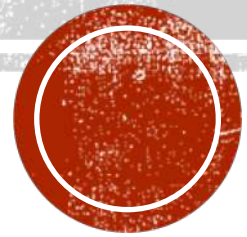
Black Holes in a nutshell



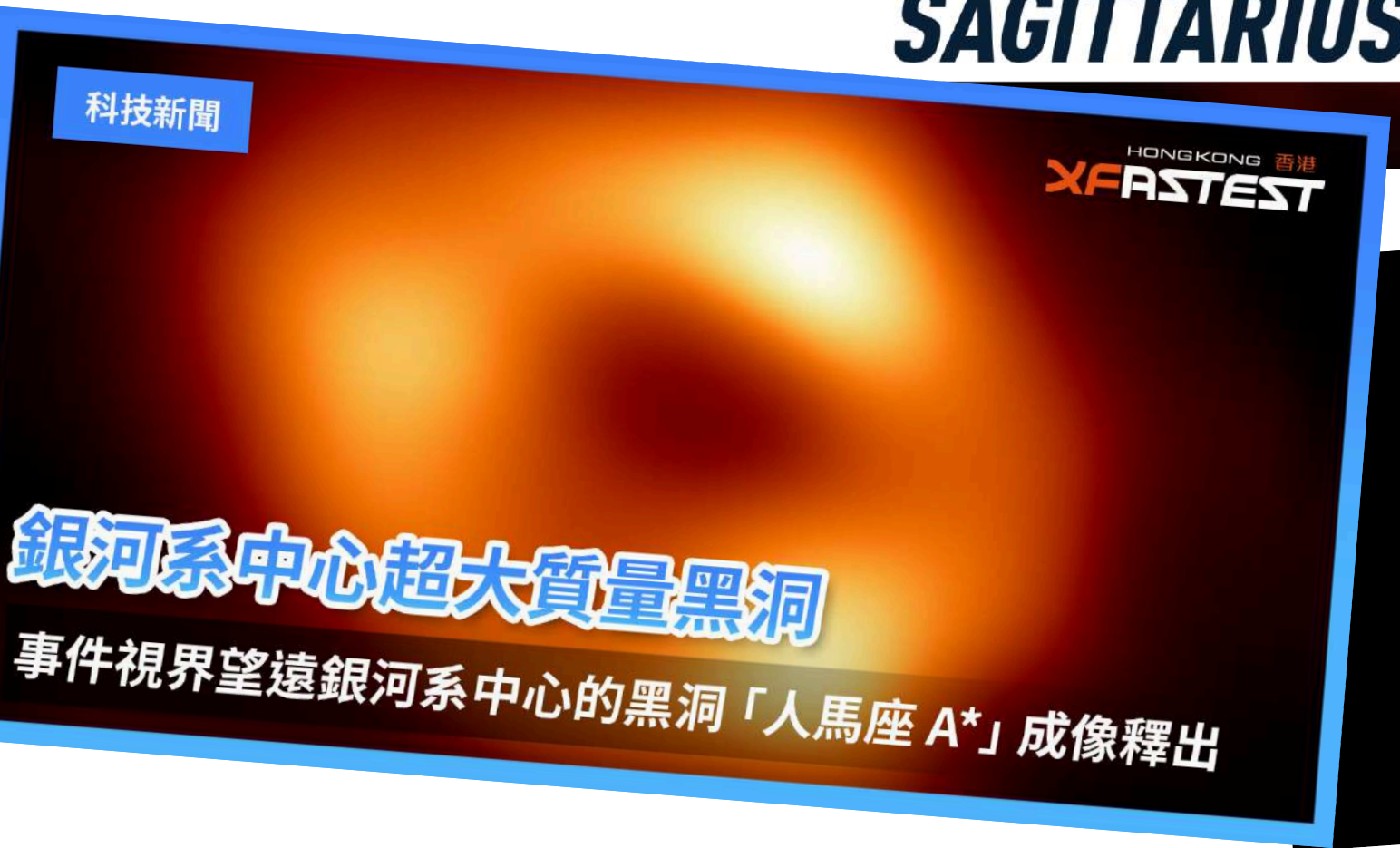
Mini-workshop of NCTS-TCA-SSP 2022

Che-Yu Chen

Institute of Physics, Academia Sinica, July 5, 2022

May 12, 2022


HELLO
SAGITTARIUS A*


科技新聞
HONGKONG 香港
XFASTEST
銀河系中心超大質量黑洞
事件視界望遠銀河系中心的黑洞「人馬座 A*」成像釋出


THE U.S.
Sun
BREAKING NEWS

April 10, 2019

THE TIMES

Britain's most trusted national newspaper Thursday April 11 2019 | thetimes.co.uk | No 72818 £1.80 Only £1 to subscribers

Best restaurants for over-50s No music, no hipster chefs

INSIDE TIMES2

Deborah Ross Forget Jude Law: my guide to an 'attainable body'

Blackmailers threaten release of Assange embassy 'sex secrets'

John Simpson Crime Correspondent

Blackmailers threatened to reveal sexual secrets of Julian Assange's life inside the Ecuadorean embassy as part of a €3million extortion attempt, it was claimed yesterday.

Security footage and audio from inside the Knightsbridge embassy had found its way into the hands of criminals, his Wikileaks group said.

The leak inflamed tensions between Mr Assange and his hosts, who want him out of the premises at which he has been living since 2012. Officials were said last week to be hours away from forcing him to leave, but Wikileaks claimed yesterday to have averted the eviction by alerting the media.

Kristinn Hrafnsson, Wikileaks's editor, described the information the blackmailers had obtained, which also included photographs and documents from Mr Assange's lawyer, as a "massive trove". He told of making contact with a blackmailer who identified himself as "PM".

"He said that this material has a price," Mr Hrafnsson said. "I was sent samples of what they had. It was photographs of Julian inside the embassy ... and for some reason they found it important to send me a snapshot [of] my own meeting with Julian in the embassy in November last year."

A source with knowledge of the case said: "This is how it was sold, that there was sensitive, possibly sexual, material."

Mr Hrafnsson did not comment on any material of a sexual nature. He said that when he asked what PM meant by price, he was told: "The price is from €3 million, or we'll start to publish our own way (media, press, etc)."

He resolved to film the group secretly at a meeting in Madrid, where he says police had arrested the individuals. The leaked images appeared to show that Mr Assange's hair and beard have grown long and matted.

Mr Assange took refuge at the embassy after being accused of two sexual assaults in Sweden. He denies the allegations — which have since lapsed — and says he remains there for fear of extradition to the US. There is an outstanding British arrest warrant for Mr Assange for breaching bail conditions in the UK while awaiting extradition.

Skateboarding in the hall, page 7

May defies Tory rebels with pledge to stay on

I can still strike Brexit deal, PM tells EU leaders

Oliver Wright, Bruno Waterfield Brussels
Francis Elliott Political Editor

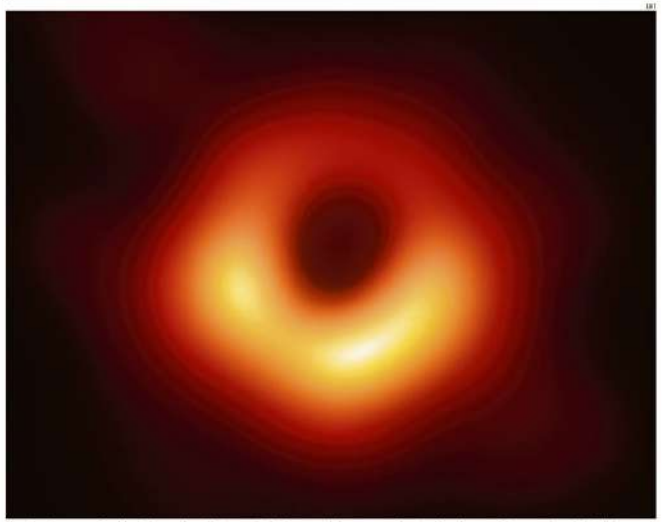
Theresa May plans to stay on as prime minister for as long as it takes for parliament to vote for her Brexit deal, senior government sources have said.

In a move that will infuriate Tory Brexiteers, Downing Street has made clear that Mrs May's pledge to step down is conditional on her withdrawal agreement being approved by MPs.

The commitment will reassure EU leaders, however, who fear that Mrs May could be replaced by a hardline Brexiteer who would try to use a long extension the year or to next March. "The [German] government believes we should give the two parties a decent amount of time so that an orderly Brexit can be achieved together with the UK," she said. "This is a historic moment: for the first time a country is leaving the EU. How will we look back on this question five or ten years from now?"

Downing Street sources said that while Mrs May had not been directly asked about her future in recent talks with Mr Macron and Mrs Merkel it was "widely known" among EU leaders that she intended to stay to see "phase one" of the negotiations to its conclusion.

They said that Mrs May had been



The first image of its kind shows the effect created when particles are accelerated by the crushing gravity of six billion suns

... and here's another inescapable black hole

Tom Whipple Science Editor

more exciting — absolute blackness.

objects. Their "event horizons" are not

THE WALL STREET JOURNAL.

THURSDAY, APRIL 11, 2019 ~ VOL. CCLXXIII NO. 84 WSJ.com ★★★★ $4.00

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DJIA 26157.28 ▲ 8.58 0.03% NASDAQ 7964.24 ▲ 0.7% STOXX 600 386.68 ▲ 0.3% 10-YR. TREAS. ▲ 5/32, yield 2.479% OIL $64.61 ▲ $0.63 GOLD $1,309.10 ▲ $5.60 EURO $1.1276 YEN 111.01

What's News

Business & Finance

...ber is aiming for a valu... ...ation in its coming IPO ...s much as $100 billion, ...w previous expecta... ...s, as rival Lyft stumbles ...s early days of trading ...public company. A1

...d officials signaled ...er conviction at their ...ng last month that ...don't need to move in... ...rates up or down. A2

...ghi indicated that ...B could take fresh ...to shore up the eu... ...'s faltering economy ...utlook darkens. A7

...eads of seven of the ...U.S. banks sparred ...mocrats during a joint ...nce before the House ...Services panel. B1

...and U.S. regulators ...king what amounts ...national stamp ...al for an expected ...MAY ops. B1

First Image Illuminates a Black Hole

Barr to Probe 'Spying' on Trump Aides

Investigation to review whether surveillance in 2016 was 'adequately predicated,' he says

WASHINGTON—Attorney General William Barr said he would form a team to examine the origins of a 2016 counterintelligence investigation that conducted what he termed as "spying" on people affiliated with the Trump campaign, a characterization Democrats said was politically motivated and echoed the president's long-standing criticism of the Justice Department's Russia probe.

By Byron Tau, Sadie Gurman and Aruna Viswanatha

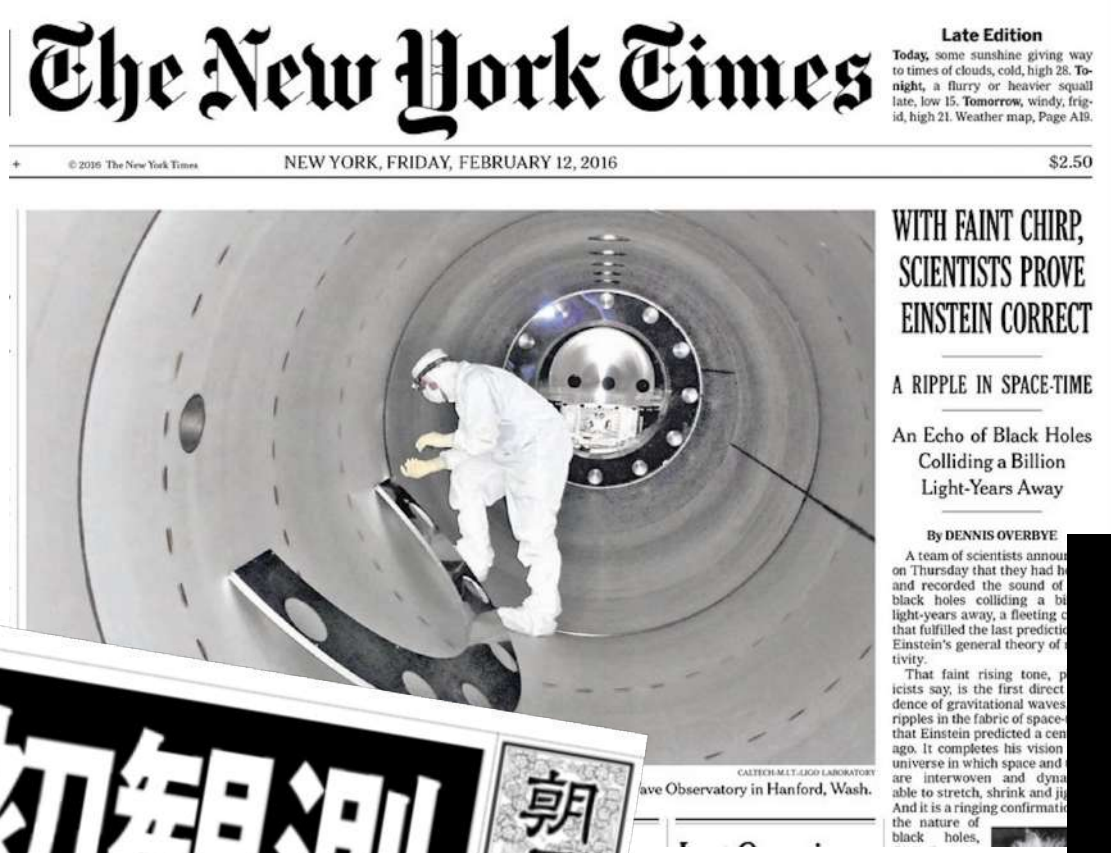
At a Senate hearing on Wednesday, Mr. Barr said the team would look at what lay behind the Federal Bureau of Investigation's probe of the Trump campaign's possible ties to Russia, which included surveillance, and was later taken over by special counsel Robert Mueller.

"I think spying on a political campaign is a big deal," Mr. Barr said, invoking Vietnam-era intelligence abuses such as the surveillance of antiwar activists as a reason to raise these questions. "Spying did occur. The question is whether it was adequately predicated."

President Trump and his Republican congressional allies have long alleged that his associates were unfairly targeted for surveillance, and that investigators in the Justice Department

Please turn to page

Feb 11, 2016



The New York Times

Late Edition

Today, some sunshine giving way to times of clouds, cold, high 28. Tonight, a flurry or heavier squall late, low 15. Tomorrow, windy, frigid, high 21. Weather map, Page A19.

© 2016 The New York Times NEW YORK, FRIDAY, FEBRUARY 12, 2016 $2.50

WITH FAINT CHIRP, SCIENTISTS PROVE EINSTEIN CORRECT

A RIPPLE IN SPACE-TIME

An Echo of Black Holes Colliding a Billion Light-Years Away

By DENNIS OVERBYE

A team of scientists announ
on Thursday that they had h
and recorded the sound of
black holes colliding a bi
light-years away, a fleeting c
that fulfilled the last predictio
Einstein's general theory of
tivity.

That faint rising tone, p
icists say, is the first direct
dence of gravitational waves
ripples in the fabric of space-
that Einstein predicted a cen
ago. It completes his vision
universe in which space and
are interwoven and dyna
able to stretch, shrink and ji
And it is a ringing confirmatio
the nature of
black holes,

CALTECH-M.I.T.-LIGO LABORATORY

ave Observatory in Hanford, Wash.

重力波を初観測

朝日新聞

2016年(平成28年) 2月12日 金曜日

号

アイン

米研究チーム発表

100年前にアインシュタインが存在を言し、世界の研究者が観測を目指してきた「重力波」について、米国の研究チームが日、初めて観測したと発表した。最終的に認されれば理論が実証されたことになり、理学の歴史的な成果となる。光や電波ではからない宇宙の姿を探る新たな天文観測に道が開ける。

重力波のイメージ

池に石を投げるイメージ

池

石

波紋

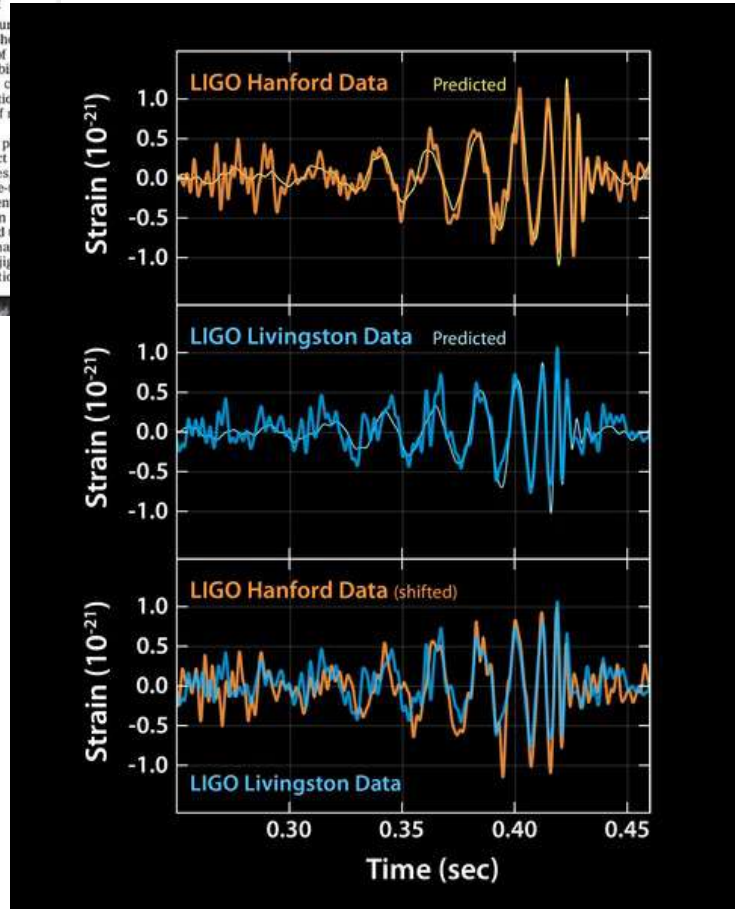
宇宙のかなたの重い星

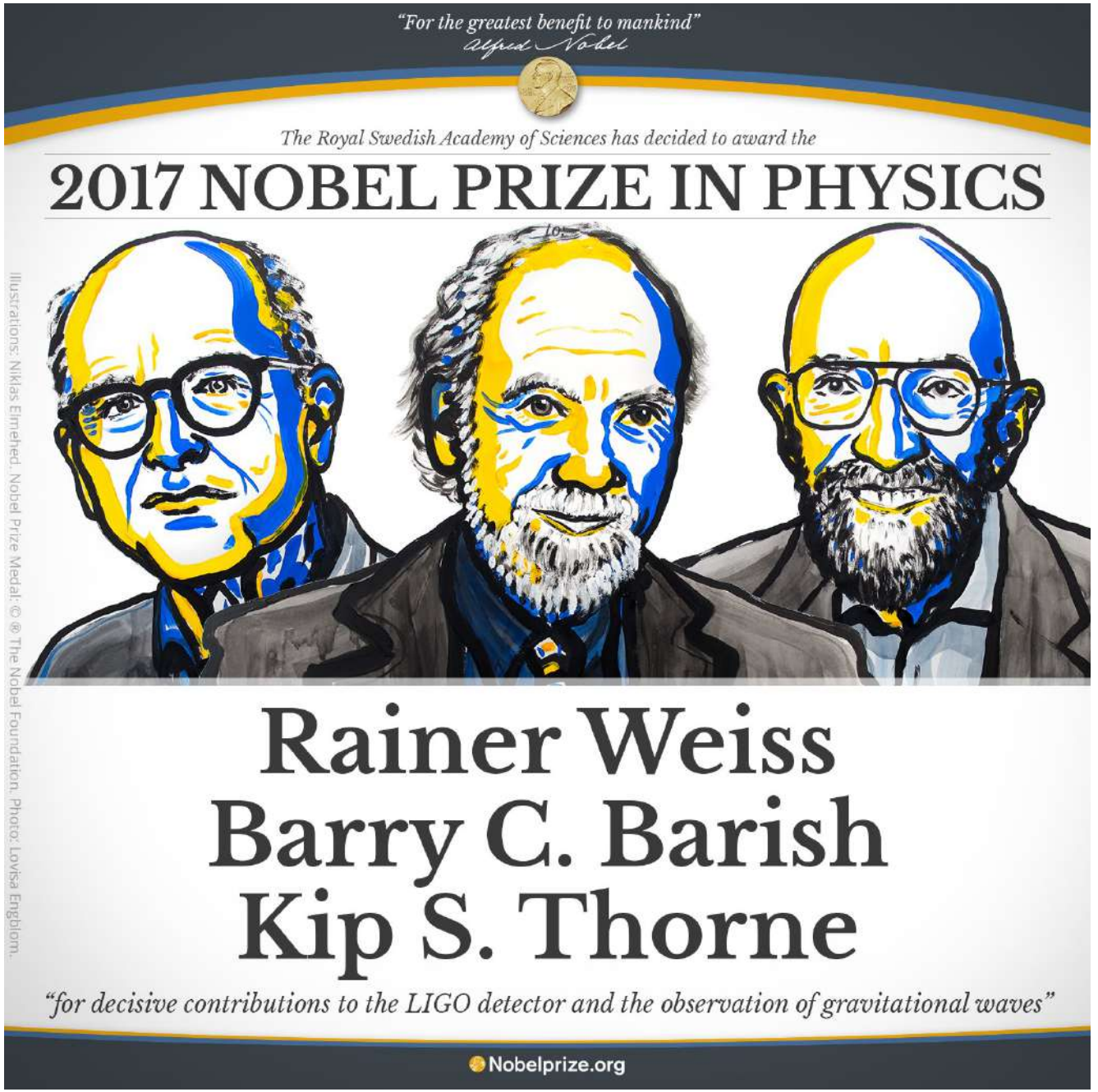
力波

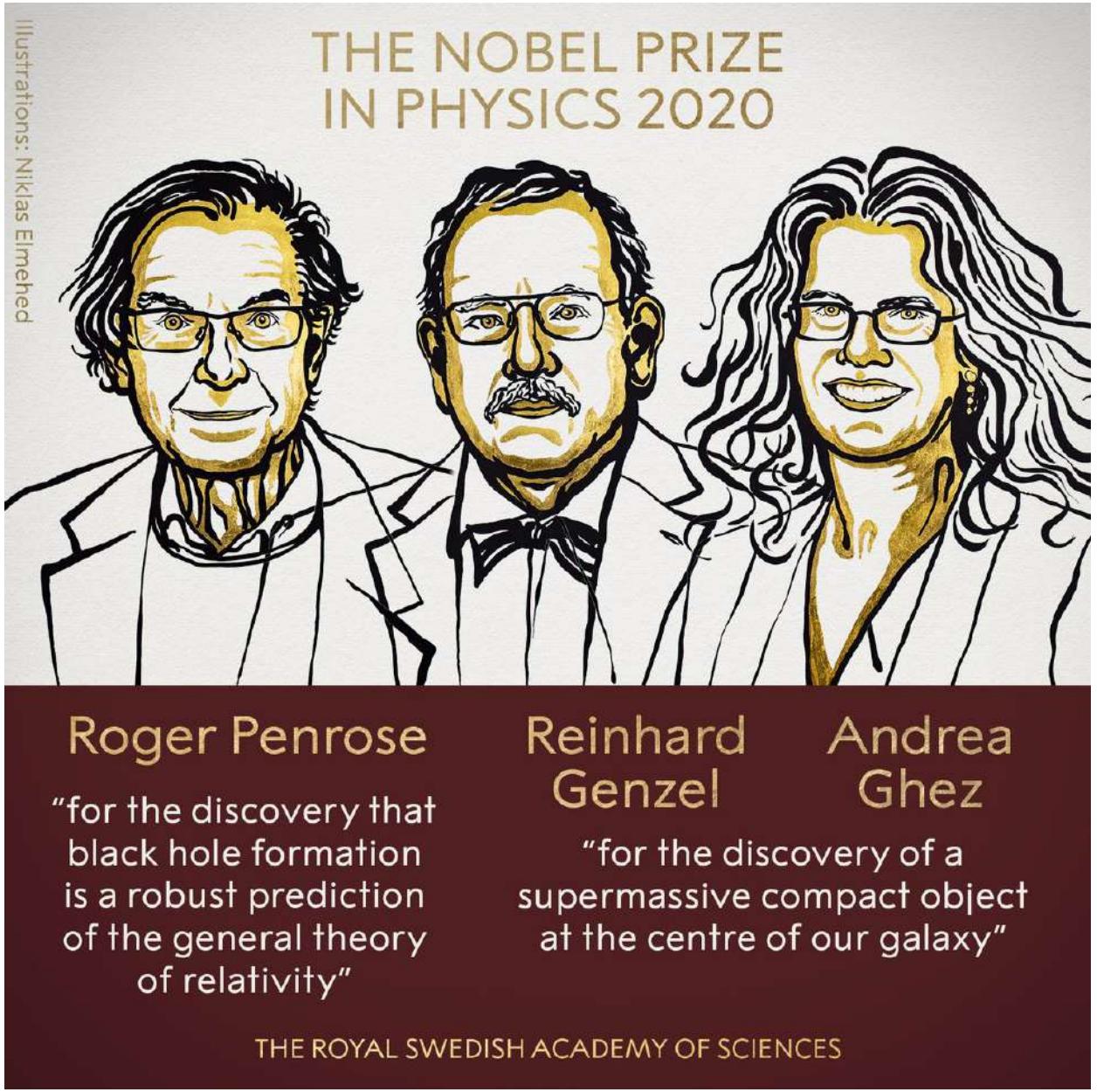
間のゆがみが して伝わる

地球

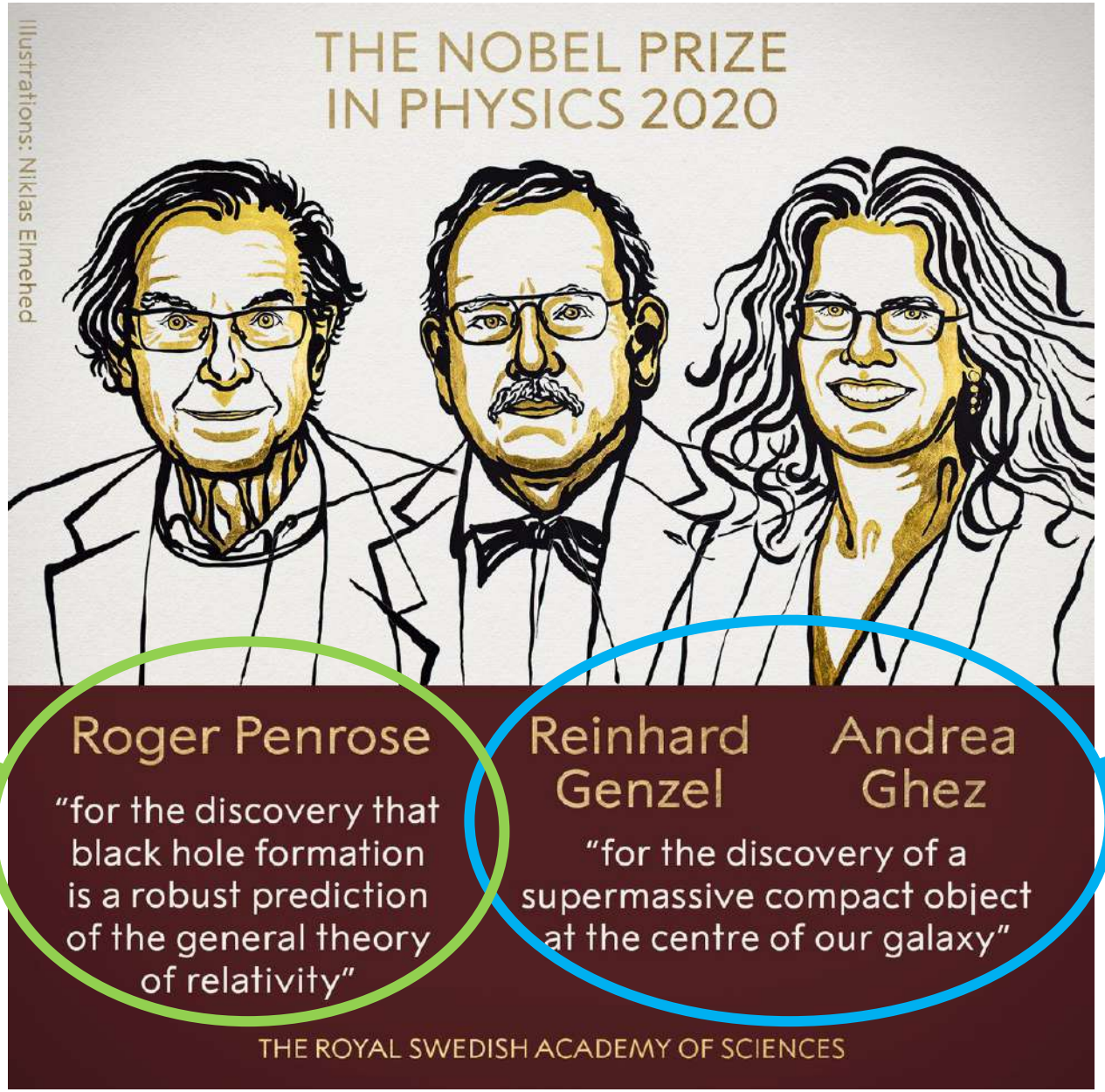
地球を含む空間もゆがむ



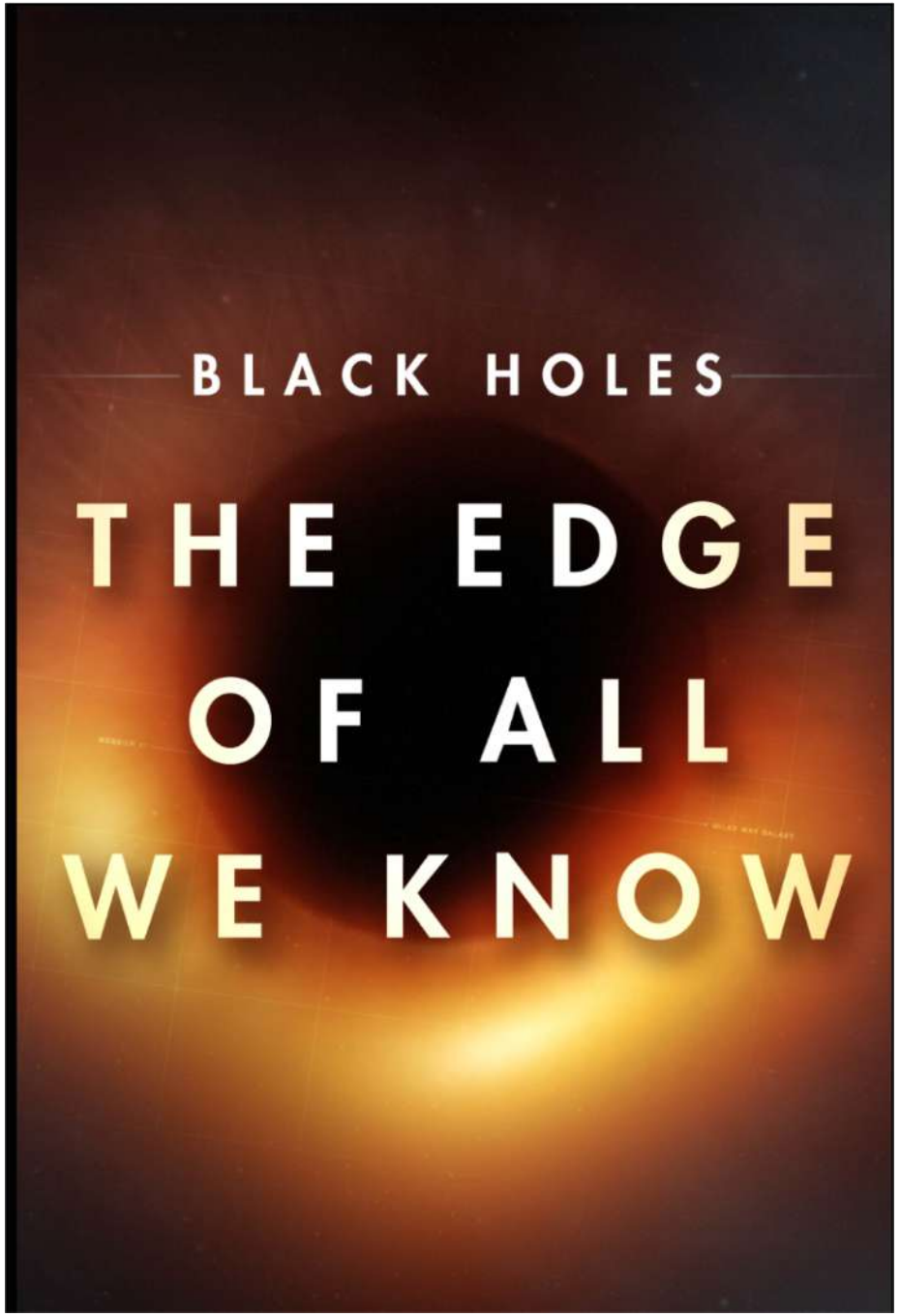

"For the greatest benefit to mankind"
Alfred Nobel
The Royal Swedish Academy of Sciences has decided to award the
2017 NOBEL PRIZE IN PHYSICS
to
Rainer Weiss
Barry C. Barish
Kip S. Thorne
"for decisive contributions to the LIGO detector and the observation of gravitational waves"
Nobelprize.org
Illustrations: Niklas Elmehed. Nobel Prize Medal: © The Nobel Foundation. Photo: Lovisa Engblom.


