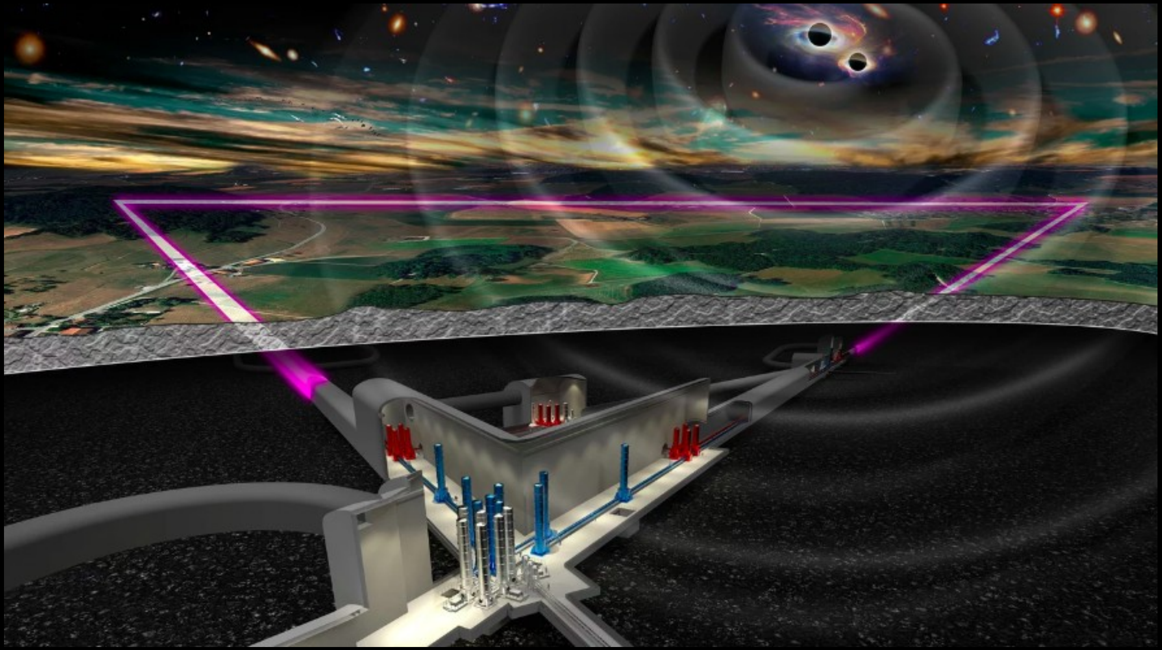
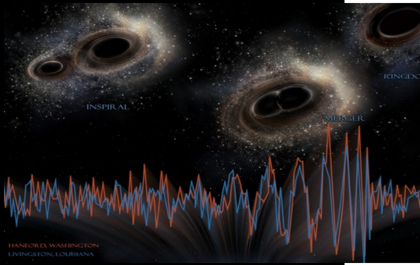
Science with the Einstein Telescope- 3rd generation GW detector

Dorota Gondek-Rosińska
Astronomical Observatory, University of Warsaw
TMEX 2025, Wietnam



Gravitational Waves Astronomy



- Advanced LIGO-Virgo (observation:O1,O2,O3,O4) → breakthrough discoveries
- - 2015 - **GW150914** - 1st detection of gravitational waves from a binary black hole merger

  29 Msol+36Msol--> 62 Msol the brightest source ever seen in the sky $L_{GW} = 200^{+30}_{-20} M_{\odot} s^{-1} = 3.6^{+0.5}_{-0.4} \times 10^{56} erg\ s^{-1}$

  → Nobel Prize in Physics 2017 R. Weiss, B. Barish, K. Thorne from Ligo-VIRGO collaboration *„For decisive contributions to the LIGO detector and the observation of gravitational waves"*

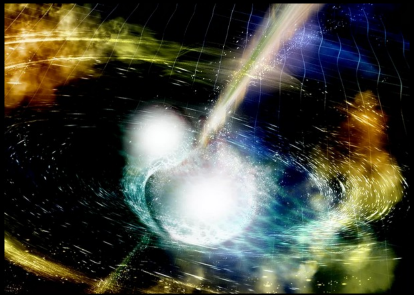
  - 2017 – **GW170817** - the 1st observation of a binary neutron star merger

  with GW and 70 EM observatories → **the era of multimessenger astronomy**
- - 2019 - **GW190521** – the 1st Intermediate Mass Black Hole of 142 Msol
- -2020 -**GW200105 and GW200115** – the 1st BH-NS
- Up to now we have confirmed 90 mergers: 84 ? BBH, 2 BNS, (3-4 ?) BH-NS

  Gravitational-Wave Transient Catalog: GWTC-3

  → important results for astrophysics, cosmology and fundamental physics

  NOW: Ligo-Virgo-Kagra O4b (GraceDB alerts) ~100 strong events



- FUTURE: 2027? O5 final Observational run with Ligo-India

  3rd generation detectors (2035 ?): Einstein Telescope (Europe), Cosmic Explorer (USA) + Space space missions: LISA, DECIGO..

What have we learned from the GW window ?

- Evidence for heavy BHs with masses heavier than those in X-ray binaries
- Their formation requires an origin from low-metallicity environments
- BBHs (binary black holes) exist and merge within the age of the Universe
- BBHs can form both dynamical processes or isolated binaries
- GW170817 -observational proof that the merger of BNS gives short GRBs
- BNSs are a major source of heavy elements in the Universe (r-process nucleosynthesis)
- The speed of gravitational waves is speed of light with accuracy $< 10^{-15}$
- Information about the structure of neutron stars
- GW170817 - independent measurement of Hubble'a constant

but still a lot of open questions ..

