Electromagnetic Emission from Compact Supermassive Black Hole Binaries

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Outline

- Introduction & Motivation
- Binary + disk interaction
- Electromagnetic signatures – PG1302

SMBH binaries should be common

1. Orbital decay slow:

- pair of BHs can spend a fair fraction of the Hubble time at small (sub-parsec) separations
- gas expected to be delivered to nucleus, can fuel BHs

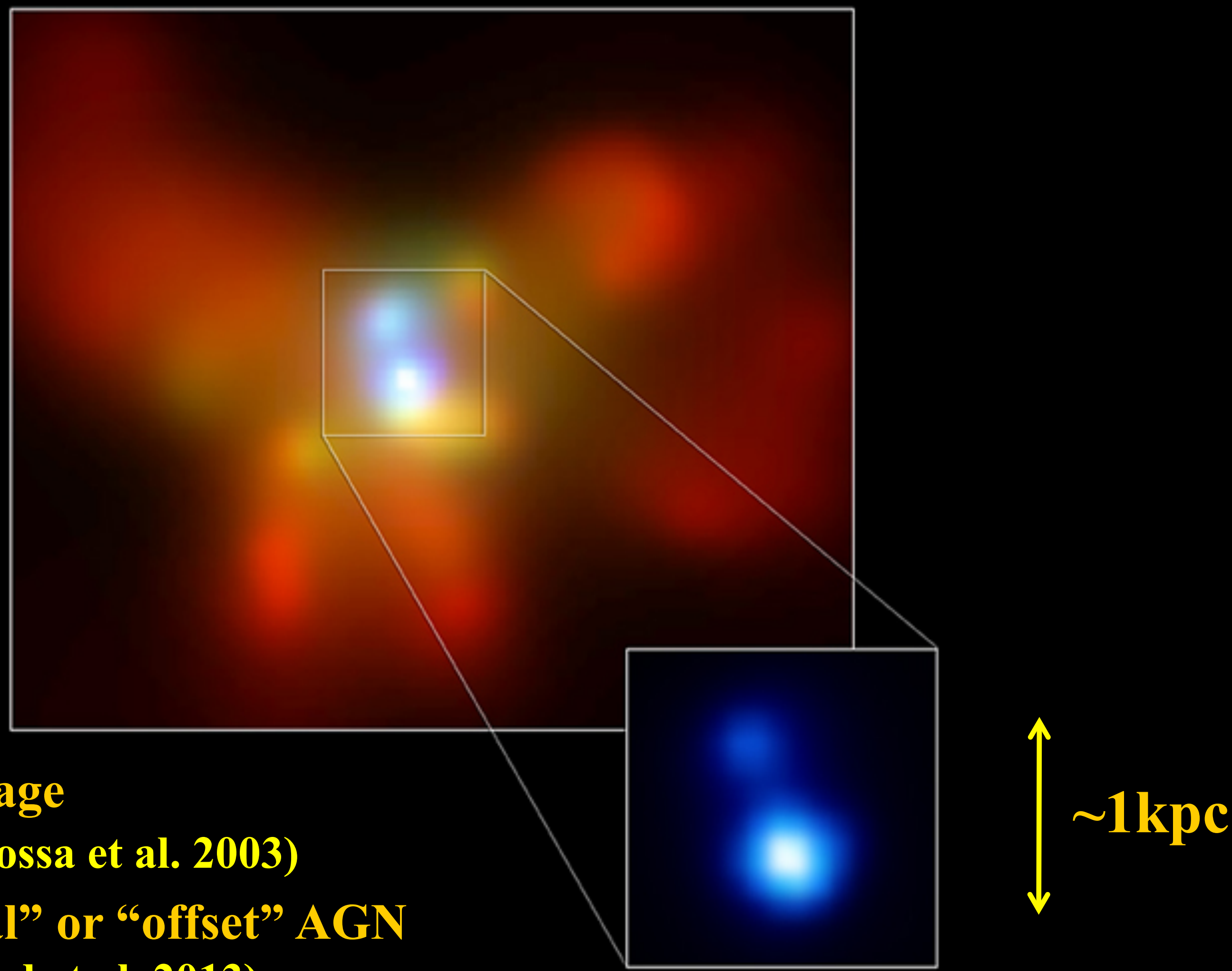
2. Observational evidence is scant:

- Binary quickly decays to unresolvable separations
- need indirect signatures in spectra, light-curves

3. Indirect searches: variability

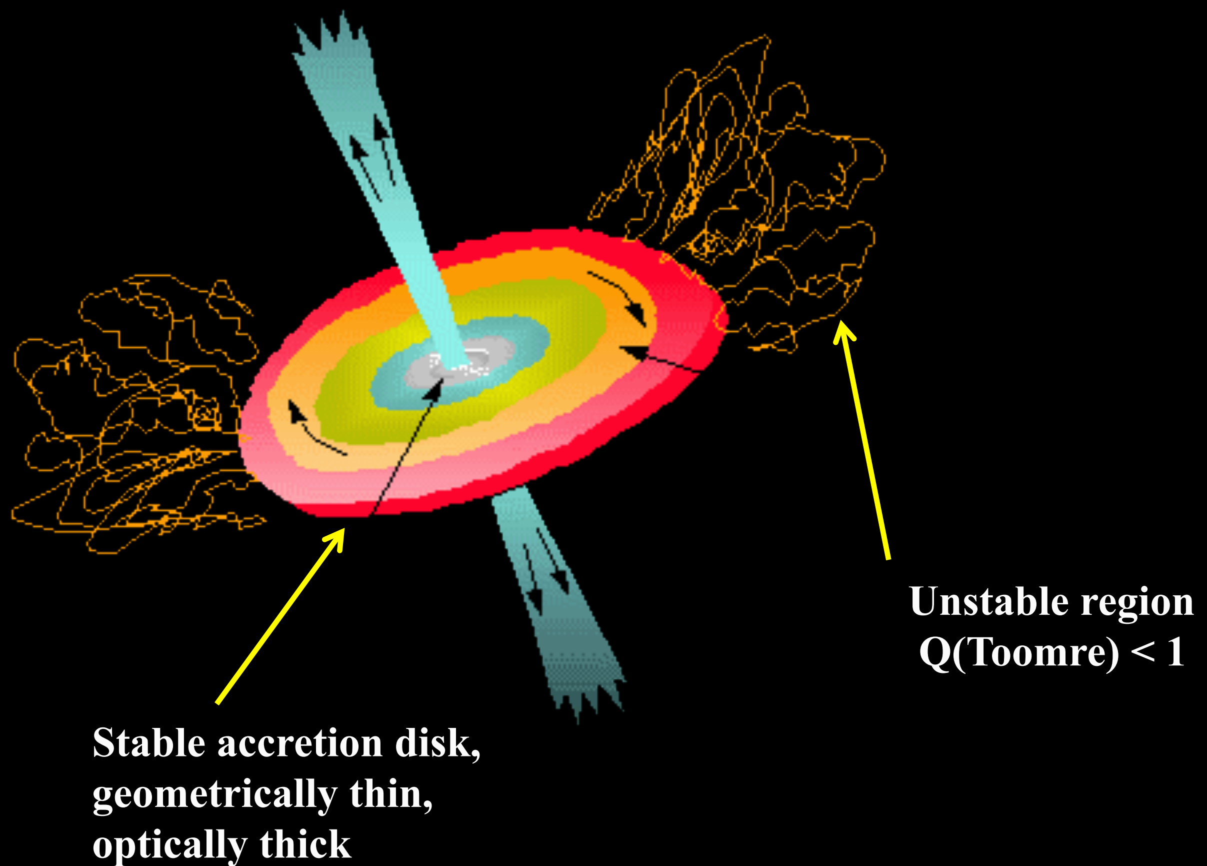
- Any emission before, during, and after coalescence is likely variable (t_{orb}<10 yr, if caught close enough)
- EM signatures alone – time-domain astronomy
- counterparts to gravitational wave sources (PTA, eLISA)

