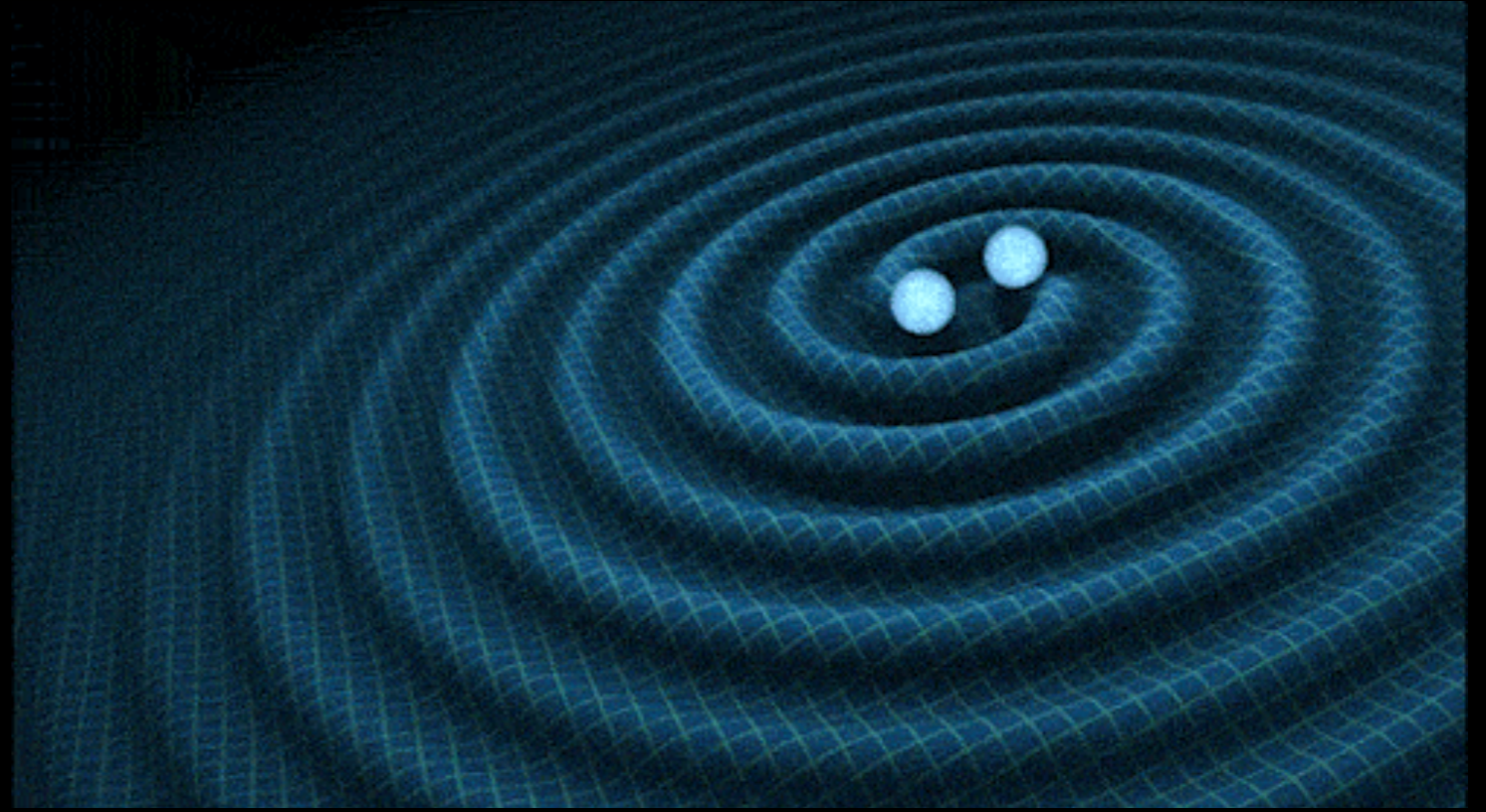
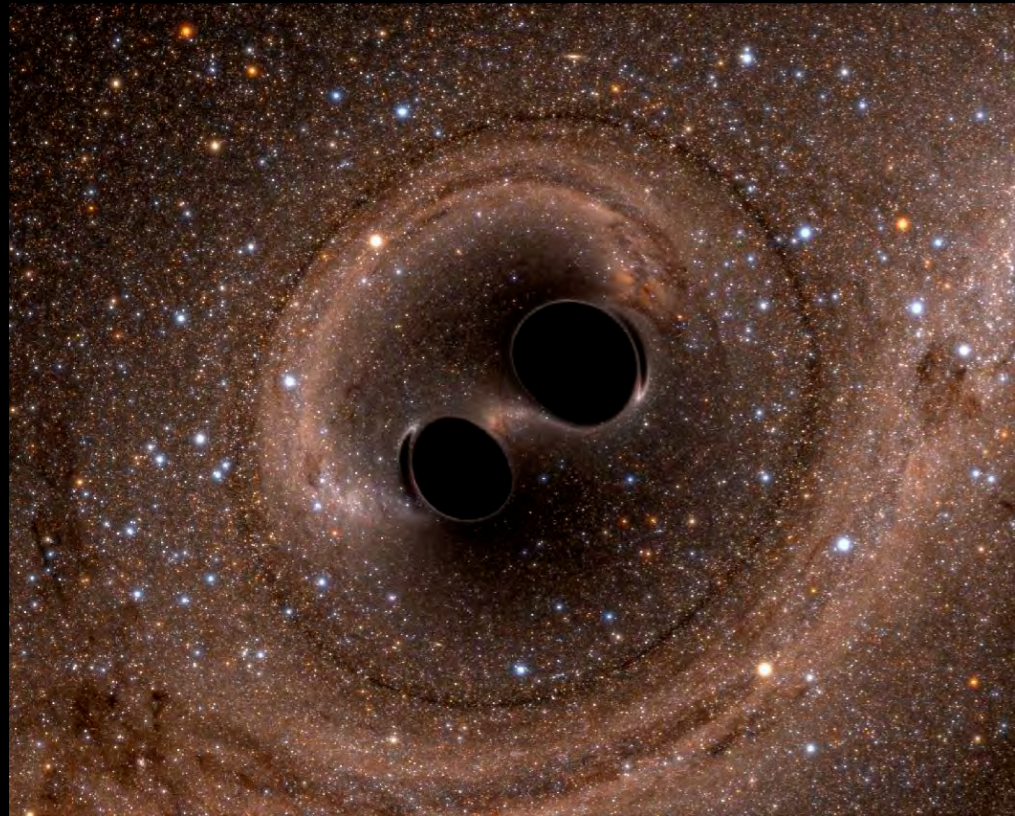


# ブラックホールを観る

# ブラックホールを聴く



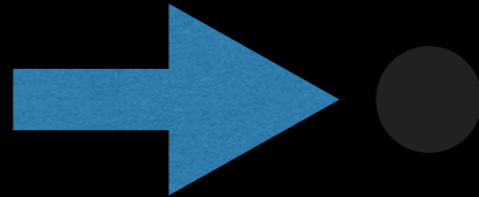
真貝寿明・大阪工業大学  
(しんかい ひさあき)

<http://www.oit.ac.jp/is/shinkai/>

# 今日の話の内容

## 1. ブラックホールとは？

★何でも吸い込む。光も脱出できない重い星



ここ

## 2. 見えないはずでは？

⇒ 見えたんです (2019年4月)

## 3. 音も聞こえないはずでは？

⇒ 重力波で聴こえたんです (2015年9月)

# 今日の話の内容

## 1. ブラックホールとは？

★何でも吸い込む。光も脱出できない重い星

★大きな恒星が燃え尽きた最後の姿

★アインシュタインの相対性理論が予言

# 重力の正体は？



by Frits Ahlefeldt

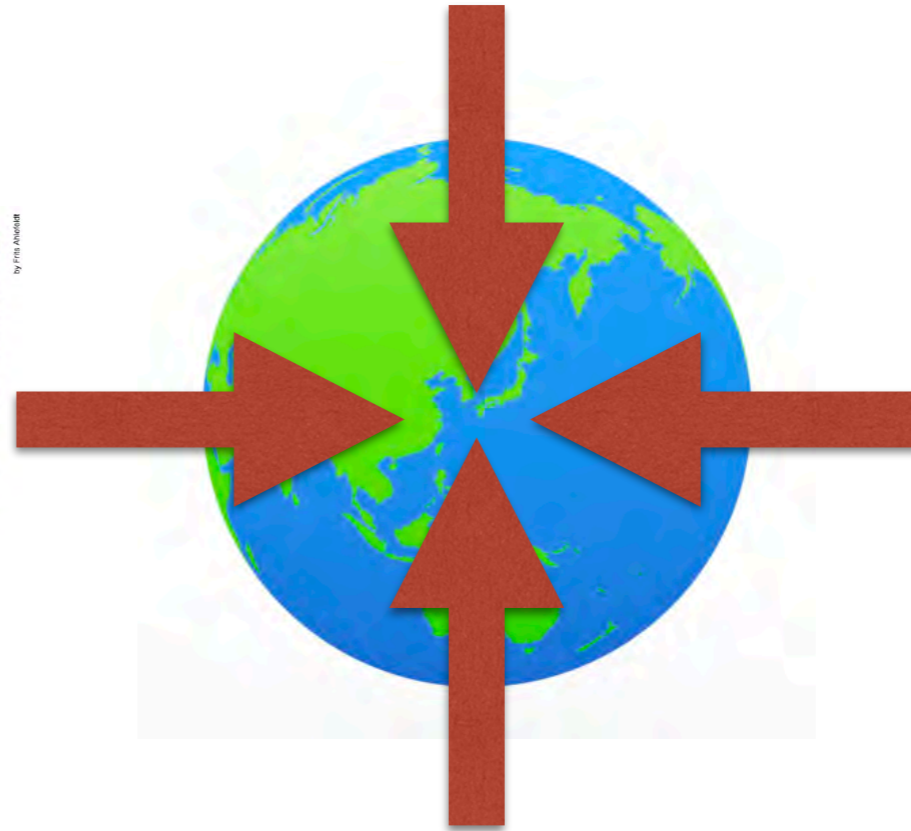
ニュートン



by Frits Ahlefeldt



by Frits Ahlefeldt



by Frits Ahlefeldt

地球がリンゴを引っ張る  
リンゴも地球を引っ張る  
⇒すべてが引力をおよぼす  
**(万有引力)**

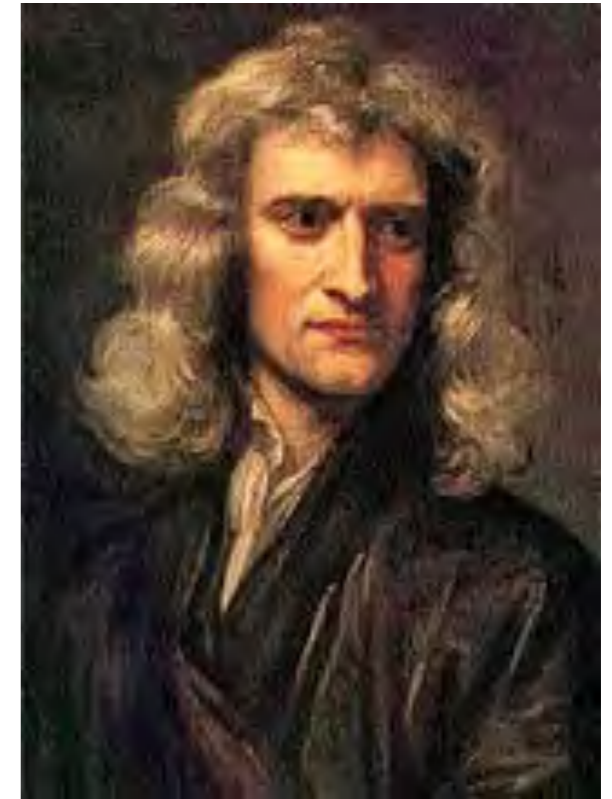
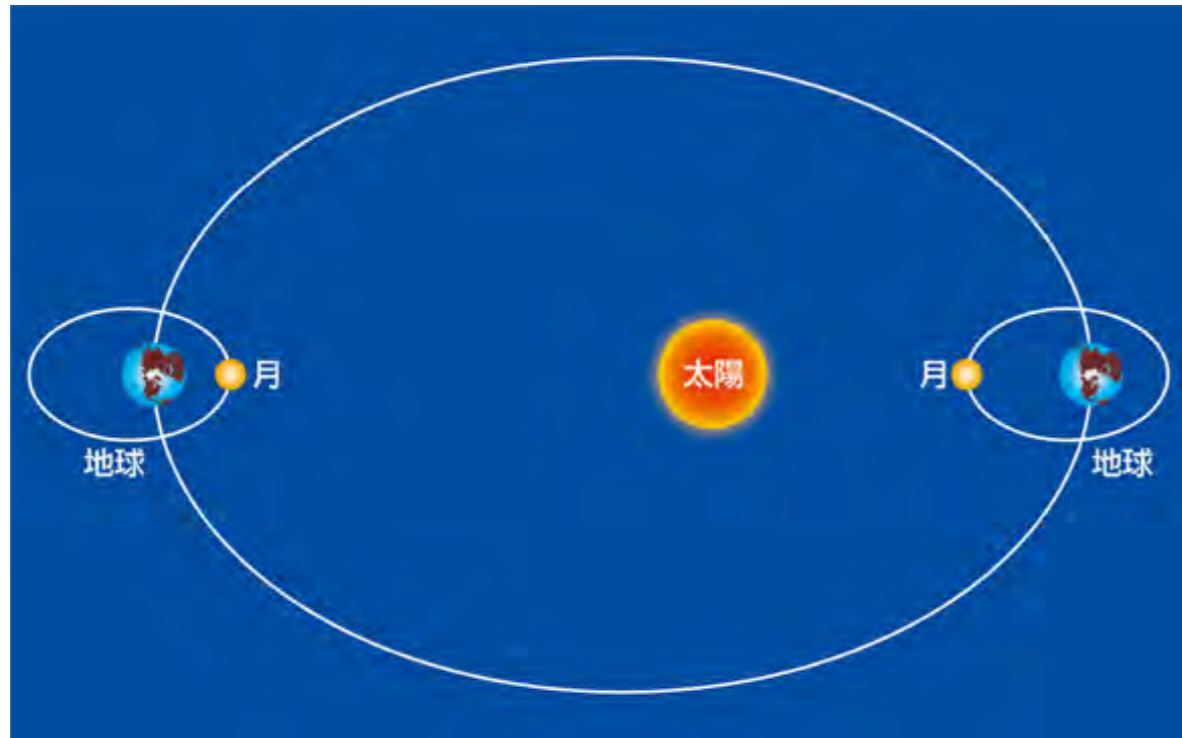


by Frits Ahlefeldt

# 重力の正体は？

万有引力  $F = G \frac{Mm}{r^2}$

＝すべてのものは引力で引き合う



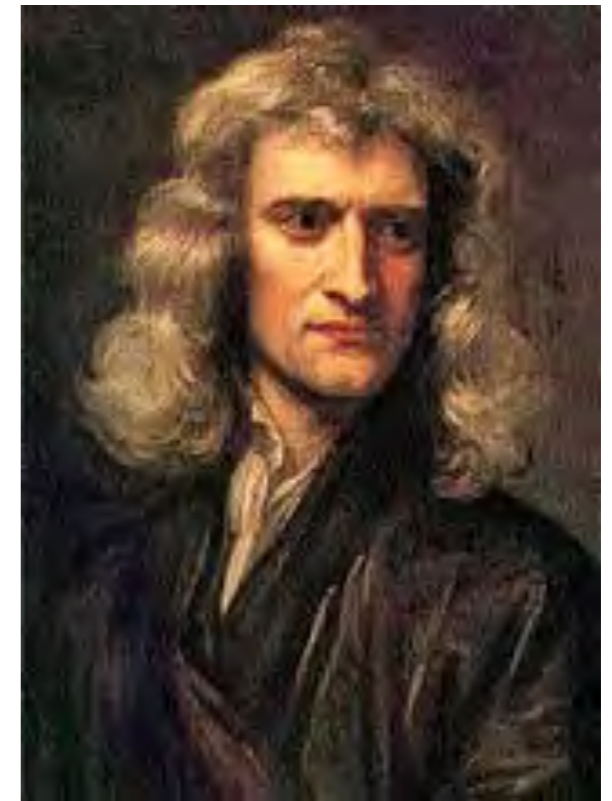
ニュートン

「月はどうして地球に落下しないのか？」

# 重力の正体は？

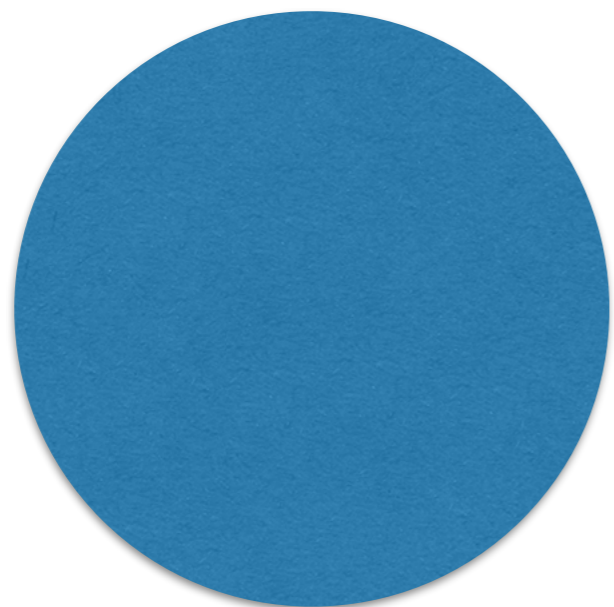
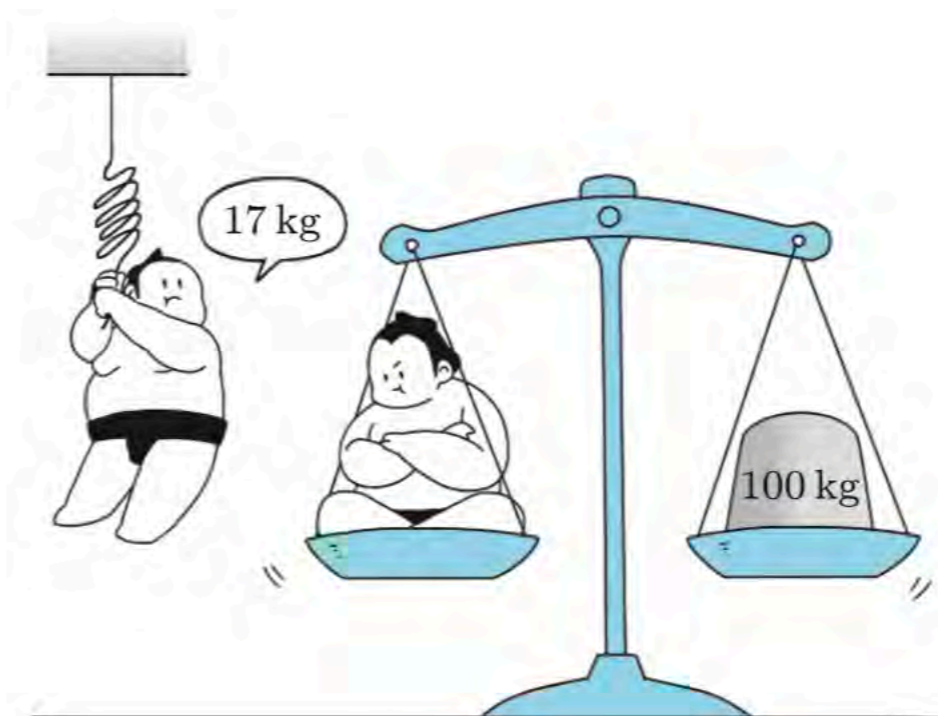
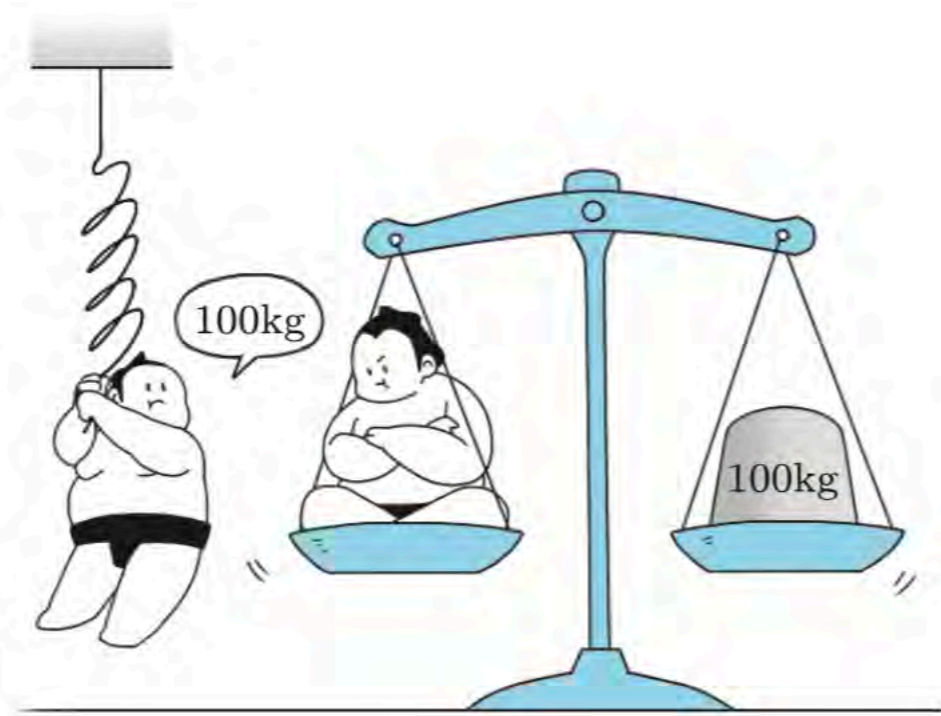
万有引力  $F = G \frac{Mm}{r^2}$

＝すべてのものは引力で引き合う

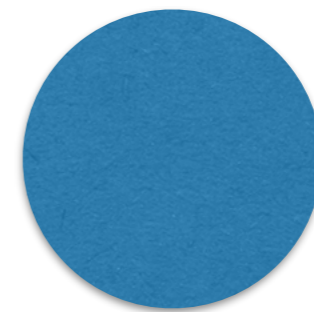


ニュートン

「月はどうして地球に落下しないのか？」



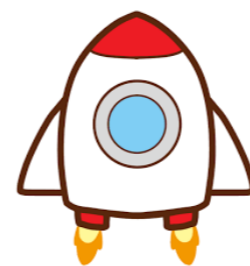
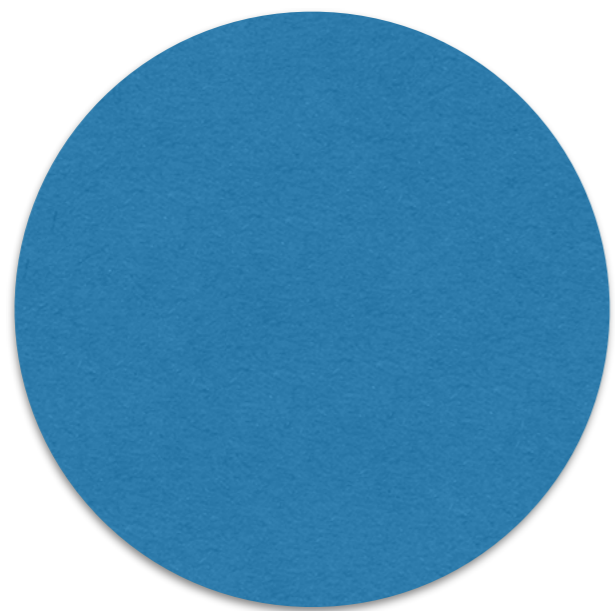
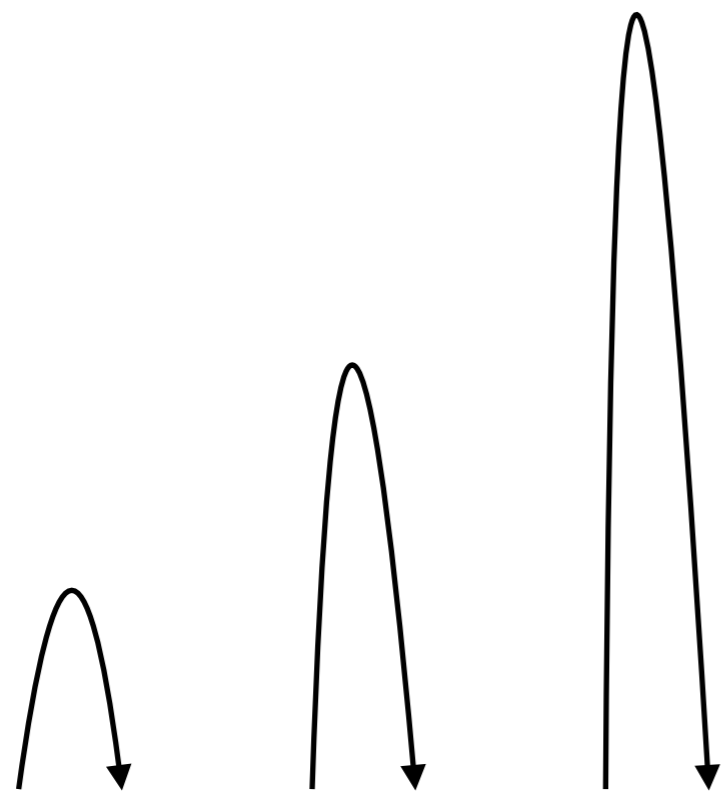
地球で100kgの体重は



月では 17kg に

木星では 250kg に

ボールを速く投げ上げると、  
高くまで飛ぶ



地球からの脱出速度  
秒速 12 km



秒速  
30万 km

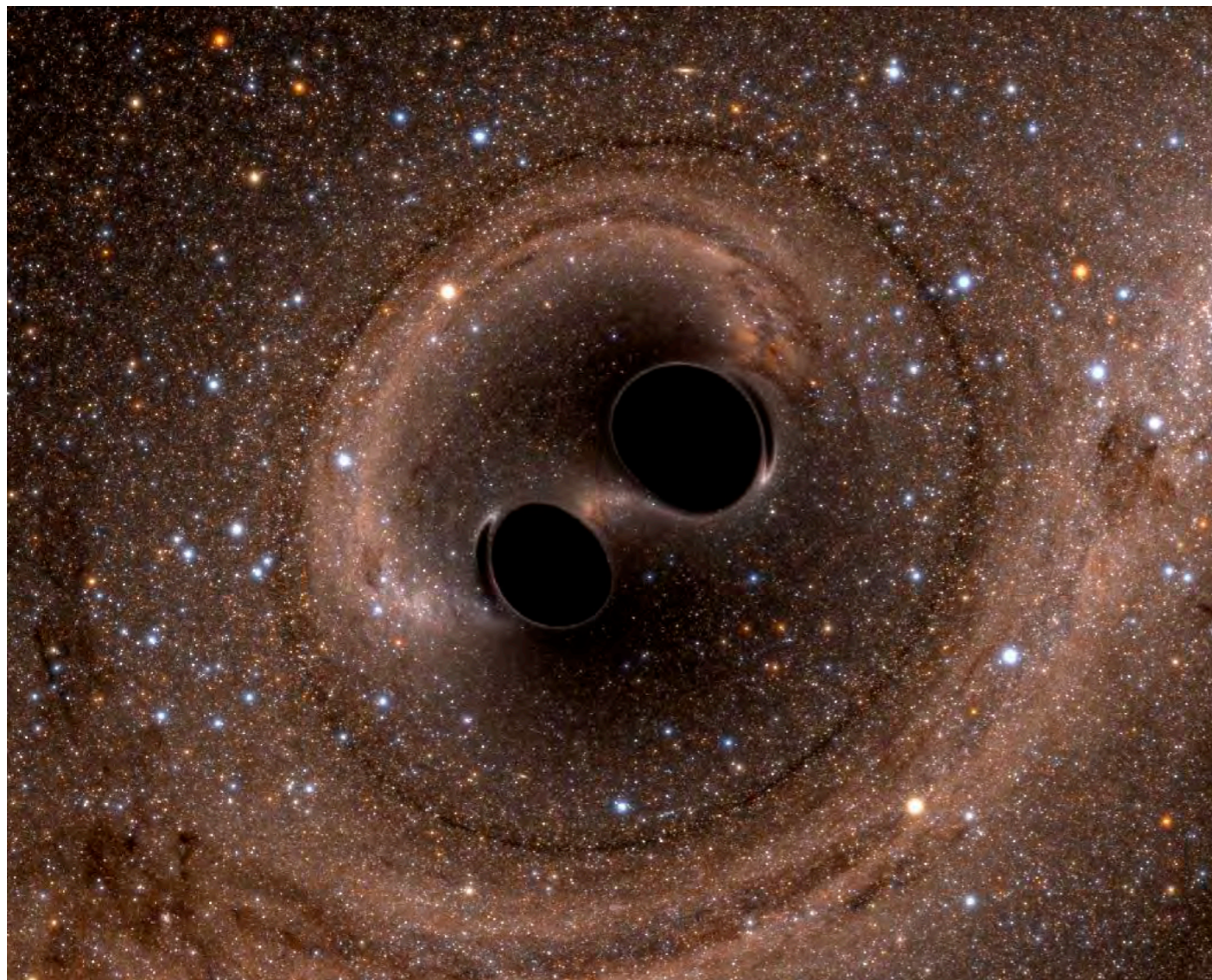
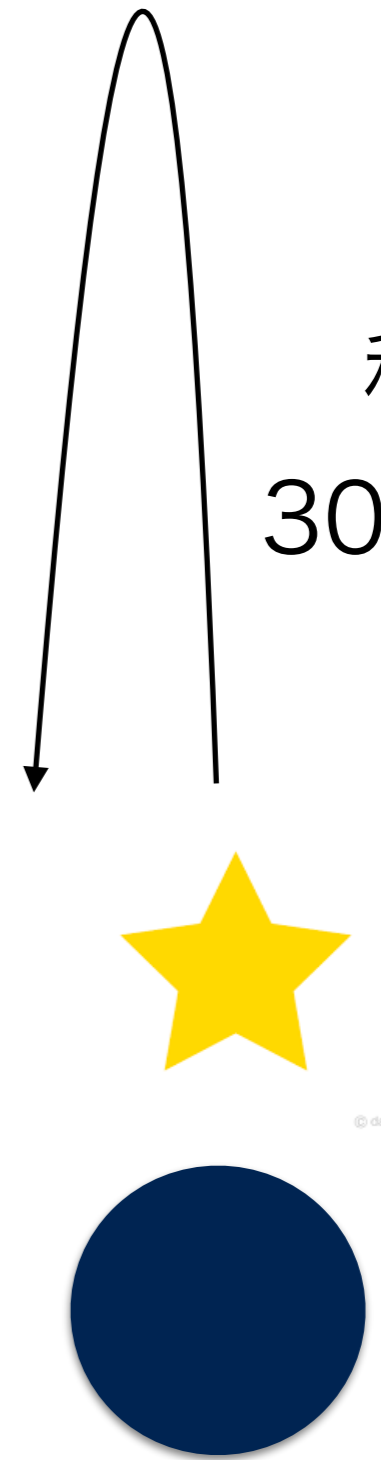
光は当然  
脱出できる



とてつもなく重くて小さな天体では

光も  
脱出できない

秒速  
30万 km



◀ブラックホール  
(シミュレーション)

