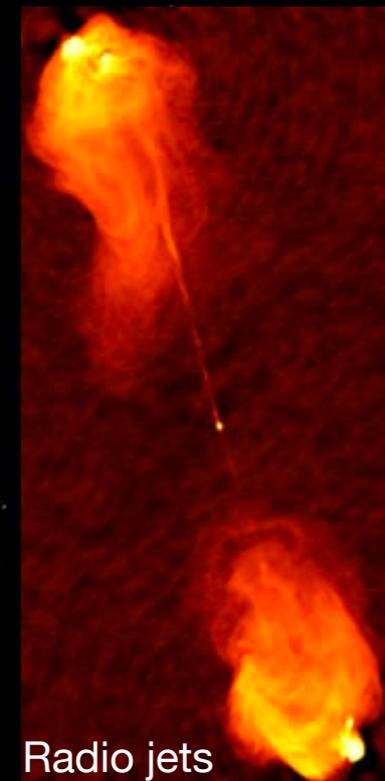
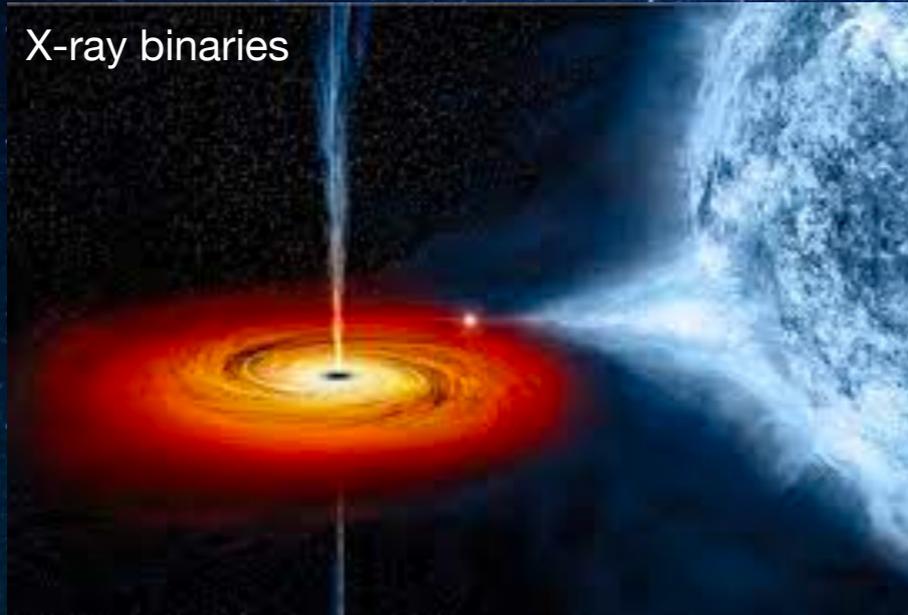


