GRAVITATIONAL WAVES:
A short review at the beginning of an era

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ADLER PLANETARIUM

COFI • Gravitational Waves
San Juan, Puerto Rico
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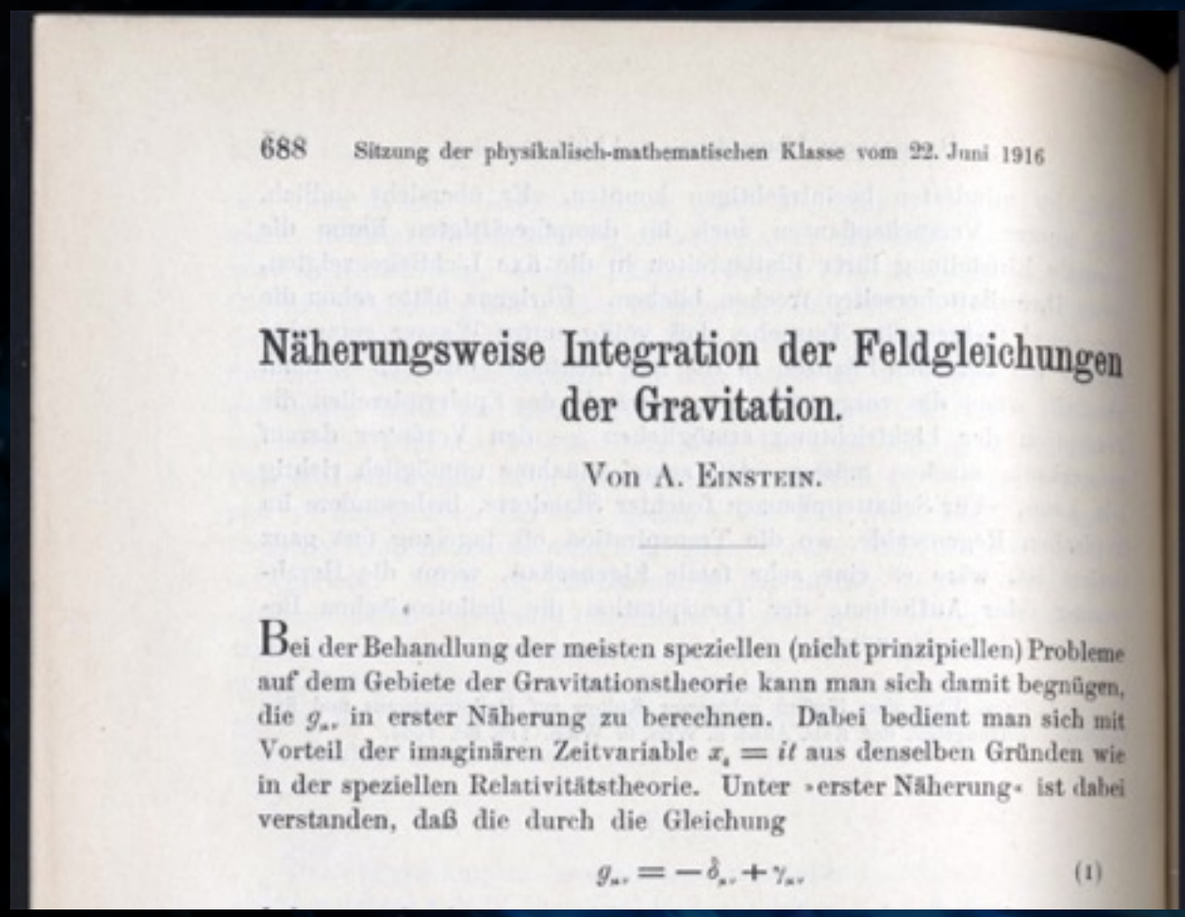
Storyline

- History & nature of gravitational waves
- Sources & Science
- Evolution of the Field
- News Now!

History

- 1915: General Relativity
  - 1916 & 1918: Gravitational Waves



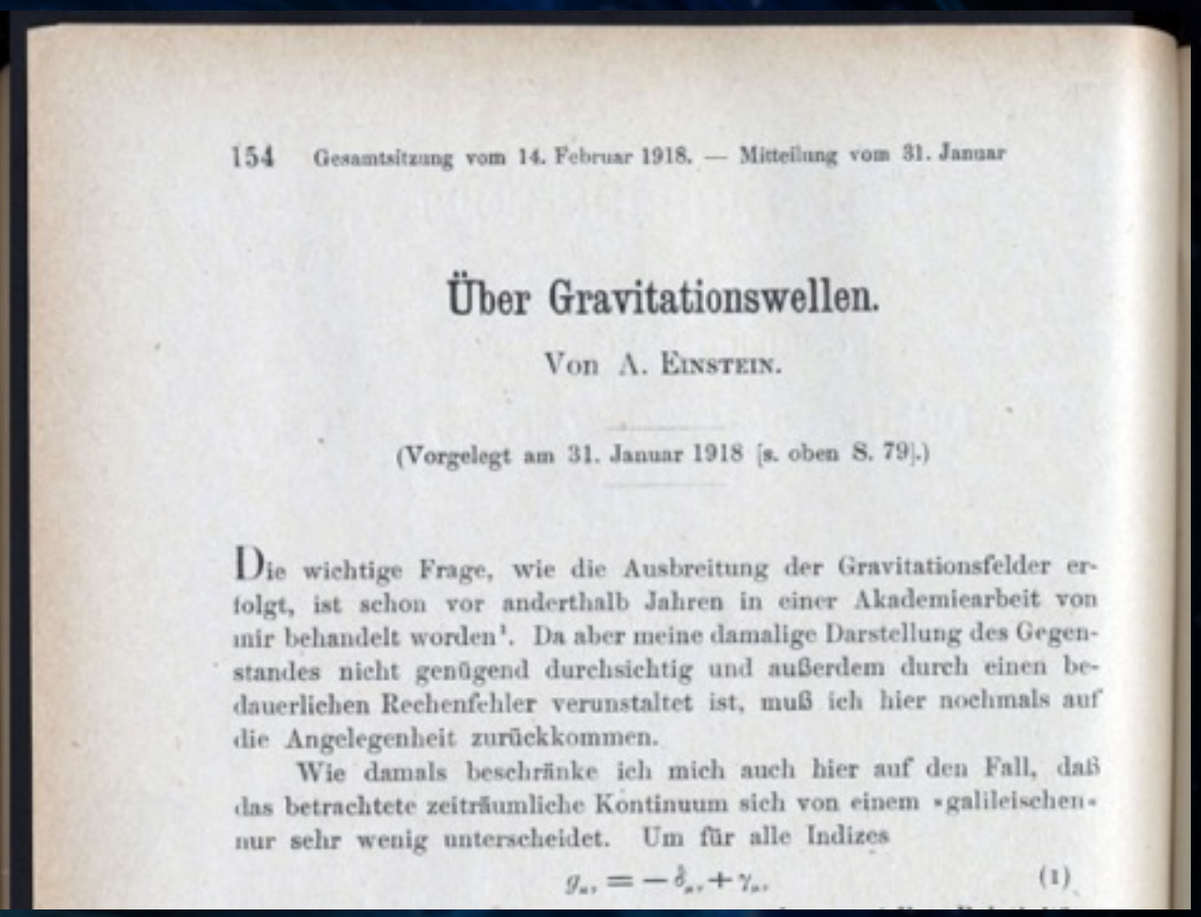
688 Sitzung der physikalisch-mathematischen Klasse vom 22. Juni 1916

Näherungsweise Integration der Feldgleichungen der Gravitation.

Von A. Einstein.

Bei der Behandlung der meisten speziellen (nicht prinzipiellen) Probleme auf dem Gebiete der Gravitationstheorie kann man sich damit begnügen, die $g_{\mu\nu}$ in erster Näherung zu berechnen. Dabei bedient man sich mit Vorteil der imaginären Zeitvariable $x_4 = it$ aus denselben Gründen wie in der speziellen Relativitätstheorie. Unter »erster Näherung« ist dabei verstanden, daß die durch die Gleichung

$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \qquad (1)$$



154 Gesamtsitzung vom 14. Februar 1918. — Mitteilung vom 31. Januar

Über Gravitationswellen.

Von A. Einstein.

(Vorgelegt am 31. Januar 1918 [s. oben S. 79].)

Die wichtige Frage, wie die Ausbreitung der Gravitationsfelder erfolgt, ist schon vor anderthalb Jahren in einer Akademiearbeit von mir behandelt worden[1]. Da aber meine damalige Darstellung des Gegenstandes nicht genügend durchsichtig und außerdem durch einen bedauerlichen Rechenfehler verunstaltet ist, muß ich hier nochmals auf die Angelegenheit zurückkommen.

