Plan of Lectures

- **I Overview**
  - Lecture duration $\sim$ 1 hr
- **II What are GWs?**
  - Lecture duration $\sim$ 2 hr
- **III Gravity Tests with GWs**
  - Lecture duration $\sim$ 1.5 hr

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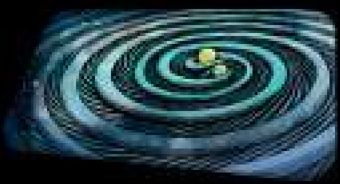
That would be one of the most fascinating things man could do, because it would tell you very much how the universe started.

— Rainer Weiss



Frontiers of GWs (I): Overview

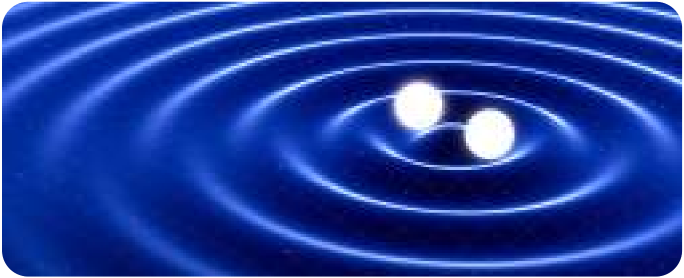
Kavli Institute for Astronomy and Astrophysics

Lijing Shao (邵立晶)

KITS Summer School · 江苏溧阳

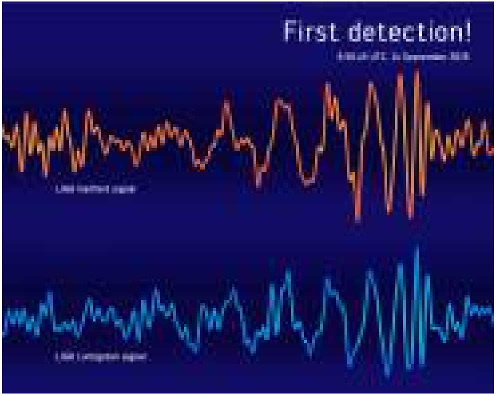
References

- M. Bailes, *et al.*, Nature Rev. Phys. **3** (2021) 344 [DOI]
- A. Buonanno, Les Houches Lecture Notes (2006) [arXiv:0709.4682]
- B. S. Sathyaprakash & B. F. Schutz, Living Rev. Rel. **12** (2009) 2 [arXiv:0903.0338]

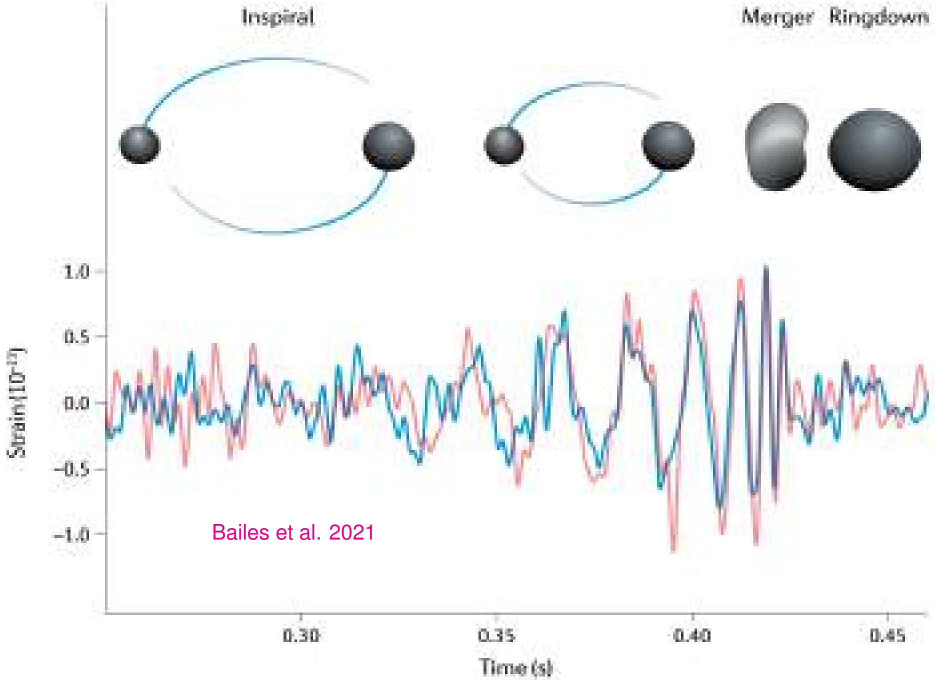


GW150914: Binary Black Hole

- **September 14, 2015**: Advanced Laser Interferometer Gravitational-Wave Observatory (AdvLIGO)



