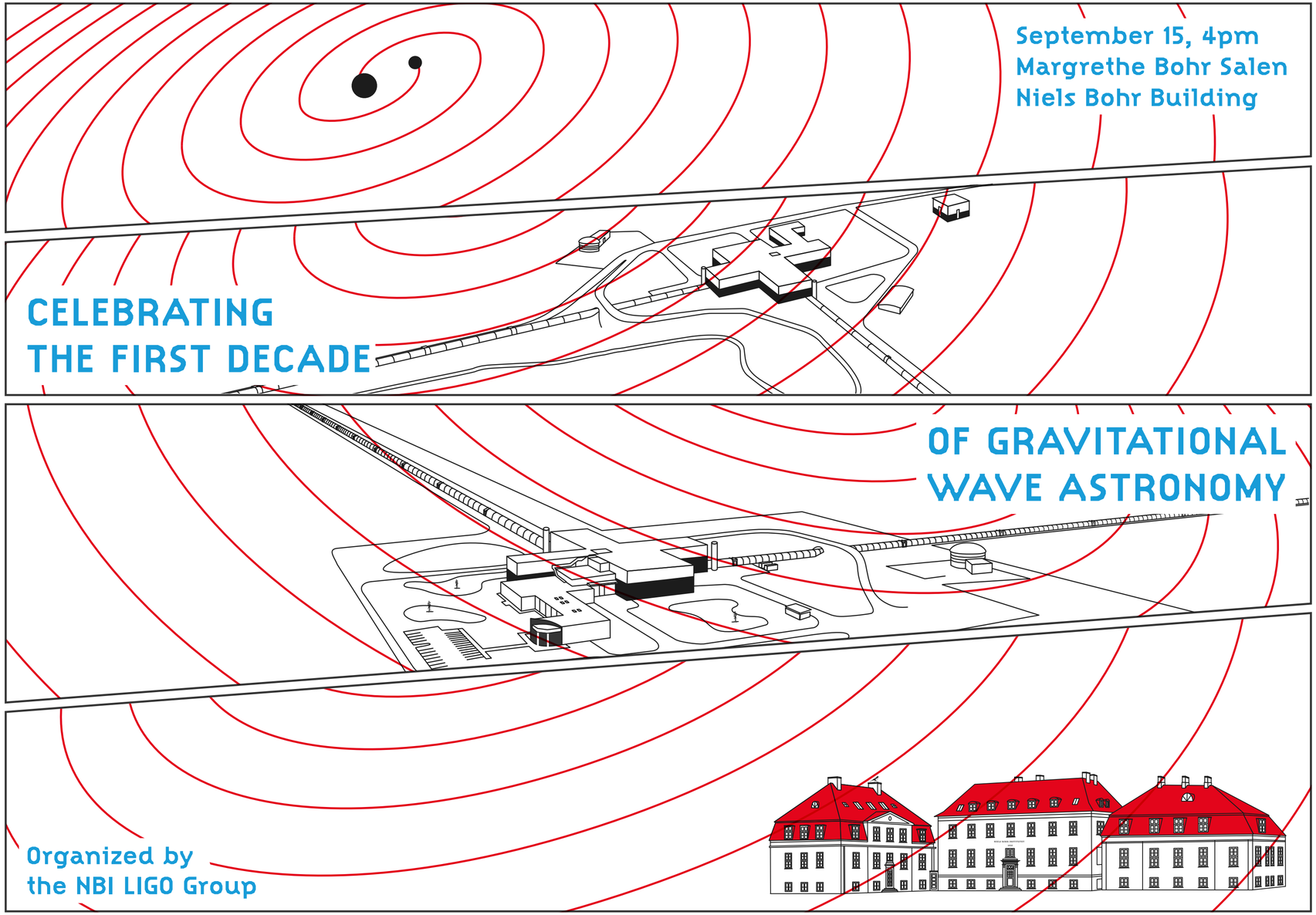


LSC LIGO Scientific Collaboration

VILLUM FONDEN

KØBENHAVNS UNIVERSITET

THE CENTER OF GRAVITY

How do black holes form?

Jose María Ezquiaga
Niels Bohr Institute
ezquiaga.github.io

JM

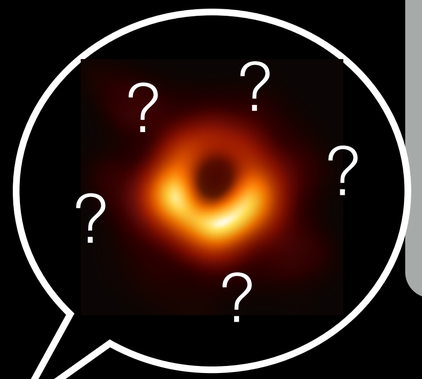
Hi ChatGPT

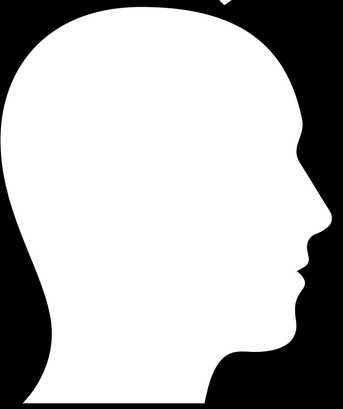
Hello! How can I assist you today?

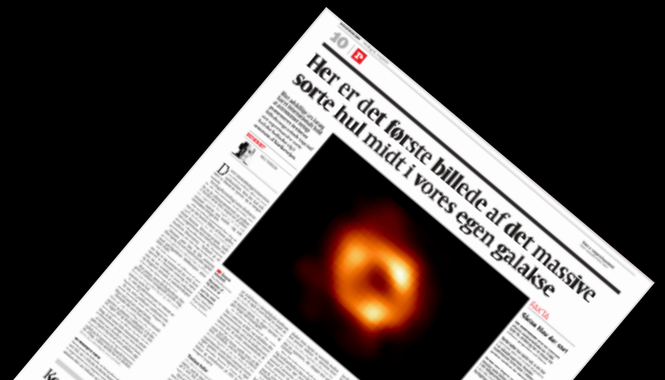
JM

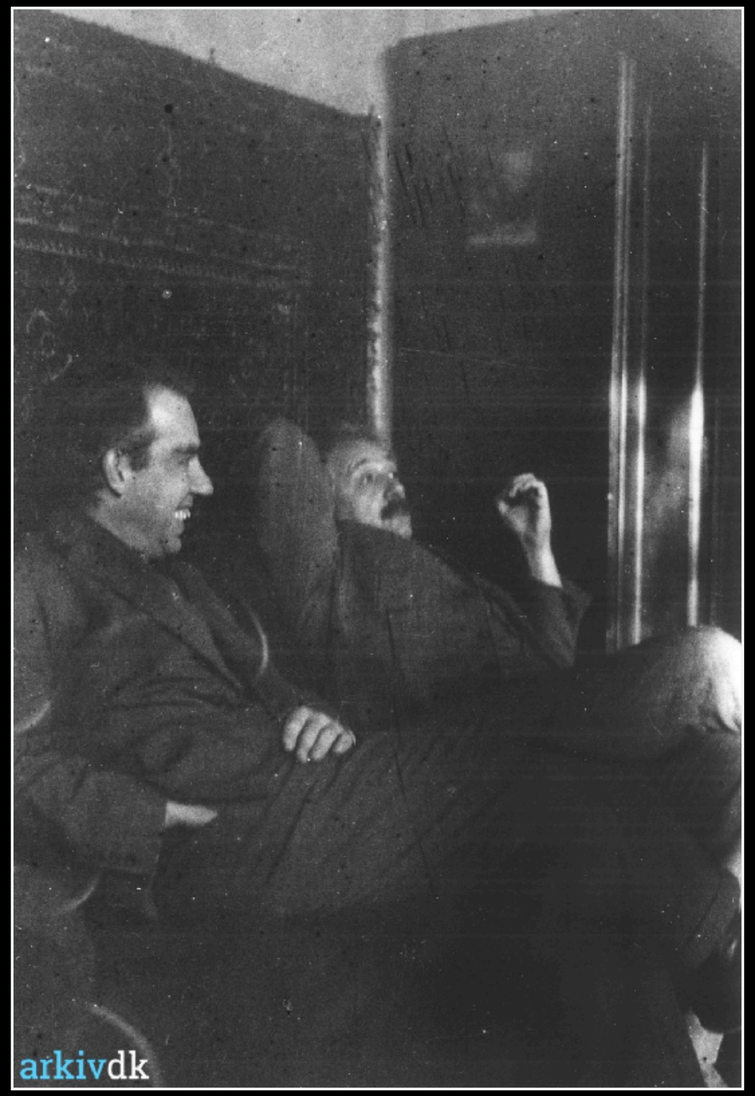
Can you explain me what is a black hole in 5 words?

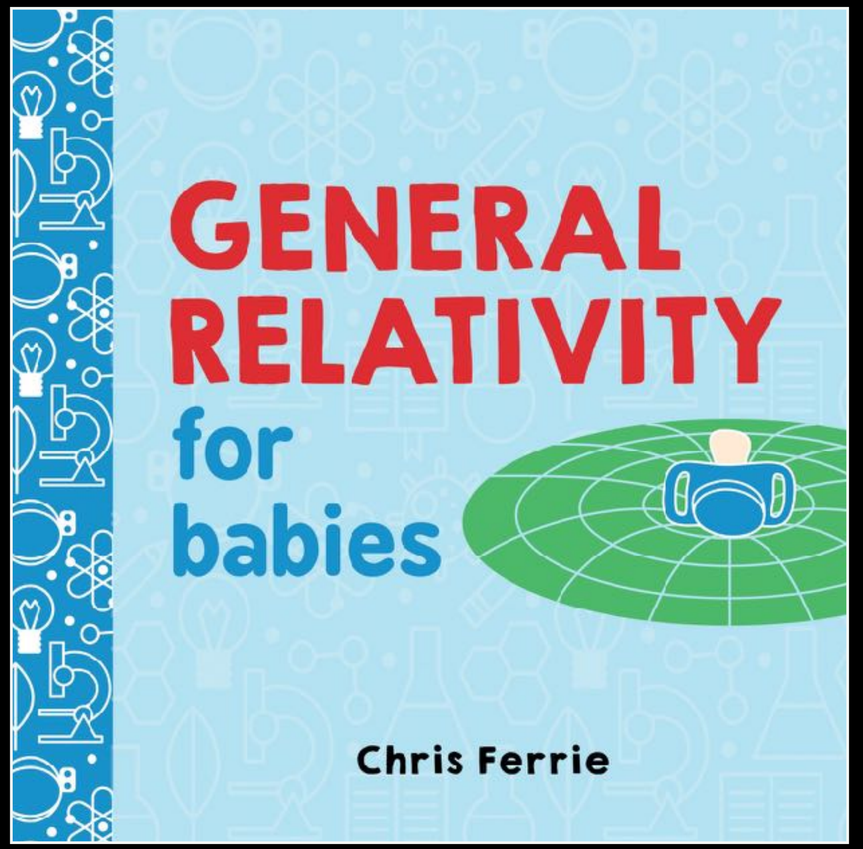
Intense gravity traps everything forever.





