Big Questions?

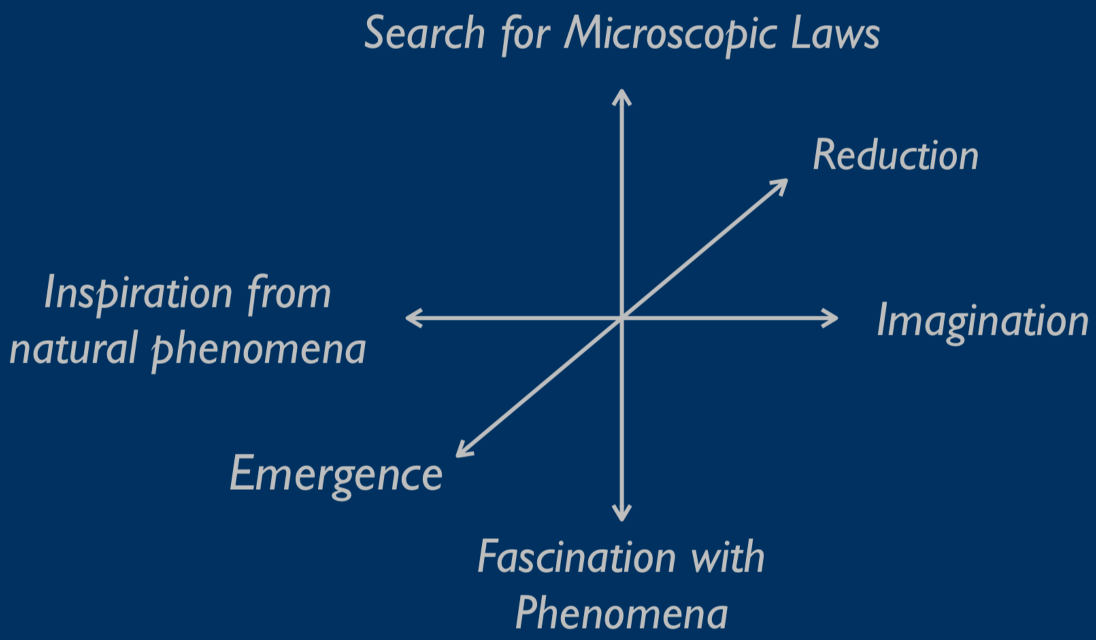
Ultima Thule, 1927, Public domain, via Wikimedia Commons

S. James Gates, Jr.

07 March 2020

Styles of investigation

Observation · Experiment · Phenomenology · Formal Theory

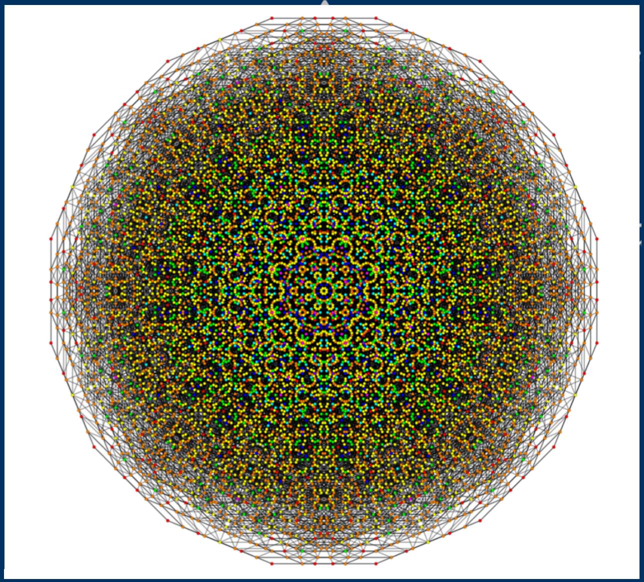


Where is your home base? How far do you roam?

Styles of investigation

Observation · Experiment · Phenomenology · Formal Theory

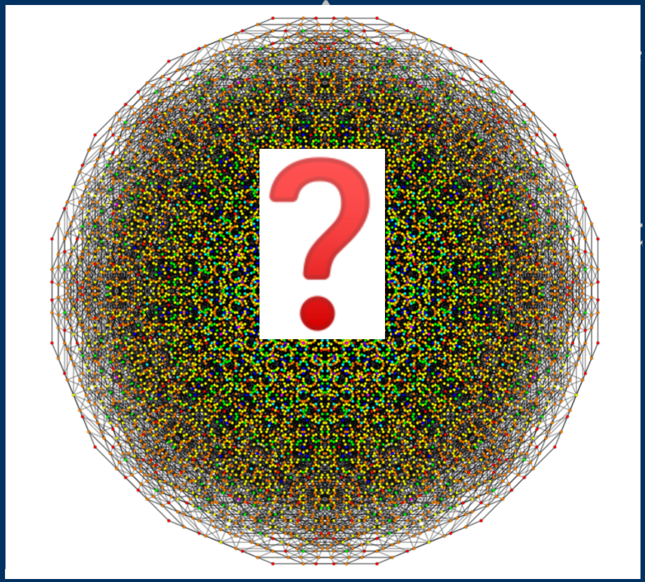
Search for Microscopic Laws



Styles of investigation

Observation · Experiment · Phenomenology · Formal Theory

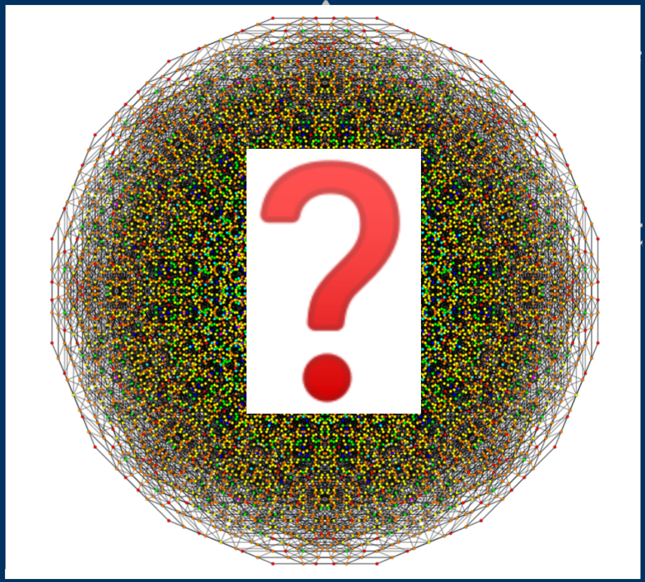
Search for Microscopic Laws



Styles of investigation

Observation · Experiment · Phenomenology · Formal Theory

Search for Microscopic Laws



Ultima Thule, 1927, Public domain, via Wikimedia Commons

Dreams Fulfilled

FERMIONS
matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2		
Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

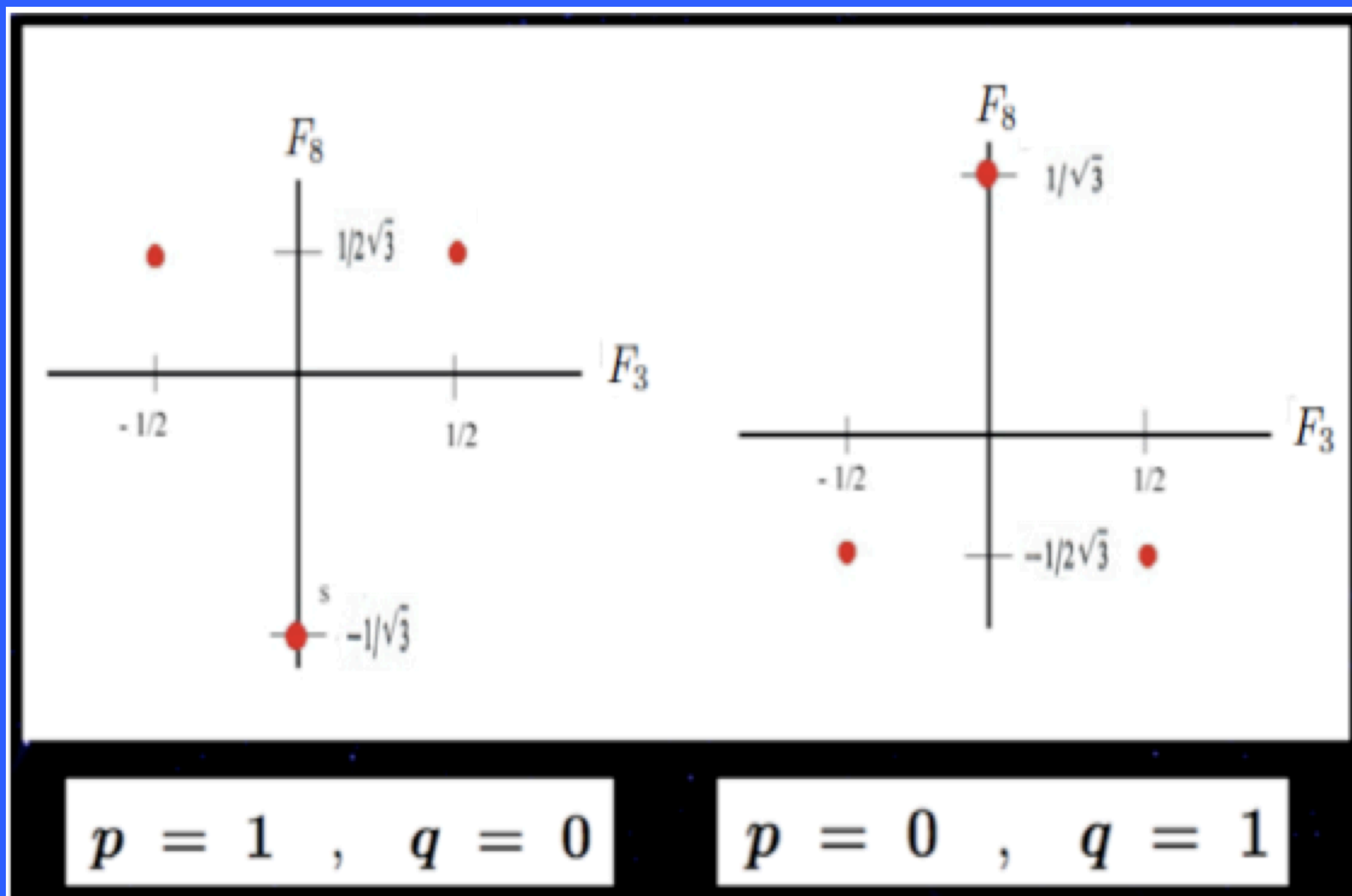
BOSONS
force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

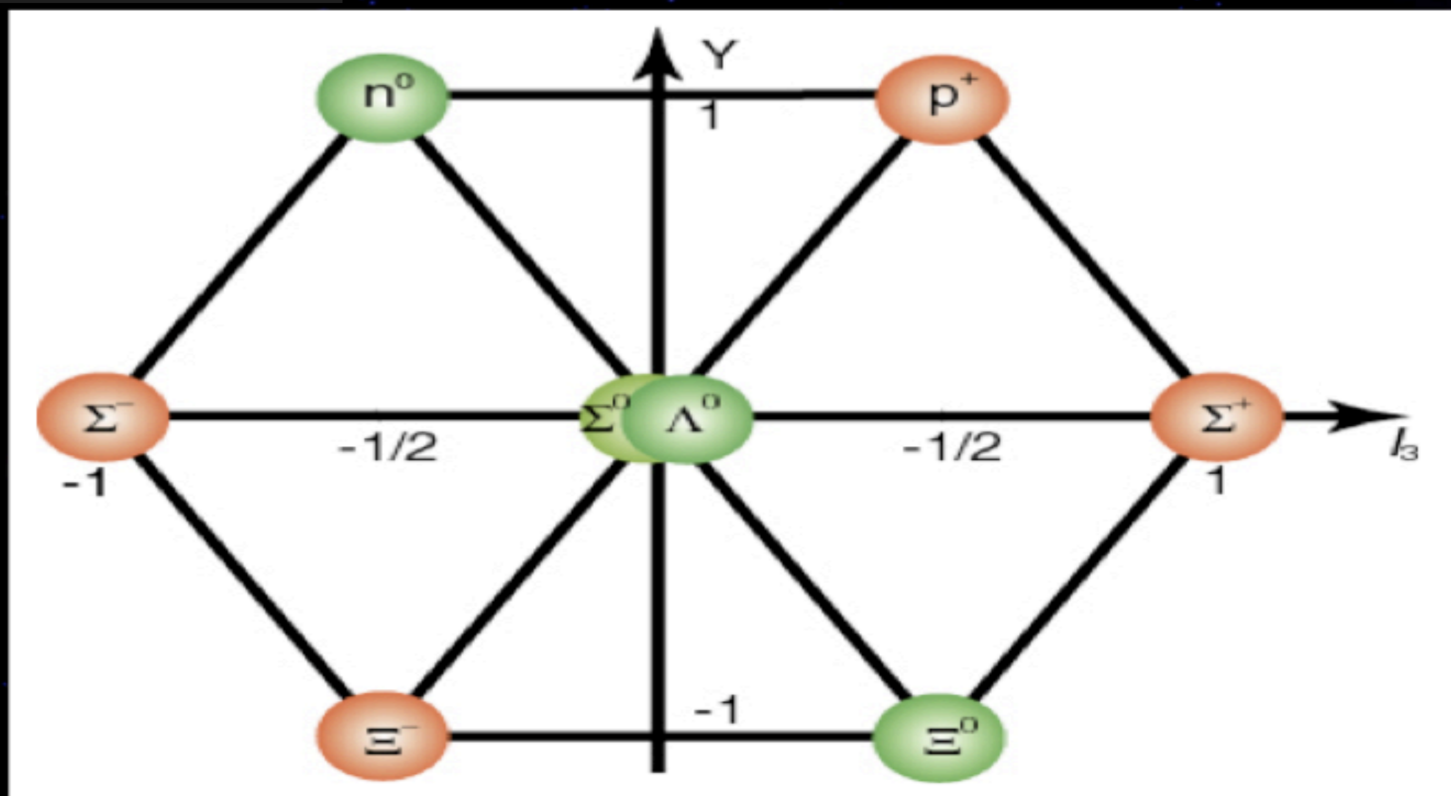
PROPERTIES OF THE INTERACTIONS

Property \ Interaction		Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:		Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:		All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:		Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at:	10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
	3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus		10^{-36}	10^{-7}	1	Not applicable to hadrons	20


F_8
$1/2\sqrt{3}$
F_3
- 1/2
1/2
$-1/\sqrt{3}$
F_8
$1/\sqrt{3}$
F_3
- 1/2
1/2
$-1/2\sqrt{3}$
$p = 1 \quad , \quad q = 0$
$p = 0 \quad , \quad q = 1$

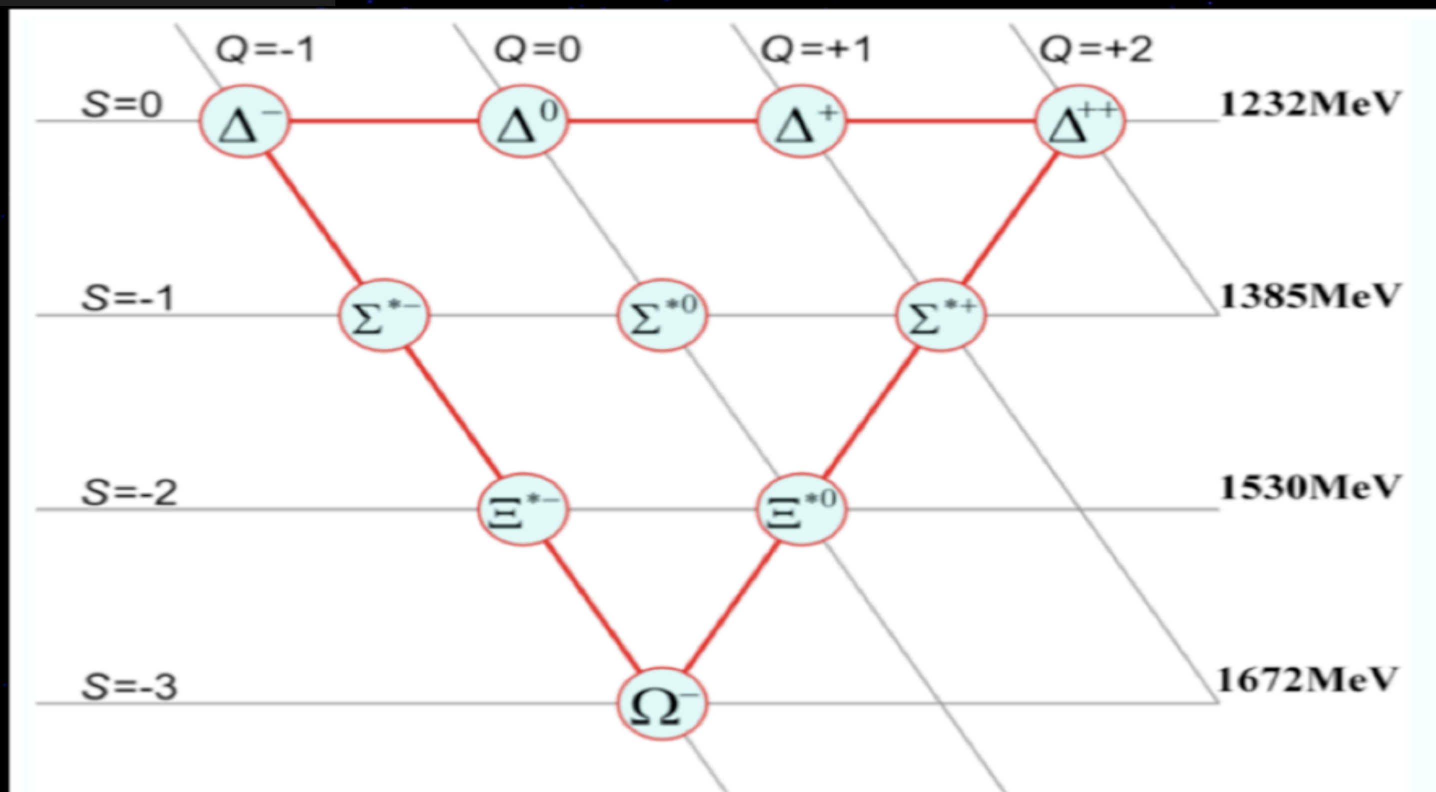
[redacted]

$$p = 1 \quad , \quad q = 1$$

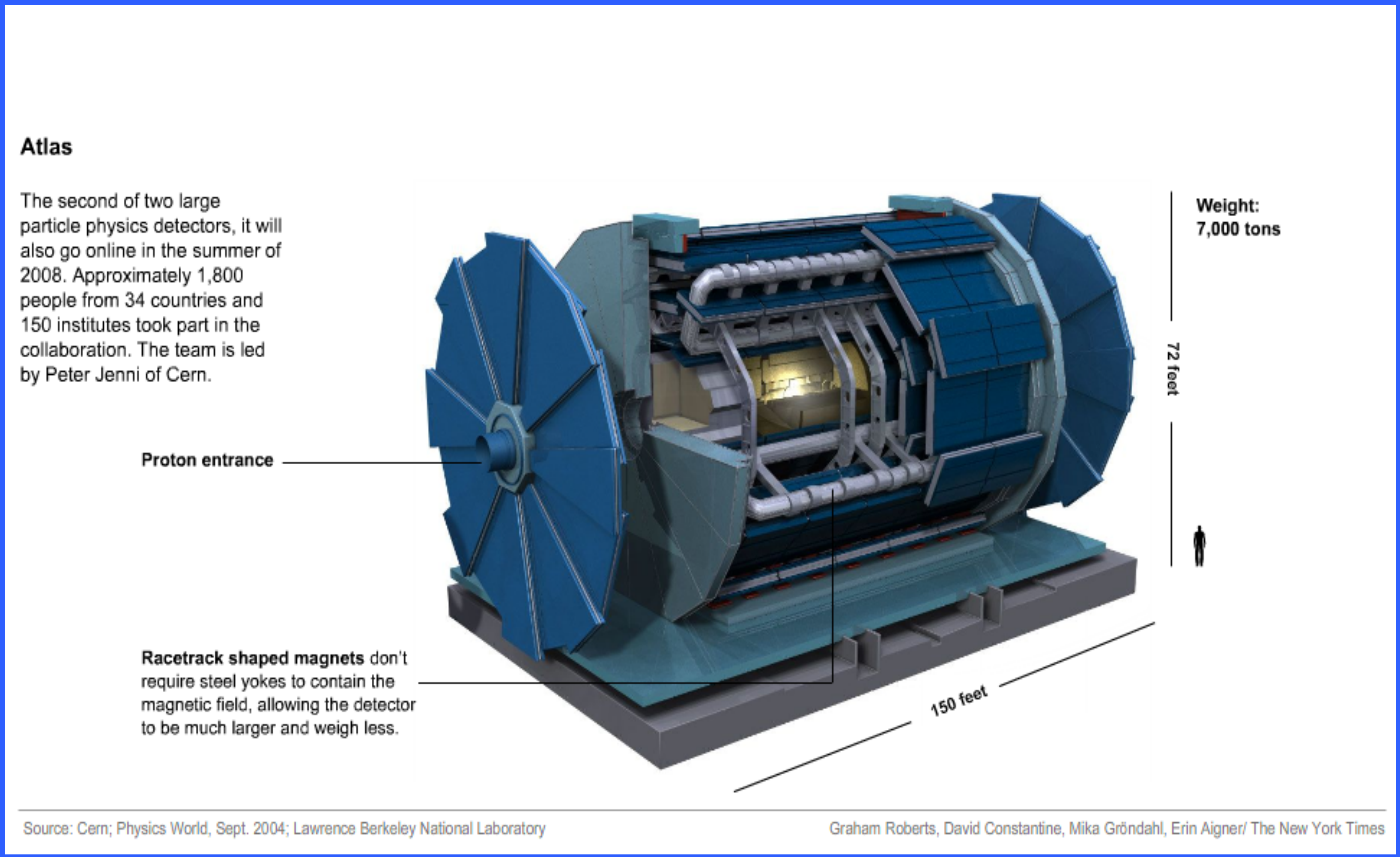


[redacted]