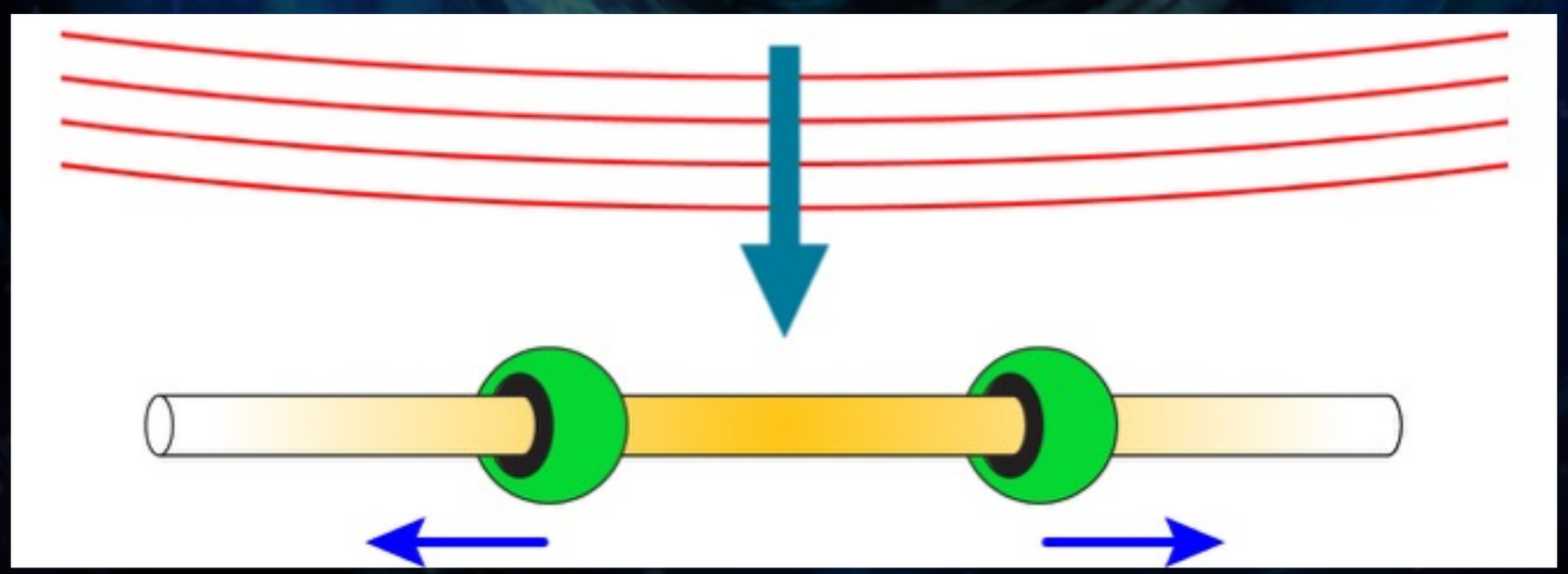
Wie damals beschränke ich mich auch hier auf den Fall, daß das betrachtete zeiträumliche Kontinuum sich von einem »galileischen« nur sehr wenig unterscheidet. Um für alle Indizes

$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \qquad (1)$$

- Confusion about reality of the waves. Coordinate effects?
  - 1922: Eddington - “GWs propagate at the speed of thought!”

History

- 1930s: Einstein & Rosen — GWs do not exist!
- Confusion for two more decades…
- 1957: The Role of Gravitation in Physics ("The Chapel Hill Conference" — www.edition-open-access.de/sources/5/)
- Pirani: Look at **geodesic motion** of particles with GW
- Feynman & Bondi : the "sticky bead argument"



Wave action on particles...

- A passing gravitational wave changes **proper distances** in a plane transverse to the direction of propagation
- Characterized by a **dimensionless strain h**

Real world input, fixed by astrophysics and is usually SMALL!

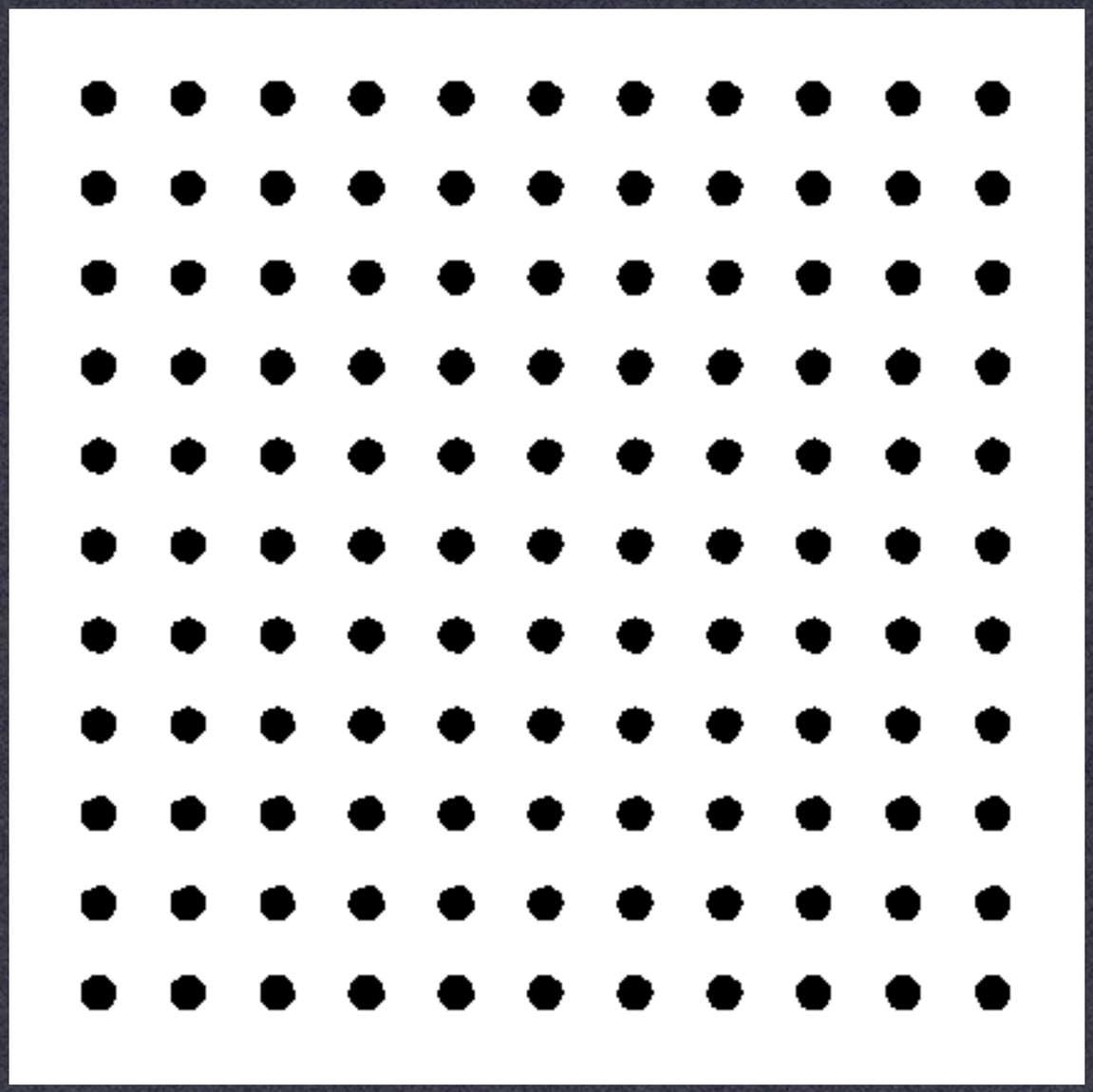
$$h = \frac{\Delta L}{L}$$

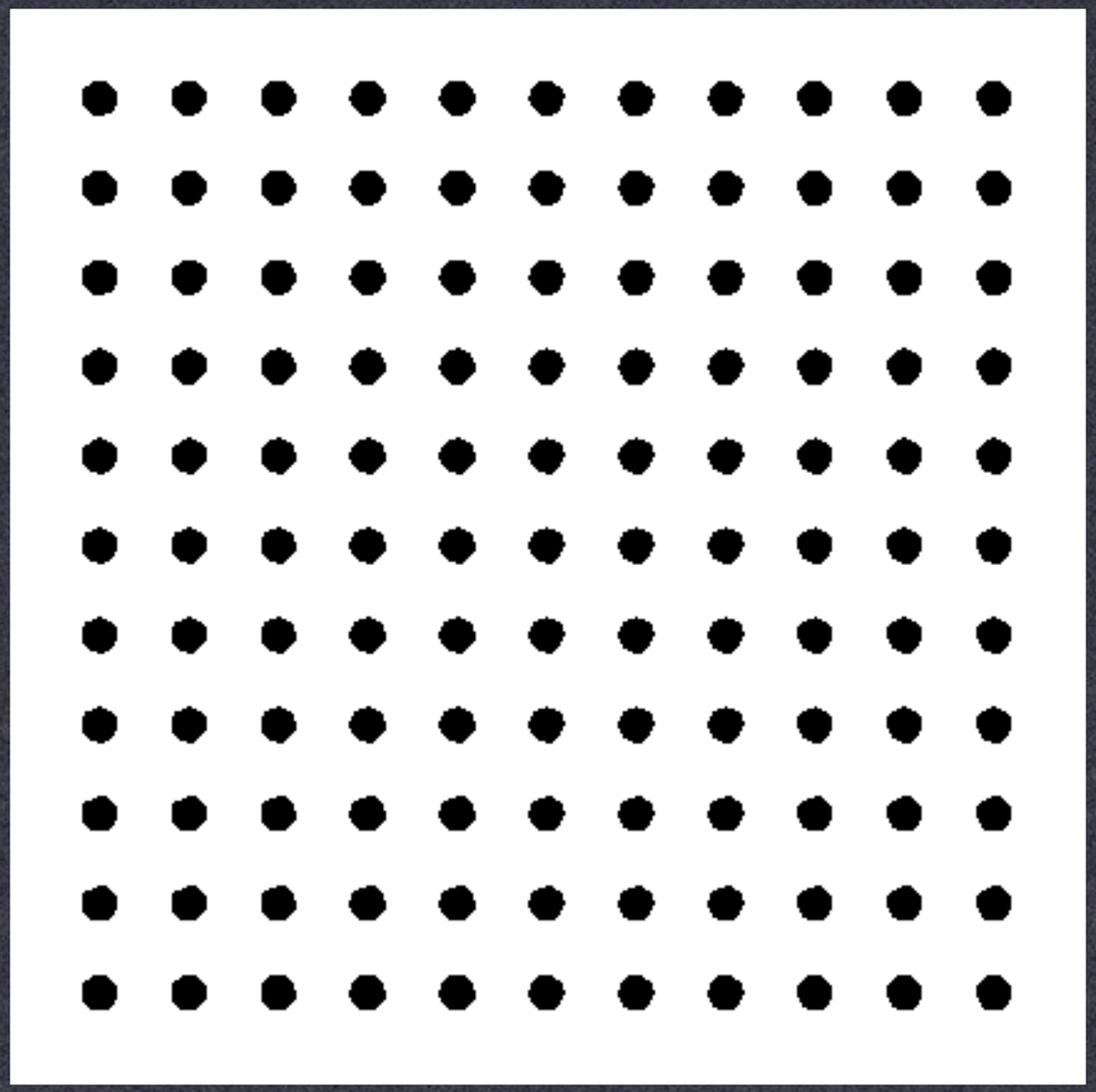
What you have to measure; fixed by your experimental capability

What you can control – the size of your experiment! Fixed by your pocketbook

How do you detect waves?

