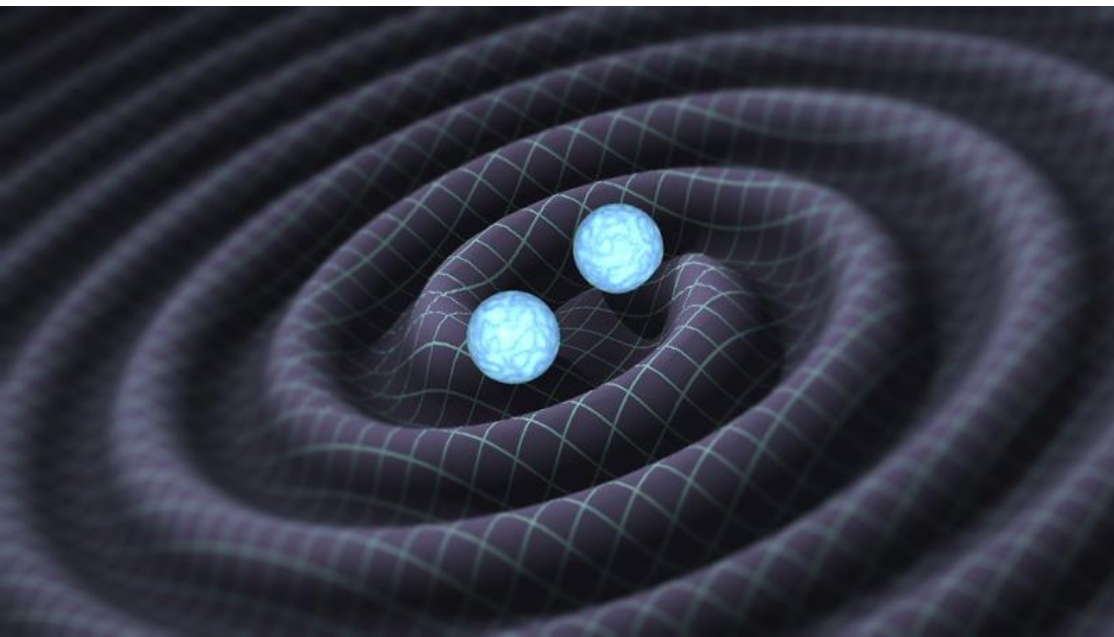
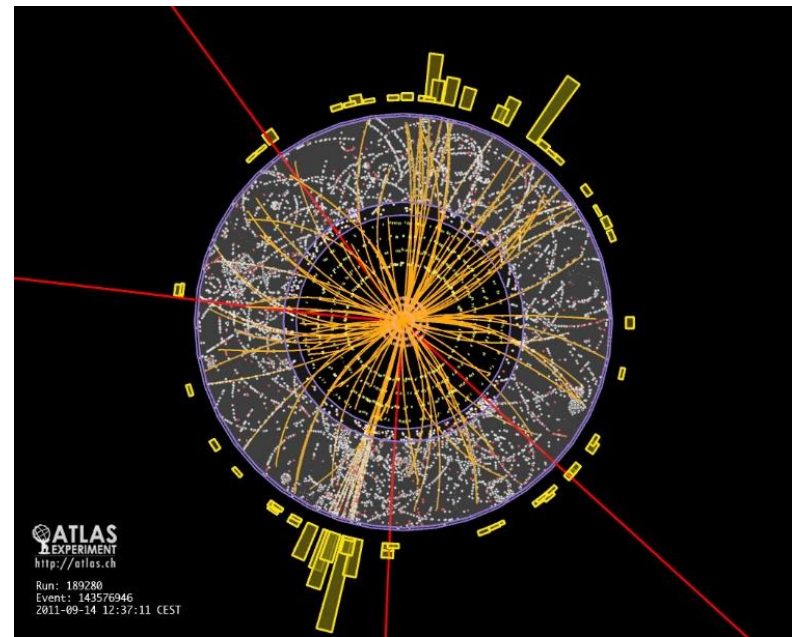


Voyage from Outer Space to Inner Space: from Gravitational Waves to the Higgs Boson – and their secret connection



LIGO/VIRGO



ATLAS/CERN



Lance Dixon
KITP Public Lecture
February 20, 2025



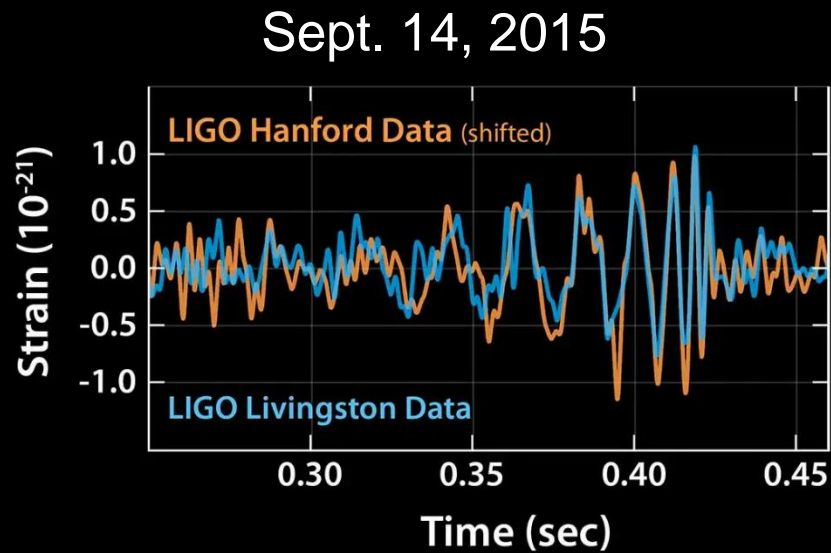
A tale of two discoveries

Both began in the 1960s

Took half a century to advance technology and consolidate theoretical motivations and expectations



Site of Gravitational Wave Discovery



LIGO, Hanford, WA; also LIGO, Livingston, LA; VIRGO, near Pisa; KAGRA, Japan



Barry C. Barish (Caltech)



Kip S. Thorne (Caltech)



Rainer Weiss (MIT)



2017 Nobel Prize in Physics

Higgs boson discovery July 4, 2012

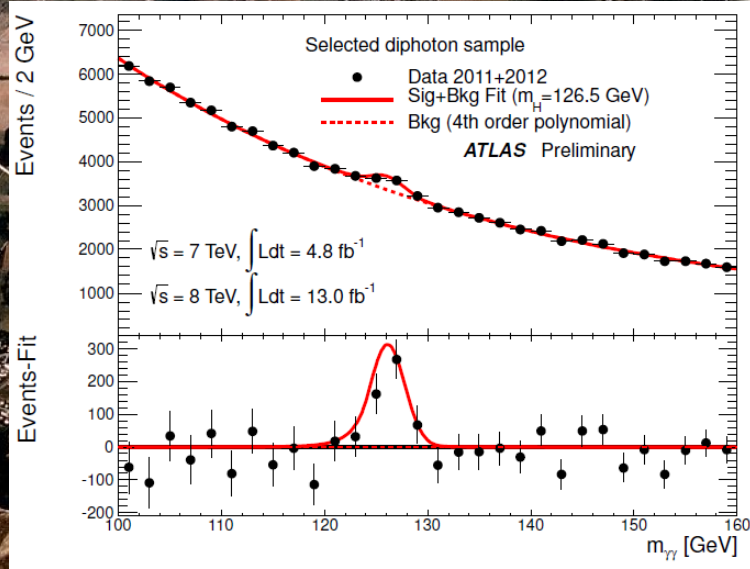
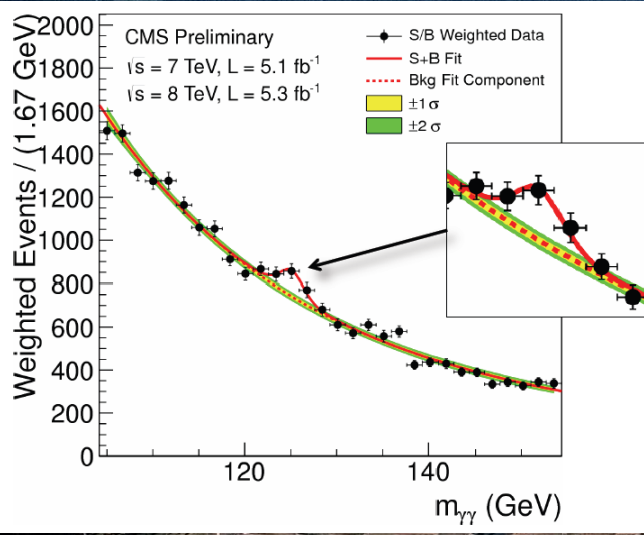
CERN, Geneva, Switzerland

CMS

LHCb



ATLAS



2013 Nobel Prize in Physics



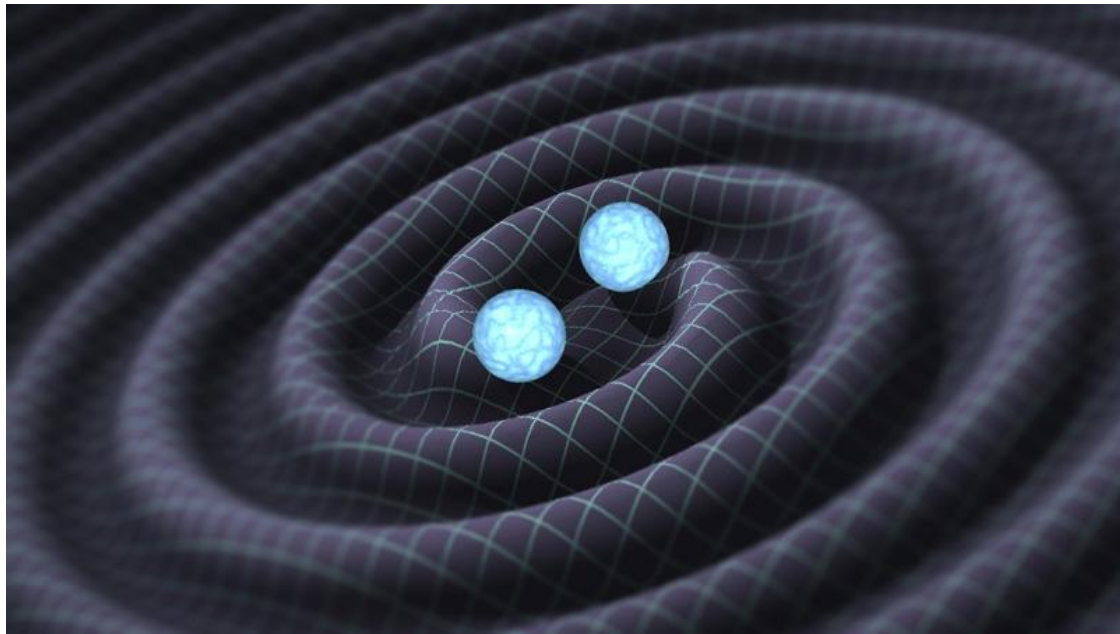
Francois Englert

Peter Higgs



Part I

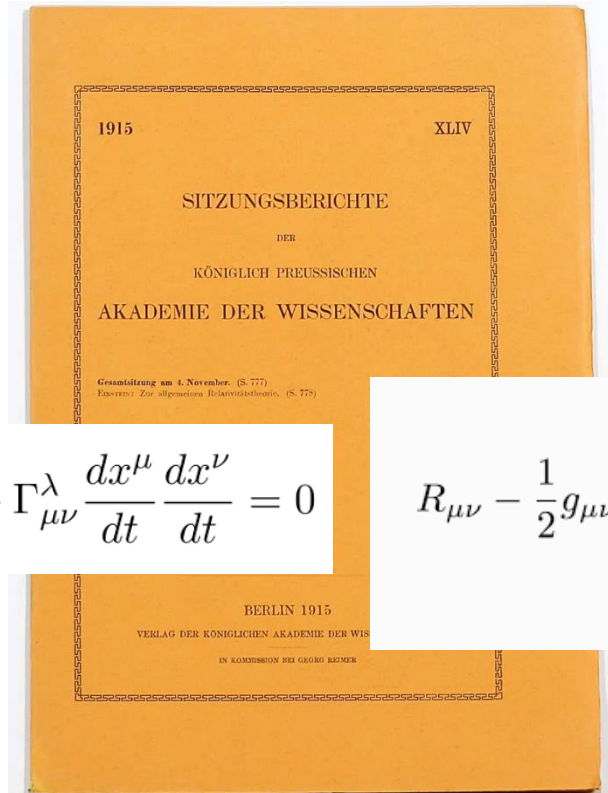
Search for gravitational waves



LIGO/VIRGO

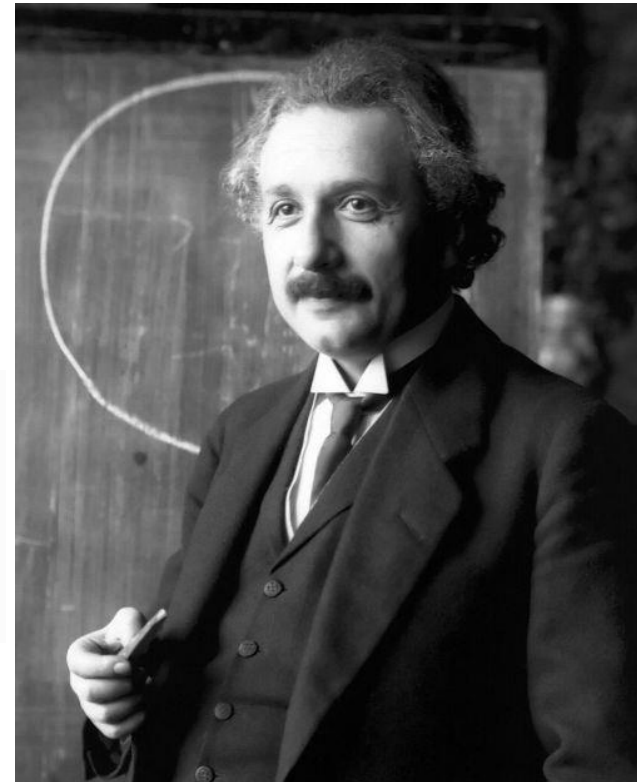
Wind the clock back a full century

Einstein's Theory of General Relativity (GR) - 1915



$$\frac{d^2 x^\lambda}{dt^2} + \Gamma_{\mu\nu}^\lambda \frac{dx^\mu}{dt} \frac{dx^\nu}{dt} = 0$$

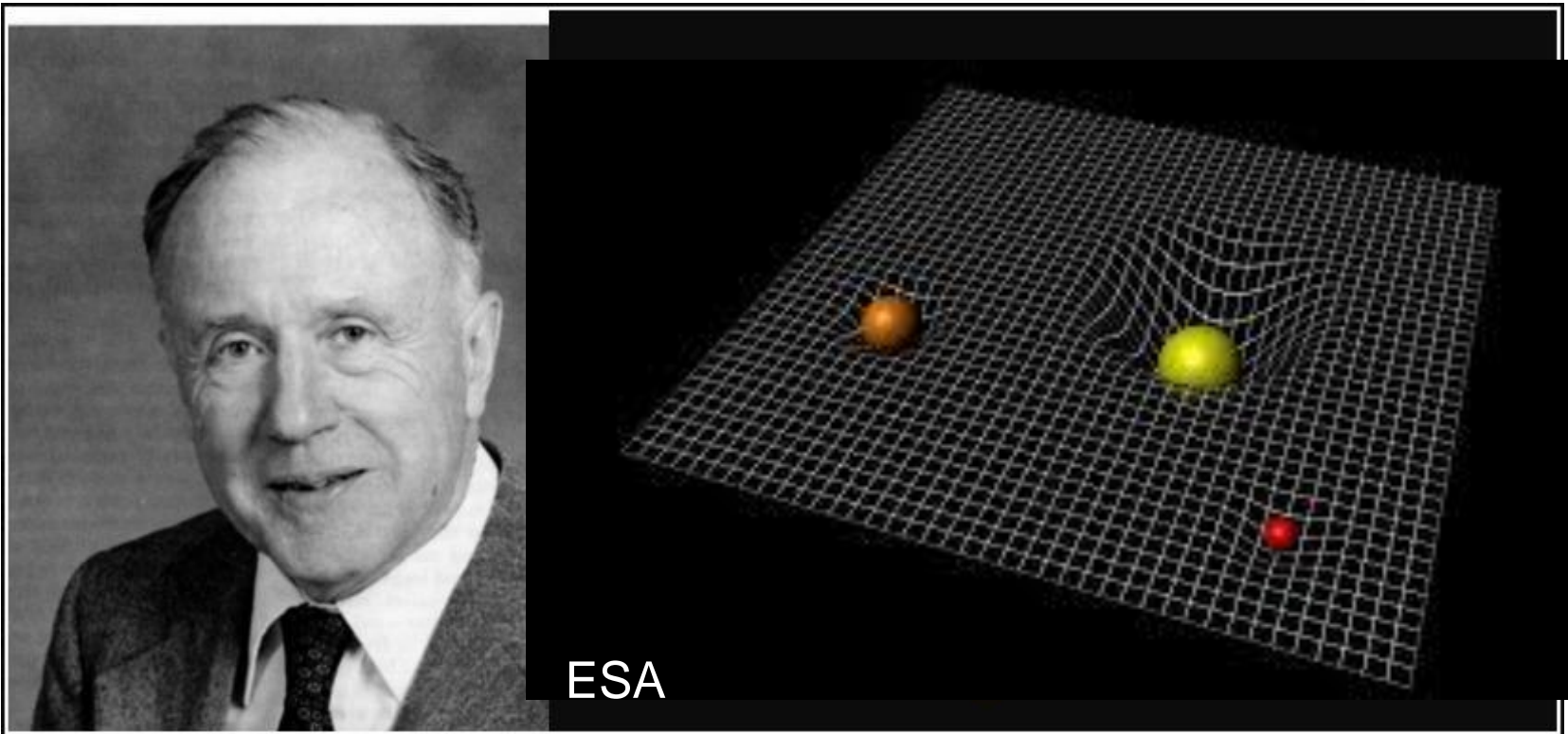
$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = \frac{8\pi G}{c^4}T_{\mu\nu}$$