# 重力の正体は？



by Frits Ahlefeldt

「万有引力があるからだ」 (ニュートン, 1687)

$$F = G \frac{Mm}{r^2}$$

$$m \frac{d^2 x}{dt^2} = F$$

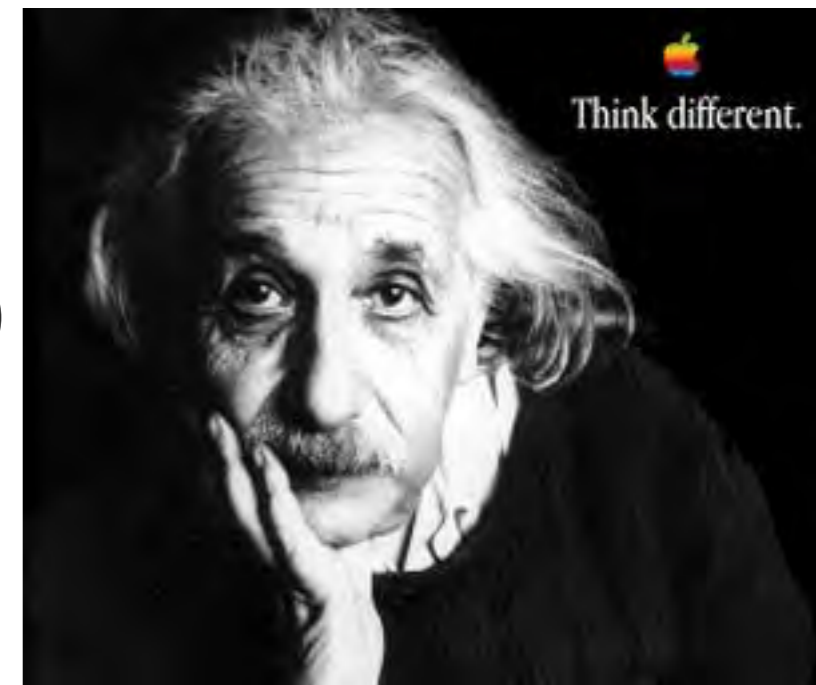
「時空のゆがみだ」

(アインシュタイン, 1915)

**一般相対性理論**

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

$$\frac{d^2 \xi^\mu}{d\tau^2} = R^\mu_{\nu\rho\sigma} \frac{d\xi^\nu}{d\tau} \frac{d\xi^\rho}{d\tau} \xi^\sigma$$

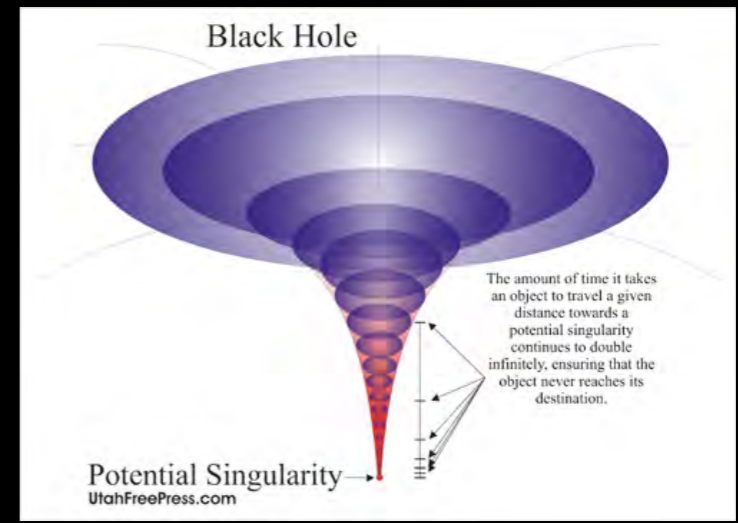




FailsShot



Subscribe UP



# 重い星が燃え尽きると 中性子星やブラックホールに

褐色矮星  
質量：太陽の0.08倍  
表面温度：1000°C  
寿命（主系列）：不明

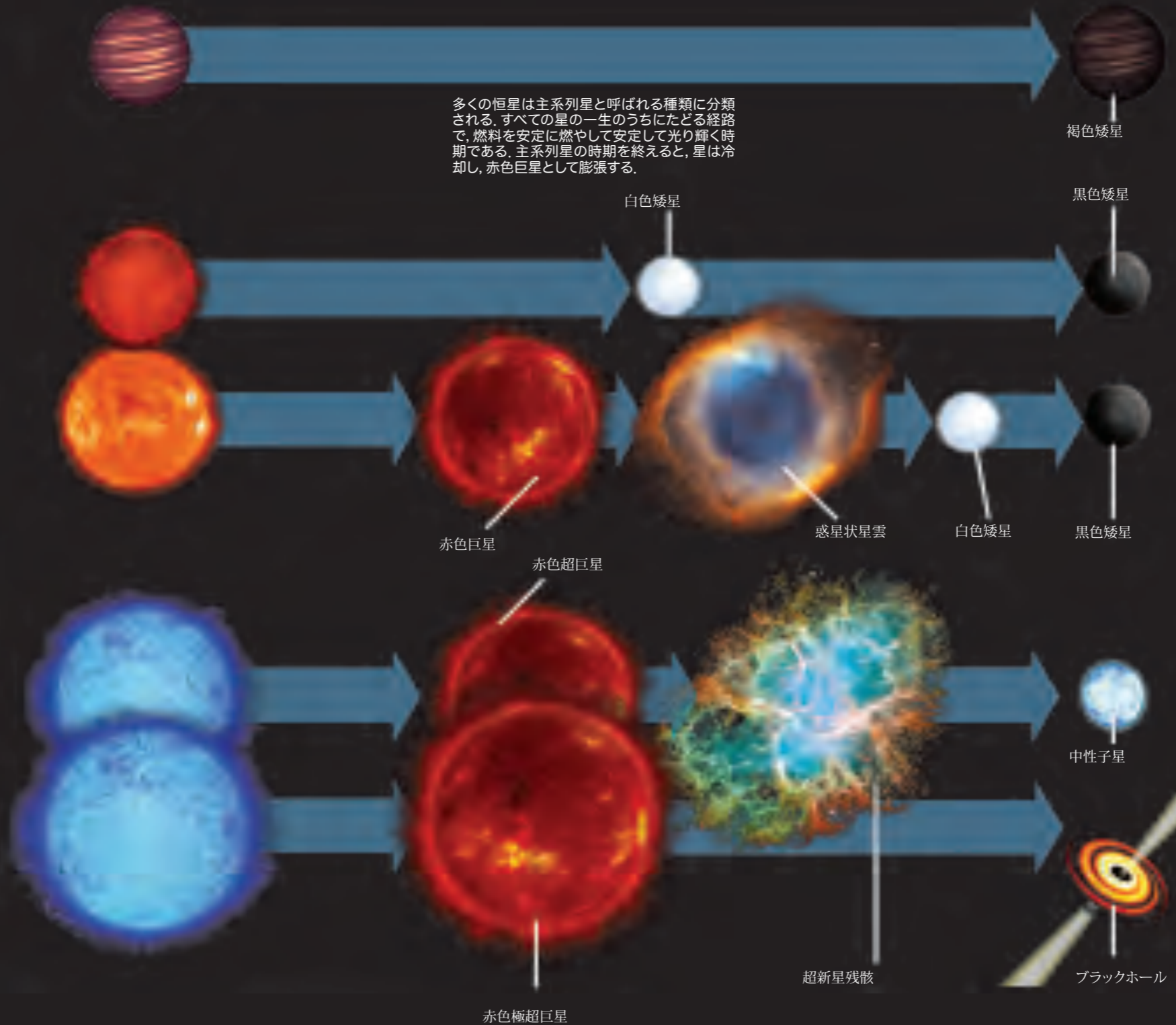
赤色矮星  
質量：太陽の0.2倍  
表面温度：3000°C  
寿命：10兆年

太陽型恒星  
質量：太陽の1倍  
表面温度：5000°C  
寿命：100億年

超巨星  
質量：太陽の20倍  
表面温度：12000°C  
寿命：50万年

極超巨星  
質量：太陽の100倍  
表面温度：40000°C  
寿命：100万年

多くの恒星は主系列星と呼ばれる種類に分類される。すべての星の一生のうちにとどる経路で、燃料を安定に燃やして安定して光り輝く時期である。主系列星の時期を終えると、星は冷却し、赤色巨星として膨張する。

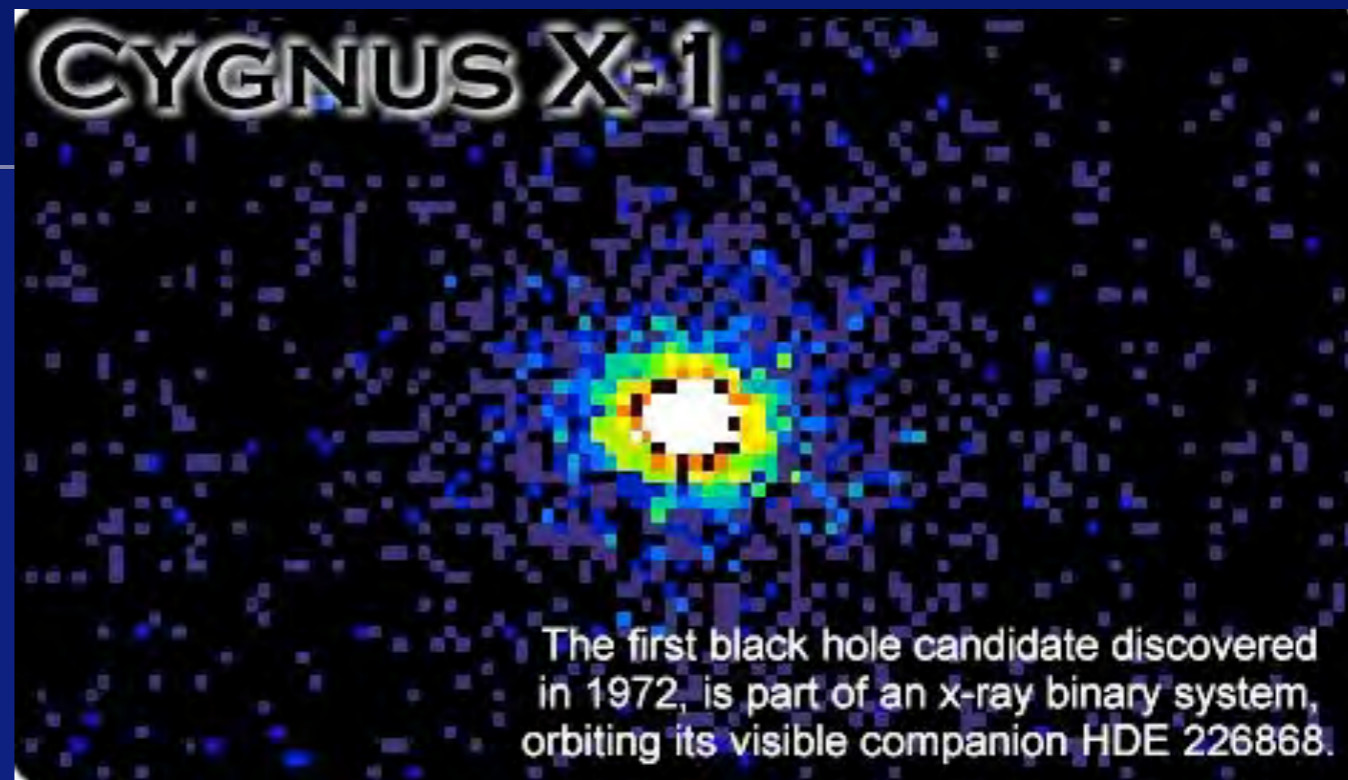


白色矮星  
 $\leq 1.4M_{\odot}$

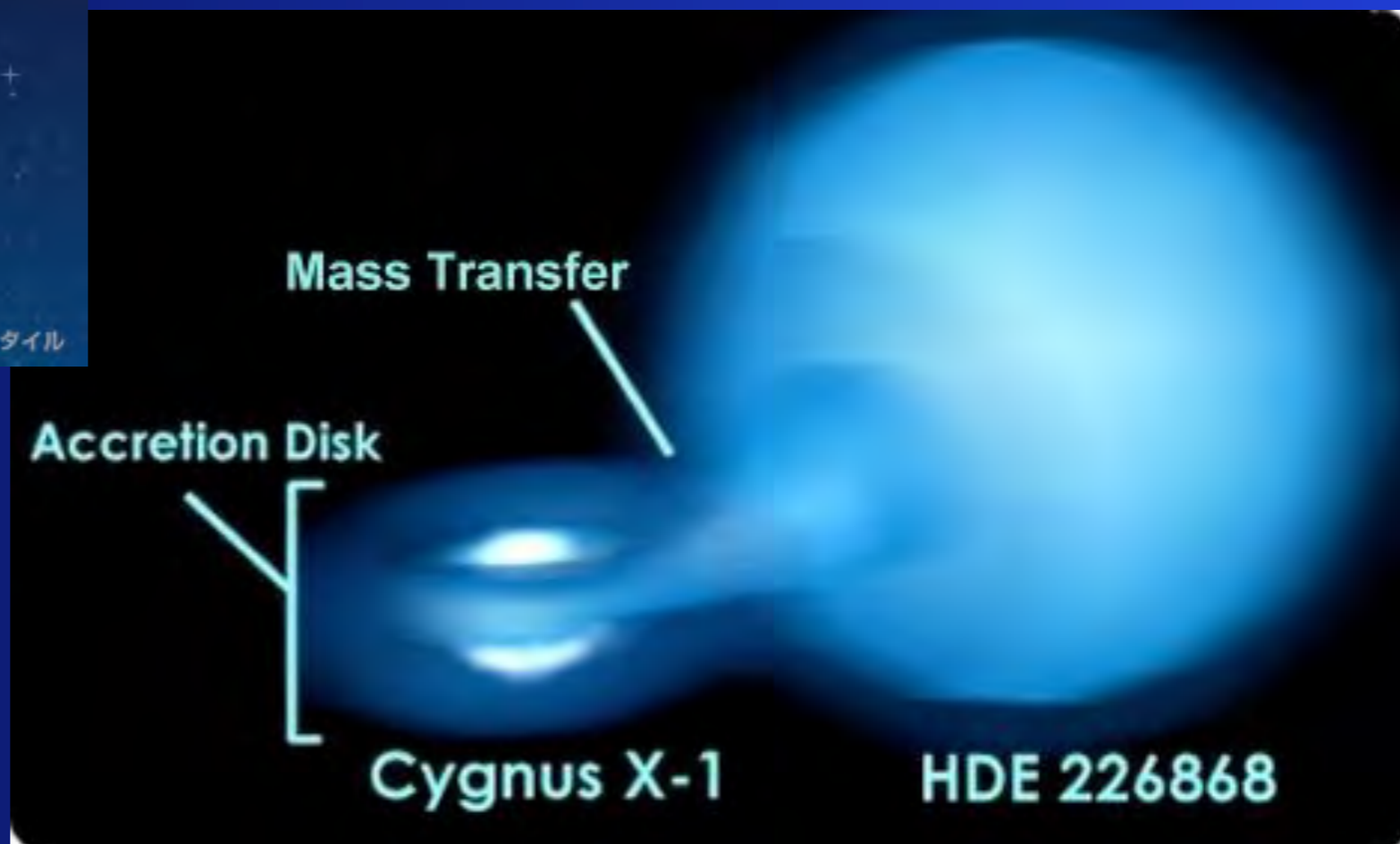
中性子星  
 $\leq 2.4M_{\odot}$

ブラックホール

# はくちょう座 X-1はブラックホール



6000光年先



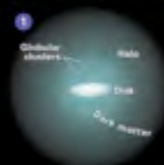
# 天の河銀河 (Milky Way)

## THE MILKY WAY

NATIONAL GEOGRAPHIC

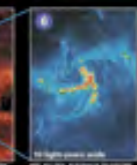
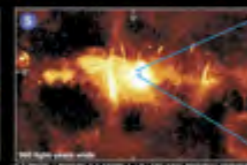
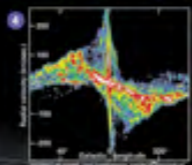
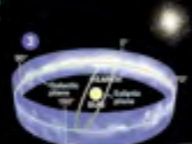
Home galaxy of Earth, the Milky Way is a spiral-shaped system of a few hundred billion stars. Bright regions of recently formed stars highlight its arms, while older stars explode or expel their outer layers as beautiful planetary nebulae, then fade away and die. A thick swarm of orange and red stars marks the galactic bulge, encapsulating the star-packed galactic center. At its core may be a black hole, a region so dense that not even light can escape its gravitational pull. All objects in the Milky Way orbit the galactic center, much like planets in Earth's solar system revolve around the sun. But the scale is staggering: Light from a star at one edge of the galaxy takes about 100,000 years to reach the opposite side.

# 3万光年先



**GUIDE TO THE GALAXY**

- Far beyond the galactic disk, yet drawn by its gravity, some stars and globular clusters wander the galaxy's halo. Regions of dark matter—regions that fall through its gravitational effects—extend beyond that.
- Star clouds of interstellar dust block much of our night sky view of the Milky Way, which from our position in the galactic disk appears as a hazy band of light. Infrared satellites can see through the dust to reveal the galaxy's structure.
- Earth's orbit around the sun lies at a severe angle to the galactic plane.



**A TURBULENT HEART**

A graph based on a radio survey reveals the widespread motion of molecular gas in the inner part of our galaxy: gas moving away from Earth (top half) and toward Earth (bottom half). The densest gas appears white; heat shows blue.

- Massive amounts of energy are released near the center of the Milky Way, producing electrons that race along magnetic field lines, illuminating remnants of stellar explosions.
- Probing even deeper into the core, a radio image detects a spiral of hot gas that is falling toward what may be a black hole source 2.6 million times as massive as the sun.

This computer-generated image of the Milky Way is one perspective of a 3-D model newly compiled for NATIONAL GEOGRAPHIC—incorporates the actual positions of hundreds of thousands of stars and nebulae.

- Galactic star cluster
  - Interstellar gas and dust
  - Nebulae
  - Thinner star region (see also)
  - Galactic bulge or center (inner star region)
- Reference numbers for galaxies, nebulae, and star clusters (where listed)
- M31 Messier 31 (Andromeda)
- M32 Messier 32 (Coma)
- Coordinate system centered



**PLANETARY NEBULA M2-9**

Basic kaleidoscopes of the Milky Way, colorful nebulae and star clusters are found throughout Earth's galaxy. Even a run-of-the-mill star may eventually give birth to a nebula of surpassing beauty. Just as our sun will die in its death throes some five billion years from now, a dying star expanded into a red giant and was transformed into the nebula M2-9 (above). At its center shines a small, hot core, which will cool and fade over time to come, by stellar odds, streams of chaotic particles, trails one way in opposite directions, like exhaust from back-to-back jet engines. This expansion, witnessed by the Hubble Space Telescope, is common among planetary nebulae. Stray light from the star heats M2-9's gases and makes them glow. Other types of nebulae exist in our galaxy, including dark nebulae that risk in microscopic dust that blocks our view of stars behind. When a star enters a dark nebula, the dust particles reflect starlight and the back

radiance, however, every star in the cluster is about the same age, billions of years older than our 4.5-billion-year-old sun.

Peering between dust clouds toward the central bulge of the Milky Way, the Hubble Space Telescope focused on a rare clear region in the Sagittarius star cloud (above right). These irregular stars formed at different times; most are older than the sun. They sparkle like an assemblage of gems on a jeweler's velvet pad. In some dark clouds, however, light is dimmed by and warmed by glowing dust, making it glow light blue. A star 20 times as massive as the sun, and 10,000 times brighter, sports a disk of even smaller stars, shown here in false color, about 20,000 times wider than Earth's orbit. Light from the hot star is absorbed by and warms the dust, making it glow light blue. As stars like the sun die, they become fuel for interstellar dust. Celestial bodies—the remnants of its red giant stage—surrounds the tiny hot central star of NGC 7527 (above right). Blown outward, the dust would obscure our view of the center of NGC 7527 were it not for this remarkable composite image in infrared and visible light from the Hubble Space Telescope.

Clouds of interstellar dust (right), shown over large regions along the central plane of the Milky Way, are not thick and opaque but seem as hazy as the head on a glass of beer. Blown outward, the dust would obscure our view of the center of NGC 7527 were it not for this remarkable composite image in infrared and visible light from the Hubble Space Telescope.

Some galaxies of the Milky Way host equally remarkable celestial phenomena. In the Large (above right), 100,000 light-years from Earth, clumpy, filamentary clouds of hydrogen gas reveal their fiery march in a radio map from the Australia Telescope Compact Array. The lower half of the cloud (left) is spiraling toward the Earth while the top half forms away.

Scouring along the spiral arms of the galaxy, bright emission nebulae mark regions where new stars are being born. The Lagoon Nebula (below), just 5,000 light-years distant, is easily detected with the naked eye as a hazy spot in the southern constellation Sagittarius. Wide-field images show that it covers more of

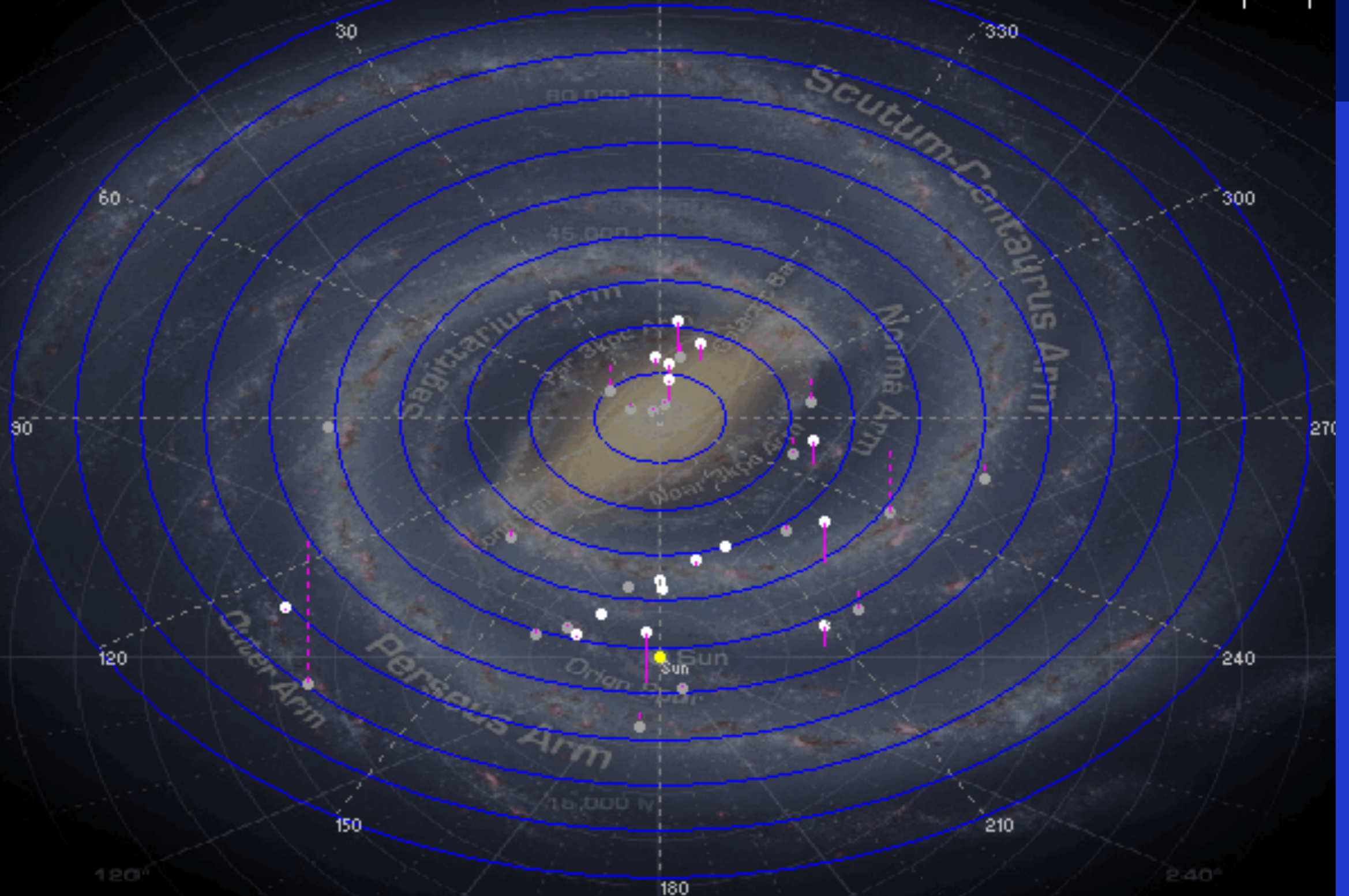
the sky than does the full moon. Where dust was once only a veiled dark cloud, radiation from the brightest and most massive young star in the nebula, M42, lit the gas and ionized the gas across a wide region. Despite the brilliance of the Lagoon Nebula and similar objects like the Tarantula Nebula, such areas are usually more than 100 light-years from Earth's harbor life.

With new tools, astronomers are unraveling the nature of the Milky Way and measuring distances to stars and nebulae with greater accuracy. Still, they ask, how did the Milky Way form in the first place? How and when did the arms form? How many more planets circle nearby stars besides the 52 already discovered? And the biggest question of all: Do any of them harbor life?

# The 37 black hole candidates within 50,000 LY of the galactic centre

5,000 LY

Galactic centric (galactic longitude and latitude)



3D Diagram by Larry McNish © 2012, All Rights Reserved

# はくちょう座



# こと座



# へびつかい座



# わし座



# いて座



# さそり座



はくちょう座



こと座



へびつかい座



わし座

銀河中心



いて座



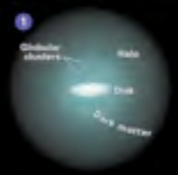
さそり座

# 天の河銀河 (Milky Way)

## THE MILKY WAY

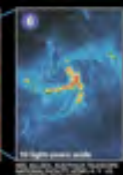
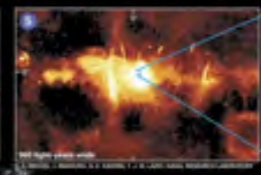
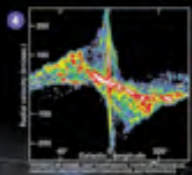
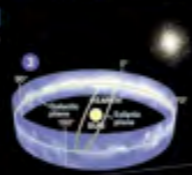


Home galaxy of Earth, the Milky Way is a spiral-shaped system of a few hundred billion stars. Bright regions of recently formed stars highlight its arms, while older stars explode or expel their outer layers as beautiful planetary nebulae, then fade away and die. A thick swarm of orange and red stars marks the galactic bulge, encapsulating the star-packed galactic center. At its core may lie a black hole, a region so dense that not even light can escape its gravitational pull. All objects in the Milky Way orbit the galactic center, much like planets in Earth's solar system revolve around the sun. But the scale is staggering: Light from a star at one edge of the galaxy takes about 100,000 years to reach the opposite side.



**GUIDE TO THE GALAXY**

- Far beyond the galactic disk, yet drawn by its gravity, some stars and globular clusters wander the galaxy's halo. Regions of dark matter—regions that fall through its gravitational effects—extend beyond that.
- Star clouds of interstellar dust block much of our night sky view of the Milky Way, which from our position in the galactic disk appears as a hazy band of light. Infrared satellites can see through the dust to reveal the galaxy's structure.
- Earth's orbit around the sun lies at a severe angle to the galactic plane.



**A TURBULENT HEART**

A graph based on a radio survey reveals the widespread motion of molecular gas in the inner part of our galaxy: gas moving away from Earth (top half) and toward Earth (bottom half). The densest gas appears white, heat shows blue.

- Massive amounts of energy are released near the center of the Milky Way, producing electrons that race along magnetic field lines, illuminating remnants of stellar explosions.
- Probing even deeper into the core, a radio image detects a spiral of hot gas that is falling toward what may be a black hole some 2.6 million times as massive as the sun.

# 3万光年先

This computer-generated image of the Milky Way is one perspective of a 3-D model newly compiled for National Geographic—incorporates the actual positions of hundreds of thousands of stars and nebulae.

- Interstellar star cluster
- Interstellar gas and dust
- Planet
- Thick star region (galactic core)
- Galactic bulge or center (inner star region)



**PLANETARY NEBULA M2-9**

Basic kaleidoscopes of the Milky Way, colorful nebulae and star clusters are found throughout Earth's galaxy. Even our own solar system may eventually pass through a nebula of surpassing beauty. Just as our sun will die in its death throes some five billion years from now, a dying star expanded into a red giant and was transformed into the nebula M2-9 (above). At its center shines a small, hot core, which will cool and fade over time to come, by stellar winds, streams of charged particles, trails one way in opposite directions, like exhaust from back-to-back jet engines. This expansion, witnessed by the Hubble Space Telescope, is common among planetary nebulae. Stray light from the star heats M2-9's gases and makes them glow. Other types of nebulae exist in our galaxy, including dark nebulae that risk in microscopic dust that blocks our view of stars behind. When a star enters a dark nebula, the dust particles reflect starlight and the back

radiance, however, every star in the cluster is about the same age, billions of years older than our 4.5-billion-year-old sun.

- Peering between dust clouds toward the central bulge of the Milky Way, the Hubble Space Telescope focused on a rare clear region in the Sagittarius star cloud (above right). These luminous stars formed at different times; most are older than the sun. They sparkle like an assemblage of gems on a jeweler's velvet pad. In some dark clouds, however, the dust, warming it glows light blue. A star 20 times as massive as the sun, and 10,000 times brighter, sports a disk of even smaller stars, shown here in false color, about 20,000 times wider than Earth's orbit. Light from the hot star is absorbed by and warms the dust, making it glow.
- As stars like the sun die, they become factors for interstellar dust. Celestial bodies—the remnants of its red giant stage—surrounds the tiny hot central star of NGC 7527 (above right). Blown outward, the dust would obscure our view of the center of NGC 7527 were it not for the narrow, stable composite image in infrared and visible light from the Hubble Space Telescope.

Clouds of interstellar dust (right), shown over large regions along the central plane of the Milky Way, are not thick and opaque but seem as hazy as the head of a glass of beer. Blown outward, the dust would obscure our view of the center of NGC 7527 were it not for the narrow, stable composite image in infrared and visible light from the Hubble Space Telescope.

Some galaxies of the Milky Way host equally remarkable celestial phenomena. In the Large Magellanic Cloud, 180,000 light-years from Earth, clumpy, filamentary clouds of hydrogen gas reveal their fiery march in a radio glow from the Antennae, Tennessee Compact Array. The lower half of the cloud (left) is spiraling toward the Earth while the top half forms away.

Scrambling along the spiral arms of the galaxy, bright emission nebulae mark regions where new stars are forming. The Lagoon Nebula (below), about 5,000 light-years distant, is easily detected with the naked eye as a hazy spot in the southern constellation Sagittarius. Wide-field images show that it covers more of

the sky than does the full moon. Where dust was once only a veiled dark cloud, radiation from the brightest and most massive young star in the nebula, M4-26, heats and ionizes the gas across a wide region. Despite the brilliance of the Lagoon Nebula and similar objects like the Tarantula Nebula, such areas are usually more than 100 light-years from Earth's harbor life.

With new tools, astronomers are unraveling the nature of the Milky Way and measuring distances to stars and nebulae with greater accuracy. Still, they ask, how did the Milky Way form in the first place? How and when did the arms form? How many more planets circle nearby stars besides the 52 already discovered? And the biggest question of all: Do any of them harbor life?



