The X-ray chirp of LISA binaries

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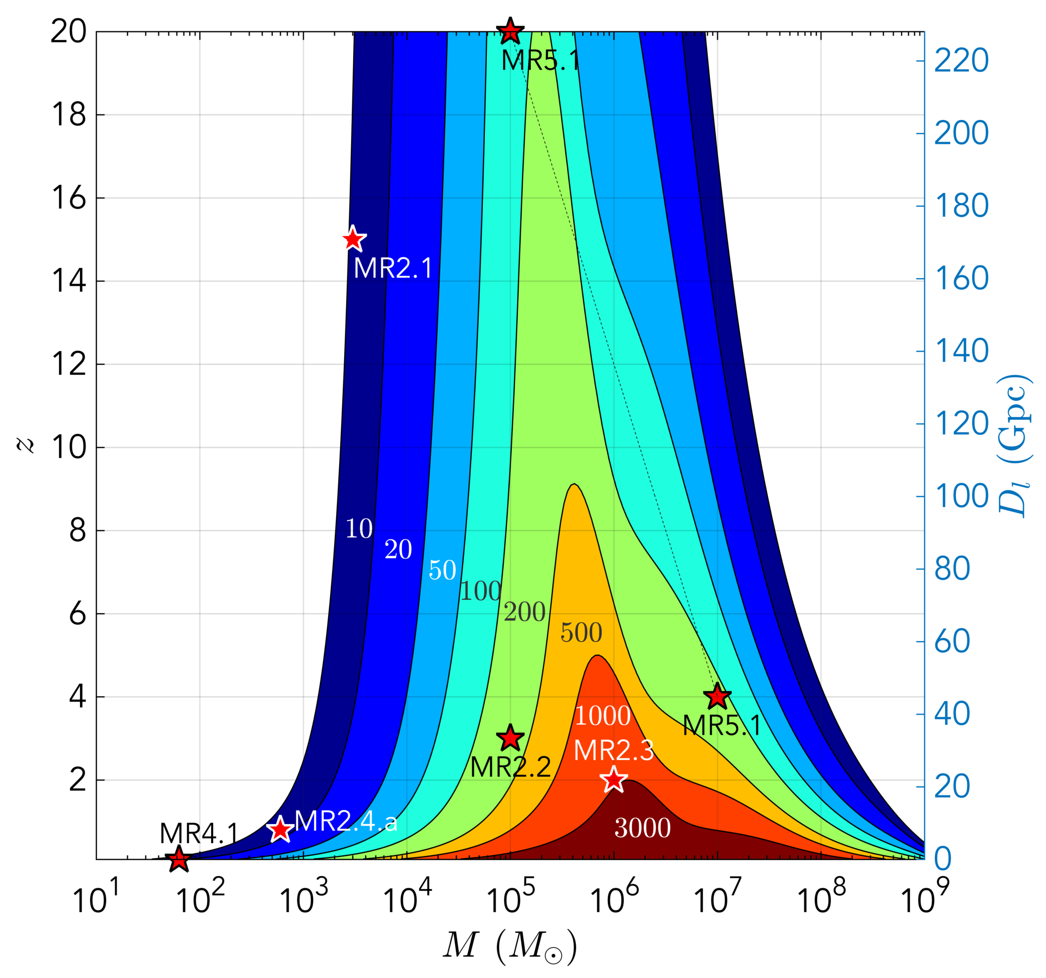
LISA binaries

(Accepted LISA proposal)



Why should you care (about photons)?

- **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

- **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

- **EM counterparts will also help with confidence of detection**

LISA binaries will 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

→ common outcome: pair of SMBHs in gas disk

Emission from a binary

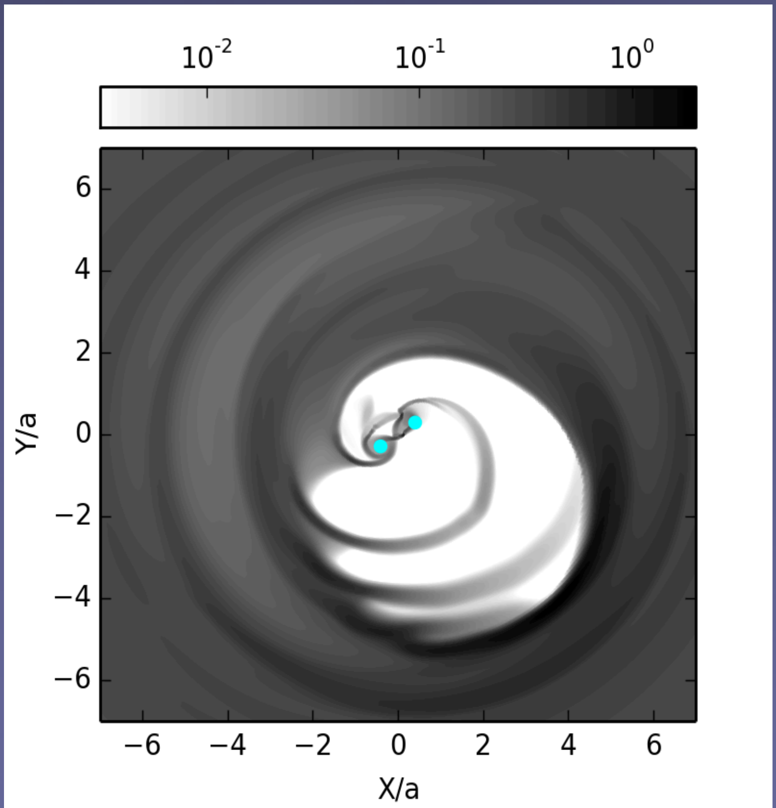
accretion rate similar to single BH, but:

(1) spectrum harder

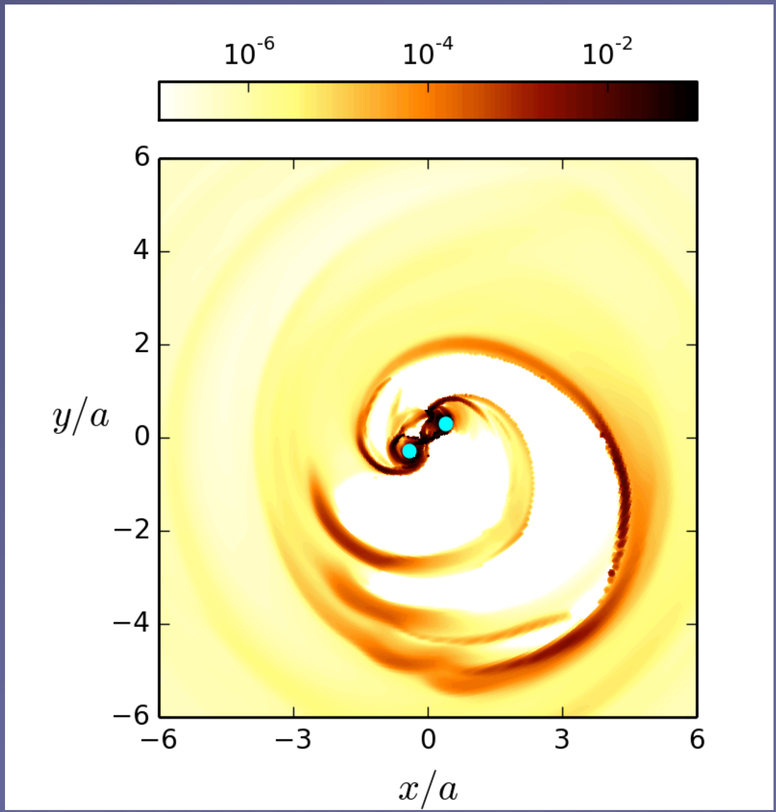
(2) periodic variability

Farris et al. (2015), Tang et al. (2018)

