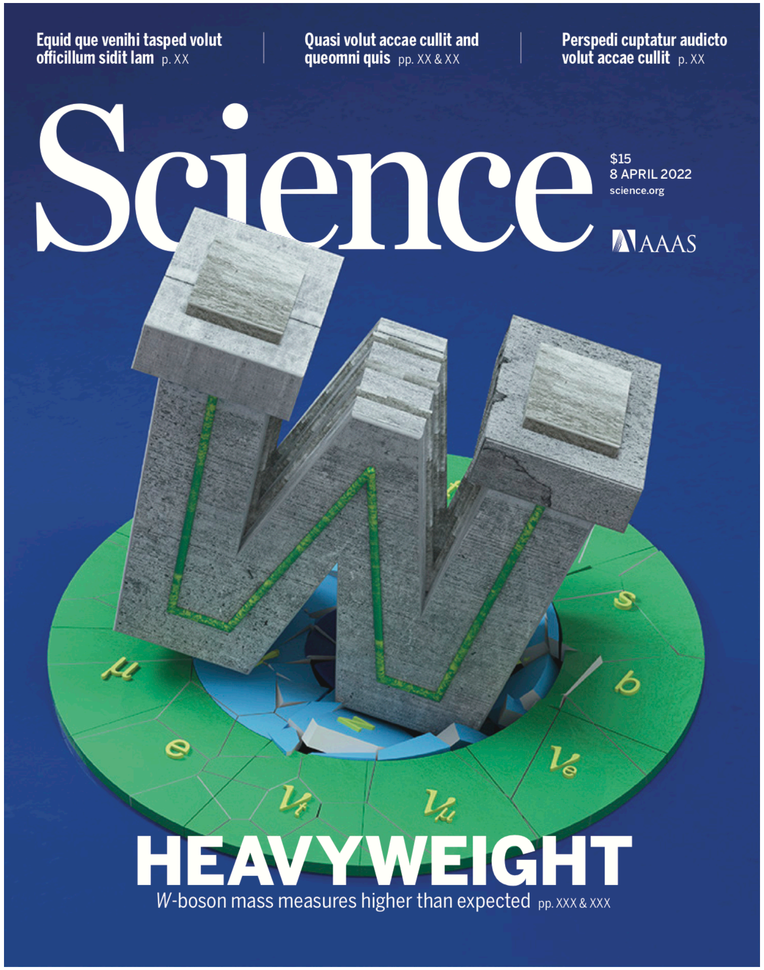
The Higgs is Not Enough

Verdict from the Heavyweight W boson



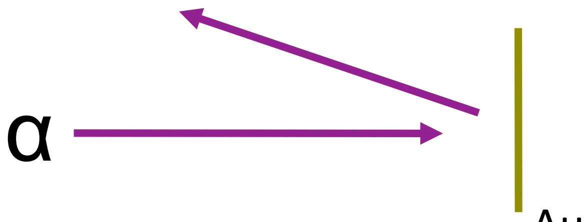
Ashutosh Kotwal
Duke University

Origin of Particle Physics

- Search for the constituents of matter has been one of the central themes of physics
- Aristotle's "elements" ⟶ earth, air, fire & water
- Chemists understood that molecules were the units carrying chemical properties of materials

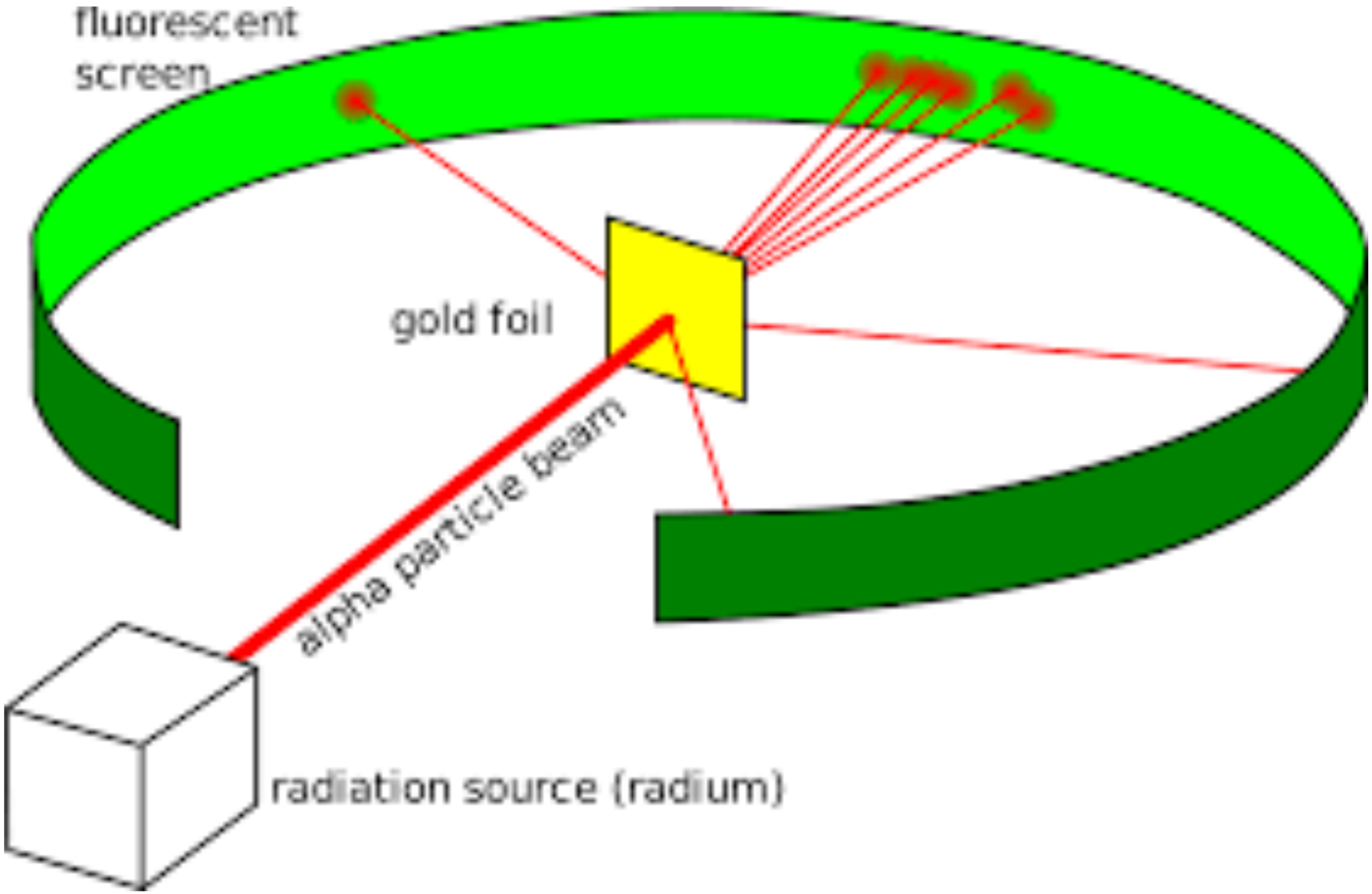
Molecules
↓
Atoms
↓
Positive and negative charges