**LAGOON NEBULA**

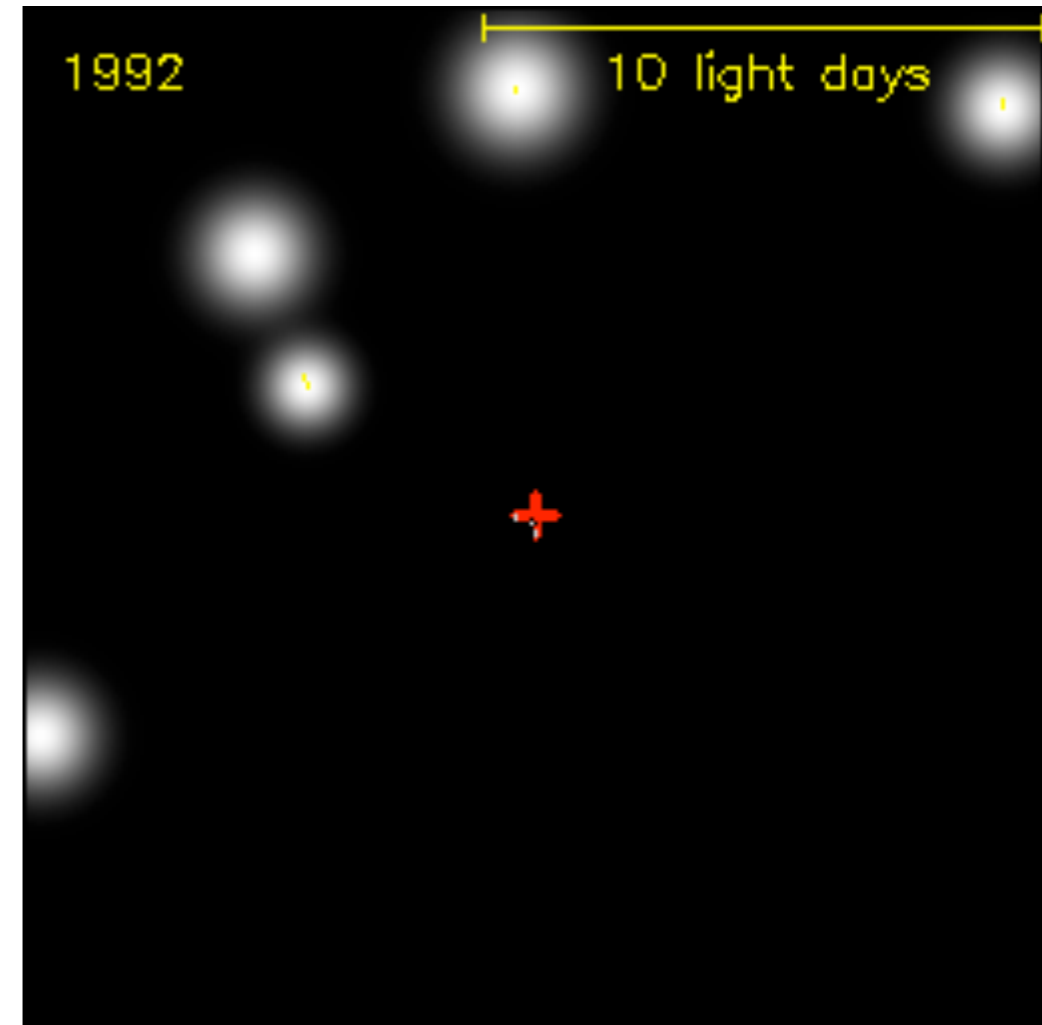
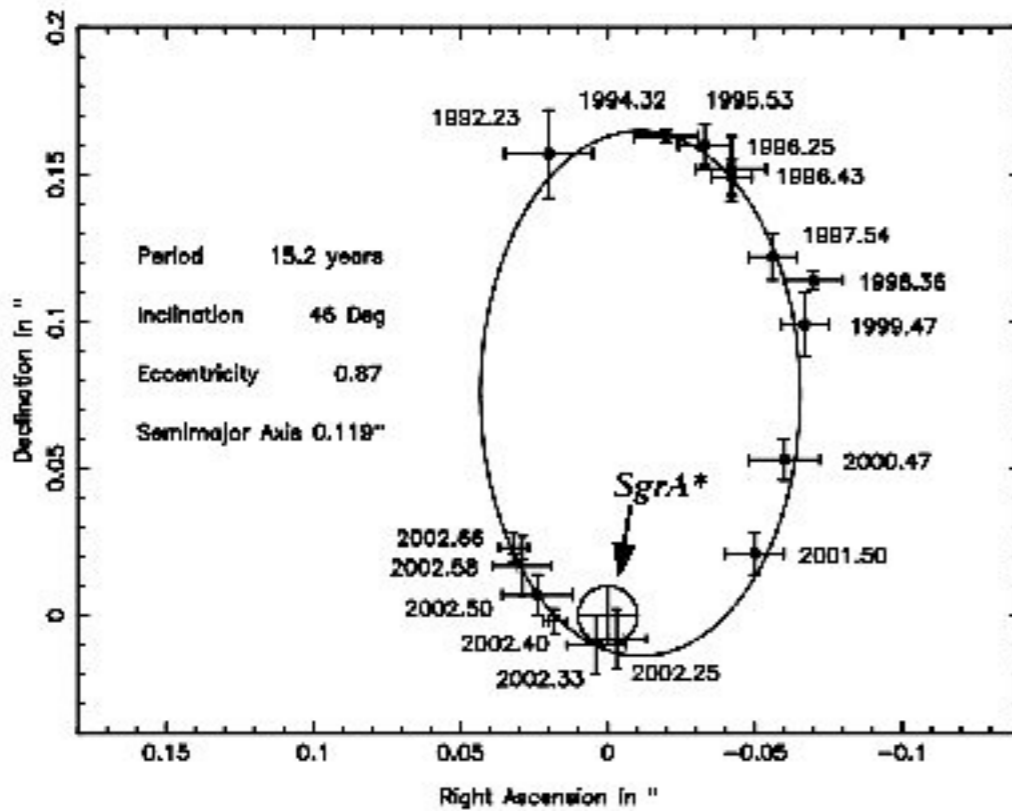
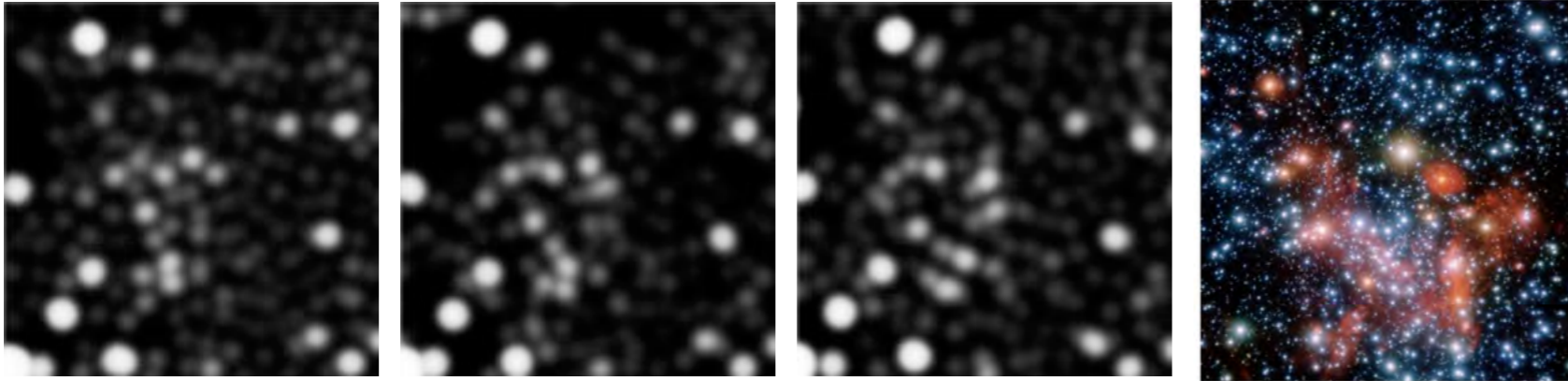
# 銀河中心へ向かってズームイン



Zooming in on the centre of the Milky Way

<http://www.youtube.com/watch?v=XhHUNvEKUY8> (1:15)

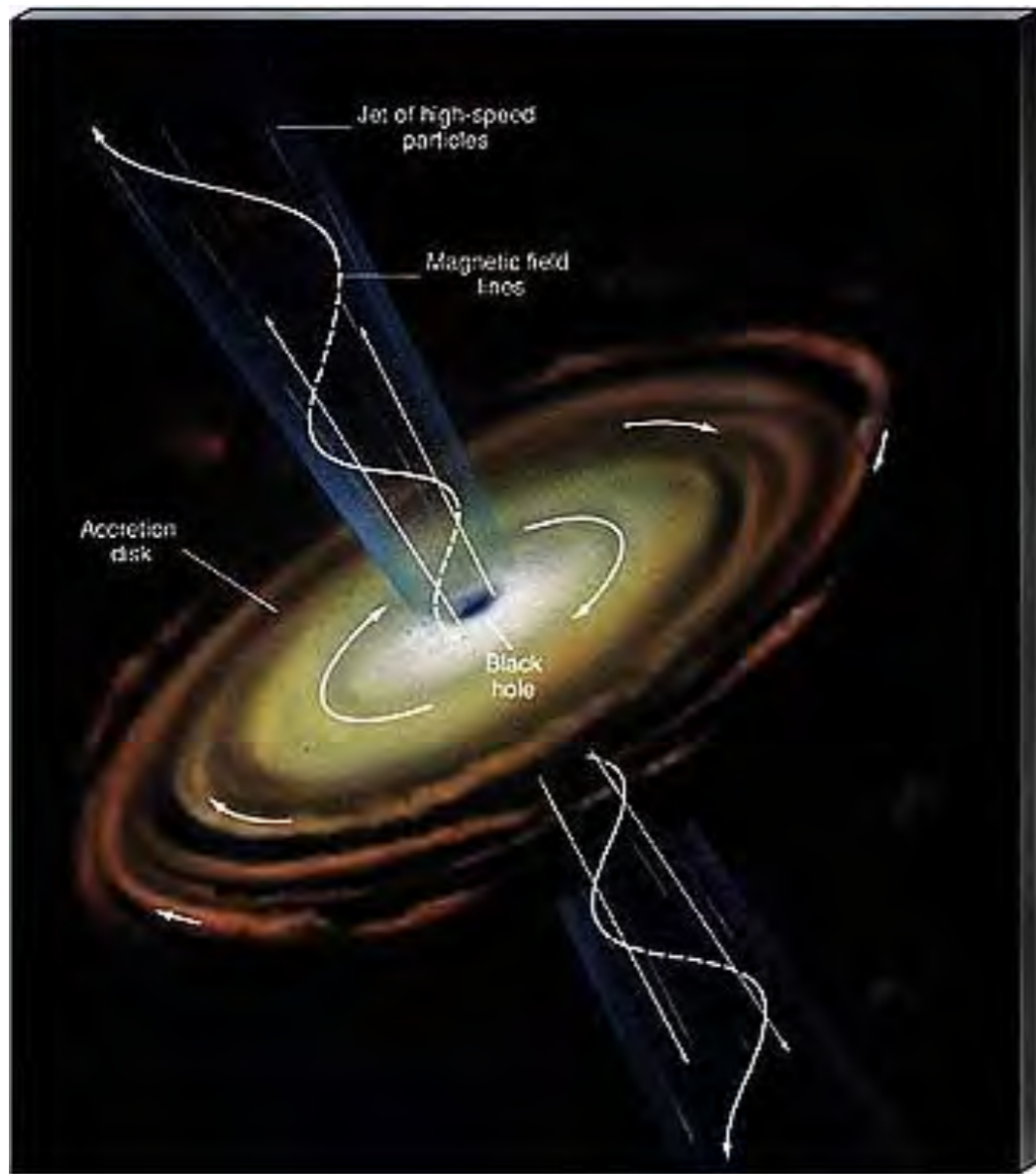
# 銀河中心 SgrA\* の近くの星 S2 の動き



我々の銀河中心には、  
太陽の420万倍の質量の  
ブラックホール！

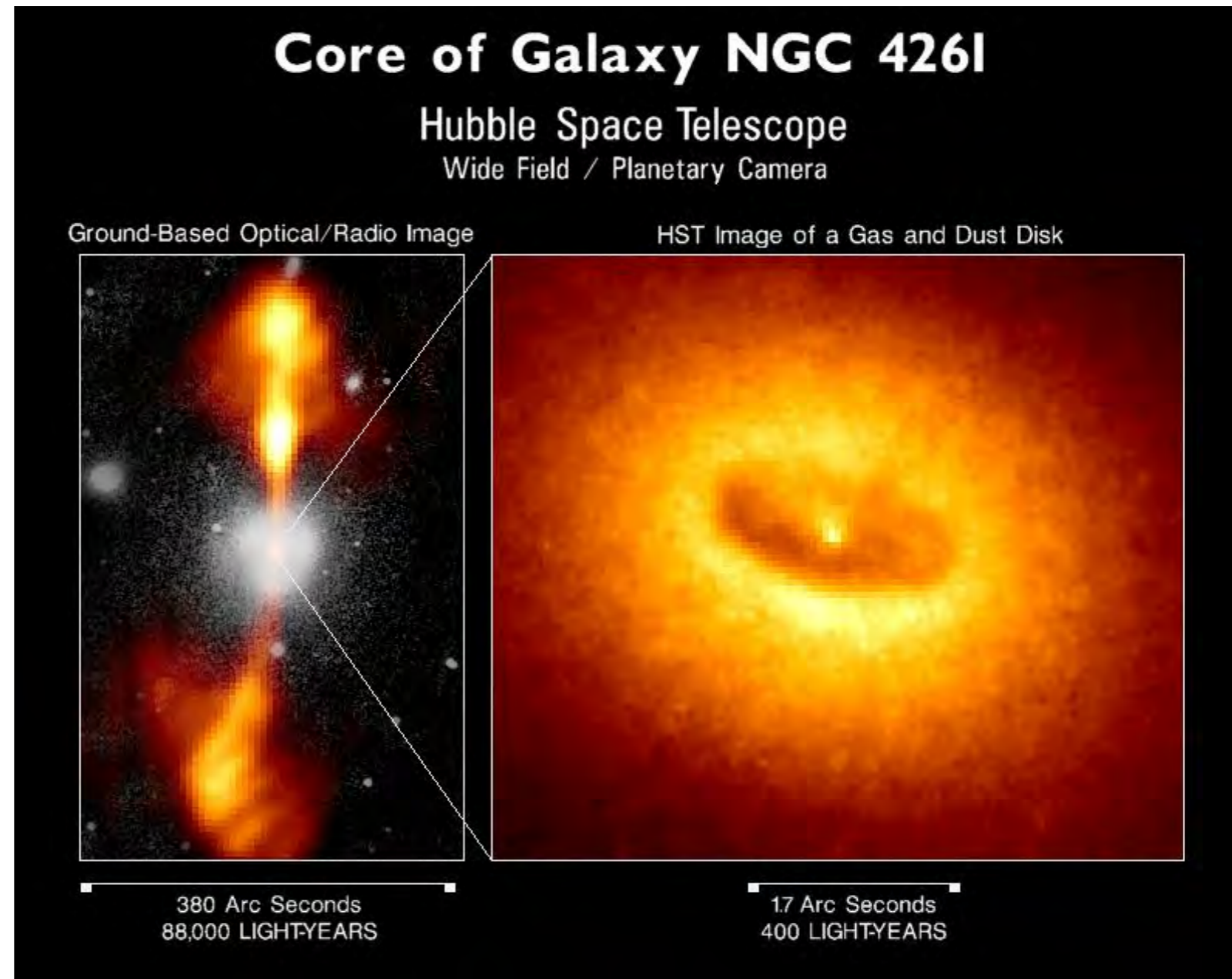
<http://www.extinctionshift.com/SignificantFindings08.htm>  
<http://www.brighthub.com/science/space/articles/13435.aspx#>

# 活動銀河核 (AGN, active galactic nuclei)



<http://www2.astro.psu.edu/users/rbc/a1/lec26n.html>

想像図



銀河中心からジェットが吹き出す

# 今日の話の内容

## 1. ブラックホールとは？

- ★何でも吸い込む。光も脱出できない重い星
- ★大きな恒星が燃え尽きた最後の姿
- ★アインシュタインの相対性理論が予言
- ★天文学では「明るい天体」（エネルギー源）

## 今日の話の内容

1. ブラックホールとは？

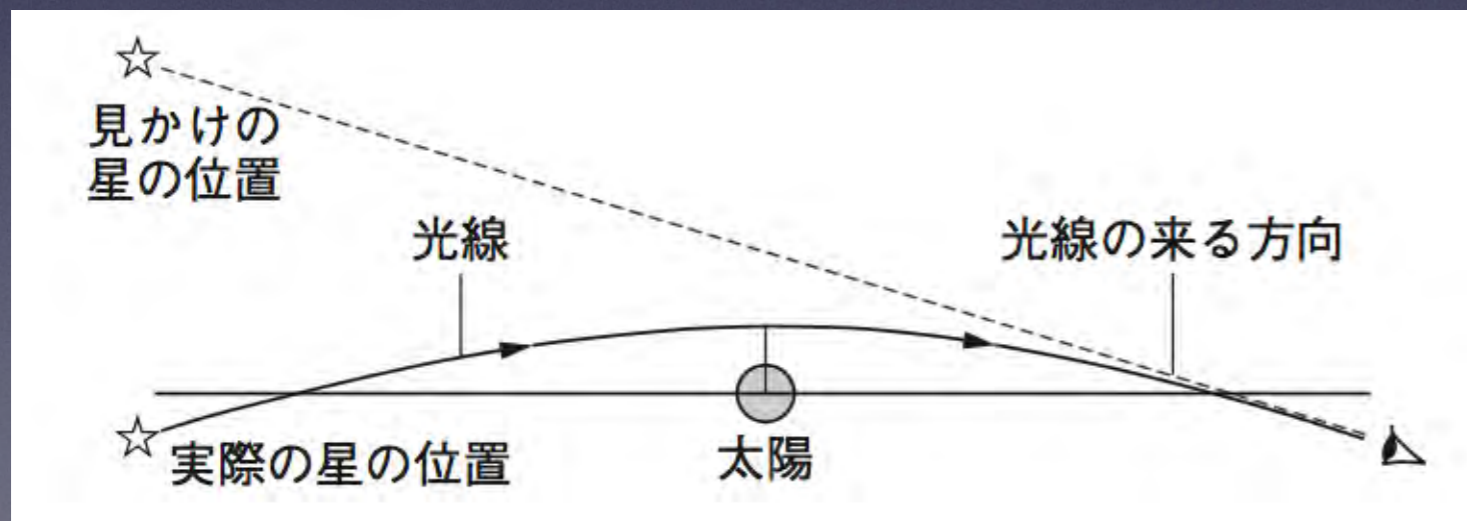
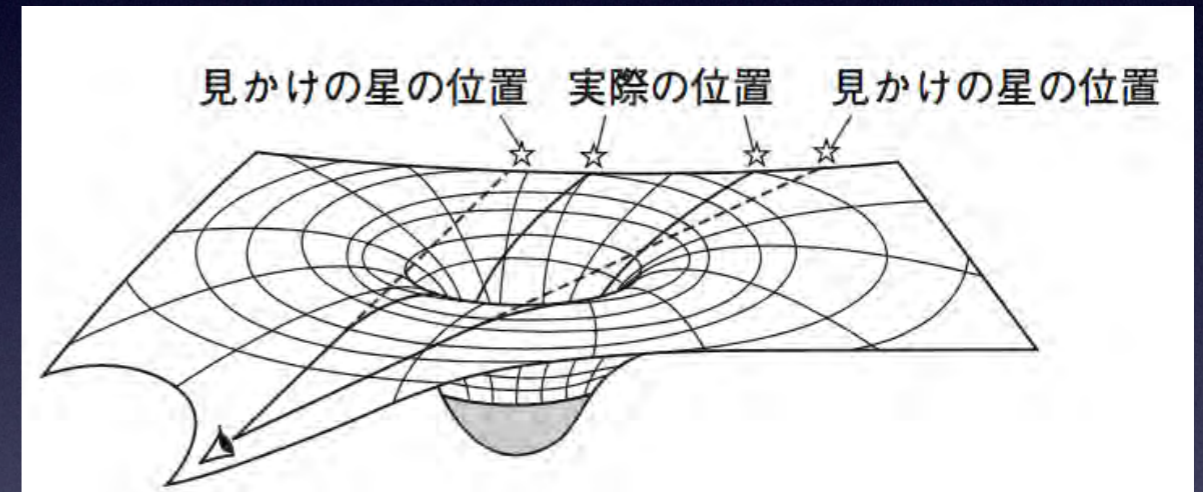
2. 見えないはずでは？

★ まわりのガスや天体の動きから  
ブラックホールの存在がわかる！

★ブラックホールの近くでは光も曲がって進む  
(重力レンズ)

# 一般相対性理論の予言【光の曲がり】

光は時空を直進するが、重い天体の周りでは、時空の歪みにより、曲がって進むことになる。



1919年、エディントンが、皆既日食を利用して、光の曲がりを確認（0.875秒角）



Taken from the 22 November 1919 edition of the Illustrated London News.

Coverage in the (more excitable) New York Times.

**LIGHTS ALL ASKEW  
IN THE HEAVENS**

**Men of Science More or Less  
Agog Over Results of Eclipse  
Observations.**

---

**EINSTEIN THEORY TRIUMPHS**

---

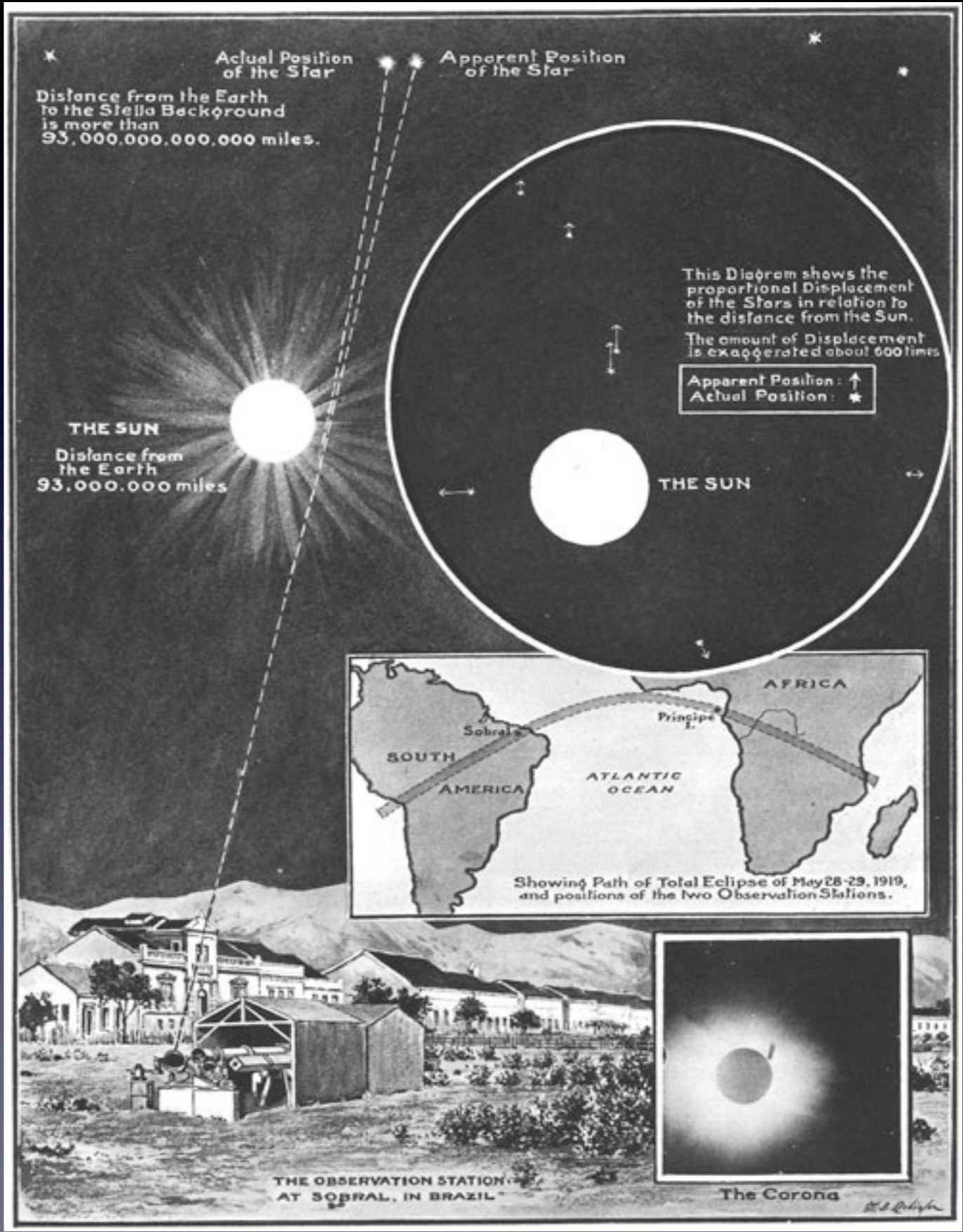
**Stars Not Where They Seemed  
or Were Calculated to be,  
but Nobody Need Worry.**

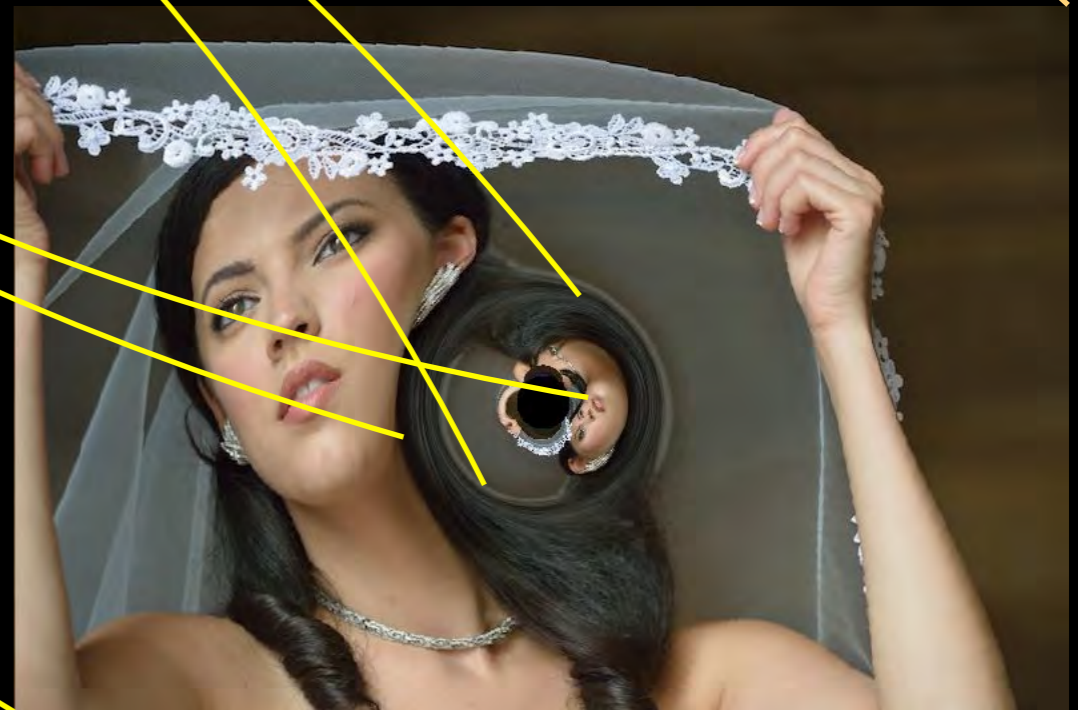
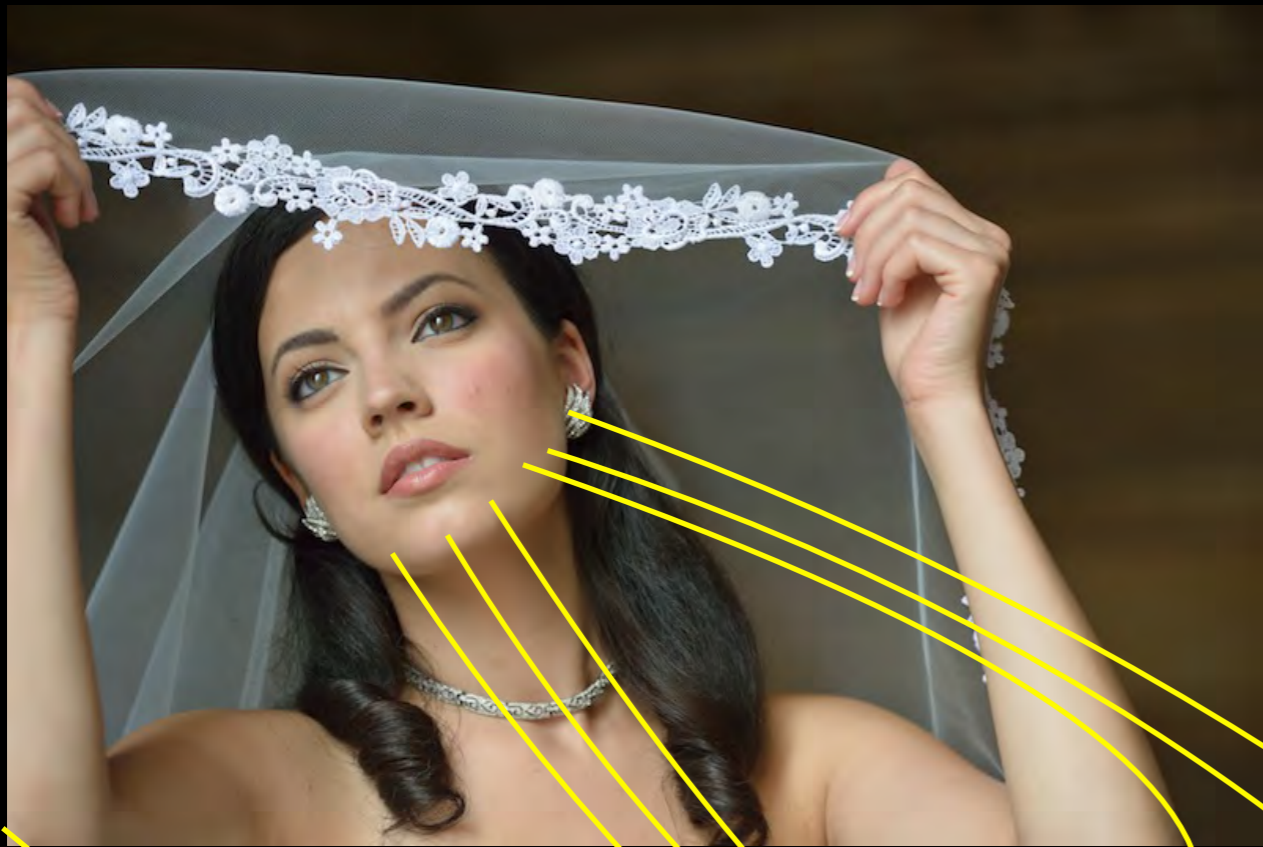
---

**A BOOK FOR 12 WISE MEN**

---

No More in All the World Could  
Comprehend It, Said Einstein When  
His Daring Publishers Accepted It.





