# Class 24: The future of gravitational wave detections

**ASTR350 Black Holes (Spring 2022)**

**Cole Miller**

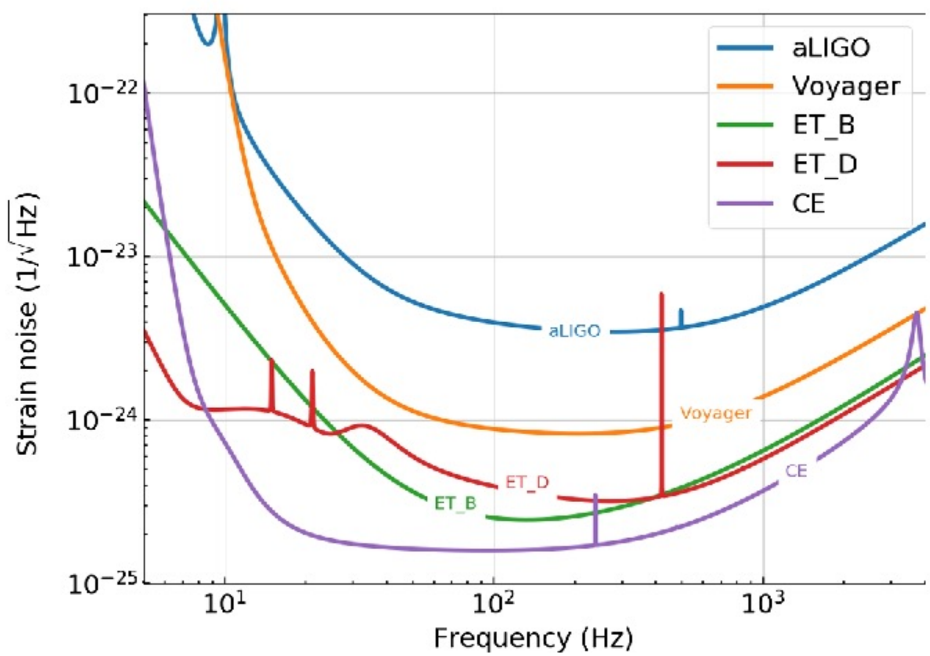
# What we have seen so far about GW

- Gravitational waves are a prediction of Einstein's theory of general relativity, but (1) he went back and forth about whether they are real, and (2) neither he nor any of his contemporaries thought they could be detected
- But the discovery of double neutron star binaries (the first in 1974) and their timing showed that GW exist
- Starting in 2015, nearly 100 GW events have been detected directly, teaching us new things about black holes, neutron stars, and gravity itself
- And today: what does the future hold?

# 3rd generation detectors

- An obvious projection to the future: better detectors in the same frequency band (and more detectors, e.g., LIGO-India)
- Einstein Telescope and Cosmic Explorer: improve by being longer or going underground, cryogenics...
- Not yet fully funded; would be mid-2030s
- Improve sensitivity by factor >~10
- But that's not our focus

Mills, Tiwari et al. 2018

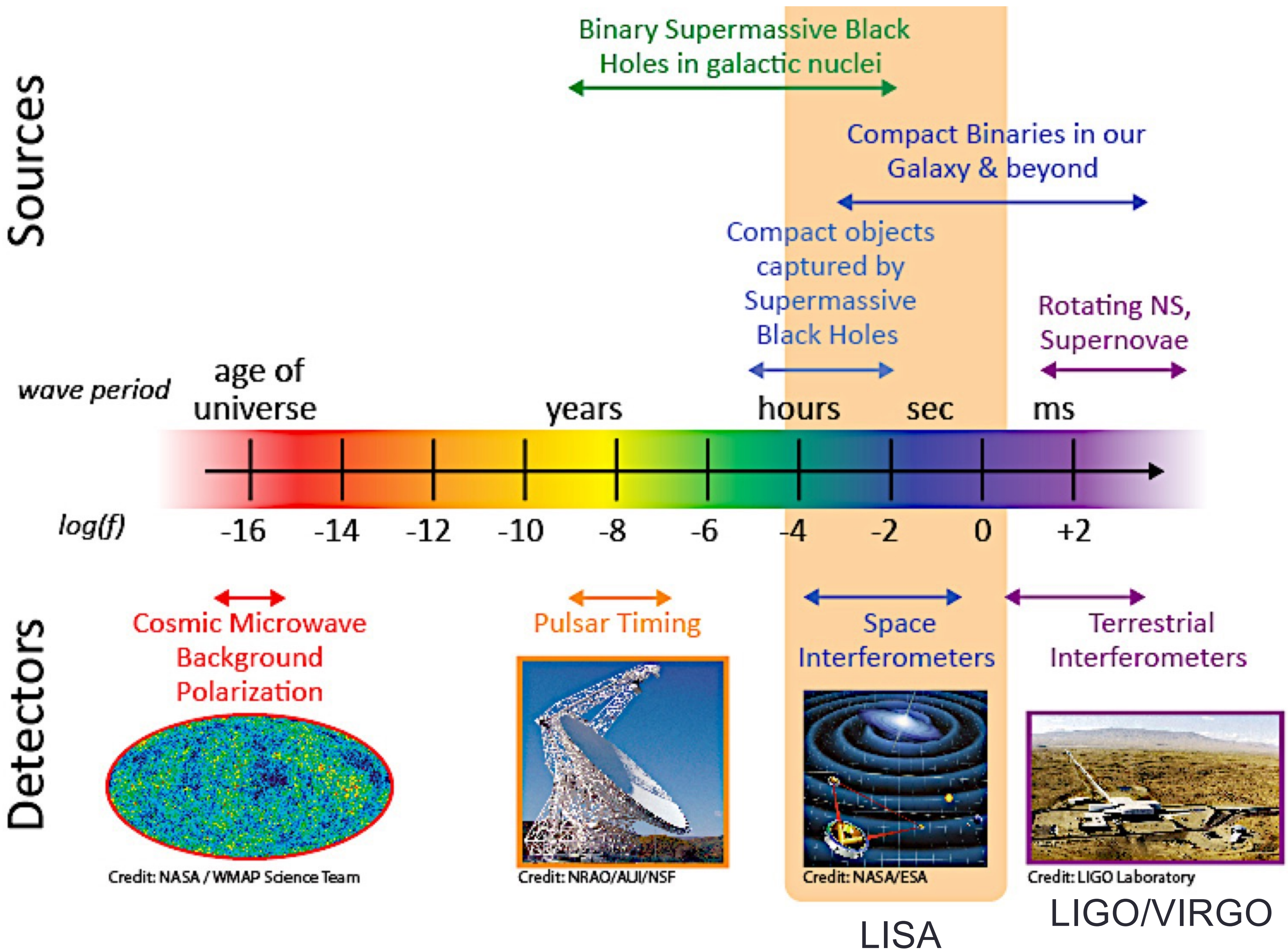



Much better localization, depth, rates, characterization of events.
Also need big improvements in numerical relativity.

# Physics and GW frequency

- Remember that for objects of mass M and radius R, the highest possible frequency is $f_{max}$~$(GM/R^3)^{1/2}$
- For BH, R~M, so $f_{max}$~1/M. Thus stellar-mass BH (~10 $M_{sun}$) can be seen with ground-based detectors, but lower frequencies are needed for SMBH
- Also see wider binaries, binary white dwarfs and ordinary stars, and other phenomena at lower frequencies
- The GW frequency spectrum ranges from ~$10^{-17}$ Hz to ~$10^4$ Hz; as broad as the EM spectrum!

