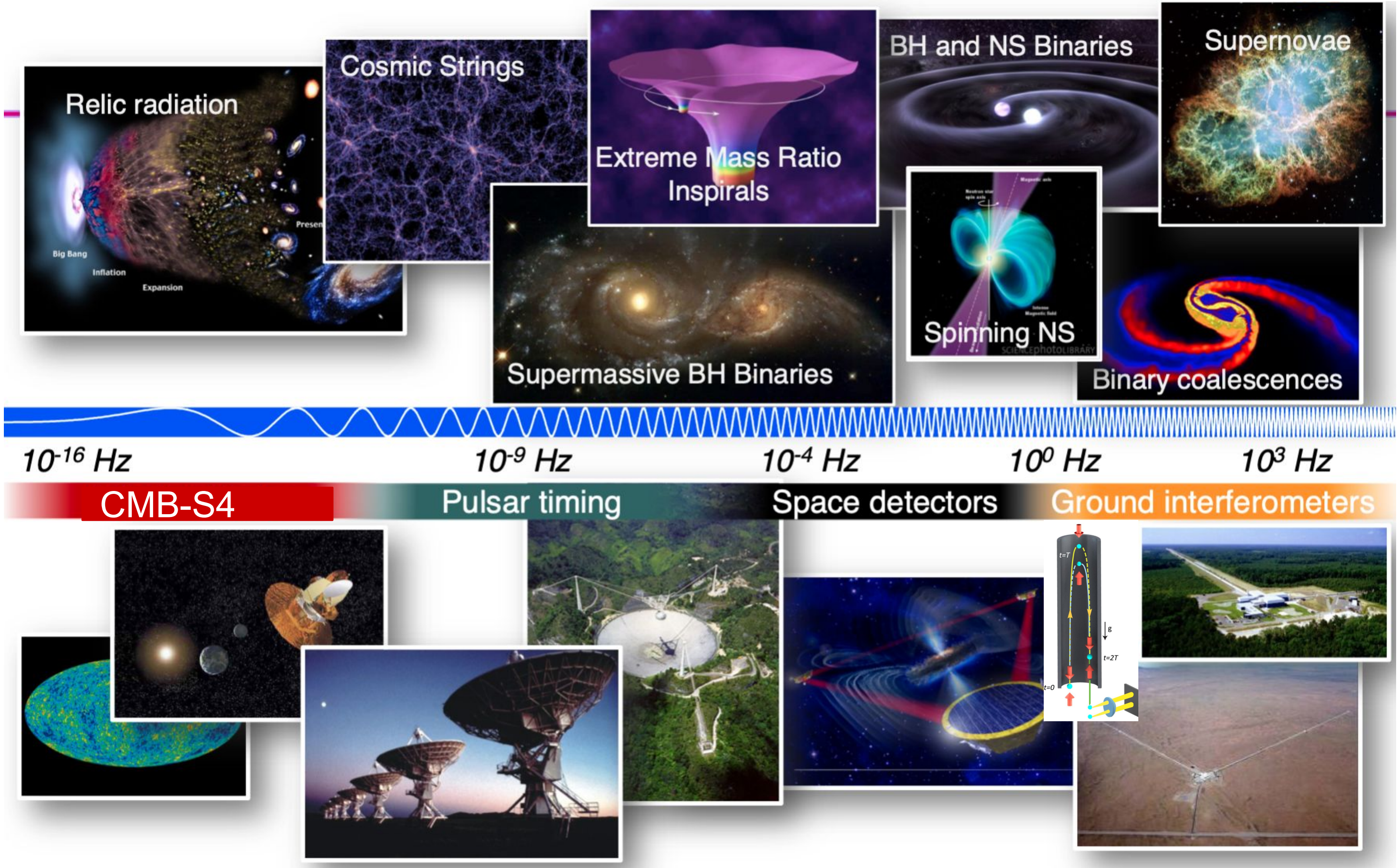
Probing Fundamental Physics with the Gravitational Wave Universe