THE NOBEL PRIZE
IN PHYSICS 2020
Illustrations: Niklas Elmehed
Roger Penrose
"for the discovery that black hole formation is a robust prediction of the general theory of relativity"
Reinhard Genzel
Andrea Ghez
"for the discovery of a supermassive compact object at the centre of our galaxy"
THE ROYAL SWEDISH ACADEMY OF SCIENCES

Proving the existence of black holes form a theoretical point of view



Revealing the existence of a supermassive compact object at the center of our galaxy



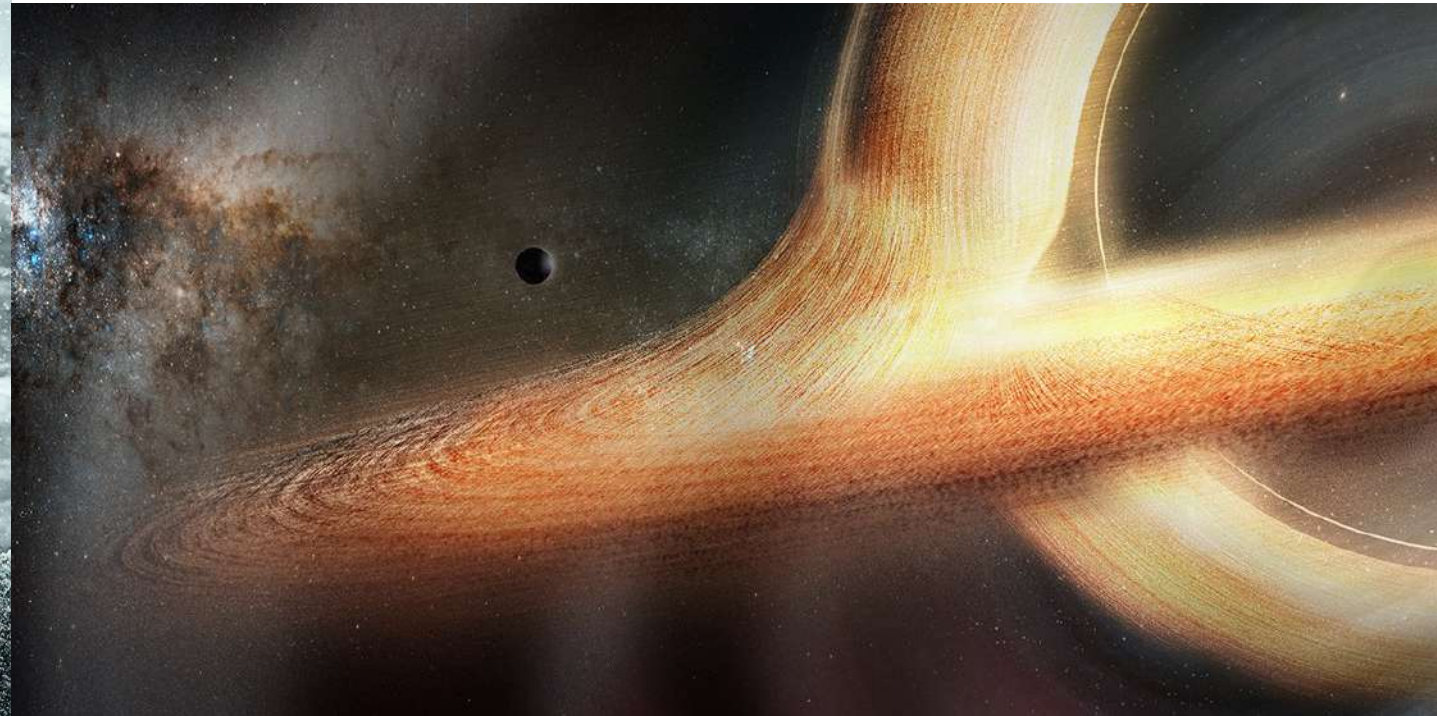
A documentary film (2020) directed by Peter Galison

Different aspects about how people try to understand black holes:

- Black hole images from EHT
- Star's motion around black holes
- Theoretical understanding of black holes (soft hair)
- Black hole simulations
- Analog black holes through water vortices

Interstellar (2014)

Scientific consultant
Kip Thorne



- What we already know about black holes
  - What is a black hole?
  - FEEL black holes
  - HEAR black holes
  - SEE black holes

- What can we learn from black holes?
  - A perfect avenue to understand universe and to probe fundamental theory

WHAT IS A BLACK HOLE?

"Black Hole" from Newtonian Gravity

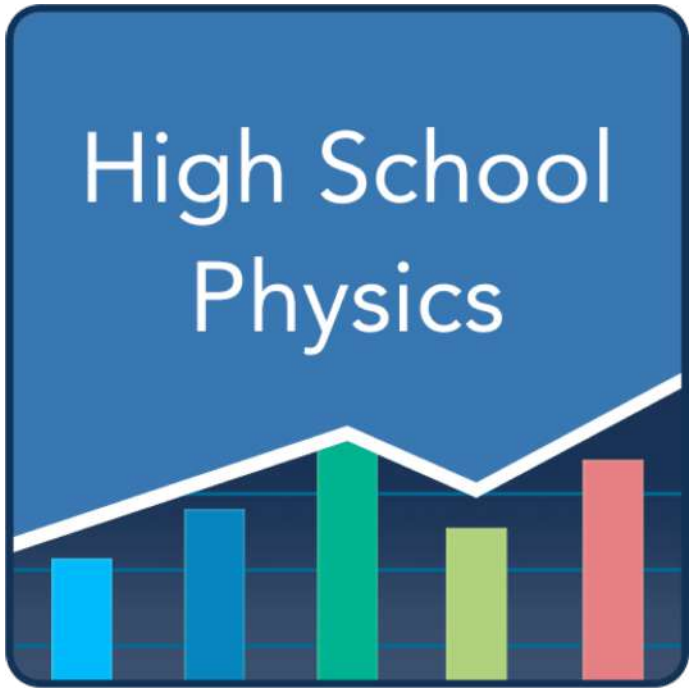
Escape velocity from a potential well:

$$v_e = \sqrt{2GM/r}$$

If $v_e = c$ (speed of light)

We get

$$r = \frac{2GM}{c^2}$$



John Michell (1784)

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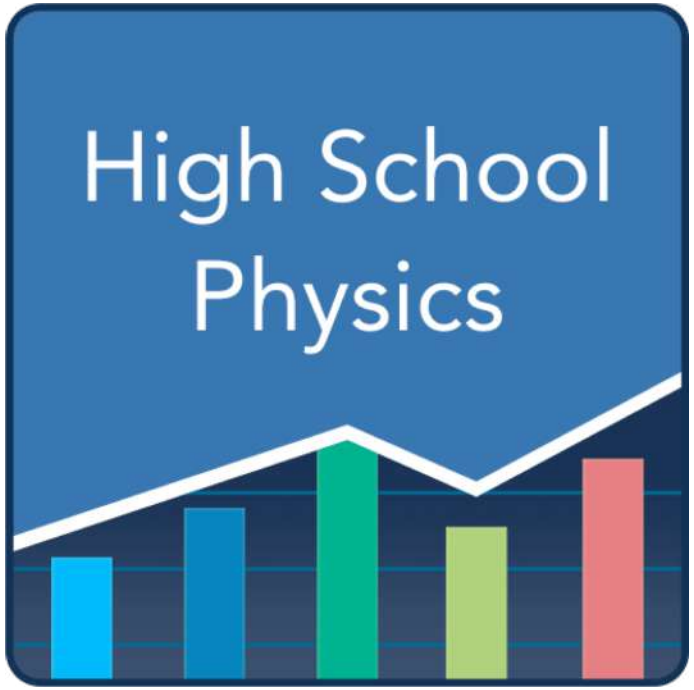
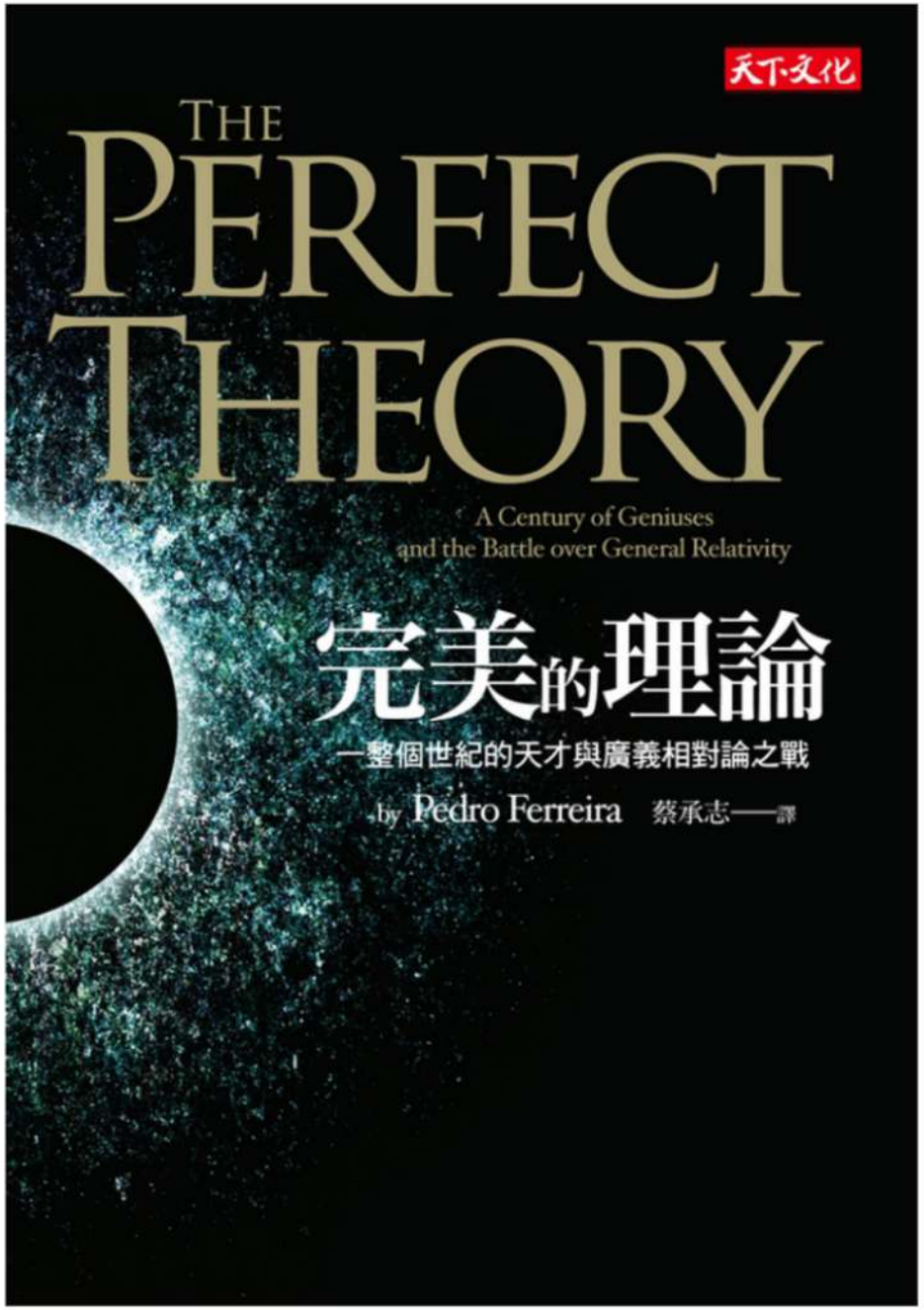


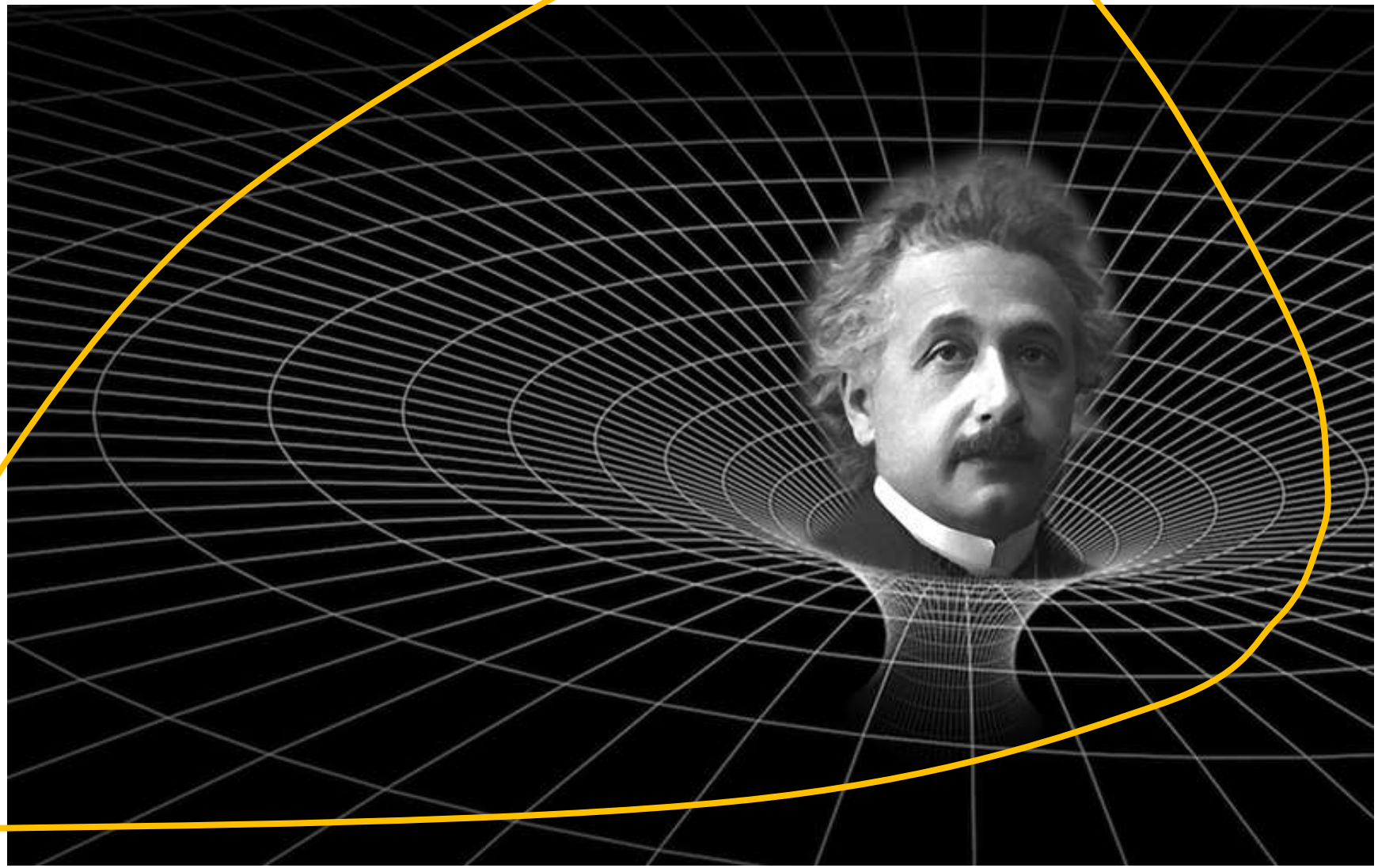
John Michell (1784)

*** A correct result from an incorrect derivation ***

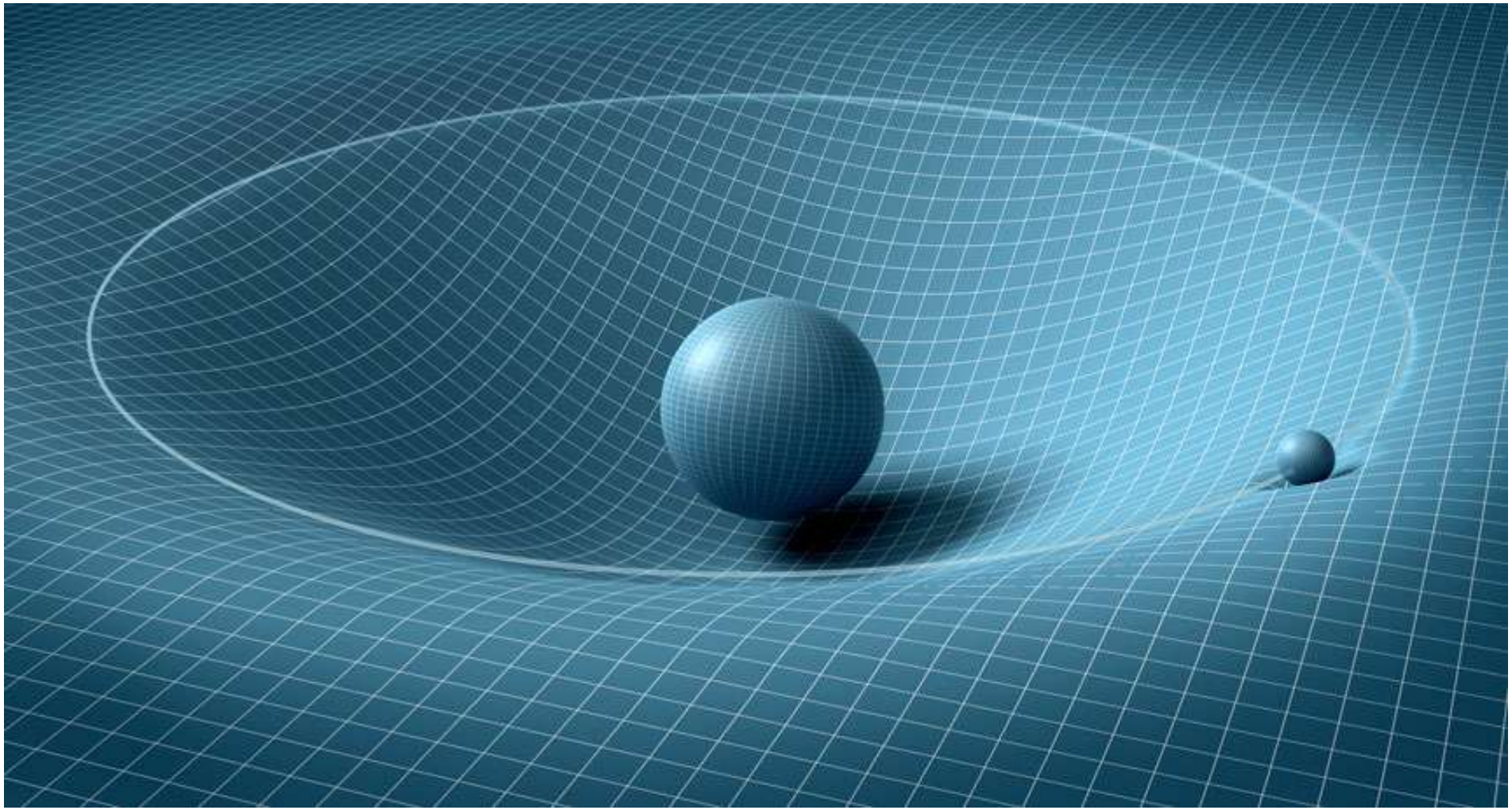


Pedro Ferreira

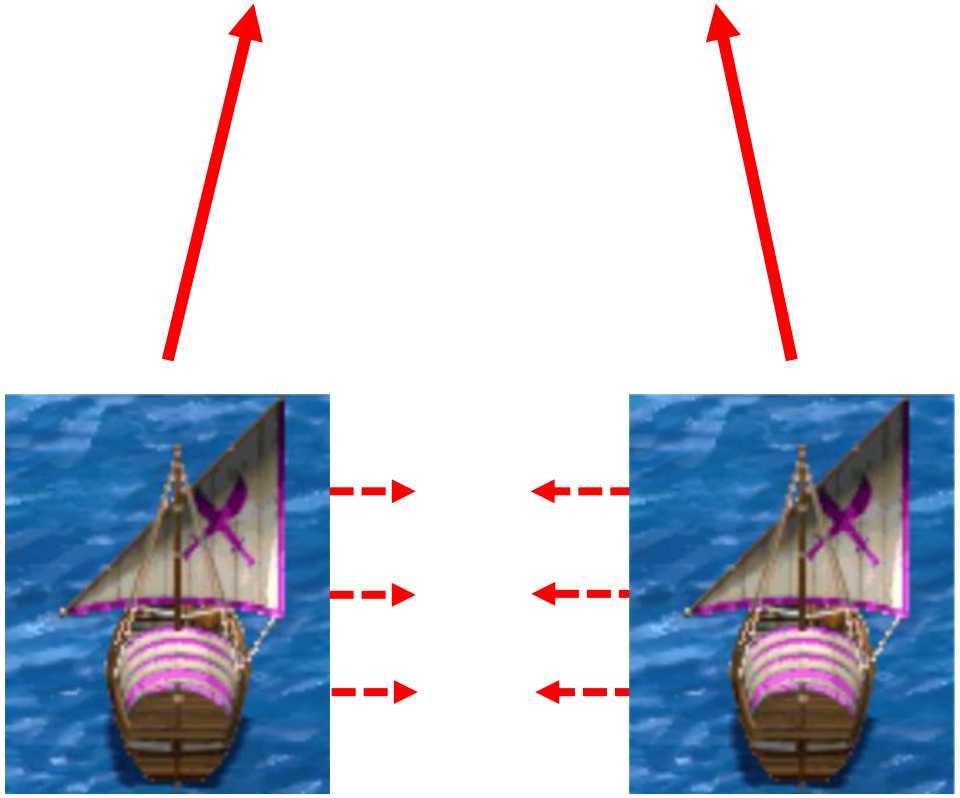
General Relativity (1915)



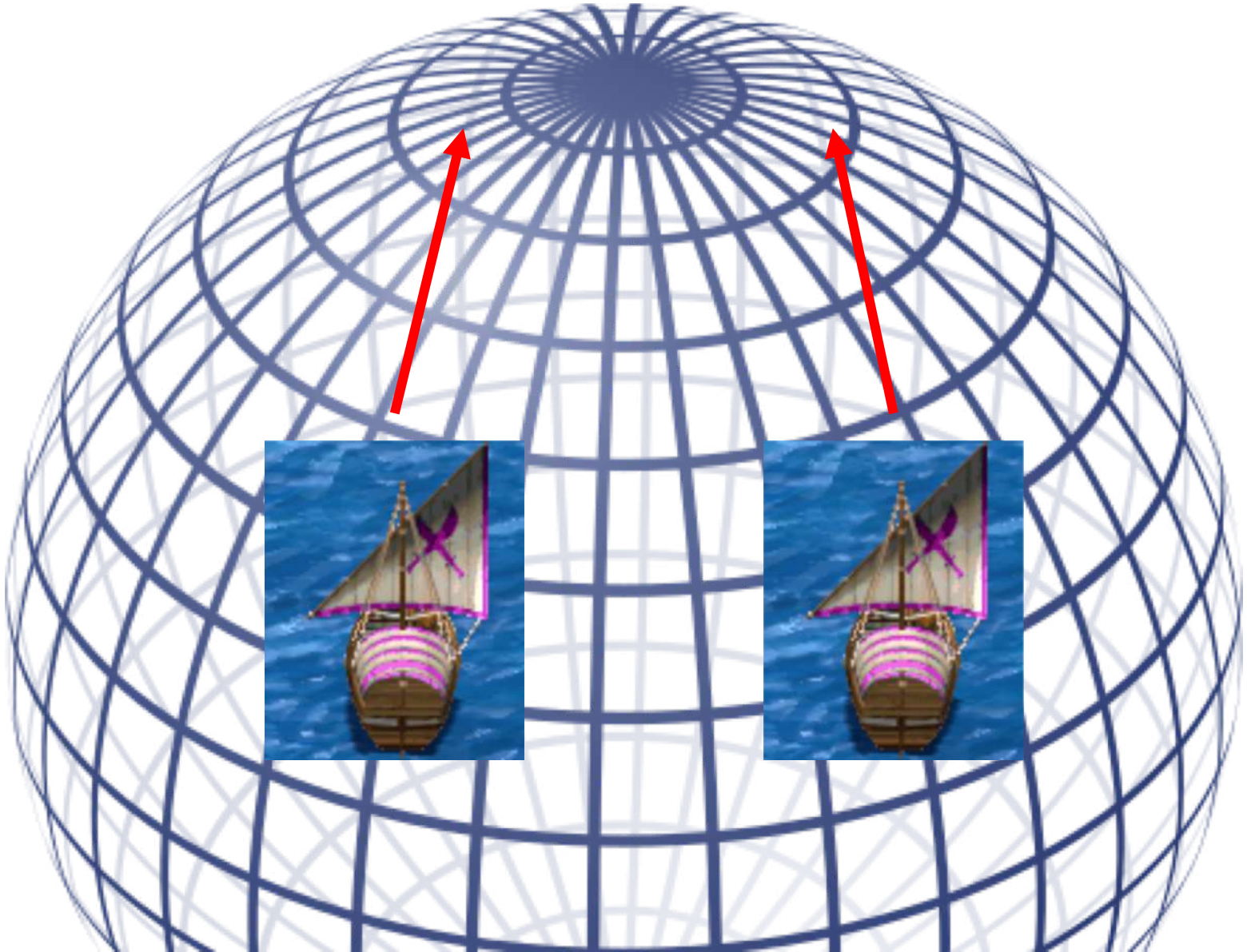
General Relativity (1915)



Force Interpretation vs. Curved Space



Force Interpretation vs. Curved Space



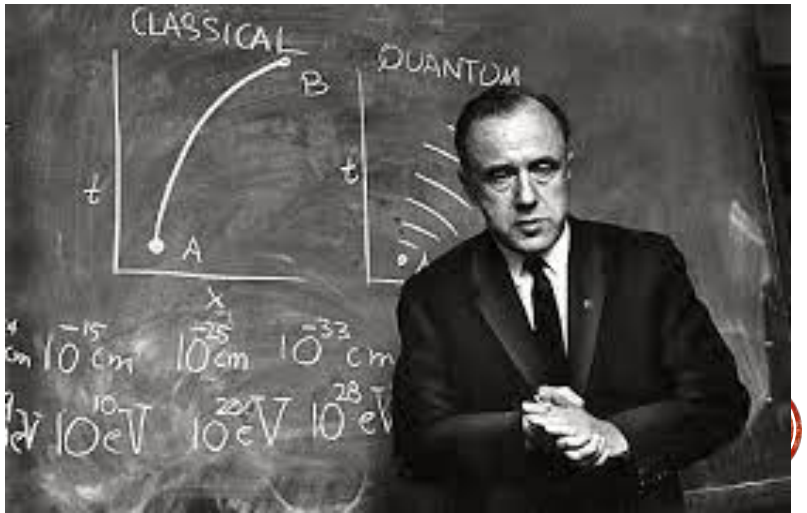
General Relativity (1915)

