# Using Photons to Find (or Not Find) Supermassive Binary Black Holes

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# Electromagnetism—the Wonder Force

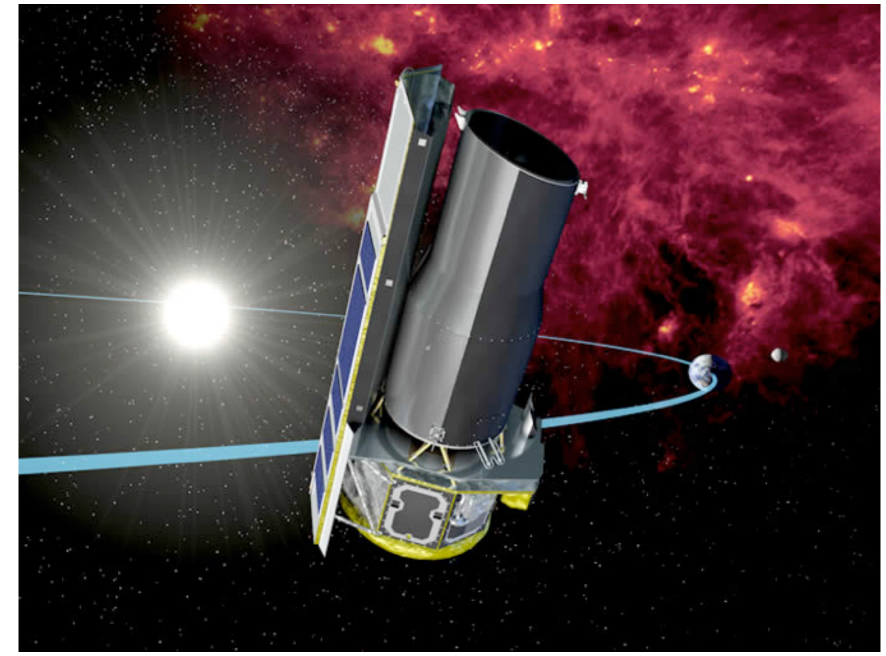
Spin1, massless excitations $10^{36}$ x gravity!

Some charge carriers with rest-mass only $5 \times 10^{-4}$ GeV—>
very easily accelerated

Broad-band scattering from common materials—>
focusing optics, wave optics spectroscopy

Significant inelasticity in scattering—> Easy detection eLISA launch: 2034??

Multiple photon telescopes operational NOW

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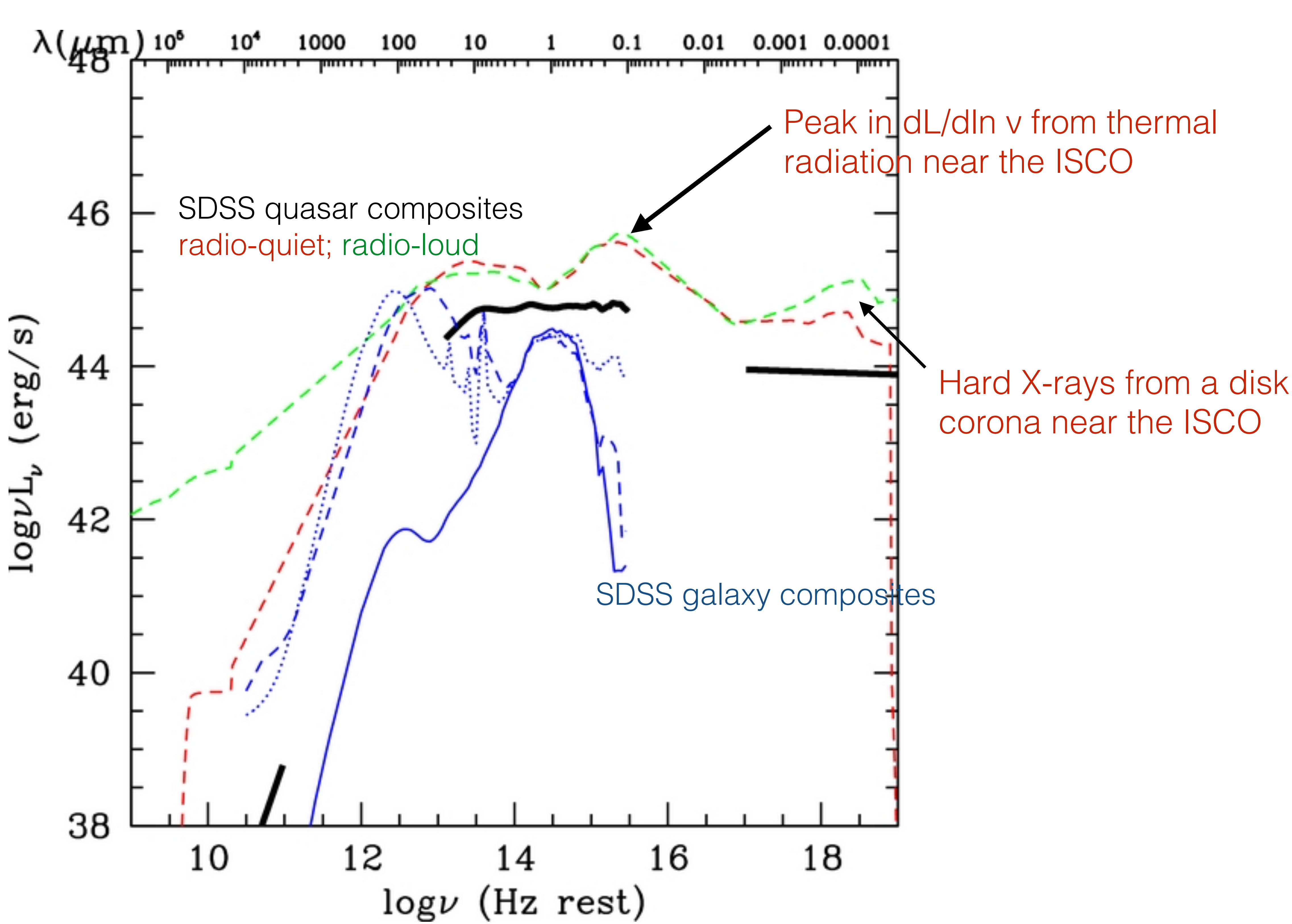
# Problem: Distinguishing Binary from Solitary Supermassive Black Holes

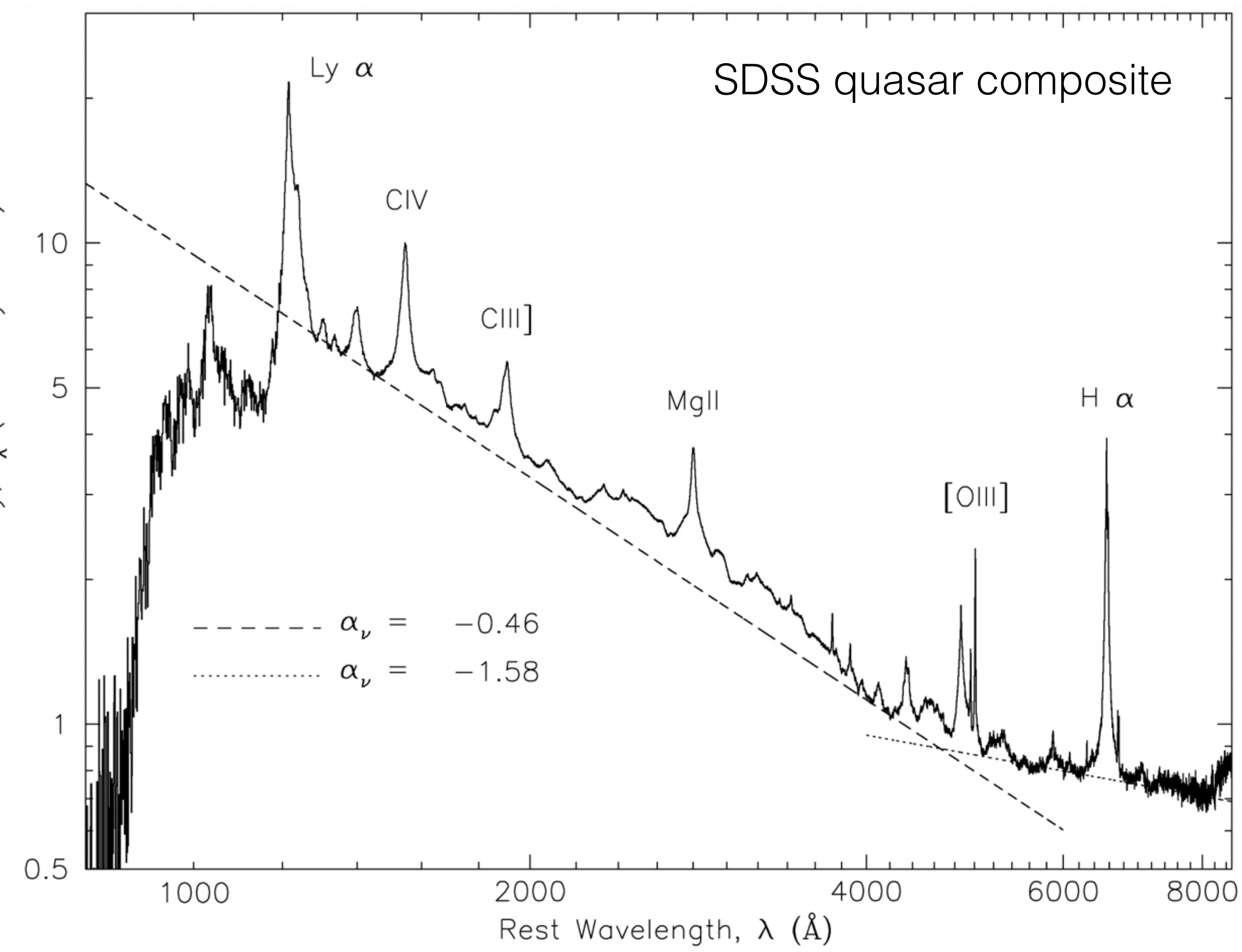
Features of solitary supermassive black holes:

Most dark, detectable only inferentially via gravitational effects on surrounding stars or by weak radio/sub-mm emission (next talk)

At present, several percent extremely bright (AGN: quasars, Seyfert galaxies, etc.); sometimes extended jets, particularly visible in radio dL/d ln ν ~ const. from ~100 μ to ~100 keV + weaker radio; for some, substantial power to ~ TeV

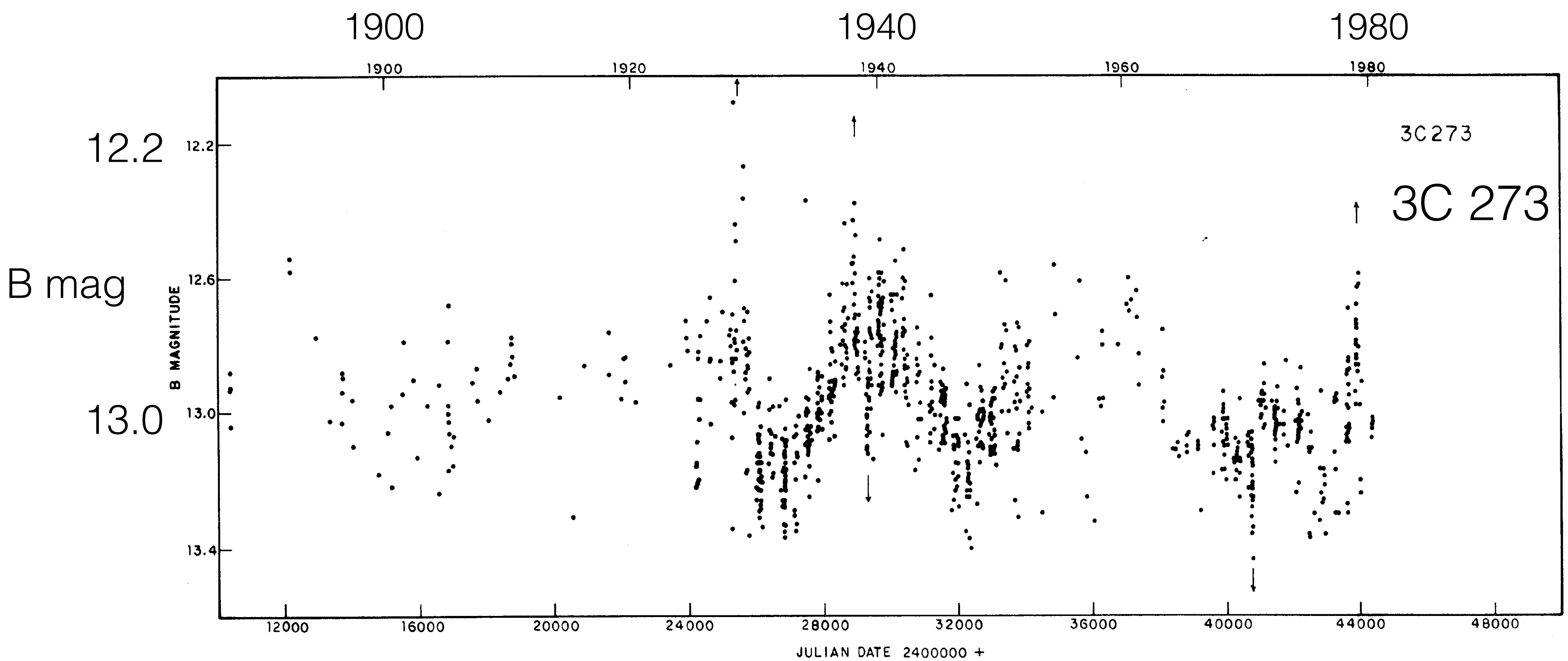


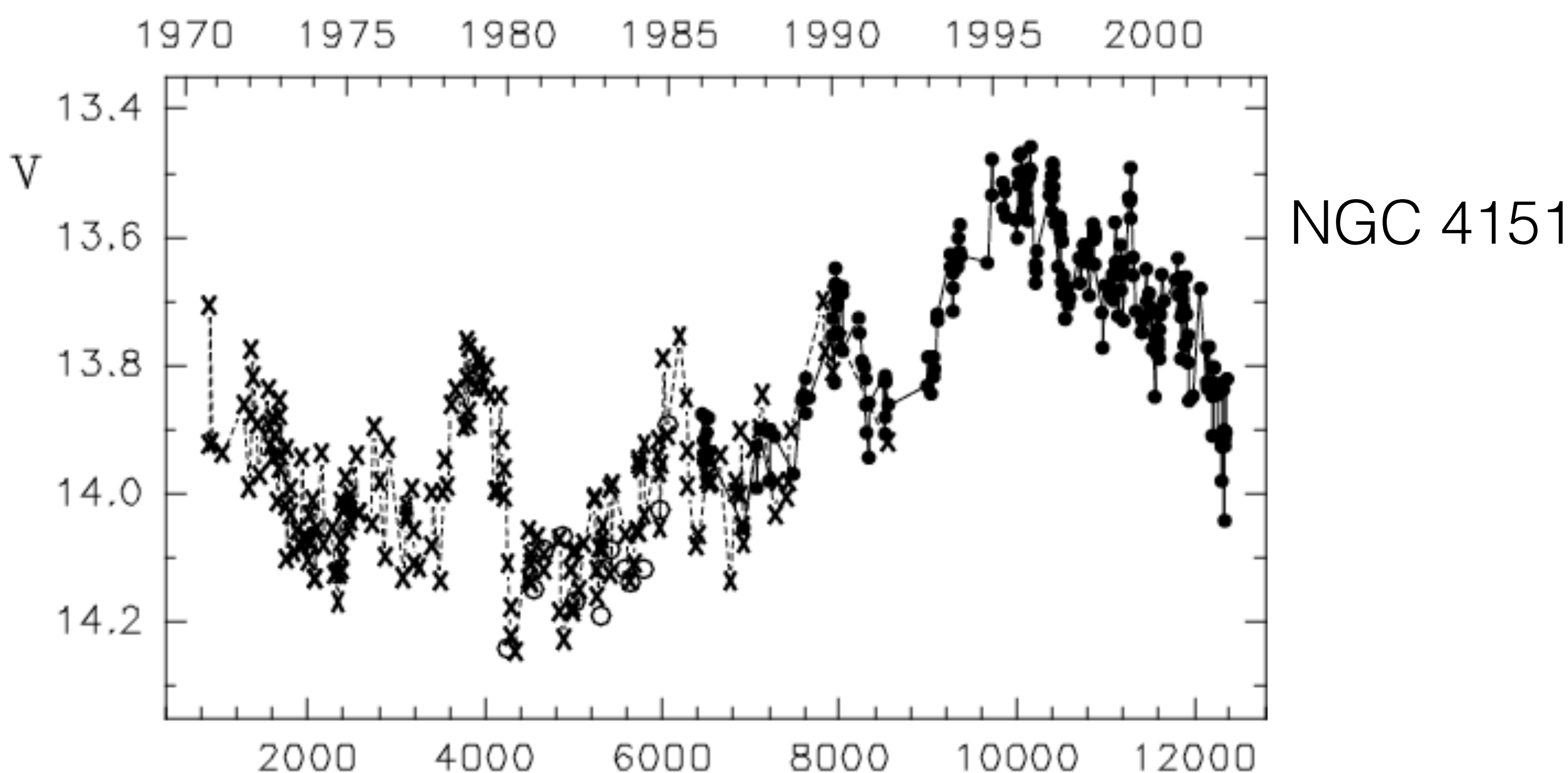
## Emission lines: optical/UV, $\Delta v/c \sim 10^{-3}$; often also $\sim 10^{-2}$; 6.4 keV Fe Kα, $\Delta v/c \sim 1$