$q = M_2/M_1 = 1$



Surface density



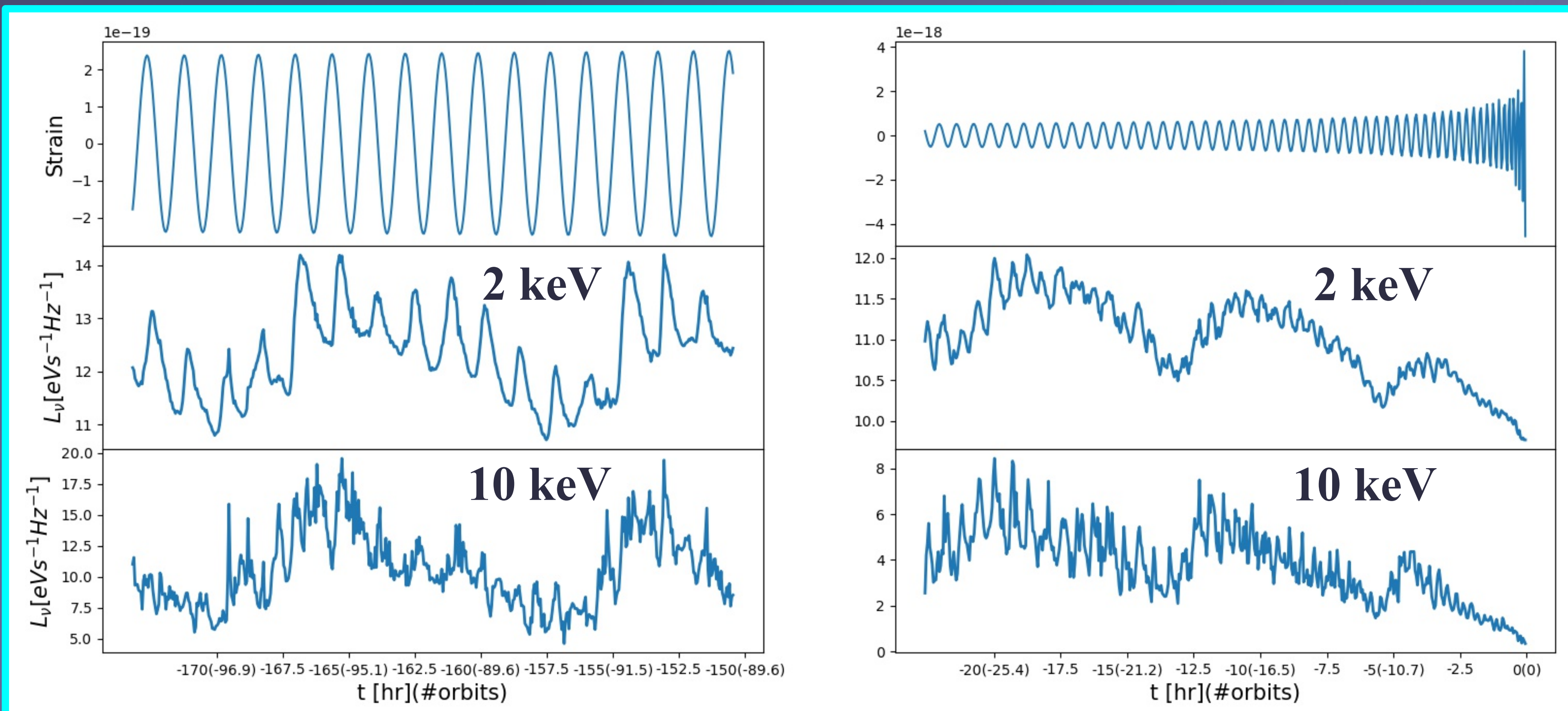
Surface luminosity:
shocks in streams and minidisks

Can GW-driven runaway binaries shine ?

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

Tang et al. (2018)

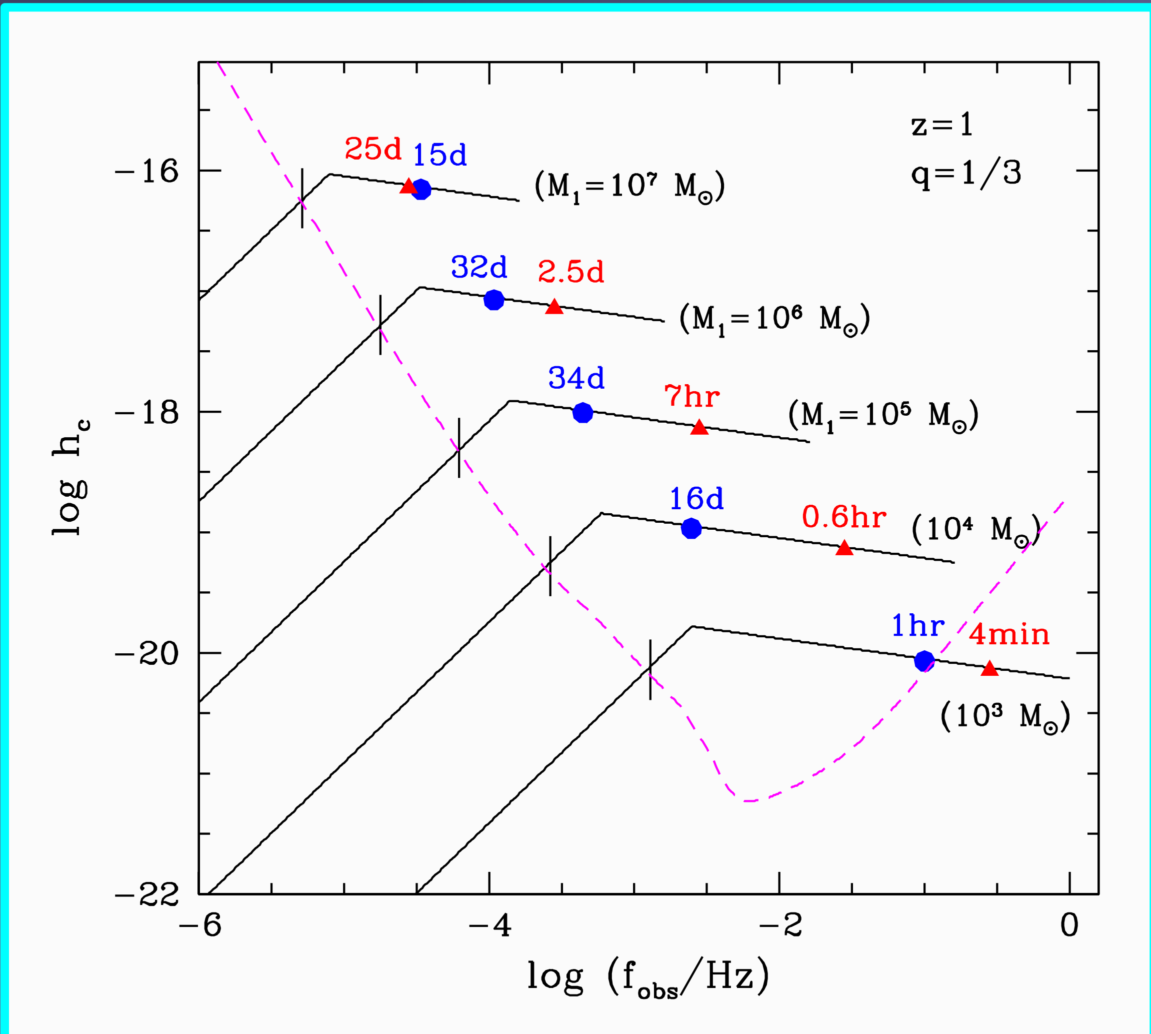
additional modulation from Doppler/lensing effects, with known phase (ZH 2017)



