Gravitational Wave Astronomy 101

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University of Houston
Clear Lake

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The 5 Questions

- What happened in the Beginning?
- What are Gravitational Waves?
- What produces Gravitational Waves?
- How can we observe Gravitational Waves?
- How do we know what Gravitational Waves look like?

The Beginning

Where the Heck did all that come from?

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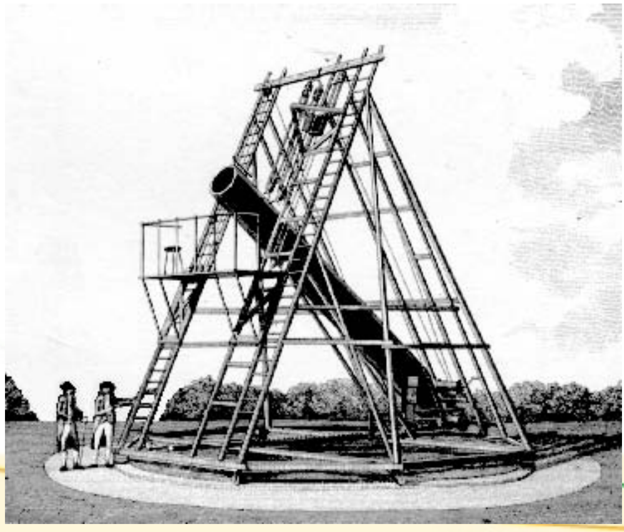
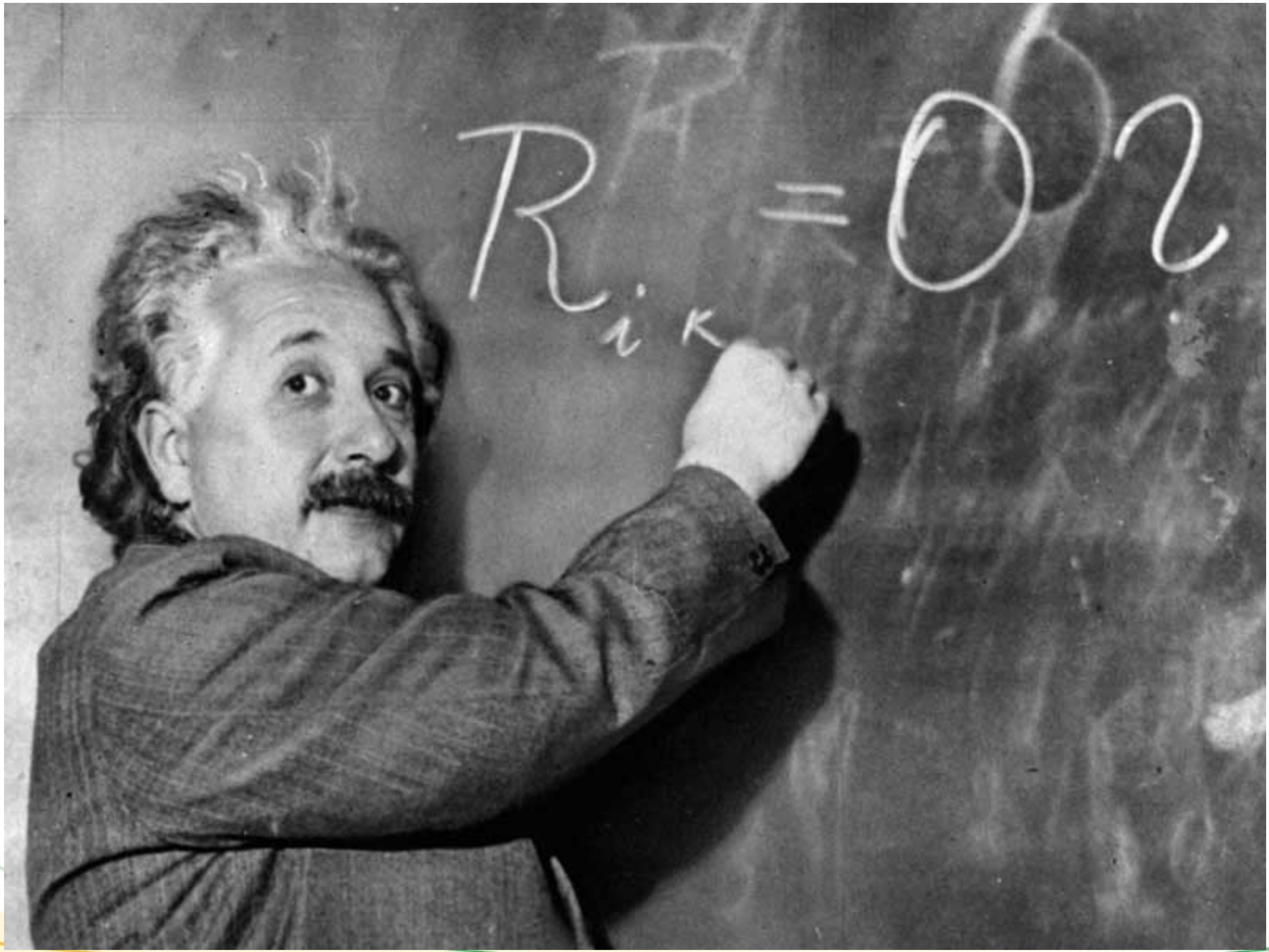
First Observatories

New Technologies



Putting it all together



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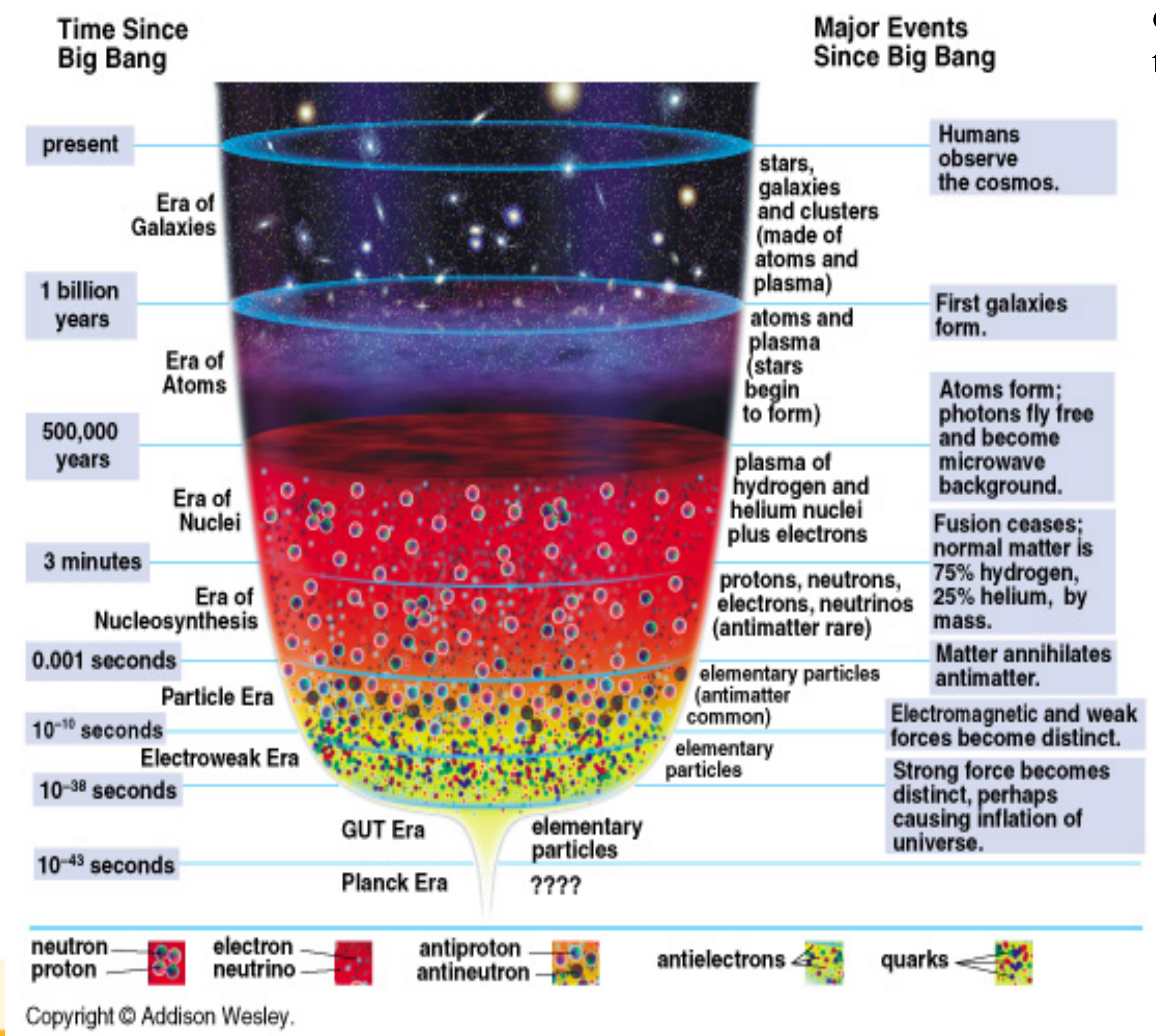
Not Everyone Understands the Theory

History of the Universe



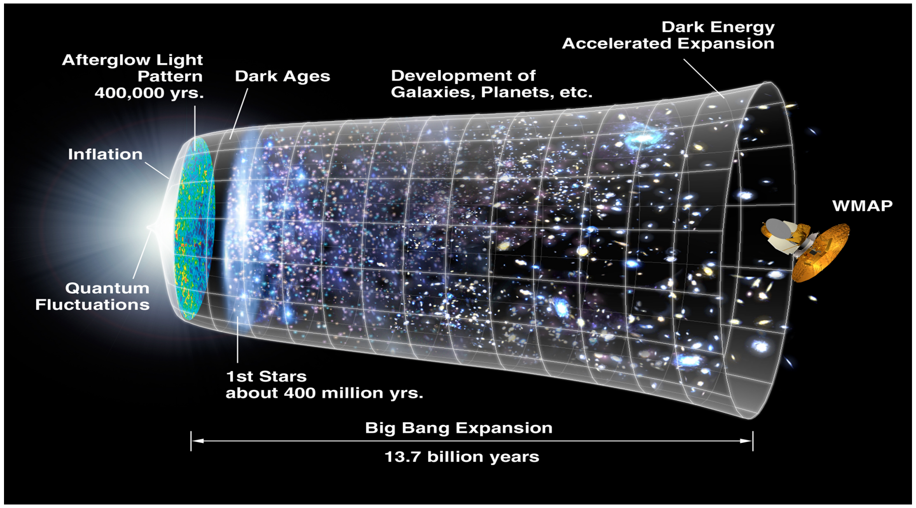
We have some idea, but don't know for sure how the universe is going to end

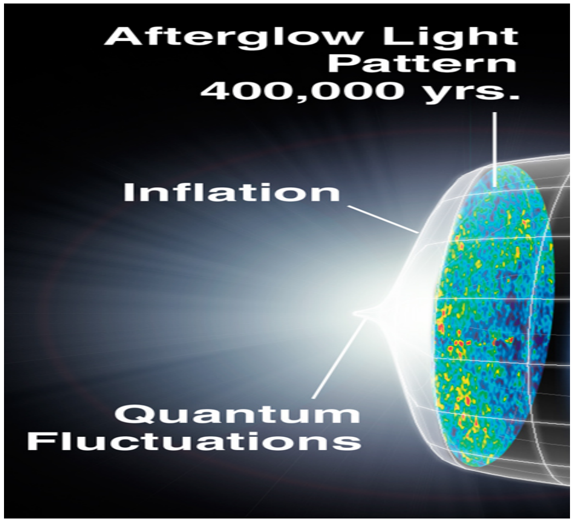
The observable universe

We know what's going on base on our knowledge of physics

We still don't know how physics works in this era yet.

