



Quantum Universe

Hitoshi Murayama (Berkeley, Kavli IPMU Tokyo, DESY)
Arnold Sommerfeld lecture, LMU, 23 July 2019



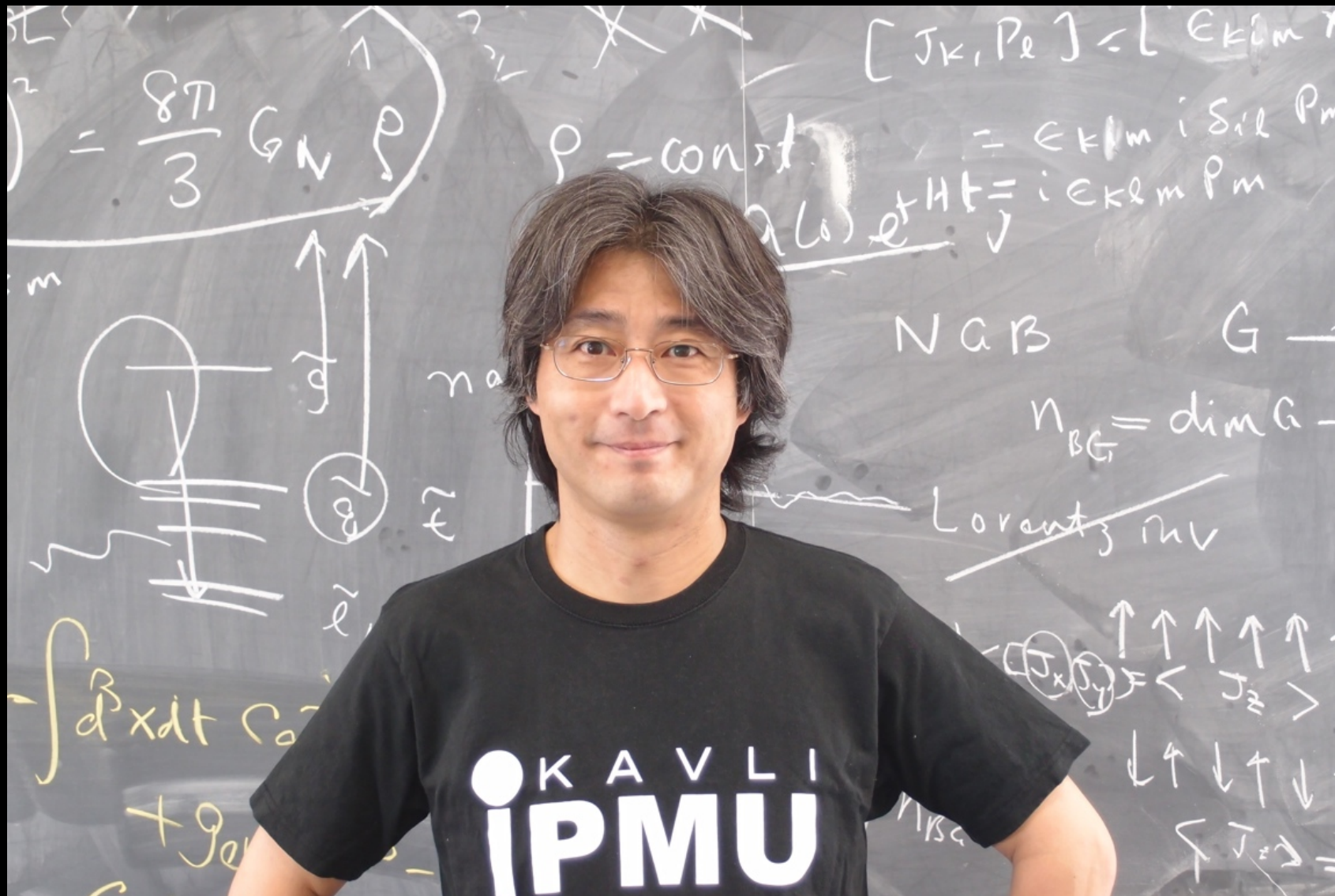


Arnold Sommerfeld 1868–1951

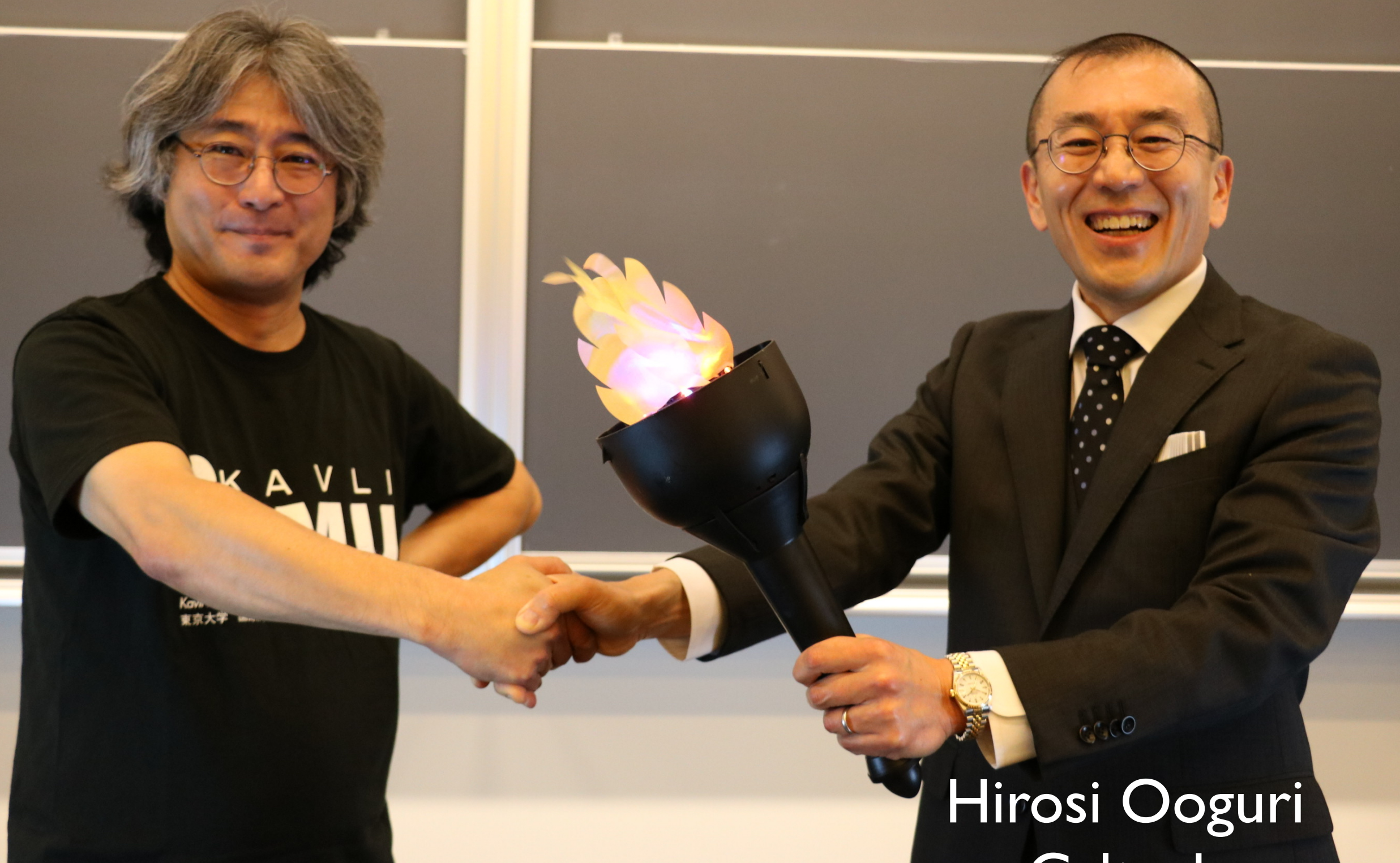


Director of the Kavli Institute for the Physics
and Mathematics of the Universe

A lot of responsibility!



Director of the Universe



Hirosi Ooguri
Caltech

Oct 2018

physicists asks simple and
profound questions

How did the Universe begin?

What is its fate?

What is it made of?

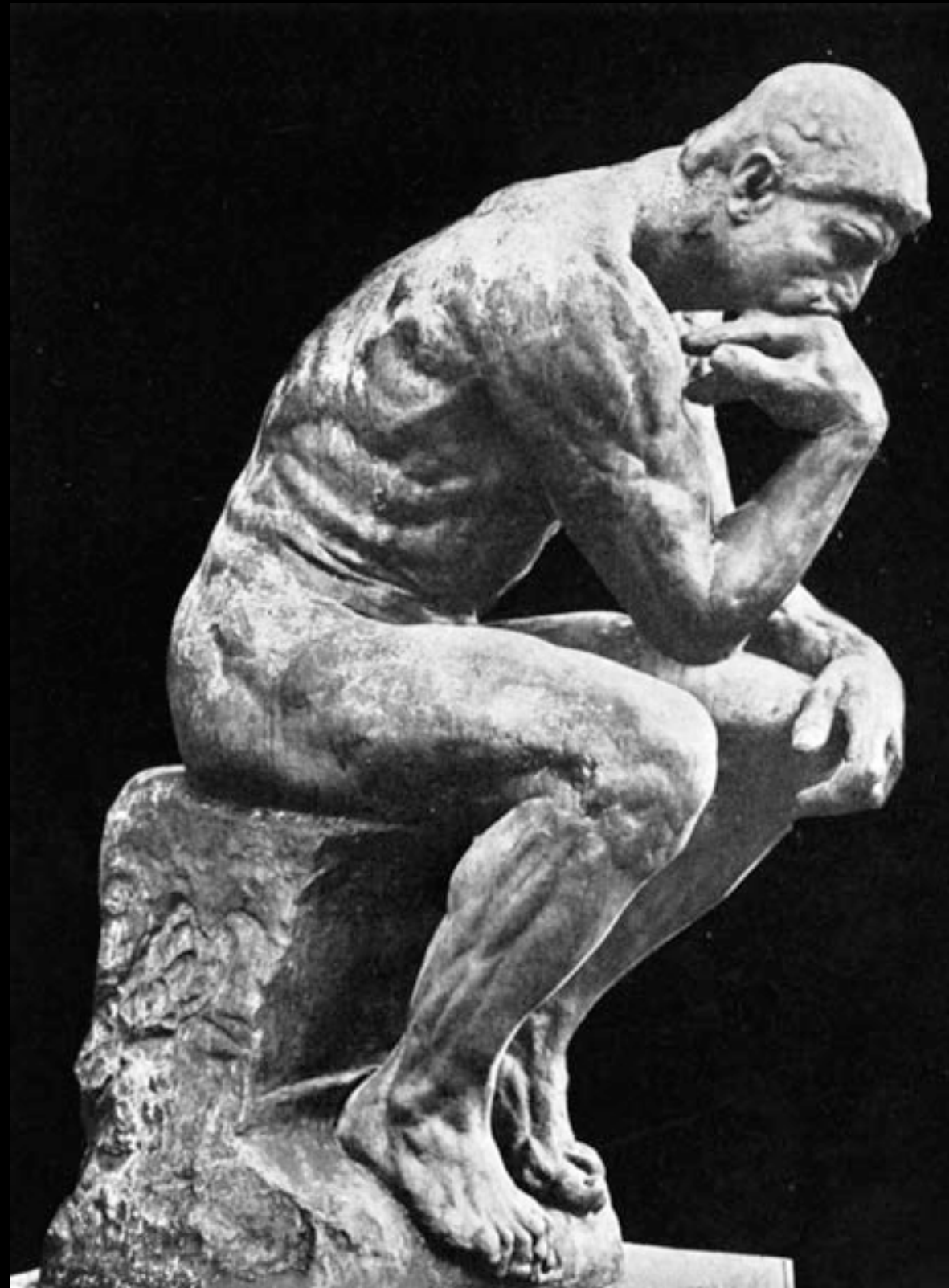
What are its basic laws?

→ Where do we come from?



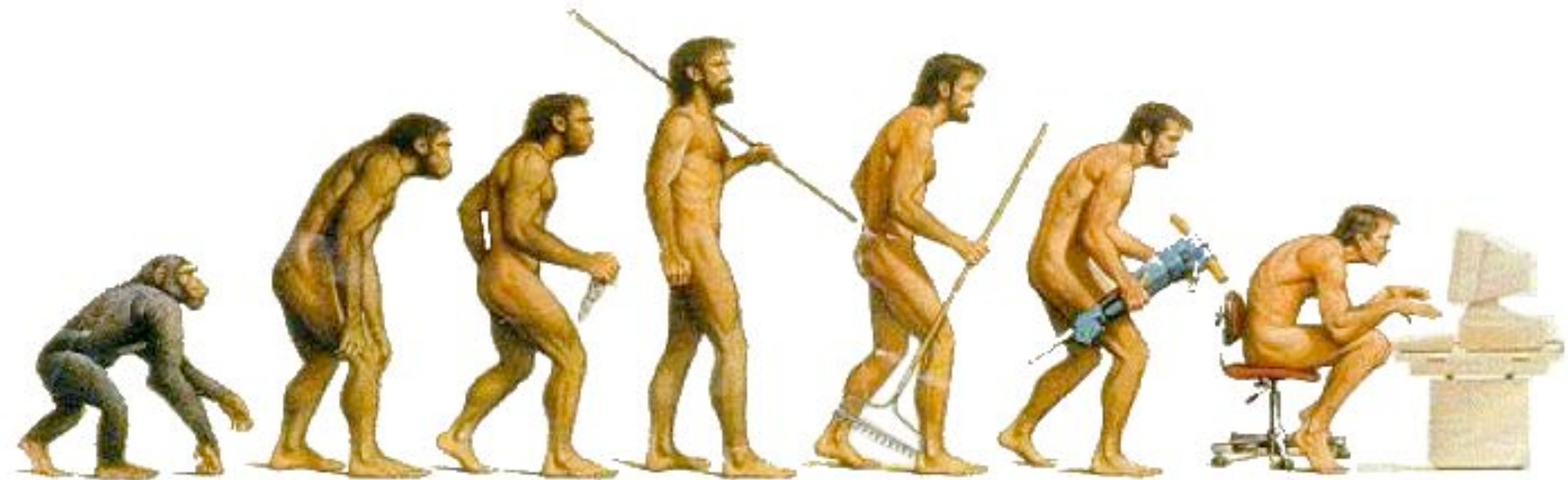
Religions





Philosophy

Evolutionary biology



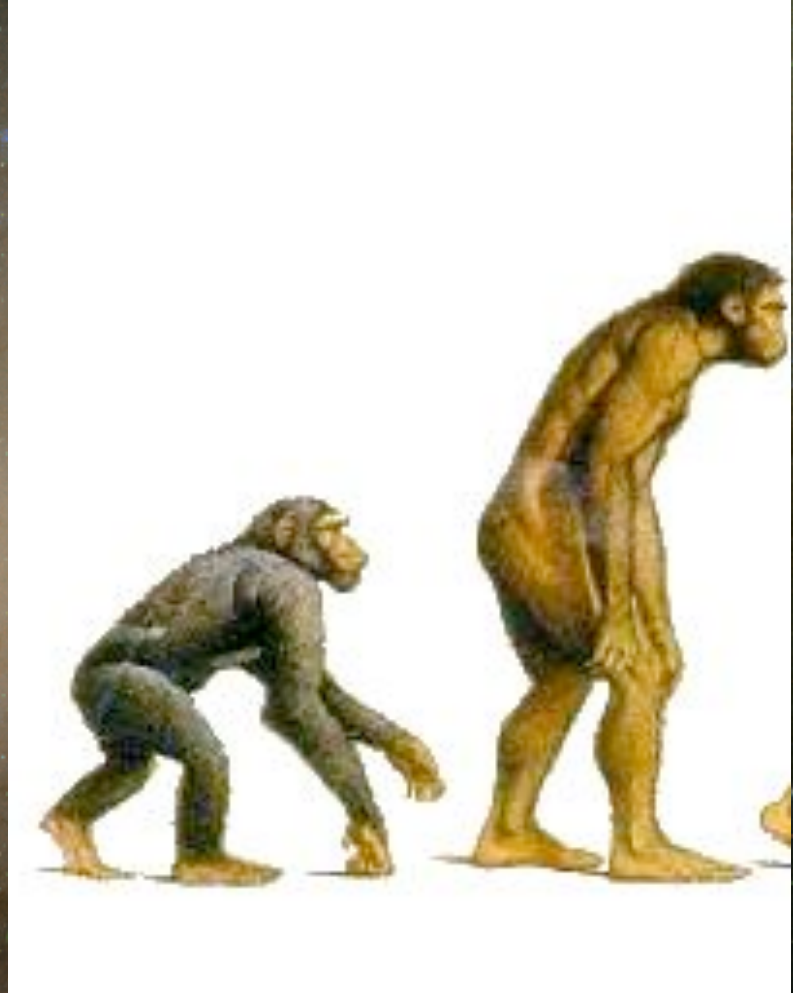




Subaru
8.2m tall and wide



LHC
27 km all around



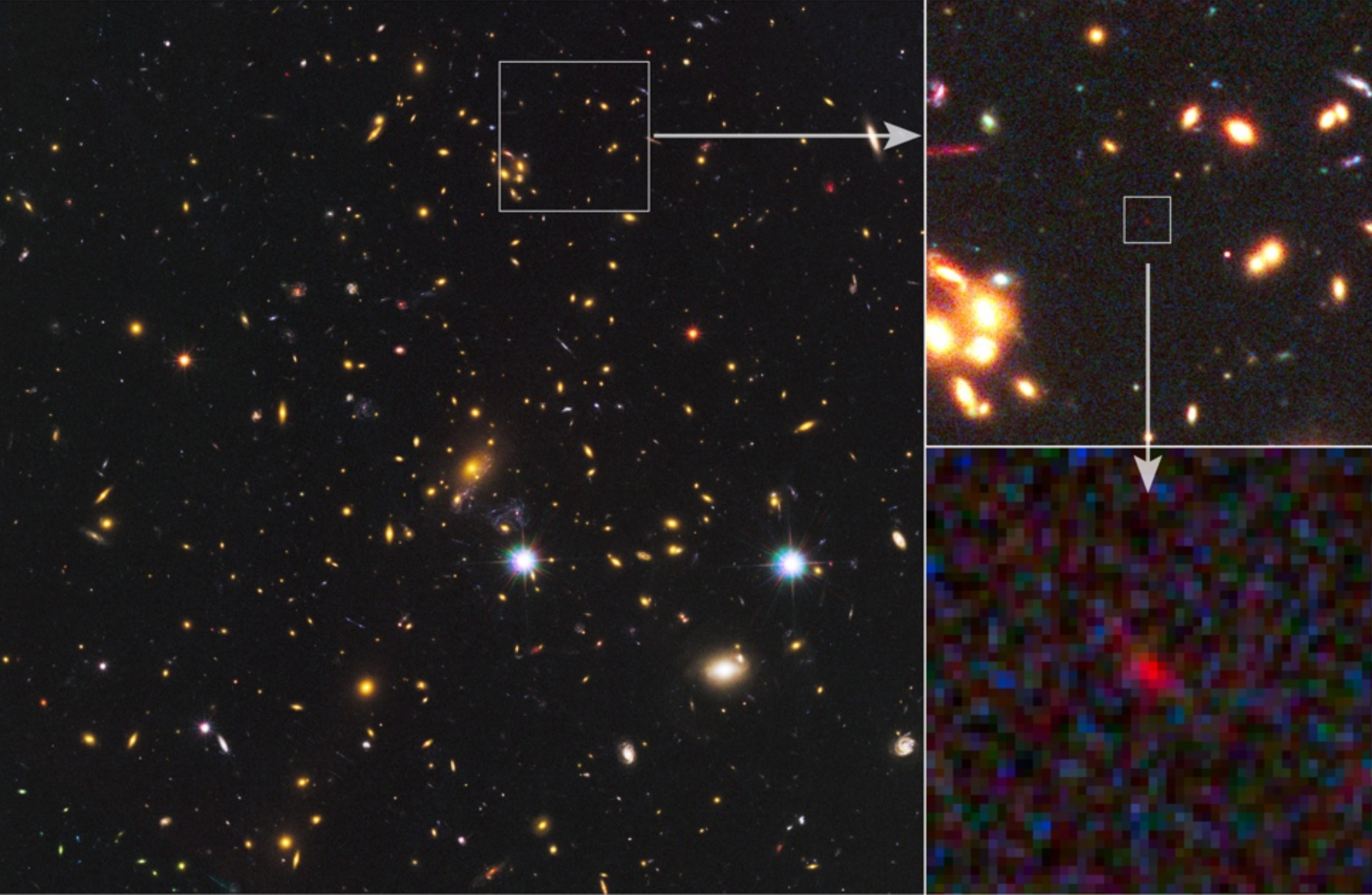
Andromeda
2.3 million light years

HSC team
Subaru
telescope

cluster of galaxies
2.1 billion light year



Abell 2218



Galaxy Cluster MACS J1149+2223

galaxy @ 13.3 billion light years

High-Redshift Galaxy MACS1149-JD

A Distant Gravitationally-Lensed Galaxy at Redshift = 9.6

Hubble Space Telescope • ACS • WFC3

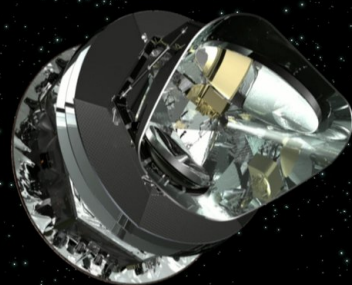
NASA / ESA / STScI / J. Hora (Harvard-Smithsonian CfA)

ssc2012-12a

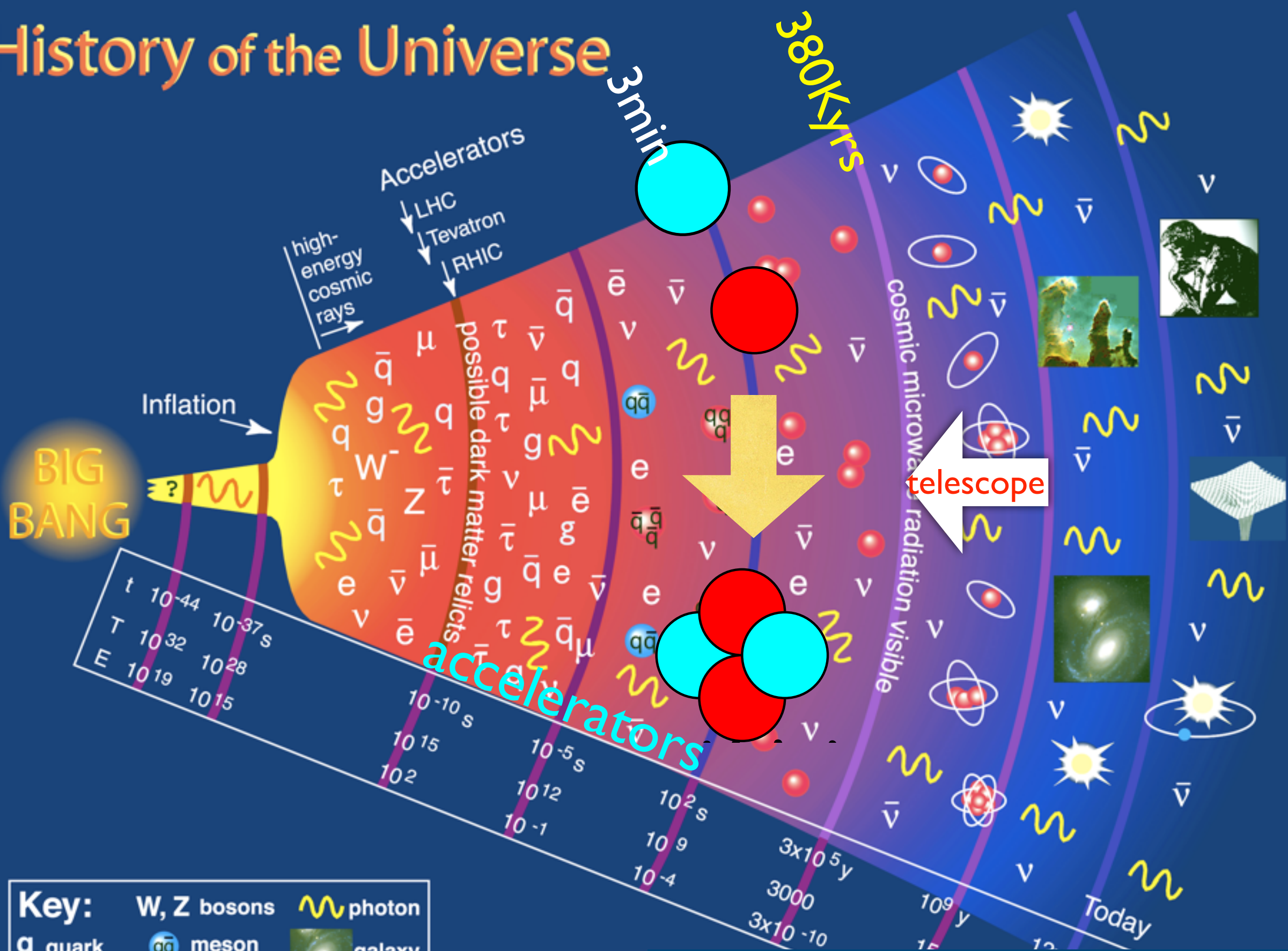
Picture of Big Bang

Temperature variation $\sim 1/100,000$

You can never “see” beyond this wall
with a telescope



History of the Universe



t	10 ⁻⁴⁴	10 ⁻³⁷ s
T	10 ³²	10 ²⁸
E	10 ¹⁹	10 ¹⁵

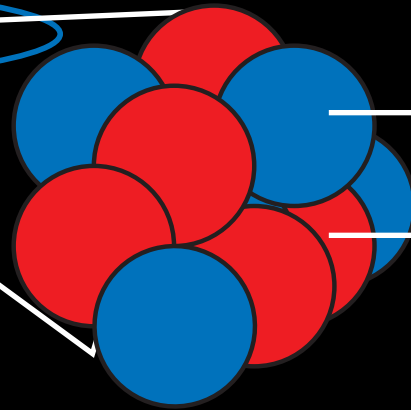
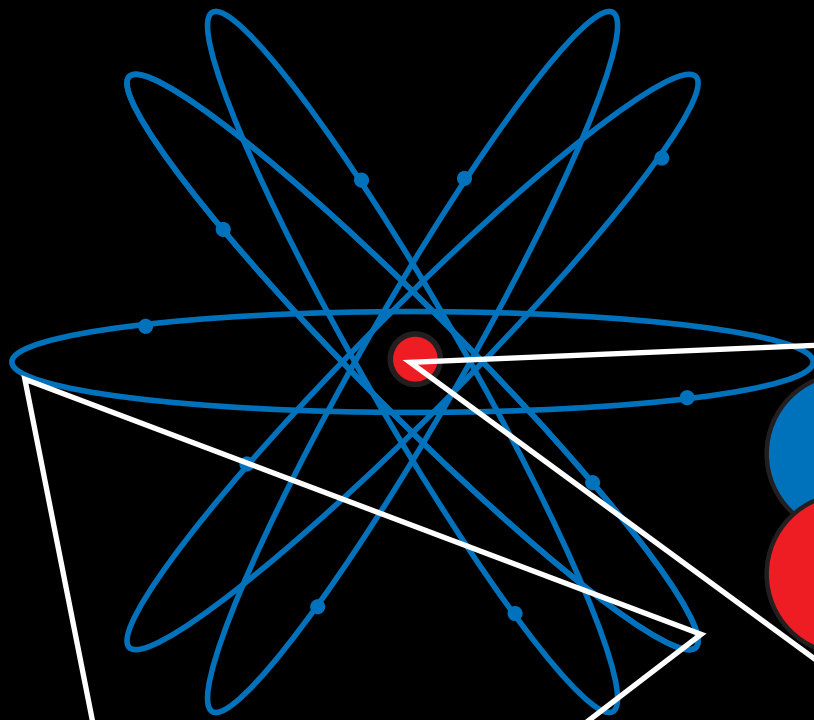
Key:

W, Z bosons		photon	
q quark		meson	
g gluon		baryon	
e electron		ion	
μ muon		τ tau	
ν neutrino		atom	
		galaxy	
		star	
		black hole	

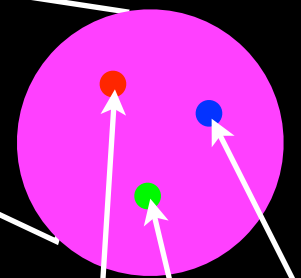
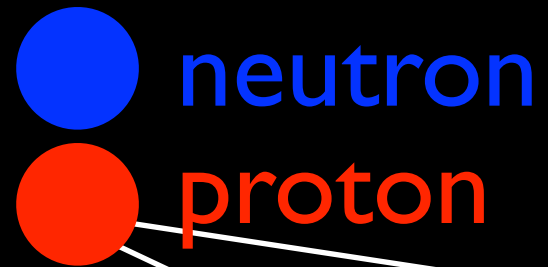
Particle Data Group, L

Big Bang predicts H:He ~ 3:1
agrees with observations

atom



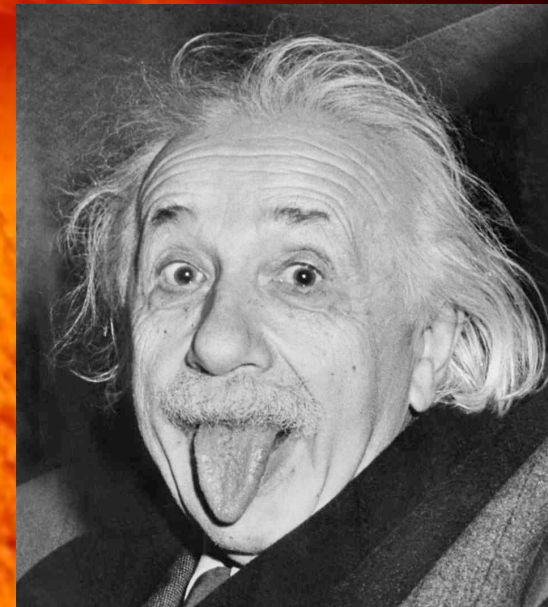
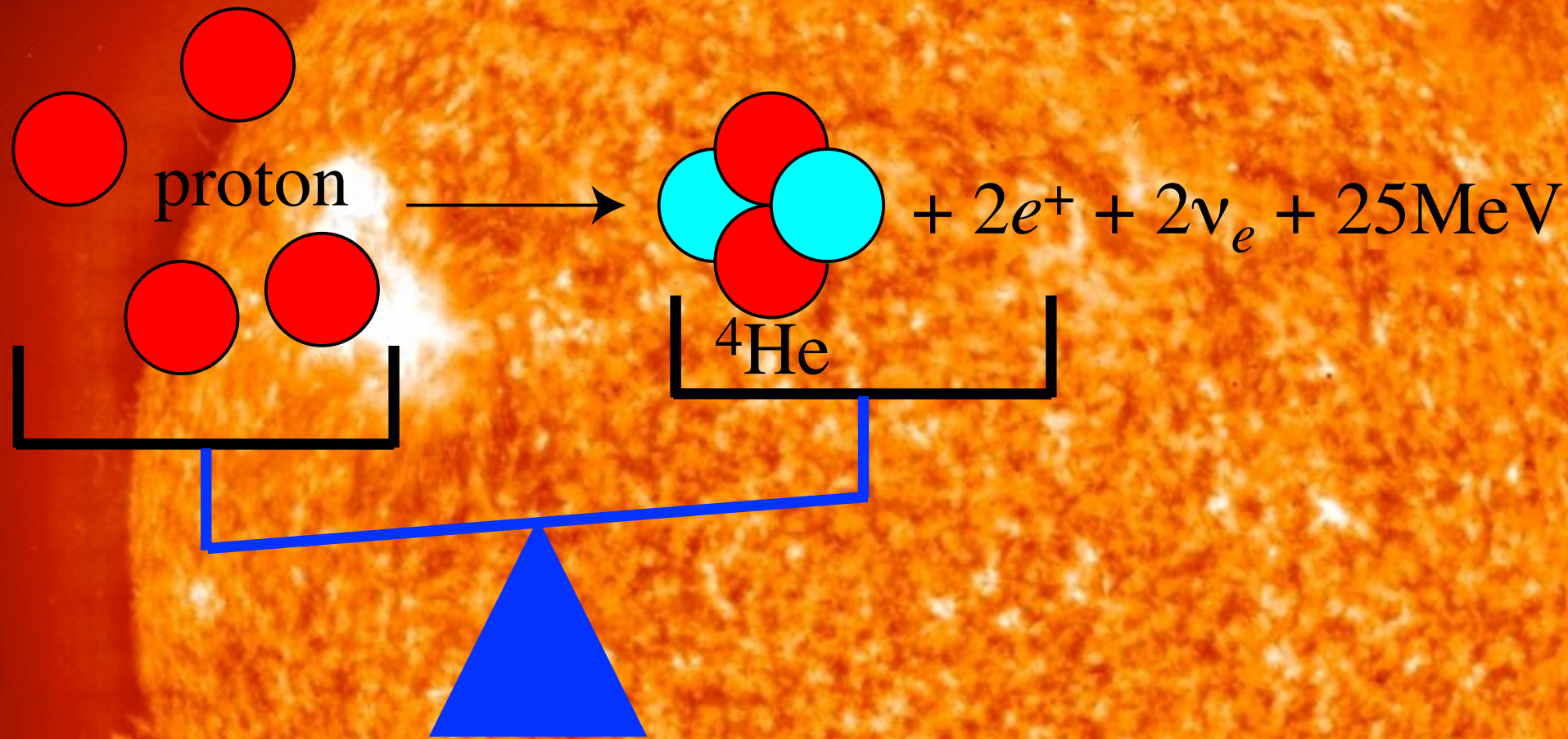
nucleus



quarks



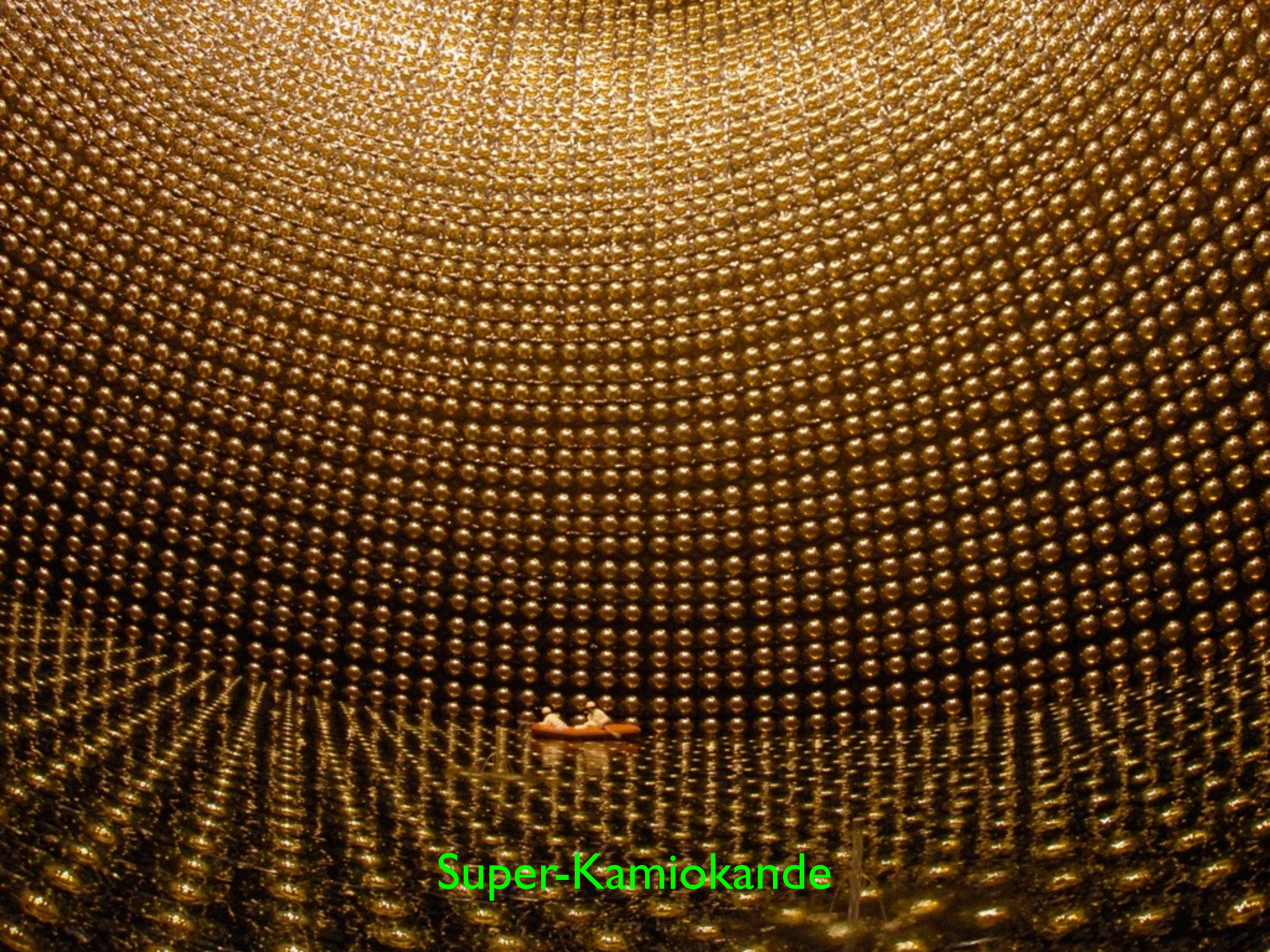
How does the Sun shine?



$$E=mc^2$$

the Sun is getting
lighter by
4 million tons
every second

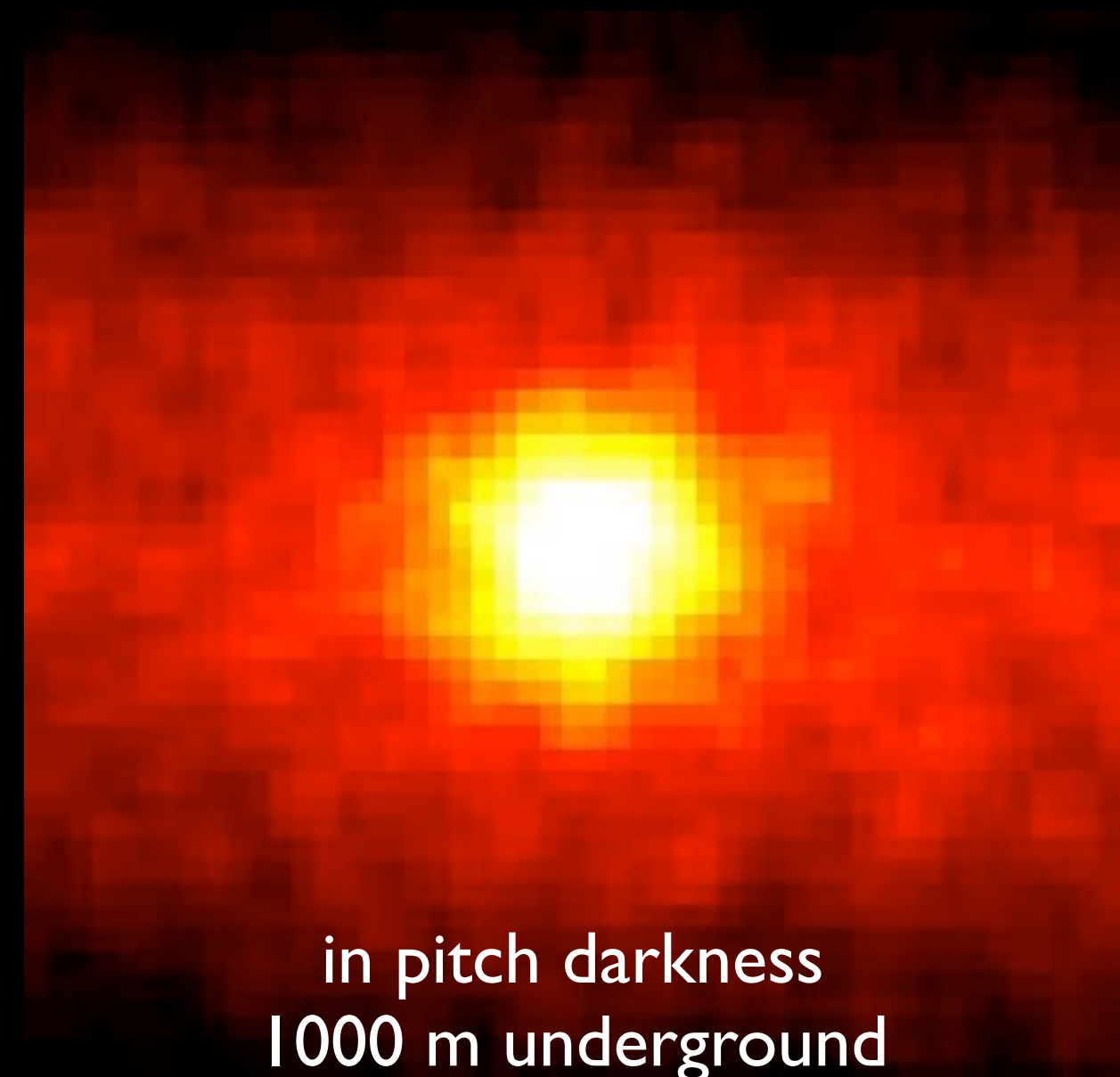
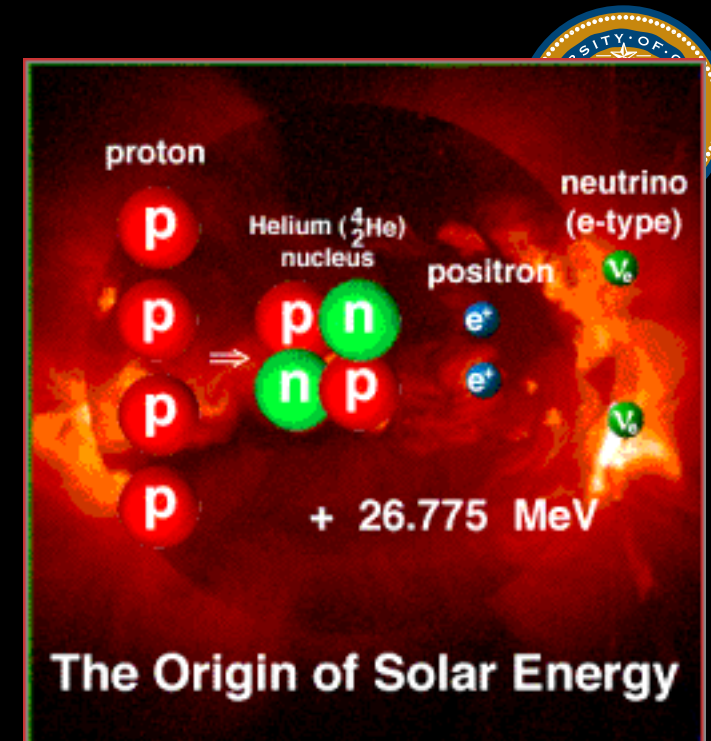
a hundred trillion
neutrinos go through
our body every second



Super-Kamiokande

evidence

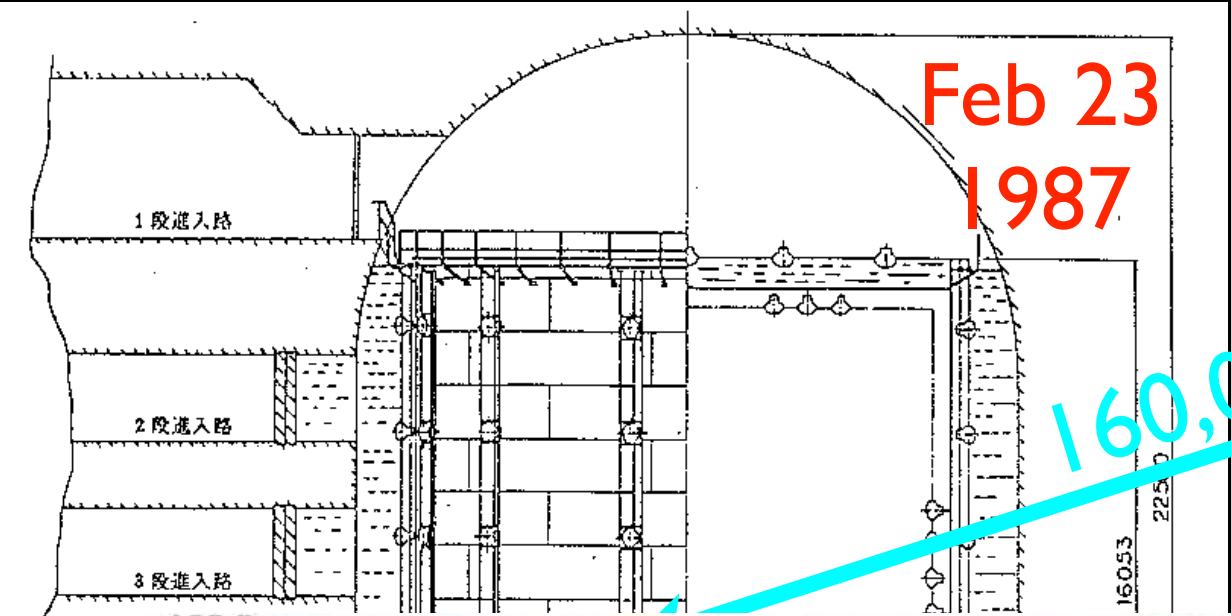
*burning atoms in the Sun produces neutrinos
trillions through our body every second*



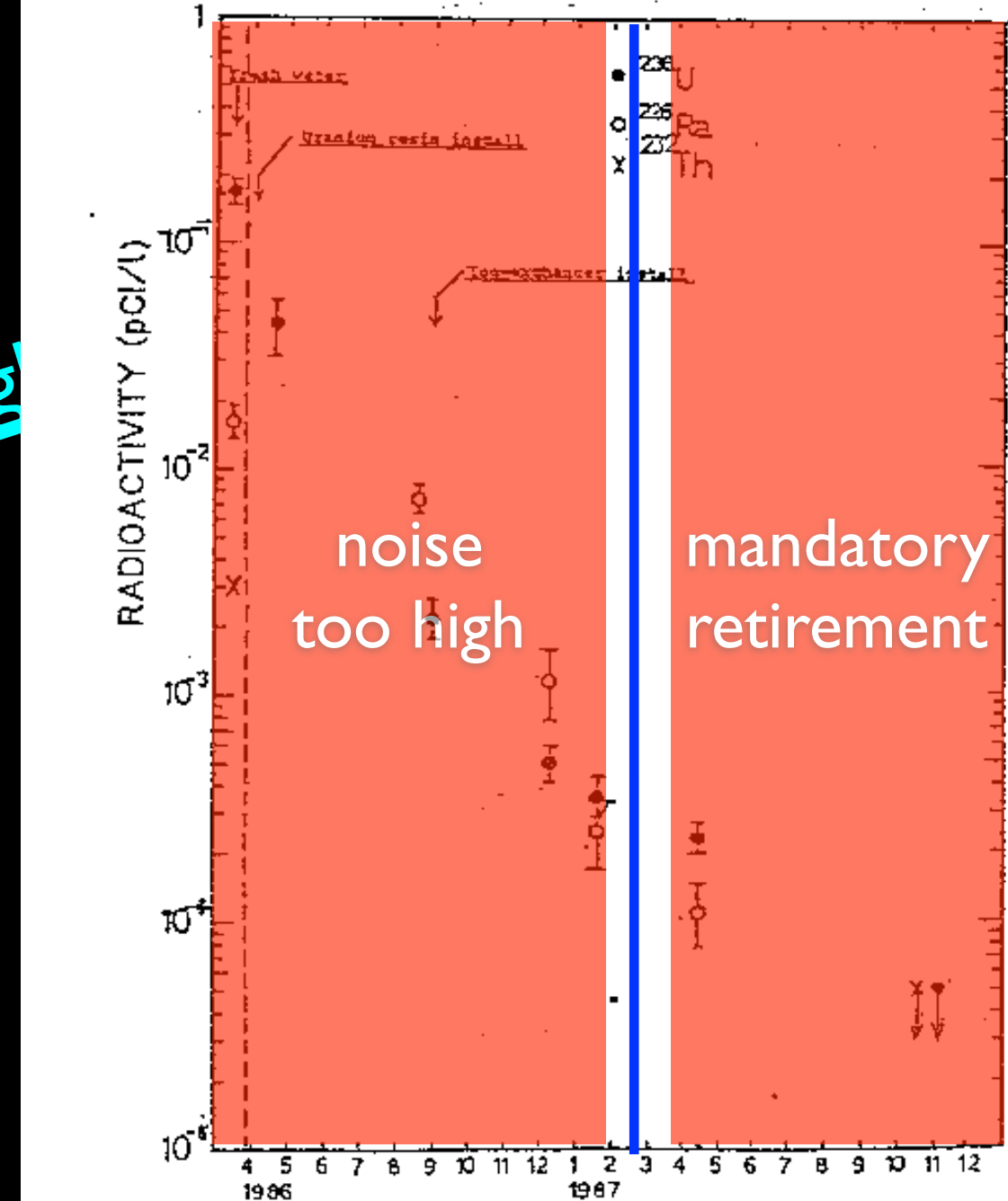
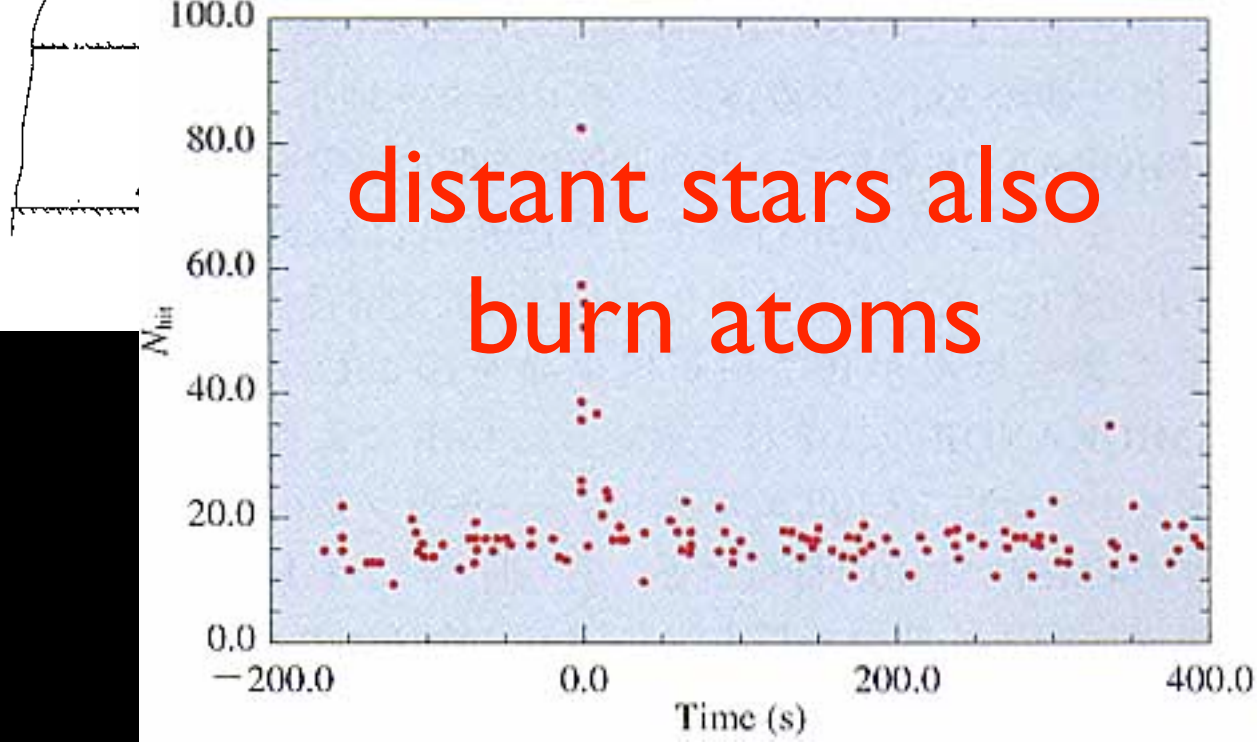
in pitch darkness
1000 m underground



