Title: The electromagnetic precursor of binary black hole mergers

Date: Mar 11, 2010 01:00 PM

URL: http://pirsa.org/10030029

Abstract: Galaxy mergers, which are a natural consequence of hierarchical assembly of galaxies, are expected to produce binary black holes, which subsequently merge. The detection and analysis of gravitational waves from these sources is the major aim of the next generation gravitational wave detector: LISA, the Laser Interferometric Space Antenna. These gravitational waves encode a tremendous amount of information, but to make the connection with astrophysics and cosmology, it is necessary to identify the galaxies hosting these mergers via the associated electromagnetic counterpart to these mergers. I will describe these mergers events and discuss the various regimes where potential electromagnetic counterparts can be found. I will also describe some recent work, which holds much promise for the prompt identification of these mergers -- an electromagnetic precursor from tidal forcing.

Electromagnetic Precursors of Binary SMBH Mergers

Philip Chang
CITA

Perimeter Institute March 11, 2010

Outline

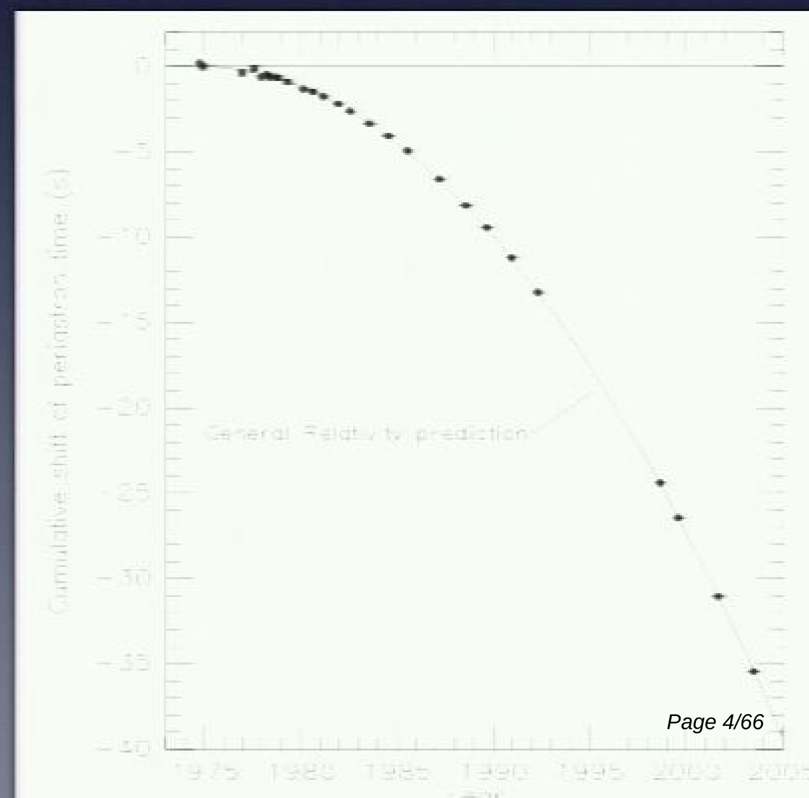
- Gravitation Waves and Binary Black Holes
- Motivation: Why do we need electromagnetic counterparts to binary black hole mergers
- Stages of Supermassive binary black hole mergers
- Electromagnetic Counterparts from Mergers
- The electromagnetic precursor (work in collaboration with L. Strubbe, K. Menou, and E. Quataert).
- Problems for the Future

Gravitational Waves

Einstein equations (linearized) admit wave solutions:

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \qquad (-\partial_t^2 + \nabla^2)\bar{h}_{\mu\nu} = -16\pi T_{\mu\nu}$$

From Weisberg and Taylor 2004



- Thus far only indirect evidence.
- Best evidence is from binary pulsar J0737-3039.
- Most famous example is PSR B1913+16.
- GR prediction is within 0.2%

Sources of Gravitational Waves

fundamental physics

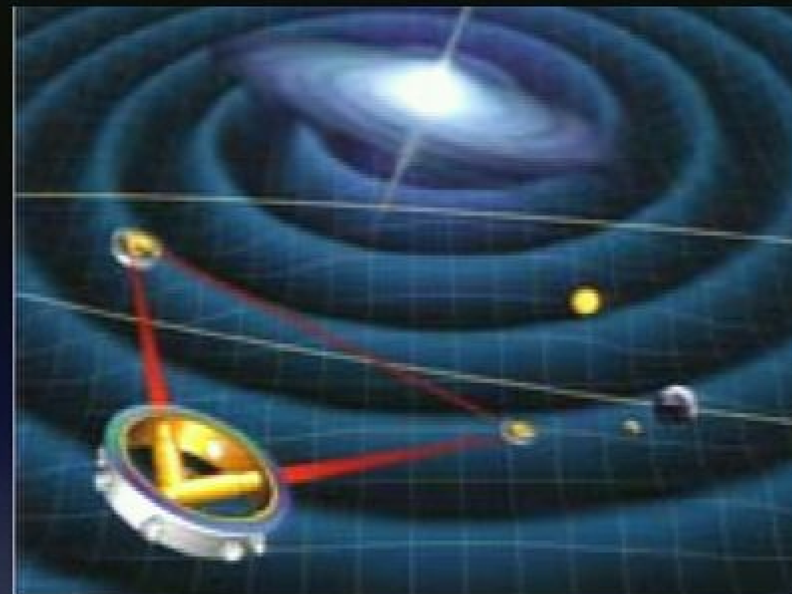
- inflation
- cosmic strings
- brane-world scenaries

astrophysics

- compact objects mergers
- supernova explosions
- galactic binaries
- binary supermassive black holes
- extreme mass ratio inspirals

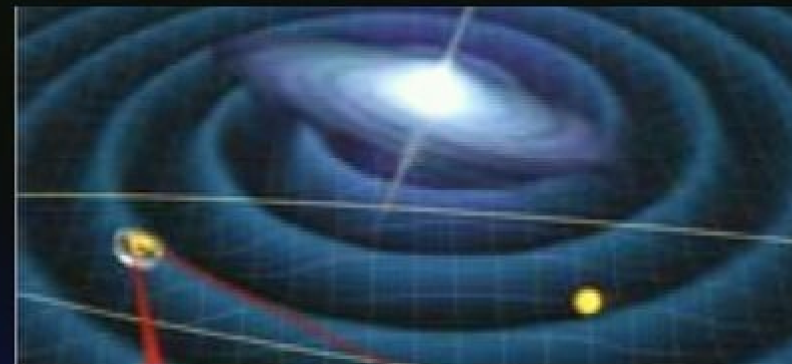
A Major Effort

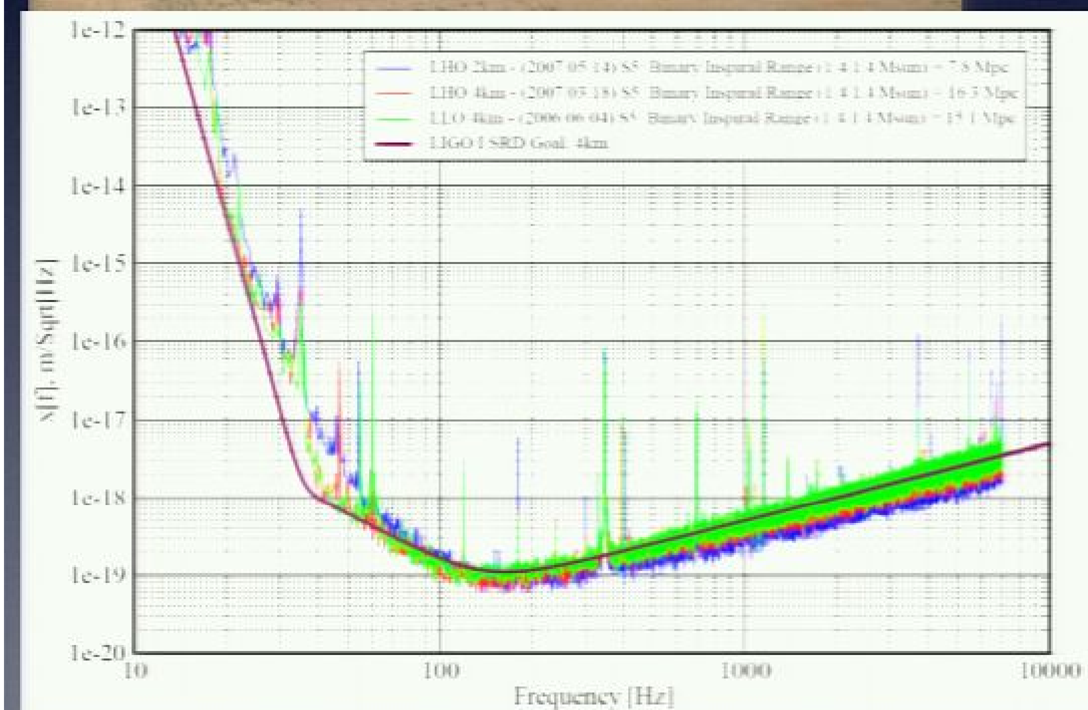
LIGO, Virgo, GEO

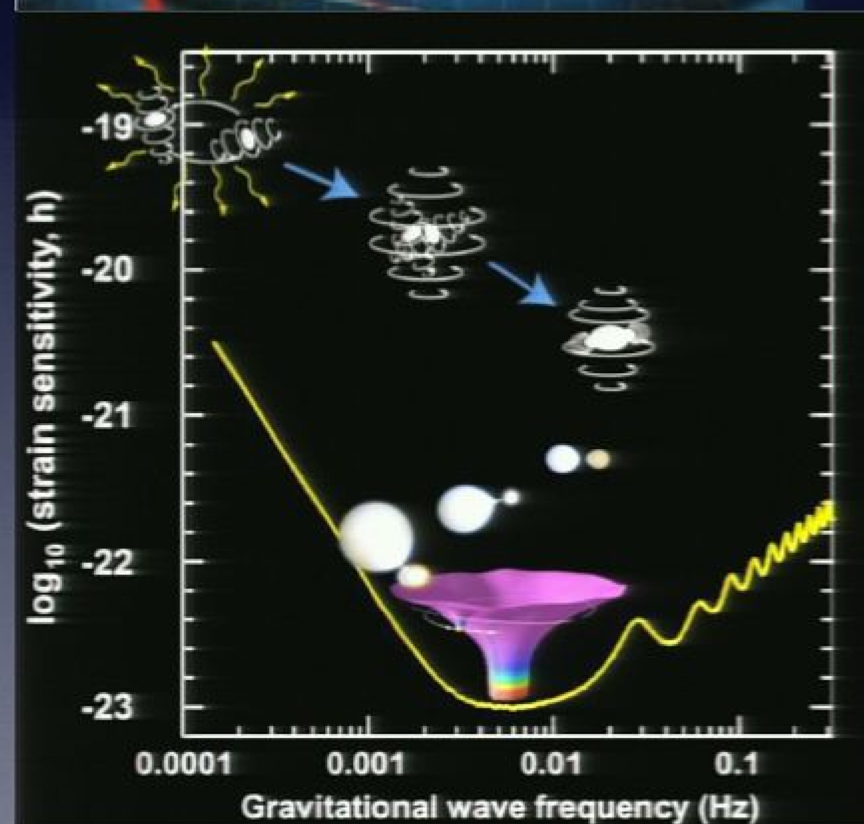


LISA

A Major Effort







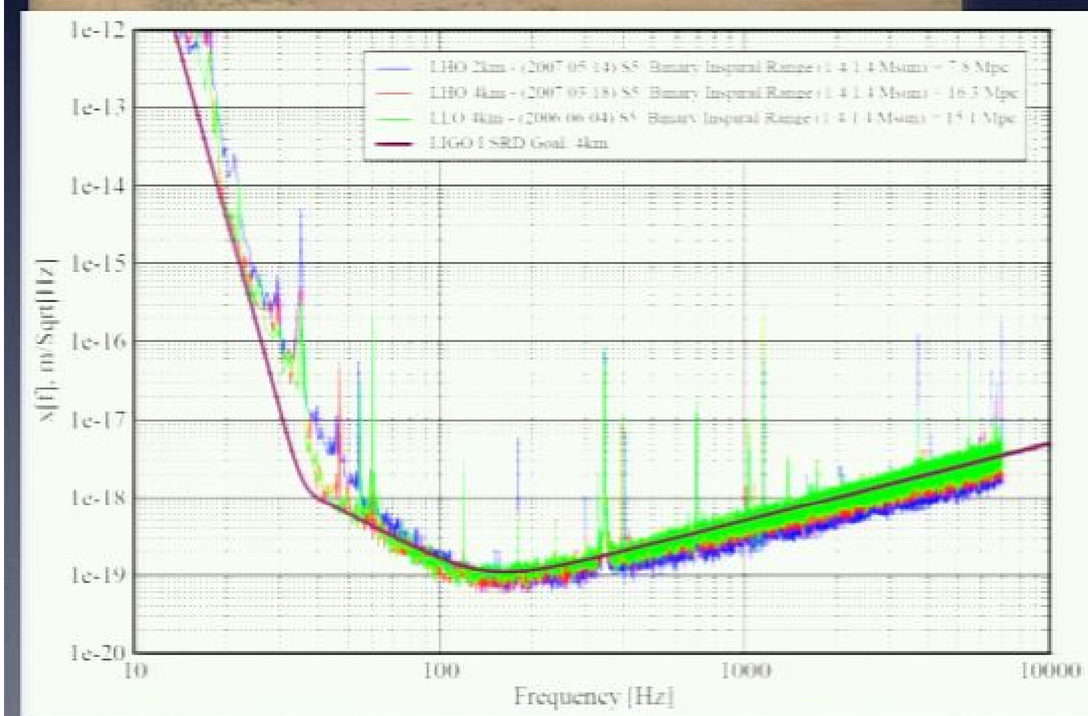
$1 - 10^2 M_\odot$

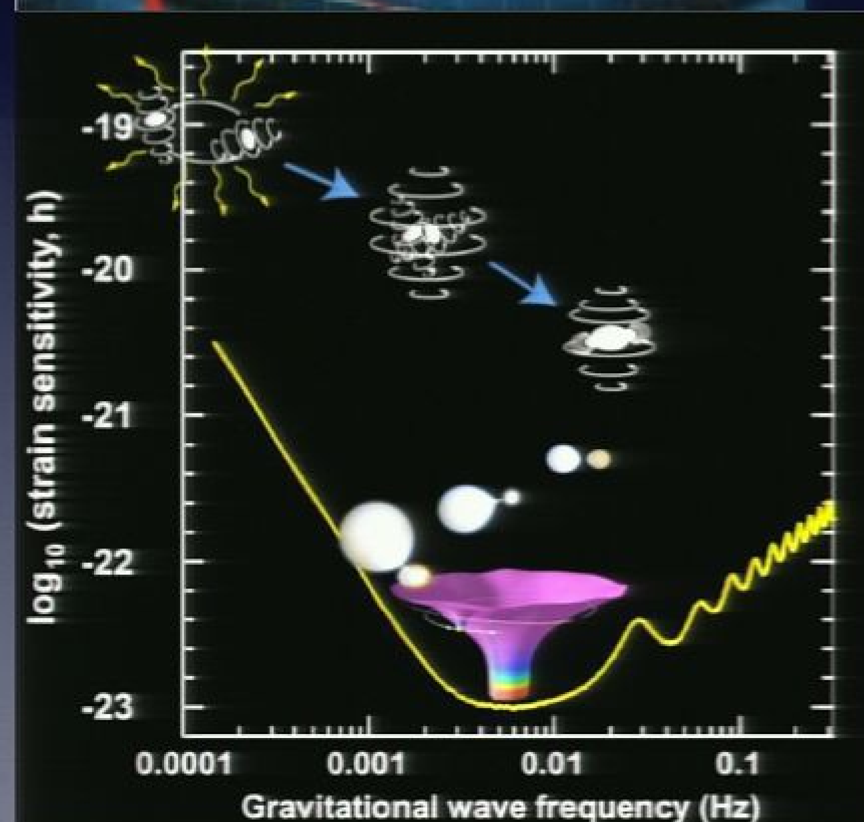
$10^4 - 10^7 M_\odot$

What can we learn about binary black holes from GWs alone?

- mass
- spin
- distance
- population dynamics
- orbital parameters
- strong field GR

A Major Effort





$1 - 10^2 M_\odot$

$10^4 - 10^7 M_\odot$

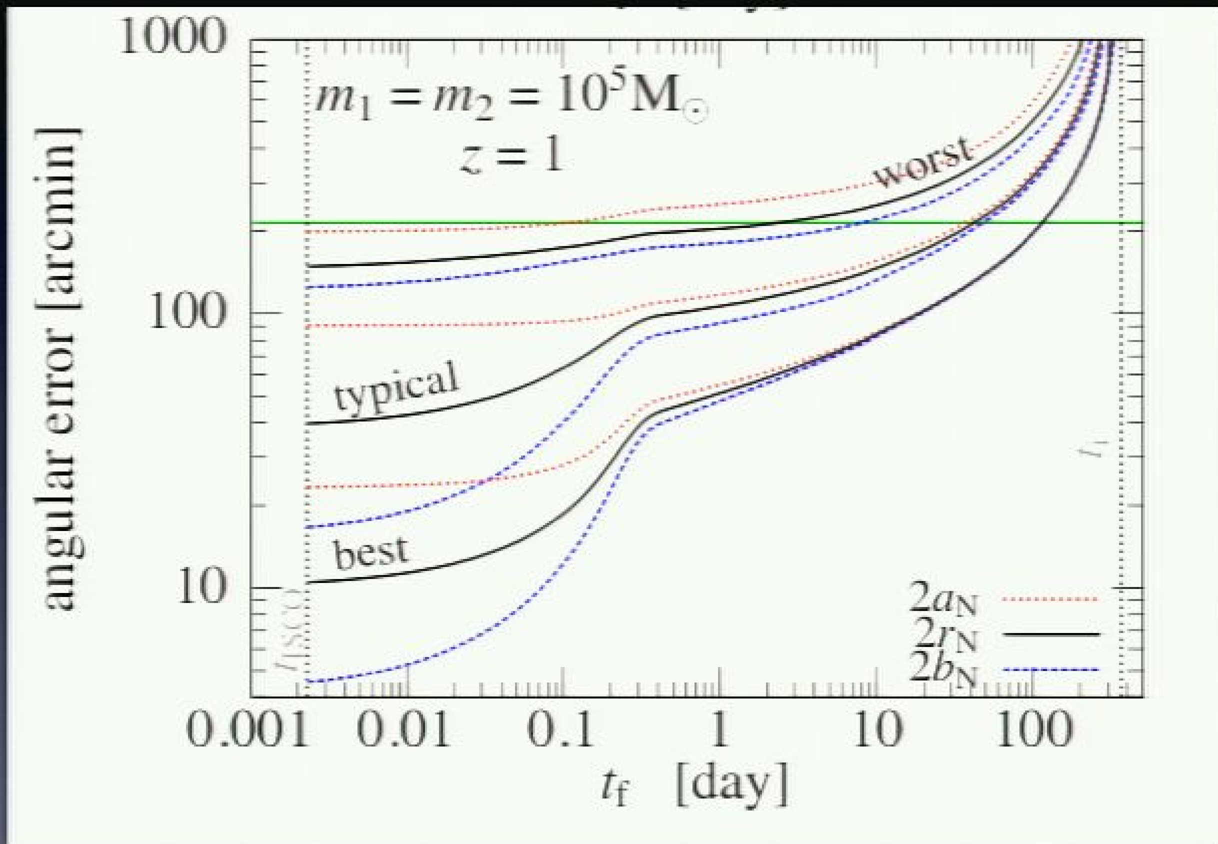
What can we learn about binary black holes from GWs alone?

- mass
- spin
- distance
- population dynamics
- orbital parameters
- strong field GR

What can we learn about binary black holes from GWs alone?

Kocsis, Haiman and Menou 2008

- mass
- spin
- distance
- population dynamics
- orbital parameters
- strong field GR



However, we have no localization!

What can we learn about binary black holes from GWs + EM?

- mass
- spin
- distance
- population dynamics
- orbital parameters
- strong field GR

- host galaxy - localization
- redshift - cosmology
- merger physics
- gas disk dynamics
- accretion physics
- galactic nucleus dynamics
- growth of SMBHs

What are the possible electromagnetic counterparts?

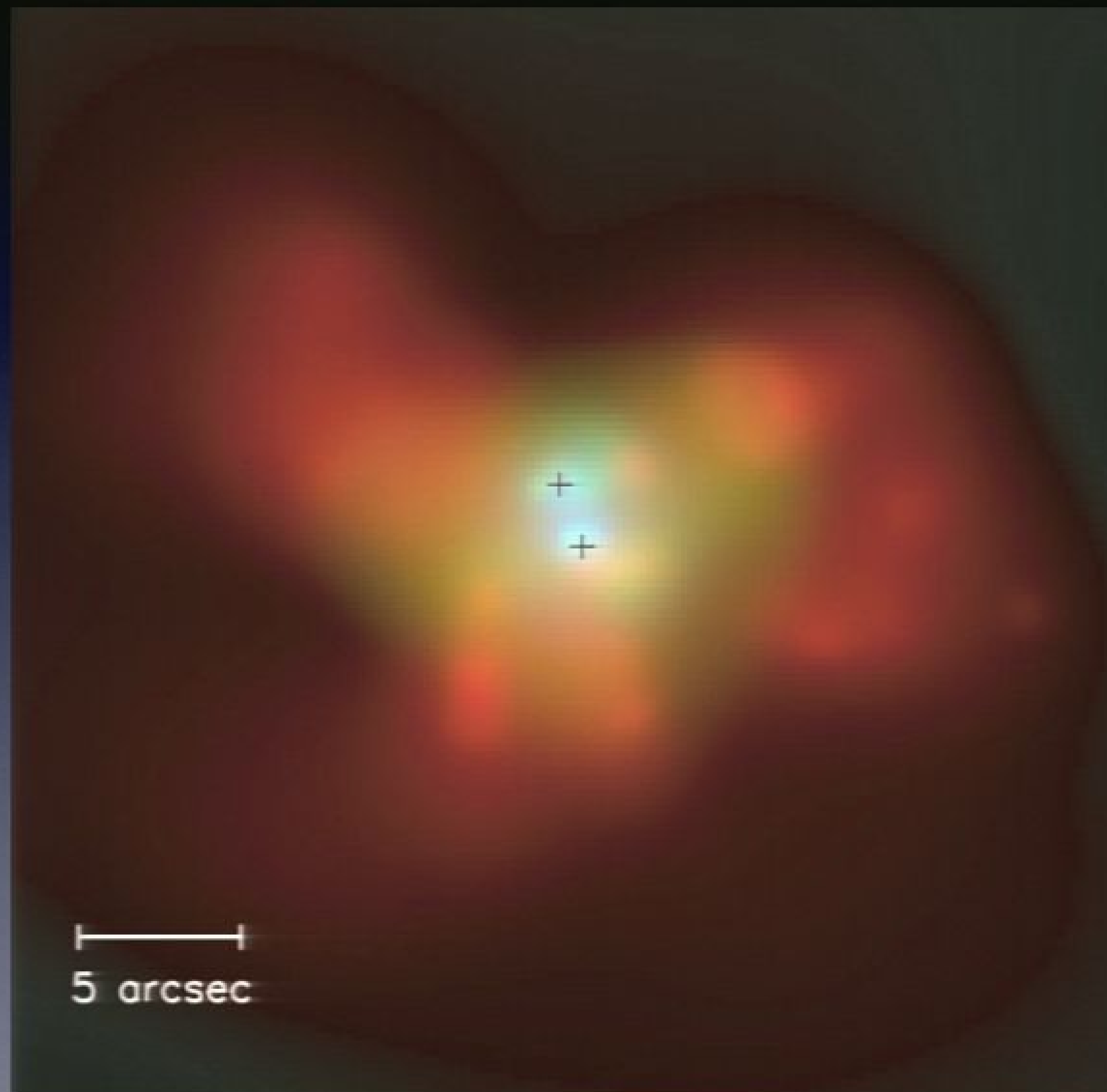
To enumerate the possibilities, we need to understand the stages of the mergers of two black holes.