Active BH pairs in galactic nuclei



* Chandra X-ray image
  of NGC 6240 (Komossa et al. 2003)
* Many ~10kpc "dual" or "offset" AGN
  in optical (Comerford et al. 2013)
* 7.3pc double AGN in radio galaxy 0402+379 by VLBA (Rodriguez et al. 2006)

Add second BH to standard AGN model



Hydrodynamics of Binary + Disk system

Three reasons to care about this:

1. EM signatures: - Is there gas near (few R_s) of the BHs?
- What is the mode of the accretion?

affects observability through total luminosity, spectral shape, variability

2. Orbital decay: - How long does binary spend at each orbital separation?
- Can BHs merge in a Hubble time?

affects observability through distribution of separations, periods

3. Gravitational waves: *can waveforms be modified by gas?*

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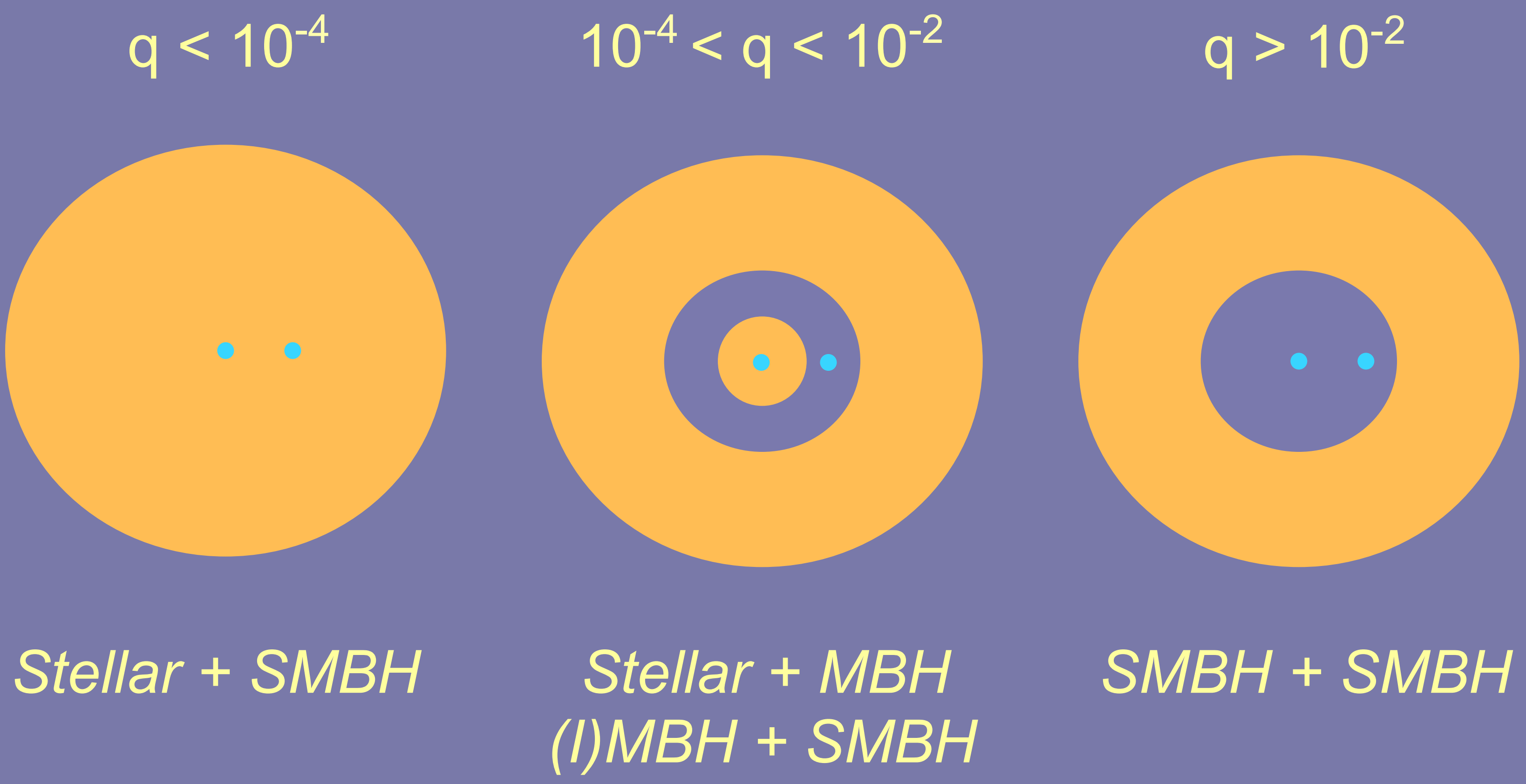
Hydrodynamics of Binary + Disk system