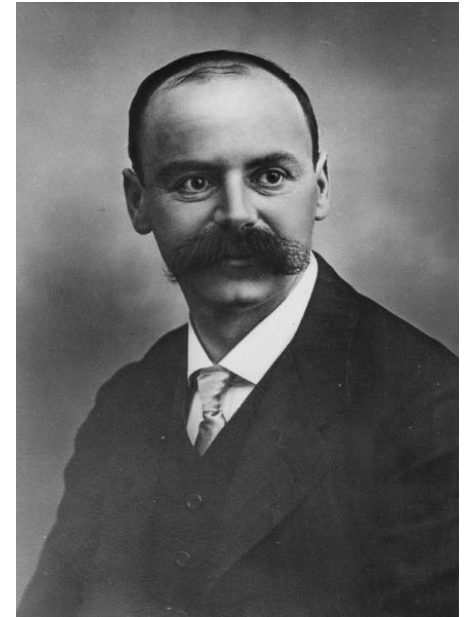
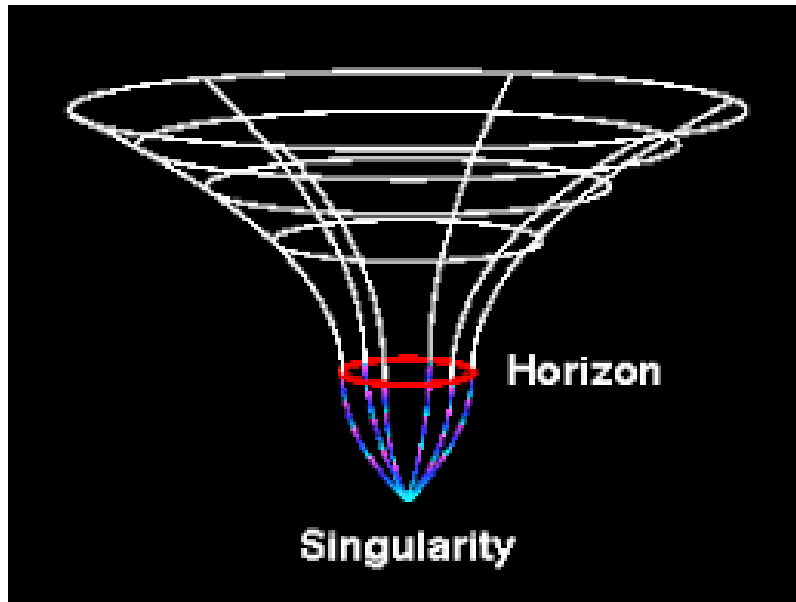
General Relativity in one sentence

$$\frac{d^2 x^\lambda}{dt^2} + \Gamma_{\mu\nu}^\lambda \frac{dx^\mu}{dt} \frac{dx^\nu}{dt} = 0$$

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = \frac{8\pi G}{c^4}T_{\mu\nu}$$



Black Hole solutions within a month

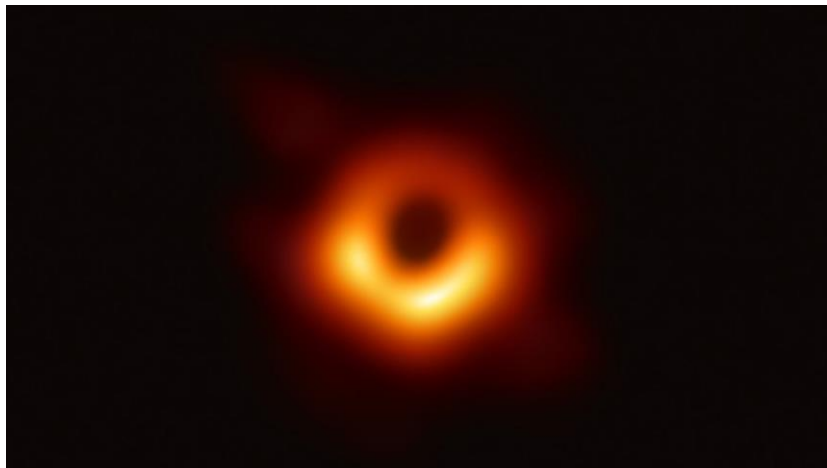
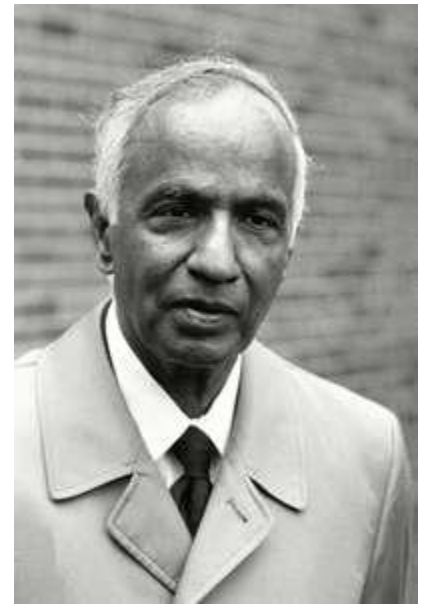


Karl Schwarzschild, 1916

Region from which no light can escape
Evidence for black holes would wait half a century

“The black holes of nature are the most perfect macroscopic objects there are in the universe: the only elements in their construction are our concepts of space and time.”

- S. Chandrasekhar (1979)



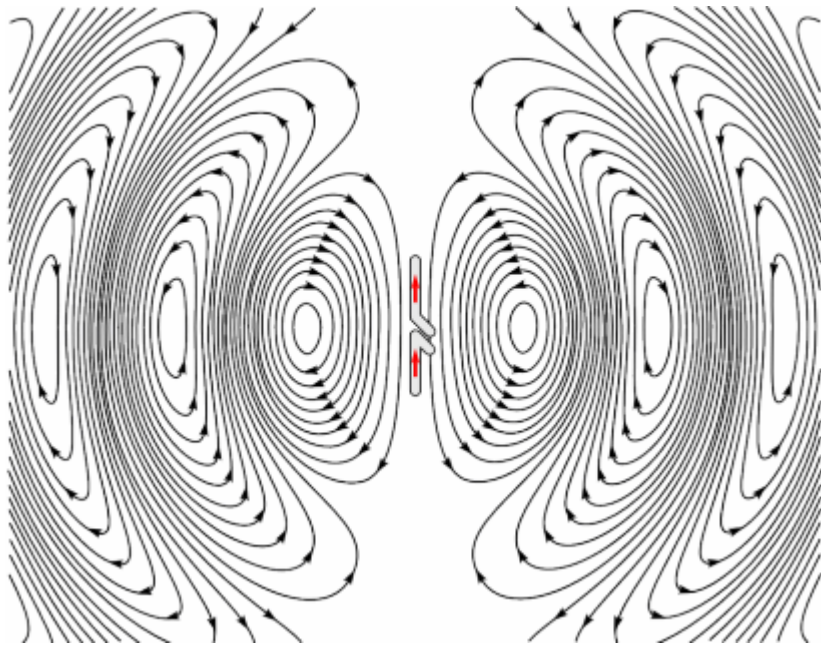
**Event Horizon Telescope
(2019)**

Gravitational waves also predicted by GR in 1915

- Spacetime no longer **static**, but **dynamical**
- **Ripples in fabric of spacetime**, produced by accelerating massive objects, **moving outward at speed of light**
- However, Einstein himself **doubted their reality** as late as 1936
- Einstein wrote a paper **refuting** GWs. Journal returned it to him requesting revisions (**peer review**). Einstein replied that he hadn't authorized them "to show it to specialists before it is printed." He would never publish in the journal again.

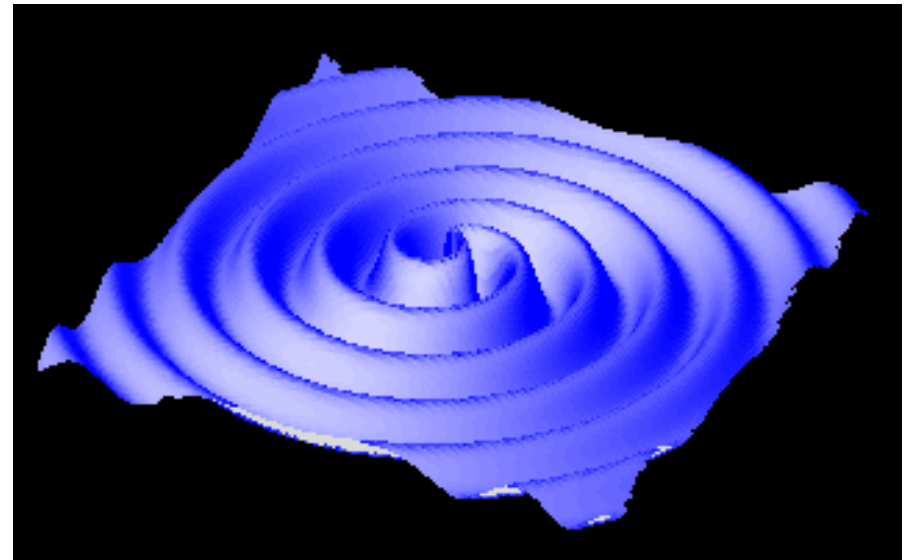
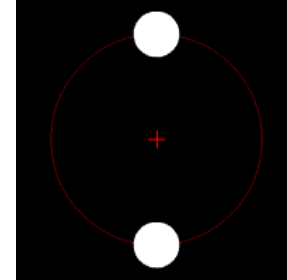
radio waves ~ gravitational waves

move electric charges – make EM fields



Chetvorno - wikipedia

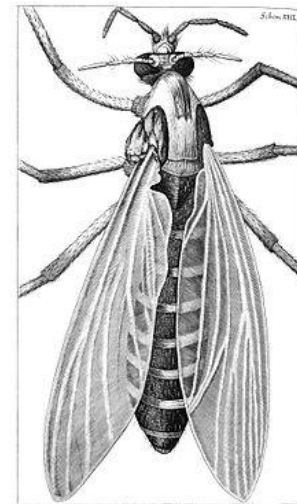
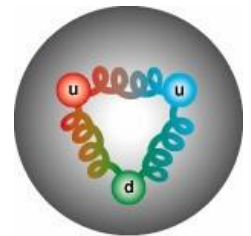
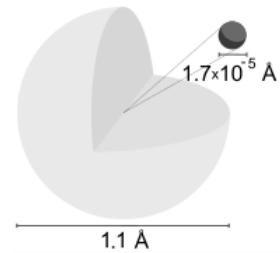
move LARGE masses FAST
– make ripples in spacetime



NASA/JPL - wikipedia

Reality of GWs well-accepted by 1960s

- But also known to be exceedingly weak
- When a GW passes by LIGO, the 1 foot diameter mirrors “move” by about **1/10,000 the diameter of a proton!**
- About 1 part in **1,000,000,000,000,000,000**
- **Way less than a gnat’s eyelash!**

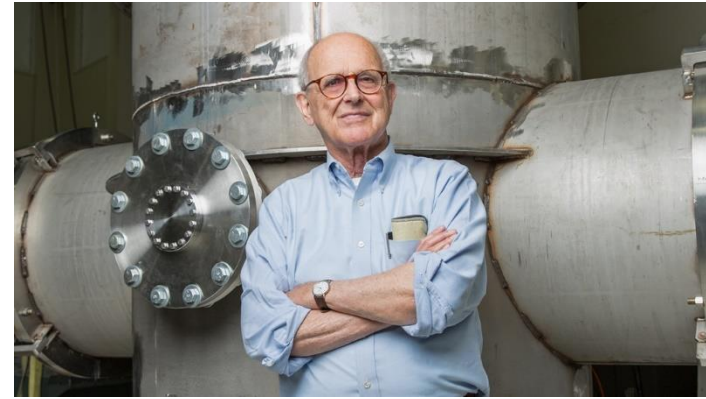


Robert Hooke - 1665

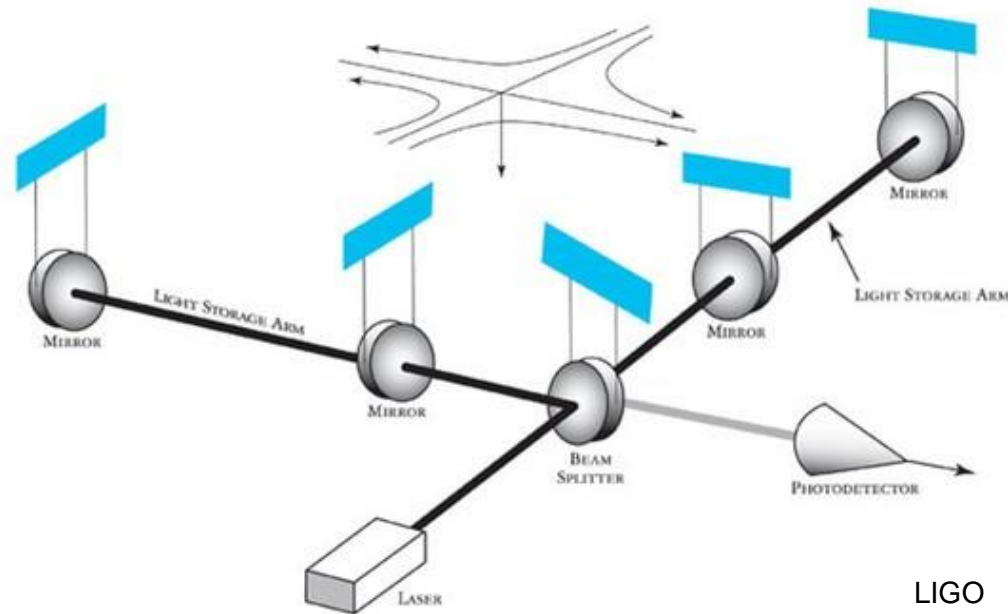
First laser interferometer proposal 1972

Rainer Weiss, MIT

Born in 1932 in Berlin, fled Nazis.
Grew up on Manhattan's Upper West Side.
Tinkerer, built and sold his own high fidelity (hi-fi) systems. Flunked out of MIT as undergrad, later struggled to get tenure there.



Ken Richardson



LIGO

Caltech joined forces with MIT

Kip Thorne, Caltech

Born in 1940 in Utah.

Undergrad at Caltech,

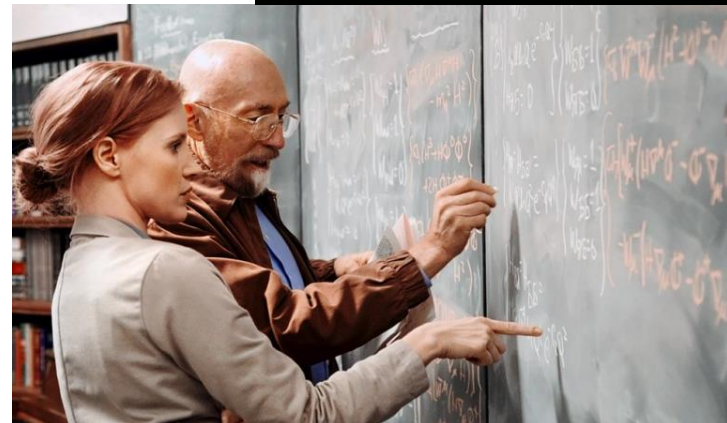
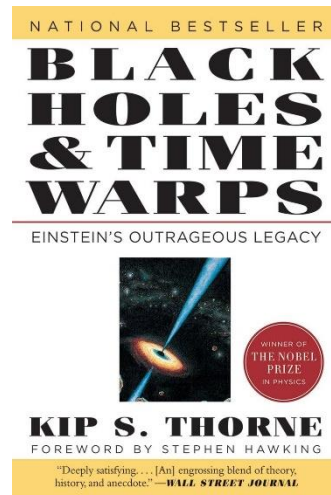
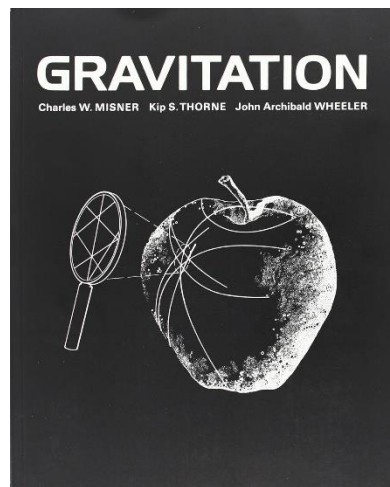
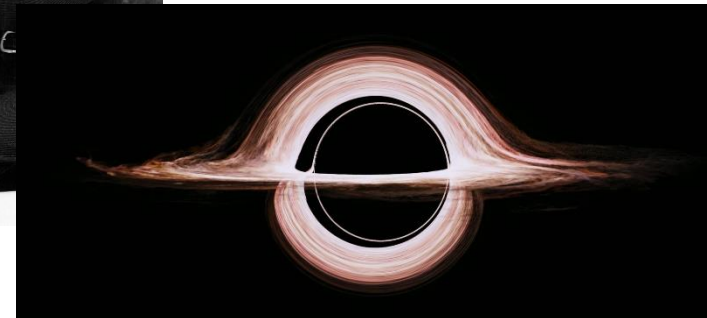
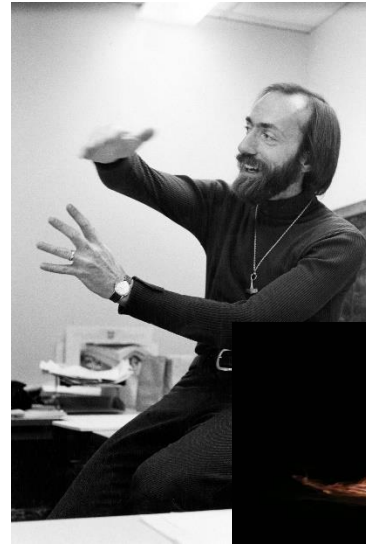
PhD at Princeton (with Wheeler).

