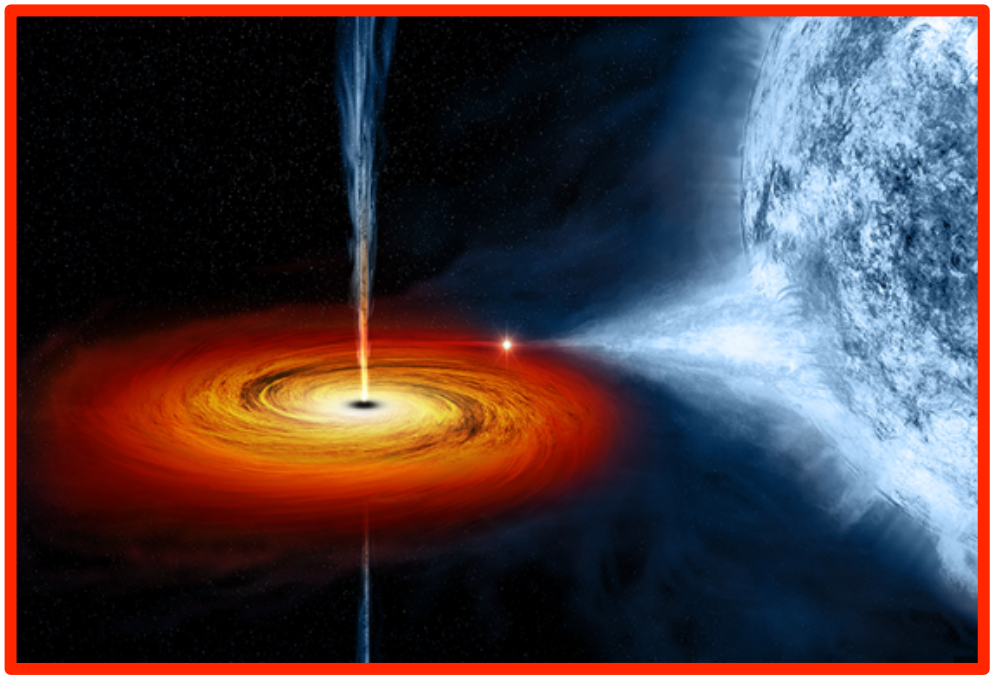
Black Holes and Gravity Waves

Michael Albrow (Fermilab)

Ask-a-Scientist
August 7th 2016



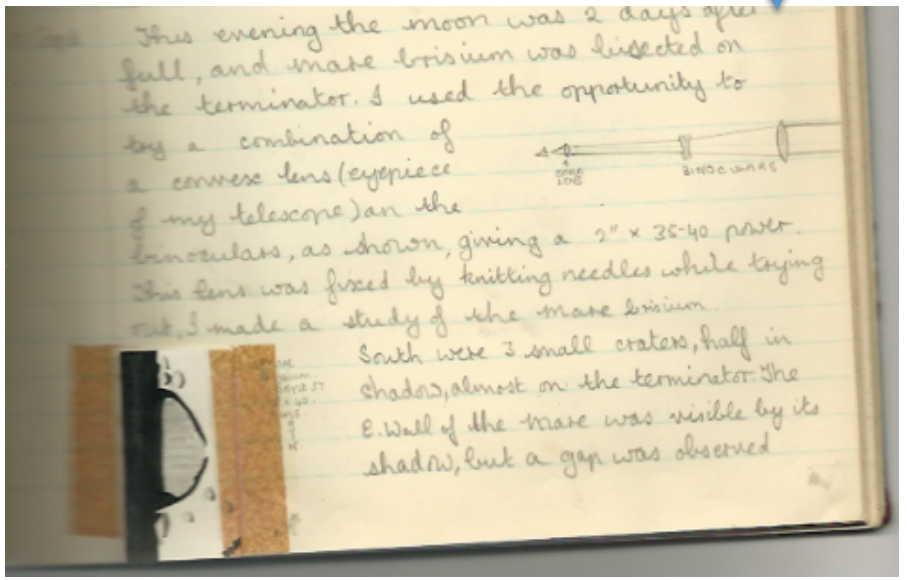
Love affair with the Moon

1946

1985 4” reflector

Same old Dad’s binoculars

1957



Story 1 & 2

Moon orbits Earth in 27.3216… days (sidereal month) … but longer seen from Sun
Distance? Elliptical orbit 364,104 km to 406,696 km :
Supermoon **perigee-syzygy** 30% brighter

Nearer to center of the Earth faster speed and shorter distance, shorter period

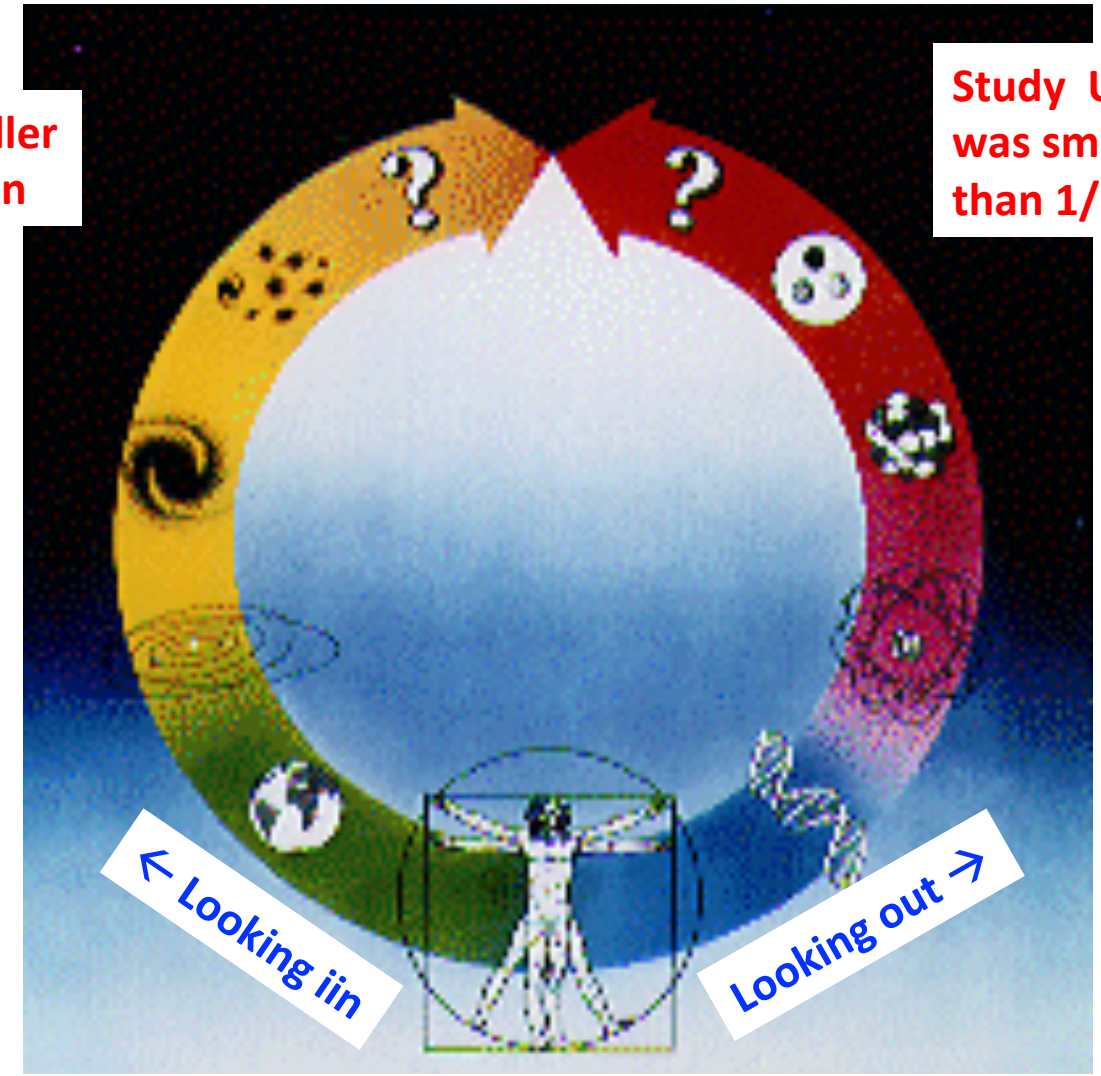
International Space Station
Orbits about every 1.5 hours

Somewhere between
These distances is a 24 - hour orbit! Goestationary

Physics of particles & physics of universe come together

We know so much, and we have many questions; it is exciting.
How can ***anyone*** leave school still thinking creation was 6000 years ago?

Study particles smaller than 1/1000th proton



Study Universe when it was smaller (?) than 1/1000th proton

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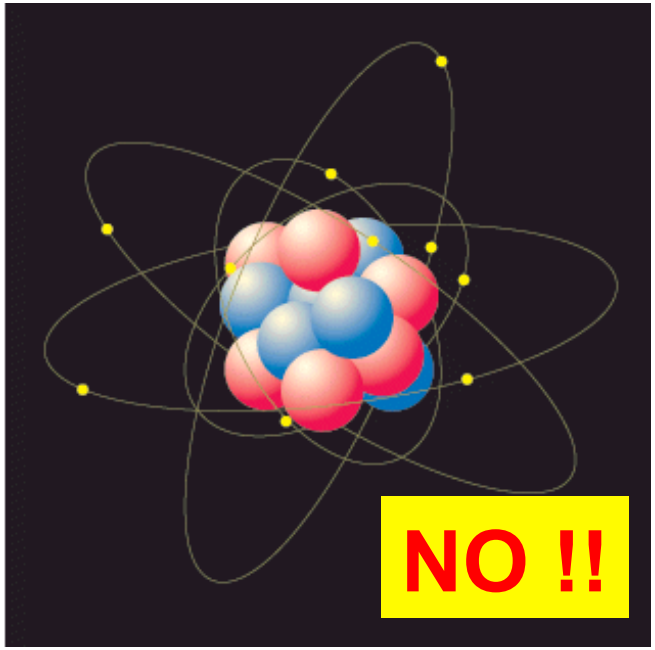
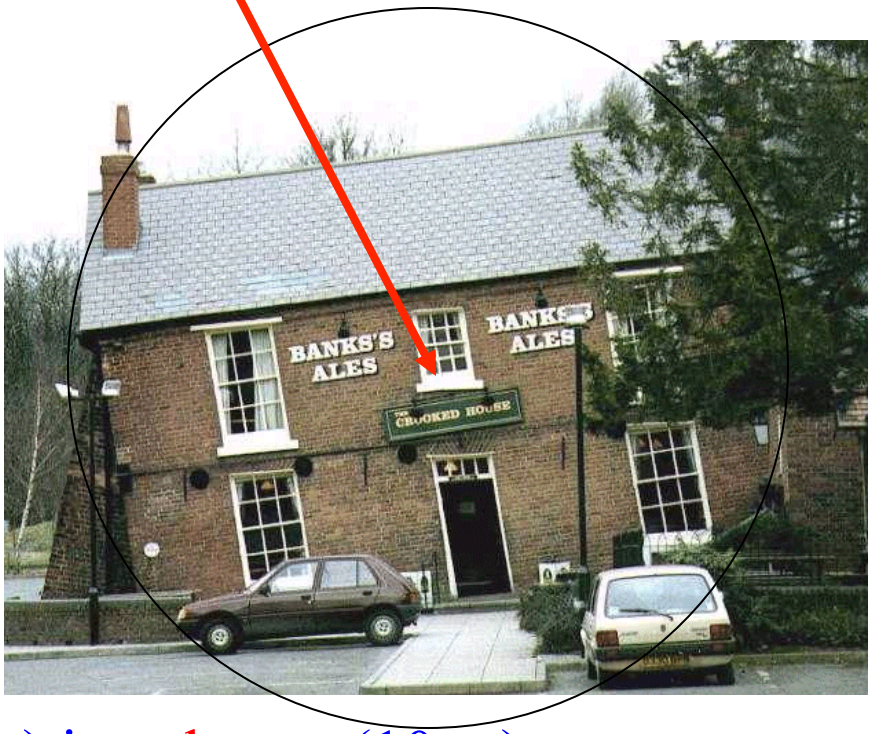
Atom with orbiting electrons.
"NASA-ESIP project for schools"



Nucleus smaller than a flea sitting on this windowsill.