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

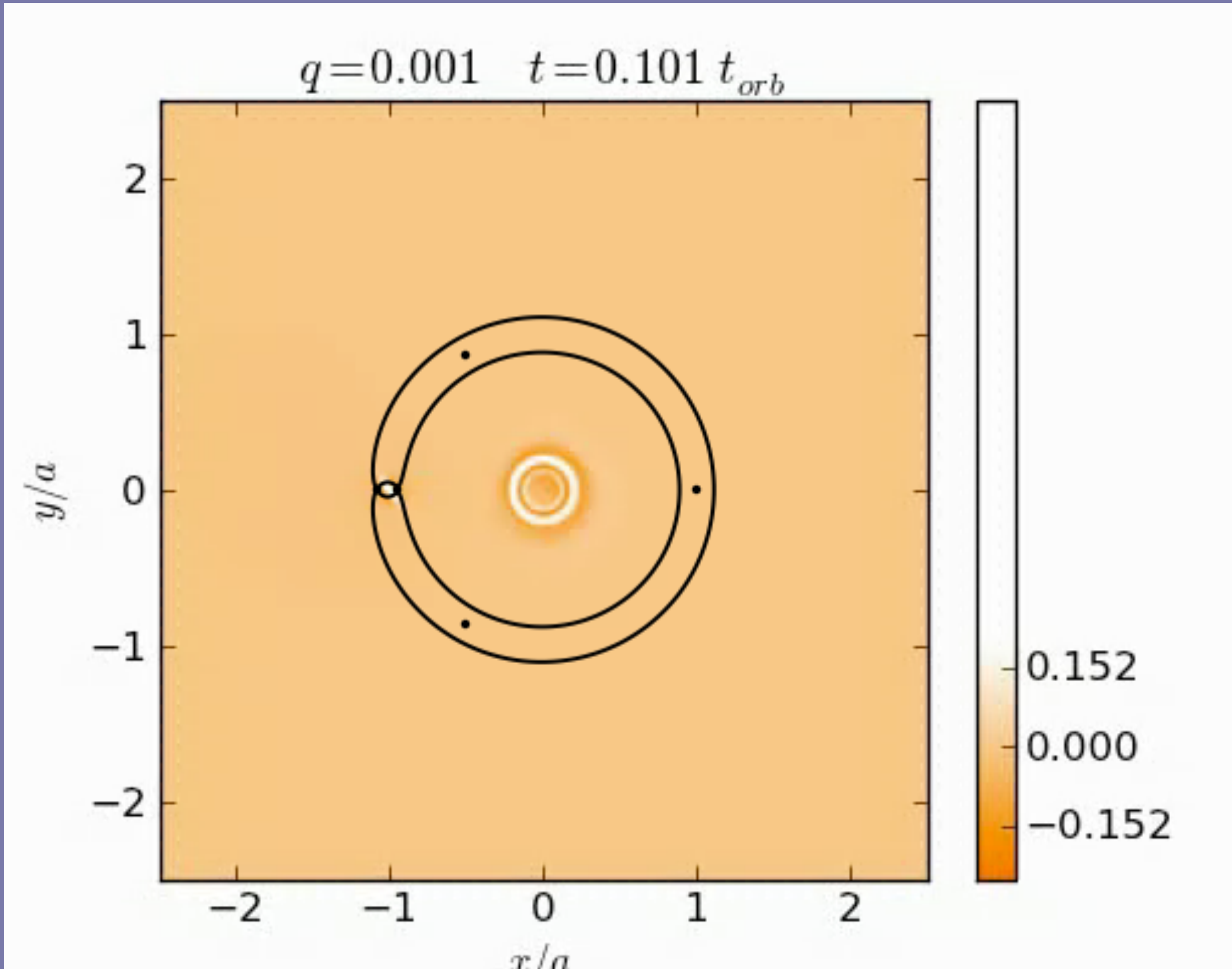


2D Hydrodynamical Simulations

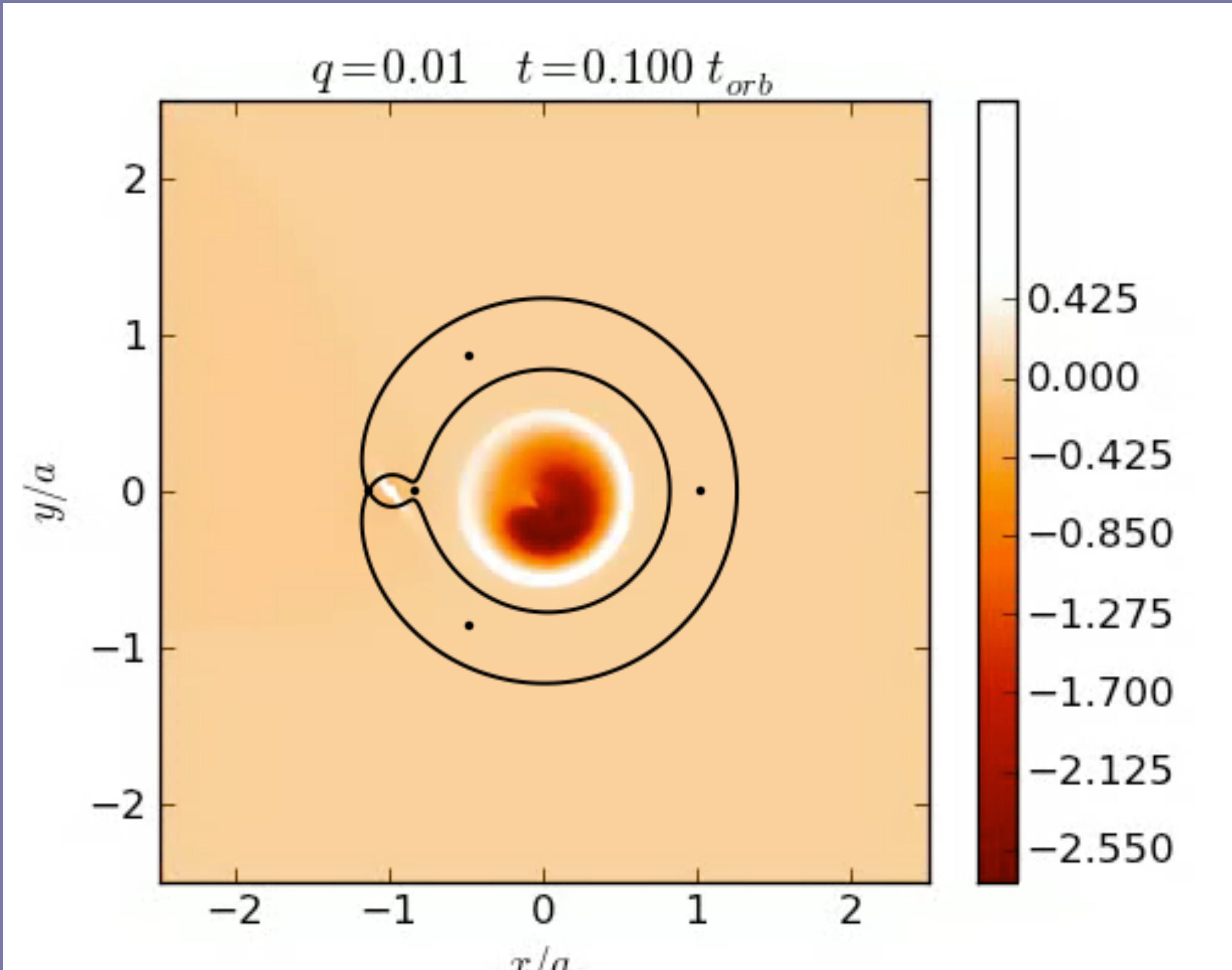
D'Orazio, ZH & MacFadyen (2013)
Farris, Duffell, MaFadyen, ZH (2014, 2015a,b)
D'Orazio et al. 2015 (in prep)

- Use moving-mesh [AMR] grid code DISCO
- 2D, hydrodynamics only (no GR or MHD)
- α-viscosity (α=0.1)
- **Cooling** (rad. diffusion) + **heating** (viscosity, shocks)
- **BHs are on the grid** (but not yet "live")
- Initial Shakura-Sunyaev disk $0 \leq r \leq 100a_{bin}$