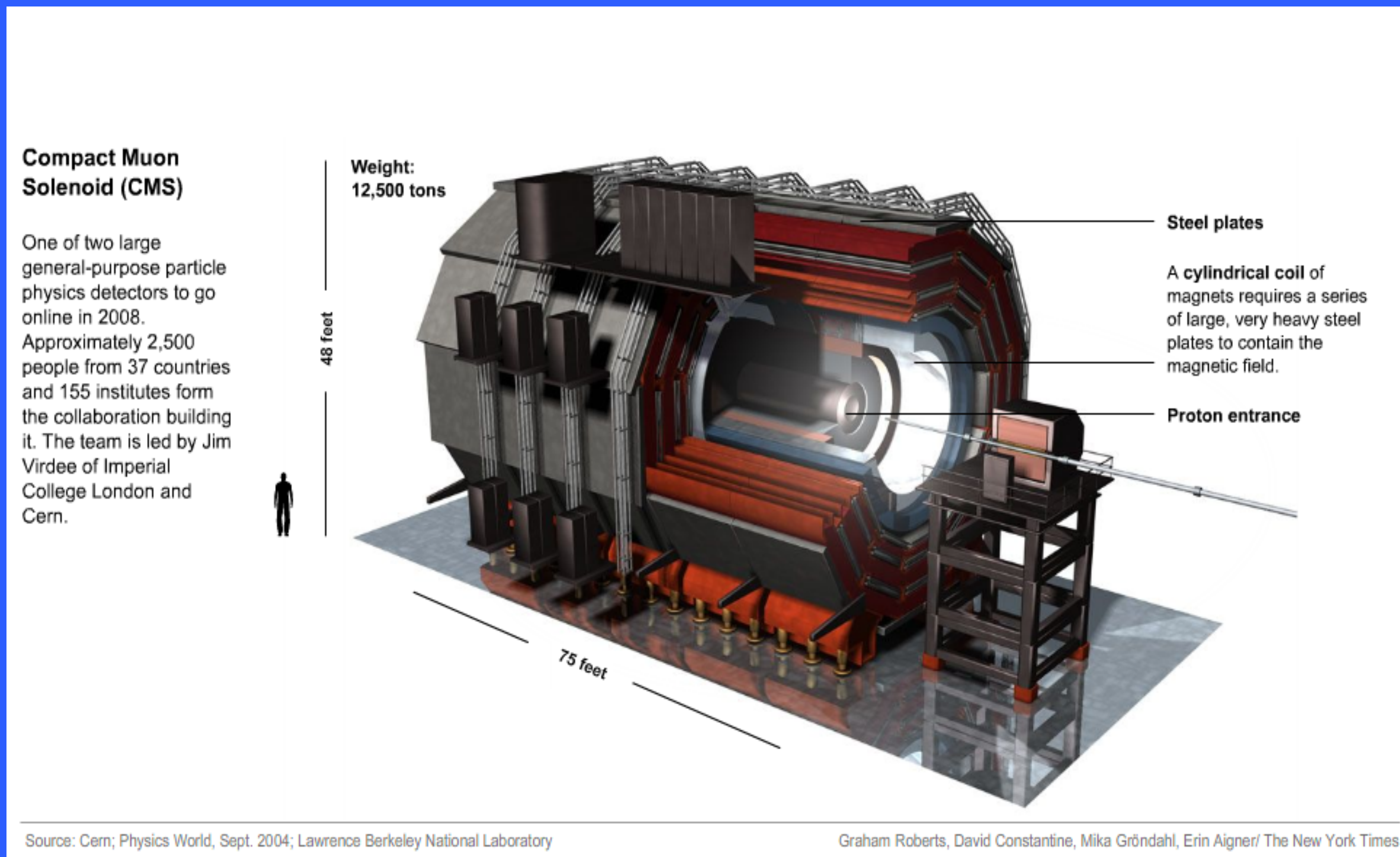
$p = 3 \ , \ q = 0$



A Dream Machine: Atlas



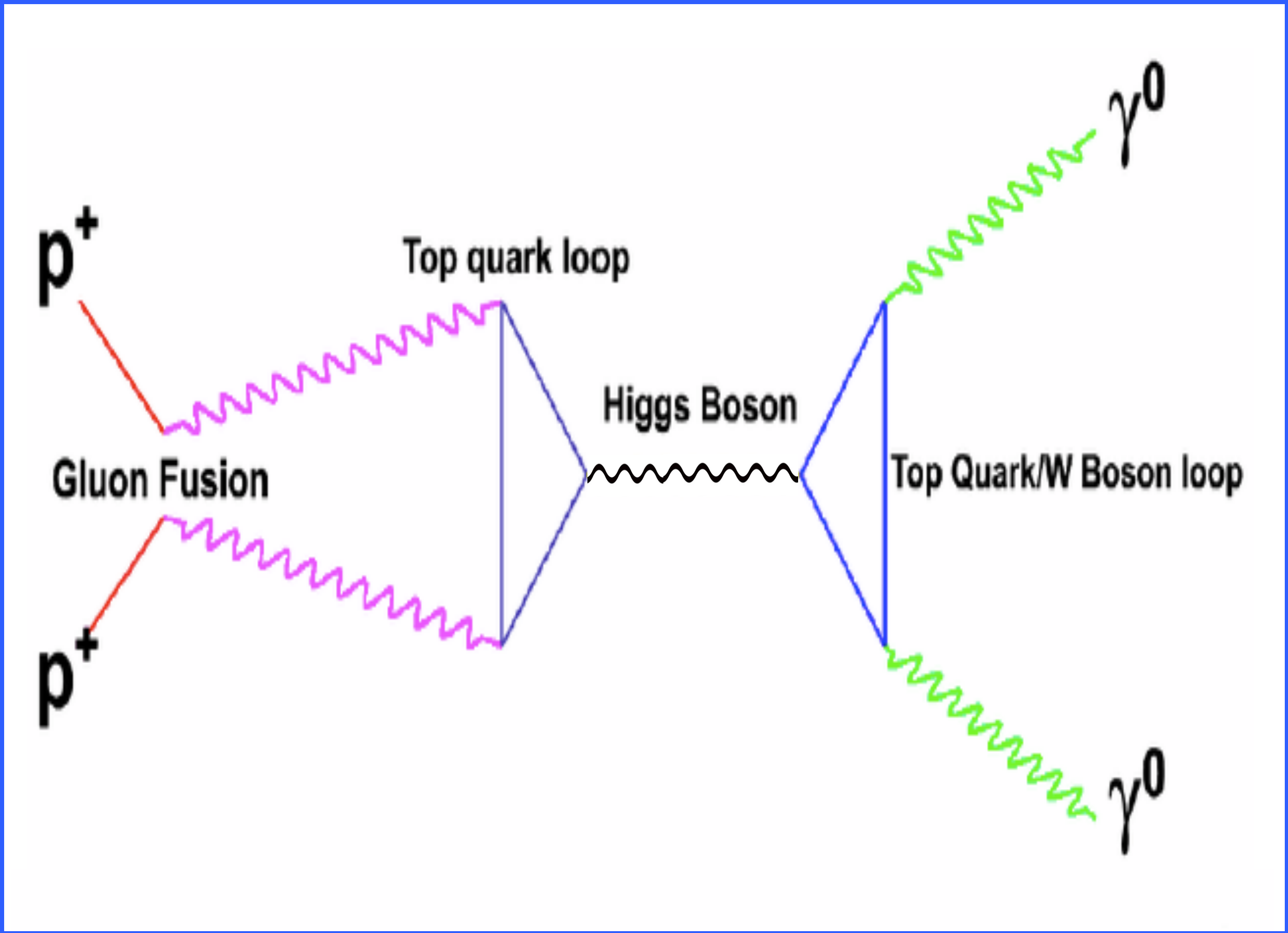
A Dream Machine: CMS



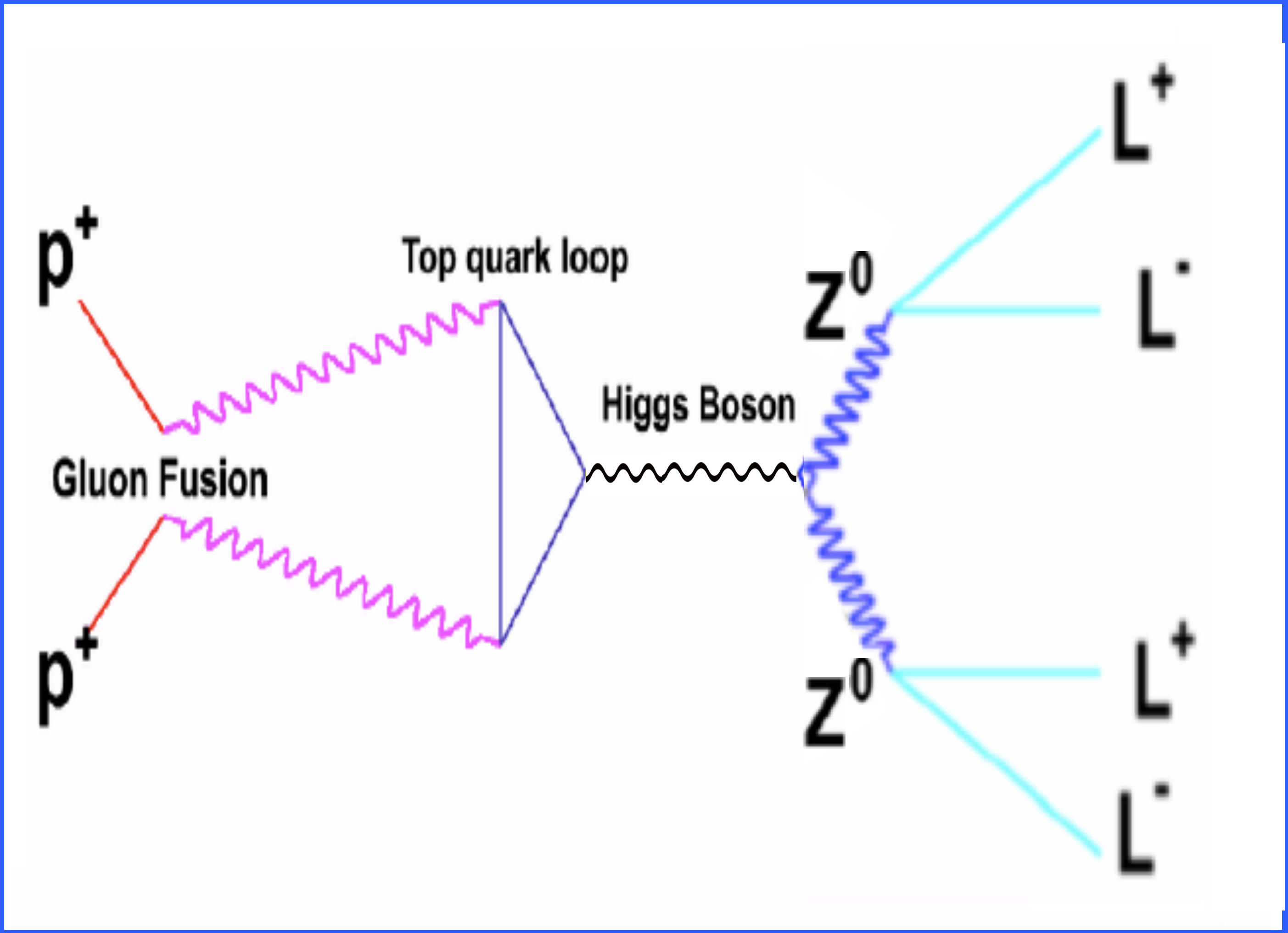
A Dream Fulfilled: The Higgs

Over 100 billion (10^{11}) protons/bunch

A Higgs Production & Decay Process



A Higgs Production & Decay Process



FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	−1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	−1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	−1

Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b bottom	4.3	−1/3

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	−1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

FERMIONS
matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2		
Flavor	Mass GeV/c²	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	−1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	−1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	−1

Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c²	Electric charge
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b bottom	4.3	−1/3

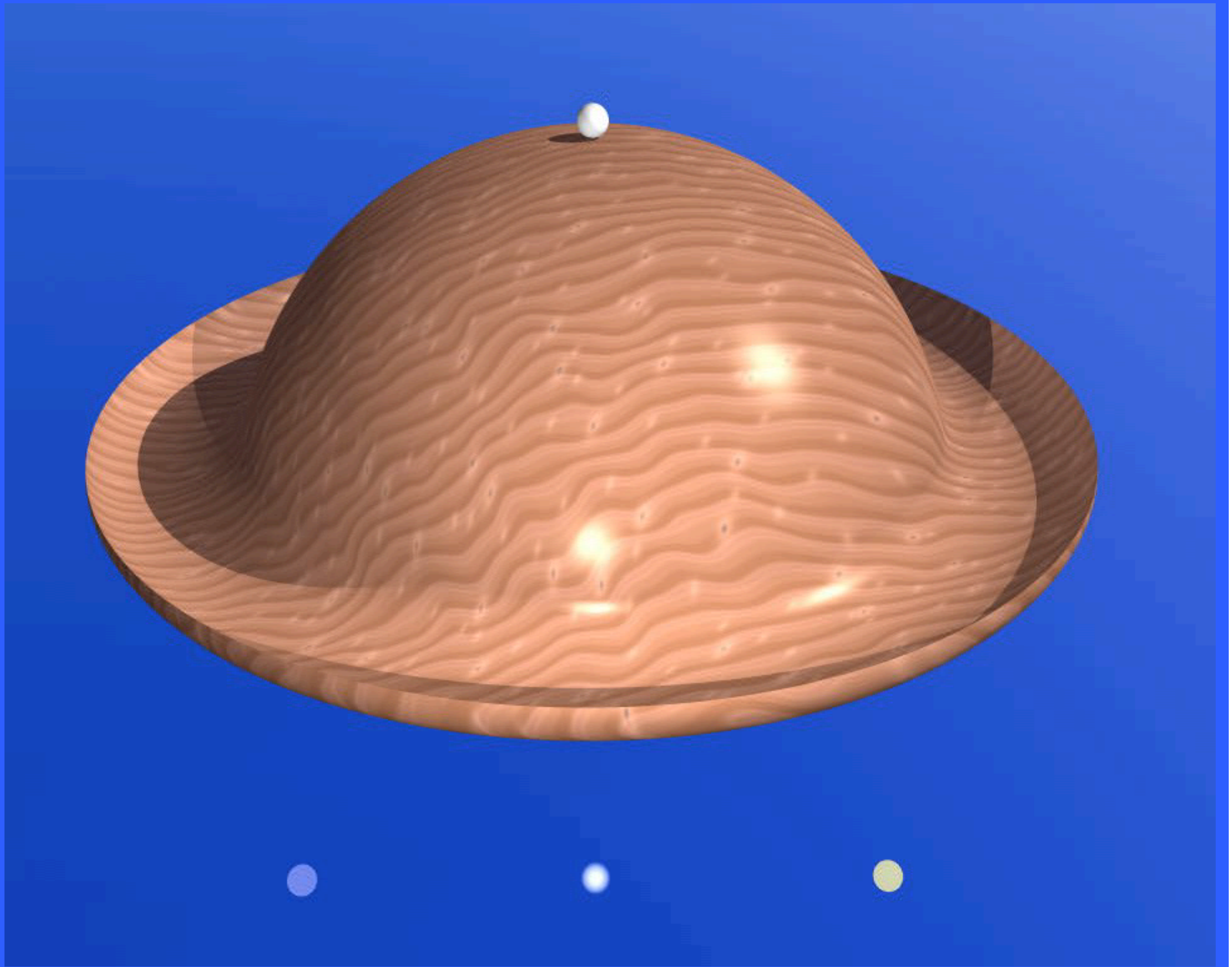
BOSONS
force carriers
spin = 0, 1, 2, ...

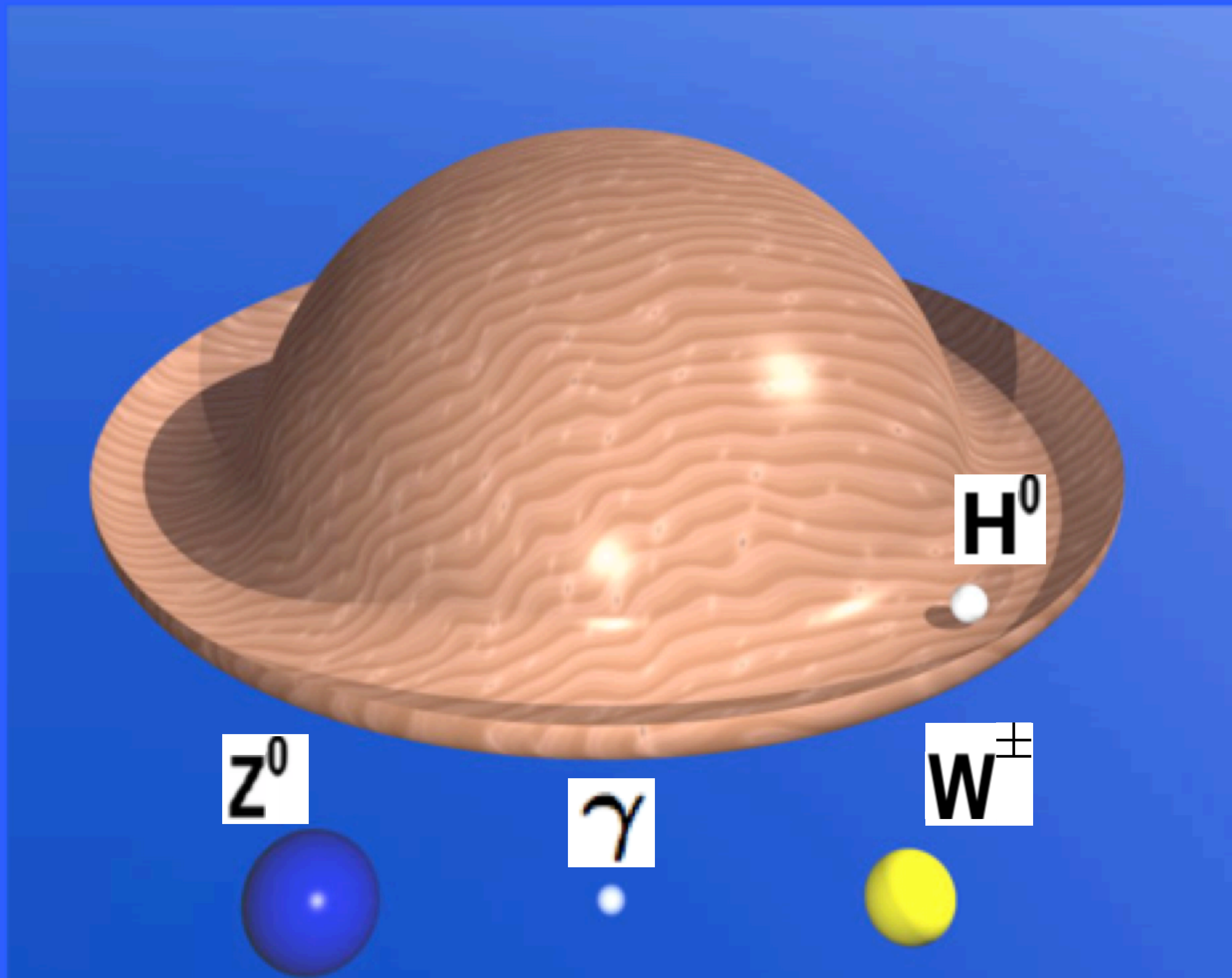
Unified Electroweak spin = 1		
Name	Mass GeV/c²	Electric charge
γ photon	0	0
W^-	80.4	−1
W^+	80.4	+1
Z^0	91.187	0
H^0	125	0

Strong (color) spin = 1		
Name	Mass GeV/c²	Electric charge
g gluon	0	0

PROPERTIES OF THE INTERACTIONS

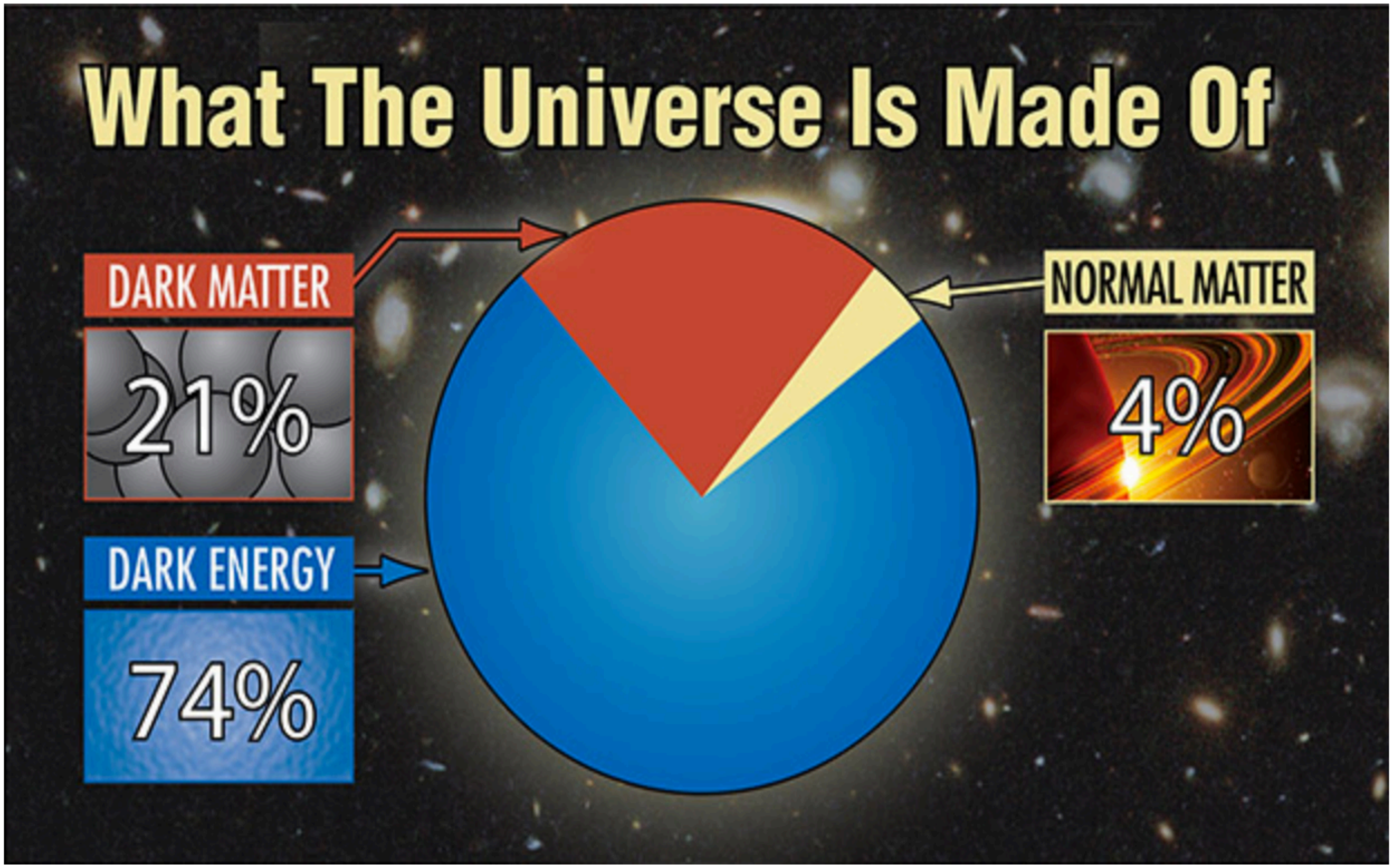
Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20