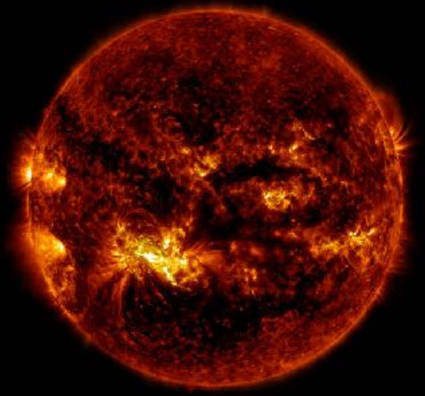


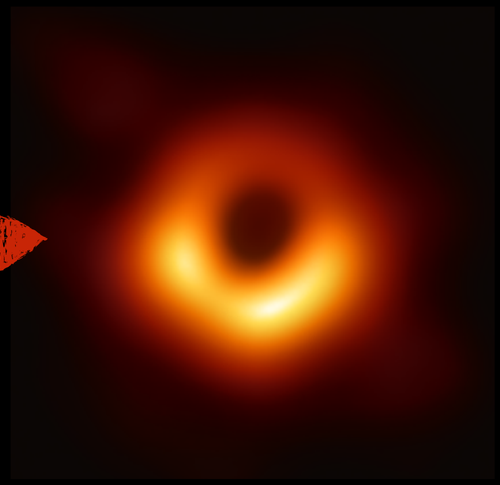

arkivdk


GENERAL
RELATIVITY
for
babies
Chris Ferrie

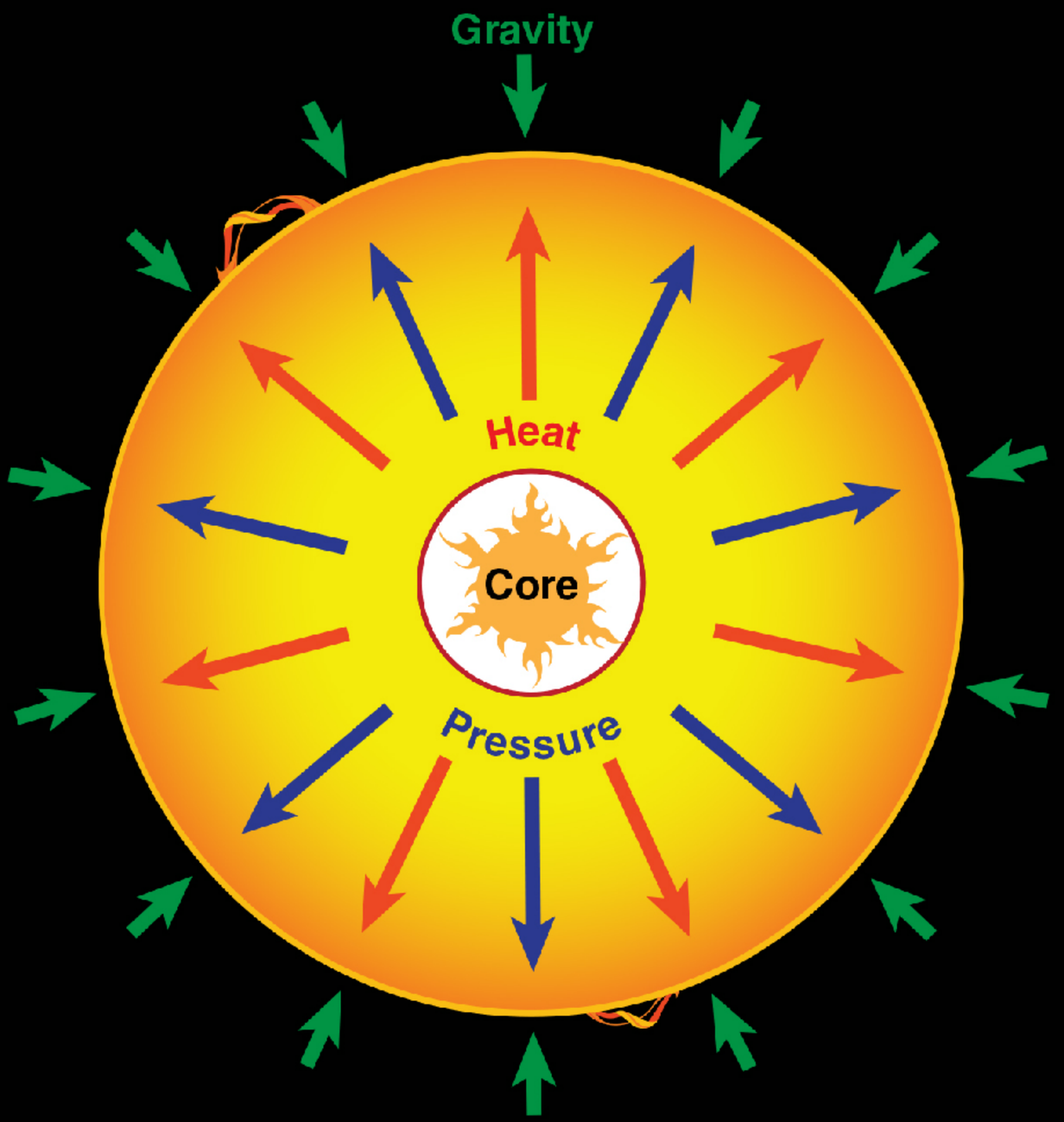
Black hole recipe:

1. Take 1 solar mass of salt
2. Put it on a plate smaller than Copenhagen
3. Enjoy :)





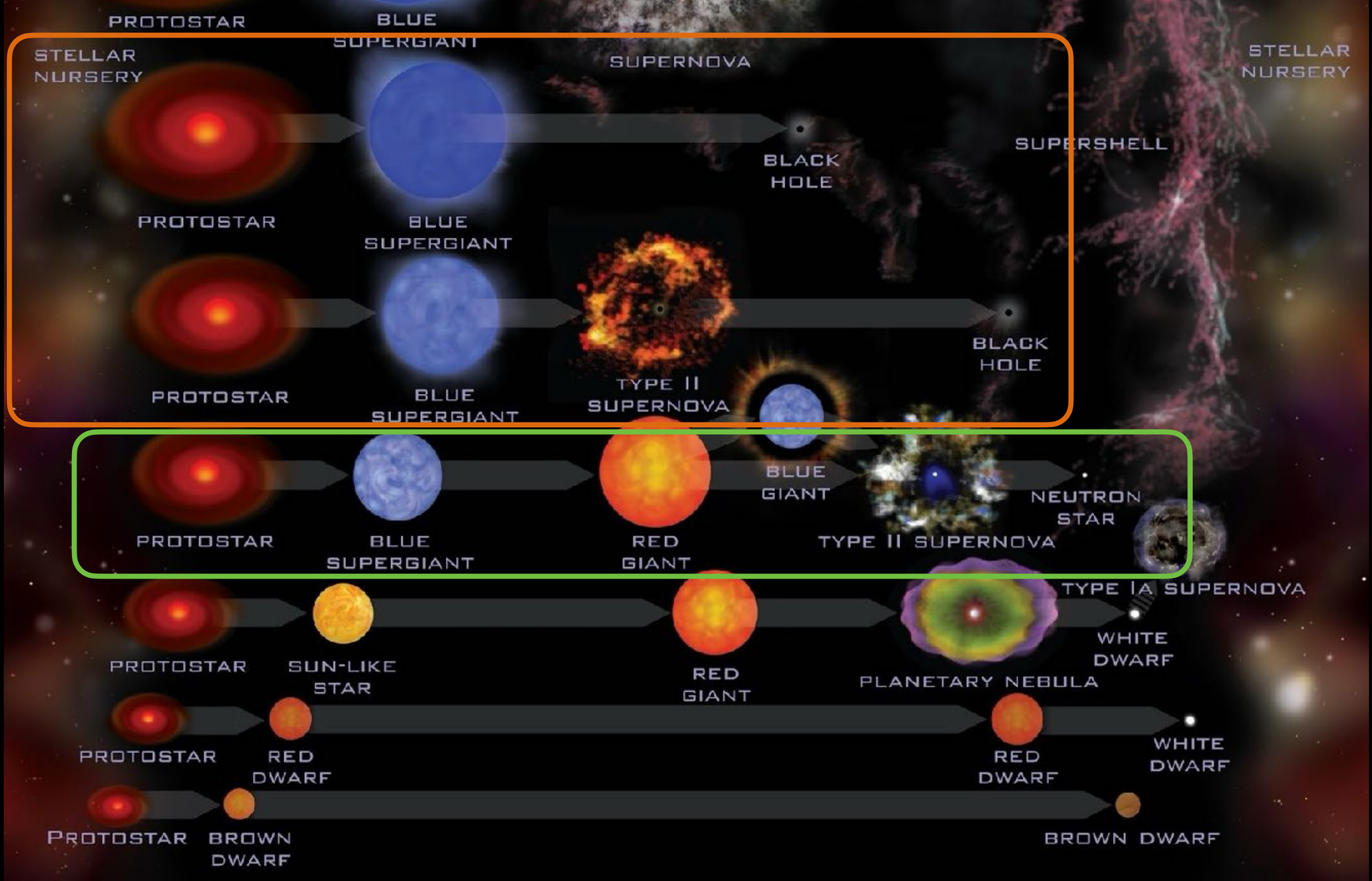
What holds a star together?



[credit NASA]

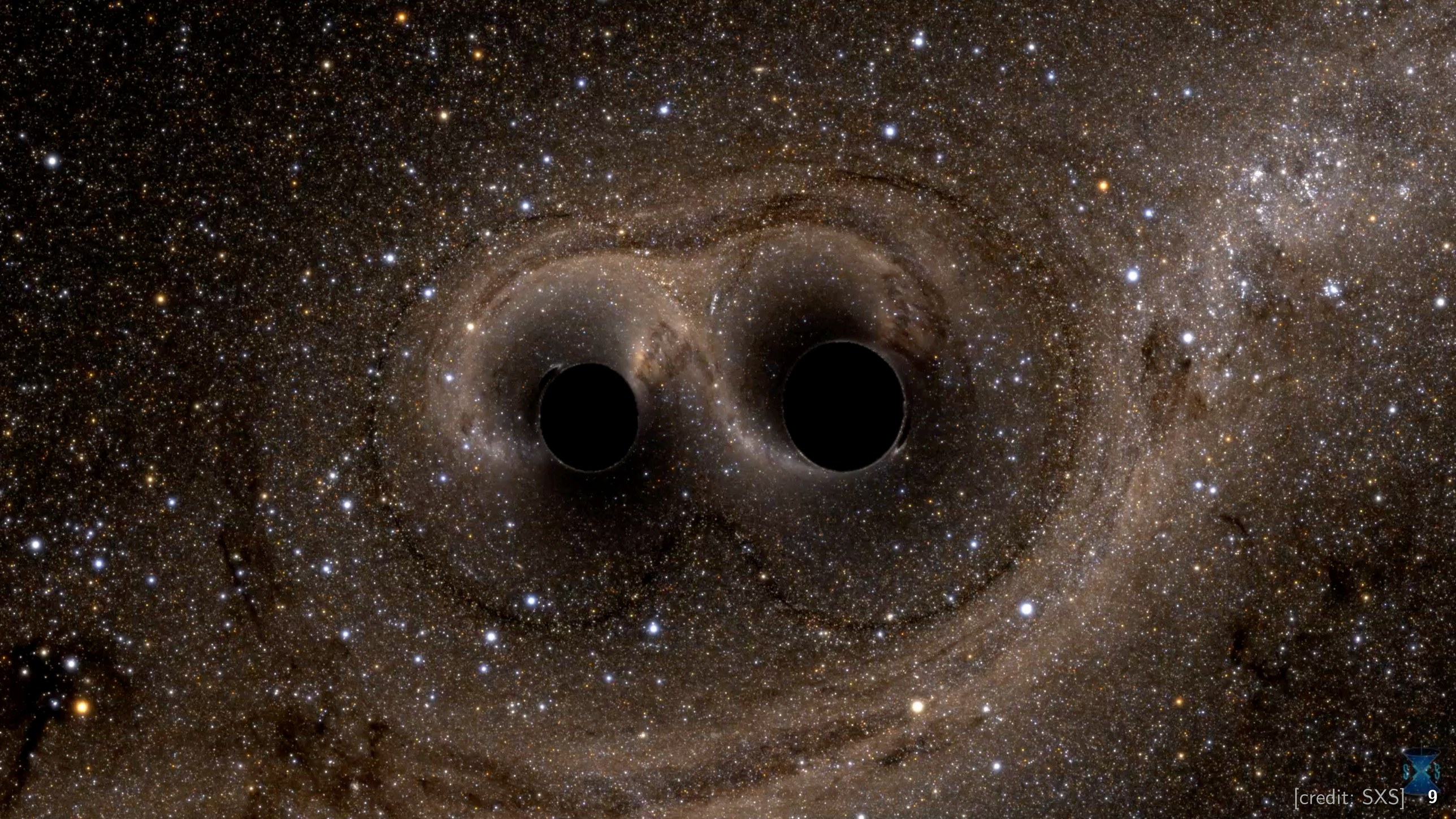
Stellar evolution

How, when, where?



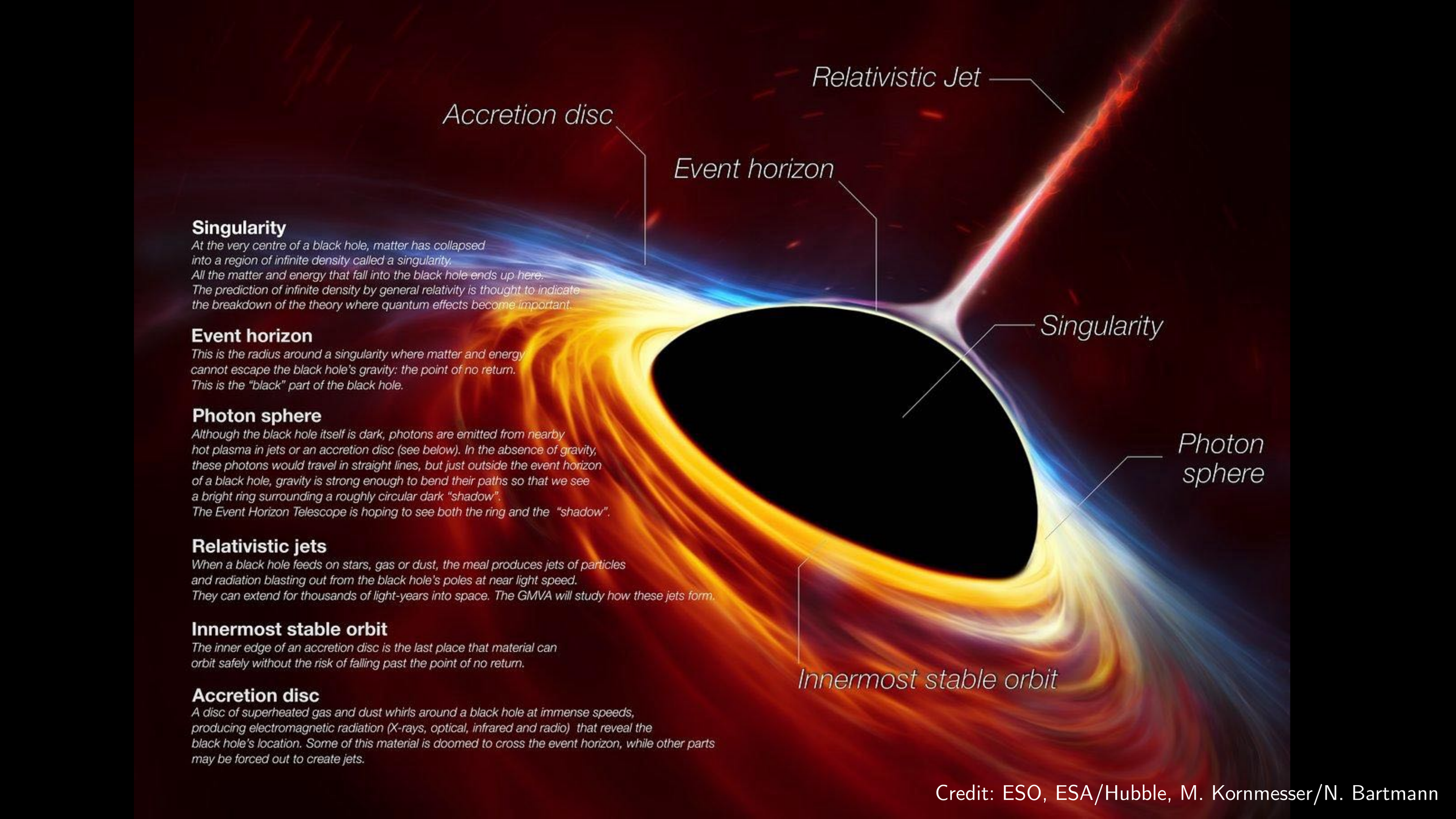
[credit Chandra]