Stages of BBH Mergers

- Galaxy Mergers

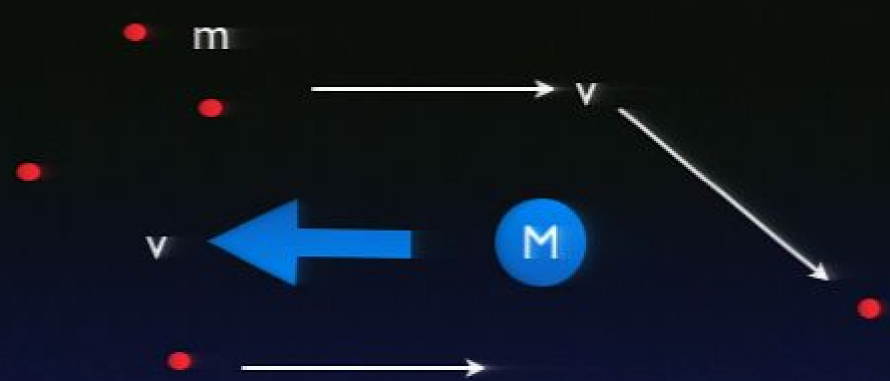
Stages of BBH Mergers

- Galaxy Mergers
- Inspiral phase



NGC 6240 Komossa et al 2003

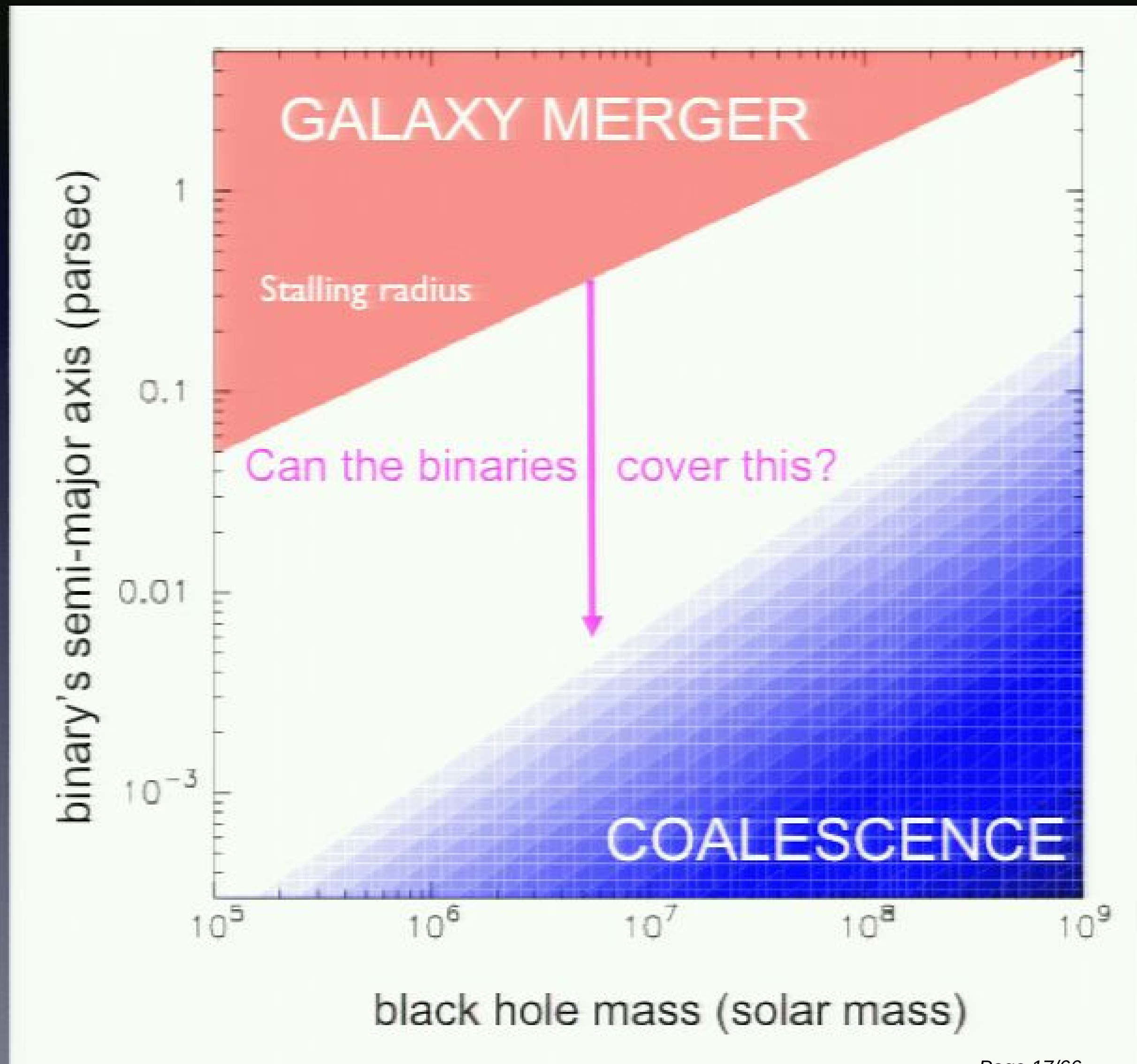
An Aside on Dynamical Friction



• Particles of mass m and velocity v are deflected around M
• Characteristic change is p = mv per deflected particle.
• To change P = Mv, I need to deflect to deflect a total mass of M
• An orbiting BH deflects it own mass in stars to sink 1/e-fold in radius.
• Toward the center of a galaxy, the stellar mass is insufficient -- radius stalls.

Stages of BBH Mergers

- Galaxy Mergers
- Inspiral phase
- Hangup (and then a miracle?)
  - Final Parsec Problem



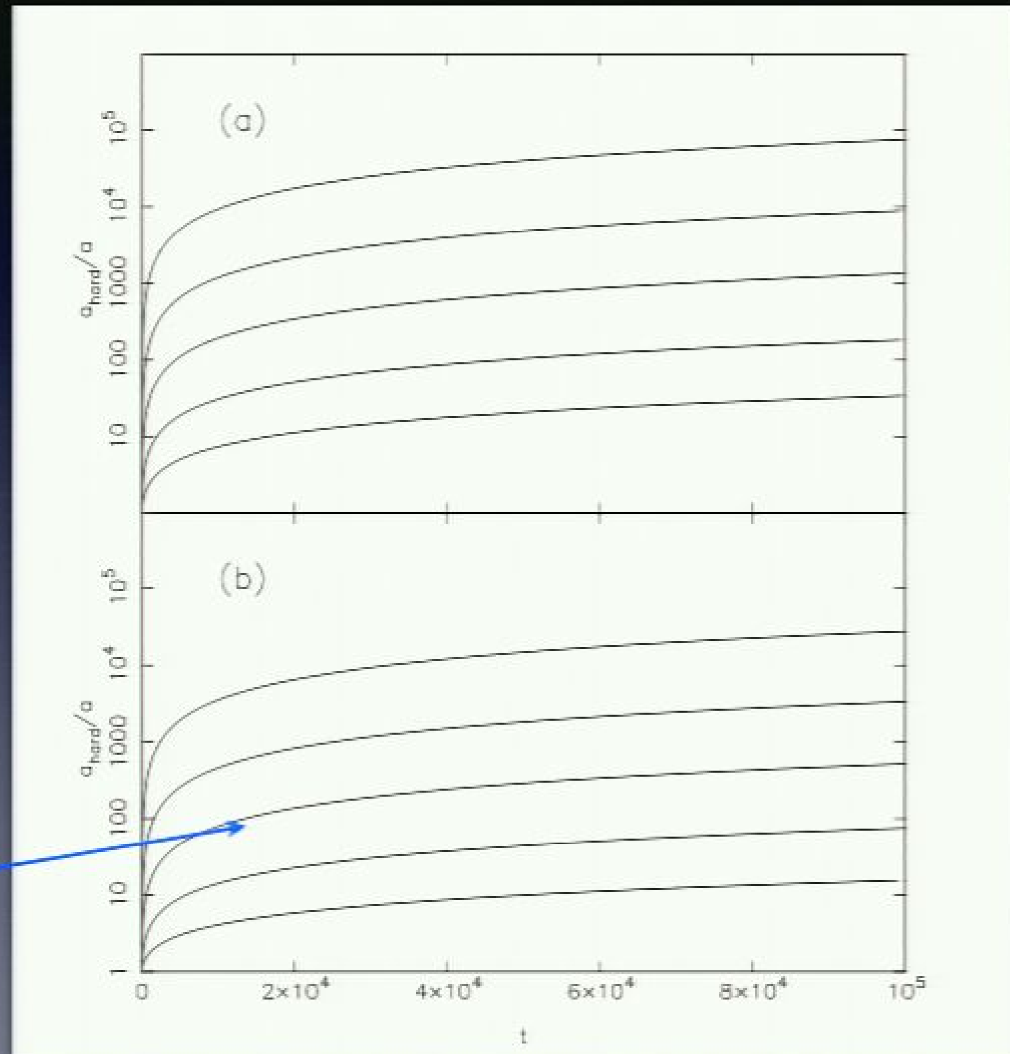
Milosavljevic

Solving the Final Parsec Problem

$m_2/m_1 = 1$

- Need to bring of order a few times the mass of the BH to the center in a time < age of the universe
- Two classes
  - Bring more stars in from larger radii e.g. chaotic orbits, molecular clouds, episodic reinjection.

$\bar{f}_c = 0.1$

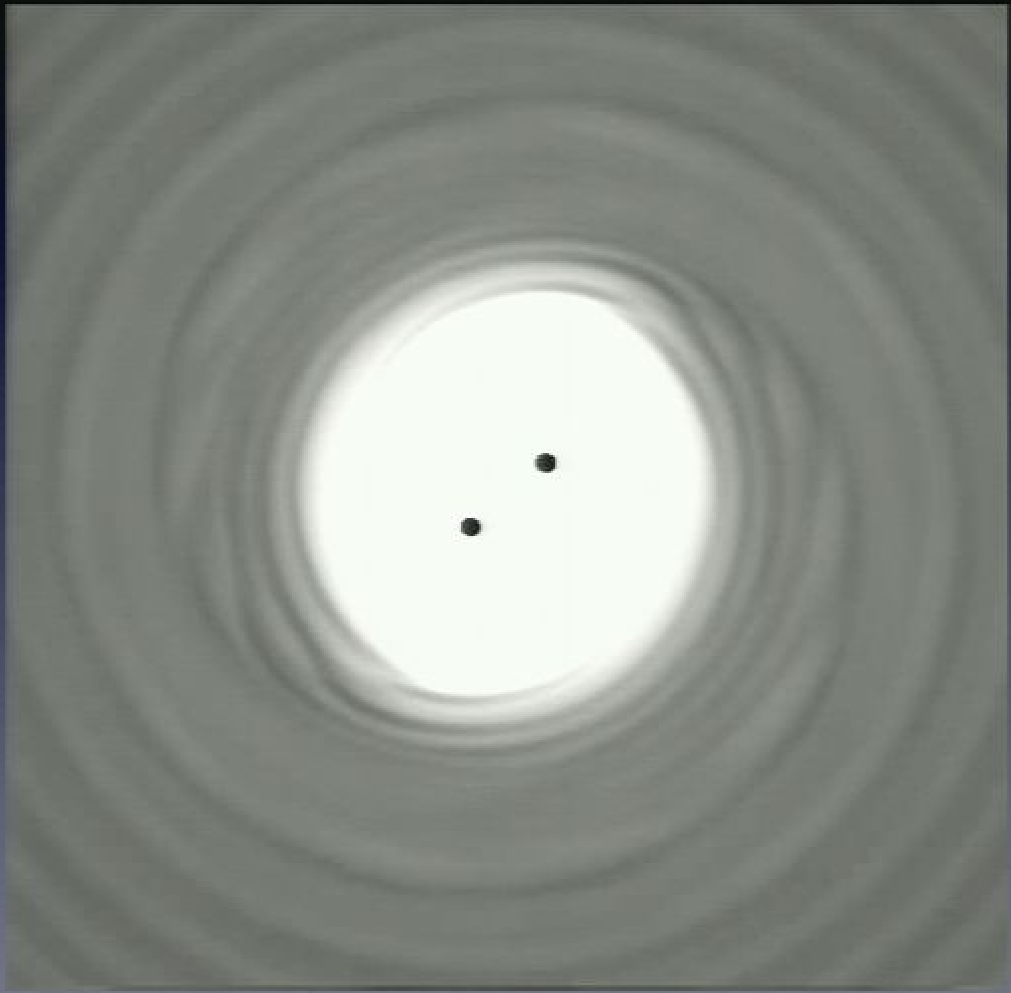


$m_2/m_1 = 0.1$

Merritt and Poon 2004

Solving the Final Parsec Problem

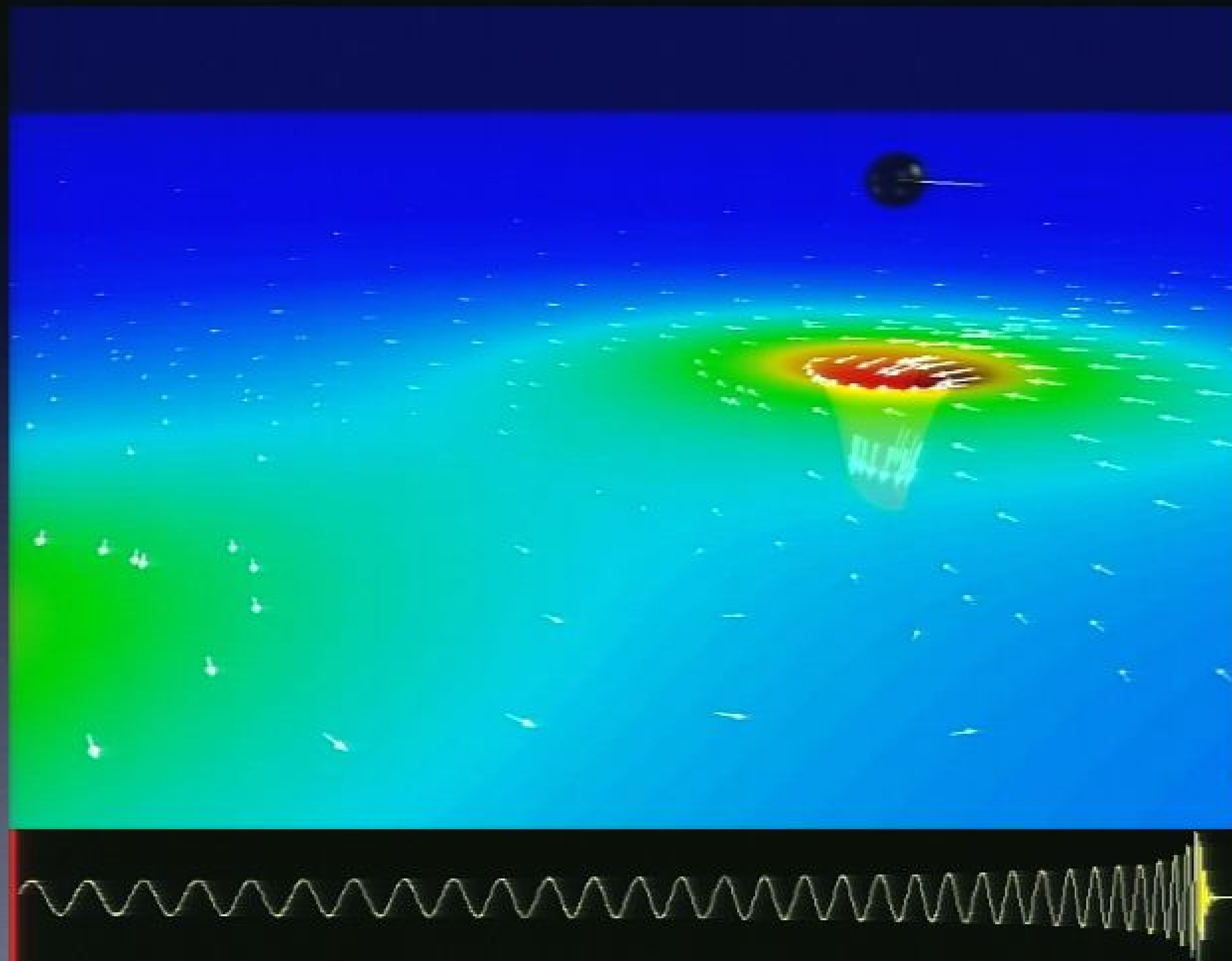
- Need to bring of order a few times the mass of the BH to the center in a time < age of the universe
- Two classes
  - Bring more stars in from larger radii e.g. chaotic orbits, molecular clouds, episodic reinjection.
  - Circumbinary gas disk which removes angular momentum efficiently



Macfayden and Milosavljevic 2008

Stages of BBH Mergers

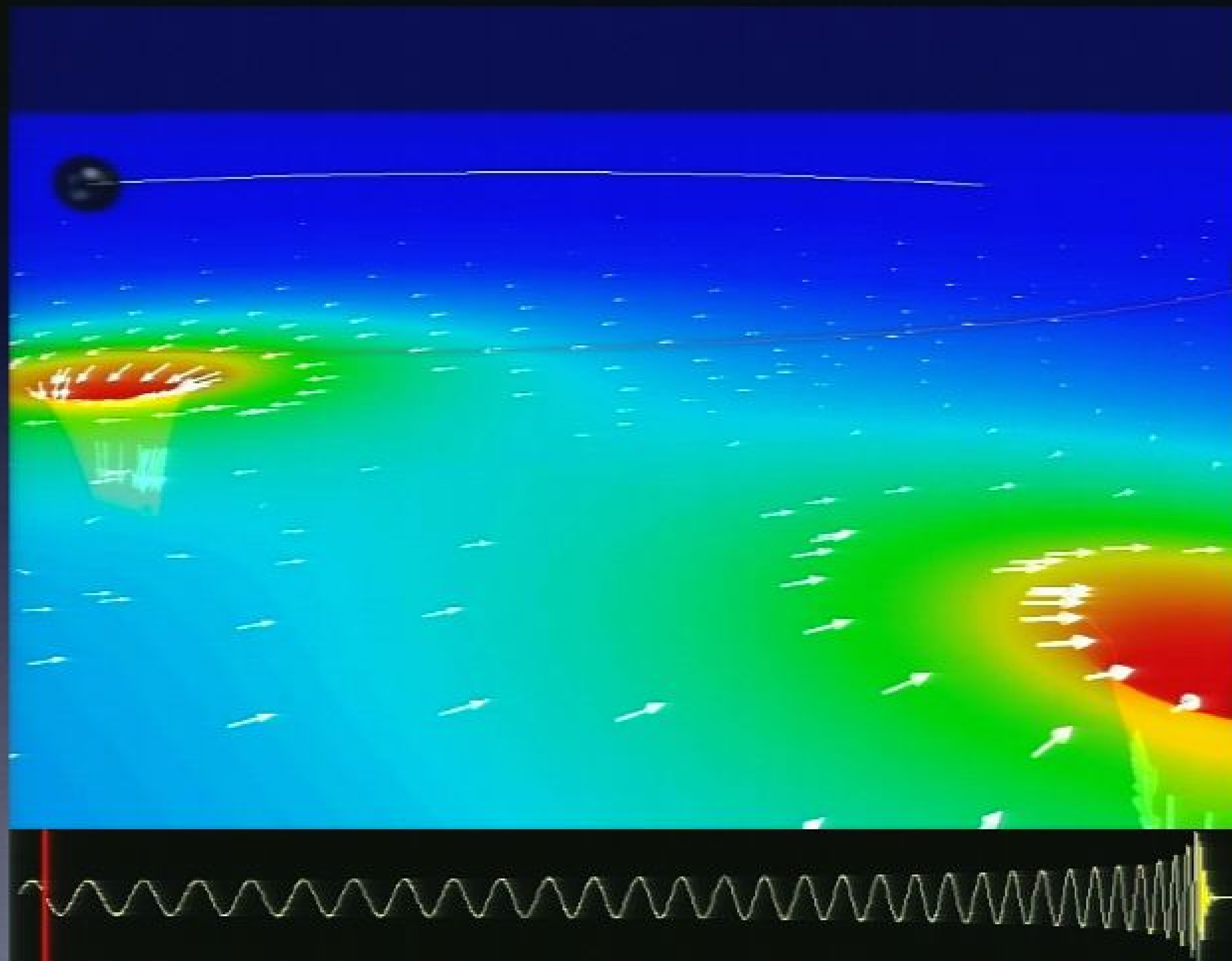
- Galaxy Mergers
- Inspiral phase
- Hangup (and then a miracle?)
  - Final Parsec Problem
- Merger and kick



