

Community Science (Ad ASTRA) Workshop
1 -3 September 2026, Pasadena, CA

CHRONOS*

A Quantum Clock Space Telescope for Gravitational Astrophysics

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1 September 2026

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*Chronometric High-precision Relativistic Observatory of Networked Optical-clocks in Space

Astro 2020 Priority Area

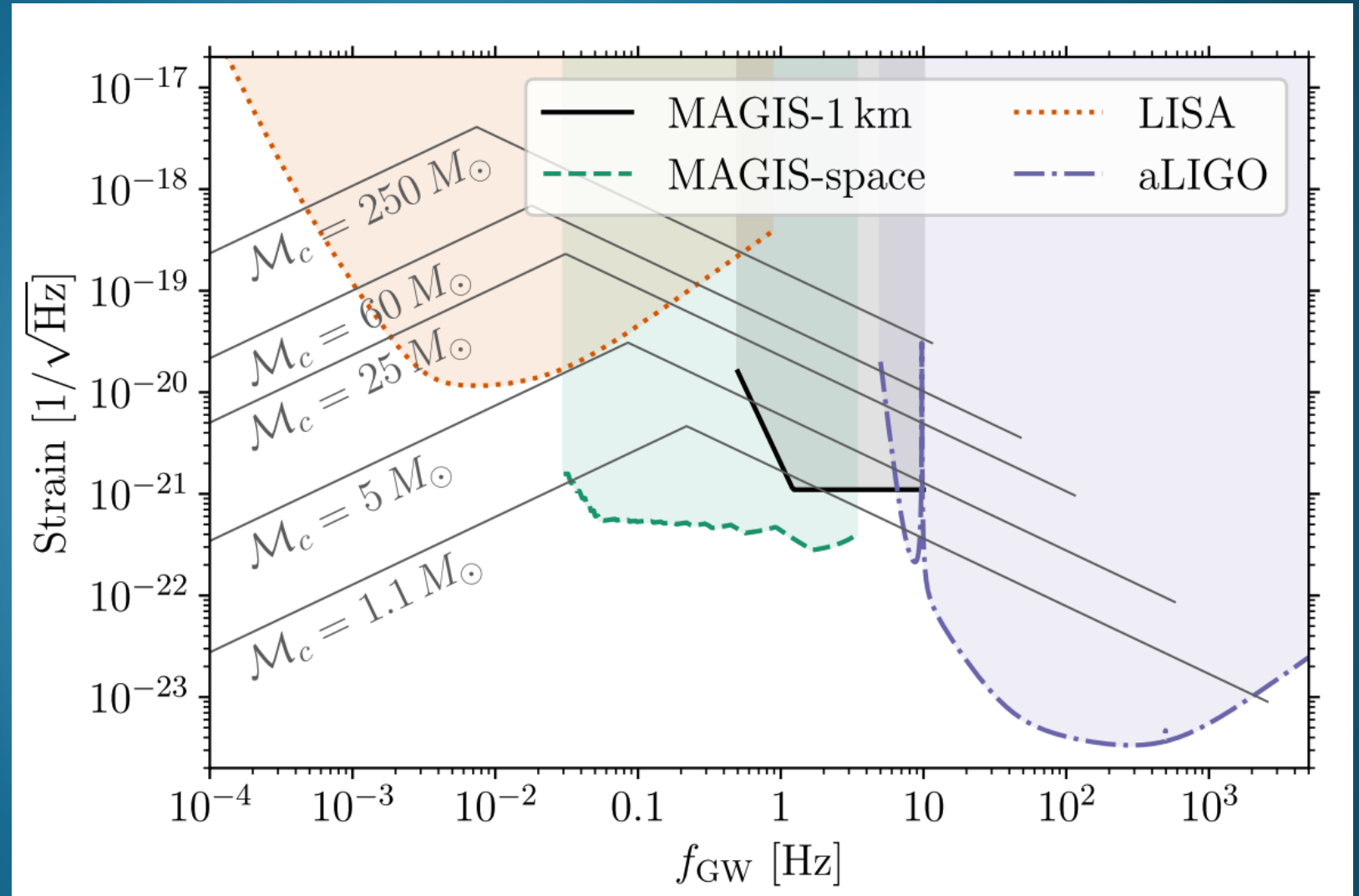
New Windows on the Dynamic Universe

Panel on Compact Objects and Energetic Phenomena

- What is the equation of state of ultra-dense matter?
- When and how are transients powered by neutron stars or black holes?
- What are the unexplored frontiers in transient phenomena?
- Why are jets emitted and what are they made of?