tremendous luck

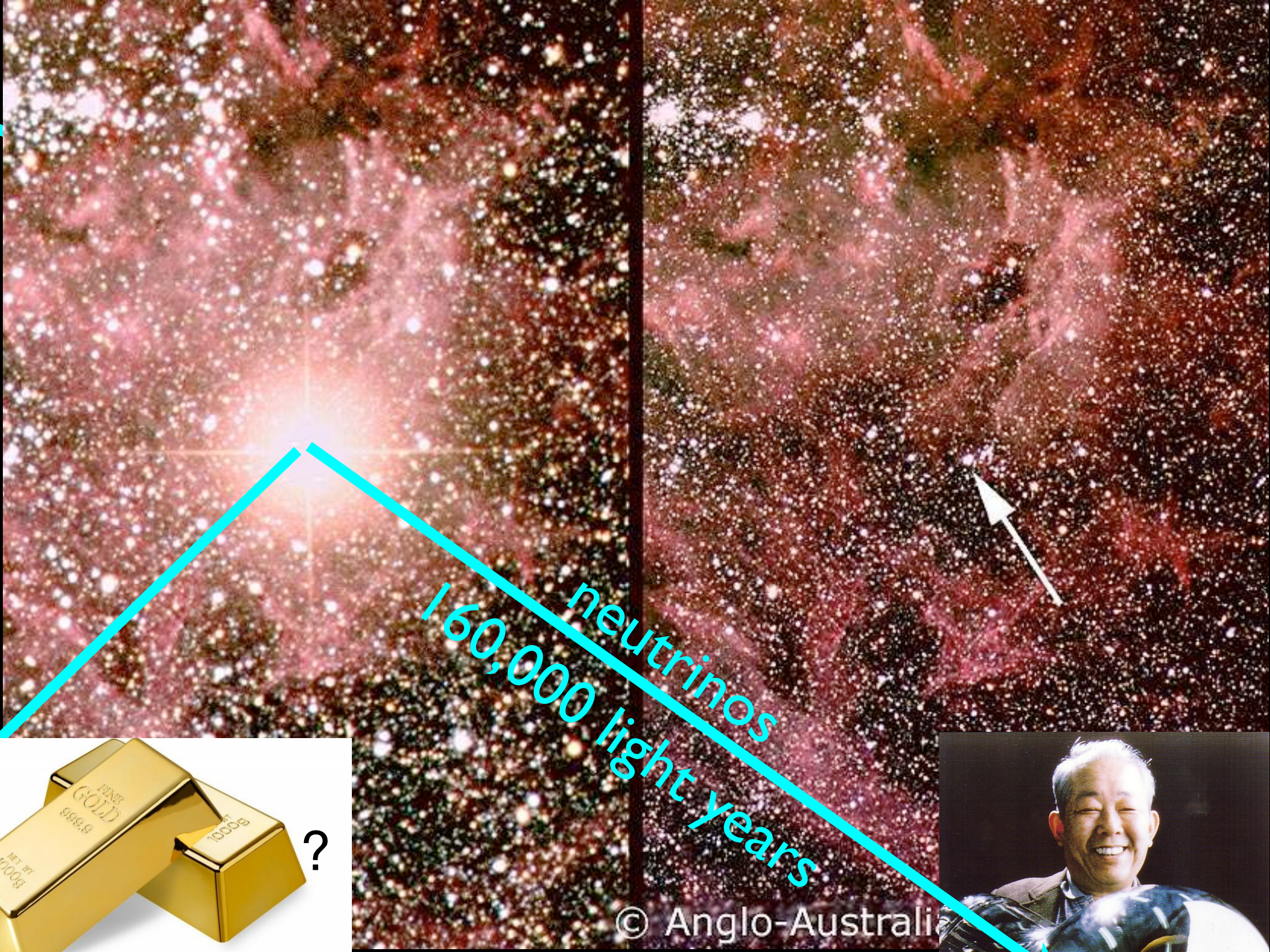


160,000 light



hydrogen
helium

carbon
nitrogen
oxygen
iron



© Anglo-Australian

We are star dust

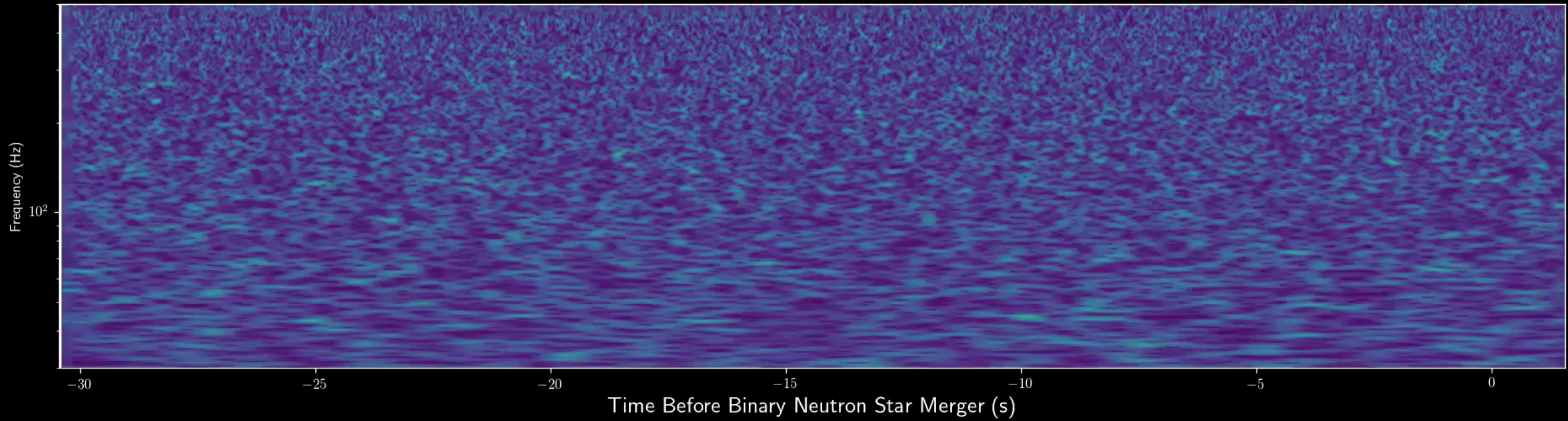
merger of neutron stars



Scale of Effect Vastly Exaggerated

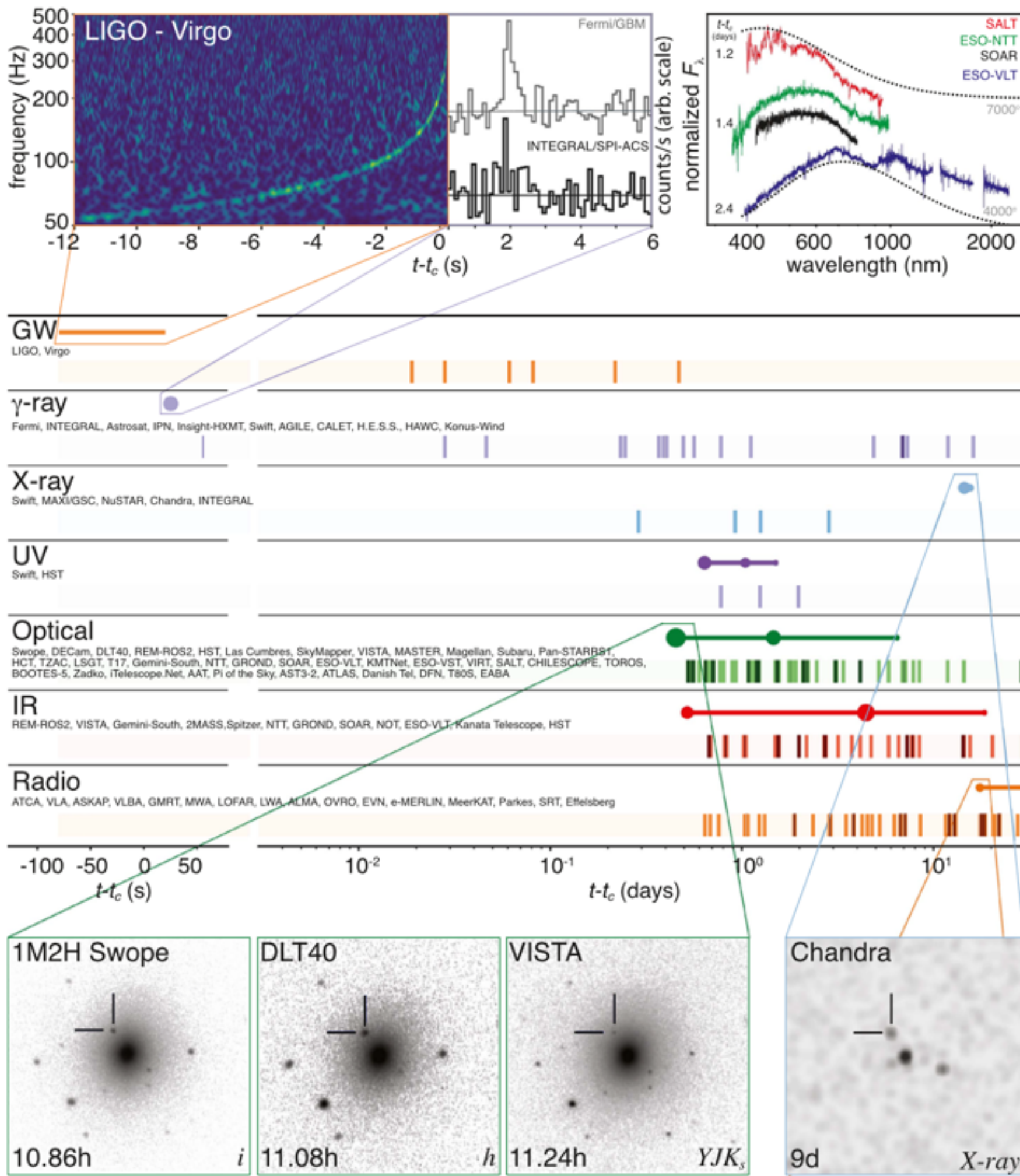
GW170817

Hanford + Livingston

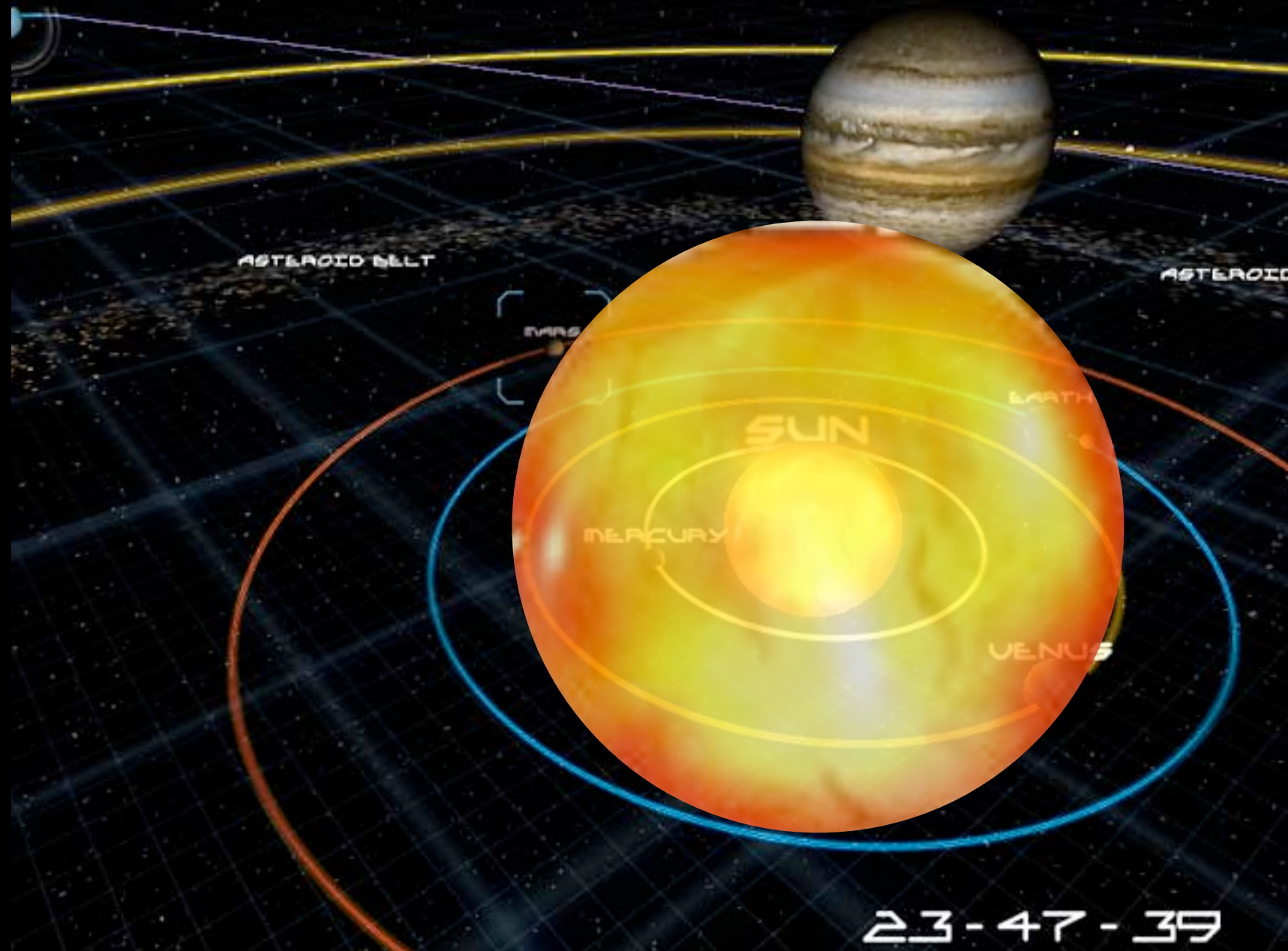


“Multi-messenger Observations of a Binary Neutron Star Merger”

