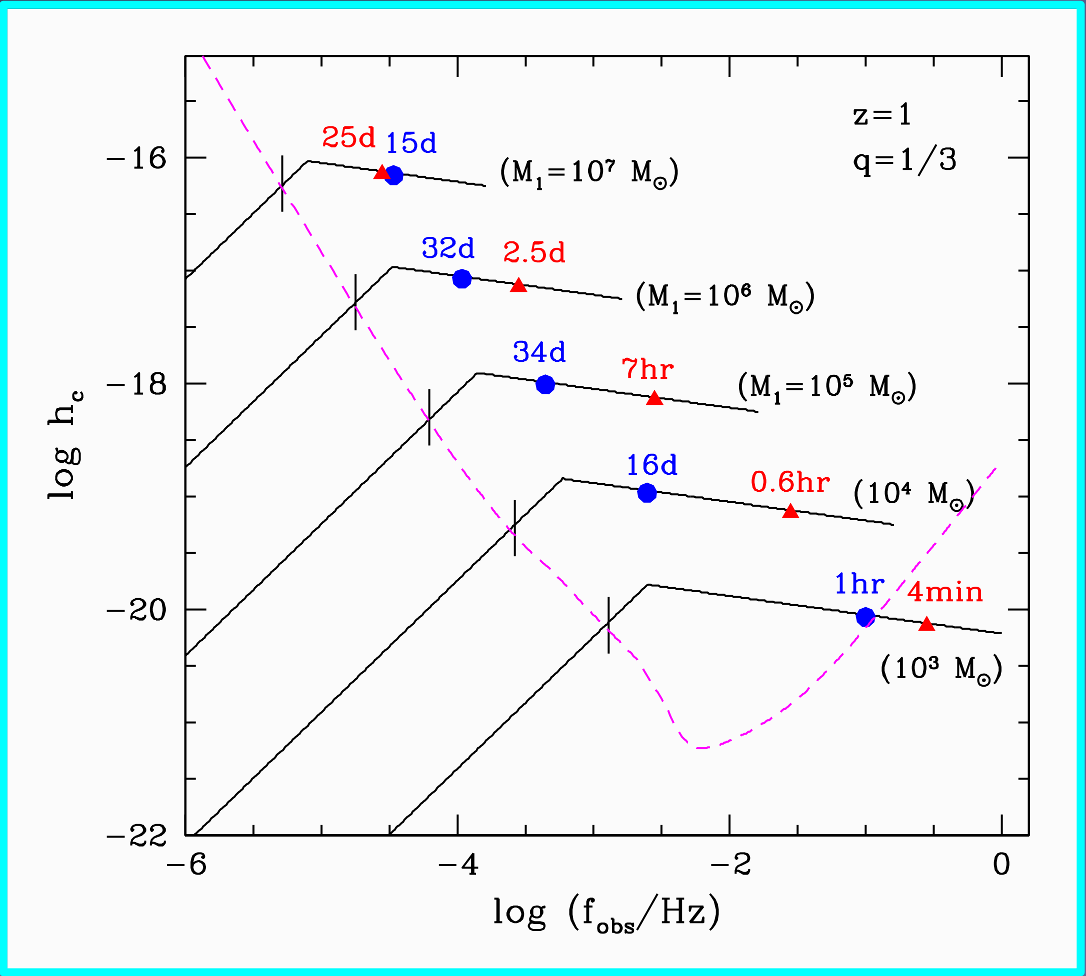
4. **Both SMBHs and gas are driven to new nucleus (~kpc)**
   - SMBHs sink by dynamical friction on stars and on DM
   - gas torqued by merger and flows to nucleus

→ natural outcome: pair of nuclear SMBHs in gas disk

LISA binaries produced in “wet” mergers

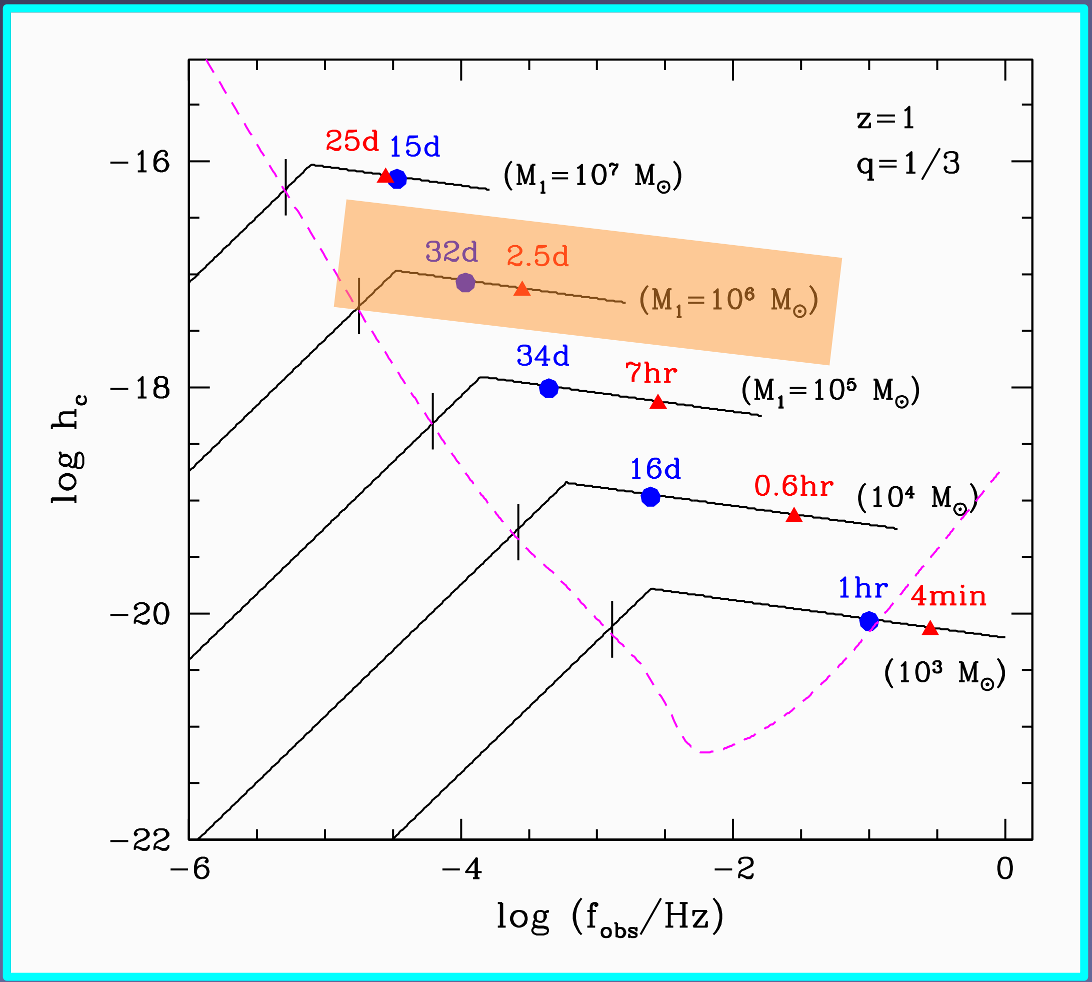
Arp 271 (credit: ESO)

