The astrophysics of black hole mergers

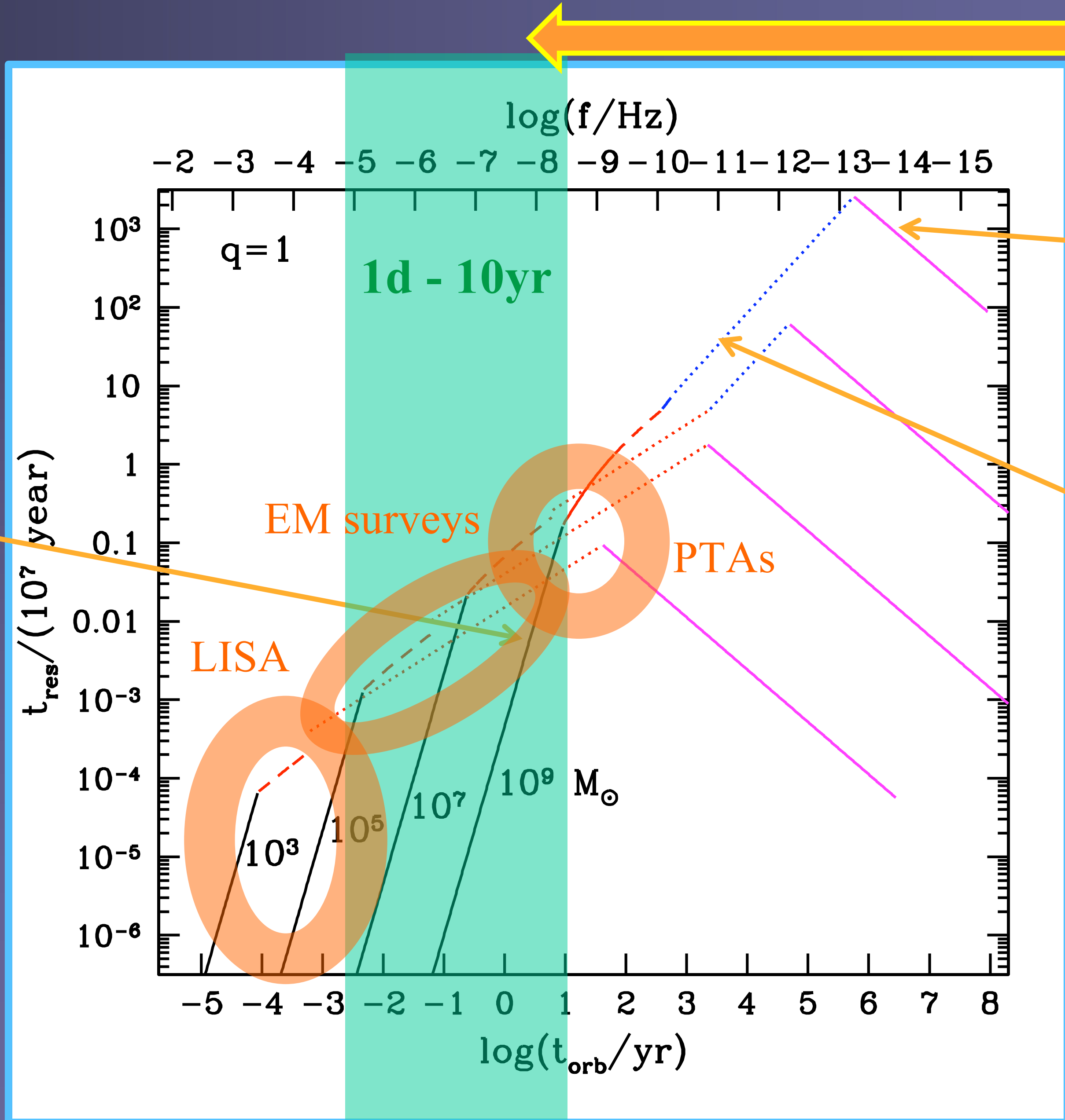
1. Pairing massive BHs in galactic nuclei
   from large to small scales, role of gas

2. Electromagnetic signatures of massive BH binaries
   in EM observations or in GW detections

3. [Where do massive BHs come from anyway?]
   protogalaxy formation after the cosmic dark age

4. [Stellar-mass BH binaries]
   in AGN accretion disks with EM signatures

Binary evolution



Stellar Scattering driven decay

GW-driven decay

Gas disk Driven decay

[sensitive to accretion disk model]

ZH, Kocsis, Menou (2009)

EM Signatures of Massive BH Binaries

Zoltán Haiman

Columbia University

Lecture 2

Science from Multi-Messenger Astrophysics

- **Astronomy and astrophysics**

— *Accretion physics*: EM emission w/known BH parameters + distorted GWs
— *Environments of massive BH mergers:* quasar/galaxy co-evolution
— *Assembly of the first BHs in the 'dark age':* mergers (GW) vs. accretion (EM)
— *Are there intermediate-mass BHs? Where do they form?*
— *Formation mechanism and fate of stellar-mass binaries*
— *Physics of mass transfer in double white-dwarfs*
— *Mapping the structure of the Milky Way through DWDs*

- **Fundamental physics and cosmology**

— *Dark Energy:* Hubble diagrams from standard sirens (& current H_0 tension)
— *Non-GR gravity:* compare $d_L(z)$ from GWs vs photons
delay between arrival time of photons and gravitons
(propagation effects, *extra dimensions*, graviton mass)
— *Lorentz violations:* frequency-dependence in delay $hf = \gamma mc^2$
— *Inflation:* Non-minimal inflation through GW background slope (cf. CMB)
— *Dark matter:* intermediate-mass ratio mergers (DM spikes)
— *NS equation of state:* mergers involving NSs

- **EM counterparts can also help with confidence of GW detection**

Science from Multi-Messenger Astrophysics

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- **EM counterparts can also help with confidence of GW detection**

Standard Sirens

310 LETTERS TO NATURE NATURE VOL. 323 25 SEPTEMBER 1986

Determining the Hubble constant from gravitational wave observations

Bernard F. Schutz

Department of Applied Mathematics and Astronomy, University College Cardiff, PO Box 78, Cardiff CF1 1XL, UK

I report here how gravitational wave observations can be used to determine the Hubble constant, H_0. The nearly monochromatic gravitational waves emitted by the decaying orbit of an ultra-compact, two-neutron-star binary system just before the stars coalesce are very likely to be detected by the kilometre-sized interferometric gravitational wave antennas now being designed[1–4]. The signal is easily identified and contains enough information to determine the absolute distance to the binary, independently of any assumptions about the masses of the stars. Ten events out to 100 Mpc may suffice to measure the Hubble constant to 3% accuracy.

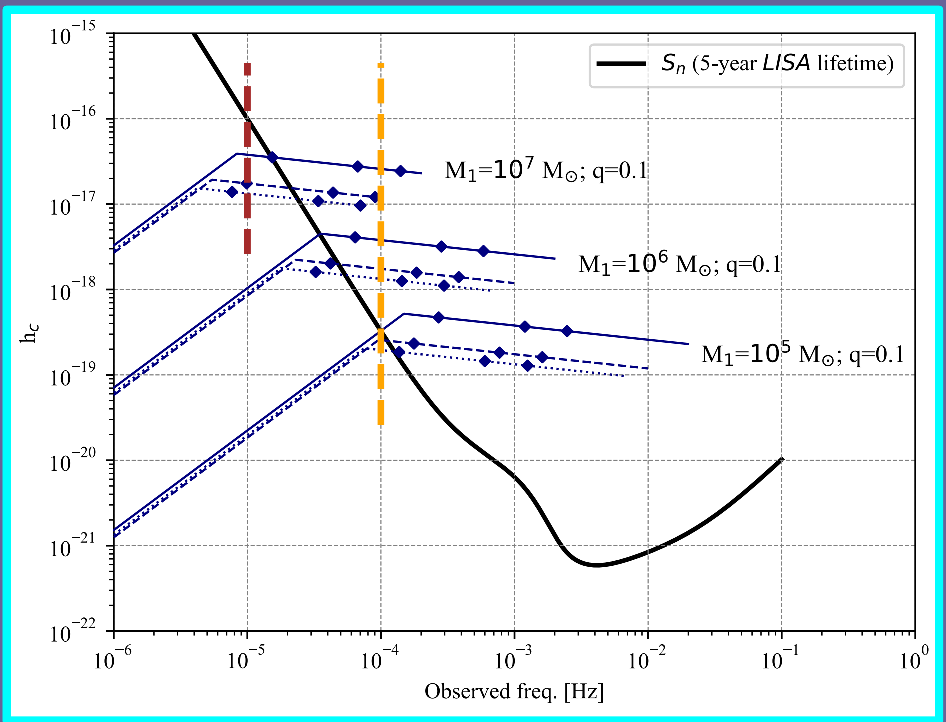
the detectors to see binary neutron star sources at 100 Hz at a distance of 100 Mpc, with a mean signal-to-noise ratio (SNR) of >30. An observation will therefore determine τ and h to perhaps 3%. The key to our method is that the stars' masses enter equations (1) and (2) in exactly the same way, so that

$$r_{100} = 7.8 f_{100}^{-2} (\langle h_{23} \rangle \tau)^{-1} \quad (3)$$

where $\langle h_{23} \rangle = \langle h \rangle \times 10^{23}$, independently of the masses of the stars.

This result is not quite so strong as it seems, as equation (1) gives the r.m.s. value of h averaged over orientations, whereas the value of h inferred from the network's observations will depend on the binary system's orientation and position relative to the detectors as well as its distance. However, these can be determined from the observations: as I show below, provided that three or more detectors register the same event, they can determine the location on the sky and the degree of elliptical polarization of the wave. (In general relativity, gravitational waves are transverse and have only two independent polarizations[6–7].) Now, the radiation emitted by the binary along its angular momentum axis is circularly polarized, whereas that in the equatorial plane is linearly polarized. The degree of eliptical

Standard Sirens



Xin & ZH 2021

(1) GW amplitude (shear)

$$h = \frac{8\pi^{2/3}}{10^{1/2}} \frac{G^{5/3}\mathcal{M}^{5/3}}{c^4 r(z)} f_r^{2/3},$$

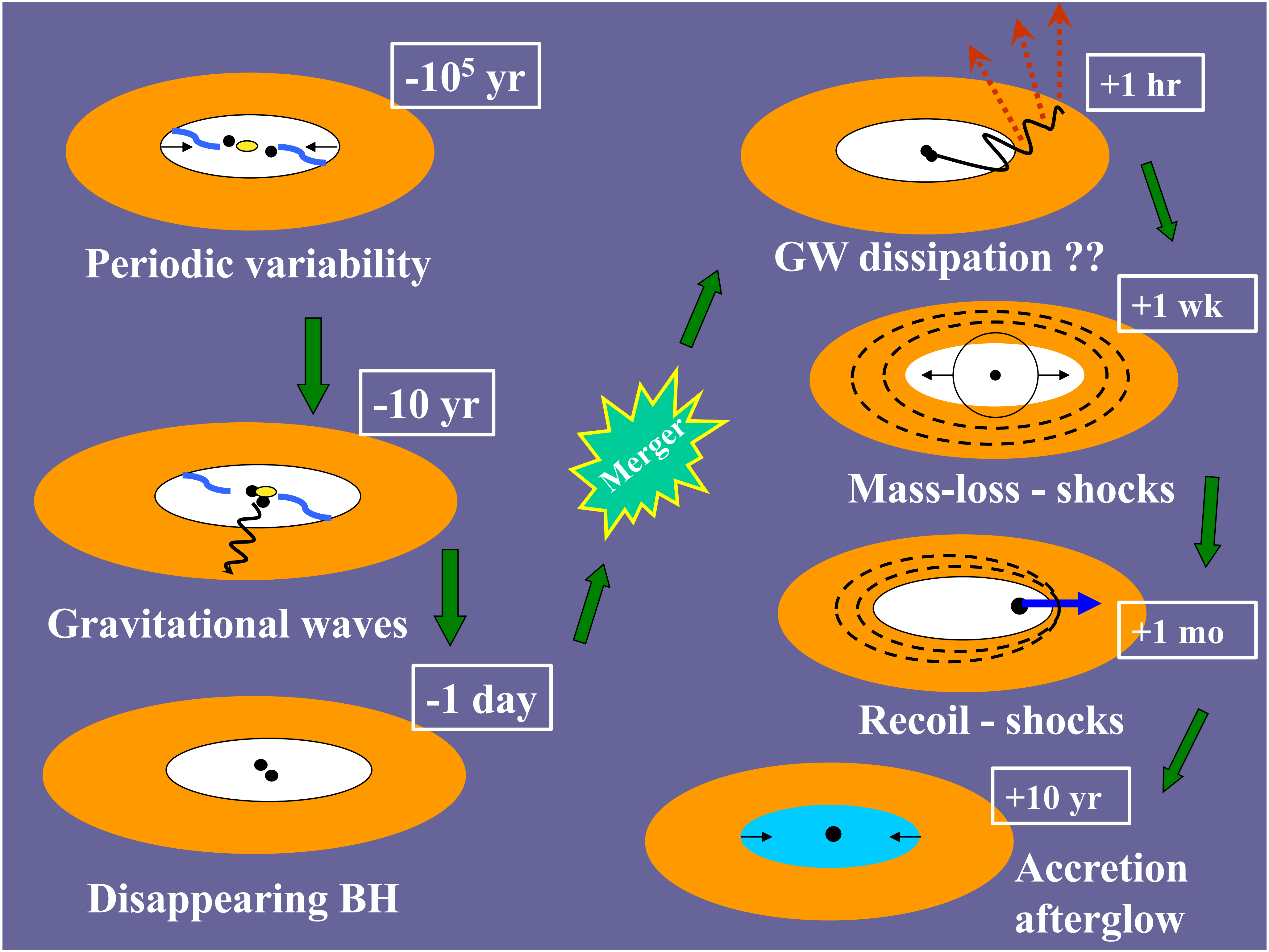
$$\mathcal{M} = (M_1 M_2)^{3/5}/(M_1 + M_2)^{1/5}$$ chirp mass

(2) Chirp

$$\dot{f}_r = \frac{df_r}{dt_r} = \frac{96\pi^{8/3} G^{5/3}}{5c^5} \mathcal{M}^{5/3} f_r^{11/3}$$

(1)/(2) → $\dot{f}_r/h = \text{const} * r(z) * f_r^3$

$$\boxed{r(z) = \text{const} * f_r^{-3}\ \dot{f}_r / h}$$



-10^5 yr
Periodic variability
-10 yr
Gravitational waves
-1 day
Disappearing BH
Merger
+1 hr
GW dissipation ??
+1 wk
Mass-loss - shocks
+1 mo
Recoil - shocks
+10 yr
Accretion
afterglow

Accretion and Variability

Three regimes based on mass ratio $q=M_2/M_1$

q=0.01 *q=0.05* *q=1*

steady accretion

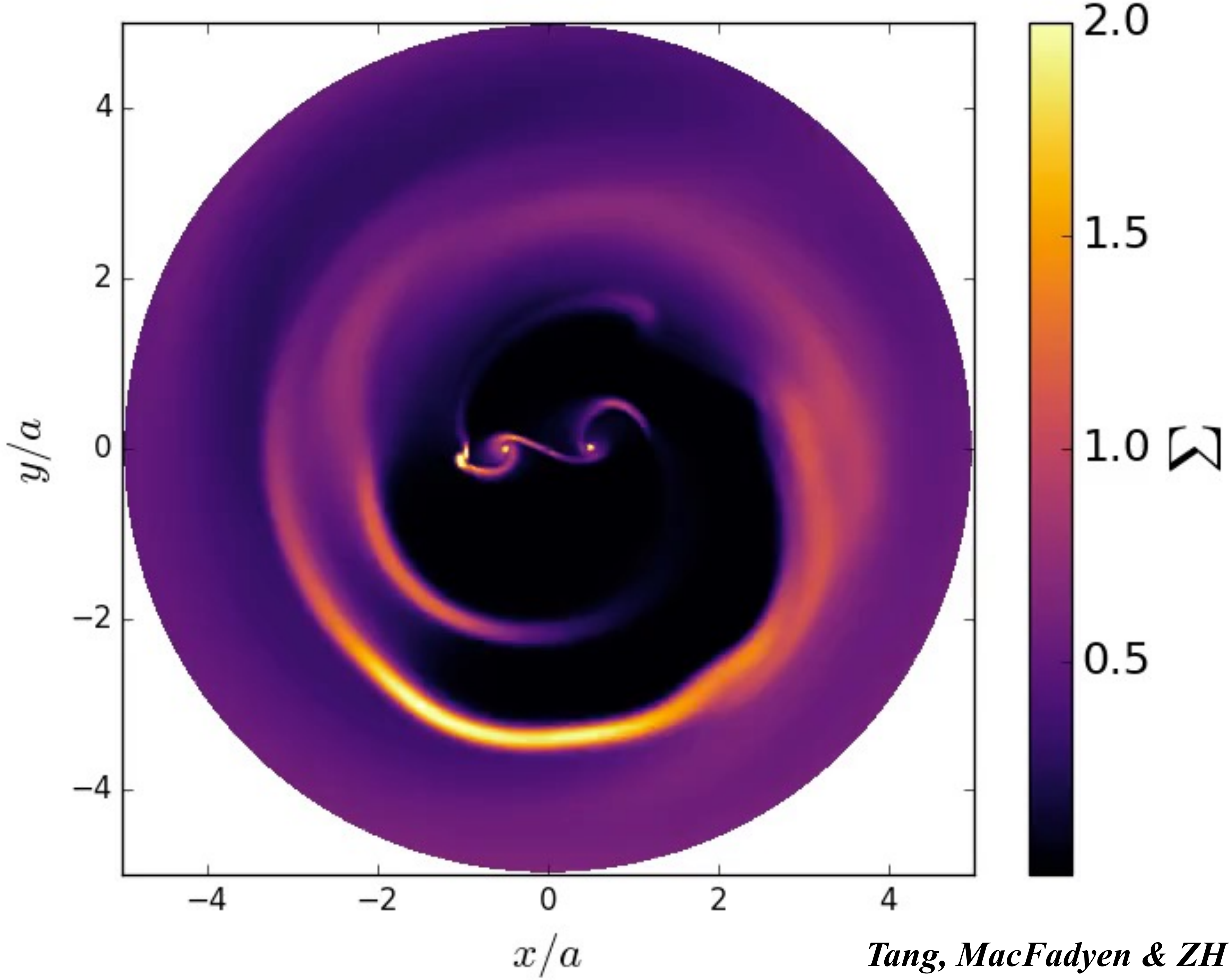
q≈0.04 loss of stable orbits

orbital time scale regime

q≈0.3 lump at cavity

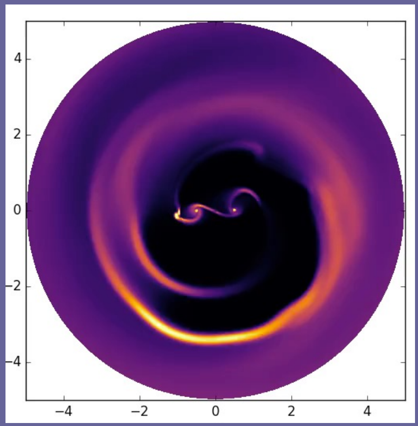
cavity wall regime

Equal-Mass Binary



Tang, MacFadyen & ZH (2018)

Key Features of Binary Accretion



Central cavity:

- Lack of stable orbits within ~twice the binary separation
- Density suppressed by factor of ~100

Lopsided cavity wall with lump:

- circumbinary disk strongly lopsided (nonlinear instability)
- dense lump appears at cavity wall, modulating accretion

Streamers:

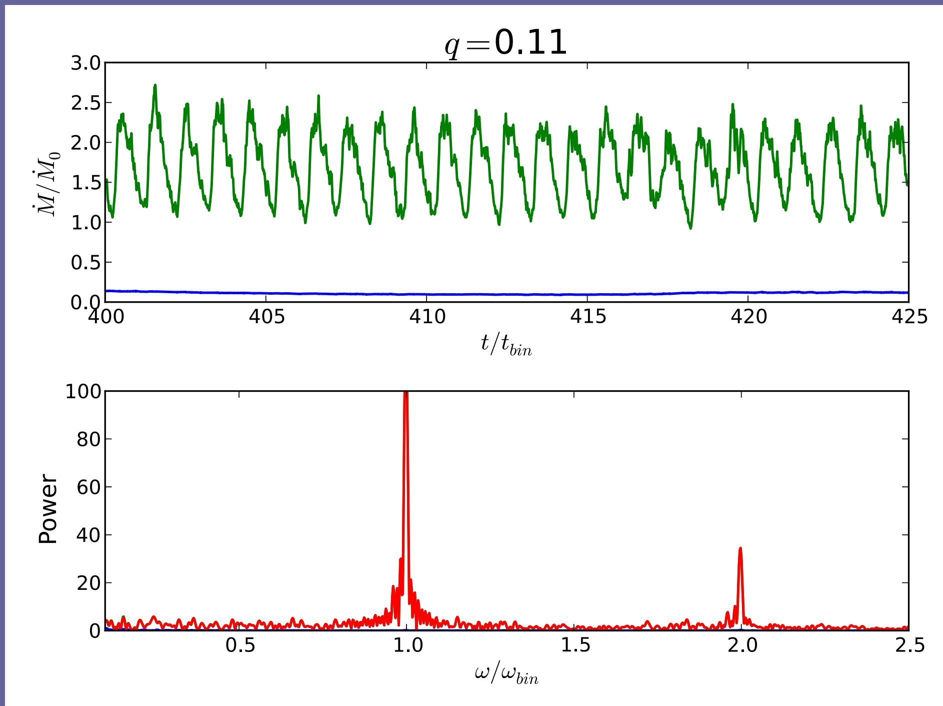
- enter cavity wall via strong shocks, extend into tidal region of BHs
- fuel accretion is via gravity and shocks --- not viscosity!

Minidisks:

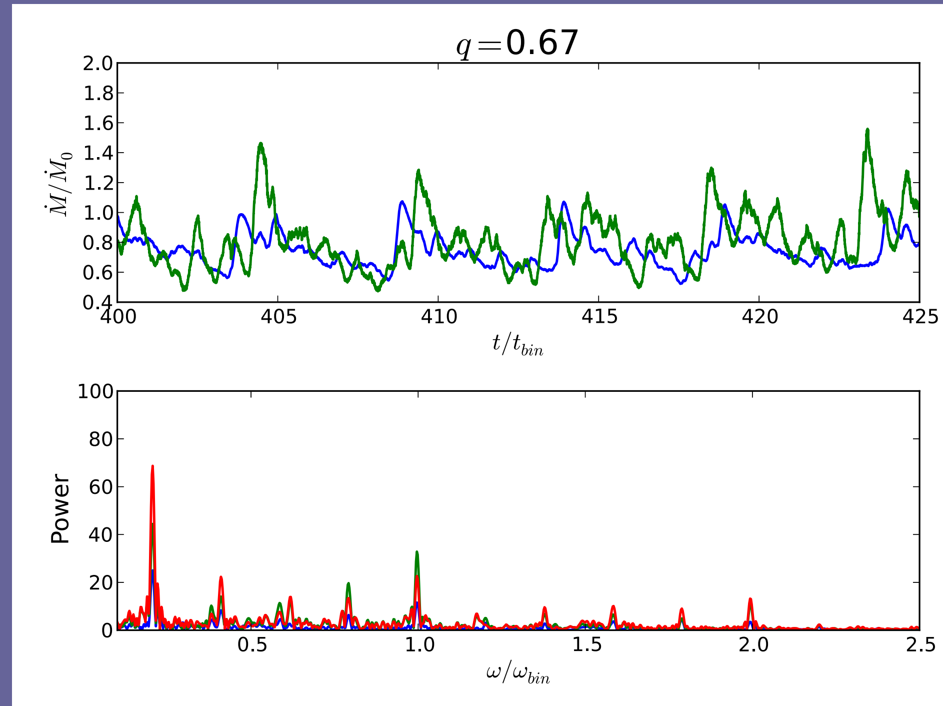
- fueled by streamers -- net accretion rate matches that of single BH
- strong shocks, periodically appear and disappear

Binary Signature I: Periodicity

0.05 < q < 0.3



0.3 < q < 1



Order unity variability, sinusoid on **orbital timescale**

secondary dominates

Order unity variability, sawtooth on **orbital time at cavity wall**

two BHs **out of phase** (cf OJ287)

Accretion rate not suppressed – similar to bright quasar

Binary Signature I: Periodicity

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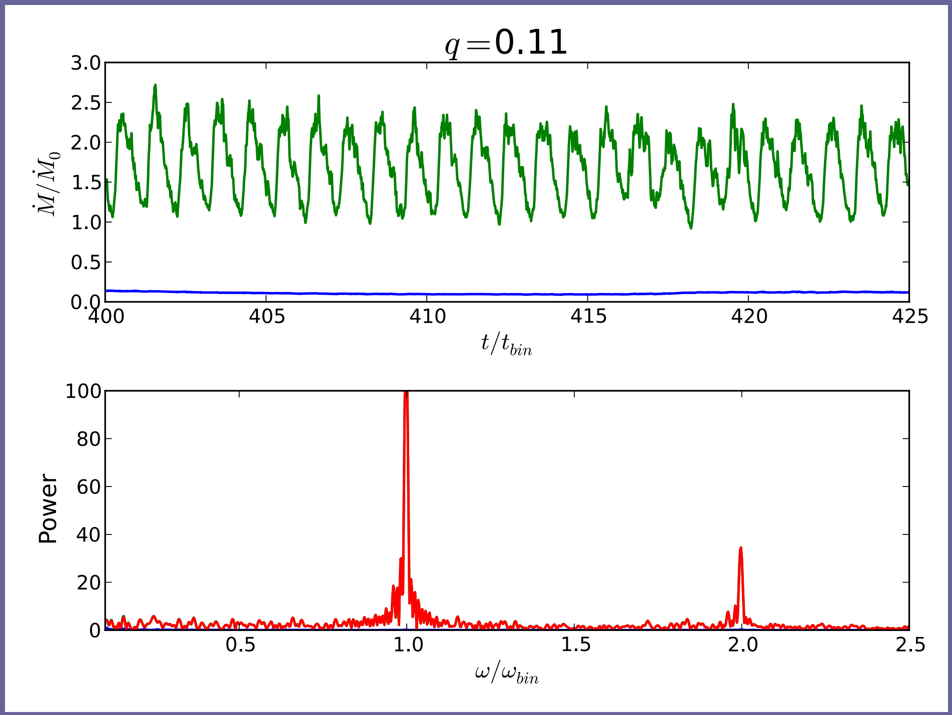
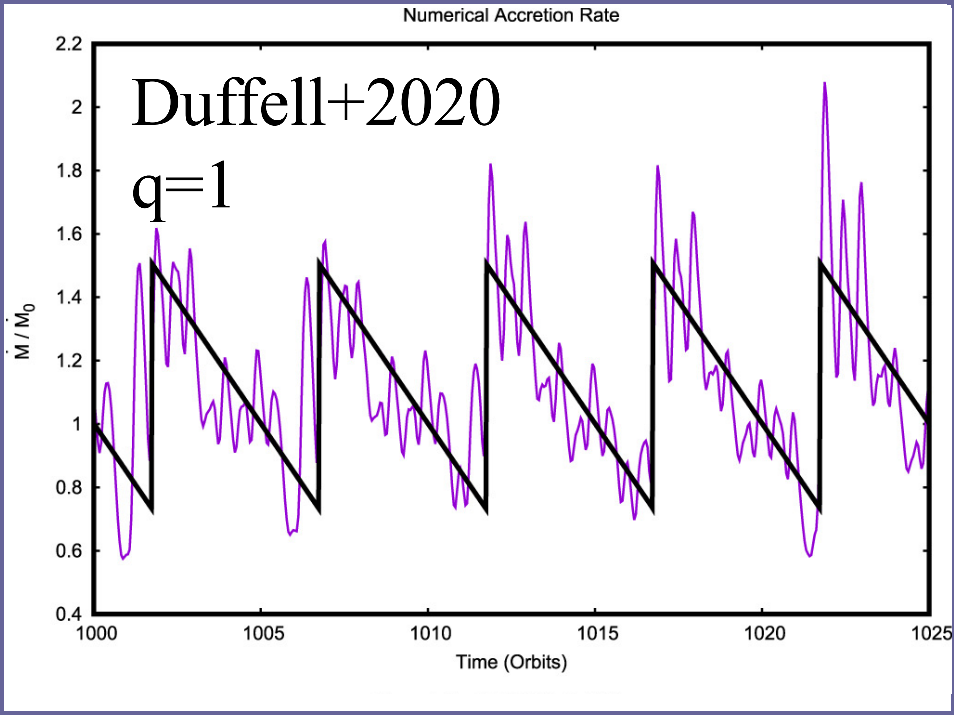


0.3 < q < 1



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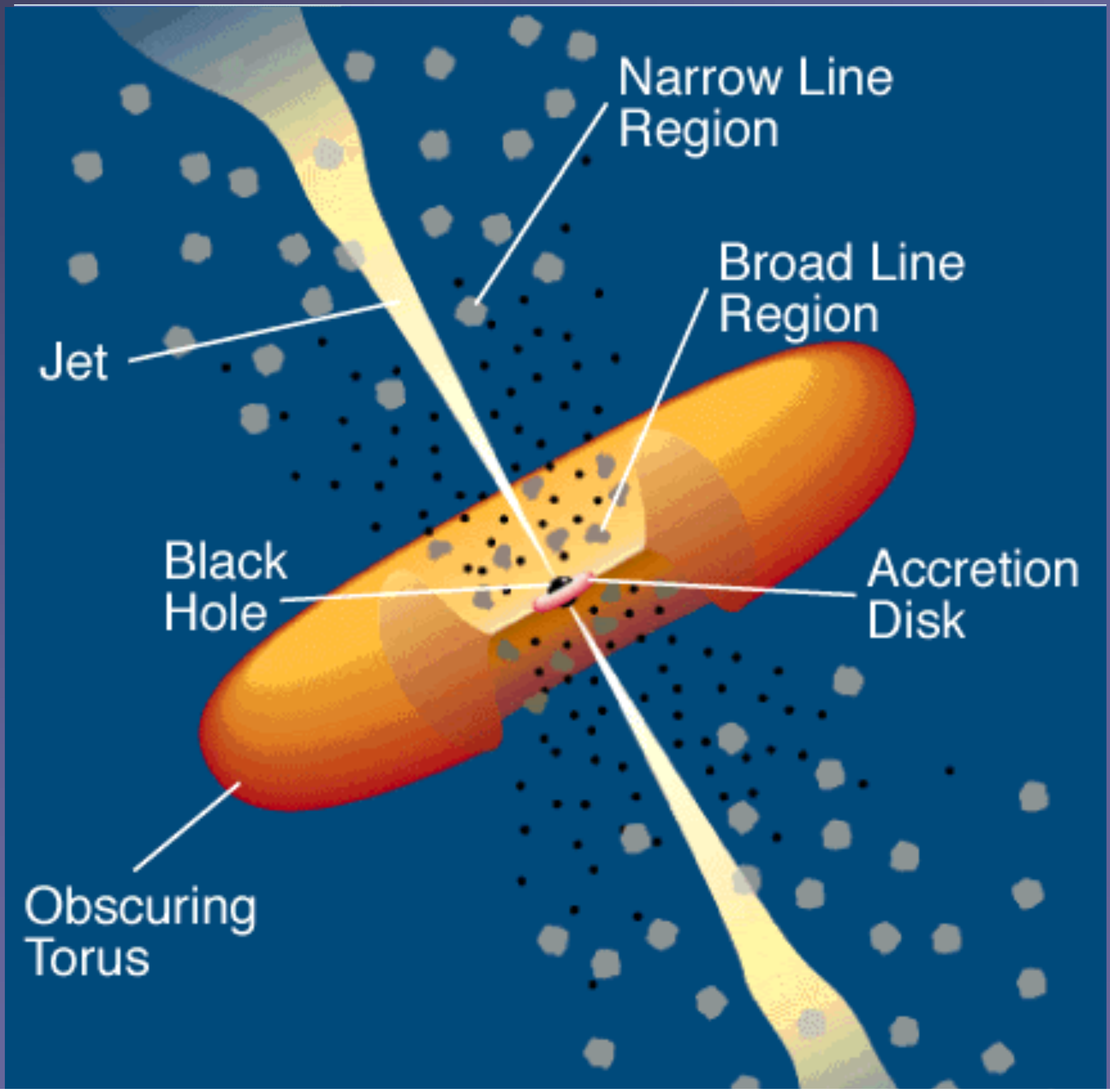
Unified model of AGN

Antonucci (1993)