Nucleus is to atom as hair (0.1 mm) is to house (10 m)

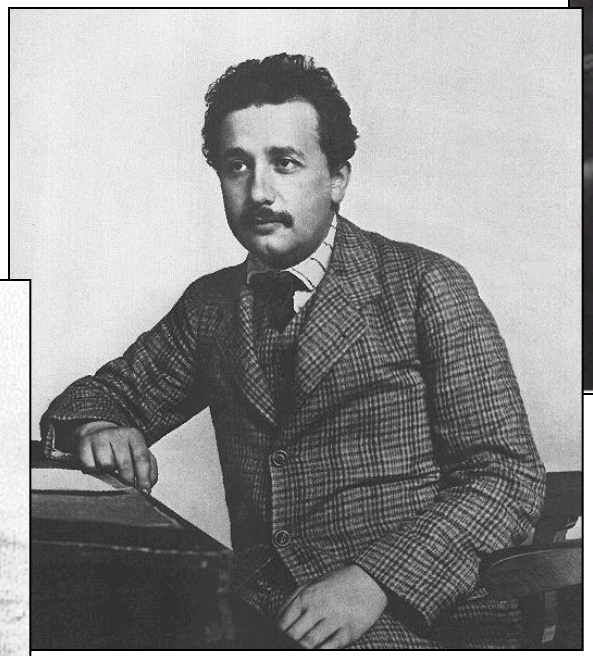
10^{-13} cm to 10^{-8} cm so factor $10^5 = 100{,}000$

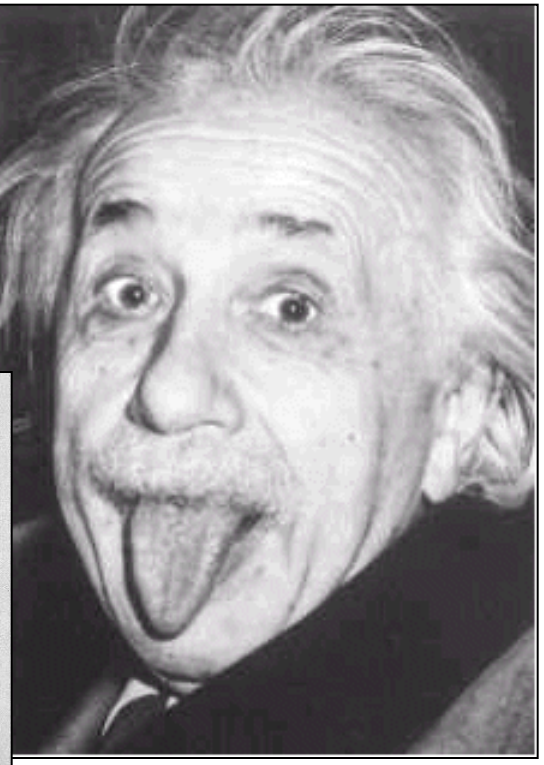
Volume ratio is $10^{15} = 100$ trillion

If squeeze Sun atoms hard enough (gravity) atoms break apart electrons + protons → neutrons, clump no spaces. **NEUTRON STAR**

Spacetime and Einstein

1905: Clerk in Patent Office





Grand Old Man!

Schoolboy

Special Relativity: One of Einstein's brilliant ideas in 1905

The speed of light is the same for everyone!

Some "unintended" consequences:

From your point of view uniformly (not accelerating) moving things seem:

Shorter
Slower
Heavier

A clock in an Earth satellite seems to run a bit slower GPS!

But the speeds have to be very big to make much difference.
You can go faster and faster but never ever reach the speed of light!
Protons in Tevatron 0.9999995 c and in LHC speed = 0.9999999 c

General Relativity: Even more brilliant idea out in 1915

Acceleration and Gravity are almost the same thing

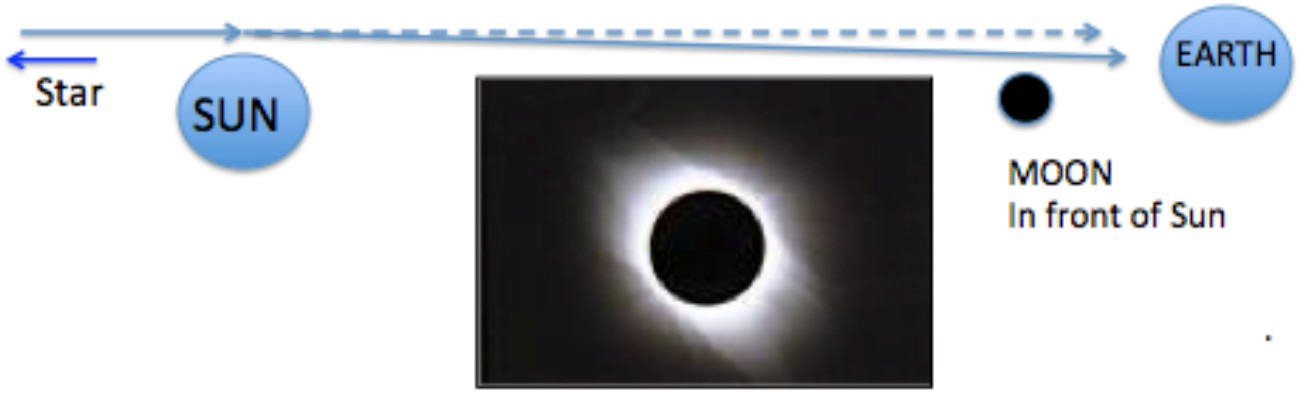
Indistinguishable elevators in space and on ground

Space and Time "Spacetime" gets bend by mass

General Relativity

>> Correctly accounted for tiny effect on Mercury's orbit (no Vulcan!)

>> Predicted bending of light by gravitational field
Want big mass M and small distance R and long lever arm
Stars behind Sun in solar eclipse? May 1919 expedition



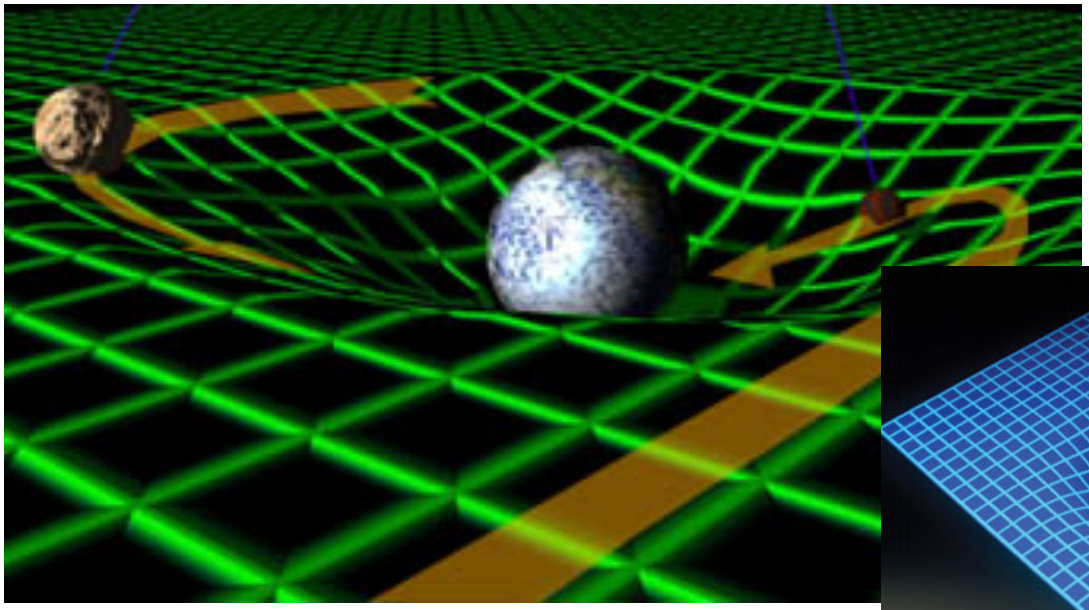
Photographs of stars near Sun showed tiny shifts out from normal
Sun something like a lens : Gravitational lens. (not concave or convex)

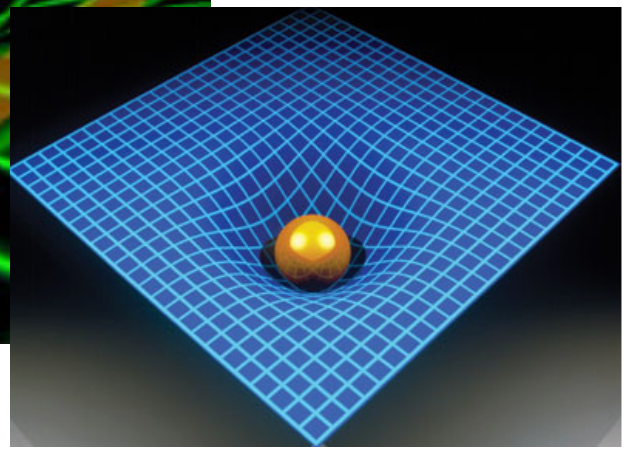
>> Predicted clocks in a stronger gravitational field or more acceleration run slower
Correction needed to GPS satellite timing (another, in opposite direction!)

Find your way by SAT NAV , GPS? Practical application of General Relativity!

Space & time are bent, or curved, by matter.

Moon orbiting around Earth's gravity well (not to scale!)
Asteroid being pulled out of its path to kill the dinosaurs





This is gravity.

Planets, moons and baseballs go
"as straight as they can, not in space but in spacetime"

Spacetime is bent by matter : gravitational lensing

Same Galaxy way behind
Massive cluster of galaxies
Light bent

See two images of same galaxy

Black Hole Masses and Sizes

Metric : Mass in **kg**, space/distance in meters **m** (or **cm** or mm), time in seconds **s**

You too can calculate using this simple formula: **$R = 2GM/R^2$**

Radius (km) = 2 . G . Mass (kg) / c^2 (I can use " . " to mean x to keep clean)

c = speed of light = 300,000 km/sec = 3 x 10^8 m/s → So c^2 = 9 x 10^{16} m^2/s^2

G = Gravitational constant = 6.674 x 10^{-11} m^3 kg^{-1} s^{-2} … KISS say 7.10^{11}
Ask Siri : M(Earth) is about 6 x 10^{24} kg

Just plug in numbers! And check dimensions:

$$R(m) = \frac{2 \cdot 7 \cdot 10^{-11}\ m^3\ kg^{-1}\ s^{-2} \cdot 6 \cdot 10^{24}\ kg}{9 \times 10^{16}\ m^2\ s^{-2}}$$

indeed RHS is m.