Mid-band (deci-Hz): an unexplored frontier

- Mid-frequency band (**green shaded region**) includes deci-Hz regime between low frequency (orange; LISA) and high frequency (purple; LIGO)
- Predicted mid-band sources include compact object inspirals, labeled by chirp mass, M_c
- Inspiring compact objects are detectable **before merger** in mid-frequency band

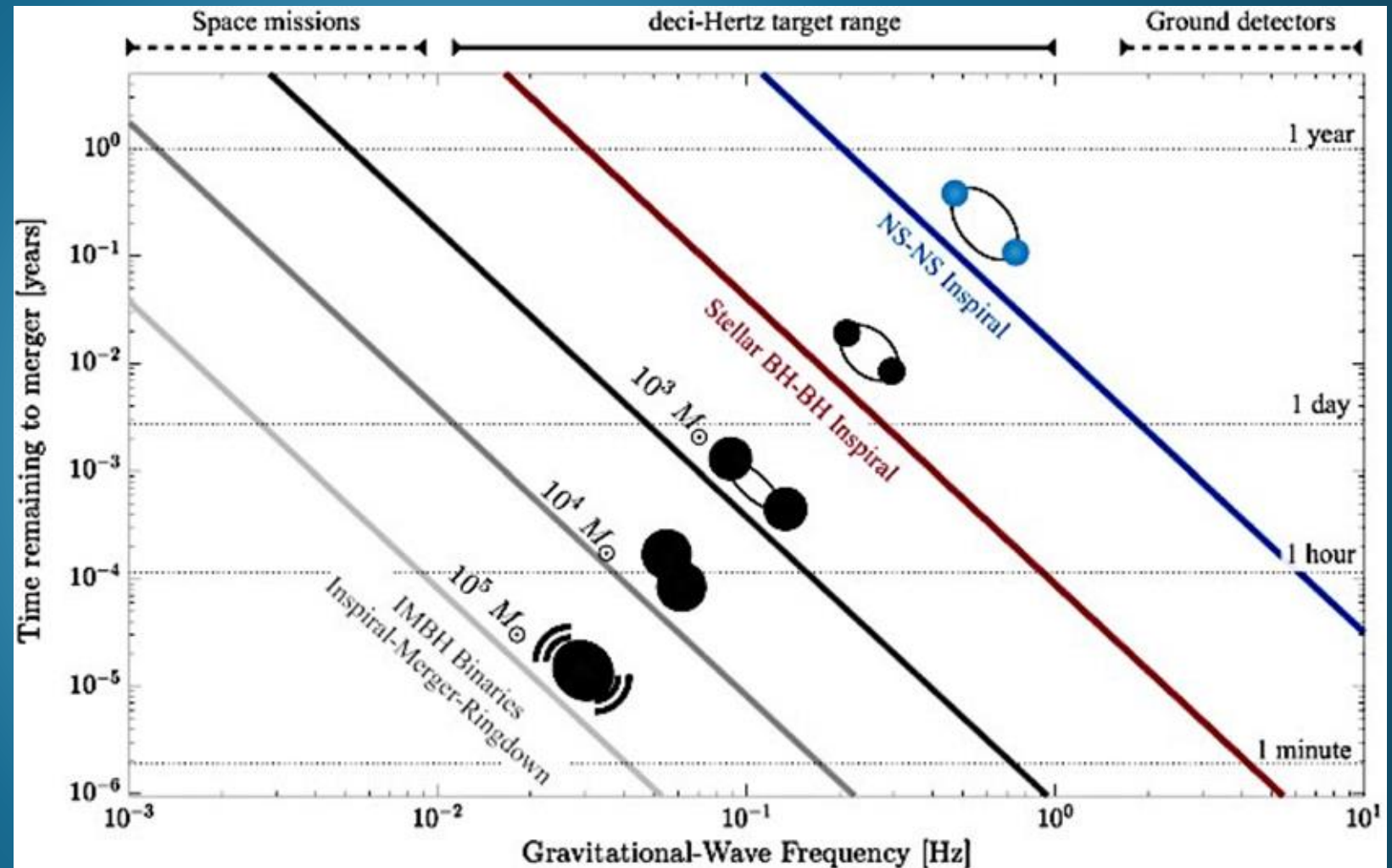


Baum, S., Bogorad, Z. & Graham, P. W. (2024). Gravitational wave measurement in the mid-band with atom interferometers. *Journal of Cosmology and Astroparticle Physics*, 2024(5), 027. <https://doi.org/10.1088/1475-7516/2024/05/027>

Abundant astrophysical sources

Mid-frequency band is also populated by compact binaries across the mass spectrum:

- intermediate mass black holes
- white dwarf binaries

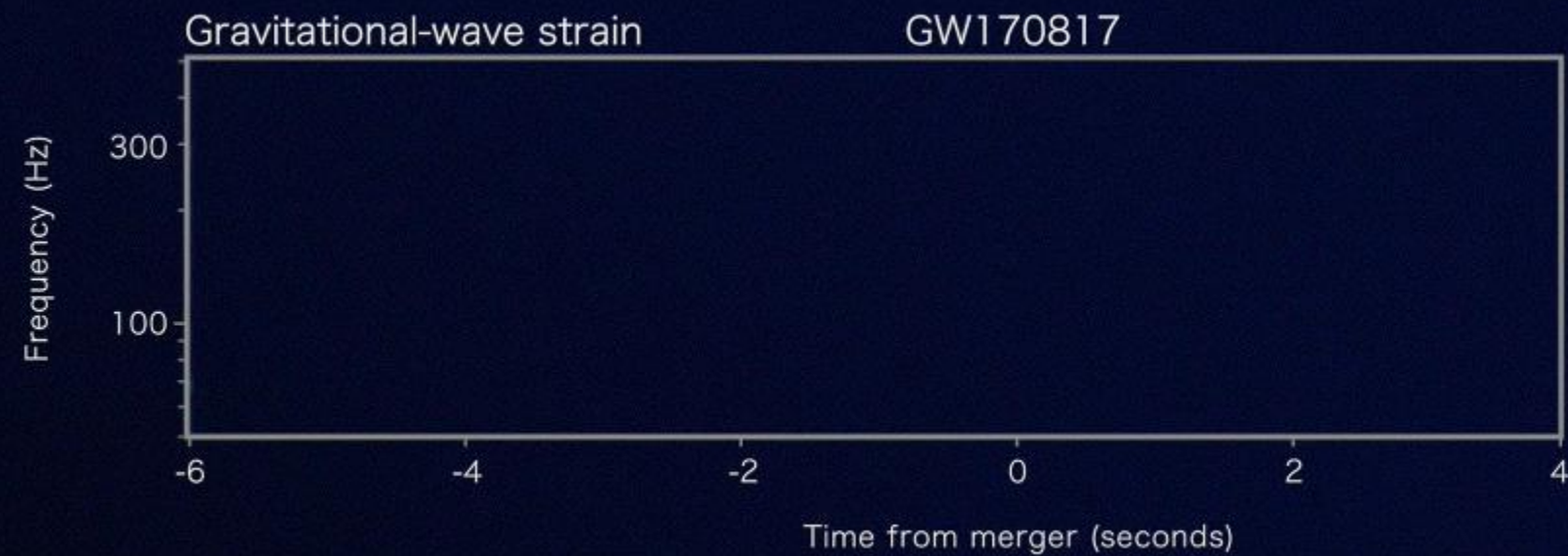


Izumi, K., & Jani, K. (2021). Detection Landscape in the deci-Hertz Gravitational-Wave Spectrum. In C. Bambi, S. Katsanevas, & K. D. Kokkotas (Eds.), Handbook of Gravitational Wave Astronomy (50). https://doi.org/10.1007/978-981-15-4702-7_50-1

