Electromagnetic and Gravitational Wave Signatures of Black Hole Mergers

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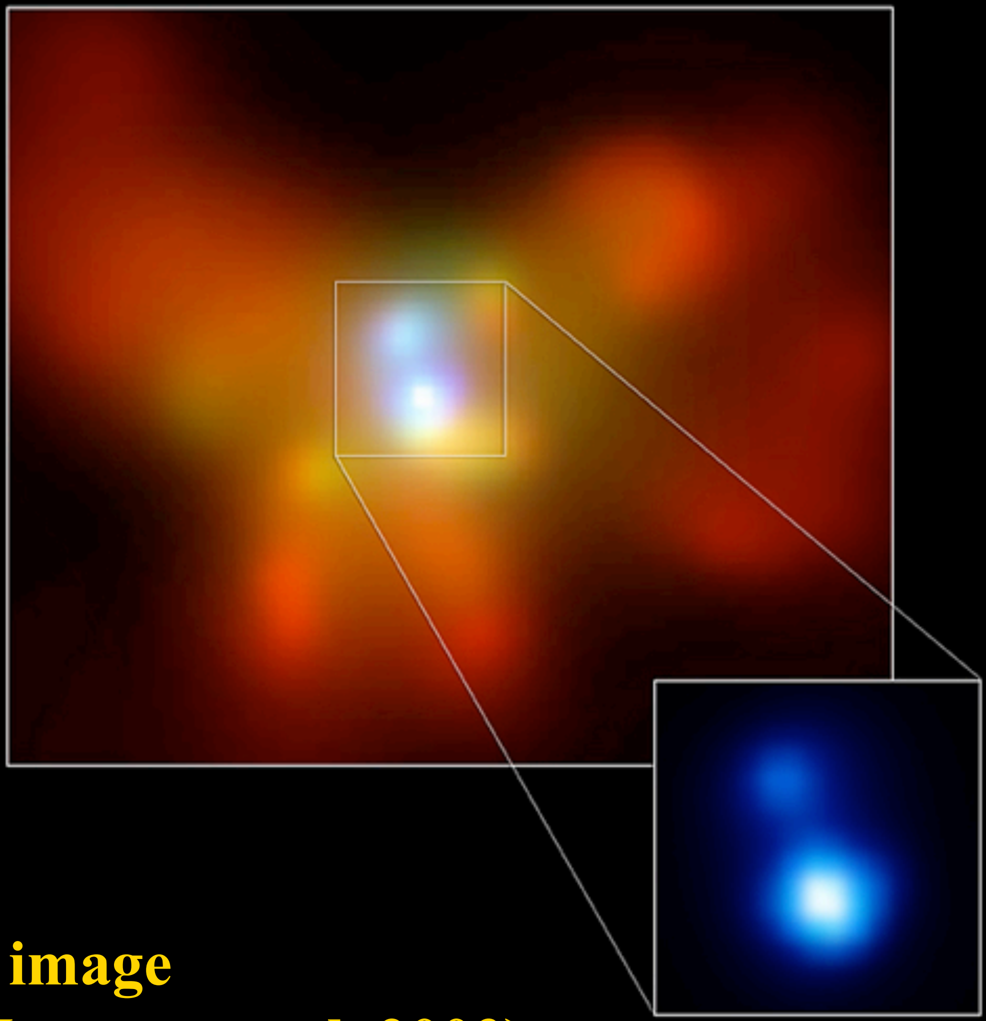
Galaxies definitely collide and merge

Colliding Galaxies NGC 4038 and NGC 4039 HST • WFPC2

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

Black hole binary in a galactic nucleus

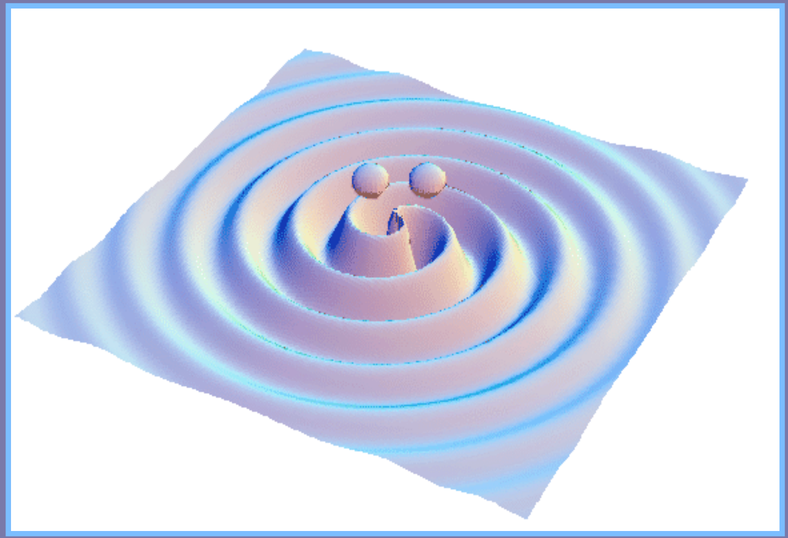


Chandra X-ray image
of NGC 6240 (Komossa et al. 2003)

Gravitational Waves by LISA

LISA can detect low-frequency gravitational waves from super-massive black hole binaries:

sensitive to total mass $(10^4\text{-}10^7)/(1+z)\ M_\odot$



Why try hard to find EM counterparts?

- **Grav. waves themselves a rich source of info on metric**

  — LISA sensitive to BH mass of $\sim(10^4\text{-}10^7)/(1+z)\ M_\odot$

- **Photons from counterparts: benefits for fundamental physics**

  — Hubble diagrams from 'standard sirens' ($f(df/dt)^{-1}$; 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: improved limits on graviton mass ($\gamma m_0 c^2 = hf$; Kocsis et al. 2008)

  — frequency-dependence in delay: test Lorentz invariance

- **Revolution for astronomy and astrophysics:**

  — *accretion physics*: Eddington ratio and spectrum, as functions of BH mass and spin, orbital parameters

  — *quasar/galaxy co-evolution:* long-standing problem

Can we find EM counterparts?

- **Sky position error from LISA is poor (~0.3 deg^2)**

— $10^{4-5} \rightarrow 10^{2-3}$ galaxies with LISA redshift info (i.e.: 3D)
— perhaps a unique near-Eddington quasar **(Kocsis et al. 2005)**

- **EM signature produced by merger is not understood**

— hard problem, requires gas physics + GR + radiation

- **But 'last parsec problem' suggests gas needed**

— without gas, orbital decay / angular momentum loss time-scale exceeds Hubble time at r ~ 1 pc

(Begelman, Blandford, Rees 1984)

- **IF gas is still present at the time of GW-emitting phase**

— accretion onto one or both holes (or to post-merger binary)
— modulations on orbital time-scale? post-merger shocks?

(Kocsis et al. 2006; 2008)

A Unique Quasar Counterpart?

TABLE 1
LISA MEASUREMENT ERRORS

	$\delta\mathcal{M}/\mathcal{M}$	$\delta\mu/\mu$	$\delta d_L/d_L$	$\delta\Omega$
best	0.8×10^{-5}	2×10^{-5}	2×10^{-3}	$0.01\,\mathrm{deg}^2$
typical	2×10^{-5}	9×10^{-5}	4×10^{-3}	$0.3\,\mathrm{deg}^2$
worst	0.8×10^{-3}	0.1	2×10^{-2}	$3\,\mathrm{deg}^2$

NOTE. — Assumed SMBH binary parameters: $m_1 = m_2 = 10^6 M_\odot$ and $z = 1$.

Vecchio (2004)

Angular and distance localization from GW signal alone depends on physical and orbital parameters and orientation

Kocsis, Frei, Haiman & Menou (2005)
Hughes & Holz (2005)

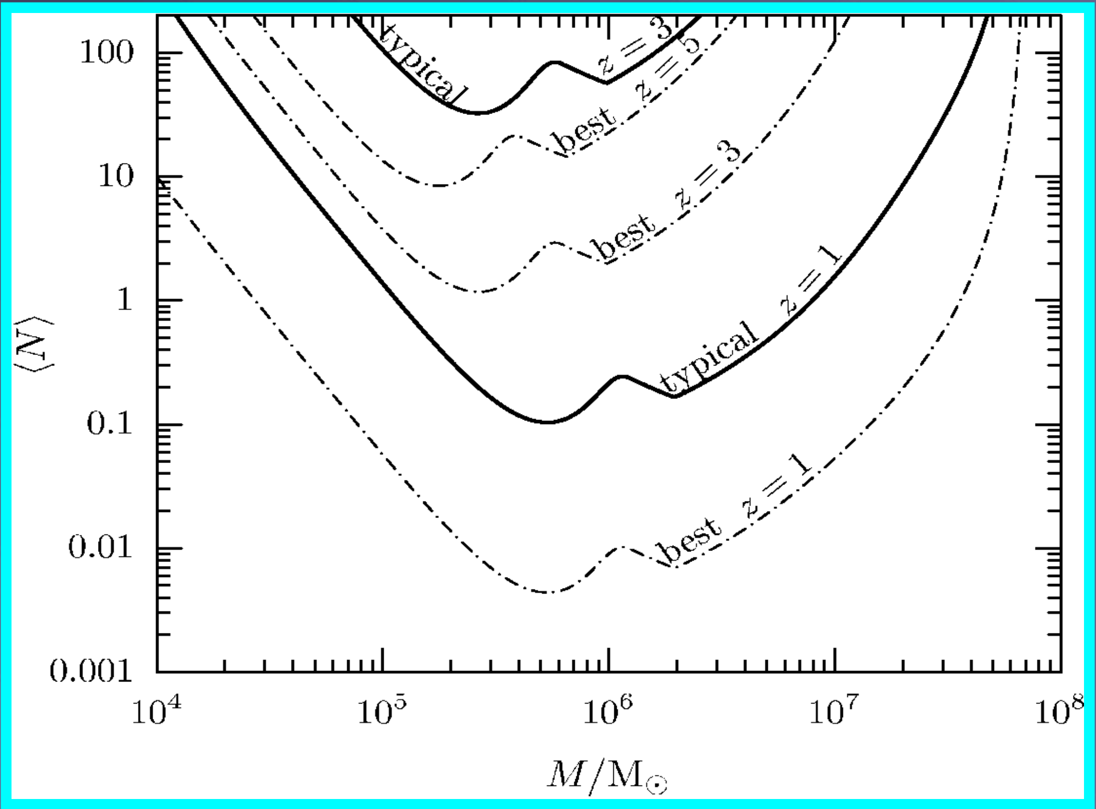
Angular Error: large LISA uncertainty (contains $10^{3\text{-}5}$ galaxies)

Distance Errors:
- LISA $d_L(z)$ measurement
- Cosmological Model
- Peculiar velocity

} $\Delta z \lesssim 0.005$

- Lensing-induced d_L-variations: $\Delta z \approx 0.002-0.03$ at $z \approx 0.3-1$

Number of Quasars in 3D LISA Error Box



Assume:
SMBH coalescence GW phase can be accompanied by luminous QSO activity

Kocsis et al. (2005)

- **Extrapolate known optical QSO LF to $M_{BH} \lesssim 3x10^7 M_\odot$**
- **Assume L/L(edd) ~ 0.3, consistent with recent obs+models**
- **Compute mean number in error box (20% lensing correction)**
- **Unique counterpart at z<1 for $4x10^5 M_\odot \lesssim M_{BH} \lesssim 10^7 M_\odot$**
- **Can be extended to z=3 if BHs spin rapidly**

Identify the Counterpart from Variability

AFTER THE MERGER IS COMPLETE:

(1) Gravitational recoil at coalescence can cause strong shocks in circumbinary gas. Monitor 3D LISA error box ~months after the merger and look for prompt transient "afterglow"

(Lippai, Frei & Haiman 2008; Corrales, MacFadyen & Haiman 2008)

BEFORE AND DURING COALESCENCE:

(2) Can real-time LISA data-stream localize the source ~month in advance, so that a word-wide search can be triggered for periodic variability on the orbital timescale?