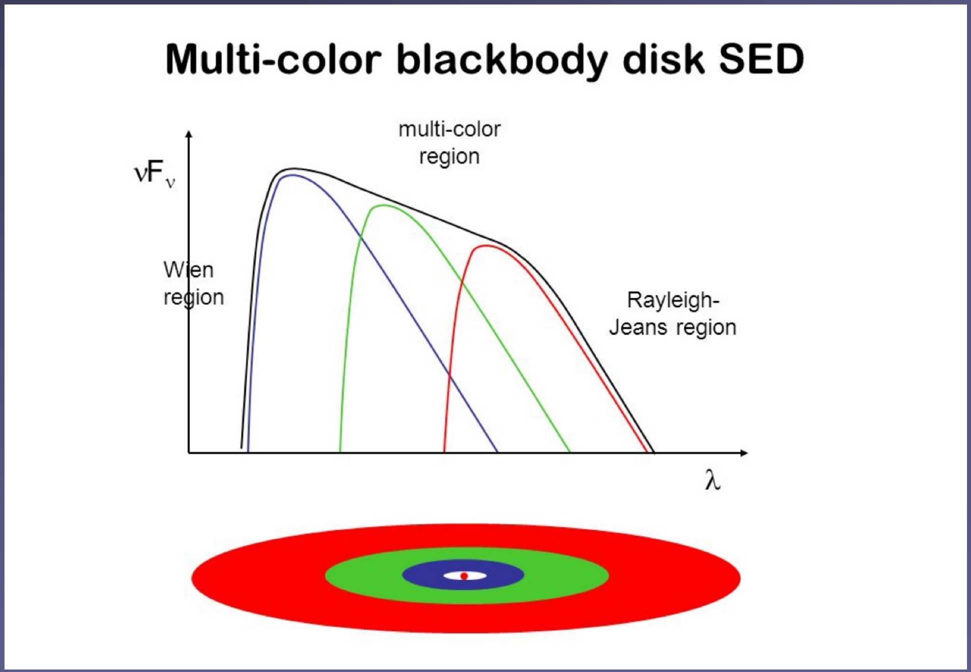
Continuum
thermal
+
nonthermal

+

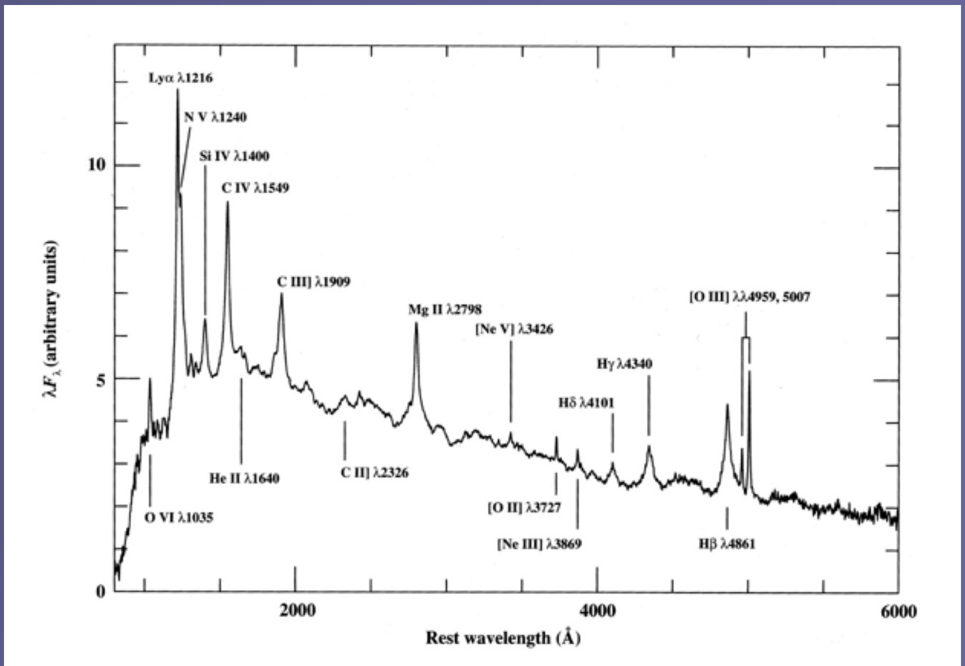
Emission lines
broad
+
narrow



Quasar spectra – optical/UV



credit: A. Dullemond



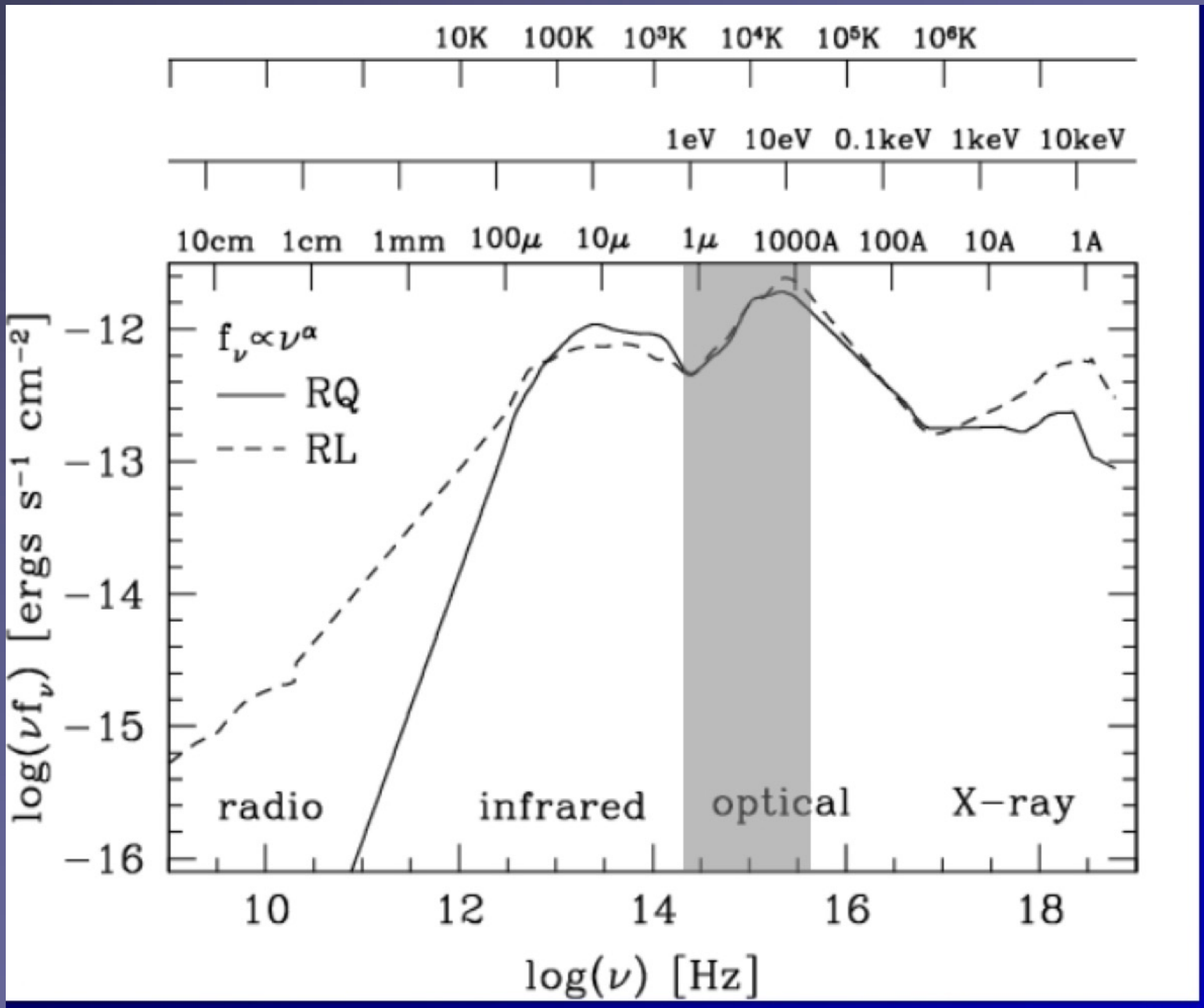
credit: SDSS

$$GM\dot{M}/r \sim \sigma T^4 \pi r^2$$

$$\rightarrow T \sim r^{-3/4}$$

$$\int_{r_{inner}}^{r_{outer}} 2\pi r B_\nu T(r) dr \propto \nu^{1/3}$$

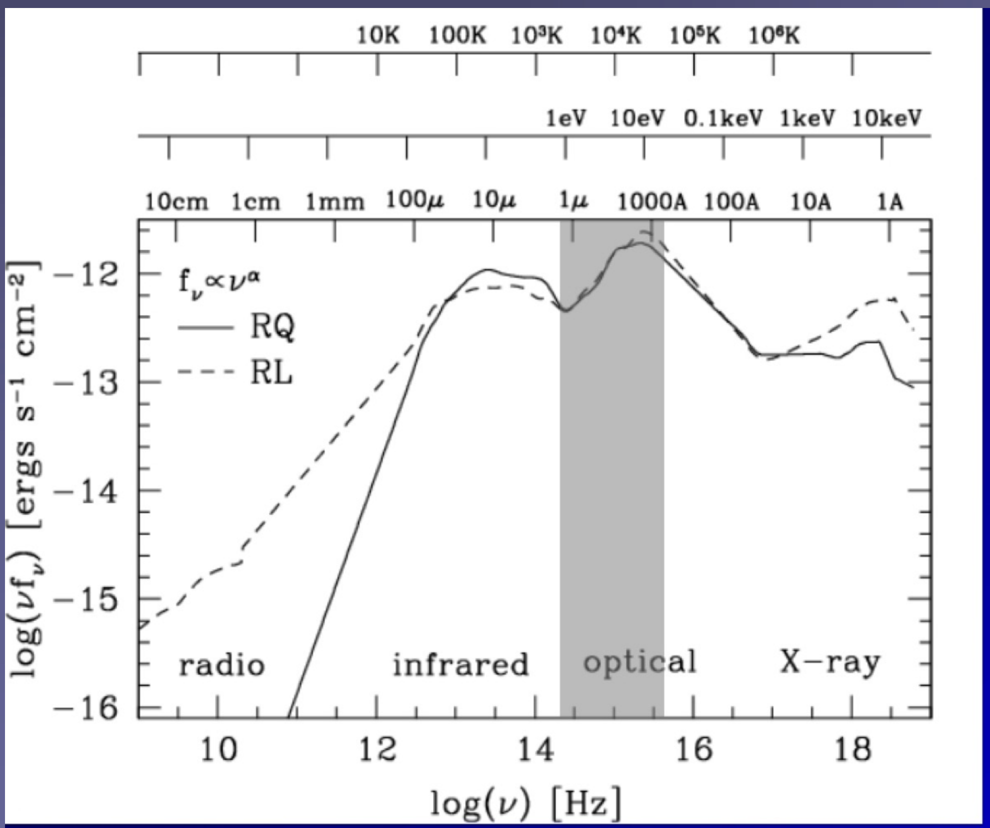
Quasar spectra – global view

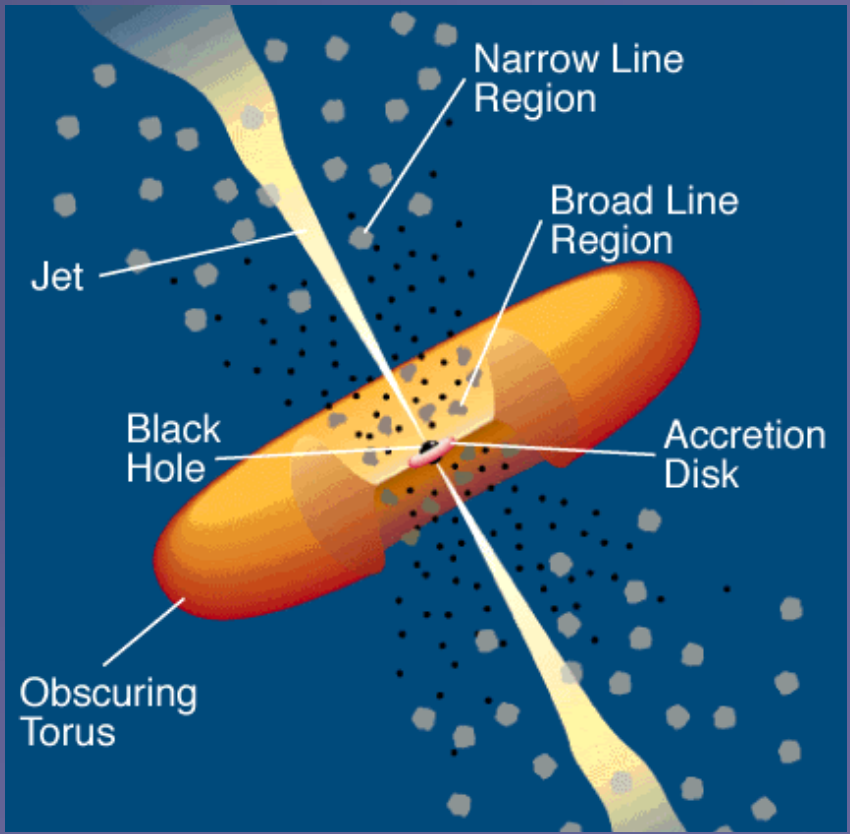


credit: Z. Ivezic, from Elvis et al. (1994)

Quasar spectra – global view

Each part of continuum from different region/process





credit: Z. Ivezic, from Elvis et al. (1994)

Periodic Quasars = Binary Candidates

systematic searches in large time-domain surveys

- Catalina Real-Time Transient Survey (CRTS)
  Graham et al. (2015)
  111 candidates with periods 1-5 years in ~33,000 deg^2
  250,000 quasars to V~20, 9-year uniformly sampled baseline

- Palomar Transient Factory (PTF) in ~27,000 deg^2
  Charisi et al. (2016)
  33 candidates with periods 60-400 days
  36,000 quasars R~22, up to 5 years non-uniform sampling

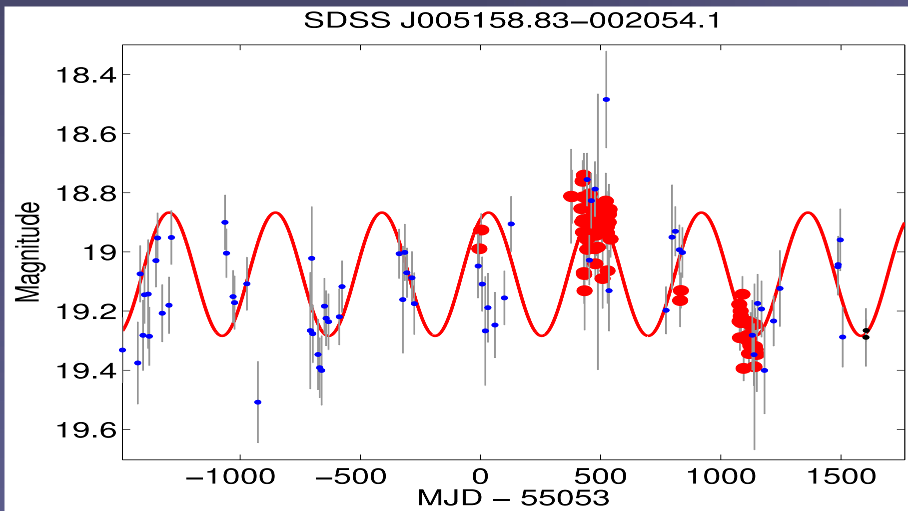
- Zwicky Transient Factory (PTF)
  Chen et al. (2022)
  127 candidates with periods 500-950 days
  143,000 quasars r~20, 5 years non-uniform sampling

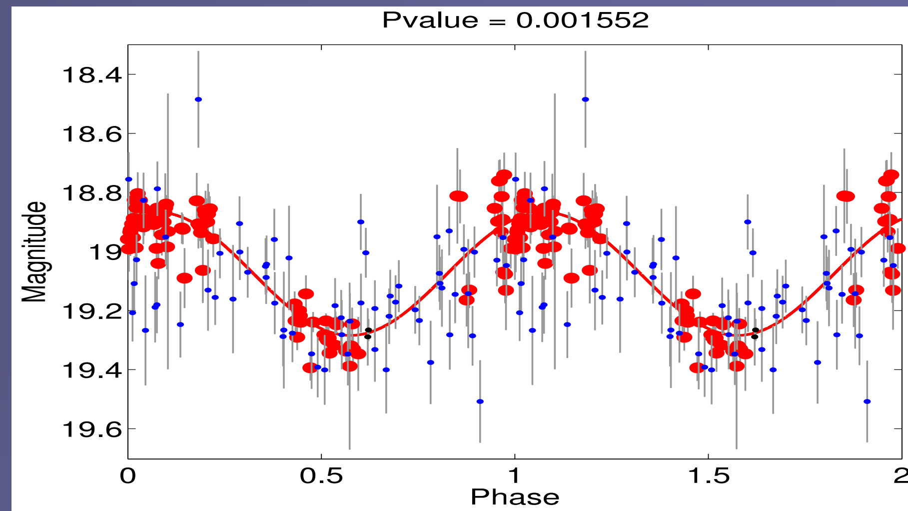
Recent Periodic Candidates- Examples

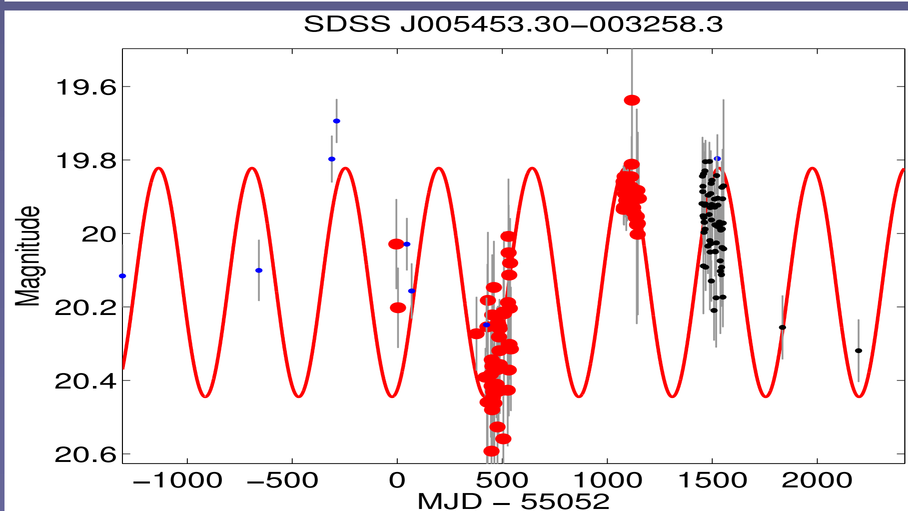
Charisi et al. (2016)

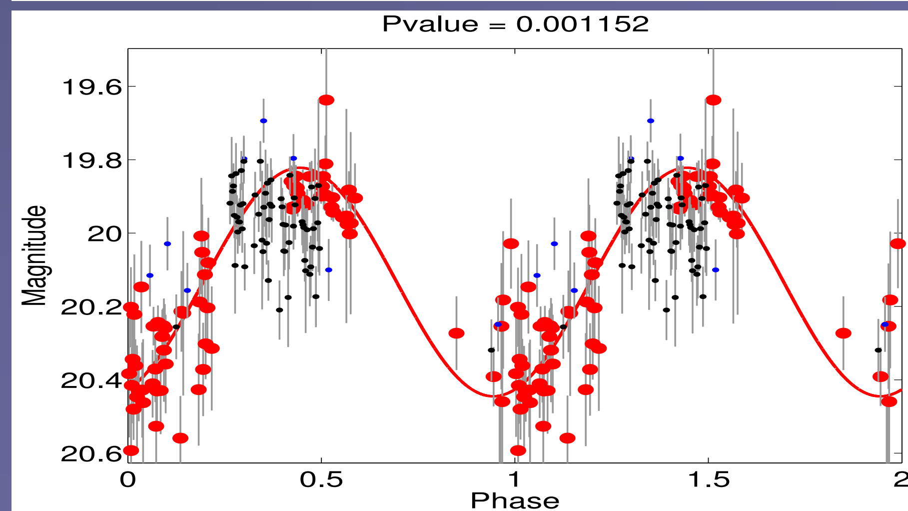
Lightcurves (PTF, CRTS, iPTF)

Phased lightcurves









SDSS J023050.06+005843.1

Pvalue = 0.01508

Stochastic quasar variability

Damped random walk **Vaughan et al. (2016)**

Correlation function:

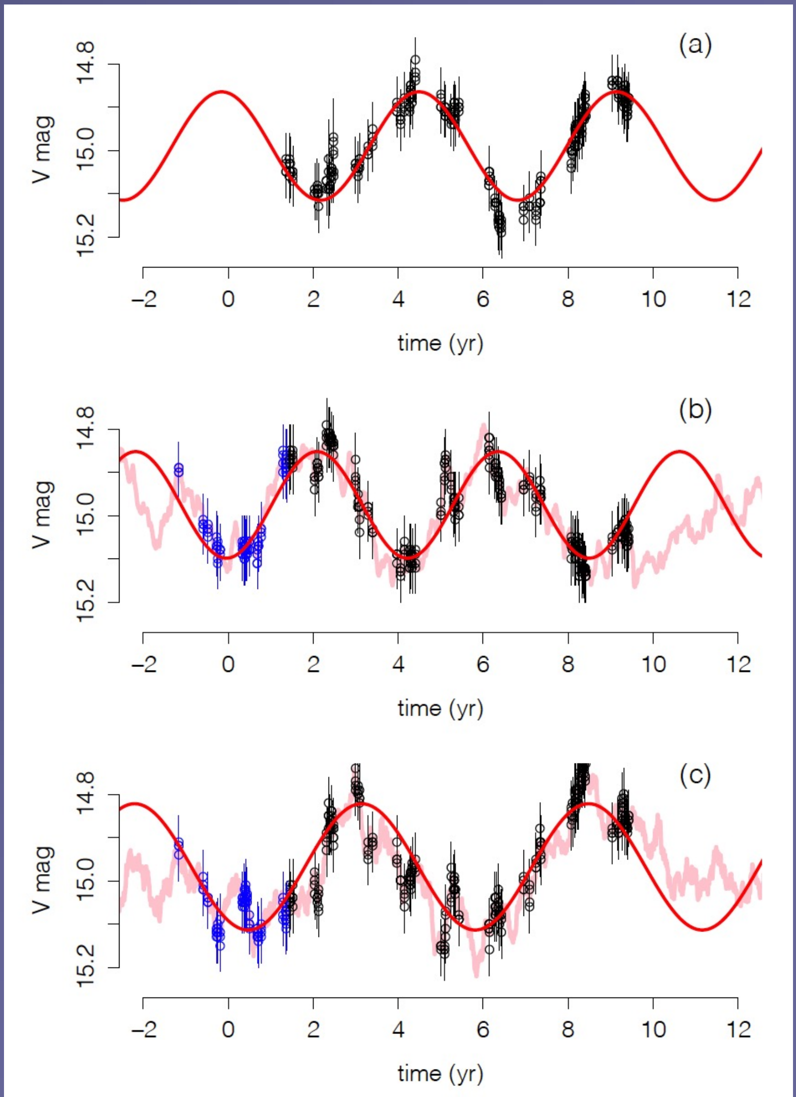
$S_{ij} =< \Delta F(t_i)F(t_j)>$

$$S_{ij} = \sigma^2 \exp(-|t_i - t_j|/\tau)$$

Power spectrum:

$P(f) =< \widetilde{\Delta F}(f)^2>$

$$P(f) = \frac{2\hat{\sigma}^2\tau^2}{1 + (2\pi\tau f)^2}$$



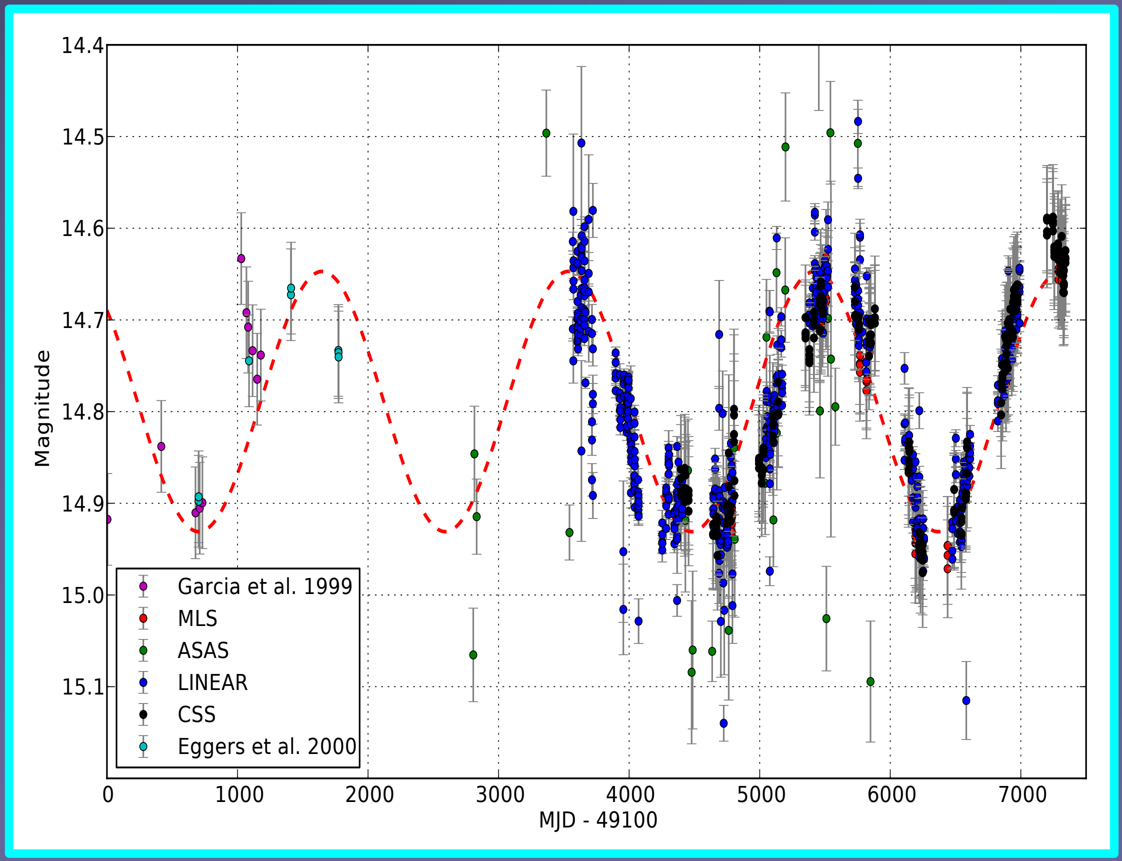
How can you tell it’s really a binary?

PG1302-102: a case study

Graham et al. 2015, D'Orazio, ZH, Schiminovich 2015

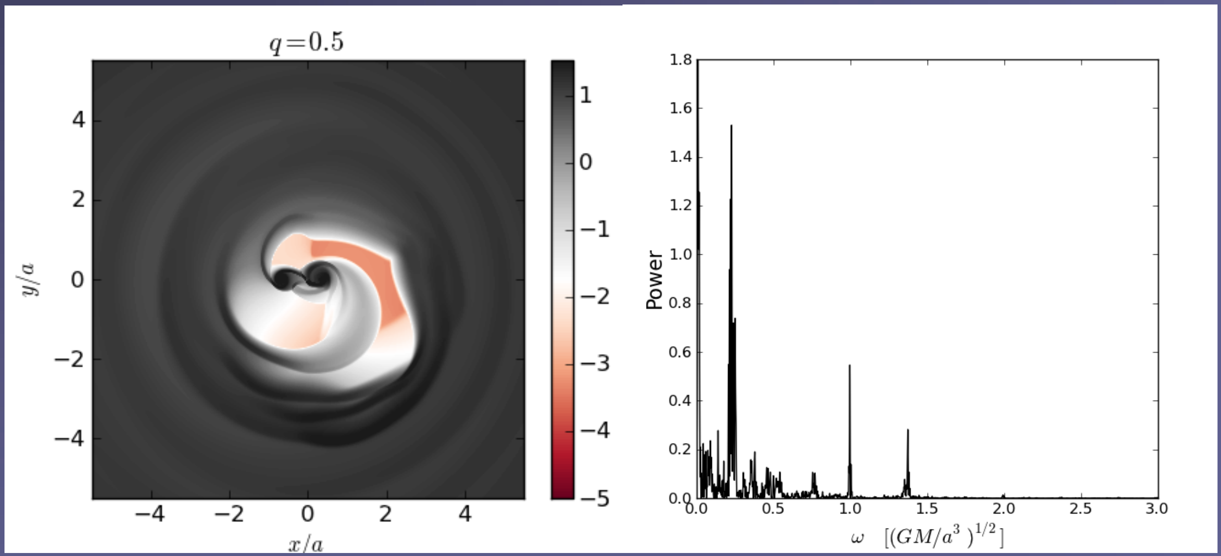
Bright z=0.3 quasar $M_{bh}=10^{8.3}$-$10^{9.4}$ $M_\odot$ a=0.01 pc (280 R_S)

±14% variability with 5.16 ± 0.2 yr period (in 250,000 quasars)



Periodogram - what is the true binary period?

D'Orazio et al. 2016

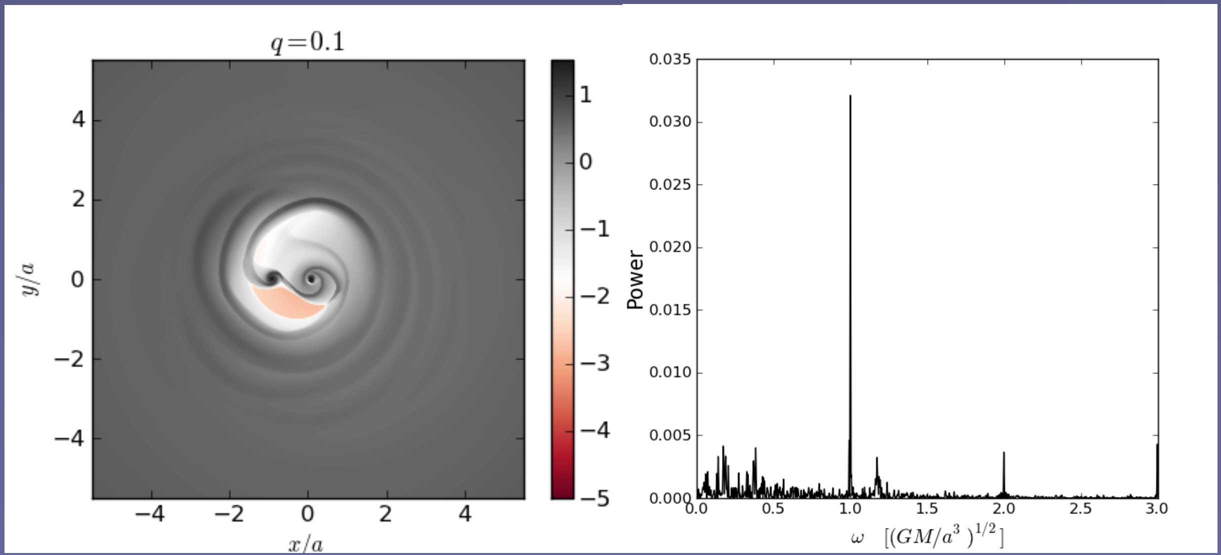


0.7 years ?

(q > 0.3)

More generally:

3 < t_{opt}/t_{bin} < 8
dep. on q, disk



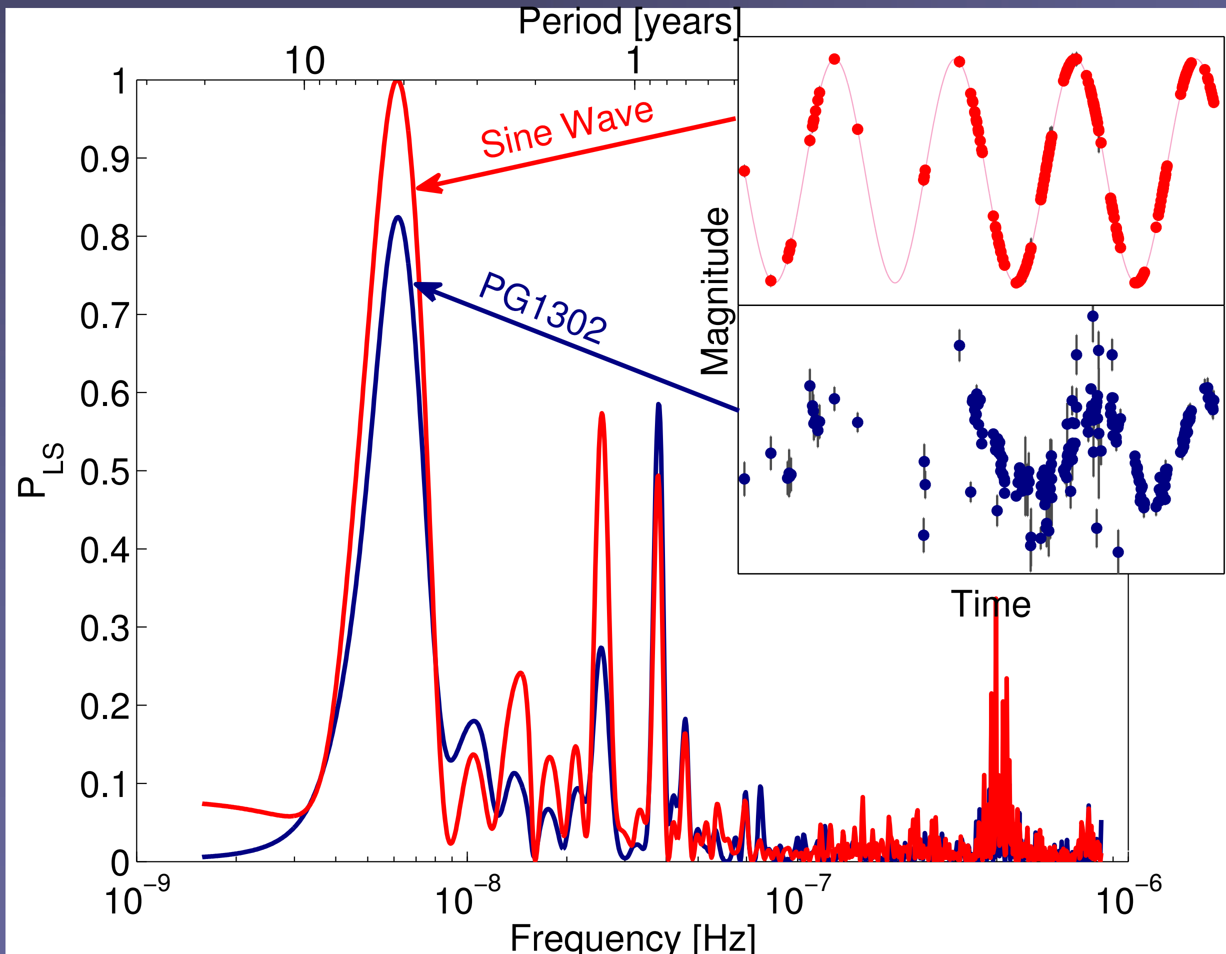
4 years ?

(0.05 < q < 0.3)

Are there secondary periods in the data?