# The Gravitational Wave Spectrum



# Laser Interferometer Space Antenna

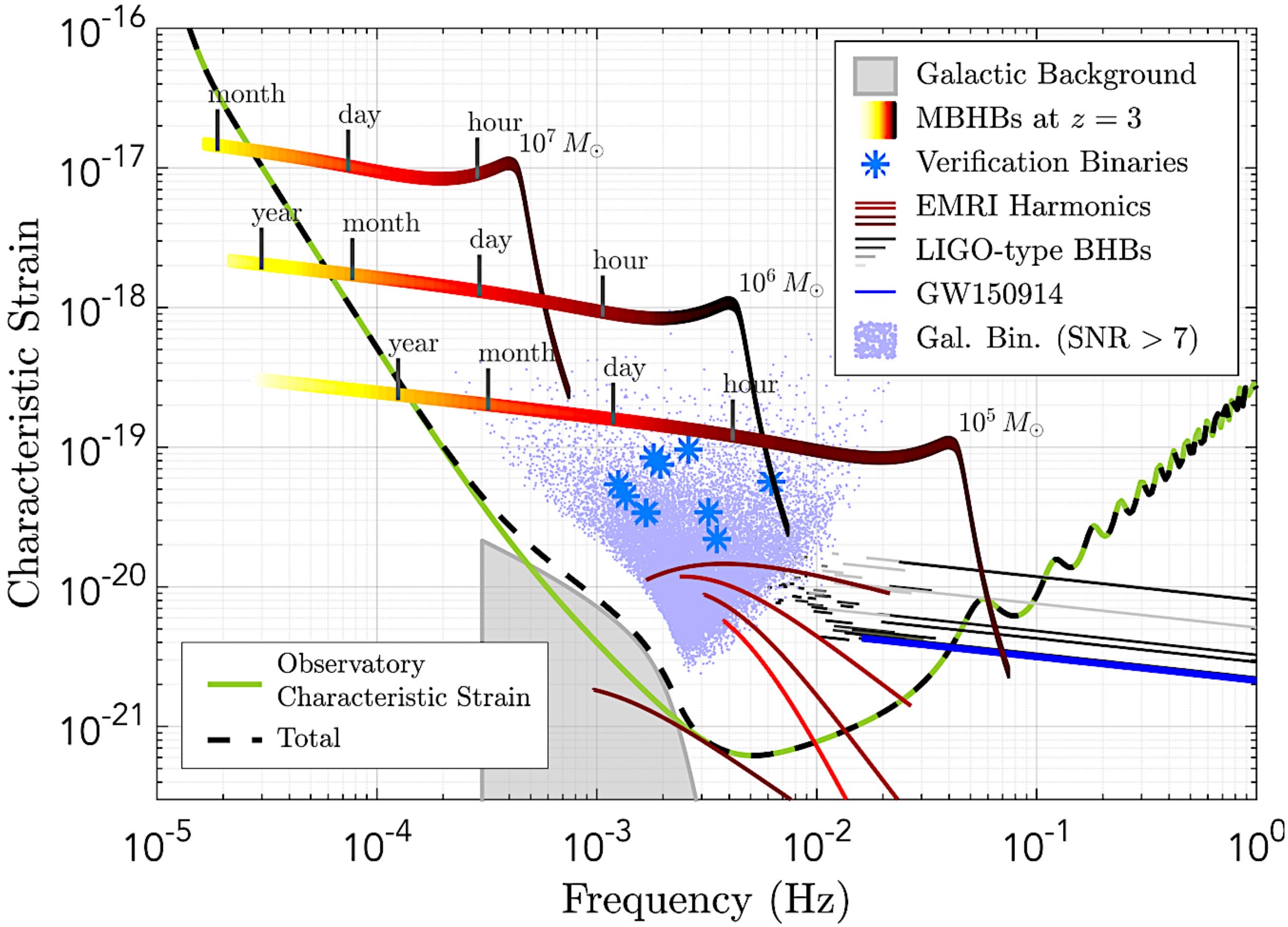
- Being sensitive to the milli-Hz frequency band, from ≈0.1 milli-Hz to 0.1Hz, LISA will probe GW sources across the mass and distance scales, from the Solar neighborhood to the Big Bang.
- LISA will detect many more BHBs outside the MW, being sensitive to the early inspiral of these systems centuries to weeks before they enter the ground-based detector sensitivity band, out to $z \approx 0.5$
- Coalescing massive black hole binaries in the mass range $10^4 M_\odot < M < 10^7 M_\odot$ can be seen anywhere in the Universe
  - -SMBHBs are expected to form in large numbers in the aftermath of galaxy mergers, thus they are tracers of structure formation in the Universe and can be seen by LISA out to $z > 20$,

# Science Goals of Space Based GW Astronomy (LISA)

- When did the first black holes form? What is their initial mass and spin?
- What is the mechanism of black hole formation in galactic nuclei? How do black holes evolve over cosmic time due to accretion and mergers?
- What can we learn about galaxy hierarchical assembly? and the  evolution of massive black holes by tracking their merger history.
- Problems:
  - relatively large positional uncertainties ~10deg$^2$
  - rate of detections and the redshifts are highly uncertain

# LISA Sources- notice for SMBH much larger strain than for LIGO

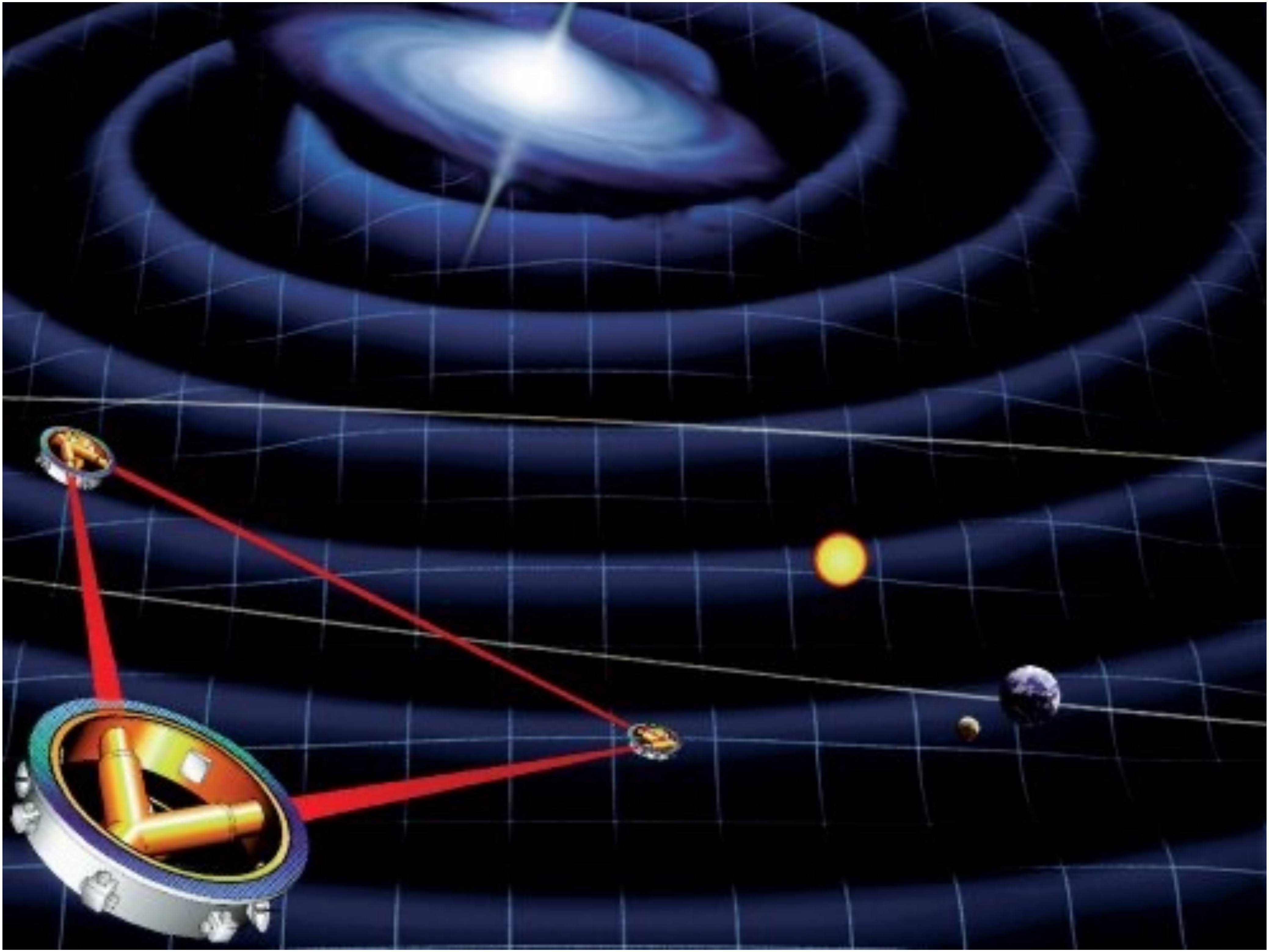
As opposed to LIGO, where the signals only last a short time, for LISA they sweep across the LISA band from low to high frequencies with time before merger, as indicated on the track.