(Kocsis, Haiman, Menou & Frei 2007; Kocsis, Haiman & Menou 2008)

Cartoon Model of Binary+Gas Evolution

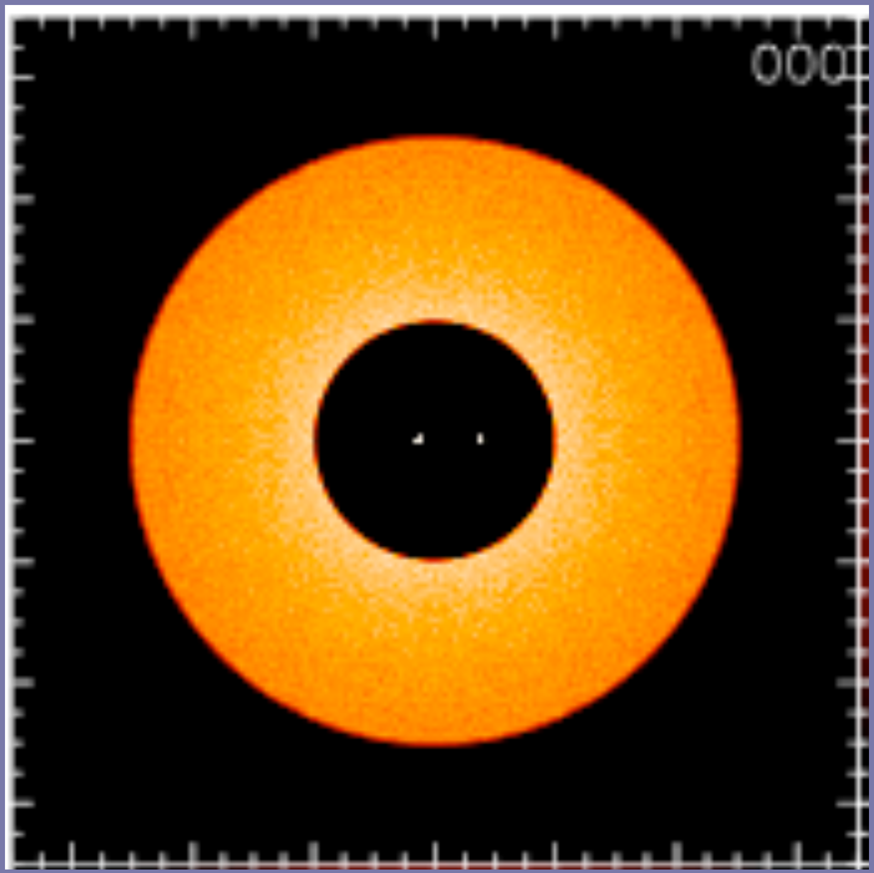
- Gas cools and settles into a thin circumbinary disk **(Barnes 2002)**
- Disk aligned with binary orbital plane **(Bardeen & Peterson 1975)**

  (Ivanov et al. 1999)
- Torques from binary evacuate central cavity r ~ 2a

  (Artymowicz & Lubov 1994)
- Binary orbit decays due to gas viscosity, cavity follows
- t_{GW} becomes shorter than t_{vis} when r ~ few 100 R_S
- Soon afterwards, disk ‘decouples’, cavity cannot follow at r $\lesssim$100 R_S
- rapid GW-driven coalescence leaves ‘punctured disk’

  (Milosavljevic & Phinney 2005)

Punctured disk



Cuadra et al. (2008)

Gravitational Recoil

- **Gravitational radiation produces sudden recoil**

— from conservation of linear momentum, near ISCO

— kick velocity depends on mass ratio and on spin vectors

— typical v(kick) ~ few × 100 km/s **(Baker et al. 2006, 2007**

— maximum v(kick) ~ 3-4,000 km/s **Gonzalez et al. 2007)**

— directed in the plane if spins aligned, generally out of the plane otherwise

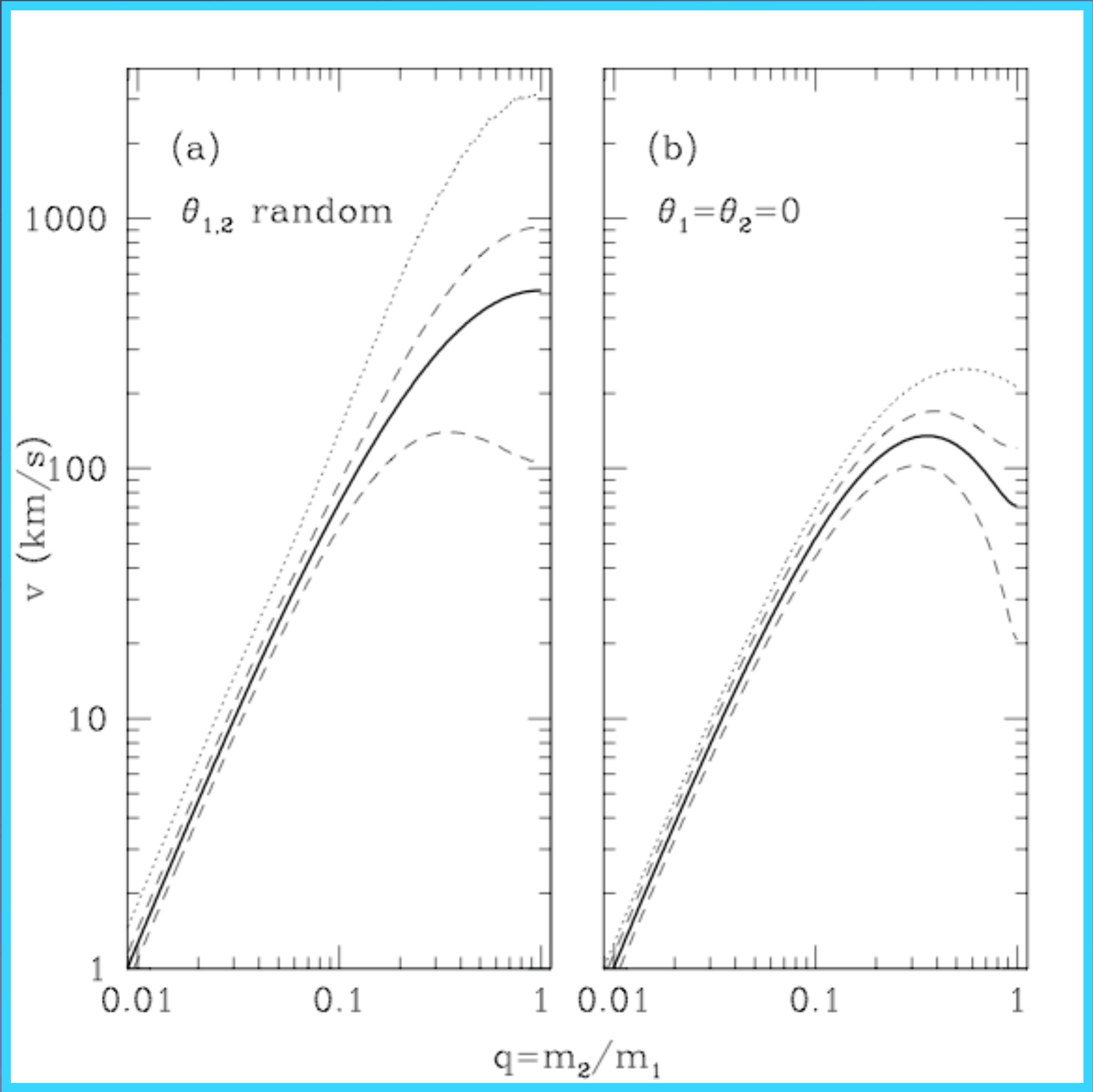
- **What is the response of the circumbinary disk?**

— can we expect prompt EM signal, within years, so that it is useful for selection among LISA candidates?

(Lippai et al. 2008)

Kick Velocity Distribution

Tanaka & Haiman (2008) from Baker et al. (2008)



10^6 realizations with random spin magnitude in the range $0< a_1,a_2 < 0.9$

($\pm1\sigma$ range shown)

Effect of Kick on Circumbinary Disk

Lippai, Frei & Haiman (ApJL 2008)

- **Properties of disk:**

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

- **Response of pressureless ("dark matter") disk:**

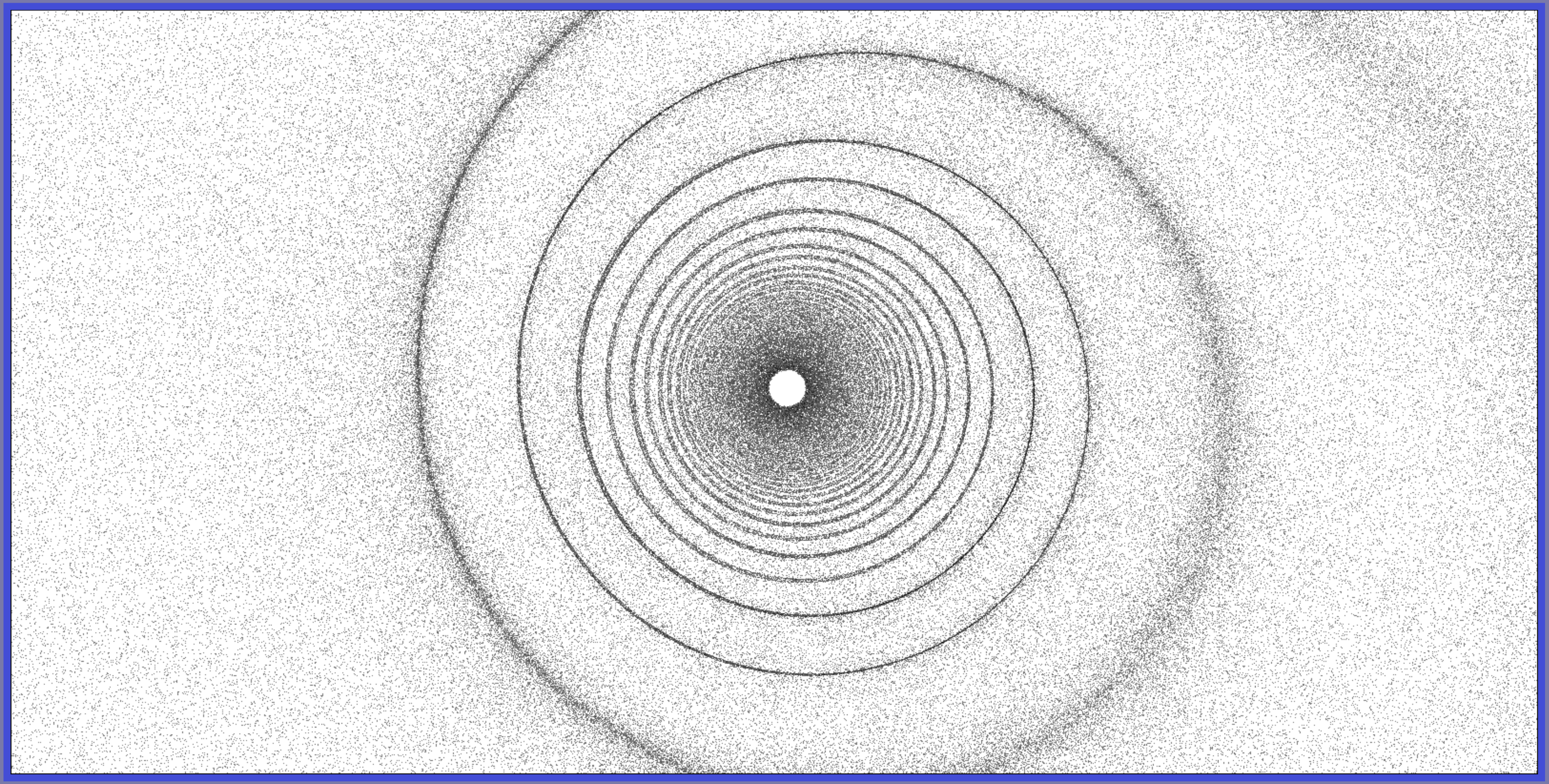
  — start with massless test particles on circular orbits
  — add instantaneous v(kick), parallel or perpendicular to disk
  — follow Kepler orbits (ellipses) for N=10^6 particles