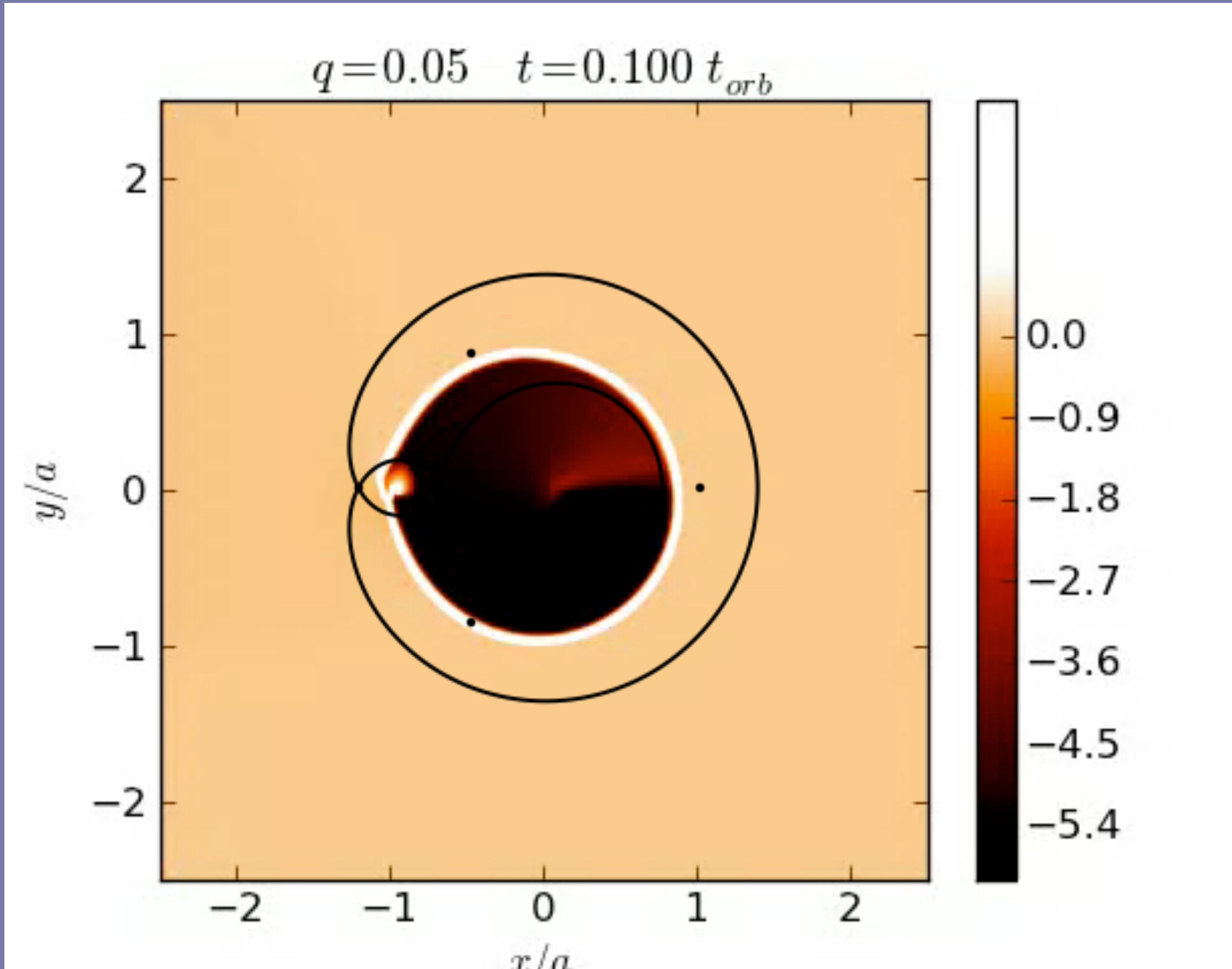
➔ *vary mass ratio over expected range* $q=M_1/M_2 = 10^{-4} - 1$
➔ *run for ~10,000 binary orbits (**>viscous time, steady-state**)*
➔ *study morphology, mass accretion rate inside cavity*



$q = 0.001 \quad t = 0.101\, t_{orb}$
y/a
x/a
2
1
0
−1
−2
−2
−1
0
1
2
0.152
0.000
−0.152



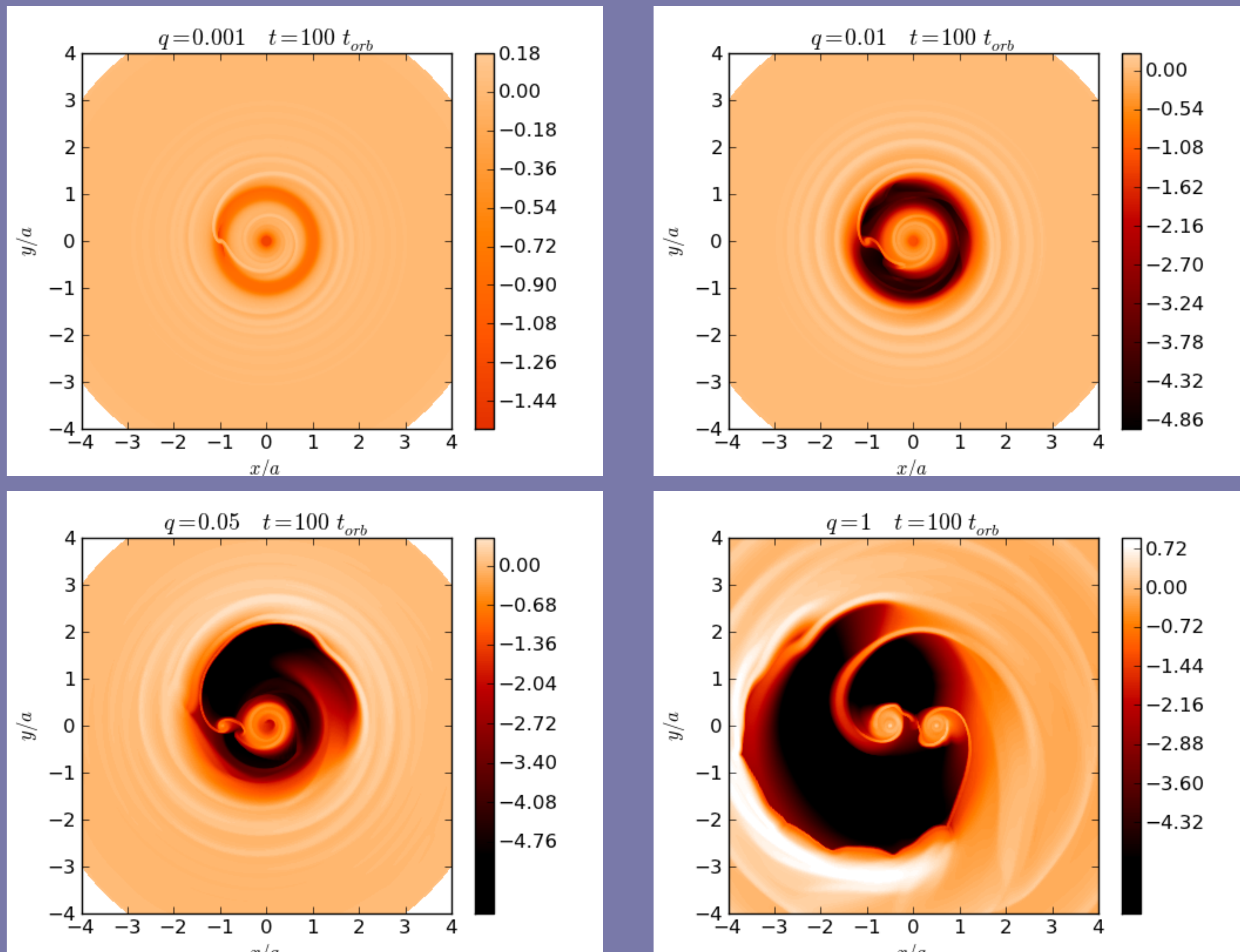
q=0.01 t=0.100 t_orb
y/a
x/a
2
1
0
−1
−2
−2
−1
0
1
2
0.425
0.000
−0.425
−0.850
−1.275
−1.700
−2.125
−2.550