Abbott et al. 2017, ApJL, 848, 12

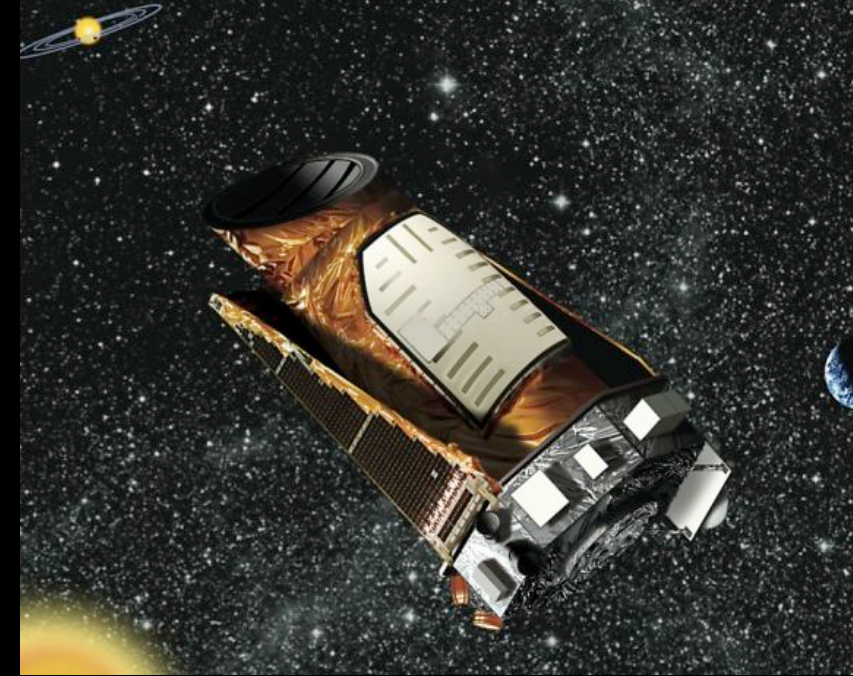


fate of the Sun in 4.5 billion years

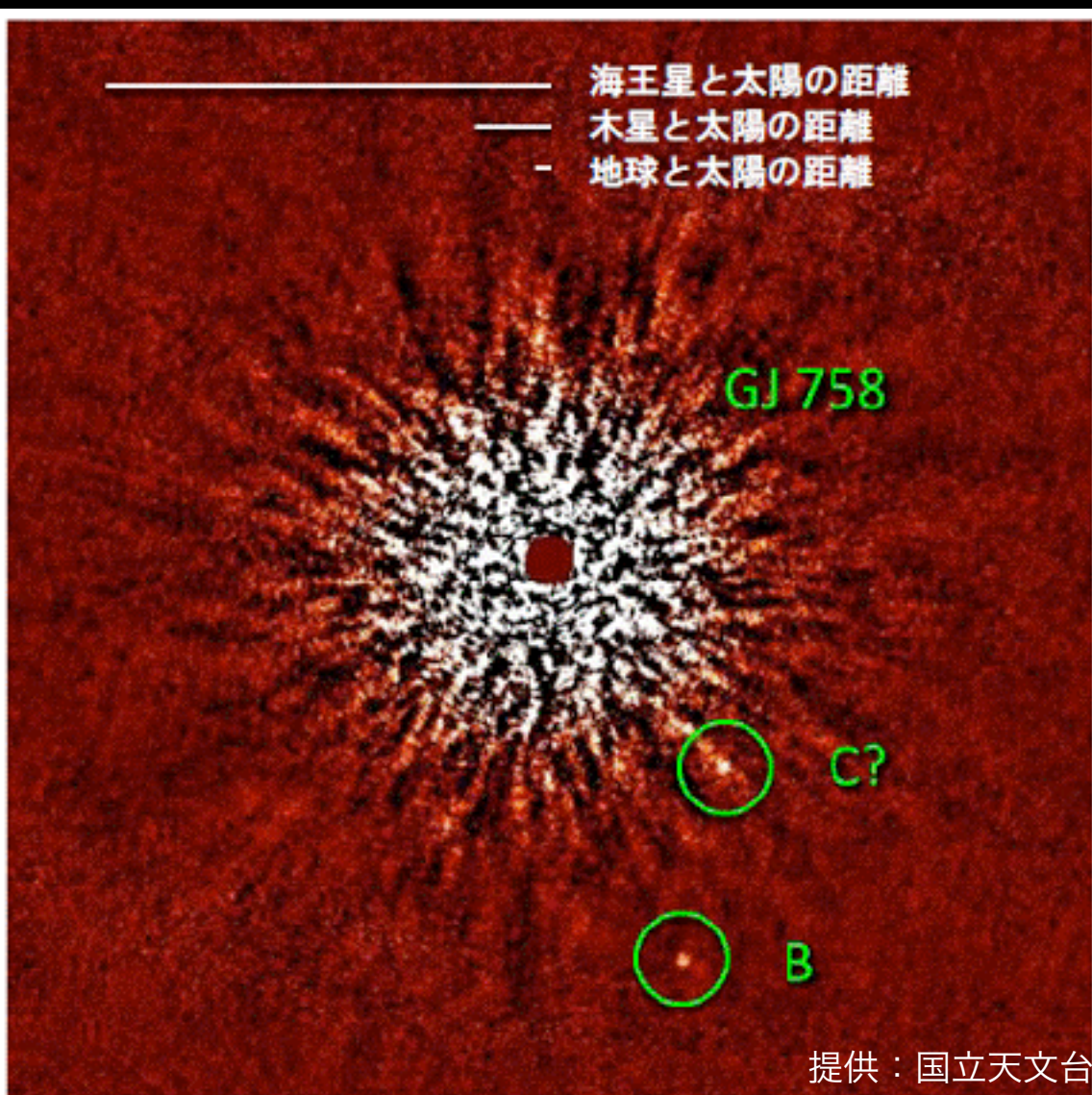


exoplanets

- thousands of candidates now

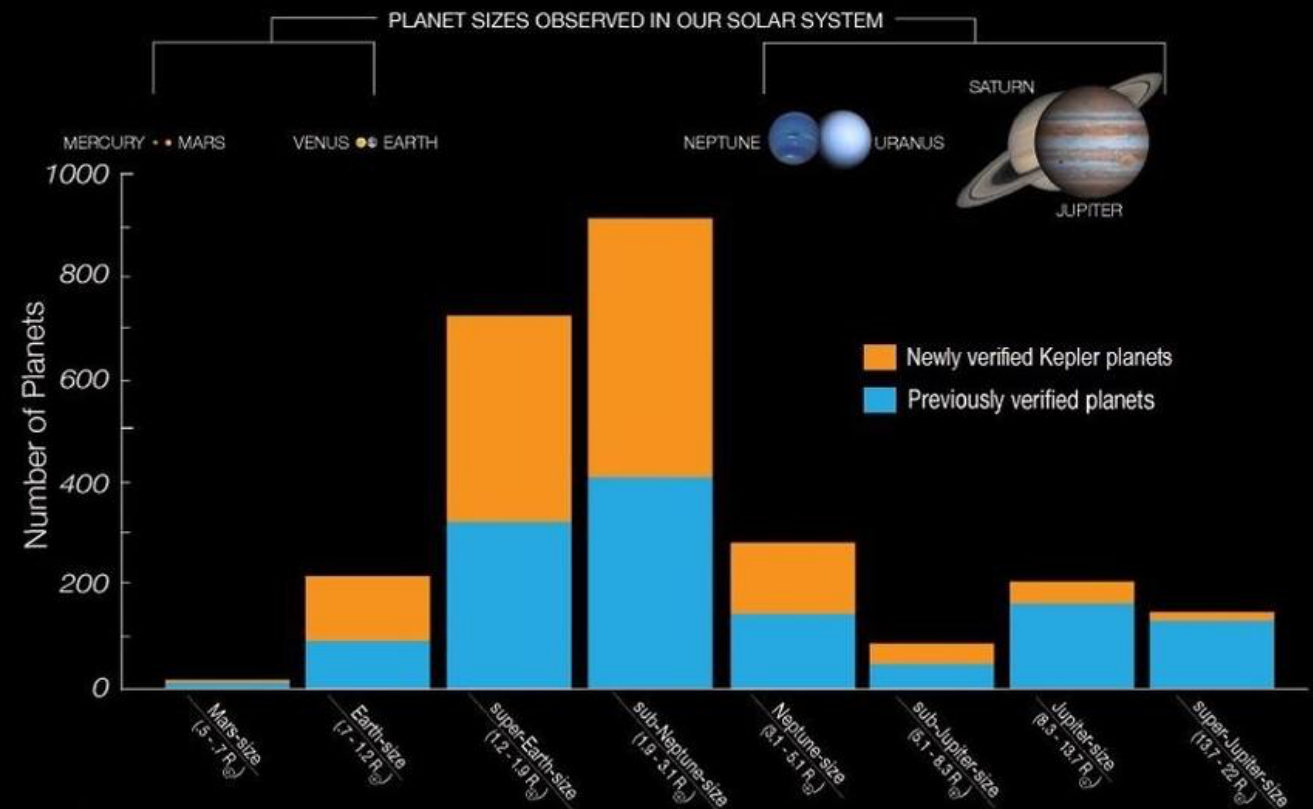


Credit: NASA/Kepler mission/Wendy Stenzel



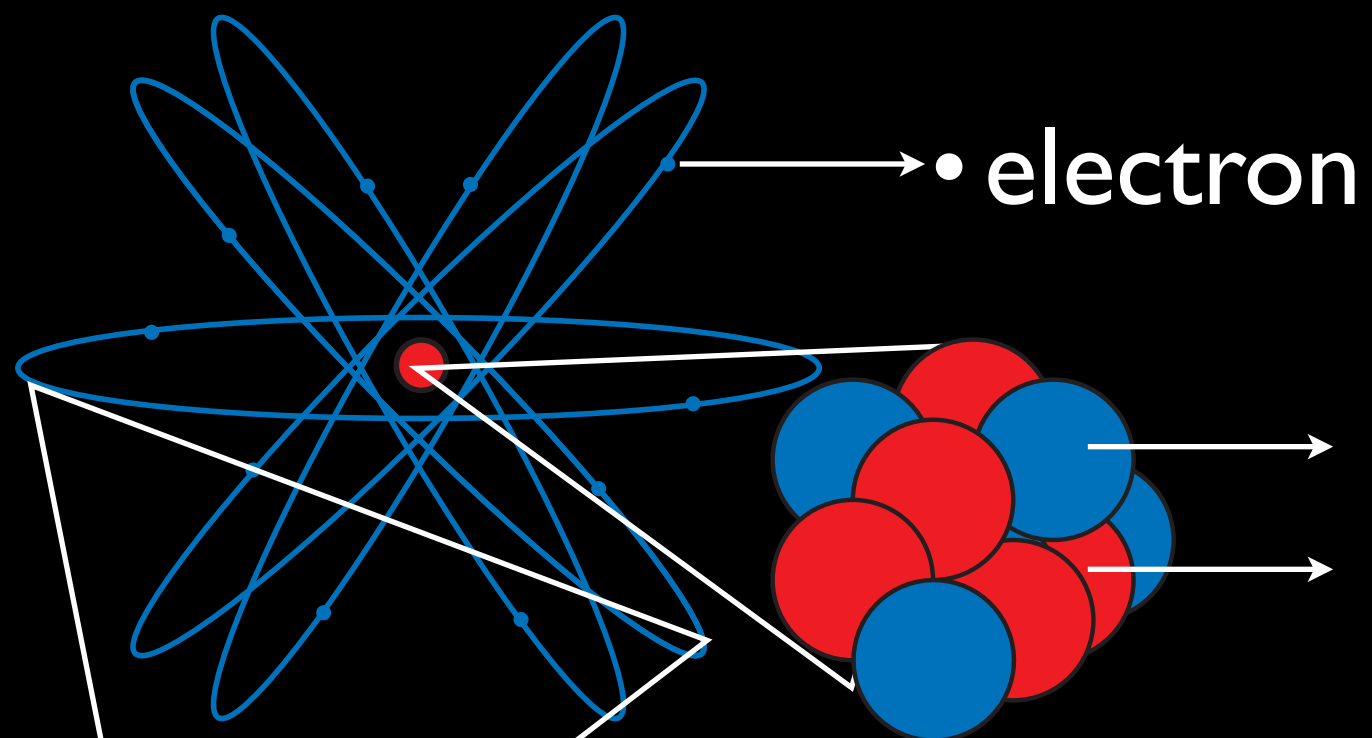
Known Planets by Size

As of May 10, 2016



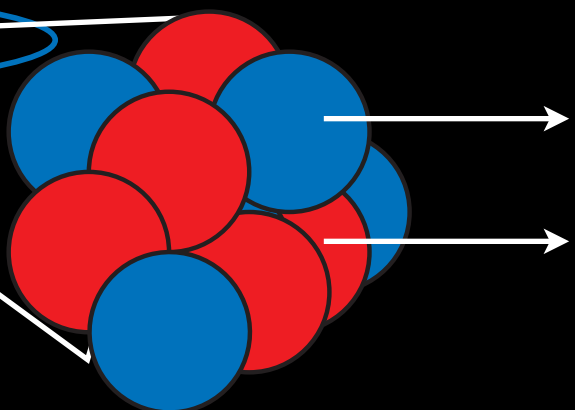
Credit: NASA Ames/Wendy Stenzel

atom



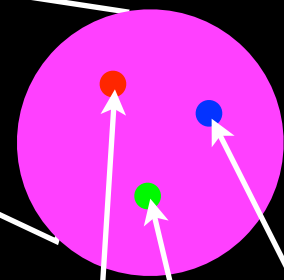
electron

Higgs boson



nucleus

neutron
proton



quarks

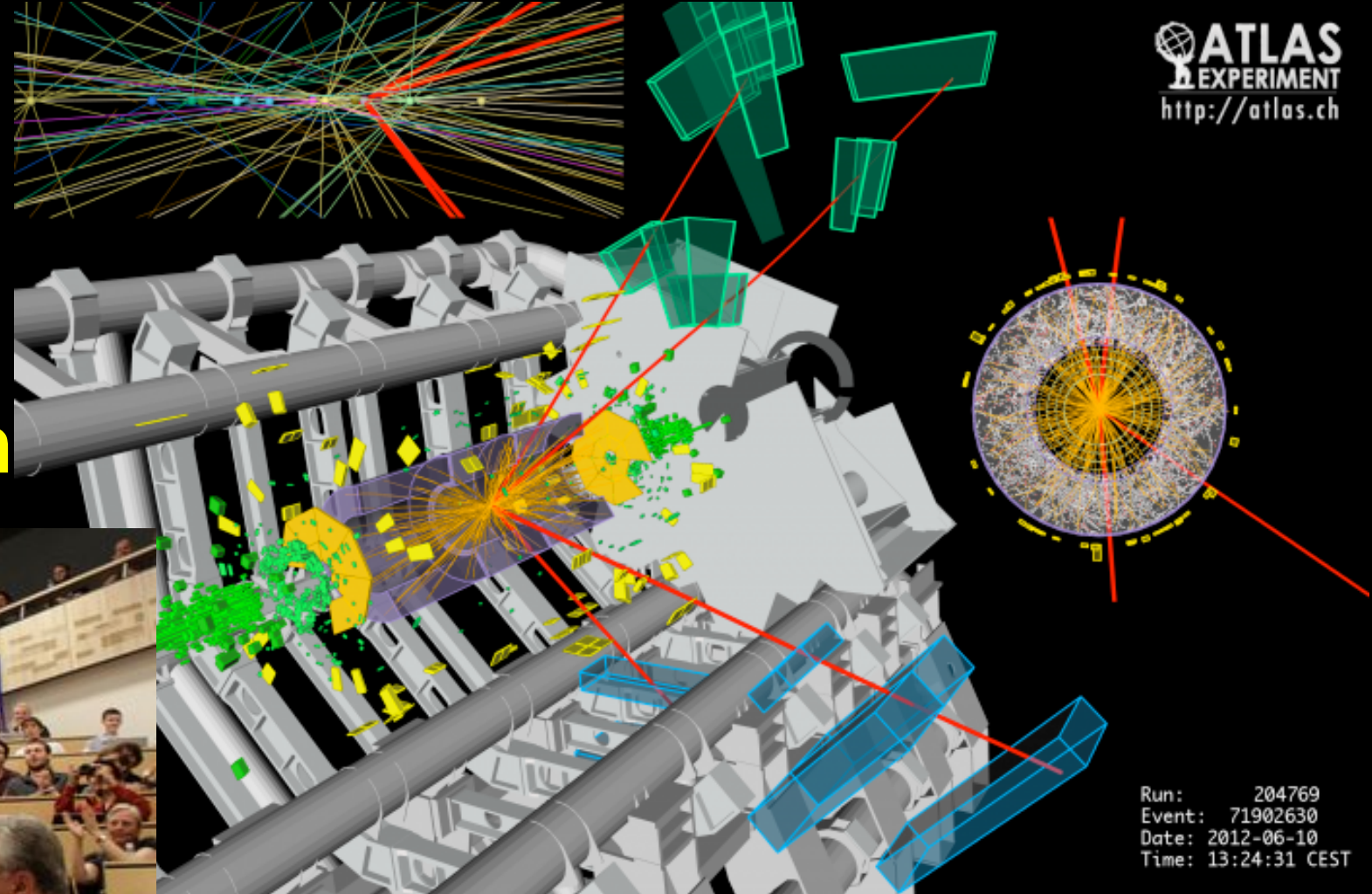






2012.7.4

discovery of Higgs boson



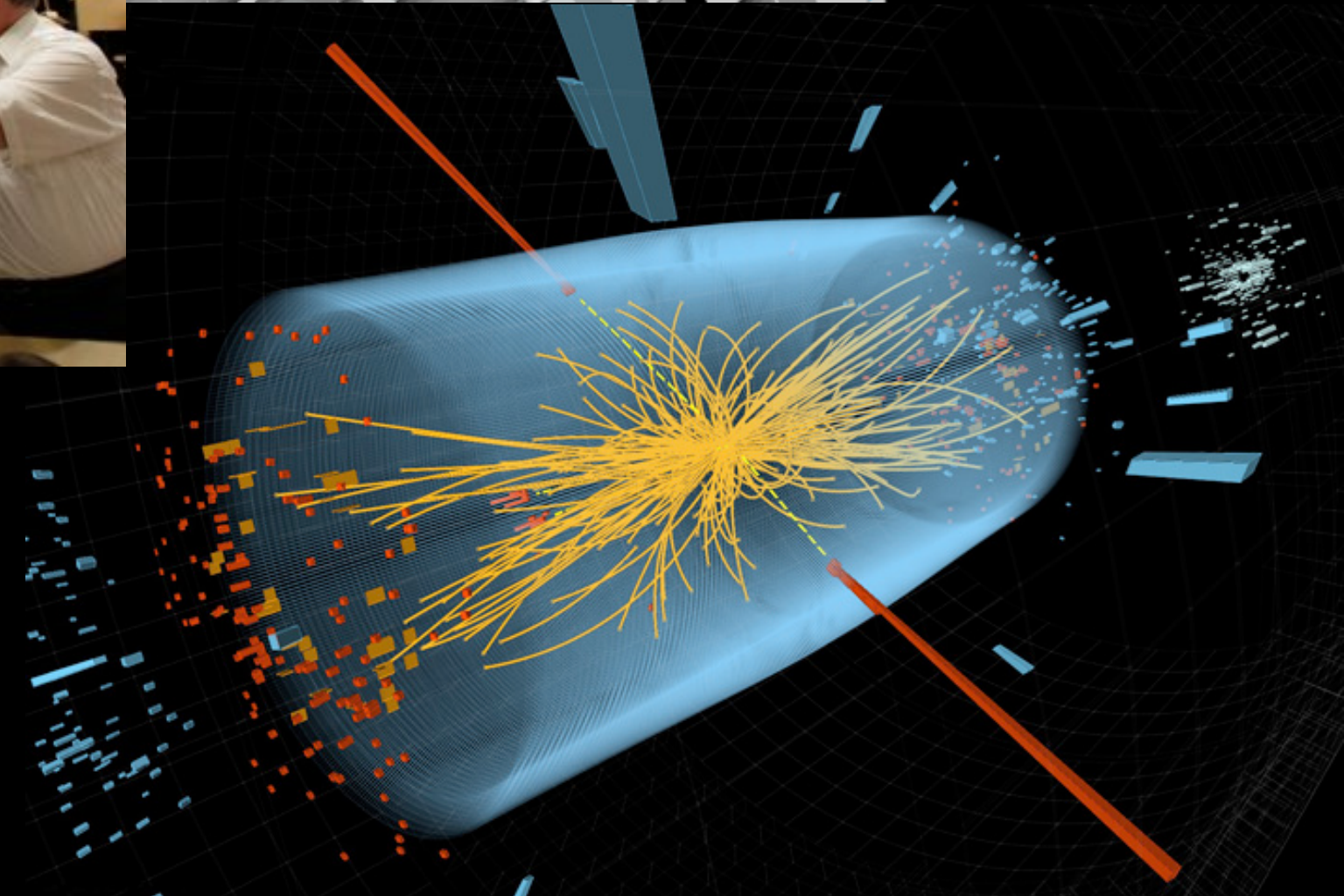
Run: 204769
Event: 71902630
Date: 2012-06-10
Time: 13:24:31 CEST