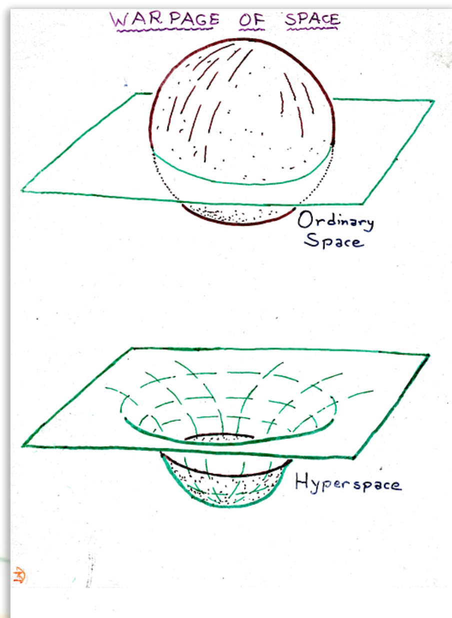
Inflation and Gravitational Waves

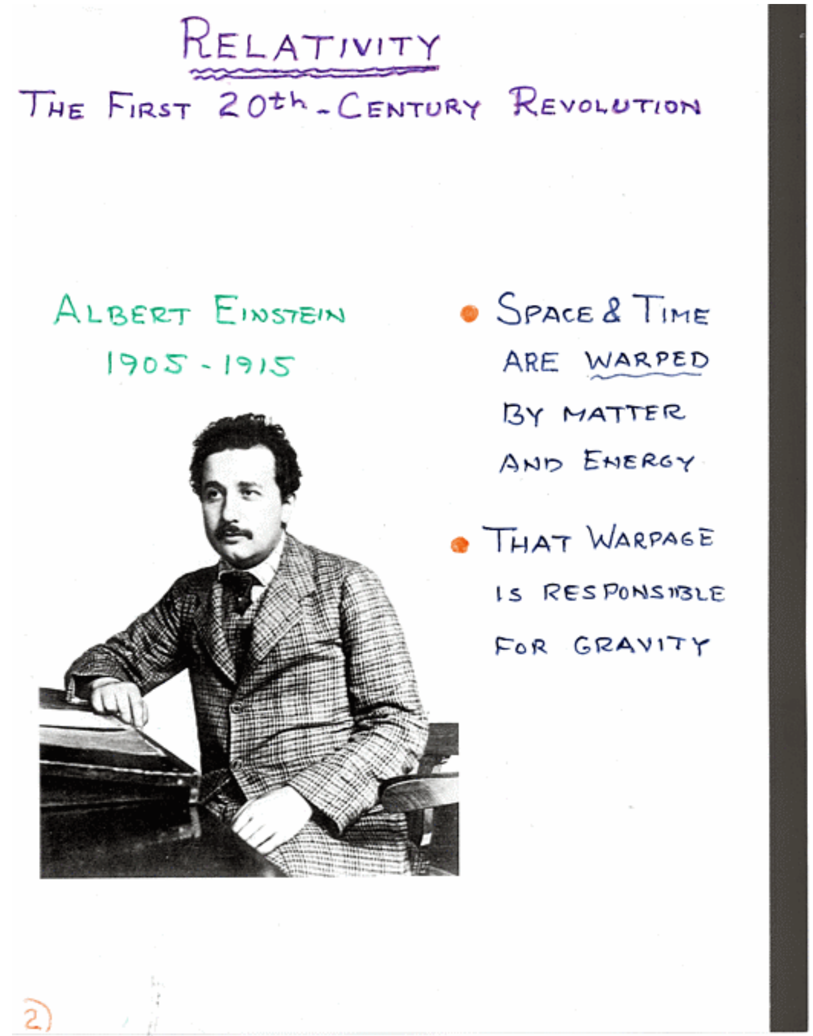




What are Gravitational Waves?

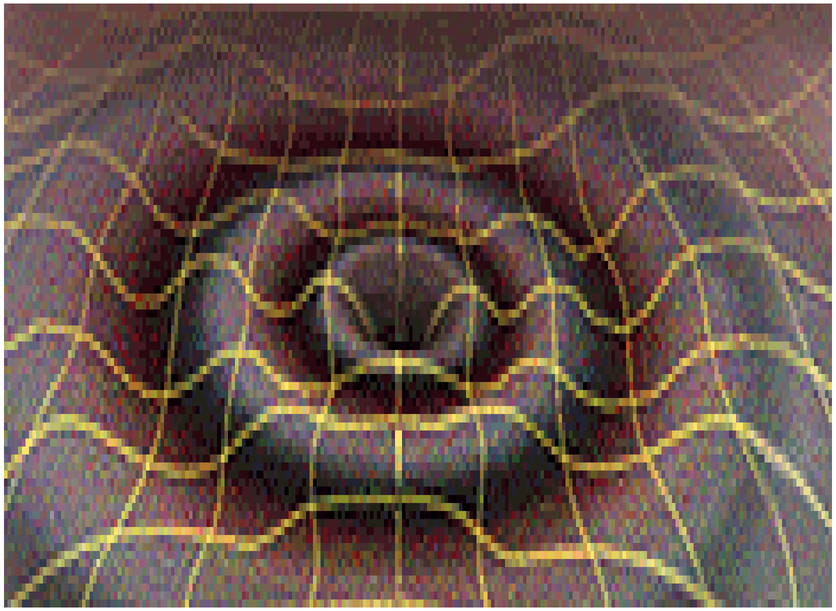
- Gravitational Waves first appeared as part of Einstein's General Theory of Relativity





Einstein’s Theory of General Relativity

- Space-time tells matter how to move
- Matter tells space-time how to curve



- **Gravitational Waves: Ripples in the fabric of space-time**
- **Black Holes: The final fate in the collapse of matter**

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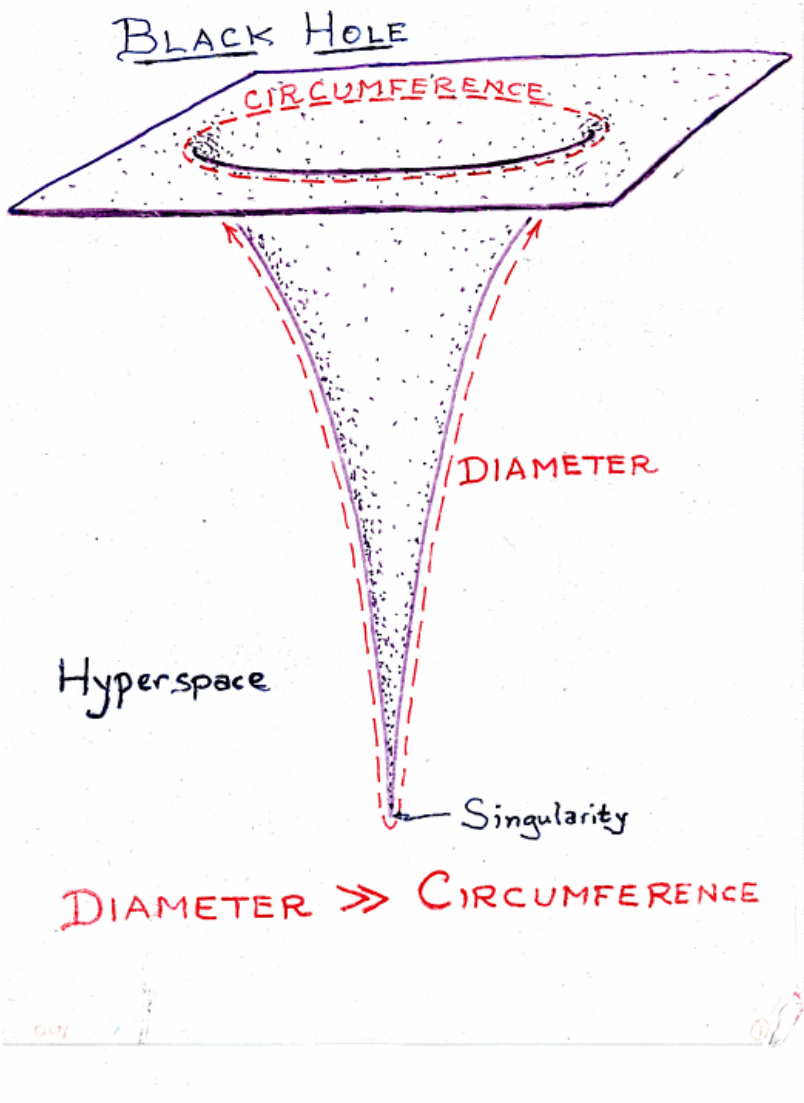
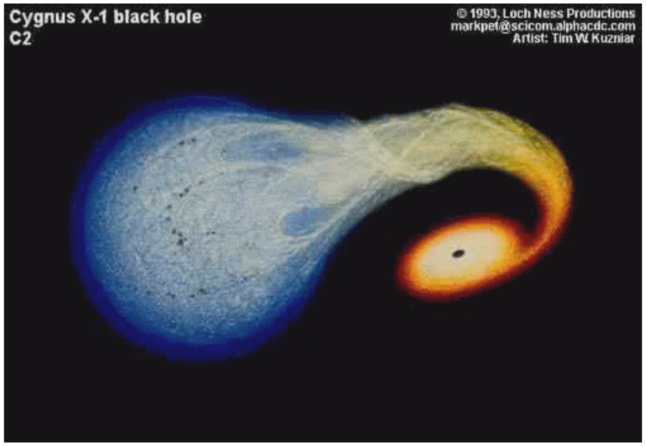
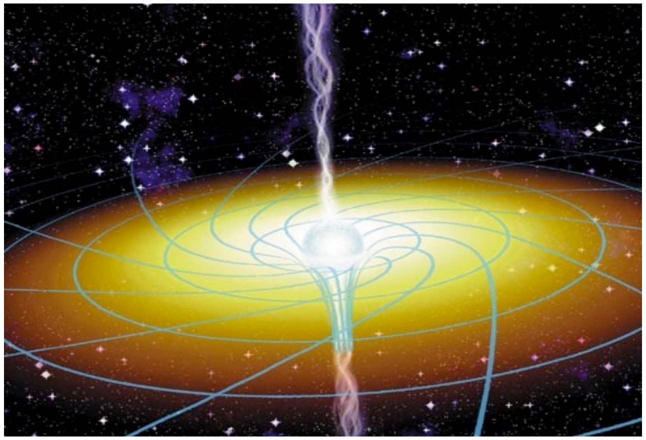


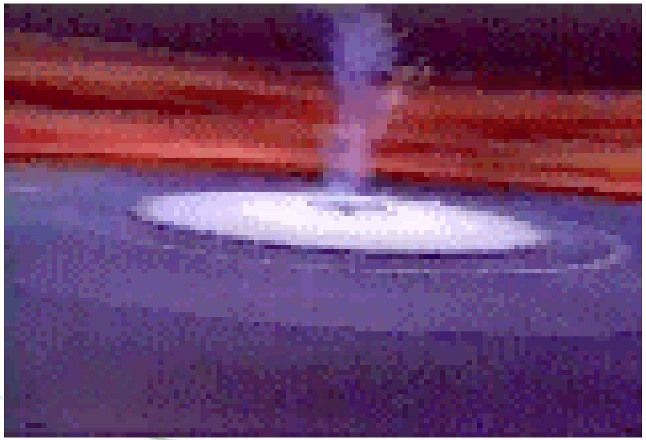
Astrophysics in the Vicinity of Black Holes



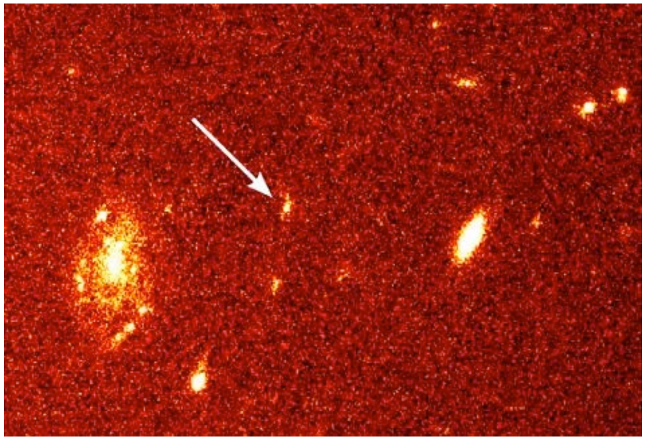
X-ray Binary Systems



Spinning Black Holes

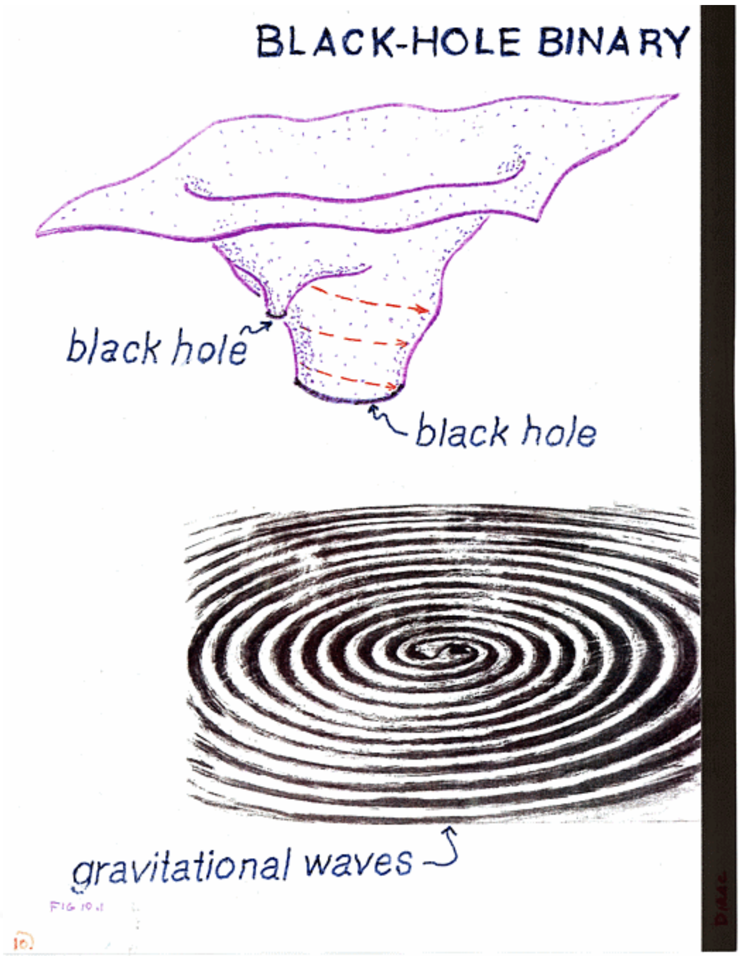


Active Galactic Nuclei



Gamma Ray Bursts

So what does this have to do with gravitational waves?