Fermi



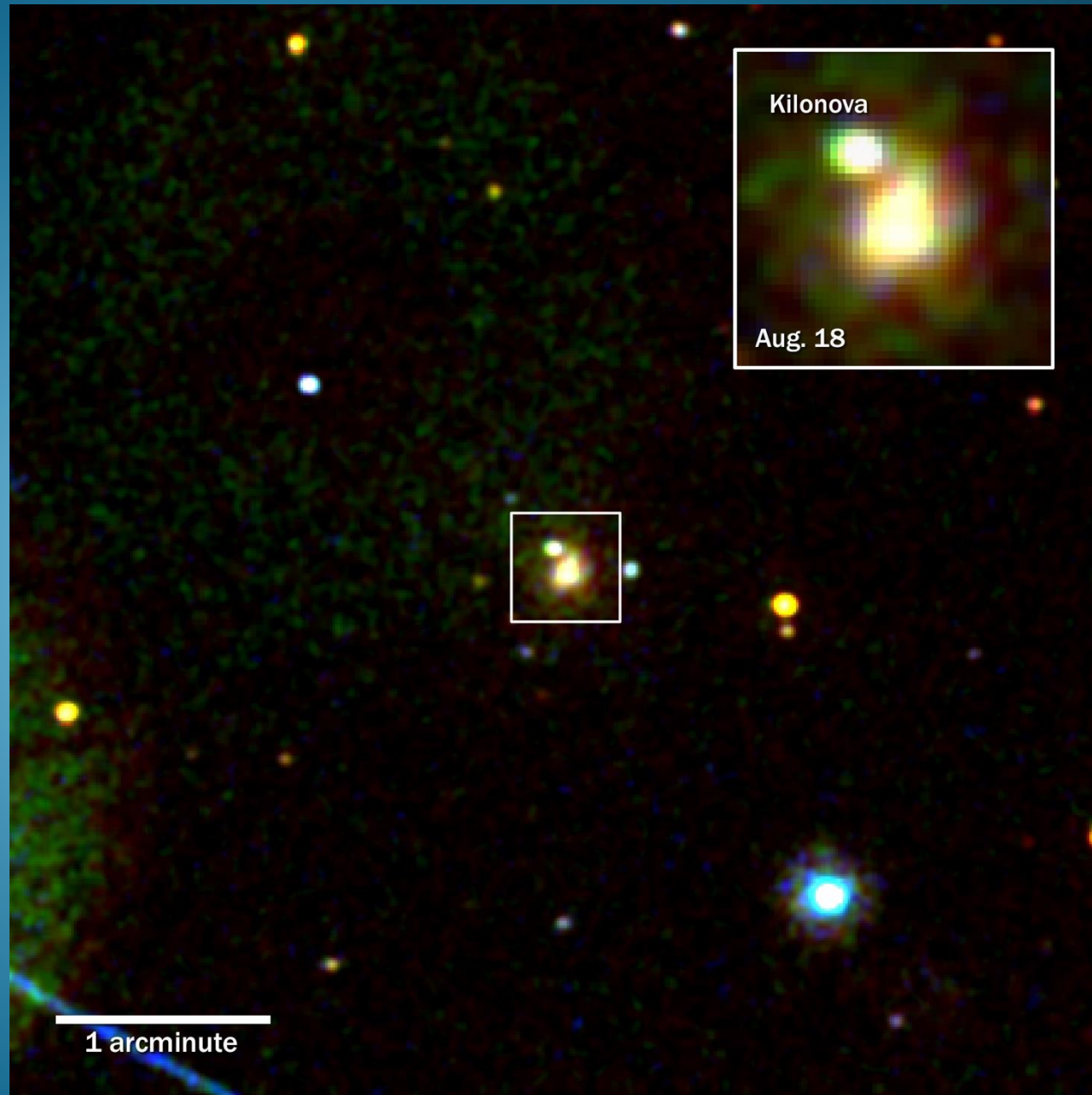
LIGO



Multi-messenger follow-up enables science discovery

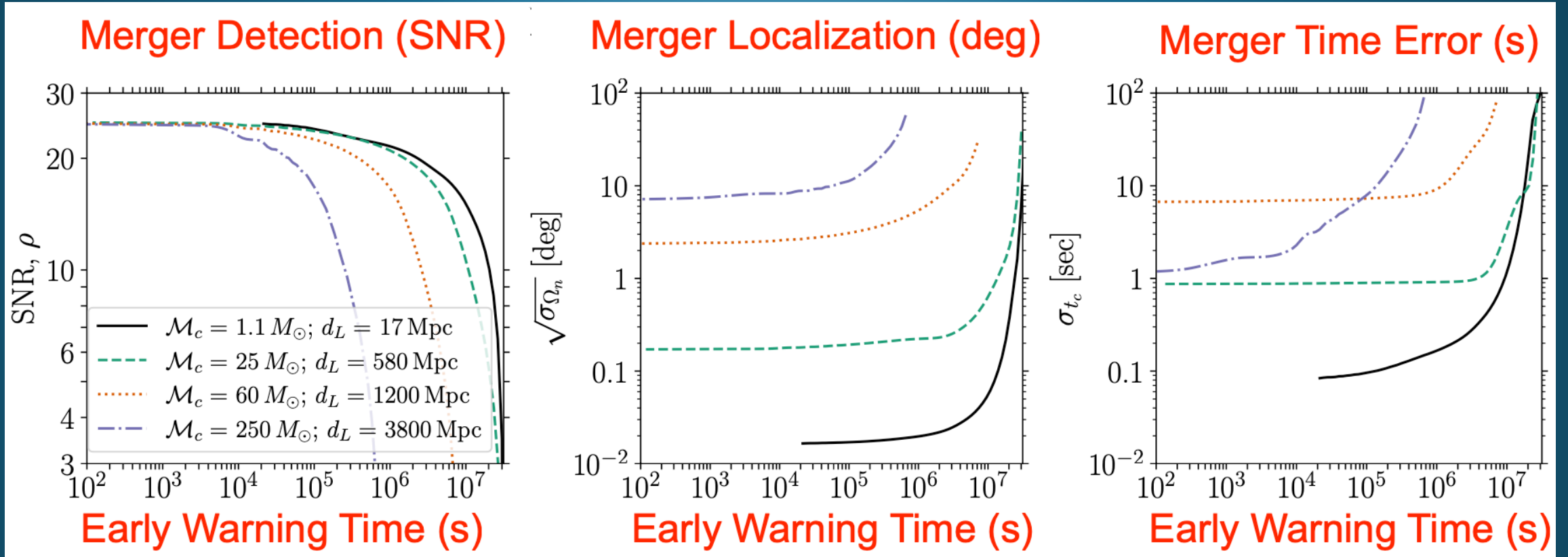
Kilonova imaged by Swift

Swift's Ultraviolet/ Optical Telescope imaged the kilonova (top left in the inset) on Aug. 18, 2017, finding that it occurred in the galaxy NGC 4993.



Combined observations lead to an astrophysical model and the basis for understanding

