

A visualization of a gravitational wave, showing a blue grid of spacetime being distorted by a passing wave. A bright orange ring highlights the wave's path, and a white wavy line represents the wave's oscillation.

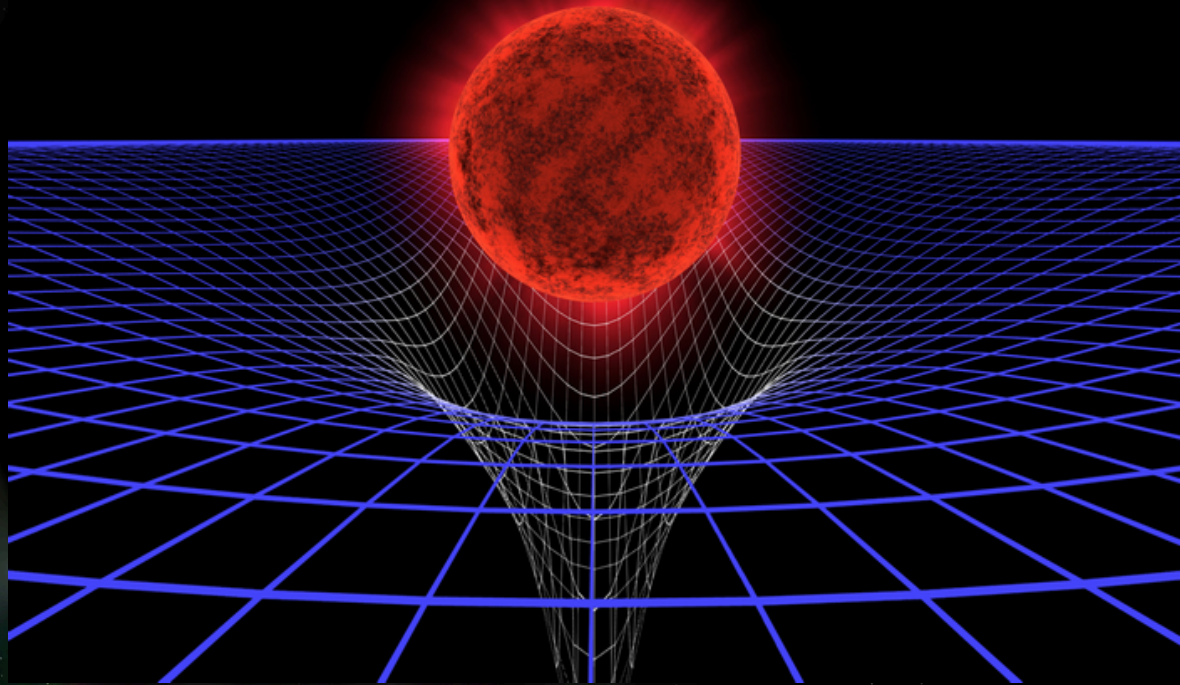
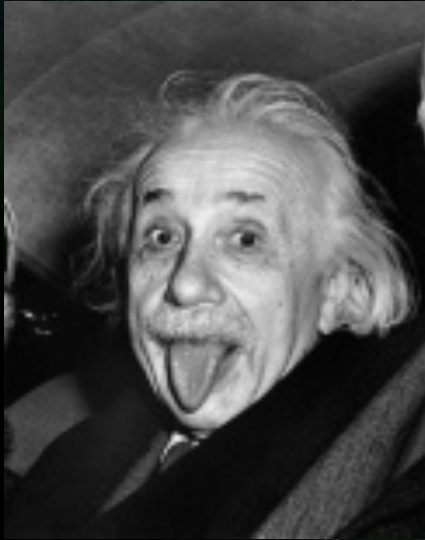
Gravitational-wave Astronomy: Current and Future