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

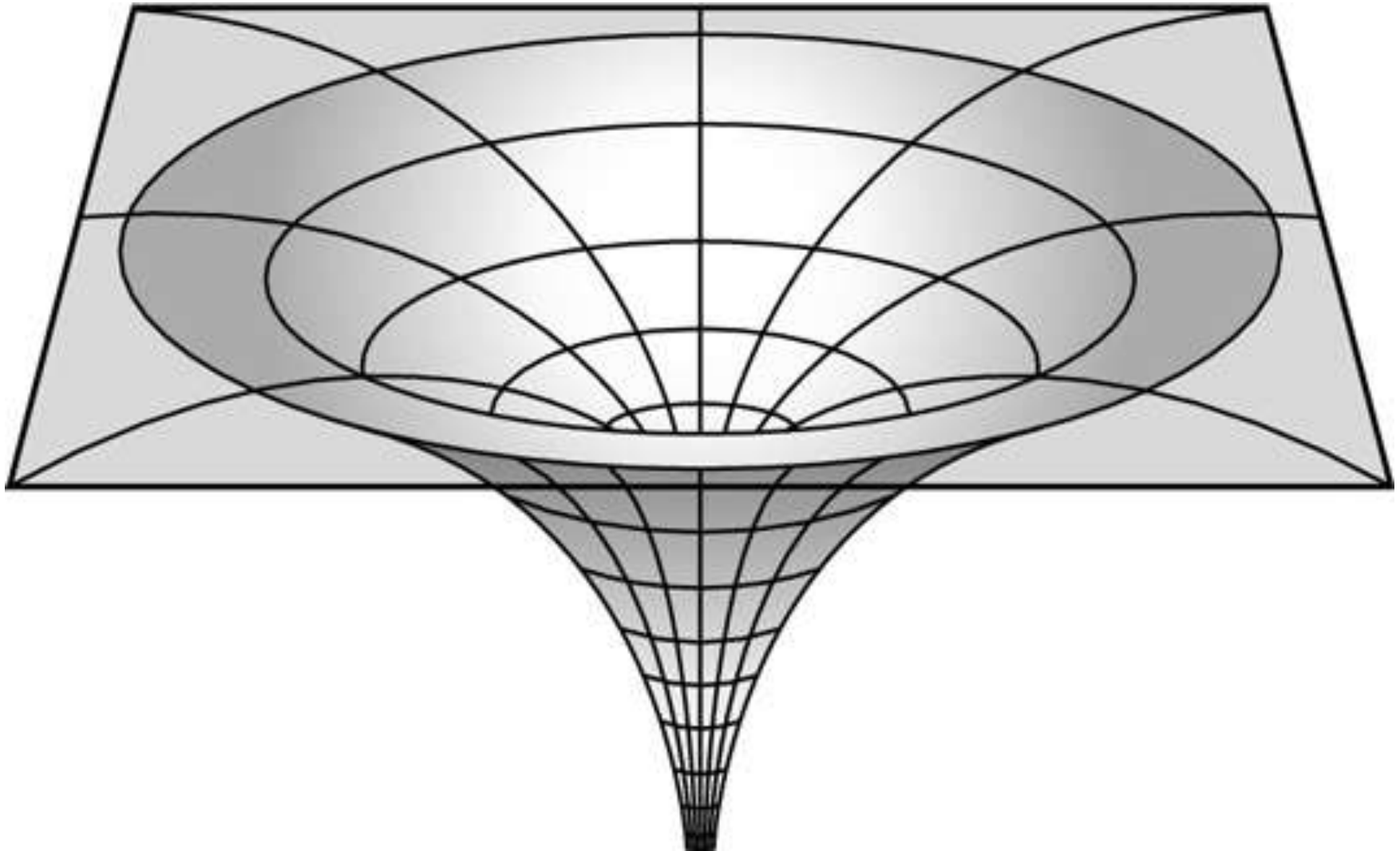
spacetime curvature matter distribution

Matter tells spacetime how to curve;
spacetime tells matter how to move

John Wheeler

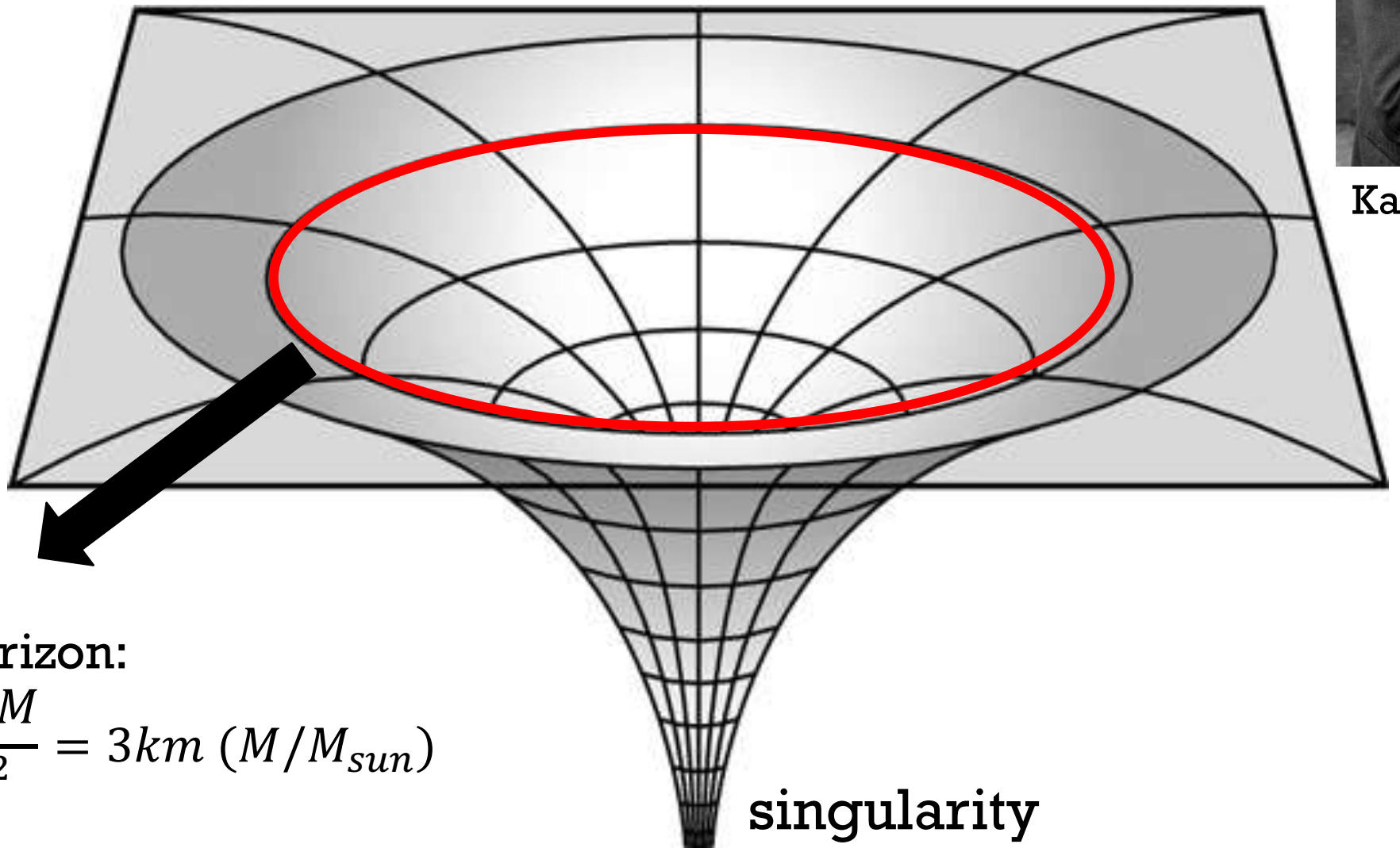


General Relativity (1915)



The First Black Hole Solution (1916)
Non-rotating Black Hole

Karl Schwarzschild

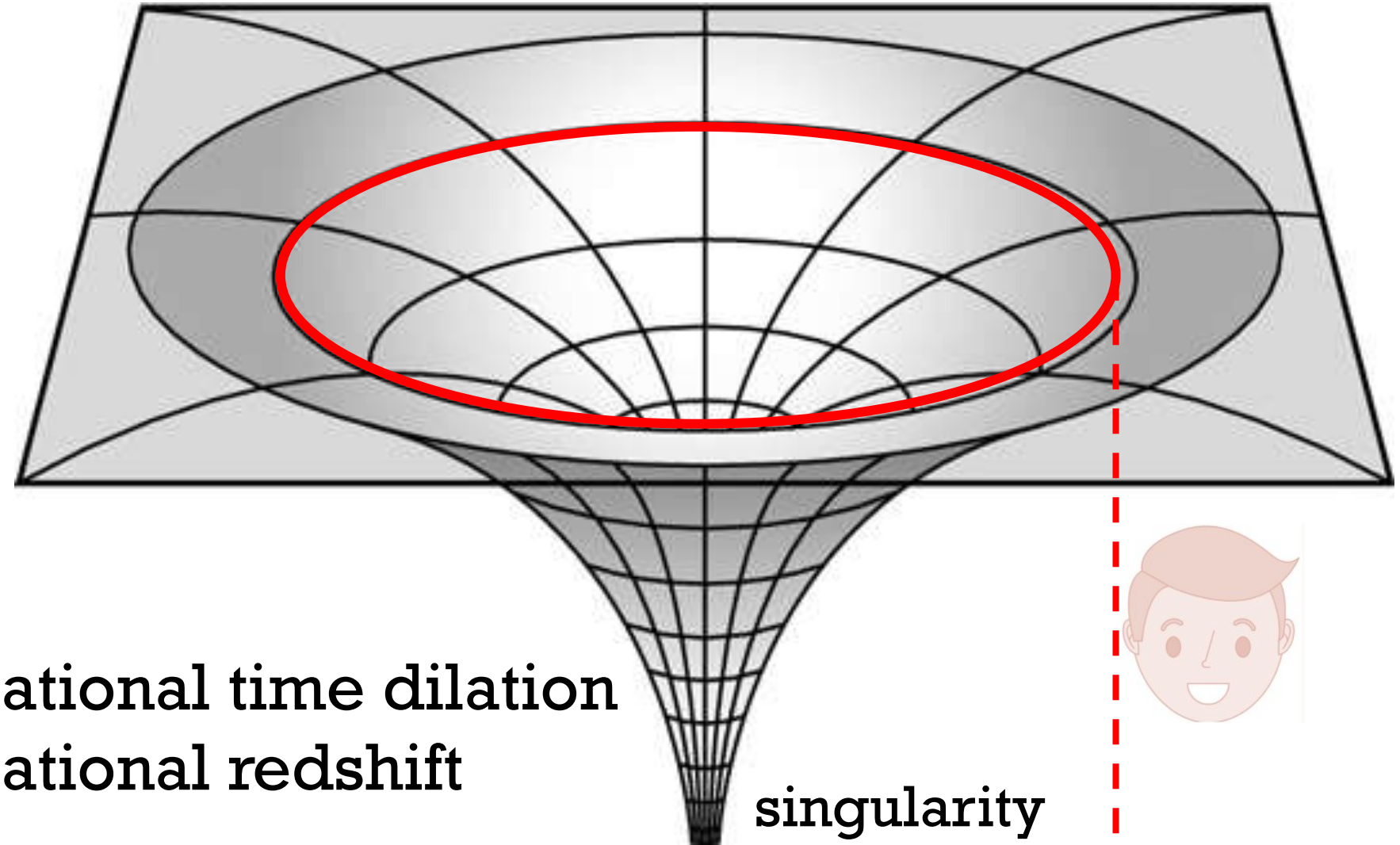


singularity

Event horizon:

$$R_g = \frac{2GM}{c^2} = 3km\ (M/M_{sun})$$

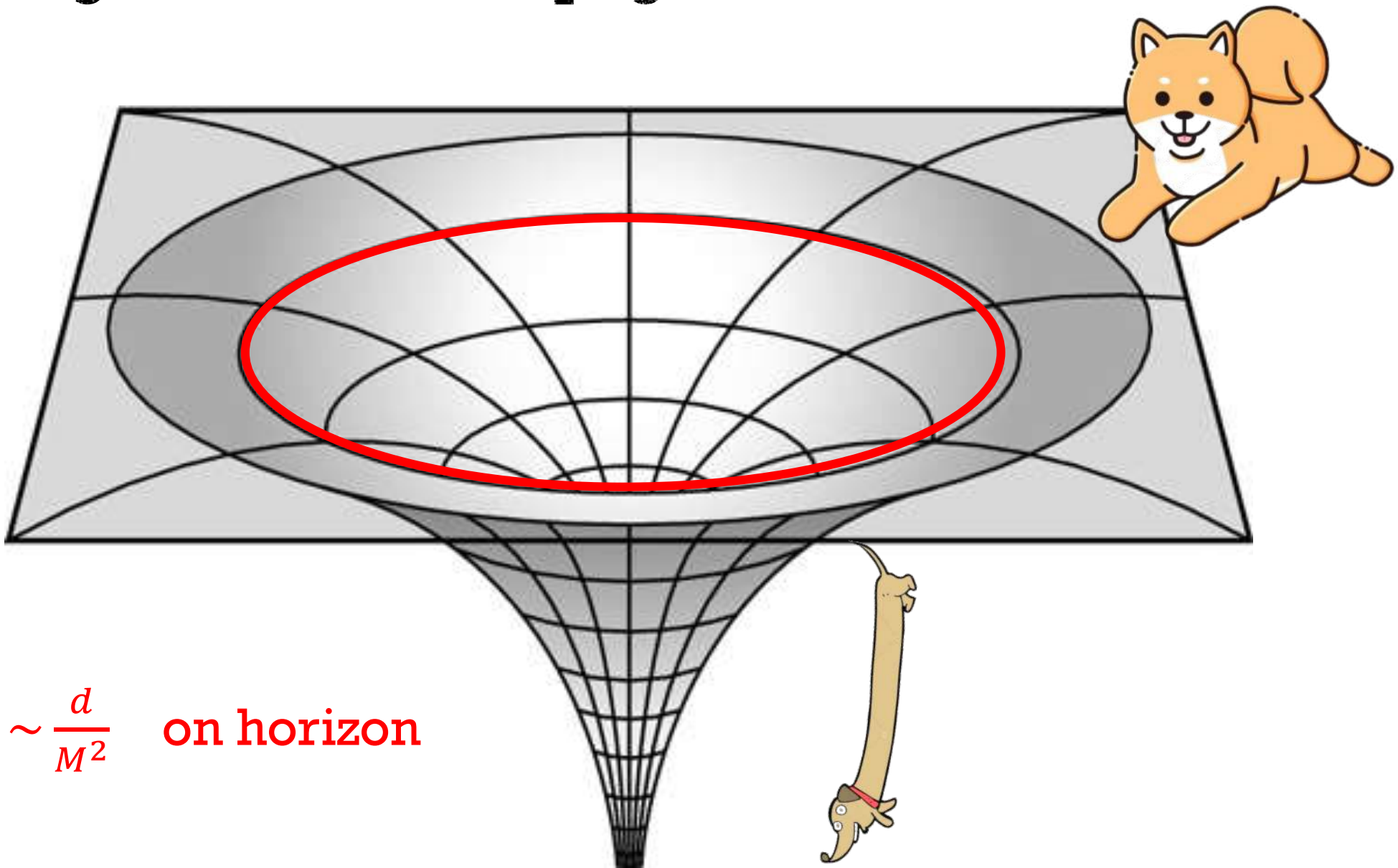
Falling into a BH: as Seen from a Distant Observer



- Gravitational time dilation
- Gravitational redshift

singularity

Falling into a BH: Spaghettification



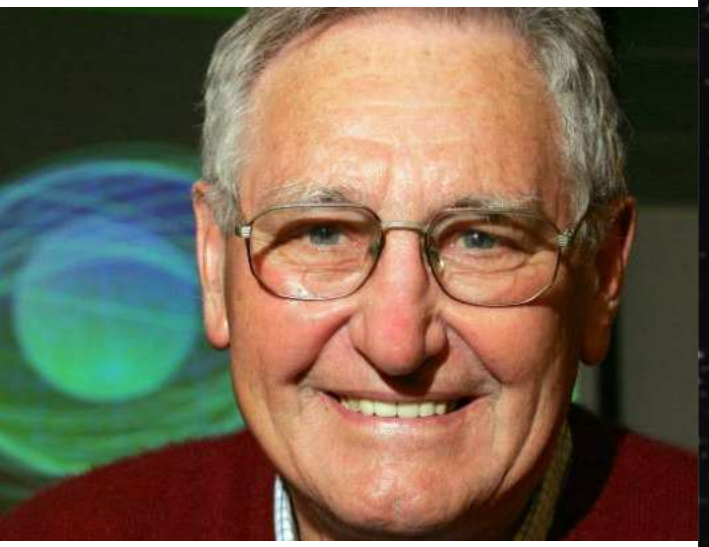
$$a = \frac{2GMd}{R^3} \sim \frac{d}{M^2}$$ on horizon

Spacetime Structure Inside a BH

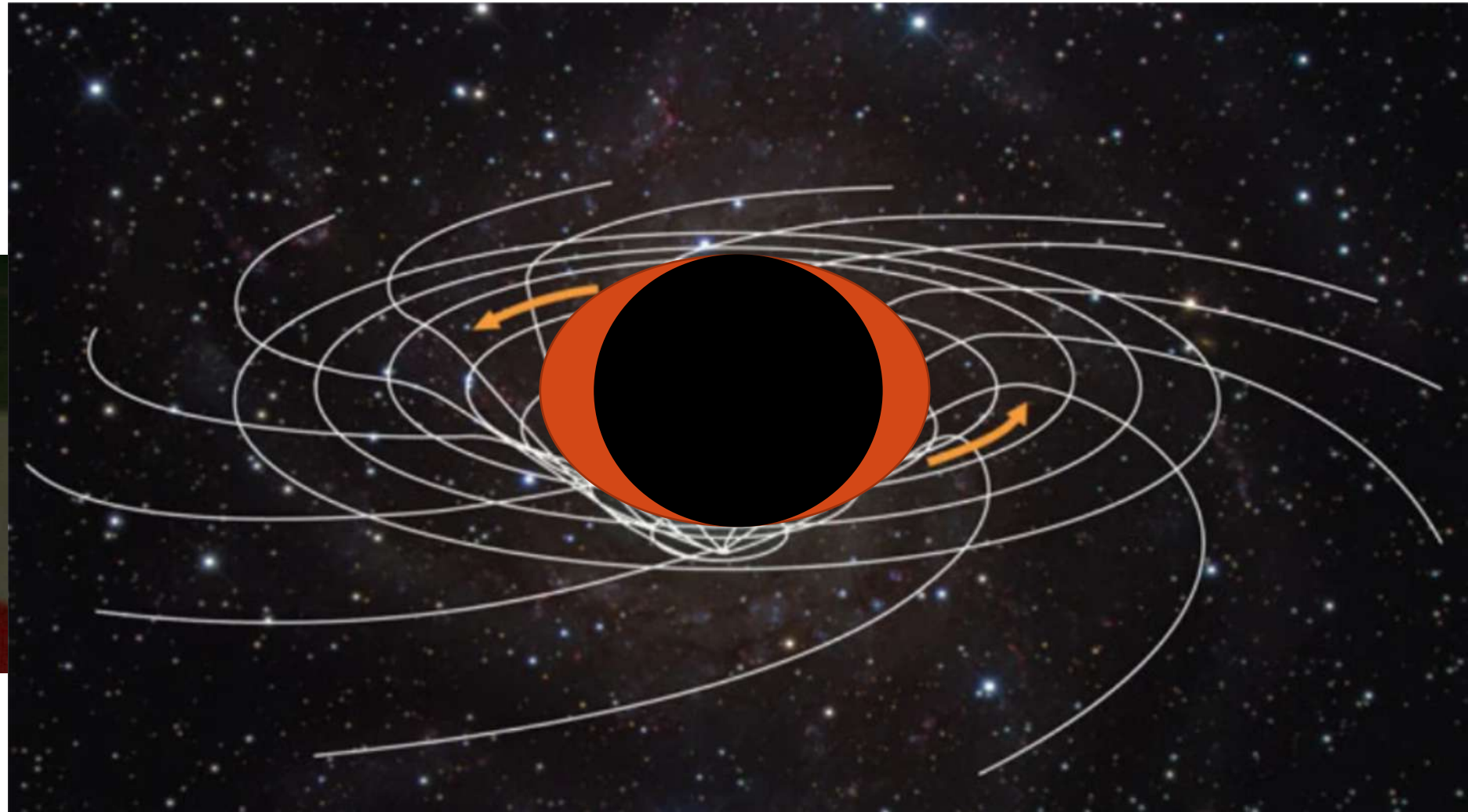
Note:

- Singularity is NOT at the center of a black hole
- It is in the FUTURE after crossing the event horizon

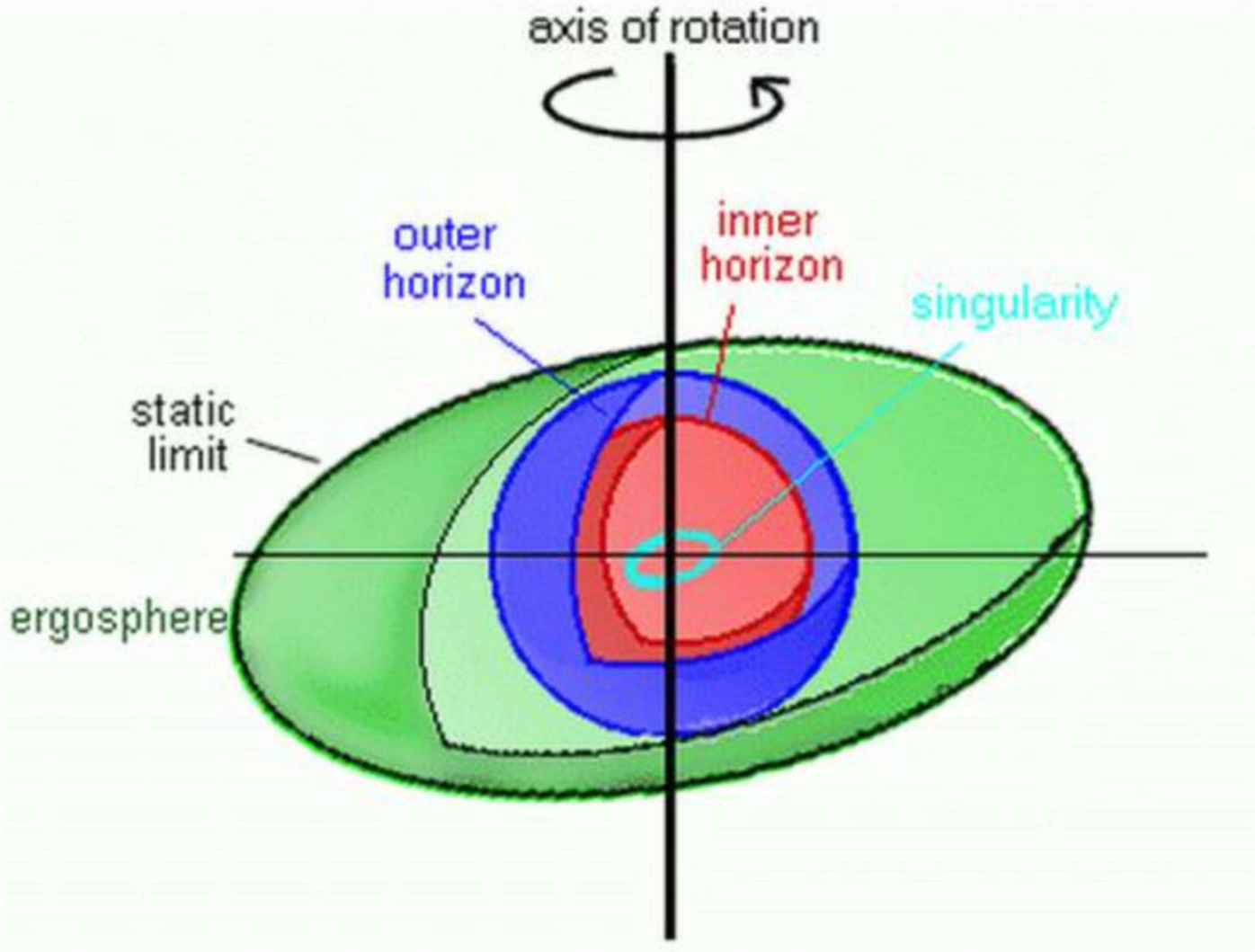
Spinning BH: Kerr Solution (1963)



Roy Kerr

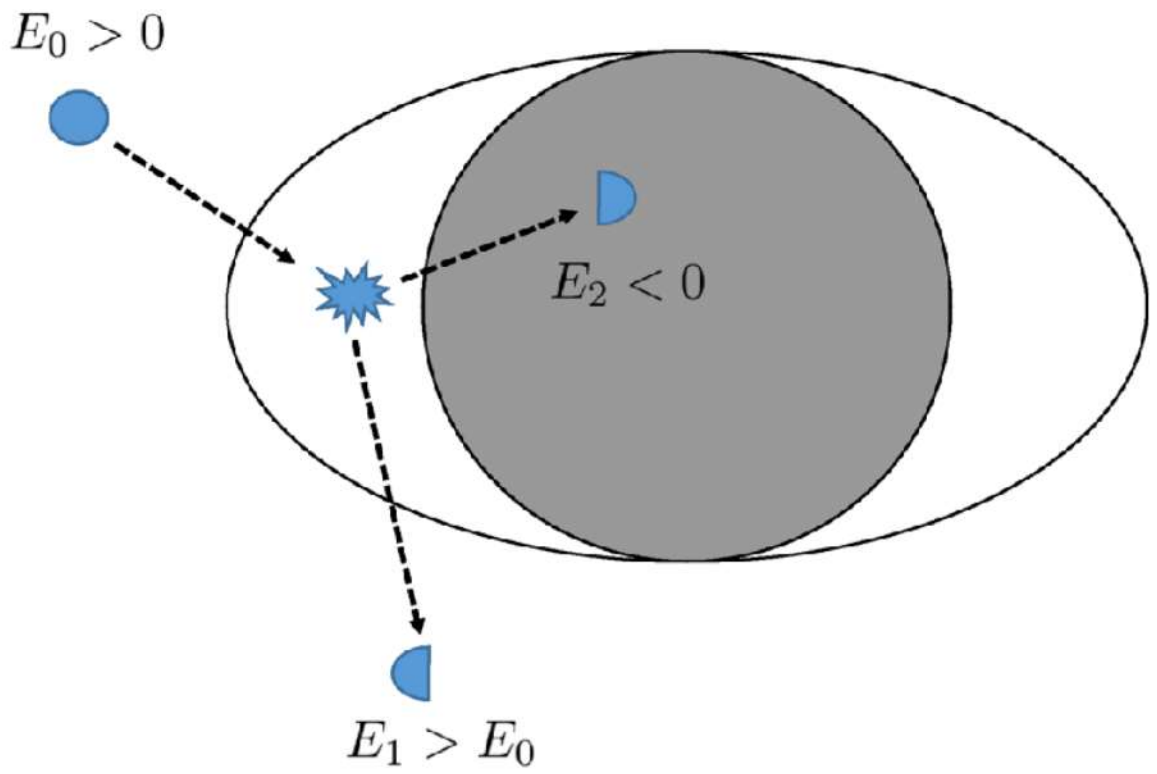


Spinning BH: Kerr Solution (1963)



Energy Extraction from BH

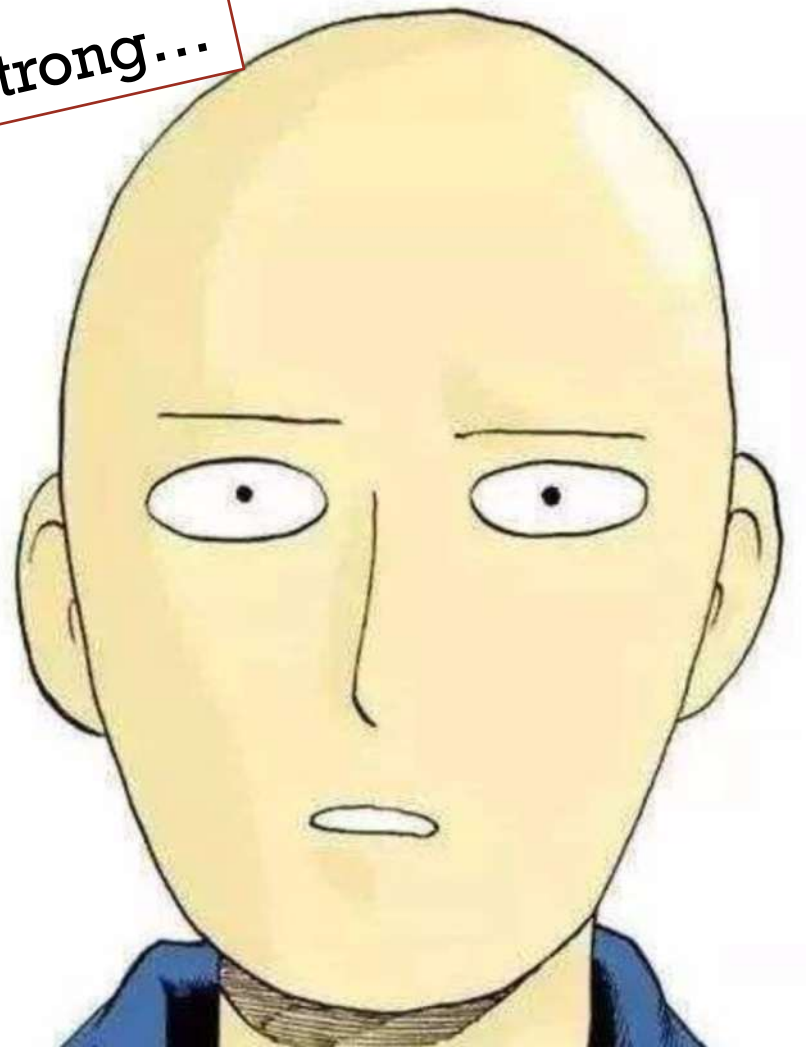
Penrose process (1971)



BH superradiance (1972): Radiation-enhancement mechanism $R > I$

BH No-Hair Theorem

Baldness
makes me strong…



An isolated BH is always described by

- Mass
- Charge (if exists)
- Angular momentum

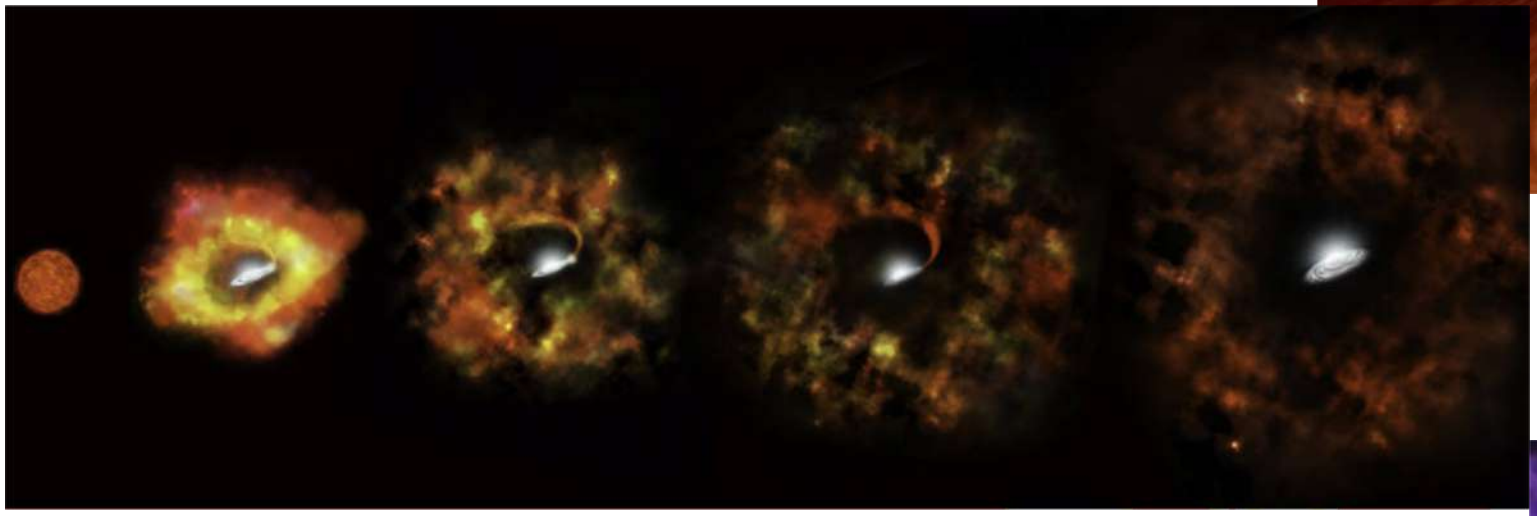
no matter how it is formed

Black holes are extremely simple objects in our universe

HOW DO WE KNOW THEY EXIST?

