Multi-messenger Astronomy

a crash-course

ASTR133, May 2021

Jose María EZQUIAGA
NASA Einstein Fellow
ezquiaga@uchicago.edu

THE UNIVERSITY OF CHICAGO

How this lecture will work?

First part: theory (be active!)

Second part: activity (hands-on)

This is a HUGE research area, tons of materials.
This is only the tip of the iceberg. Explore!

K: key concepts

Q/A: questions for you (✋)

R: research about it!

All materials will be shared

Contents

0. **Basic concepts**

   Our universe and the standard model of cosmology

1. **Cosmic messengers**

   Electromagnetic radiation, neutrinos, gravitational waves

2. **Examples of multi-messenger astronomy**

   Supernovas, binary neutron stars and supermassive black holes

Activity

Cosmology and fundamental physics with multi-messenger GW astronomy

Contents

Solar System (Copernicus 1473-1543)

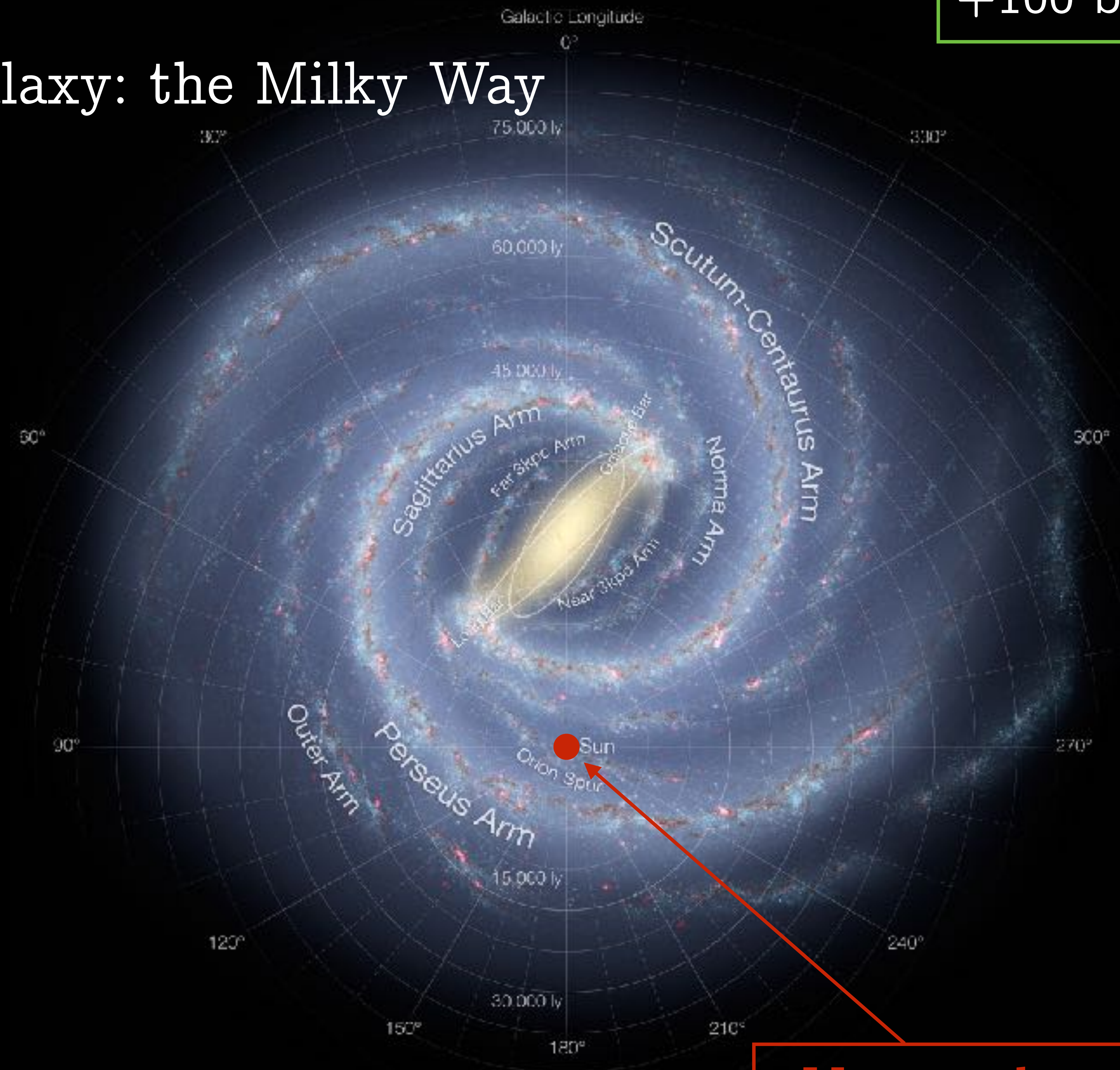
You are here


NICOLAI COPERNICI

net, in quo terram cum orbe lunari tanquam epicyclo contineri diximus. Quinto loco Venus nono menſe reducitur. Sextum deniq; locum Mercurius tenet, octuaginta dierum ſpacio circũ currens. In medio uero omnium reſidet Sol. Quis enim in hoc

Our galaxy: the Milky Way

+100 billion stars



You are here

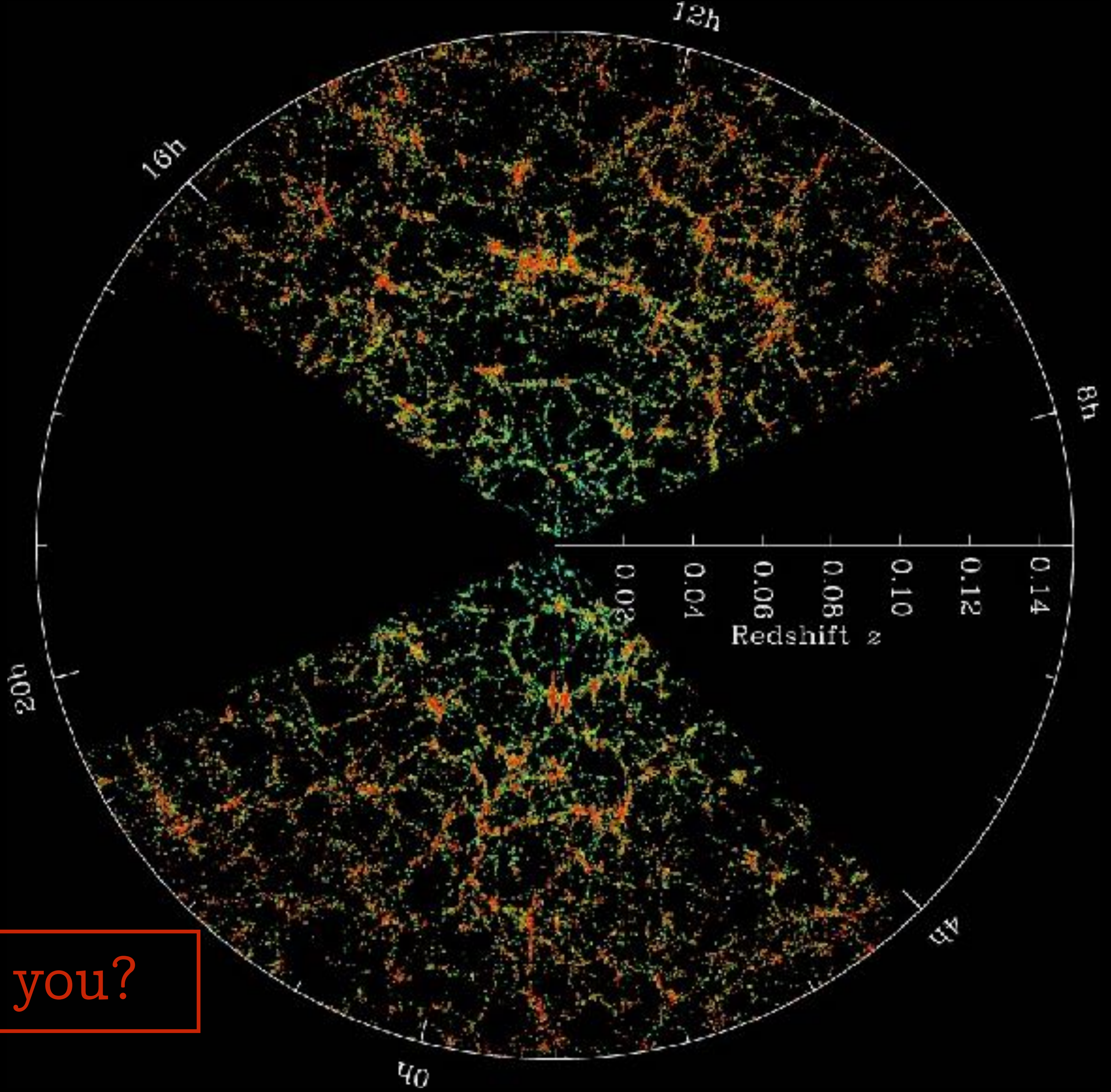
54 galaxies in the local group

1920s. Galaxies beyond Milky Way

You are here

aprox. 100 billion galaxies

1990s. There are many, many more galaxies

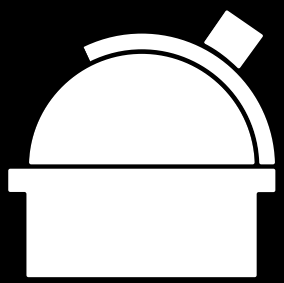


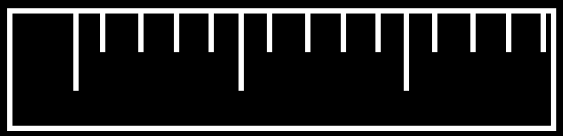
Where are you?

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



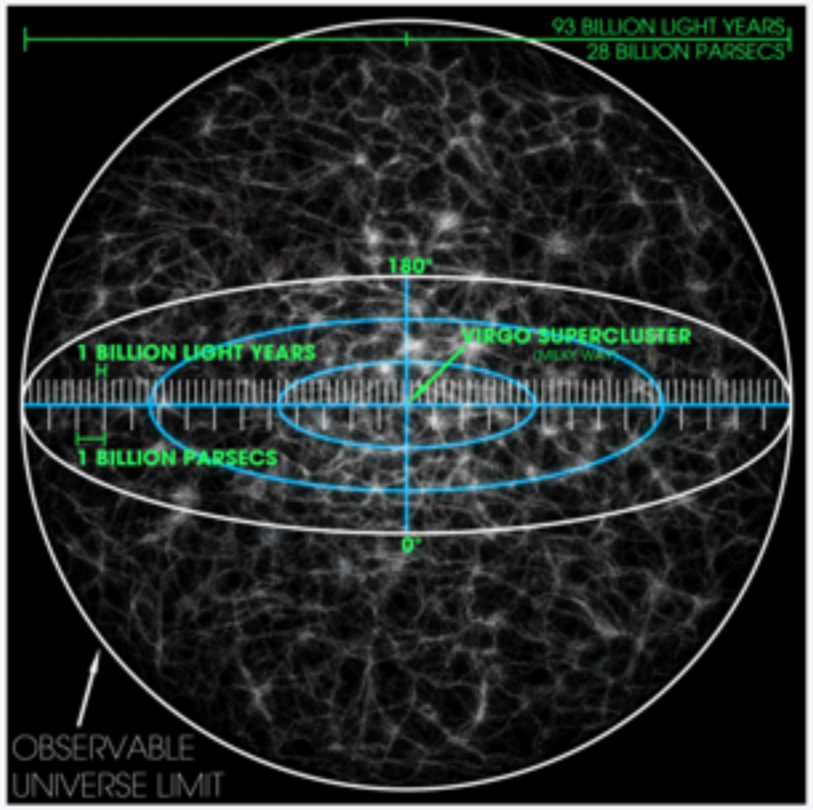


*speed of light 300,000 km/s

K: the universe is BIG

… but almost empty on average

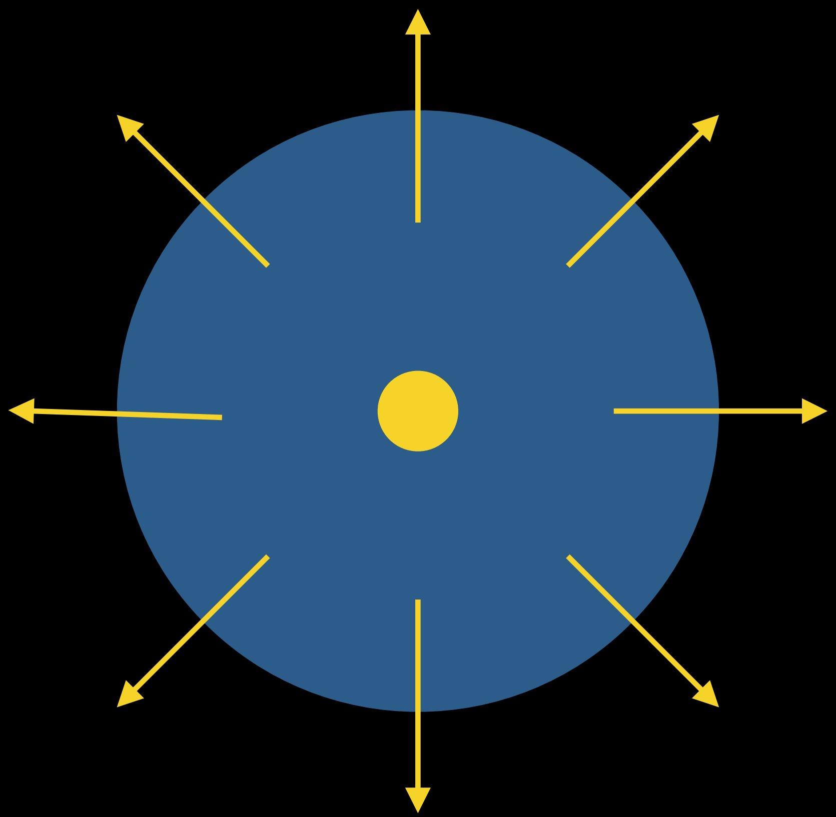
Observable universe



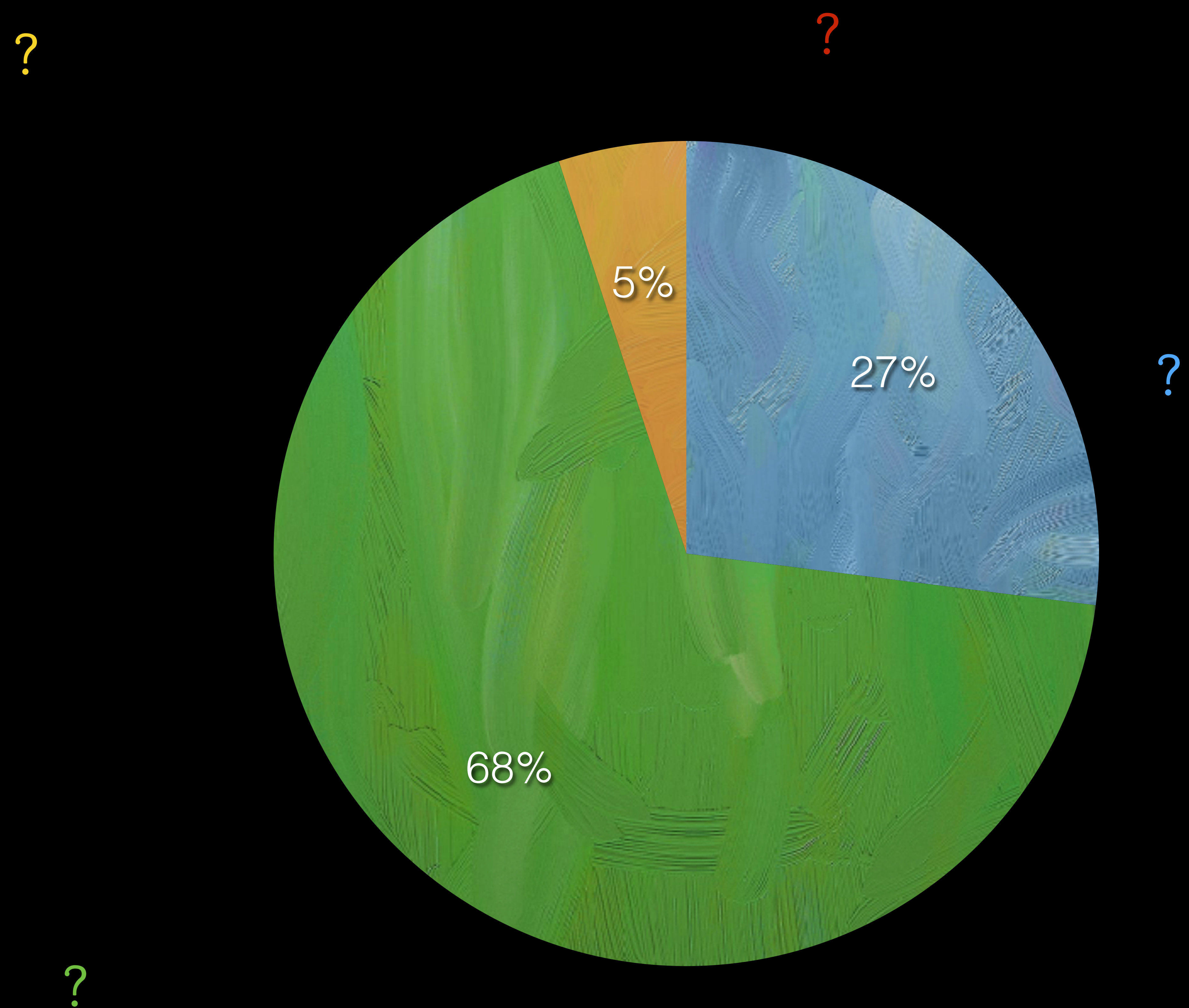
Visualization of the whole observable universe. The scale is such that the fine grains represent collections of large numbers of superclusters. The Virgo Supercluster —home of Milky Way—is marked at the center, but is too small to be seen.

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]

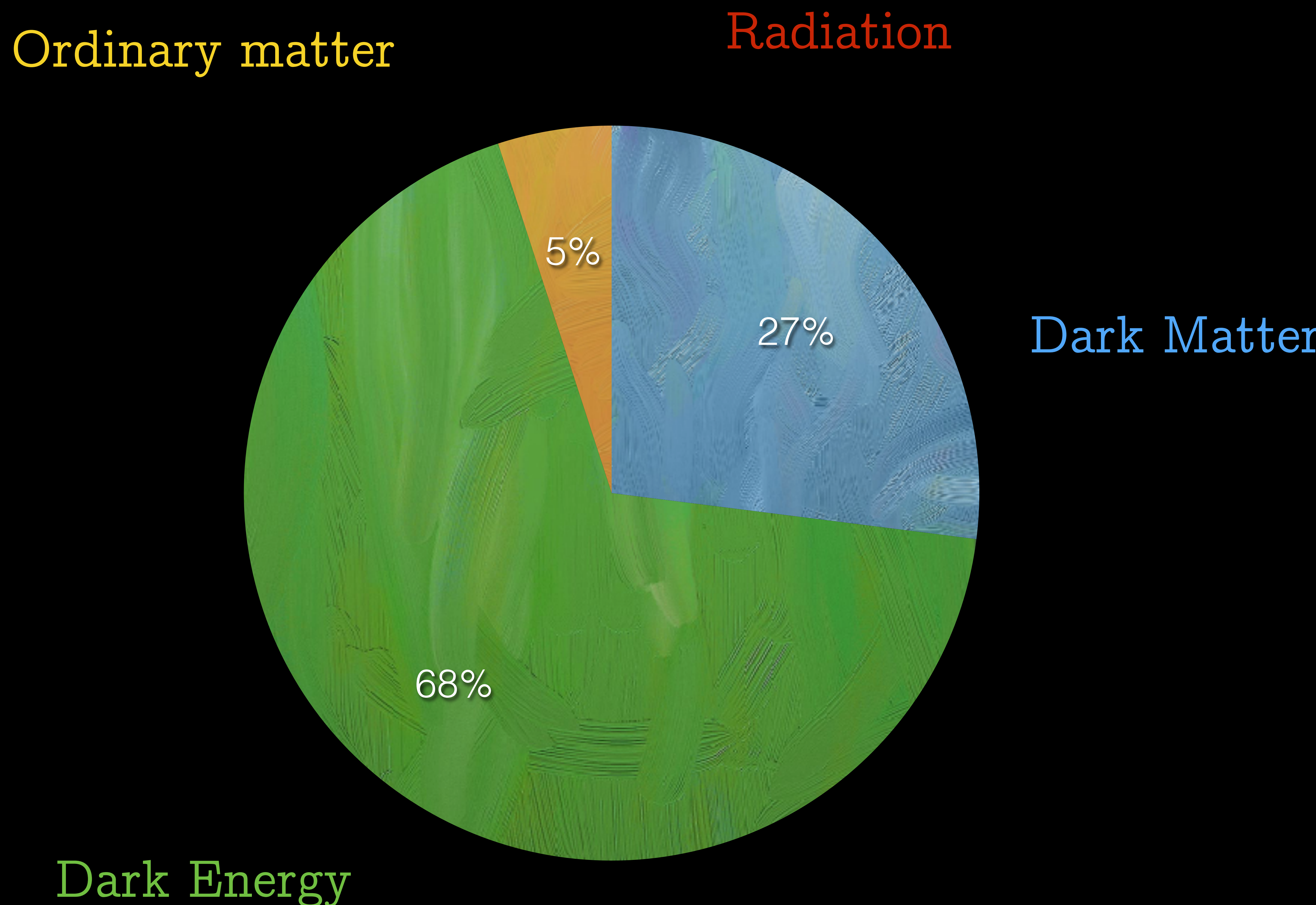
Energy flux $\propto 1/\text{distance}^2$



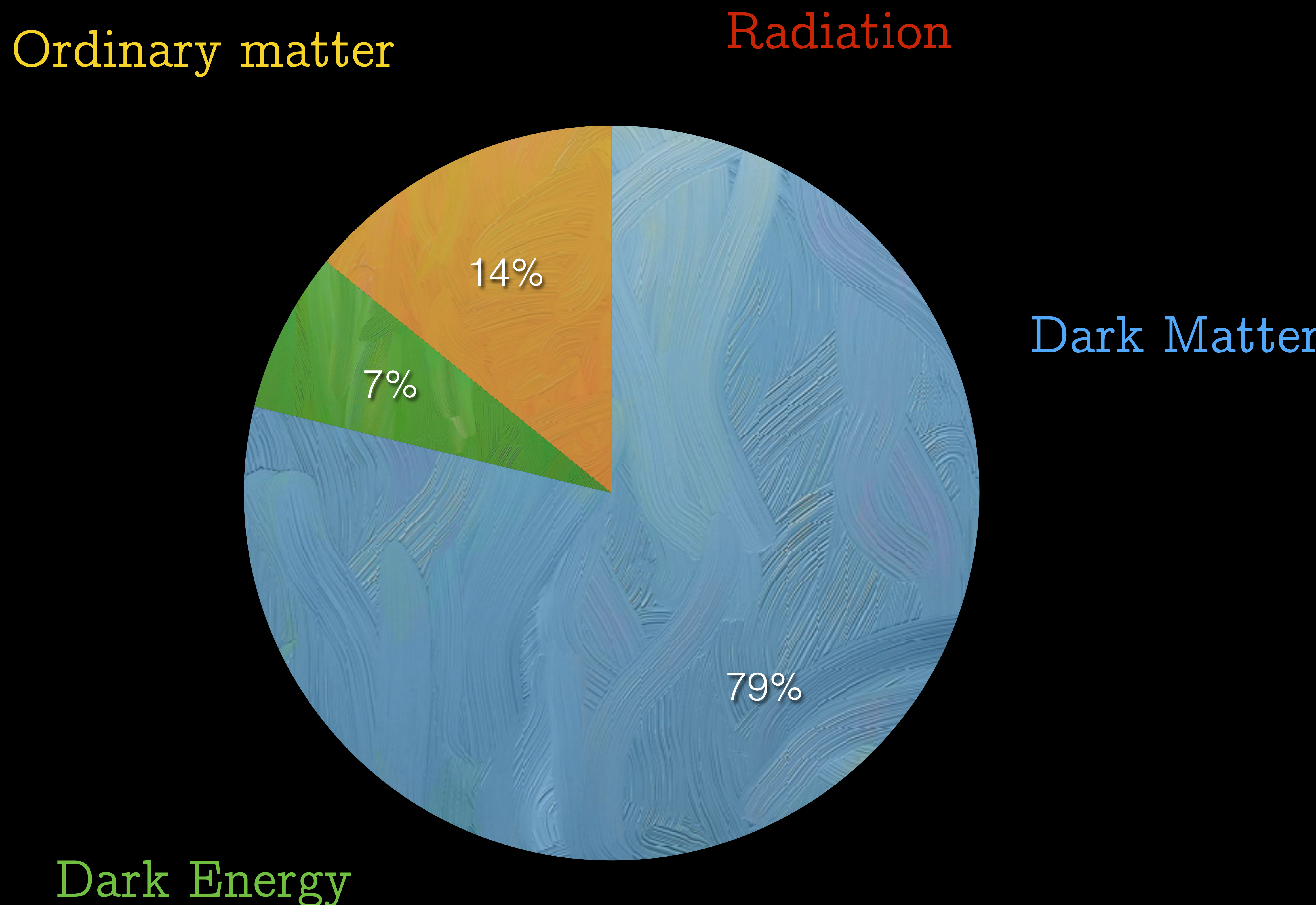
K: need extremely energetic phenomena!