Movie courtesy of Harald Pfeiffer

Stages of BBH Mergers

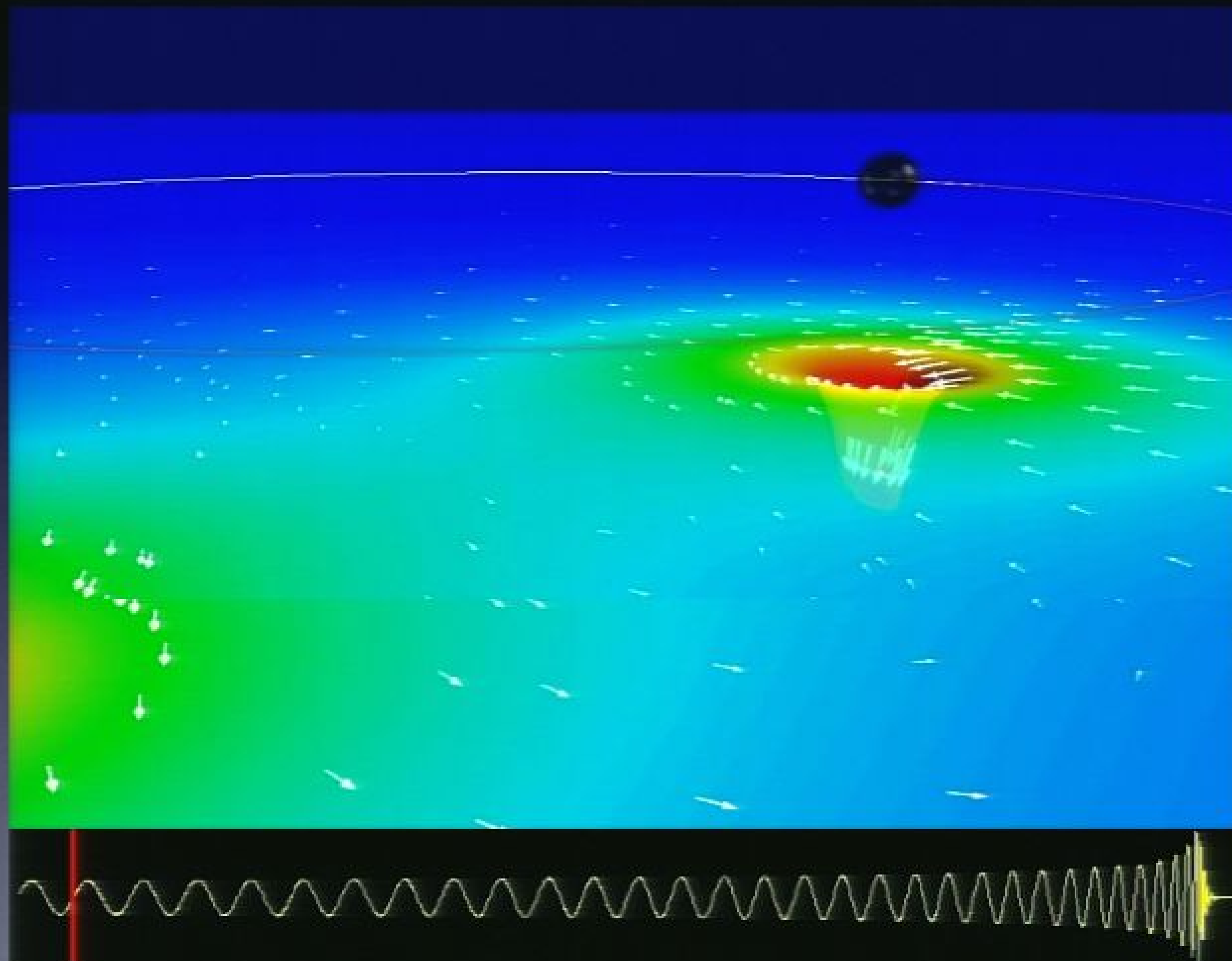
- Galaxy Mergers
- Inspiral phase
- Hangup (and then a miracle?)
  - Final Parsec Problem
- Merger and kick



Movie courtesy of Harald Pfeiffer

Stages of BBH Mergers

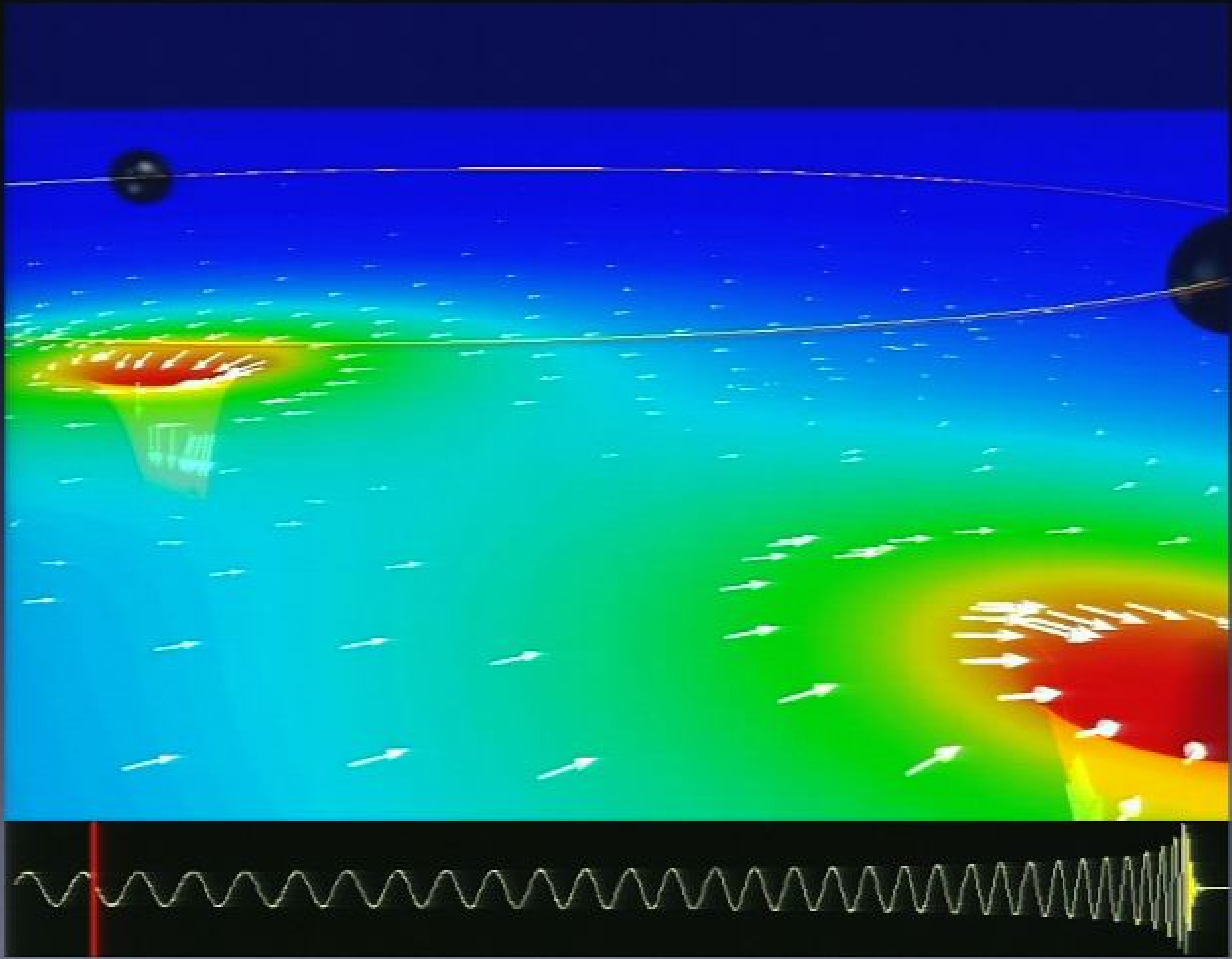
- Galaxy Mergers
- Inspiral phase
- Hangup (and then a miracle?)
  - Final Parsec Problem
- Merger and kick



Movie courtesy of Harald Pfeiffer

Stages of BBH Mergers

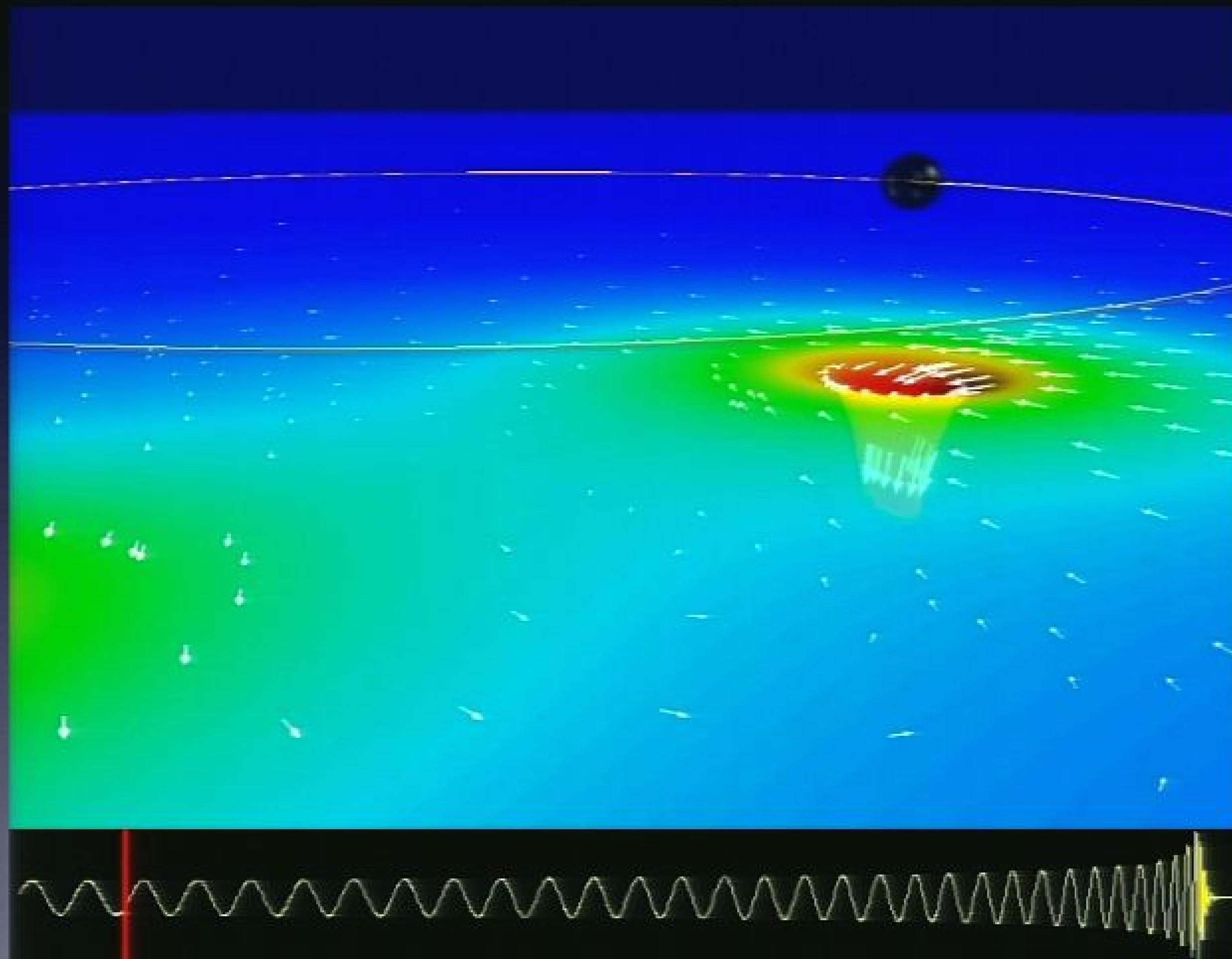
- Galaxy Mergers
- Inspiral phase
- Hangup (and then a miracle?)
  - Final Parsec Problem
- Merger and kick



Movie courtesy of Harald Pfeiffer

Stages of BBH Mergers

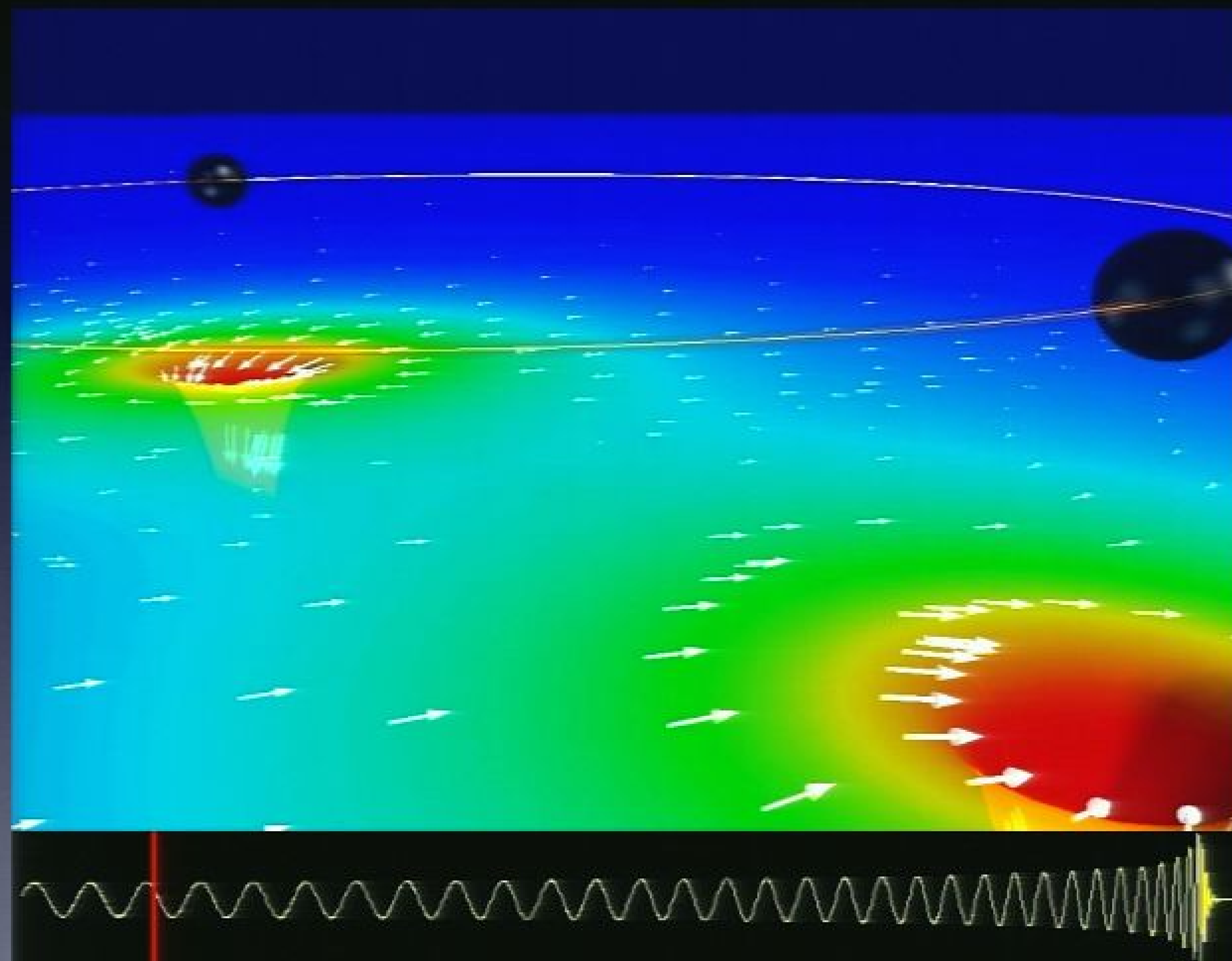
- Galaxy Mergers
- Inspiral phase
- Hangup (and then a miracle?)
  - Final Parsec Problem
- Merger and kick



Movie courtesy of Harald Pfeiffer

Stages of BBH Mergers

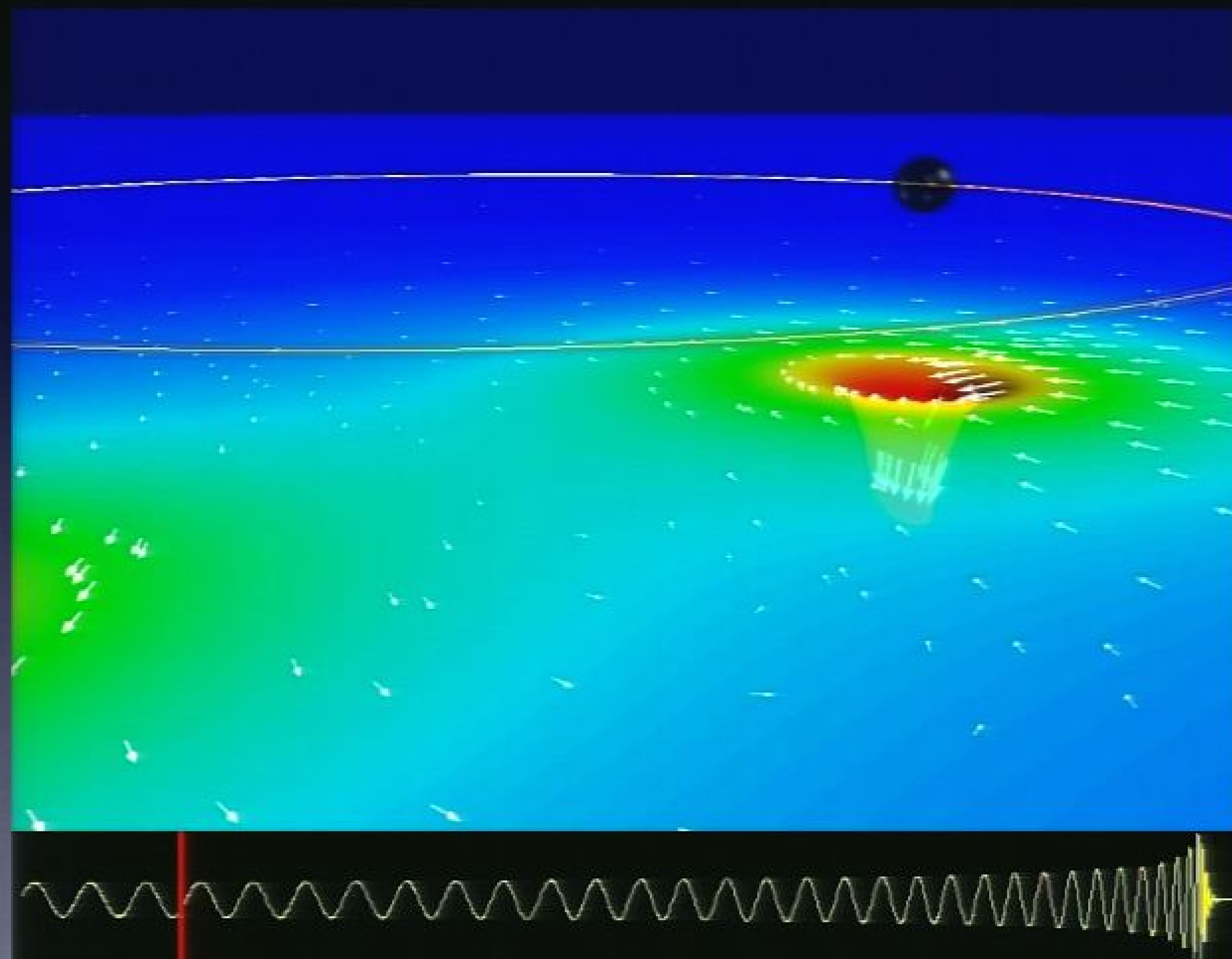
- Galaxy Mergers
- Inspiral phase
- Hangup (and then a miracle?)
  - Final Parsec Problem
- Merger and kick



Movie courtesy of Harald Pfeiffer

Stages of BBH Mergers

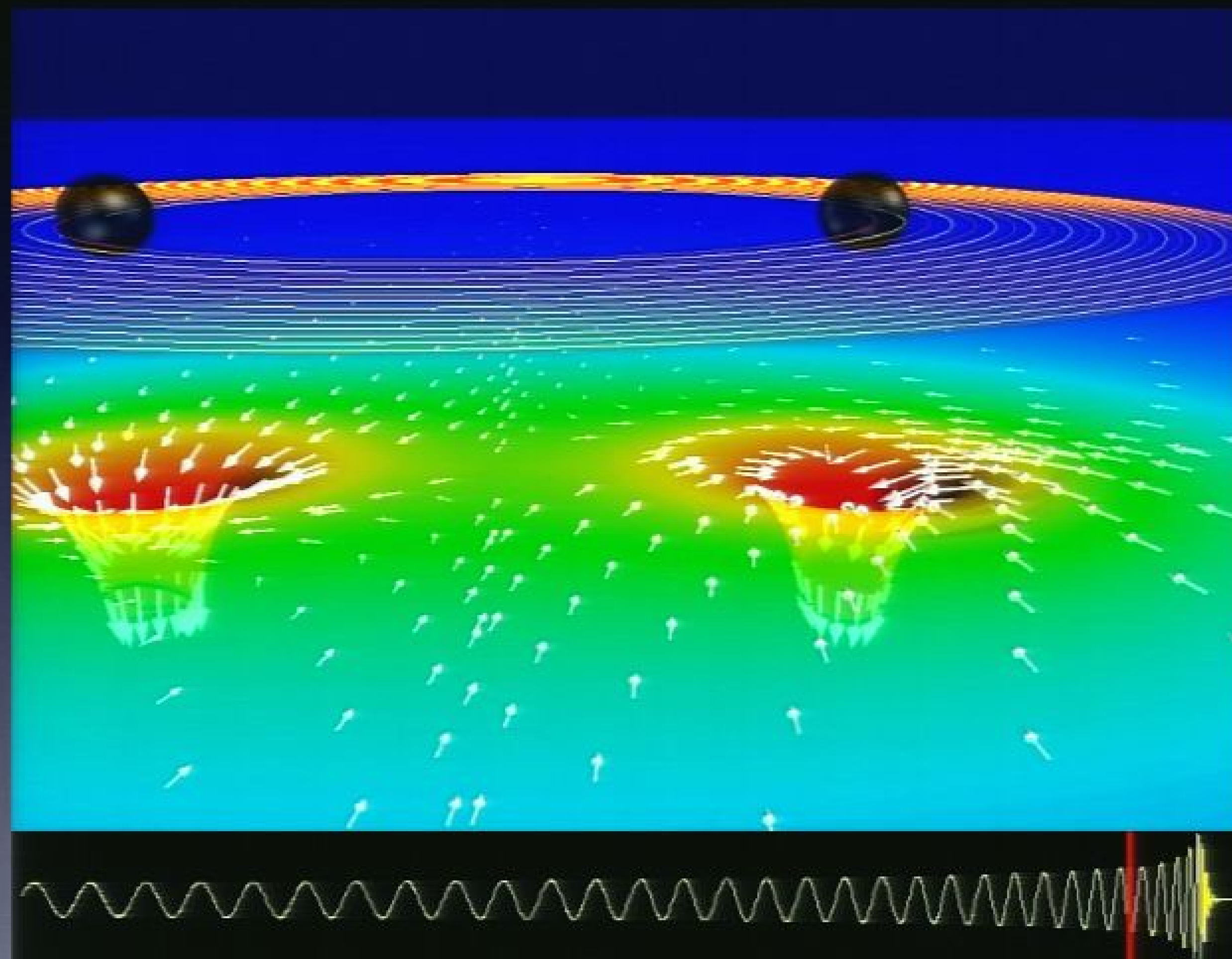
- Galaxy Mergers
- Inspiral phase
- Hangup (and then a miracle?)
  - Final Parsec Problem
- Merger and kick



