

Multi-messenger Astronomy

a crash-course

ASTR133, May 2021

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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

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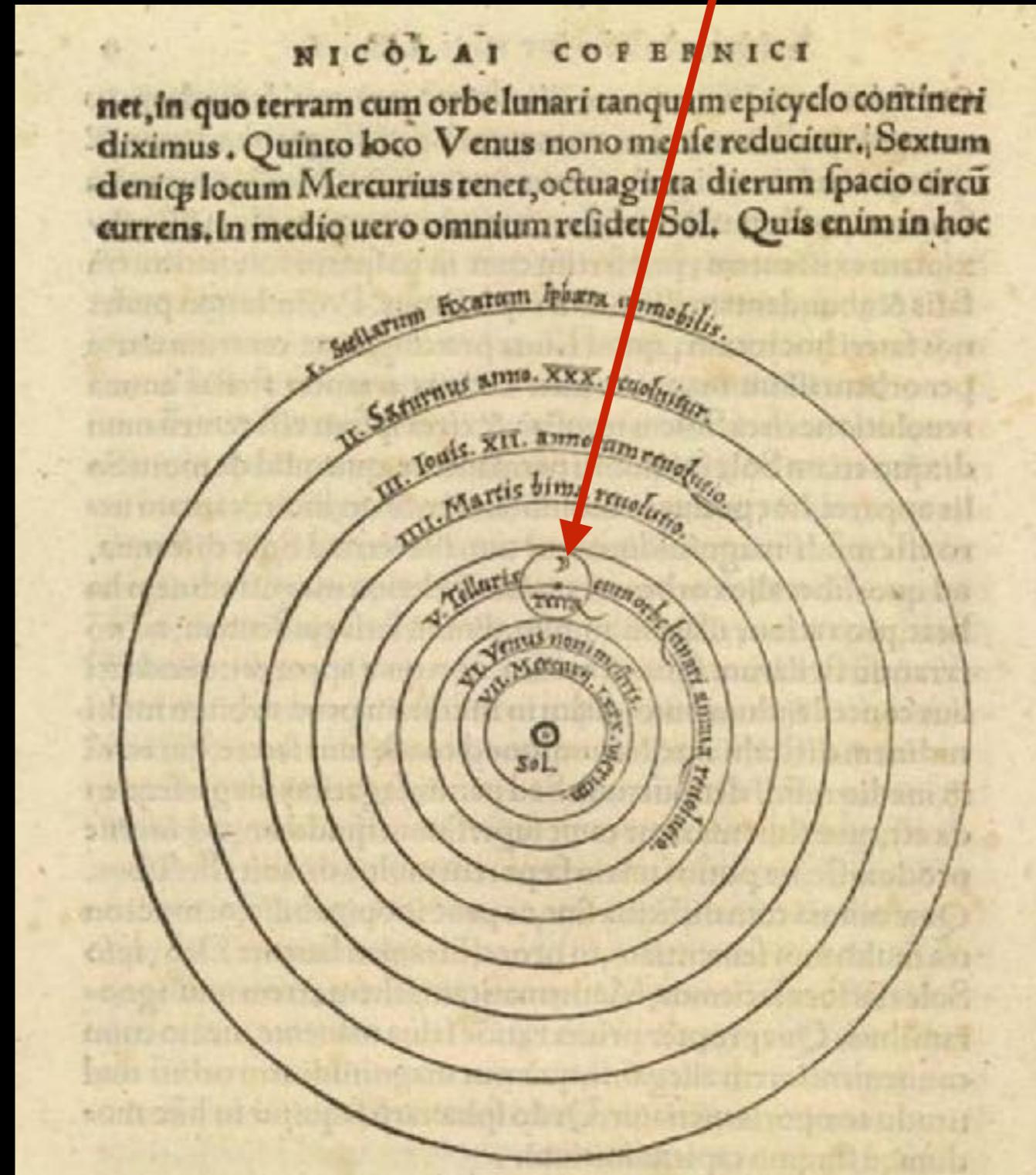
Supernovas, binary neutron stars and supermassive black holes

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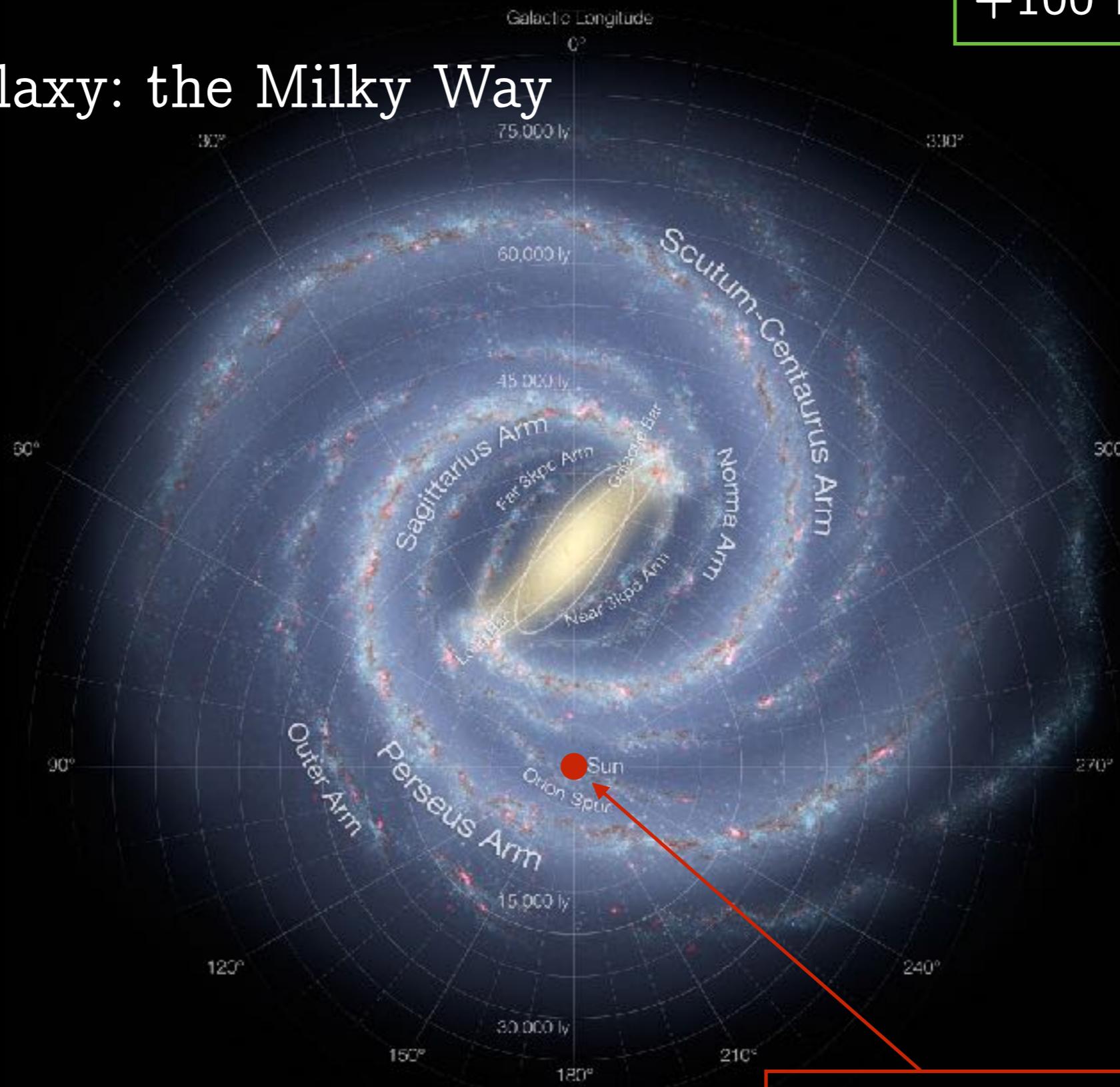
Solar System (Copernicus 1473-1543)

You are here



+100 billion stars

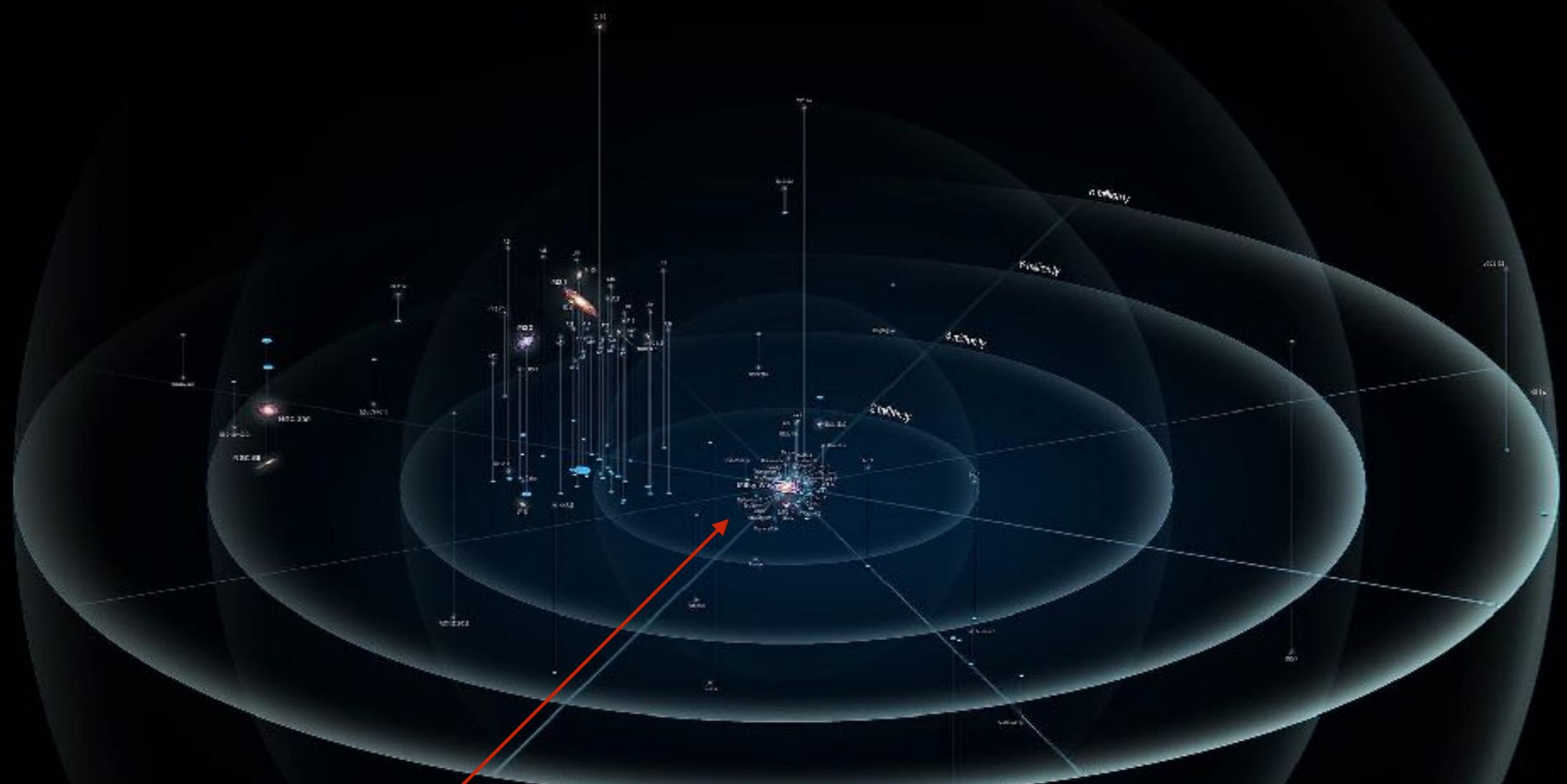
Our galaxy: the Milky Way



You are here

54 galaxies in the local group

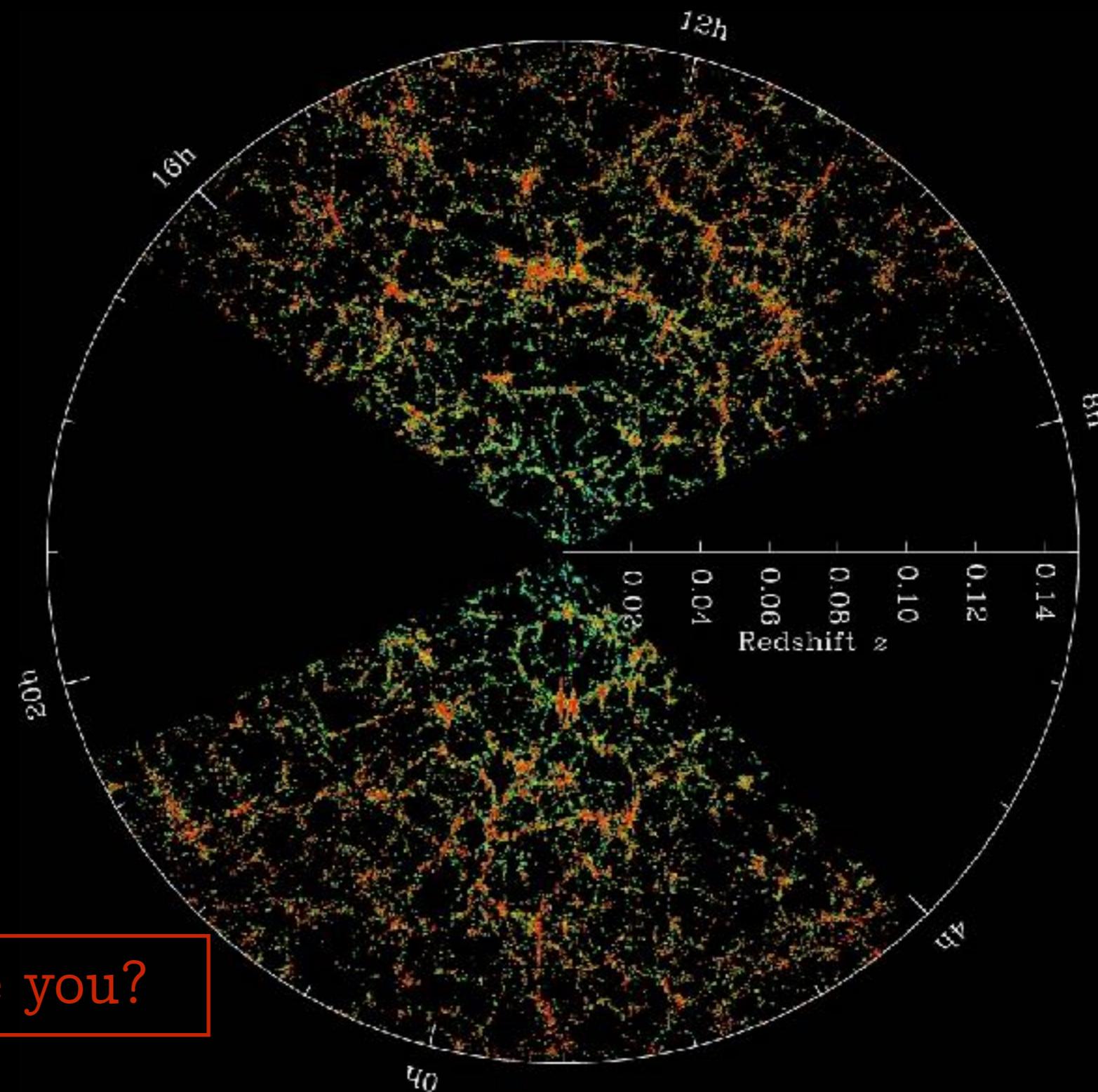
1920s. Galaxies beyond Milky Way



You are here

aprox. 100 billion galaxies

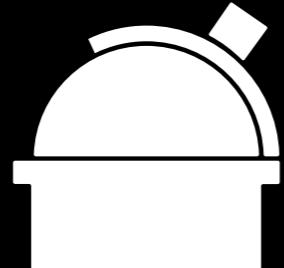
1990s. There are many, many more galaxies



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

[in light travel time]

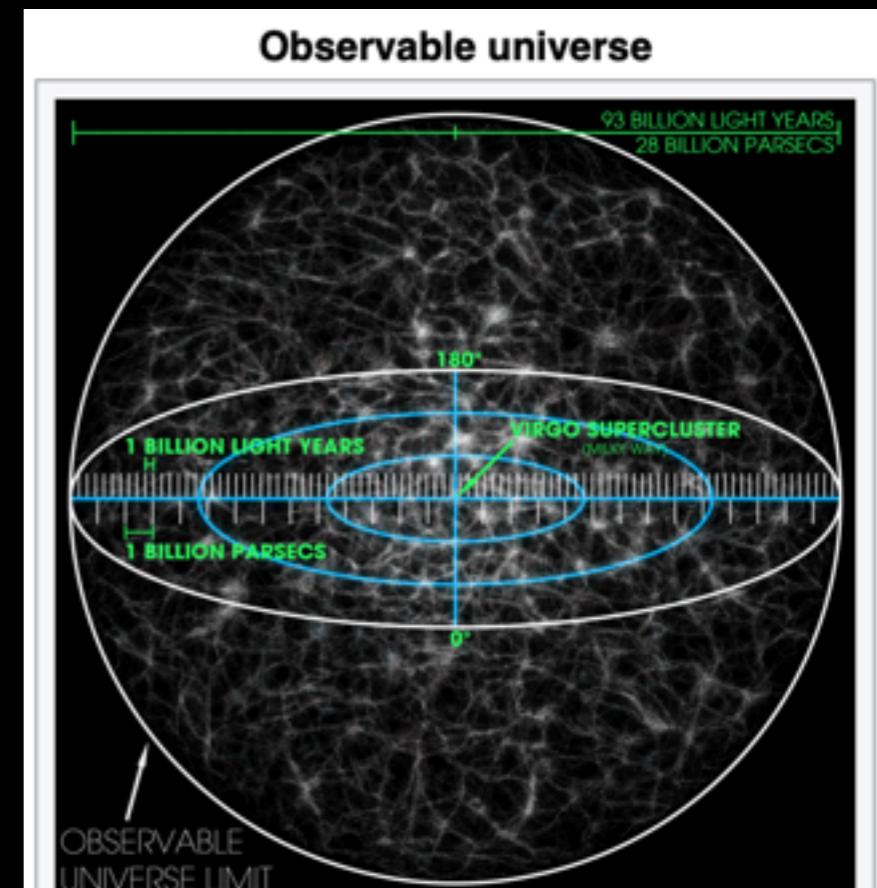
Moon ...	1.2 s
Sun ...	8.3 min
Closest star (proxima centauri)...	37 hours
Galactic center ...	26,000 years
Andromeda galaxy (M87) ...	2.5 million years
Cosmic Microwave Background ...	13.4 billion years



*speed of light 300,000 km/s

K: the universe is BIG

... but almost empty on average



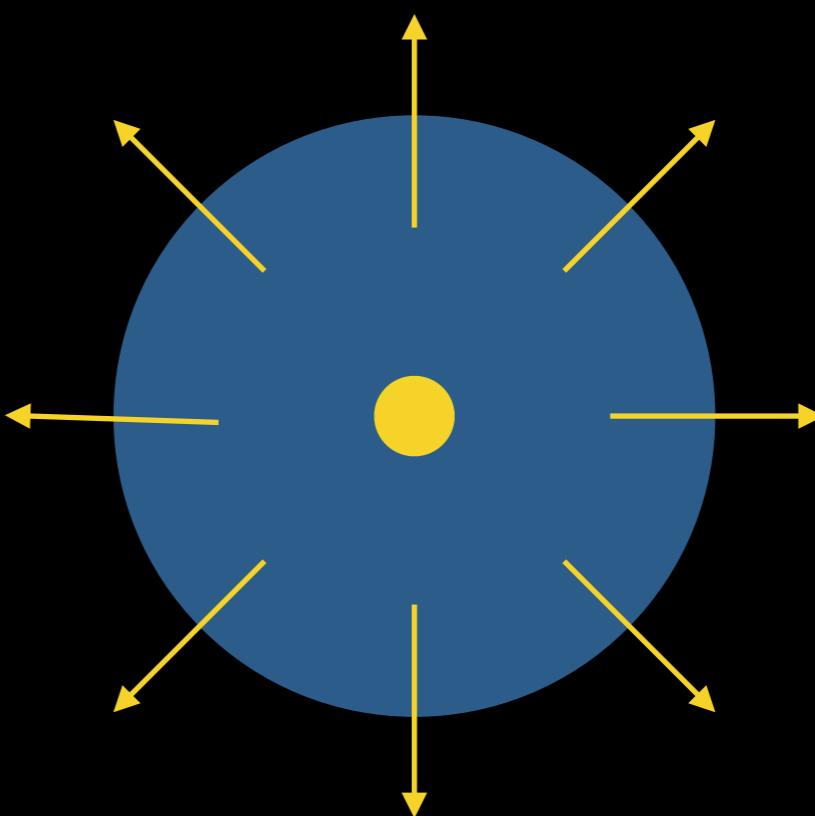
Visualization of the whole observable universe. The scale is such that the fine grains represent collections of large numbers of superclusters. The [Virgo Supercluster](#) —home of Milky Way—is marked at the center, but is too small to be seen.

