Formation & evolution of galaxies & SMBHs

Cedric Lacey

Durham University

Outline of lectures

1. Structure formation & assembly of dark halos
2. Gas cooling & angular momentum
3. Star formation & feedback
4. Galaxy mergers & morphologies
5. Cosmic evolution of galaxies
6. Formation of black holes
7. BH binaries & spin
8. Co-evolution of galaxies & AGN

Lecture 7:
SMBH binaries & spin

Further reading for lecture 7

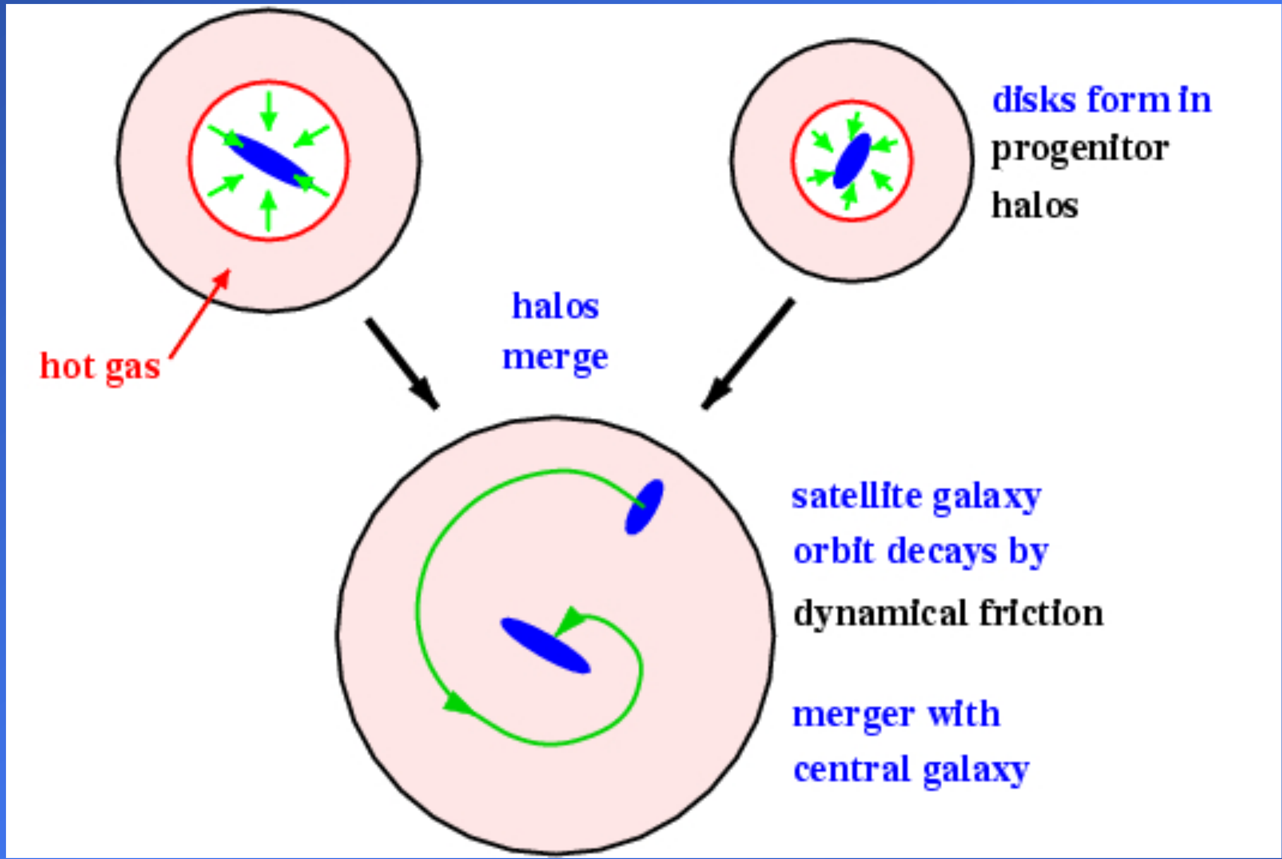
- Single & binary black holes & their influence on nuclear structure by David Merritt (extended version at arXiv:astro-ph/0301257, 2003)
- Evolution of massive black hole spins by Marta Volonteri (arXiv:1002.3827, 2010)

Lecture 7 outline

- SMBH binaries & SMBH spin
  - SMBH binaries & mergers
  - gravitational radiation & recoil
  - origin of SMBH spin through gas accretion & mergers