Goals of Gravitational Waves Astronomy
Fundamental Physics,Astrophysics, Cosmology

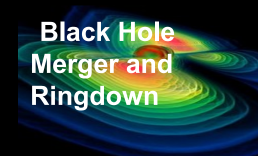


Image credit: W. Benger

2D detectors (LVK) opened a new window into the Universe
3D ground based detectors will look deeply into this window

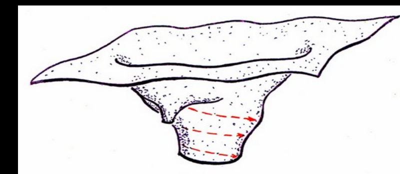
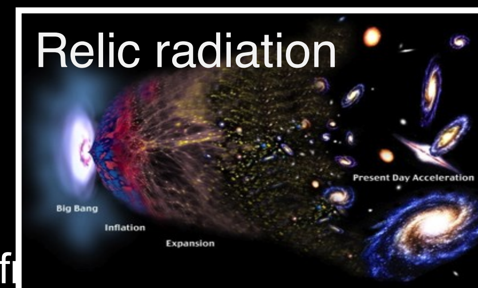
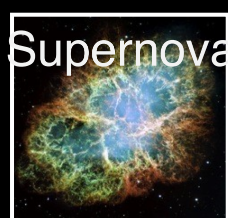


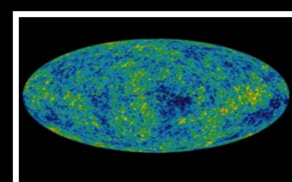
Image credit: NASA

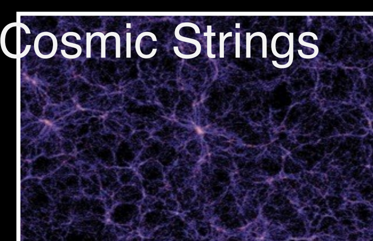
- Is Einstein theory the correct theory of gravity?
- Is the nature of gravitational radiation as predicted by Einstein ?
- What is the nature of black holes?
- How did IMBHs and massive black holes form and evolve?
- What were the physical conditions at the begining of Universe?
- What is the origin of gamma ray bursts?
- What is the structure of neutron stars?
- What is the nature of gravitational collapse? What can we learn f backgrounds?
- ….

we expect unexpected



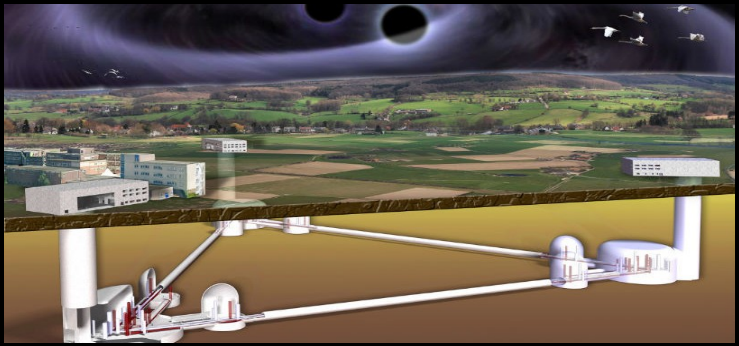






3G Gravitational Waves Detectors (>2035)
10 times more sensitive than Advanced 2D detectors

-Einstein Telescope (Europe) underground, triangle 10 km arms or two L shape 15km ?
$f_{GW} \sim$ 1 Hz – 10 kHz