Movie courtesy of Harald Pfeiffer

Stages of BBH Mergers

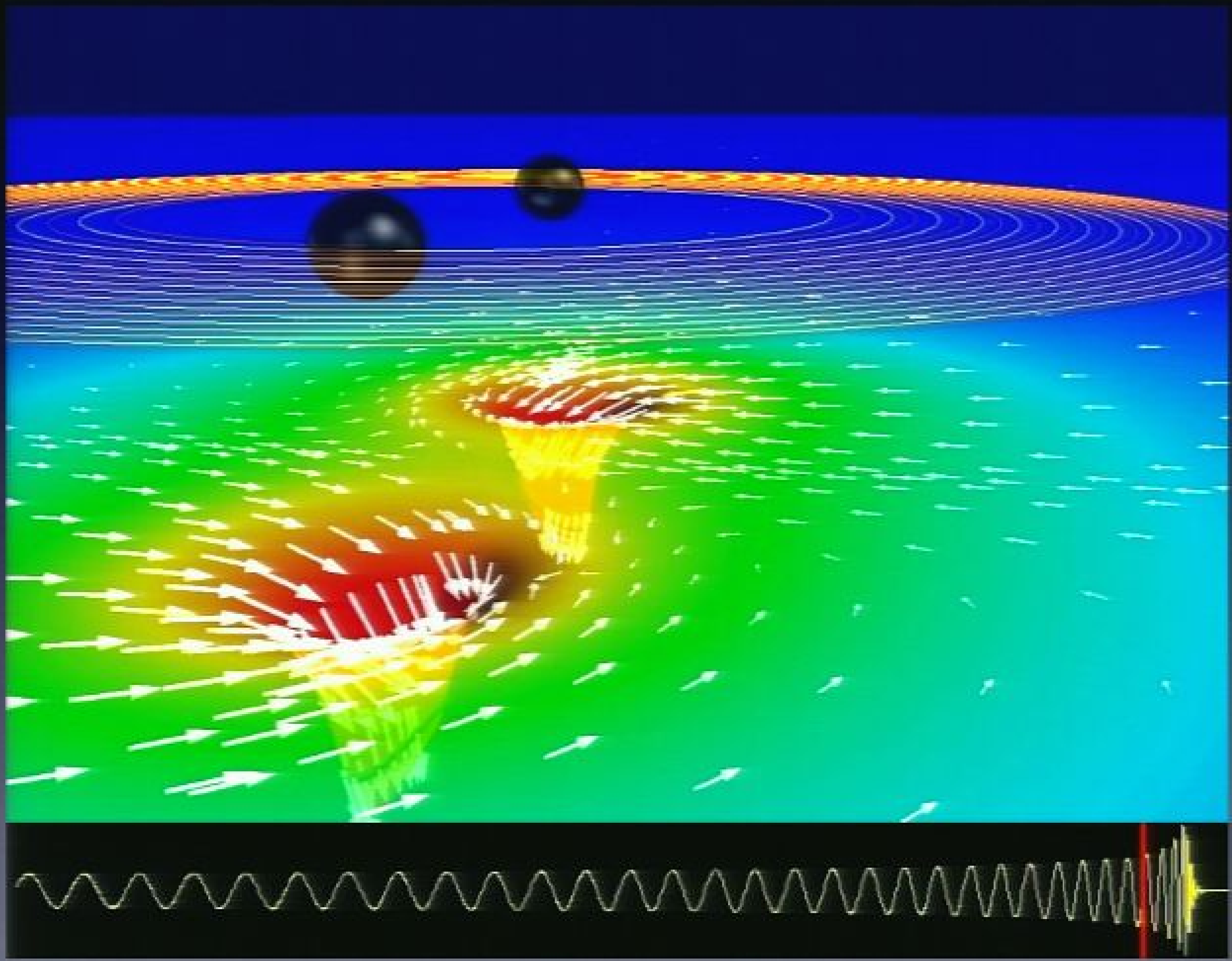
- Galaxy Mergers
- Inspiral phase
- Hangup (and then a miracle?)
  - Final Parsec Problem
- Merger and kick



Movie courtesy of Harald Pfeiffer

Stages of BBH Mergers

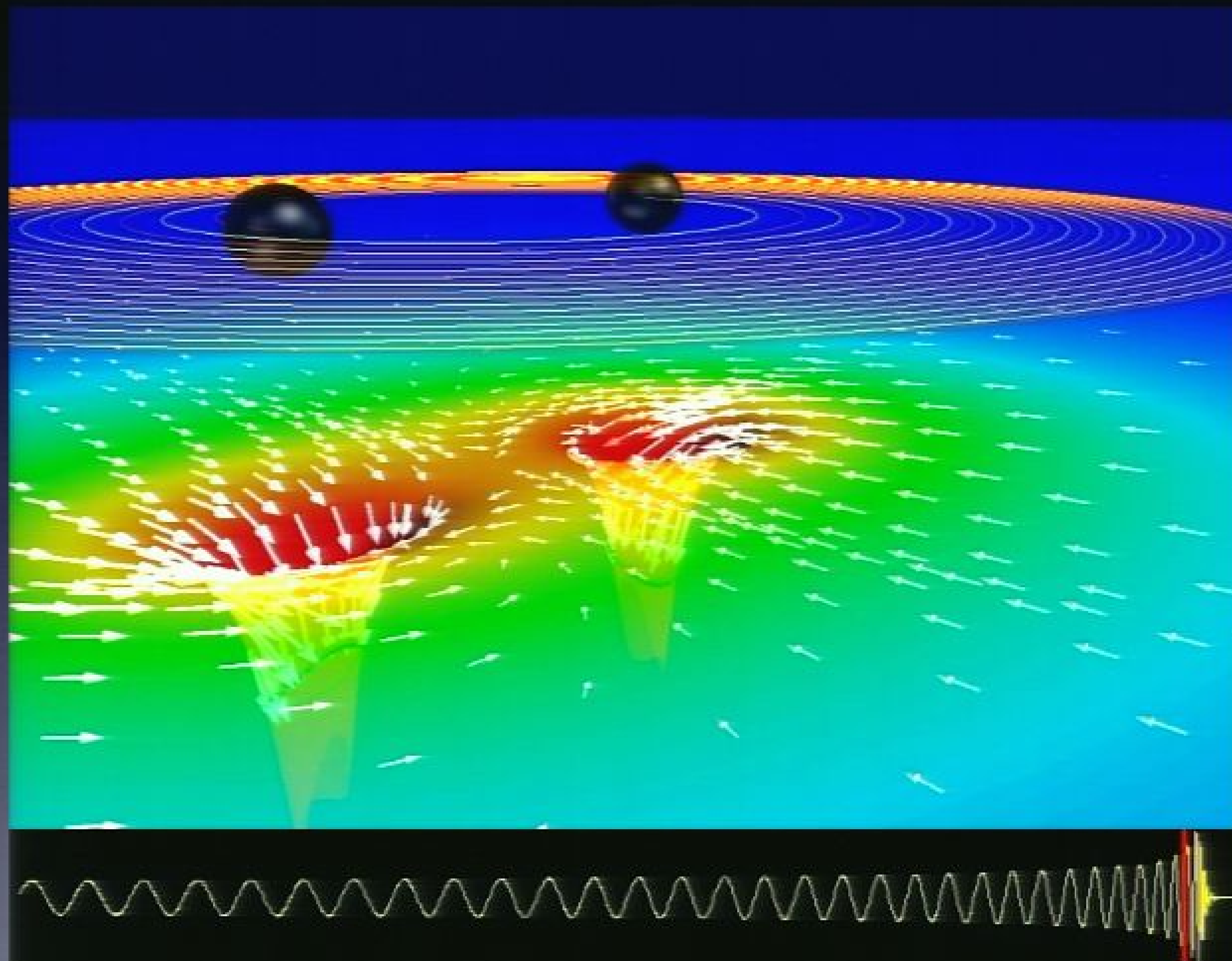
- Galaxy Mergers
- Inspiral phase
- Hangup (and then a miracle?)
  - Final Parsec Problem
- Merger and kick



Movie courtesy of Harald Pfeiffer

Stages of BBH Mergers

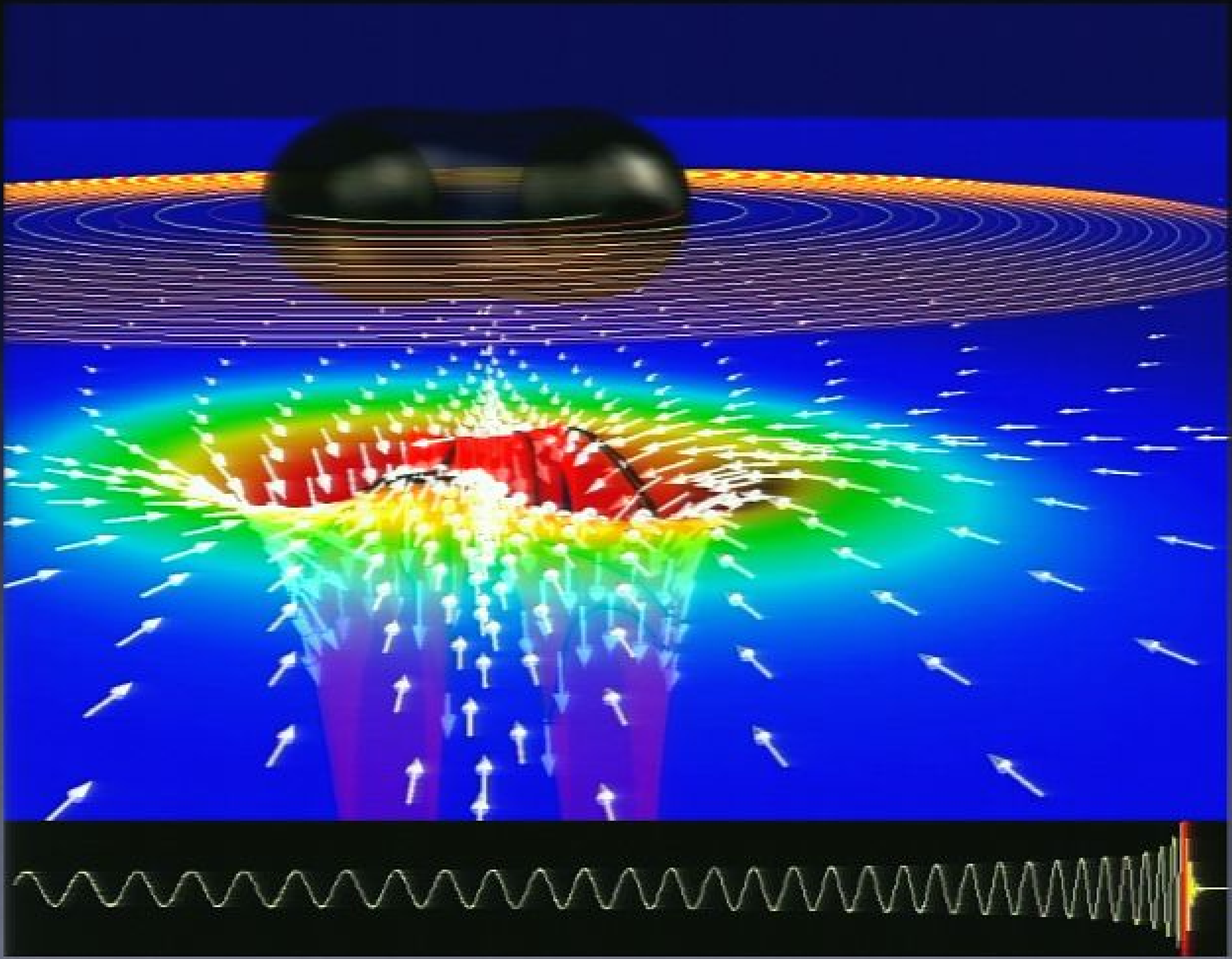
- Galaxy Mergers
- Inspiral phase
- Hangup (and then a miracle?)
  - Final Parsec Problem
- Merger and kick



Movie courtesy of Harald Pfeiffer

Stages of BBH Mergers

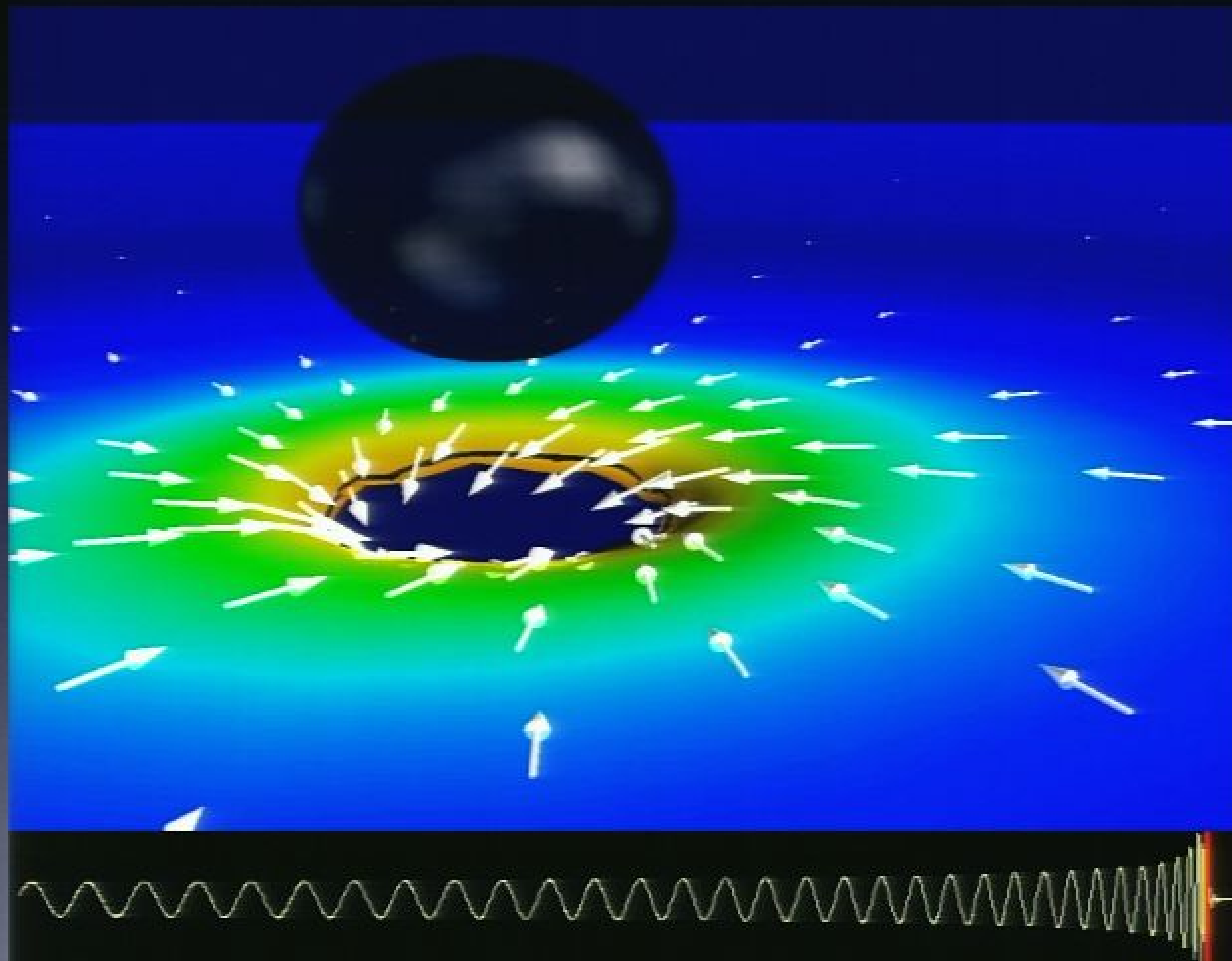
- Galaxy Mergers
- Inspiral phase
- Hangup (and then a miracle?)
  - Final Parsec Problem
- Merger and kick



Movie courtesy of Harald Pfeiffer

Stages of BBH Mergers

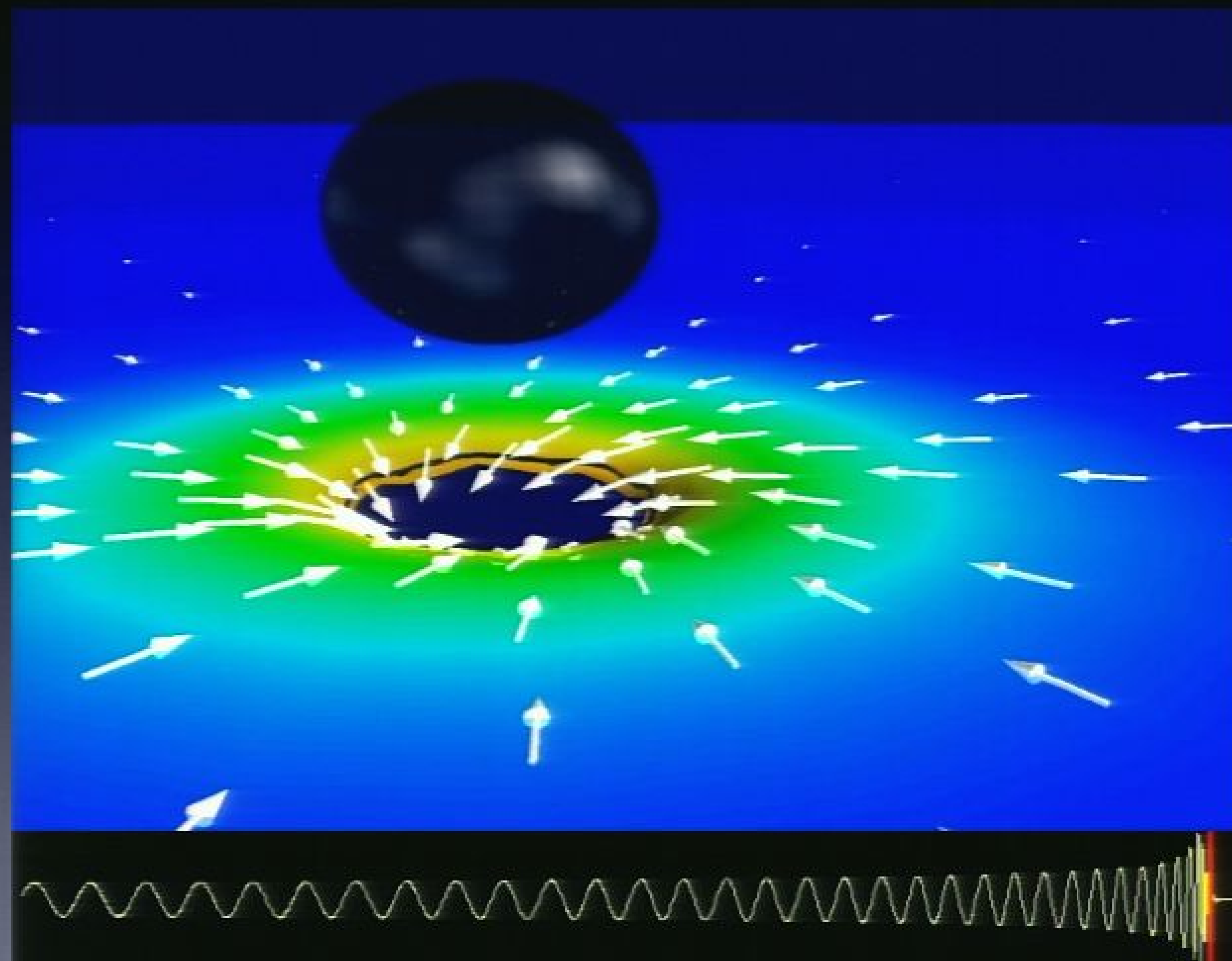
- Galaxy Mergers
- Inspiral phase
- Hangup (and then a miracle?)
  - Final Parsec Problem
- Merger and kick



Movie courtesy of Harald Pfeiffer

Stages of BBH Mergers

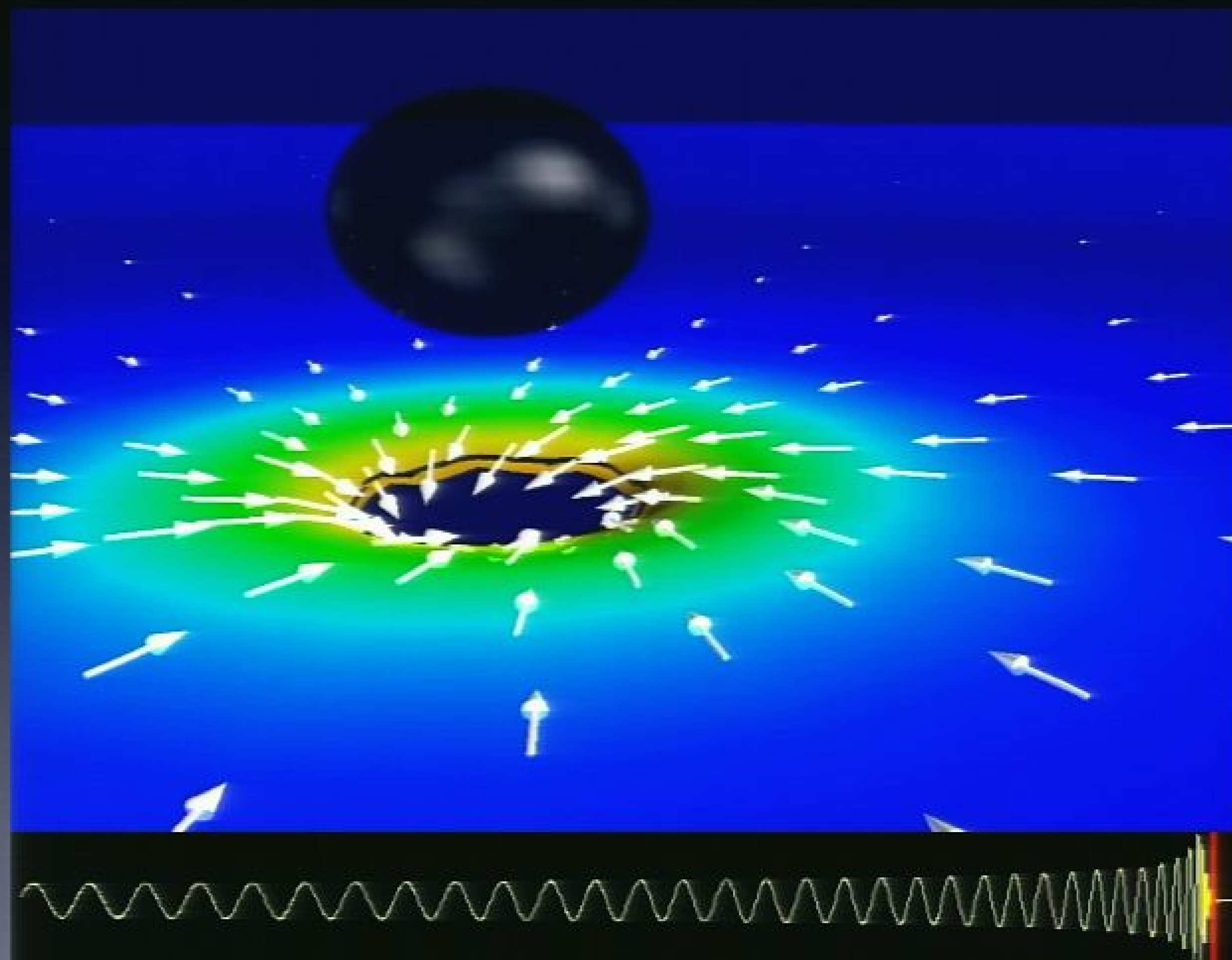
- Galaxy Mergers
- Inspiral phase
- Hangup (and then a miracle?)
  - Final Parsec Problem
- Merger and kick



