SELF-CONSISTENT ANALYTIC MODEL OF CIRCUMBINARY ACCRETION DISKS AND TYPE 1.5 MIGRATION

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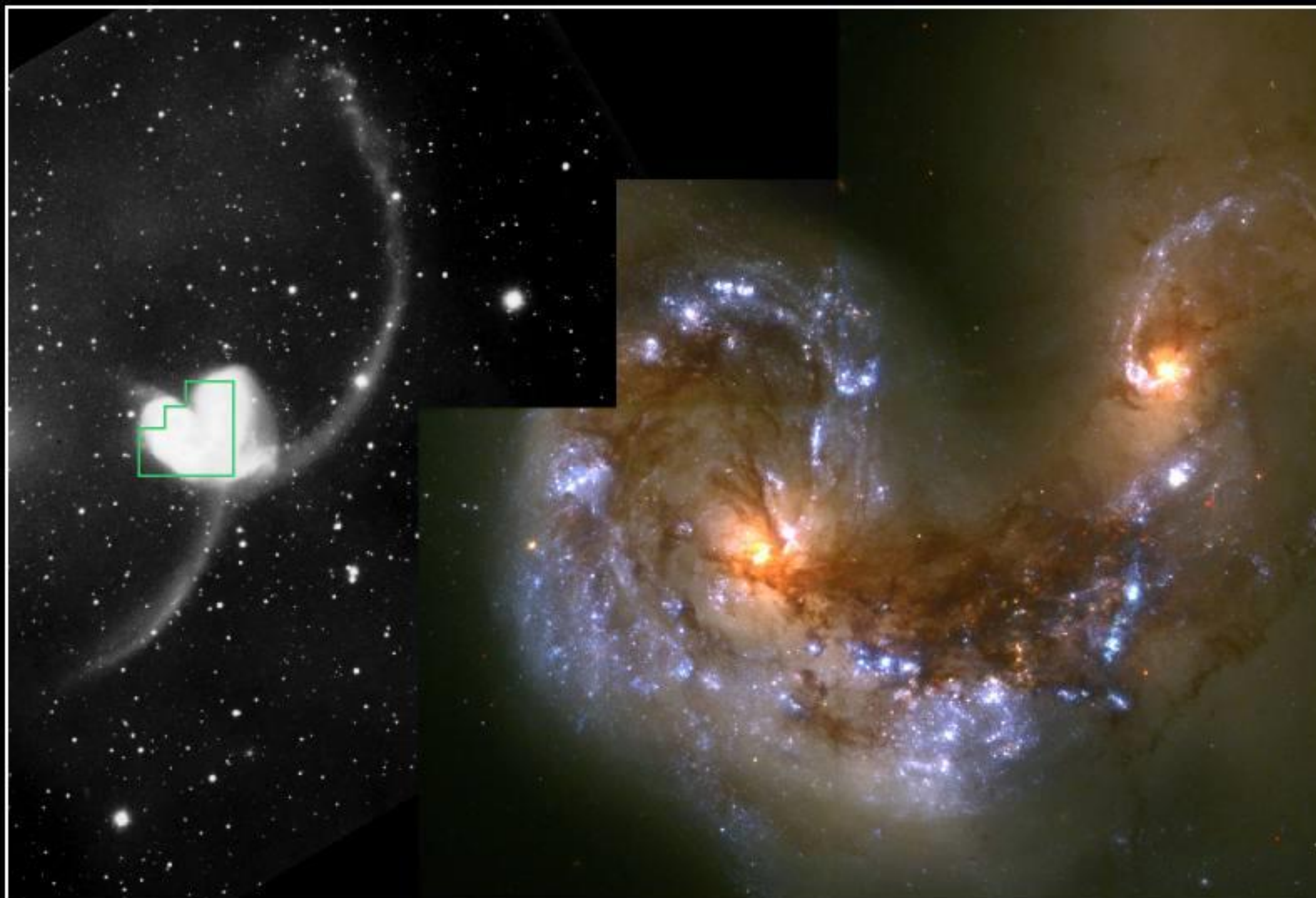
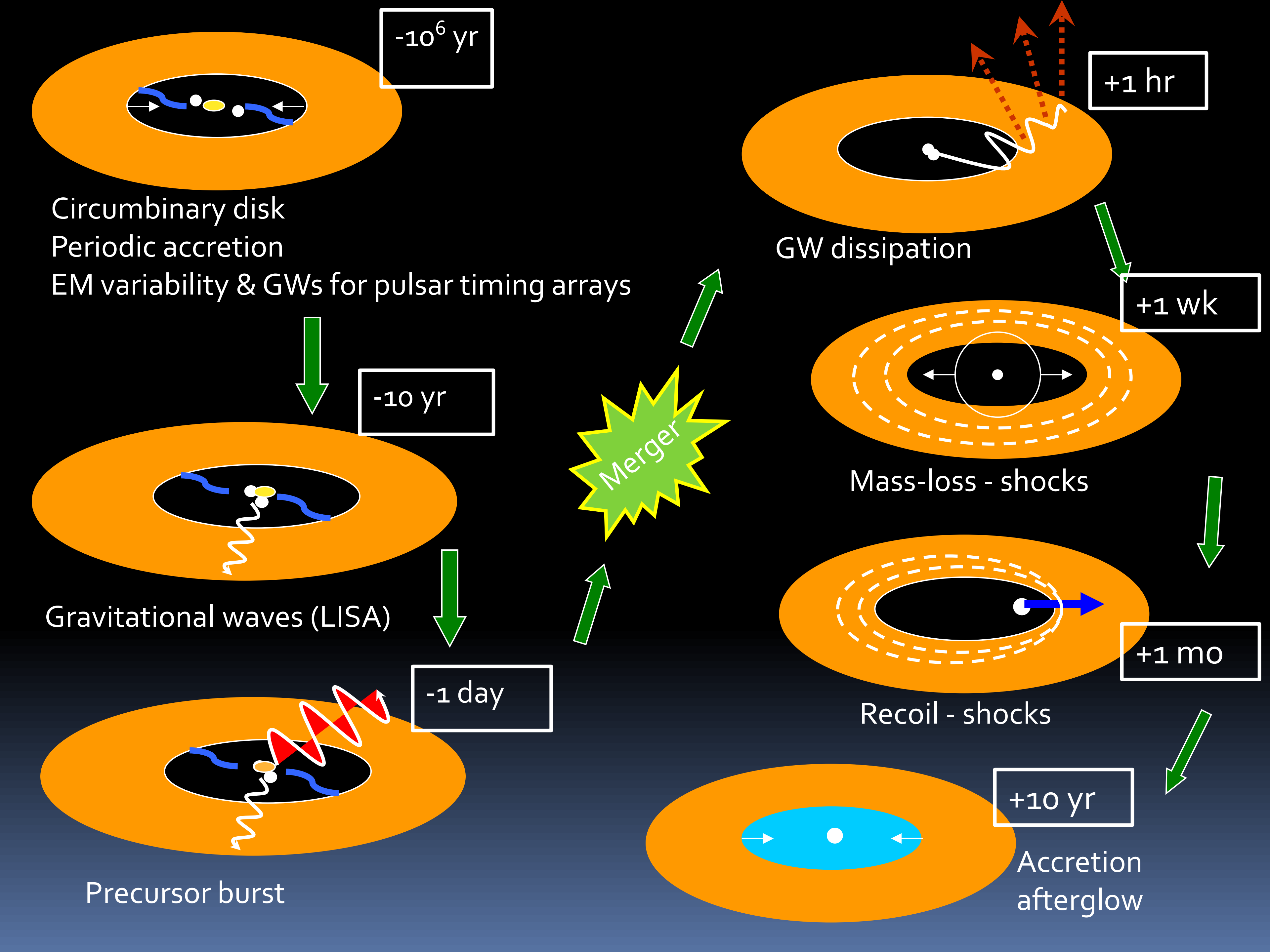
XXVII. Relativistic Astrophysics Symposium, Texas, December 11, 2013

Galaxies frequently collide and merge



Colliding Galaxies NGC 4038 and NGC 4039 HST • WFPC2

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


-10^6 yr
Circumbinary disk
Periodic accretion
EM variability & GWs for pulsar timing arrays
-10 yr
Gravitational waves (LISA)
-1 day
Precursor burst
Merger
+1 hr
GW dissipation
+1 wk
Mass-loss - shocks
+1 mo
Recoil - shocks
+10 yr
Accretion
afterglow

What should we expect to see

- Doppler effect (talks on Monday)
  - velocity offset in AGN broad lines
  - time variable broad lines
- Periodic accretion
- Gap/minidisks, gas pile up
  - missing blue/UV component
  - optical/infrared bump
  - features in X-ray iron lines
- Gravitational waves (pulsar timing, LISA)
  - Gas affects binary migration → GW spectrum
  - eccentricity → GW spectrum

Why is this an open problem?

Gas
+ radiation

Disk-satellite
interaction

Viscosity – MHD
turbulence

Vast timescales

Vast spatial scales (3D)

Boundary conditions

Initial conditions?

General
Relativity

Heating-cooling

Plasma physics:
electrons + ions

- What does the steady-state configuration look like?
  - assume unequal mass binary
  - initial condition for simulations
- How fast does the binary merge?