[so far, a cautionary tale]

Charisi et al. 2016

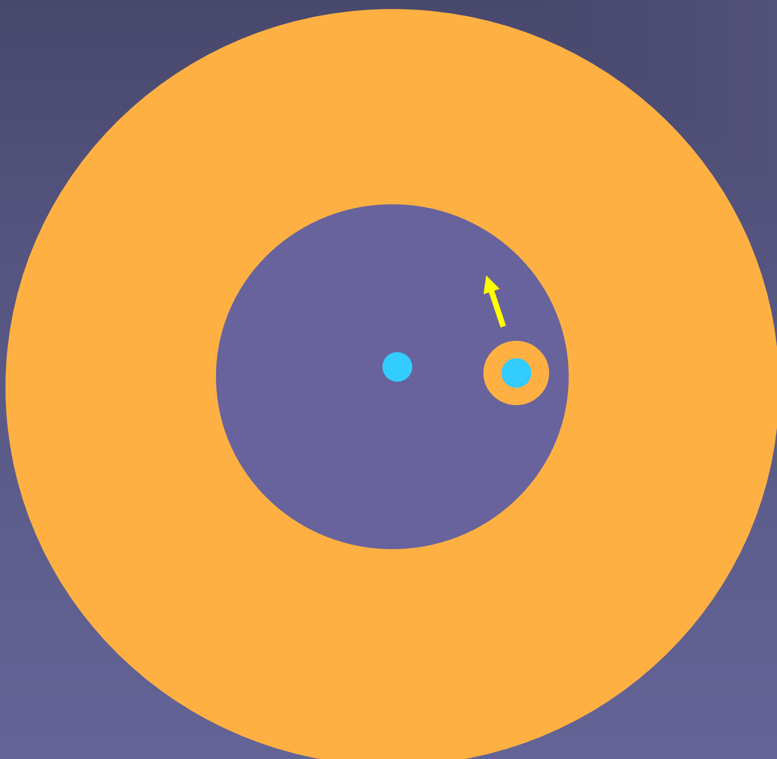


Peaks at ~300 and ~500 days

caused by aliasing

no significant secondary peaks with amplitude within factor of ~2 of main 5.2-yr peak

Is the sinusoidal modulation caused entirely by relativistic Doppler boost?



$$v_2 = \left(\frac{2\pi}{1+q}\right)\left(\frac{GM_{\rm tot}}{4\pi^2 P}\right)^{1/3} =$$

$$8,500\left(\frac{1.5}{1+q}\right)\left(\frac{M_{\rm tot}}{10^{8.5}\,{\rm M}_\odot}\right)^{1/3}\left(\frac{P}{4.04\ {\rm yr}}\right)^{-1/3}\ {\rm km\ s^{-1}},$$

$F_\nu^{obs} = D^{3-\alpha} F_\nu^{0}$

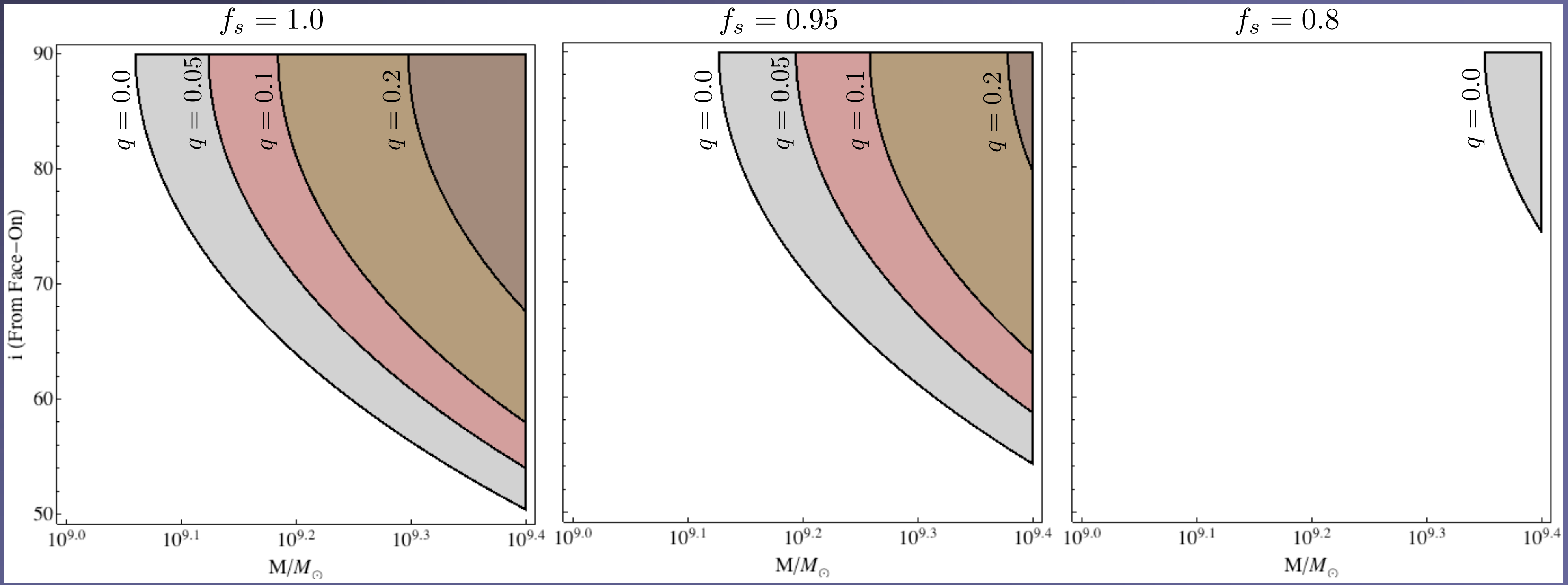
$D = \Gamma(1-\beta\cos\theta)^{-1}$ $\alpha = d\ \ln F_\nu / d\ \ln \nu$

$\Delta F_\nu^{obs} / F_\nu^{0} = (3-\alpha)(v/c)\cos\theta \sin i$

Need: $v \sin i = 22{,}000$ km s^{-1}

or $(v/c) \sin i = 0.074$

Relativistic boost



Observed ±14% modulation expected if:

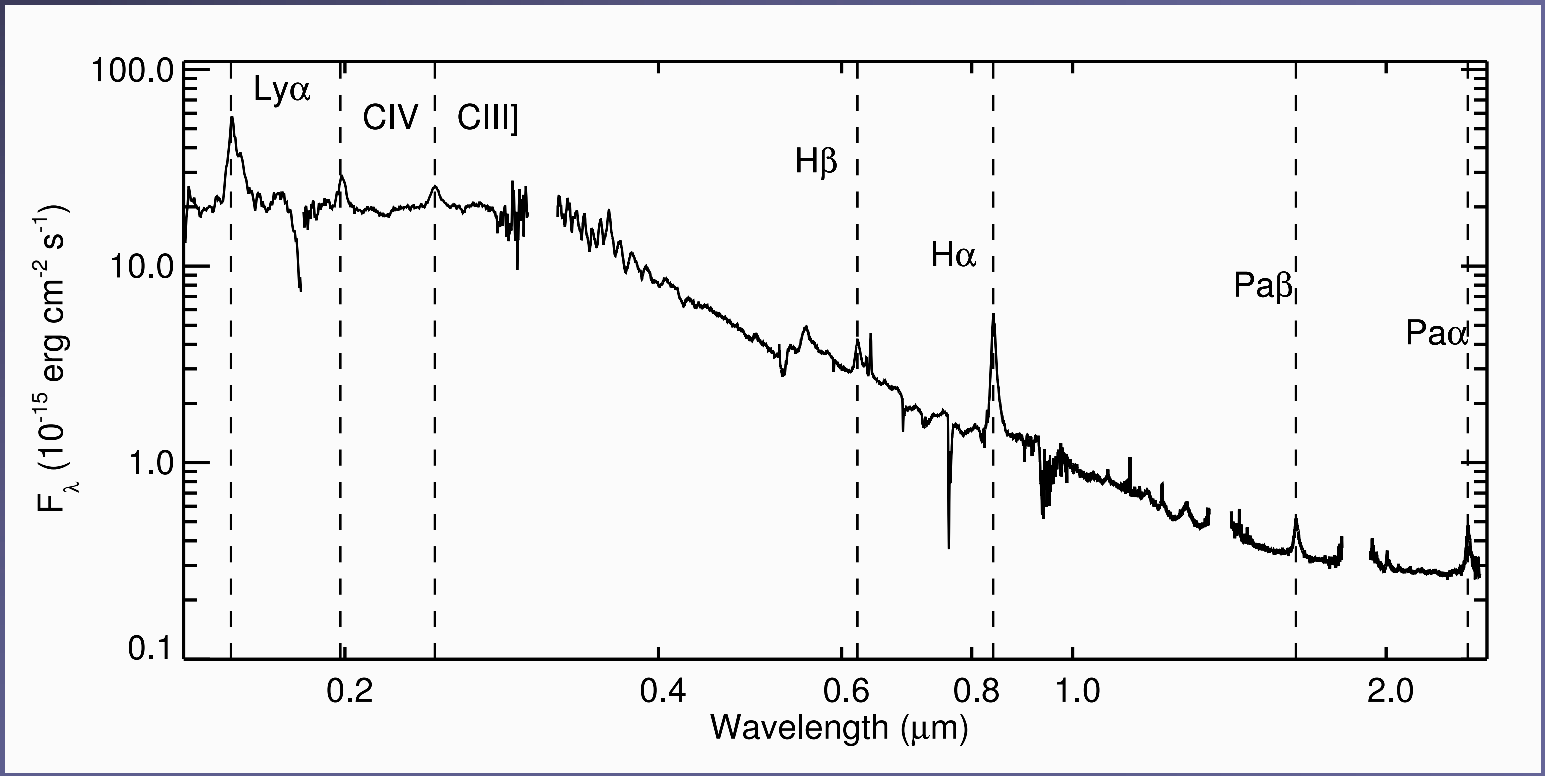
Total mass large ($M_{tot} > 2 \times 10^9 M_\odot$)

Mass ratio low ($q < 0.2$)

Luminosity mostly from secondary (>90% → $0.03<q< 0.1$)

Not too far from edge-on (±30°)

How can we verify / falsify this ?



$$\Delta F_\nu^{obs} / F_\nu^{0} = (3-\alpha)(v/c)\cos\theta \sin i$$

Optical (V-band): $\alpha \approx 1.1$ → $3-\alpha \approx 1.9$

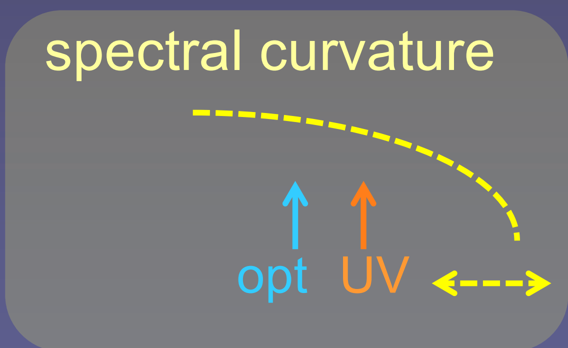
UV (~0.2 μm): $\alpha \approx -2$ → $3-\alpha \approx 5$

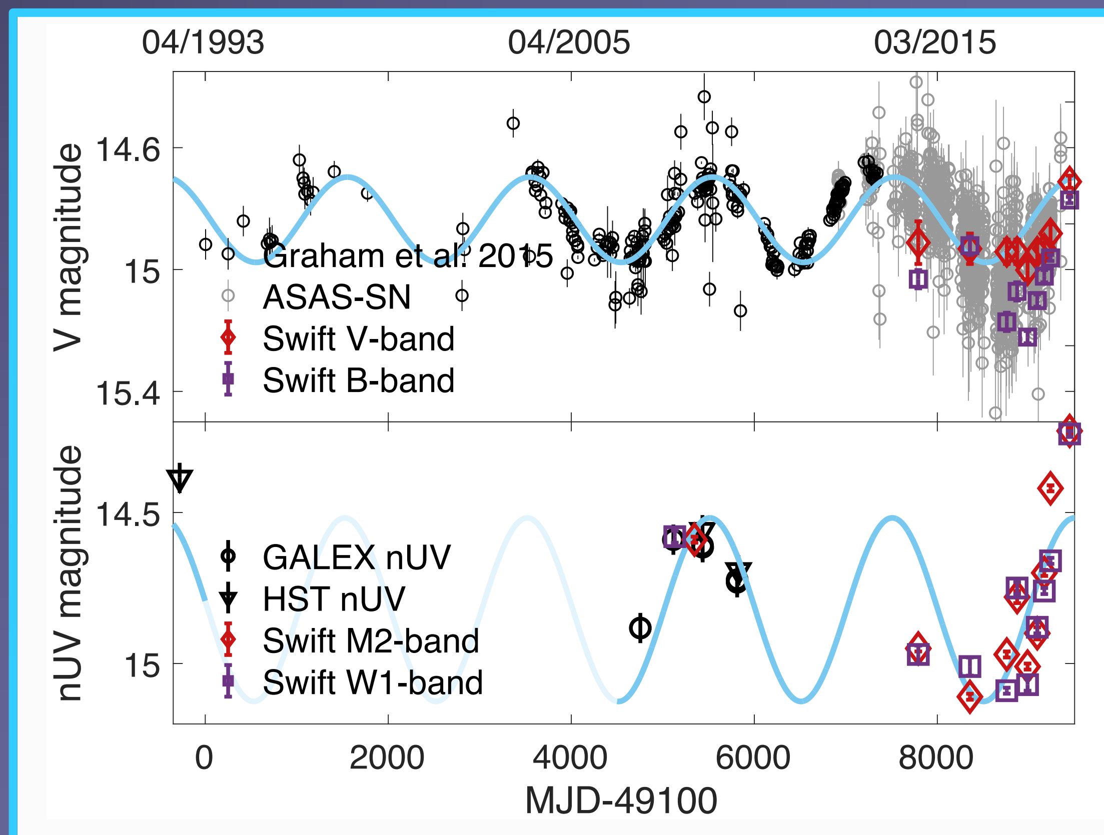
→ $\Delta F/F_{(UV)} \approx 2.6 \times \Delta F/F_{(opt)}$

Doppler-modulation is chromatic

PG1302-102 D'Orazio, ZH, Schiminovich (Nature, 2015)

Incl. follow-up Swift data (Xin, Charisi, ZH et al. 2020)





optical

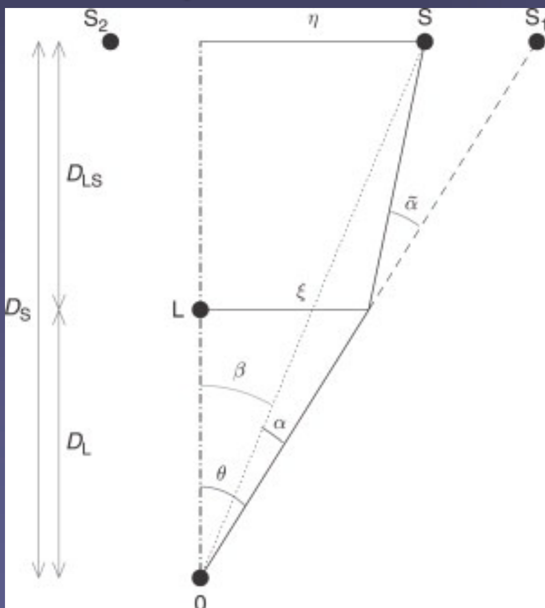
nUV

Optical variability vs. **UV** variability consistent with spectral curvature [α_{opt} vs α_{uv}] and Doppler boost

Gravitational Lensing

Bending of light in general relativity
--- for a point mass, in the limit of small deflection ---

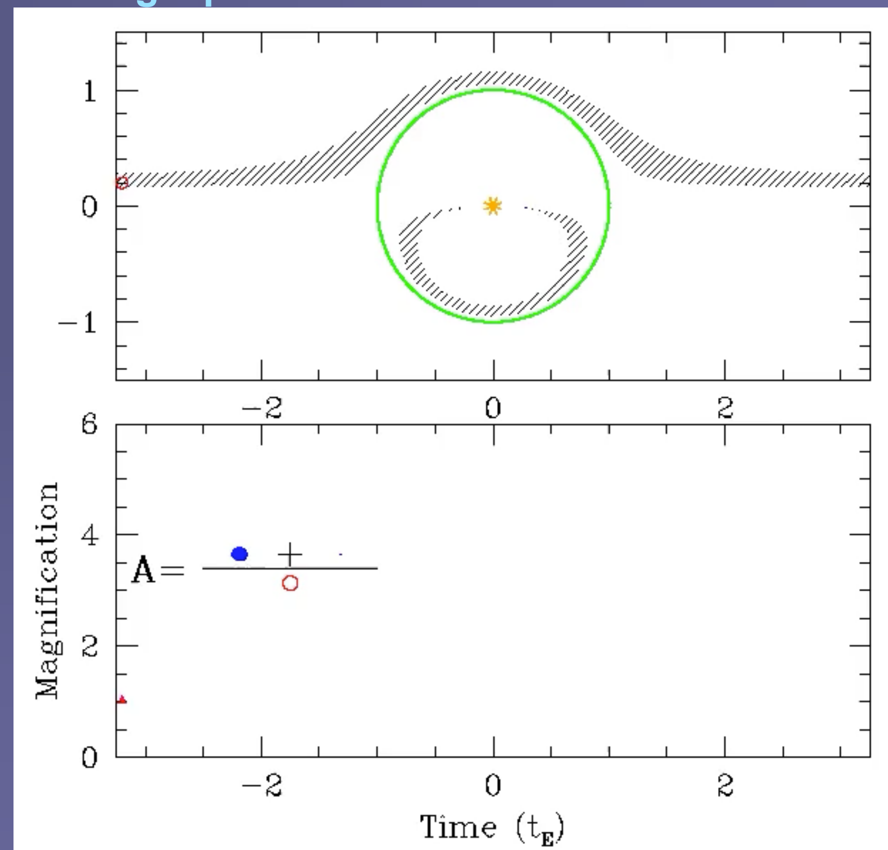
Geometry:



Deflection angle:

$$\tilde{\alpha}(\xi) = \frac{4GM(\xi)}{c^2}\frac{1}{\xi}$$

- flat background
- small deflection
- single point mass



Lens equation:
β= θ-α(θ)

$$\boldsymbol{\beta} = \boldsymbol{\theta} - \theta_E^2 \frac{\boldsymbol{\theta}}{|\boldsymbol{\theta}|^2}$$

Two solutions: $$\theta_{\pm} = \frac{1}{2}\left(\beta \pm \sqrt{\beta^2 + 4\theta_E^2}\right)$$

Magnification: $$\mu = \left|\det\left(\frac{\partial\boldsymbol{\beta}}{\partial\boldsymbol{\theta}}\right)\right|^{-1}$$ =(θ/β) (dθ/dβ)

Einstein radius:

$$\theta_E = \left(\frac{4GM}{c^2}\frac{D_{LS}}{D_L D_S}\right)^{1/2}$$

Magnification ($u=\beta/\theta_E$):

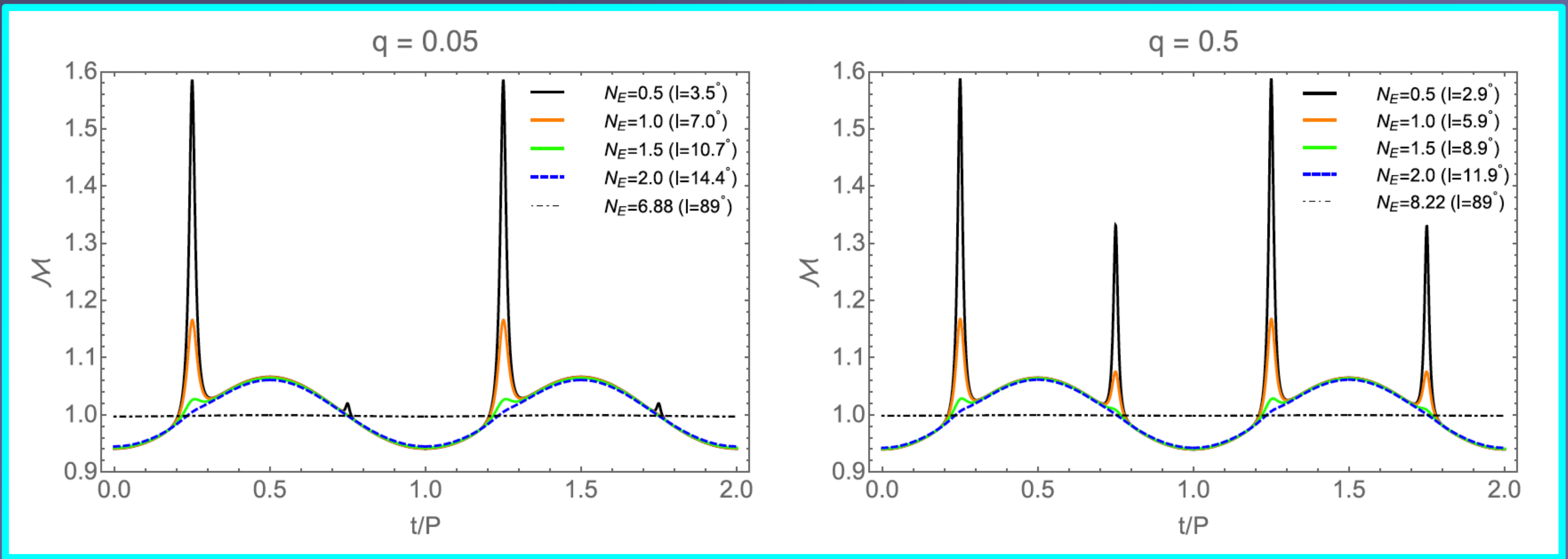
$$\mu = |\mu_+| + |\mu_-| = \frac{u^2+2}{u\sqrt{u^2+4}}$$

credit: Scott Gaudi (OSU)

Recurring Self-Lensing Spikes

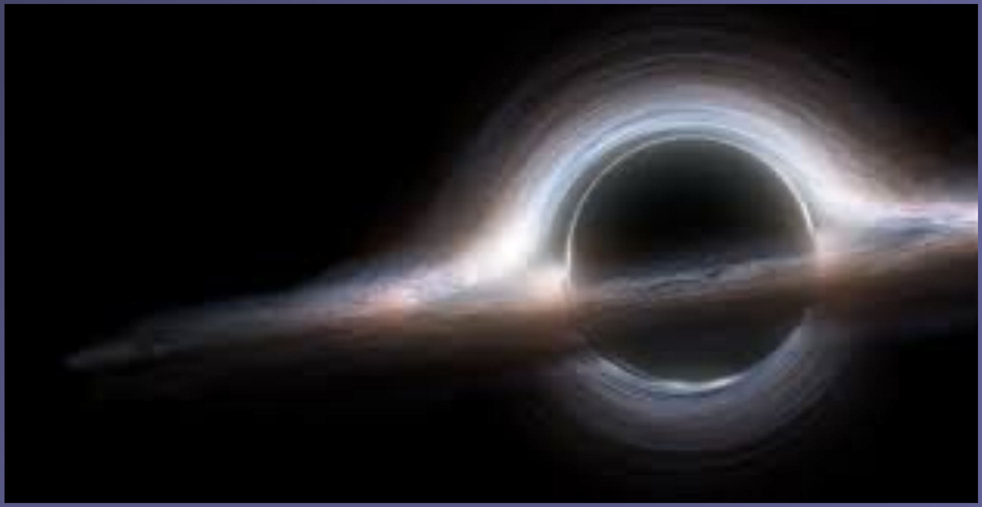
ZH2017, D'Orazio & Di Stefano (2018)

For compact binary, not too far from edge on (few degrees)

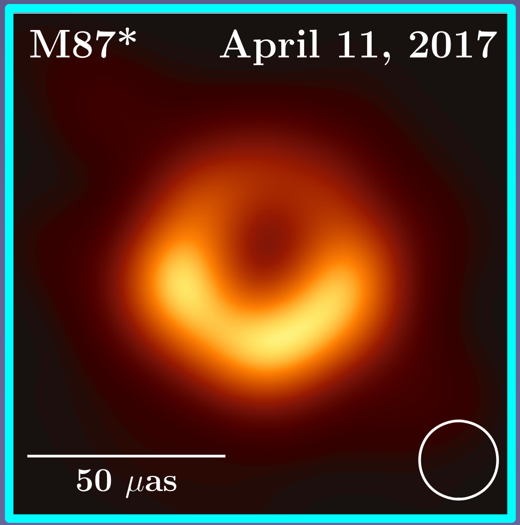


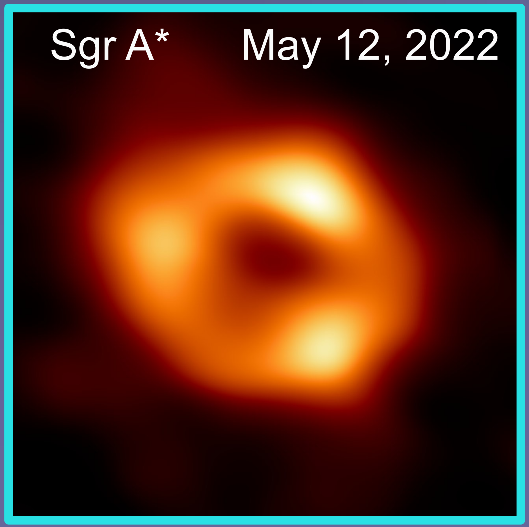
Periodic binary self-lensing

Interstellar (2014)



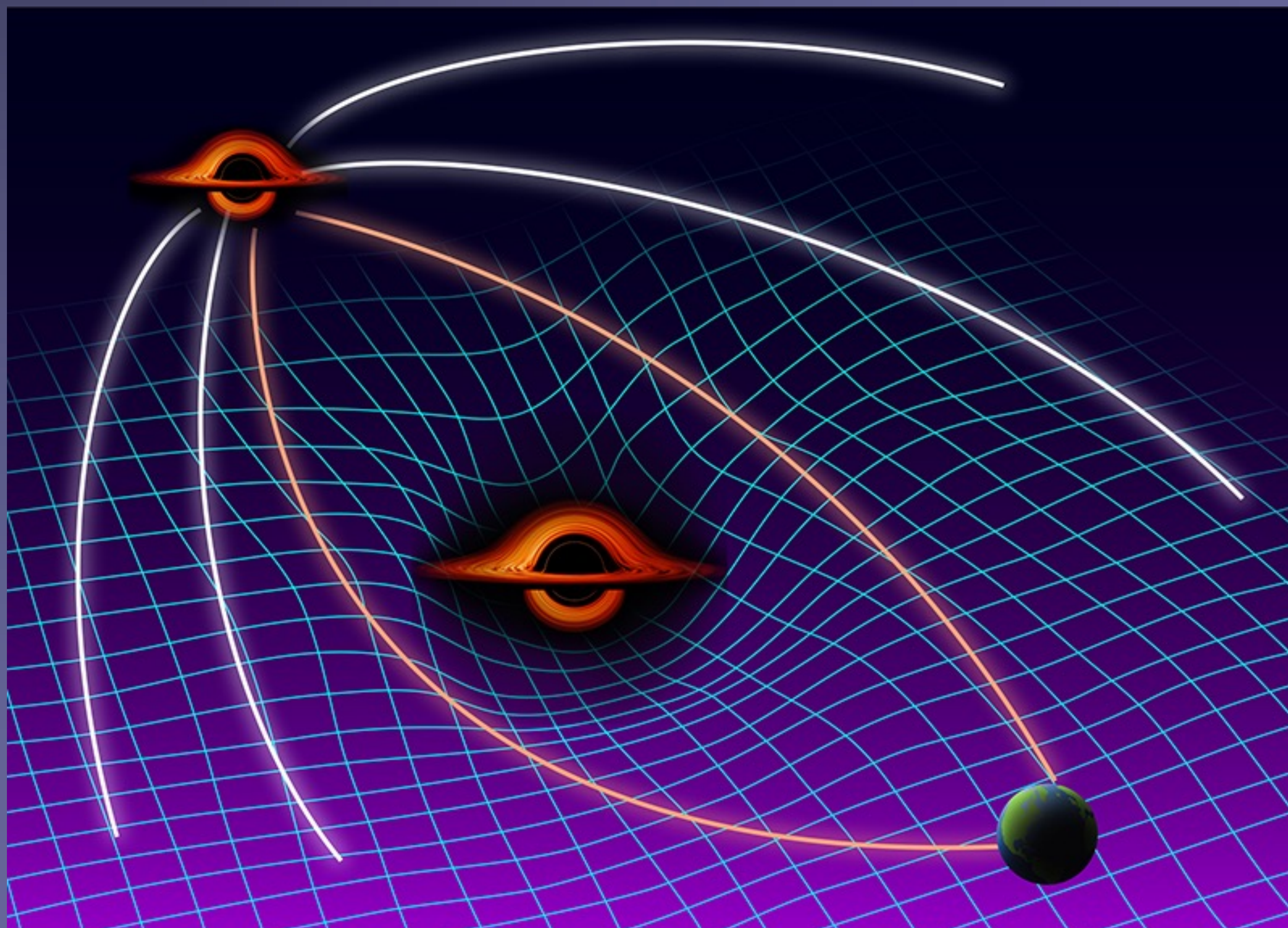
Event Horizon Telescope (EHT) 2017, 2022





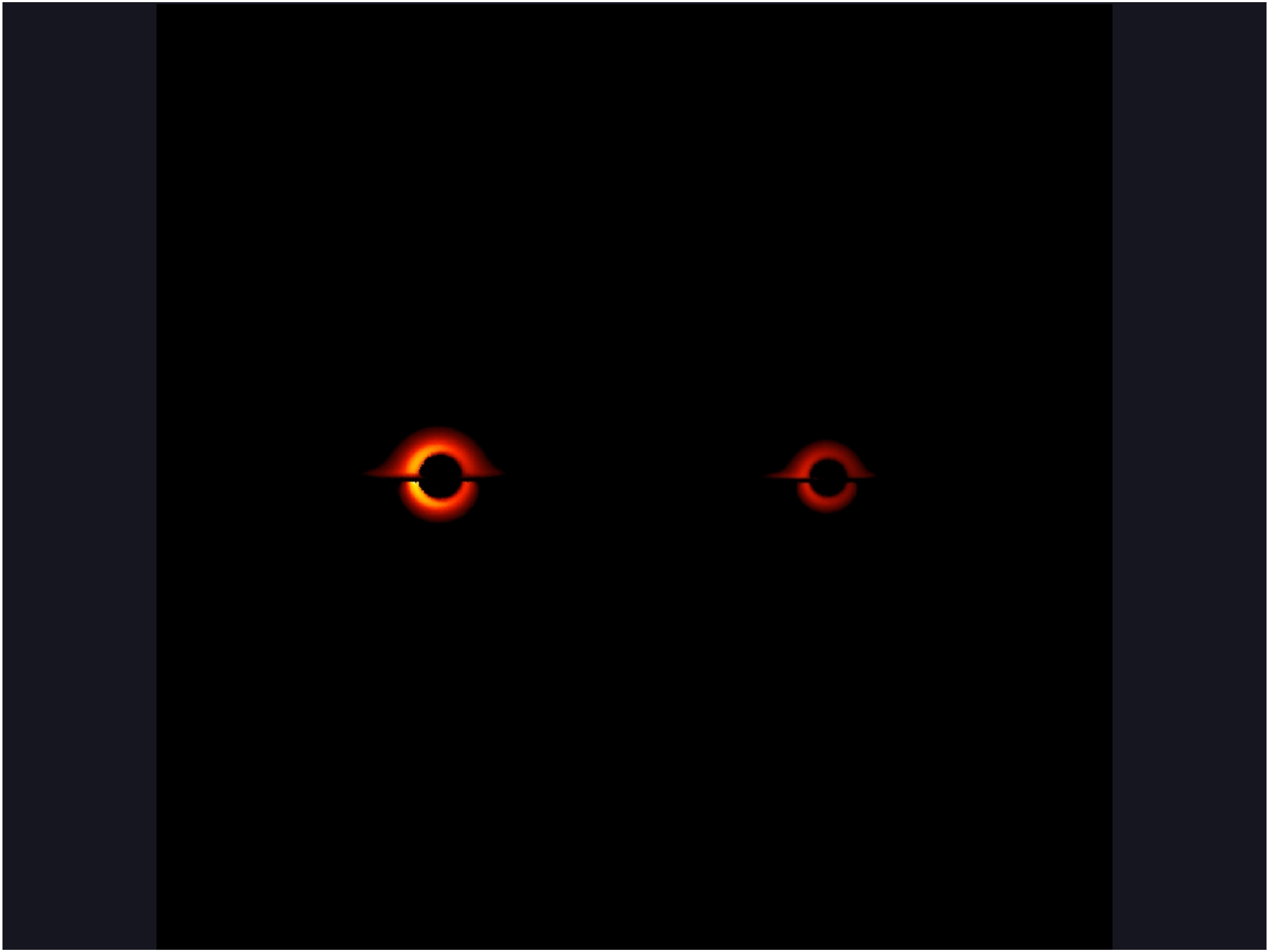
Binary self-lensing

Jordy Davelaar & ZH (2022a,b – PRL, PRD)