$q = M_2/M_1 = 1$

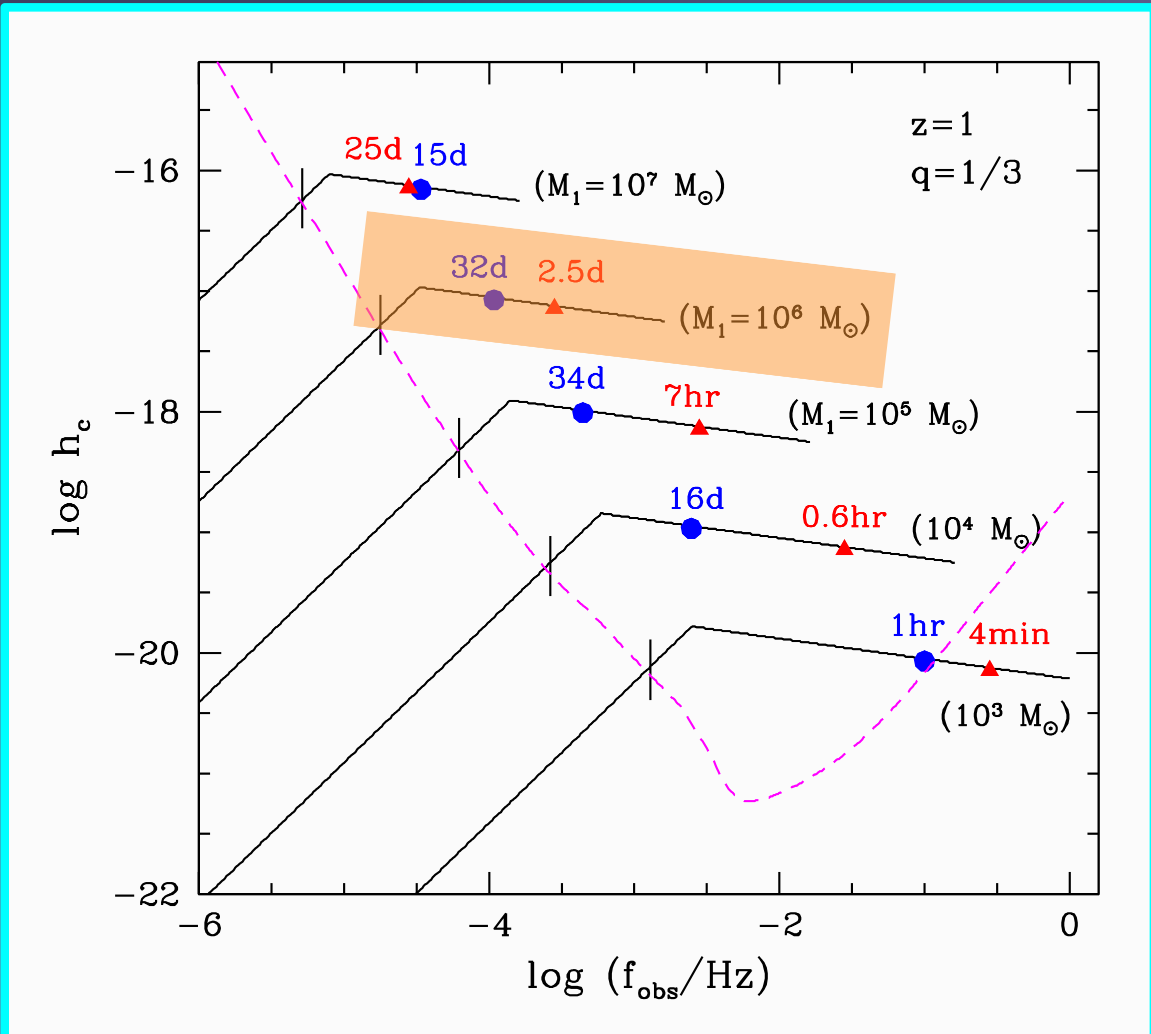
LAST 7 DAYS **LAST 1 DAY**

Track of binary in the LISA band



(Haiman 2017)

Track of binary in the LISA band

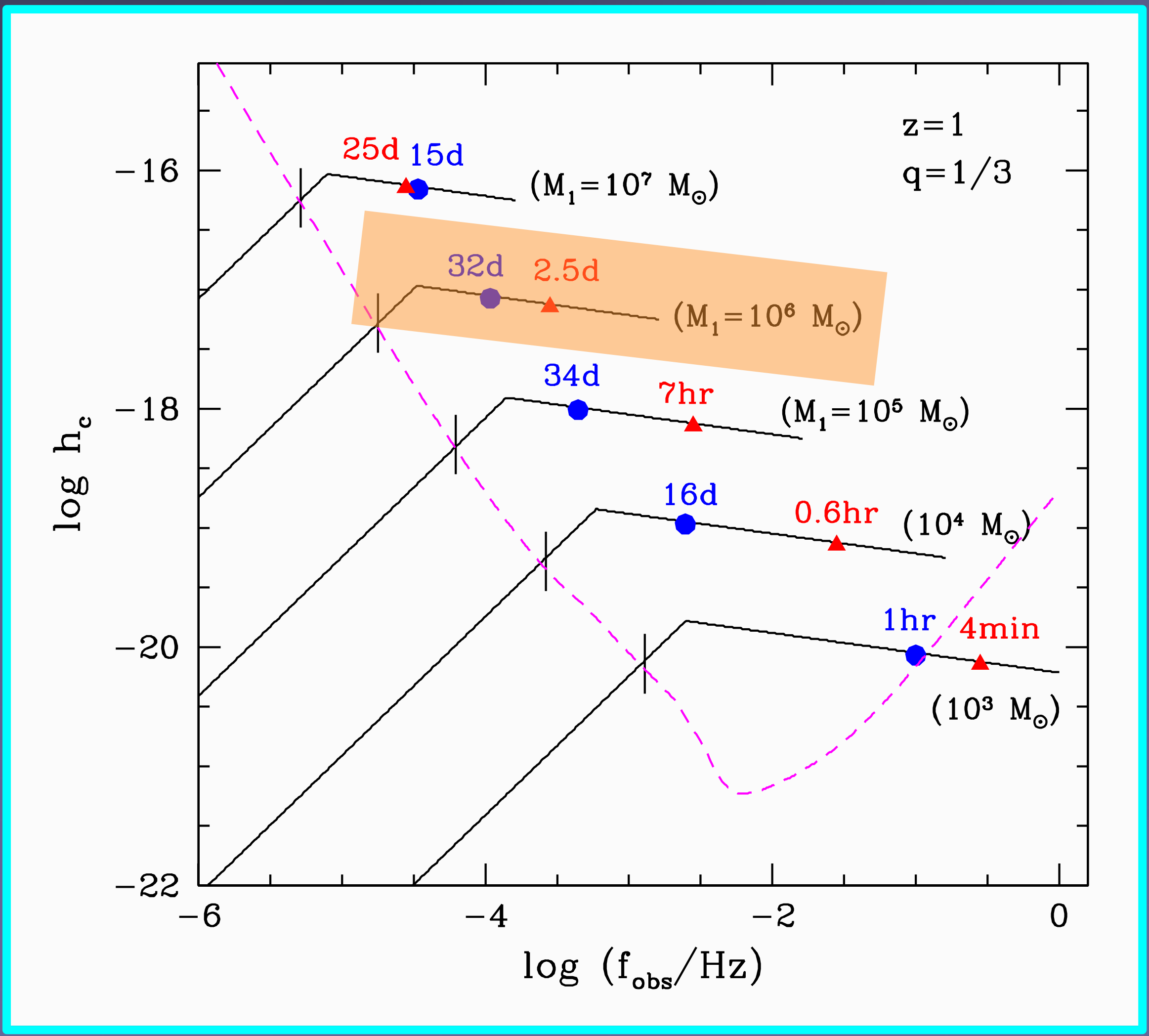


Example:

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

(Haiman 2017)

Track of binary in the LISA band



(Haiman 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

10^6 M$_\odot$ binary, q=1/3, z=1

→ $D/c = 3 \times 10^{18}$ s $t_{orb} = (1+z)2\pi 10 R_S/c \sim$ 4000 sec (at merger)

→ $\Delta c/c \sim t_{orb} / [D/c] \sim 10^{-15}$ (10-100 × better from S/N=$10^{2\text{-}3}$) $\sim 10^{-17}$

→ Improve bounds from LIGO BNS ($\sim 10^{-13}$) and from GWphasing alone ($\lambda_g \gtrsim 10^{16}$ km) Berti+(2005), Will (2006)

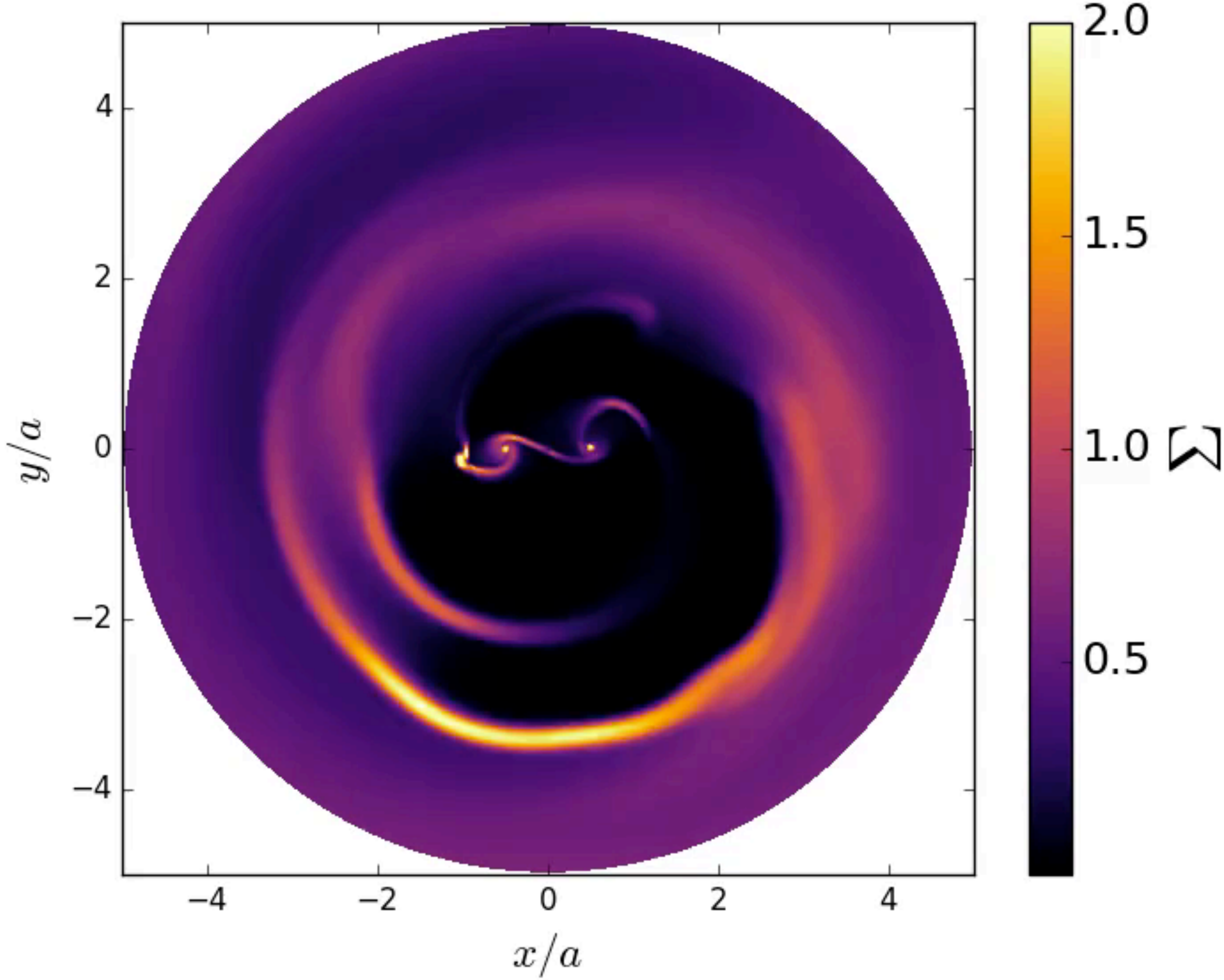
What is required ?