- Ernest Rutherford: scattering of probe particles off matter as a means of investigating substructure



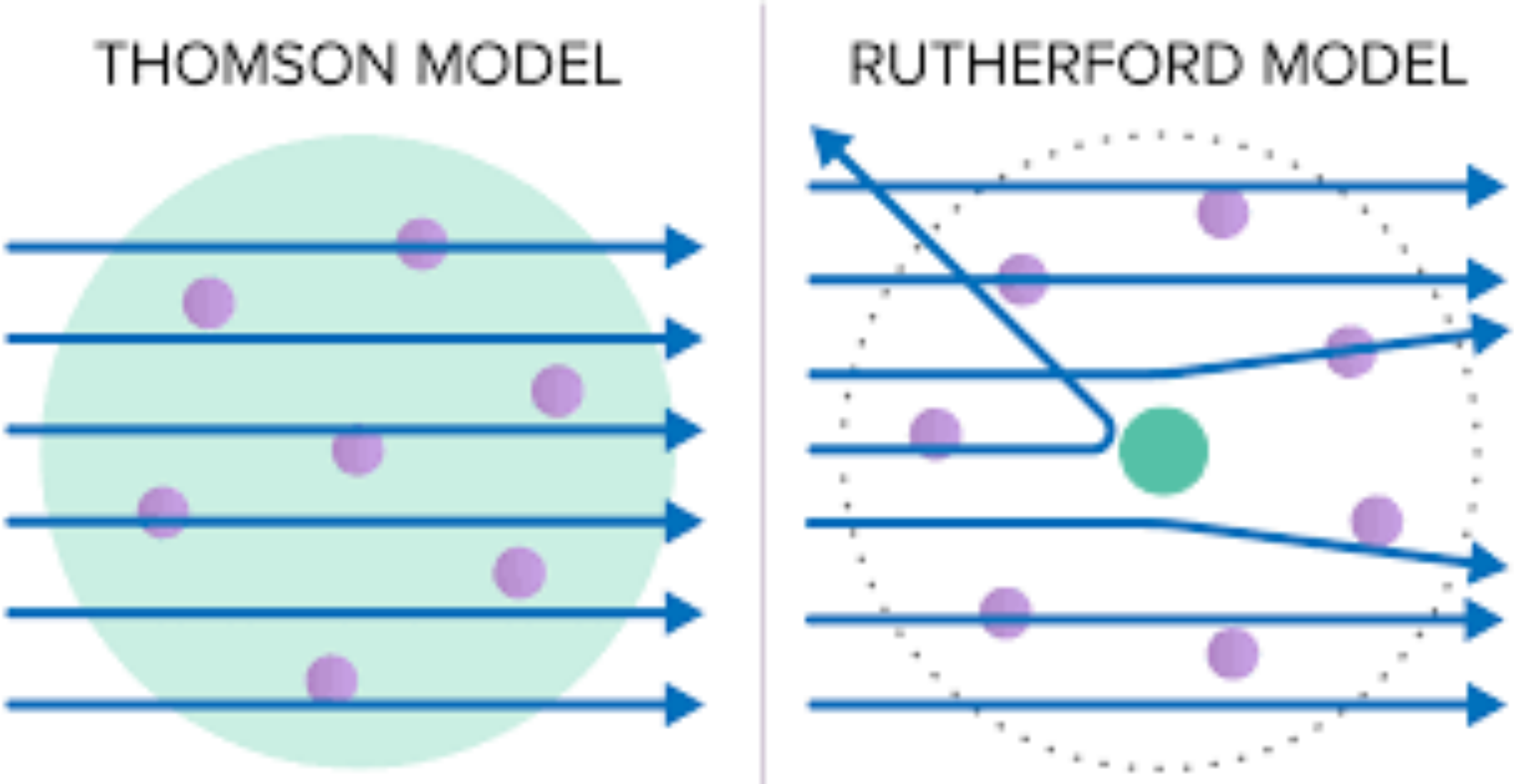
Scattering at large angle due to small, heavy charged core: atomic nucleus