Track of binary in the LISA band



(ZH 2017)

Track of binary in the LISA band



Example:

$M_{tot}=10^6 M_\odot$, $q=1/3$, $z=1$

(ZH 2017)

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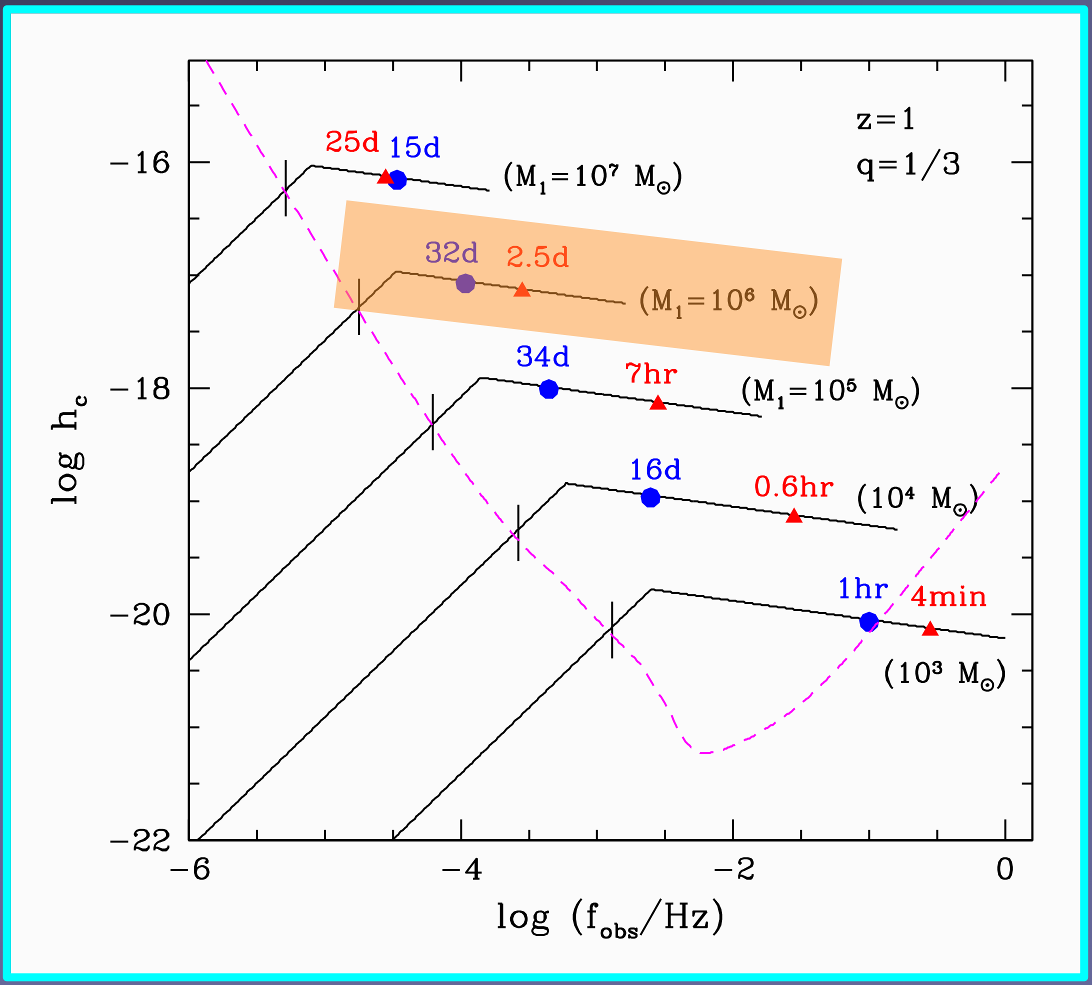


Example:

$M_{tot}=10^6 M_\odot$, $q=1/3$, $z=1$

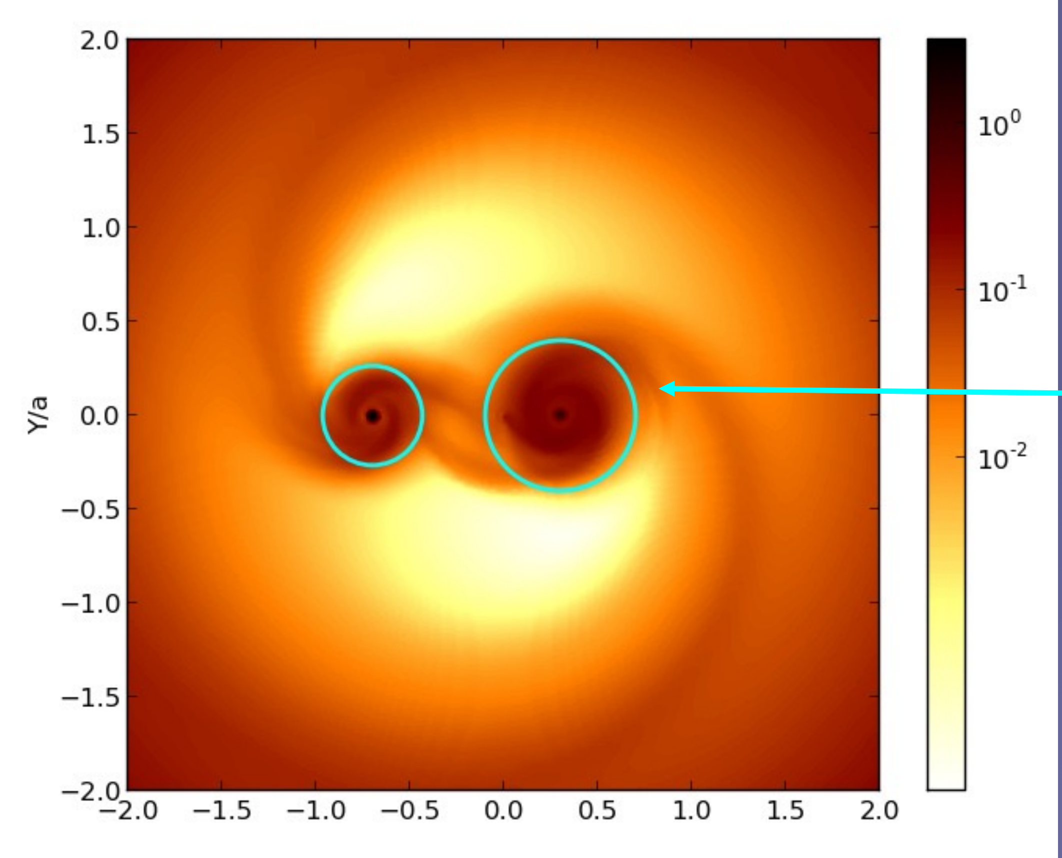
Enter LISA band: $125\ R_g$

(ZH 2017)

X-ray chirp inevitable(?)

