Stochastic gravitational-wave backgrounds from astrophysical sources

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Intro: Gravitational-wave astronomy
Intro: Stochastic gravitational-wave backgrounds

**Cosmological**: intrinsically stochastic signal

- Inflation
- First order phase transitions
- Cosmic strings

\[ \hat{\Omega}_{GW}(f) = \frac{1}{\rho_c} \frac{d\rho(f)}{d \ln f} = \frac{2\pi^2}{3H_0^2} f^2 h_c^2(f) \]

**Astrophysical**: incoherent superposition of unresolved sources

- Individual sources too faint
- Individual sources overlap in time (confusion noise)

[Abbott+2016]
High frequency: stellar-mass binaries

Masses in the Stellar Graveyard

in Solar Masses

LIGO-Virgo Neutron Stars

LIGO-Virgo Black Holes

GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

Local merger rates:

[LVK 2020]

\[ \mathcal{R}_{\text{BBH}} = 23.9^{+14.3}_{-8.6} \text{ Gpc}^{-3} \text{ yr}^{-1} \]

\[ \mathcal{R}_{\text{BNS}} = 320^{+490}_{-240} \text{ Gpc}^{-3} \text{ yr}^{-1} \]
High frequency: stellar-mass binaries

- Incoherent superposition of unresolved binaries creates a stochastic background
- Binary black holes: ‘popcorn noise’
- Binary neutron stars: signals overlap in time

[Meacher+2015]

[LVC 2015]
High frequency: stellar-mass binaries

- Energy density of the stochastic background:
  \[
  \Omega_{GW}(f; \theta_k) = \frac{f}{\rho_c H_0} \int_0^{z_{\text{max}}} dz \frac{R_m(z; \theta_k) \frac{dE_{GW}}{df}(f_s; \theta_k)}{(1 + z) E(\Omega_M, \Omega_\Lambda, z)}
  \]

- Probe of high-redshift source population

[Callister+2020]

500 mock detections

Individual detections + stochastic background

[Callister+2020]
Current upper limits: LIGO O1+O2+O3a

- Upper limits from past runs consistent with expected signal
- Possible detection in the coming years: better sensitivity, more data...

Power-law background:

\[ \Omega_{GW}(f) = \Omega_{\text{ref}} \left( \frac{f}{f_{\text{ref}}} \right)^\alpha \]
High frequency - next generation: stellar-mass binaries

- 3G detectors will detect sources out to very high redshifts
- Fewer unresolved sources
- Better sensitivity
- Binary neutron stars: overlap in time

From GWIC-3G science case

[Perigois+2021]
High frequency: collapsing stars

Generation of GW in the central region of the supernova
- Assymetrical flows (neutrino convection, hydro instabilities)
- Proto-neutron star oscillations and rotating non-axisymmetric shape
- Aspherical shock expansion

Unique information on:
- Mechanism of the central engine
- Dynamics that produced the explosion
- Structure of the inner region

If a black hole forms: GW from ringdown

[Persival 2016]

[Burrows & Vartanyan 2021]

[Radice+2019]
High frequency: collapsing stars

- Predictions for stochastic background difficult because of uncertainties in the waveform
- What is dependence on the progenitor?
- Does rotation influence the signal?

\[ f_e |\tilde{h}(f_e)| = \frac{G}{\pi c^4 D} E_\nu(q) \left(1 + \frac{f_e}{a}\right)^3 e^{-f_e/b}, \]

2D numerical simulations

[Buonanno+2005]

Analytic fits to waveform

[Crocker+2017]

Ringdown from newly formed BH

[ID+2016]
Intermediate frequencies: the LISA mission
Intermediate frequencies: stochastic backgrounds from stellar-mass binaries

- Stochastic background from stellar-mass binary black holes: foreground for cosmological signals!

- Local rate measurements with LIGO/Virgo/Kagra will allow to provide precise models for LISA

[see also Zhao&Lu 2020]
Intermediate frequencies: double white dwarfs

- $10^8$ double white dwarfs in Milky Way
- Monochromatic sources in LISA band
- Confusion noise dominates instrument noise in the mHz band
Stellar-mass black holes orbiting massive black holes Expected to form in dense galactic centers

LISA detection rates: $1 - 10^4 \text{ yr}^{-1}$ [Babak+2017]

$M_{BH} \sim 10^5 - 10^7 M_\odot$

$m_{BH} \sim 10 - 50 M_\odot$

Intermediate frequencies: extreme mass ratio inspirals

$\sqrt{\int S_x(f) T_{obs}} = 4.0 \text{ yr}$
Most galaxies have massive black holes in their centers.

When galaxies merge, their black hole can form a bound binary and eventually merge.

Key processes still unknown:
- Seeds of massive black holes
- Co-evolution with host galaxies
- Interactions with surrounding gas and stars

\[ M_{BH} \sim 10^7 - 10^9 M_\odot \]

[Khan et al. (2016)]
Massive and super-massive black hole binaries

- Massive black hole binaries are prime target for LISA
- Large uncertainties in expected rates:

**Semi-analytic models:**

\[ 10 \text{ – } 100 \text{ yr}^{-1} \]

**Hydro simulations:**

\[ 0.5 \text{ – } 2 \text{ yr}^{-1} \]

[e.g. Barausse 2012; Sesana+2014; Klein+2016; Dayal+2019; Bonetti+2019; Katz+2019; ...]

[Barausse, ID, Tremmel, Volonteri, Bonetti 2020]
Low frequencies: super-massive black hole binaries

- Super-massive binaries create a stochastic background in the nHz band which is less sensitive to differences between the models
- Very probable upcoming detection with pulsar timing arrays

[e.g. Wyithe&Loeb 2003; Sesana+2008; McWilliams+2014; Bonetti+2017; Kelly+2017; Sesana+2018; Chen+2019 …]

[Barausse, ID, Tremmel, Volonteri, Bonetti 2020]
Tentative detection of a correlated signal by the NANOGrav PTA

Evidence for a common-spectrum process, but not the correlation expected from a GW signal

In tension with previous upper limits

Consistent with signal from black hole binaries

Consistent with cosmological signals (primordial black holes, cosmic strings…)

[e.g. De Luca+2021; Vaskonen&Veermäe 2021; Ellis&Lewicki 2021; Blasi+2021; Nakai+2021; Ratzinger&Schwaller 2021; Addazi+2020]
Conclusions

- Variety of astrophysical backgrounds across different frequencies
- Stochastic backgrounds are highly complementary to individual detections
- Tightening upper limits from LIGO/Virgo/Kagra
- Tentative detection of a common process by NANOGrav
- Expect a firm detection soon?…
Additional slides
Stochastic background: detection methods

Signal is stochastic and buried in noise!

Cross-correlating outputs from two detectors and hoping noise is uncorrelated with the signal and between detectors

\[
\hat{C}(f) = \frac{2 \operatorname{Re}[\tilde{s}_1^*(f)\tilde{s}_2(f)]}{T \gamma_T(f) S_0(f)}
\]

Noise can be correlated…

- Power/instrumental lines
- Signal injections
- Non-stationary noise (glitches)
- Schumann resonances

Credit: LIGO/Virgo
[Bonetti & Sesana 2020]