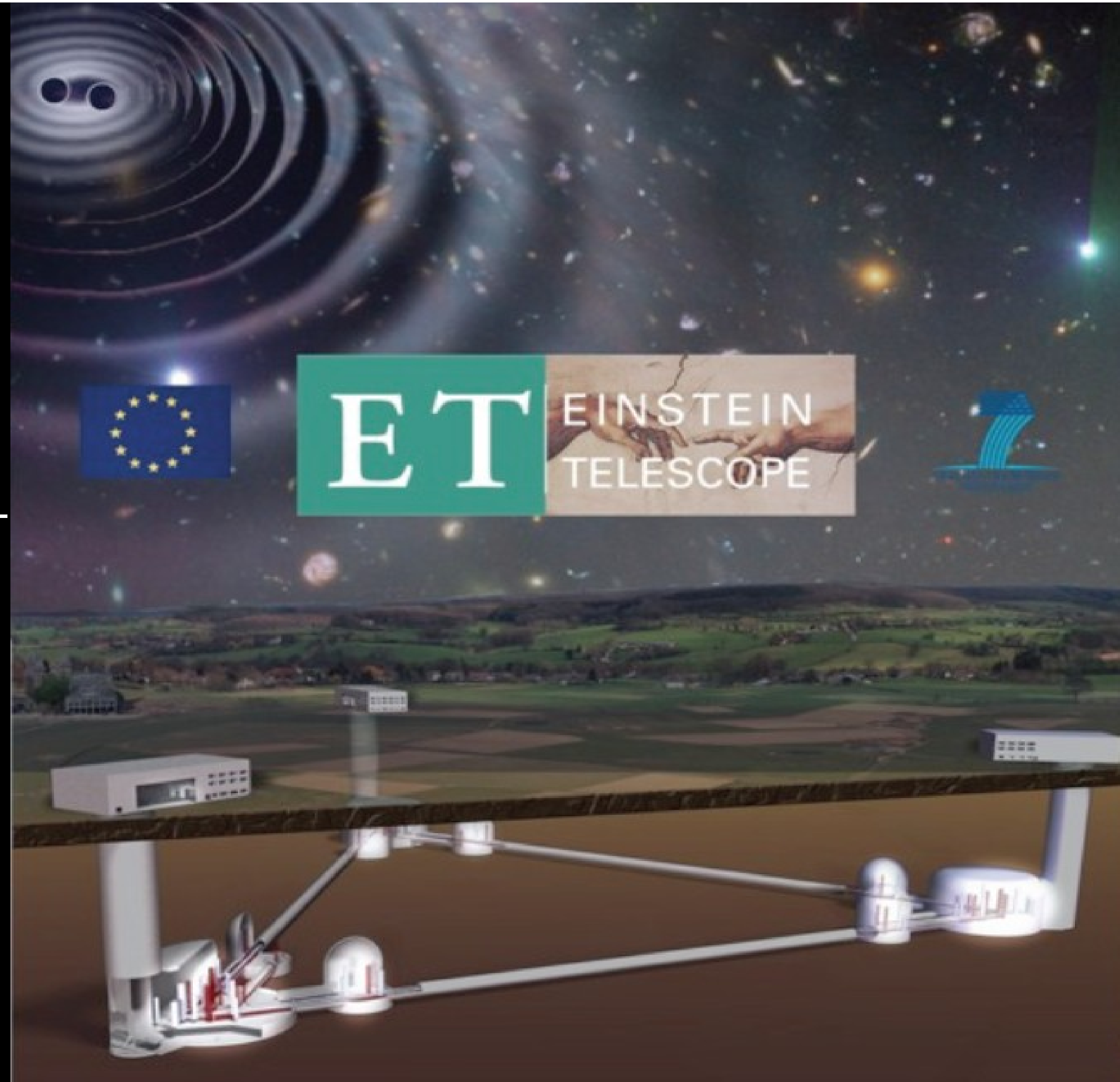


-Cosmic Explorer (USA)
L shape 40 km, 5Hz -10 kHz

3rd generation underground GW detector ET 1Hz-10kHz

Approved in the 2021 ESFRI roadmap

ET Preparatory Phase (2022-2026)



- 10 x better sensitivity than Adv Ligo --> 10^3 events,

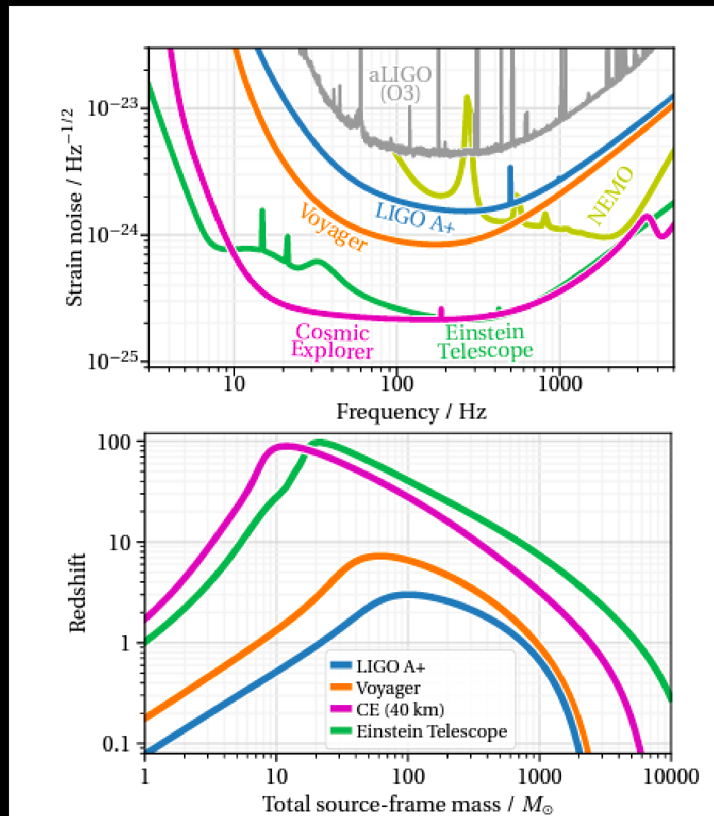
  triangular shape 10 km arms or 2 L 15km (*M. Branchesi et al. 2023 Science with the ET: comparison of different designs*)