Good old models (steady state)

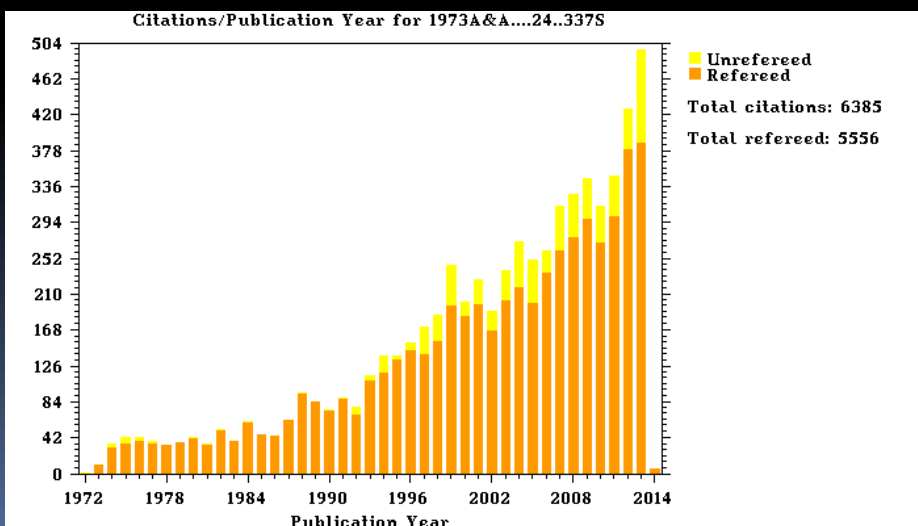
Gas
+ radiation

Viscosity – turbulence

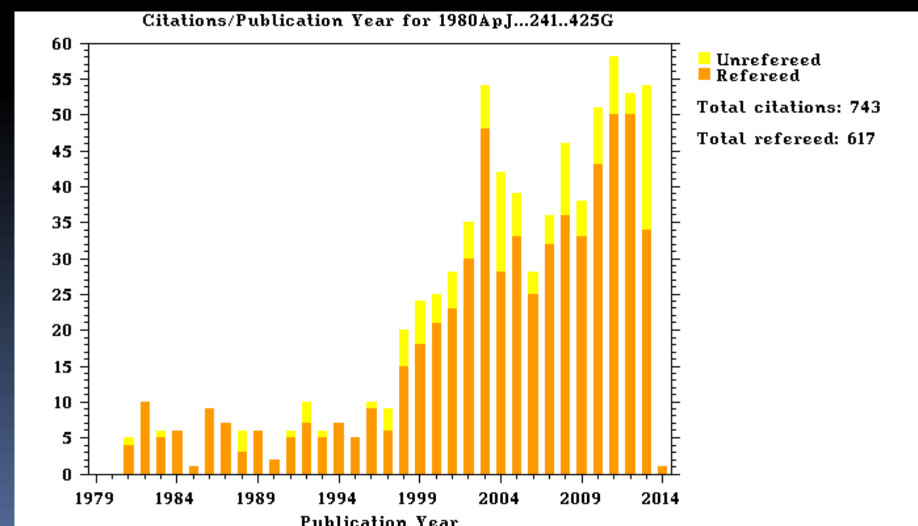
Heating-cooling

Disk-satellite interaction

Shakura-Sunyaev 1973



Goldreich-Tremaine 1980



Steady state model without satellite

- Angular momentum flux = viscous torque

$$\dot{M}\partial_r(r^2\Omega) = \partial_r T_\nu$$

$$T_\nu = -2\pi r^3(\partial_r\Omega)\,\nu\Sigma$$

- Viscous heating = radiative cooling

$$D_\nu = \frac{(\partial_r\Omega)T_\nu}{4\pi r} = \frac{9}{8}\Omega^2\nu\Sigma$$

$$=$$

$$F = \sigma T_s^4 = \frac{4}{3}\frac{\sigma T_c^4}{\tau}$$

optical depth $\tau = \kappa\Sigma/2$

Three unknowns: Σ(r), T_c(r), ν(r)

- Viscosity: a prescription (Shakura-Sunyaev 1973)

$$\nu = \alpha c_s H \beta^b$$

$$\beta = p_{gas}/p$$

- Scaleheight ← vertical gravity = gas + rad. pressure

$$H = \frac{c_s}{\Omega}$$

$$c_s = \sqrt{p/\rho}$$

$$p_{gas} = \rho k T_c/(\mu m_p)$$

$$p_{rad} = \tfrac{1}{3} a T_c^4$$

Steady state model with satellite

- Angular momentum flux = viscous + tidal torque

$$\dot{M}\partial_r(r^2\Omega) = \partial_r T_\nu - \partial_r T_d$$

$$T_\nu = -2\pi r^3(\partial_r\Omega)\,\nu\Sigma$$

$$\partial_r T_d = 2\pi r\,\Lambda\Sigma$$

- Viscous heating = radiative cooling

$$D_\nu + D_d = \frac{9}{8}\Omega^2\nu\Sigma + \frac{1}{2}(\Omega_s - \Omega)\Lambda\Sigma \;=\; F = \sigma T_s^4 = \frac{4}{3}\frac{\sigma T_c^4}{\tau}$$

optical depth $\tau = \kappa\Sigma/2$

Three unknowns: $\Sigma(r)$, $T_c(r)$, $\nu(r)$

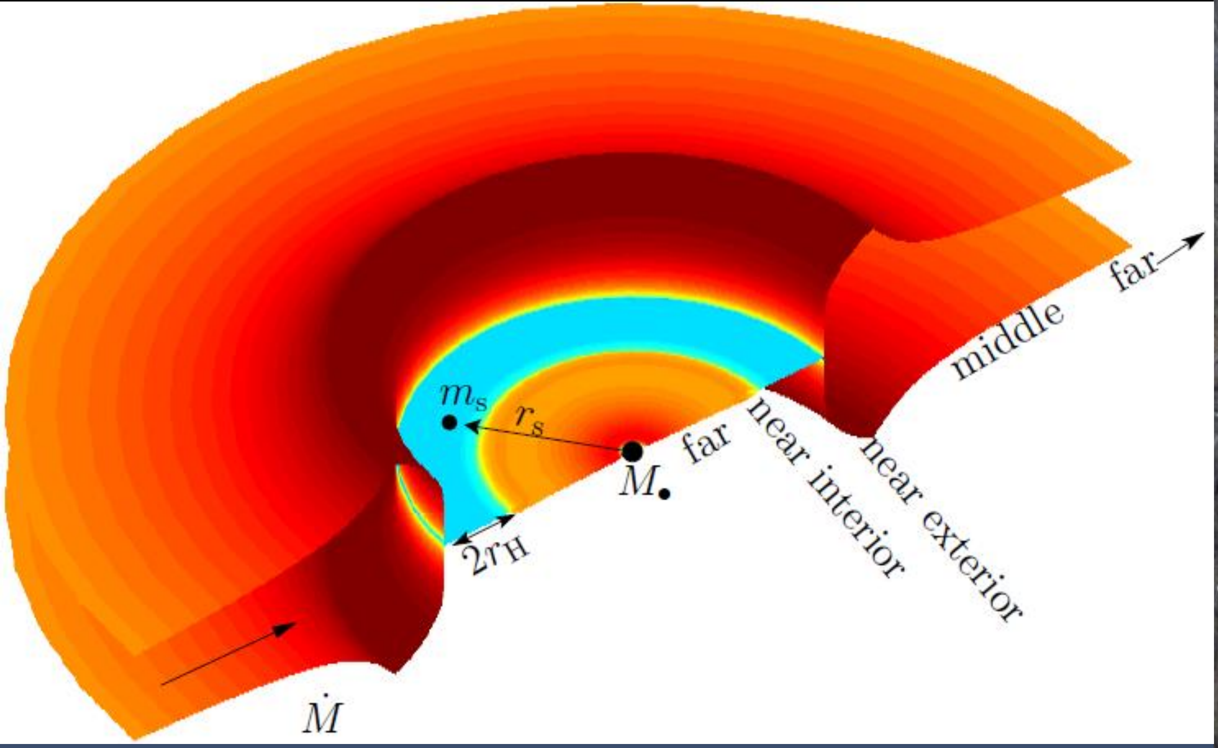
Specific tidal torque density

specific tidal torque density:

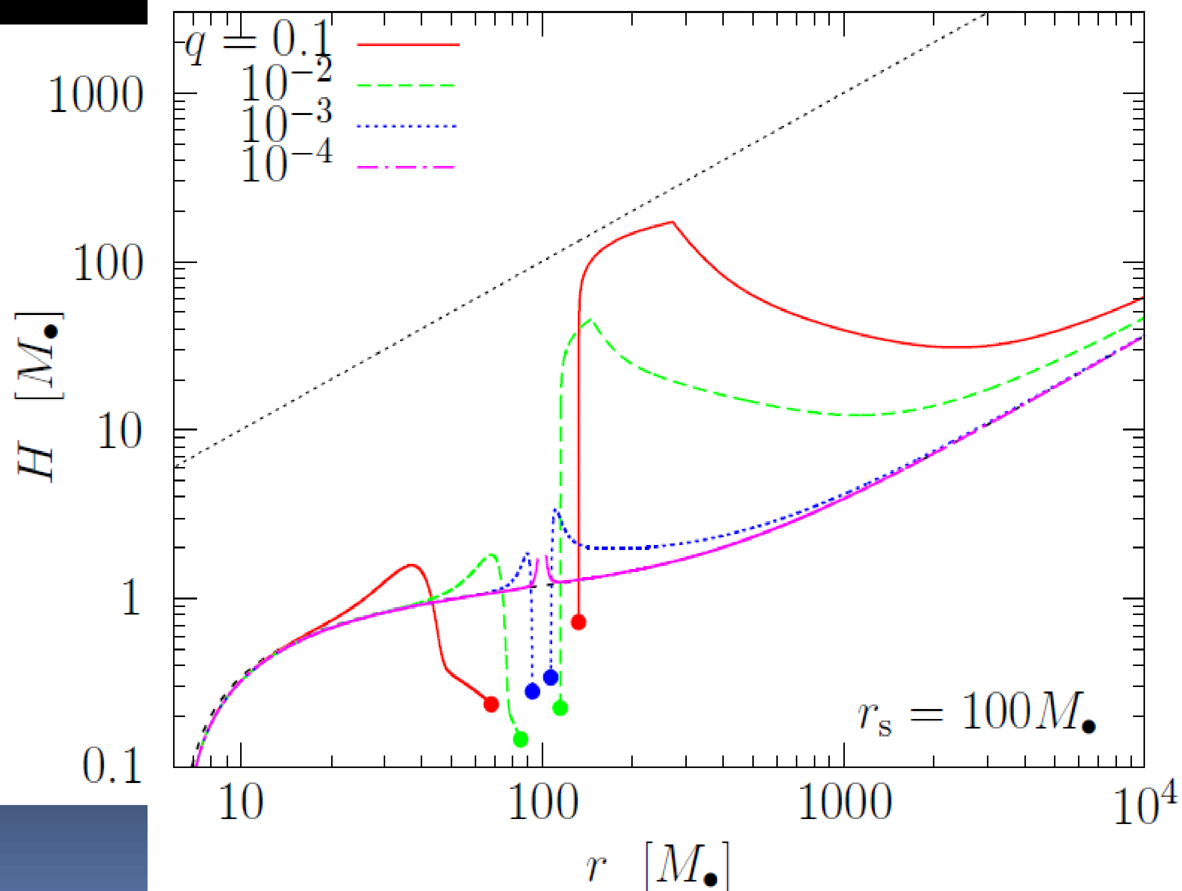
$$\Lambda \approx \begin{cases} -\frac{1}{2} f q^2 r^2 \Omega^2 r^4/\Delta^4 & \text{if} \quad r < r_s - r_H\,, \\ +\frac{1}{2} f q^2 r^2 \Omega^2 r_s^4/\Delta^4 & \text{if} \quad r > r_s + r_H\,, \end{cases}$$

