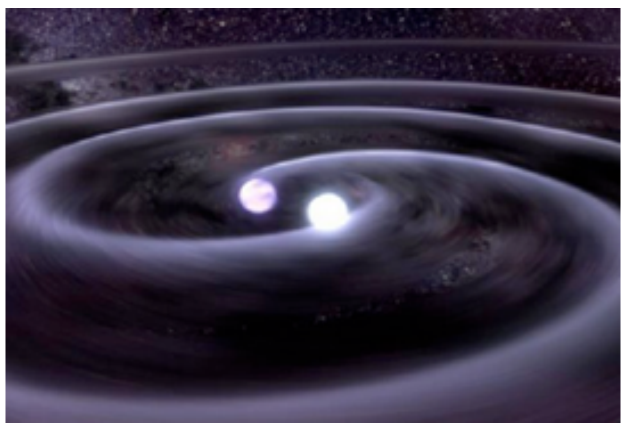
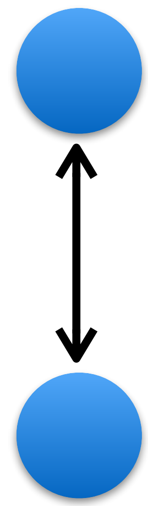
now go to “board”

Gravitational Wave Detection

across the
universe



in the lab

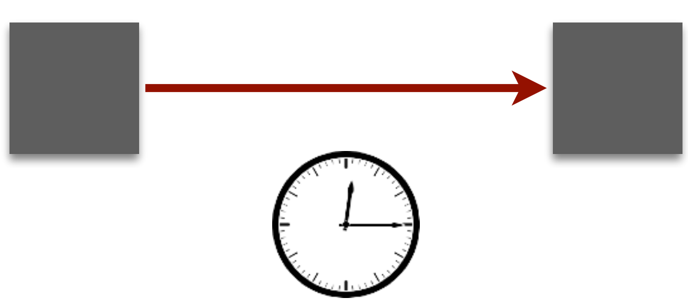


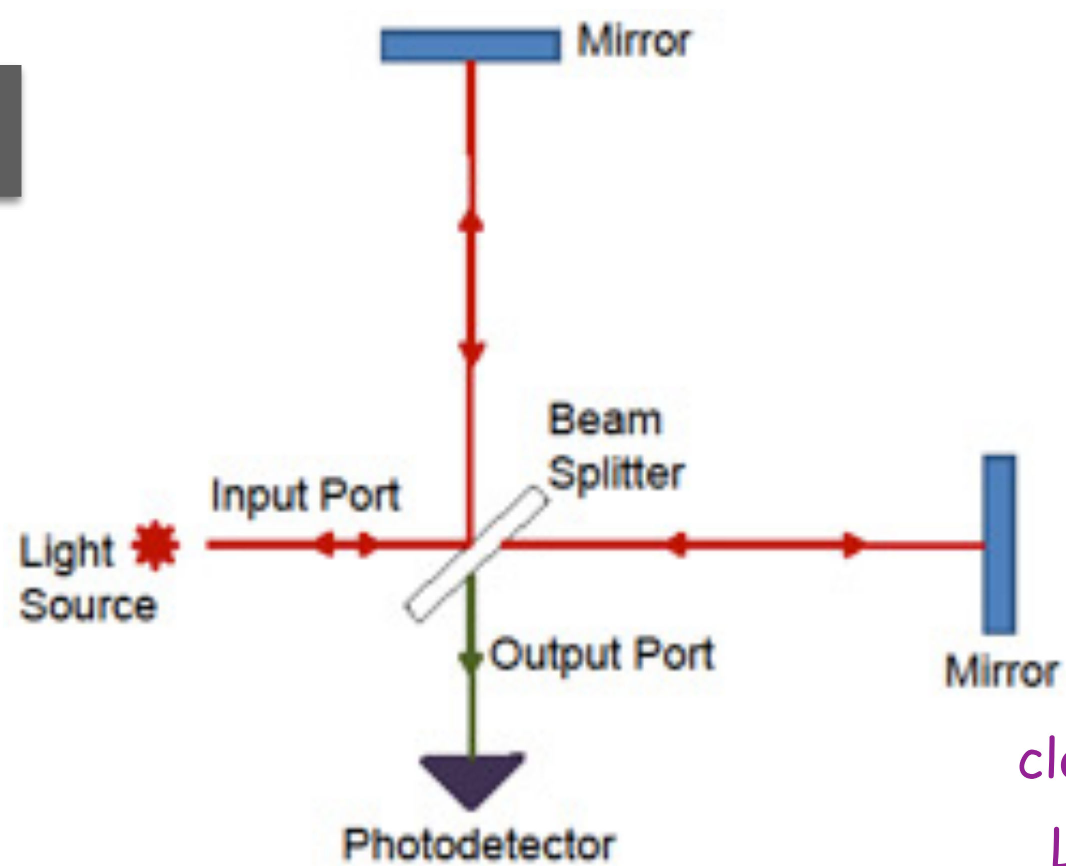
$$L\,(1 + h\cos(\omega t))$$

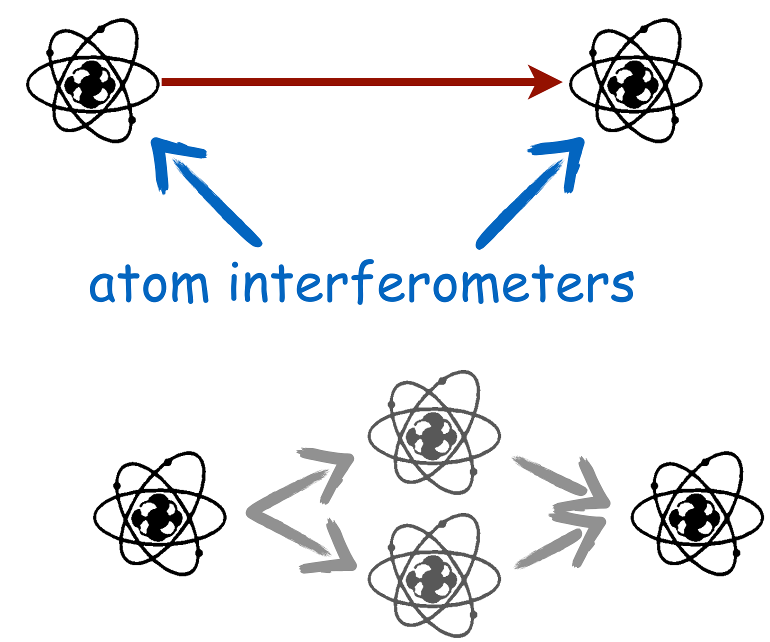
strain   frequency

Gravitational Wave Detection

Gravitation Wave Detector	LIGO	Atom Interferometry
inertial test masses	mirrors	atoms
baseline	laser	laser
good clock	second arm	atoms