Kent Yagi
University of Virginia

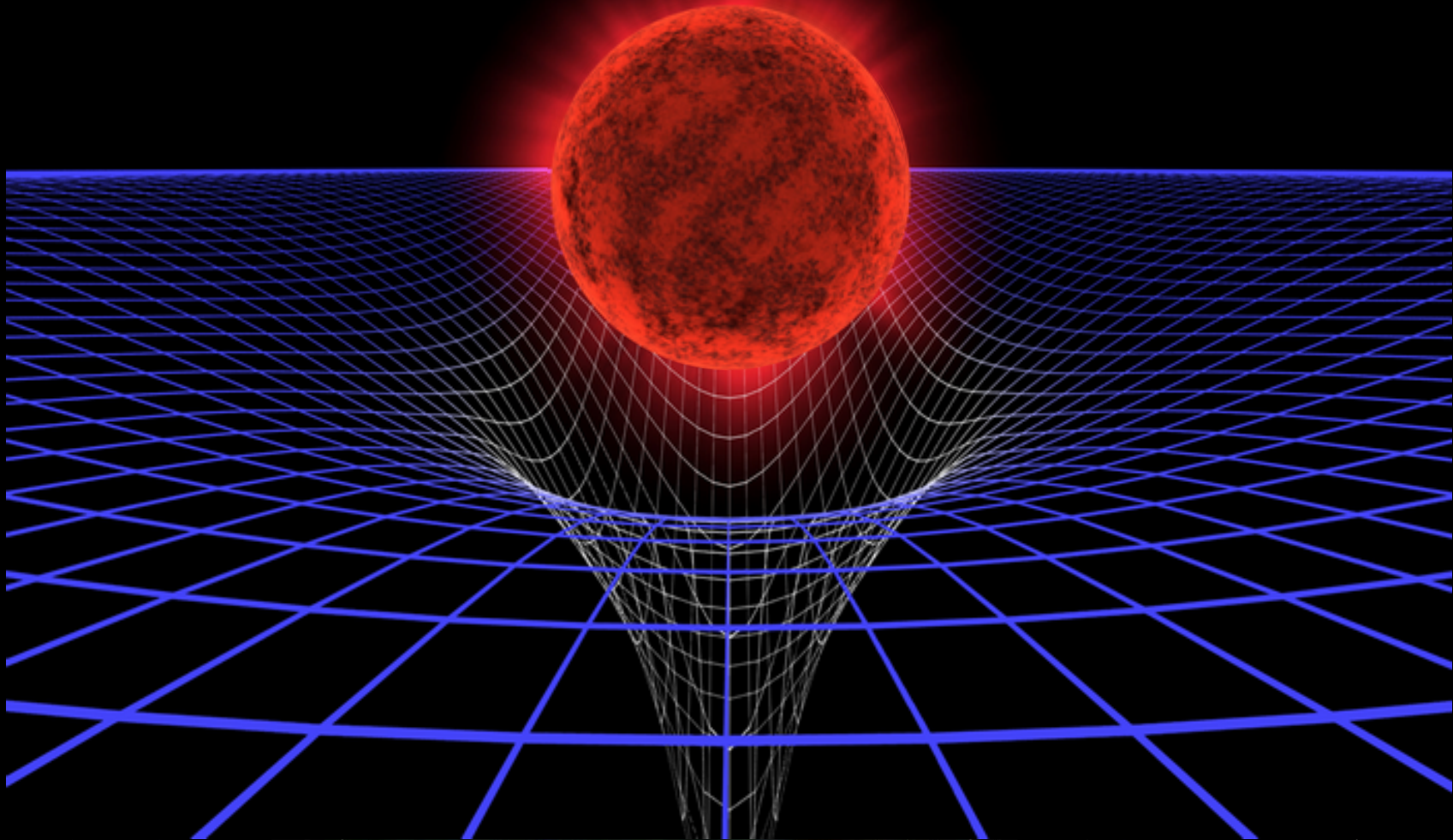
CSAAPT Spring 2022
April 2nd 2022

General Relativity (1915)