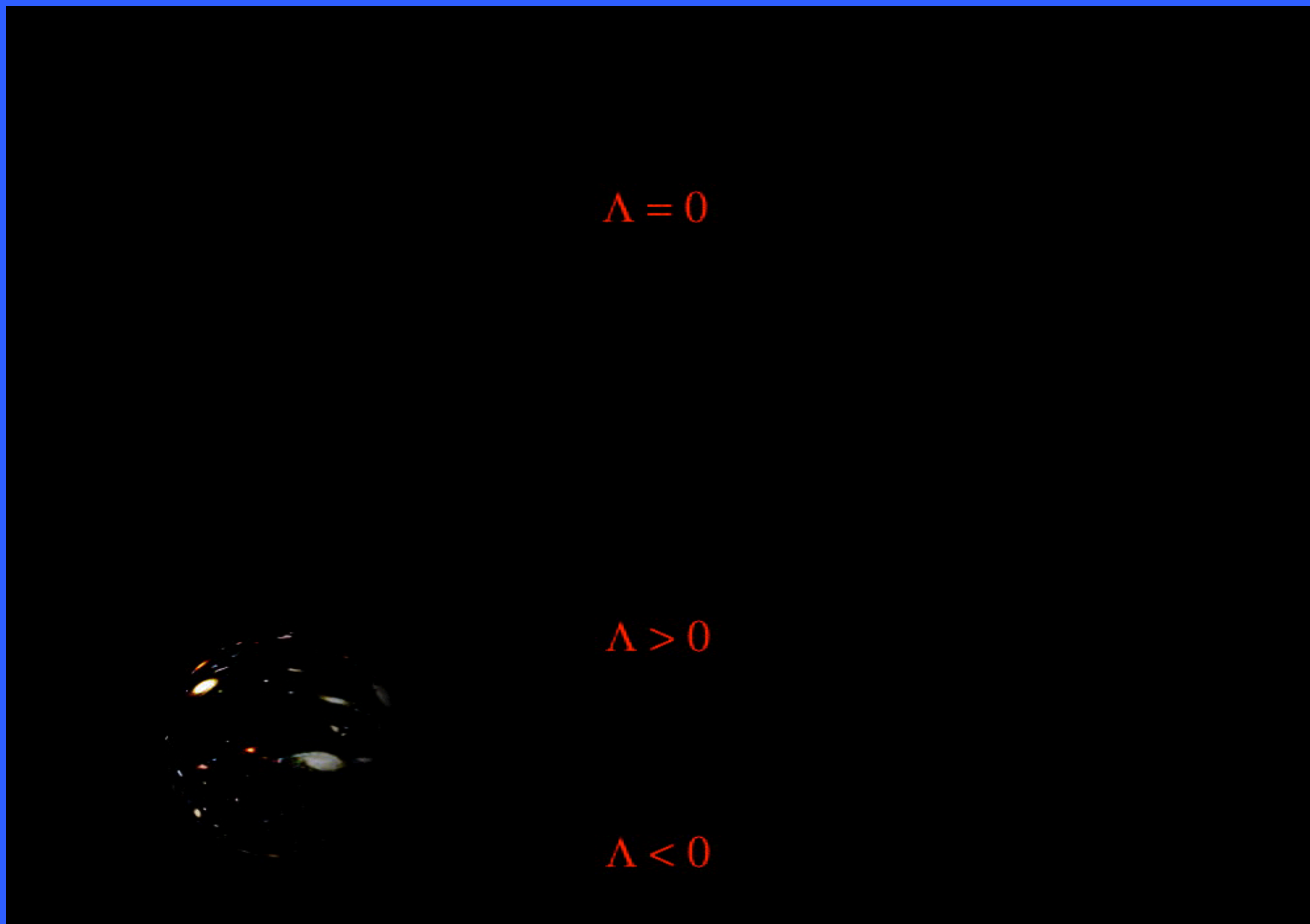


H^0
Z^0
γ
$W^\pm$

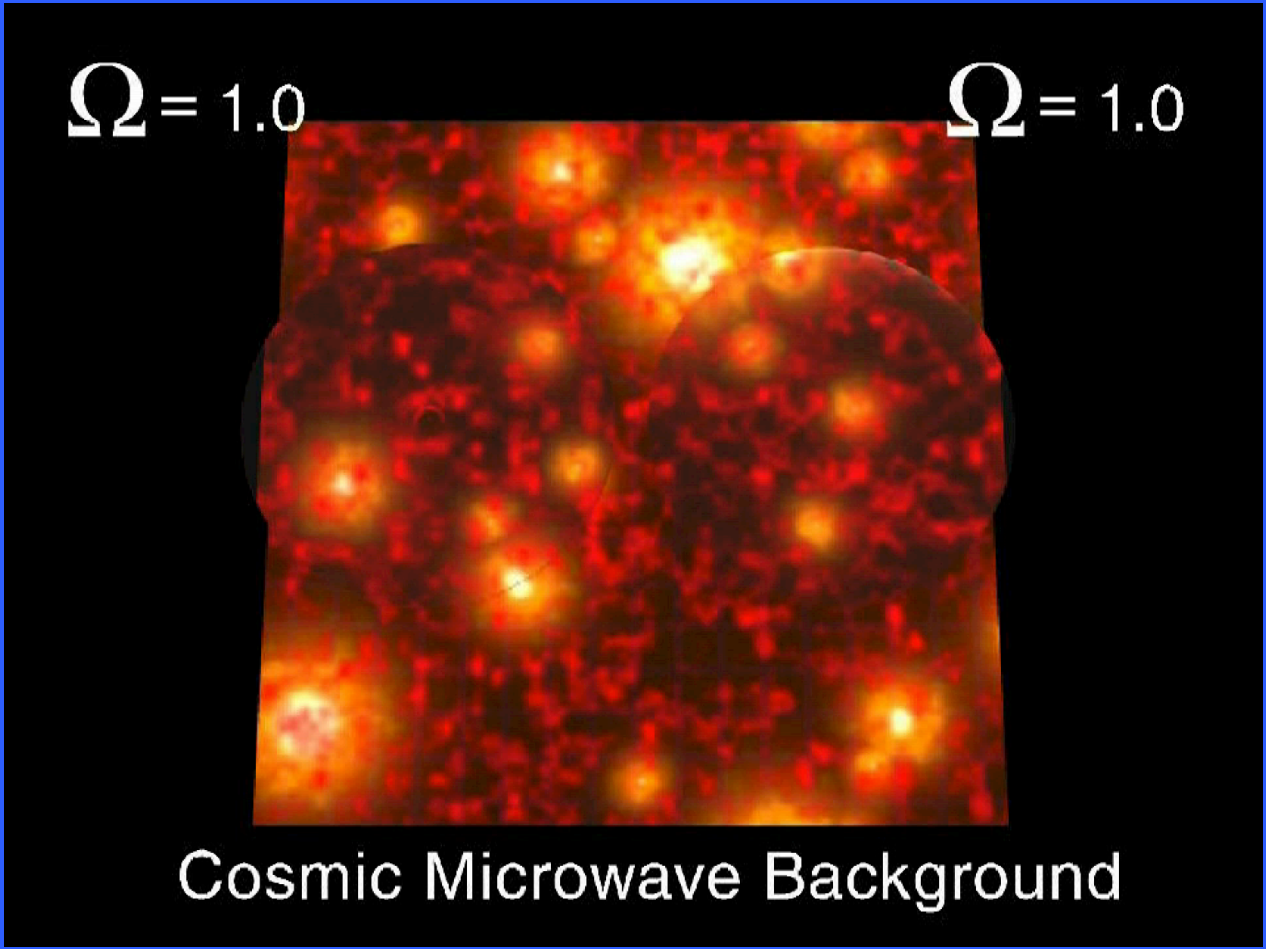
A playground: The Cosmological Collider



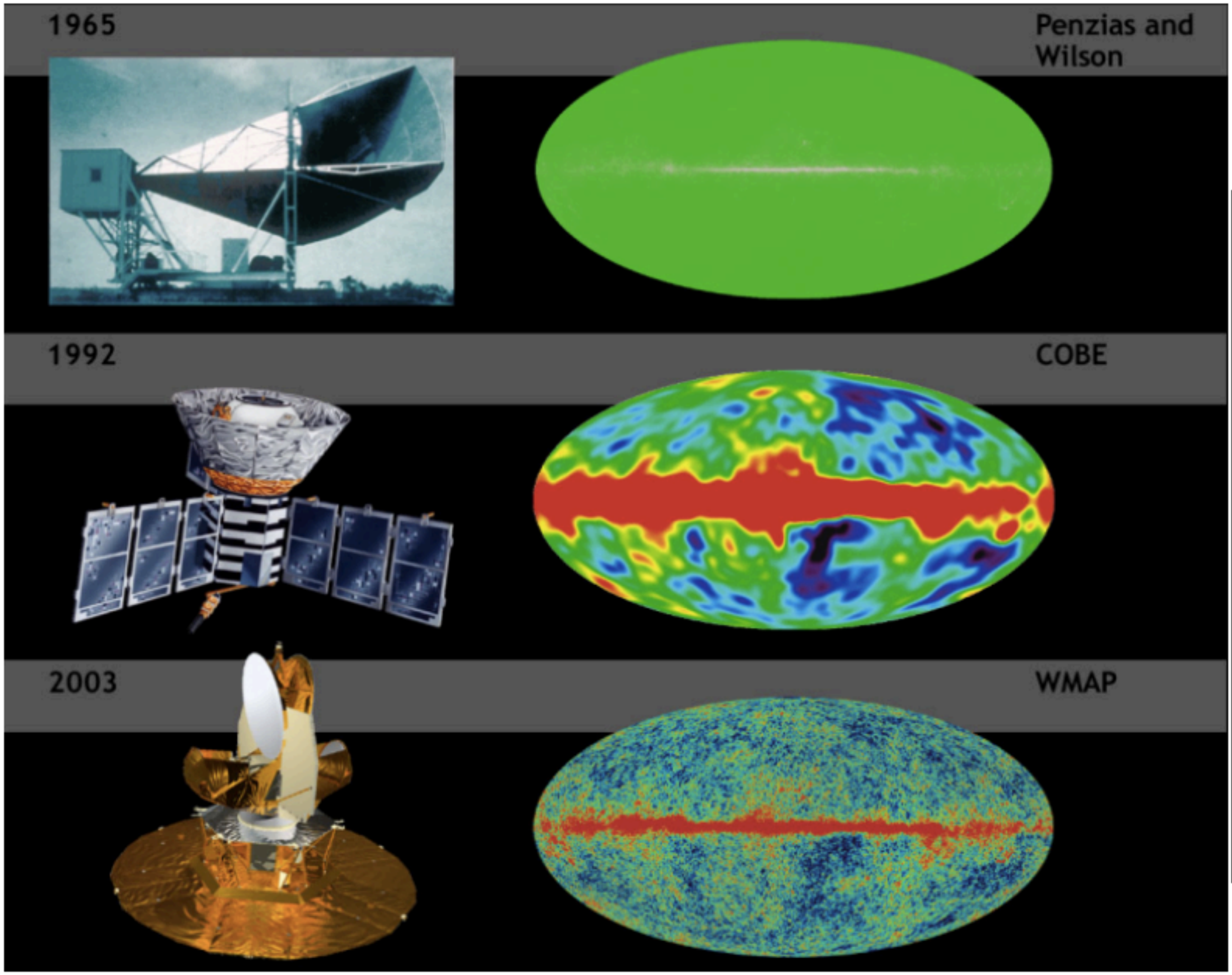
At the Beginning



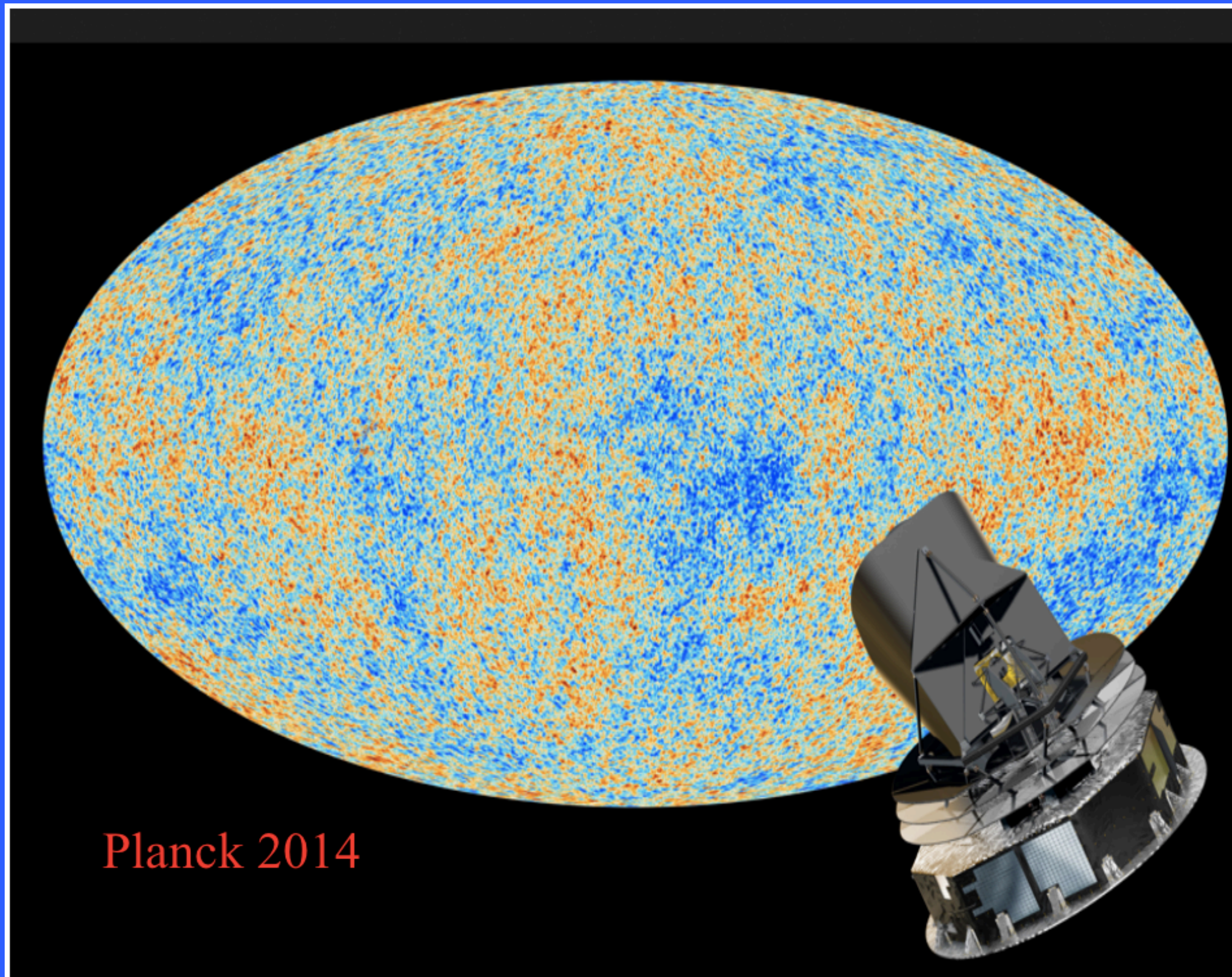
A playground: The Cosmological Collider



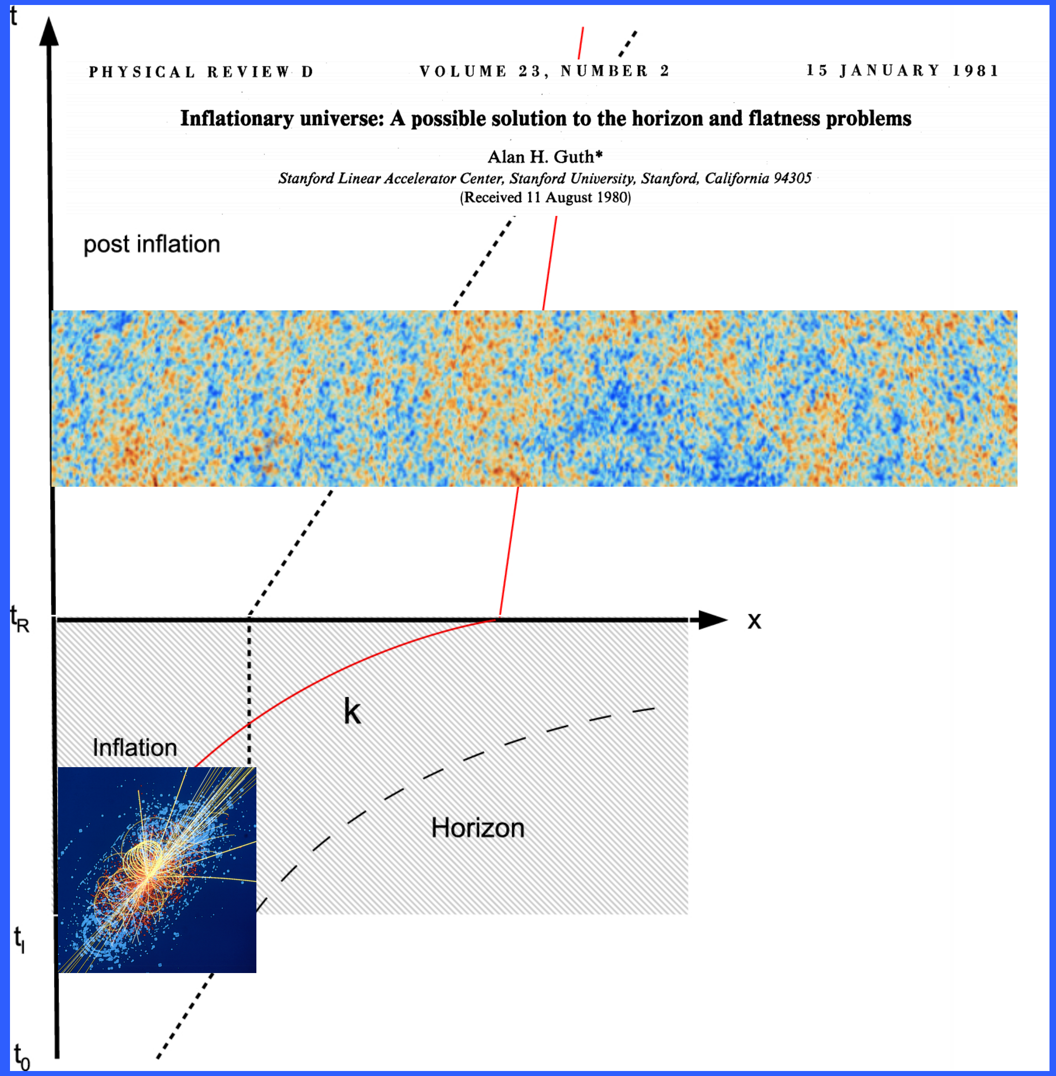
A playground: The Cosmological Collider



A playground: The Cosmological Collider

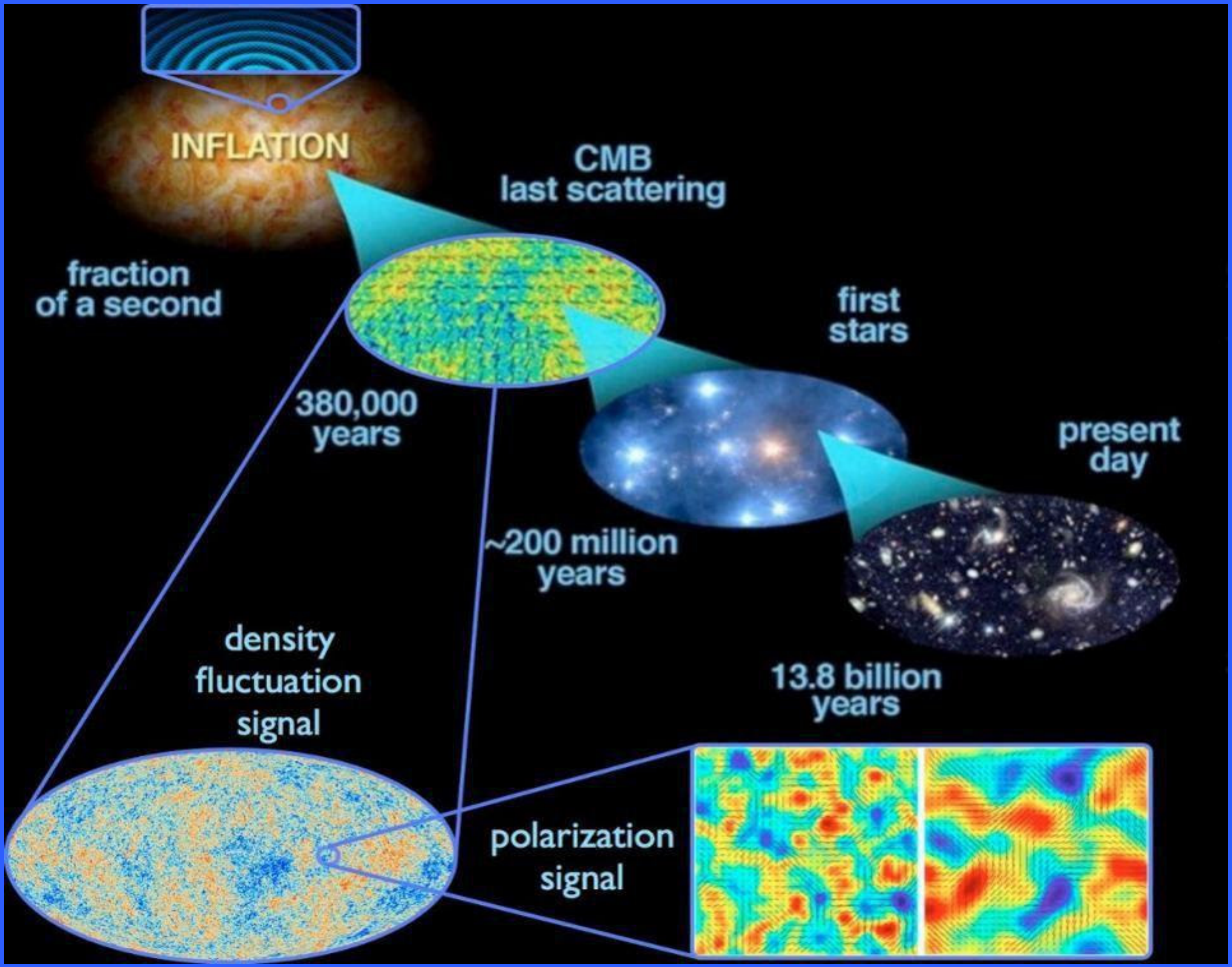


A playground: The Cosmological Collider



Slide credit
[E. McDonough]

A playground: The Cosmological Collider



Slide credit
[E. McDonough]

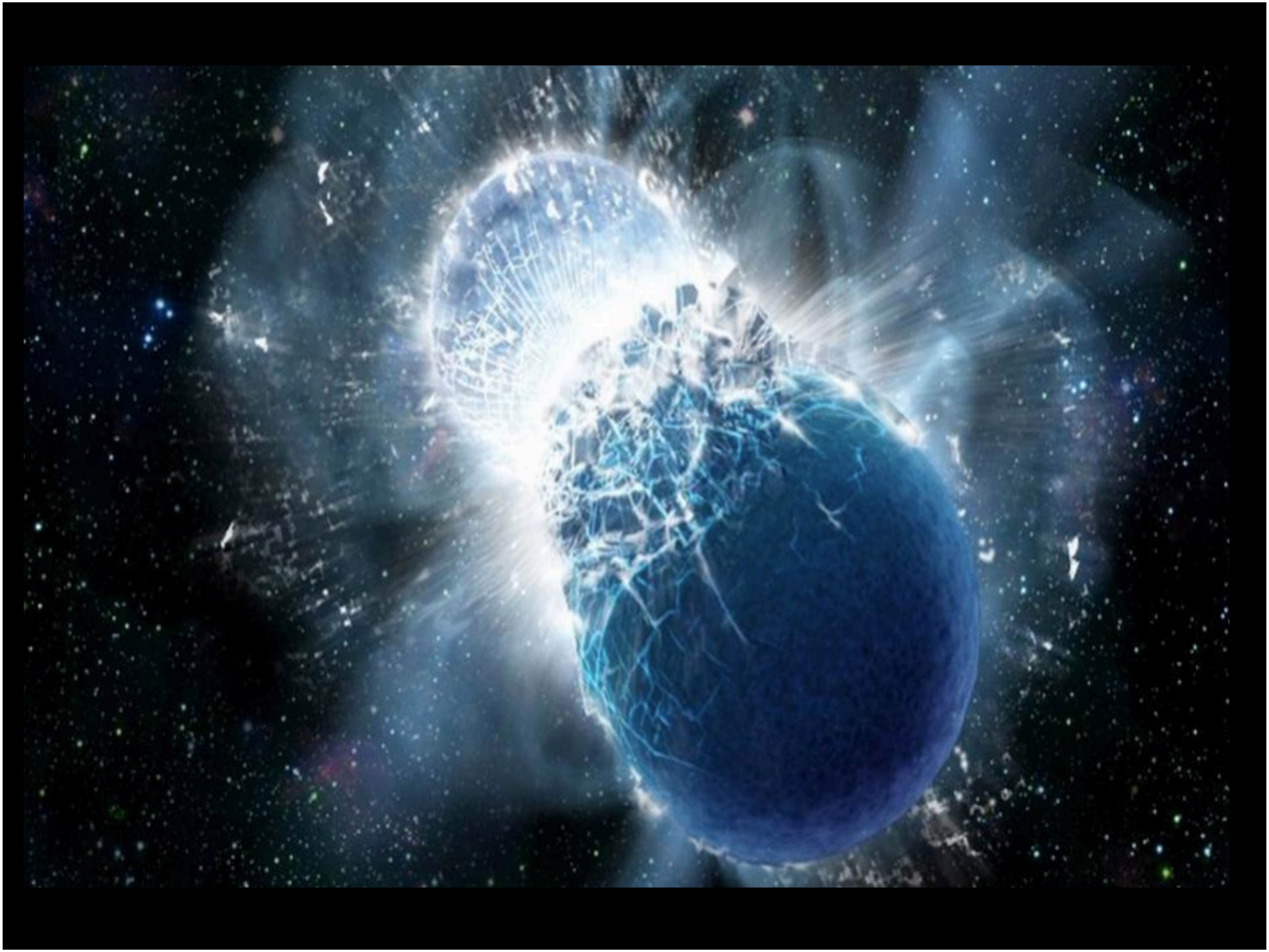
GRAVITATIONAL-WAVE DETECTORS:

Substantial effort has gone into the design and construction of kilometer-scale Michelson interferometers to detect gravitational waves. There is now a global network of such detectors: the two LIGO detectors, one in in Hanford, Washington and one in Livingston, Louisiana (built by Caltech and MIT for the US National Science Foundation); the Virgo detector in Pisa, Italy (built by teams from France and Italy); the GEO 600 detector in Hanover, Germany (built by teams from the United Kingdom and Germany); and the TAMA and CLIO detectors in Japan.

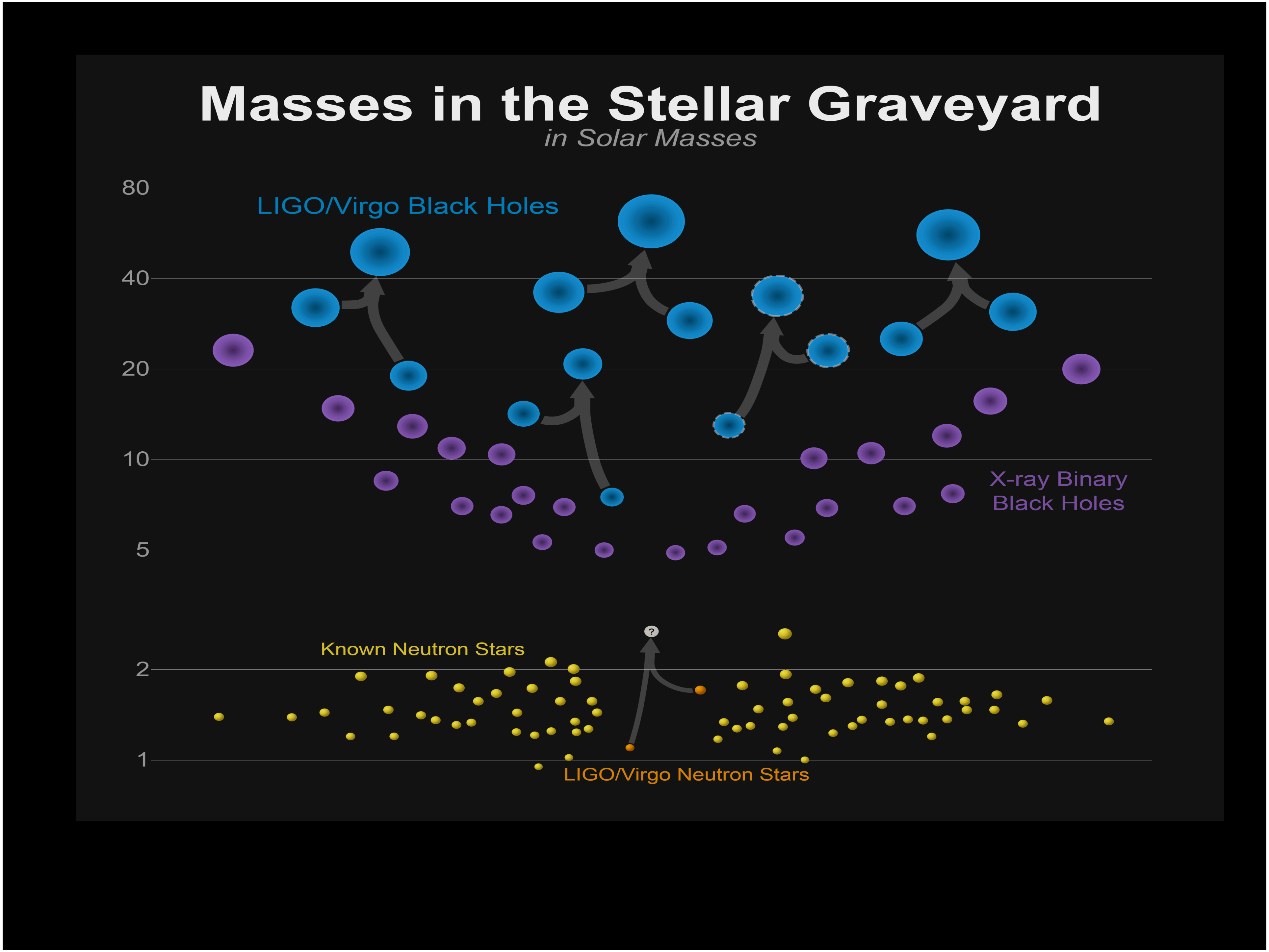
L-R: The LIGO Livingston Observatory, LIGO Hanford Observatory, and Virgo

These are "first-generation" detectors, designed to demonstrate the technologies that can sense motions at the level of one-ten-thousandth of the diameter of a proton (or 10^{-19} meter), which may only be barely sensitive enough to detect the waves.

The next generation of detectors coming online in the next 3-5 years -- the Advanced LIGO detectors, Advanced Virgo, LCGT in Japan, and the proposed LIGO Australia --- will be ten times more sensitive. Based on our current understanding of the abundance of gravitational wave sources, these detectors will certainly find the waves and study their properties and the sources in detail. They will allow us to explore the universe in a completely new way, complementary to electromagnetic observations.



Earth
Space
LIGO Hanford
Virgo
LIGO Livingston



Masses in the Stellar Graveyard
in Solar Masses
80
40
20
10
5
2
1
LIGO/Virgo Black Holes
X-ray Binary Black Holes
Known Neutron Stars
?
LIGO/Virgo Neutron Stars

letters to nature

Nature 340, 126 - 128 (13 July 1989); doi:10.1038/340126a0

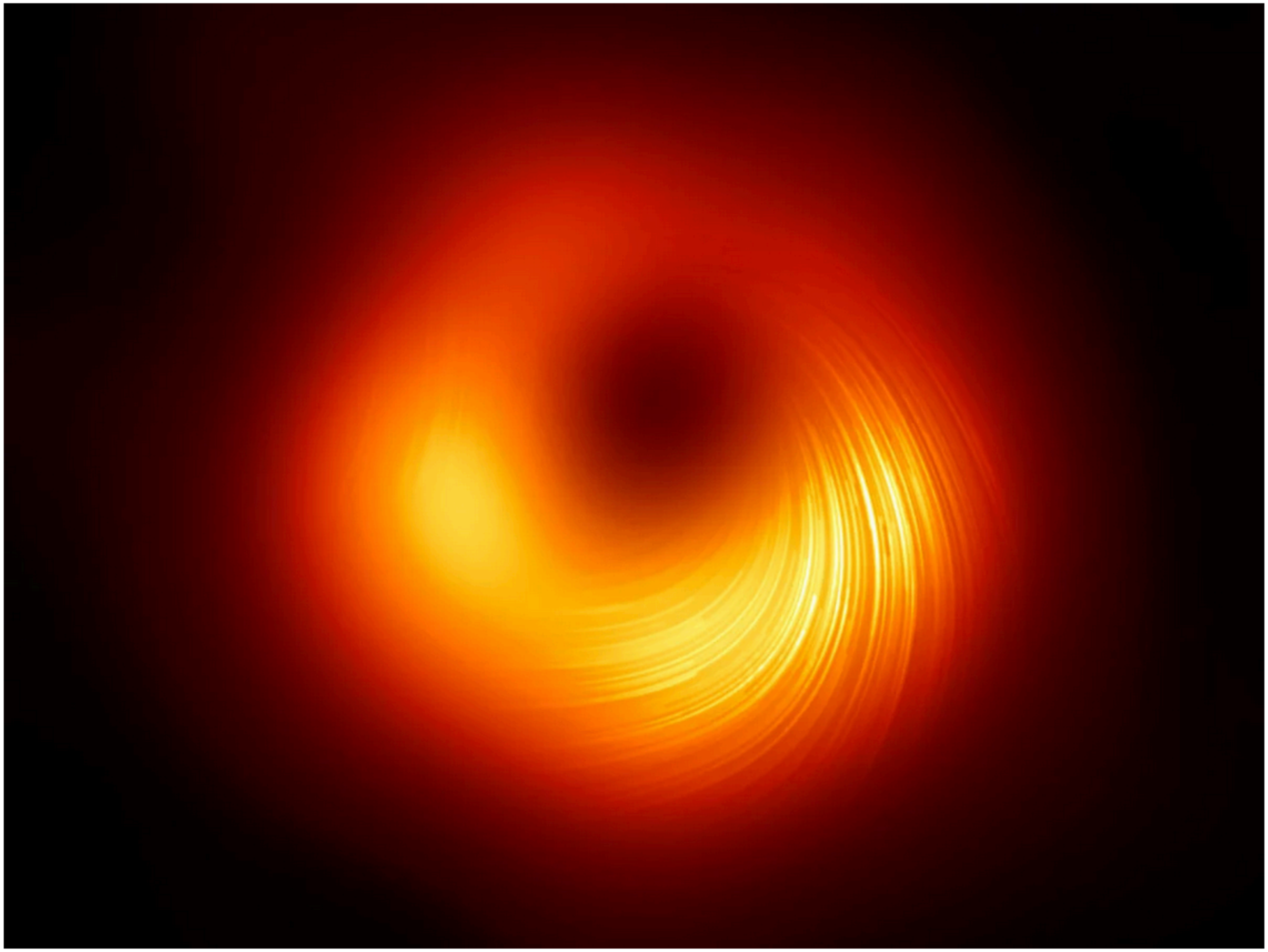
Nucleosynthesis, neutrino bursts and γ-rays from coalescing neutron stars

DAVID EICHLER*, MARIO LIVIO†, TSVI PIRAN‡ & DAVID N. SCHRAMM§

*Department of Physics, Ben Gurion University, Beer Sheva, Israel, and Astronomy Program, University of Maryland, College Park, Maryland 20742, USA
†Department of Physics, The Technion, Haifa, Israel
‡Racah Institute for Physics, Hebrew University, Jerusalem, Israel, and Princeton University Observatory, Princeton, New Jersey 08544, USA
§Departments of Physics and Astrophysics, University of Chicago, 5640 Ellis Avenue, Chicago, Illinois 60637, USA, and NASA/Fermilab Astrophysics Center, Batavia, Illinois 60510, USA

NEUTRON-STAR collisions occur inevitably when binary neutron stars spiral into each other as a result of damping of gravitational radiation. Such collisions will produce a characteristic burst of gravitational radiation, which may be the most promising source of a detectable signal for proposed gravity-wave detectors[1]. Such signals are sufficiently unique and robust for them to have been proposed as a means of determining the Hubble constant[2]. However, the rate of these neutron-star collisions is highly uncertain[3]. Here we note that such events should also synthesize neutron-rich heavy elements, thought to be formed by rapid neutron capture (the r-process)[4]. Furthermore, these collisions should produce neutrino bursts[5] and resultant bursts of γ-rays; the latter should comprise a subclass of observable γ-ray bursts. We argue that observed r-process abundances and γ-ray-burst rates predict rates for these collisions that are both significant and consistent with other estimates.

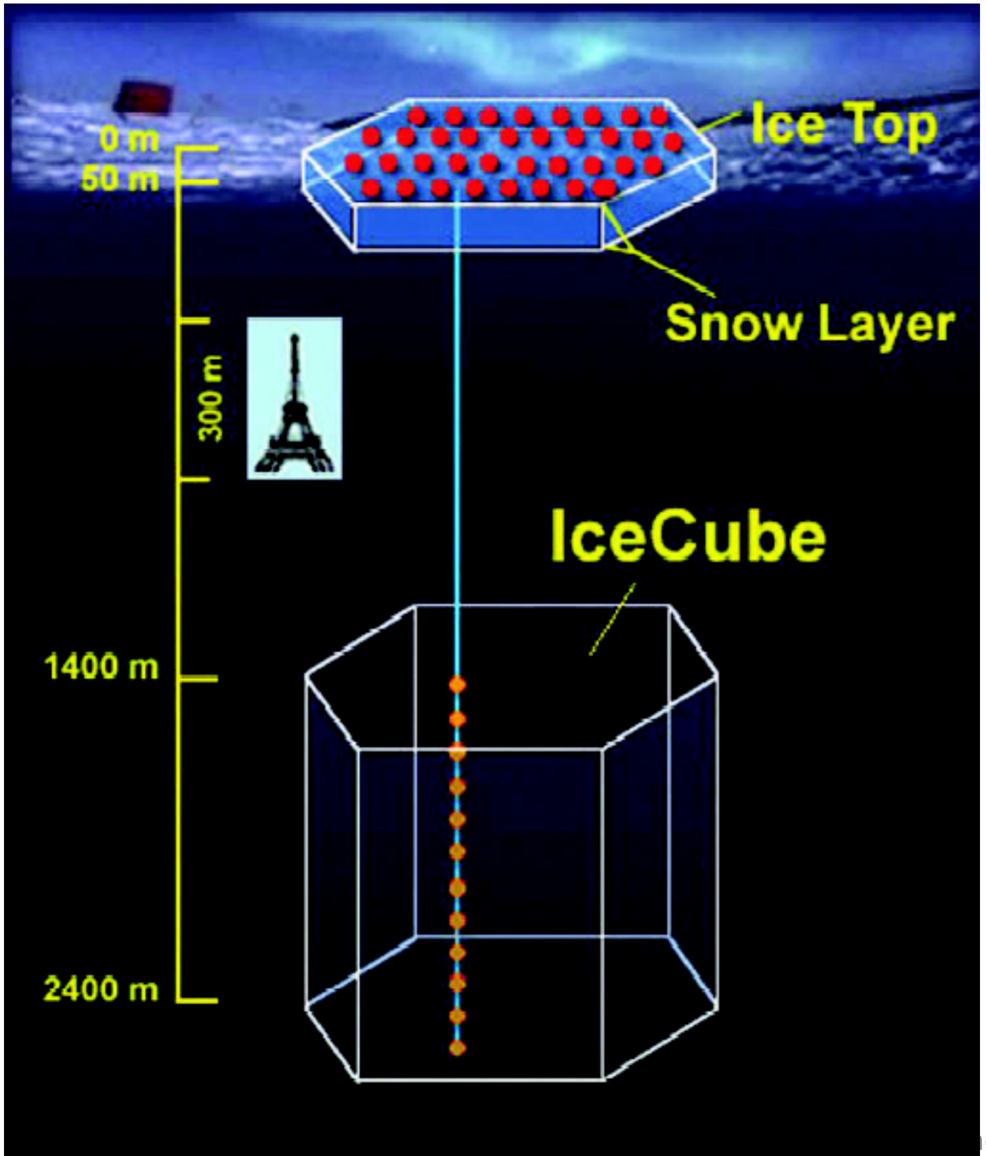
EVENT HORIZON TELESCOPE



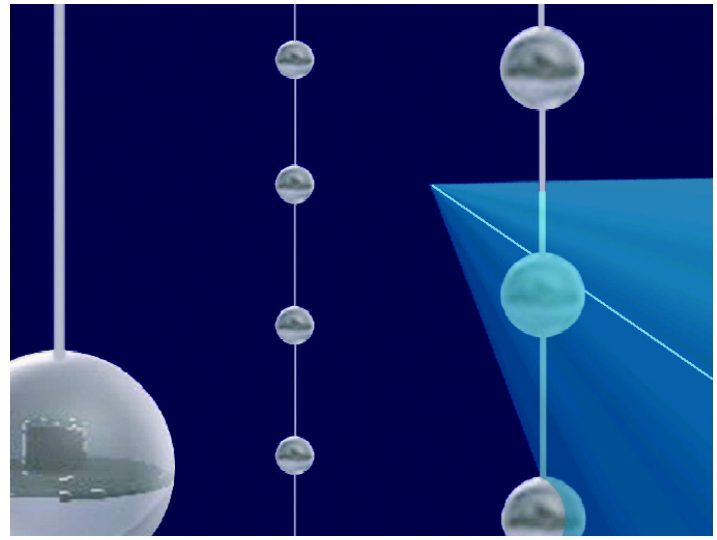
The Event Horizon Telescope collaboration, which released the world's first image of a black hole in 2019, unveiled a new view on Wednesday showing how the object at the center of the M87 galaxy looks in polarized light.