ブラックホールの周りで  
光は曲がる



## 大阪工業大学 元学長 井上正崇 名誉教授

2015年8月 工学実感フェアにて撮影, 重力レンズプログラムで画像処理

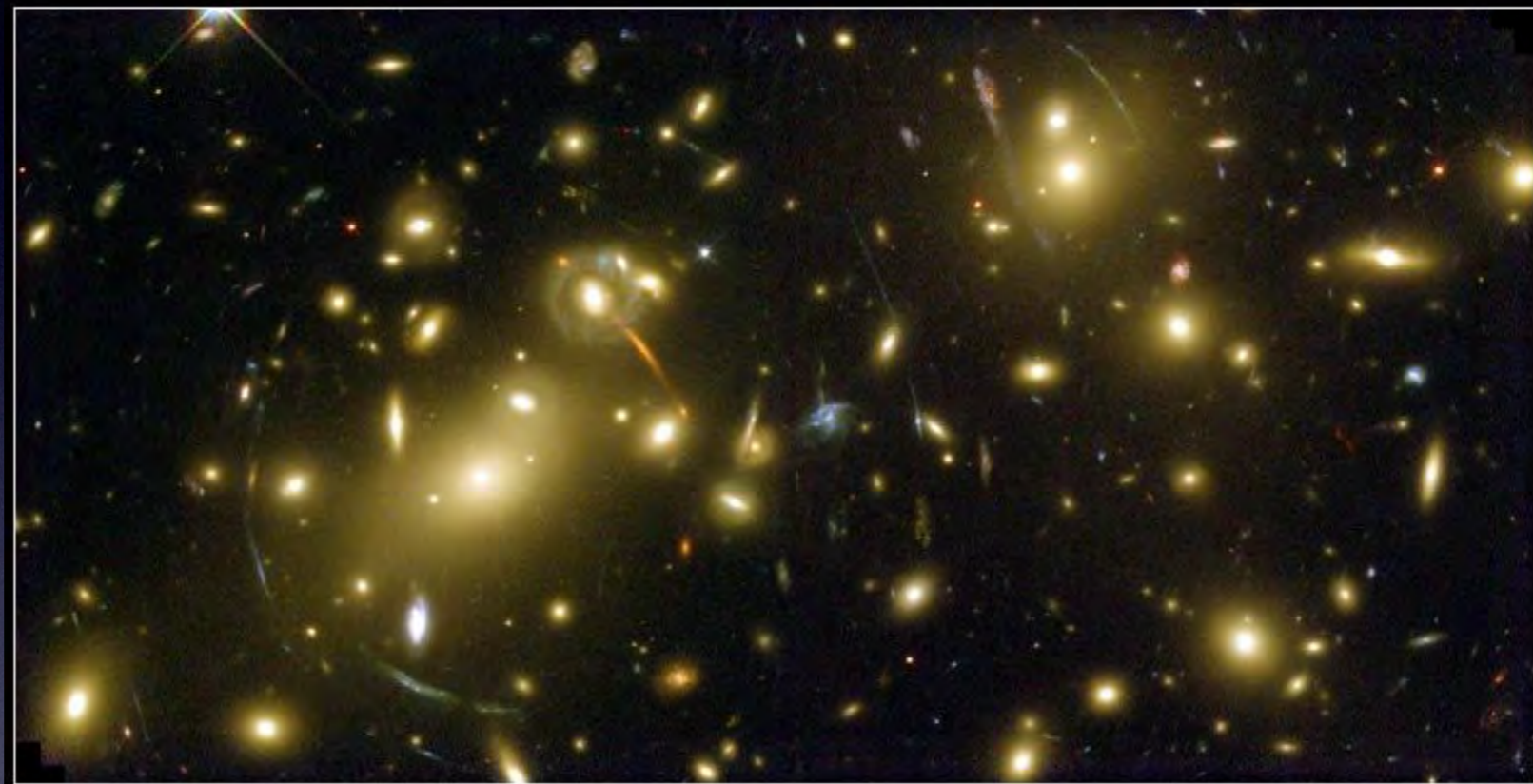


## 大阪工業大学 前学長 西村泰志 教授

2015年8月 工学実感フェアにて撮影, 重カレンズプログラムで画像処理

# 一般相対性理論の予言 【光の曲がり】

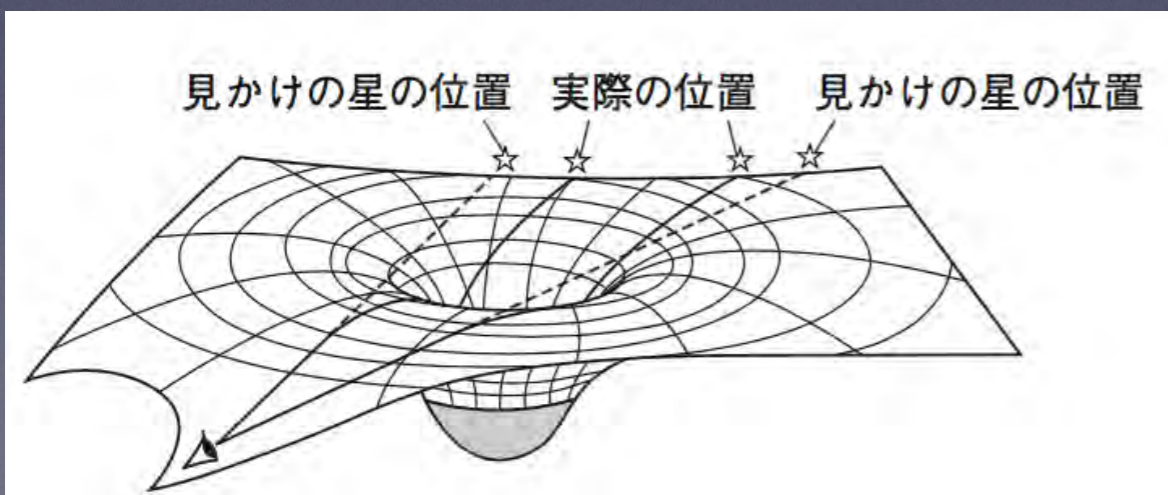
## 重力レンズ



Galaxy Cluster Abell 2218

HST • WFPC2

NASA, A. Fruchter and the ERO Team (STScI, ST-ECF) • STScI-PRC00-08



# 映画 インターステラー (2014)



# 映画 インターステラー (2014)



Interstellar (2014)



Executive Producer: Kip Thorne

<https://www.youtube.com/watch?v=qZZ9jRan9eo>

2019年4月10日, 国立天文台グループ「ブラックホールの直接撮像に初めて成功」

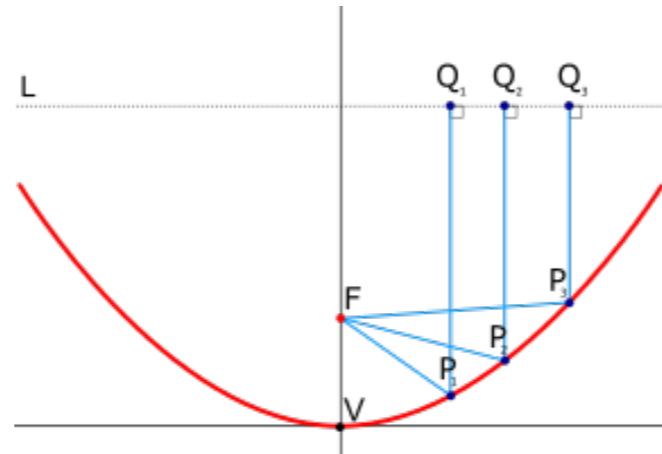


地球から5500万光年

<https://alma-telescope.jp/news/press/eht-201904>



# パラボラ (parabolla) = 放物線

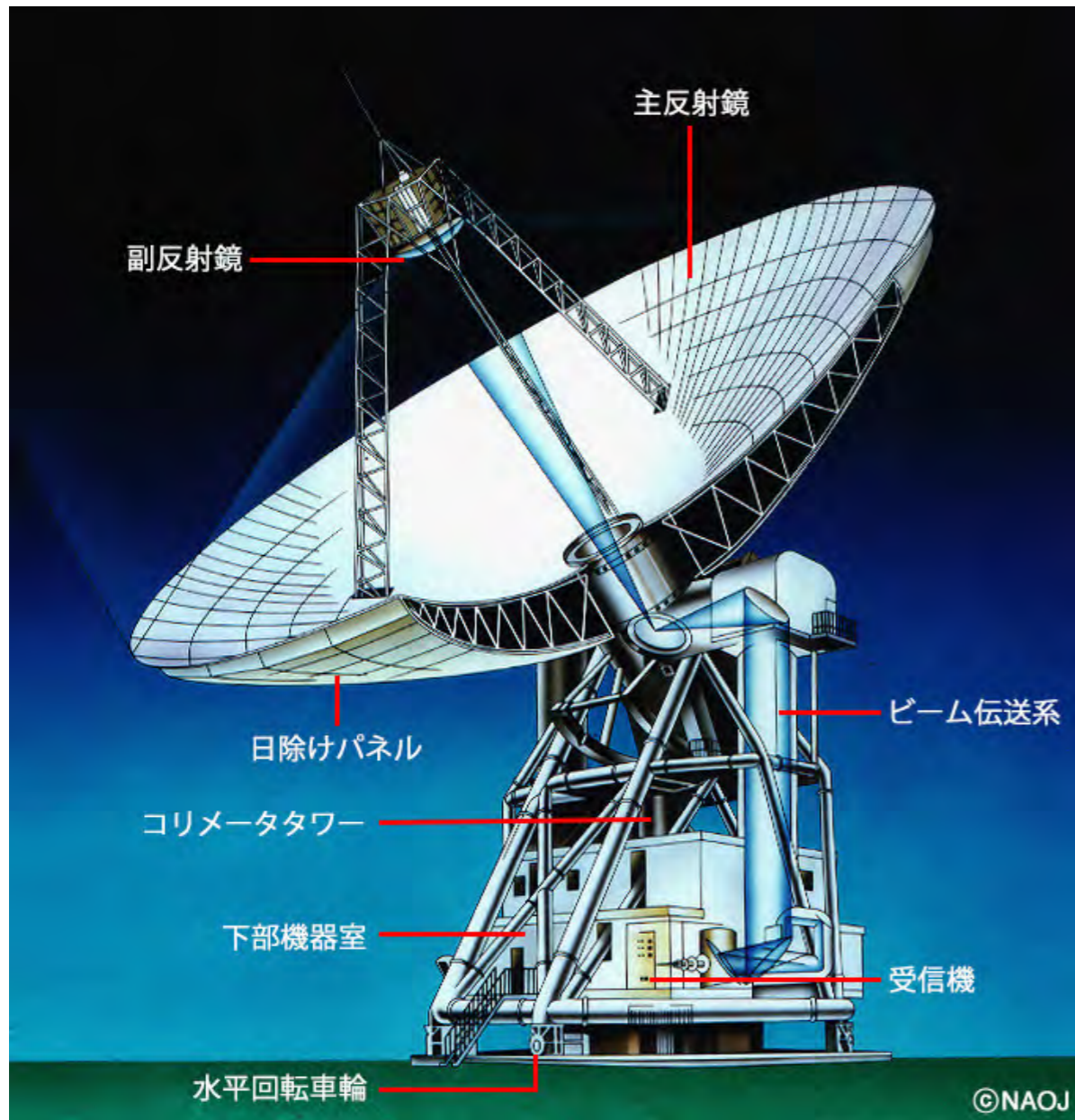


NHK「大科学実験」  
みんなここに集まってくる

Click on Start, 3min



# 電波望遠鏡 口径が大きいほど集光力高い, 分解能高い

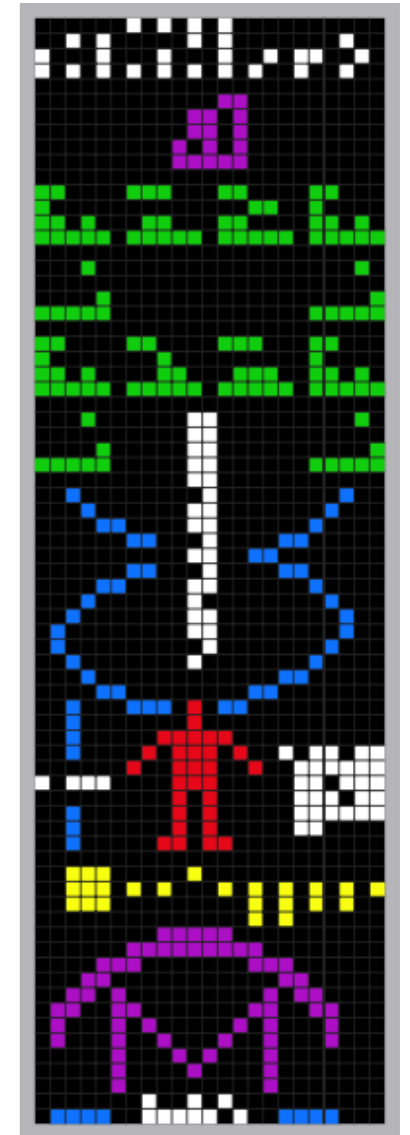


$$\text{分解能} = \text{波長} / \text{口径}$$

野辺山45m望遠鏡

# アレシボ電波望遠鏡 305メートル球面電波望遠鏡 (1963—)

(Arecibo Observatory, プエルトリコ)



- 1964 水星の自転周期55日の発見
- 1968 かにパルサー中心に中性子星発見
- 1974 連星中性子星発見
- 1989 小惑星カスタリア直接観測
- 1992 パルサーを公転する太陽系外惑星発見

アレシボ・メッセージ (1974)  
SETI (1999—)

# 中国「天眼（FAST）」 500メートル球面電波望遠鏡（2016一） (Five-hundred-meter Aperture Spherical radio Telescope: FAST)



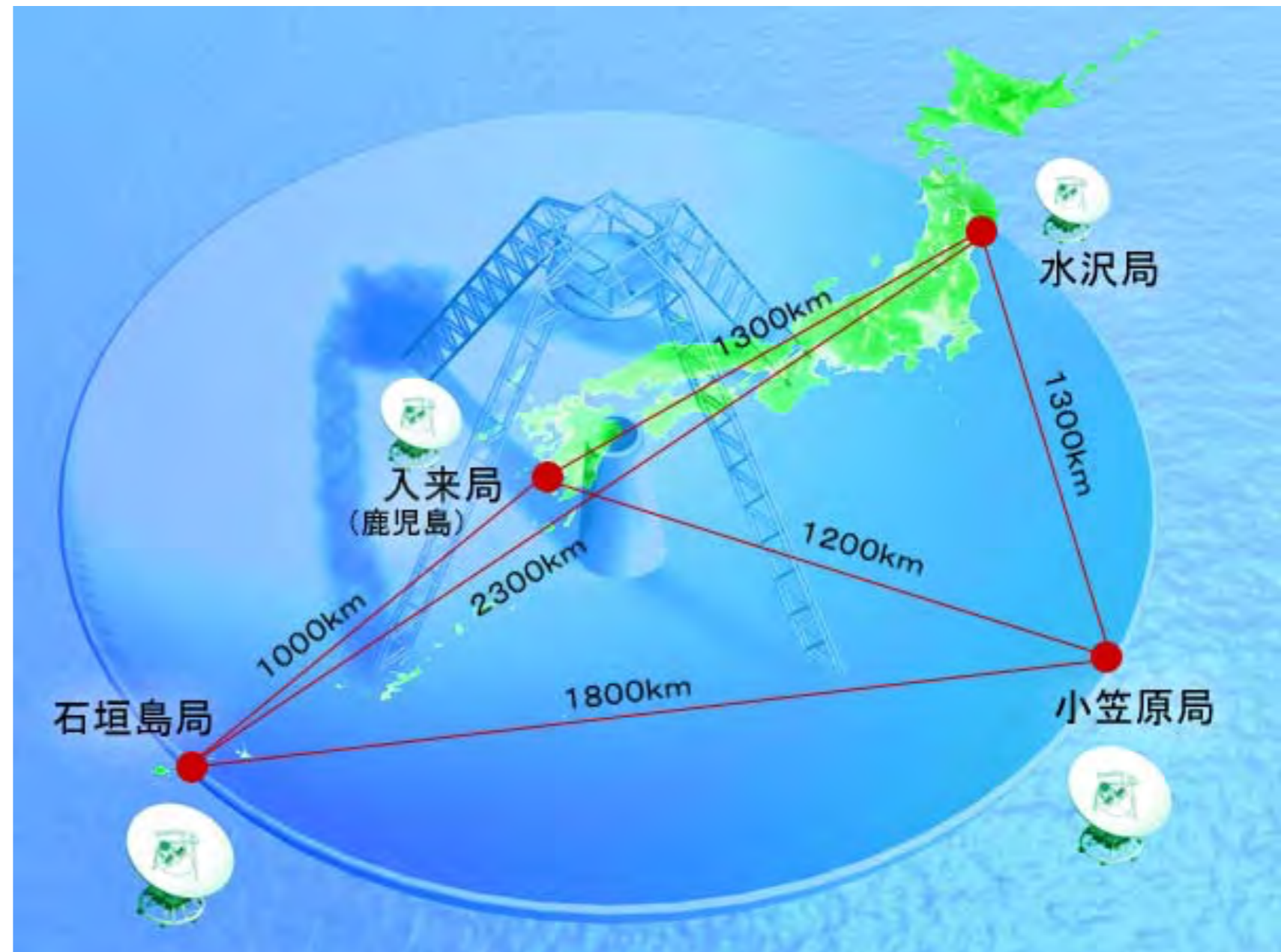
中国南西部の貴州省，185億円，天頂から40度の範囲を観測可能，  
1万人強制移住，半径5 km以内携帯電話禁止

[http://japanese.china.org.cn/business/txt/2016-07/04/content\\_38806293.htm](http://japanese.china.org.cn/business/txt/2016-07/04/content_38806293.htm)

# 電波干渉計

VLBI = Very Long Baseline Interferometer

VERA = VLBI Exploration of Radio Astrometry



<http://veraserver.mtk.nao.ac.jp/system/index.html>

# イベント・ホライズン・テレスコープ (EHT)

— 各地の電波望遠鏡をつなぎ、地球サイズの仮想望遠鏡を構成 —



<https://www.nao.ac.jp/news/science/2019/20190410-eht.html>

# ブラックホールシャドウのメカニズム解説映像

*EHT image*

<https://www.nao.ac.jp/news/sp/20190410-eh/ideos.html>

0'58"

太陽の25億倍の質量をもつブラックホール, 5000万光年先のM87銀河中心

## 今日の話の内容

1. ブラックホールとは？

2. 見えないはずでは？

★ まわりのガスや天体の動きから  
ブラックホールの存在がわかる！

★ブラックホールの近くでは光も曲がって進む  
(重力レンズ)

★ 見えたんです (2019年4月)  
まわりの光で黒い部分が見えた!!!



## 今日の話の内容

1. ブラックホールとは？
2. 見えないはずでは？
3. 音も聞こえないはずでは？

★ 重力波をつかまえた (2015年9月)

重力波

= 時空のゆがみ (トランポリンのゆれ) が  
波として伝わる

IMAGINE THAT SPACE IS A GIANT SHEET OF RUBBER...

THINGS THAT HAVE MASS CAUSE THAT RUBBER SHEET TO BEND, LIKE A BOWLING BALL ON A TRAMPOLINE.

THE MORE MASS, THE MORE THAT SPACE GETS BENT AND DISTORTED BY GRAVITY.

FOR EXAMPLE, THE REASON THE EARTH GOES AROUND THE SUN IS THAT THE SUN IS VERY MASSIVE, CAUSING A BIG DISTORTION OF THE SPACE AROUND IT.

IF YOU JUST TRY TO MOVE IN A STRAIGHT LINE AROUND SUCH A BIG DISTORTION, YOU WILL FIND YOURSELF ACTUALLY MOVING IN A CIRCLE.

THAT'S HOW ORBITS WORK: THERE'S NO ACTUAL FORCE PULLING THE PLANETS AROUND, JUST A BENDING OF THE SPACE.

GRAVITATIONAL WAVES ARE PRODUCED WHENEVER MASSES ACCELERATE, CHANGING THE DISTORTION OF SPACE.

EVERYTHING WITH MASS AND/OR ENERGY CAN MAKE GRAVITATIONAL WAVES.

IF YOU AND I STARTED TO DANCE AROUND EACH OTHER, WE WOULD ALSO CAUSE RIPPLES IN THE FABRIC OF SPACE AND TIME.

BUT THESE WOULD BE EXTREMELY SMALL, PRACTICALLY UNDETECTABLE.

AND ANYTIME THERE'S A NEW WAY TO INVESTIGATE THE UNIVERSE WE DISCOVER THINGS THAT WE DIDN'T EXPECT.

IT'S REALLY ABOUT LOOKING FOR NEW THINGS THAT WE DIDN'T KNOW EXISTED...

...EXAMINING THE EXTREME EDGES OF OUR KNOWLEDGE OF PHYSICS...

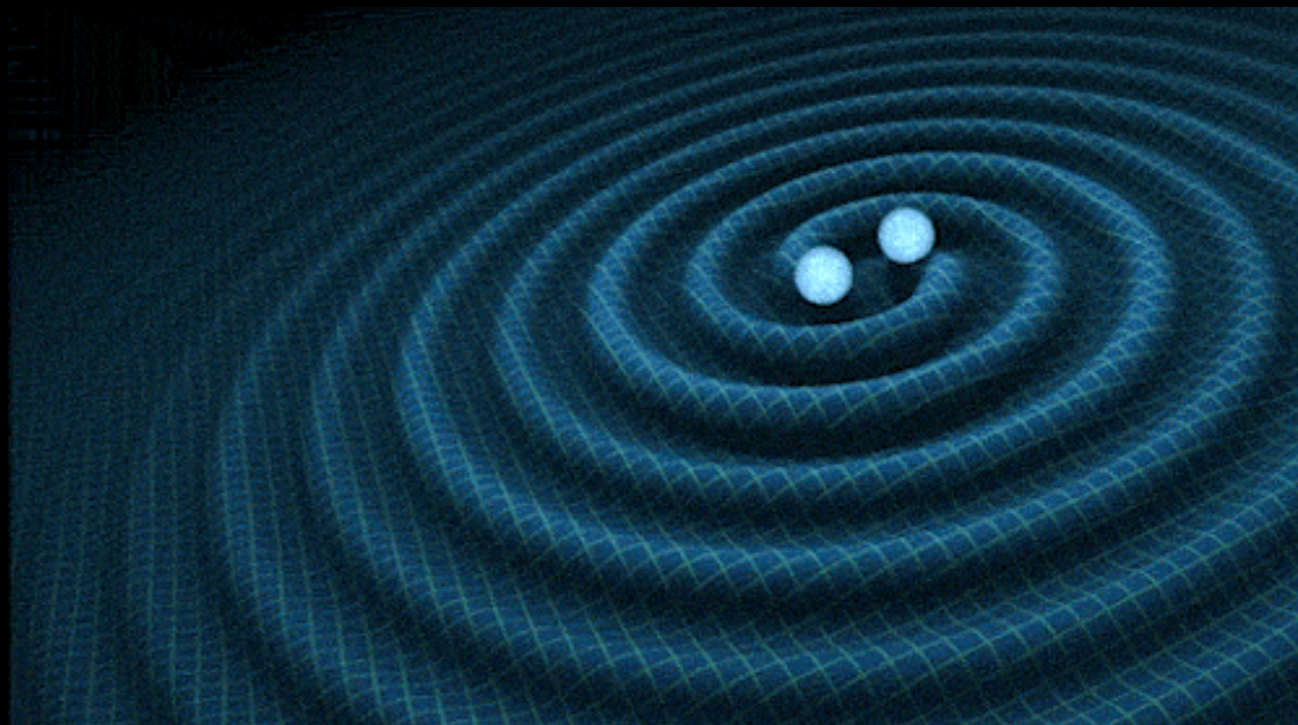
...AND TESTING OUR THEORIES ABOUT HOW THE UNIVERSE WORKS.

WWW.PHDCOMICS.COM

CREATED BY: UMBERTO CANNELLA, DANIEL WHITESON AND JORGE CHAM  
SPECIAL THANKS TO AIDAN BROOKS, FLIP TANEDO AND LIGO!

JORGE CHAM © 2016

JORGE CHAM © 2016



IMAGINE THAT SPACE IS A GIANT SHEET OF RUBBER...

THINGS THAT HAVE MASS CAUSE THAT RUBBER SHEET TO BEND, LIKE A BOWLING BALL ON A TRAMPOLINE.

THE MORE MASS, THE MORE THAT SPACE GETS BENT AND DISTORTED BY GRAVITY.

JORGE CHAM © 2016

FOR EXAMPLE, THE REASON THE EARTH GOES AROUND THE SUN IS THAT THE SUN IS VERY MASSIVE, CAUSING A BIG DISTORTION OF THE SPACE AROUND IT.

IF YOU JUST TRY TO MOVE IN A STRAIGHT LINE AROUND SUCH A BIG DISTORTION, YOU WILL FIND YOURSELF ACTUALLY MOVING IN A CIRCLE.

THAT'S HOW ORBITS WORK: THERE'S NO ACTUAL FORCE PULLING THE PLANETS AROUND, JUST A BENDING OF THE SPACE.

GRAVITATIONAL WAVES ARE PRODUCED WHENEVER MASSES ACCELERATE, CHANGING THE DISTORTION OF SPACE.

EVERYTHING WITH MASS AND/OR ENERGY CAN MAKE GRAVITATIONAL WAVES.

IF YOU AND I STARTED TO DANCE AROUND EACH OTHER, WE WOULD ALSO CAUSE RIPPLES IN THE FABRIC OF SPACE AND TIME.

BUT THESE WOULD BE EXTREMELY SMALL, PRACTICALLY UNDETECTABLE.

AND ANYTIME THERE'S A NEW WAY TO INVESTIGATE THE UNIVERSE WE DISCOVER THINGS THAT WE DIDN'T EXPECT.

IT'S REALLY ABOUT LOOKING FOR NEW THINGS THAT WE DIDN'T KNOW EXISTED...

...EXAMINING THE EXTREME EDGES OF OUR KNOWLEDGE OF PHYSICS...

...AND TESTING OUR THEORIES ABOUT HOW THE UNIVERSE WORKS.

JORGE CHAM © 2016

WWW.PHDCOMICS.COM

CREATED BY: UMBERTO CANNELLA, DANIEL WHITESON AND JORGE CHAM  
SPECIAL THANKS TO AIDAN BROOKS, FLIP TANEDO AND LIGO!

[www.phdcomics.com](http://www.phdcomics.com)

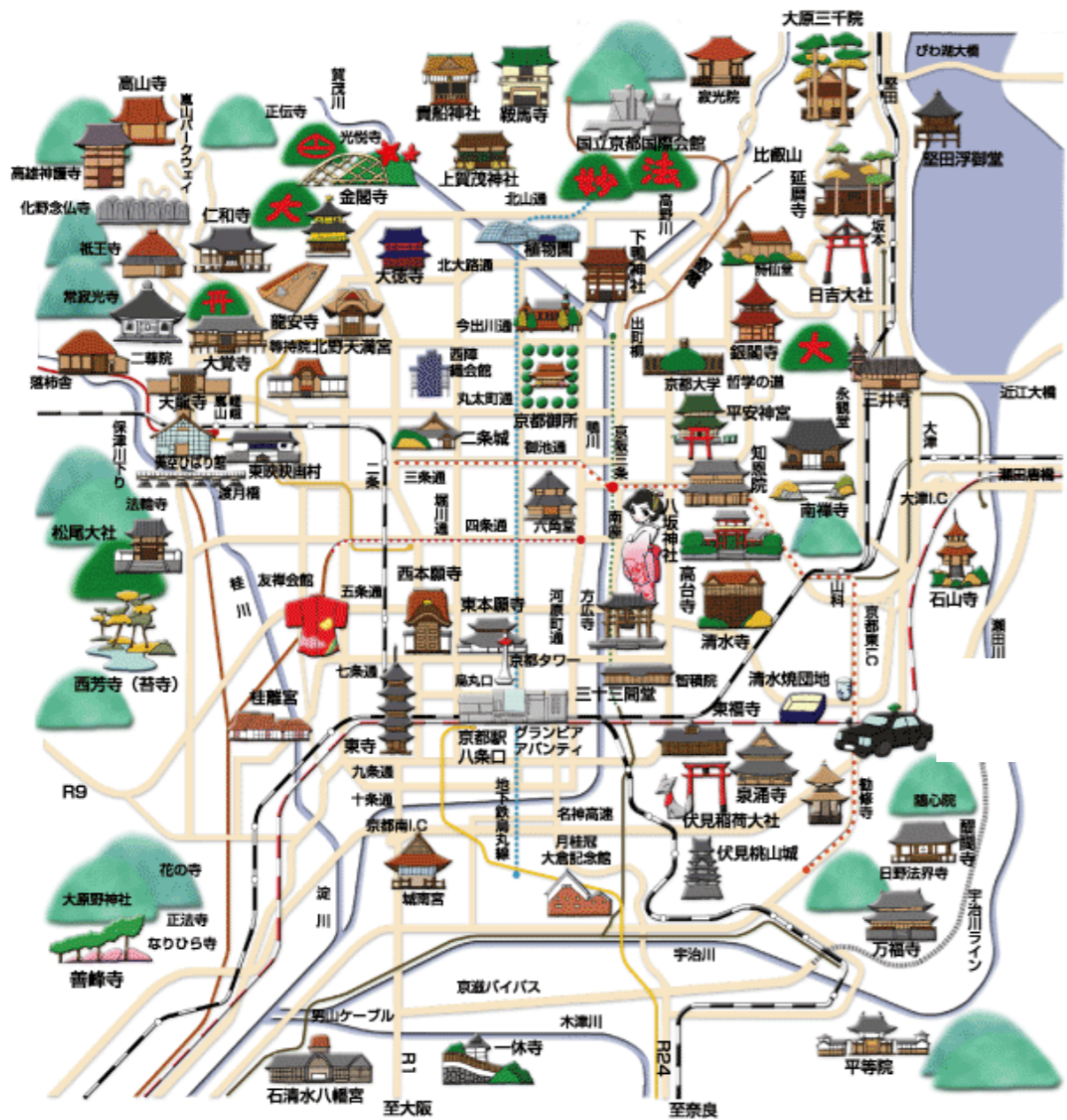
“gravitational waves explained”

THE EFFECT OF A GW IS SO MINUSCULE AND EASILY CONFUSED WITH RANDOM NOISE, YOU NEED A SMART DATA ANALYSIS TECHNIQUE.

SCIENTISTS HOPE TO IDENTIFY THE PATTERNS OF GRAVITATIONAL WAVES BY COMPARING THE WIGGLES THEY MEASURE IN THE EXPERIMENT TO THE WIGGLES THEY EXPECT FROM GRAVITATIONAL WAVES.

IT'S LIKE TRYING TO IDENTIFY A SONG BEING HUMMED AT A NOISY PARTY. A VERY VERY NOISY PARTY.

