A galaxy without its SMBH: implications for feedback

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What happens when the SMBH is displaced or even ejected by GW from the center of its galaxy?

How does this influence the SFR, galaxy growth, mass, etc.?
• SMBH binaries are a consequence of galaxy formation

• SMBHs may be able to merge efficiently, especially in gas-rich galaxies

• SMBH mergers are a key component of SMBH-galaxy co-evolution

• Strongest gravitational wave (GW) sources in the Universe

GALAXY-GALAXY DANCE

1. Approaching
2. Interacting
3. Merging
4. Ejecting

→ GW recoil kick
Gravitational-Wave (GW) Recoil

Requires an asymmetric binary (unequal BH mass, spin, or spin orientation; Peres 1962, Bekenstein 1973)

Asymmetry causes GW beaming, which imparts a kick to the BH at the moment of merger
SMBH recoils

• Max. recoil velocity for non spinning BHs: 
  \[ v_{\text{kick}} < 200 \text{ km/s} \] → offset SMBHs (sub parsecs)

Kicks are small because spins are small, or because spins become aligned via a gas disk or GR precession (Bogdanović et al. 2007, Dotti et al. 2009, Kesden et al. 2010)

• Max. velocity for maximally-spinning, optimally-oriented BHs: 
  **up to 5000 km/s!** (Campanelli+ 2007, Lousto +2011) → isolated SMBHs

For major mergers \((q \geq 0.25)\), high spins \((a = 0.9)\), & random orientations, fraction of kicks with 
\[ v_k > 500 \text{ km s}^{-1}: 62-70\% \]
\[ v_k > 1000 \text{ km s}^{-1}: 25-36\% \]
Possible signatures of GW recoil

• Prompt EM counterparts
• Long-lived signatures:
  • Scatter/offset in BH-bulge relations
  • Effects on central stellar population
  • Offset AGN
• Enhanced tidal disruption rate \cite{Stone2010}
• Ejected stellar clusters \cite{Oleary2009}
• BHs may be ejected during a rapid growth phase
• Recoil events could produce under-massive BHs and over-massive galaxies
• May create scatter (factor of 2), offset, and/or outliers in $M_{\text{BH}} - \sigma_*$ relation

($v_k = 0$
$v_k = 0.9v_{\text{esc}}$

(Volonteri 2007, Blecha et al. 2011)
The displacement of AGN feedback after a recoil event enhances central SFR in the merger remnant.

→ The starburst phase of the merger is extended

→ 3% increase of the total stellar mass at the end of the simulation in the recoil case

Blecha et al. (2011)
Enhance SF in central region

→ A denser, more massive stellar cusp is created at the center.

→ Bluer than in the no-recoil simulation. The (blue) starburst phase may be prolonged.

→ The transition to red elliptical slightly delayed, solely due to the effect of GW recoil.

Blecha et al. (2011)
Recoiling SMBH may carry along some gas when ejected \( (r_{\text{ej}} \sim G M / v_{\text{kick}}^2) \):

- **Kinematic offsets**: offset broad lines in spectra
- **Spatial offsets**: resolved offset from galactic center
Recoiling SMBH Candidates

Intensive searches in SDSS yielded a null result (Bonning et al. 2007)

1. SDSSJ092712.65+294344.0 (Komossa et al. 2008)
2. SDSS J105041.35+345631.3 (Shields et al. 2009)
3. z=0.047 SDSS galaxy (Jonker et al. 2010)
4. M87 (Batcheldor et al. 2010)
5. Quasar E1821+643 (Robinson et al. 2010)

CID-42: candidate GW recoiling SMBH with both SPECTROSCOPY and IMAGING signatures (Civano et al. 2010)
HST – 2 deg$^2$ optical images (600 orbits)
XMM – 2 deg$^2$ X-ray imaging (1.5 Msec)
Galex – ultraviolet imaging
Spitzer – Mid IR w/ IRAC (620 hrs)
Chandra – 1 deg$^2$ X-ray imaging (2deg$^2$ coming soon)
Herschel – GTO
Subaru – multiple color imaging
VLA – radio imaging (~300 hrs)
MAMBO – 1.2 mm survey
ESO-VLT – zCOSMOS LP ~ 20,000 gal.
Magellan – optical spectr. ~ 2,000 redshifts
Keck DEIMOS- optical spectra ~ 2,000 redshifts
NIR – NOAO, UH88, UKIRT …

COSMOS area ~20x area of other surveys

COMPLETE MULTI-COVERAGE on CONTIGUOUS 2deg$^2$
How many off-nuclear SMBHs?