theory : 1964

design : 1984

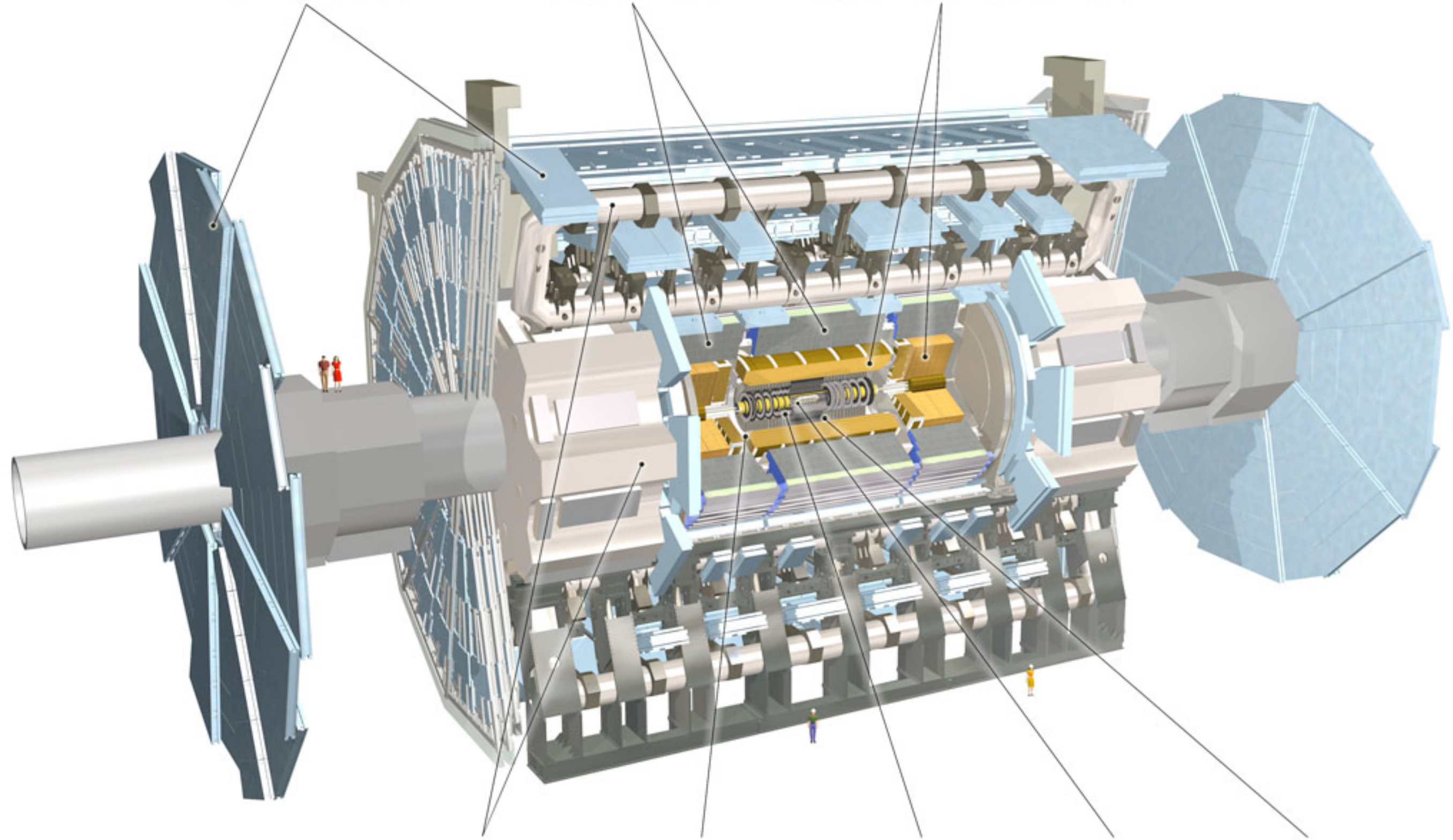
construction : 1998



Muon Detectors

Tile Calorimeter

Liquid Argon Calorimeter



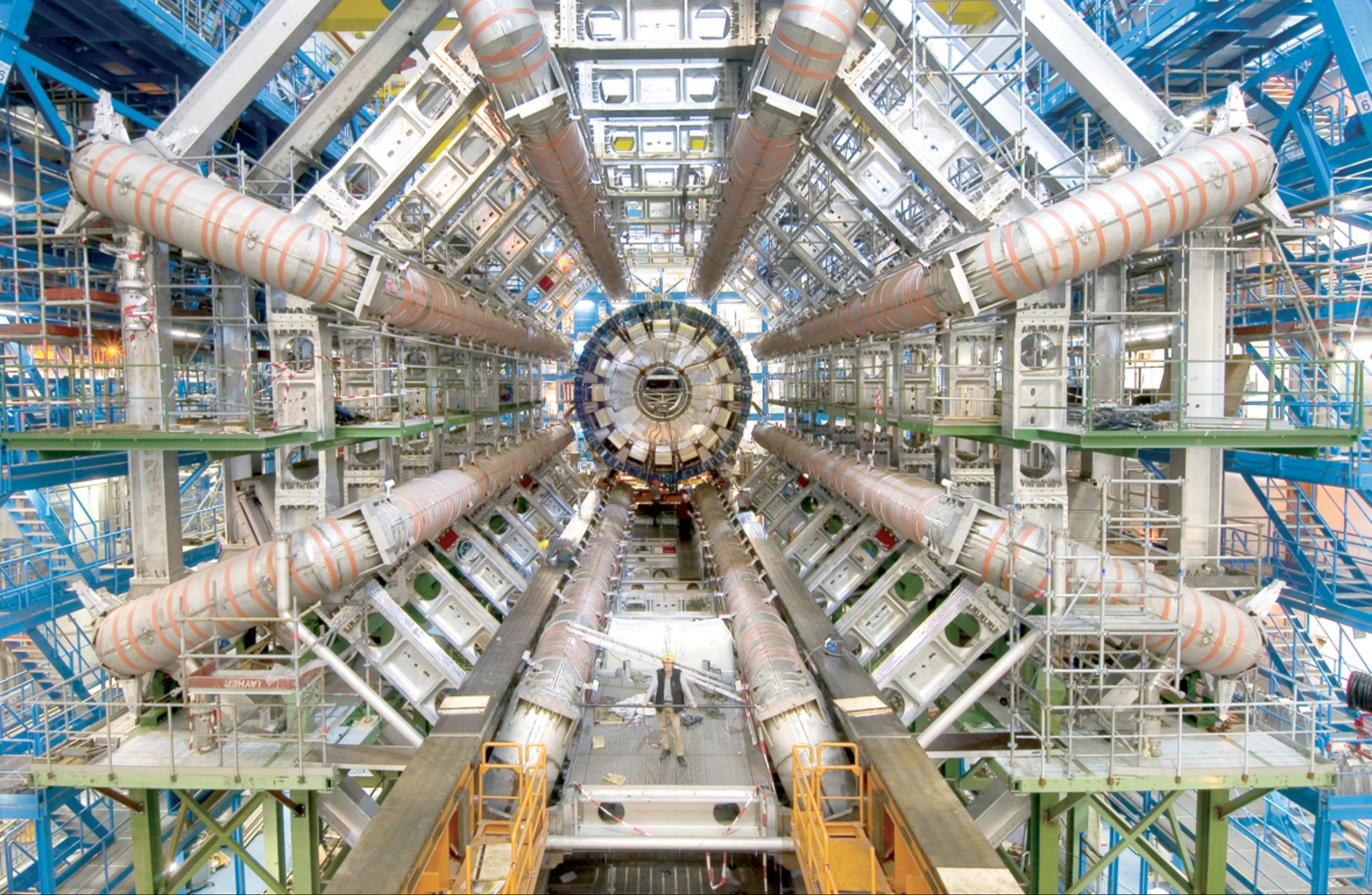
Toroid Magnets

Solenoid Magnet

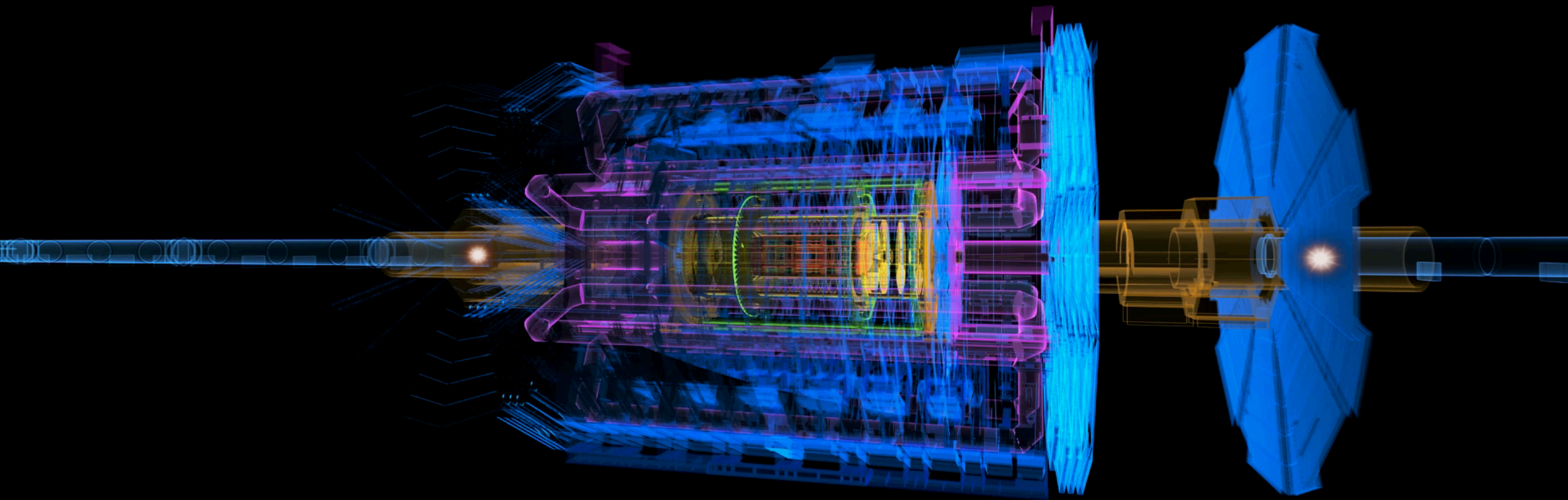
SCT Tracker

Pixel Detector

TRT Tracker

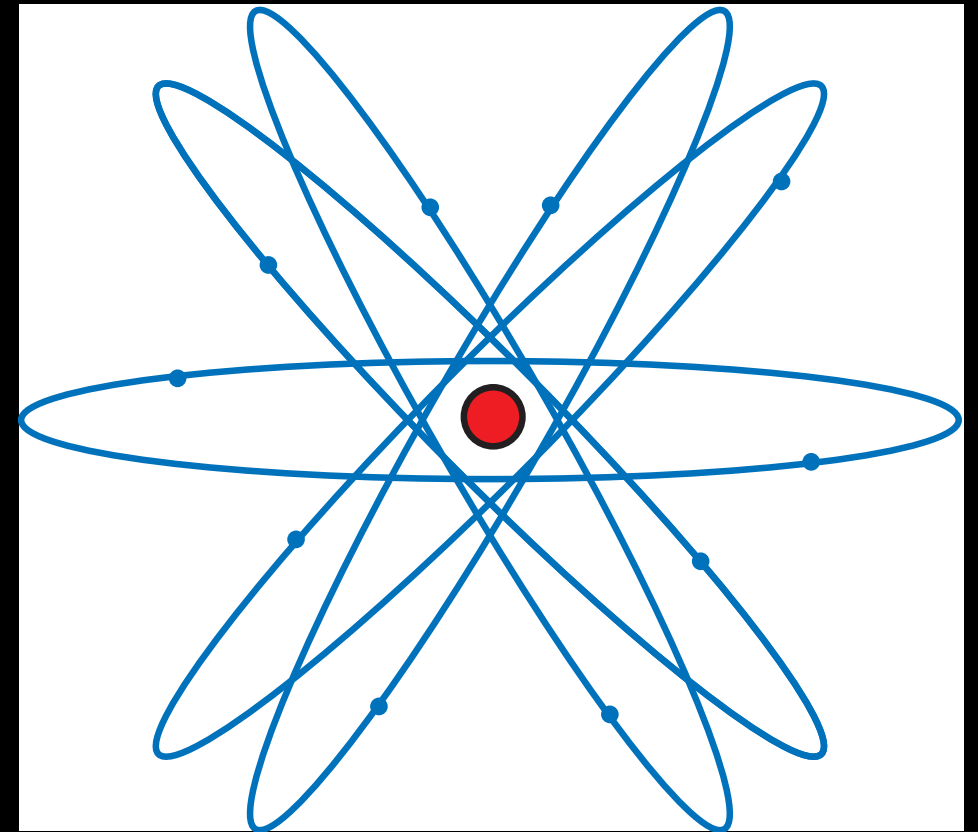
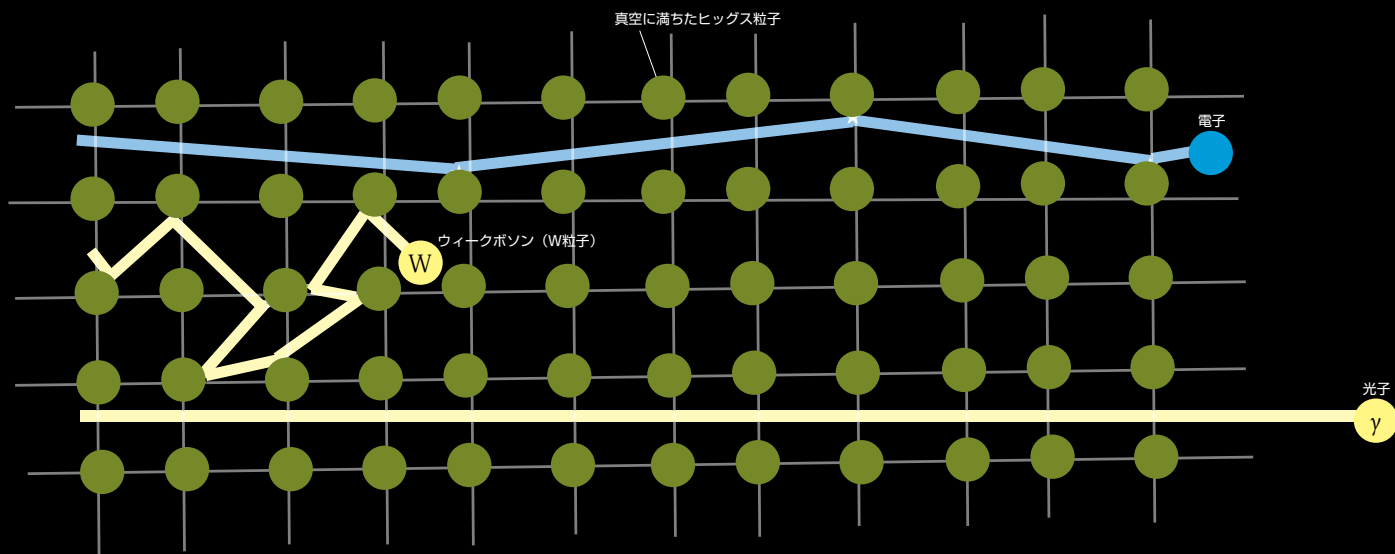


ATLAS detector



Higgs boson decays into two photons

Universe is filled with Higgs



Particles slow down

Without Higgs,
we evaporate in
a billionth of a second



Spin



- every elementary particles spin forever
- electrons, photons, quarks,
- only Higgs boson doesn't spin
- Faceless! *A spooky particle*
- I had proposed “Higgsless theories”
- *Is it the only one?*
- *does it have siblings? relatives?*
- *Maybe it's spinning in extra dimensions?*
- *maybe composite?*
- *why did it freeze in?*

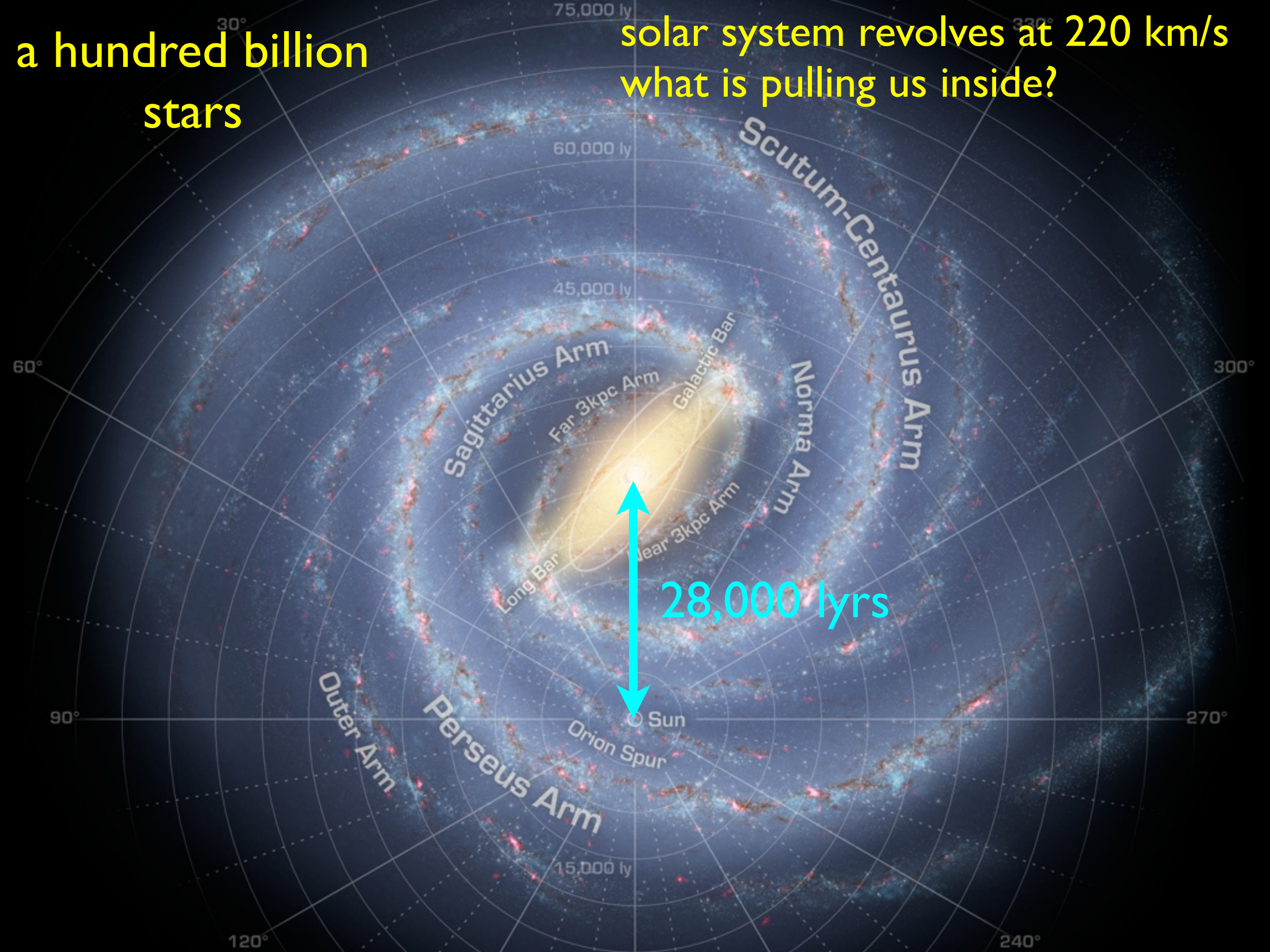


A deep-field astronomical image showing a vast field of galaxies. The galaxies are scattered across the frame, appearing in various colors (yellow, orange, blue, purple) and orientations (spiral, elliptical, and irregular). The background is a dark, almost black, space filled with numerous small, distant stars and galaxies. The overall scene is a rich, multi-colored galaxy field.

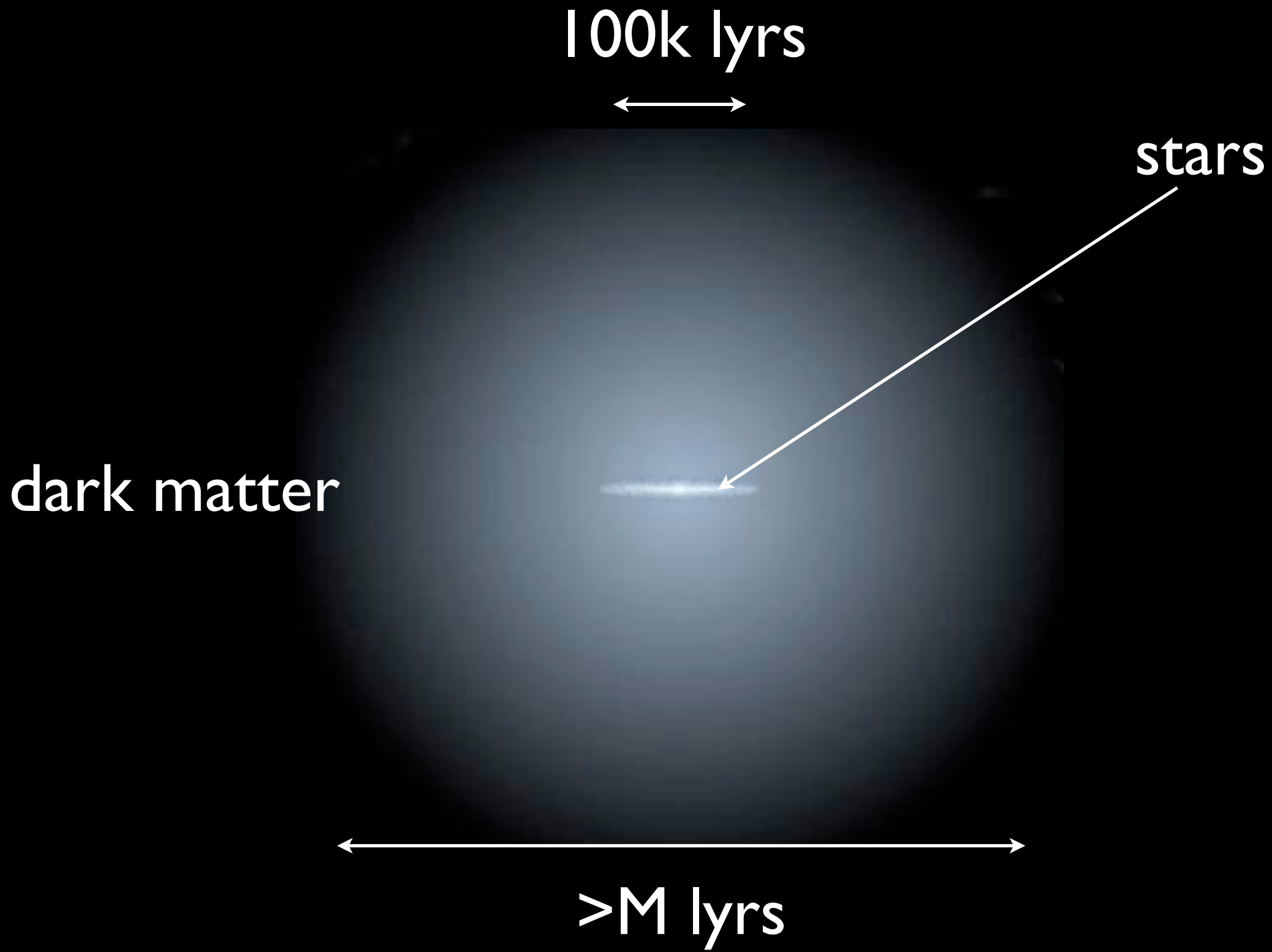
Dark Matter

a hundred billion stars

solar system revolves at 220 km/s
what is pulling us inside?



true nature of galaxies

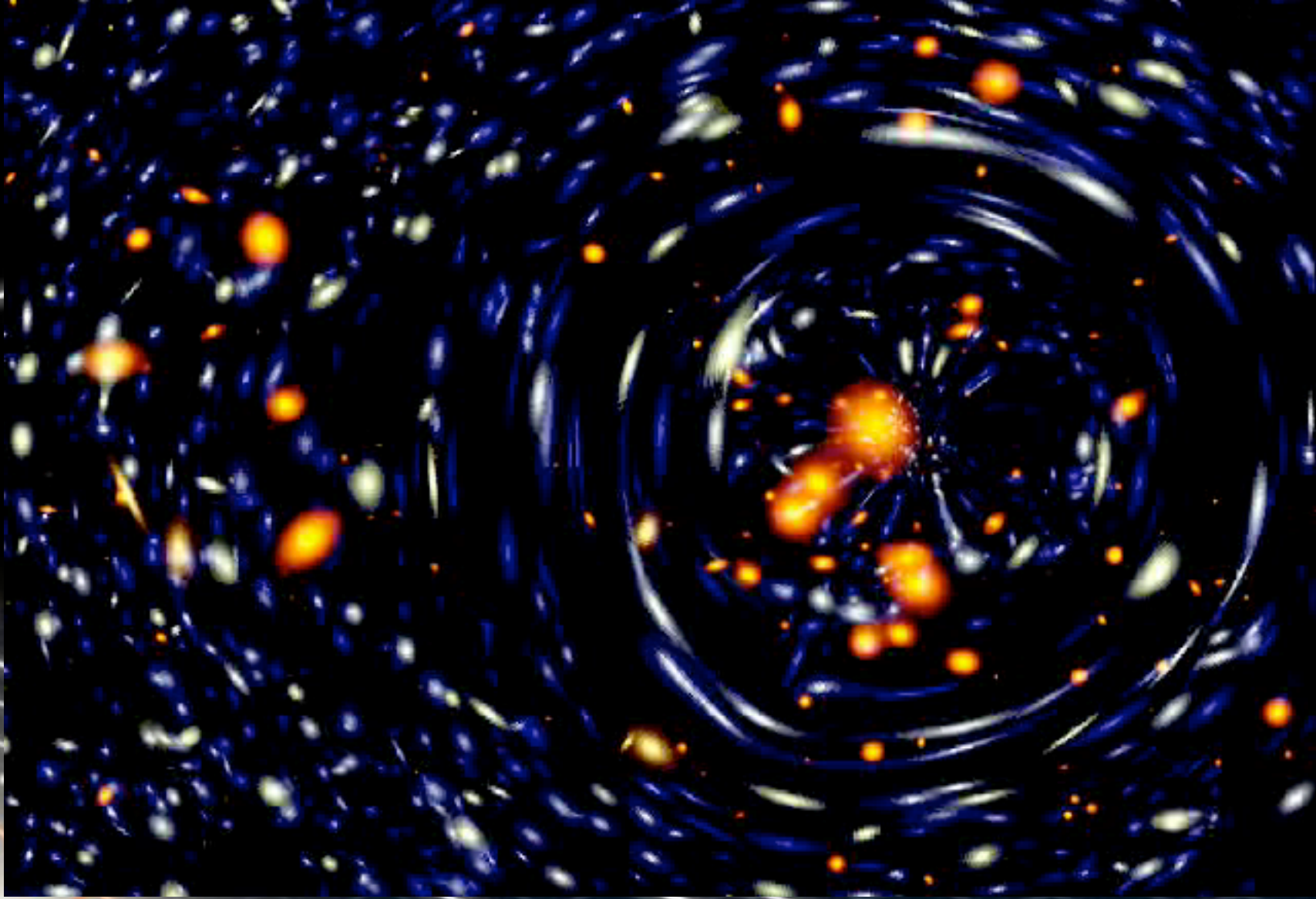
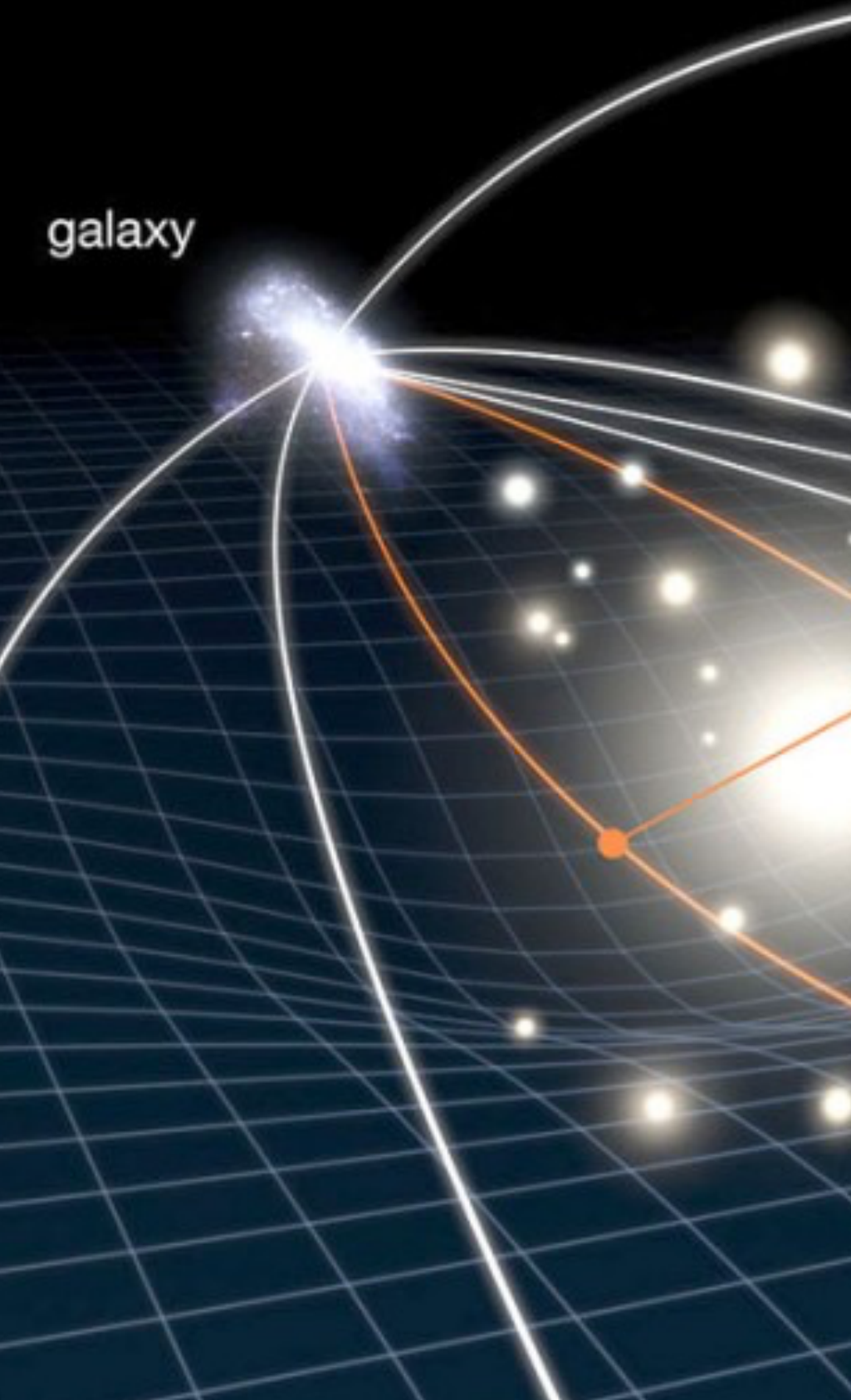