- < 10 Hz to eliminate noises go underground 150-200 m

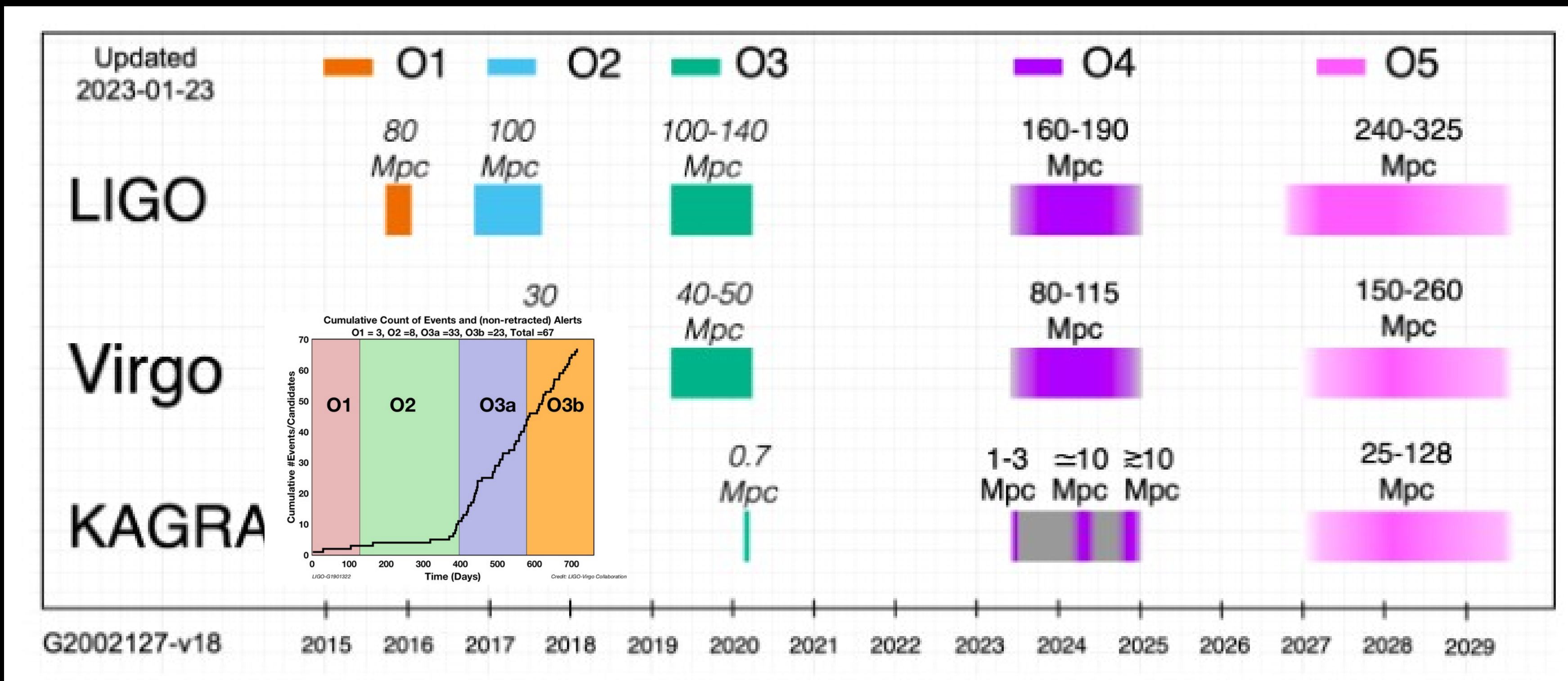
- > 1 kHz, cool mirrors to 10 K

Einstein Telescope potential localization

Sensitivity of the future GW detectors

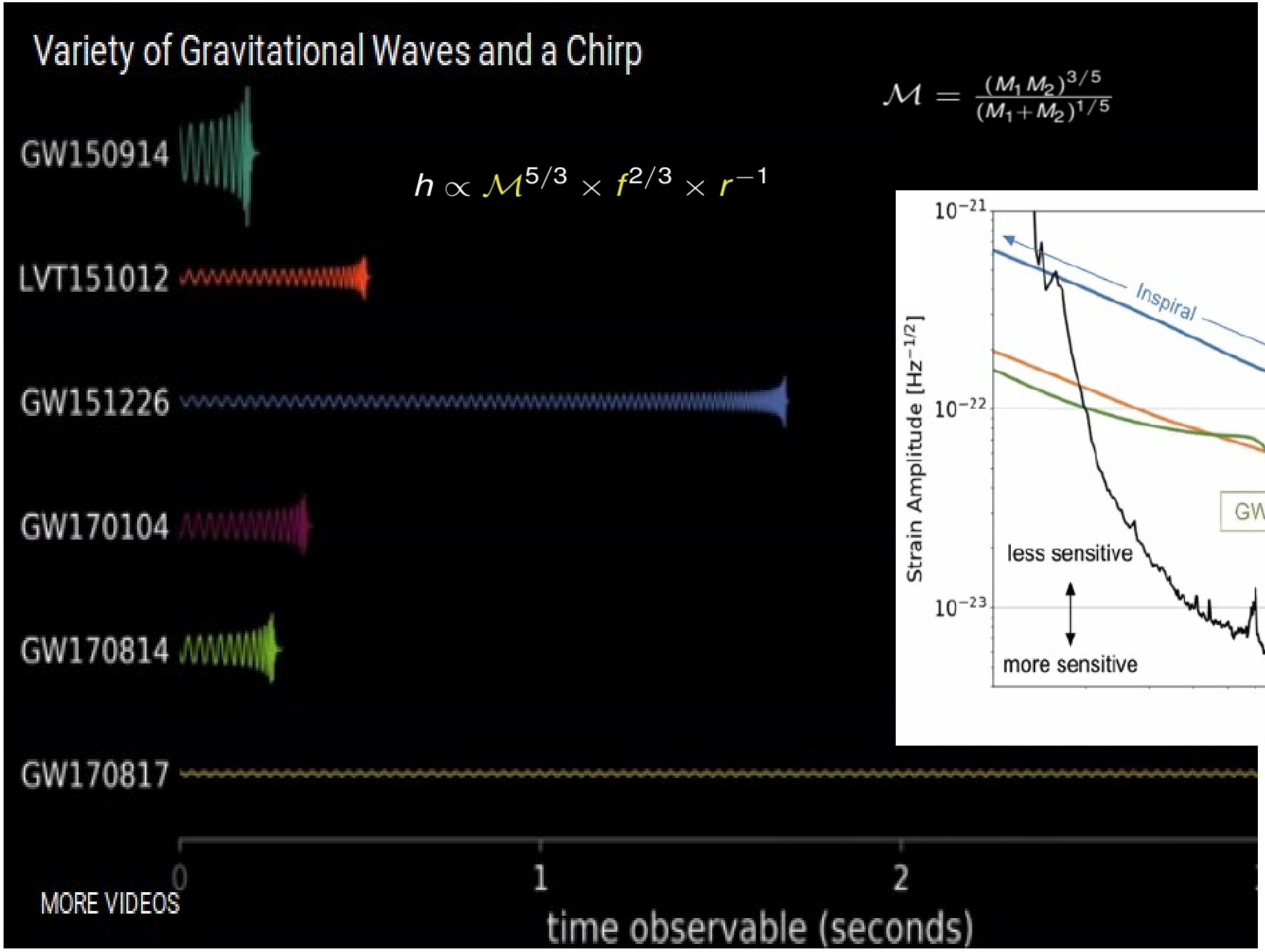


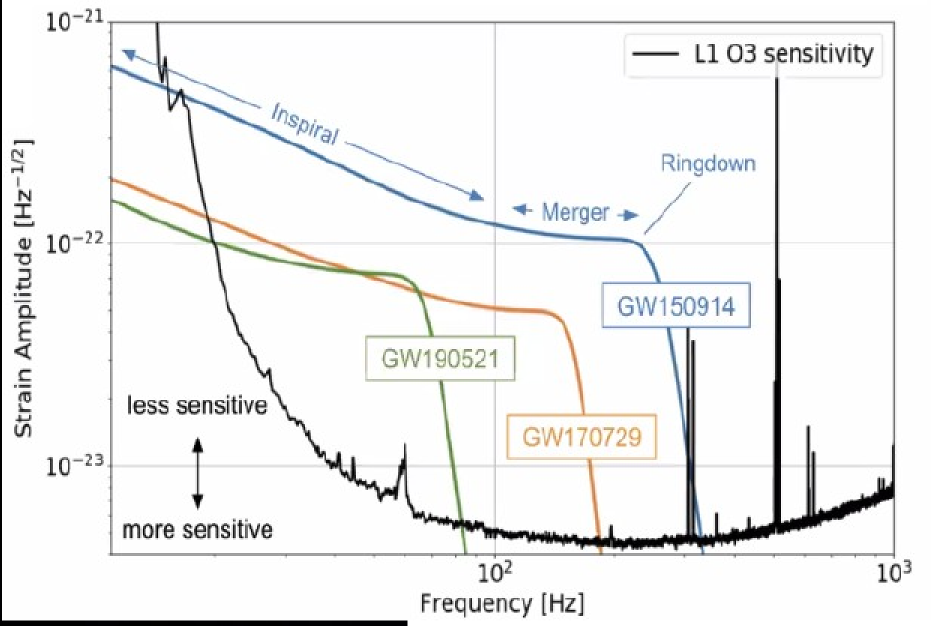
LIGO-VIRGO-KAGRA observing runs
Average sensitive distance to optimally oriented NS-NS binaries