Number counts of off-nuclear AGNs

In COSMOS (2deg$^2$) 0.01-10 sources

Volonteri & Madau 2008
Chandra COSMOS Survey

- 1.8 Ms exposure time (2.8 Ms just awarded)
- 1 sq deg
- 36 ACIS-I pointings
- $F_{\text{lim}} \sim 2 \times 10^{-16} \text{ cgs}$ (0.5-2 keV)
- 1761 X-ray sources (3x CDFS+CDFN)
- 2600 X-ray sources (Chandra+XMM)

Elvis et al. 2009
Puccetti et al. 2009
Civano et al. 2012
SE nucleus (20.51 mag) $\Rightarrow$ POINT SOURCE a unobscured AGN
NW nucleus (19.67 mag) $\Rightarrow$ EXTENDED Obscured AGN or a star cluster?
+ galaxy ($\sim$15 kpc, 18.6 mag)
+ tail and overall light

Tail suggests a recent major merger
3 optical spectra with high S/N:
• 1 Magellan/IMACS R=700
• 2 VLT/VIMOS R=700
+ obtained in February 2010
1 Keck/DEIMOS R=2700

Offset between broad and narrow Hβ:
Δν~1300 km/s

Line ratio of narrow system is consistent with nuclear emission
1) **GW Recoil BH: 1 AGN**

- $T=1000\text{km/s} / 2.5\text{kpc}$
- $\sim 5 \text{ Million years, ejection time}$
- Broad lines
- Narrow lines: ionized ISM
- $\Delta \nu$: normal for a GW kick
- Inverse P-Cygni: $0.1c$
- **inflow** at few tens of $R_S$

**Ejected BH**

**Post BH merger System**

1 SMBH

**Center of the merged galaxy, now without a BH**

**NO X-ray emission**
2) Slingshot Recoil: 2 AGNs

Pre BH merger system
2 SMBHs

**Unobscured BH**
- Bright X-rays
- Broad Hβ
- Moving away

**Obscured BH**
- Weak X-rays
- High X-ray obscuration
- Narrow Lines (Hβ and OIII)
1 or 2 active SMBHs?

**HST data:**
- SE: Point source
- NW: extended source ??

**Optical spectra:**
- 1 System of Broad lines
- 1 System with Narrow lines ??
X-ray emission: test for the presence of 1 or 2 active SMBHs (as in NGC6240)
NEW Chandra High-resolution data

- Chandra HRC 0.14”/pix
- HST/ACS F814W 0.03”/pix

~380 counts in the full band
Fx=9x10^{-14} cgs

2D spatial fitting analysis:
- 3σ upper limit on the NW source intensity
- NW source 4-5% of the total Fx<3x10^{-15} cgs

1. **SE source** emission is the strongest one; X-rays tell it is a unobscured AGN (as seen in the optical)

2. **NW source** upper limit ($L_x < 10^{42}$) could be due to
   1. Star formation
   2. Very obscured Active SMBH
   3. Quiescent SMBH → not expected in such a system
SED to study the NW source

From HST image modeling we can derive the luminosity of the optical sources separately.
Fitting using Trichas et al. 2012

BEST FIT:
Young SF galaxy

$L_{\text{IR}} = 6 \times 10^{44}$

SFR = 25 $M_\text{sun}/\text{yr}$

X-ray UL is consistent with the $L_{\text{IR}}$ and the SFR measured (Ranalli et al. 2003)
Simulating the case of CID-42


For the movie look at  http://chandra.harvard.edu/photo/2012/cid42/cid42 Merger_sm_web.mov
Hydrodynamic galaxy merger simulations (GADGET-3) coupled with radiative transfer (SUNRISE)

Observed

Recoiling

T=t_{obs}

Binary

T=t_{obs}

Each progenitor galaxy contains dark matter, star, and gas particles, as well as an accreting, central SMBH. GADGET-3 also contains sub-resolution models for star formation and for supernova and AGN feedback.

Simulations match as closely as possible the observed properties of CID-42 (spatial offset, v_{los} and morphology)
Recoiling Dual AGN

Simulation results

Time of merger
Comparison with Simulations

• Morpology and galaxy mass for a later stage major merger

• Epoch of the recoil: 1-6 Myr after the merger
  ✓ Epoch of the dual AGN: 50 Myr before the merger

• SFR measured for the recoiling SMBH is 21 $M_{\text{sun}}$, consistent with the observed one
  ✓ Dual AGN SFR is 4 times lower than the observed

• Accretion rate and Luminosity of the SMBH are consistent with the observed
  ✓ Dual AGN luminosity is much lower than the observed one
✓ The presence of recoiling SMBHs needs to be taken into account while discussing about BH/galaxy growth

✓ In CID-42: optical and X-ray data suggest the presence of 1 unobscured SMBH (still accreting) → consistent with GW recoiling scenario

✓ Nature of the NW optical source is not clear yet: the presence of a star cluster is favored instead of that of an obscured SMBH.

**MORE DATA needed for CID-42:** HST and/or IFU spectroscopy, VLBA and JVLA coming soon

**More candidates** needed to better study how this kind of sources influence the whole scenario.