cluster of galaxies



Abell 2218
2.1 B lyrs

galaxy

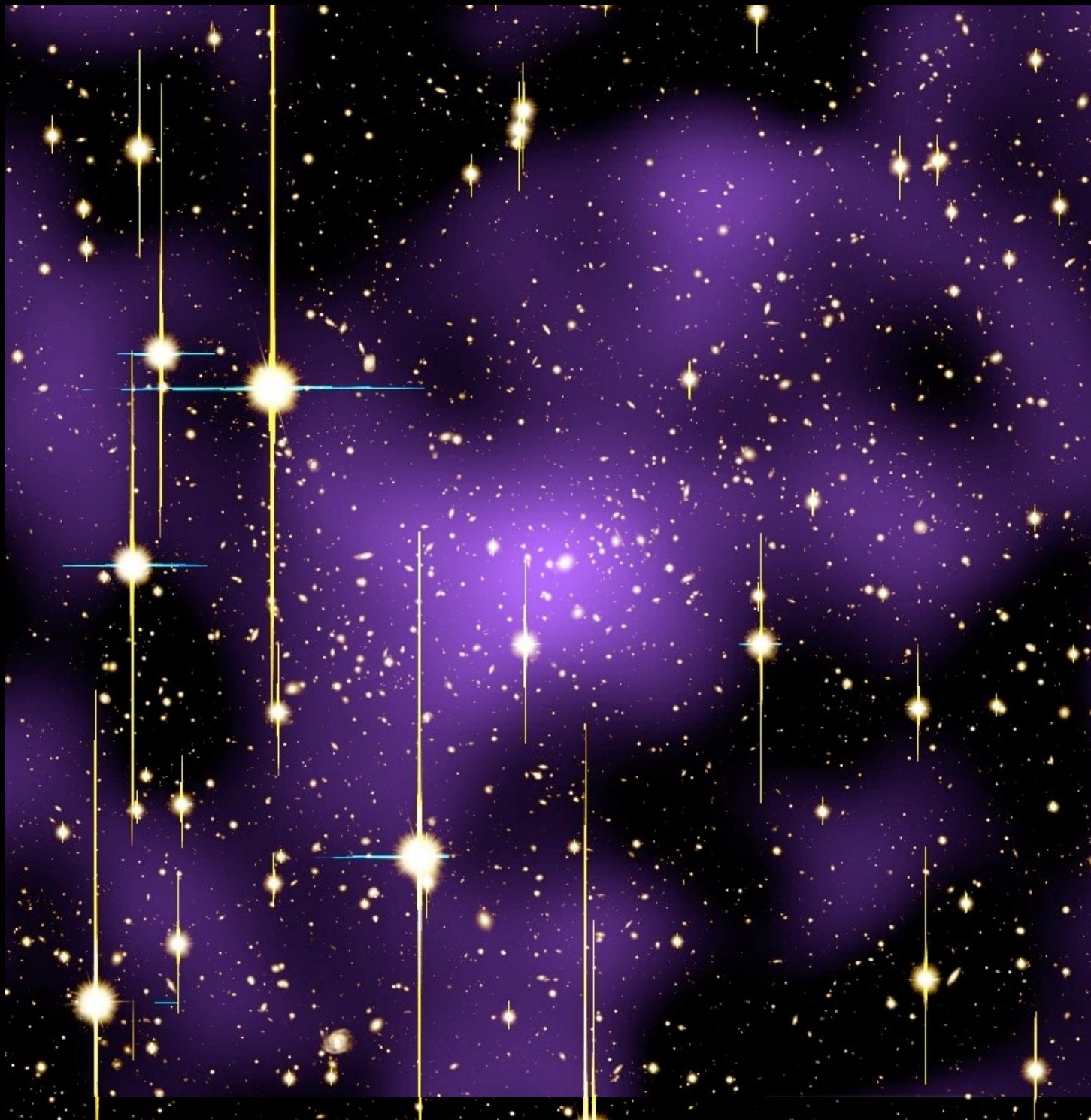


distorted light-rays

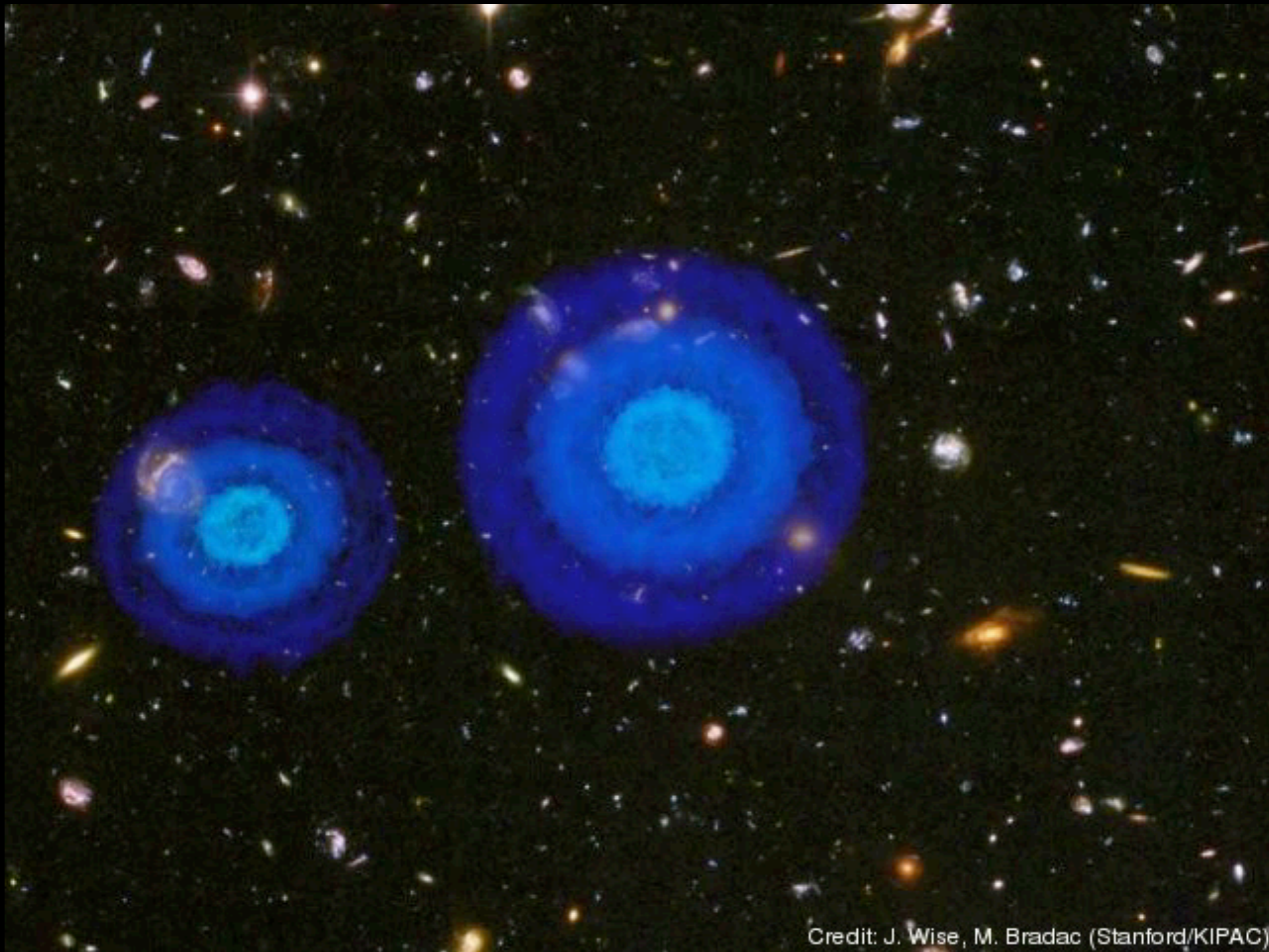
Earth



image invisible dark matter

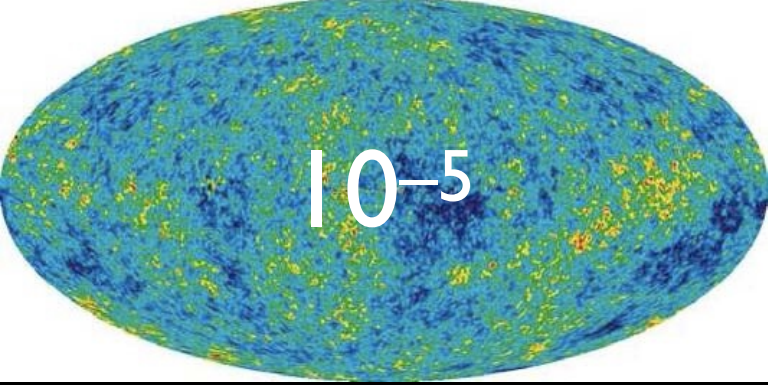


more than 80% of matter in the Universe is not atoms



two clusters collided at 4500km/sec

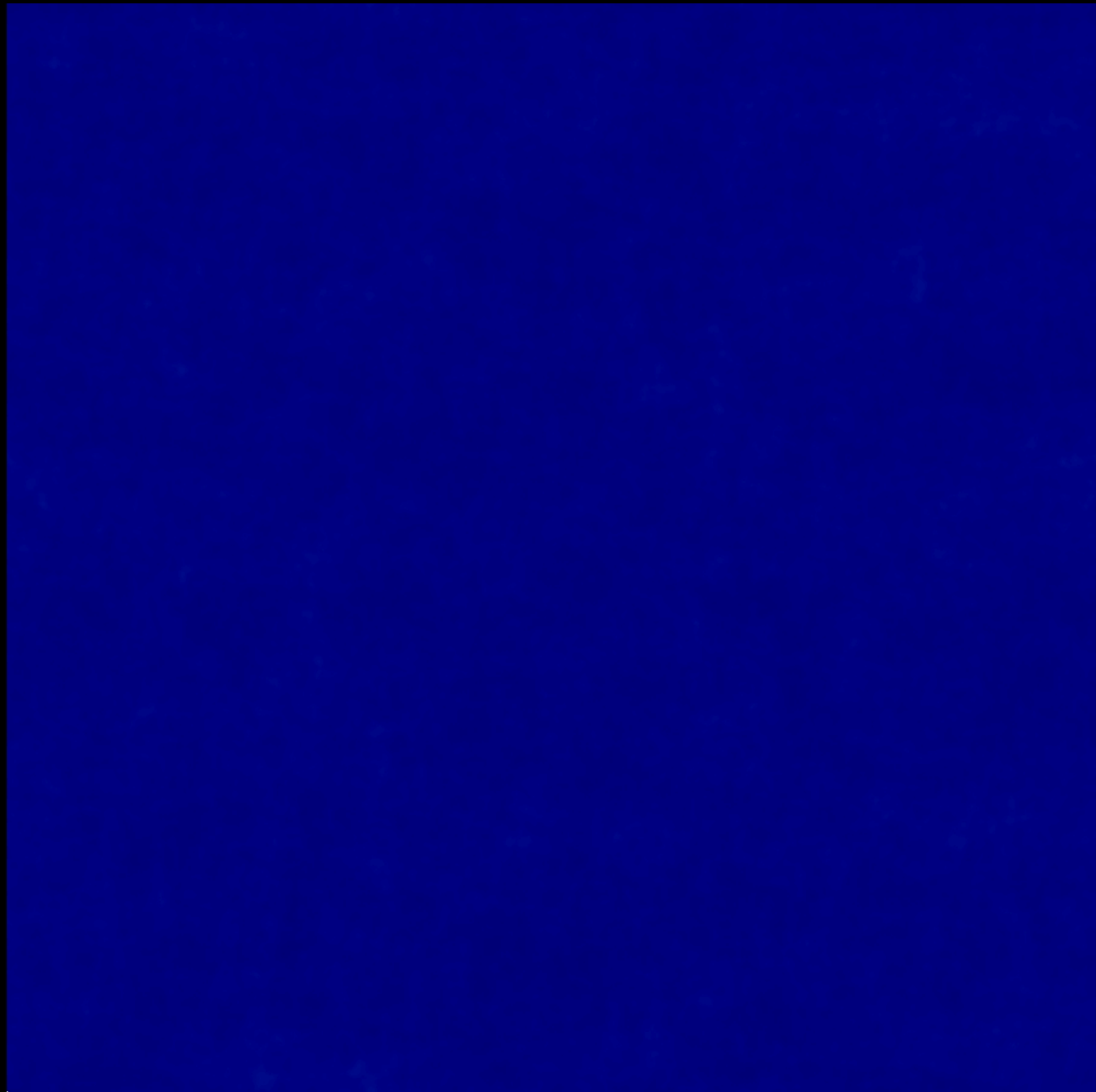
4B lyrs away



Dark Matter is our Mom

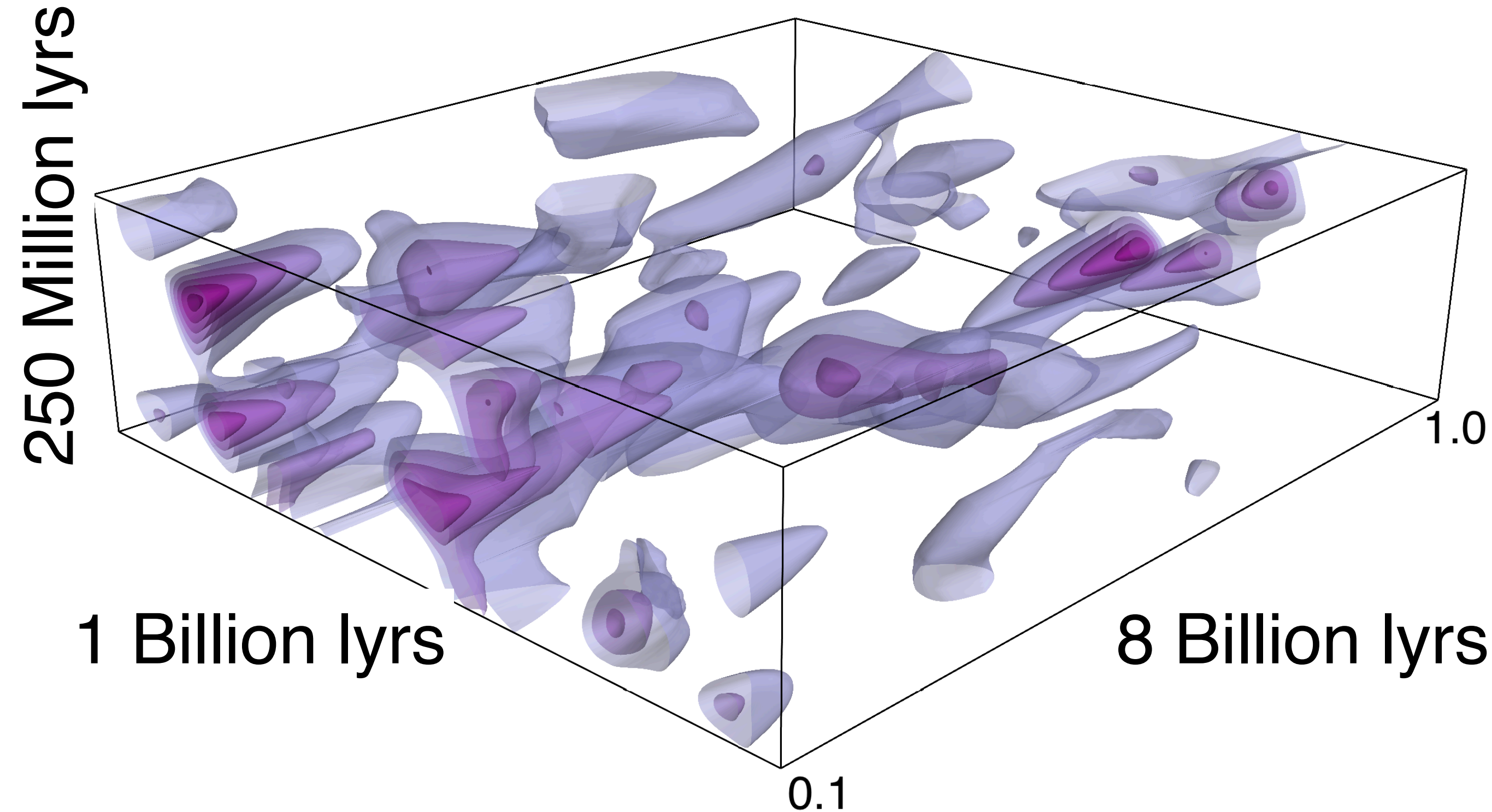


without dark matter

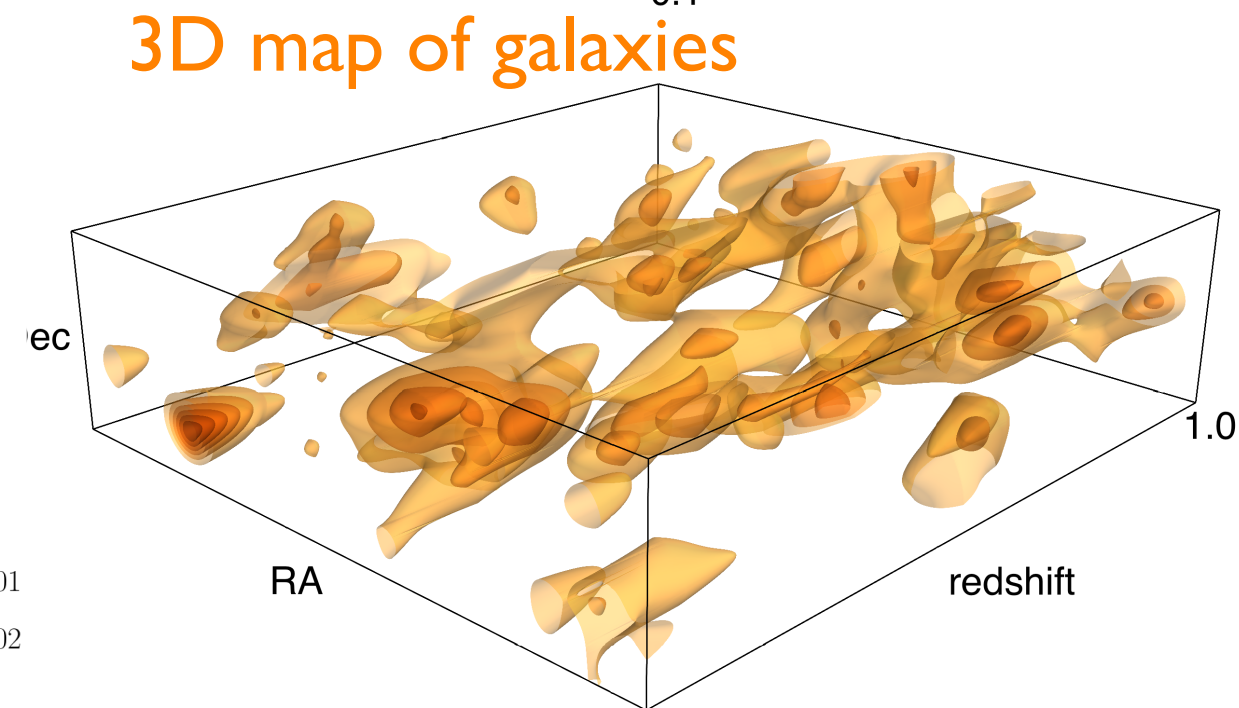
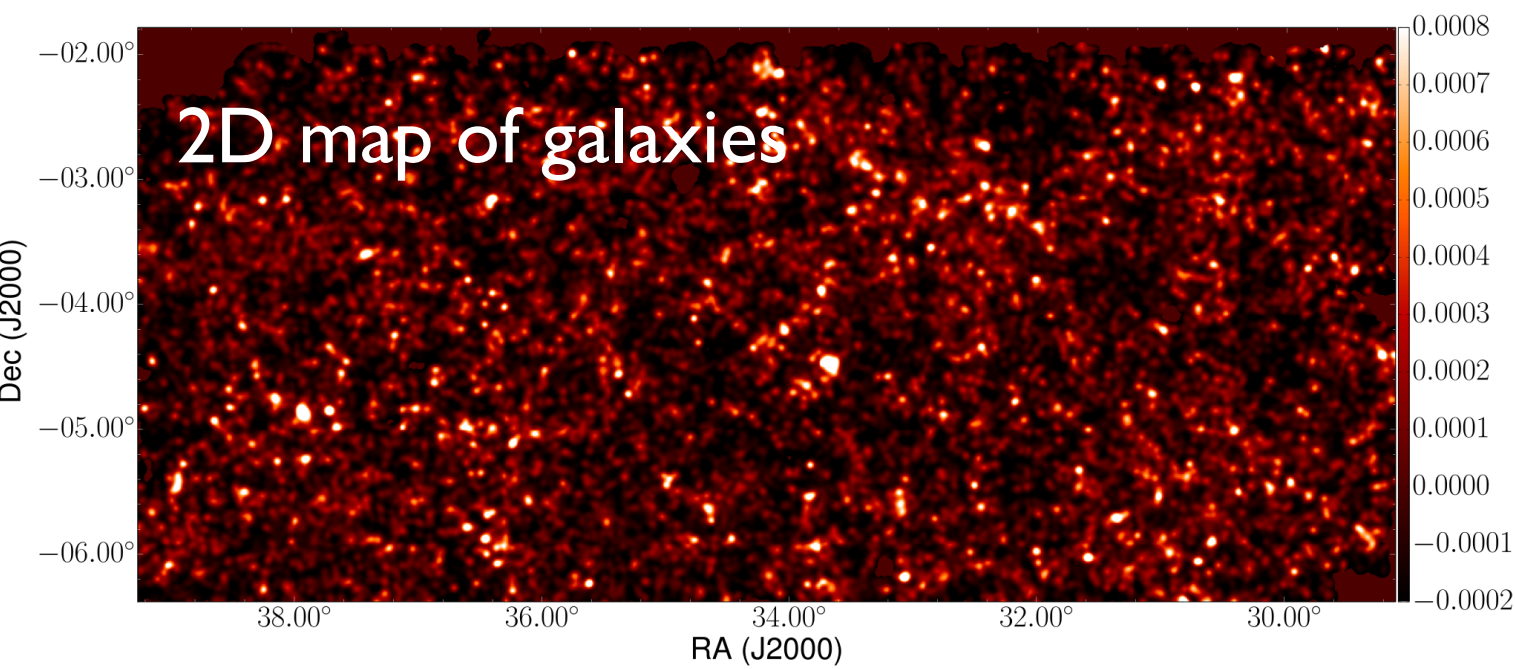
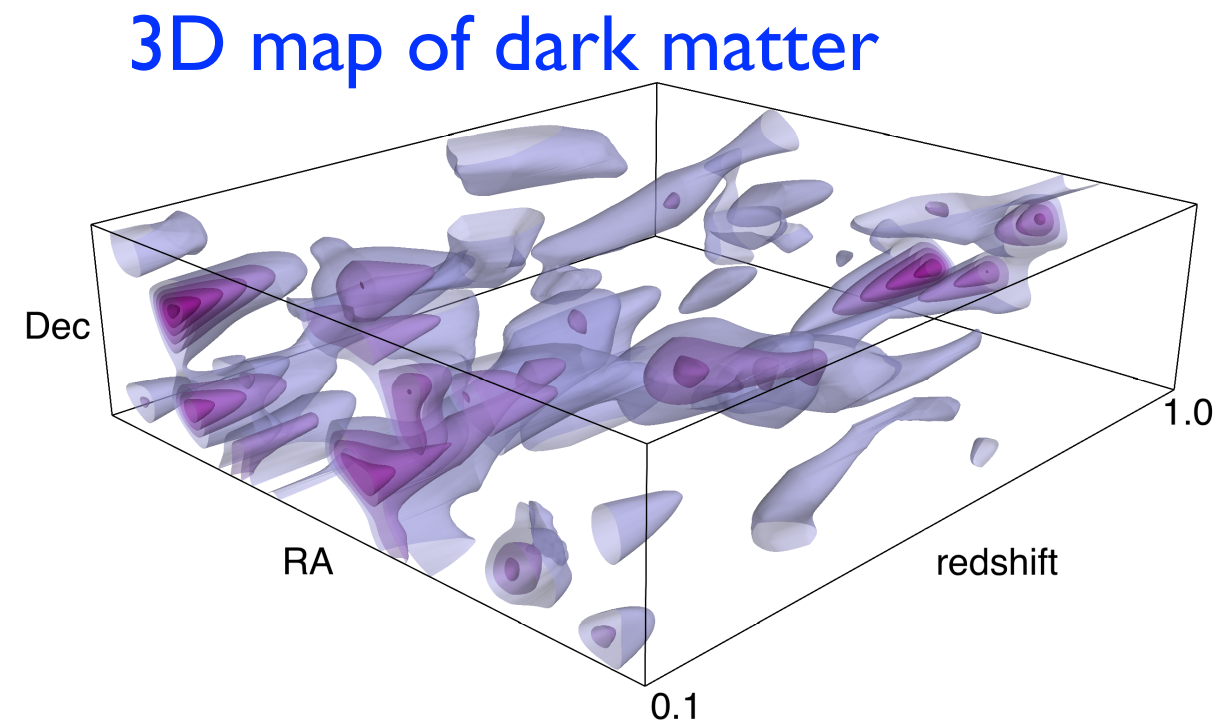
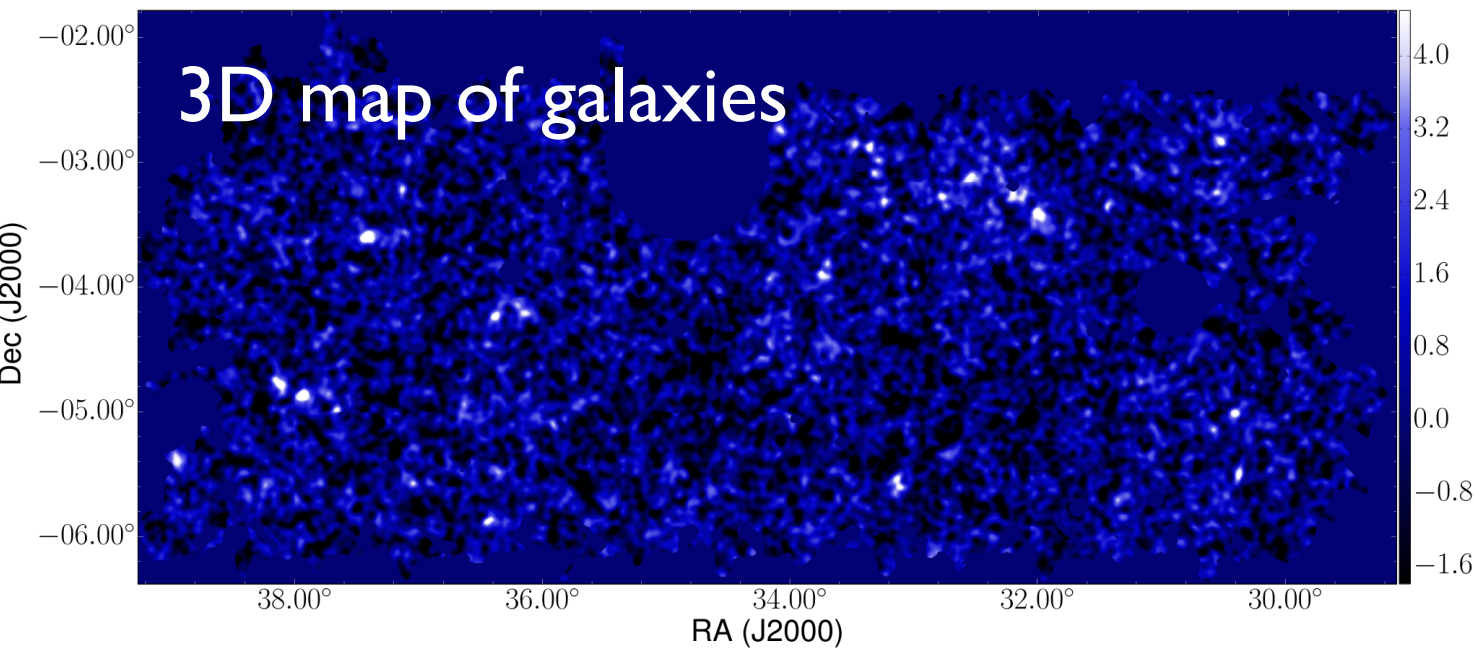


with dark matter

largest 3D map ever



Indeed, dark matter is our Mom!





