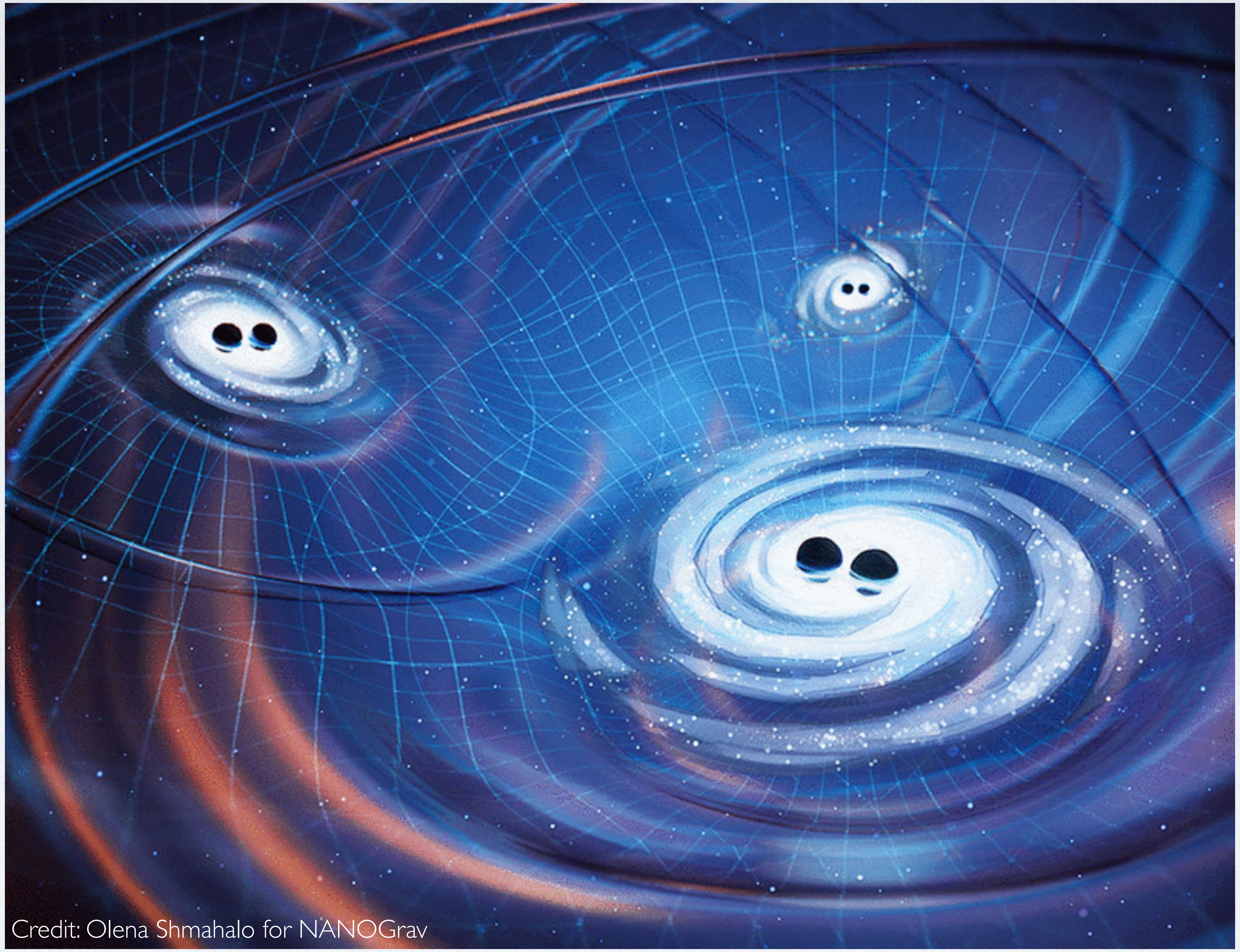
OBSERVING GRAVITATIONAL WAVES



Credit: Olena Shmahalo for NANOGrav

Joseph Simon

NSF Astronomy & Astrophysics Postdoctoral Fellow

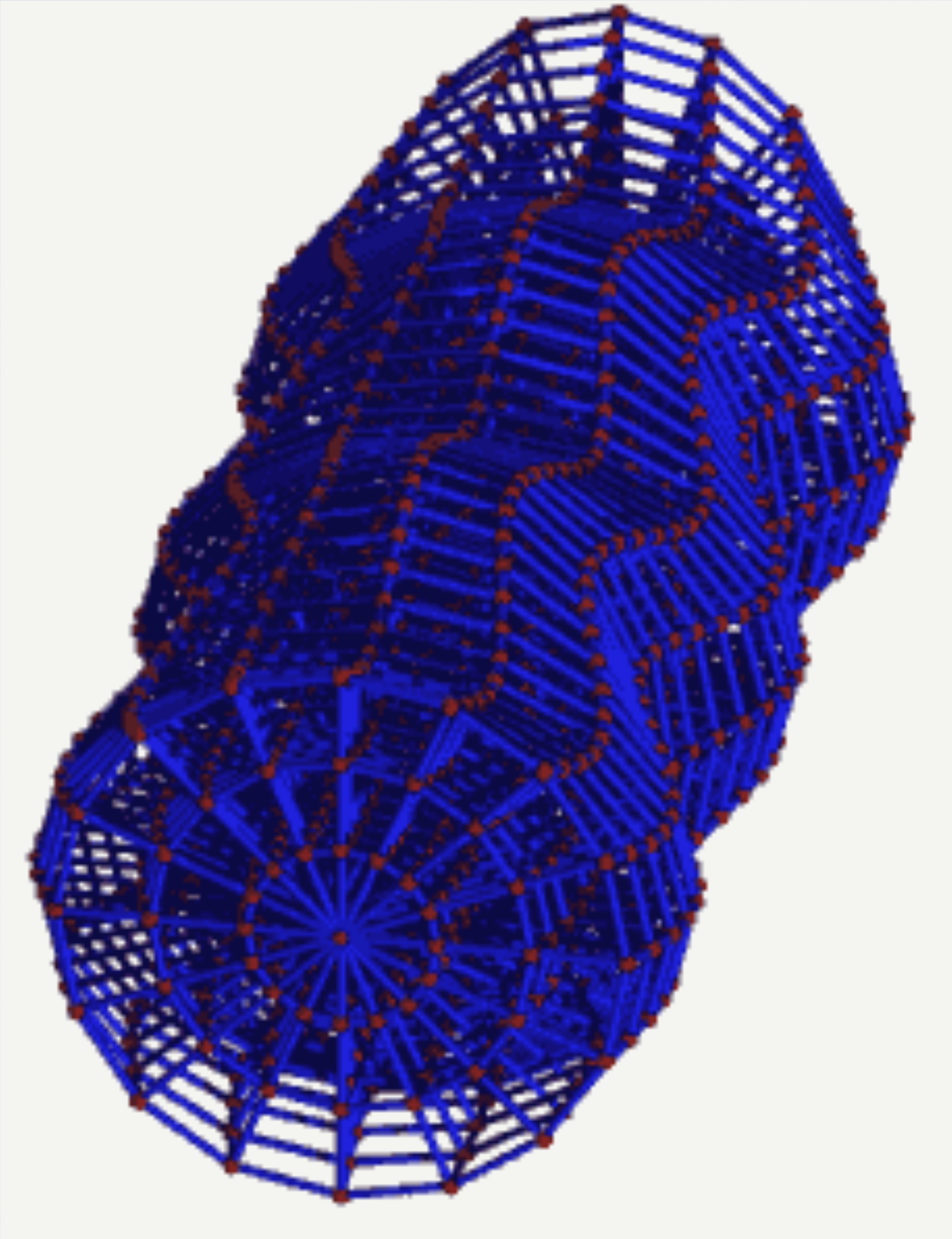
University of Colorado Boulder

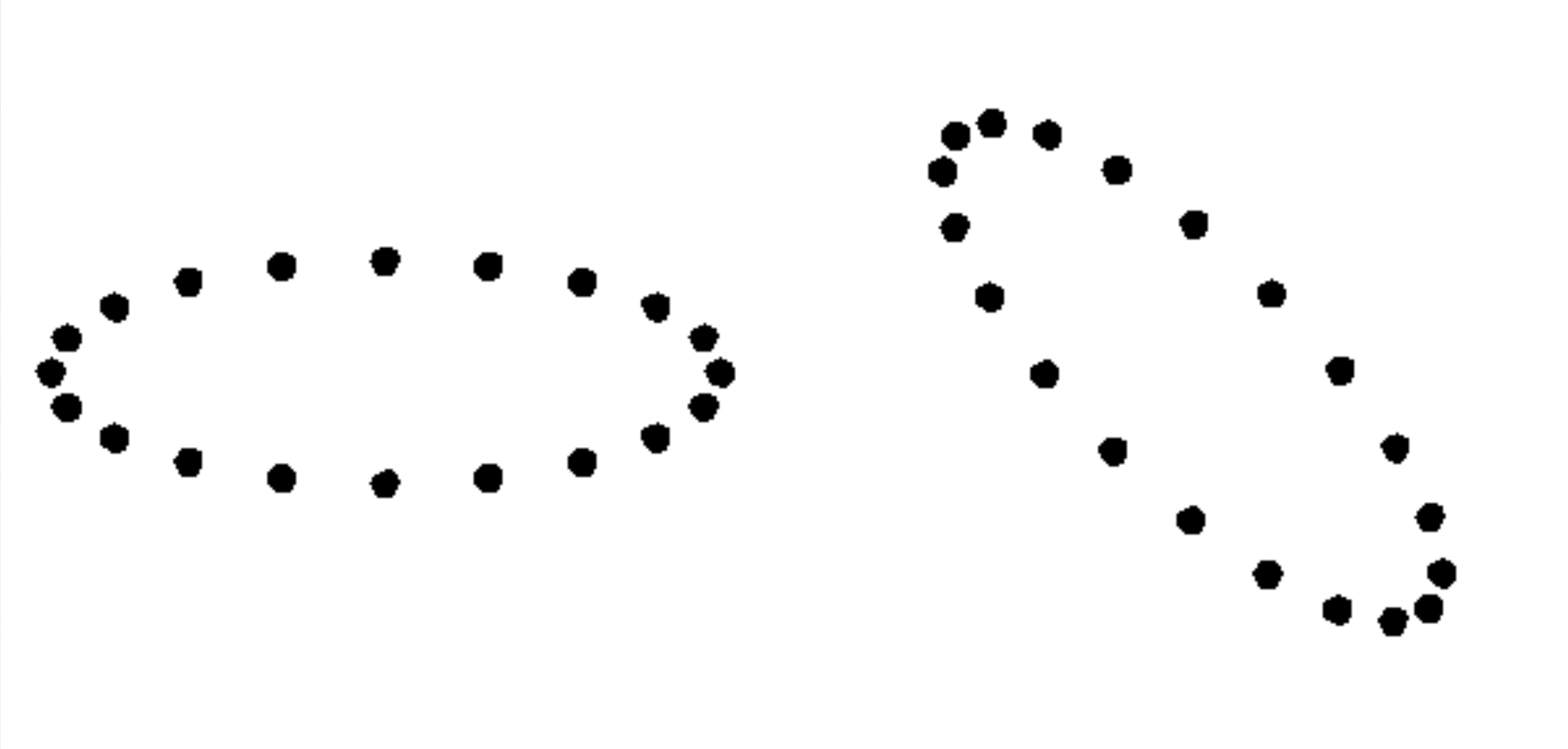
Wednesday, July 19, 2023

EMIT Summer School — Vanderbilt University

What Is A Gravitational Wave?

A Quick Recap





Strain ~ Chirp Mass ^ 5/3 / Distance

GW Frequency = n * Orbital Frequency

For Circular Orbits, n = 2

What Is A Gravitational Wave?

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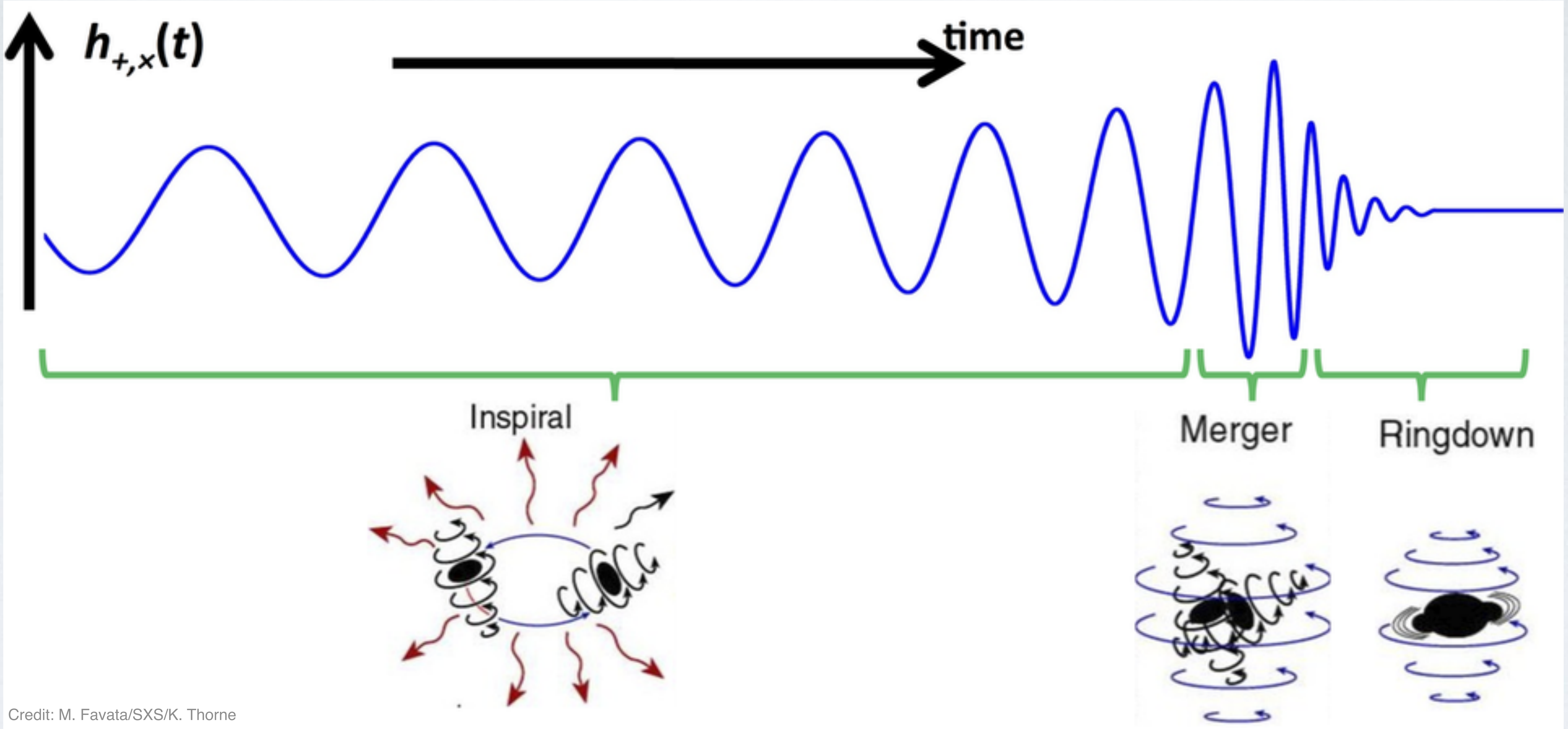
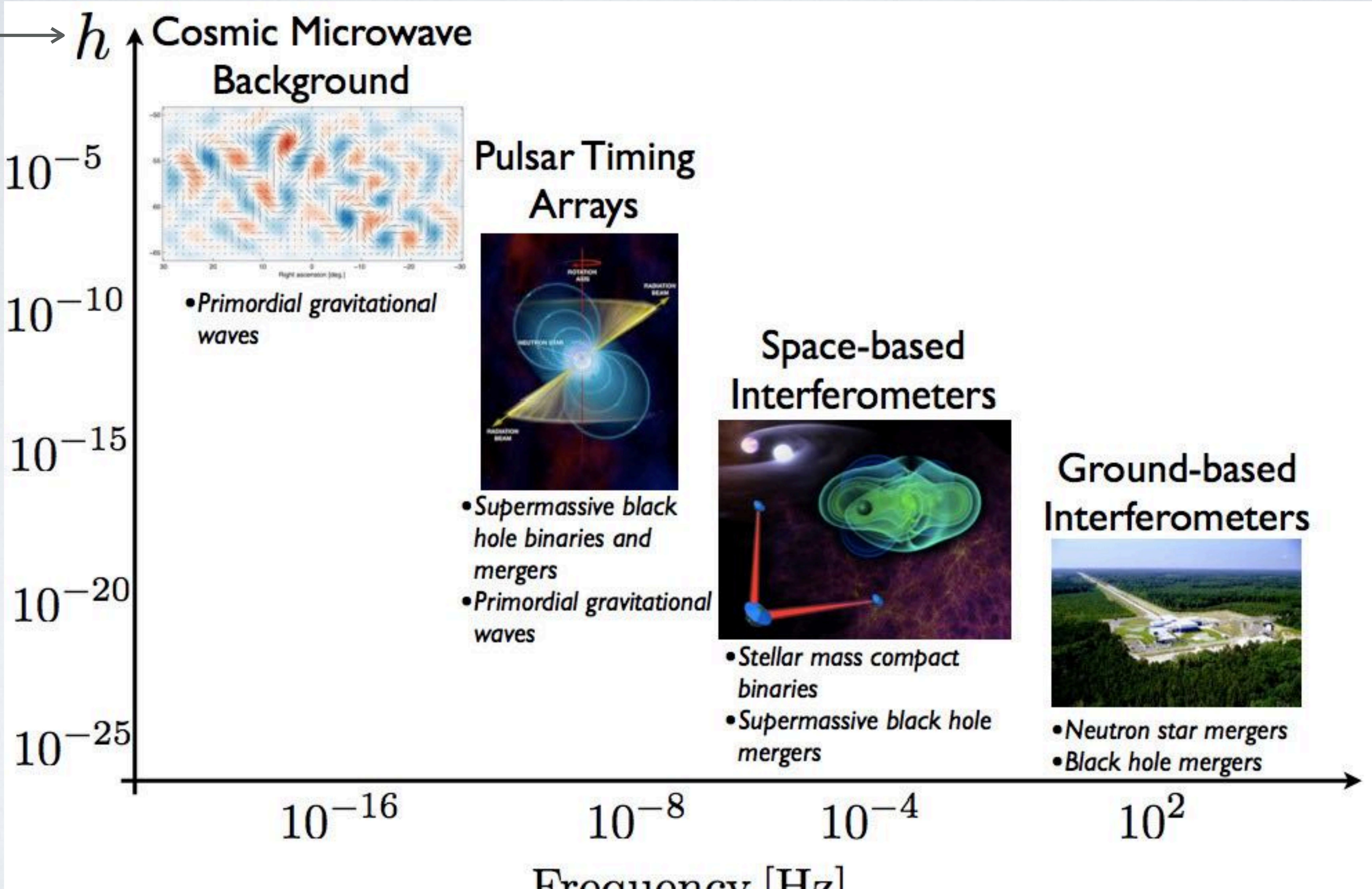


Credit: M. Favata/SXS/K. Thorne

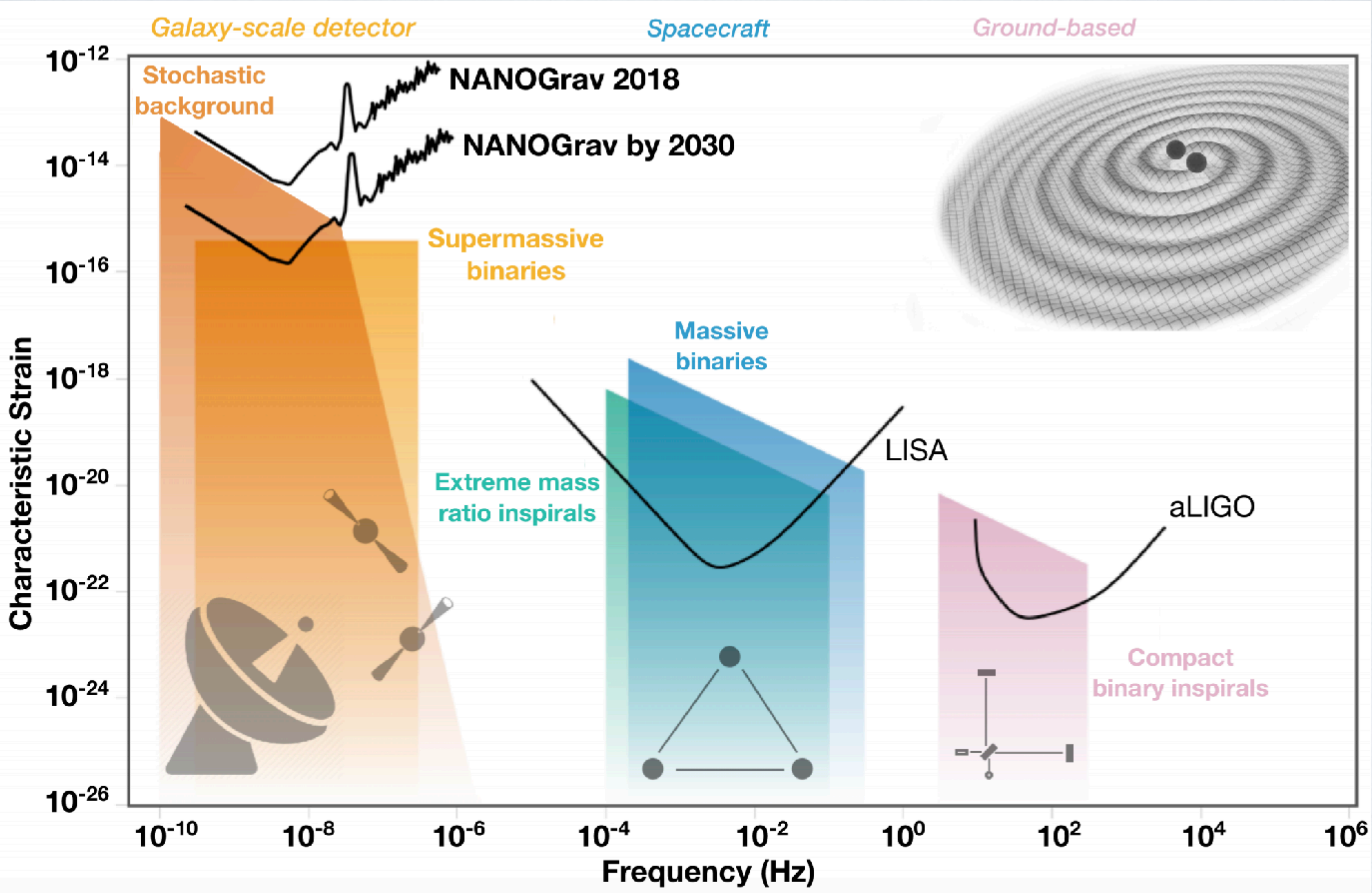
The Gravitational Wave Spectrum

GW Strain →



Credit: NANOGrav

The Gravitational Wave Spectrum



S. Taylor & C. Mingarelli, adapted from gwplotter.org (Moore, Cole, Berry 2014) and based on a figure in Mingarelli & Mingarelli (2018). Illustration of merging black holes adapted from R. Hurt/Caltech-JPL/EPA

