

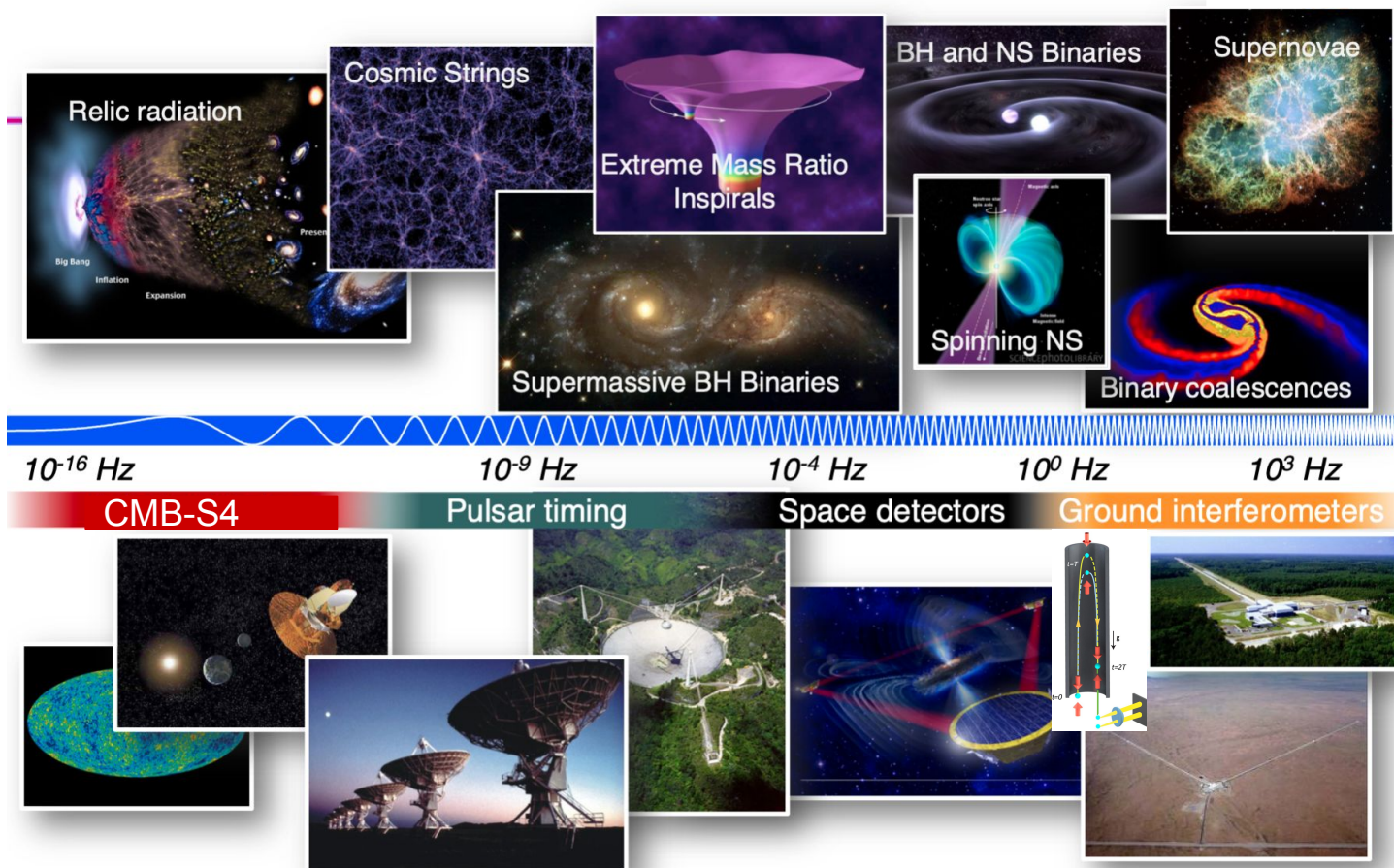
Probing Fundamental Physics with the Gravitational Wave Universe