- When two massive objects, such as Black Holes, interact Gravitational Waves are produced.

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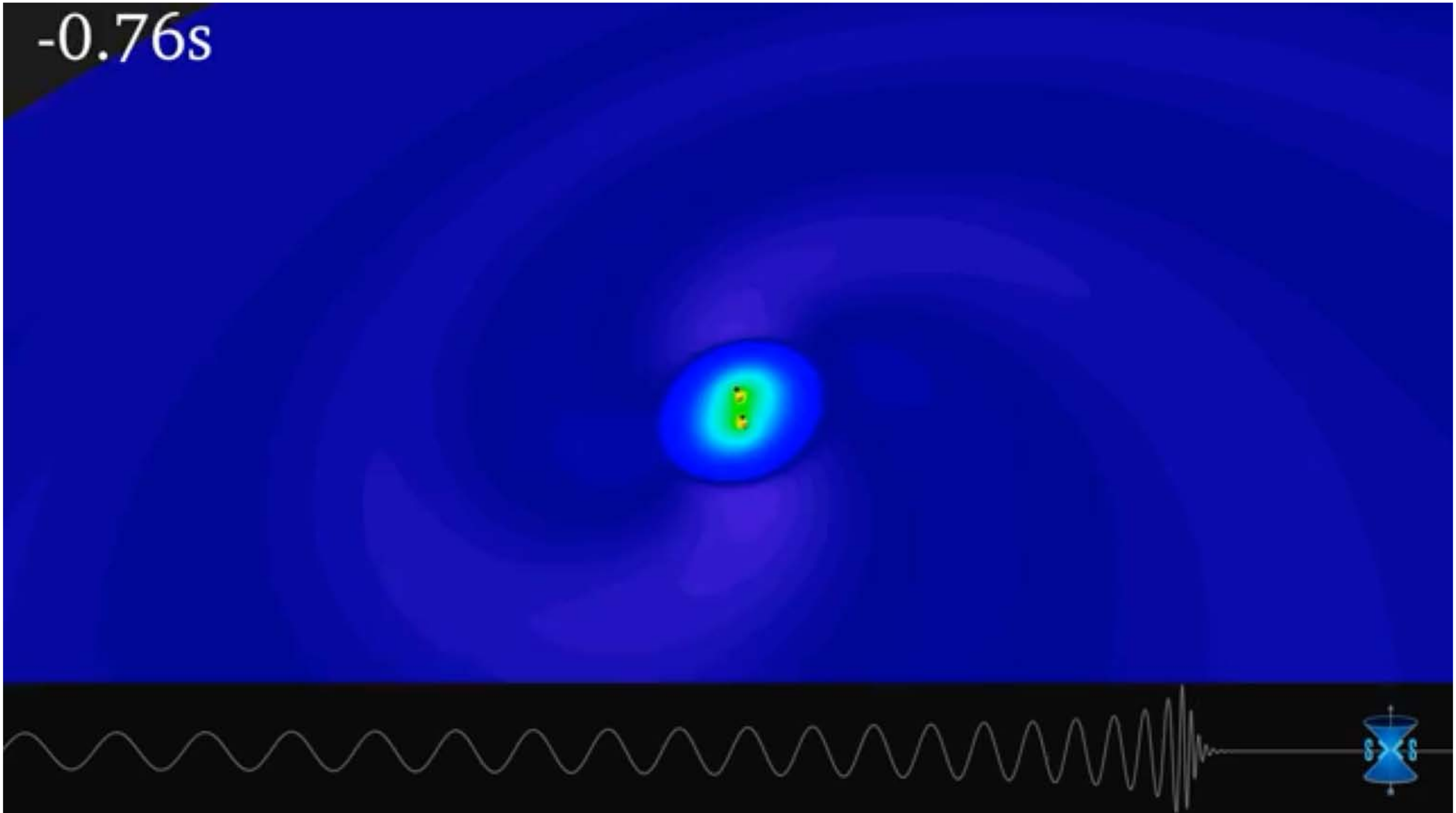

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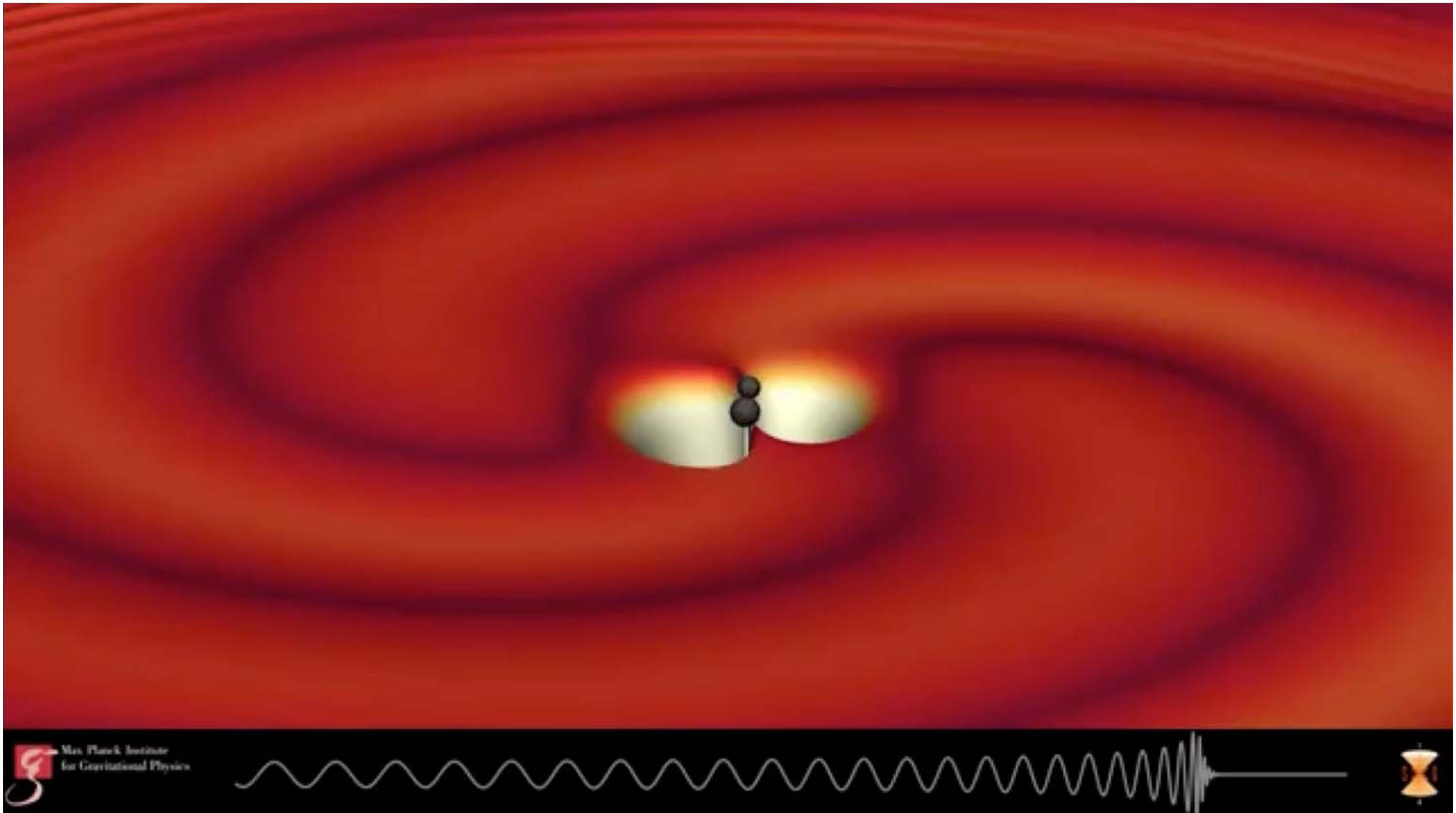
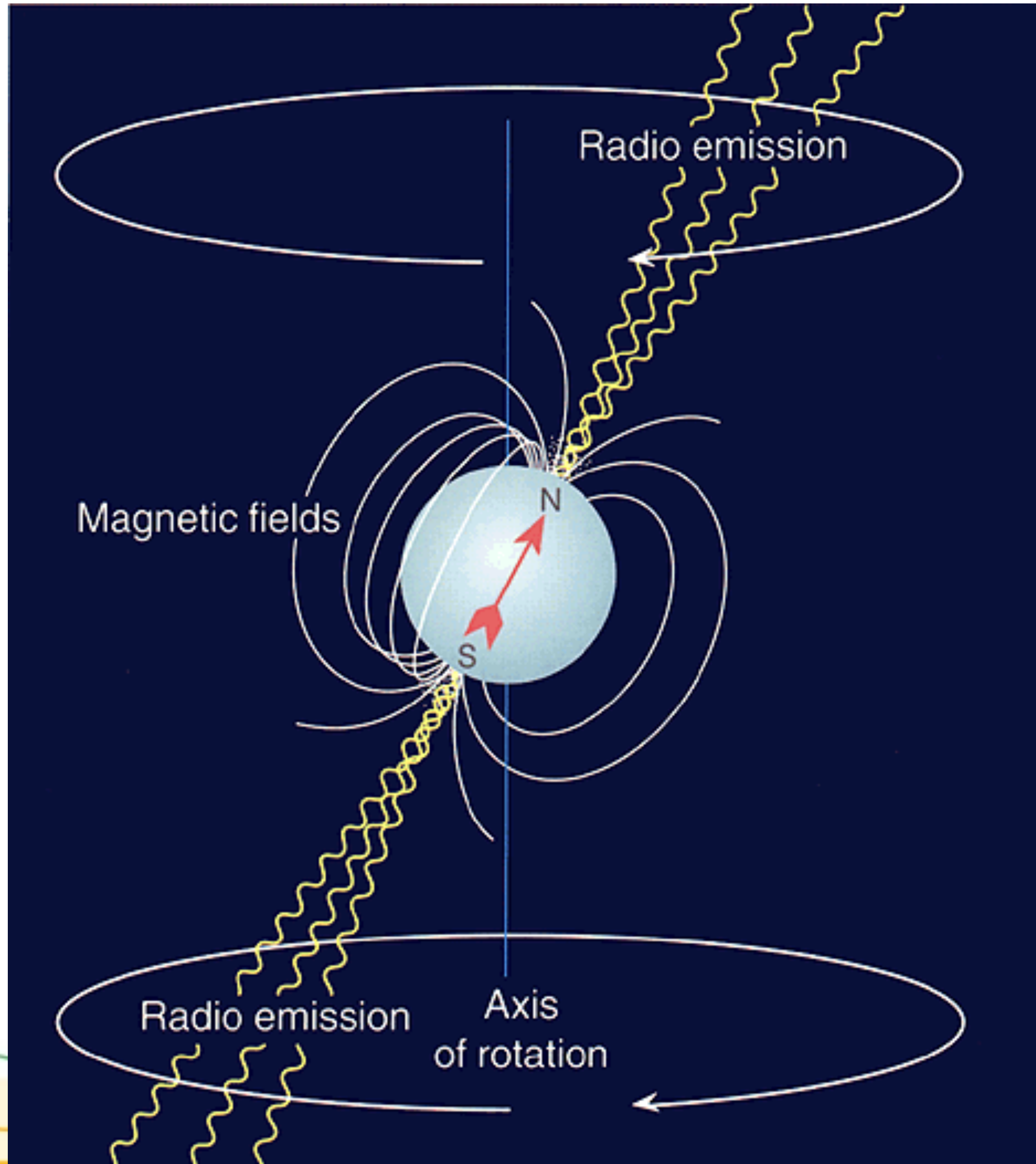