Origin of Particle Physics



Rutherford's scattering experiment of 1911

Origin of Particle Physics



From Atoms to Quarks

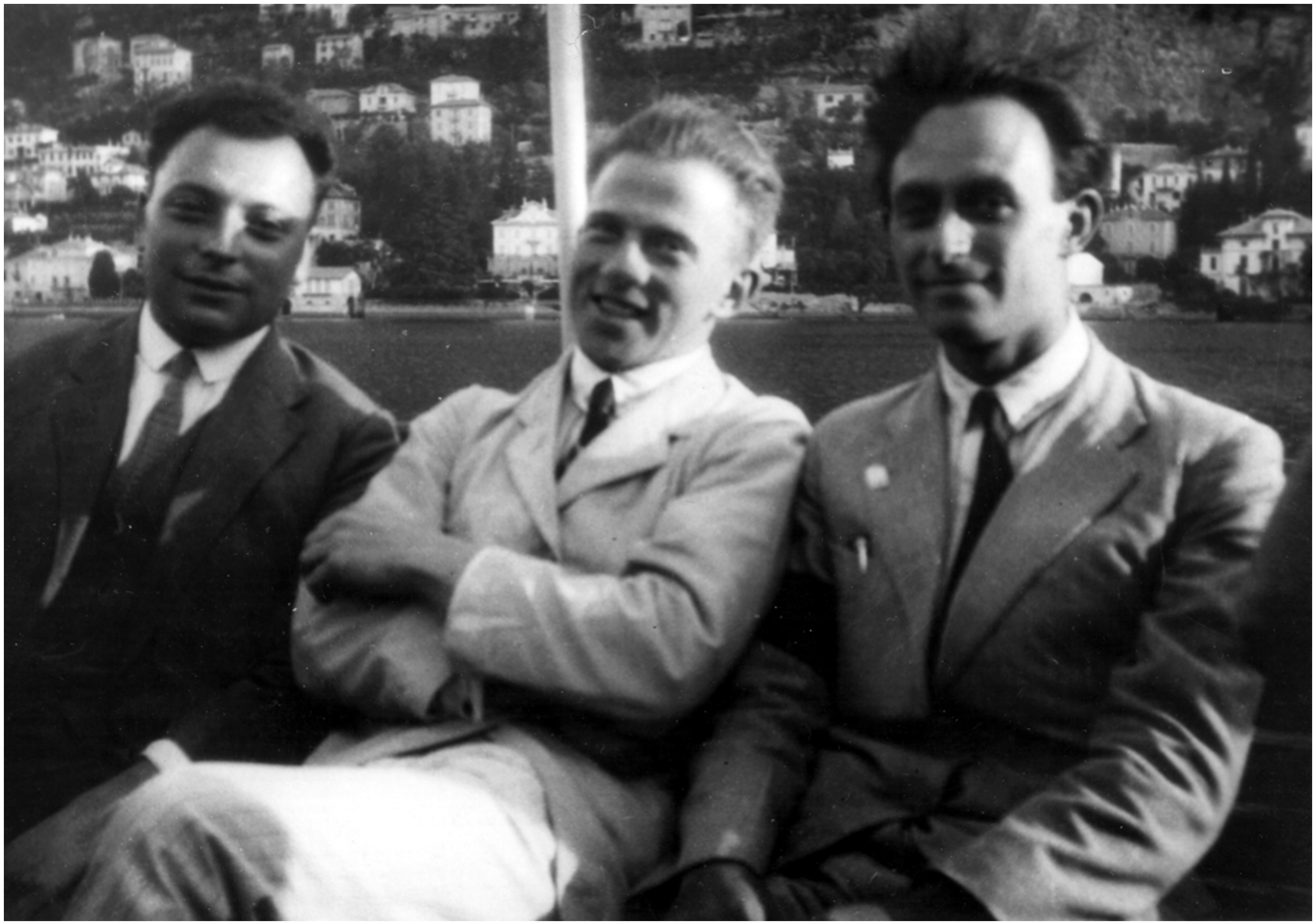
- Technique of scattering exploited repeatedly with beams of higher energy to probe smaller distances