# Gravitational Wave Astrophysics at the NBIA

Johan Samsing  
Daniel J. D'Orazio  
Martin Pessah  
Bin Liu

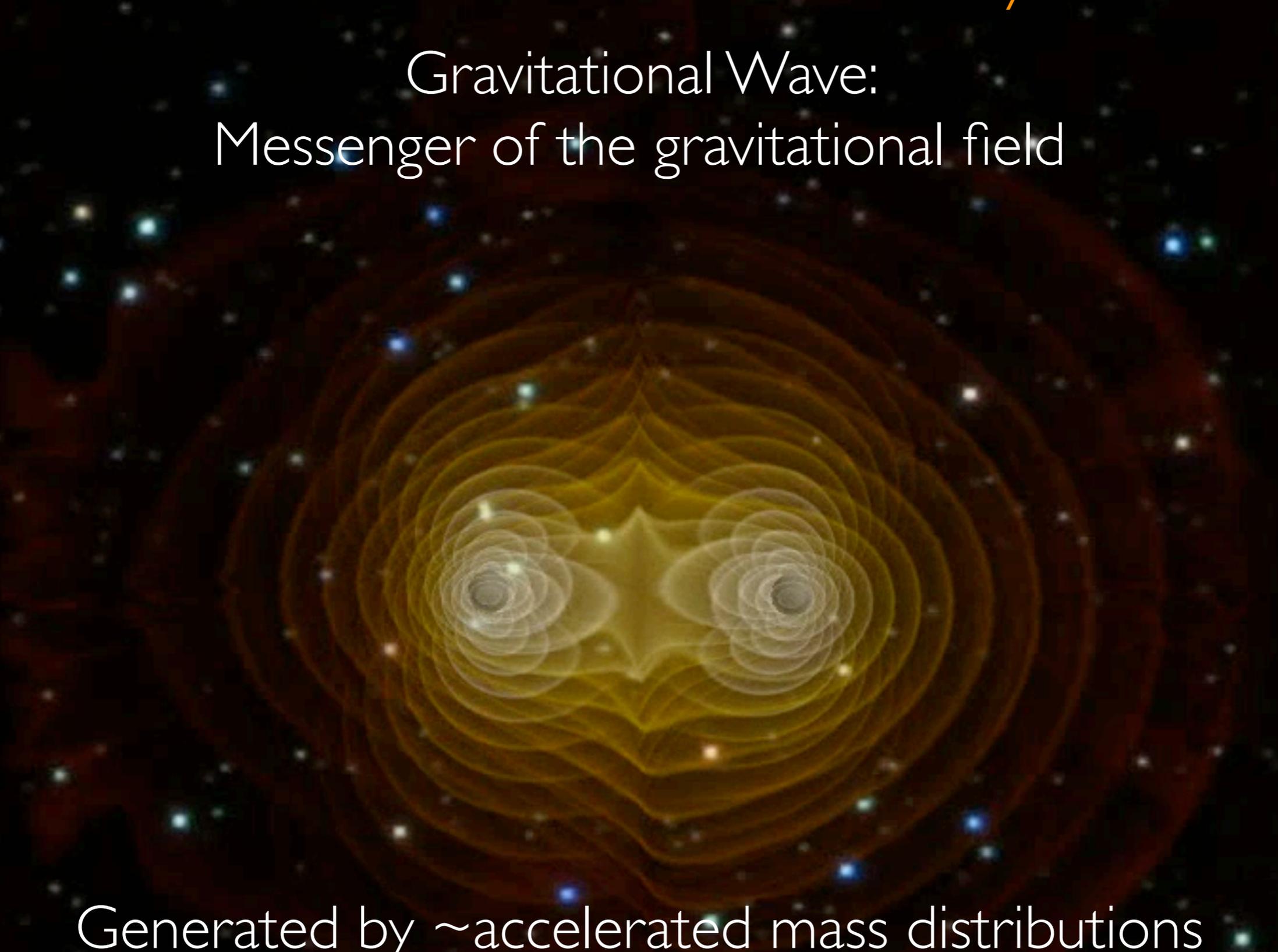
Alejandro Vigna-Gomez  
Sophie Schröder

# The Electromagnetic Sky: Conventional Astrophysics



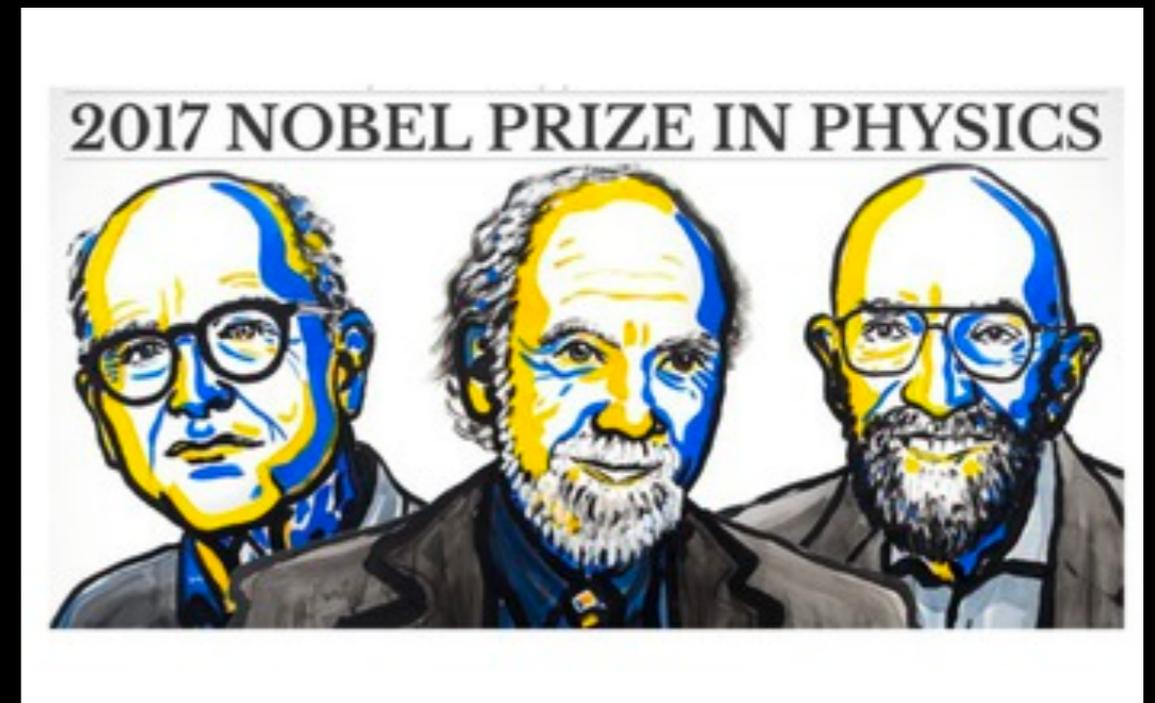
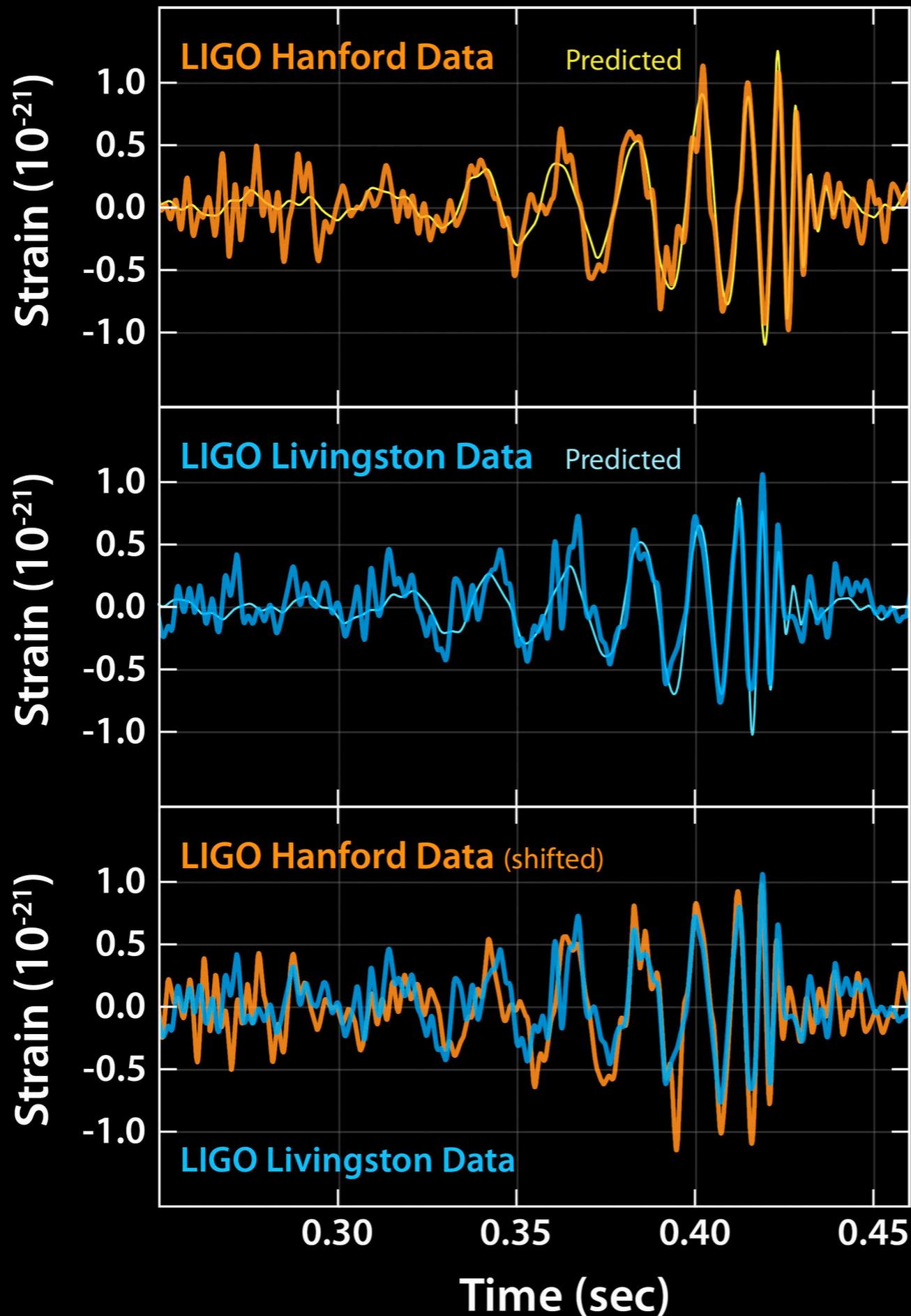
# The Gravitational Wave Sky?

Gravitational Wave:  
Messenger of the gravitational field



Generated by  $\sim$ accelerated mass distributions  
Most extreme example: Black Hole Binaries