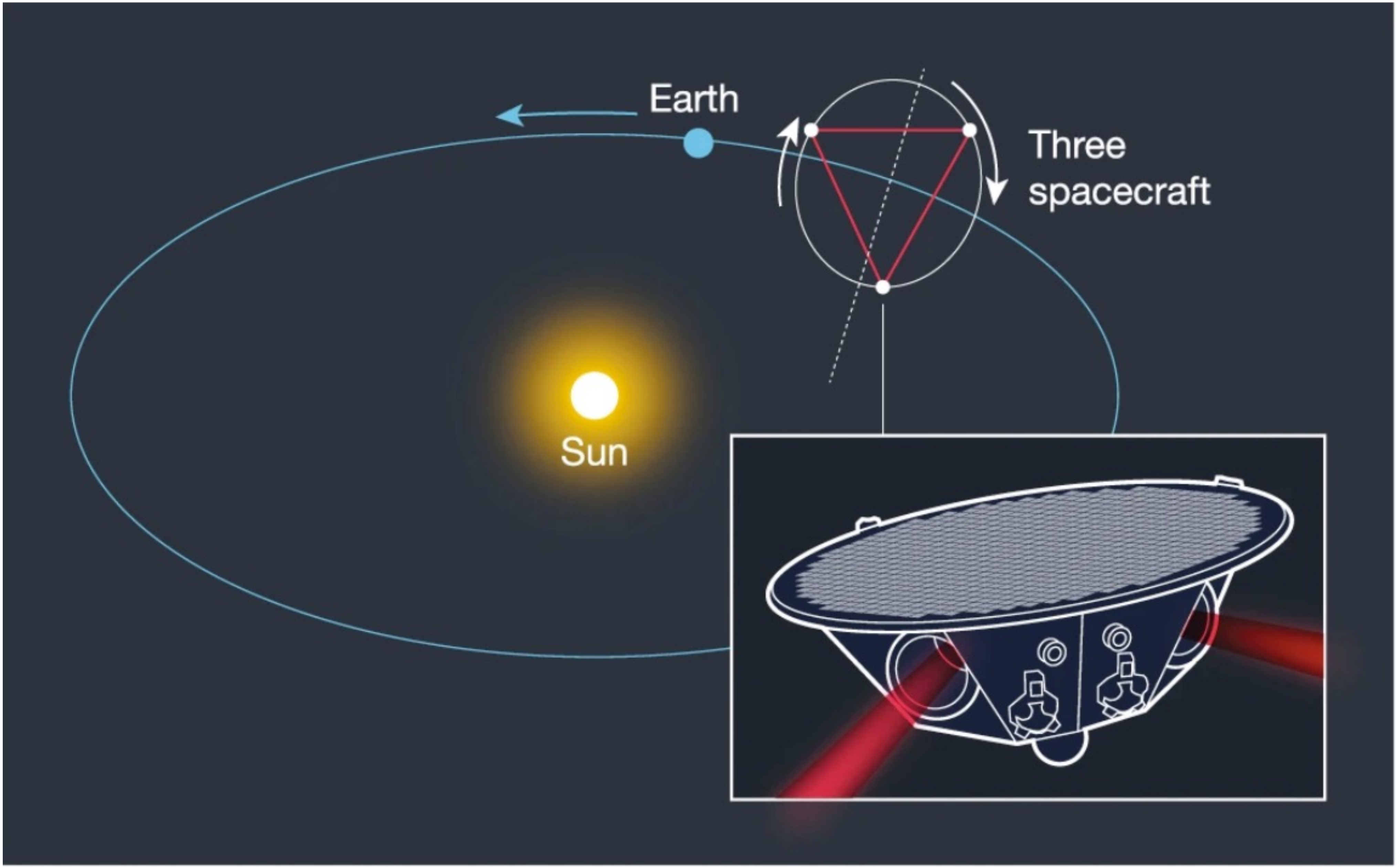



bigger BHs lower frequency

# LISA and the Growth of BHs

- *LISA* measures certain *redshifted* combinations of masses with good accuracy of the merger: if a system has some mass parameter $m$, then *LISA* measures $(1+z)m$, where z is the redshift
- *LISA* can also measure the luminosity distance $D$ of a coalescence accurately.
  - Knowing the cosmological parameters (particularly the mean density, the cosmological constant and the Hubble constant) we can obtain $z$ from $D$ and break the degeneracy. This makes it possible to untangle the mass and redshift and to study the mass and merger history of black holes.
  - Or, if we can identify the redshift from an electromagnetic counterpart, then we can do cosmology D(z) using LISA

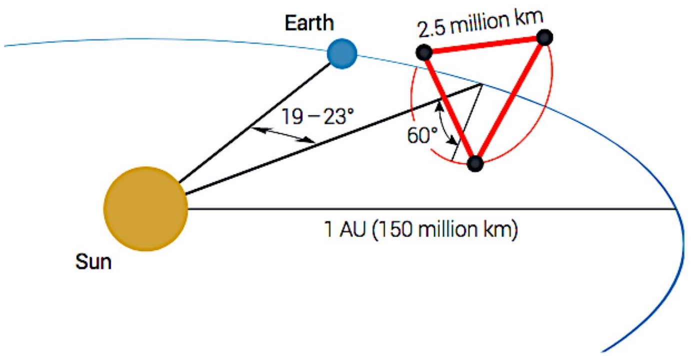





Unlike ground-based detectors, such as LIGO and Virgo, in LISA the stations are free-floating test masses in orbit around the Sun. Figure adapted from ref. 93 (Springer Nature). Miller, M.C., Yunes, N. The new frontier of gravitational waves. Nature **568,** 469–476 (2019).

# LISA- European Space Agency and NASA collaboration

3 spacecraft that are separated by ~2.5 million km and trailing 50 million km, more than one hundred times the distance to the Moon, behind the Earth as it orbits the Sun.




These three spacecraft relay laser beams back and forth between the different spacecraft and the signals are combined to search for gravitational wave signatures that come from distortions of spacetime.

Need a detector bigger than the size of Earth to catch gravitational waves from orbiting black holes millions of times more massive than our sun since the wavelength of their gravitational waves is very large ($R_s$ for $10^6 M_\odot$ ~$3\text{x}10^6$km).

If all goes well LISA should launch in the mid-2030s

# Calibration binaries

- One interesting aspect of LISA, in contrast to LIGO/Virgo/KAGRA etc., is that there are certain binaries we can point to in the sky and know their GW frequency and amplitude; these involve white dwarfs
- These "calibration binaries" allow us to determine whether the instrument is working!
- And since WD-WD binaries are a great candidate for precursors of the types of supernova used to measure the universe's accelerated expansion, they have broad interest
- Some BH-BH binaries might be seen with LISA, then by ground-based instruments a few years later

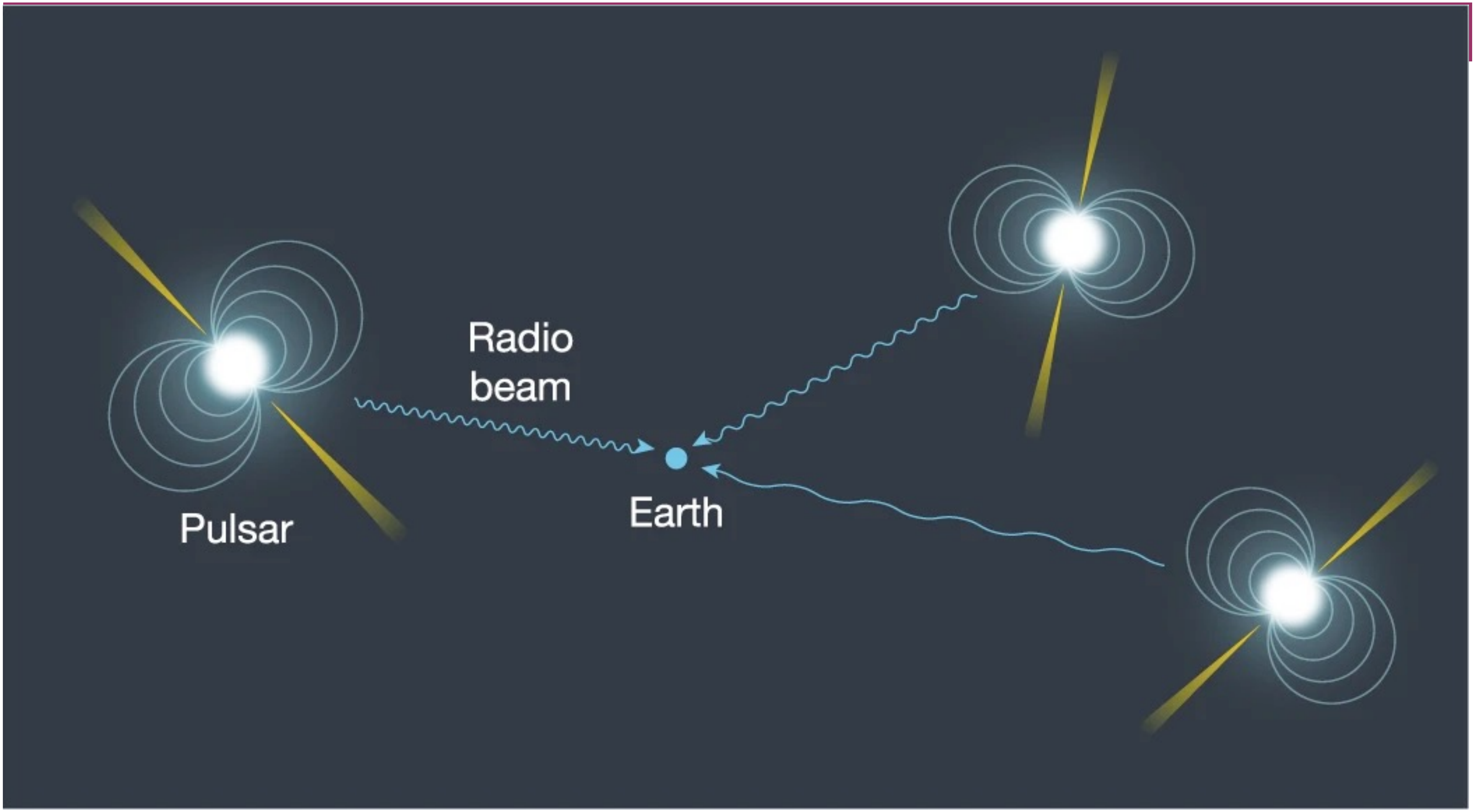
# Another Way of Detecting Gravitational Waves