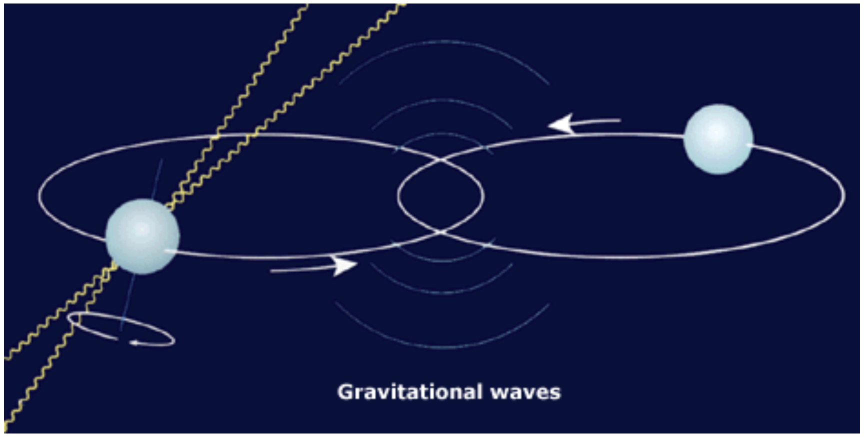
Pulsars

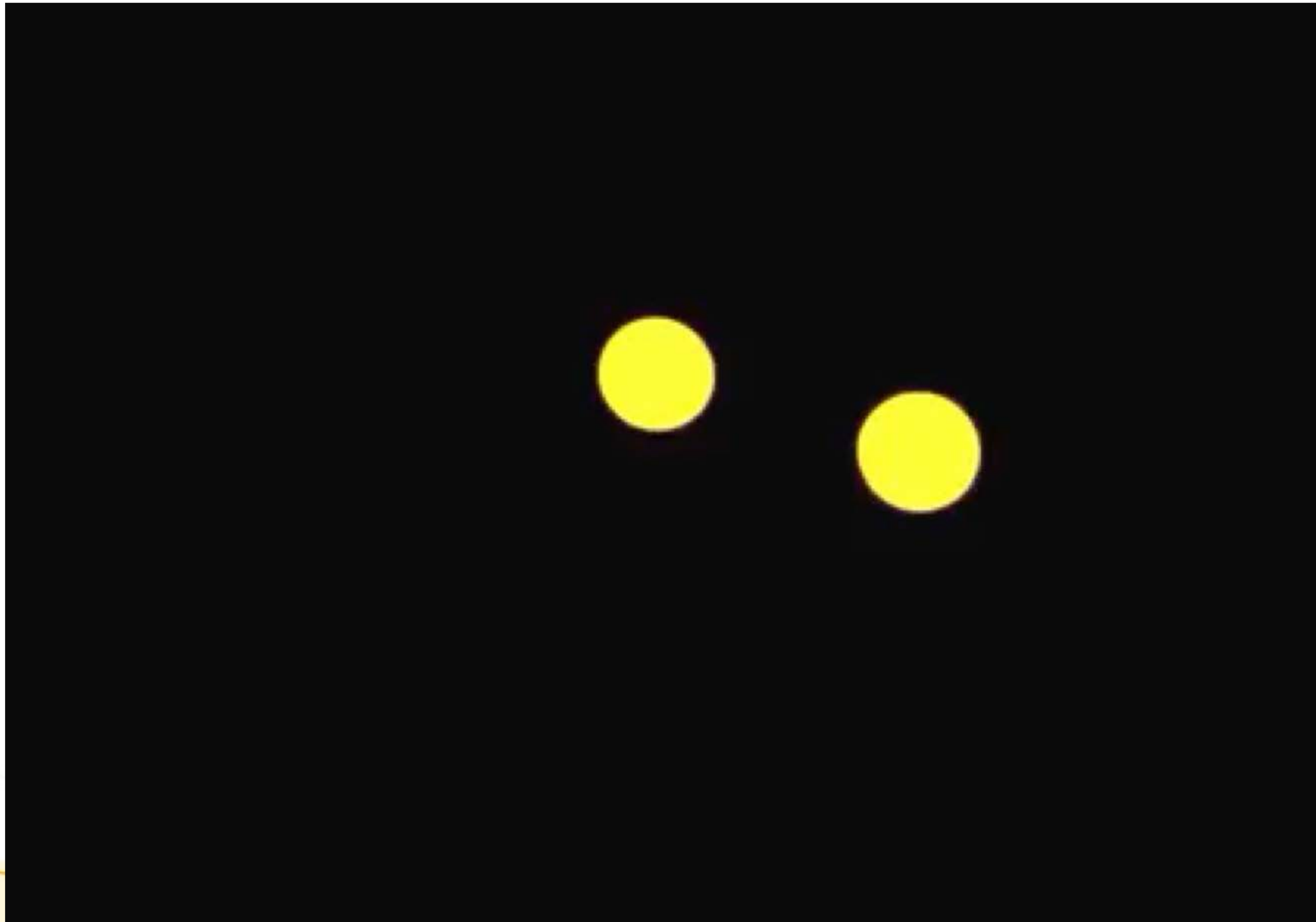


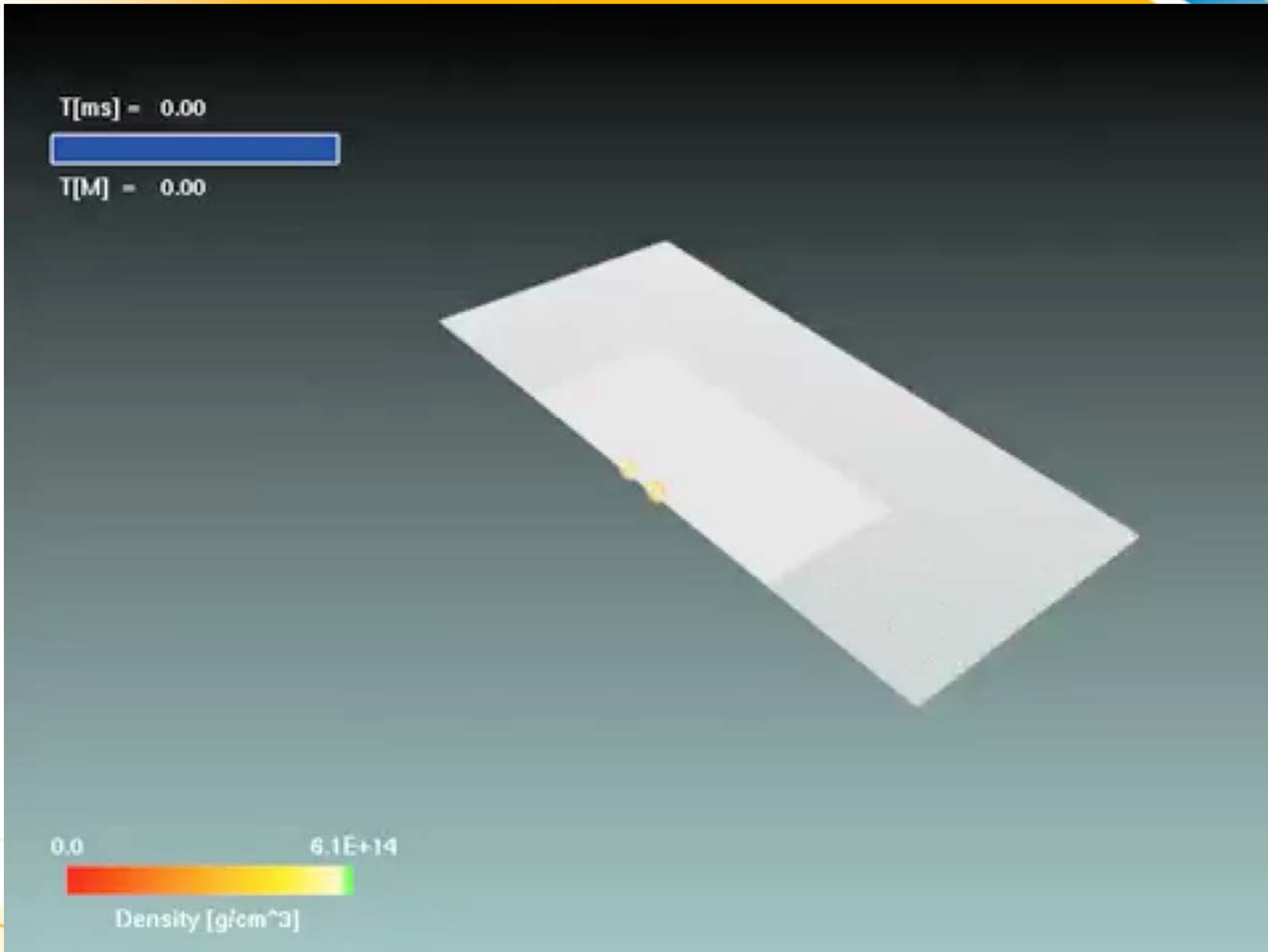
Radio emission
Magnetic fields
N
S
Radio emission
Axis
of rotation

How do we know GWs exist?

- In 1974, Joseph H. Taylor Jr. and Russell A. Hulse discovered a Binary Pulsar System
- This discovery earned them the 1993 Nobel Prize in Physics

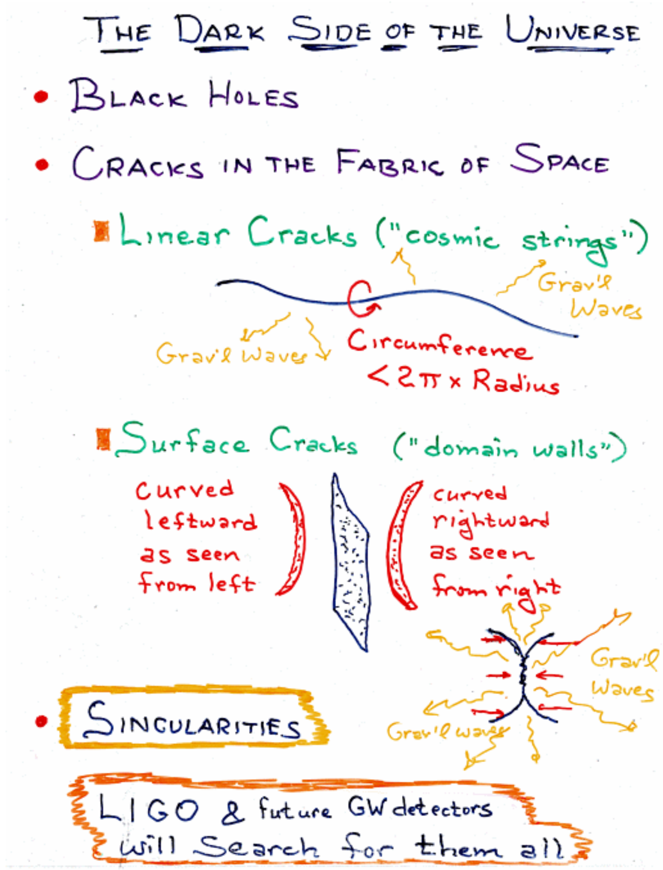





T[ms] = 0.00
T[M] = 0.00
0.0
6.1E+14
Density [g/cm^3]

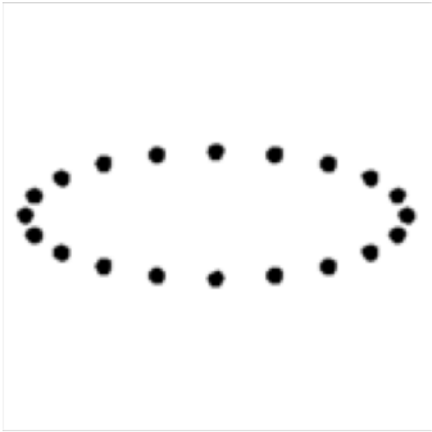
What are other sources of GWs?

- Binary Black Holes
- Binary Neutron Stars
- Supernova Explosions
- Stochastic Sources
- Cosmology
- Exotic Sources



What Do Gravitational Waves Look Like?

- Plus Polarization



- Cross Polarization

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Gravitational vs EM Radiation

GRAVITATIONAL WAVES CONTRASTED WITH ELECTROMAGNETIC WAVES

ELECTROMAGNETIC	GRAVITATIONAL
Oscillations of EM field propagating through spacetime	*Oscillations of the "fabric" of spacetime itself*
Incoherent superposition of waves from molecules, atoms, and particles	*Coherent emission by bulk motion of matter and energy*
Frequencies ~ 1 MHz and upward 20 orders	*Frequencies ~ 1 kHz and downward 20 orders*
Easily absorbed and scattered	*Never significantly absorbed or scattered*
Emitted from surfaces of objects (where optically thin and gravity is weak)	*Emitted most strongly by massive, compact, highly dynamical objects (where gravity is strong)*

IMPLICATIONS:

Gravitational waves are the ideal tool for probing strong-gravity regions of spacetime (general relativity)

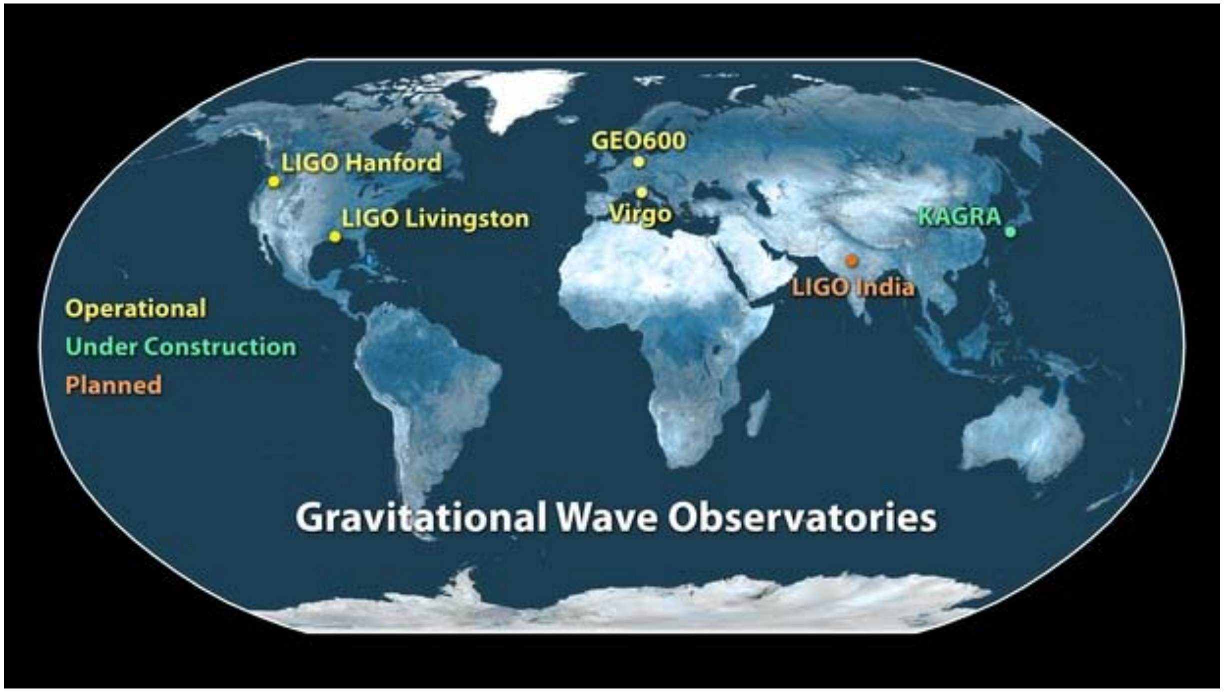
Gravitational waves have the potential to bring us great surprises --- a "revolution" in our understanding of gravity and the Universe

