RELATIVITY OF SPACE AND TIME IN POPULAR SCIENCE

RICHARD ANANTUA

MIDTERM PRESENTATION (WED JUL 26 & FRI JUL 28)

- Choose a course topic from the syllabus and describe
  - Historical setting (e.g., state of physics) early in the development of the topic
  - Events spurring research in the topic
  - Key contributors to our modern understanding of the topic
  - Experiments (thought or physical) leading to this understanding
- 12 min PowerPoint + 3 min Q & A

MIDTERM PAPER (DUE FRI JUL 28)

- In 3-4 double-spaced pages, explain 5 key concepts in relativity using popular science or science fiction. As a guideline, a key concept is at the level of generality of a lecture slide title, but do not hesitate to email about whether a list of concepts is suitable.
  - Option A: Popular Science – Clearly state and answer 5 questions on relativity topics which may or may not directly relate to one another. Confer http://magazine.ivy.com/2017/02/why-are-we-here-in-the-universe/
  - Option B: Science Fiction – Make a coherent and captivating storyline in which events and discussions clearly illustrate and explain the 5 concepts

REVIEW OF JUL 21

- Written in 1884 by English novelist Edwin Abbott, *Flatland – A Romance of Many Dimensions* satyrically chronicals the real and imagined journeys of a heretical square though ____land, ____land, Flatland and the World of _____ Dimensions. Important themes include:
  - Geometry as destiny – one's destiny is encoded in one's form at birth
  - Upward, not northward – transcending one's lived experience
  - Practice what you preach – hypocrites fail to see in themselves the limitations they see in others

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- Written in 1884 by English novelist Edwin Abbott, *Flatland – A Romance of Many Dimensions* satyrically chronicals the real and imagined journeys of a heretical square though Pointland, Lineland, Flatland and the World of Three Dimensions. Important themes include:
  - Geometry as destiny – one's destiny is encoded in one's form at birth
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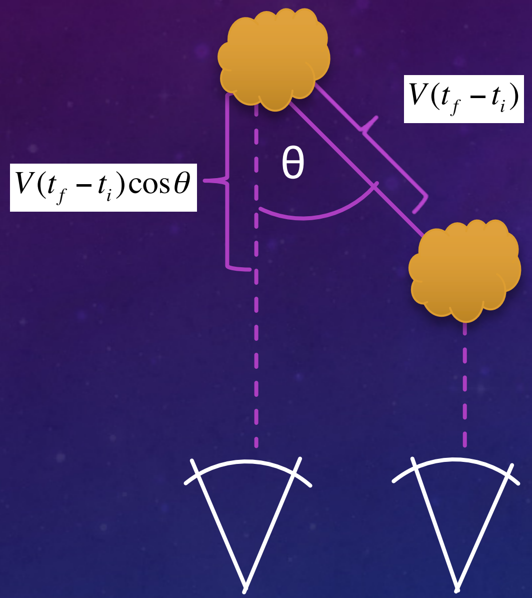
SUPERLUMINAL FEATURES IN M87 JET?

- Features moving with apparent speed 6c in M87 observed by Hubble (Biretta, J. A., Sparks, W. B., & Macchetto, F., 1999, ApJ 520, 621)
- Projection/finite c effect for blob moving at speed V from t_i to t_f shortens observed time difference by τ:



$$V_{\mathrm{t,app}} =?\,, \tau =?$$

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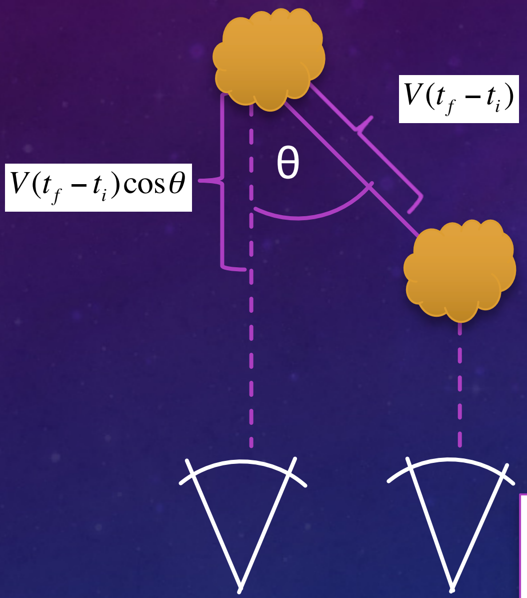