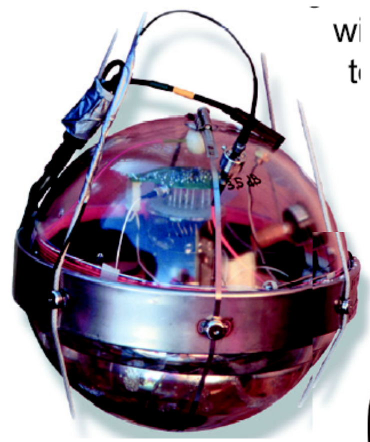
EHT Collaboration

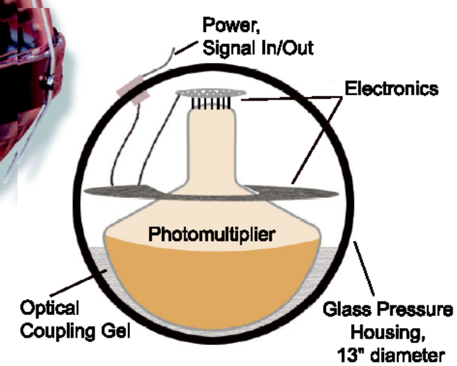
Ice Cube



Ice Top
0 m
50 m
Snow Layer
300 m
IceCube
1400 m
2400 m

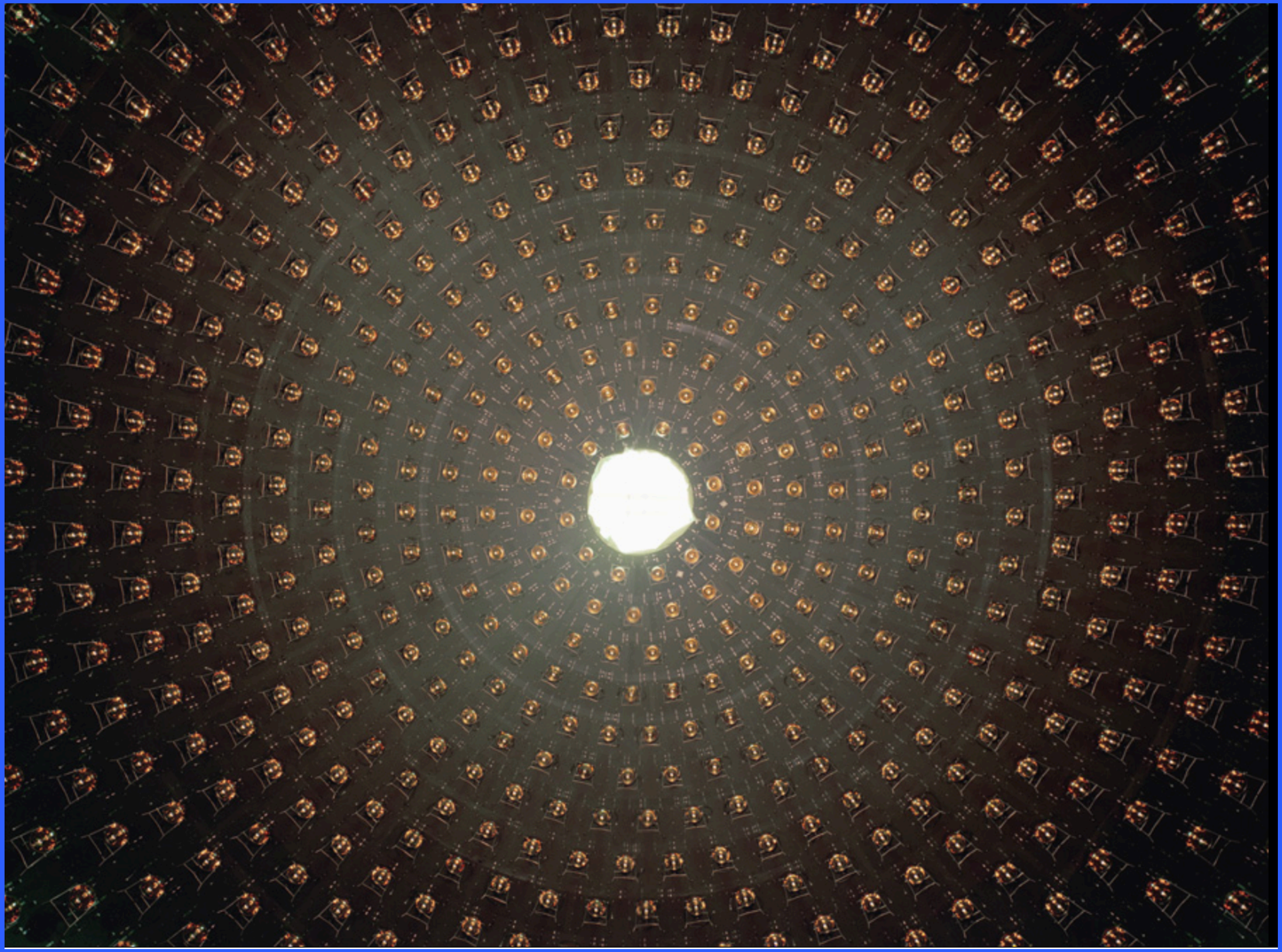


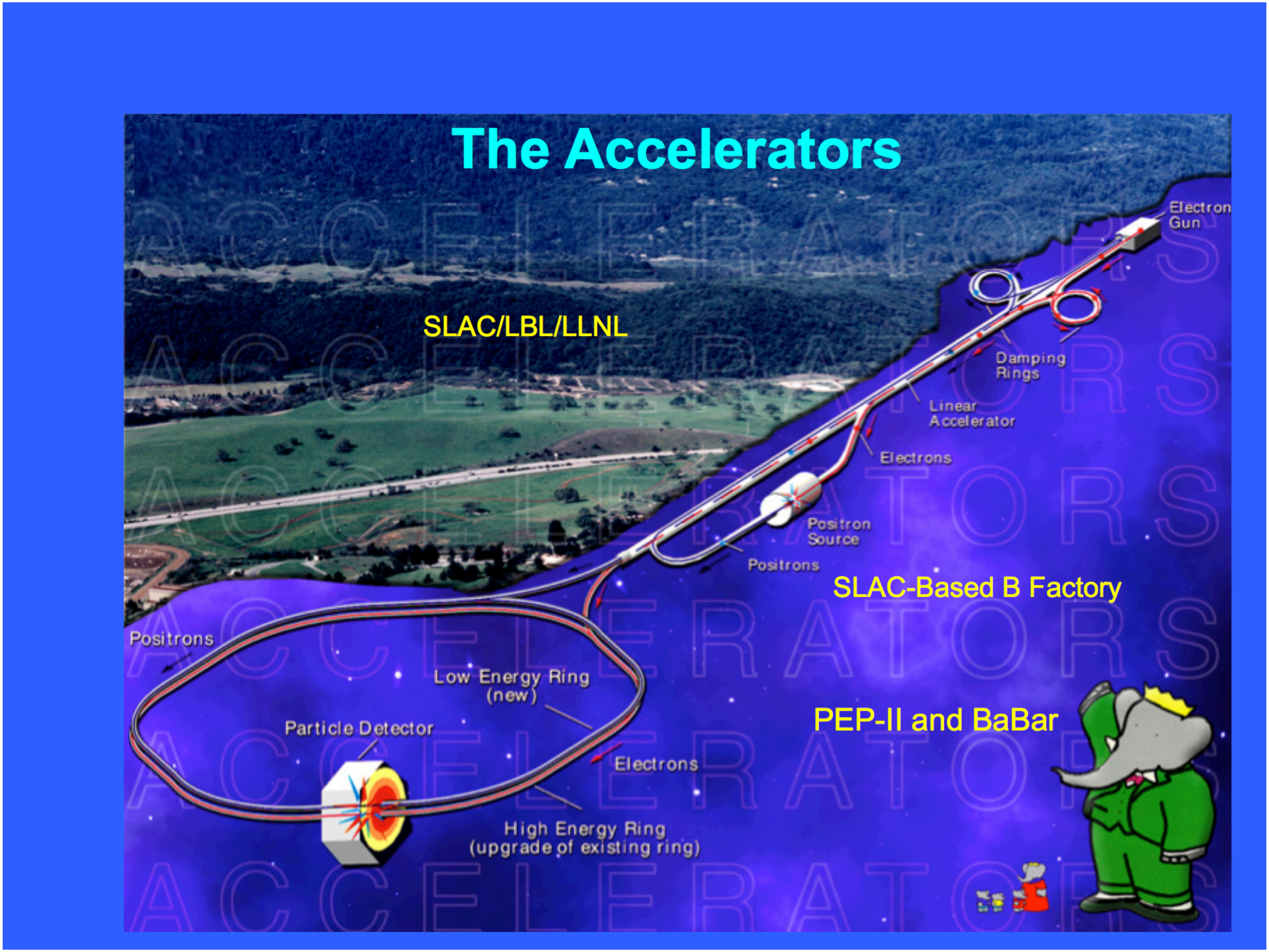




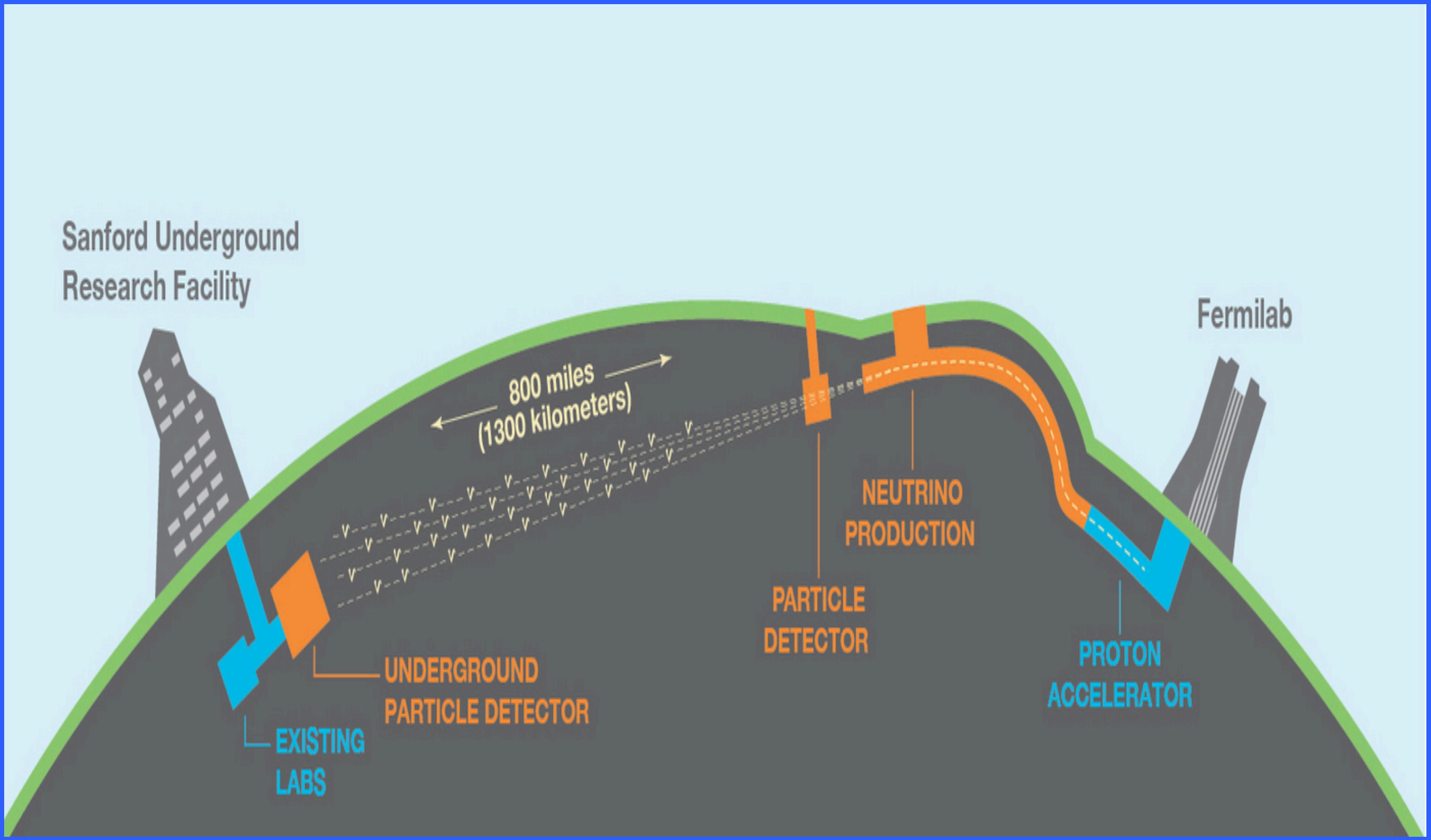
Power, Signal In/Out
Electronics
Photomultiplier
Optical Coupling Gel
Glass Pressure Housing, 13" diameter

Mini BooNE




The Accelerators
SLAC/LBL/LLNL
Electron Gun
Damping Rings
Linear Accelerator
Electrons
Positron Source
Positrons
SLAC-Based B Factory
Positrons
Low Energy Ring (new)
Particle Detector
Electrons
High Energy Ring (upgrade of existing ring)
PEP-II and BaBar

Du NE

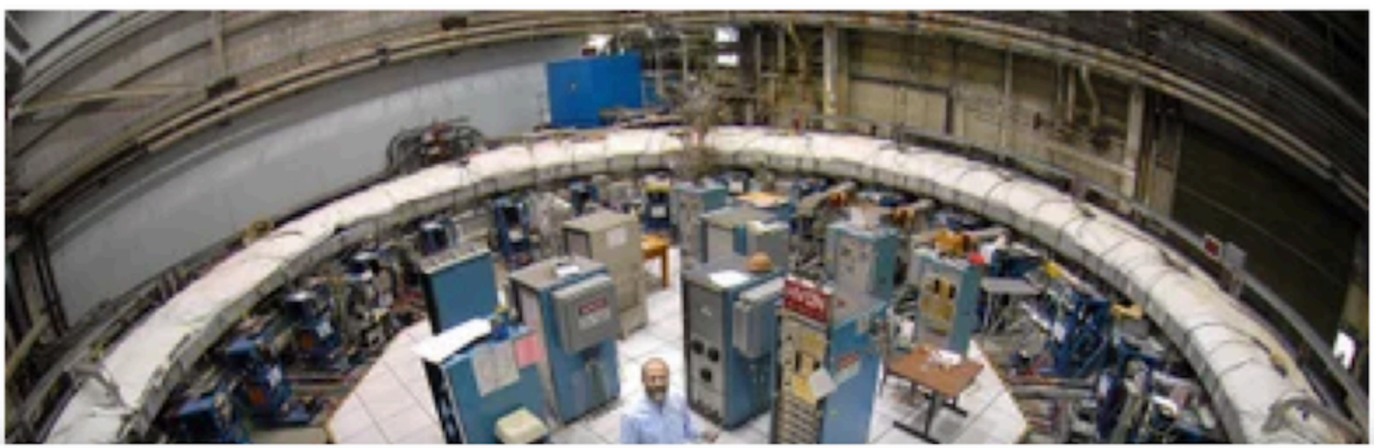

Sanford Underground
Research Facility
800 miles
(1300 kilometers)
Fermilab
NEUTRINO
PRODUCTION
PARTICLE
DETECTOR
PROTON
ACCELERATOR
UNDERGROUND
PARTICLE DETECTOR
EXISTING
LABS

PHYSICS

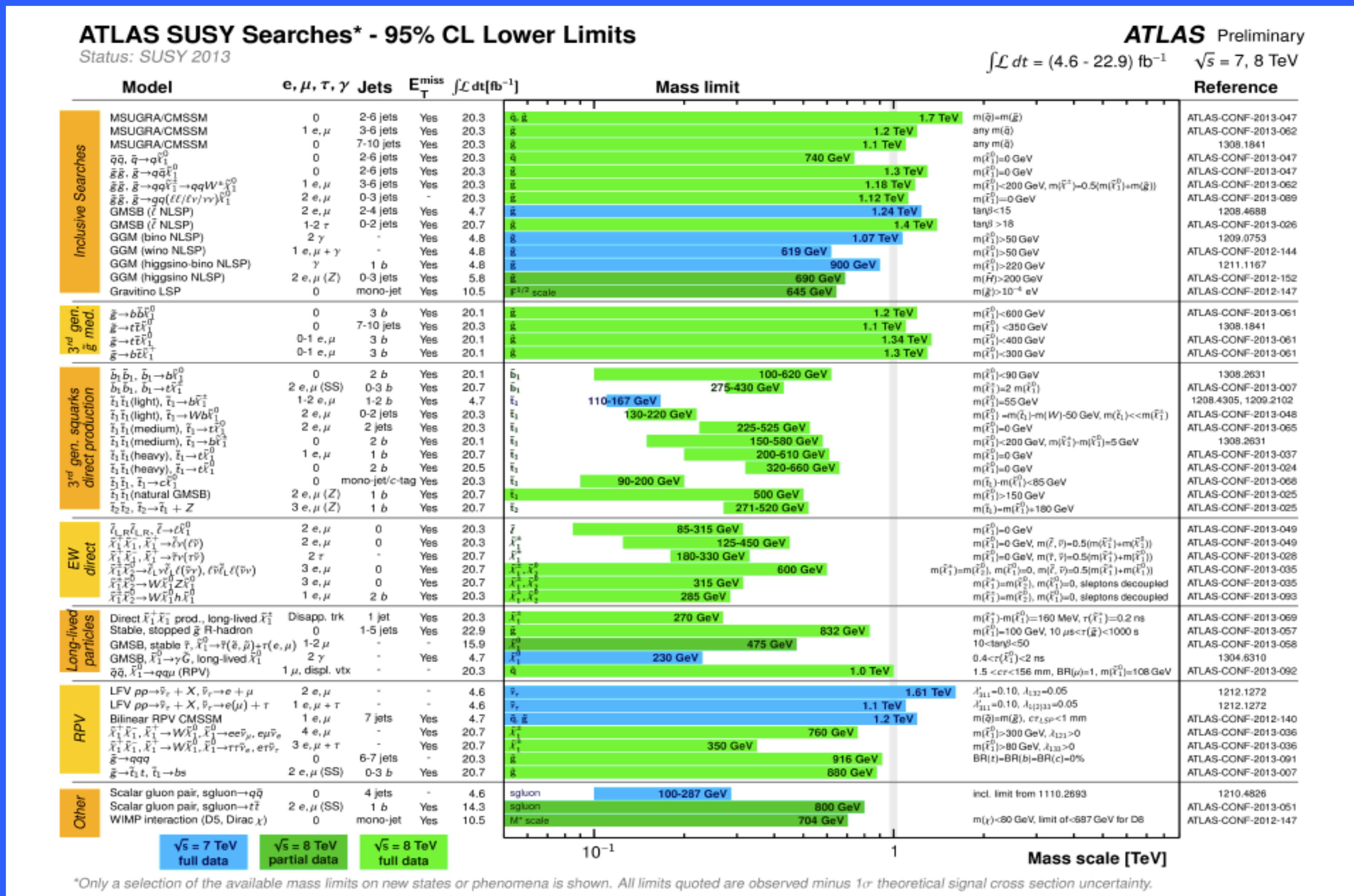
Long-Awaited Muon Measurement Boosts Evidence for New Physics

Initial data from the Muon g-2 experiment have excited particle physicists searching for undiscovered subatomic particles and forces