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]



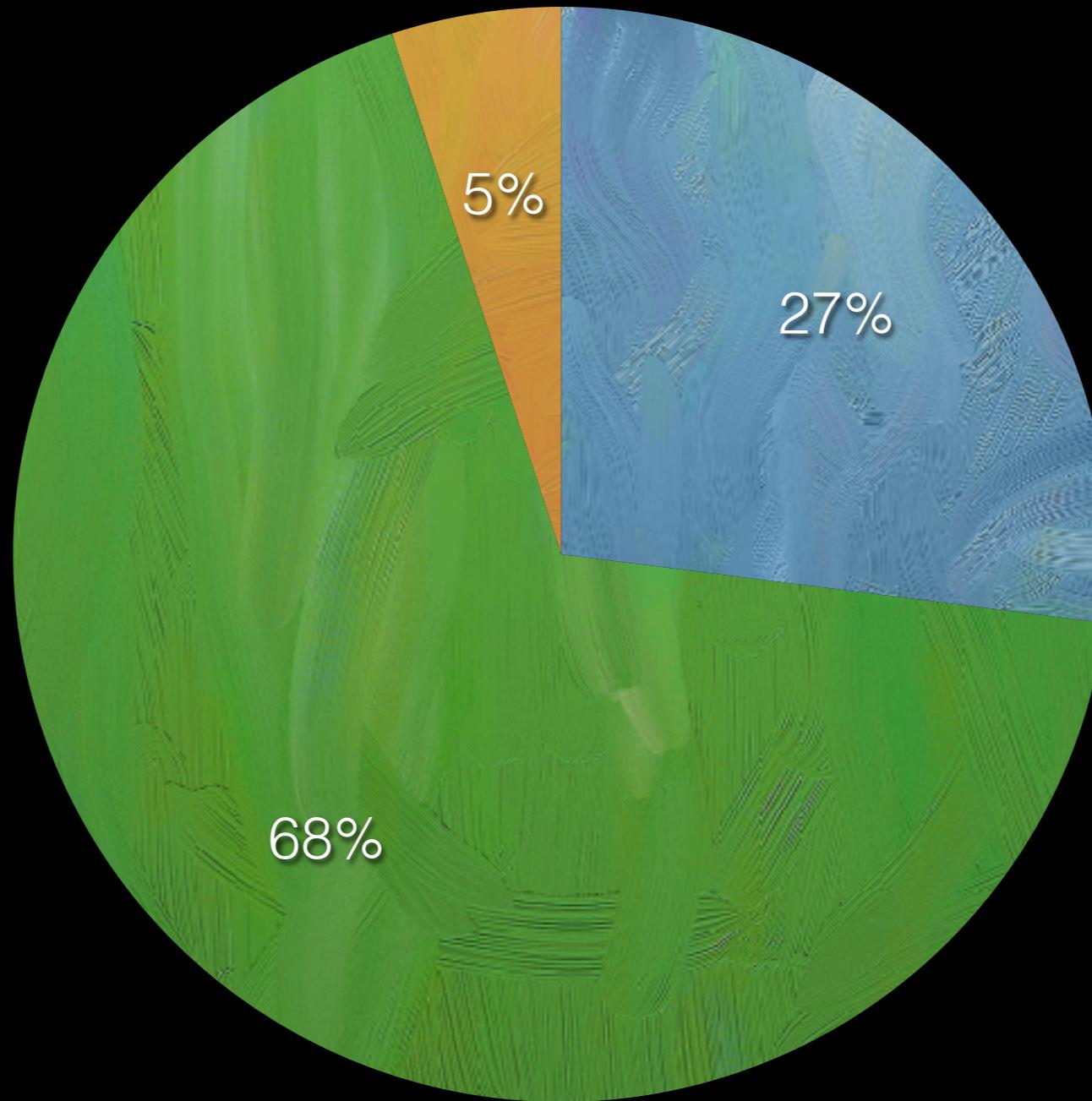
Gauss

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



K: need extremely energetic phenomena!



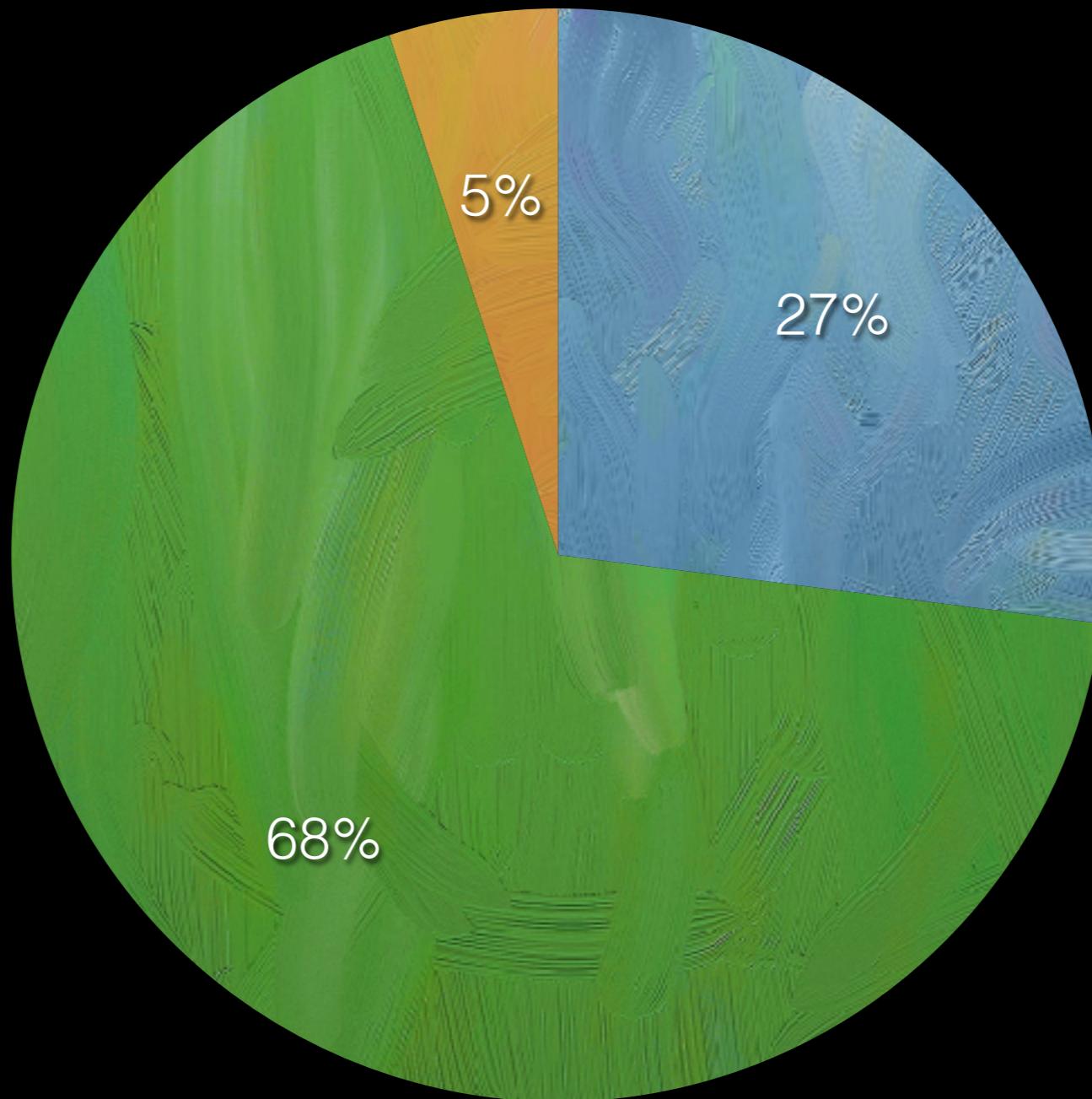


Q/A: What is the universe made of?

Ordinary matter

Radiation

Dark Matter



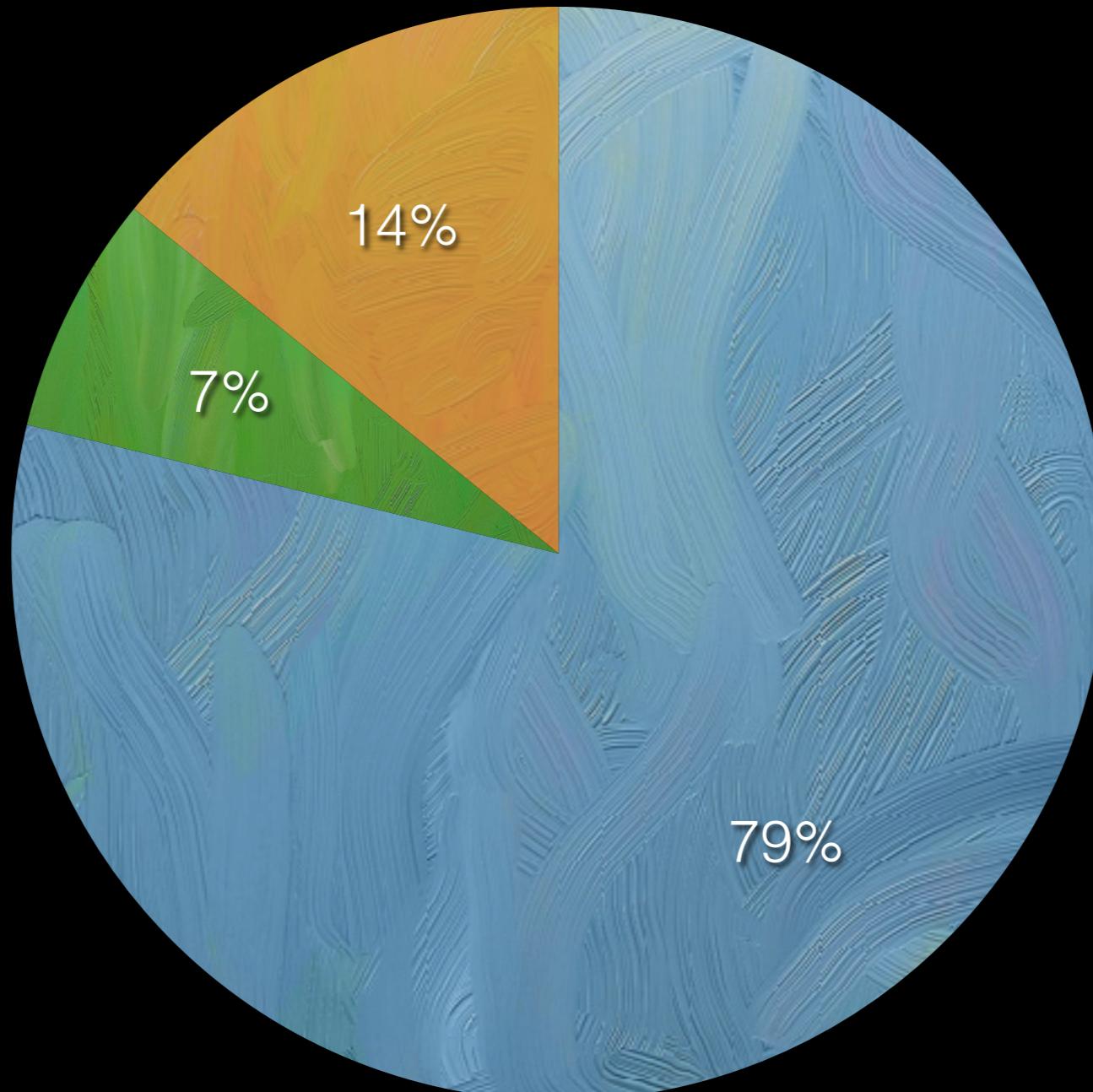
Dark Energy

TODAY, 13.8 billion years
after Big Bang

Ordinary matter

Radiation

Dark Matter



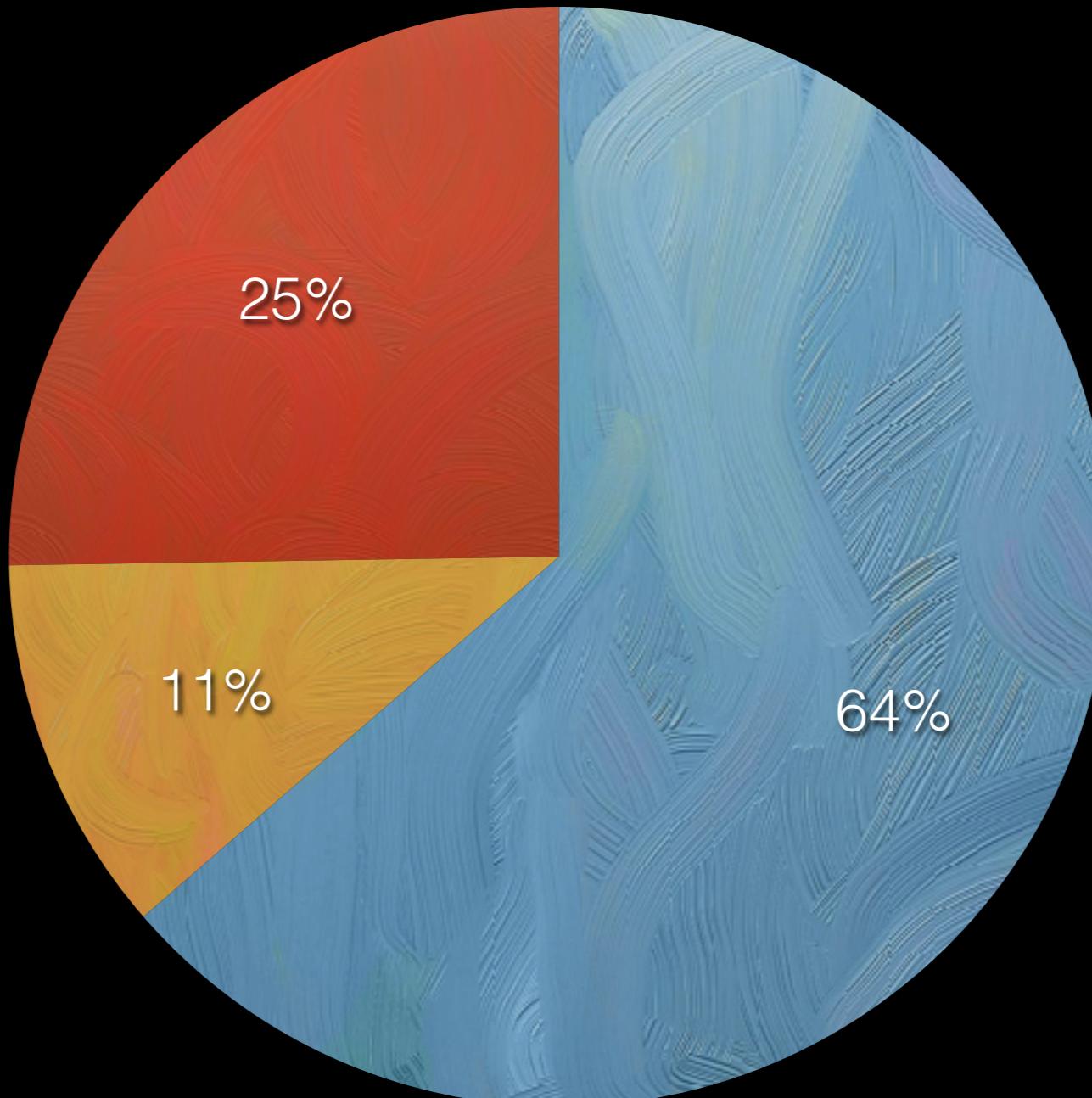
Dark Energy

First stars, 200 million years
after Big Bang

Ordinary matter

Radiation

Dark Matter



Dark Energy

CMB, 380.000 years after
Big Bang

Ordinary matter

Radiation

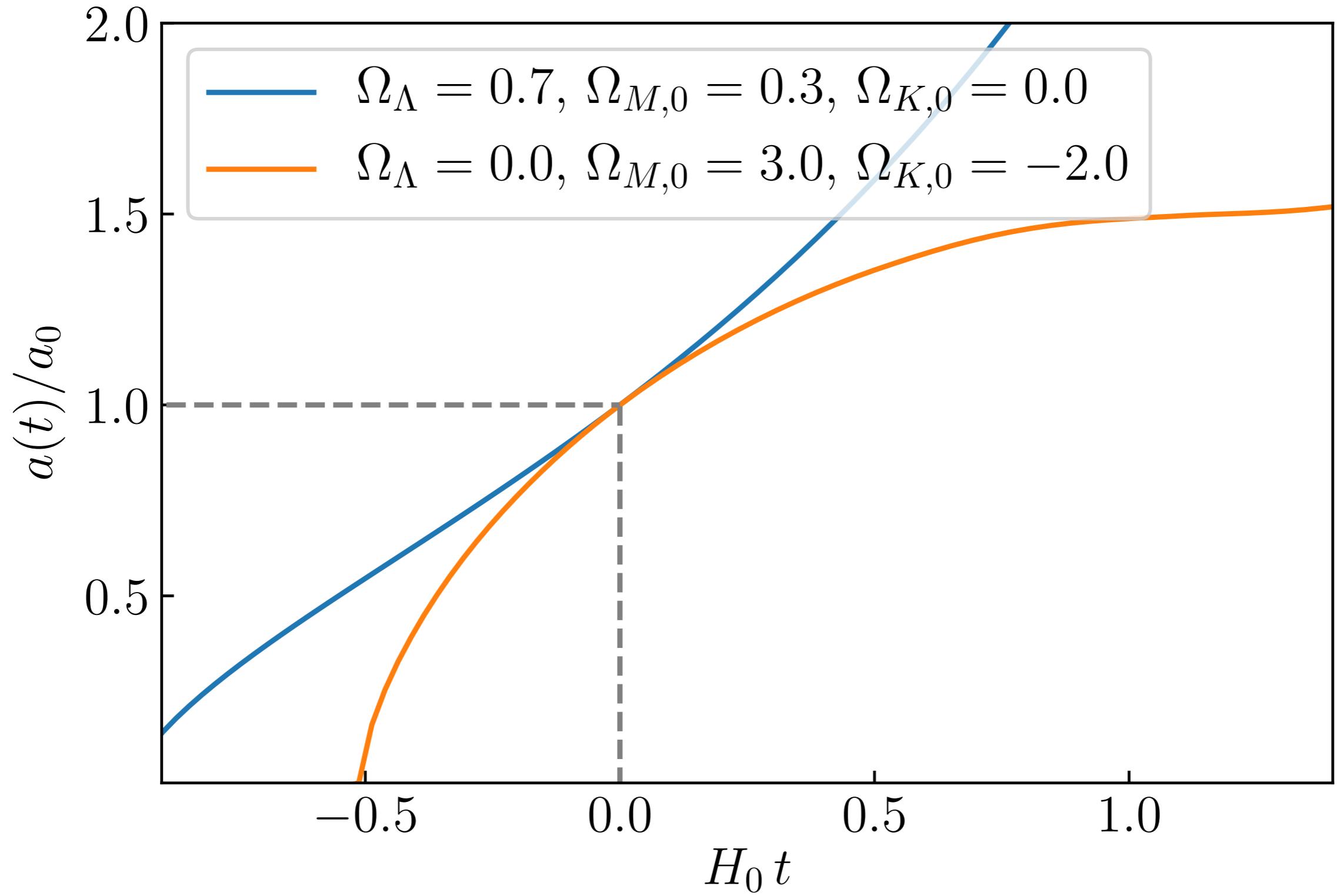
Dark Matter

100%

Dark Energy

Nuclei form, 100 seconds
after Big Bang

Universe content determines its fate!



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

Standard Model of Particle Physics

-everything but DM and DE-

QUARKS		GAUGE BOSONS			
LEPTONS					
mass →	$\approx 2.3 \text{ MeV}/c^2$	$\approx 1.275 \text{ GeV}/c^2$	$\approx 173.07 \text{ GeV}/c^2$	0	$\approx 126 \text{ GeV}/c^2$
charge →	2/3	2/3	2/3	0	0
spin →	1/2	1/2	1/2	1	0
	u	c	t	g	H
	up	charm	top	gluon	Higgs boson
mass →	$\approx 4.8 \text{ MeV}/c^2$	$\approx 95 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	0	
charge →	-1/3	-1/3	-1/3	0	
spin →	1/2	1/2	1/2	0	
	d	s	b	γ	
	down	strange	bottom	photon	
mass →	$0.511 \text{ MeV}/c^2$	$105.7 \text{ MeV}/c^2$	$1.777 \text{ GeV}/c^2$	0	
charge →	-1	-1	-1	0	
spin →	1/2	1/2	1/2	1	
	e	μ	τ	Z	
	electron	muon	tau	Z boson	
mass →	$< 2.2 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 15.5 \text{ MeV}/c^2$	0	
charge →	0	0	0	1	
spin →	1/2	1/2	1/2	1	
	ν _e	ν _μ	ν _τ	W	
	electron neutrino	muon neutrino	tau neutrino	W boson	

What makes a good messenger?