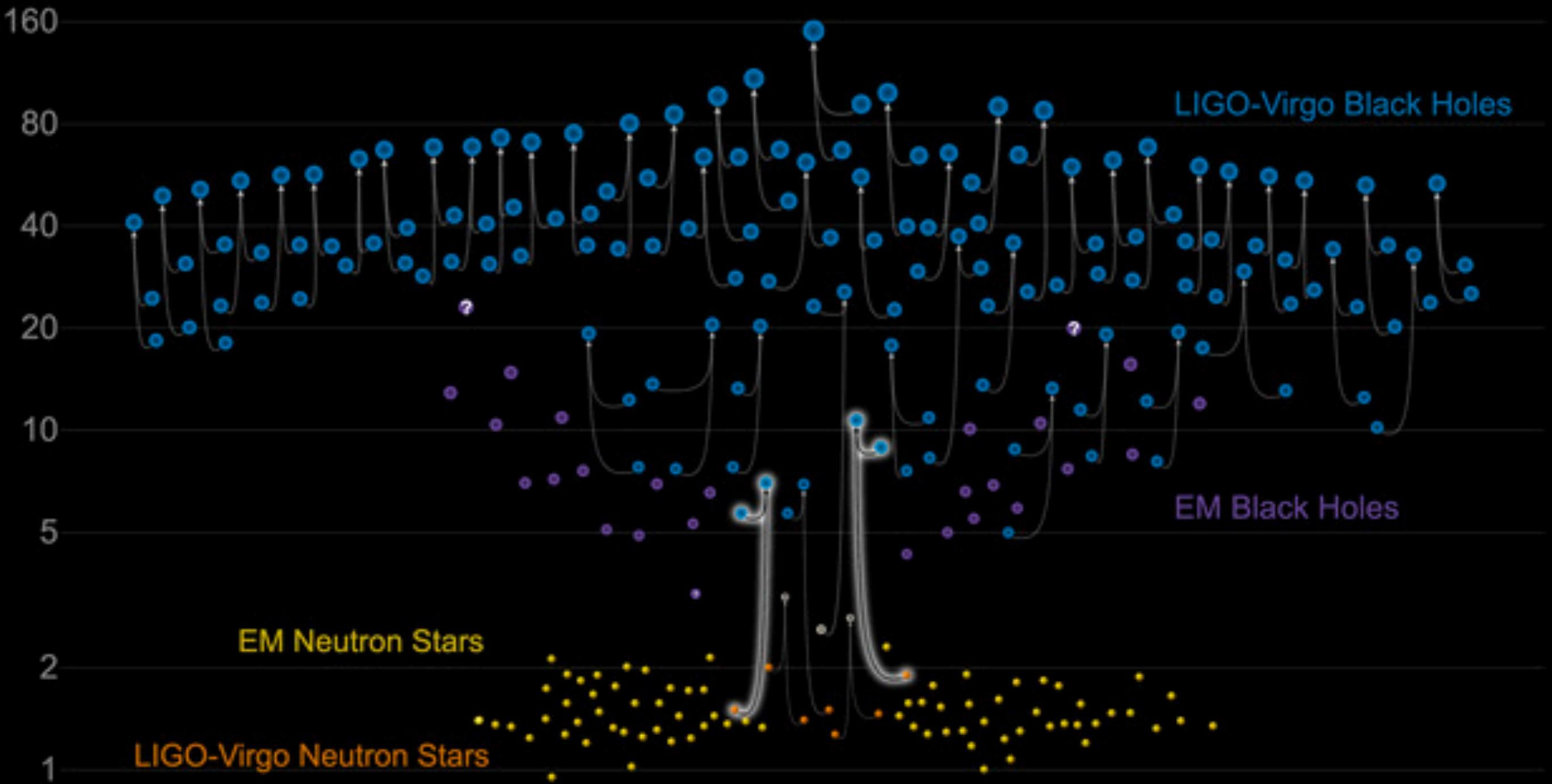
# 2015 Discovery of Gravitational Waves



**L**aser **I**nterferometer **G**ravitational  
**W**ave **O**bservatory

# Masses in the Stellar Graveyard

*in Solar Masses*



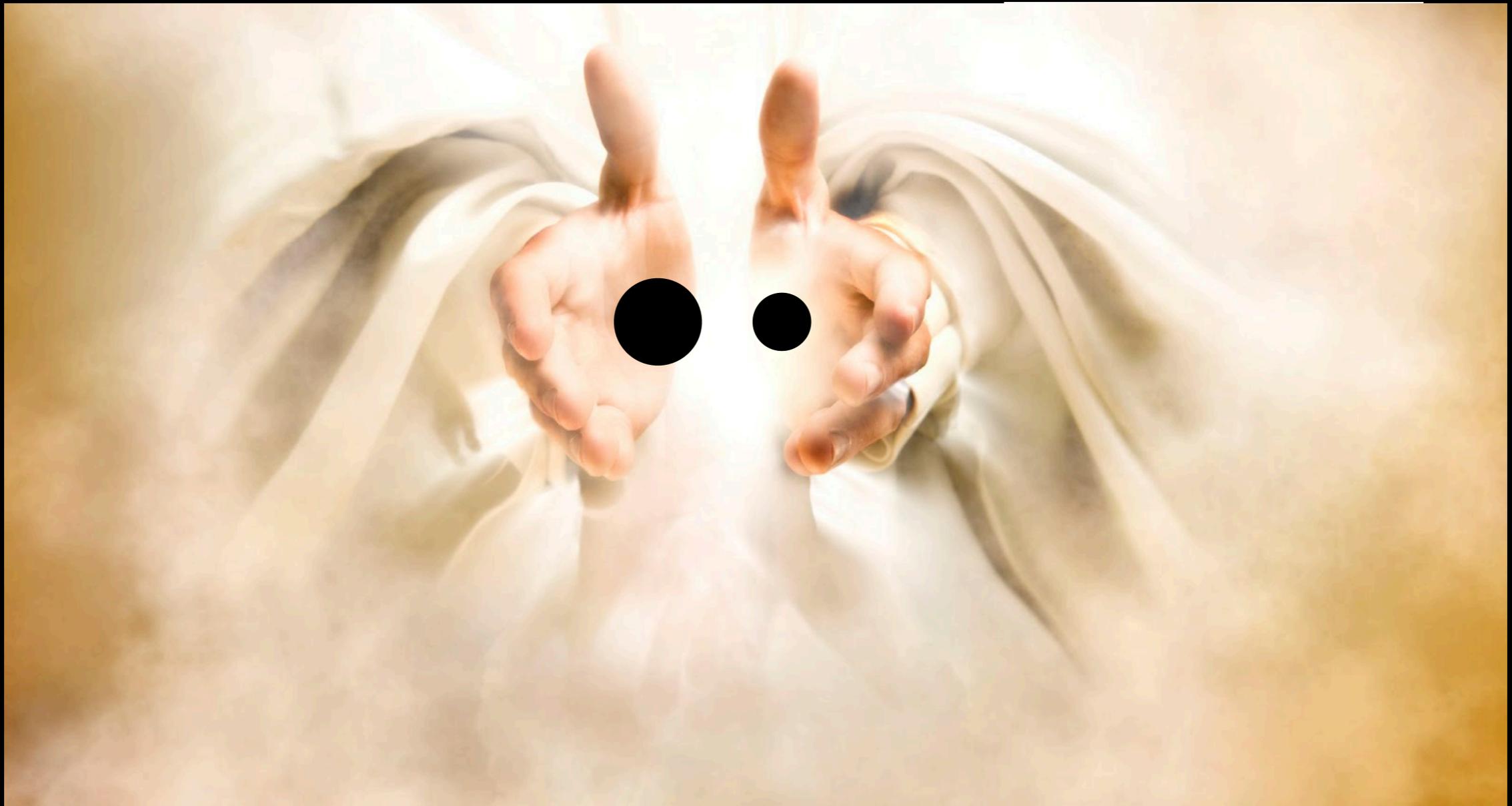
[The LIGO Orrery](#)

Open Question: How did these form!?