WWW.PHDCOMICS.COM



# 2016年2月, LIGOが重力波を初めて検出した, と発表した



四国新聞だけ  
ちがった... 残念 (笑)

県内うどん店100店調査  
**かけうどん235.7円**

うどん種別	単品	お替り	お替り
かけうどん	228.7円	235.7円	244円
ざるうどん	202.0円	199.4円	244円
うどん	214.8円	208.0円	47円

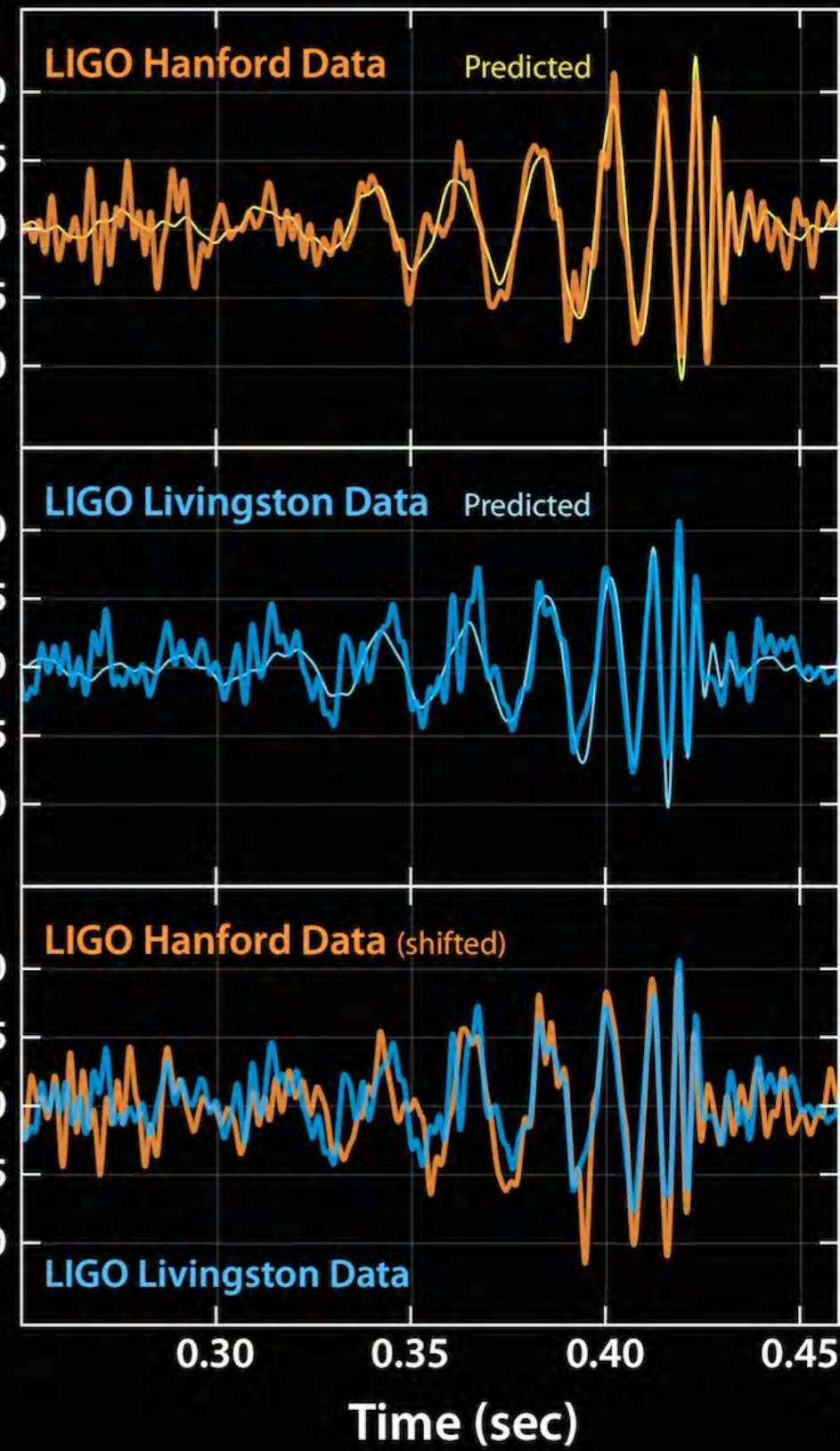
増税以降3.2円値上がり

**四国新聞**

加齢太りに  
負けない  
**BODY MAKING**

きょうの  
きょうの

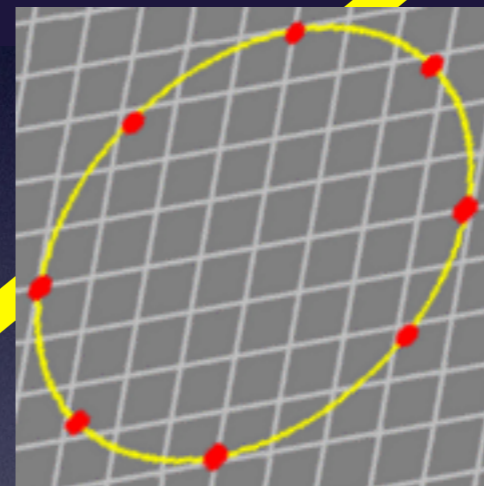
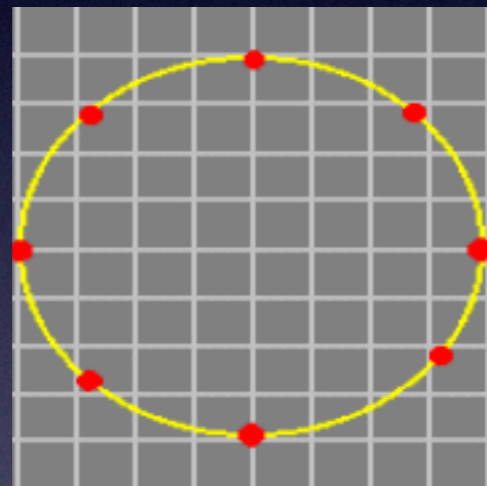
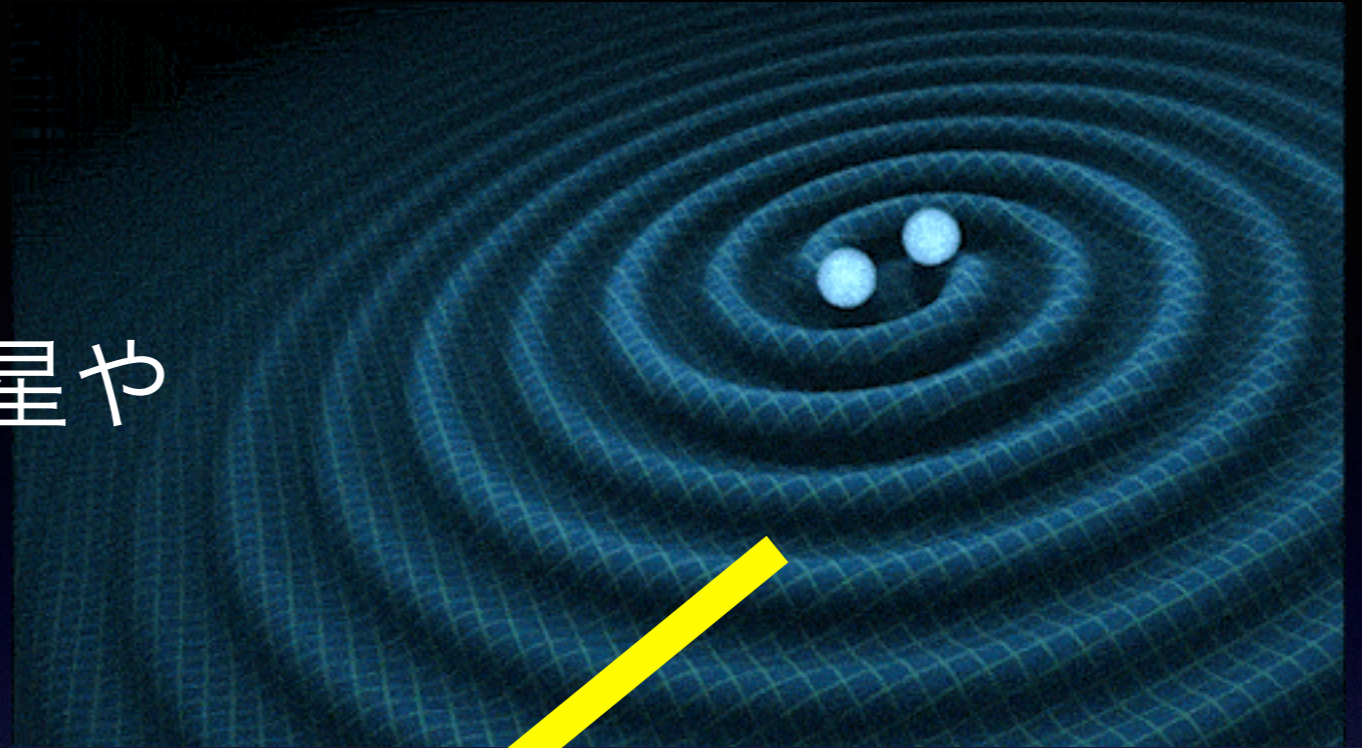
# 2016年2月, LIGOが重力波を初めて検出した, と発表した 2015年9月14日



ブラックホール連星の合体  
によって生じた重力波だった

# 重力波の発生と伝播

ブラックホール連星や  
中性子星連星



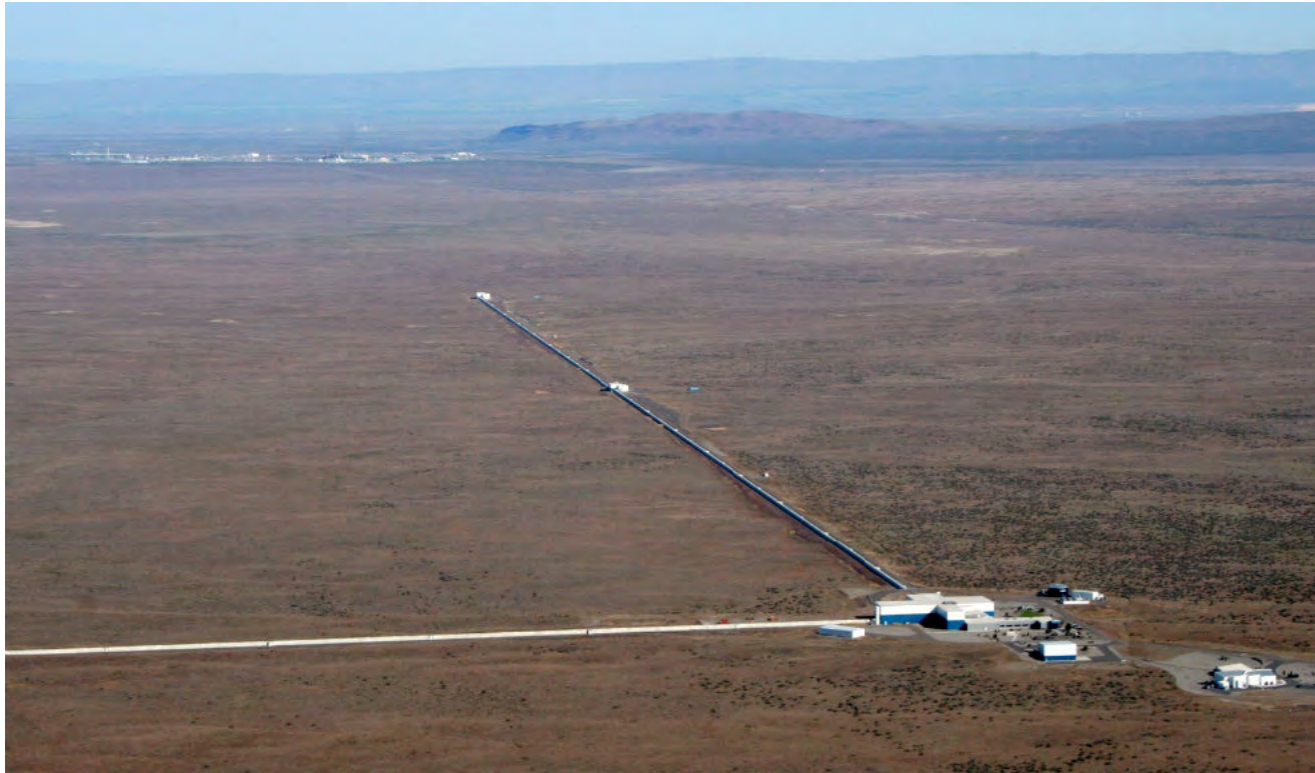
レーザー干渉計

LIGO=Laser Interferometer

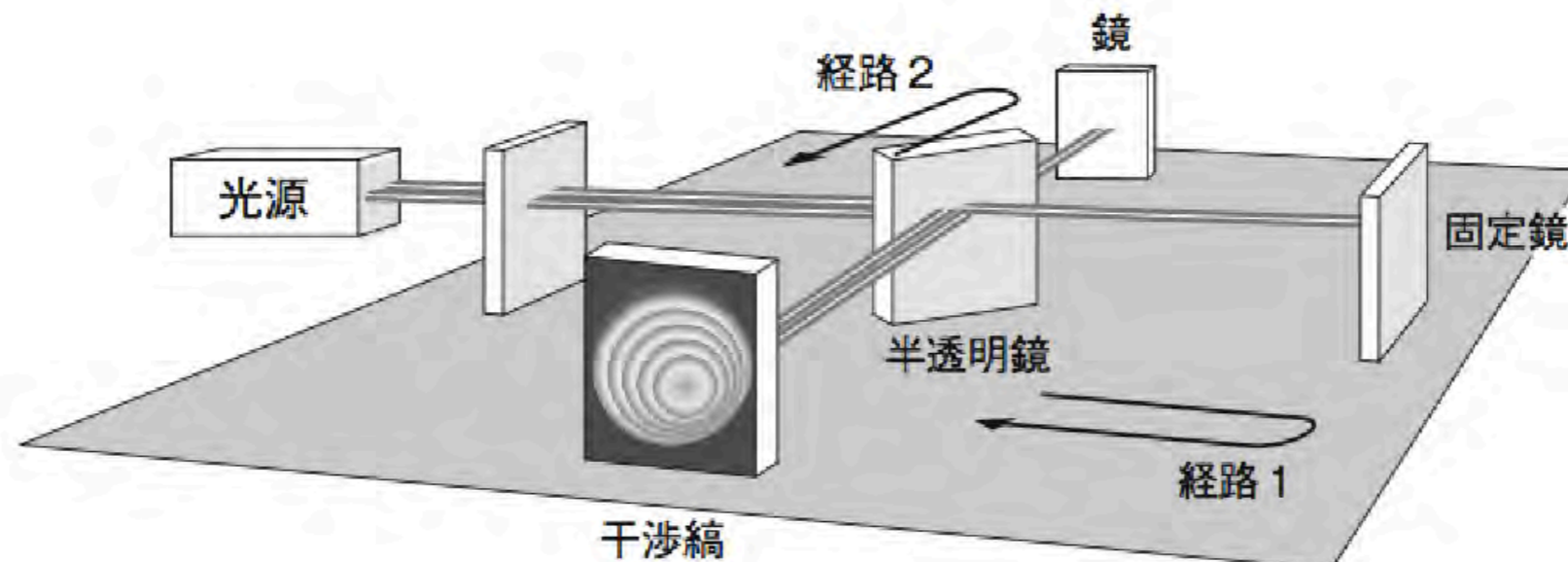
Gravitational-Wave Observatory

# LIGO (ライゴ: レーザー干渉計重力波天文台)

Laser Interferometer Gravitational-Wave Observatory (1992年予算承認)



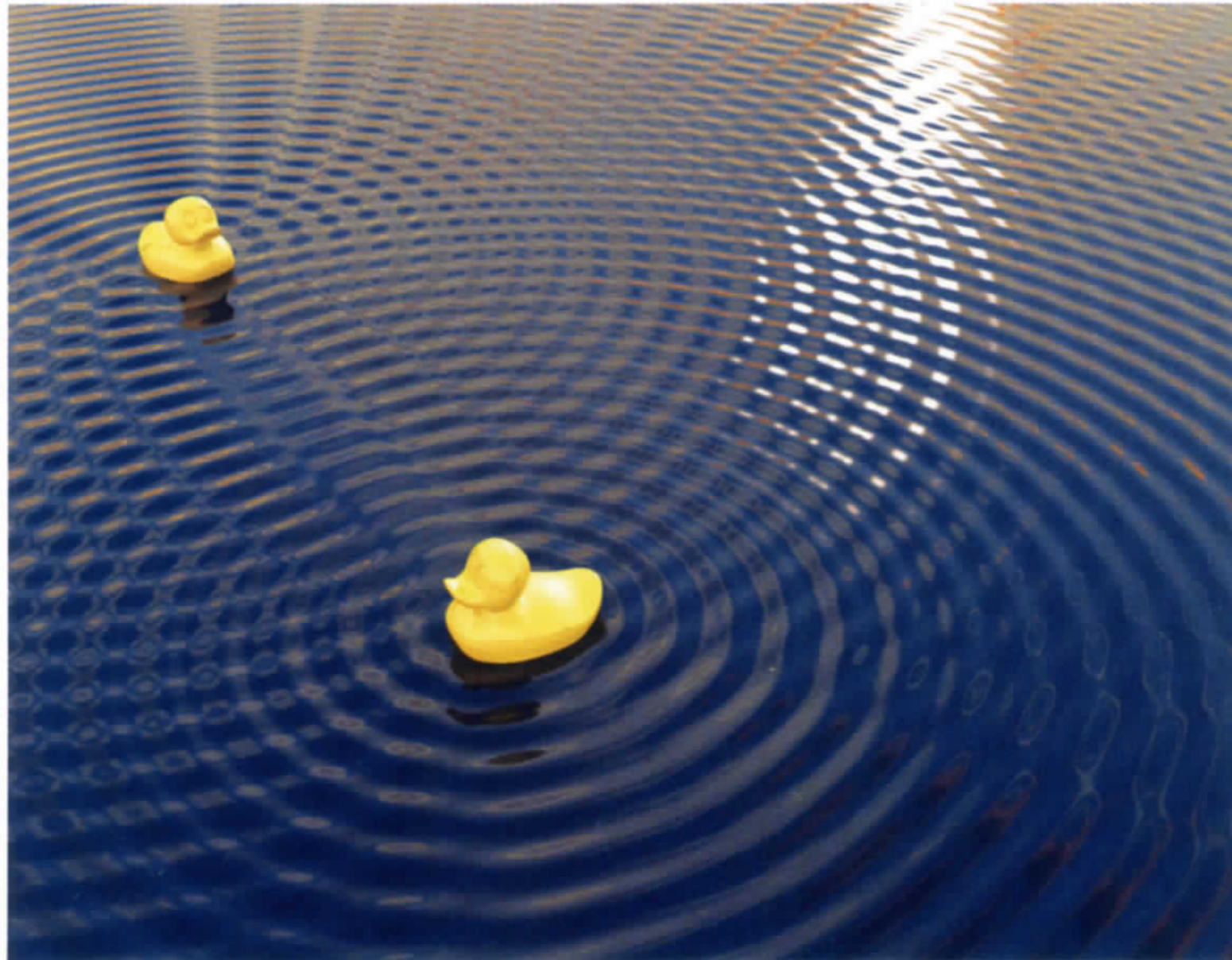
<https://mediaassets.caltech.edu/gwave>





干渉計のしくみを理解しよう

## 波の干渉（かんしょう）



**Puddle Interference** The concept of interference shows up in everyday life in bodies of water, from puddles to oceans.

# 波は重ね合わせで強くなったり弱くなったり

山 + 山 = 強め合う

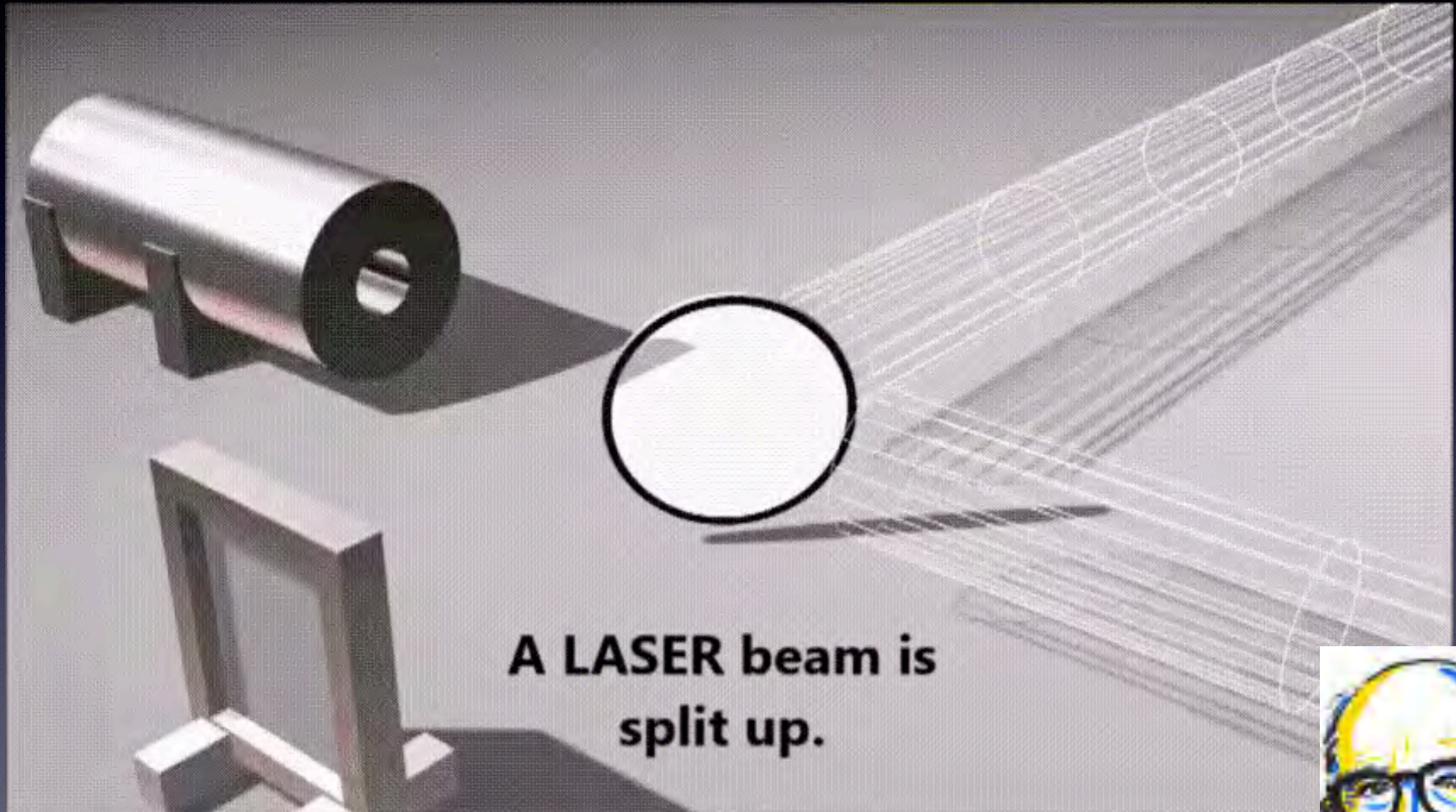
山 + 谷 = 弱め合う

山と山の重ねあわせ

山と谷の重ねあわせ

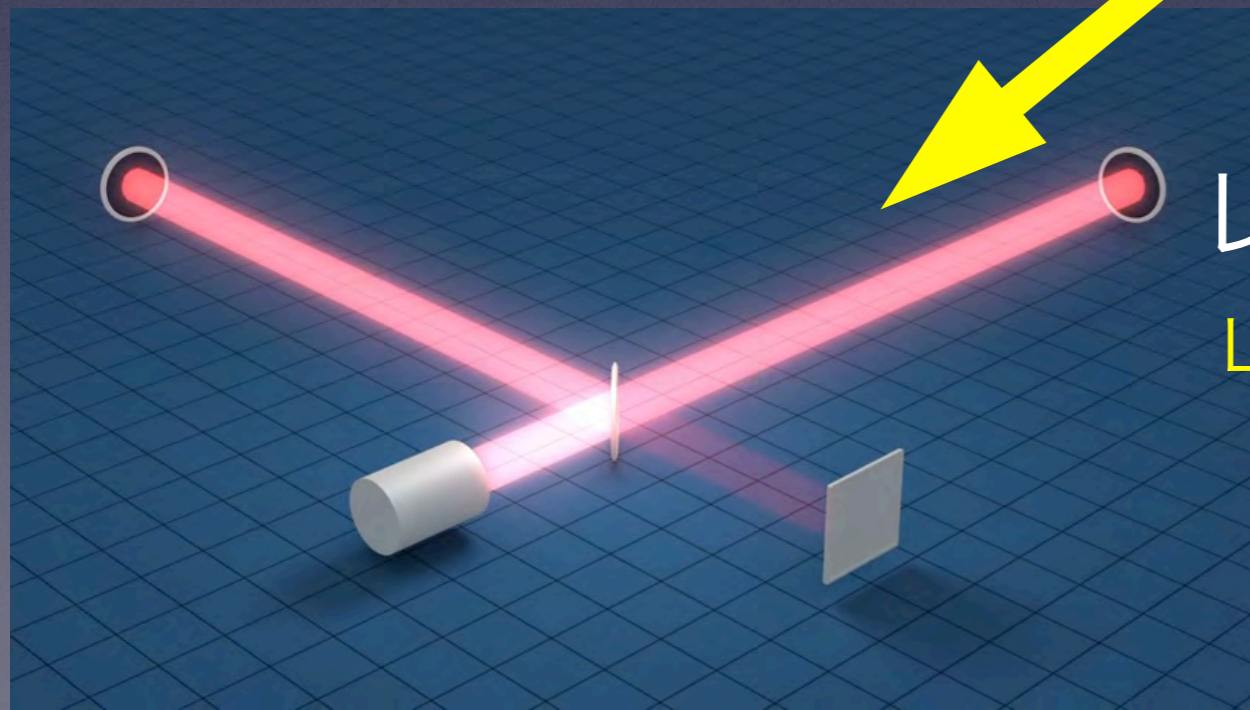
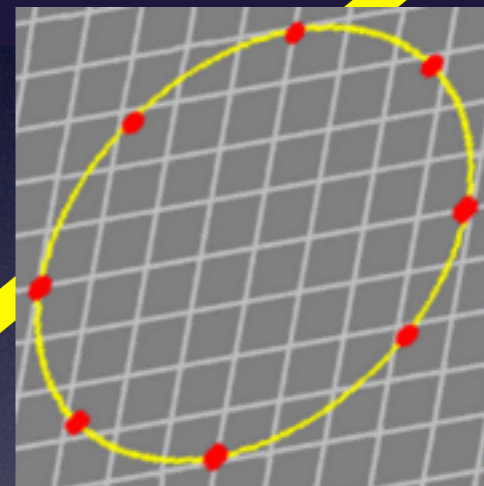
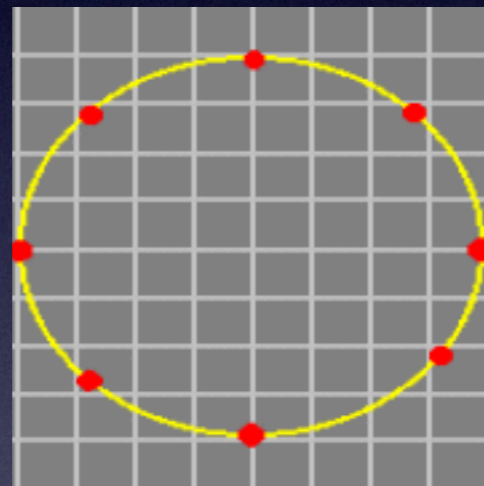
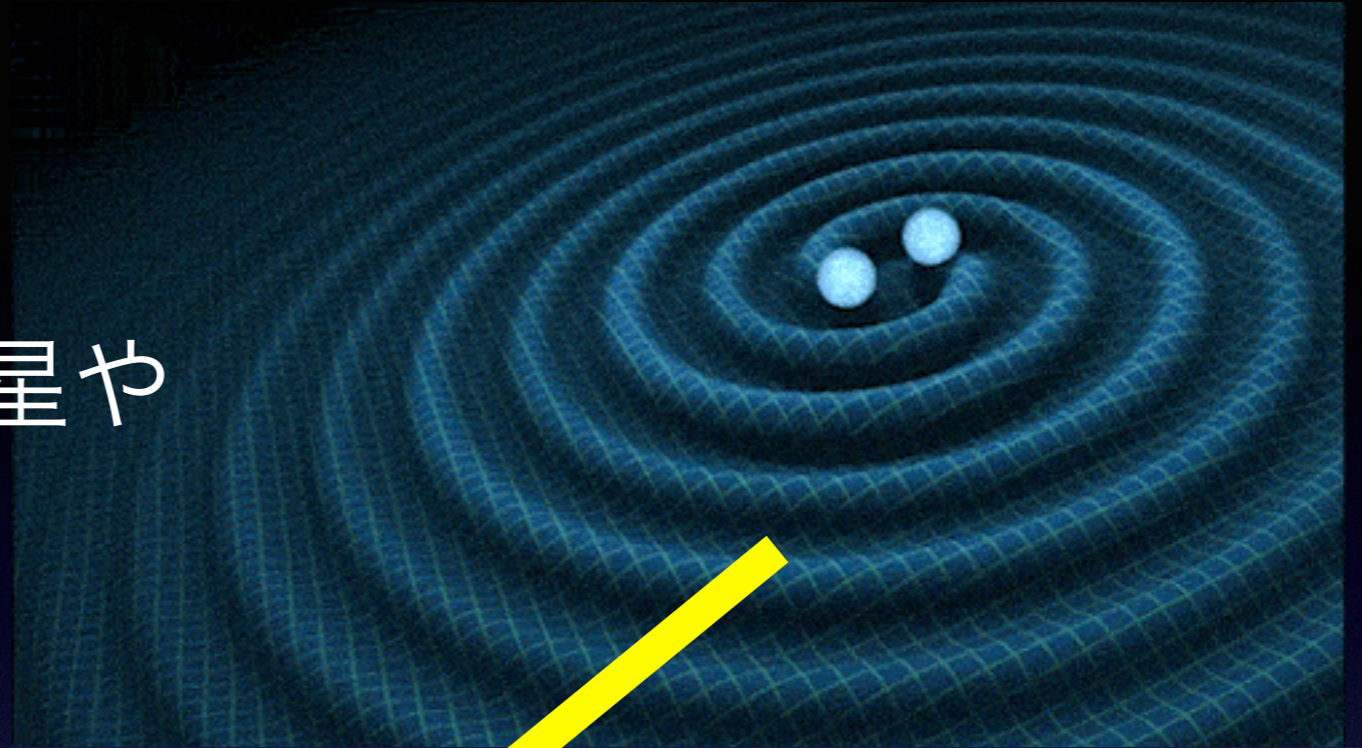
「干渉」 (かんしょう) という