LIGO/Virgo 2016


Inspiral
Merger
Ringdown
1.0
0.5
0.0
−0.5
−1.0
Strain (10⁻²¹)
0.30
0.35
0.40
0.45
Time (s)
Bailes et al. 2021

GW170817: Binary Neutron Star

- **August 17, 2017**: Advanced LIGO & Advanced Virgo

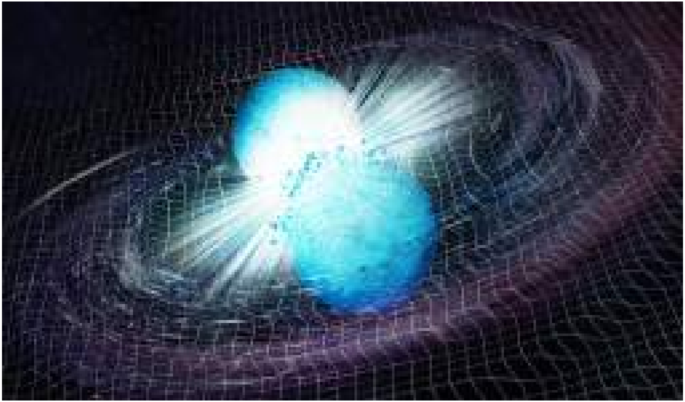
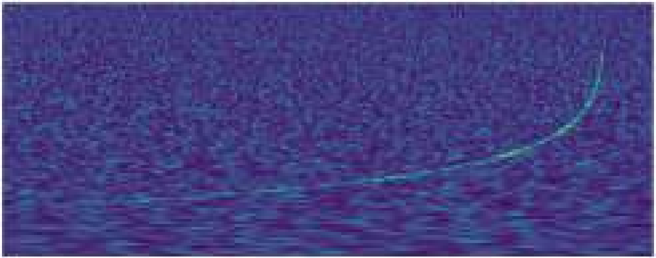


Figure Credit: M. Weiss

GW170817: Binary Neutron Star

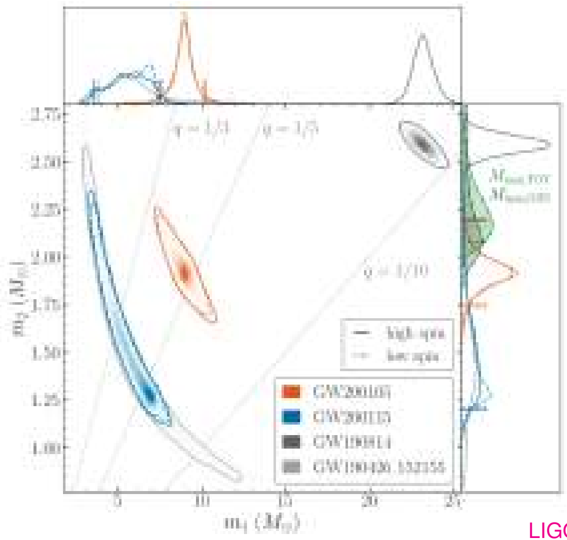
- **August 17, 2017**: Advanced LIGO & Advanced Virgo