= [2 . 7 . 6 / 9] x $10^{[13-16]}$ = 3.1 10^{-3} m that is about **3 mm**

Other interesting masses, just scale by mass:
M(sun) = 2 . 10^{30} kg so Sun/Earth = 2.10^{30} / 6.10^{24} = 1/3 x 10^6 so R(SunBH) = 1 km
M(30 solar mass BH) R = 30 km
M(5 billion tons ~ big mountain ~ 5.10^{12} kg) → R = 10^{-13} cm (Size of proton)

Black Hole Masses and Sizes

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R (Earth as Black Hole) about **3 mm**

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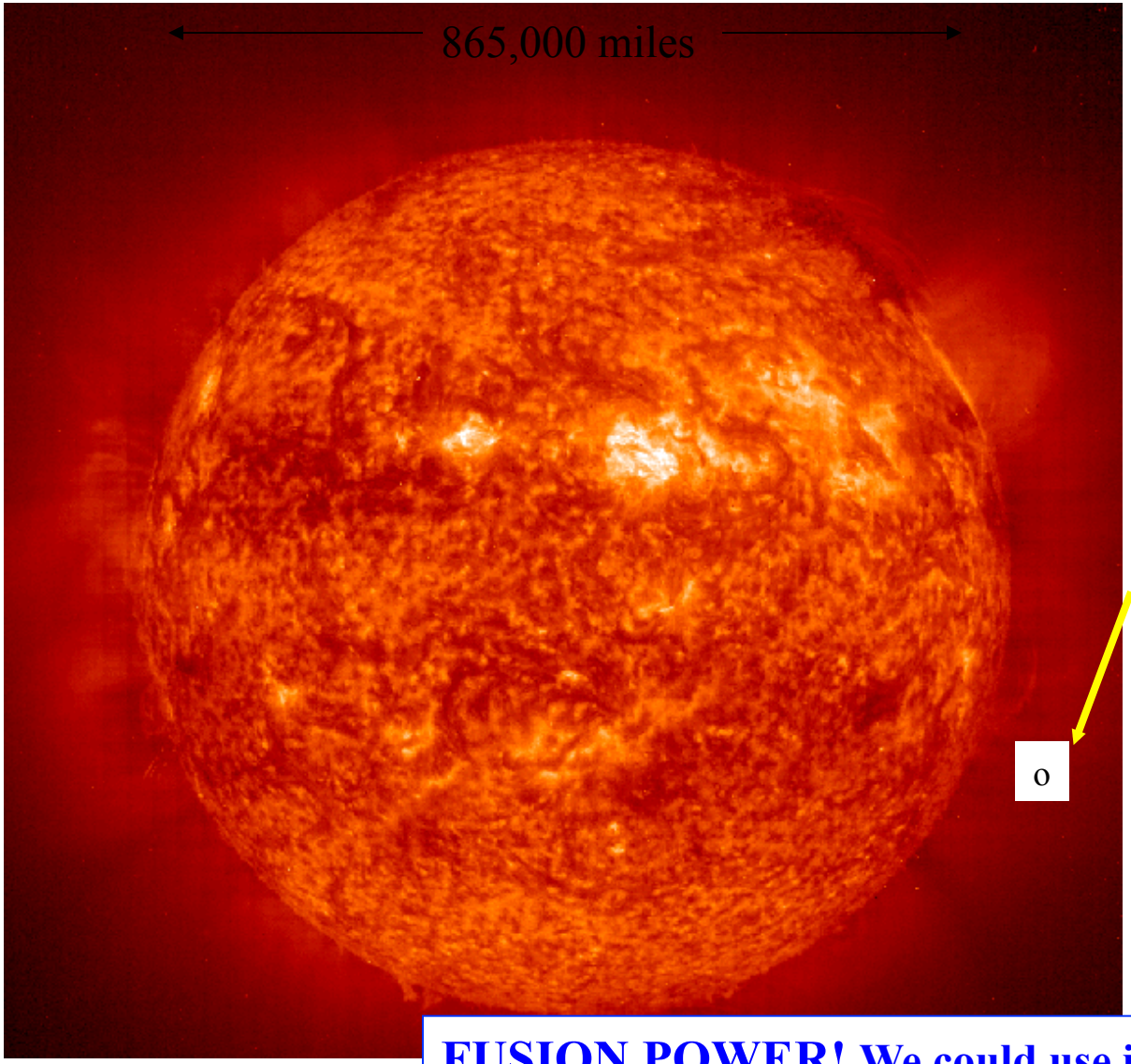
Imagine squashing the Earth

Earth circumference = 40,000 km (old definition of km, easy to remember)
So radius = 40,000 / 2π = 6366 km
As radius (atom's nucleus) = 10^{-5} or 0.00001 x atom,
squashed Earth to giant nucleus radius = 63.66 m across (compare to Fermilab High Rise!)

R (Earth as Black Hole) about **3 mm**

Probably we will need (clean) energy. (Hydrogen as auto fuel is **not** clean)



FUSION POWER! We could use it!
But Tokamak (d-t) is NOT the same reaction.
Center of Sun ~ 150Tons at 13M^{o} → ~50W/m^{3}!

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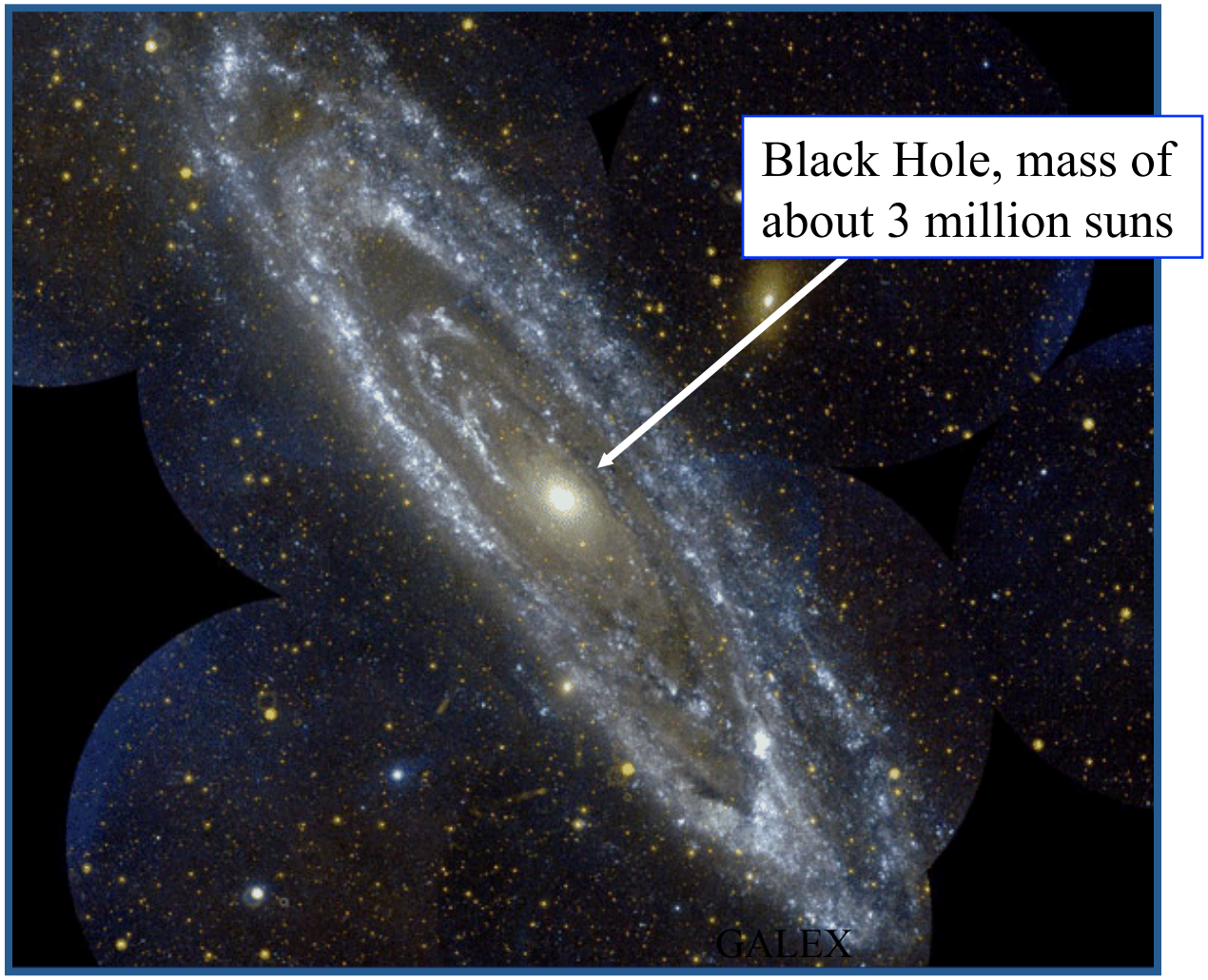
Andromeda Galaxy (like ours) in Ultraviolet --- 3 million light years away!



Stars orbiting around center. Orbit speed → How much matter inside
→ about 5 x more than stars, dust, gas, planets.

Dark Matter (Zwicky, Vera Rubin)

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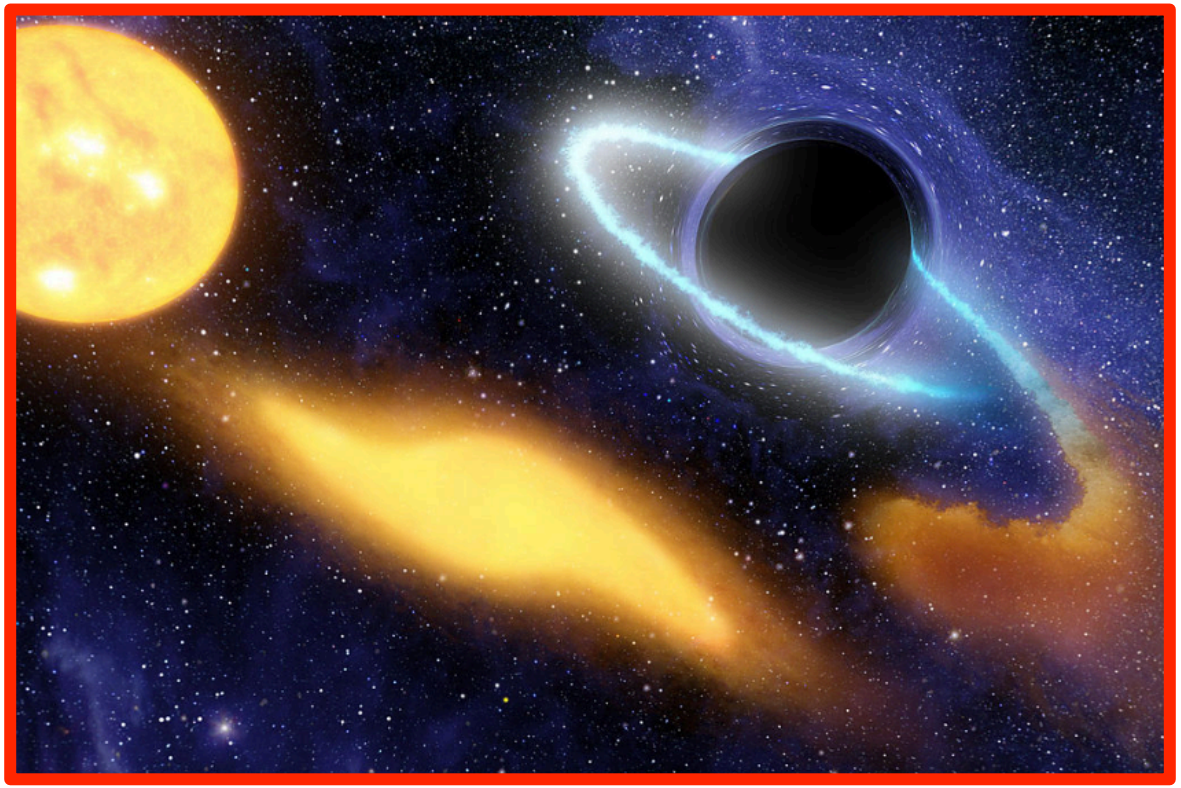
Supermassive Black Holes

At the center of most, if not all, spiral galaxies we think there is a black hole with a mass maybe 10 million x mass of the Sun (big range: 10^5 – 10^9 Ms



When gas, dust, stars, planets get too close:
Goodbye for ever!