Full Professor at Caltech by age 30.

Author of textbook,

popular book,

and screenplay (Interstellar)



LIGO Timeline



Caltech MIT

1970s	Early work on gravitational-wave detection by laser interferometers, including a 1972 MIT study describing a kilometer-scale interferometer and estimates of its noise sources
1979	U.S. National Science Foundation (NSF) funds Caltech and MIT for laser interferometer research and development
1983	MIT and Caltech jointly present results of the kilometer-scale interferometer study to NSF. Receive NSF committee endorsement on new large programs in physics.
1984	LIGO founded as a Caltech/MIT project. National Science Board approves LIGO development plan.
1986	Physics Decadal Survey and special NSF panel on gravitational wave interferometers endorse LIGO
1990	National Science Board (NSB) approves LIGO construction proposal, which envisions initial interferometers followed by advanced interferometers
1992	NSF selects LIGO sites in Hanford, Washington, and Livingston, Louisiana. LIGO Cooperative Agreement signed by NSF and Caltech.
1994-95	Site construction begins at Hanford and Livingston locations
1997	The LIGO Scientific Collaboration (LSC) is established and expands LIGO beyond Caltech and MIT, including the British/German GWO Collaboration, which operates the GEO600 interferometer in Hannover, Germany.
1999	LIGO inauguration ceremony
2002	First coincident operation of Initial LIGO interferometers and the GEO600 interferometer
2004	NSB approves Advanced LIGO
2006	LIGO design sensitivity achieved. First gravitational wave search at design sensitivity. Science Education Center inaugurated at the LIGO Livingston Observatory.
2007	Joint data analysis agreement ratified between LIGO and the Virgo Collaboration , which operates the Virgo interferometer in Cascina, Italy. Joint observations with enhanced initial LIGO interferometer and Virgo.
2008	Construction of Advanced LIGO components begins
2010	Initial LIGO operations conclude; Advanced LIGO installation begins at the observatories.
2011 - 2014	Advanced LIGO installation and testing
2014	Advanced LIGO installation complete
2014-2015	Advanced LIGO sensitivity surpasses Initial LIGO
Sept 14, 2015	Advanced LIGO detects gravitational waves from collision of two black holes

I was Caltech undergrad then



Kip Thorne, Ron Drever, Robbie Vogt

now:
LIGO 1200+ collaborators
VIRGO 800+
KAGRA 400+

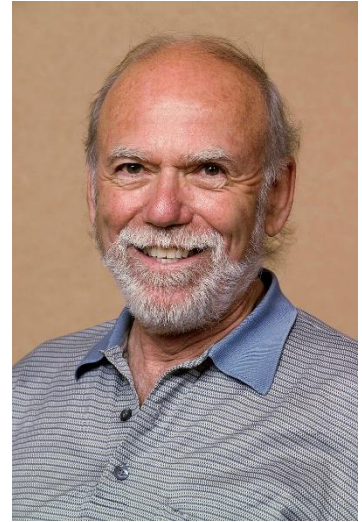


Twists & Turns until a Steady Hand

Barry Barish, Caltech

Born in 1936 in Nebraska to recent immigrants, grew up in LA. Undergrad and PhD, UC Berkeley. Experimental particle physicist.

Led one of the large detector collaborations at the Superconducting Supercollider in Texas until it was cancelled in the early 1990s, when he became the director of LIGO.



R. Hahn - wikipedia

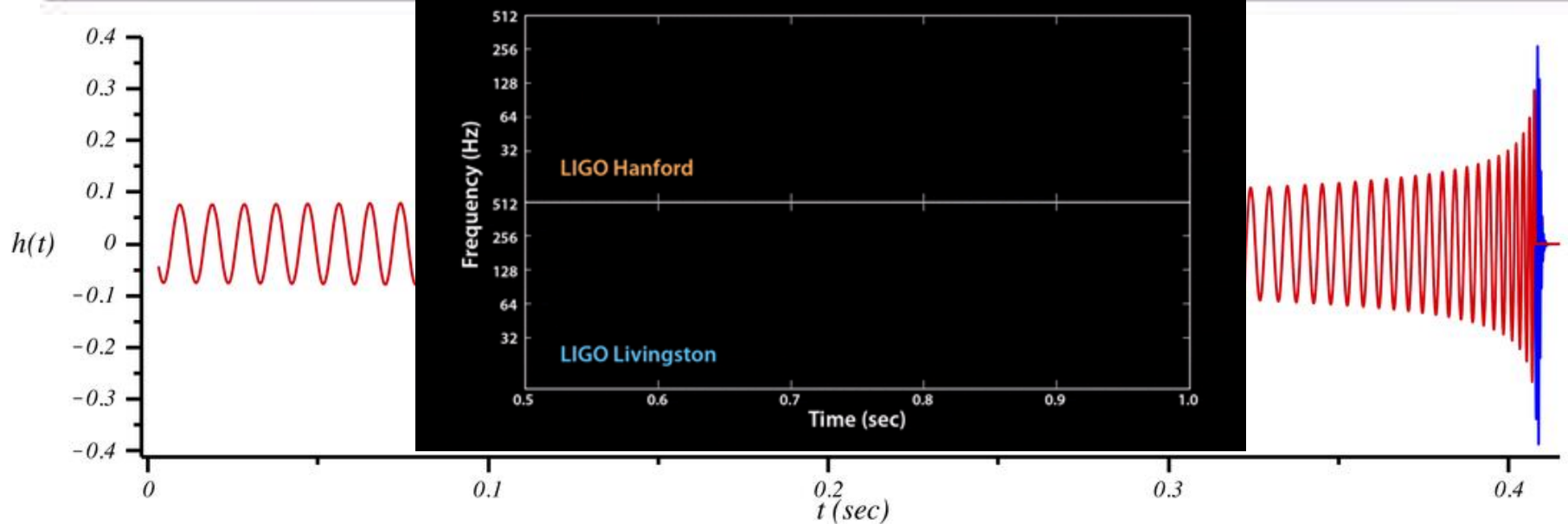


2 LIGO detectors, WA & LA

- To reduce spurious signals and help localize source on sky
- Also VIRGO in Italy

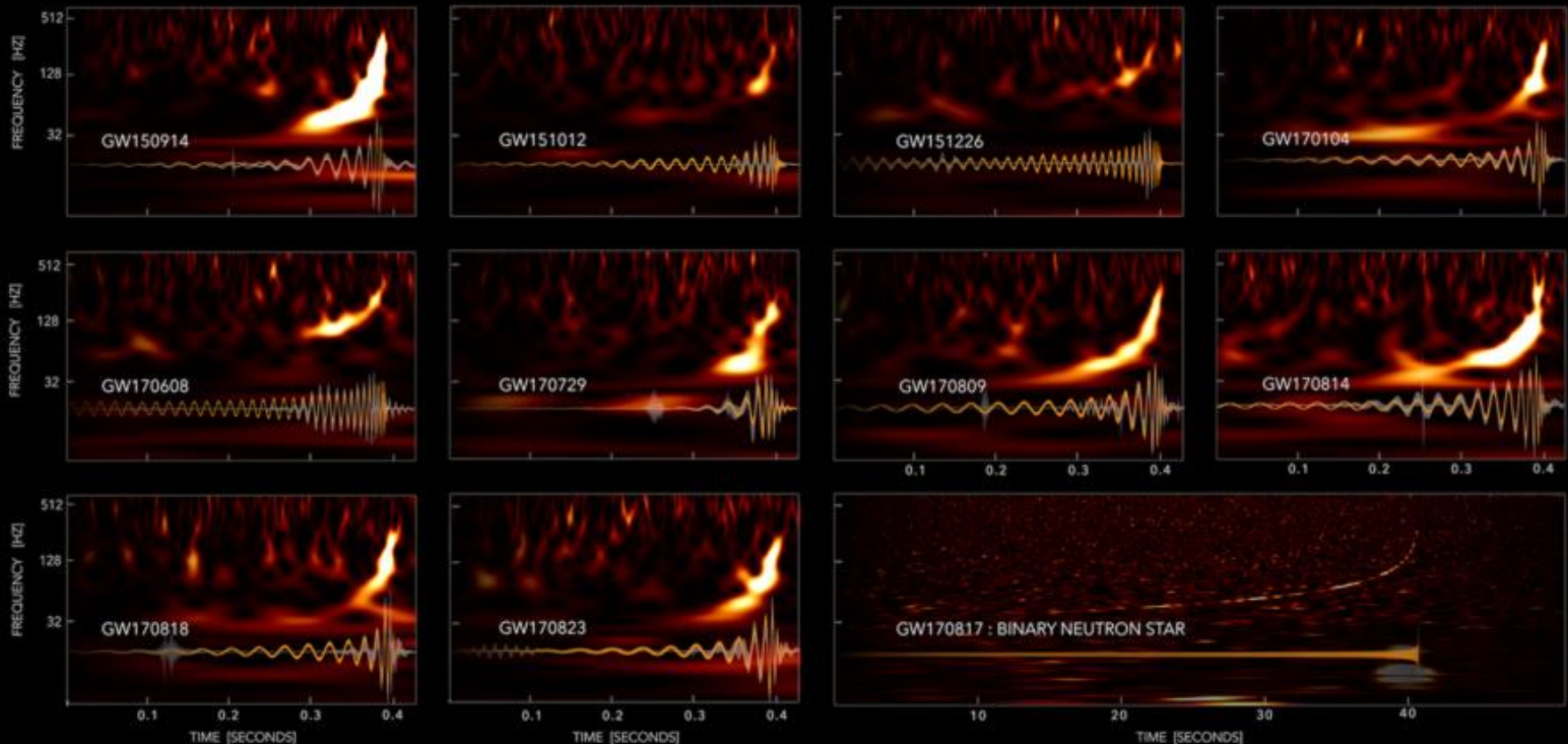


Last stages of binary inspiral



A few events, out of hundreds

GRAVITATIONAL-WAVE TRANSIENT CATALOG-1



LIGO-VIRGO DATA: [HTTPS://DOI.ORG/10.7935/82H3-HH23](https://doi.org/10.7935/82H3-HH23)

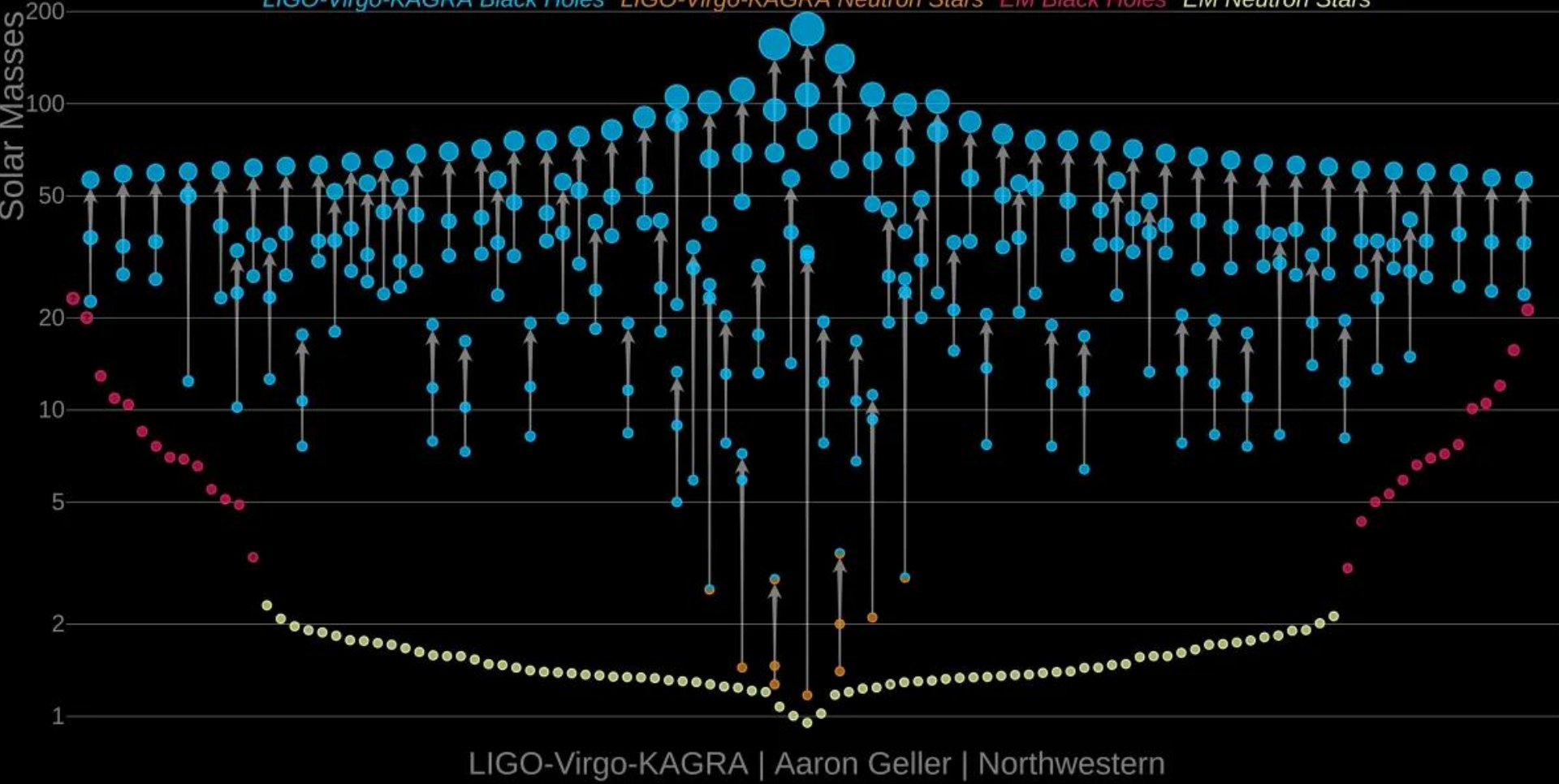
WAVELET (UNMODELED)

EINSTEIN'S THEORY

S. GHONGE, K. JANI | GEORGIA TECH

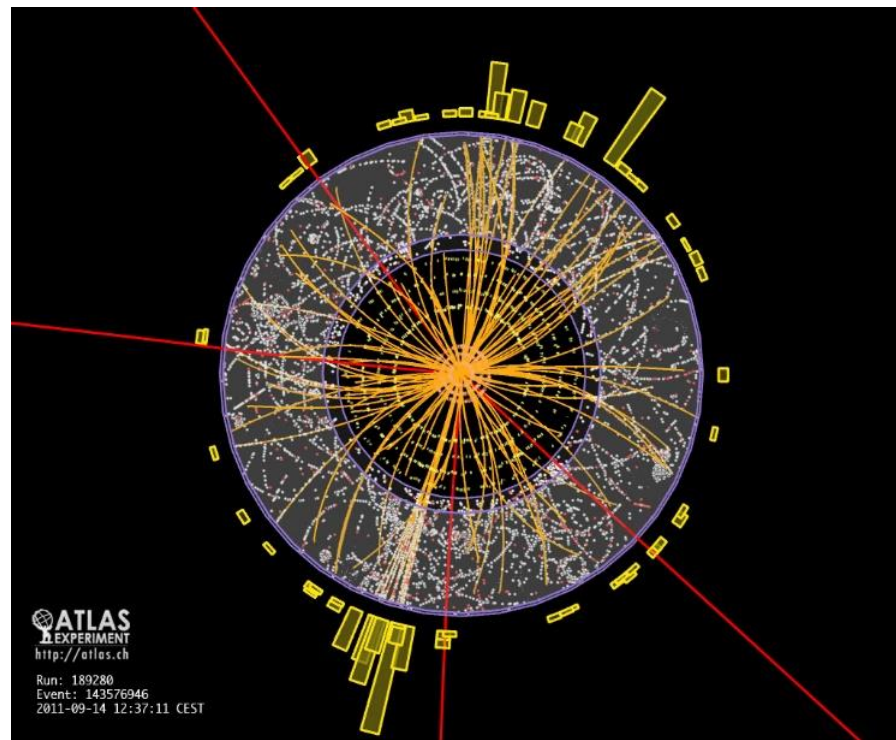
Masses in the Stellar Graveyard

LIGO-Virgo-KAGRA Black Holes LIGO-Virgo-KAGRA Neutron Stars EM Black Holes EM Neutron Stars