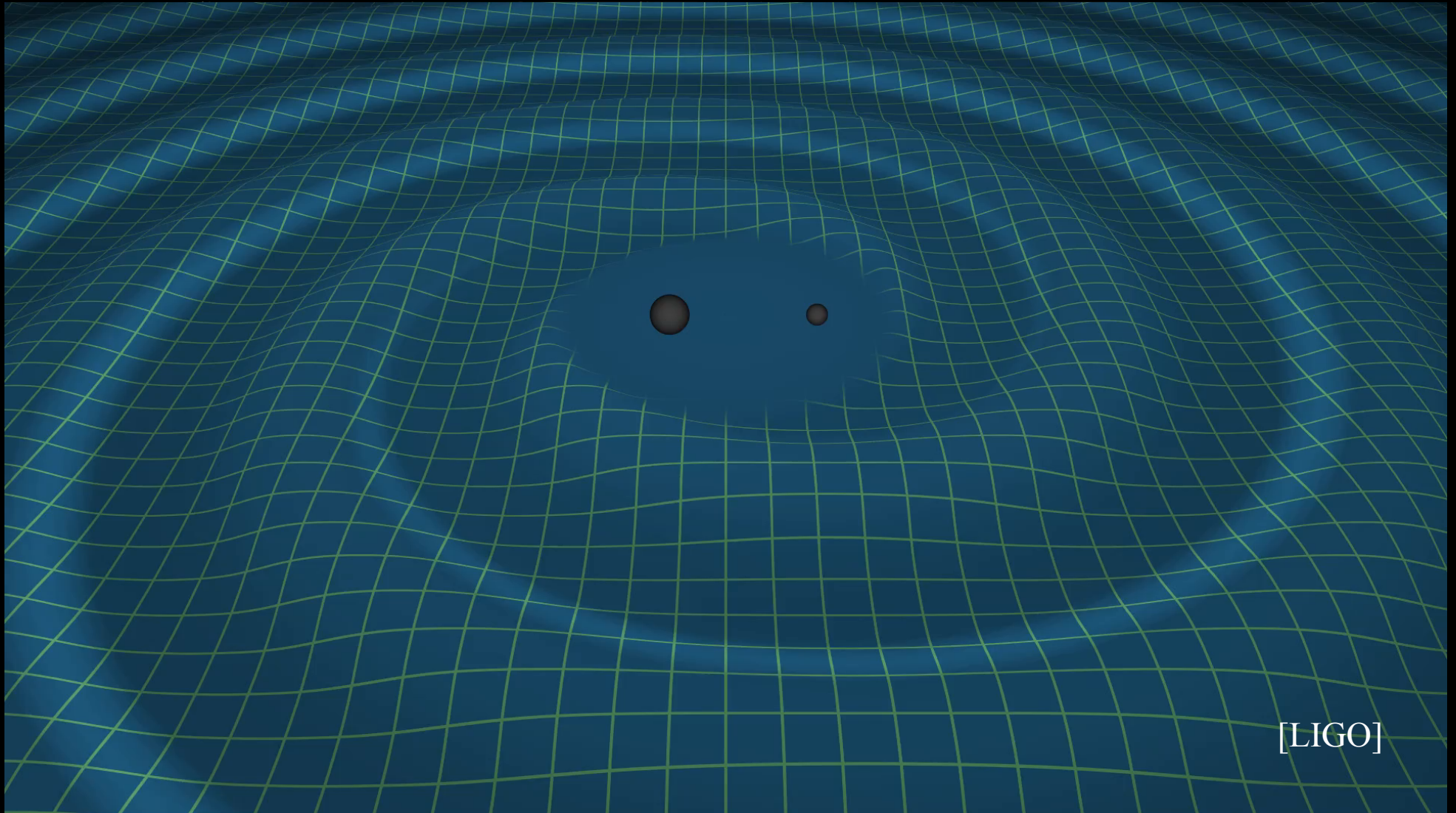
Gravity = Curvature of Spacetime



We feel spacetime curvature as gravity!