Movie courtesy of Harald Pfeiffer

Stages of BBH Mergers

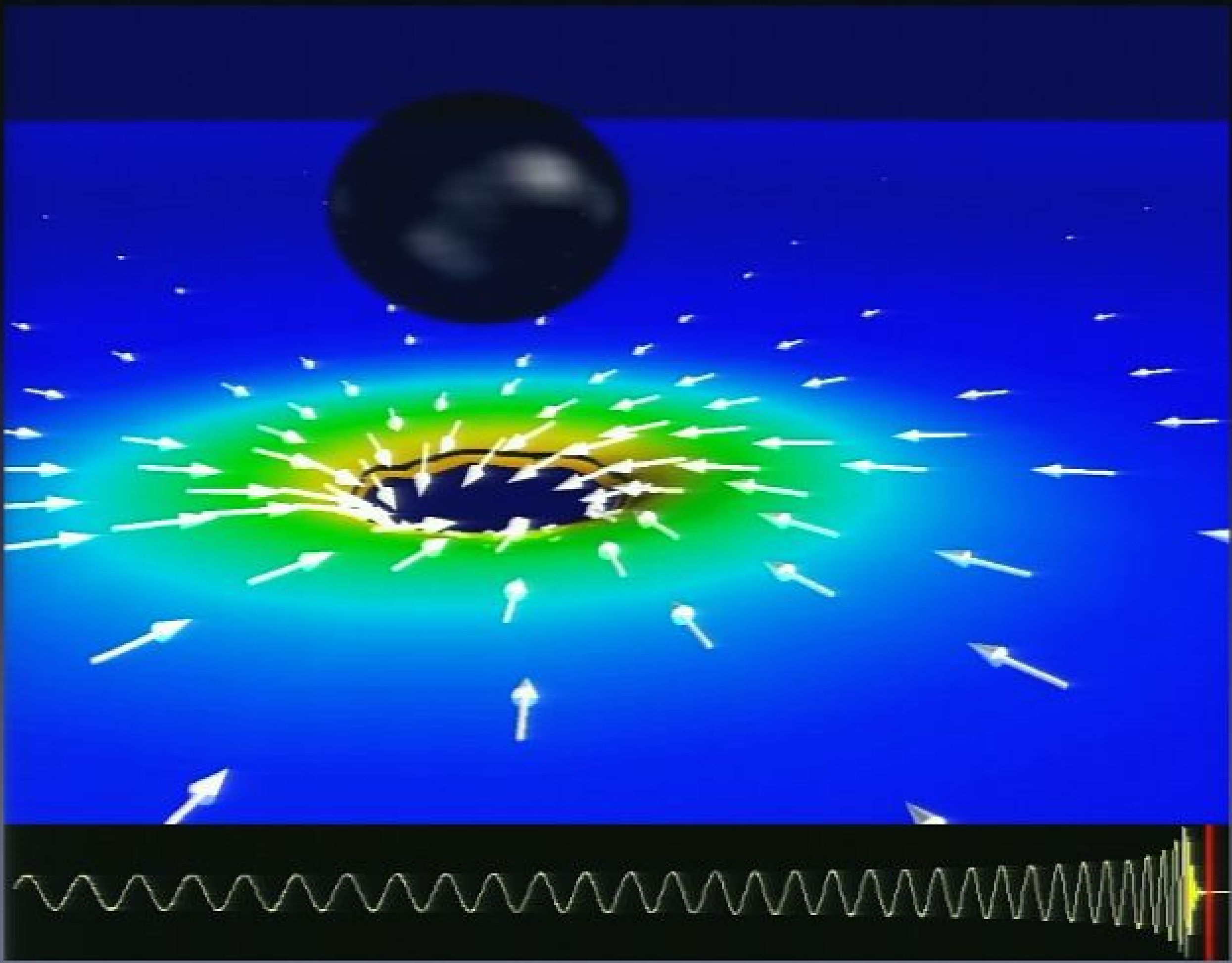
- Galaxy Mergers
- Inspiral phase
- Hangup (and then a miracle?)
  - Final Parsec Problem
- Merger and kick



Movie courtesy of Harald Pfeiffer

Stages of BBH Mergers

- Galaxy Mergers
- Inspiral phase
- Hangup (and then a miracle?)
  - Final Parsec Problem
- Merger and kick



Movie courtesy of Harald Pfeiffer

Merger and Kick

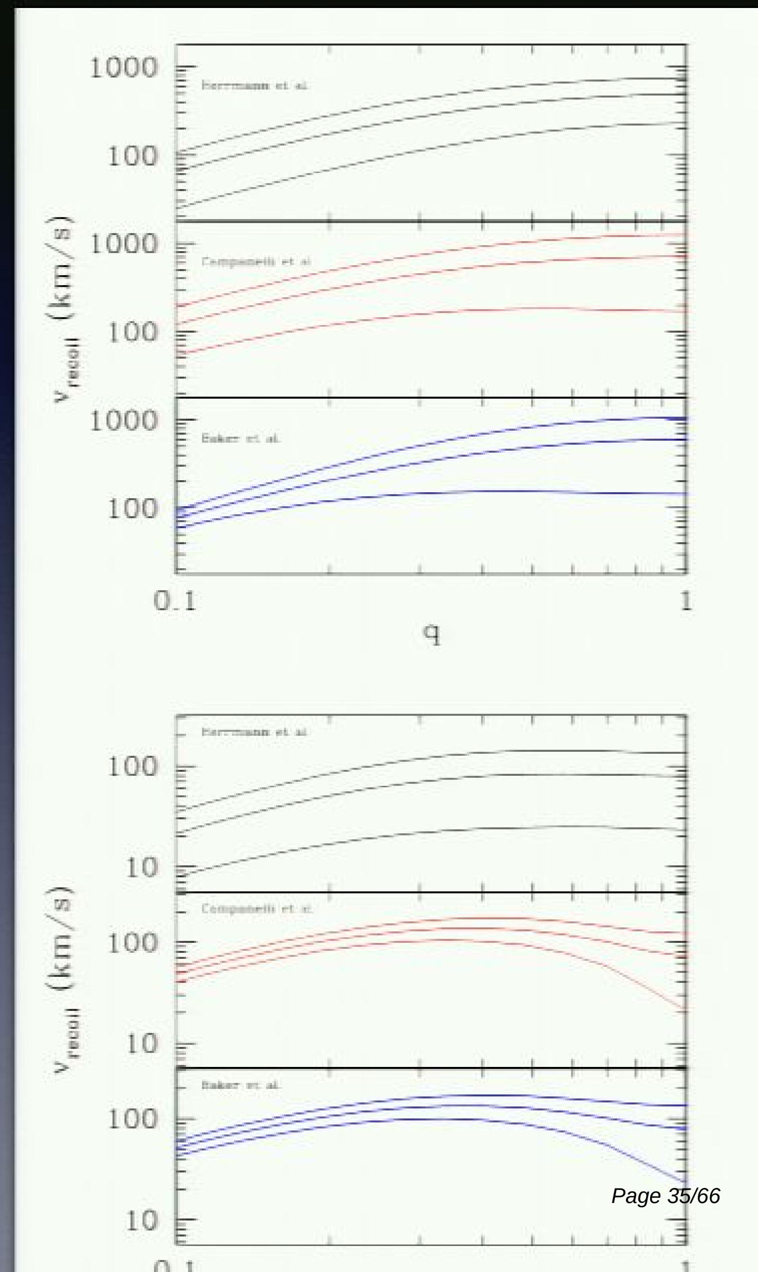
Volonteri et al 2010

- Asymmetric emission of GW leads to kicks.

- Highly dependent on mass ratio and orientation of spins.

- Superkicks of 1000s km/s are possible for unaligned BHs

- However, the gas disk would align these BHs giving lower kick velocities.

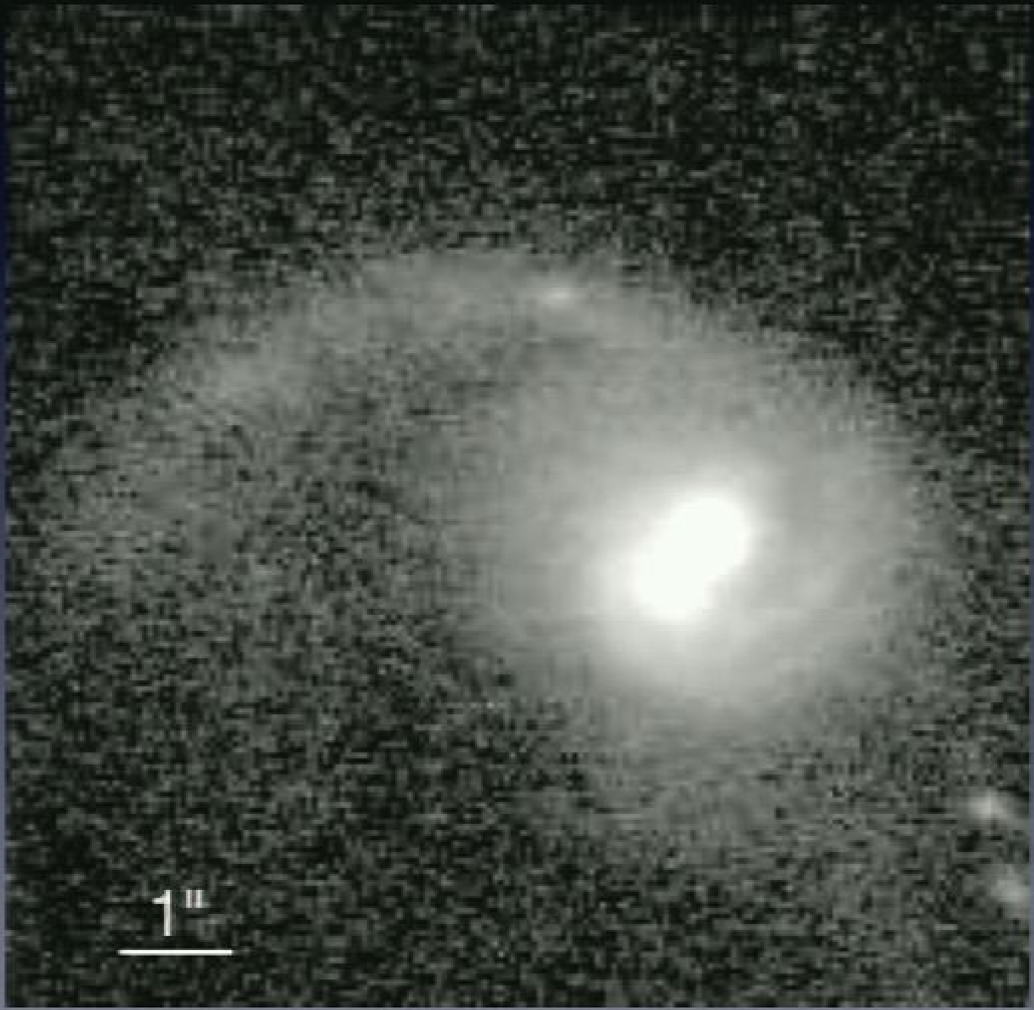


Different Stages - Different Counterparts

- galaxy mergers -- quasar pairs disturbed galaxies, star formation.

Different Stages - Different Counterparts

- galaxy mergers -- quasar pairs, disturbed galaxies, star formation.
- inspiral -- small separation binary agn



COSMO J100043+20 Comerford et al 2009

Different Stages - Different Counterparts

- galaxy mergers -- quasar pairs, disturbed galaxies, star formation.
- inspiral -- small separation binary agn
- final parsec -- no evidence of binary black holes
- mergers and kicks -- regime of interest for GW astronomy

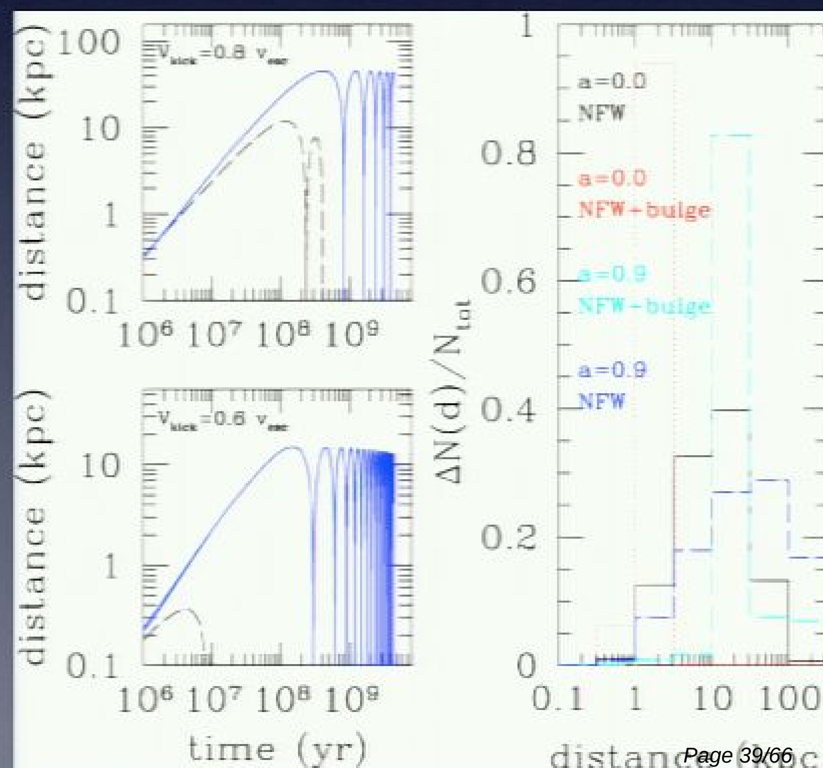
EM Counterparts from Kicks

- In order to get an EM counterpart, require dissipation; need gas.

- Assume that a gas disk exists around the SMBH.

- If part of the gas disk is carried off and accretes, this gives an off-centered AGN.

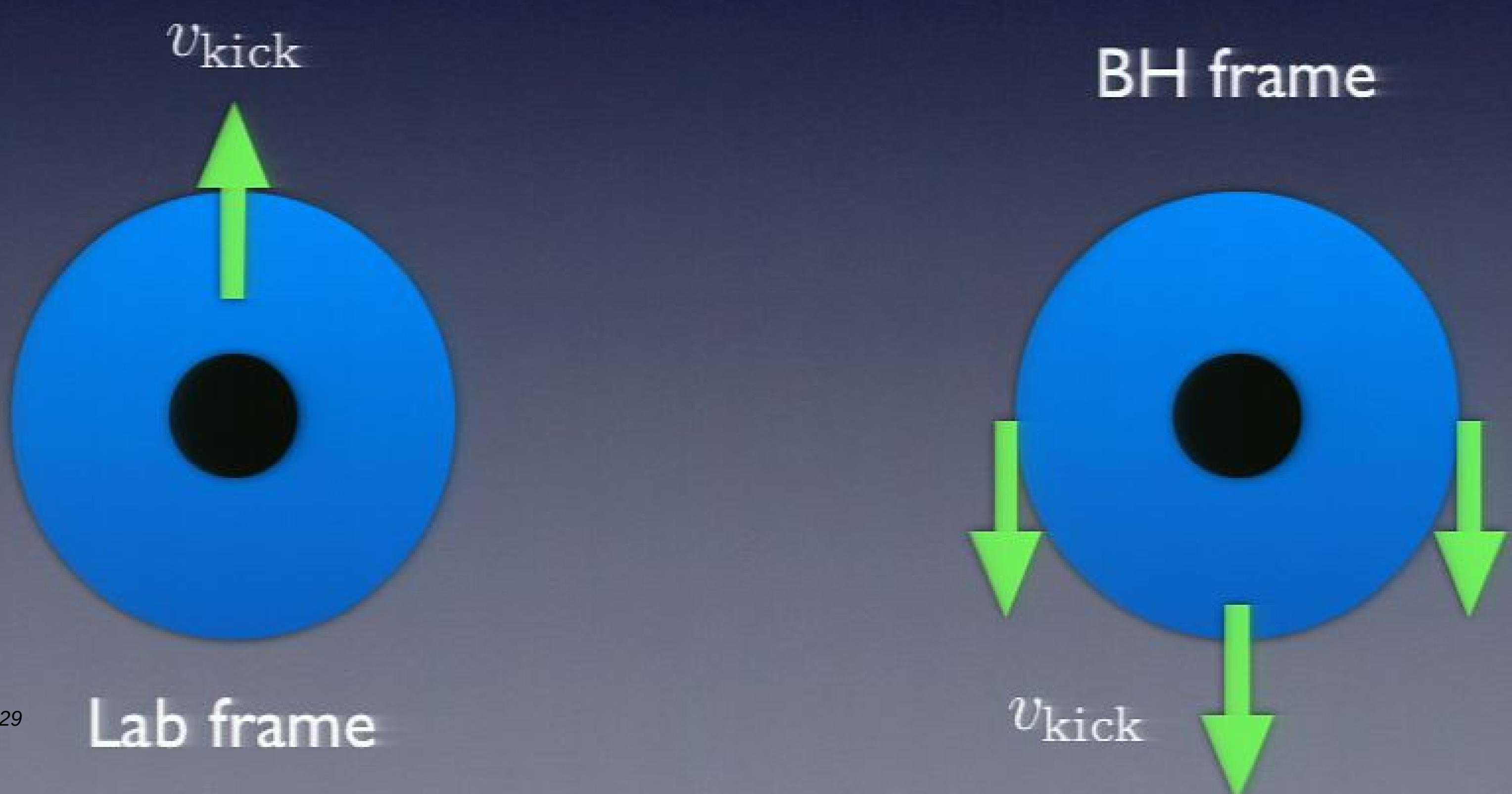
- Typical displacement is 1-10 kpc; timescales ~ 1 Myr



EM Counterparts from Kicks

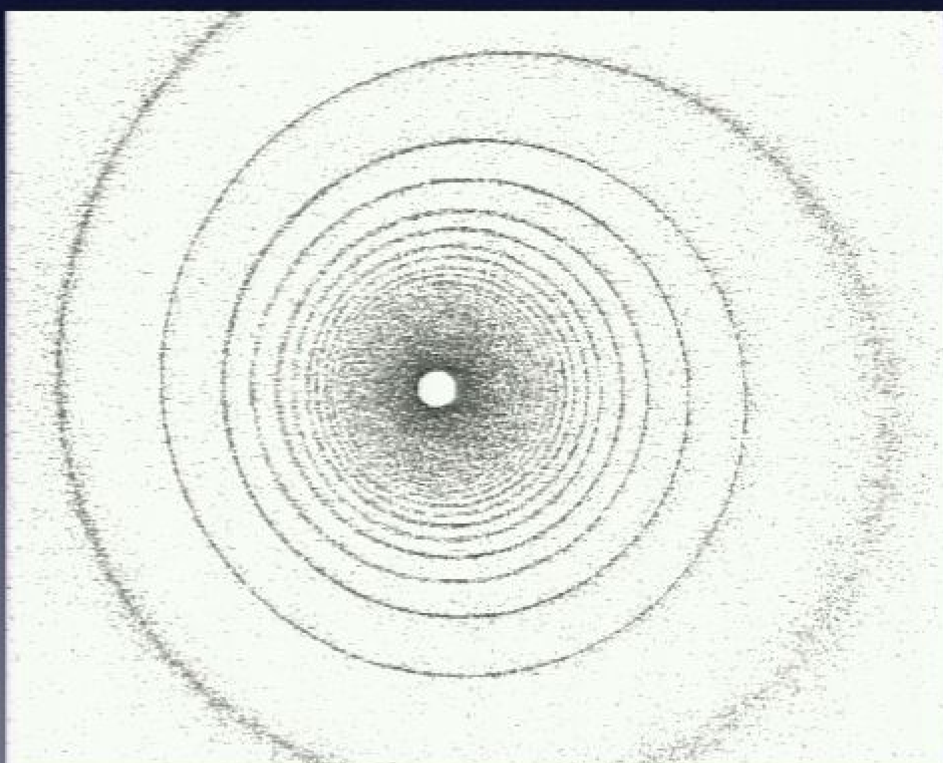
- Kick can also directly affect the gas disk.

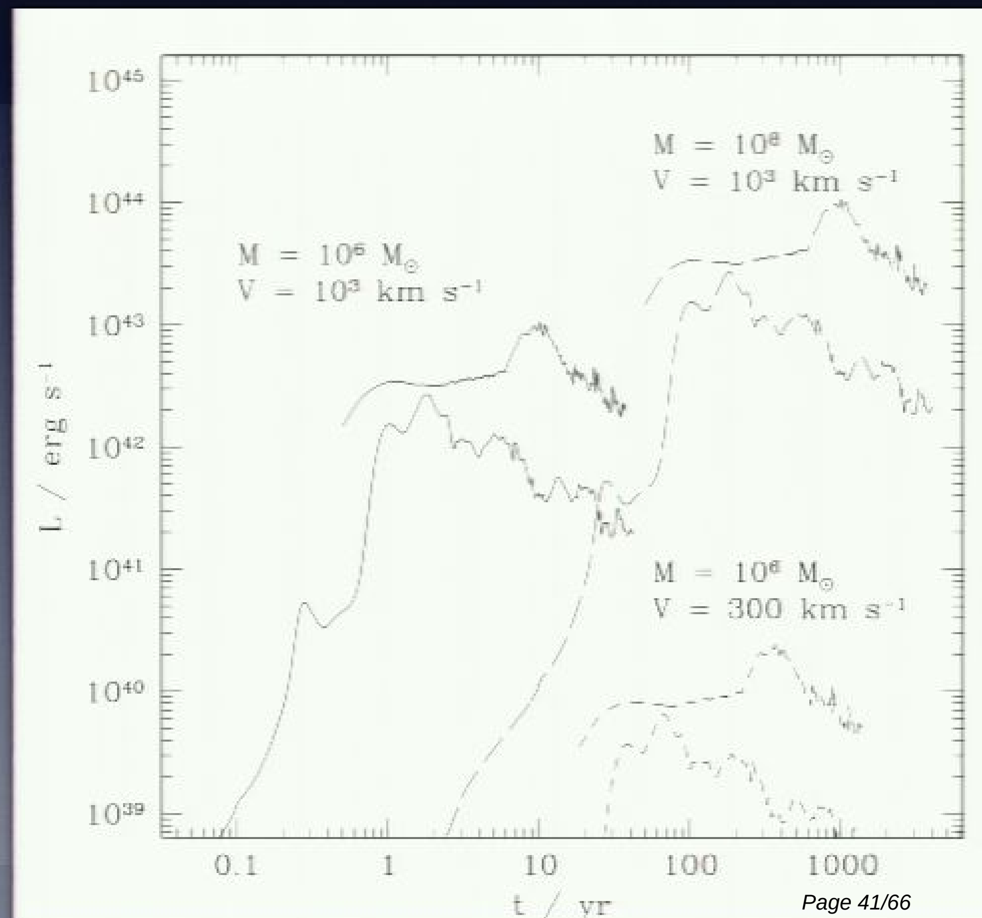
- In the BH frame the disk receives a kick in opposite direction.



EM Counterparts from Kicks

- Gas moves in elliptical orbits which cross and shock
- Luminosity can be quite substantial over years timescale.