Part II

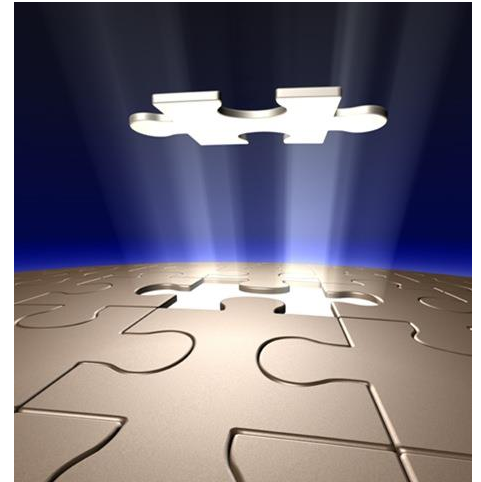
Search for the Higgs boson



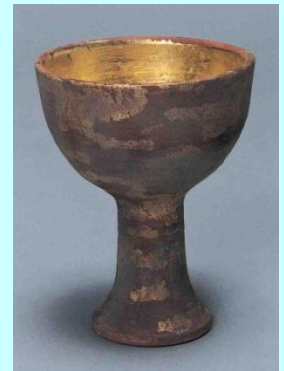
ATLAS/CERN

The elusive Higgs boson

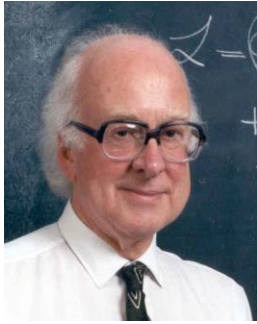
Last missing piece in
a theory of matter and
subatomic forces,
five decades in the making



- Conceived in 1964
- Experimental searches began around 1980
- More seriously in 1990s and 2000s
- Eluded thousands of clever physicists working at increasingly powerful particle accelerators around the world



An explanation for **origin of mass** given 60 years ago



Peter Higgs



idea came to Higgs
in 1964 while walking
in the Cairngorms,
Scotland

Requires a new particle – **the Higgs boson**

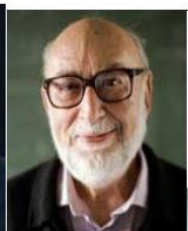
Many similar ideas percolating at same time

→ **Higgs boson** **sometimes** known as

“Anderson-Brout-Englert-Guralnik-Hagen-Higgs-Kibble boson”



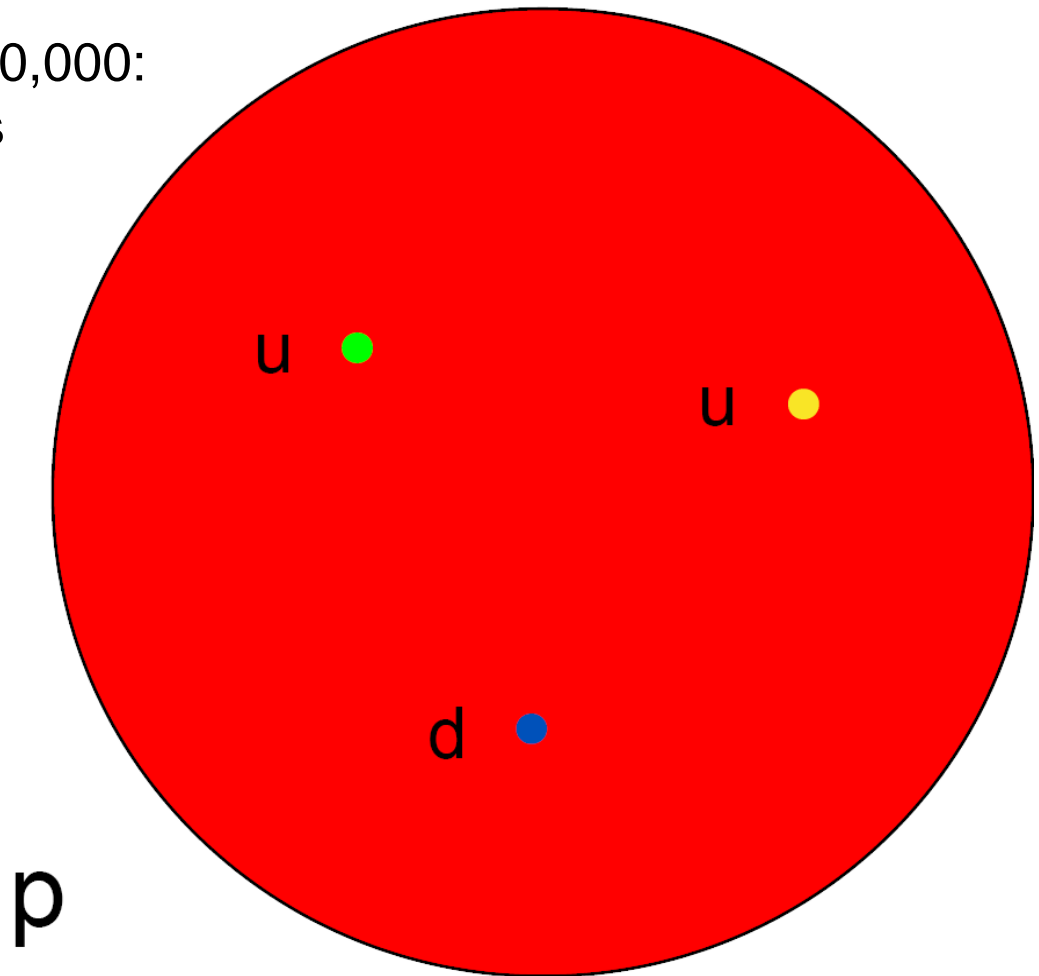
L. Dixon Voyage from Outer to Inner Space



KITP Feb. 20, 2025

All ordinary matter made of atoms

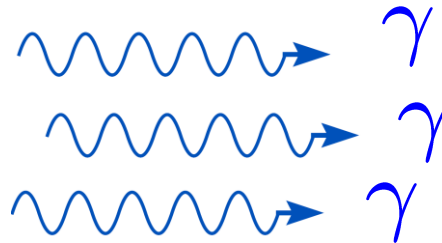
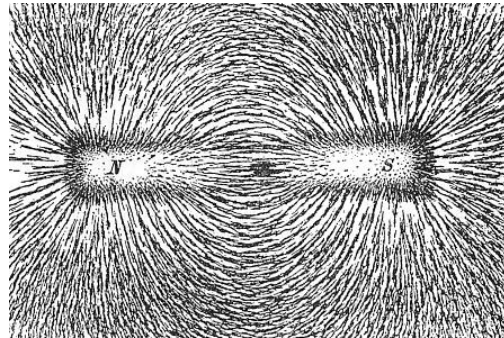
zoom in by another 100,000:
proton made of quarks
[SLAC, 1960s]



Where do masses of u and d (and other) quarks come from?

Matter particles interact via **forces**

- Three known subatomic forces, plus gravity
- **Electromagnetism**: force holding atoms together
- Electricity, magnetism, light, radio waves, ...
- “Carried” by **photon**, a packet of light



Quantum Mechanics particle-wave duality

LIGHT IS A
WAVE!

A World Without Mass



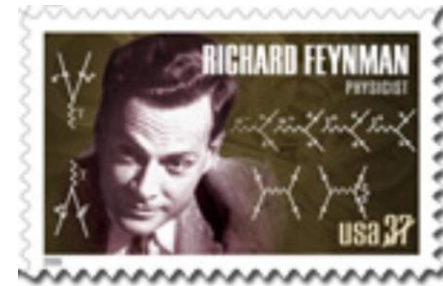
Without mass for elementary particles,
the world would look very different

Photons have
no mass,
zip around
at speed of light

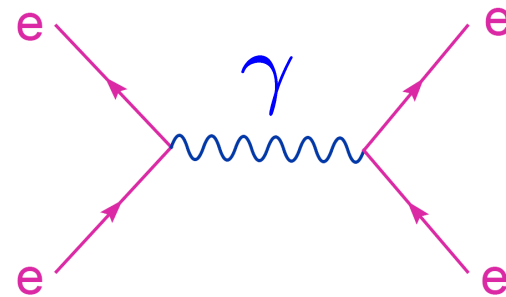
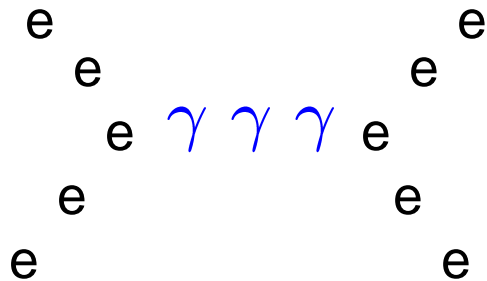
If electrons also had no mass,
they would zip around at speed of light too

→ All atoms, all matter would instantly fly apart!

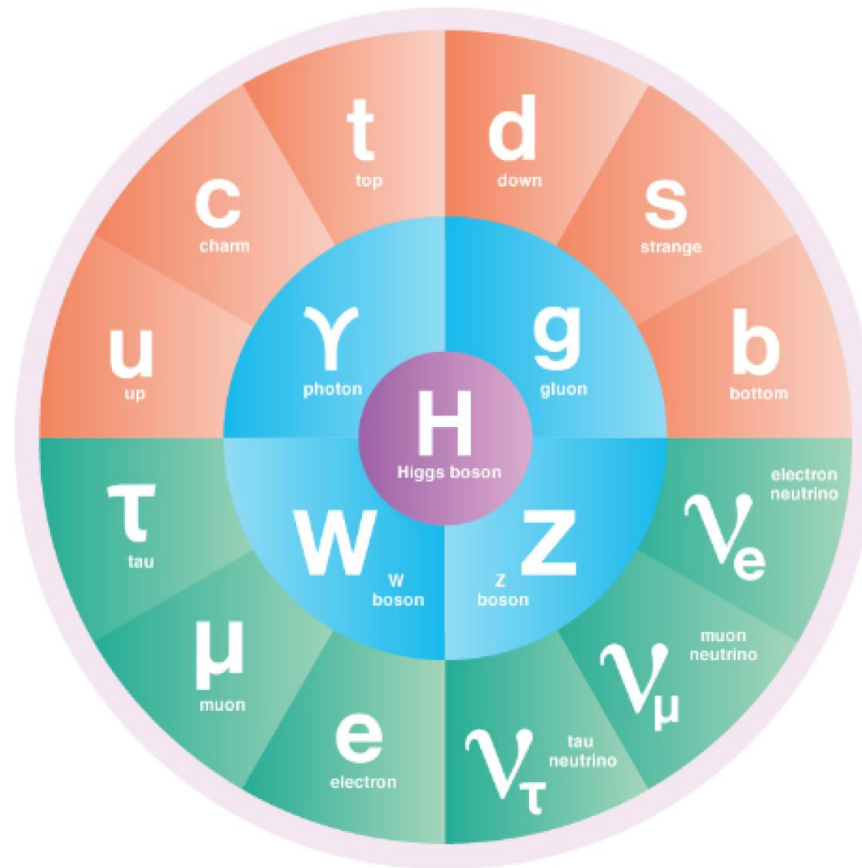
Exchanging particles (bosons) makes forces



Feynman diagram



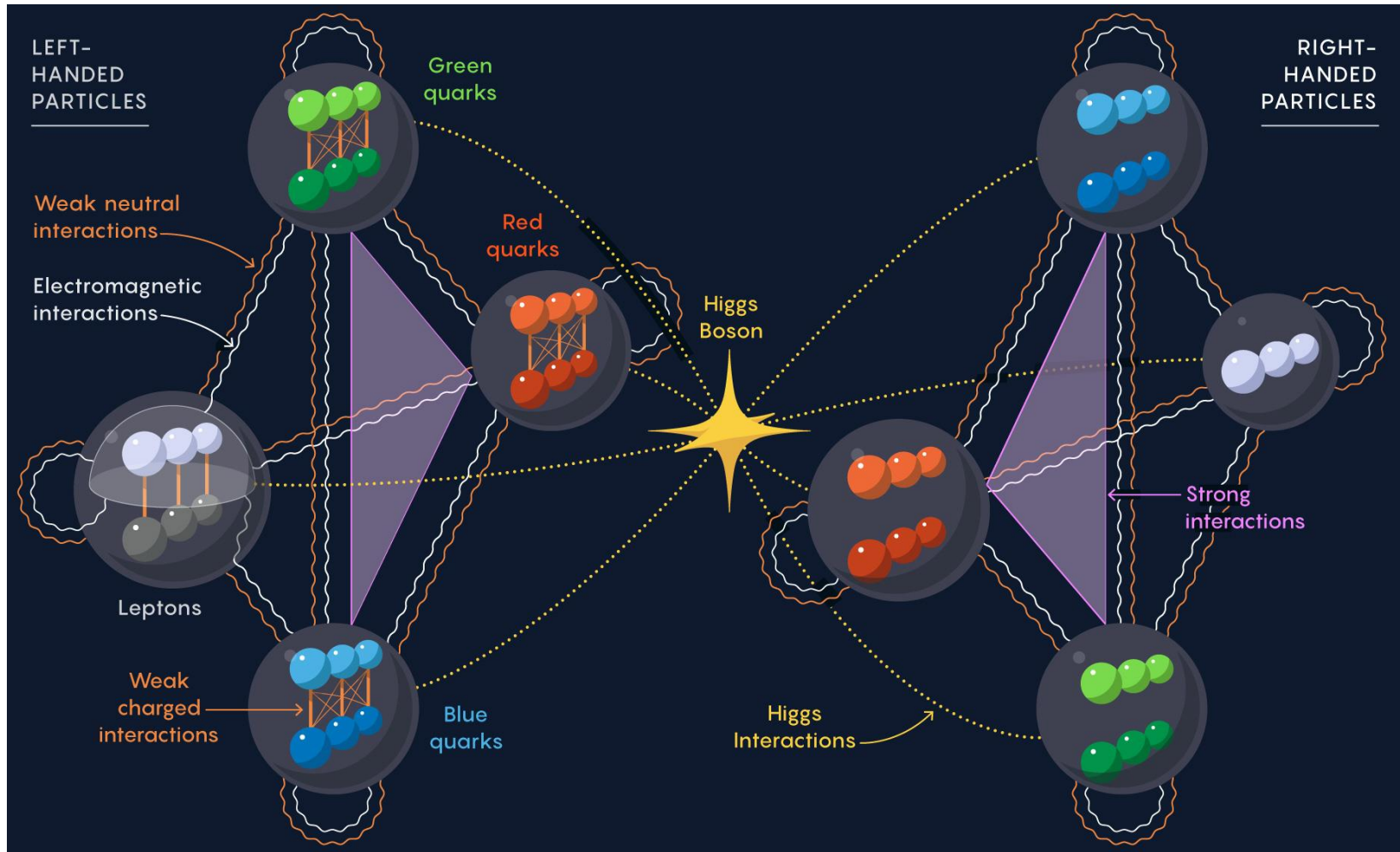
Particles of the Standard Model



● QUARKS ● LEPTONS ● BOSONS ● HIGGS BOSON

US Dept. of Energy

SM Particles and Interactions

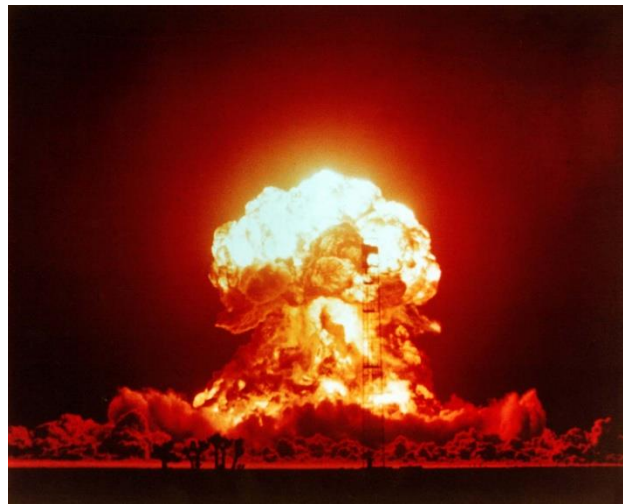


Chris Quigg / Quanta Magazine

Energy \leftrightarrow mass

Einstein: $E = mc^2$

All matter contains energy, stored in its mass



Conversely, need lots of energy to make a massive particle like the Higgs boson

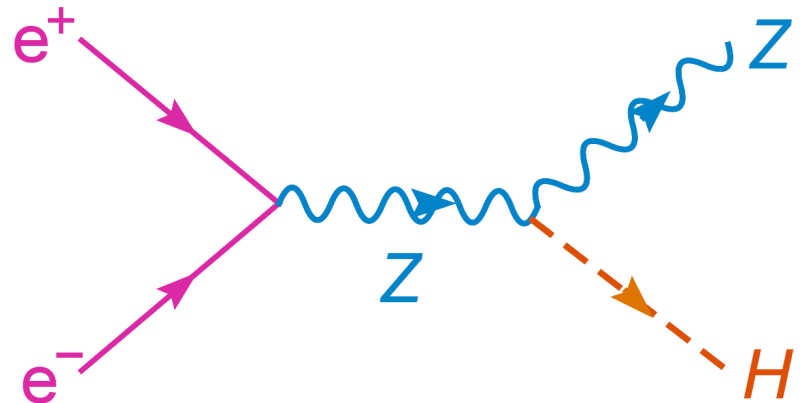
Particle Physics in late 1990s

- **All other particles** of Standard Model except Higgs boson had been detected
- Indirect “**virtual effects**” of Higgs boson suggested it could be within range of three large particle accelerators, so **direct search began in earnest**

Direct Search – late 1990's



LEP2 at CERN, 1996-2000
– enough energy to make
Higgs boson (if light enough)



“Clean machine” – could see Higgs boson no matter how it decays

Unfortunately, ran out of energy and didn't see it

→ Higgs mass more than 120 proton masses (114 GeV)