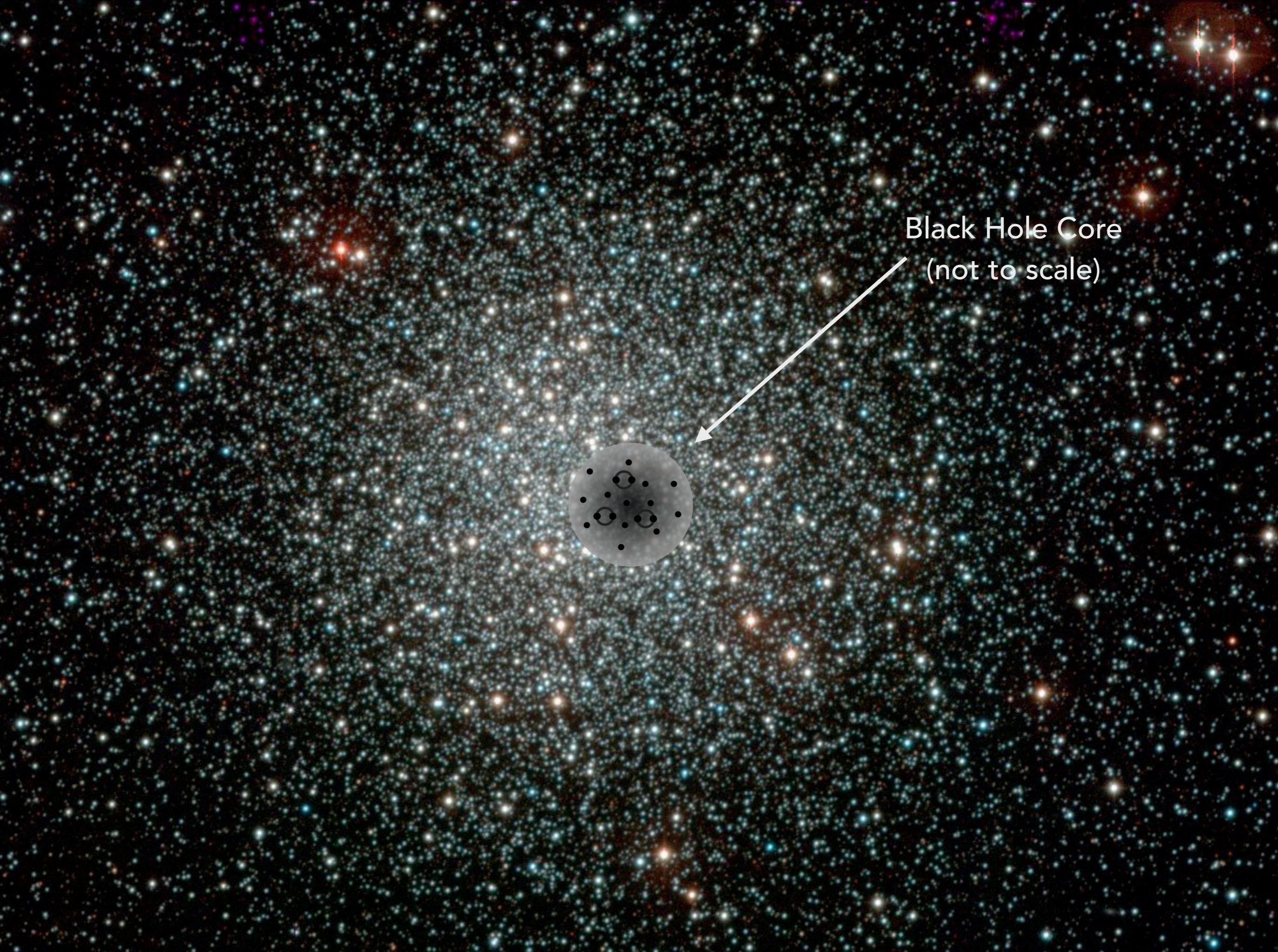
**'Field'?**

**'Dynamically'?**

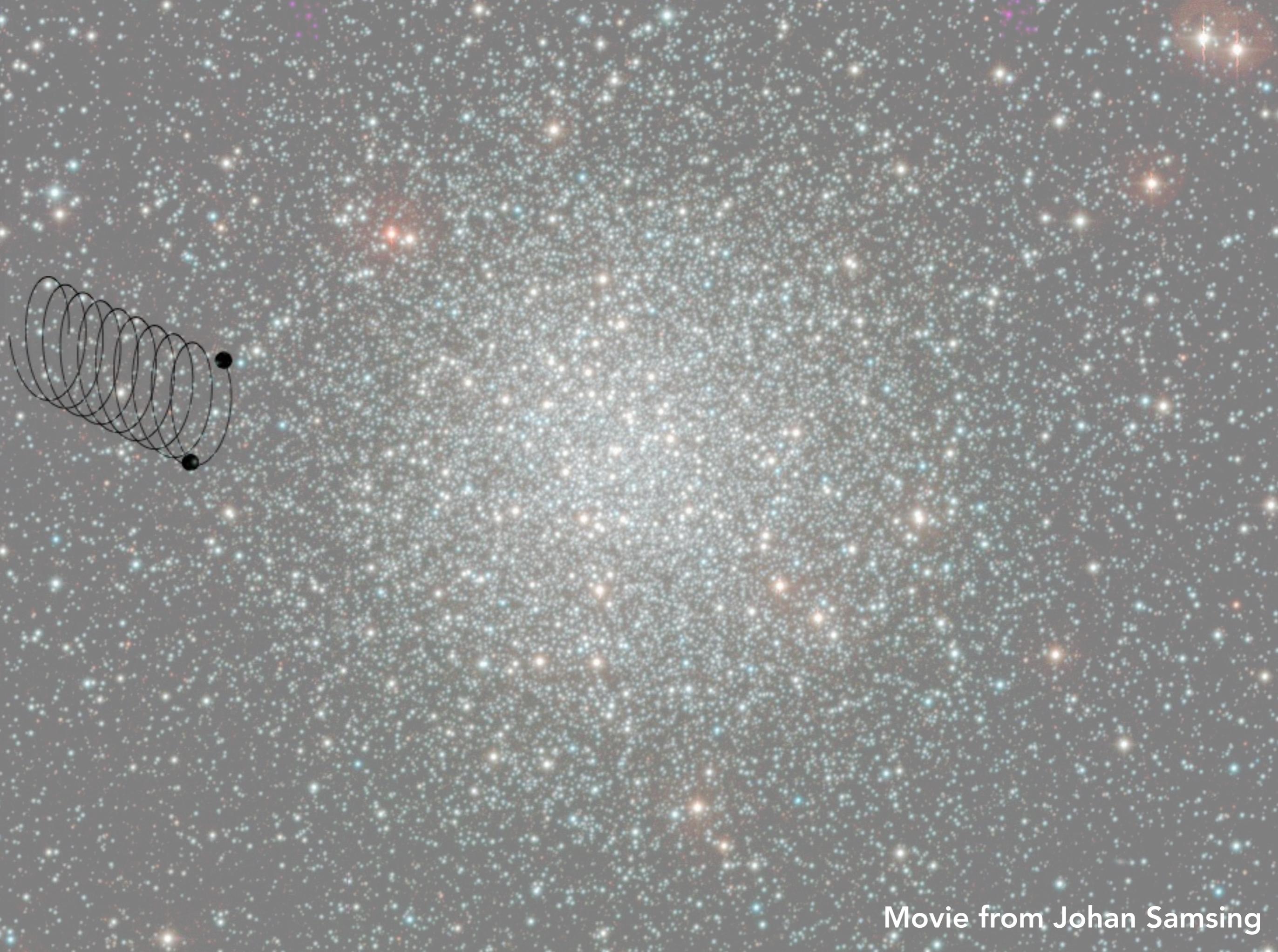
**'Other'?**



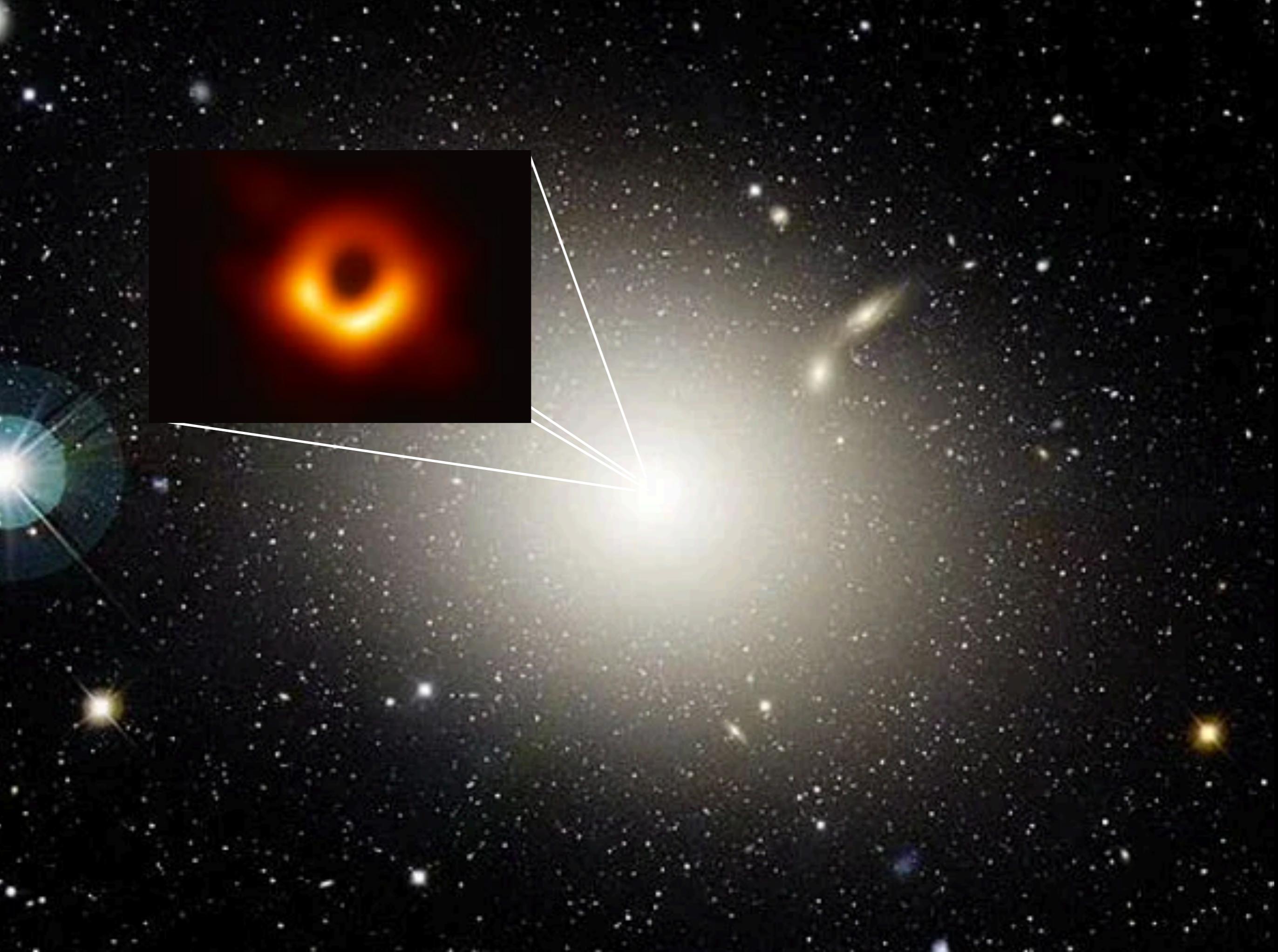
Work being carried out at the NBIA by:  
D. D'Orazio, J. Samsing, B. Liu, A. Vigna-Gomez, Sophie Schröder, +



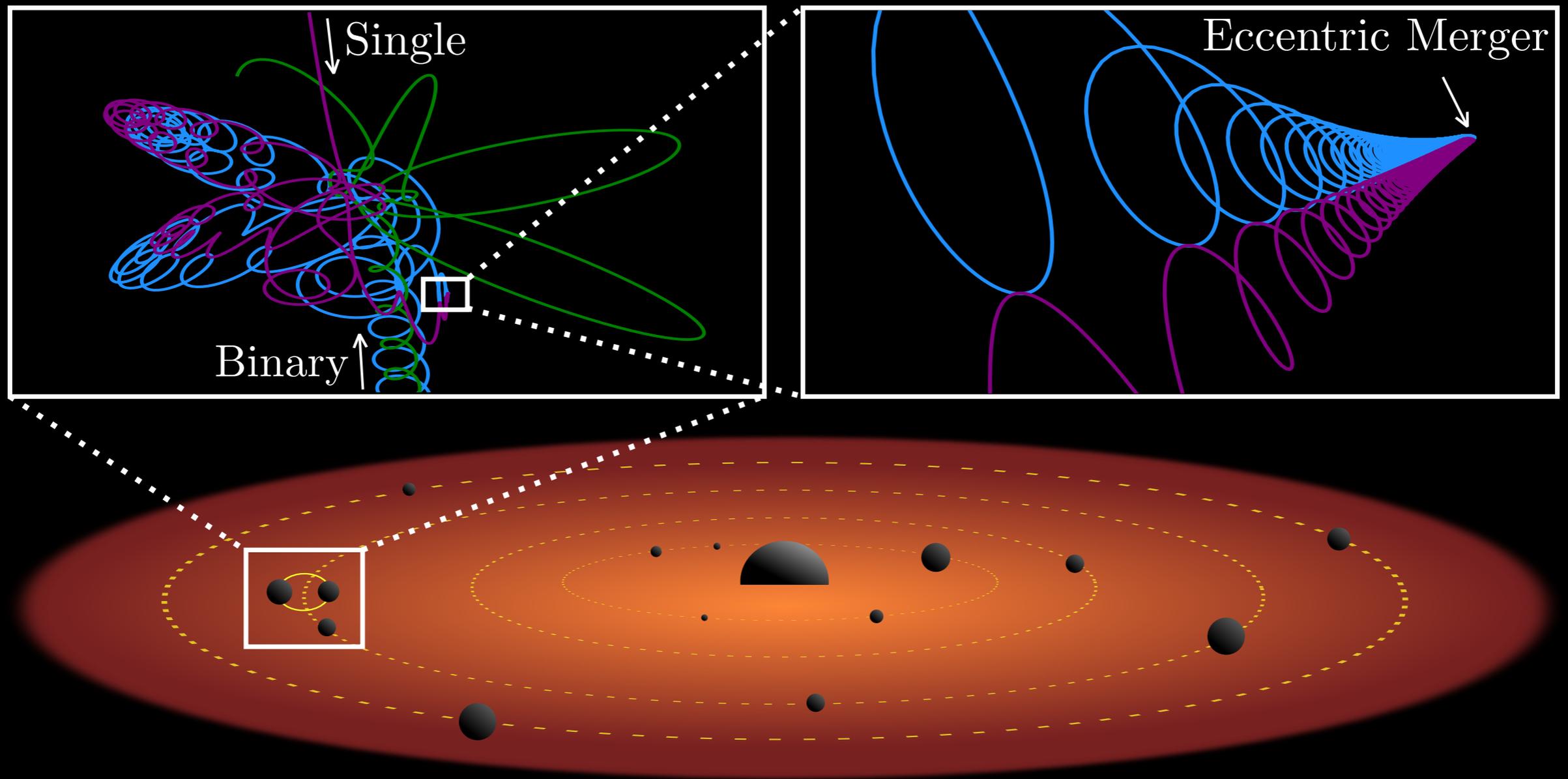
Black Hole Core  
(not to scale)