$$\Delta r \sim \hbar c \,/\, \Delta E$$

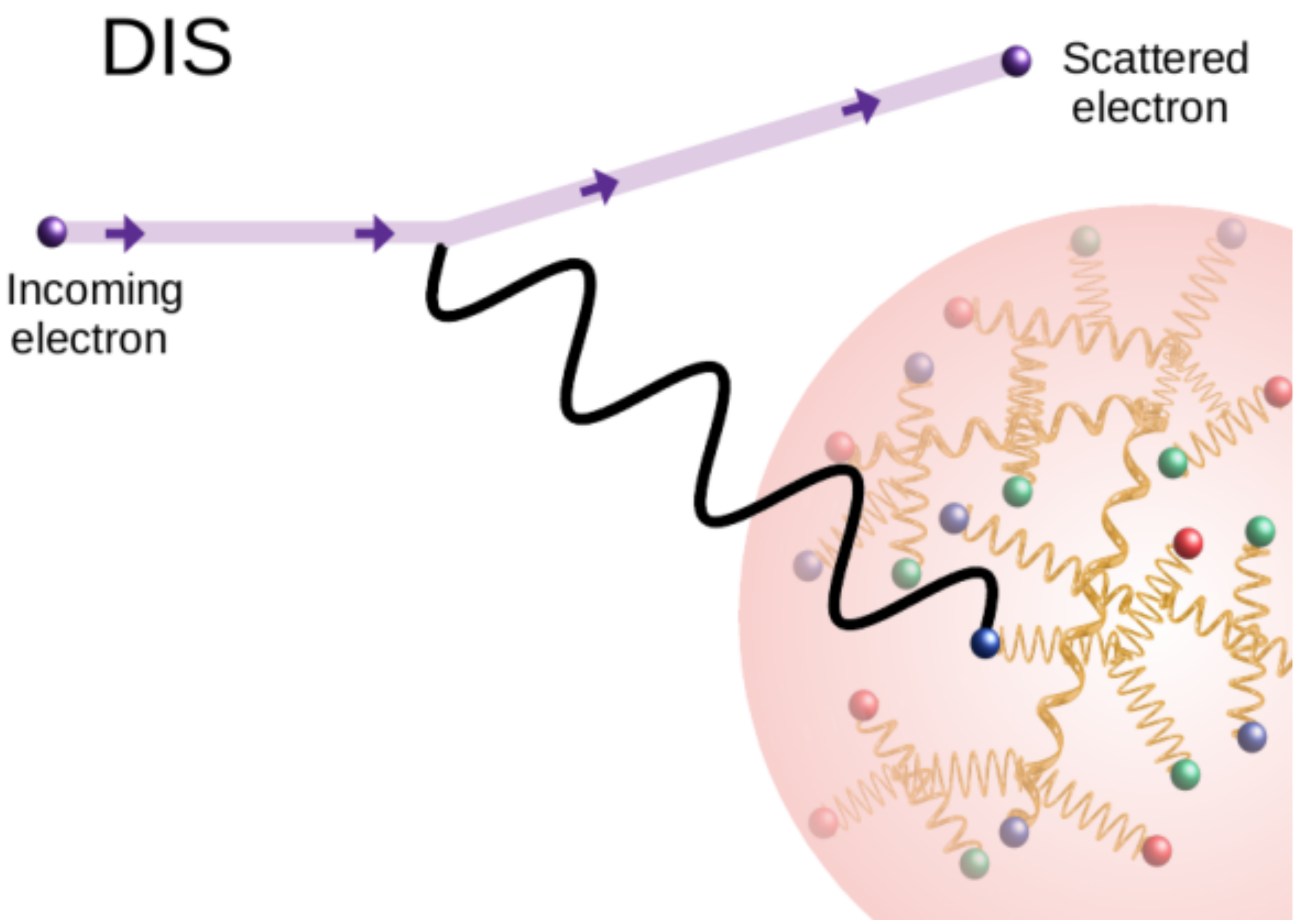
	r	Energy
Atom	10^{-10} m	10 electron-Volts (eV)
↓ Nucleus	10^{-15} m	10^{6} eV (MeV)
↓ Proton, neutron	10^{-18} m	1000 MeV (GeV)
↓ 'partons'	$<10^{-18}$ m	> GeV

- Scattering of electrons at high energy (early 1970's at Stanford Linear Accelerator Center) provided evidence of nucleon constituents: quarks
- Many particles explained as different combinations of few quarks