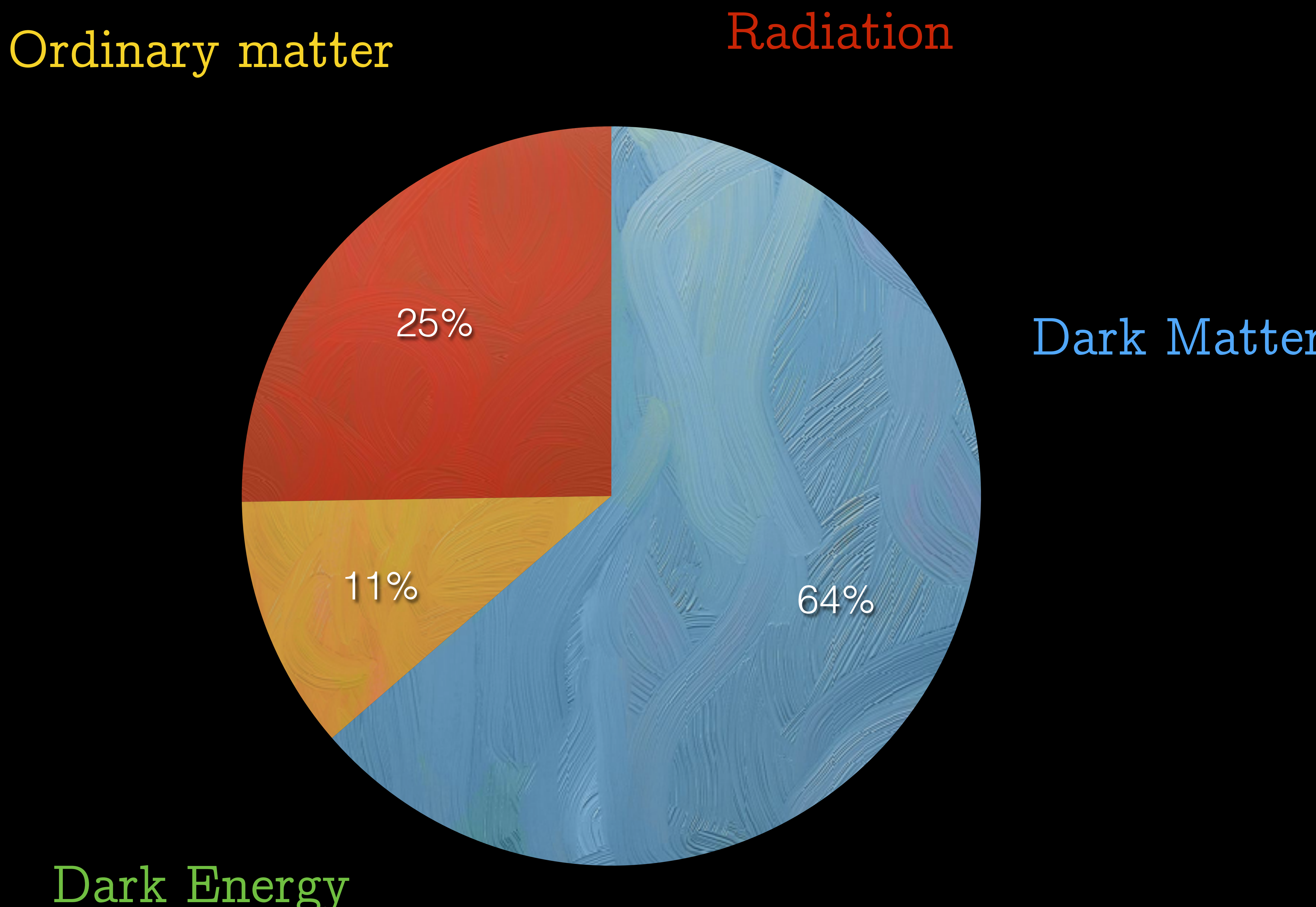
Q/A: What is the universe made of?



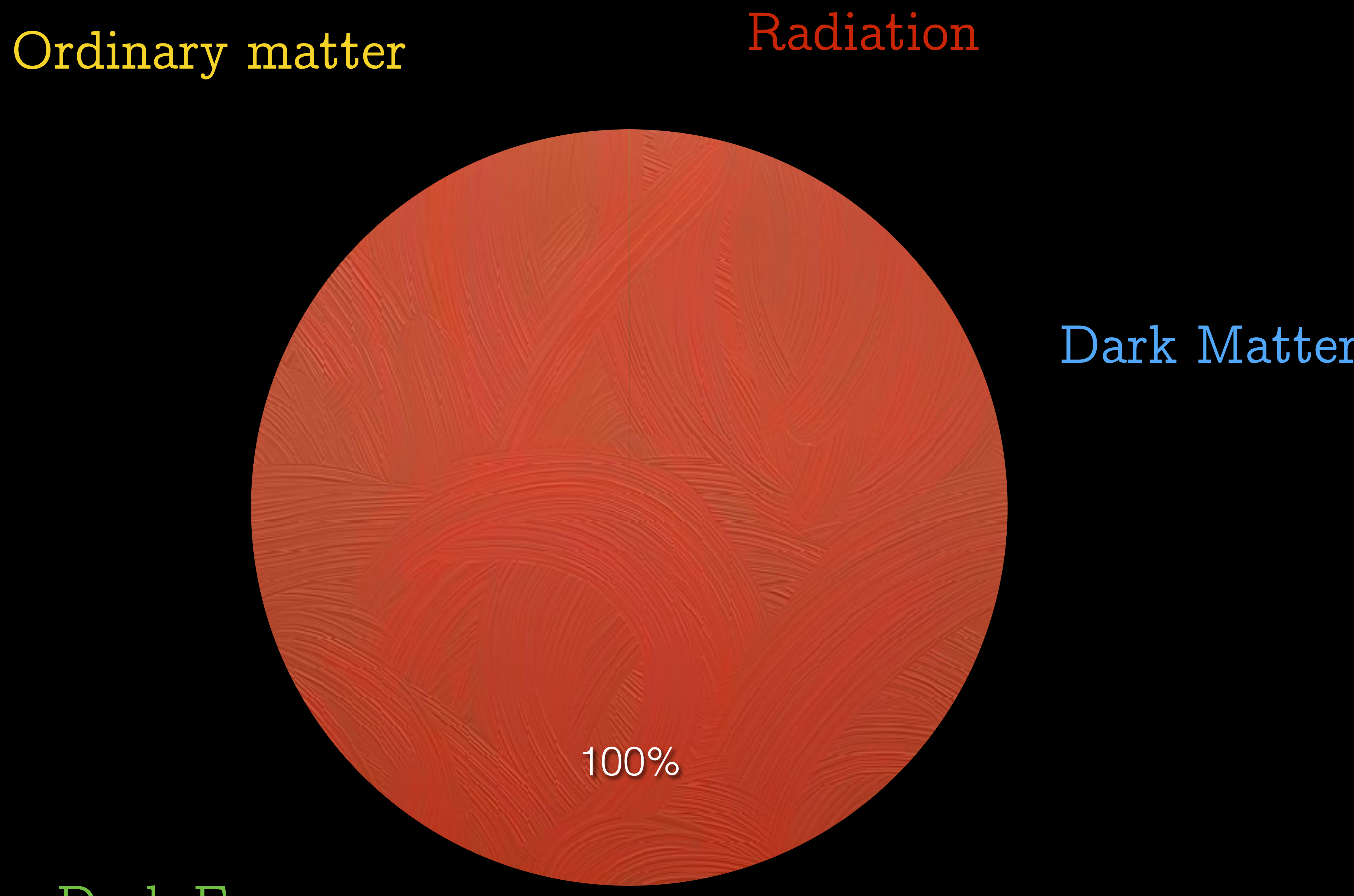
TODAY, 13.8 billion years after Big Bang



First stars, 200 million years after Big Bang

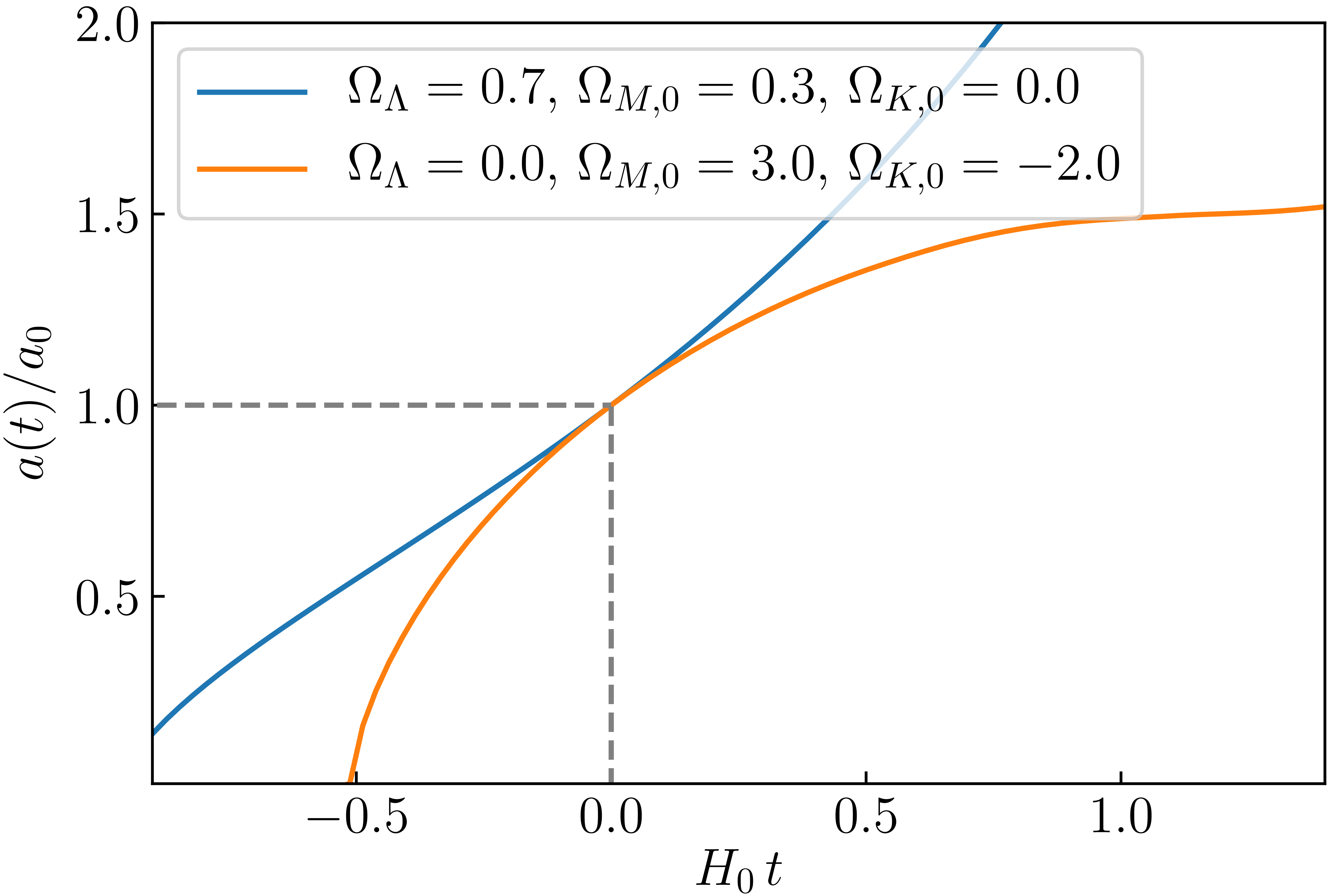


CMB, 380.000 years after Big Bang



Nuclei form, 100 seconds after Big Bang

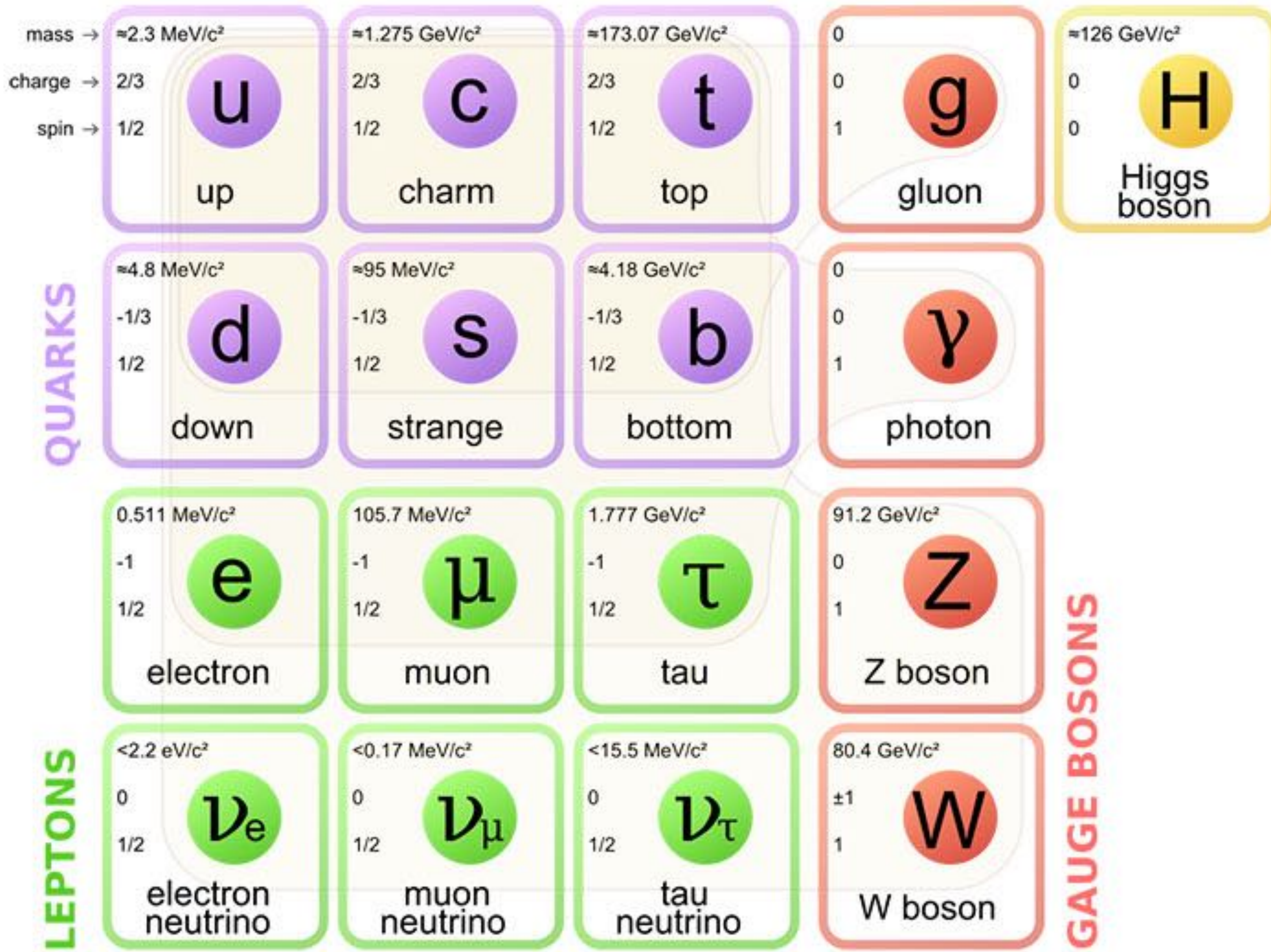
Universe content determines its fate!



$$\boxed{H^2 = H_0^2\left(\Omega_{R,0}(1+z)^4 + \Omega_{M,0}(1+z)^3 + \Omega_{K,0}(1+z)^2 + \Omega_\Lambda\right)}$$

Standard Model of Particle Physics

-everything but DM and DE-



What makes a good messenger?