But density is low:
Radius grows like mass
Volume grows like $R^3 = M^3$

So density can be low and tidal forces low outside Radius

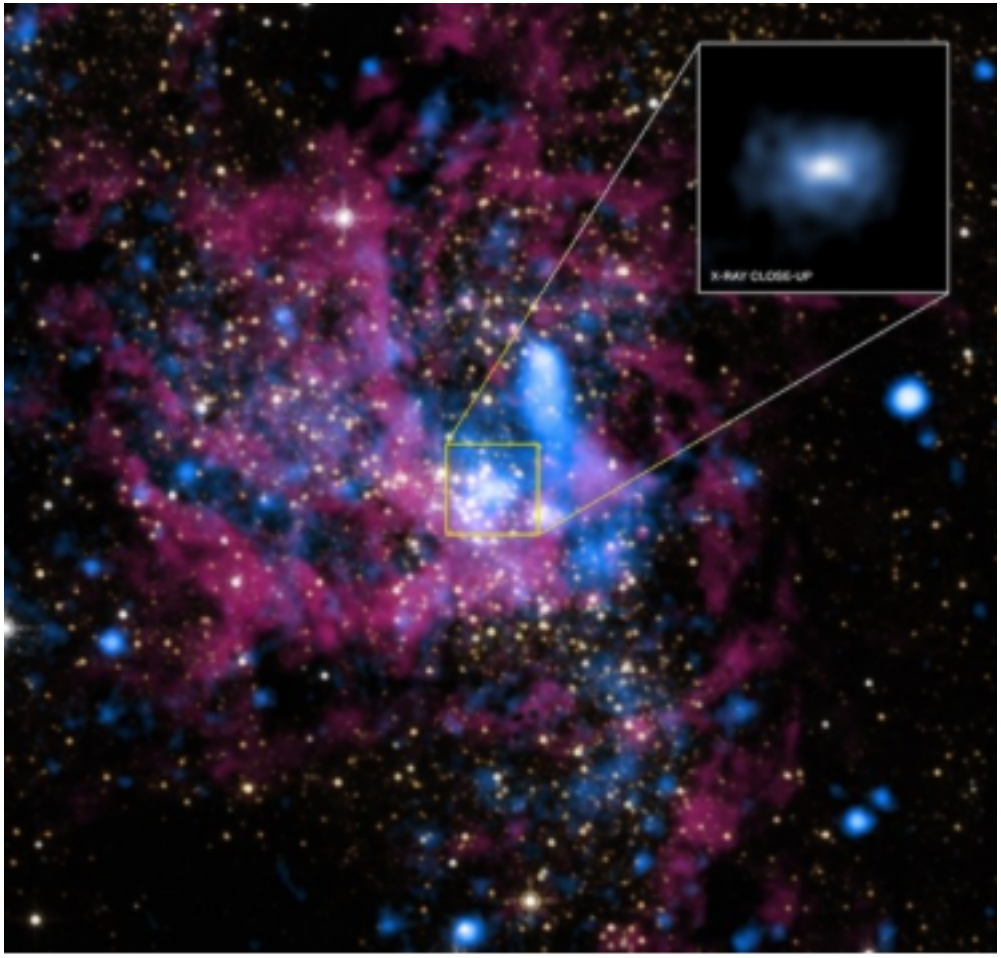
A star (and planets? Life?)
Gets close, stretched apart
and swirls in : light and UV flashes

Artist's impression OF COURSE!
Rotating … movie?

https://en.wikipedia.org/wiki/Supermassive_black_hole

Two black holes we know and love (but have never seen!)

At the center of our Milky Way galaxy in the constellation Sagittarius, see emissions.



Sagittarius A in infrared (red and yellow, from the Hubble Space Telescope) and X-ray (blue, from the Chandra space telescope). Credit: X-ray: NASA/UMass/D.Wang et al., IR: NASA/STScI

M(BH) 14.8 Msun so R ~ 44 km
Blue giant star at 0.2 AU
Orbit period = 5.599829 days
Discovered as X-ray (brightest in sky) 1964

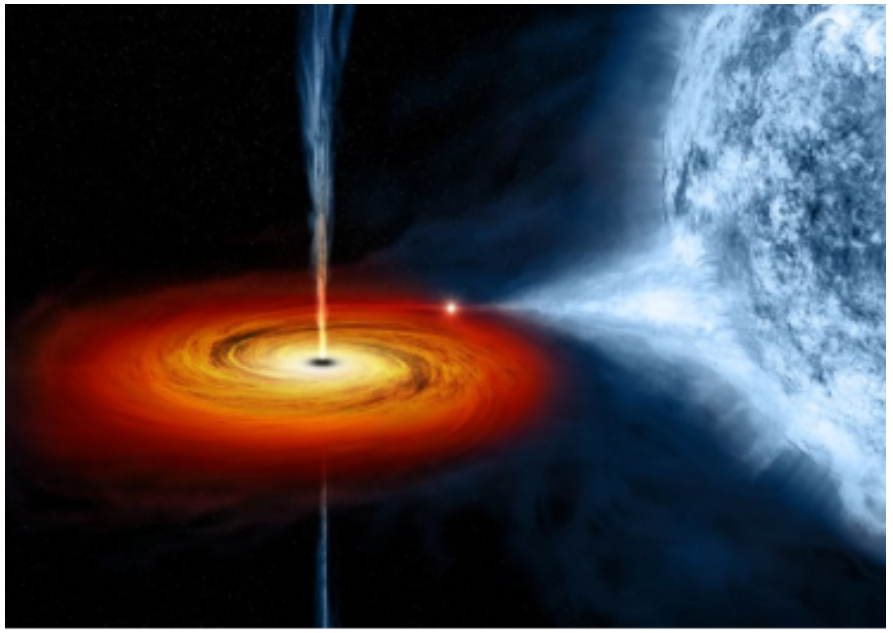
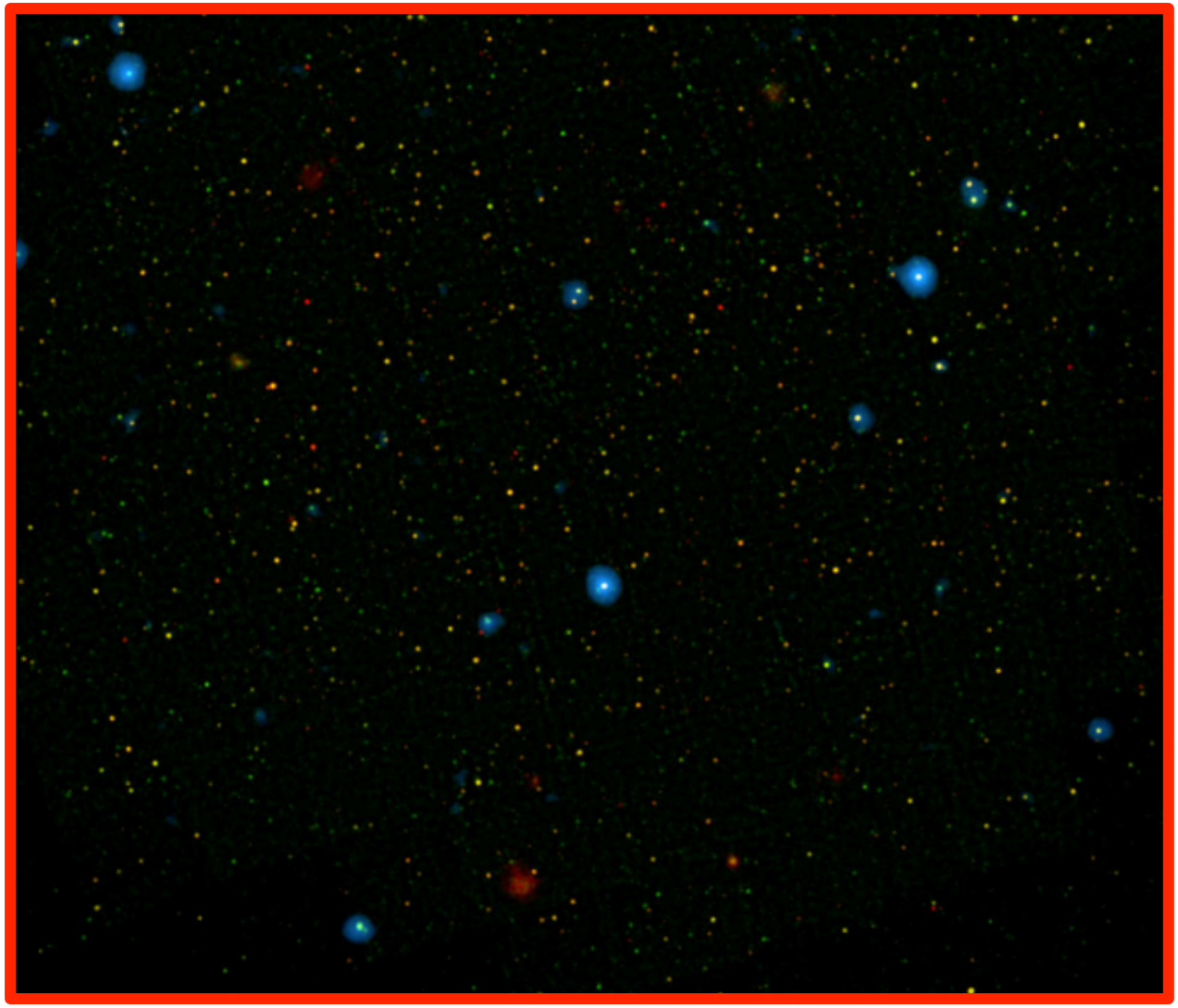


Illustration of Cygnus X-1, another stellar-mass black hole located 6070 ly away. Credit: NASA/CXC/M.Weiss

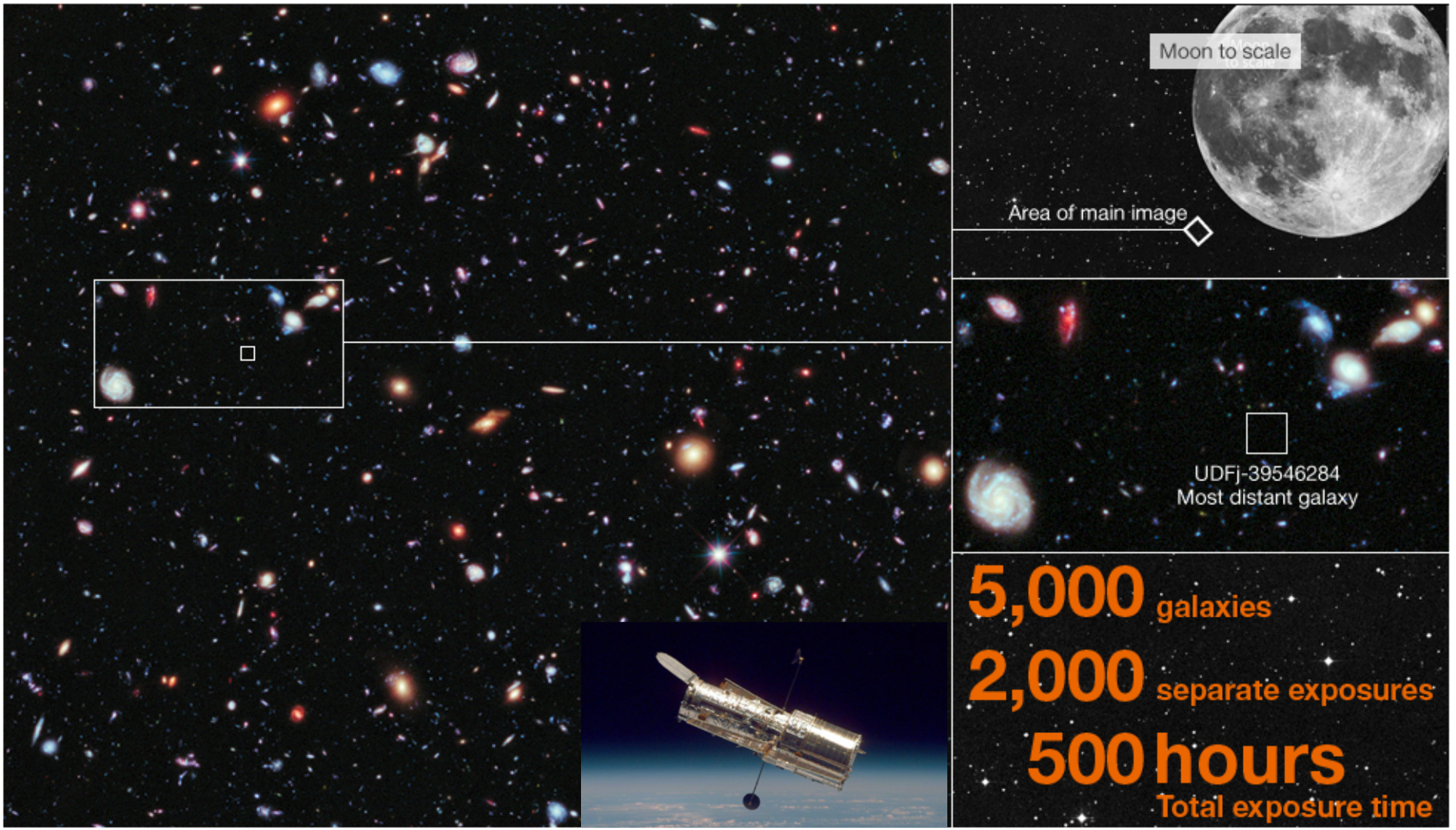
It flickers in X-rays on a millisecond time scale

It's a wild wild world up there, out there, way back when!