GROUND-BASED OBSERVATORIES

LIGO-like Detectors using Laser Interferometry

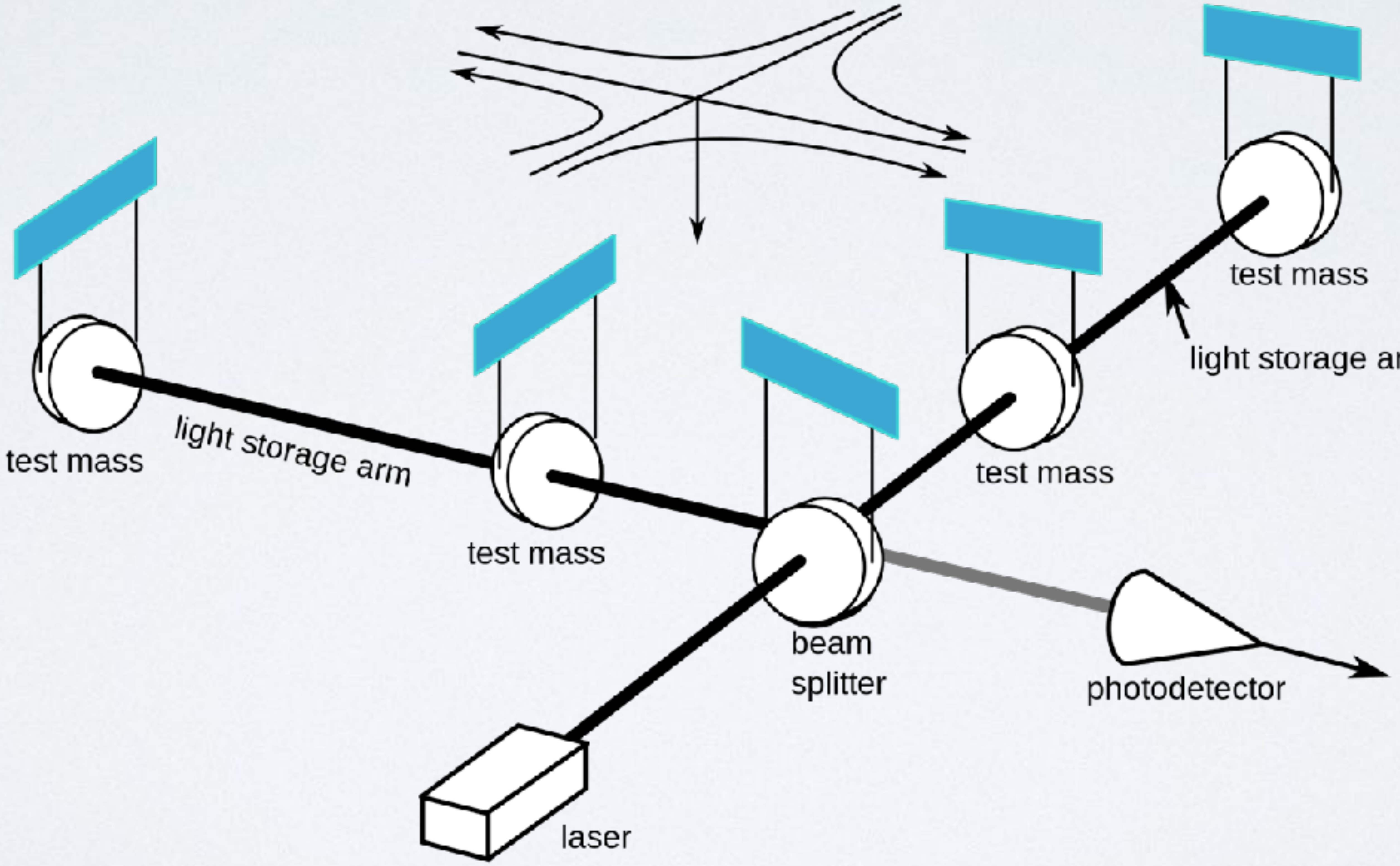
Frequency Coverage: 1-1000 Hz

Primary Source: Stellar-mass Compact Binary Coalesence

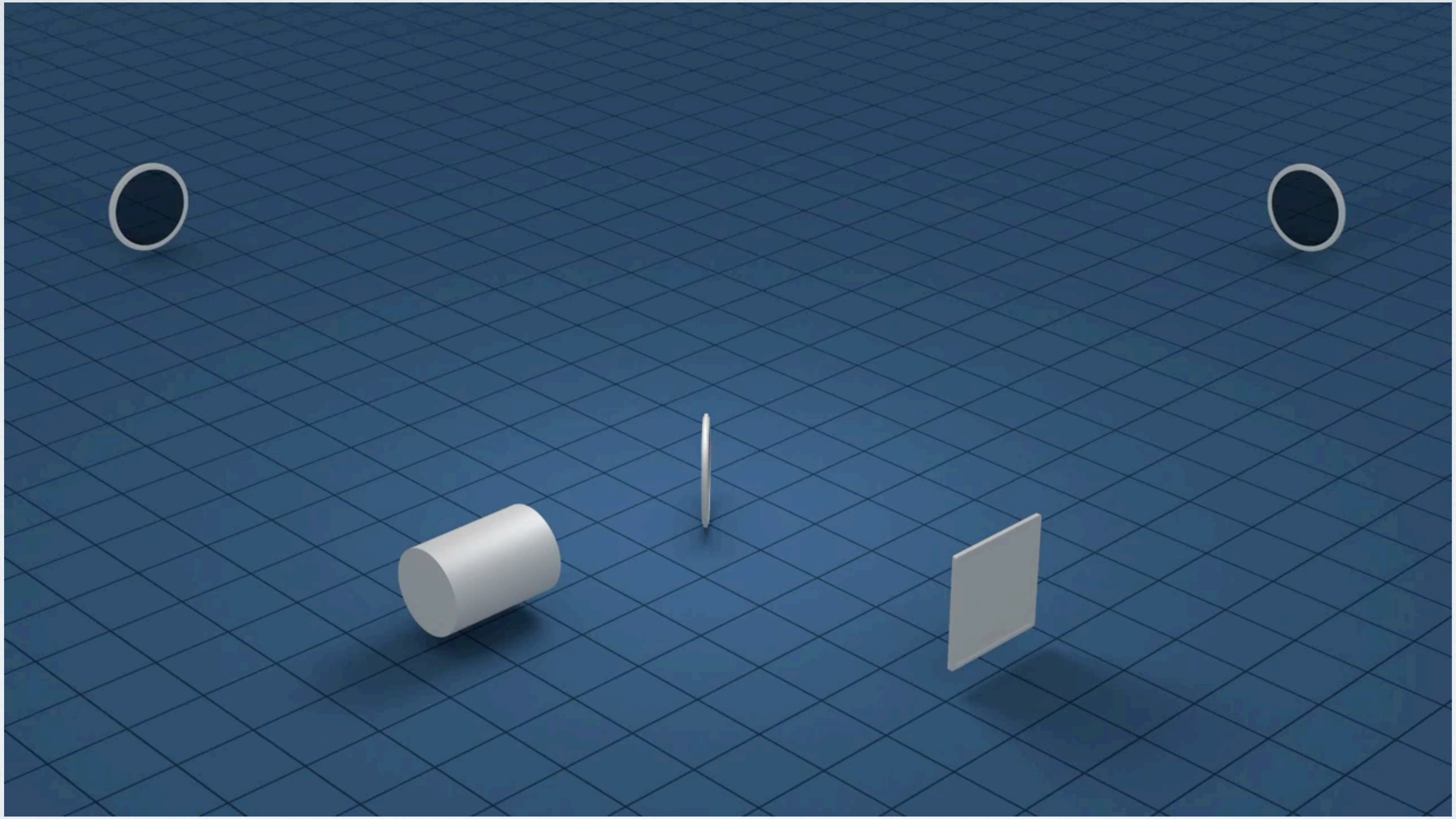
How Do LIGO-like Detectors Observe GWs?

"L-shaped" Detectors

- Measure GW effect on mirrors in orthogonal directions
- Use Laser Interferometry

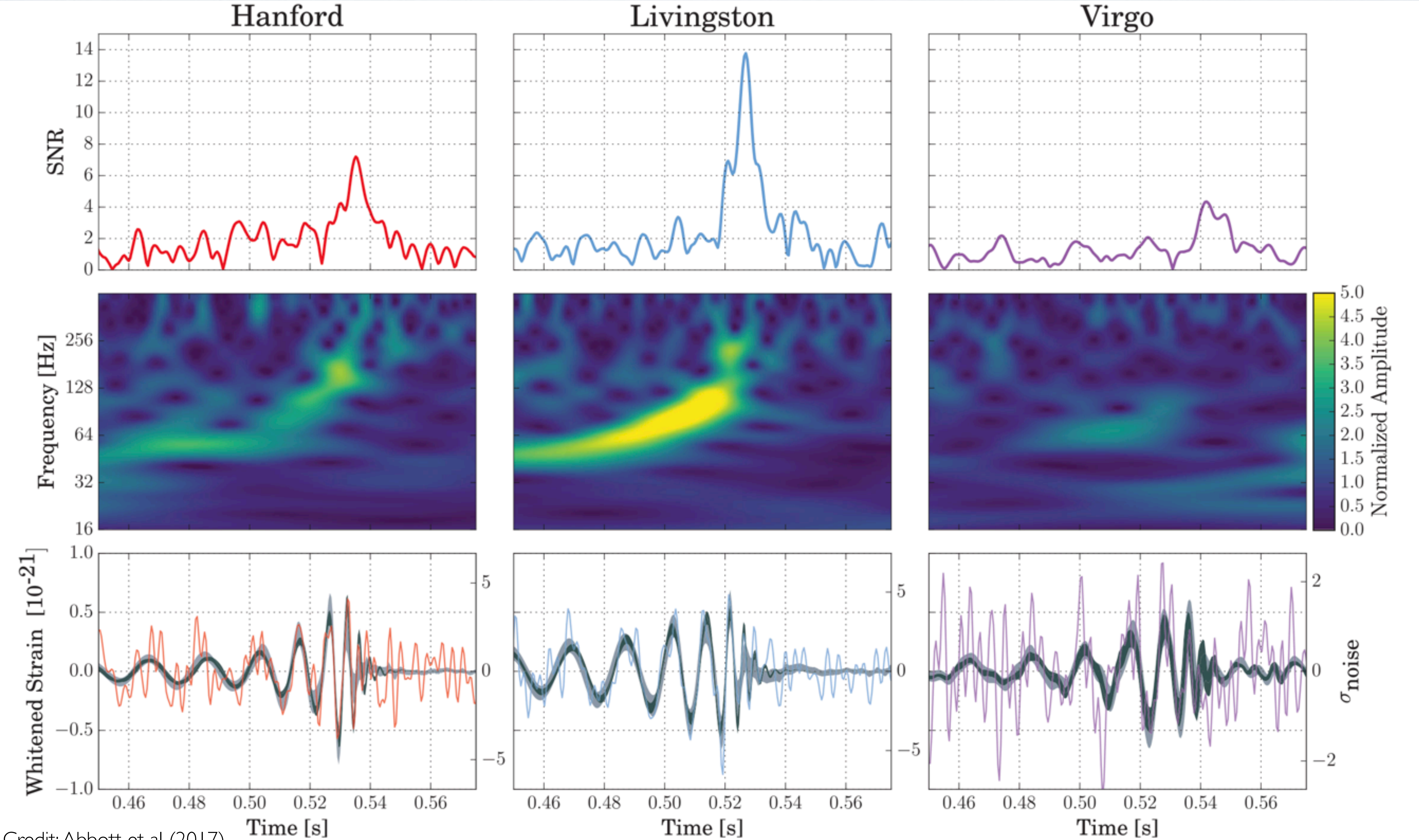


How Do LIGO-like Detectors Observe GWs?



How Do LIGO-like Detectors Observe GWs?

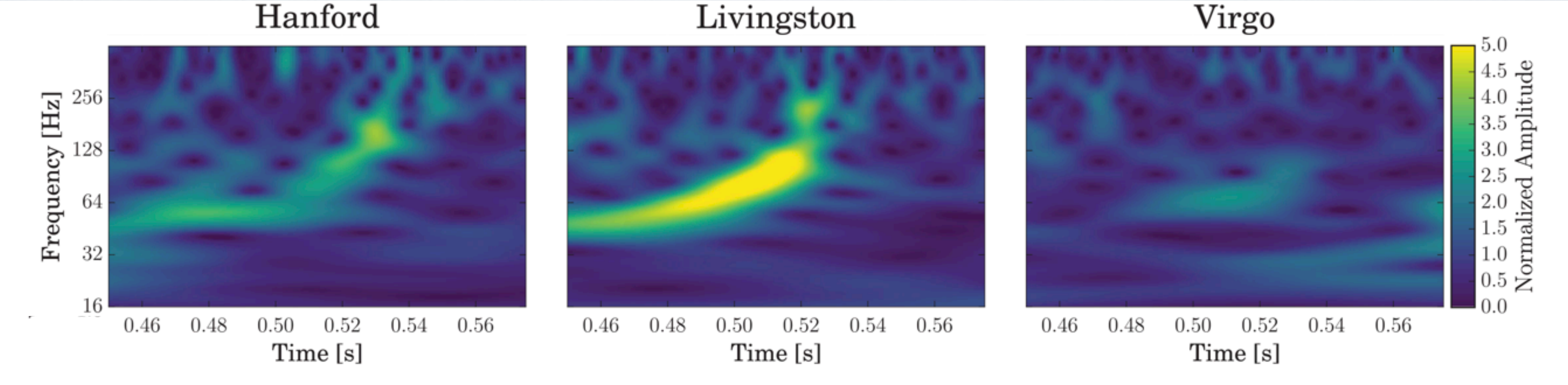
GW170714: The Importance Of Multiple Detectors!



Credit: Abbott et al (2017)

How Do LIGO-like Detectors Observe GWs?

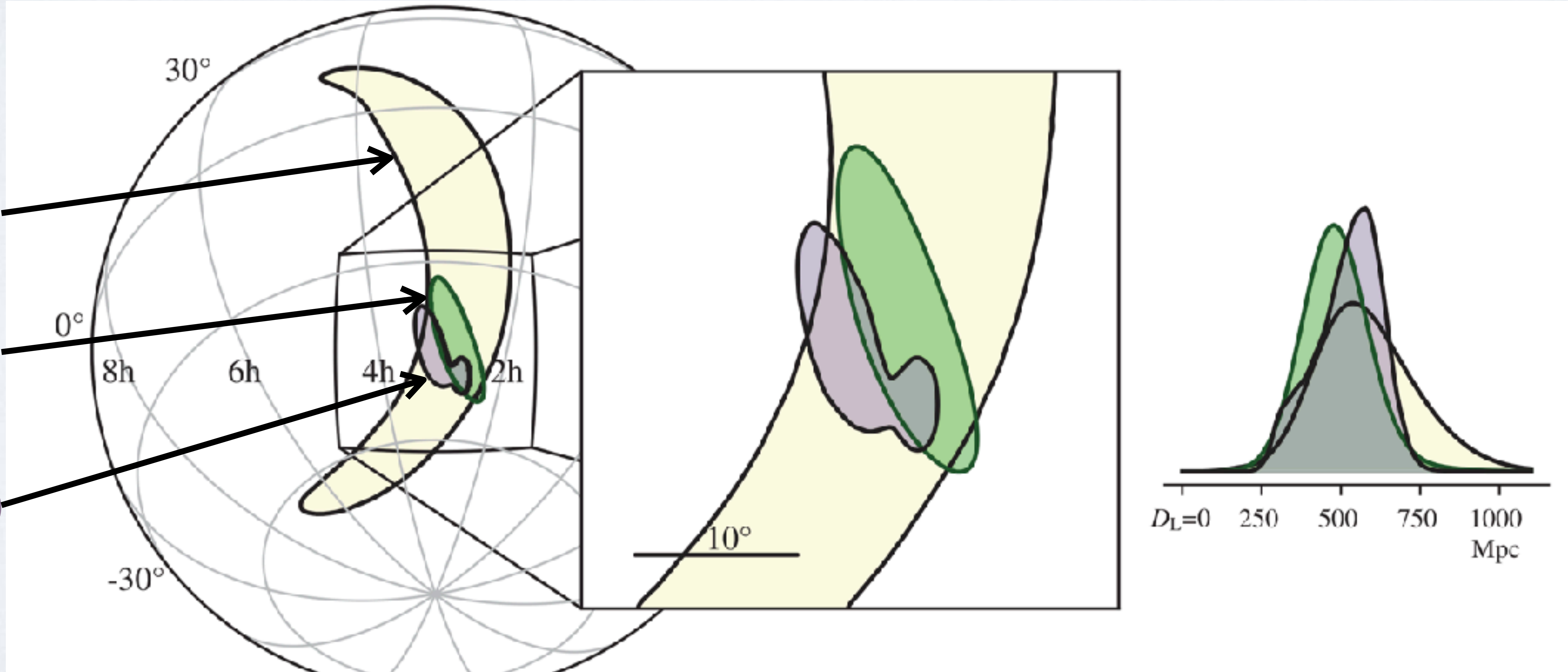
GW170714: The Importance Of Multiple Detectors!



Hanford + Livingston (rapid)

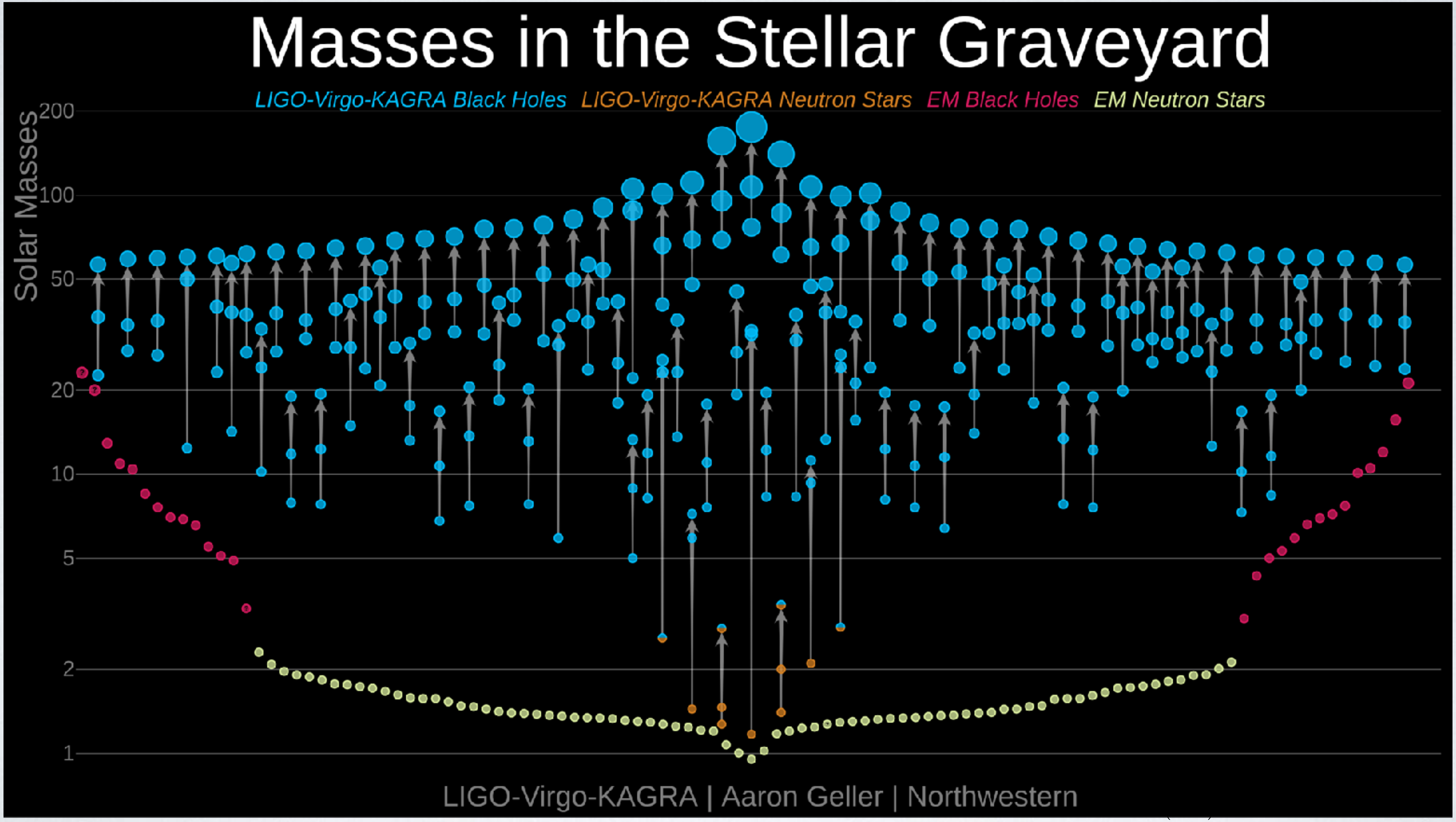
H+L + Virgo (rapid)

H+L+V (full Bayesian)



Credit: Abbott et al (2017)

What Has LIGO Seen So Far?