Speed - massless

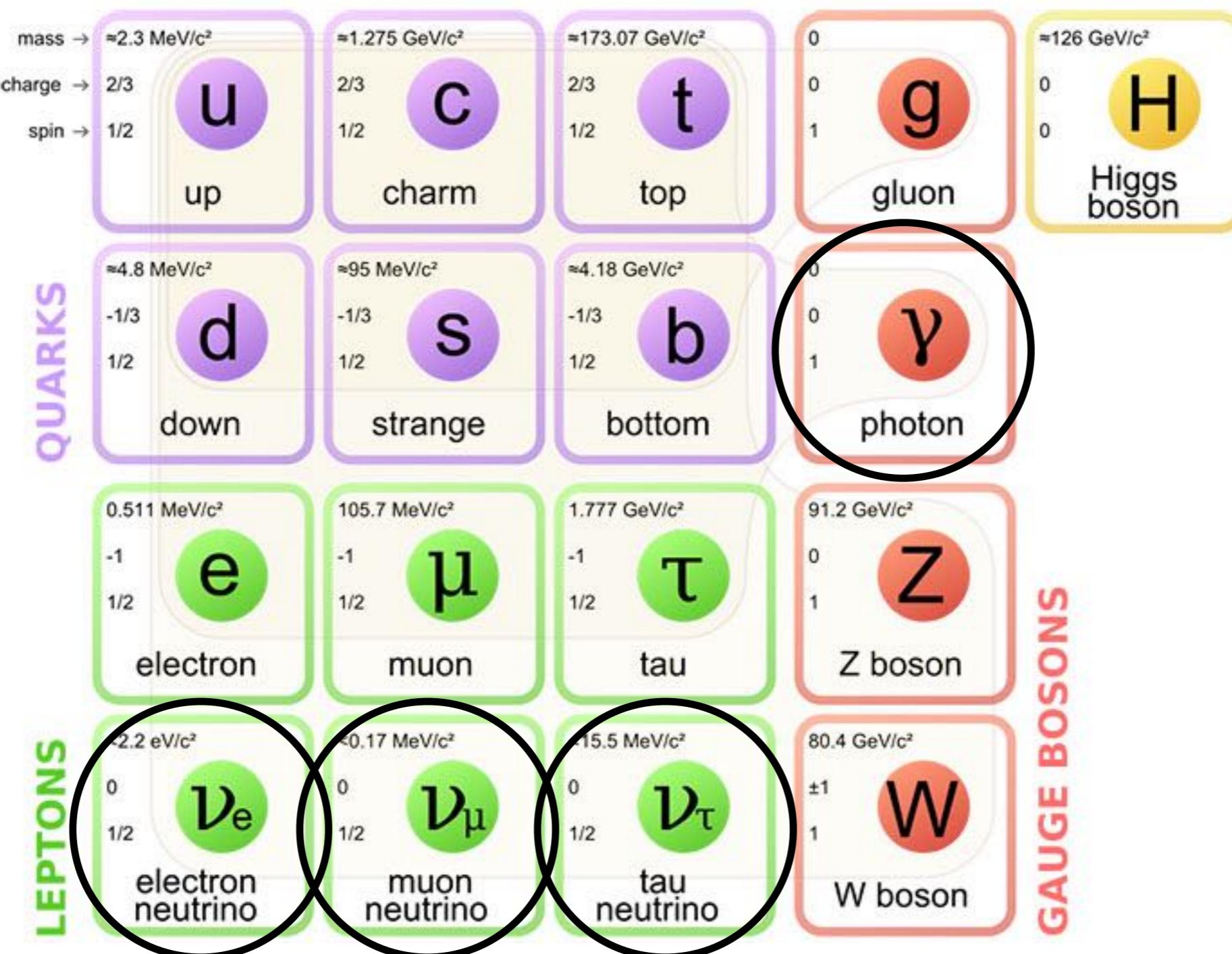
Avoid interactions - neutral

Endurance - stable

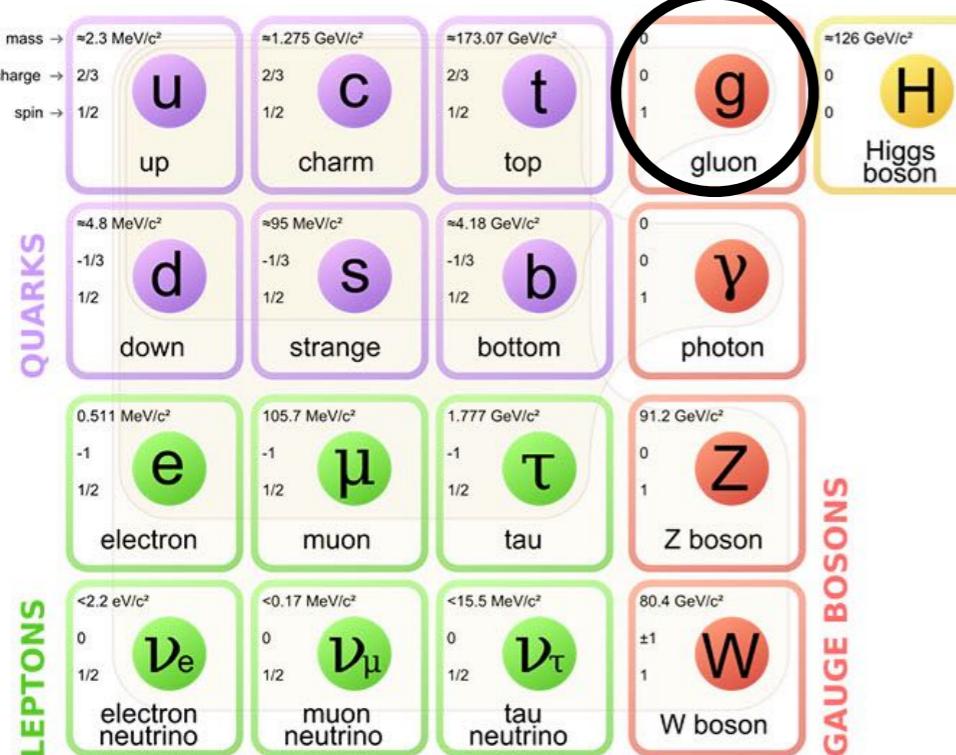


Standard Model of Particle Physics

-everything but DM and DE-



R: why not the gluon?



PDG
particle data group

Home pdgLive Summary Tables Reviews, Tables, Plots Particle Listings

Mobile Particle Physics Booklet

Web Version

- No installation needed - runs in any browser (iOS, Android, Windows, ...)
- [Full screen tip for iOS](#)

PDG
particle data group
2020
PARTICLE PHYSICS BOOKLET

Constants
Summary tables
Reviews
About
PDG website (Listings, all review articles...)

Version 0.4.2, December 18, 2020

Android App

- [PDG Particle Physics Booklet app](#) on Google Play
- Works without Internet access

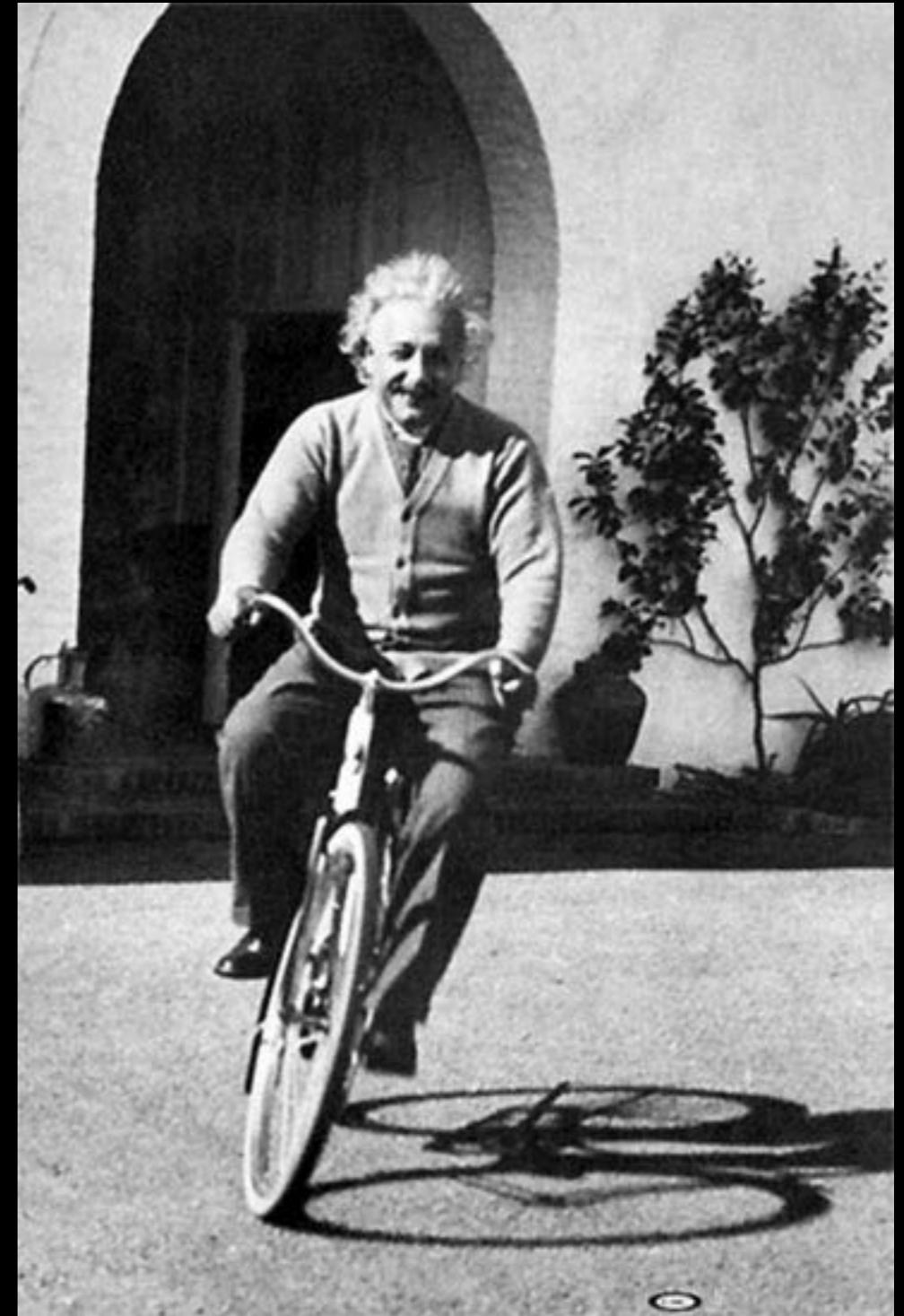
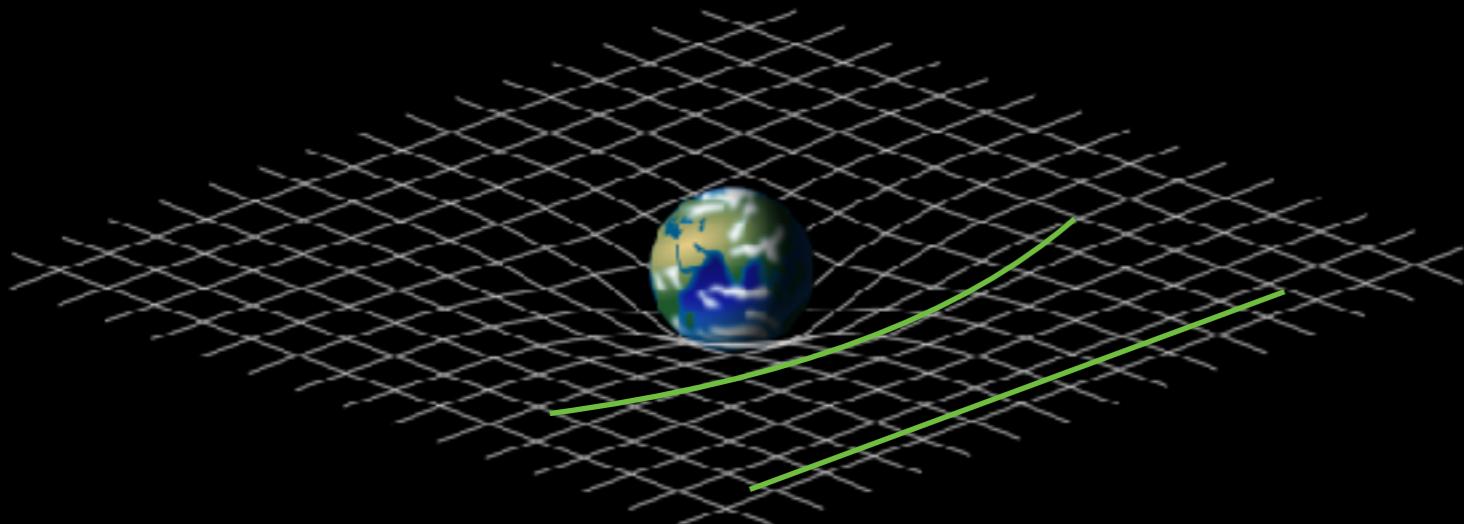
Why no app for iOS (Apple)?

- Our iOS app was seen by Apple as being primarily a book, so it is not available in the Apple App Store

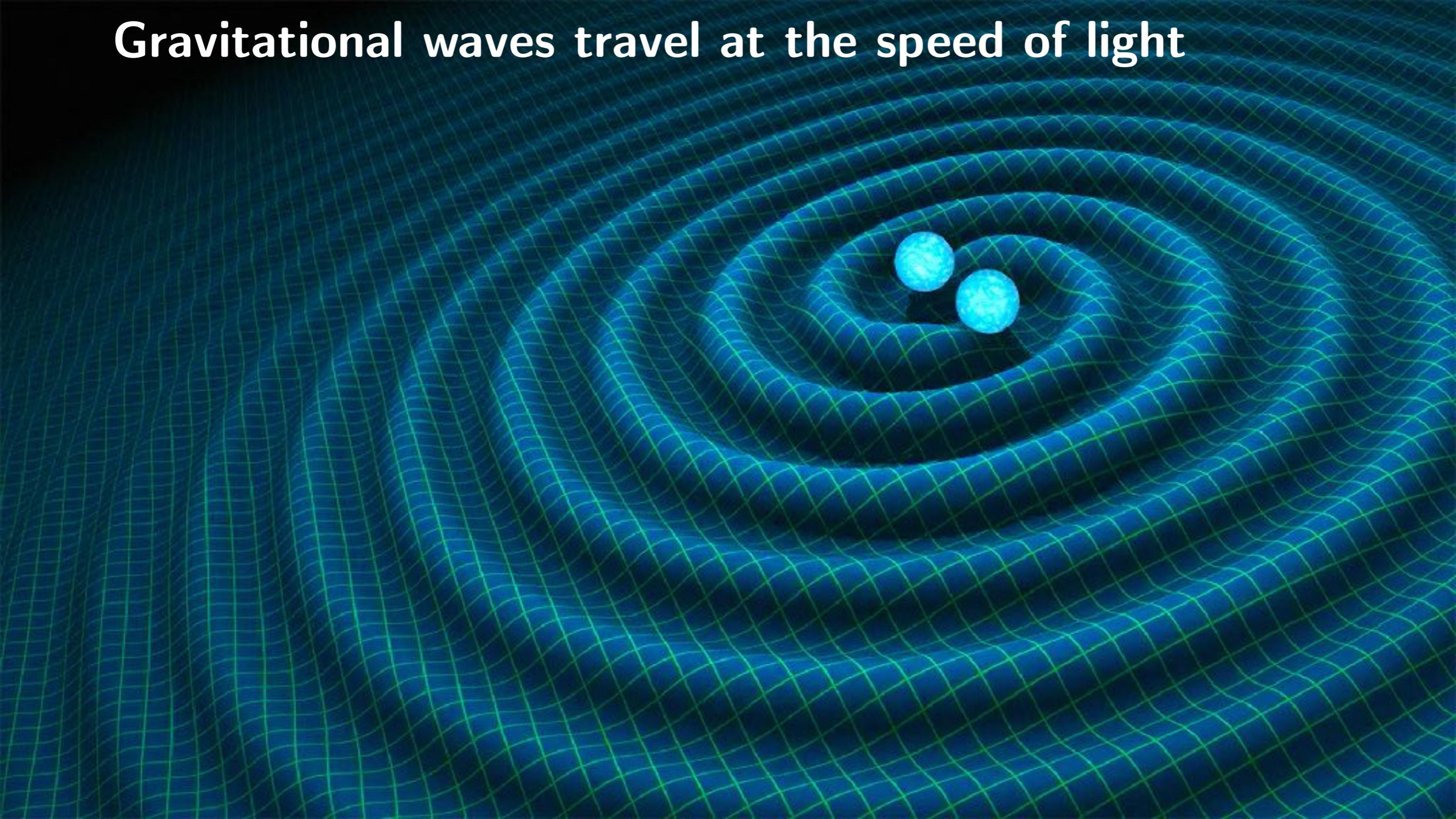
What about gravity?

1915. “Massive objects curve space-time”

Trajectories bend



Gravitational waves travel at the speed of light



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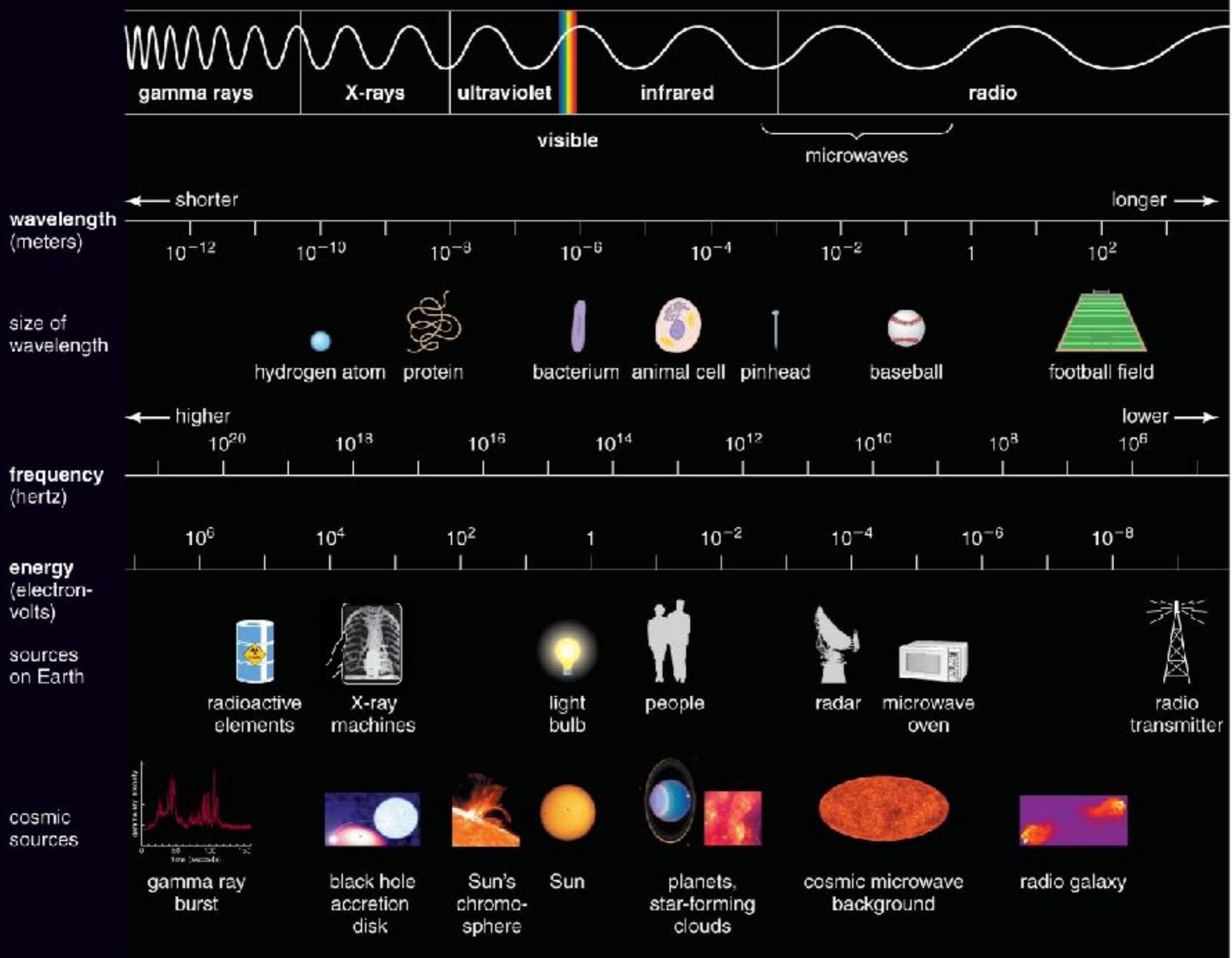
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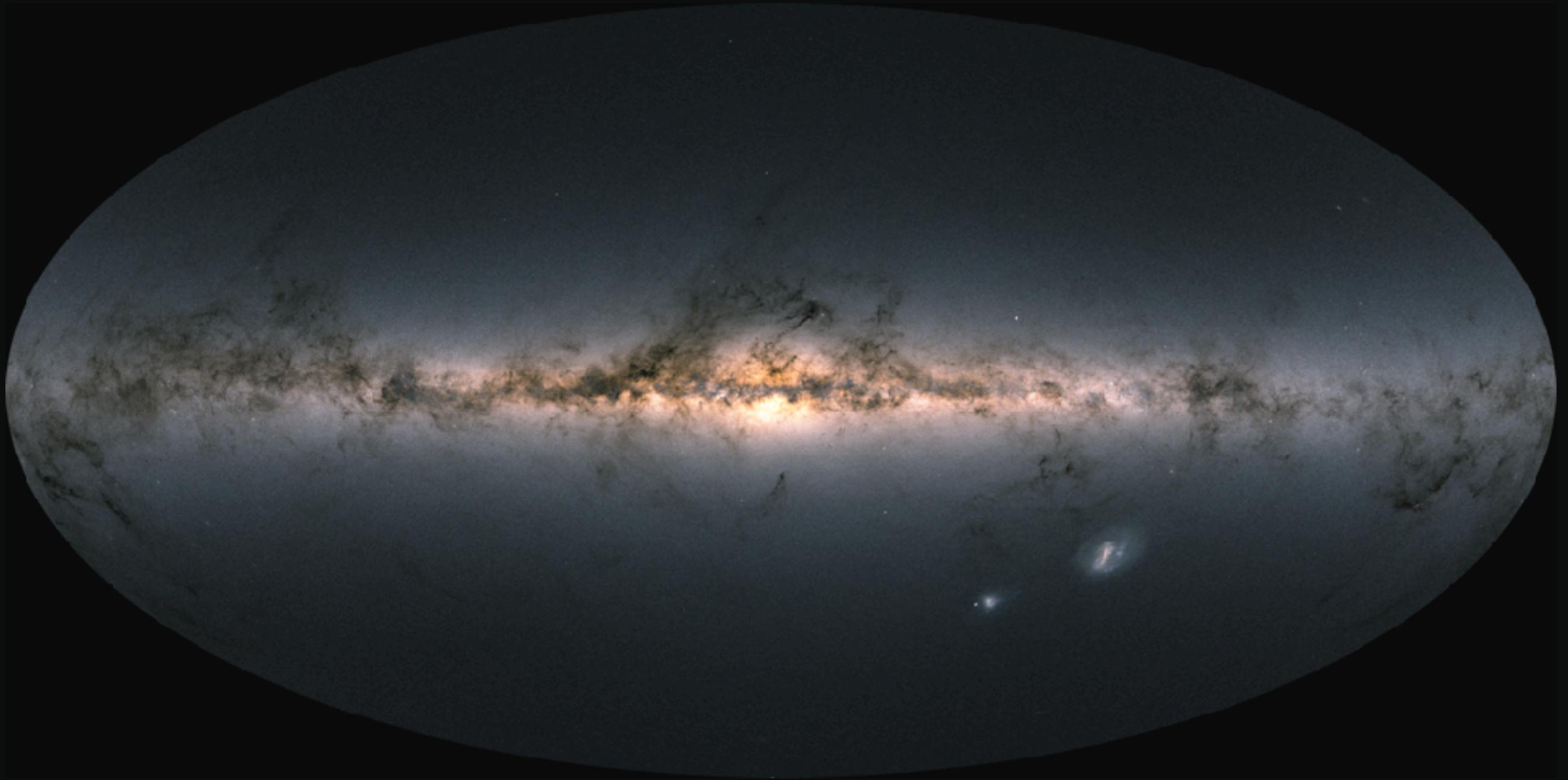
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Cosmology and fundamental physics with multi-messenger GW astronomy