WP on Future GW Detector Facilities:
<https://arxiv.org/abs/2203.08228>



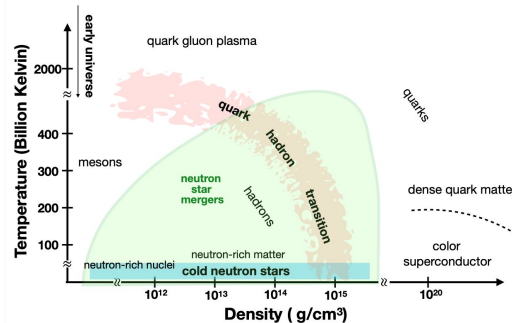
Rana X Adhikari

The GW Spectrum



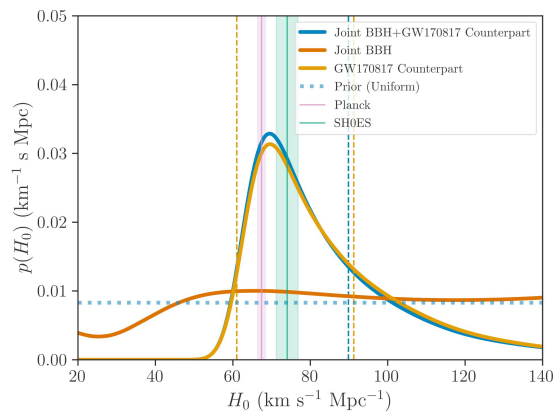
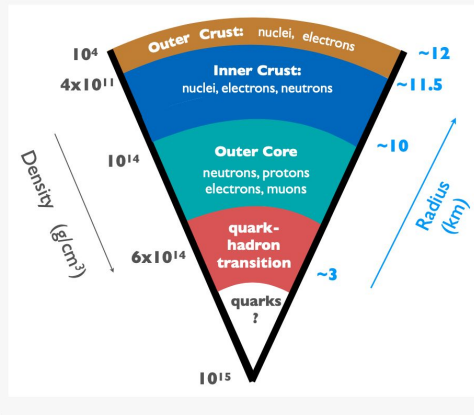
“Top” 5 GW Science targets

1. Confirm/resolve the Hubble “tension”
2. Search for particle-like, wave-like and macroscopic dark matter
3. Constrain QCD phase transition and measure EoS of dense nuclear matter
4. Infer the nature of dark energy and determine if it is just a cosmological constant or depends on redshift
5. What is the true structure of spacetime?



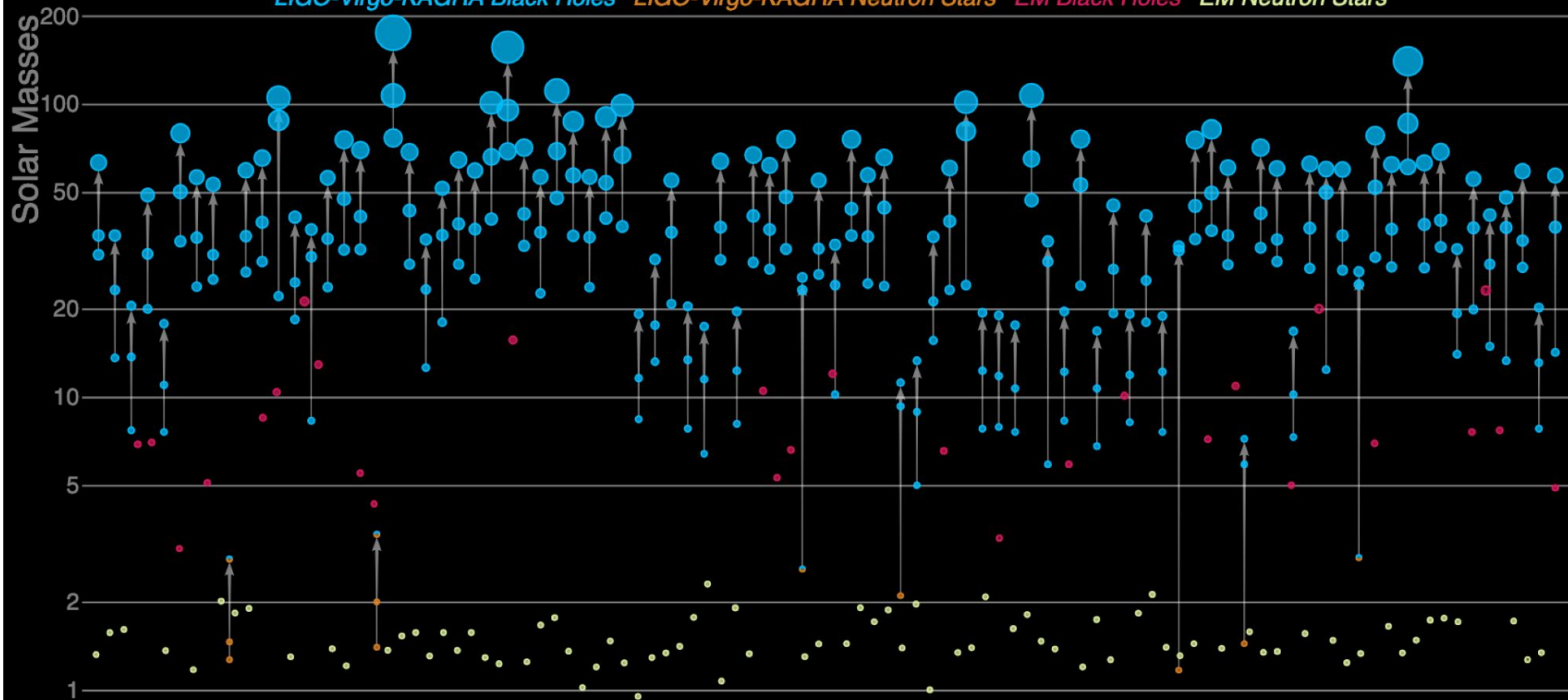
INTERNAL STRUCTURE OF A NS

Figure 2.1: Composition of matter in the interior of a NS predicted by theory. Quark degrees of freedom become important at the densities encountered in the inner core. The nature of the transition to matter containing de-confined quarks is unknown.