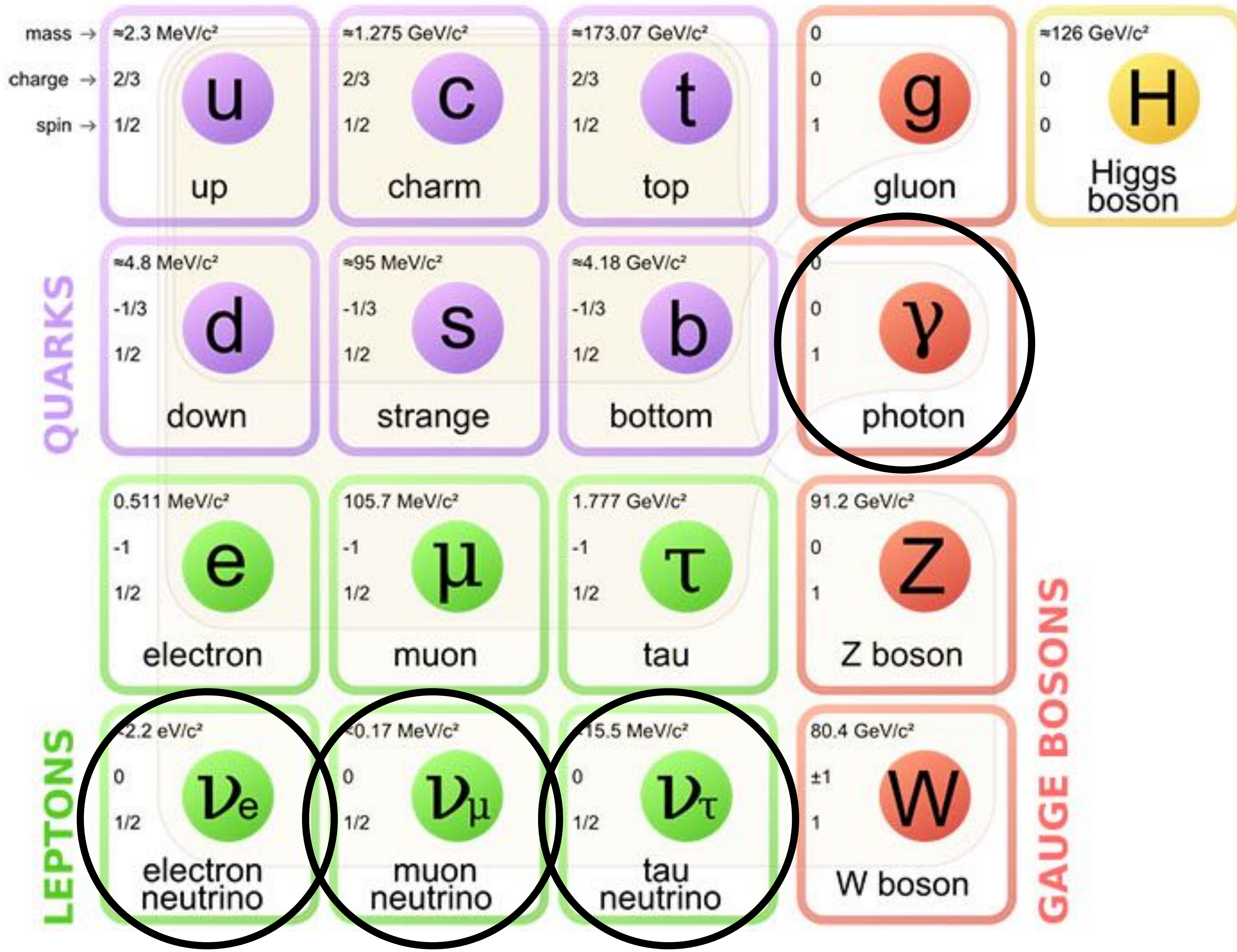
Speed - massless

Avoid interactions - neutral

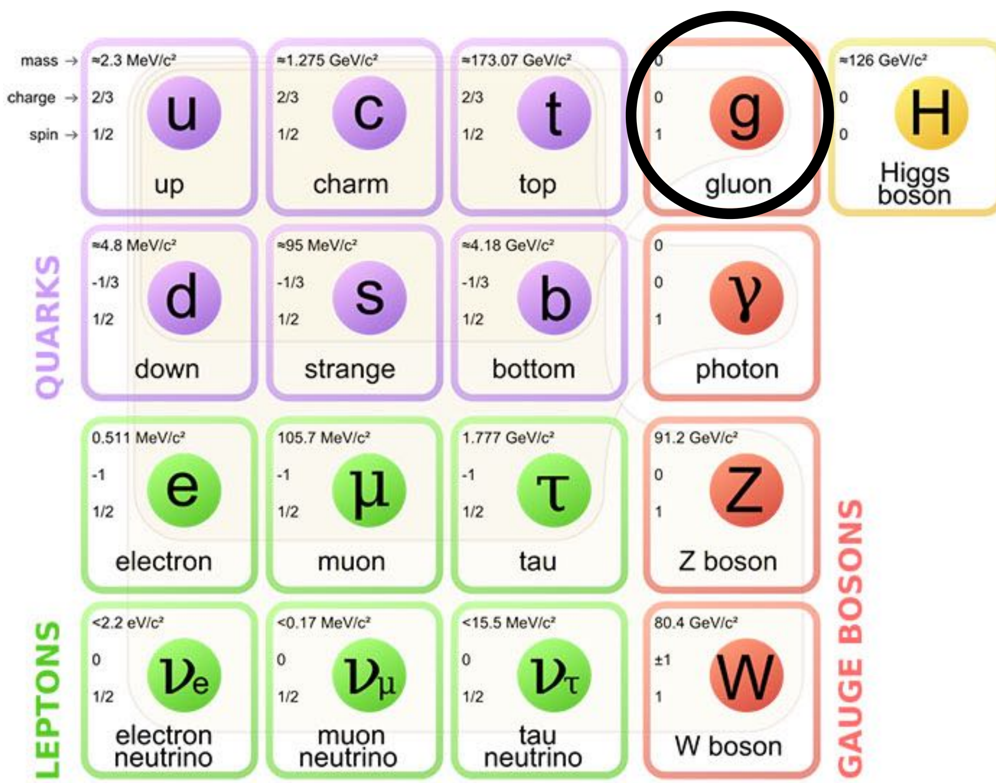
Endurance - stable

Standard Model of Particle Physics

-everything but DM and DE-



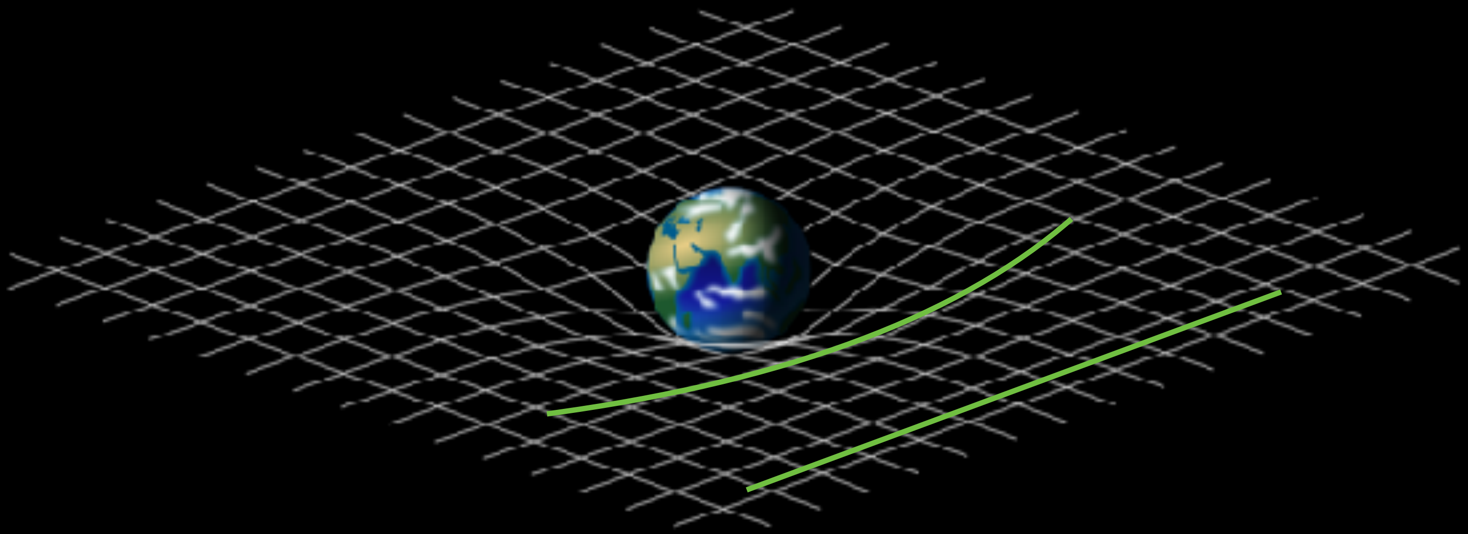
R: why not the gluon?

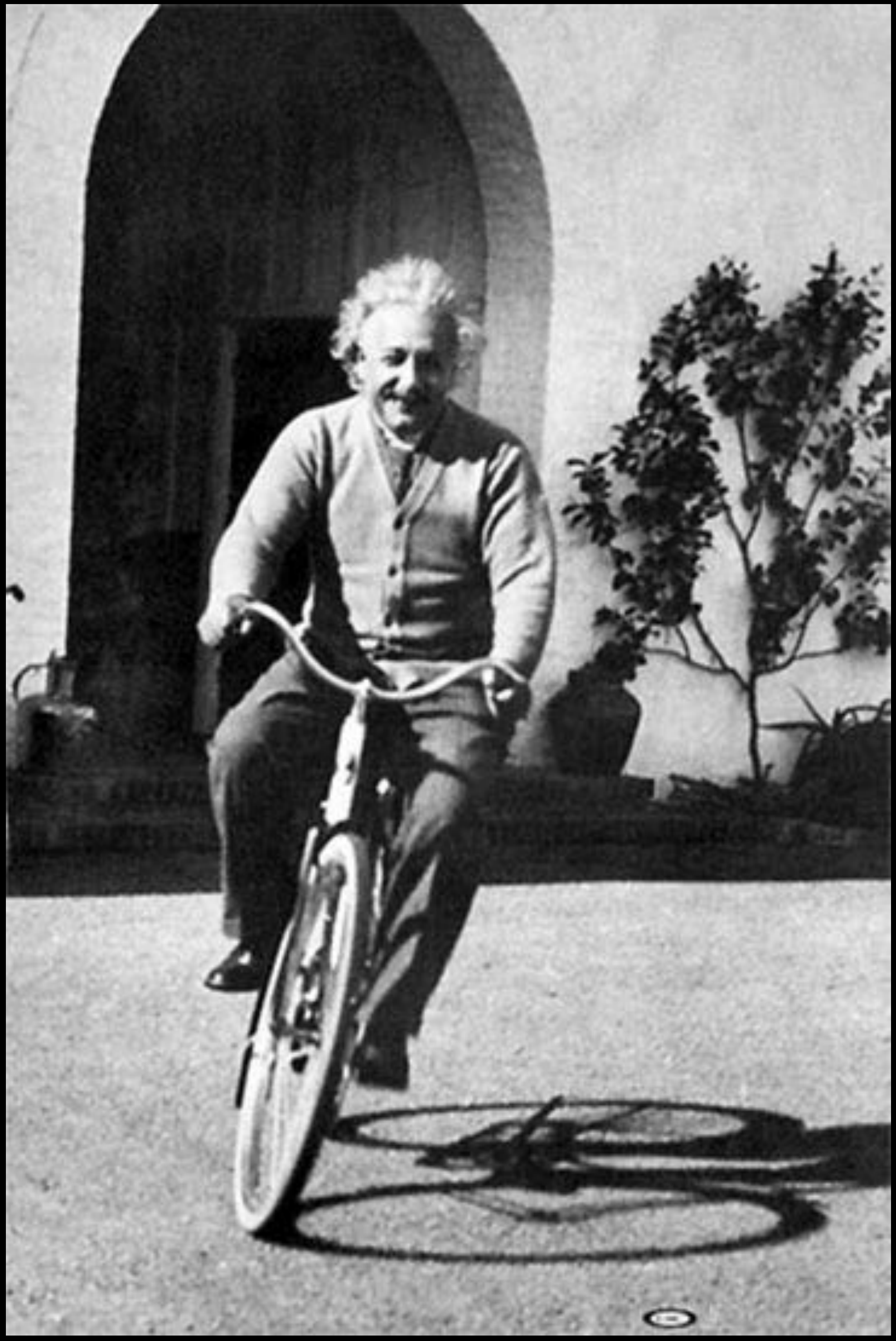


What about gravity?

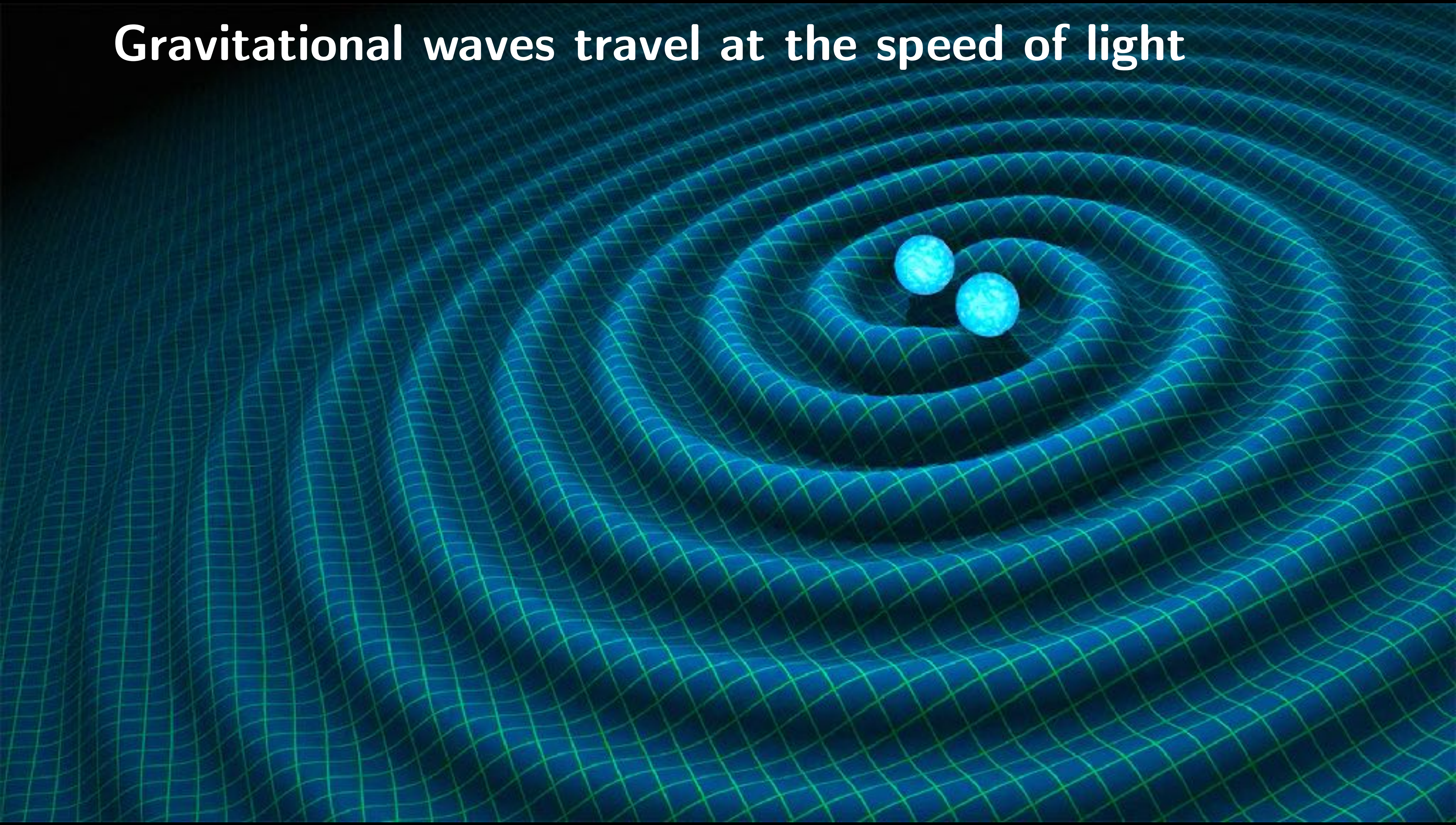
1915. "Massive objects curve space-time"

Trajectories bend





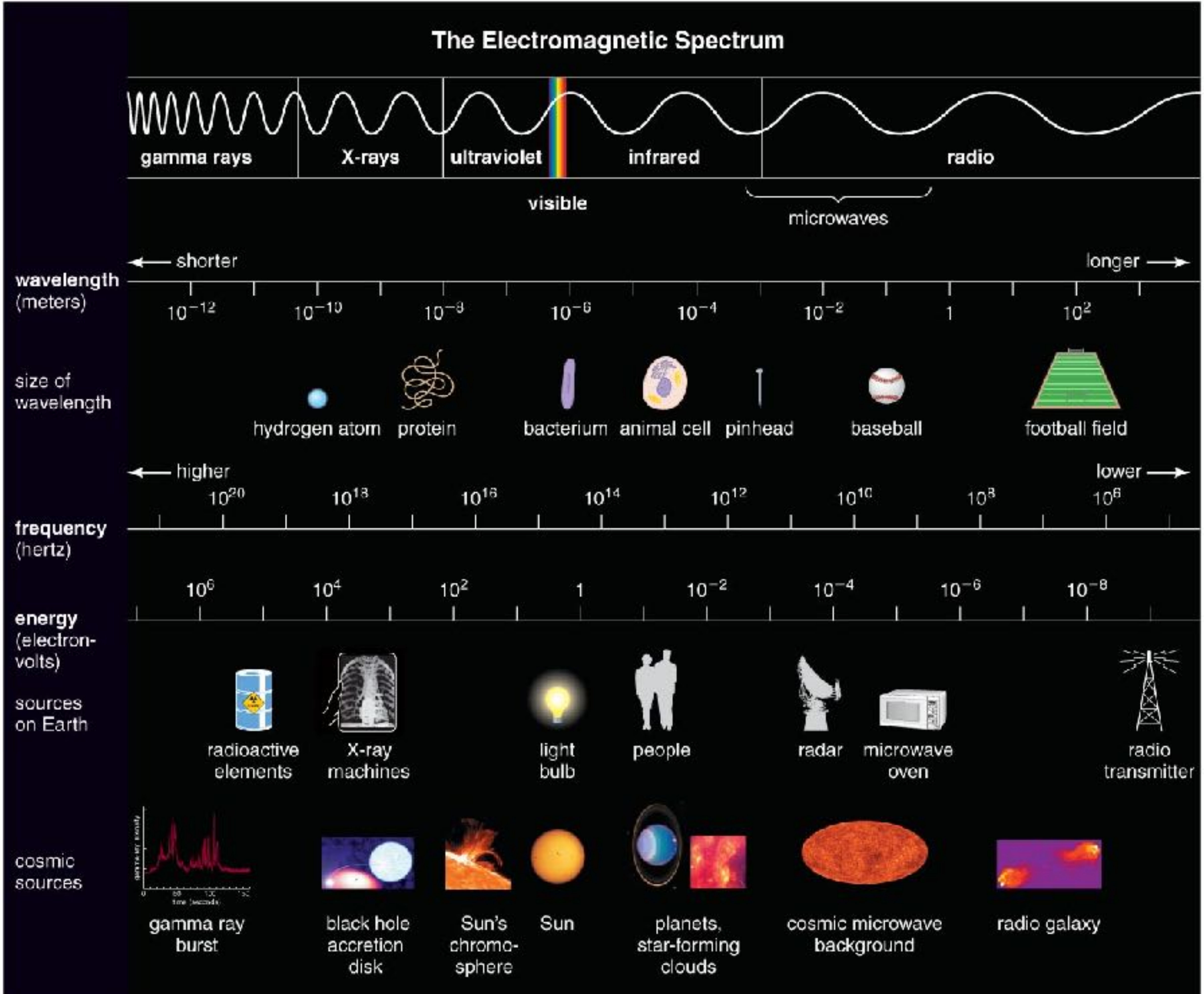
Gravitational waves travel at the speed of light

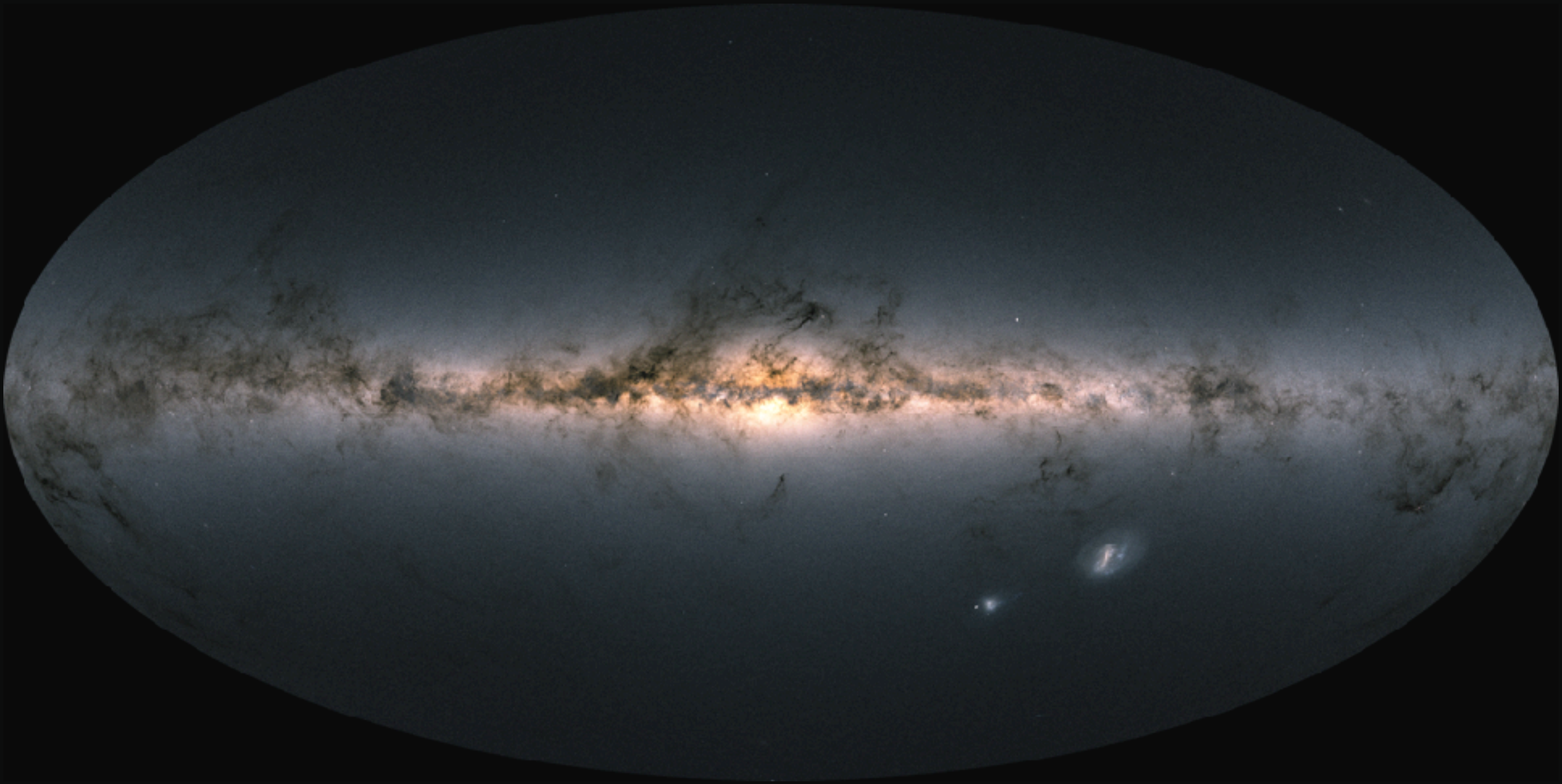


Contents

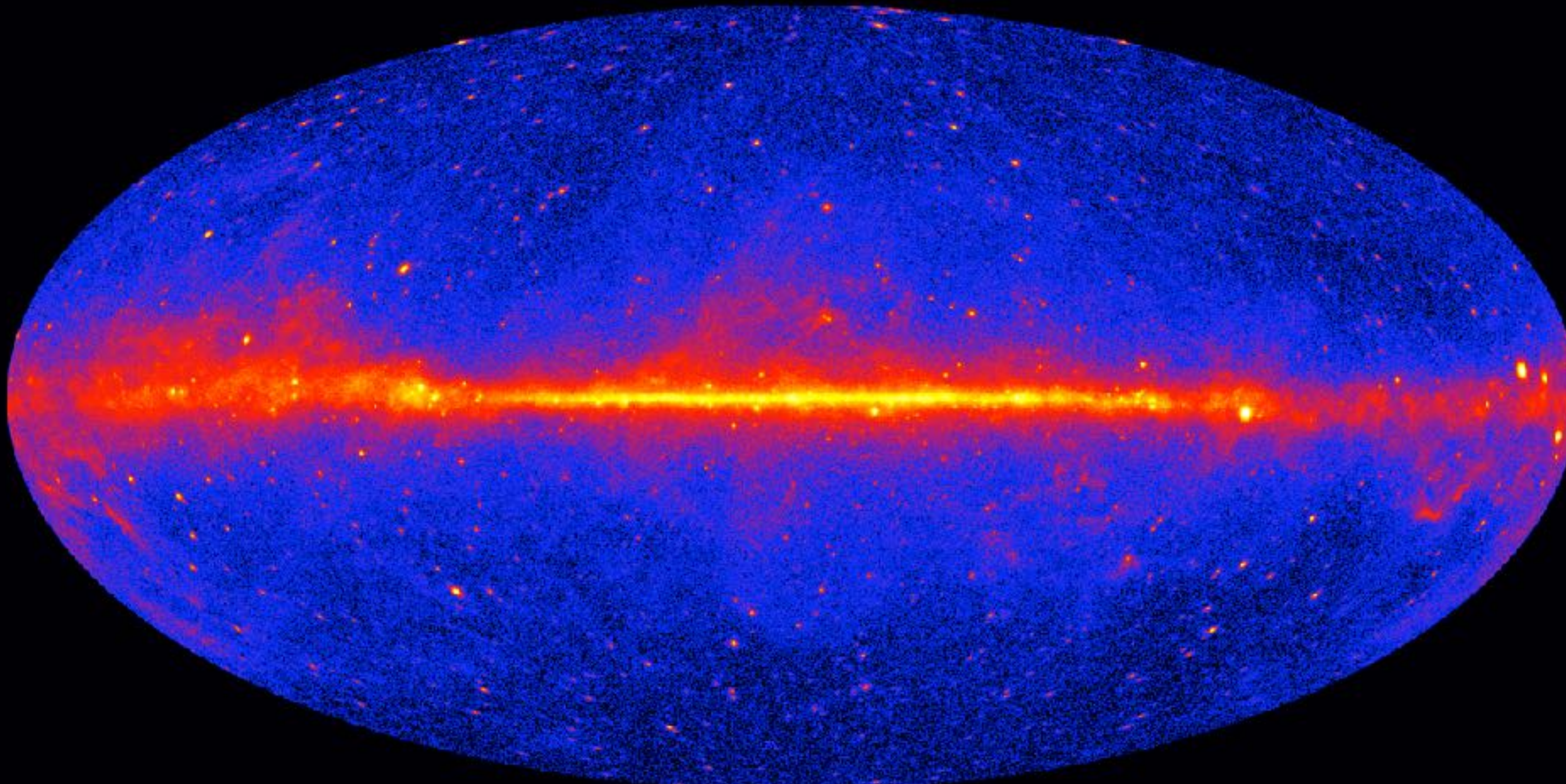





The Electromagnetic Spectrum
gamma rays
X-rays
ultraviolet
infrared
radio
visible
microwaves
shorter
longer
wavelength (meters)
10^{-12} 10^{-10} 10^{-8} 10^{-6} 10^{-4} 10^{-2} 1 10^{2}
size of wavelength
hydrogen atom
protein
bacterium
animal cell
pinhead
baseball
football field
higher
lower
10^{20} 10^{18} 10^{16} 10^{14} 10^{12} 10^{10} 10^{8} 10^{6}
frequency (hertz)
10^{6} 10^{4} 10^{2} 1 10^{-2} 10^{-4} 10^{-6} 10^{-8}
energy (electron-volts)
sources on Earth
radioactive elements
X-ray machines
light bulb
people
radar
microwave oven
radio transmitter
cosmic sources
gamma ray burst
black hole accretion disk
Sun's chromo-sphere
Sun
planets, star-forming clouds
cosmic microwave background
radio galaxy