Jordy Davelaar

Illustration: APS, Carin Cain

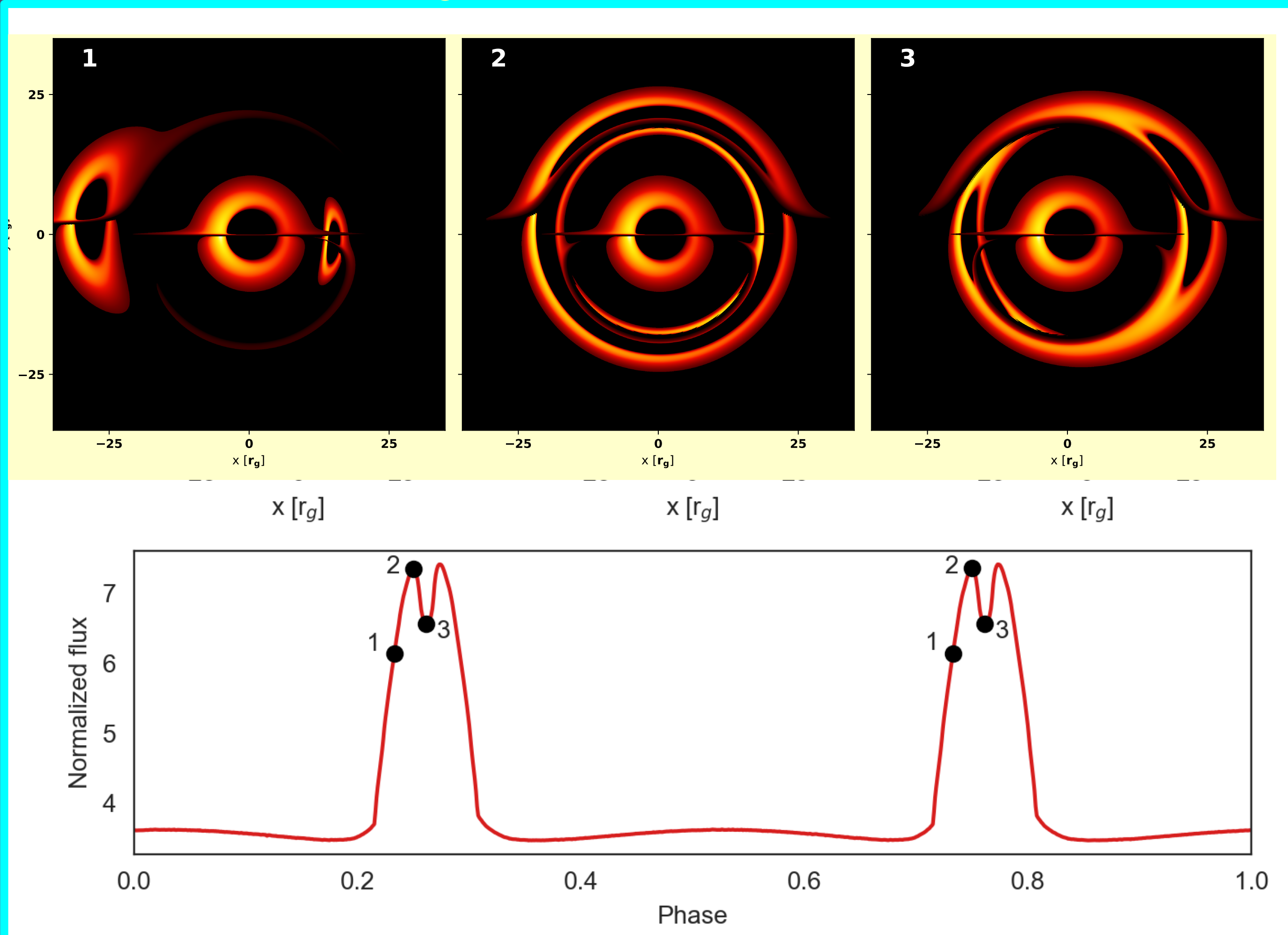


Recurring Self-Lensing Spikes

Davelaar & ZH (2022a,b)

note: $\theta_e/\theta_{bin} = (2a_{bin}/R_s)^{-1/2}$

compact (d=100 R_g) edge-on binary i= 90°



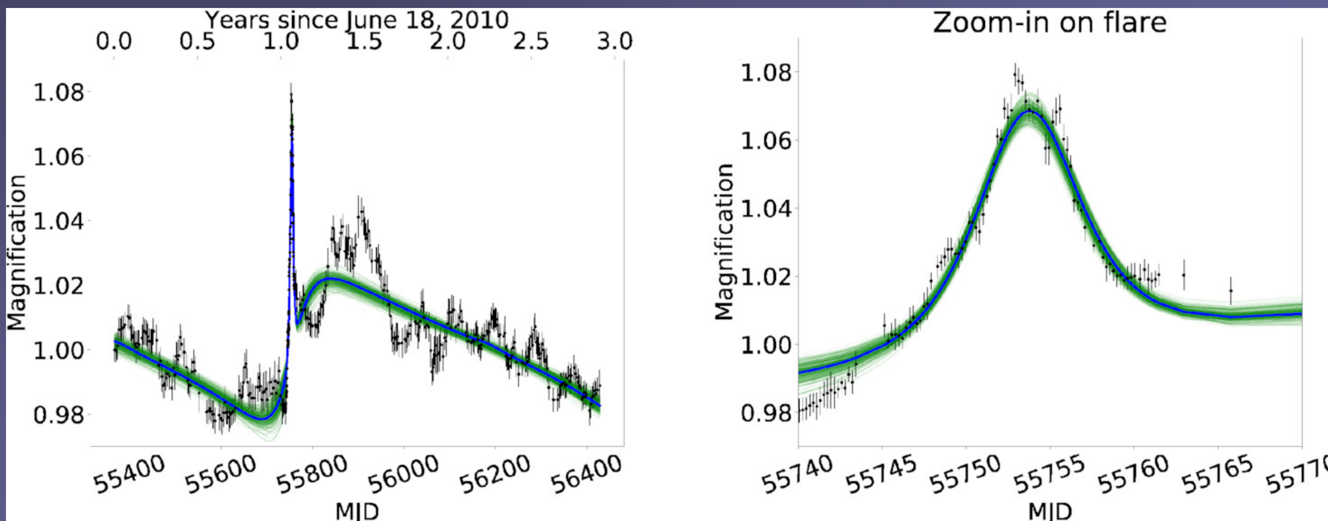
- flares visible within ±3-30° of edge-on
- shadow visible if ±1-10° of edge-on
- week-long flares in periodic quasars
- 10x higher chance for LISA binaries (already compact)

→ 100s detectable by Vera Rubin Observatory (LSST, 2024+)

A self-Lensed binary candidate

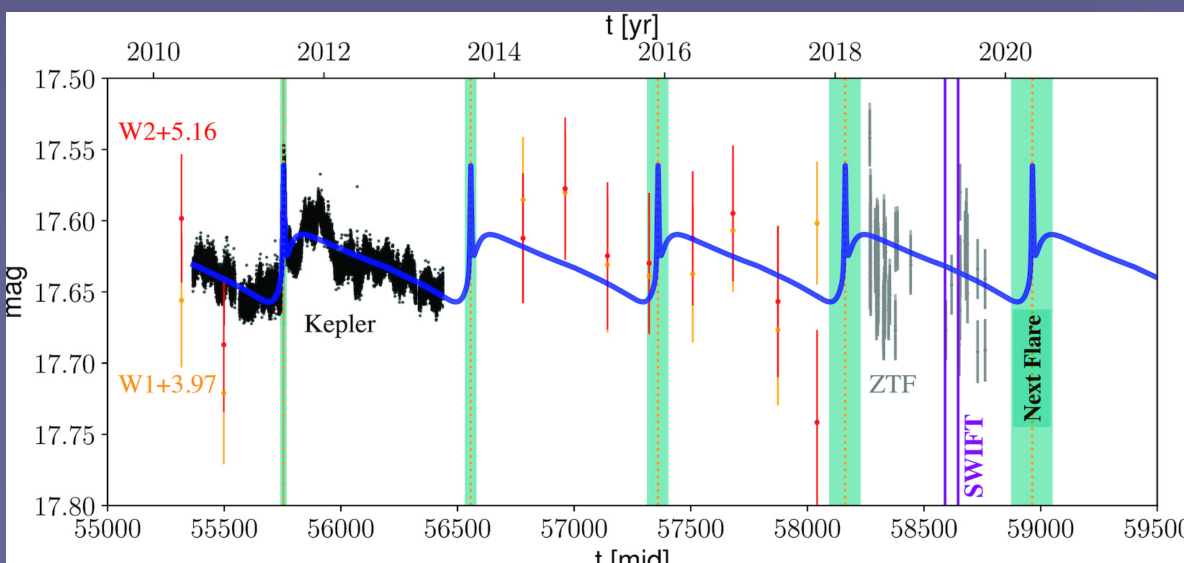
KIC 11606854, a.k.a. "Spikey" Betty Hu, Dan D'Orazio, ZH et al. (2020)

Rare case of a quasar in the Kepler field (z=0.92), with symmetric spike

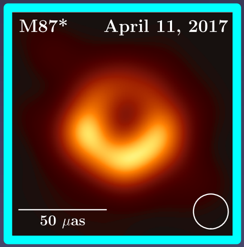


Well fit by eccentric SMBH binary with

$M_{tot}=3\times10^{7}M_{\odot}$,
q = 0.2
T = 418 d,
e = 0.5,
inclination = 8°

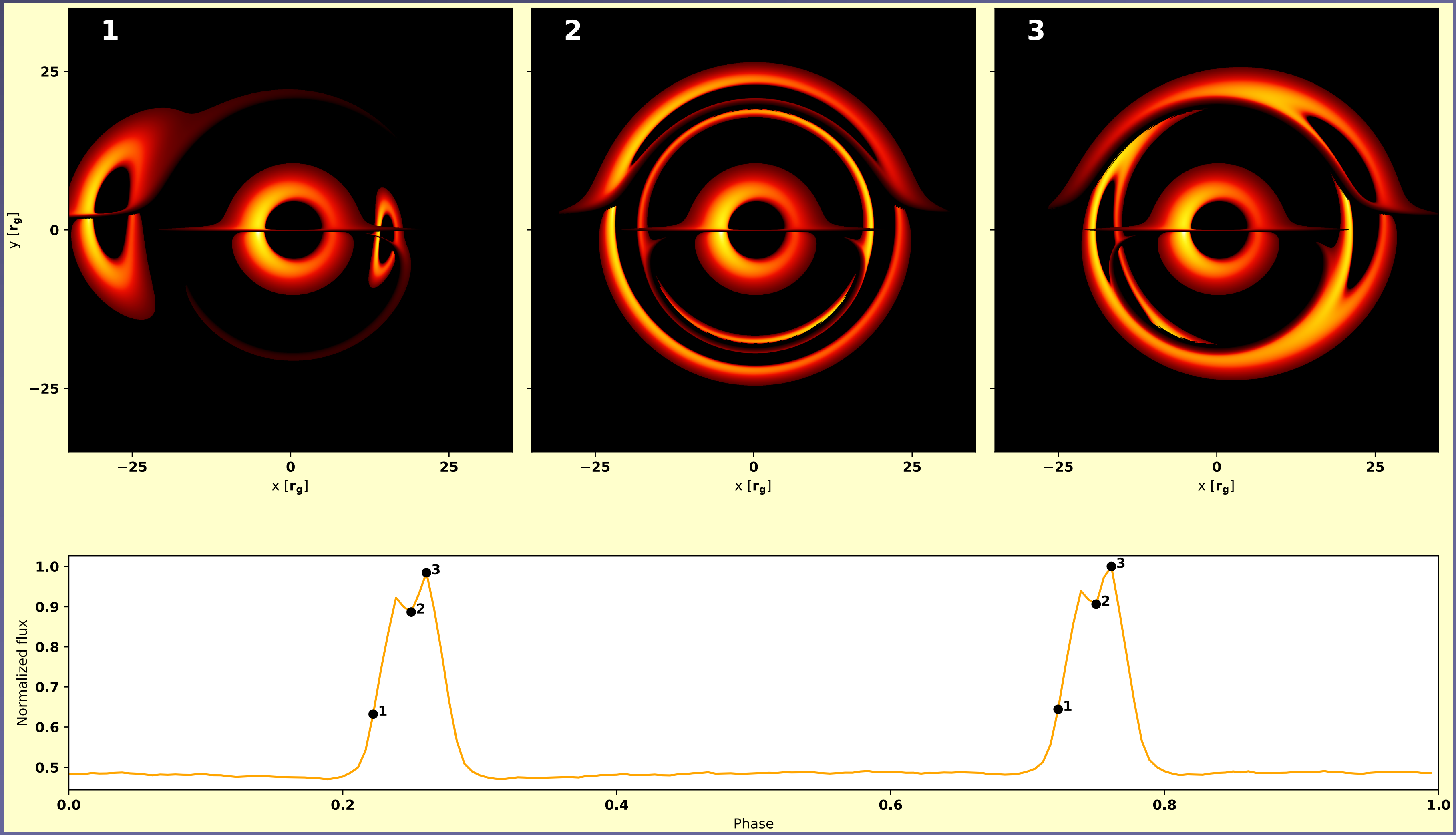


Recurring Self-Lensing Spikes



Davelaar & ZH (in prep)

compact (d=100 R_g) edge-on binary i= 89°



Chengcheng Xin

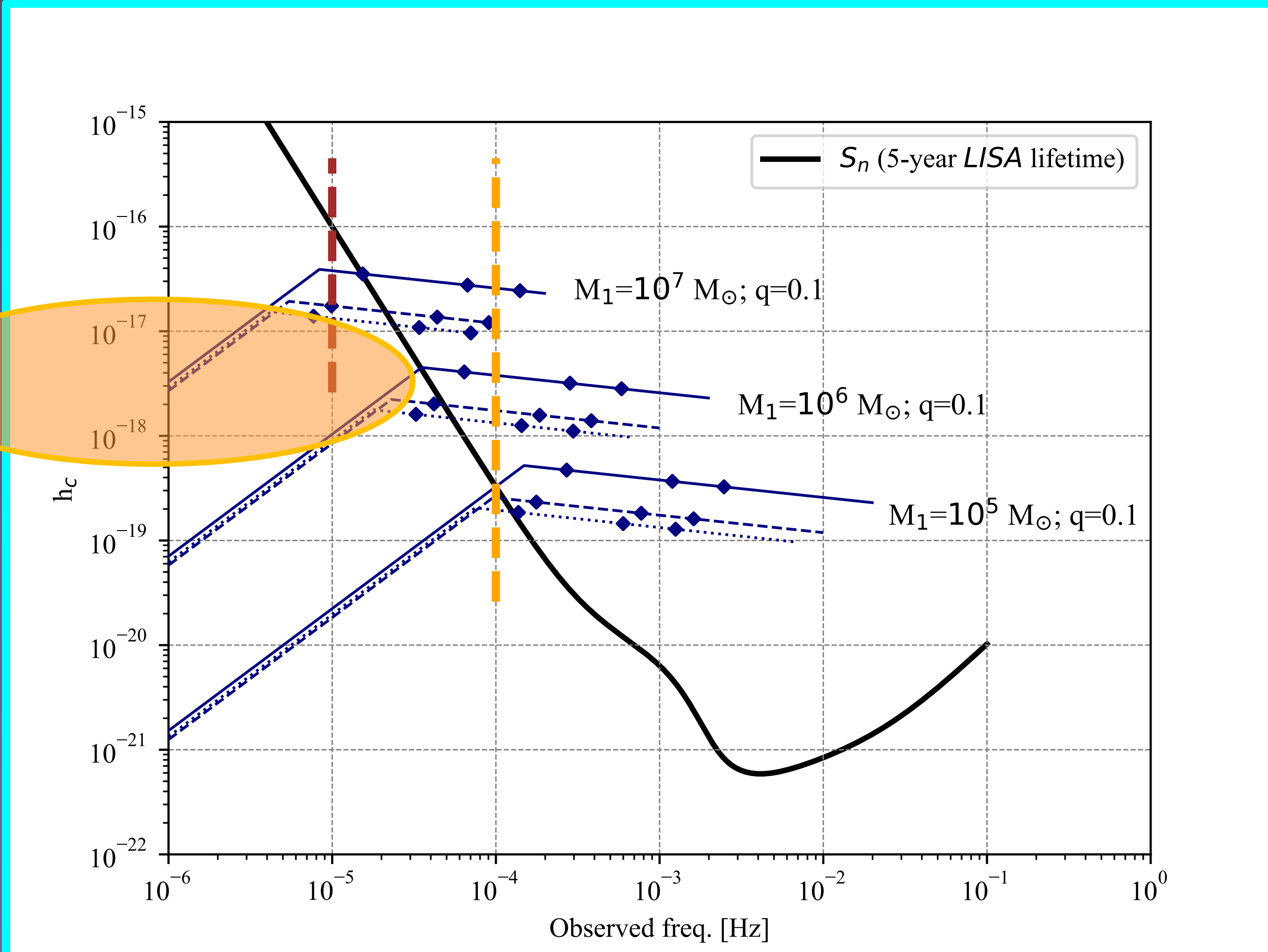
The future: binaries in (e.g.) LSST
including compact LISA sources

Xin & ZH (2021)

LSST →

perfect for
this search:

1. wide
2. deep
3. high cadence

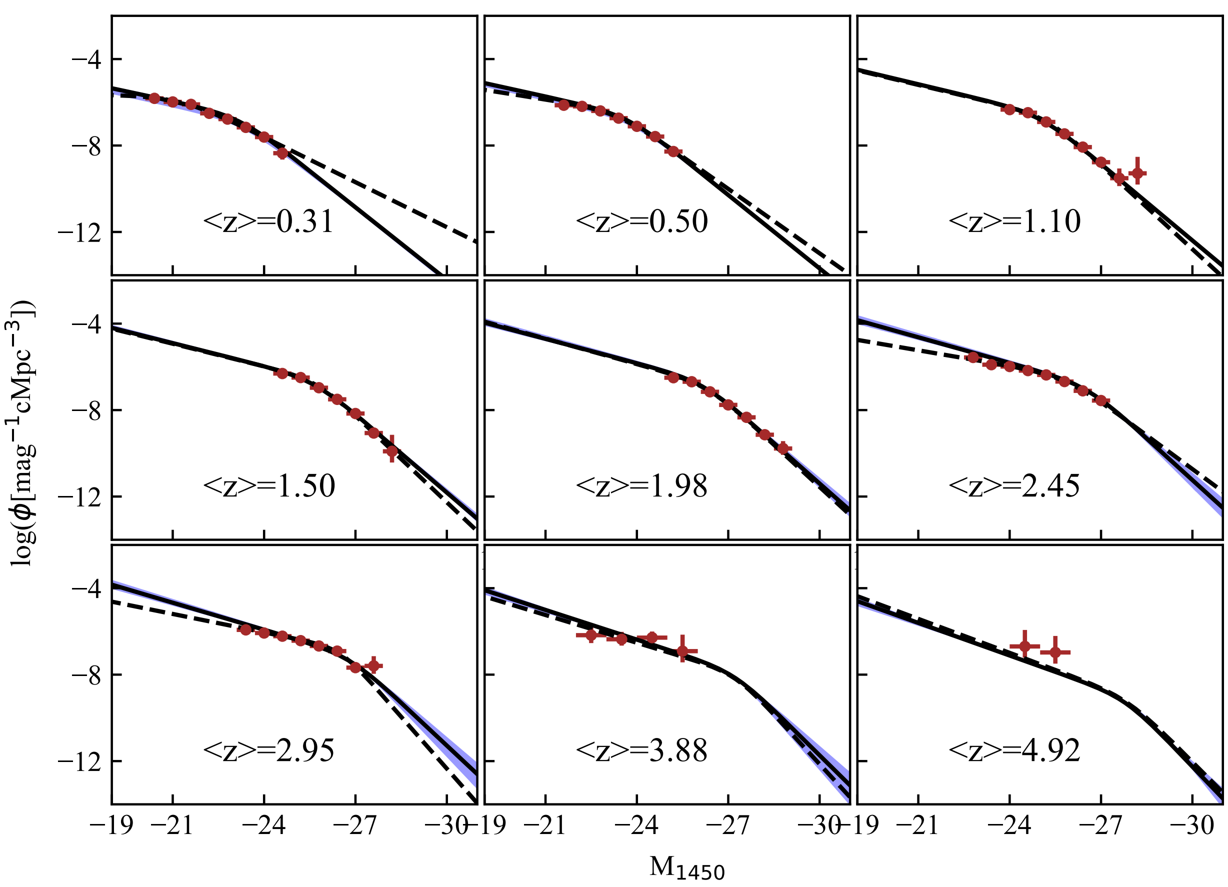


↑ 1 year

↑ 1 day

How many do we expect in LSST?

Xin & ZH (2021)



Extrapolate quasar LF

Assume fraction f_{bin} of quasars are binaries:

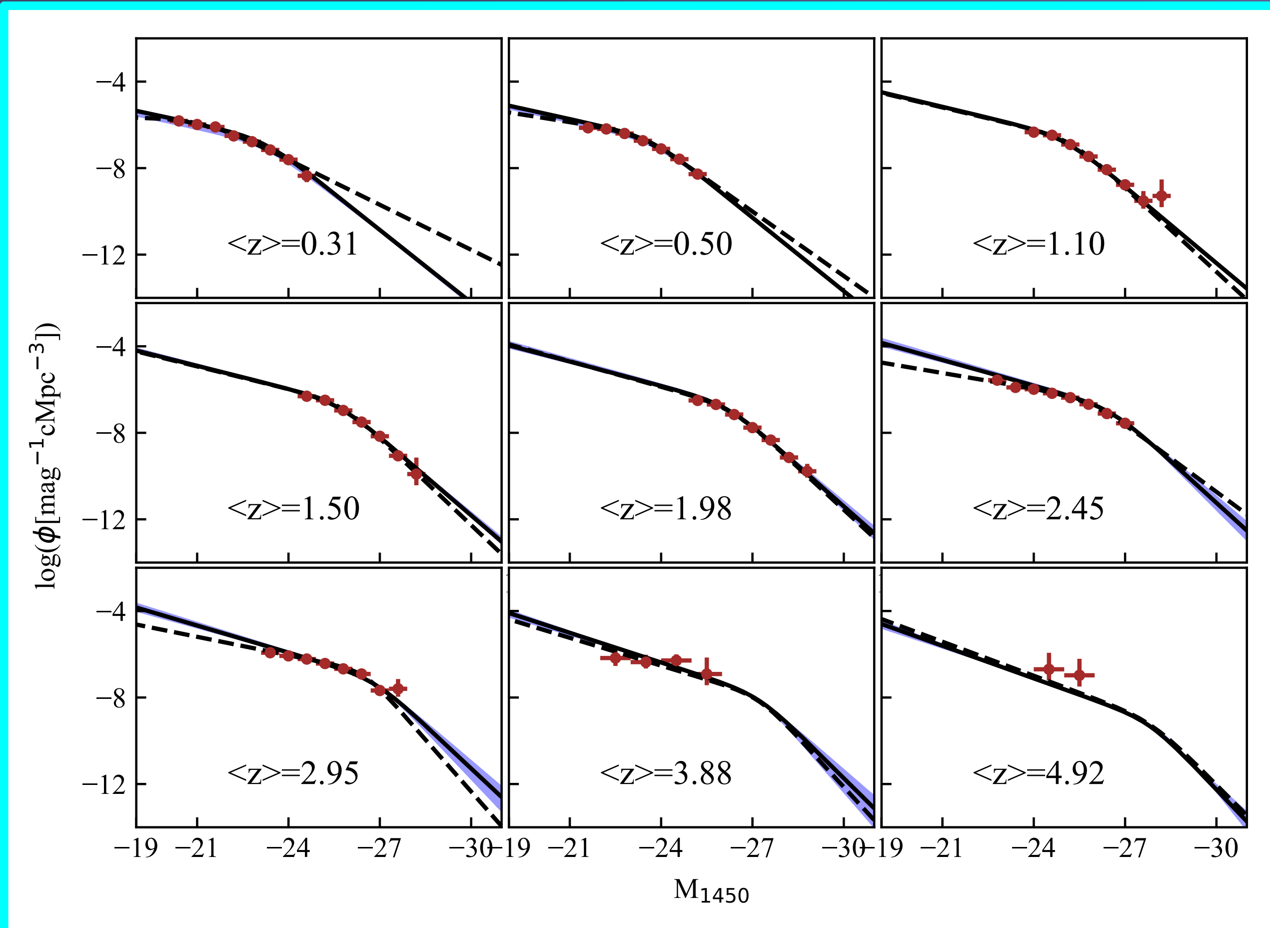
N_{bin} (P_{orb}) =

[t_{res} (P_{orb}) / t_Q] f_{bin} N_Q

Side-steps modeling of cosmology/mergers

How many do we expect in LSST?

Xin & ZH (2021)



Extrapolate quasar LF

Assume fraction f_{bin} of quasars are binaries:

$N_{bin}(P_{orb}) =$

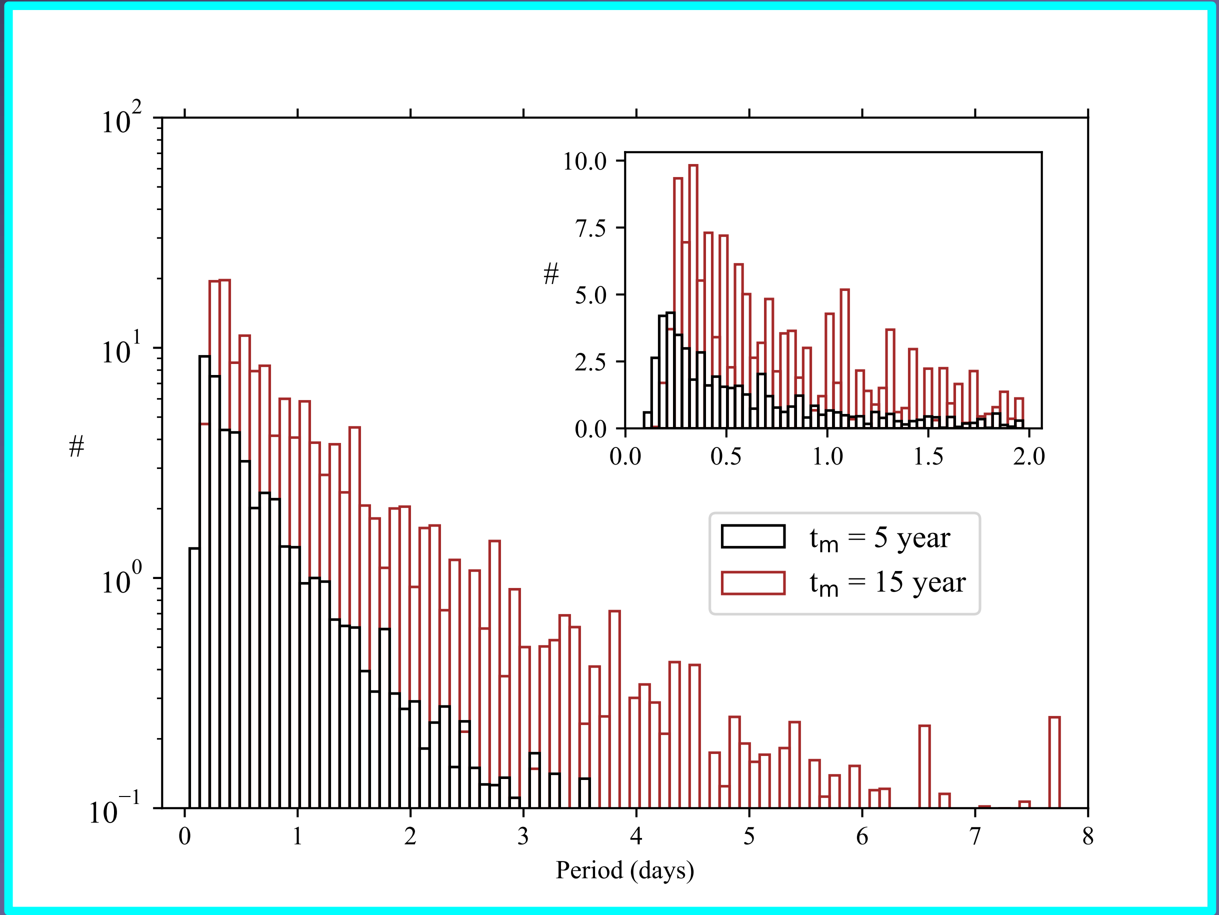
$[\, t_{res}(P_{orb}) / t_Q \,]\, f_{bin} N_Q$

Side-steps modeling of cosmology/mergers

→ 20-100 million AGN in total

LISA "verification" binaries in LSST

Xin & Haiman (2021)



* O(100) binaries with P $\lesssim$ 1 day: Redshift $z \sim$ 1-2 Mass ~10^5 - 10^6 $M_\odot$
* Many more at longer periods but still well in GW inspiral regime
* Can identify them in archival data after LISA detection

The future: EM emission from LISA sources?

Can GW-driven run-away binaries still shine?

Cavity is cleared by binary “propeller” well before merger

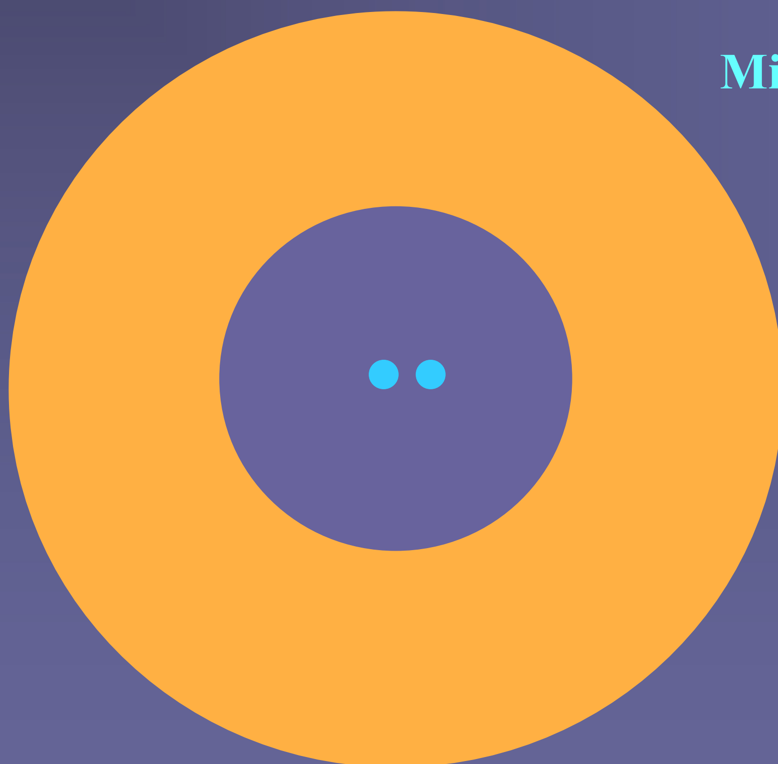
The future: EM emission from LISA sources?

Can GW-driven run-away binaries still shine?

Cavity is cleared by binary "propeller" well before merger

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

Milosavljevic & Phinney (2005)



???

Electromagnetically 'silent' merger, in vacuum ?

Can run-away LISA binaries still shine?