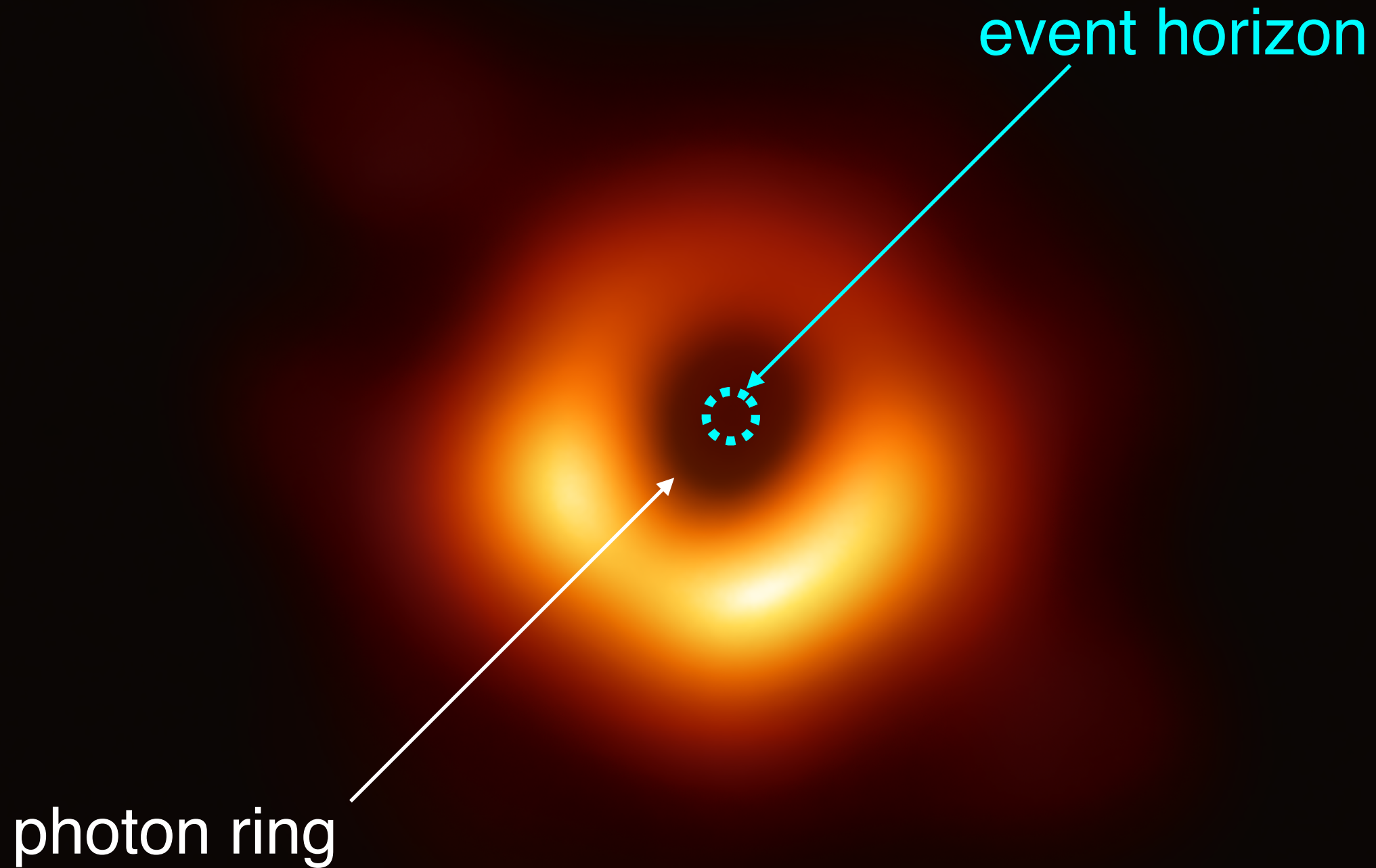
Reenacting the Big Bang with Cal Marching Band





M87 galaxy

but the M87 galaxy weighs as much as 2 trillion Suns

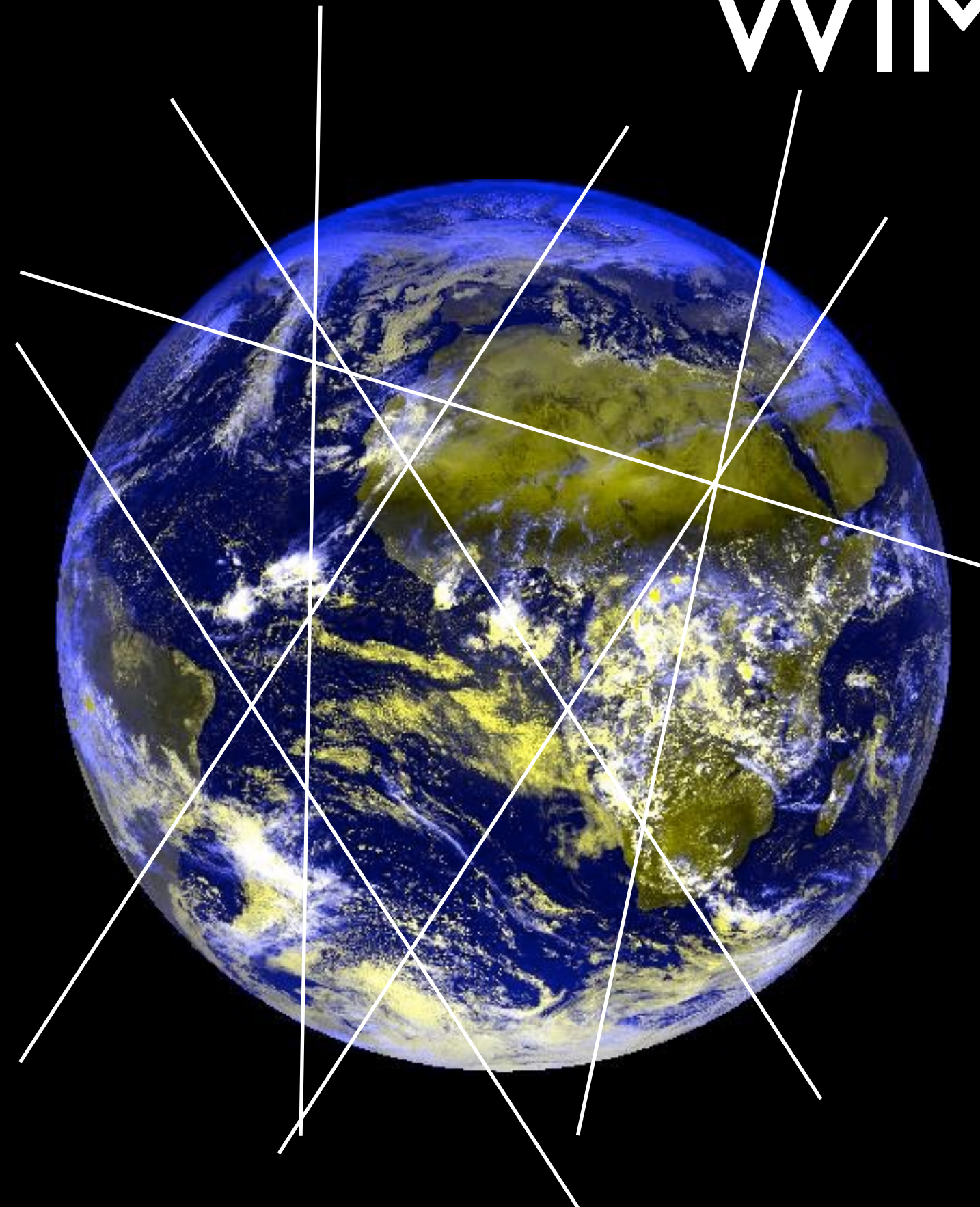


6.5 billion times the mass of the Sun

What is dark matter?

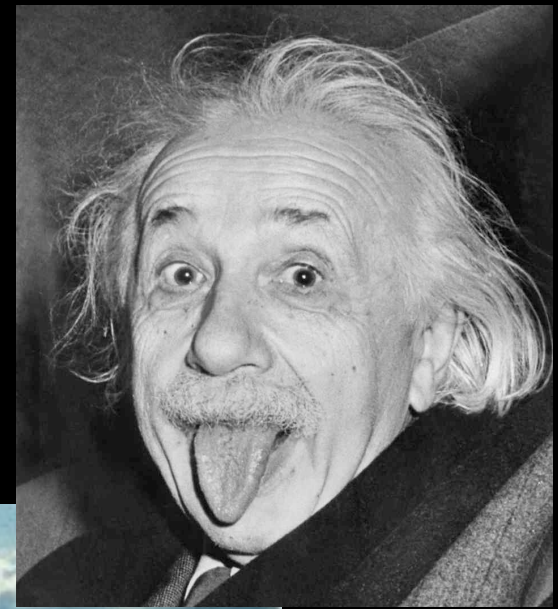
- not atoms
- not dark stars
- not even black holes
- not neutrinos
- everything “known” doesn’t work!

WIMPs

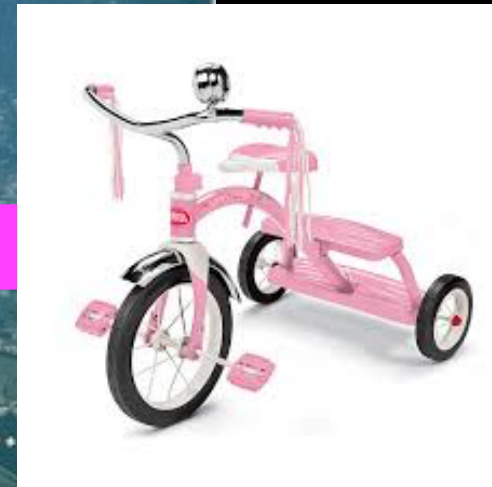
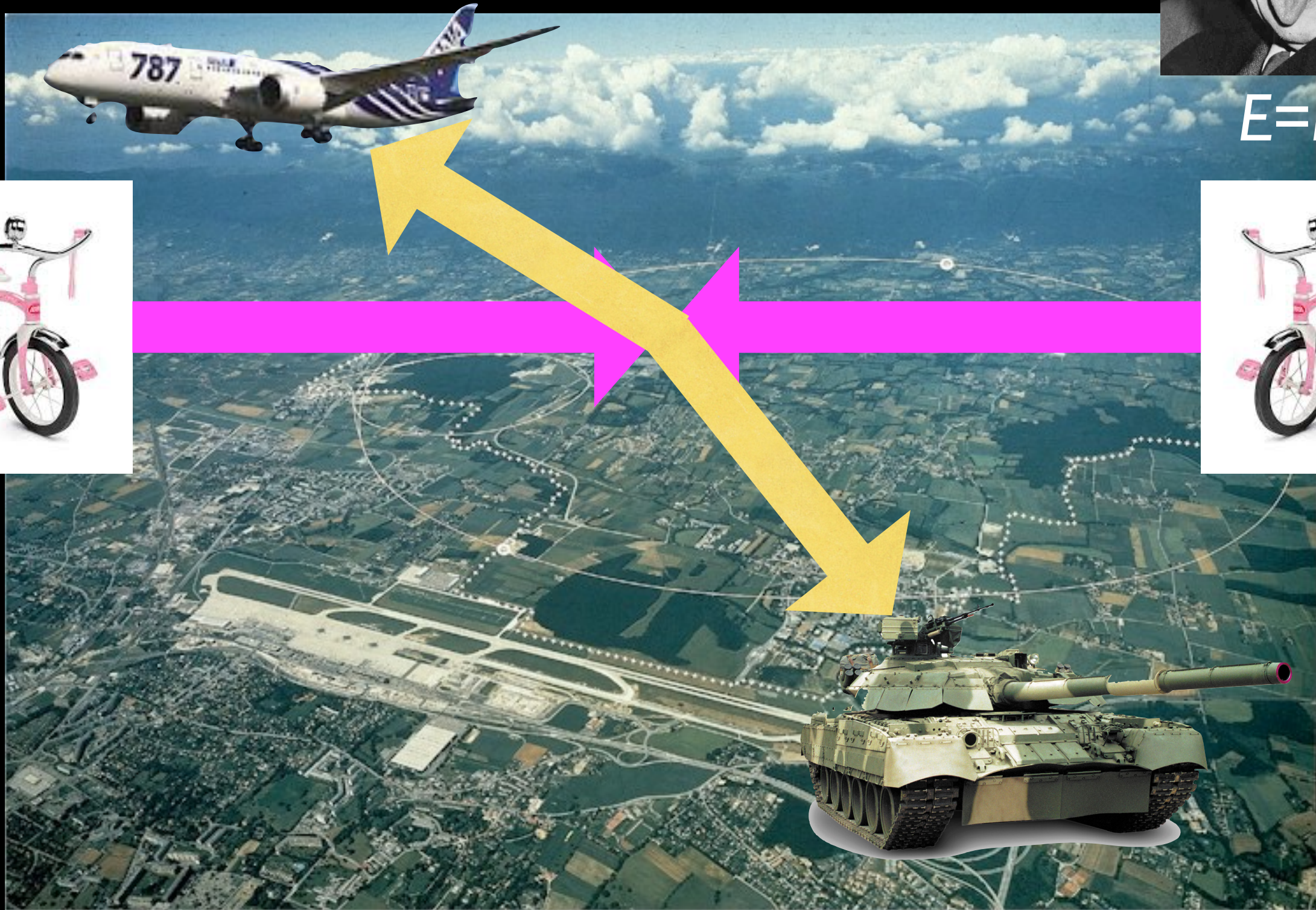


- It is probably **WIMP** (Weakly Interacting Massive Particle)
- Stable heavy particle produced in early Universe, **left-over from near-complete annihilation**

Can we make it?



$$E=mc^2$$



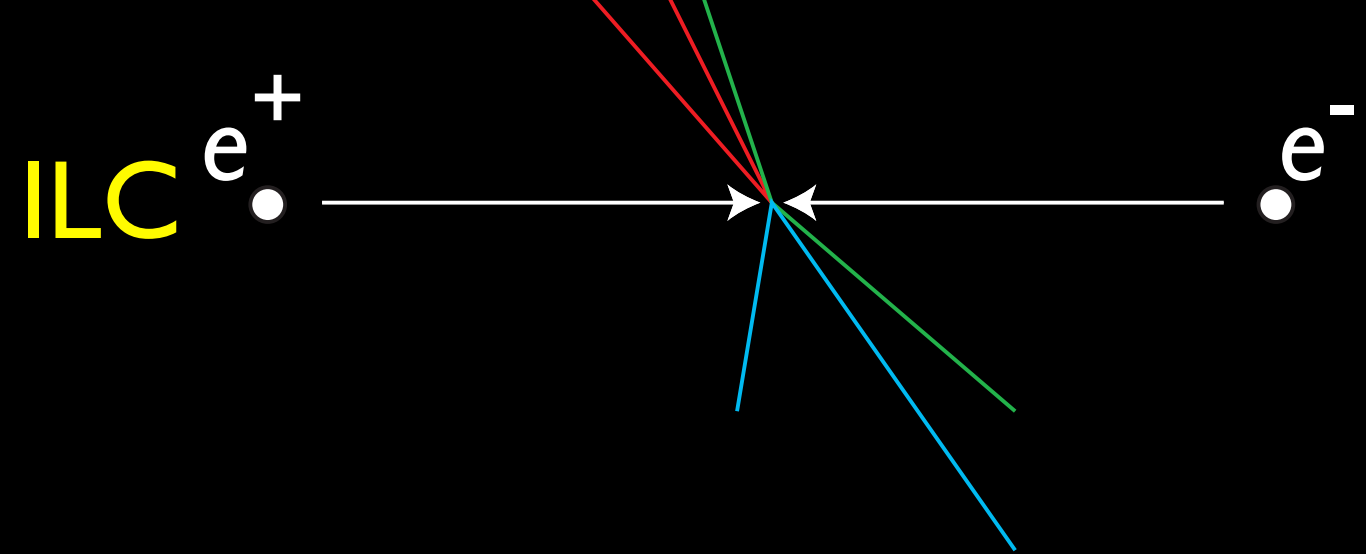
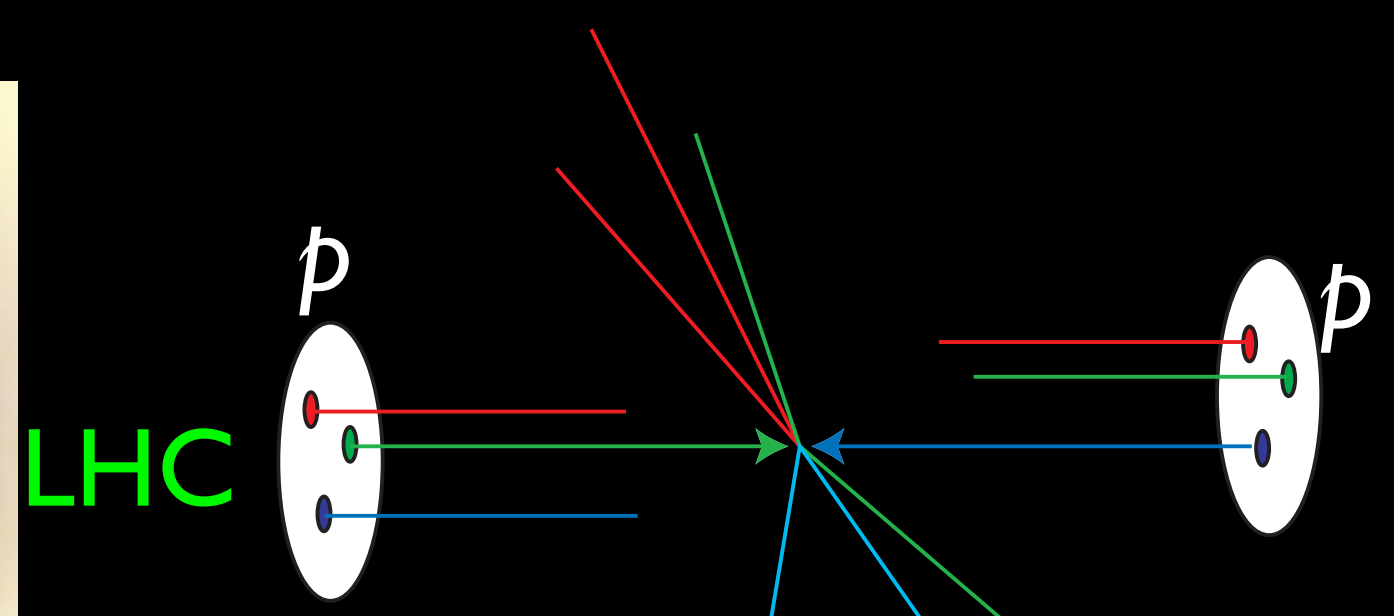
LHC

$Z \rightarrow \mu\mu$ event from 2012 data with 25 reconstructed vertices

$Z \rightarrow \mu\mu$

pick up tens out of million billions

Intl Linear Collider



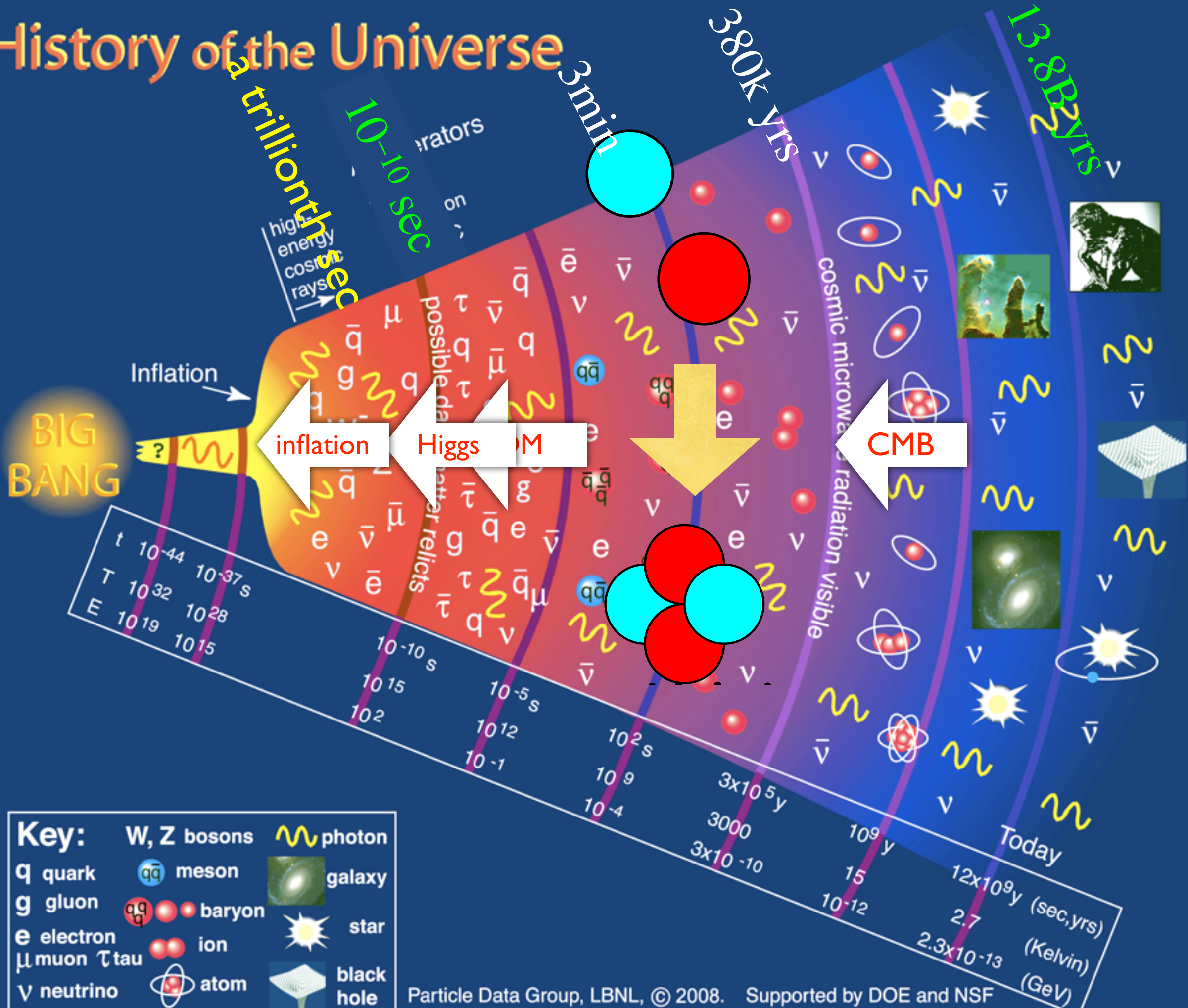


Prof. Dr. Ralf Bender



<http://sumire.ipmu.jp/pfs/intro.html>

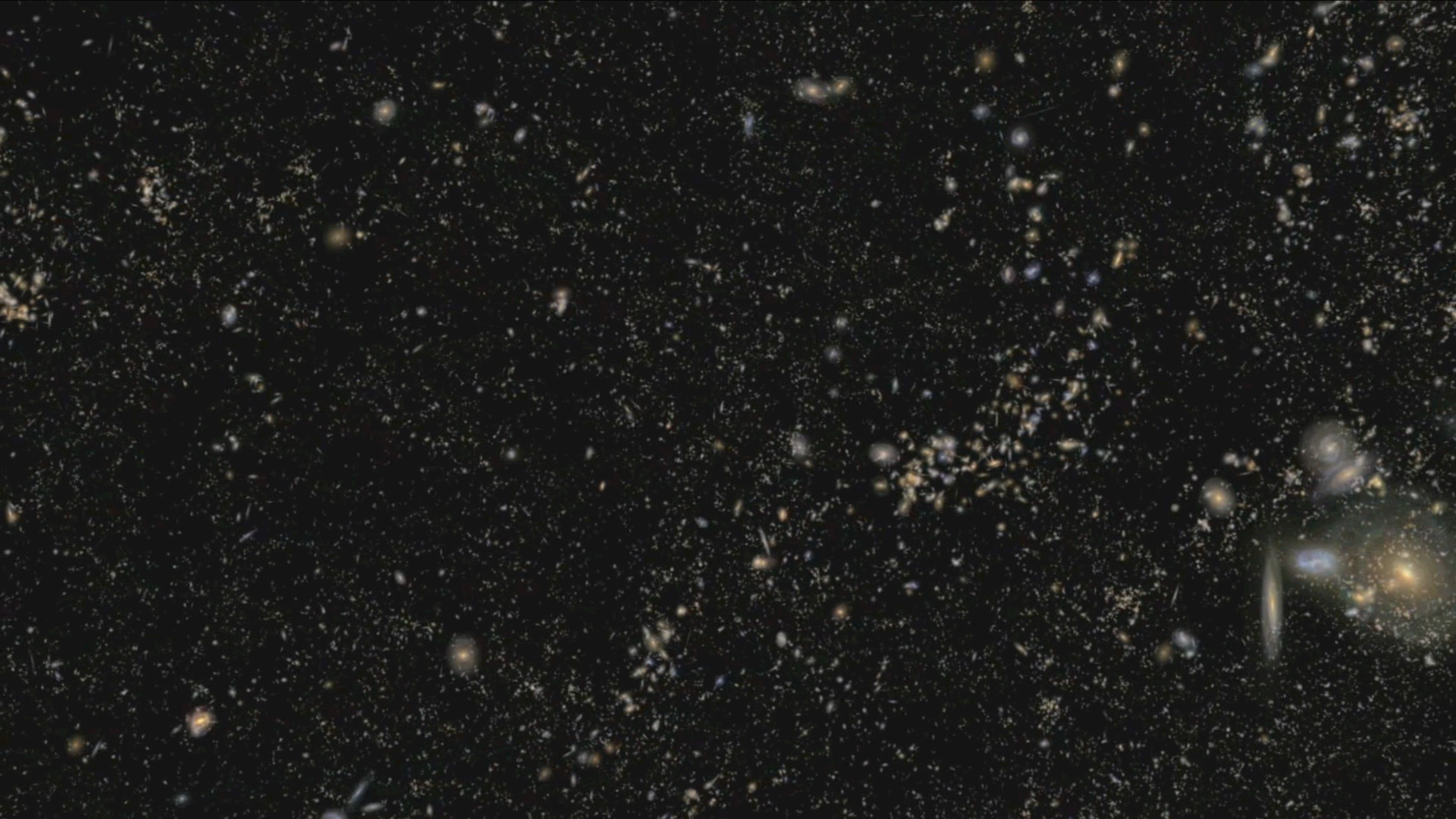
History of the Universe



A deep-field astronomical image showing a vast field of galaxies in various colors and orientations against a black background. The galaxies are scattered across the frame, with some appearing as bright, distinct points of light and others as more complex, multi-colored structures. The colors range from yellow and orange to blue and purple, indicating different types of galaxies or different stages of their evolution. The overall appearance is that of a rich, multi-colored galaxy population.