Pauli, Heisenberg and Fermi



From Atoms to Quarks

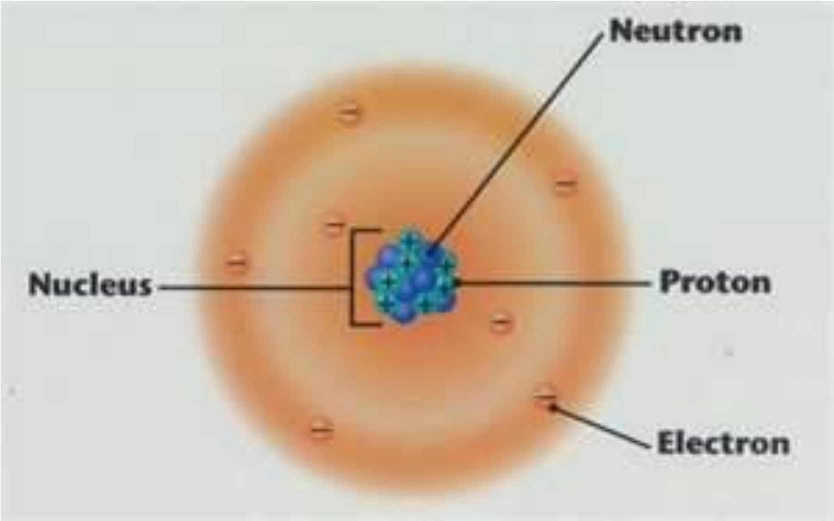


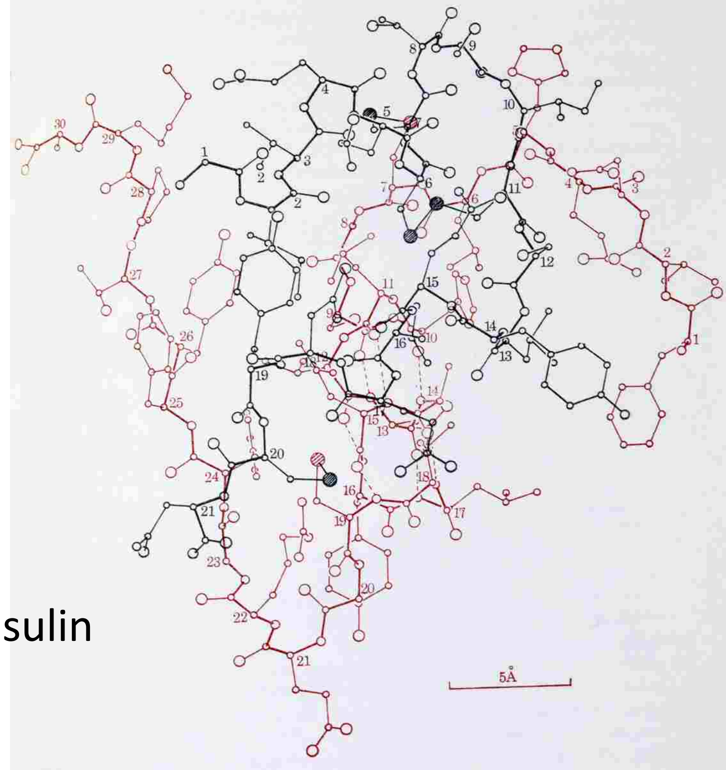
DIS = Deep Inelastic Scattering

20^{th} Century Built on Quantum Mechanics

- The scientific advances of the 20^{th} century have transformed our lifestyle

- Impact of Quantum Mechanics
  - All electronics devices, computers and communication
  - Nuclear power
  - Atomic and molecular manipulation of materials for chemical and biological applications