$$V_{t,app} = \frac{V(t_f - t_i)\sin\theta}{(t_f - t_i) - \tau}, \tau = \frac{V(t_f - t_i)\cos\theta}{c}$$

$$\Rightarrow V_{t,app} = \frac{V\sin\theta}{1 - \dfrac{V\cos\theta}{c}}$$

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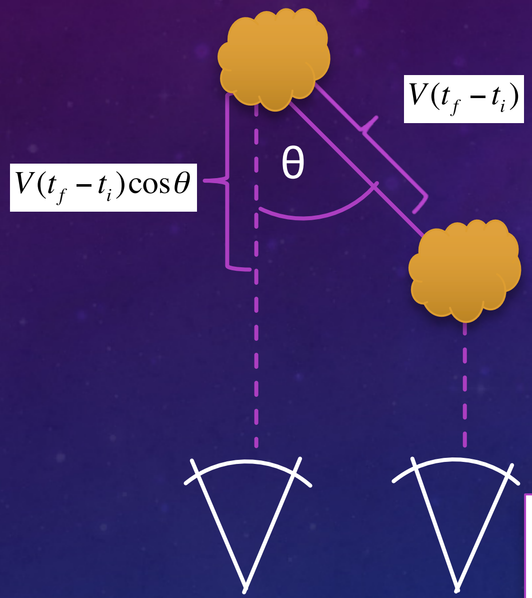

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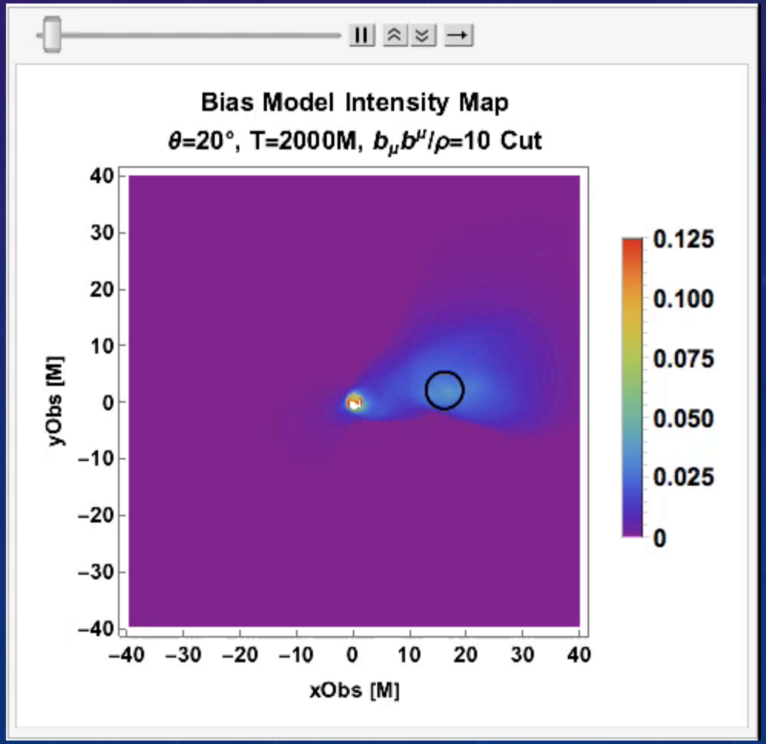
$(\Theta_{Obs},\Phi_{Obs})=(20°,0°)$, TObs=2000M,2056M,…,2560M
Emissivity: $j'_\nu \sim b'^{1.5}$ Disk subtraction: $b_\mu b^\mu/\rho>10$



TESTS OF RELATIVITY

- Flying atomic clocks
- Muon decay
- Light bending around stars
- LIGO’s gravitational wave detection

FLYING ATOMIC CLOCKS (GROUP ACTIVITY)