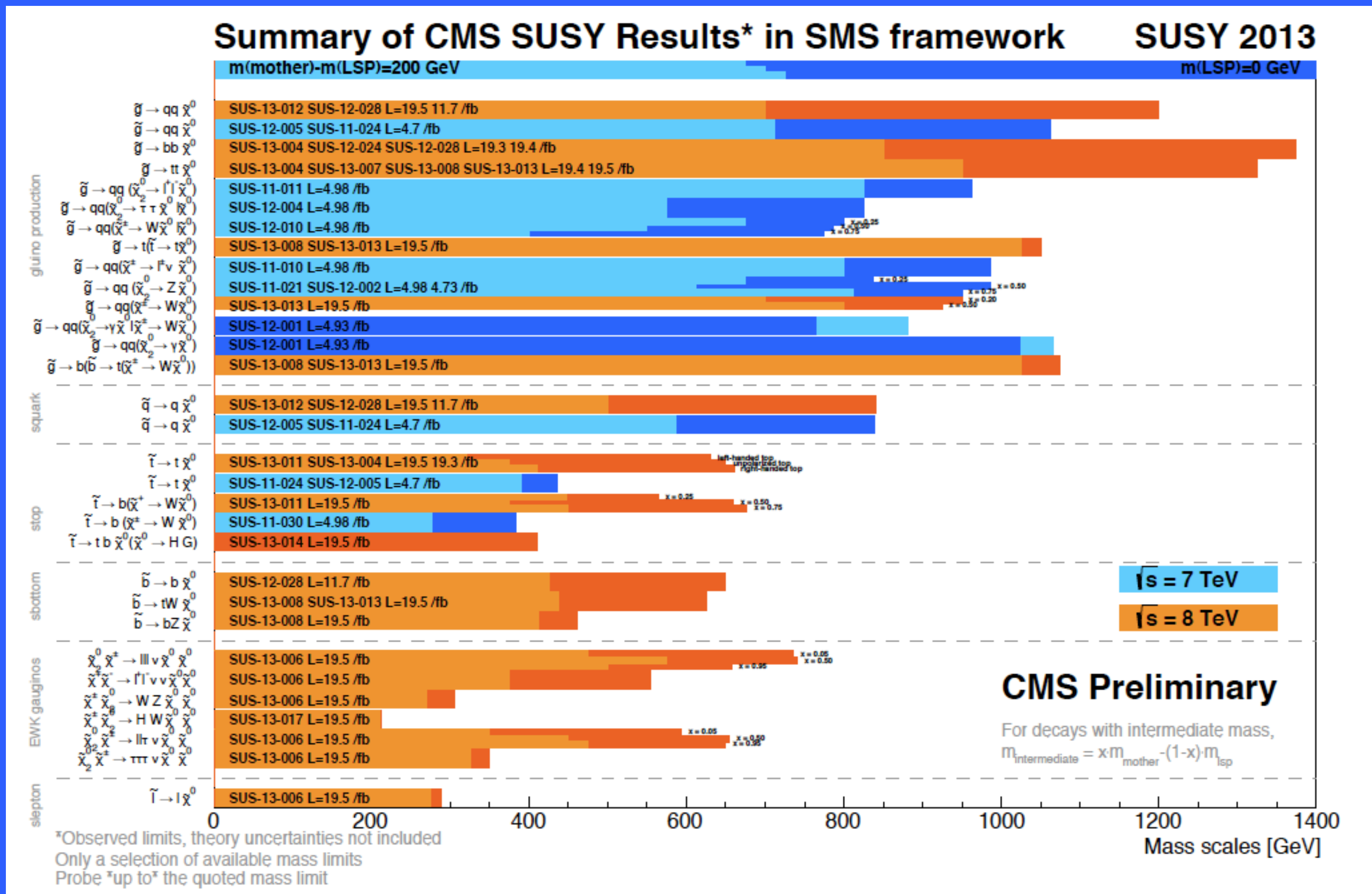
By Daniel Garisto on April 7, 2021



Dreams Unfulfilled



ATLAS SUSY Searches* - 95% CL Lower Limits
Status: SUSY 2013
ATLAS Preliminary
$\int \mathcal{L} dt$ = (4.6 - 22.9) fb^{-1}
$\sqrt{s}$ = 7, 8 TeV
Model
e, μ, τ, γ
Jets
E_T^{miss}
$\int \mathcal{L} dt [fb^{-1}]$
Mass limit
Reference
Inclusive Searches
MSUGRA/CMSSM 0 2-6 jets Yes 20.3 $\tilde{q}, \tilde{g}$ 1.7 TeV m($\tilde{q}$)=m($\tilde{g}$) ATLAS-CONF-2013-047
MSUGRA/CMSSM 1 e, μ 3-6 jets Yes 20.3 $\tilde{g}$ 1.2 TeV any m($\tilde{q}$) ATLAS-CONF-2013-062
MSUGRA/CMSSM 0 7-10 jets Yes 20.3 $\tilde{g}$ 1.1 TeV any m($\tilde{q}$) 1308.1841
$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$ 0 2-6 jets Yes 20.3 $\tilde{q}$ 740 GeV m($\tilde{\chi}_1^0$)=0 GeV ATLAS-CONF-2013-047
$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$ 0 2-6 jets Yes 20.3 $\tilde{g}$ 1.3 TeV m($\tilde{\chi}_1^0$)=0 GeV ATLAS-CONF-2013-047
$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^{\pm}\to qqW^{\pm}\tilde{\chi}_1^0$ 1 e, μ 3-6 jets Yes 20.3 $\tilde{g}$ 1.18 TeV m($\tilde{\chi}_1^0$)<200 GeV, m($\tilde{\chi}^{\pm}$)=0.5(m($\tilde{\chi}_1^0$)+m($\tilde{g}$)) ATLAS-CONF-2013-062
$\tilde{g}\tilde{g}, \tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$ 2 e, μ 0-3 jets - 20.3 $\tilde{g}$ 1.12 TeV m($\tilde{\chi}_1^0$)=0 GeV ATLAS-CONF-2013-089
GMSB ($\tilde{\ell}$ NLSP) 2 e, μ 2-4 jets Yes 4.7 $\tilde{g}$ 1.24 TeV tanβ<15 1208.4688
GMSB ($\tilde{\ell}$ NLSP) 1-2 τ 0-2 jets Yes 20.7 $\tilde{g}$ 1.4 TeV tanβ >18 ATLAS-CONF-2013-026
GGM (bino NLSP) 2 γ - Yes 4.8 $\tilde{g}$ 1.07 TeV m($\tilde{\chi}_1^0$)>50 GeV 1209.0753
GGM (wino NLSP) 1 $e, \mu + \gamma$ - Yes 4.8 $\tilde{g}$ 619 GeV m($\tilde{\chi}_1^0$)>50 GeV ATLAS-CONF-2012-144
GGM (higgsino-bino NLSP) γ 1 b Yes 4.8 $\tilde{g}$ 900 GeV m($\tilde{\chi}_1^0$)>220 GeV 1211.1167
GGM (higgsino NLSP) 2 e, μ (Z) 0-3 jets Yes 5.8 $\tilde{g}$ 690 GeV m($\tilde{H}$)>200 GeV ATLAS-CONF-2012-152
Gravitino LSP 0 mono-jet Yes 10.5 F$^{1/2}$ scale 645 GeV m($\tilde{g}$)>10^{-4} eV ATLAS-CONF-2012-147
3rd gen. $\tilde{g}$ med.
$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$ 0 3 b Yes 20.1 $\tilde{g}$ 1.2 TeV m($\tilde{\chi}_1^0$)<600 GeV ATLAS-CONF-2013-061
$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$ 0 7-10 jets Yes 20.3 $\tilde{g}$ 1.1 TeV m($\tilde{\chi}_1^0$) <350 GeV 1308.1841
$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$ 0-1 e, μ 3 b Yes 20.1 $\tilde{g}$ 1.34 TeV m($\tilde{\chi}_1^0$)<400 GeV ATLAS-CONF-2013-061
$\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$ 0-1 e, μ 3 b Yes 20.1 $\tilde{g}$ 1.3 TeV m($\tilde{\chi}_1^0$)<300 GeV ATLAS-CONF-2013-061
3rd gen. squarks direct production
$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}_1^0$ 0 2 b Yes 20.1 $\tilde{b}_1$ 100-620 GeV m($\tilde{\chi}_1^0$)<90 GeV 1308.2631
$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to t\tilde{\chi}_1^{\pm}$ 2 e, μ (SS) 0-3 b Yes 20.7 $\tilde{b}_1$ 275-430 GeV m($\tilde{\chi}_1^{\pm}$)=2 m($\tilde{\chi}_1^0$) ATLAS-CONF-2013-007
$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to b\tilde{\chi}_1^{\pm}$ 1-2 e, μ 1-2 b Yes 4.7 $\tilde{t}_1$ 110-167 GeV m($\tilde{\chi}_1^0$)=55 GeV 1208.4305, 1209.2102
$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to Wb\tilde{\chi}_1^0$ 2 e, μ 0-2 jets Yes 20.3 $\tilde{t}_1$ 130-220 GeV m($\tilde{\chi}_1^0$) =m($\tilde{t}_1$)-m(W)-50 GeV, m($\tilde{t}_1$)<<m($\tilde{\chi}_1^{\pm}$) ATLAS-CONF-2013-048
$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to t\tilde{\chi}_1^0$ 2 e, μ 2 jets Yes 20.3 $\tilde{t}_1$ 225-525 GeV m($\tilde{\chi}_1^0$)=0 GeV ATLAS-CONF-2013-065
$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}_1^{+}$ 0 2 b Yes 20.1 $\tilde{t}_1$ 150-580 GeV m($\tilde{\chi}_1^0$)<200 GeV, m($\tilde{\chi}_1^{\pm}$)-m($\tilde{\chi}_1^0$)=5 GeV 1308.2631
$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$ 1 e, μ 1 b Yes 20.7 $\tilde{t}_1$ 200-610 GeV m($\tilde{\chi}_1^0$)=0 GeV ATLAS-CONF-2013-037
$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$ 0 2 b Yes 20.5 $\tilde{t}_1$ 320-660 GeV m($\tilde{\chi}_1^0$)=0 GeV ATLAS-CONF-2013-024
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$ 0 mono-jet/c-tag Yes 20.3 $\tilde{t}_1$ 90-200 GeV m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)<85 GeV ATLAS-CONF-2013-068
$\tilde{t}_1\tilde{t}_1$(natural GMSB) 2 e, μ (Z) 1 b Yes 20.7 $\tilde{t}_1$ 500 GeV m($\tilde{\chi}_1^0$)>150 GeV ATLAS-CONF-2013-025
$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1 + Z$ 3 e, μ (Z) 1 b Yes 20.7 $\tilde{t}_2$ 271-520 GeV m($\tilde{t}_1$)=m($\tilde{\chi}_1^0$)+180 GeV ATLAS-CONF-2013-025
EW direct
$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}_1^0$ 2 e, μ 0 Yes 20.3 $\tilde{\ell}$ 85-315 GeV m($\tilde{\chi}_1^0$)=0 GeV ATLAS-CONF-2013-049
$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$ 2 e, μ 0 Yes 20.3 $\tilde{\chi}_1^{\pm}$ 125-450 GeV m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\ell}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$)) ATLAS-CONF-2013-049
$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$ 2 τ - Yes 20.7 $\tilde{\chi}_1^{\pm}$ 180-330 GeV m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\tau}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$)) ATLAS-CONF-2013-028
$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$ 3 e, μ 0 Yes 20.7 $\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$ 600 GeV m($\tilde{\chi}_1^{\pm}$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$)) ATLAS-CONF-2013-035
$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$ 3 e, μ 0 Yes 20.7 $\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$ 315 GeV m($\tilde{\chi}_1^{\pm}$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, sleptons decoupled ATLAS-CONF-2013-035
$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 h\tilde{\chi}_1^0$ 1 e, μ 2 b Yes 20.3 $\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$ 285 GeV m($\tilde{\chi}_1^{\pm}$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, sleptons decoupled ATLAS-CONF-2013-093
Long-lived particles
Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$ Disapp. trk 1 jet Yes 20.3 $\tilde{\chi}_1^{\pm}$ 270 GeV m($\tilde{\chi}_1^{\pm}$)-m($\tilde{\chi}_1^0$)=160 MeV, τ($\tilde{\chi}_1^{\pm}$)=0.2 ns ATLAS-CONF-2013-069
Stable, stopped $\tilde{g}$ R-hadron 0 1-5 jets Yes 22.9 $\tilde{g}$ 832 GeV m($\tilde{\chi}_1^0$)=100 GeV, 10 μs<τ($\tilde{g}$)<1000 s ATLAS-CONF-2013-057
GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e}, \tilde{\mu})+\tau(e, \mu)$ 1-2 μ - - 15.9 $\tilde{\chi}_1^0$ 475 GeV 10<tanβ<50 ATLAS-CONF-2013-058
GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$ 2 γ - Yes 4.7 $\tilde{\chi}_1^0$ 230 GeV 0.4<τ($\tilde{\chi}_1^0$)<2 ns 1304.6310
$\tilde{q}\tilde{q}, \tilde{\chi}_1^0\to qq\mu$ (RPV) 1 μ, displ. vtx - - 20.3 $\tilde{q}$ 1.0 TeV 1.5 <$c\tau$<156 mm, BR(μ)=1, m($\tilde{\chi}_1^0$)=108 GeV ATLAS-CONF-2013-092
RPV
LFV $pp\to\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\to e + \mu$ 2 e, μ - - 4.6 $\tilde{\nu}_\tau$ 1.61 TeV λ'_{311}=0.10, λ_{132}=0.05 1212.1272
LFV $pp\to\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\to e(\mu) + \tau$ 1 $e, \mu + \tau$ - - 4.6 $\tilde{\nu}_\tau$ 1.1 TeV λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05 1212.1272
Bilinear RPV CMSSM 1 e, μ 7 jets Yes 4.7 $\tilde{q}, \tilde{g}$ 1.2 TeV m($\tilde{q}$)=m($\tilde{g}$), $c\tau_{LSP}$<1 mm ATLAS-CONF-2012-140
$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$ 4 e, μ - Yes 20.7 $\tilde{\chi}_1^{\pm}$ 760 GeV m($\tilde{\chi}_1^0$)>300 GeV, λ_{121}>0 ATLAS-CONF-2013-036
$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$ 3 $e, \mu + \tau$ - Yes 20.7 $\tilde{\chi}_1^{\pm}$ 350 GeV m($\tilde{\chi}_1^0$)>80 GeV, λ_{133}>0 ATLAS-CONF-2013-036
$\tilde{g}\to qqq$ 0 6-7 jets - 20.3 $\tilde{g}$ 916 GeV BR(t)=BR(b)=BR(c)=0% ATLAS-CONF-2013-091
$\tilde{g}\to\tilde{t}_1 t, \tilde{t}_1\to bs$ 2 e, μ (SS) 0-3 b Yes 20.7 $\tilde{g}$ 880 GeV ATLAS-CONF-2013-007
Other
Scalar gluon pair, sgluon$\to q\bar{q}$ 0 4 jets - 4.6 sgluon 100-287 GeV incl. limit from 1110.2693 1210.4826
Scalar gluon pair, sgluon$\to t\bar{t}$ 2 e, μ (SS) 1 b Yes 14.3 sgluon 800 GeV ATLAS-CONF-2013-051
WIMP interaction (D5, Dirac χ) 0 mono-jet Yes 10.5 M^* scale 704 GeV m(χ)<80 GeV, limit of<687 GeV for D8 ATLAS-CONF-2012-147
$\sqrt{s}$ = 7 TeV full data
$\sqrt{s}$ = 8 TeV partial data
$\sqrt{s}$ = 8 TeV full data
10^{-1}
1
Mass scale [TeV]
*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.



Summary of CMS SUSY Results* in SMS framework
SUSY 2013
m(mother)-m(LSP)=200 GeV
m(LSP)=0 GeV
gluino production
SUS-13-012 SUS-12-028 L=19.5 11.7 /fb
SUS-12-005 SUS-11-024 L=4.7 /fb
SUS-13-004 SUS-12-024 SUS-12-028 L=19.3 19.4 /fb
SUS-13-004 SUS-13-007 SUS-13-008 SUS-13-013 L=19.4 19.5 /fb
SUS-11-011 L=4.98 /fb
SUS-12-004 L=4.98 /fb
SUS-12-010 L=4.98 /fb
SUS-13-008 SUS-13-013 L=19.5 /fb
SUS-11-010 L=4.98 /fb
SUS-11-021 SUS-12-002 L=4.98 4.73 /fb
SUS-13-013 L=19.5 /fb
SUS-12-001 L=4.93 /fb
SUS-12-001 L=4.93 /fb
SUS-13-008 SUS-13-013 L=19.5 /fb
squark
SUS-13-012 SUS-12-028 L=19.5 11.7 /fb
SUS-12-005 SUS-11-024 L=4.7 /fb
stop
SUS-13-011 SUS-13-004 L=19.5 19.3 /fb
left-handed top
unpolarized top
right-handed top
SUS-11-024 SUS-12-005 L=4.7 /fb
SUS-13-011 L=19.5 /fb
SUS-11-030 L=4.98 /fb
SUS-13-014 L=19.5 /fb
sbottom
SUS-12-028 L=11.7 /fb
SUS-13-008 SUS-13-013 L=19.5 /fb
SUS-13-008 L=19.5 /fb
EWK gauginos
SUS-13-006 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-13-017 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-13-006 L=19.5 /fb
slepton
SUS-13-006 L=19.5 /fb
√s = 7 TeV
√s = 8 TeV
CMS Preliminary
For decays with intermediate mass,
$m_{intermediate} = x \cdot m_{mother} - (1-x) \cdot m_{lsp}$
0
200
400
600
800
1000
1200
1400
Mass scales [GeV]
*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probe *up to* the quoted mass limit

Constrained Minimal Supersymmetric

Phenomenological Minimal Supersymmetric

Symbol	Description	number of parameters
$\tan\beta$	the ratio of the vacuum expectation values of the two Higgs doublets	1
M_A	the mass of the pseudoscalar Higgs boson	1
μ	the higgsino mass parameter	1
M_1	the bino mass parameter	1
M_2	the wino mass parameter	1
M_3	the gluino mass parameter	1
$m_{\tilde{q}}, m_{\tilde{u}_R}, m_{\tilde{d}_R}$	the first and second generation squark masses	3
$m_{\tilde{l}}, m_{\tilde{e}_R}$	the first and second generation slepton masses	2
$m_{\tilde{Q}}, m_{\tilde{t}_R}, m_{\tilde{b}_R}$	the third generation squark masses	3
$m_{\tilde{L}}, m_{\tilde{\tau}_R}$	the third generation slepton masses	2
A_t, A_b, A_τ	the third generation trilinear couplings	3

Constrained Minimal Supersymmetric Standard Model (CMSSM)

G. L. Kane, C. F. Kolda, L. Roszkowski and J. D. Wells, Phys. Rev. D 49 (1994) 6173

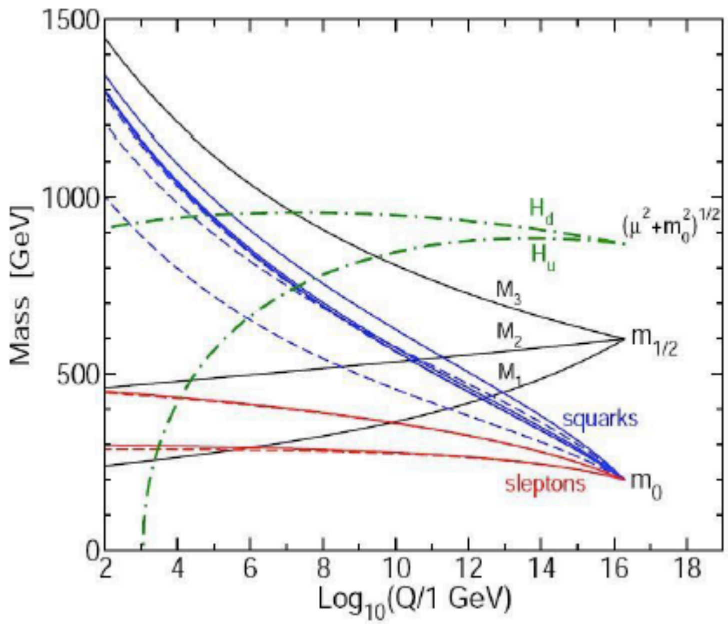


figure from hep-ph/9709356

At $M_{\mathrm{GUT}} \simeq 2 \times 10^{16}\,\mathrm{GeV}$:

- gauginos $M_1 = M_2 = m_{\tilde{g}} = m_{1/2}$
- scalars $m^2_{\tilde{q}_i} = m^2_{\tilde{l}_i} = m^2_{H_b} = m^2_{H_t} = m^2_0$
- 3–linear soft terms $A_b = A_t = A_0$
- radiative EWSB $\mu^2 = \frac{m^2_{H_b} - m^2_{H_t} \tan^2\beta}{\tan^2\beta - 1} - \frac{m^2_Z}{2}$
- five independent parameters: $m_{1/2},\ m_0,\ A_0,\ \tan\beta,\ \mathrm{sgn}(\mu)$
- well developed machinery to compute masses and couplings

In general supersymmetric SM too many free parameter

PHYSICS TODAY

Is string theory phenomenologically viable?

S. James Gates Jr

String theory is entering an era in which its theoretical constructs will be confronted by experimental data. Some cherished ideas just might fail to pass the test.

Jim Gates is the John S. Toll Professor of Physics and director of the Center for String and Particle Theory at the University of Maryland in College Park.

Physics Today **59**, 6, 54 (2006); https://doi.org/10.1063/1.2218556

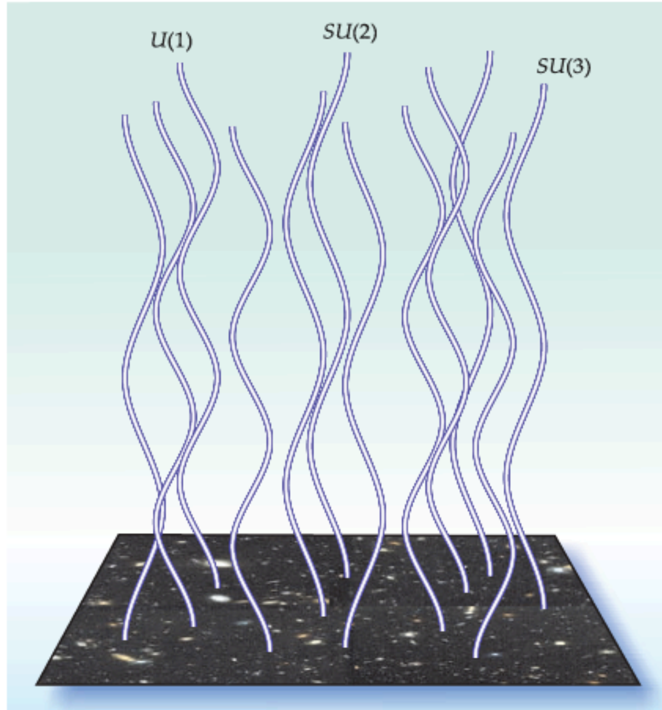


Figure 1. A fiber bundle is built from a base that has a fiber emerging from each of its points. In the standard model, the base is the four-dimensional spacetime of our universe, and each of the fibers, the simple depictions notwithstanding, is one of the gauge groups *SU*(3), *SU*(2), or *U*(1) that mathematically define the gauge transformations of the model. In 4D string theories, fibers can represent gauge groups that are not part of the standard model. (Hubble Deep Field image courtesy of Robert Williams, Space Telescope Science Institute, the Hubble Deep Field team, and NASA.)

The experimental observation of supersymmetry would provide a big, albeit indirect, piece of evidence validating the superstring paradigm. The most spectacular result would be the direct production of a particle that is the superpartner of a known particle. However, it will take great fortune for a superparticle to be directly observable. The range of masses discussed in the literature for superpartners is something like 1000 to 30 000 times the mass of the proton, which is roughly 1 GeV/c^2. With the dates of discovery and masses of the neutron and W bosons as benchmarks, one can crudely estimate the rate at which humanity is progressing in its ability to detect massive particles: about 1.5 GeV/c^2 per year. Thus, if Nature is kind enough to provide light superpartners, one might still expect about a century to pass before a superparticle is directly observed.

Much more likely, evidence for supersymmetry will emerge by indirect means. Such evidence might be provided by precision measurements of the rates of change of coupling constants, anomalies in lifetimes or branching ratios in decays of known particles, and so forth. Even the detection of a Higgs boson and an indication of its mass would be relevant to the question of whether supersymmetry exists in Nature. The community of particle physicists has, over the past two decades, been working with great energy to explore the experimental signatures associated with superparticle production.[6]

With the dates of discovery and the masses of the neutron and W boson as benchmarks, one can crudely estimate the rate at which humanity is progressing in its ability to detect massive particles… about 1.5 GeV/c^2 per year.

"Thus, if Nature is kind enough to provide light superpartners, one might still expect about a century to pass before a superparticle is directly observed."

"Much more likely, evidence for supersymmetry will emerge by indirect means. Such evidence might be provided by precision measurements of the rates of change of coupling constants, anomalies in lifetimes or branching ratios in decays of known particles, and so forth. "

– *Physics Today, 59N6 (2006) 54.*

What's SUSY (if anything) Got To Do With It?

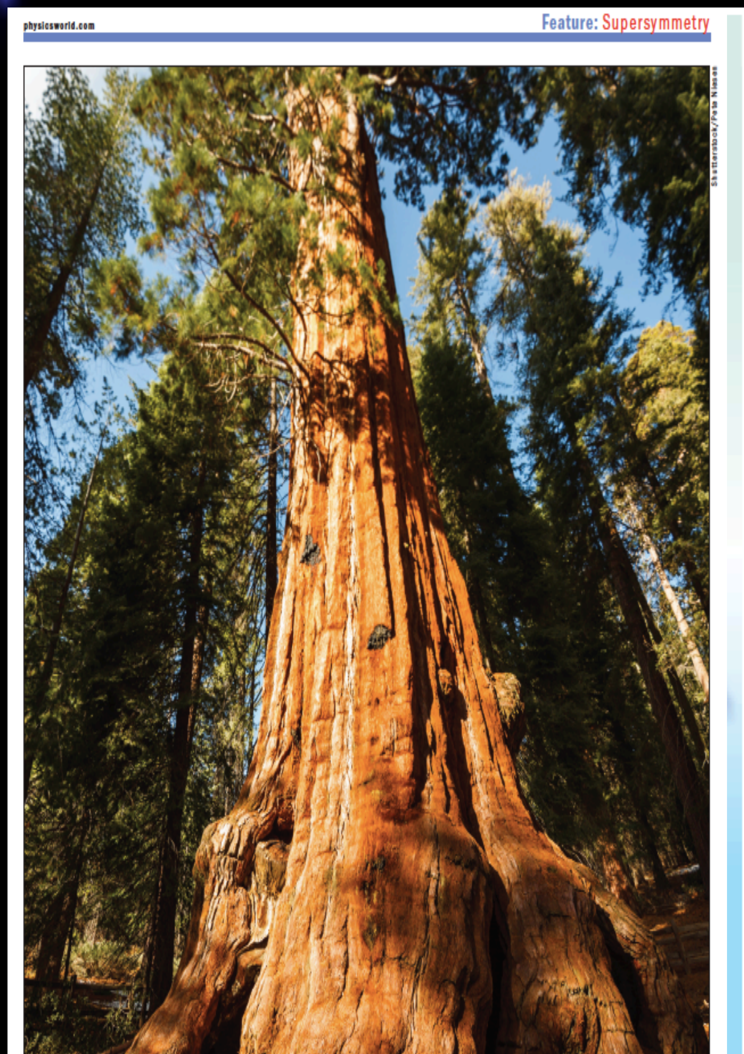
"SUSY, I strongly believe, will in the end be figuratively like Mark Twain who is often misquoted as having said, "The reports of my death have been greatly exaggerated."

– SJG 2008 in Waves and Packets: https://multibriefs.com/briefs/nsbp/extrapage.html

Sticking with SUSY

When CERN's Large Hadron Collider failed to uncover evidence of new "superpartner" particles during its first run, some claimed that the theory that predicts them – known as supersymmetry, or SUSY – should be abandoned. **S James Gates, Jr**, however, argues that giving up on SUSY now would be like concluding that giant sequoia trees do not exist after surveying only the east coast of North America, and that there is more at stake than meets the eye

Shutterstock/Pete Niesen



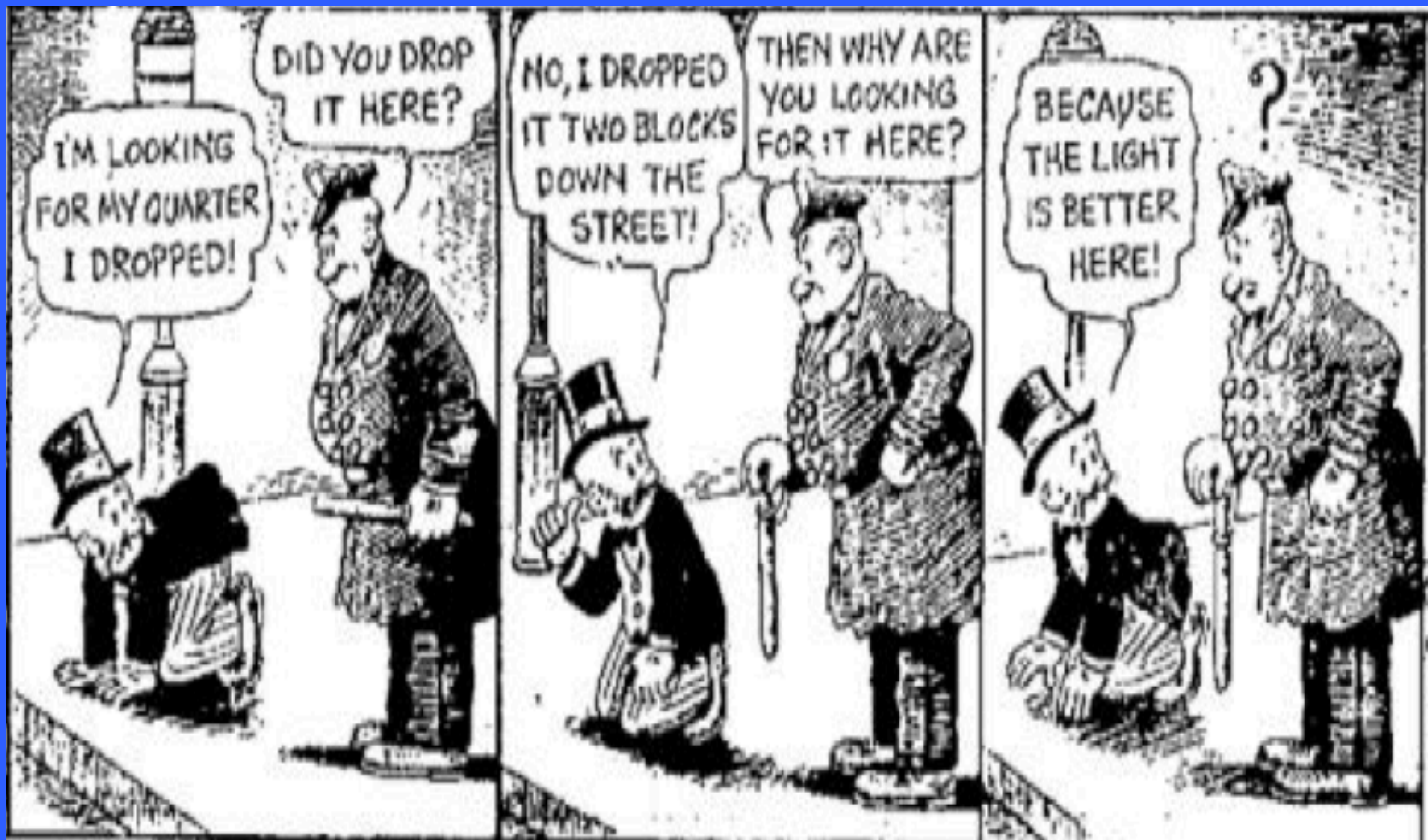
In my view, the current situation is akin to that of an explorer who, having scoured the eastern seaboard of North America, concludes that no groves of *Sequoiadendron giganteum* exist in the entire continental USA. As with this hypothetical hunt for giant sequoia trees, finding evidence for SUSY depends on the observer looking in the right place.

Only careful observation of nature can bring the clarity needed in this field. As experimentalists at the LHC prepare for upgraded operations in the next year, they will take the lead in settling the question of SUSY. At the same time, we need to be alert to the work of scientists who are looking for indications of SUSY elsewhere in the cosmos, particularly those involved in the continued search for dark matter as well as other possible astrophysical anomalies.

Shutterstock/Pete Niesen

In my view, the current situation is akin to that of an explorer who, having scoured the eastern seaboard of North America, concludes that no groves of *Sequoiadendron giganteum* exist in the entire continental USA. As with this hypothetical hunt for giant sequoia trees, finding evidence for SUSY depends on the observer looking in the right place.

Only careful observation of nature can bring the clarity needed in this field. As experimentalists at the LHC prepare for upgraded operations in the next year, they will take the lead in settling the question of SUSY **At the same time. we need to be alert to the work of scientists who are looking for indication of SUSY elsewhere in the cosmos, particularly those involved in the continued search for dark matter as well as other possible astrophysical anomalies.**


I'M LOOKING FOR MY QUARTER I DROPPED!
DID YOU DROP IT HERE?
NO, I DROPPED IT TWO BLOCKS DOWN THE STREET!
THEN WHY ARE YOU LOOKING FOR IT HERE?
BECAUSE THE LIGHT IS BETTER HERE!
?

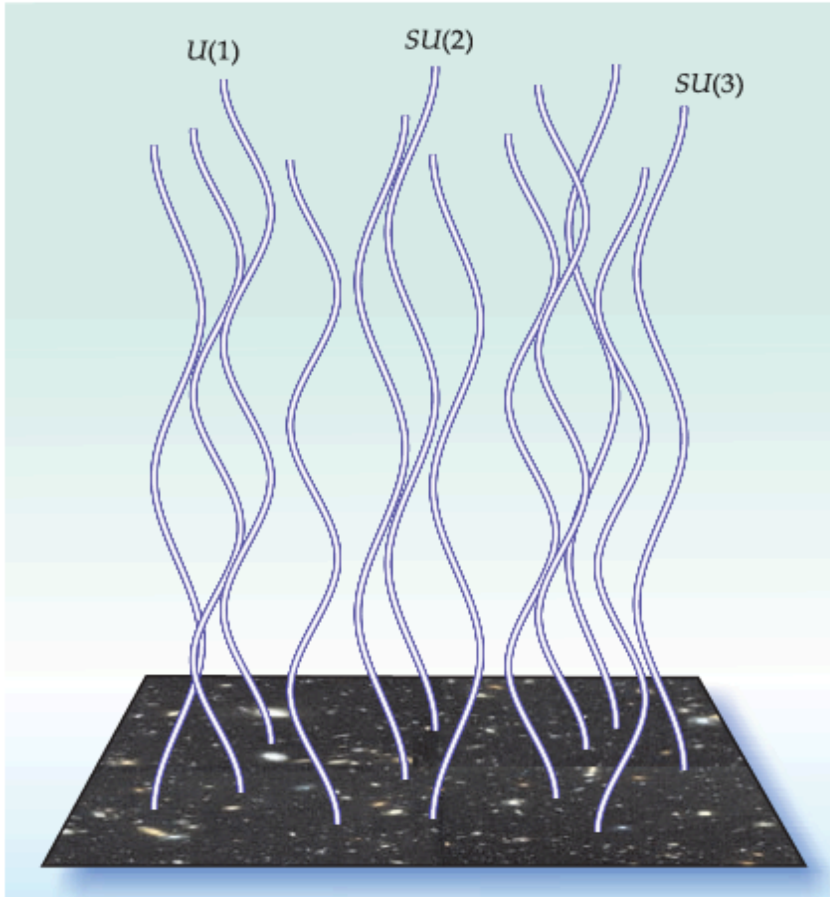


Figure 1. A fiber bundle is built from a base that has a fiber emerging from each of its points. In the standard model, the base is the four-dimensional spacetime of our universe, and each of the fibers, the simple depictions notwithstanding, is one of the gauge groups $SU(3)$, $SU(2)$, or $U(1)$ that mathematically define the gauge transformations of the model. In 4D string theories, fibers can represent gauge groups that are not part of the standard model. (Hubble Deep Field image courtesy of Robert Williams, Space Telescope Science Institute, the Hubble Deep Field team, and NASA.)