SPACE-BASED OBSERVATORIES

LISA-like Detectors Using Laser Interferometry

Frequency Coverage: 10^{-5} – 0.01 Hz

How Will LISA Observe GWs?

3 Drag-Free Spacecraft

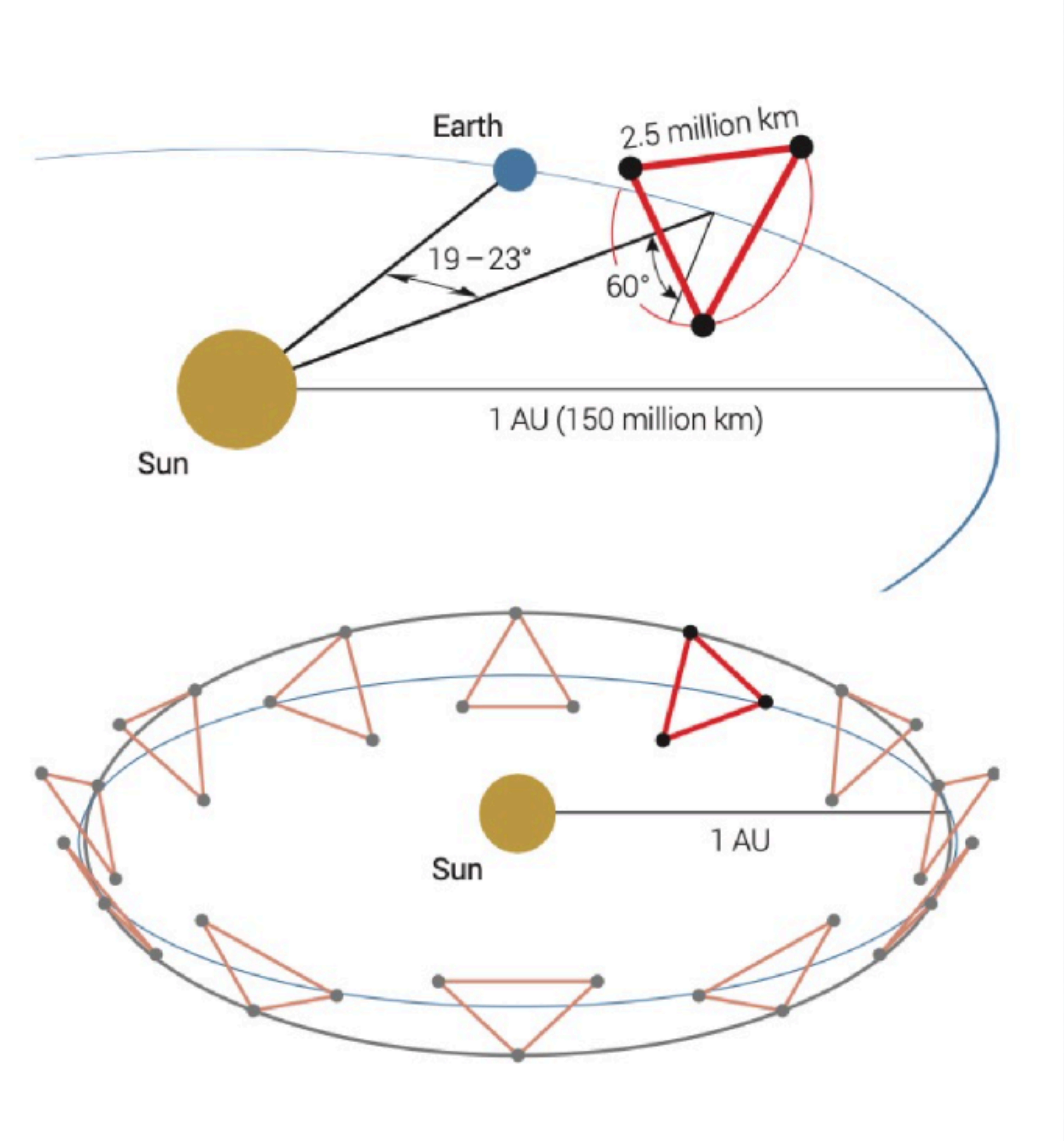
- 2.5 million km apart
- "Cartwheeling" orbit following Earth
- 2W lasers linking spacecraft together
- Uses "time-delay interferometry"

LISA Pathfinder Mission

- Very successful proof of concept mission.

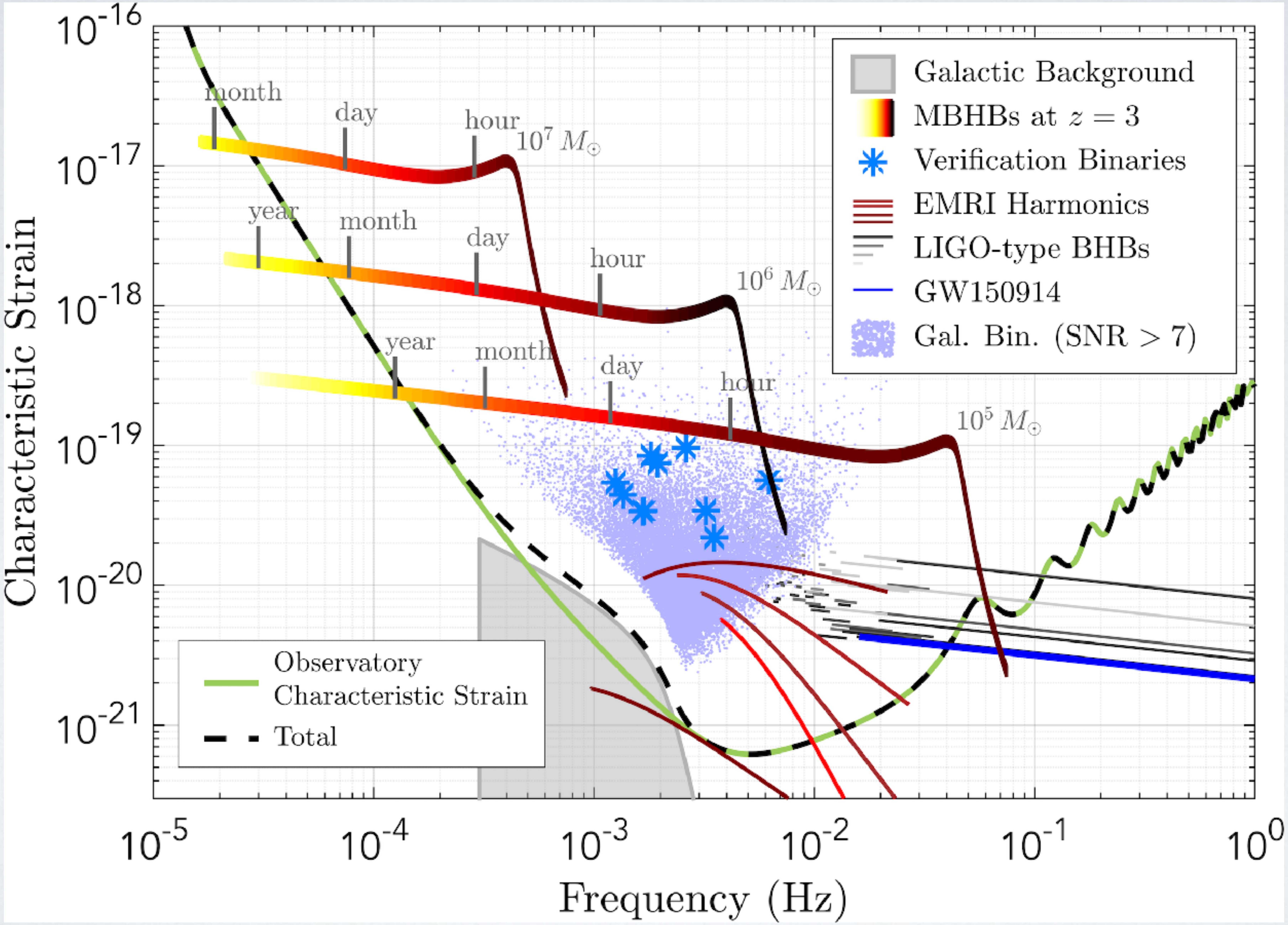
Full LISA Observatory

- Set for launch in mid-2030s.



Depiction of LISA Orbit

Many Exciting Sources in the mHz GW Band!



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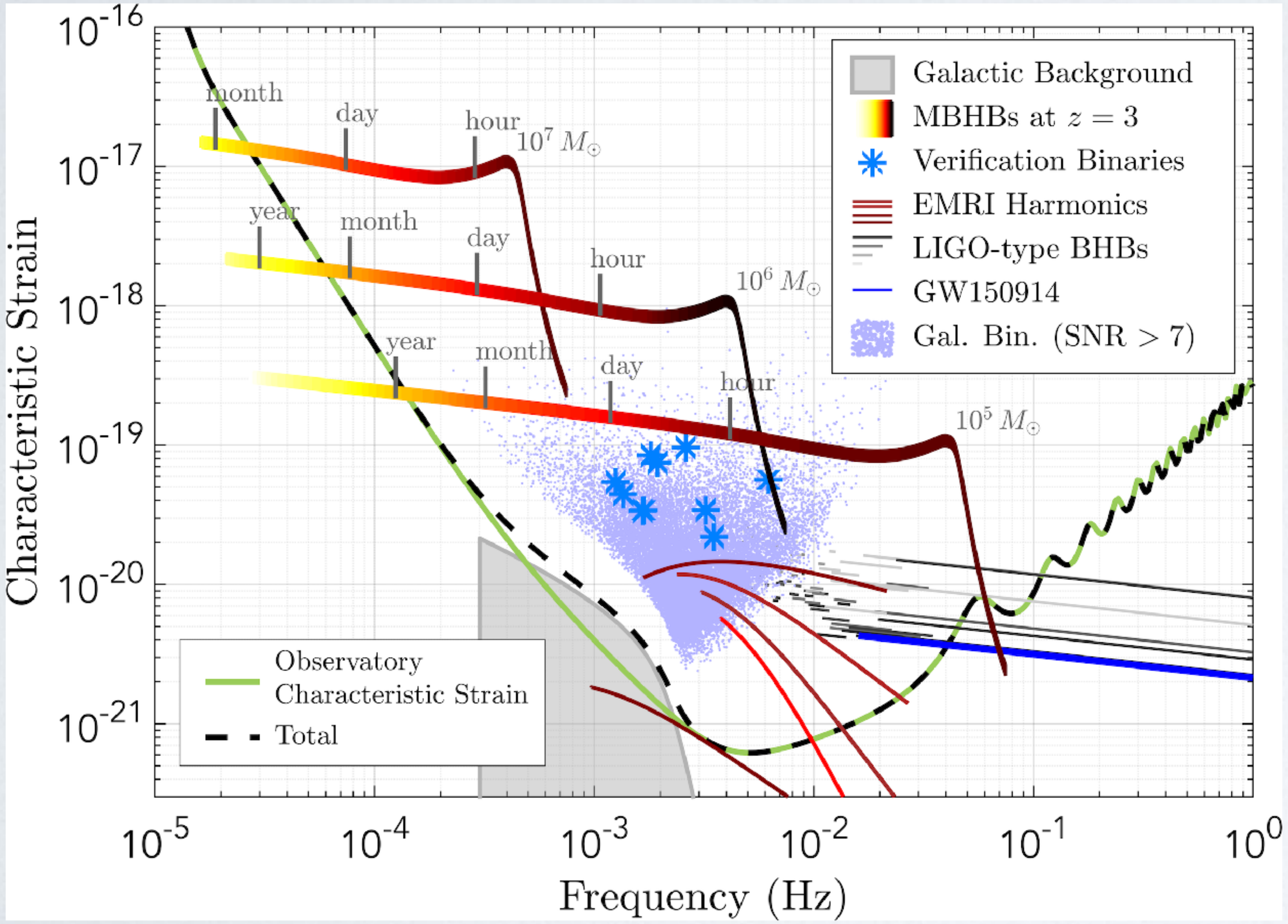
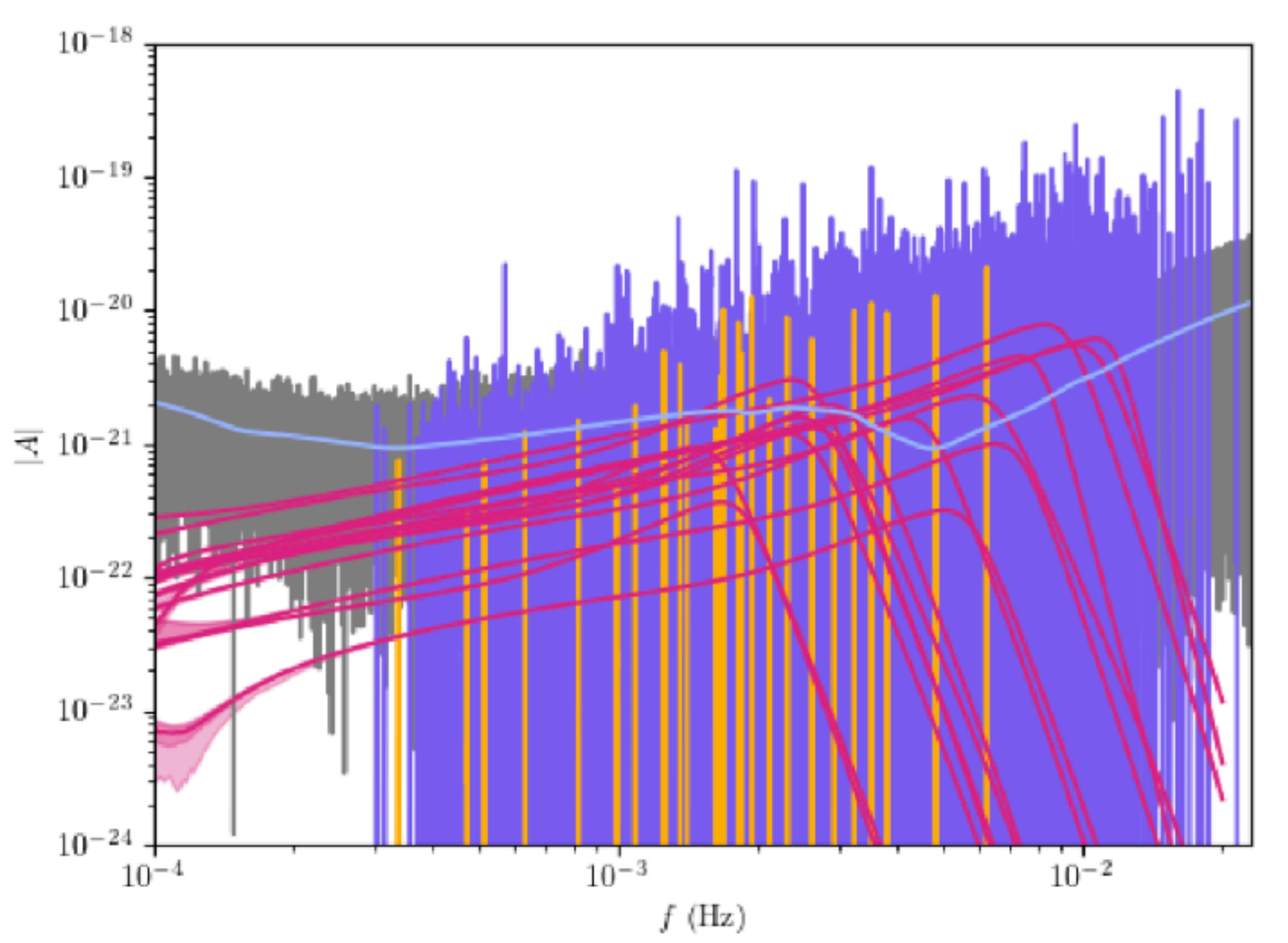


Complicated Data Analysis Problem



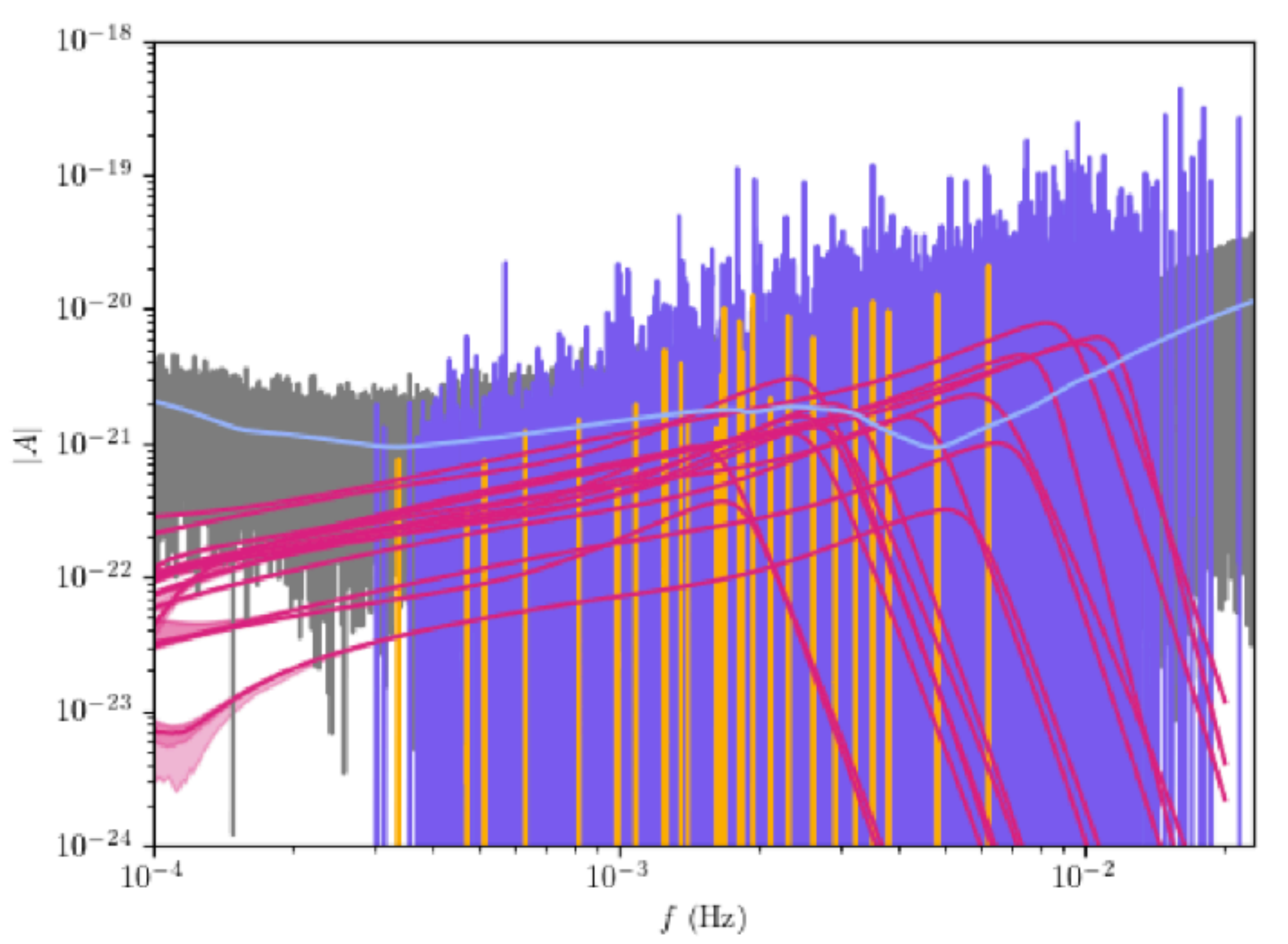
Credit: Littenberg & Cornish (2023)

Many Exciting Sources in the mHz GW Band!

- Many GW signals are simultaneous, requiring a "Global Fit" to be performed.

- Ability to extract parameters of one GW signal is dependent on how well other GW signals can be modeled.

Complicated Data Analysis Problem



Credit: Littenberg & Cornish (2023)

GALAXY-BASED OBSERVATORIES

Pulsar Timing Arrays

Frequency Coverage: 10^{-9} – 10^{-7} Hz

Primary Source: Supermassive Black Hole Binaries

How Do PTAs Observe GWs?