Examples of observed chirp signals (names GWYYMMDD)

$f_{gw,merger}$ ~2 kHz/(M1+M2), M1 and M2 in solar masses





Evidence of Intermediate Mass Black Holes (IMBH, 10^2 – 10^5 Msol)
GW190521,GW190426_190642,GW190403_051519, GW200220_061928

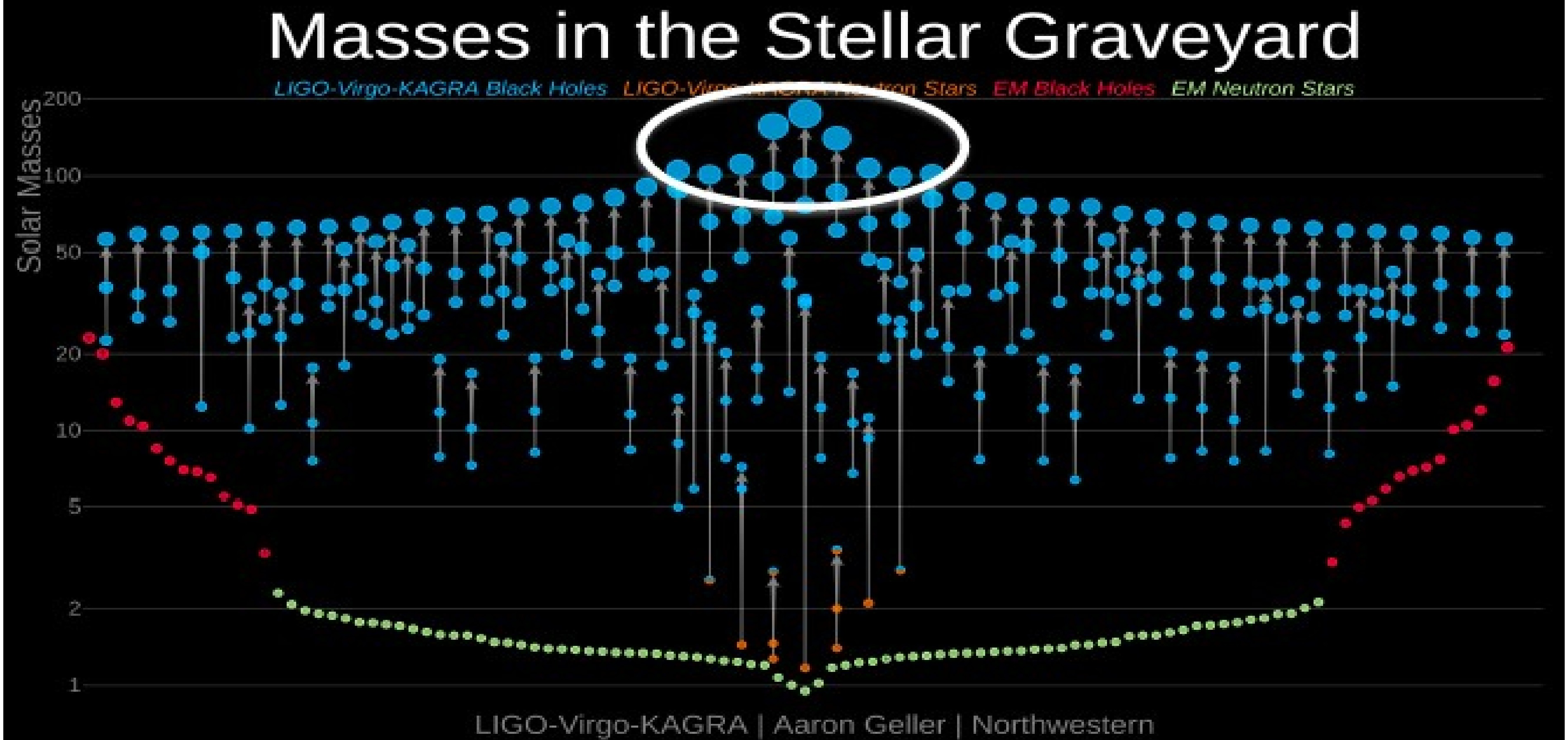
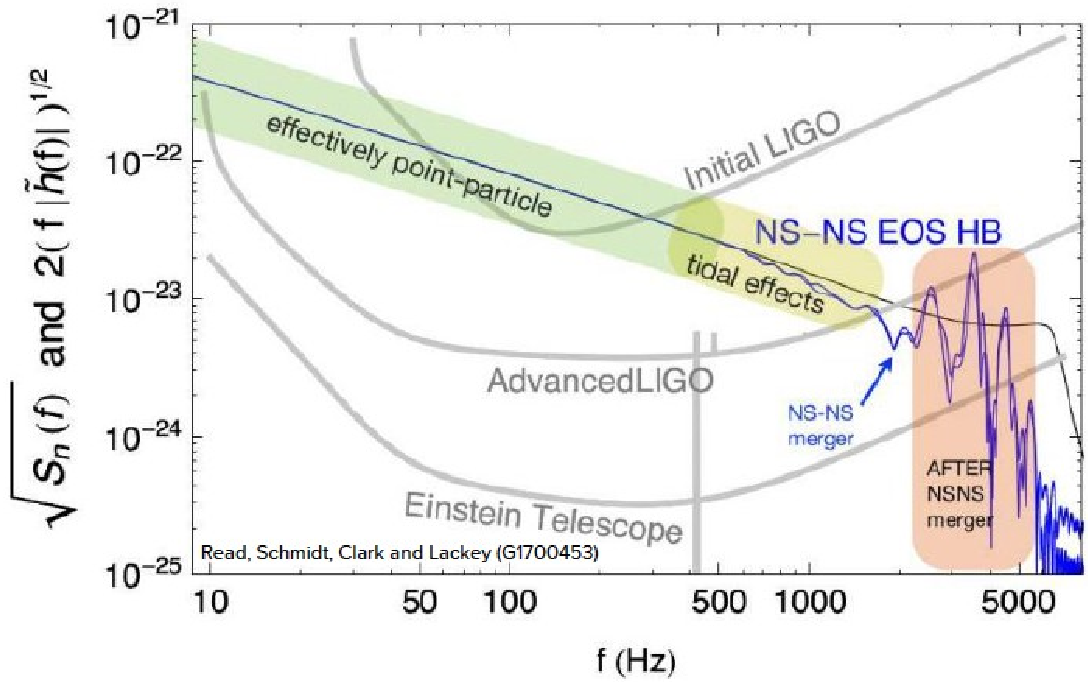
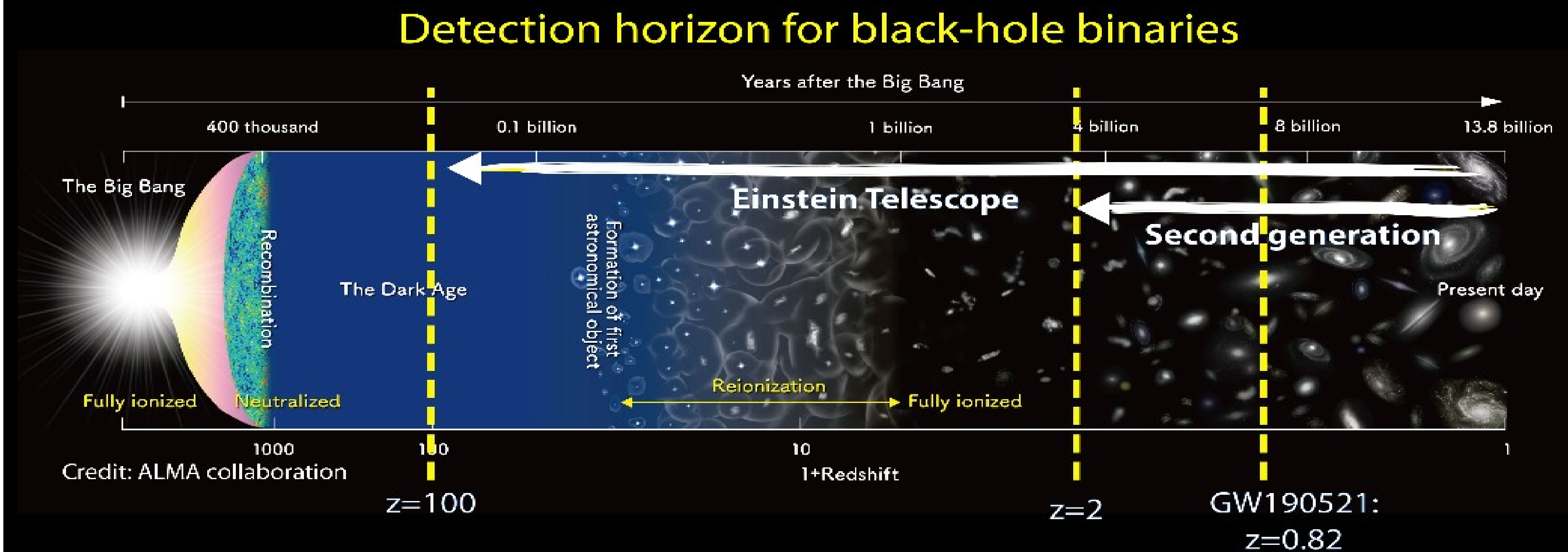