# レーザー干渉計による重力波検出のしくみ



# 重力波の発生と伝播

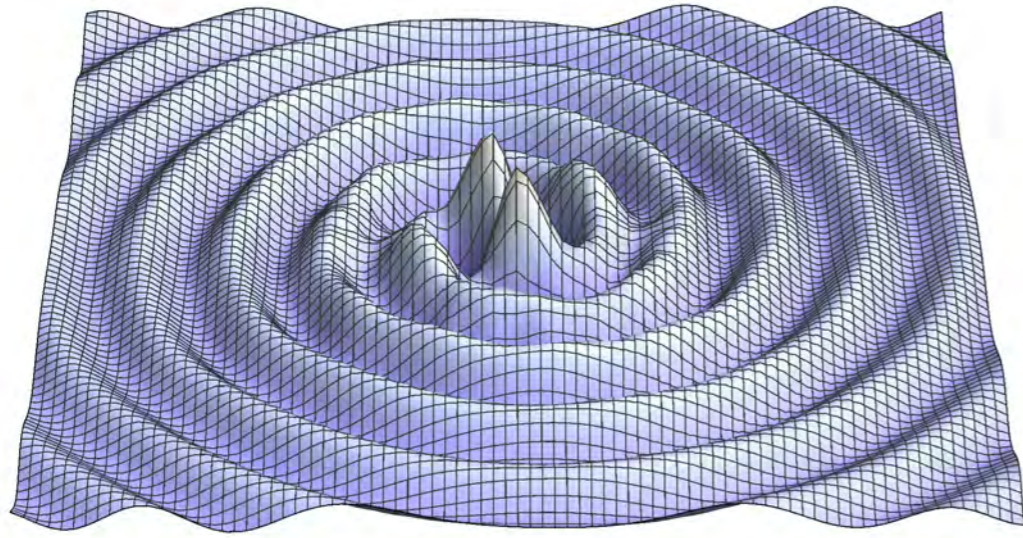
ブラックホール連星や  
中性子星連星



レーザー干渉計

LIGO=Laser Interferometer

Gravitational-Wave Observatory



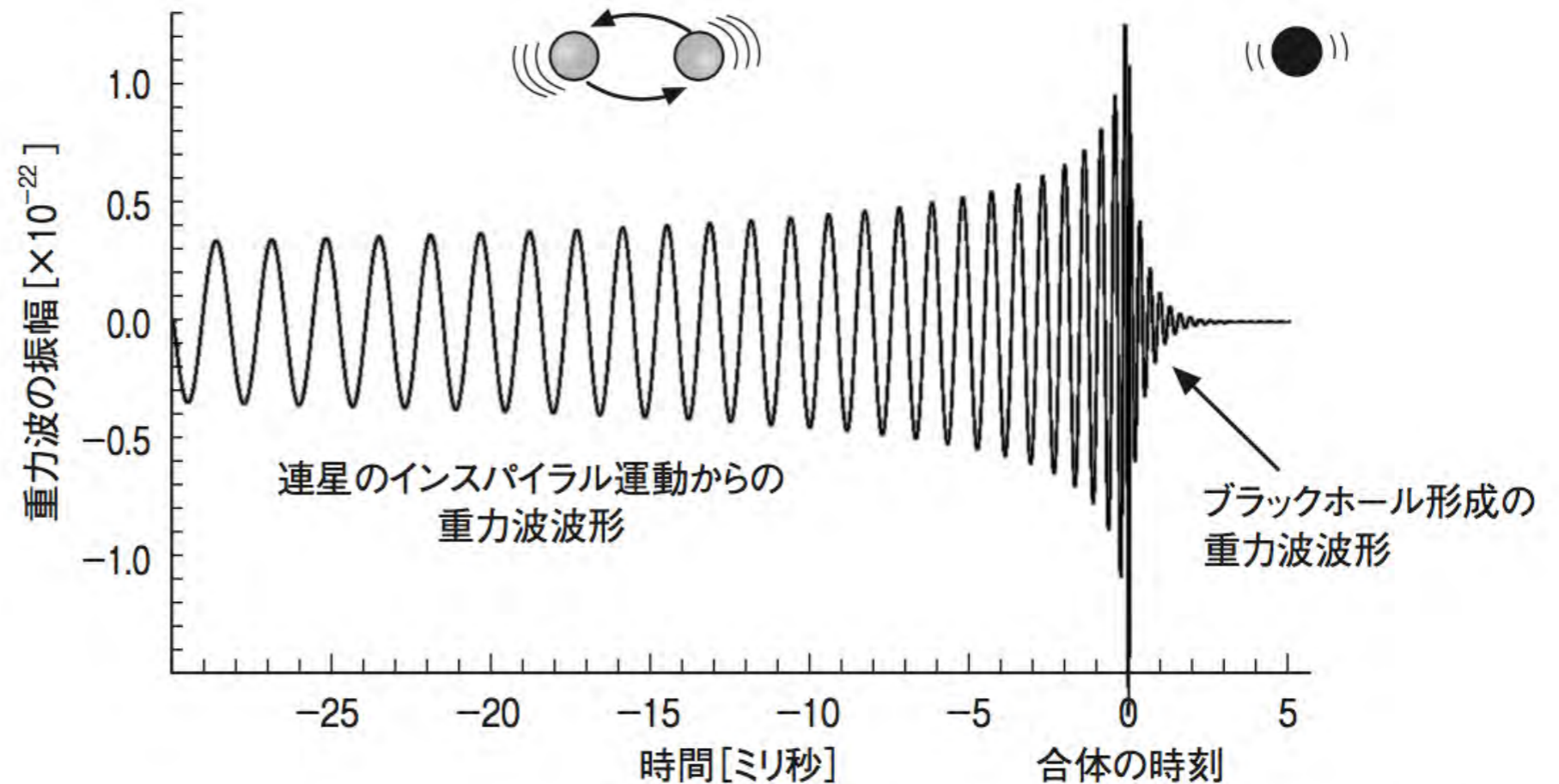
重力波の直接観測をしたい！

連星中性子星  
連星ブラックホール

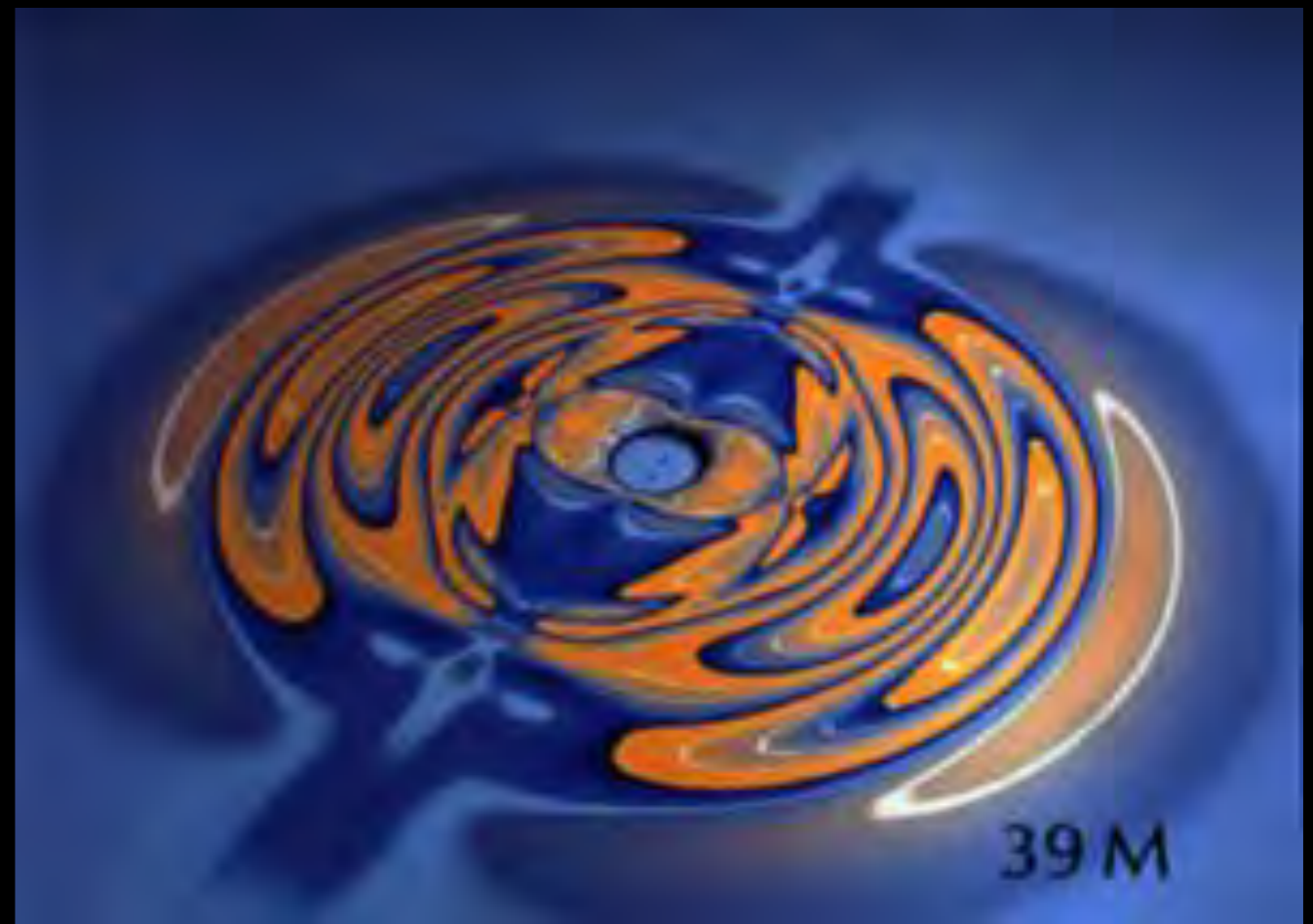
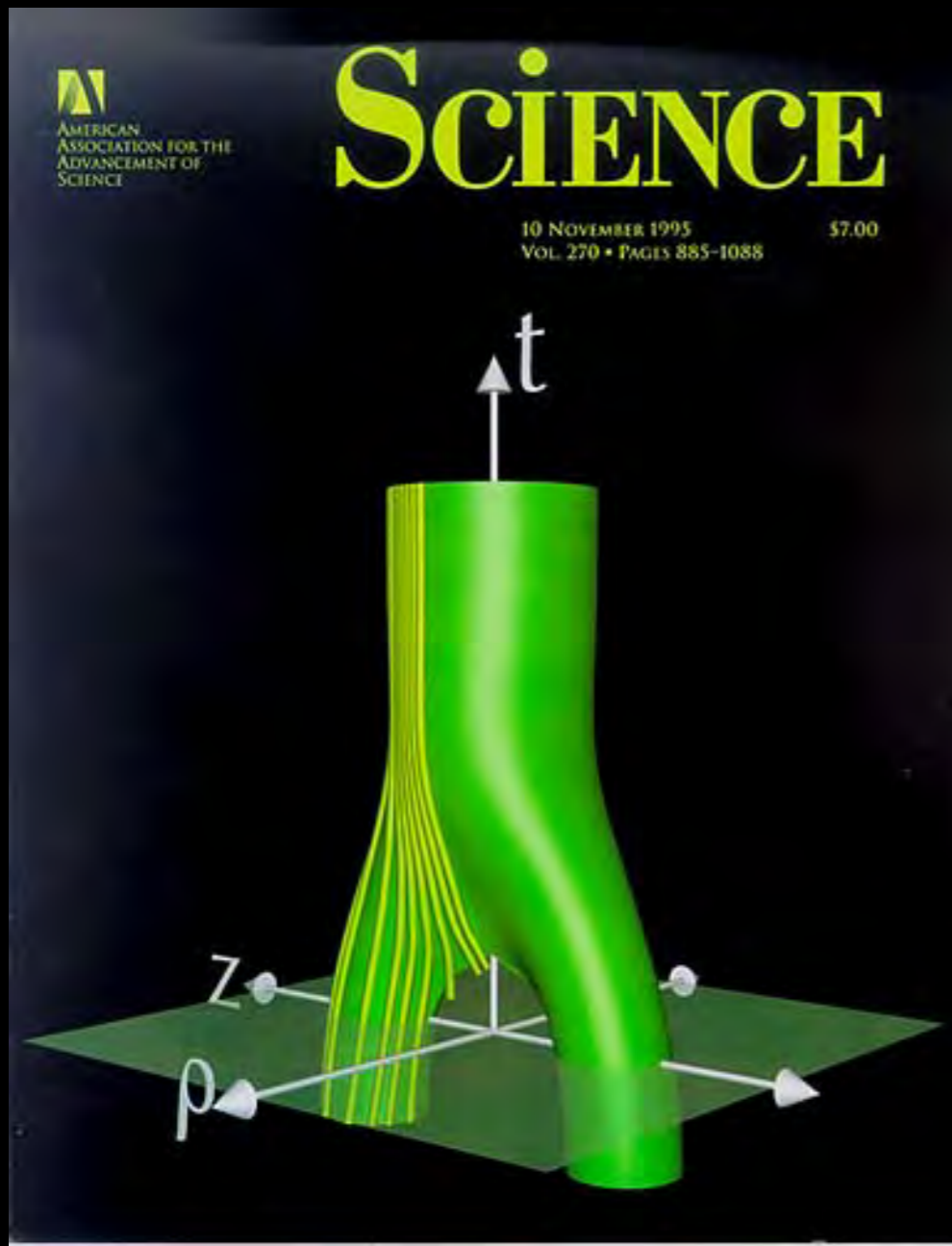
インスパイラル

合体

リングダウン

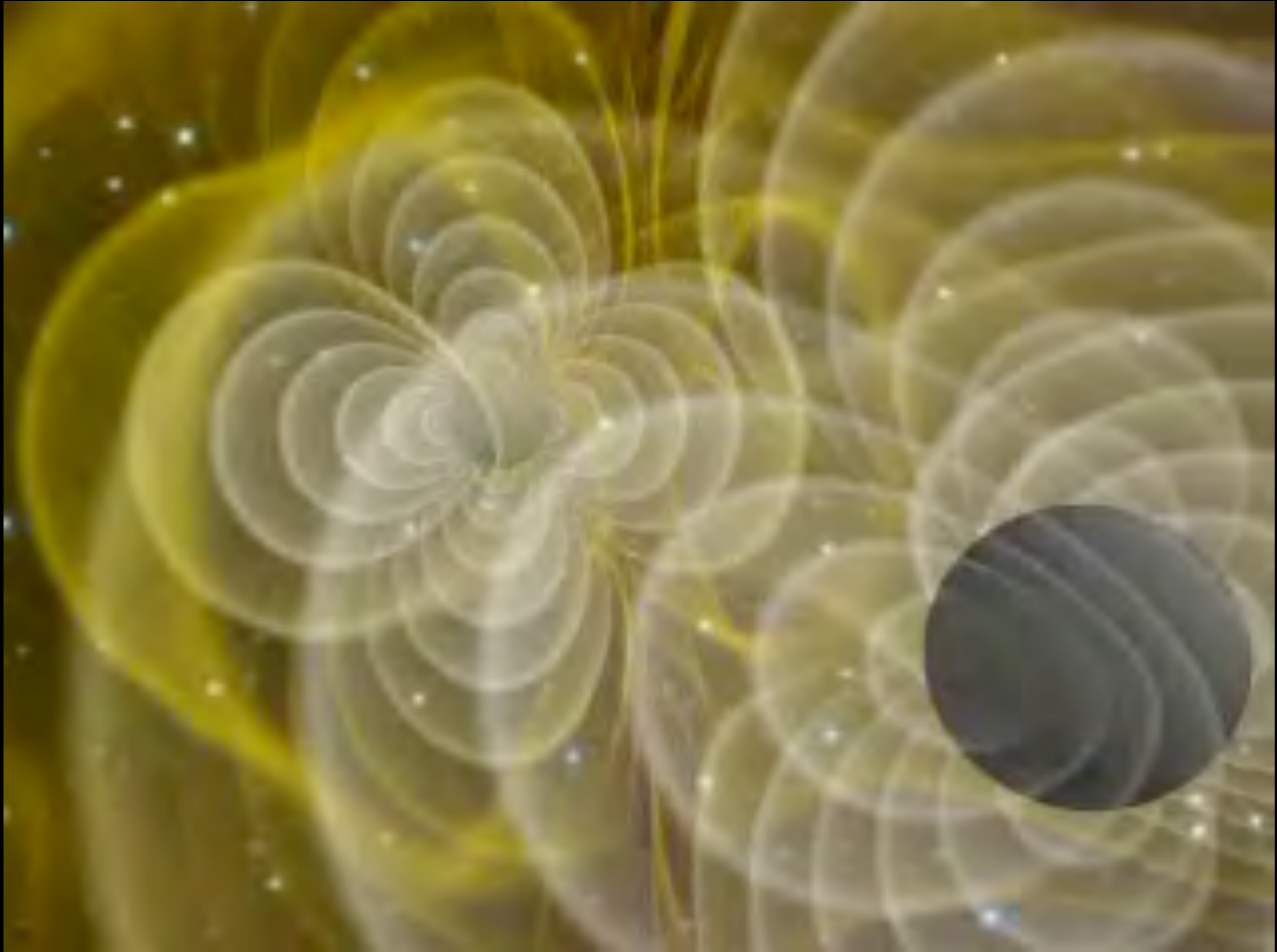


# ブラックホールの合体シミュレーション



2つのブラックホールの合体と重力波放出  
(90年代, NCSAグループ)

# ブラックホールの合体シミュレーション



NCSA-AEI group (1998)

# 重力波初検出を発表するライツィLIGO所長

2016年2月11日



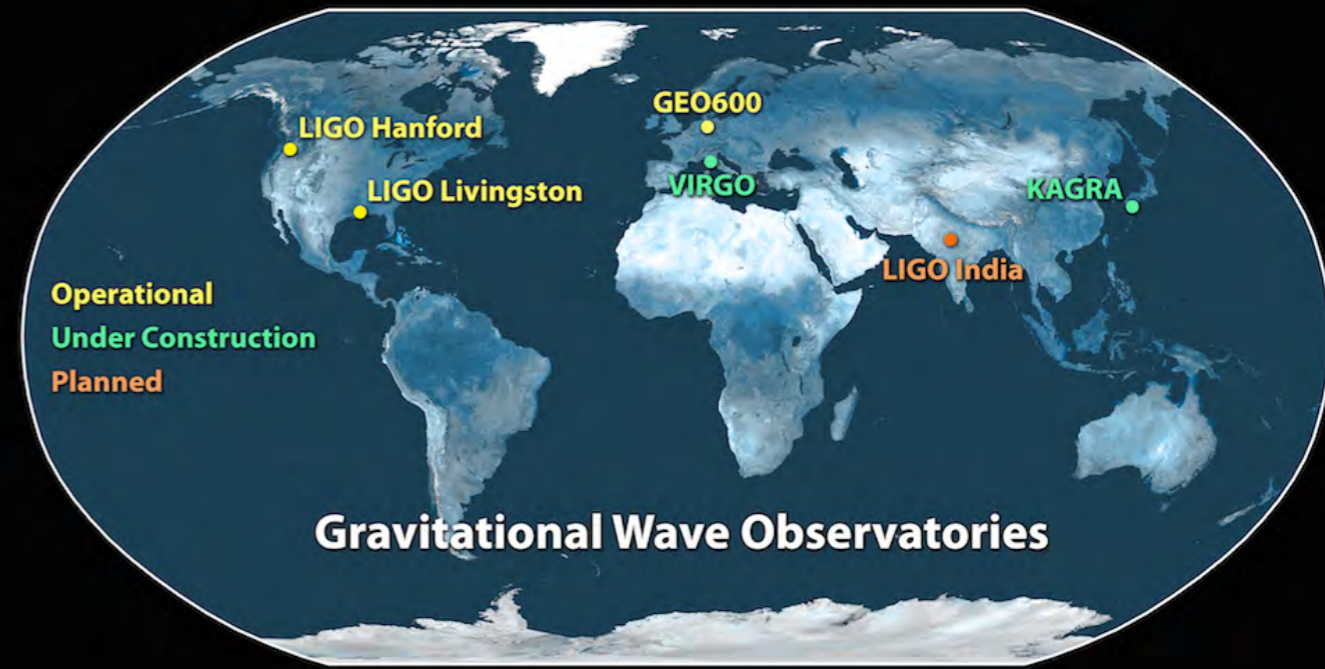
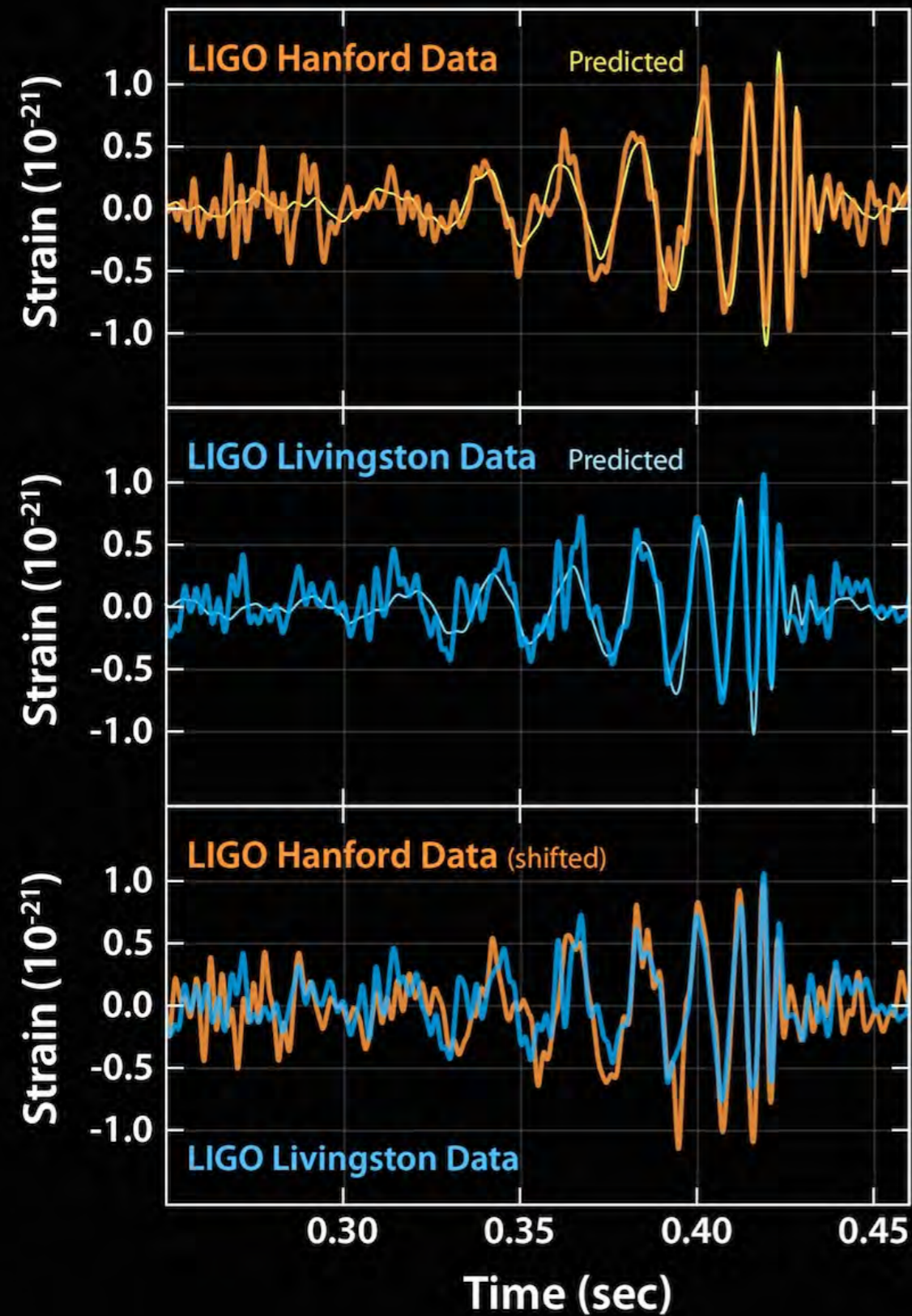
**“We had detected gravitational waves. We did it.”**

**“我々は、重力波を検出した。 やり遂げたのだ。”**

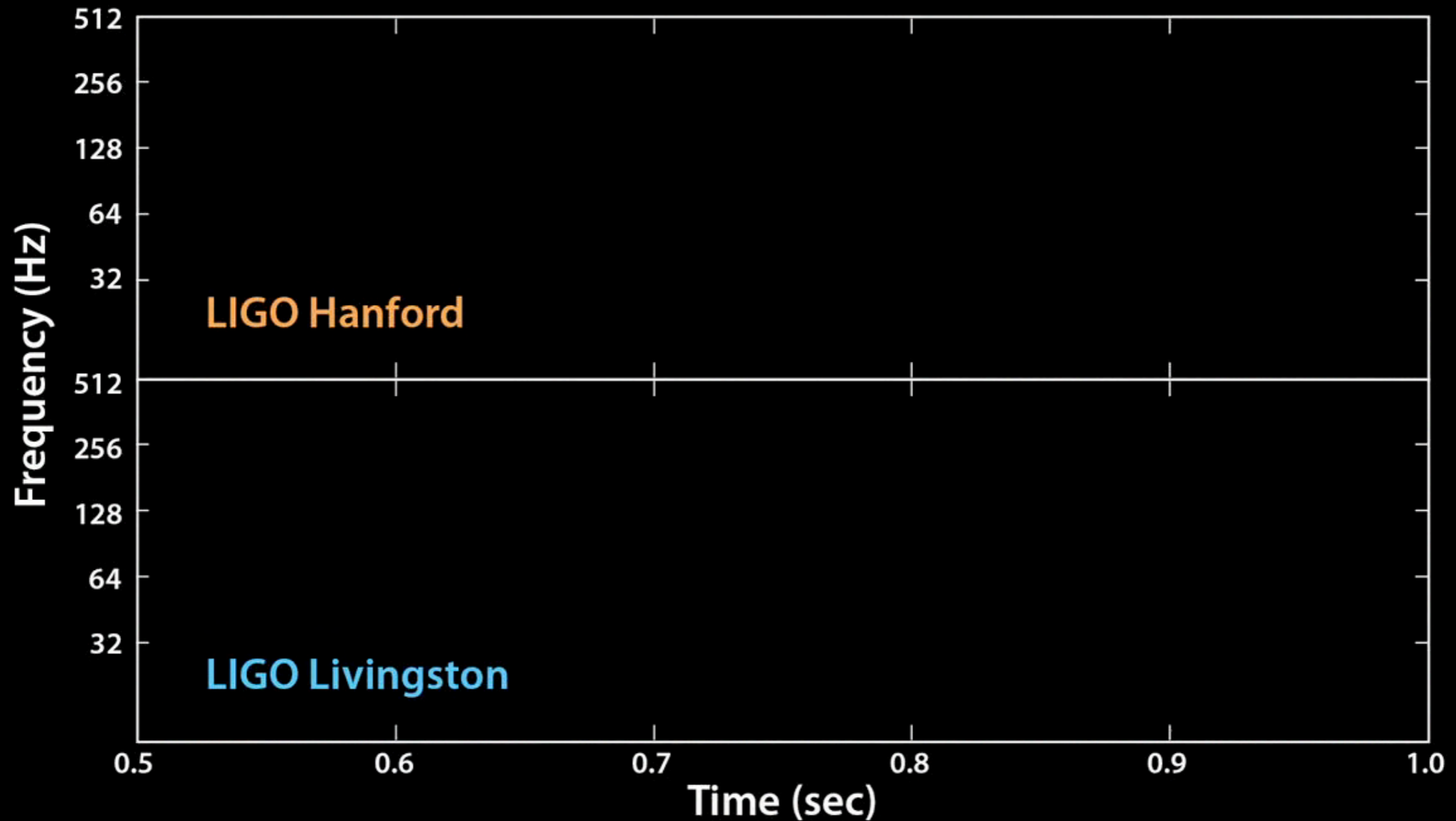
<https://www.youtube.com/watch?v=aEPlwEJmZyE>



# 2015年9月14日



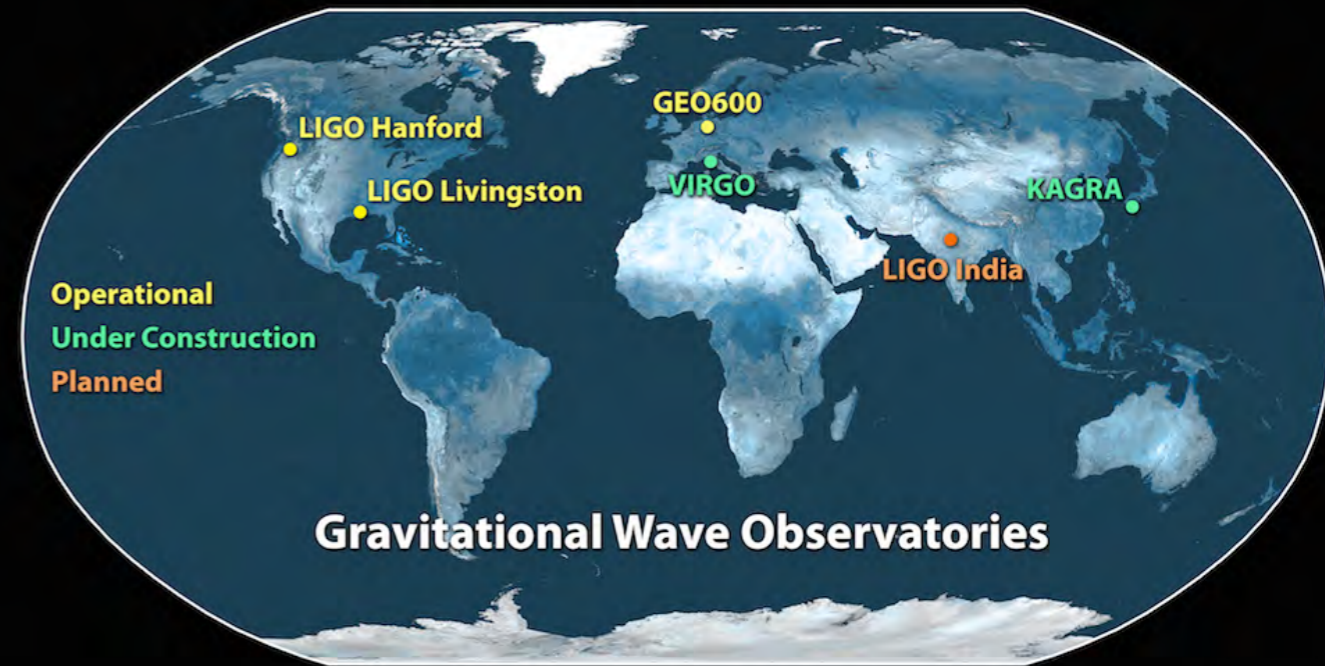
# 重力波波形を音にすると. . .