$q = 0.05 \quad t = 0.100\, t_{orb}$
2
1
0
−1
−2
y/a
−2
−1
0
1
2
x/a
0.0
−0.9
−1.8
−2.7
−3.6
−4.5
−5.4

Binary-disk interaction

Abrupt change in behavior at q~0.05

$q=10^{-3}$ $q=10^{-2}$



$q=0.05$ $q=1$

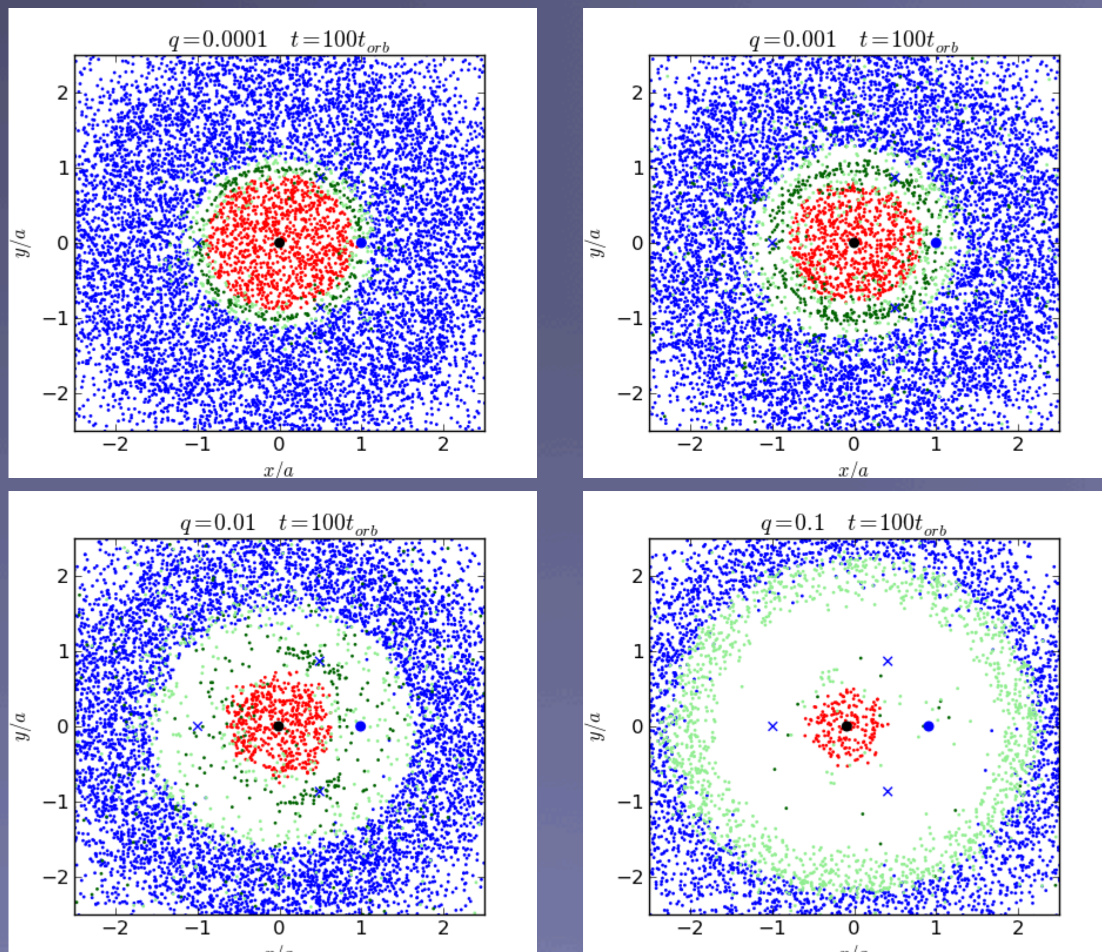
Origin of transition: loss of stable orbits

Restricted 3-body orbits: morphology similar to hydro

D'Orazio et al. 2015, in prep

$q=10^{-4}$

$q=10^{-3}$



$q_{crit}=0.04$

$q=10^{-2}$

$q=10^{-1}$

Abrupt change in behavior for $q > 0.05$

A "phase transition":

(1) Accretion rate becomes strongly variable

(2) Annular gap → central cavity

(3) Circumbinary disk becomes strongly lopsided

(4) Strong eccentricity growth for binary

Accretion rate never suppressed

Accretion rate is same (or enhanced) compared to single BH

Secondary out-accretes the primary (by factor of up to 20)

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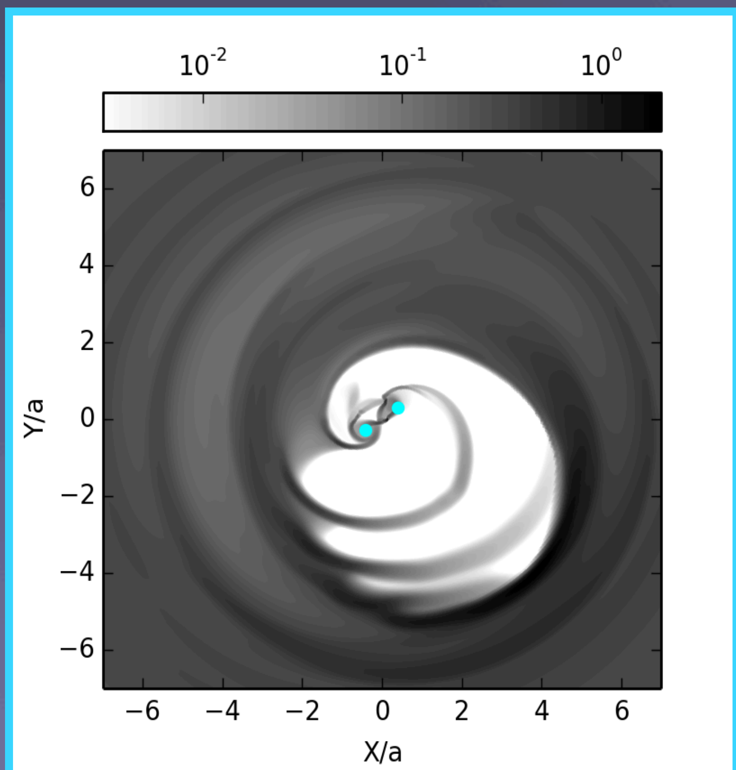
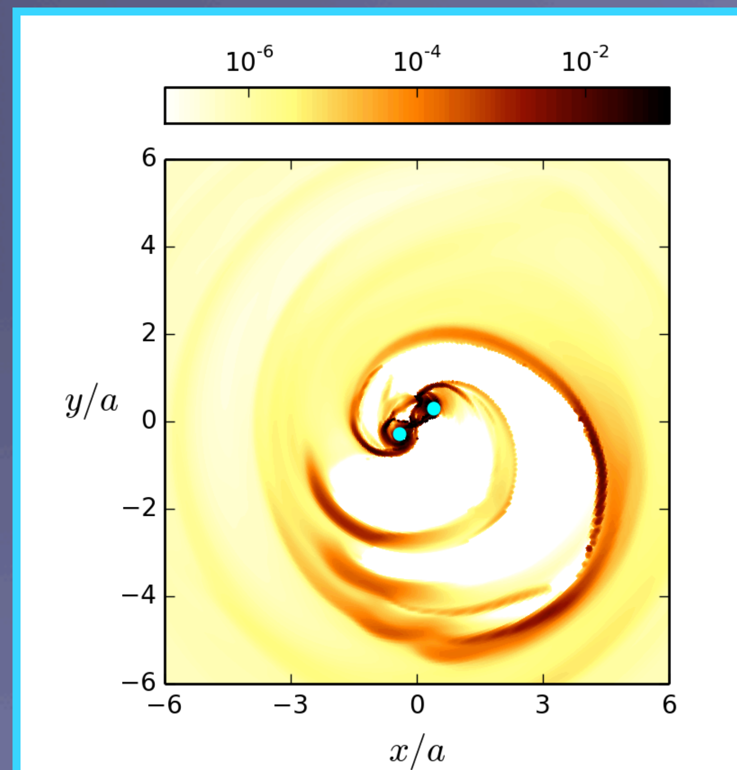
Thermal Emission from Cavity