$$\Delta \equiv \max(|r - r_s|, H) \qquad r_H \equiv (q/3)^{1/3} r_s$$

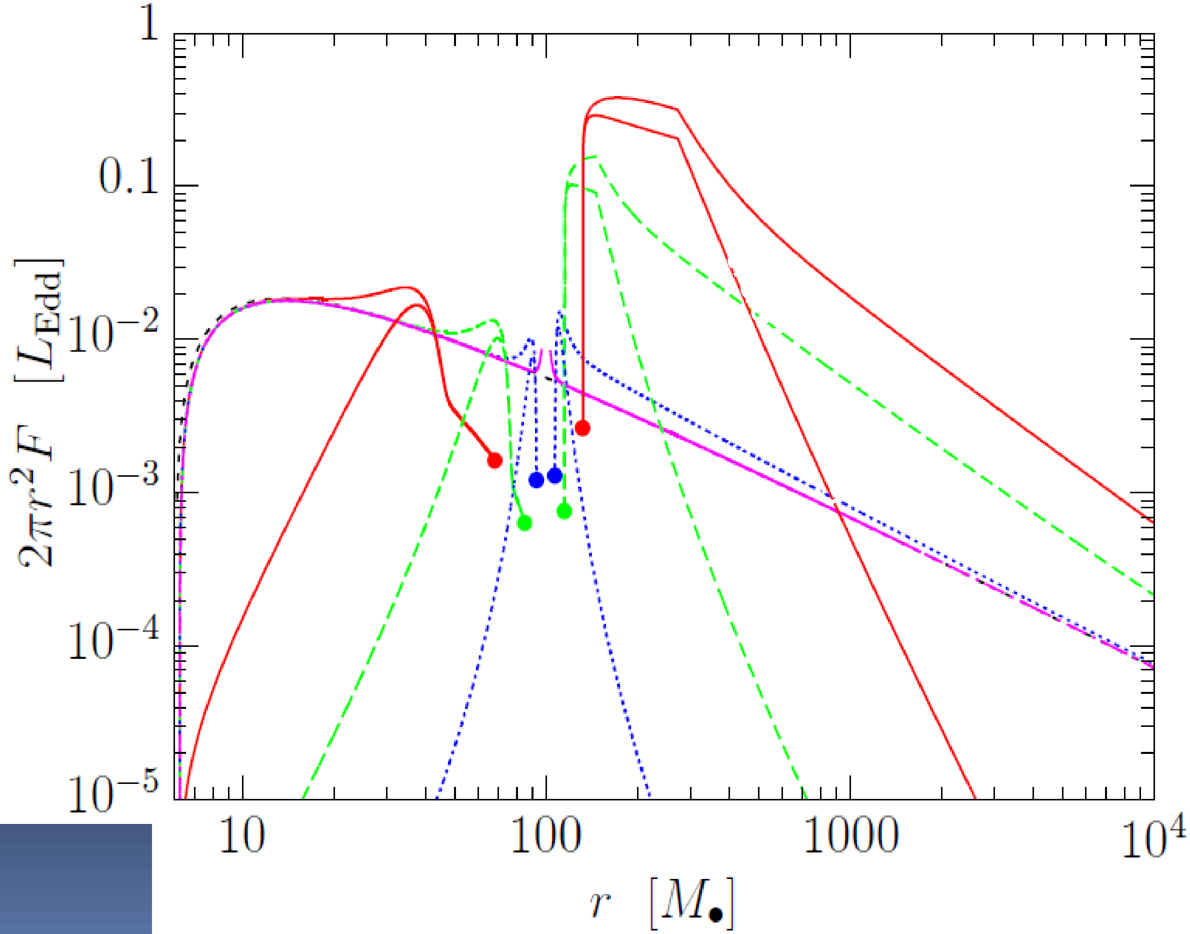
Steady-state circumbinary disk



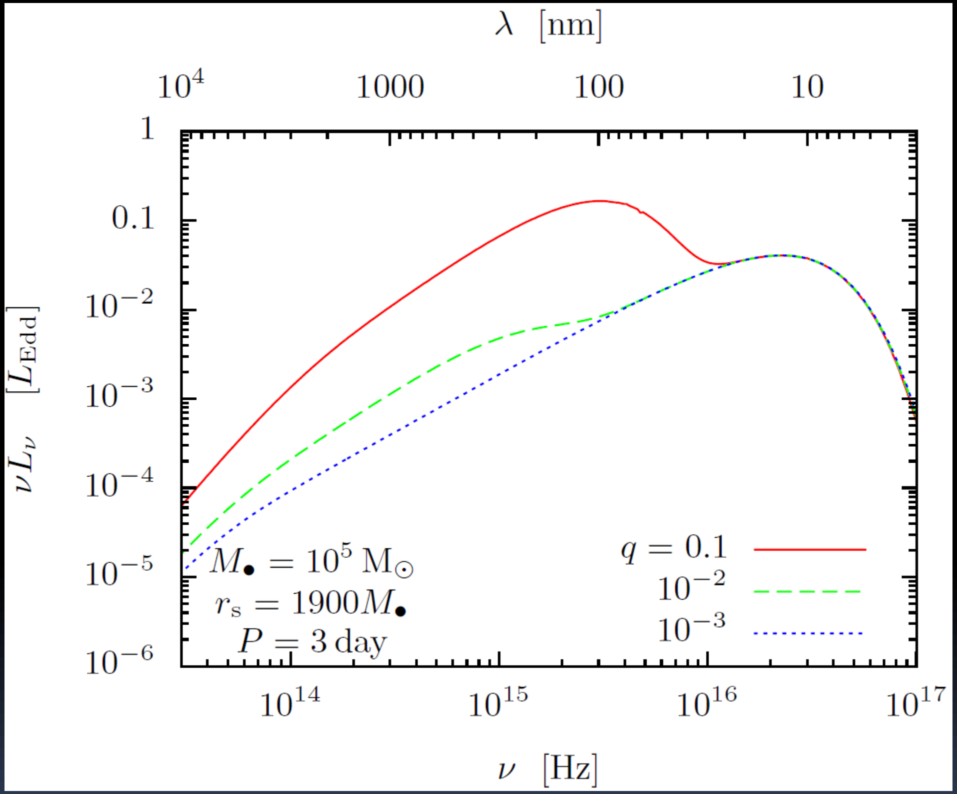
Disk scaleheight vs radius



Viscous and tidal heating vs. radius



disk spectrum



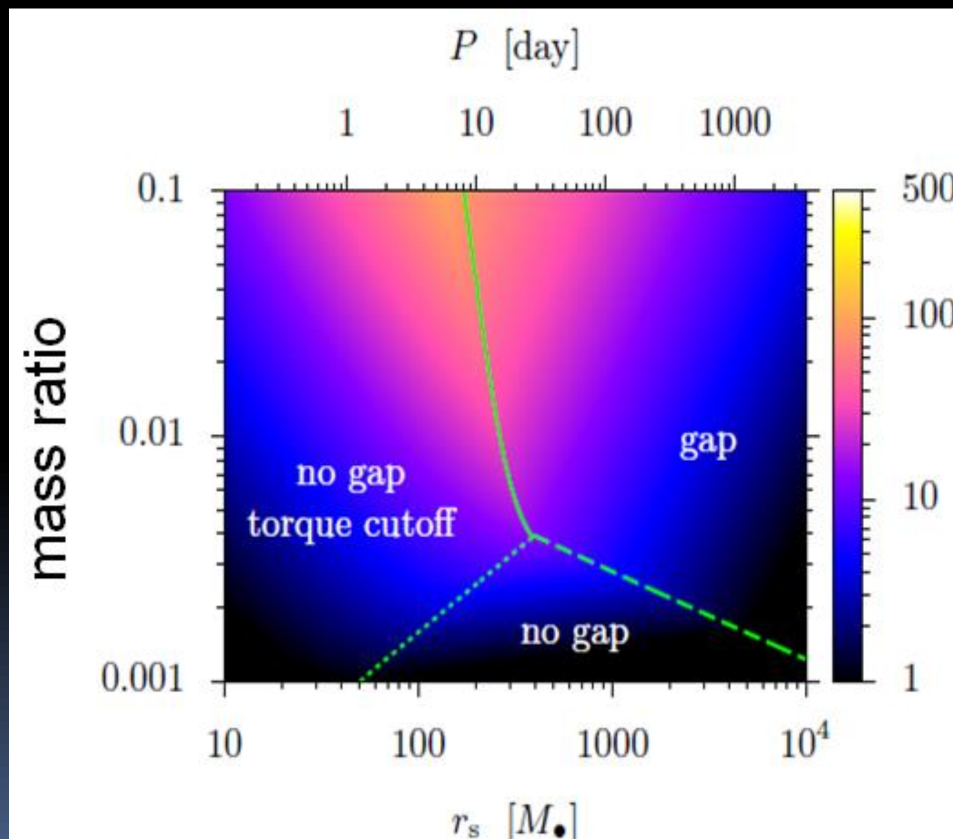
optical brightening!