[Gobular cluster]



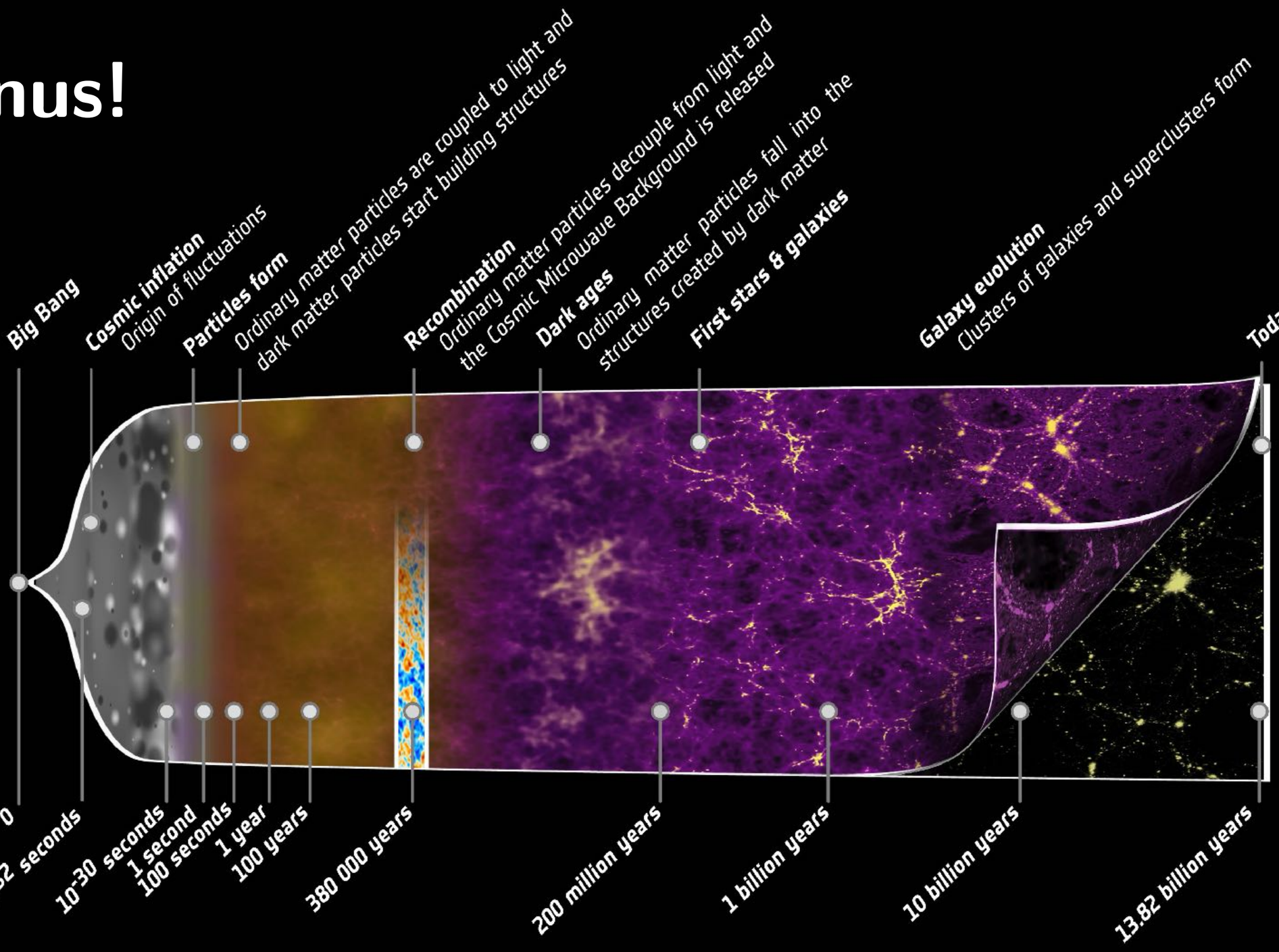
[credit: SXS]

Credit: EHT



Credit: ESO, ESA/Hubble, M. Kornmesser/N. Bartmann

Bonus!



[Credit: ESA]

Solar System (Copernicus 1473-1543)

You are here

Our galaxy: the Milky Way

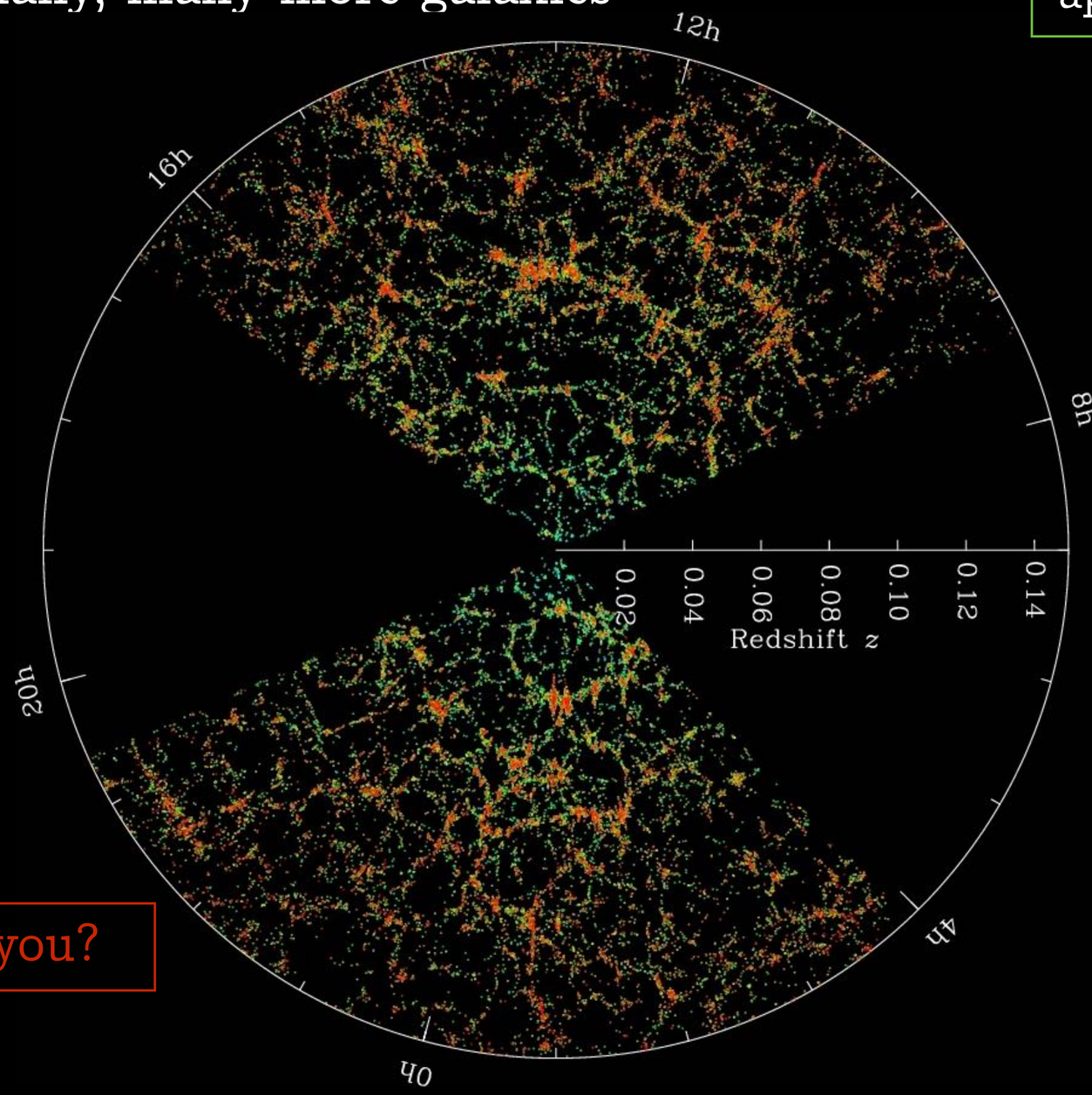
+100 billion stars

1920s. Galaxies beyond Milky Way

54 galaxies in the local group

1990s. There are many, many more galaxies

aprox. 100 billion galaxies

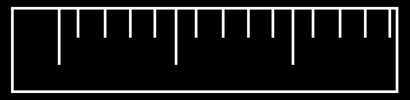


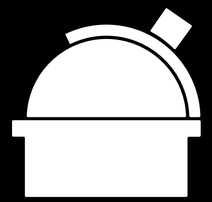
Where are you?

Q/A: Distances from us to the...

[in light travel time]

Moon ...	1.2 s
Sun ...	8.3 min
Closest star (proxima centauri)...	37 hours
Galactic center ...	26,000 years
Andromeda galaxy (M87) ...	2.5 million years
Cosmic Microwave Background ...	13.4 billion years



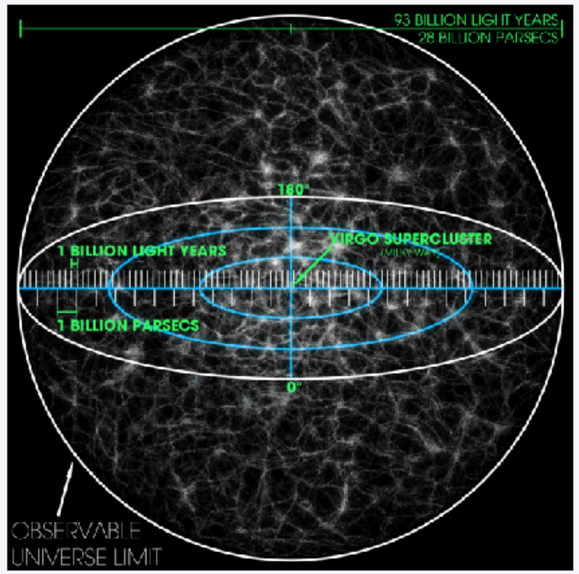


*speed of light 300,000 km/s

The universe is BIG

... but almost empty on average

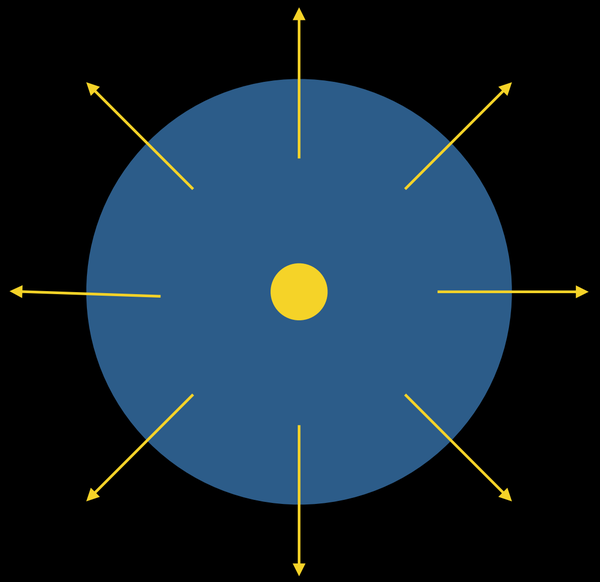
Observable universe



Visualization of the whole observable universe. The scale is such that the fine grains represent collections of large numbers of superclusters. The Virgo Supercluster —home of Milky Way—is marked at the center, but is too small to be seen.