Molecule of Insulin

Foundations of 20^{th} Century Physics

- Quantum Mechanics

- Special Relativity

- Combination of these fundamental principles – Relativistic Quantum Theory

Founders of 20th Century Physics

Founders of 20th Century Physics

Foundations of 20th Century Physics

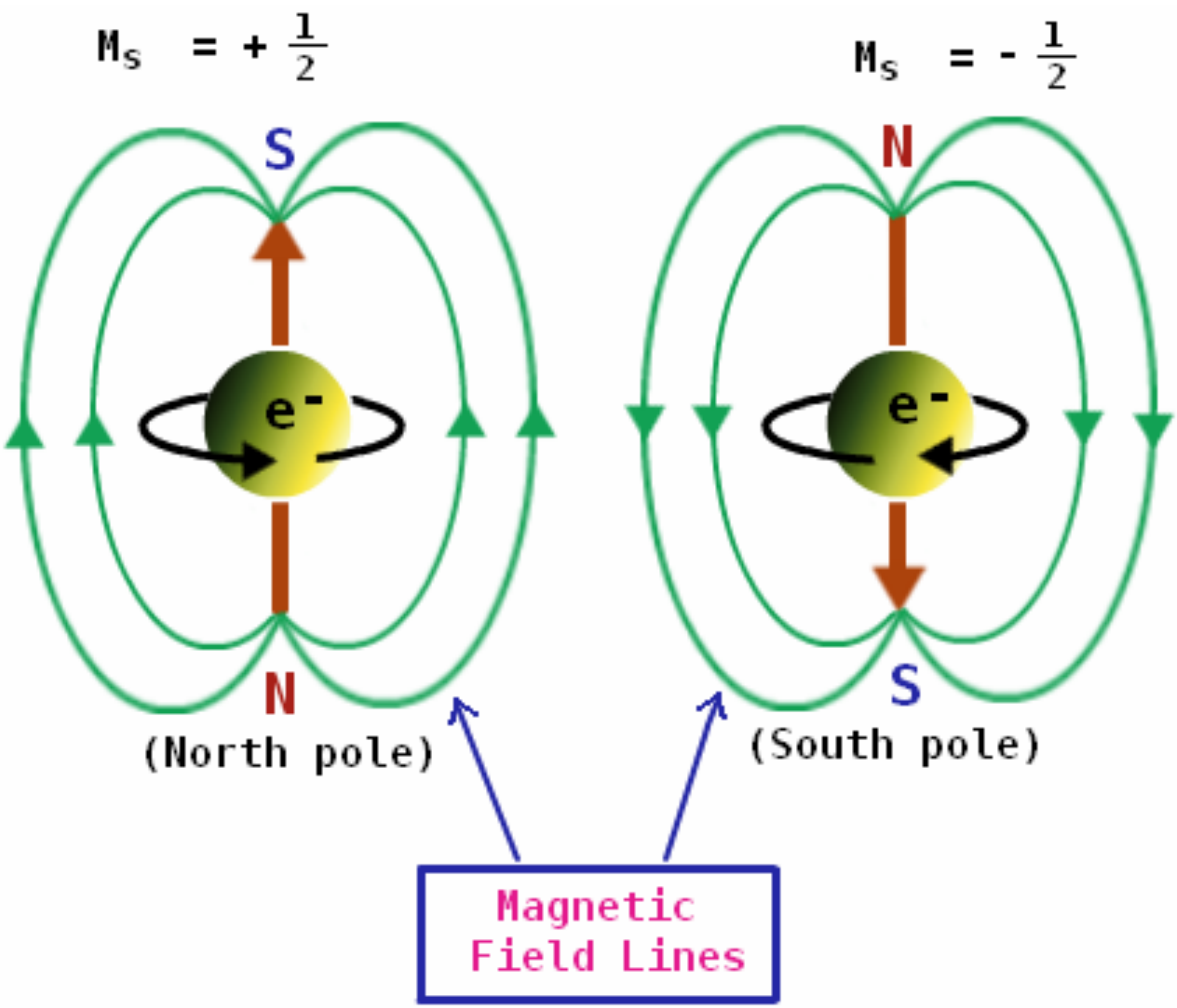
- Quantum Mechanics

- Special Relativity

- Combination of these fundamental principles – Relativistic Quantum Theory

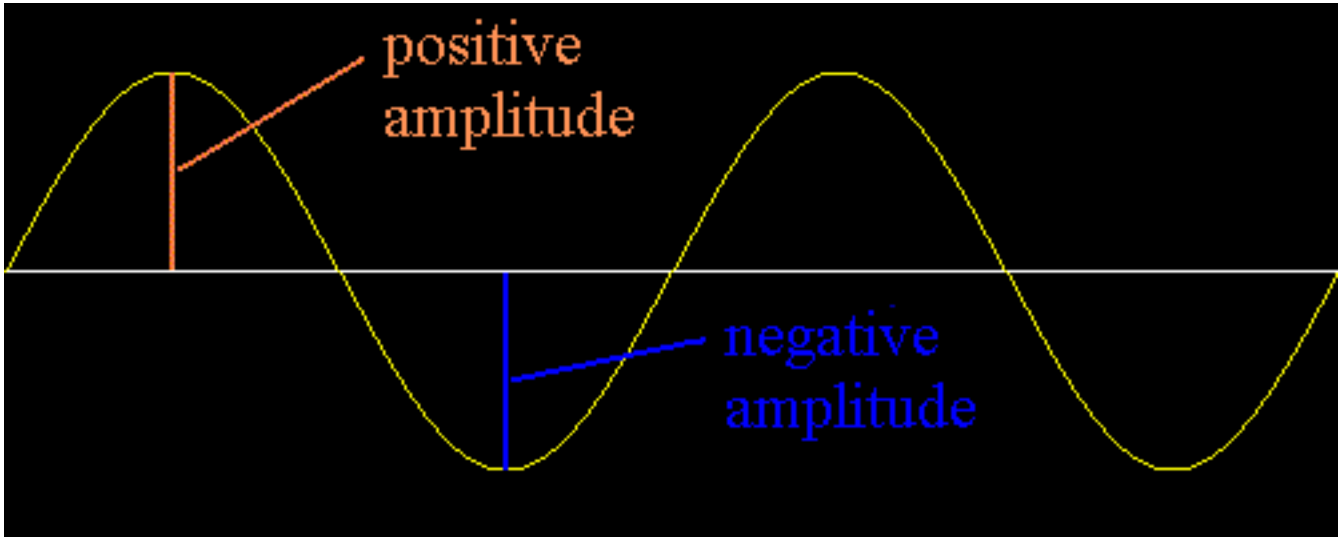
  – Initiated by Paul Dirac

Fundamental Properties of Electrons



Effect of Complete Rotation

- Quantum Mechanics + Special Relativity =>
  Dirac and others showed mathematically that electron can be the type of particle that becomes negative of itself under a complete rotation



Identical Particles are Indistinguishable

- Bose solved a major puzzle in quantum mechanics by proving that particles of the same type are indistinguishable

