# Gravitational-wave Astronomy Lecture 4



VOL. CLXV ... No. 57,140 +

NEW YORK, FRIDAY, FEBRUARY 12, 2016

#### **Clinton Paints** Sanders Plans As Unrealistic

#### New Lines of Attack at Milwaukee Debate

#### By AMY CHOZICK and PATRICK HEALY

MILWAUKEE - Hillary Clin ton, scrambling to recover from her double-digit defeat in the New Hampshire primary, repeat-edly challenged the trillion-dollar policy plans of Bernie Sanders at their presidential debate on Thursday night and portrayed him as a big talker who needed to "level" with voters about the dif-ficulty of accomplishing his agen-

Foreign affairs also took on unusual prominence as Mrs. Clinton sought to underscore her experi-ence and Mr. Sanders excoriated her judgment on Libya and Iraq, as well as her previous praise of former Secretary of State Henry A. Kissinger. But Mrs. Clinton A Klassinger, But Mrs. Cliniton was frequently on the offensive as well, seizing an opportunity to talk about leaders she admired and turning it against Mr. Sand-ers by bashing his past criticism of President Obama — a remark that Mr. Sanders called a "low how"

With tensions between the two ocrats becoming increasing-vious, the debate was full of lines of attack from Mrs. Clinton, who faces pressure to puncture Mr. Sanders's growing popularity before the next nomi-nating contests in Nevada and South Carolina.

South Carolina. She is wagering that even vot-ers excited by Mr. Sanders's in-spiring message will reconsider their support when they learn of his lack of experience in foreign policy and his vague explana-tions for how he will pay for his expansive government pro-grams.

grams. Mrs. Clinton pounced from the start, after Mr. Sanders de-murred in saying how much his proposals would increase the size of the federal government. She stepped in and said that by econ-omists' estimates, the govern-ment would grow 40 percent un-der Mr. Sanders.

ch as his proposed expansion government health care. This is not about math. This is

tinued on Page A16

Going Back to Trenton Gov. Chris Christie has re-irned to New Jersey to tend to a e he at times abandoned in run for president. Page A21.

A worker installed a baffle in 2010 to control light in the Laser Interferometer Gravitational-Wa

#### Long in Clinton's Corner, Blacks Notice Sander.

Courted Hard in South

Carolina, Loyalists

Listen Closely

A A A

#### By RICHARD FAUSSET

© 2016 The New York Times

ORANGEBURG, S.C. - When elen Duley was asked whom she would vote for in the South Carolina primary, she answered as if the very question were ab-

"What I'm seeing is a bunch of confusion, hearsay and foolish-ness," said Ms. Duley, 60, a re-tired nursing assistant who is Af-rican-American, shortly after fin-sishing breakfast at the downtown two and an overwhelming victory toward an overwhelming victory McDonald's. "What I also see is a in the New Hampshire Demo-veteran who's already been in the White House eight years. A vet-

And rather than bashing him as she did at their debate last Thursday, she appeared to try to get under his skin by implying that he had not been transparent about the cost of his programs, such as his proceed coordinate

Reginald Abraham, left, an organizer for Hillary Clinton, at a barbershop in Orangeburg, S.C.

#### Lawmaker's Hedge Fund Intrudes on Day Job Officer Is Cont

WASHINGTON - The hedge fund manager boasted that he had traveled to "every country" in the world, studying overseas stock markets as he fine-tuned an investment stratement to consider

NATIONAL A10-19

will be tough.



#### GRAVITATIONAL WAVES CONFIRMED

IN NEWS **Clinton, Sanders** agree systems in U.S. are broken Sixth debate has candidates trying to win minority support.

In Japan, the girls give guys gifts on Valentine's Day







The New Yorker









SPORTS FRIDAY B8-12 Sports' Top Court Faces a Test No Quick Fix for Flint's Woes Michigan officials are still scrambling with local leaders on a plan to undo the damage to the water. A look at why that will be tungh A suit by a German speedskater called into question the fairness of the Court of Arbitration for Sport, possibly upending the court's international power. PAGE B8 PAGE A13



makes me feel good," she sai chuckling, "that young peop are listening to the elderly pe ple." She now said she was an u decided voter and planned to a me homework on Mr. Sander Mrs. Clinton has long looke forward to the Feb. 27 Dem cratic contest in South Carolin the first state where blacks w make up a dominant part of th primary vote. African-American accounted for more than half th

voters in the 2008 Democrat

primary, and she has been cou

ing on them as a bulwark, not j

Continued on Page A18

TODAY Sports, retired start analyst gig.











euronews

101

Was that you I heard just now, or was it two black holes colliding? -

### September 14, 2015 at 09:50:45 GMT



LVC, PRL 116, 061102 (2016)

GW150914 found within 3 minutes of arriving.

# Confirming Gravitational Waves



# Confirming Gravitational Waves



# Implications of This Discovery

- First direct detection of gravitational waves.
- First direct evidence of black holes in nature.
- First direct evidence of very massive stellarmass black holes.
- First observation of a binary black hole system.
- First event to test Einstein's GR in strong field



# December 26, 2015 at 03:38:53 GMT



#### LVC, PRL 116, 241103 (2016)

GW151226 found within 70 seconds of arriving.