Masses in the Stellar Graveyard

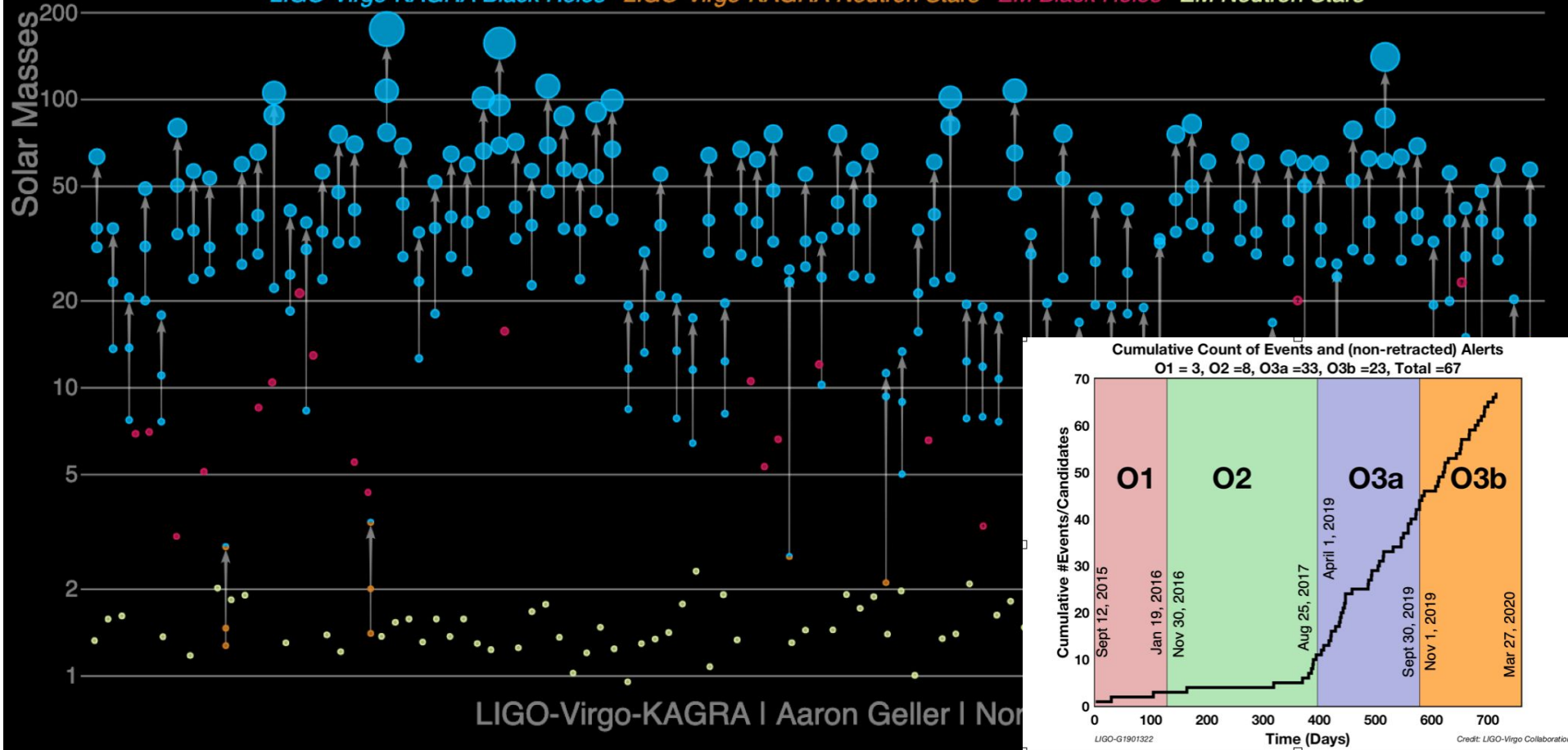
LIGO-Virgo-KAGRA Black Holes *LIGO-Virgo-KAGRA Neutron Stars* *EM Black Holes* *EM Neutron Stars*