Satyendra Nath Bose in 1920's

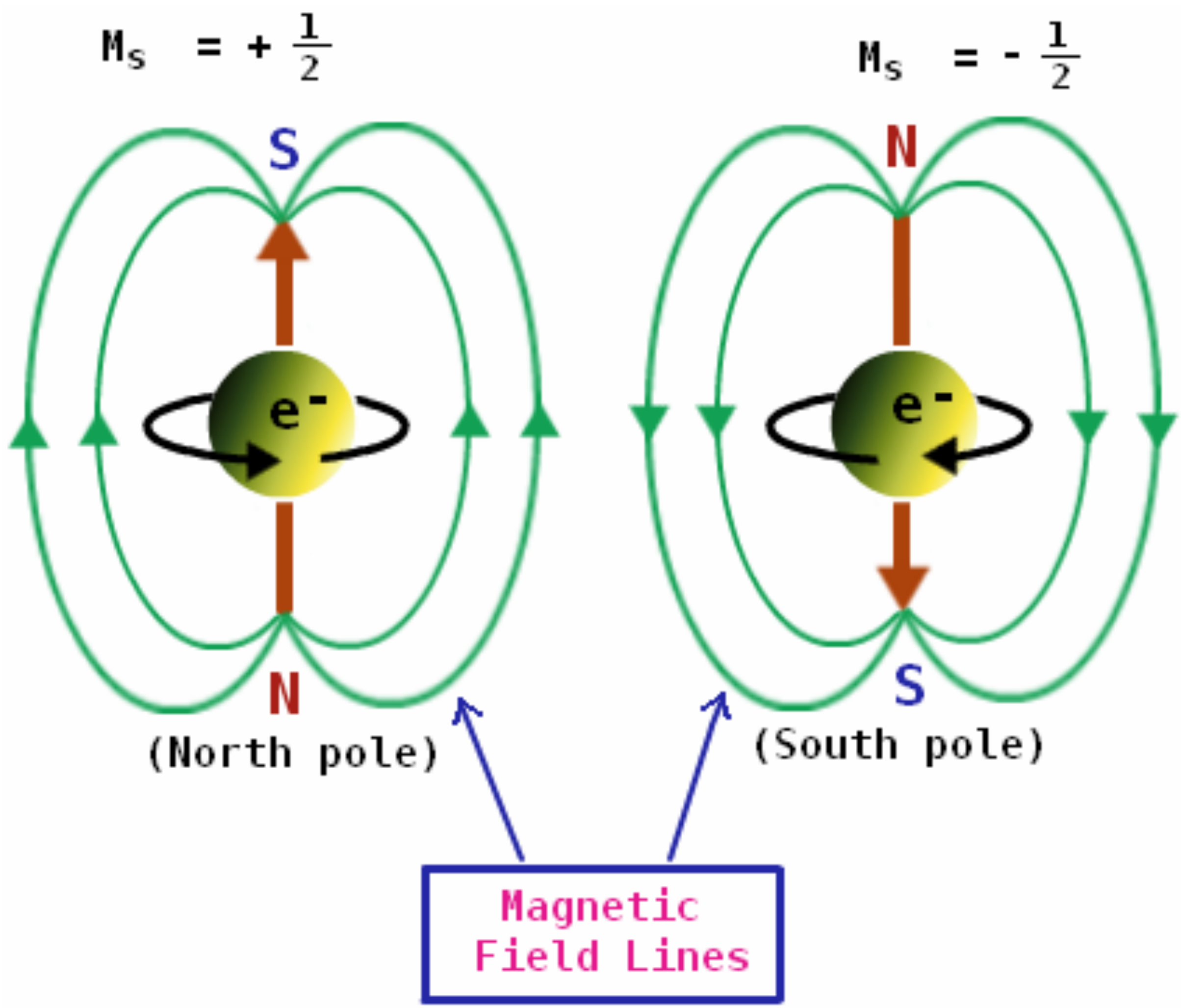
Towards a Fundamental Theory of Matter

Interchange between two electrons ⇔ rotate one by 360 deg.

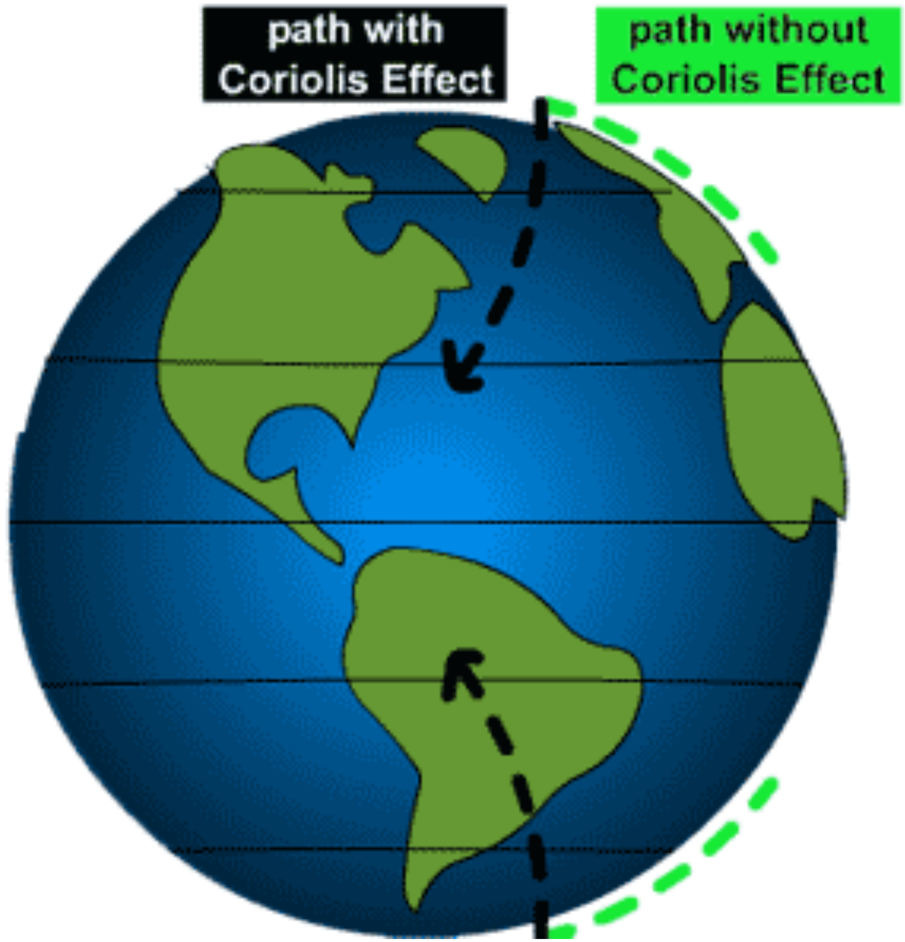
Why Matter Occupies Volume

- $\psi(e_1, e_2) = -\psi(e_2, e_1)$
- But if two electrons occupied the same spot in space
- $\psi(e_1, e_2) = \psi(e_2, e_1)$
- Wave that both equal to itself and equal to negative of itself must be ZERO
- Pauli Exclusion Principle – identical particles like electrons, protons, neutrons cannot be at the same point in space at the same time
- This is a fundamental explanation for why matter is made up of fermions and why matter occupies volume

Dirac's Theory of Matter Particles (Fermions)