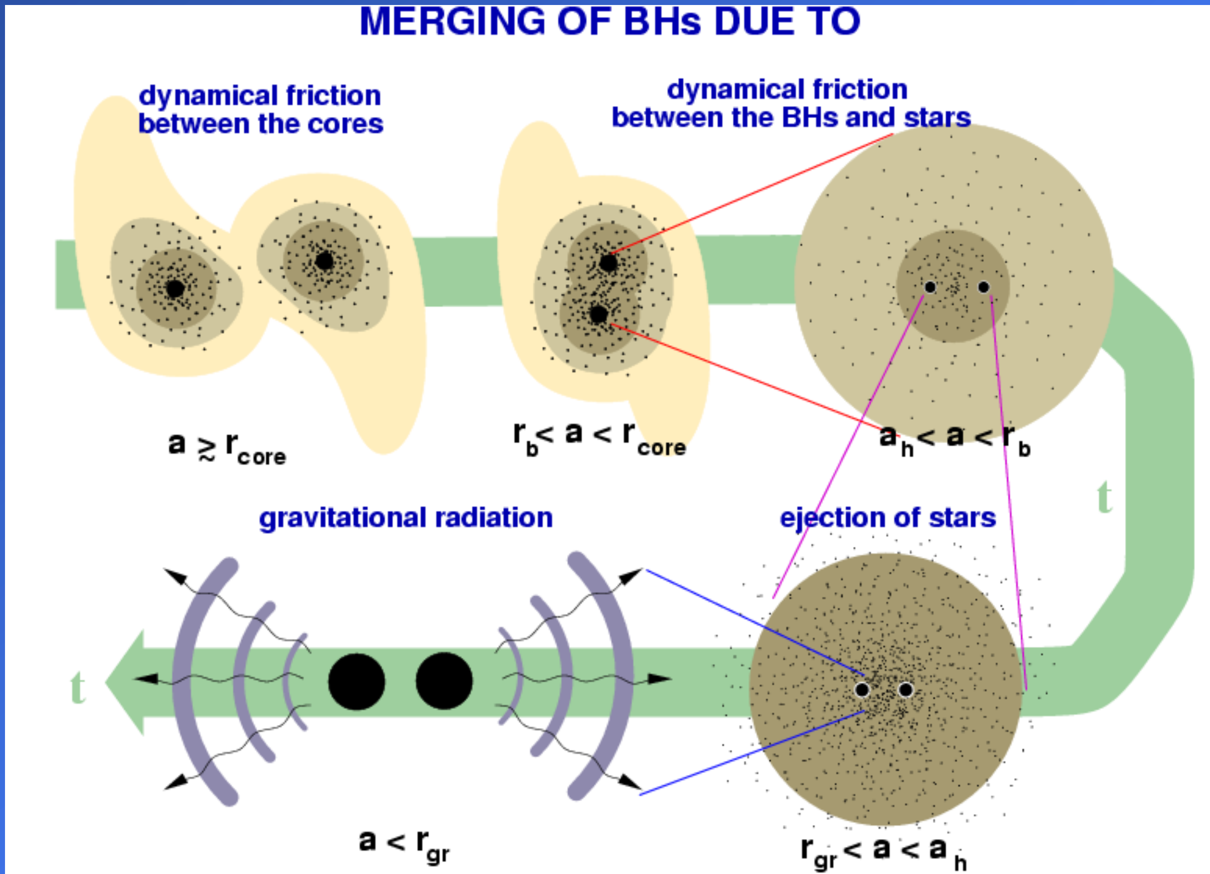
SMBH mergers

Merging of central BHs in galaxies - galaxy merger



- BH merger in multiple stages:
  - DM halos merge (structure formation)
  - galaxies merge in common halo (dynamical friction against halo)

Merging of central BHs in galaxies
- BH-BH merger within galaxy nucleus



different processes dominate on different scales:
- dynamical friction of BH against stars
- dynamical friction of BH in gas disk
- gravitational radiation

Dynamical friction against stars & loss cone

- dynamical friction against stars, orbits shrink on timescale

$$t_{fric} = \frac{1.17}{\ln \Lambda} \frac{r^2 V_c}{G M_{BH}} = \frac{1.17}{\ln \Lambda} \frac{M(< r)}{M_{BH}} t_{orb}$$

- effective until BH binary becomes self-gravitating at separation:

$$a_b = \frac{G(M_1 + M_2)}{2\sigma^2}$$

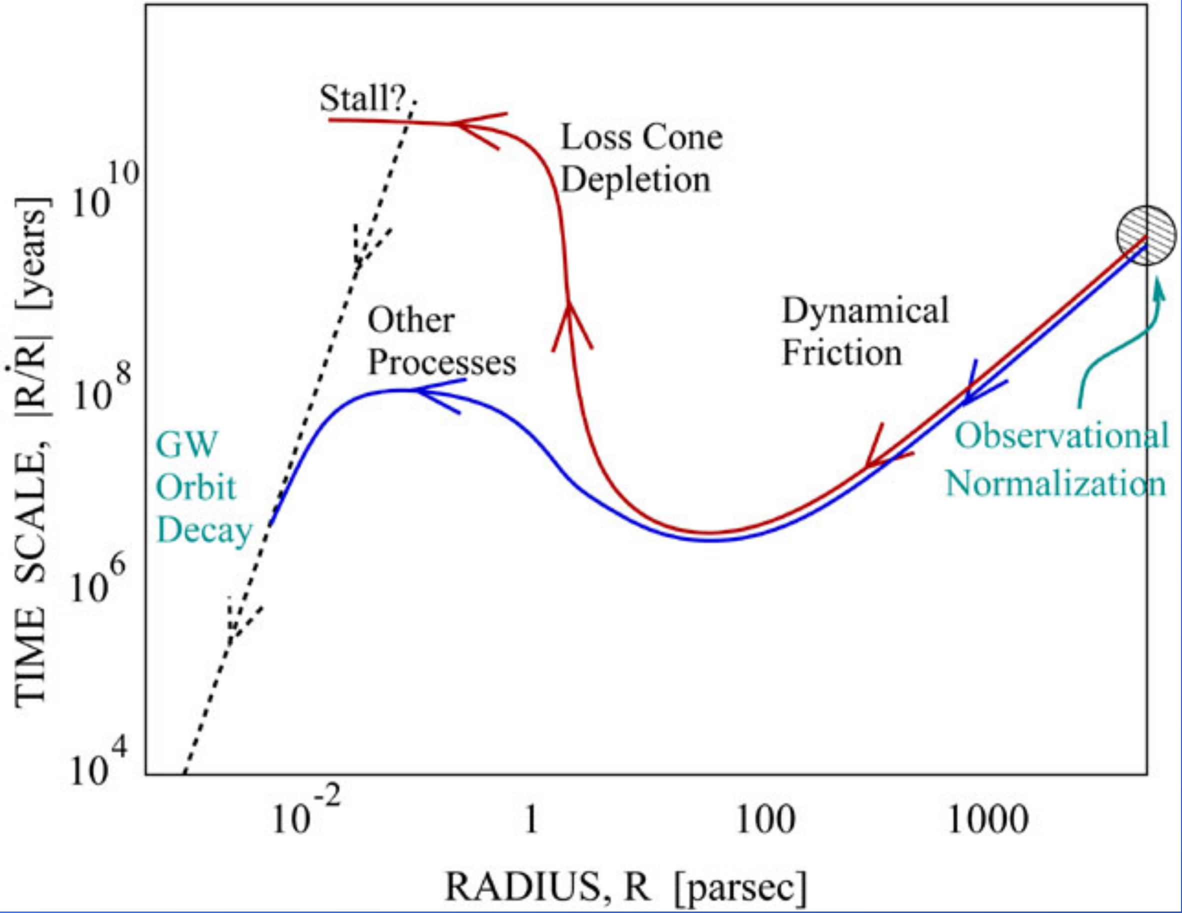
where σ = velocity dispersion of stars

- following this, BH binary hardens ($V>\sigma$), further shrinkage is due to 3-body interactions (BH+BH+star) , on timescale (where H~15):

$$t_h = \frac{\sigma}{G \rho_\star a H}$$

- however, this results in ejection of stars on orbits taking them close to binary – "loss cone" – so orbit shrinkage timescale becomes v. long