Image Credit: LIGO-Virgo-KAGRA/Northwestern Univ./Aaron Geller

An example of a coalescing binary neutron stars (high frequency)

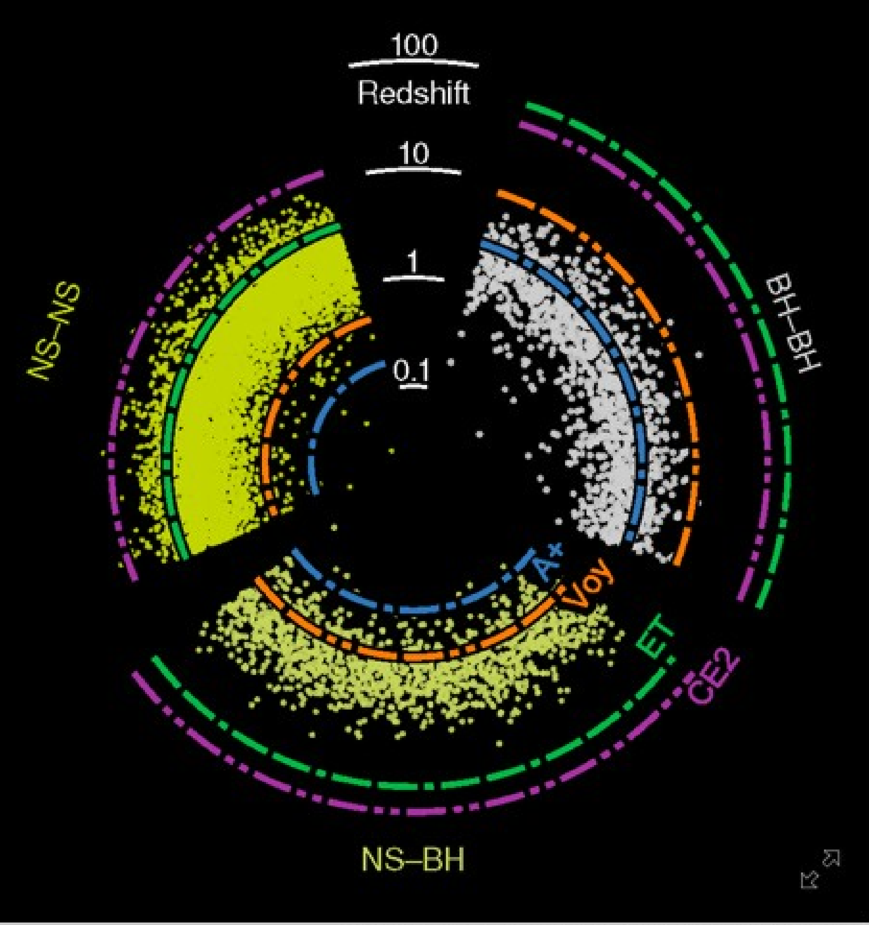


Einstein Teleskop (1Hz-10 kHz) will observe all BH-IMBH in Universe



Next-generation observatories will allow researchers to observe binary mergers from the dark ages when the Universe was only a few hundred million years old.