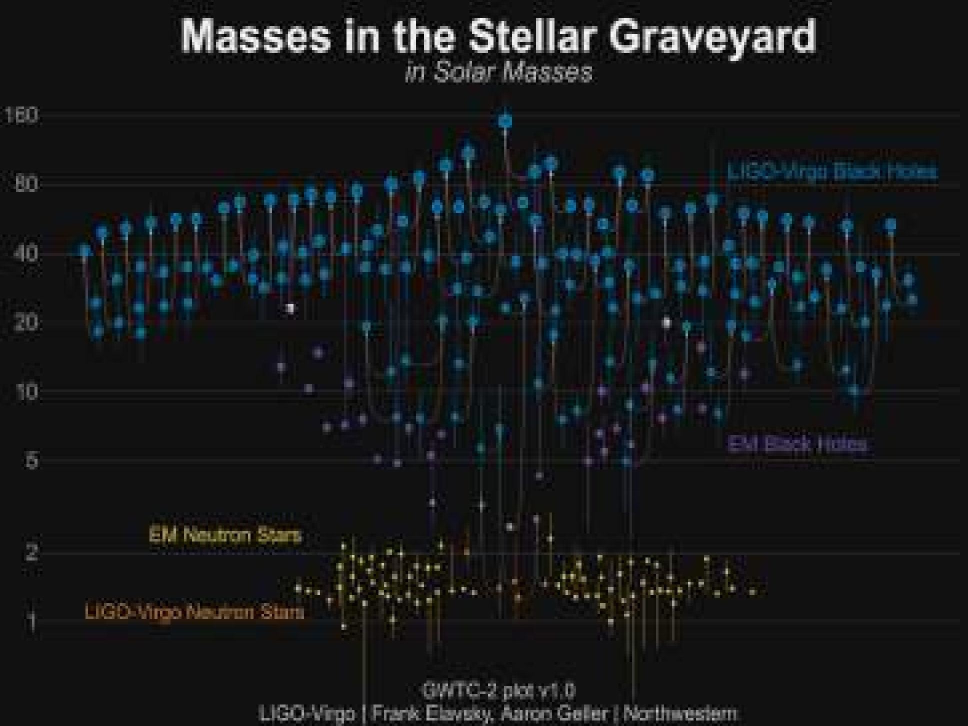
How do data tell stories?

LIGO/Virgo 2017

GW200105 & GW200115: BH-NS Binaries

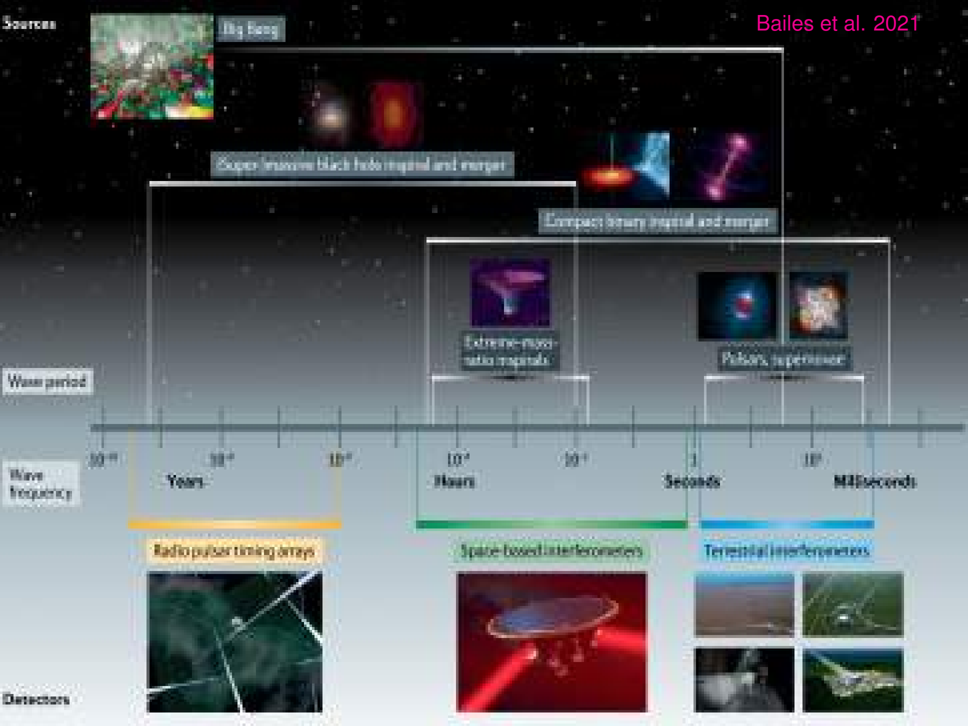


LIGO/Virgo 2021



Masses in the Stellar Graveyard
in Solar Masses
160
80
60
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

What is the next?



Bailes et al. 2021

GW Roadmap in the 2020s and 2030s

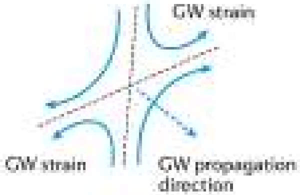
Past: BH & NS binaries by LIGO/Virgo

Opened a completely new window on the Universe!