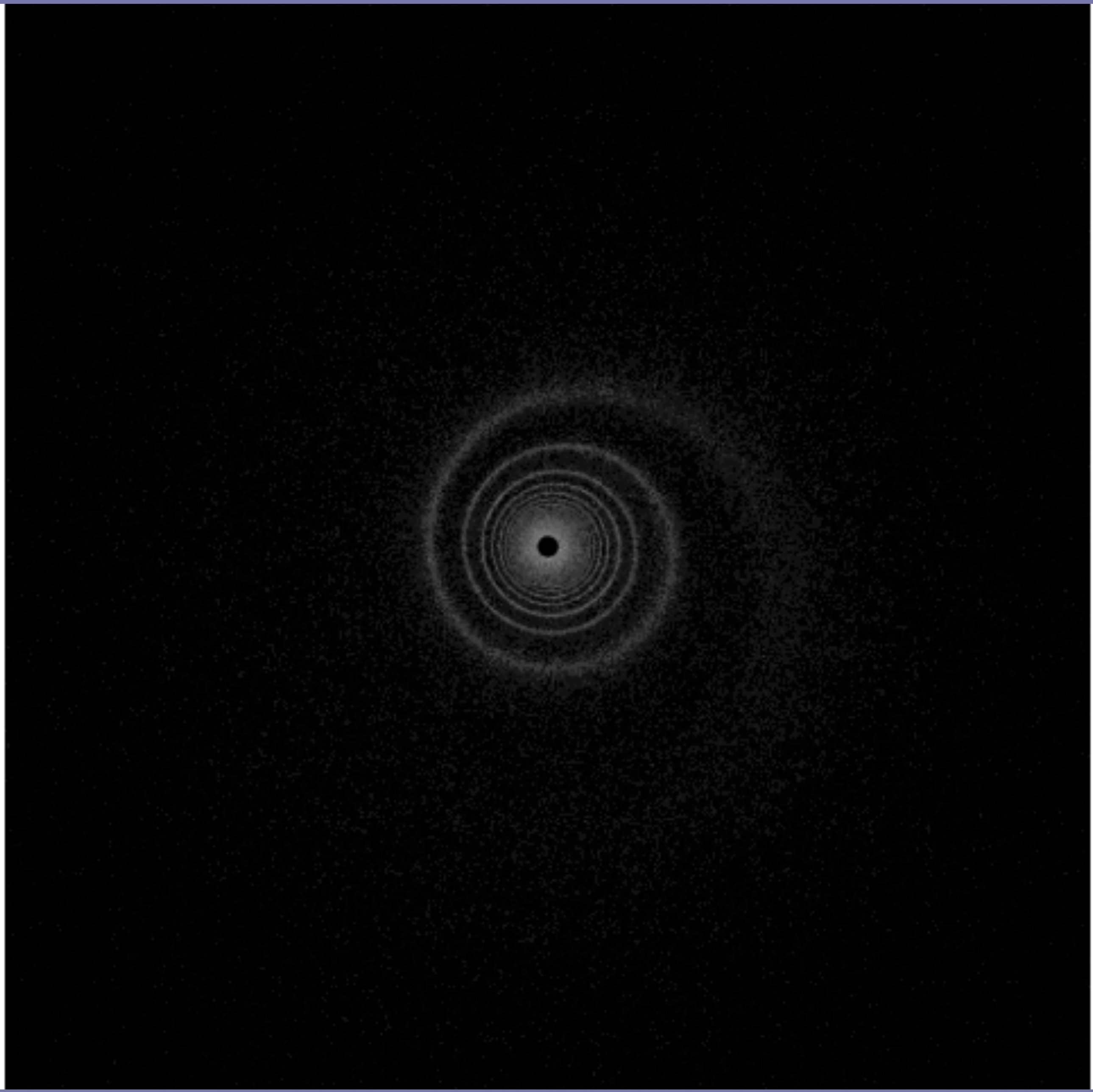
Planar Kick Results in a Spiral Caustic

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

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

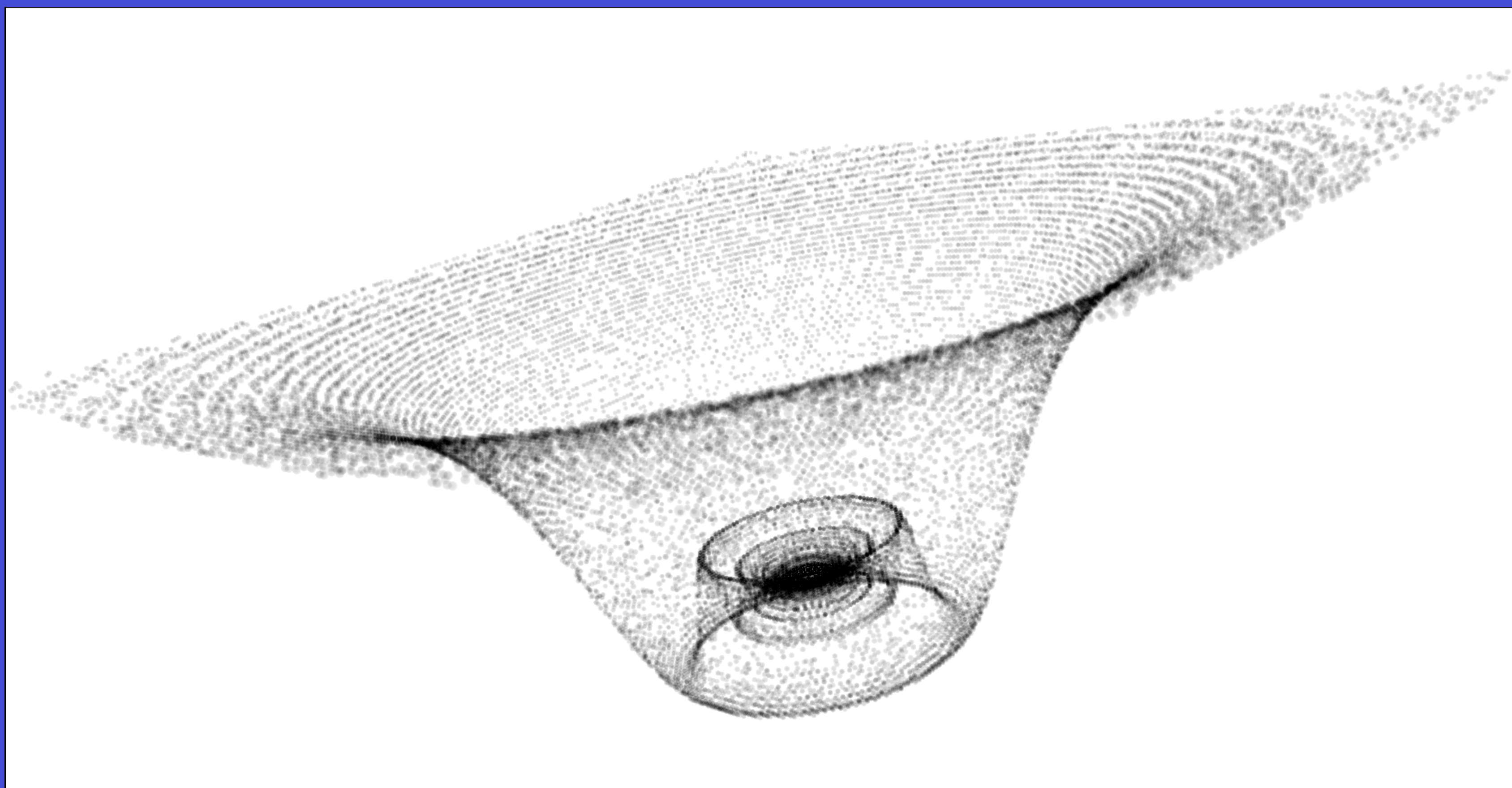
$t = 90$ days ($t_{cavity} = R_{cavity} / v_{kick} = 7$ days)





Perpendicular kick: Concentric Density Enhancements

(otherwise same parameters)



Expected Caustic Properties

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: $\mathbf{R/t = v_{kick}}$

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

Implications of prompt spiral caustics

- **Suggests prompt "afterglow" for SMBH coalescence:**

— caustic propagates outward with speed ~ v_{kick}
— infall speed into caustic is $v_{caustic} \sim v_{kick}^2/v_{orbit}$
— $v_{caustic}$ becomes supersonic beyond ~700 R_s (at > 25 km/s)
— gas shocks may produce strong emission (at >50 days)

- **Can speculate about properties of afterglow:**

— shocked gas heated to $v_{shock} \sim v_{caustic}$ ~ 25 - 80 km/s

— $L_{disk} \sim 1/2\ M_{disk}\ v_{shock}^2\ /\ t_{shock}$

— $M_{disk} \sim$ 50-1,200 $M_\odot$ $t_{shock} \sim$ 50 days - 2 years

— $L_{disk} \sim 6 \times 10^{-4} - 2 \times 10^{-2}\ L_{edd}$ not negligible.