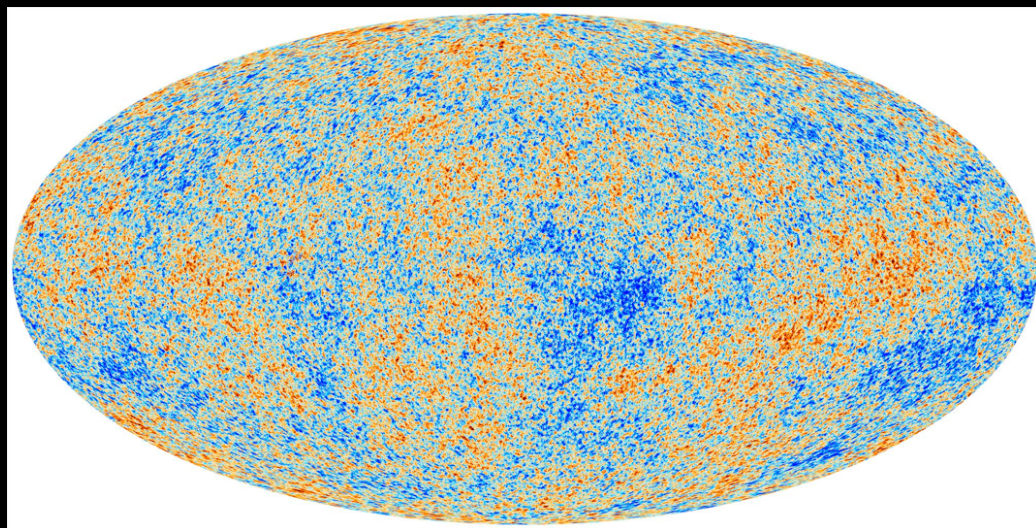
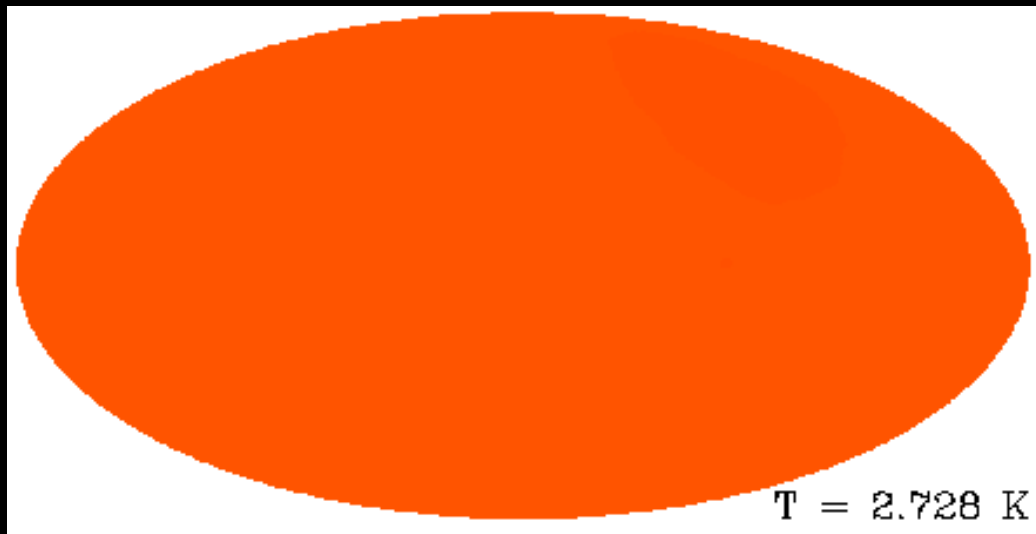
Inflation

fly-by simulation based on real data



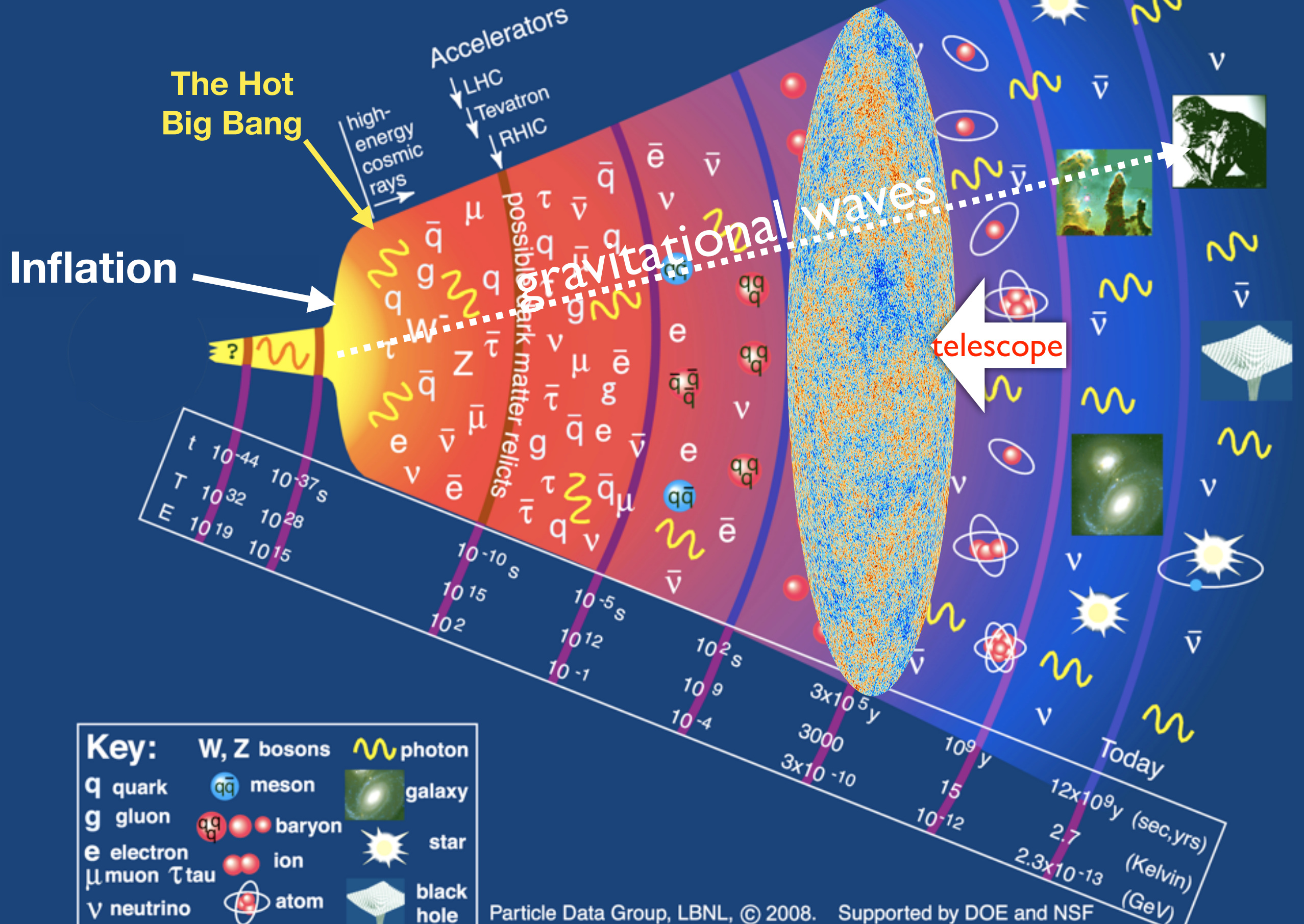
about ten trillion times faster than light
practically the same no matter how far you go

How do they know each other?

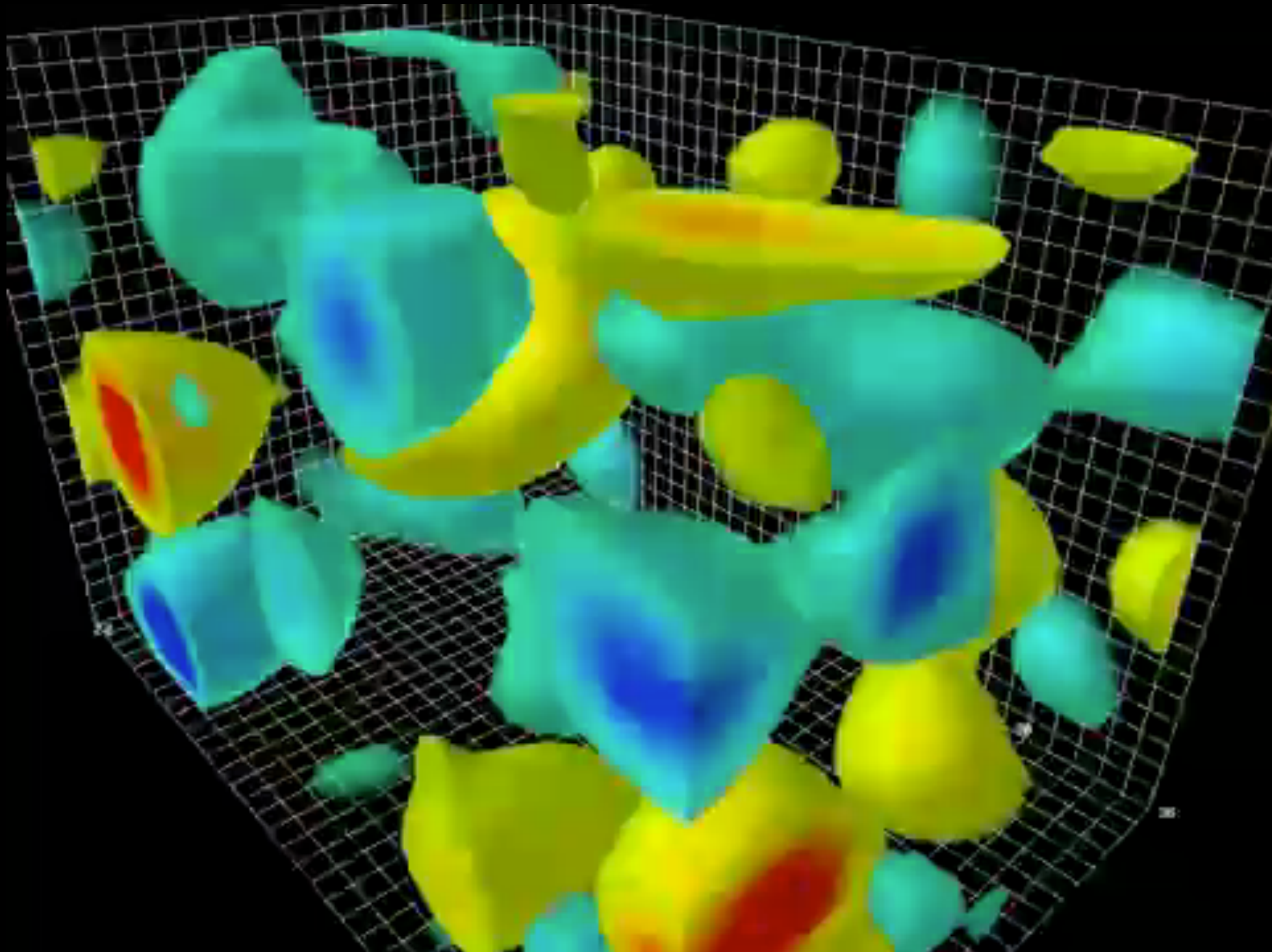


- Like having discovered two remote islands in very different parts of the world, but people speak the same language
- we suspect they were together at some point

History of the Universe

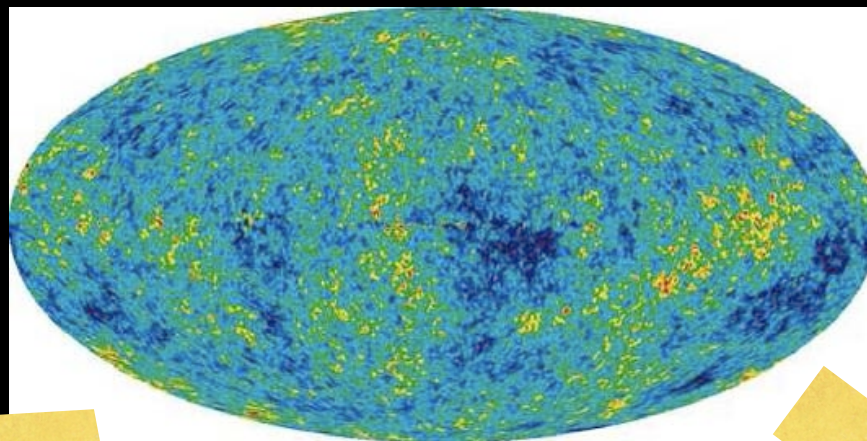


vacuum is active



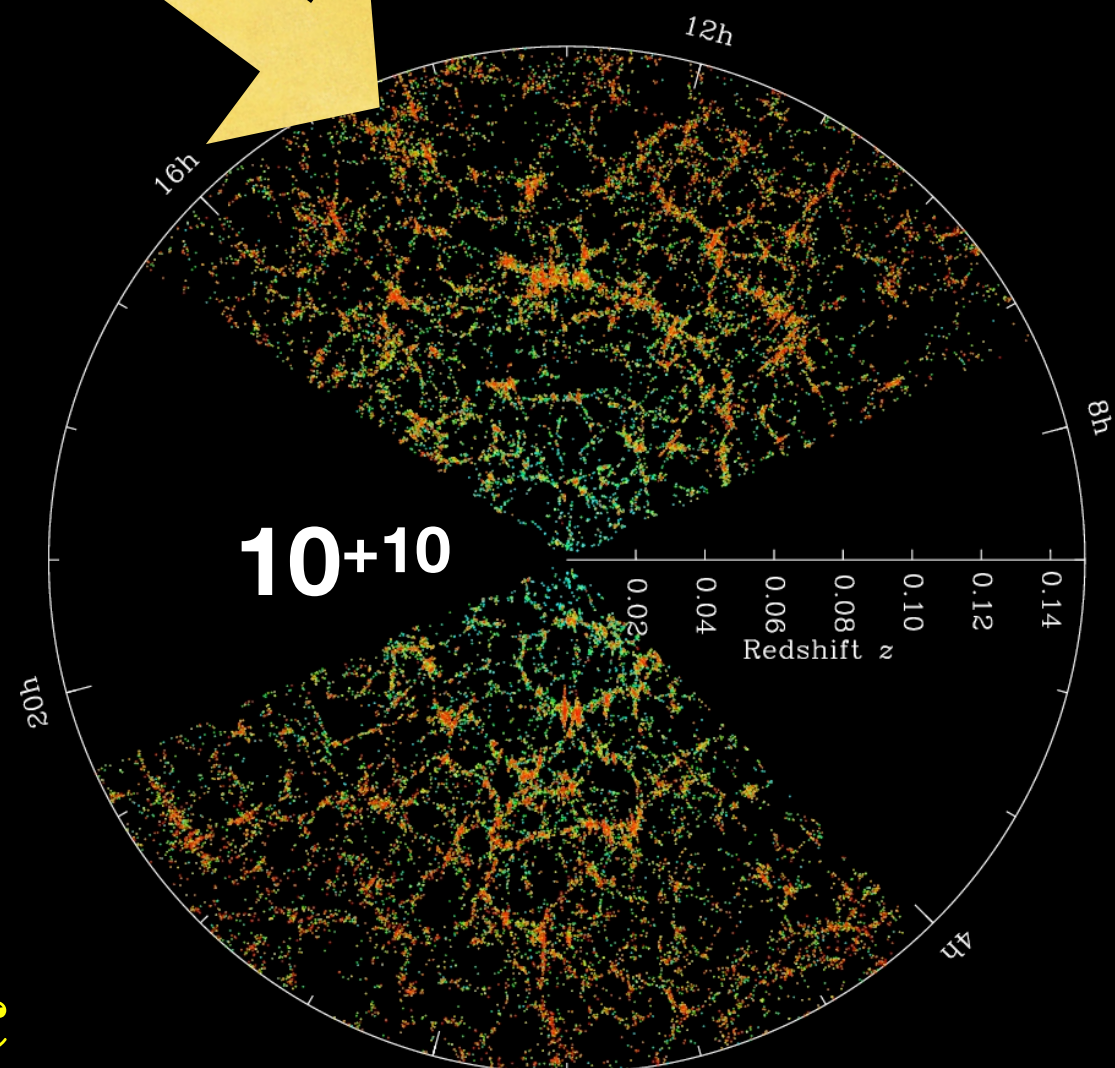
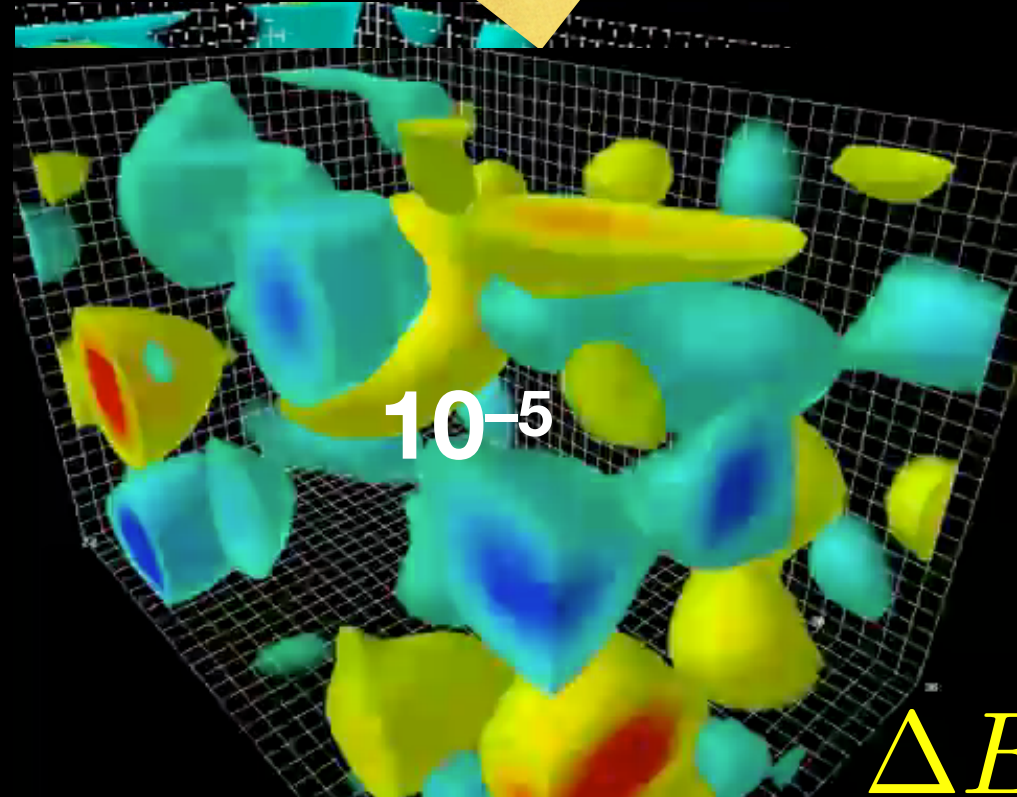
<http://www.youtube.com/watch?v=uxlOMa6pdr4>

Seeds for structure



Dark Matter

Inflation

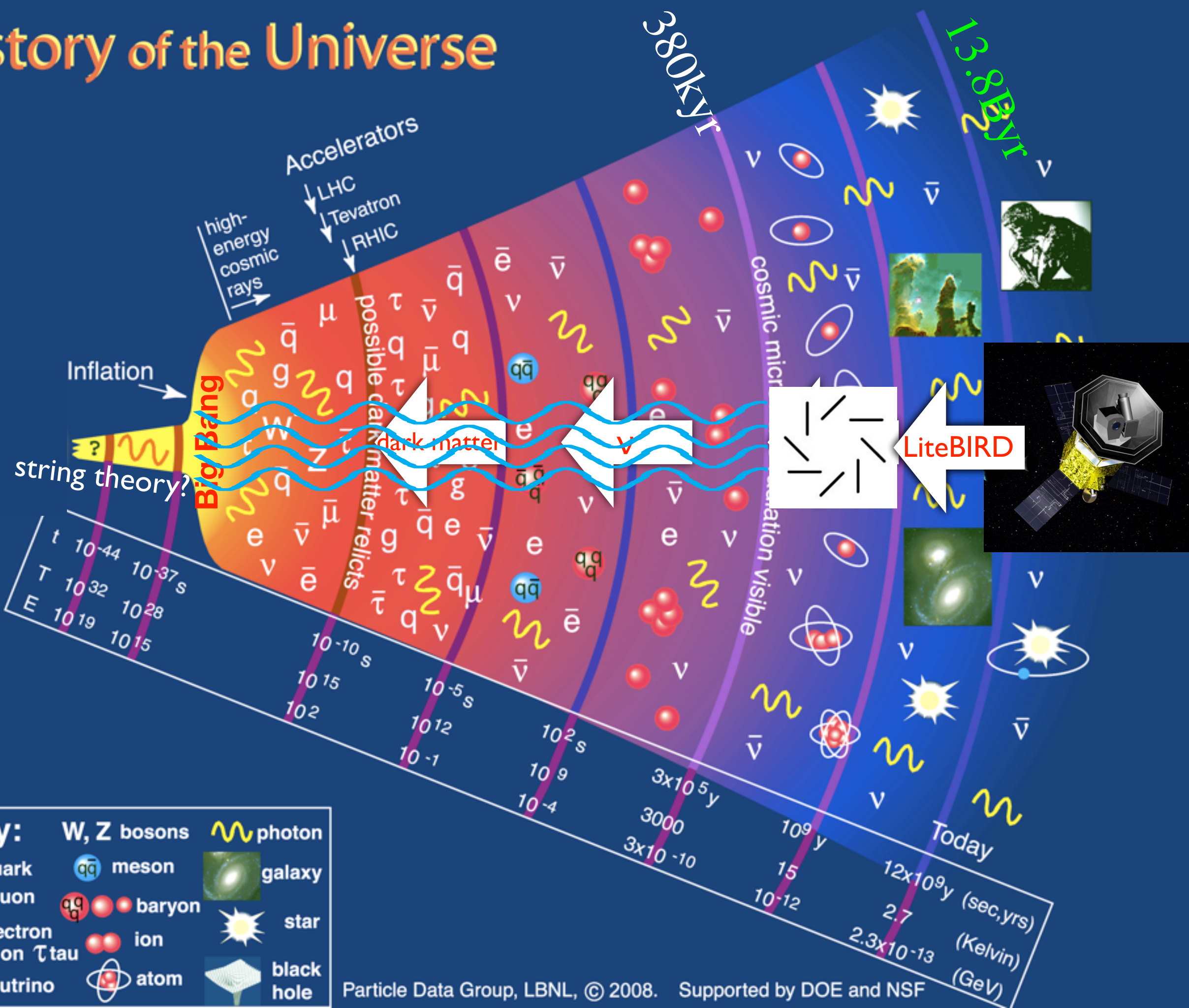


$$\Delta E \Delta x \gtrsim \hbar c$$



Inflation is Dad
Dark Matter is Mom

History of the Universe



t	10 ⁻⁴⁴	10 ⁻³⁷ s
T	10 ³²	10 ²⁸
E	10 ¹⁹	10 ¹⁵

	10 ⁻¹⁰ s	10 ⁻⁵ s	10 ² s	10 ⁹ y	10 ⁹ y	Today
	10 ¹⁵	10 ¹²	10 ⁹	3x10 ⁵ y	15	12x10 ⁹ y (sec,yrs)
	10 ²	10 ⁻¹	10 ⁻⁴	3000	10 ⁻¹²	2.7 (Kelvin)
				3x10 ⁻¹⁰		2.3x10 ⁻¹³ (GeV)

Key:

W, Z bosons		photon	
q quark		meson	
g gluon		baryon	
e electron		ion	
μ muon		τ tau	
ν neutrino		atom	
		galaxy	
		star	
		black hole	

physicists ask simple but
profound questions

How did the Universe begin?

What is its fate?

What is it made of?

What are its basic laws?

→ Where do we come from?