- Because of differences in EM and Gravitational Radiation, observing GWs is very different and so requires a different kind of astronomy

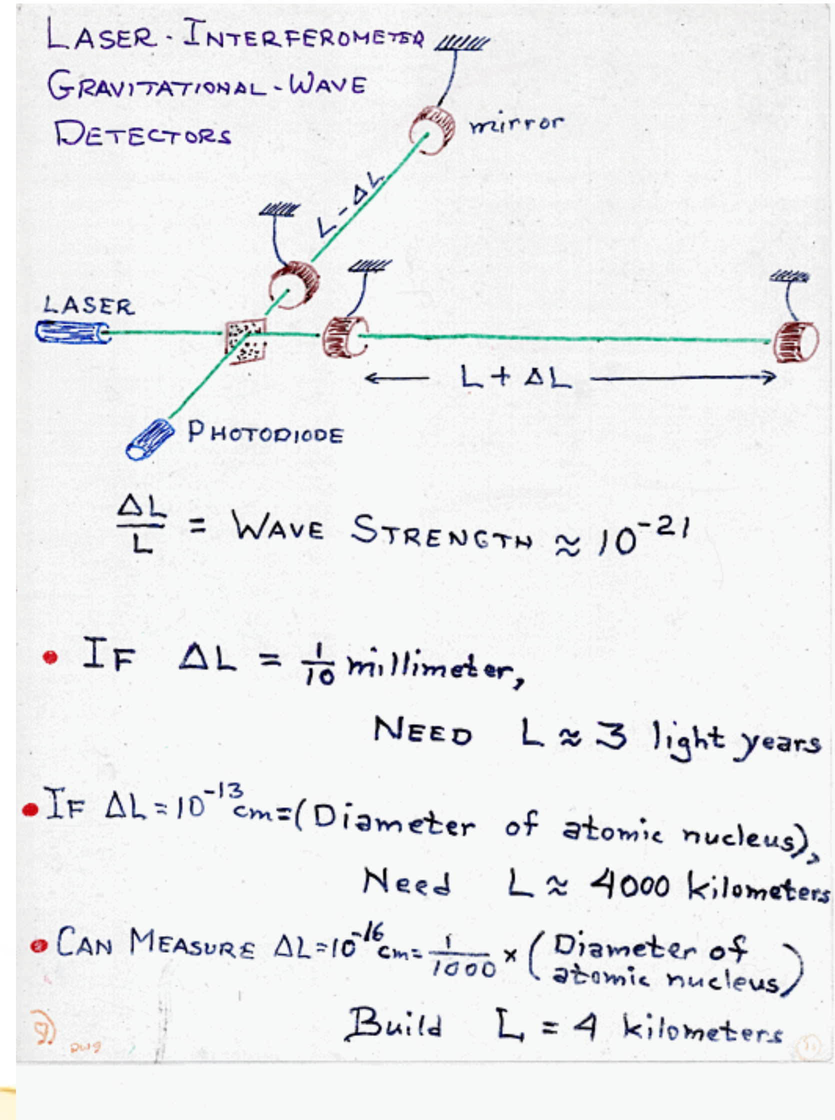
Conventional methods of Astronomy

Gravitational Wave Astronomy

- Several Gravitational Wave Interferometers began looking for GW in 2002 and 2003



How GW interferometers work



- This is a cut-away of LIGO

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LIGO Hanford Washington

Laser Interferometer Gravitational-wave Observatory

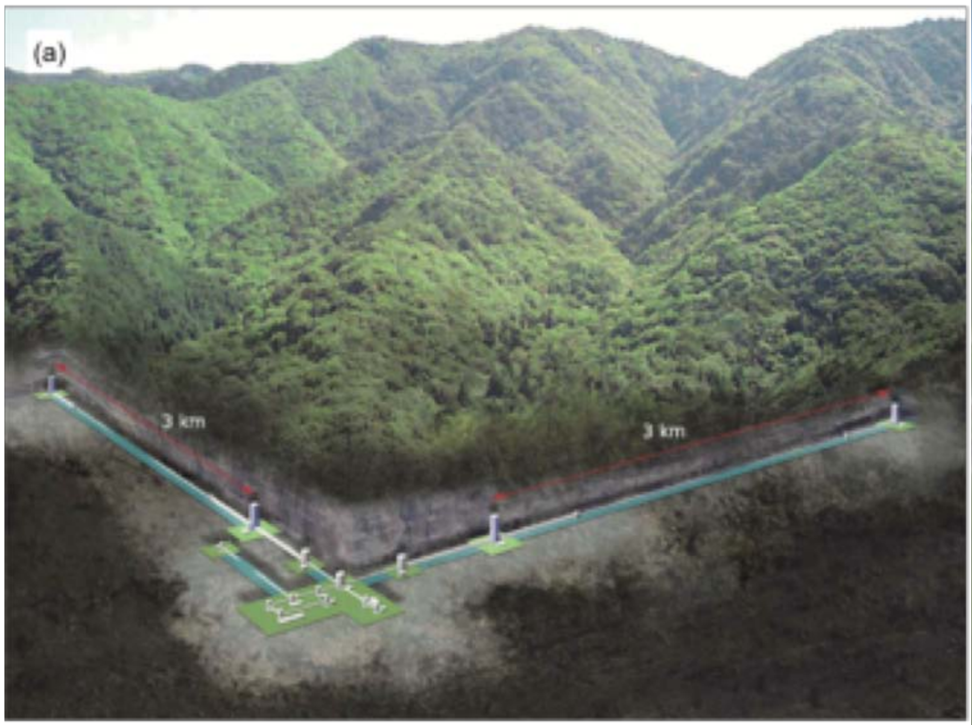
LIGO

LIGO Livingston Louisiana

VIRGO Pisa, Italy

GEO600 Hanover, Germany

KAGRA Japan

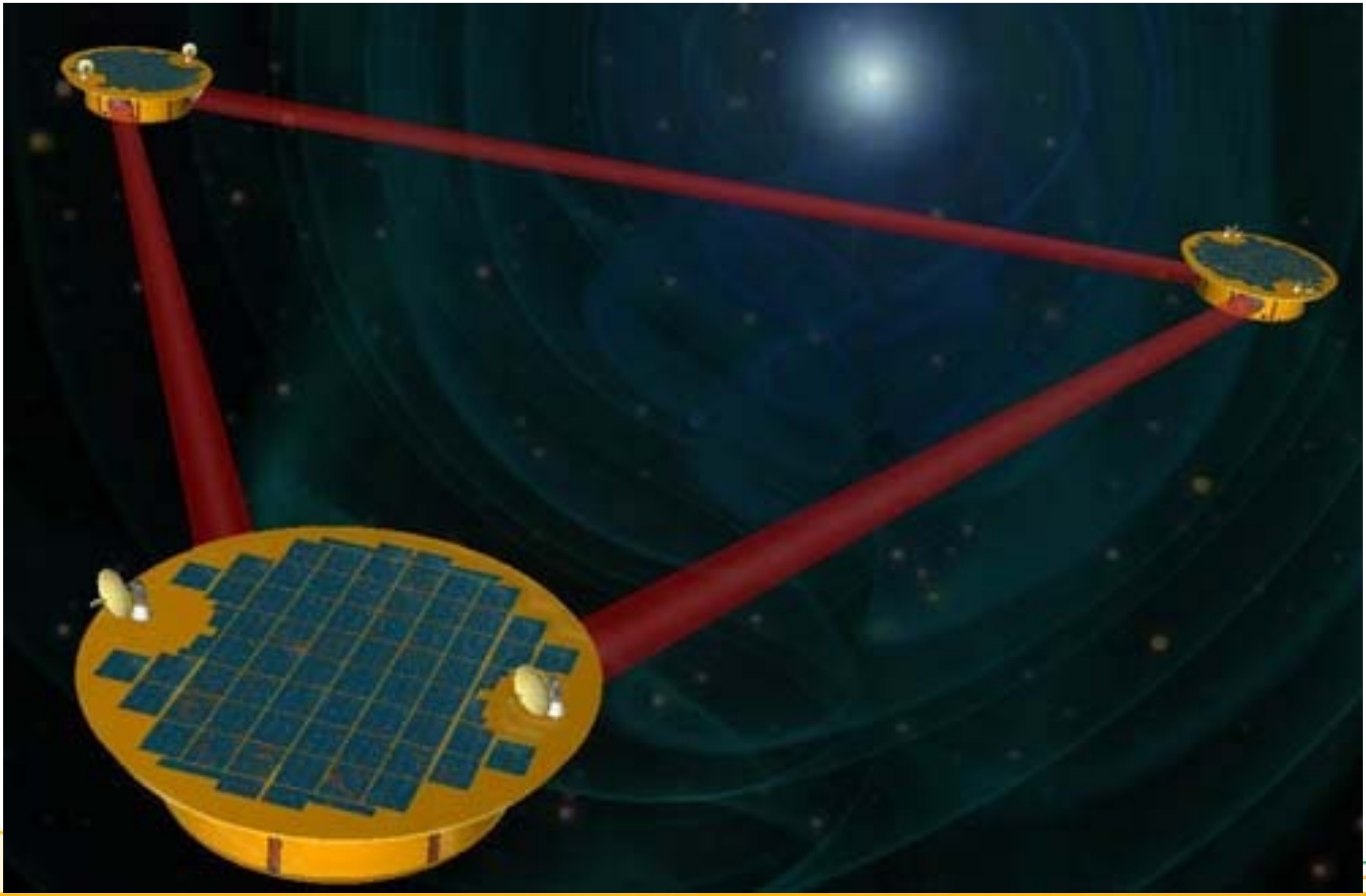

(a)
3 km
3 km

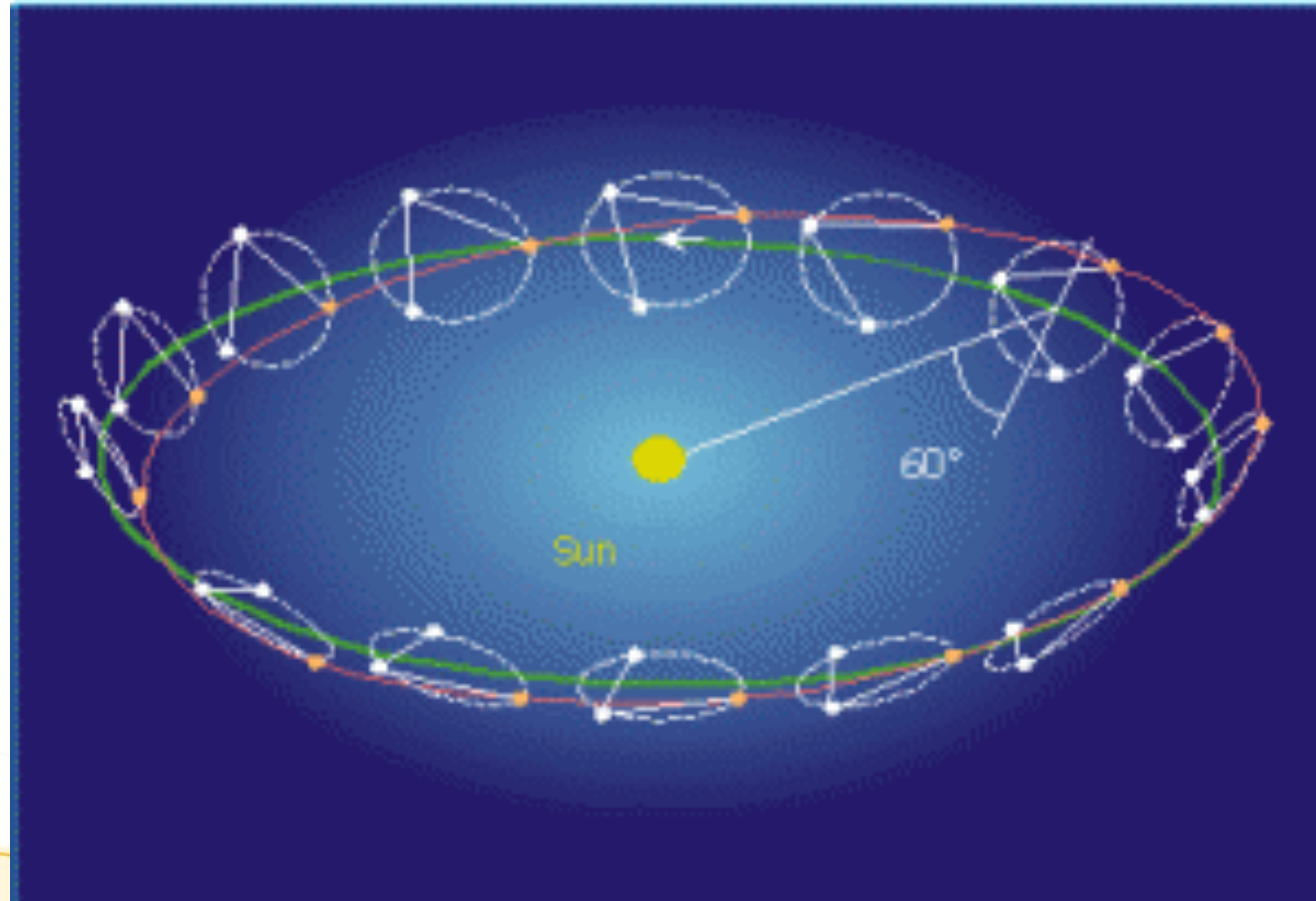

LCGT
Kamioka mine
Kamioka
Gifu Prefecture
of Japan
Neutrino Detector
Super Kamiokande
3 km
LCGT
Atotsu Entrance