— Hardens from UV to soft X-ray (opposite of GRB afterglow)

Impact of Gas Dynamics

Corrales, MacFadyen & Haiman (2009)

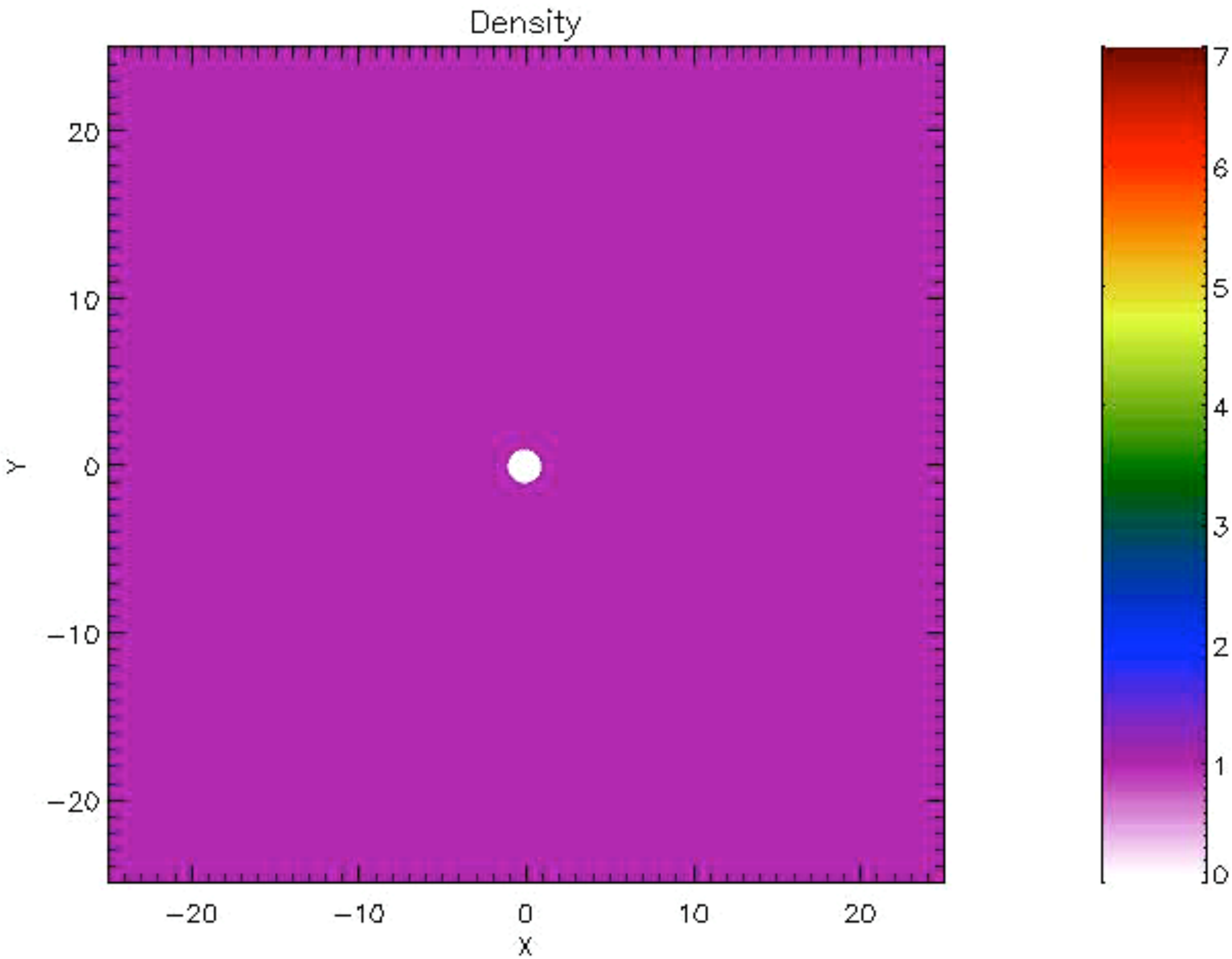
- **Sudden 'shaking' of disk launches prompt sound waves**
- **Sound waves can steepen into shocks**
- **Hydro simulation**

  — adaptive mesh refinement (AMR) code FLASH

  — $v_{kick} = 500$ km/s

  — equation of state: isothermal or adiabatic

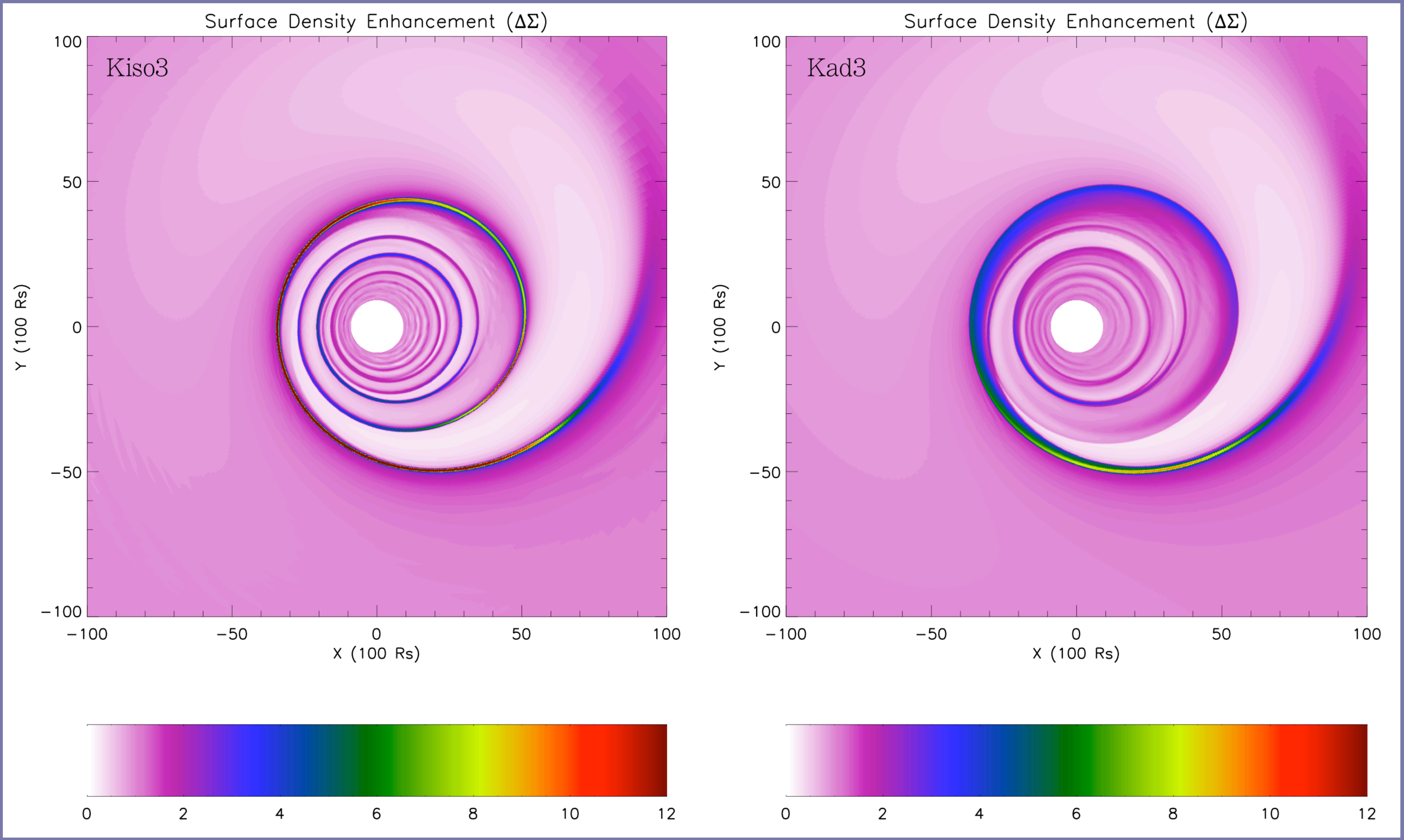
  — vary temperature: $5000 - 5 \times 10^5$ K



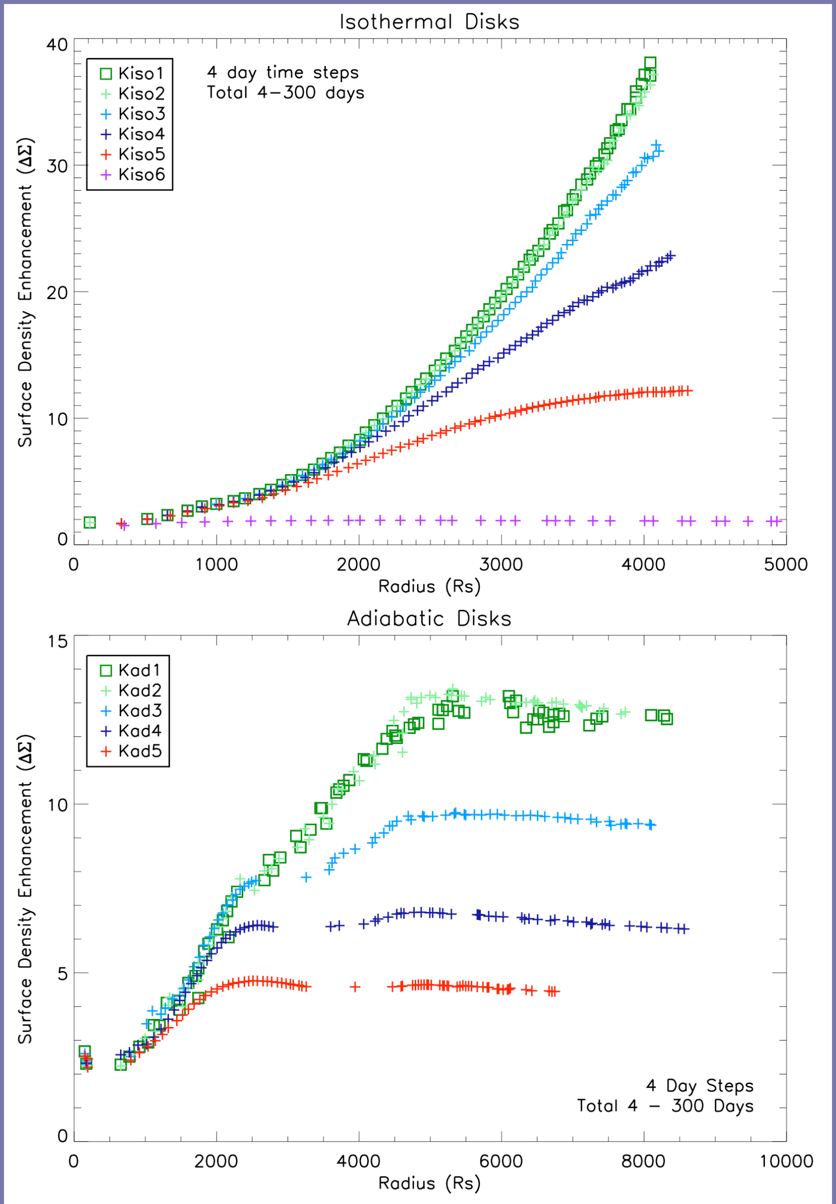
time = 0.000 ps
number of blocks = 7808
AMR levels = 5

Disk Surface Density

Corrales, MacFadyen & Haiman (2009)