If motions of broad line material are gravitational (?), $r_{BLR} \sim 10^4\ r_g$

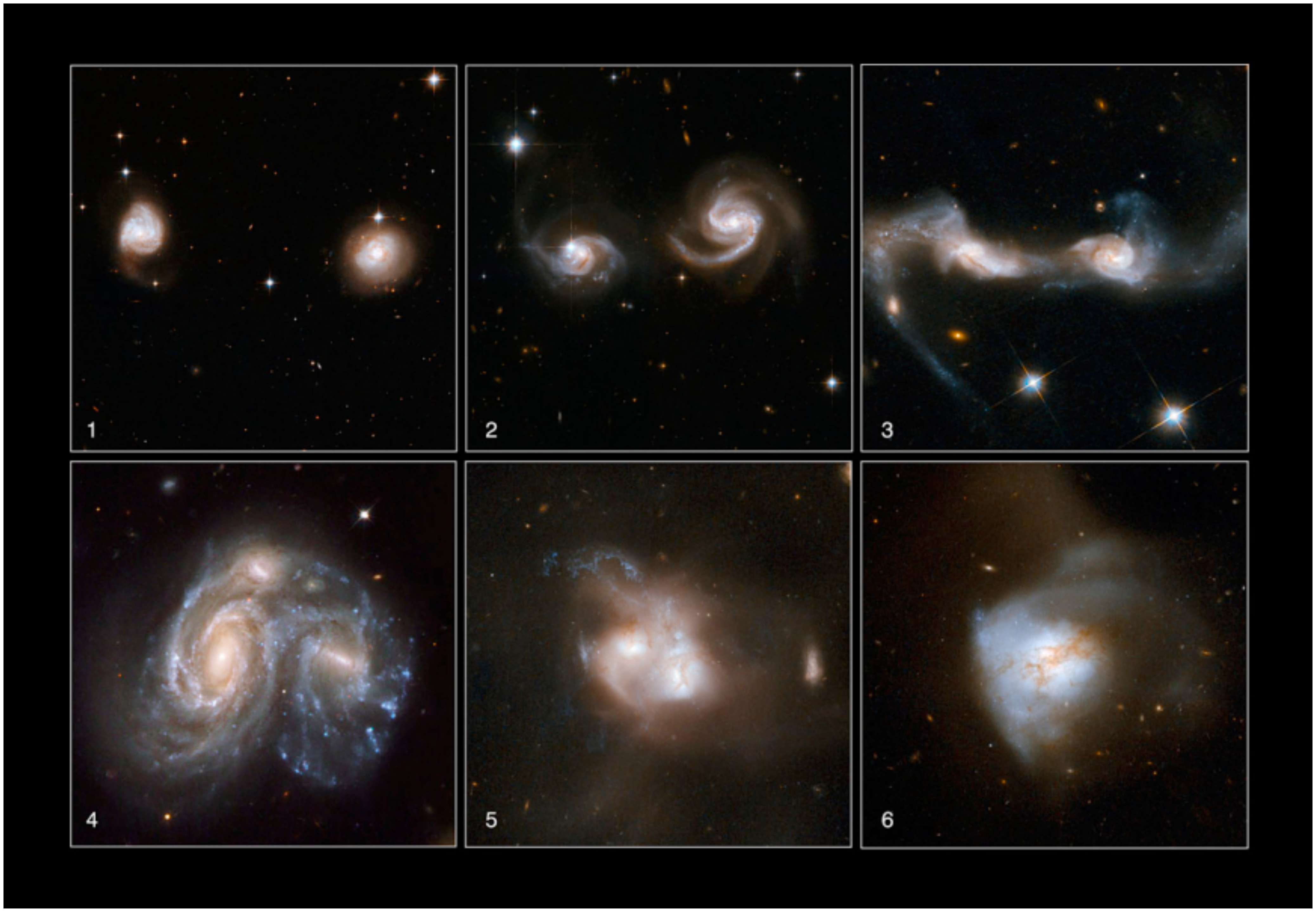
# Variable: “red noise” power spectra; for some, larger, coherent fluctuations



# How Binary Supermassive Black Holes Might Differ

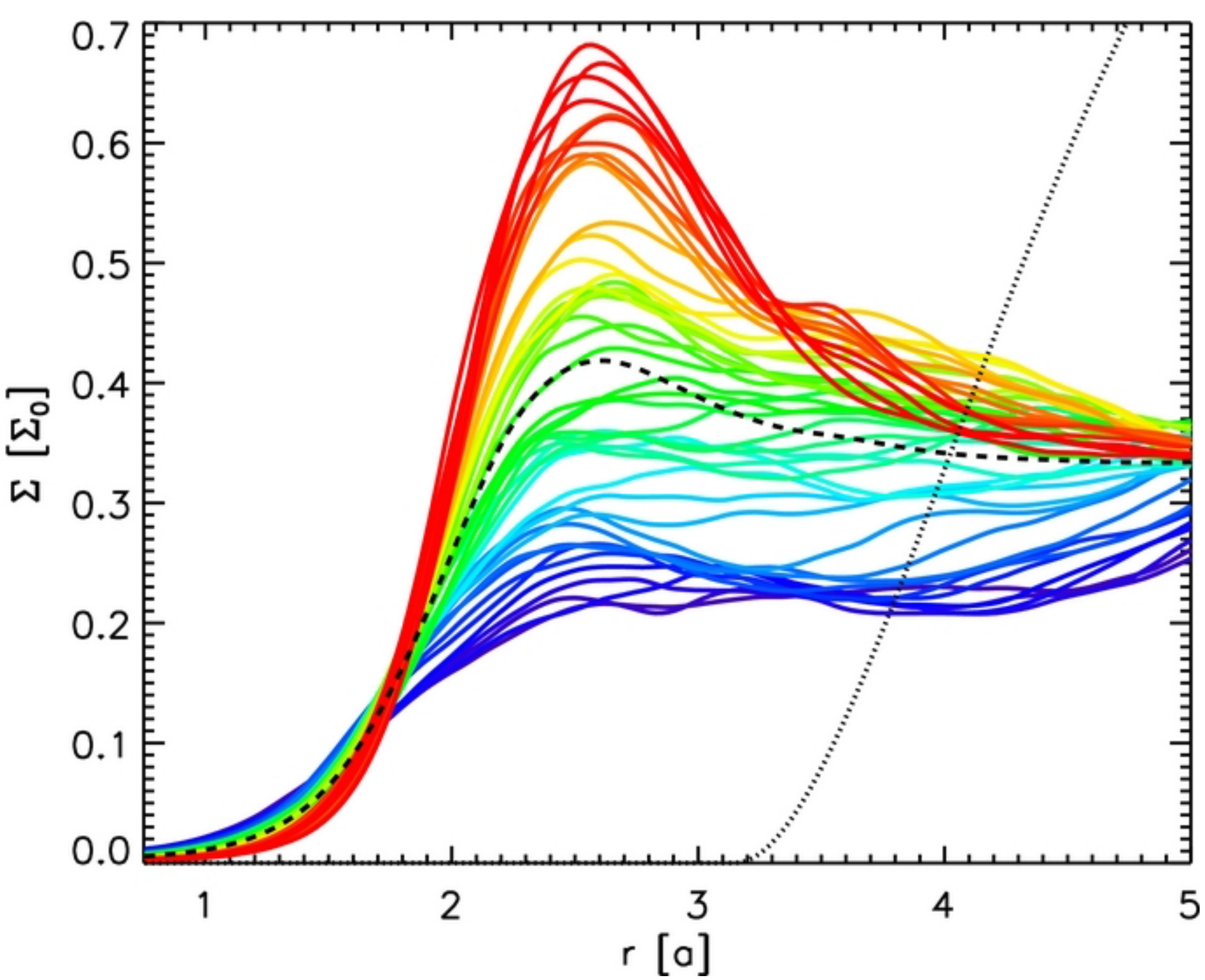
# Supermassive Black Hole Binaries Form after Galaxy Mergers