LIGO India

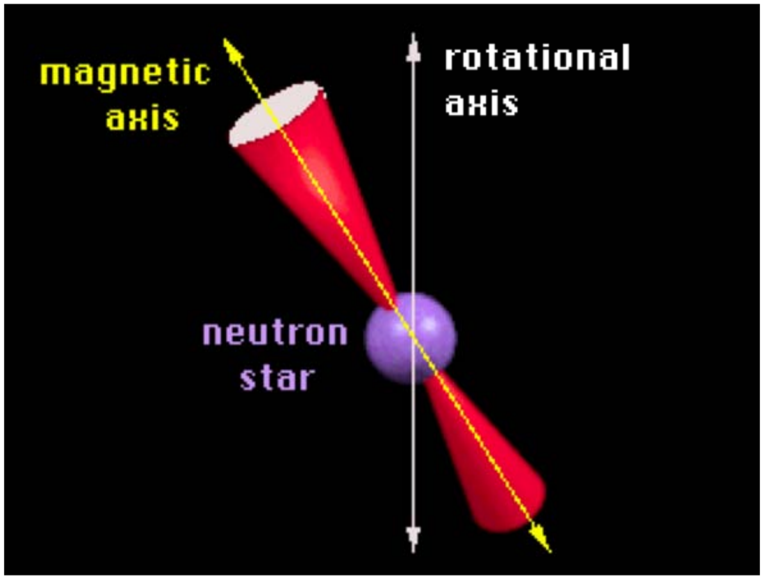
AIGO Perth Australia

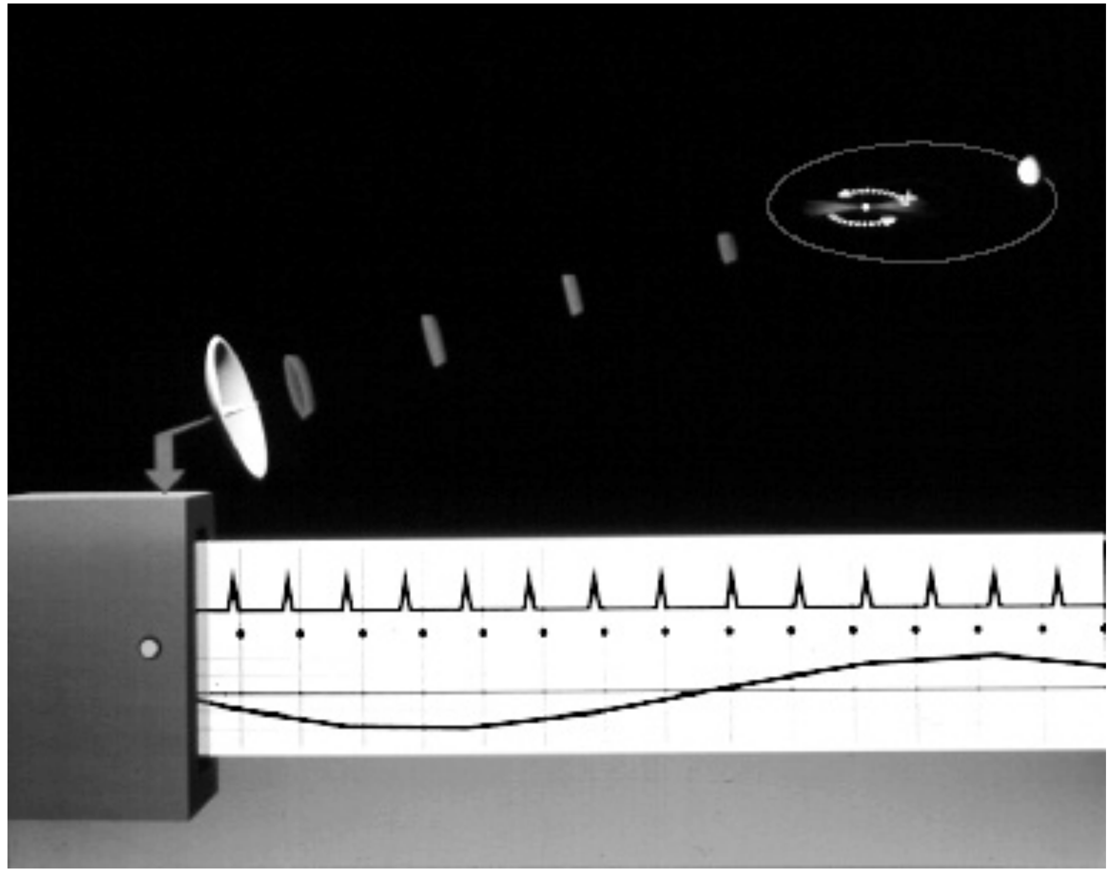
eLISA Space-based



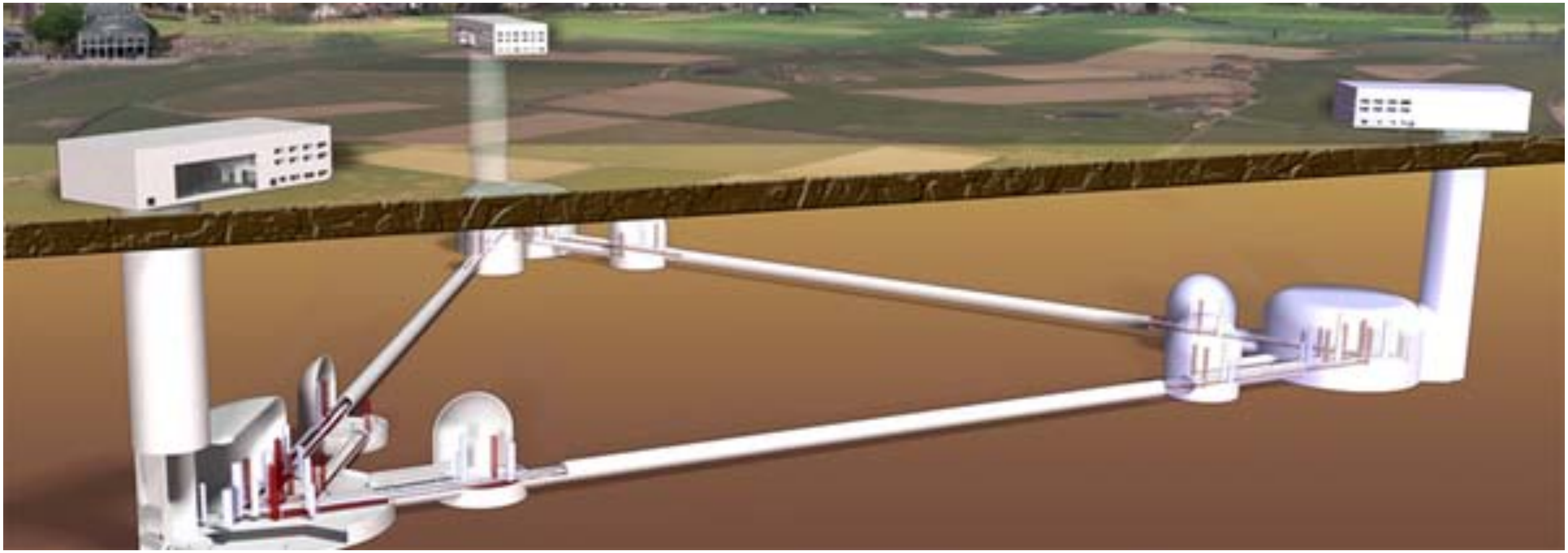

60°
Sun

Pulsar Timing

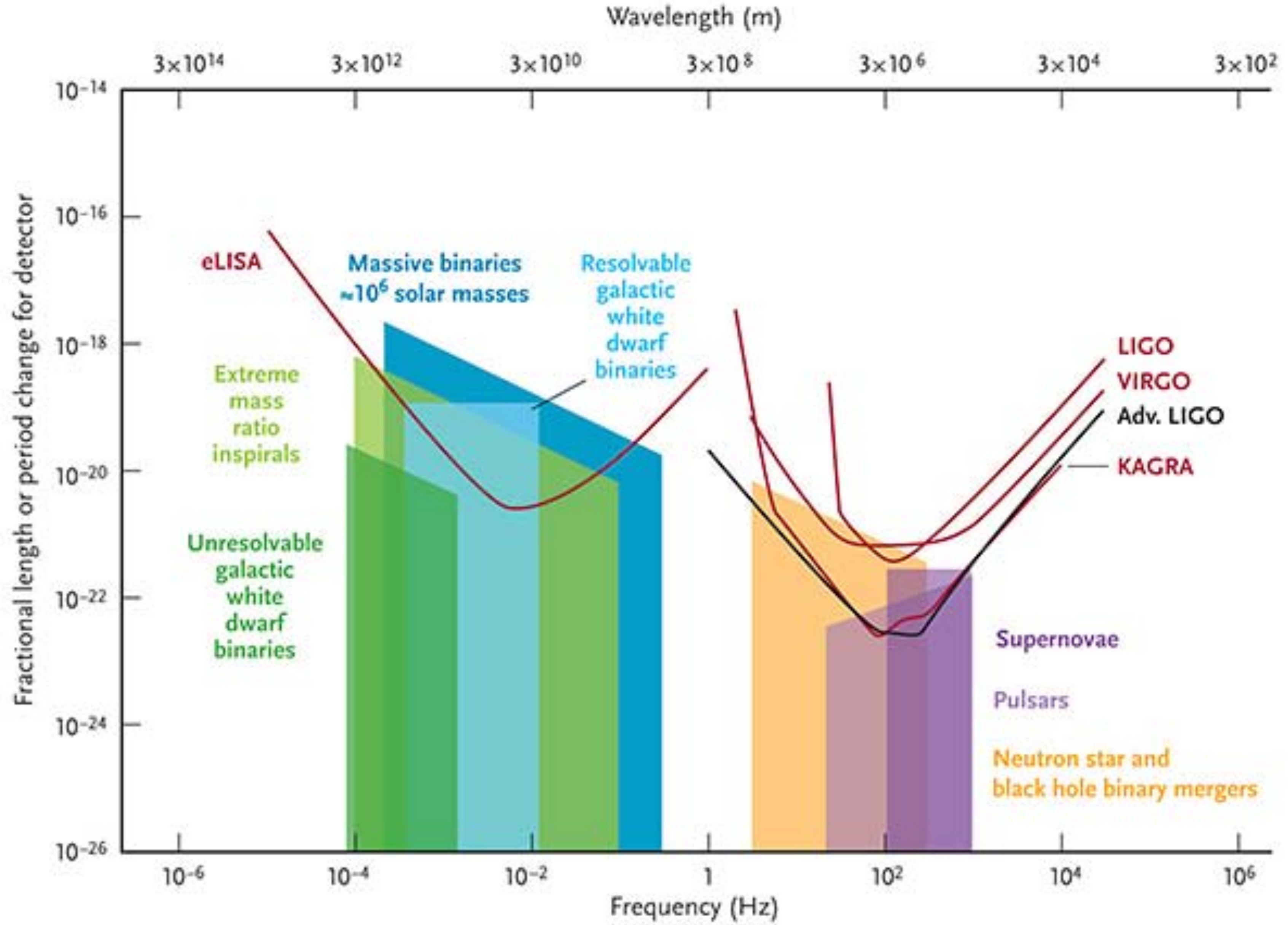




Einstein Telescope



GW Spectrum RMS Amplitude vs Frequency



4 Reasons why we must know what the signals look like in advance

- Justify the money spent on detectors
- Understand what the GW observatories are seeing
- Test different theories of gravity
- Observe new Astrophysical events

How do we determine what GW signals look like?