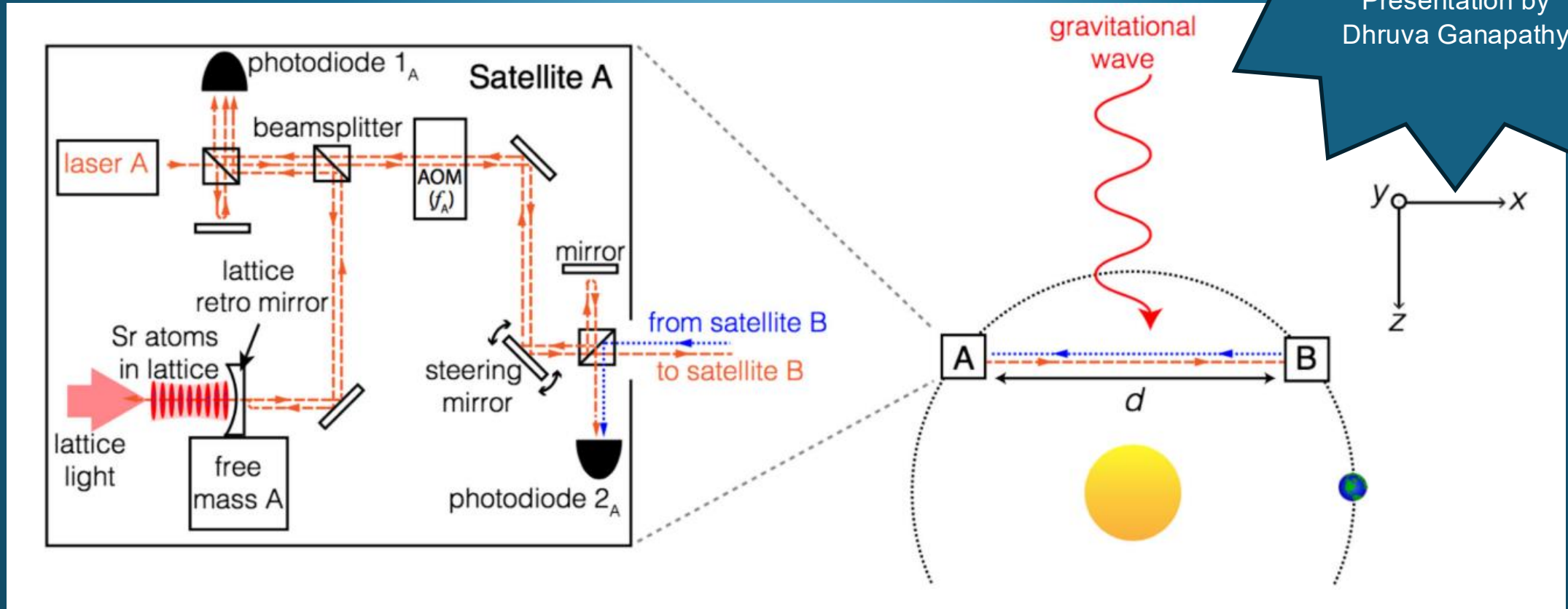
Next steps: early warning for astrophysical transients



Baum, S., Bogorad, Z. & Graham, P. W. (2024). Gravitational wave measurement in the mid-band with atom interferometers. *Journal of Cosmology and Astroparticle Physics*, 2024(5), 027. <https://doi.org/10.1088/1475-7516/2024/05/027>

Optical clocks are a promising mid-band gravitational wave detector

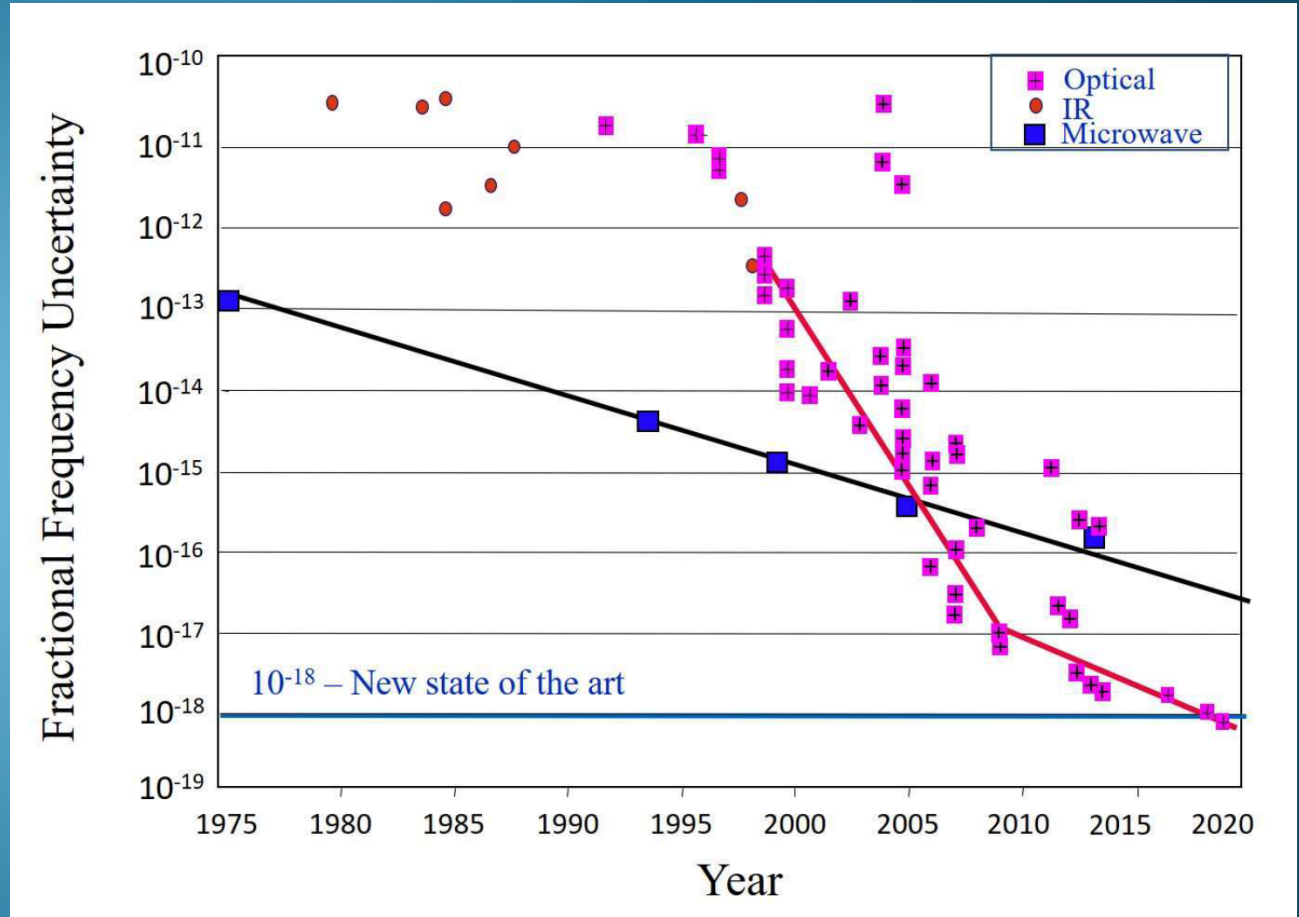
See also Day 2
Grav. Waves &
Fundamental
Physics
Presentation by
Dhruva Ganapathy