NASA's NuStAr : Nuclear Spectroscopic Array COSMOS field Check out nasa.gov and APOD
Blue dots: Galaxies containing SMBH emitting high energy X-rays 8 – 24 keV
Other colored dots: Galaxies emitting lower energy X-rays 0.5 – 7 keV

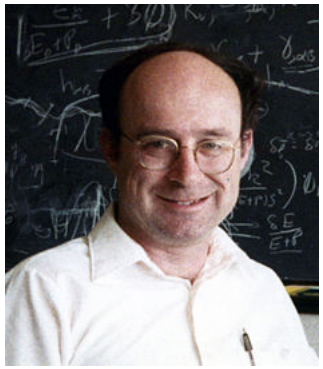
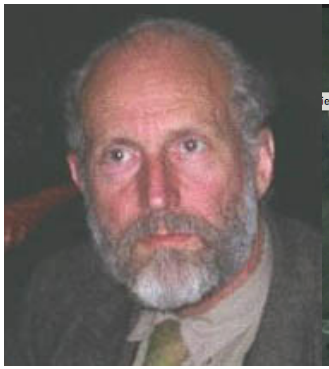
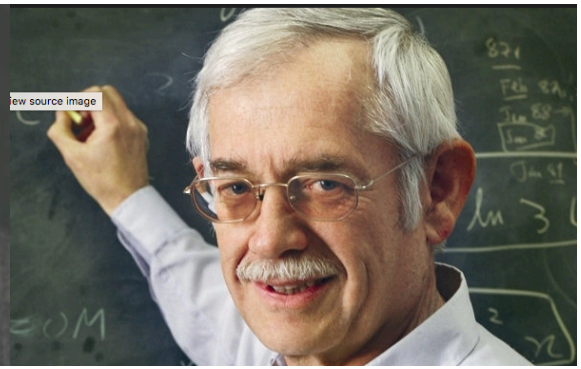
Hubble captures extraordinary view of Universe



If done over whole sky about 100,000,000,000 galaxies in visible light, long long ago!

Black holes (we think) have only 3 properties : **MASS, CHARGE** and **SPIN**
Charge = Electric charge (probably almost none, but … it is a long-range force)
Make it out of gold or diamonds or mud, or antimatter ::: identical (from outside!)
Not 100% sure if at center (if you go in!) spacetime curvature becomes infinite
(a singularity) or not, because we do not know about spacetime at the very smallest scales:
No quantum theory of gravity : Homework for you kids!
Is the core (if any) of a matter-made BH different from an antimatter-made BH?

Are black holes really black? Do they glow as if hot?
According to Stephen Hawking, Jim Bardeen, Brandon Carter, (Jacob Bekenstein …)

Black holes have a temperature T and radiate like a black body : but from the outside.
Smaller (= less massive) == hotter
Radiate, lose energy = mass, get still hotter! Radiate faster! Explode in flash of gamma-rays!
Observation /discovery of exploding BH →likely Nobel for HBC **BUT IS IT TRUE?**
(but Bardeen's dad already got two physics NP !! **Superconductivity and transistor**

Suppose it is true that BH have temperature:

$$T(BH) = \frac{\hbar . c^3}{8\pi\, G . M . k_B}$$

They are in a bath with temperature > = the microwave background from the big bang.
That is 2.7 K, so if BH is colder it will absorb radiation not be a net emitter.
So it will grow in mass and get colder!

BH with T = 2.7 K has M = 2.82 10^{23} kg
BH with T = 27,000 K has M = 28 10^{23} tons

Catch one (!) and throw garbage into it to keep it at that temperature
All you garbage mass converted to energy 100%

EXPLODING BH

Solve the Energy problem for ever!

A *tiny* spot from the Hubble Space Telescope

Every blob is a galaxy with ~100,000,000,000 stars.

All are rushing away from us,

RED SHIFT . . . expanding Universe!

Dr. Hubble (Wheaton) discovered that.

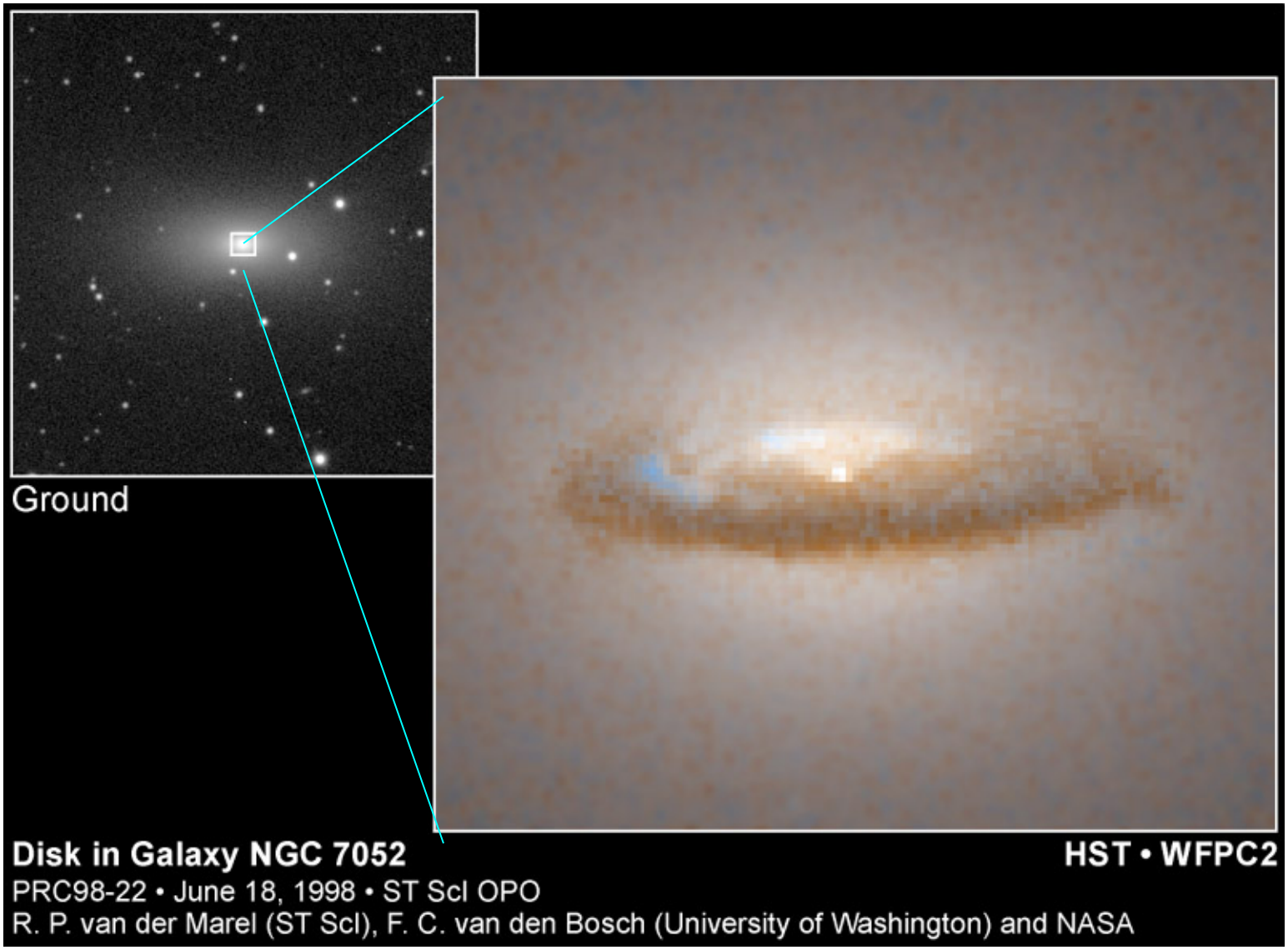
13.5 billion years ago

But not BIG, TINY!

Much smaller than a proton,
then inflated to "baseball" (?)

BIG BANG !!

Hubble sees dust disk around a massive black hole



First claim to have discovered gravitational waves
Joseph Weber, Univ., Maryland

AIP Emilio Segrè Visual Archives

Solid aluminum cylinders 2m long
Suspended on wires. 1660 Hz ringing frequency
Piezoelectric crystals to detect tiny vibrations.

1969 :Claimed some coincidence "kicks"
between Argonne – Maryland, published Phys Rev Lett.

1970 claimed 311 "events" in7 months coming from center of Milky Way. WOW!

Others tried to reproduce and did not, this was wrong!!

Weber was not trained as a physicist but
an electrical engineer … but physicists can be wrong too!

VERY HIGH STANDARDS REQUIRED

Cold fusion

Claimed by chemists

etc. etc.

X(750)

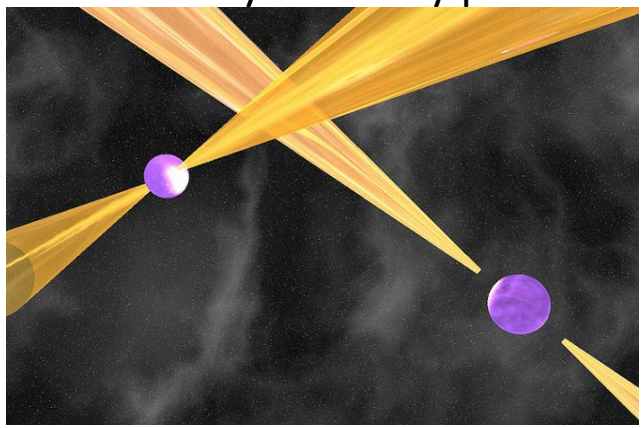
Not claimed by expts
at LHC … but huge interest!

Crab pulsar : A neutron star binary in the Crab Nebula

First evidence for Gravity Waves (but did not detect them, that's OK)

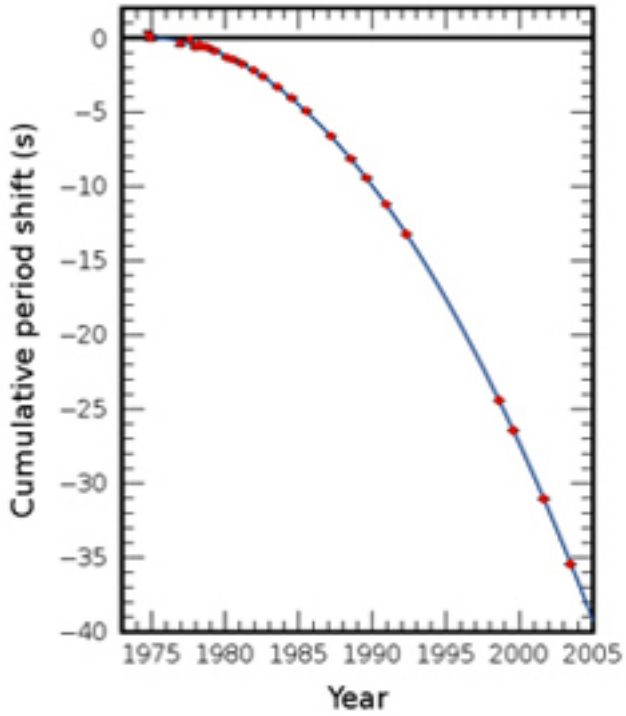
Hulse and Taylor
1993 Nobel Prize

Hulse-Taylor Binary pulsar



Artist's impression of orbiting pulsars (compact neutron stars)
One radio beam sweeps across earth every

1974
Arecibo



LIGO: Laser Interferometer Gravitational-Wave Observatory

Long history, many people, setbacks etc.
Approved by NSF 1990
Here are some of the leaders (NP 2017?)