→ Telescope: FOV = 0.5 deg^2 Area=1 m^2 (Athena)
FOV = 0.1 deg^2 Area=2 m^2 (Lynx)

→ Source: L_X=0.05 L_{Edd}

→ Tiling LISA error box ($\Delta\Omega$=3 deg^2) takes: 1.7-3.8 hours
→ 200-400 points feasible over 4 weeks
→ Feasible! (possibly better from improved $\Delta\Omega$, target early candidates)

The End

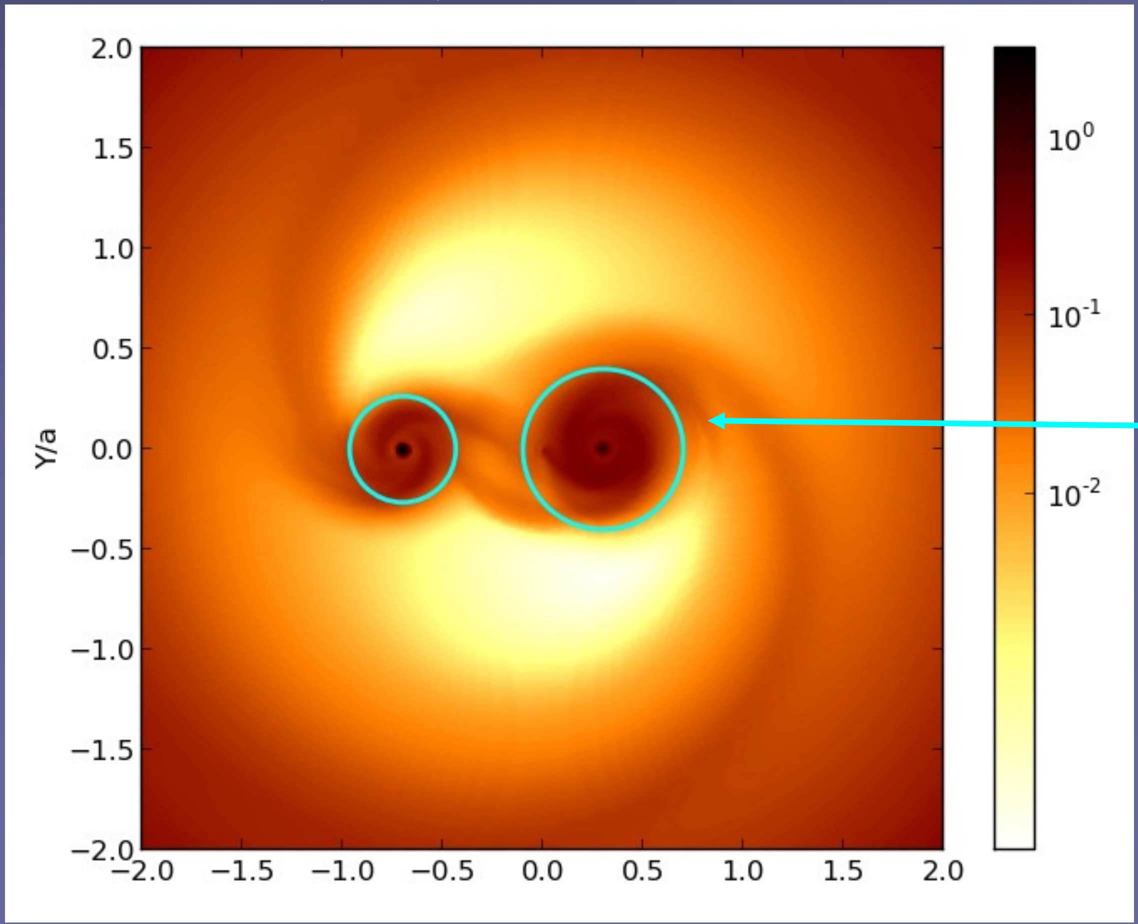


2.0
1.5
1.0
0.5
Σ
4
2
0
−2
−4
y/a
x/a

X-ray chirp inevitable

- X-ray [optical] emission from quasars from 10 R_g [few 100 R_g]
- Smaller than tidal truncation radius for wide binary
- Minidisk ~ quasar disk
- Doppler effect modulates brightness at O(v/c) ~ O(0.1)

Farris et al. (2015)



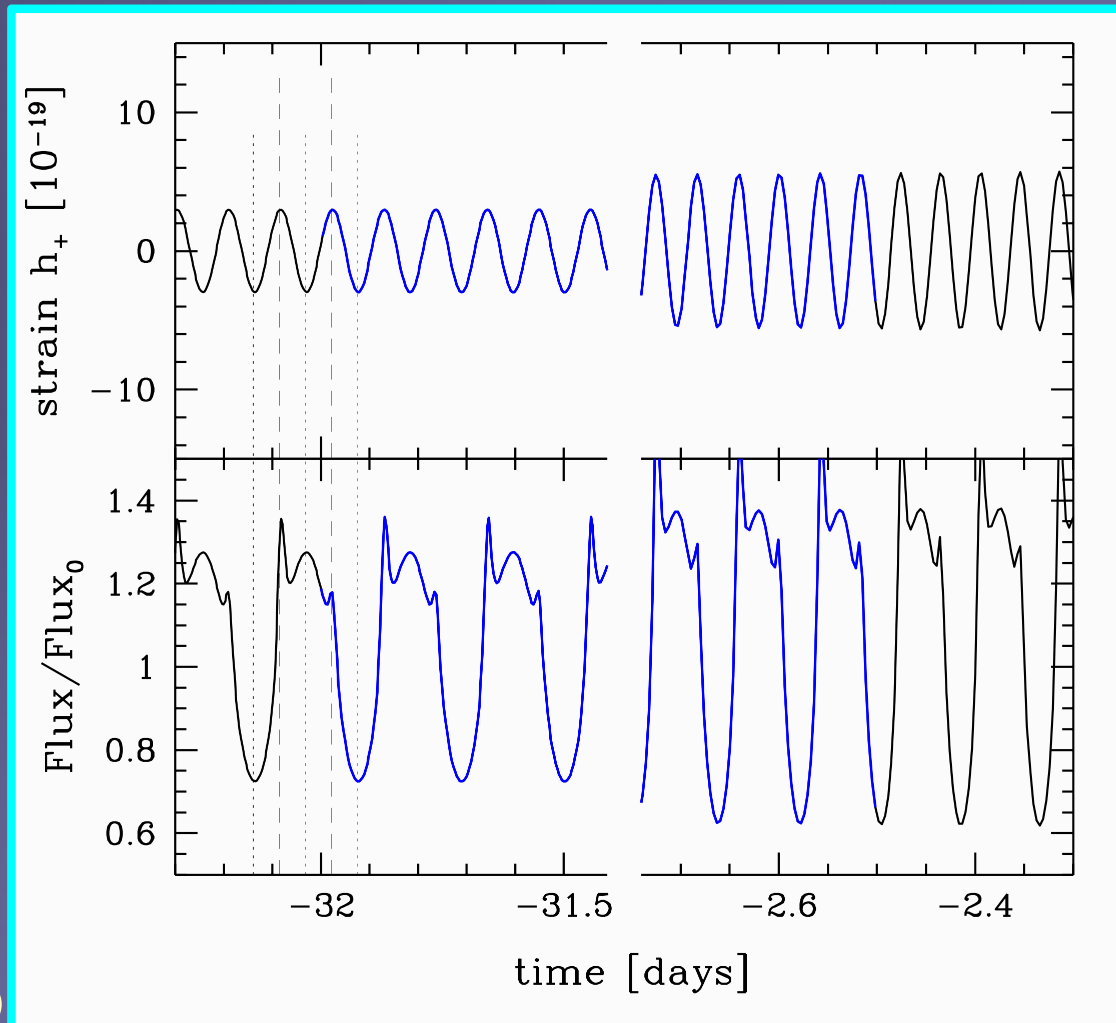
$\Delta F_\nu/F_\nu=(3-\alpha)(v_{||}/c)$