- Build your experiment to detect the physical phenomenon
- GW **change the proper spacetime distance between points.**





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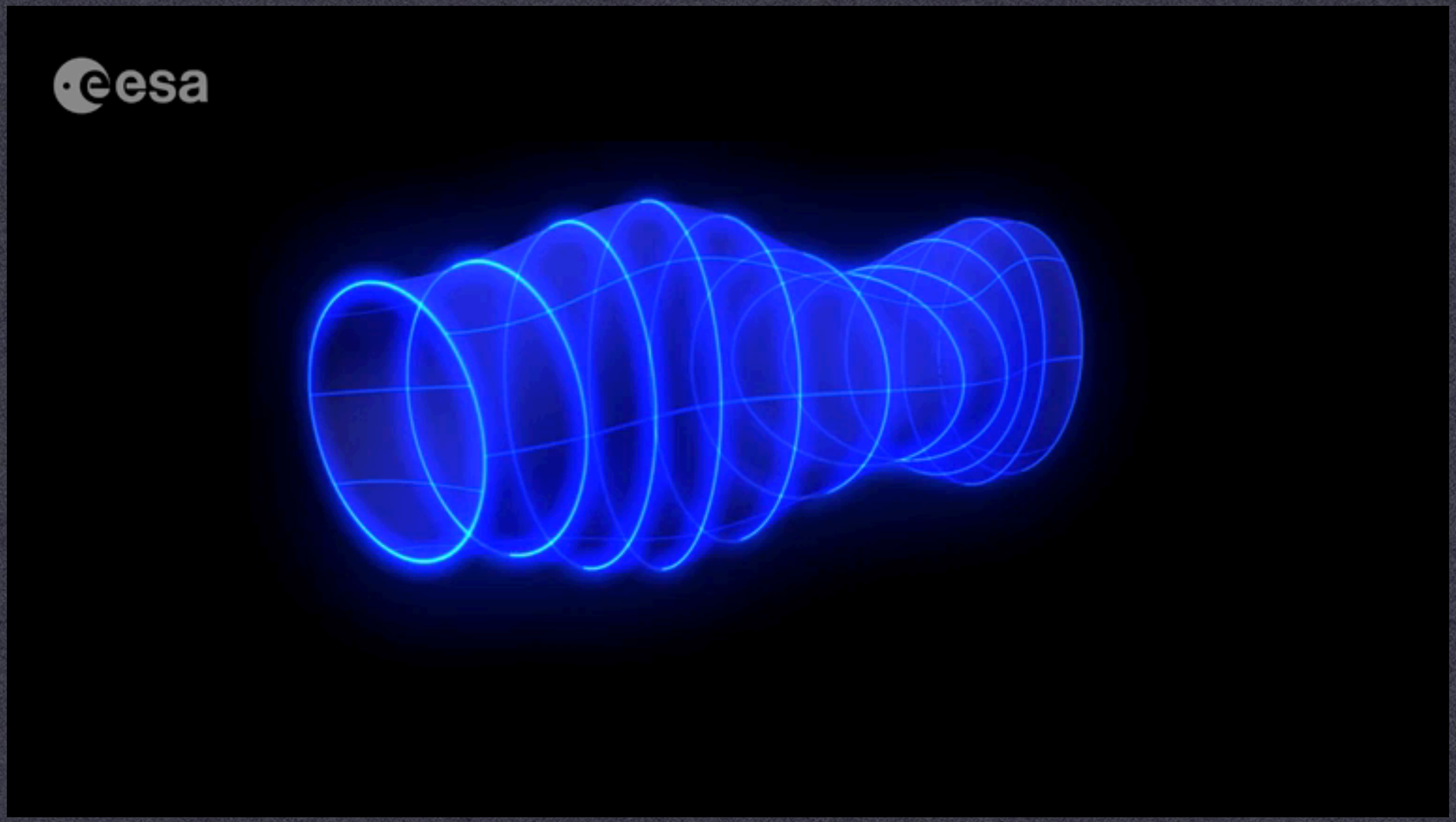
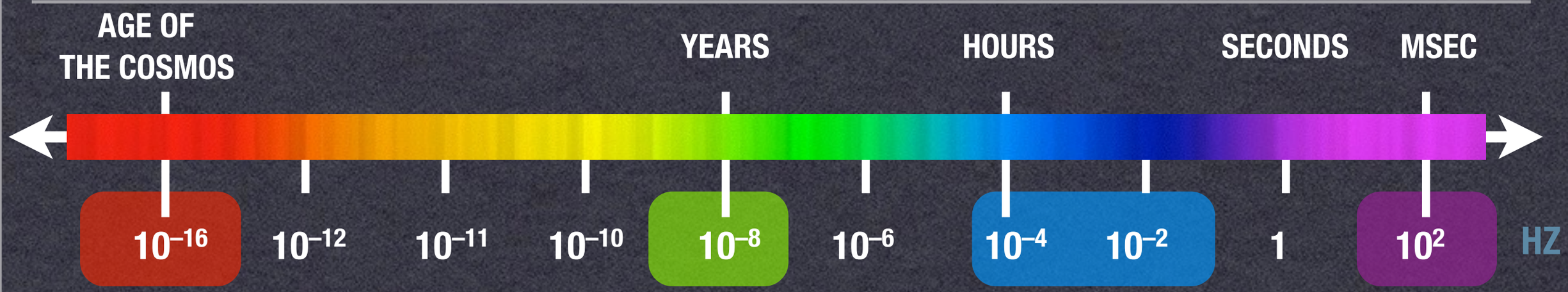
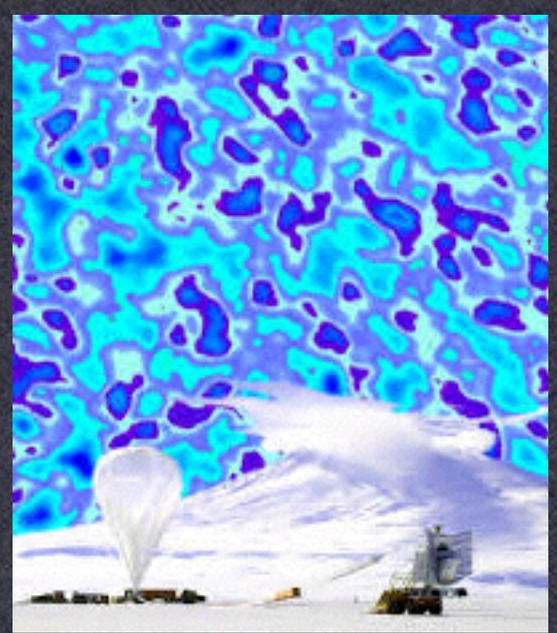


Gravitational Wave Spectrum

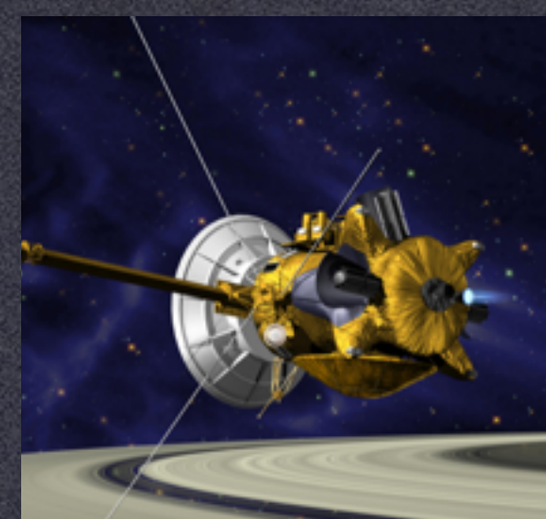


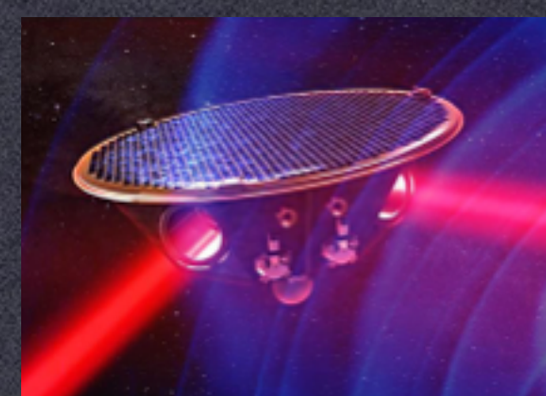


CMB Polarization

Pulsar Timing

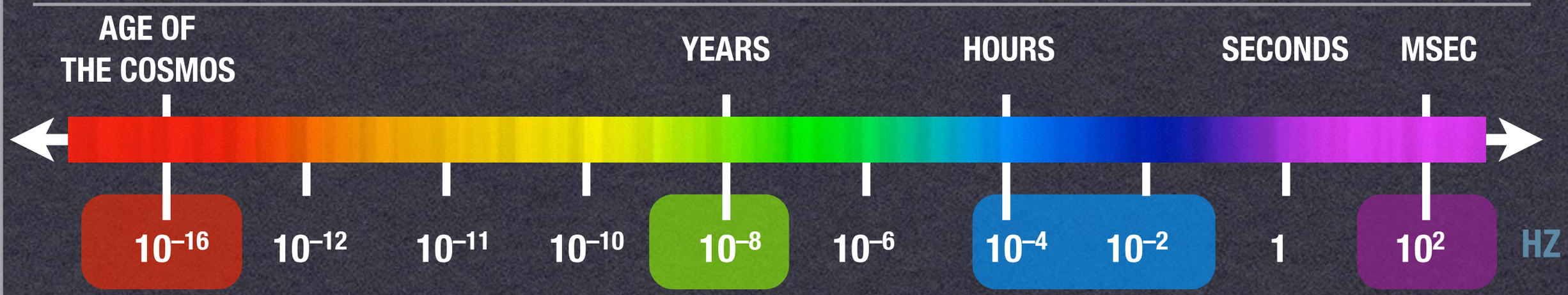
Space





Ground

Gravitational Wave Spectrum



Big Bang waves; inflationary epoch

Early Universe exotic physics
- phase transitions, cosmic strings, domain walls...