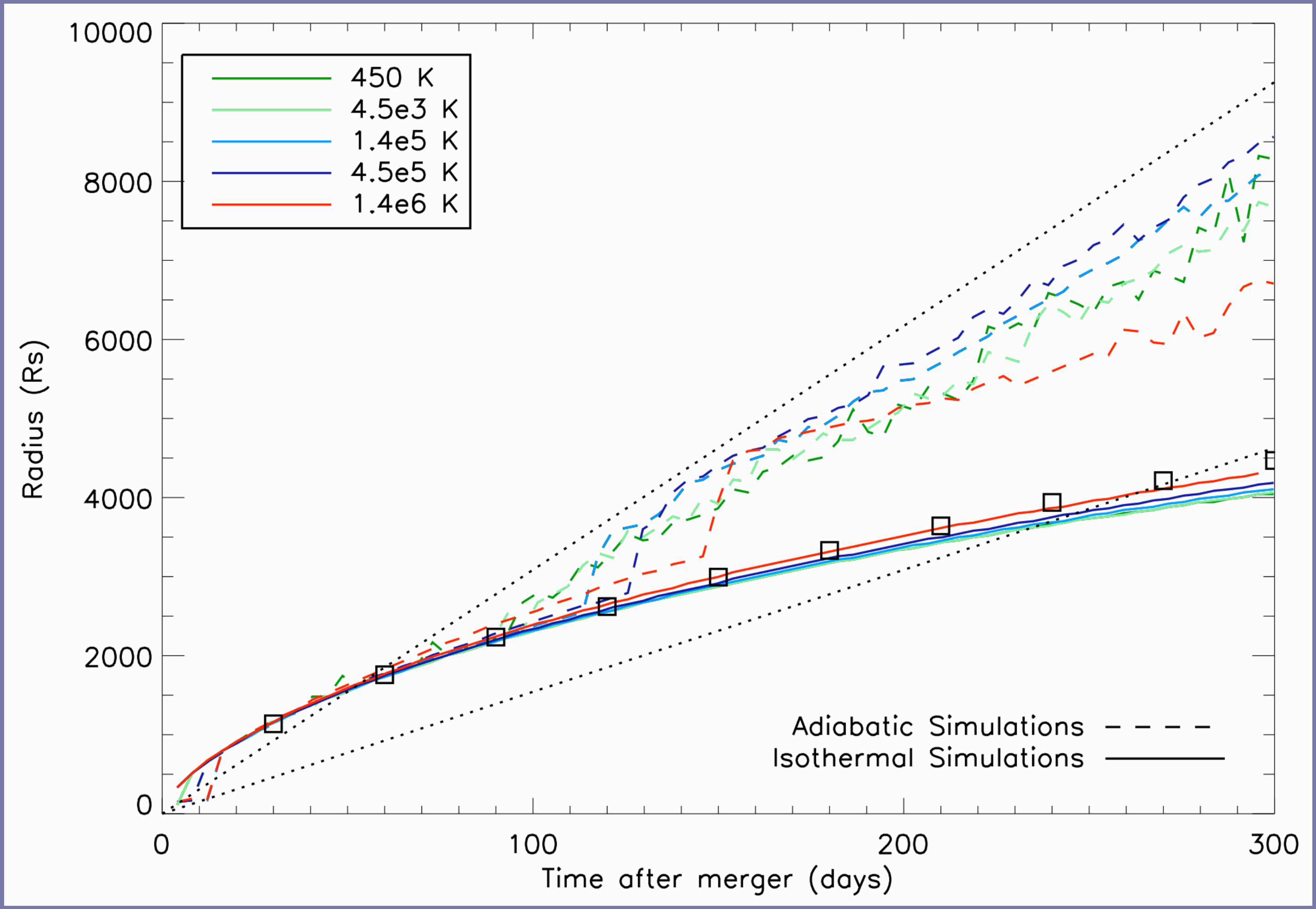
Over-density in Spiral Shocks



Corrales, MacFadyen Haiman (2009)

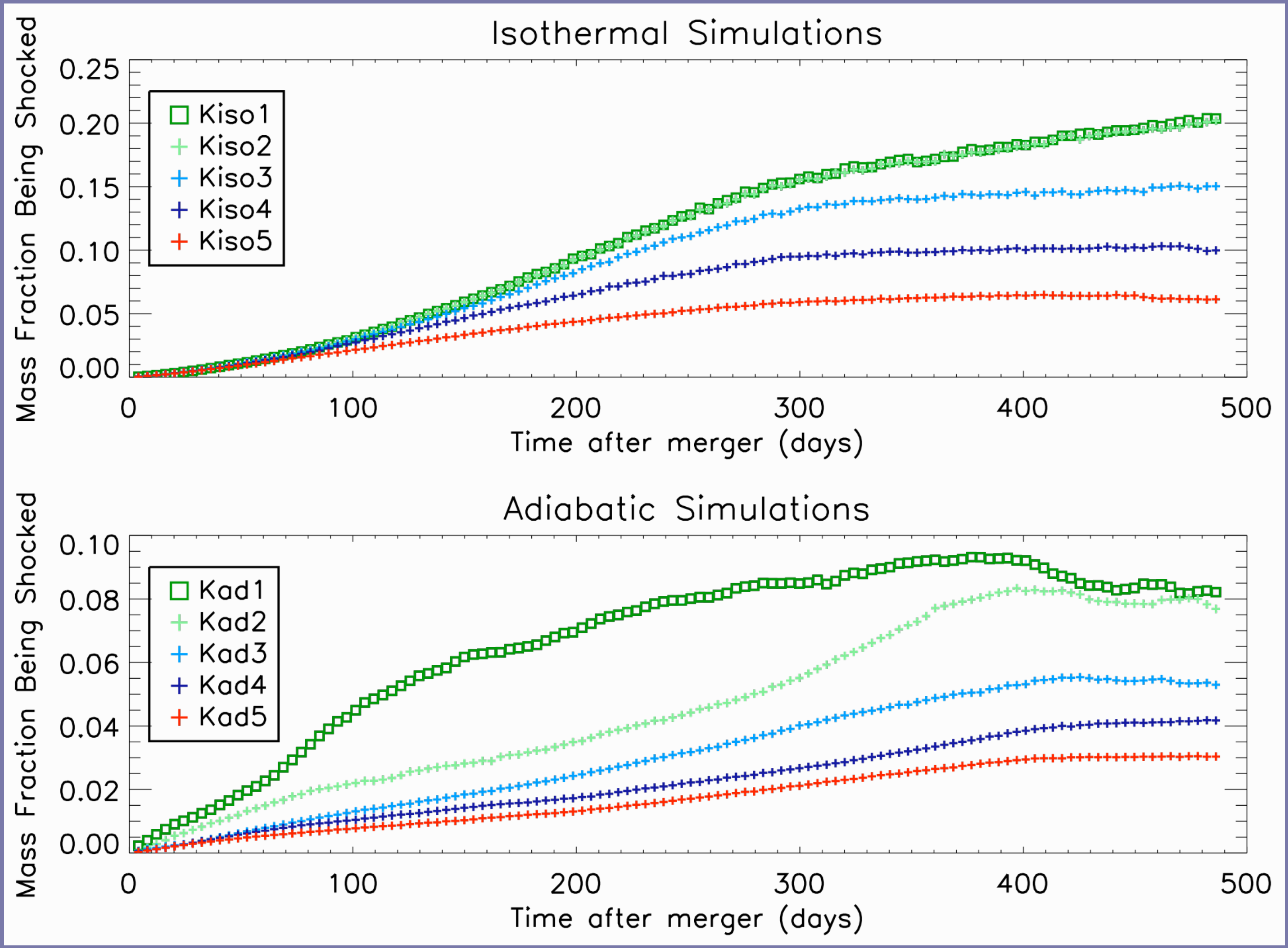
Shock Propagation

Corrales, MacFadyen & Haiman (2009)



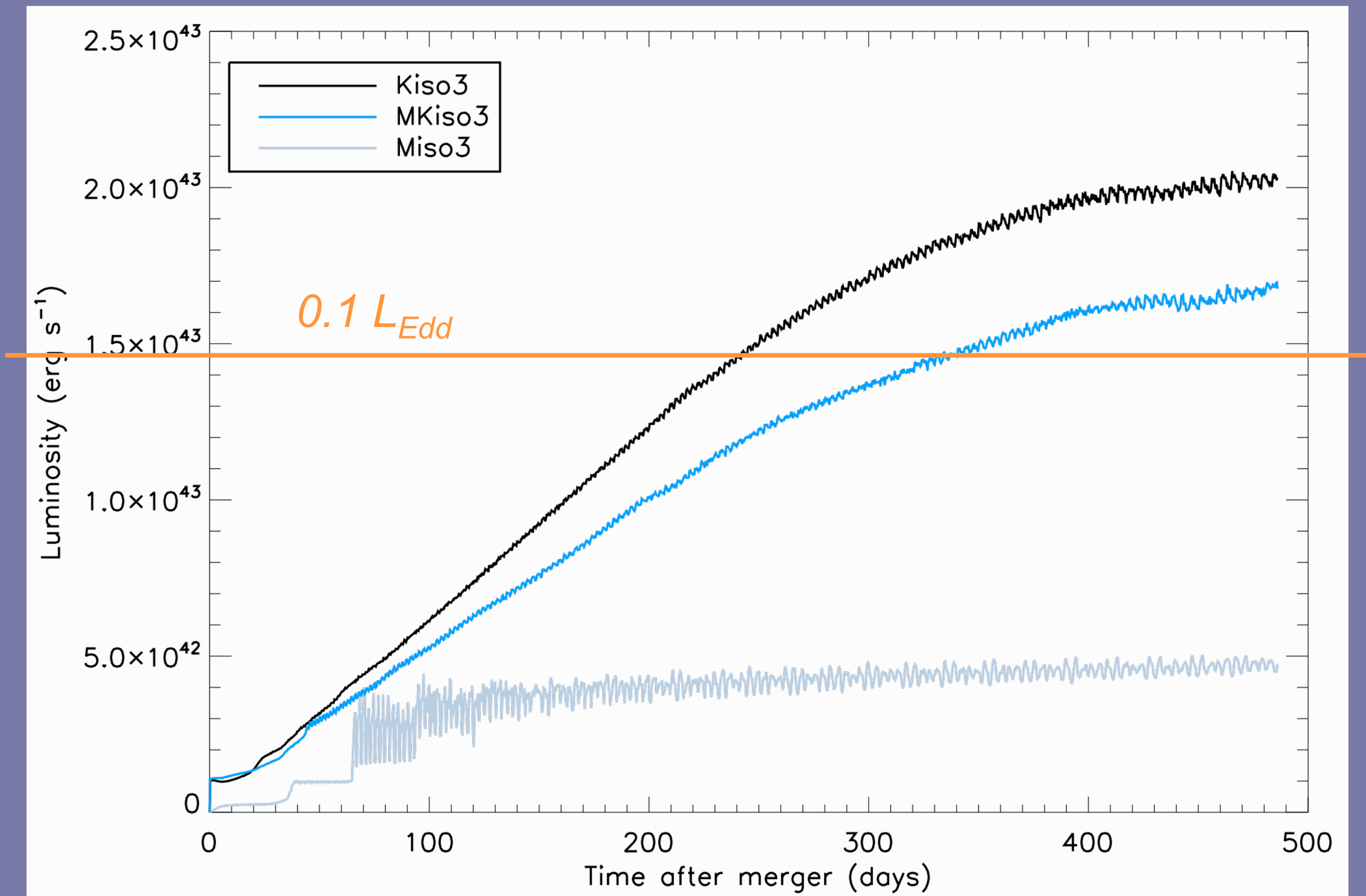
Shocked gas fraction

Corrales, MacFadyen & Haiman (2009)



Light Curve

Corrales, MacFadyen & Haiman (2009)