- In 1971, Joseph Hafele and Richard Keating flew Cs atomic clocks around the world Eastward and Westward
- Suppose there a master clock at the center C of the Earth that advances $\Delta\tau$
- Taylor expand the kinematic time dilation formula to 2nd order in velocity to find the time elapsed on
    - a.) The surface of the Earth $(\Delta T)_{SC}$
    - b.) The Eastbound flight $(\Delta T)_{EC}$
    - c.) The Westbound flight $(\Delta T)_{WC}$
- What is the time difference relative to the Earth's surface for Eastbound and Westbound flights?
- The kinematic time dilation contribution to time elapsed on flying clocks may take either sign. What signs may the gravitational contribution take?

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$$\Delta T = \left(1 - \frac{\mathrm{v}^2}{c^2}\right)^{-1/2} \Delta\tau \approx \left(1 + \frac{1}{2c^2}\mathrm{v}^2\right)\Delta\tau \Rightarrow$$

$$(\Delta T)_{SC} \approx \left(1 + \frac{\mathrm{R}^2\omega^2}{2c^2}\right)\Delta\tau$$

$$(\Delta T)_{EC} \approx \left(1 + \frac{(\mathrm{v} + R\omega)^2}{2c^2}\right)\Delta\tau$$

$$(\Delta T)_{WC} \approx \left(1 + \frac{(\mathrm{v} - R\omega)^2}{2c^2}\right)\Delta\tau$$

- What is the time difference relative to the Earth's surface for Eastbound and Westbound flights?

$$(\Delta T)_{EC} - (\Delta T)_{SC} \approx \left(\frac{2R\omega\mathrm{v} + \mathrm{v}^2}{2c^2}\right)\Delta\tau, \qquad (\Delta T)_{WC} - (\Delta T)_{SC} \approx \left(\frac{-2R\omega\mathrm{v} + \mathrm{v}^2}{2c^2}\right)\Delta\tau$$

- The kinematic time dilation contribution to time elapsed on flying clocks may take either sign. What signs may the gravitational contribution take?

Positive, since clocks flying at high altitude run faster in the weaker gravitational field relative to the surface

FLYING ATOMIC CLOCKS

- In 1971, Joseph Hafele and Richard Keating flew Cs atomic clocks around the world Eastward and Westward
- The results of the experiment (Hafele and Keating, 1972) were:

	nanoseconds gained, predicted			nanoseconds gained, measured	difference
	gravitational (general relativity)	kinematic (special relativity)	total		
eastward	+144 ±14	−184 ±18	−40 ±23	−59 ±10	0.76 σ
westward	+179 ±18	+96 ±10	+275 ±21	+273 ±7	0.09 σ

MUON DECAY

- Exercise: In 1977 at CERN, muons (specifically μ^+ particles) were accelerated to v/c=0.9994 in a 14m circumference storage ring. If a muon's lifetime (before decaying into positrons and neutrinos) at rest is $\tau=2.2\text{x}10^{-6}$s, what does special relativity predict is the expected lifetime T of the boosted muon?

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$$T = \gamma\tau = \frac{\tau}{\sqrt{1 - v^2/c^2}} = \frac{2.2 \cdot 10^{-6}}{\sqrt{1 - (0.9994)^2}}\text{s} = 6.4 \cdot 10^{-5}\text{s}$$

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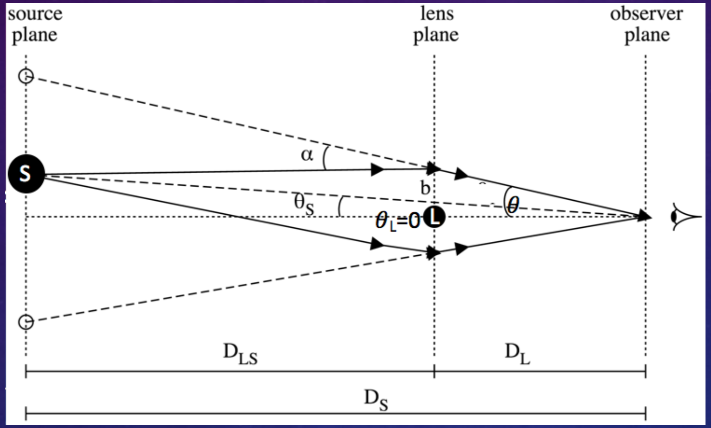
- The experimentally (Bailey et al. 1977) measured lifetimes were related as

$$\frac{T_{\mathrm{Exp}}}{\gamma\tau_{\mathrm{Exp}}} = 1 + (9 \pm 2) \cdot 10^{-4}$$