**Pulsar timing arrays**: a set of pulsars which is analyzed to search for correlated signatures in the pulse arrival times.

Gravitational waves cause the time of arrival of the pulses to vary by a few tens of nanoseconds over their wavelength (so, for a frequency of 3 x $10^{-8}$ Hz, one cycle per year, you might find that pulses arrive 20 ns early in July and 20 ns late in January)

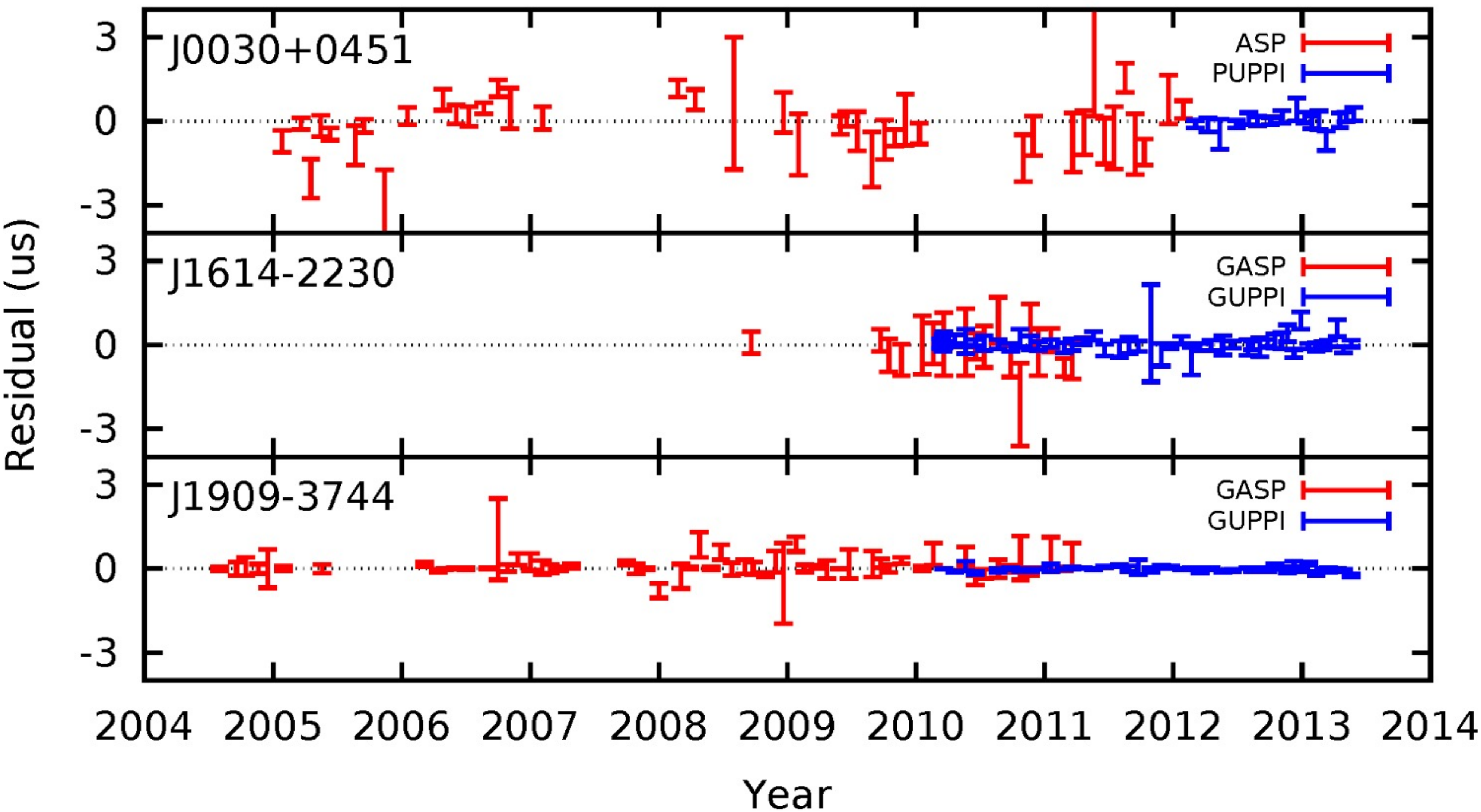
Need extremely stable pulsars- they do exist
Use ~20 to 50 pulsars to help eliminate systematic errors

Very difficult to find 'a source': main goal is to measure the amplitude of background gravitational waves caused by the cosmic history of supermassive black hole mergers.




The signals from the pulsars travel through spacetime that is dynamically warped by gravitational waves, which changes the timing of the pulsars in a correlated way.

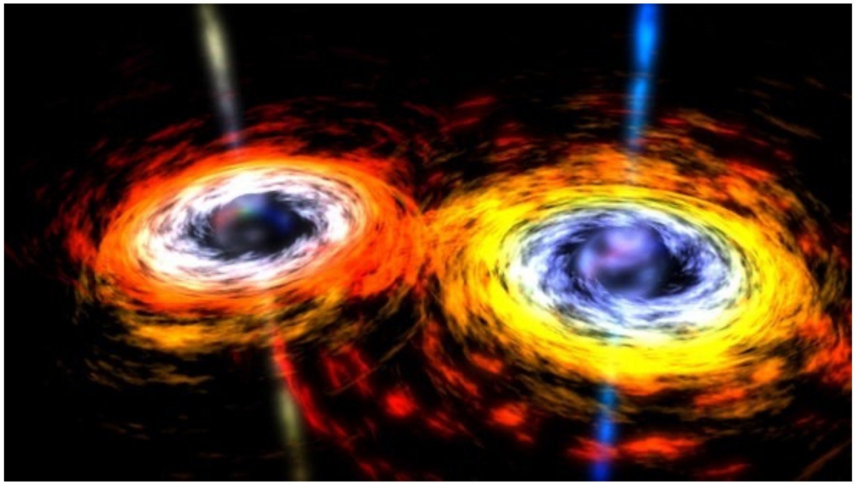
# Amazing Timing Accuracy for Some Neutron Stars




Can model their pulse periods so accurately that one does not miss by microseconds over 10 years