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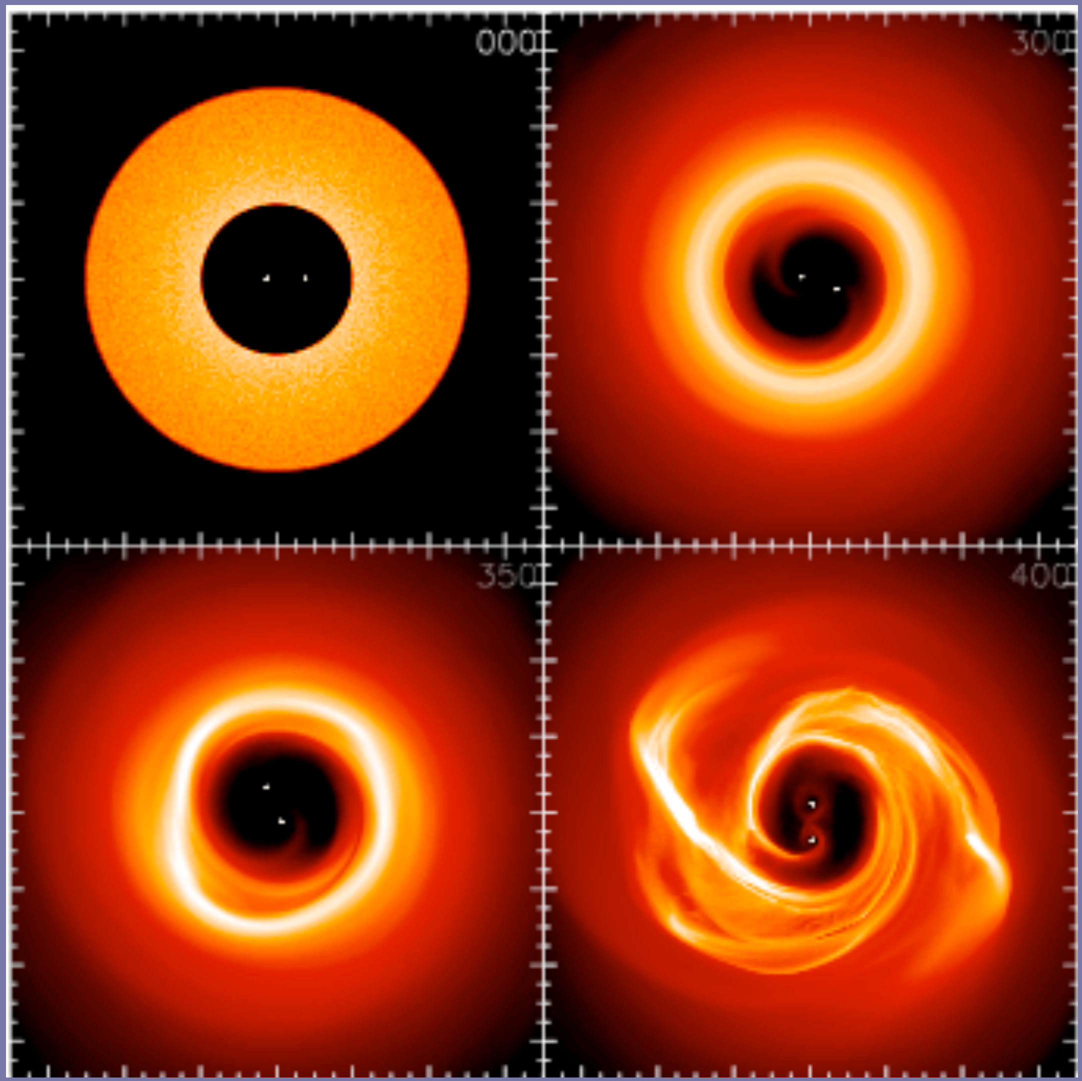
Gas Near BHs Prior to Merger

Cuadra et al. (2008)

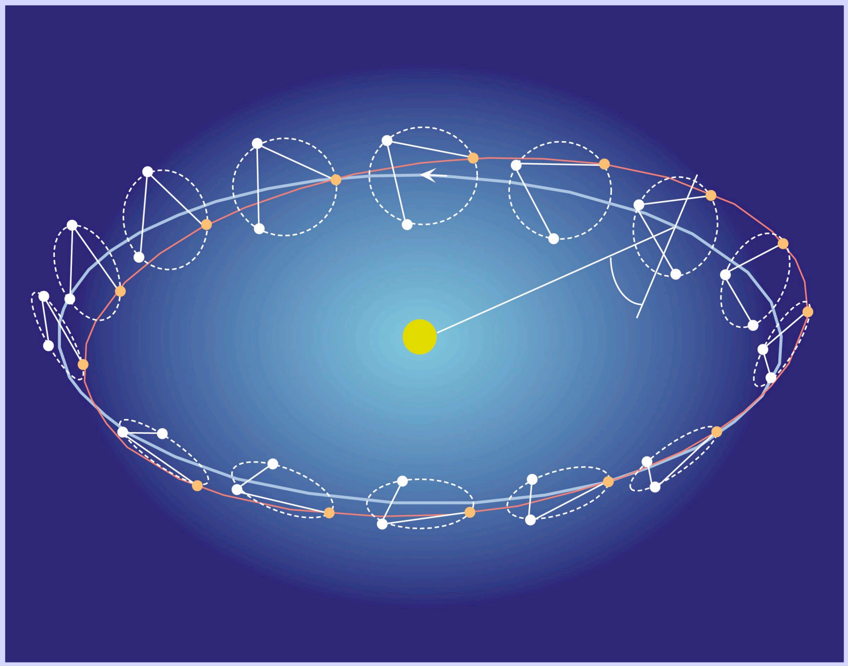


Localizing a LISA source

What is the sky position error (and shape) in last weeks of merger?

* Orbital modulation of the GW signal

$$h(t) = \frac{G(\Omega, \dot{\Omega}, t)}{d_{\rm L}} h_0(t, \mathcal{M}_z, \mu_z, \text{spins}) + \text{noise}(t)$$



Detector orientation: (Ξ_D, Φ_D)

Source direction: (θ_N, ϕ_N)

Source orientation: (θ_L, ϕ_L)

* Amplitude modulation is periodic with $f_\oplus \equiv \frac{1}{\text{yr}} \ll f_{\rm GW}(t)$

Harmonic Mode Decomposition

(Kocsis, Haiman & Menou 2007)

- Measured GW signal can be written in an equivalent form

$$h^{\mathrm{I,II}}(p;t) = h_{\mathrm{c}}(p_{\mathrm{fast}}, p_{\mathrm{spin}}; t) \times h_{\mathrm{m}}^{\mathrm{I,II}}(p_{\mathrm{slow}}; t)$$

- Parameters dependence decoupled in three groups:

$$\begin{aligned} p_{\mathrm{slow}} &\equiv \{d_{\mathrm{L}}, \Omega\}, \\ p_{\mathrm{fast}} &\equiv \{\mathcal{M}_z, \mu_z, t_{\mathrm{merger}}, \phi_{\mathrm{ISCO}}\}, \\ p_{\mathrm{spin}} &\equiv \{2 \text{ spin magnitudes}, 4 \text{ spin angles}\} \end{aligned}$$

- The angular piece can be further simplified

$$h_{\mathrm{m}}(p_{\mathrm{slow}}(0), t) = d_{\mathrm{L}}(z)^{-1} \sum_{j=-4}^{4} g_j(p_{\mathrm{slow}}(0))\, e^{ij\omega_{\oplus} t}$$

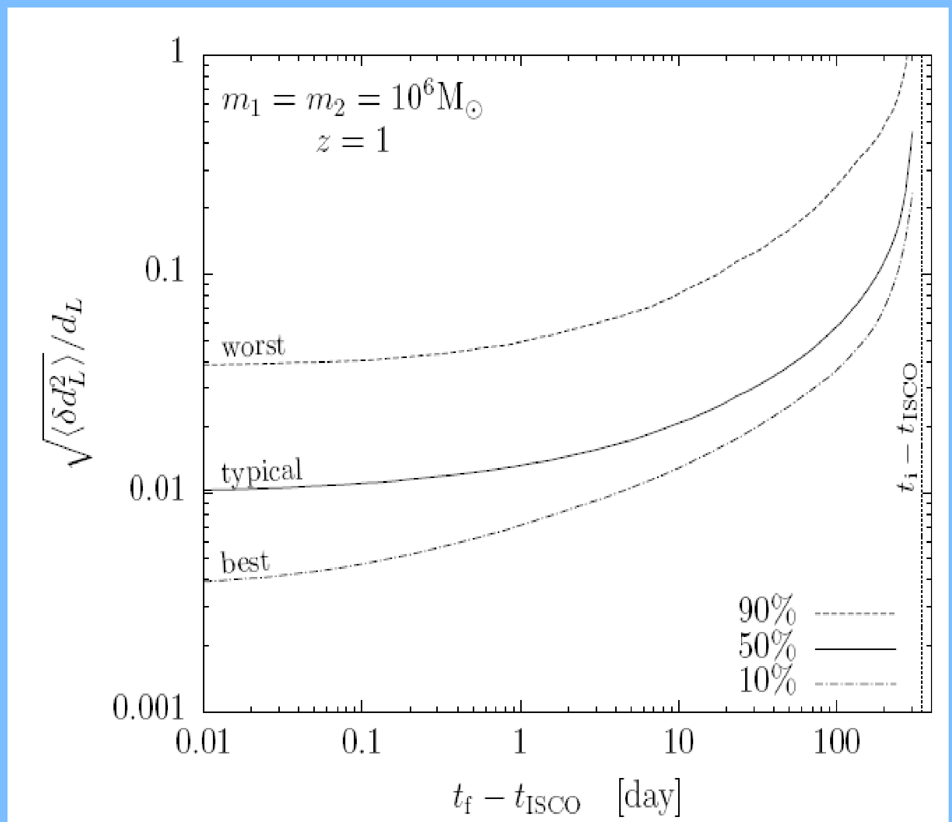
Time independent angular dependence — $g_j(p_{\mathrm{slow}}(0))$

Orbital harmonics — $e^{ij\omega_{\oplus} t}$

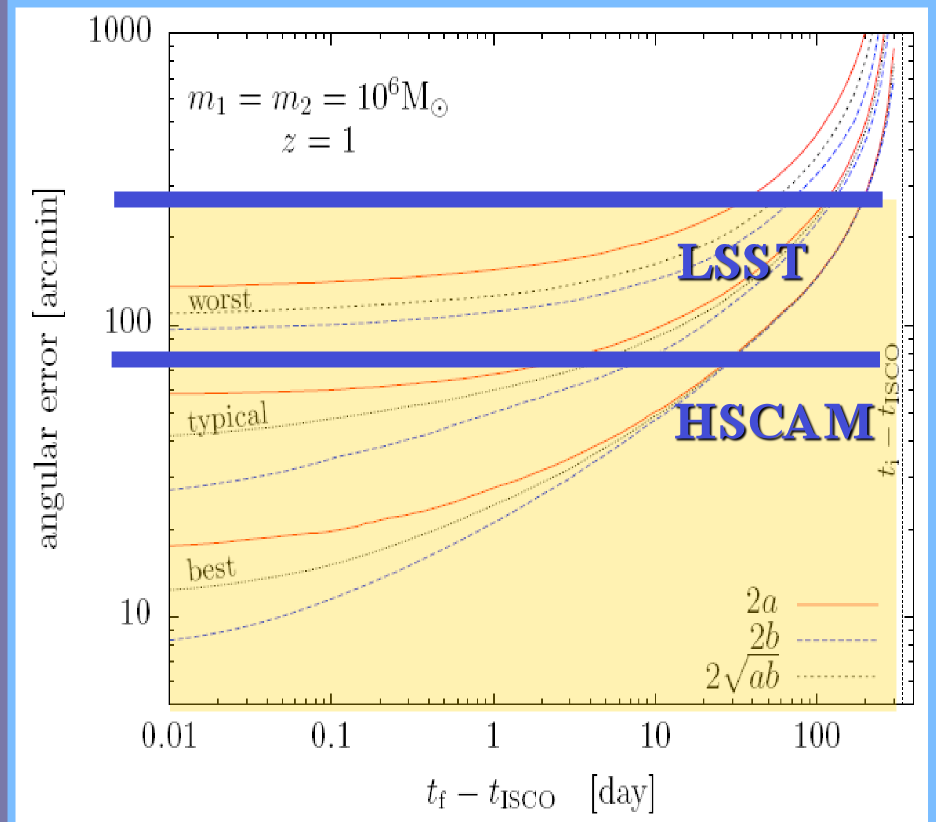
Time dependence of localization

(HMD method + Fisher matrix: Kocsis, Haiman, Menou & Frei 2007)