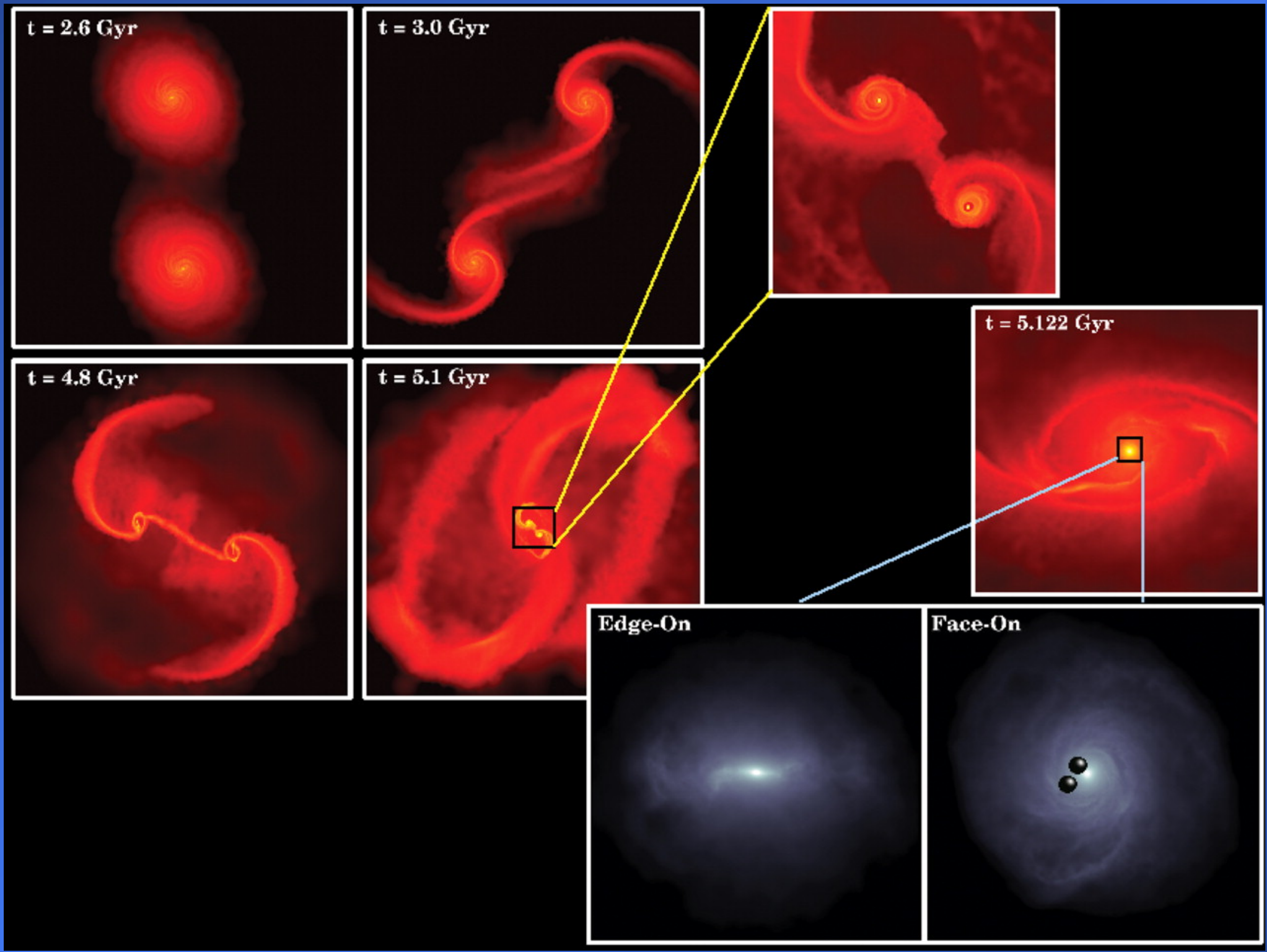
Evolution of BH binary separation



Role of gas in BH mergers

- loss cone effects may cause orbital shrinkage of BH binary to stall before reaches separation at which GW loss effective
- BH drag against gas may play crucial role
- obs => massive self-gravitating gas disks at centres of many merging galaxies
- BH moving through gaseous disk gravitationally excites wake in gas which exerts orbital drag on BH, similar to dynamical friction from stars
- unlike stars, gas dissipates energy so not ejected by BH interaction
- can cause BH orbits to shrink rapidly

simulation of merger of 2 galaxies containing black holes & gas



two $3x10^6M_o$ BHs followed to separation ~ 1pc
- merge in nuclear gas disk M~ $3x10^9M_o$, r~80pc

Mayer etal 2007

Gravitational radiation

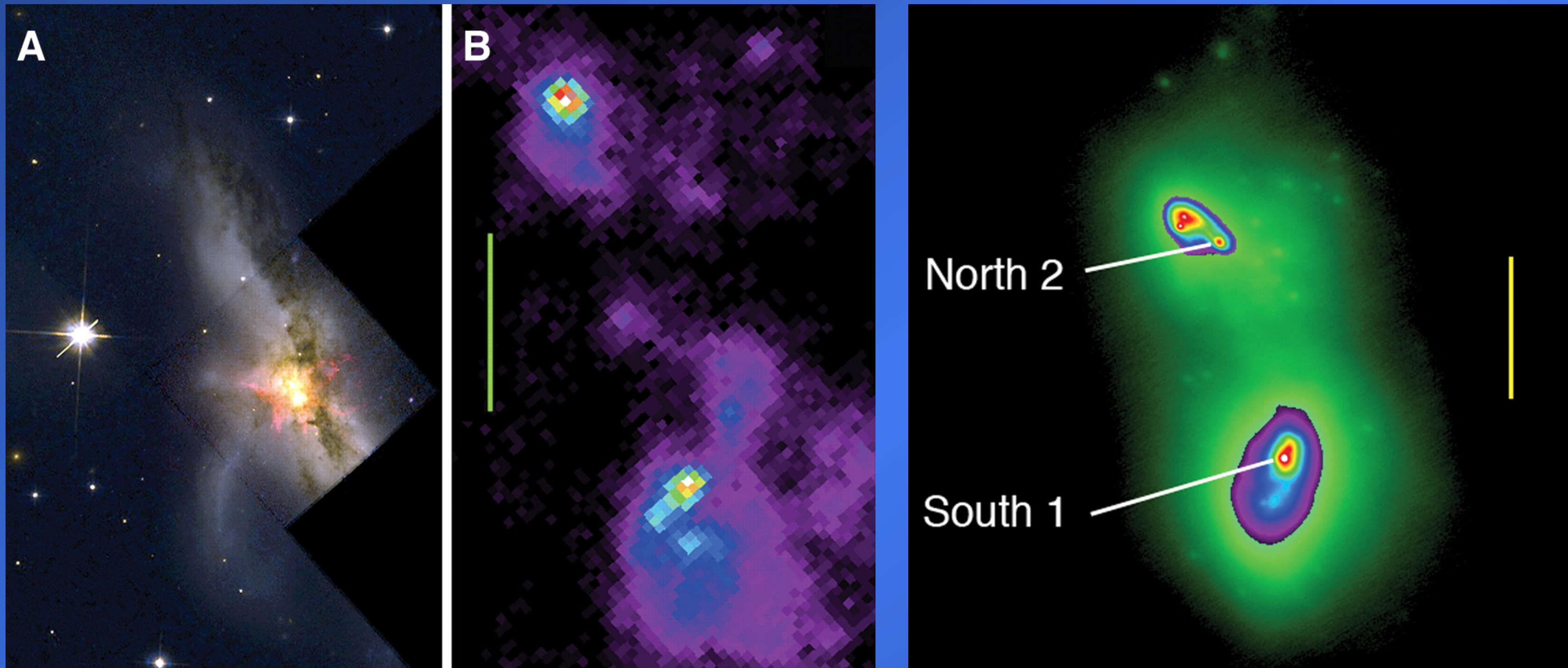
- emission of gravitational waves from BH binary carries away energy & angular momentum, causing orbit to shrink on timescale:

$$t_{\rm GR} = \frac{5c^4a^4}{256G^3M_1M_2(M_1+M_2)}$$

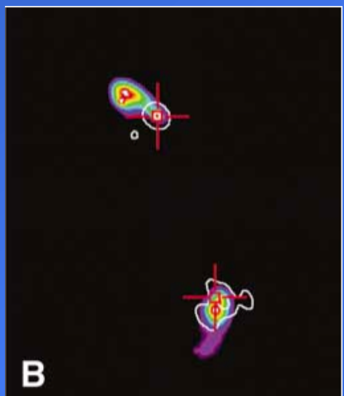
- NB strong dependence on binary separation
- v.slow at first, but final stages v. rapid

Observational evidence for binary BHs

optical | optical (zoom) | K-band (zoom)

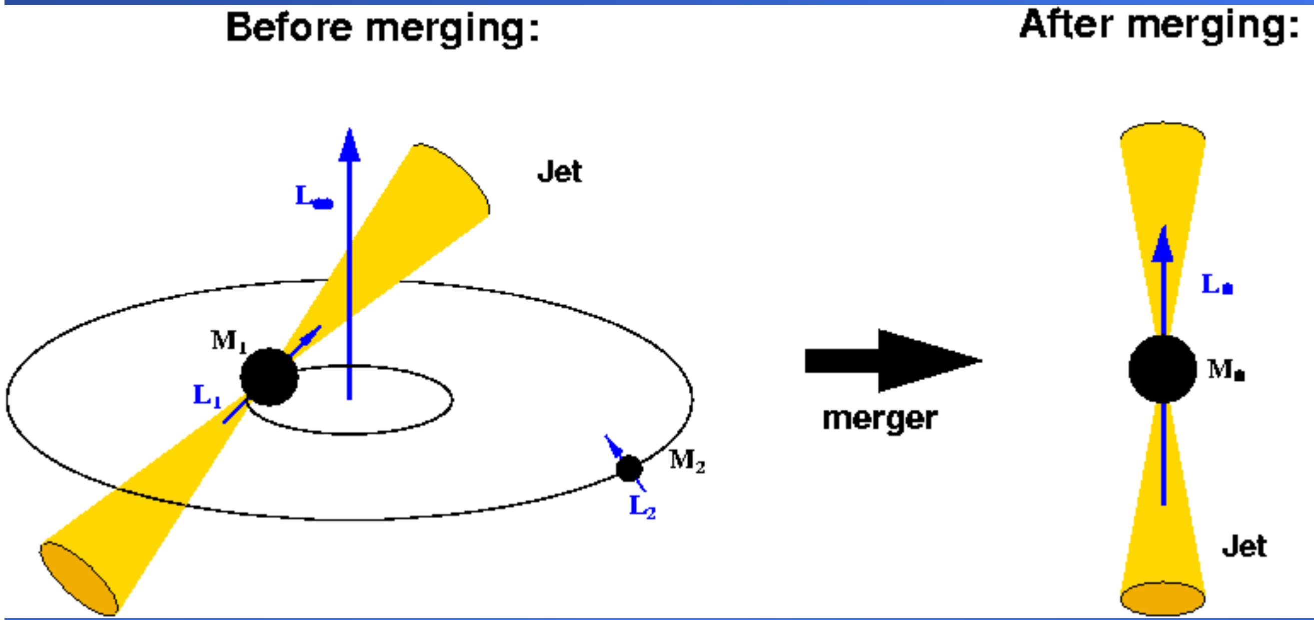


Max etal 2007

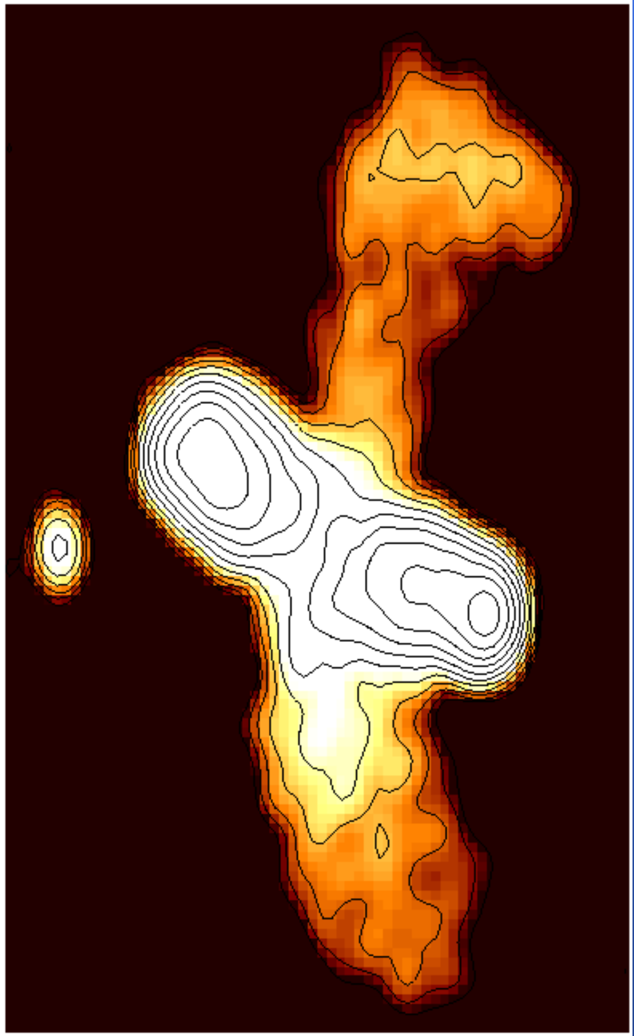


- NGC 6240: merger of 2 spiral galaxies
- double stellar nucleus seen in optical & K-band, sepn ~ 800 pc
- each nucleus hosts AGN seen radio & X-rays
- each AGN surrounded by dust disk, seen in mid-IR

Observational signature of BH mergers



B2 0828+23 (608 MHz)



(Parma et al., 1985; Rottmann 2000)

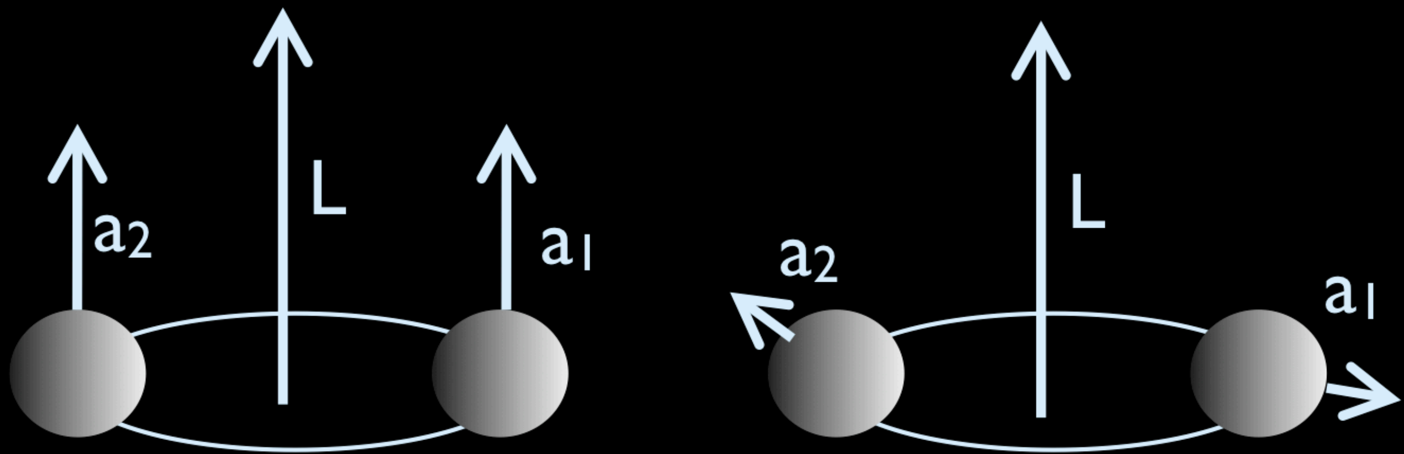