- BBH up to $z \approx 50$!!
  10^6 BBH/yr
  masses up to $10^3\ M_\odot$
- BNS to $z \approx 2$ 10^5 BNS/yr
  (possibly O(10-100/yr)
  with counterpart)
- high SNR



Evan Hall and Salvatore Vitale/Massachusetts Institute of Technology

Contiuous wave sources

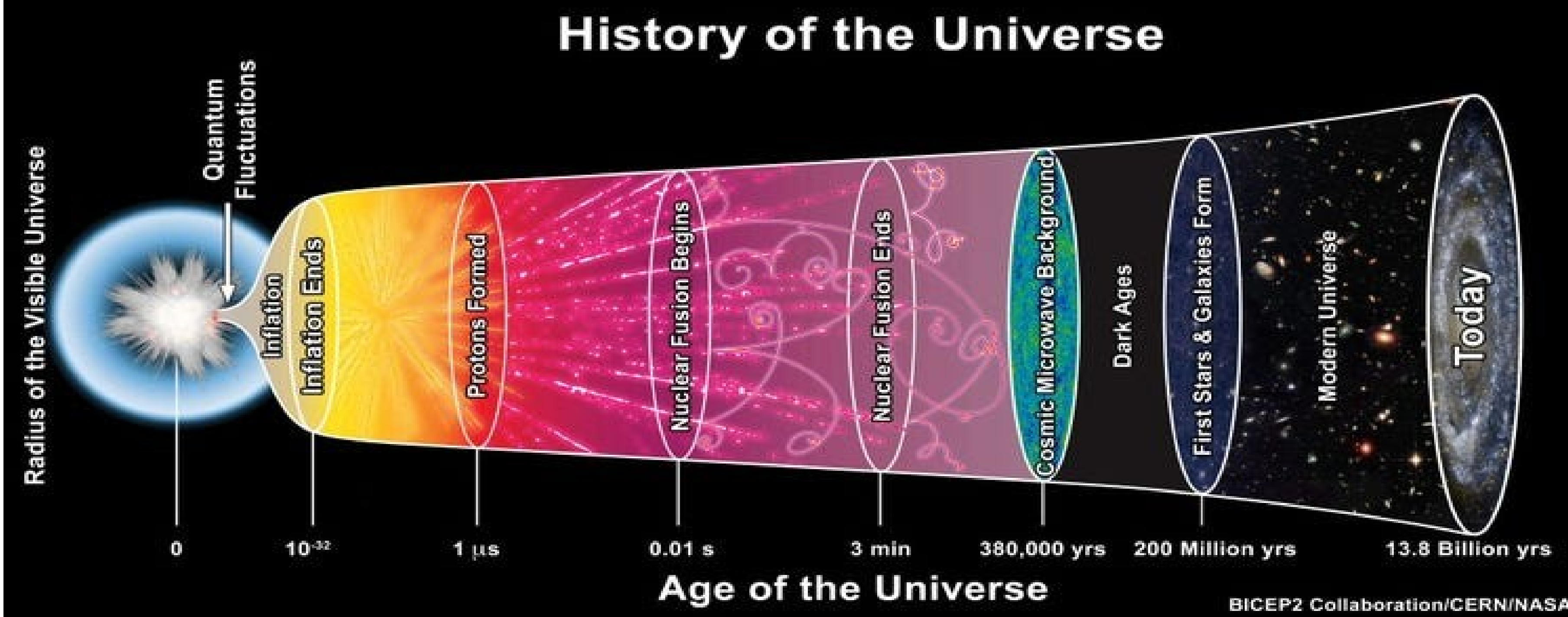
- Elasticity, persistence of magnetic fileds
- Magnetar flares
- NS oscillations
- Binaries – spin evolution

Strong gravity, modified theories

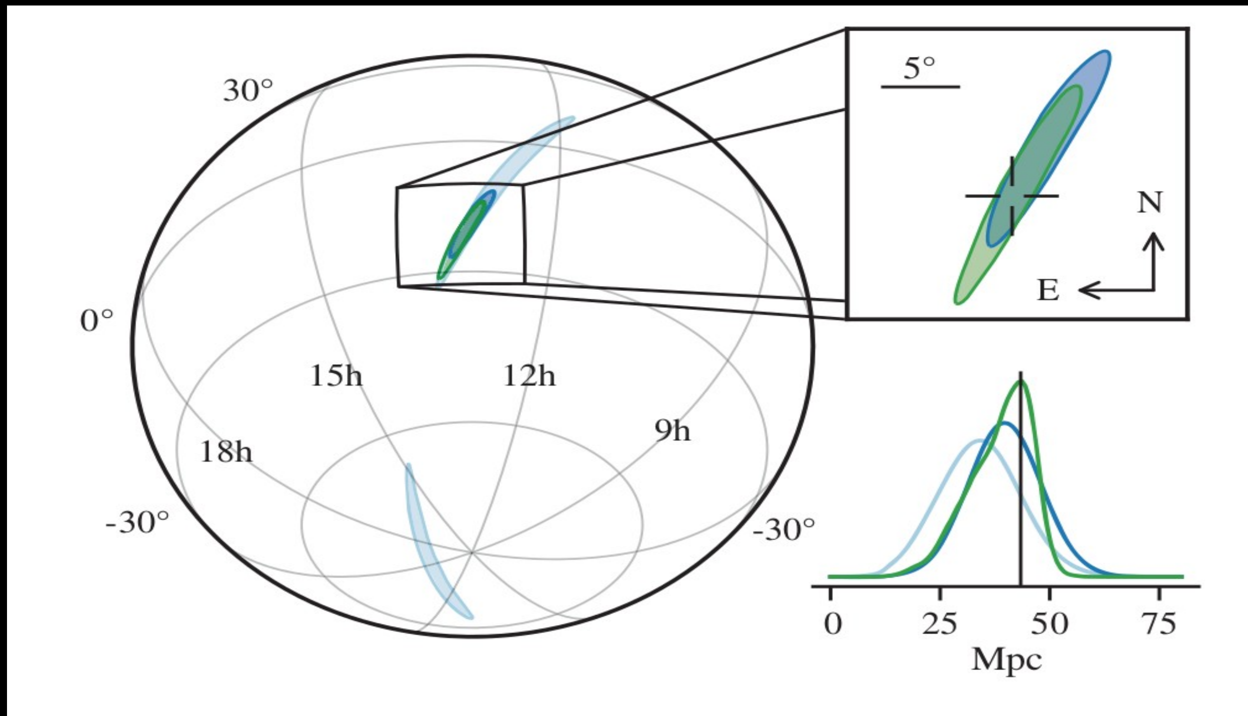
- So far GR succesful
- But problems persist:
  - BH information loss,
  - GR vs quantum theory
  - Planck scale structure of horizons…