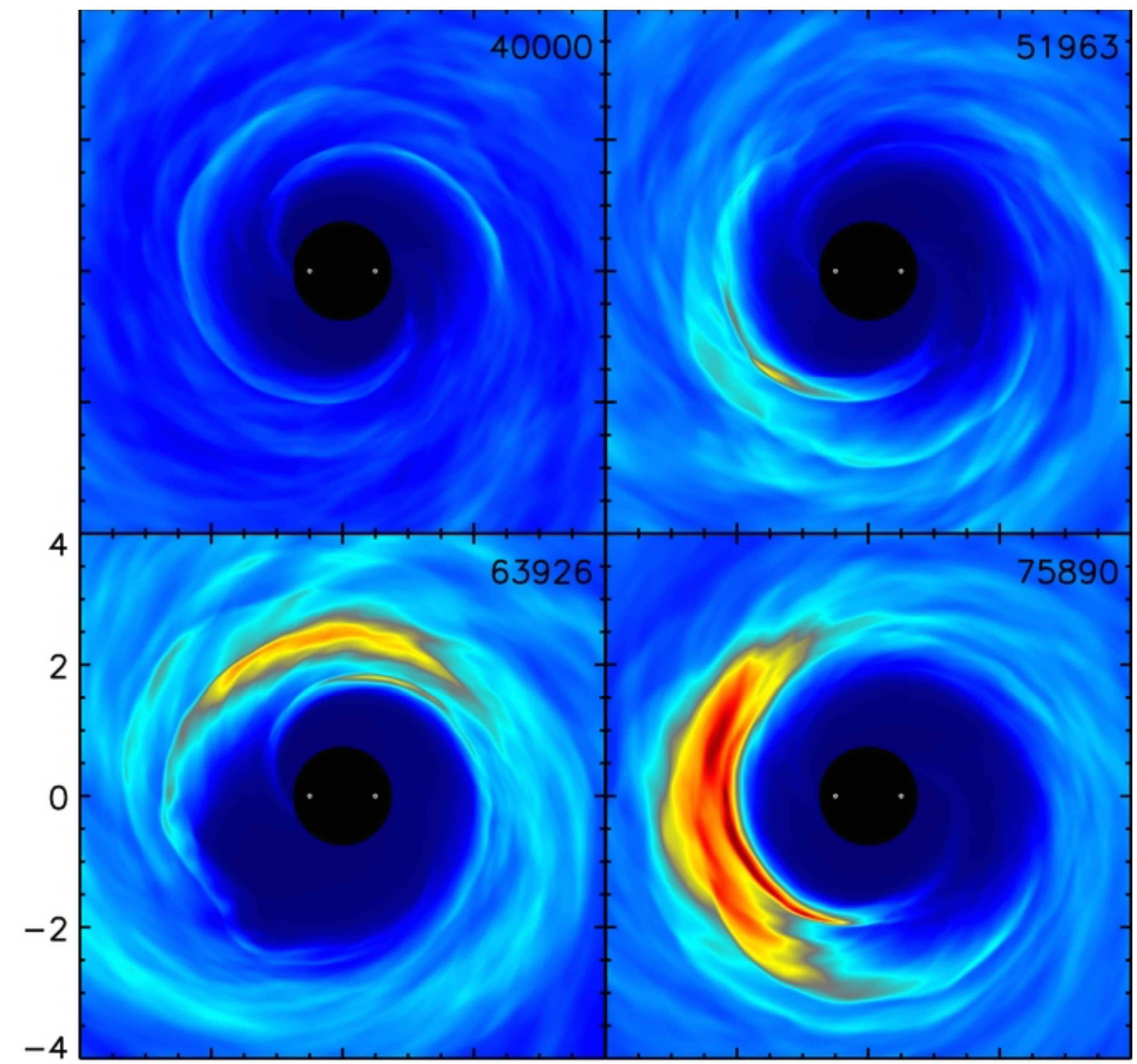


# Special Features of Binaries: Structural

Expect significant gas inflow in aftermath of galaxy merger, settling into a disk

For $q = M_2/M_1 > 4(h/r)\left(\int dz\, T_{r\phi}/\int dz\, p\right)^{1/2}$, a low surface density gap around the binary, and sometimes growing asymmetries near the outer disk's inner edge



# Special Features of Binaries: Structural

When **prograde**, binary torques strong for r/a <~ 2 —> surface density peak at r/a ~ 2—2.5, but inflow continues across the gap (Farris et al. 2014, Shi & K 2015)

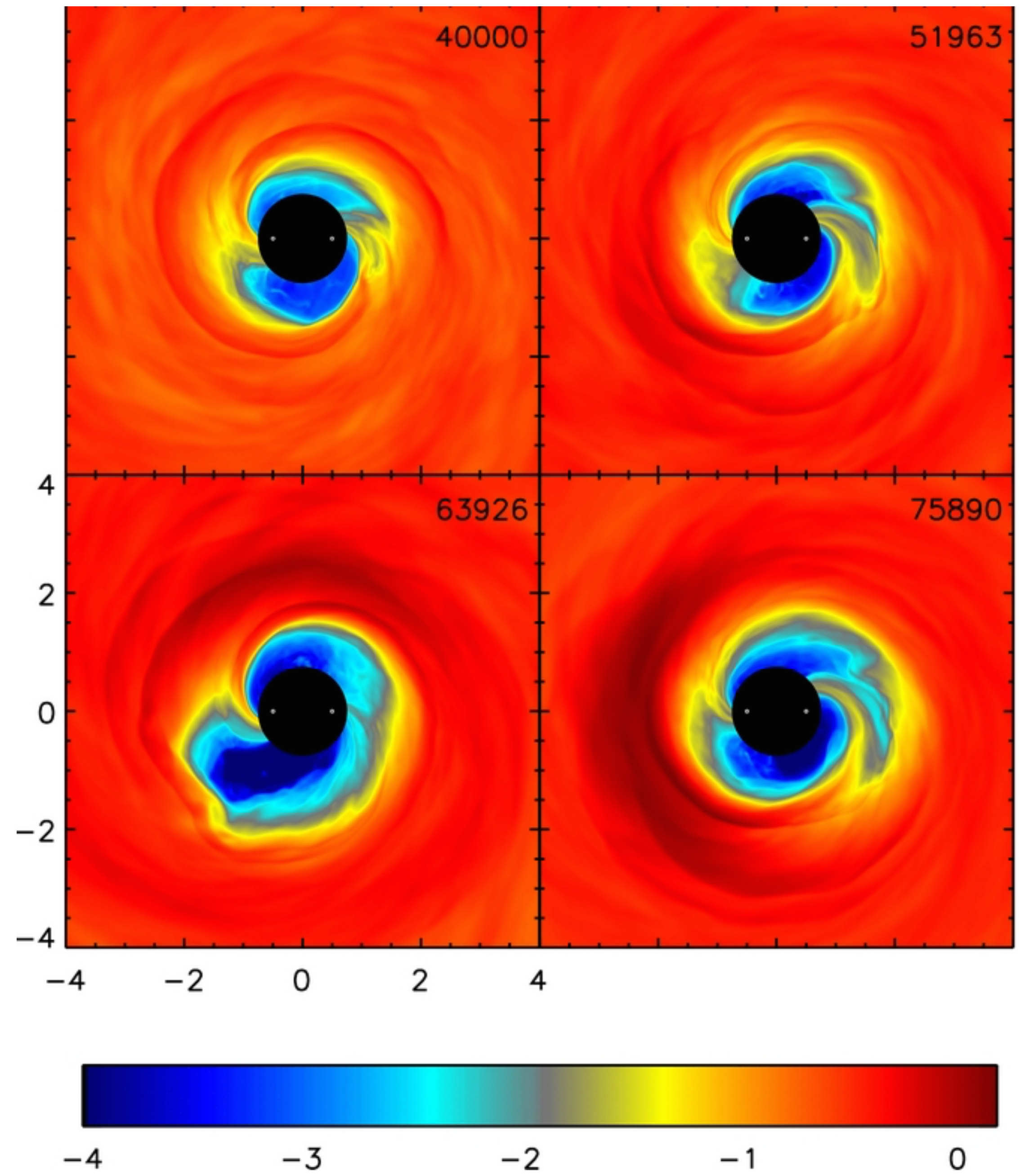
e —> 0.6? (Roedig et al. 2012)