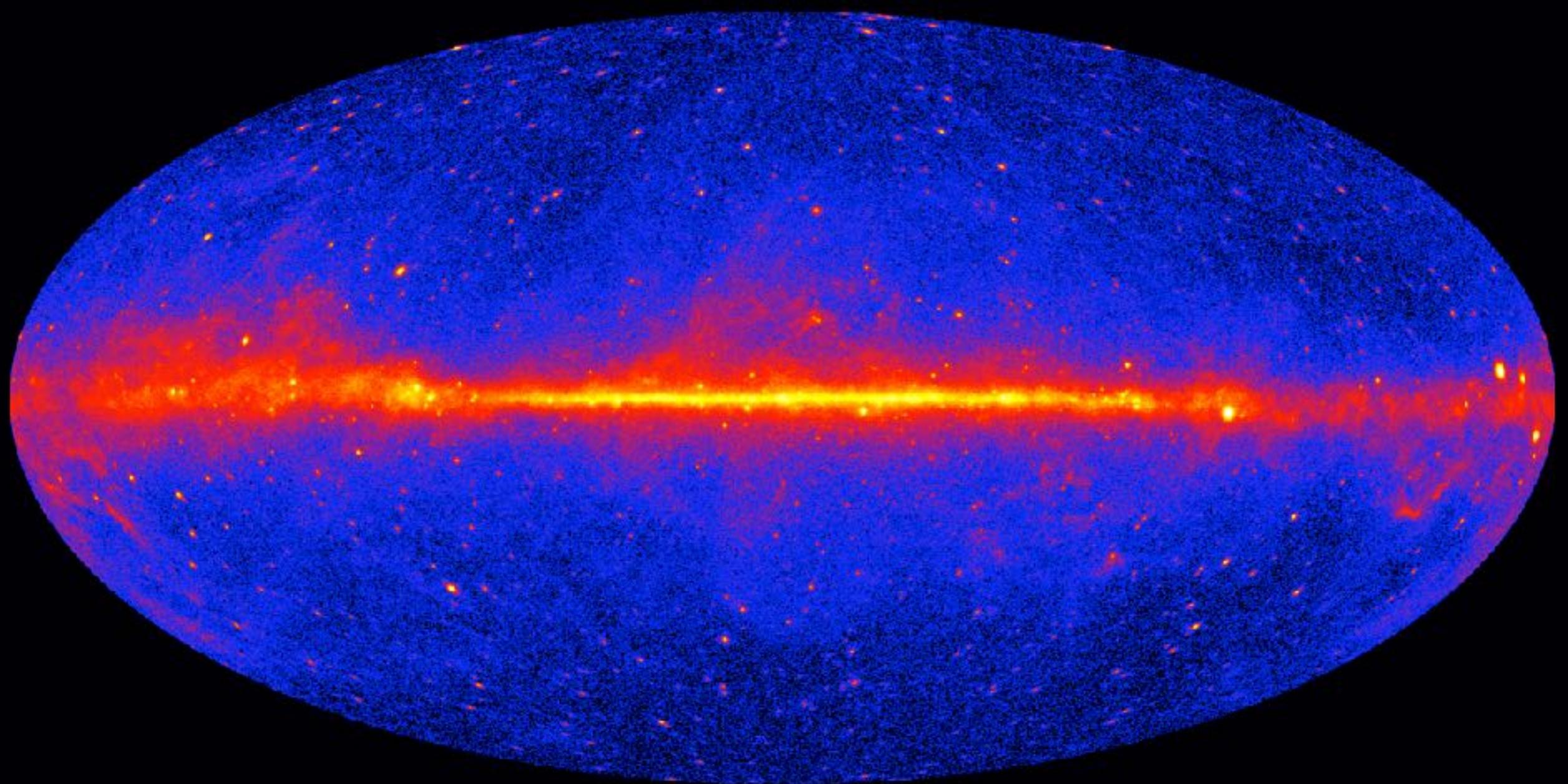


The Electromagnetic Spectrum



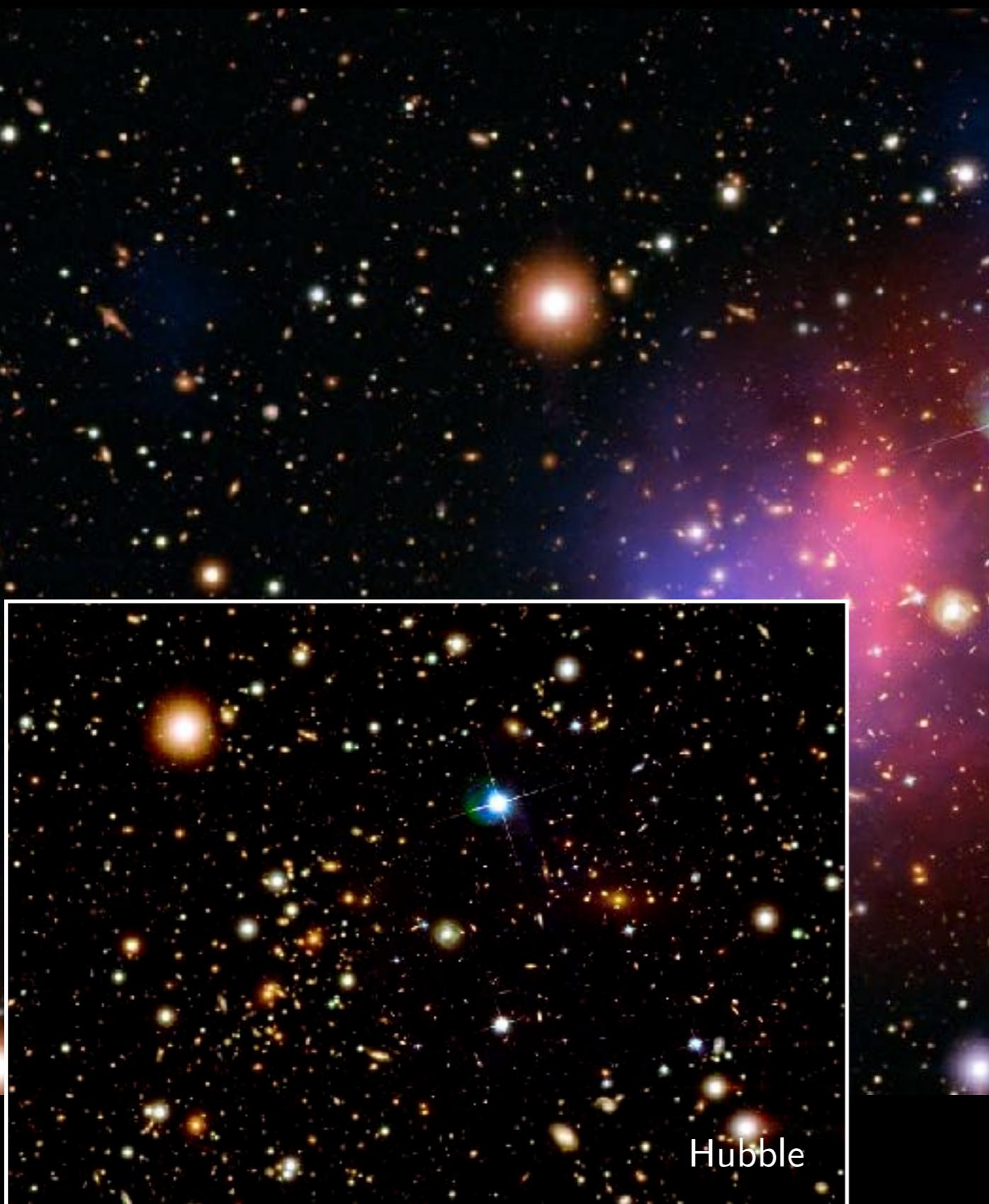


[Image credit: ESA/GAIA]

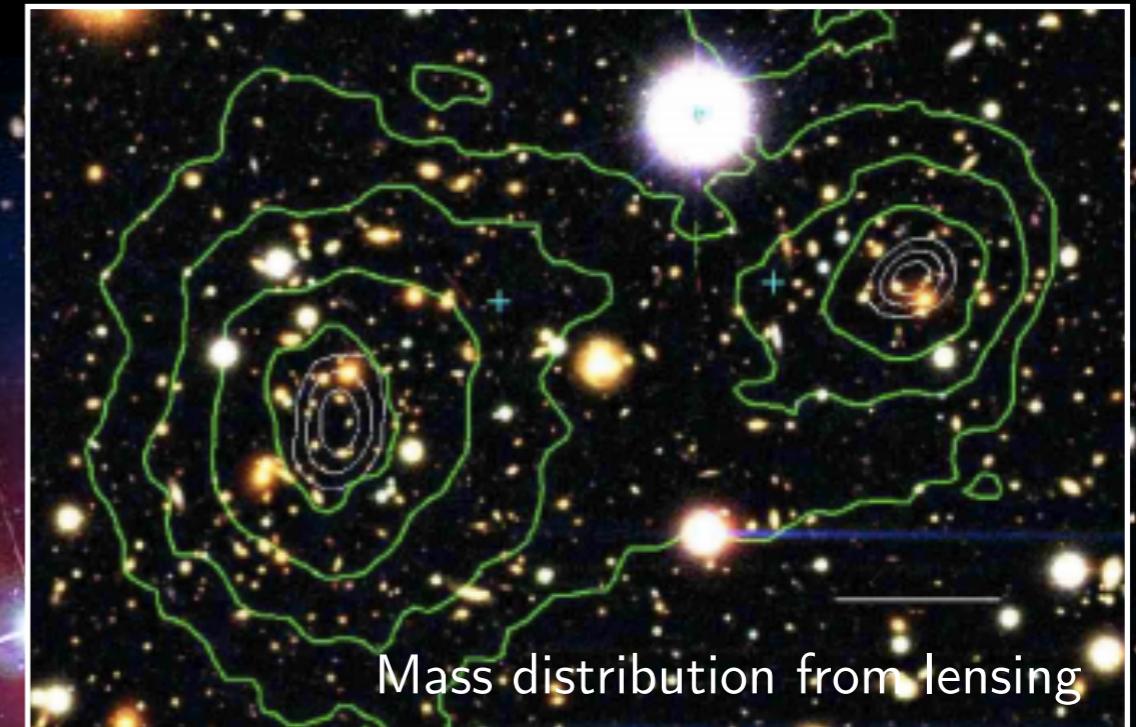


[Image credit: NASA/DOE/Fermi LAT Collaboration]

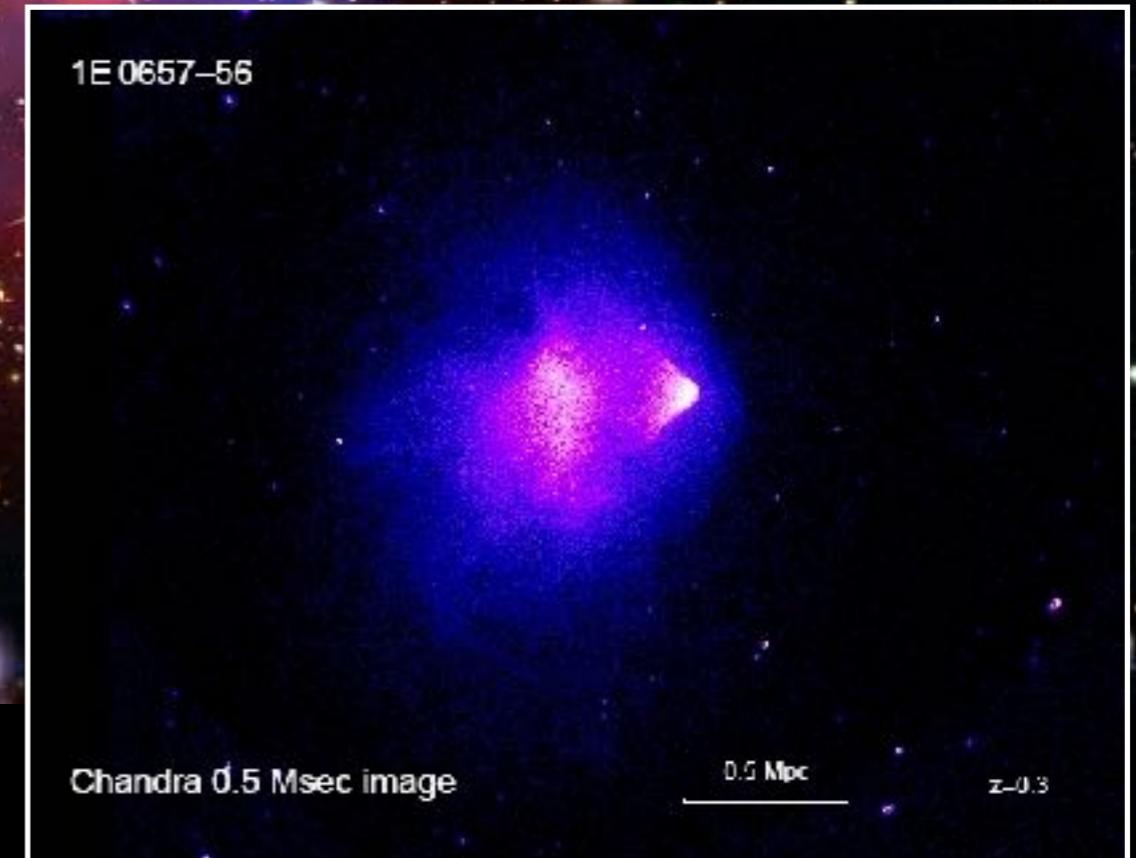
Bullet cluster

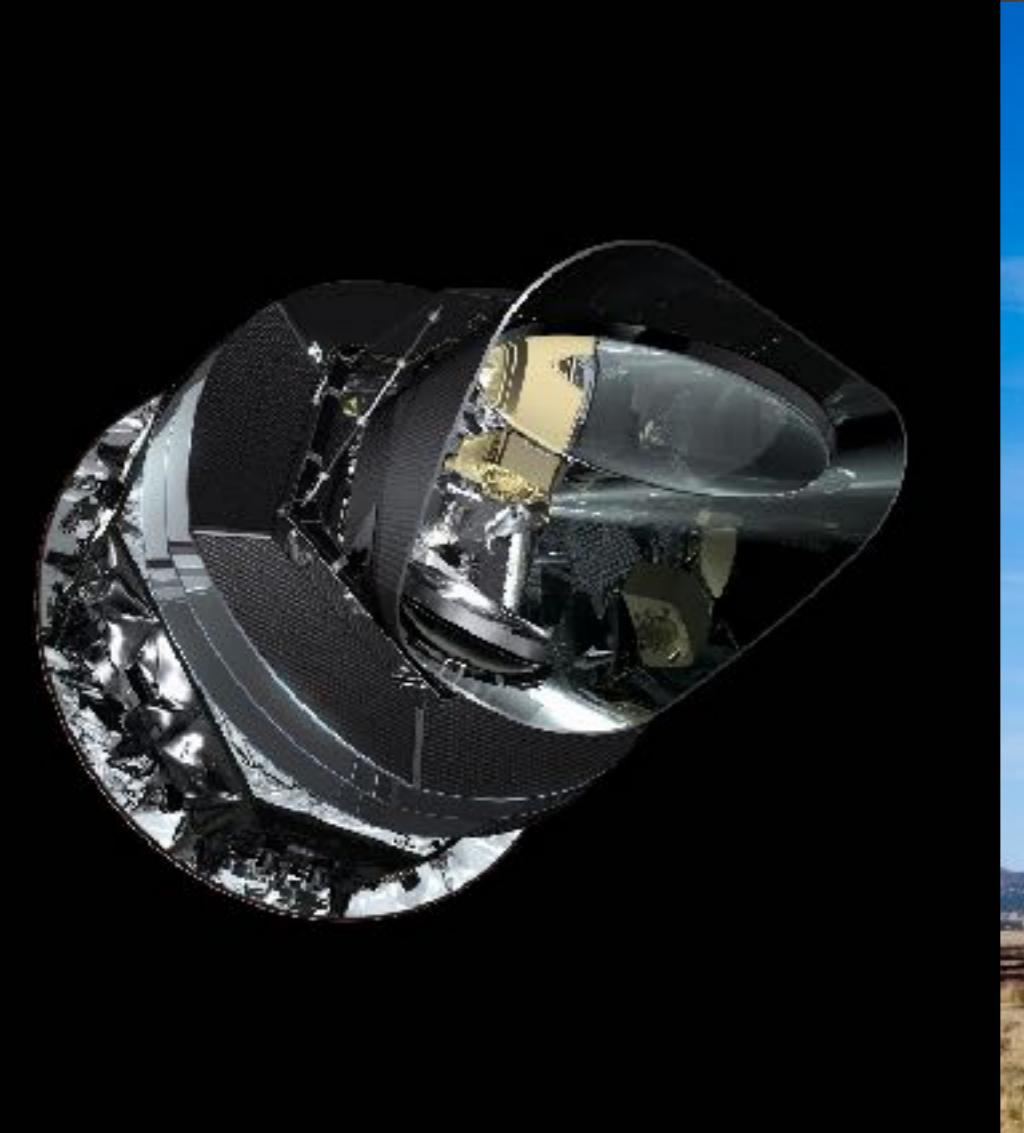


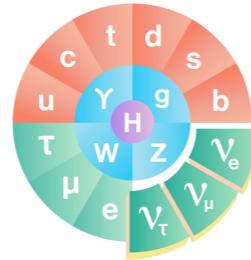
Hubble



1E 0657-56







FUNDAMENTAL

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



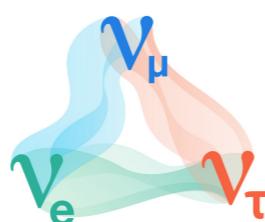
ABUNDANT

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.

NEUTRINOS ARE...



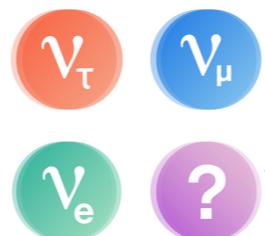
LIGHTWEIGHT

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.



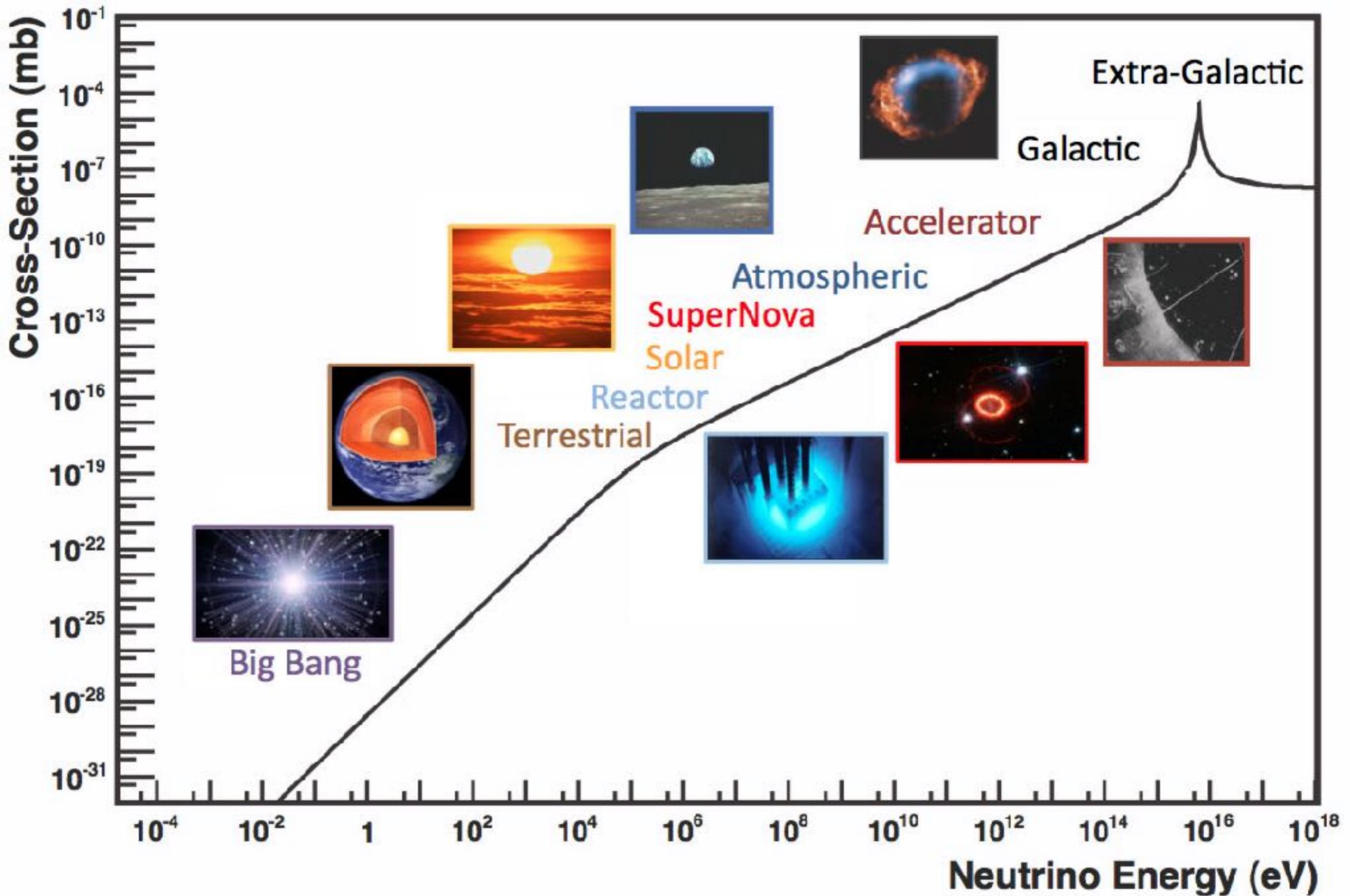
MYSTERIOUS

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.