はじめ2回は実周波数, 後の2回は聞きやすいように+400Hz

<https://mediaassets.caltech.edu/gwave>

2015年9月14日

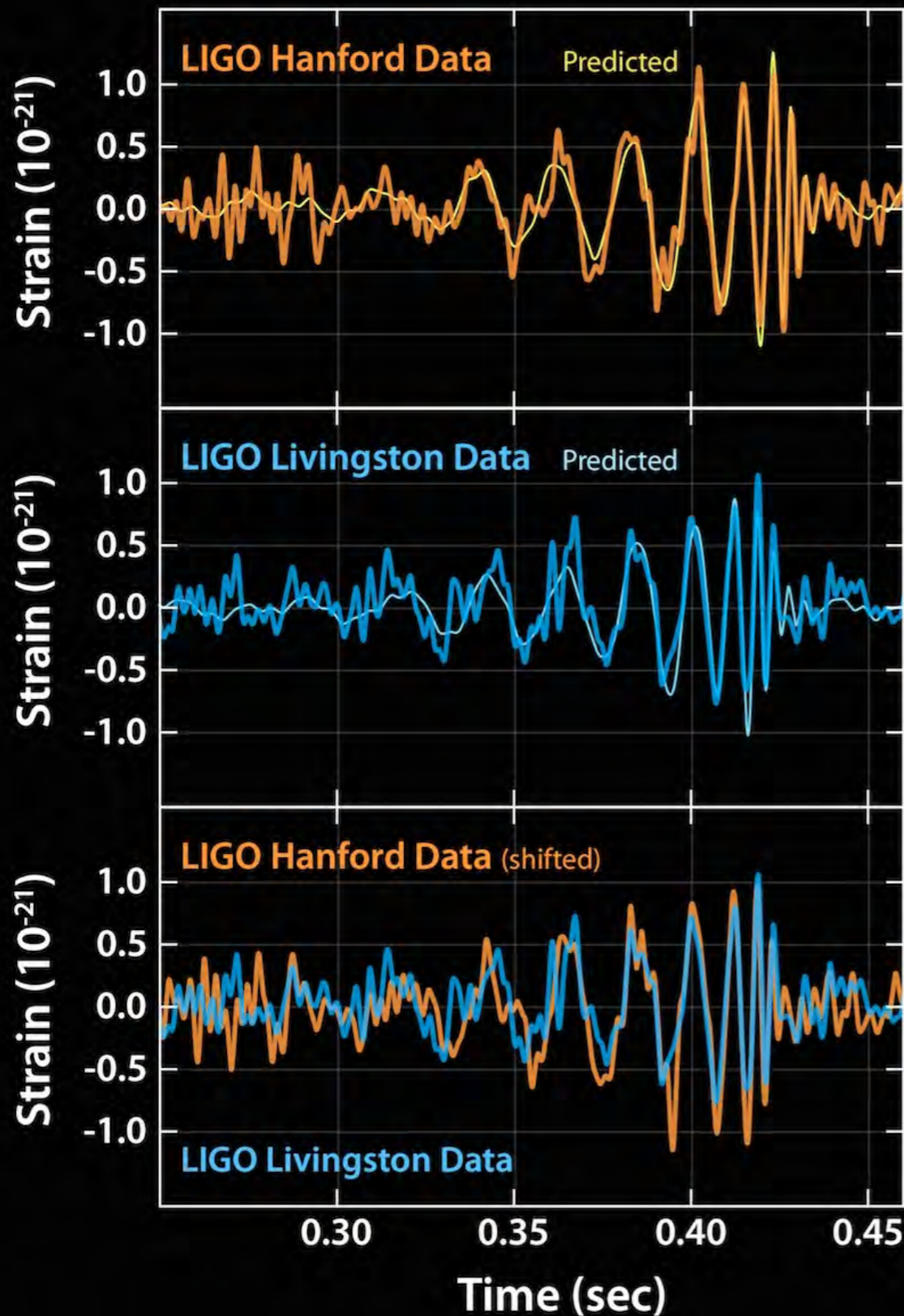


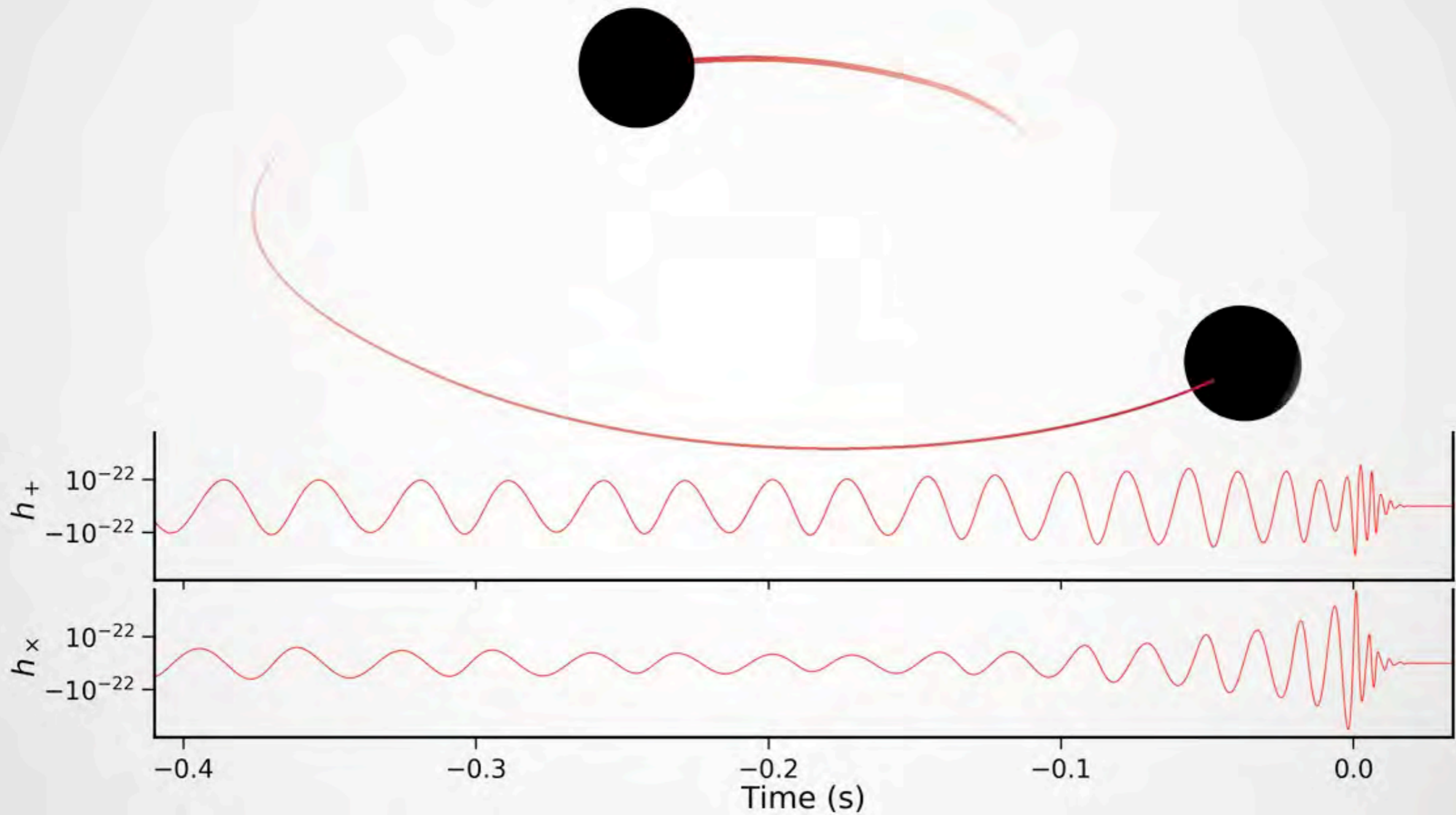
太陽の36倍と29倍のブラックホールが合体して、  
太陽の62倍のブラックホールになった。

3倍の質量が消失

$$E = mc^2$$

13億光年先





**Animation of the inspiral and collision of two black holes consistent with the masses and spins of GW170104.** The top part of the movie shows the black hole horizons (surfaces of "no return"). The initial two black holes orbit each other, until they merge and form one larger remnant black hole. The shown black holes are spinning, and angular momentum is exchanged among the two black holes and with the orbit. This results in a quite dramatic change in the orientation of the orbital plane, clearly visible in the movie. Furthermore, the spin-axes of the black holes change, as visible through the colored patch on each black hole horizon, which indicates the north pole.

The lower part of the movie shows the two distinct gravitational waves (called 'polarizations') that the merger is emitting into the direction of the camera. The modulations of the polarizations depend sensitively on the orientation of the orbital plane, and thus encode information about the orientation of the orbital plane and its change during the inspiral. Presently, LIGO can only measure one of the polarizations and therefore obtains only limited information about the orientation of the binary. This disadvantage will be remedied with the advent of additional gravitational wave detectors in Italy, Japan and India.

Finally, the slowed-down replay of the merger at the end of the movie makes it possible to observe the distortion of the newly formed remnant black hole, which decays quickly. Furthermore, the remnant black hole is "kicked" by the emitted gravitational waves, and moves upward. (Credit: A. Babul/H. Pfeiffer/CITA/SXS.) - See more at: <http://ligo.org/detections/GW170104.php#sthash.NZPaW2LT.dpuf>

# 2016年2月, LIGOが重力波を初めて検出した, と発表した

2016年(平成28年)2月12日(金曜日) 12版 総合 2

## 宇宙の謎解き 国際競争

### 「予想通りで驚いた」 —重力波初観測の報道に接して

真貝 寿明

本年(二〇一六年)は、アインシュタインが一般相対性理論の本論文を発表してちょうど一〇〇年になる。その一〇〇年を祝うかのように、二月二日深夜(米国時間一日)、アメリカのLIGO(ライゴ、注1)のグループは、ブラックホールが衝突・合体して発生した重力波を捉えることに成功した、と発表した。重力波は、一般相対性理論が予言する物理現象だが、一世紀を経て、ようやく直接観測されたことになる。

私は、一般相対性理論の理論研究に関わって四半世紀になる。これまで重力波を研究の中心に据えてきたわけではないが、この瞬間を待ち望んでいた一人

重力波はアインシュタインが残した百年来の宿題だ。その答えはブラックホールの謎解きにもつながる。日欧米では高精度の大型装置(重力波望遠鏡)をつくらせて検出を狙ってきた。(永井理)

実験チームの二つの望遠鏡

ナダ

州

ワシントン

イジアナ州

500m

LIGO提供

## 重力波 初の直接観測

# 「研究者勇気づけた」

### 大阪市大院・神田教授 学生らに解説

米国を中心とした国際研究チームが「重力波」を初めて直接観測したとの発表を受け、重力波の研究が専門の神田展行・大阪市立大学院教授(51)は12日、発表内容についての説明会を大阪市住吉区の同大杉本キャンパスで開いた。成果を詳しく理解してもらおう狙い。学生ら約100人が参加し、真剣な表情で聴き入った。

【島山哲郎】

神田教授は、岐阜県飛騨市の大型低温重力波望遠鏡「KAGRA」のプロジェクトでもデータ管理グループのリーダーを務める。説明会では観測されたデータの見方などを解説し「我々にとっても勇気づけられるものだった」と語った。発表を受けて、研究室の学生

が締め切り間際の論文を慌てて書き換えたエピソードを披露すると、会場は笑いに包まれた。

同大大学院理学研究科2年の和知慎吾さん(23)は「重力波だけでなく、ブラックホールも直接観測したことになると分かり、ためになった」と話していた。

重力波は、質量を持った物体が動いた時に周囲の時空にゆがみが生じ、そのゆがみが光速でさざ波のように宇宙空間に伝わる現象。物理学者のアインシュタインが「一般相対性理論」で存在を予言し、世界中の研究者が観測に挑戦していた。

三行で!

1. 一般相対性理論から重力波の存在が予言された。
2. ブラックホールが衝突・合体した時に重力波が放出される。
3. 重力波の検出が実現された。



重力波観測について解説する大阪市立大学大学院理学研究科の神田展行教授—大阪市住吉区で、川平愛撮影

大阪工大「予想通りで驚いた」  
真貝教授

大阪工業大情報科学部の真貝寿明教授(一般相対性理論)は「祝・重力波の直接検出」と題して、研究室のウェブページに一般向けの緊急解説記事を掲載した。昨年には一般向けの解説書「ブラックホール・膨張宇宙・重力波 一般相対性理論の100年と展開」を出版している。「こんなにも予想通りのものが見つかるのかと驚いた。素晴らしい発見だ」と感想を語った。今後の研究については「日本でもKAGRAを使い、改めて重力波を確認したり、海外のチームと協力して重力波がどこから来たものなのかを調べたりしていくことが重要だ」と話した。

【島山哲郎】

sport

2016/4/21

## Cameron McEvoy wears his passion on his swimming cap

Swimmer and physics student Cameron McEvoy is sporting the signature of a gravitational wave on his cap.



Cameron McEvoy wins a 100m heat with the gravitational wave on his Bond University club cap. *Source:AAP*

The discovery has made a big impression on McEvoy, 21, whose heroes tend to be scientists rather than swimmers.

“It’s the 100th anniversary of Einstein’s general theory of relativity, which is his theory of gravity and coincidentally, physicists at Advanced LIGO (observatory) discovered gravitational waves, which is the stretching and contraction of space-time itself — everything we move in and pretty much what the universe is,” he said.



2017/10





### GRAVITATIONAL WAVES DRESS

★★★★★ 6 reviews

\$179.00

- SIZE
- X-SMALL
  - SMALL
  - MEDIUM
  - LARGE
  - XX-LARGE
  - X-SMALL WITH 15" SLEEVES
  - SMALL WITH 15" SLEEVES
  - MEDIUM WITH 15" SLEEVES
  - LARGE WITH 15" SLEEVES
  - X-LARGE WITH 15" SLEEVES
  - XX-LARGE WITH 15" SLEEVES

ADD TO CART

Want to wear the fabric of space time?  
 Celebrate the discovery of gravitational waves. At first glance, you see plaid. Look a bit further and you see data from the LIGO detectors. It's a classic educational twist.



**Laura Cadonati**  
 10月11日 1:22

Posting for a bit of comic relief: "It's like a better version of Ms Frizzle!!" Thanks to [Gabriela Gonzalez](#) for the dress, a rite of passage of sort?

Instagram post by Georgia Tech • Oct 4, 2017 at 7:14pm UTC

いいね! コメントする シェアする

あなた、 Jorge Pullinさん、 Deirdre Shoemakerさん、 他83人



Search for products

100% Satisfaction Sell on Zazzle Sign in

Create Your Own Invitations & Cards Clothing & Accessories Home & Living Electronics Office Baby & Kids Art Weddings Gifts

LAST DAY Up to 50% Off Greeting Cards, Custom Postage, Stickers & More | 15% Off Sitewide | Use Code: CREATIVEDEAL | See Details

Accessories > Ties

# Gravitational Waves Tie

★★★★☆ 4.4 (1254)

\$44.30 per tie

Qty: 1

Add to Cart

15% Off with code CREATIVEDEAL



Designed for you by Shenova by Zazzle

Customize



Independent artist's content may not match model depicted, RealView™ technology illustrates fit and usage only.

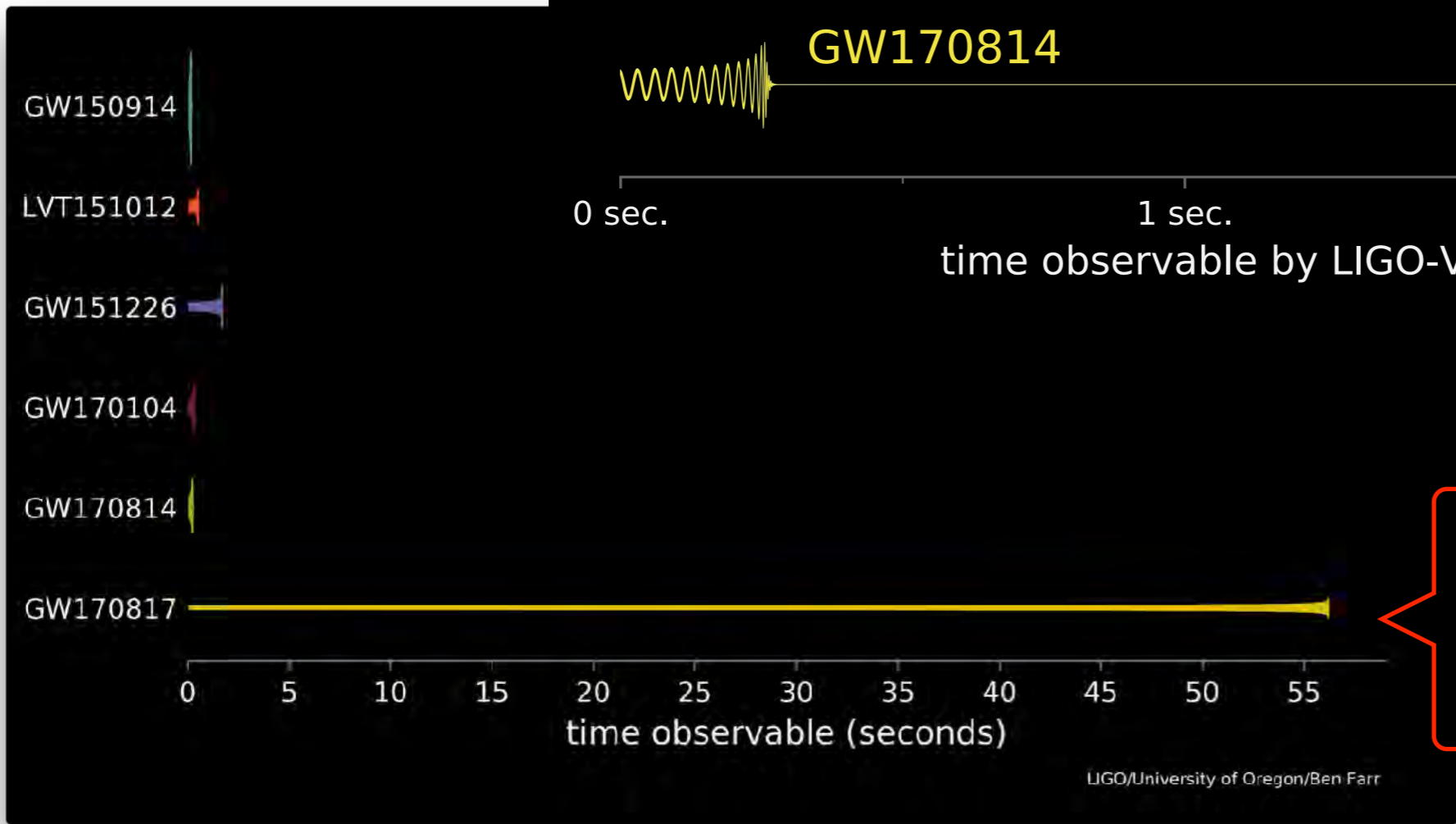
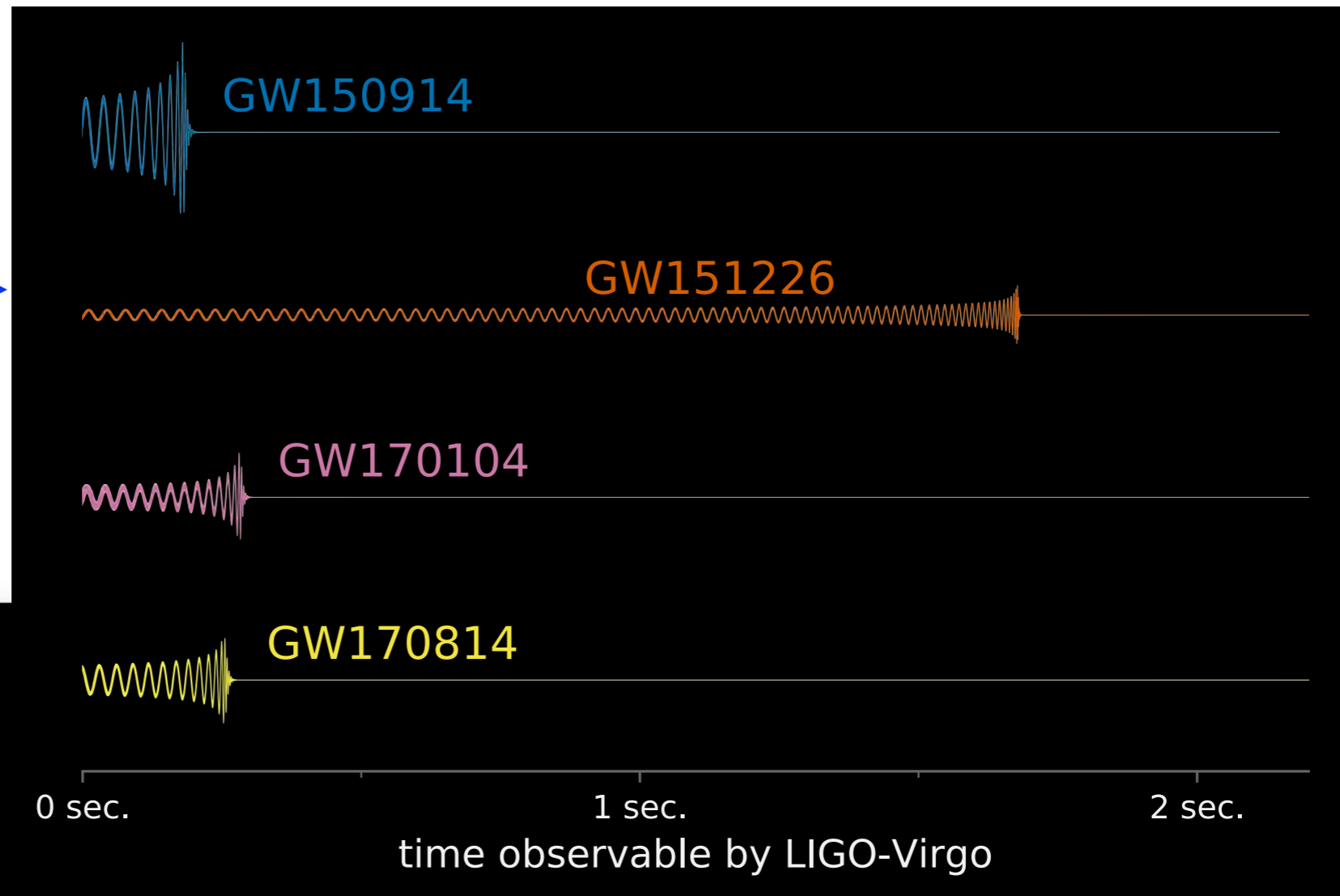




# 連星中性子星合体 重力波検出, 多くの天文台が同時観測

GW170817

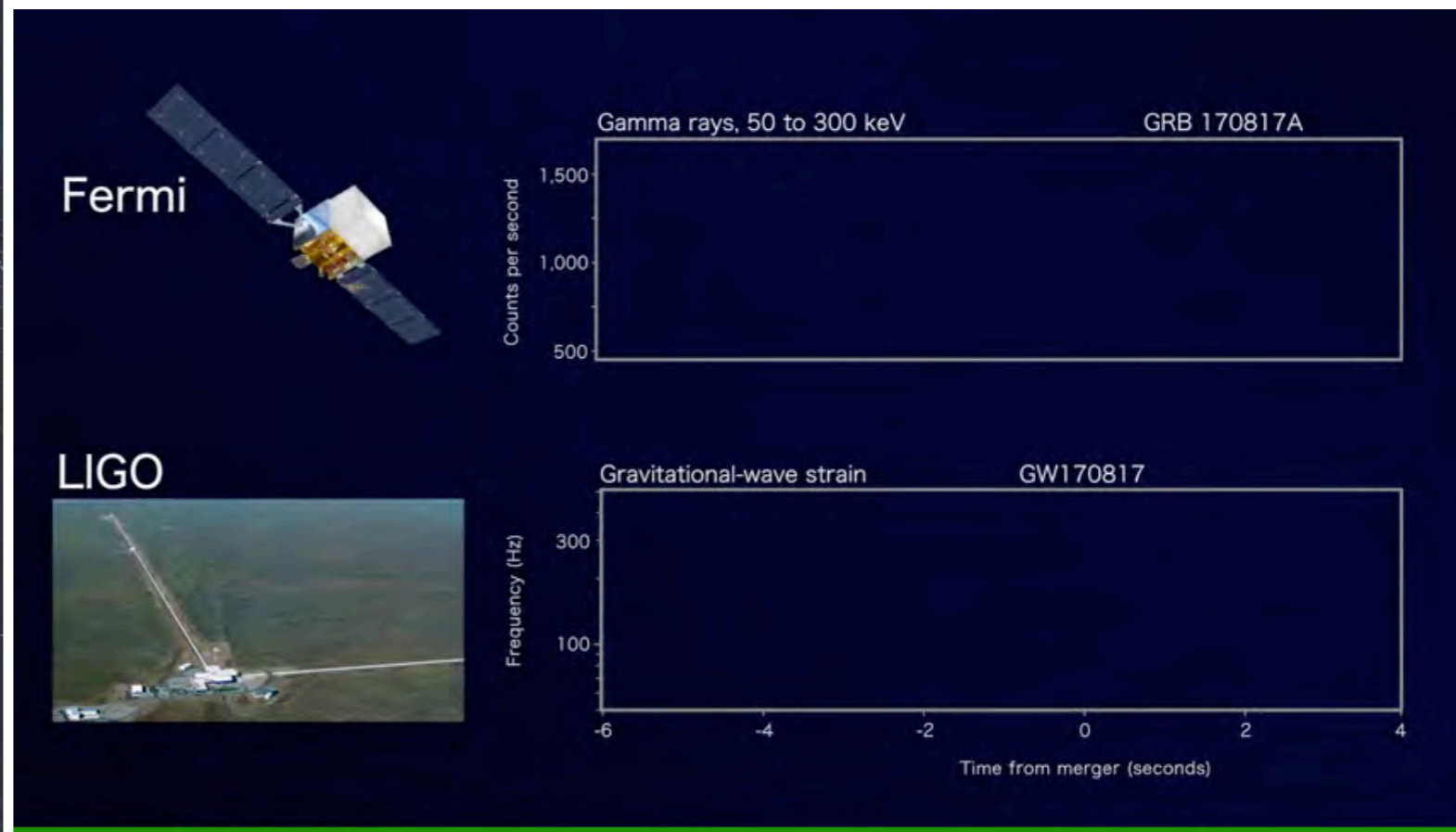
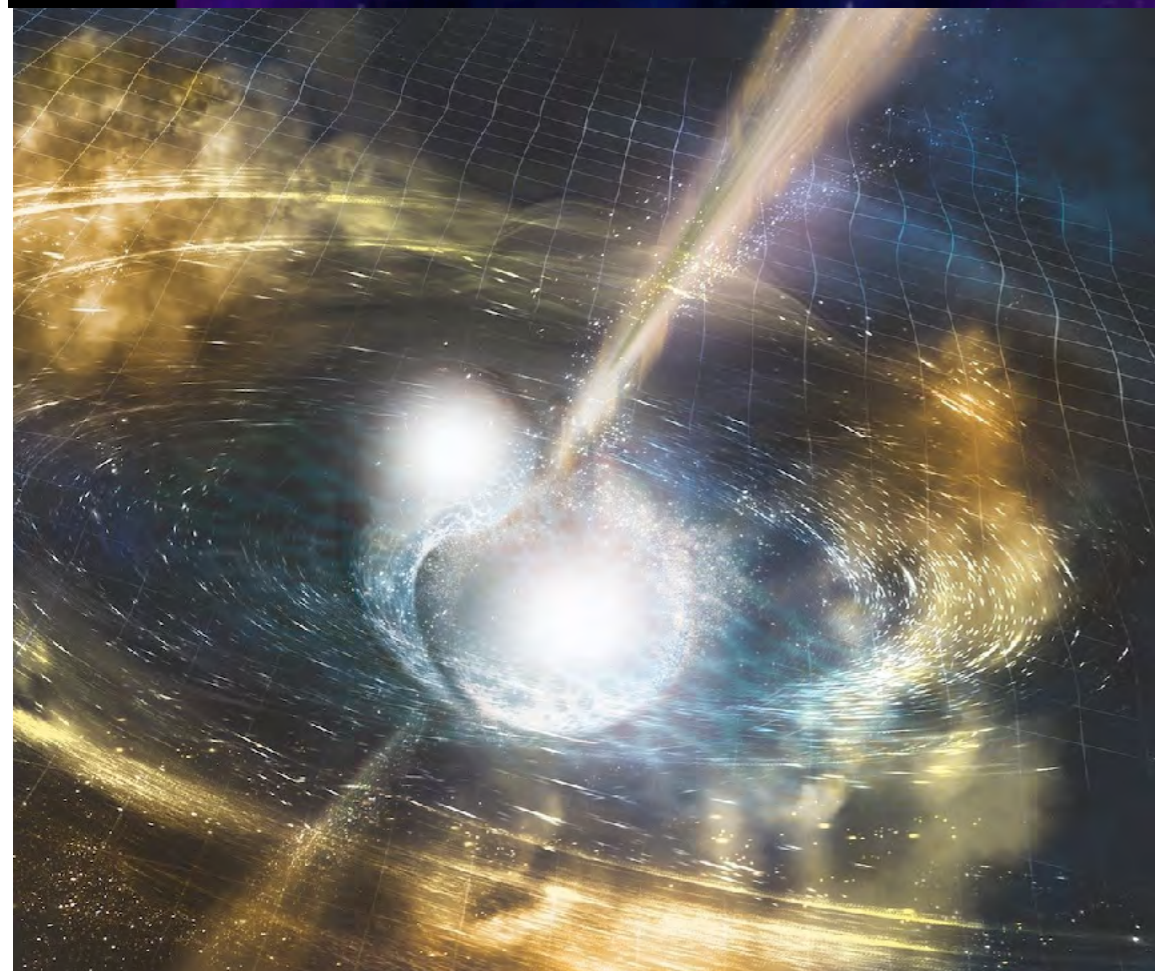
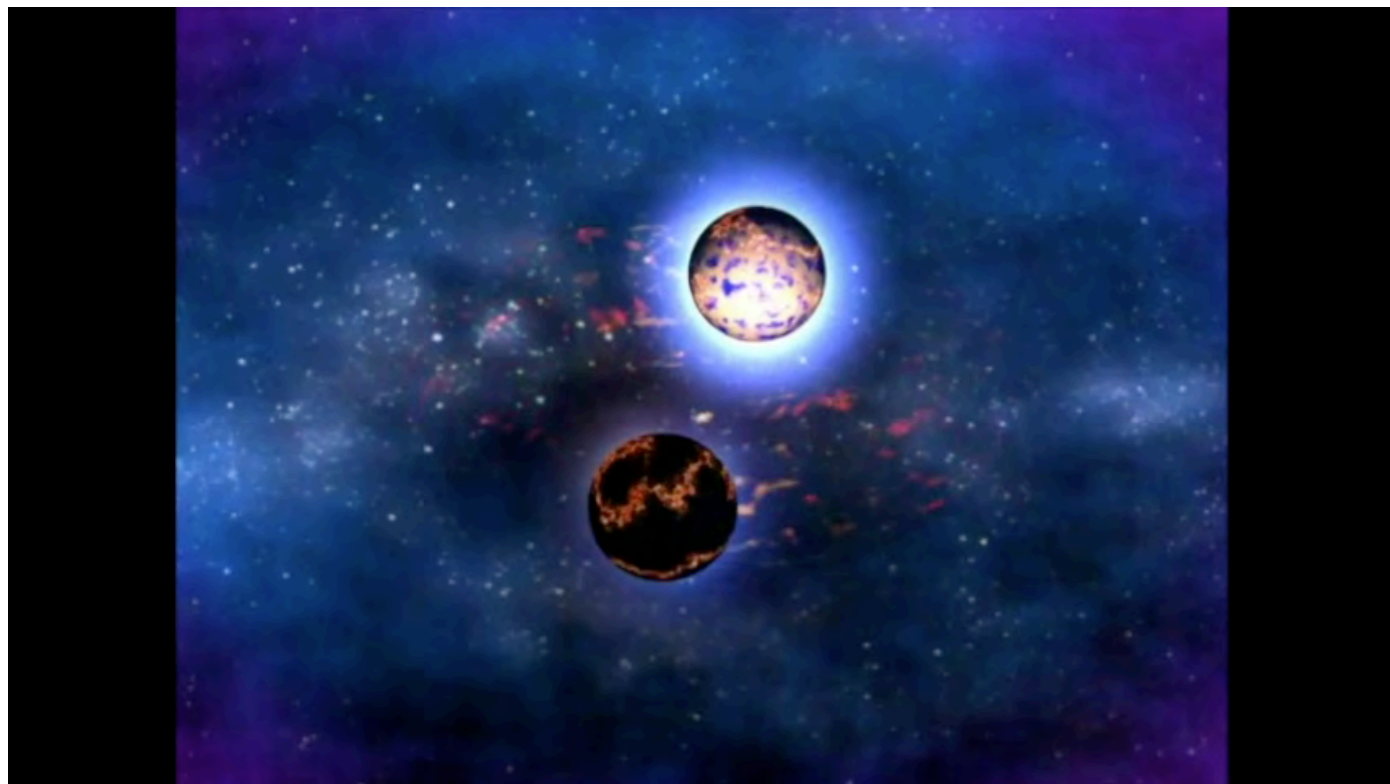
これまでの  
BHBH合体  
による重力波



今回のNSNS  
合体による重力波

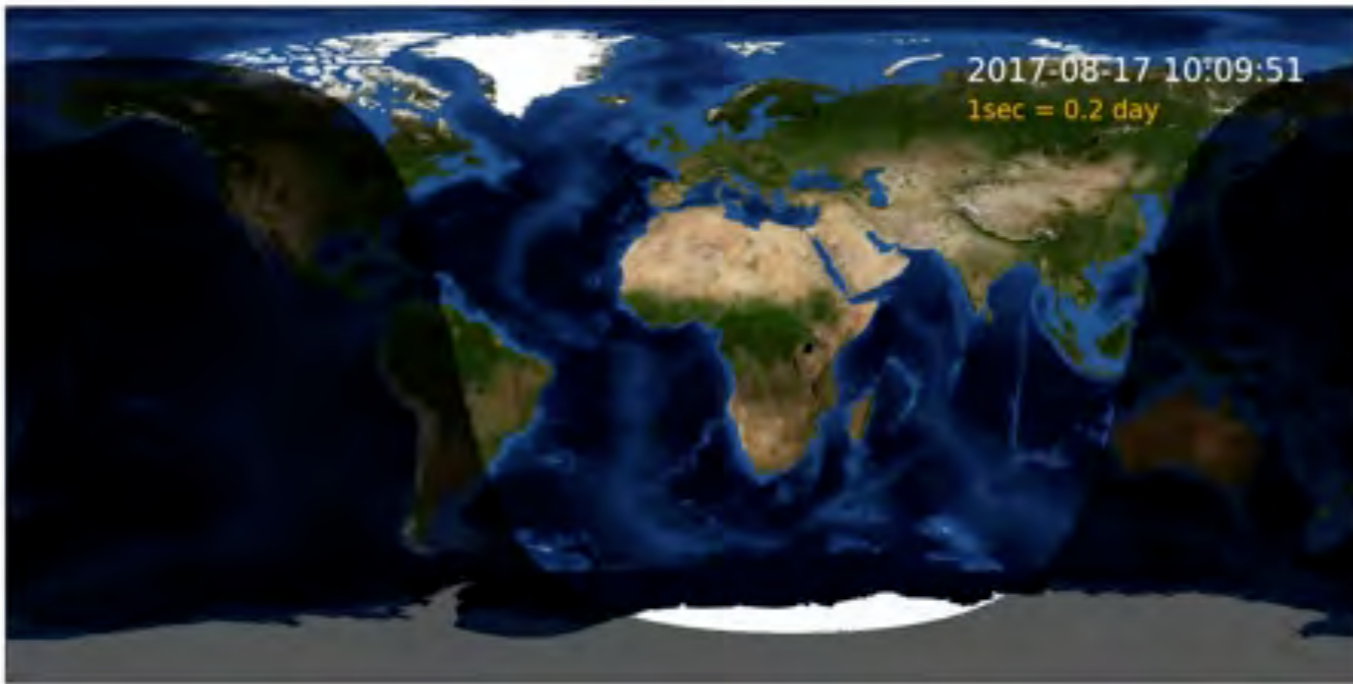
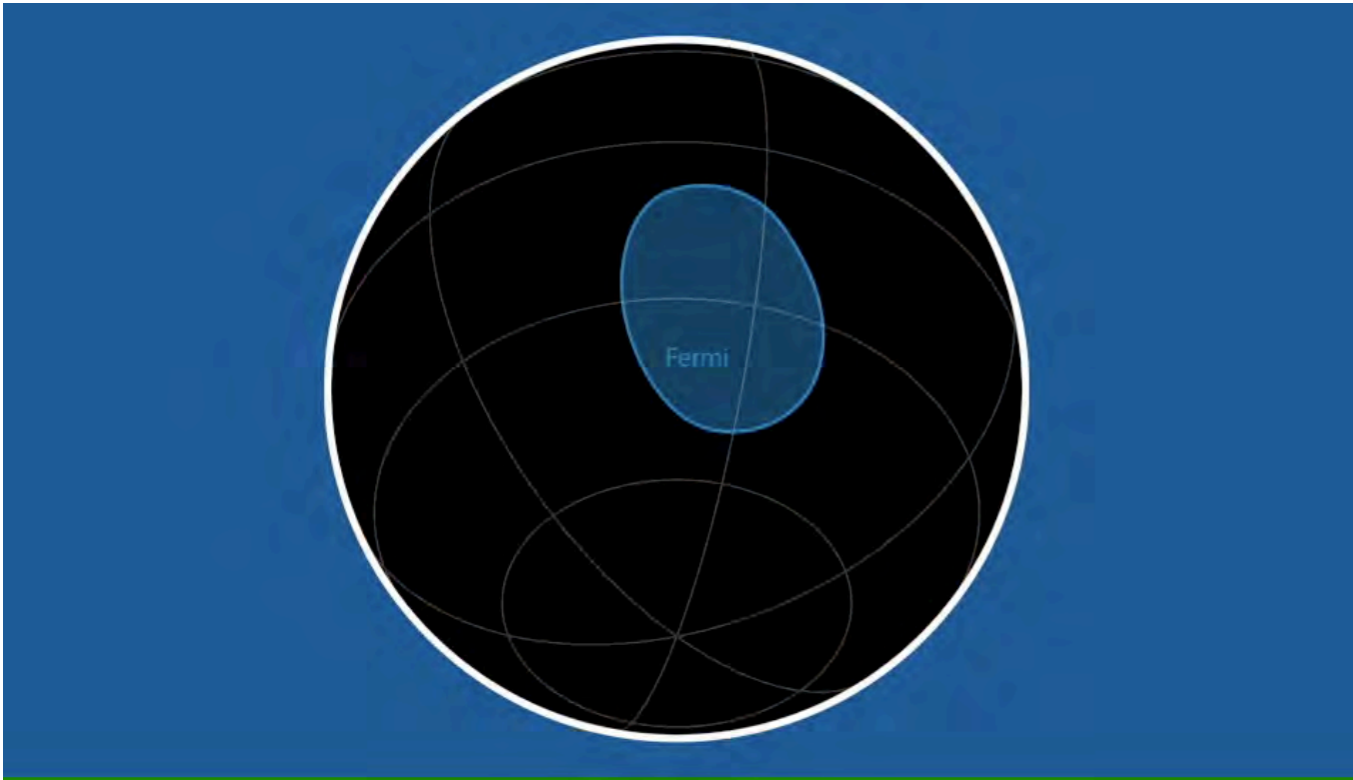
# 連星中性子星合体 重力波検出, 多くの天文台が同時観測

GW170817



# 連星中性子星合体 重力波検出, 多くの天文台が同時観測

## GW170817



波源はNGC4993 (40Mpc先) !