distance uncertainty



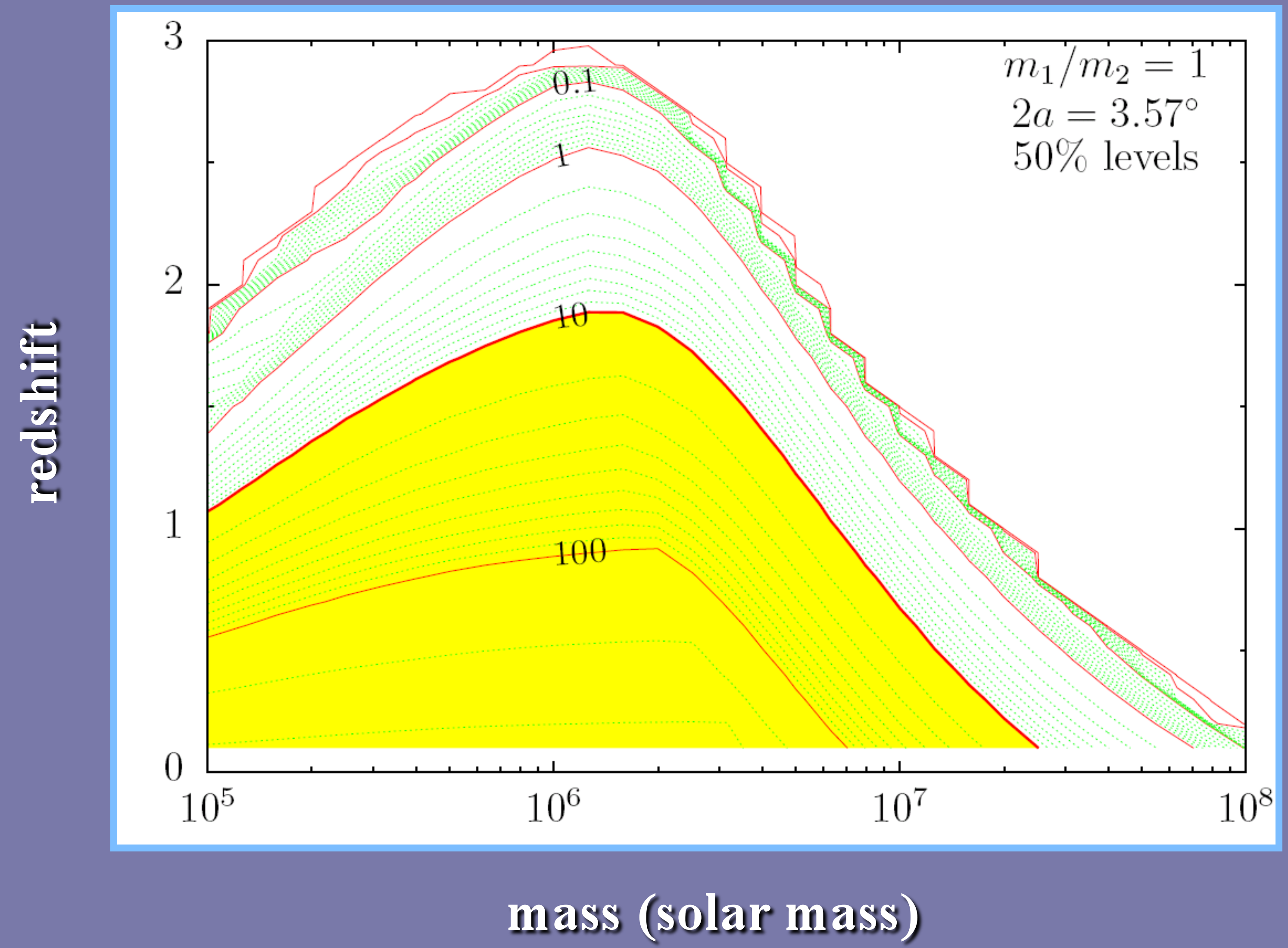
sky position uncertainty



Errors typically stop improving ~10 days before ISCO

How much advance notice?

Look-back time when sky position error shrinks down to ~10 deg²



A world-wide monitoring campaign with wide FOV instruments

(Kocsis, Haiman & Menou 2008)

GW source localized ~2-3 weeks before merger

- Monitor sources in few × deg^2 field
- variability 24-27 mag on timescales of <u>hours</u> to <u>minutes</u>
  (1-10% $L_{Eddington}$ for $M_{BH} = 10^{6-7} M_\odot$ at z=1-2)
- Correlate EM signal with GW template over 10^{2-3} cycles

- Sky position error shrinks to ~ ten arcmin in last few days
- Events with favorable geometry can be identified in advance

Do we have to wait for LISA?

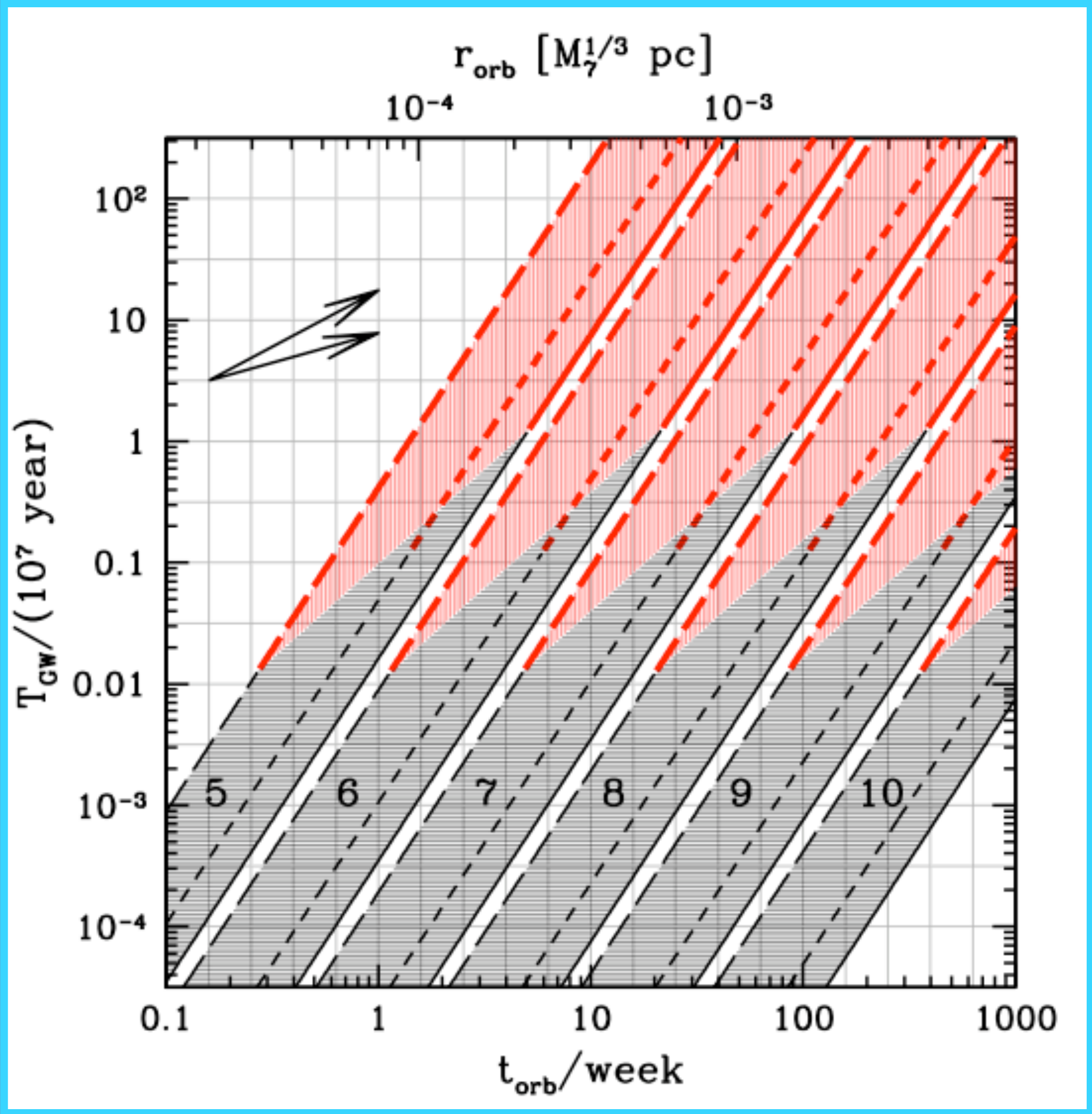
(Haiman, Kocsis & Menou 2008)

- **OPTIMISTIC ASSUMPTIONS:**
  — binary is producing bright emission (~30% L_{edd})
  — non-negligible fraction (~10%) of this emission is variable
  — clearly identifiable period $t_{var} \sim t_{orbit}$
  — orbital evolution driven by GWs below $r \lesssim 10^4\, R_S$
  — one-to-one correspondance between BH mergers and quasars

- **CAN WE IDENTIFY SUCH GW-DRIVEN BINARIES ?**
  — GW-driven binary = periodically variable quasar
  — fraction of quasars with period t_{var} :

$$f_{\rm var} = \frac{N_{\rm var}}{N_{tot}} = \left(\frac{10^7\,{\rm yr}}{{\rm t_Q}}\right)\left(\frac{t_{\rm var}}{19.8\,{\rm weeks}}\right)^{8/3}\left(\frac{(1+z)M_{tot}}{10^6\,M_\odot}\right)^{-5/3}\left(\frac{4q}{(1+q)^2}\right)^{-1}$$