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

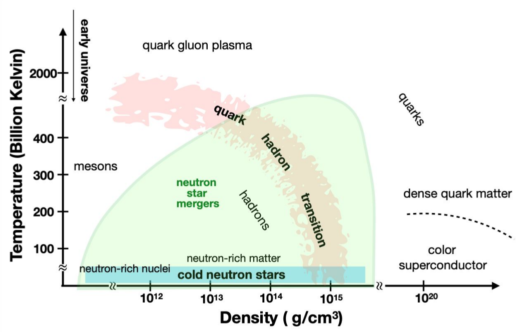
Rana X Adhikari

The GW Spectrum



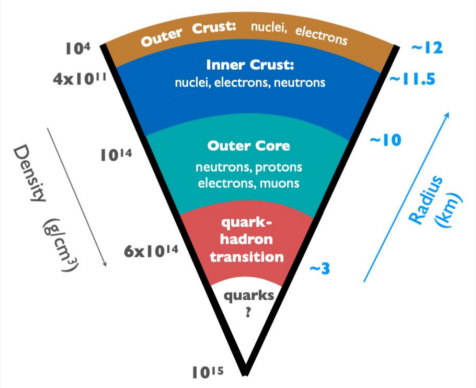
“Top” 5 GW Science targets

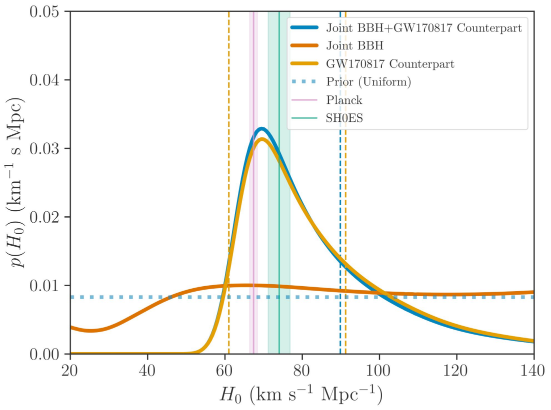
1. Confirm/resolve the Hubble “tension”
2. Search for particle-like, wave-like and macroscopic dark matter
3. Constrain QCD phase transition and measure EoS of dense nuclear matter
4. Infer the nature of dark energy and determine if it is just a cosmological constant or depends on redshift
5. What is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