Rainer Weiss
1967 created laser interferometer with minimal noise

Kip Thorne
1968 + CalTech research group

(Misner, Thorne, and Wheeler)

Ron Drever
1979 Glasgow - CalTech

Hanford, Washington State

The two LIGO sites

Each has two lasers 4 km long
At 90^{o}
Light reflected back

Livingston, Louisiana

LIGO : Very high precision, super clean apparatus

Restarted last September after improvements. Will be further improved

Stretching and compression of the 4km long arms by an amount 10^{-18} m

Which is about 1/1000th the size of a proton **!!!**

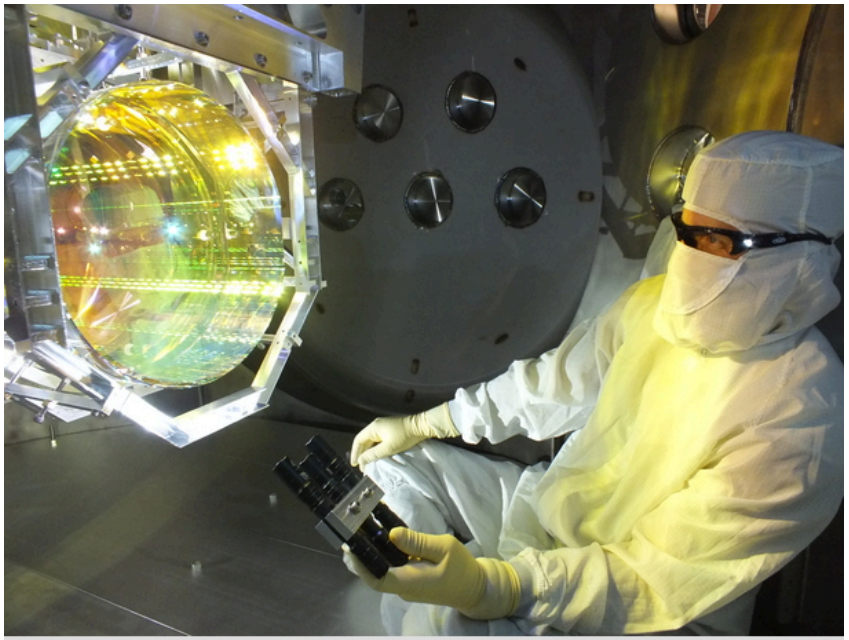
Impossible ? It helps to have about 10^{16} atoms per cm^2 on the mirror

In a central building

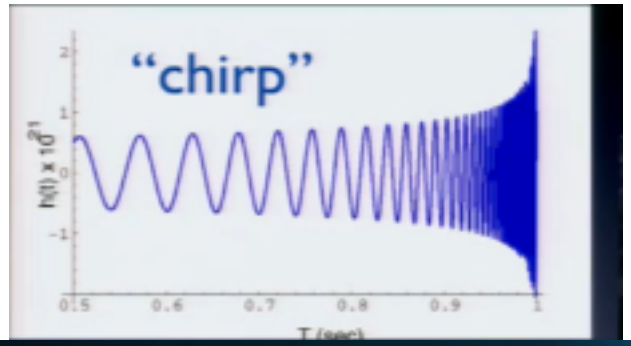
LIGO Hanford laser and vacuum equipment area

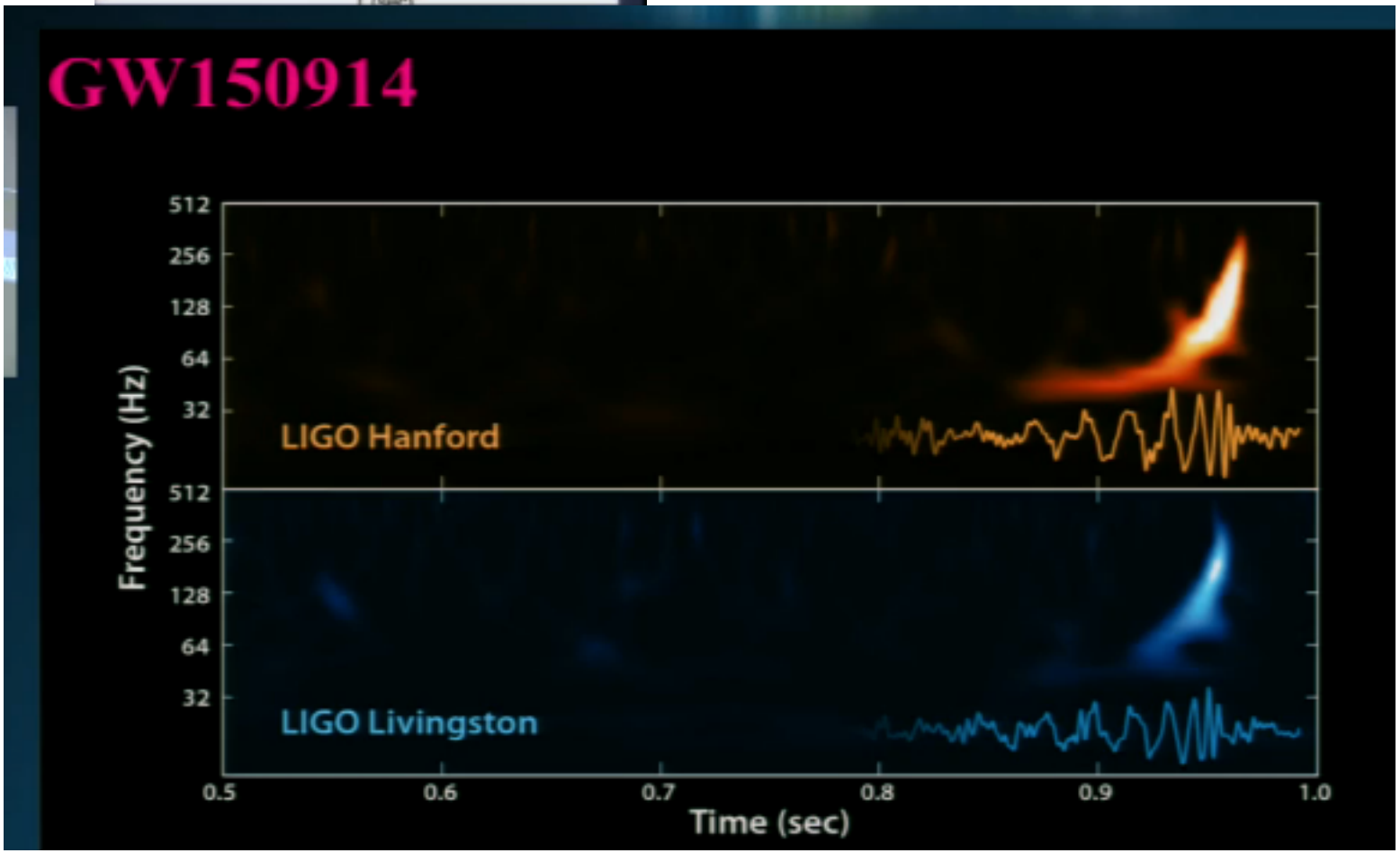
A bird's eye view of LIGO Hanford's laser and vacuum equipment area (LVEA). The LVEA houses the pre-stabilized laser, beam splitter, input test masses, and other equipment.

Reflecting far-end mirrors hanging on vibration eliminating threads:
Reduce all shaking AMAP.



Inspecting LIGO's optics for contaminants

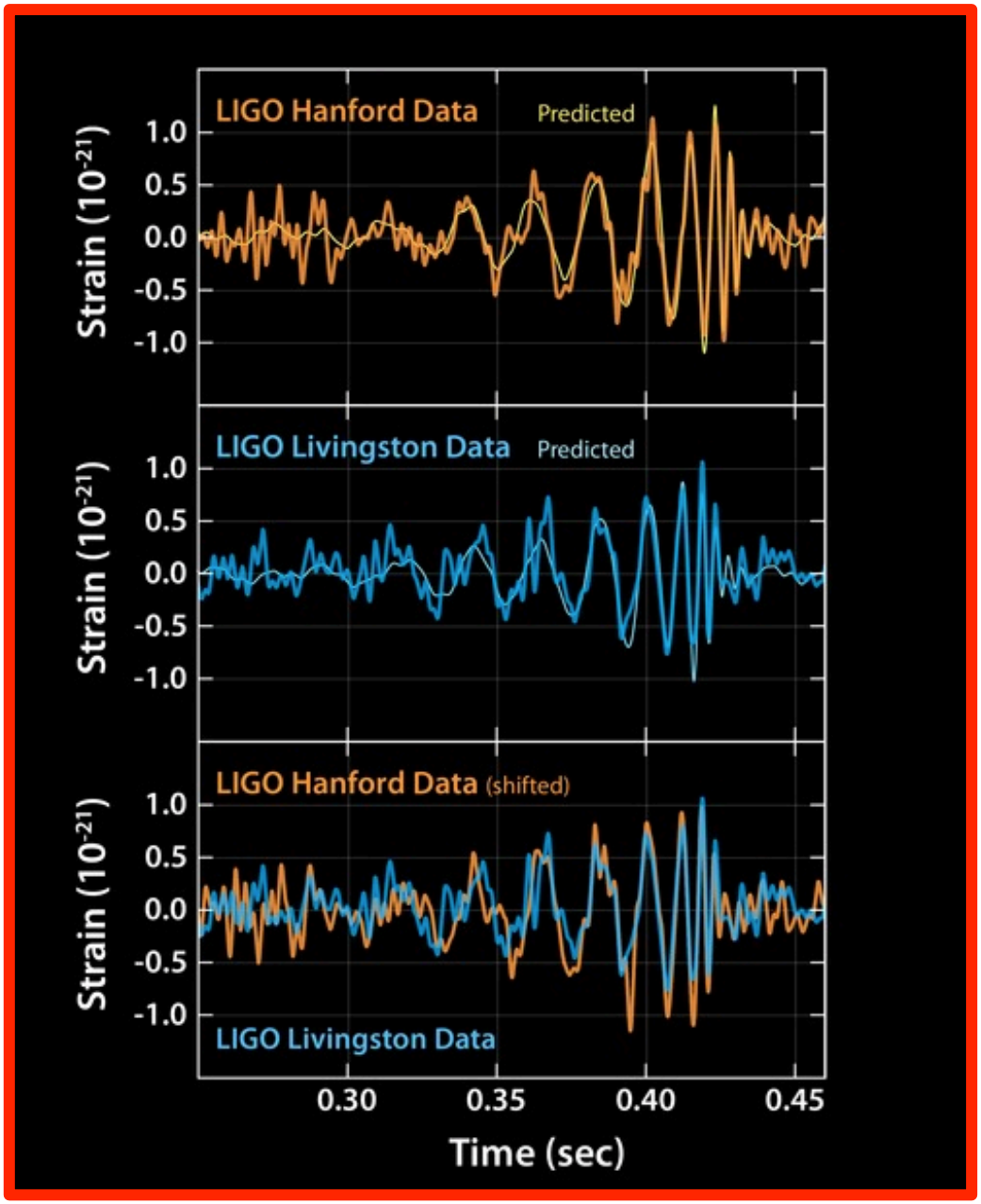

"chirp"
h(t) x 10^21
2
1
0
-1
0.5
0.6
0.7
0.8
0.9
1
T (sec)


GW150914
512
256
128
64
32
LIGO Hanford
512
256
128
64
32
LIGO Livingston
Frequency (Hz)
0.5
0.6
0.7
0.8
0.9
1.0
Time (sec)

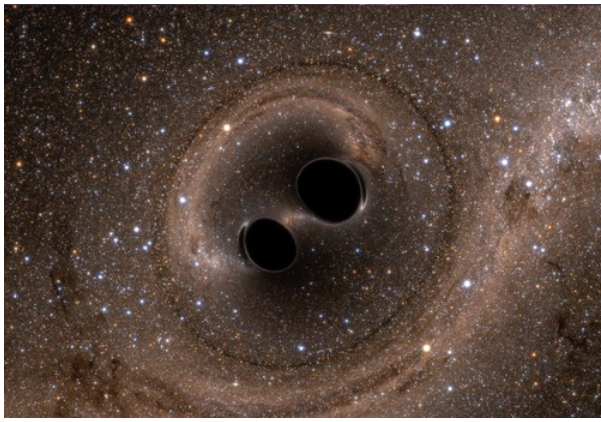
VIDEOS

https://youtu.be/1agm33iEAuo

https://www.youtube.com/watch?v=B4XzLDM3Py8


LIGO Hanford Data
Predicted
LIGO Livingston Data
Predicted
LIGO Hanford Data (shifted)
LIGO Livingston Data
Strain (10-21)
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)

Some WOW facts!