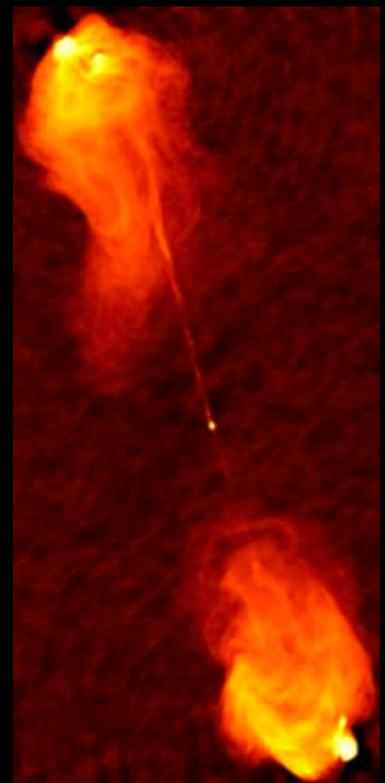
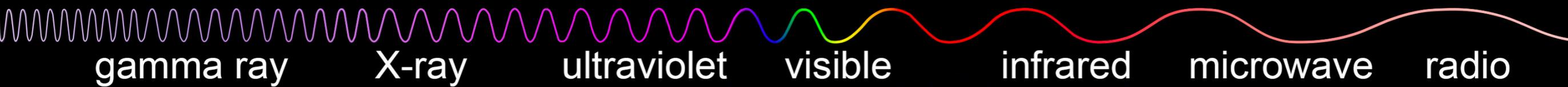
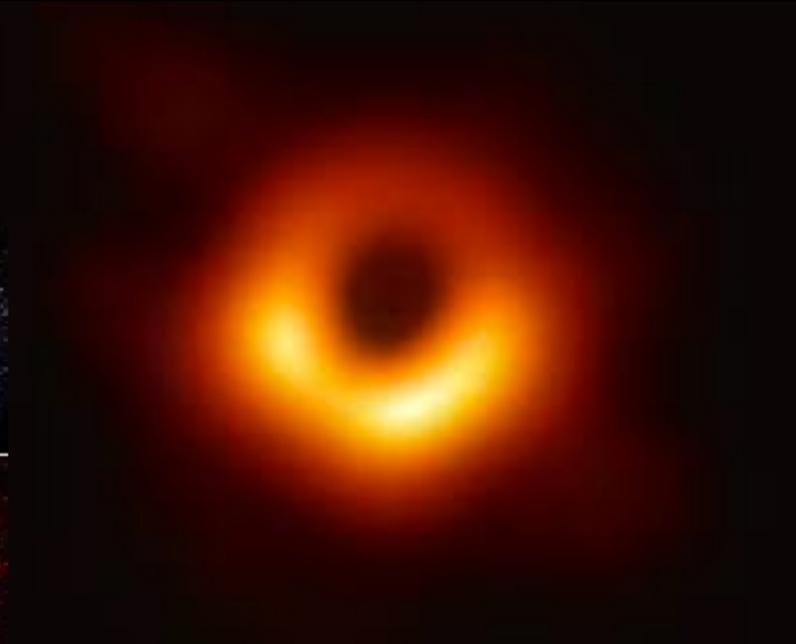
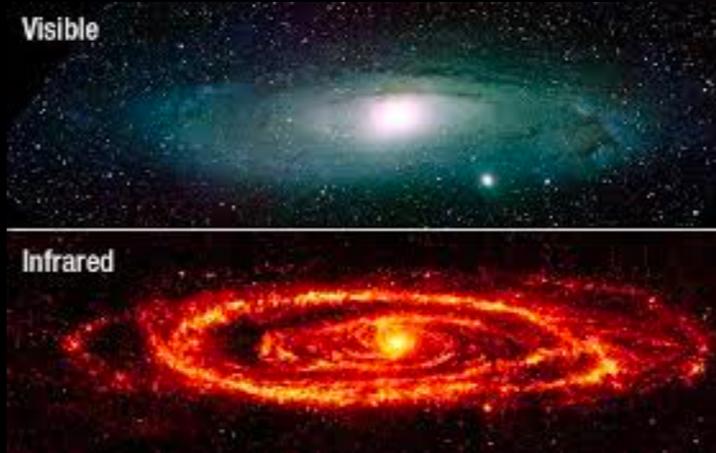
Movie from Johan Samsing



# Dynamical Formation in Gas Disk (AGN channel)



# The Electromagnetic Sky: Conventional Astronomy



# The Gravitational Wave Sky

The Gravitational Wave Spectrum

Sources

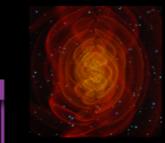
Detectors



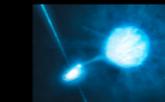
Big Bang



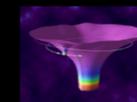
Supermassive Black Hole Binary Merger



Compact Binary Inspiral & Merger



Extreme Mass-Ratio Inspirals



Pulsars, Supernovae



age of the universe

Wave Period

years

hours

seconds

milliseconds

$10^{-16}$

$10^{-14}$

$10^{-12}$

$10^{-10}$

$10^{-8}$

$10^{-6}$

$10^{-4}$

$10^{-2}$

$10^2$

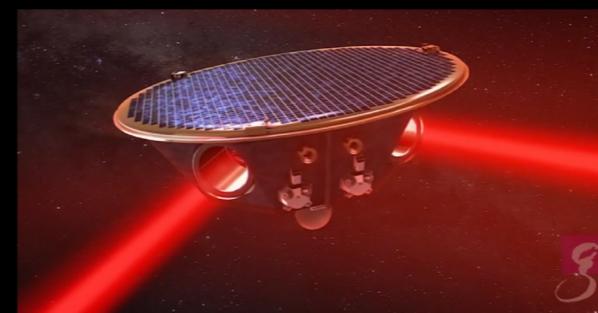
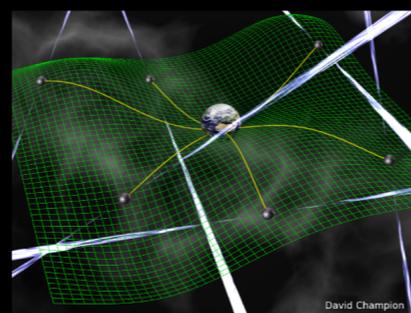
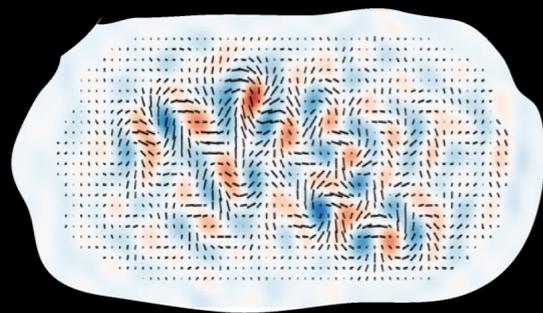
Wave Frequency