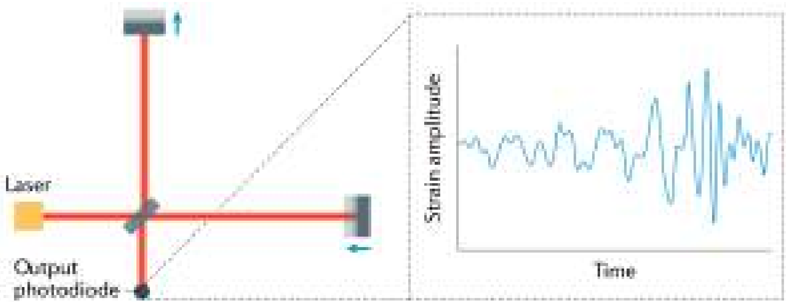
Future: **GW (10^{-18} to 10^{4} Hz)** $\Rightarrow$ exploring fundamental questions

- **Einstein Telescope** and **Cosmic Explorer**
  $\Rightarrow$ a tenfold increase in sensitivity $\Rightarrow$ study compact object evolution to the beginning of the star formation era
- **LISA (mHz to 0.1 Hz)** $\Leftarrow$ evolution of BHs from the early Universe through the peak of the star formation era
- **PTAs (nHz to μHz)** $\Leftarrow$ past mergers of SMBHBs

Michelson Interferometer



- Quadrupolar $h \sim \delta L/L$
  - “$+$” and “$\times$” modes



Bailes et al. 2021

Optics

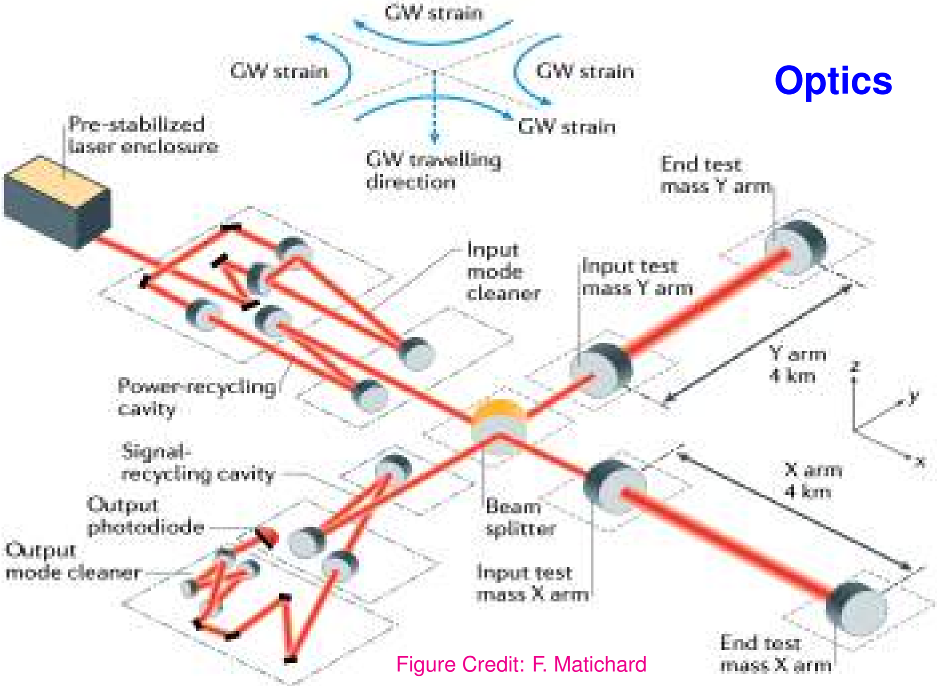
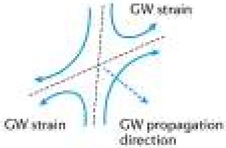
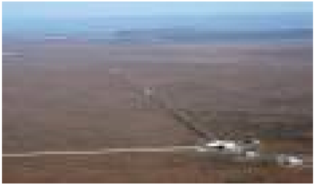