- SMBH ~billions of solar masses
- SMBH noise

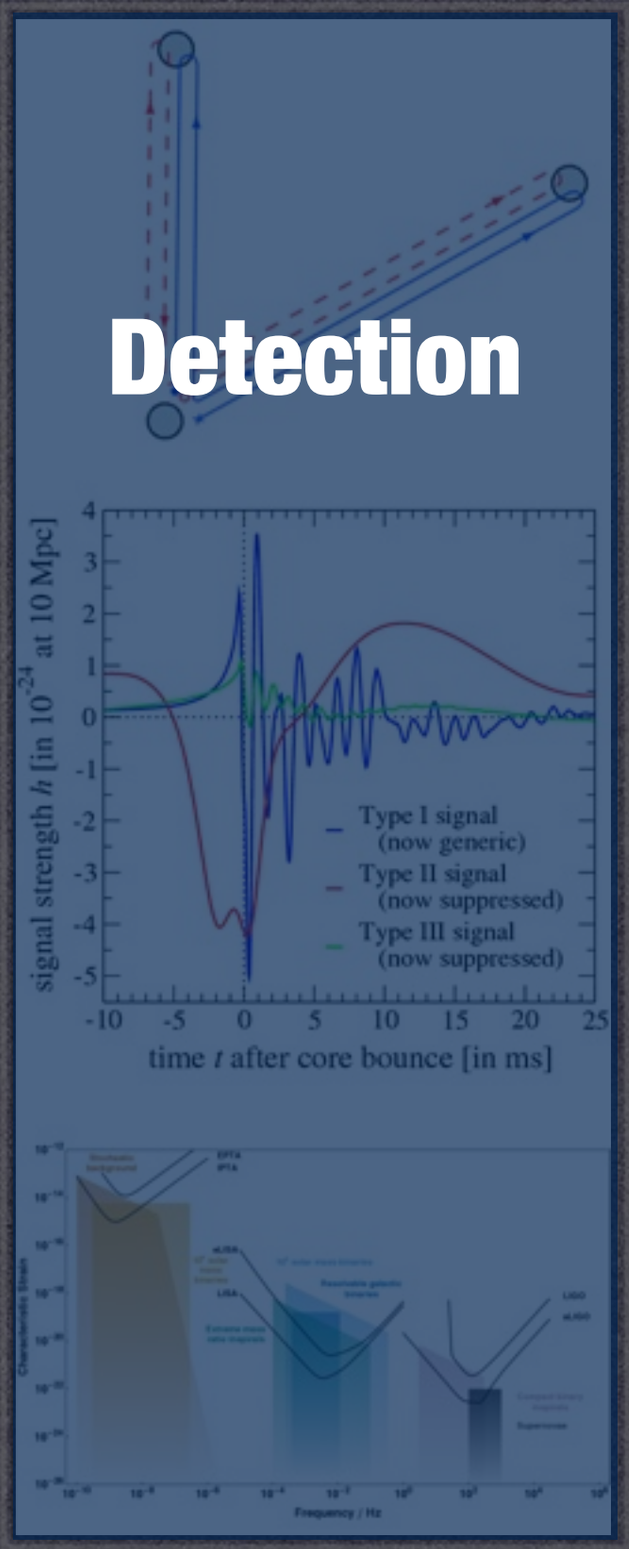
- Massive BH ~300 to 30 million solar masses
- Compact Binaries
- EMRi

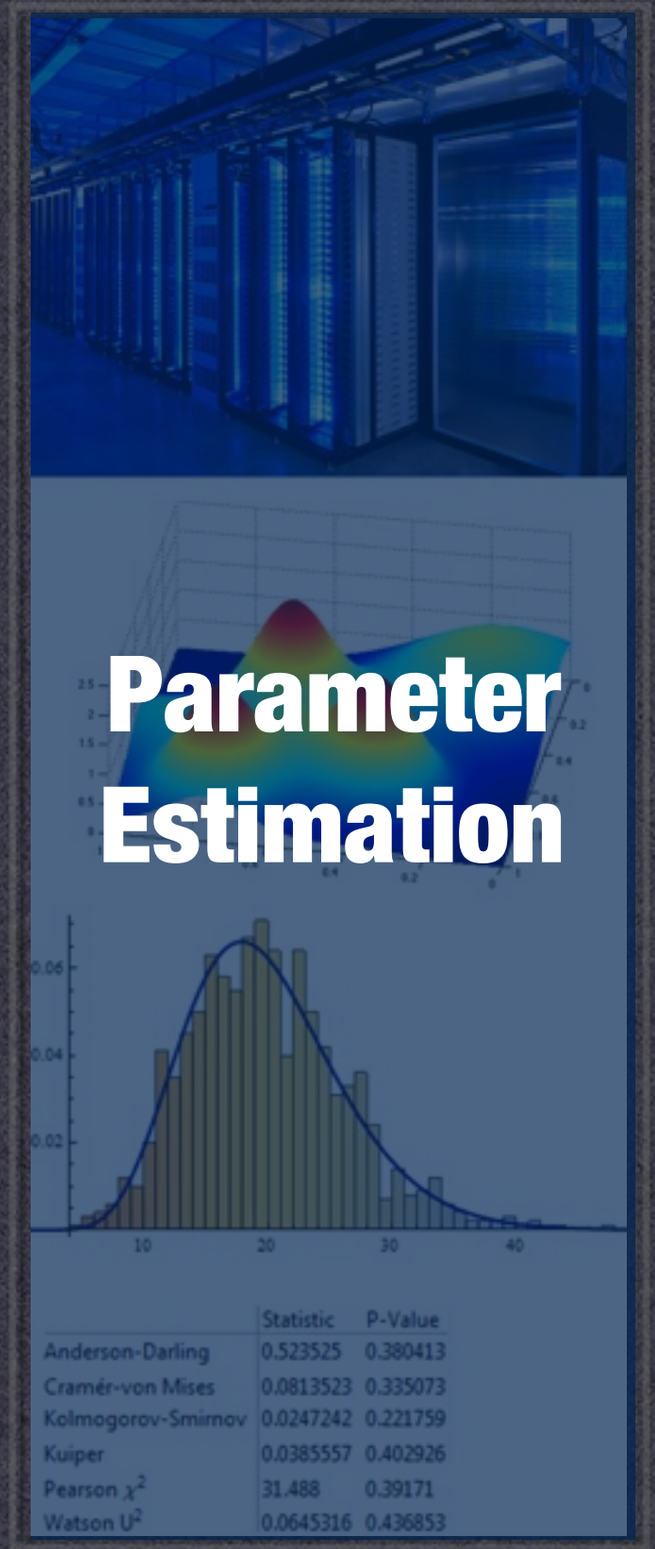
- "Small" BBH ~2 to 100 solar masses
- Neutron stars
- Supernovae

Singularities? Exotic stars?

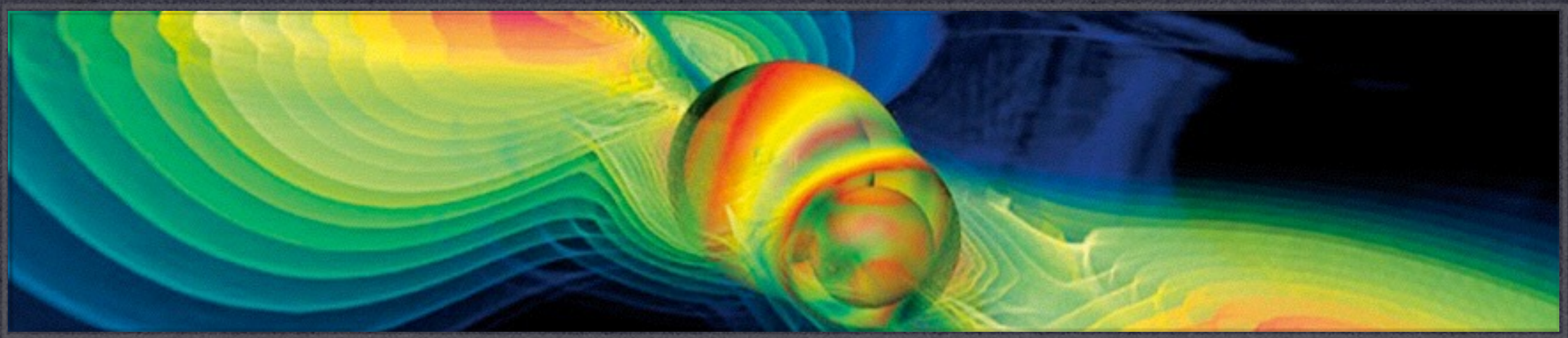
? ? ?