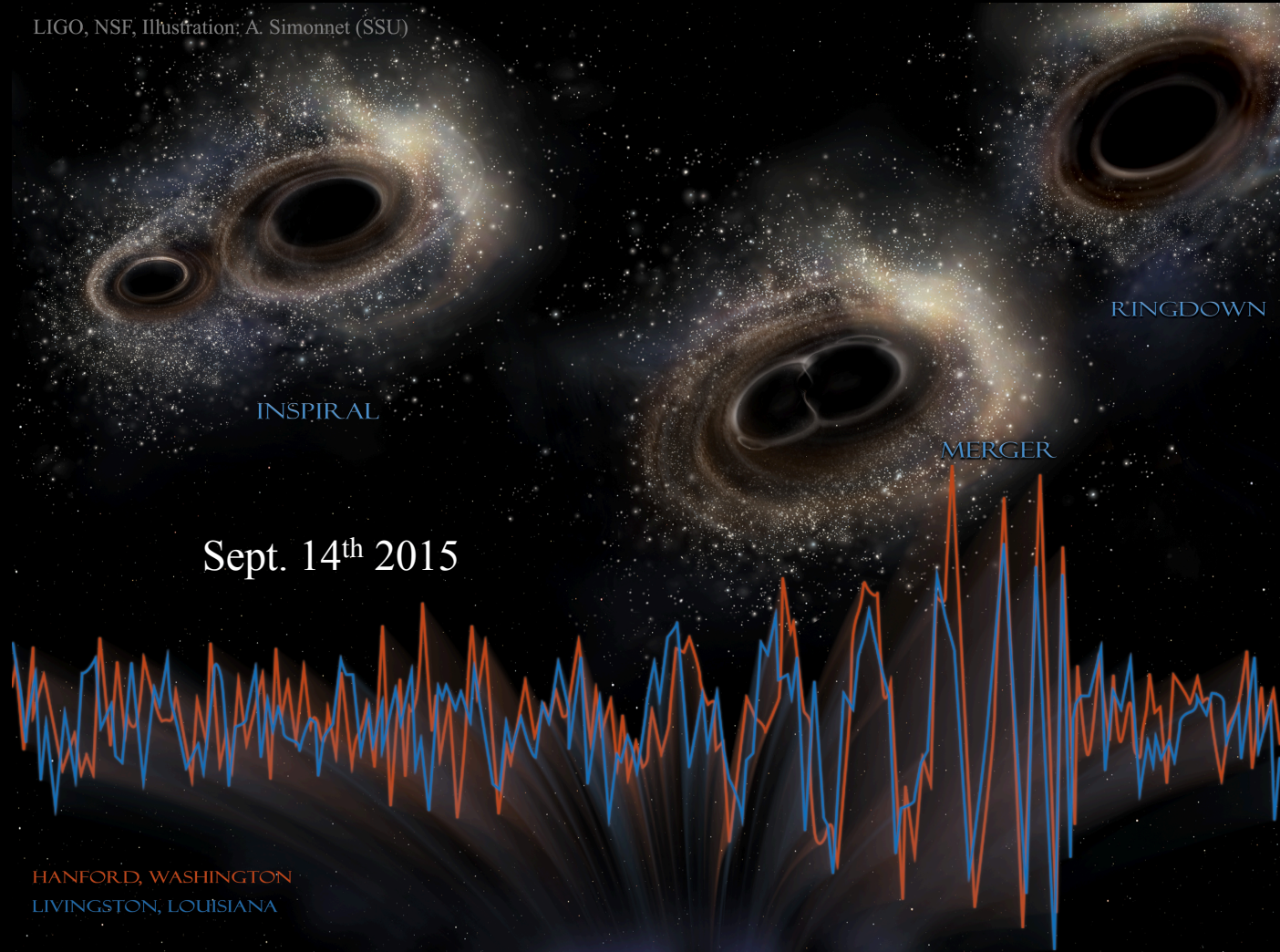
Black Hole Merger! (Sept. 2015)



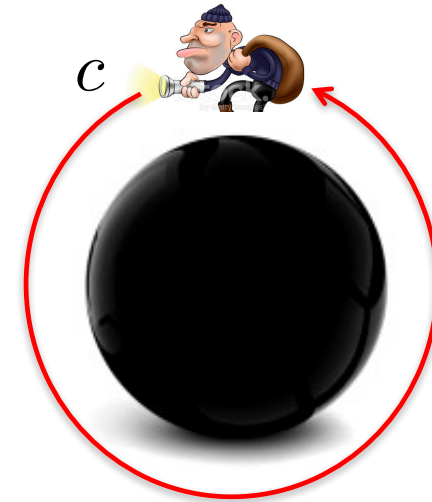
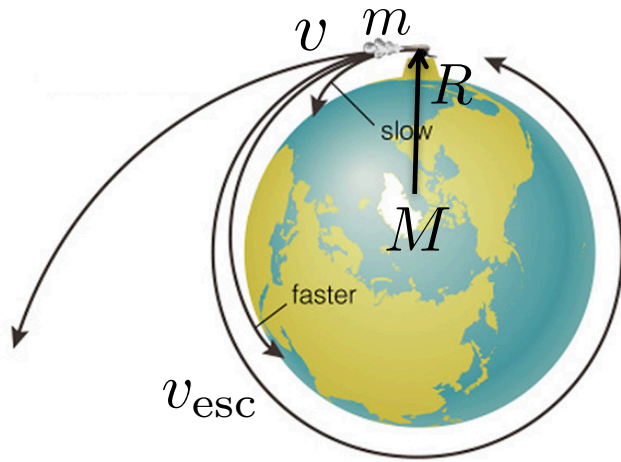
[LIGO]

Gravitational wave signal, at last!!

LIGO, NSF, Illustration: A. Simonnet (SSU)



How Large is a Black Hole?



escape velocity

$$E_{\text{tot}} = \frac{1}{2}mv^2 - G\frac{mM}{R}$$

$$v = v_{\text{esc}} \text{ when } E_{\text{tot}} = 0$$

$$\begin{aligned} \rightarrow v_{\text{esc}} &= \sqrt{\frac{2GM}{R}} \\ &= 11.2\text{km/s} \left(\frac{M}{M_{\text{Earth}}}\right)^{1/2} \left(\frac{R}{R_{\text{Earth}}}\right)^{-1/2} \end{aligned}$$

Black Hole radius

$$v_{\text{esc}} \rightarrow c$$

$$\begin{aligned} \rightarrow R_{\text{BH}} &= \frac{2GM}{c^2} \\ &= 30\text{km} \left(\frac{M}{10M_{\text{Sun}}}\right) \end{aligned}$$

