Panorama of GW sources:

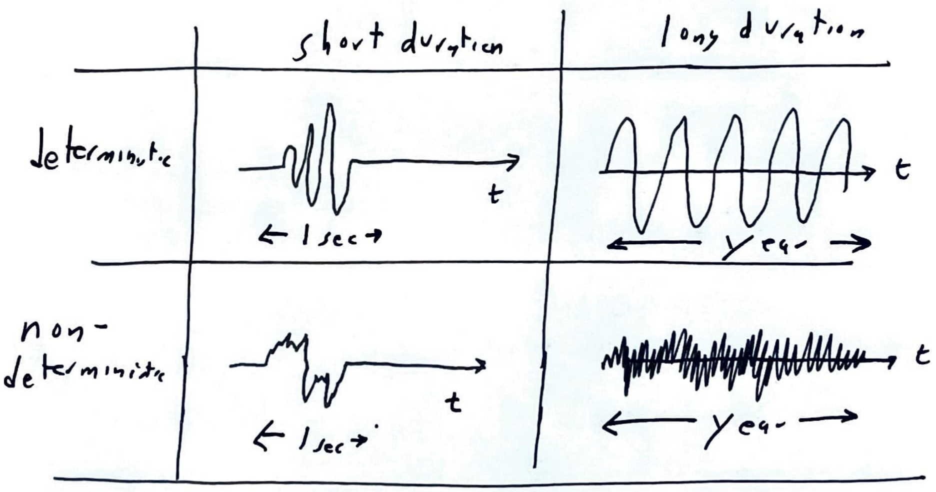
- overview, no detailed mathematical derivations
- classify sources either by:
  - i) physical objects / processes that produce GWs
  - ii) properties of the associated GW signals
- As a data analyst, I often focus on the latter, asking what properties of the GW signals will allow me to identify / separate the different sources.

signal properties (in time domain)

i) short duration
ii) long duration
} short / long with respect to observation time (e.g., years)

iii) deterministic — predictable phase evolution

iv) non-deterministic — stochastic, random, non-predictable phase evolution



possible source:

BBH merger	rotating NS
supernova	population of SMBH binaries

LVK search groups:
(LIGO-Virgo-KAGRA)

CBC (compact binary coalescence)	CW (continuous wave)
burst	stochastic

CBC : compact binary coalescence

compact → WD, NS, or BH

coalescence → inspiral and merger

WD has $M \sim M_\odot$, $R \sim R_{Earth}$

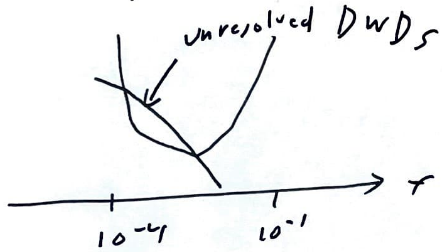
NS has $M \sim M_\odot$, $R \sim 10$ km

BH have masses from $\sim 1 M_\odot$ to $10^{10} M_\odot$ (astrophysical BHs)

NOTE: primordial BHs created in early universe can have much smaller masses, but the smallest mass PBHs will have already ~~evap~~ evaporated due to Hawking radiation.

~~The~~ Galactic white dwarf binaries (DWD: double white dwarfs) are a prime source for LISA

→ In fact the combined (stochastic) signal from the DWD population will dominate the LISA noise curve at low frequencies



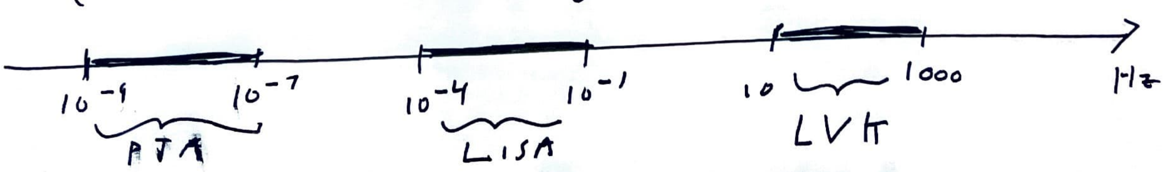
— loud individual DWDs can be seen above the unresolved background ≡ "verification binaries" for LISA

Different BH masses → binary systems emitting GWs in different frequency bands

- CW from individual SMBH binary
- population of SMBH binaries (10^8–$10^{10} M_\odot$)

- DWD binary background
- MBH binaries 10^4–$10^6 M_\odot$

- NS-NS inspiral & merger (GW170817)
- NS-BH " (GW200105, 200115)
- BH-BH " (GW150914)



stochastic sources signal properties

continuous

t — e.g., population of SMBH binaries

modulated

t — DWD binaries for LISA (period ≈ 6 months due to orbital motion of LISA constellation)

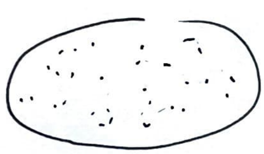
intermittent
"
"popcorn" noise

t — population of stellar-mass BBHs for LVK searches

(duration ≲ 1sec, average time between successive mergers 5-10 minutes)

NOTE: population of BNs → continuous background since time in band ~200s while average time between mergers is ~15 seconds.

sky maps:



statistically isotropic: (like CMB) mostly likely from cosmological sources

anisotropic (e.g., DWD binaries tracing matter distribution of Milky Way galaxy

stochastic signals do not have deterministic waveforms.
→ characterize in terms of power spectrum

$$h(t) \rightarrow \tilde{h}(f) \rightarrow S_h(f) = \frac{2}{T}\langle |\tilde{h}(f)|^2 \rangle, \quad \Omega_{gw}(f) = \frac{f}{\rho_{crit}} \frac{d\rho_{gw}}{df}$$