Gravitational Wave Analysis





Science Questions

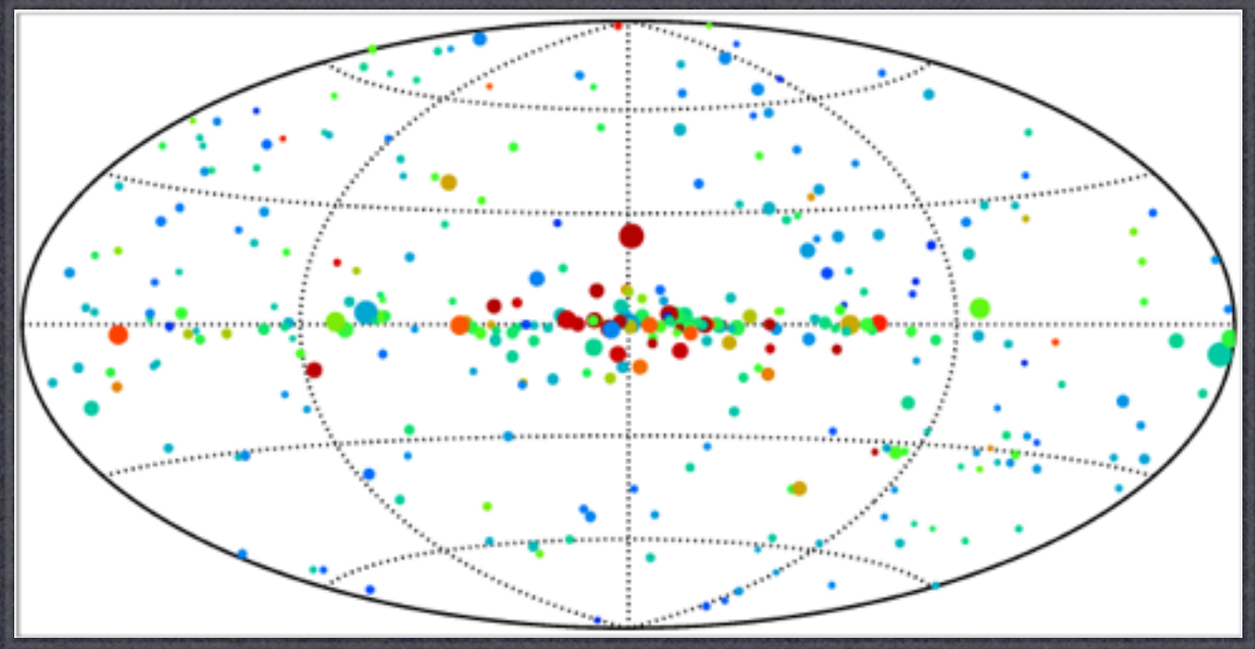


After the first detection, science questions will be the focus!

- What is the equation of state of a neutron star?
- Do black holes have hair?
- What is the shape of the Hubble flow?
- Is the area theorem upheld in black hole mergers?
- Is there a mass gap between black holes and neutron stars?
- Do black holes grow by accretion of gas, or merger with other objects?
- What mass transfer phases occur in UCB evolution?
- And so on…

Pillars of the Gravitational Wave Data

- ***The Event/Source Catalog***
  - Enumeration of all detections
  - List of extracted parameters
  - Detected Waveforms
  - Multi-messenger counterparts



With a catalog of detections and waveforms, what can you do?