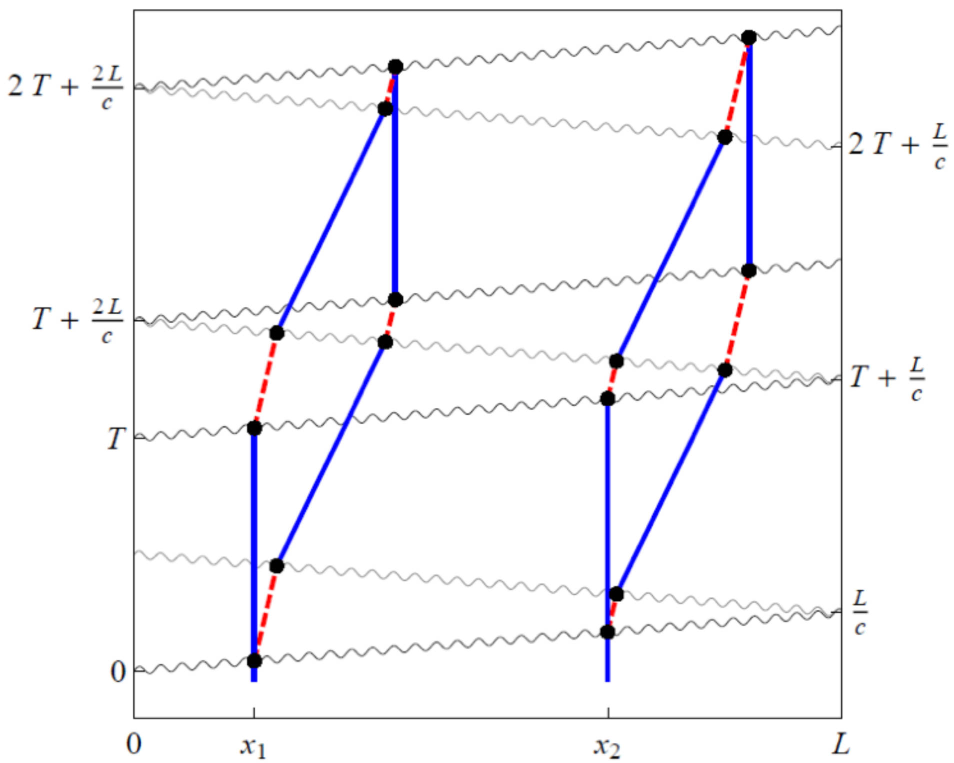






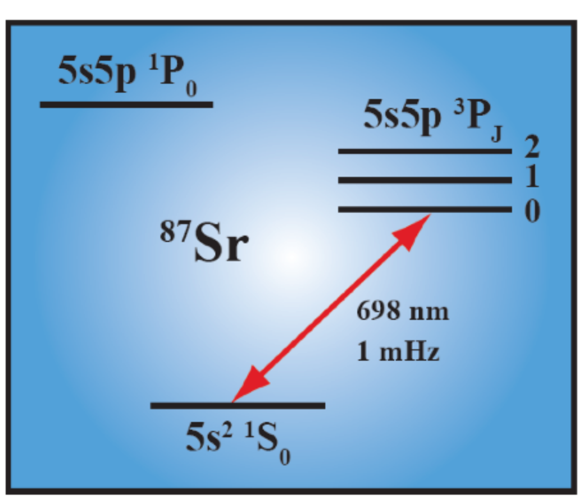
clocks: Kolkowitz, Pikovski, Langellier, Lukin, Walsworth & Ye, **PRD** (2016)

Mid-band Atomic Gravitational wave Interferometric Sensor (MAGIS)



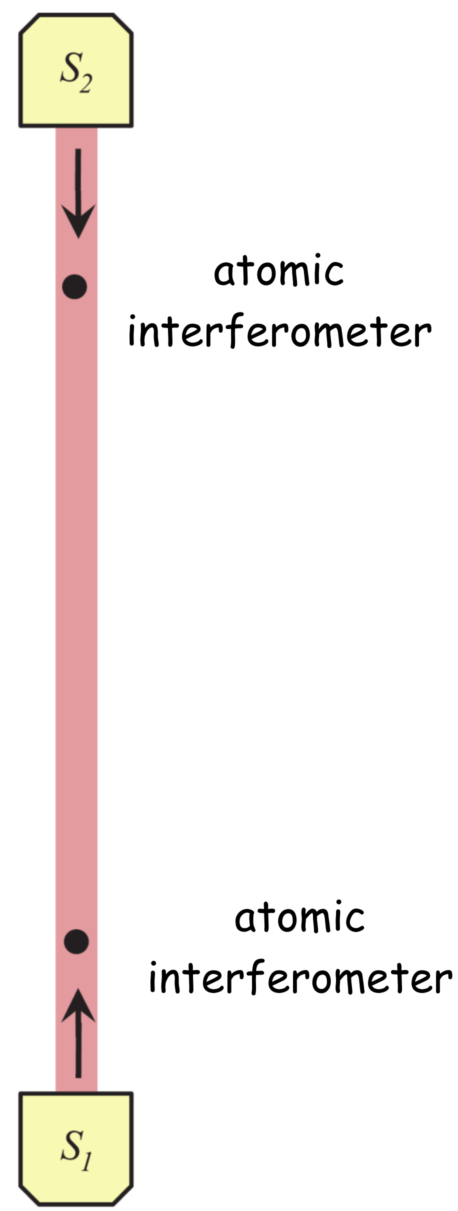
run as hybrid clock/accelerometer

PWG, Hogan, Kasevich, Rajendran PRL **110** (2013)



Clock transition in candidate atom ^{87}Sr

gravitational wave detection:



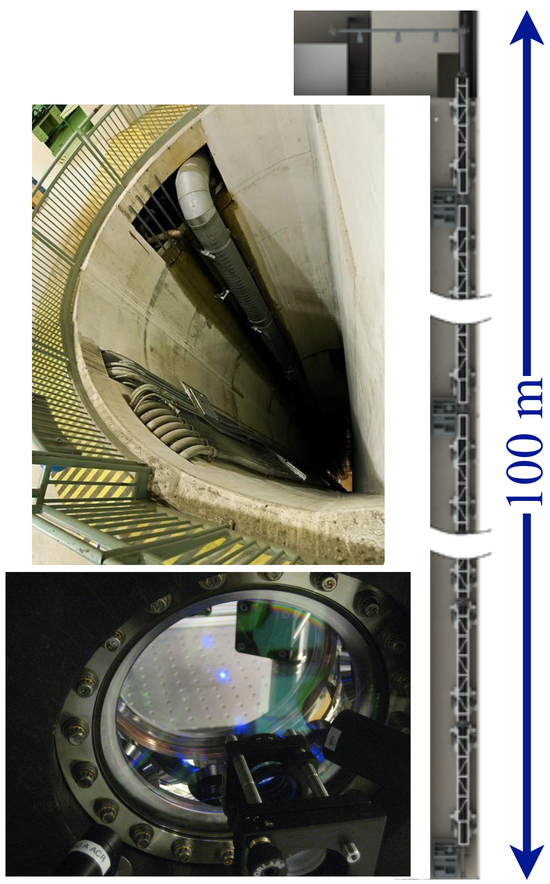
- based on atomic clock technology
- atoms measure light travel time
- accelerometer ➜ can use atoms as good inertial proof masses
- differential measurement allows reduction of many noise sources
- e.g. seismic noise removed ➜ observe frequencies below LIGO

International Efforts in Gravitational Wave Detection with Atom Interferometry

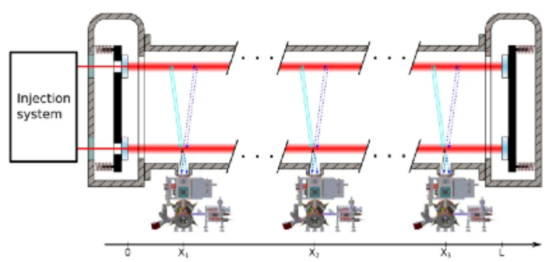
Terrestrial Detectors under construction now:

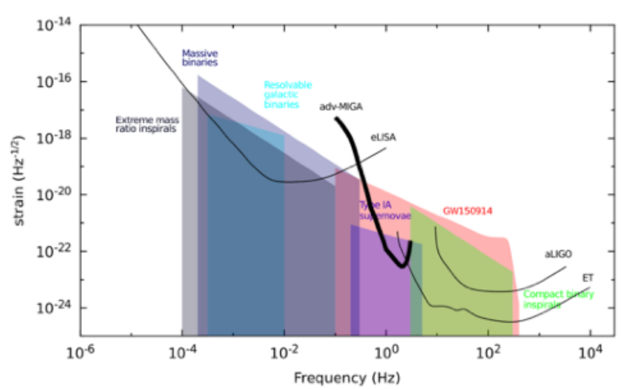
Project	Baseline Length	Number of Baselines	Orientation	Atom	Atom Optics	Location
MAGIS-100	100 m	1	Vertical	Sr	Clock AI, Bragg	USA
AION [10]	100 m	1	Vertical	Sr	Clock AI	UK
MIGA [5]	200 m	2	Horizontal	Rb	Bragg	France
ZAIGA [8]	300 m	3	Vertical	Rb, Sr	Raman, Bragg, OLC	China

MAGIS-100 (Fermilab)

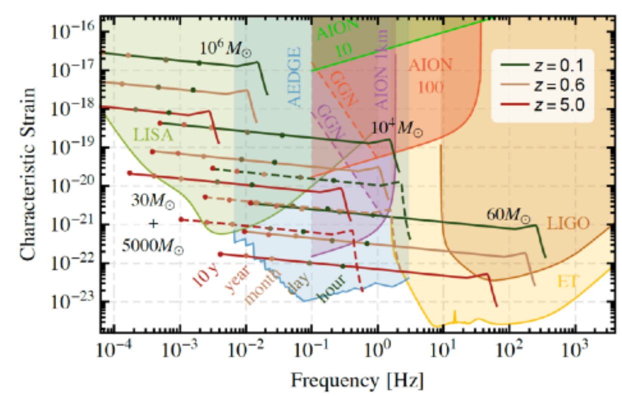


MIGA (France)