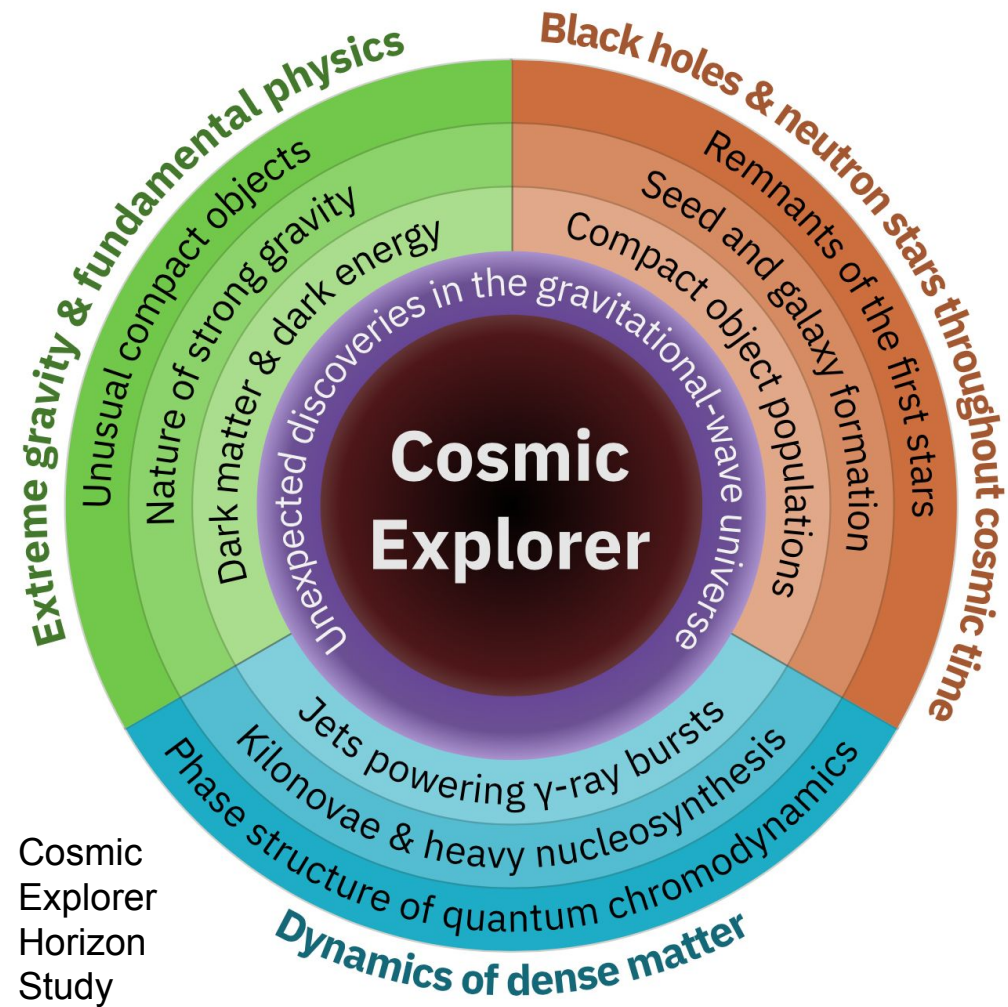


LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

Masses in the Stellar Graveyard

LIGO-Virgo-KAGRA Black Holes LIGO-Virgo-KAGRA Neutron Stars EM Black Holes EM Neutron Stars





GW170817

Binary neutron star merger

A LIGO / Virgo gravitational wave detection with associated electromagnetic events observed by over 70 observatories.



Distance
130 million light years

Discovered
17 August 2017

Type
Neutron star merger



12:41:04 UTC

A gravitational wave from a binary neutron star merger is detected.

gravitational wave signal

Two neutron stars, each the size of a city but with at least the mass of the sun, collided with each other.



GW170817 allows us to measure the expansion rate of the universe directly using gravitational waves for the first time.



Detecting gravitational waves from a neutron star merger allows us to find out more about the structure of these unusual objects.



This multimessenger event provides confirmation that neutron star mergers can produce short gamma ray bursts.



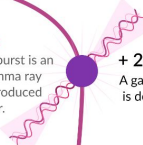
The observation of a kilonova allowed us to show that neutron star mergers could be responsible for the production most of the heavy elements, like gold, in the universe.



Observing both electromagnetic and gravitational waves from the event provides compelling evidence that gravitational waves travel at the same speed as light.

gamma ray burst

A short gamma ray burst is an intense beam of gamma ray radiation which is produced just after the merger.



+ 2 seconds

A gamma ray burst is detected.



kilonova

Decaying neutron-rich material creates a glowing kilonova, producing heavy metals like gold and platinum.

+10 hours 52 minutes

A new bright source of optical light is detected in a galaxy called NGC 4993, in the constellation of Hydra.

+11 hours 36 minutes

Infrared emission observed.

+15 hours

Bright ultraviolet emission detected.

+9 days

X-ray emission detected.

radio remnant

As material moves away from the merger it produces a shockwave in the interstellar medium - the tenuous material between stars. This produces emission which can last for years.