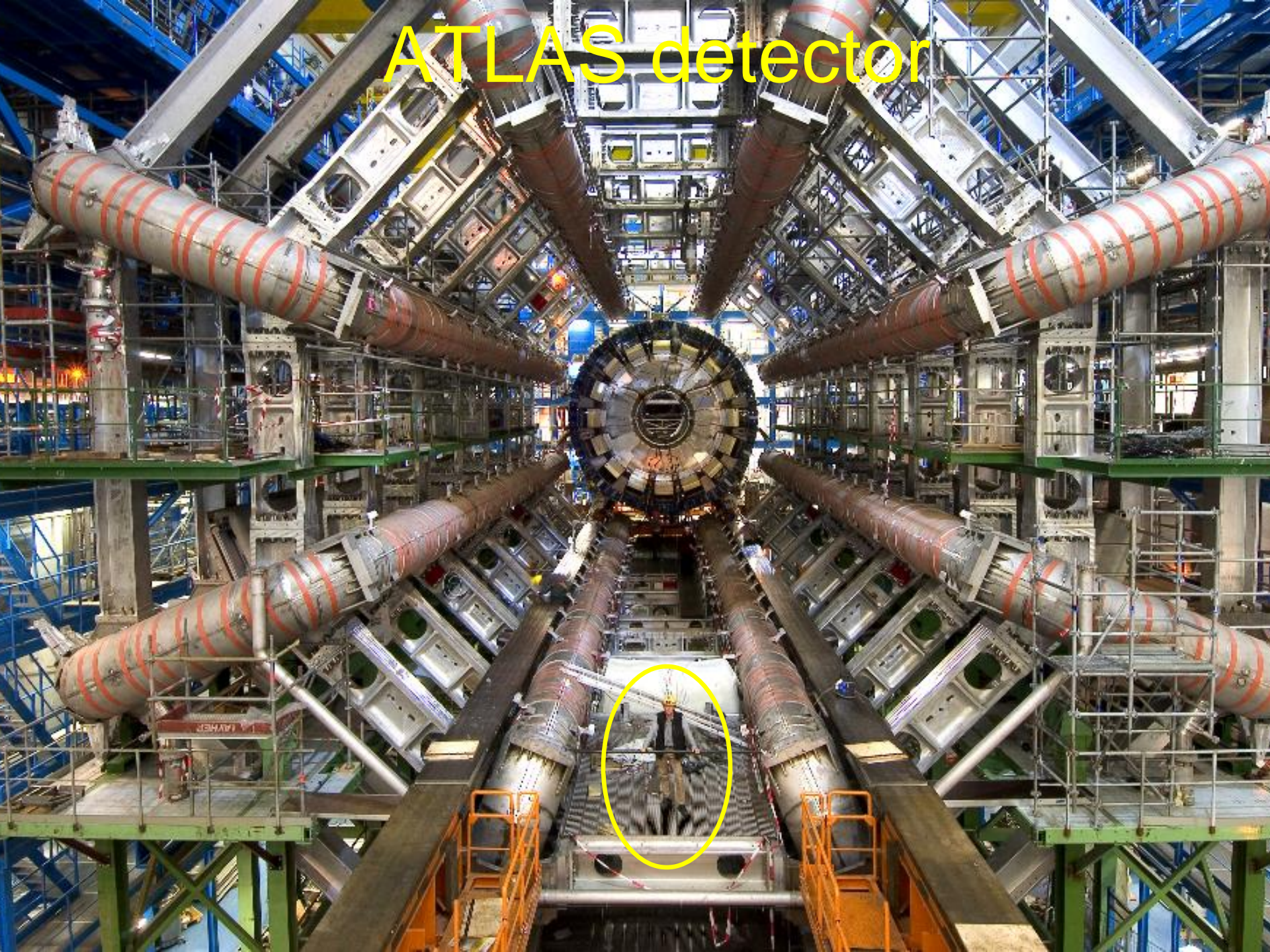
→ By year 2000, Higgs had to be between 120 and 180 proton masses (or else Standard Model was wrong)

The Large Hadron Collider

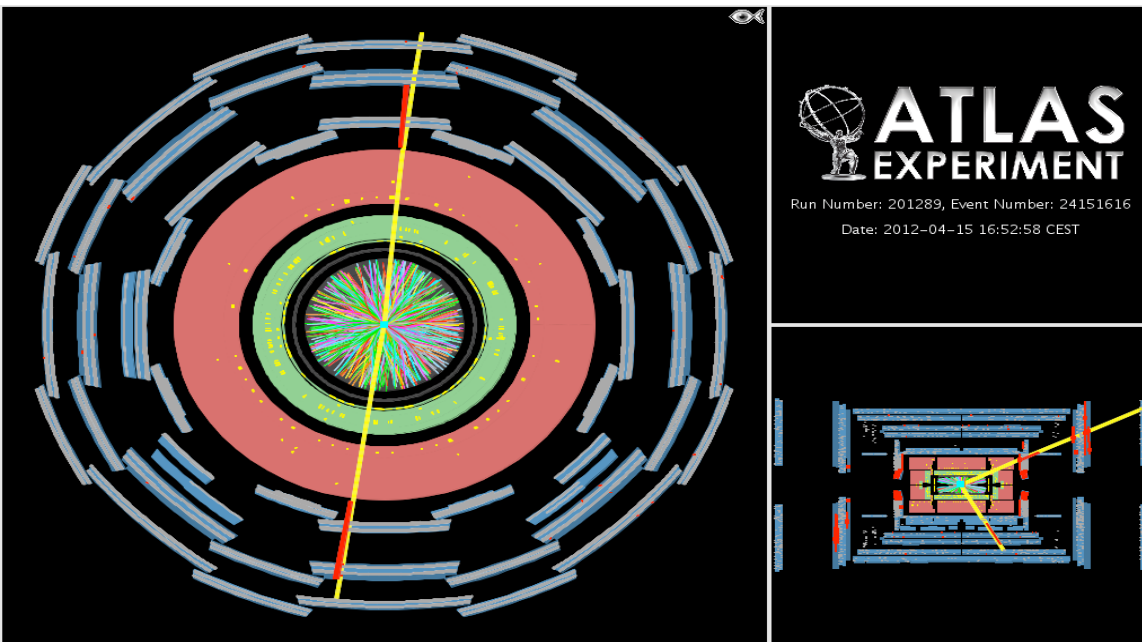


- proton-proton collider in LEP tunnel at CERN: 2008 → 2042
- World's highest energy particle collider by factor of 7
- Very complex collisions!

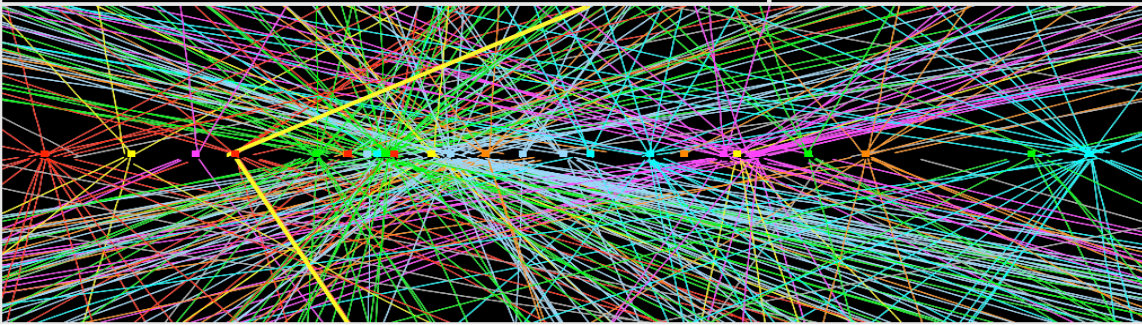
ATLAS detector



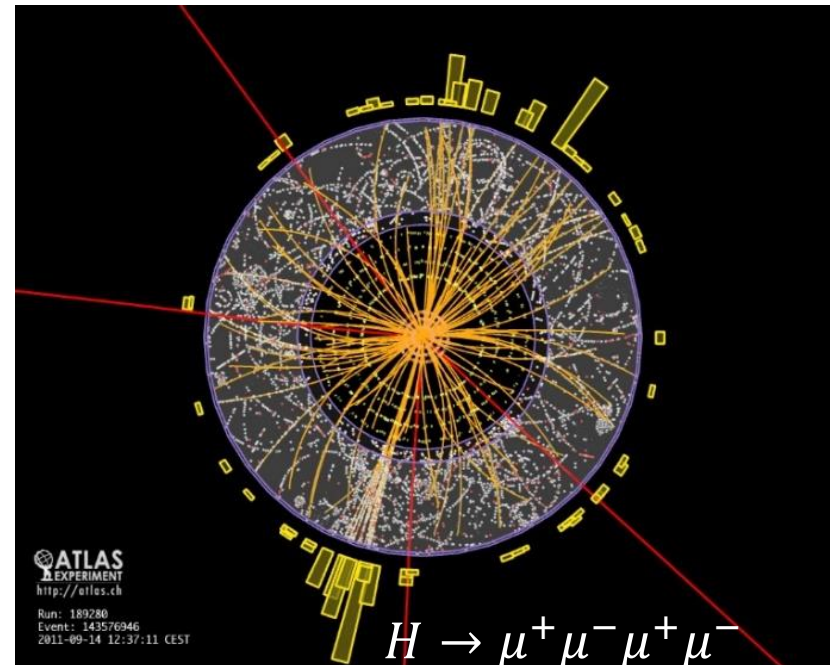
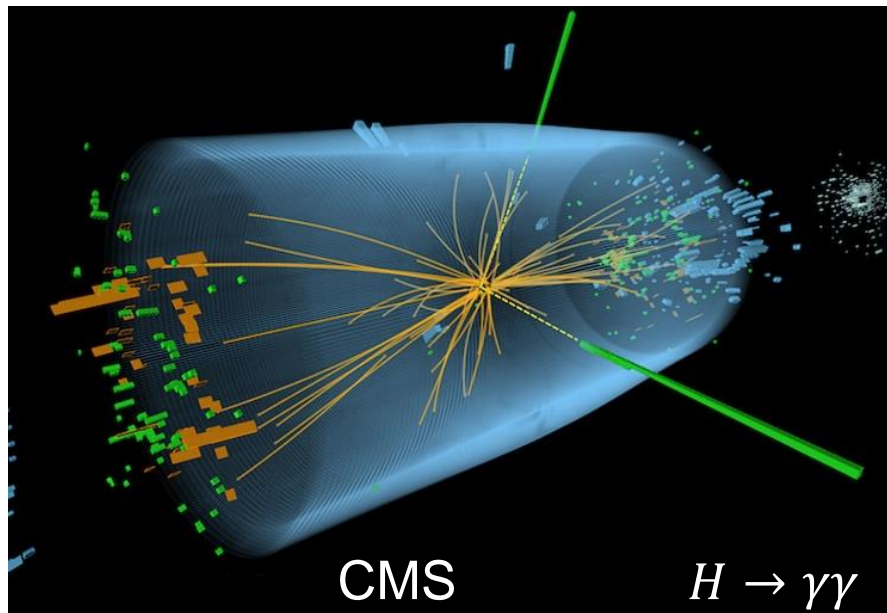
LHC: the ultimate data firehose



- 25 - 100 simultaneous proton-proton collisions
- Repeated **20 million times a second!**
- Can only afford to save hundreds of events per second for later study.
- Electronics decides **very quickly** which events to keep.



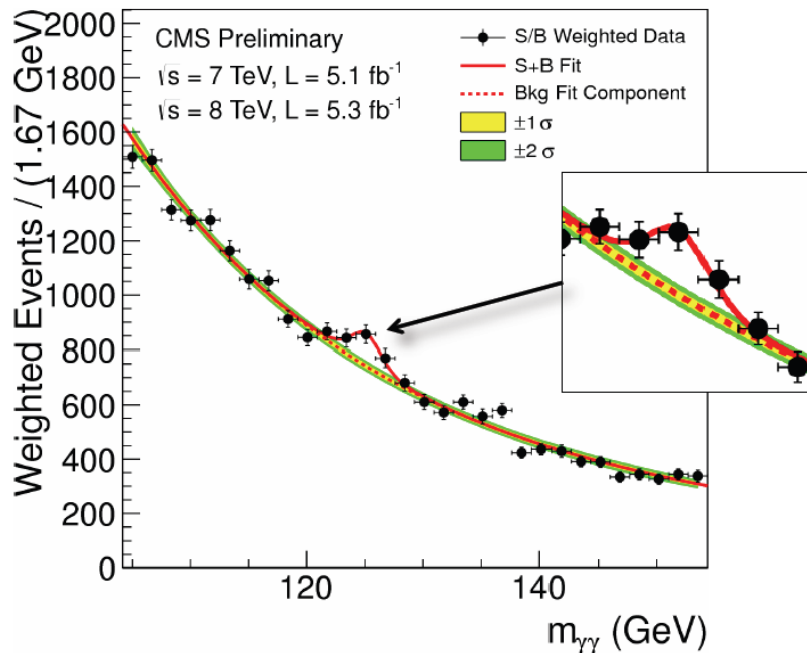
A few events, out of trillions



After a long hunt, culminating at the Large Hadron Collider, Higgs boson was found!

Mass = 133 proton masses = 125 GeV

July 4, 2012



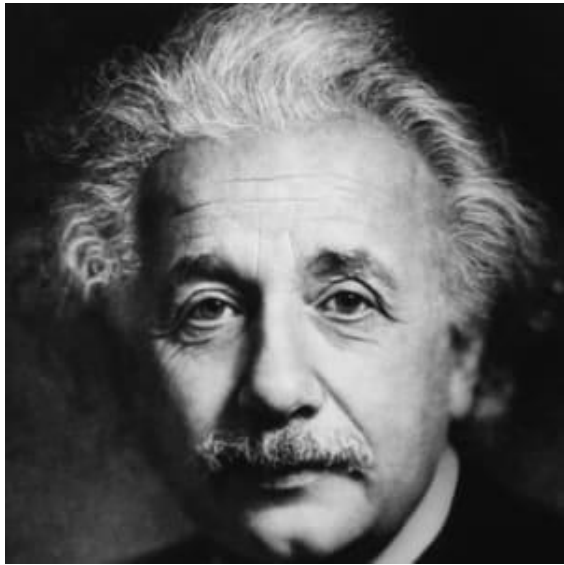
July 4, 2012

Joe Incandela, UCSB

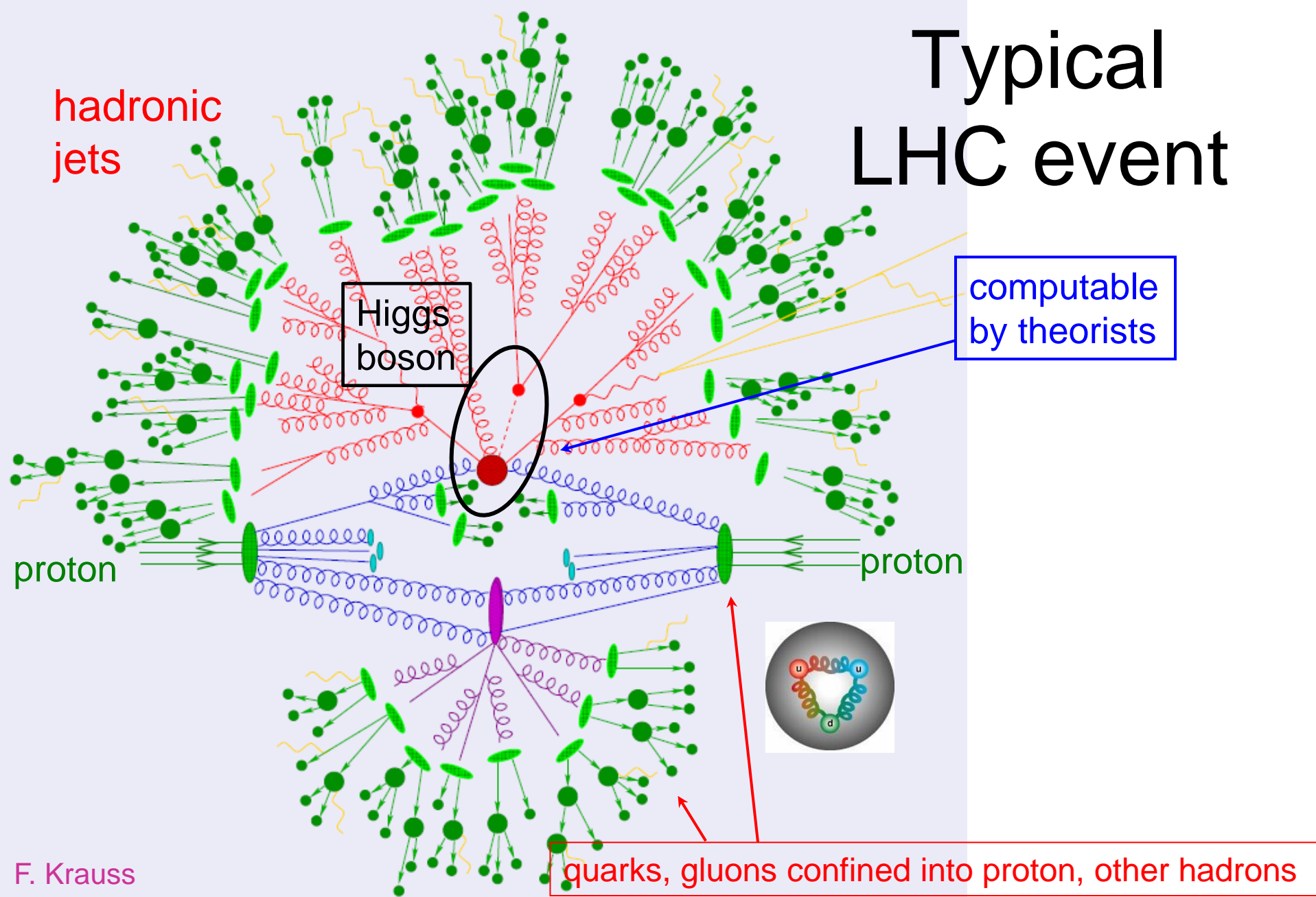


Part III

A secret connection

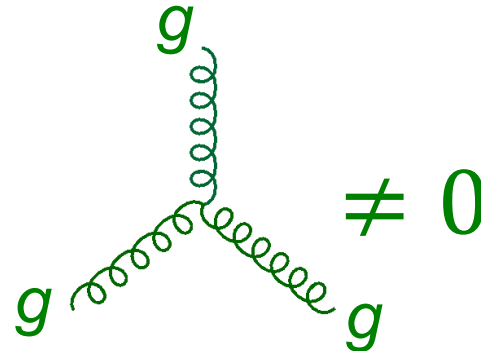
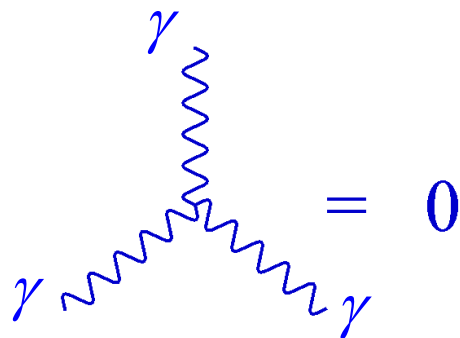


