Learning about Black-Hole Formation by Observing Gravitational Waves

Michael Kesden (UT Dallas)
PPC 2017 Meeting
Corpus Christi, TX – May 22, 2017
Outline

• What are gravitational waves (GWs) and how do observatories like the Laser Interferometer Gravitational-wave Observatory (LIGO) detect them?

• How do binary black holes (BBHs) form in our Universe?
  – Cluster channel – BHs form first, binaries later
  – Field channel – Binaries form first, BHs later

• What BH masses and spins are predicted by these astrophysical formation channels?

• How do these spins evolve between BBH formation and merger?

• Can LIGO distinguish the formation channels?
What are gravitational waves?

**Electromagnetic**
- Electromagnetic fields $E, B$
- Solutions to $(\partial^2/\partial^2 t - \nabla^2)X = 0$
- Propagate at speed of light
- 2 transverse polarizations
- Sourced by time-varying charges

**Gravitational**
- Metric perturbations $h_{\mu\nu} = g_{\mu\nu} - \eta_{\mu\nu}$
- same
- same
- same
- Sourced by time-varying stress-energy
Observing gravitational waves

- BBHs emit GWs that cause incomplete destructive interference between lasers in arms of LIGO interferometer.
- Supermassive BBHs are GW source for PTAs, LISA.
GW150914 “The Event”

- Two BBH mergers (also GW151226) in 4 months of O1 data.
- Many more expected in O2 and beyond as Virgo, KAGRA, LIGO-India added to network later this decade.
- Two key goals of LIGO: test GR and discover origin of these BBHs.
• Upper bounds on discrepancies between measured post-Newtonian (PN) coefficients and GR predictions.
• LIGO estimates the mass $M_f$ and spin $a_f$ of final BH produced in merger self consistently in all 3 stages.
• GR allows any value for $M_f$ and $0 \leq a_f \leq 1$; what determines the BH masses and spins LIGO actually sees?
Origin of stellar-mass black holes

- Stars are powered by nuclear fusion \(\Rightarrow\) fusion ends when most stable element (Fe) is produced.

- Fe core above 1.4 \(M_\odot\) cannot be supported by electron degeneracy pressure \(\Rightarrow\) core collapse triggers supernova.

- Nuclear pressure cannot support cores above 2 \(M_\odot\) \(\Rightarrow\) these cores collapse to BHs.

- BHs can accrete from stellar companions, we see X-rays emitted by accretion disk. Cygnus X-1 discovered in 1964.
Cluster channel – BHs form first

- Energy equipartition between stars in cluster ⇒ heavy BHs sink to center
- BHs form tight binaries through 3- and 4-body processes (Rodriguez+ 2016)
- BBHs ejected from cluster and later merge through GW emission
- Predicts heavy masses, isotropic spins
Field channel – binary forms first

- Begin with massive main-sequence binary (Gerosa, Kesden+ 2013)
- Primary transfers envelope to secondary, mass-ratio reversal?
- Primary core collapse, asymmetric explosion tilts orbital plane
- Common-envelope evolution, tidal alignment of secondary?
- 2\textsuperscript{nd} core collapse, 2\textsuperscript{nd} orbital tilt, primary spin more misaligned
- GW-driven inspiral from $r \sim 10^7 r_g$ into LIGO band, must evolve spins
Post-Newtonian spin precession

- EOM can be expanded about Newtonian solution when:
  - $v \ll c, r \gg r_g = \frac{GM}{c^2}$
- Very good approximation for astrophysics:
  - $\frac{r_g}{r} \approx 10^{-6} \left( \frac{M}{10 M_\odot} \right) \left( \frac{r}{10 R_\odot} \right)^{-1}$
- 3 timescales for BBH evolution
  - Orbital time $t_{\text{orb}} \sim \left( \frac{r^3}{GM} \right)^{1/2}$
  - Precession time $t_{\text{pre}} \sim \left( \frac{t_{\text{orb}}}{\eta} \right) \left( \frac{r}{r_g} \right) \gg t_{\text{orb}}$
  - Radiation-reaction time $t_{\text{RR}} \sim \left( \frac{t_{\text{orb}}}{\eta} \right) \left( \frac{r}{r_g} \right)^{5/2} \gg t_{\text{pre}}$
- Solved BBH spin precession analytically at 2PN (Kesden+ 2015)
BBH Precession Animation
• Keplerian orbital shape determined by $a$, $e$
• Spin-precession morphology determined by $L$, $J$, $\xi$
BBHs in LIGO band remember their birth!

- Cluster formation ⇒ isotropic spins ⇒ uniform distribution
- Field formation ⇒ spins aligned ⇒ top right corner
- $\theta_1^\infty \neq \theta_2^\infty$ if tides realign secondary spin between SNs
  - $\theta_1^\infty > \theta_2^\infty$ if primary evolves to more massive BH (red region)
  - $\theta_1^\infty < \theta_2^\infty$ if secondary evolves to more massive BH due to mass ratio reversal before first SN (blue region)
- *Final* spin morphologies set by *initial* spin directions
Bayesian astrophysical model selection

- Identify fraction \( f_a \) of aligned spins with \(~100\) BBH detections, possible by end of O3 observing run (Vitale+ 2017).
- Estimate contributions \( \lambda_i \) from 4 formation models (Stevenson+ 2017)
LIGO can measure spin morphologies!

- Spin precession modulates GWs; more modulation for $\Delta \Phi \sim 0$ morphology because spin components $\perp L$ add constructively.
- LIGO can measure total angular momentum $J$ and projected effective spin $\xi$, correctly identify morphology (Trifirò, Kesden+ 2016).
Conclusions

• LIGO observed GWs from two BBH mergers.
• BBH spins are misaligned with the orbital angular momentum, modulating the GWs they emit.
• Stellar evolution of BBH progenitors determines spin misalignments at BBH formation:
  – Cluster channel ⇒ BHs form first ⇒ isotropic spins
  – Field channel ⇒ binaries form first ⇒ spins partly aligned with orbital angular momentum, morphology set by mass ratio reversals, tidal alignment
• LIGO can measure spin directions, morphologies, unlocking origins of astrophysical BH formation.