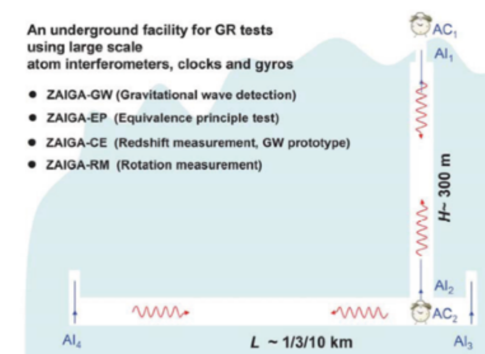


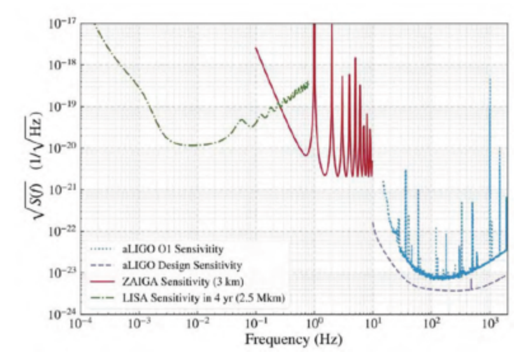


AION (UK)



ZAIGA (China)



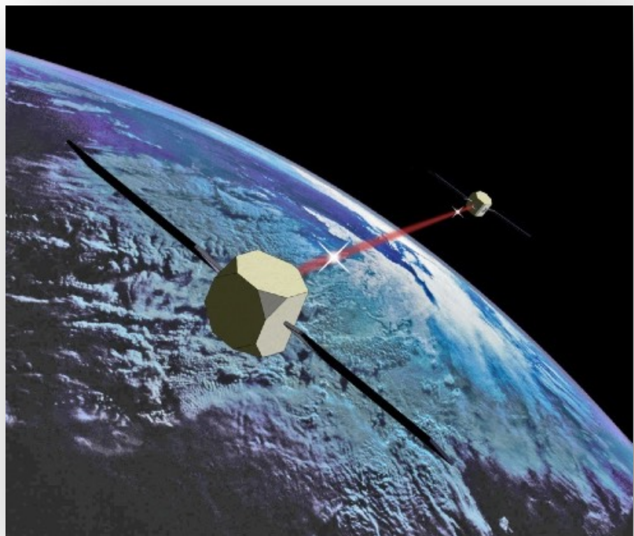


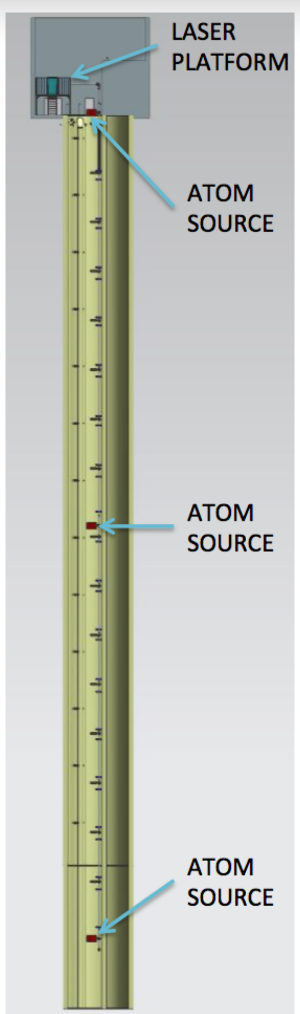
Plans (only) for satellite detectors, e.g. MAGIS and AEDGE leverage technology developed in these terrestrial detectors

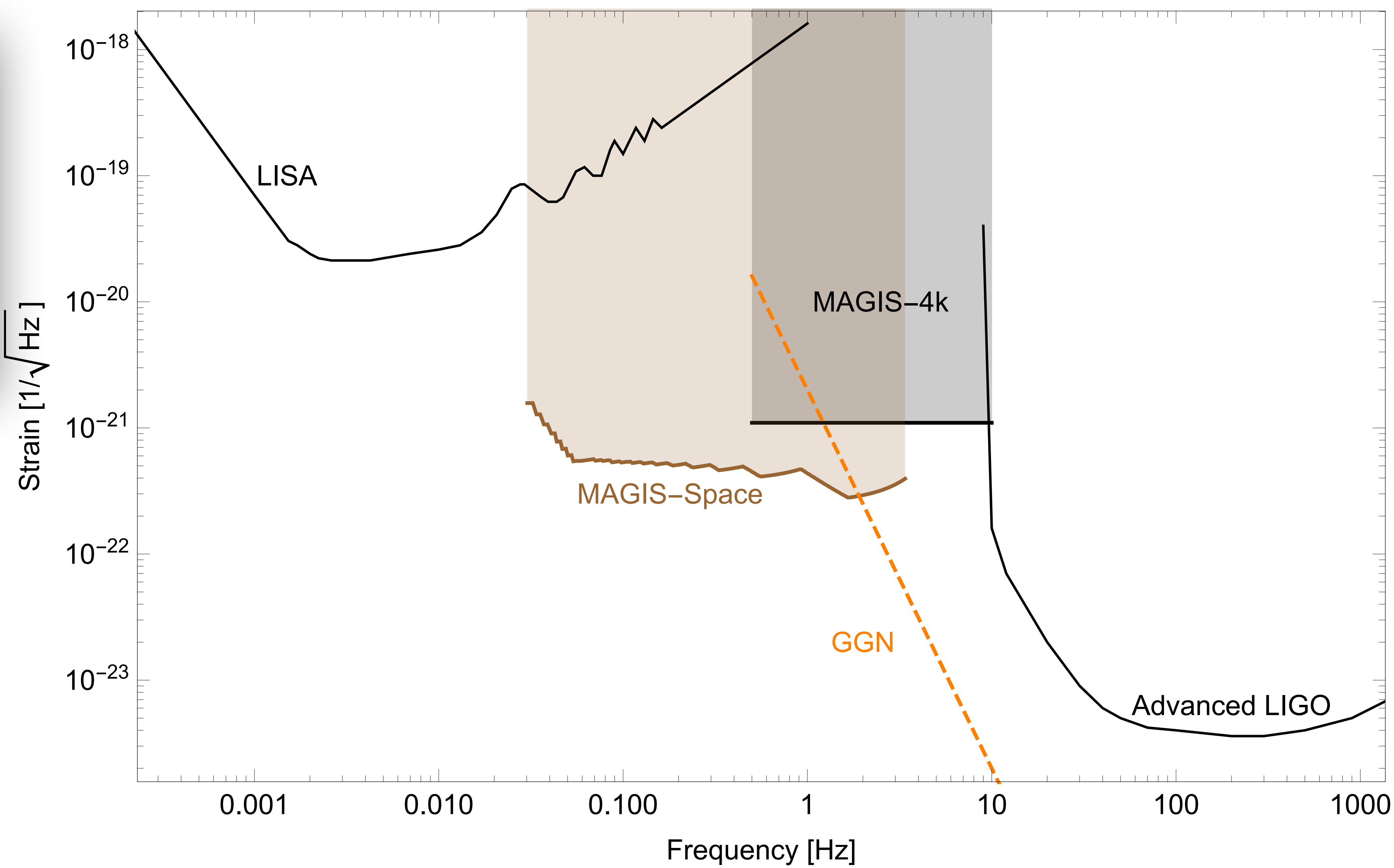
rest of talk I'll focus on science with these, use MAGIS as example

Atom Interferometry for Gravitational Waves

Future detectors (terrestrial + satellite) could access mid-frequency band:







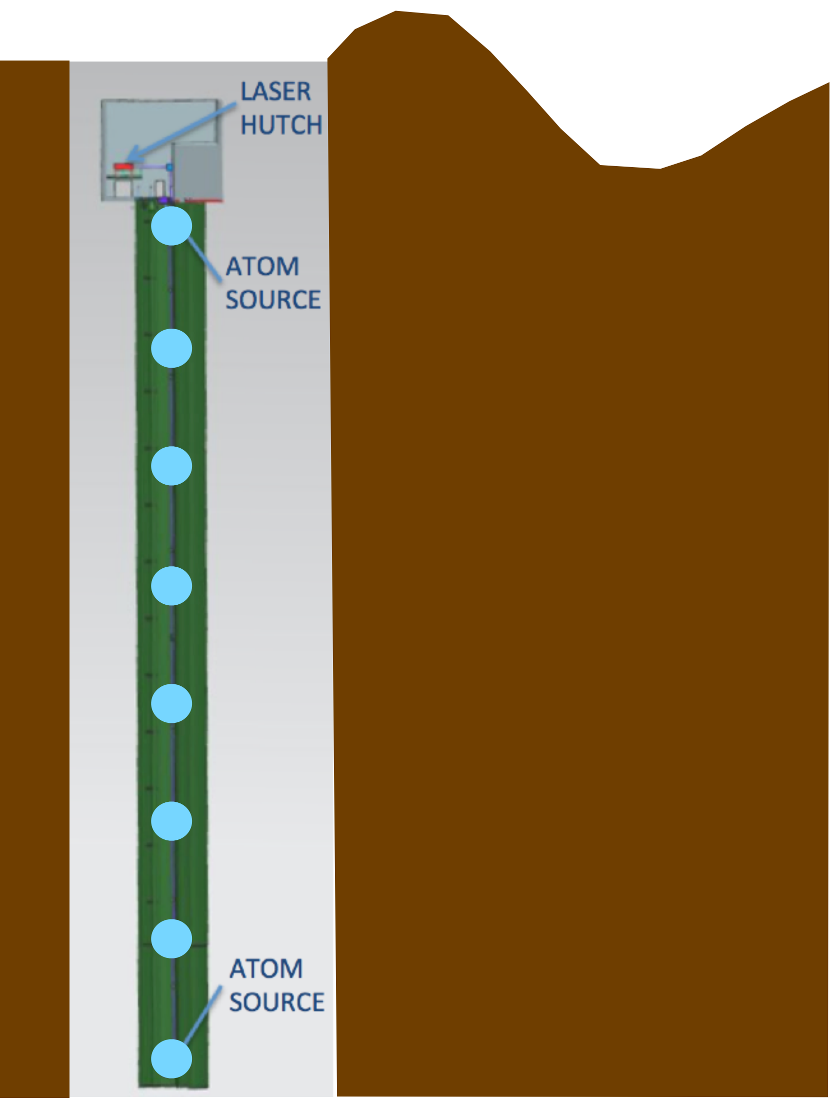
Gravity Gradient Noise

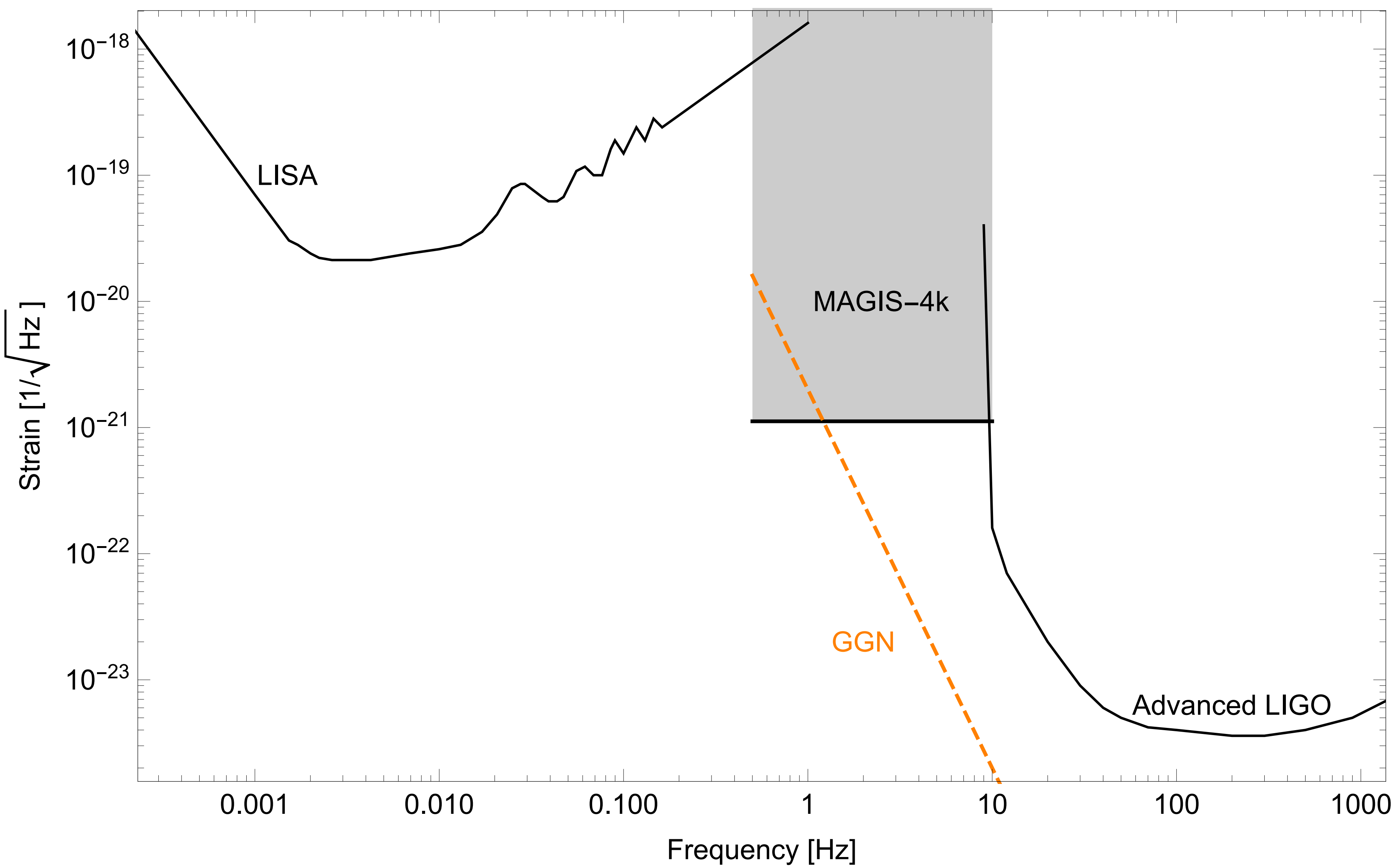
no direct seismic noise, but still couples via Newtonian gravity

the major background for terrestrial experiments

- motivates underground or satellite experiments

e.g. J. Harms, Liv.Rev.Rel **18** (2015)





atoms allow a possible new way to reduce: "string of pearls"

- multiple atom interferometers along baseline
- GW is a plane wave, response is linear along baseline
- surface waves have $\lambda \sim$ km

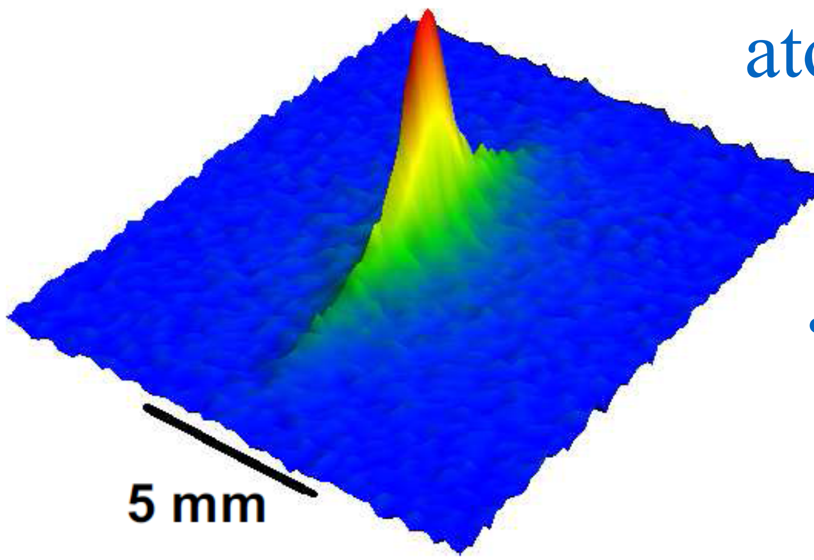
Chaibi et. al. PRD **93** (2016)