ASTROPHYSICS OF SINGLE SOURCES

TEMPORAL EVOLUTION OF THE CATALOG

POPULATIONS OF SOURCES

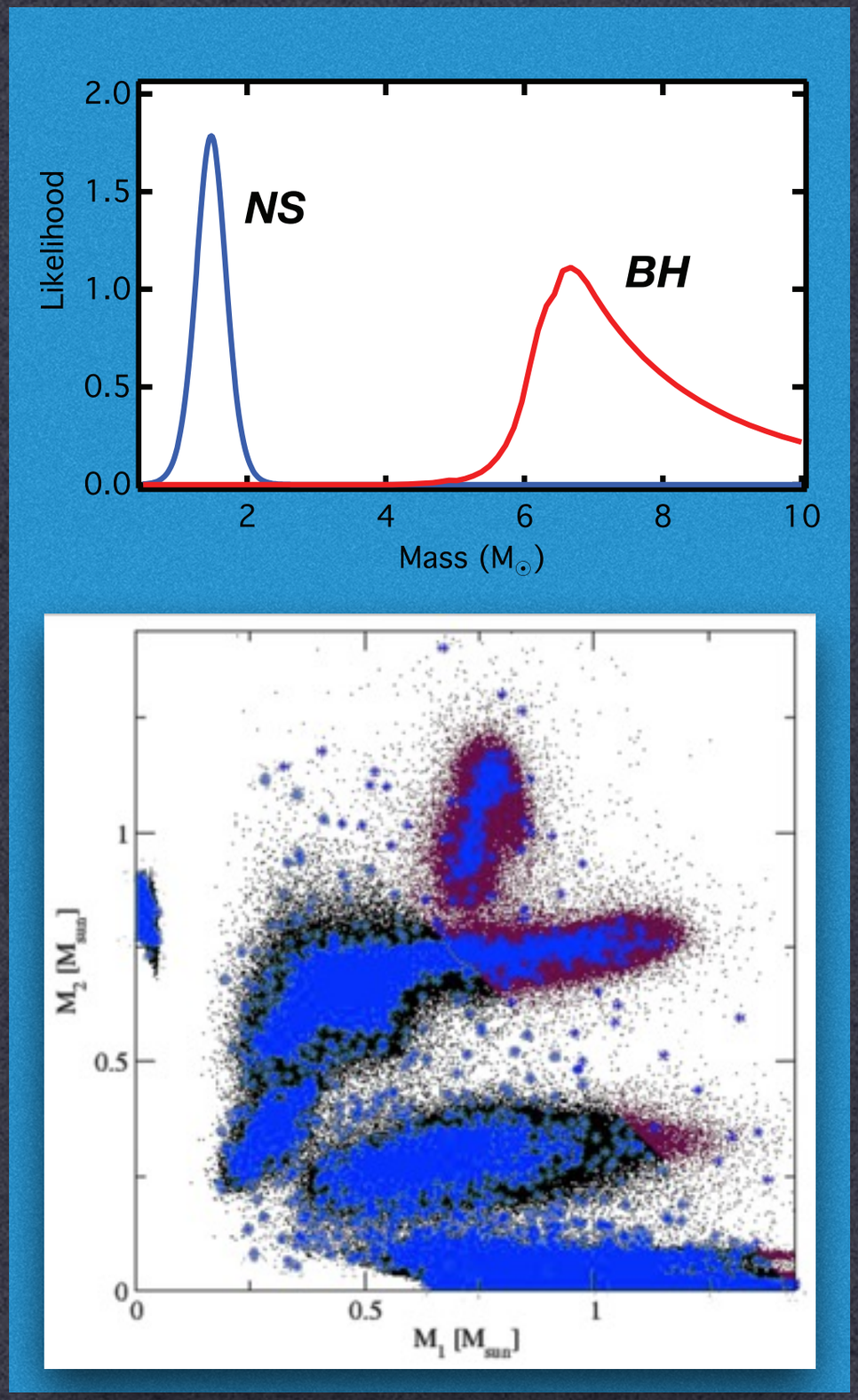
Future Fruitful Research

POPULATION STUDIES

MULTI-MESSENGER ASTRONOMY

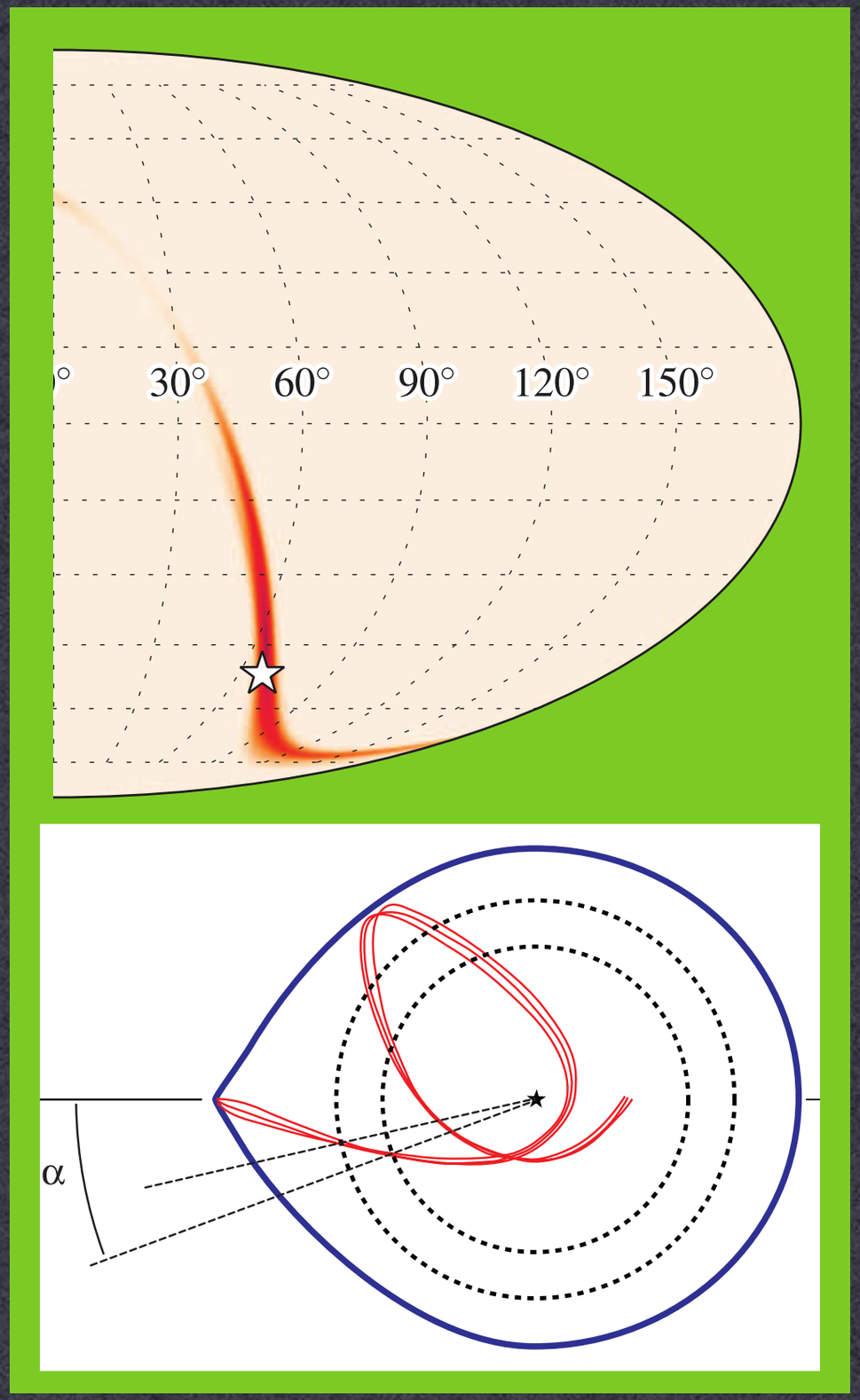
PURE GW ASTRONOMY

Population Studies



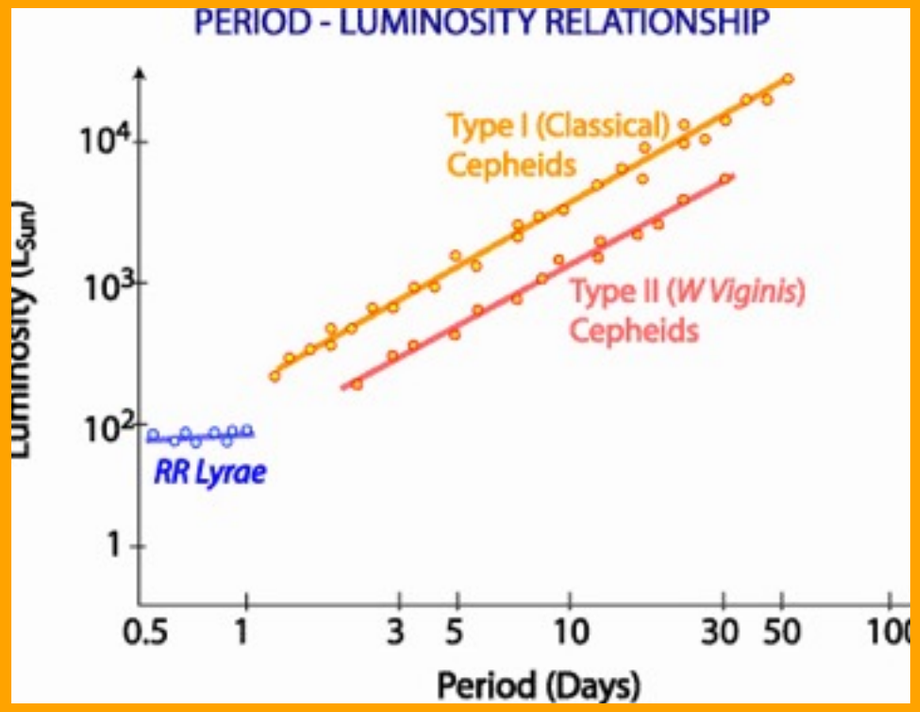
- The first detections are going to be "OMG! We saw some!"
  - Over time, a Catalog will grow
  - Taxonomy of the catalog
- **What is the underlying physics that governs the catalog?**
- Strong interface with modeling
  - Population synthesis
  - Merger trees
  - Cosmological simulations
- Now, modeling is used for **event rates**!

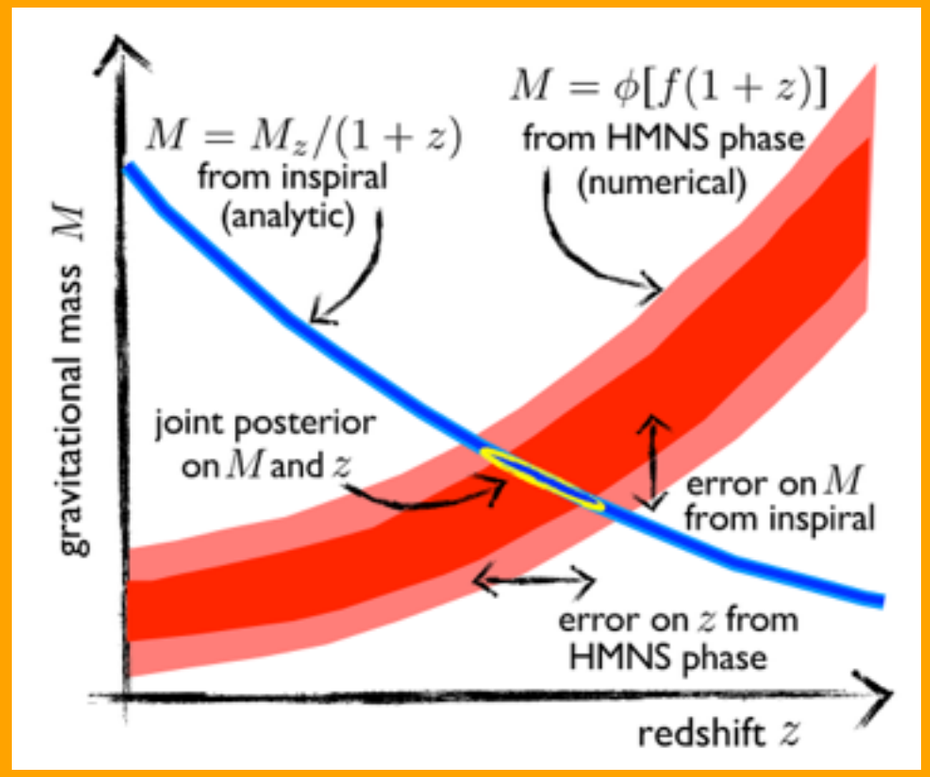
Multi-Messenger Astronomy



- Biggest Challenge:
  - **Localization on sky (GW)**
- For some sources, near term follow-up is just as good as simultaneous observing (GRB after glows)
- Marshaling resources -- when is commandeering a telescope worth the **scientific payoff** of followup?
- GW & EM observations have different strengths and weaknesses.
  - Combine and align?
  - This is poorly explored

Pure GW Astronomy

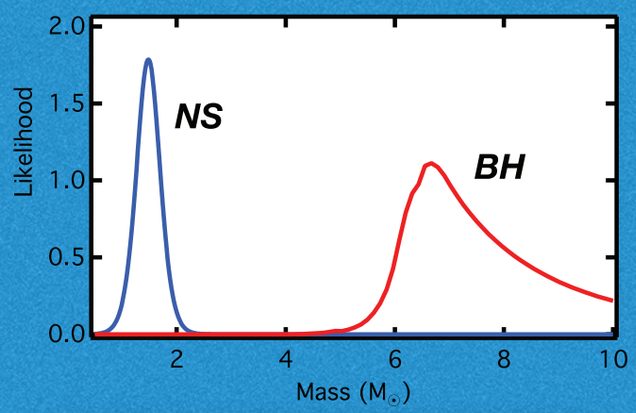


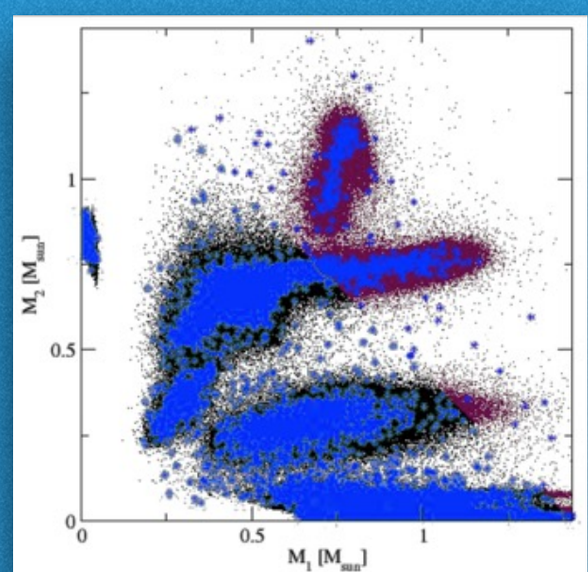


- What can we learn from pure GW sources?
- Sources are **more than just lists of parameters**. What will trends and clusters in GW catalogs gain us? [ex: Baade + Cepheids, 1940s]
- How will knowledge evolve in time? We live in an age of powerful methods of inference, and we're eager to say something!
- Statistical results?
- Assumed Cosmology?
- Higher order GW effects [eg. Messenger et al. PRX 2014]