Typical LHC event

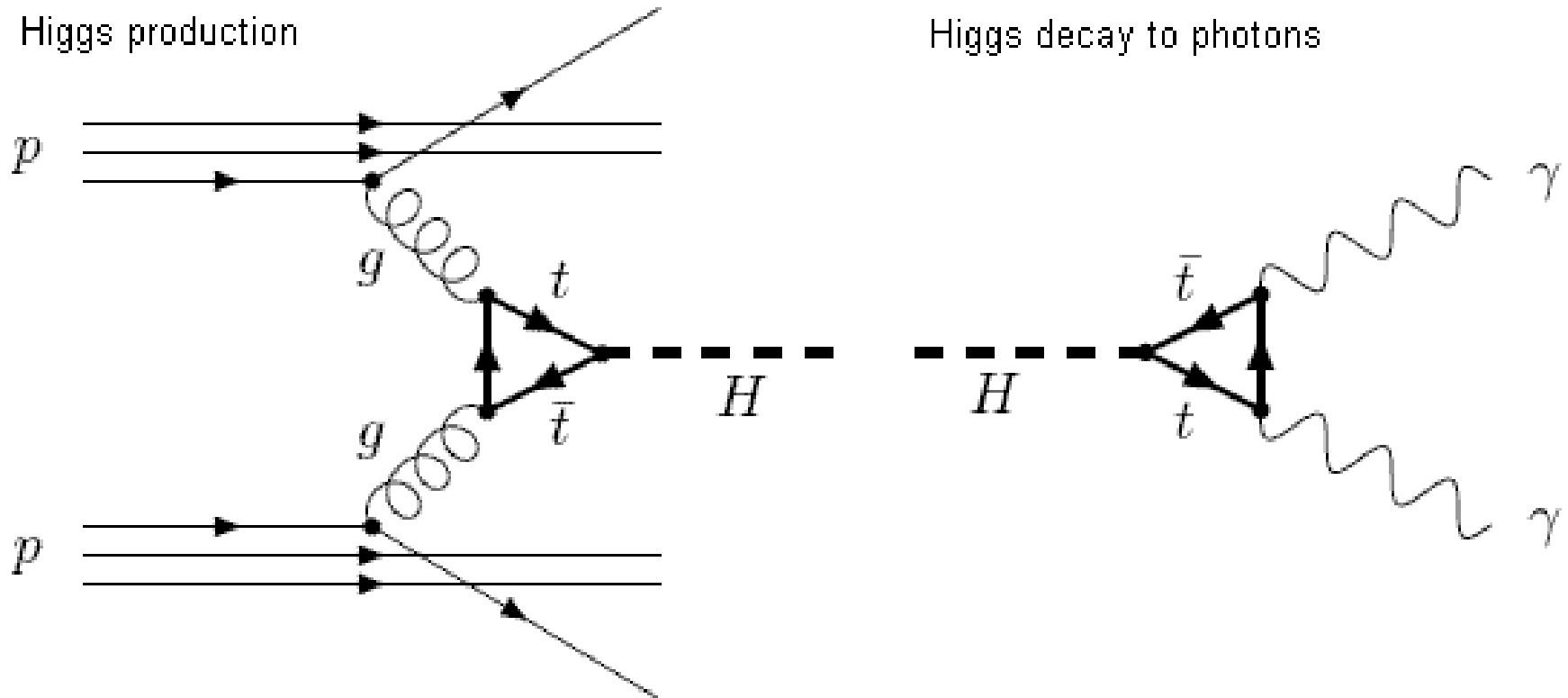


At the heart of the LHC

- Most events due to the **strong force**, called **quantum chromodynamics (QCD)**, a Yang-Mills theory
- Force carried by **gluons (g)**, a nonlinear cousin of the **photon (γ)**

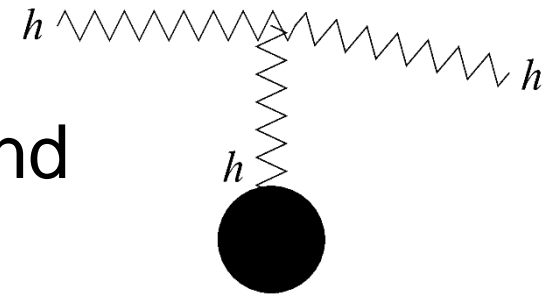


Gluons used to produce most Higgs bosons at LHC



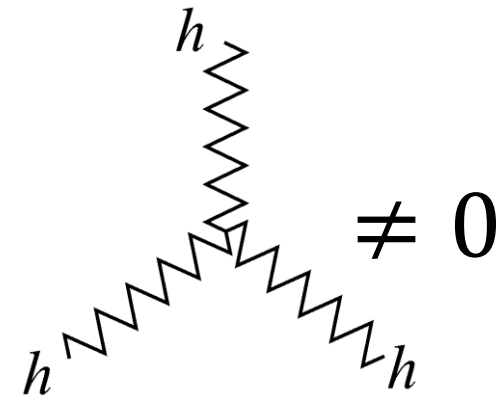
Gravity nonlinear too

- Black holes “made out of” curved space-time, bend both light and gravitational waves
- Can interpret as due to nonlinear interactions of particles called gravitons h



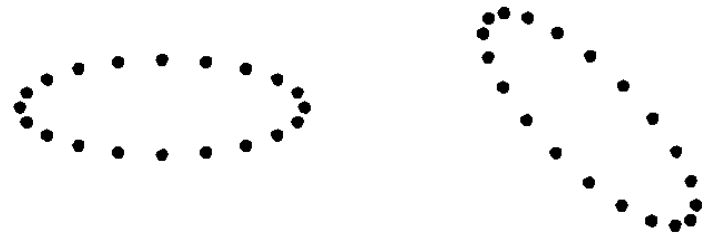
GRAVITY IS A

WAVE!

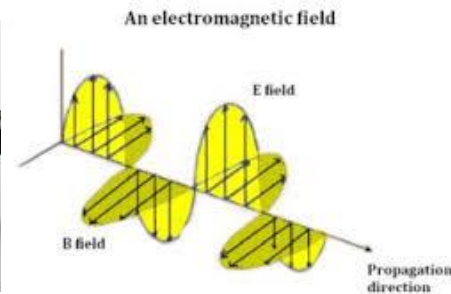


Both theories have massless spinning particles

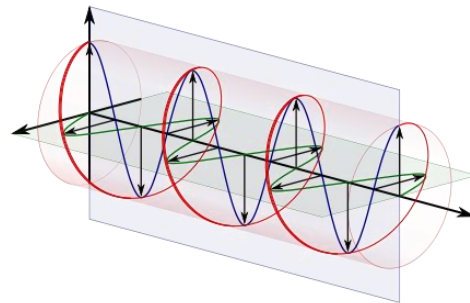
- Graviton: 2 polarizations at $45^\circ \rightarrow$ spin 2
- Gluon, like photon, has 2 polarizations at $90^\circ \rightarrow$ spin 1



D. Zawischa



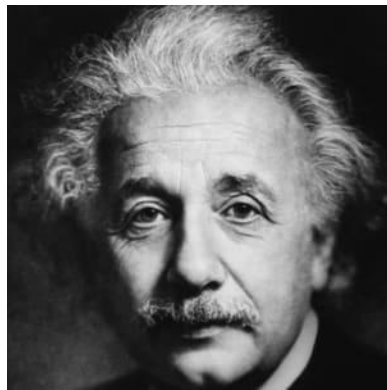
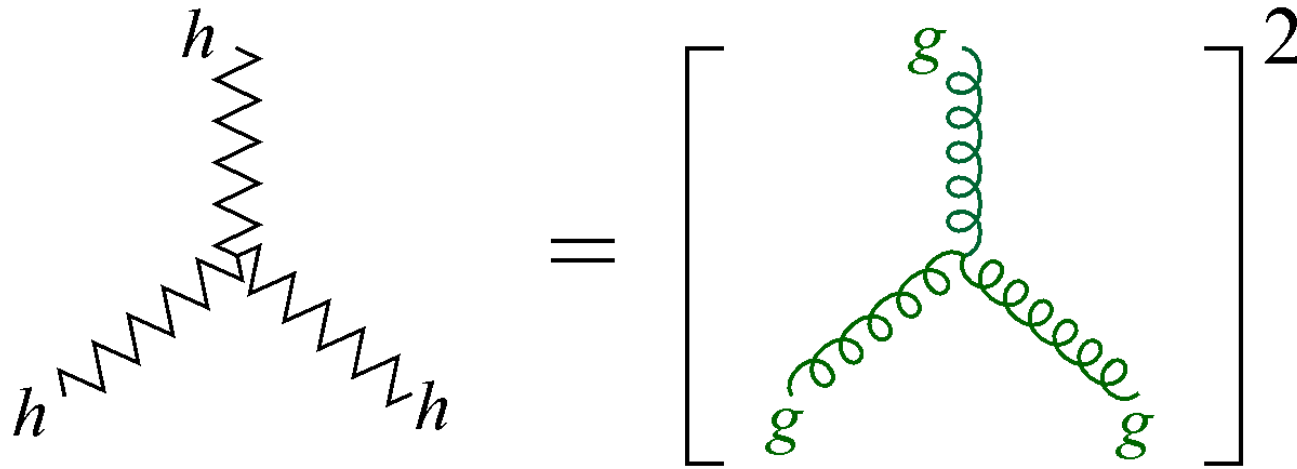
Circular polarization
 \Leftrightarrow helicity basis



$$(\hat{x} + i\hat{y})^2$$

$$\hat{x} + i\hat{y}$$

The Secret: Gravity = (Yang-Mills)²



=

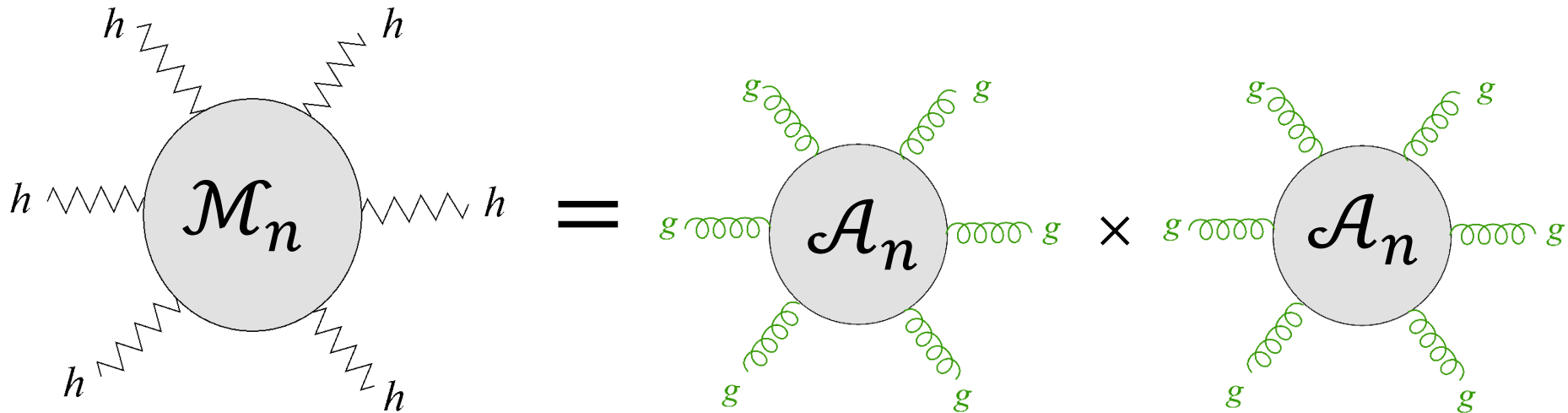
(



)²

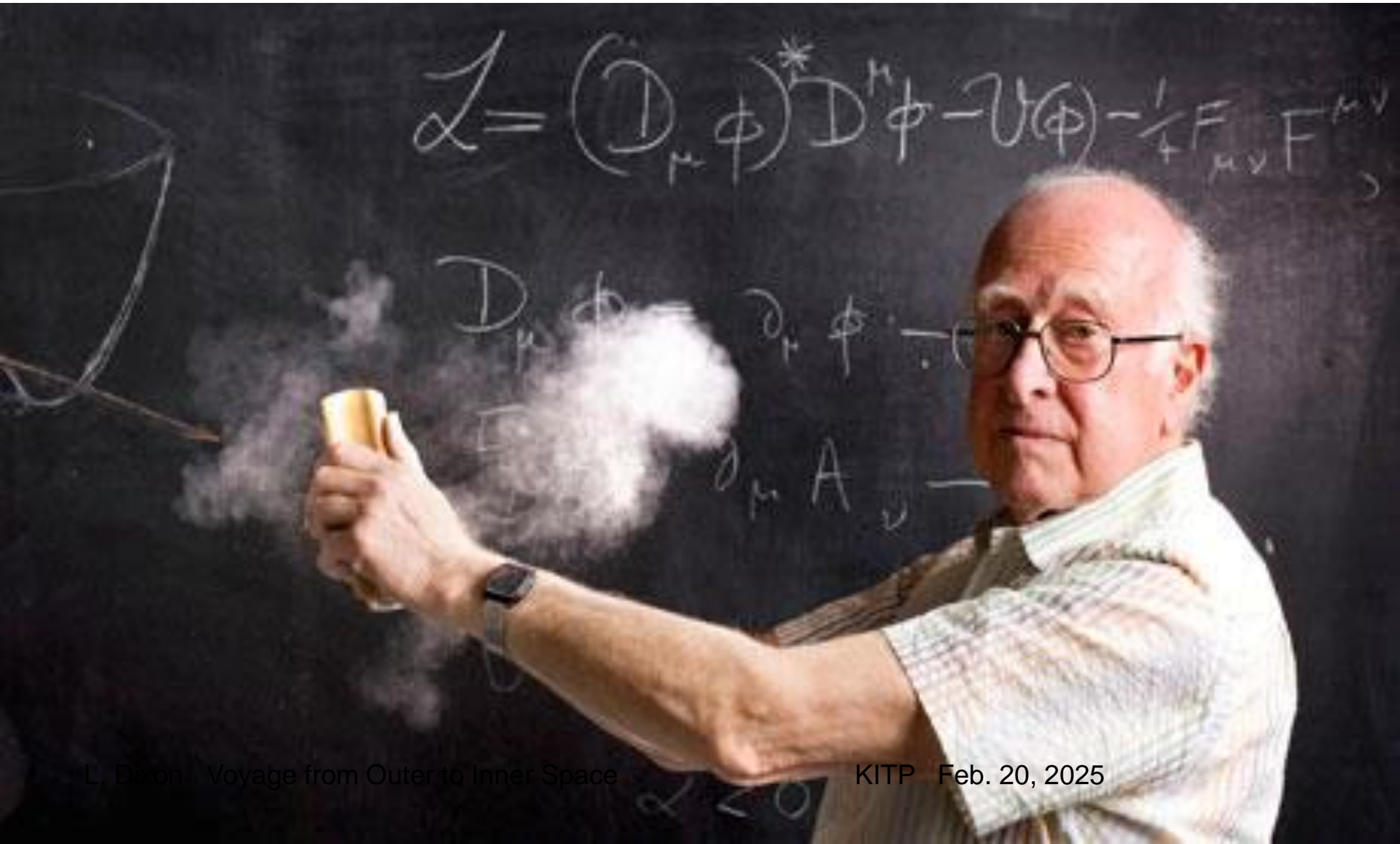
Gravity = YM^2 beyond 3 particles

Kawai, Lewellen, Tye (1985); Bern, Carrasco, Johansson (2008)



- Can actually use such mathematical relations to help predict gravitational waveforms more precisely for LIGO!
- Inner and outer space are secretly related!

Are we done?



GWs – Absolutely Not!

- A previously **unseen universe** has been opened up by LIGO!
- It and future ground-based laser interferometers will see **far more**
- **Space-based interferometer** (LISA) will see events involving **supermassive** black holes
- Ideas for GW detectors using **atom interferometry**
- **Pulsar timing arrays** may have seen **very low frequency** GWs already (NanoGrav)

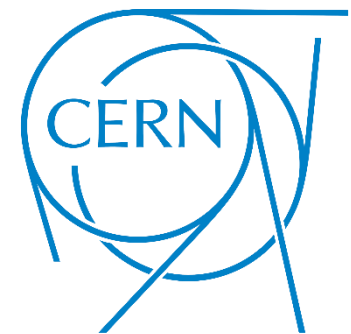
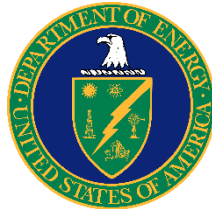
The Higgs boson – Absolutely Not!