Three Types of BHs

Supermassive BH (millions to billions of solar mass)



Stellar size BH (several to tens of solar mass)

Primordial BH (induced around Big Bang, still hypothetical)

BHs Cannot Be Directly Observed via EM

- We can
  - feel them (star motions around BH, Keck, VLTI, GRAVITY)
  - hear them (gravitational waves, LIGO/Virgo, KAGRA)
  - see them (BH images, EHT, ngEHT)

- They all use interferometer techniques

BHs Cannot Be Directly Observed via EM

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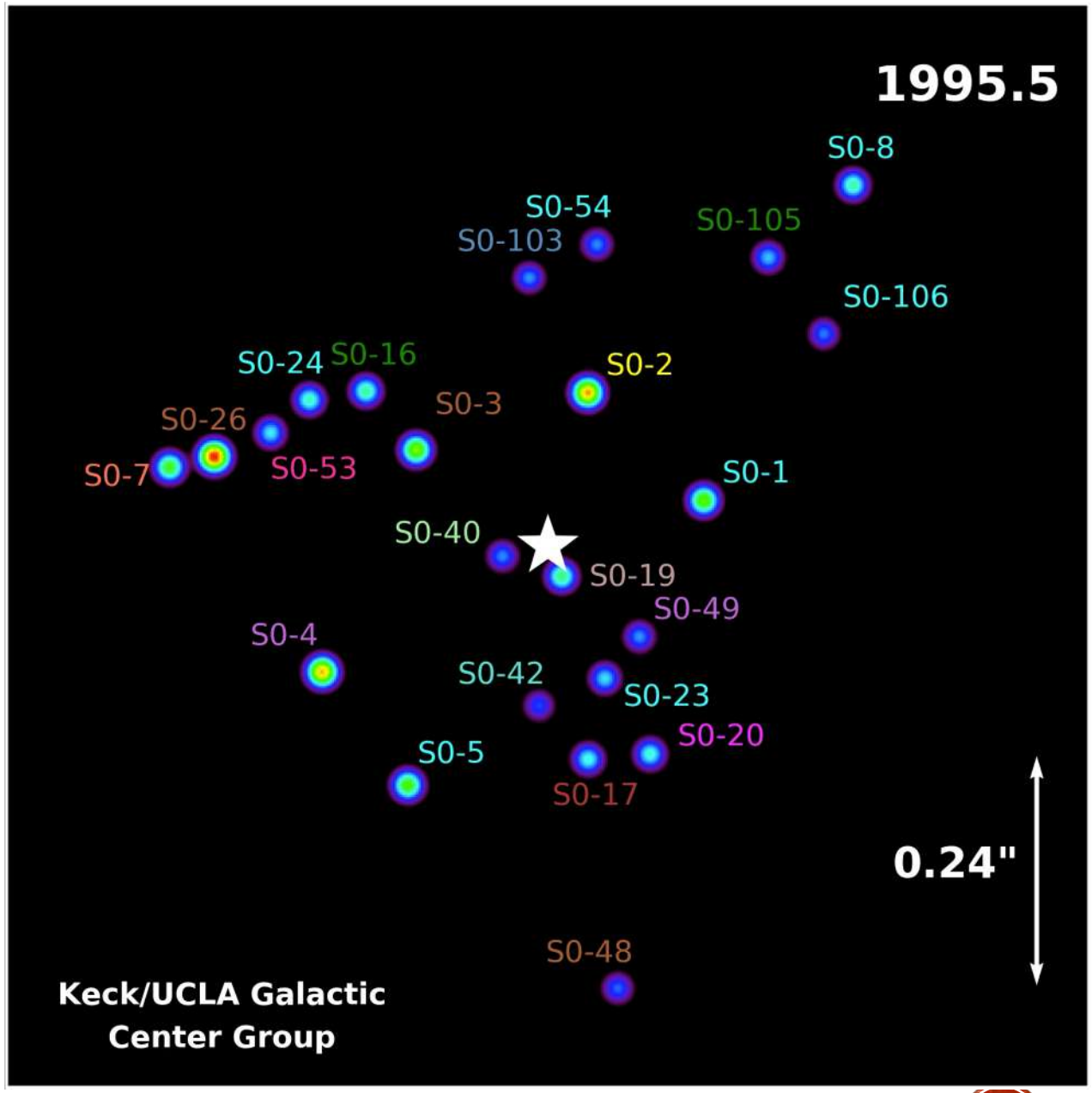
Nobel prize winning works

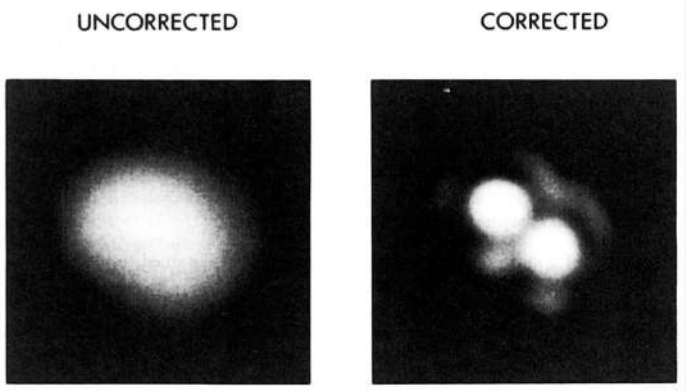
We Can Feel Them

- The motion of stars (S2) around Sgr A*
  - More than 20-year observations
  - S2 star has period ~ 16y
  - Andrea Ghez – KecK/UCLA
  - Reinhard Genzel (MPE) – VLTI



Precision Defines the Prize

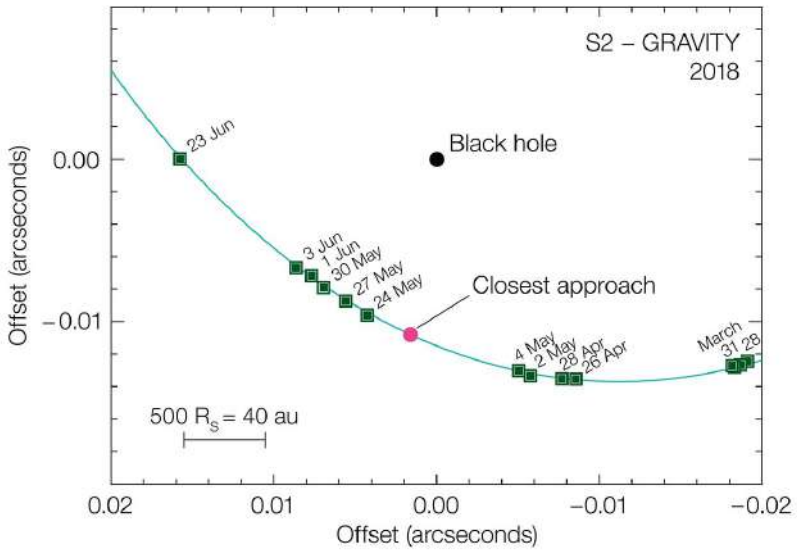
- Interferometer
  - Fixing the wavelength, we need large telescopes $\theta = \lambda/D$
  - Combining an array of telescopes, we can increase the effective diameter of telescopes
  - Adaptive Optics (AO): Using deformable mirrors and a guide star to compensate for atmospheric turbulences

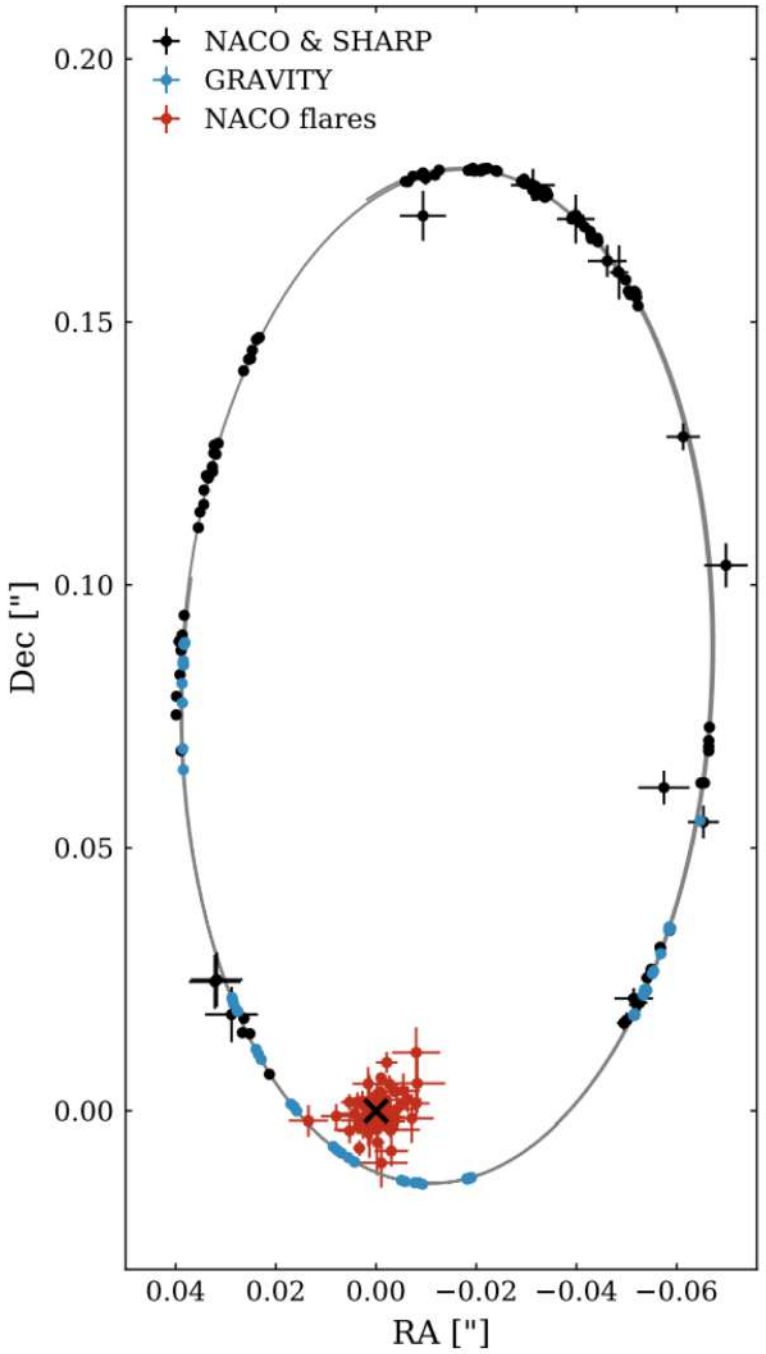


GR Precession Detection

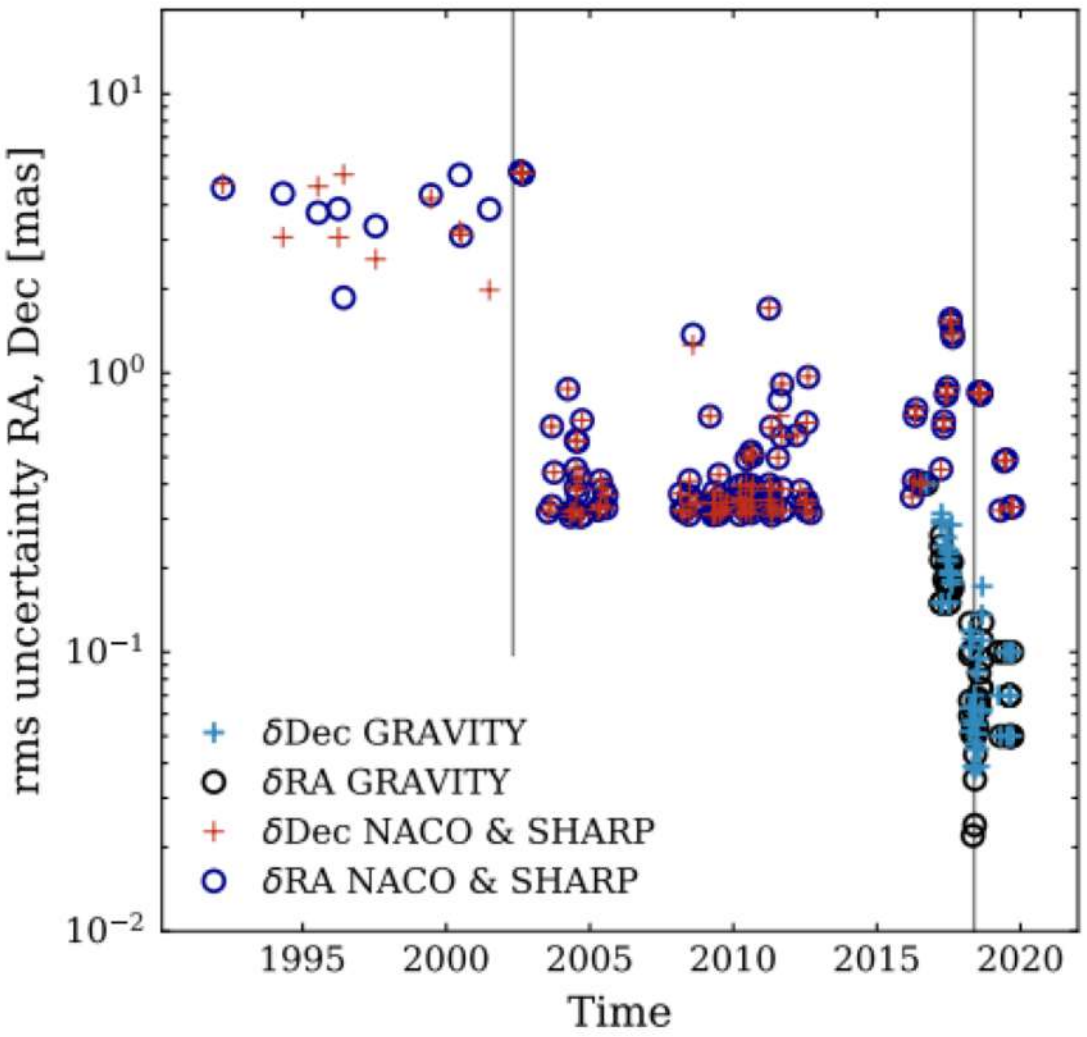
- GRAVITY (2018)
  - An improved VLTI, measure the position, velocity (3% light speed), redshift at the closest point very accurately
  - Trajectory well described by GR
- Mass & Distance

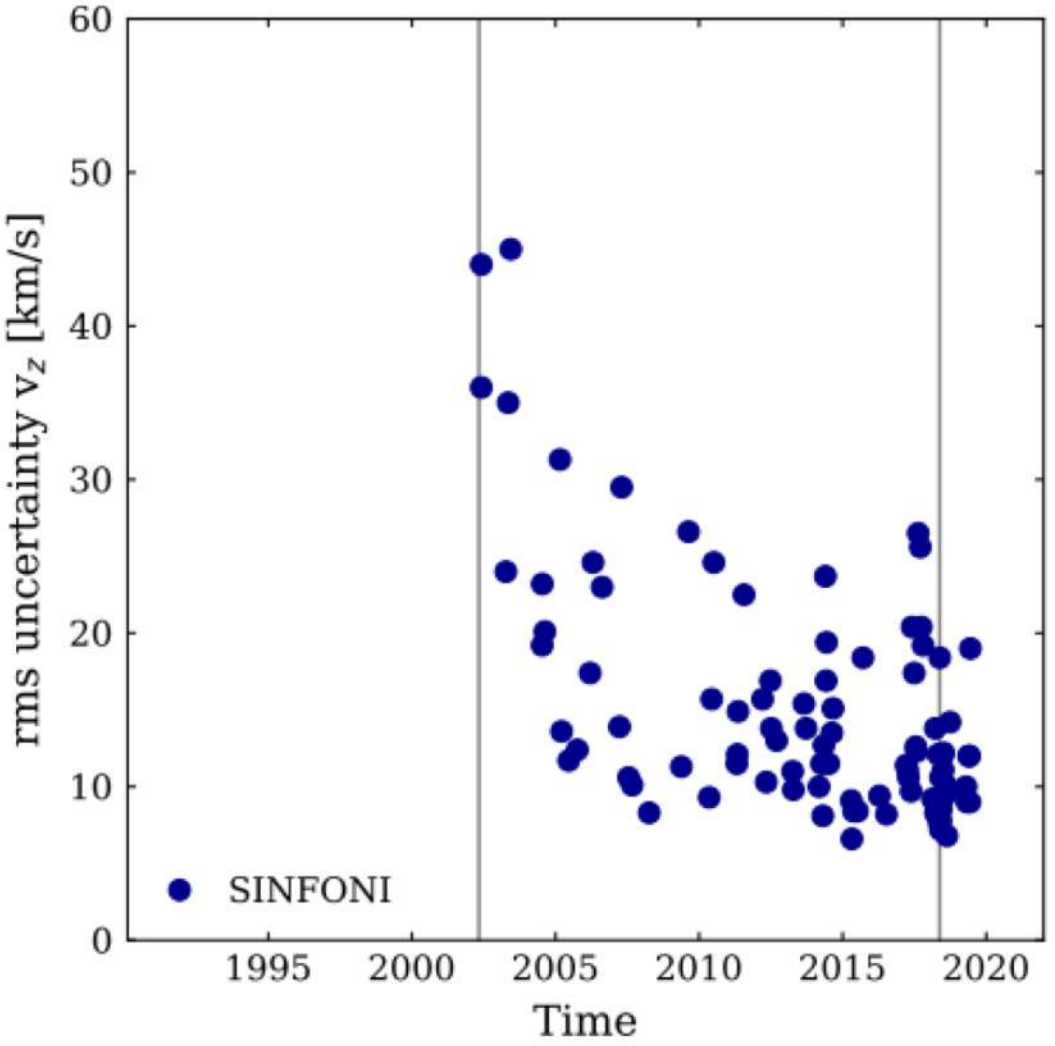
(important to EHT images)





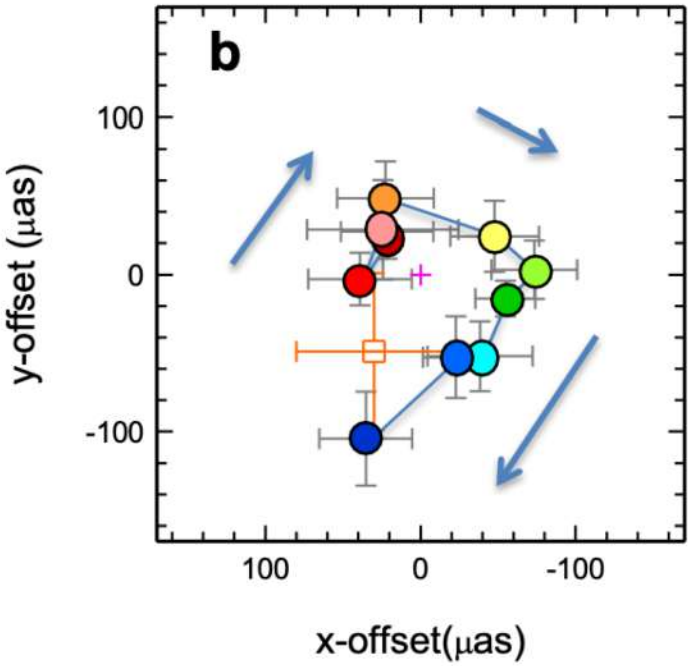
Precision Defines the Prize

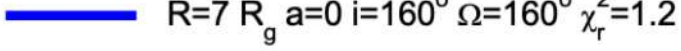


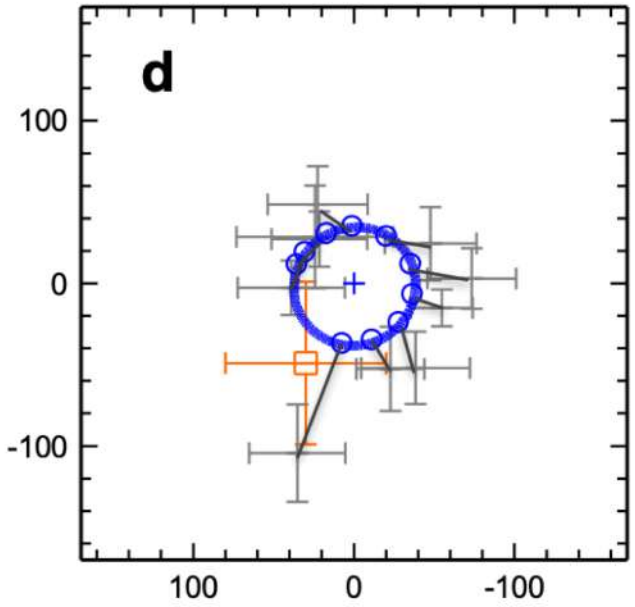


Hotspot Detection Near ISCO

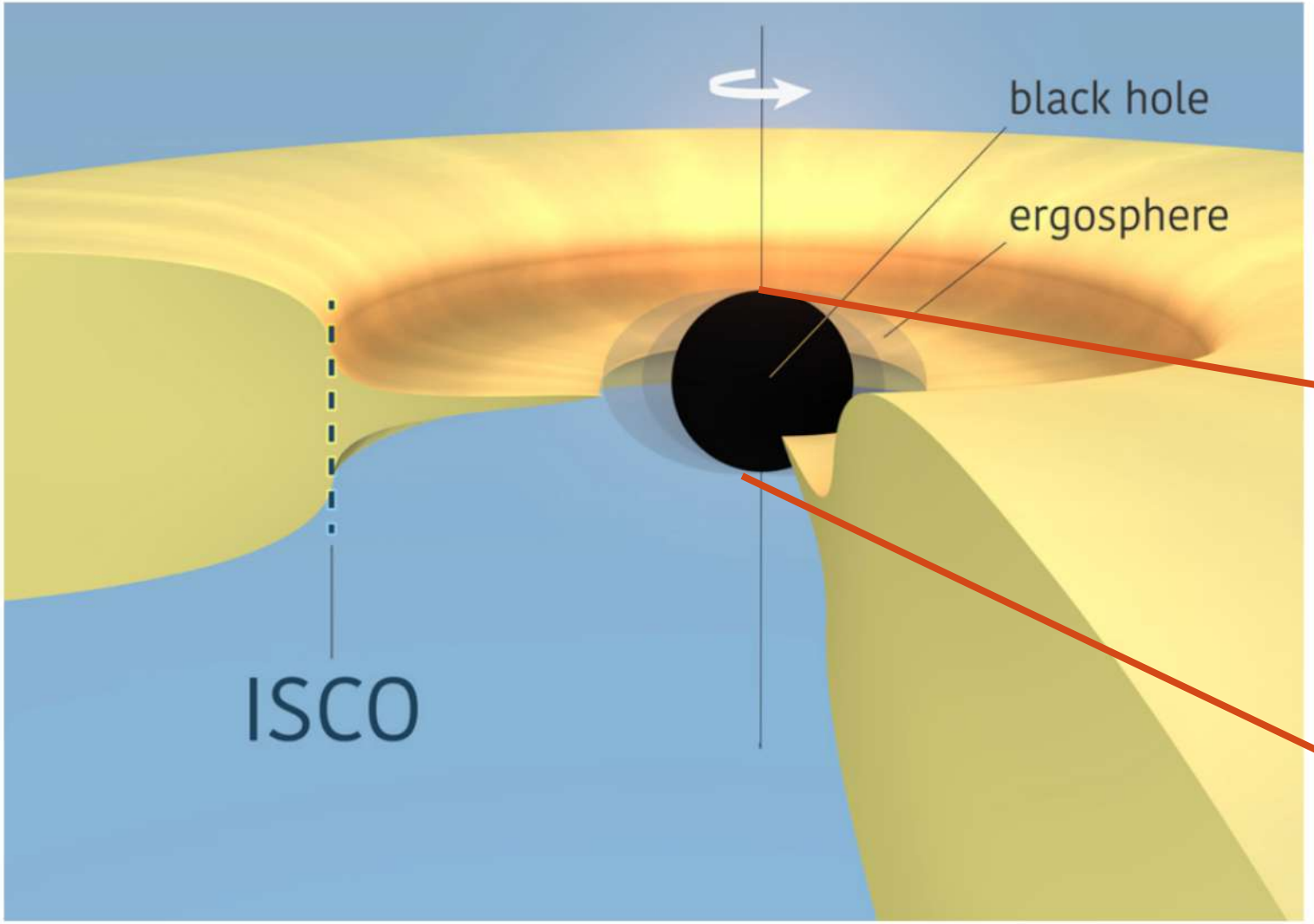
- GRAVITY (2018)
  - Flares detection at July 22, 28, May 27, 2018, lasted for 30-90 min
  - 30% light speed!!!
- Consistent with a circular, near face-on orbit with R~6-10 R_g (just outside the ISCO)
- ISCO: Innermost Stable Circular Orbit
- Commonly regarded as the inner edge of accretion disks







ISCO



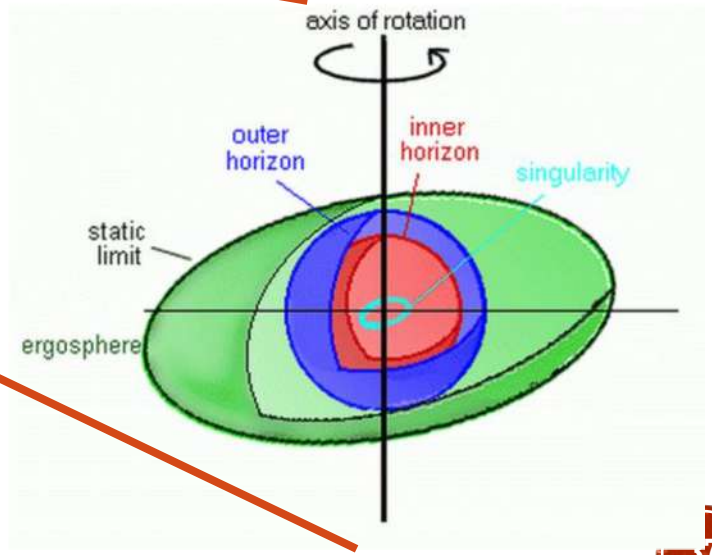
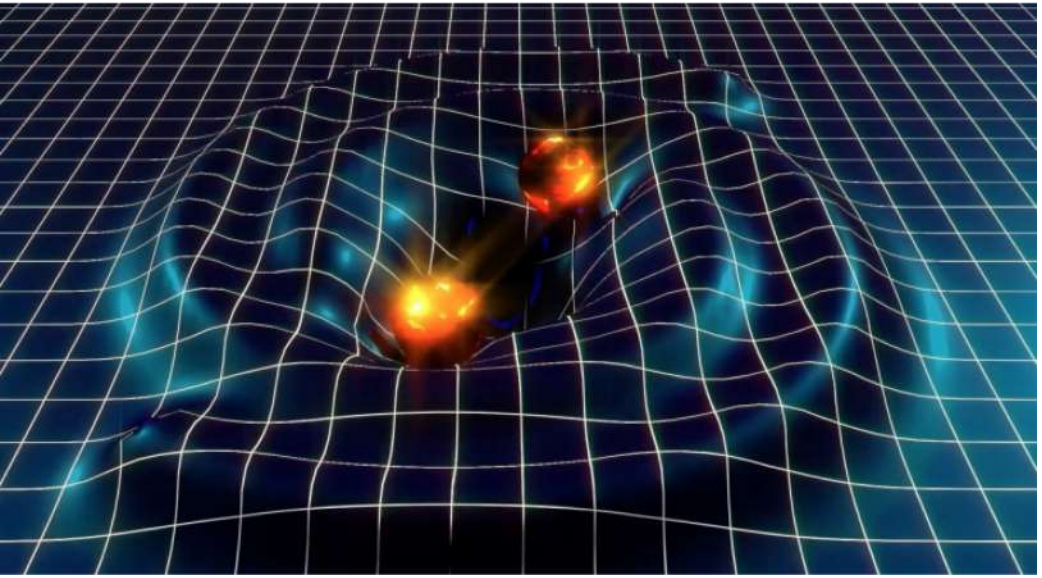
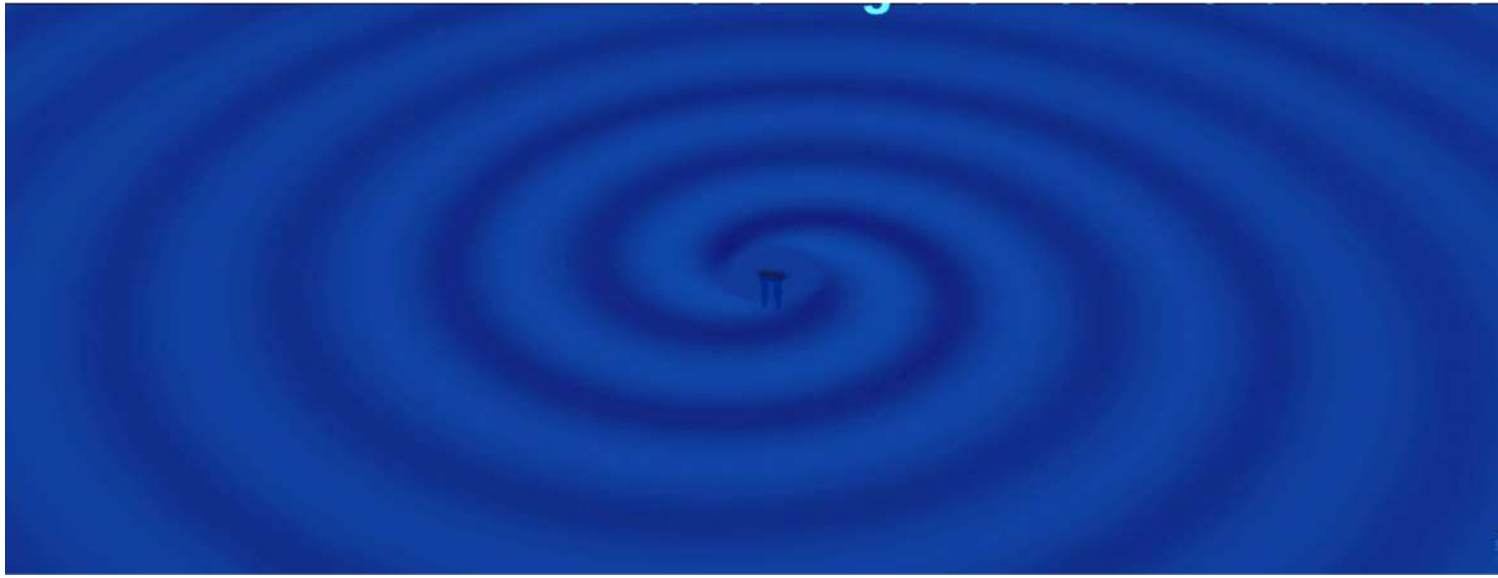


Figure courtesy of Amanda Smith (Institute of Astronomy, Cambridge).