Extracting Physical Parameters from Data

merger separation: [Kepler's 3rd Law]

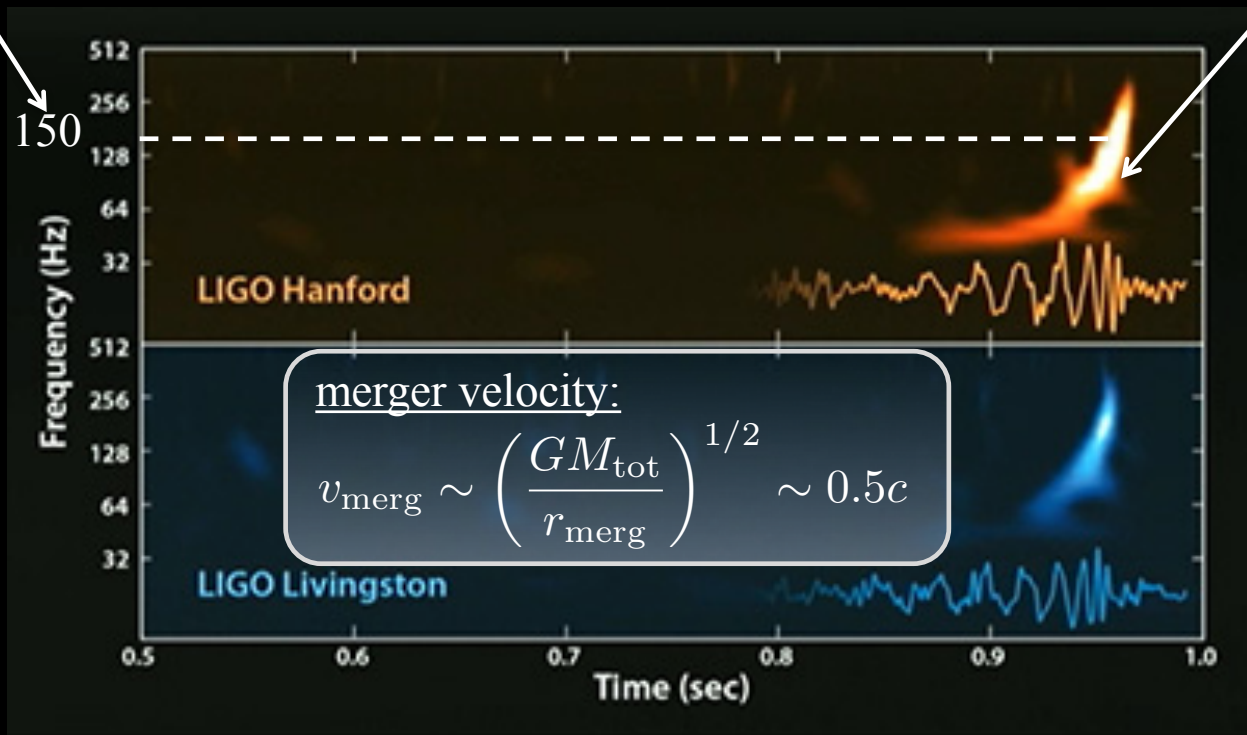
$$r_{\text{merg}} \sim \left(\frac{G M_{\text{tot}}}{\pi^2 f_{\text{merg}}^2} \right)^{1/3} \sim 350\text{km}$$

total mass:

$$M_{\text{tot}} \sim \frac{c^3}{G} f^{-11/5} \dot{f}^{3/5} \sim 65 M_{\text{Sun}}$$

[Kepler's 3rd law]

$$\frac{P^2}{r^3} = \frac{4\pi^2}{GM}$$



merger velocity:

$$v_{\text{merg}} \sim \left(\frac{G M_{\text{tot}}}{r_{\text{merg}}} \right)^{1/2} \sim 0.5c$$