Local brightening of disk due to secondary

orbital period [days]

$10^7\,M_\odot$

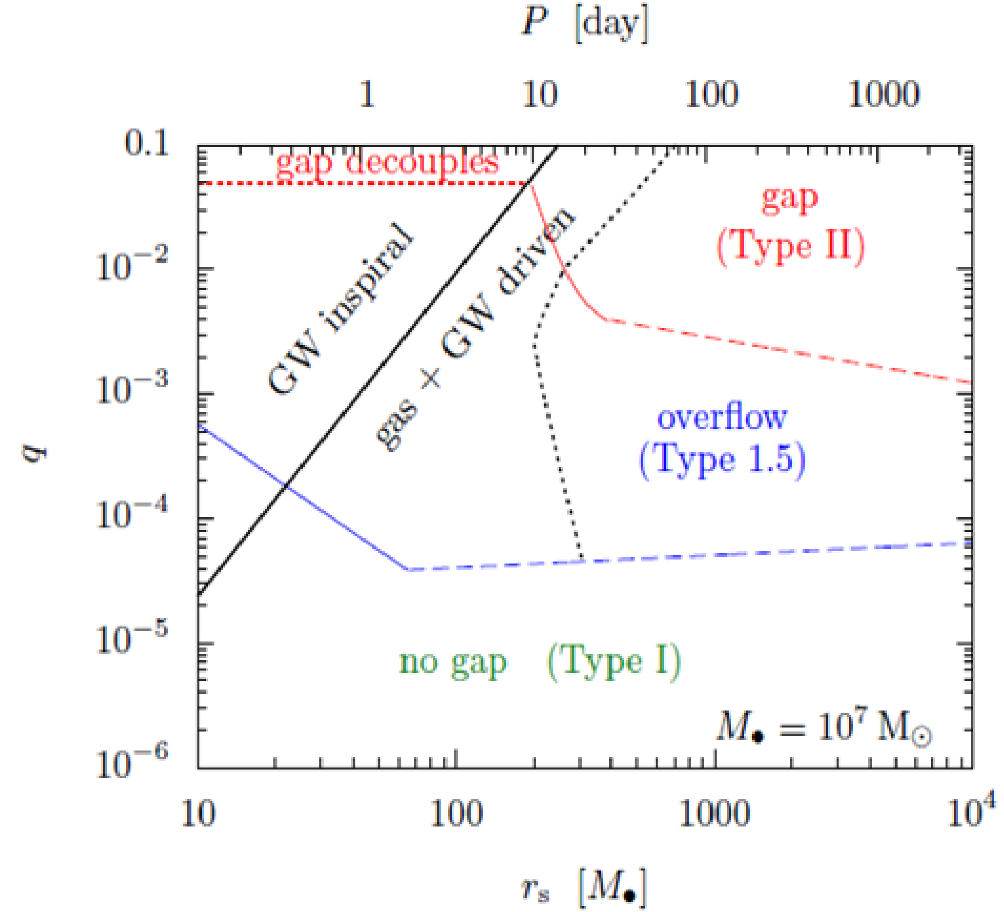
mass ratio



orbital radius [r_g]

Phase diagram

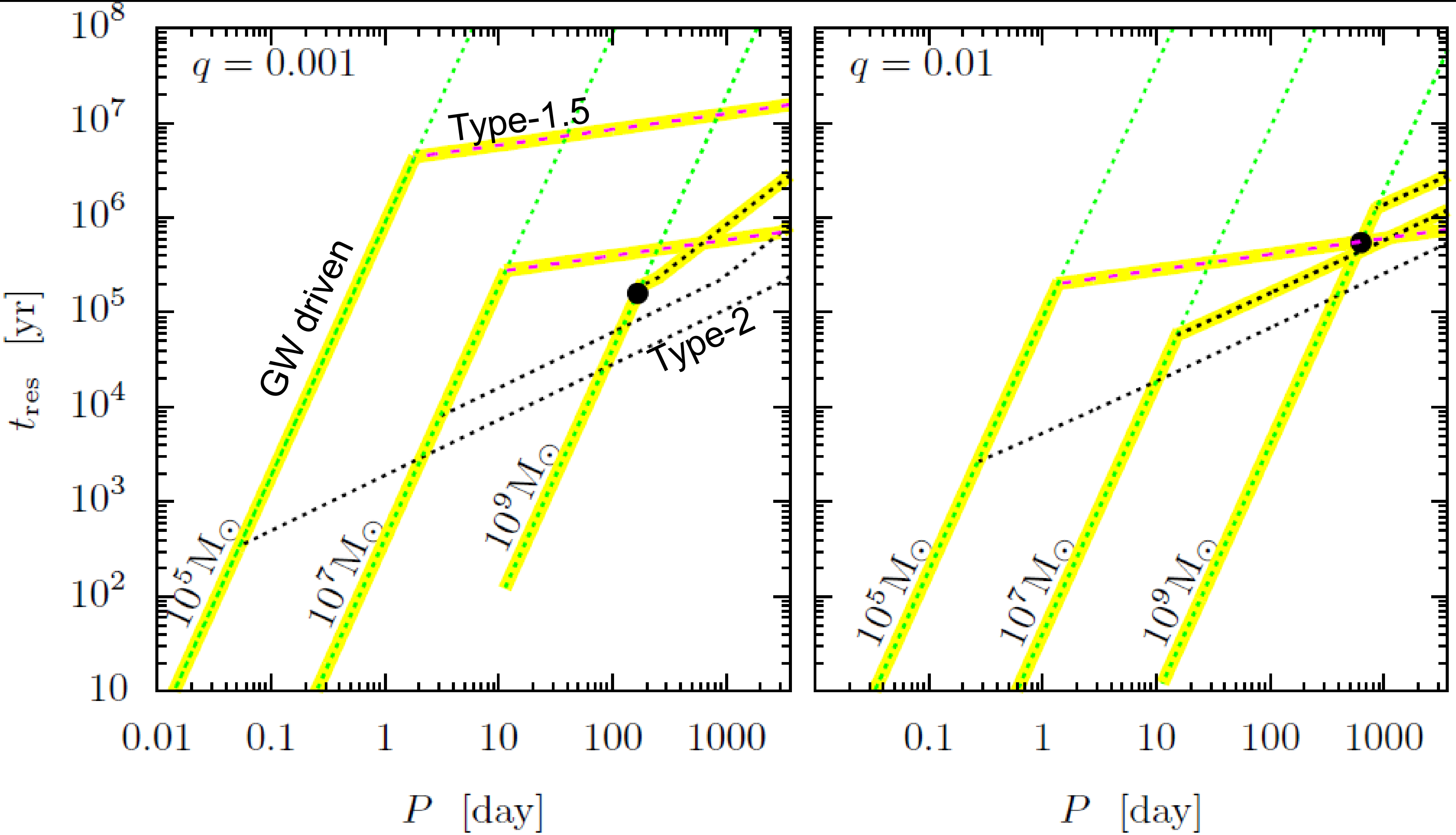
orbital period [days]



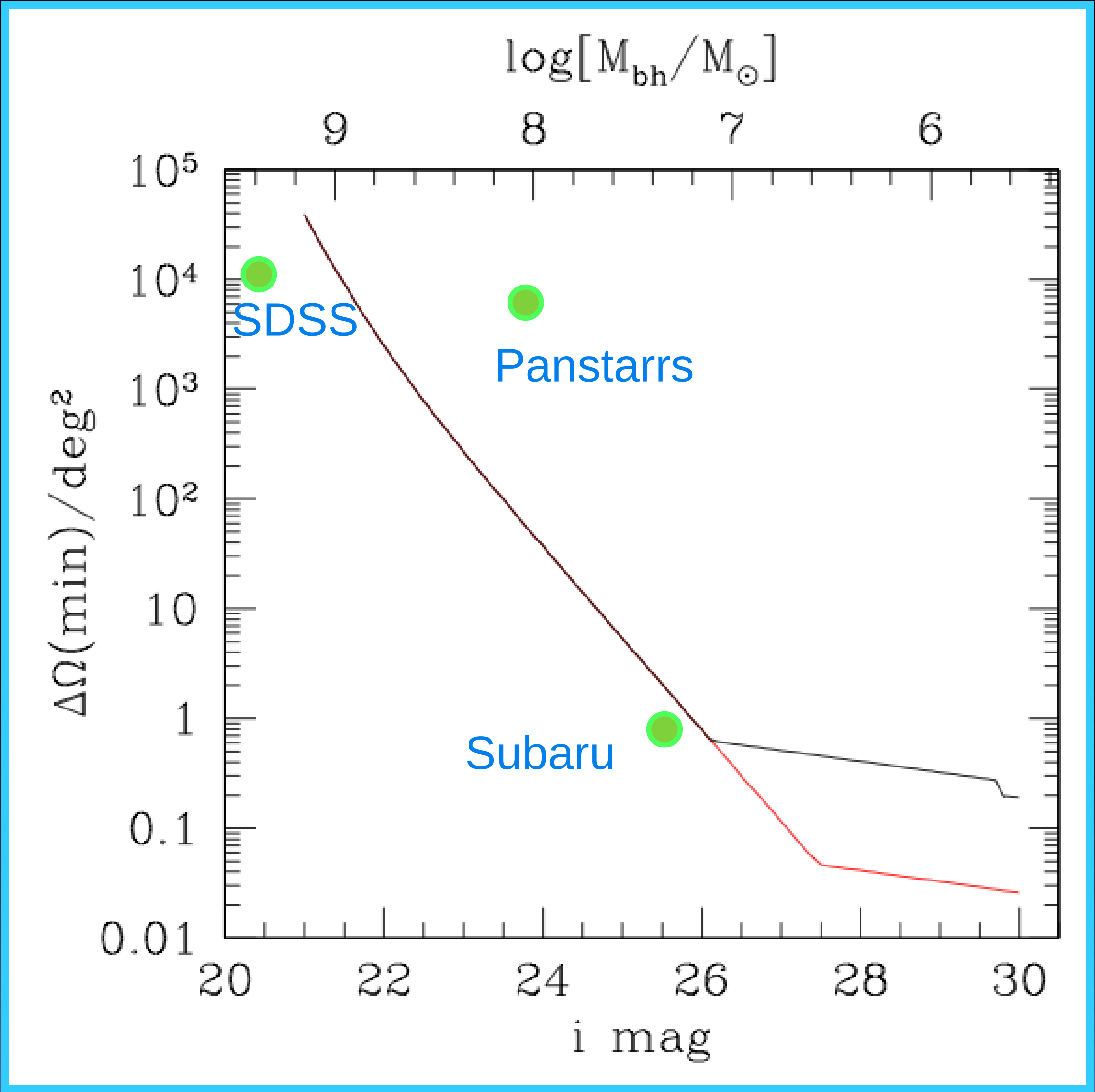
mass ratio

orbital radius [r_g]