We Can Hear Them

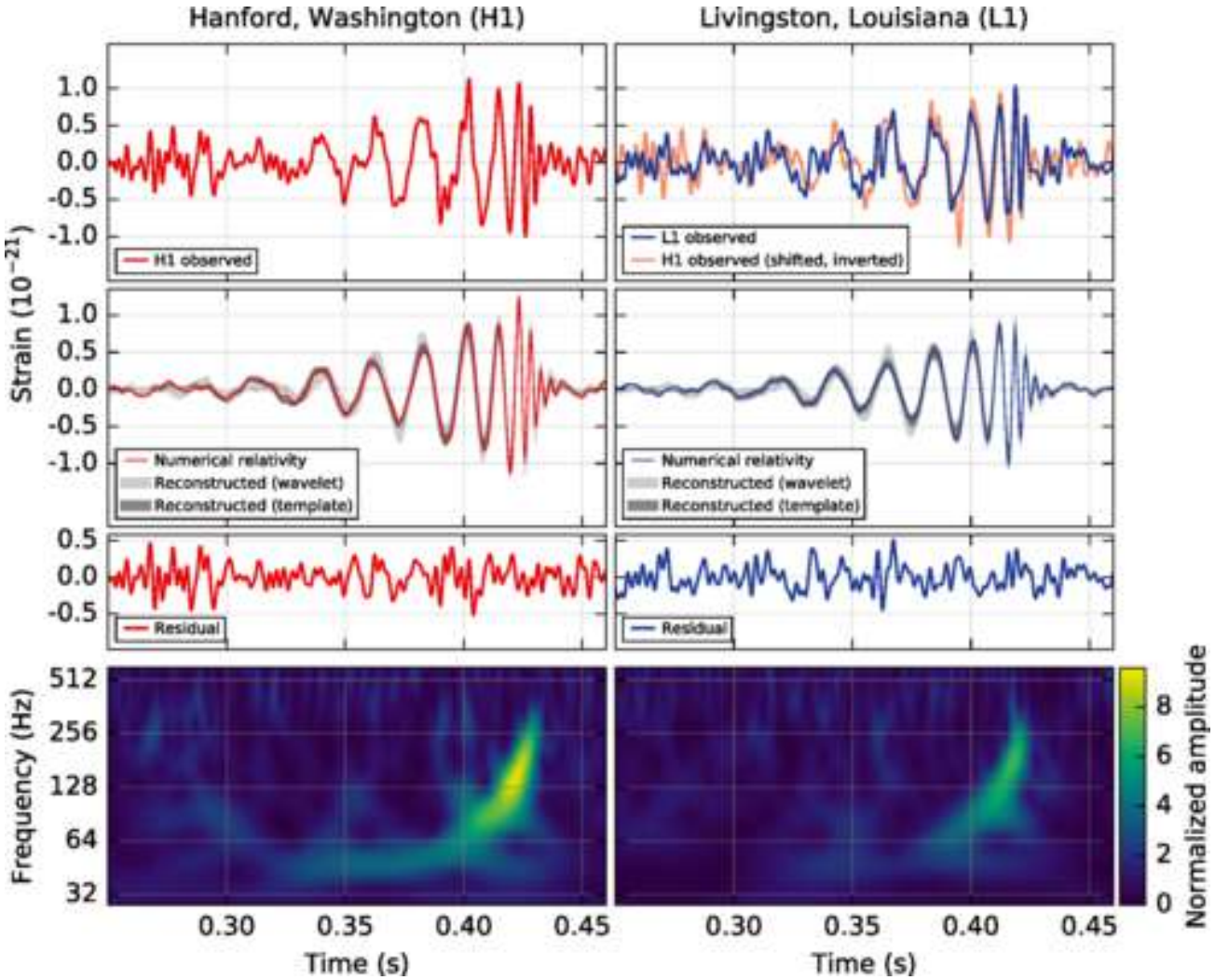
- Gravitational waves
  - Spacetime distortion propagates outwards at the speed of light
  - A new "type" of telescope other than EM
  - Two most likely targets: Supernova explosion, binary merger events



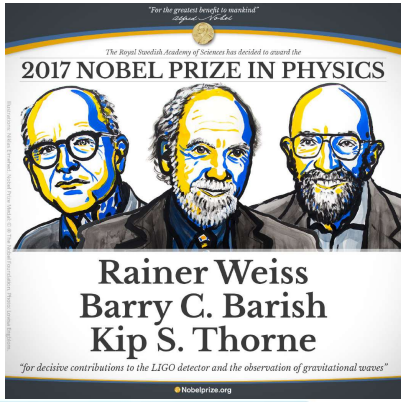


First Detection: Binary BH Merger

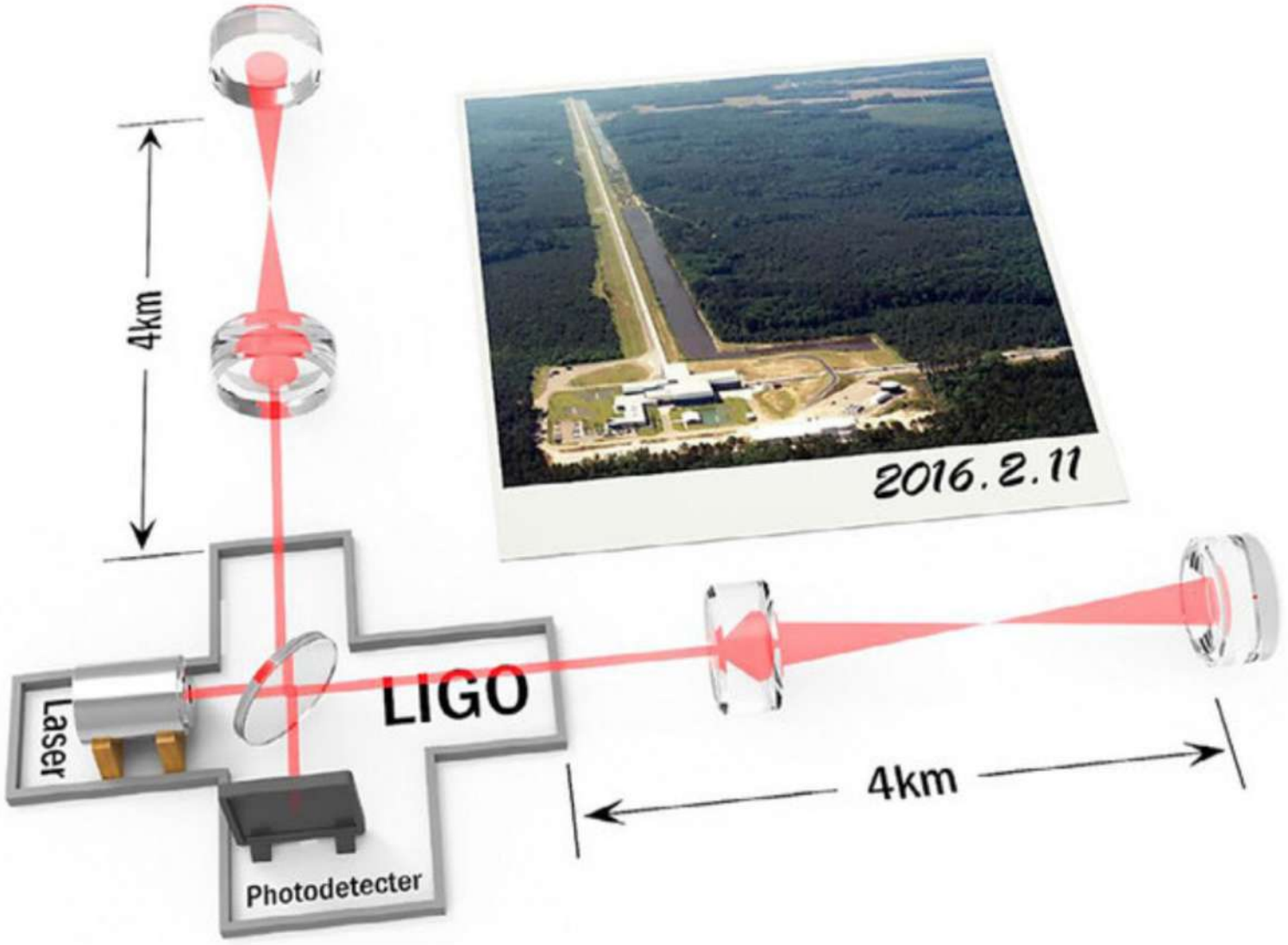
GW150914



The Laser Interferometer Gravitational-Wave Observatory (LIGO)



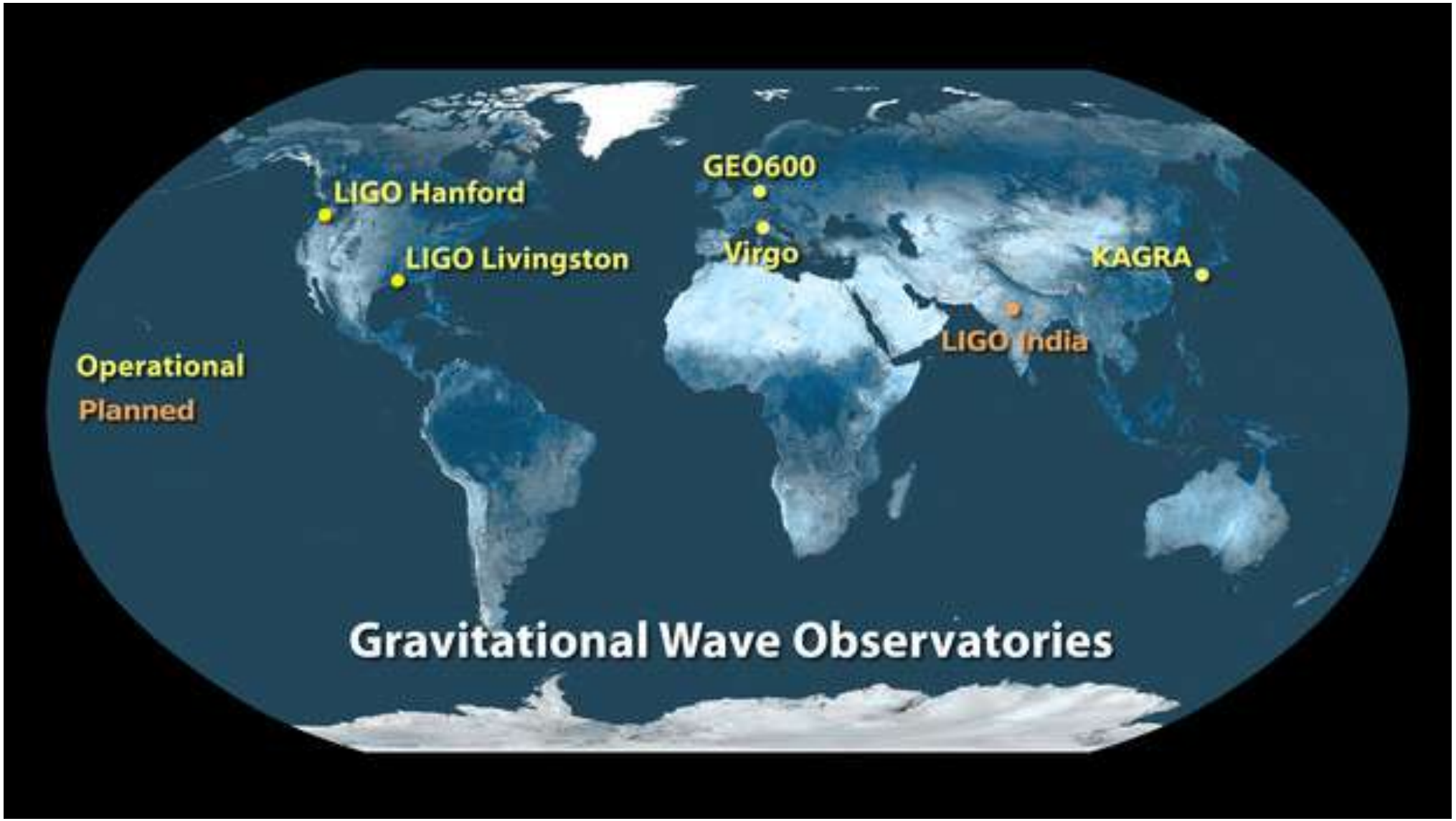
Interferometer "Again"

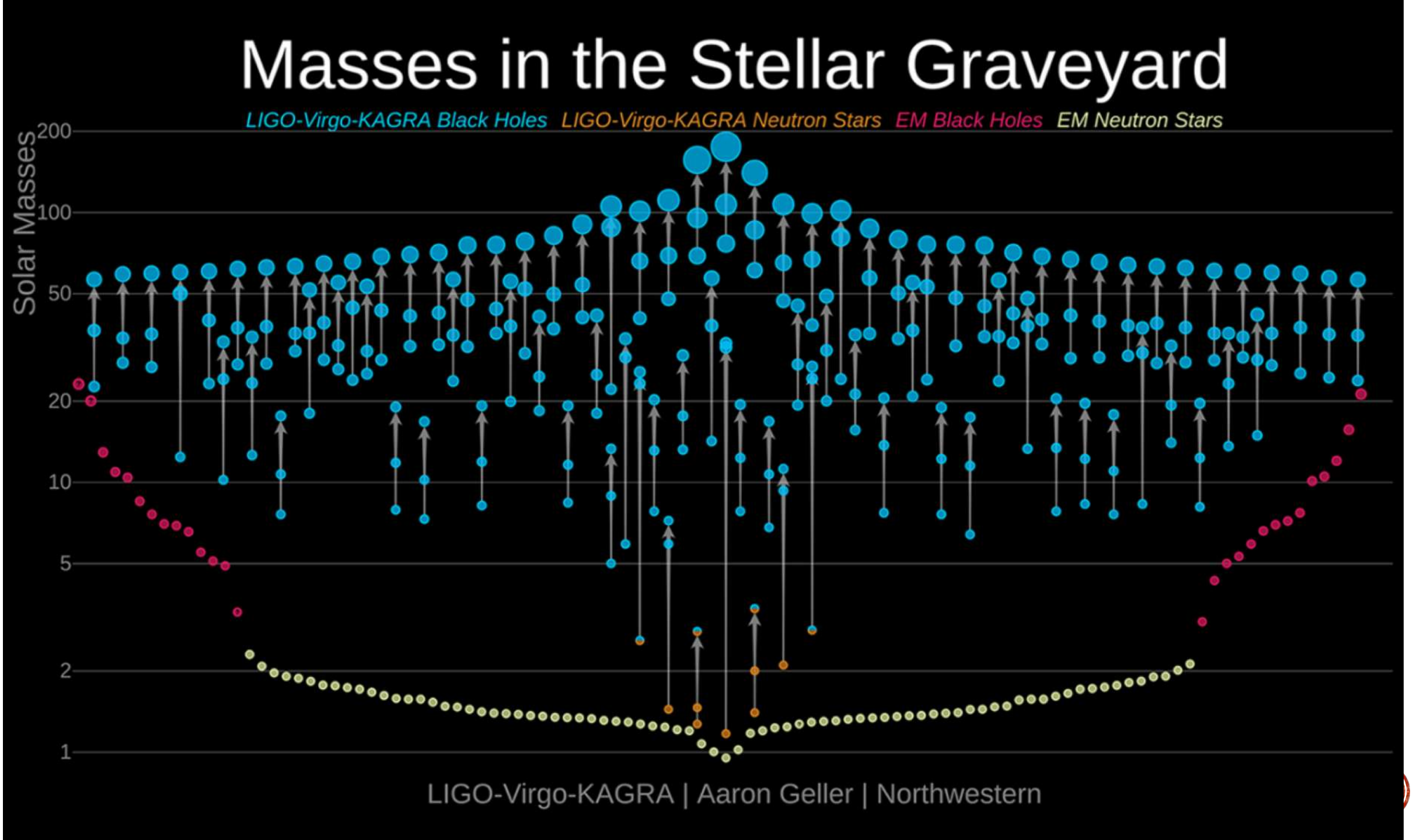


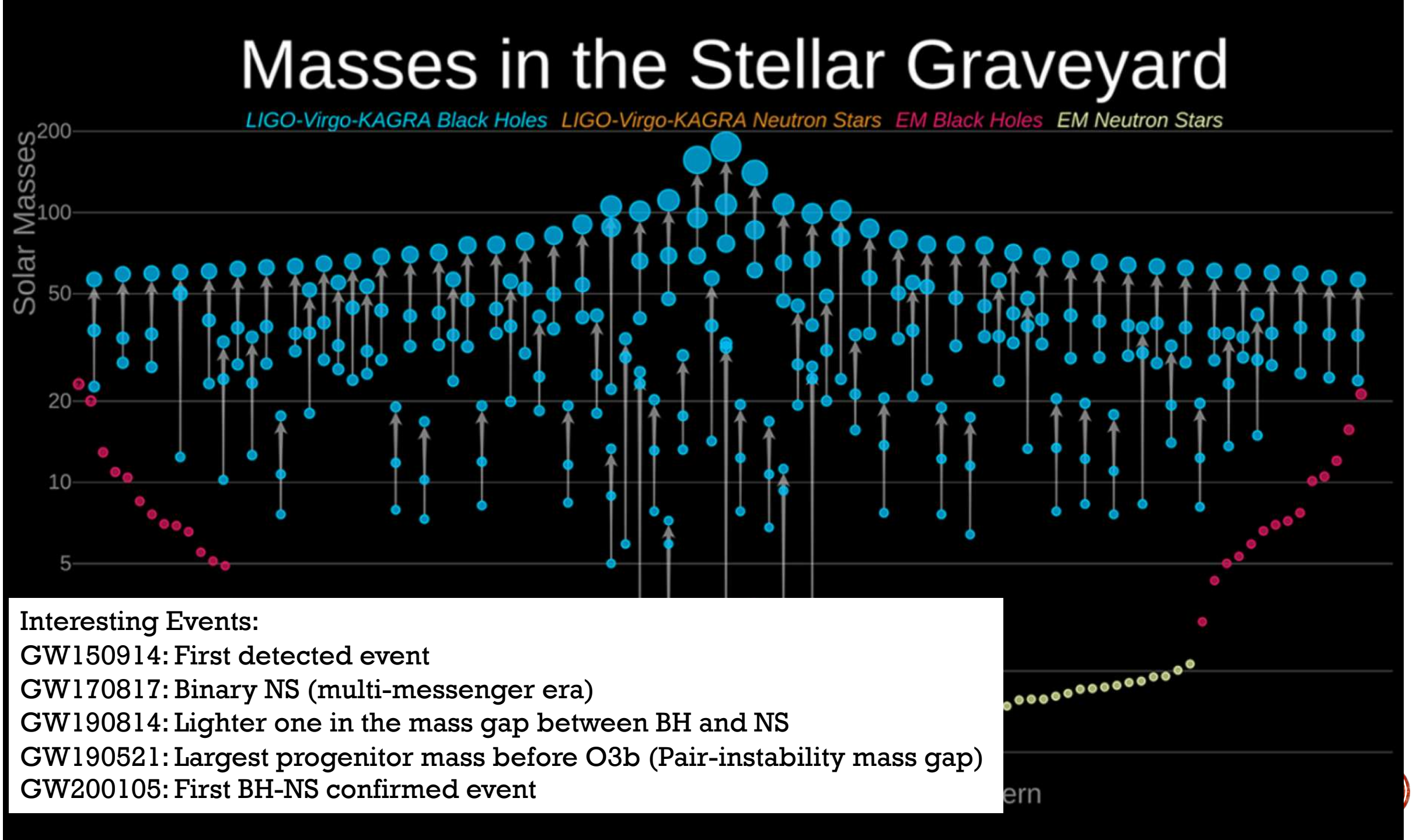
GW strain h: 10^{-21}

Width of hairs in a few light years

Gravitational Wave Network




Masses in the Stellar Graveyard
LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
EM Black Holes
EM Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern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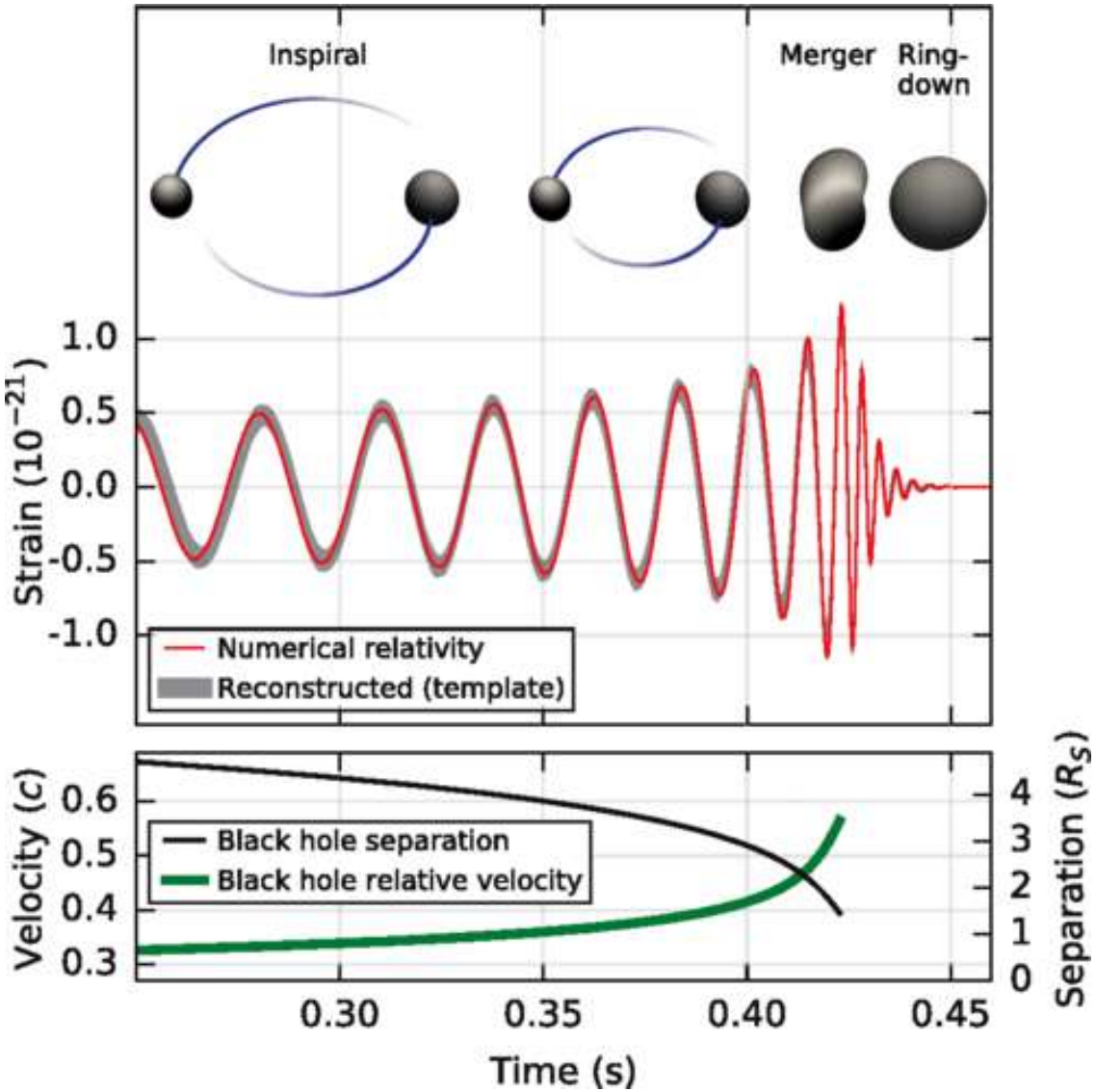
EM Neutron Stars
Solar Masses
200
100
50
20
10
5
Interesting Events:
GW150914: First detected event
GW170817: Binary NS (multi-messenger era)
GW190814: Lighter one in the mass gap between BH and NS
GW190521: Largest progenitor mass before O3b (Pair-instability mass gap)
GW200105: First BH-NS confirmed event

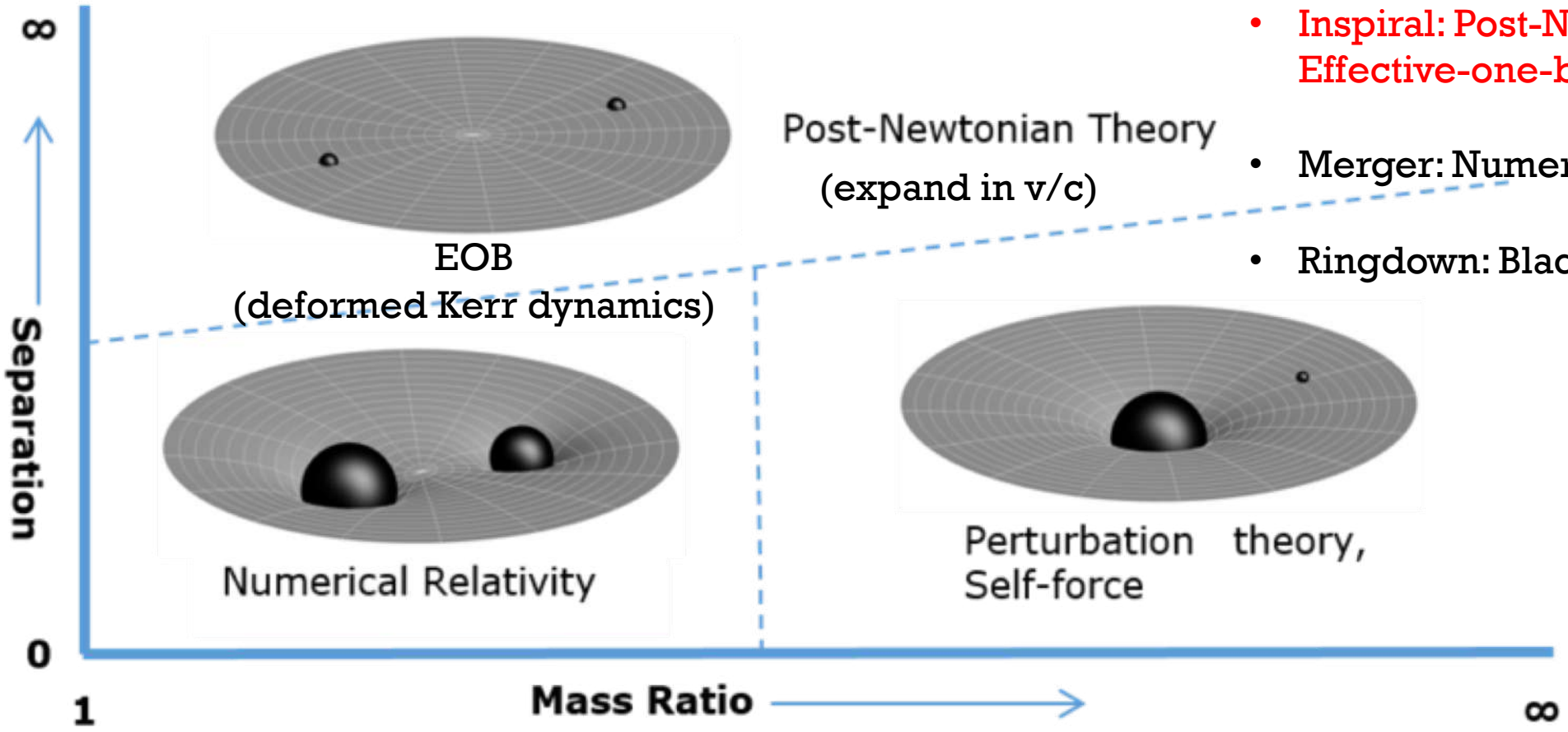
Three Stages in a Merger



Waveform modeling is important!!!

- Inspiral: Post-Newtonian expansion, Effective-one-body formalism (EOB)
- Merger: Numerical Relativity
- Ringdown: Black hole perturbations

Waveform Modelings: Insprial



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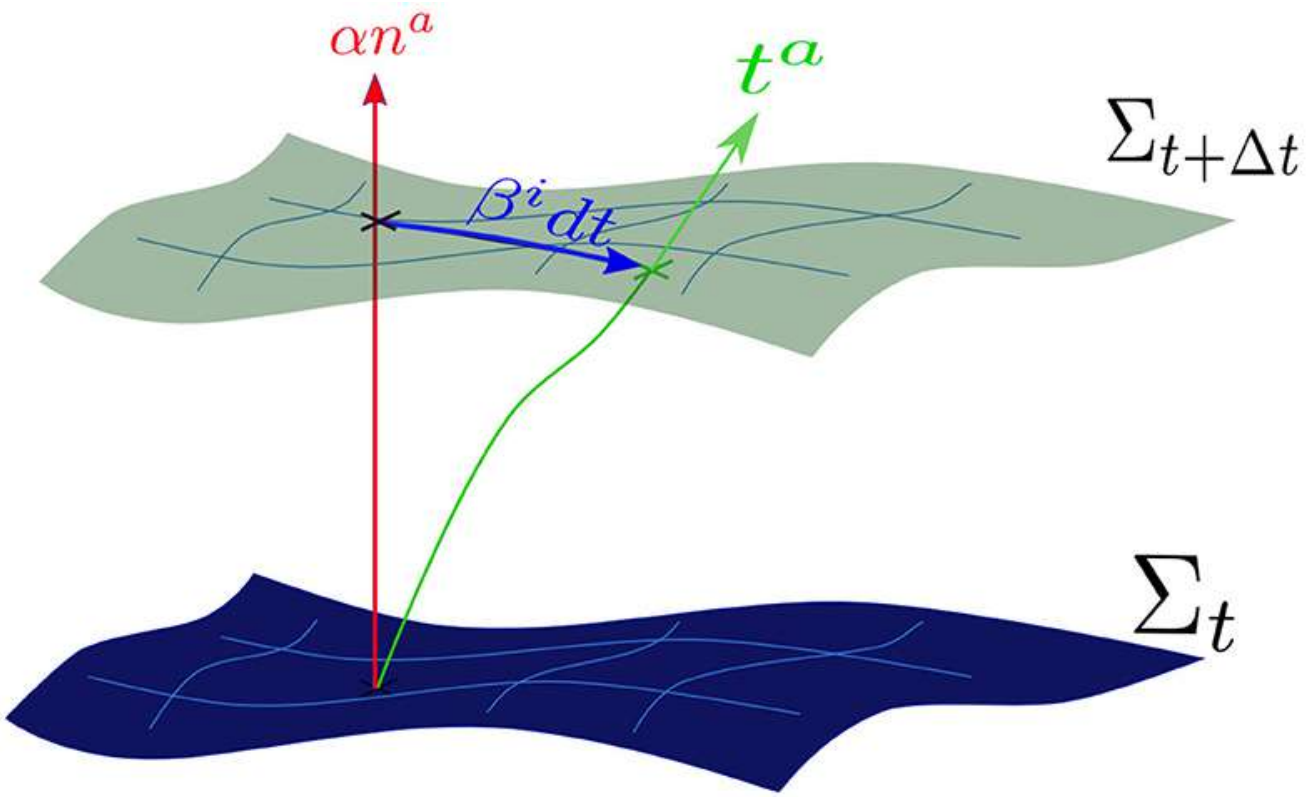
Waveform Modelings: Merger



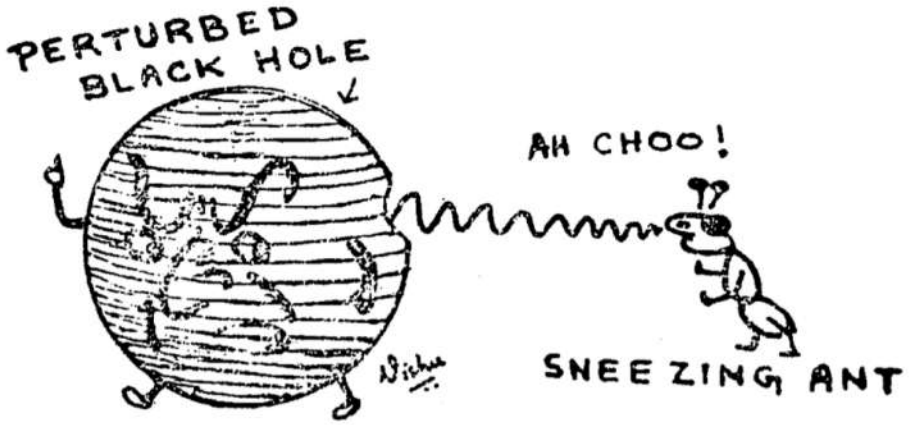
- 3+1 decomposition
- Put the initial data into Einstein's eq.
- Ask supercomputers

Waveform modeling is important!!!

