Gravitational wave opportunities in the deci-Hertz range

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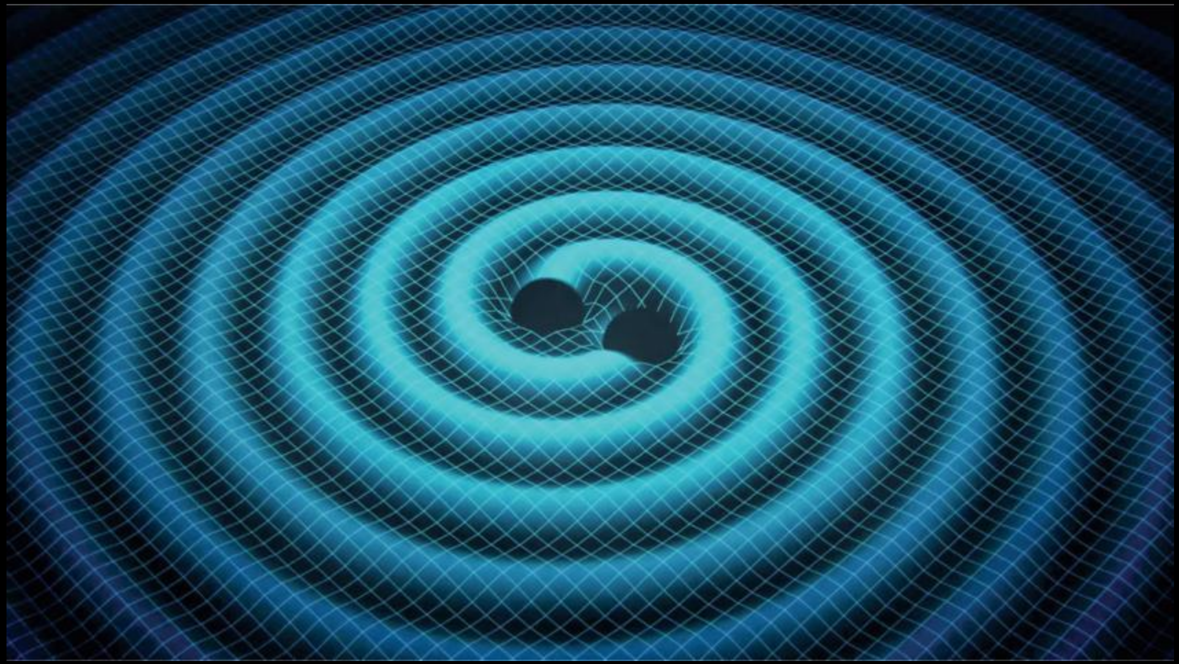
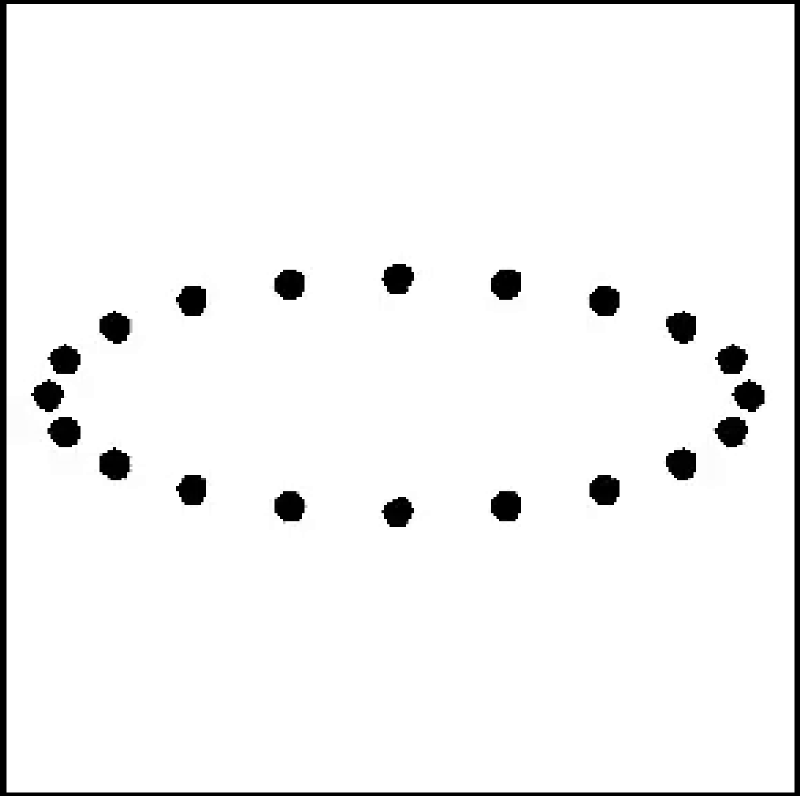
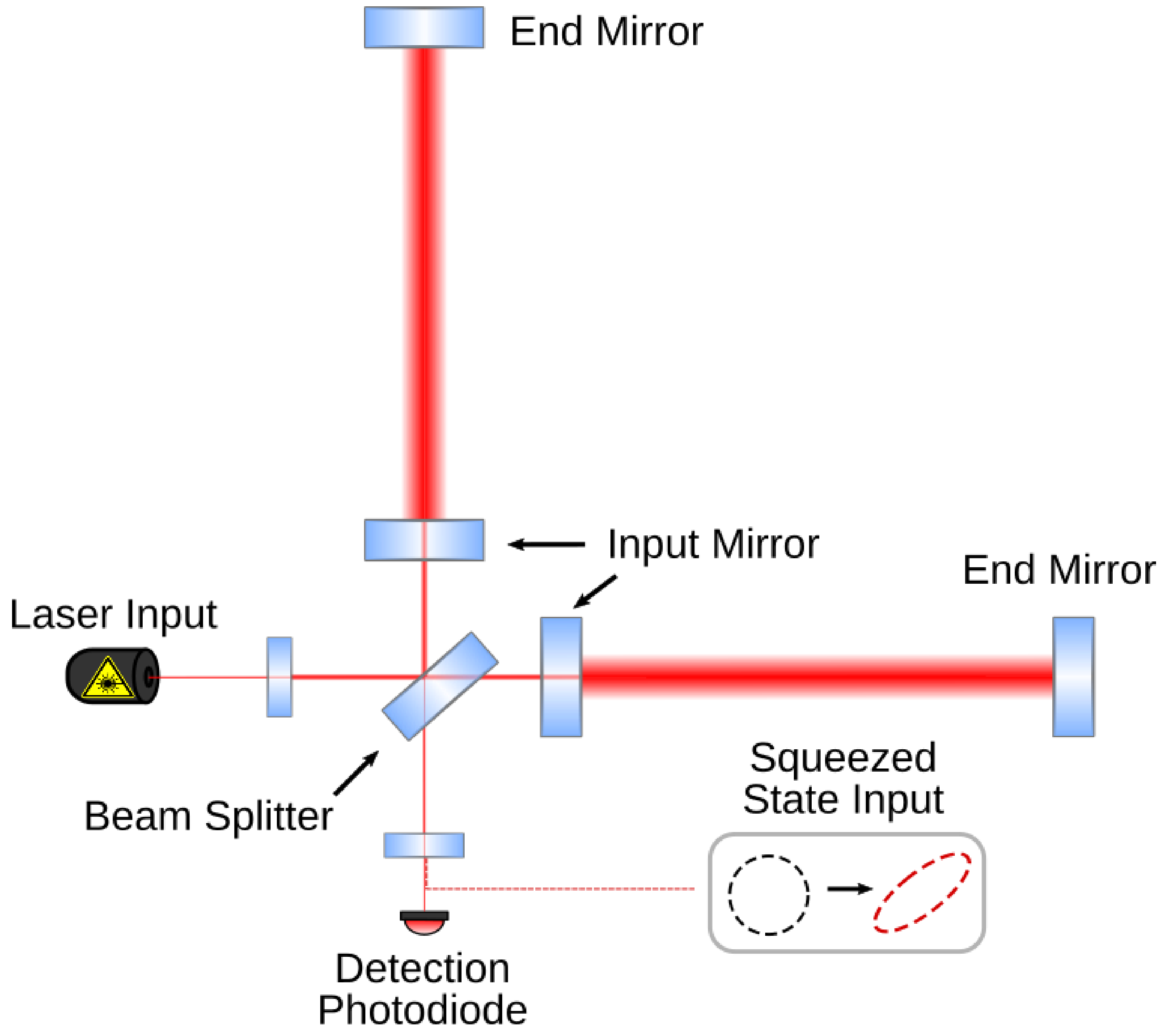
Gravitational Waves