Residence time



Requirements for an (optical) survey for finding periodic variable



Require:

≥ 100 sources @ t_{var} ≤ 1 yr

≥ 5 sources @ t_{var} ≤ 20 wk

Assume:

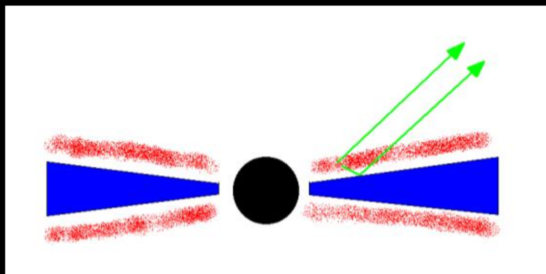
- f_{Edd} = 0.3
- f_{var} = 0.1
- $t_Q = 10^7$ yr
- Hopkins et al. QSOLF @ z=2

Conclude:

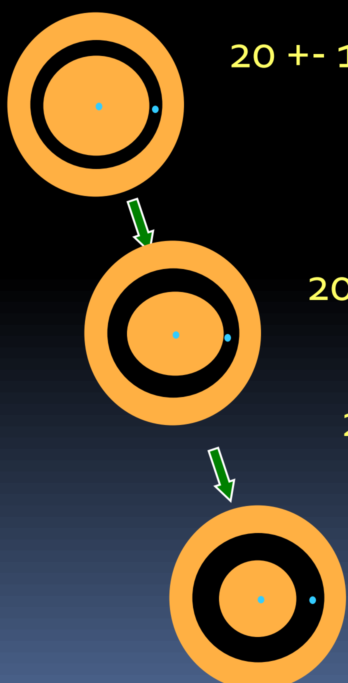
- wide survey best to probe GW-decay
- disk physics at i~26.5

Haiman, Kocsis , Menou (2009)

X-ray iron line features



Changing gap width

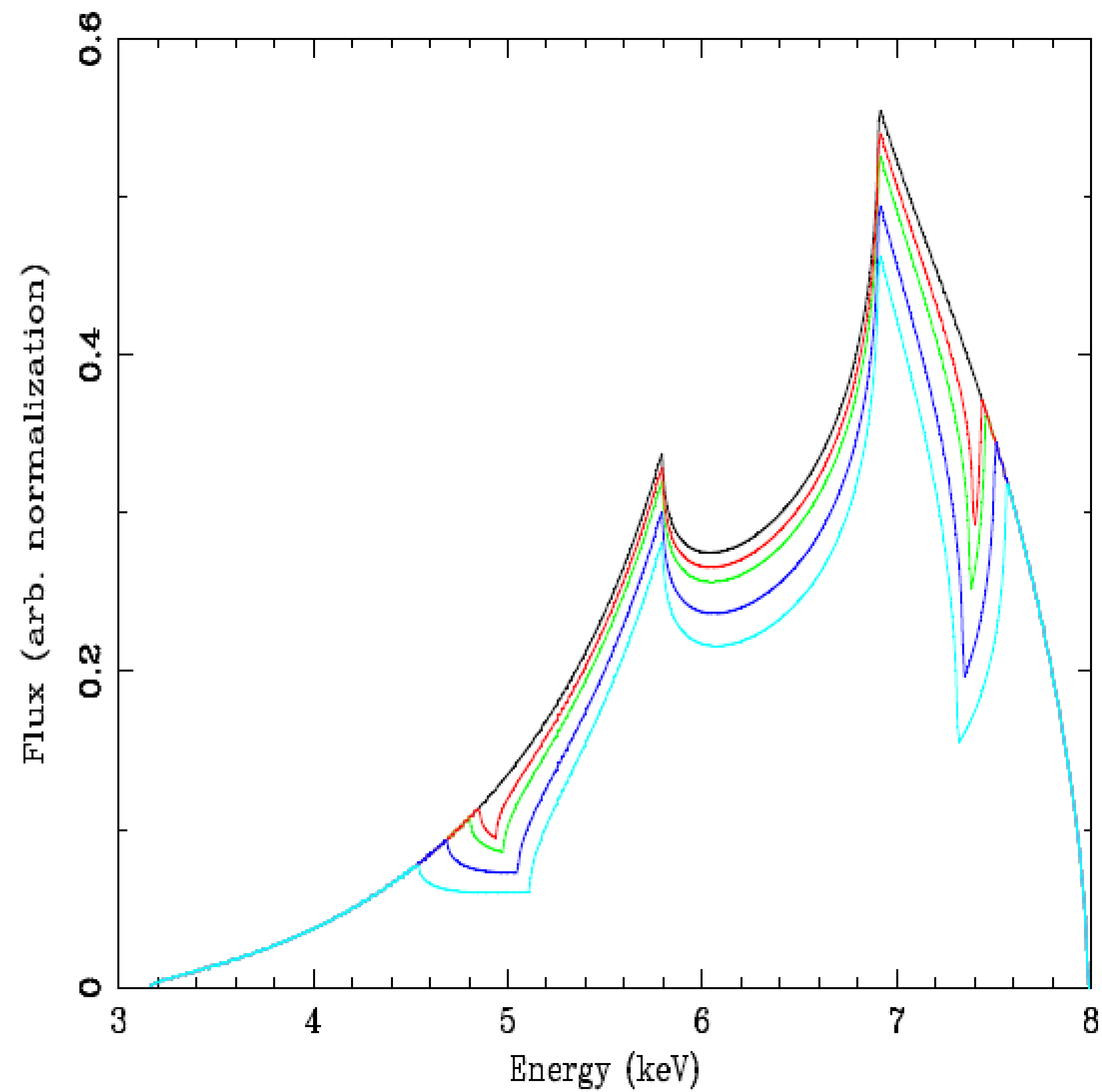


20 +- 1 r_g

20 +- 2 r_g

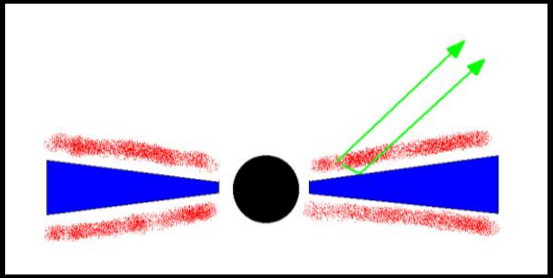
20 +- 4 r_g

20 +- 6 r_g

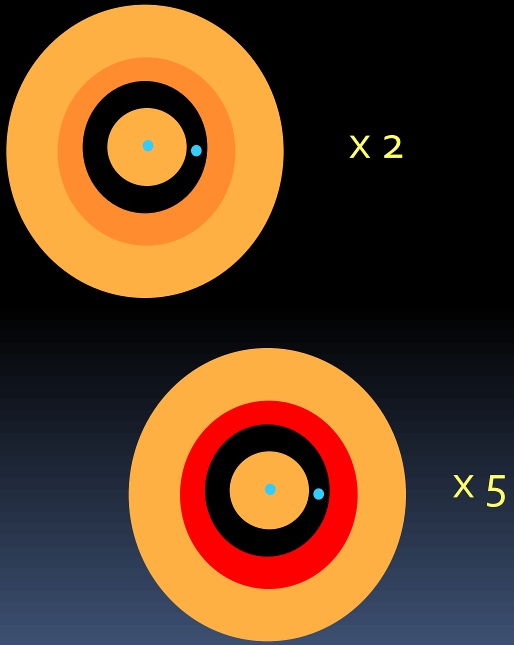


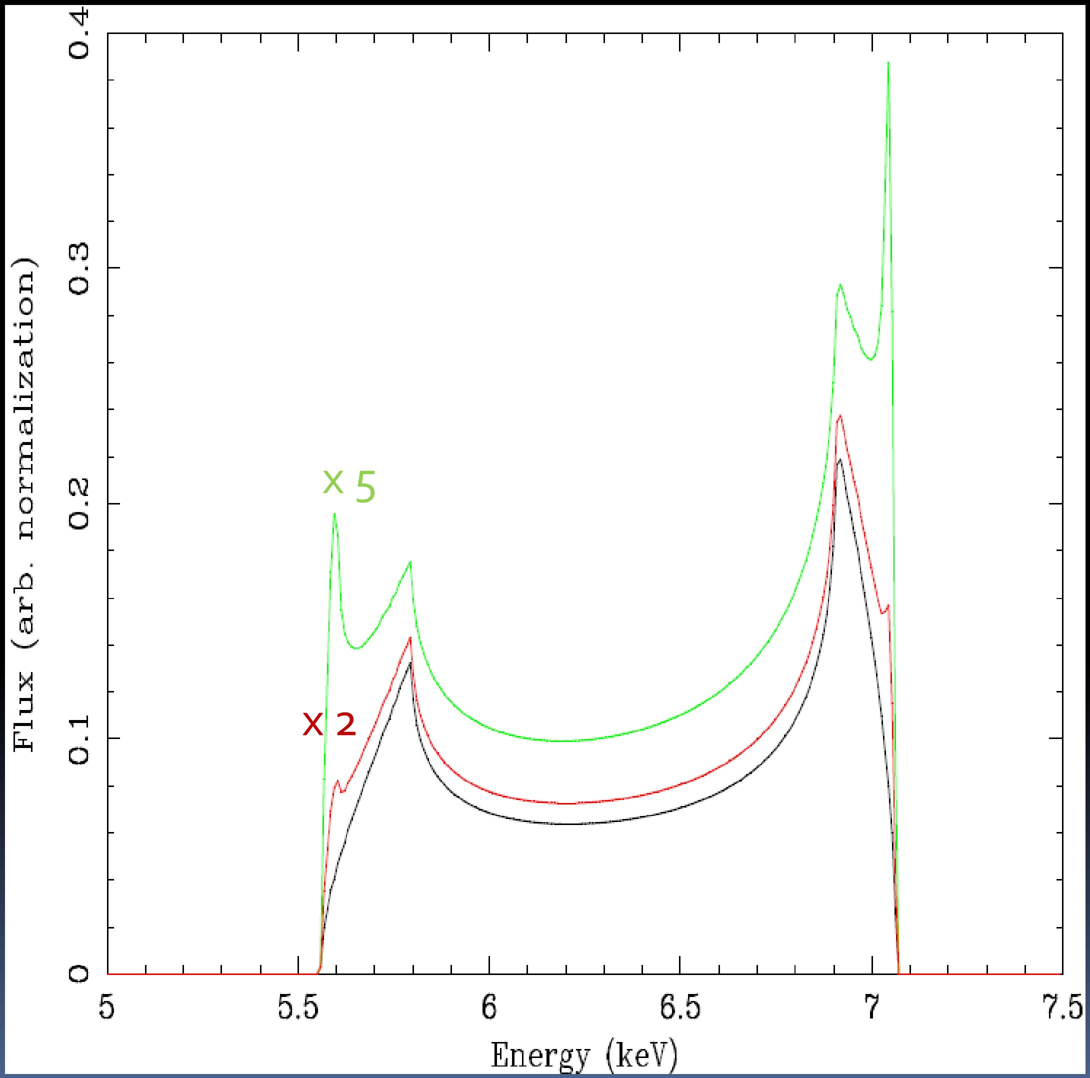
McKernan, Ford, Kocsis & Haiman (2013)