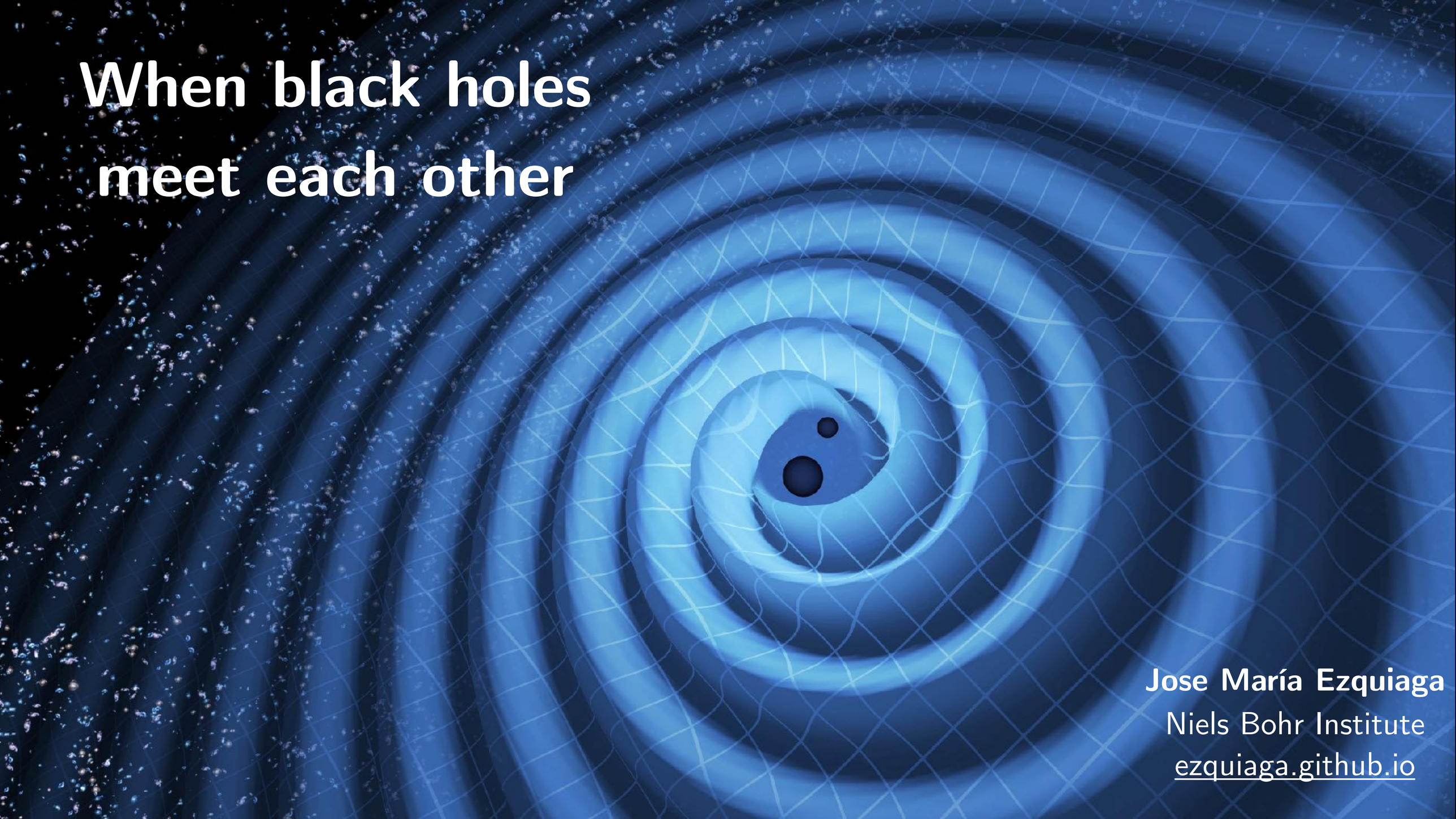
Diameter	8.8×10^{26} m or 880 Ym (28.5 Gpc or 93 Gly)[1]
Volume	3.566×10^{80} m^3[2]
Mass (ordinary matter)	1.5×10^{53} kg[note 1]
Density (of total energy)	9.9×10^{-27} kg/m^3 (equivalent to 6 protons per cubic meter of space)[3]
Age	13.799 ±0.021 billion years[4]
Average temperature	2.72548 K[5]
Contents	Ordinary (baryonic) matter (4.9%) Dark matter (26.8%) Dark energy (68.3%)[6]

$$\text{Energy flux} \propto 1/\text{distance}^2$$



Need extremely energetic phenomena!

When black holes meet each other



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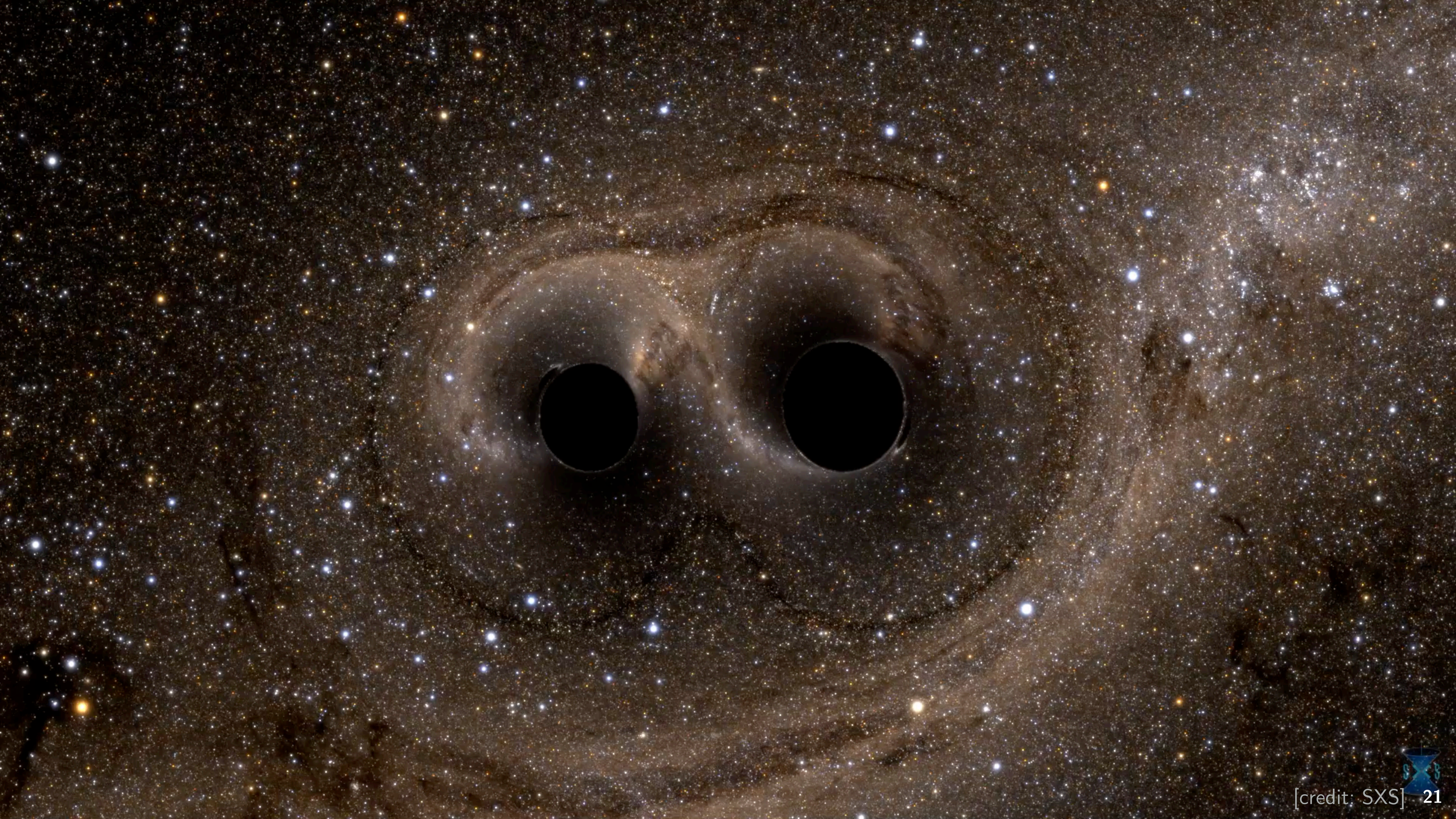
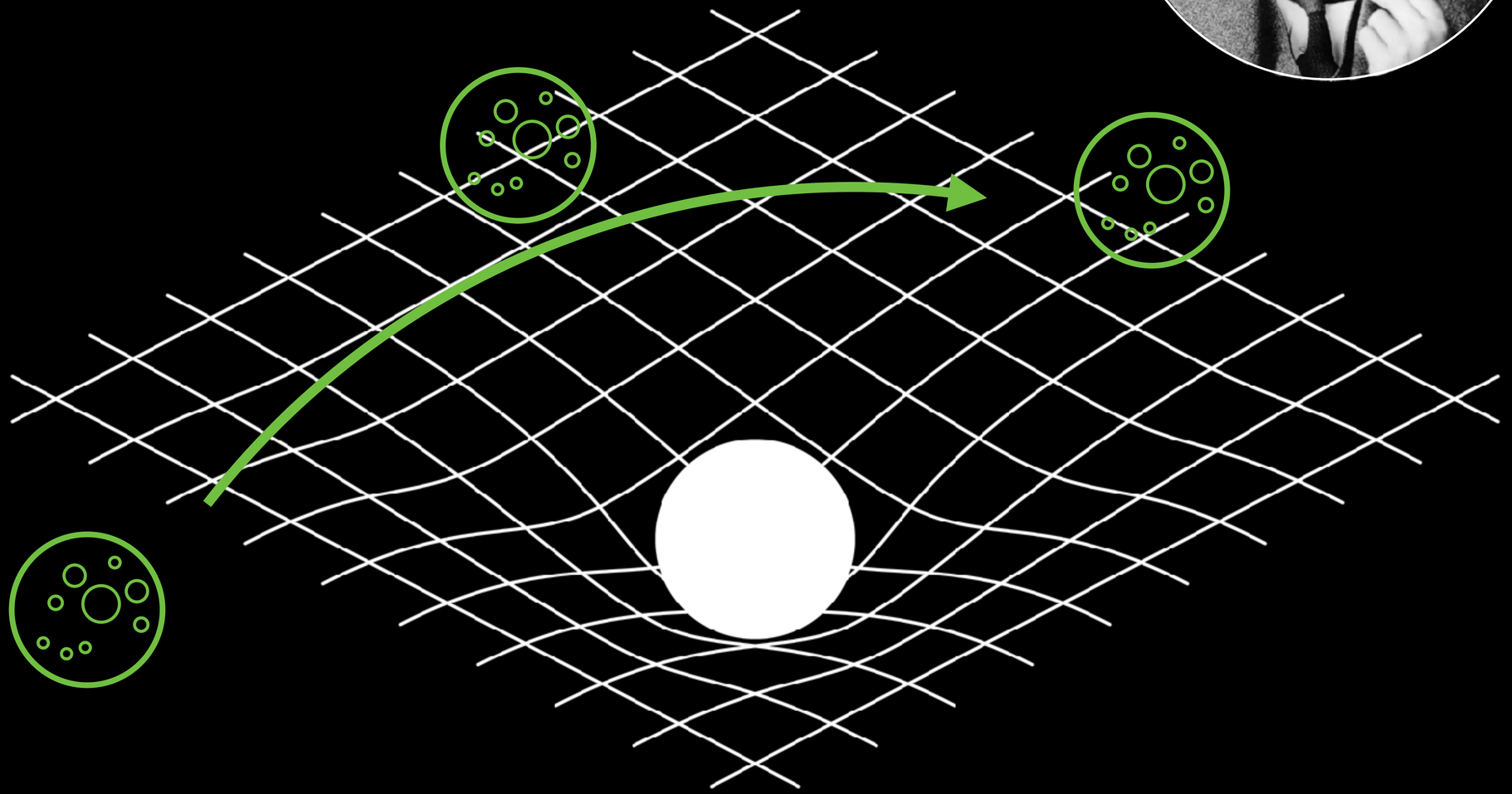