Fourier transform — strain power spectrum — energy density spectrum (normalized by critical energy density)

$$\Omega_{gw}(f) \propto f^3 S_h(f), \quad \Omega_{gw}(f) \sim f^{2/3}$$

for binary inspiral

To "prove" $\Omega_{gw}(f) \sim f^{2/3}$ for binary inspiral calculate

$$f \frac{dE_{gw}}{df} = - f \frac{dE_{orb}}{df} \quad \text{(energy balance)}$$

using $E_{orb} \sim \frac{1}{a}$ and $\omega^2 a^3 = GM$ (Kepler's third law)

thus, $E_{orb} \sim \frac{1}{a} \sim \omega^{2/3}$

$$\rightarrow f \frac{dE_{orb}}{df} \sim \omega \frac{dE_{orb}}{d\omega} = \omega\, \omega^{-1/3} = \omega^{2/3}$$

Physical sources for stochastic GWs:

(1) Astrophysical (produced by stars or stellar remnants $\gtrsim$ 1 billion years after the Big bang)

a) NS / stellar mass BHs (LVK)
b) DWD (LISA)
c) SMBH binaries (PTAs)

(2) Cosmological (produced by processes in the early universe)

[illegible]

→ gives picture of universe well before the CMB (stochastic background of EM radiation produced ≈ 380,000 yrs after the Big bang)

a) relic GWs associated with inflation (QM fluctuation in spacetime metric driven to macroscopic scales by a period of rapid expansion)
└ exponential growth of scale factor

b) cosmic strings — topological defects associated with symmetry breaking phase transitions

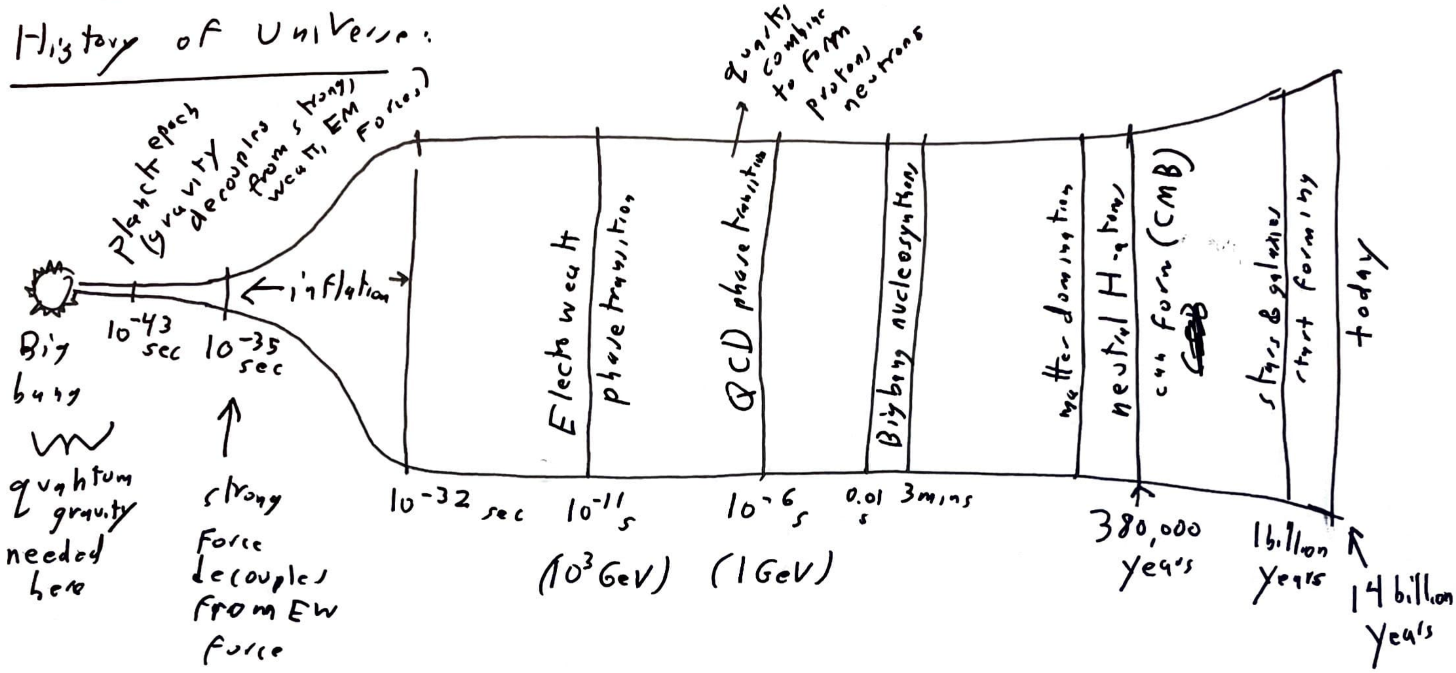
c) 1st order phase transitions — nucleation of vacuum bubbles (new phase) → lead to collisions → GWs

like water → steam or water → ice (discontinuity in 1st derivative of energy vs. temp)

NOTE. standard model of particle physics does not predict 1st order phase transition.

- so ~~evidence~~ detection of a GW signal having the properties of a 1st-order phase transition would be ~~a sign of the~~ evidence for "new physics" beyond the standard model

History of Universe:



Energy density spectrum: (for different sources)