# SMBH binaries as sources

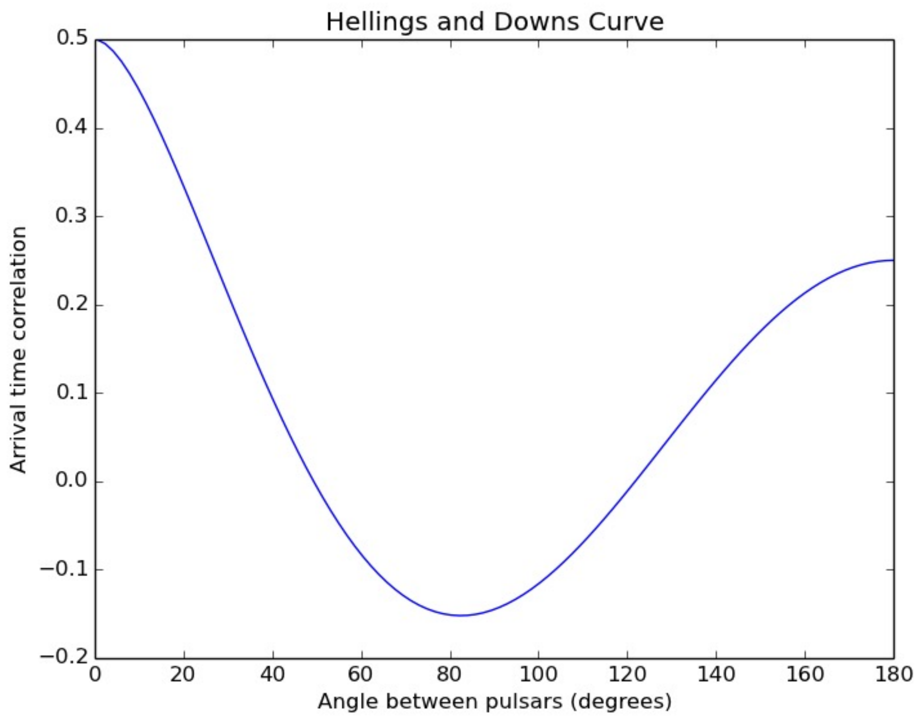
- In contrast to the LIGO/Virgo detections, which are individual transient events, when you go to much lower frequencies ($10^{-9}$ Hz to $10^{-7}$ Hz for pulsar timing arrays), these are supermassive black holes in binaries lasting thousands to millions of years
- Thousands of such binaries at once; they form a *stochastic background*



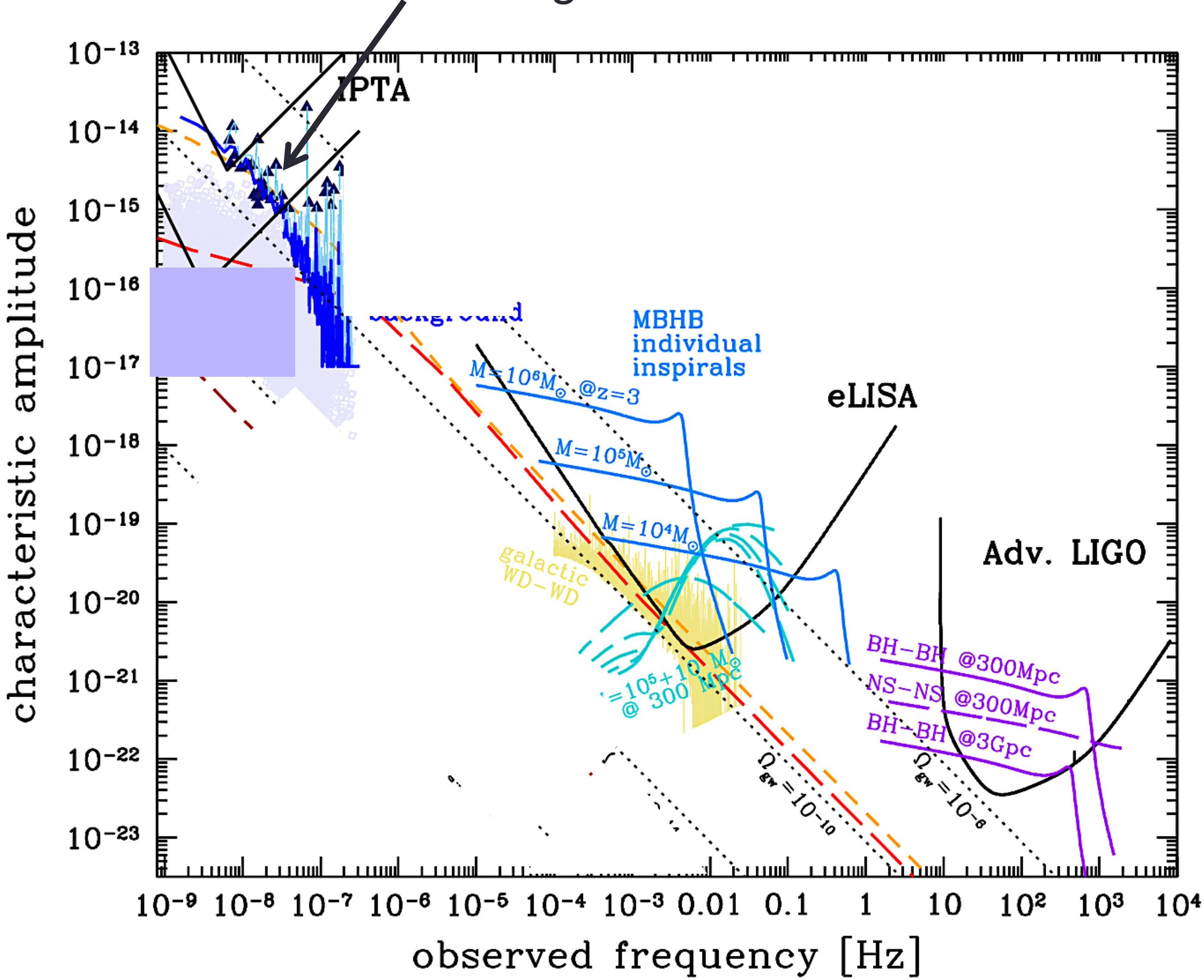
From the NANOGrav collaboration

# Correlations between residuals

- Residuals are small.  But we have another ace up our sleeve: if GW come from stochastic background of many sources, then timing residuals between pulsars should be correlated
- Function of their angular separation in the sky
- Not quite seen yet, but there ***is*** evidence for correlated noise
- ~5 yr for detection?