Originate from accelerating masses

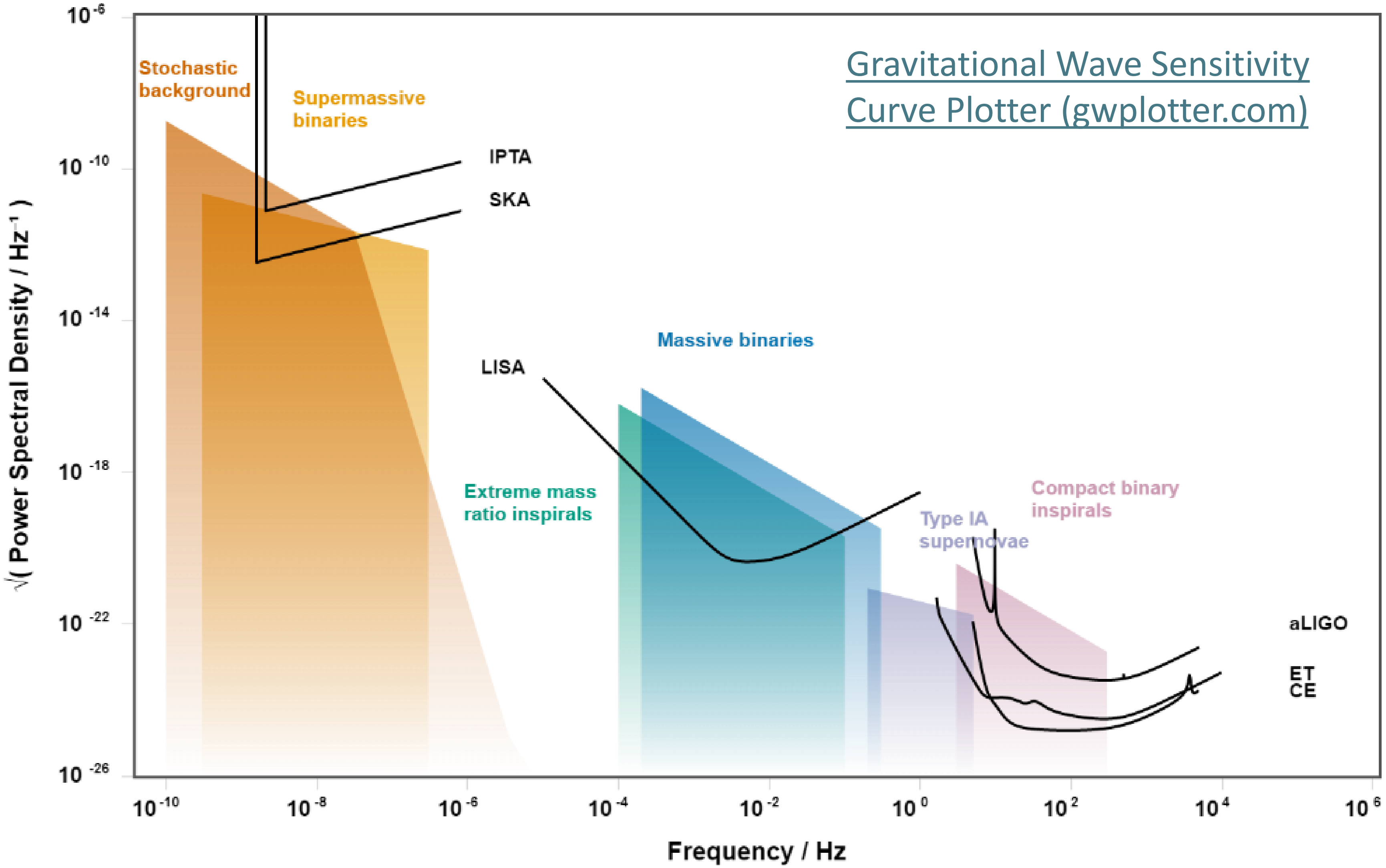




Laser Interferometer Gravitational Wave Detectors



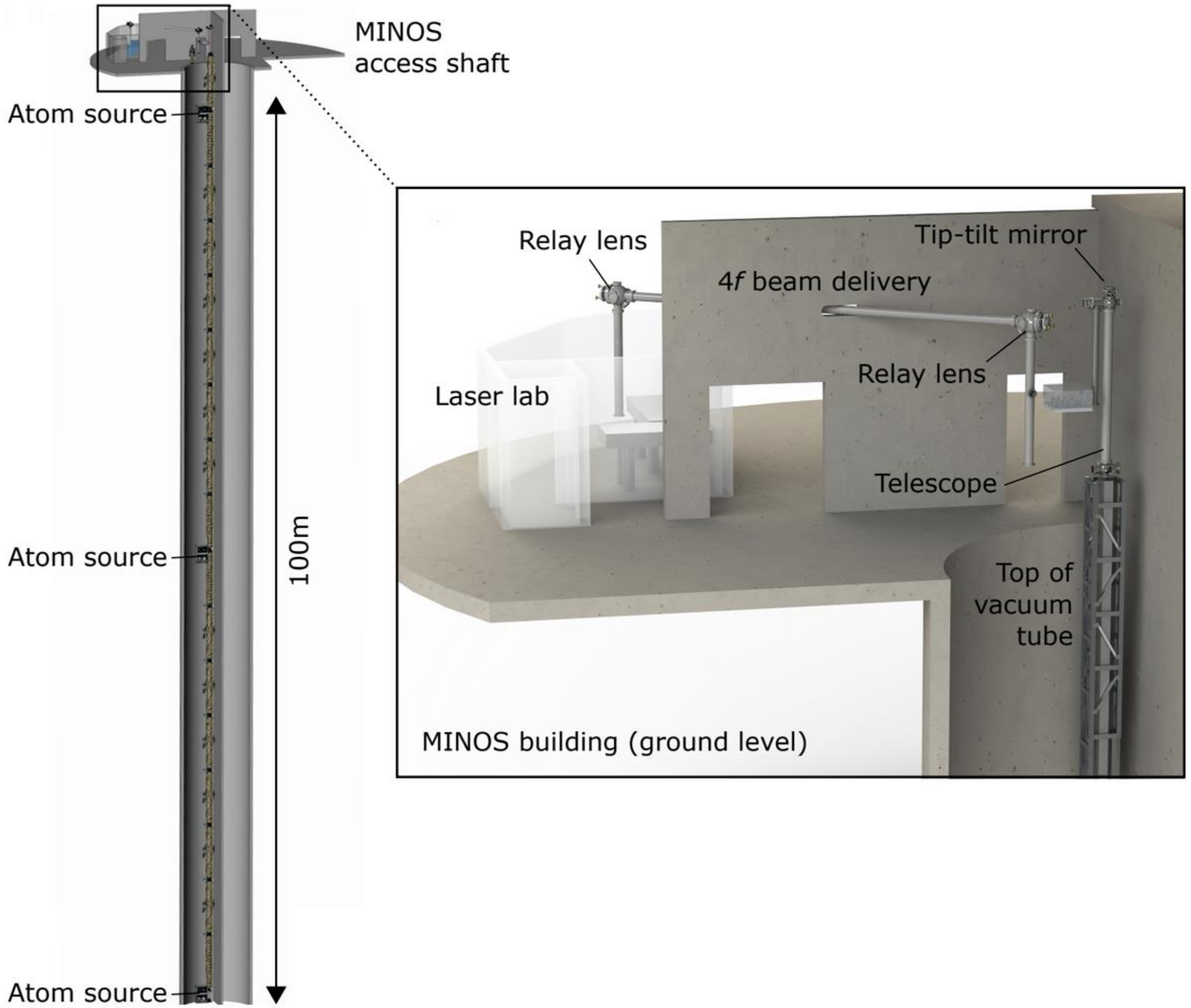
Gravitational Wave Detectors and Sources



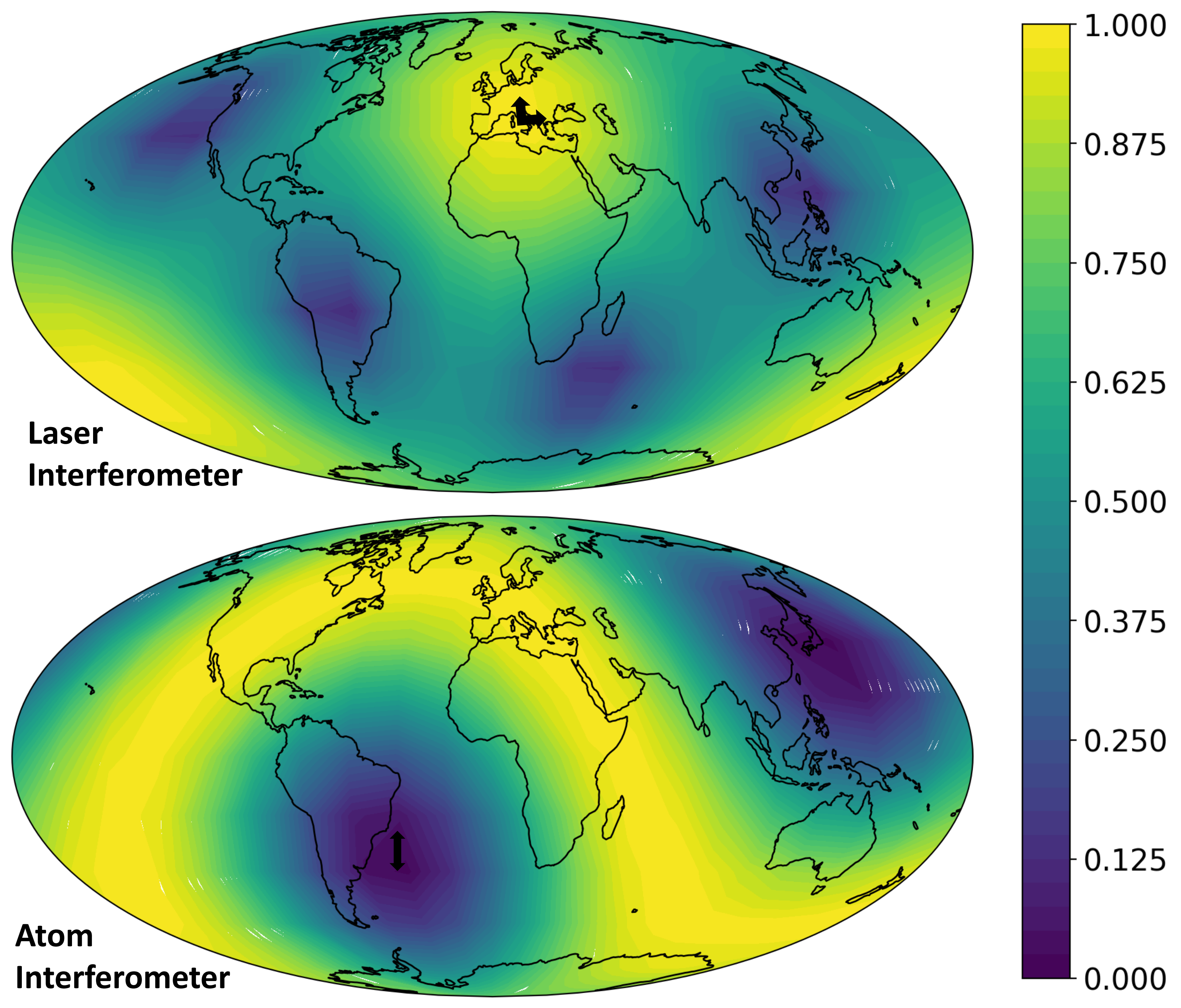
[Gravitational Wave Sensitivity Curve Plotter (gwplotter.com)](gwplotter.com)