X-ray iron line features



Pile-up outside the gap



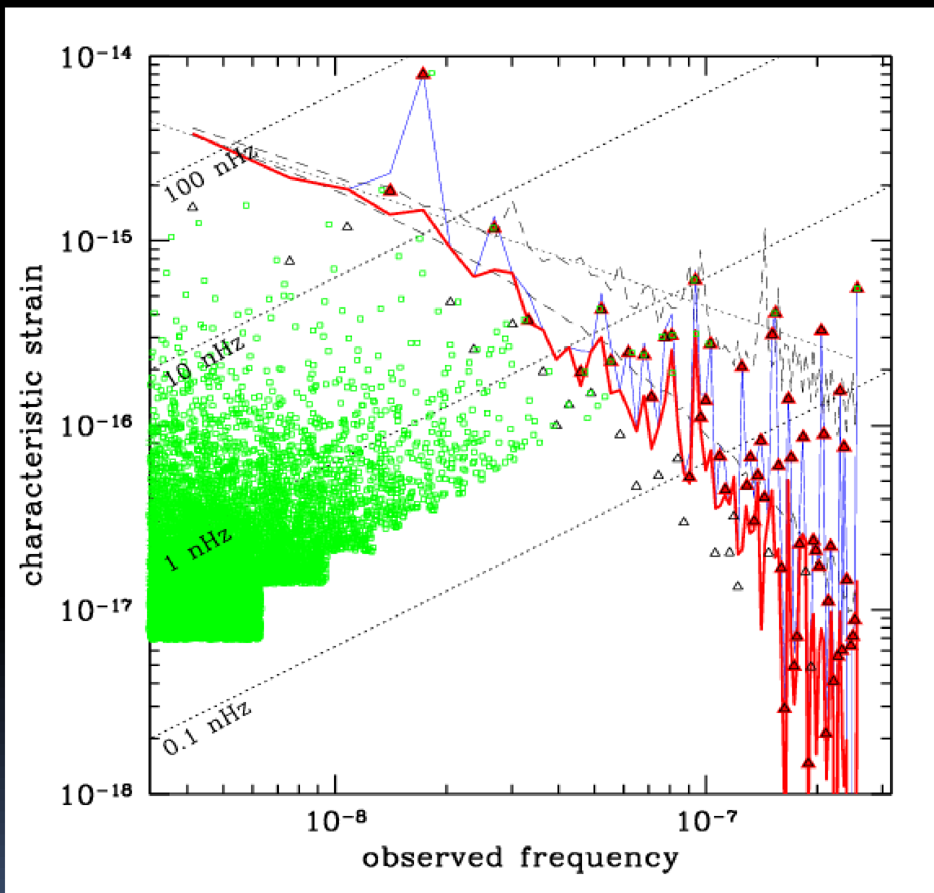


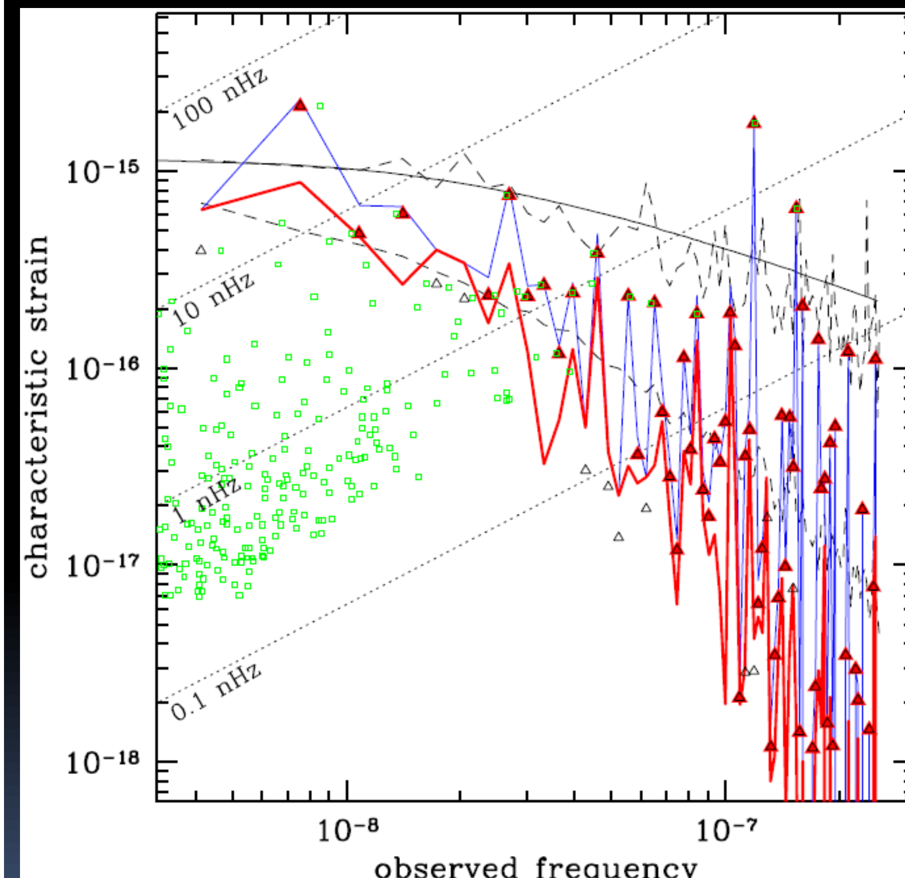
McKernan, Ford, Kocsis & Haiman (2013)

Gravitational Waves – Pulsar Timing Arrays

Gas OFF

Gas ON (Type-II)





Contribution of individual sources

Unresolved background

Total signal

Spectrum averaged over 1000 Monte Carlo realizations

Kocsis & Sesana (2011)

Conclusions

- Steady state circumbinary disk model
  - Gas pile up, overflow into gap
  - merger in gas (no gap decoupling M< 10^7 Msun)
  - migration slower than previously thought
- Observational signatures
  - missing UV component
  - red/IR excess
  - periodic variability (P ~ weeks to years)
  - peculiar iron line
  - pulsar timing array GW background