Kolkowitz, S. et al 2016, Physical Review D, 94, 124043

Precision timing capability needed

- Accuracy of optical atomic clocks has rapidly improved to better than 10^{-18} *
- Clock accuracies could reach 10^{-21} in next two decades (e.g. by the time Habitable Worlds Observatory is launched, gravitational waves could be directly observed with optical clocks)
- There is no known limit to achievable accuracy of atomic clocks



Derevianko, A., Gibble, K., Hollberg, L., Newbury, N. R., Oates, C., Safronova, M. S., et al. (2022). Fundamental physics with a state-of-the-art optical clock in space. *Quantum Science and Technology*, 7(4), 044002, IOP. <https://doi.org/10.1088/2058-9565/ac7df9>

* The SI second is currently defined to (only?!) 10^{-16}

Conclusions

- Unexplored mid-frequency band has tremendous discovery potential for astrophysics
- Mid-band detectors: early warning for multi-messenger follow up of transients like kilonovae
- Precision clocks can be enabling in the coming decades

For more, see
Day 2 breakout
session:
Gravitational
Waves &
Fundamental
Physics

See my other talk
on Day 2
Asteroids for
 μHz Gravitational
Wave Detection

Extra slides

THE SPECTRUM OF GRAVITATIONAL WAVES



Observatories
& experiments

Ground-based
experiment



Space-based observatory



Pulsar timing array



Cosmic microwave
background polarisation



Timescales

milliseconds

seconds

hours

years

billions of years

Frequency (Hz)