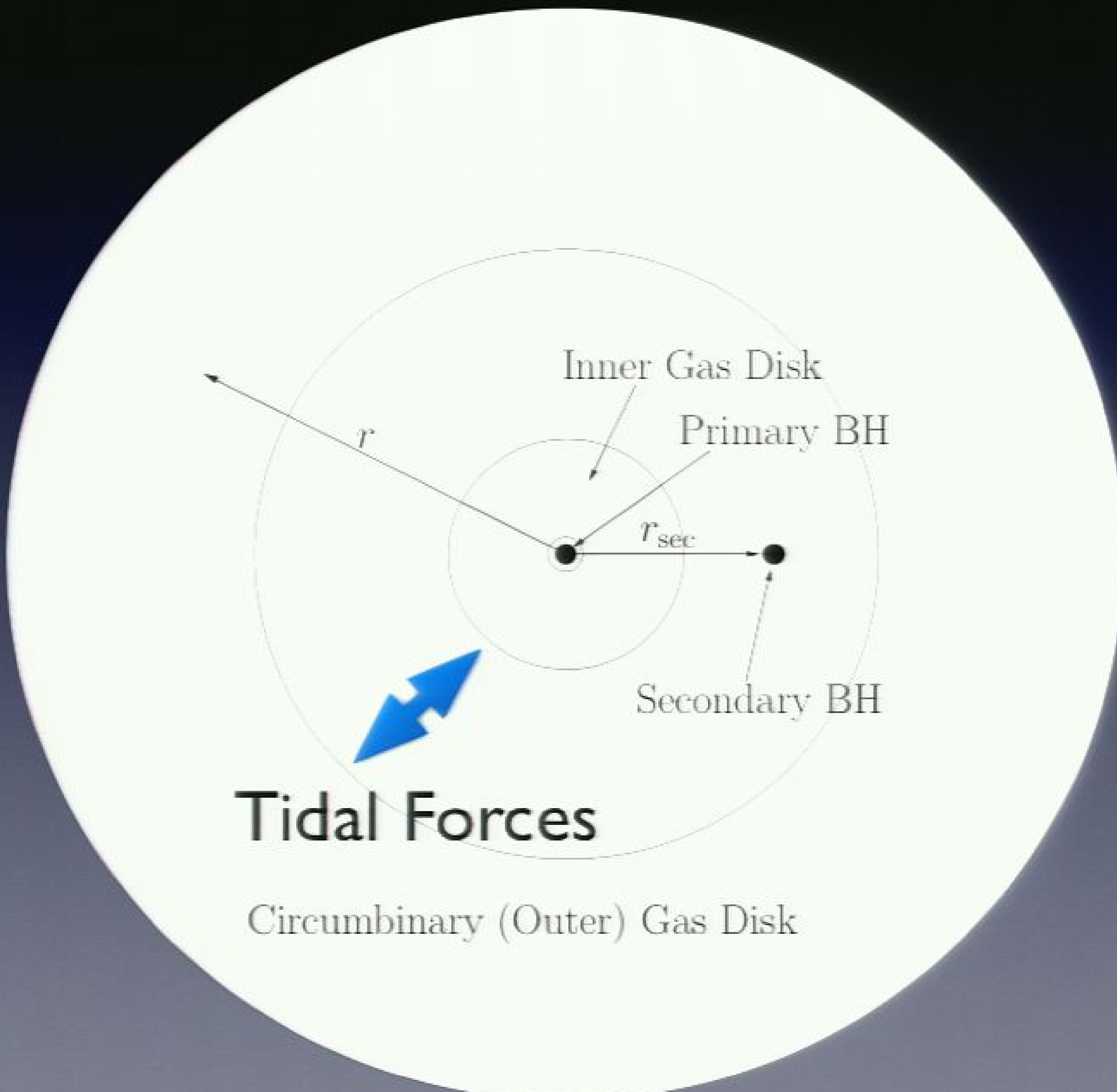
Lippai, Frei, and Haiman 2008

Rossi et al 2009

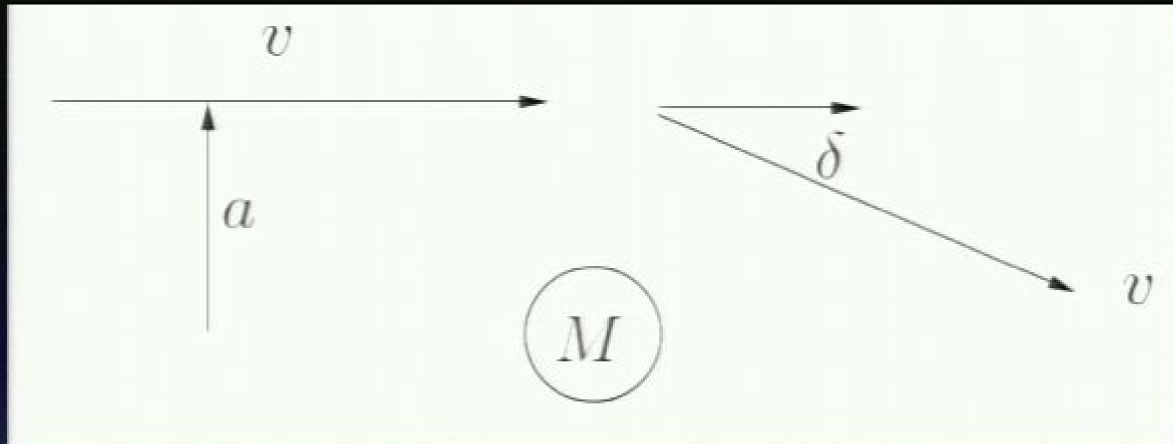
EM Counterparts from Kicks

- Black hole kicks are expected from mergers, but their strength is not clear.
- Depends on the mass of the outer disk, which is over-estimated in many studies.
- However, they appear to be the most promising avenue by which a prompt EM counterpart can be
- Could there be emission the precedes the merger?

The electromagnetic precursor



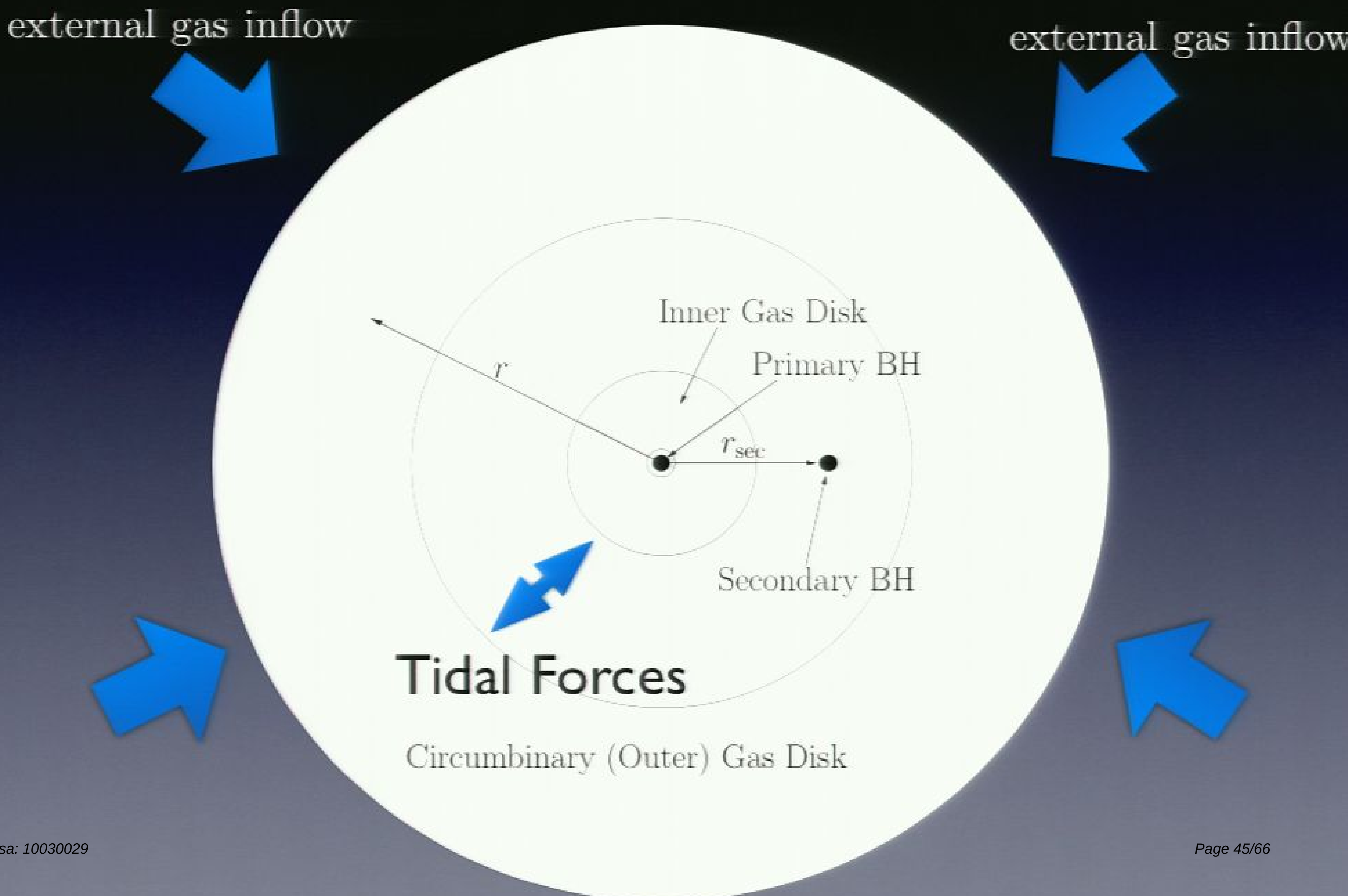
Satellite-Disk Interactions



- Acceleration is $a = \frac{GM}{\Delta r^2}$ over a timescale $t_{\rm dyn}$
- Since $\Delta v_\perp \equiv v \sin\delta = a t_{\rm dyn}$, the angle of deflection is $\delta = \frac{M}{M_{\rm dyn}} \left(\frac{r}{\Delta r}\right)^2$
- The change in the *parallel* component is $\Delta v_{||} = v - v\cos\delta \sim v\delta^2$
- Per encounter, the change in specific angular momentum is $\Delta l = \Delta v_{||} r$
- Timescale between encounters is $\Delta t \sim t_{\rm dyn} \frac{r}{\Delta r}$
- So the torque is

$$T_{\rm d} \sim M_{\rm d} \frac{\Delta l}{\Delta t} \sim \frac{GM^2}{r} \frac{M_{\rm d}}{M_{\rm dyn}} \left(\frac{r}{\Delta r}\right)^3$$

The electromagnetic precursor



Equations

$$\frac{\partial \Sigma}{\partial t} + \frac{1}{r}\frac{\partial (r\Sigma v_r)}{\partial r} = 0$$

Continuity

$$\frac{\partial (\Sigma r^2 \Omega)}{\partial t} + \frac{1}{r}\frac{\partial (r v_r \Sigma r^2 \Omega)}{\partial r} = -\frac{1}{2\pi r}\left(\frac{\partial T_{\rm visc}}{\partial r} - \frac{\partial T_{\rm d}}{\partial r}\right)$$

Angular momentum conservation in disk

$$\frac{1}{2} M_{\rm sec} \Omega_{\rm sec} r_{\rm sec} \frac{\partial r_{\rm sec}}{\partial t} = T_{\rm d} - T_{\rm GW}$$

Angular momentum conservation in secondary BH

Equations

$$\frac{\partial \Sigma}{\partial t} + \frac{1}{r}\frac{\partial (r\Sigma v_r)}{\partial r} = 0$$

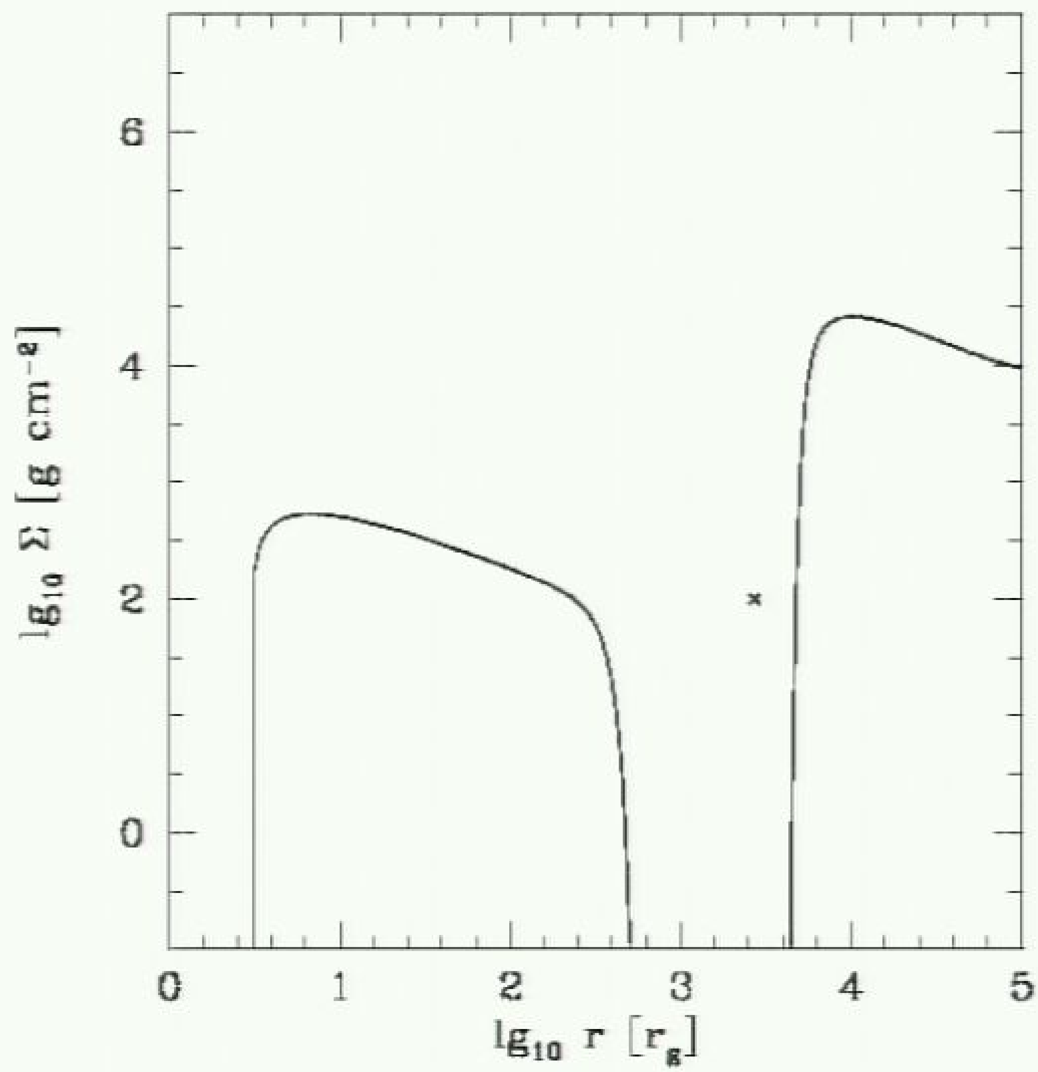
Continuity

$$\frac{\partial (\Sigma r^2 \Omega)}{\partial t} + \frac{1}{r}\frac{\partial (r v_r \Sigma r^2 \Omega)}{\partial r} = -\frac{1}{2\pi r}\left(\frac{\partial T_{\rm visc}}{\partial r} - \frac{\partial T_{\rm d}}{\partial r}\right)$$

Angular momentum conservation in disk

$$\frac{1}{2} M_{\rm sec} \Omega_{\rm sec} r_{\rm sec} \frac{\partial r_{\rm sec}}{\partial t} = T_{\rm d} - T_{\rm GW}$$

Angular momentum conservation in secondary BH



6
4
2
0
0
1
2
3
4
5
lg10 Σ [g cm-2]
lg10 r [rg]

Equations

$$\frac{\partial \Sigma}{\partial t} + \frac{1}{r}\frac{\partial (r\Sigma v_r)}{\partial r} = 0$$

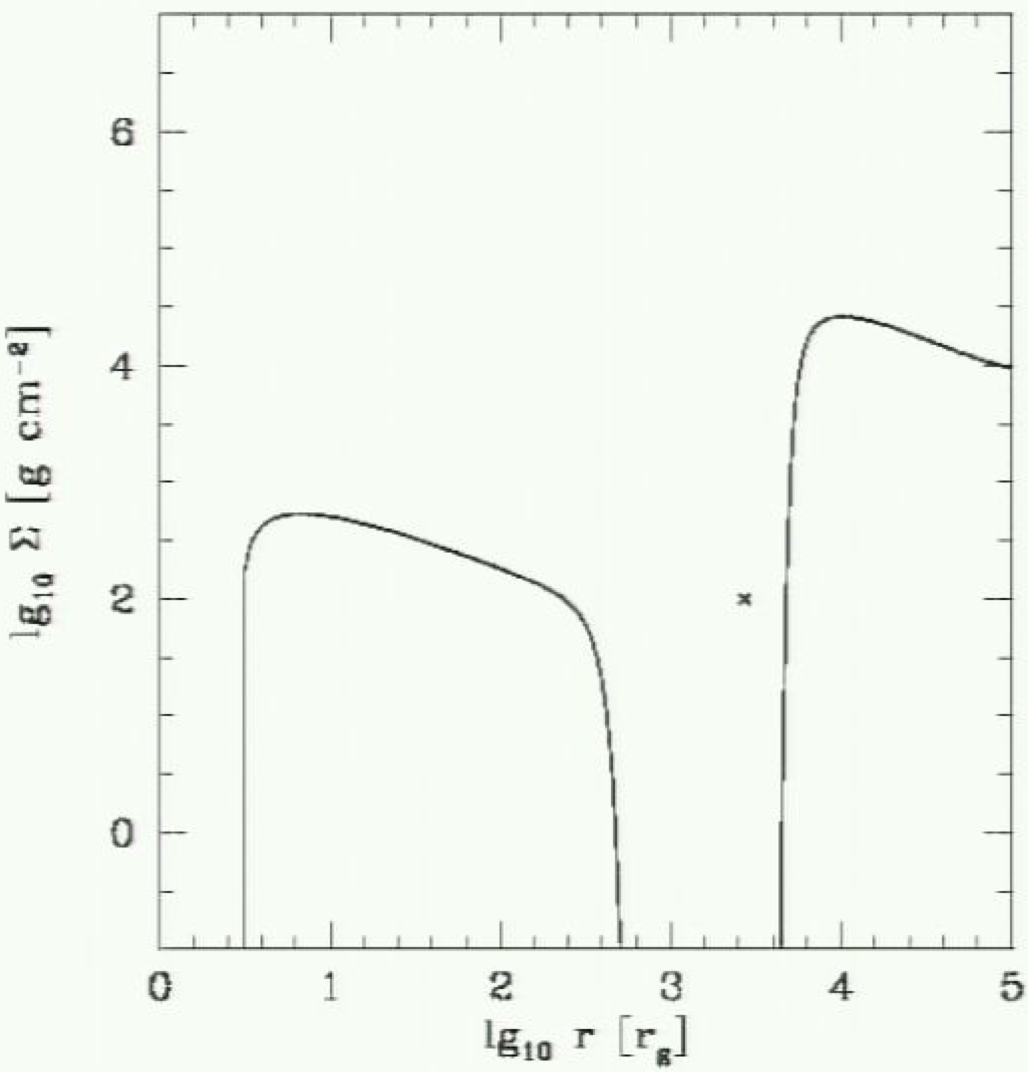
Continuity

$$\frac{\partial (\Sigma r^2 \Omega)}{\partial t} + \frac{1}{r}\frac{\partial (r v_r \Sigma r^2 \Omega)}{\partial r} = -\frac{1}{2\pi r}\left(\frac{\partial T_{\rm visc}}{\partial r} - \frac{\partial T_{\rm d}}{\partial r}\right)$$

Angular momentum conservation in disk

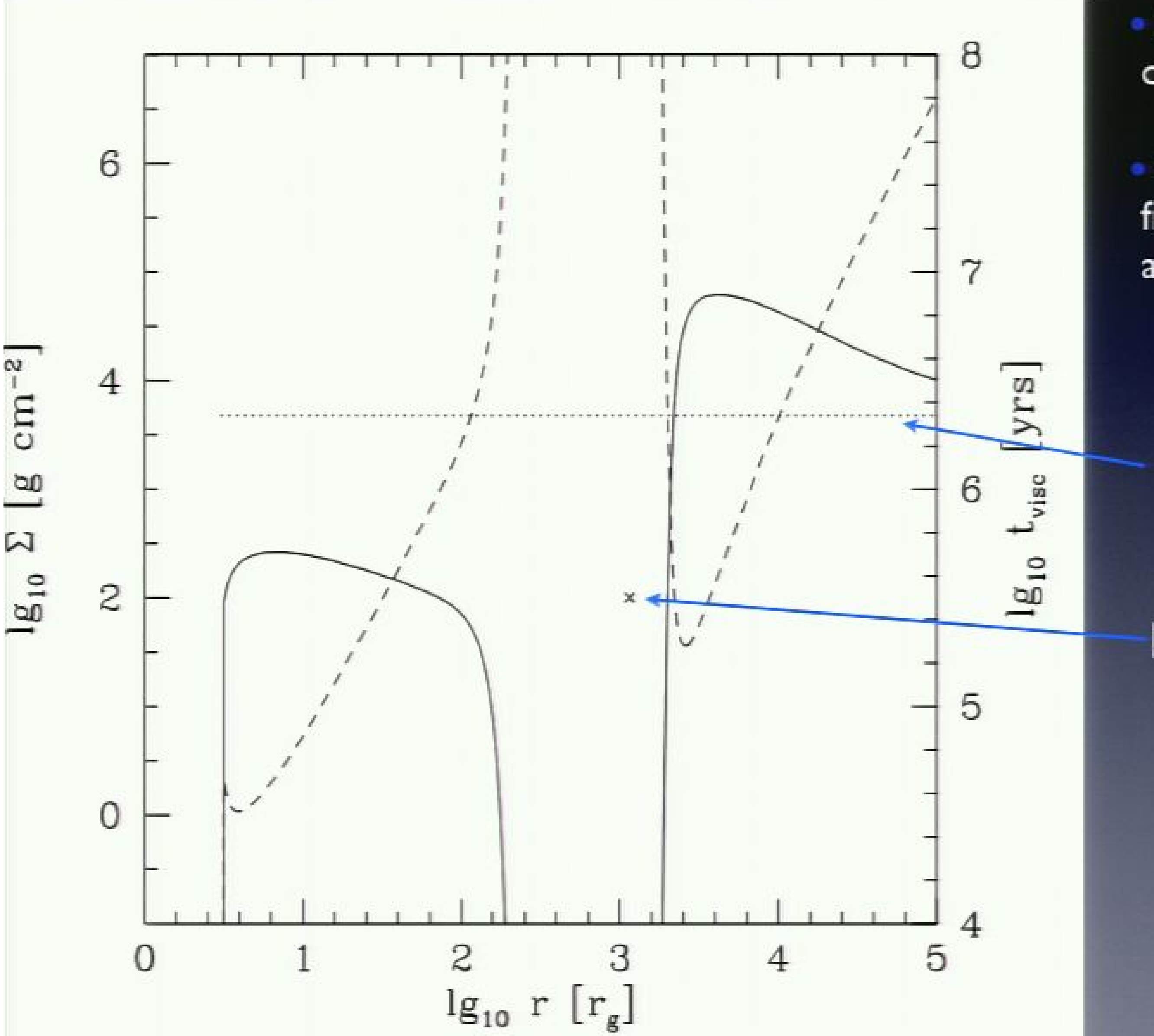
$$\frac{1}{2} M_{\rm sec}\Omega_{\rm sec} r_{\rm sec}\frac{\partial r_{\rm sec}}{\partial t} = T_{\rm d} - T_{\rm GW}$$