When **retrograde**, no torques—> disk edge at r/a ~ (1+e); rapid increase in e until GW emission dominates evolution (Schnittman & K 2015)

**Obliquity** short-lived due to radially-varying quadrupole torques, precession-induced radial mixing (Scheuer & Feiler 1996, Miller & K 2013, Schnittman & K 2015)

# Special Features of Binaries: Structural

Gas flows across gap in distinct streams, modulated on orbital period if e > 1 or inner circumbinary disk asymmetric



# Special Features of Binaries: Structural

Accretion rate may be relatively large because associated with late stages of galactic mergers; no “damming” at inner edge of circumbinary disk

Majority of accretion flow acquired by secondary—> $q \longrightarrow 1$ (Roedig & Sesana 2014, Farris et al. 2014)

“Mini-disks” can exist around each black hole within tidal limits—> $r_t/a \sim 0.3\, Q^{0.3} (1-e)$ (Paczynski 1977, Sepinski et al. 2007)

Main energy release near and outside each black hole’s ISCO

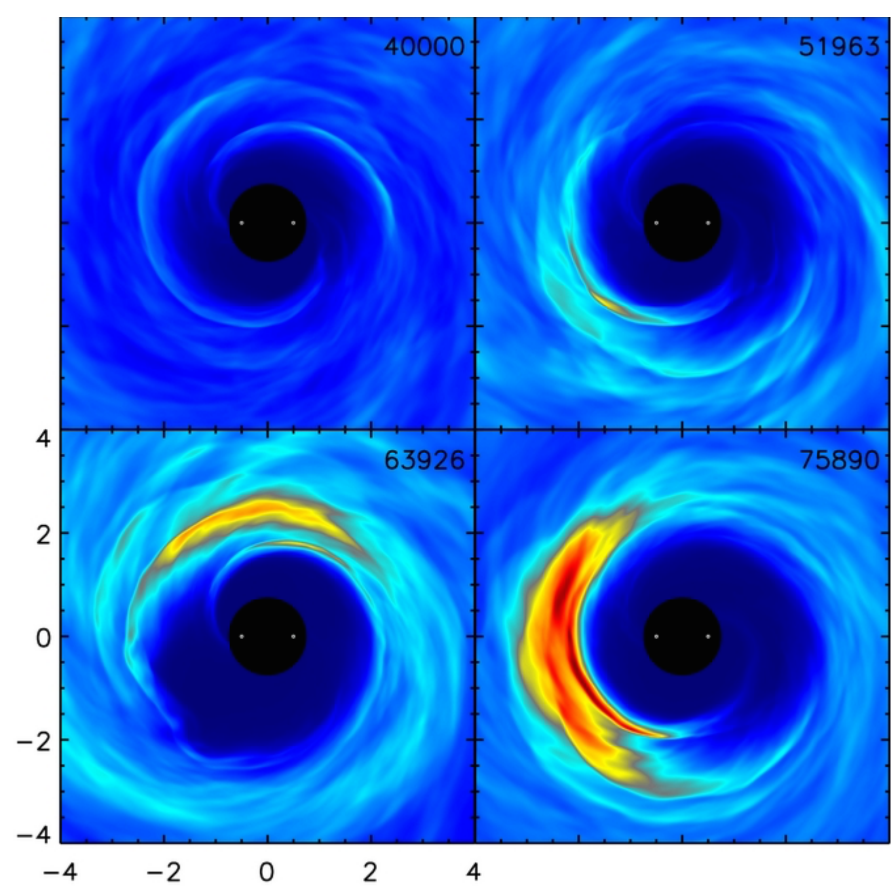
# Potential Radiative Contrasts between Binaries and Solitaries

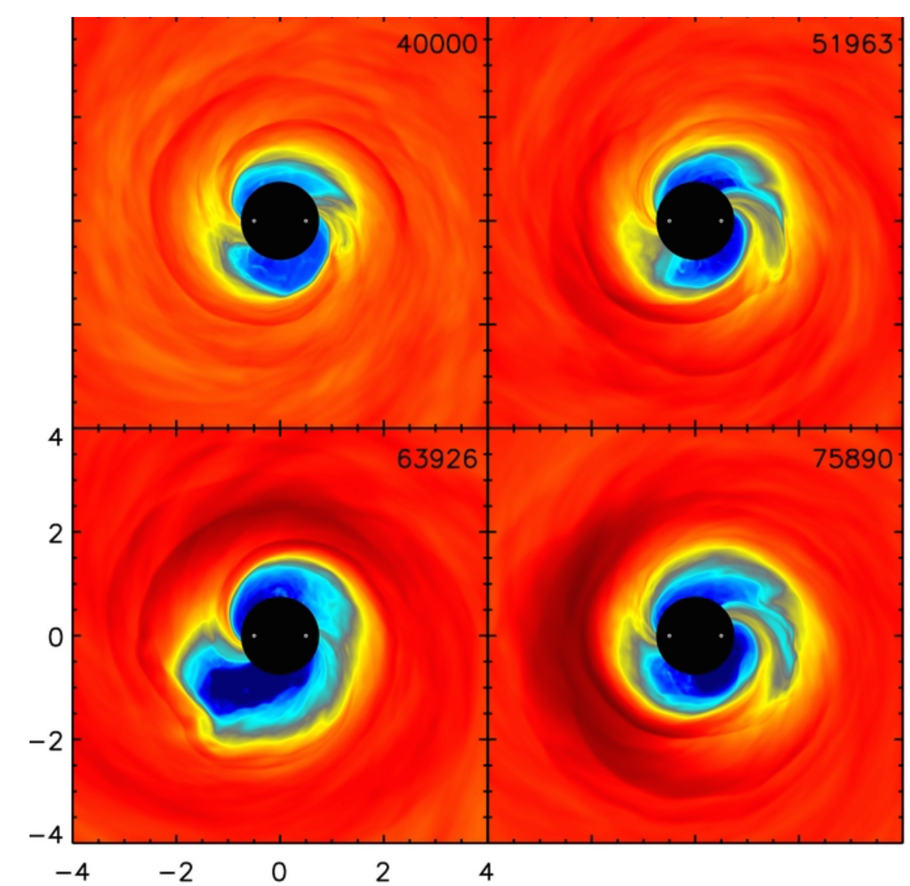
## The gap:

Does low surface density imply low surface brightness and a spectral gap?

Streams shock against the mini-disks: a different radiation regime?

Torqued streams shock against the circumbinary disk: another different radiation regime?



# Potential Radiative Contrasts between Binaries and Solitaries

Orbital modulation, either amplitude or frequency:

Affecting either of the two shock locations?

Fe K$\alpha$ from the mini-disks?

Optical emission lines, broad or narrow?

Accretion rate, therefore luminosity—in which band(s)?