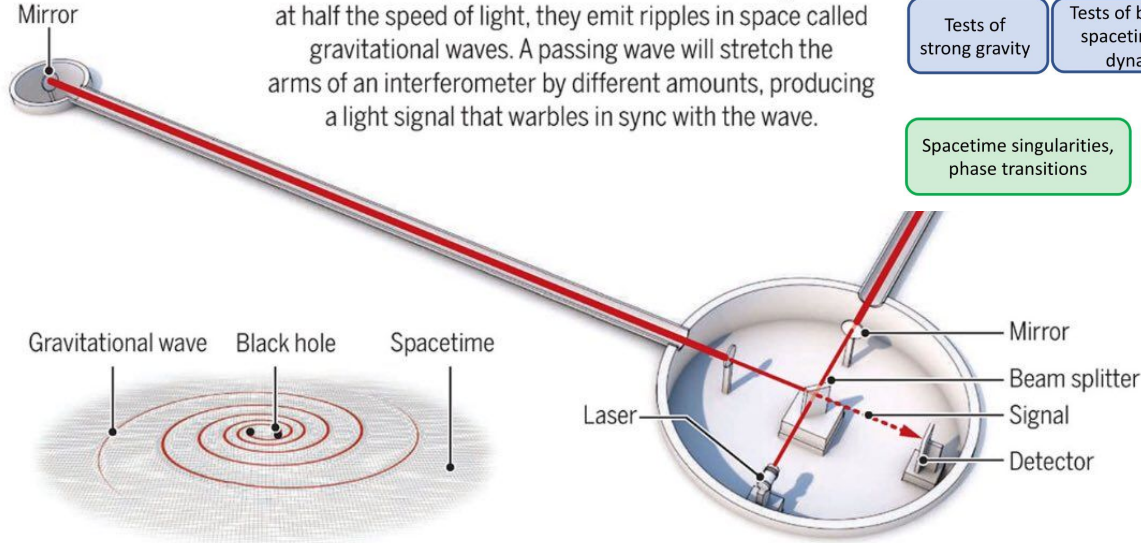


+16 days

Radio emission detected.

Wave catchers

As massive objects such as black holes swirl together at half the speed of light, they emit ripples in space called gravitational waves. A passing wave will stretch the arms of an interferometer by different amounts, producing a light signal that warbles in sync with the wave.



Big new ideas

Current gravitational wave detectors (red) are huge. The ones scientists hope to build next (blue) are even bigger and more complex.

LIGO
4 km



Virgo
3 km



KAGRA
3 km



Golden Gate Bridge
2.7 km



Cosmic Explorer
40 km

Einstein Telescope
10 km



Experiments

Ground-based
GW detectors

Space-based
GW detectors

Pulsar Timing Arrays

Electromagnetic
observations

Science investigations

Tests of
strong gravity

Tests of black hole
spacetimes and
dynamics

Cosmological
gravitational waves

Gravitational signatures
of dark matter

Multimessenger
cosmology

Fundamental physics

Spacetime singularities,
phase transitions

QFT in curved spacetime,
information paradox

BSM physics,
modified gravity

Astroparticle
physics

Sensitivity Comparison

LISA: launch date ~2034

aLIGO: scheduled upgrades over the next decade: ~2-3x increase in range (Mpc)

Voyager: ~\$200M (existing 4km LIGO facilities) + 1 in India.