Millisecond Pulsars (MSPs),
Nature's celestial clocks,
rotate rapidly with long-term
stability that rivals atomic clocks.

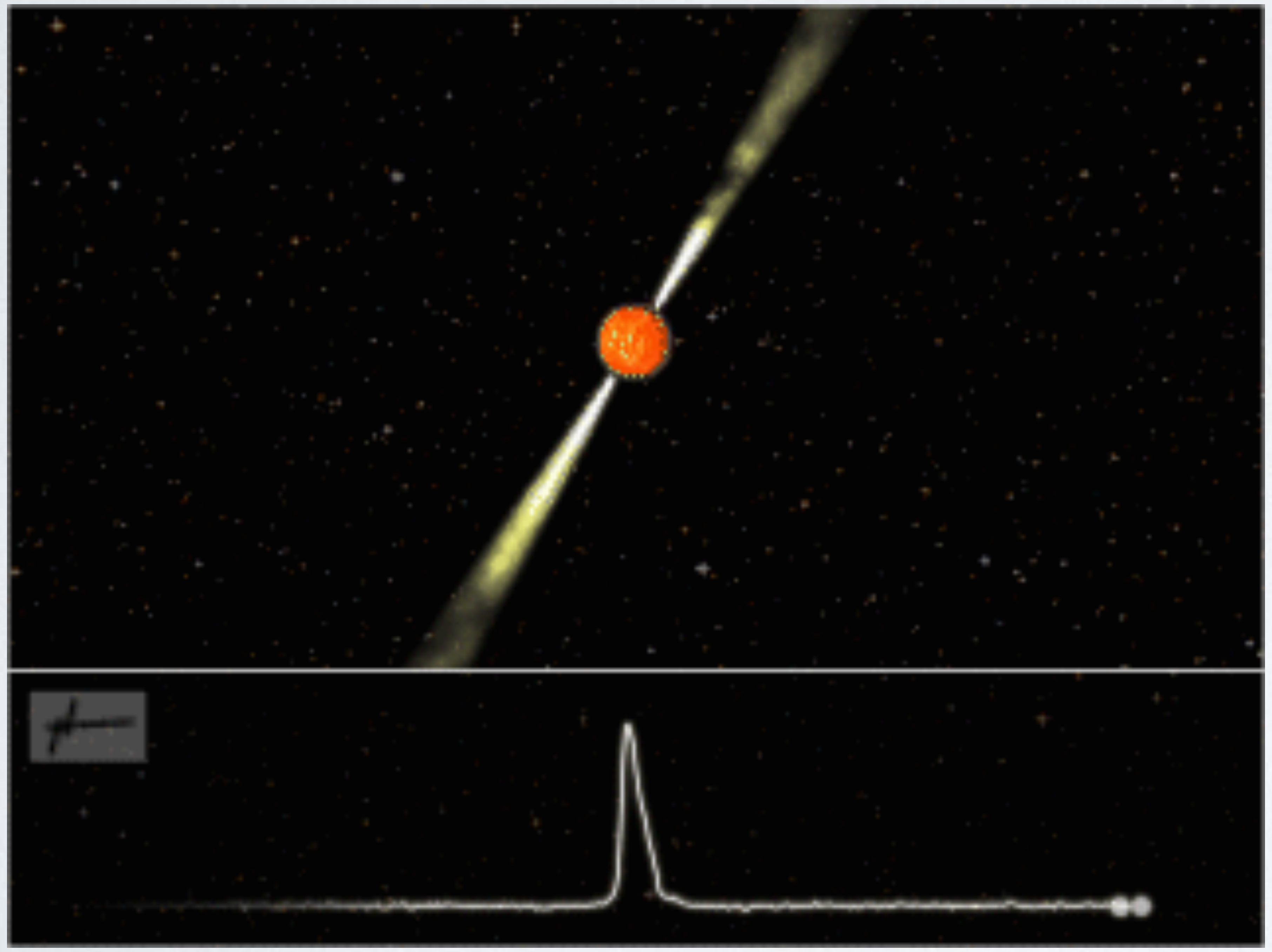
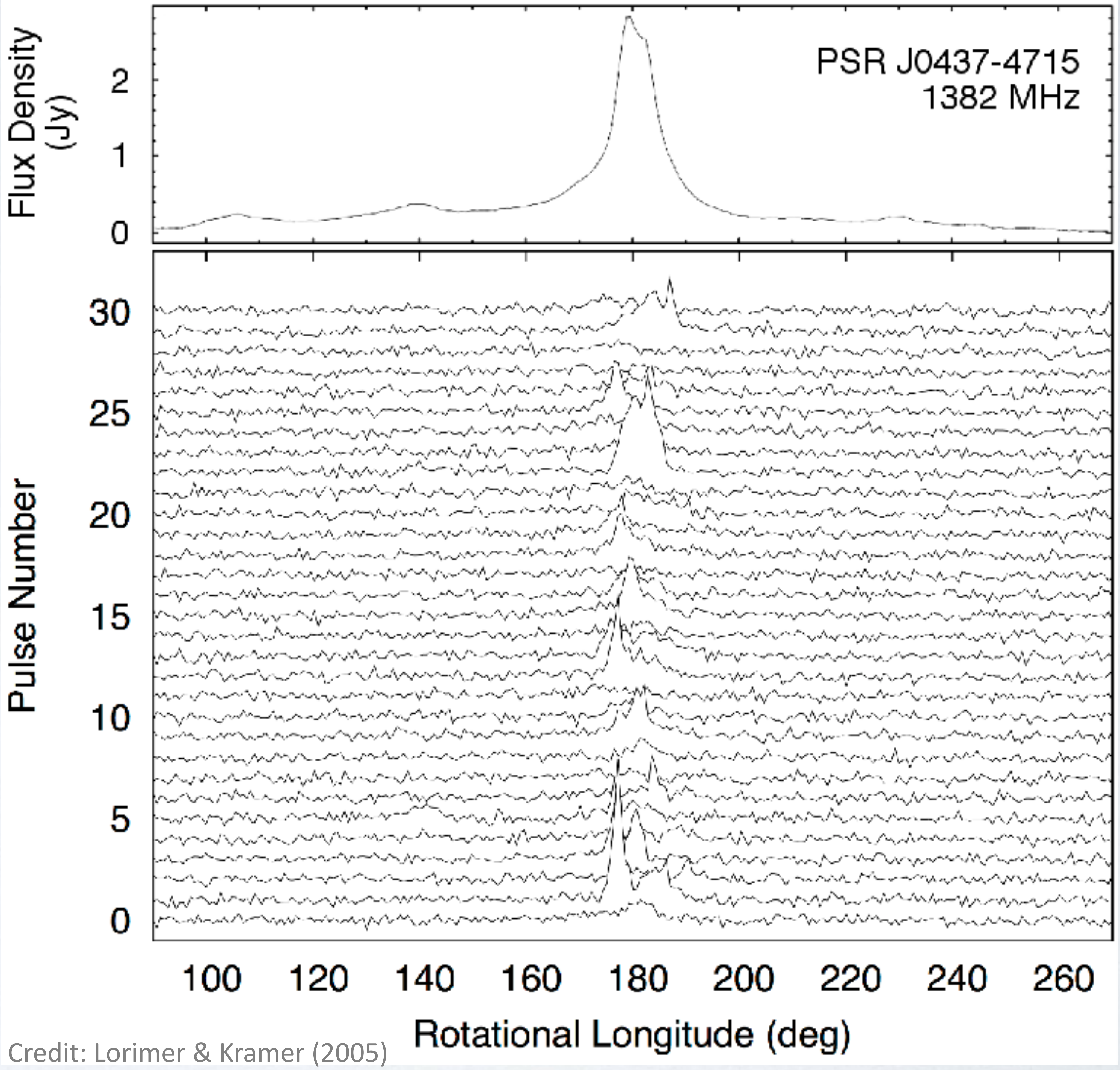
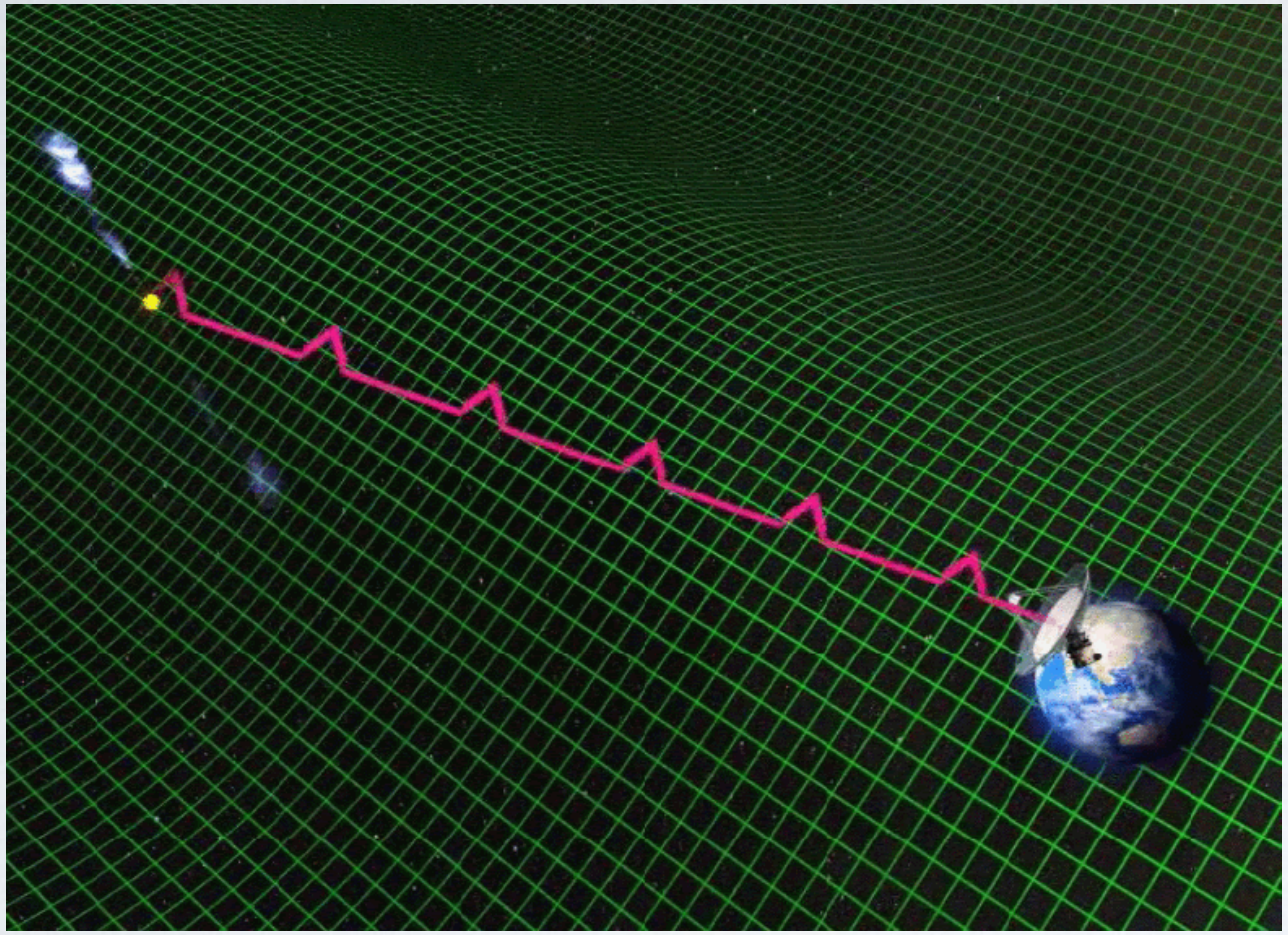


Image Credit: J. Van Leeuwen



Credit: Lorimer & Kramer (2005)

How Do PTAs Observe GWs?


Video Credit: John Rowe/CSIRO

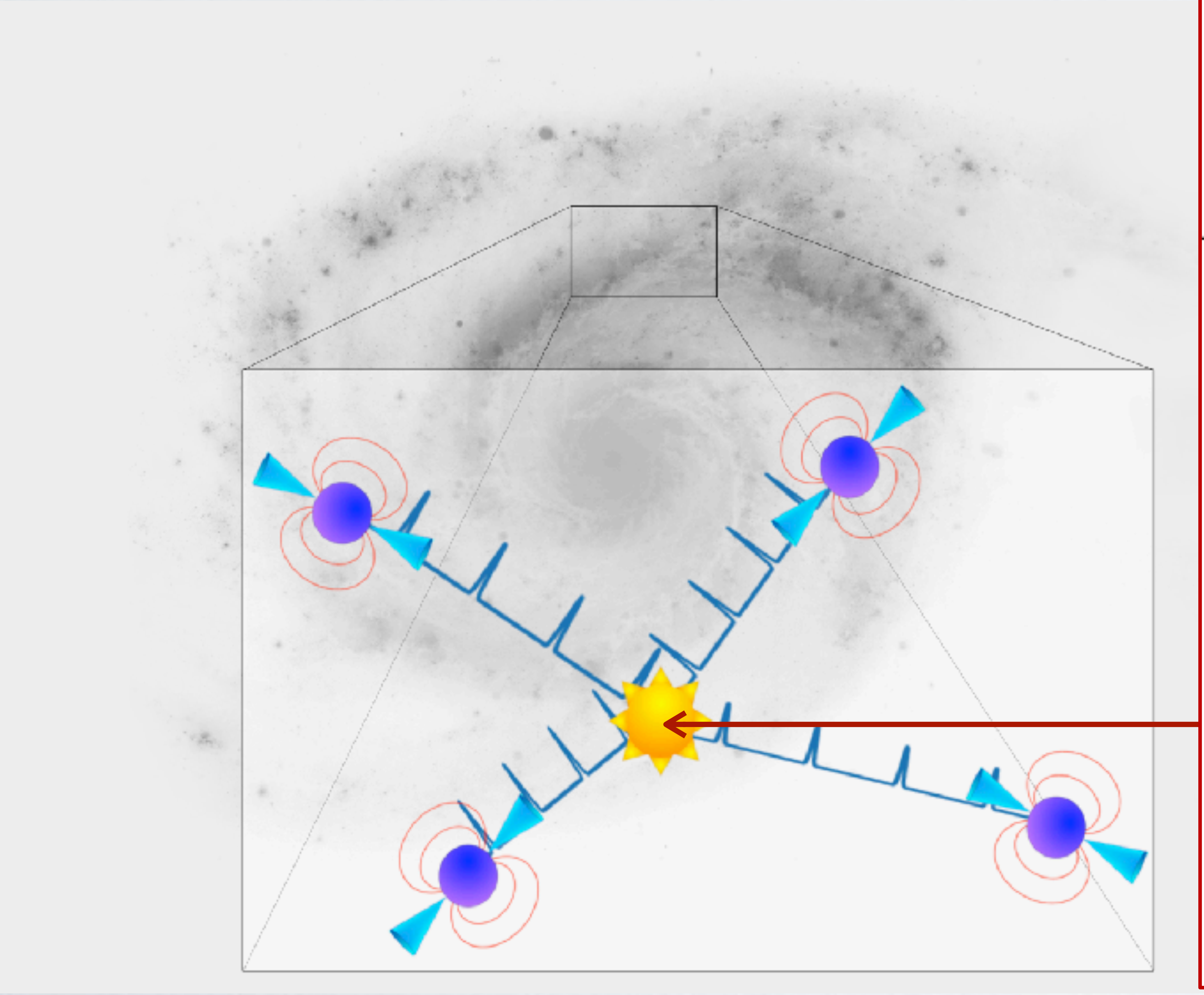
Gravitational Waves perturb the pulses from each pulsar.

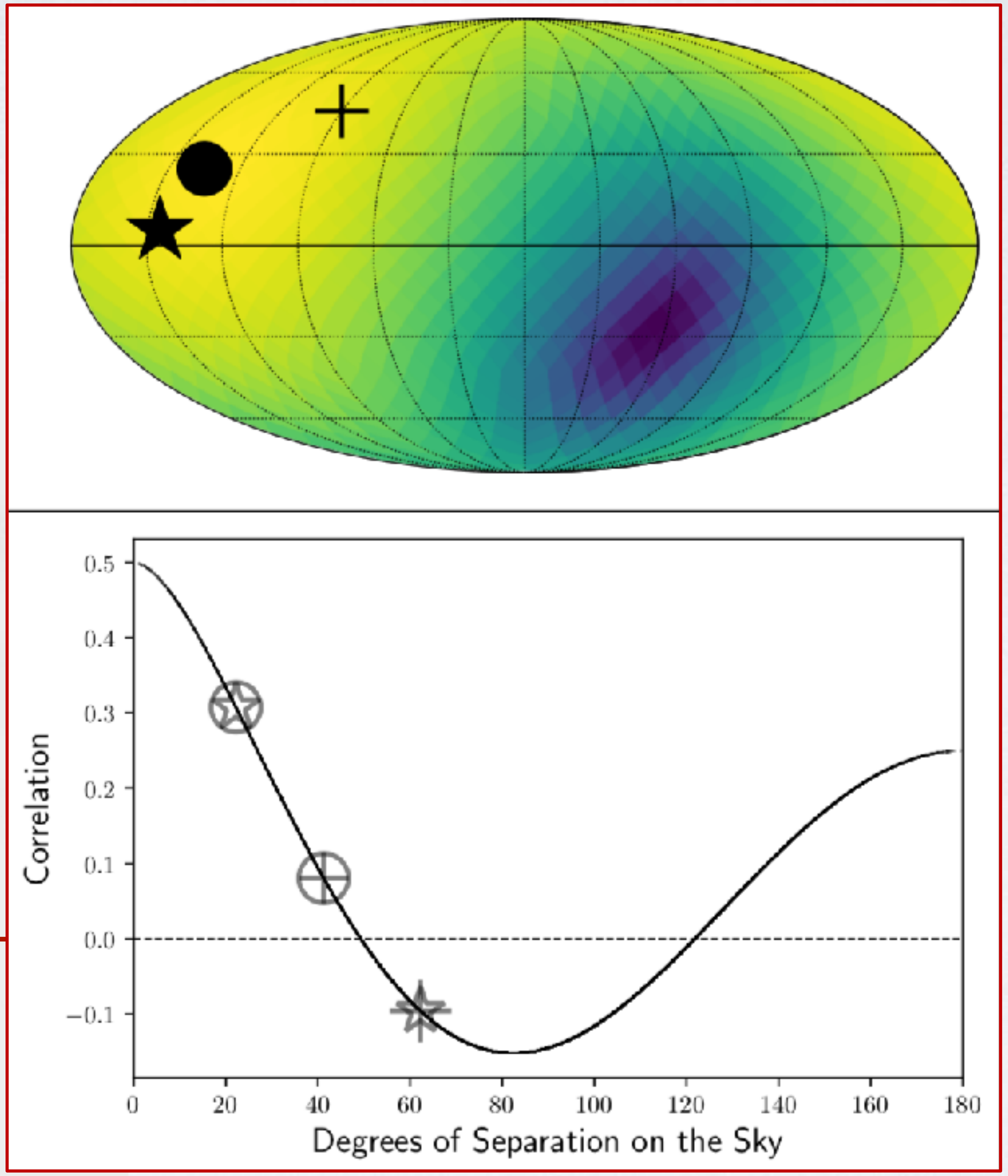
The gravitational-wave background imprints a specific correlated pattern across all of the pulsars in the array.

How Do PTAs Observe GWs?

Search For Correlated Perturbation From GWB

Use quadrupolar nature of GWB to search for correlated perturbation





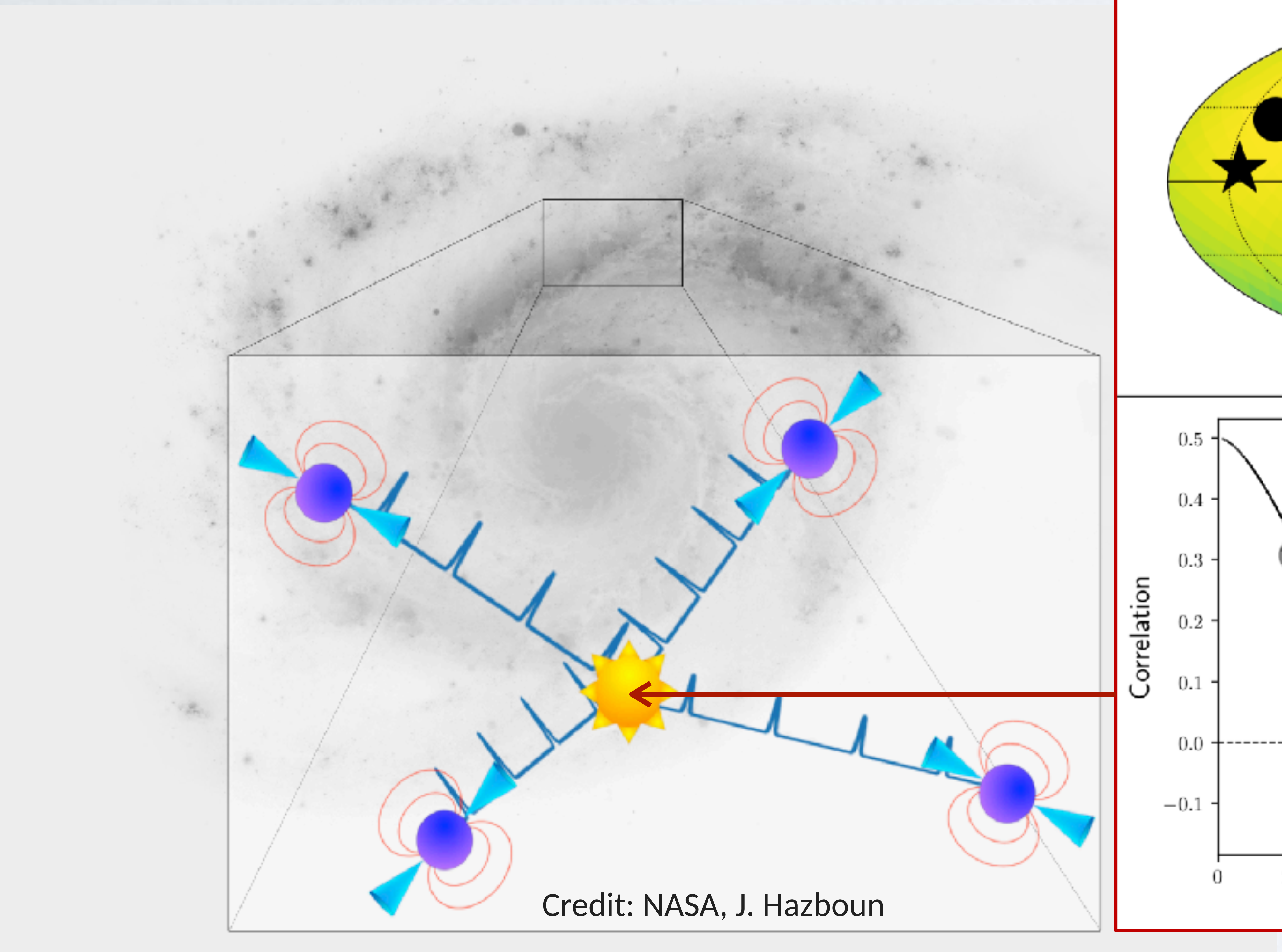
Correlated perturbations are dependent on the angular separation of pulsar pairs.