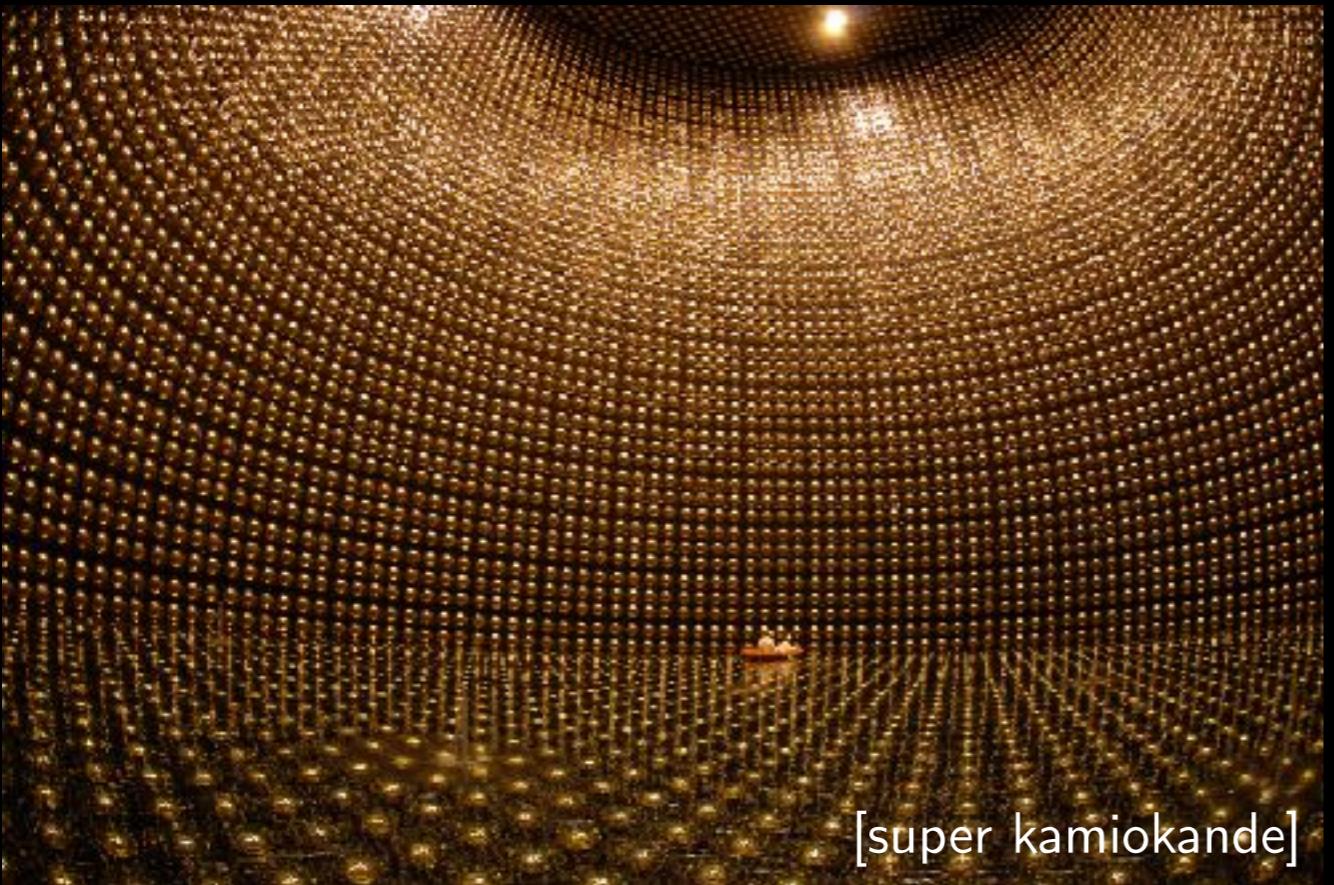


VERY MYSTERIOUS

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.



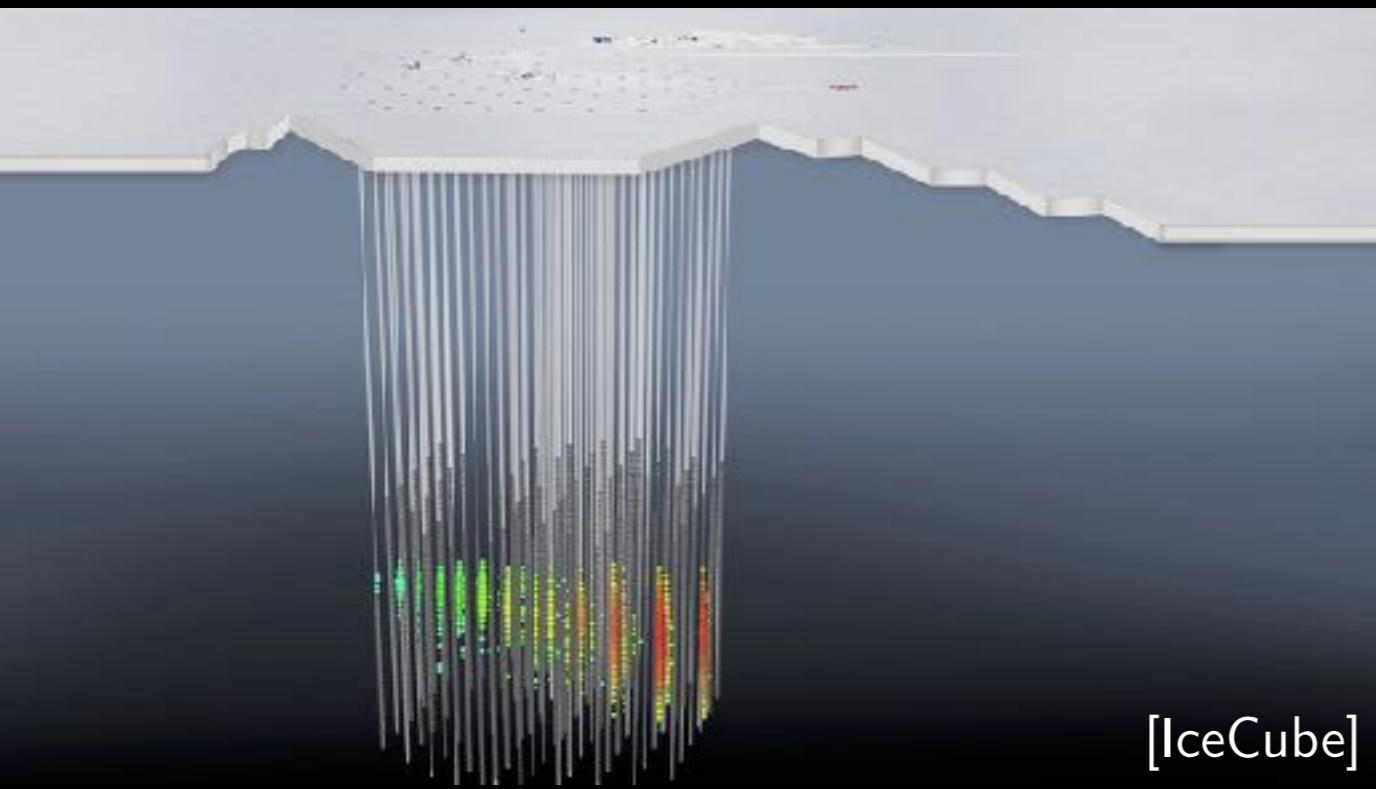
[Credit: J.A. Formaggio and G.P. Zeller]



[super kamiokande]



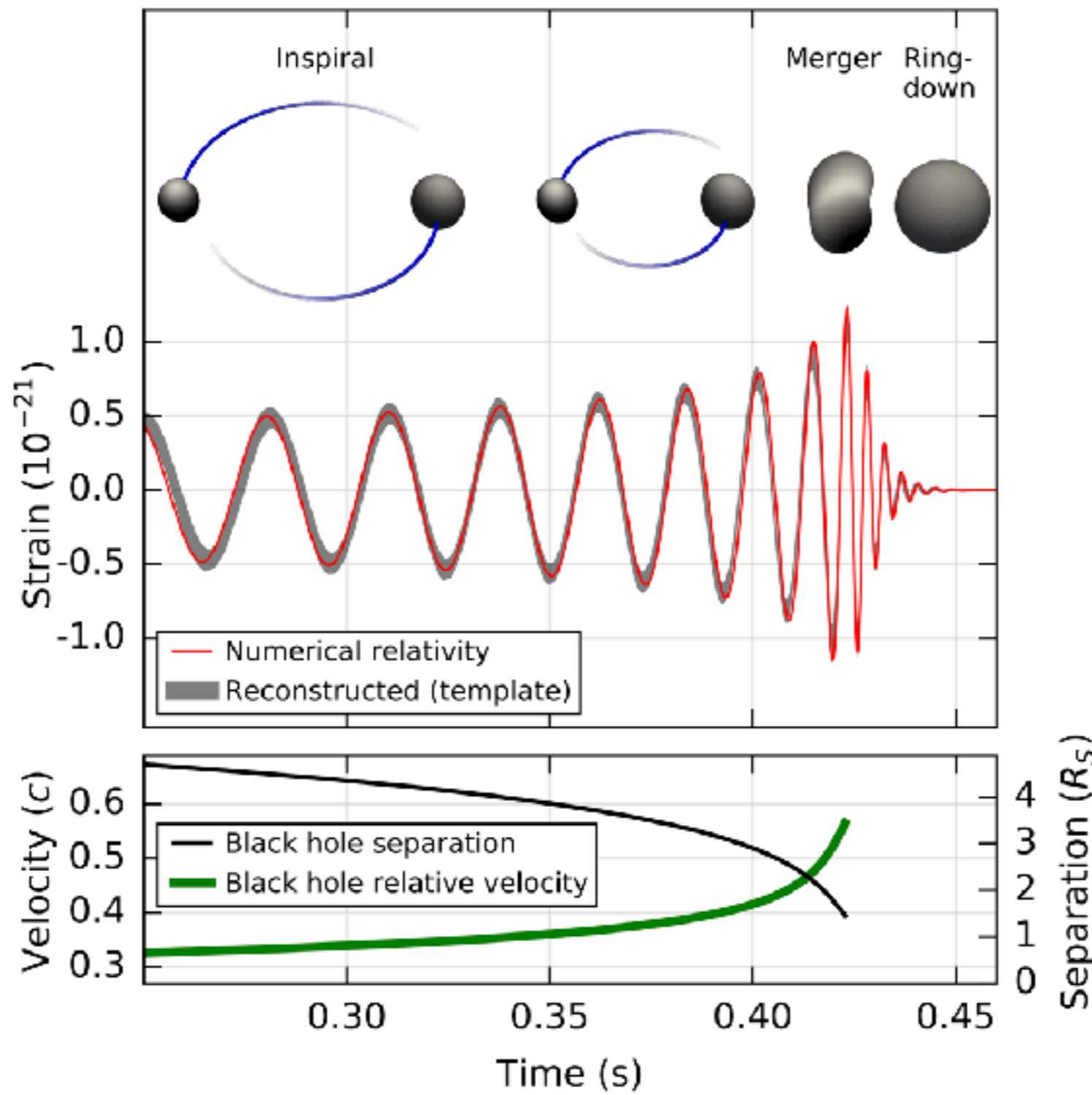
[ANTARES]



[IceCube]

K: neutrino detectors
need big volumes!

New era of Gravitational Wave Astronomy



[Credit: LIGO]

How large is the effect?

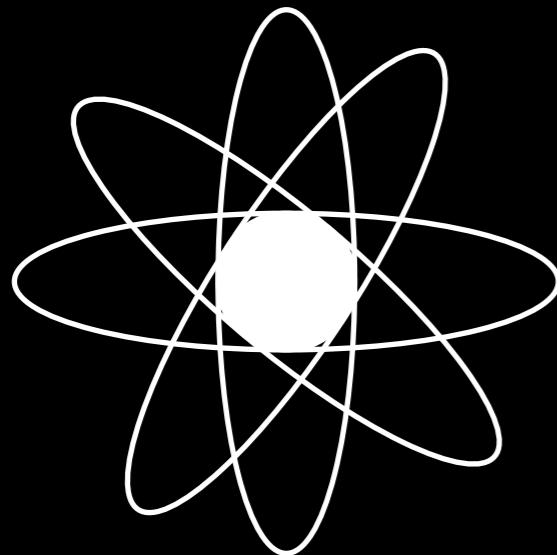


Scale of Effect Vastly Exaggerated

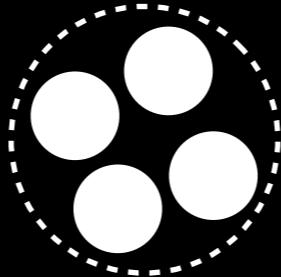
[Credit: R. Hurt, Caltech/MIT/LIGO Lab]

The variation in the distance is minuscule

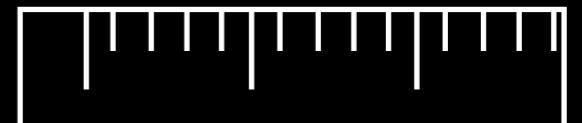
0.0000000000000001 meters



atom: 10^{-10} meters



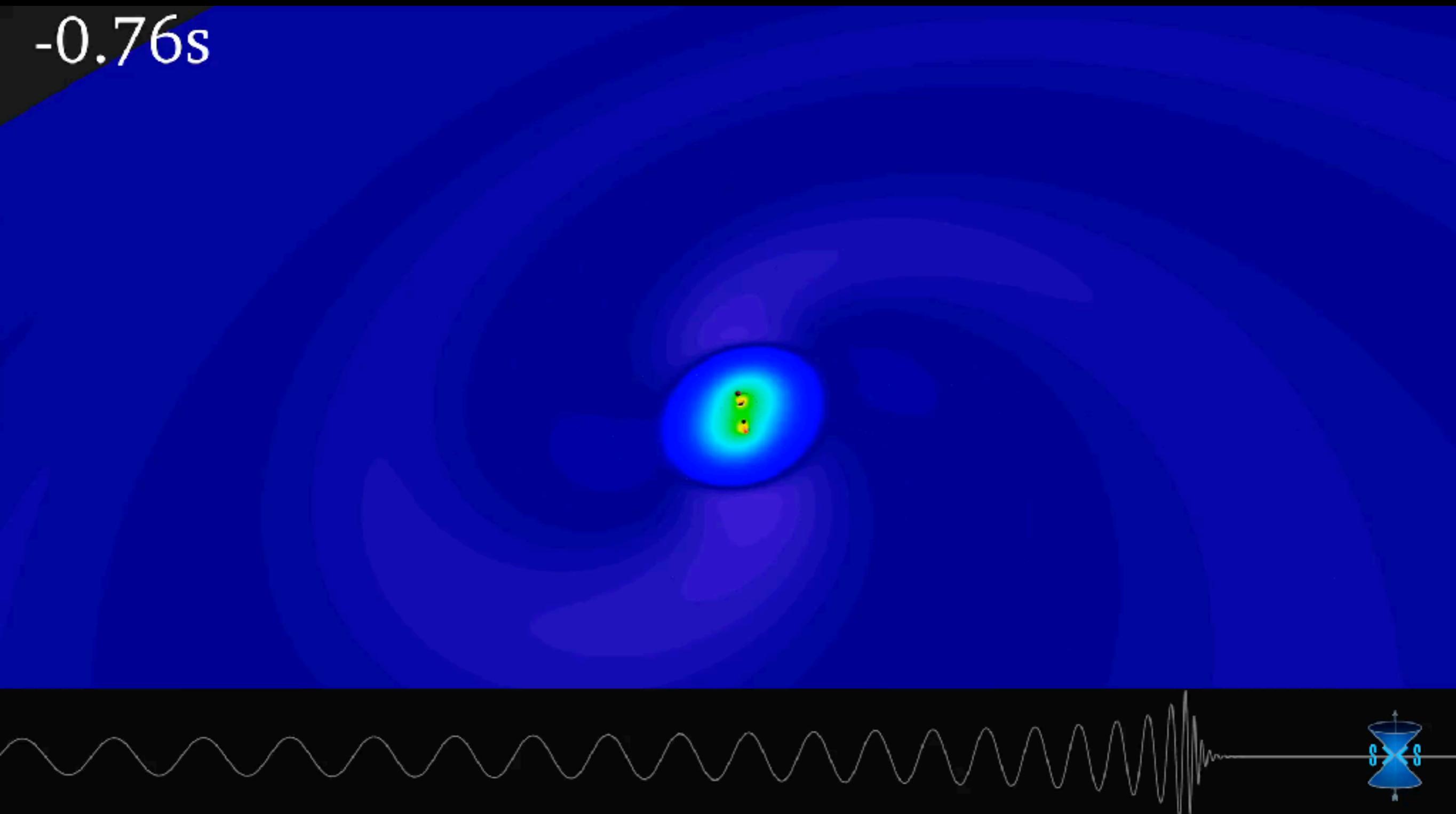
nucleus: 10^{-15} meters



GW effect: 10^{-18} meters

BINARY BLACK-HOLE MERGER

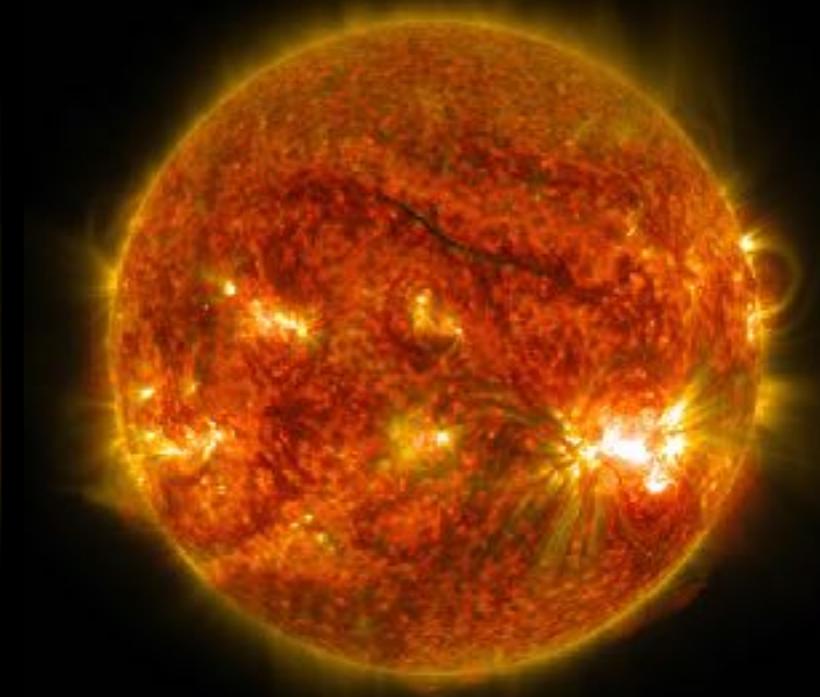
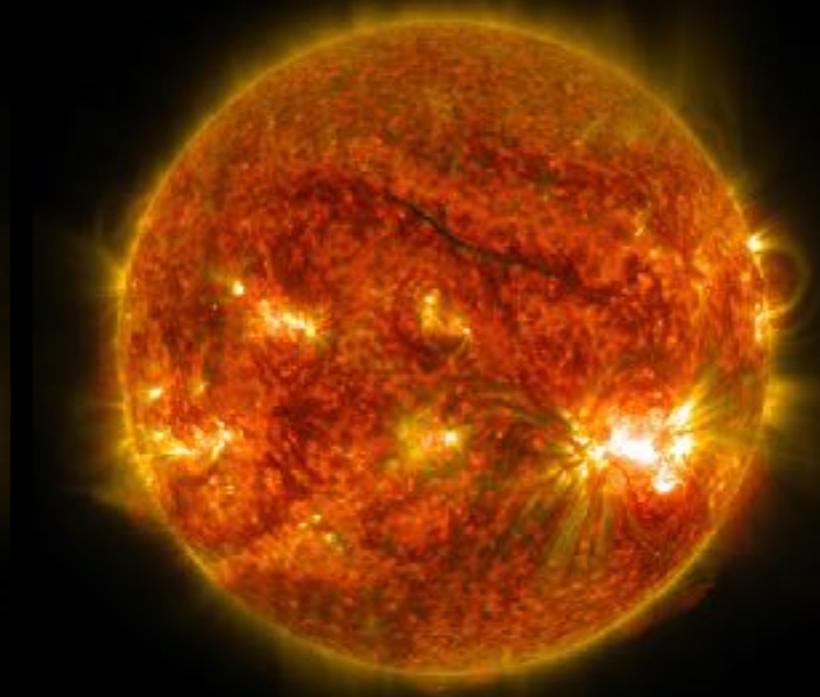
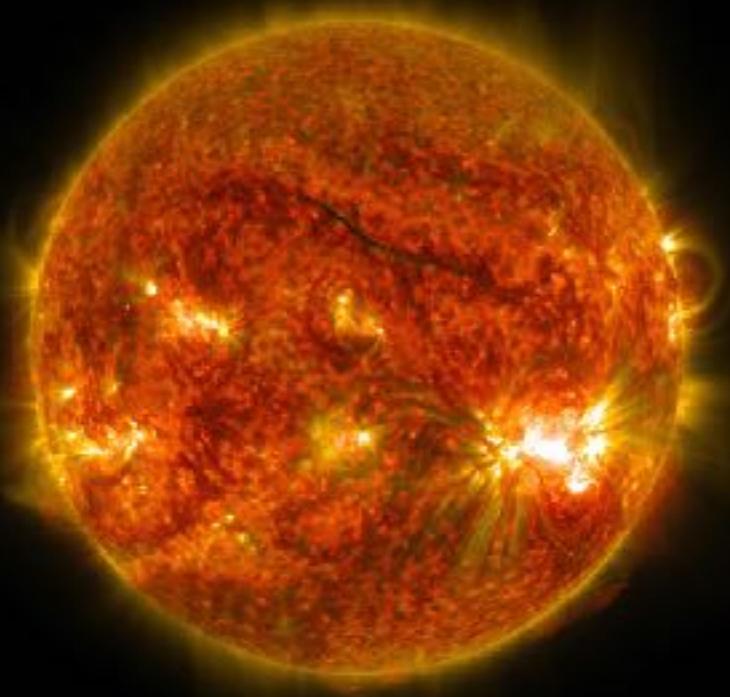
-0.76s