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

Tidal force from companion truncates minidisk

GW vs. X-ray chirp

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



10^6 $M_\odot$ binary, q=1/3, z=1

→ $D/c = 3 \times 10^{18}$ s

→ $t_{orb} = (1+z)2\pi 10R_S/c \sim$ 4000 sec

(orbital time at merger)

=> $\Delta c/c \sim t_{orb}$ / [D/c] $\sim 10^{-15}$

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Improve bounds from LIGO BNS ($\sim 10^{-13}$) and From GWphasing alone ($\lambda_g \gtrsim 10^{16}$ km)

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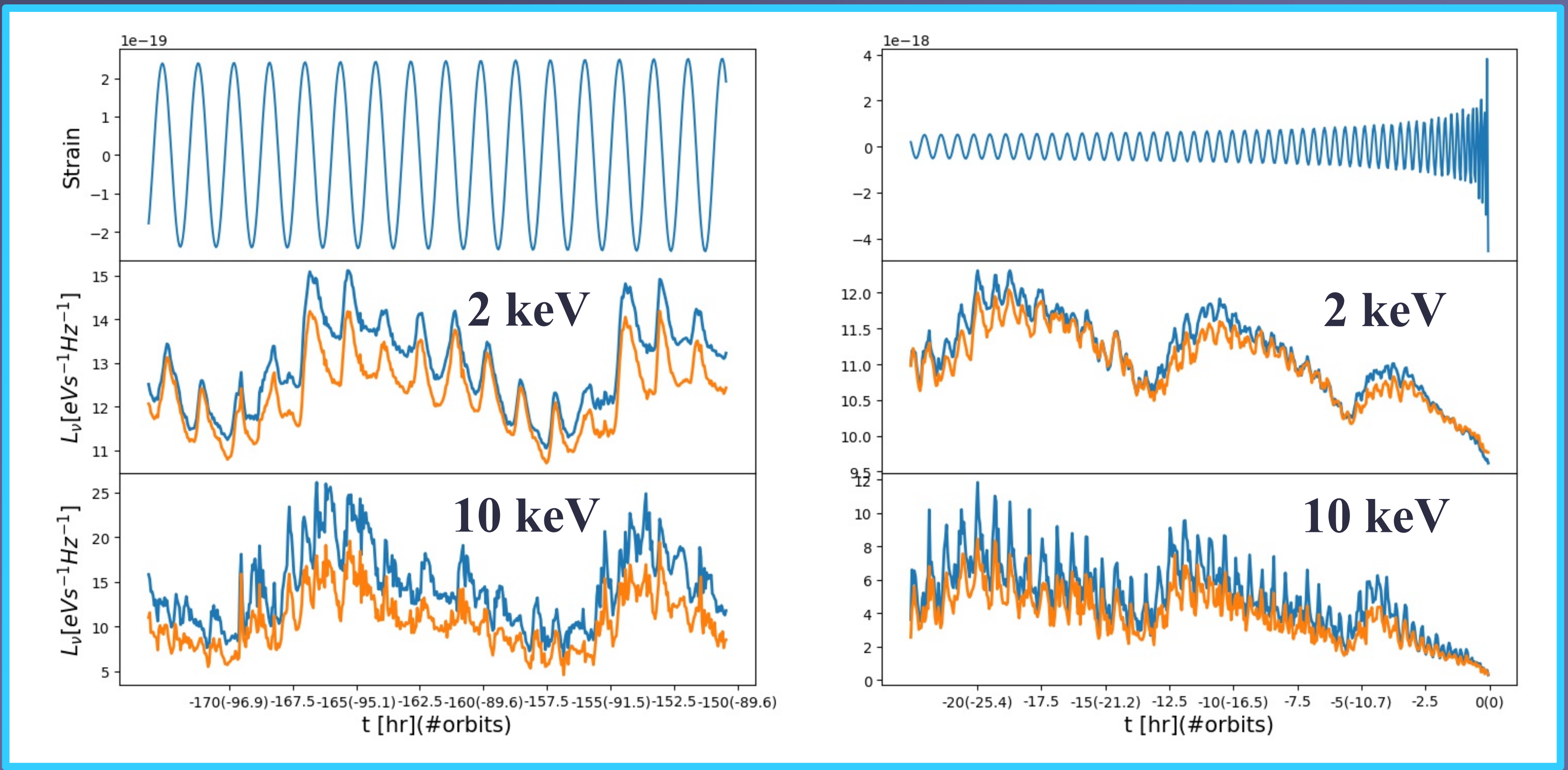