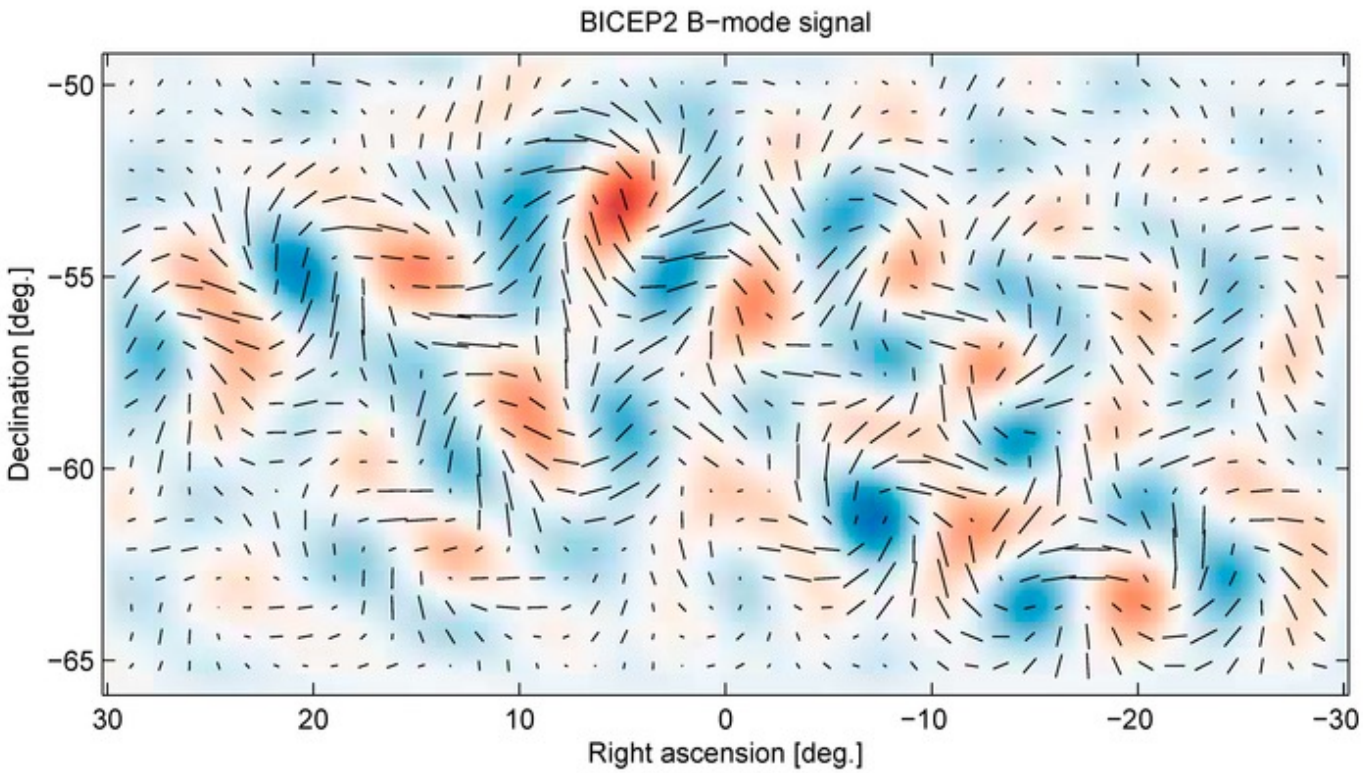


Sum over all BH mergers over all time



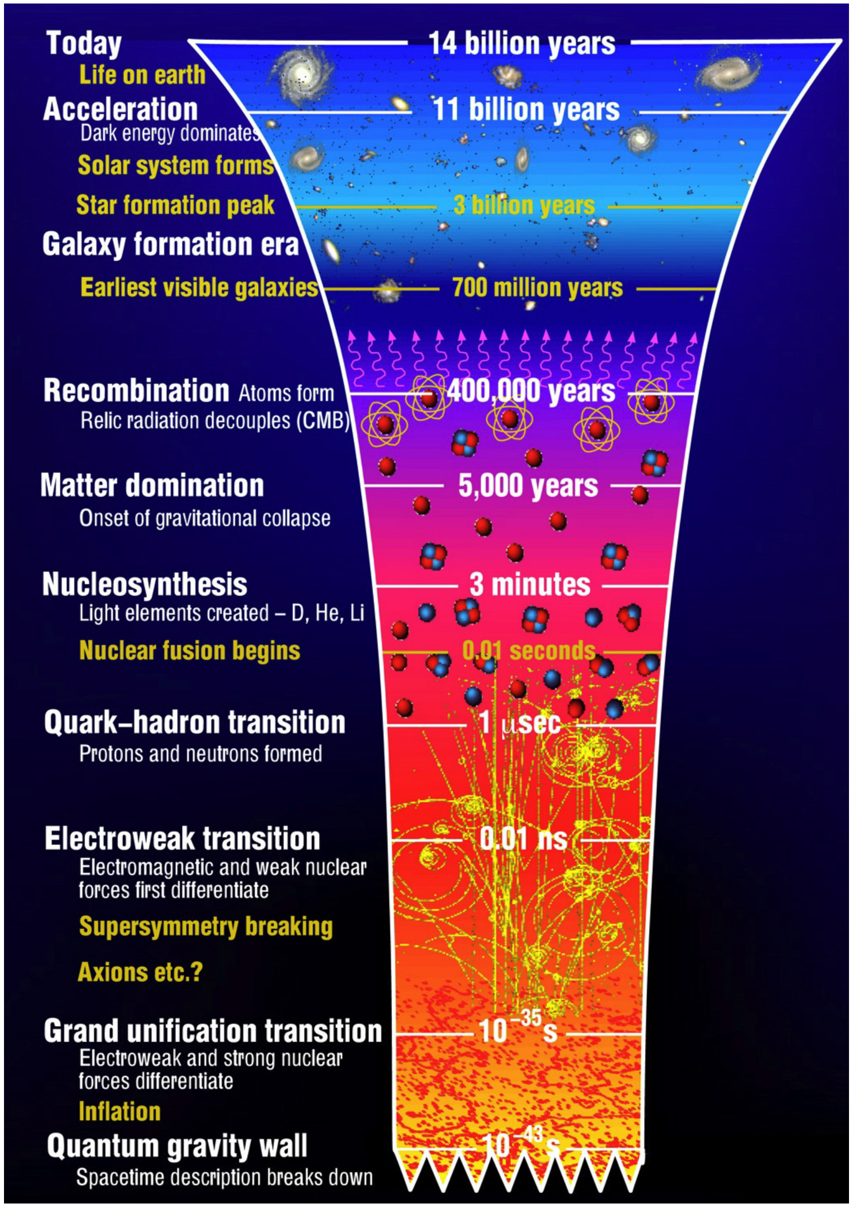
# Next method: CMB

- Another method: look at the polarization of the cosmic microwave background (CMB)
- But to understand this, we need some cosmological context...



# Evolution of the Universe

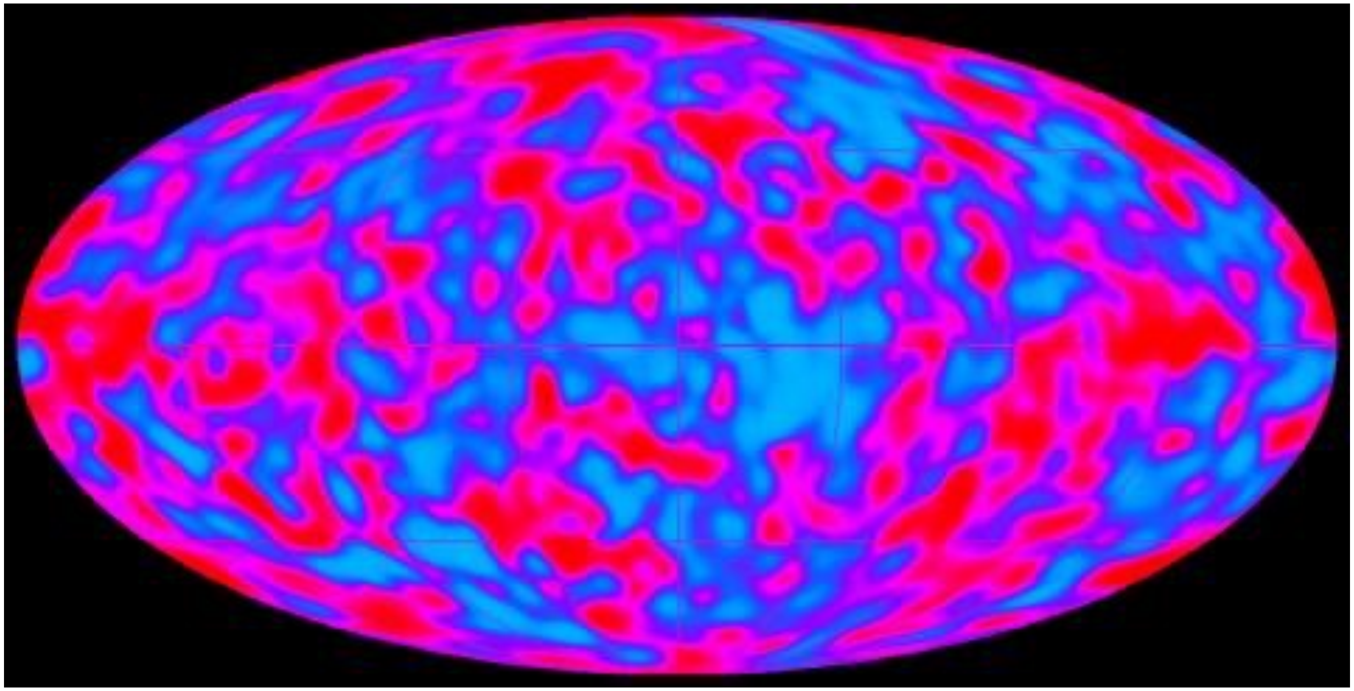
- It all started with a Big Bang!
- Then the universe expanded
- First it was very opaque
- About 380,000 years after BB, became transparent
- Photons from that era are now mainly microwaves; thus, the cosmic microwave background




Stephen Hawking Centre for Th. Cosm.