[Credit: SxS Collaboration]

ENERGY EMITTED IN GWs

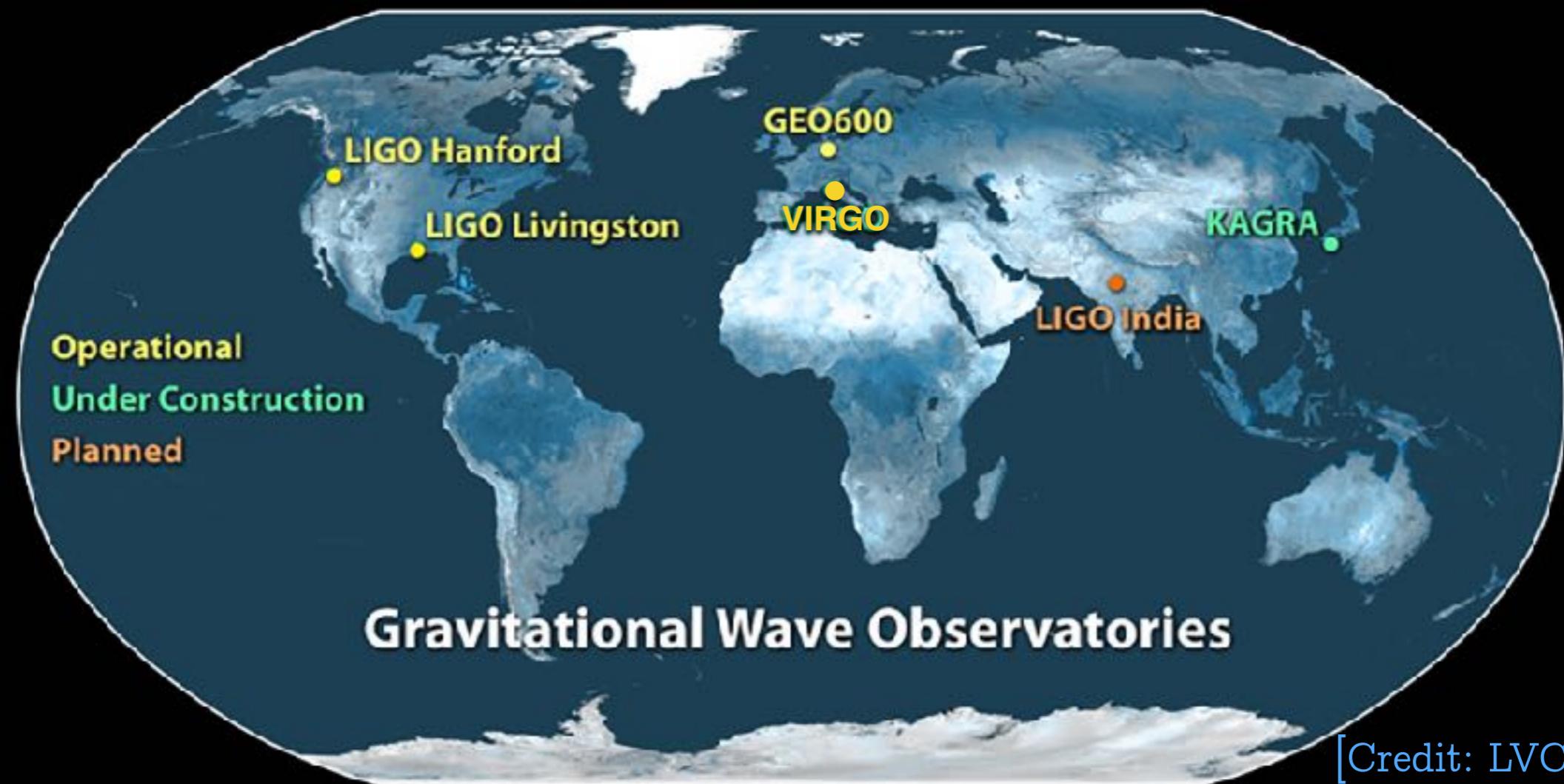
=



>

10 times luminosity
of all stars in the
universe

Global network of ground-based detectors



[Credit: LVC]



[Hanford, US]



[Livingston, US]



[Virgo, Italy]

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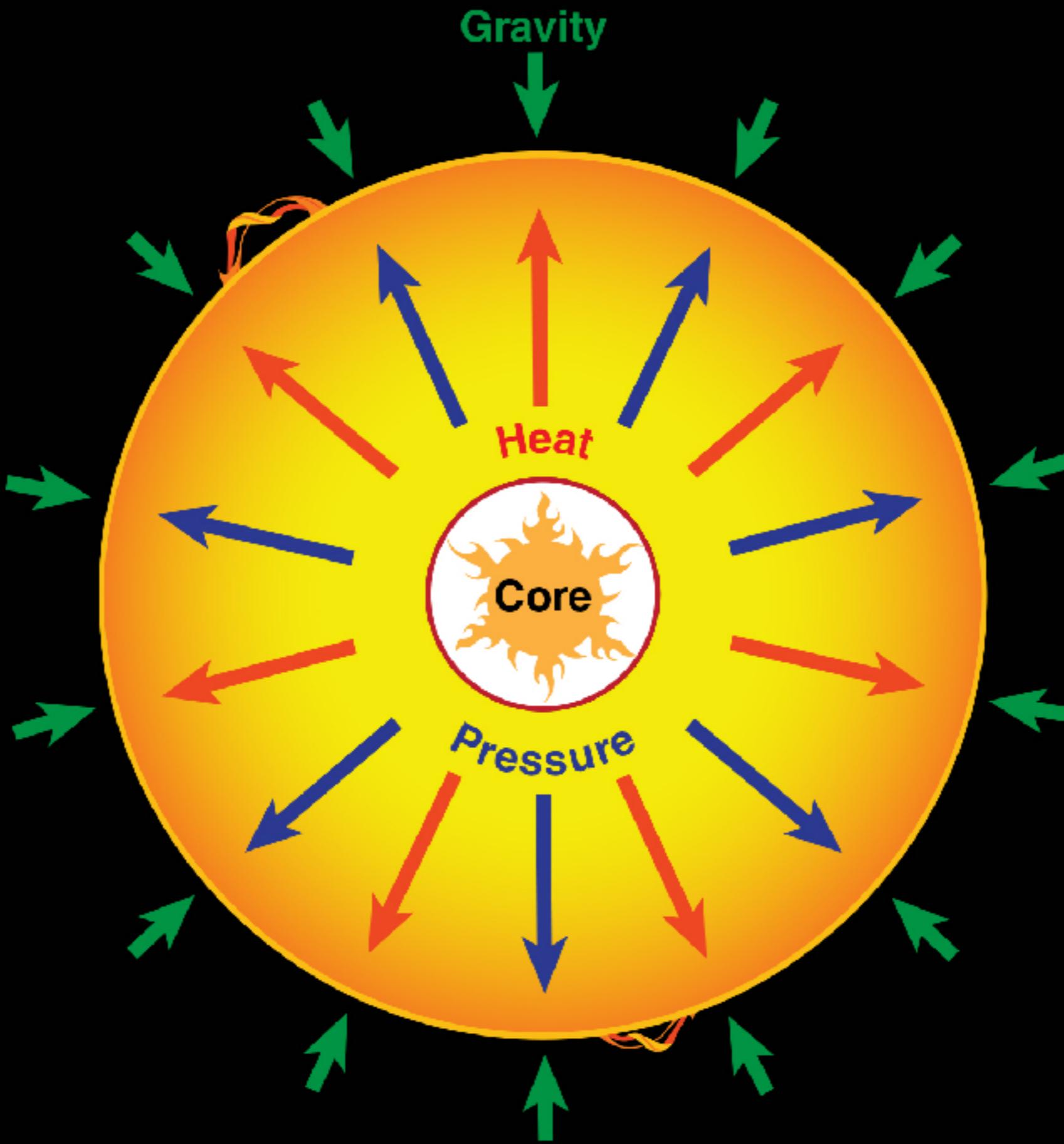
Supernova

- SN1987-



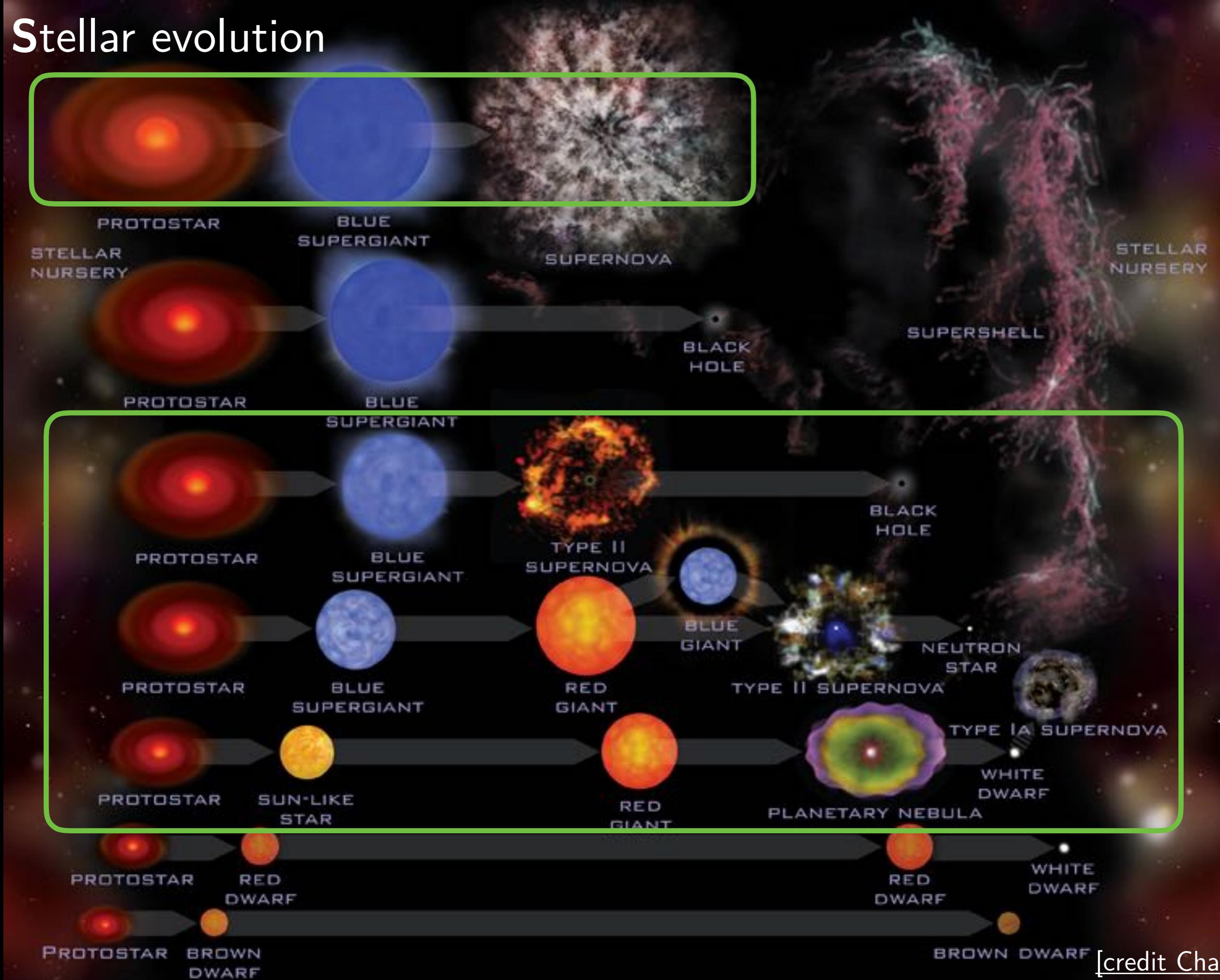
NASA web

What holds a star together?



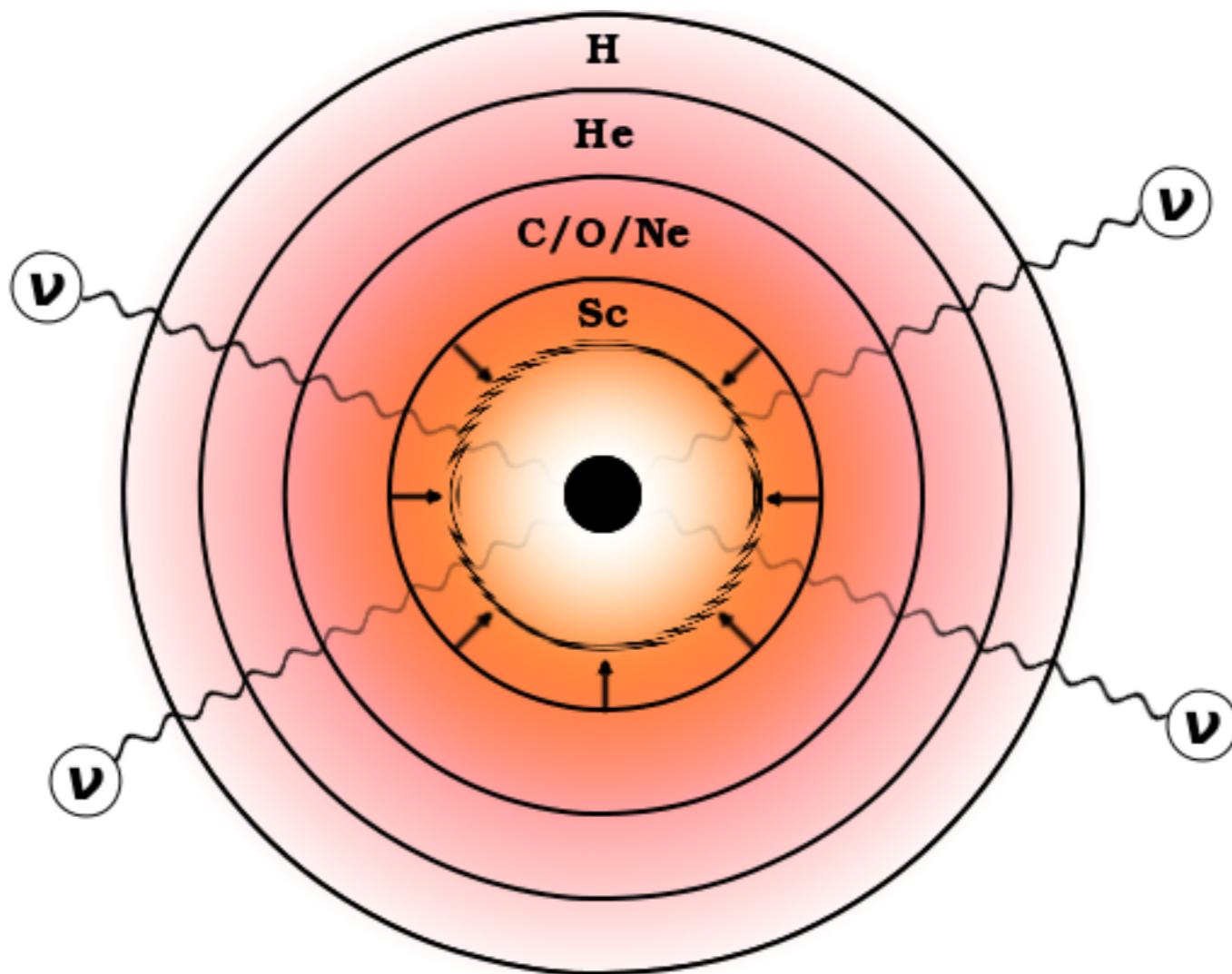
[credit NASA]

Stellar evolution

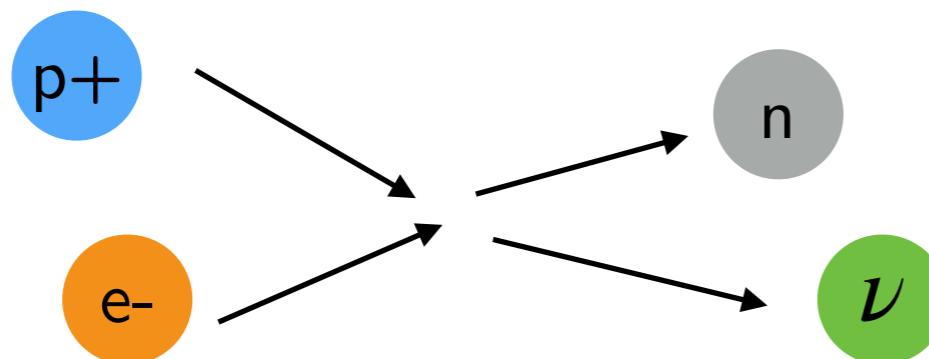


[credit Chandra]

K: 99% of emitted energy in neutrinos!

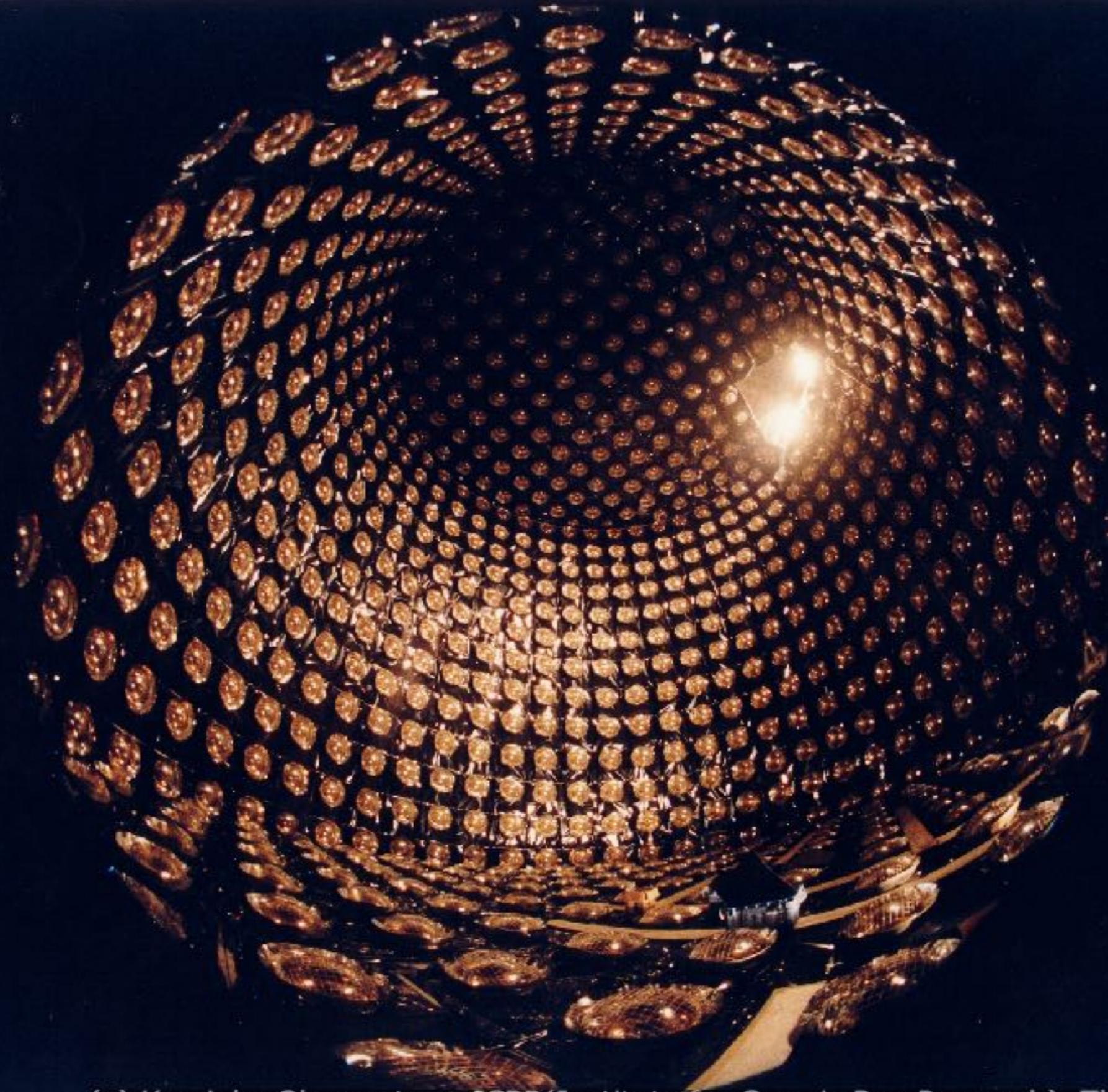


Electron capture + neutrino trapping + bounce back



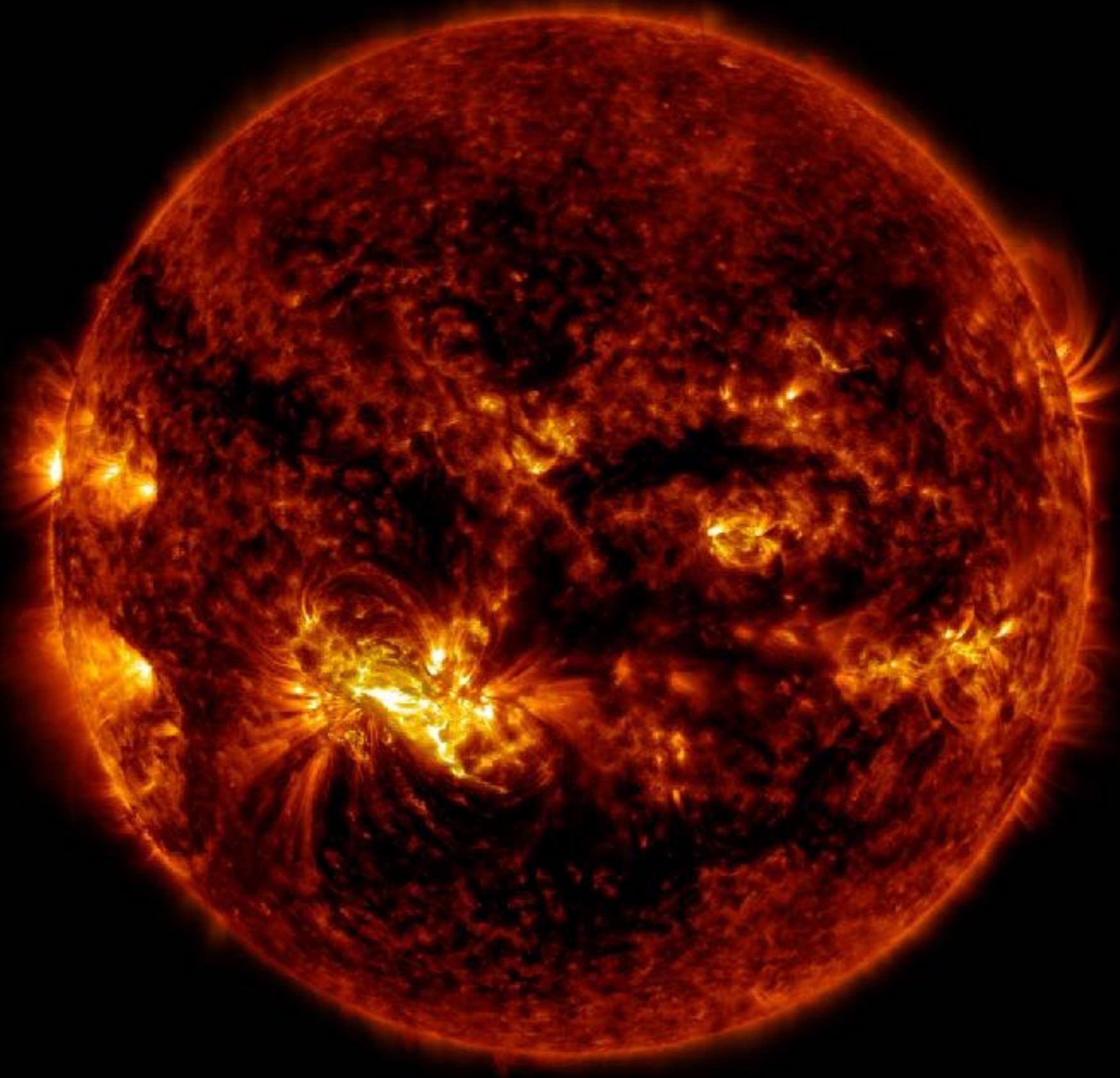
Q/A: What is the rate of nearby supernovae?