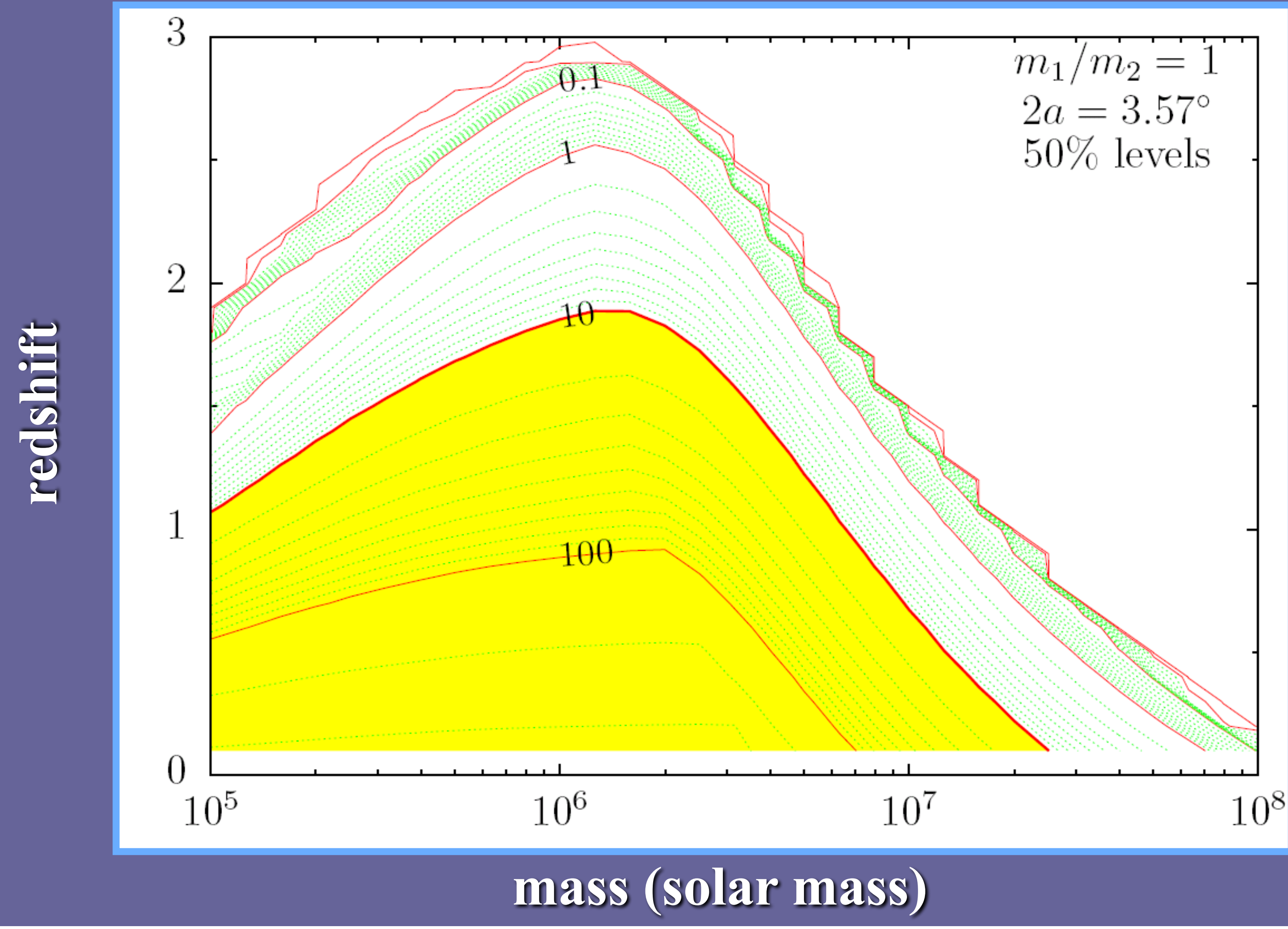
LAST 7 DAYS

LAST 1 DAY

Advanced sky localization

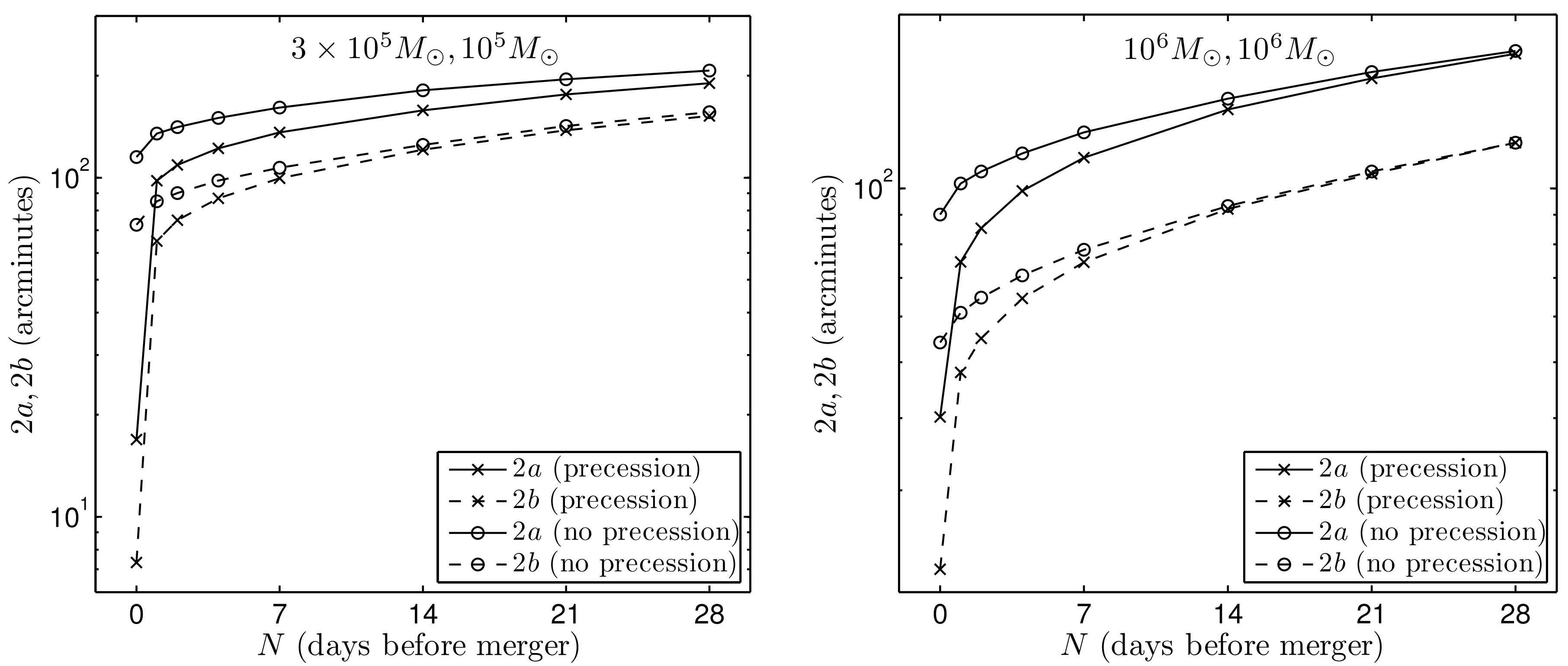
Look-back time when sky position error shrinks down to ~10 deg^2

(Kocsis et al. 2007; 2008; Lang & Hughes 2008)



LISA sky localization

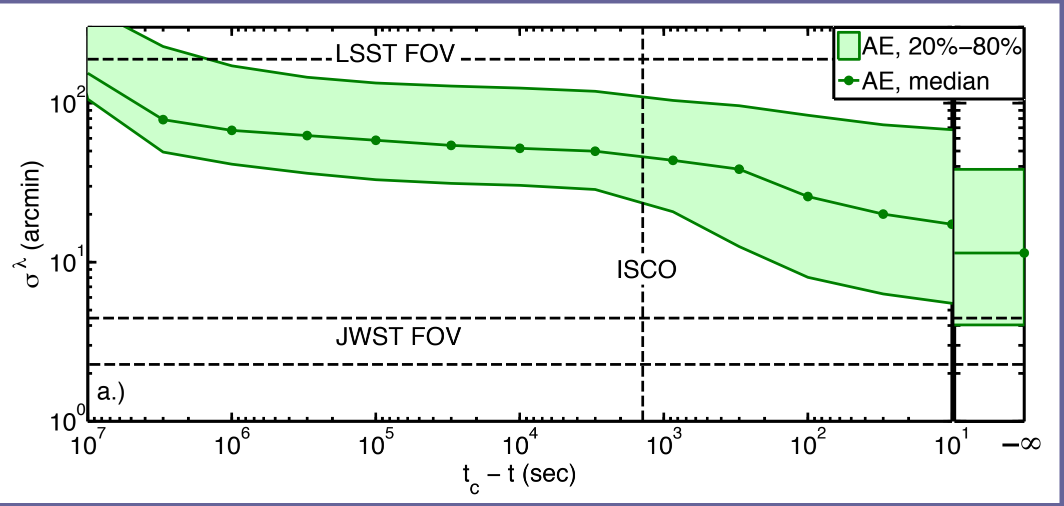
(Kocsis et al. 2008; Lang & Hughes 2008)



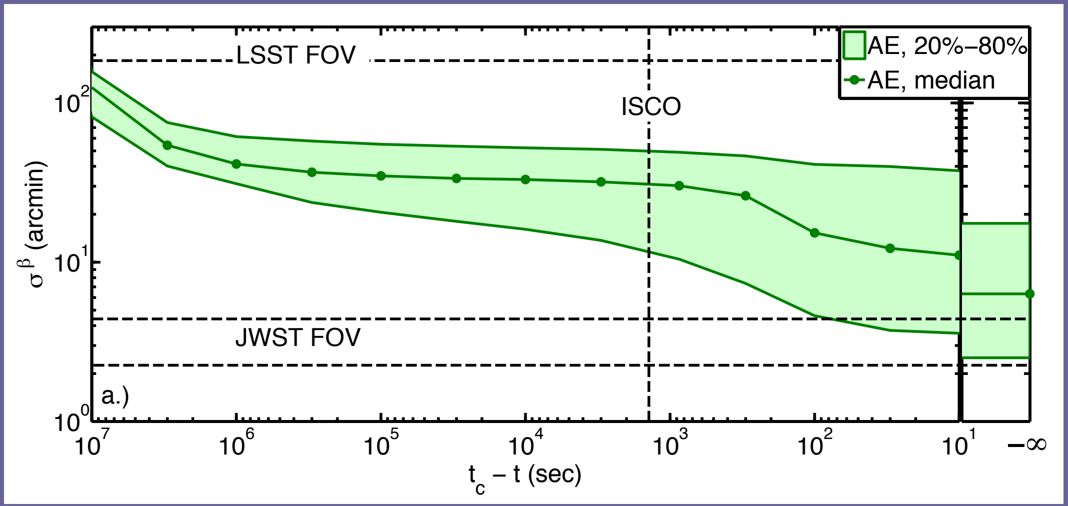
LISA sky localization

(Mc Williams et al. 2011)