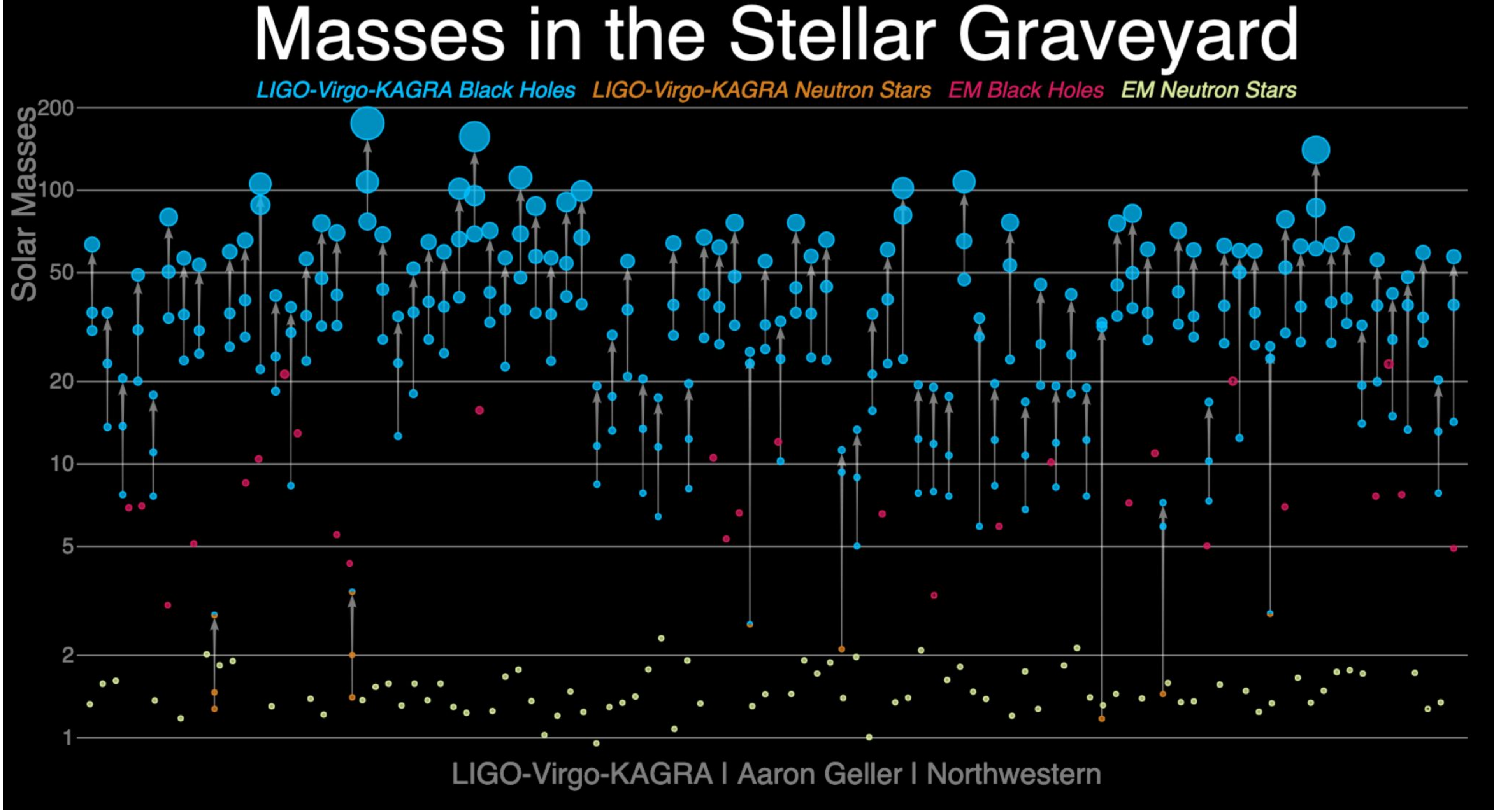


INTERNAL STRUCTURE OF A NS

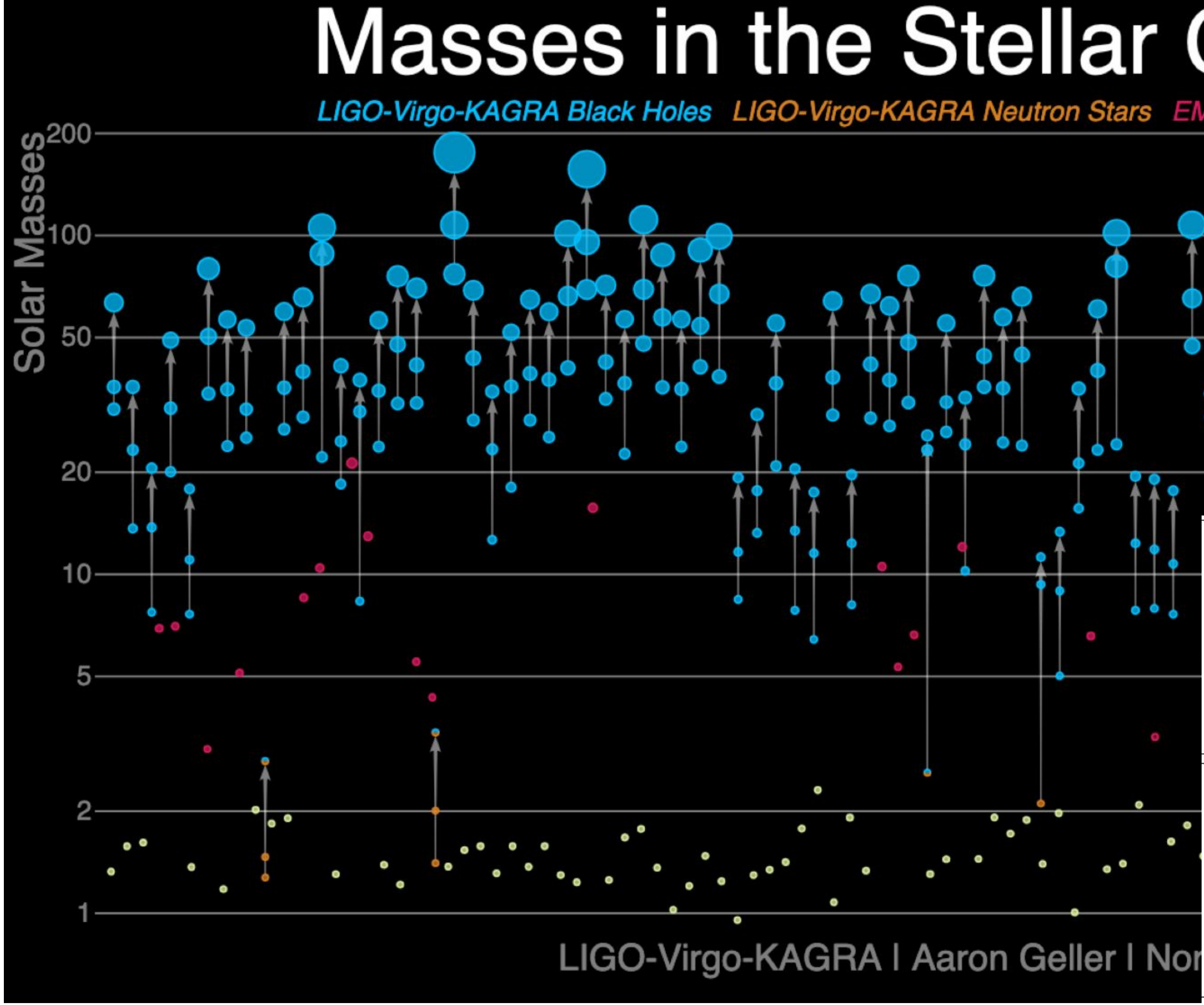
Figure 2.1: Composition of matter in the interior of a NS predicted by theory. Quark degrees of freedom become important at the densities encountered in the inner core. The nature of the transition to matter containing de-confined quarks is unknown.