# Binary Modulation of Optical/UV Continuum

(Graham et al. 2015, Liu et al. 2015)

A few problems:

If modulation due to streams, the time to radiate is

if $r_t >> r_{ISCO}$, h/r << 1 as usual;

$$t_{\rm inflow} \sim \left[2\pi\alpha(h/r)^2\right]^{-1}(r_t/a)^{3/2}P_{\rm bin} \gg P_{\rm bin} \qquad \alpha \equiv \int dz\, T_{r\phi}/\int dz\, p$$

if $r_t$ isn't >> $r_{ISCO}$, limited dissipation and therefore limited radiation;
and the system lifetime is

$$t_{\rm GW} \sim 10(\eta_{\rm symm}/0.25)^{-1}(a/10r_g)^4 M_7 \ {\rm hr}$$

If modulation due to orbit, O(1) amplitude requires $v_{orb}/c$ ~ O(1)

"Red" noise creates spurious periodicity ~ 1/3 duration

# Orbital Frequency Modulation of Emission Lines

(Boroson & Lauer 2009, Dotti et al. 2009, Bogdanovic et al. 2009, Decarli et al. 2010, Liu et al. 2014)

Problem 1: How to distinguish line profile structure due to orbital motion from internal structure

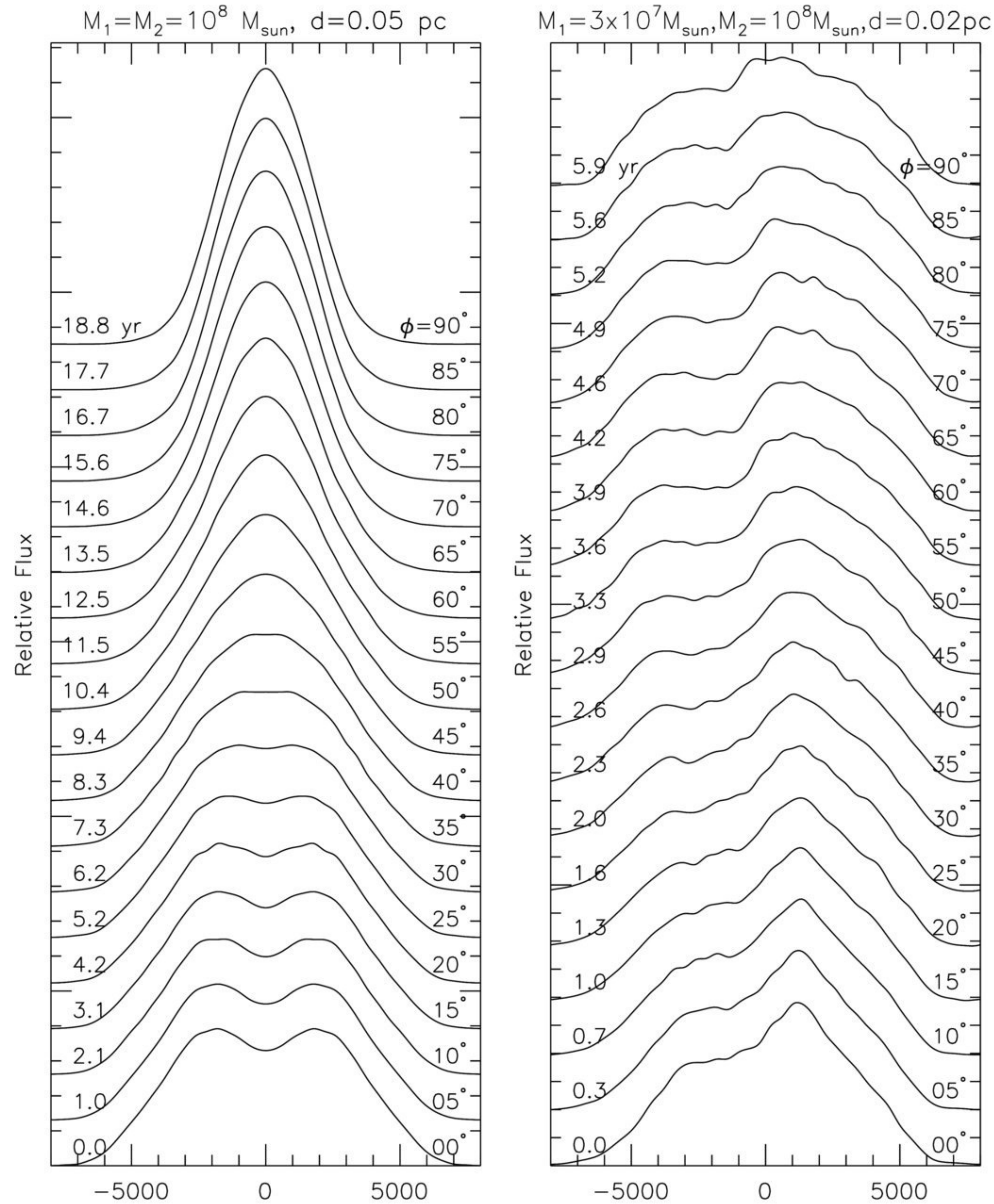
Problem 2: If broad line widths scale with orbital speed around one of the black holes, the line profiles almost always merge (Shen & Loeb 2010)

$$\Delta v_{\rm BLR} = f\,[(1,2)/(1+q)]^{1/2}\,(GM/r_{\rm BLR})^{1/2}$$

$$\Delta v_{\rm orb} = v_{\rm orb}\sin i = (GM/a)^{1/2}\sin i$$

To separate profiles requires $\Delta v_{BLR} < \Delta v_{orb}$, but binding each BLR to its own black hole requires $r_{BLR} < r_t$. Combining for e=0,

$$[f(1,q)/(1+q)]^{1/2} < \Delta v_{\rm BLR}/v_{\rm orb} < \sin i$$




Best and more typical case as functions of orbital phase ($r_{BLR}$ = 0.5a, sin i = 1) (Shen & Loeb 2010)

# Orbital Frequency Modulation of Fe Kα

(McKernan & Ford 2015)

Line profiles are generically relativistically broad; profile separation therefore requires $a/r_g < \sim 10$—20

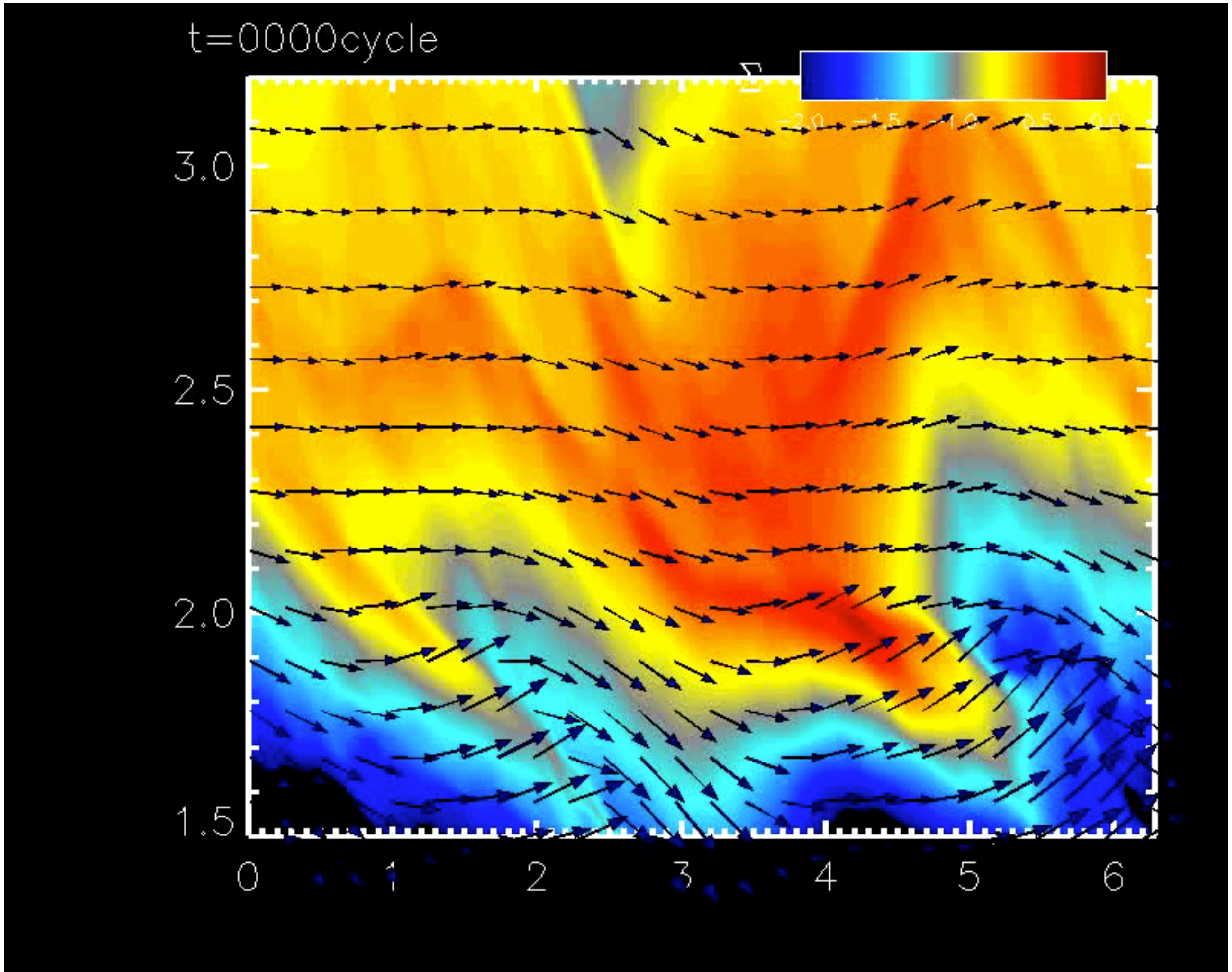
Periodicity essential to distinguish orbital effects from intrinsic variations