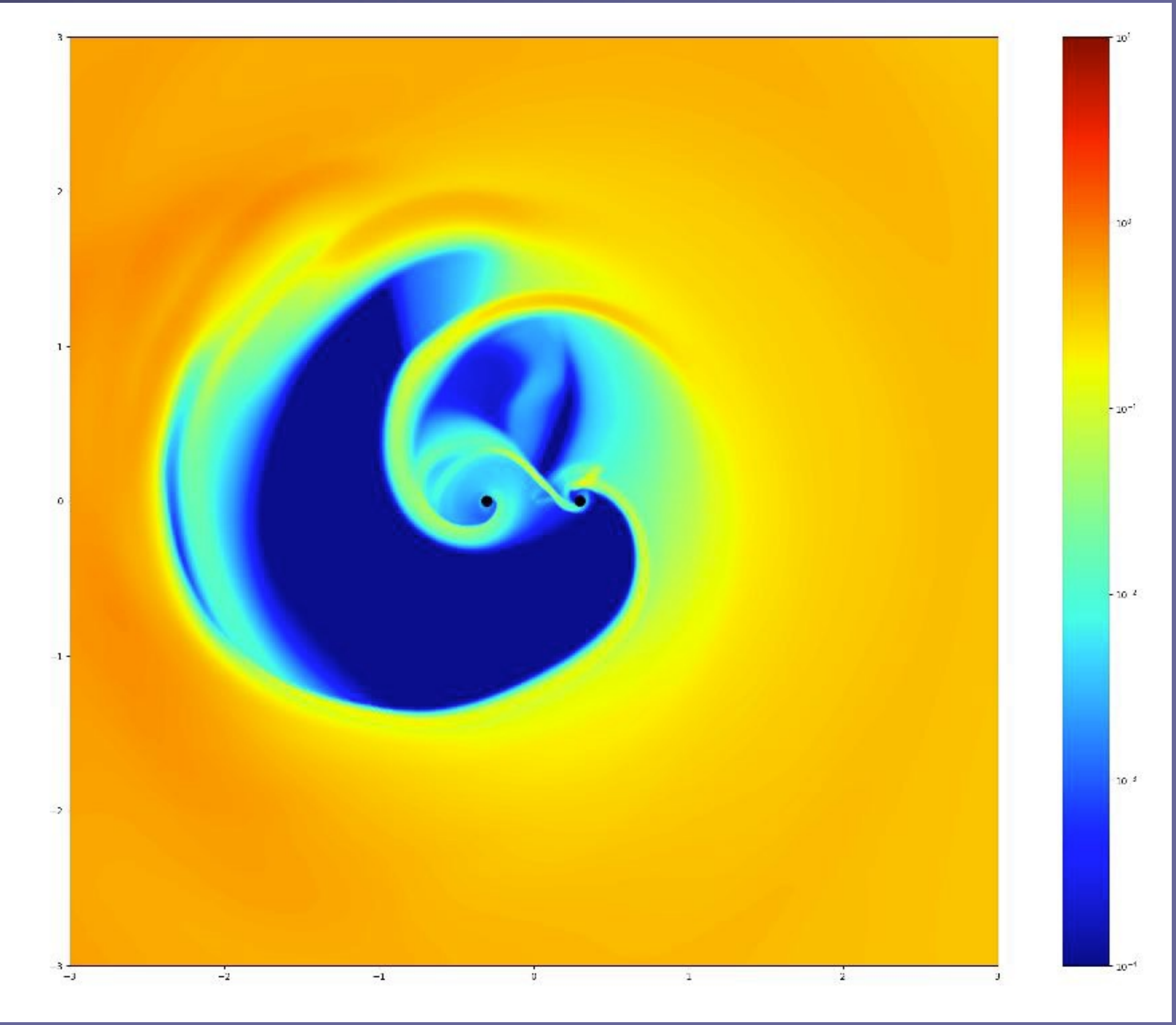
simulate evolution from 60M to merger

Tang, ZH, MacFadyen 2018

Orbital decay prescribed by GW inspiral

Pseudo-Newtonian (Wiita-Paczynski) potential

ISCO resolved directly (NO sink)

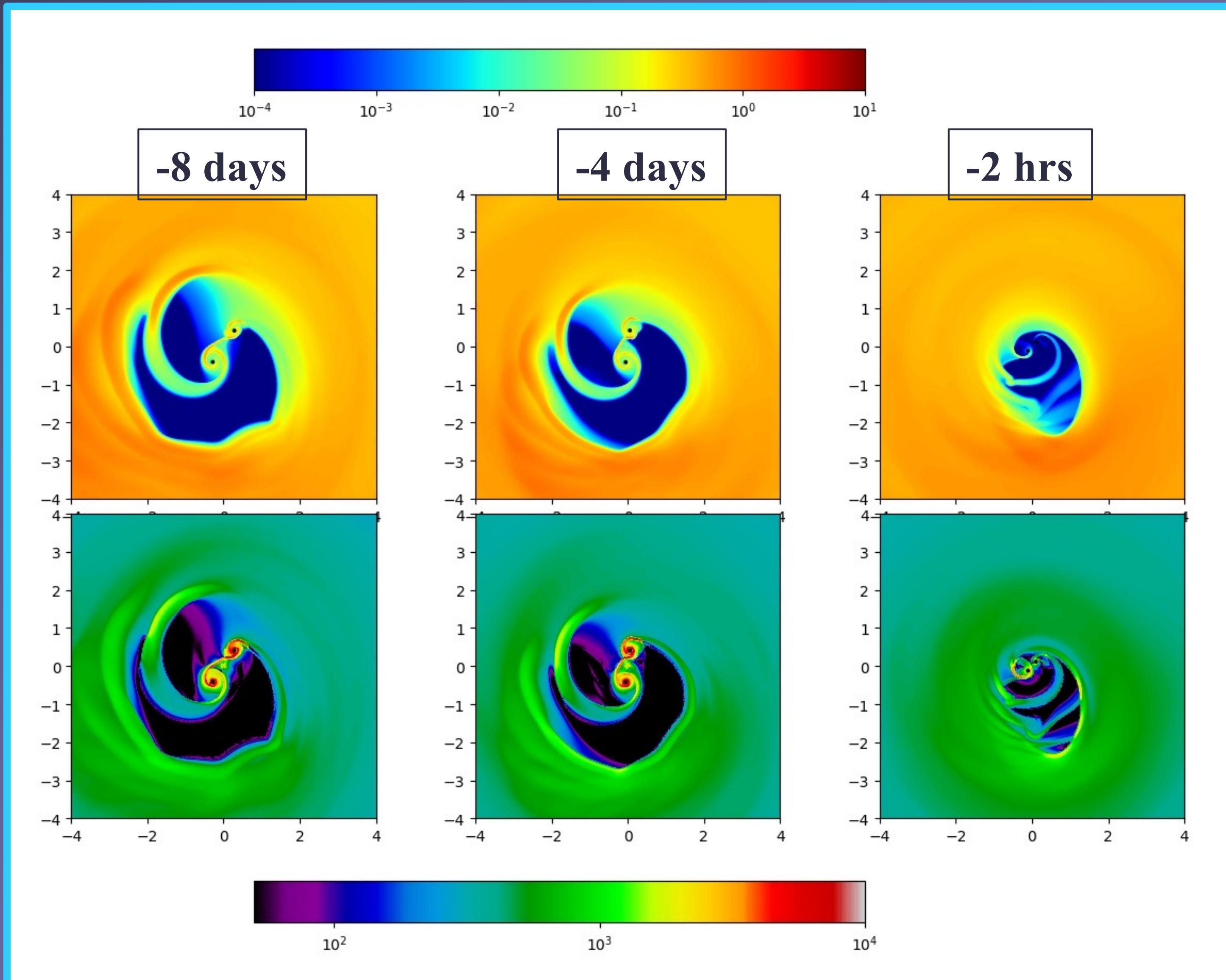


Inspiral

Tang et al. 2018

density

temperature

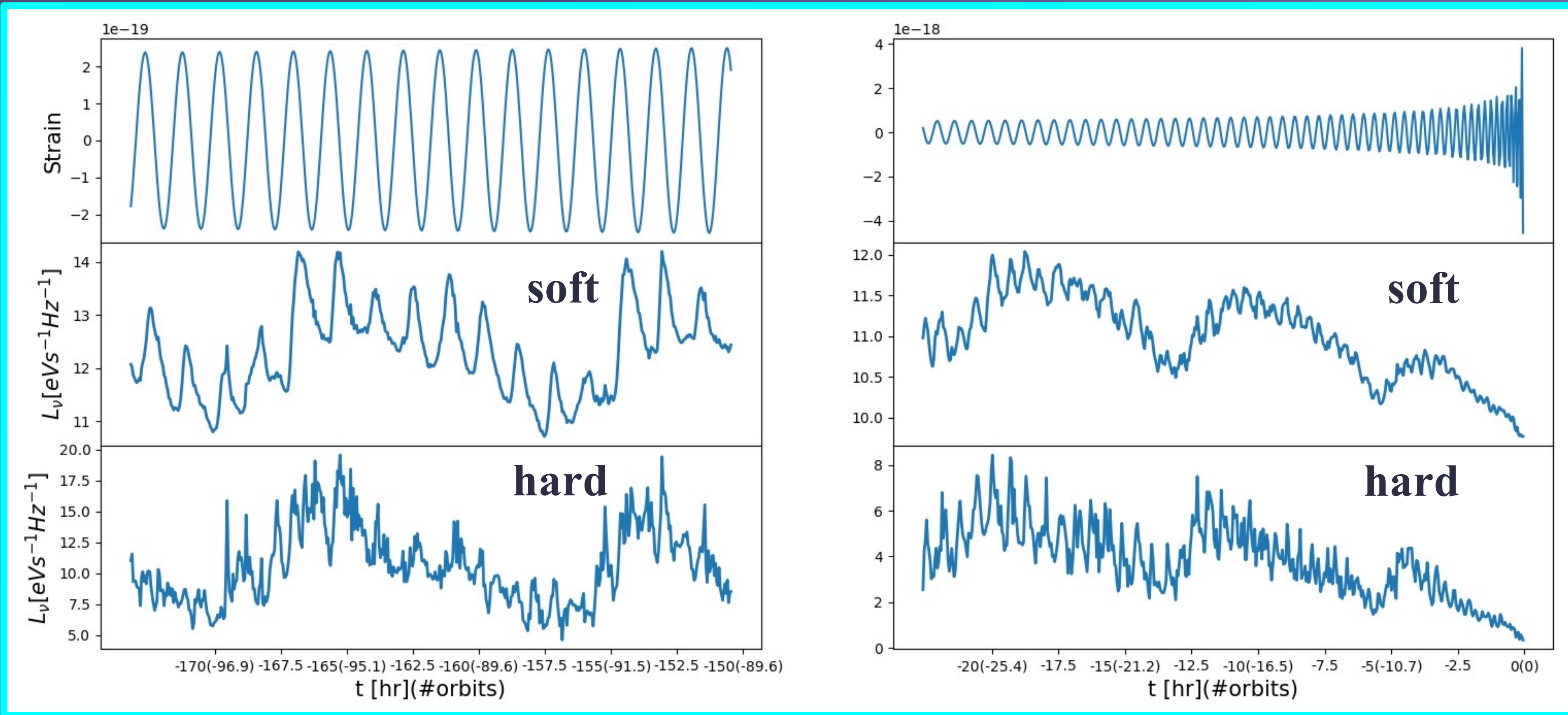


Lightcurve - EM chirp

Tang et al. (2018)

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

(even if face-on)



LAST 7 DAYS **LAST 1 DAY**

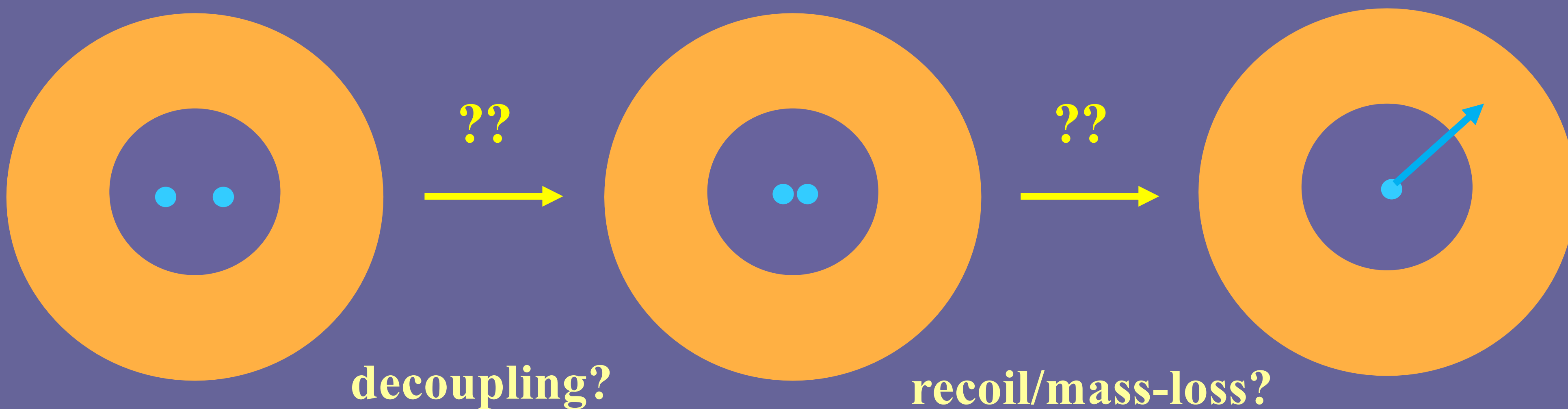
EM signatures near merger

Luke Krauth et al. (2023)

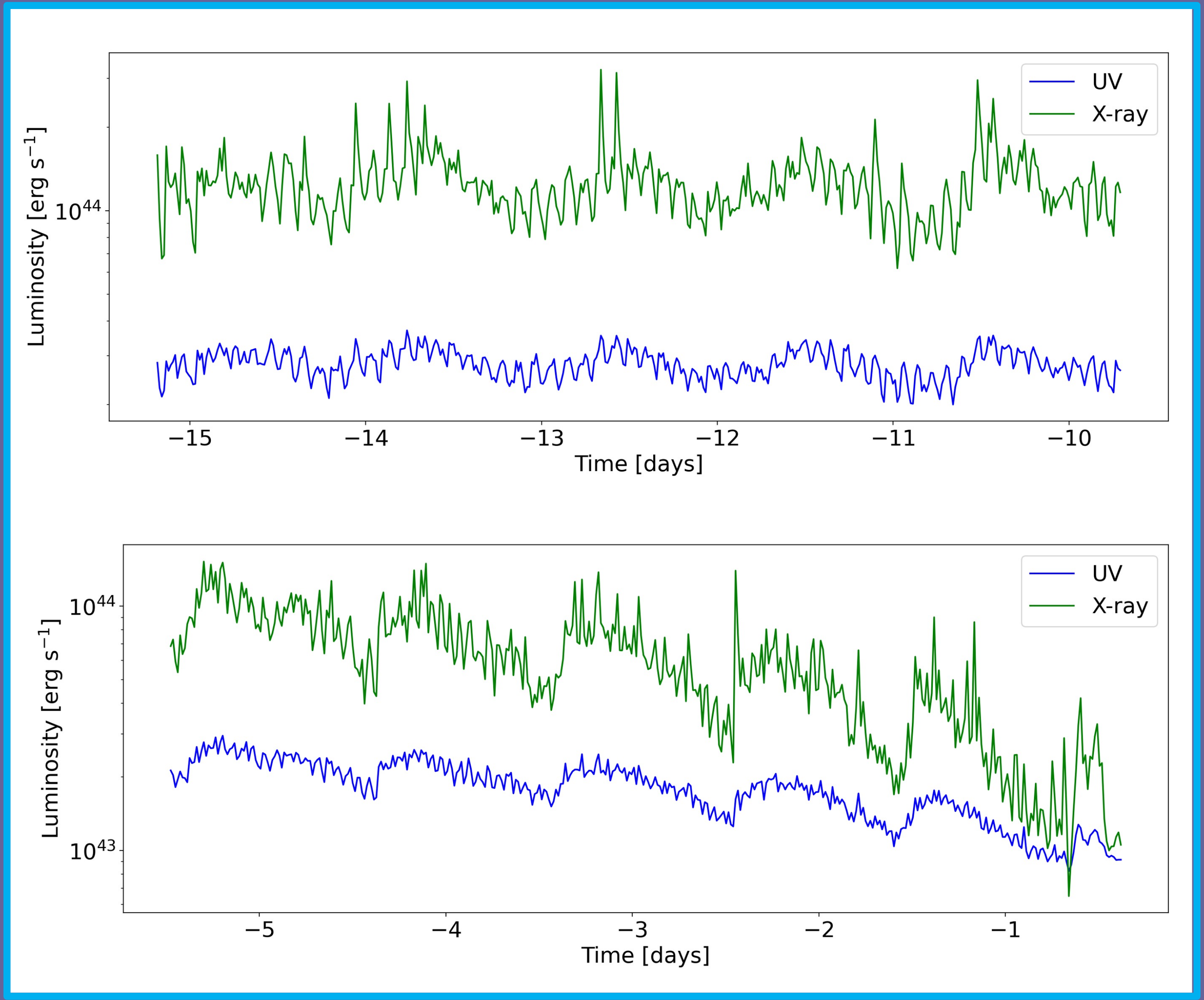
Luke Krauth

Follow GW inspiral (10^6 $M_\odot$) for last ~month before merger (~400 orbits)

Follow post-merger disk including recoil and mass-loss of remnant



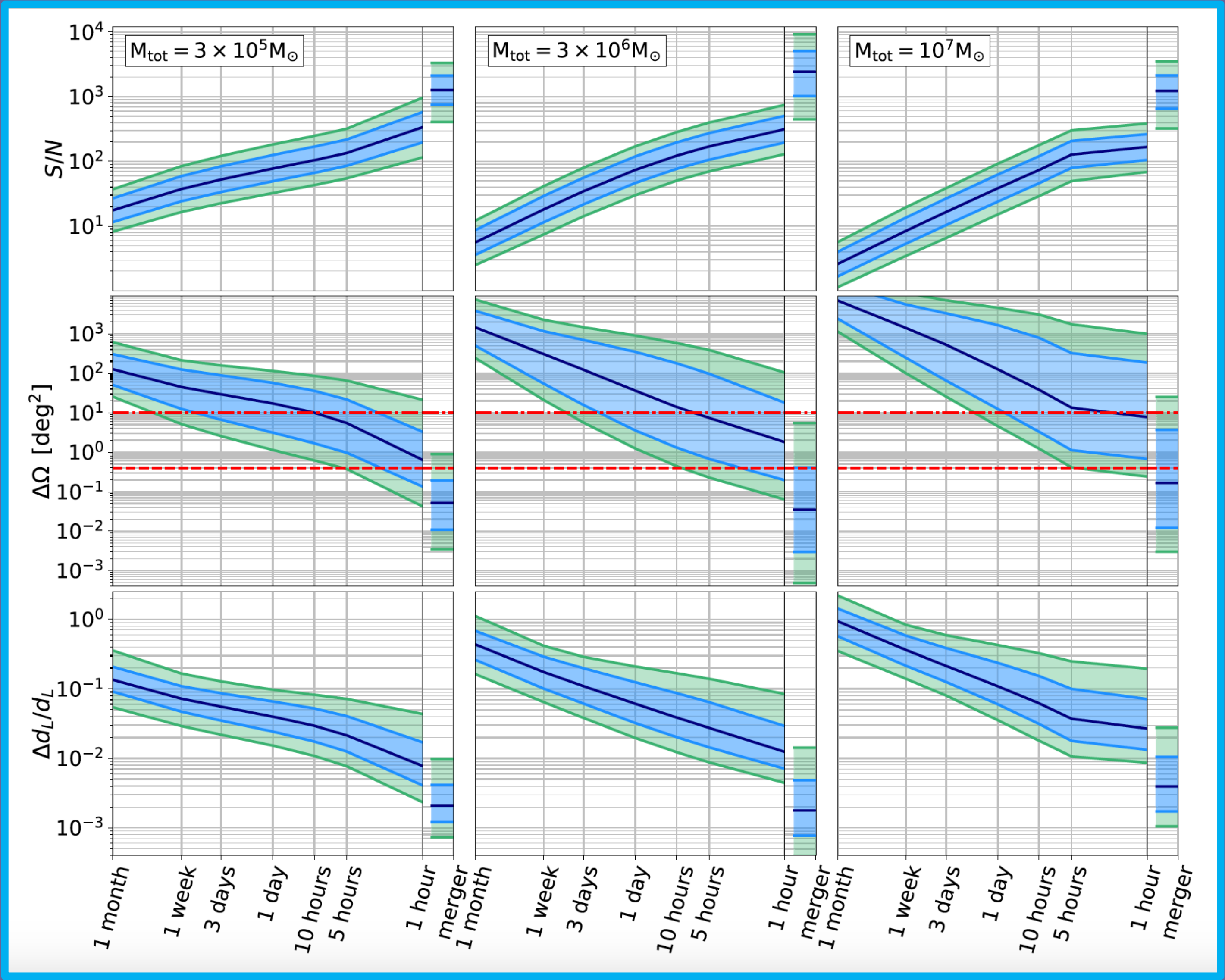
EM chirp follows GW chirp



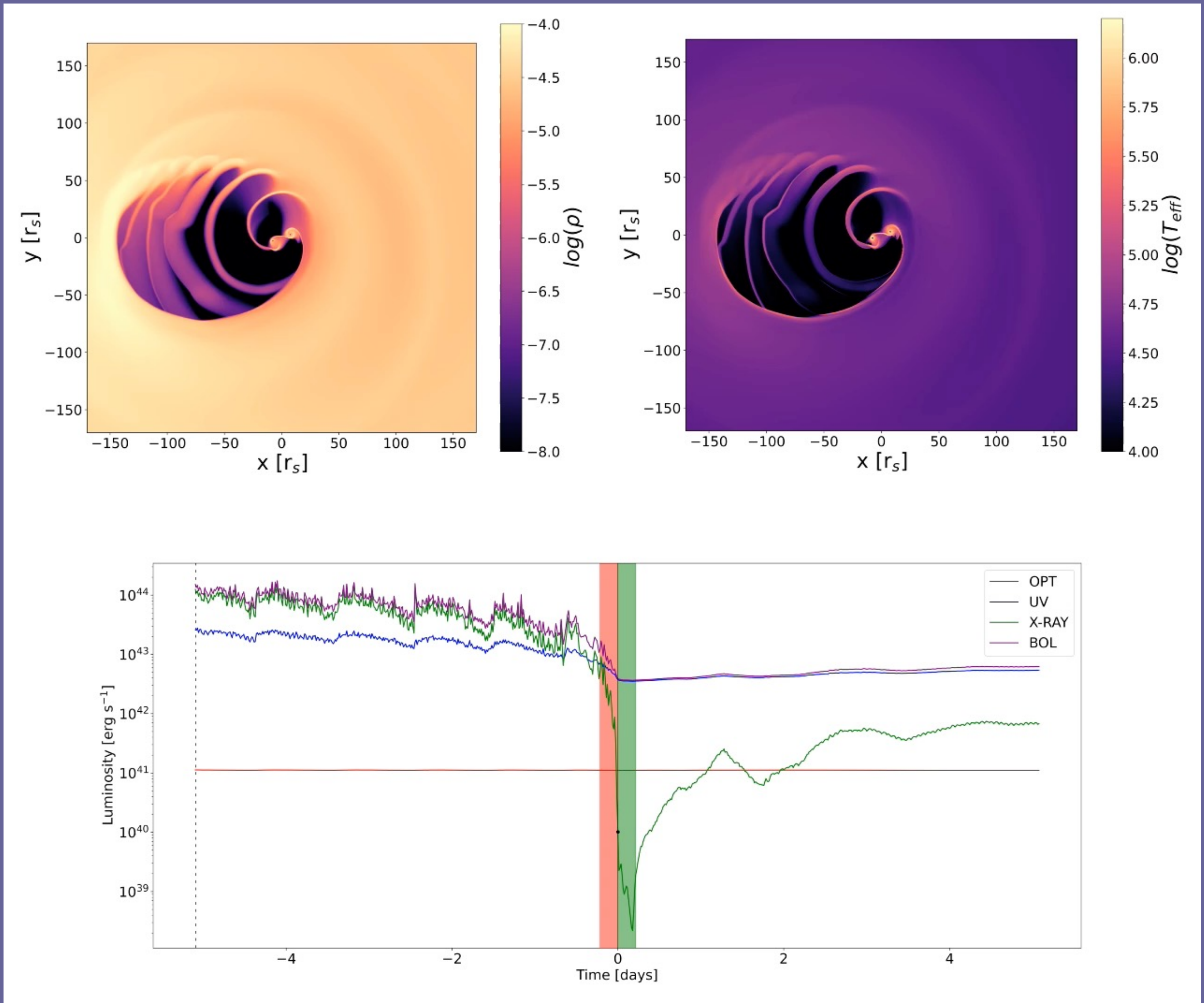
cf. earlier work by Tang et al. 2018

Pre-merger localization - ouch

Mangiagli et al. 2020



Disappearing black holes!



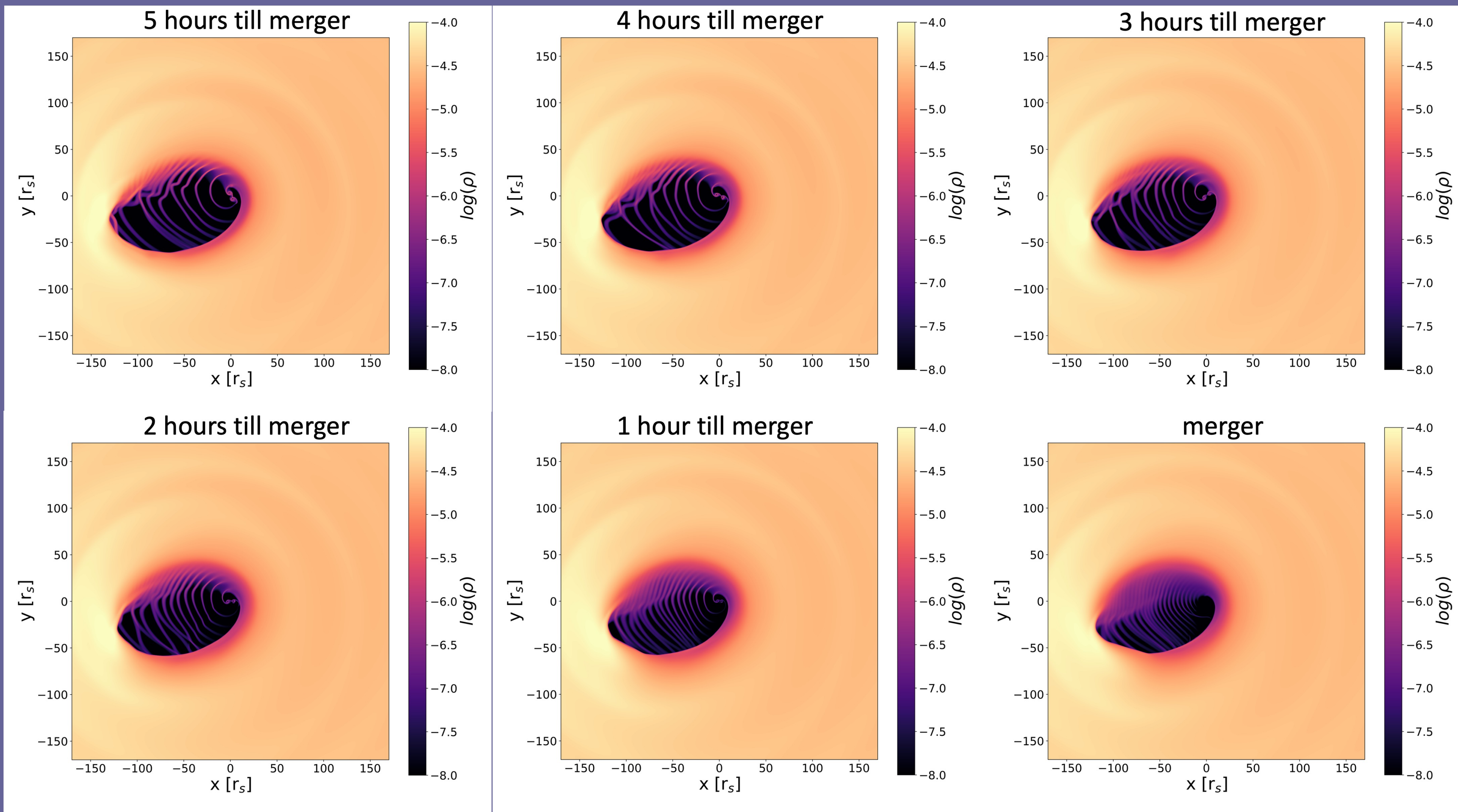
Binary suddenly vanishes in X-rays

But stays in optical UV and infrared

Can catch this with Athena (use LSST or its archival data)

No immediate effect of mass-loss or recoil

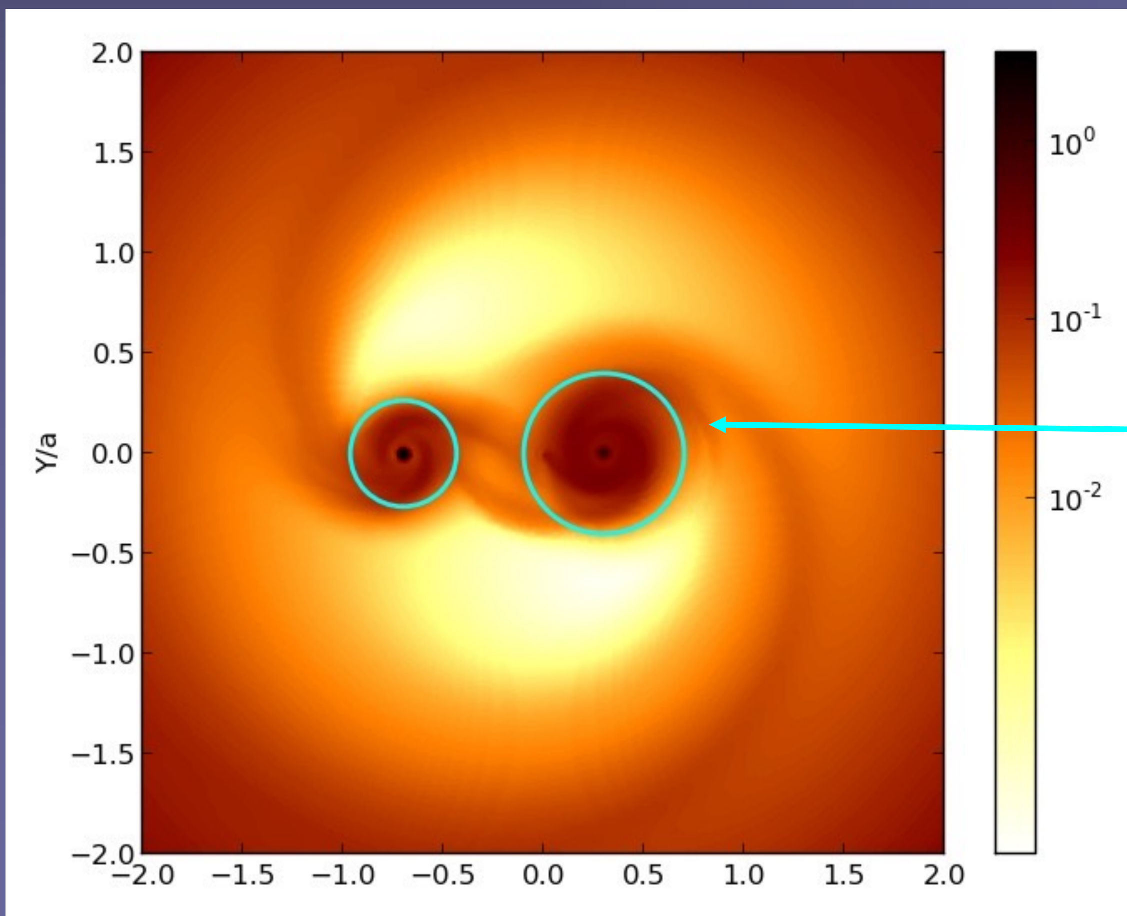
Disappearing minidisks and streams



EM chirp from LISA sources inevitable

ZH 2017

- X-ray emission from quasars from few R_g [optical: ~ 100 R_g]
- Smaller than tidal truncation radius for binary entering LISA band
- Minidisk = quasar disk (or X-ray corona), bound to individual BH
- Doppler effect modulates brightness at O(v/c) ~ O(0.1)



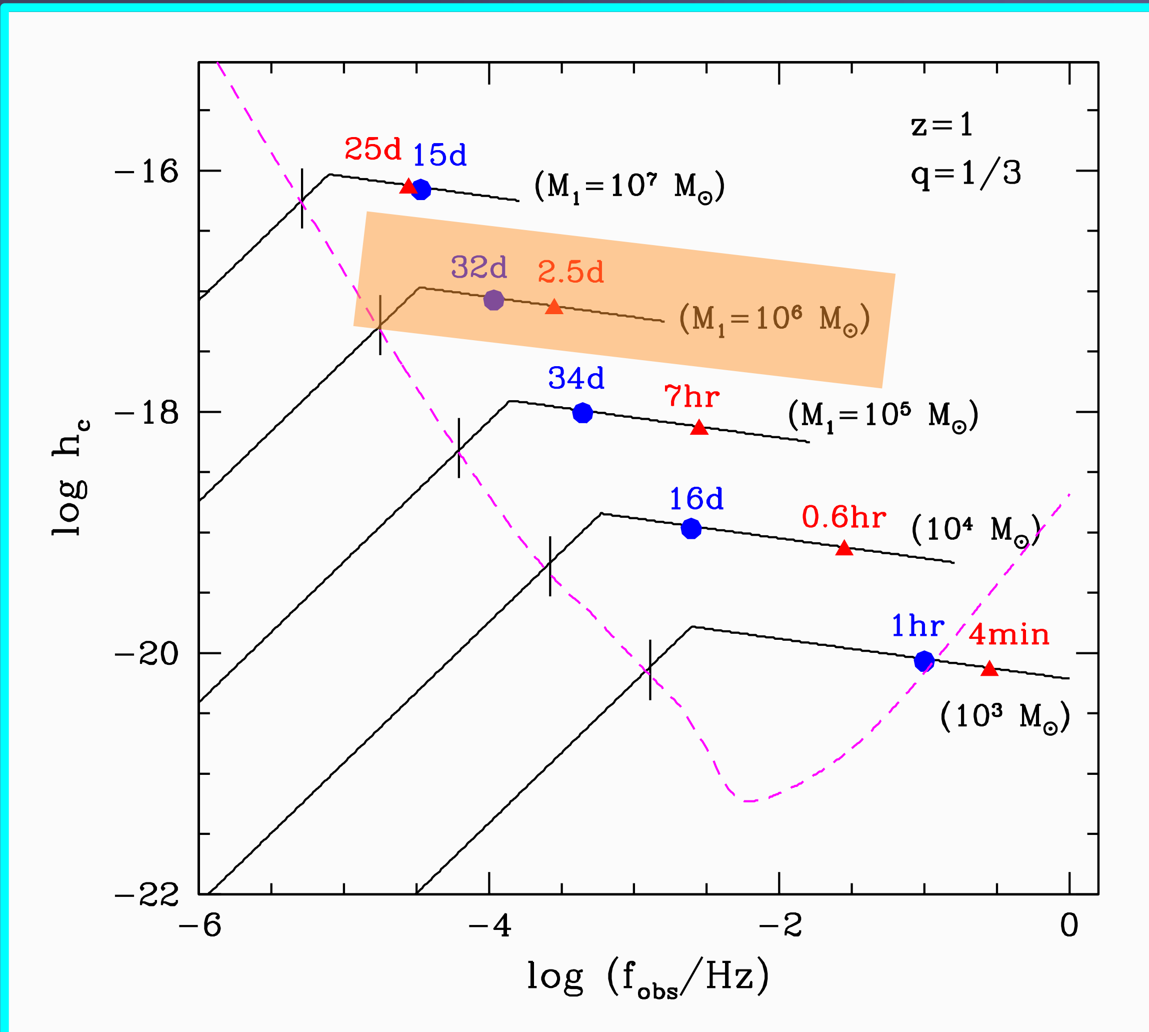
$$\Delta F_\nu / F_\nu = (3-\alpha)\,(v_{||}/c)$$

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

Tidal force from companion truncates minidisk

Farris et al. (2015)

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

Localized (10 deg^2): 40 R_g

Tidal radius < 10 R_g: 400 cycles

V(orb) ~ O(0.1c)
T(orb) ~ O(hr)

(ZH 2017)