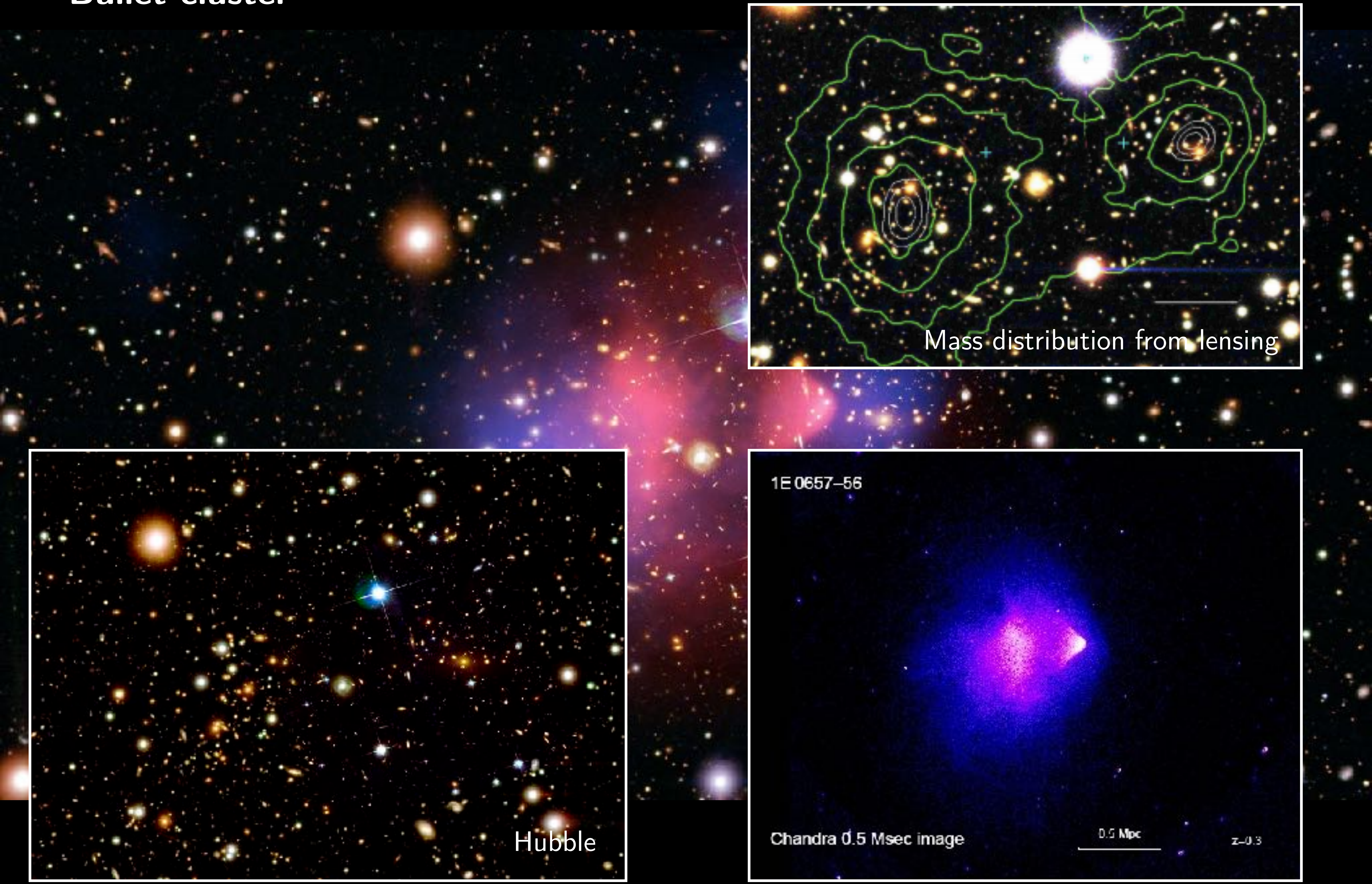


[Image credit: ESA/GAIA]

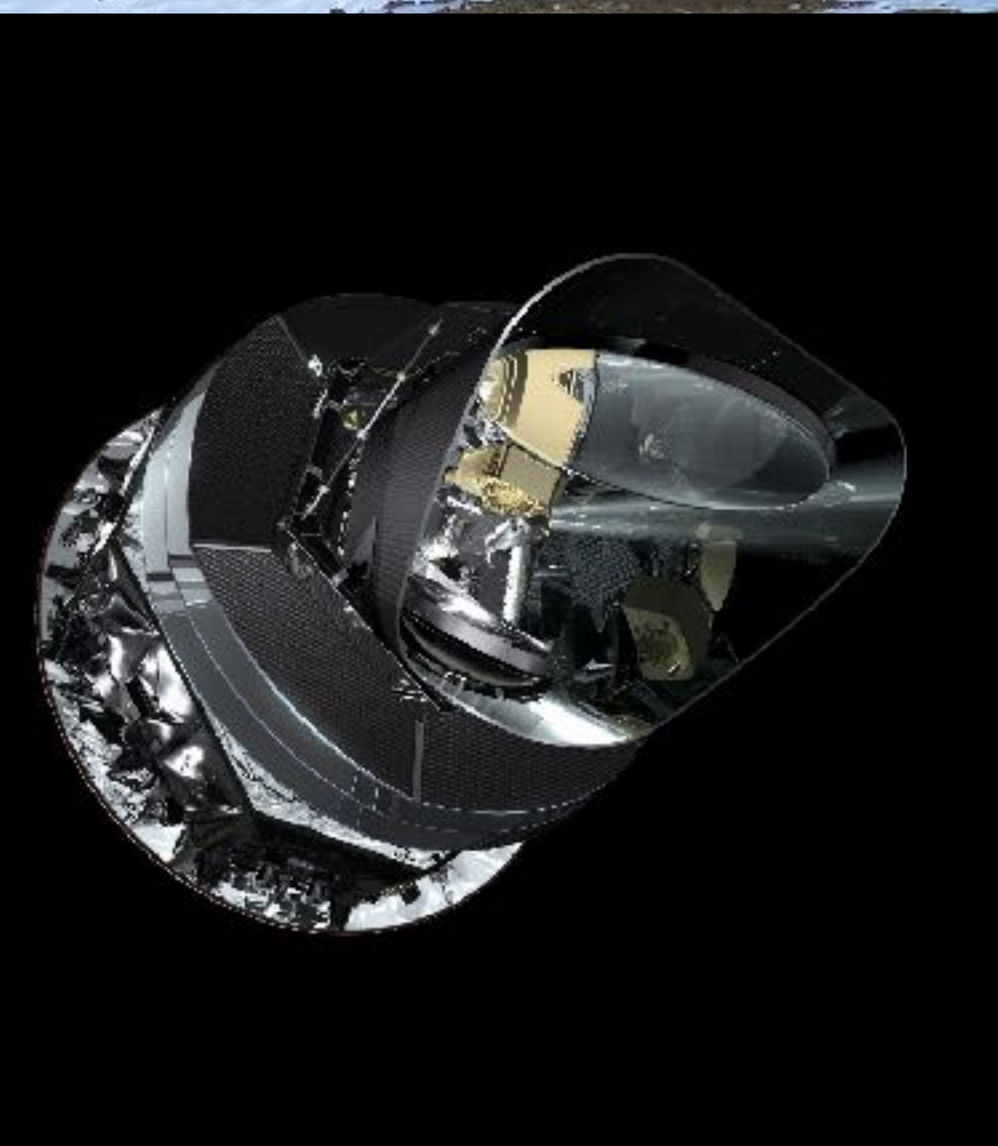


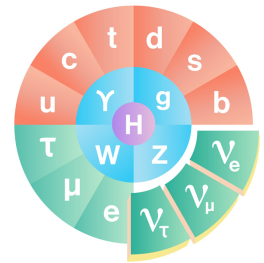
[Image credit: NASA/DOE/Fermi LAT Collaboration]

Bullet cluster







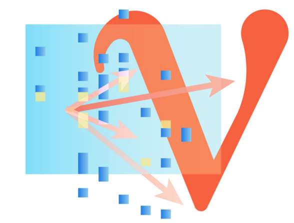



FUNDAMENTAL

Neutrinos are fundamental particles, which means that—like quarks and photons and electrons—they cannot be broken down into any smaller bits.

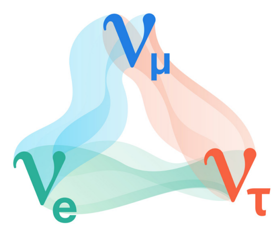
ABUNDANT

Of all particles with mass, neutrinos are the most abundant in nature. They're also some of the least interactive. Roughly a thousand trillion of them pass harmlessly through your body every second.



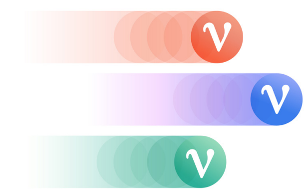
ELUSIVE

Neutrinos are difficult but not impossible to catch. Scientists have developed many different types of particle detectors to study them.



OSCILLATING

Neutrinos come in three types, called flavors. There are electron neutrinos, muon neutrinos and tau neutrinos. One of the strangest aspects of neutrinos is that they don't pick just one flavor and stick to it. They oscillate between all three.

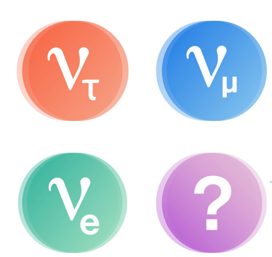


LIGHTWEIGHT

Neutrinos weigh almost nothing, and they travel close to the speed of light. Neutrino masses are so small that so far no experiment has succeeded in measuring them. The masses of other fundamental particles come from the Higgs field, but neutrinos might get their masses another way.

DIVERSE

Neutrinos are created in many processes in nature. They are produced in the nuclear reactions in the sun, particle decays in the Earth, and the explosions of stars. They are also produced by particle accelerators and in nuclear power plants.



MYSTERIOUS

Neutrinos are mysterious. Experiments seem to hint at the possible existence of a fourth type of neutrino: a sterile neutrino, which would interact even more rarely than the others.

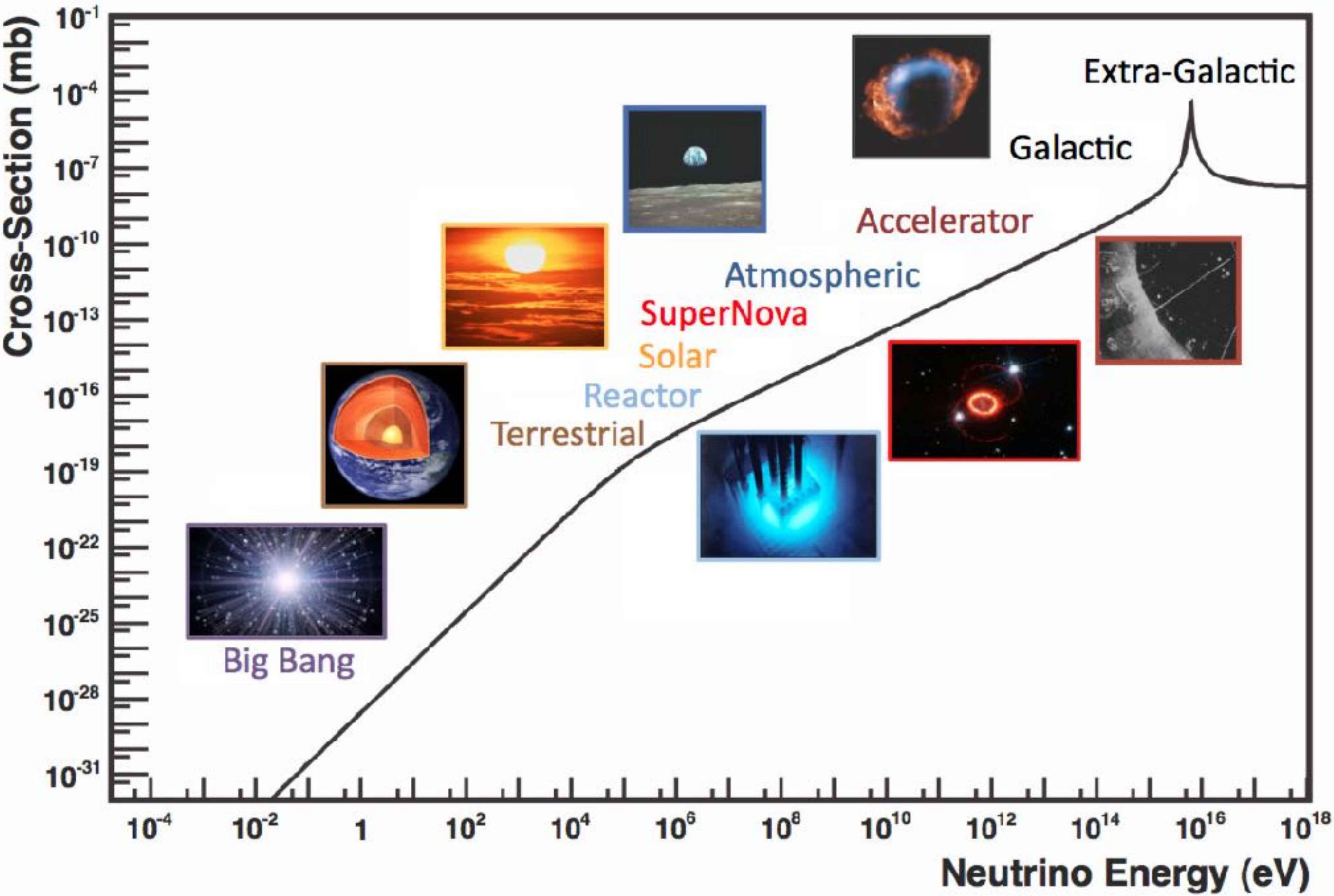
VERY MYSTERIOUS

Scientists also wonder if neutrinos are their own antiparticles. If they are, they could have played a role in the early universe, right after the big bang, when matter came to outnumber antimatter just enough to allow us to exist.

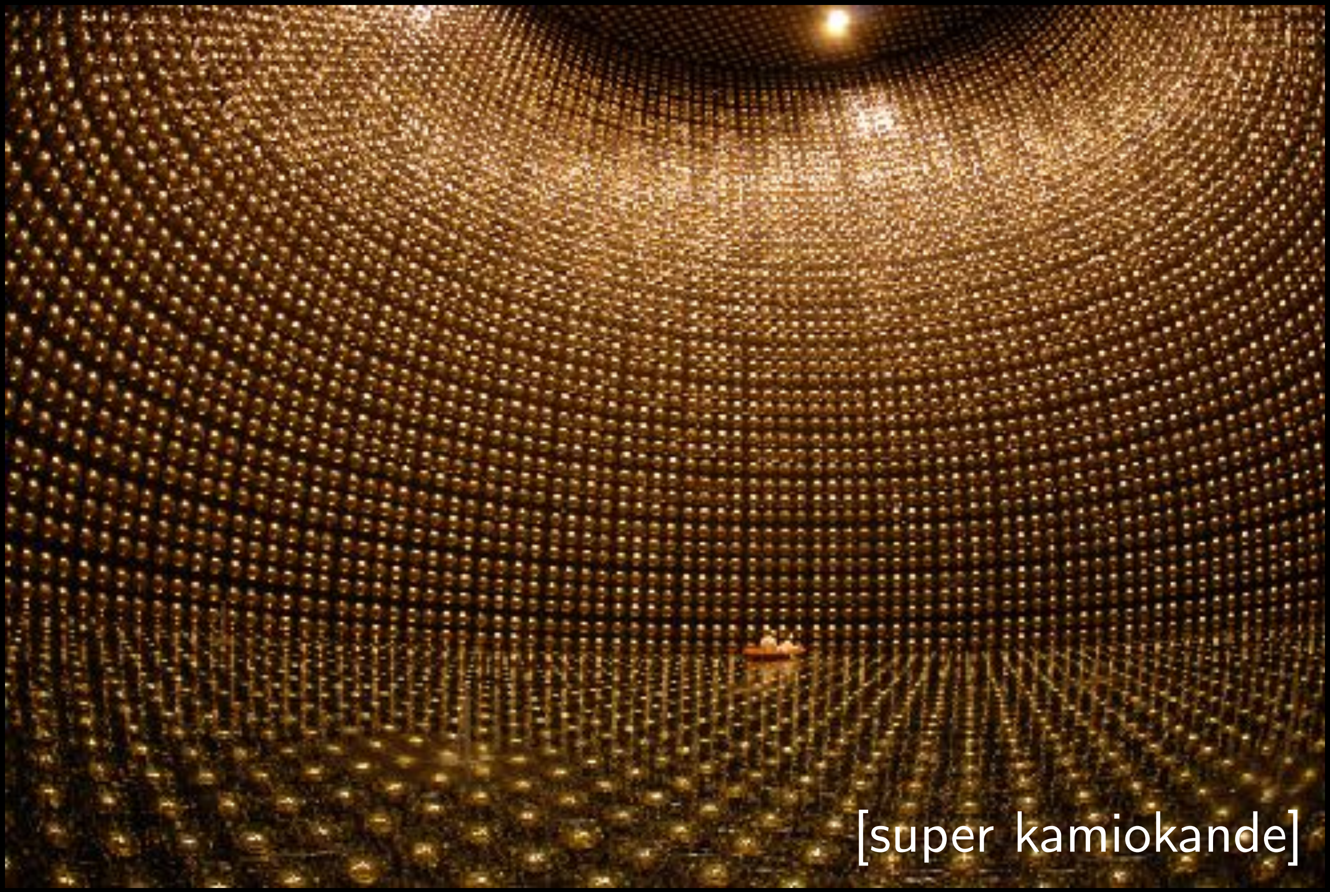
Interested in how the universe works? Read *symmetry*, an online magazine about particle physics and its connections to life and other areas of science. Published by Fermi National Accelerator Laboratory and SLAC National Accelerator Laboratory. symmetrymagazine.org

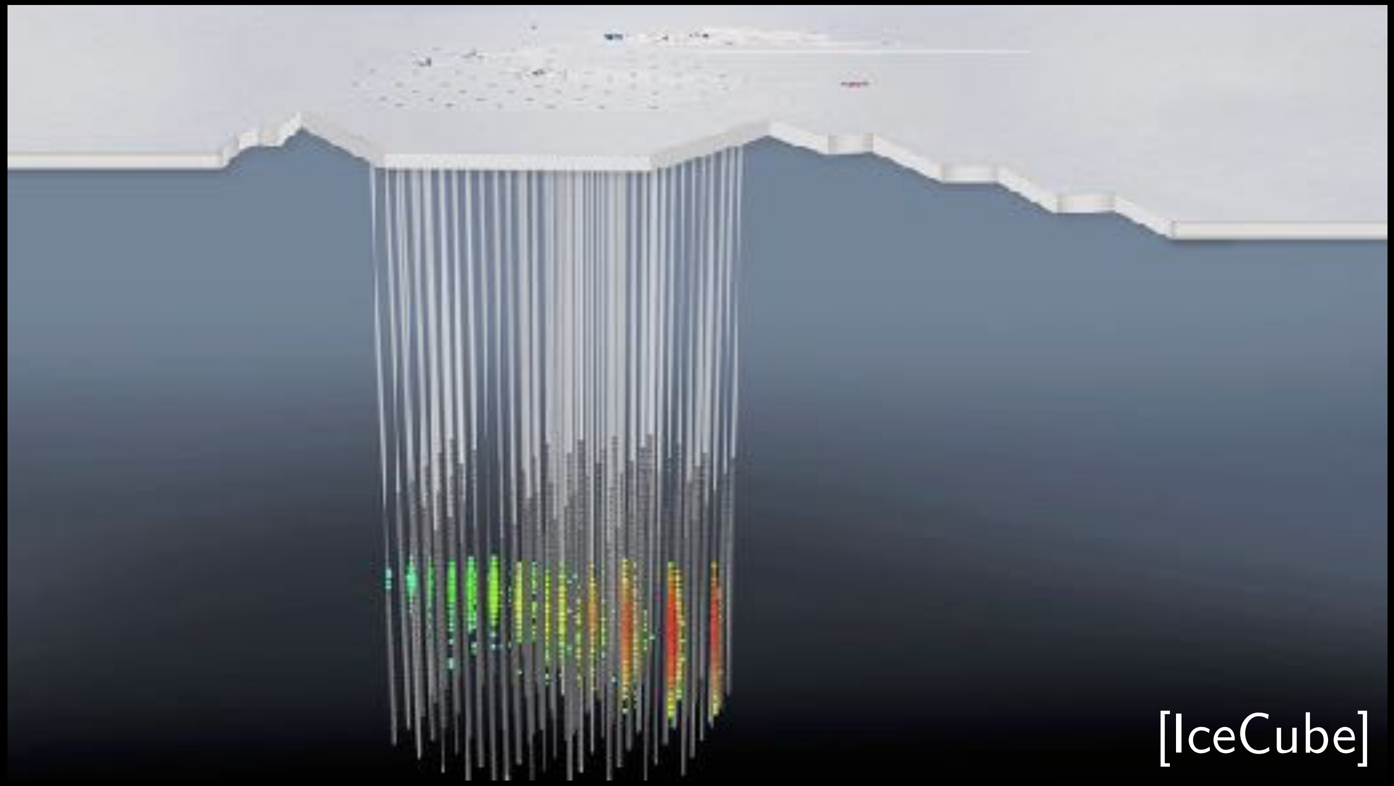
symmetry | U.S. DEPARTMENT OF ENERGY | Office of Science