Time spent at each orbital separation



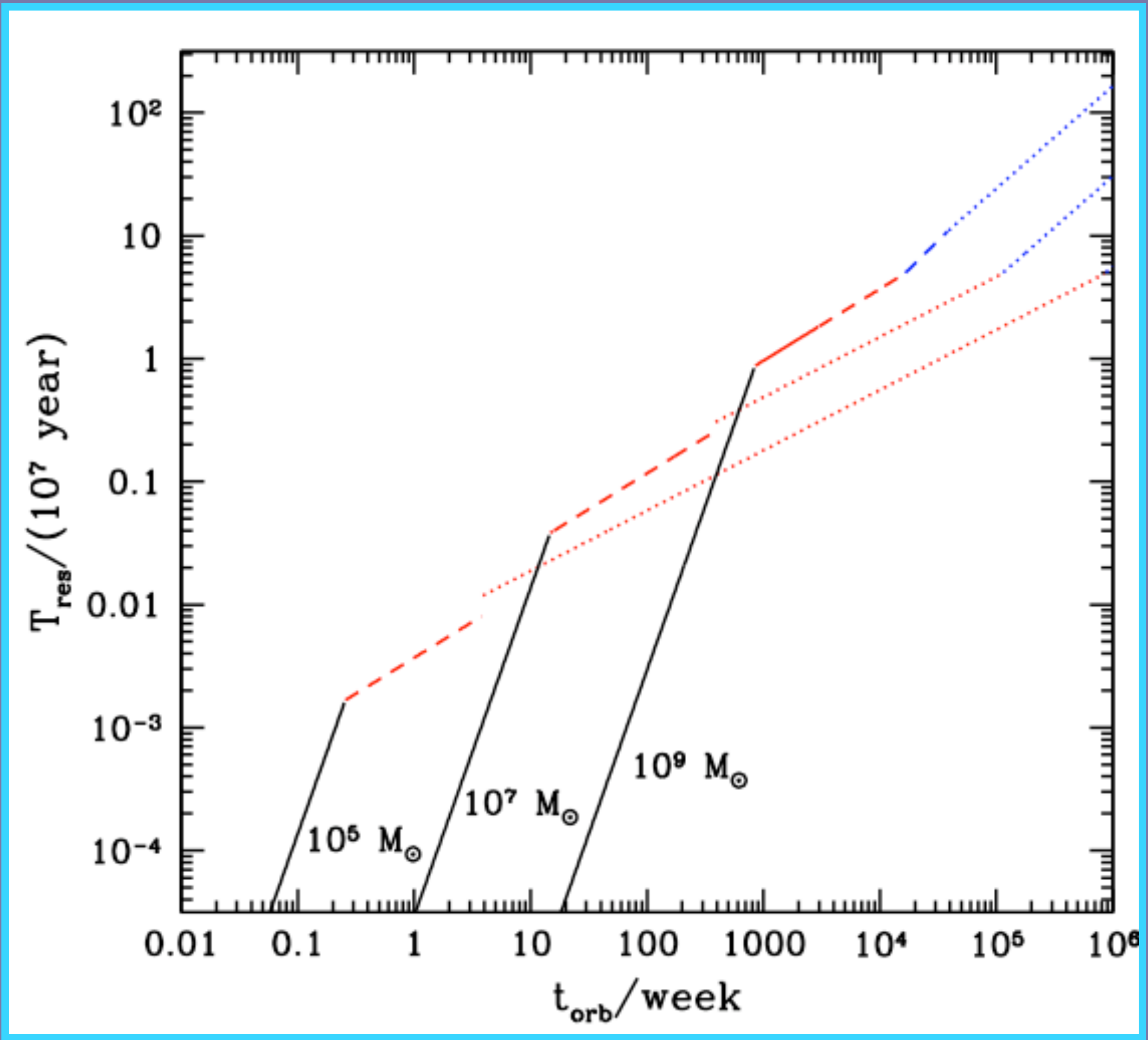
Assume:

- t_{mg} = time-to-merger (Newtonian approx.)

Trade-off:

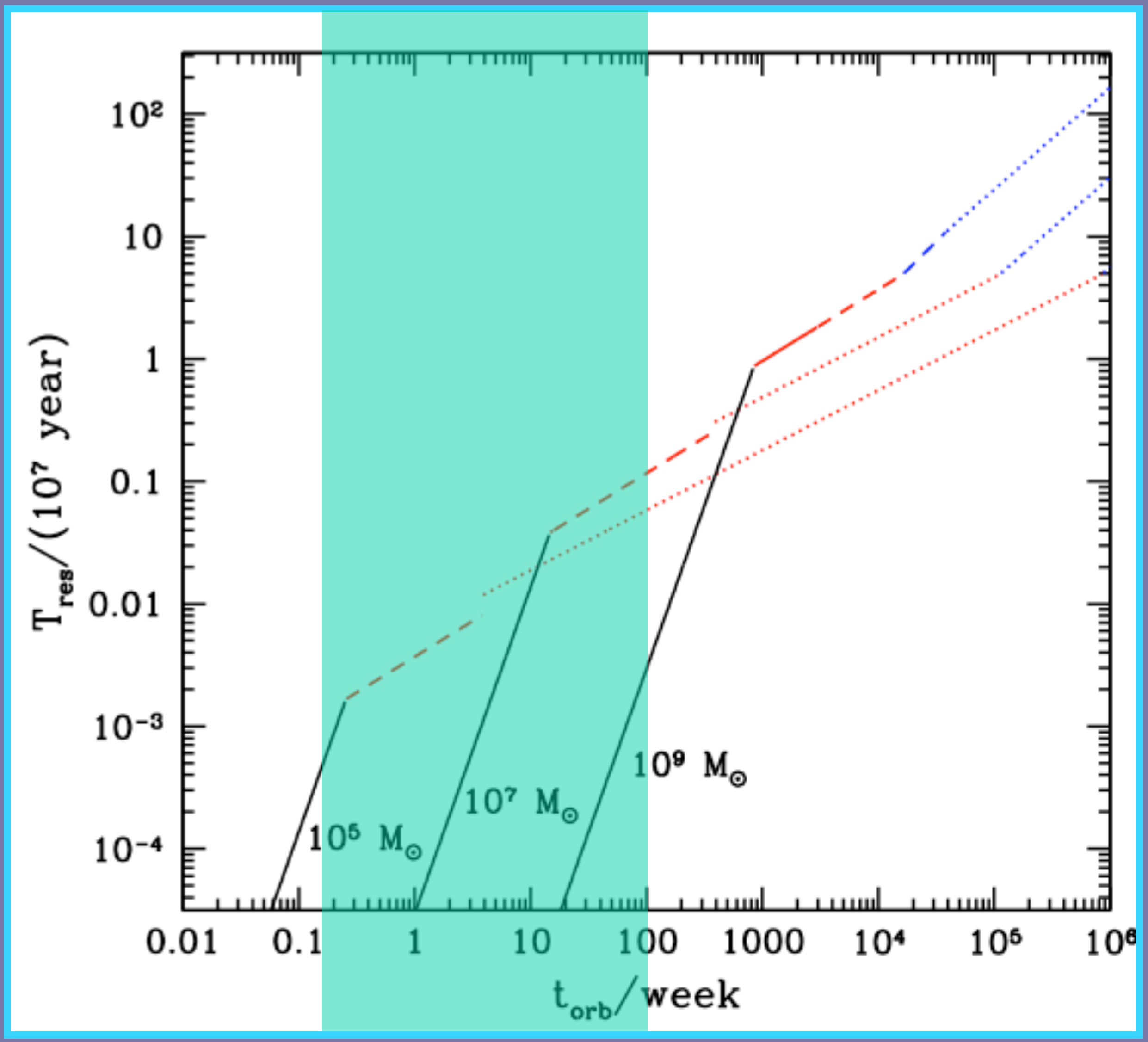
- periodicity more common among low-mass BHs, but they are faint
- high-mass BHs, are brighter, but periodic sources are more rare

Residence time: disk physics



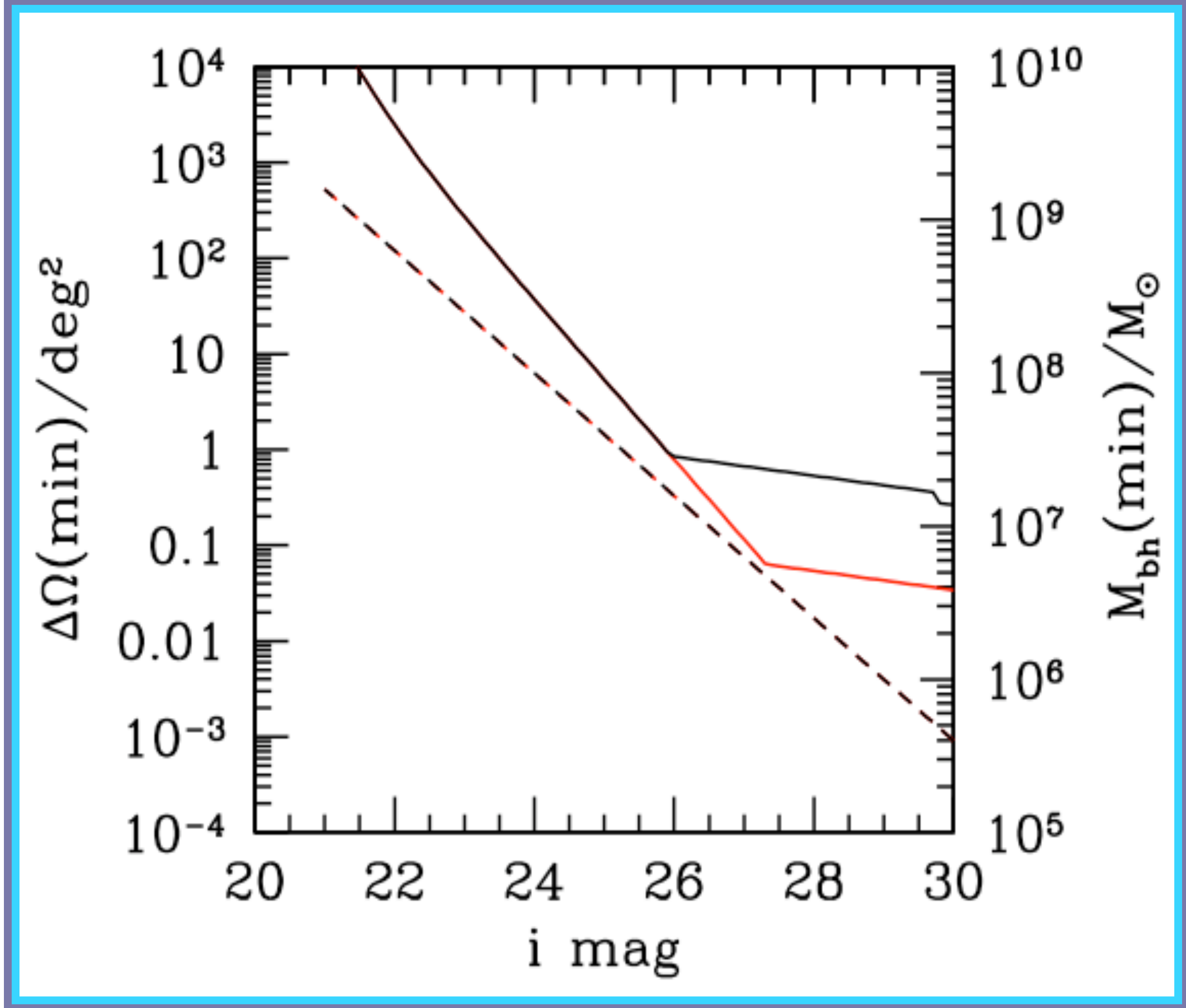
- "alpha disk"
- steady state
- equal-mass
- piece-wise power-law asymptotic solutions

Residence time: disk physics



- “alpha disk”
- steady state
- equal-mass
- asymptotic piece-wise power-law solutions

Requirements for an (optical) survey for finding periodic variable sources



Require:

≥ 5 sources @ t_{var}≤ 20 wk

≥ 100 sources @ t_{var}≤ 1 yr

Assume:

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

Conclude:

- wide survey best to probe GW-decay
- disk physics at i~25

Conclusions

1. Gravitational recoil launches prompt outward-moving spiral shock wave in circumbinary disk → produce a detectable transient afterglow (hardening with time?)
2. Advance localization possible weeks-months before merger, to within a few square degrees, triggering monitoring campaign with wide FOV telescopes
3. decaying binaries may be identifiable in a search for periodic variability among AGN, even before LISA, utilizing the scaling of occurrence rate (*e.g.* $f_{var} \propto t_{var}^{8/3}$)