Many pulsar pairs are required for successful identification of a gravitational wave background.

How Do PTAs Observe GWs?

Search For Correlated Perturbation From GWB

Use quadrupolar nature of GWB to search for correlated perturbation



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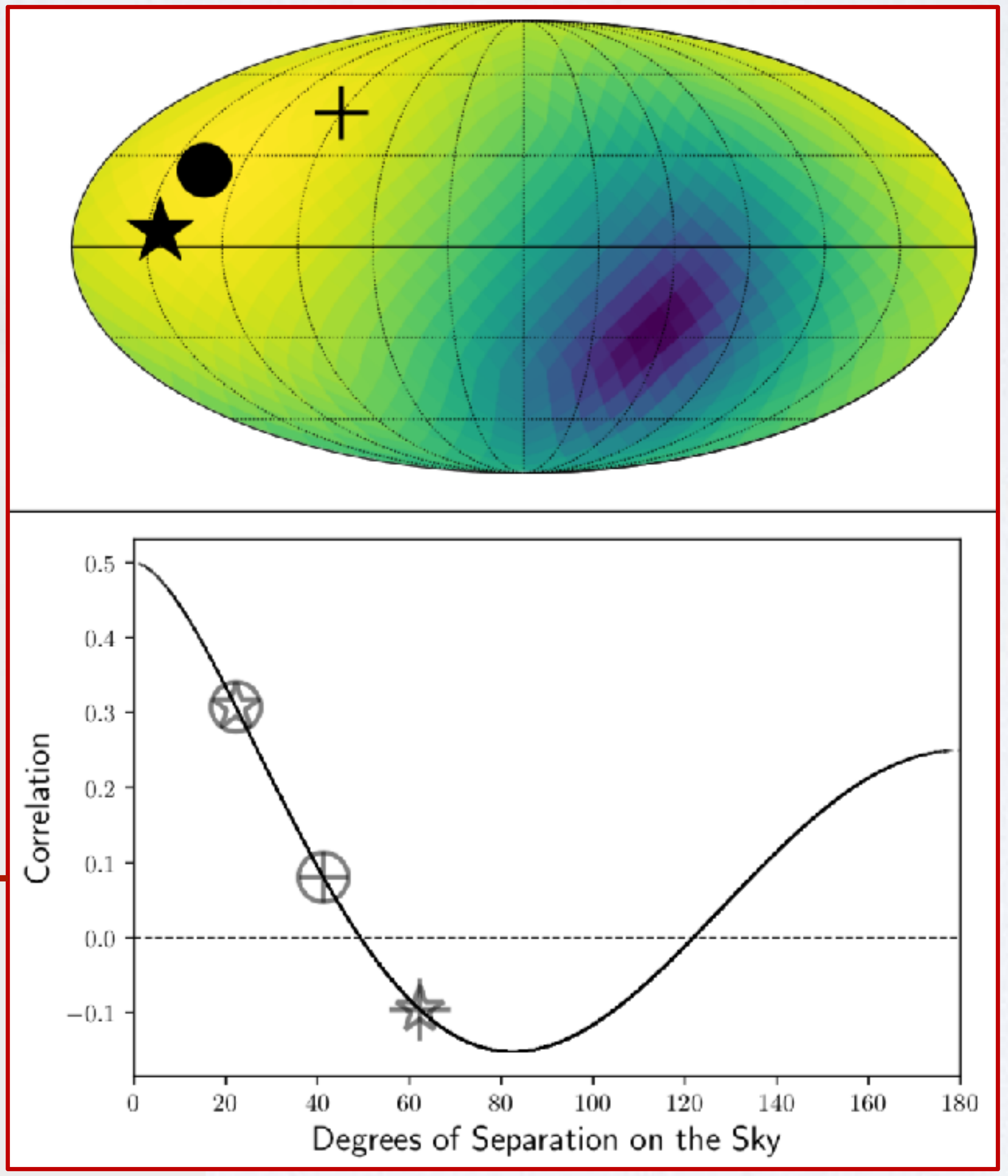
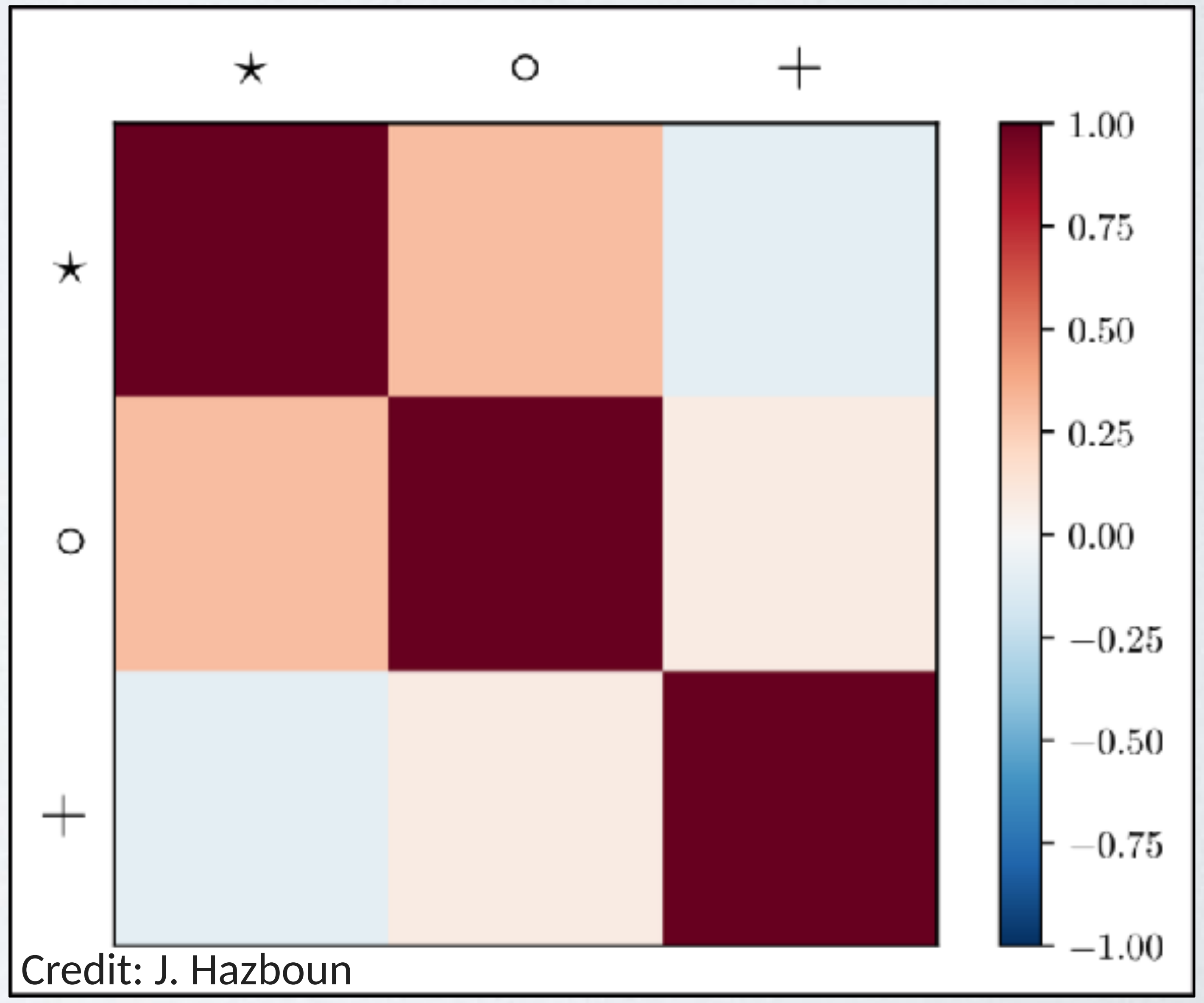


Auto-correlation is much louder than the cross-correlation.

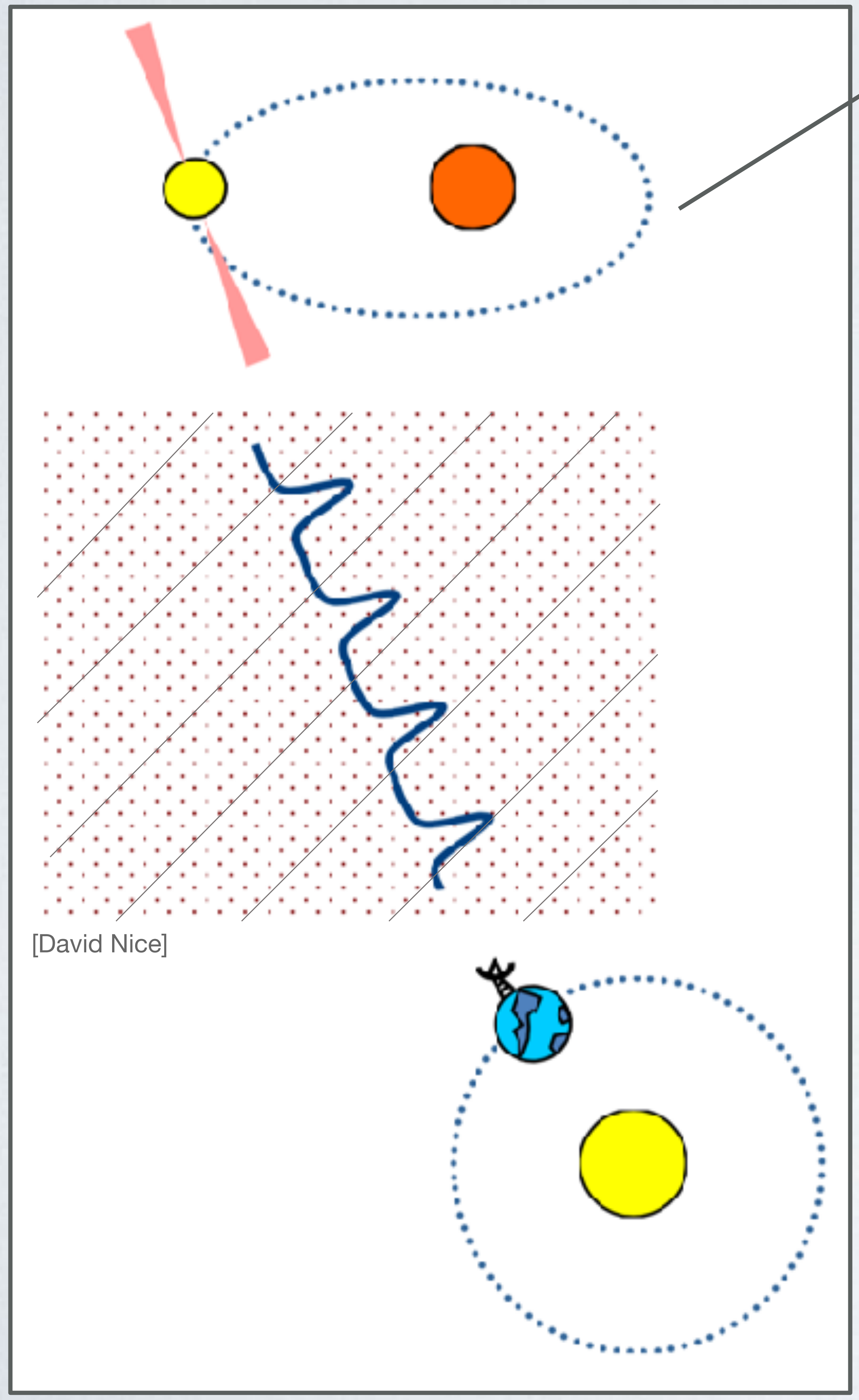
Cartoon Correlation Matrix



How Do PTAs Observe GWs?

Simultaneous Search For GWB & Noise

Correcting For Pulse Propagation Effects

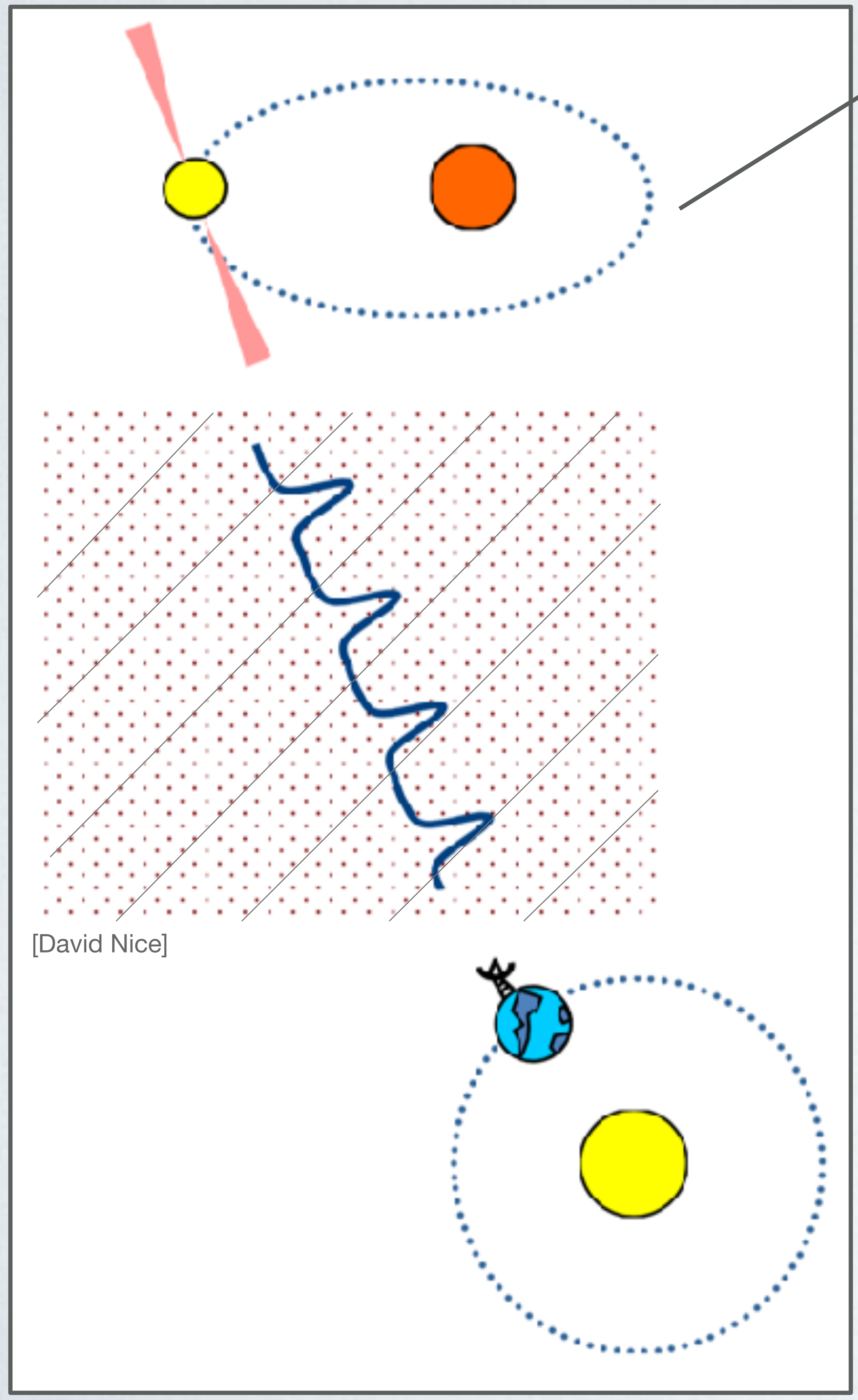


Many MSPs have binary companions.

How Do PTAs Observe GWs?