sudden change of spin axis of BH due to BH-BH merger => change in direction of radio jet

Gravitational radiation & BH recoil

BH recoil from gravitational radiation

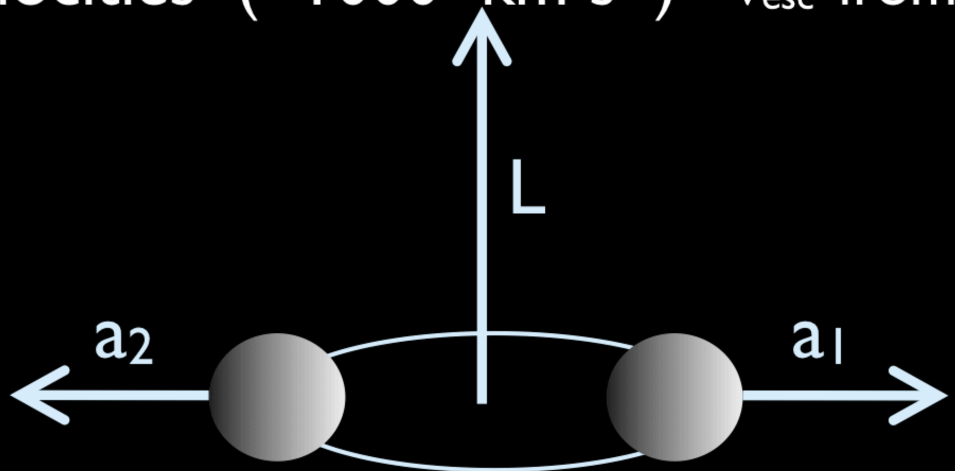
- final in-spiral of BH binary due GW emission very rapid => anisotropic distribution of GW emission
- but GWs carry momentum => BH formed by BH-BH merger has recoil velocity
- V_{rec} depends strongly on mass ratio $q=M_2/M_1$ & on BH spins & orientations
- max V_{rec} for $q\sim0.4$, V_{rec} small for $q<<1$
- non-spinning BHs: V_{rec} up to ~ 200 km/s
- spinning BHs: V_{rec} up to ~ 3000 km/s
  - depends on alignment of spins rel to orbital plane:
  - aligned or anti-aligned with orbital axis => low V_{rec}
  - spins in opposite dirns in orbital plane => high V_{rec}