Basic Physics of Binary Black Hole Merger

Ann. Phys. (Berlin) 529, No. 1–2, 1600209 (2017) / DOI 10.1002/andp.201600209

annalen
der **physik**

The basic physics of the binary black hole merger GW150914

*LIGO Scientific and VIRGO Collaborations**,**

Received 5 August 2016, revised 21 September 2016, accepted 22 September 2016

Published online 4 October 2016

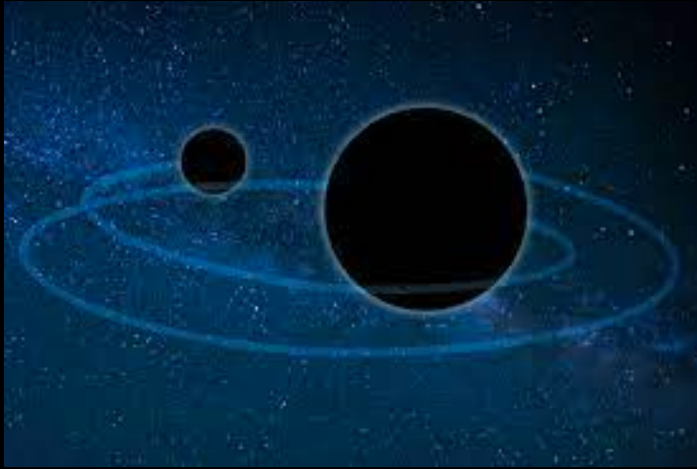


[arXiv: 1608.01940]

Original Paper

Where are we at...?

~ 85 black hole mergers

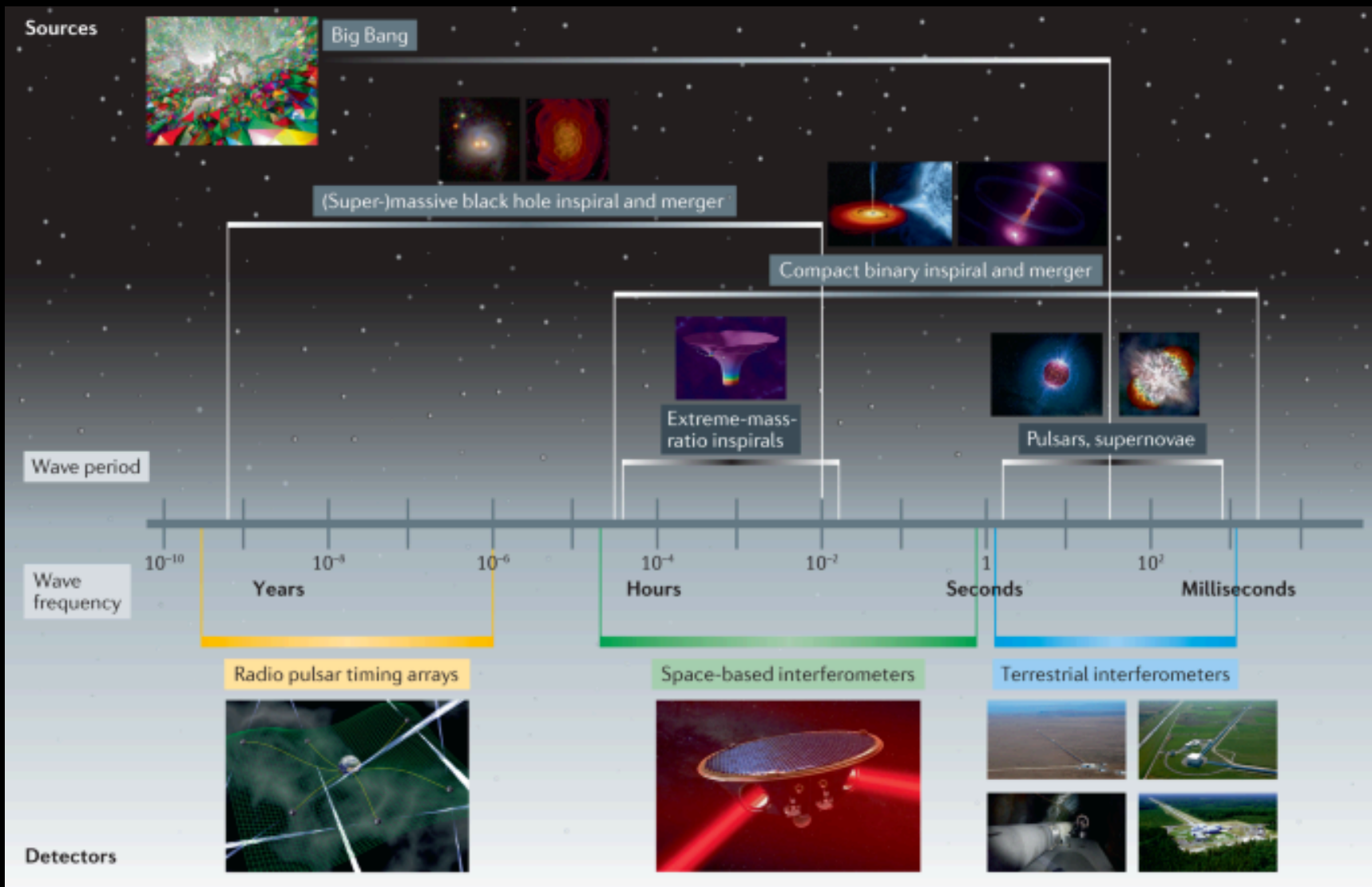


~ 2 neutron star mergers



~ 2 black hole /
neutron star mergers

What comes next...?