  - Does speed of GW depend on frequency?

Stochastic backgrounds

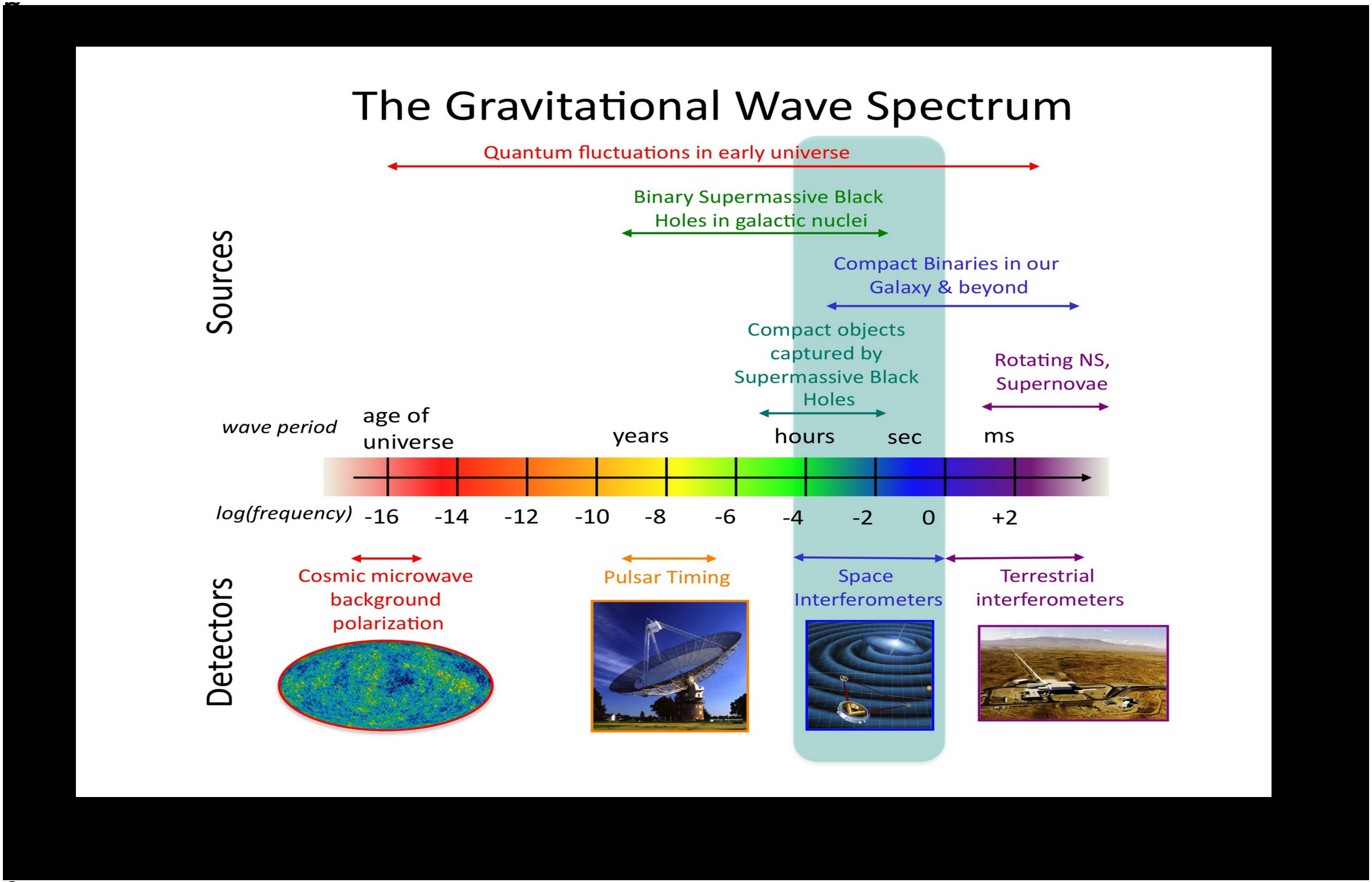


Multimessenger astronomy



Summary

- 3D detectors (ET and CE) in ~10 yr – breakthrough discoveries!
- Important contribution to astrophysics, cosmology and fundamental physics
- Testing GR in strong gravitational field
- Nature of black holes and EOS of neutron stars
- New tool for measuring cosmic distances
- Constraints on the cosmological models
- Expansion of the Universe and dark matter
- New discoveries: stochastic background, core collapse supernovae, rotating neutron stars, unexpected
- And a lot more!!!


The Gravitational Wave Spectrum
Sources
Quantum fluctuations in early universe
Binary Supermassive Black Holes in galactic nuclei
Compact Binaries in our Galaxy & beyond
Compact objects captured by Supermassive Black Holes
Rotating NS, Supernovae
wave period
age of universe
years
hours
sec
ms
log(frequency)
-16
-14
-12
-10
-8
-6
-4
-2
0
+2
Detectors
Cosmic microwave background polarization
Pulsar Timing
Space Interferometers
Terrestrial interferometers

e
k