[neutrinos.fnal.gov]



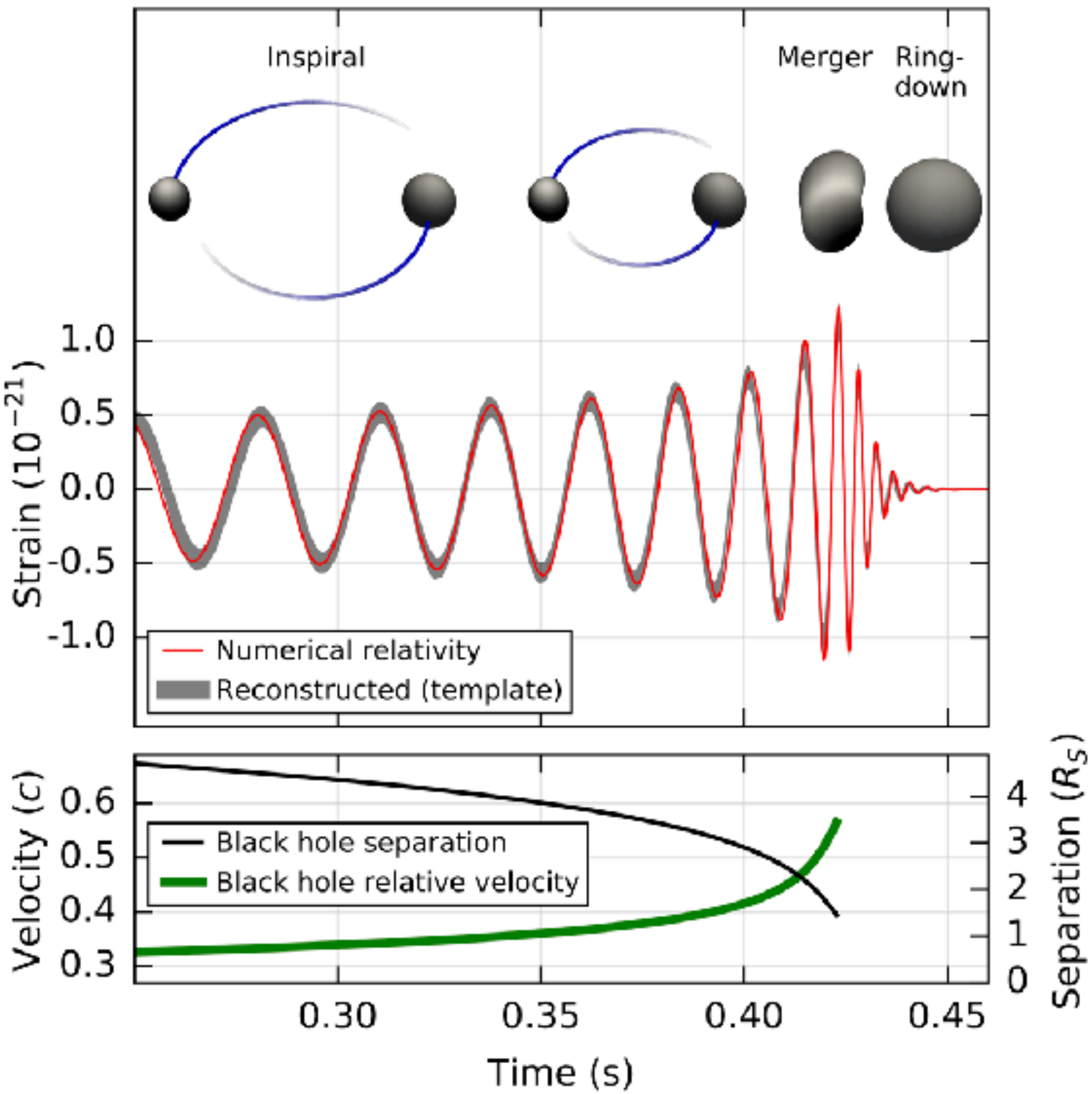
[Credit: J.A. Formaggio and G.P. Zeller]





K: neutrino detectors need big volumes!

New era of Gravitational Wave Astronomy



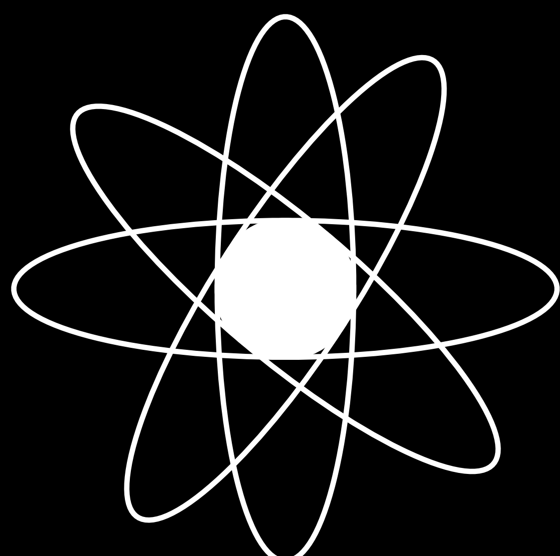
[Credit: LIGO]

How large is the effect?

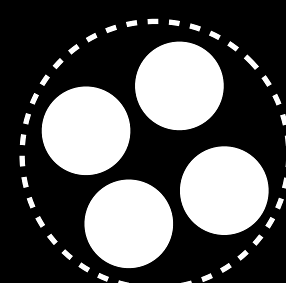
[Credit: R. Hurt, Caltech/MIT/LIGO Lab]

The variation in the distance is minuscule

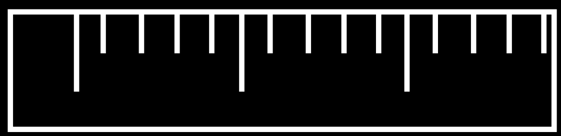
0.000000000000000001 meters



atom: 10^{-10} meters

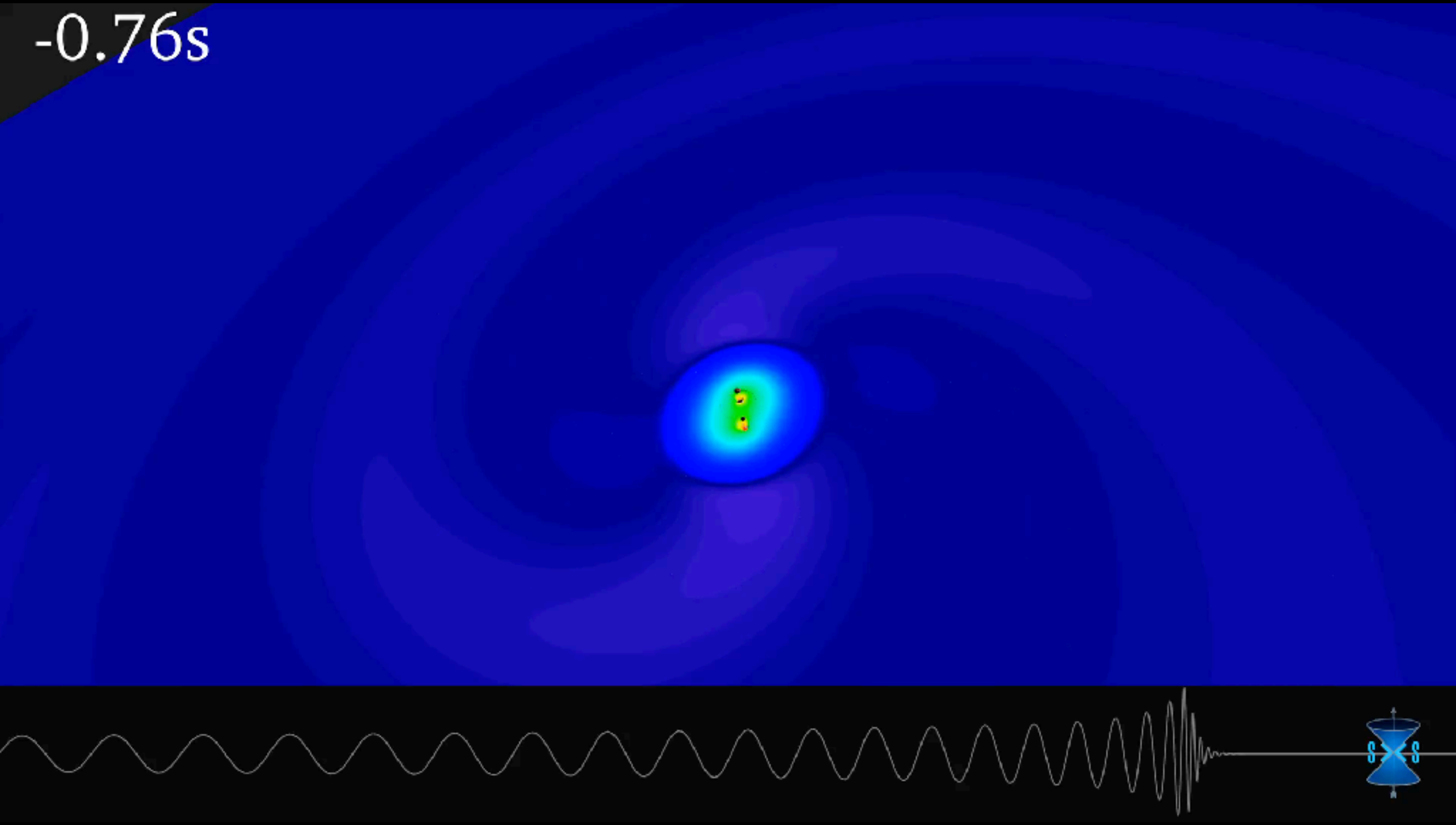


nucleus: 10^{-15} meters



GW effect: 10^{-18} meters

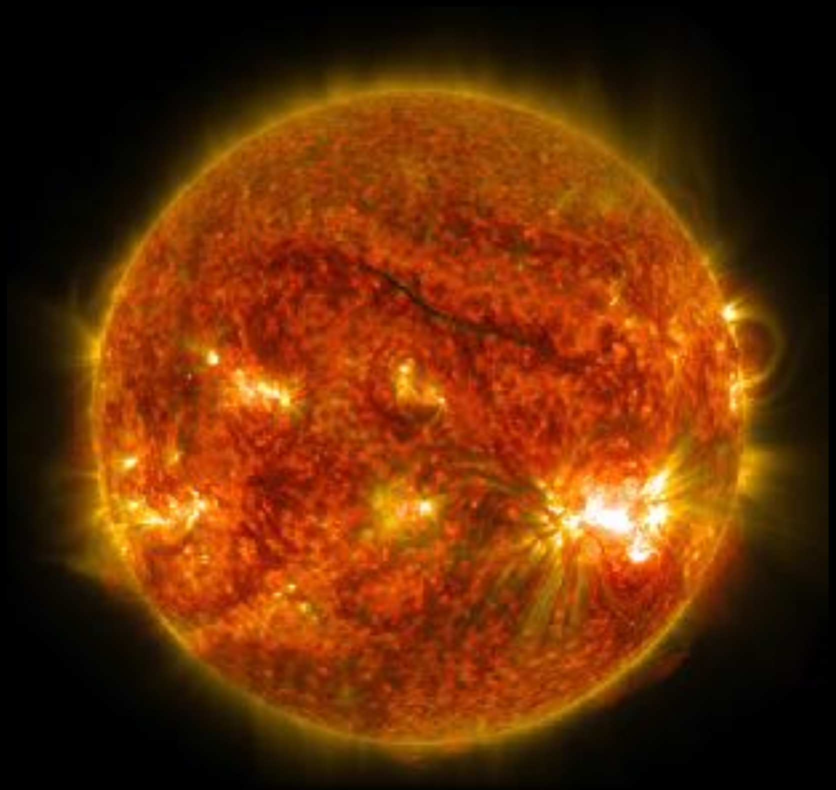
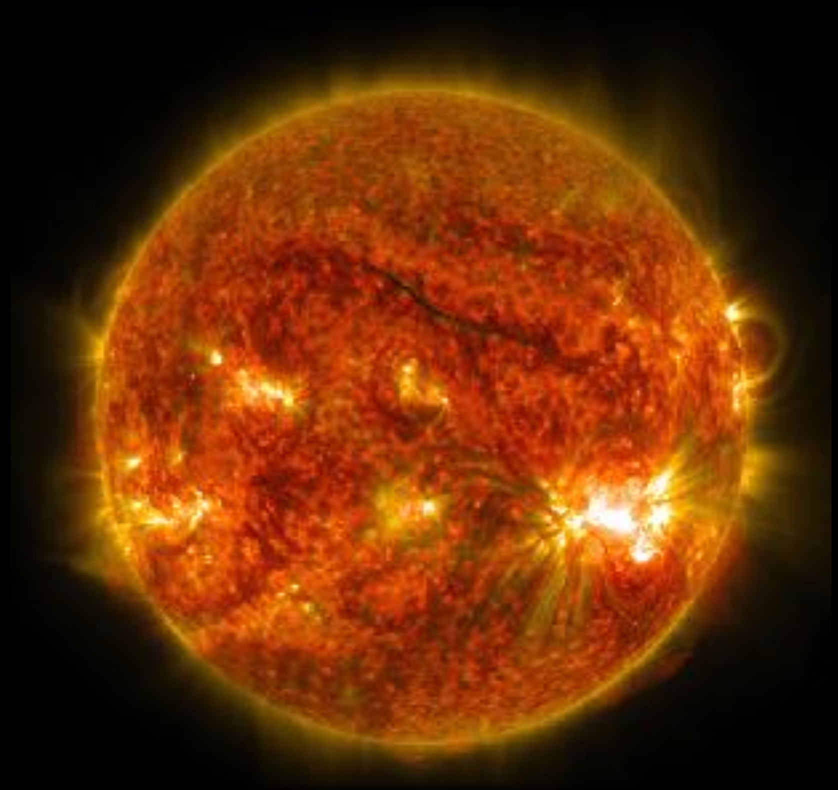
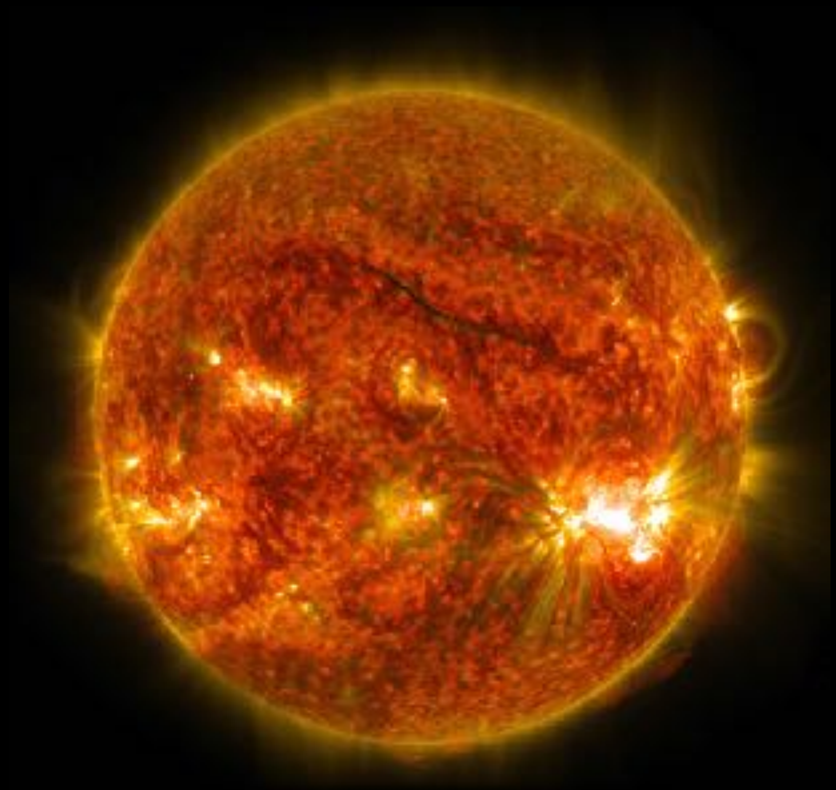
BINARY BLACK-HOLE MERGER



[Credit: SxS Collaboration]

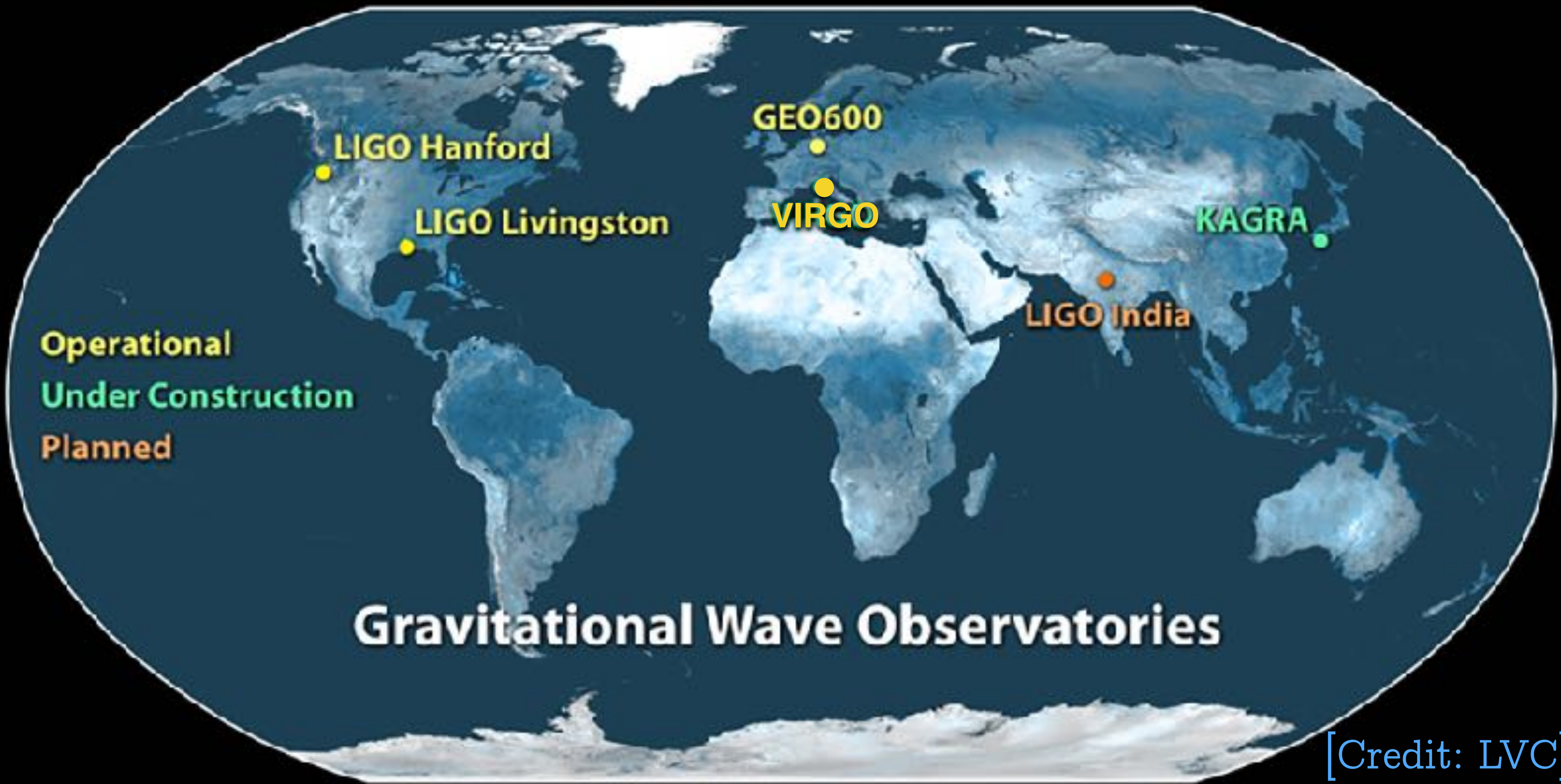
ENERGY EMITTED IN GWs

=

>

Global network of ground-based detectors



[Credit: LVC]

[Hanford, US]

[Livingston, US]