CMB Polarization

Radio Pulsar Timing Arrays

Space-based interferometers

Terrestrial interferometers



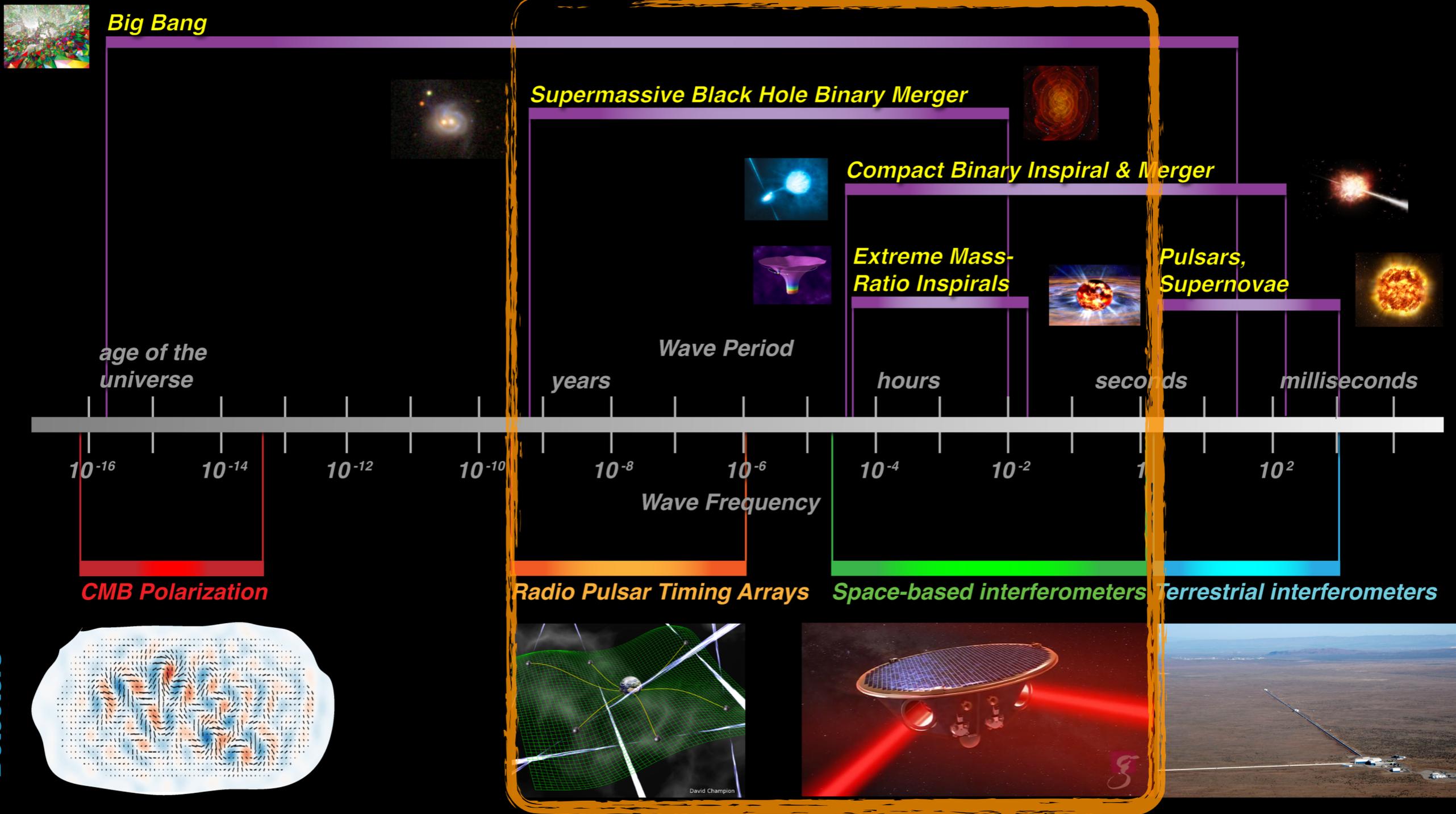
David Champion

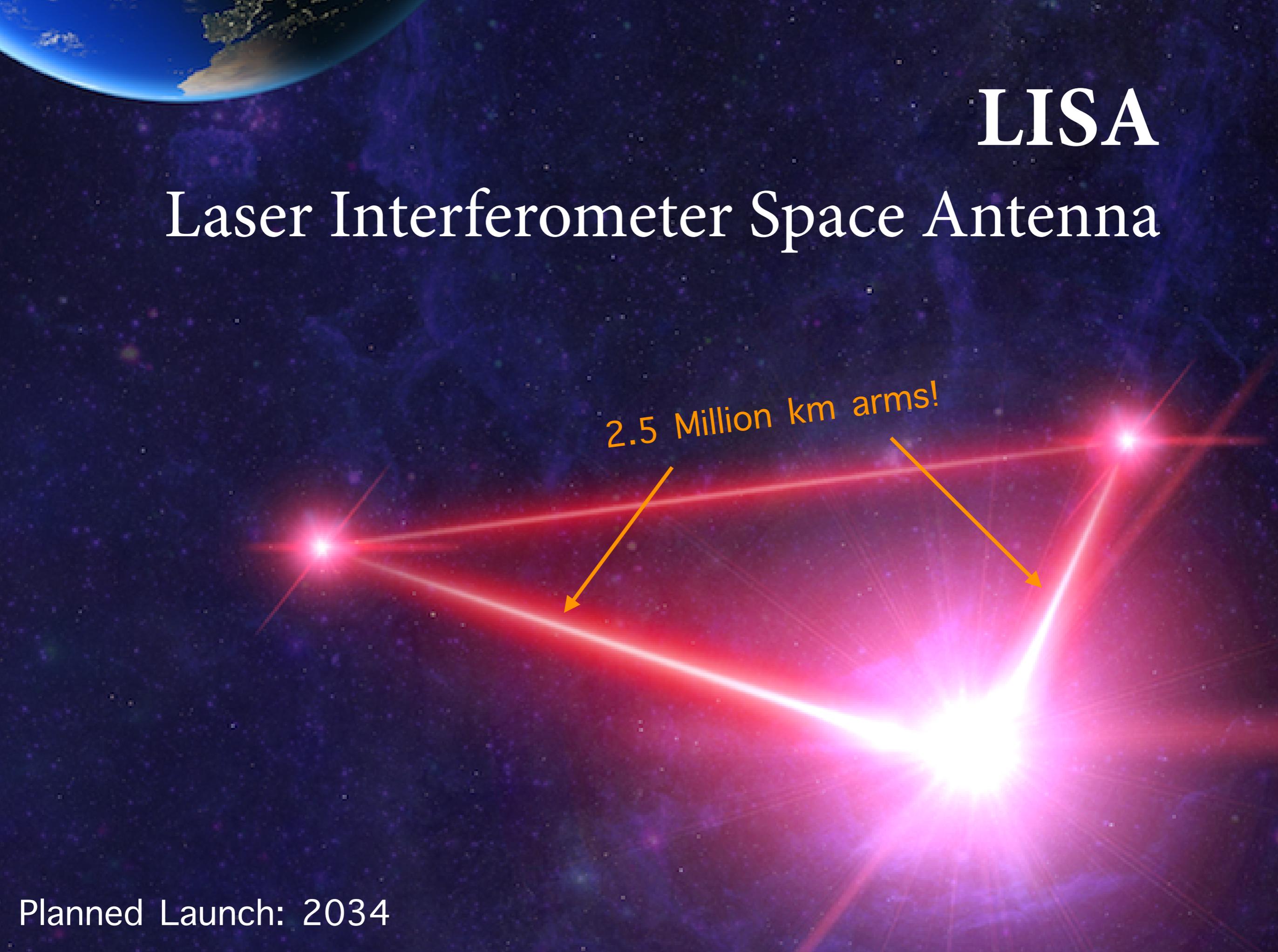
# The Low Frequency Gravitational Wave Sky

The Gravitational Wave Spectrum

Sources

Detectors



The image shows a diagram of the LISA mission. In the top left corner, a portion of the Earth is visible. The background is a dark blue space filled with stars. A bright white star is in the lower right. Three red laser beams originate from this star and extend to three separate red star-like points representing spacecraft. Two yellow arrows point to the beams with the text '2.5 Million km arms!'.