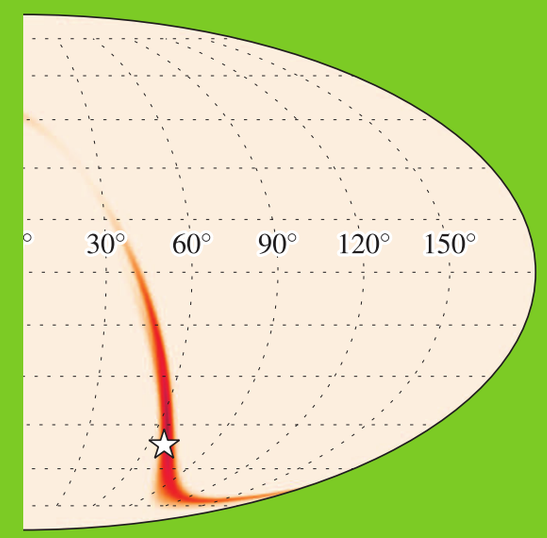
Future Fruitful Research

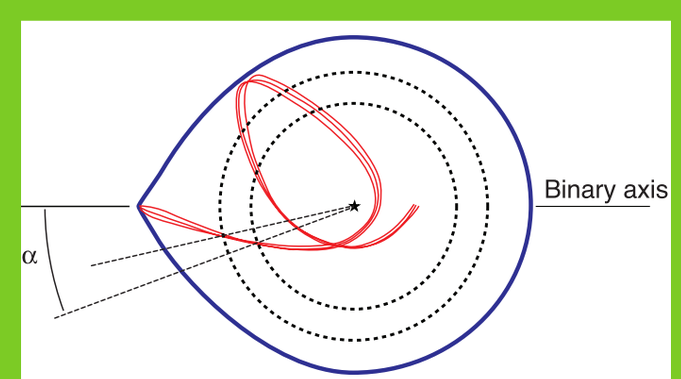
POPULATION STUDIES



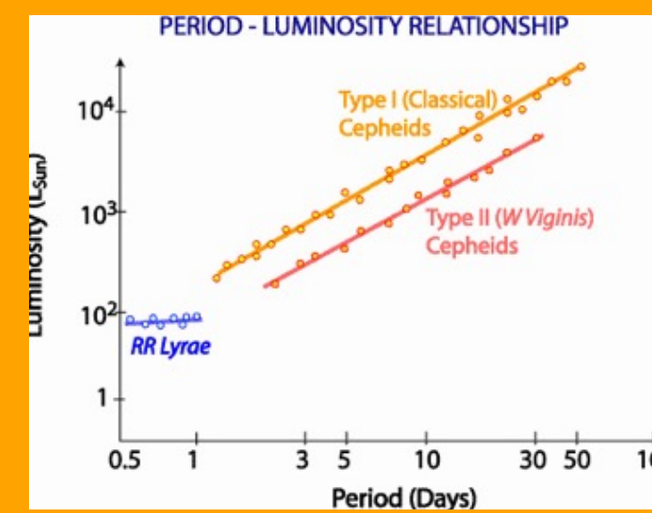


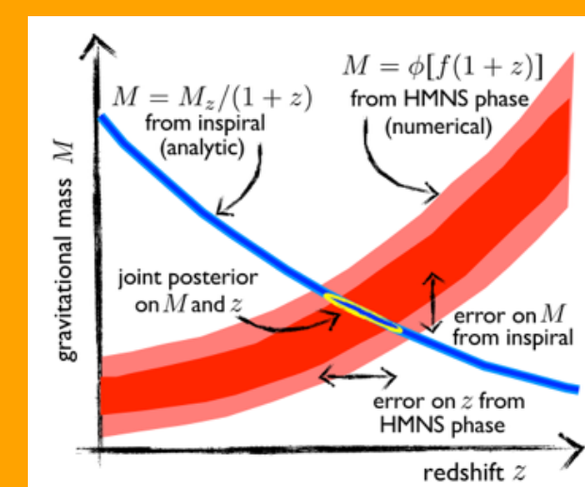
MULTI-MESSENGER ASTRONOMY





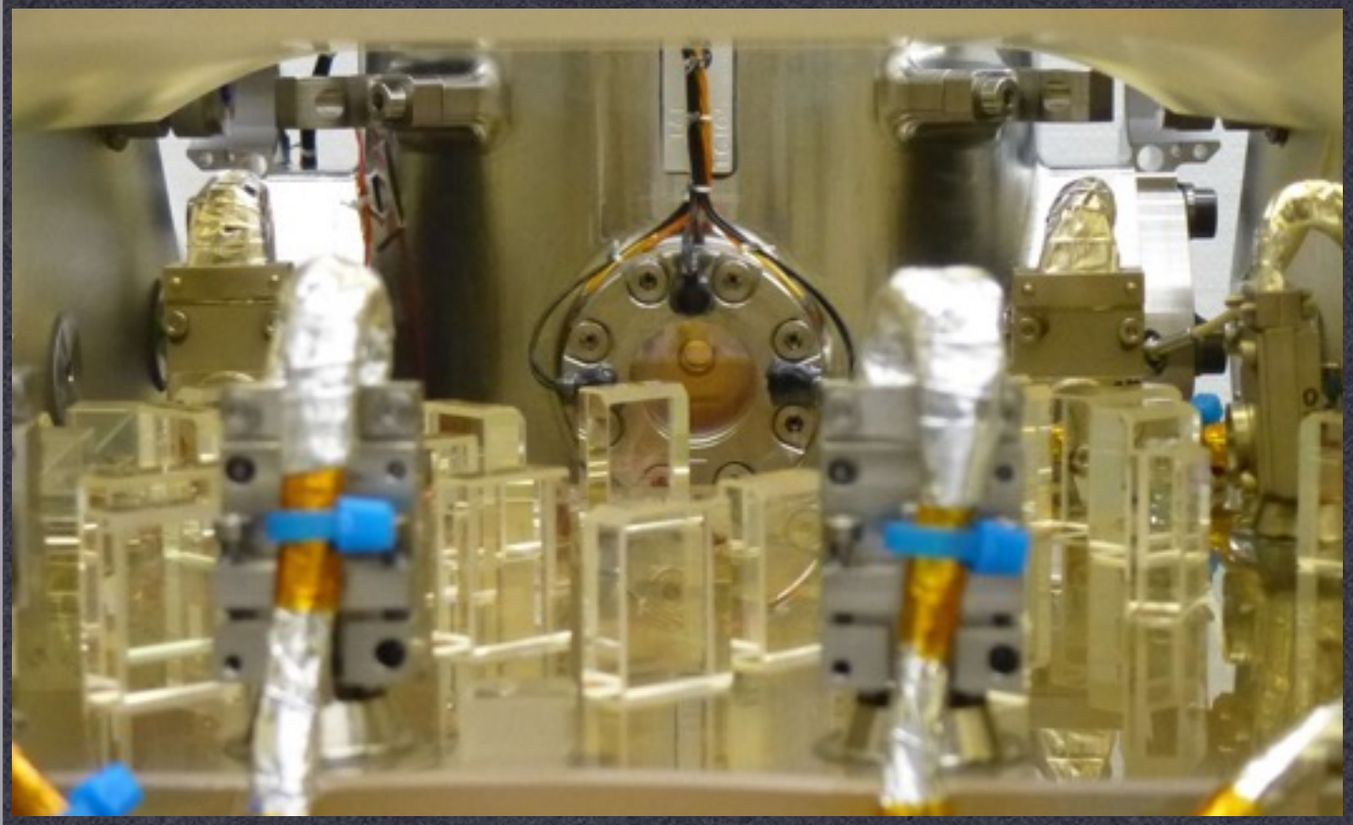
PURE GW ASTRONOMY





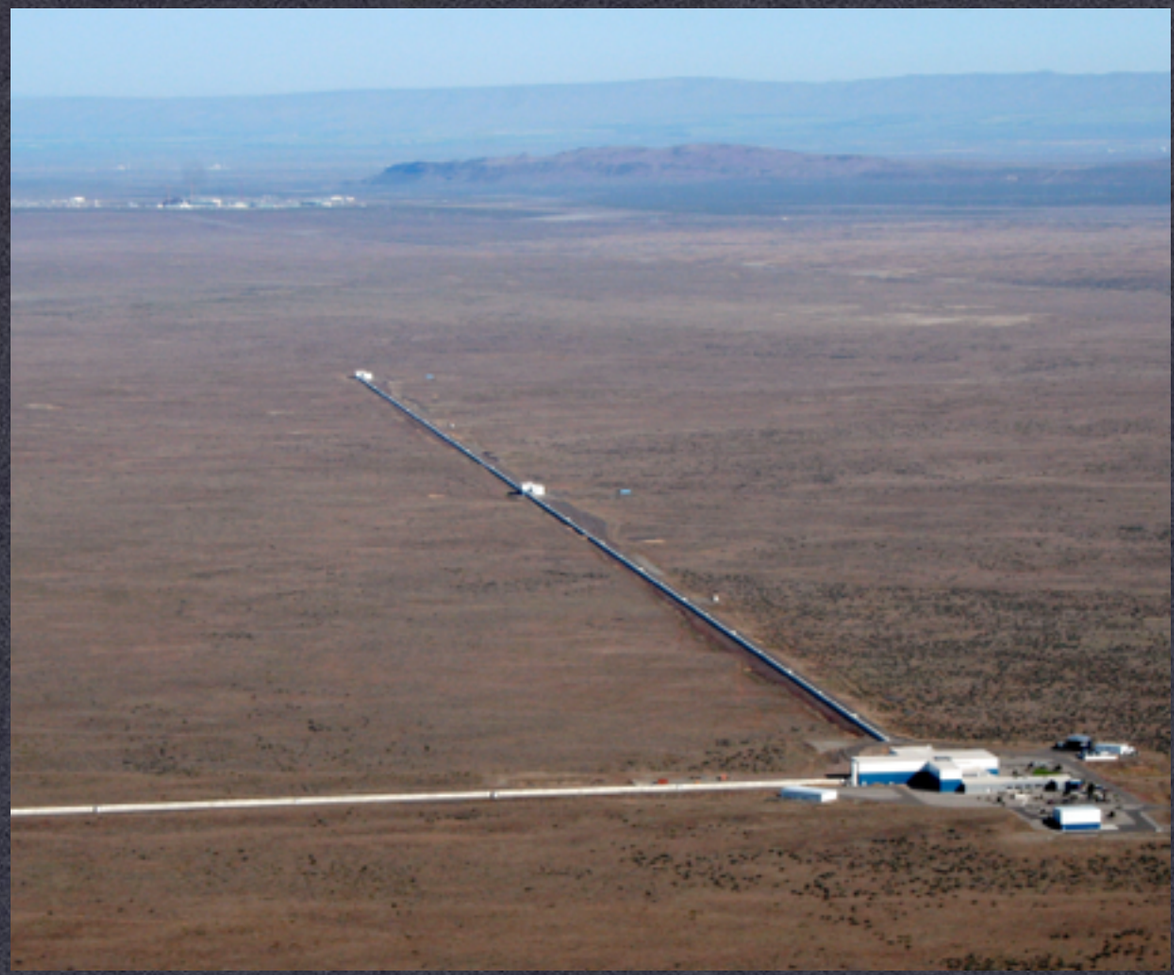
STRONG FIELD/ UNKNOWN SOURCES

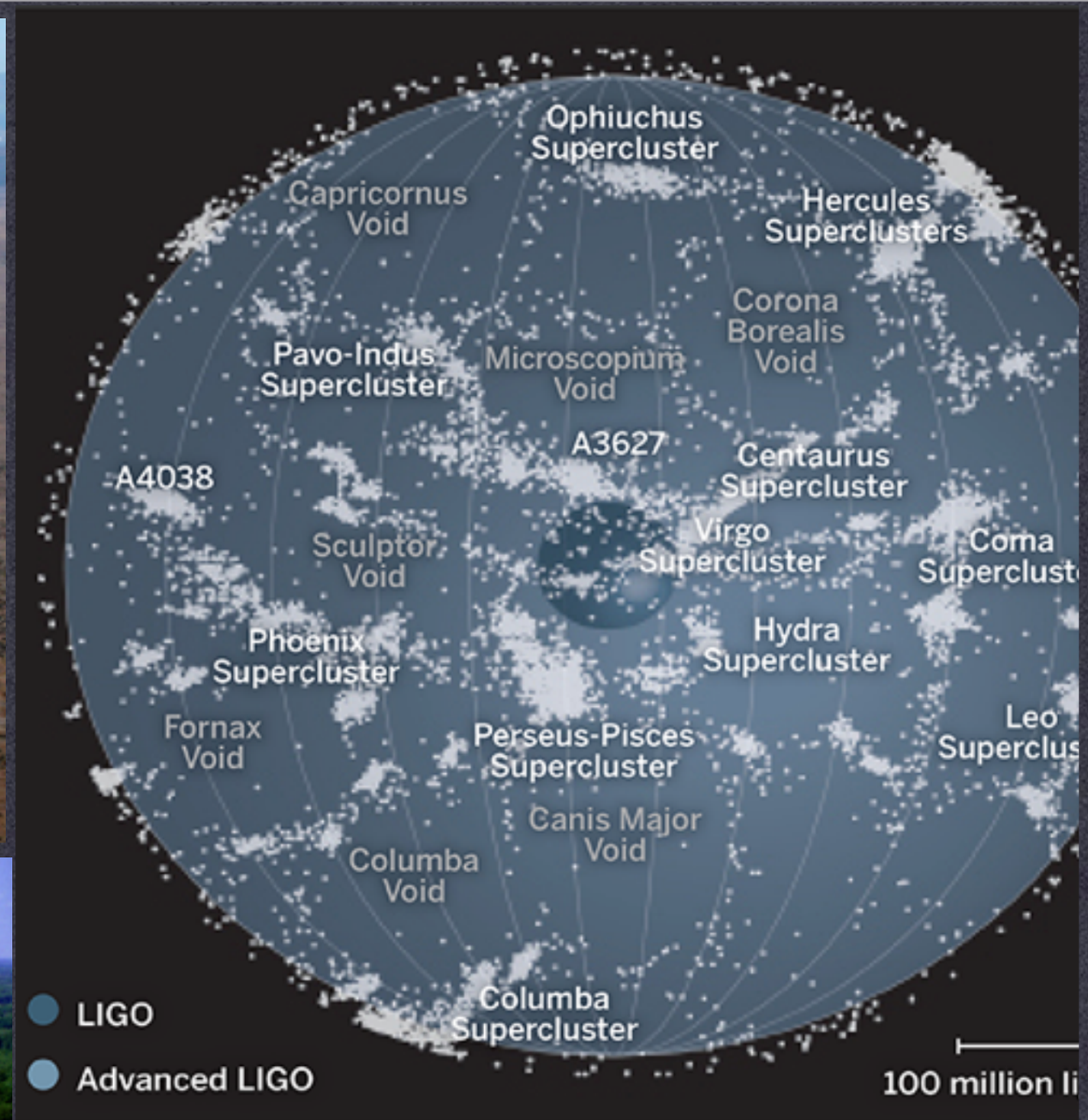
Hardest to know. Will we recognize sources? Observations could lead theory — there are interesting sources (cosmic strings, boson stars)



LAUNCH DATE:
3 DEC 2015

LISA Pathfinder





LIGO

NOW IN O1, THRU ~JAN

ARXIV/1304.0670

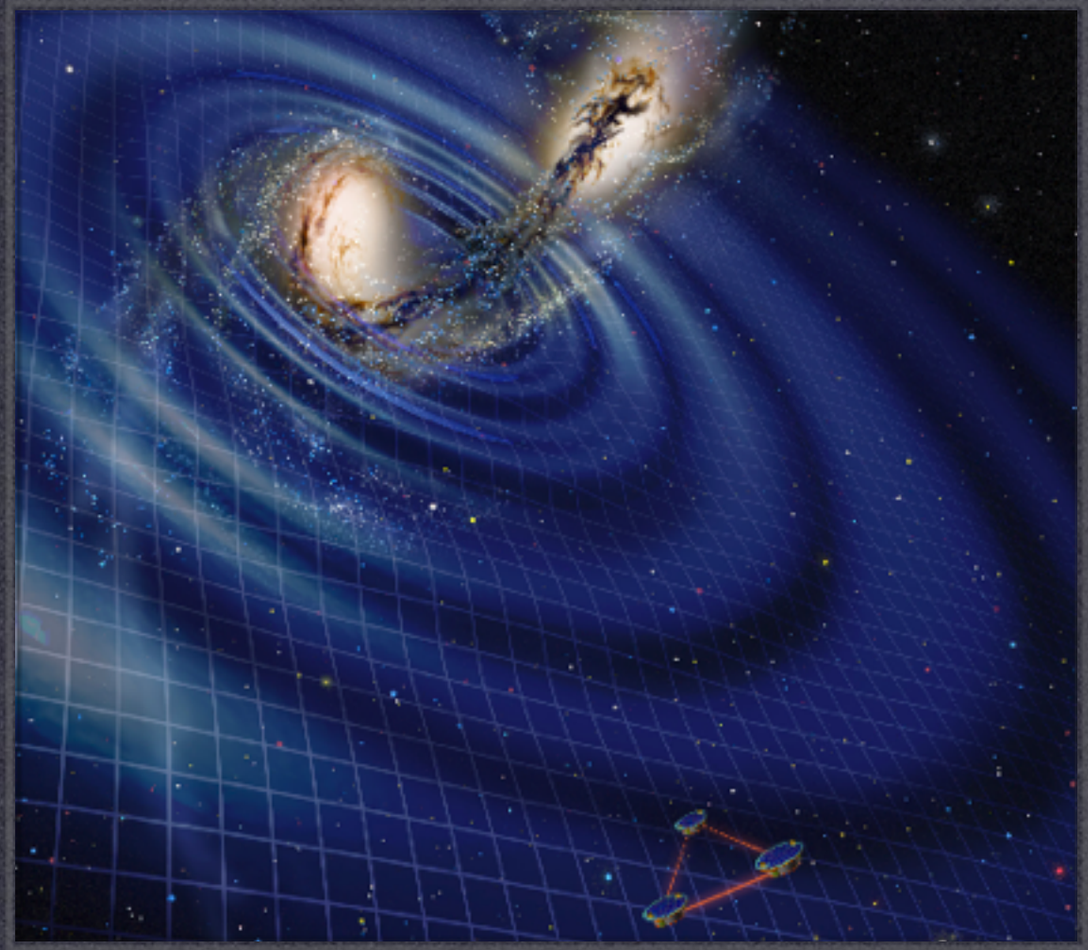
Last Thoughts

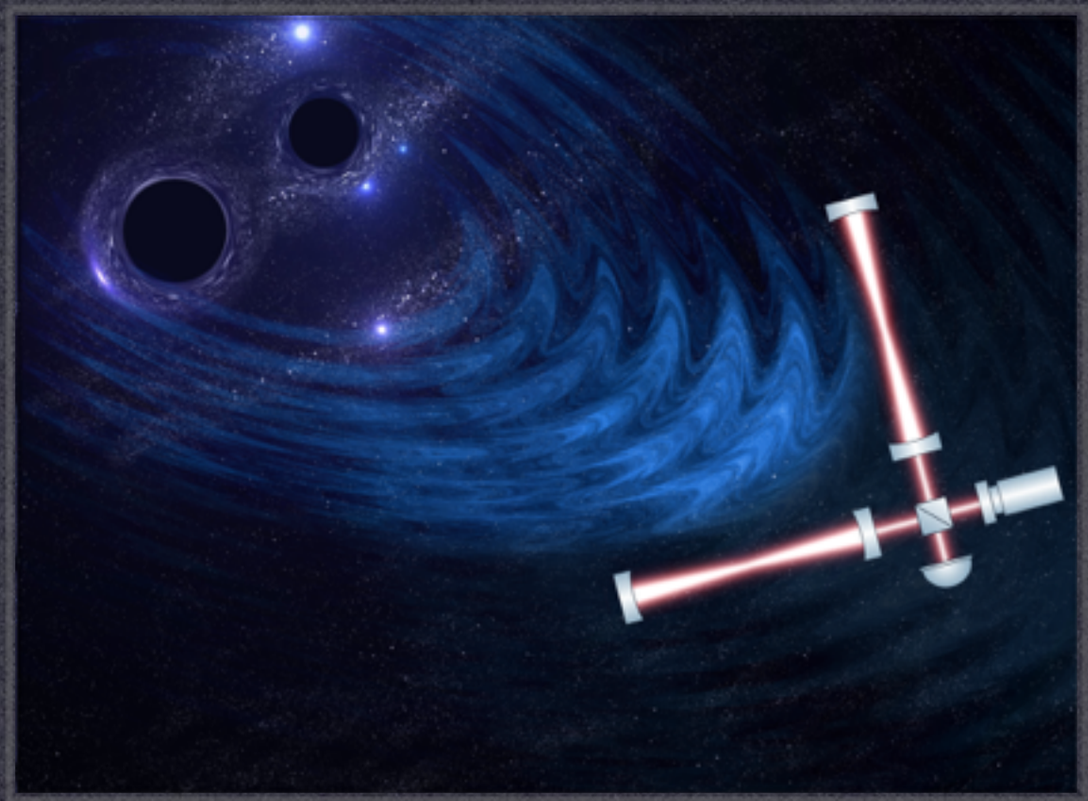
- This is a tiny scratch on the surface of what we can learn. There are many questions yet to be fully explored in **black holes**, **galaxy evolution**, **stellar evolution**, and **tests of gravity**

- We are just learning how to **process and interpret** gravitational wave data

- Learning what kinds of questions can be answered with such data is a **fledging science unto itself**

- There are almost certainly going to be **surprises and new discoveries**





THANK YOU!

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EXTRA SLIDES

What we have to do...

- Astrophysics told me ***h***
- My construction friends told me what ***L*** could be
- ***ΔL*** is what I have to be able to measure...

10^{-19}

$$h = \frac{\Delta L}{L}$$

10^{-15} m

10 km

Why gravitational waves rock

- ***Gravitational waves are excellent astrophysical probes***
  - ***GW are not attenuated*** (Universe became transparent at about 10^{-34} sec)
  - ***GW sources are "clean and simple"*** (BH have mass and spin, and they radiate coherently)
  - ***GW sources are strong*** (high signal to noise allows precision measurements)
  - ***GW sources are standard candles*** (luminosity distances are measured with ~1% accuracy). ***Luminosity distance from gravitational physics only***