Figure Credit: F. Matichard

Ground-based Detectors

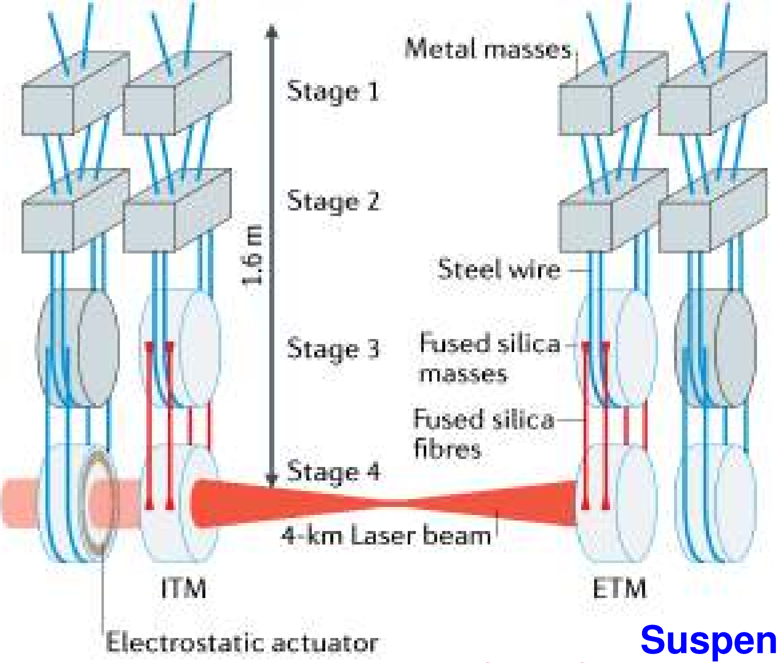


- **Frequency**: 10 Hz to 10 kHz
- **Sources**: $h \sim 10^{-21}$ and $\delta L \sim 10^{-18}$ m
  - Stellar-mass compact sources: BHs and NSs
  - Supernovae
  - Isolated NSs
- **Detectors**: can be effectively treated as in **free fall** (i.e. local inertial frame) in the direction of light propagation **(Why?)**



Ground-based Detectors

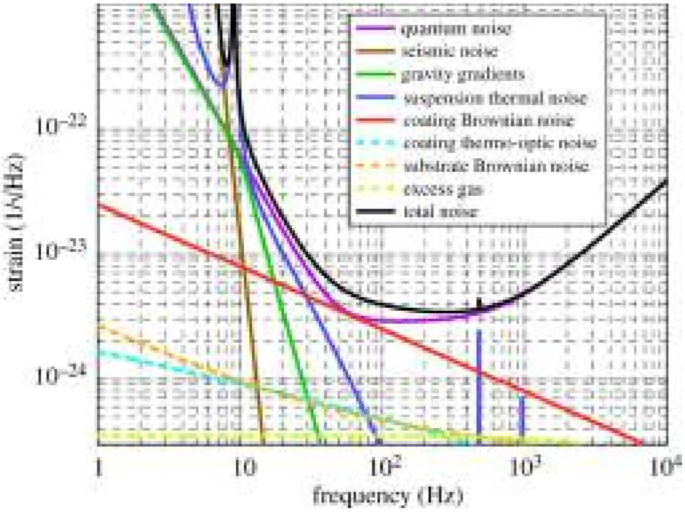
- **Noise budget**
  - **Seimic noise**: suspension system reduces by $\sim 10^{12}$ from 1 Hz to 10 Hz
  - **Thermal noise**: thermally fluctuating stresses in the mirror coatings, substrates and suspensions
  - **Newtonian noise** (or, dynamic gravity gradient): earth and atmospheric density perturbations
  - **Quantum noise**: vacuum fluctuations of EM field (a.k.a. shot noise) and quantum radiation pressure noise (by photons' "kicks")
  - **Others**: laser frequency and intensity noises, acoustically and seismically driven scattered light noises, sensor and actuator noises, stochastic forces from electrical and magnetic fields, energy deposited by energetic particles, etc.