Atom Interferometer Gravitational Wave Detectors

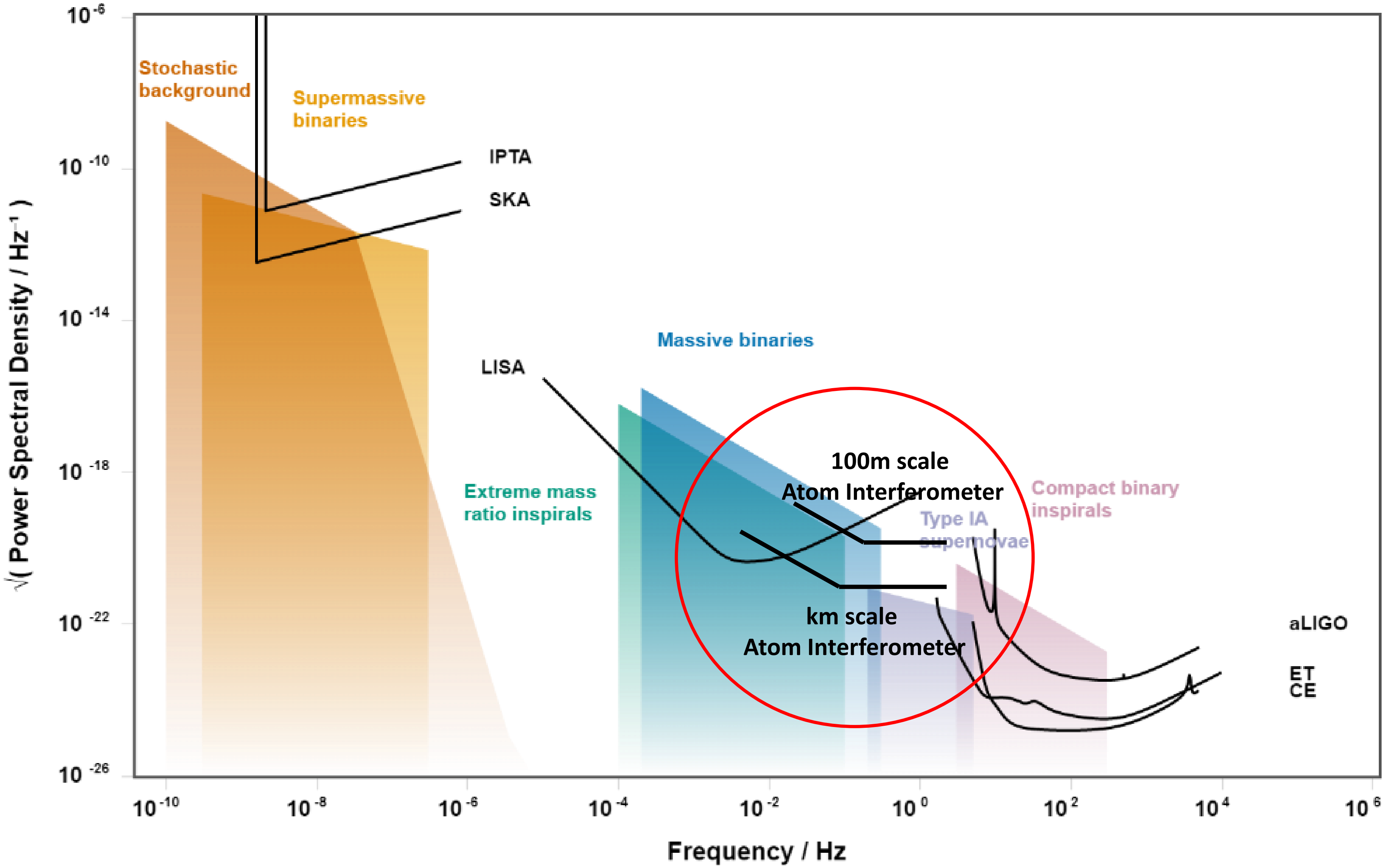
MAGIS-100 – A next-generation atom interferometer to search for new physics (fnal.gov)