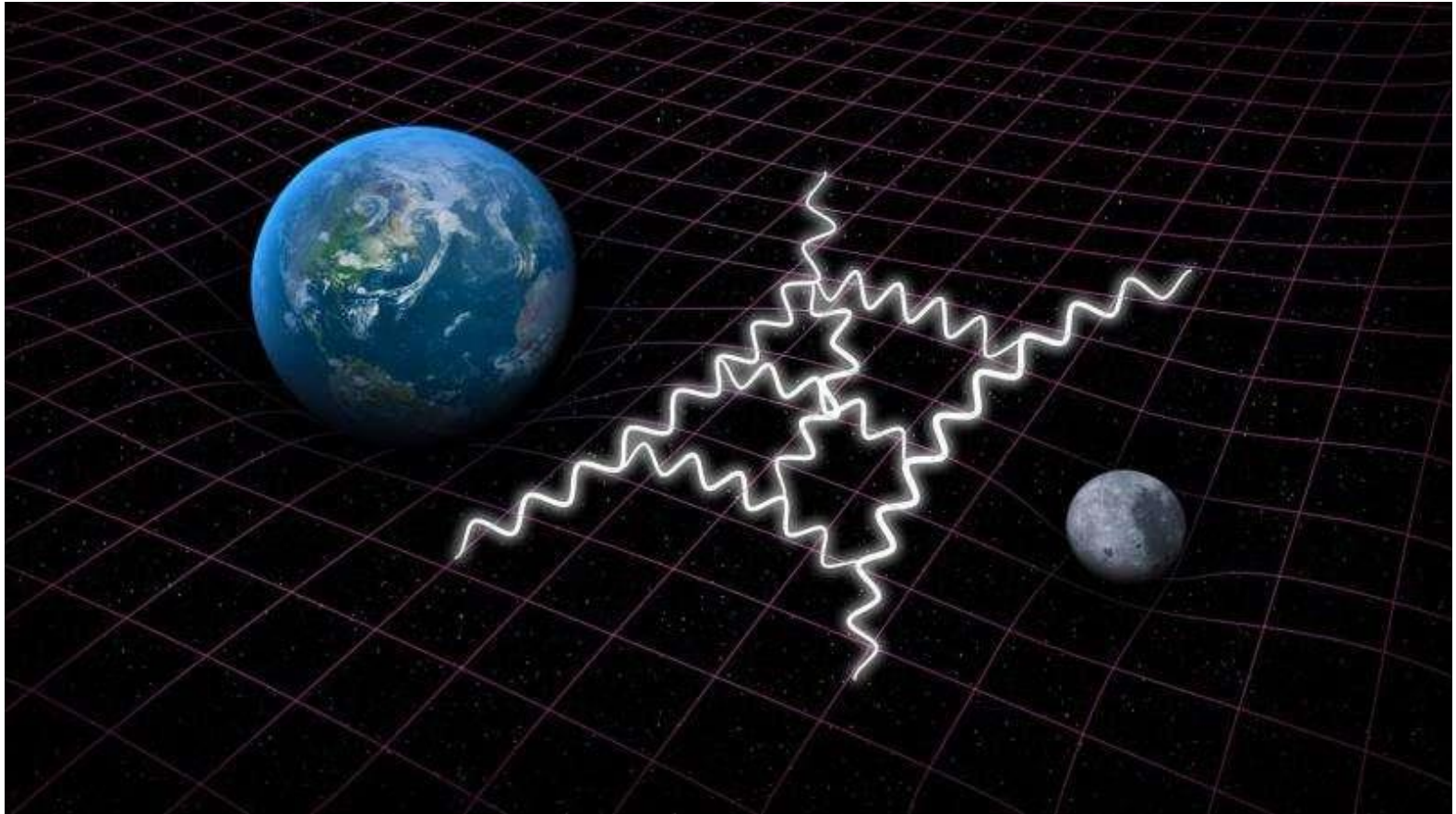
- We need to study this particle **very closely** because it is such a **central part** of the **Standard Model**
- It might be a **portal or window** to physics **beyond** the Standard Model, including **dark matter**
- **LHC can still improve our understanding, but other, future colliders could go much further**

Enabling voyages of discovery

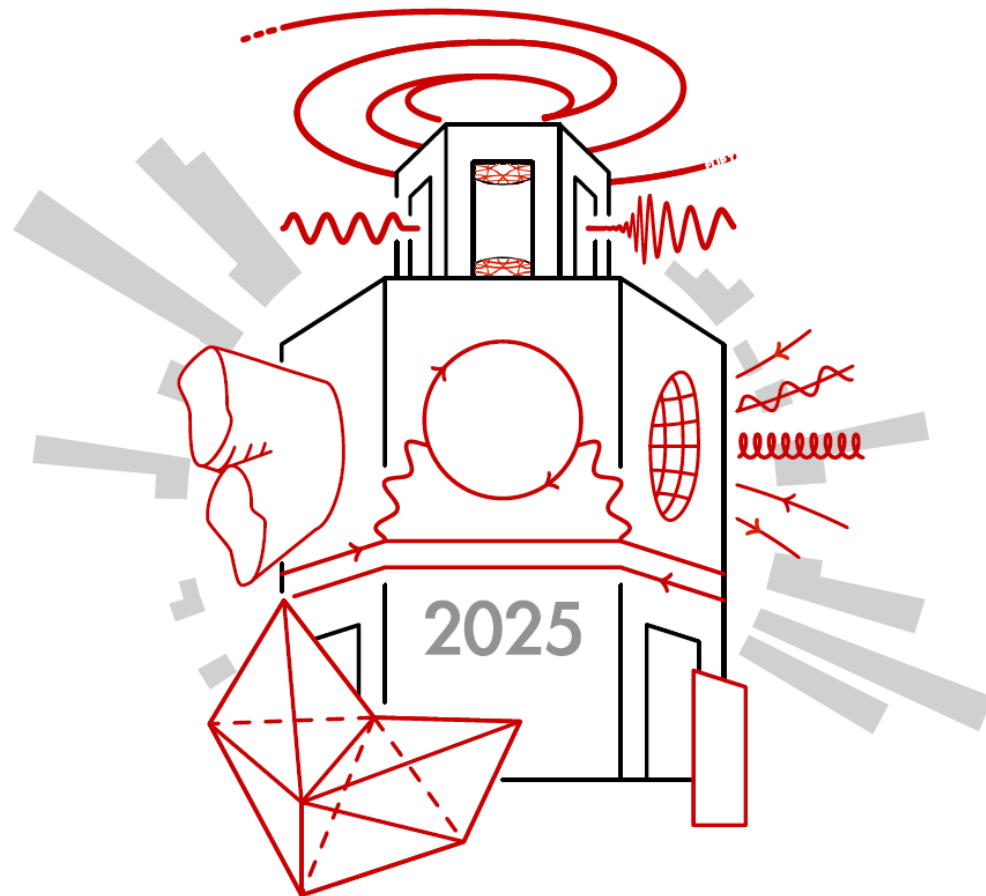
- Research at a scale **beyond individual investigators and universities**
- Funded by far-seeing **national governmental agencies**
- And an **international laboratory with member countries**, to which the US contributes



Many thanks to you, the taxpayer,
for enabling this journey!



Extra slides



KITP Program "What is Particle Theory?" – logo by Flip Tanedo

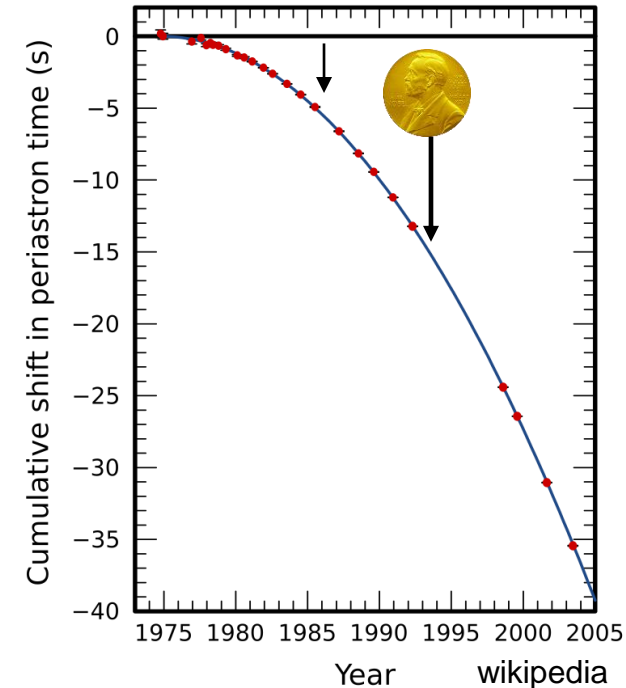
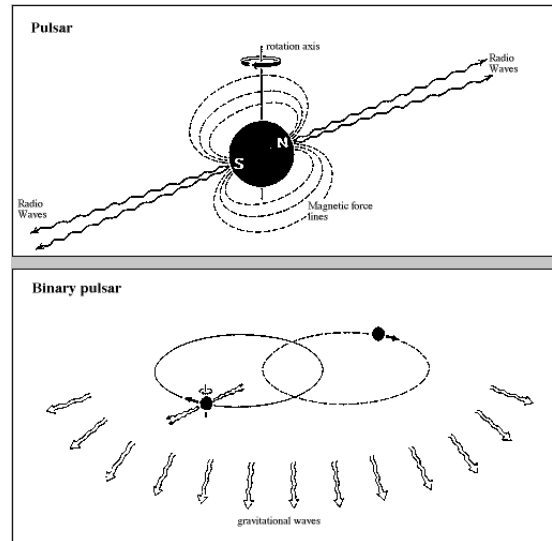
Precursor to GW discovery

on my PhD oral exam committee

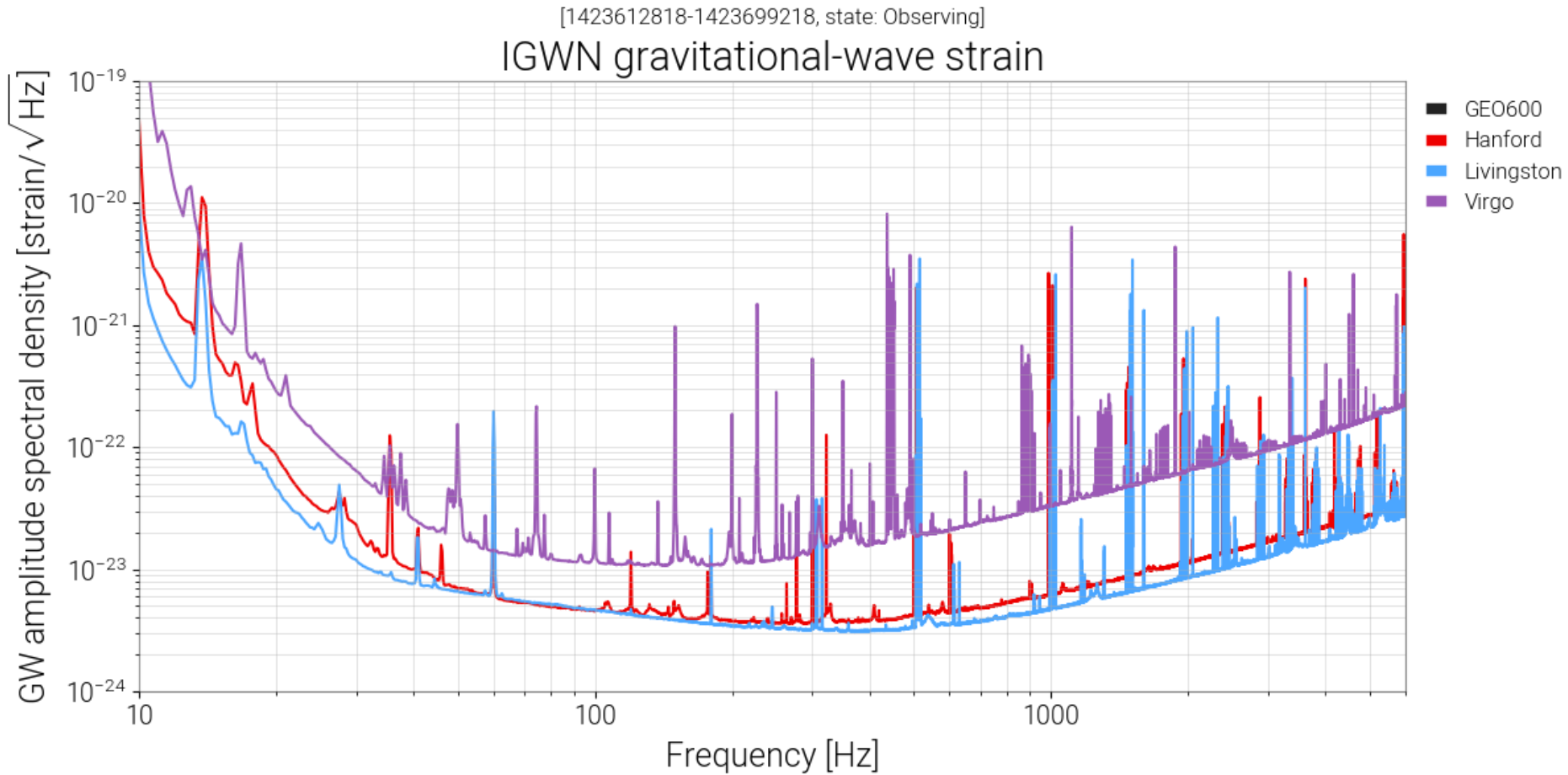
- Russell Hulse, Joseph Taylor
- Binary Pulsar:** 2 neutron stars orbiting at
~ earth-moon distance → very precise clock.



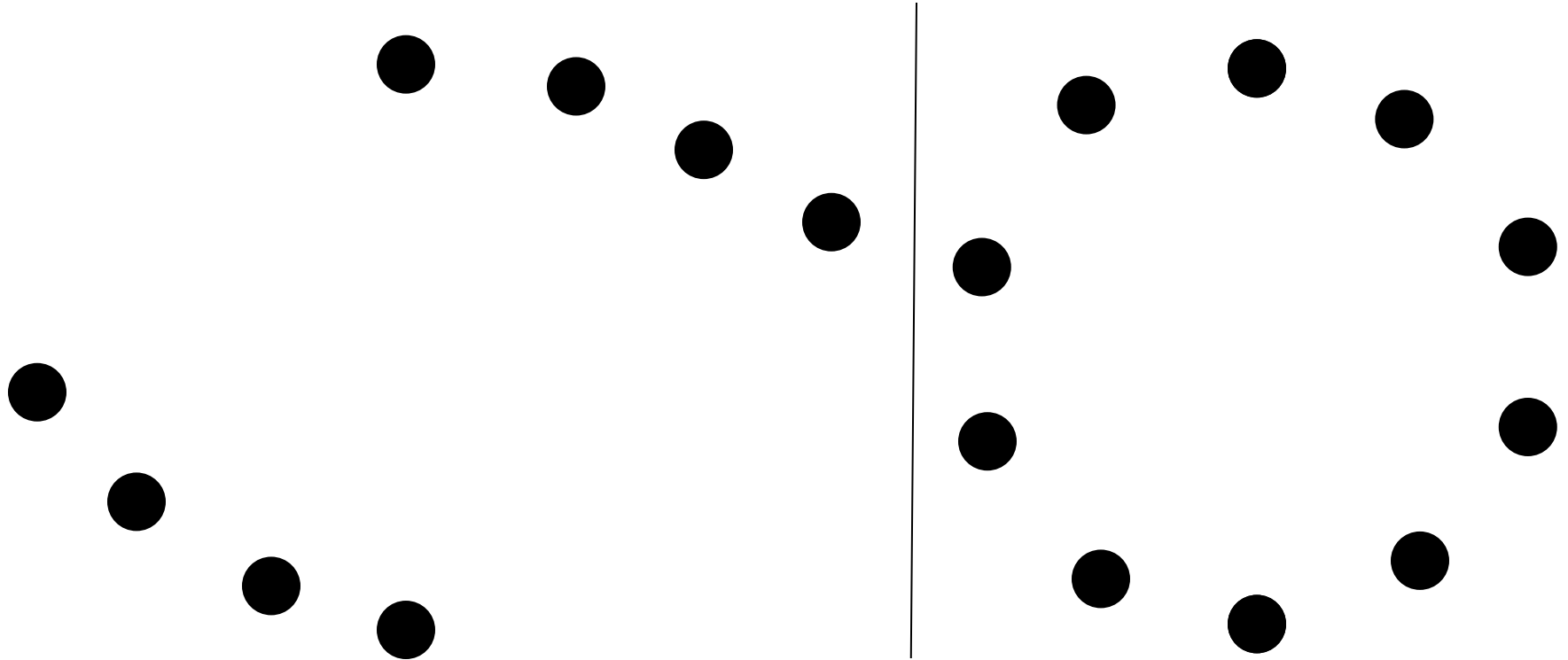
- Watch orbit decay
and precess
due to **loss of energy to GWs**