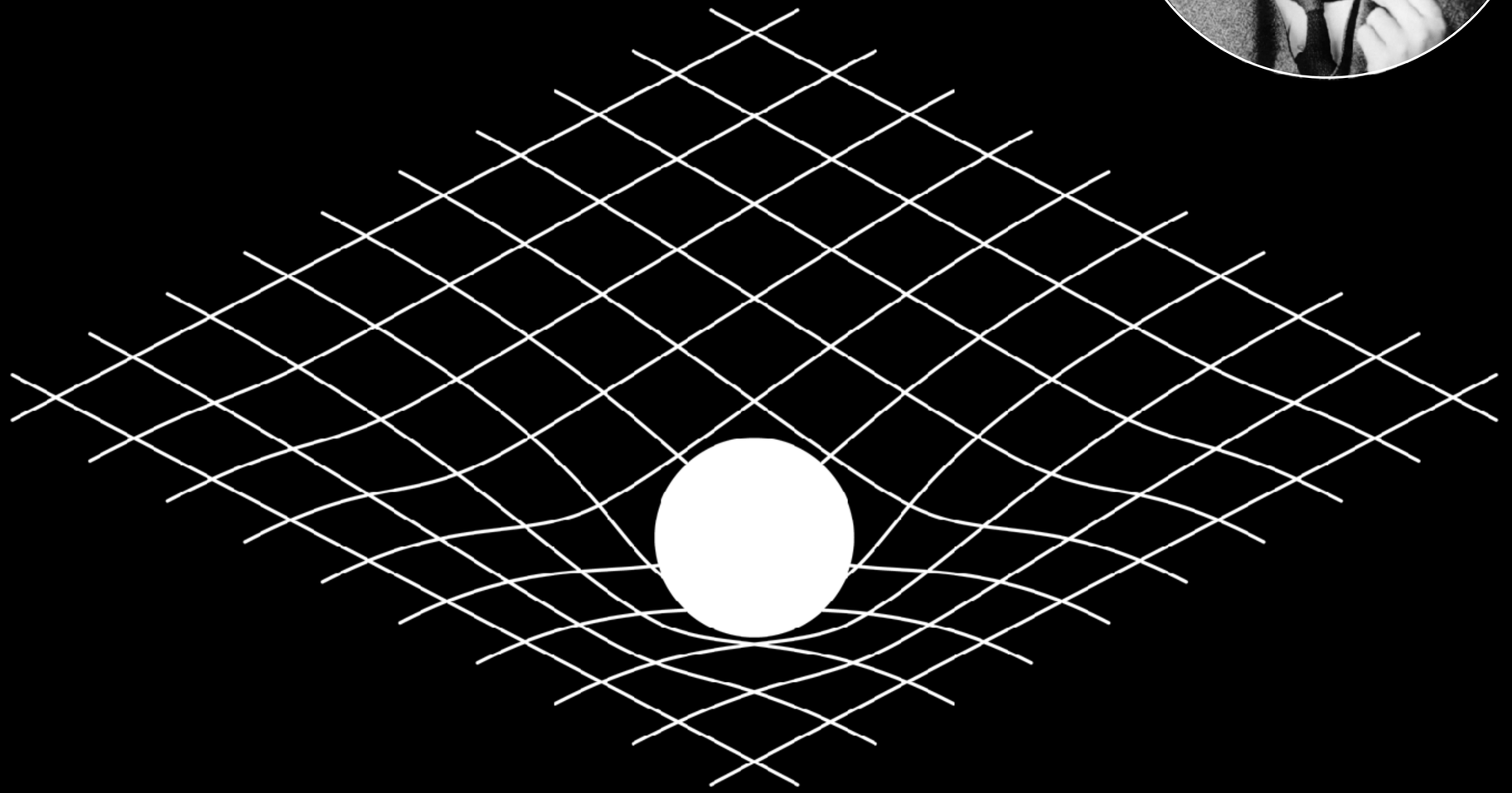
[credit: SXS]

Space-time curves

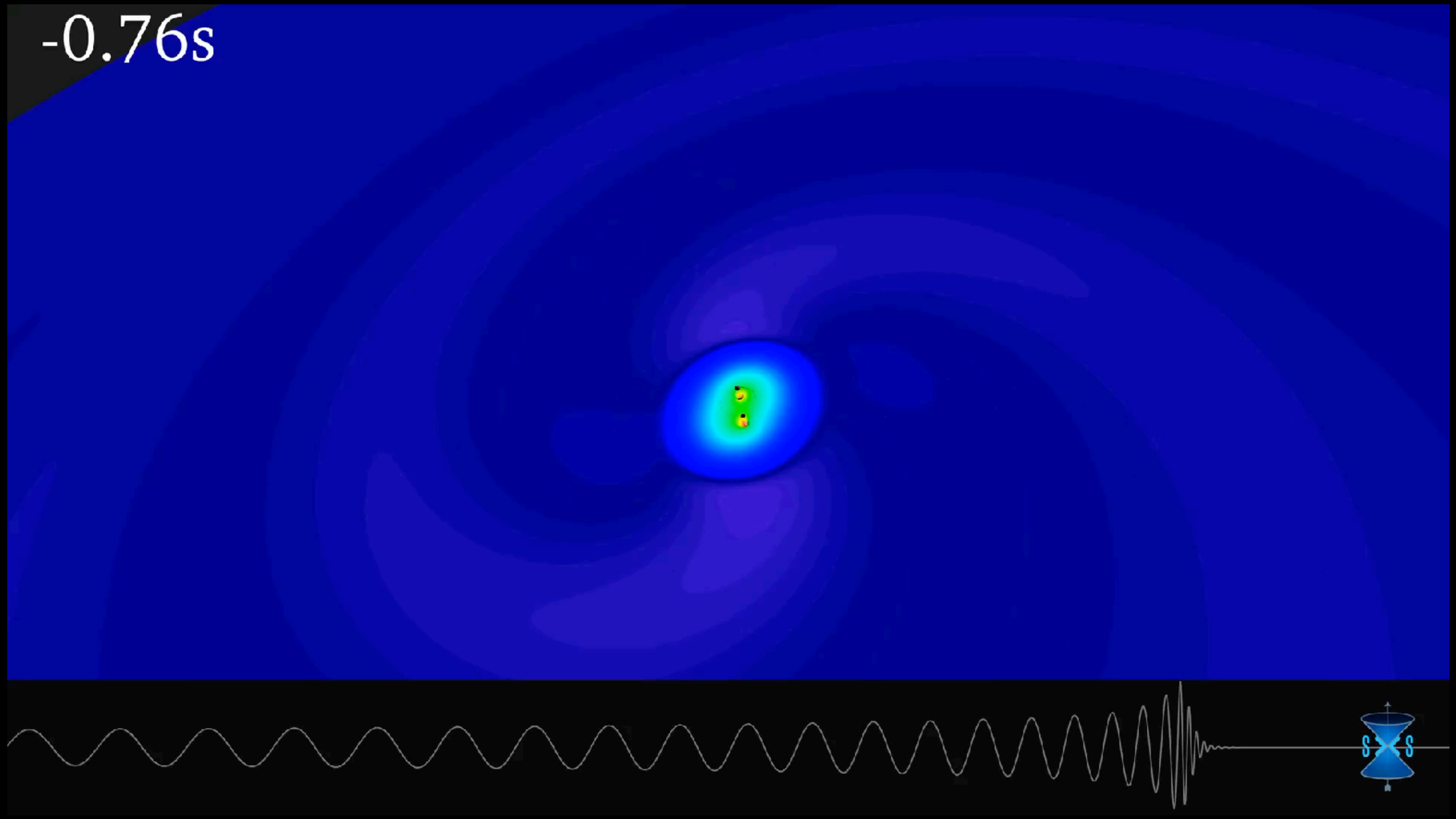


Space-time curves

Space-time is dynamic



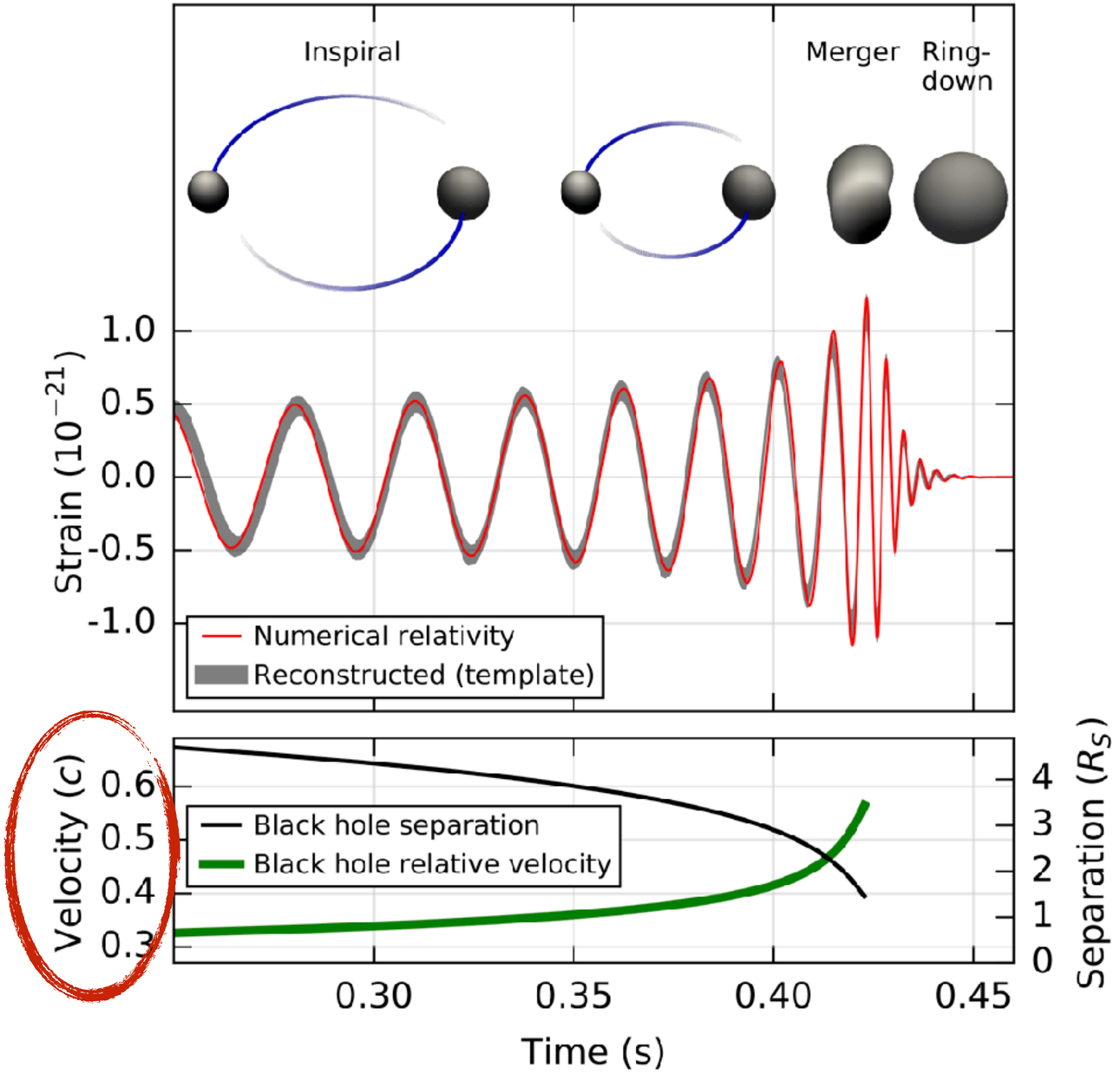
Numerical simulation of a binary black hole merger



[Credit: SXS]

Gravitational waves from stellar-mass **binary black holes**

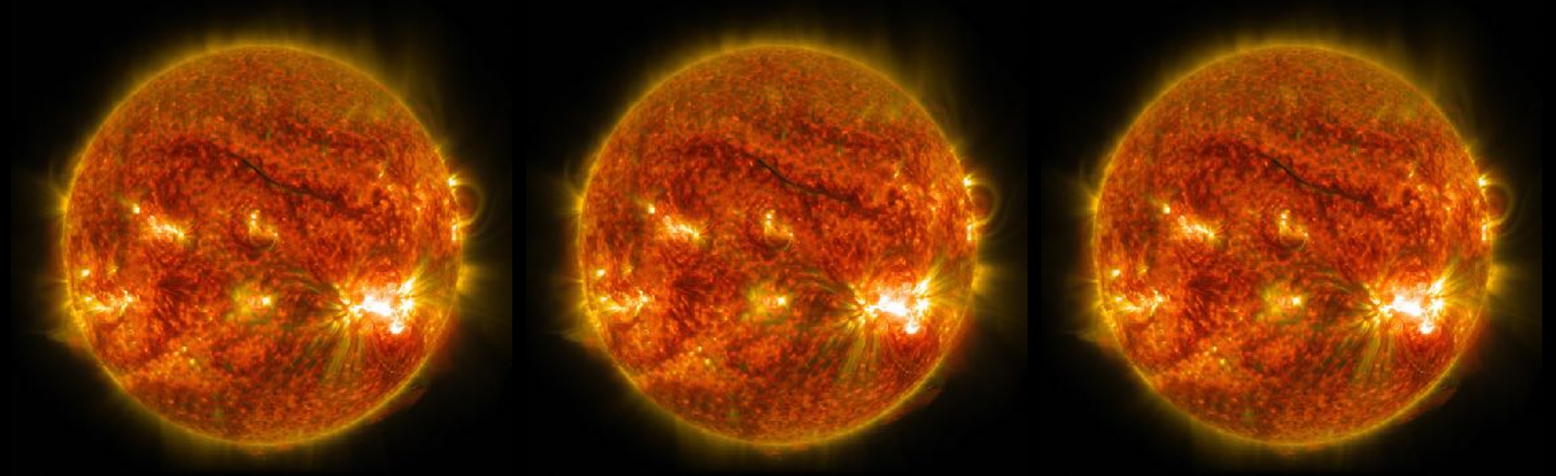
Strong-field gravity



[First detection, GW150914]

Energy emitted in gravitational waves

=



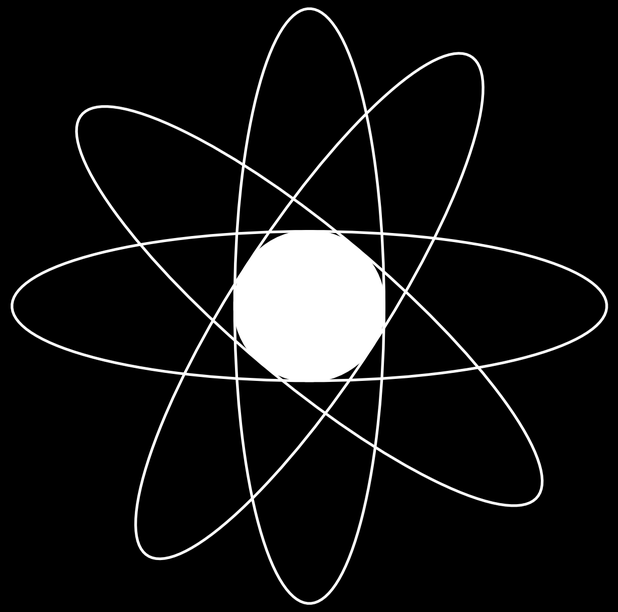
>

How large is the effect?

