according to hierarchical models of galaxy formation, BBHs should be common

GW emission is a key process in SMBBH dynamics, leading to binary hardening and recoil.

[Diagram: A diagram illustrating the evolution of SMBBHs through dynamical friction and GW emission, with key parameters and references indicated.]
supermassive binary BHs in astrophysical context

• galaxy mergers are the sites of major BH growth
  - when does accretion start, are one or both BHs active, how long does accretion last, how much gas is accreted before vs after coalescence, and in which mode, when do BHs coalesce,... ?

• coalescing BBHs are powerful emitters of grav. waves; & e.m. radiation
  - GWs: test GR predictions, precisely measure BH mass & spin, merger rate
  - e.m.: identify ctpart, host galaxy, z → cosmological studies \((H_0)\), → structure of host galaxy, \(t_{\text{stalling}}\) → iron lines, accretion physics around BHs with known masses & spins

• GW recoil: BHs oscillate about gal. cores, or escape → wealth of potential astrophysical applications

• central to our understanding of assembly history & demography of BHs, & galaxy-BH (co-)evolution
recoiling supermassive black holes: kicks & superkicks

- NR simulations of BBH mergers predict BH "kicks" with velocities up to 3800 km/s; highest for $m_1=m_2$, $a_1=-a_2=$ max & in orb. plane

→ recoiling BH will oscillate about galaxy core, or could even leave massive elliptical

[e.g., Peres 1962, Bekenstein 73, Redmount & Rees 89, ... / Baker+ 06,07,08, Brügmann+ 08, Campanelli+ 06, 07a,b, 08, Dain+08, Gonzales+ 06, 07a,b, Healy+ 08, Herrman+ 07a,b, Koppitz+ 07, Lousto & Zlochower 08, Lousto+ 09,10, Pretorius 05, 07, Pollney+07, Schnittman+ 07, 08, Tichy & Maronetti 07, vanMeter+ 10, ...]
key questions:

(1) what are the astrophysical implications?

(2) how common are the (medium-large)kick configurations in nature?

(3) what are the expected electromagnetic signatures of kicks, and what do we actually observe?

especially: are there any unsolved puzzles, which are naturally explained, when including recoil ---- or, vice versa ---- are there certain observations which immediately constrain the (super)kick fraction?
recoiling supermassive black holes: astrophysical implications

- galaxy assembly at the epoch of structure formation & BH growth
- feedback
- scatter in $M-\sigma$ relation
- redshift dependence of GW signals detectable with LISA (heavy BH seeds, late formation; vs. light seeds, early formation)

- large population of low-mass BHs in galaxy halos (incl. MW) ?
- unified models of AGN, # of type-2 quasars, modelling of X-ray bg
- time delays between SB and AGN activity after merging
- ........

[e.g., Madau+ 04, Favata+ 04, Merritt+ 04, Haiman 04, Boylan-Kolchin+ 04, Volonteri+ 05, 06, 07, Libeskind+ 06, Schnittman 07, Sesana 07, Gualandris & Merritt 08, Yu & Lu 08, Blecha & Loeb 08, Tanaka & Haiman 08, Volonteri & Madau 08, Holley-Bockelman+ 2008, Komossa & Merritt 08b, Colpi+ 10, Volonteri+ 10, ...]
fraction of high-$v$ recoils among gas-poor major mergers (assuming random mass and spin distributions), and based on Baker et al. 08 [sim. for Lousto & Zlochower 08] kick formula:

- mass mix between $q=0.3-1$, and spin mix between $a=0.5-0.9$
- $q=1, a=0.9$
- low-spin solution with $a=0.3, q=0.3-1$

fraction smaller in gas-rich systems [e.g., Perego+09]
recoiling SMBHs – e.m. signatures long after coalescence

most tightly bound matter remains bound after recoil →

• off-nuclear „quasars“
• kinematically off-set „Broad Line Regions“
  - ideally at v >> few 100 km/s, to distinguish from „BLR physics“
  - lack of „ionization stratification“ in NLR
  - symmetric broad lines, (and MgII at same v as Balmer lines)