LIGO/VIRGO noise curve last Saturday

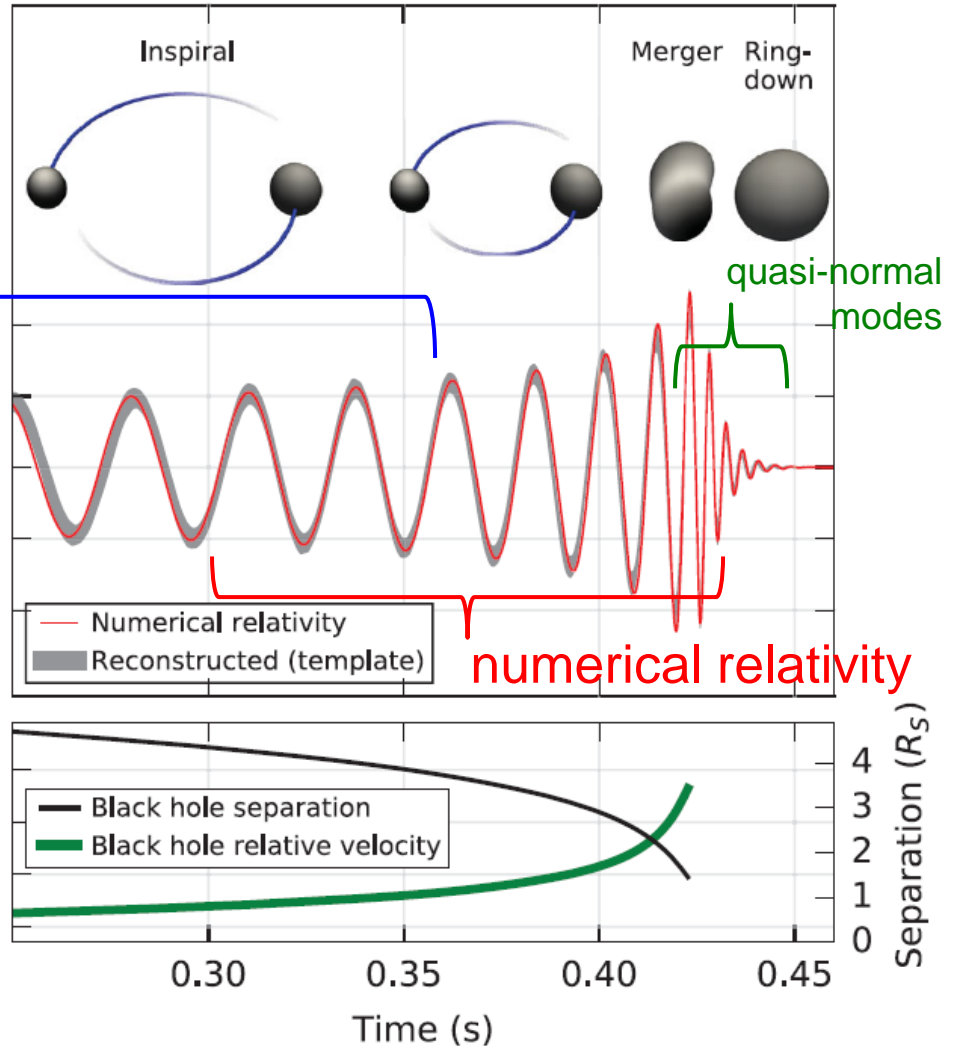


Black hole scattering vs. inspiral



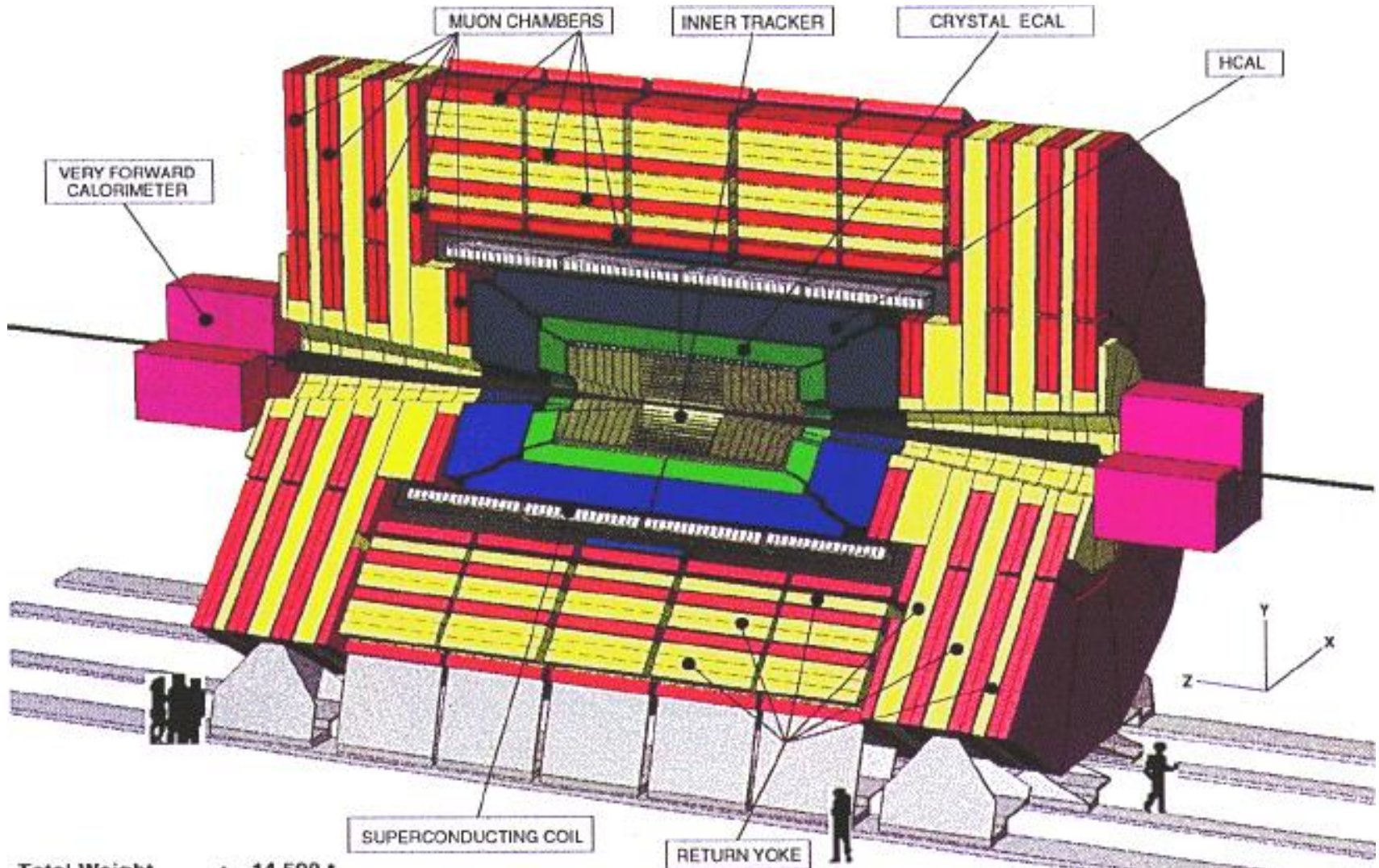
Typical LIGO Event

nonlinearities small,
perturbatively
calculable



NS-NS mergers @ LIGO/VIRGO/...
or BH's @ LISA
→ many, many cycles
in perturbative regime
→ phase of orbit can be measured
very precisely

CMS detector

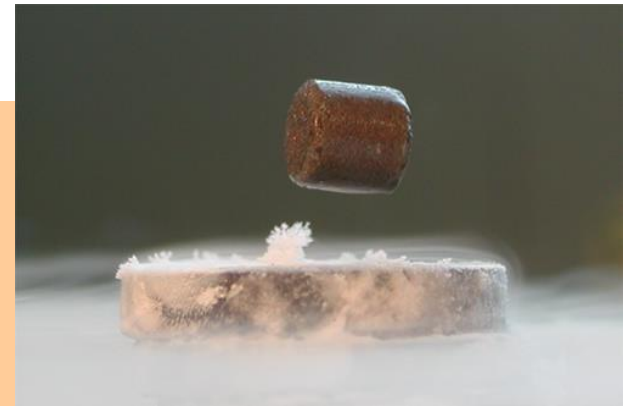


Total Weight : 14,500 t.
Overall diameter : 14.60 m
Overall length : 21.60 m
Magnetic field : 4 Tesla

Higgs mechanism

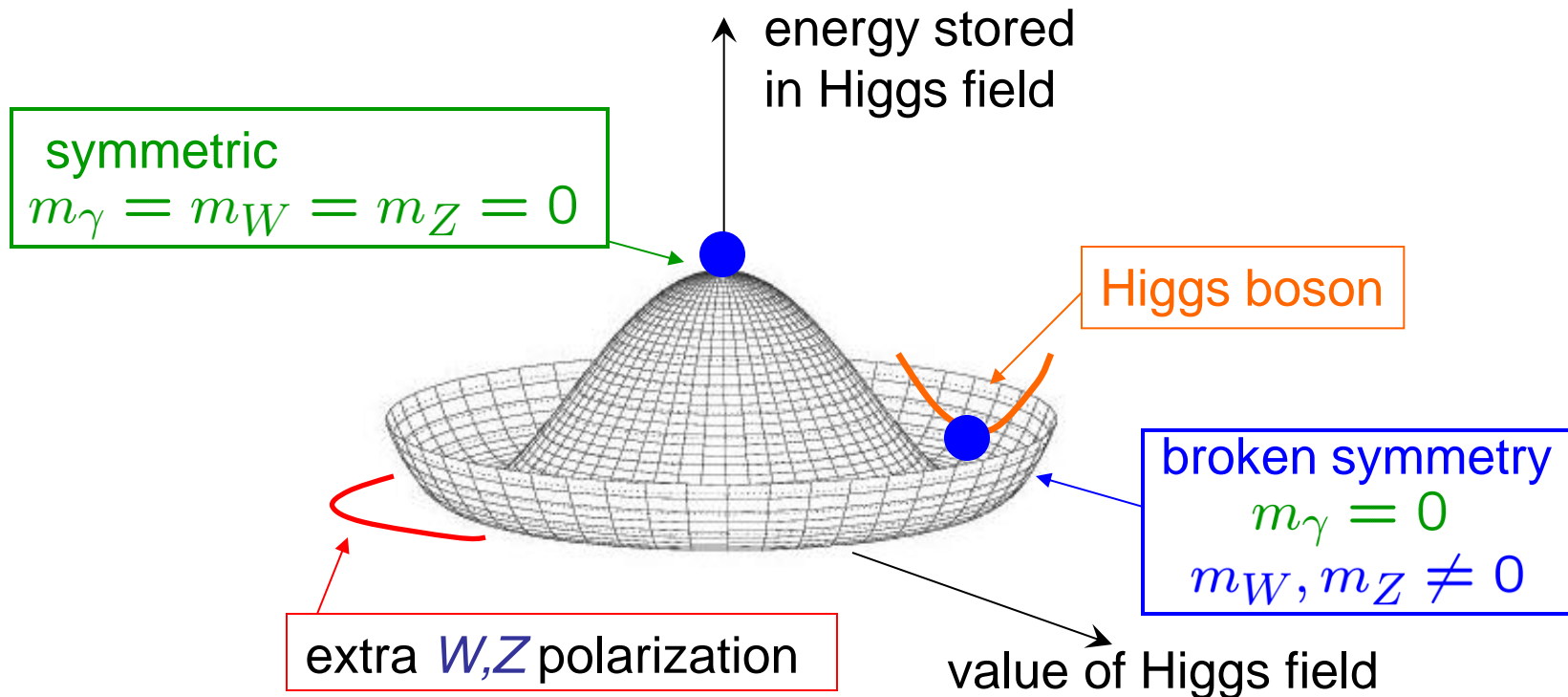
– the ultimate superconductor

- Fills entire universe
- Universe has been superconducting since a billionth of a second after the Big Bang
- Excludes **weak** magnetic fields a trillion times more effectively than the strongest **electromagnetic** superconductor (1/100th of proton radius is really short!)



Higgs mechanism & broken symmetry

- “Mexican hat” describes energy contained in Higgs field as a function of its value.
- Minimized for nonzero values.
- Why energy should have this form is still a mystery.



“I want to be considered the **Michael Jordan of subatomic particles**. Michael Jordan might not have been the most physically gifted player in



the history of the N.B.A., but nobody worked harder at his game than he did. That’s what I’m all about. Whether it’s **giving mass to matter, breaking electroweak symmetry,** or explaining the origin of the universe and whatnot, I believe I can do it all.”

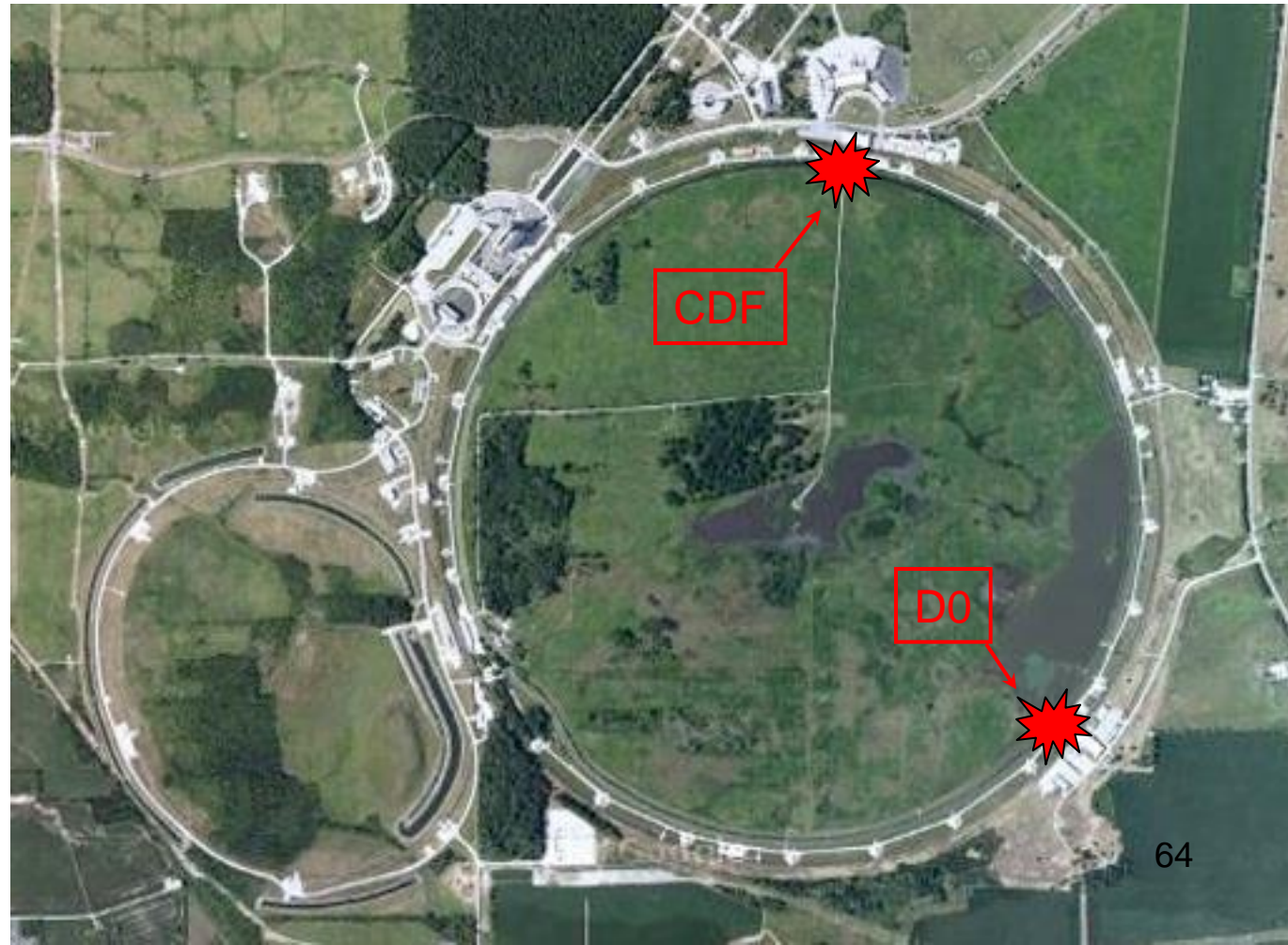
- Higgs Boson, interviewed in the New Yorker

On to the Proton Colliders: Tevatron and then LHC

Tevatron, Fermilab, Illinois 2001 → 2011

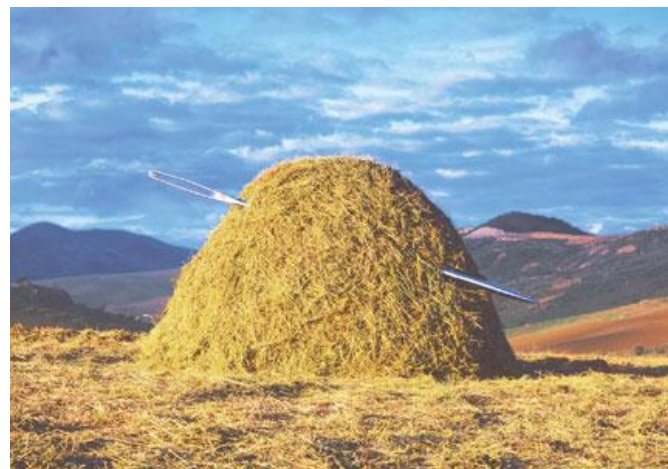
10 times energy
of LEP2

collisions very
complicated,
lots of particles,
difficult
backgrounds
(as at LHC)



Tevatron oh so close...

Over 1000 Higgs bosons made, but **almost** all hopelessly buried in backgrounds



In the end, Tevatron experiments could not claim **discovery** of Higgs boson (5σ)



- Found **evidence** (3σ) for Higgs boson in decay to pair of ***b*** quarks – a decay also observed later at LHC