Angular momentum conservation in secondary BH



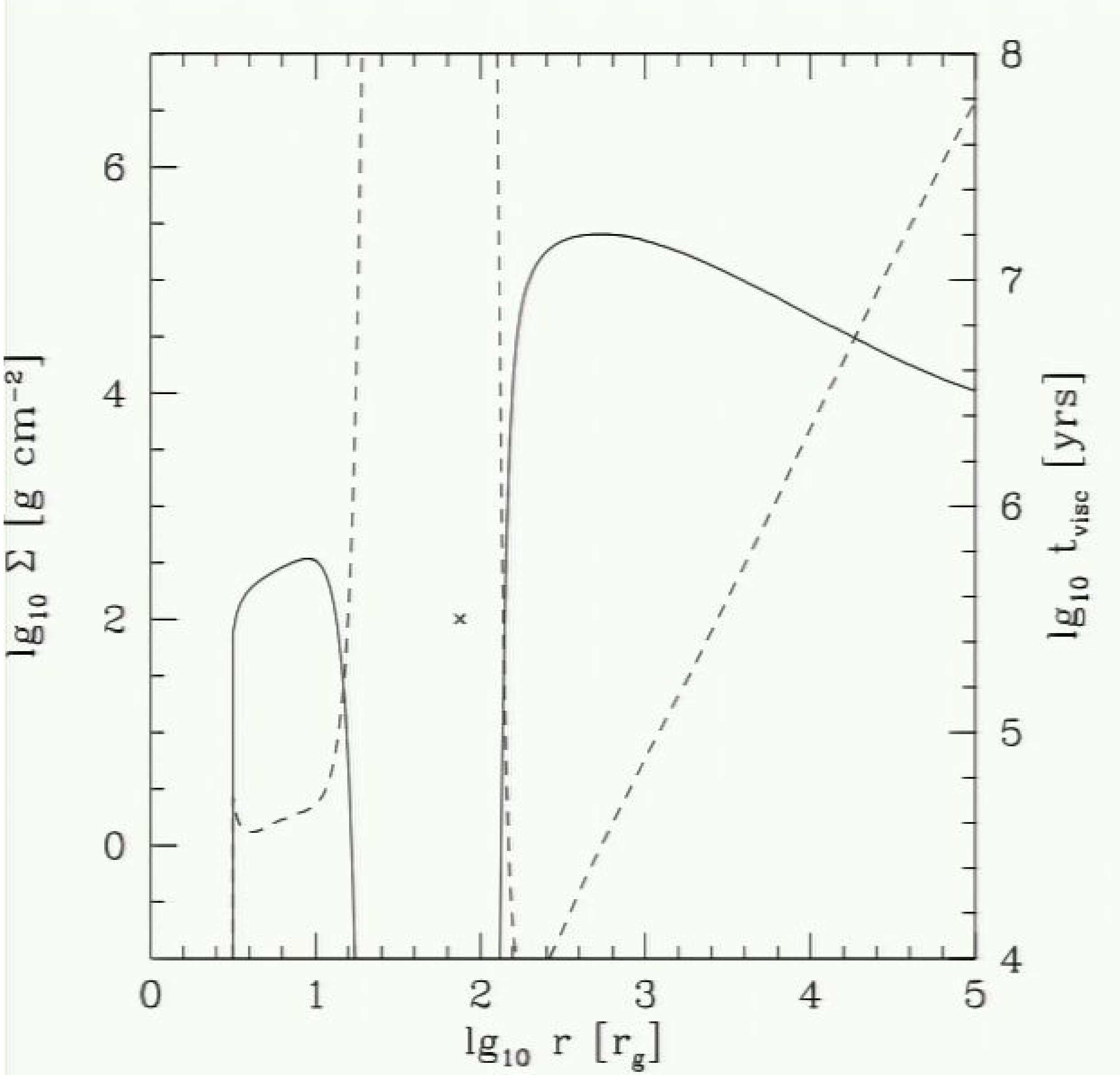
6
4
2
0
0
1
2
3
4
5
$\lg_{10} \Sigma$ [g cm^{-2}]
$\lg_{10} r$ [r_g]

Disk Evolution



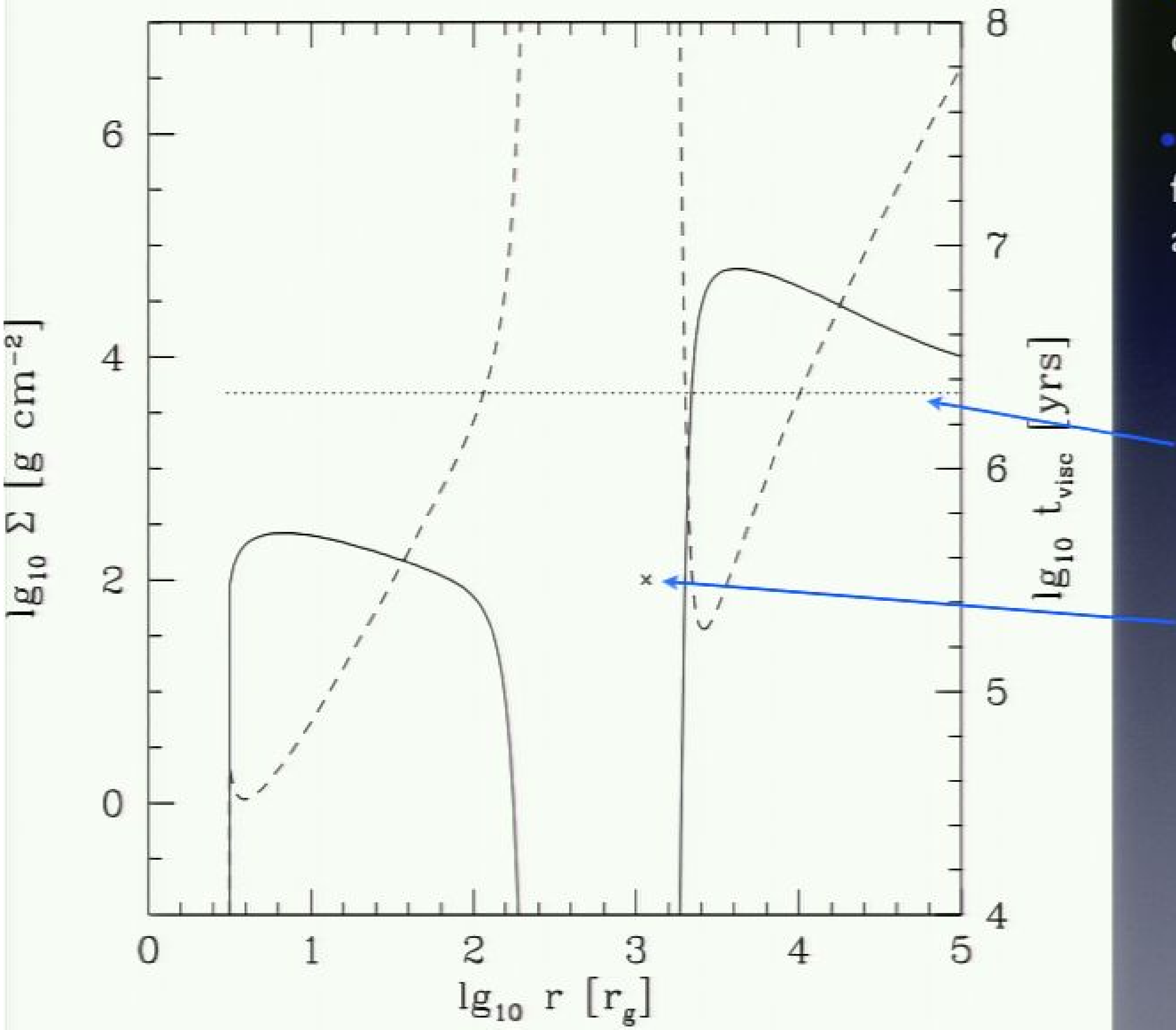
- Initial evolution driven by the outer disk's viscous evolution.
- inner disk evolves passively from one viscous equilibria to another.

Disk Evolution



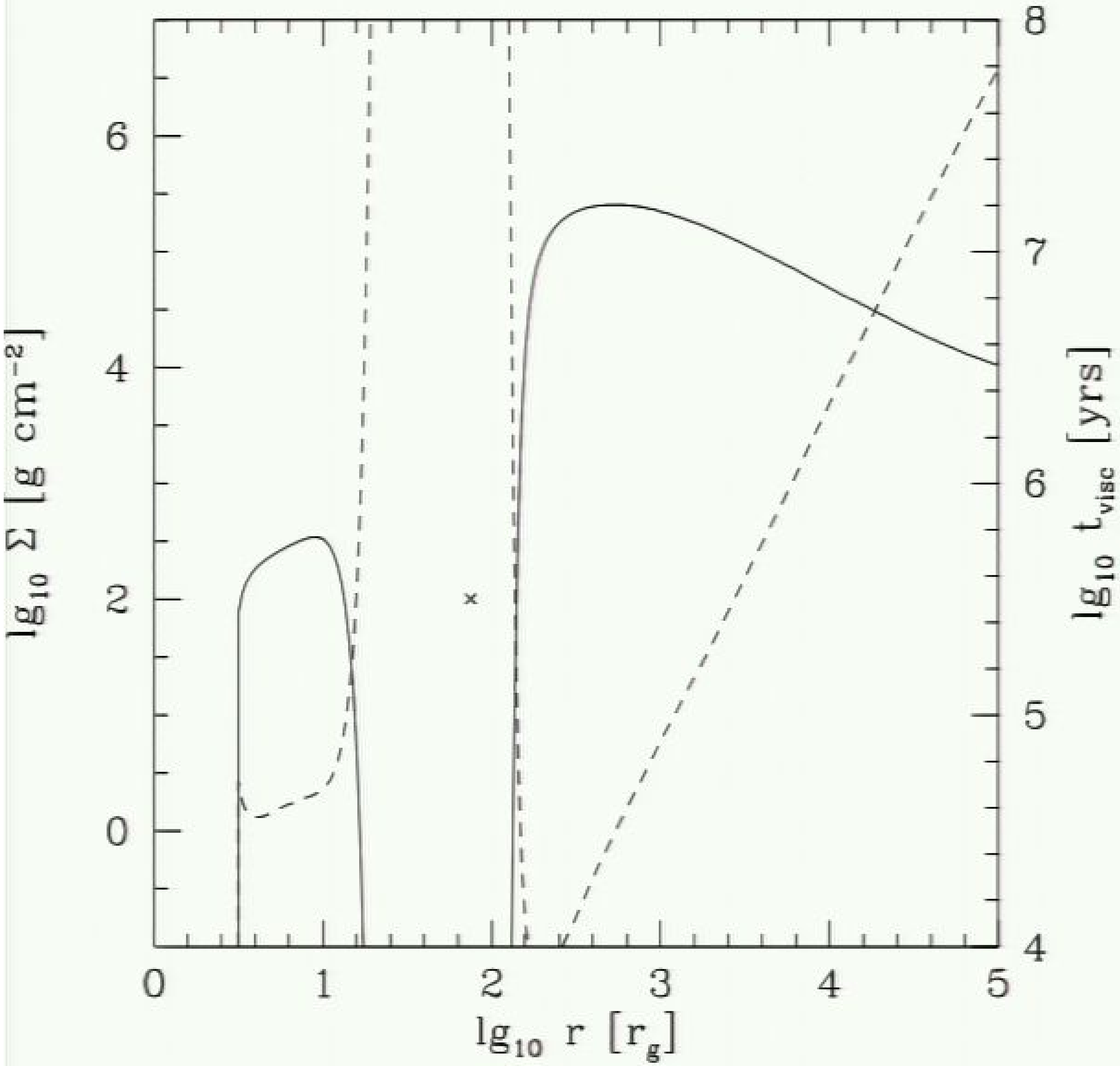
- Initial evolution driven by the outer disk's viscous evolution.
- inner disk evolves passively from one viscous equilibria to another.
- GW take over
- Inner disk no longer can respond viscously to the inspiralling BH

Disk Evolution



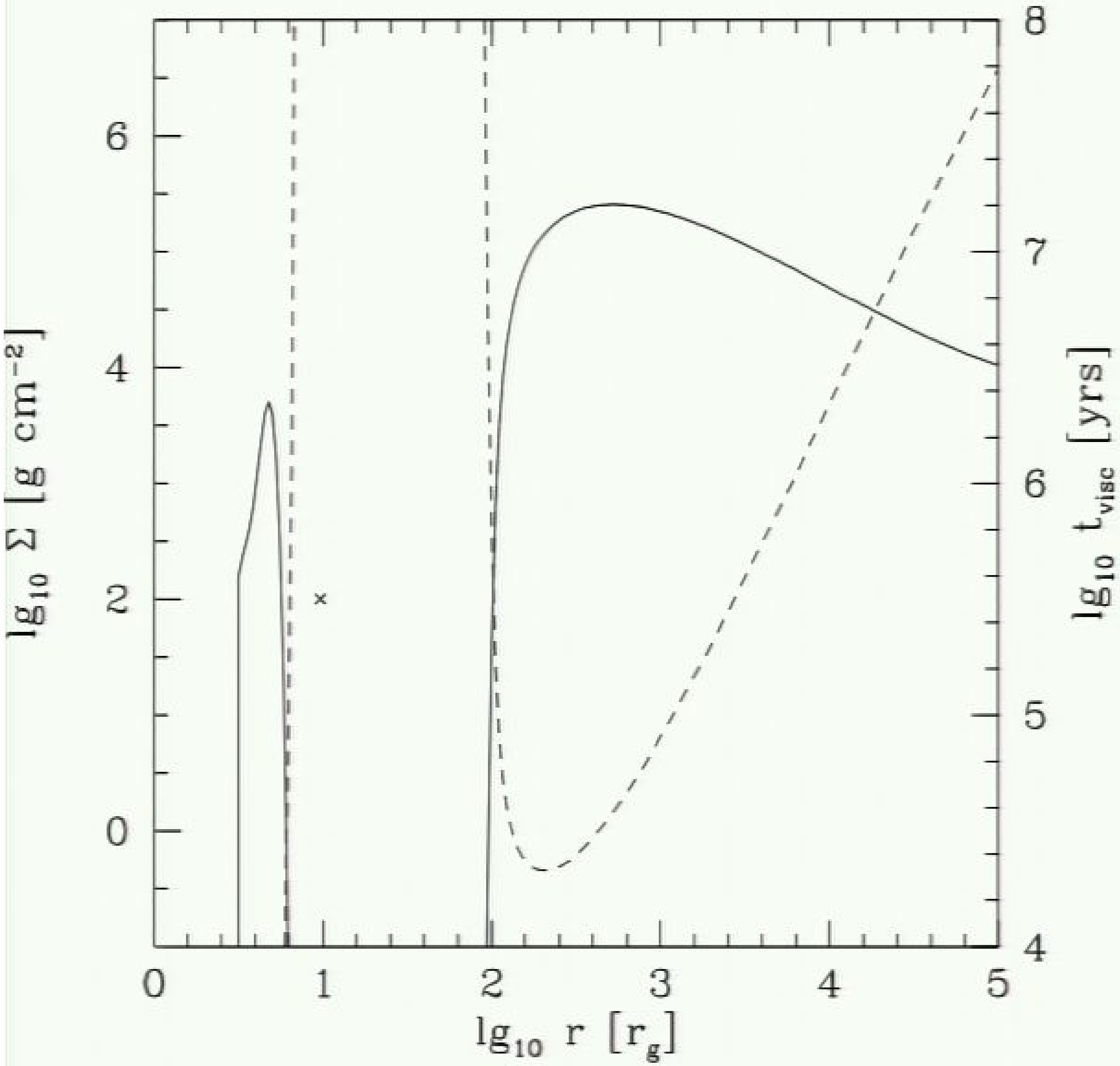
- Initial evolution driven by the outer disk's viscous evolution.
- inner disk evolves passively from one viscous equilibria to another.

Disk Evolution



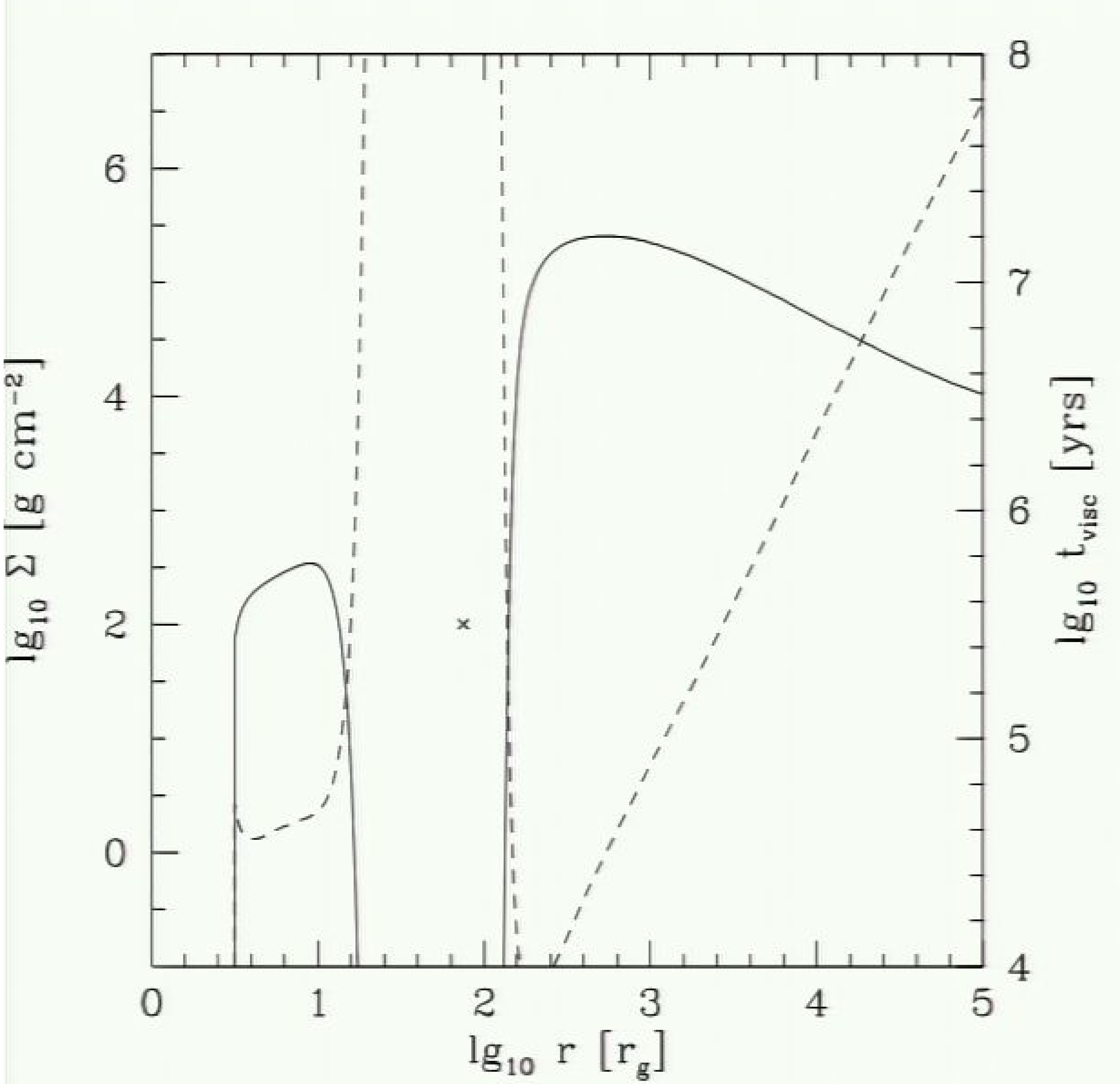
- Initial evolution driven by the outer disk's viscous evolution.
- inner disk evolves passively from one viscous equilibria to another.
- GW take over
- Inner disk no longer can respond viscously to the inspiralling BH

Disk Evolution



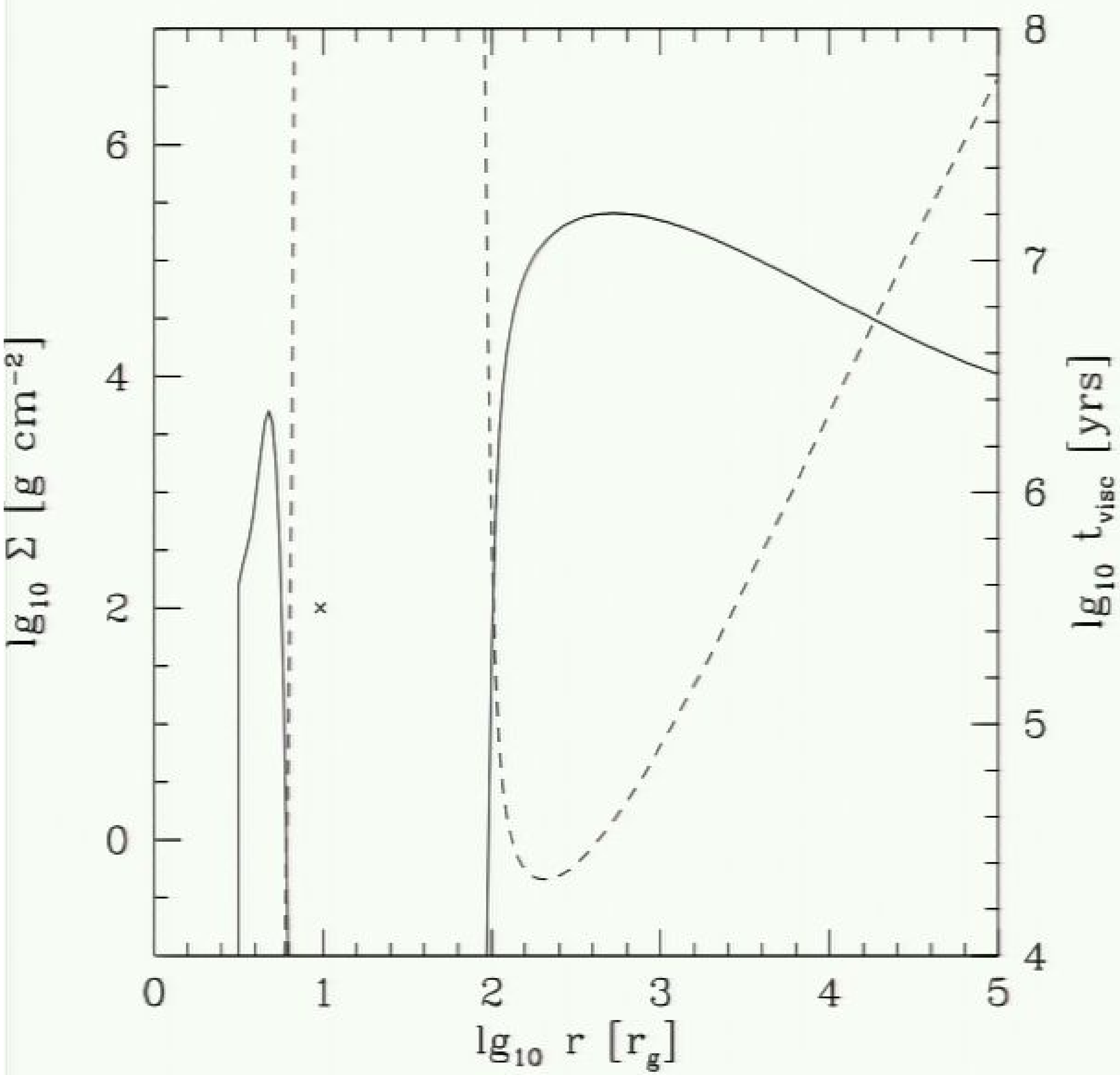
- Initial evolution driven by the outer disk's viscous evolution.
- inner disk evolves passively from one viscous equilibria to another.
- GW take over
- Inner disk no longer can respond viscously to the inspiralling BH
- Evolution is fast. Outer disk is effectively "frozen"
- Inner disk's evolution is driven completely by tides.
- HUGE luminosity from tidal forcing of inner disk BEFORE merger