Suspension

Figure Credit: D. Sigg

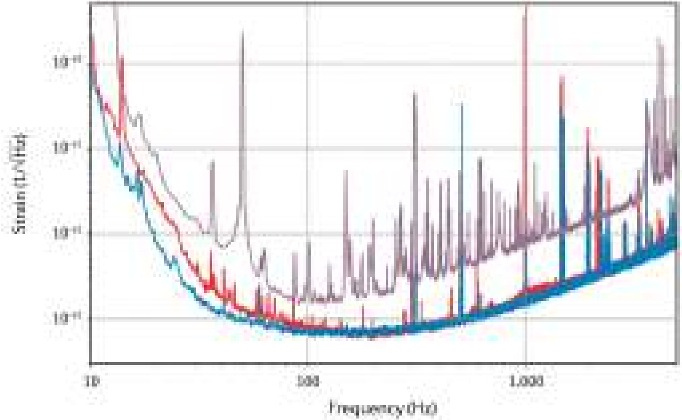
Ground-based Detectors



van Veggel 2018

Ground-based Detectors

- **O2 Noise Curve**



LIGO/Virgo 2019, PRX

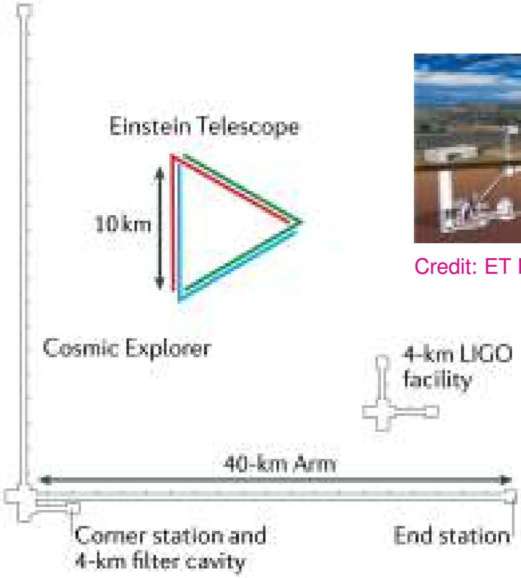
Ground-based Detectors

- **What have we learned? (BBHs)**
  1. There is a population of BHs paired in orbitally bound binary systems that evolve through the emission of GWs and merge in less than a Hubble time
  2. BHs of many tens and even hundreds of $M_\odot$ exist in nature
  3. Properties of the observed BHs are entirely consistent with GR to within current measurement limits

Ground-based Detectors

- **What have we learned? (BNSs)**
- 1st demonstration of **GW-EM multi-messenger astronomy**
  1. 1st definitive link between **BNS mergers** and **short GRBs**
  2. 1st definitive observation of a **kilonova**
  3. conclusive spectroscopic proof that BNS mergers produce heavy elements through ***r*-process nucleosynthesis**
  4. 1st demonstration that GWs travel at the **light speed** to better than $\sim 10^{15}$
  5. an independent method for measuring the **Hubble constant** using detected GWs as a **"standard siren"**

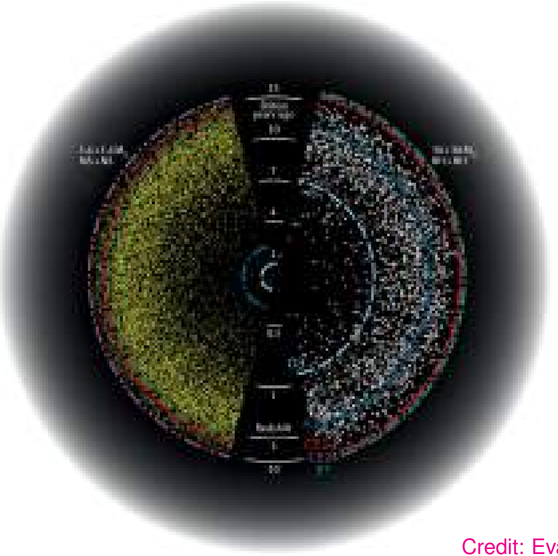
3G Ground-based GW Detectors



Credit: ET Design Study Team

Bailes et al. 2021

3G Ground-based GW Detectors

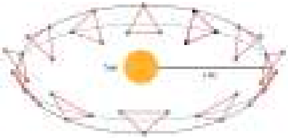


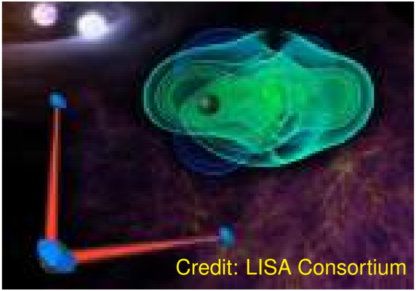
- Cosmic Explorer
- Einstein Telescope

Credit: Evan Hall

Space-based Detectors

- **LISA**: 100 μHz–100 mHz, 2.5×10^9 m
  - seed BHs @ $z \sim 20$
  - IMBHs and SMBHs: 10^2–10^7 $M_\odot$
  - EMRIs: extreme mass ratio inspirals
  - Galactic binaries: mapping Milky Way