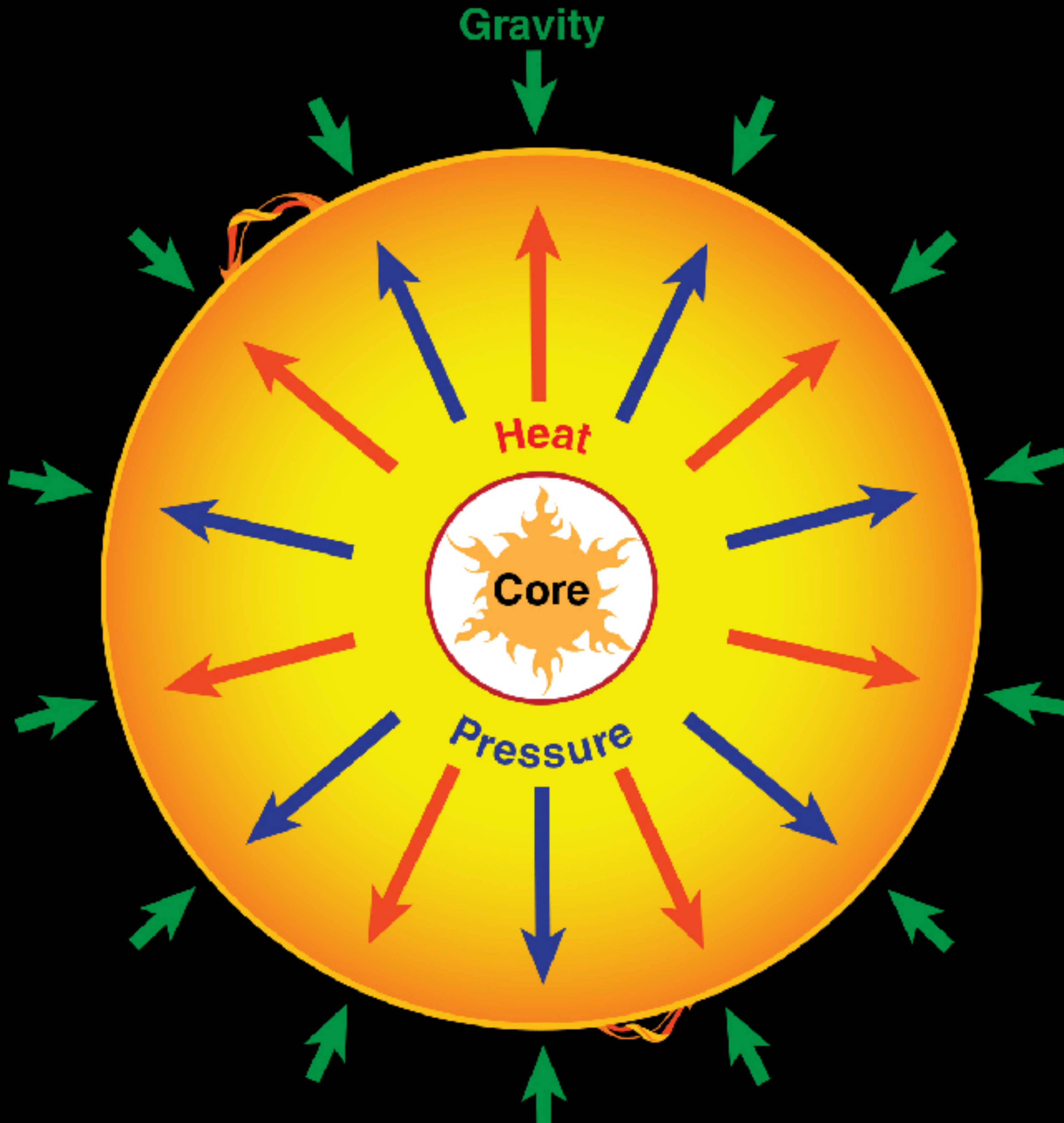
[Virgo, Italy]

Contents

Supernova
- SN1987-

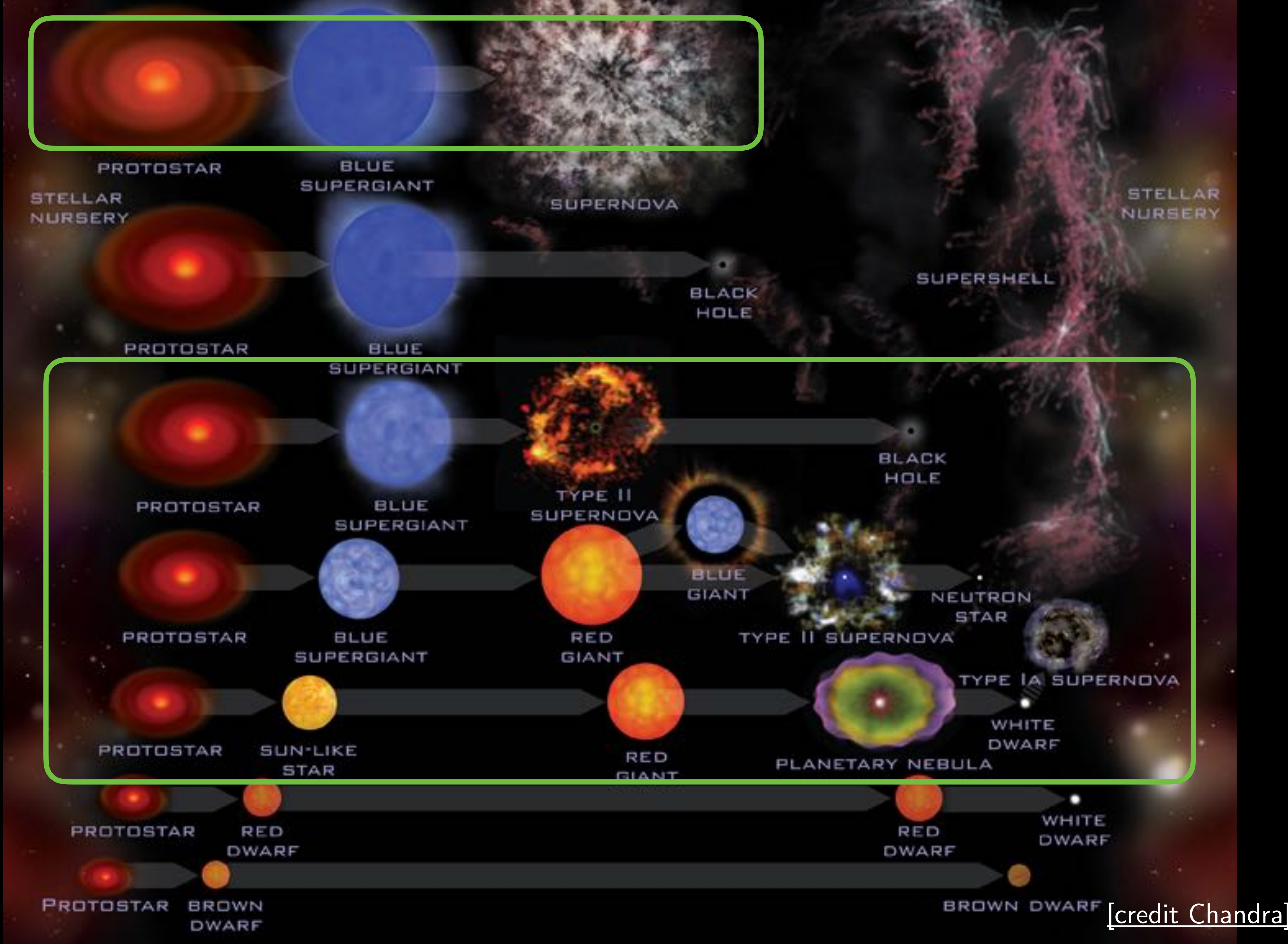
NASA web

What holds a star together?



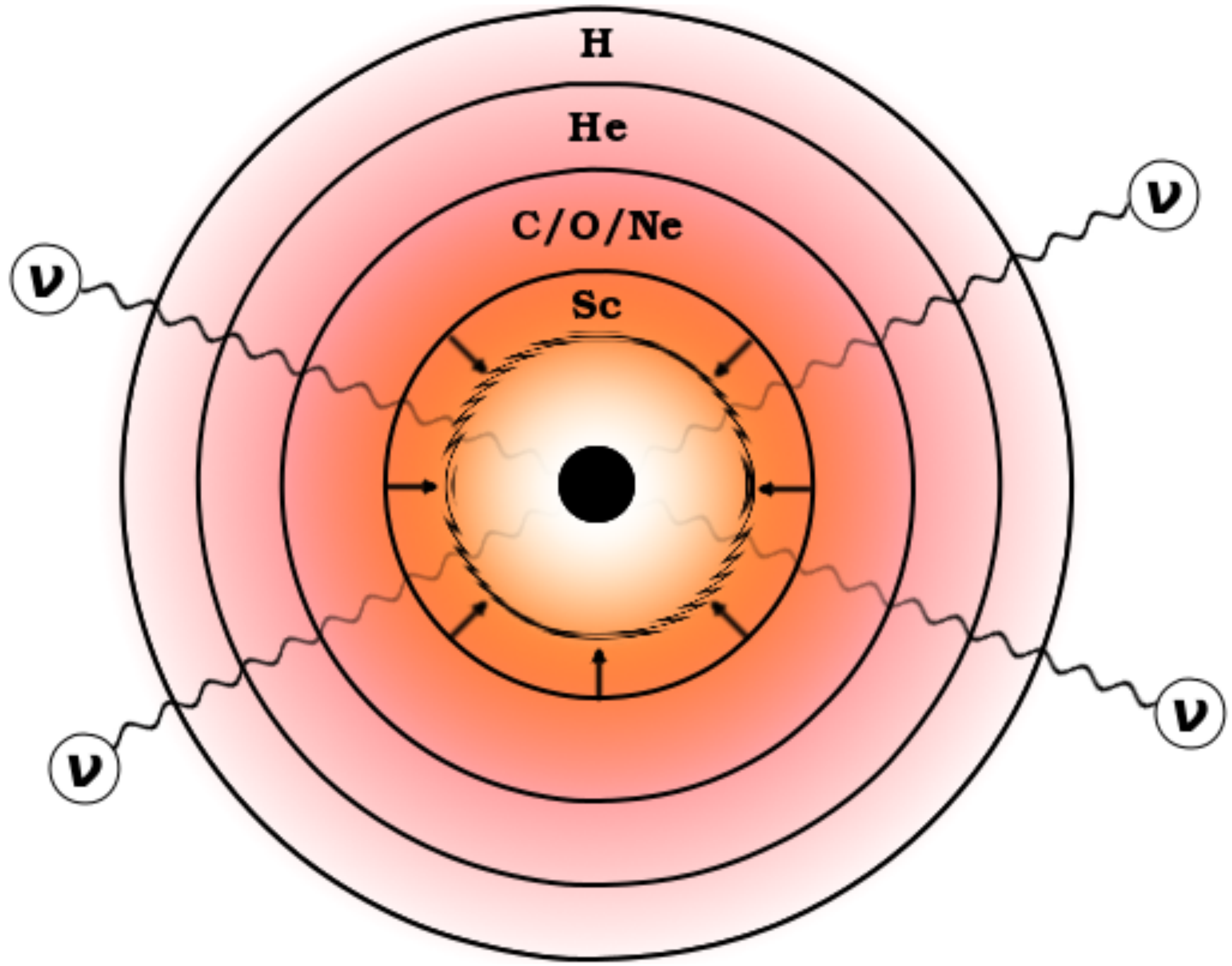
[credit NASA]

Stellar evolution

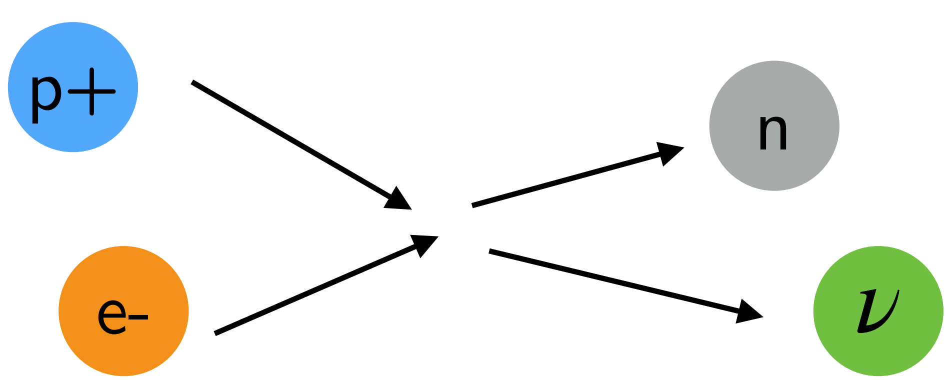


[credit Chandra]

K: 99% of emitted energy in neutrinos!

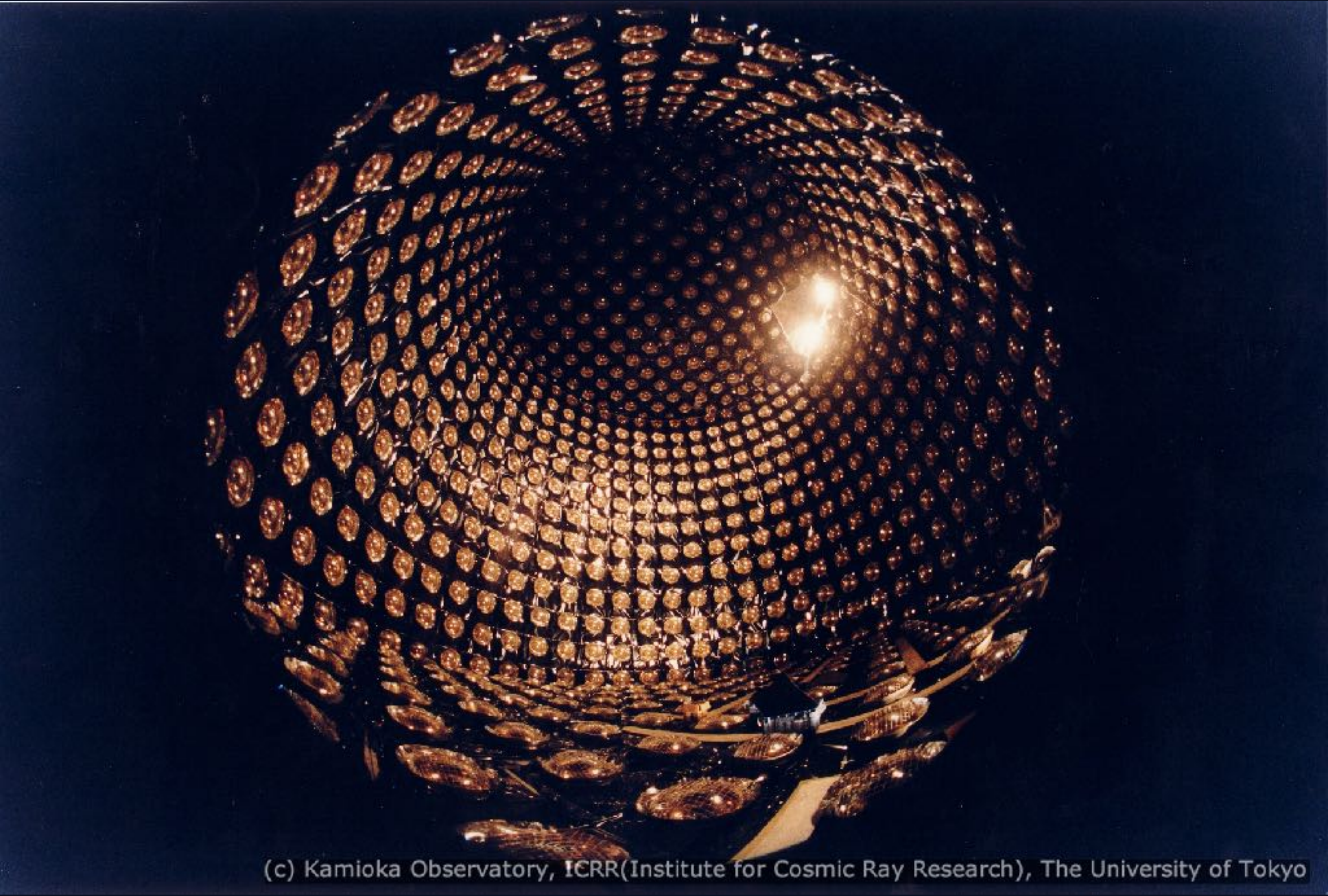


Electron capture + neutrino trapping + bounce back

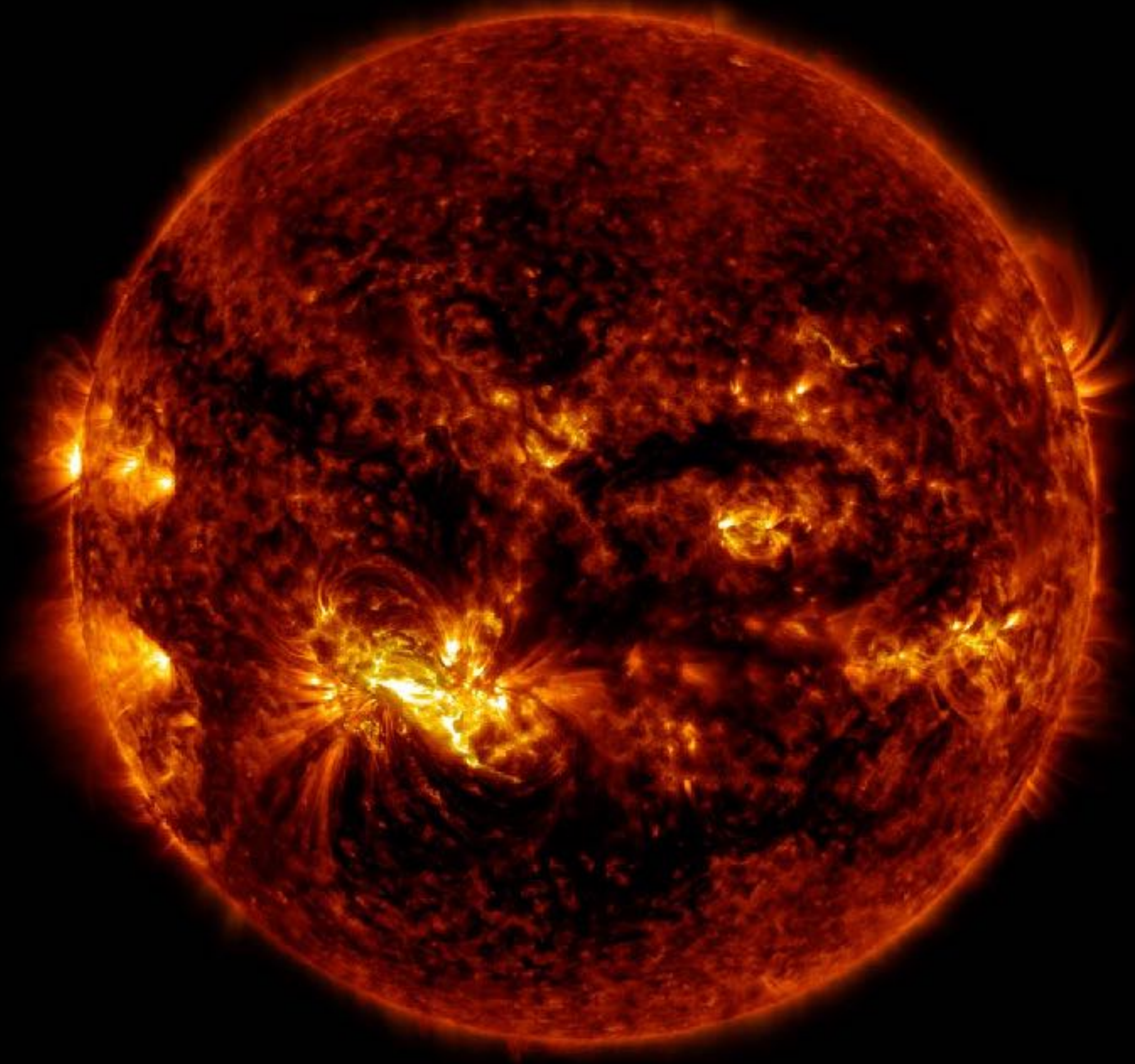


Q/A: What is the rate of nearby supernovae?

Dozen neutrinos detected at Kamioka in 1987



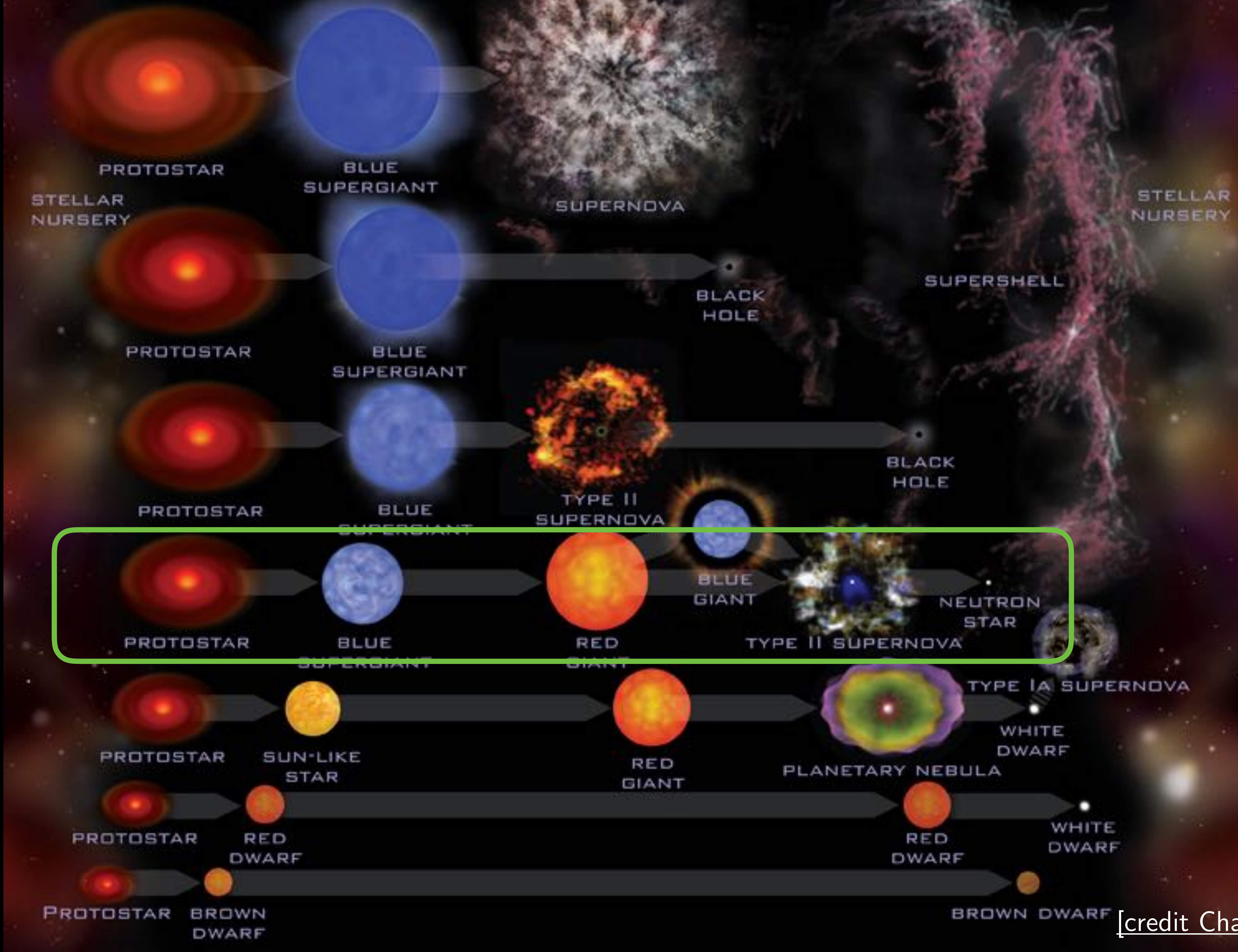
R: why are solar neutrinos important?