- Inspiral: Post-Newtonian expansion, Effective-one-body formalism (EOB)
- Merger: Numerical Relativity
- Ringdown: Black hole perturbations

Waveform Modelings: Ringdown

$$\delta G_{\mu\nu} = \delta T_{\mu\nu}$$



Waveform modeling is important!!!

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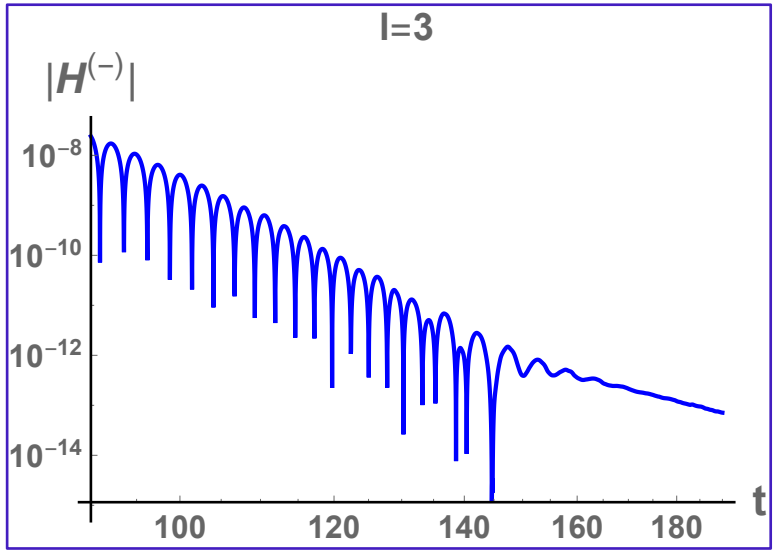


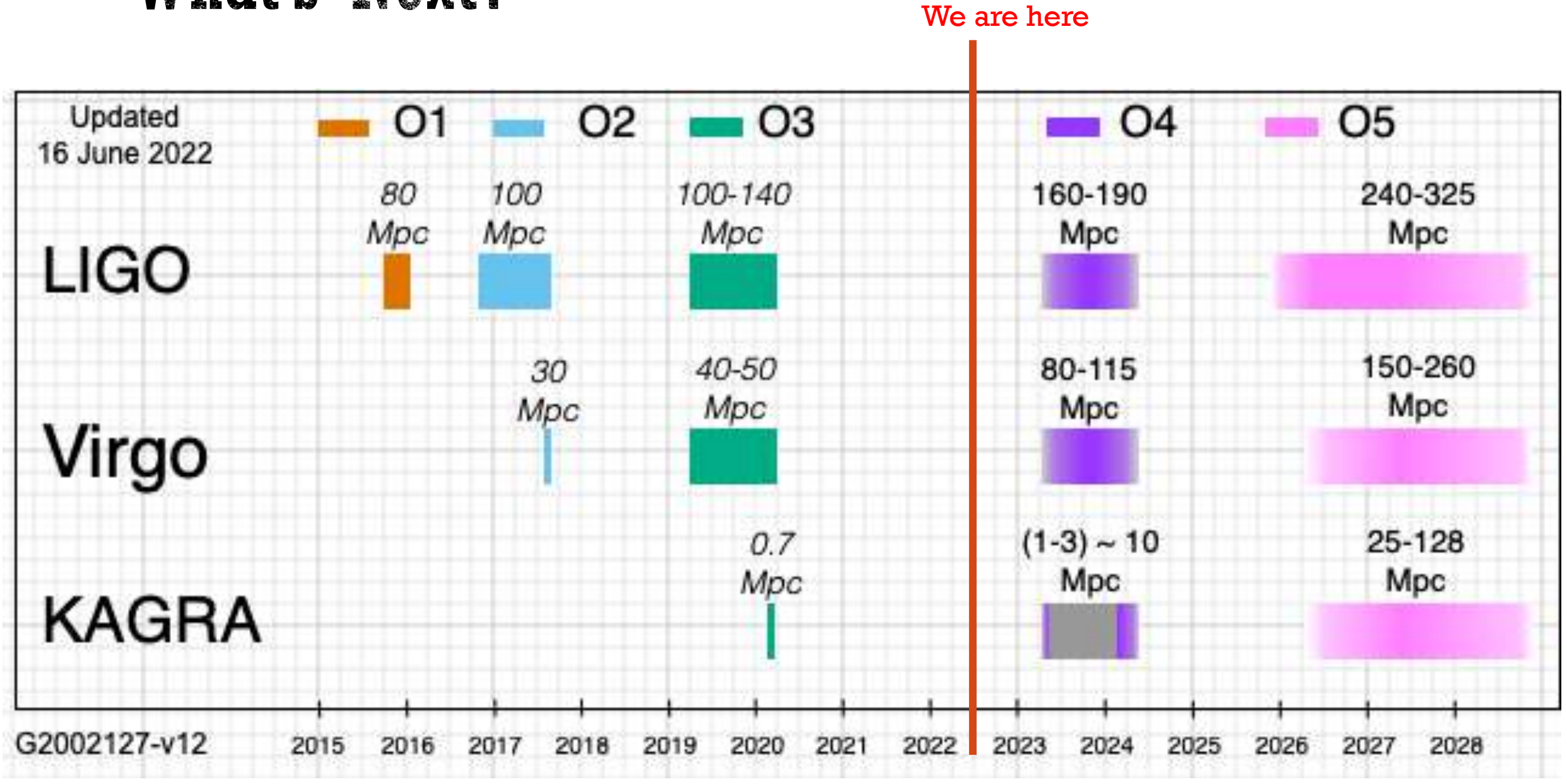
Quasi-normal modes (QNMs):

- Exponential sinusoidal ω_R, ω_I
- Spectrum satisfies no-hair theorem
- Testing GR

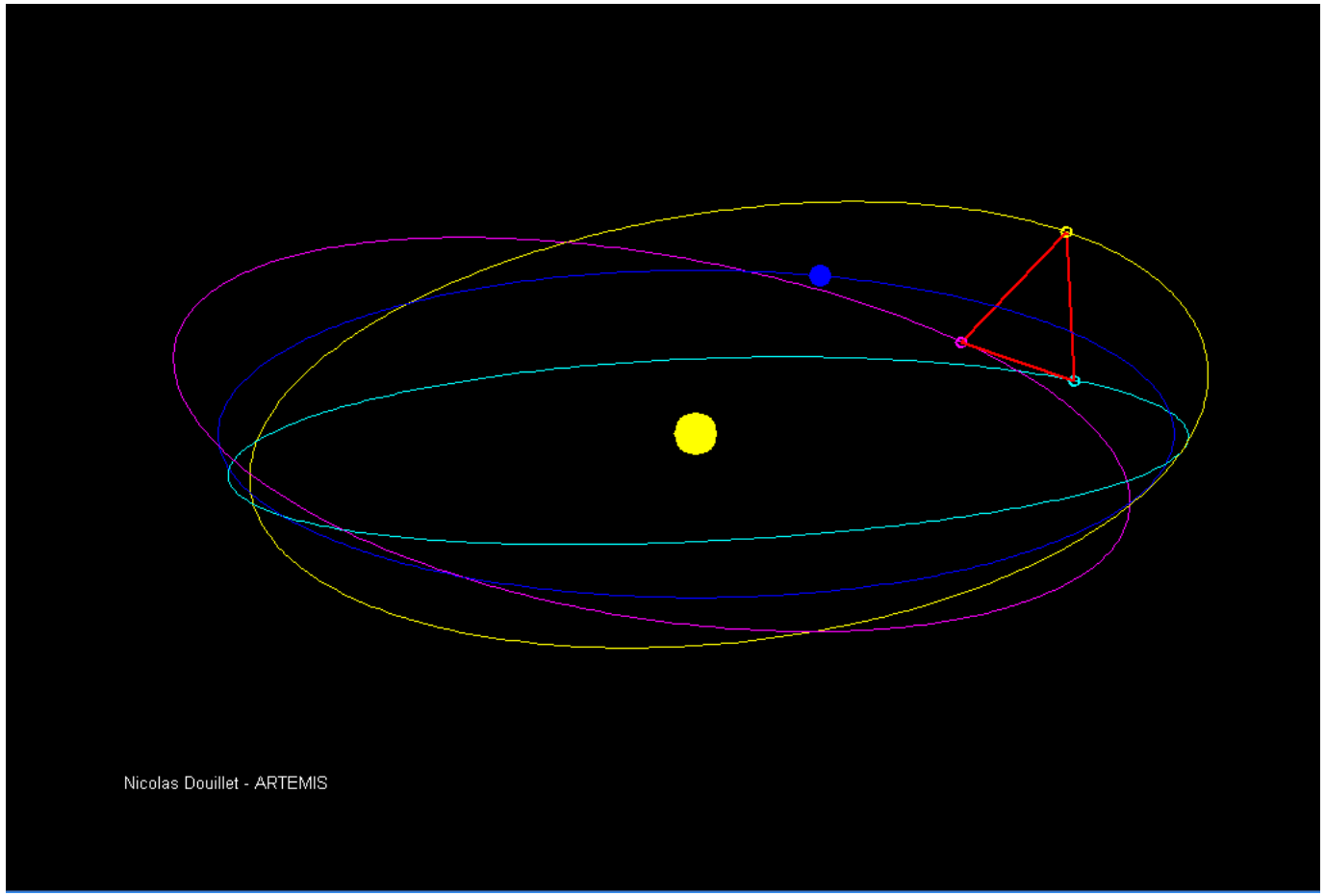
$$f = \omega_R/2\pi = 1.207 \left(\frac{10\ M_\odot}{M}\right) \text{kHz}$$

$$\tau = 1/|\omega_I| = 0.5537 \left(\frac{M}{10\ M_\odot}\right) \text{ms}$$

What's Next?


We are here
Updated
16 June 2022
O1
O2
O3
O4
O5
LIGO
80 Mpc
100 Mpc
100-140 Mpc
160-190 Mpc
240-325 Mpc
Virgo
30 Mpc
40-50 Mpc
80-115 Mpc
150-260 Mpc
KAGRA
0.7 Mpc
(1-3) ~ 10 Mpc
25-128 Mpc
G2002127-v12
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028

Laser Interferometer Space Antenna

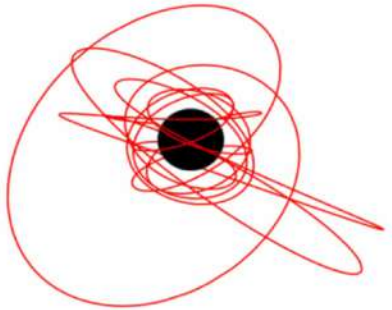


Space-based detector

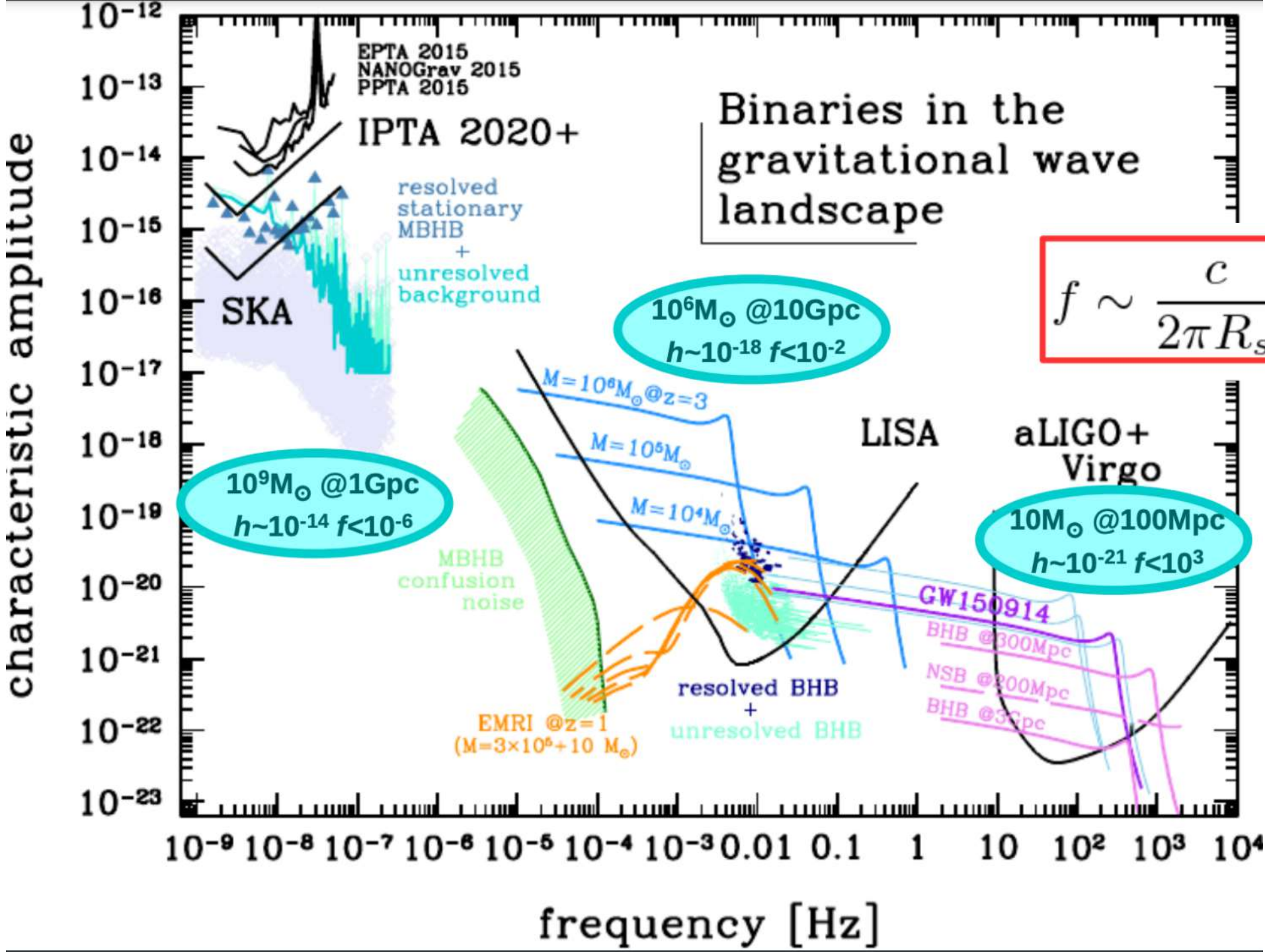
- Triangular shape with 2.5M km armlength
- mHz frequency band
- Expected launch 203X
- 4yr lifetime (10 yr goal)

$$f \sim \frac{c}{2\pi R_s} \sim 10^4 \mathrm{Hz} \frac{M_\odot}{M}$$

- Targets:
  - Massive Black Hole Binaries
  - Galactic Compact Binaries
  - Extreme-Mass-Ratio-Inspiral (EMRI)
  - Cosmic Standard Sirens

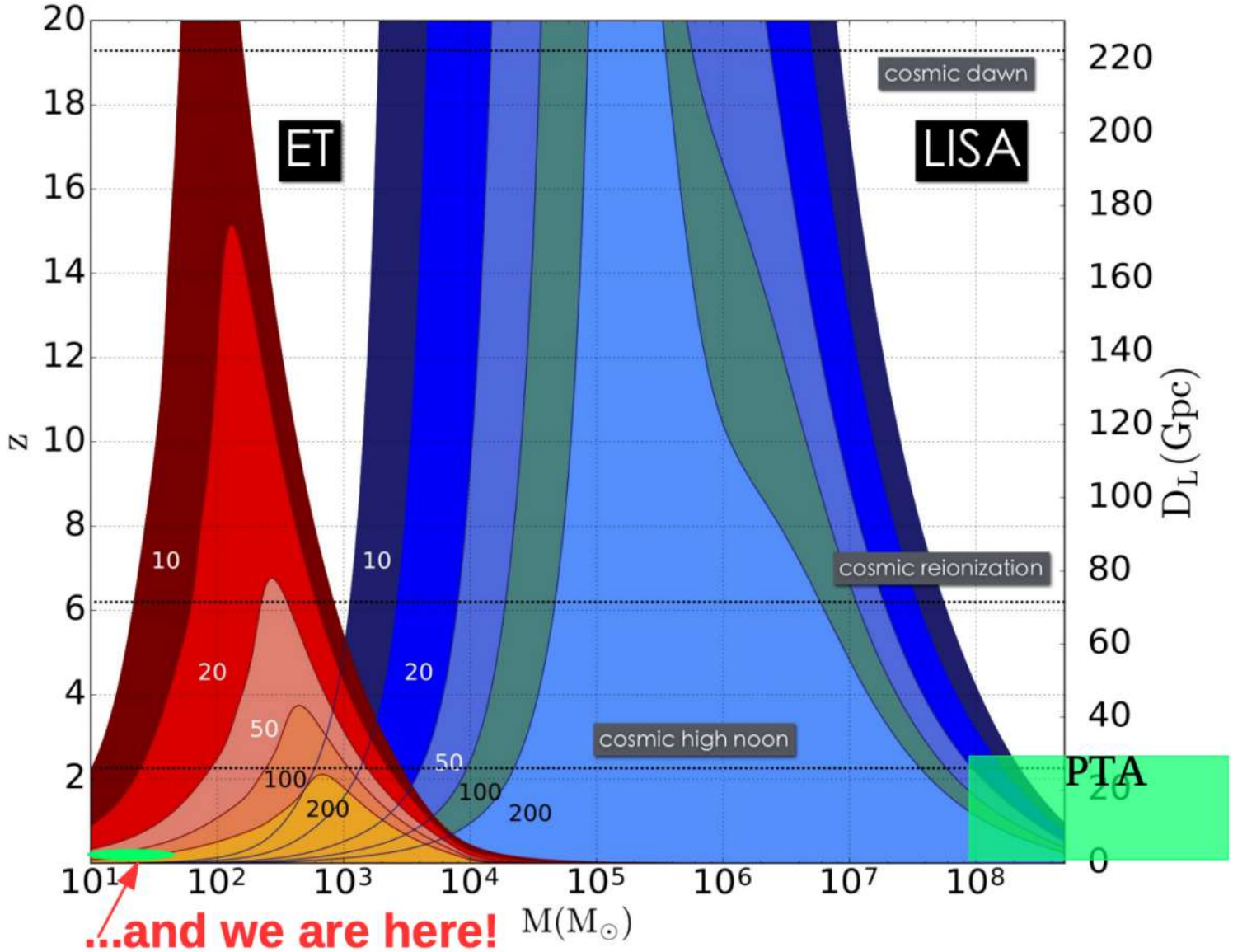


EMRI: 10^5 periods matched-filtering:
Accurate parameter extraction



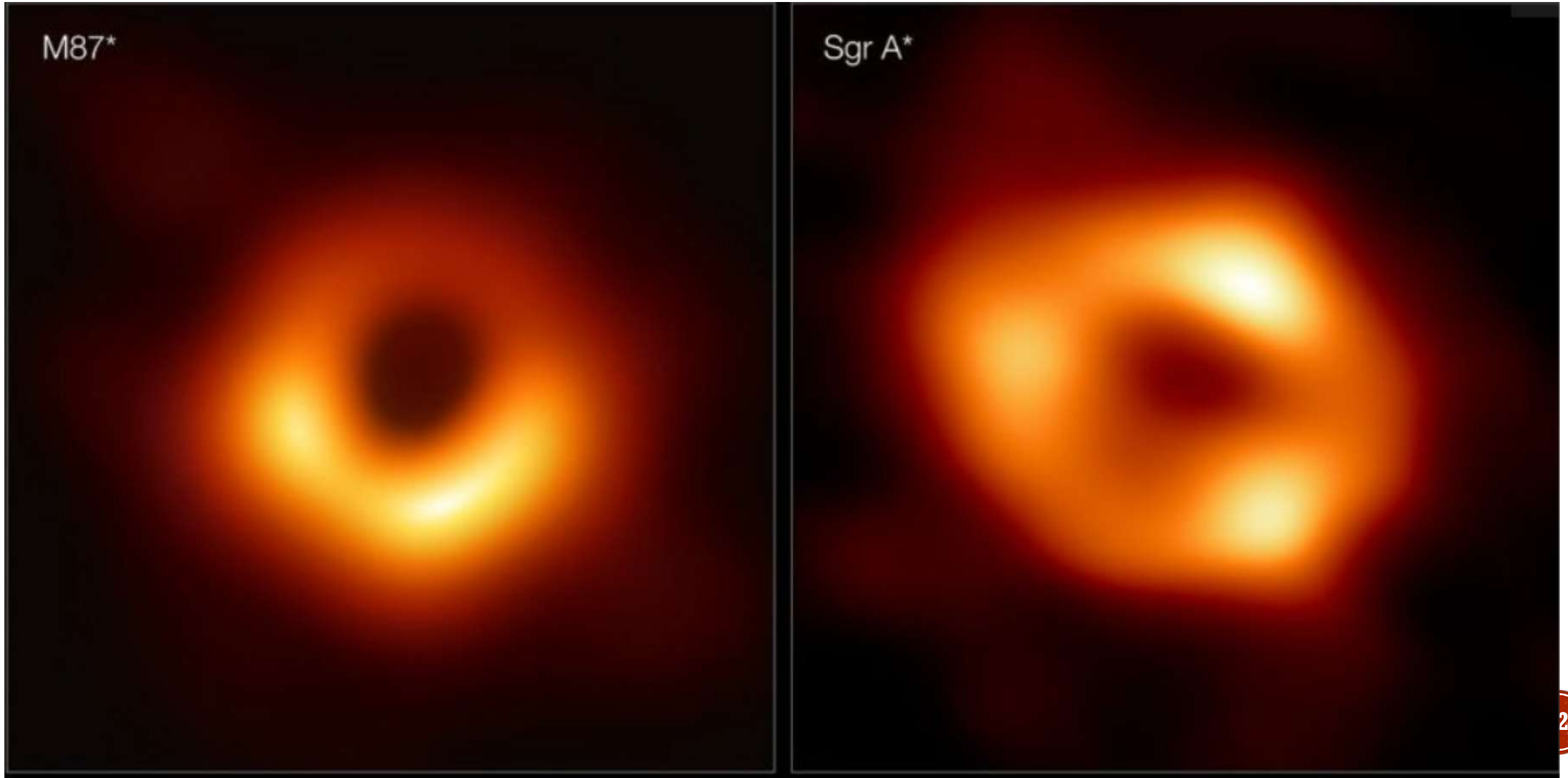
$$f \sim \frac{c}{2\pi R_s} \sim 10^4 \mathrm{Hz} \frac{M_\odot}{M}$$

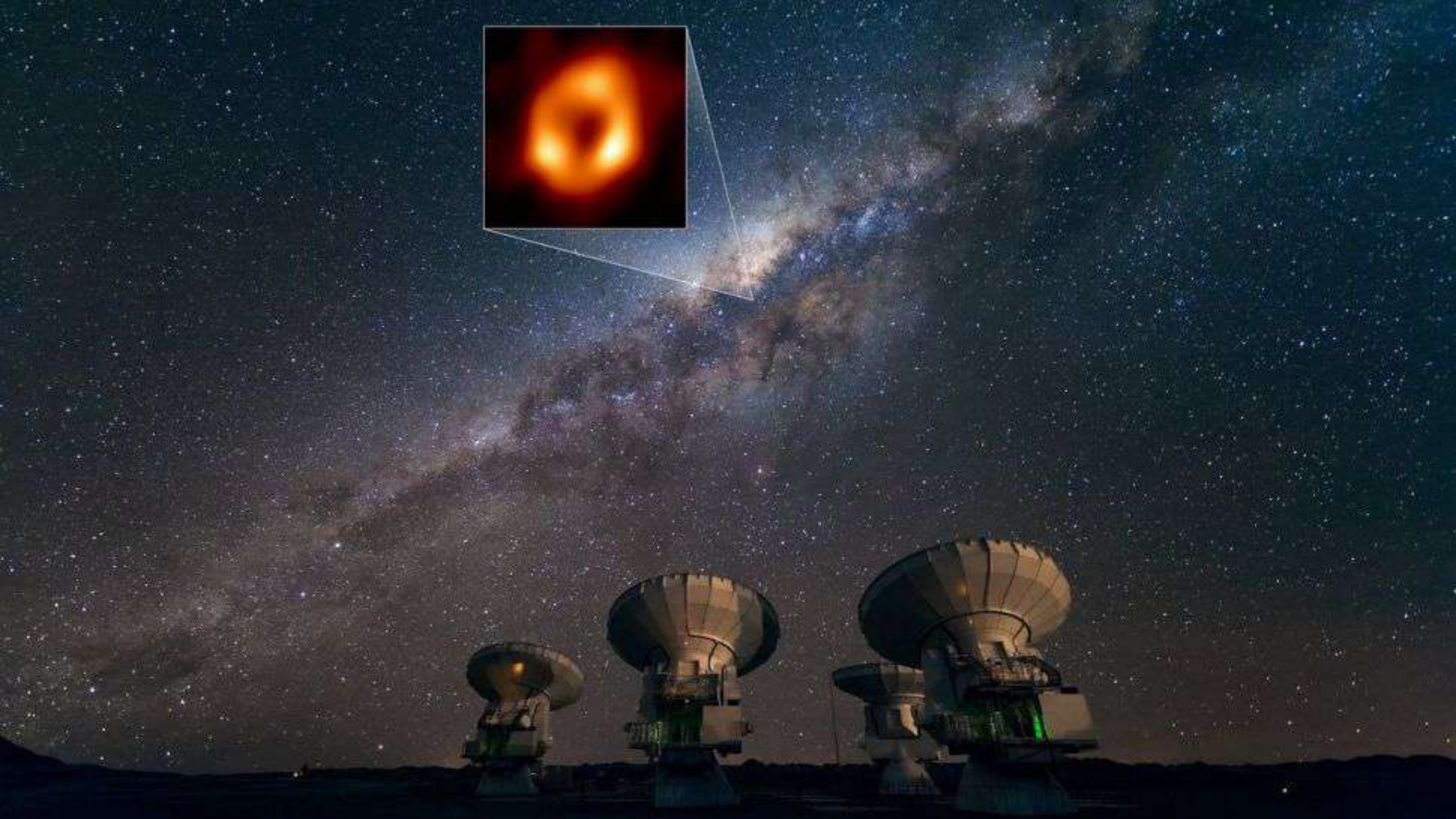
3G detectors (Einstein Telescope, Cosmic Explorer)



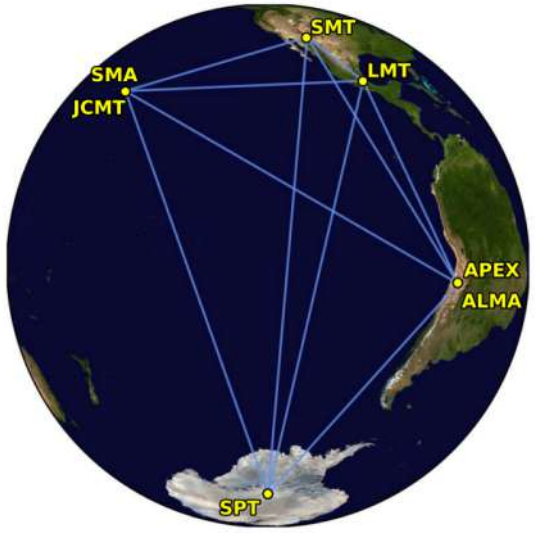
GW future is bright and exciting!

