The kick is in the waveform: detection of black-hole recoils

Davide Gerosa
NASA Einstein Fellow
California Institute of Technology

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with Chris Moore and Riccardo Barbieri

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dgerosa@caltech.edu
www.tapir.caltech.edu/~dgerosa
Outline

1. Black-hole (super)kicks
2. Kicked waveforms
3. Is this detectable?
4. Future prospects, looking for suggestions
It’s momentum conservation on black holes

Black hole merger
- Asymmetries in the binary
- Preferential direction of GW emission
- Conservation of linear momentum
- Final BH recoils

Does the kick leave an imprint on the emitted GWs? Can we measure black-hole kicks with GW observations?
Black-hole (super)kicks

- **Mass kicks**: smaller object moves faster… up to ~160 Km/s [Gonzales+ 2007]
- **Spin kicks**: frame dragging comes into play “Superkick” up to ~4000 Km/s “Hang-up kick” up to ~5000 Km/s

![Graph showing velocity vs. mass ratio]

Velocity is dimensionless:
**same kicks for stellar-mass and supermassive black holes**

To get large kicks you need:
- Similar BH masses
- High spins
- Large spin misalignment
- Lucky orbital phase at merger
**Empty galaxies, lonely black holes**

- Kicks can be larger than the escape speed of most galaxies!  
  Redmount Rees 1989

**Black hole ejections**

- Smaller kicks: displacement of supermassive BHs  
  Gualandris Merritt 2008

**Off-nuclear quasars**

Several electromagnetic candidates, but no unambiguous detection  
review Komossa 2012

**How about GWs?**
Look at big galaxies!

**BCGs:** brightest cluster galaxies

\[
M_{\text{BCG}} \sim 10^{12} M_\odot \quad M_{\text{BH}} \sim 10^{10} M_\odot
\]

A factor 2-4 in mass growth since z=1
High merger rate: 0.4/Gyrs
Up to 4 major mergers since z=1!

Lidman et al. 2013

**SMBH ejections do happen!**

DG and Sesana 2015

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ESO 325-G004 (ESO, NASA)
Mass-redshift degeneracy

- In GW measurements, total mass and redshift are degenerate.
- Kicks show up as a red/blueshift in the GW waveform!

Cosmology:

entire waveforms is shifted

\[ M \rightarrow M(1 + z) \]

Kicks:

differential Doppler shift

\[ M \rightarrow M \left(1 + \frac{v_k(t)}{c} \cdot \hat{n}\right) \]
Back of the envelope argument

\[ h(t) = h_i(t) + h_r(t) \]

\[ M_r = M_i(1 + v_k \cdot \hat{n}) \]

To observe kicks, \( v_k = 0.01c \sim 3000 \text{km/s} \) we need to measure \( M_r \) at 1%

Ringdown SNR

\[ \rho_r^2 = \frac{1}{S_n} \int_0^\infty h_r(t)^2 \, dt \]

1d Fisher matrix

\[ \left( \frac{1}{\Delta M_r} \right)^2 = \frac{1}{S_n} \int_0^\infty (\frac{\partial}{\partial M} h_r(t))^2 \, dt \]

Schw. QNM

\[ h_r(t) \propto \exp\left(-\frac{0.089}{M_r}\right) \sin\left(-\frac{0.37t}{M_r}\right) \]

\[ \frac{\Delta M_r}{M_r} \approx \frac{0.322}{\rho_r} \]

To measure \( v_k \sim 900 \text{km/s} \) one needs \( \rho_r \sim 100 \)

Tough for LIGO... but 3rd generation detectors and LISA will make it!
The shape of the kick

How does the kick accumulate?

Large kicks tend to be **Gaussian**

![Graph showing Gaussian distribution of kick velocities](image1)

... but then the effect depends on the line of sight!