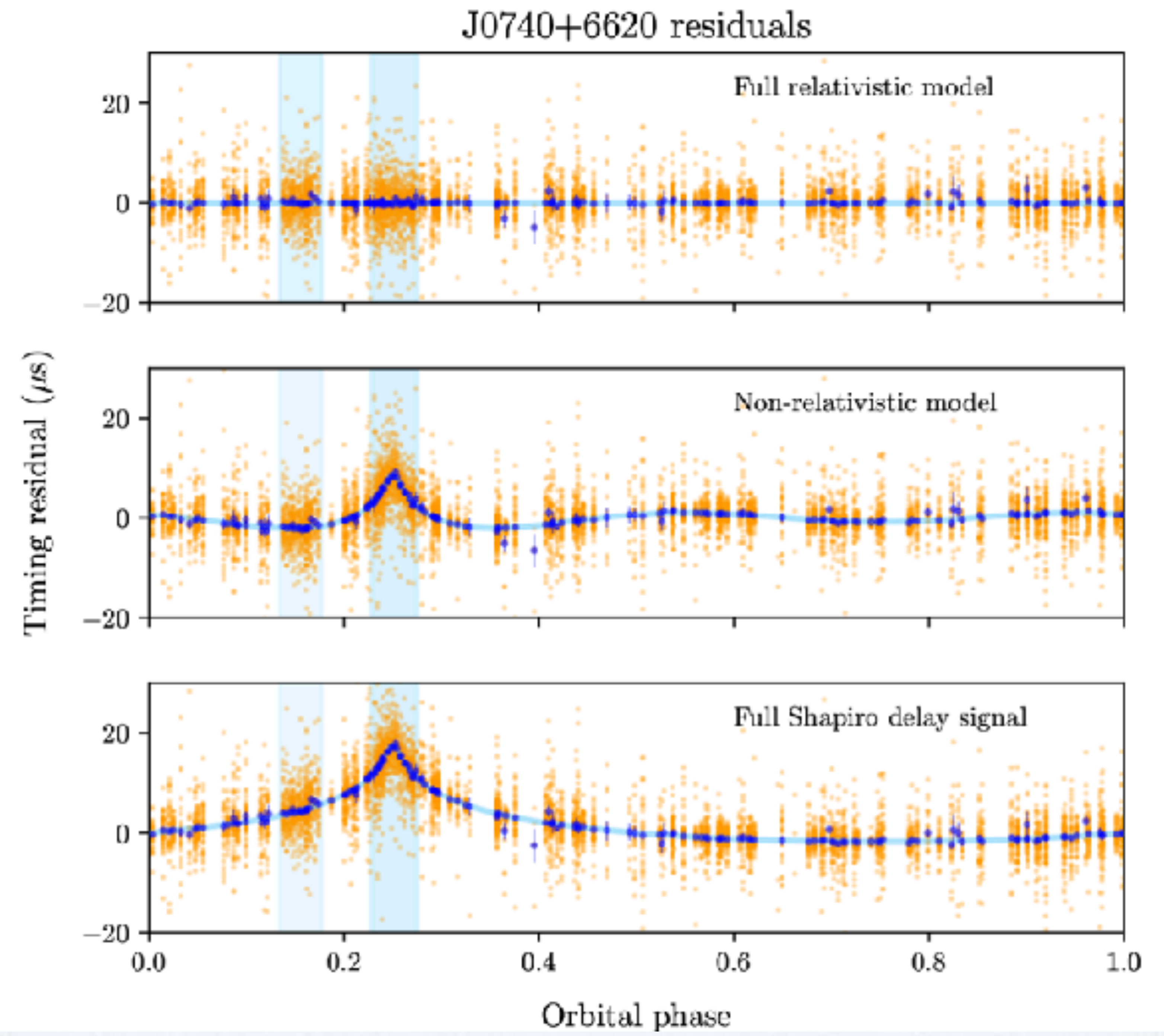
Simultaneous Search For GWB & Noise

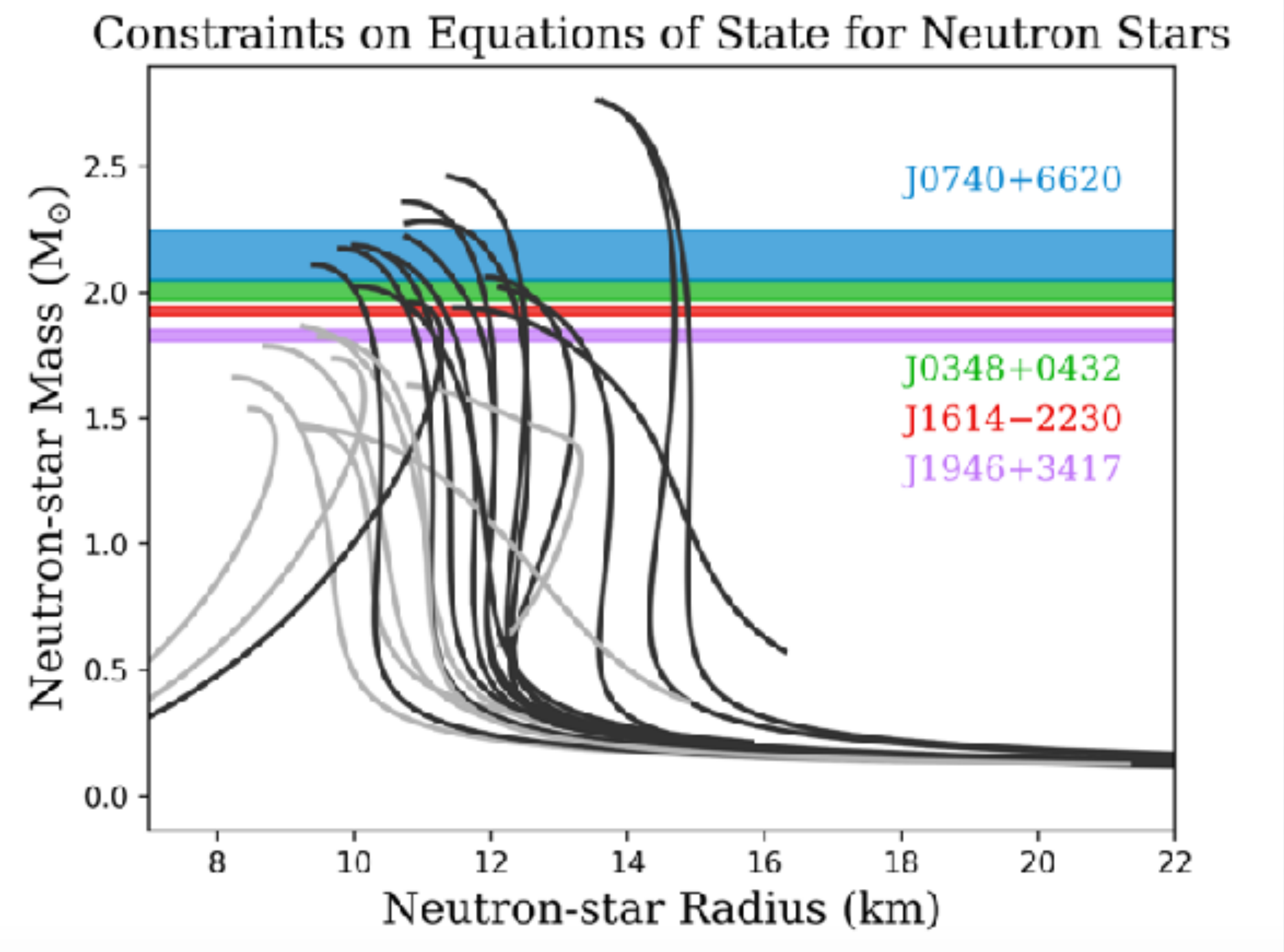
Correcting For Pulse Propagation Effects



Many MSPs have binary companions.

NANOGrav data has discovered the most massive neutron star using the Shapiro delay from a binary companion.



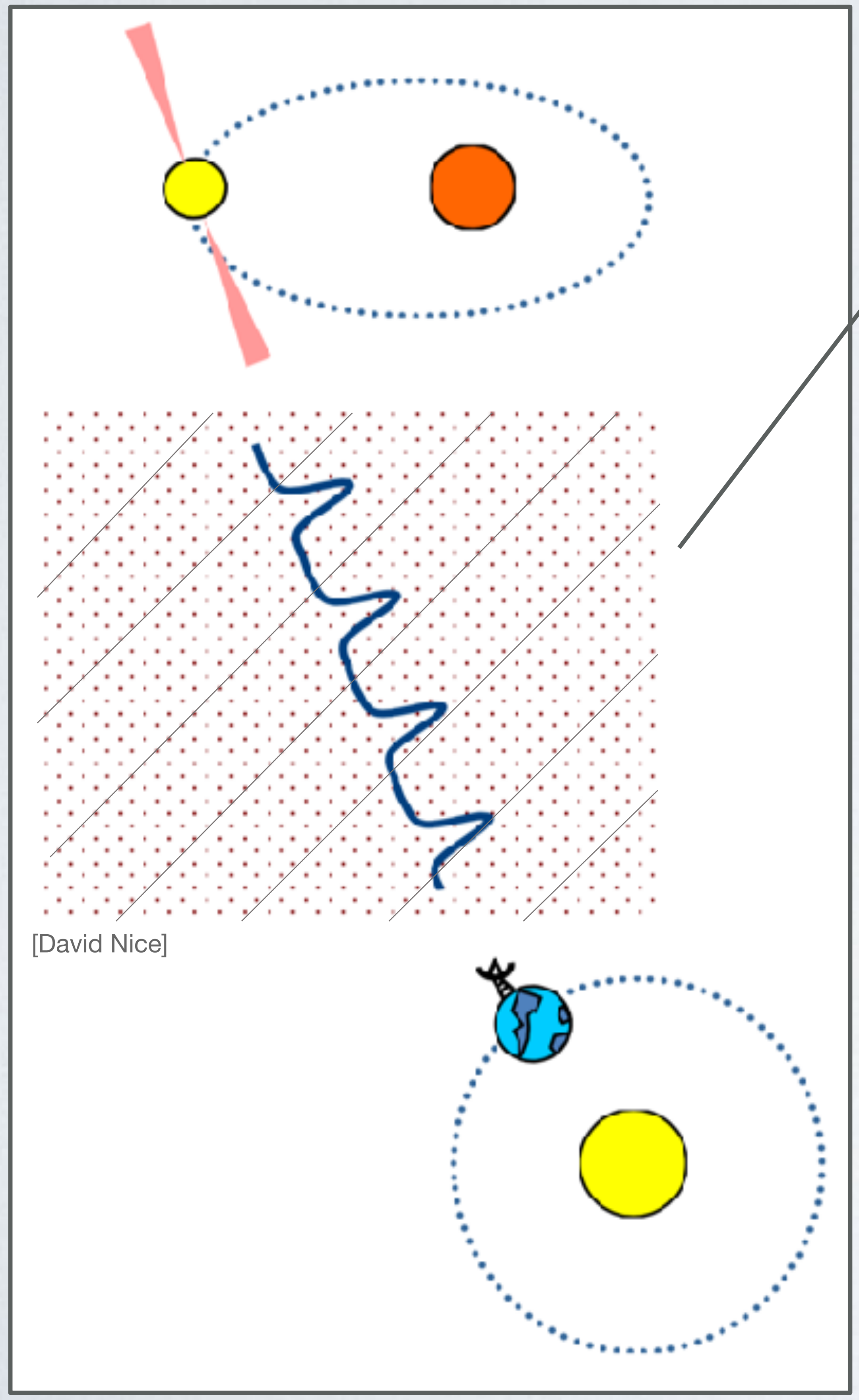


Credit: **Cromartie** et al., Nature Astronomy (2020), Fonseca et al., arXiv:1903.08194

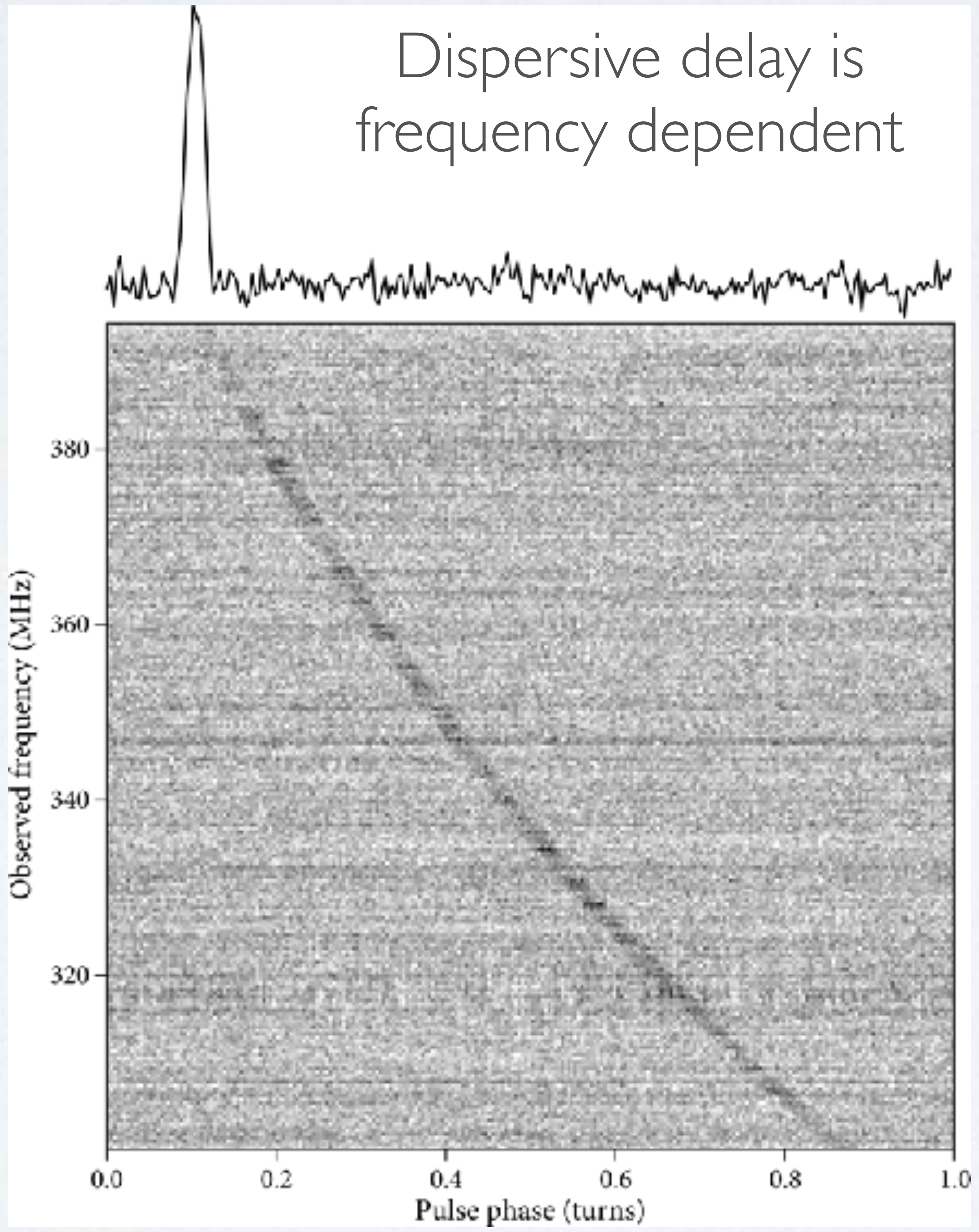
How Do PTAs Observe GWs?

Simultaneous Search For GWB & Noise

Correcting For Pulse Propagation Effects

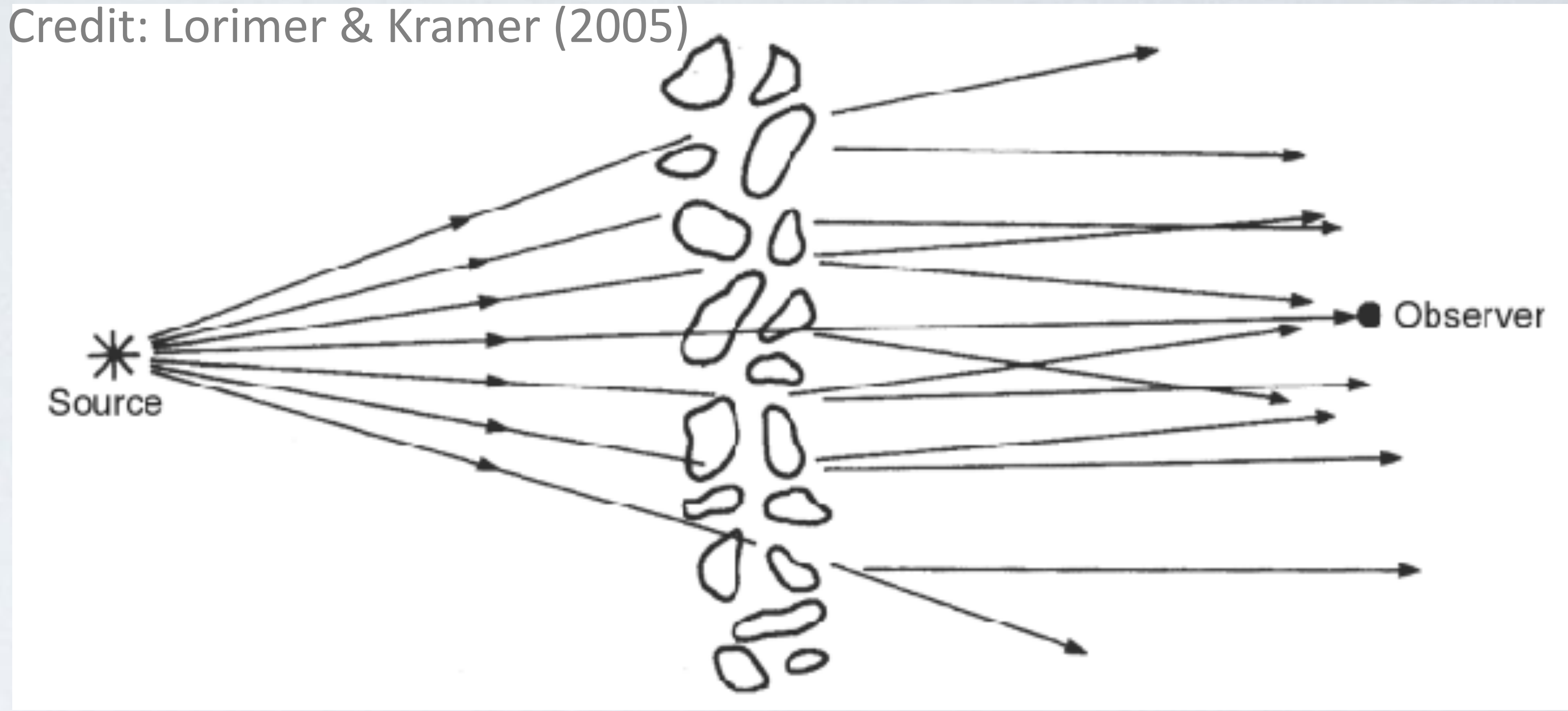


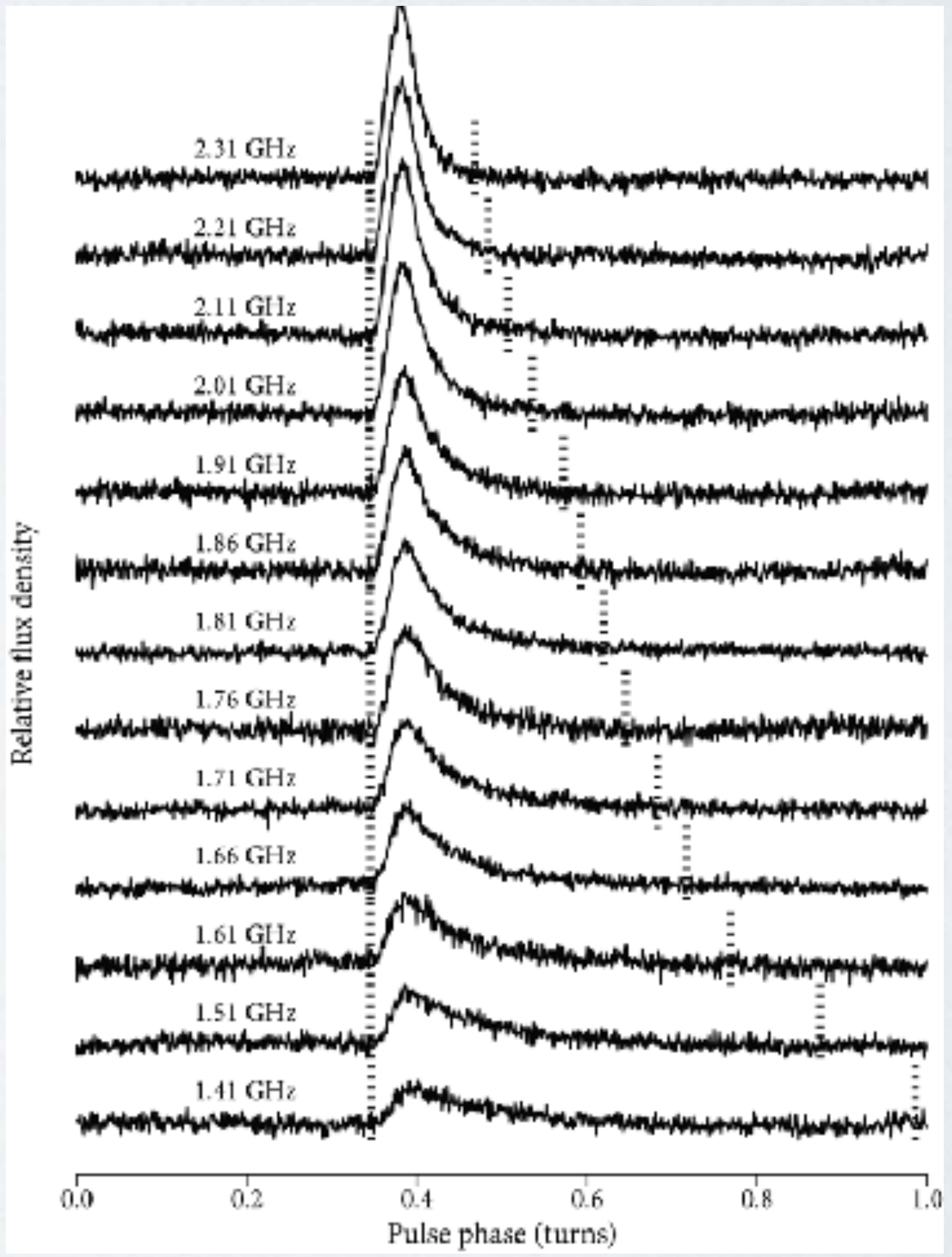
Dispersion and scattering from the Interstellar Medium (ISM)



Credit: Condon & Ransom (2018)

Credit: Lorimer & Kramer (2005)





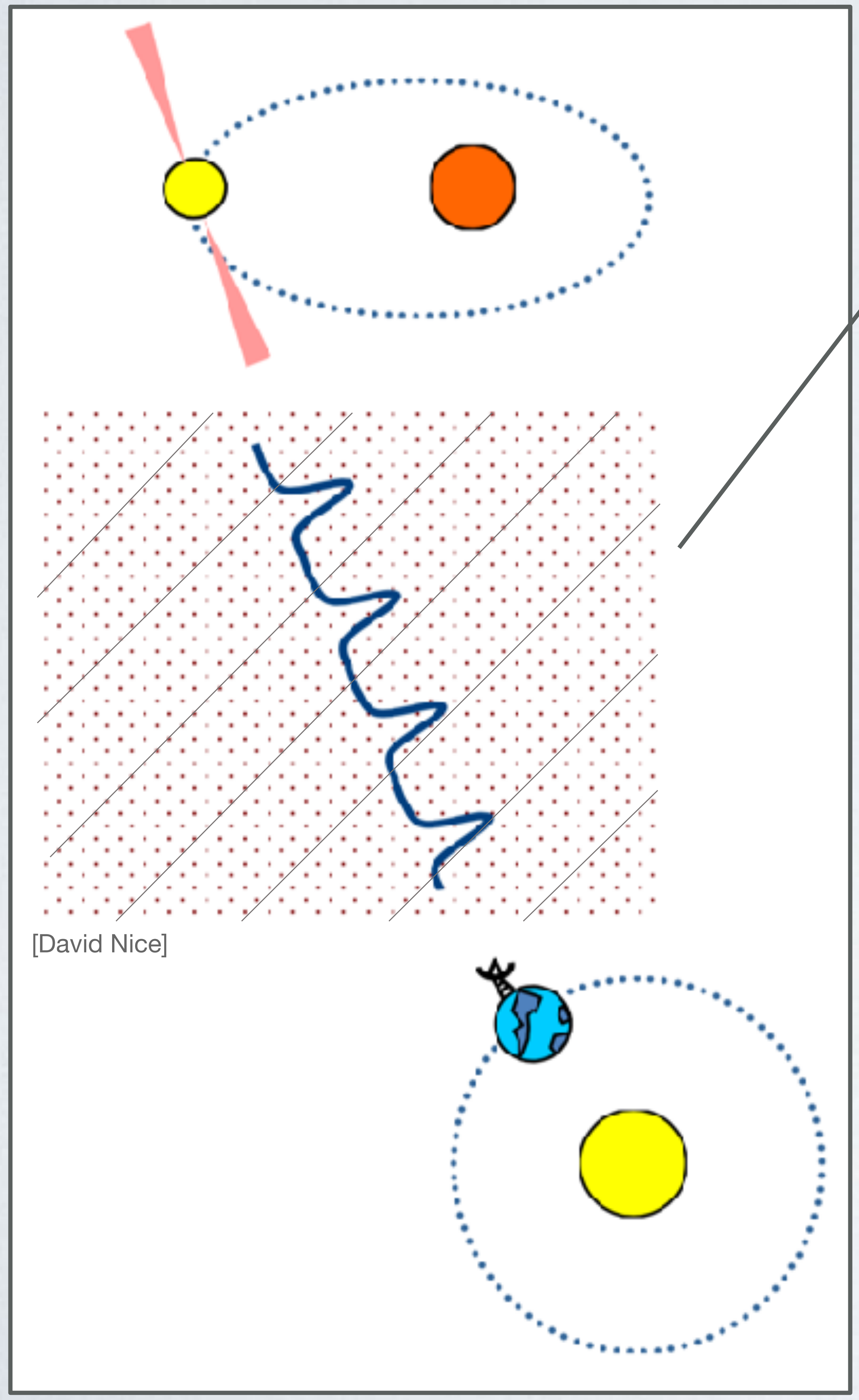
Scattering causes pulse broadening at lower frequencies

Credit: Condon & Ransom (2018)

How Do PTAs Observe GWs?