Directional Sensitivity



Gravitational Wave Detectors and Sources



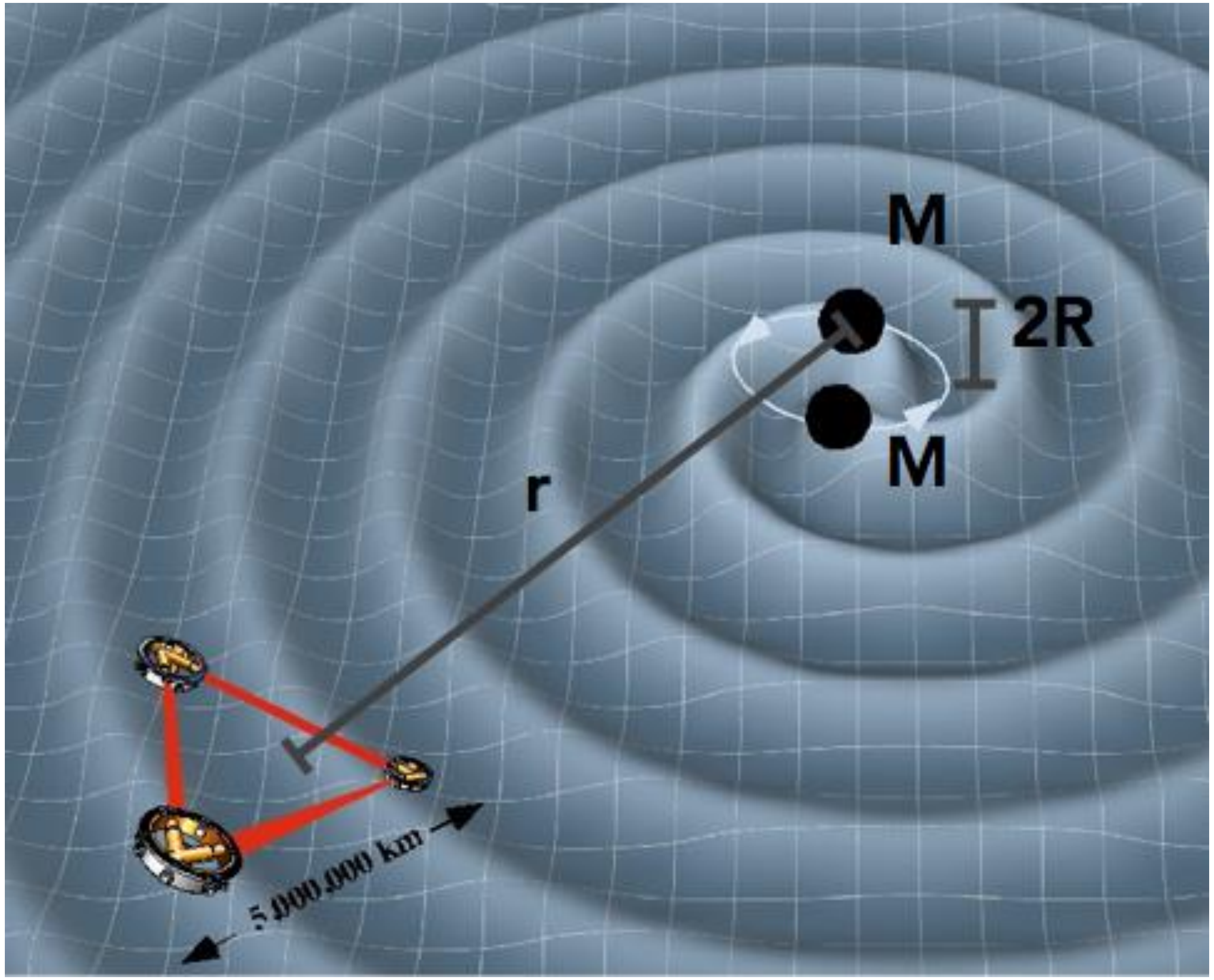
Generating gravitational waves

- Time varying mass quadrupole generates gravitational waves

- Binary system is ideal

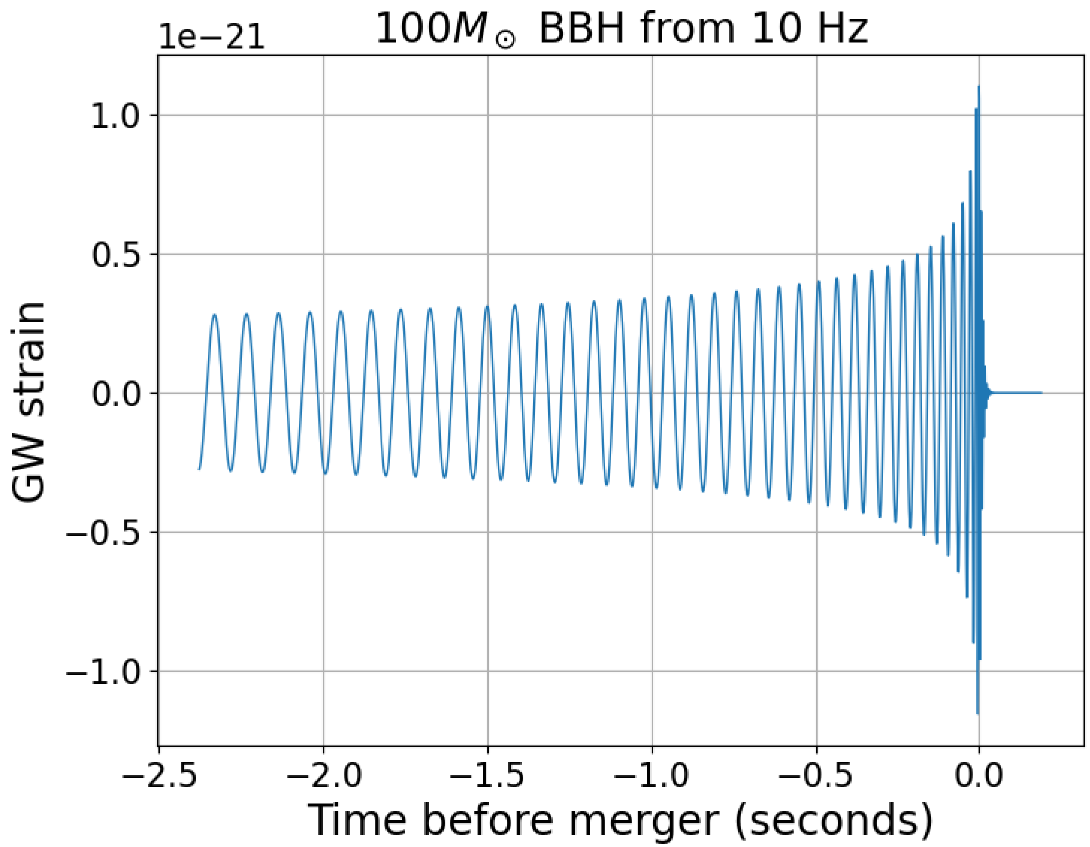
$$h \sim \left(\frac{GM}{c^2 R}\right)\left(\frac{GM}{c^2 r}\right)$$

$$P \sim \frac{GM^2 v^6}{c^5 R^2}$$



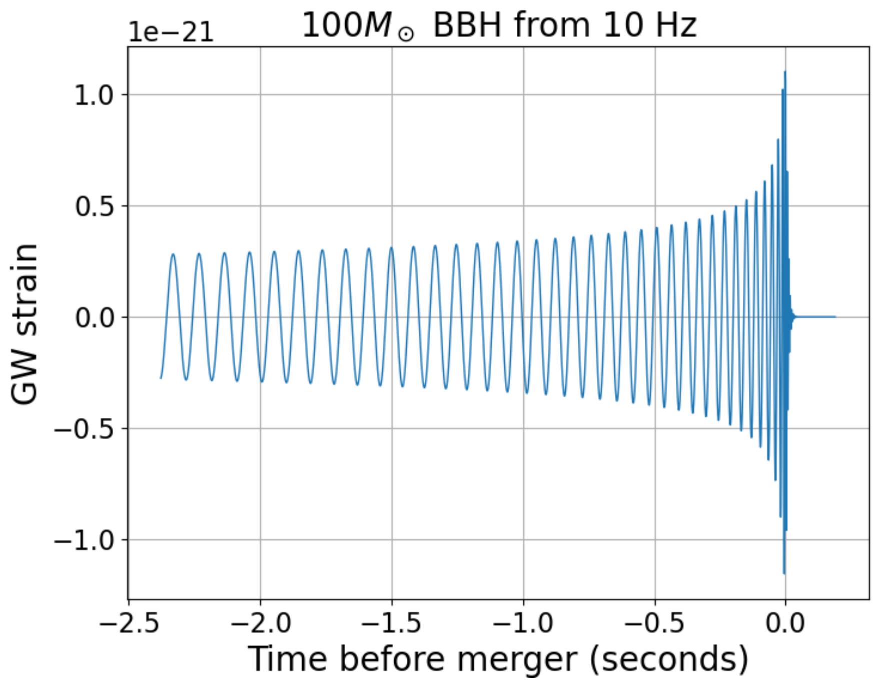
Black Hole Binary Mergers

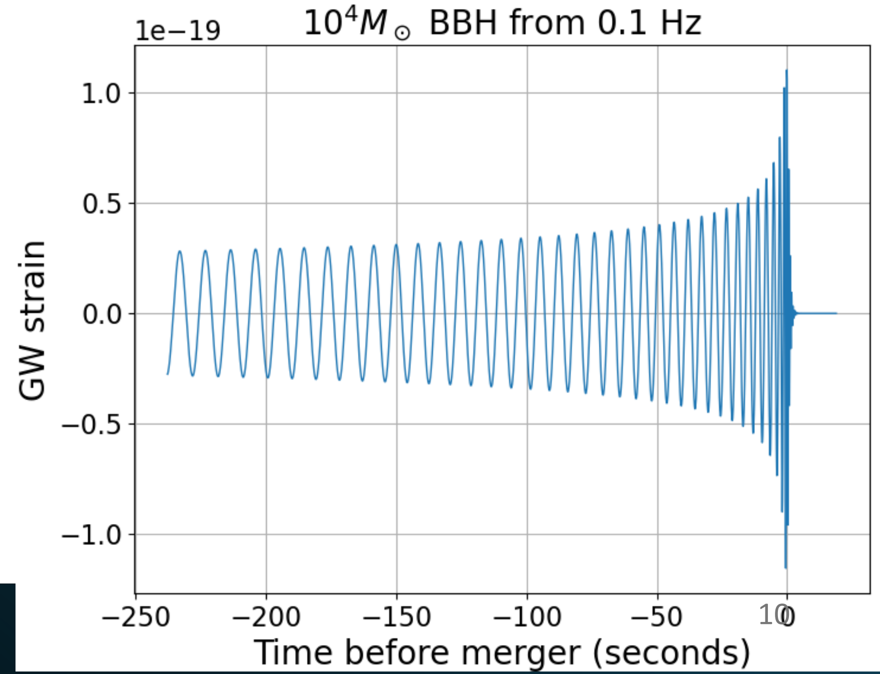
- Orbits decay due to emission of gravitational waves
- Both amplitude and frequency of gravitational waves increase as binary approaches merger



Black Hole Binary Mergers

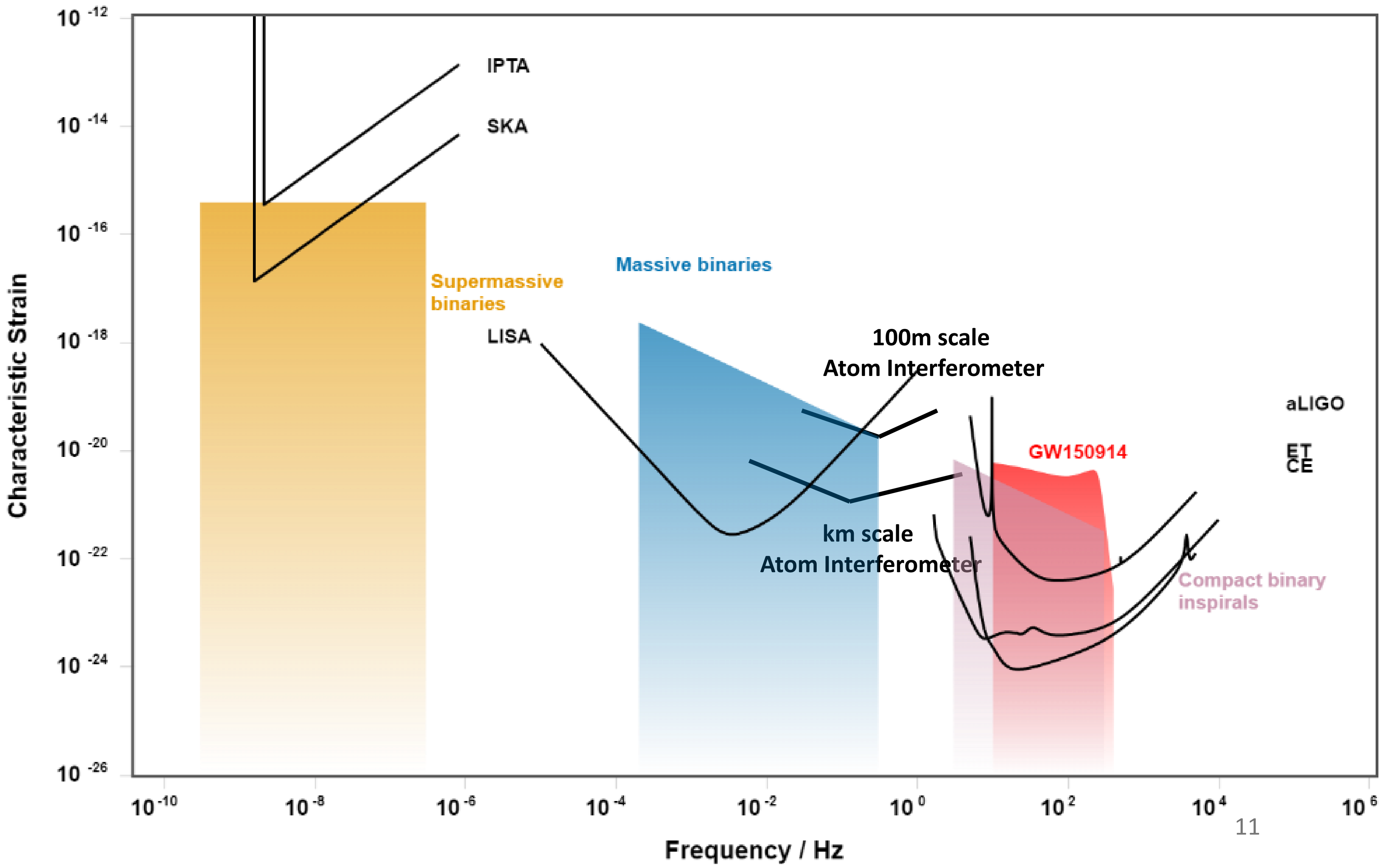
- General relativity has no intrinsic length scale → waveform looks the same for different mass black holes
  - Frequency scales with mass^{-1}
  - Amplitude and duration scale with mass
- Other features, such as mass ratio and spins, also impact the waveform
- For neutron star or white dwarf binaries, matter effects become important before merger
- For distant sources, signal is redshifted to lower frequency