Disk Evolution



- Initial evolution driven by the outer disk's viscous evolution.
- inner disk evolves passively from one viscous equilibria to another.
- GW take over
- Inner disk no longer can respond viscously to the inspiralling BH

Disk Evolution

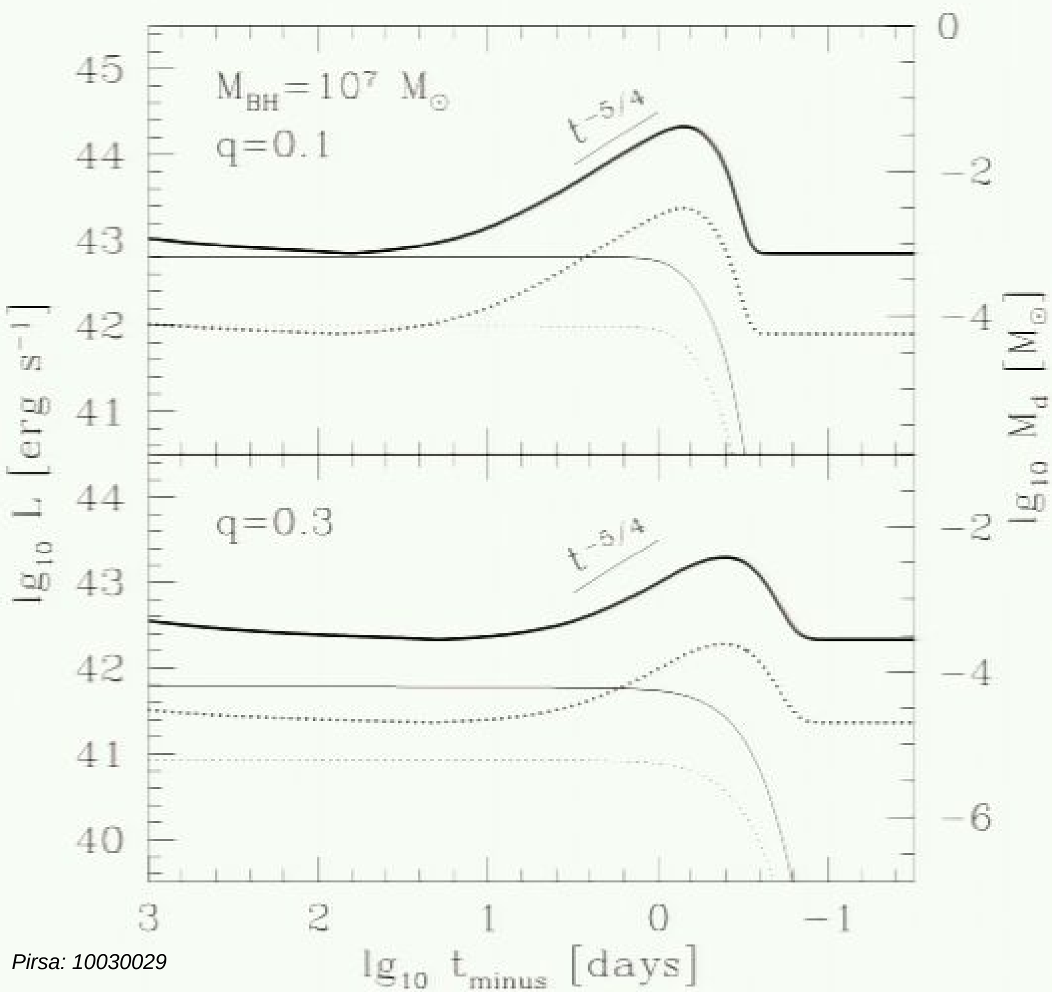


- Initial evolution driven by the outer disk's viscous evolution.
- inner disk evolves passively from one viscous equilibria to another.
- GW take over
- Inner disk no longer can respond viscously to the inspiralling BH
- Evolution is fast. Outer disk is effectively "frozen"
- Inner disk's evolution is driven completely by tides.
- HUGE luminosity from tidal forcing of inner disk BEFORE merger

Luminosity Evolution

scous evolution of outer disk

Tidal-forcing of inner disk

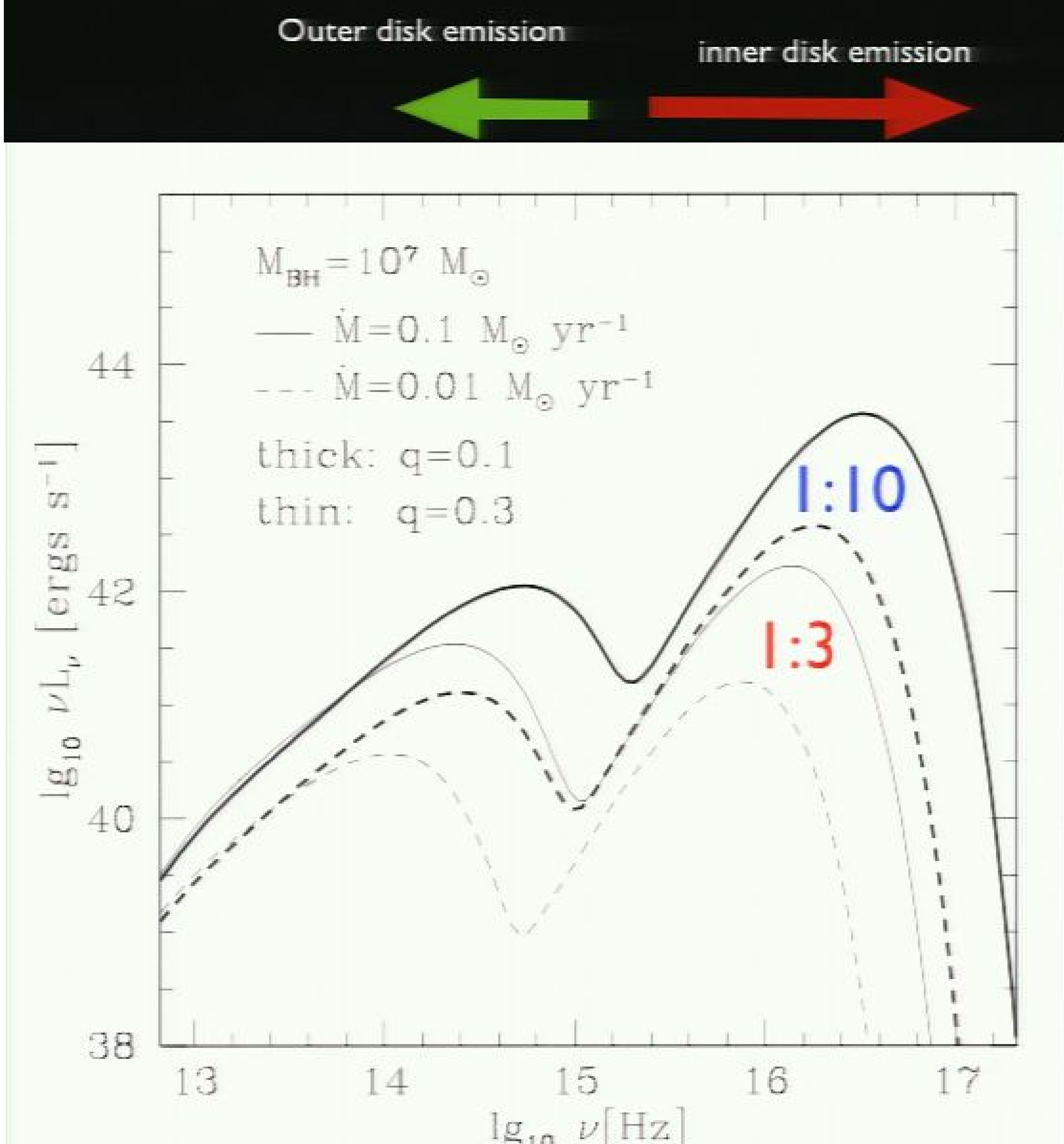


- Inner disk initially does not contribute to luminosity.
- As rate of inspiral increases, inner disk is forced to smaller and smaller radii.
- Dissipation of orbital energy gives a power-law rise in luminosity that peaks at ~ 1 day -- EM precursor.
- Characteristic power-law is given by:

$$t_{\rm merge} = \frac{5}{8}\frac{r_g}{c}\frac{M_{\rm BH}}{M_{\rm sec}}\left(\frac{r}{r_g}\right)^4$$

$$L = \frac{GM_{\rm BH}M_{\rm d}}{r}t_{\rm merge}^{-1} \propto t_{\rm merge}^{-5/4}$$

Peak Spectra

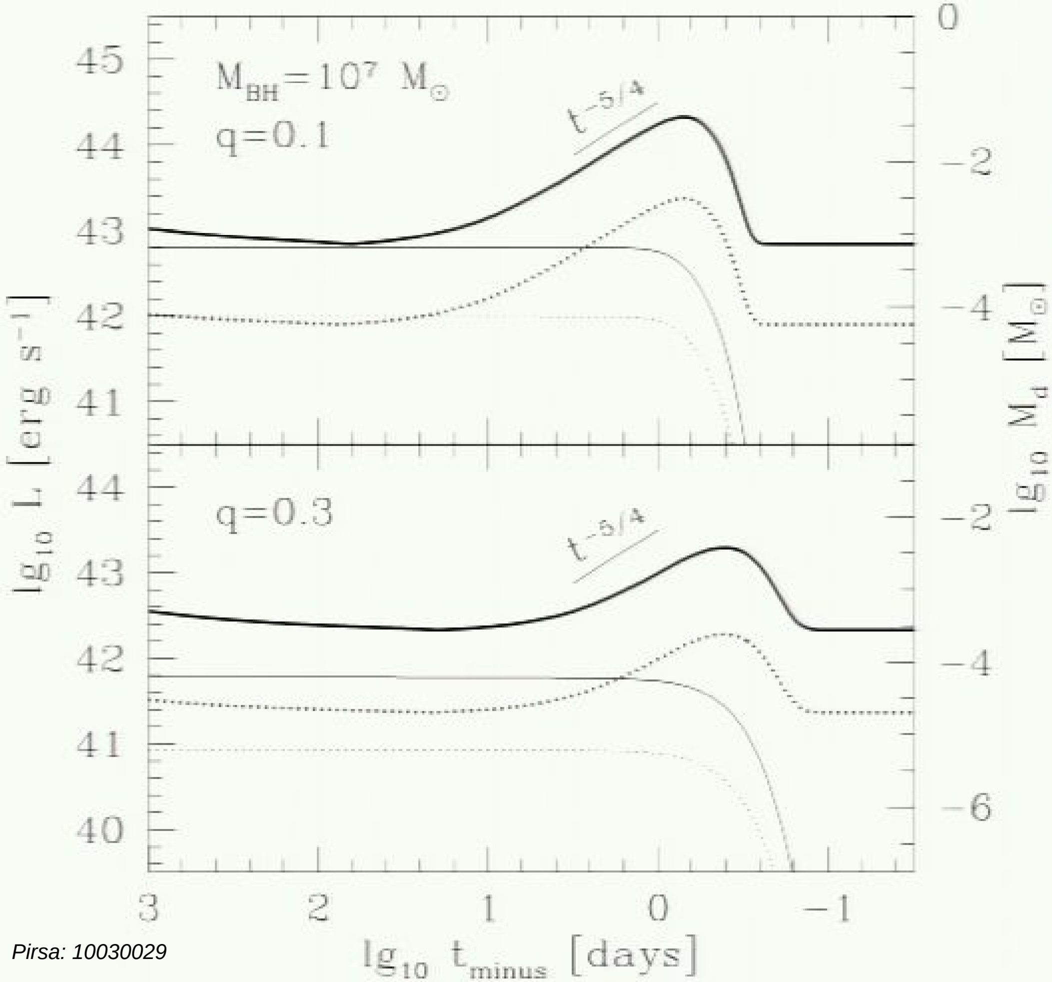


- Combination of inner disk and outer disk emission
- Inner disk Bright in the soft X-rays ~ 0.1 keV.
- Gap in the spectra is due to gap in the disk.

Luminosity Evolution

scous evolution of outer disk

Tidal-forcing of inner disk

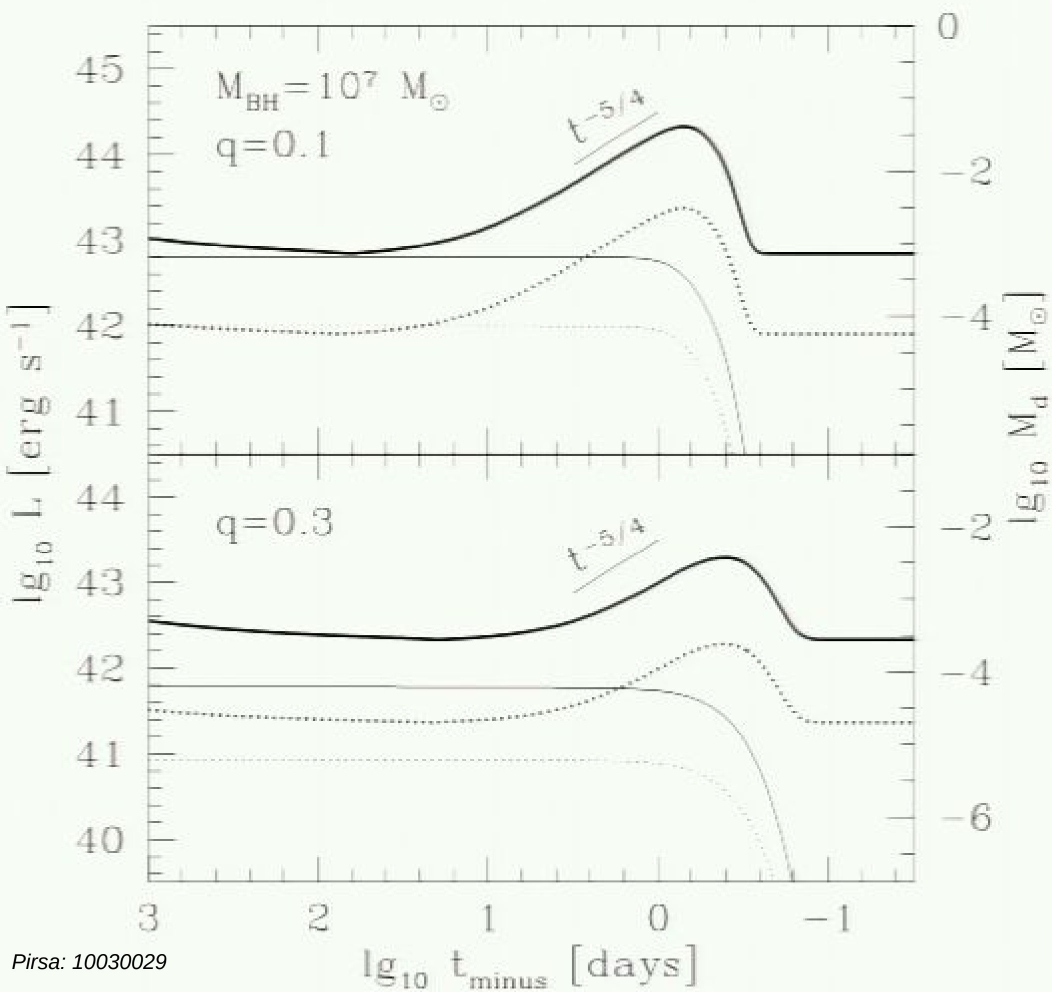


- Inner disk initially does not contribute to luminosity.
- As rate of inspiral increases, inner disk is forced to smaller and smaller radii.
- Dissipation of orbital energy gives a power-law rise in luminosity that peaks at ~ 1 day -- EM precursor.
- Characteristic power-law is given by:

$$t_{\rm merge} = \frac{5}{8}\frac{r_g}{c}\frac{M_{\rm BH}}{M_{\rm sec}}\left(\frac{r}{r_g}\right)^4$$

$$L = \frac{GM_{\rm BH}M_{\rm d}}{r}t_{\rm merge}^{-1} \propto t_{\rm merge}^{-5/4}$$

Luminosity Evolution

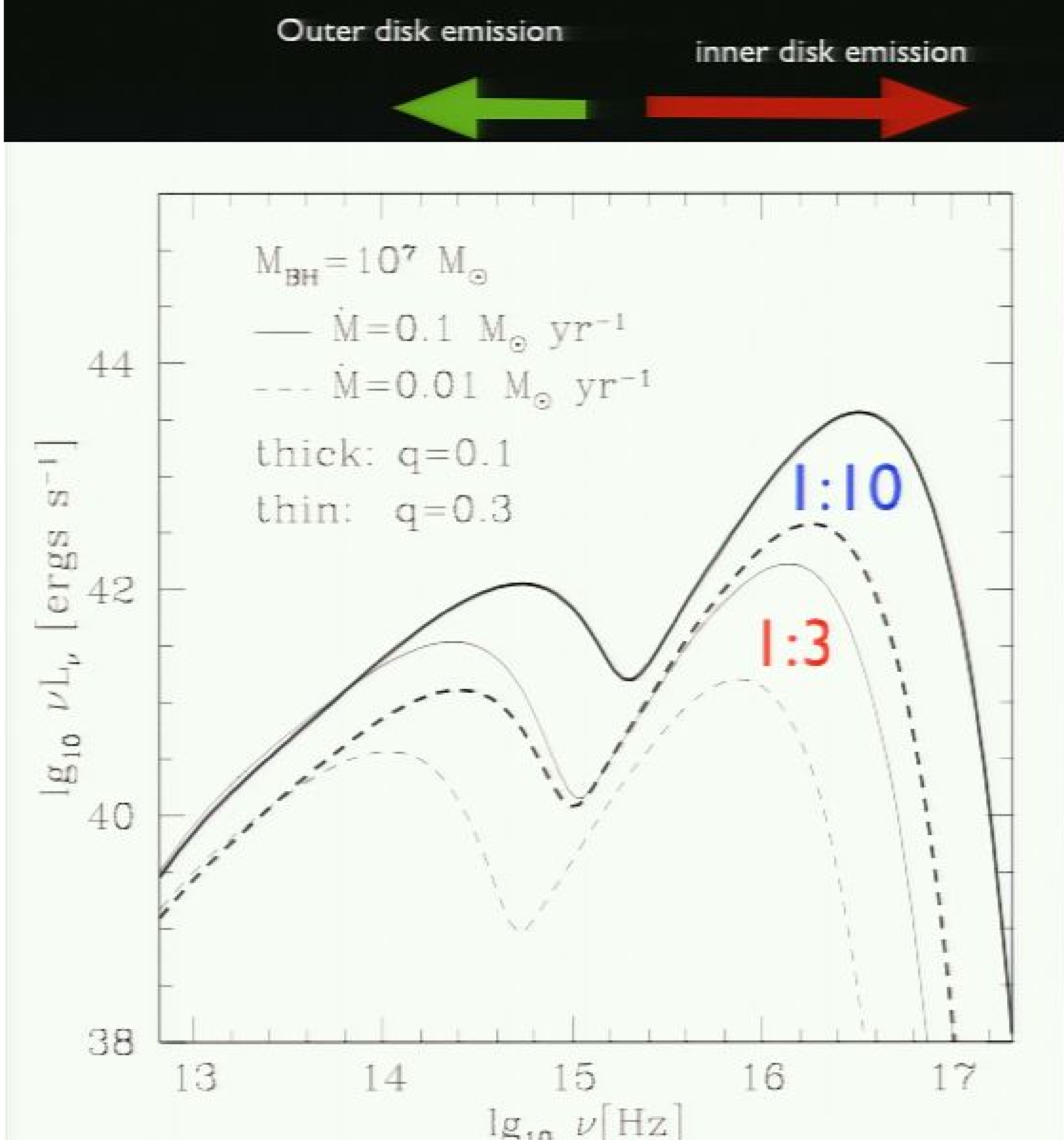


- Inner disk initially does not contribute to luminosity.
- As rate of inspiral increases, inner disk is forced to smaller and smaller radii.
- Dissipation of orbital energy gives a power-law rise in luminosity that peaks at ~ 1 day -- EM precursor.
- Characteristic power-law is given by:

$$t_{\rm merge} = \frac{5}{8}\frac{r_g}{c}\frac{M_{\rm BH}}{M_{\rm sec}}\left(\frac{r}{r_g}\right)^4$$

$$L = \frac{GM_{\rm BH}M_{\rm d}}{r}t_{\rm merge}^{-1} \propto t_{\rm merge}^{-5/4}$$

Peak Spectra



- Combination of inner disk and outer disk emission
- Inner disk Bright in the soft X-rays ~ 0.1 keV.
- Gap in the spectra is due to gap in the disk.

Electromagnetic Precursors

- Presence of an inner accretion disks -- accretion physics.
- tidal forcing of the inner disk -- periodic signal that can be unambiguously identified the LISA source.
- Rising lightcurve with $t_{\rm merge}^{-5/4}$ can be directly identified as a result of tidal forcing

Unanswered Questions

1. How clean is the gap?

2. Are there direct modes of the accretion which can boost up the mass.

3. Reprocessing of the precursor flare. i.e. soft X-ray to optical/IR radiation.

The Future

- Better numerical computations.

- There are other possibilities for EM counterparts.

- Much work has been done on optical/X-ray counterparts. Less work has been done on radio counterparts e.g. Bode et al 2009.

Conclusions

- Observations of GW from merging BHs will teach us much about the physics but astrophysics will need EM counterparts.

- Different Stages of Black Hole mergers will give different EM signatures.

- EM signatures from kicks and precursor offer hope for identification if there is gas.

- Much work remains to be done.