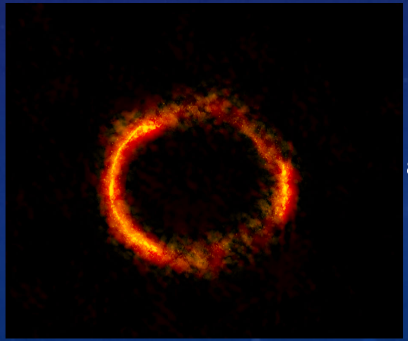
LIGHT BENDING AROUND STARS – ASTROMERIC MICROLENSING

- In astrometric microlensing, light from a source at D_s is deflected by a gravitationally lensing star of mass M at D_L into at least 2 images



and possibly Einstein ring of angular width

$$\theta_E = \sqrt{\frac{4GM}{c^2 D_r}}, \quad D_r \approx \left(\frac{1}{D_S} - \frac{1}{D_L}\right)^{-1} = \frac{D_S D_L}{D_S - D_L}$$



Einstein ring of gravitationally lensed galaxy SDP 81. Courtesy of ALMA (NRAO/ESO/NAOJ); B. Saxton NRAO/AUI/NSF

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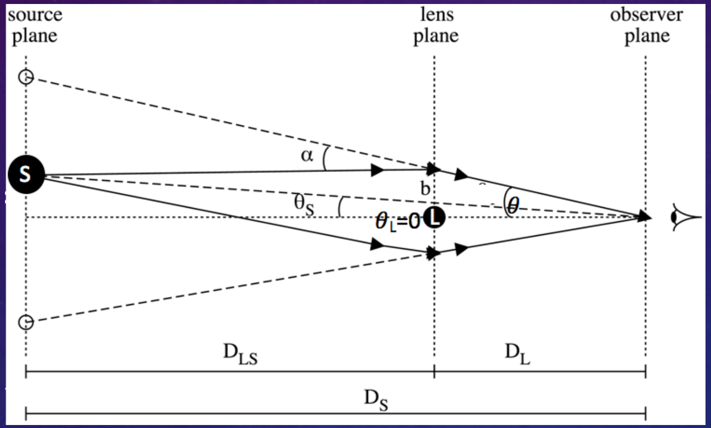
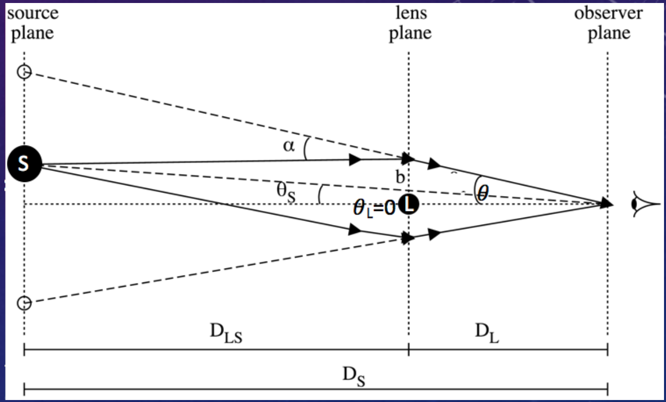


- The deflection α of light from the source rays in the absence of the lens is given by

$$\alpha = \delta\theta = \theta_E \frac{\sqrt{\left(\frac{\Delta_{SL}\theta}{\theta_E}\right)^2 + 4} - \frac{\Delta_{SL}\theta}{\theta_E}}{2}, \qquad \Delta_{SL}\theta = \theta_S - \theta_L$$

LIGHT BENDING AROUND STARS

- Exercise: Read http://science.sciencemag.org/content/early/2017/06/06/science.aal2879.ful and determine which are the source and the lensing stars. Assume the lens is directly in front of the observer



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to determine the angular deflection α (in arc seconds (")) of a source separated 0.5" from a lens resulting in Einstein radius 31 mas (where 1 mas = 1×10^{-3}"). If $\Delta_{SL}\theta \to 0$, how do source and image relate and what does the observer see?