[NASA's Solar Dynamics Observatory, Oct. 21, 2014]

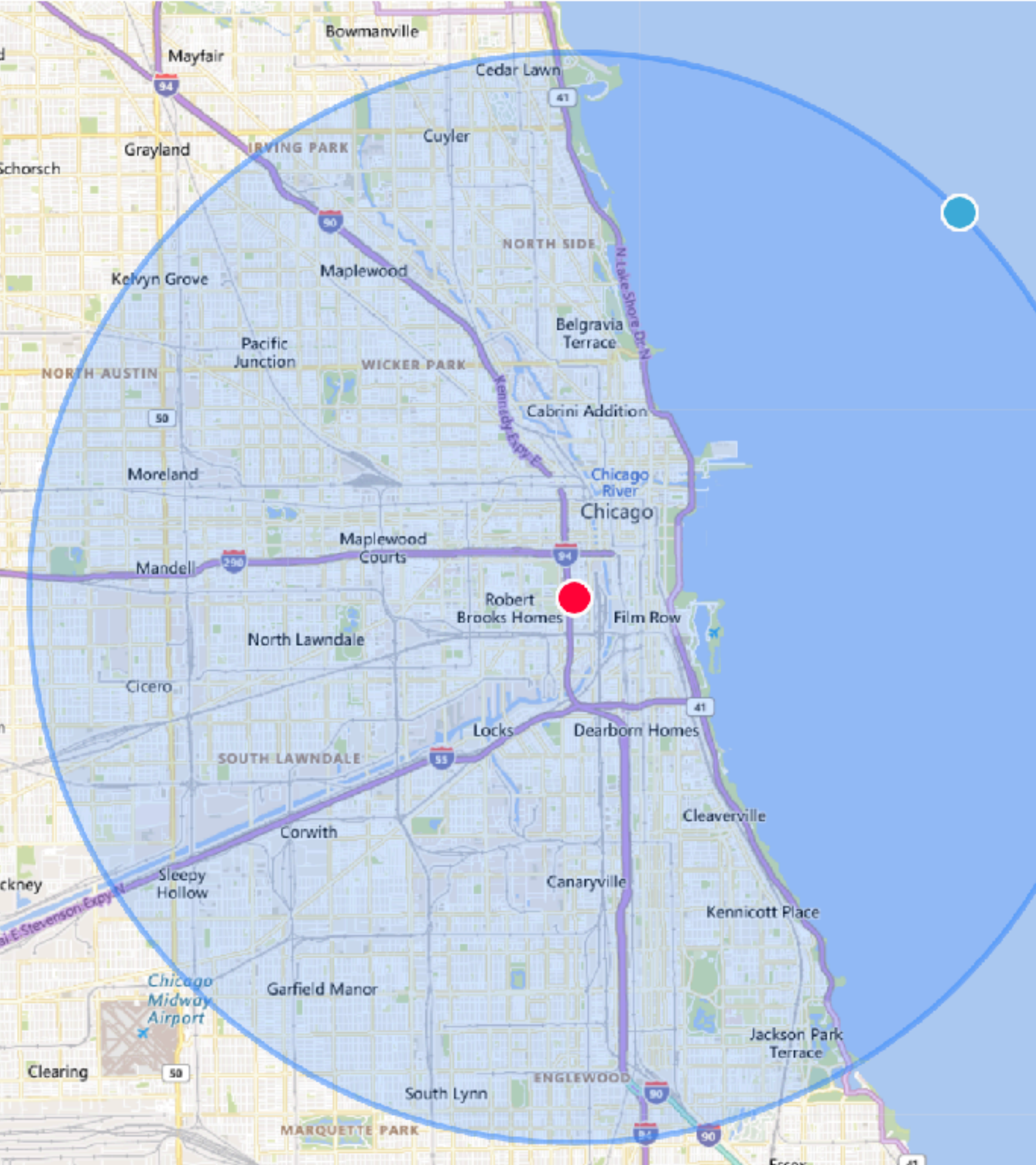
Binary neutron stars
- GW170817 -

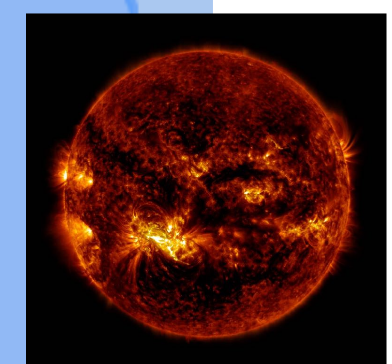
Stellar evolution



[credit Chandra]

Q/A: What is the radius of a neutron star?

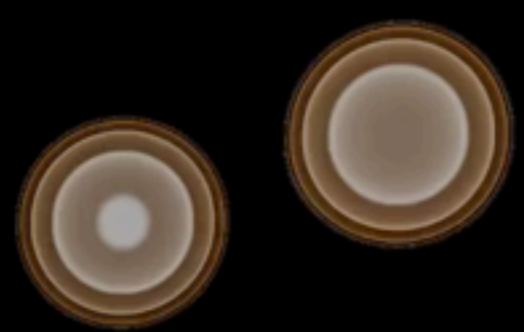

Bowmanville
Mayfair
Cedar Lawn
Grayland
Irving Park
Cuyler
Kelvyn Grove
Maplewood
North Side
N Lake Shore Dr N
Belgravia Terrace
Pacific Junction
North Austin
Wicker Park
Kennedy Expy E
Cabrini Addition
Moreland
Chicago River
Chicago
Maplewood Courts
Mandell
Robert Brooks Homes
Film Row
North Lawndale
Cicero
Locks
Dearborn Homes
South Lawndale
Corwith
Cleaverville
Sleepy Hollow
Canaryville
Kennicott Place
Chicago Midway Airport
Garfield Manor
Jackson Park Terrace
Clearing
Englewood
South Lynn
Marquette Park



x 1.5

Neutron stars get deformed

GW170817: The Merger of Two Neutron Stars



Matter density

Gravitational Waves

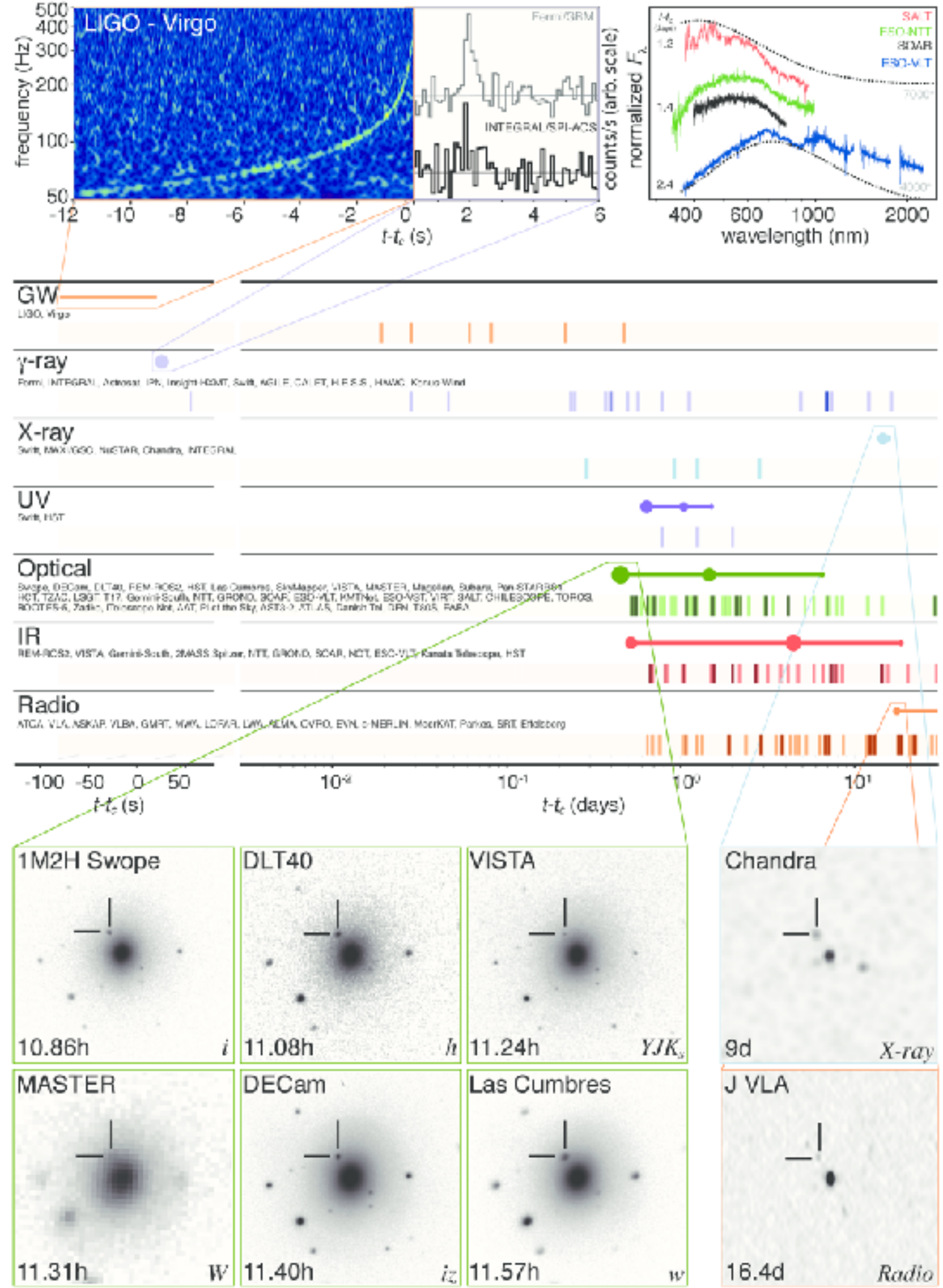
Georgia Tech

[Credit: Christopher W. Evans/Georgia Tech]

Multi-messenger event: GW + EM

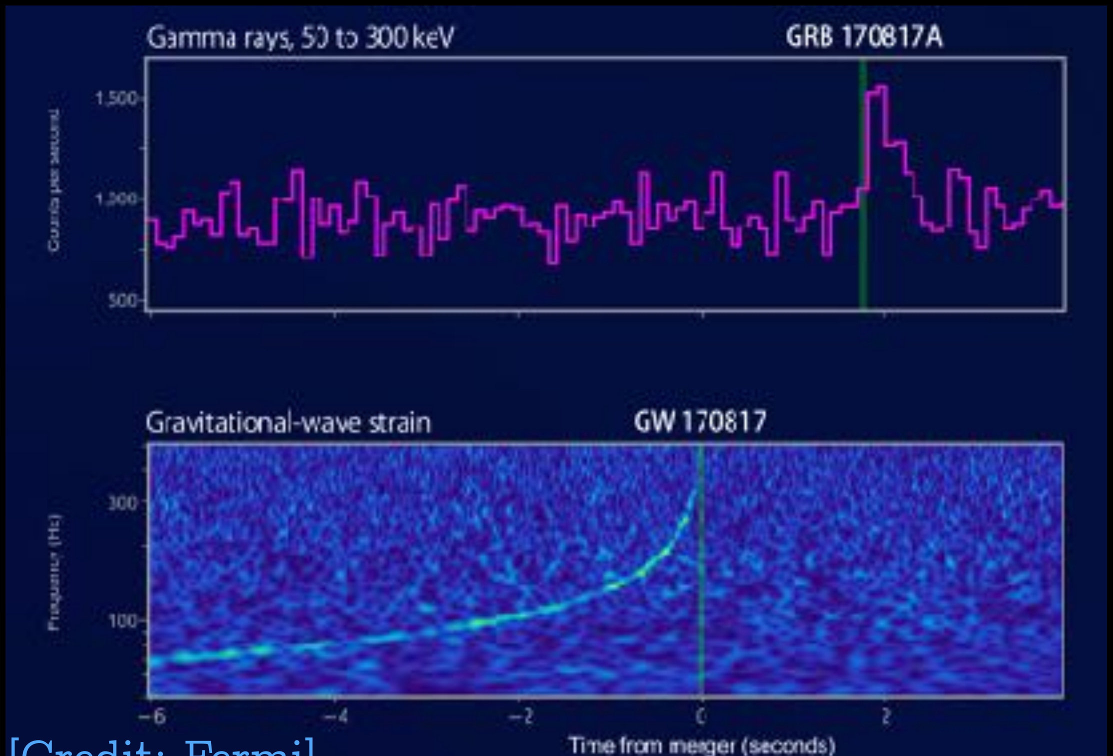
[Credit: NASA's Goddard Space Flight Center/CI Lab]

Seen across entire EM spectrum!

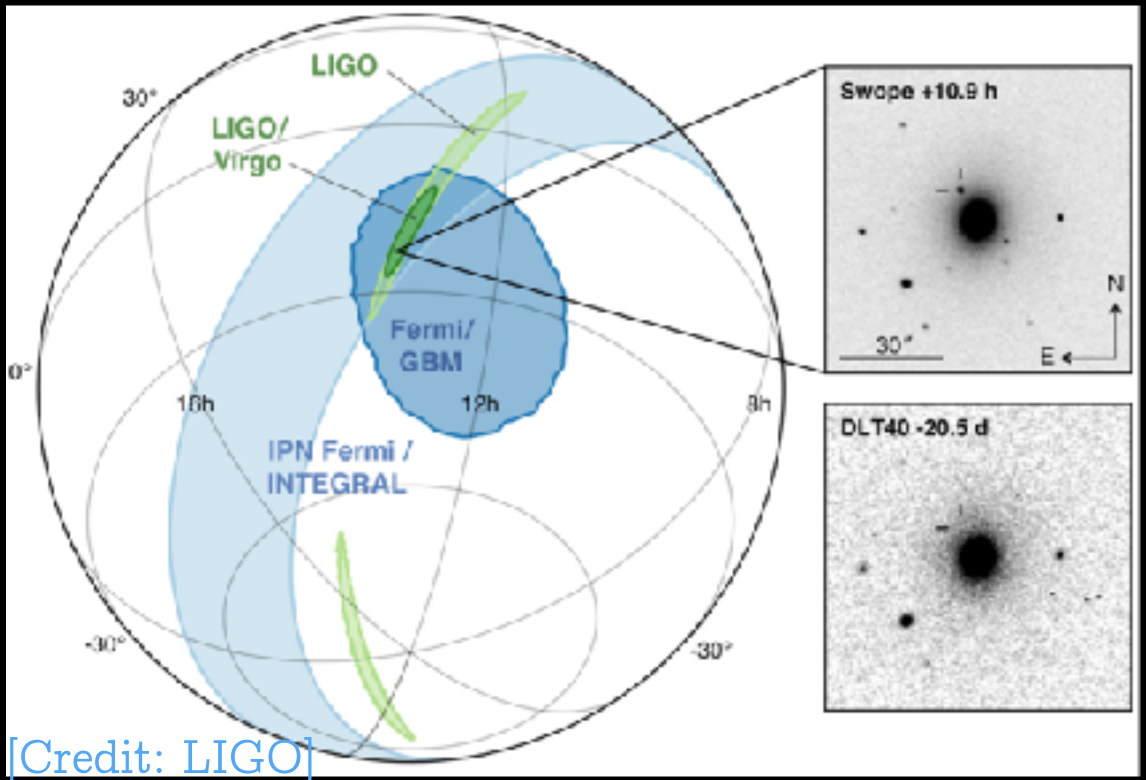


What have we learned with GW170817?

Gravitational waves travel at the speed of light!



[Credit: Fermi]



[Credit: LIGO]

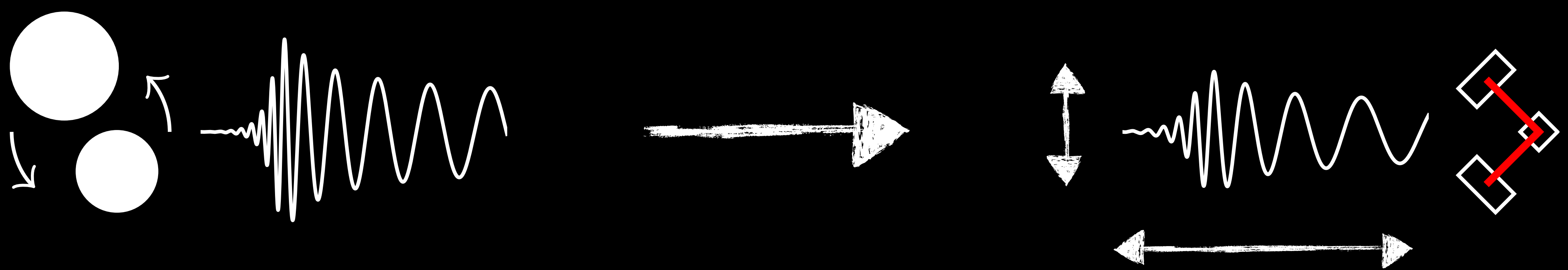
Both the GWs and the sGRB arrived almost simultaneously

$$\Delta t = 1.74 \pm 0.05\,\mathrm{s}$$

after traveling approx. 100 million light years $(40^{+8}_{-14}\,\mathrm{Mpc})$.

$$\boxed{-3 \cdot 10^{-15} \leq c_g/c - 1 \leq 7 \cdot 10^{-16}}$$

Standard Sirens

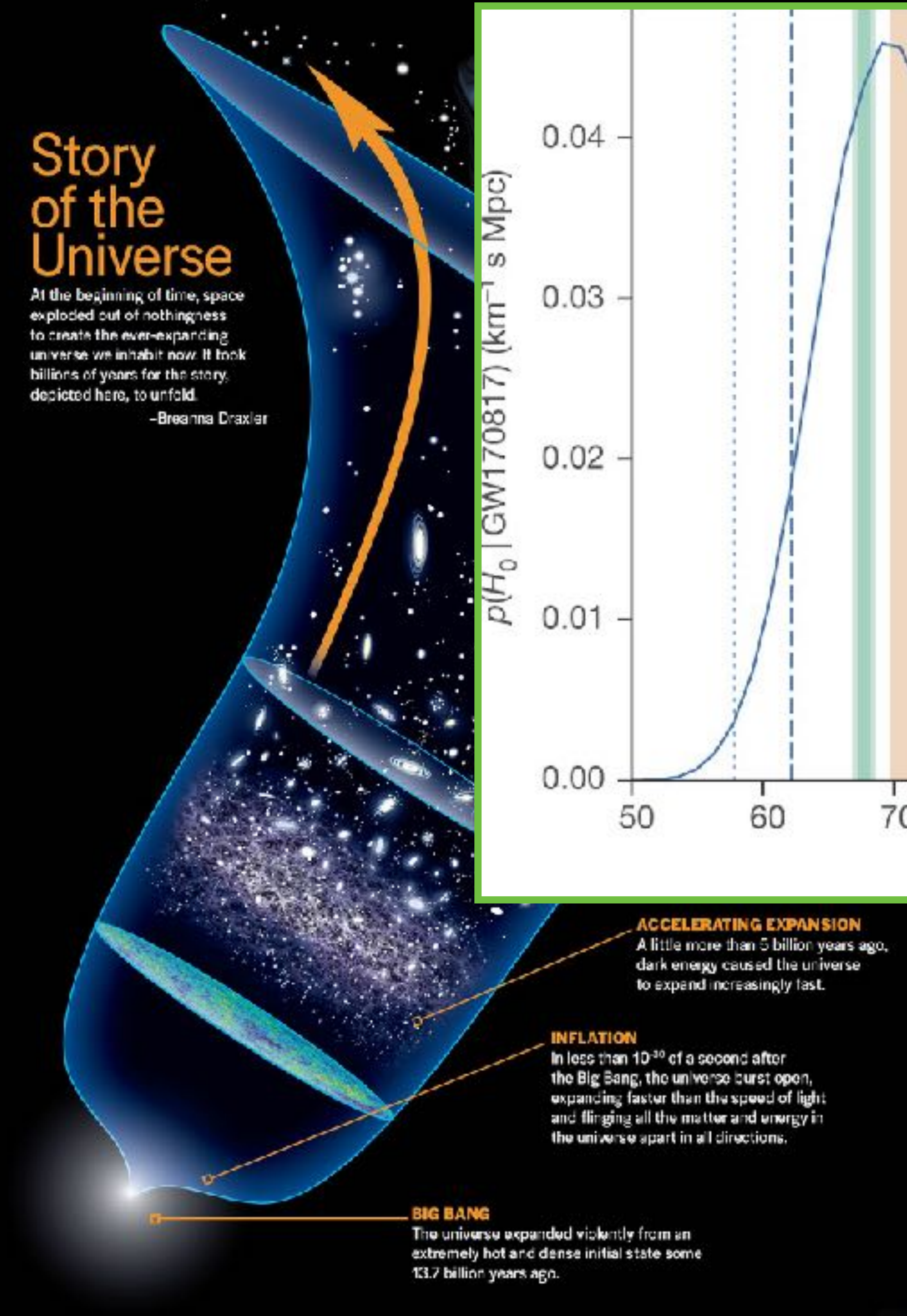


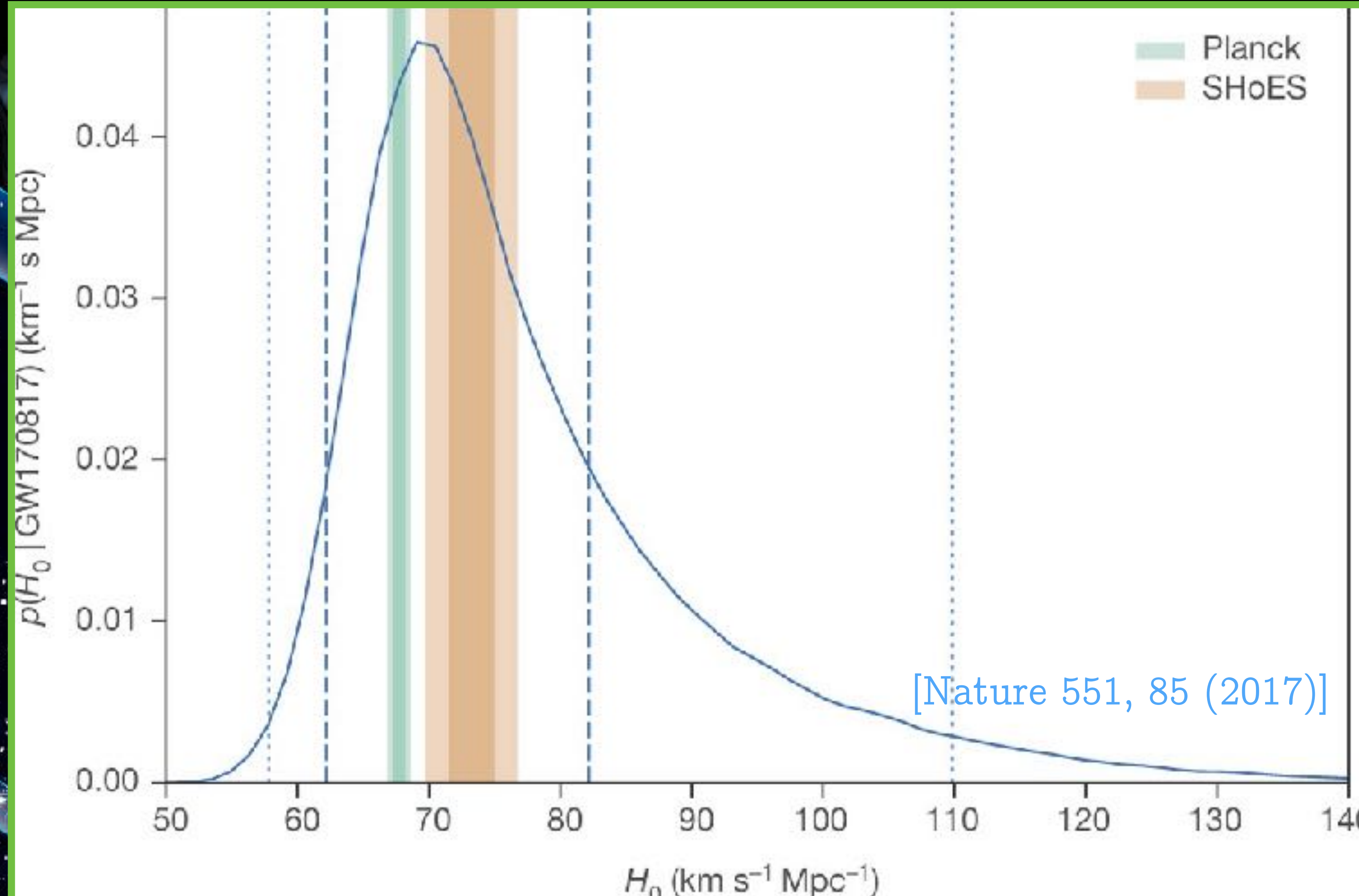
- Gravitational waves are directly sensitive to the luminosity distance, which depends on the cosmology

$$h \propto 1/d_L \qquad\qquad d_L(z) = (1+z)\int_0^z \frac{c\,dz}{H(z)}$$

- With additional redshift information GWs constrain expansion rate!