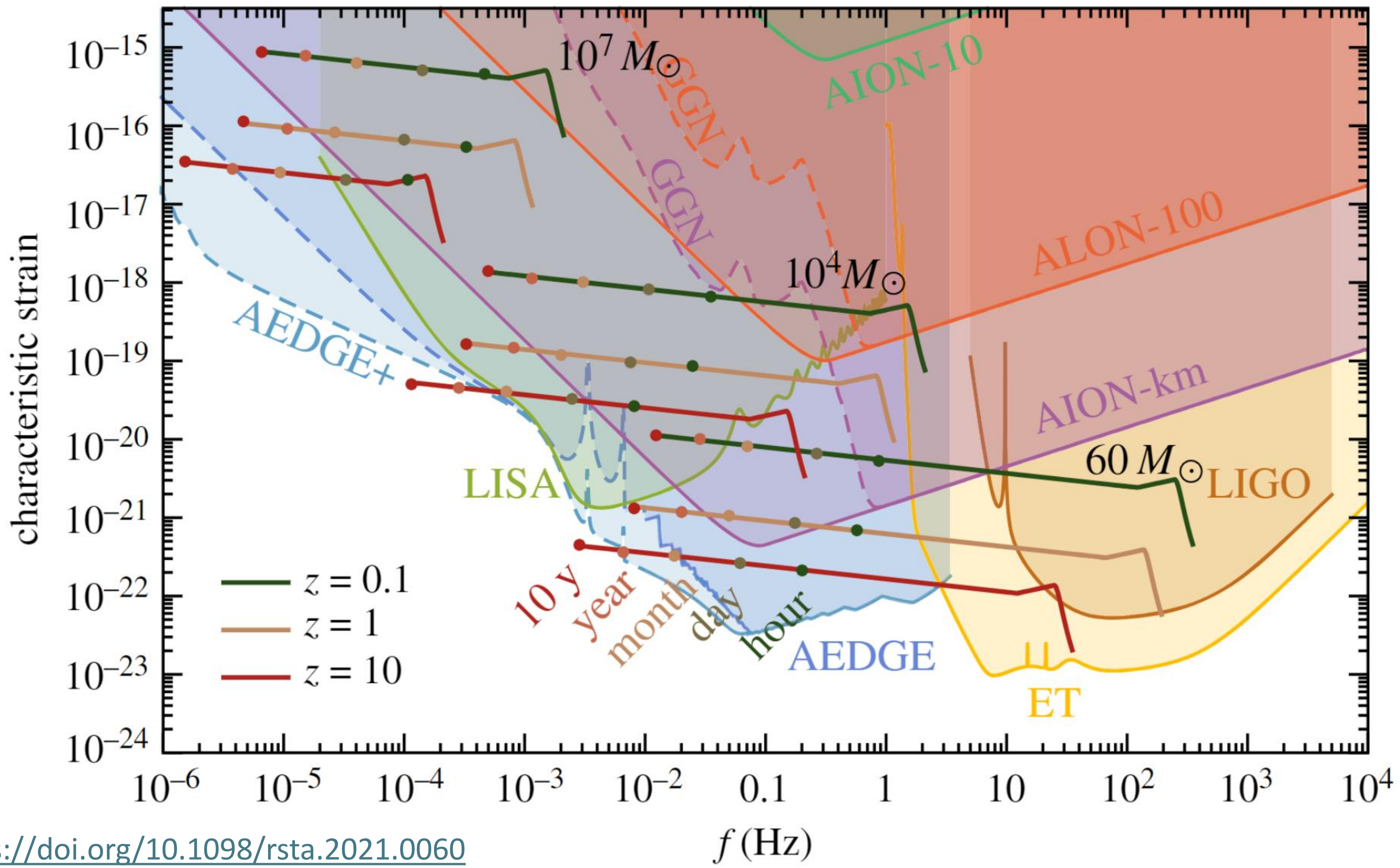


Gravitational Wave Detectors and Binary Mergers

- Plot sensitivity in terms of “characteristic strain”
- Can “integrate by eye” so that area between signal and noise curve gives the signal to noise ratio
- Although amplitude increases at later times, binary spends longer at low frequencies, giving more power