# Images of the CMB

- Better and better images
- From COBE



# Images of the CMB

- Better and better images
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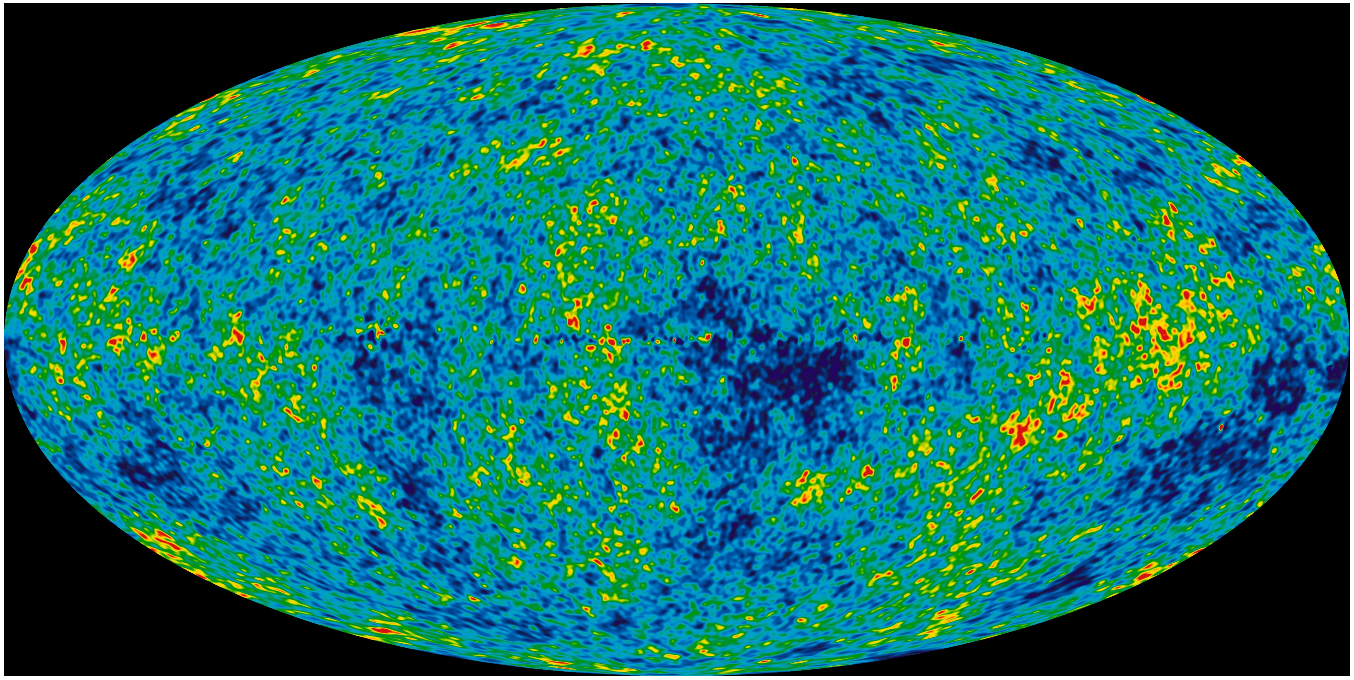
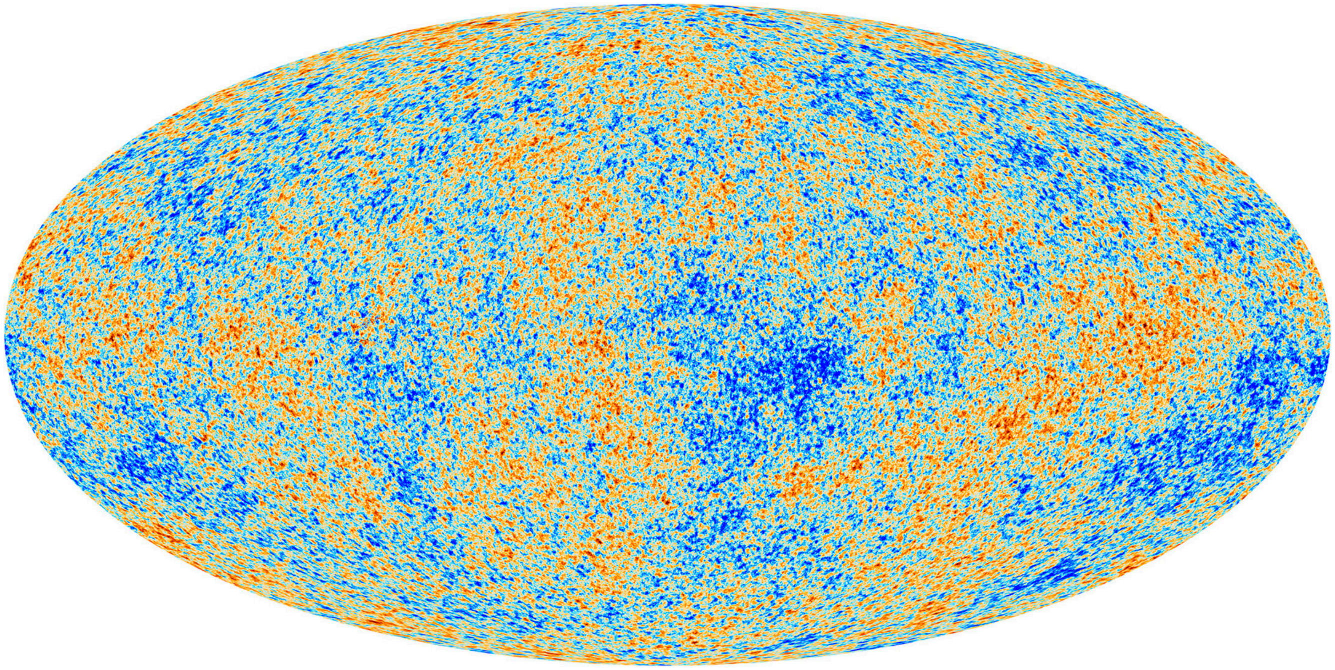