- Few signals can be determined analytically
- Numerical Simulations are needed
- Numerical Relativity is the science of solving Einstein's Equations numerically

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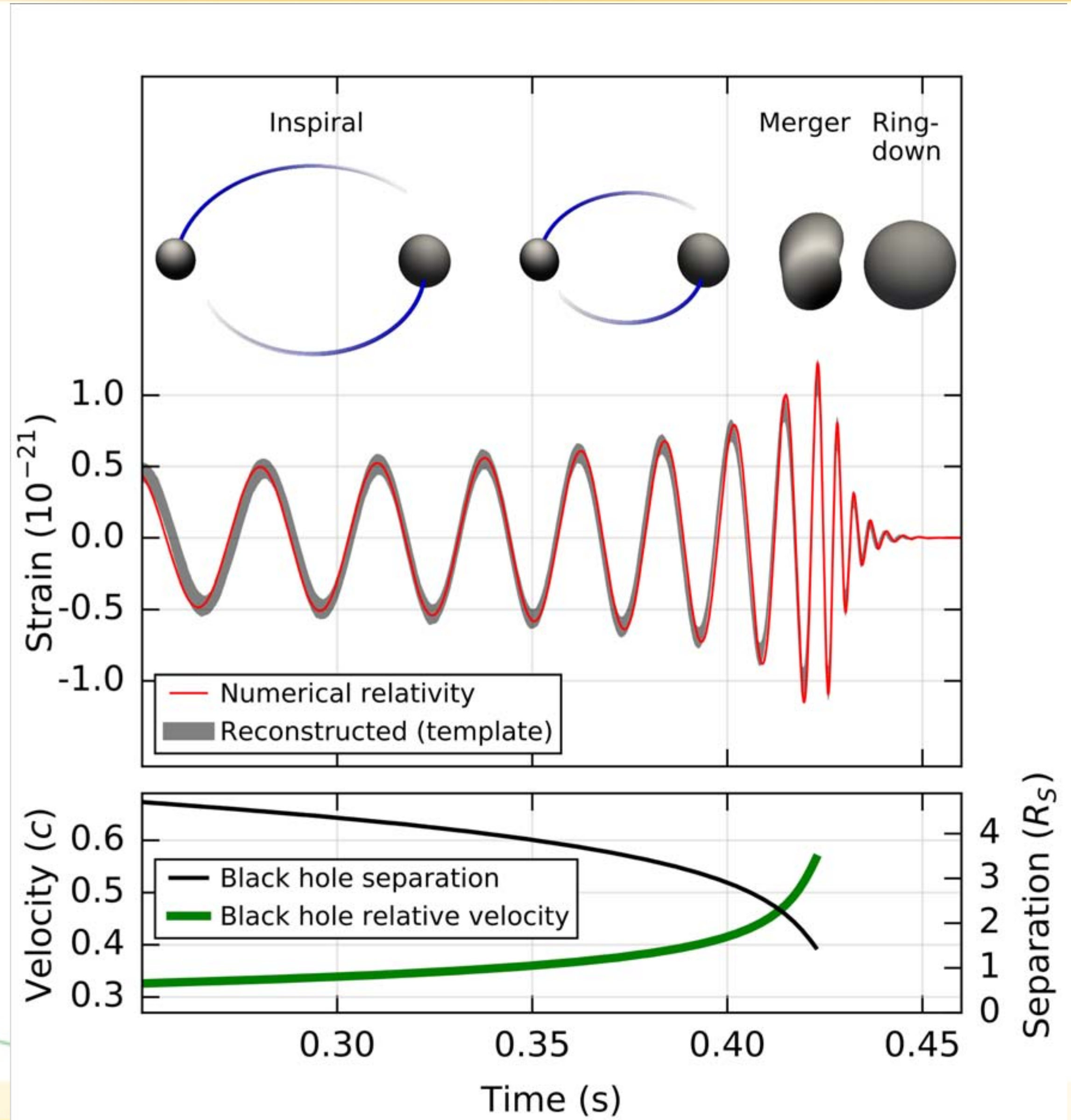

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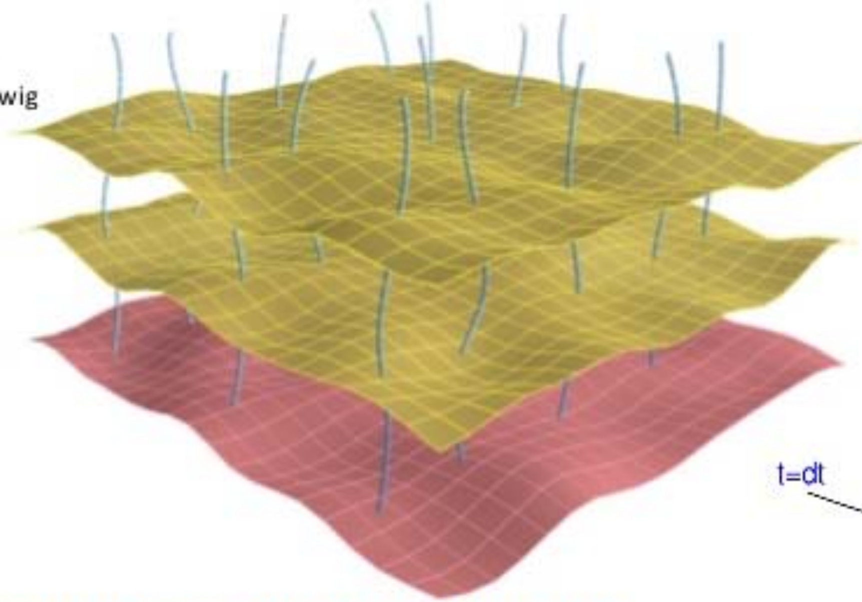
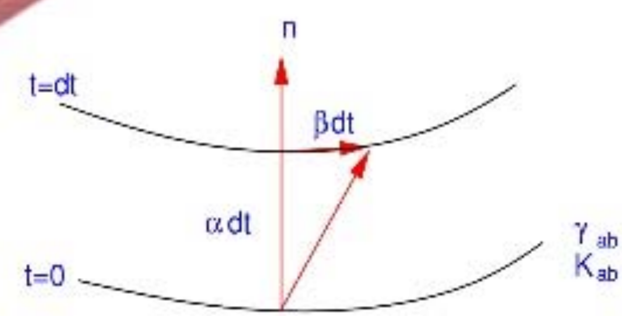
How Numerical Simulations Work

Basic Idea of Numerical Relativity

Figure: C. Reisswig

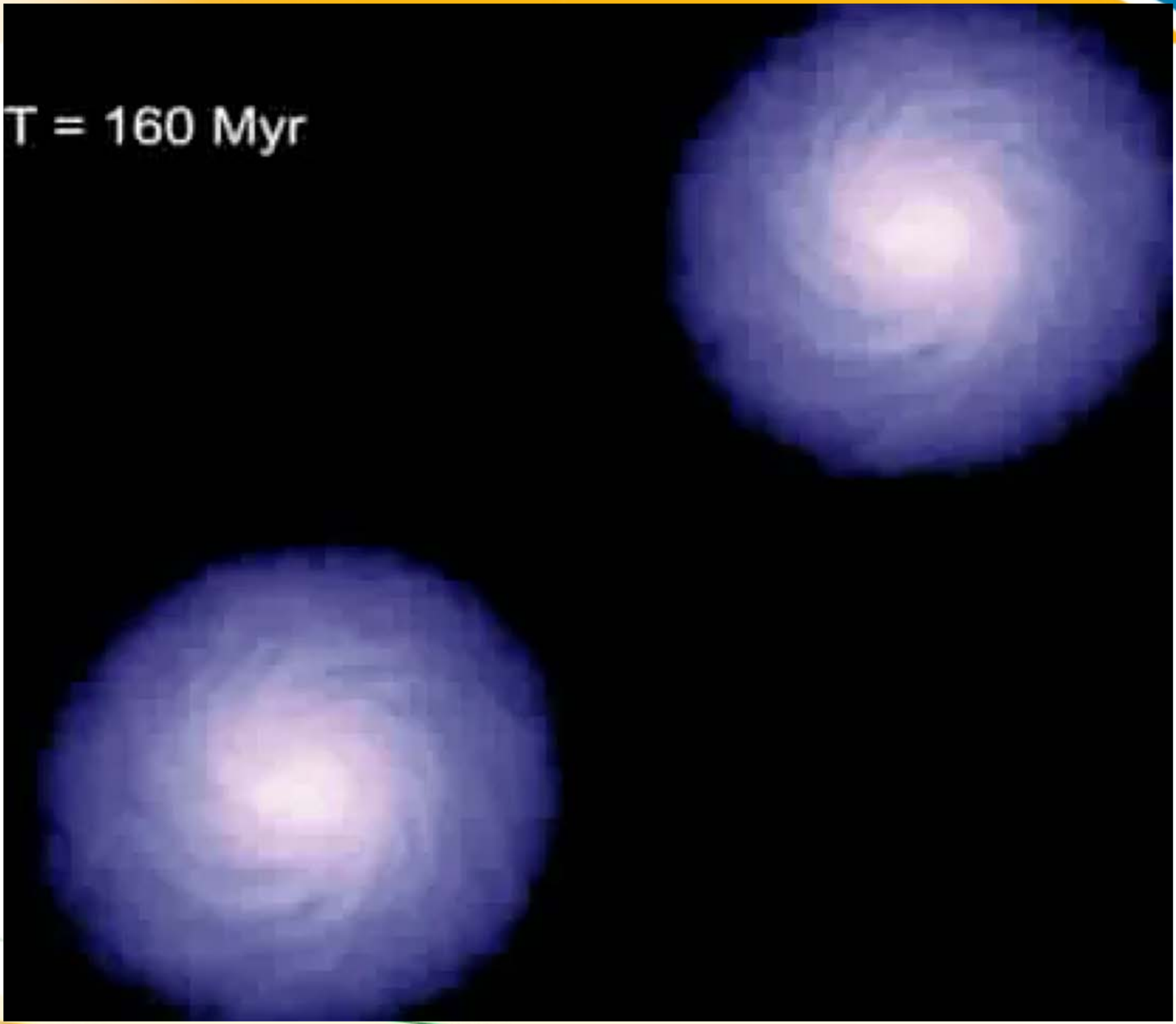


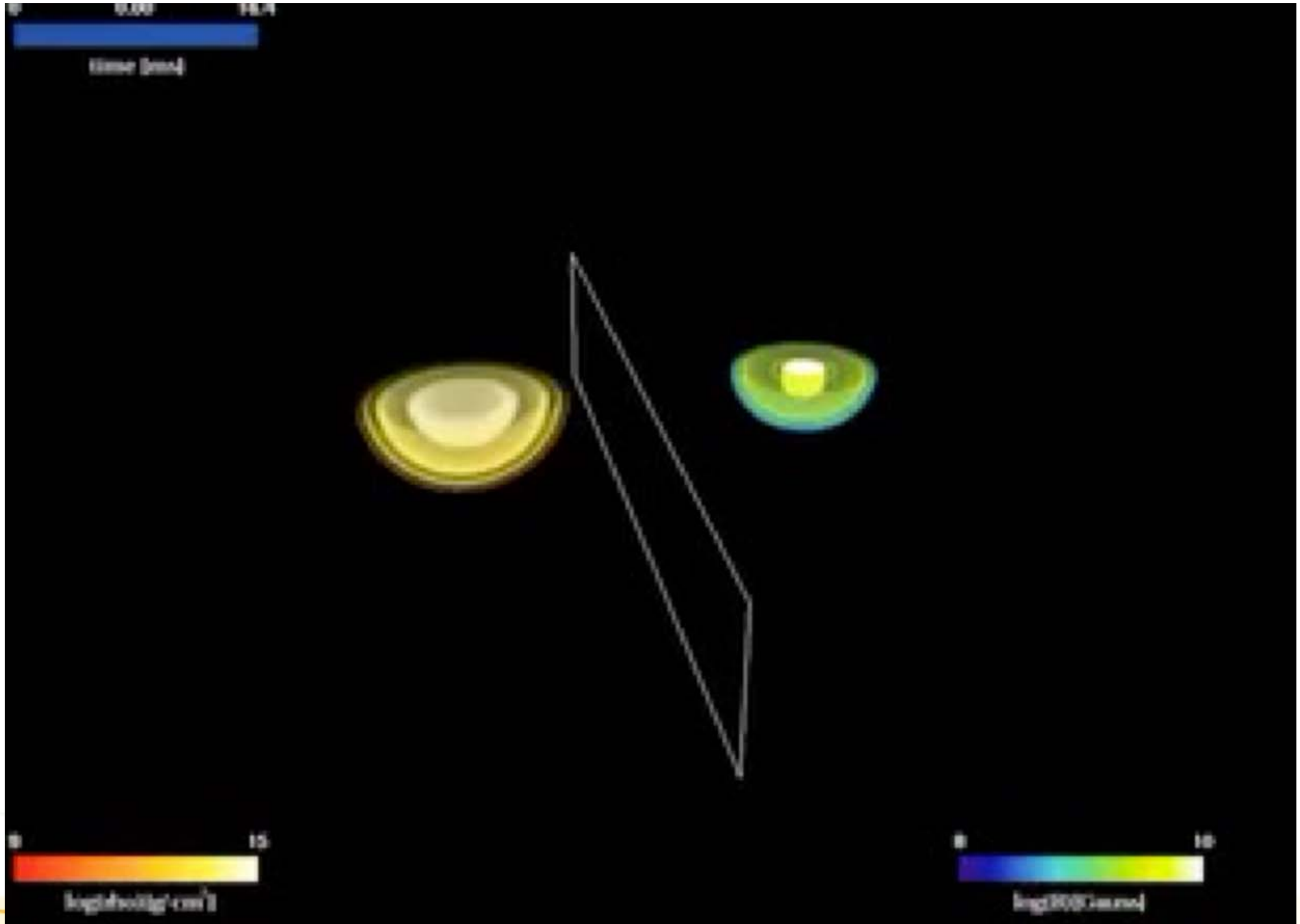
Arnowitt-Deser-Misner, Lichnerowitz
3+1 split of spacetime



$$G^{\mu\nu} = \frac{8\pi G}{c^4} T^{\mu\nu}$$

- 12 first-order hyperbolic *evolution* equations.
- 4 elliptic *constraint* equations
- 4 coordinate gauge degrees of freedom: α, β^i.