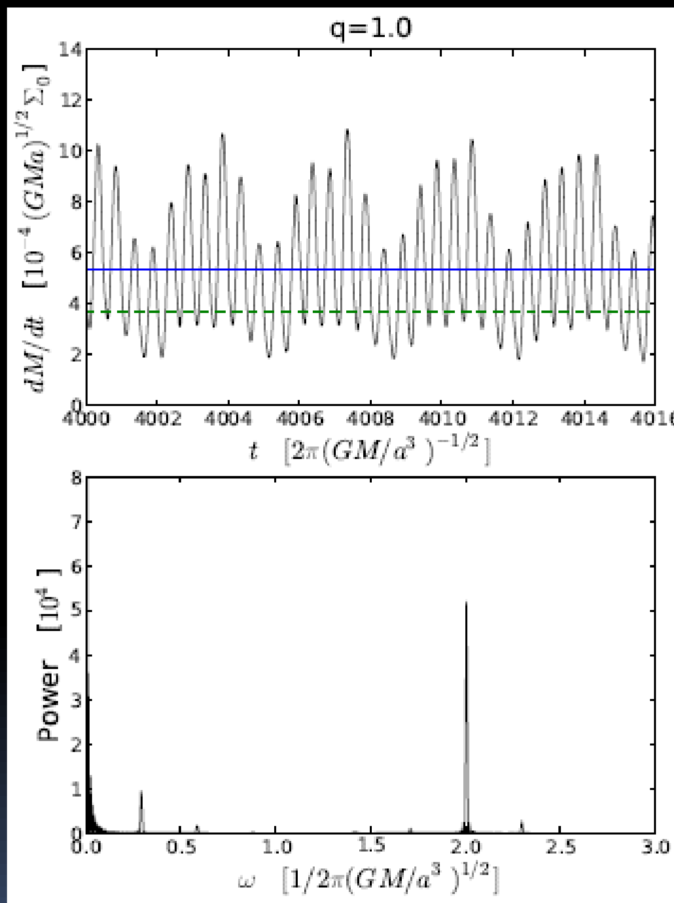
Simulations

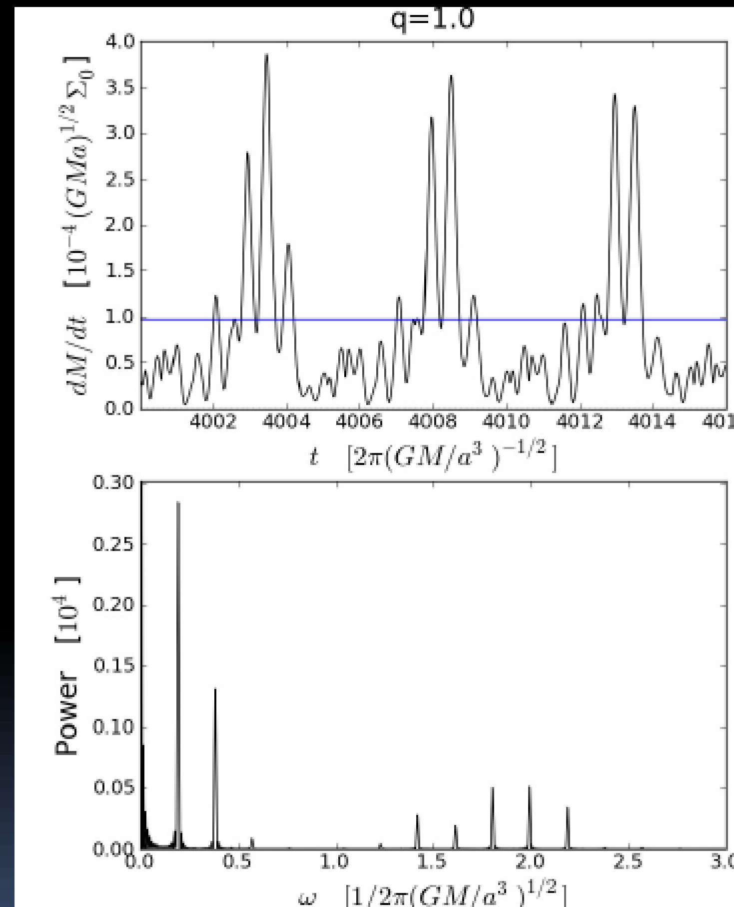
SMBH binaries approaching merger

- HD: MacFadyen & Milosavljevic (2008); Hayasaki (2007); Cuadra et al. (2009); Roedig et al. (2012); D'Orazio, Haiman, MacFadyen (2012)
  - **Central cavity, periodic accretion**
- HD+inspiral: Baruteau, Ramirez-Ruiz, Masset (2012)
  - **No central cavity**
- GR+D: van Meter et al. (2010)
  - Launch outflow with high Γ
- GR+EM: Palenzuela et al. (2009, 10), Mösta et al. (2010)
  - Periodic variability in Pointing flux, dual jets
- MHD: Shi et al. (2011)
- PN+MHD: Noble et al. (2012)
- GR+HD: Bogdanovic et al. (2011), Bode et al. (2012)
- GR+MHD: Farris, Liu, & Shapiro(2011), Giacomazzo et al. (2012)
- GR+MHD+"artificial gas cooling": Farris et al. (2012,2013)

- **Still to do:**
  - Radiation pressure and plasma physics
  - Initial and boundary conditions
  - Run for many viscous times

Circumbinary accretion rates





0.01

$\alpha = 0.005$

D'Orazio, Haiman, MacFadyen (2012)

Steady state model without satellite

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$$\nu = \alpha c_s H \beta^b \qquad \beta = p_{gas}/p$$

- Scaleheight ← vertical gravity = gas + rad. pressure

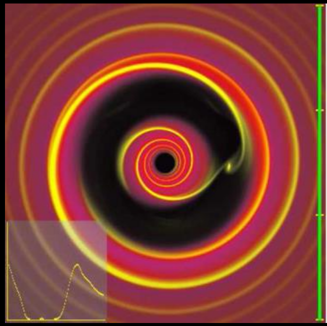
$$H = \frac{c_s}{\Omega} \qquad c_s = \sqrt{p/\rho} \qquad p_{gas} = \rho k T_c/(\mu m_p) \qquad p_{rad} = \tfrac{1}{3} a T_c^4$$

Conclusions

- Self-consistent steady-state model of strongly perturbed accretion disks with a secondary
  - analytical solution
- accumulation of gas → gap overflow
- new type of migration: Type-1.5
  - slower than Type-2
- Premerger glow
  - 10–500 x optical brightening,
  - truncated spectrum at NUV frequencies
  - periodic variability on orbital timescale
    → statistical measurement of migration and GWs
- mergers are embedded in gas
  - electromagnetic signal coincident with merger
  - PTA sigal is not suppressed

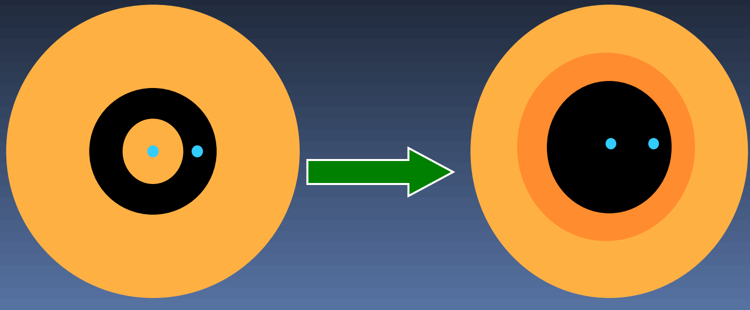
Evolution of binary+disk

- Binary excites spiral density waves in the disk
- Waves carry away angular momentum
  → migration (Goldreich & Tremaine 1980)



- Type 1 (weakly perturbed disk)
  - small secondary
  - linear theory for unperturbed disk

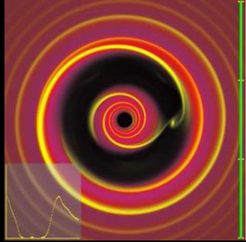
- Type 2 (gap forms in the disk)
  - large secondary
  - viscous gas inflow rate = migration rate



Indirect detection of GWs with AGN statistics

- Look for periodically variable AGN in large scale surveys (e.g. PanSTARRS, LSST)
- Measure number of binaries as a function of orbital period
  - Residence time at each radius depends on
    - GW inspiral
    - Disk driven migration

A labyrinth of disk effects



SMBH mass increase

- Eddington limited accretion of mass (so that radiation pressure doesn't blow the gas away)
- changes M → time dependent
- phase shift ~ 0.01 rad / yr

Secondary mass increase

- Bondi-Hoyle accretion of mass
- changes m → time dependent
- supply limited
- quenched by radiation pressure, etc.
- phase shift ~ 1-10 rad/yr

Radial Wind

- Bondi-Hoyle accretion of momentum → radial force
- Changes Ω for a given radius
- phase shift extremely small

Azimuthal Wind

- headwind: gas orbital velocity is slower
- Bondi-Hoyle accretion of momentum → azimuthal force
- changes L'
- phase shift ~ 0.01 – 1 rad / yr

Axisymmetric Gravity

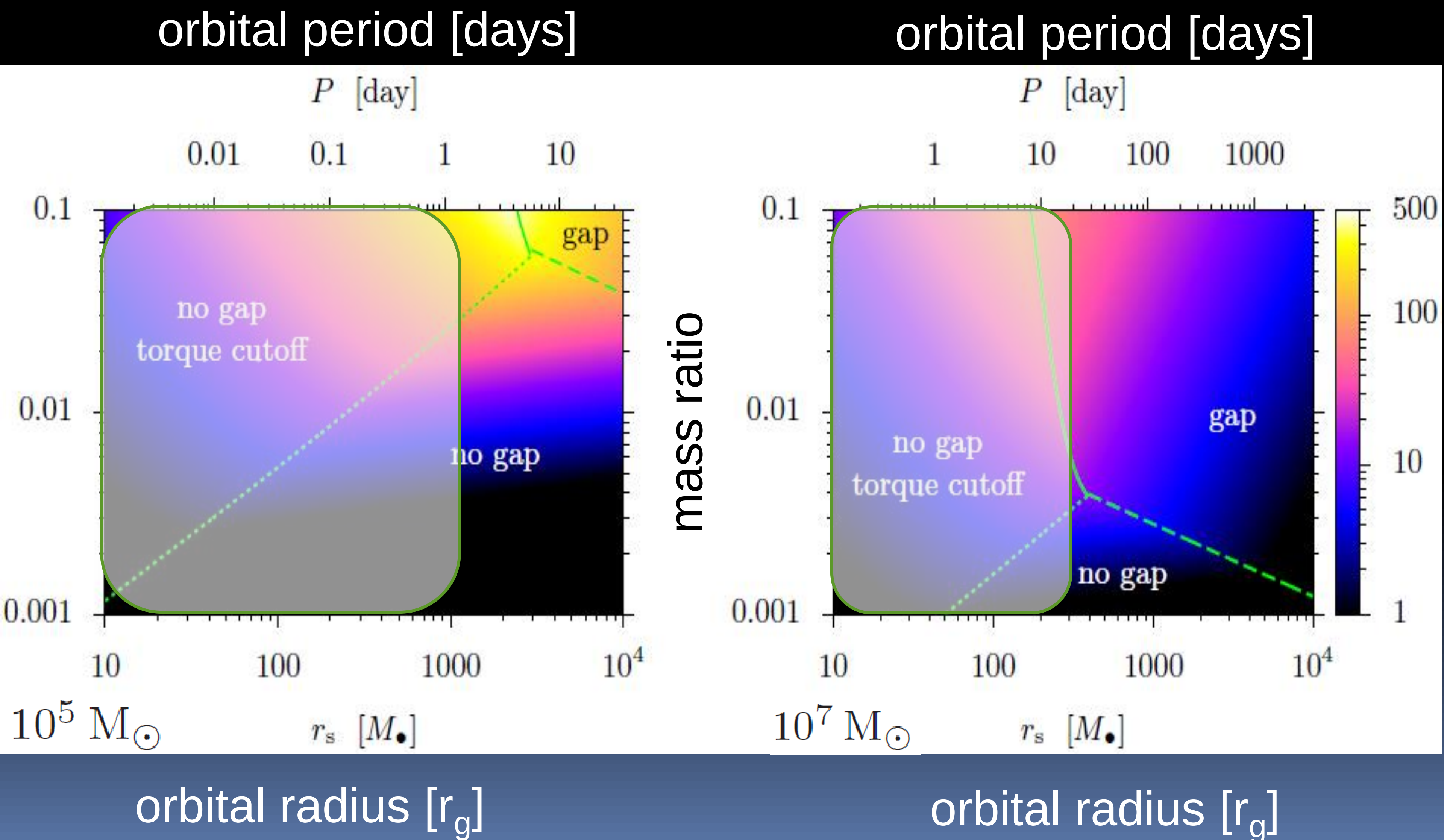
- Changes E, E', Ω,
- decompose disk into concentric rings
- each ring attracts the CO
- phase shift very small