GW vs. X-ray chirp

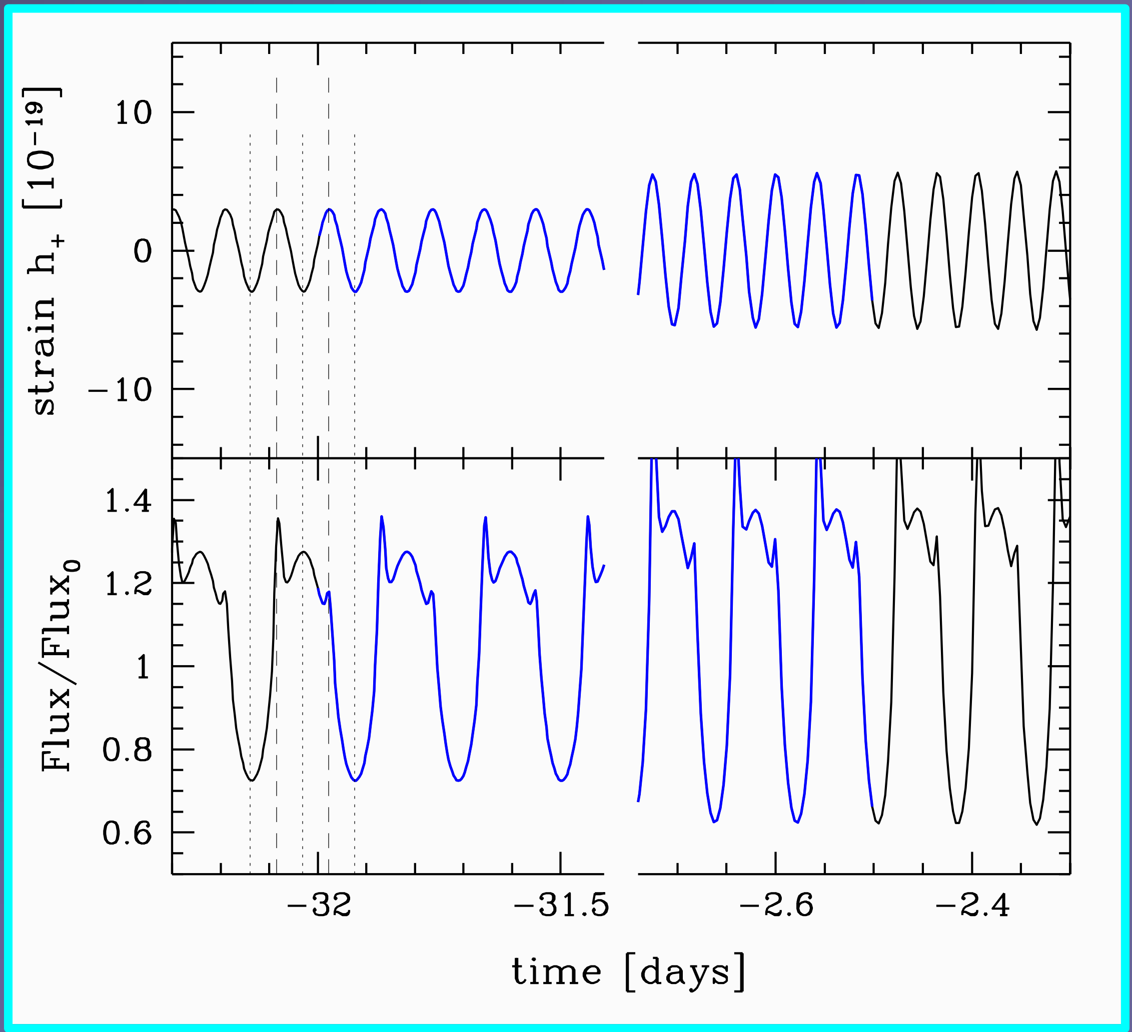
Test $A_{gw} \propto f^{2/3}e^{-i2\varphi}$ *vs* $A_\gamma \propto f^{1/3}e^{-i\varphi}$

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)

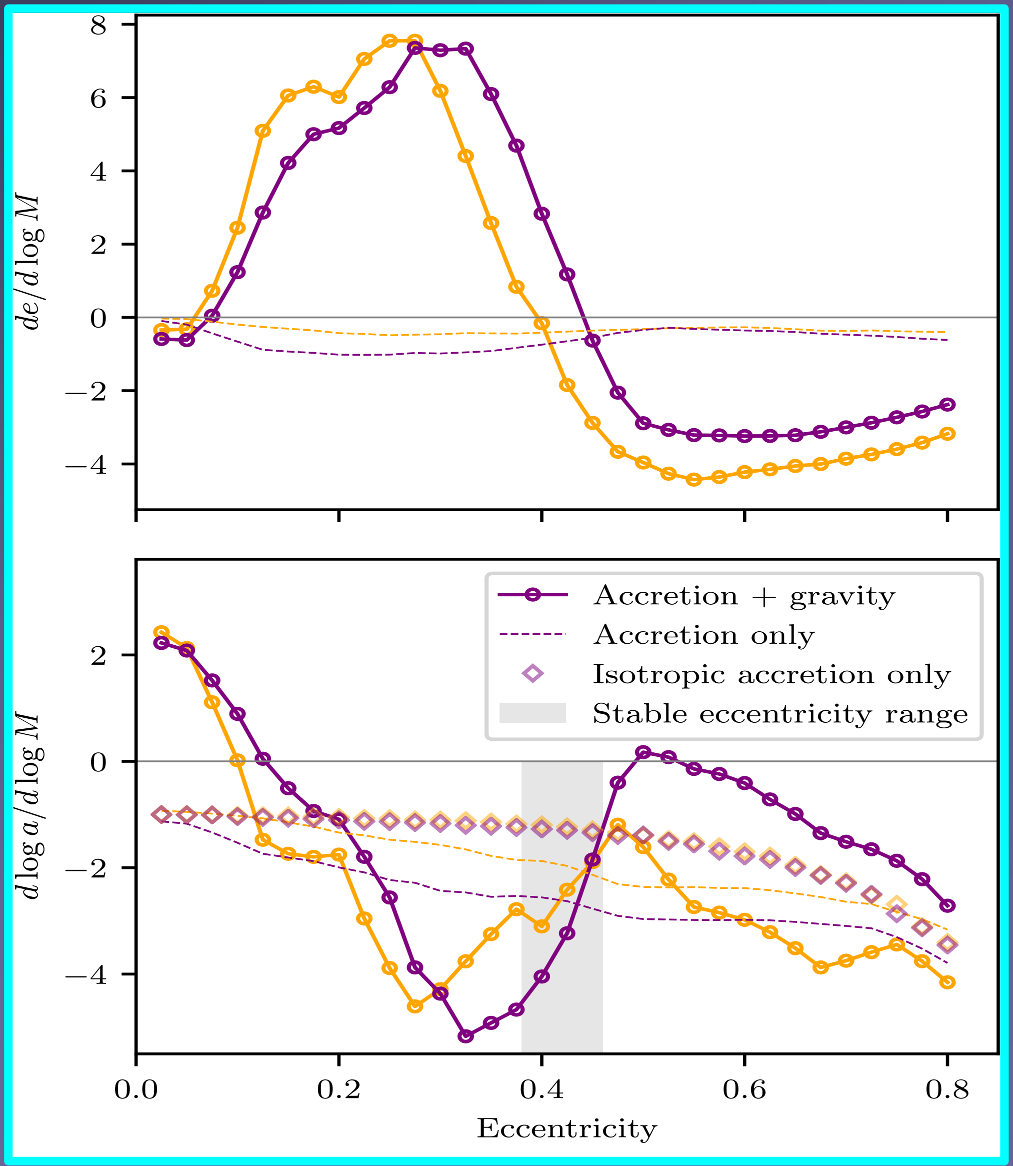
$M=10^6\, M_\odot$, $q=1/3$, $z=1$, $i=10°$ ZH (2017)



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

Inspiral or outspiral? Impact of eccentricity

Zrake et al. 2021



e → 0.45

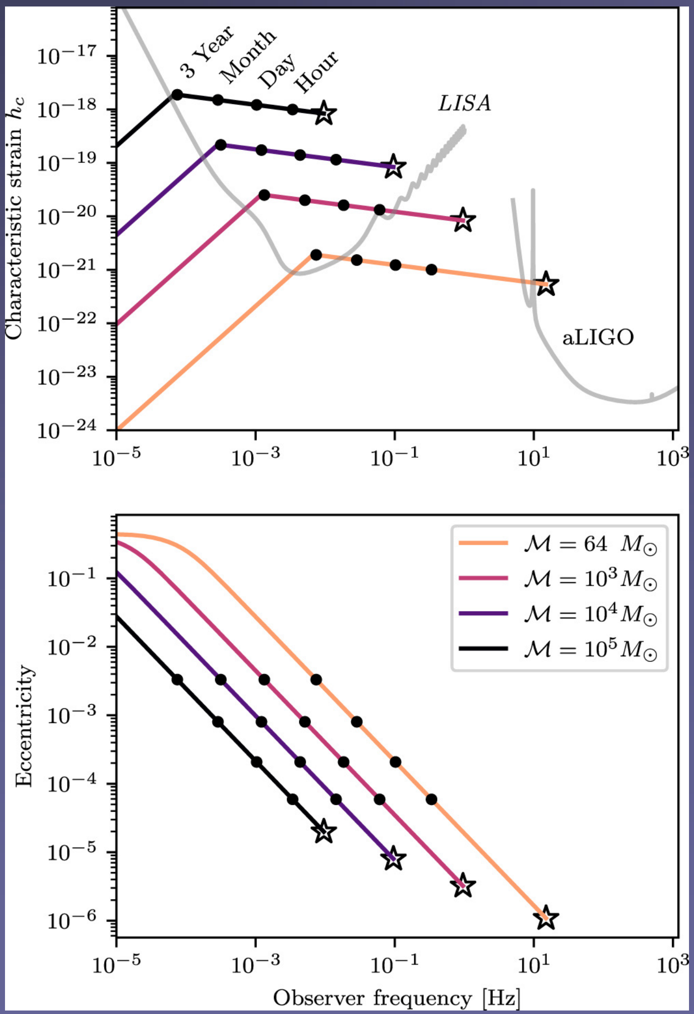
outspiral

inspiral

inspiral for e ≳ 0.15

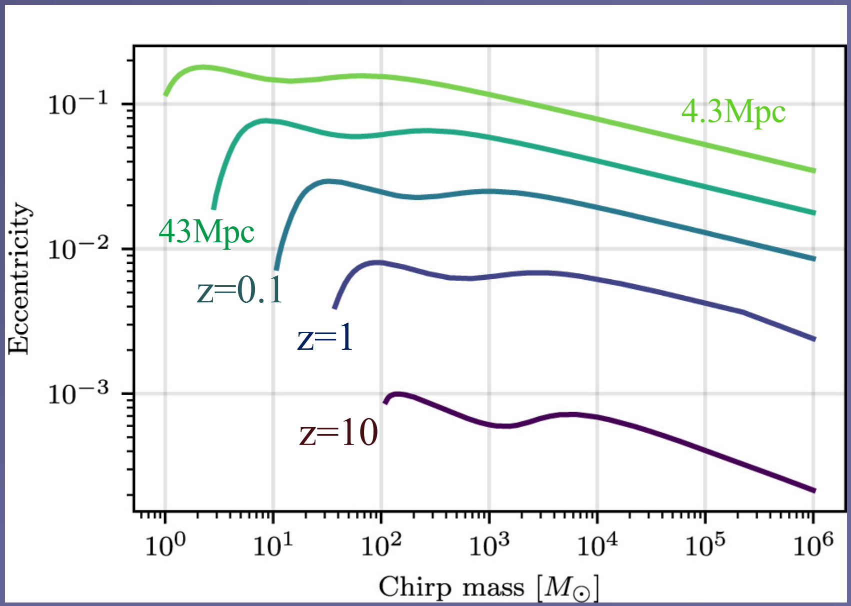
Eccentricity in LISA band?

Zrake et al. 2021



e → 0.45 → circulatization

Eccentricity entering LISA band:



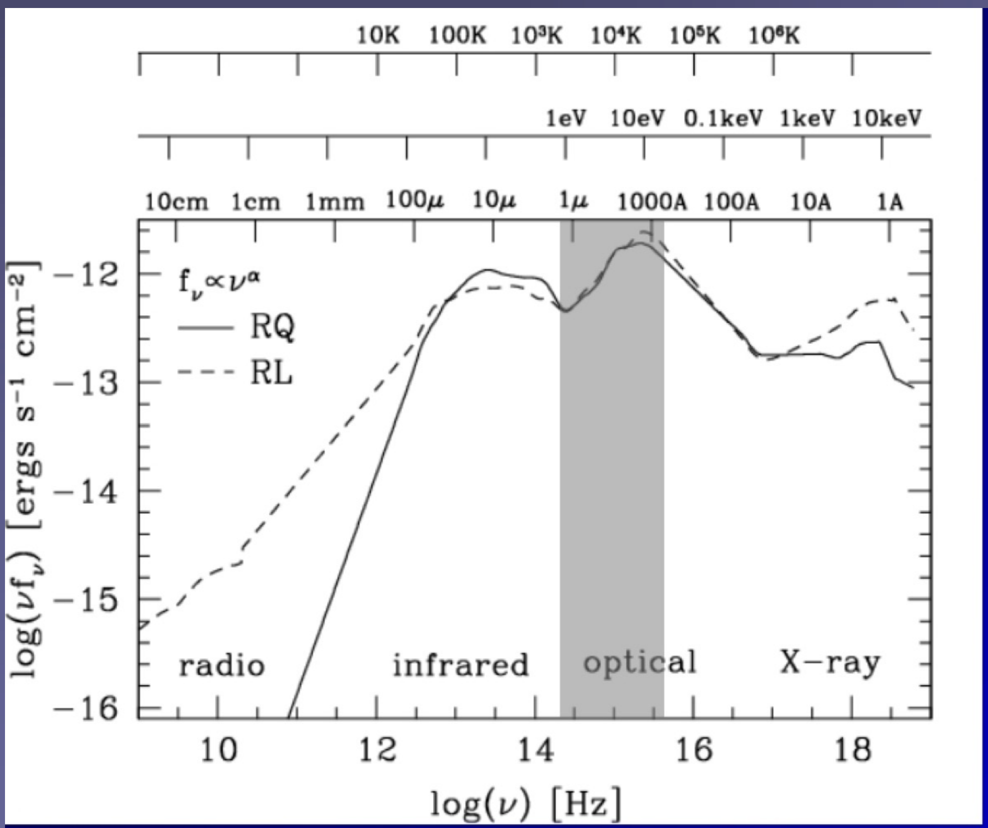
e ~ 0.01 for low-mass nearby binaries

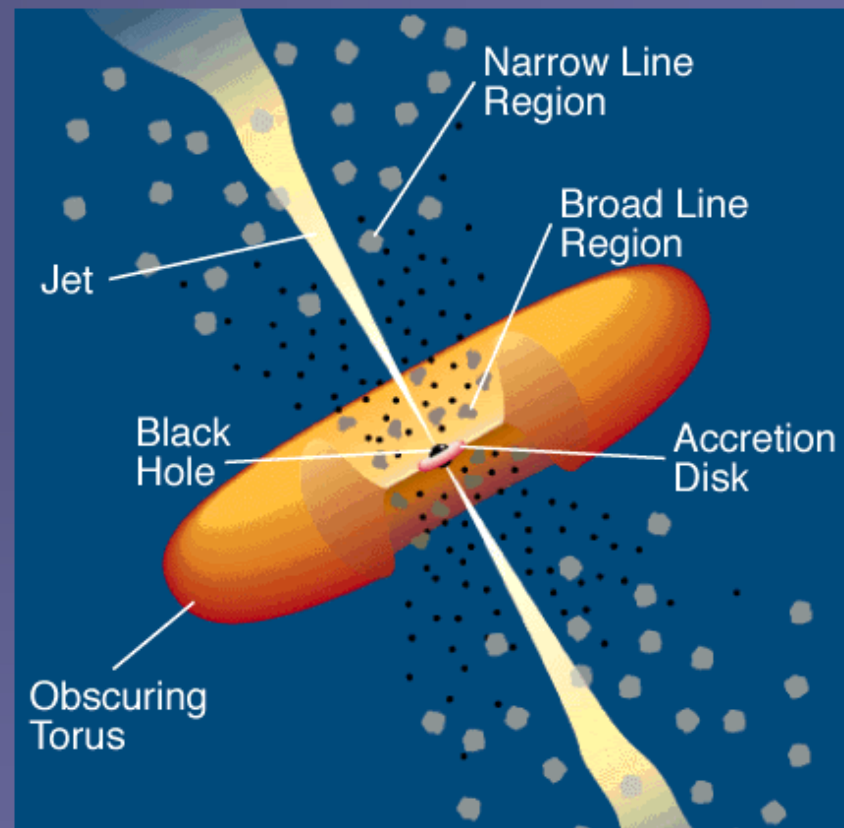
II. Possible spectral signatures

- **AGN spectra** from single SMBHs – several 100k spectra, lot of phenomenology
- **Rudimentary** or poor theoretical ab-initio modeling
- Look for unusual features in case of 2 as opposed to 1 SMBH

Quasar spectra – global view

Each part of continuum from different region/process





credit: Z. Ivezic, from Elvis et al. (1994)

II. Possible spectral signatures

- **Hot spots** from shocks in UV/X-rays as material from accretion streams strike circum-secondary **disk** and/or **cavity wall**
  Saade+2020, 2023 null results with Chandra and NuStar

- **Broad lines** powered by UV from minidisks: lines strong, periodic shape/width reverberation, Doppler shift
  Eracleous+2012, 2019, Decarli+2013, Runnoe+2017

- Signatures in relativistic **iron Kα** line
  McKernan+2013

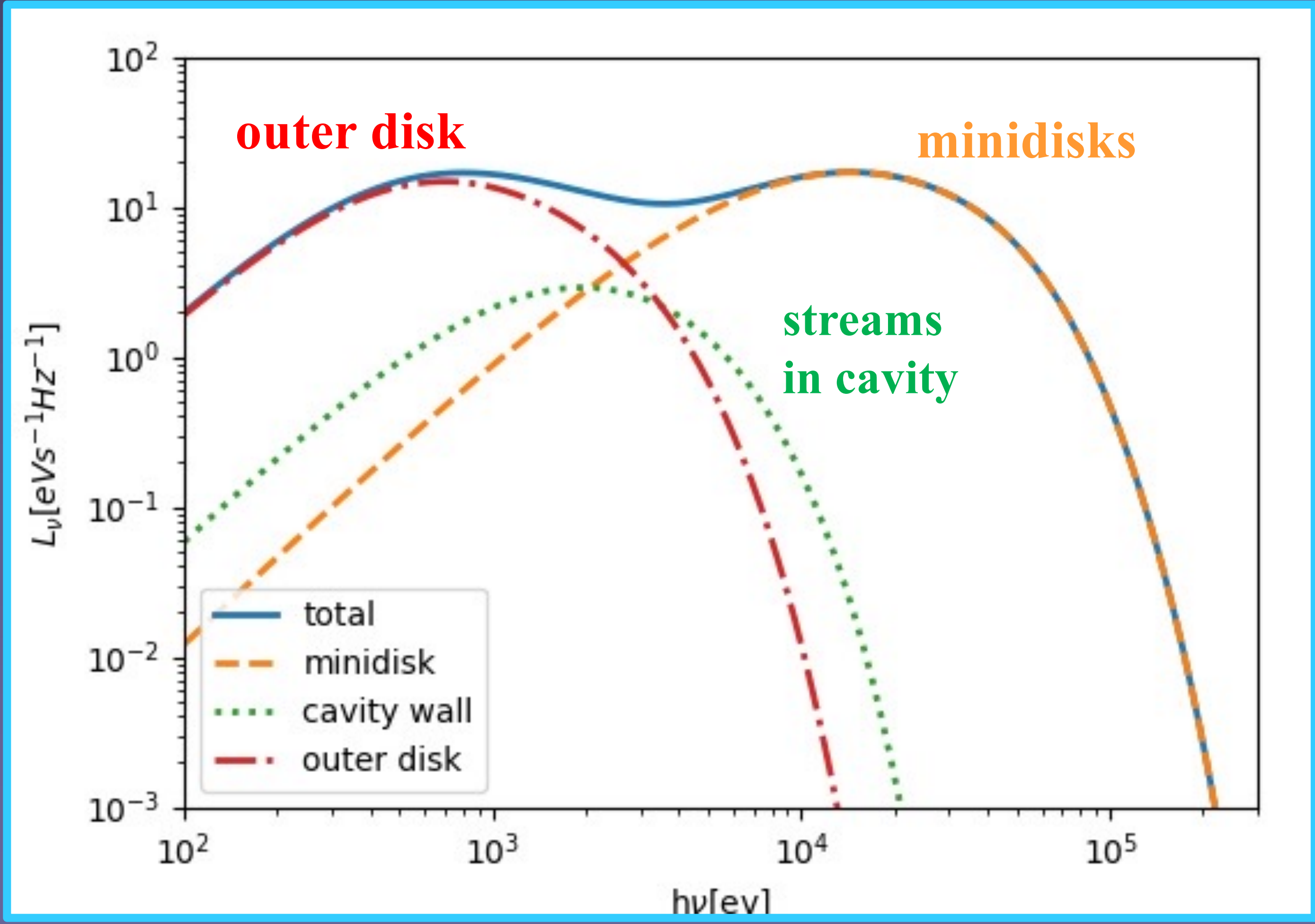
- **Infrared echo** from "lighthouse" scattered off dusty torus
  D'Orazio+ZH 2017

- **Polarization** varies periodically
  Dotti+2021

Hard spectrum

Tang et al. (2017)

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



$q = M_2/M_1 = 1$

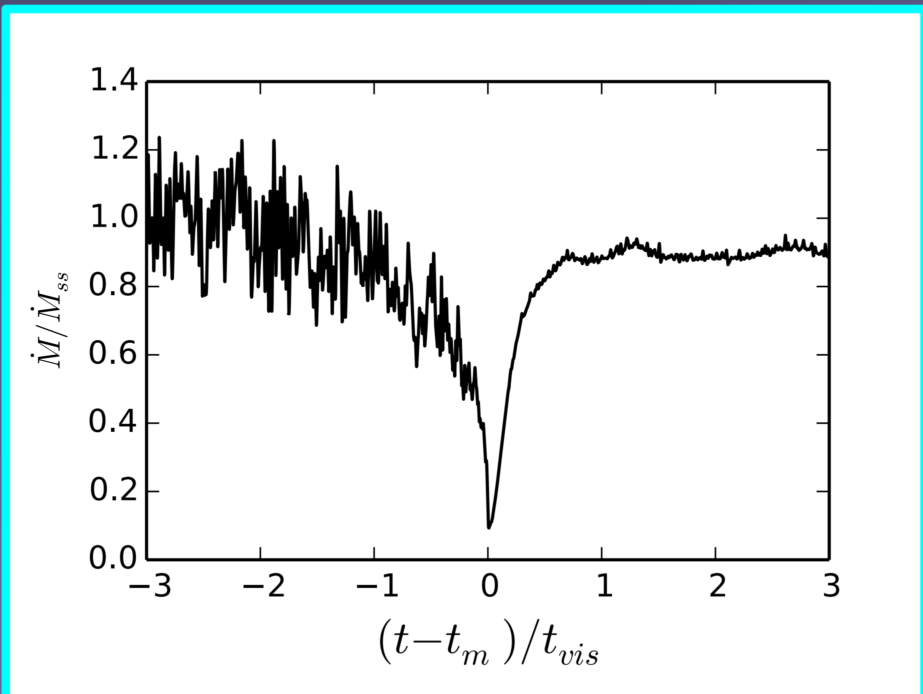
Spectral evolution at merger

Milosavljevic & Phinney (2005): disk decouples, left behind at ~100 R_S

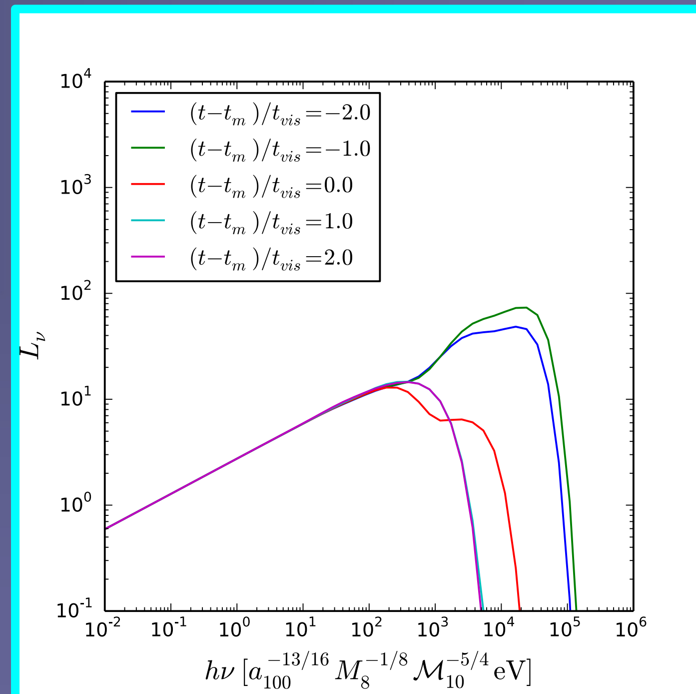
Farris et al. (2015a) strong accretion all the way through merger

Tang+2018, Krauth+2023 binary remains luminous until last day

$q = M_2/M_1 = 1$



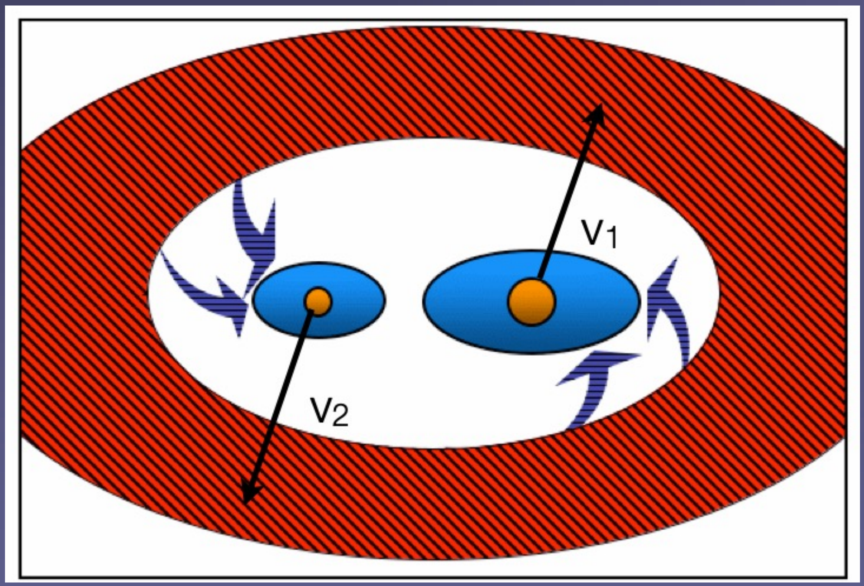
Accretion rate



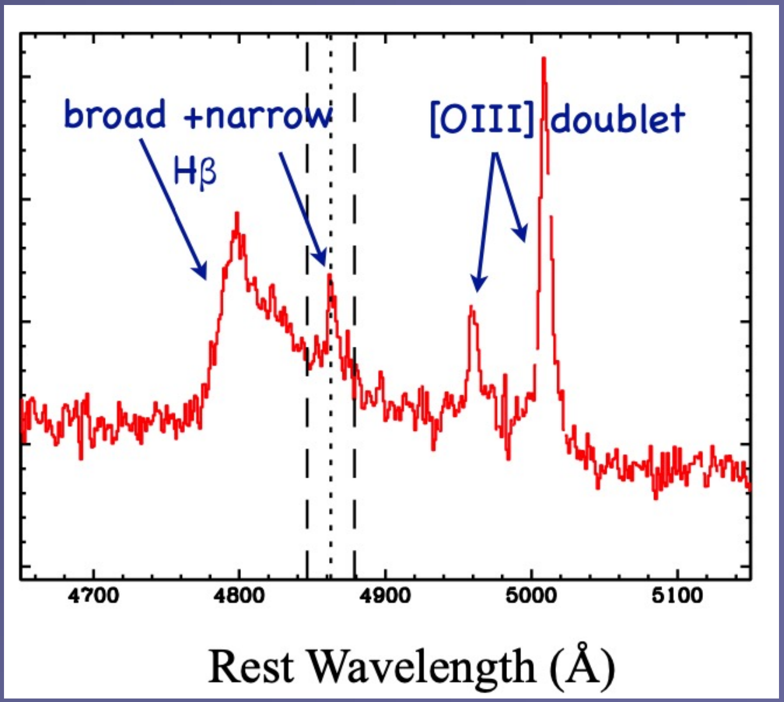
Spectra before, at, and after the merger

Shifted Broad Emission Lines

Dozen of candidates from (mostly) Hβ line



Nguyen, Bogdanovic et al, 2016, 2019, 2020

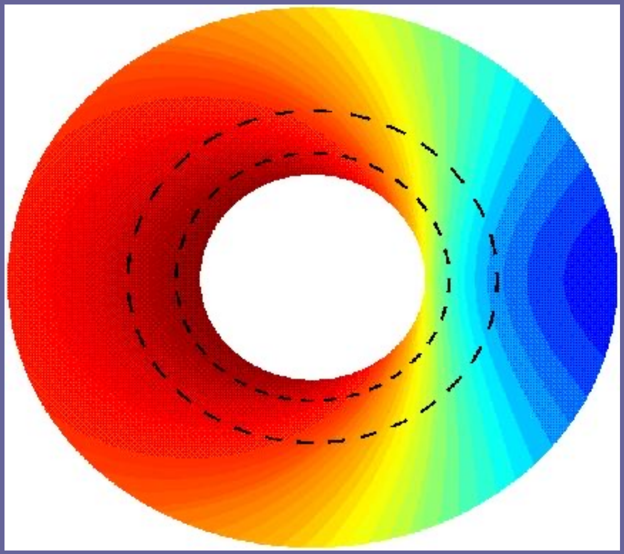


- Double peaks: several candidates
  caveat: can be wind, disk hotspot..
- Offset lines: 16000 quasars from SDSS → 88 offset candidates
  caveat: can be wind, disk hotspot.. Eracleous+2012
- Moving lines: ~3 candidates with lines moving
  caveat: shape changes Shen+2013, Liu+2016, Runnoe+2015,2017

Relativistic FeKα line

Narrow line at 6.4 keV, powered by X-rays

(Fabian et al. 2000)



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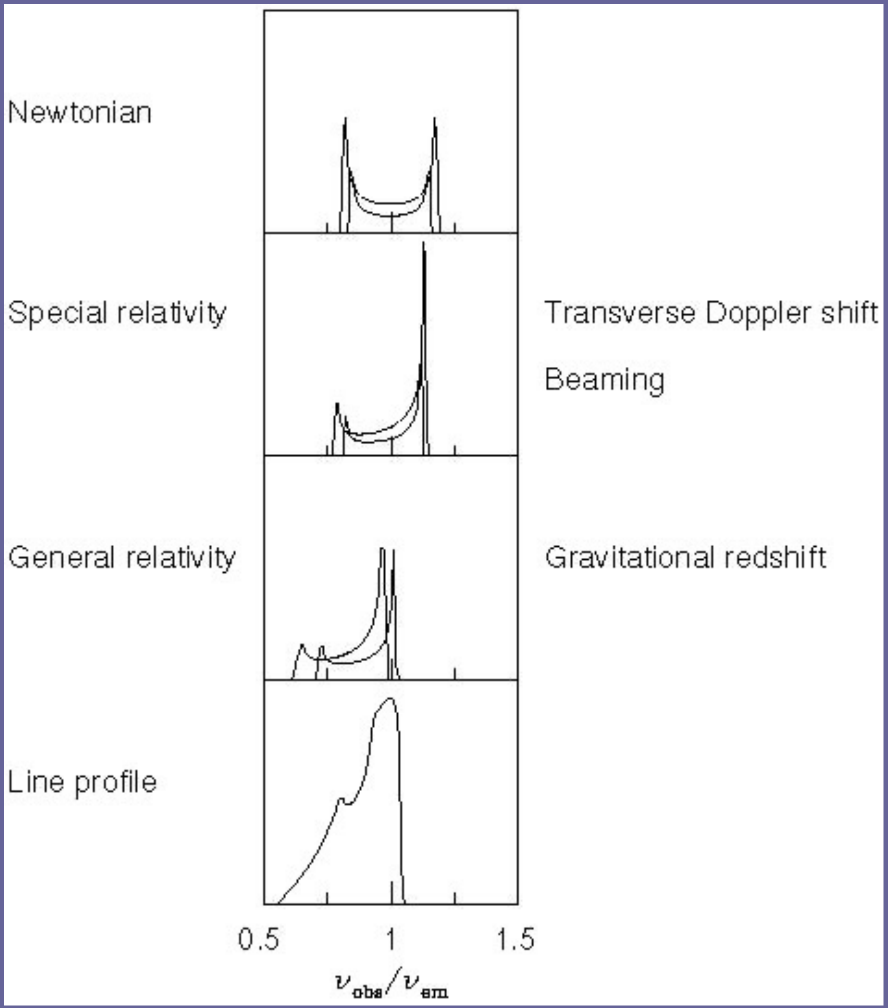
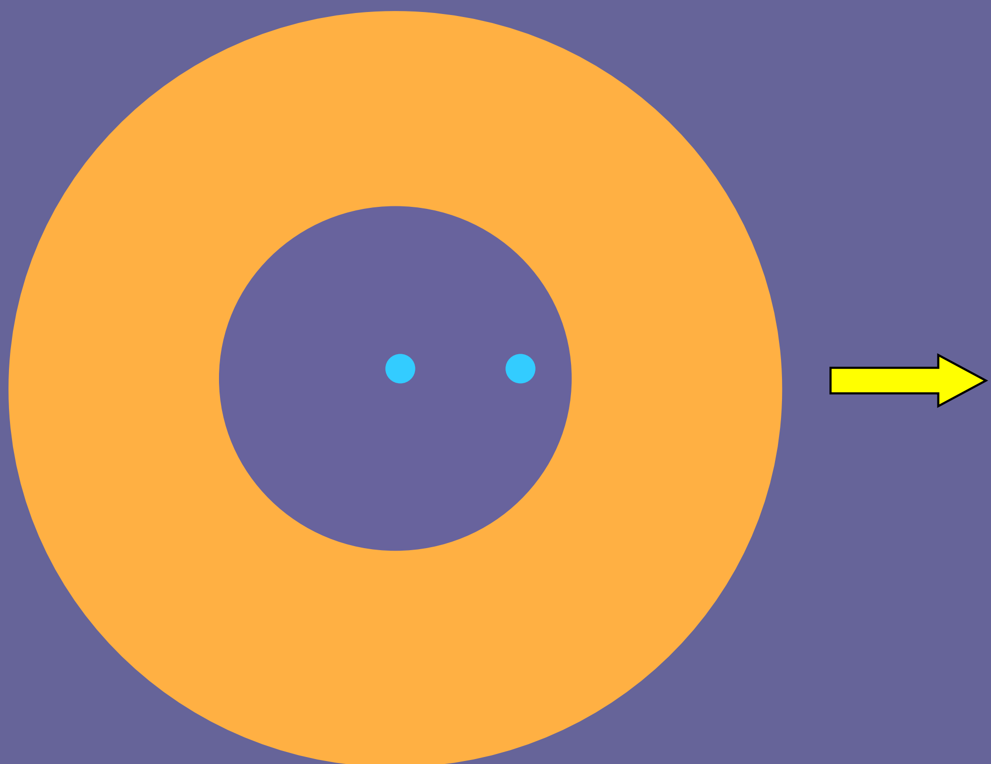
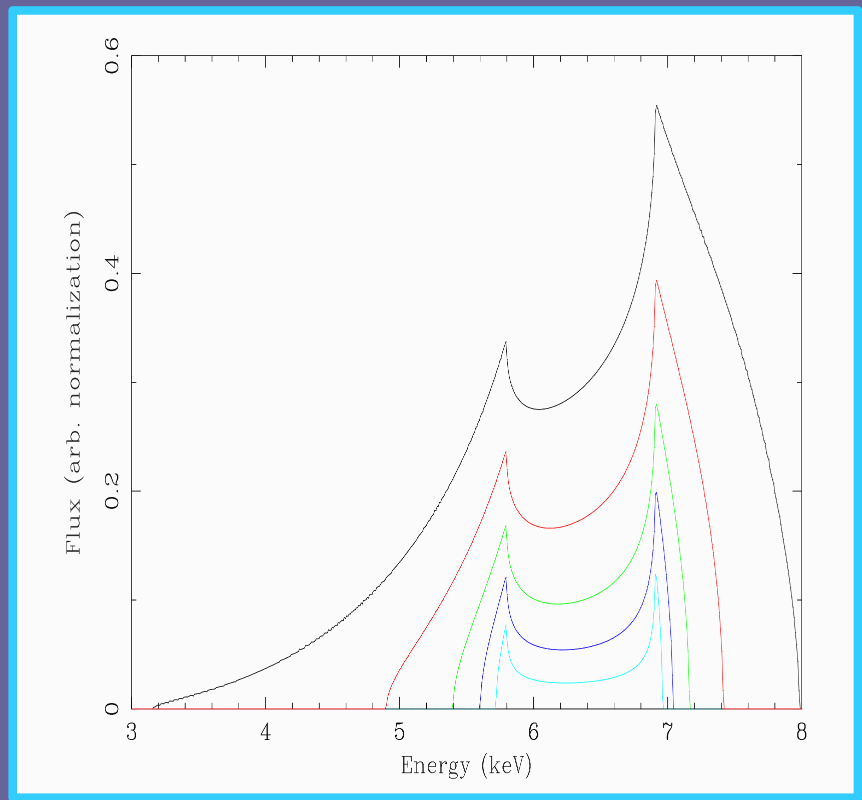