What's SST (if anything) Got To Do With It?

$$
\begin{aligned}
S_{HET-4D} = & \frac{1}{4\pi\alpha'}\int d^2\sigma d\zeta^- E^{-1}[\, i\eta_{\underline{mn}}\, (\nabla_+ X^{\underline{m}})\, (\nabla_= X^{\underline{n}})\,] \\
& -\frac{1}{2\pi}\int d^2\sigma d\zeta^- E^{-1} i \tfrac{1}{2} Tr\{\, R_+ R_= \; + i\Lambda_=^{\;=} R_+ \nabla_+ R_+ \\
& \qquad\qquad + \; \tfrac{2}{3}\Lambda_=^{\;=}\{\, R_+ \,,\, R_+ \,\}\; R_+ \\
& \quad + \int_0^1 d\,y\; [\, (\frac{d\widetilde{U}}{dy}\widetilde{R}^{-1}\,)[\, \nabla_=((\nabla_+\widetilde{R})\widetilde{R}^{-1}) \;\; - \\
& \qquad\qquad + \;\; \nabla_+((\nabla_=\widetilde{R})\widetilde{R}^{-1})\,]\,\} \\
& -\frac{1}{2\pi}\int d^2\sigma d\zeta^- E^{-1} i \tfrac{1}{2} Tr\{\, L_+ L_= \; + \; \Lambda_+^{\;=} L_= L_= \\
& \quad - \int_0^1 d\,y\; [\, (\frac{d\widetilde{L}}{dy}\widetilde{L}^{-1}\,)[\, \nabla_=((\nabla_+\widetilde{L})\widetilde{L}^{-1}) \;\; + \\
& \qquad\qquad - \;\; \nabla_+((\nabla_=\widetilde{L})\widetilde{L}^{-1})\,]\,\}
\end{aligned}
$$

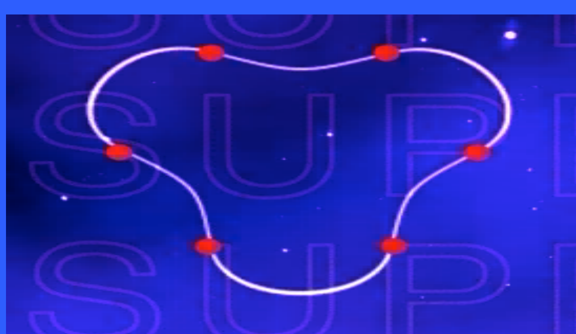
What's SST (if anything) Got To Do With It?

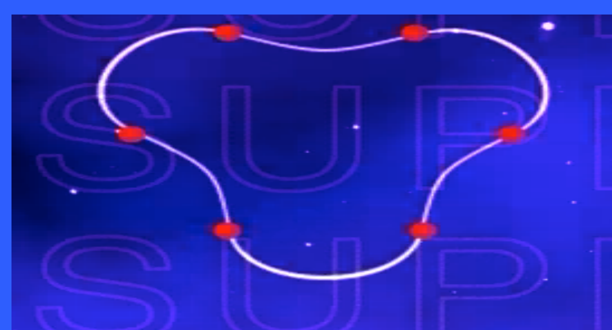
$$
\begin{aligned}
S_{HET-4D} = {} & \frac{1}{4\pi\alpha'}\int d^2\sigma d\zeta^- E^{-1}[\, i\eta_{mn}\,(\nabla_+ X^m)(\nabla_= X^n)\,] \\
& -\frac{1}{2\pi}\int d^2\sigma d\zeta^- E^{-1} i\tfrac{1}{2} Tr\{\, R_+ R_= + i\Lambda_=^{\;=} R_+ \nabla_+ R_+ \\
& \qquad + \tfrac{2}{3}\Lambda_=^{\;=}\{\, R_+\,,\, R_+\,\}\, R_+ \\
& \qquad + \int_0^1 dy\, [\,(\frac{d\widetilde{U}}{dy}\widetilde{R}^{-1})[\,\nabla_=((\nabla_+\widetilde{R})\widetilde{R}^{-1}) \;- \\
& \qquad + \nabla_+((\nabla_=\widetilde{R})\widetilde{R}^{-1})\,]\,\} \\
& -\frac{1}{2\pi}\int d^2\sigma d\zeta^- E^{-1} i\tfrac{1}{2} Tr\{\, L_+ L_= + \Lambda_+^{\;=} L_= L_= \\
& \qquad - \int_0^1 dy\, [\,(\frac{d\widetilde{L}}{dy}\widetilde{L}^{-1})[\,\nabla_=((\nabla_+\widetilde{L})\widetilde{L}^{-1}) \;+ \\
& \qquad - \nabla_+((\nabla_=\widetilde{L})\widetilde{L}^{-1})\,]\,\}
\end{aligned}
$$

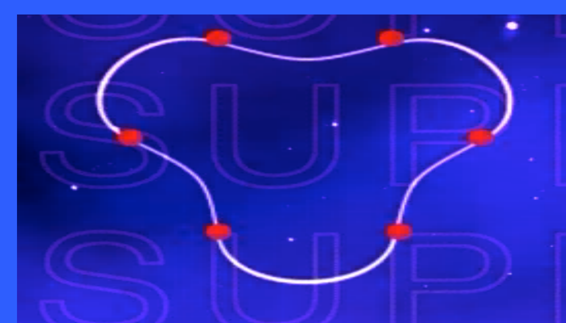
Spacetime Currents

Gauge Group currents

Family Currents



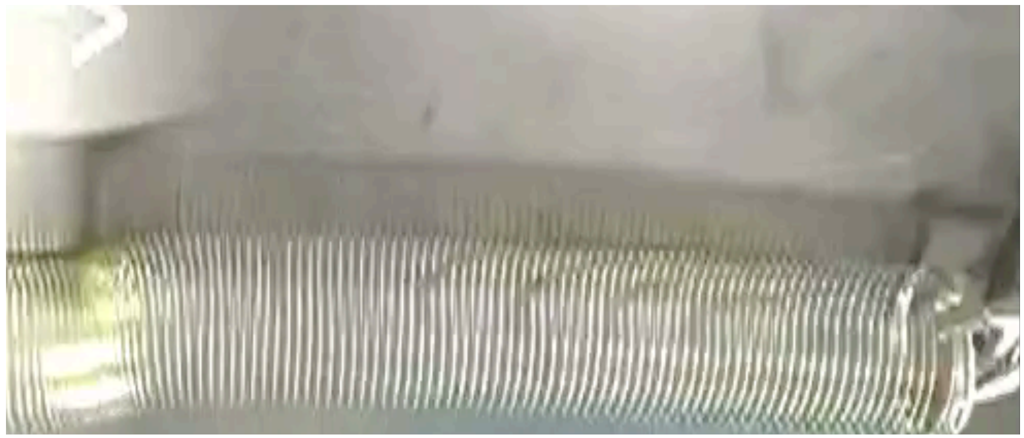




The Stern-Gerlach Legacy

The Higgs Boson is "spinless."

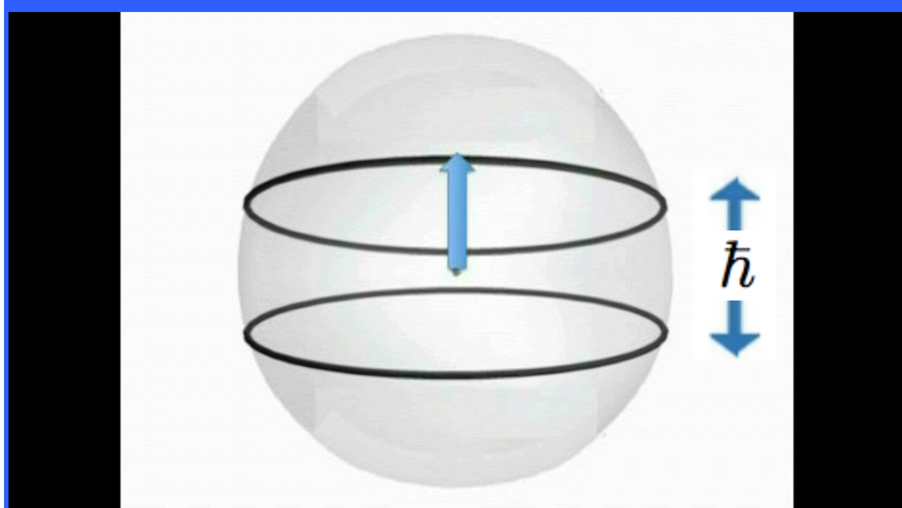
$$|\vec{s}|^2 = 0\,\hbar^2 \quad j = 0$$

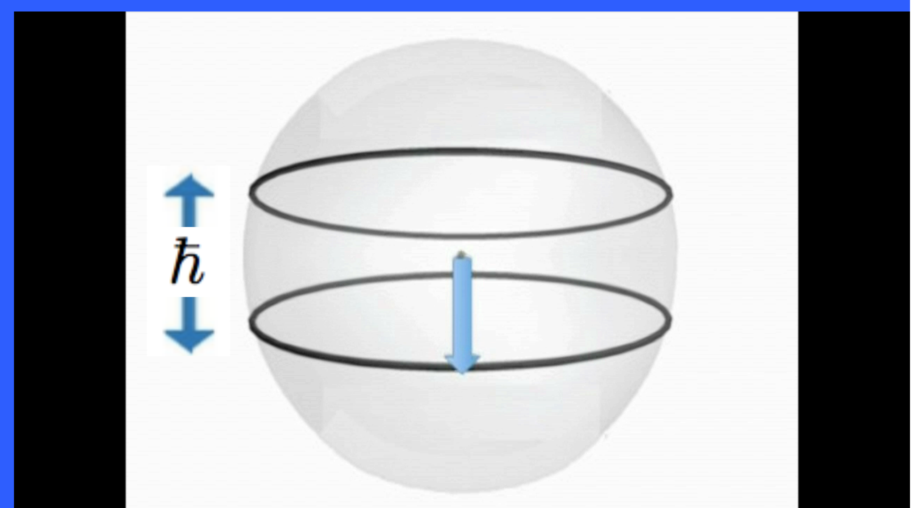


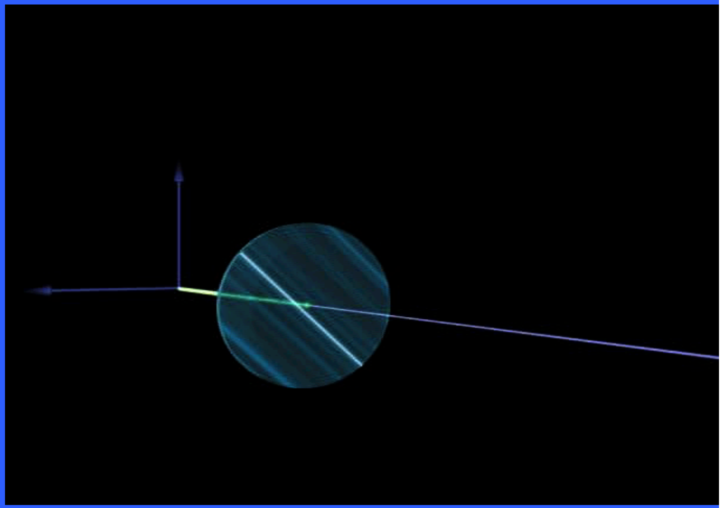
https://www.youtube.com/watch?v=fMJrtheQfZw

Degree of Freedom (DoF) = 1

Spin implies that electrons act like magnets that can only point at certain angles relative to their direction of motion.



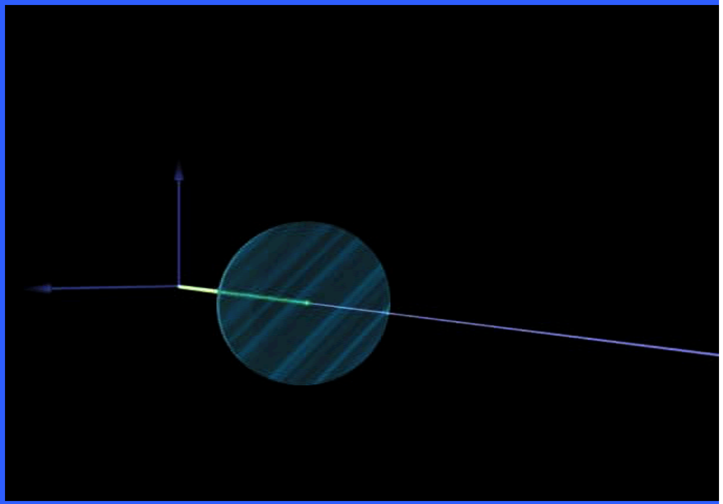




Positive Helicity

Right-Handed Circularly Polarized

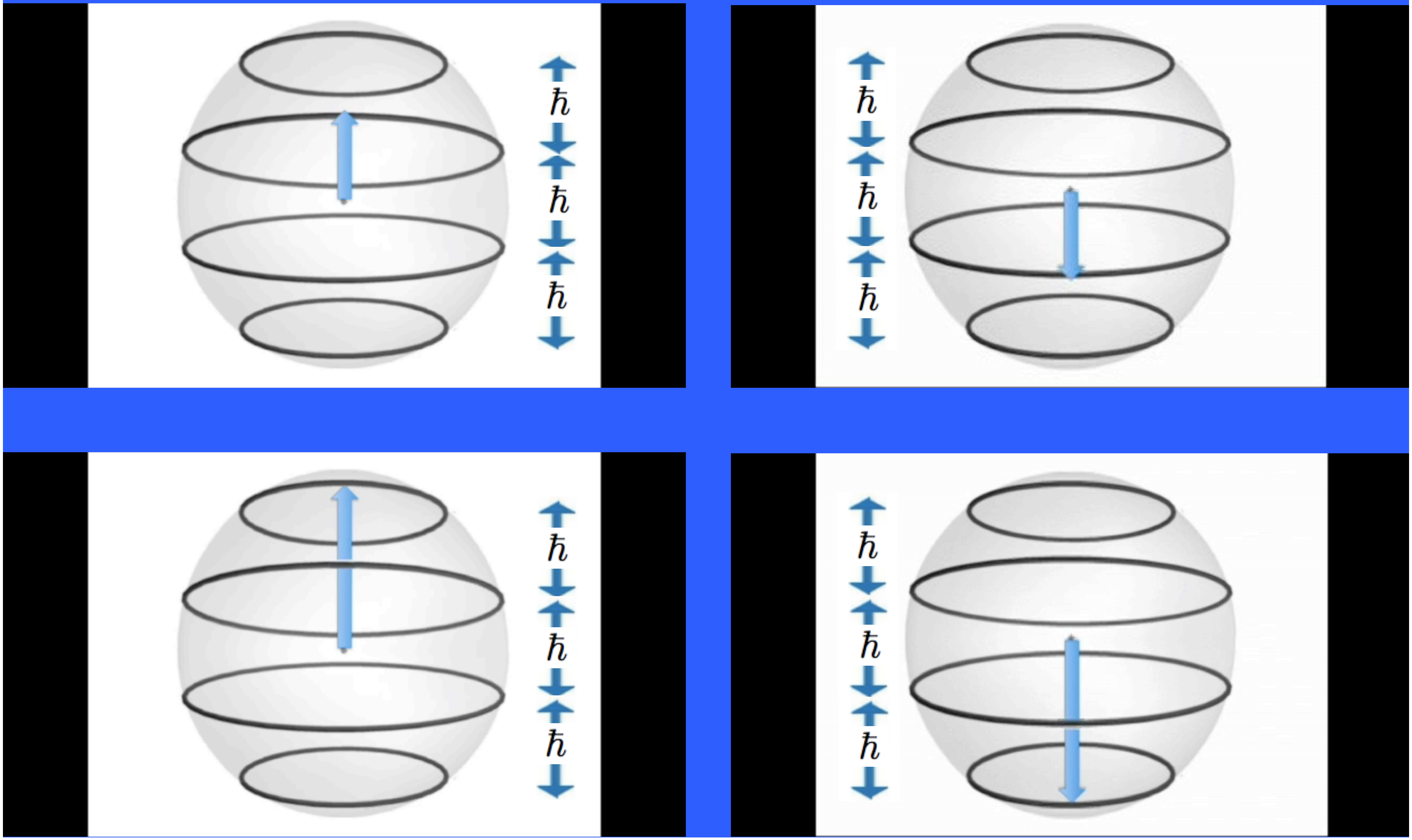
$$j = 1$$



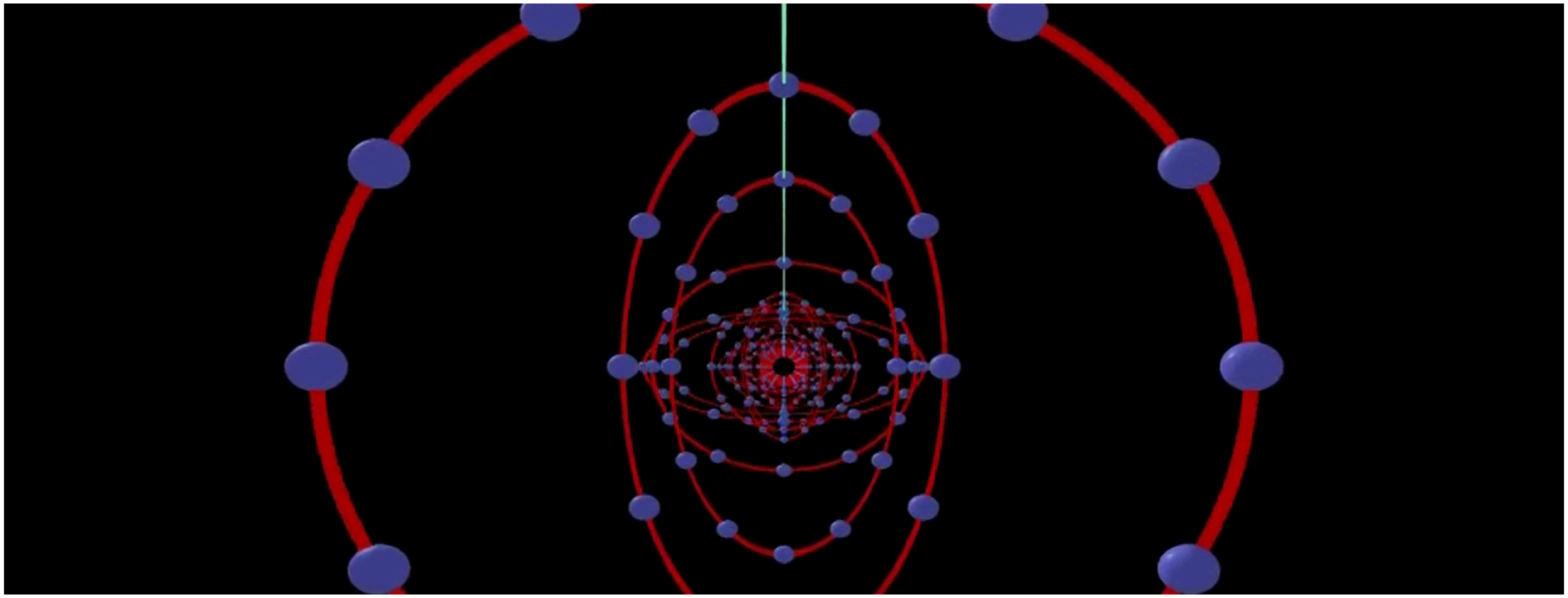
Negative Helicity

Left-Handed Circularly Polarized

Spin implies that j = 3/2 particles have a "spin vector" that can only point at certain (but more) angles relative to their directional motion.