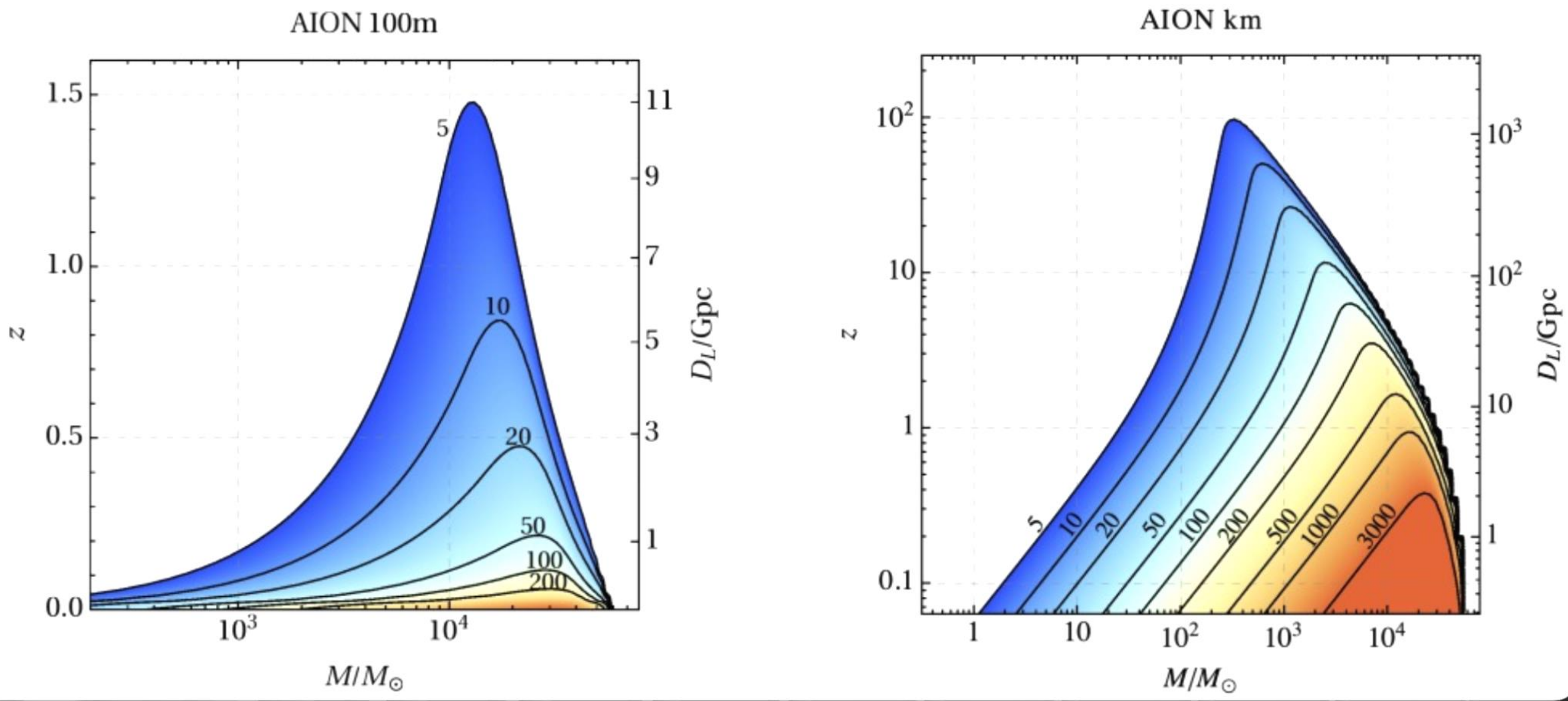


Future Atom Interferometer Sensitivity



From Badurina et al, https://doi.org/10.1098/rsta.2021.0060

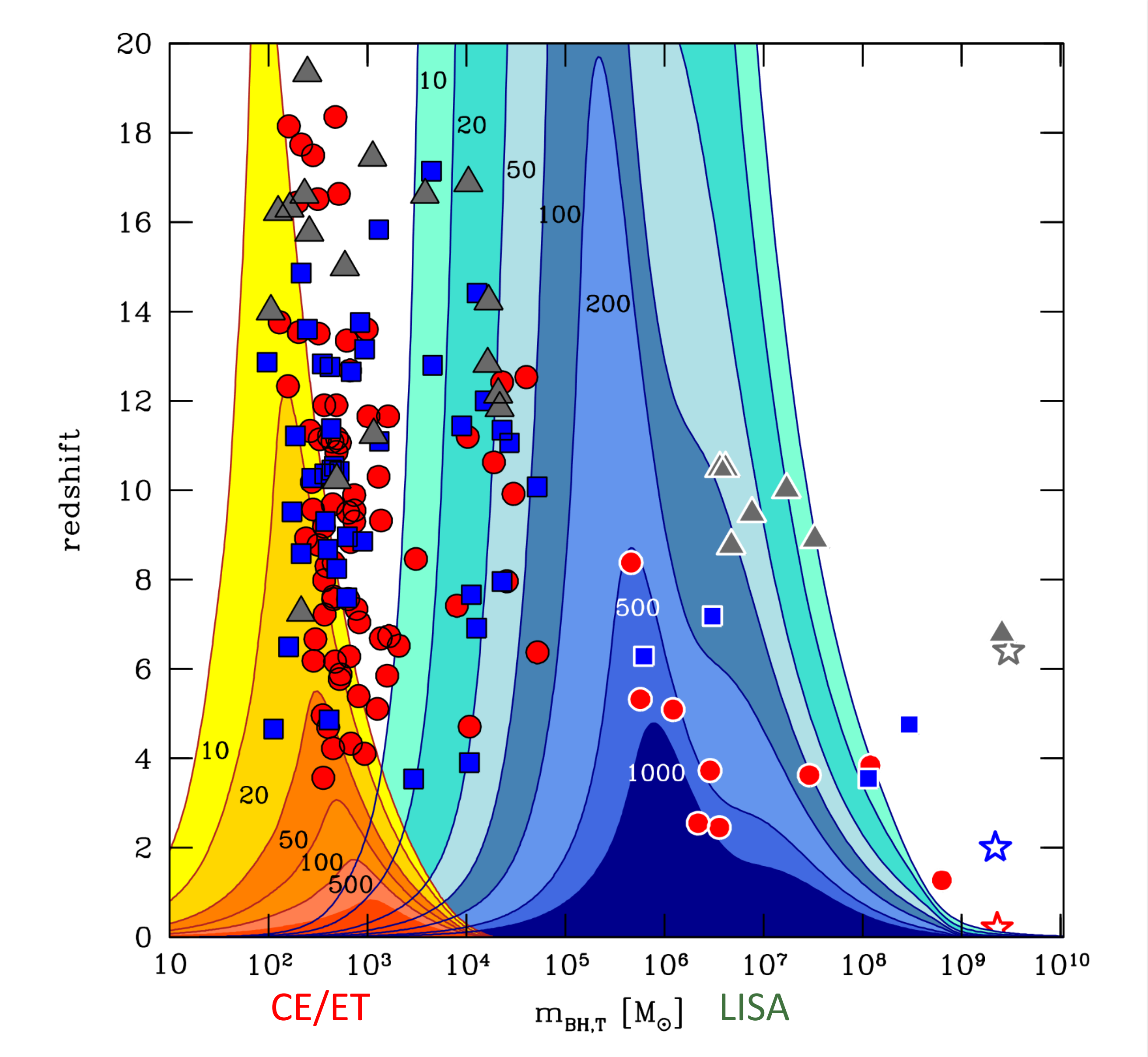
Future Atom Interferometer Sensitivity



From Badurina et al, https://doi.org/10.1088/1475-7516/2020/05/011

Seed black holes

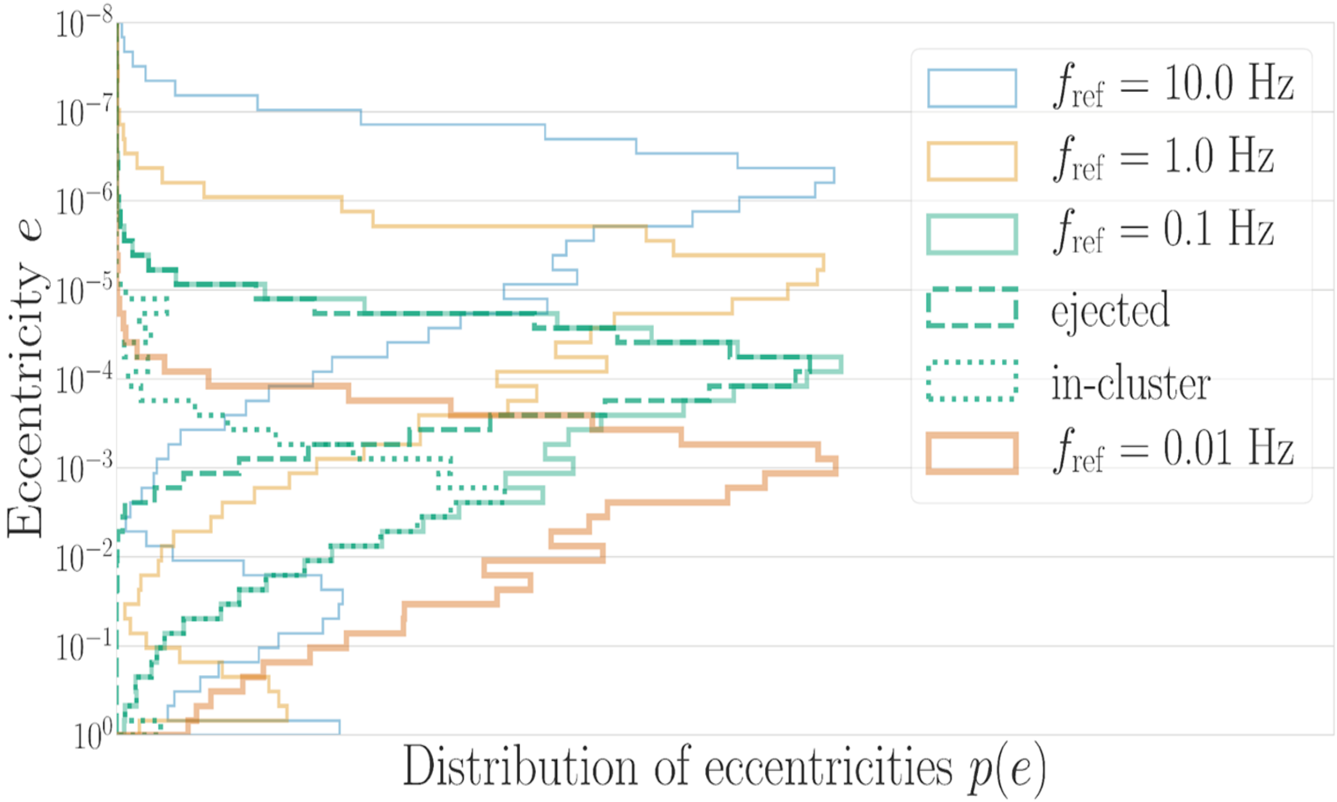
- Quasars observed at redshift z > 7 [less than 1 billion years after the big bang] are powered by black holes with mass > 10^9 $M_\odot$
- Likely population of seed black holes at high redshifts that grow through accretion and mergers to form supermassive black holes
- Light seeds will be observable to next-generation GW observatory
- Growing seeds (around 10^3 -10^4 $M_\odot$) are a clear target for deci-Hertz observatories



From Valiante et al https://arxiv.org/abs/2010.15096

Stellar mass black holes: Eccentricity

- Binary black holes are expected to form in eccentric orbits
- Eccentricity is radiated at a faster rate than orbit shrinks → binaries circularize
- Observing at lower frequencies is best way to measure eccentricity and identify formation scenario



From Sedda et al, https://doi.org/10.1088/1361-6382/abb5c1

Type 1A Supernovae

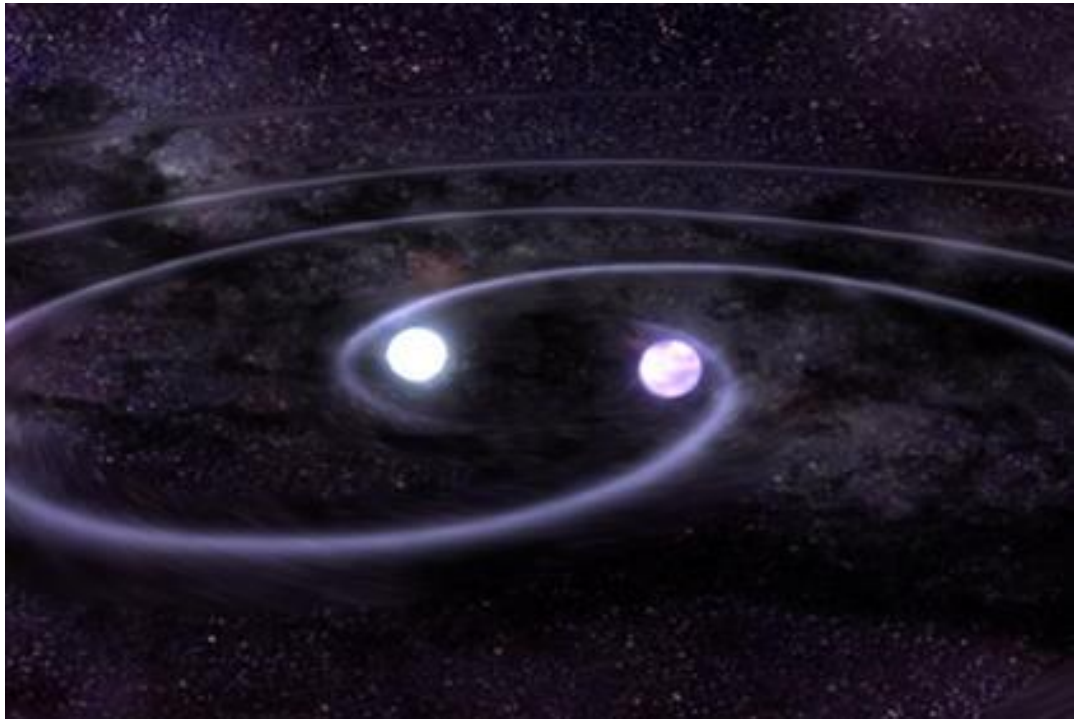
Believed to originate from either

- The merger or two white dwarfs (double degenerate channel)
- Accretion onto a white dwarf (singe degenerate channel)

Gravitational wave observation associated with nearby 1A supernova (or lack of) would provide clear evidence of the channel.