Relativistic FeKα line

Effect of central cavity: ‘clipped wings’

(McKernan et al. 2013)





R_{out}=100 R_g

Θ = 60 °

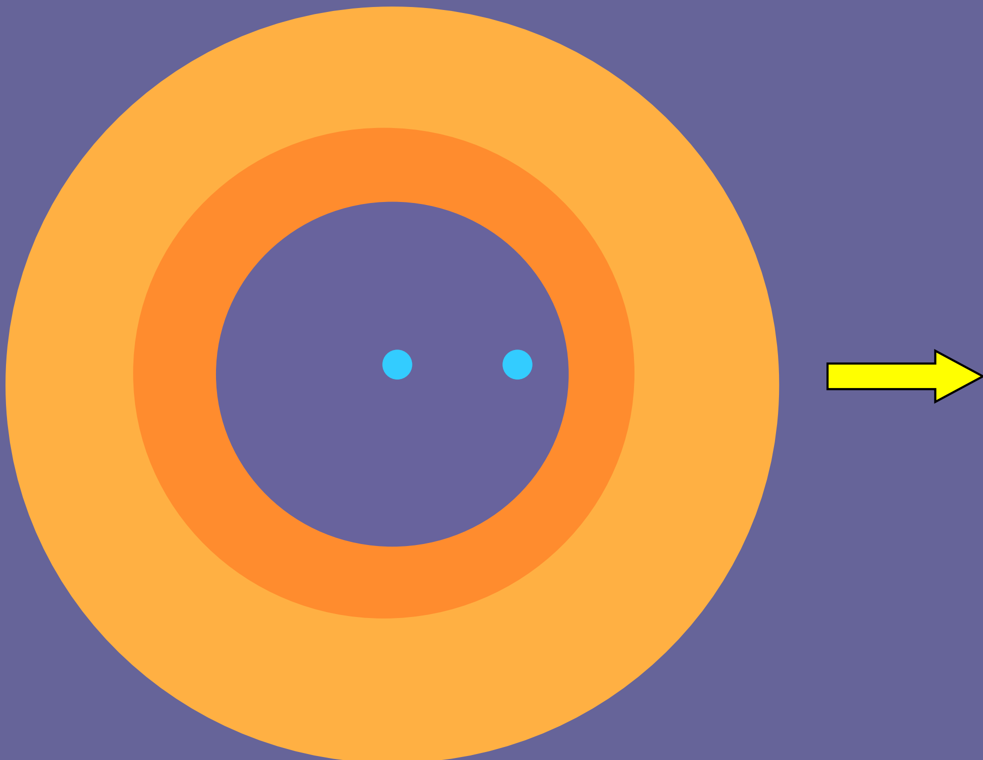
$\varepsilon(r) \sim r^{-2.5}$

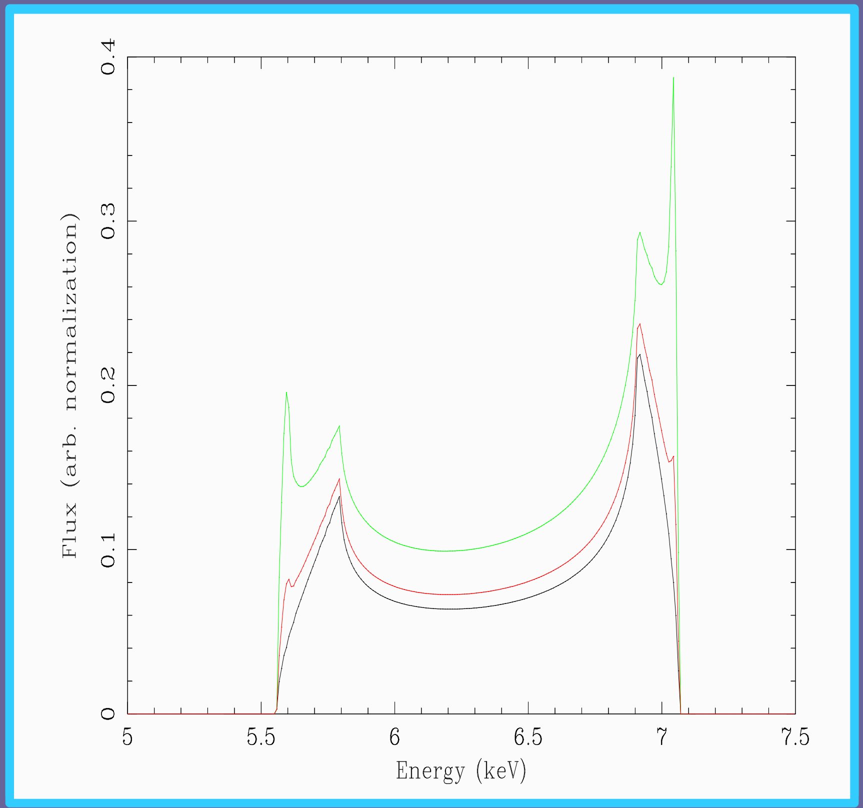
R_{in}=6, 20, 40, 60, 80 R_g

Relativistic FeKα line

Effect of central pile-up: 'double-twin horns'

(McKernan et al. 2013)





R_{out}=100 R_g

Θ = 60 °

$\varepsilon(r) \sim r^{-2.5}$

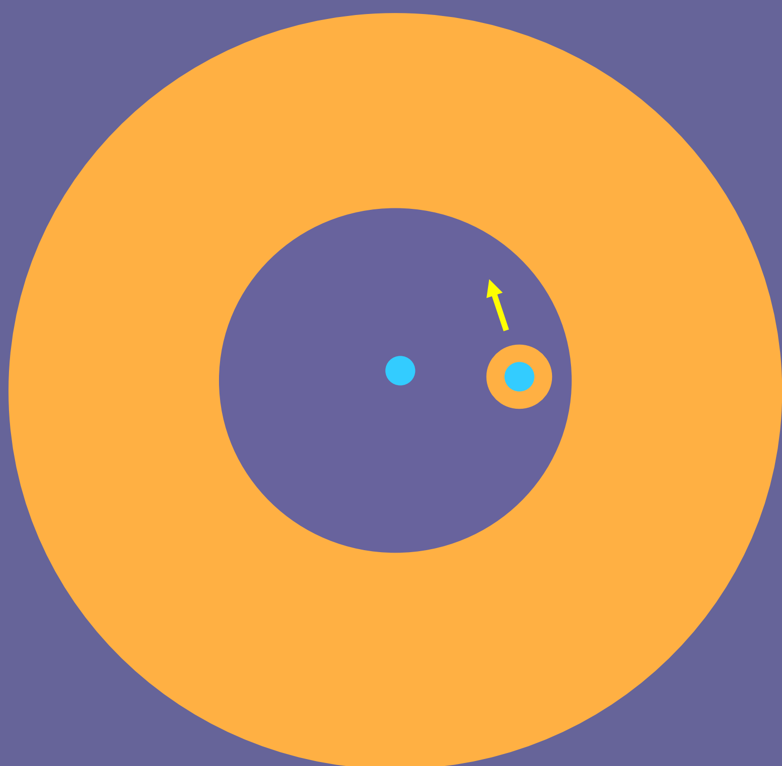
R_{in}=55 R_g

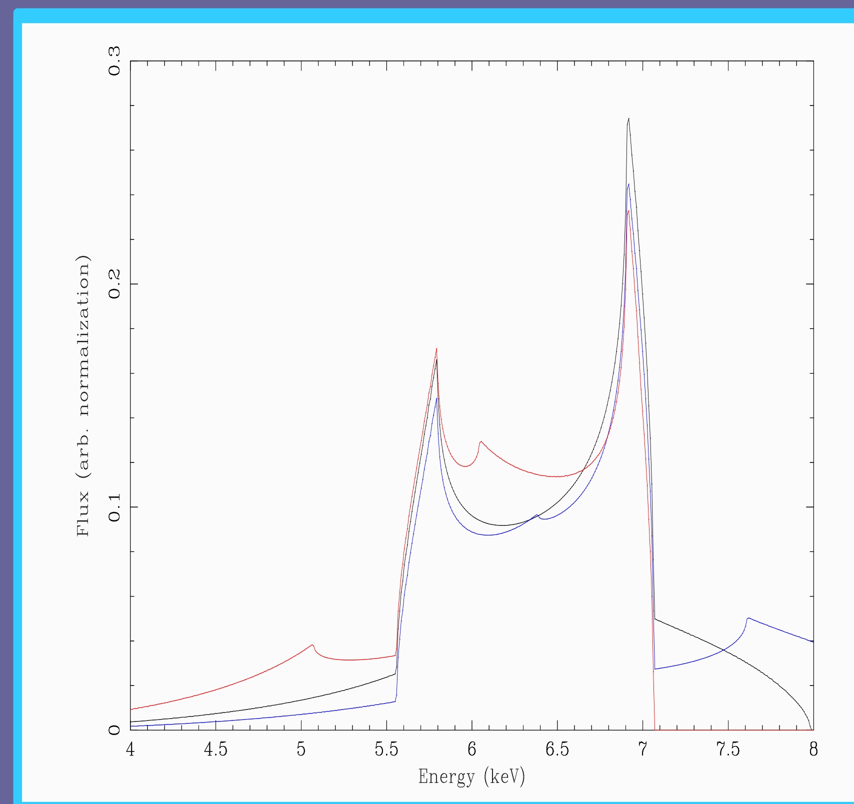
Pile-up by ×1, ×2, ×5

Relativistic FeKα line

Effect of circum-secondary minidisk: 'see-saw wings'

(McKernan et al. 2013)





R_{out}=100 R_g

Θ = 60°

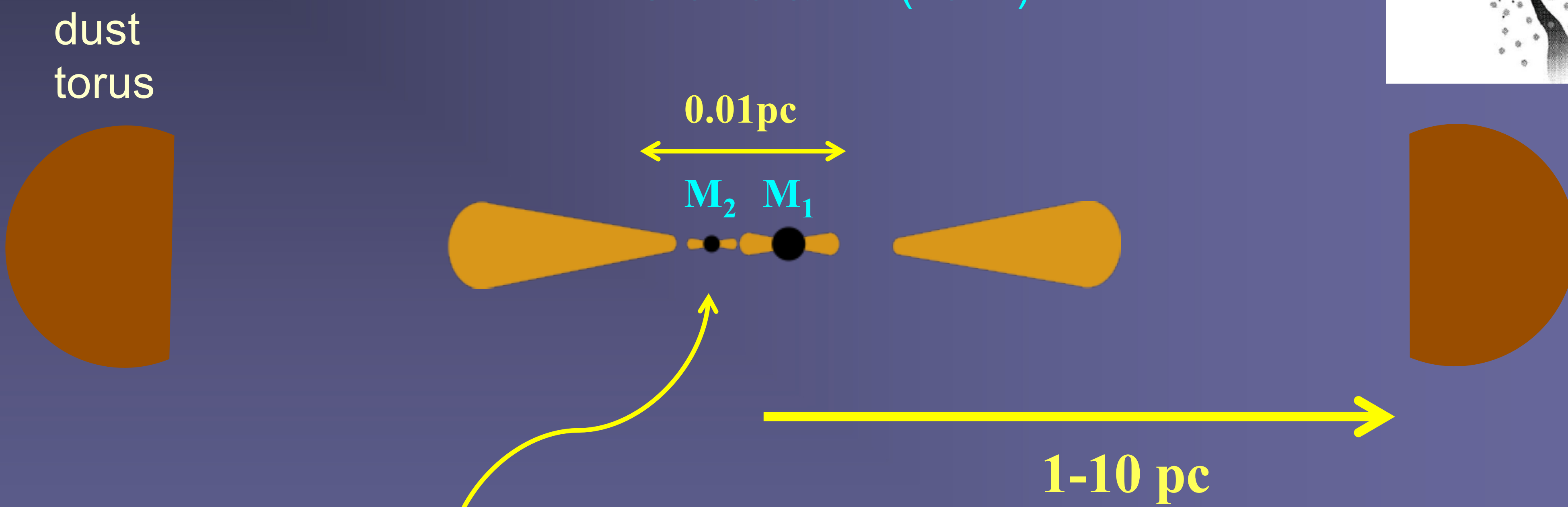
$\varepsilon(r) \sim r^{-2.5}$

R_{in}= 55 R_g

R_2= 30 R_g

Infrared Light(house) Echo

D'Orazio & ZH (2017)

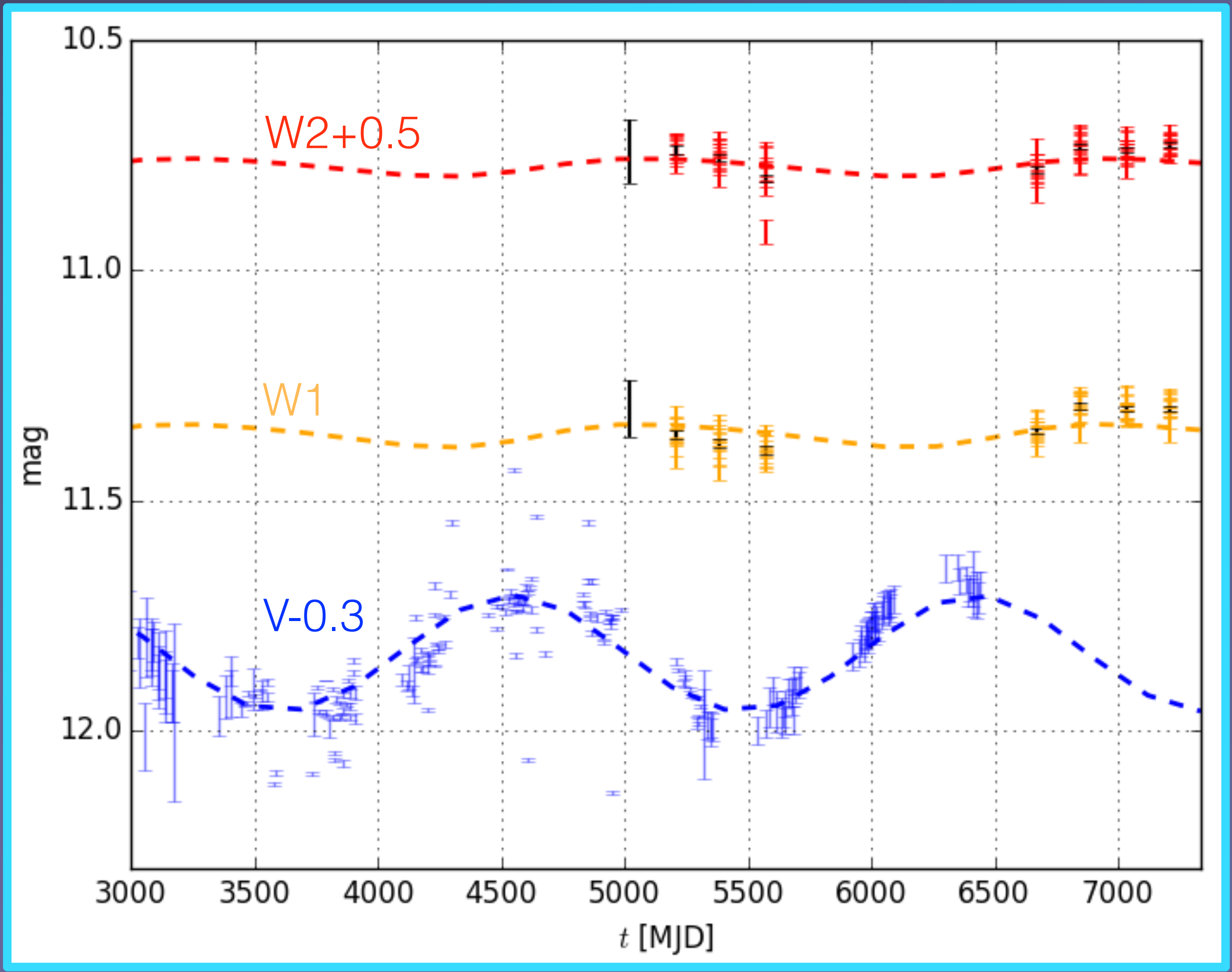


- Dust torus echoes optical/UV from central anisotropic source
- Expect periodic IR emission with:
  (1) time delay (years)
  (2) reduced amplitude

Infrared Echo

Jun et al. (2016): variability found in WISE data

consistent with echo from dust torus around Doppler-boosted binary



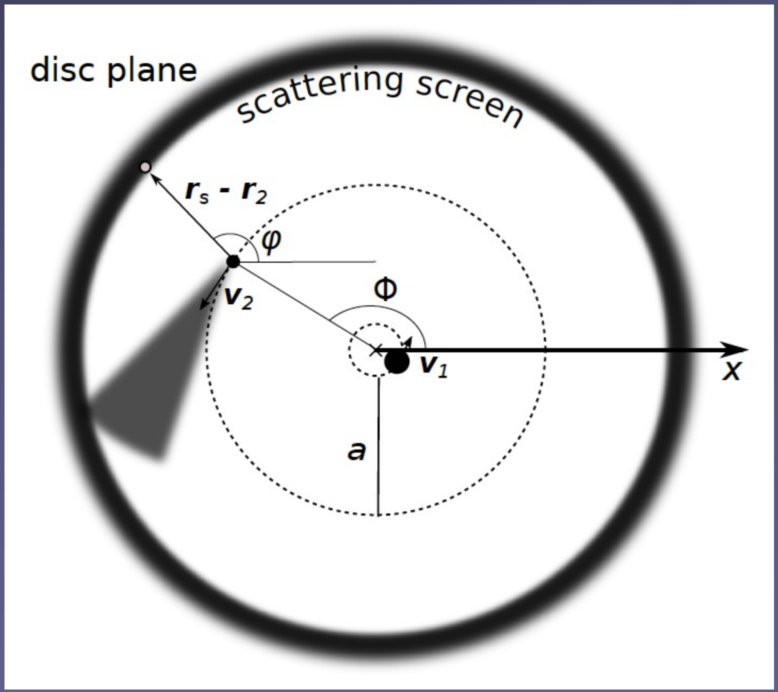
Optically thick torus with

R_T ~ 1-4 pc
Θ_T ~ 20 deg
i $\lesssim 70^\circ$ (not face-on)

D'Orazio & ZH (2017)

Polarization

Dotti, Bonetti, Dorazio, ZH, Ho. arXiv 2103.14652



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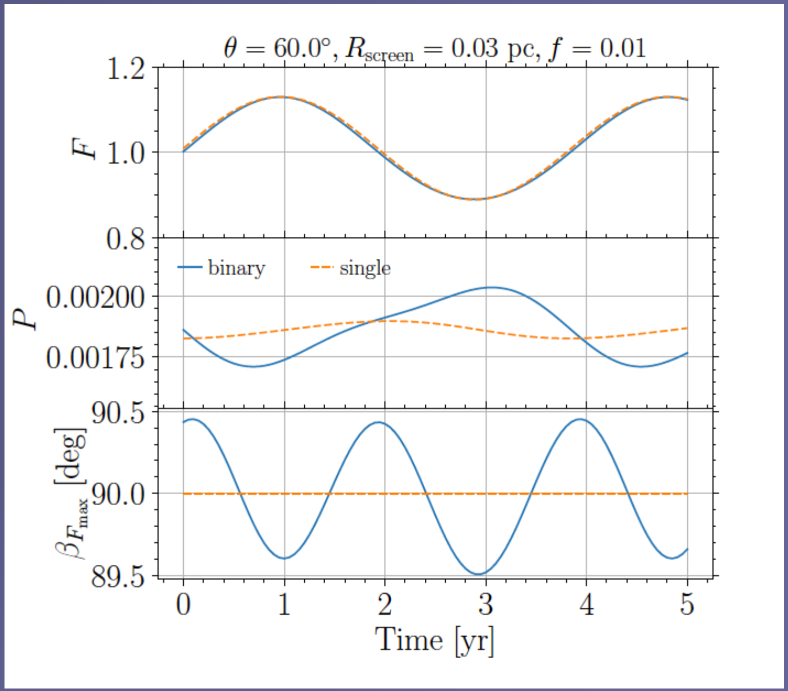
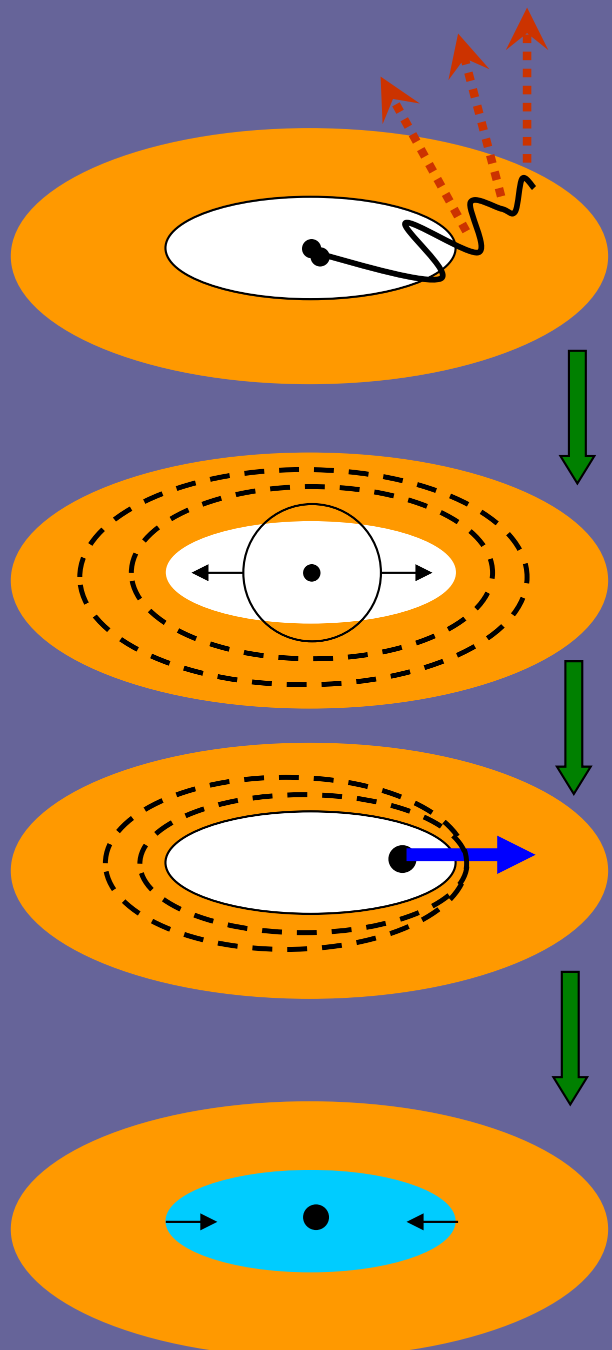


- Effects: periodic fluctuations, different scattering angle, anisotropic (Doppler) emission, time-delays
- Signatures: periodic fluctuation in both polarization fraction (*0.1-1 %)* and angle (*± 1 deg).* Polarization minimum at ~ peak of flux
- Orientation of orbit: from polarization angle on the sky

Signature III: Afterglow



GW dissipation — **+1 hr**

$t \approx R_{gap}/c$

(Kocsis & Loeb 2008)

Mass-loss - shocks — **+1 wk**

$t \approx (M/\Delta M)\, t_{orb}(gap)$

Recoil – shocks — **+1 mo**

$t \approx R_{gap}/v_{kick}$

Accretion afterglow — **+10 yr**

$t \approx t_{visc}(gap)$

Disk Response to Mass-loss & Recoil

Lippai, Frei & Haiman 2008; Shields & Bonning 2008; Schnittman & Krolik 2008

- **Properties of standard Shakura-Sunyaev accretion disk:**

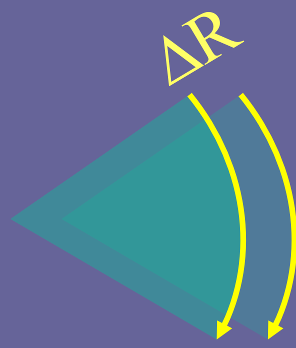
  — geometrically thin (cold) accretion disk, susceptible to shocks
  — inner cavity due to torques (out to ~100 R_s)
  — disk gravitationally unstable beyond ~10,000 R_s
  — v(orbit) ~ 20,000 km/s $\rightarrow$ 2,000 km/s
  — inner disk tightly bound to binary, outer disk weakly bound
  — disk mass low ($M_{disk} \sim 10^{-4} M_{BH}$): no effect on BH trajectory

- **Instant response of pressureless ("dark matter") disk:**

  — start with massless test particles on co-planar circular orbits
  — add instantaneous v(kick) and/or ΔM
  — Kepler orbits (ellipses)

Kick-Induced Caustics

Consider caustic formed from material with annulus $\Delta R \ll R$ and use epicyclic approximation:



epicyclic amplitude: $\Delta R \sim (v_{kick}/v_{orbit}) \times R$

caustic forms at time: $t \sim [(d\Omega/dR) \times \Delta R]^{-1}$

$\rightarrow t \sim [(d\Omega/dR) \times (v_{kick}/v_{orbit}) \times R]^{-1}$

use $d\Omega/dR \propto \Omega/R$

$\rightarrow t \sim [\Omega\,(v_{kick}/v_{orbit})]^{-1} = \mathbf{R/v_{kick}}$

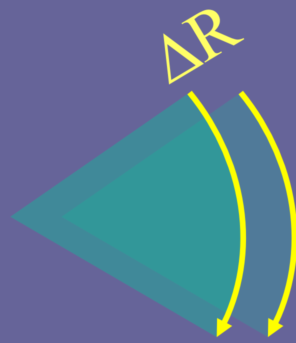
propagation speed: $\mathbf{R/t = v_{kick}}$ **(CONSTANT)**

collision speed: $\mathbf{v_{shock}} \sim \Delta R/t \sim \Delta R/(R/v_{kick}) \sim \mathbf{v_{kick}^2/v_{orbit}}$

(INCREASES OUTWARD)

Mass-Loss Induced Caustics

Impact of mass loss comparable to kick out to a radius where $\Delta M/M \approx v_{kick}/v_{orbit}$. Transition near cavity edge (few 100 R_s).



epicyclic amplitude: $\Delta R \sim (\Delta M/M) \times R$

caustic forms at time: $t \sim [(d\Omega/dR)\times\Delta R]^{-1}$

$\rightarrow t \sim [(d\Omega/dR) \times (\Delta M/M) \times R]^{-1}$

use $d\Omega/dR \propto \Omega/R$

$\rightarrow t \sim [\Omega\,(\Delta M/M)]^{-1} \sim (\Delta M/M)^{-1} R^{3/2}$

propagation speed: $\mathbf{R/t \sim (\Delta M/M)\, R^{-1/2}}$ **(SLOWS DOWN)**

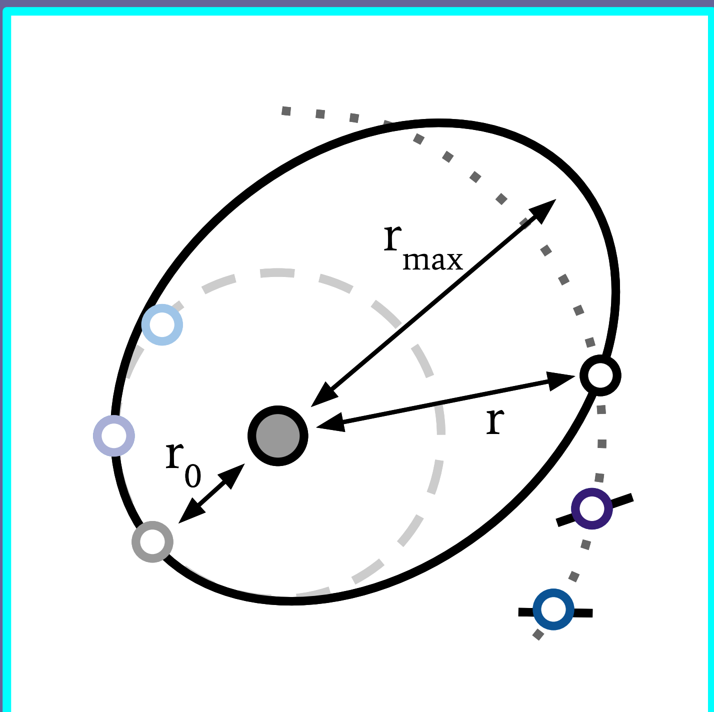
collision speed: $\mathbf{v_{shock}} \sim \Delta R/t \sim (\Delta M/M)^2 R^{-1/2} \sim \mathbf{(\Delta M/M)^2\, v_{orbit}}$

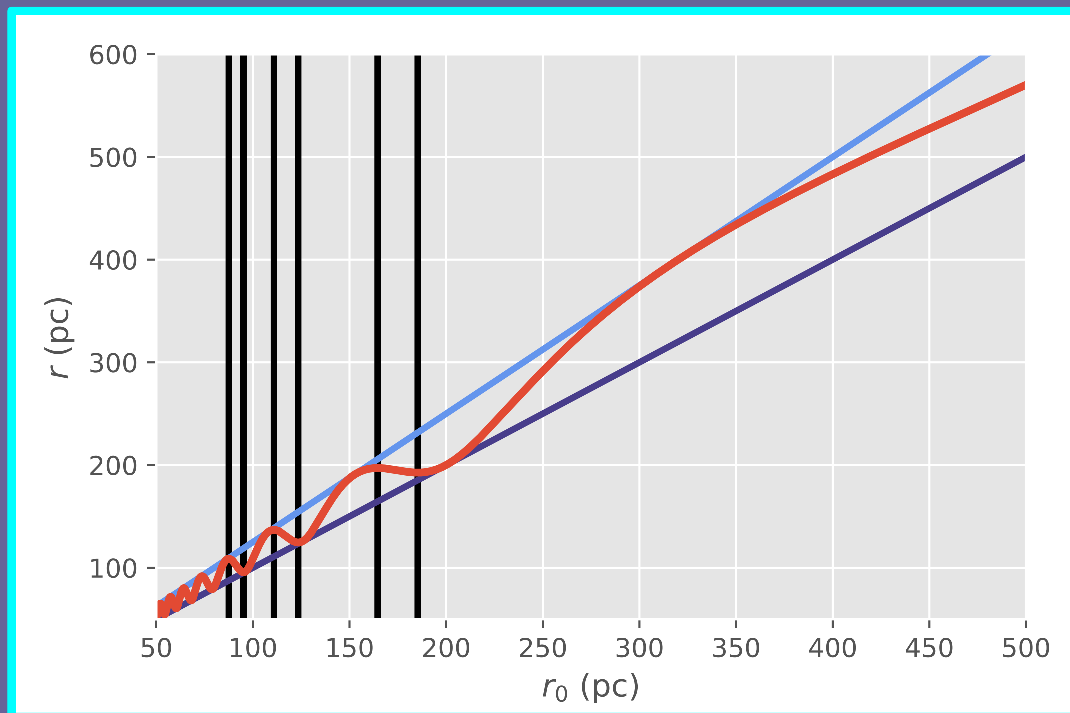
(DECREASES OUTWARD)