General Relativity theory calculations using computer Simulations can match data very well and tell us:

→ Another confirmation of GR prediction of gravity waves

→ In the final merger & ring-down about two solar masses of energy $E = MC^2$ were emitted as gravity waves in 0.1 secs. If that was emitted as light it would be briefly 2 10^18 x brighter than the Sun, outshining all the stars in about 10 million galaxies But it was not light but invisible gravity waves, shaking up spacetime

→ The Sun loses mass at a rate of 10 million tons/second At this rate it would disappear in about 6 billion years

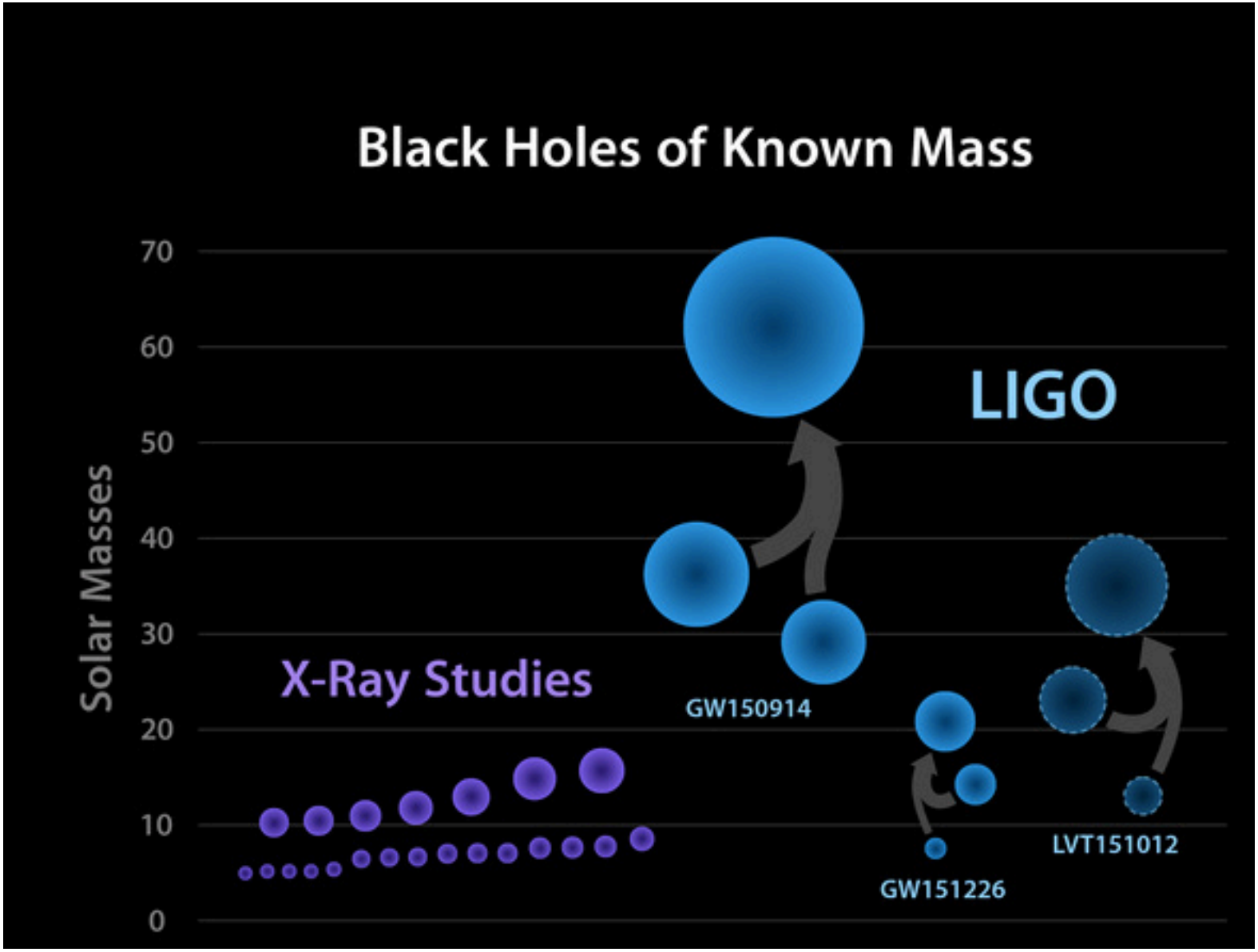
→ The two black holes, about 30 solar masses merged about 1.3 billion light years away and so 1.3 billion years ago. Only simple (single cell ?) life on Earth then.

13.7 billion years mapped onto 365 days

Jan 1st 00:10 Atoms form, universe becomes transparent
Jan 20th ? Galaxies and first stars forming
Aug 1st Sun and solar system, Earth form
Aug 20th First life
Dec 1st Pair of Massive Black Holes merge, emit GW
Dec 25th (Christmas Day-ish) Dinosaurs roaming

Dec 31st midnight minus
12 minutes Neanderthal
4 minutes ? GW enters our Galaxy (? 100,000 yrs ?)
2 minutes Humans leave Africa
25 seconds Civilizations
2 seconds Invention of printing
0.1 seconds Invention of Nuclear Weapons
1.7 ms (milliseconds) ago GW shakes Earth, LIGO, and all
.....can civilization survive another second? (500 yrs)

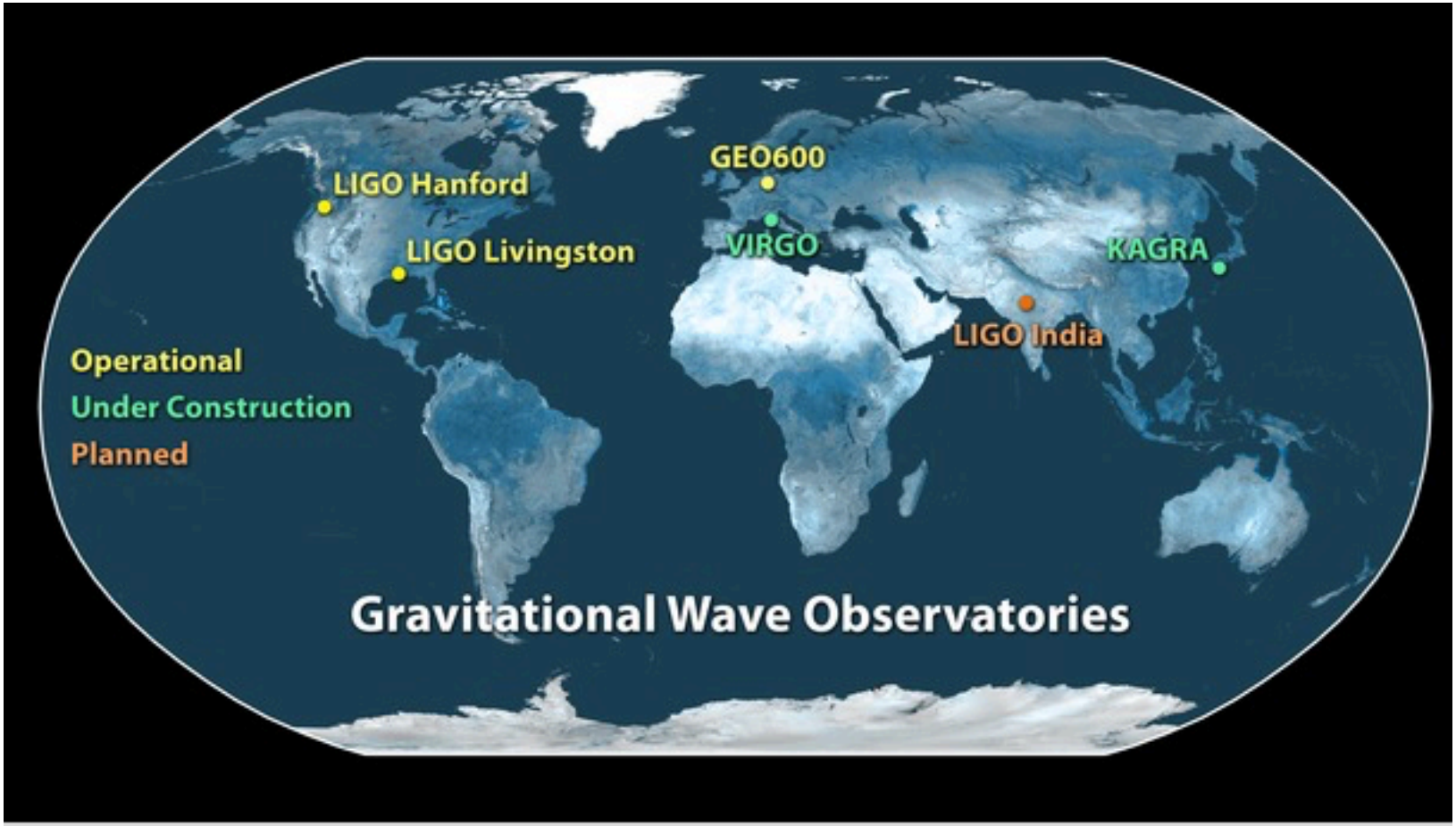
Plenty of time for evolution!


Black Holes of Known Mass
Solar Masses
70
60
50
40
30
20
10
0
X-Ray Studies
LIGO
GW150914
GW151226
LVT151012

Present and future … growth spurt?

Better directional location, sensitivity, wave shape measurement etc ...

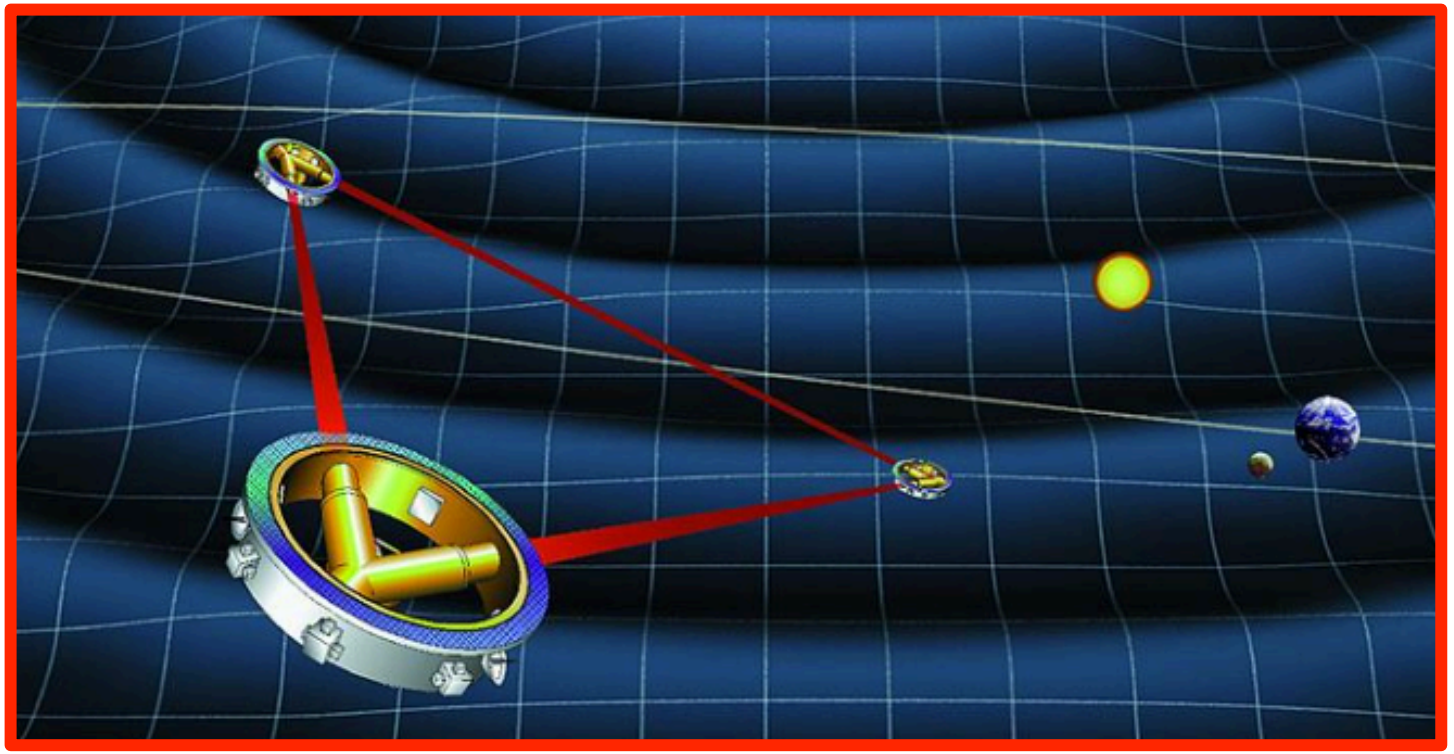
To “see” the Universe with new “eyes”