Masses in the Stellar Graveyard
LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
EM Black Holes
EM Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern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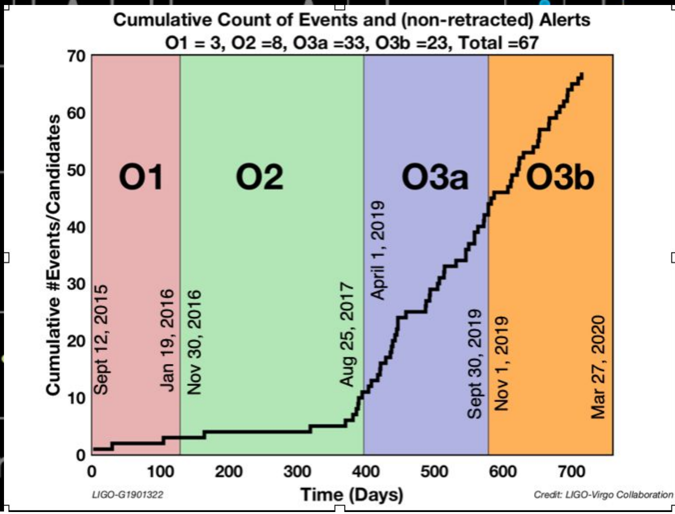
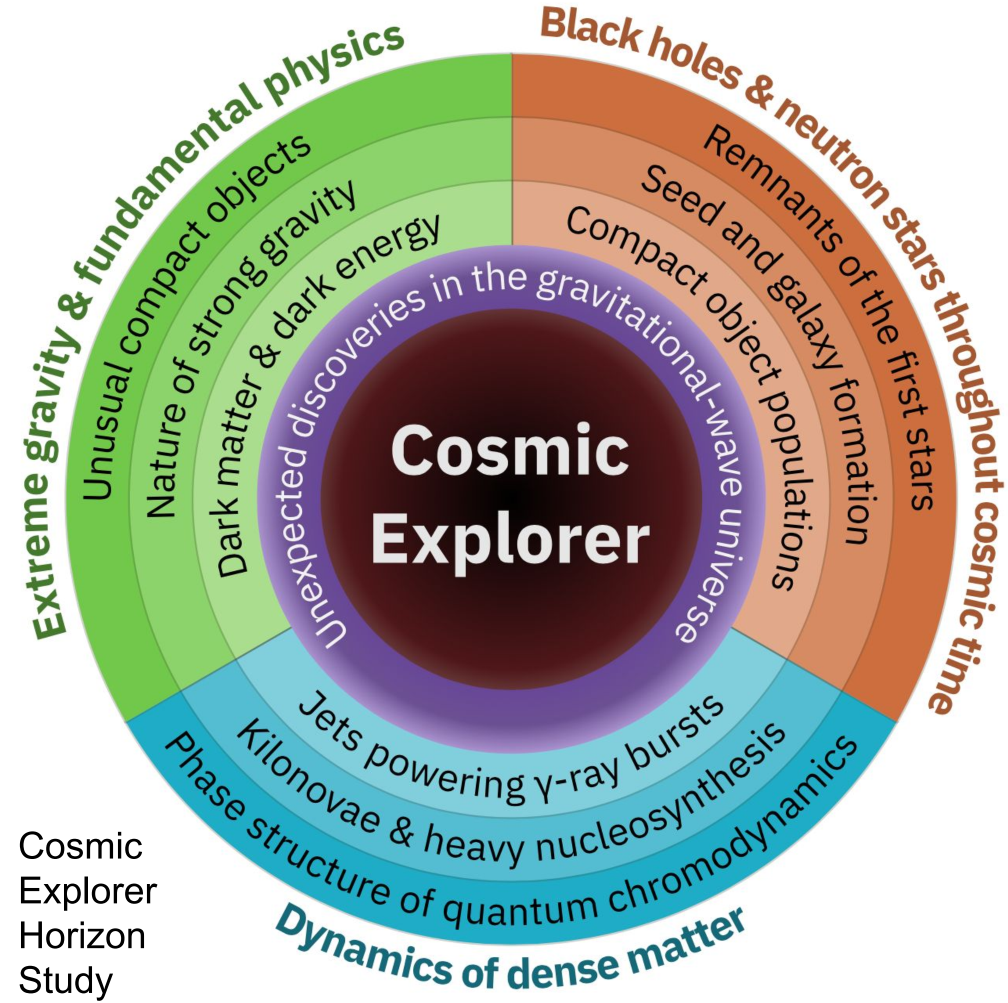
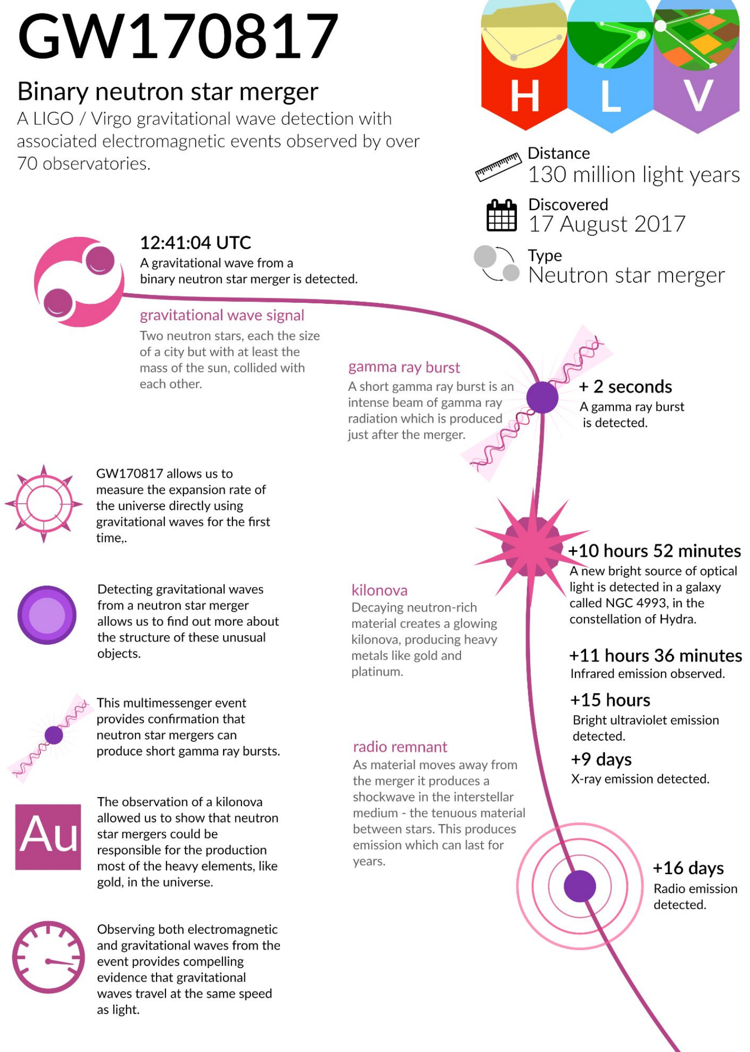
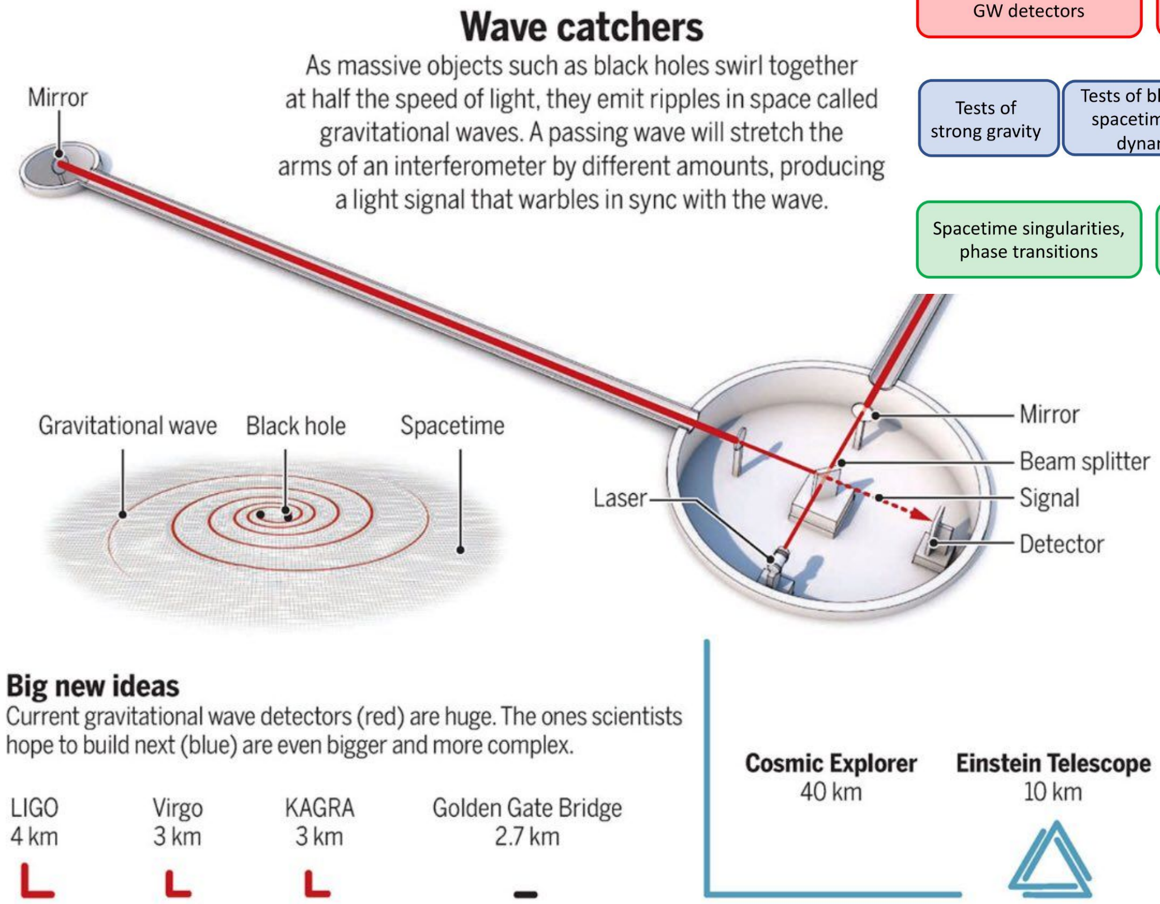