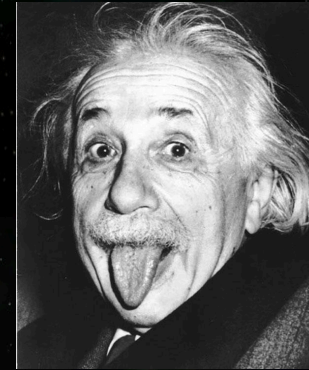


“Big Questions”

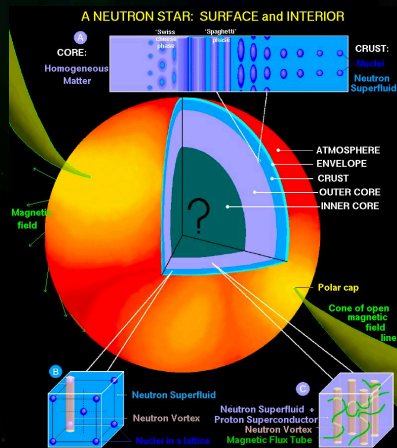
Astrophysics



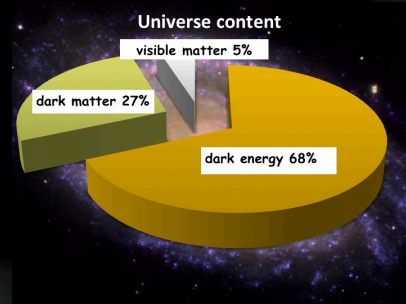
Gravitational Physics



Gravitational Waves



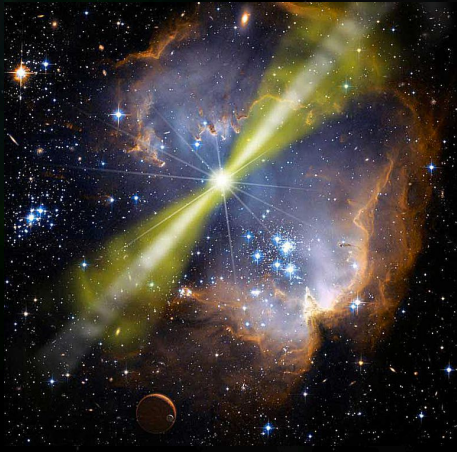
Nuclear Physics



Cosmology

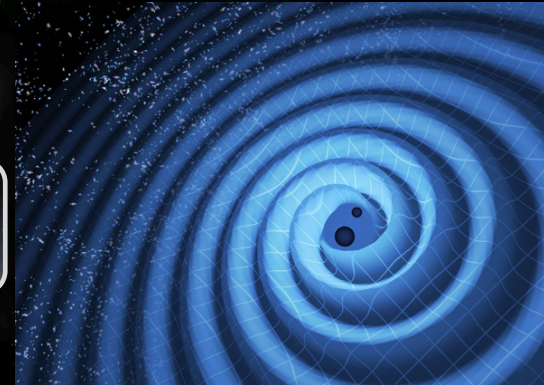
“Big Questions”

Astrophysics



- ✓ What is the origin of gamma-ray bursts?
- ✓ How do black hole binaries form?

Gravitational Physics



Gravitational Waves

Nuclear Physics

Cosmology

“Big Questions”

Astrophysics

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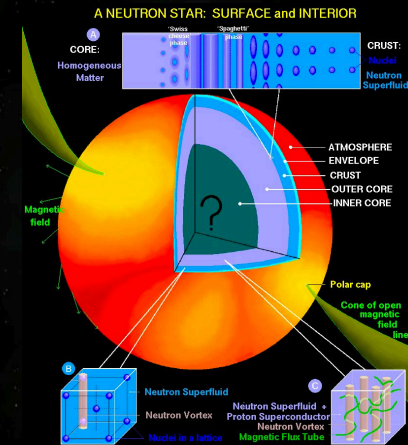
Gravitational Physics

Gravitational Waves

- ✓ What are the properties of **supranuclear matter**?
- ✓ How do **heavy elements** form?