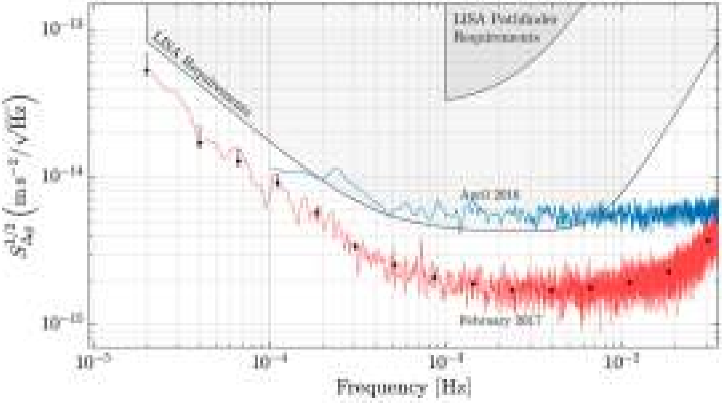




Credit: LISA Consortium

Space-based Detectors

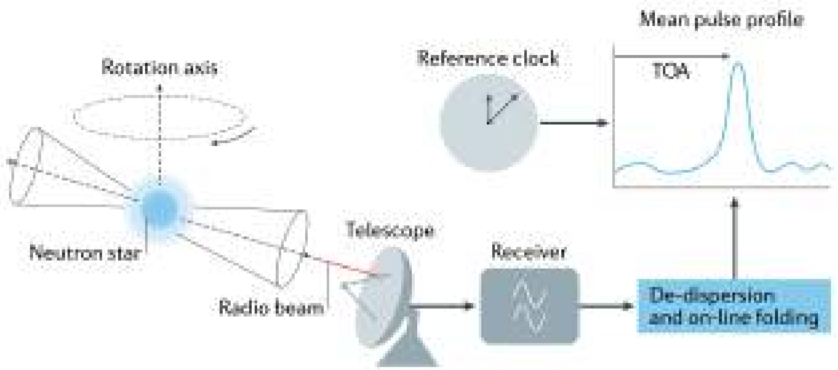
- **LISA Pathfinder**: 2015 – mid-2017



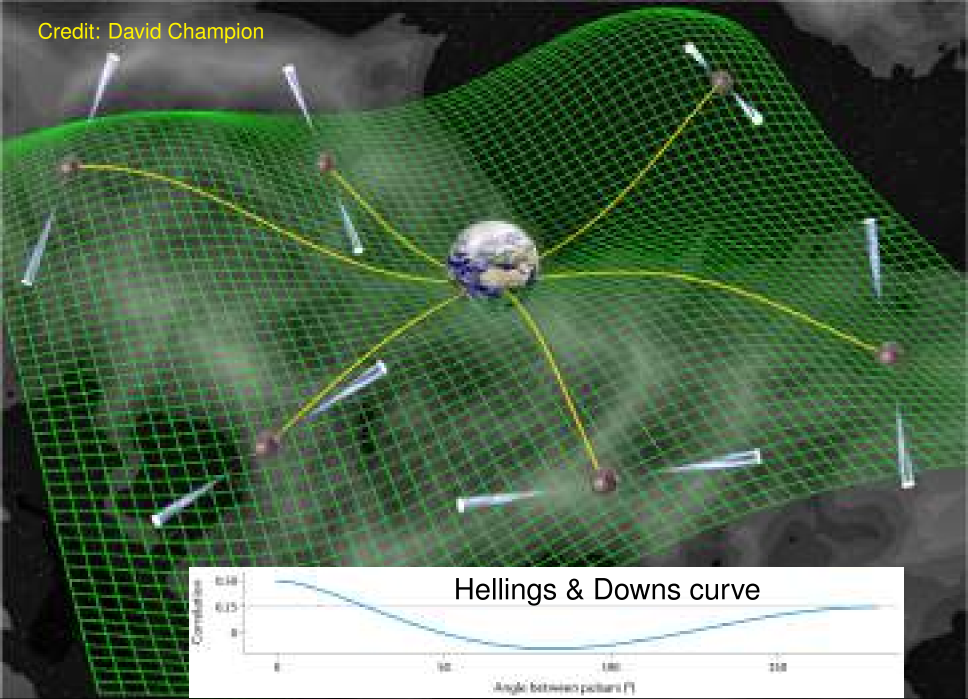
Armano et al. 2018, PRL

Pulsar Timing Arrays

- **Pulsars**: magentized rotating NSs $\Rightarrow$ lighthouse
  - TOAs: time of arrivals ($\sigma \lesssim 1\,\mu\mathrm{s}$)