- X-ray [optical] emission from quasars from few R_g [few 100 R_g]
- Smaller than tidal truncation radius for wide binary
- Minidisk = quasar disk (or corona)
- Doppler effect modulates brightness at O(v/c) ~ O(0.1)

Farris et al. (2015)

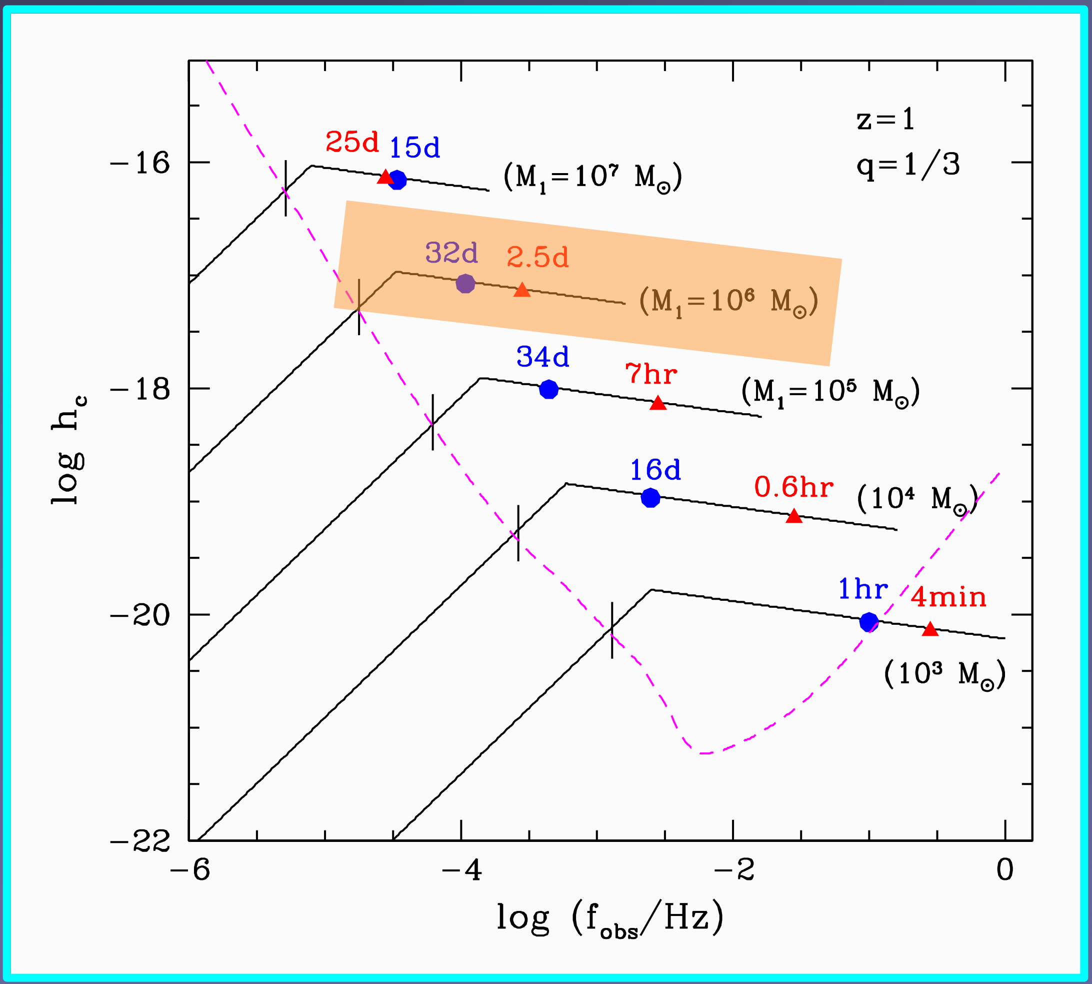


$\Delta F_\nu / F_\nu = (3-\alpha)(v_{||}/c)$

$\alpha = d\ln F_\nu / d\ln \nu$

Tidal force from companion truncates minidisk

Track of binary in the LISA band



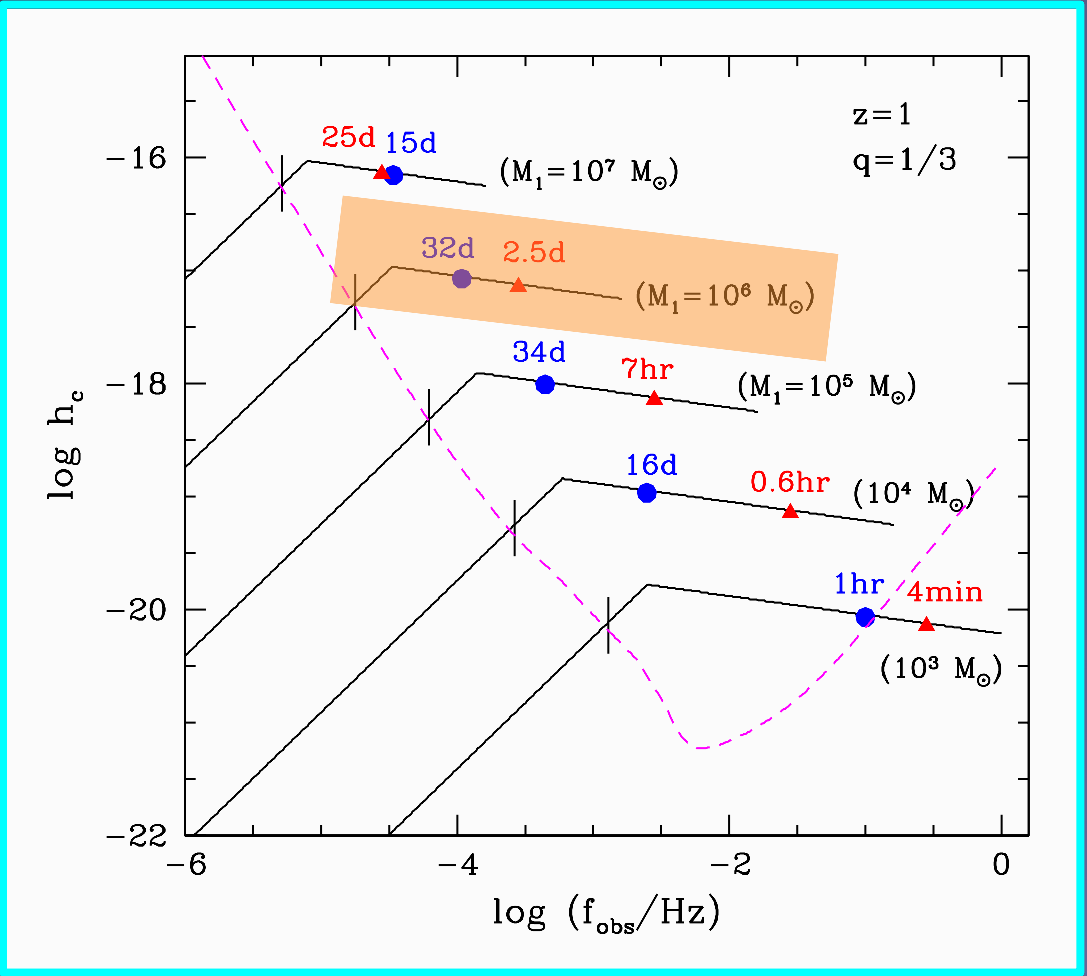
Example:

$M_{tot}=10^6 M_\odot$, q=1/3, z=1

Enter LISA band: 125 R_g

(ZH 2017)

Track of binary in the LISA band



(ZH 2017)

Example:

$M_{tot}=10^6 M_\odot$, q=1/3, z=1

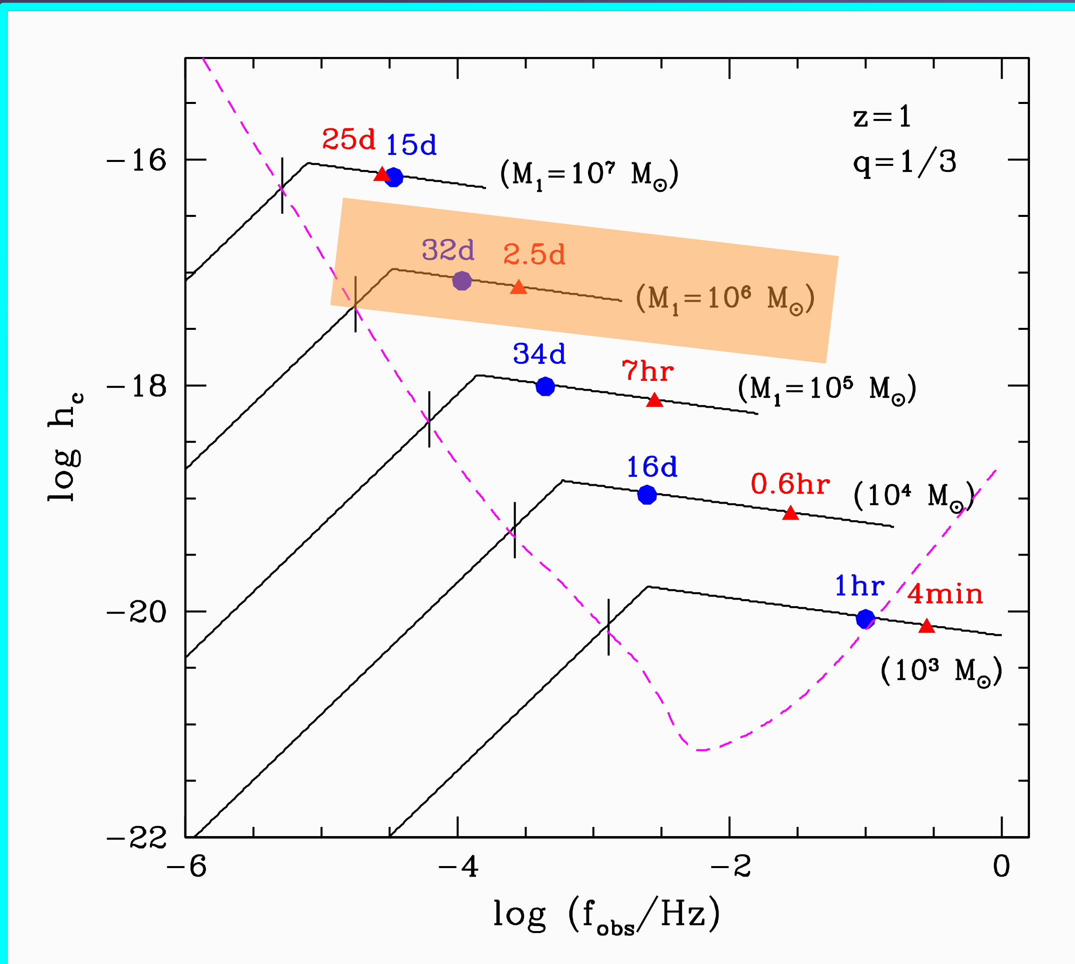
Enter LISA band: $125\ R_g$

Localized (3 deg^2): $40\ R_g$

V(orb) ~ O(0.1c)

T(orb) ~ O(hr)

Track of binary in the LISA band



(ZH 2017)

Example:

$M_{tot}=10^6 M_\odot$, q=1/3, z=1

Enter LISA band: 125 R_g

Localized (3 deg^2): 40 R_g

Tidal radius < 10 R_g: 400 cycles

V(orb) ~ O(0.1c)

T(orb) ~ O(hr)