Dozen neutrinos detected at Kamioka in 1987



(c) Kamioka Observatory, ICRR(Institute for Cosmic Ray Research), The University of Tokyo

R: why are solar neutrinos important?

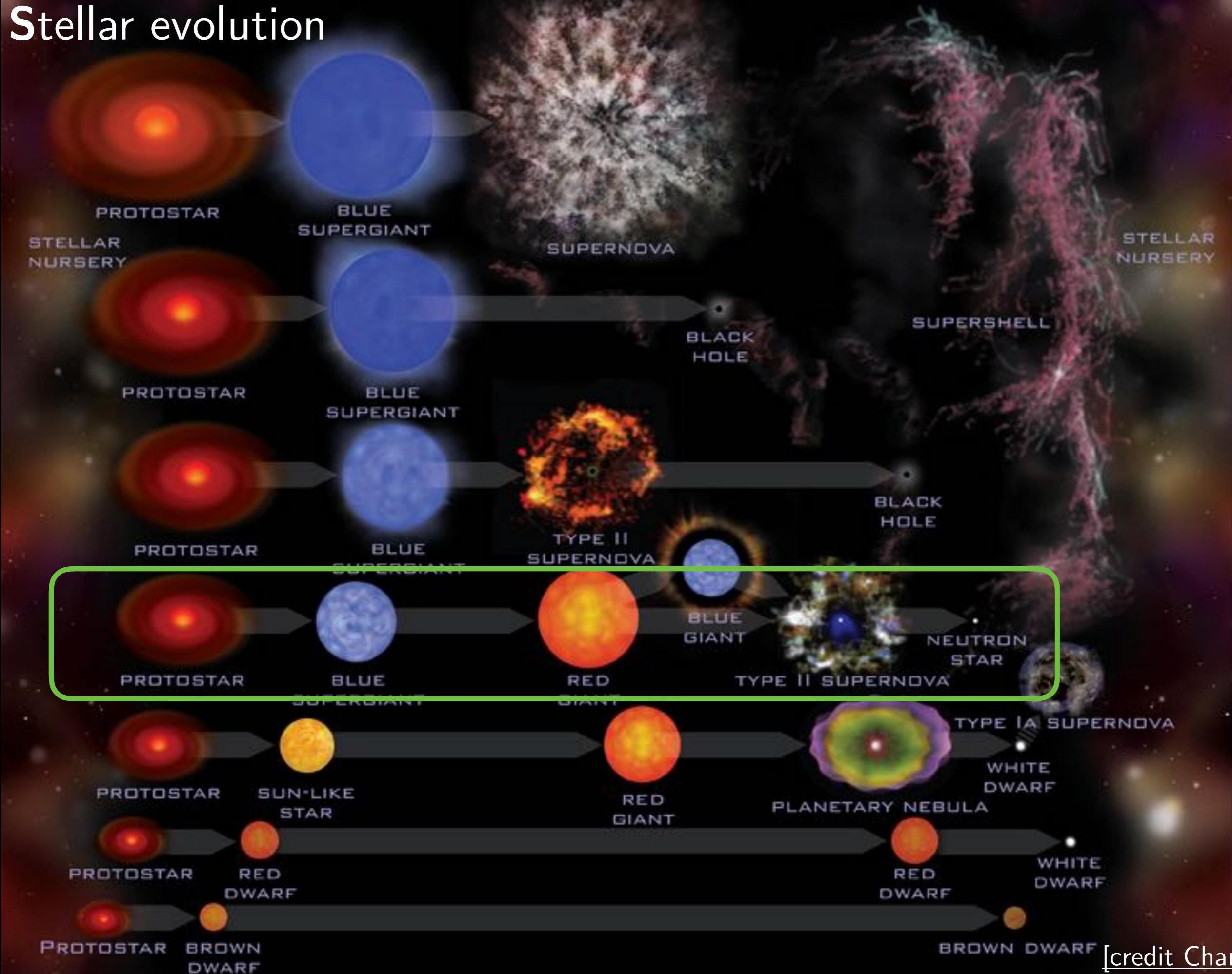


[NASA's Solar Dynamics Observatory, Oct. 21, 2014]

Binary neutron stars

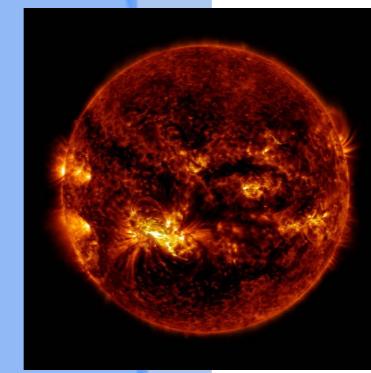
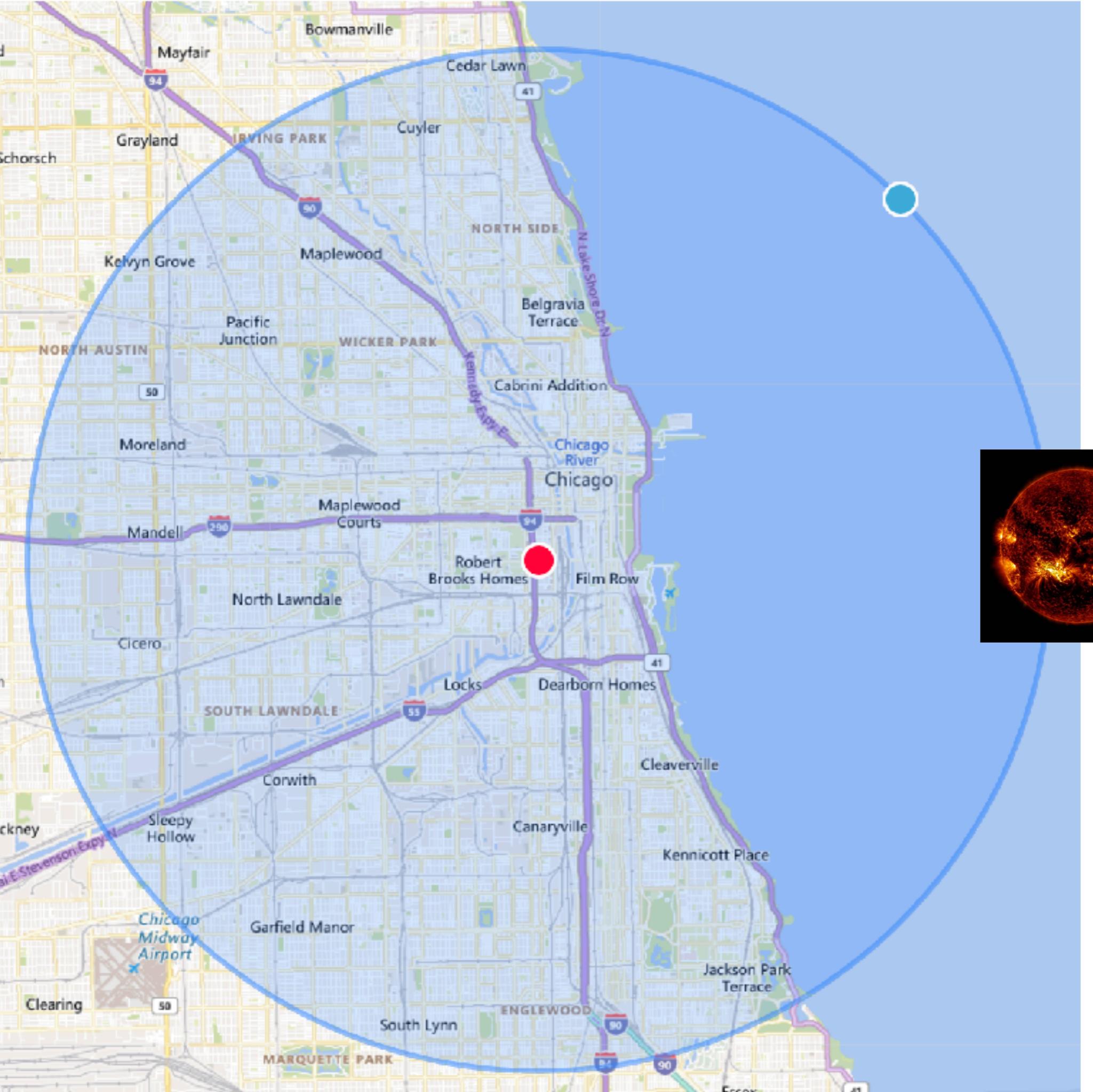
- GW170817 -

Stellar evolution



[credit Chandra]

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



$\times 1.5$

Neutron stars get deformed

GW170817: The Merger of Two Neutron Stars



Matter density

Gravitational Waves

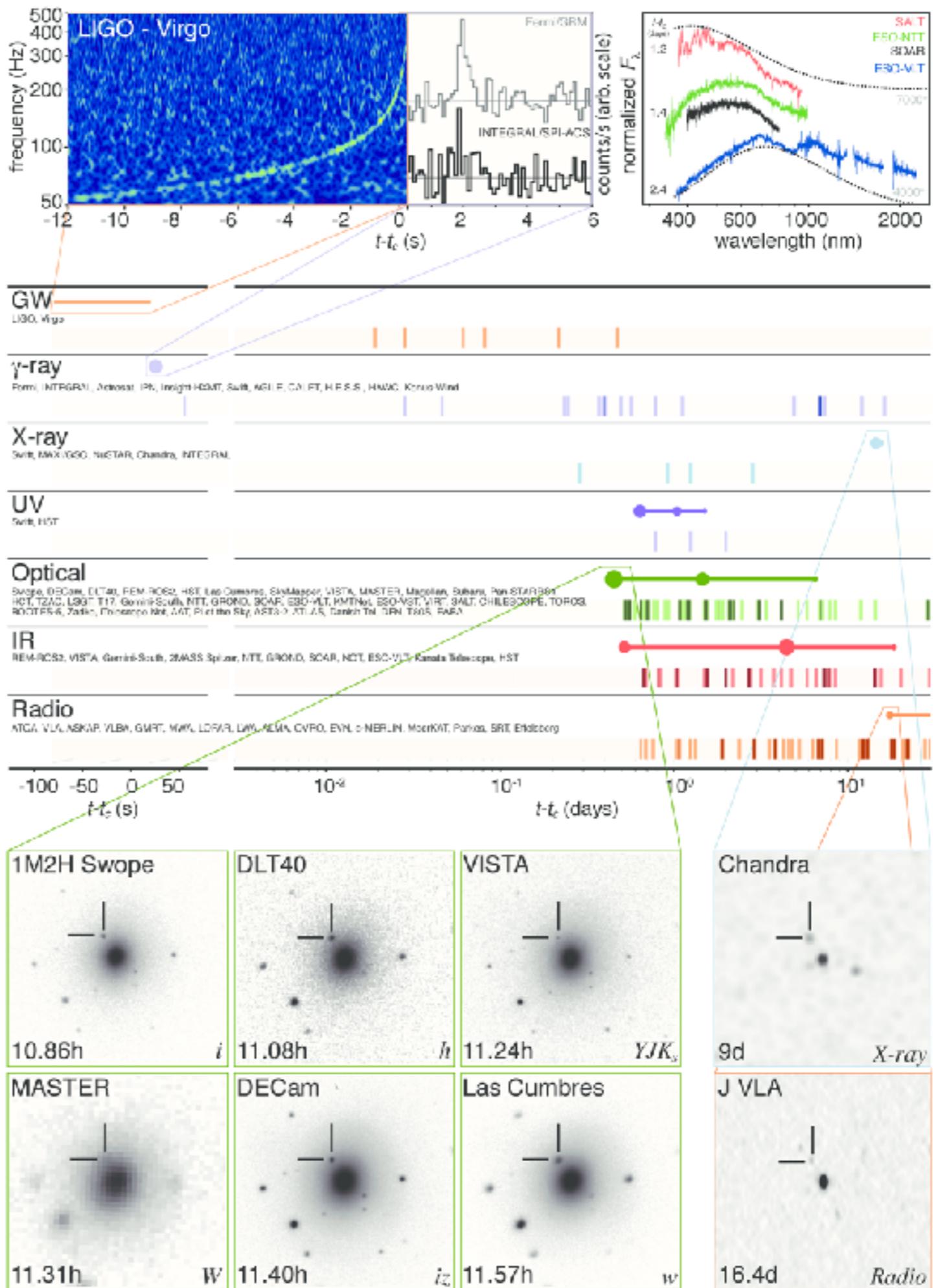


[Credit: Christopher W. Evans/Georgia Tech]

Multi-messenger event: GW + EM

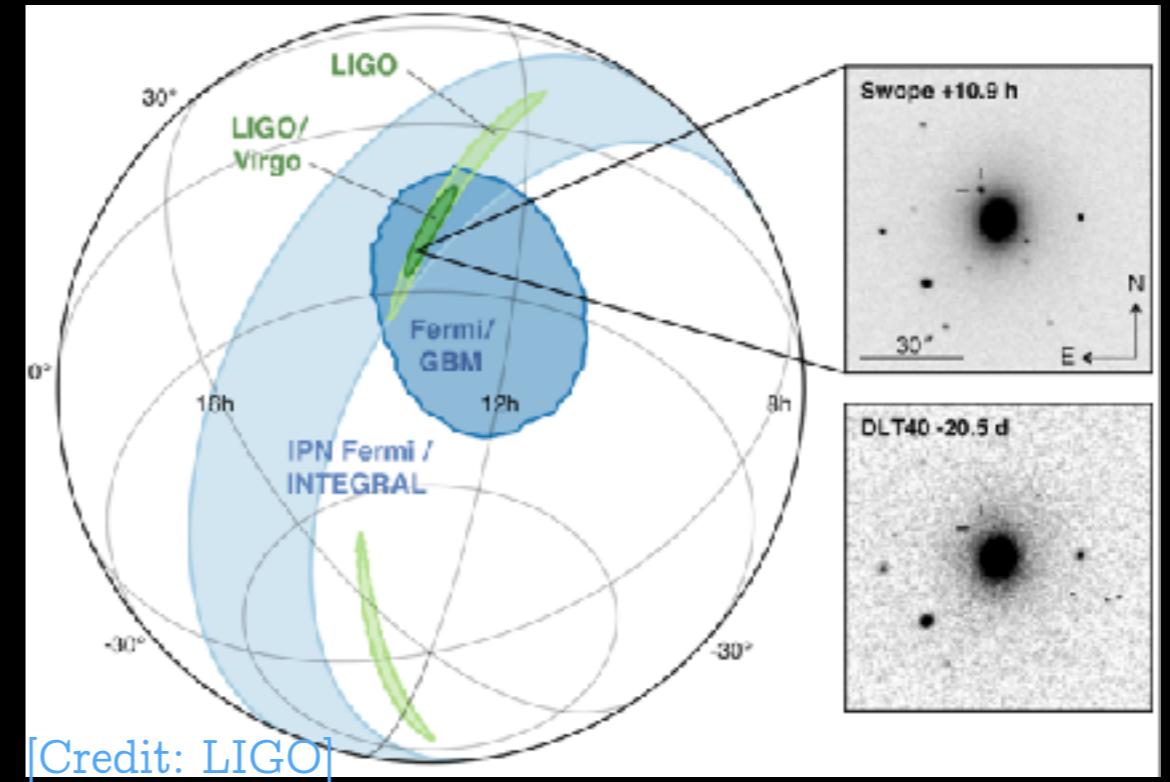
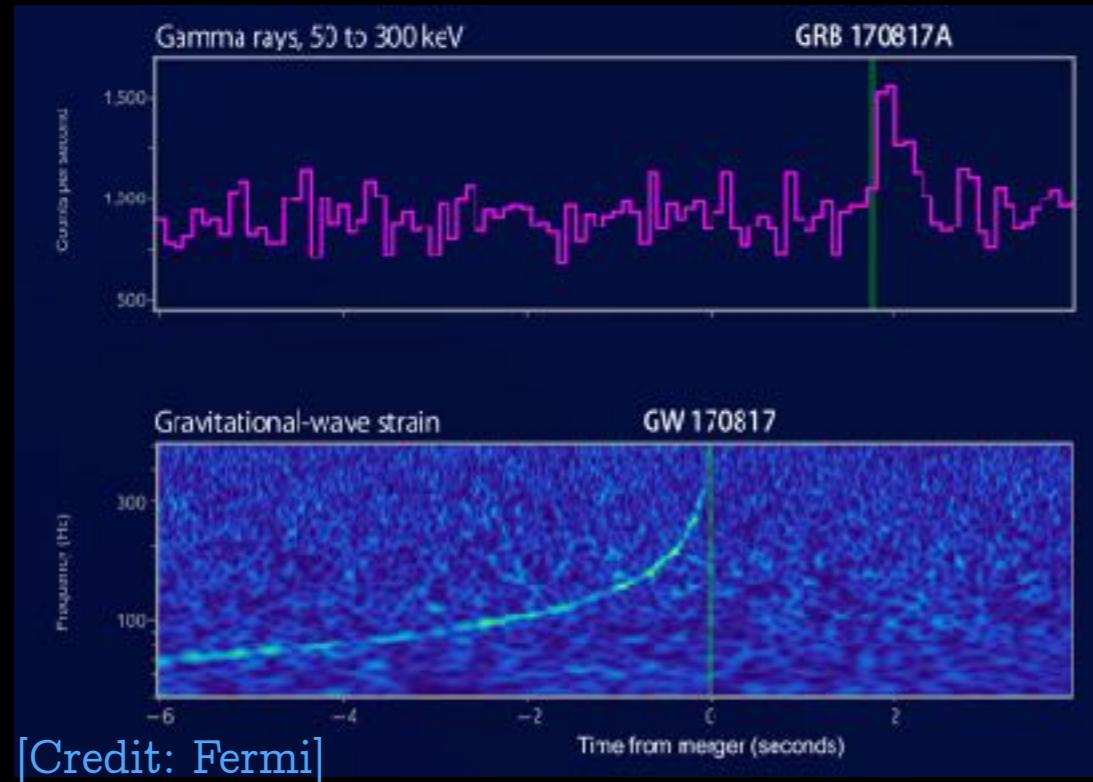
[Credit: NASA's Goddard Space Flight Center/CI Lab]

Seen across entire EM spectrum!



What have we learned with GW170817?

Gravitational waves travel at the speed of light!