Recoiling MBHs

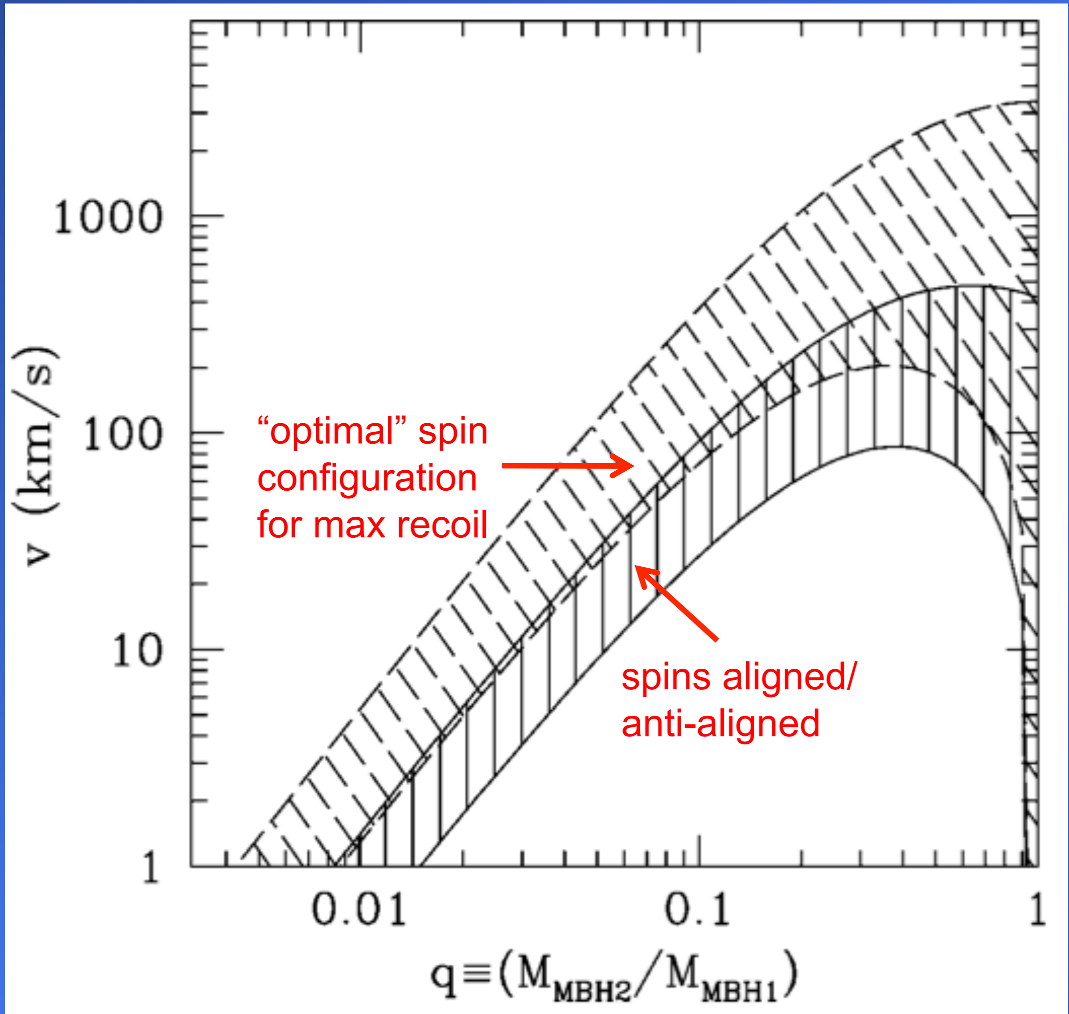


Low kick velocities (~100 km s^{-1}) ~v_{esc} from high-z galaxies

High kick velocities (~1000 km s^{-1}) ~v_{esc} from today's galaxies



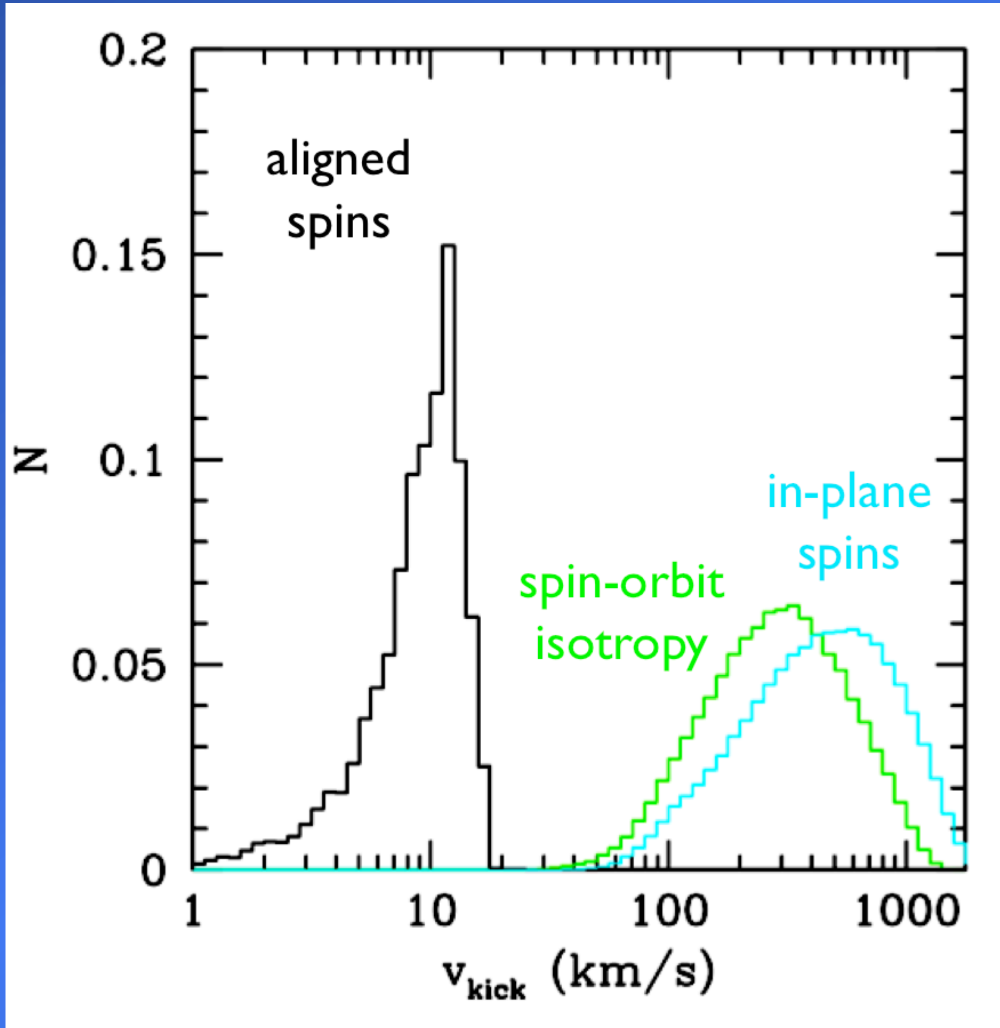
Recoil velocities in BH mergers



results based on results of GR simulations of merging BHs

Volonteri 2007

Distribution of kick velocities



results from theoretical model for BH formation & merging, for different assumptions about alignmnet of spins