Cumulative Count of Events and (non-retracted) Alerts
O1 = 3, O2 =8, O3a =33, O3b =23, Total =67
Cumulative #Events/Candidates
0
10
20
30
40
50
60
70
O1
O2
O3a
O3b
Sept 12, 2015
Jan 19, 2016
Nov 30, 2016
Aug 25, 2017
April 1, 2019
Sept 30, 2019
Nov 1, 2019
Mar 27, 2020
0
100
200
300
400
500
600
700
Time (Days)
LIGO-G1901322
Credit: LIGO-Virgo Collaboration



Cosmic Explorer Horizon Study





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

https://doi.org/10.1126/science.371.6534.1089

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

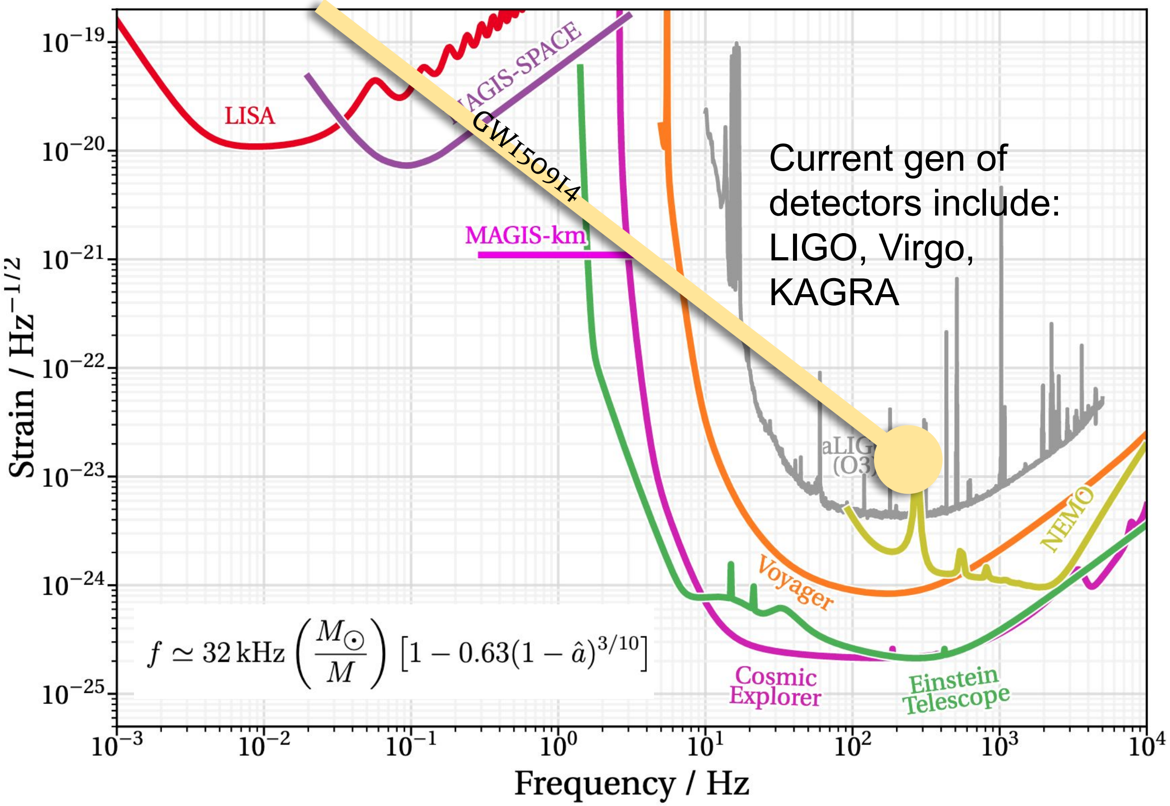
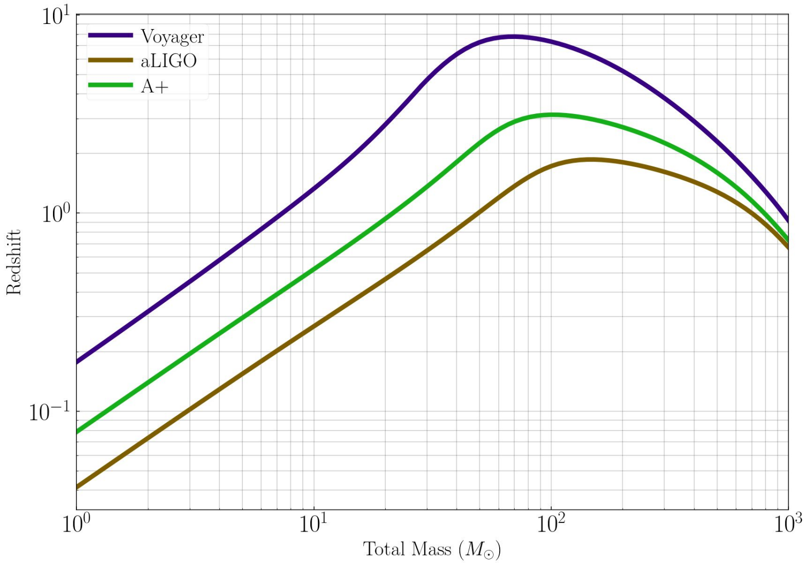
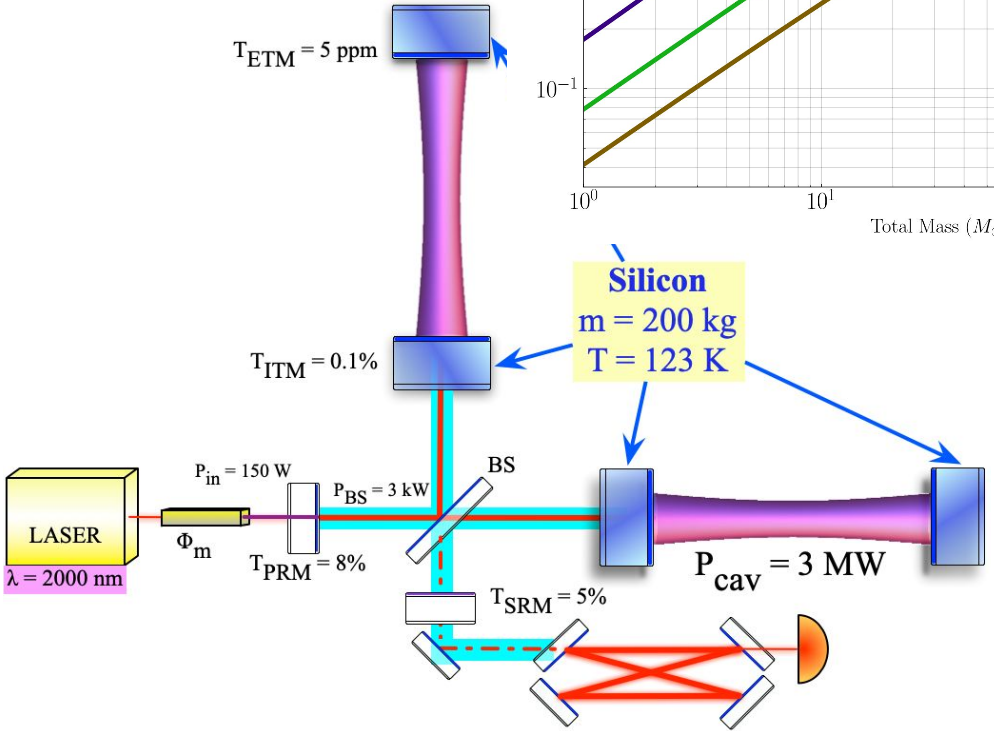