![Antikick: some deceleration after merger](image2)

**Antikick**: some deceleration after merger
**The shape of the kick**

Actually, lot of diversity in the kick profile! from the SXS catalog

**Agnostic approach. Basis:**

\[
a(t) = \sum_n \alpha_n \phi_n(t)
\]

\[
\phi_n(t) = \frac{1}{\sigma \sqrt{2\pi \sqrt{n}}!} \exp \left( -\frac{(t - t_c)^2}{2\sigma^2} \right) H_n\left(\frac{t - t_c}{\sigma}\right)
\]

\[
\psi_3
\]

\[
\psi_2
\]

\[
\psi_1
\]

\[
\psi_0
\]

Familiar solutions of quantum harmonic oscillator: first term is a Gaussian, each term adds an oscillation

**Kicked waveforms**

1. Start from some approximant (here IMRPhenomP) Hanam+ 2014
2. Evolve system once and estimate kick magnitude from fitting formulae Lousto Zlochower 2013
3. Assume some accumulation profile
4. Evolve system again with time-dependent Doppler-shift
A controlled experiment

\[ h_0 : \text{standard} \quad \text{SNR} \quad \rho = \sqrt{\langle h_0 | h_0 \rangle} \]

\[ h_k : \text{kicked} \quad \text{Overlap} \quad \mathcal{O} = \max_{t_c, \phi_c} \frac{(h_0 | h_k)}{\sqrt{(h_0 | h_0)(h_k | h_k)}} \]

Distinguishable if

\[ \mathcal{O} < 1 - \frac{1}{\rho^2} \]

- Six inspiral cycles, merger and ringdown
- Flat PSD
- Blue/red shifts equally detectable
- Non trivial dependence on the kick shape: more work needed here!

\[
a(t) = \sum_n \alpha_n \phi_n(t)
\]

\[
\phi_n(t) = \frac{1}{\sigma \sqrt{2^n n! \sqrt{\pi}}} \exp \left( -\frac{(t-t_c)^2}{2\sigma^2} \right) H_n \left( \frac{t-t_c}{\sigma} \right)
\]

\[ \sigma : \text{width of the kick} \]

\[ \alpha_0 : \text{Gaussian} \]

\[ \alpha_1 : \text{antikick} \]
Can kick shifts be detected?

\[ h_0 : \text{standard} \quad h_k : \text{kicked} \]

\[ \rho = \sqrt{\langle h_0 | h_0 \rangle} \]

\[ \mathcal{O} = \max_{t_c, \phi_c} \frac{(h_0|h_k)}{\sqrt{(h_0|h_0)(h_k|h_k)}} \]

Distinguishable if \( \mathcal{O} < 1 - \frac{1}{\rho^2} \)

\[ \mathcal{F} = 0 \]

\[ \mathcal{F} = 0.06 \]

\[ \rho \]

\[ 1 - \mathcal{O} \left[ 10^{-5} \right] \]

\[ LIGO \]

\[ LISA \]

Kicks as low as \( 500 \text{ km/s} \) are distinguishable

For a ‘superkick’ \( \Delta v_k \sim 200\text{km/s} \quad \Delta \alpha \sim 10\% \)

...similar numbers are found for 3rd gen detectors like ET
Food for thought

1. We pointed out **kicks are within the reach of future detectors**
2. Kicked waveforms *probably* not the best strategy. Higher harmonics? Surrogate models?
3. (in principle) consistency check of GR
4. (but actually) can the kick deteriorate ringdown tests?
5. Stacking? \( \rho_{\text{eff}} \sim \rho \sqrt{N} \)? Can LIGO make it?
6. Multi-band? Inspiral and ringdown at very different frequencies
7. More/less kicks in some evolutionary channels? Eg. coherent vs. chaotic accretion
Kicks are cool

- Hulse-Taylor pulsar: first evidence GWs carry energy
- GW150914: first direct evidence of GWs themselves
- Kicks: first direct evidence GWs carry linear momentum

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and more coming...