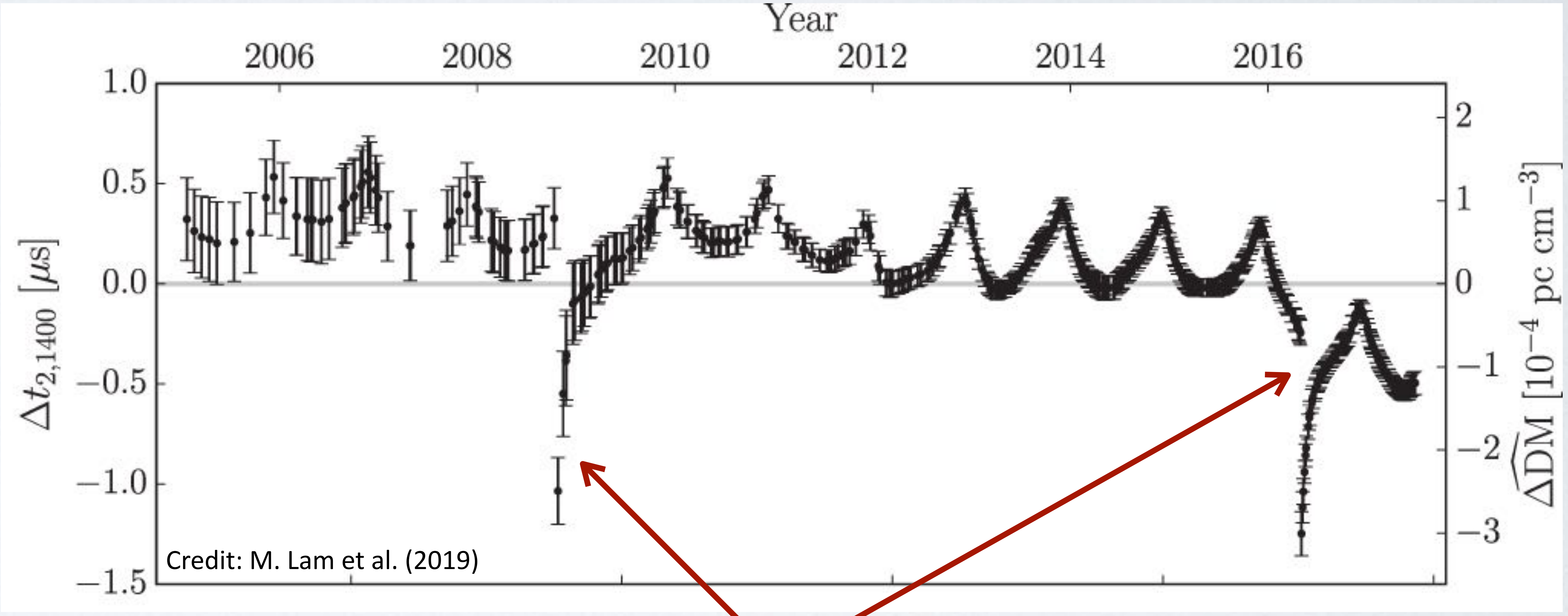
Simultaneous Search For GWB & Noise

Correcting For Pulse Propagation Effects



Dispersion and scattering from the Interstellar Medium (ISM)

PSR J1713+0747 Dispersion Measure Variations

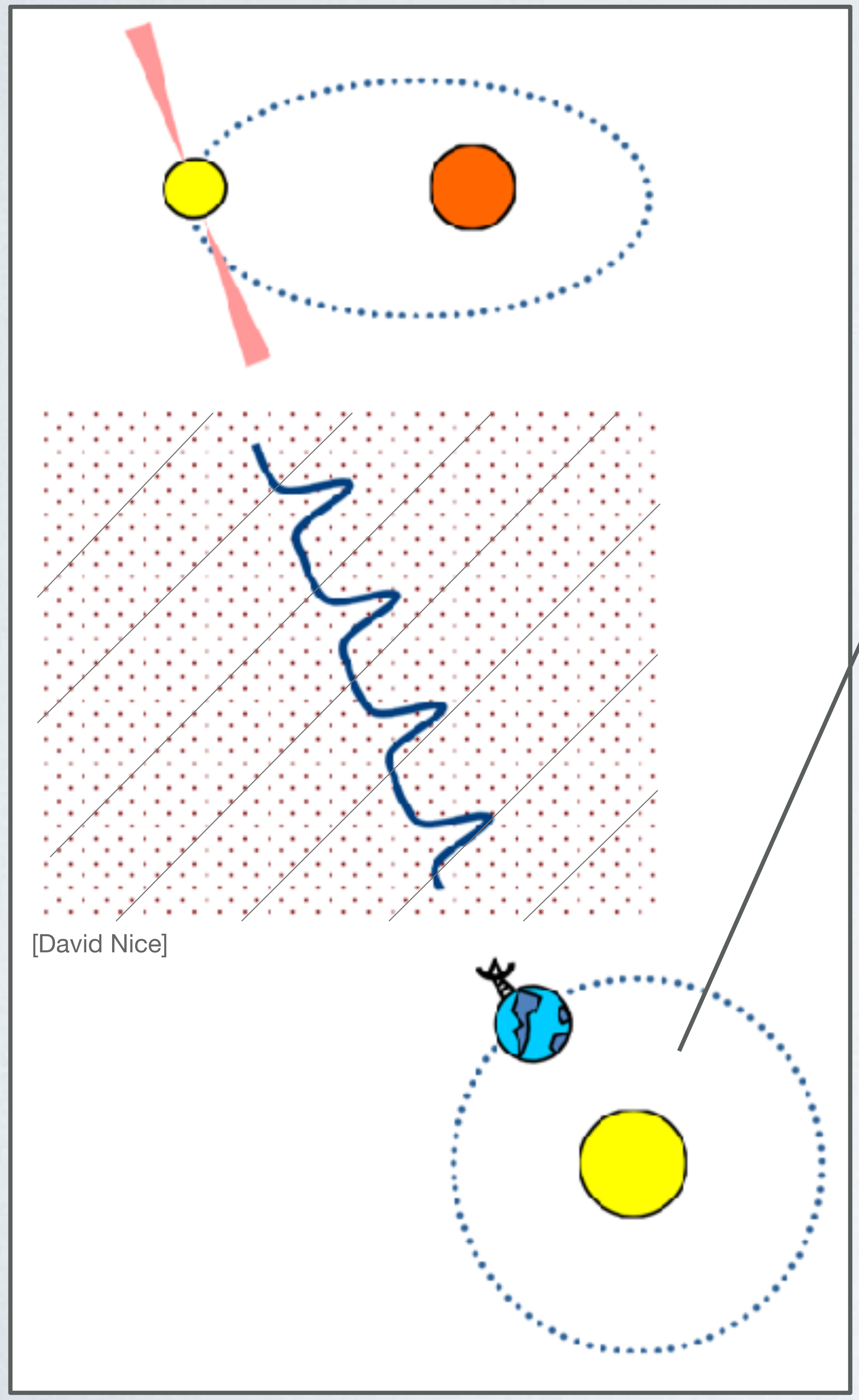


Two "ISM Events" showing local *voids* in the ISM around PSR 1713+0747.

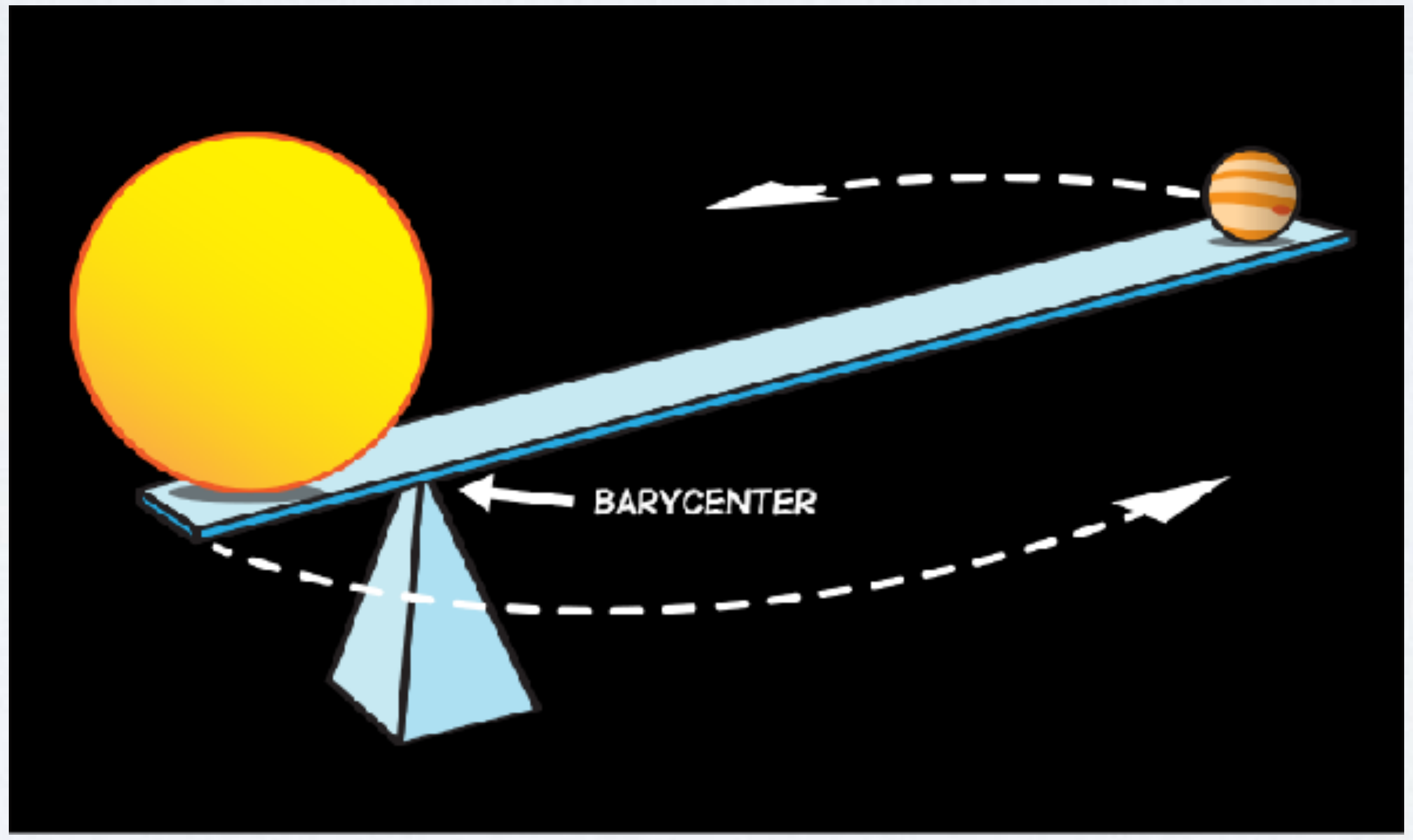
How Do PTAs Observe GWs?

Simultaneous Search For GWB & Noise

Correcting For Pulse Propagation Effects

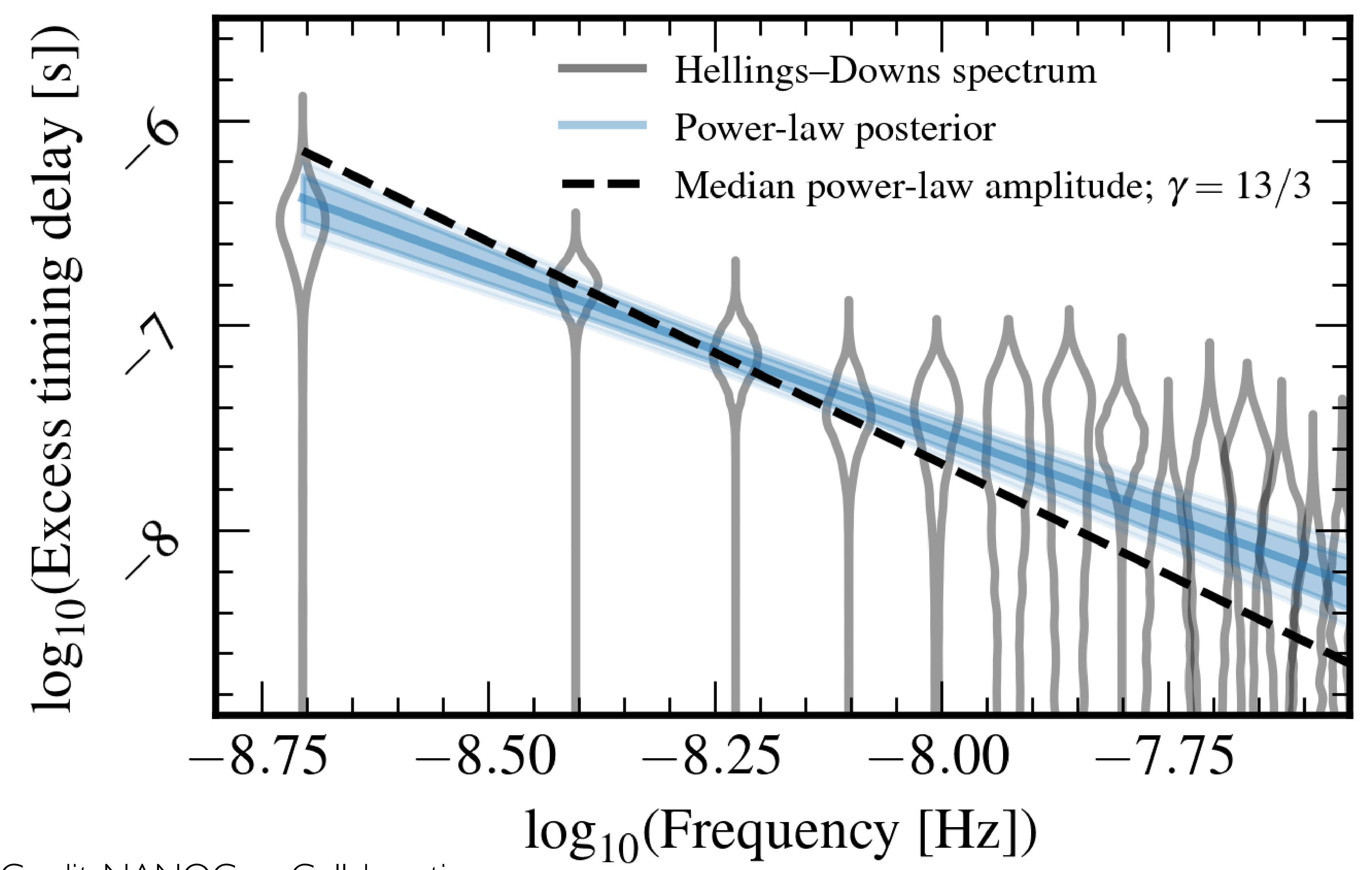


Roemer delay from the Earth's motion around the Solar System Barycenter

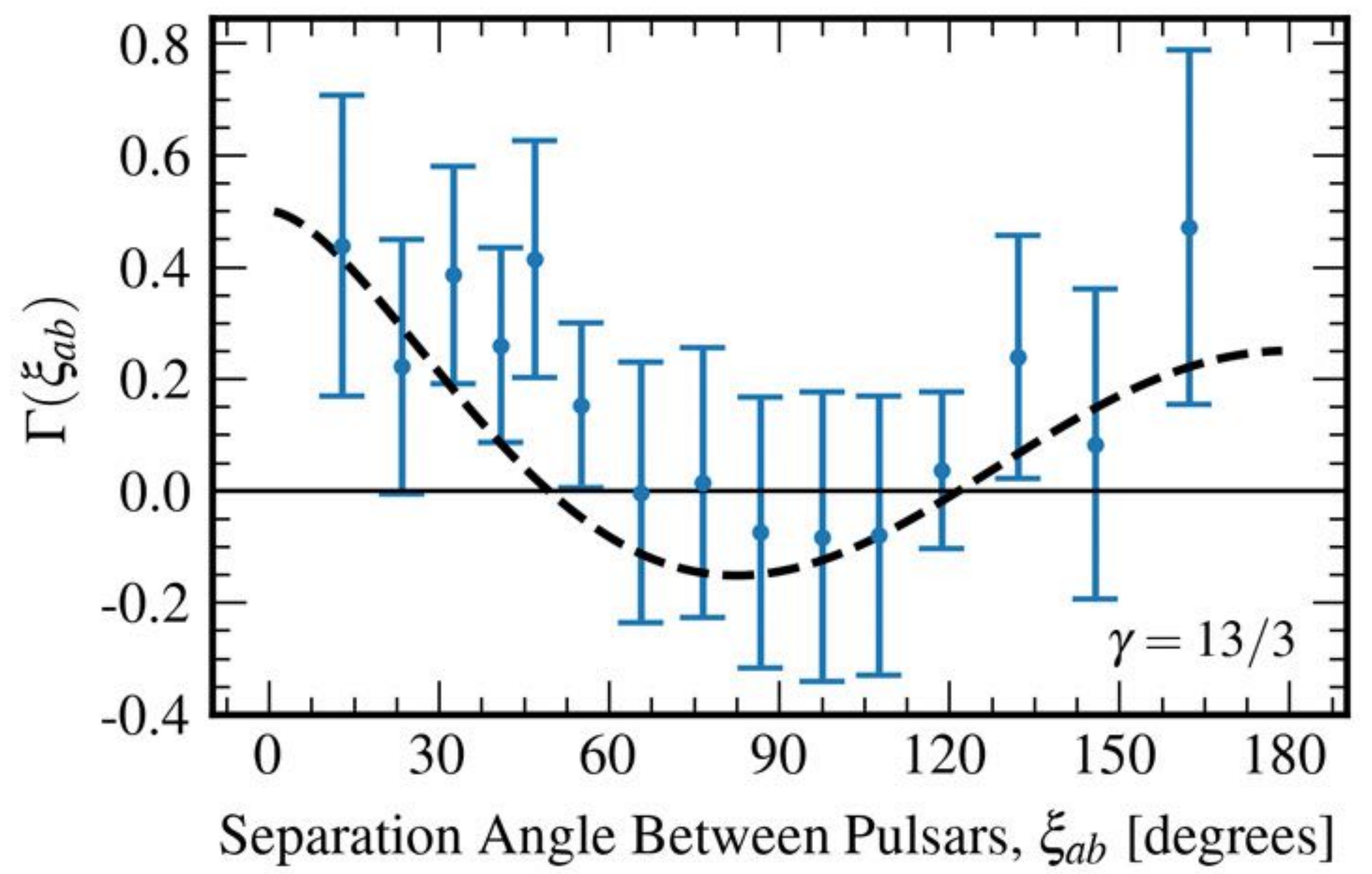


How Do PTAs Observe GWs?