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

$q = M_2/M_1 = 1$



Surface density

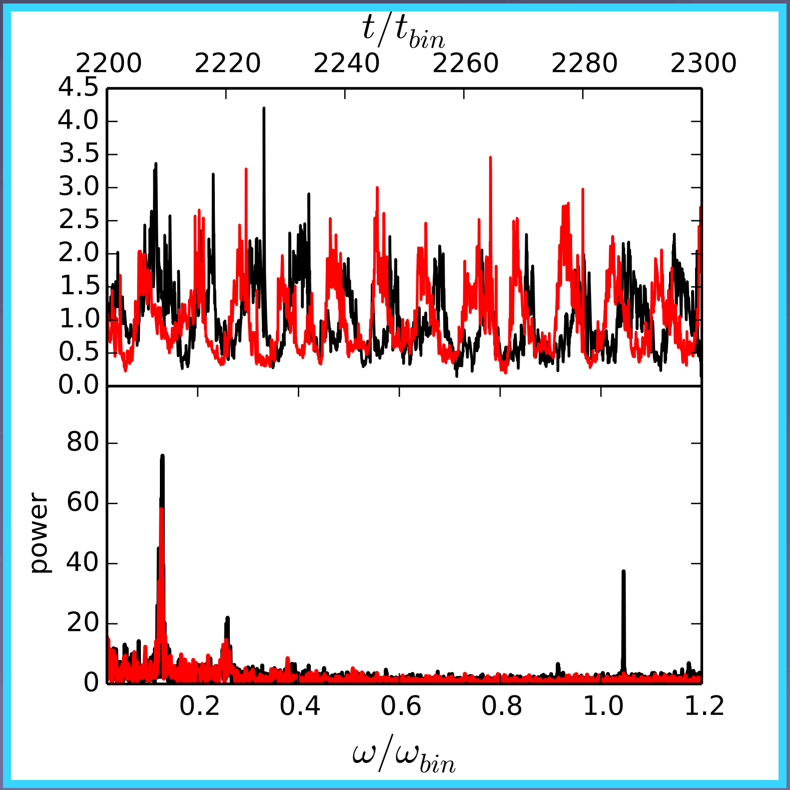


Surface luminosity:
shocks in streams and minidisks

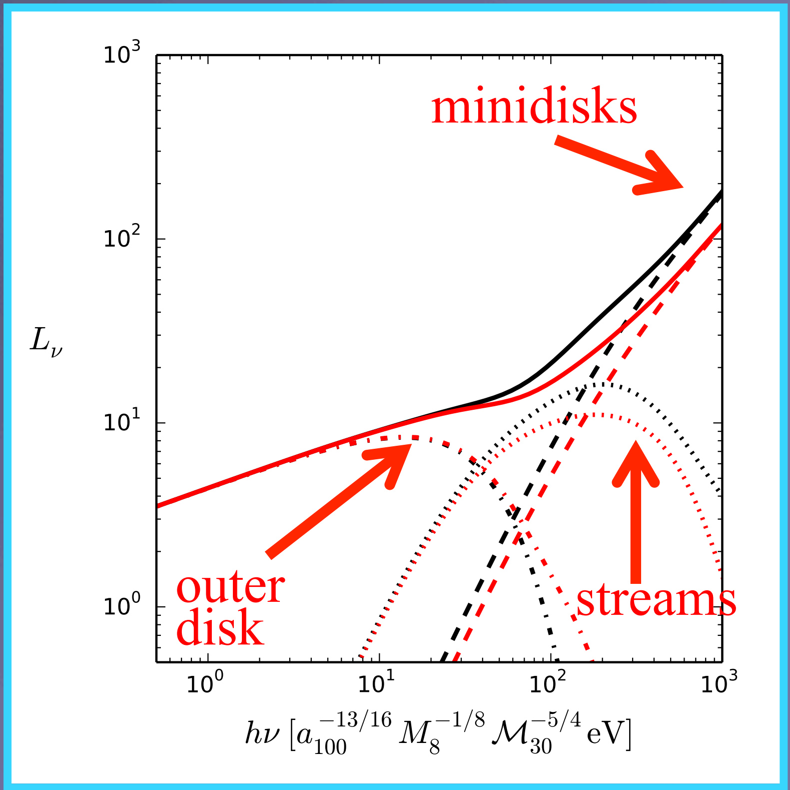
Composite Spectrum

Farris et al. (2015b)