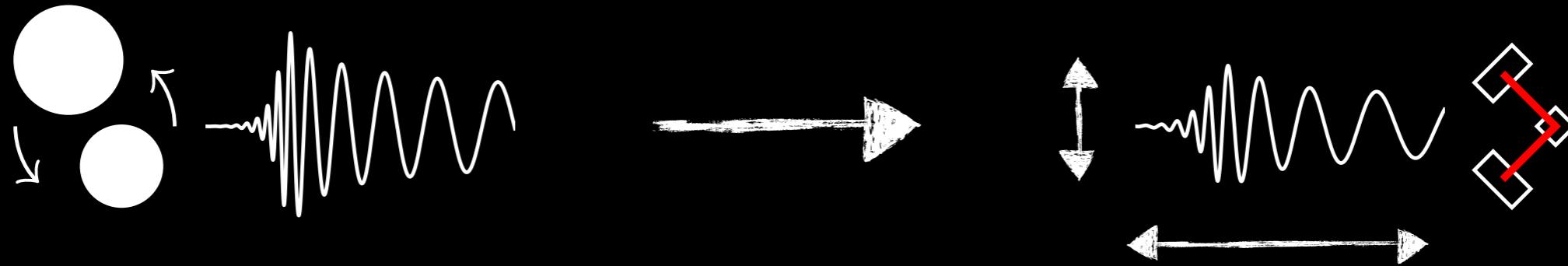
Both the GWs and the sGRB arrived almost simultaneously

$$\Delta t = 1.74 \pm 0.05 \text{ s}$$

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

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

Standard Sirens



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

$$h \propto 1/d_L$$

$$d_L(z) = (1+z) \int_0^z \frac{cdz}{H(z)}$$

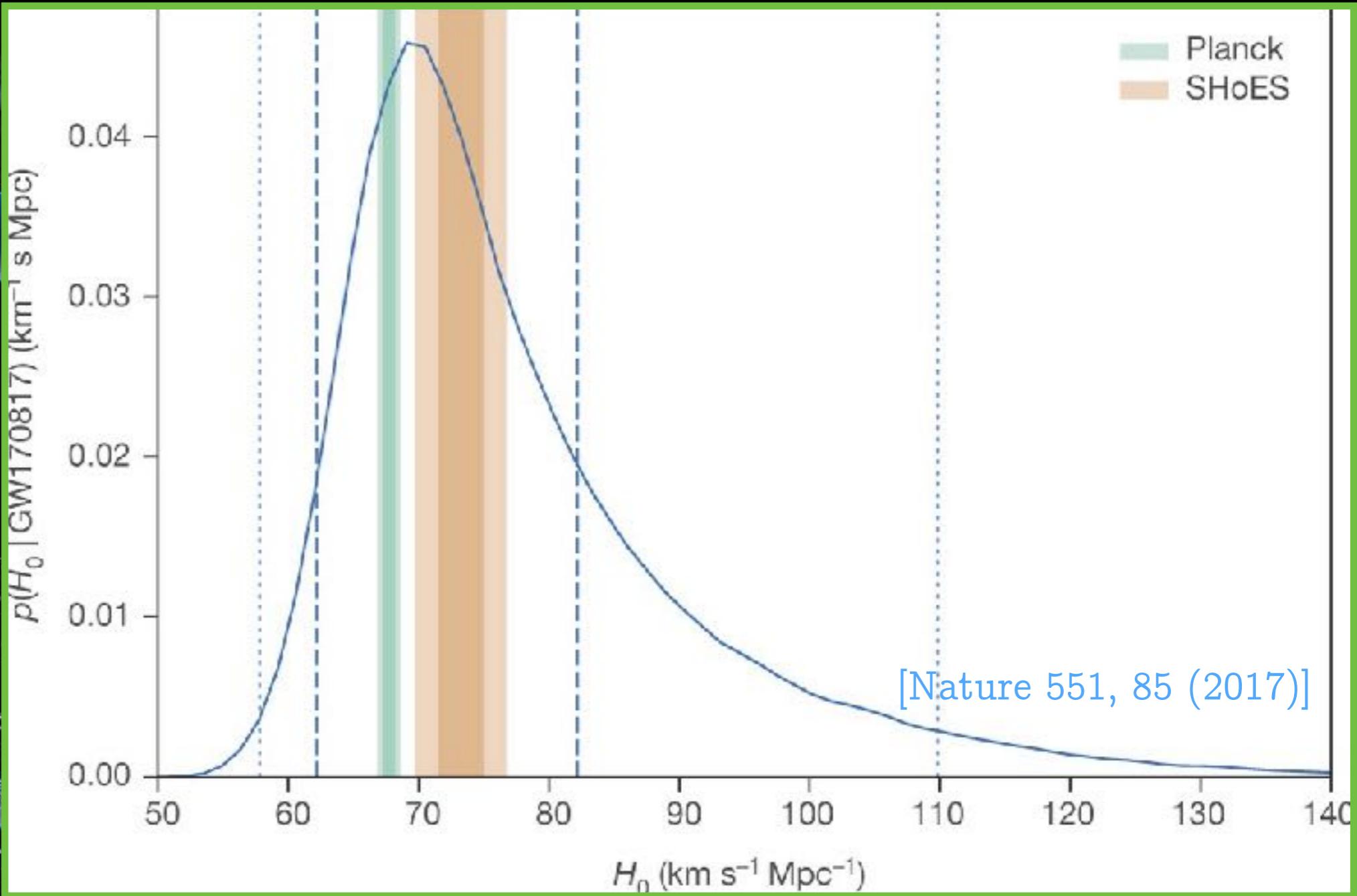
- With additional redshift information GWs constrain expansion rate!

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

Story of the Universe

At the beginning of time, space exploded out of nothingness to create the ever-expanding universe we inhabit now. It took billions of years for the story, depicted here, to unfold.

-Brenna Draxler



ACCELERATING EXPANSION

A little more than 5 billion years ago, dark energy caused the universe to expand increasingly fast.

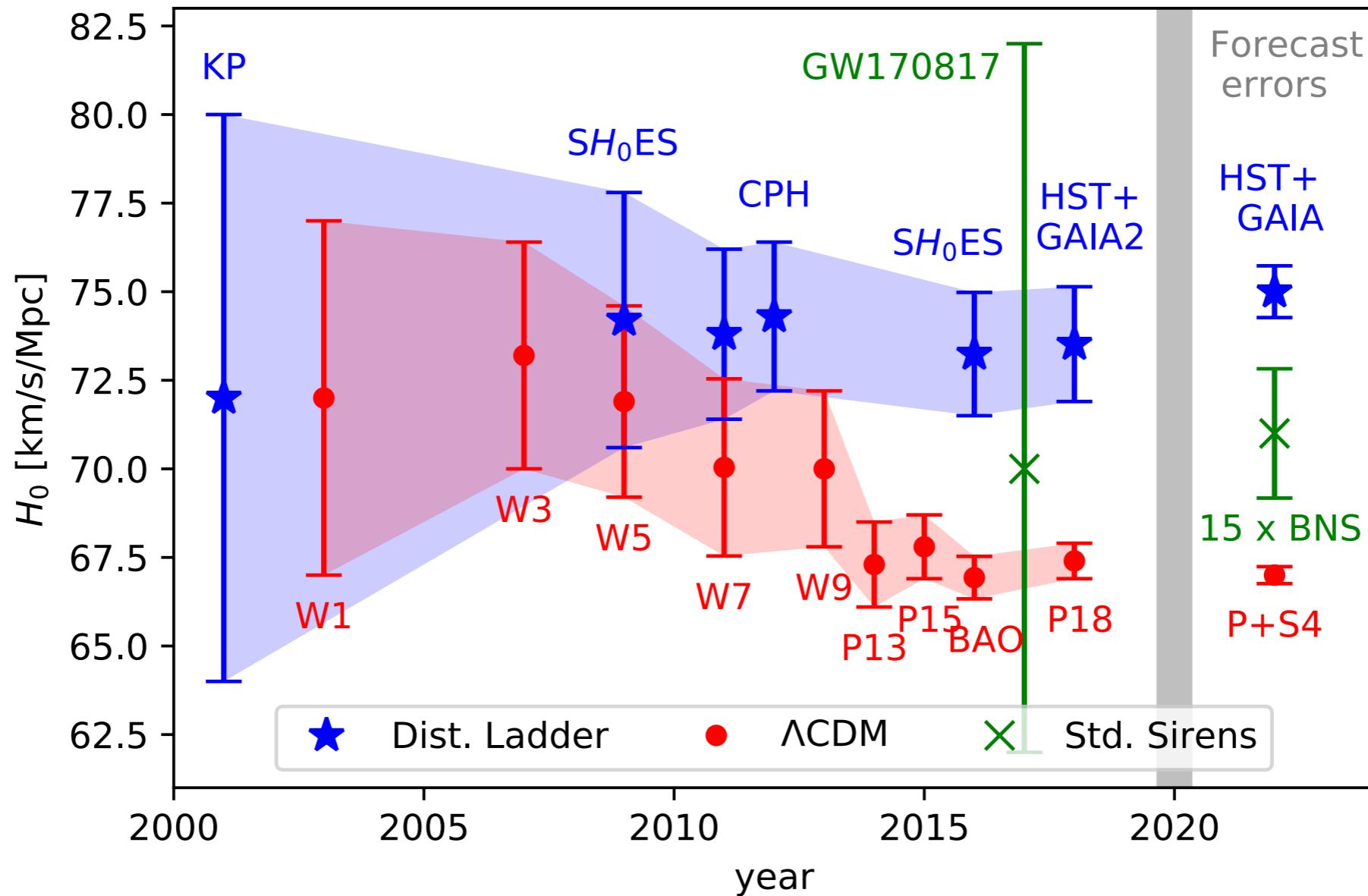
INFLATION

In less than 10^{-30} of a second after the Big Bang, the universe burst open, expanding faster than the speed of light and flinging all the matter and energy in the universe apart in all directions.

BIG BANG

The universe expanded violently from an extremely hot and dense initial state some 13.7 billion years ago.

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

Element Origins

1 H																			2 He
3 Li	4 Be																		
11 Na	12 Mg																		
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr		
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe		
55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn		
87 Fr	88 Ra																		
57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu					
89 Ac	90 Th	91 Pa	92 U																

Merging Neutron Stars
Exploding Massive Stars
Exploding White Dwarfs

Dying Low Mass Stars

Exploding Massive Stars
Exploding White Dwarfs

Big Bang
Cosmic Ray Fission

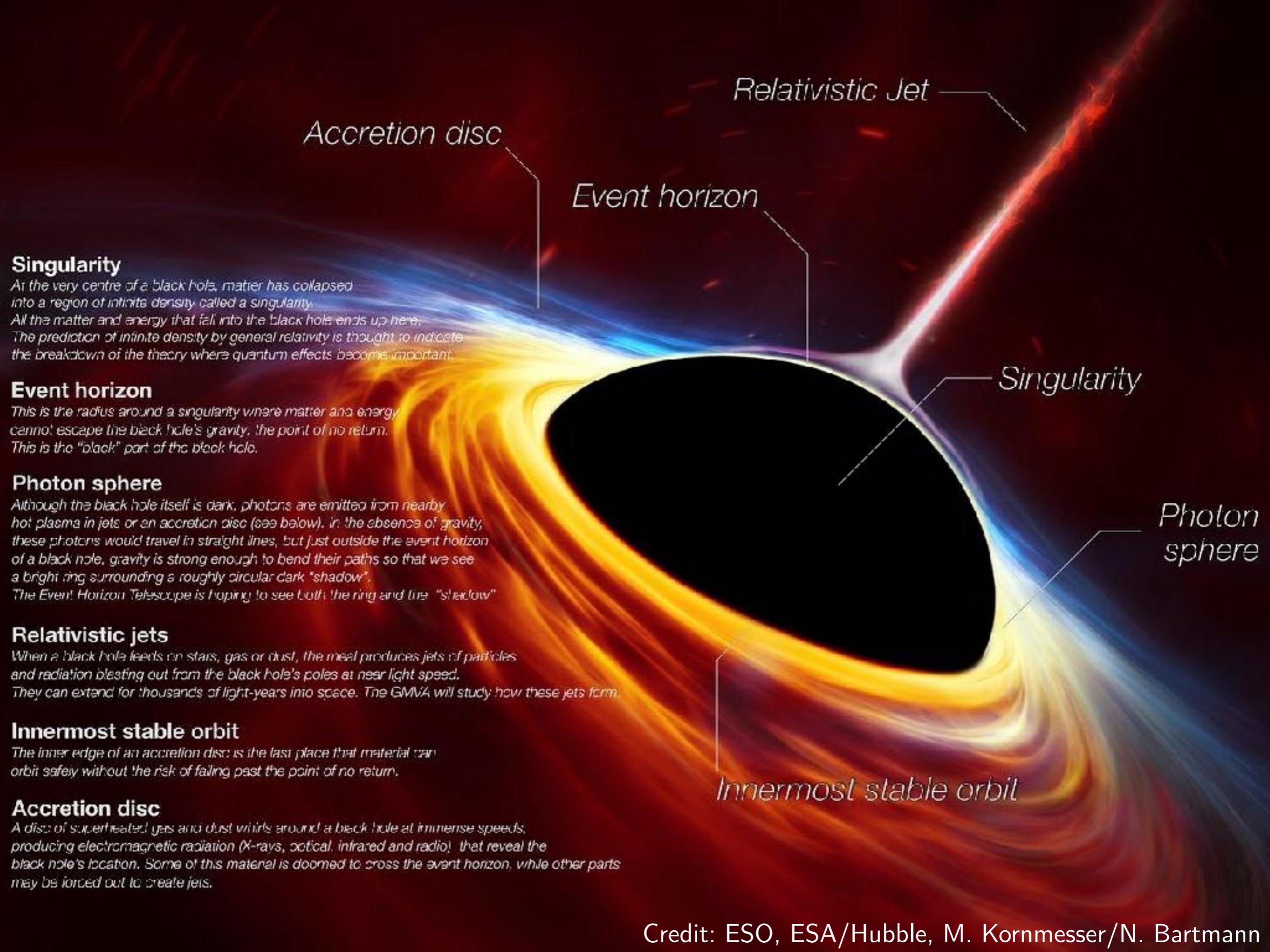
Based on graphic created by

Supermassive black holes

- TXS 0506+056, IceCube-170922A -

A black hole with a bright orange and yellow accretion disk.

Credit: EHT



Singularity

At the very centre of a black hole, matter has collapsed into a region of infinite density called a singularity.

All the matter and energy that fall into the black hole ends up here.

The prediction of infinite density by general relativity is thought to indicate the breakdown of the theory where quantum effects become important.

Event horizon

This is the radius around a singularity where matter and energy cannot escape the black hole's gravity, the point of no return.

This is the "black" part of the black hole.

Photon sphere

Although the black hole itself is dark, photons are emitted from nearby hot plasma in jets or an accretion disc (see below). In the absence of gravity, these photons would travel in straight lines, but just outside the event horizon of a black hole, gravity is strong enough to bend their paths so that we see a bright ring surrounding a roughly circular dark "shadow".

The Event Horizon Telescope is hoping to see both the ring and the "shadow".

Relativistic jets

When a black hole feeds on stars, gas or dust, the meal produces jets of particles and radiation blasting out from the black hole's poles at near light speed.

They can extend for thousands of light-years into space. The GMVA will study how these jets form.

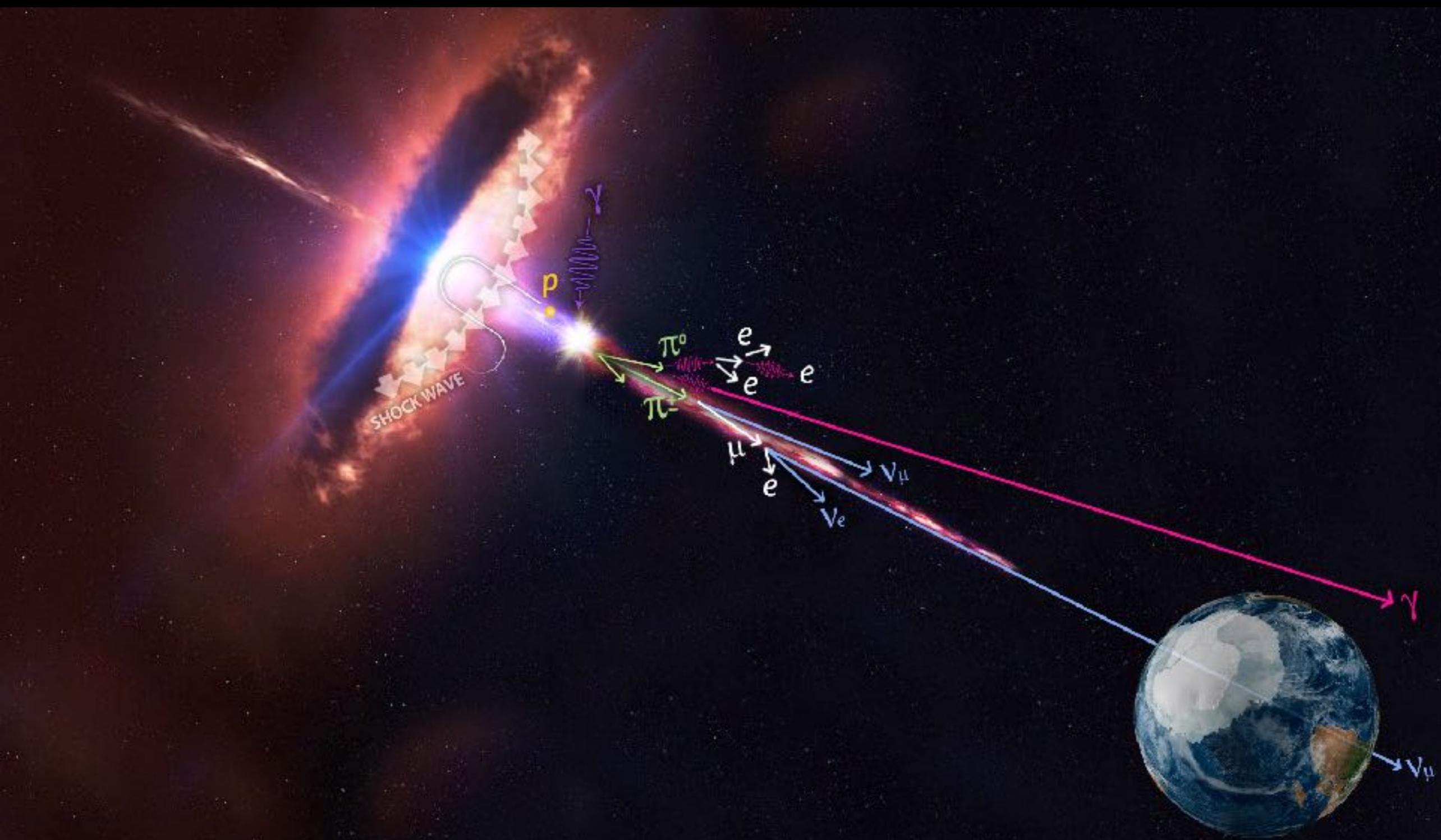
Innermost stable orbit

The inner edge of an accretion disc is the last place that material can orbit safely without the risk of falling past the point of no return.

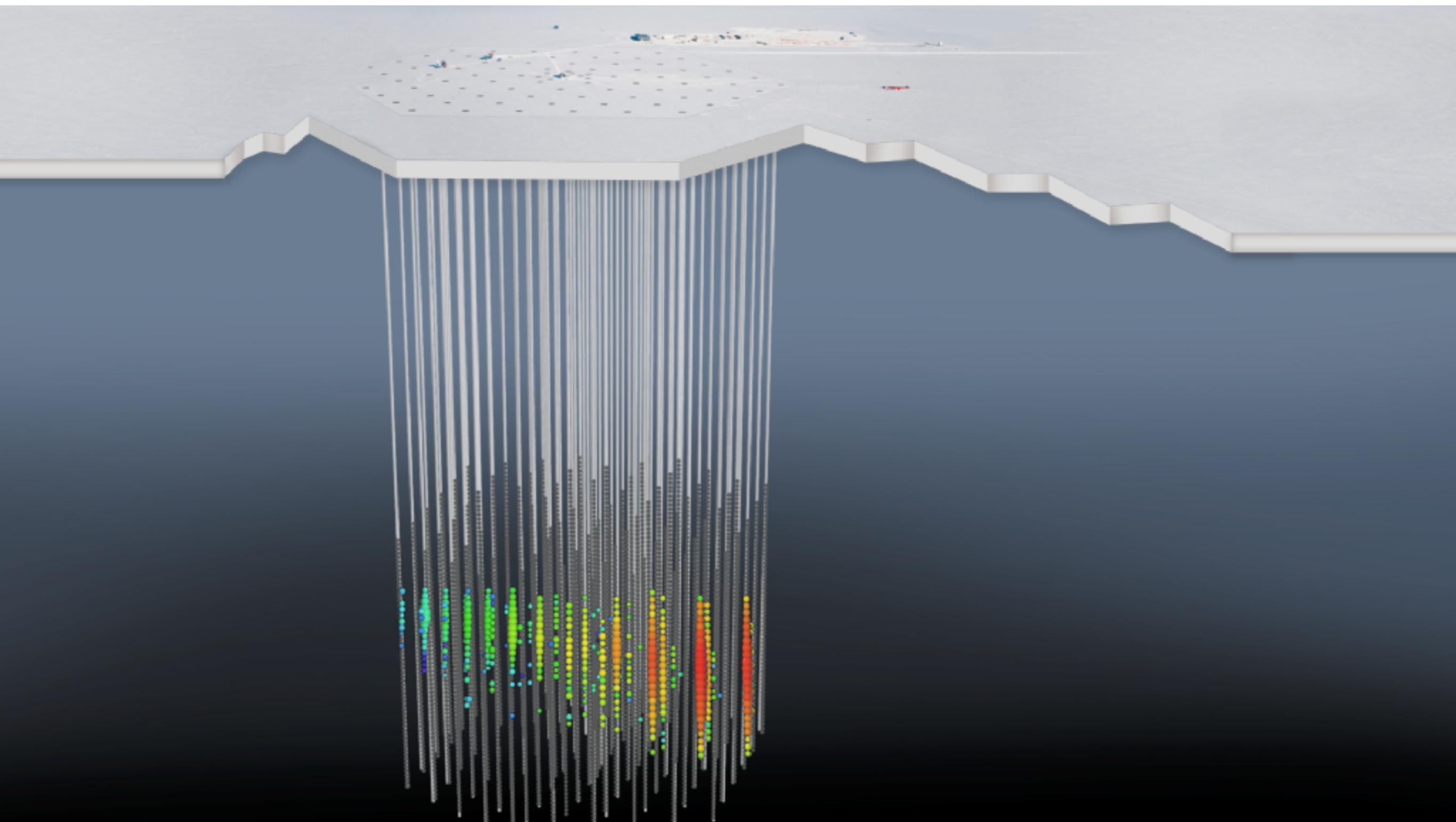
Accretion disc

A disc of superheated gas and dust whirls around a black hole at immense speeds, producing electromagnetic radiation (X-rays, optical, infrared and radio) that reveal the black hole's location. Some of this material is doomed to cross the event horizon, while other parts may be forced out to create jets.

Blazar at $z=0.3$



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



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Cosmology and fundamental physics with multi-messenger GW astronomy

Super massive black hole mergers