Mandel et al, https://doi.org/10.1088/1361-6382/aaa7e0

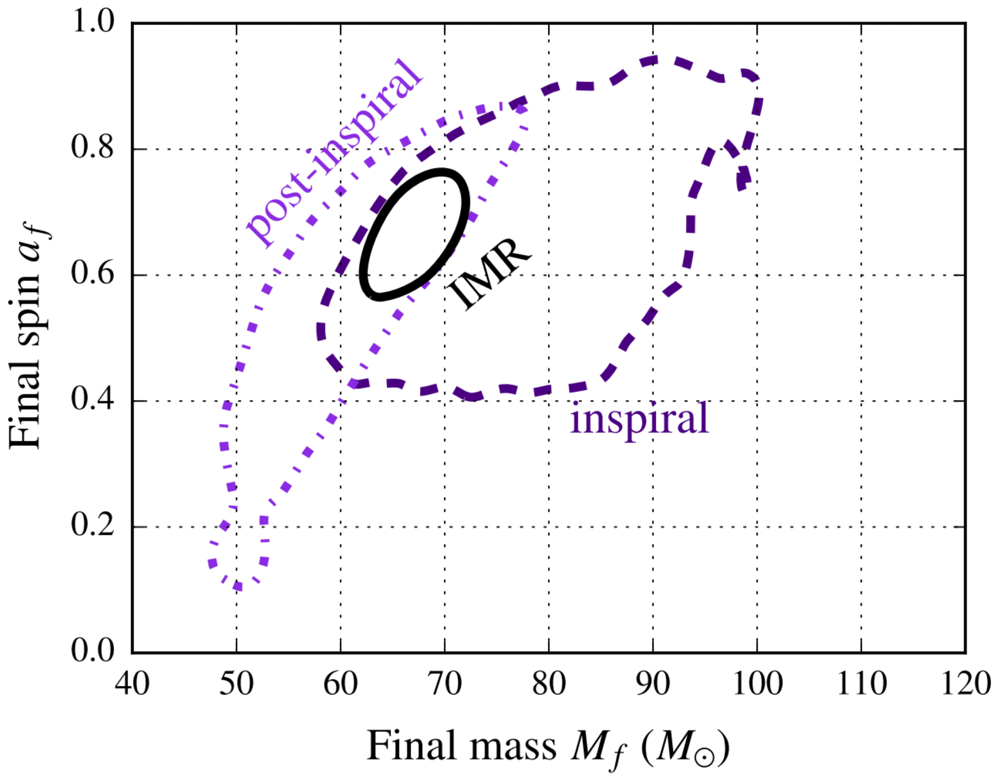
Kinugawa et al, https://doi.org/10.3847/1538-4357/ac9135



Need sensitivity to signals to tens of Mpc to observe ~1 event per year.

Fundamental Physics: Testing Relativity

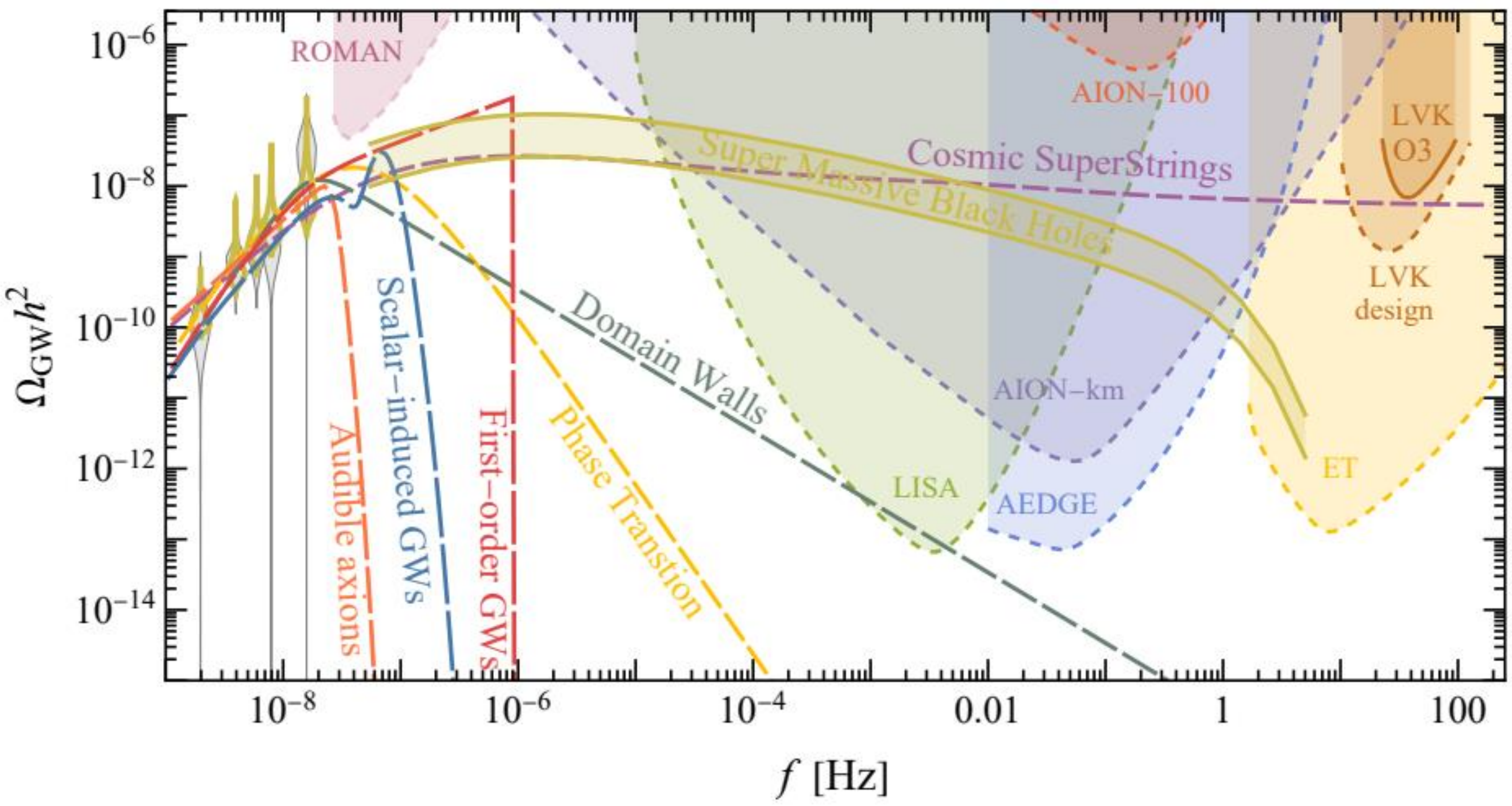
- Gravitational waves provide ideal laboratory for testing relativity
  - Strong field GR in merging binaries
  - Propagation of GWs
- Ability to measure/bound deviations from GR scales with signal to noise ratio in (part of) signal being used
- Some alternative theories predict features in the deci-Hertz range



e.g. measuring consistency of mass and spin from Inspiral and ringdown parts of GW150914 signal
From Abbott et al, https://doi.org/10.1103/PhysRevLett.116.221101

Stochastic Gravitational Wave Background

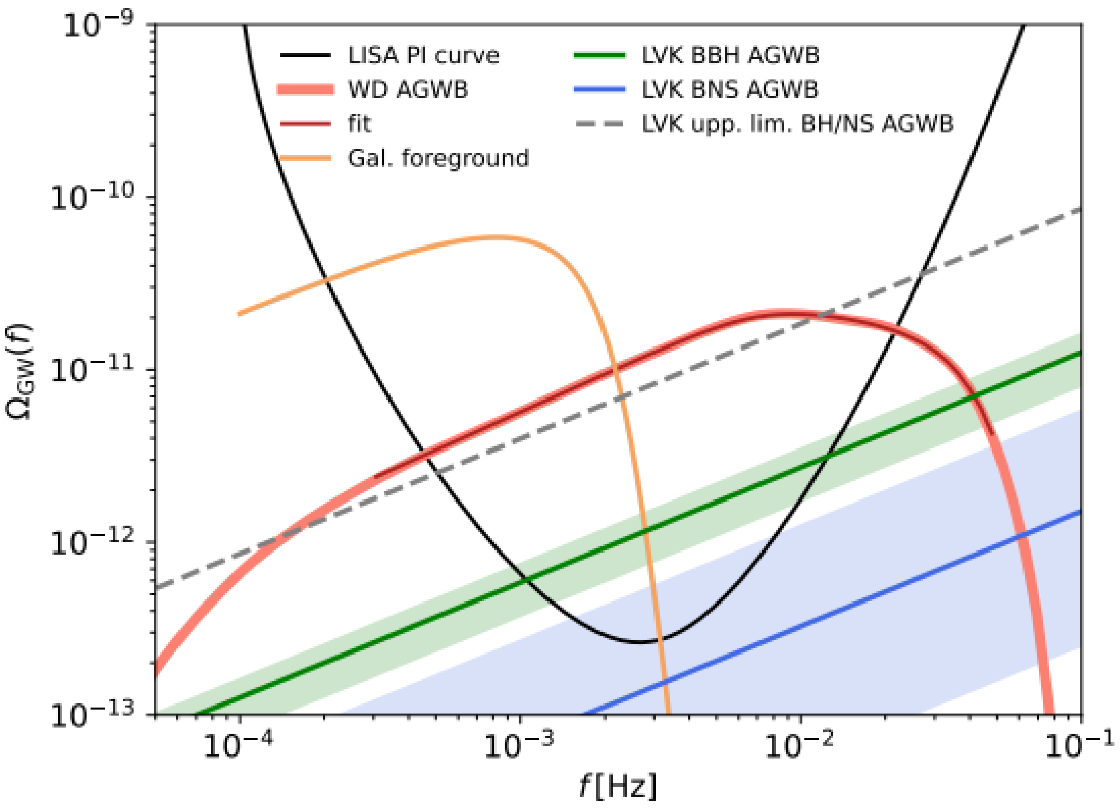
- Expected to be a GW background, similar to the CMB
- Exact features model dependent
- e.g. fitting to the observed PTA signal