**LISA**

**Laser Interferometer Space Antenna**

2.5 Million km arms!

Planned Launch: 2034

# Pulsar Timing Arrays:

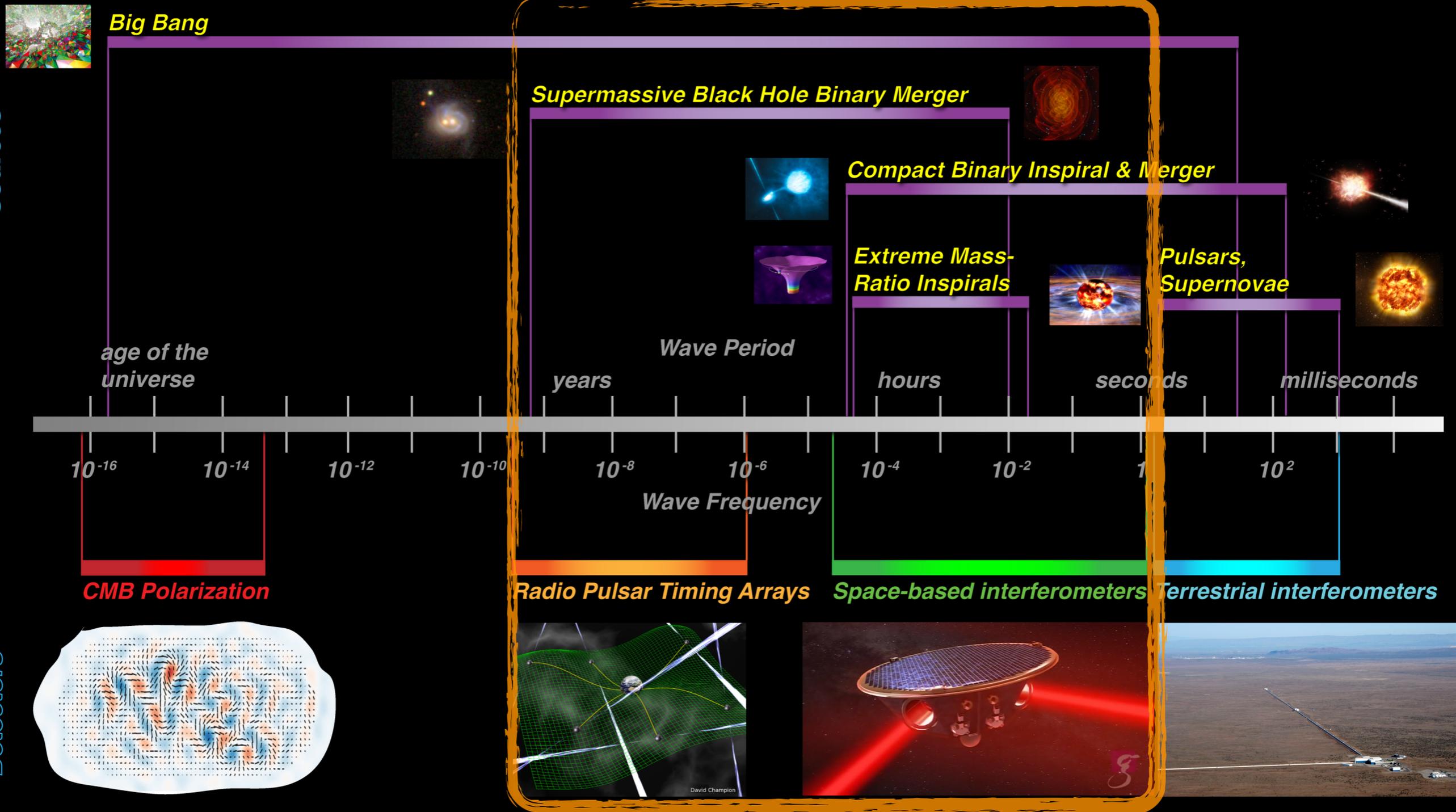


# The Low Frequency Gravitational Wave Sky

The Gravitational Wave Spectrum

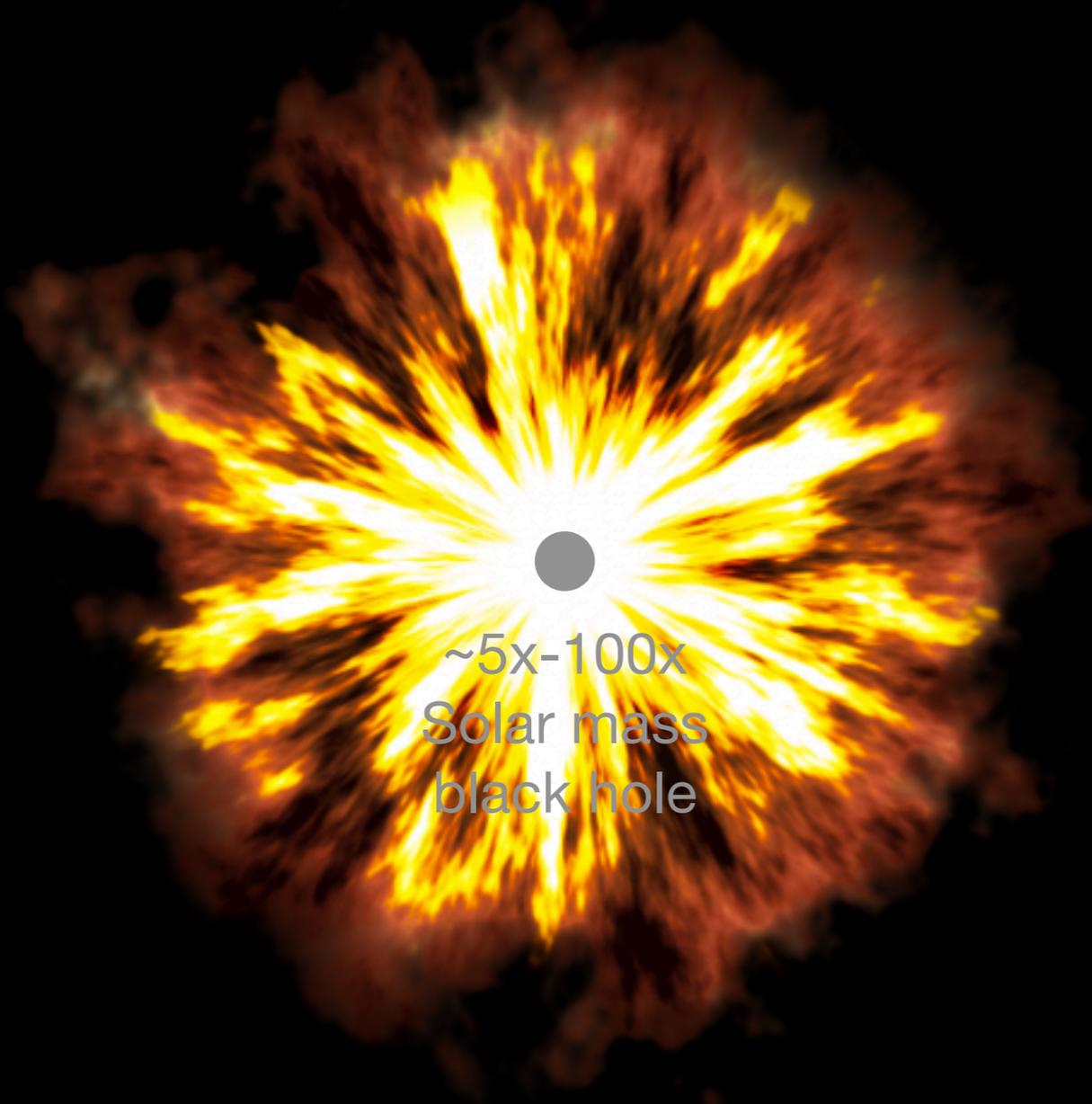
Sources

Detectors



# Black Holes in the Universe

## Stellar Mass Black Holes

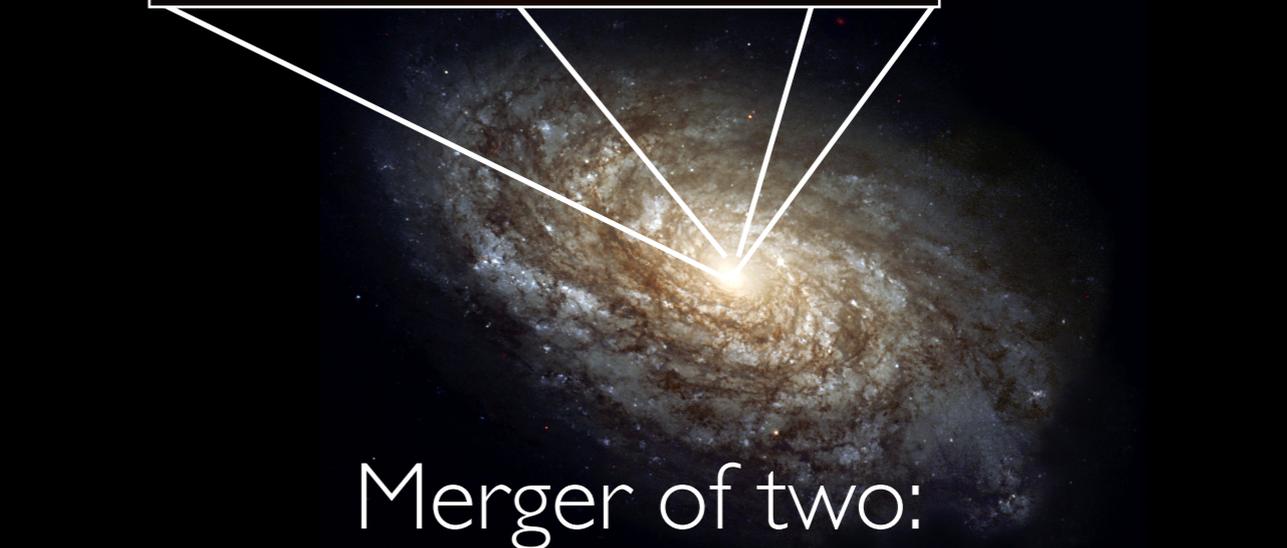
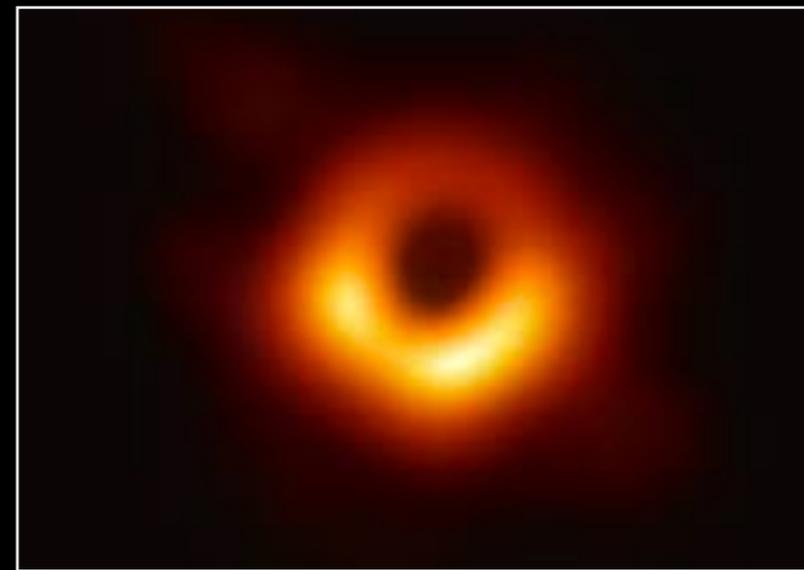


~5x-100x  
Solar mass  
black hole

Merger of two:  
High frequency GWs, LIGO

## Supermassive Black Holes

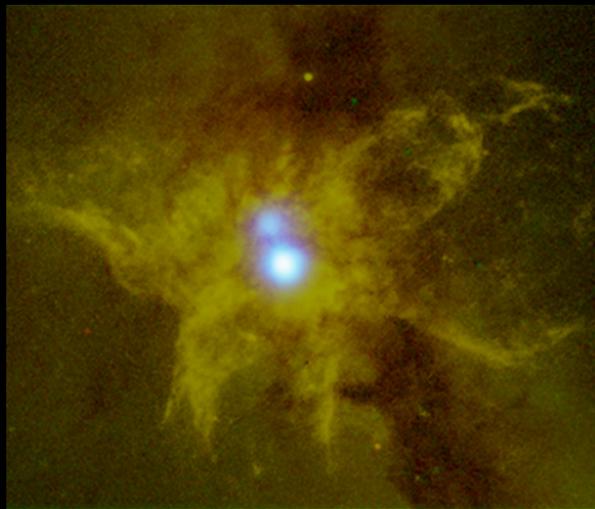
~100 Thousand to 10 Billion  
Solar mass black hole



Merger of two:  
Low frequency GWs, LISA and PTAs

# GALAXIES MERGE, BUT DO THE BLACK HOLES (AND HOW)?

- \* **Step 1:** *Galaxy merger* forms a supermassive black hole binary



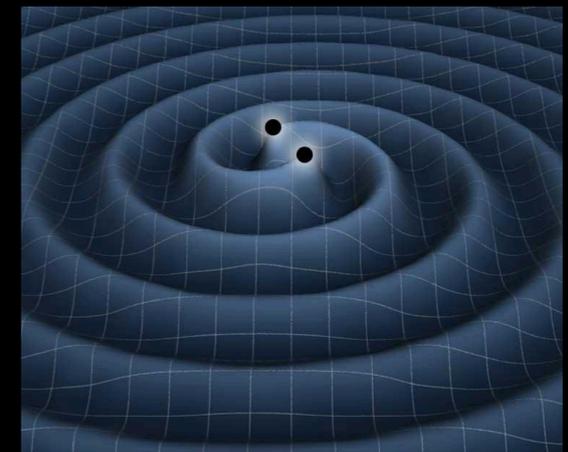
Far apart

Closer together

- \* **Step 2:** ???

Open Question:

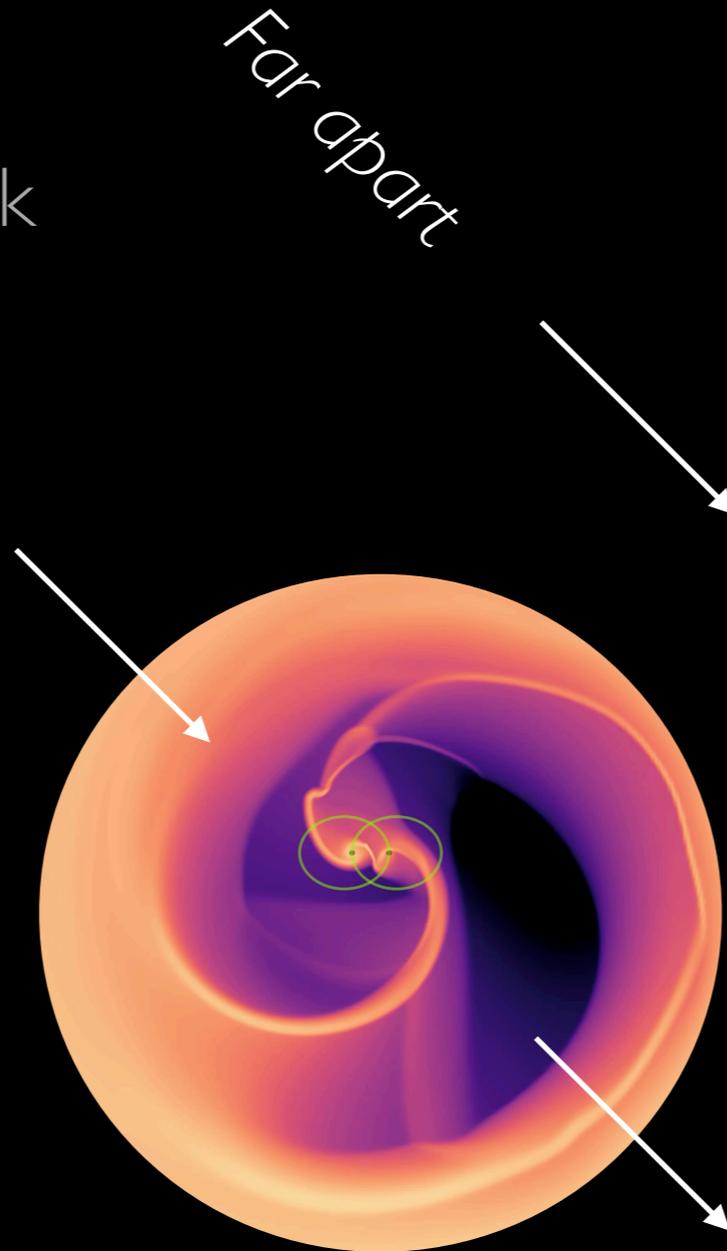
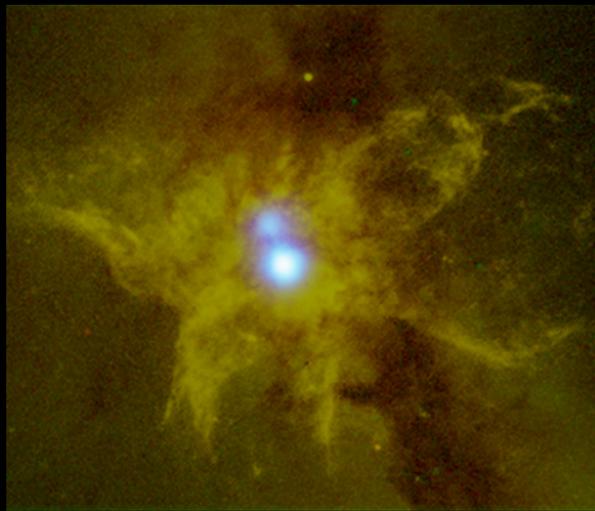
*How do supermassive black hole binaries get close enough to merger? Do they?*