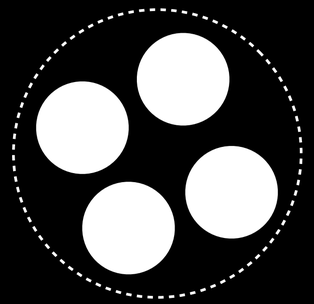
[Credit: R. Hurt, Caltech/MIT/LIGO Lab]

The variation in the distance at the detector is minuscule

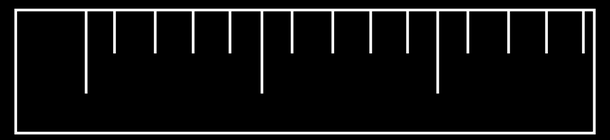
0.00000000000000001 meters



atom: 10^{-10} meters

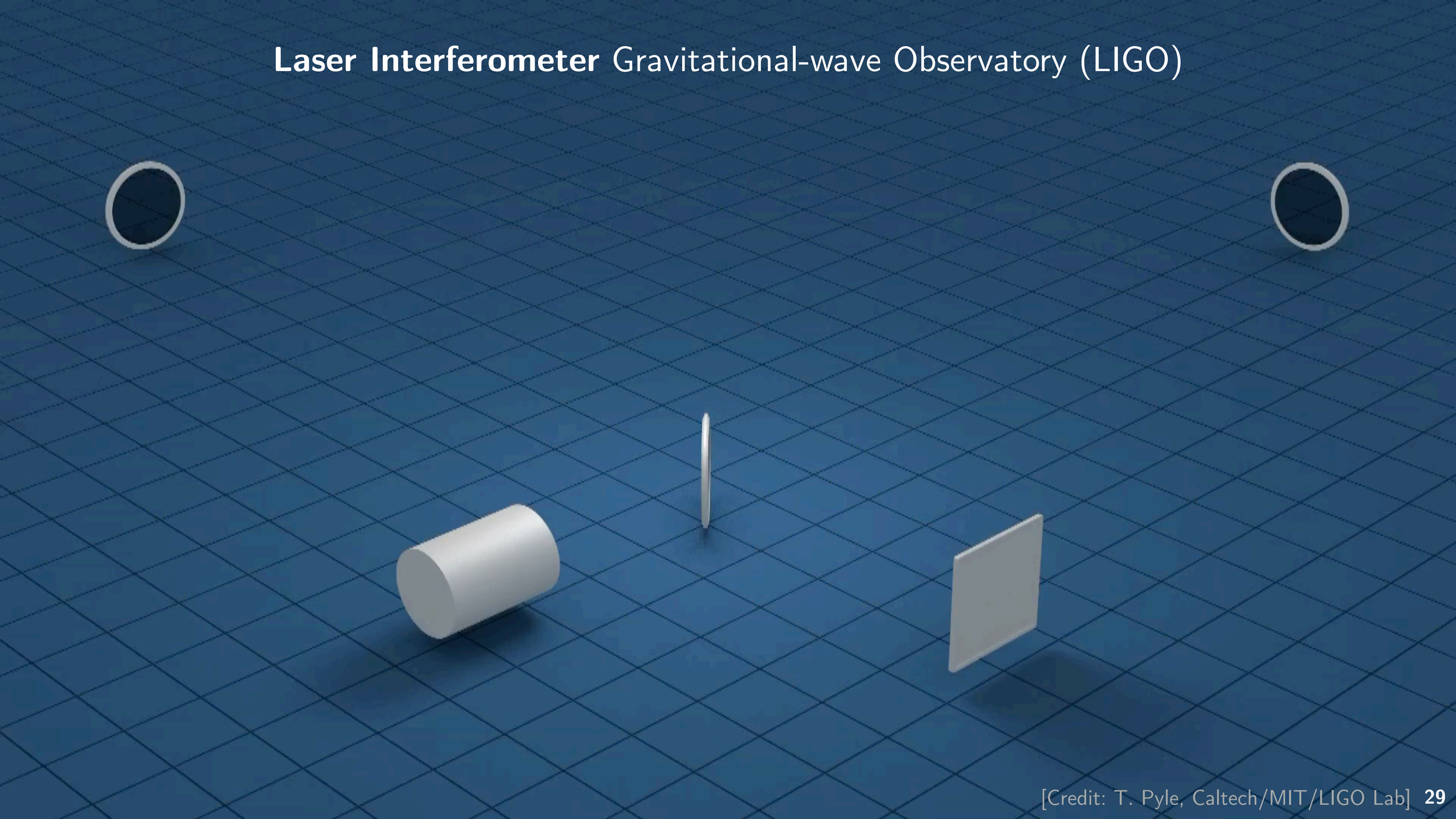


nucleus: 10^{-15} meters

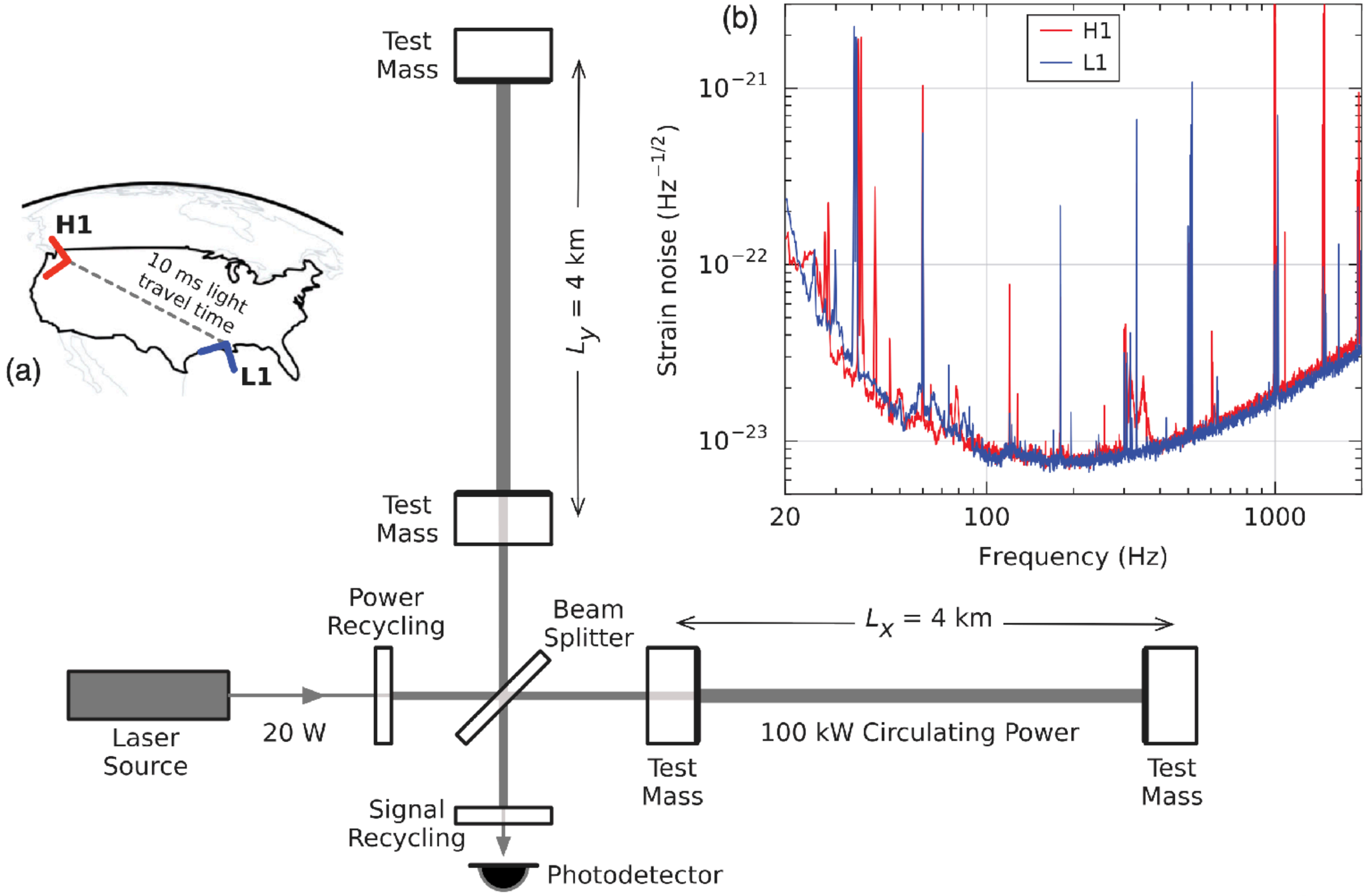


GW effect: 10^{-18} meters

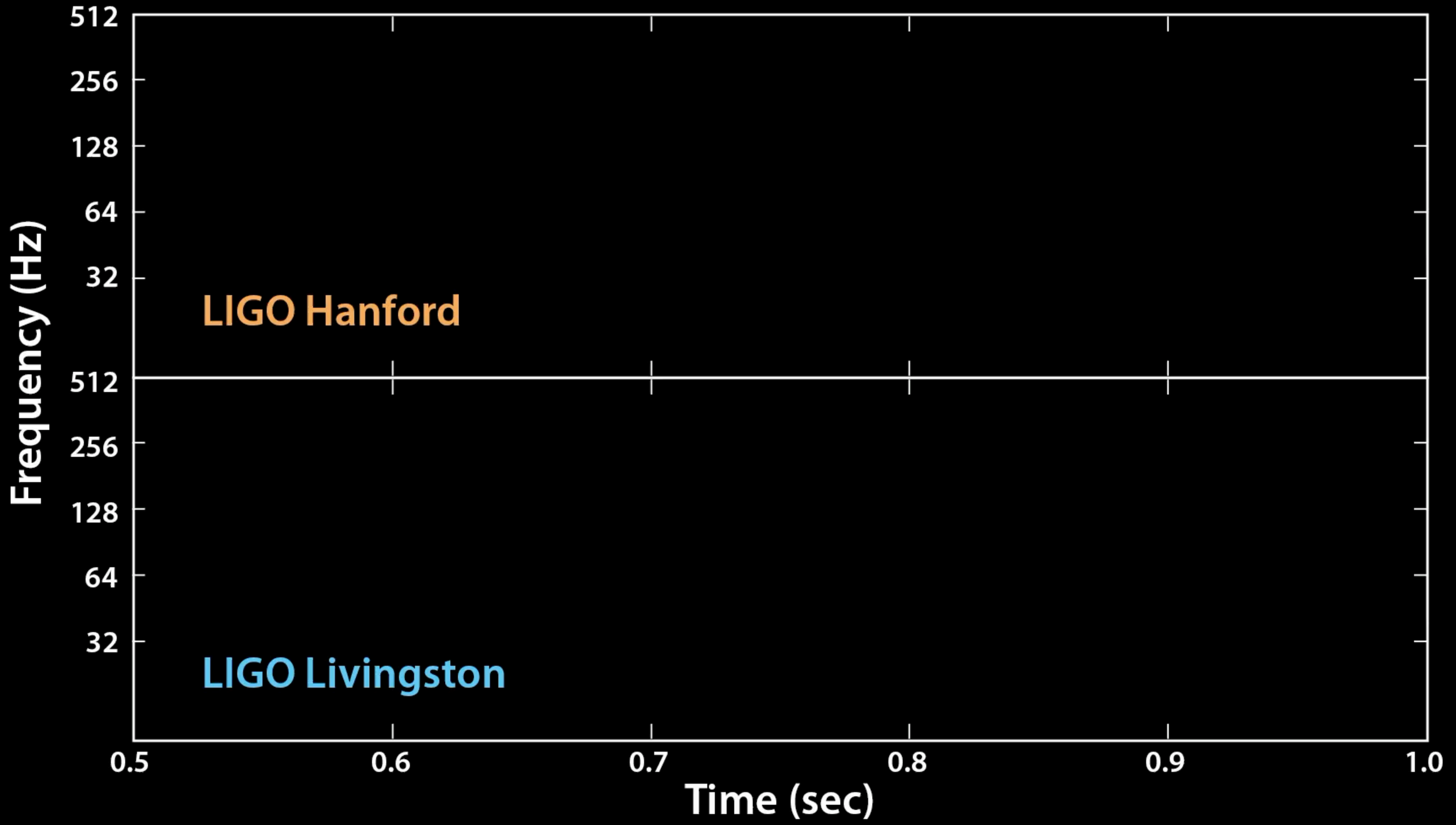
Laser Interferometer Gravitational-wave Observatory (LIGO)



[Credit: T. Pyle, Caltech/MIT/LIGO Lab]