Recent Evidence For A Stochastic GW Background



Credit: NANOGrav Collaboration

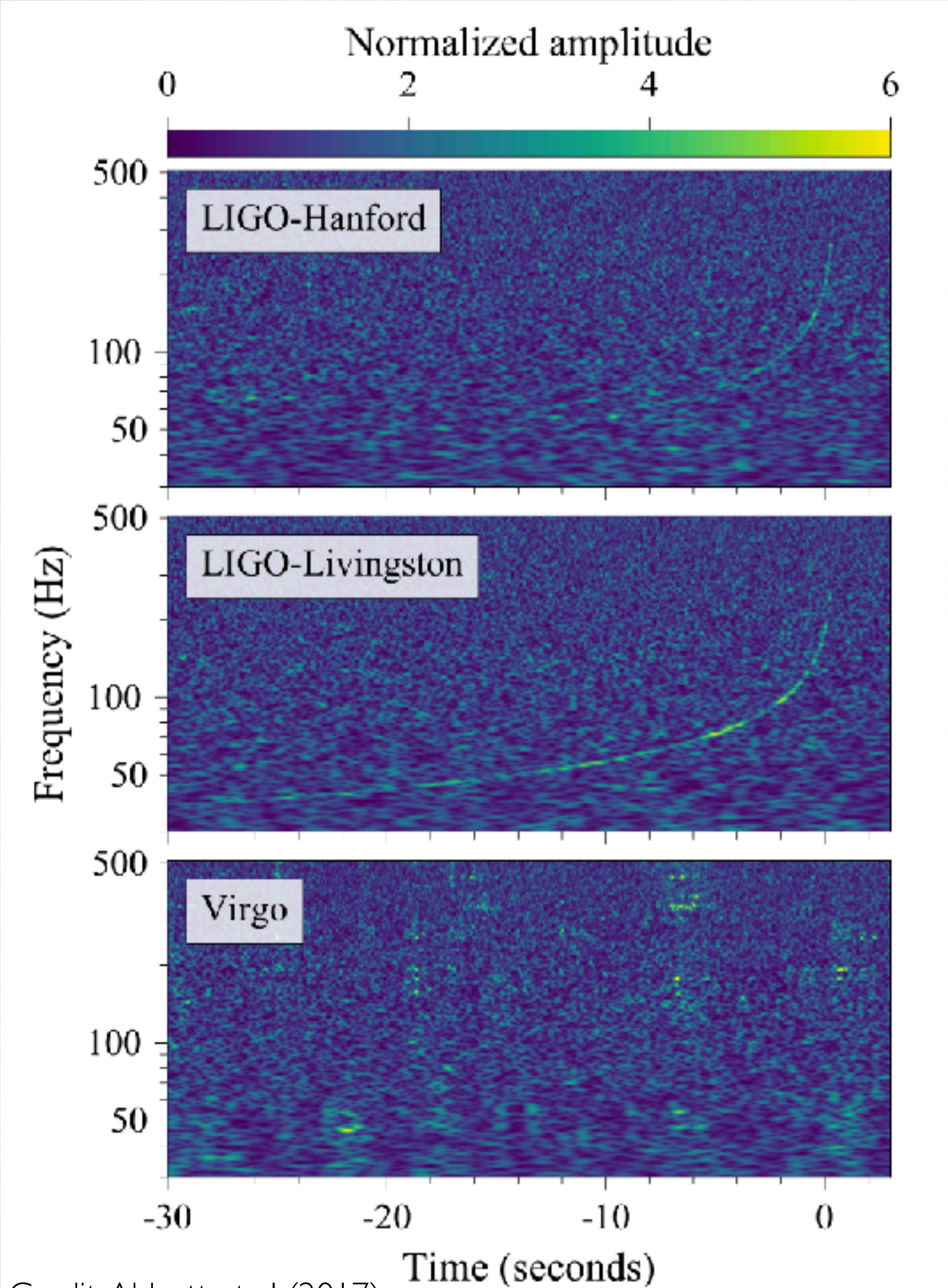


MULTI-MESSENGER CAPABILITIES

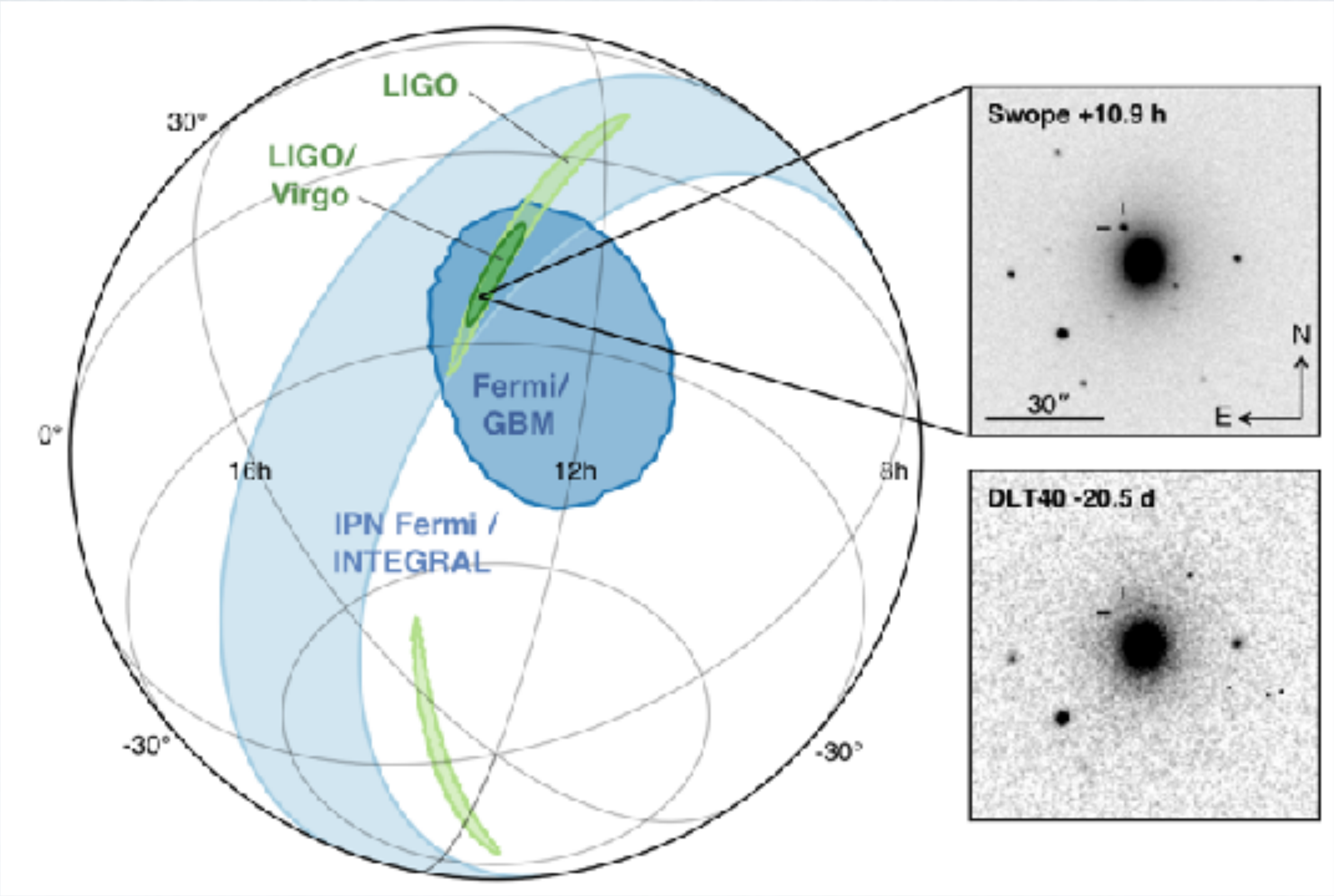
Combining GWs & EM

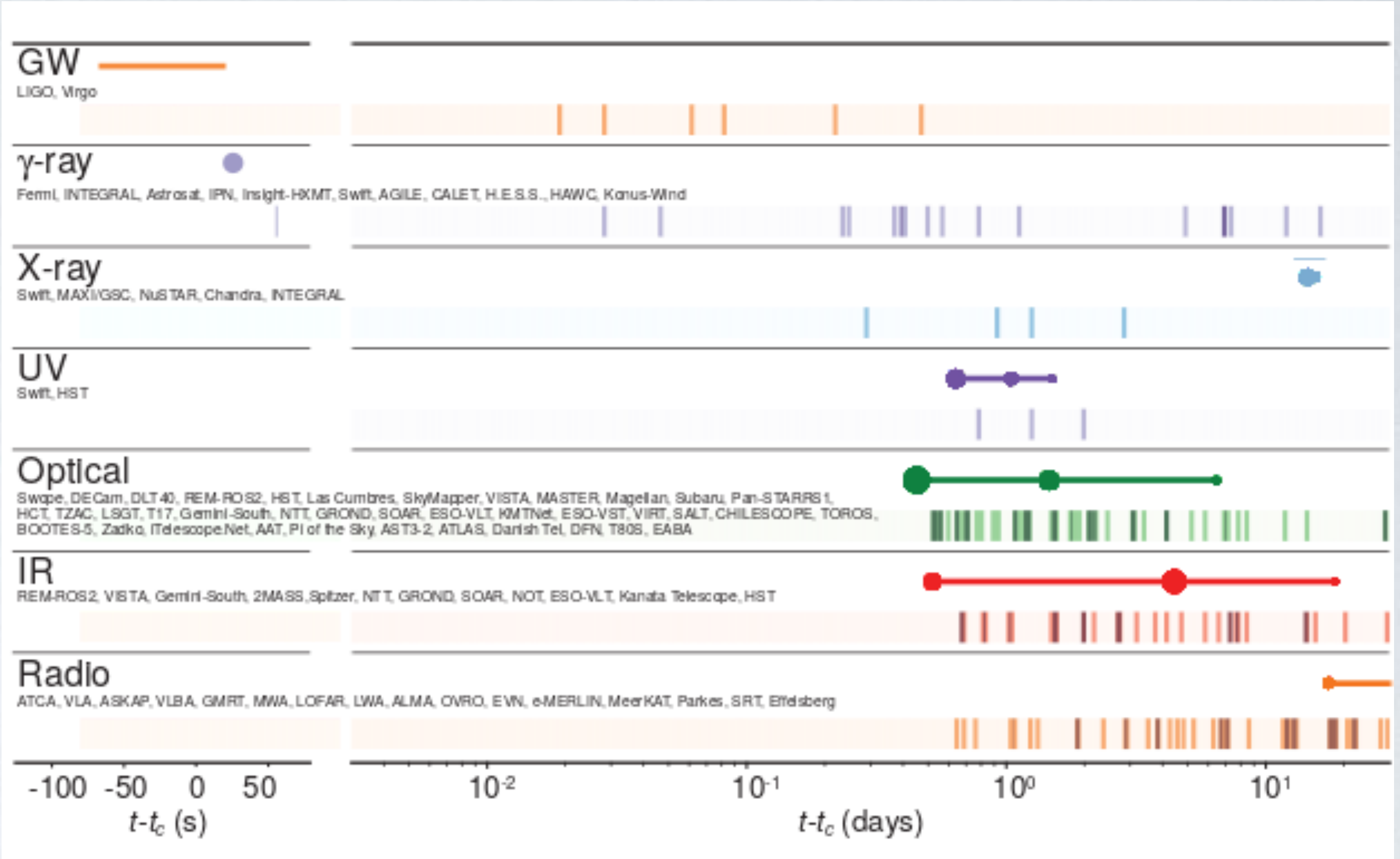
LIGO-like Detectors: Multi-Messenger Counterparts

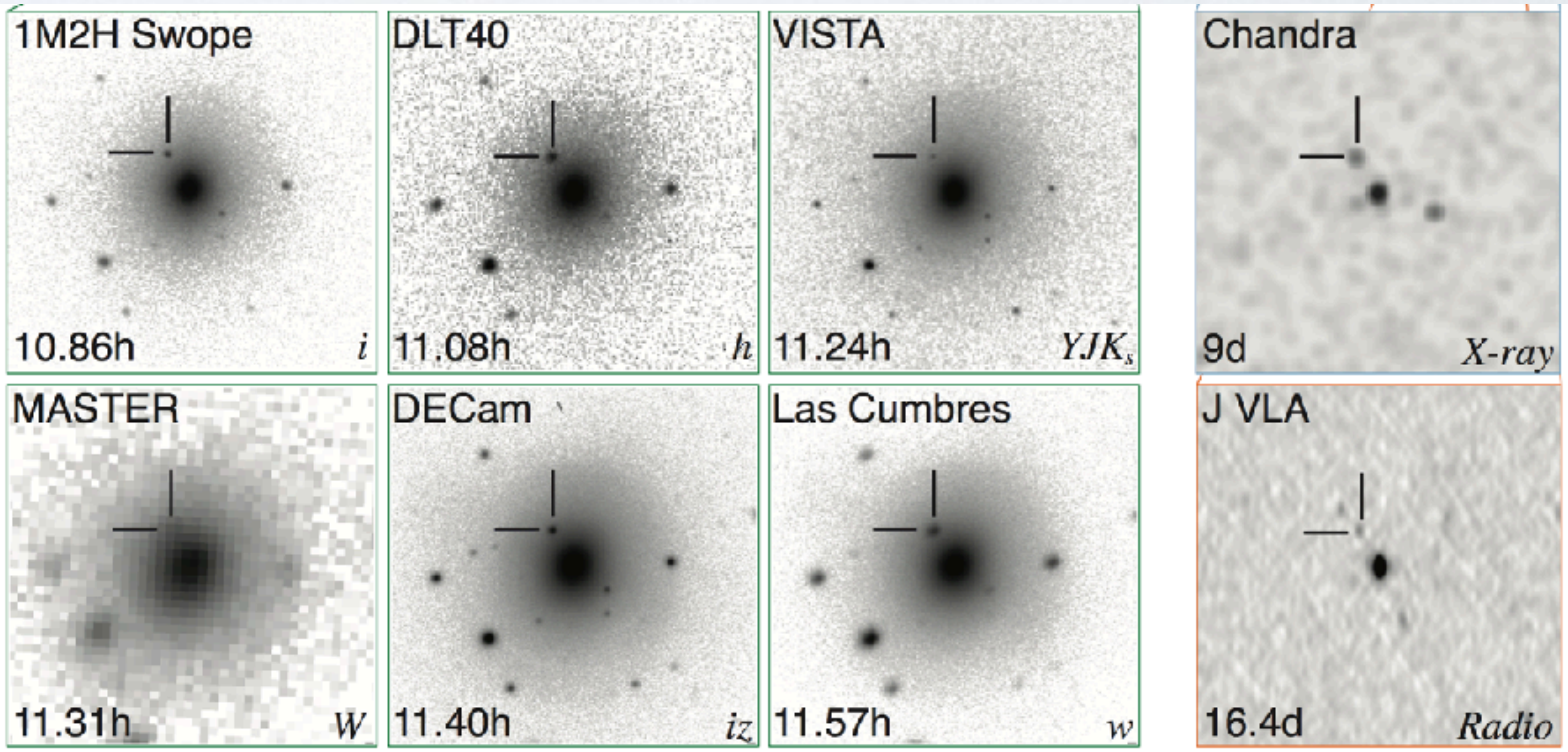
GW170817: A Multi-Messenger Timeline



Credit: Abbott et al (2017)

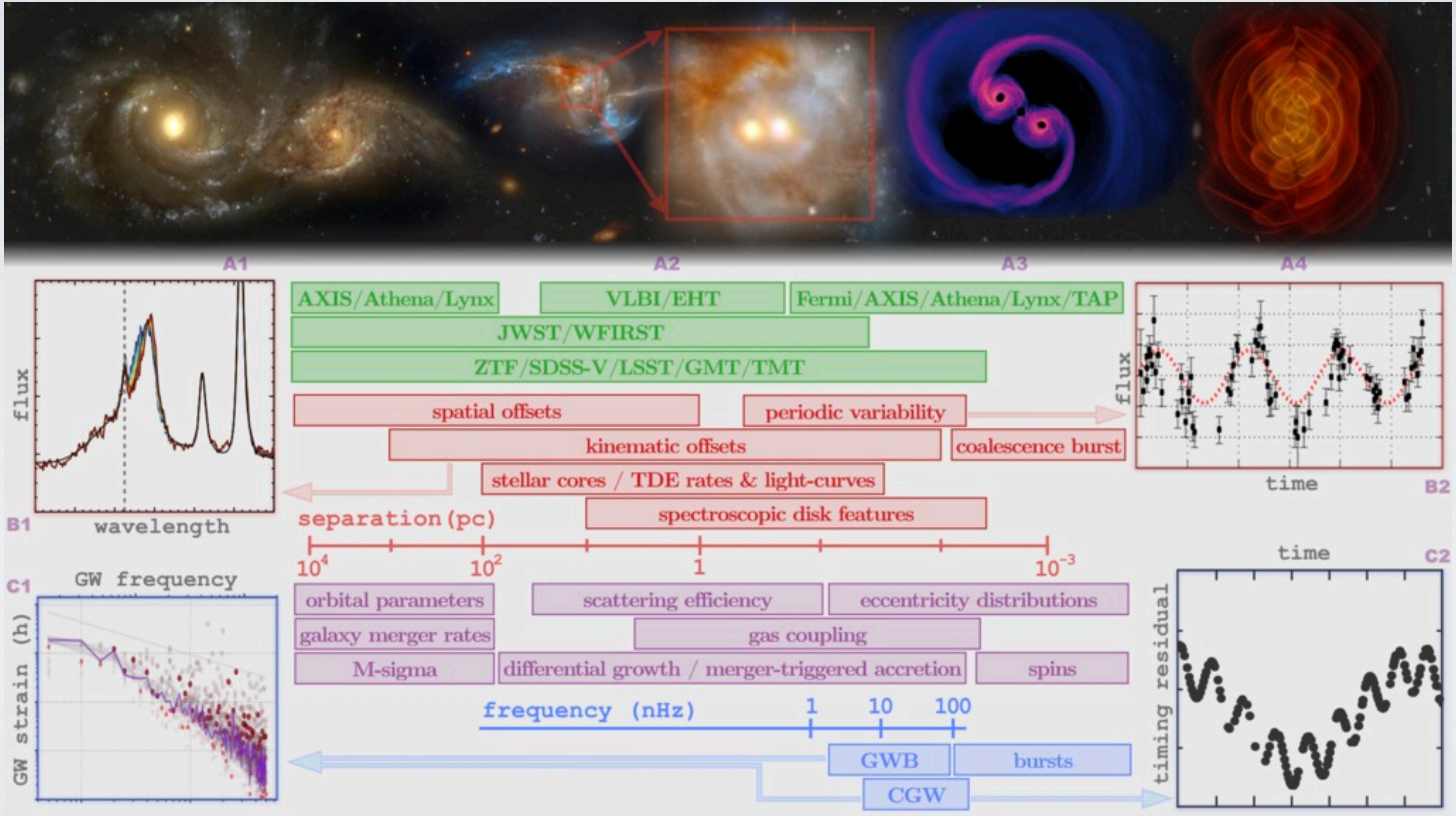






Massive Black Hole Binaries

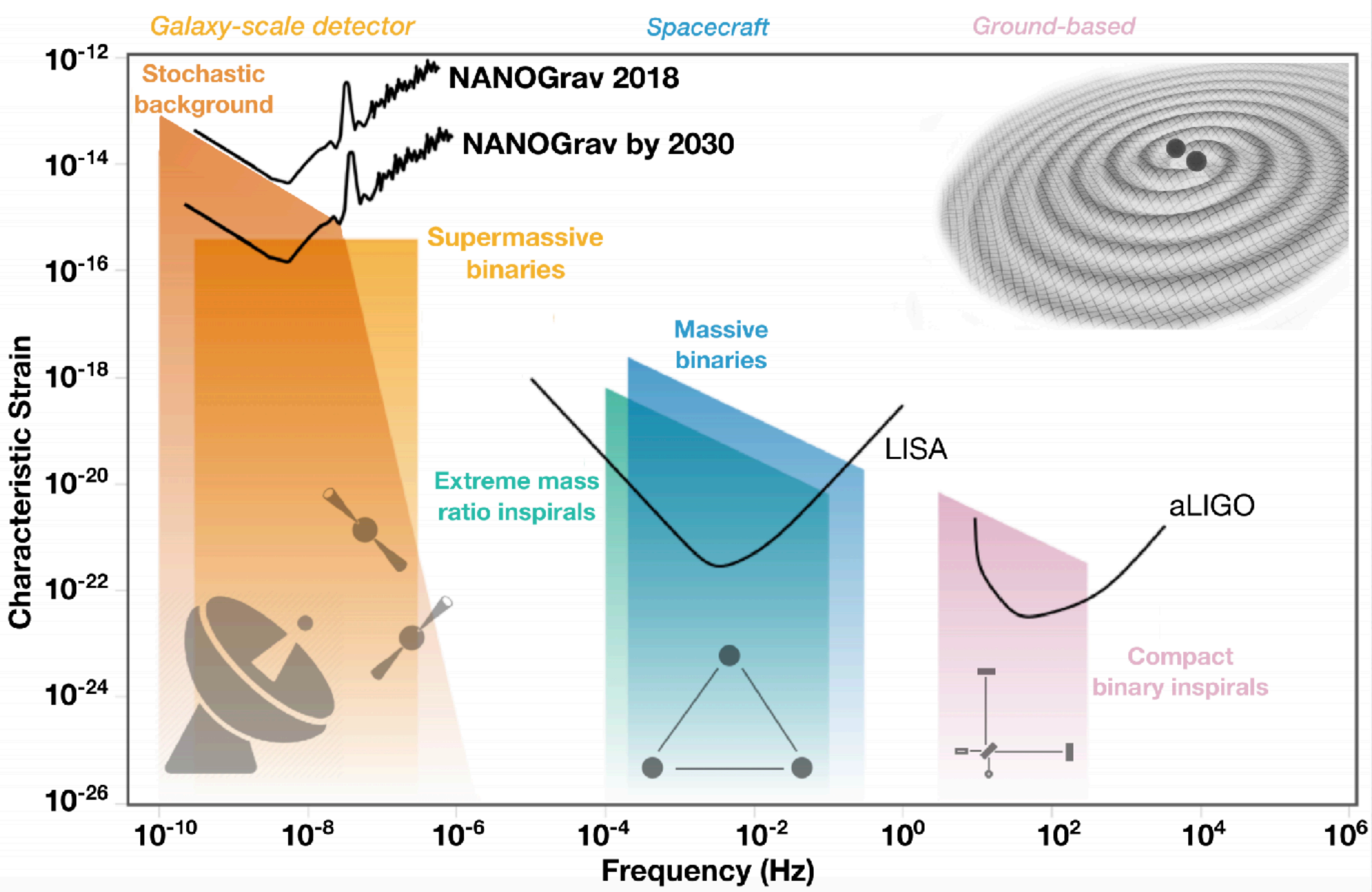
A Multi-Messenger Treasure Trove



THE FUTURE LANDSCAPE OF GW OBSERVATORIES

Filling In The Gaps

The Gravitational Wave Spectrum



S. Taylor & C. Mingarelli, adapted from gwplotter.org (Moore, Cole, Berry 2014) and based on a figure in Mingarelli & Mingarelli (2018). Illustration of merging black holes adapted from R. Hurt/Caltech-JPL/EPA

The *Future* Gravitational Wave Spectrum