But $P_{orb} = 3\ (a/10r_g)^{3/2}\ M_7$ hr, and S/N often requires many hours of integration; in addition,

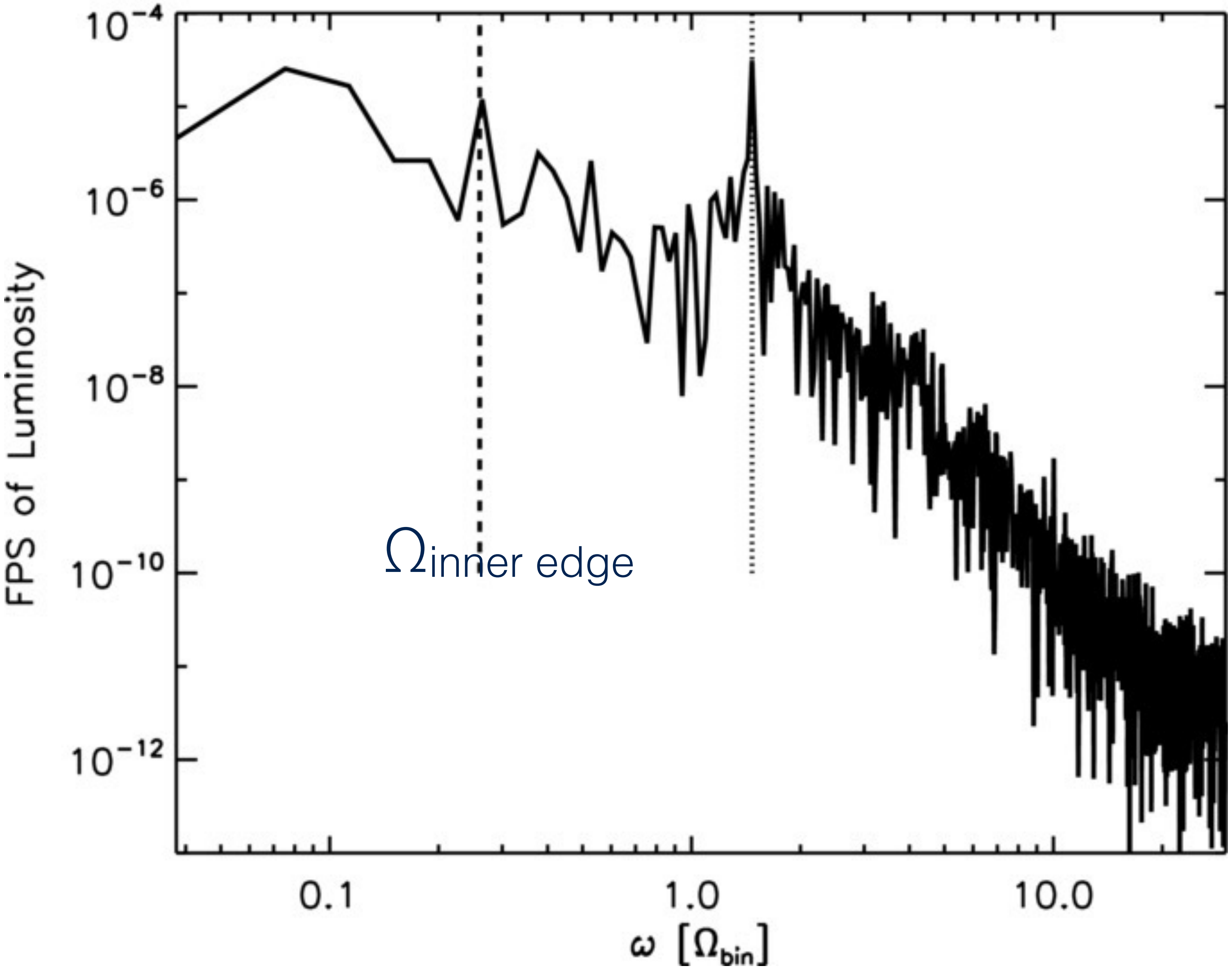
$$t_{\rm GW} \sim 10(\eta_{\rm symm}/0.25)^{-1}(a/10r_g)^4 M_7\ {\rm hr}$$

# Streams Shocking Against the Circumbinary Disk

(Shi et al. 2012, Noble et al. 2012)



# Shocks Heat the Gas at a Frequency $\Omega_{binary}$ - $\Omega_{inner\ edge}$




For q=1, $\omega = 2(\Omega_{binary} - \Omega_{inner\ edge})$

Maximum modulation amplitude $\sim r_{ISCO}/(2a)$; can be reduced if photon diffusion time > period

# Shocks where Streams Strike Inner Disks

(Roedig, K & Miller 2014)

Accretion streams join “mini-disks” around each black hole, with majority of accretion going to the secondary

Streams shock at edges of “mini-disks” with high temperature

$$T_{s1,2} \simeq 6 \times 10^{10}(a/100r_g)^{-1}(1+q)^{-1}(q^{0.3}, q^{0.7}) \text{ K}$$

assuming a circular binary, as GW likely enforces

But cool quickly

$$t_{\rm cool}\Omega_{\rm mini} \simeq 0.01\dot{m}^{-1}(a/100r_g)^{-1/2}(1+q)^{-3/2}(q^{0.15}, q^{1.35})$$