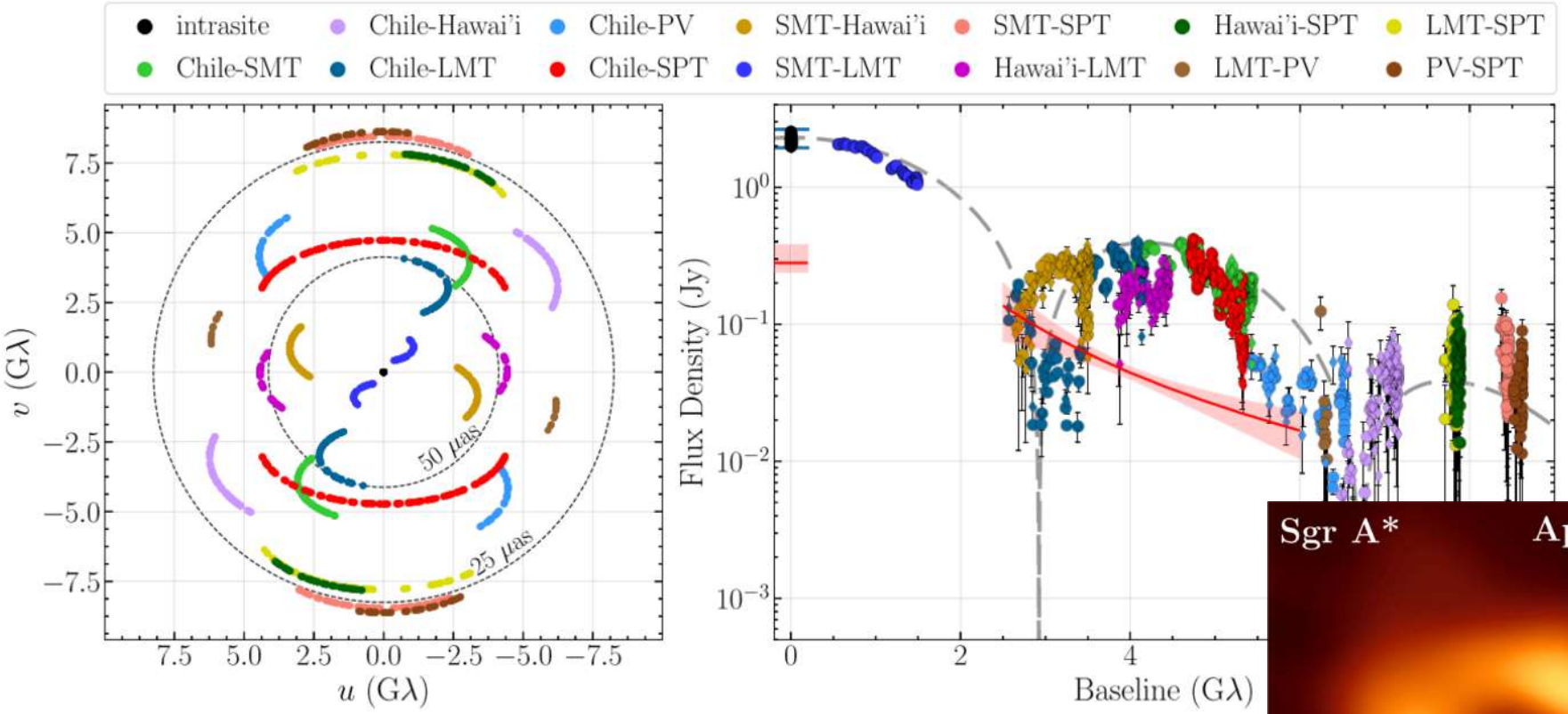
We Can See Them

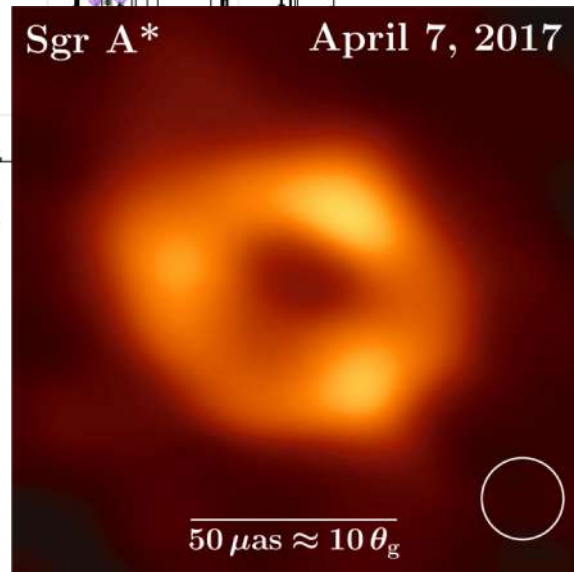




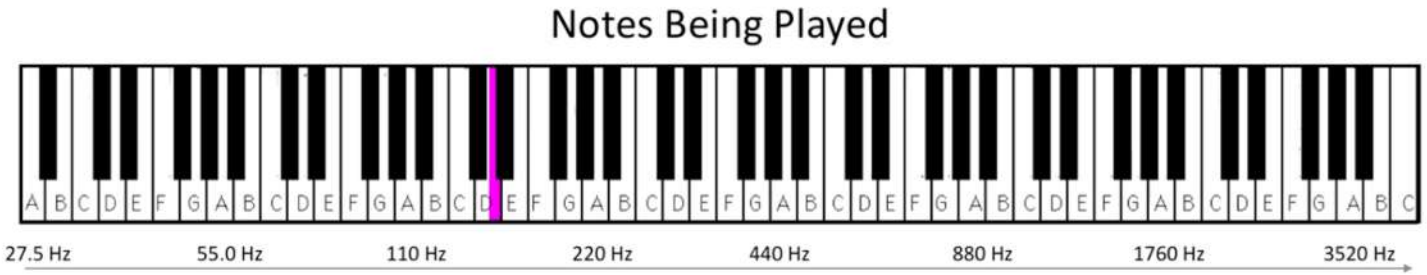
Event Horizon Telescope



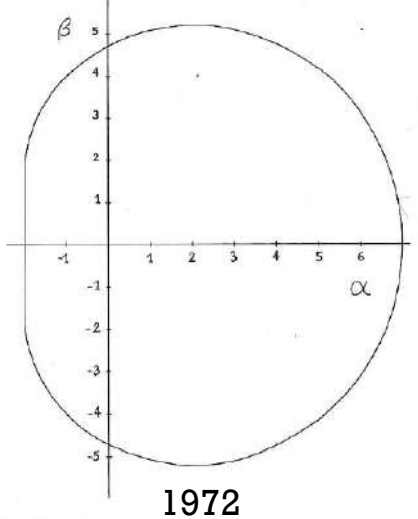




It's Like Playing a Broken Piano

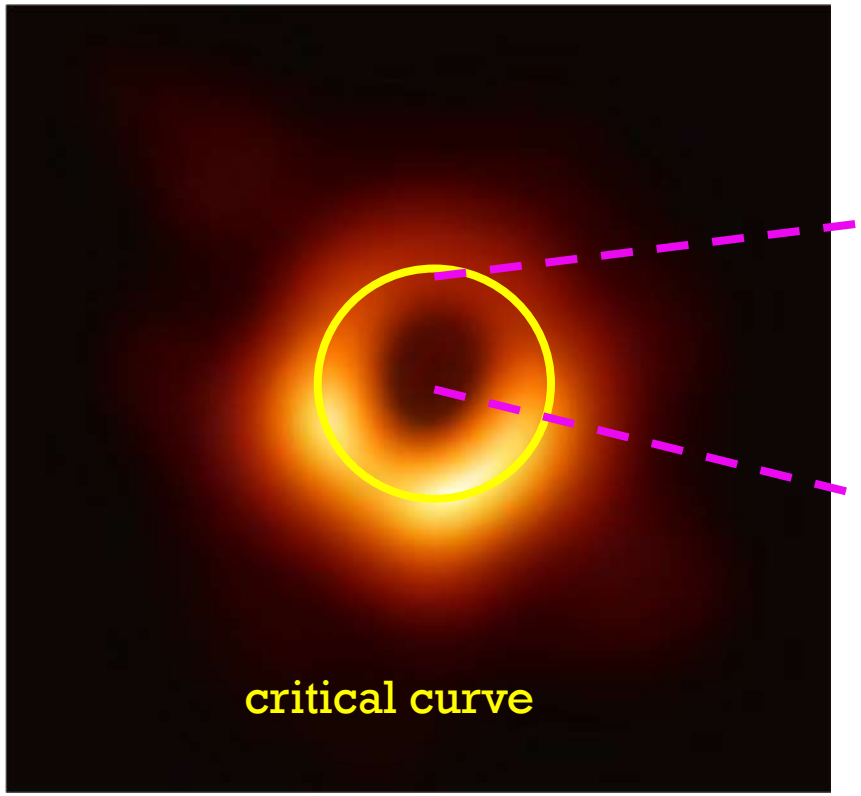


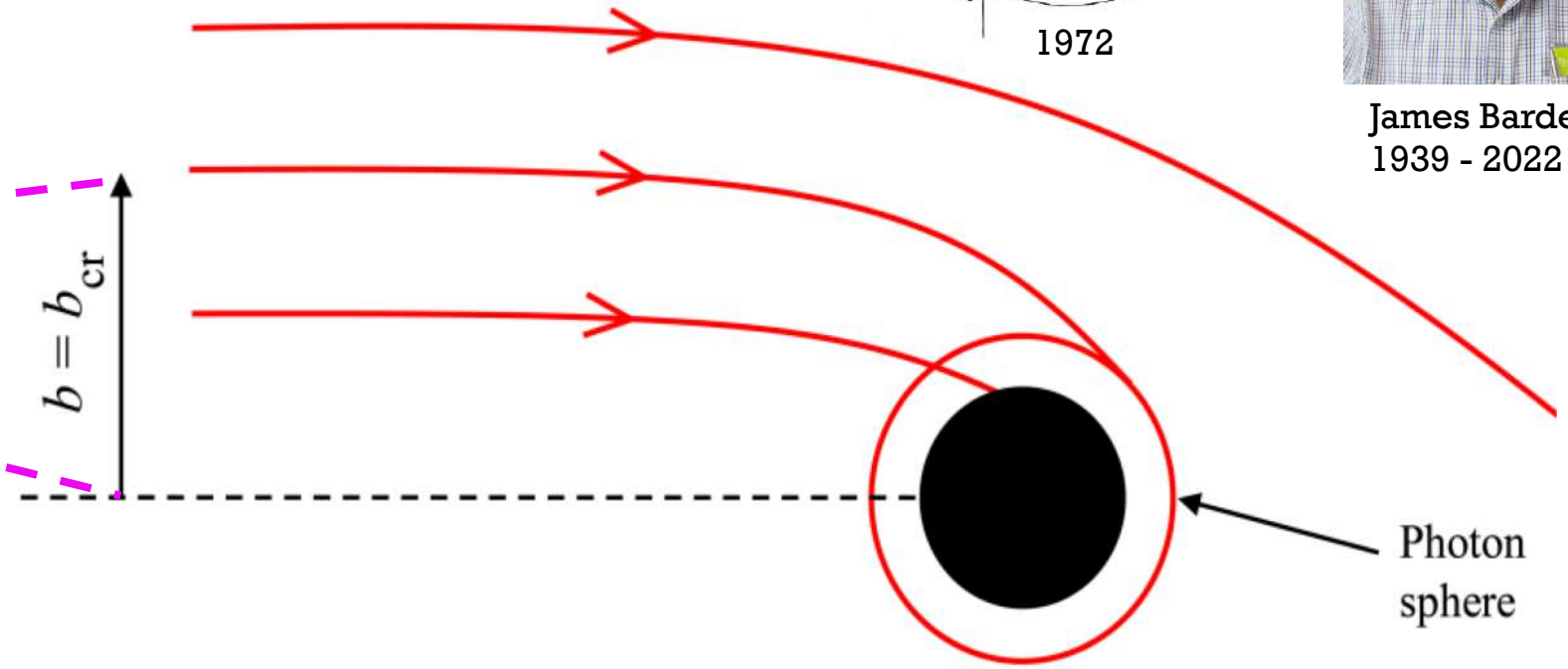
Black Hole Shadows



1972

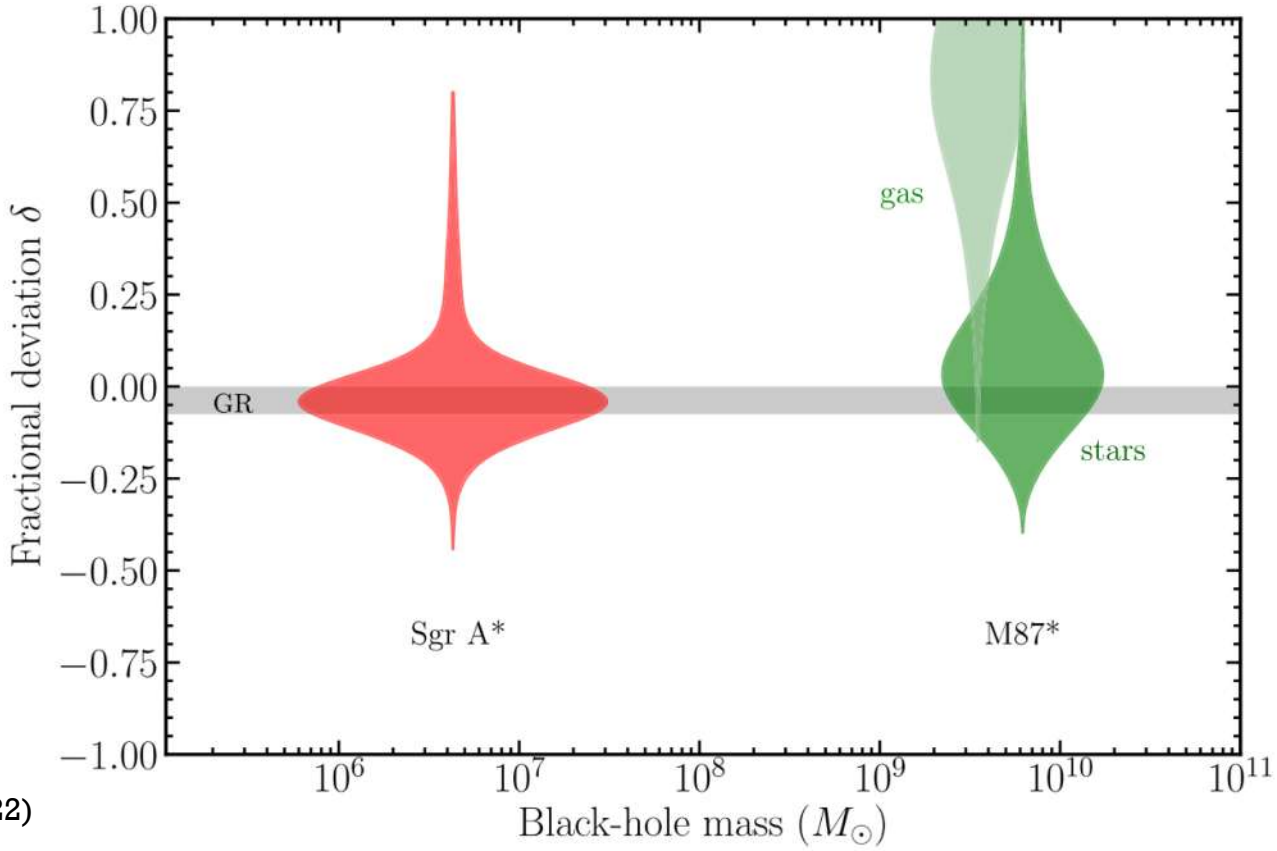
James Bardeen
1939 - 2022





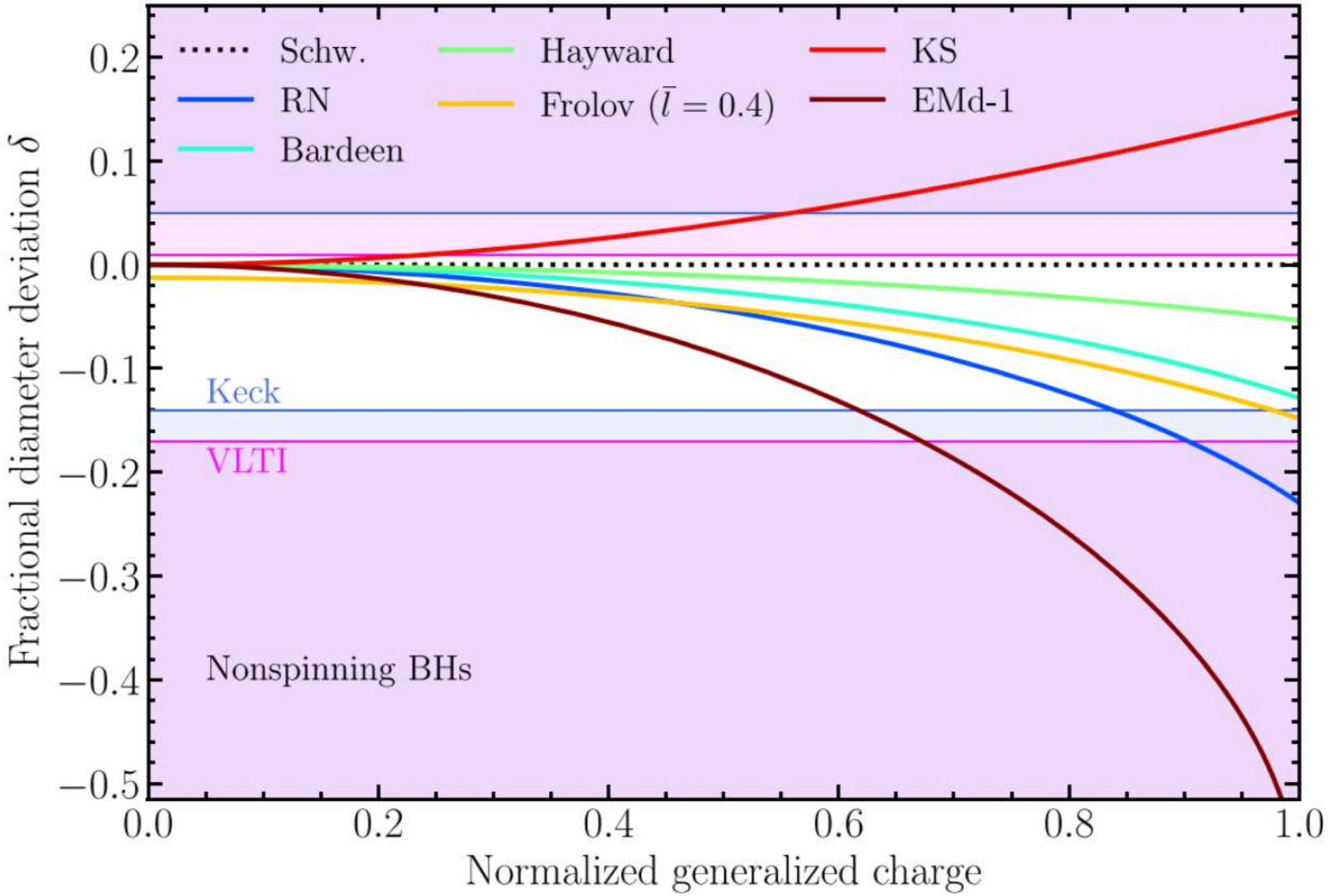
M87* v.s. Sgr A*

- Similar angular diameter: $\theta_g = R_g/D$
- Things around Sgr A* vary on shorter timescales (~hours) so more difficult to analyze
- Sgr A*: Dirtier line of sight
- Sgr A*: More accurate mass and distance measurements from star's motion (VLTI, GRAVITY, Keck)
- Ring structures consistent with Kerr spacetime (Sgr A* within 10%)
- BH uniqueness theorem?



EHT (2022)

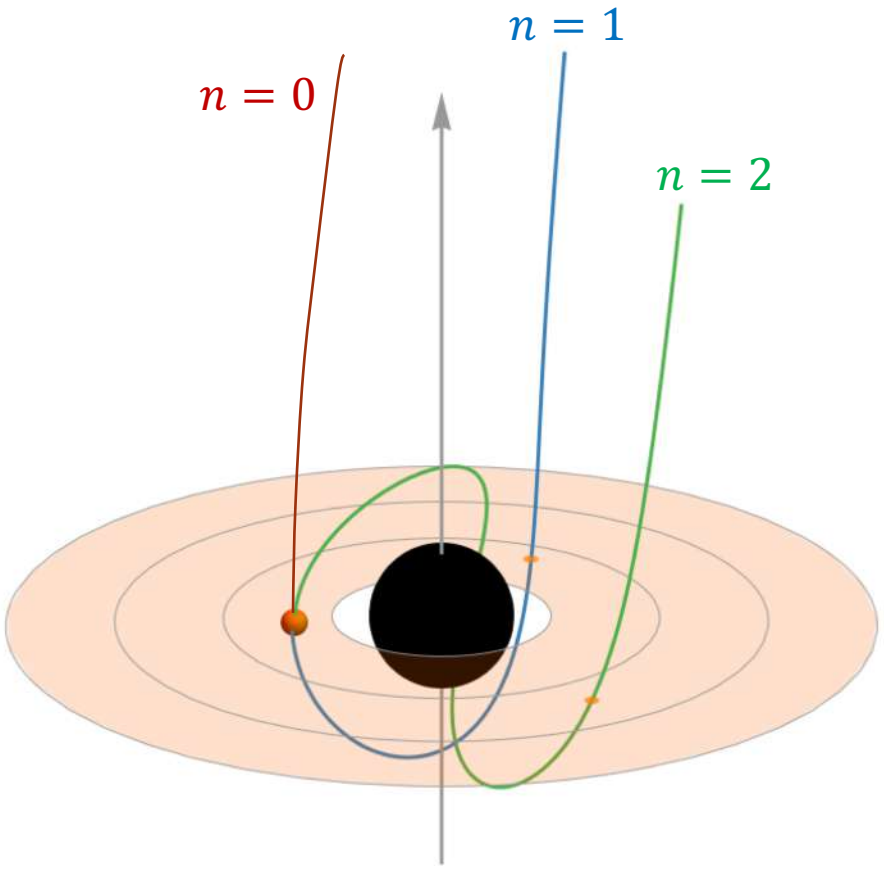
Testing Non-GR BHs

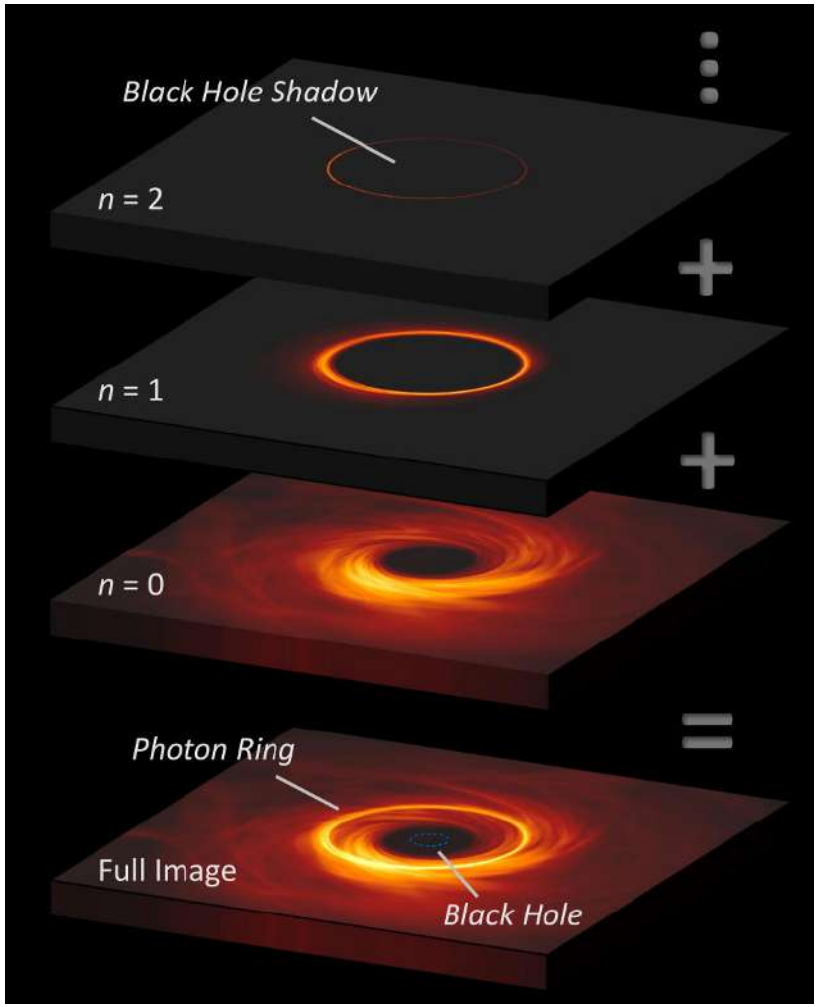


EHT (2022)

What is Next for ngEHT?

- Targets:
  - Photon subrings, photon ring autocorrelations, achromaticity, central brightness suppression…

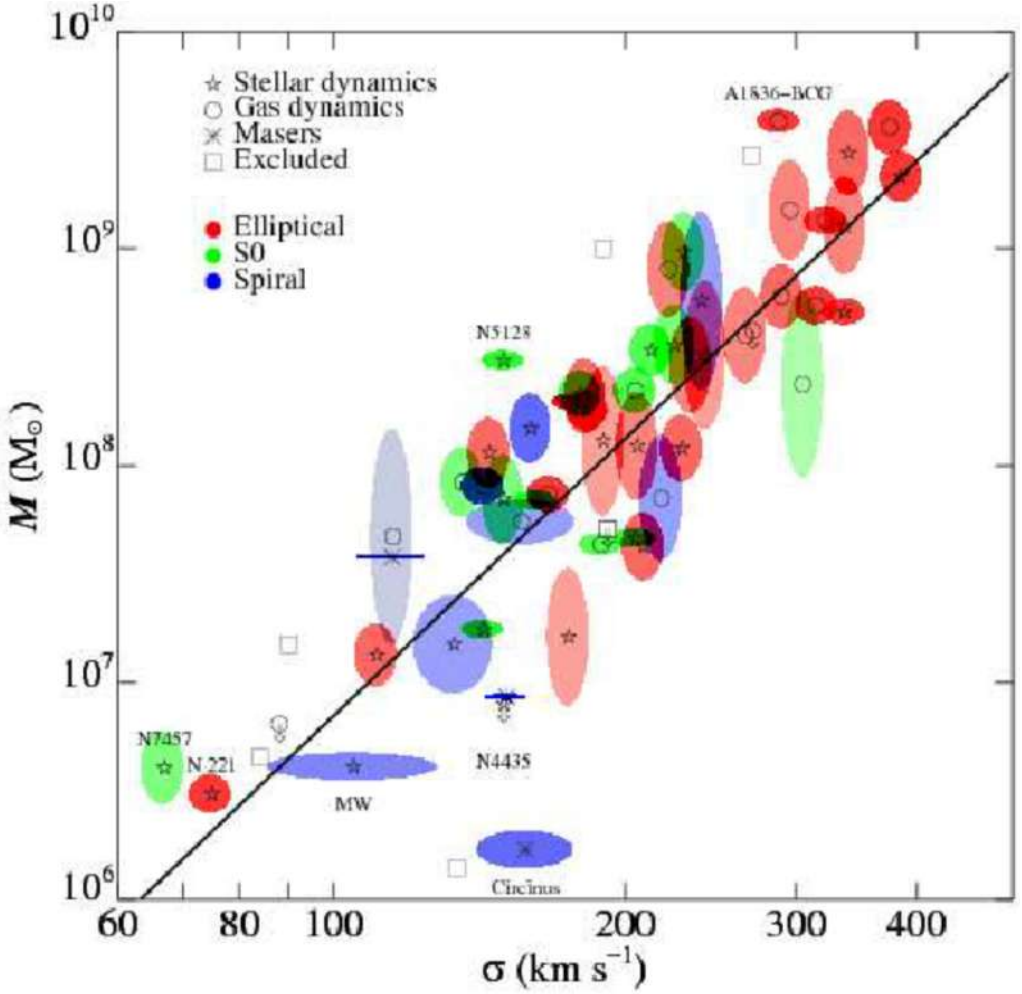




Gralla, et al. (2020)

WHAT CAN WE LEARN FROM BH?

Galactic and SMBH evolution

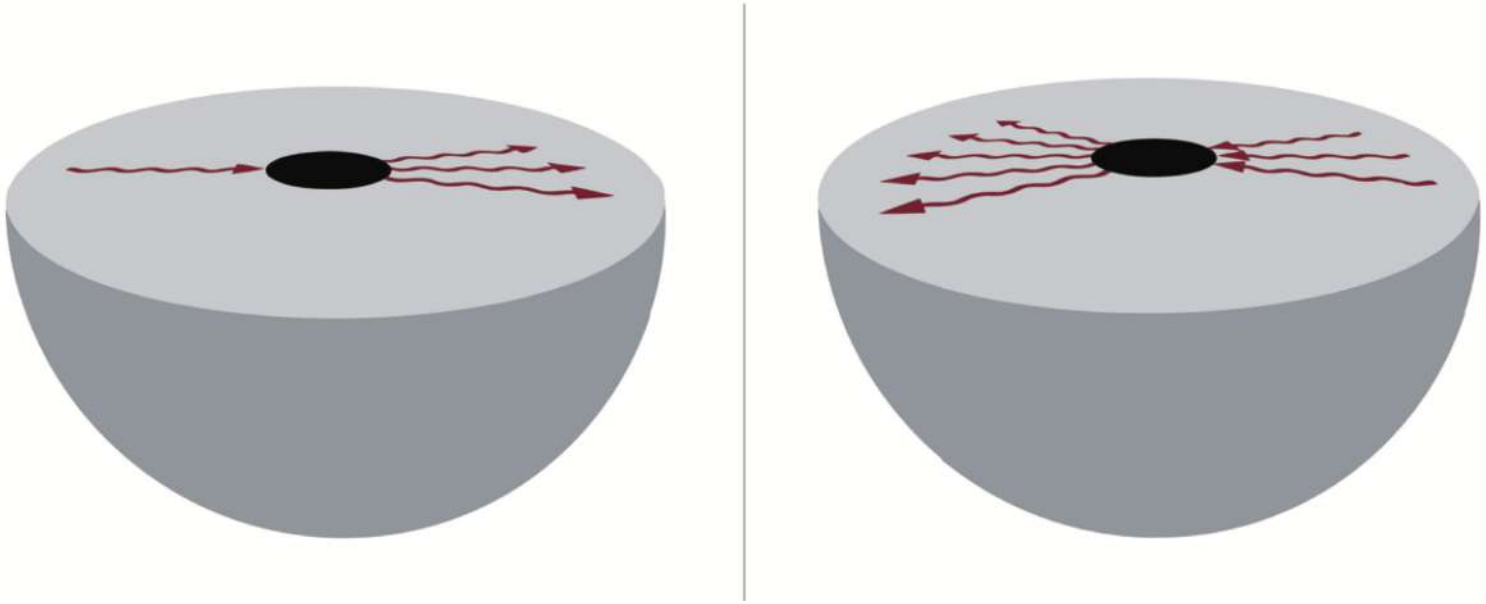


Stellar velocity dispersion

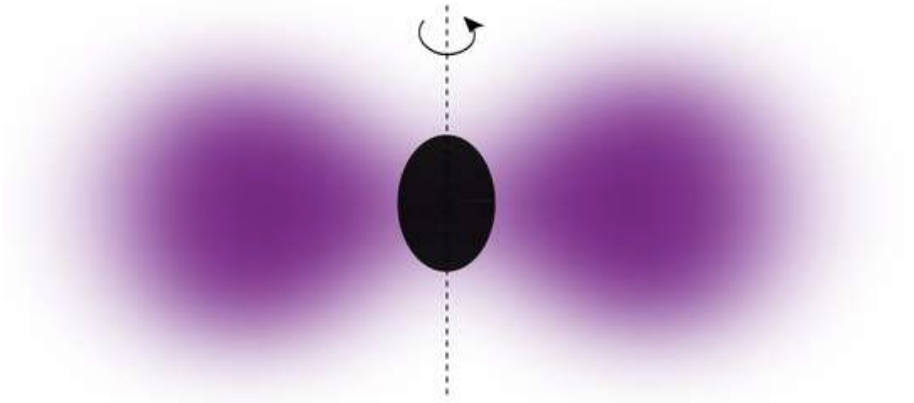
- M-sigma relation
- SMBH and galaxy co-evolve
- But how? AGN feedback