CE/ET: new GW facilities at the 10-40 km & ~\$1-2B scale, operating ~2030-2040

MAGIS: Atom based laser interferometers

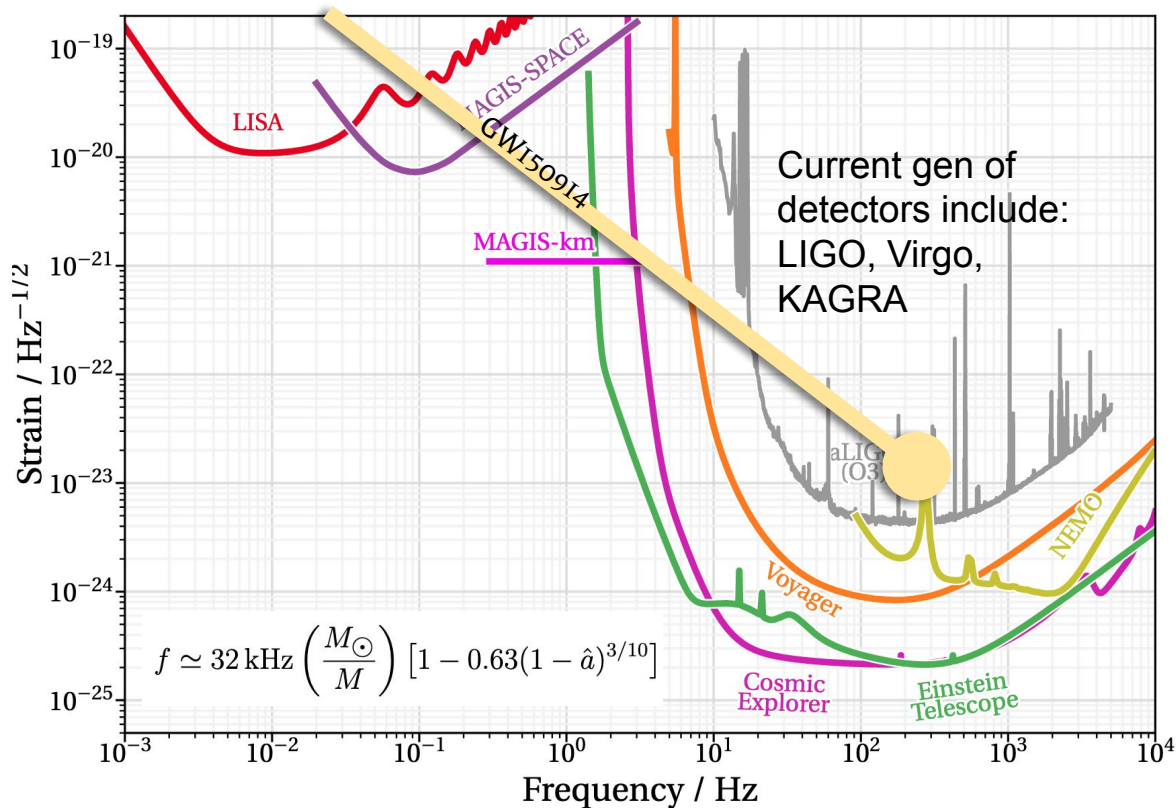
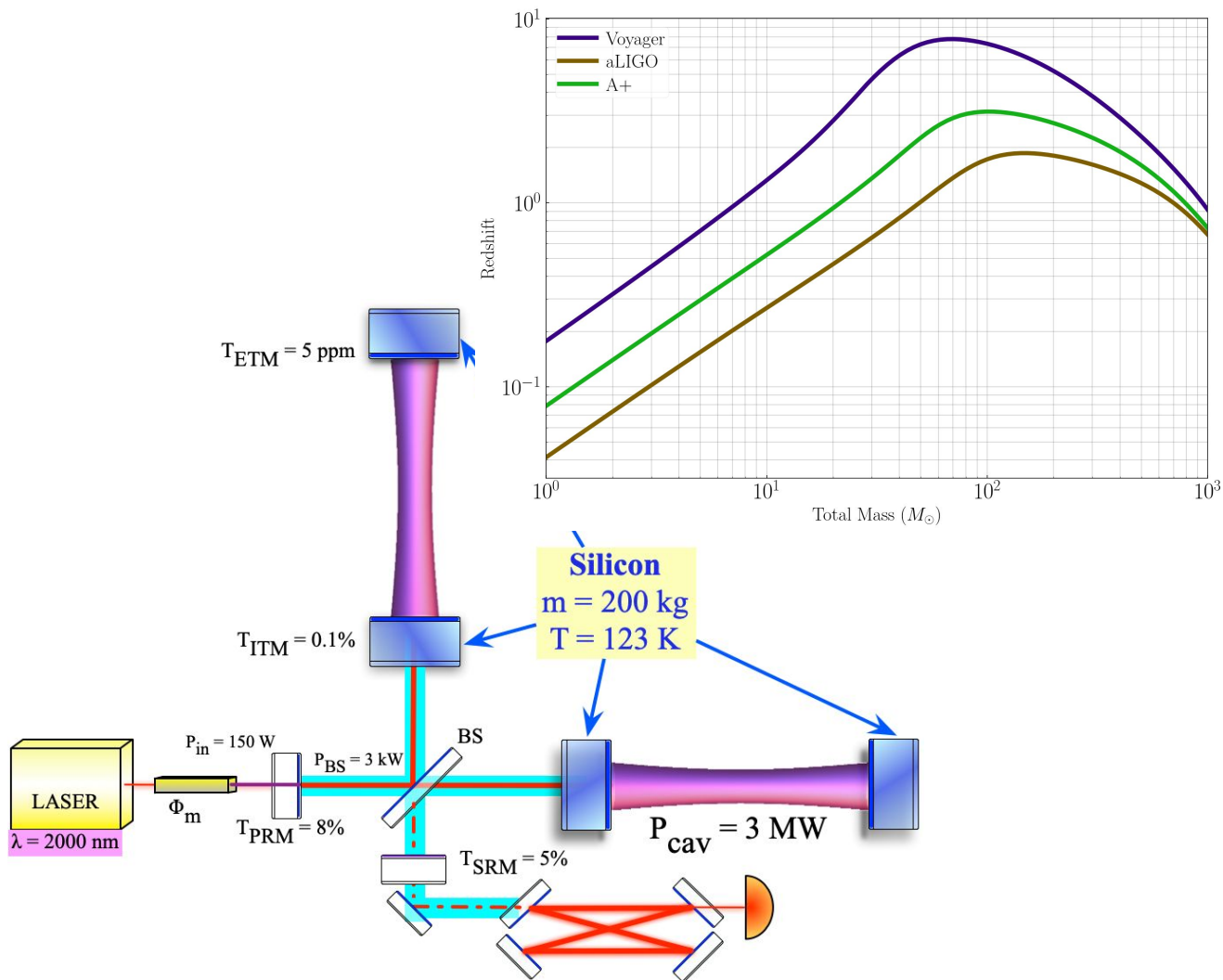
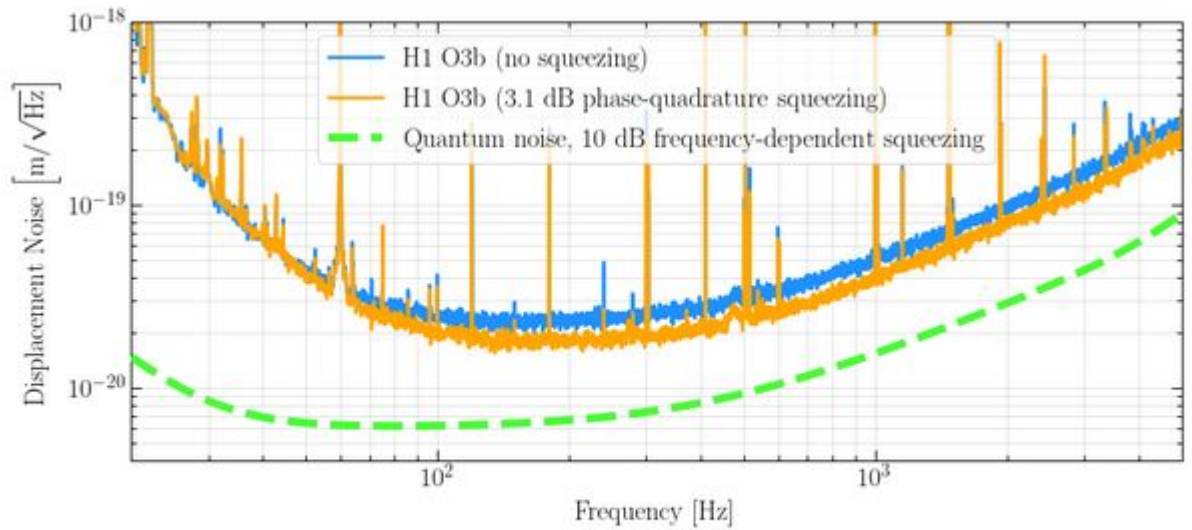
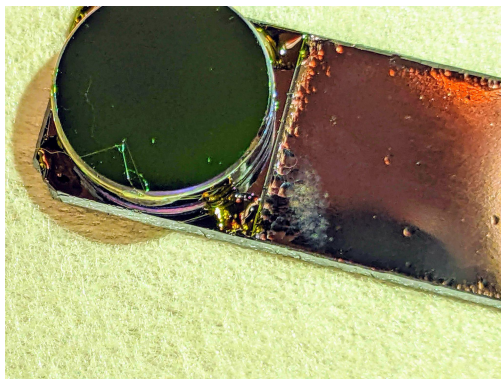