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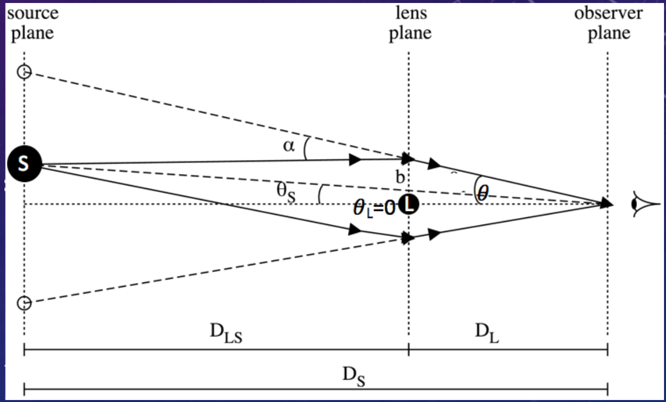

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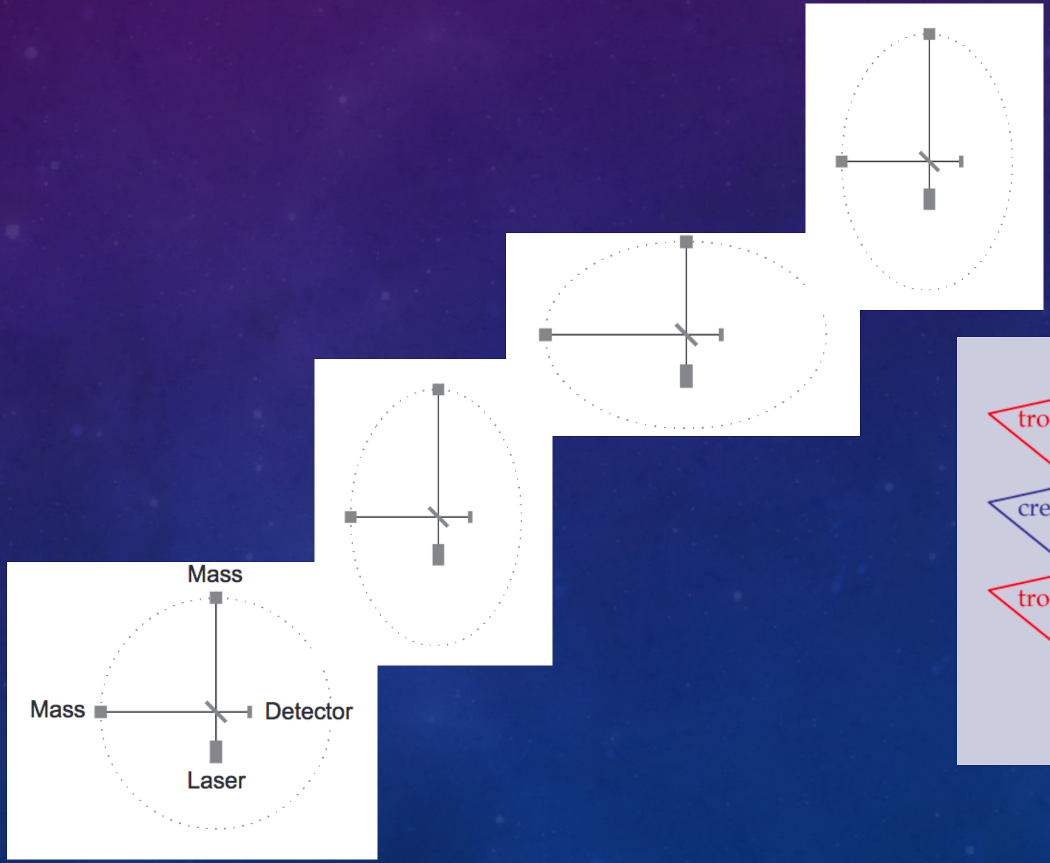
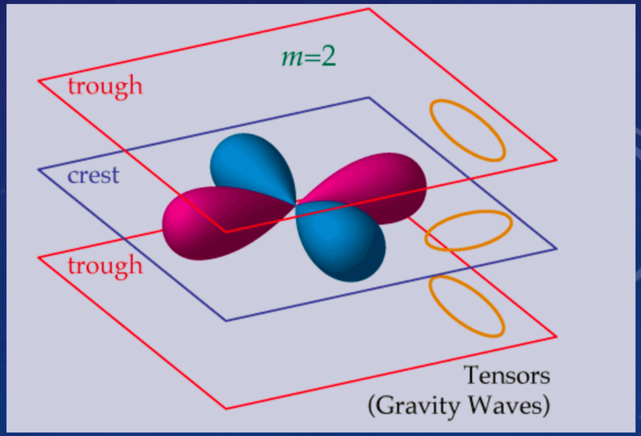
L