BHs as Bosonic Particle Detectors

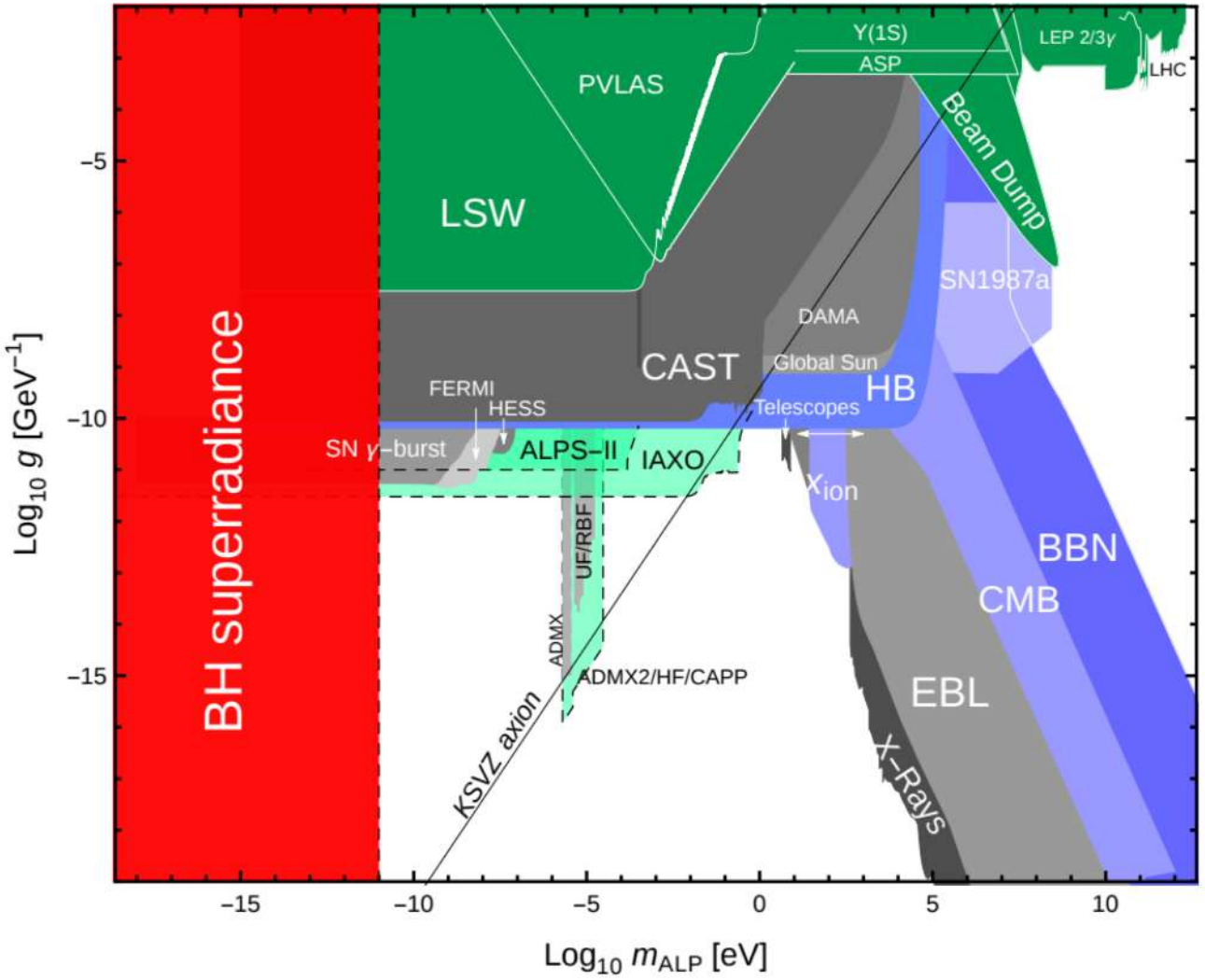
Superradiance instability



Bosonic clouds



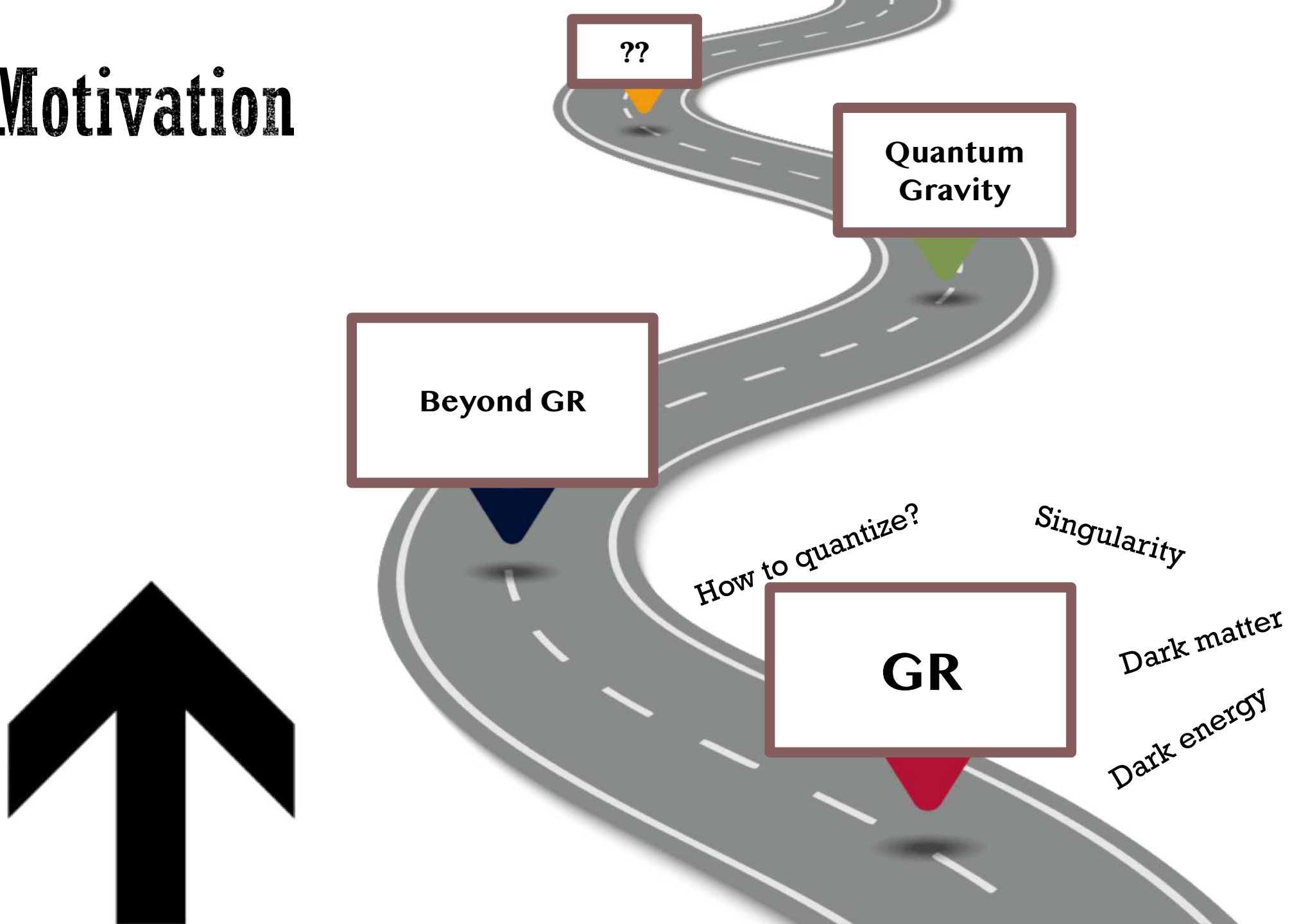
Finding Evidence of Clouds



Cardoso, et al. (2018)

TESTING GR

Motivation

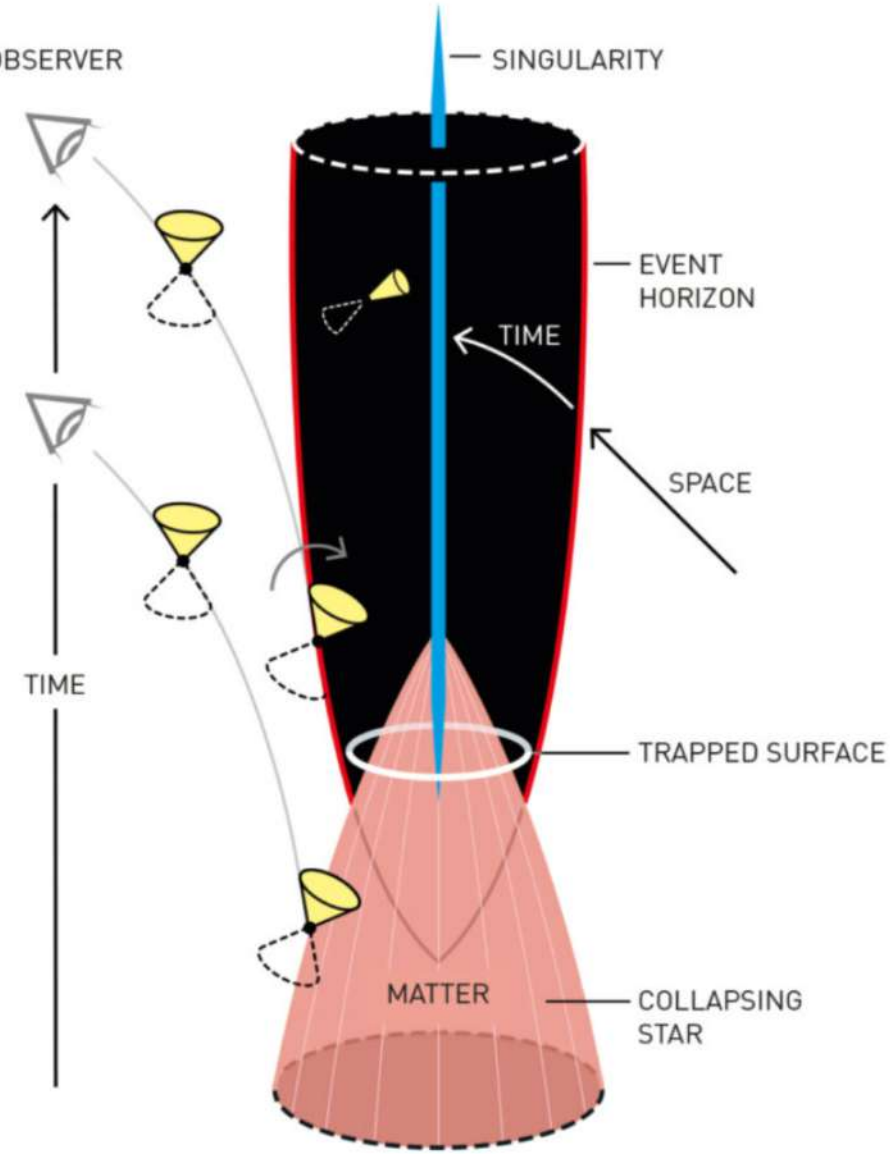

??
Quantum Gravity
Beyond GR
How to quantize?
Singularity
GR
Dark matter
Dark energy

Hawking-Penrose Singularity Theorem (Nobel prize 2020)

GR + reasonable matter

SINGULARITY !!

The theory breaks down!!



Go Beyond GR

- The question is NOT "whether" GR will be corrected or not
- It is WHEN, and HOW the corrections may enter

- If corrections enter at Planck scales, there is no way to test them

- It is possible that the corrections enter at horizon scales, hence maybe detectable

BLACK HOLE MIMICKERS?

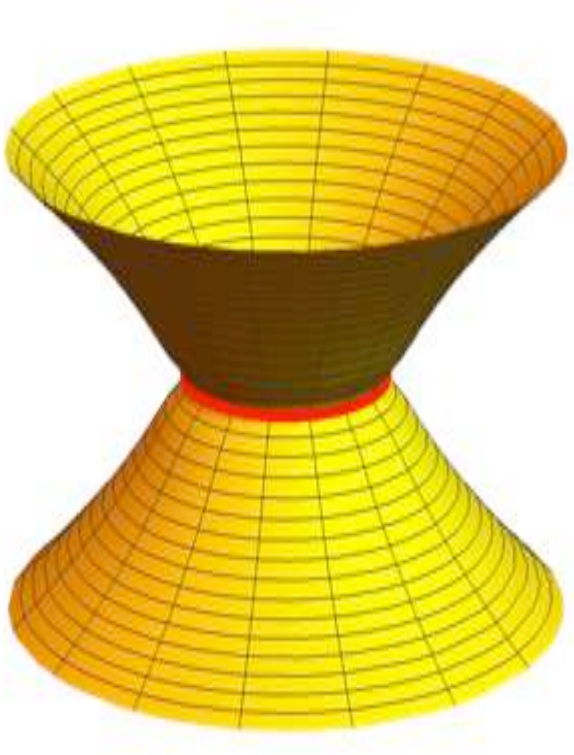
Possible Candidates

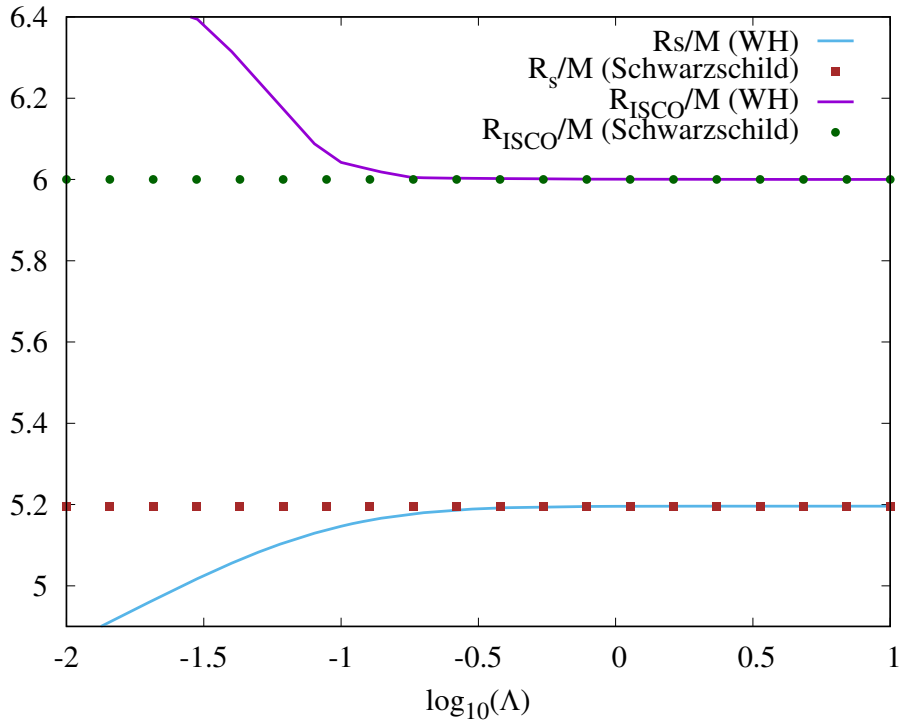
- Boson stars, Proca stars
- Fuzzball
- Wormholes
- Regular black holes
- Non-Kerr spacetimes

Horizonless compact objects

Wormholes as BH Mimickers

- Repulsive forces provided by some exotic matters near the throat
- The throat connects to other "spacetimes"
- May have shadow critical curve similar to Kerr BH

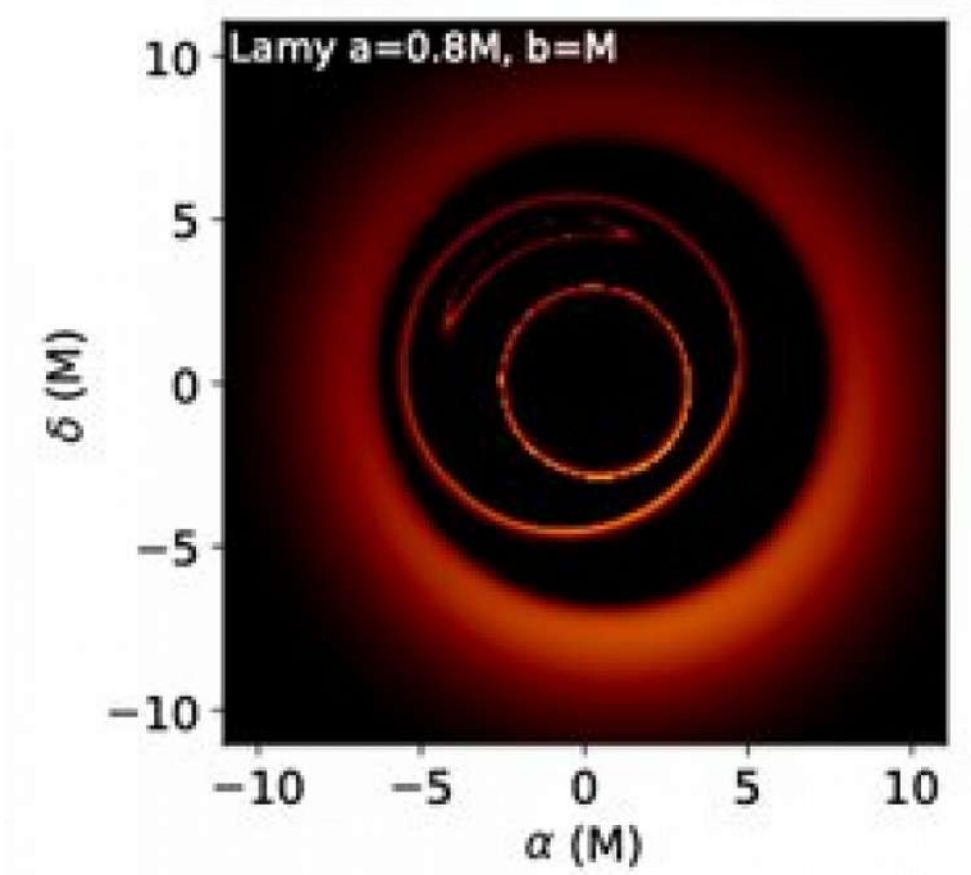




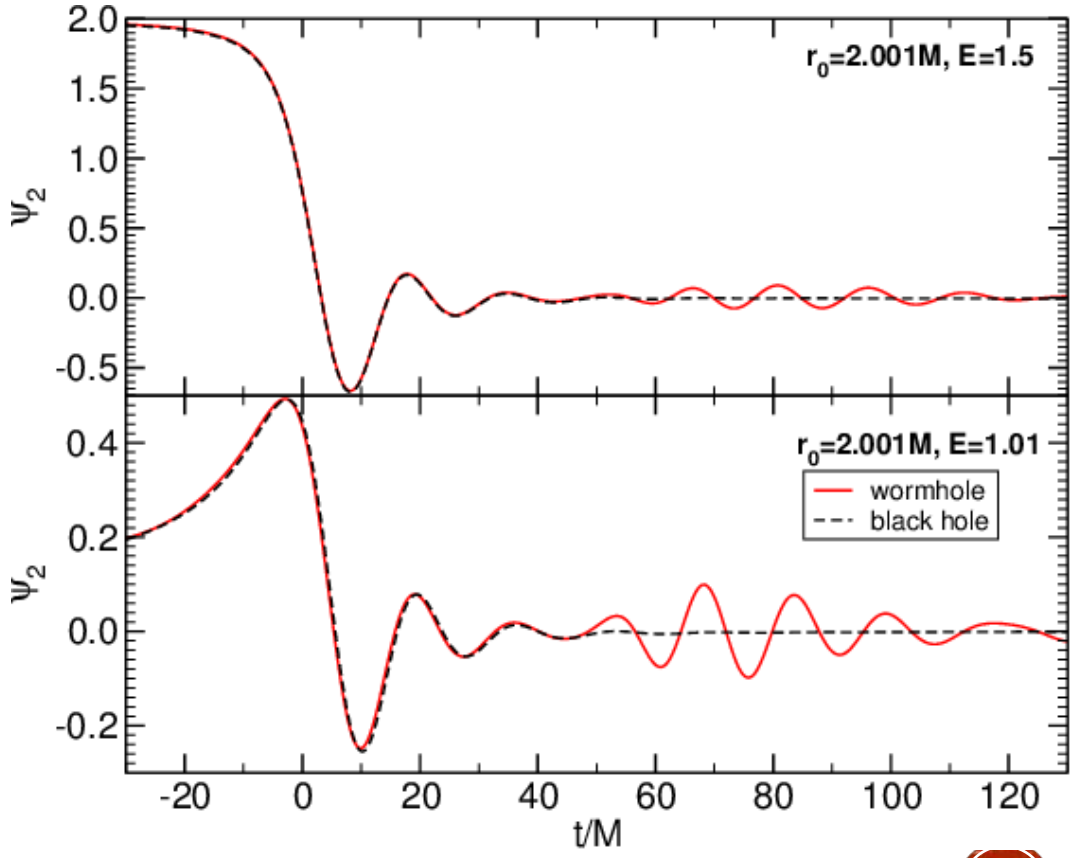
MBL, CYC, XYC, YCO, DY, *JCAP* (2021)

Wormholes as BH Mimickers

- Lights from the other side of the throat may be visible
- May also be distinguished via GW (model-dependent)



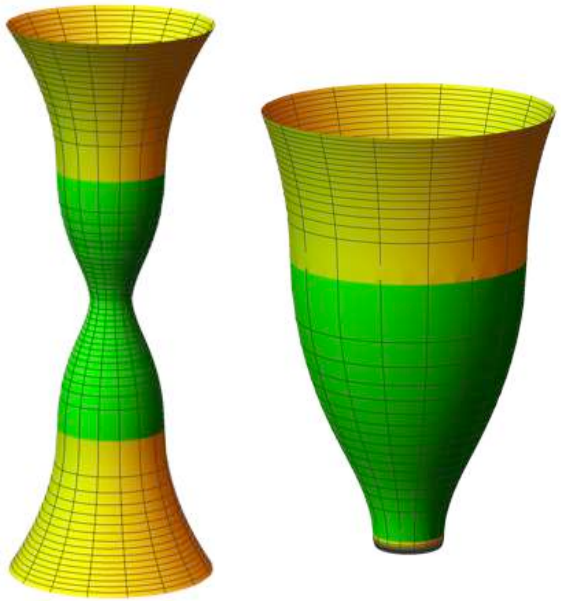
Vincent et al. (2020)

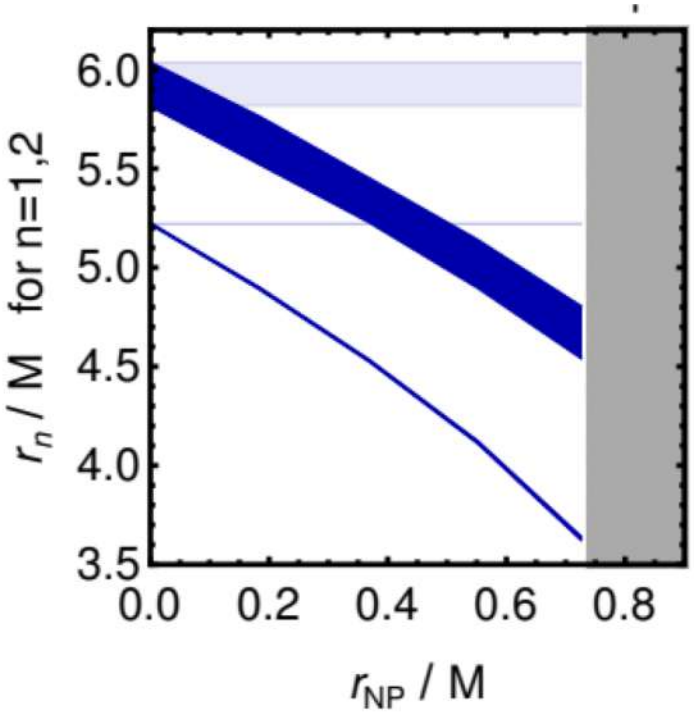


Cardoso et al. (2016)

Regular BHs

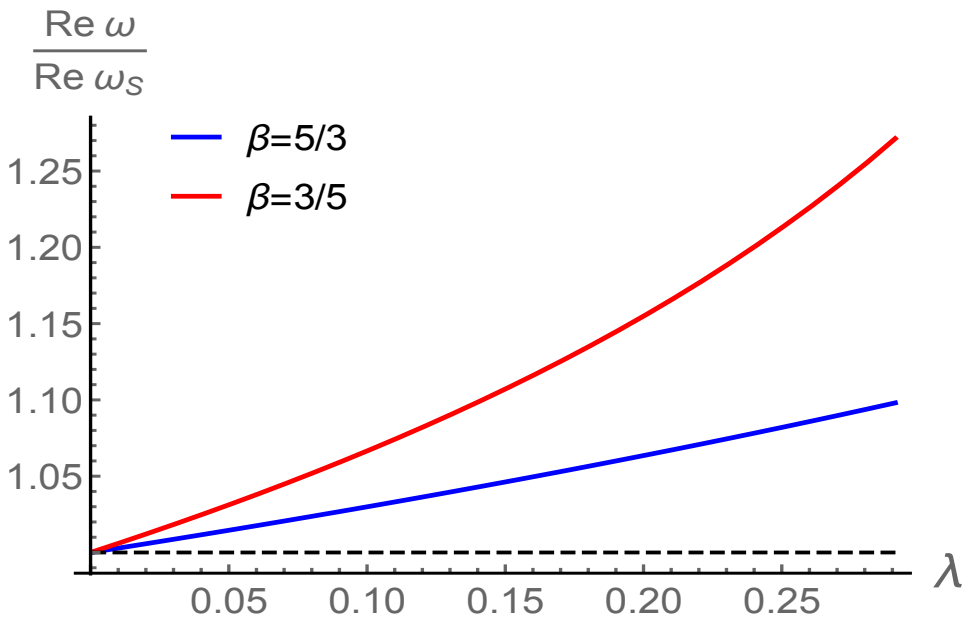
- Violate Hawking-Penrose theorem by relaxing some of its assumptions
- Tons of models in the market
- More difficult to be distinguished





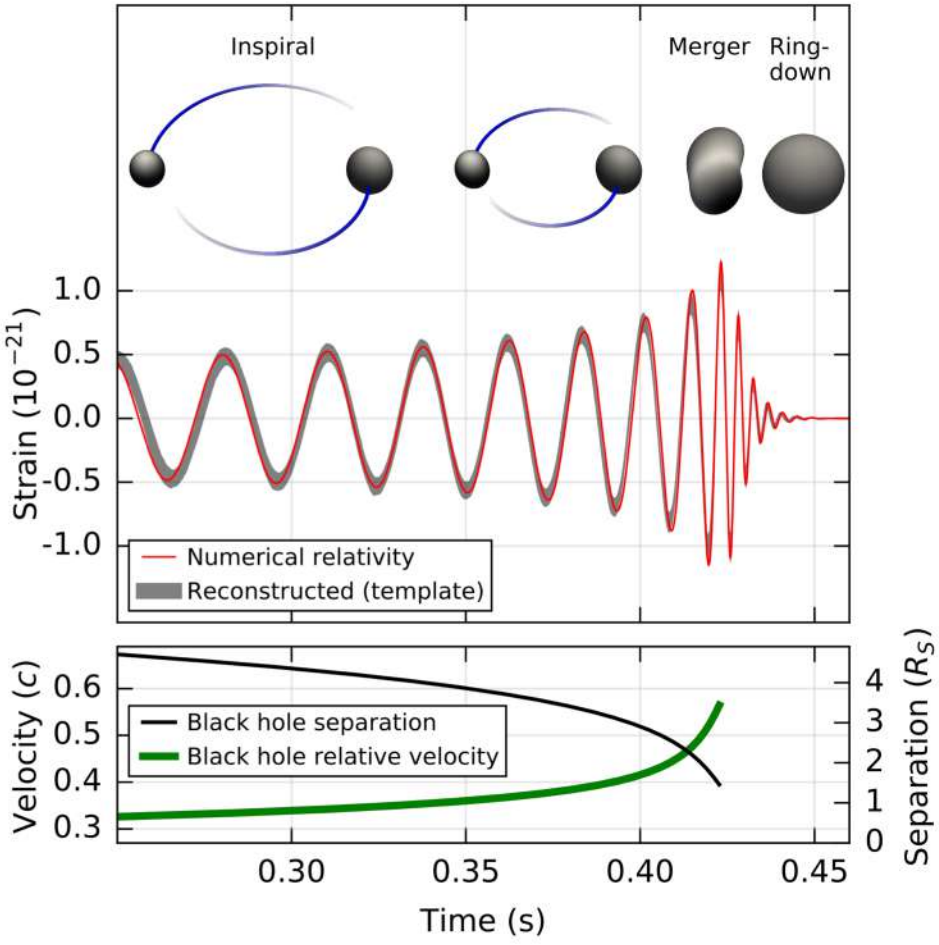
Eichhorn et al. (2022)

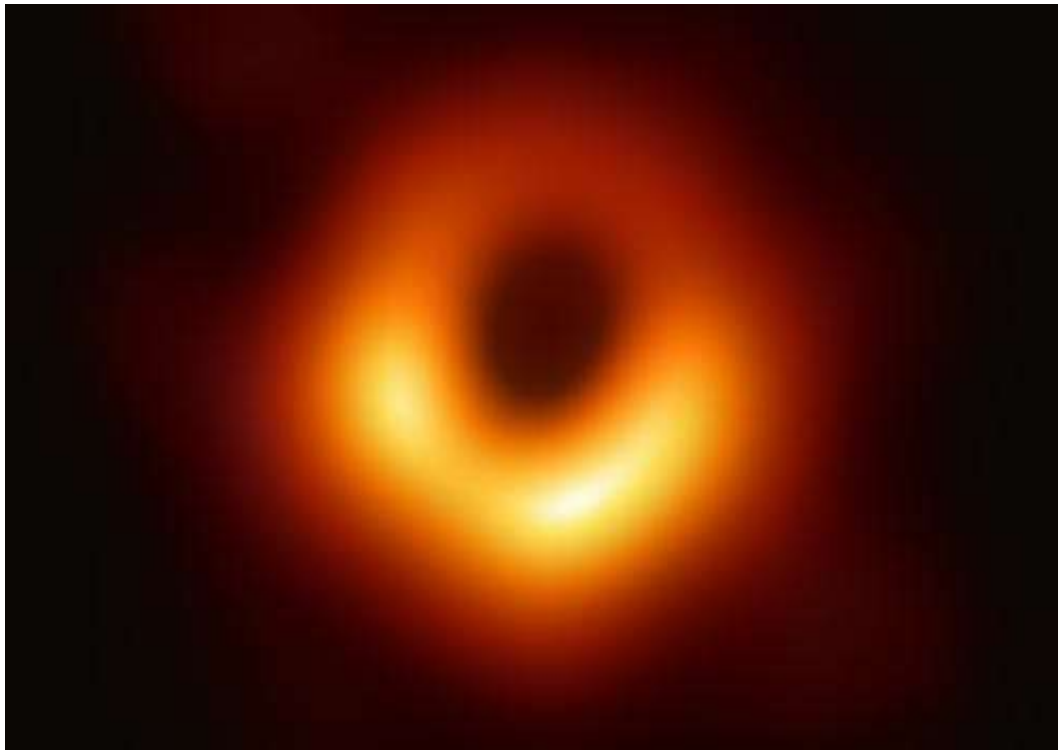
Ringdown tests



MBL, SB, CYC, PC, DY, *JCAP* (2020)

Perfect tools (GWs, EHT) and perfect targets (BH)





- BH is extremely simple! (No-hair)
- Probing astrophysics at strong gravity regimes
- Test GR

Recommended References

- Sgr A* images M87* images
- LIGO detection
- GRAVITY: S2 motion, Hot Spot
- The Mathematical Theory of Black Holes, Chandrasekhar
- Black hole superradiance
- Black hole QNMs, Shadows, photon subrings, PN expansion, effective-one-body, Numerical Relativity
- Modified gravity
- Testing fundamental physics using BHs