• feedback trails
• stellar tidal „recoil flares“
• hypercompact stellar systems

[e.g., Madau & Quataert 04, Merritt+ 06, Bonning+ 07, Loeb 07, 09 Bogdanovic+ 07, Gualandris & Merritt 08, Kornreich & Lovelace 08, Devecchi+ 08, Fukujita 08, Lippai+ 08, Volonteri & Madau 08, Komossa & Merritt 08b, Haiman+ 08, Merritt+09, O’Leary&Loeb 09, Schnittman 10, Sijacki+ 10, ...]
recoiling SMBHs – search for candidates via spectroscopic signatures

- SDSSJ0927+2943, with broad-line shift of 2650 km/s shows all predicted (B07) spectral features of a recoiling BH, plus an extra peculiar syst. of NELs which is not yet well understood [Komossa et al. 08]

- BH mass (from BL width, and $L_{5100}$): $\sim$sev. $10^8 M_{\odot}$
- gas with $v > v_{\text{kick}}$ remains bound $\rightarrow r > 3r_{BLR}$
- X-ray detection (pt-source with ROSAT & Chandra)
- accretion at $\sim 0.1L_{\text{edd}}$

- for $M_b \sim 0.01 M_{\text{BH}}, L/L_{\text{edd}}=0.1, \eta=0.37$: $t_q \sim 10^7$ yr
- emission-line ratios constrain location $r < \sim$ few kpc
- `d travel few kpc within $10^6$ yr at $v_{\text{max}}$

J0927 alternatives: no pre-merger orbital motion detected [Shields+ 09] & no super-massive cluster detected [Decarli+09, K+10]
recoiling SMBHs – search for candidates via spectroscopic signatures

- perhaps, one more from SDSS ?, @ 3650 km/s [Shields+ 09]

- COSMOSJ1000+0206, @ 1200 km/s [Civano+ 10]
  - re-interpretation of earlier pre-merger „dual AGN“ scenario [Comerford+ 09] as GW recoil, or 3body slingshot
  - extra (faint) narrow lines at $v_{BLR}$

- E1821+643, polarimetry + kinematics, @ ~2100 km/s
  - highly asymm. Hβ, extra broad component @ 450 km/s of unclear origin
  - $t_{recoil} \sim 10^4$ yrs [Robinson+ 10]
gas-poor mergers: recoiling SMBHs – tidal disruption flares

- stars will remain bound to the BH within $r_k < GM_{BH}/v_k^2 \sim 0.4 \left( M_{BH}/10^8 M_{\odot} \right) \left( v_k/10^3 \text{ km/s} \right)^{-2} \text{ pc}$
- $\rightarrow$ stellar tidal disruption X-ray flares, of quasar-typical luminosity – off-nuclear or even intergalactic
- from bound and unbound stellar population, at high “early“ rate, and “late“ rate comparable to “non-recoil rate“
- + accretion from stellar mass loss $\rightarrow$ reservoir of NL gas at $v_{\text{kick}}$
- + feedback trails
- + intergal. SNe & peculiar WD detonations, no-host GW signals, ....
- system of bound stars itself detectable

[Komossa & Merritt 08a]
recoiling SMBHs – implications for unified models of AGN

- typically, $r_{BLR} < r_{kick} < r_{torus}$
  $\Rightarrow$ BH recoil oscillations change the quasar, from type 2 $\Rightarrow$ type 1
- this may explain deficiency of type 2s at high $L$ (where mergers are common)
- using N-body simulations [Gualandris & Merritt 08] of BH oscillating in galaxy:
  above $v_{kick} \sim 450$ km/s, $t_{osci}$ approx $t_{quasar} \sim 10^{7-8}$ yr

- small-scale oscillations behind clumpy torus:
  - change in X-ray abs. on $\Delta t \sim$ weeks
  - repeated accretion (=flaring) activity at each turning point

[Komossa & Merritt 08b]
• recoiling BHs:
  - astrophysical implications for: galaxy & BH assembly at epoch of structure formation, BH growth, z-dependence of GW signals & LISA rates, AGN statistics & unified models, time delays between SB and AGN activity, ...

- predicted e.m. signatures: spatially & spectroscopically off-set "quasars", flaring disks, variable quasar absorption, off-nuclear tidal disruption flares, hypercompact stellar systems
- several candidates @ v ~ 1000-3000 km/s

summary
thanks for your attention!