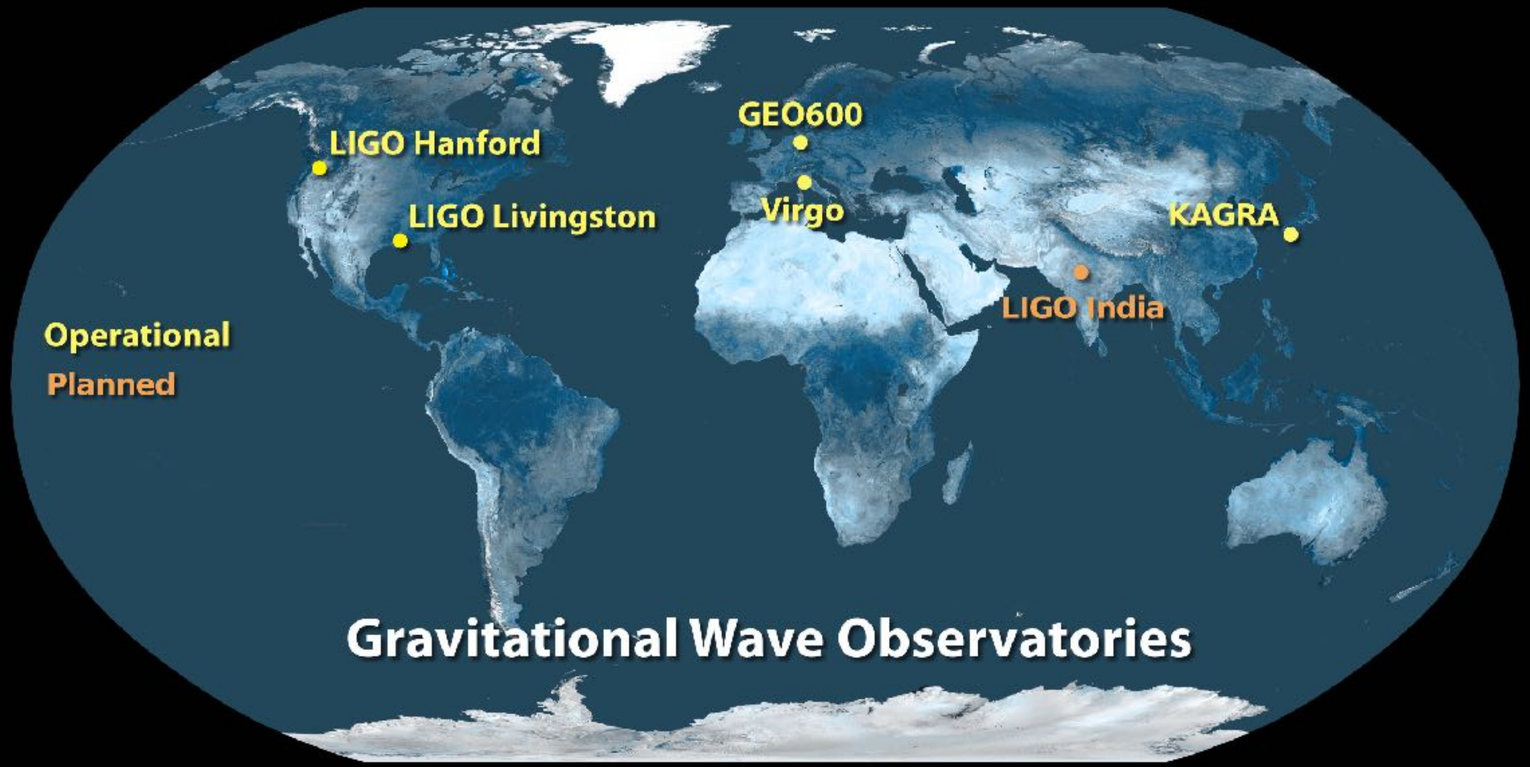

H1
10 ms light travel time
L1
(a)
Test Mass
L_y = 4 km
Test Mass
Power Recycling
Beam Splitter
L_x = 4 km
Laser Source
20 W
Test Mass
100 kW Circulating Power
Test Mass
Signal Recycling
Photodetector
(b)
H1
L1
10^{-21}
10^{-22}
10^{-23}
Strain noise ($Hz^{-1/2}$)
20
100
1000
Frequency (Hz)

[Credit: LIGO]



[Credit: LIGO/VIRGO]

A *global* gravitational wave detector network



[Hanford, US]

[Livingston, US]

[Virgo, Italy]

[KAGRA, Japan]

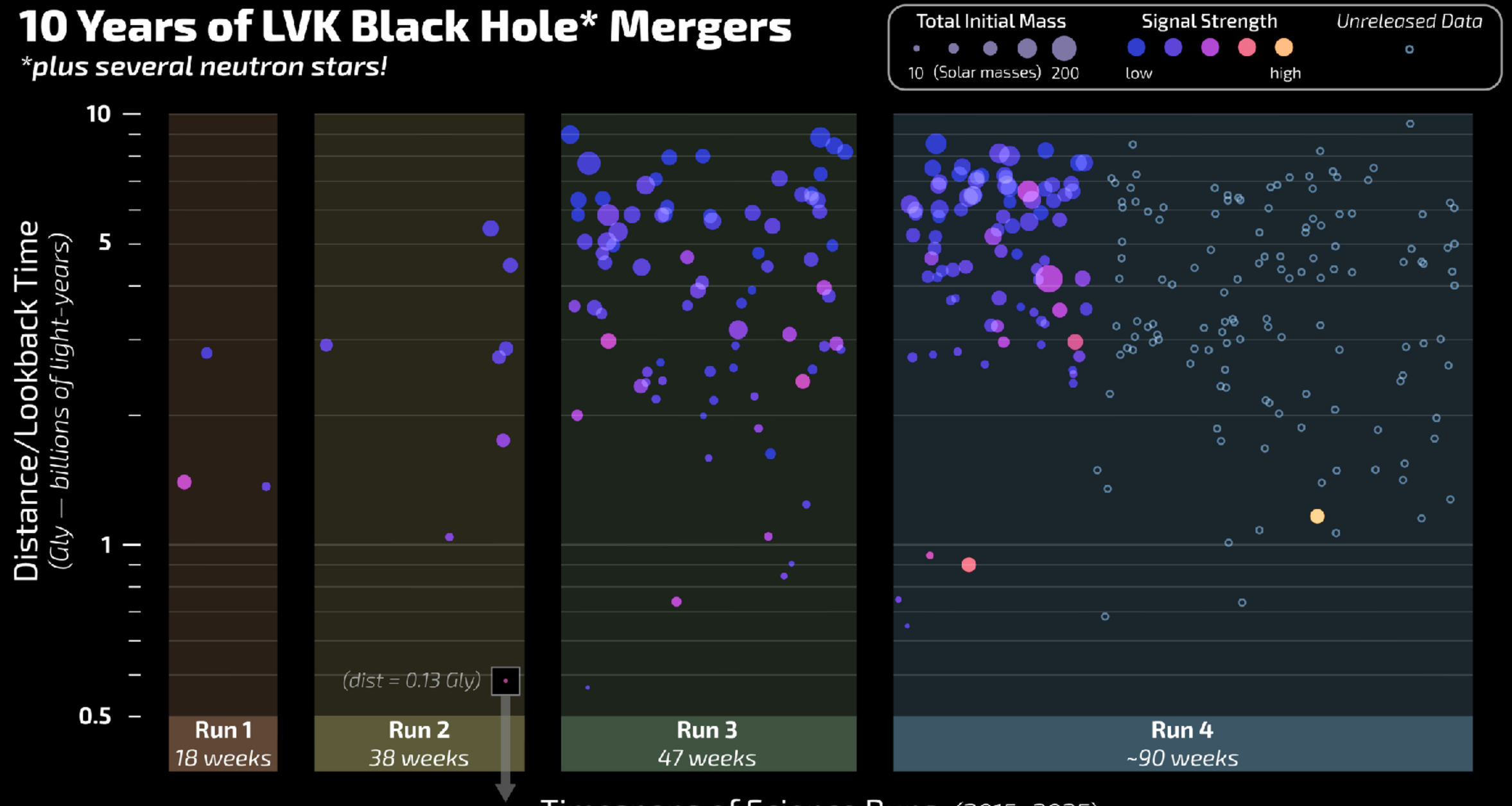
[Lorena @LIGO Livingston, 2015]

[Juno @Virgo, 2018]

[Rico & Jose @KAGRA, 2023]

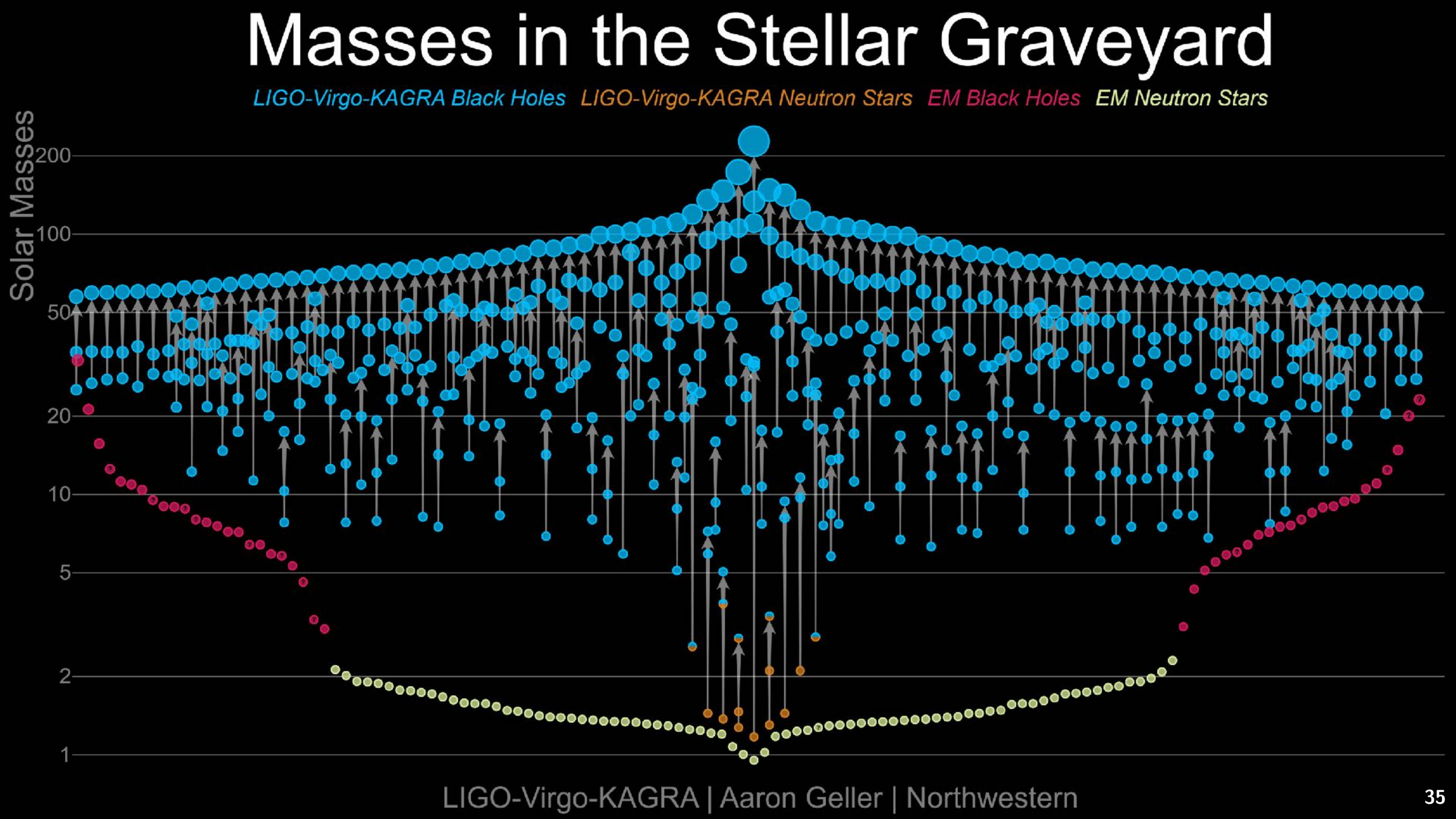
10 Years of LVK Black Hole* Mergers

**plus several neutron stars!*



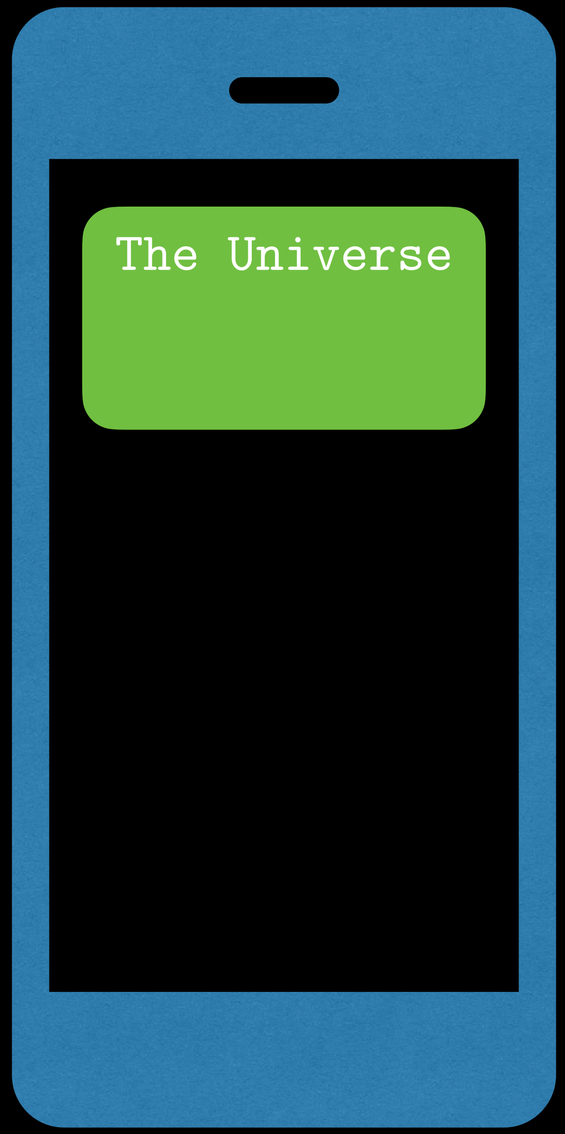
[Credit: LIGO/Caltech/MIT/R. Hurt (IPAC)]