Volonteri 2009

Consequences of GW recoil for SMBH growth

- GW recoil can eject merging BHs from halo if $V_{rec}>V_{esc}$, preventing buildup of SMBHs by multiple mergers
- recoil largest when merging BHs have similar masses
- potentially serious problem for SMBH growth from Pop III remnants, since these form in halos with very low V_c (=> low V_{esc}) which then merge
- also problem for BH seeds formed in dense star clusters, since cluster has low V_{esc}
- lesser problem for massive BH seeds fomed in larger halos, since V_{esc} larger & equal mass BH mergers less likely

Spin directions of merging BHs

- orientation of BH spins in merger relative to orbital plane depends on whether BHs brought together by dynamical friction against stars or against gas disk
- stars => isotropic distribution of BH spins
- gas disk => BH spins may become aligned with ang momentum of gas disk, if BHs have accretion disks (effect of gravitational torques)

Origin of SMBH spin

Dimensionless spin parameter: $a = cJ_{BH} / GM_{BH}^2$

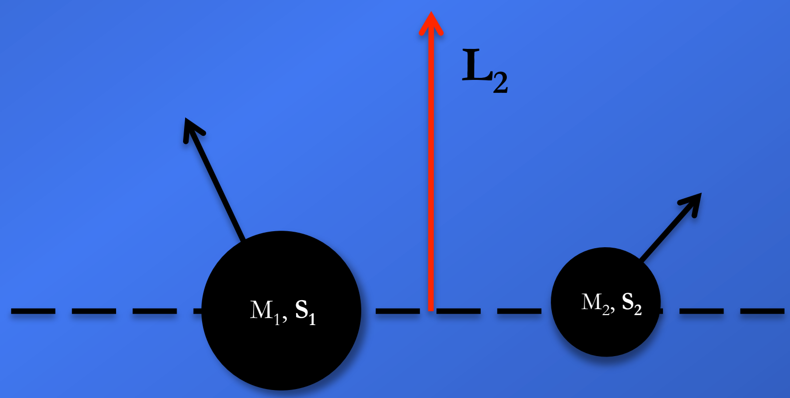
$$0 \le a \le 0.998 : \begin{cases} a = 0 \rightarrow \text{Schwarzschild BH} \\ a = 0.998 \rightarrow \text{Maximally rotating BH} \end{cases}$$

Growth of mass & angular momentum of black holes

- main processes for growing mass of BHs are:
  - BH-BH mergers
  - accretion of gas from an accretion disk
- both of these also effective at changing angular momentum

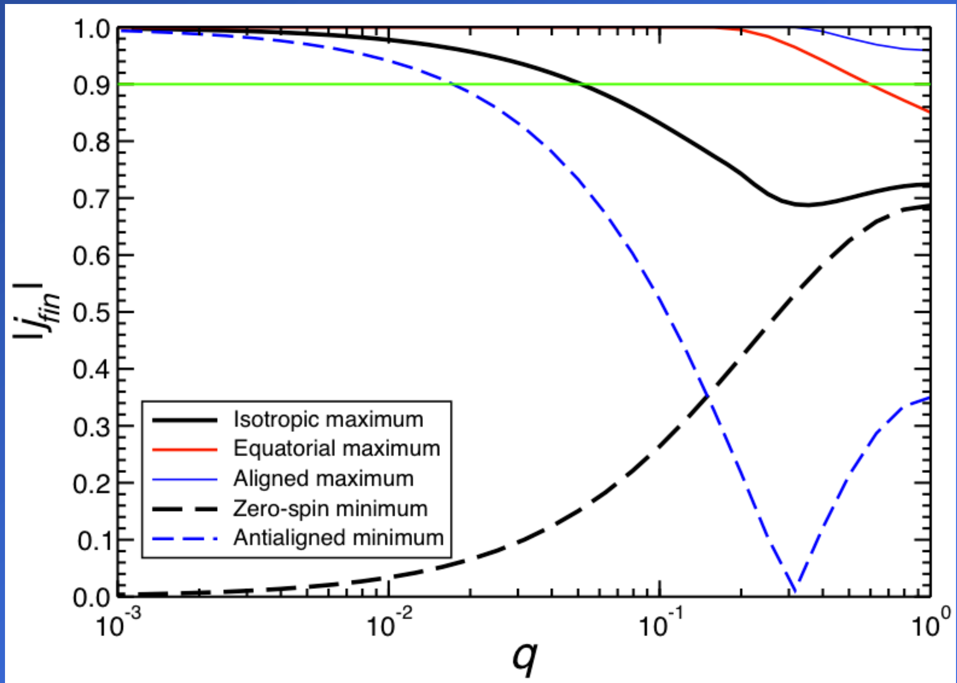
Change of spin in BH-BH mergers

- Binary BHs form during galaxy mergers
- The binary hardens due to emission of gravitational waves
- During the merger the satellite BH transfers its orbital angular momentum and spin to the central BH
- The final remnant is always a rotating BH



Spin in BH-BH mergers

final BH spins averaged over initial spins & angles



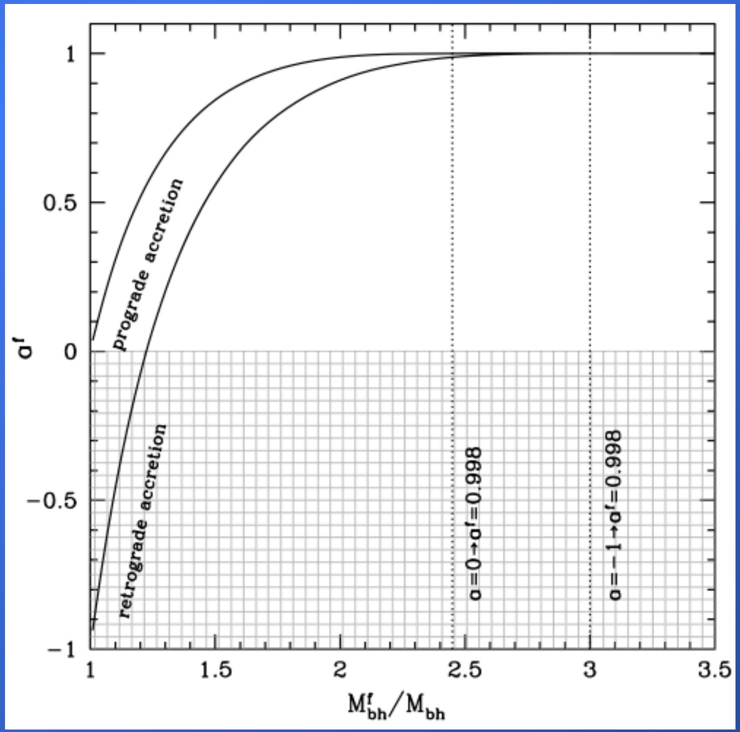
Berti & Volonteri 2008

- final spin depends on $q=M_2/M_1$, on spins of both BHs, and on orientation of spins relative to orbital ang mtm
- merge equal mass non-spinning BHs -> a=0.69
- equal-mass maximally spinning BHs with spins aligned with orb ang mtm -> a=0.96
- isotropic distribns of spins -> lower average final spins