Gravitational-Wave Observatories Across the Globe

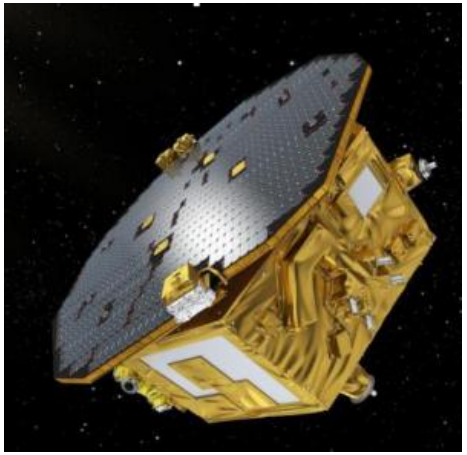
Image Credit: Caltech/MIT/LIGO Lab

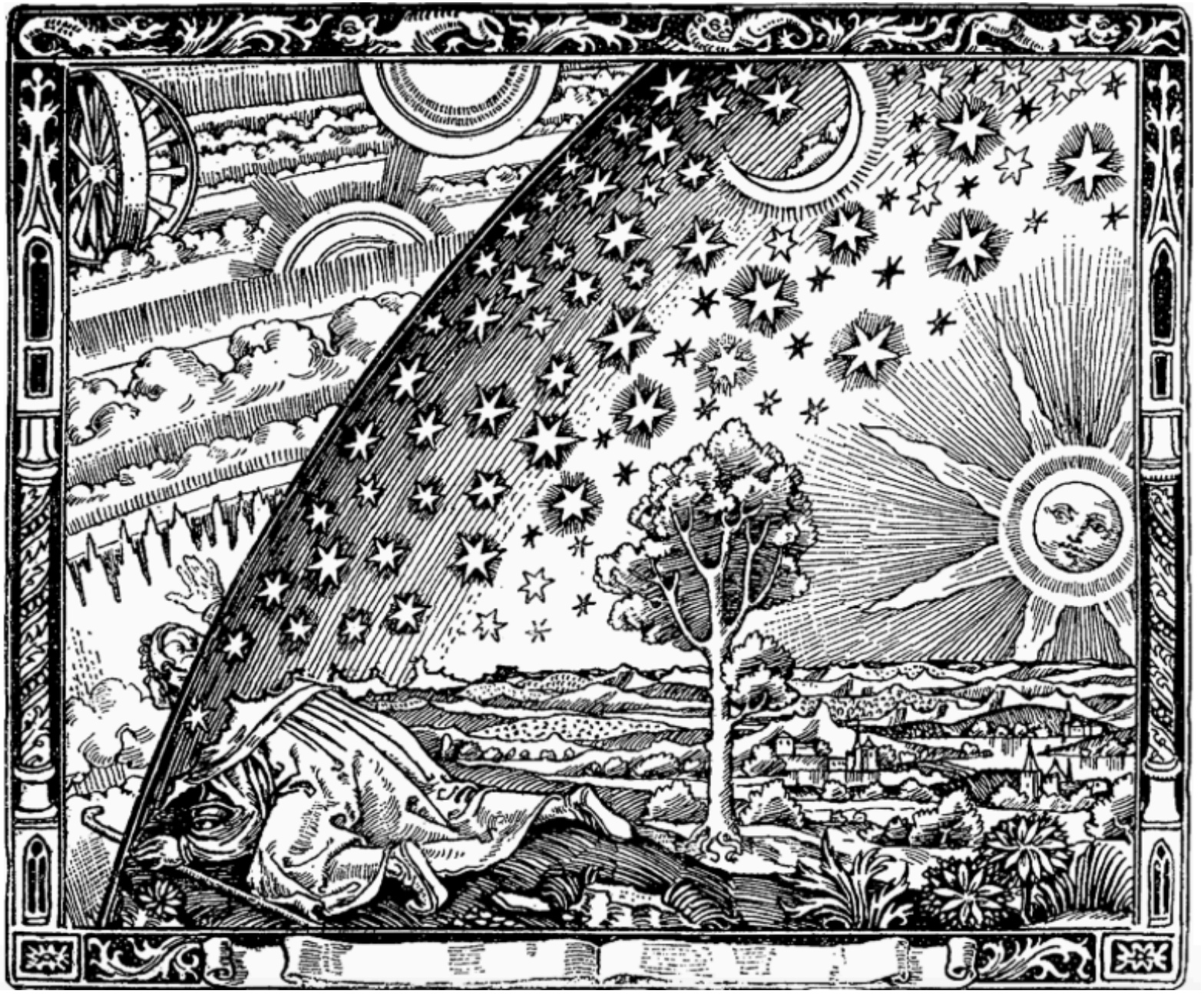
One day (2034?) maybe: eLISA = evolved Laser Interferometer Space Antenna
Three stations 1 million km apart orbiting Sun but detecting tiny vibrations!



Should detect thousands of sources at any time.

Technology test : LISA Pathfinder launched December 2015
Success!



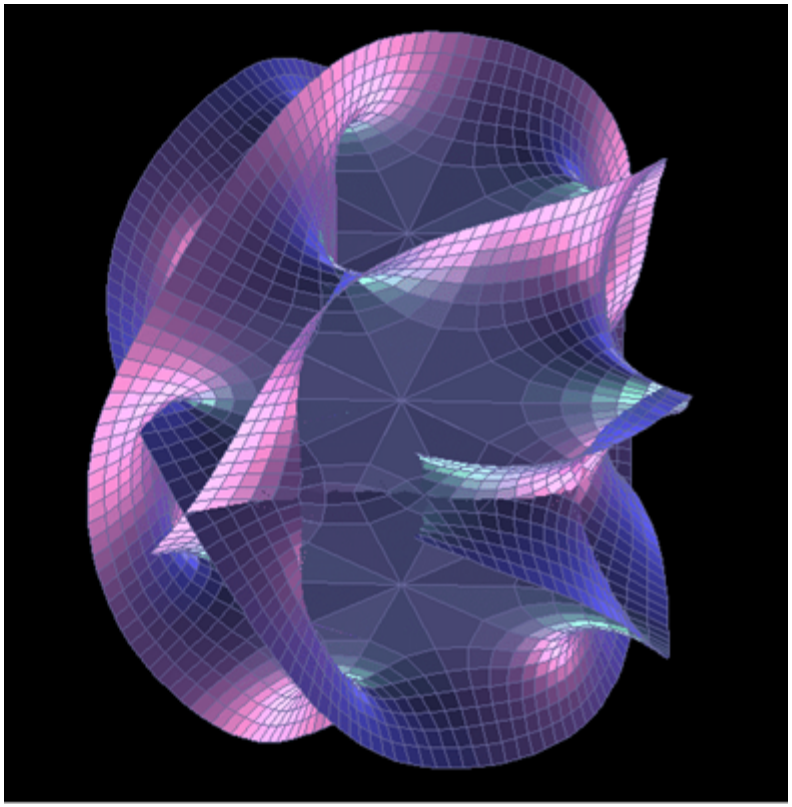


Thank You

Questions?

https://www.youtube.com/watch?v=tQ_teIUb3tE

Superstring theories: fundamental particles are tiny strings vibrating in 10/11 dimensions of spacetime.



3-dimensional representation of 6-dimensional manifold + 3 large space dimensions + time = 10 dim

Drinking straw:

ZOOM IN

1-dimensional (line)

2-dimensional (surface)

3-dimensional (volume)

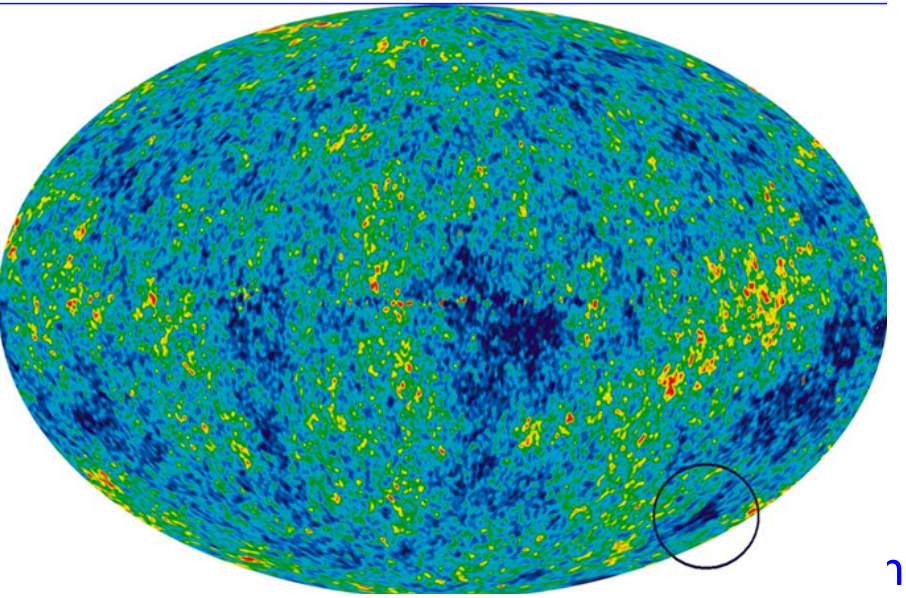
Mathematics, not (yet) physics

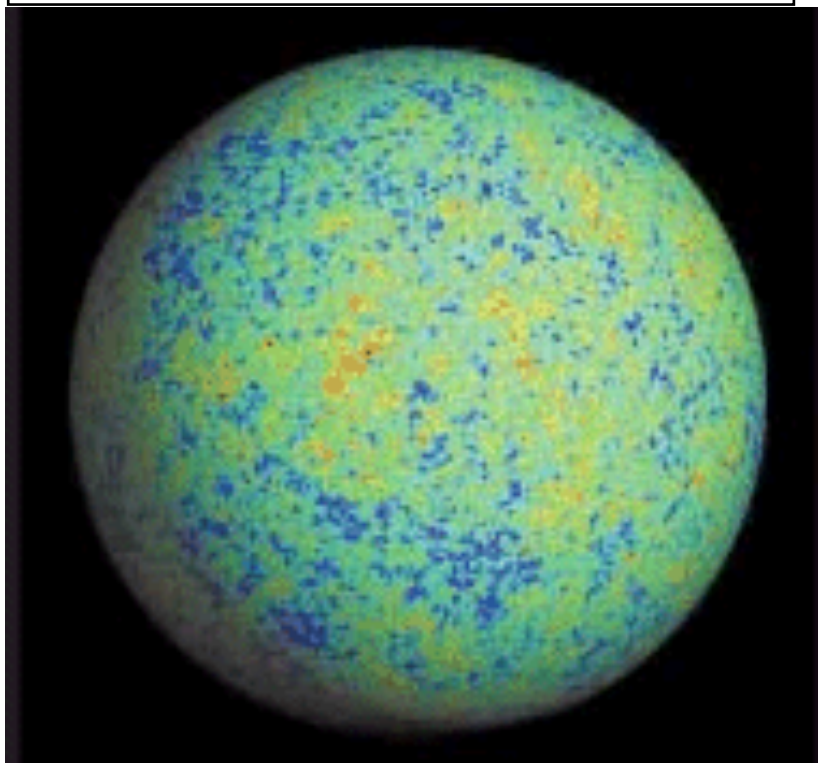
Cosmic Microwave Background

The glow from the hot Big Bang, cooled by the Universe's expansion
Now about 2.73° = -450° F with tiny variations:

False colors showing
colder & hotter, 1/1000th deg

Universe age: 13.7 Byr
Matter we know: ~ 4%
Dark Matter: ~ 26%
Dark Energy ~ 70%





ıe Universe seen in microwaves
at ~ 300,000 years old from inside looking out!