https://www.youtube.com/watch?v=F4stTzxYrN0

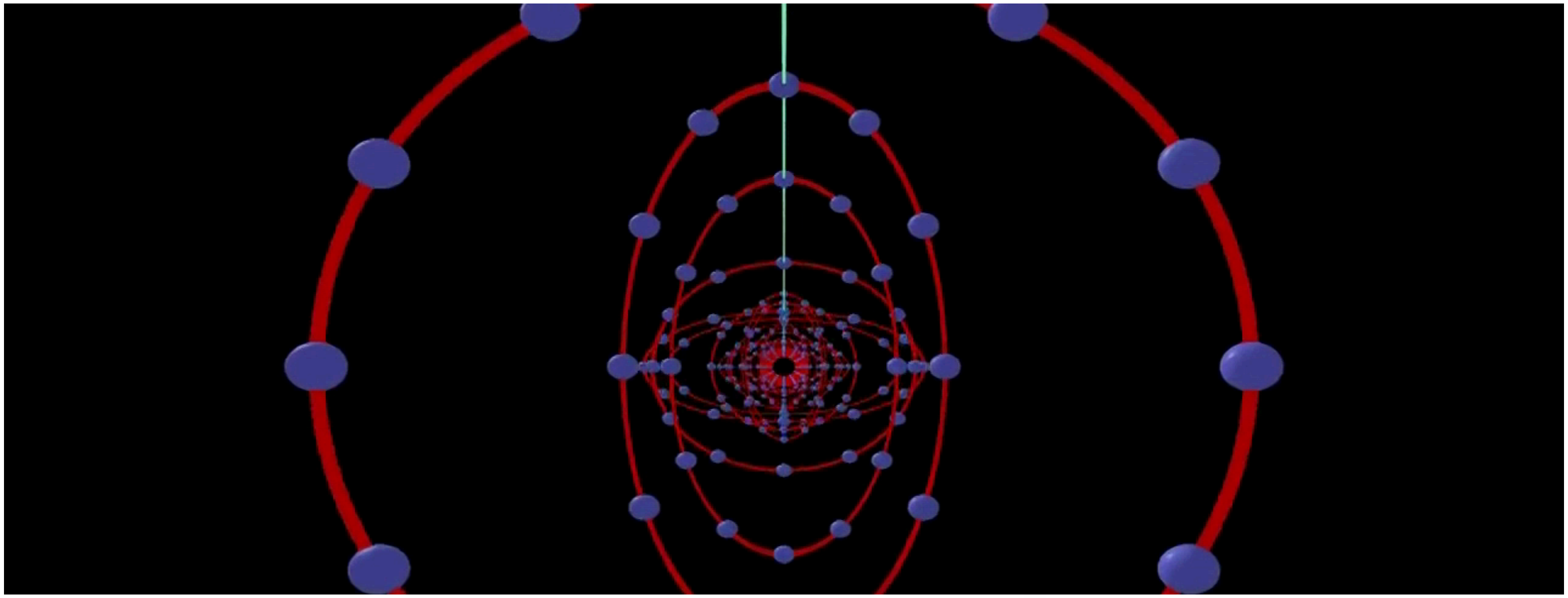


Linearly Polarized Gravitational Wave

$$j = 2$$

Degree of Freedom = 2

https://www.youtube.com/watch?v=F4stTzxYrN0

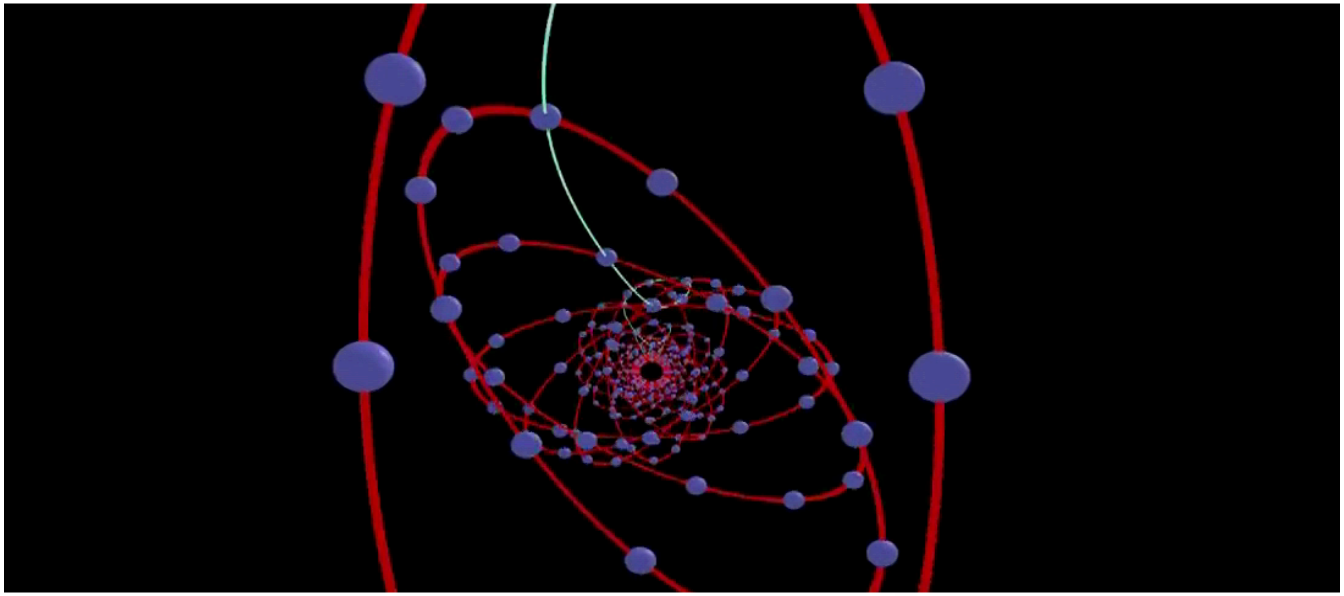


Linearly Polarized Gravitational Wave

$$j = 2$$

Degree of Freedom = 2

https://www.youtube.com/watch?v=F4stTzxYrN0

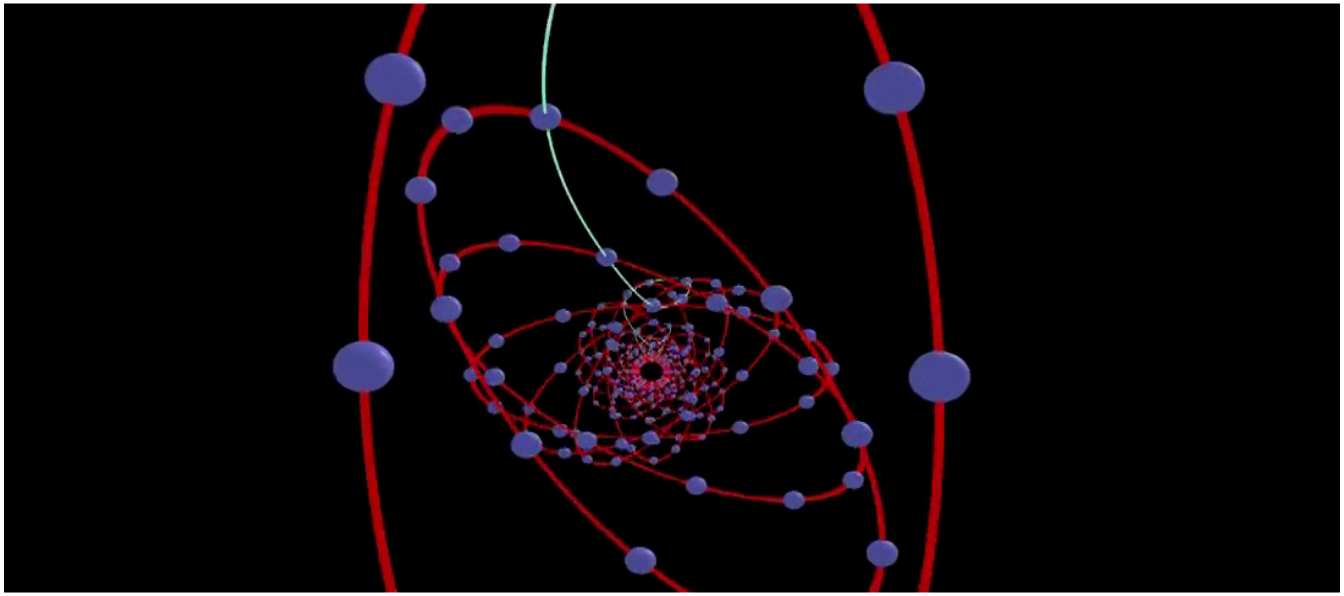


+ Helicity Polarized Gravitational Wave

$$j = 2$$

Degree of Freedom $= 1$

https://www.youtube.com/watch?v=F4stTzxYrN0

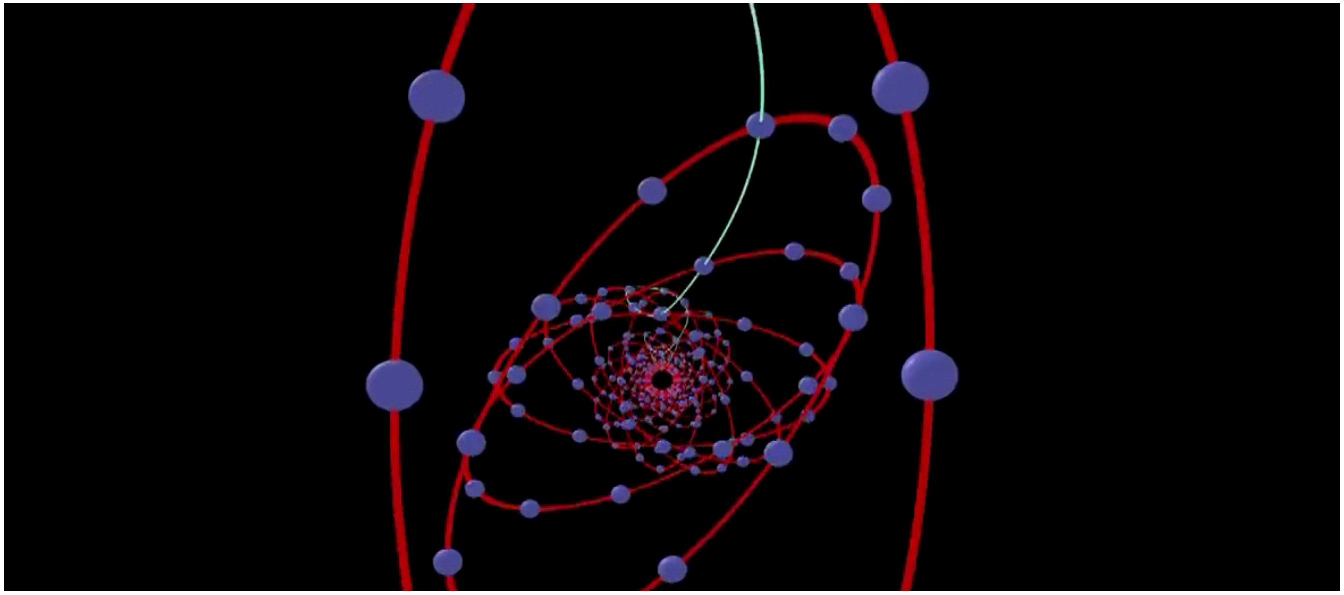


+ Helicity Polarized Gravitational Wave

$$j = 2$$

Degree of Freedom $= 1$

https://www.youtube.com/watch?v=F4stTzxYrN0

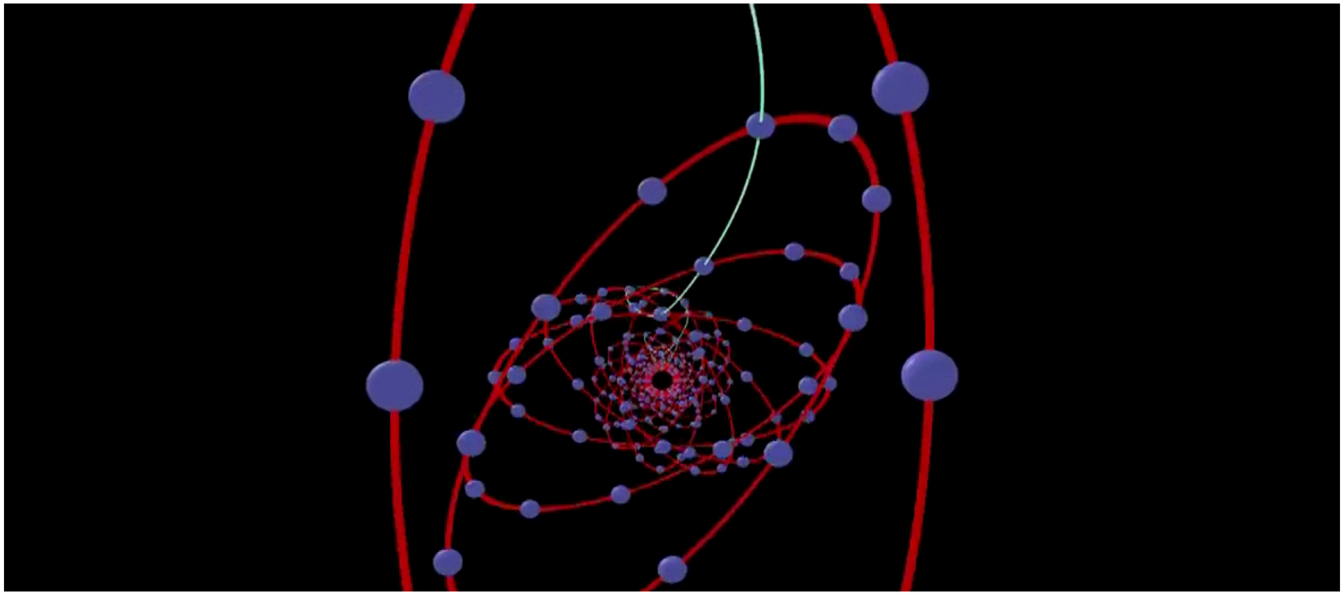


- Helicity Polarized Gravitational Wave

$$j = 2$$

Degree of Freedom $= 1$

https://www.youtube.com/watch?v=F4stTzxYrN0



- Helicity Polarized Gravitational Wave

$$j = 2$$

Degree of Freedom $= 1$

Big Question:

What did the Stern-Gelach experiment really tell us about our Universe?

Big Question:

Are group-like structures beyond the Lorentz Group and the Compact Lie Groups Relevant for the Laws of our Universe?

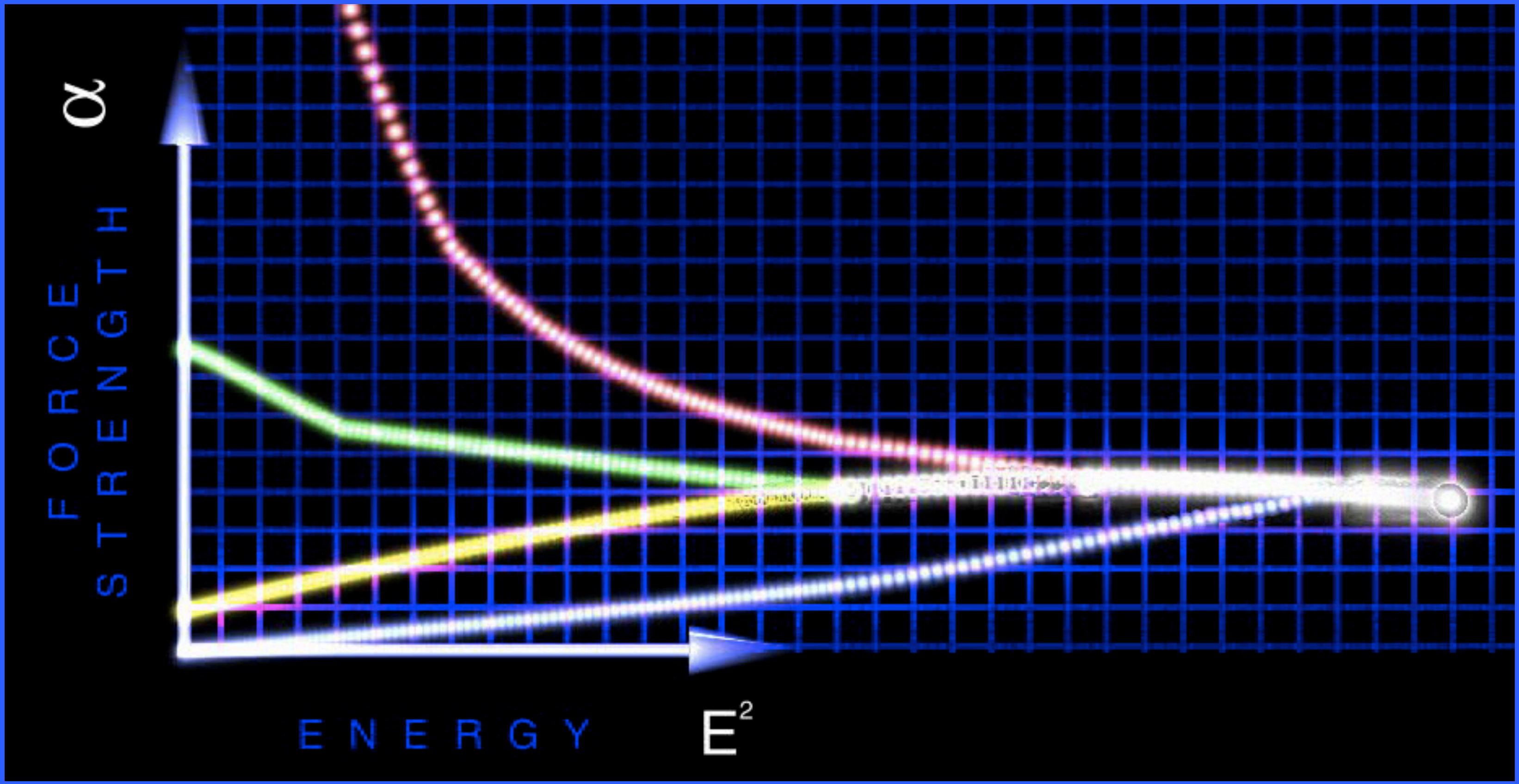
Big Question:

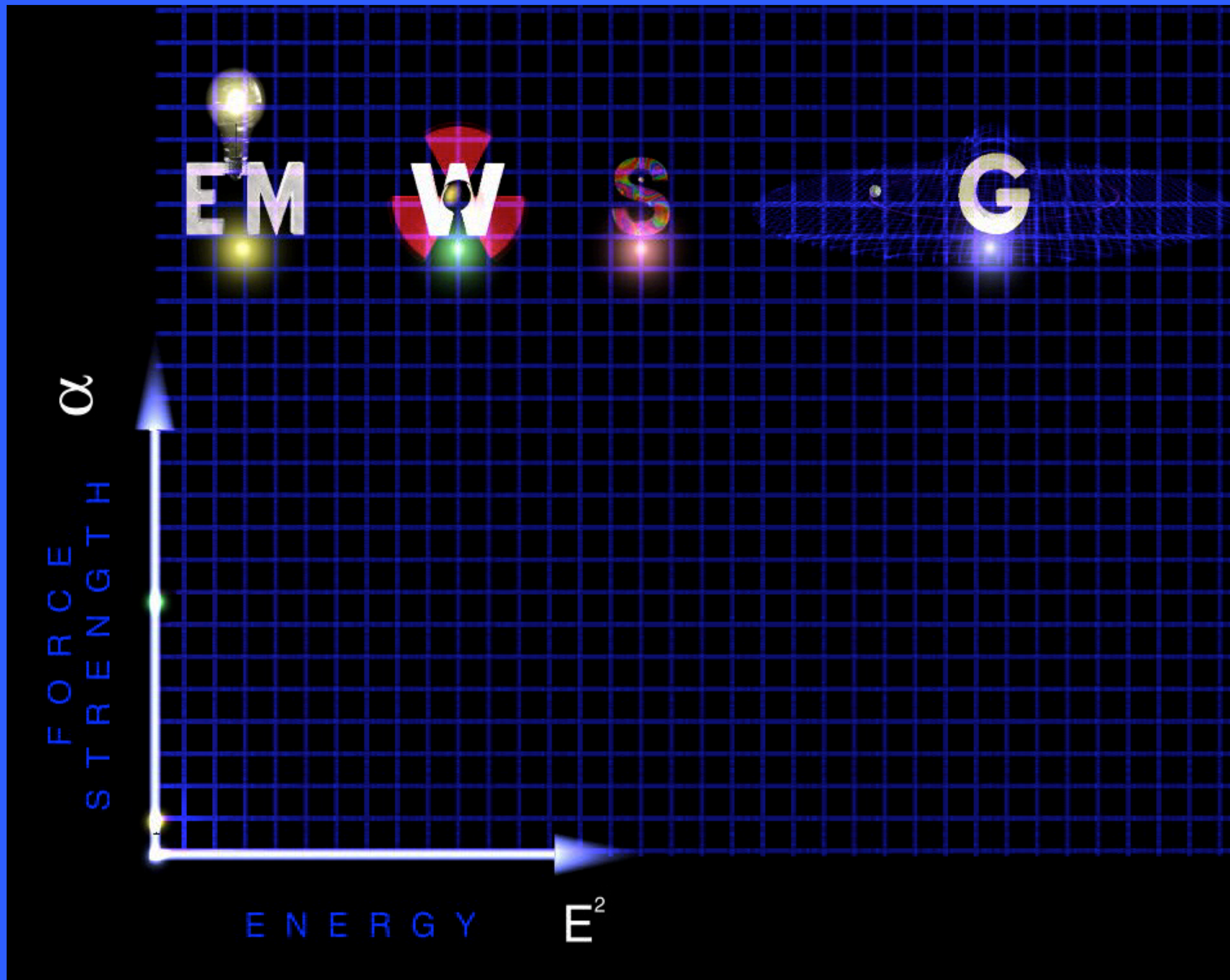
What is the maximal extent of Wigner's observation about the relation of particles to representation theory in mathematics?

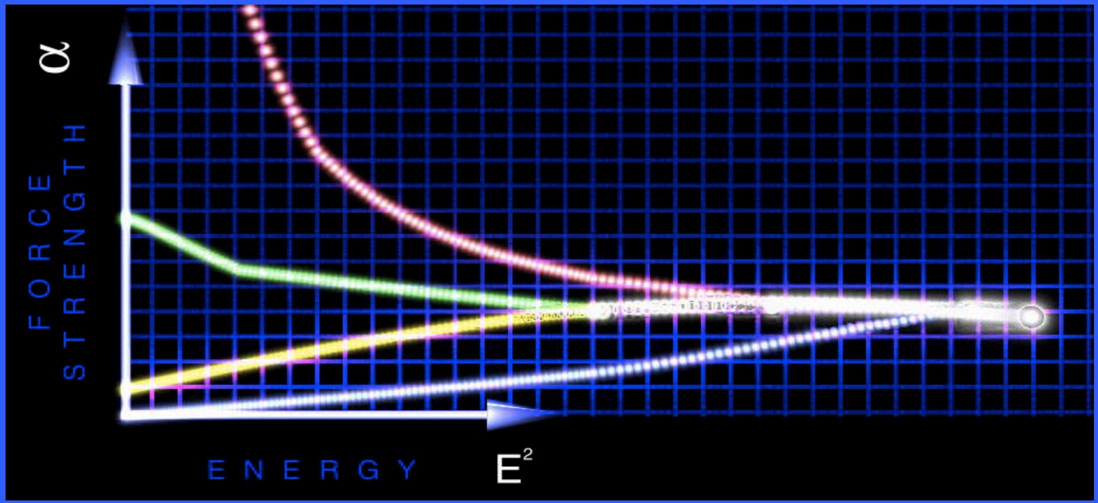
*It is my belief that
these are all the same,
if not closely related
questions, and humanity
must continue to query
Nature for answers.*

On the observational side, the community will bring the energy frontier together with the precision frontier in unprecedented ways.

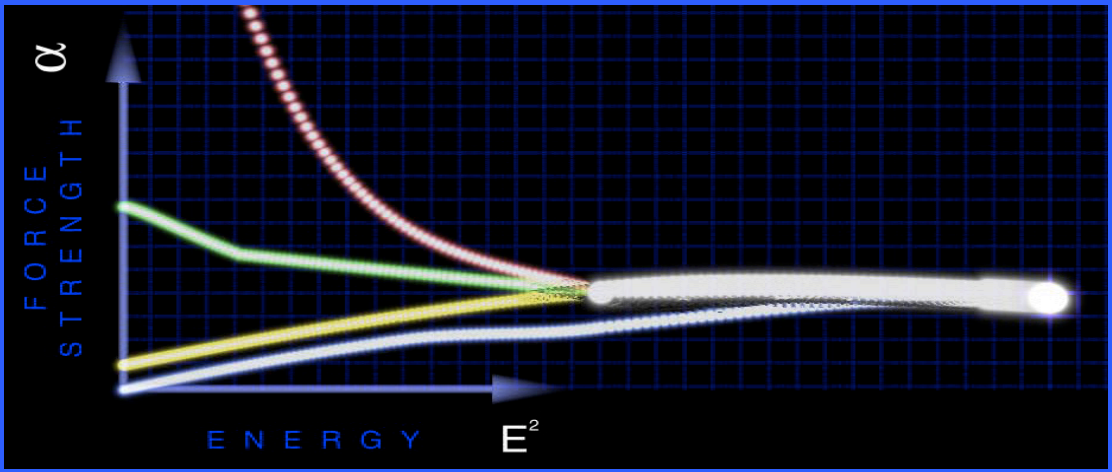
‘Running Constants’



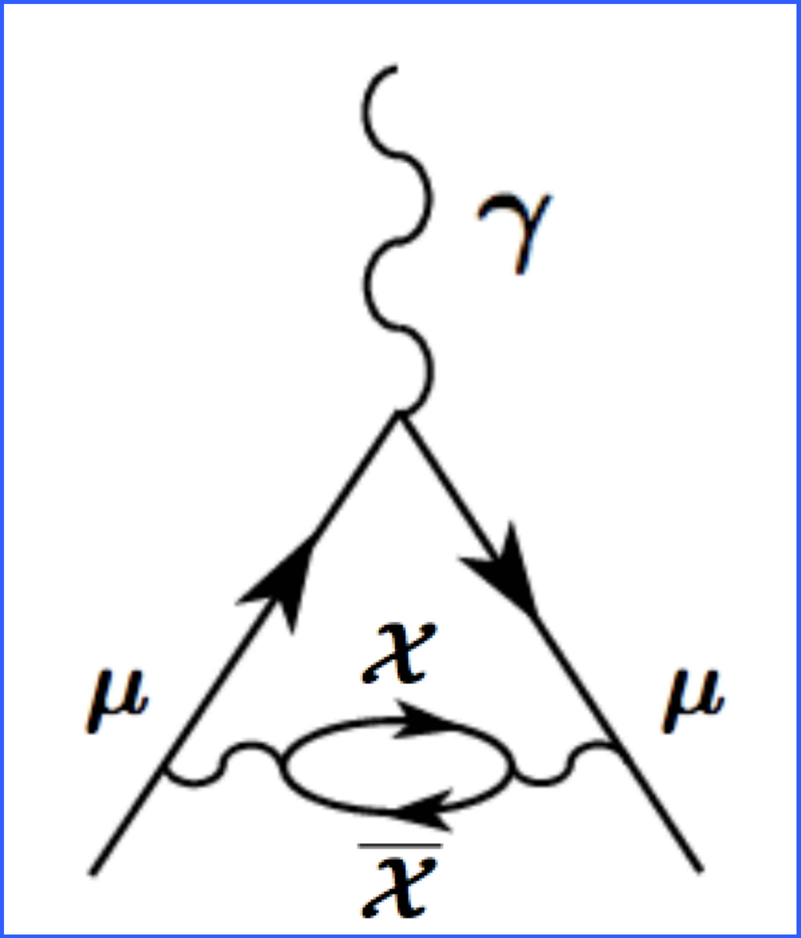

EM
W
S
G
FORCE STRENGTH
α
ENERGY
E^2



A Comparison




e-
e-
γ
e-
γ
ē+
e-
e-

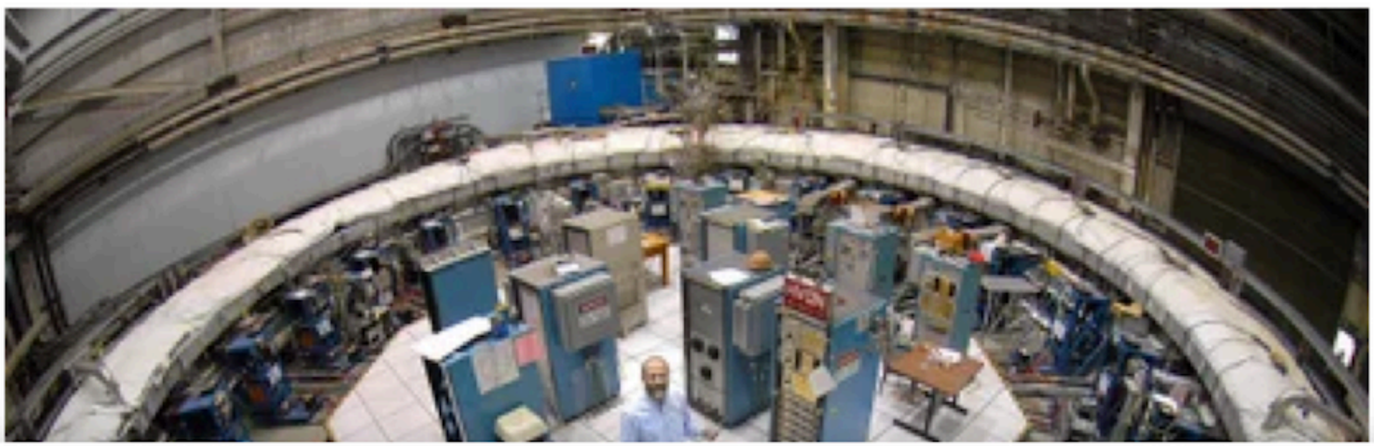

γ
μ
χ
μ
$\overline{\chi}$

PHYSICS

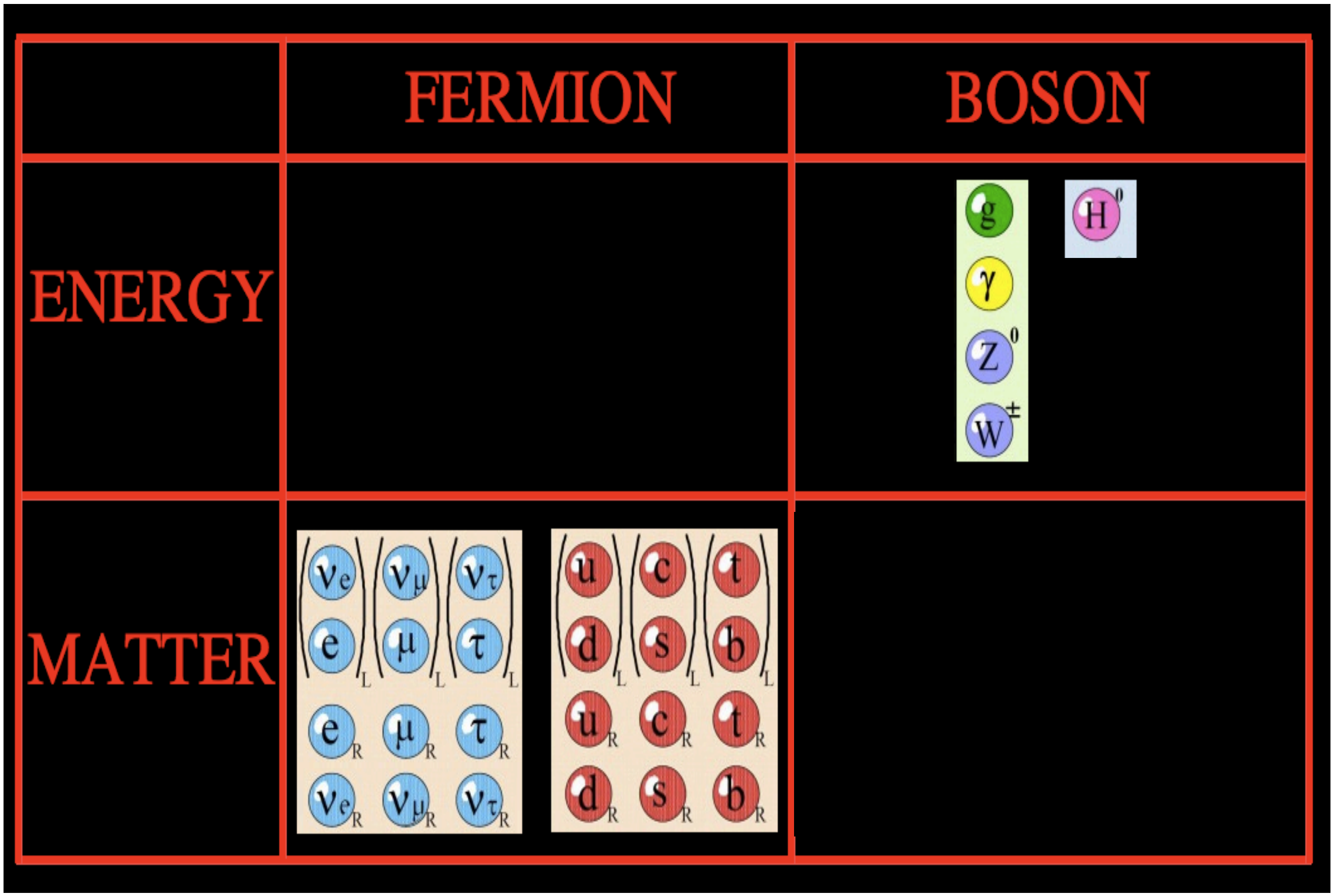
Long-Awaited Muon Measurement Boosts Evidence for New Physics

Initial data from the Muon g-2 experiment have excited particle physicists searching for undiscovered subatomic particles and forces

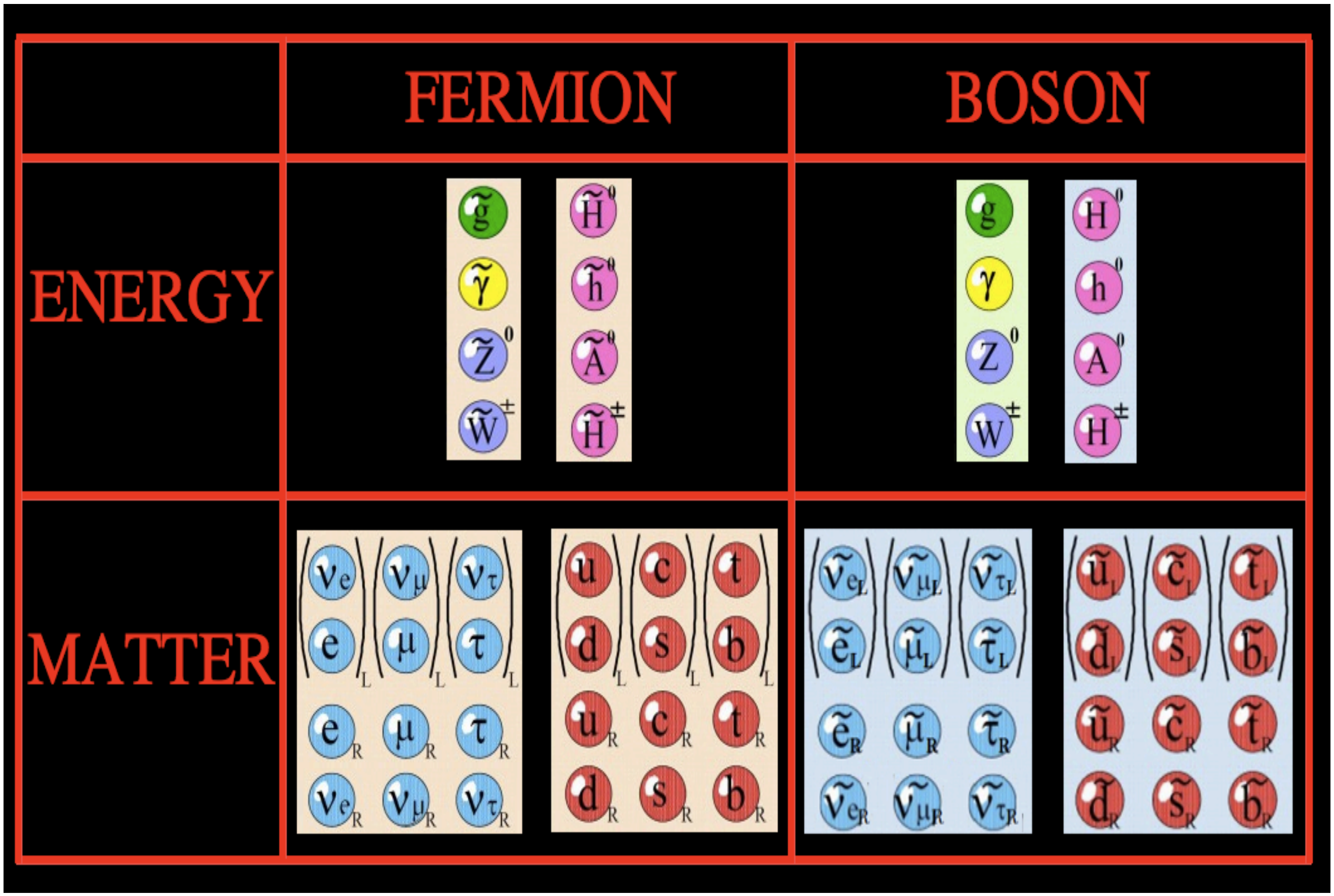
By Daniel Garisto on April 7, 2021



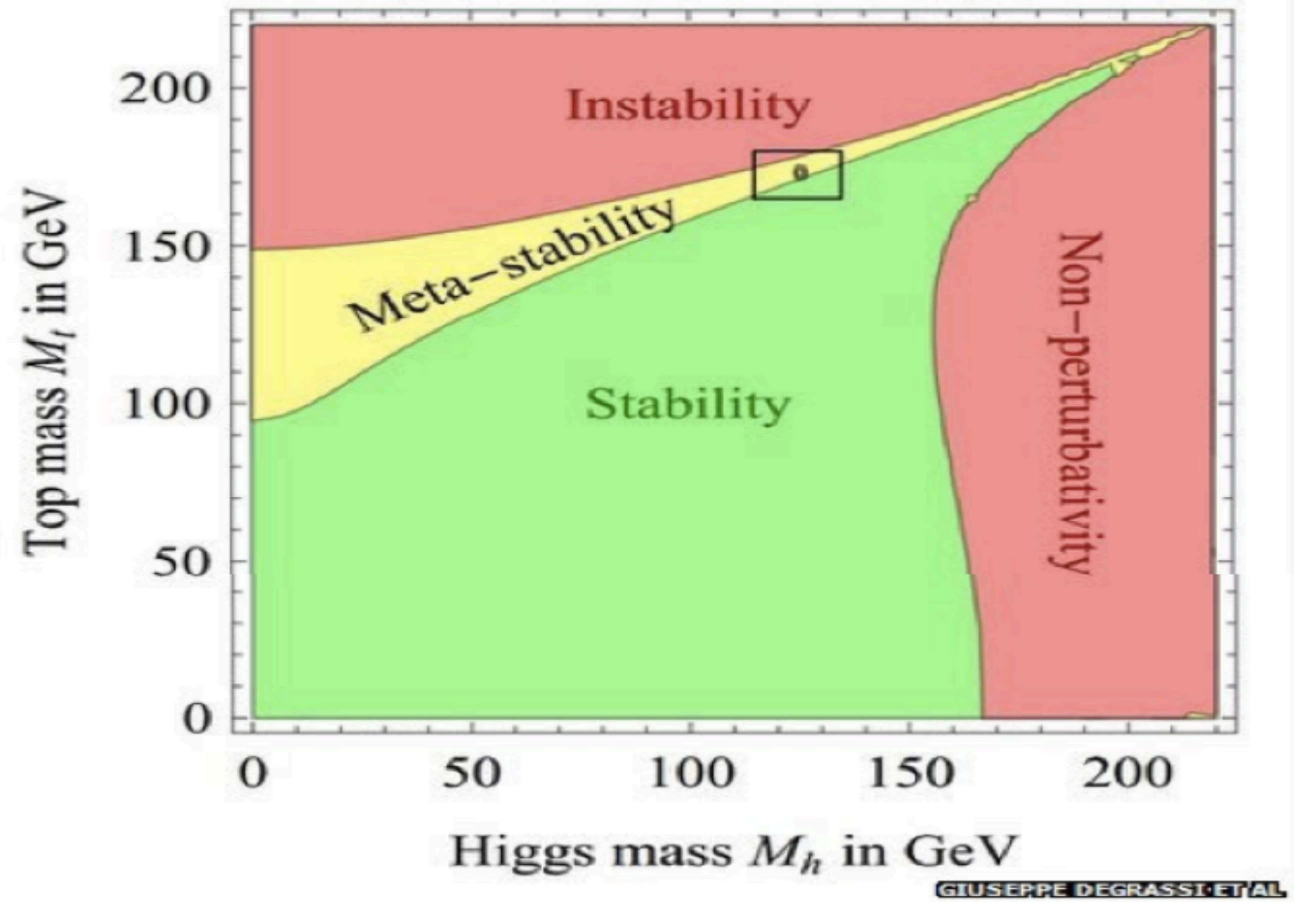
When all the particles of today's Standard Model are classified according to their spins (bosons or fermions) and matter/energy properties, the image is highly asymmetrical.