## October 12, 2015 at 09:54:43 GMT A third detection?



LVC, CQG 33, 134001 (2016)

- 2% chance LVT151012 could be due to noise.
- It would also be a binary black hole.

### Detections from LIGO's First Observing Run



### January 4, 2017 at 10:11:58 GMT



GW170104 was the first signal detected in LIGO's second observing run.

### Summary of Signals Seen So Far



## Measured Component Masses



	$m_1 (\mathrm{M}_{\odot})$	$m_2 (\mathrm{M}_{\odot})$
GW150914	$36.2^{+5.2}_{-3.8}$	$29.1^{+3.7}_{-4.4}$
LVT151012	$23^{+18}_{-6}$	$13^{+4}_{-5}$
GW151226	$14.2^{+8.3}_{-3.7}$	$7.5^{+2.3}_{-2.3}$

### Measured Component Masses



#### Measured Effective Spins and Mass Ratio



 $\boldsymbol{q}$  $\chi_{\mathrm{eff}}$ 0.140.14-0.170.06 0.81GW150914 .20380.5LVT151012 2 37 0.2400.210.52GW151226 0.29

## Measured Effective Spins





![](_page_16_Figure_1.jpeg)

![](_page_17_Figure_1.jpeg)

![](_page_18_Figure_1.jpeg)

![](_page_19_Figure_1.jpeg)

#### Measured Final Black Hole Parameters

![](_page_20_Figure_1.jpeg)

LVC, PRX 6, 041015 (2016)

#### GW170104: Measured Final Black Hole Parameters

![](_page_21_Figure_1.jpeg)

### **Black Holes of Known Mass**

![](_page_22_Figure_1.jpeg)

# Sky Localization

![](_page_23_Figure_1.jpeg)

## Sky Localization

![](_page_24_Picture_1.jpeg)

## Sky localization if we had Virgo...

![](_page_25_Picture_1.jpeg)

# External Triggers

![](_page_26_Picture_1.jpeg)

Gamma-ray Coordination Network

GraceDB

Time Coincidence? Location Coincidence?

## External Alerts

AOFISICA Murchison V	Videfield Array		
DI 4	EM Partner	First observation	
WALL OF	Fermi	12-27-15	
1012414	ZTF	12-28-15	
SkyMapper	J-GEM	12-29-15	UNS
A CONTRACTOR OF THE OWNER OWNER OF THE OWNER OWNER OWNER OWNER OF THE OWNER OW	INAF	12-29-15	
	SkyMapper	12-30-15	Carlos C
	LOFAR-TKSP	01-03-16	
	Swift	01-04-16	Carrie Carlos
	MWA	01-26-16	
	EWE	03-14-16	
	GOTO	04-15-16	

XinJiang Astronomical Observatory, Chinese Academy of Sciences

## Possible Formation Pathways

![](_page_28_Figure_1.jpeg)

K. Belczynski, et. al. Nature 534, 512-515 (2016)

C. Rodriguez, et al. ApJL 824 (2016)

# How many more GWs from binary black holes?

![](_page_29_Figure_1.jpeg)

# We should see at least several more BBH signals in O2.

\* LVC, Class. Quant. Grav. 27. 173001 (2010)

## Testing General Relativity

Phase of waveform characterized by coefficients:  $\{p_i\}$ 

Allow for departures from GR:  $\{p_i\} \rightarrow (1 + \delta \hat{p}_i) p_i$ 

Inspiral:  $\left\{\delta\hat{\phi}_i\right\}$  Intermediate:  $\left\{\delta\hat{\beta}_i\right\}$  Merger/Ringdown:  $\left\{\delta\hat{\alpha}_i\right\}$ 

![](_page_30_Figure_4.jpeg)

## Testing General Relativity

Phase of waveform characterized by coefficients:  $\{p_i\}$ 

Allow for departures from GR:  $\{p_i\} \rightarrow (1 + \delta \hat{p}_i) p_i$ 

Inspiral:  $\{\delta \hat{\phi}_i\}$  Intermediate:  $\{\delta \hat{\beta}_i\}$  Merger/Ringdown:  $\{\delta \hat{\alpha}_i\}$ 

![](_page_31_Figure_4.jpeg)

LVC, PRX 6, 041015 (2016)

![](_page_32_Figure_0.jpeg)

LVC, PRX 6, 041015 (2016)

#### Binary Neutron Stars and Neutron-Star-Black-Hole Mergers

![](_page_33_Figure_1.jpeg)

Much potential for interesting BNS and NSBH science and discovery starting in O2.

# Keep Listening...

### www.ligo.org

![](_page_34_Picture_2.jpeg)

Feb 11, 2016

### facebook

![](_page_34_Picture_4.jpeg)

#### twitter

discovery at US Congres

![](_page_34_Picture_6.jpeg)

### Detection paper available: http://dcc.ligo.org