- See Problem Set 3

GRAVITATIONAL WAVES

- Gravitational waves are tensor perturbations $\sim Y_l^m$ in space distorting mass distributions in |m|=2 perpendicular directions

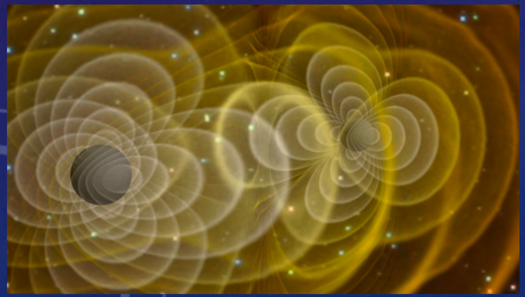


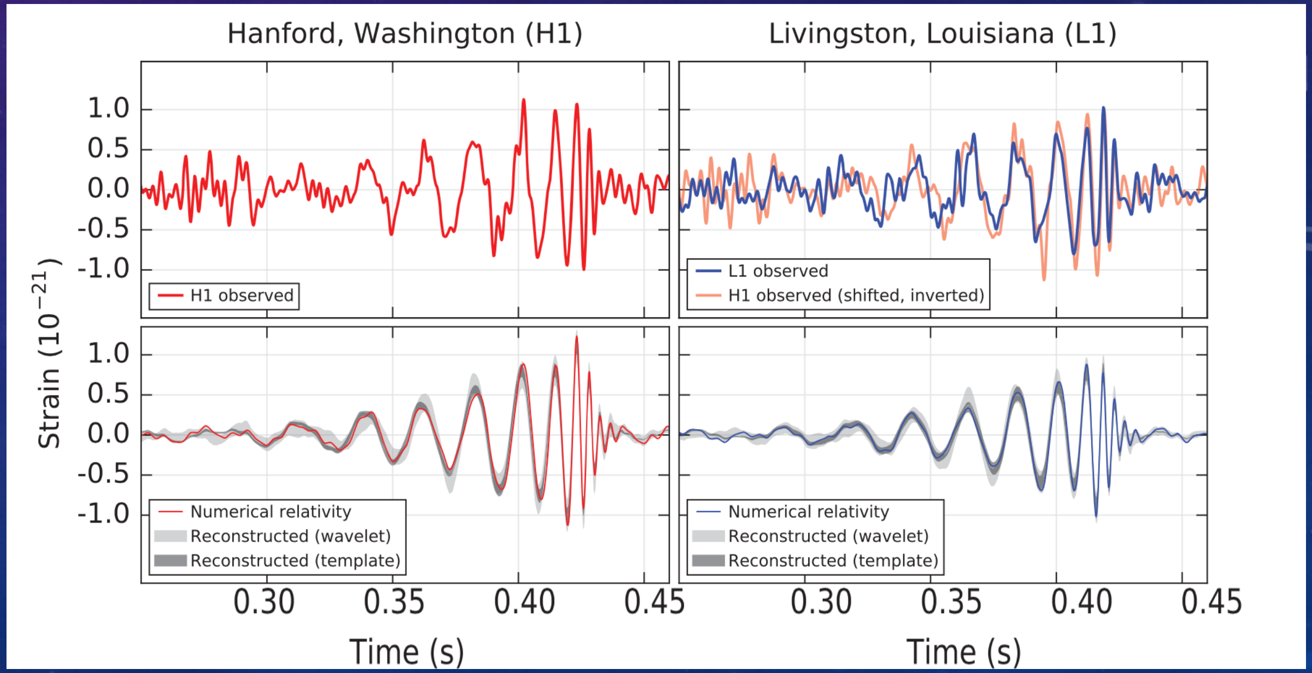


GRAVITATIONAL WAVES

- In 2015, the Laser Interferometer Gravitational-Wave Observer (LIGO) detected gravitational waves matching the general relativistic predicted signal due to a black hole merger:

https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.116.061102





THE TIME MACHINE- SPACE VS. TIME

- What are fundamental differences between space and time dimensions? Consider p. 6:

> ‘But,’ said the Medical Man, staring hard at a coal in the fire, ‘if Time is really only a fourth dimension of Space, why is it, and why has it always been, regarded as something different? And why cannot we move in Time as we move about in the other dimensions of Space?’

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- Unlike other spacetime dimensions, time has a fixed direction (arrow of time) in which events progress

THE TIME MACHINE- SPACE VS. TIME

- In relativity, what can move in space at the same rate it moves in time? Consider p. 6:

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- Only massless particles can move in null (light-like) geodesics

THE TIME MACHINE-TIME TRAVEL

- Compare the time machine described pp. 12 and 56 to time travel predicted in relativity

'It took two years to make,' retorted the Time Traveller. Then, when we had all imitated the action of the Medical Man, he said: 'Now I want you clearly to understand that this lever, being pressed over, sends the machine gliding into the future, and this other reverses the motion. This saddle represents the seat of a time traveller. Presently I am going to press the lever, and off the machine will go. It will vanish, pass into future Time, and disappear. Have a good look at the thing. Look at the table too, and satisfy yourselves there is no trickery. I don't want to waste this model, and then be told I'm a quack.'