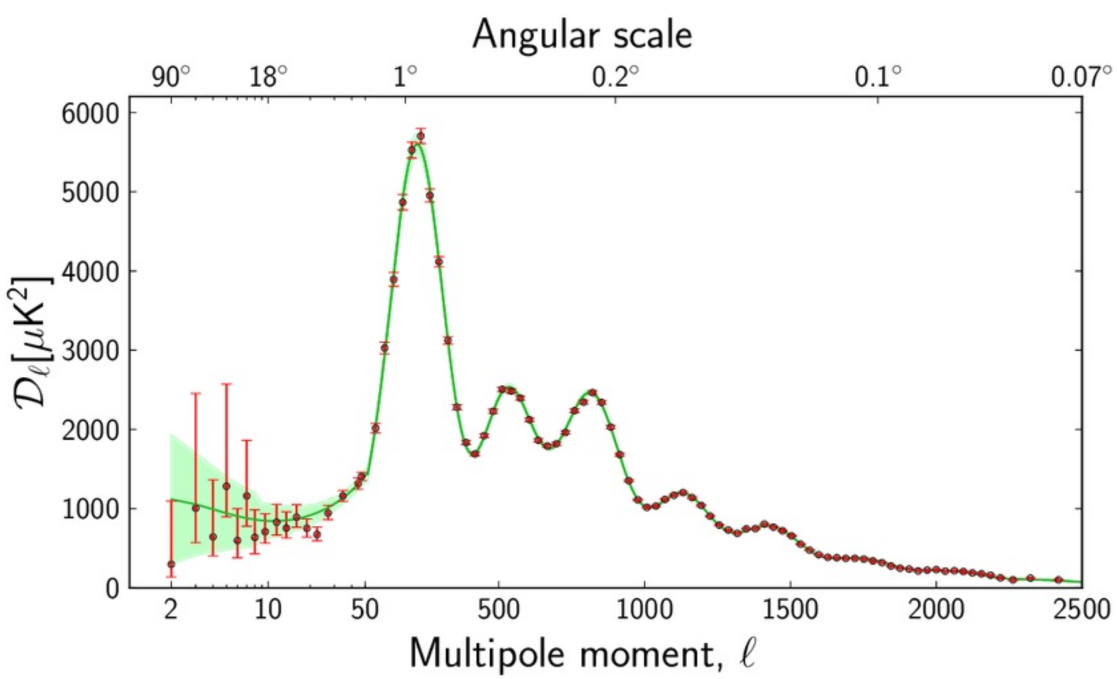
# Images of the CMB

- Better and better images
- From COBE...to WMAP...to Planck



# Tremendous source of information!

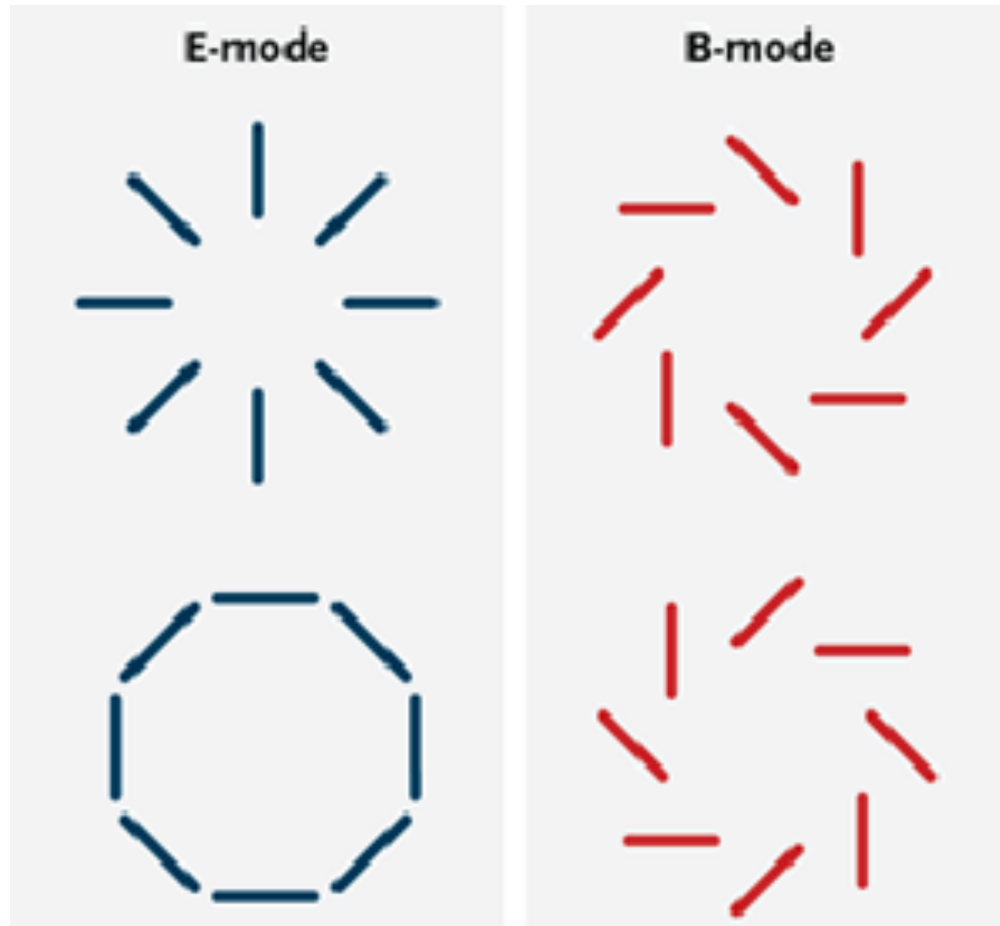
- Incredibly precise data. Measures the universe, tells us of likely existence of dark matter, constrains content of the universe, and so on
- But this is all temperature variations (how hot or cold in one place vs another; only varies by $10^{-5}$!). Polarization?




Planck power spectrum; most variation is on the ~1 degree scale

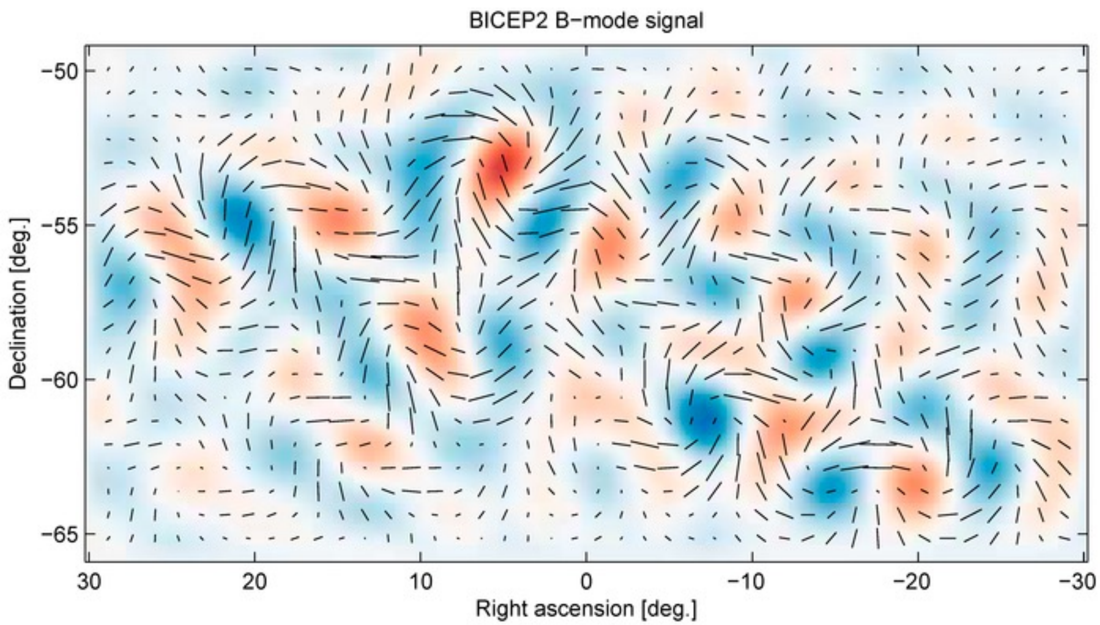
# Back to polarization

- Light has polarization, and that polarization can make patterns
- One type of pattern ("E-mode") can be produced normally (e.g., lines coming from center)
- But in the early universe, the other type ("B-mode") can only be produced by gravitational waves
- Would probe epoch of inflation!



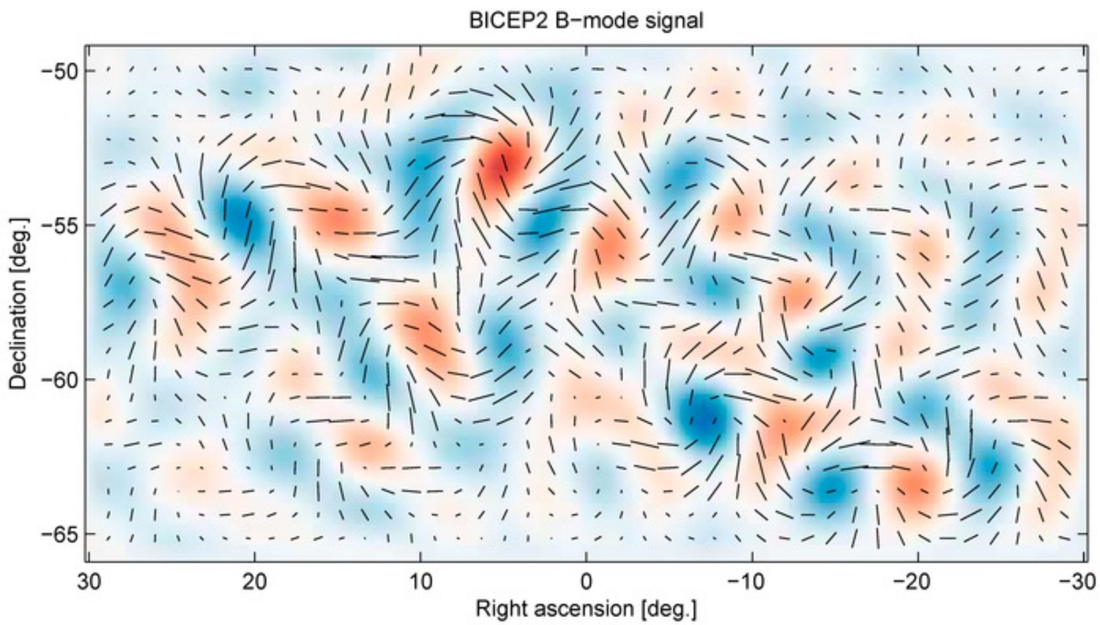
# Claim of detection

- In 2014, the BICEP-2 team announced the discovery of B-mode polarization in the CMB!
- Amazing! Incredibly fundamental. Visions of a Nobel Prize danced in the heads of the team...



# Claim of detection

- ...but it was dust. Although early-universe B-mode polarization can only be produced by GW (inflation!), late-time scattering from dust can do it as well
- “All we are is dust in the wind, dude” --- Theodore “Ted” Logan



# Sociology and science

- So what went wrong?
- They knew that dust was a possibility.  The best dust map came from the Planck mission... but instead of collaborating with the Planck team (which would have spread out credit) they used a photo of a Planck dust map presented at a conference(!)
- There was also a lot of pressure to publicize
- These things happen; scientists are human, too
- Many efforts are underway to do more sensitive expts
- A challenge: there is no useful prediction of how strong the inflationary-era signal should be; a detection would be great, but a non-detection isn't very meaningful

# Conclusion: GW in the future

- By mid-2030s we’ll have super-LIGOs that give us 10-20x better sensitivity and the worldwide network will localize bursts much better and improve network duty cycle
- In space: 2037+, LISA; SMBH, WD binaries, etc.
- Pulsar timing arrays: maybe there is a signal now; within a few years we’ll either know or be disappointed ☺
- CMB B-mode polarization; an exciting possibility with no guarantees
- GW astronomy is a huge development in our understanding of the universe!