FIG. 1. Amplitude spectral densities of detector noise for the next-generation laser interferometers Cosmic Explorer, LIGO Voyager, the proposed Australian NEMO detector, and the three paired detectors of the triangular Einstein Telescope. Detector noise curves are also shown for the proposed MAGIS-km atom interferometer and envisioned space-based follow-on detector (MAGIS-SPACE). The sensitivity curves of Advanced LIGO's last observation run (aLIGO O3) and of the Laser Interferometer Space Antenna (LISA) are shown for comparison.

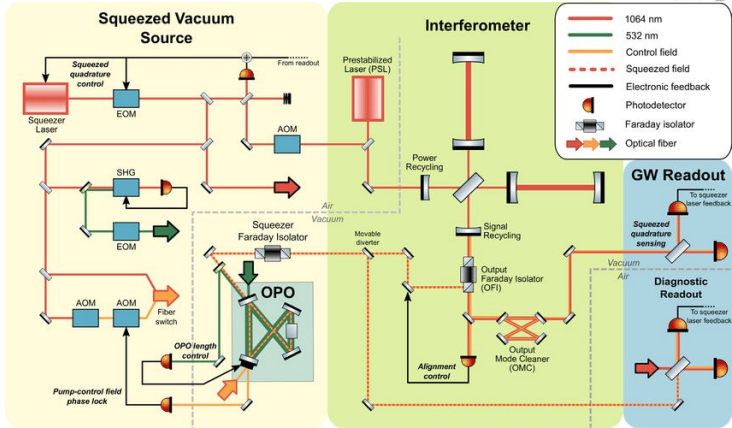
LIGO Voyager

- Replacing LIGO glass optics with cryogenic silicon
- High thermal conductivity to avoid thermal distortion instabilities
- Leverages existing facilities
- 4-5x improvement over Advanced LIGO (2023)
- Uses newer, less established technologies