$2{\times}10^6\ M_\odot$ binary, q=1, z=1

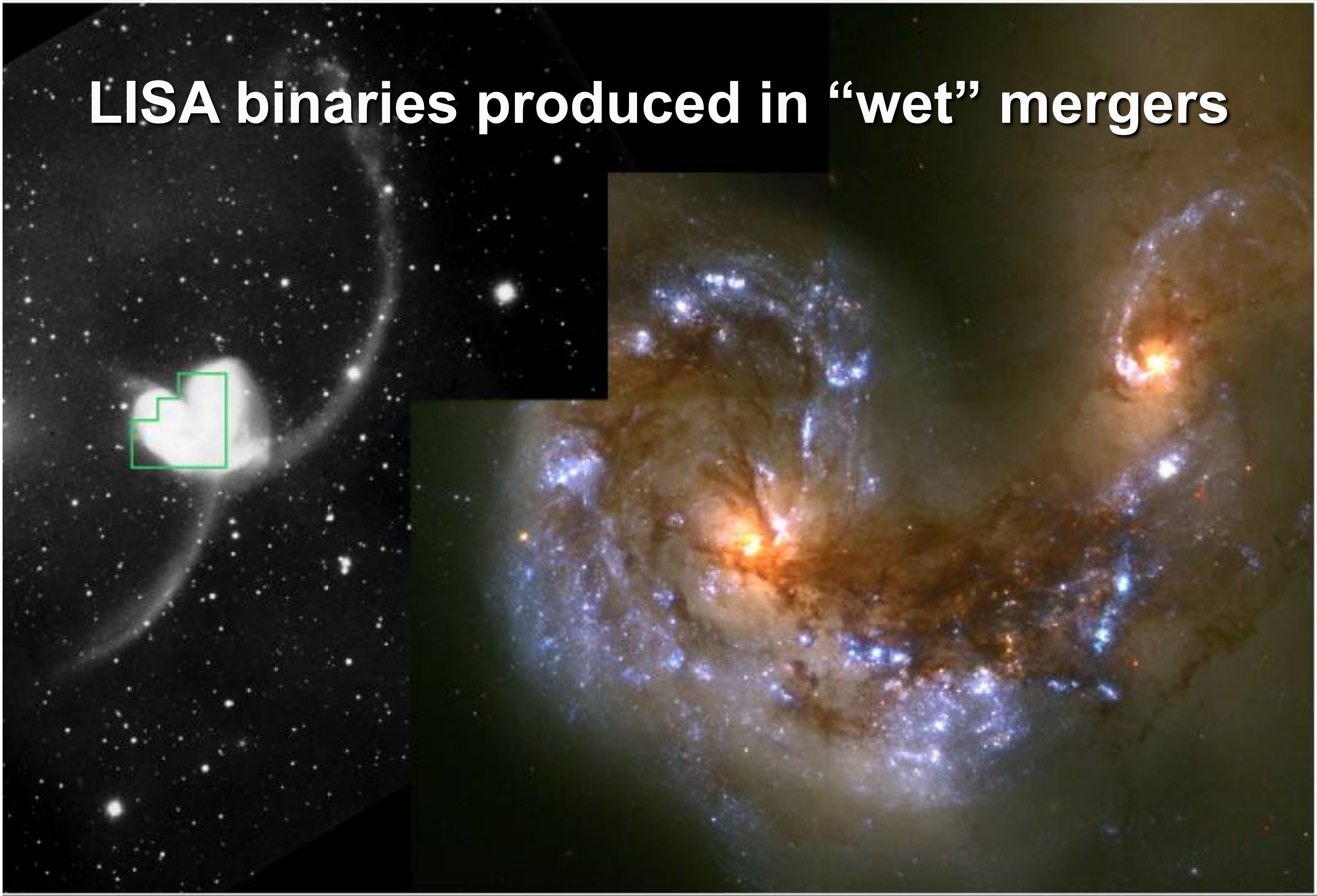


Error on latitude



Error on longitude

LISA binaries produced in “wet” mergers

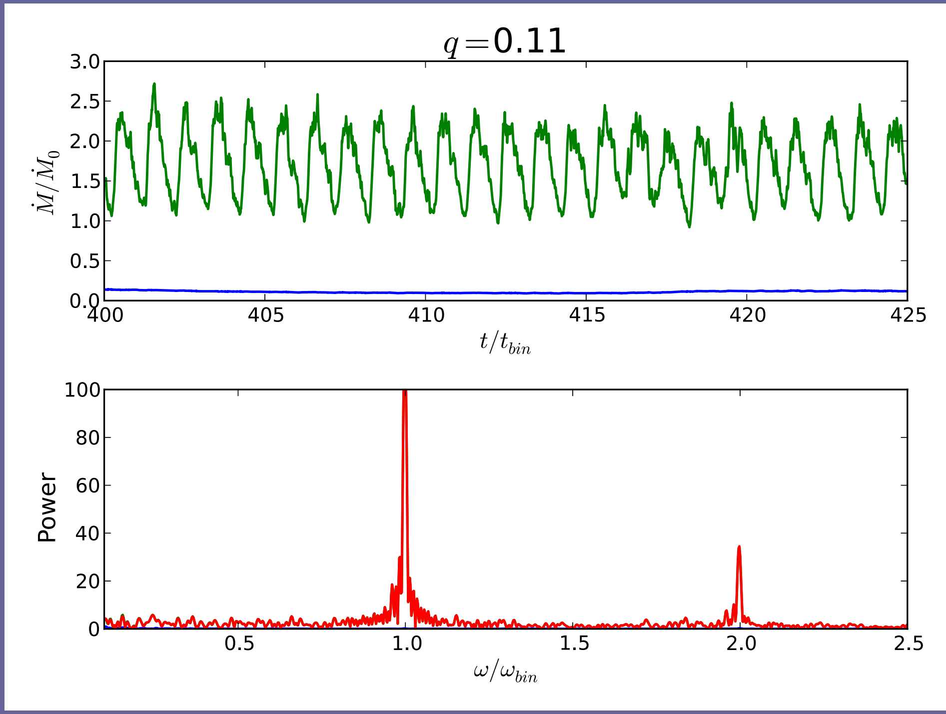


Colliding Galaxies NGC 4038 and NGC 4039 HST • WFPC2

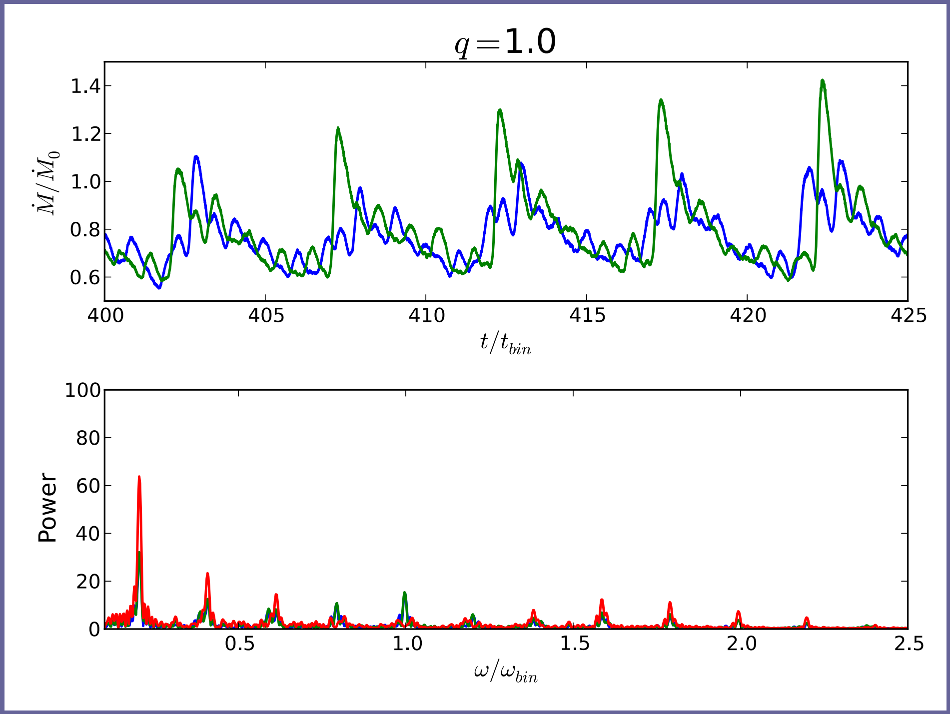
PRC97-34a • ST ScI OPO • October 21, 1997 • B, Whitmore (ST ScI) and NASA

Accretion onto BHs

0.05 < q < 0.3



0.3 < q < 1



Factor of ~two variability on **orbital timescale**

Factor of ~two variability on **orbital time at cavity wall**

Total accretion is **not suppressed** by binary

Gravitational lensing size scales of quasars

X-rays: **Chartas, Rhea, Kochanek et al. (2015)**

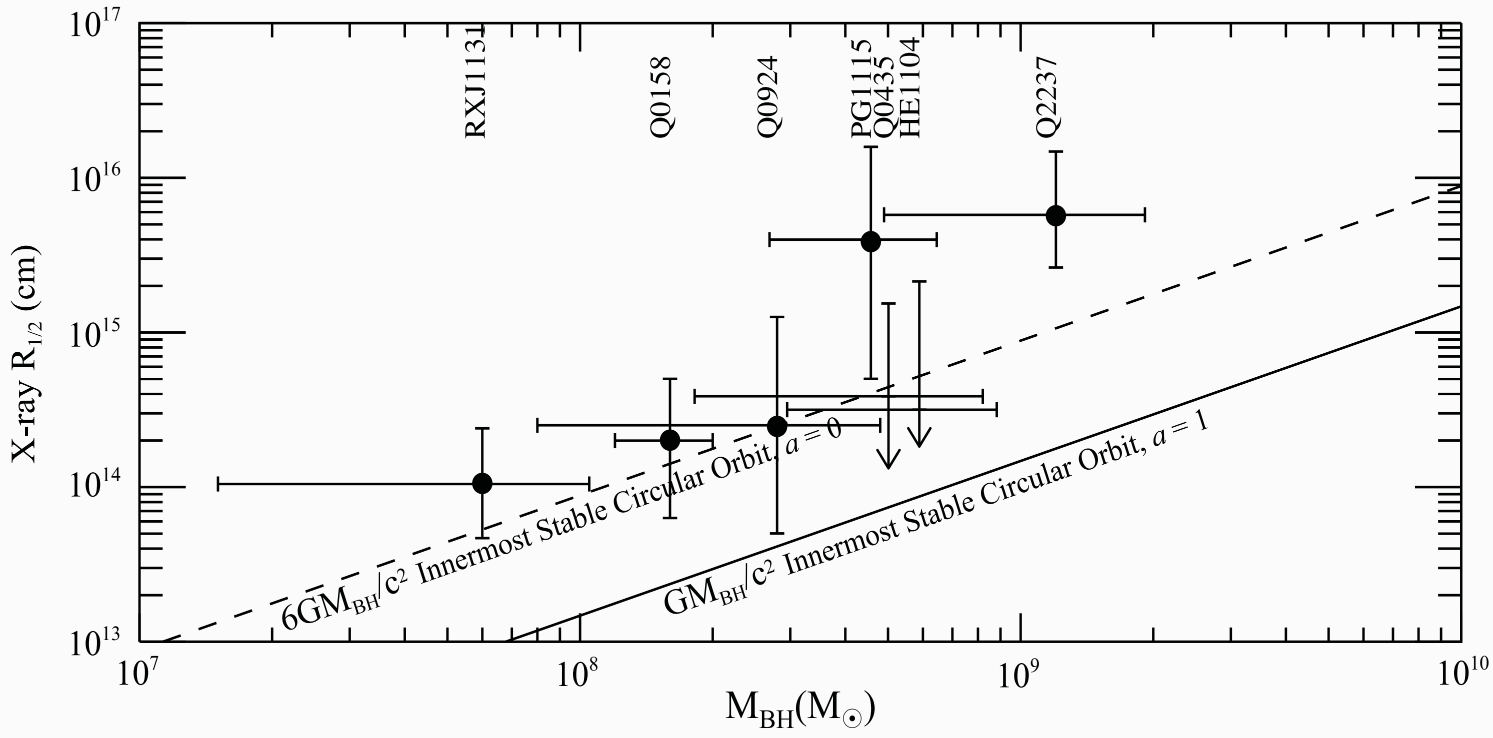


Fig. 1 X-ray half-light radii of quasars as determined from our microlensing analysis versus their black hole masses.