GW vs. X-ray chirp

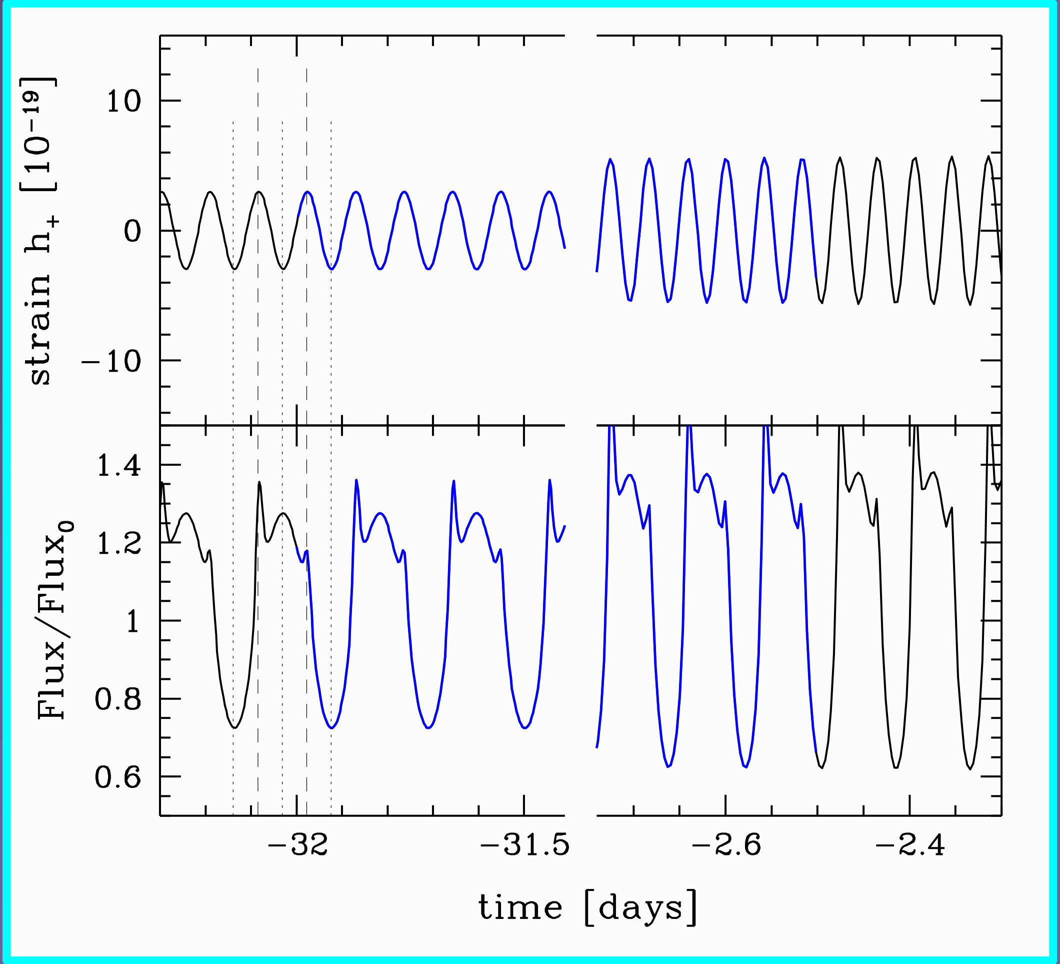
Test $A_{gw} \propto f^{2/3} e^{-i2\varphi}$ *vs* $A_\gamma \propto f^{1/3} e^{-i\varphi}$

Overlap integral for phase shift:
$\Rightarrow \Delta v/c \sim [S/N] \times t_{orb} / [D/c] \sim 10^{-17}$

Improve bounds from LIGO BNS and from GW dispersion/phasing
Berti+(2005), Will (2006)

$\Rightarrow$ New constraints on scalar-tensor theories (beyond LIGO)
De Rham & Melville (2018)

$M=10^6\ M_\odot$, $q=1/3$, $z=1$, $i=10^\circ$ — ZH (2017)



Chirp detectable by wider-field telescopes (e.g. Athena / Lynx)

Can GW-driven runaway binaries shine ?

There are no stable periodic orbits around binary at r $\lesssim$ 2a

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There are no stable periodic orbits around binary at $r \lesssim 2a$

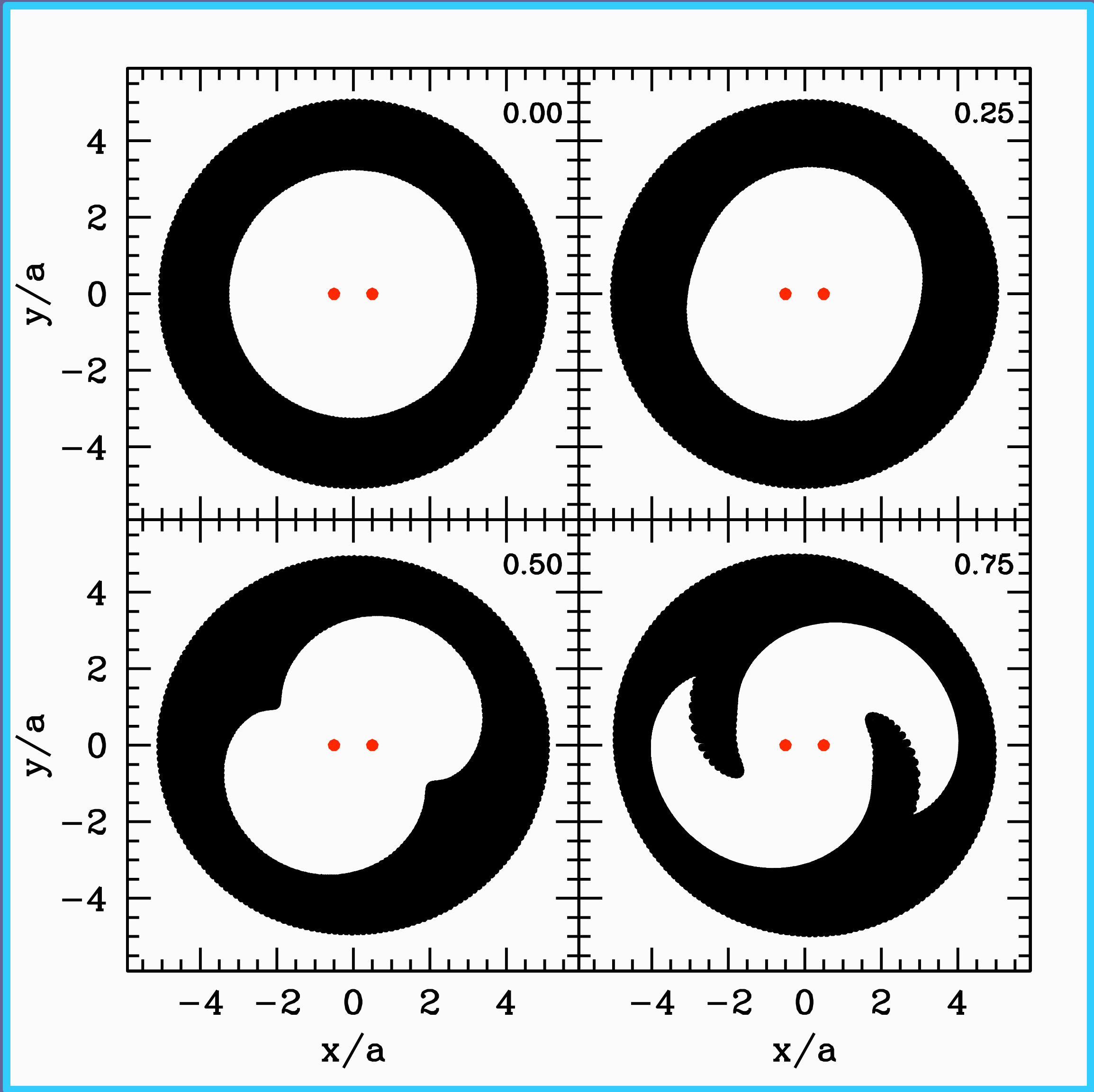
When t(GW) < t(visc), disk “decouples”, left behind at ~100 R_S

Milosavljevic & Phinney (2005)

???