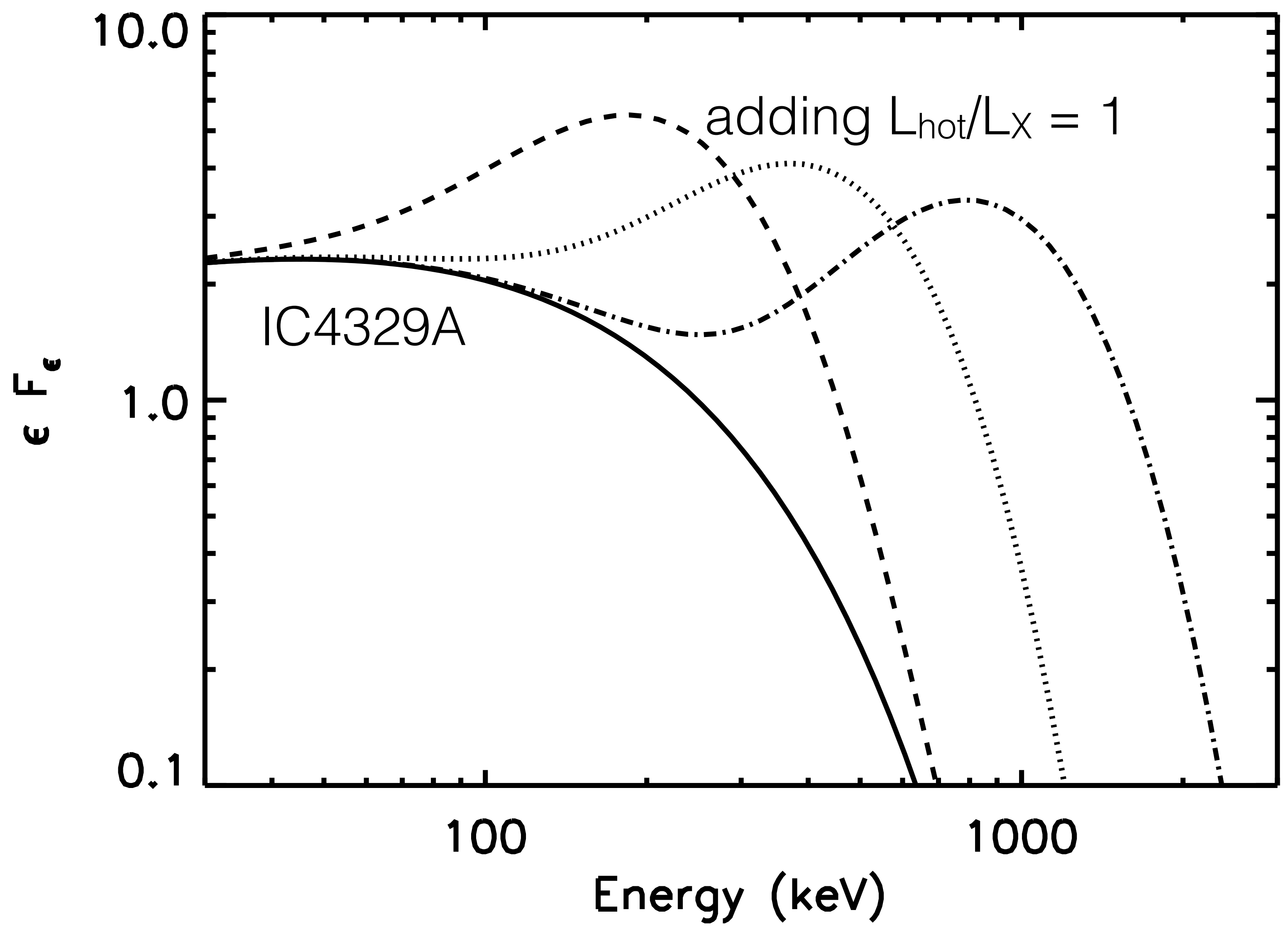
and brightly

$$L_{\rm hot}/L_X \simeq 0.35(a/100r_g)^{-1}(1+q)^{-1}(f_1 q^{0.3} + f_2 q^{0.7})$$

$$q \equiv M_2/M_1$$

$$f_{1,2} \equiv \dot{M}_{1,2}/\dot{M}_{\rm tot}$$

# Distinctive Very Hard X-ray Components




q=1, fiducial parameters

*Expect modulation* on the binary orbital period

# Strong Hard X-ray Components As Merger Pointers

Phrased in terms of $L_{hot}/L_X$, detection of these shocks could point to a merger in not many years:

$$T_{\rm GW} = (3/4)(1+z)(L_{\rm hot}/L_X)^{-4}\left[q(1+q)^2\right]^{-1}\left(f_1 q^{0.3} + f_2 q^{0.7}\right) M_7 \ {\rm yr}$$

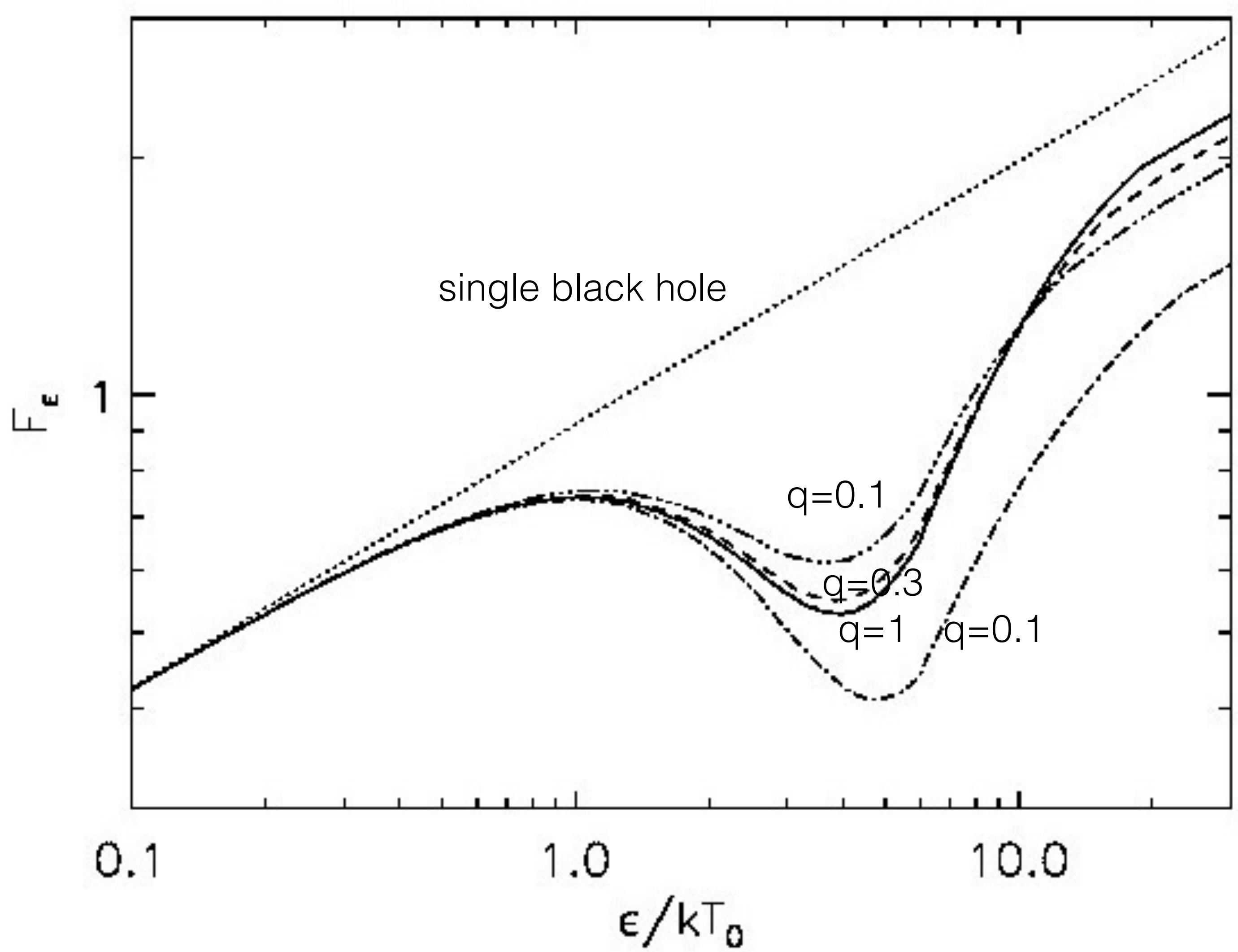
# "Notches" Made by the Gap

(Roedig, K & Miller 2014)

See partial accounts in Roedig et al. 2012, Tanaka et al. 2012, Gultekin & Miller 2012, Kocsis et al. 2012, Tanaka & Haiman 2013, Tanaka 2013; also Farris et al. 2015

## Absence of thermally-radiating material removes spectrum for a factor ~3 on either side of $T_0$

$$h\nu_0/4k_B \simeq 3.3\times 10^4 \left[\dot{m}(\eta/0.1)^{-1} M_8^{-1}(a/100r_g)^{-3}\right]^{1/4}\ \mathrm{K}$$




$$\dot{m} \equiv L/L_E$$

$$\eta \equiv L/\dot{M}c^2$$

# What Conditions Allow an Observable Notch?

Notch falls in middle of visible band for $\dot{m}(\eta/0.1)^{-1} M_8^{-1} (a/100r_g)^{-3} \simeq 2 \times 10^{-3} (1+z)^4$

Notched quasar is bright enough if $\dot{m} M_8 (a/100r_g)^{-1} \gtrsim 0.05$

And gives a somewhat greater lead-time:

$$T_{\rm GW} \simeq 50(1+z)^{-13/3} q(1+q)^{-2} \dot{m}^{4/3} (hc/\lambda k T_0)^{16/3} (\lambda/5000\mathring{A})^{16/3} M_8^{-1/3}\ {\rm yr}$$

# Photons from the Merger Proper?

Key uncertainty: quantity and location of gas immediately around the merging binary:

- Persistence of accretion through “decoupling” phase
- Inflow time in mini-disks vs. GW evolution time
- Fate of gas tidally-stripped from mini-disks by orbital compression
- Optical depth of gas can stretch post-merger cooling time well beyond GW emission; $L_E$ characteristic timescale for electron scattering-regulated radiation in point-mass potential

# Conclusions

- Orbital modulation harder to achieve than widely thought
- Emission line separation only in special cases
- Best bet distinctive features:  spectral “notch” in optical/IR; hard X-ray bump: both found in last ~century—decades before merger