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



bolometric luminosity varies, tracks accretion



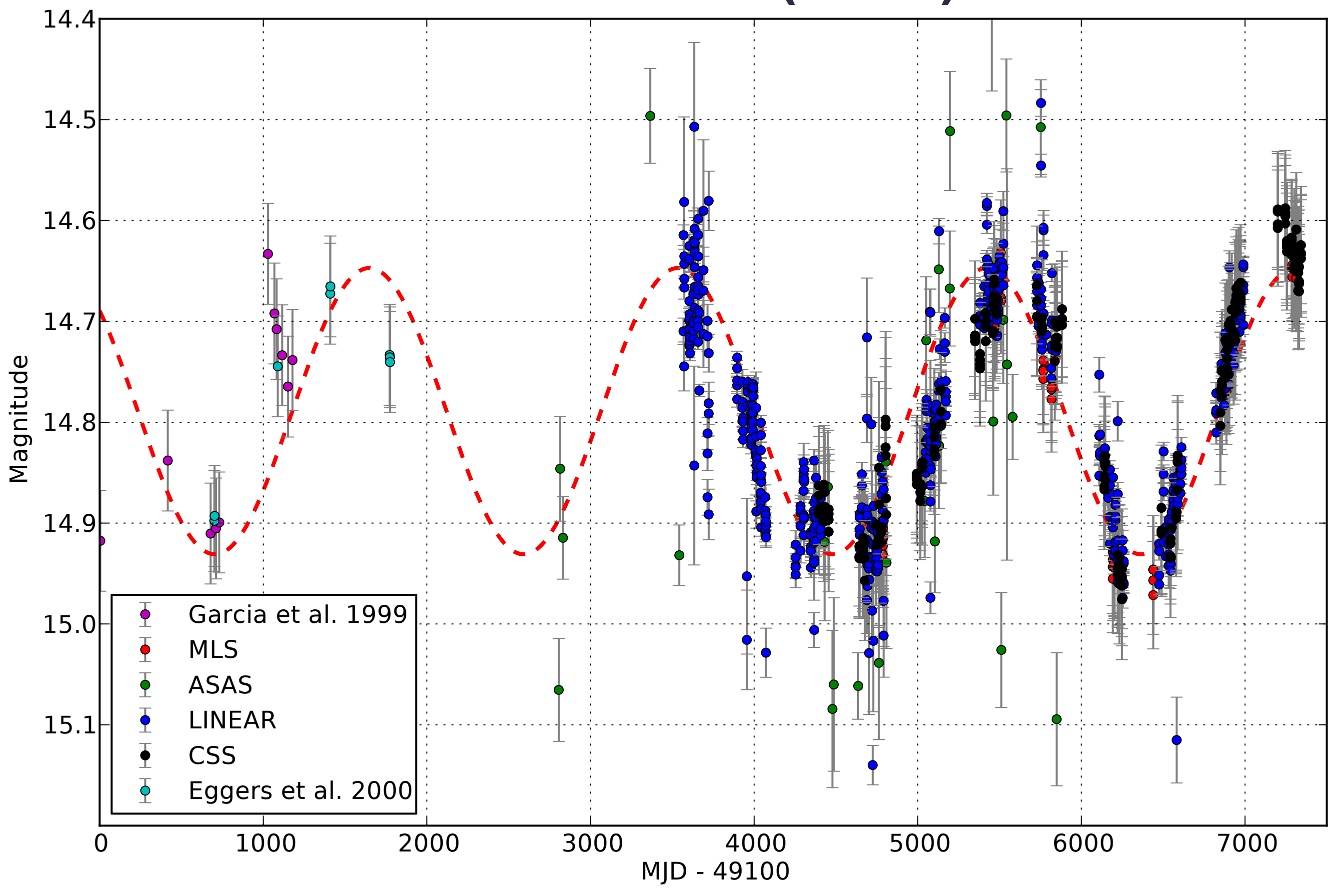
periodic spectral variability at high energies (~6 t_{orb})

PG1302-102

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)

Graham et al. (2015)

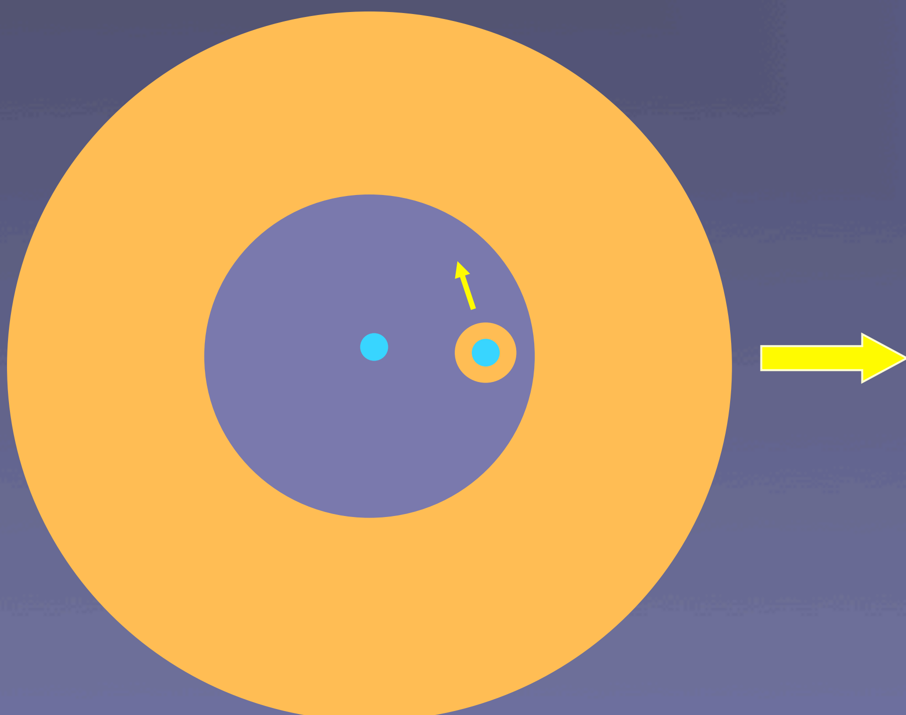


Is the sinusoidal modulation caused by relativitistic boost, not hydrodynamics?

D'Orazio, Haiman, Schiminovich (Nature, 2015)

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

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



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

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

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

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

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

Requirements for Doppler boost

Observed ±14% modulation expected if:

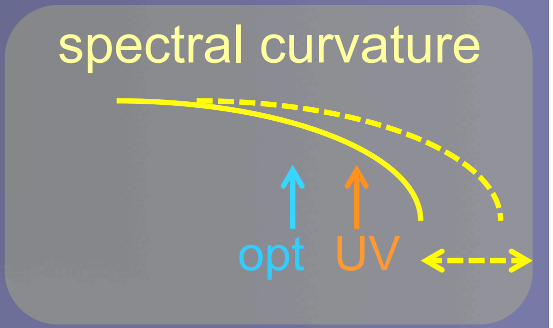
- Total mass large ($M_{tot} > 2\times10^9\, M_\odot$)
- Mass ratio low (q < 0.2 → q<0.05 from hydro)
- Luminosity mostly from secondary (>90% → 0.03<q< 0.1)
- Not too far from edge-on (±30°)

How can we verify / falsify Doppler boost hypothesis?