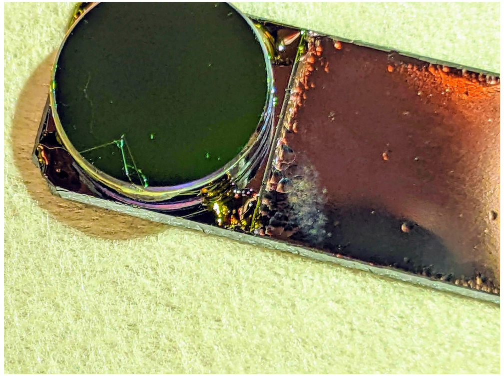
FIG. 1. Amplitude spectral densities of detector noise for the next-generation laser interferometers Cosmic Explorer, LIGO Voyager, the proposed Australian NEMO detector, and the three paired detectors of the triangular Einstein Telescope. Detector noise curves are also shown for the proposed MAGIS-km 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.

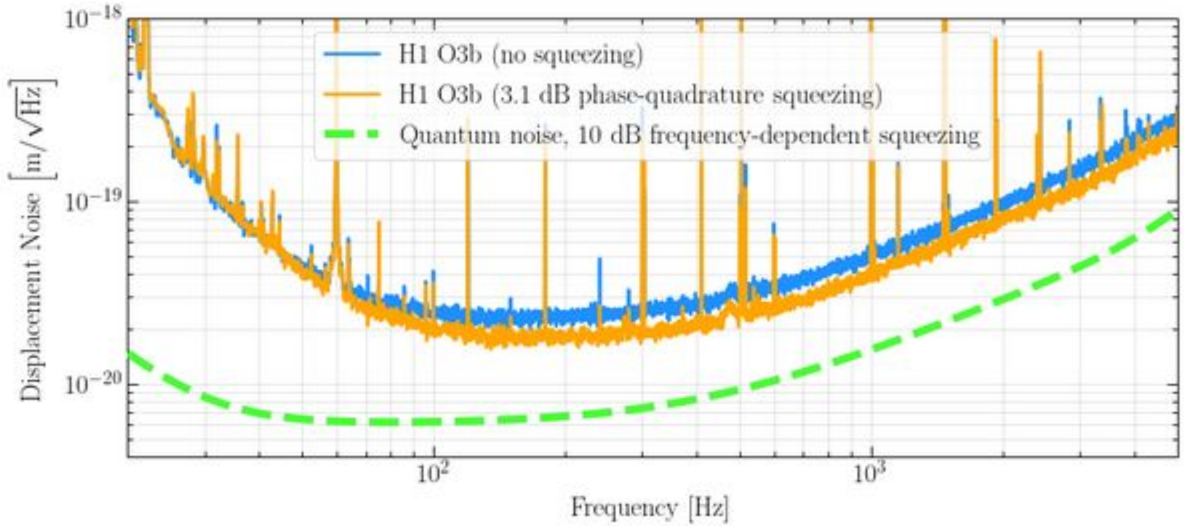
LIGO Voyager

- 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

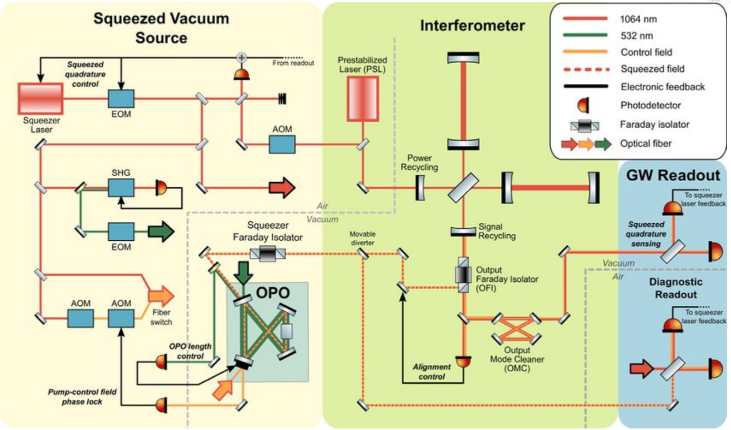