- aligned spins => v.rapidly rotating BHs (a>0.9)
- isotropic spins:
  - major merger (q~1) => moderate rotation – typical a~0.7
  - many minor BH mergers (q<<1) => low spin

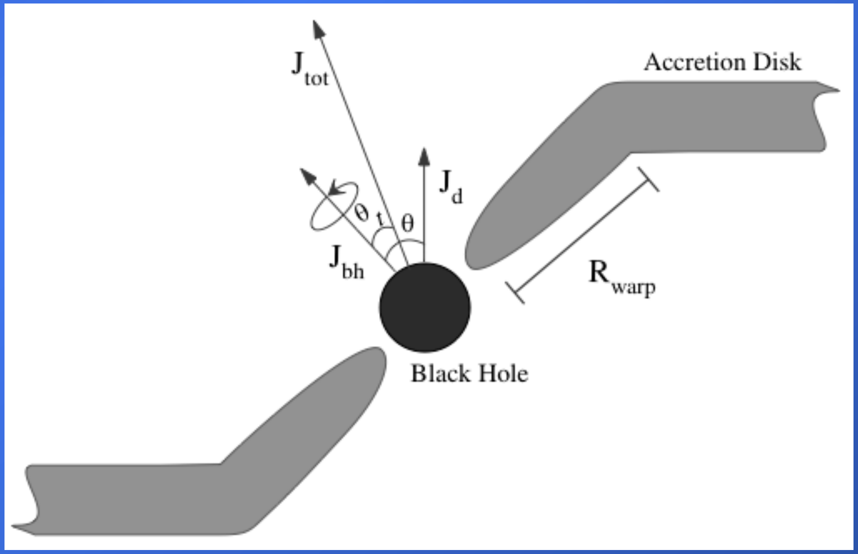
Change of BH spin by gas accretion

- Gas accreted via an accretion disk transfers its angular momentum at the last stable orbit to the BH
- Co-rotating gas – spin up
- Counter-rotating gas – spin down
- gas accretion very effective at changing spin:
  - non-rotating BH gets spun up to max rotation (a=0.998) after increasing mass by factor 2.44
  - maximally rotating BH in counter-rotating disk gets spun down to a=0 after increasing mass by factor 1.22



Alignment of BH spin with accretion disk

- Lens-Thirring torque (GR effect) + accretion disk viscosity -> align or anti-align inner accretion disk with BH
- grav torque of outer disk on inner -> BH spin eventually aligns with angular momentum of outer accretion disk (if $J_{disk} > 2J_{BH}$)
  - -happens rapidly for thin accretion disk
  - - more slowly for thick disk



Evolution of BH spin for accreting BH (A) Prolonged/coherent accretion

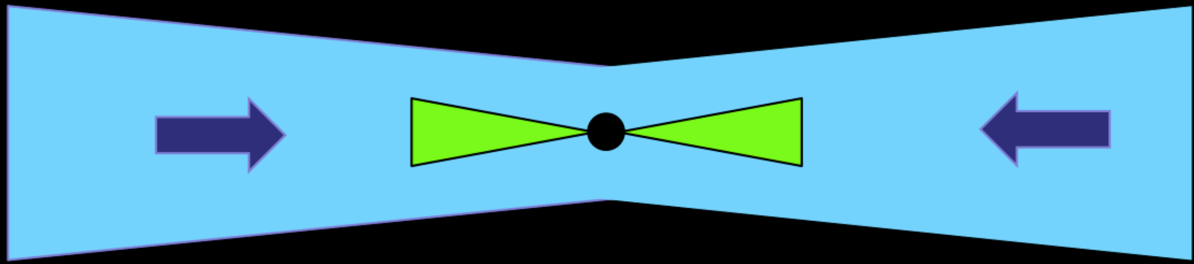
- PROLONGED accretion of gas (leading to M_{BH} increasing by factor >2-3) from gas disk which maintains CONSTANT orientation should therefore lead to maximally spinning (a=0.998) BH aligned with accretion disk

  => BHs which grow mainly by coherent gas accretion should be very rapidly spinning

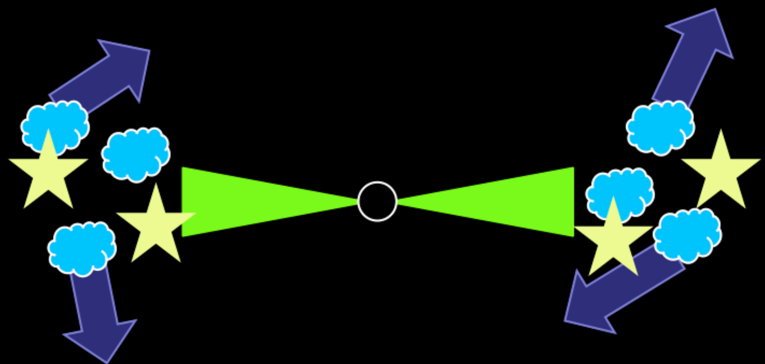
Evolution of BH spin for accreting BH (B) Chaotic accretion

- Alternative idea is that accretion from disk with mass M_{acc} split into many small episodes $\Delta M_{episode} << M_{acc}$ each having RANDOM orientation of ang mtm – CHAOTIC accretion (King & Pringle 2006)
  - physical mechanism producing random orientations of different episodes not clear, but might be due to energy injection by star formation triggered by grav instability of accretion disk
  - chaotic accretion should lead to slowly rotating BHs (a ~ 0.1-0.3) with randomly oriented spins

Coherent vs Chaotic accretion



Coherent: accreted material has ~ constant direction of angular momentum vector



Chaotic: accretion of droplets of material with random direction of the angular momentum vector

(King & Pringle 2006)