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

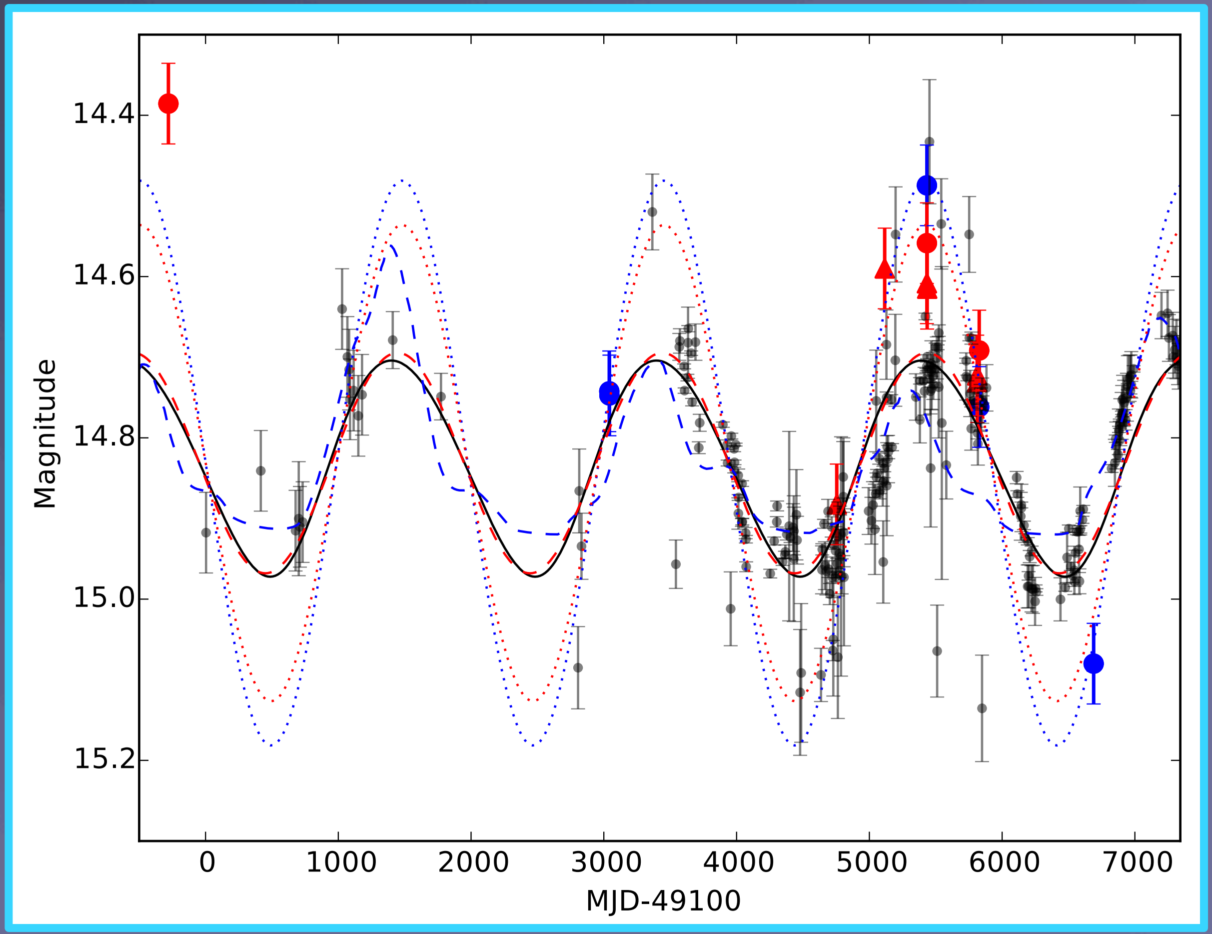
Optical (V-band): $\alpha \approx 1.1$ → $3-\alpha \approx 1.9$

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



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

Archival UV data consistent with boost

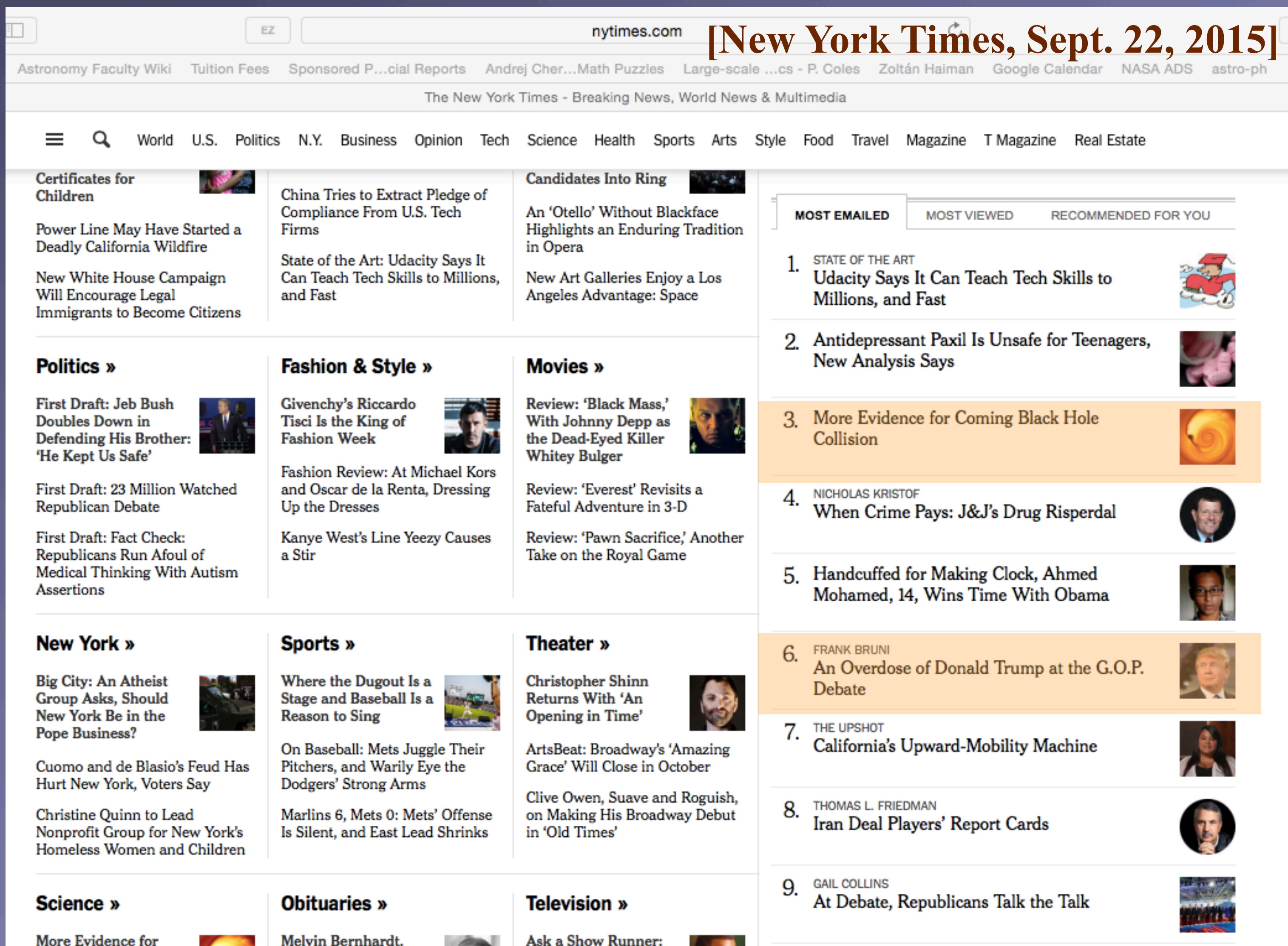


July 17, 1992 (HST FOS) --- NUV
Aug 21, 2001 (HST STIS) --- FUV
Mar 8, 2008 and Apr 6, 2009 (GALEX) --- FUV/NUV
Jan 28, 2011 (HST COS) -- FUV

A binary overcame the final pc bottleneck!
OK, but who cares?

A binary overcame the final pc bottleneck!
OK, but who cares?

[New York Times, Sept. 22, 2015]



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Conclusions

1. Binaries can be **bright**: gas accretion rate into cavity via streams is not reduced by the binary "propeller"
2. Accretion onto minidisks strongly **periodic for $q \gtrsim 0.05$**
3. Period dominated by lump in cavity, **t = few x t_{orb},** for q>~0.3
4. Migration: periodic sources with t_{orb} < 10 yr **not rare**
5. **PG 1302** optical periodicity consistent with ~1 or 4 yr binary
6. UV + optical data favors 4 yr orbital period, arising from **Doppler-boosted emission** from secondary in circular orbit