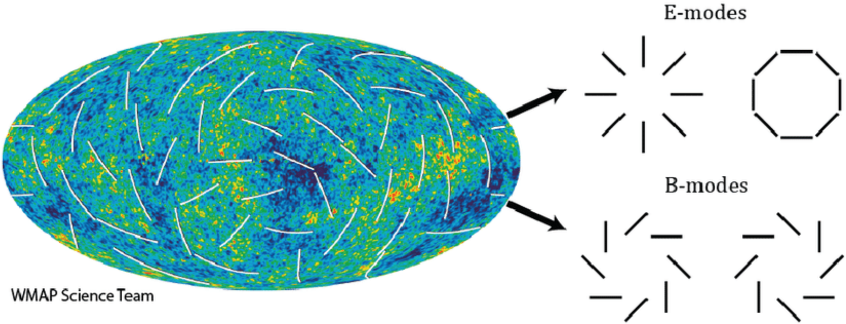
Bailes et al. 2021


Credit: David Champion
Hellings & Downs curve

Credit: Shami Chatterjee

CMB Polarization

- B-mode polarization: down to 10^{-18} Hz
  - remnant primordial GWs



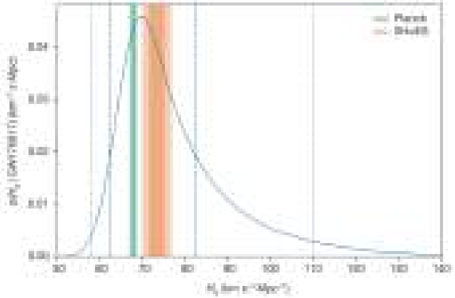
Fundamental Physics

- Testing GR and modified theories of **gravity**
  - information loss, contradicting quantum, singularity, late-time acceleration ⇒ quantum gravity?
- **Equation of state** of ultra-high density matter
  - low-energy QCD ⇒ nonperturbative
  - phase transition?
- Exploring **dark matter** properties with GW observations
  - WIMPs, axions ⇒ superradiance, primordial BHs

Sathyaprakash & Schutz 2009; Bailes et al. 2021

Cosmology

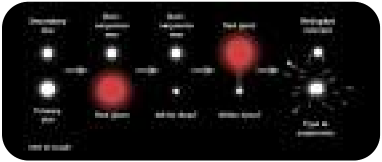
- **Standard Sirens**
  - Hubble constant
  - dark energy equation of state
  - energy Universe ⇐ stochastic backgrounds

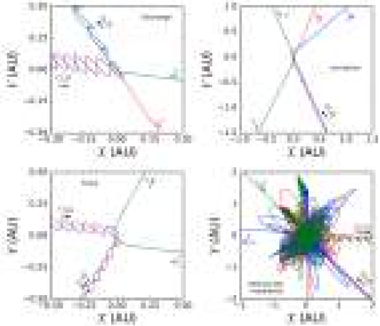


LIGO/Virgo + EM Groups 2017, Nature

Astrophysics

- Formation and evolution of compact stars
  - BH-BH, BH-NS, NS-NS, supernovae, etc.
- SMBH growth and evolution

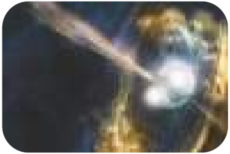




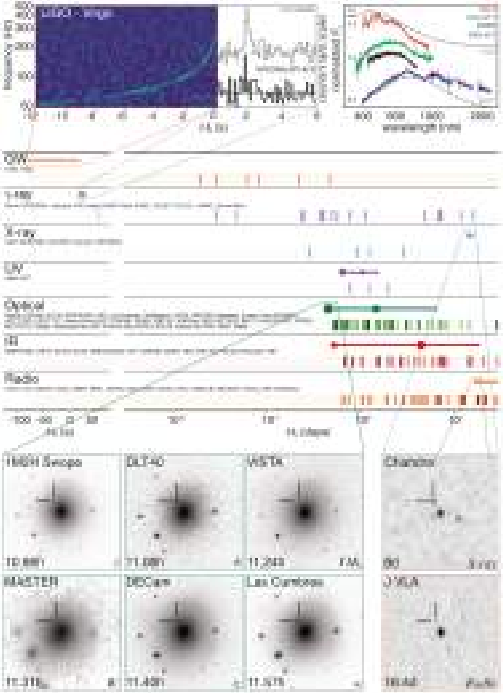
Zhang, Shao, Zhu 2019

Multi-messenger

- Gravitational waves
  - γ-ray, X-ray
  - UV, optical, IR
  - Optical
- γ-ray bursts
- kilonovae
- afterglows



Abbott et al. 2017, ApJL




Thanks!!!
Any question?

Thank you!