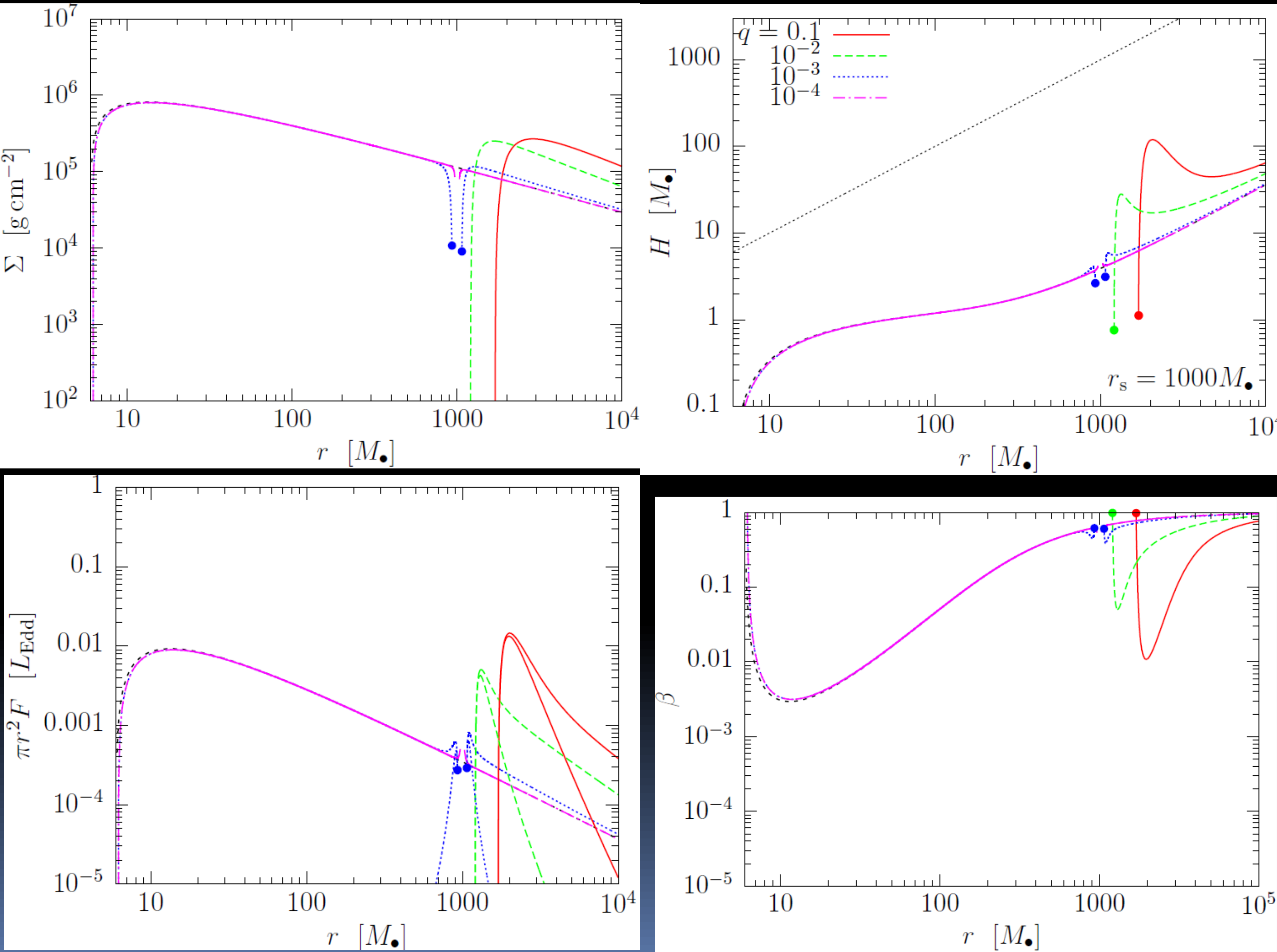
Migration

- CO generates a spiral density wave
- spiral wave torques the binary
- Changes L'
- Gap opens at large separations, then refills
- phase shift may be very large: 1–1000 rad/yr
- sensitive to accretion disk model
- dominates over GWs for wide binaries

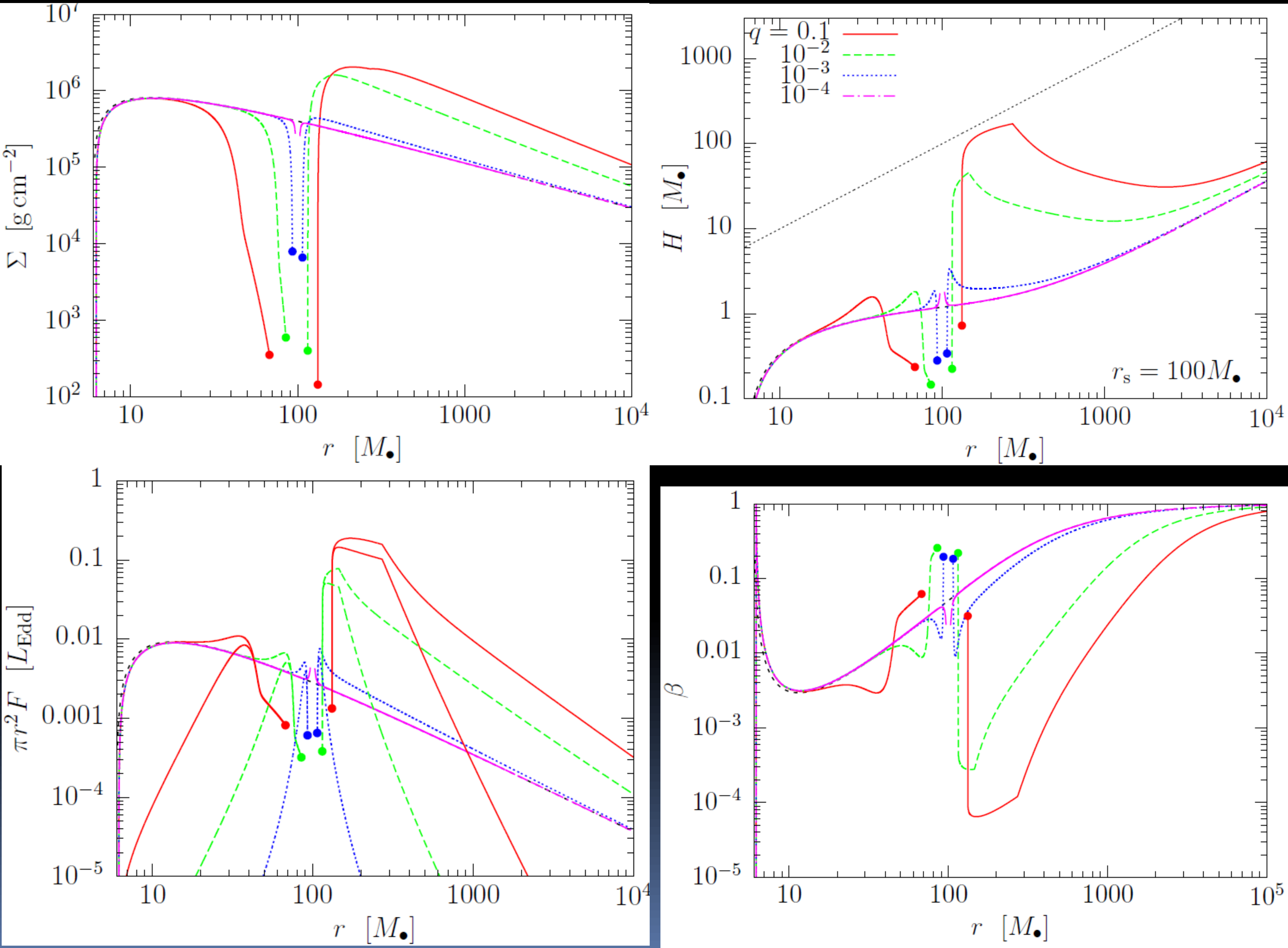
Kocsis et al., astroph/0701629

Local brightening of disk due to secondary





Σ [g cm^{-2}]
r [$M_\bullet$]
$q = 0.1$
10^{-2}
10^{-3}
10^{-4}
H [$M_\bullet$]
$r_s = 1000 M_\bullet$
$\pi r^2 F$ [$L_{\rm Edd}$]
β



Σ [g cm^−2]
r [M•]
q = 0.1
10^−2
10^−3
10^−4
H [M•]
r_s = 100M•
πr^2F [L_Edd]
β

Circumbinary Cavity

1. *Annular gap opens for massive secondary*
2. *Secondary migrates inward on viscous timescale*
3. *When $M_2 \sim M_{disk}$, secondary stalls, inner disk drains, dam forms*
4. *Secondary pushed in by dam until $a \sim 100\ R_{sch}$.*

Bad news for emission: central disk “missing” ?

Motivation

- Planet formation
  - How did hot Jupiters get to their observed proximity to the stars?
- Mergers of supermassive or intermediate mass BHs
  - Can gas solve the final parsec problem?
    - Controversial claims: 'Yes' Escala et al. (2005), 'No' Lodato et al. (2011)
    - Does this remove the GW background for pulsar timing array observations?
  - Electromagnetic effects to catch sub-parsec supermassive binaries?
    - Premerger optical glow, truncated spectra
    - Periodic variability (PanSTARRS, LSST)
    - Iron line features (XMM Newton, Astro-H, IXO)