Nuclear Physics

Cosmology



H	He																	He					
1	2																	2					
Li	Be																	B	C	N	O	F	Ne
3	4																	5	6	7	8	9	10
Na	Mg																	Al	Si	P	S	Cl	Ar
11	12																	13	14	15	16	17	18
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr						
19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36						
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe						
37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54						
Cs	Ba	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn							
55	56	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86							
Fr	Ra																						
87	88																						
		La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu							
		57	58	59	60	61	62	63	64	65	66	67	68	69	70	71							
		Ac	Th	Pa	U	Np	Pu																
		89	90	91	92	93	94																

Legend:

- Big Bang fusion
- Dying low-mass stars
- Exploding massive stars
- Cosmic ray fission
- Merging neutron stars
- Exploding white dwarfs

“Big Questions”

Astrophysics

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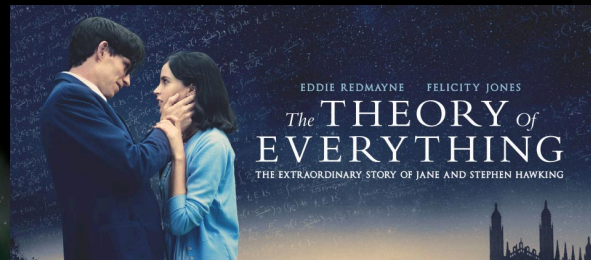
Gravitational Physics

- ✓ Is General Relativity correct everywhere?
- ✓ Is there a **theory of everything**?

Gravitational Waves

- ✓ What are the properties of **supranuclear matter**?
- ✓ How do **heavy elements** form?

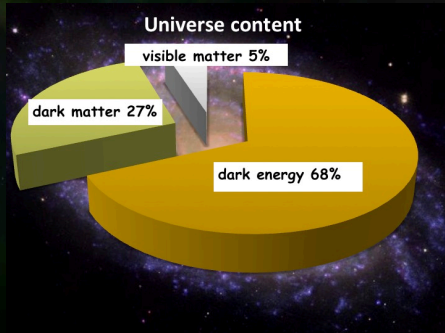
Nuclear Physics



Cosmology

“Big Questions”

Astrophysics

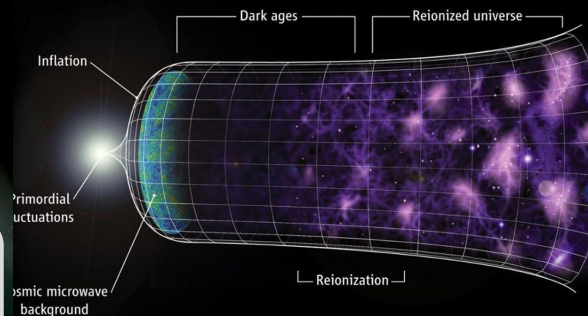


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Nuclear Physics

- ✓ What is the origin of **gamma-ray bursts**?
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Gravitational Waves



Gravitational Physics

- ✓ Is General Relativity correct everywhere?
- ✓ Is there a **theory of everything**?

- ✓ What is **dark matter**?
- ✓ What is **dark energy**?
- ✓ What is **inflation**?

Cosmology

Planetarium Show on Gravitational Waves at Radford U.

Oct. 30 2021

(Thank you Rhett for your help!)



Planetarium Show on Gravitational Waves at Radford U.

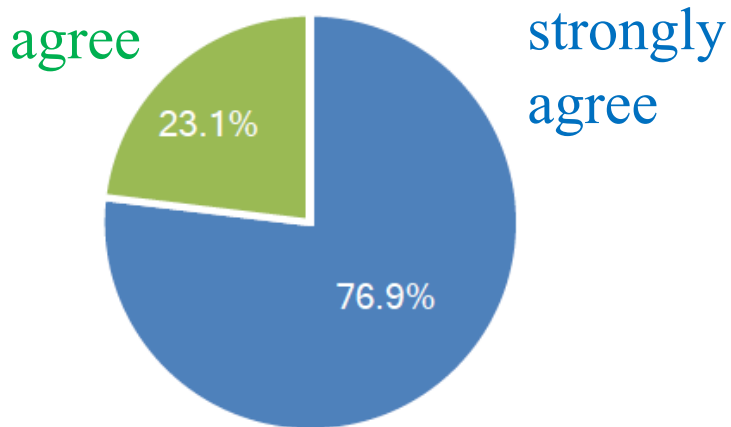
Oct. 30 2021

(Thank you Rhett for your help!)

**EINSTEIN'S
GRAVITY
PLAYLIST**

Overall, are you satisfied with today's event?

■ Strongly agree ■ Agree ■ Neutral ■ Disagree ■ Strongly disagree



~ 40 attendees answered