From Ellis et al, arXiv:2308.08546

Stochastic Gravitational Wave Background

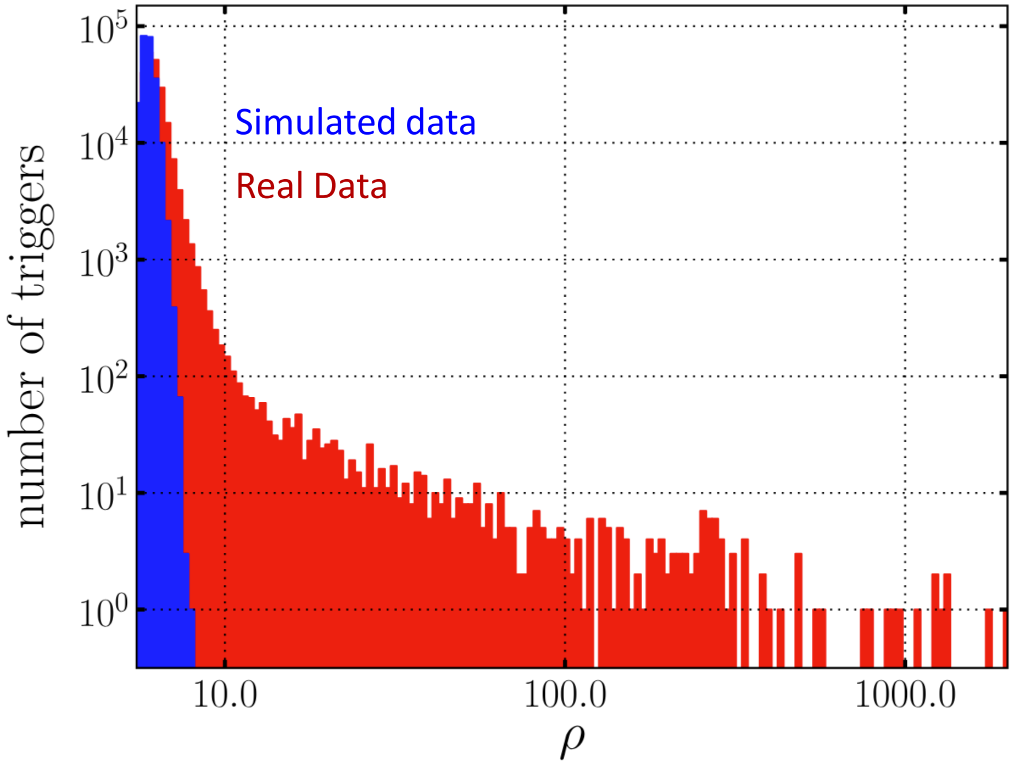
- Cosmological background likely obscured by astrophysical background(s)
- Deci-Hertz range is ideal for searching for the GW background, as it's above the galactic and white-dwarf binary astrophysical background



From Staelens et al, arXiv:2310.19448

Benefits of a network: Detection

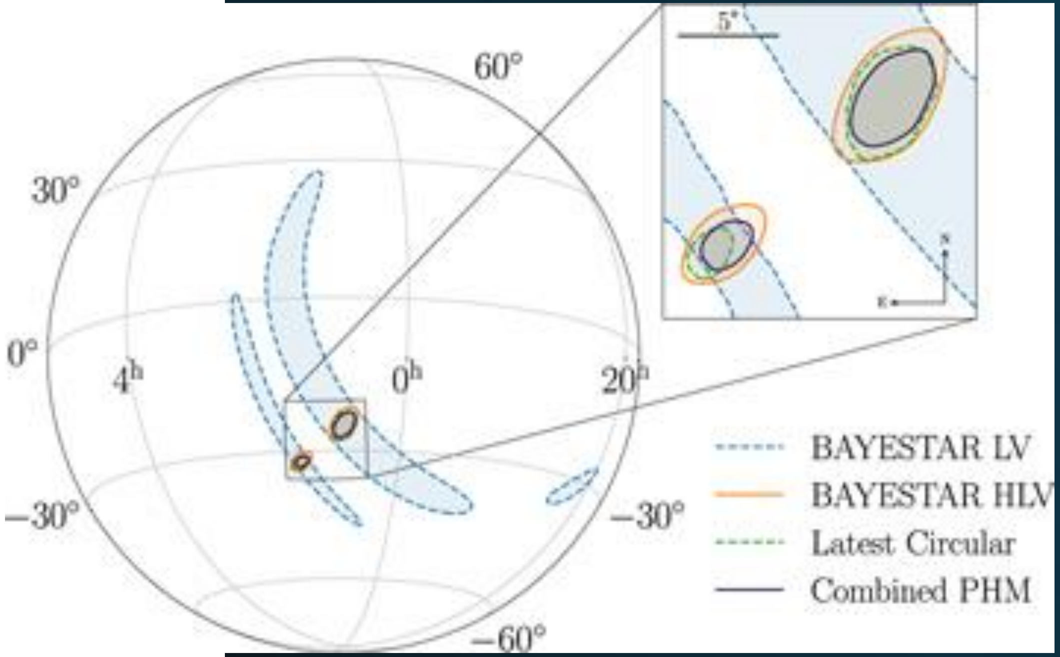
- Increased detection confidence through coincident observation
- Improved sky coverage and live-time
- Ability to observe both gravitational-wave polarizations



From Babak et al, arXiv: 1208.3491

Benefits of a network: Signal Interpretation

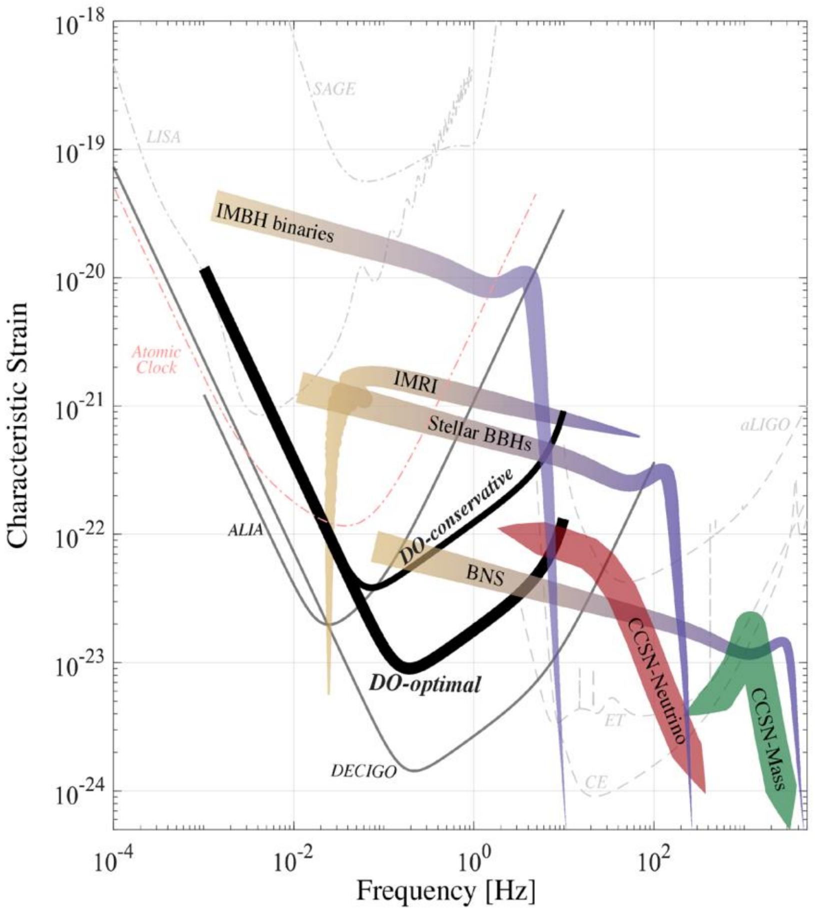
- Higher signal to noise ratio from network of detectors
- Multiple measurements break parameter degeneracies, e.g. between sky location, orientation, distance
- Localization will be challenging in deci-Hertz
  - Timing accuracy ~ $(\rho\, f_{band})^{-1}$ comparable to light travel between sites
  - Earth rotation/orbit should enable localization of long-lived sources



Example: GW190814 localization with 2 or 3 detectors

Summary: Deci-Hertz Opportunities

From Sedda et al, https://doi.org/10.1088/1361-6382/abb5c1



Several unique observing opportunities in the deci-Hertz band

- Observation of intermediate mass BH binaries providing insight into supermassive BH formation
- Eccentricity in stellar mass BH binaries
- White dwarf binaries associated with Type 1A supernovae
- Possible stochastic backgrounds