T = 160 Myr



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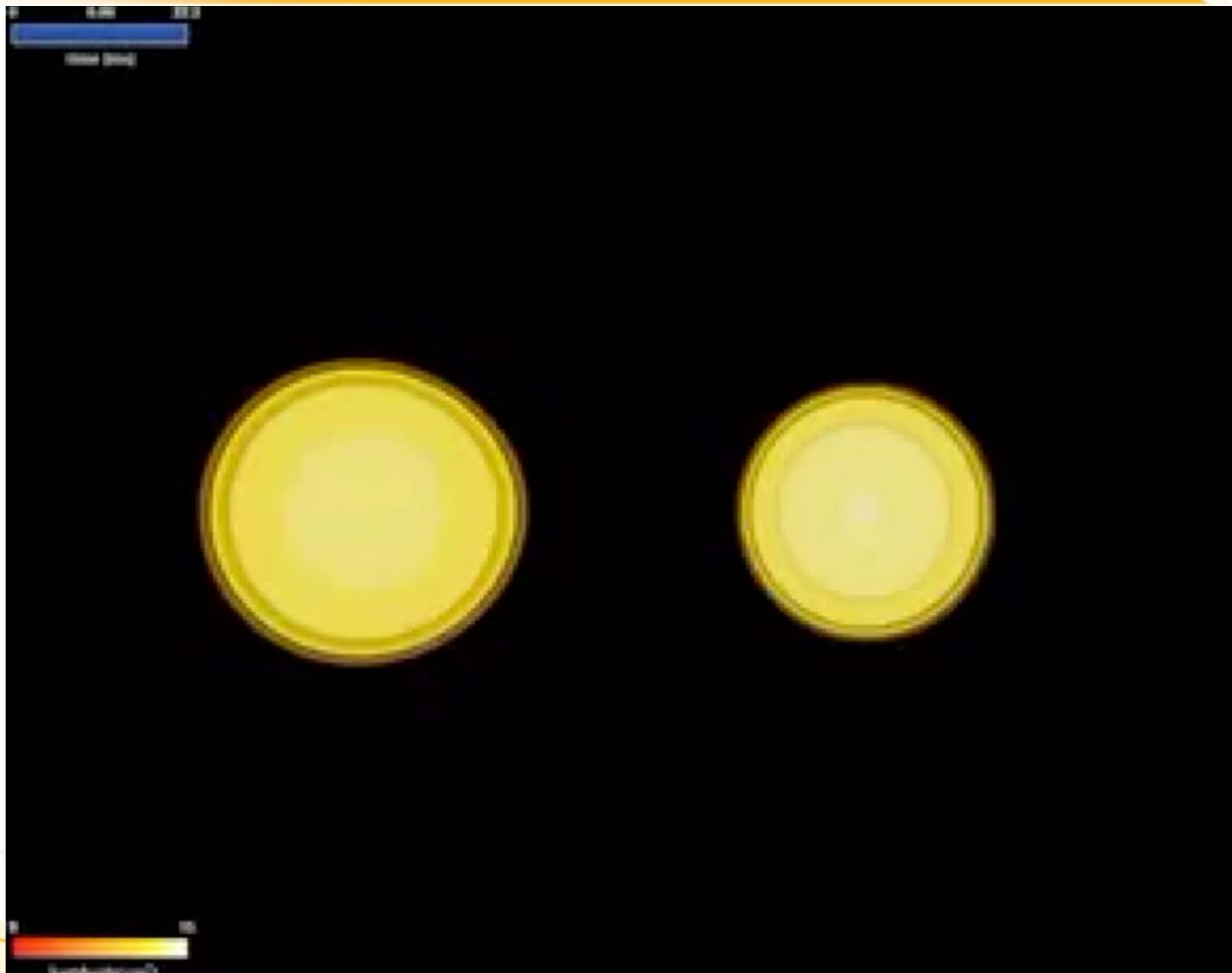

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ECCENTRIC BINARY NEUTRON STAR MERGERS: A SIMULATION IN FULL GENERAL RELATIVITY

- Ludwig Jens Papenfort (ITP, Germany)
- Luciano Rezzolla (ITP, Germany)

COST Action MP1340
Exploring fundamental physics with compact stars (NewCompStar)

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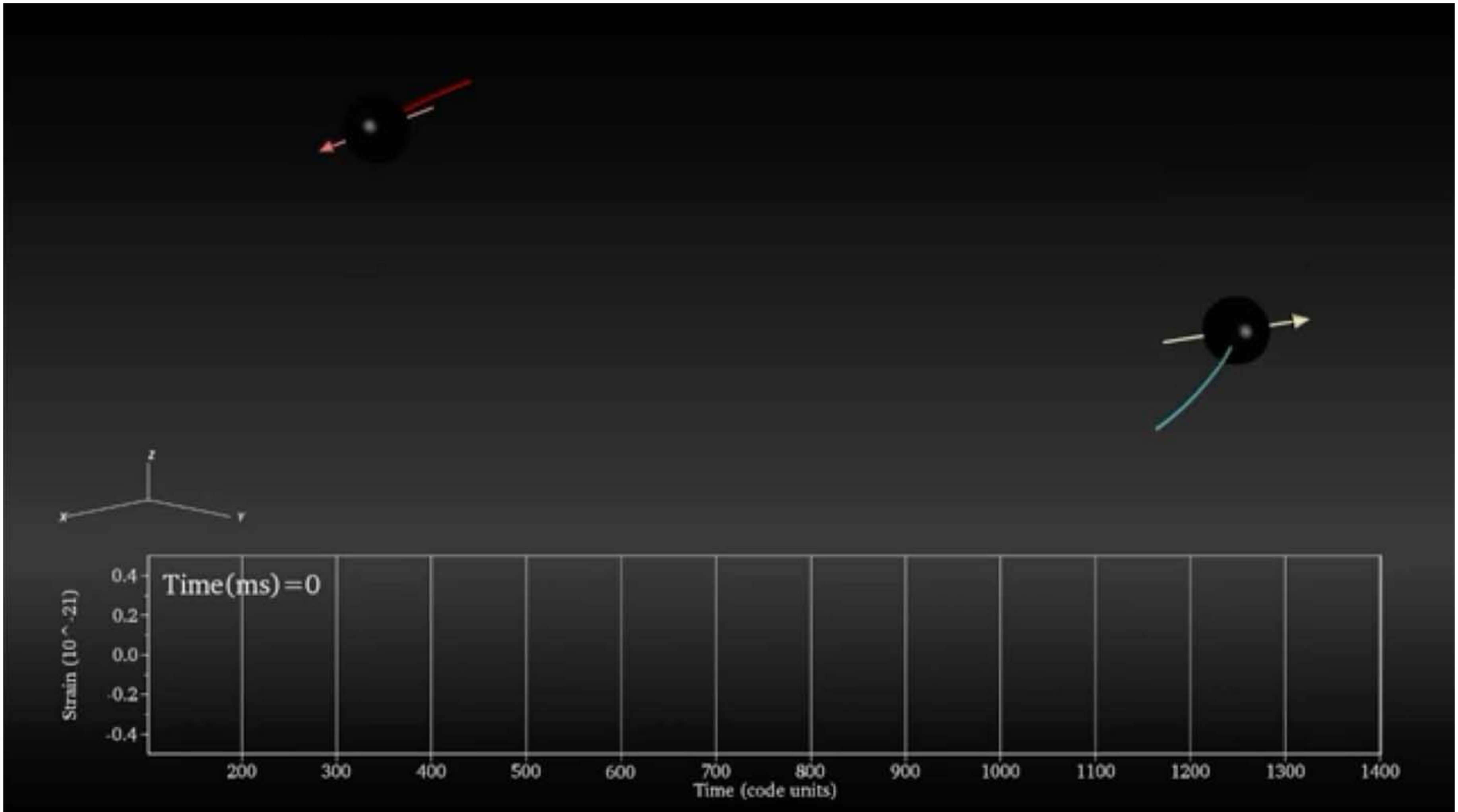
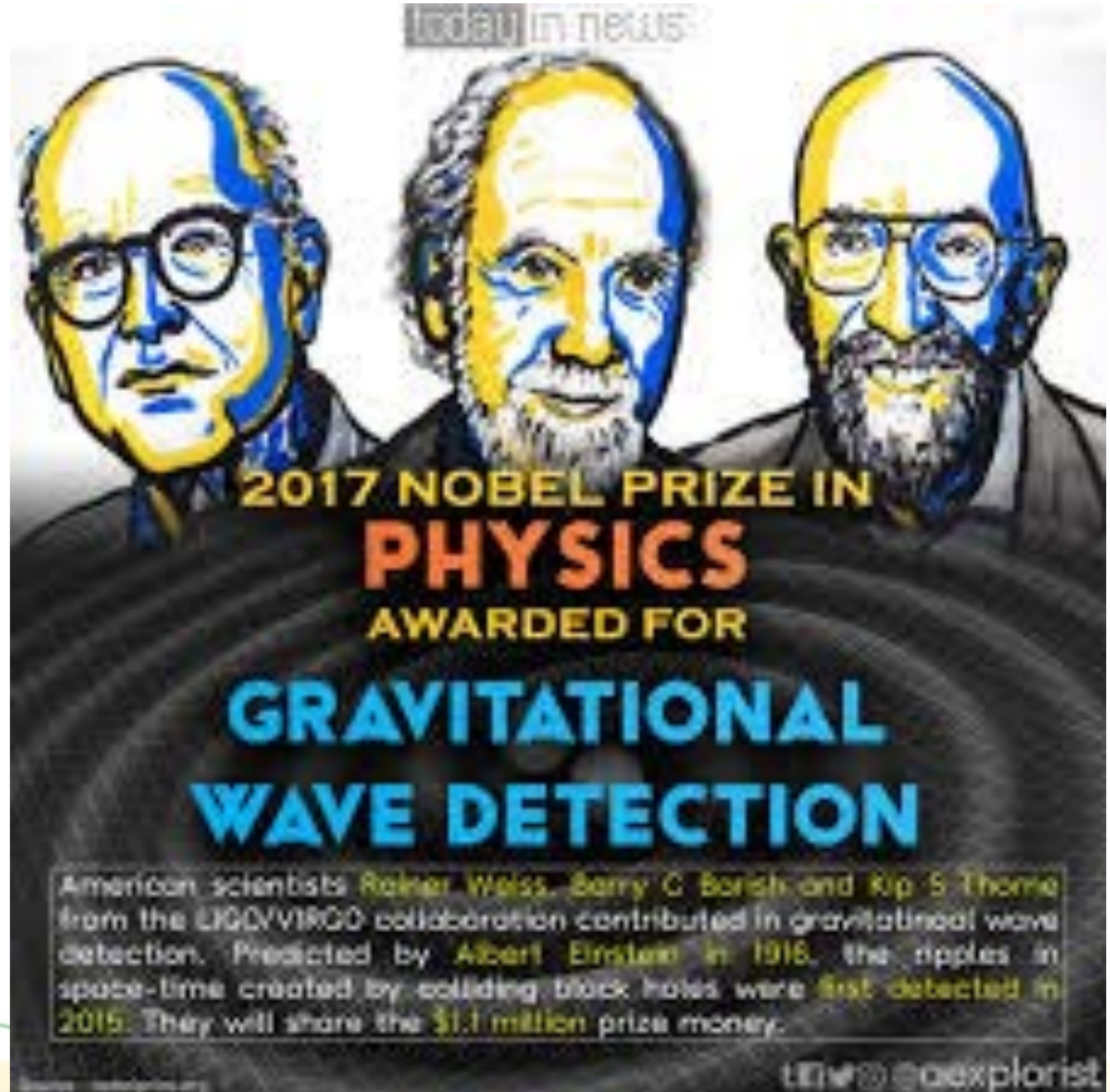


2017 Nobel Prize in Physics



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Conclusion

- Gravitational Wave physics is an important part of modern physics
- There is currently a large international effort to observe and study gravitational waves
- Numerical simulations are needed to get useful information out of the observations

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Questions?