my invention had vanished. Yet, for one thing I felt assured: unless some other age had produced its exact duplicate, the machine could not have moved in time. The attachment of the levers—I will show you the method later— prevented any one from tampering with it in that way when they were removed. It had moved, and was hid, only in space. But then, where could it be?

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- Time dilation can change the amount proper time advances on different worldlines

THE TIME MACHINE - PROPER TIME AND 4-VELOCITY

- Classically, the rate at which an object travels through space is $d\mathbf{x}/dt$, but there is no natural way to express a rate of passage through time.
- Consider p. 15

> delightfully. We cannot see it, nor can we appreciate this machine, any more than we can the spoke of a wheel spinning, or a bullet flying through the air. If it is travelling through time fifty times or a hundred times faster than we are, if it gets through a minute while we get through a second, the impression it creates will of course be only one-fiftieth or one-hundredth of what it would make if it were not travelling in time. That's plain

- How do we express velocity through space and time in relativity?

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- In relativity, we can write the rate of travel through space AND through time as $dx^i/d\tau = \gamma \mathbf{v}$ and $dx^0/d\tau = \gamma c$

$$x^\mu = (x^0, \vec{x}\,) = (ct, \vec{x}\,) = (\gamma c\tau, \vec{x}\,)$$

$$U^\mu = \frac{dx^\mu}{d\tau}$$

POP QUIZ - THE TIME MACHINE: TIME DILATION

- Can clocks ever seem to run fast in relativity (think gravitational time dilation)?

intellect had tricked me. Then I noted the clock. A

26 *of* 148

The Time Machine

moment before, as it seemed, it had stood at a minute or so past ten; now it was nearly half-past three!

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The Time Machine DEBENU PDF FREEDOM

moment before, as it seemed, it had stood at a minute or so past ten; now it was nearly half-past three!

- Just as strengthening the gravitational field slows the period of light, weakening the gravitational field around an object makes time appear to elapse faster for the object.