Should 'sparticles' or 'superpartners' be later observed in laboratories, once more there would he a high symmetrical table to describe physical reality.

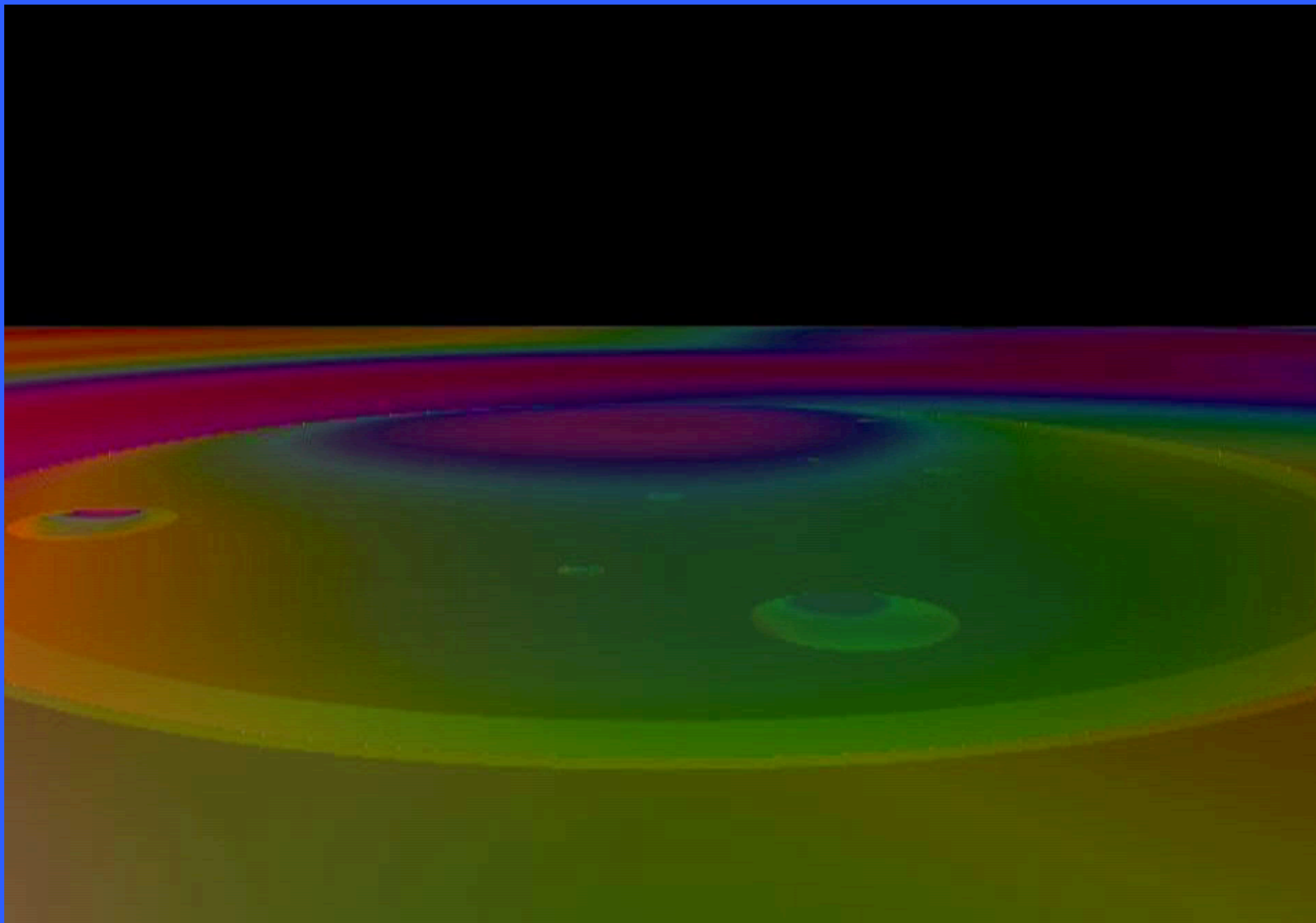


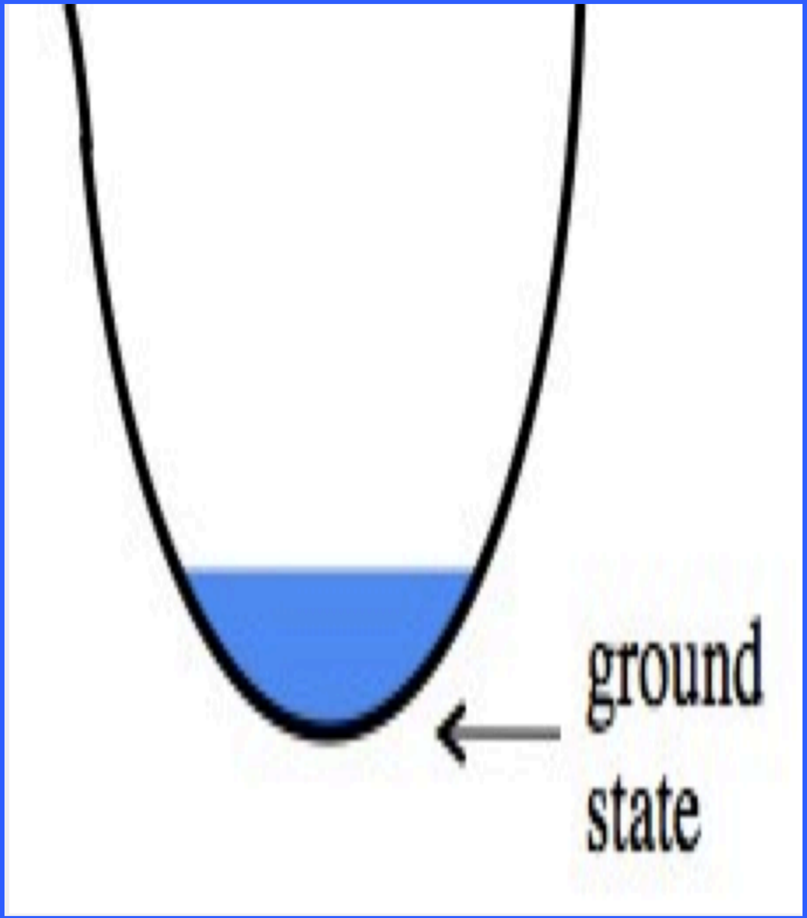

UNITED STATES OF AMERICA
LIBERTY
NEW HAMPSHIRE

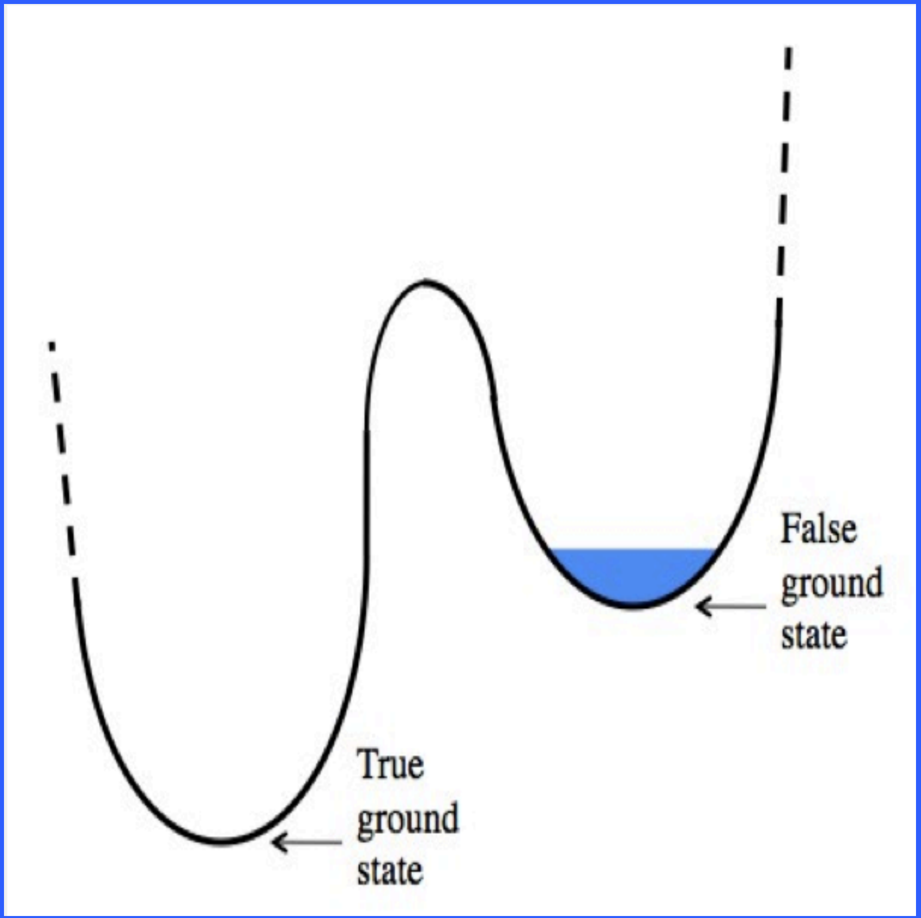


Higgs mass and vacuum stability in the Standard Model at NNLO

Giuseppe Degrassi[a], Stefano Di Vita[a], Joan Elias-Miró[b], José R. Espinosa[b,c],
Gian F. Giudice[d], Gino Isidori[d,e], Alessandro Strumia[g,h]







Ask a Mathematician / Ask a Physicist

On the formal side, the tools will likely consists (over well-established ones):

(1.) algebraic topology,

(2.) graph theory,

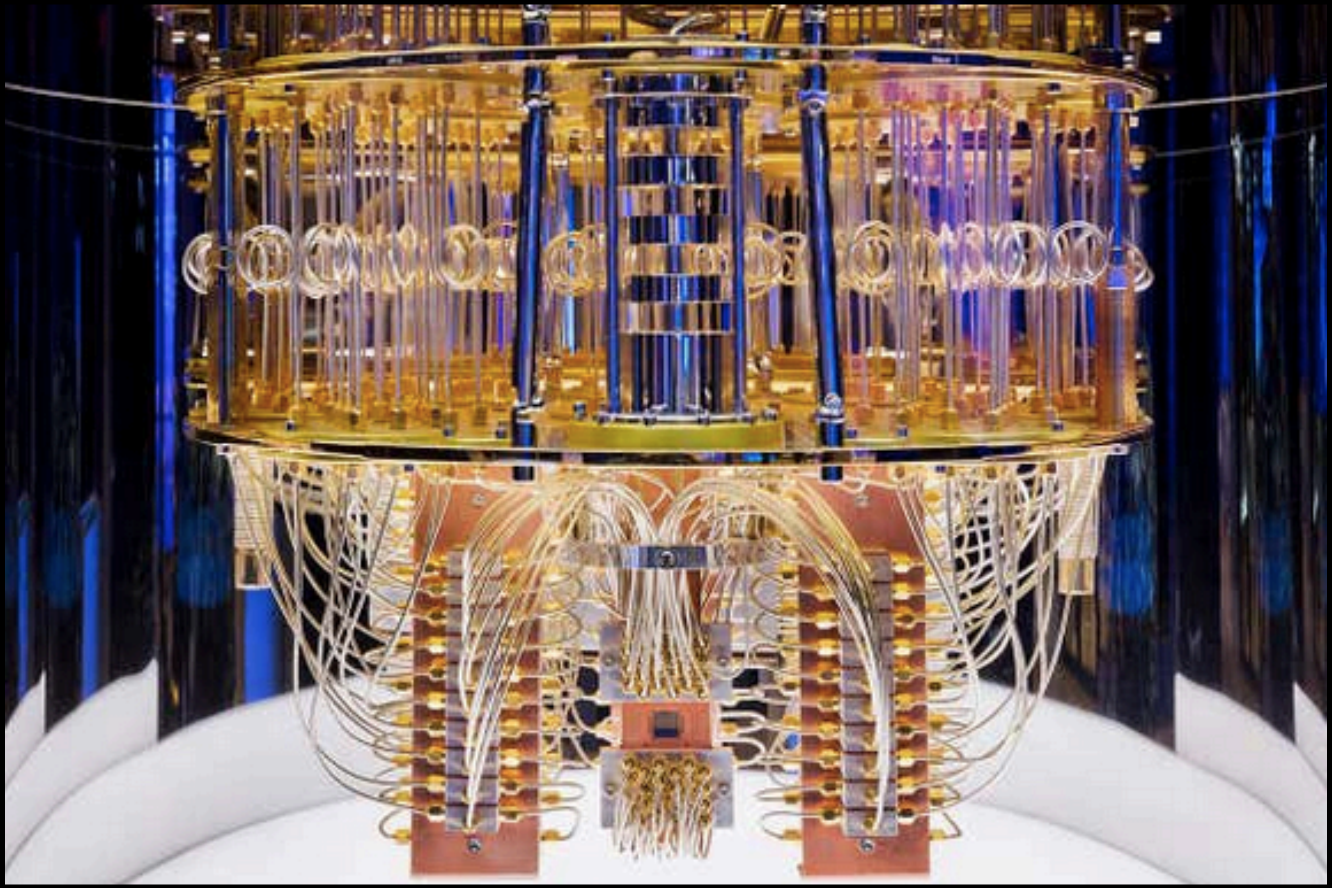
(3.) information theory,

(4.) computer-aided-conceptualization, and

(5.) possibly evolutionary theory.

Corporations and countries are in a race to build Quantum Computers based on electronic spin!

NewScientist



https://www.newscientist.com/article/2252933-quantum-computers-may-be-destroyed-by-high-energy-particles-from-space/

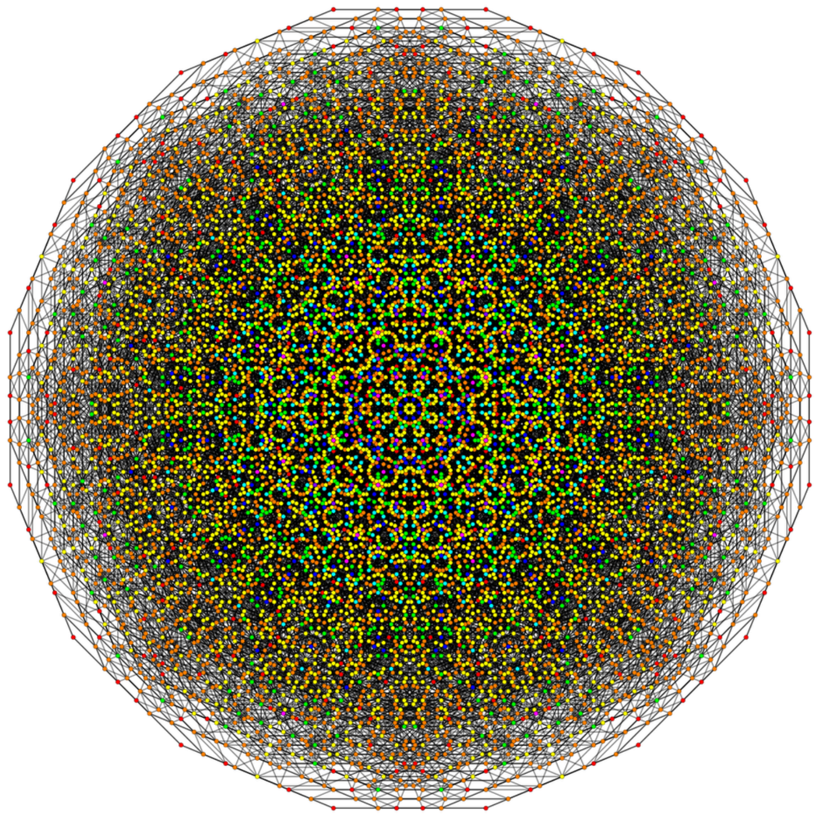

"Learning to use coding is like putting on the maths version of the Iron Man suit."

Omnitruncated 7-simplex	
Type	uniform 7-polytope
Schläfli symbol	$t_{0,1,2,3,4,5,6}\{3^6\}$
Coxeter-Dynkin diagrams	
6-faces	
5-faces	
4-faces	
Cells	
Faces	
Edges	141120
Vertices	40320
Vertex figure	Irr. 6-simplex
Coxeter group	A_7, $[[3^6]]$, order 80640
Properties	convex

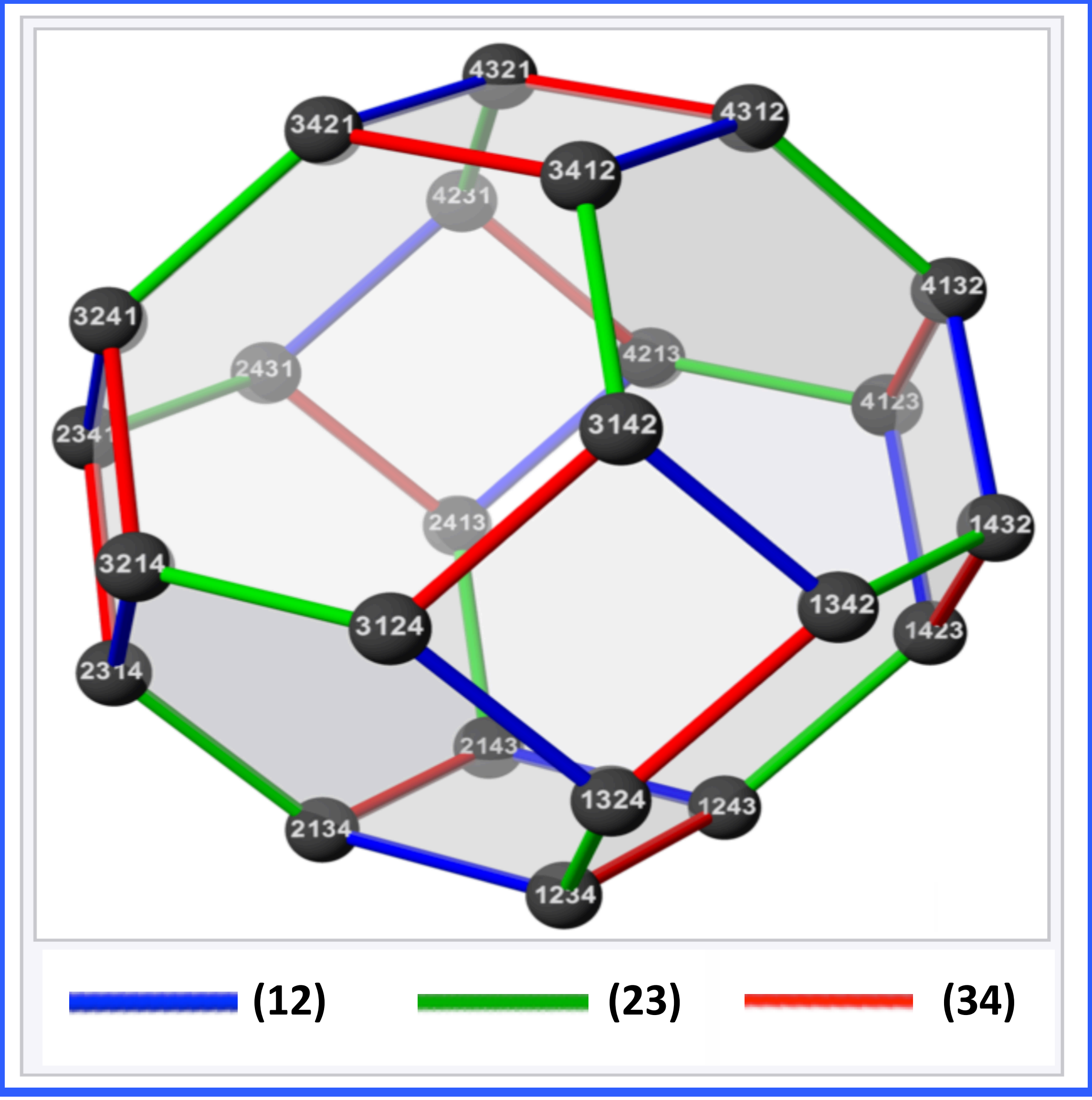
Hexipentiruncitruncated 7-simplex

Omnitruncated 7-simplex, also known as the

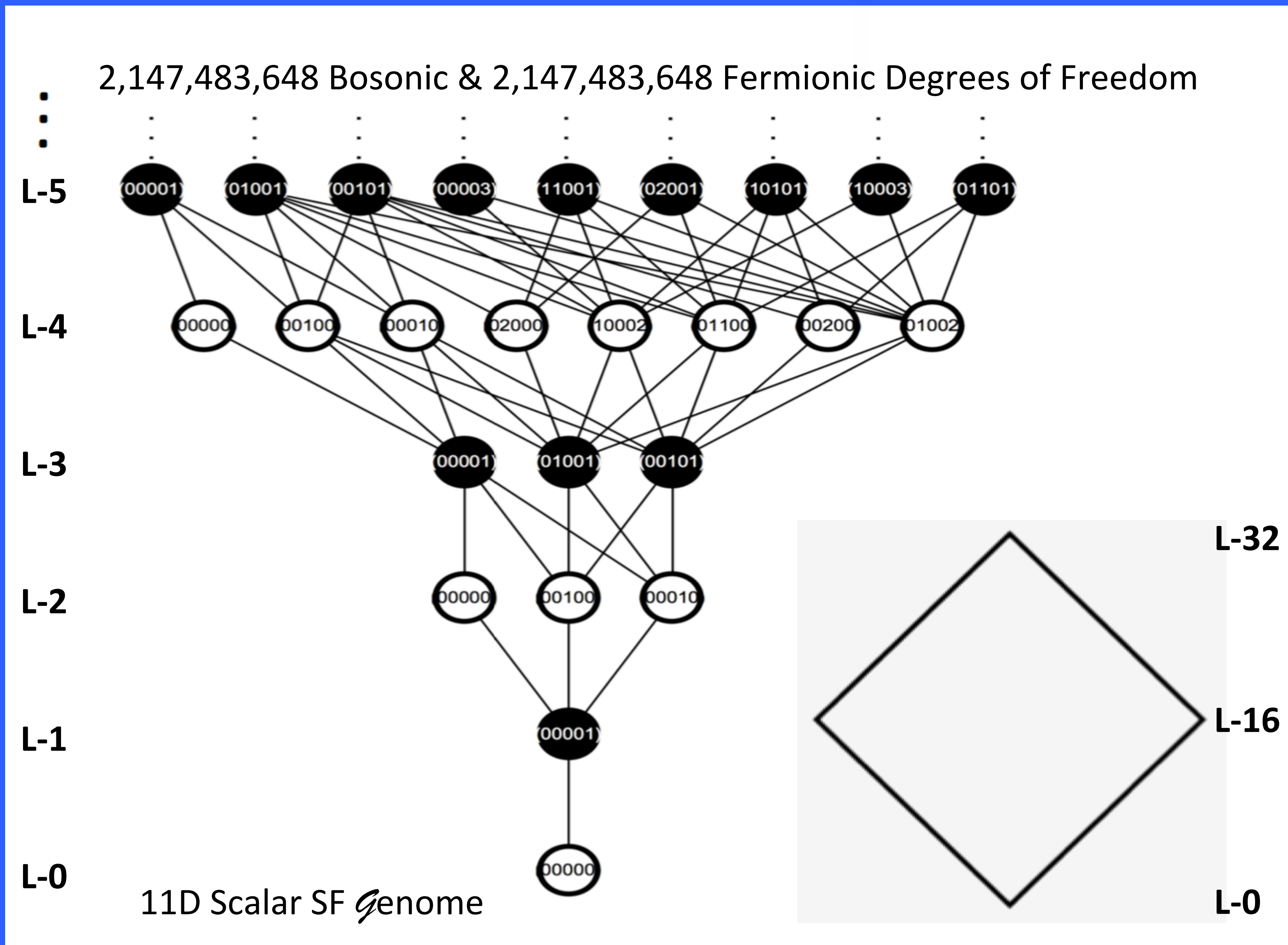
Hexipentiruncitruncated 7-simplex, aka the ***8-permutahedron***



Hexipentiruncitruncated 7-simplex



4321
3421
4312
3412
4231
3241
4132
2431
4213
2341
4123
3142
2413
1432
3214
1342
3124
1423
2314
2143
1324
1243
2134
1234
(12)
(23)
(34)



2,147,483,648 Bosonic & 2,147,483,648 Fermionic Degrees of Freedom
L-5
(00001)
(01001)
(00101)
(00003)
(11001)
(02001)
(10101)
(10003)
(01101)
L-4
00000
00100
00010
02000
10002
01100
00200
01002
L-3
00001
01001
00101
L-2
00000
00100
00010
L-1
(00001)
L-0
00000
11D Scalar SF 𝒢enome
L-32
L-16
L-0

Acknowledgment

Prof. Gates also wishes to acknowledge
The Teaching Company for the use of
some CGI units that appear in

"Superstring Theory: The DNA of Reality."