Mass-Loss Induced Caustics

Analytic solution for location of caustics

Penoyre & ZH 2018



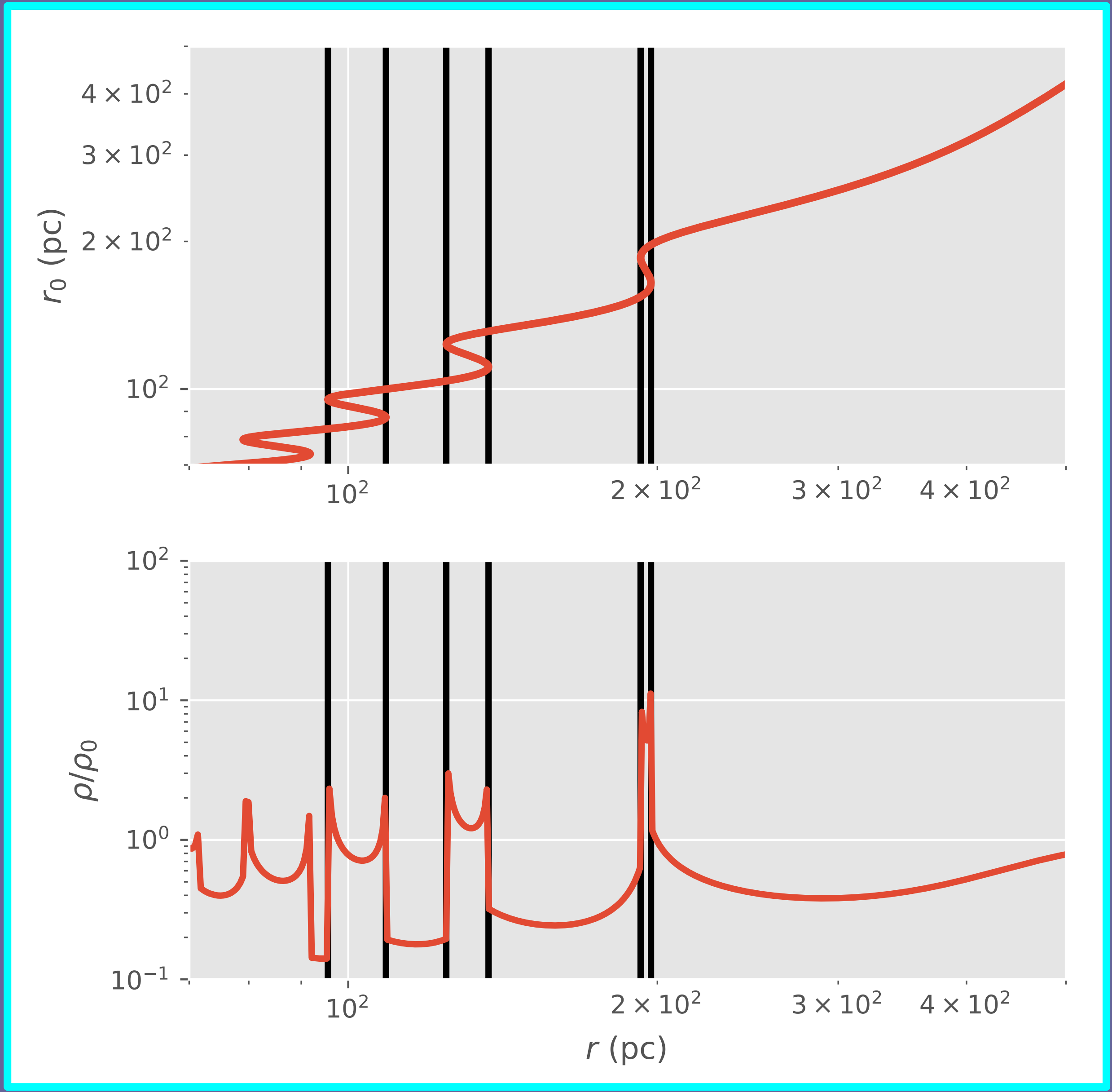


Density profile:

$$\rho(r,t) = \sum_{r_i(r_0,t)=r} \left|\frac{dV_0}{dV}\right|_{r_i} \rho_0(r_{0,i}).$$

$$\left|\frac{dV_0}{dV}\right| = \frac{r_0^2}{r^2}\left|\frac{dr_0}{dr}\right|.$$

Mass-Loss Induced Caustics



Shock formation in post-merger disk

Corrales, MacFadyen & Haiman (2009);
O'Neill et al. (2009), Megevand et al. (2009); Rossi et al. (2009)

- **Sudden 'shaking' of disk launches prompt sound waves**
- **Sound waves can steepen into shocks**
- **2D hydro simulation:**

— adaptive mesh refinement (AMR) code FLASH

— $M_{BH} = M_1 + M_2 = 10^6\ M_\odot$ $\quad$ $R_{cavity} = 100\ R_s = 2$ AU

— $v_{kick} = 500$ km/s (in the plane)

— equation of state: isothermal or non-radiative ("adiabatic")

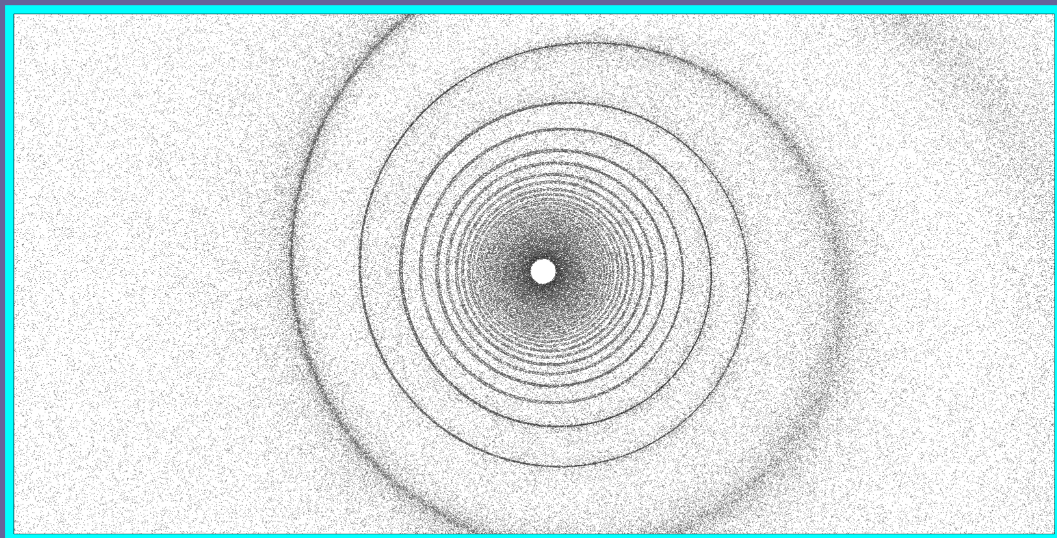
— $t_{cavity} = R_{cavity} / v_{kick} = 7$ days

- **Estimate energy dissipation and "light curve"**

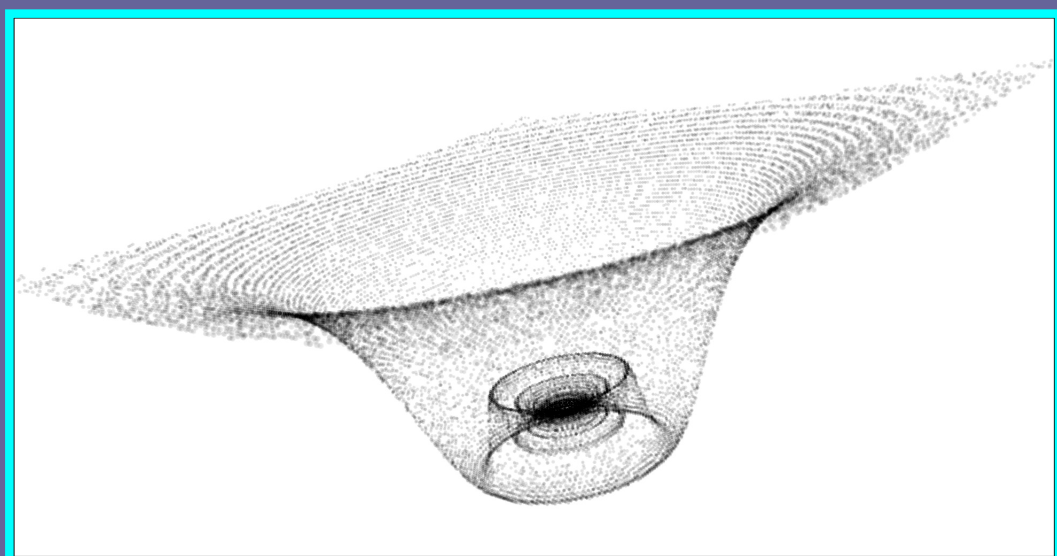
— compute pdV work from isothermal vs. non-radiative runs

— corresponds to assuming rapid cooling (marginally justified)

Post-merger Disk response: R3B

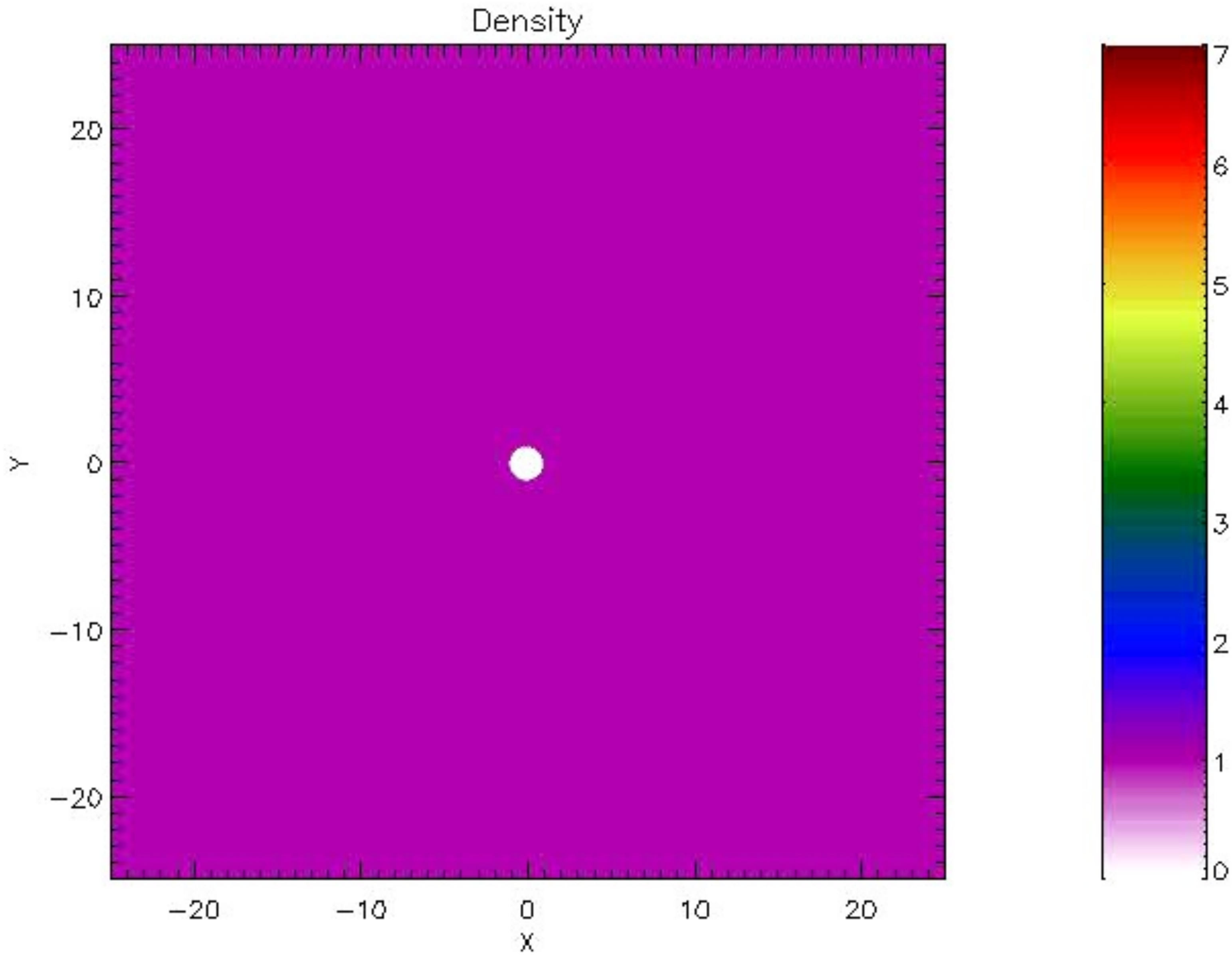


recoil in disk plane



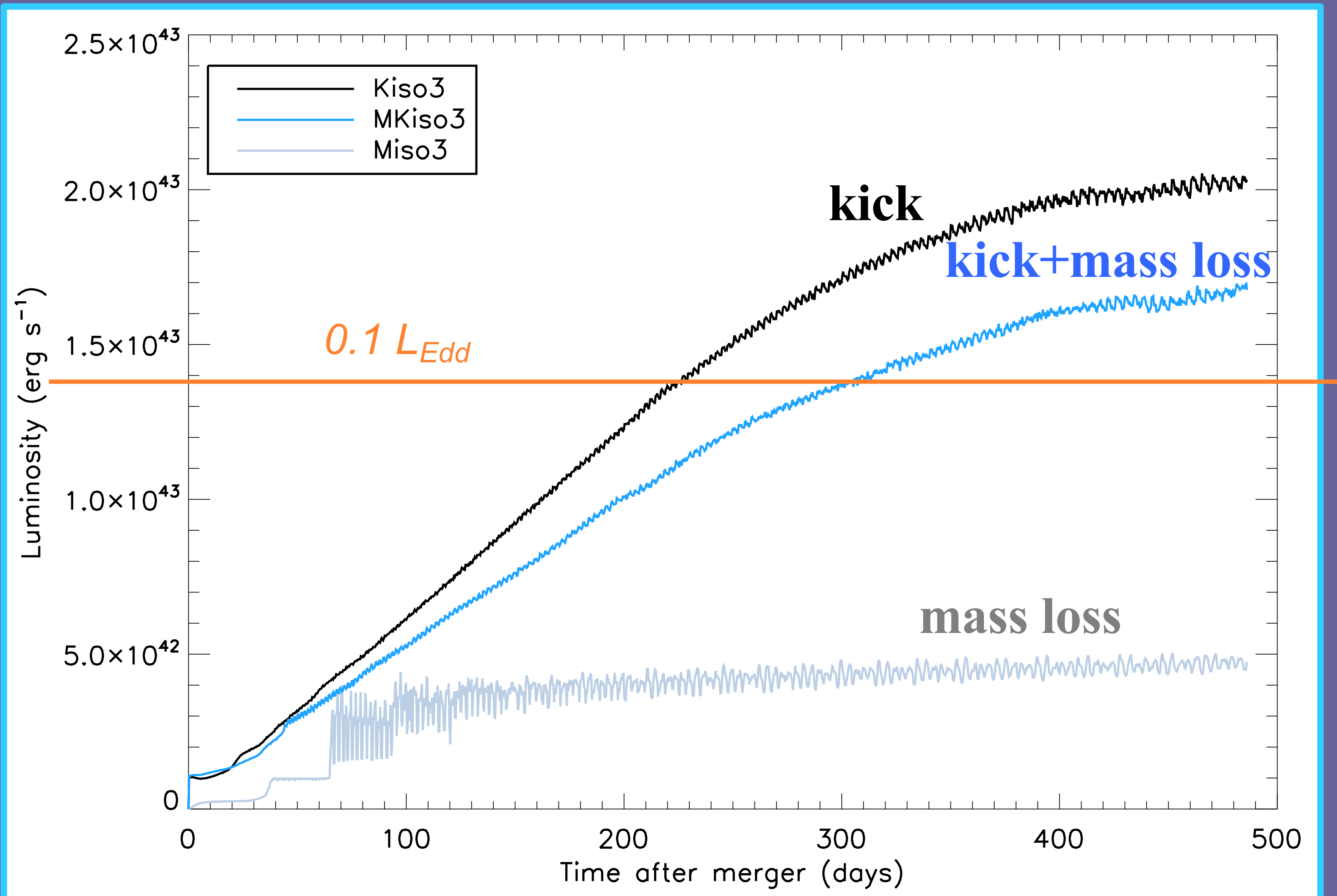
recoil $\perp$ to disk plane

Lippai, Frei & ZH 2008

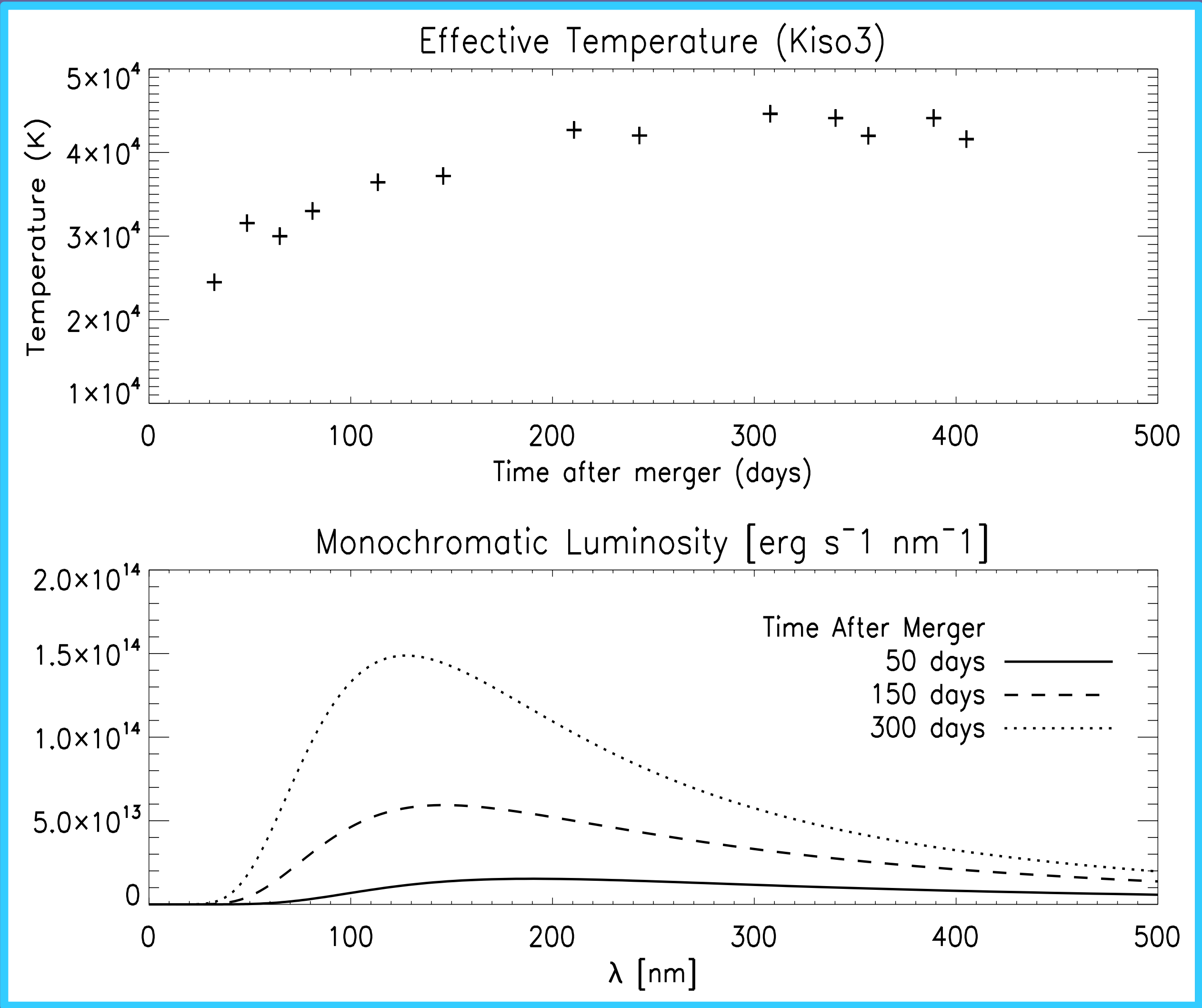


time = 0.000 ps
number of blocks = 7808
AMR levels = 5

Disk Light Curve (“afterglow”)



Afterglow Spectrum



Standard accretion disks are optically thick (τ~few × 10^3) at ~10^3 R_s

Sum black-body emission from each patch of the disk

- ***emission peaks in UV***
- ***tell-tale signature: disk hardens AND brightens with time***

Can gas affect gravitational waveforms?

- **Consider BH binary in gravitational inspiral stage**

  - Pulsar timing arrays $M=10^{8\text{-}9}M_\odot$
  - LISA: $M=10^{4\text{-}7}M_\odot$
  - advanced LIGO (stellar-mass BHs)

- **Many previous works on impact of ambient gas**

  - hydrodynamical drag, accretion onto BHs, migration

  (Kocsis et al. 2011; Barausse et al. 2014)

- **Order-unity impact on massive PTA binaries**

  - typical binary is observed near 'decoupling', at O(100 R_S*) separation*

  (Tanaka et al. 2014; Roedig et al. 2014)

- **Effects less important near merger (LISA) except for E/IMRIs**

  - 1% speed up in decay rate in LISA regime (10^3 *fewer cycles)*

  (Yunes et al. 2011)

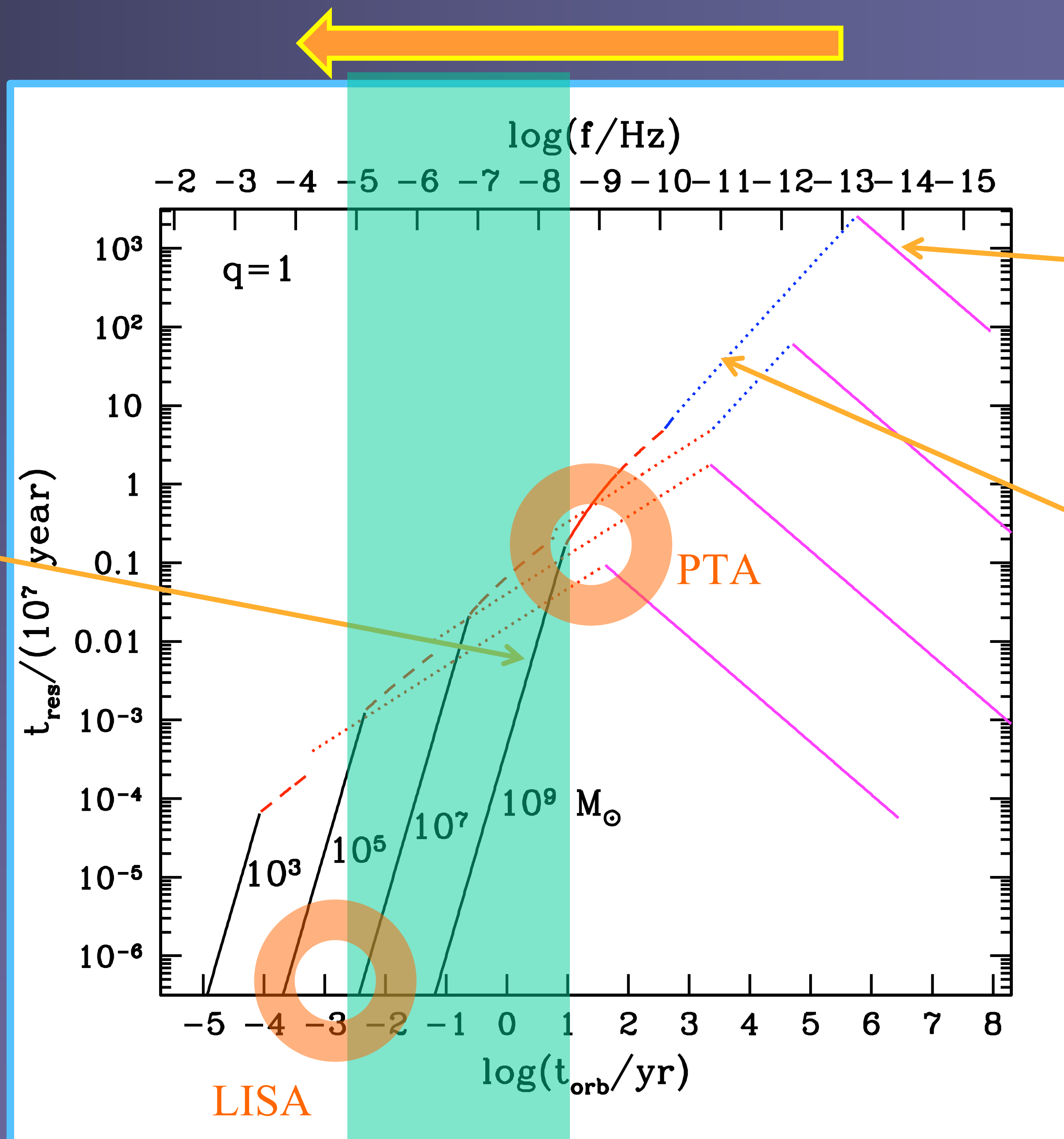
- **Sign of effect is reversed: few % more cycles**

  - for inspirals with $q>10^{-4}$ *(EMRIs or IMBH-SMBH coalescence)*

Are gas torques important in GW band?

“Final parsec” bottleneck (Begelman Blandford & Rees 1984)

GW-driven decay



Stellar Scattering driven decay

Gas disk Driven decay

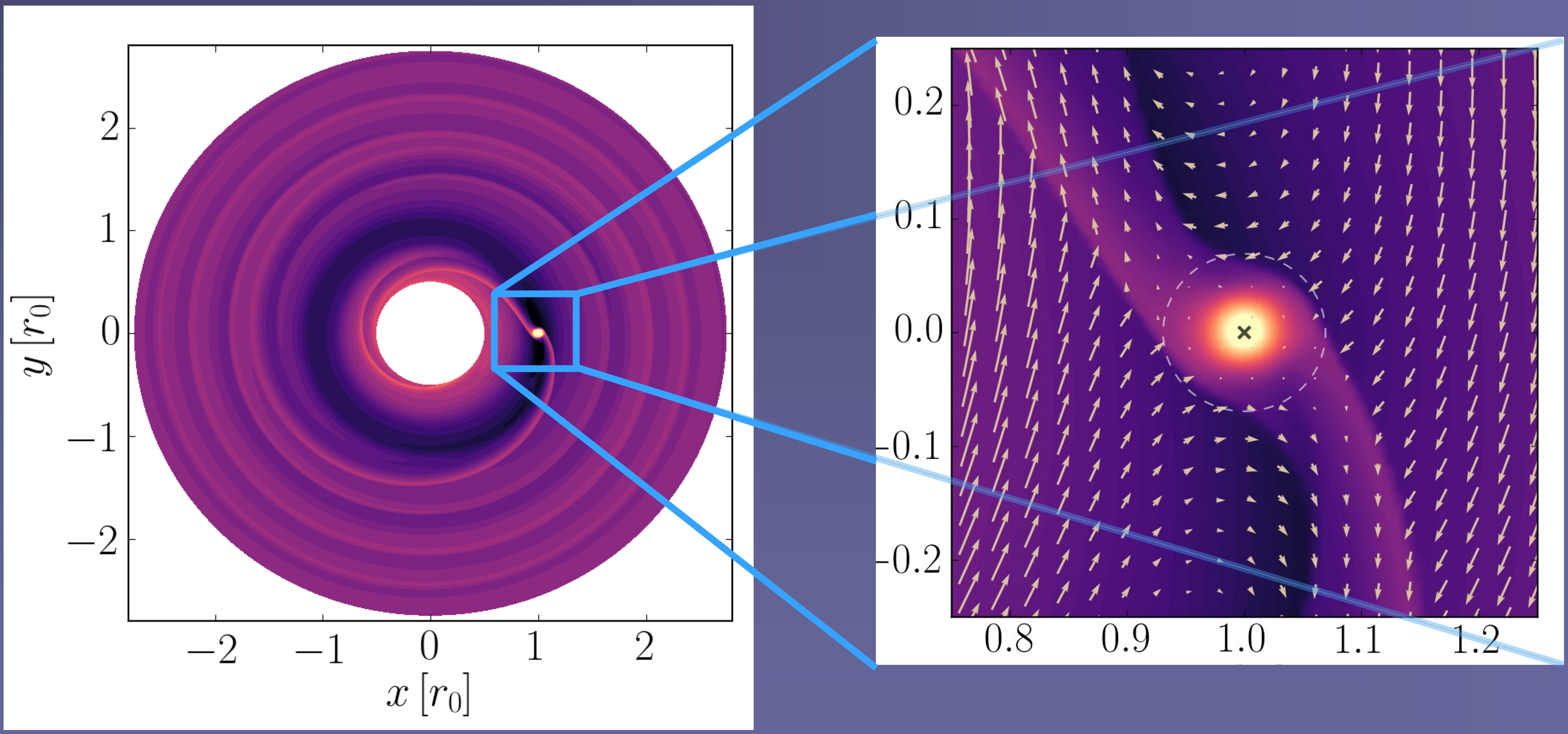
[sensitive to accretion disk model]

ZH, Kocsis, Menou (2009)

Can gas affect gravitational waveforms?

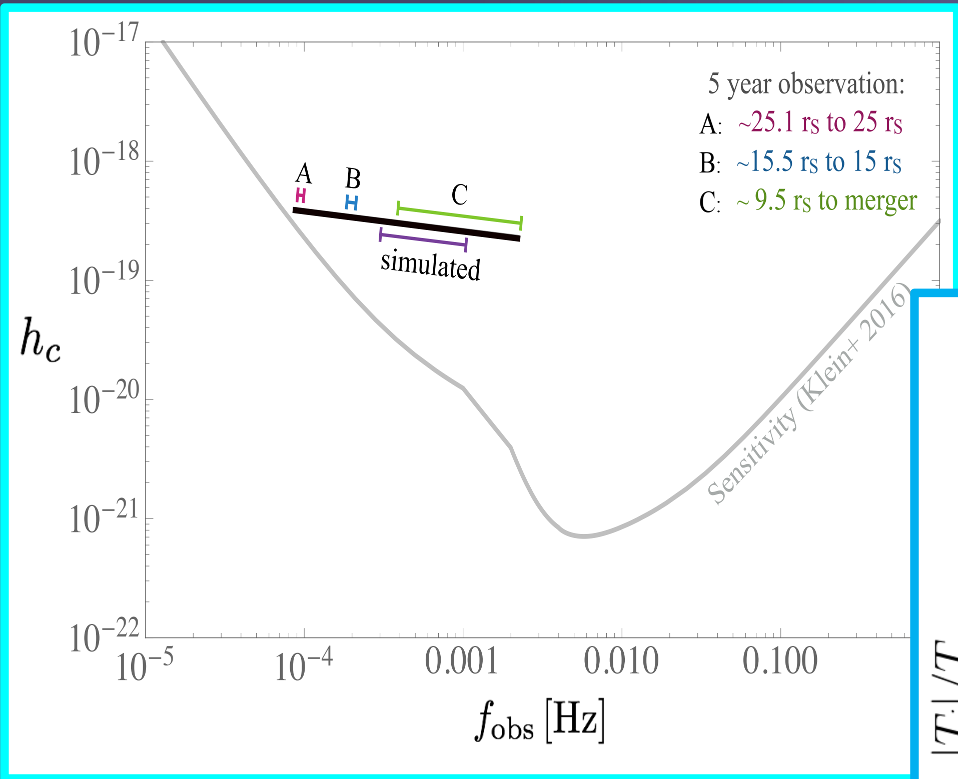
Derdzinksi et al. (2019,2021)

simulation of EMRI with $q=10^{-3}$

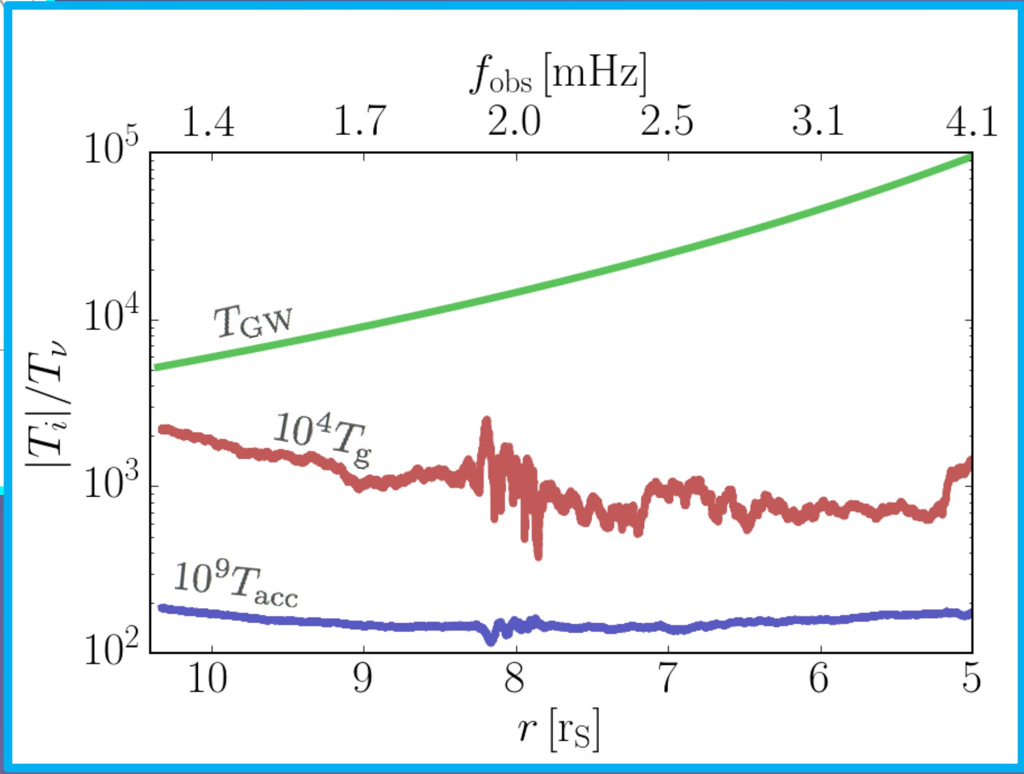


Gas impact on LISA EMRIs

Derdzinksi et al. (2019)



Effect of fiducial disk: decelerate inspiral by 0.01 % → few extra cycles



Detectable for $\Sigma \gtrsim 10^{2\text{-}3}$ g cm^{-2}

Conclusions

1. SMBH binaries can be bright: gas accretion rate into cavity via streams is not reduced by the binary "propeller"
2. Emission from minidisks+ cavity strongly periodic for q > 0.04

   -- // --

3. 150 periodic quasars discovered in optical: binary candidates
4. UV + optical data for PG 1302 consistent with periodicity from Doppler-boosted emission from a less-massive secondary BH
5. This would allow clean measurement of GW vs EM time delay

   -- // --

6. Unusual afterglow due to GW mass loss and recoil lasts from weeks to months, hardening and brightening over time

The End