Masses in the Stellar Graveyard

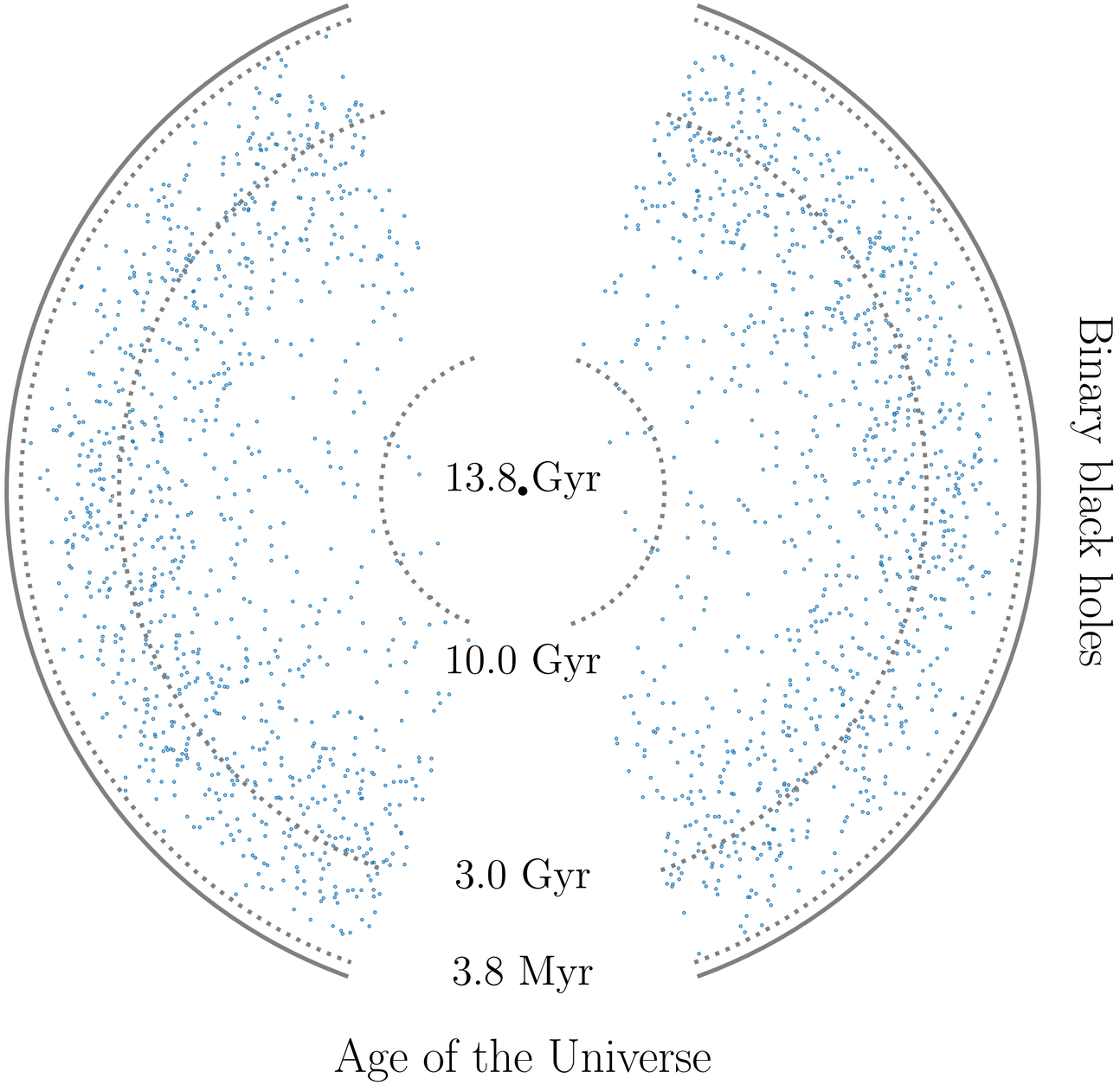


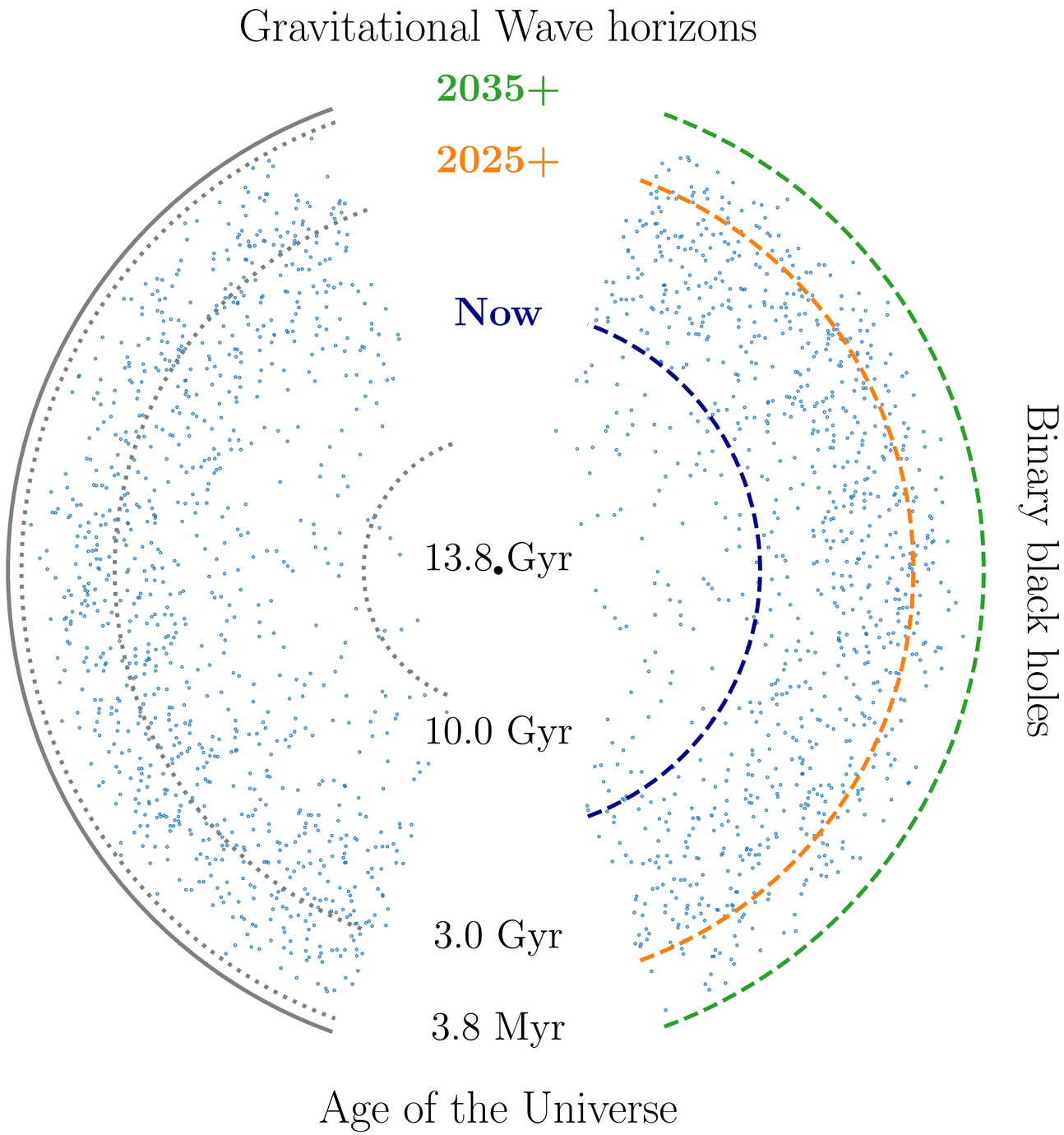
And if you want more, we are still taking data!

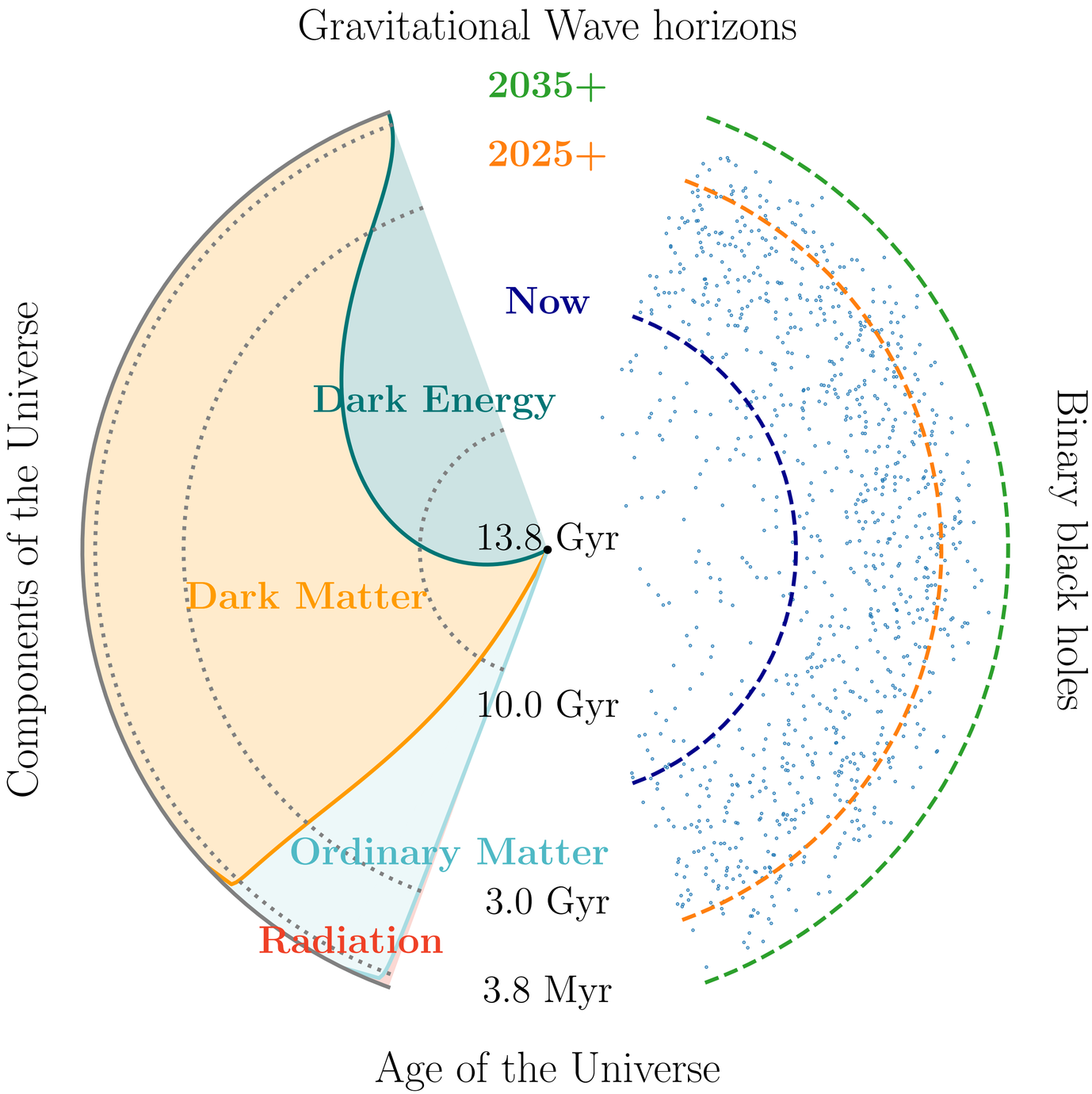
https://gracedb.ligo.org/superevents/public/O4/#



[get alerts for new candidates]


13.8 Gyr
10.0 Gyr
3.0 Gyr
3.8 Myr
Age of the Universe
Binary black holes


Gravitational Wave horizons
2035+
2025+
Now
13.8 Gyr
10.0 Gyr
3.0 Gyr
3.8 Myr
Binary black holes
Age of the Universe


Gravitational Wave horizons
2035+
2025+
Now
Components of the Universe
Dark Energy
13.8 Gyr
Dark Matter
10.0 Gyr
Ordinary Matter
3.0 Gyr
Radiation
3.8 Myr
Binary black holes
Age of the Universe


? ? ? ? ?
CBS