Electromagnetically ‘silent’ merger, in vacuum ?

Gas flow into the Cavity - kinematics



particle distribution evolved with restricted three-body approximation

Hydrodynamical Simulations

well posed problem: gas + two point masses

Tang, ZH, MacFadyen (2018, 2017) D'Orazio et al. (2016), Farris, Duffell, MacFadyen, ZH (2014, 2015a,b), D'Orazio, ZH & MacFadyen (2013)

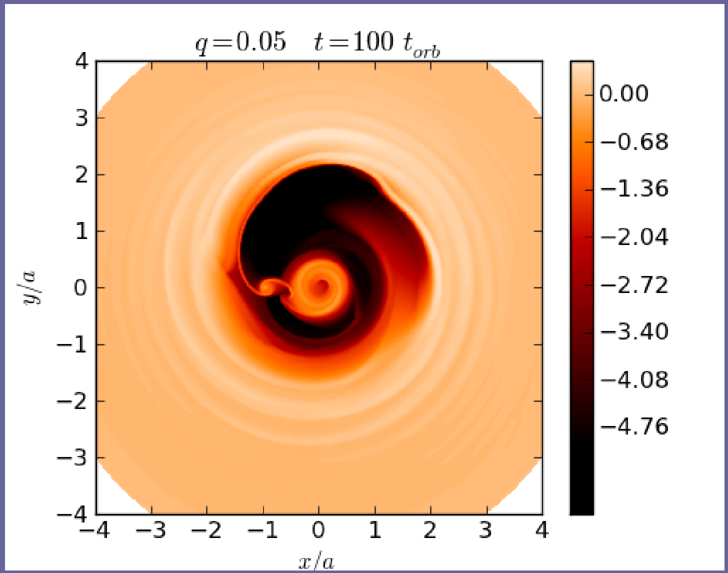
- 2D moving-mesh grid code **DISCO**
- pseudo-Newtonian hydrodynamics (no GR/MHD/radiation)
- α-viscosity (α=0.1)
- **heating** (viscosity, shocks) + **Cooling** (rad. diffusion)
- **BHs are on the grid,** accretion via **ISCO resolved**
- Initial Shakura-Sunyaev disk $0 \leq r \leq 60\ a_{bin}$

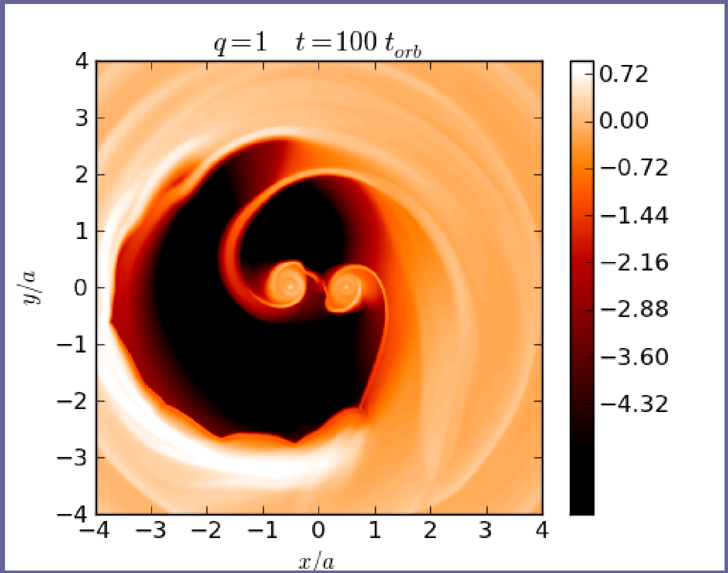
*run for ~1000 binary orbits (**>viscous time near binary**)*

follow last ~month of the LISA inspiral self-consistently

Binaries with circumbinary disks

q=0.05 *q=1*





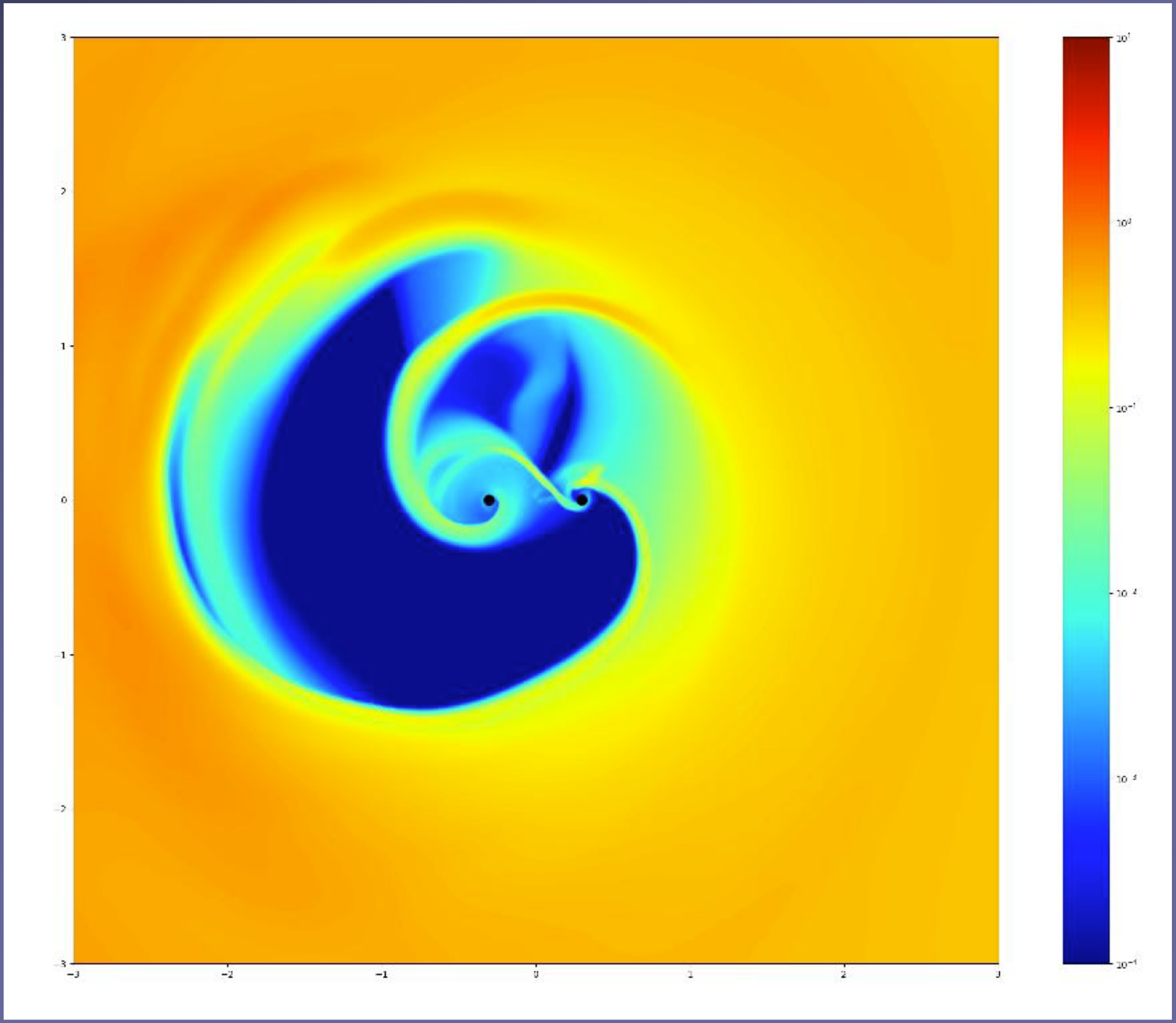
Common features:

(1) Large cavity
(2) Strong accretion via narrow streams feeds "*minidisks*"
(3) Cavity lopsided with lump (for $q \gtrsim 0.3$)
(4) Strong periodicity at t_{orb}
(5) Additional periodicity at ~$5 \times t_{orb}$ (for $q \gtrsim 0.3$)

Can run-away LISA binaries still shine?

from 60M to merger

Tang et al. 2018

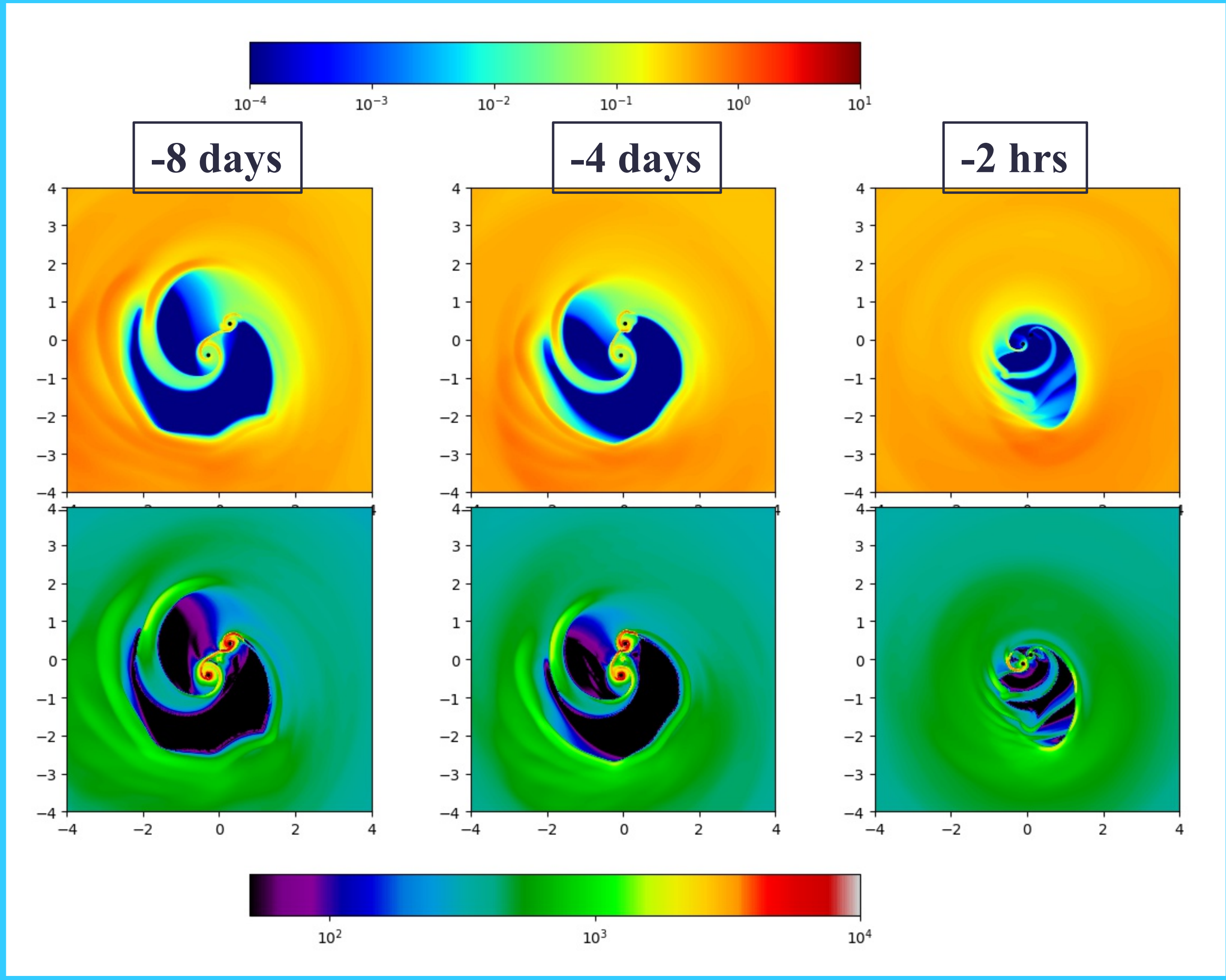


Inspiral

Tang et al. 2018

density

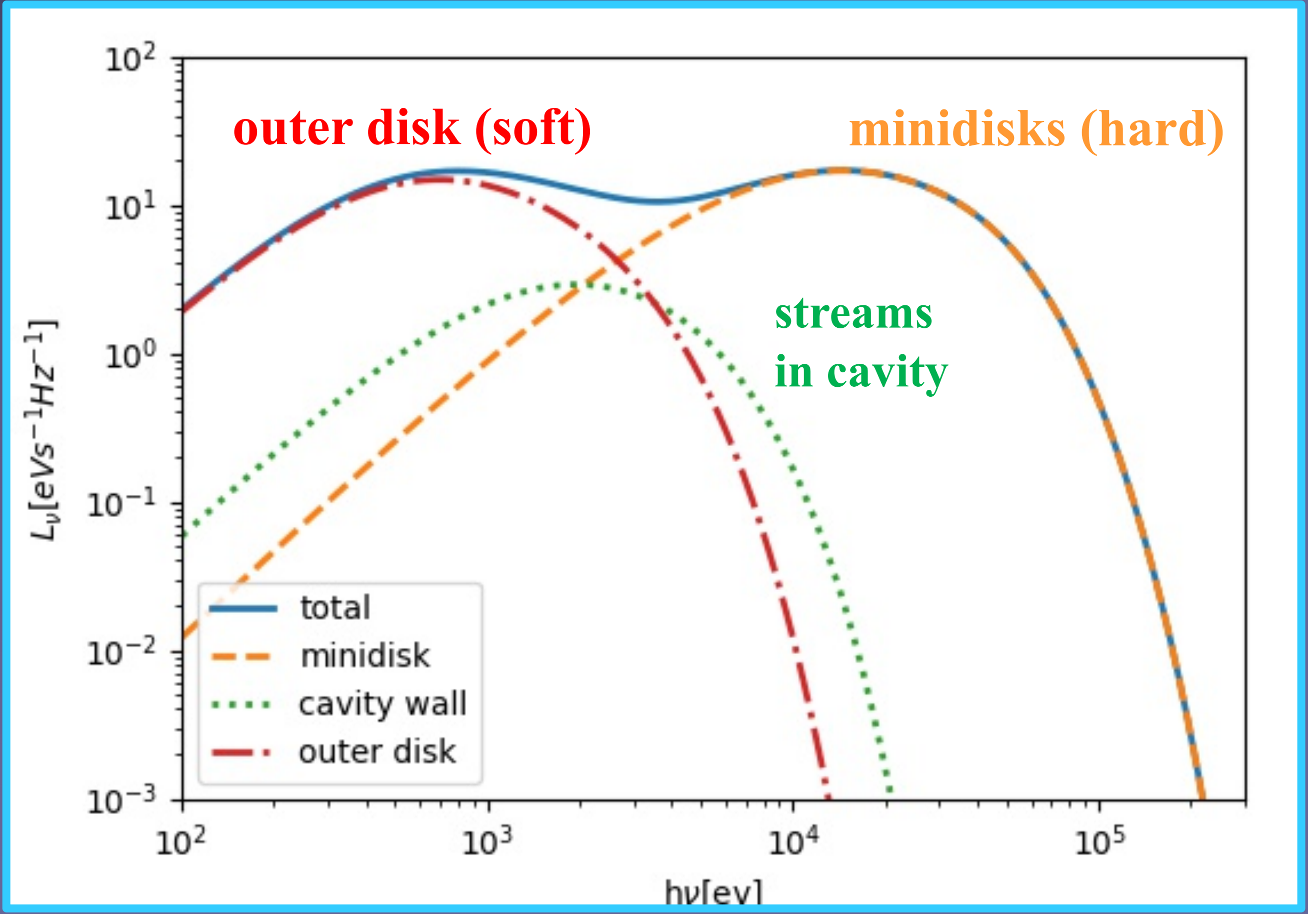
temperature



Spectrum

Tang et al. (2018)

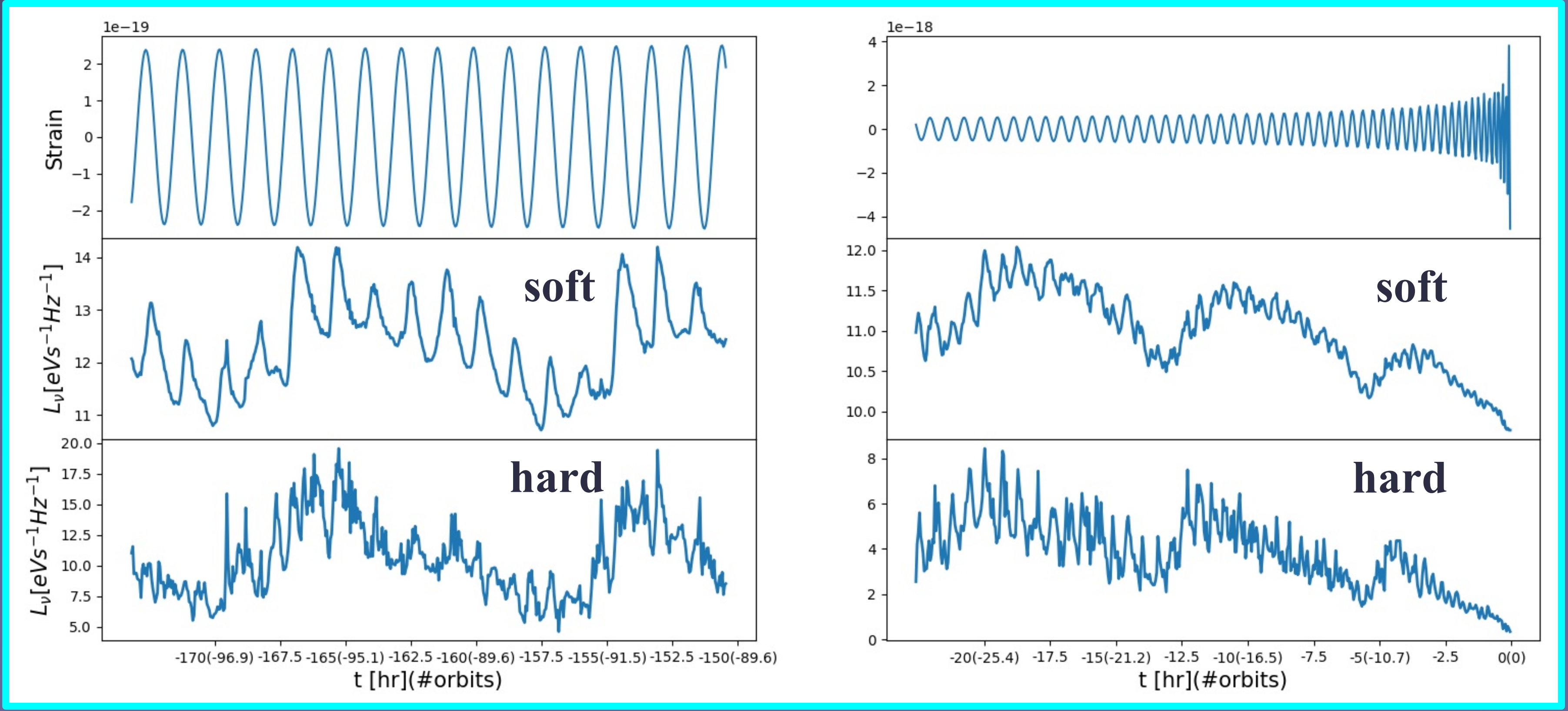
Thermal emission extends to X-rays from inner regions around each BH



Lightcurve

Tang et al. (2018)

strong accretion all the way to merger: binary remains luminous & periodic



LAST 7 DAYS **LAST 1 DAY**

Conclusions

1. LISA binaries bright: efficient accretion across cavity (to merger)
2. Accretion onto minidisks strongly periodic on ~orbital timescale
3. Such EM chirp is inevitable in LISA band, tracking GWs
4. Wide-field UV & X-ray telescopes should be able to detect chirp
5. New probe of propagation speed of GWs vs photons

The End