100

1

10^{-2}

10^{-4}

10^{-6}

10^{-8}

10^{-16}

Cosmic fluctuations in the early Universe

Cosmic
sources



Supernova



Pulsar



Compact object falling
onto a supermassive
black hole



Merging supermassive black holes



Merging neutron
stars in other galaxies



Merging stellar-mass black holes
in other galaxies



Merging white dwarfs
in our Galaxy

#lisa



Image: Colpi, M et al. 2024 LISA Definition Study Report, arxiv:2402.07571

Gravitational strain power and amplitude spectral density

Strain

$$h(t) = \frac{\Delta L}{L}$$

Units: dimensionless

Power Spectral Density

$$S_{h(f)} \propto |\langle \tilde{h}(f) \rangle|^2$$

Units: 1 / Hz

Strain
ASD
 $\sqrt{S_{h(f)}}$

Amplitude Spectral Density

$$ASD = \sqrt{S_{h(f)}}$$

Units: 1 / $\sqrt{\text{Hz}}$

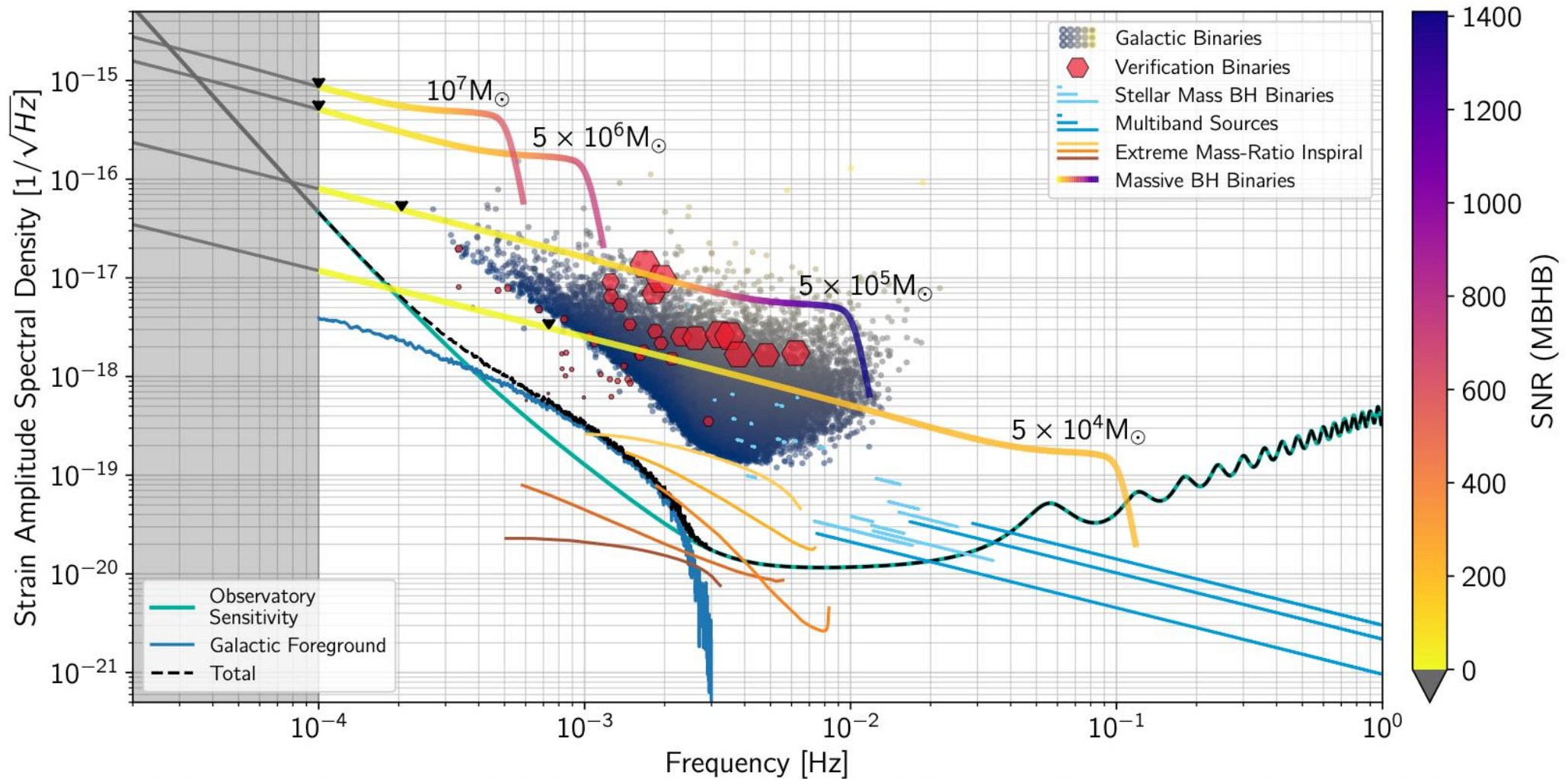
Strain sensitivity curve

Acceleration
Noise
 $S_{h(f)} \propto 1 / f^4$

Optical Path Noise
 $S_{h(f)} \approx \text{const.}$

Frequency (log f)

LISA strain sensitivity



CHRONOS*: A Quantum Clock Space Telescope for Gravitational Astrophysics

Innovation

A gravitational wave telescope enabled by spaceborne precision timing

Open new discovery space in astrophysics
Identify astrophysical transients *before they happen*
Explore dark matter and quantum gravity

Leverages quantum technology boom
Simpler than other similar concepts

Mission

Two spacecraft, heliocentric orbit;
quantum optical clocks, linked laser

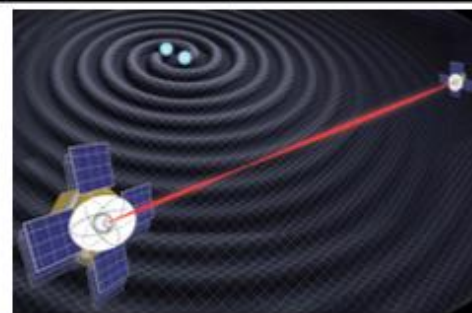
LISA pathfinder-like spacecraft
Sensitive to neutron star, black hole collisions
On-sky localization (1°); early warning ($\sim$ months)
Enabled by projected advances in quantum optical clocks by 2040's

Impact

Multi-messenger astrophysics
Beyond Standard Model physics

Geodesy (Earth to $< \text{cm}$ scale, real time)
Autonomous navigation; global time standard

Broad advocacy within NASA
Transformative science, even if mission concept is in-feasible