Experimental Demonstrations

(Kasevich and Hogan groups)

Stanford 10 m Test Facility

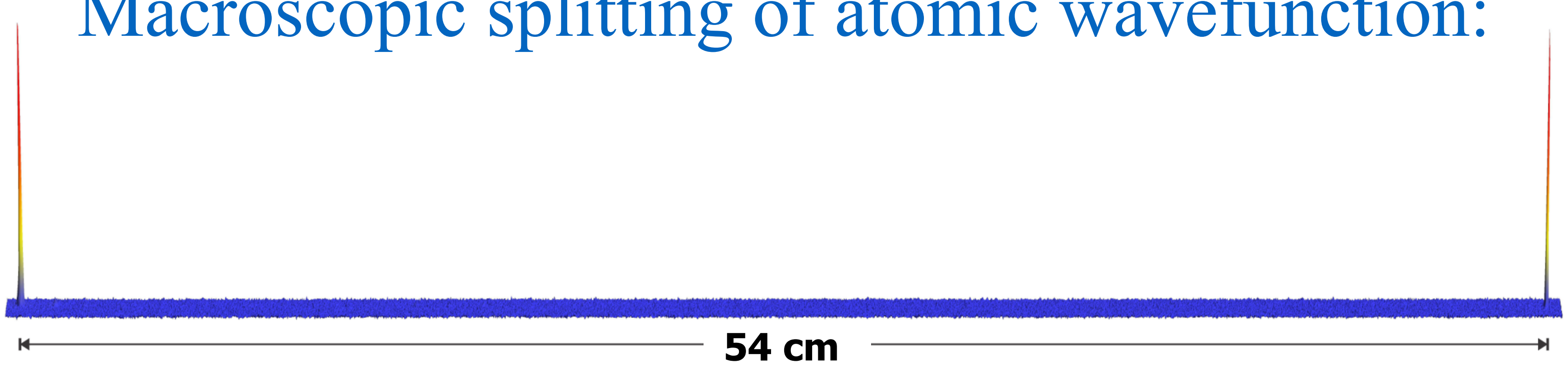
demonstrate necessary technologies (in Rb):



atom cooling

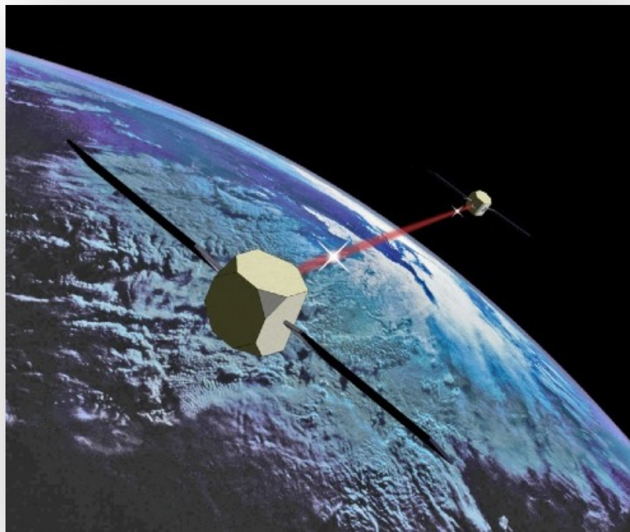
→ 50 pK

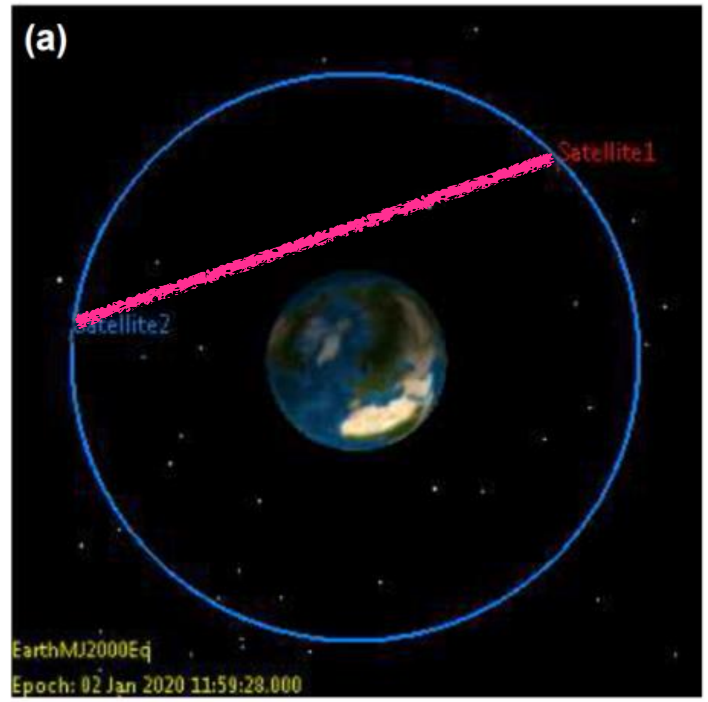
Macroscopic splitting of atomic wavefunction:



Kovachy et. al, *Nature* (2015)

Satellite Configuration





Orbital simulations indicate

- can be earth-orbiting
- baselines ~ 30,000 km
- avoid atmosphere
- laser power sufficient

Single baseline (2 satellite) detector may reduce risk/complexity + cost of mission

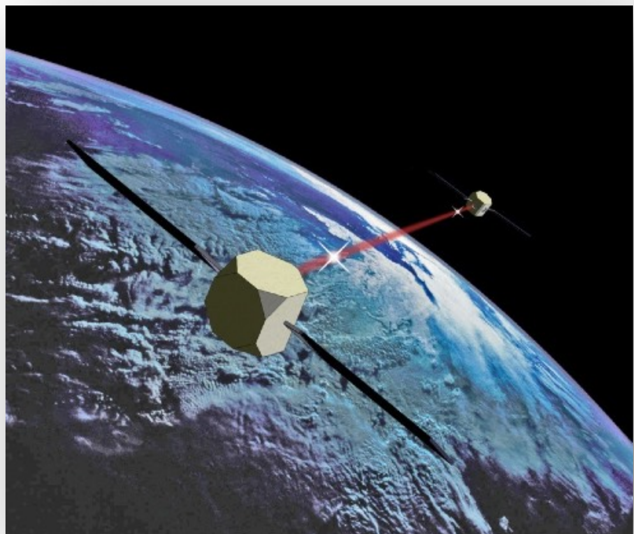
But can measure polarization/localization with single baseline (on earth or in space)?

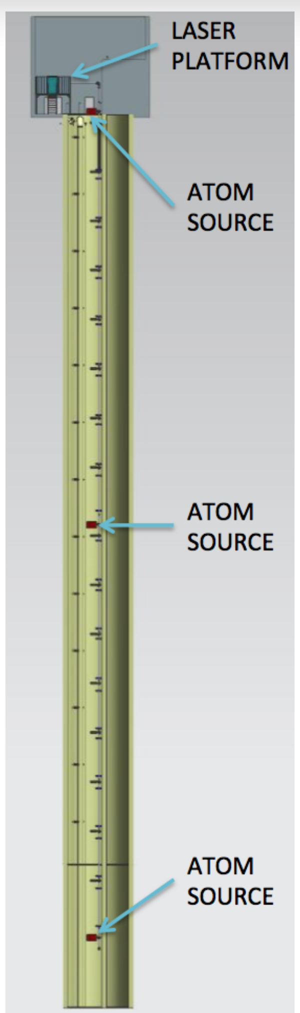
Yes! detector moves: reorients and changes position
sources live long in mid-band (days - years) and orbital period ~ hours - days