Squeezed-Light-Enhanced Interferometry



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

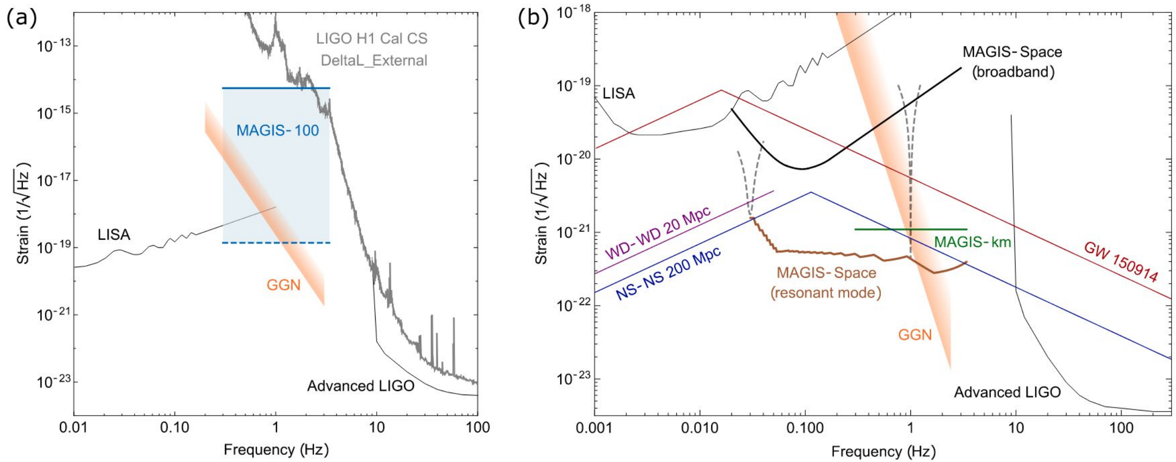
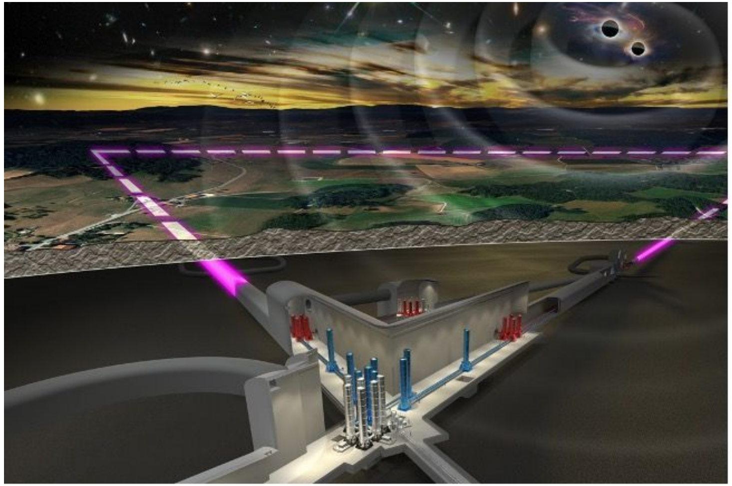


FIG. 5. (a) Projected gravitational wave strain sensitivity for MAGIS-100 and follow-on detectors. The

Cosmic Explorer / Einstein Telescope



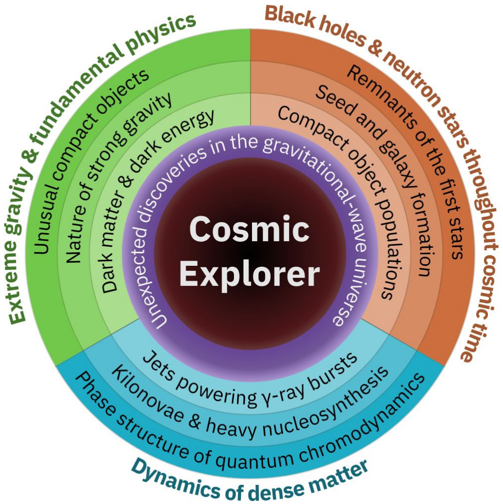
New, very large, GW Facilities

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~10 in the next decade
6. What is the structure of spacetime and how do DM and DE look with gravitational vision?