

Gravitational Wave Astronomy 101

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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



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Where the Heck did all that come from?





First Observatories







New Technologies







Putting it all together





Not Everyone Understands the Theory

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University of Houston Time Since Big Bang Major Events Since Big Bang We have some idea, but don't know for sure how the universe is going to end

the universe is going to end Humans present observe stars. the cosmos. galaxies Era of and clusters Galaxies (made of atoms and The observable plasma) 1 billion **First galaxies** universe atoms and years form. plasma Era of (stars Atoms begin Atoms form: to form) photons fly free 500.000 and become microwave years plasma of hydrogen and background. Era of We know what's helium nuclei Nuclei Fusion ceases: plus electrons normal matter is going on base on 3 minutes 75% hydrogen, protons, neutrons, Era of 25% helium, by our knowledge of electrons, neutrinos Nucleosynthesis mass. (antimatter rare) physics Matter annihilates 0.001 seconds elementary particles antimatter. Particle Era (antimatter Electromagnetic and weak common) 10⁻¹⁰ seconds forces become distinct. elementary Electroweak Era particles Strong force becomes 10⁻³⁸ seconds distinct, perhaps causing inflation of elementary GUT Era universe. We still don't particles 10⁻⁴³ seconds Planck Era ???? know how physics works neutron electron antiproton antielectrons 42 quarks neutrino antineutron proton in this era yet.

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Inflation and Gravitational

Waves







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

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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



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.







Pulsars



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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









What are other sources of GWs?

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

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• Exotic Sources

THE DARK SIDE OF THE UNIVERSE
· BLACK HOLES
· CRACKS IN THE FABRIC OF SPACE
Linear Cracks ("cosmic strings") Grav's Waves Circumference <2TT x Radius
Surface Cracks ("domain walls")
Curved leftward 35 seen from left Gravel
SINCULARITIES Gravil wover
LIGO & future GW detectors [will Search for them all]



• Plus Polarization

Gravitational vs EM Radiation

GRAVITATIONAL WAVES CONTRASTED WITH ELECTROMAGNETIC WAVES

ELECTROMAGNETIC GRAVITATIONAL

propagating through spacetime

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> Oscillations of EM field Oscillations of the "fabric" of spacetime itself

Incoherent superposition Coherent emission by bulk of waves from molecules, motion of matter and energy atoms, and particles

Frequencies ~ 1 MHz and upward 20 orders Easily absorbed and scattered

Emitted from surfaces of objects (where optically thin and gravity is weak)

Frequencies ~ 1 kHz and downward 20 orders Never significantly absorbed or scattered

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

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Gravitational Wave Astronomy

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

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How GW interferometers work

LASER - INTERFEROMETER MIM GRAVITATIONAL - WAVE mirror DETECTORS LASER C L+AL PHOTODIODE $\frac{\Delta L}{L} = WAVE STRENGTH \approx 10^{-21}$ • IF AL = to millimeter, NEED L = 3 light years • IF AL=10 cm= (Diameter of atomic nucleus), Need L = 4000 kilometers · CAN MEASURE AL=10 Cm= 1000 × (Diameter of atomic nucleus) Build L = 4 kilometers g) pus

• This is a cut-away of LIGO

LIGO Hanford Washington

Laser Interferometer Gravitational-wave Observatory

LIGO Livingston Louisiana

VIRGO Pisa, Italy

GEO600 Hanover, Germany

KAGRA Japan

LIGO India

AIGO Perth Australia

eLISA Space-based

Pulsar Timing

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Einstein Telescope

GW Spectrum RMS Amplitude vs Frequency

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

• Justify the money spent on detectors

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- 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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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)

2017 Nobel Prize in Physics

REAL IN THE REAL

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> 017 NOBEL PRIZE IN AWARDED FOR GRAVITATIONAL WAVE DETECTION American scientists Rainer Weiss, Barry C Barish and Kip SiThome

> American scientists Relier Weiss, Barry C Barish and Kip S Thome from the LIGO/VIRGO collaboration contributed in gravitatineal wave detection. Predicted by Albert Einstein in 1916, the ripples in space-time created by colliding block holes were first detected in 2015: They will share the \$1.1 million prize money.

> > tew mac according terms

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