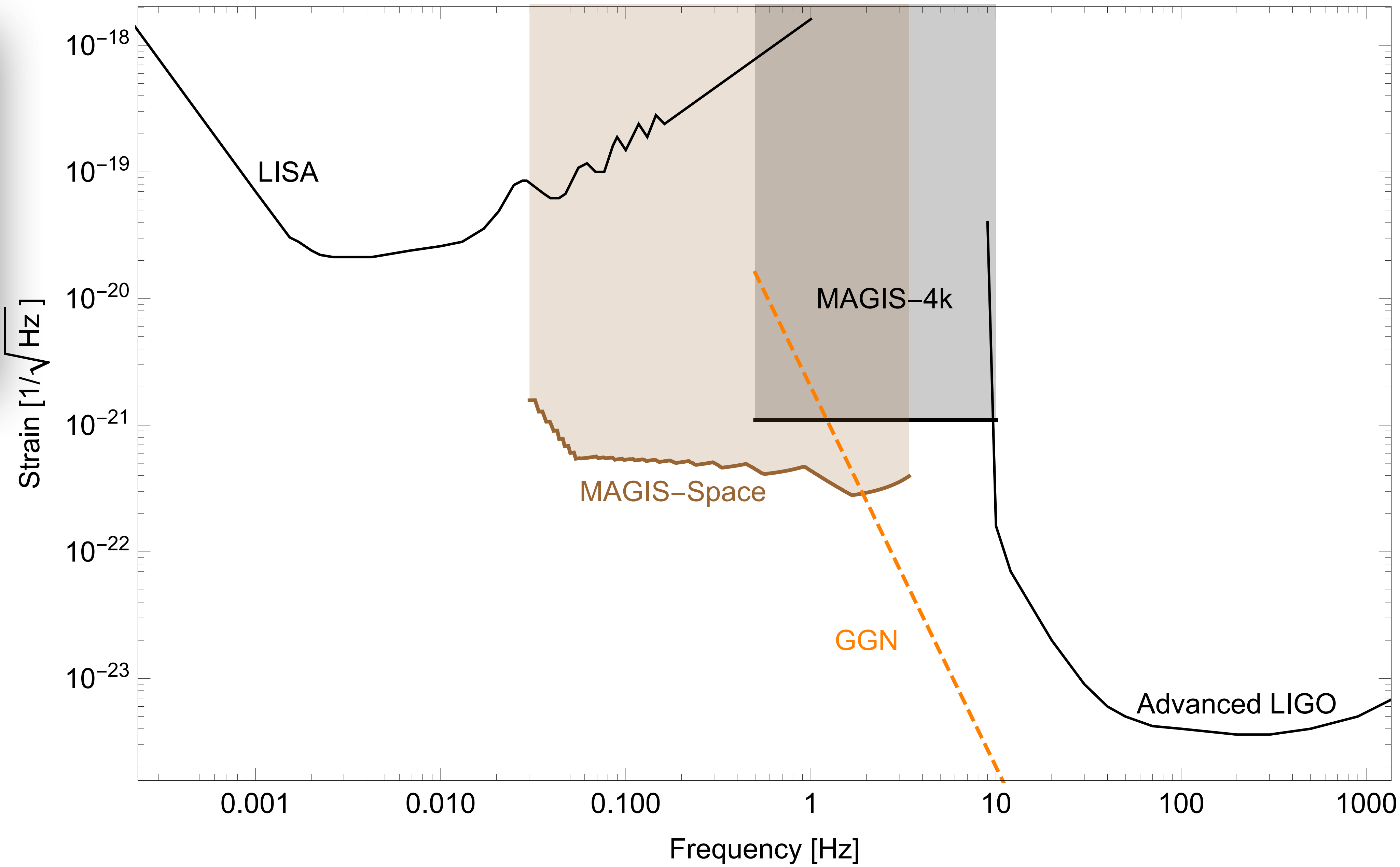
What science do we get from these new detectors?

Atom Interferometry for Gravitational Waves

Future detectors (terrestrial + satellite) could access mid-frequency band:

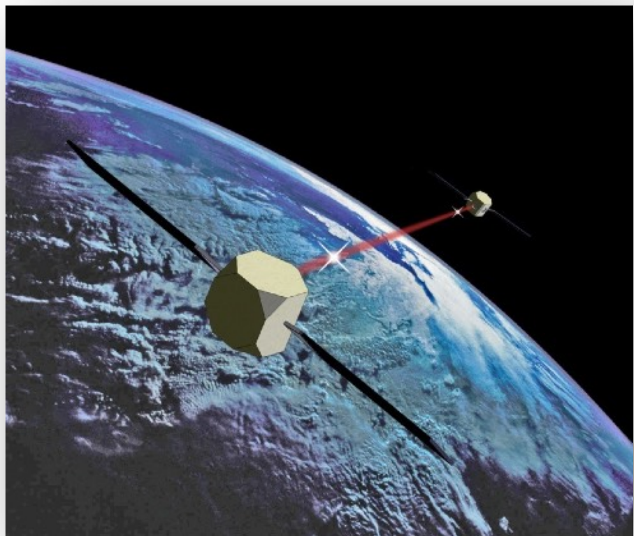


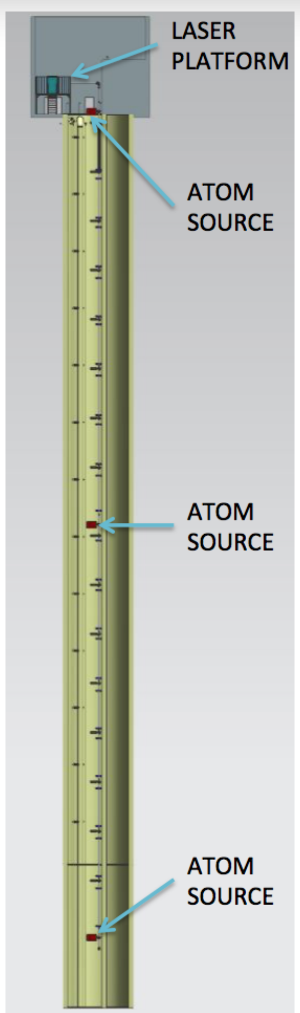


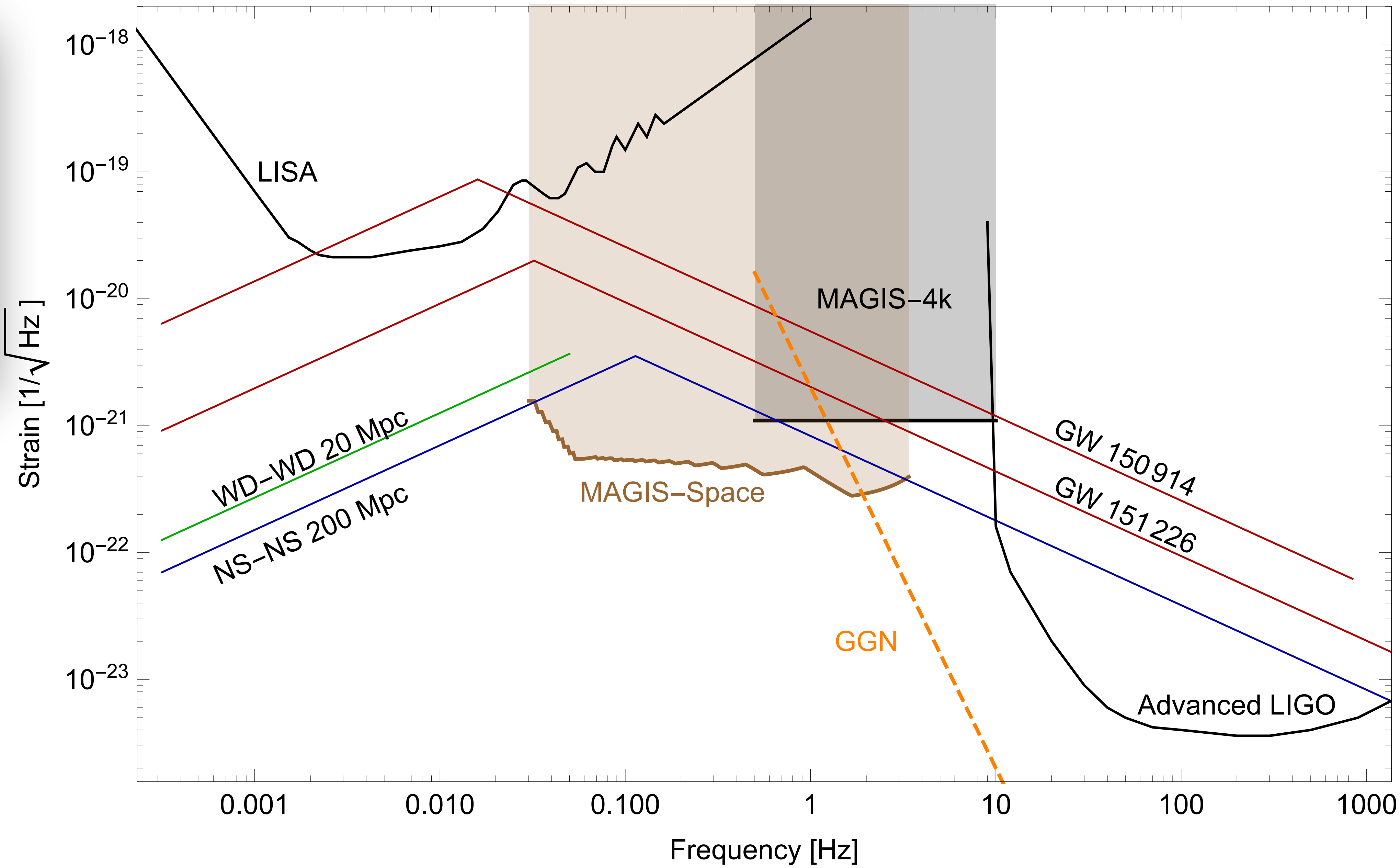


Atom Interferometry for Gravitational Waves

Future detectors (terrestrial + satellite) could access mid-frequency band:







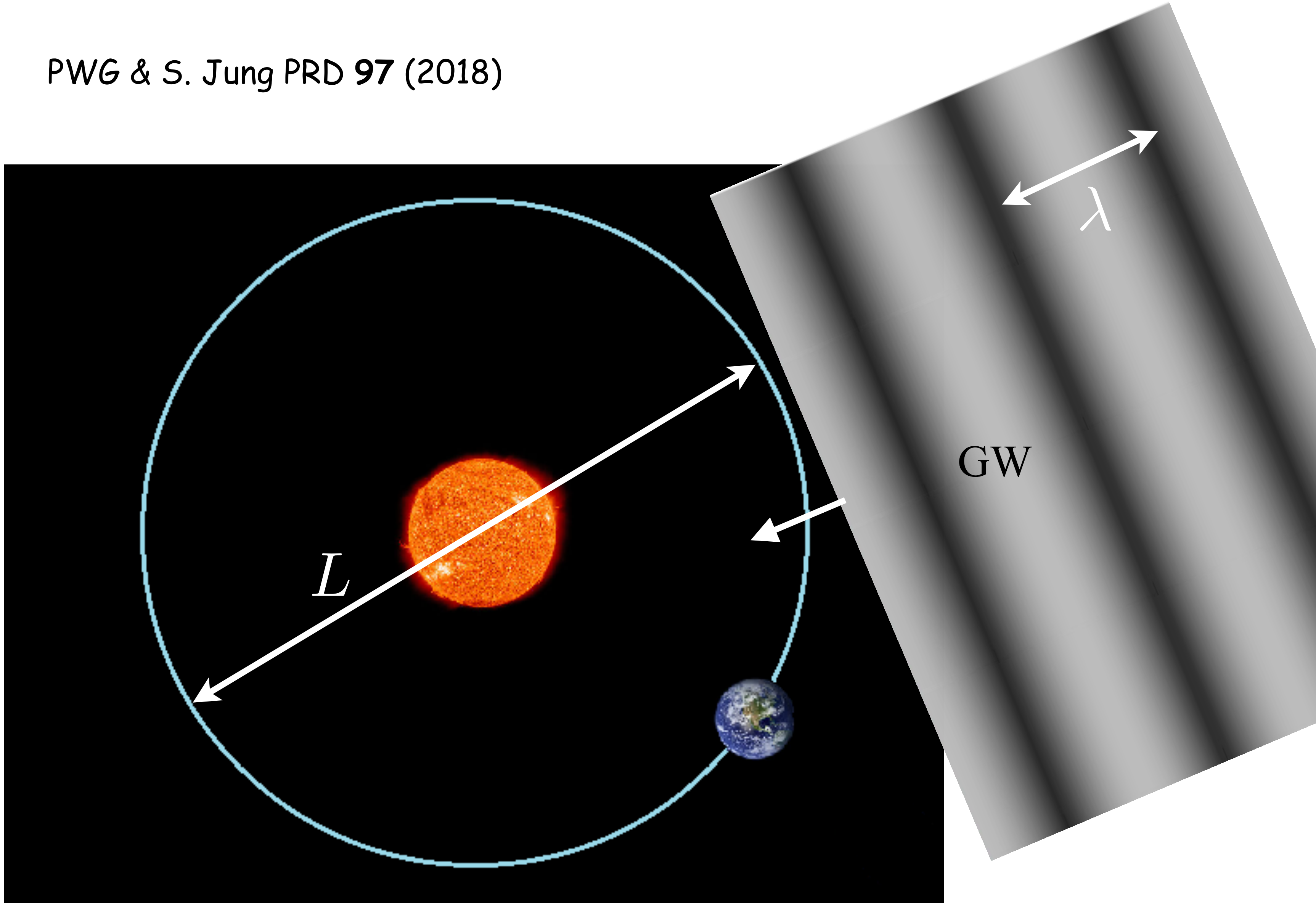
Angular Localization

PWG & S. Jung PRD **97** (2018)

phase advance across orbit enhances angular resolution

$$\Delta\theta \sim \left(\mathrm{SNR} \cdot \frac{L}{\lambda}\right)^{-1}$$

➜ highest frequencies where source lasts 6 months are best

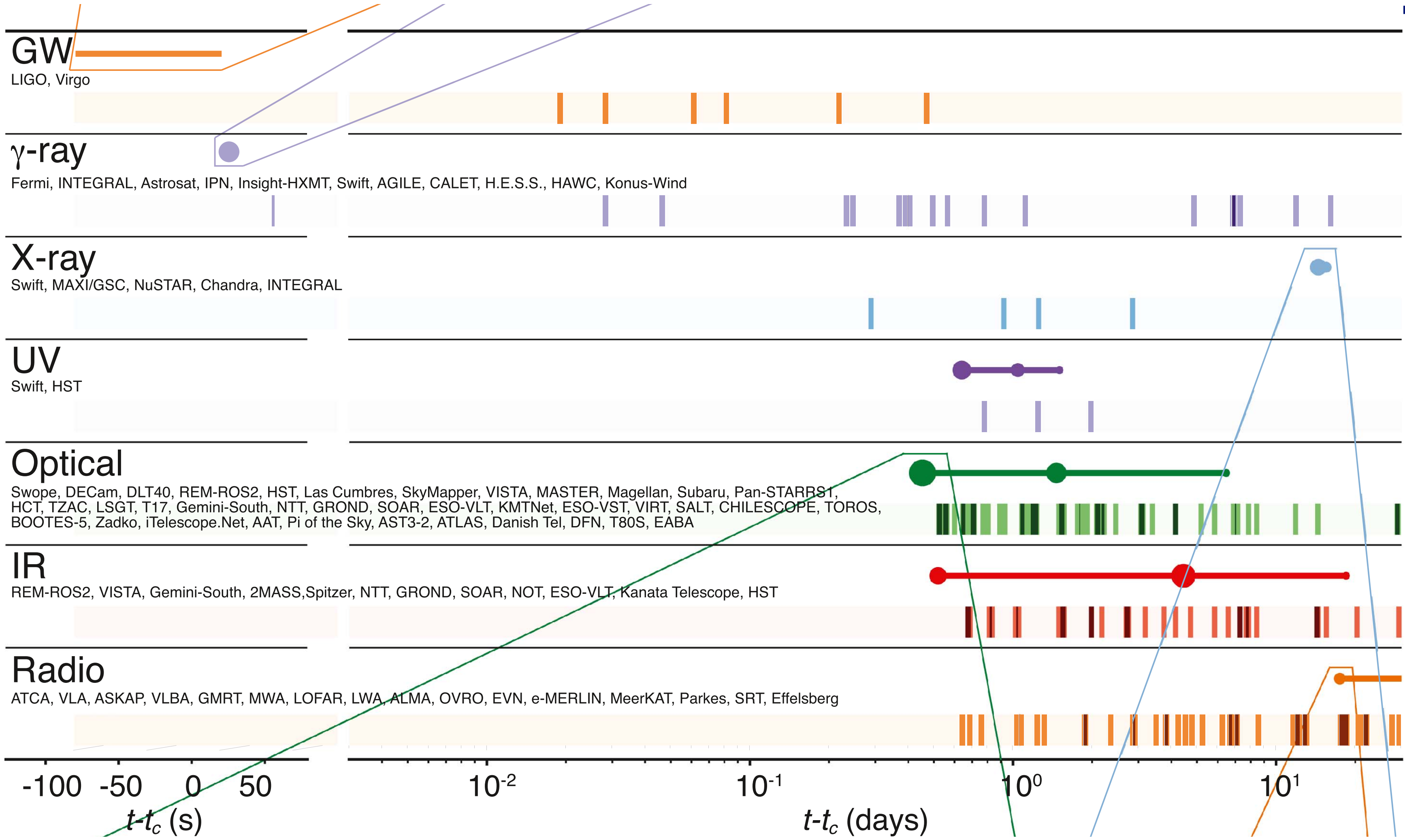


mid-frequency band is ideal for angular localization

Can accurately predict merger time and location on sky (sub-degree)

allows significant science objectives:

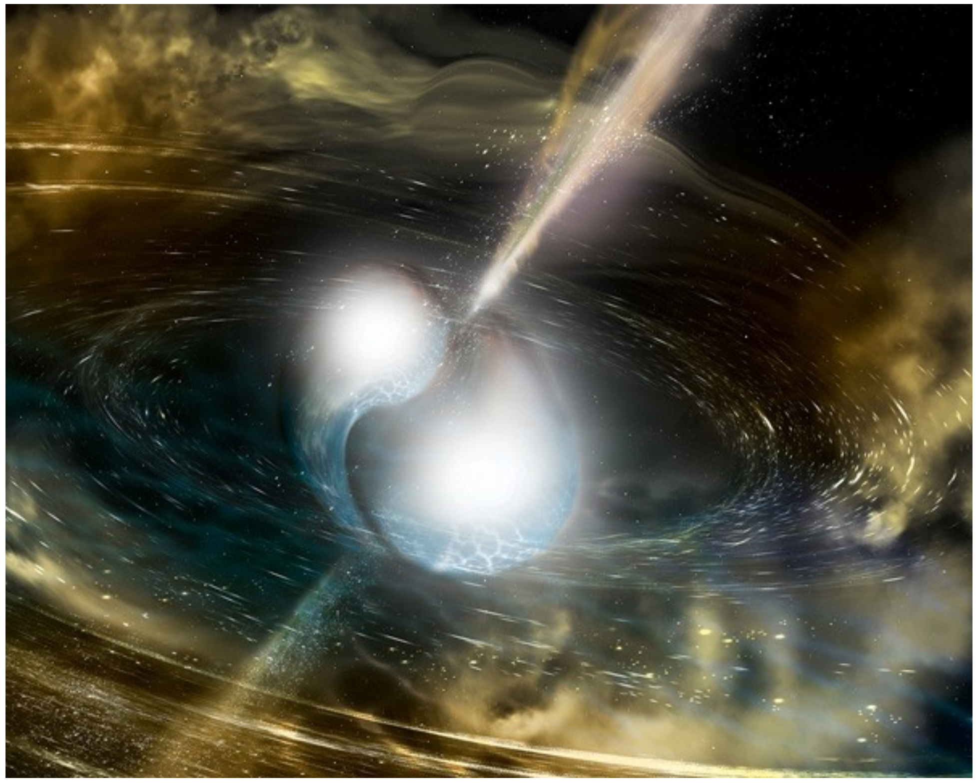
Neutron Star Mergers



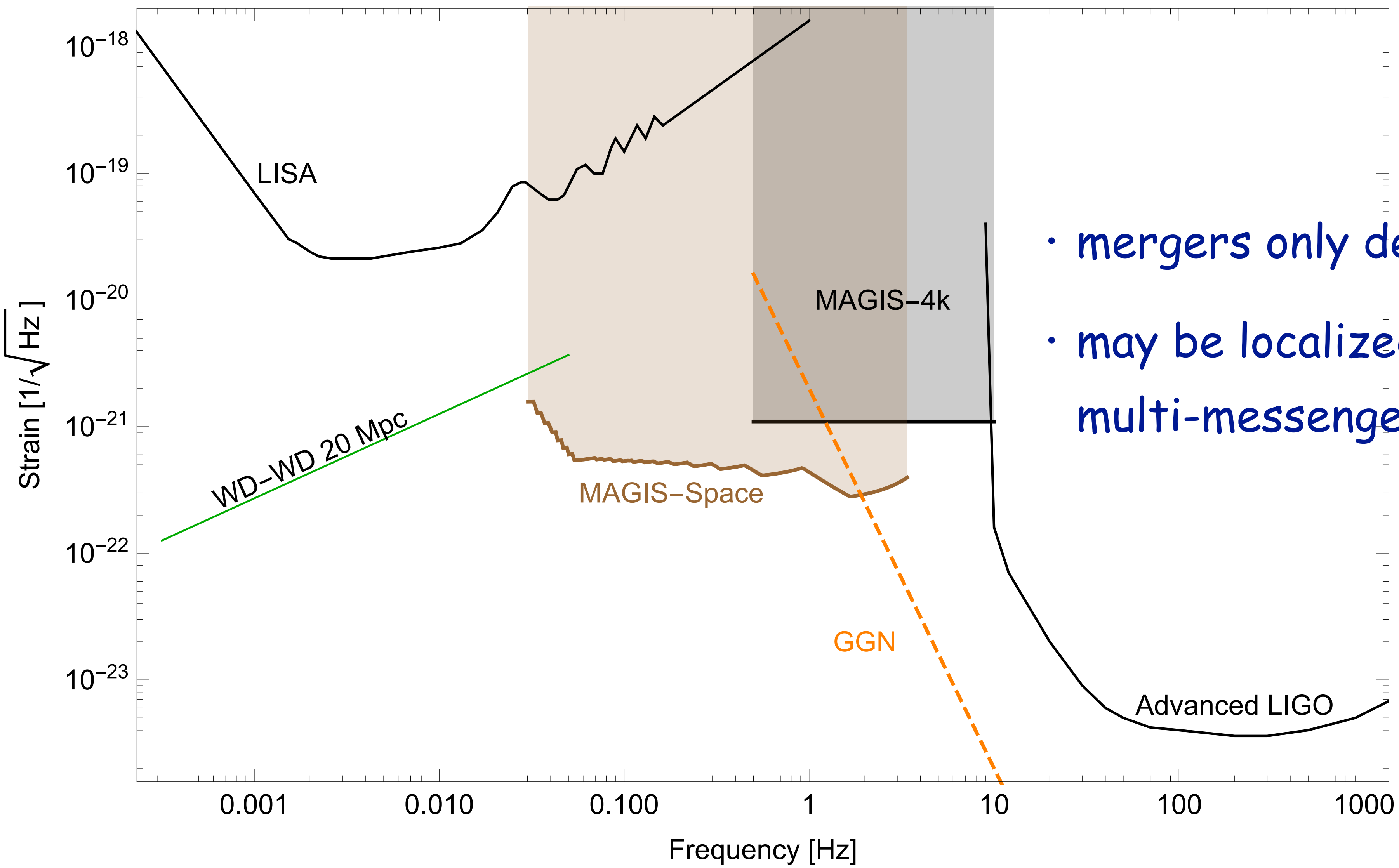
Ap.J.Lett. **848** (2017)

would allow EM telescopes to observe merger as it happens

e.g. learn more about NS mergers, kilonovae, origin of r-process elements, etc.



White Dwarf Mergers



- mergers only detectable in mid-band
- may be localized and predicted in advance ➜ multi-messenger astronomy

What do we learn?

- What does a WD-WD collision look like? (Some of) Type Ia SN?
- measure rate, double degenerate vs single degenerate model of type Ia

Mid-band GW Science

Complementary to LIGO and LISA, observing with atoms in the mid-band may allow:

- Excellent angular resolution
- Identify upcoming NS (and BH) mergers allowing EM telescopes to observe event
- Standard siren measurements for cosmology: measure Hubble, dark energy EOS…
- Study WD mergers, type Ia supernovae, double degenerate vs single degenerate, etc.
- Measure BH spins and orbital eccentricities, learn about formation, heavier BH's
- Possibly early universe sources of GW's (inflation/reheating, cosmic strings, etc.)
- … Likely surprises too!

Gravitational waves will be major part of future of astrophysics and cosmology

must observe in all possible bands

Questions on GW's or atoms?