Timing the universe with light and gravity

Approach

9-month mission concept study

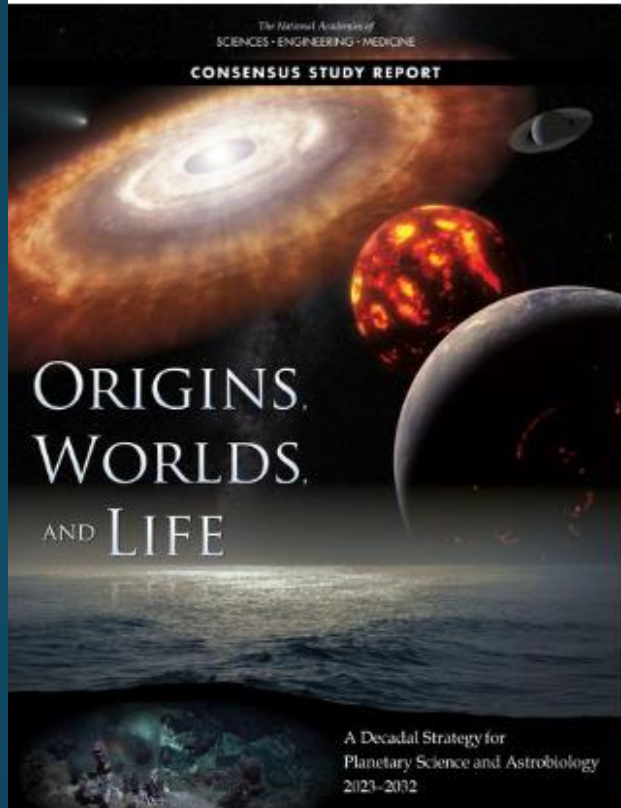
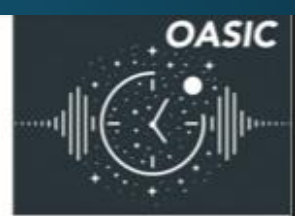
Science-engineering trade space
Technology development roadmap
Sensitivity and localization error budgets

Compare with other mission concept
using existing analysis software

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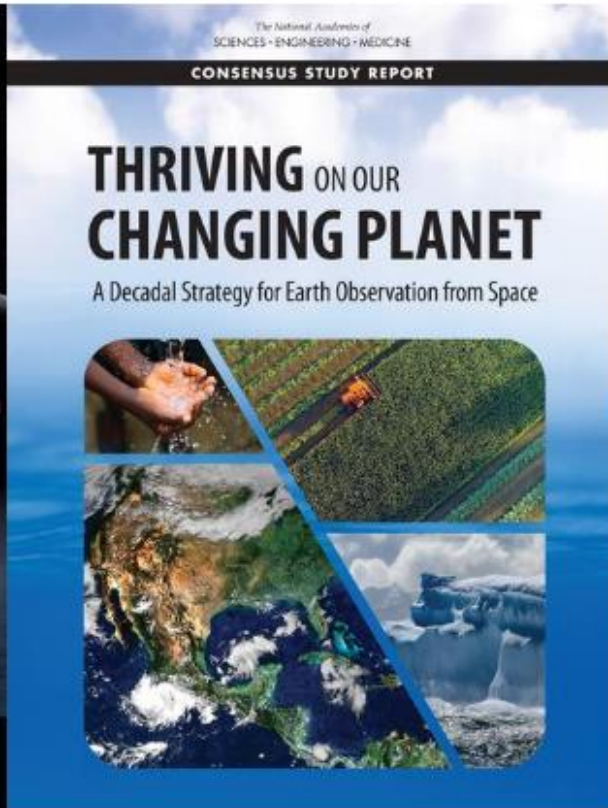


NASA needs atomic clocks for precise timing



Planetary Science:

- Mission to outer planets
 - Uranus
- Real-time spacecraft navigation
- Mars Ice Mapping



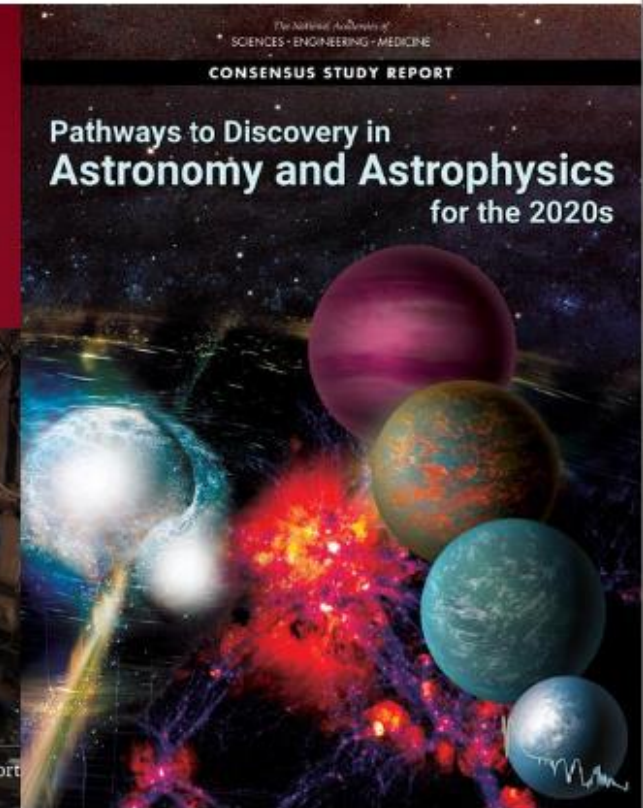
Earth Science:

- Relativistic geodesy
- Time-variable gravity gradient measurements of Earth



Fundamental Physics:

- Probing the Fabric of Spacetime
- Dark Matter searches
- Search for new physics



Astronomy and Astrophysics:

- Imaging Black Holes
- Gravitational waves

Slide: Holly Leopardi, NASA/GSFC

Dark matter & fundamental physics

goes here