Gravitational lensing size scales of quasars

UV: **Morgan et al. (2007)**

e.g. $R=10^{14}$ cm → $R=600\ R_g$ for $M=10^6\ M_\odot$:

QUASAR ACCRETION DISK SIZES 3

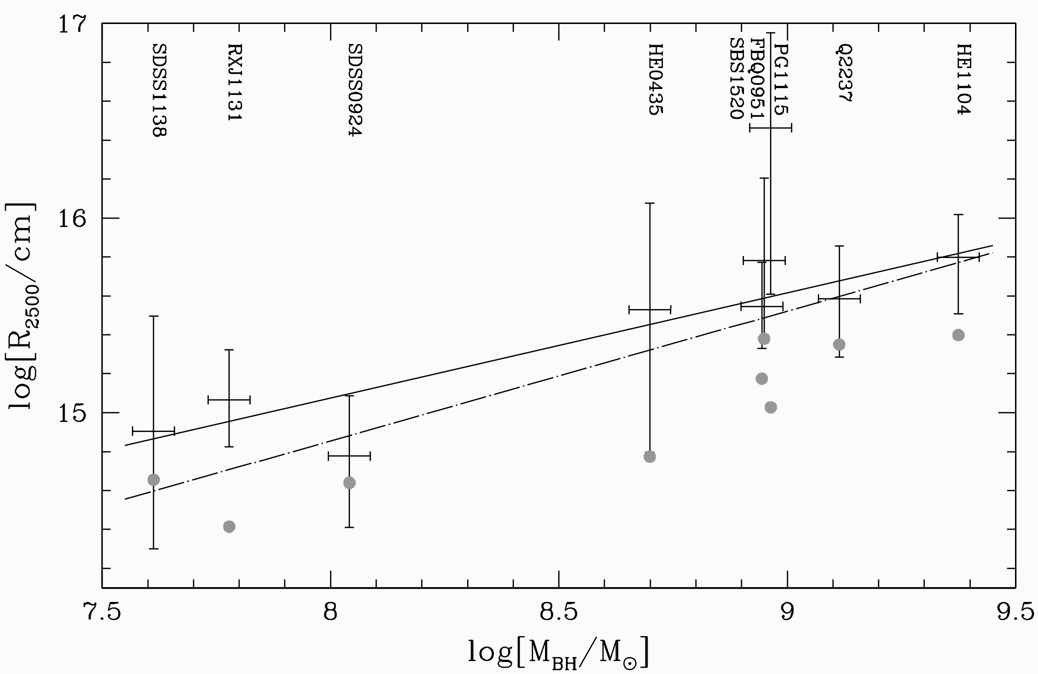
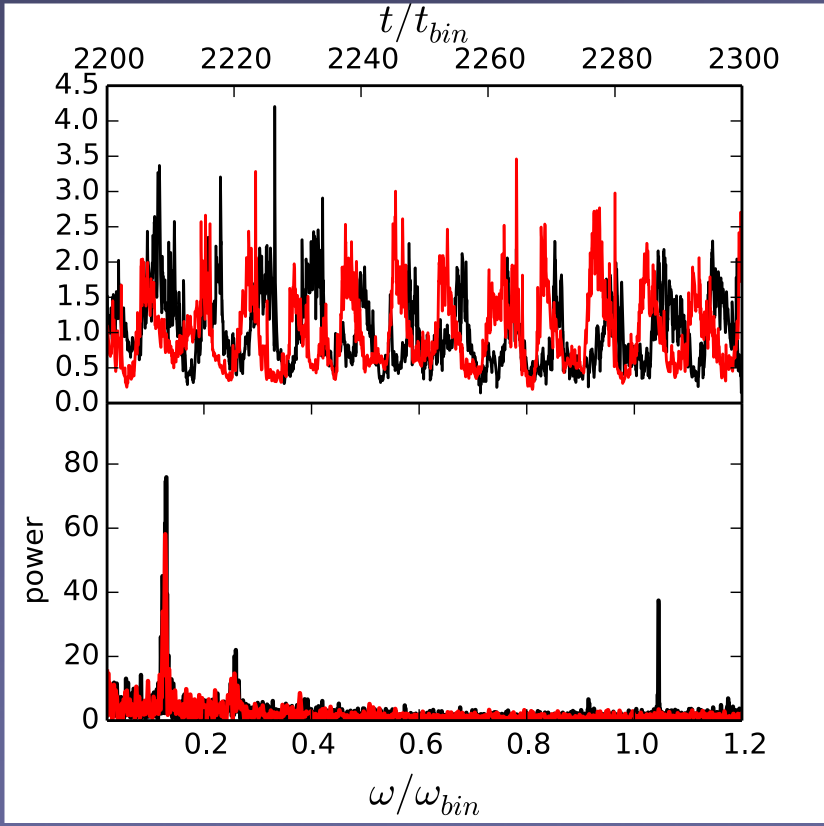


FIG. 1.— Inclination-corrected accretion disk size R_{2500} versus black hole mass M_{BH}. The solid line shows our best power-law fit to the data and the dot-dashed line shows the prediction from thin disk theory ($L/L_E = 1$ and $\eta = 0.1$). Disk sizes are corrected to a rest wavelength of $\lambda_{rest} = 2500$Å and the black hole masses were estimated using emission line widths. The filled points without error bars are R_{2500} estimates based on the observed, magnification-corrected I-band fluxes. They have typical uncertainties of 0.1-0.2 dex.

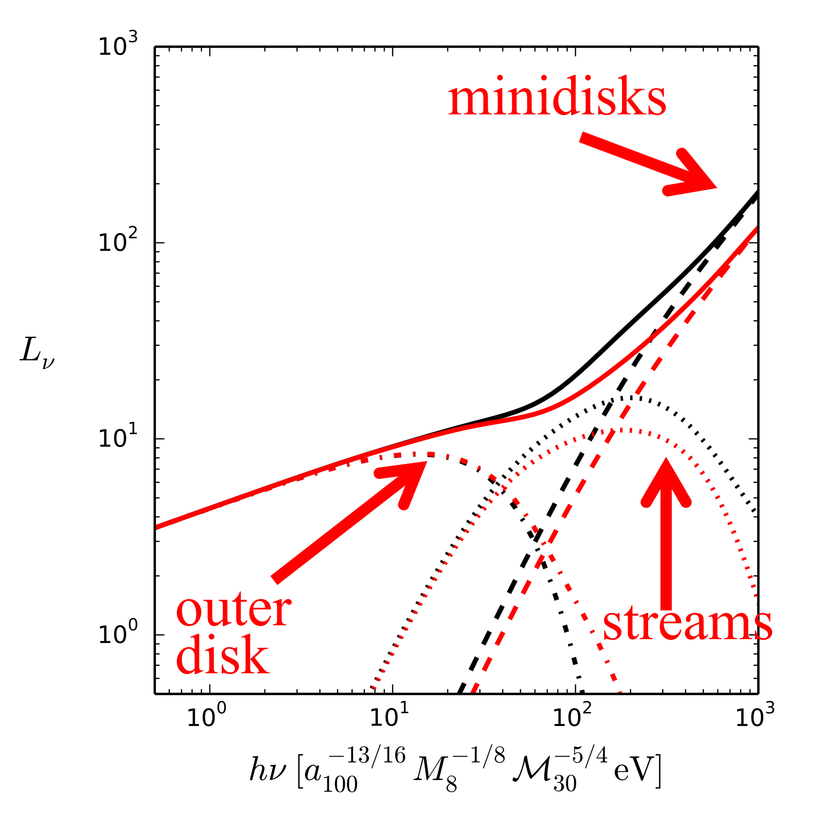
Composite Spectrum

Farris et al. (2015a)

- Spectrum **brighter, harder, variable** compared to single BH
- **opposite** of previous expectations based on empty cavity!



bolometric luminosity varies, tracks accretion



periodic spectral variability at high energies (~6 t_{orb})