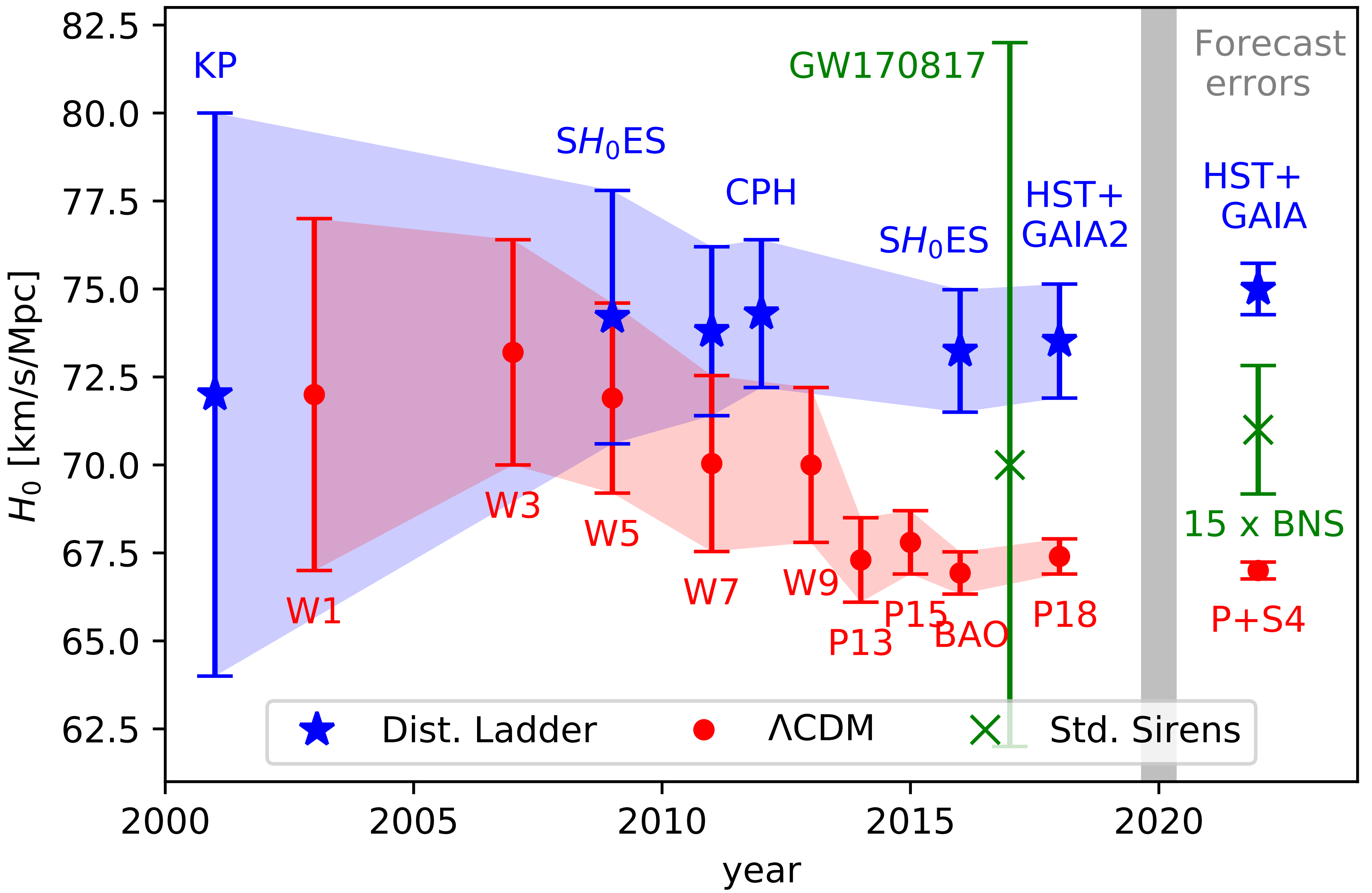
$$H(z) = H_0\sqrt{\Omega_M(1+z)^3 + \Omega_\Lambda}$$





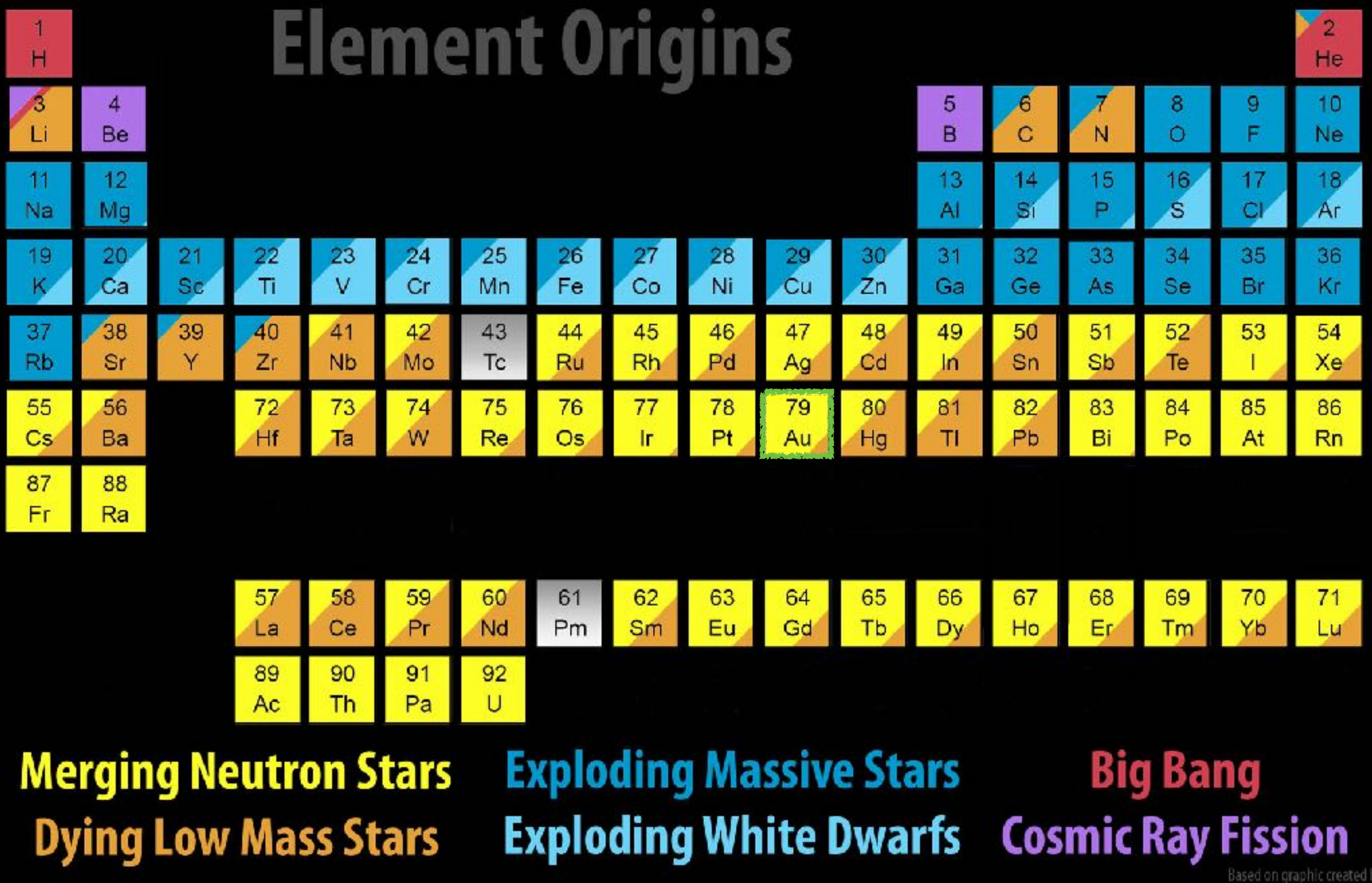
[Nature 551, 85 (2017)]

R: what is the Hubble tension?



Q/A: How are the different elements produced?

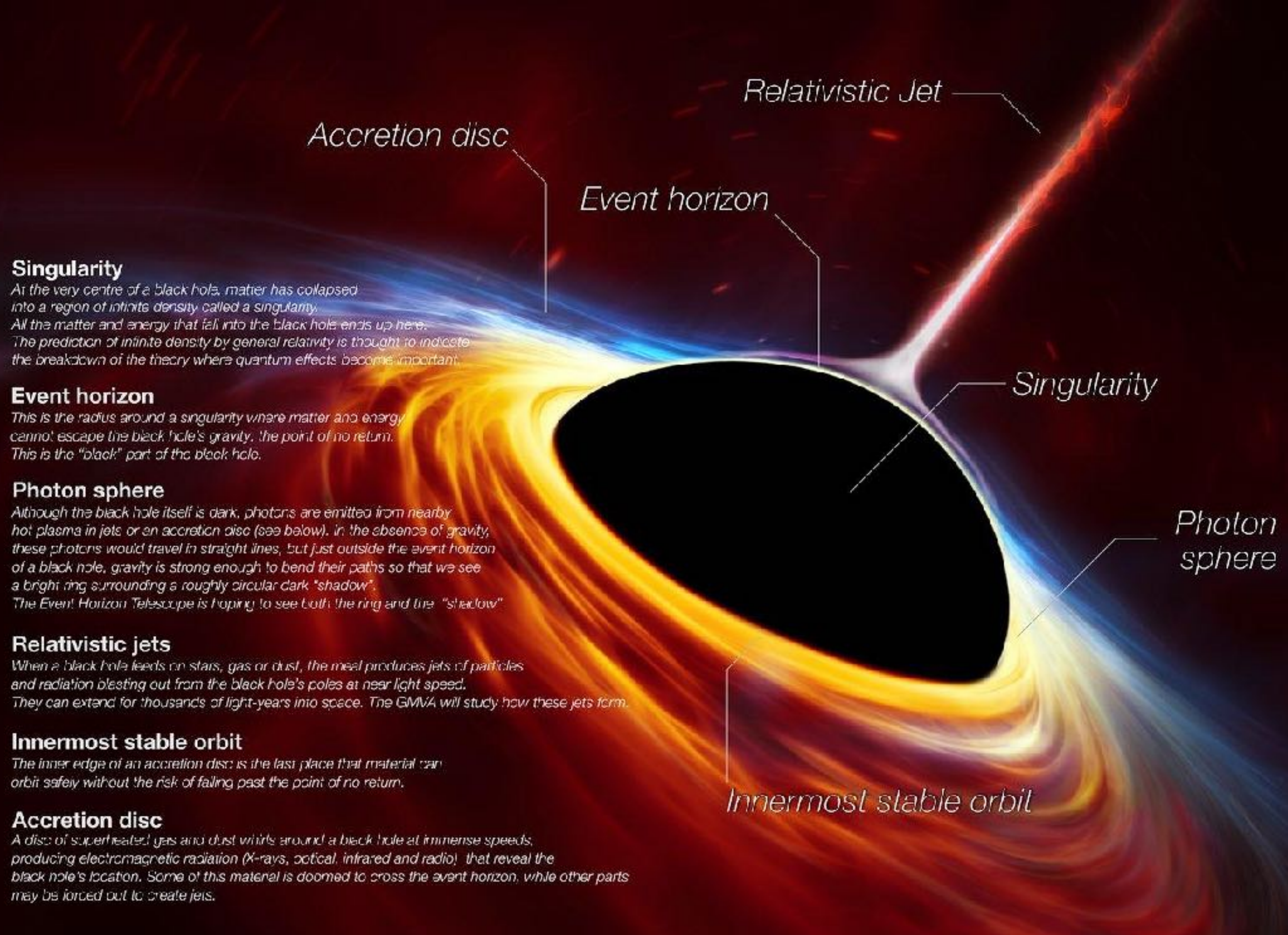
Probably, the gold of your ring comes from a neutron star merger



Supermassive black holes

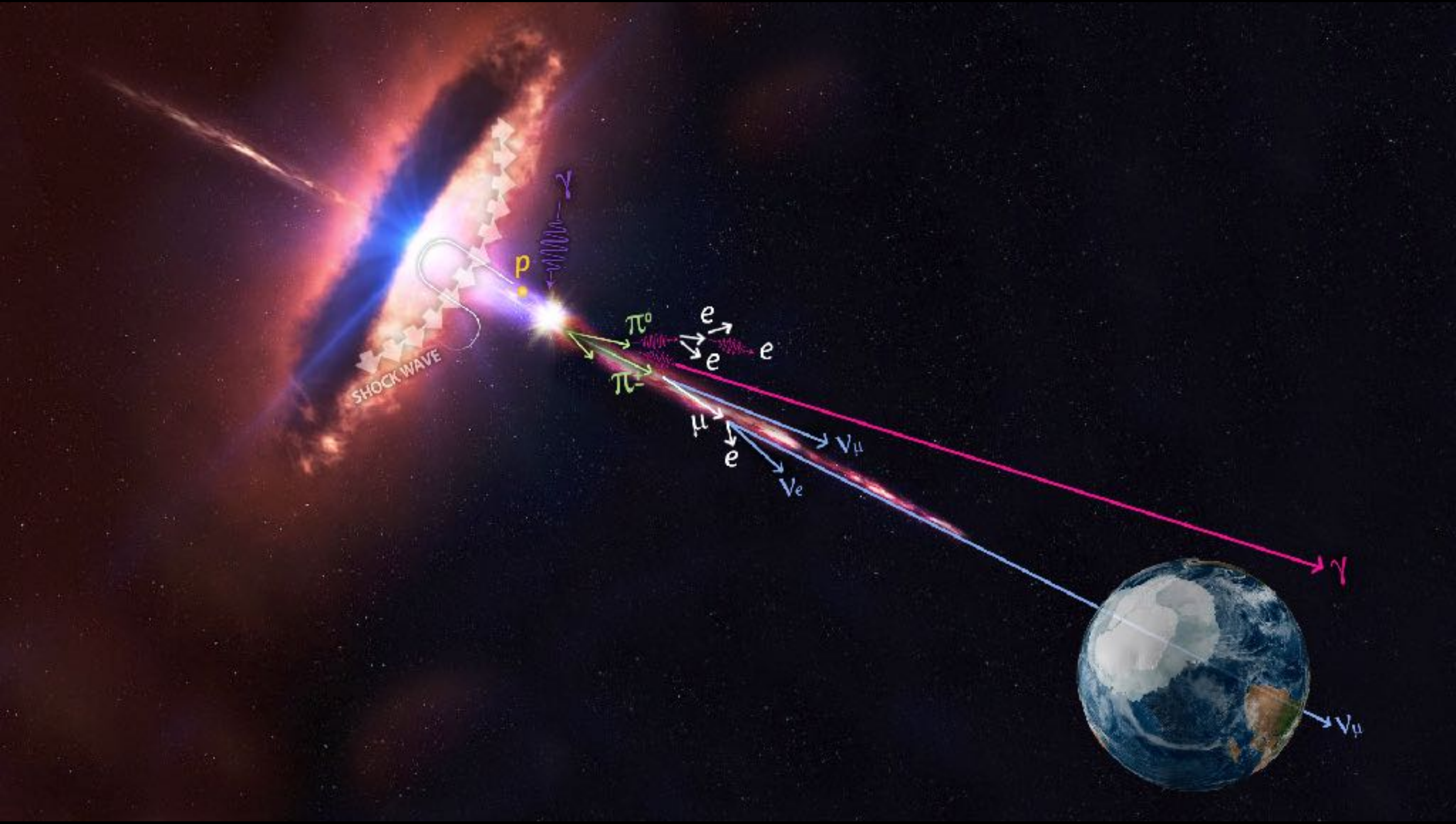
- TXS 0506+056, IceCube-170922A -

Credit: EHT

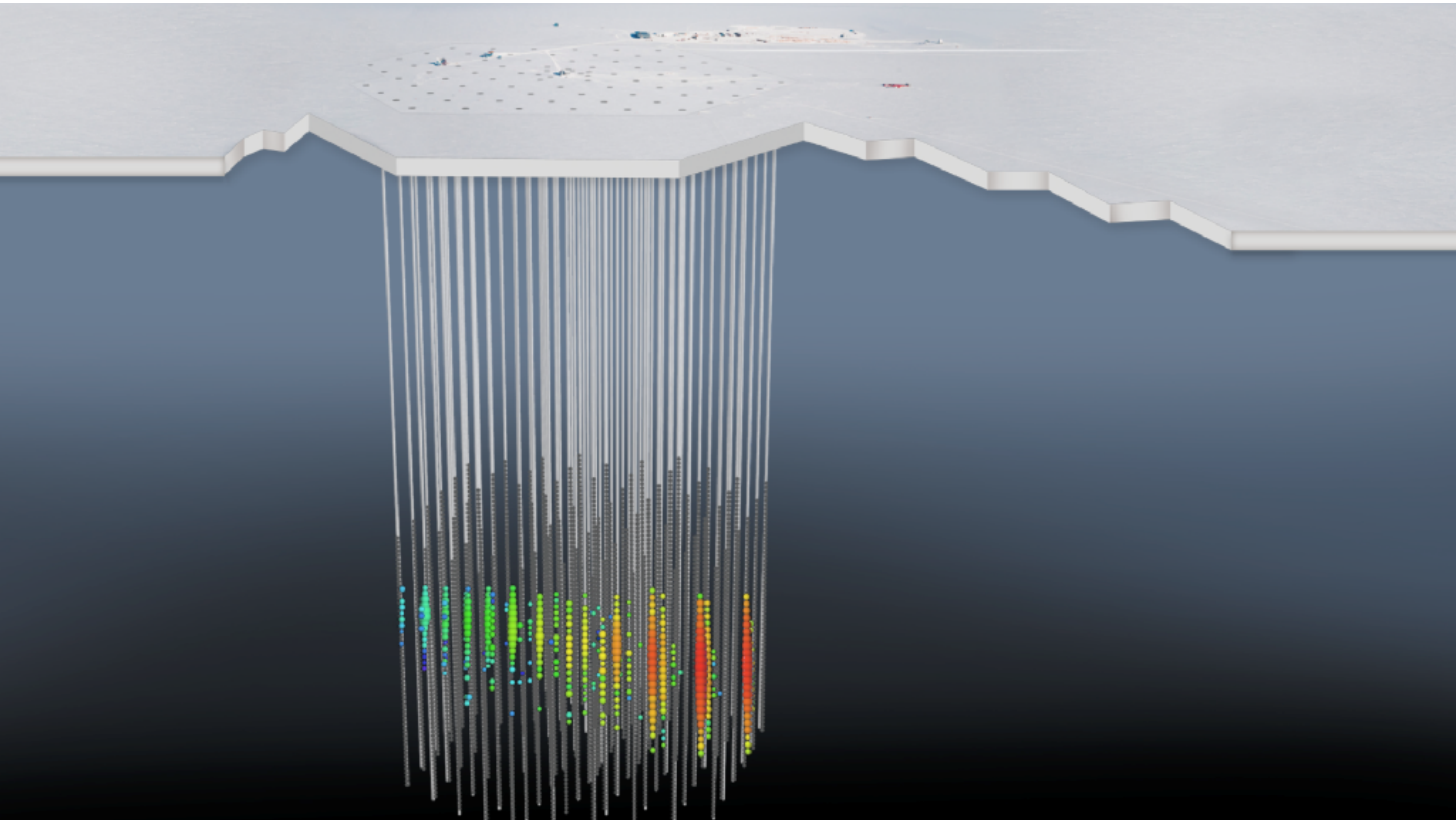


Credit: ESO, ESA/Hubble, M. Kornmesser/N. Bartmann

Blazar at z=0.3



Following neutrino's trace, IceCube can "point" in the sky



Contents

Super massive black hole mergers