1億3000万光年先

ASTROPHYSICAL JOURNAL LETTERS, 848:L12 (59pp), 2017 October 20

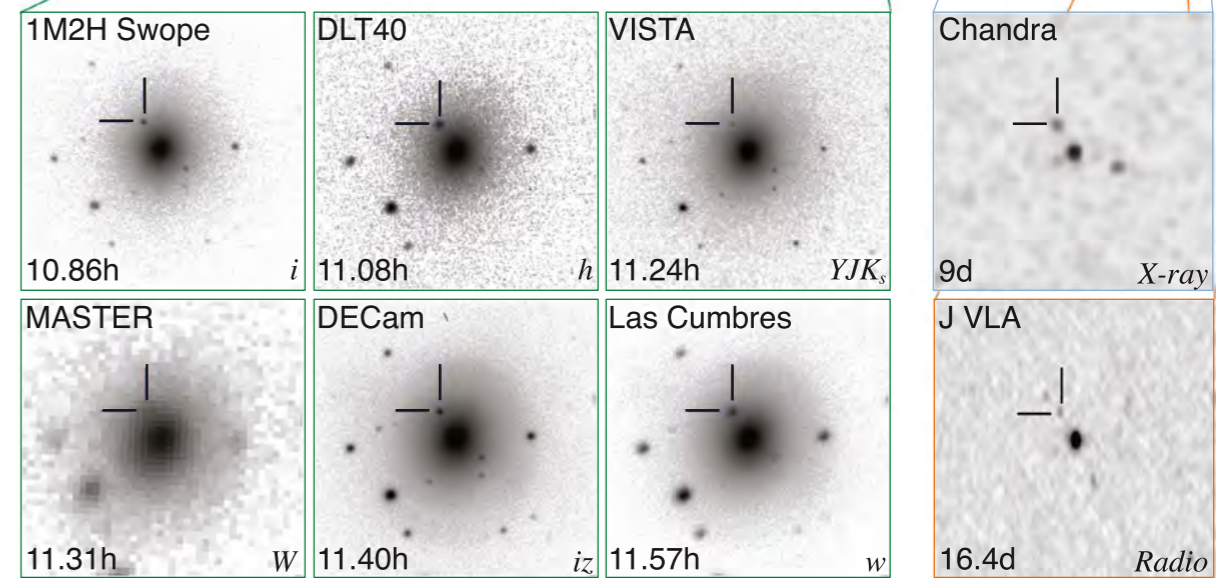
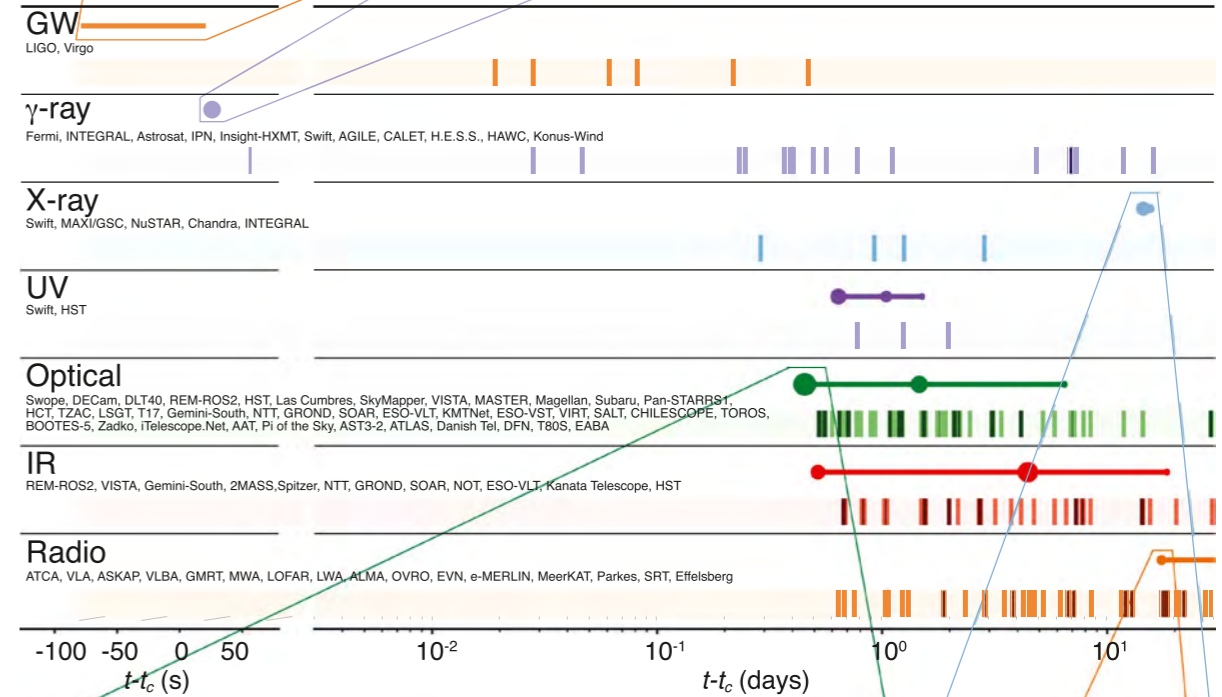
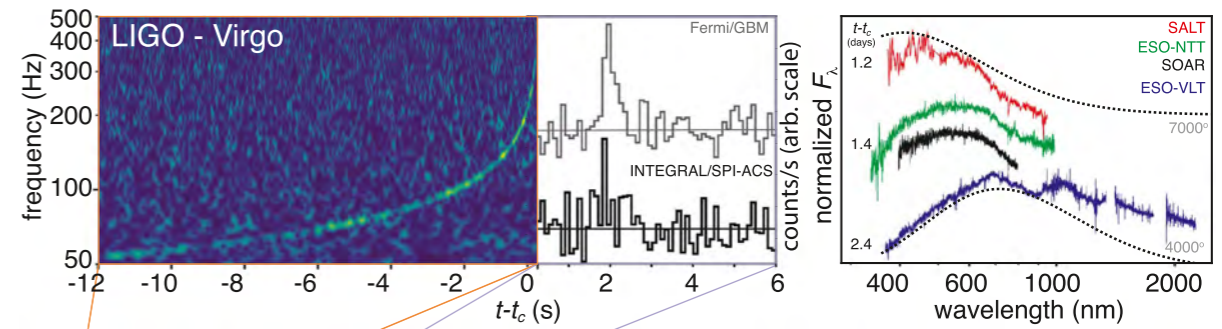


Figure 2. Timeline of the discovery of GW170817, GRB 170817A, SSS17a/AT 2017gfo, and the follow-up observations are shown by messenger and wavelength relative to the time  $t_c$  of the gravitational-wave event. Two types of information are shown for each band / messenger. First, the shaded dashes represent the

# 世界の重力波干渉計

LIGO Hanford  
USA



LIGO Livingston  
USA



GEO600 Hanover  
Germany



Virgo Pisa  
Italy



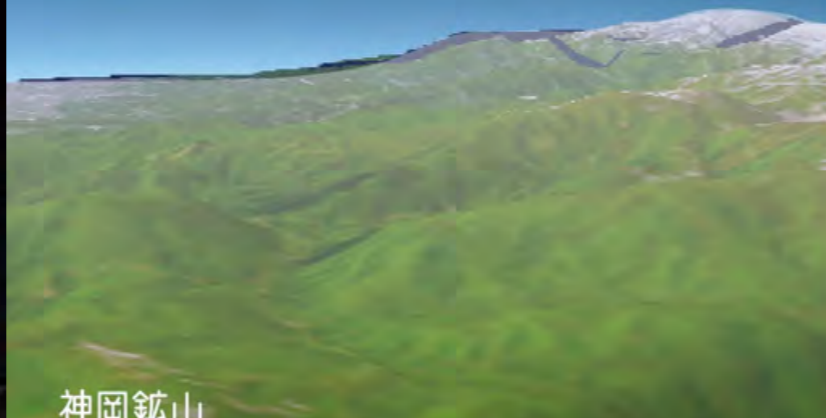
KAGRA Hida  
Japan



# KAGRA (かぐら : 大型低温重力波望遠鏡)

Kamioka Gravitational wave detector

## 大型低温重力波望遠鏡



神岡鉱山  
(岐阜県飛騨市神岡町)



望遠鏡の大きさ : 基線長 3km

望遠鏡を神岡鉱山内に建設

鏡をマイナス250度 (20K) まで冷却

熱雑音を小さくするため

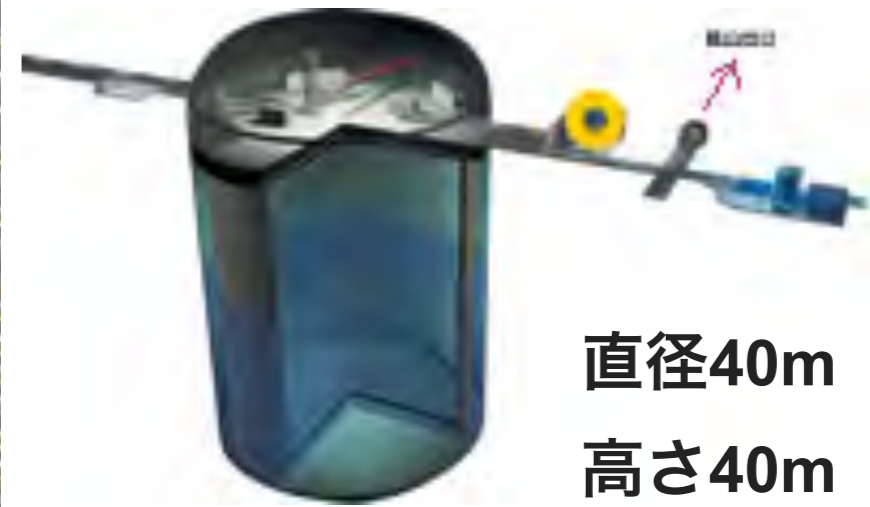
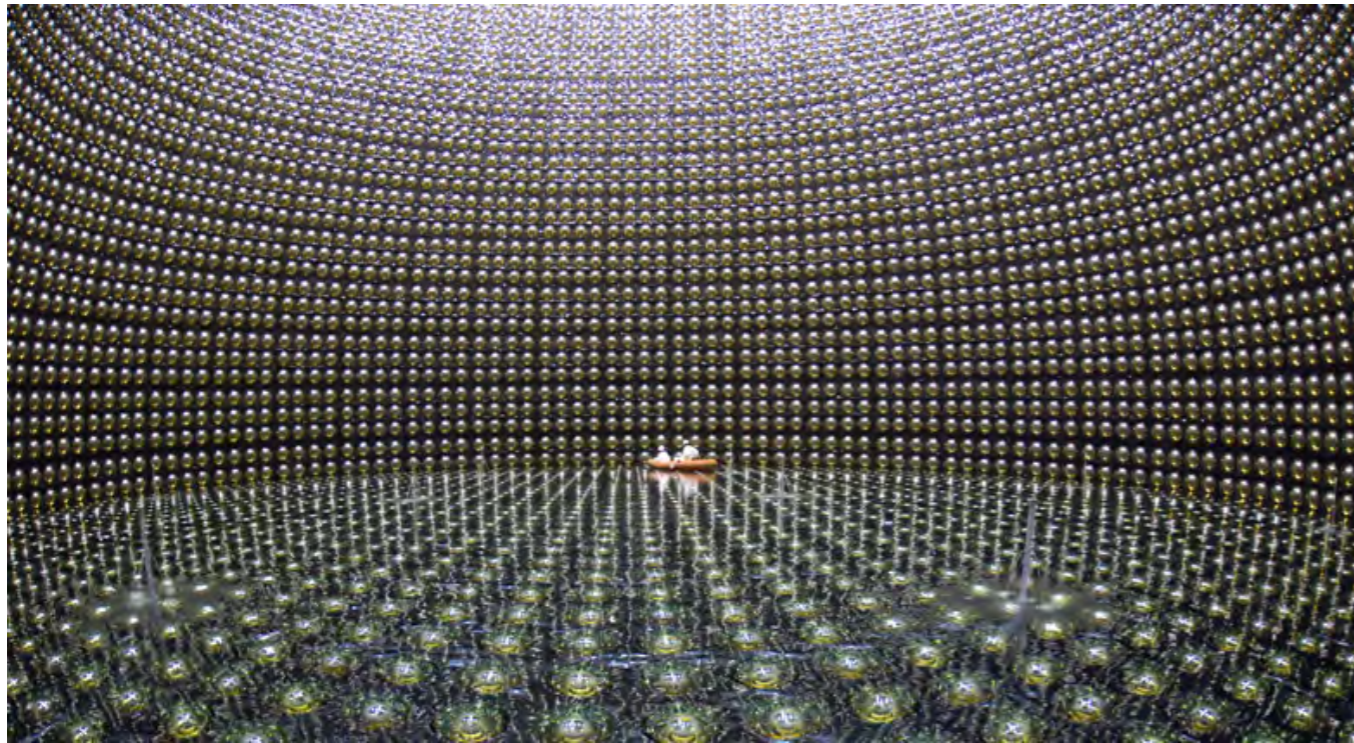
鏡の材質としてサファイア

光学特性に優れ、低温に冷却すると熱伝導や機械的損失が少なくなる

# スーパー・カミオカンデ (ニュートリノ観測装置)

Super-Kamiokande

<http://www-sk.icrr.u-tokyo.ac.jp/sk/>



直径40m

高さ40m

岐阜県・神岡の鉱山跡の空洞に巨大な水槽をつくり、  
宇宙から飛来するニュートリノを観測する。



ノーベル物理学賞を受賞

小柴昌俊 (2002年)

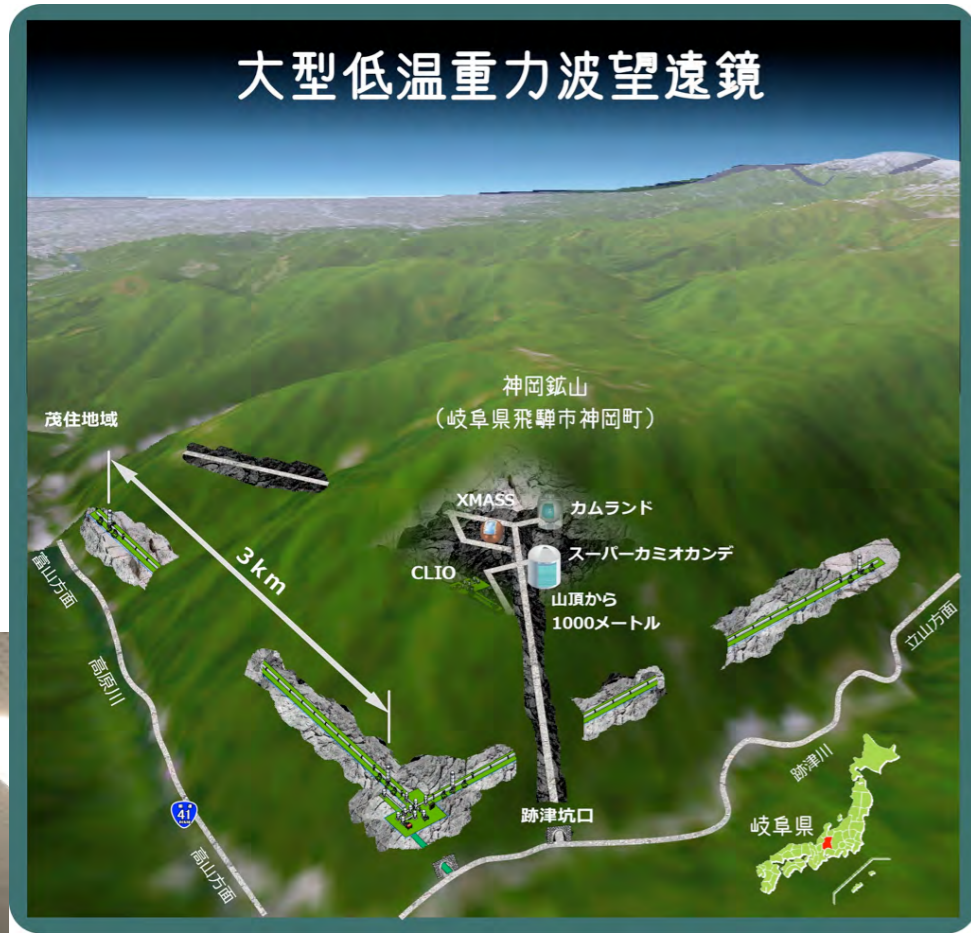


梶田隆章 (2015年)



# KAGRA (かぐら：大型低温重力波望遠鏡)

2016年4月

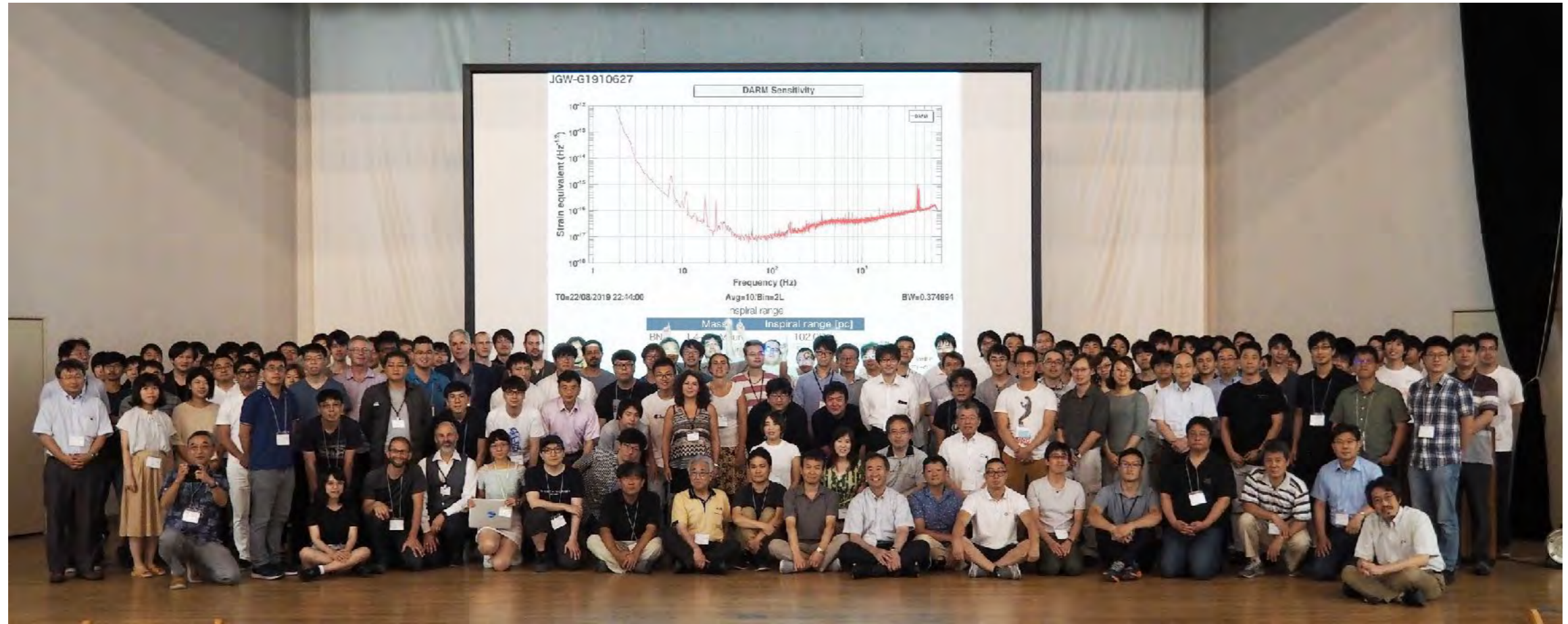


# KAGRA (かぐら : 大型低温重力波望遠鏡)





# KAGRA (かぐら : 大型低温重力波望遠鏡)



**KAGRA**

360 members

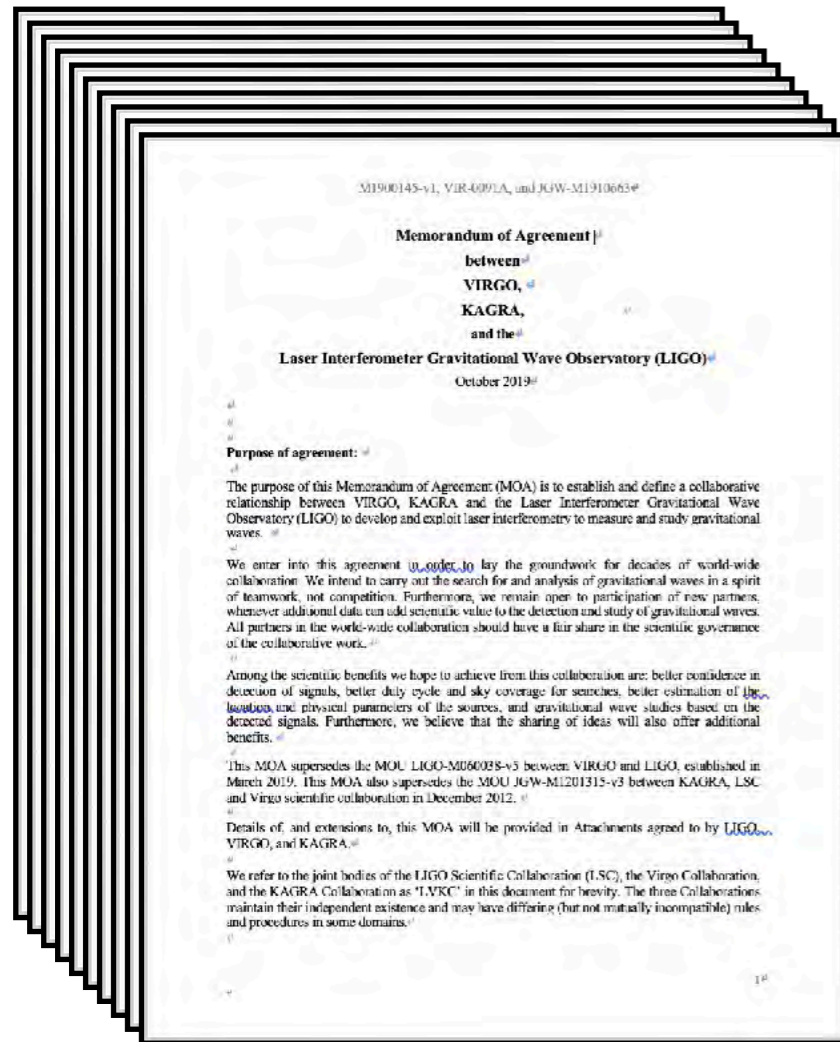
200 authors

110 groups

14 regions



# KAGRA (かぐら : 大型低温重力波望遠鏡)



2019年10月, アメリカ・ヨーロッパとの研究協定に調印

# 国際重力波観測ネットワーク



**LIGO** **LSC**  
**LIGO Scientific Collaboration**

Abilene Christian University  
Albert-Einstein Institut  
Andrews University  
American University  
California Institute of Technology  
California State Univ., Fullerton  
Canadian Inst. Th. Astrophysics  
Caldwell College  
College of William and Mary  
Columbia U. in the City of New York  
Embry-Riddle Aeronautical Univ.  
Eötvös Loránd University  
Georgia Institute of Technology  
Goodard Space Flight Center  
Hobart & William Smith Colleges  
ICTP-SAIFR  
IndIGO  
IAP-Russian Acad. of Sciences  
Inst. Nacional Presquisas Espaciais  
Kenyon College  
Korean Gravitational-Wave Group  
Louisiana State University  
Montana State University  
Montclair State University  
Moscow State University  
National Tsinghua University  
Northwestern University

LIGO Laboratory, California Institute of Technology, Massachusetts Institute of Technology, LIGO Hanford Observatory, LIGO Livingston Observatory  
Australian Consortium for Interferometric Gravitational Astronomy (ACIGA):  
Australian National University, Charles Sturt University, Monash University, University of Adelaide, University of Melbourne, University of Western Australia  
German/British Collaboration for the Detection of Gravitational Waves (GEO600):  
Caird University, Leibniz Universität Hannover, Albert-Einstein Institut, Hannover, King's College London, Rutherford Appleton Laboratory,  
University of Birmingham, University of Cambridge, University of Glasgow, University of Hamburg, University of Sheffield,  
University of Southampton, University of Strathclyde, University of the West of Scotland

**Virgo Collaboration**  
Virgo is a European collaboration with about 360 authors from 89 institutes

Advanced Virgo (AdV) and AdV+ upgrades of the Virgo interferometric detector  
Participation by scientists from France, Italy, Belgium, The Netherlands, Poland, Hungary, Spain, Germany

- Institutes in Virgo Steering Committee

- APC Paris	- INFN Perugia	- LAPP Arnecey	- RMKI Budapest
- ARTEMIS Nice	- INFN Pisa	- LKB Paris	- UCLouvain, ULiege
- IFAE Barcelona	- INFN Roma La	- LMA Lyon	- Univ. of Barcelona
- ILM and Navier	- Sapienza	- Maastricht University	- University of Sannio
- INFN Firenze-Urbino	- INFN Roma Tor Vergata	- Nikhef Amsterdam	- Univ. of Valencia
- INFN Genova	- INFN Trento-Padova	- POLGRAW(Poland)	- University of Jena
- INFN Napoli	- LAL Orsay ESPCI Paris	- University Nijmegen	

Advanced Virgo project has been formally completed on July 31, 2017  
Part of the international network of 2nd generation detectors  
Started O3 run on April 1, 2019

8 European countries



**1330 members**  
**860 authors**  
**101 groups**  
**20 countries**

**465 members**  
**360 authors**  
**96 groups**  
**8 countries**

**360 members**  
**200 authors**  
**110 groups**  
**14 regions**

# 重力波

時空のゆがみ（トランポリンのゆれ）が伝わる

- ⇒ 小さな小さな波をとらえることができた!
- ⇒ 衝突したときの音を聴くことができた!

重力波天文学で何がわかる？

- ⇒ どういうブラックホールか
- ⇒ 銀河系がどうできてきたのか
- ⇒ 宇宙のはじまりはどうなっていたのか
- ⇒ アインシュタインは正しかったのか

# マルチ・メッセンジャー天文学の誕生



	宇宙線	ガンマ線	X線	光			電磁波							
				紫外線	可視光線	赤外線	マイクロ波	超短波	短波	中波	長波	超長波		
波長[m]	$10^{-13}$	$10^{-10}$	$10^{-9}$	$3.8 \times 10^{-7}$	$7.7 \times 10^{-7}$	$10^{-4}$	1	10	$10^2$	$10^3$	$10^4$			
波長[nm]				380	770									
振動数[Hz]		$3 \times 10^{18}$	$3 \times 10^{17}$				$3 \times 10^{12}$	$3 \times 10^8$	$3 \times 10^7$	$3 \times 10^6$	$3 \times 10^5$	$3 \times 10^4$		
利用例		医療／食品照射	医療／X線写真	殺菌	光学機器	赤外線写真	携帯電話	電子レンジ	テレビ	F Mラジオ	短波ラジオ	A Mラジオ	電波時計	飛行機の通信

ガンマ線

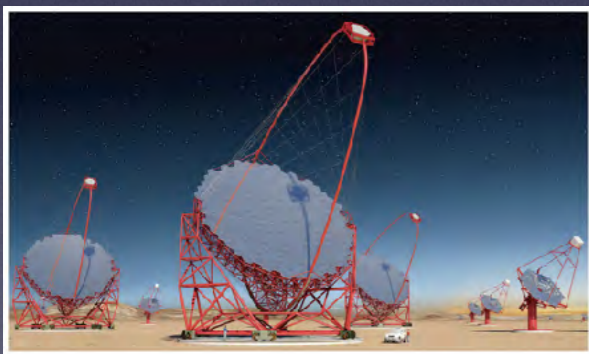
X線

可視光

赤外

電波

重力波



重力波天文学  
はじめました。