- \* **Step 3:** *Gravitational Waves* merge the supermassive black holes

# GALAXIES MERGE, BUT DO THE BLACK HOLES (AND HOW)? HOW DO WE FIND OUT?

- \* **Step 1:** *Galaxy merger* forms a supermassive black hole binary



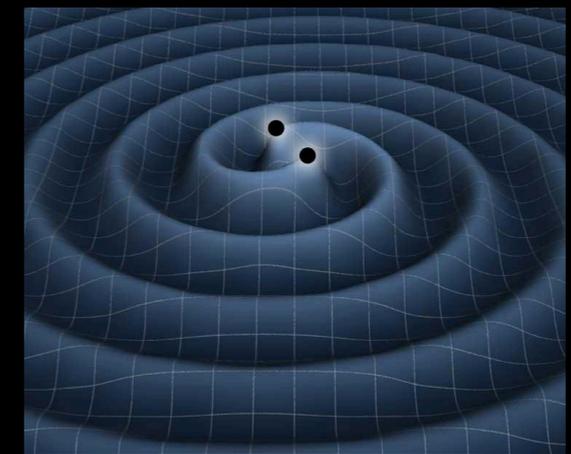
Far apart

Closer together

- \* **Step 2:** ???

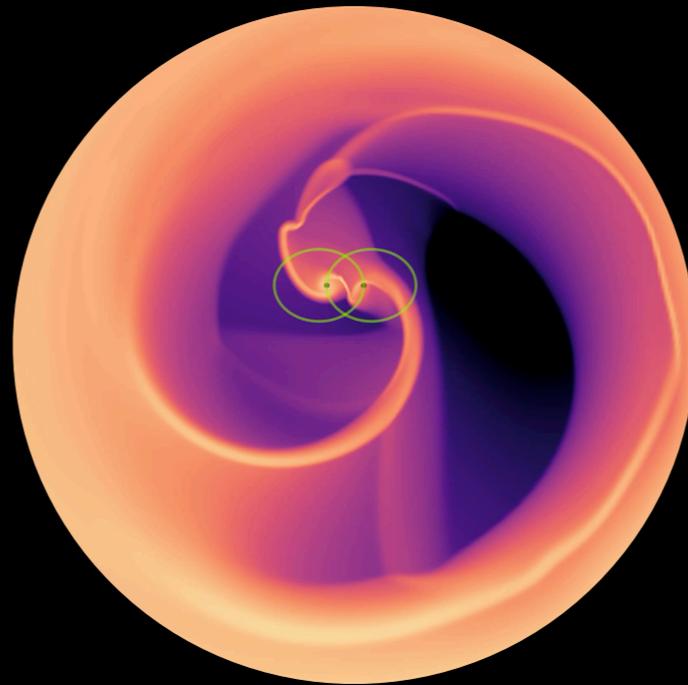
Work at the NBIA:

*Understanding binary+gas interactions*



- \* **Step 3:** *Gravitational Waves* merge the supermassive black holes

# GALAXIES MERGE, BUT DO THE BLACK HOLES (AND HOW)? HOW DO WE FIND OUT?



## Population Predictions

How does gas affect the orbit and drive the black holes to merge?

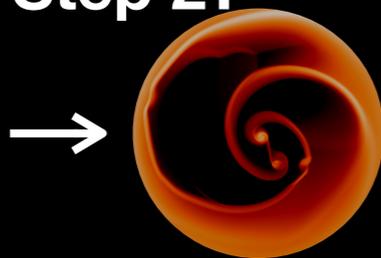
## Discovery in EM spectrum

How does the accretion of gas make the binary EM bright?

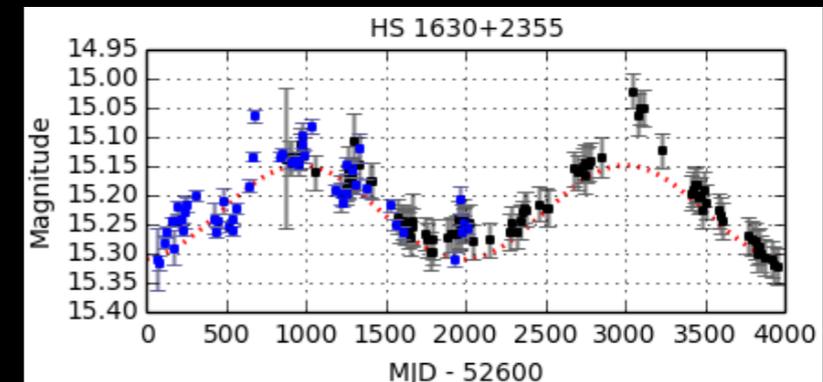
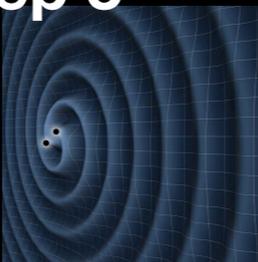
Step 1



Step 2?

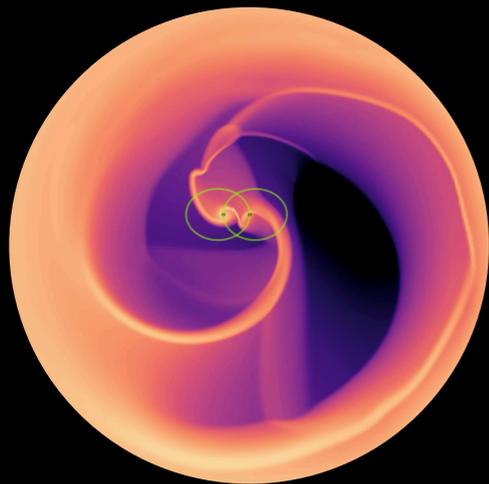
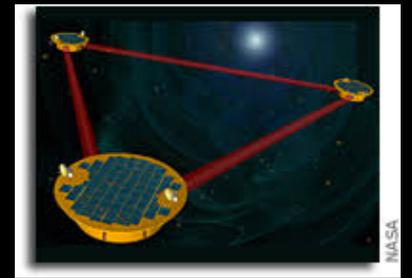
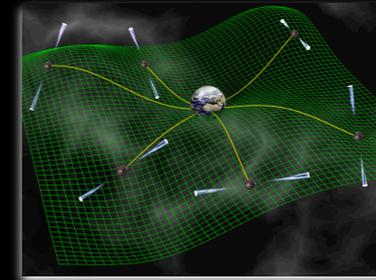


Step 3



# SUMMARY

- \* **Multi-messenger Astrophysics:** Gravitational waves have opened a new window to the gravitational universe that must now be paired with our picture of the electromagnetic universe
- \* **LIGO** has detected mergers of **stellar-mass black holes** — We are tackling many **open questions** about their origin
- \* A new part of **the gravitational wave sky** is about to be opened now and in the next two decades with **LISA** and the **Pulsar Timing Arrays**



- \* These **low frequency gravitational waves** will teach us about the supermassive black hole binaries
- \* We are **preparing for this coming era** by advancing theoretical understanding of supermassive black hole binary pairing and merger

# People

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Martin Pessah, Johan Samsing, Daniel D'Orazio  
[mpessah@nbi.ku.dk](mailto:mpessah@nbi.ku.dk), [jsamsing@nbi.ku.dk](mailto:jsamsing@nbi.ku.dk), [daniel.dorazio@nbi.ku.dk](mailto:daniel.dorazio@nbi.ku.dk)

## Research Topics

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- \* Theory at interface with observations: pencil-paper and numerics
- \* Gravitational Waves and Black Hole Astrophysics
- \* Many-body (relativistic) gravitational dynamics
- \* Gas Accretion, Gravitational Lensing

## Open Questions

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- \* How do black hole binaries (across the mass scale) form and merge?
  - \* How do we find evidence for supermassive black hole binaries?
  - \* Where/How do the stellar mass black hole binaries form/merge?
  - \* What Electromagnetic and Gravitational Wave observables can we predict and use to find the answers?