Squeezed-Light-Enhanced Interferometry



Squeezing More from GW Detectors:
<https://physics.aps.org/articles/v12/139>

Atom based Interferometers

MAGIS - 100

MAGIS - KM

MAGIS - SPACE

Also efforts in UK, China, Europe

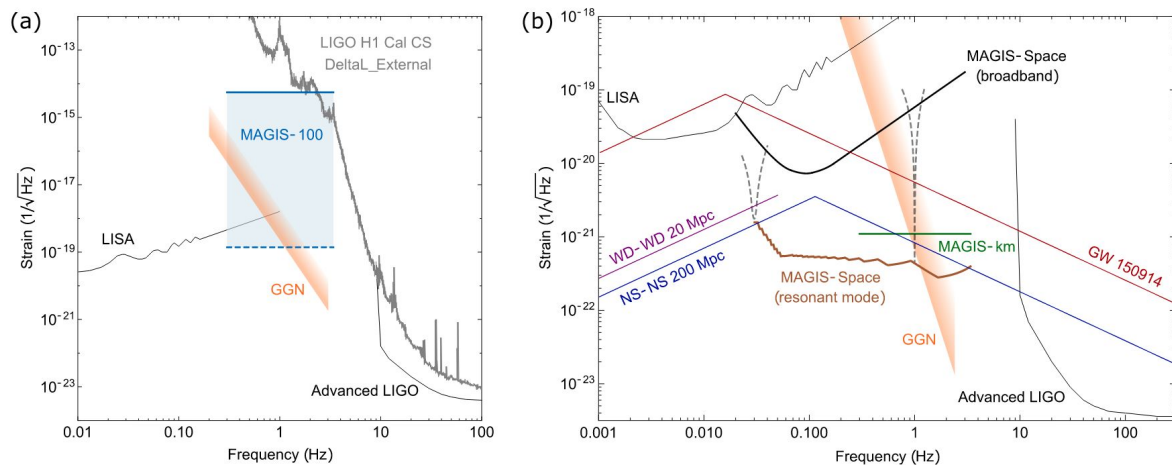


FIG. 5. (a) Projected gravitational wave strain sensitivity for MAGIS-100 and follow-on detectors. The

Cosmic Explorer / Einstein Telescope

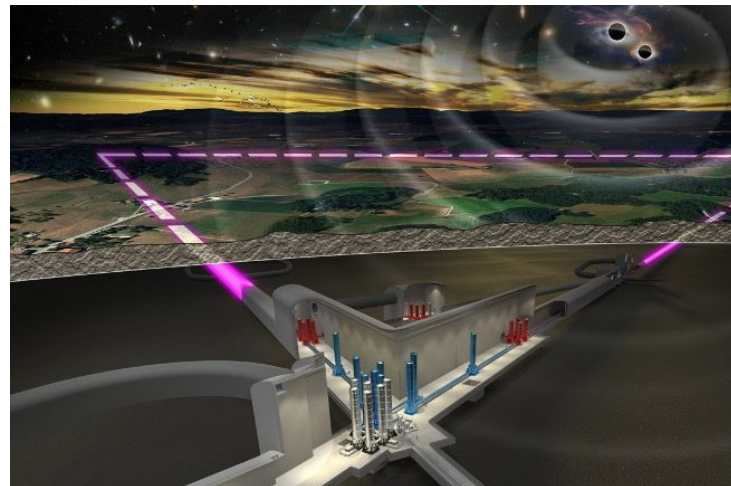
New, very large, GW Facilities

ET: 10 km, underground in Europe

- New technologies

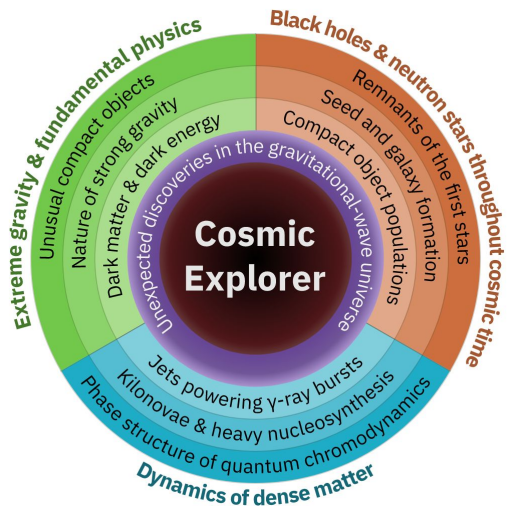
CE: 1 or 2, 20-40 km, probably USA

- Mostly scaling up of existing LIGO technologies; lower risk



“The Next Generation Global Gravitational Wave Observatory: The Science Book”

<https://arxiv.org/abs/2111.06990>



Summary

1. GW Detectors (on the ground and in space) cover many decades in energy/frequency.
2. GWs are unique messengers carrying unique messages.
3. Synergy with Electromagnetic, neutrino, ...: multi-messenger astrophysics
4. Nature of matter in the universe
5. Expansion history: back to $z \sim 10$ in the next decade
6. What is the structure of spacetime and how do DM and DE look with gravitational vision?