How to Predict Fundamental Forces



“fictitious” forces observed in accelerating frame of reference

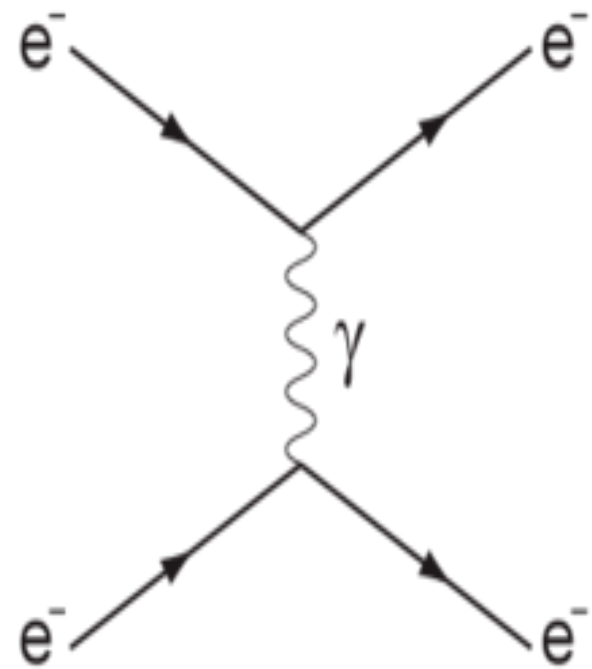
Manifestation of Coriolis Force

Hurricanes appear to rotate in Earth's frame of reference

Quantum Mechanics
force ⇔ particle exchange

Feynman Diagram: Force by Particle Exchange

Richard Feynman



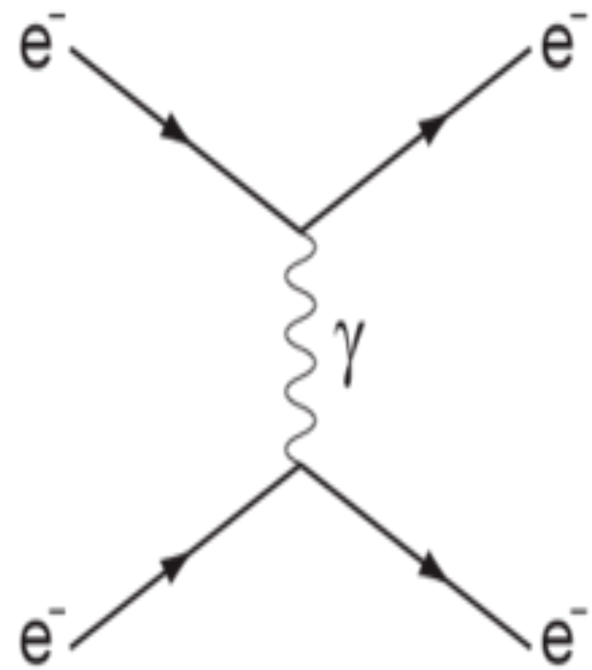
Electromagnetic force between two electrons mediated by "photon" exchange

Feynman Diagram: Force by Particle Exchange

The most precisely tested theory, ever:

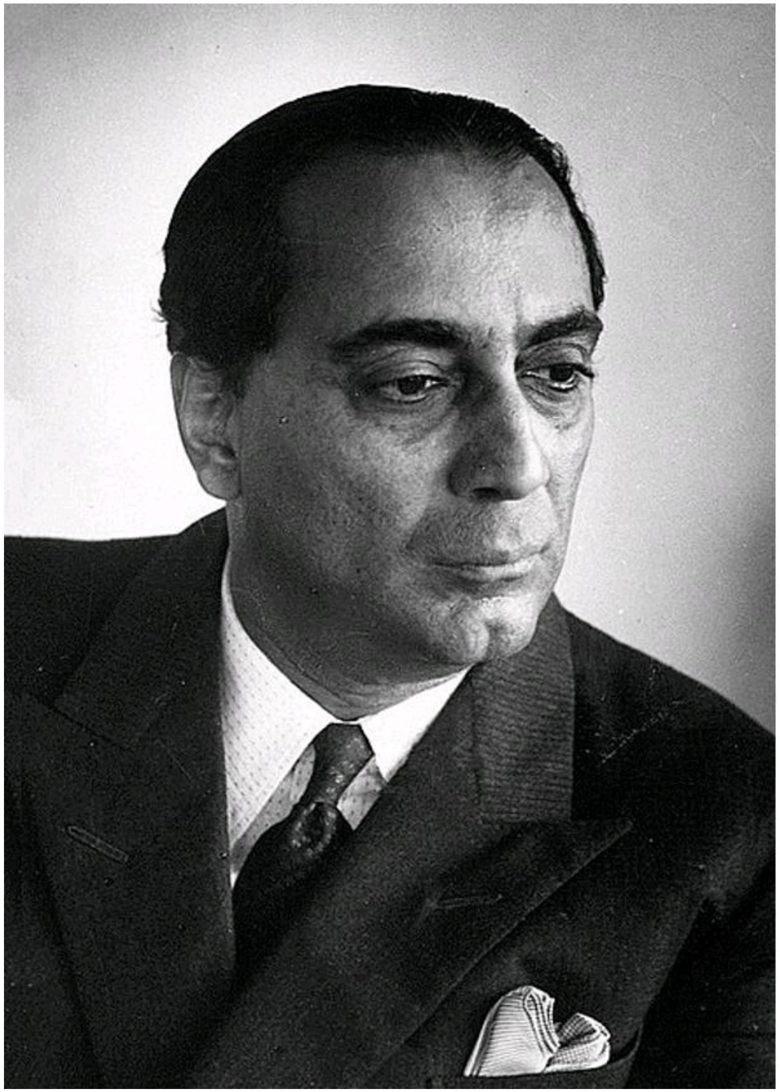
The quantum theory of the electric and magnetic forces, radio waves, light and X-rays:

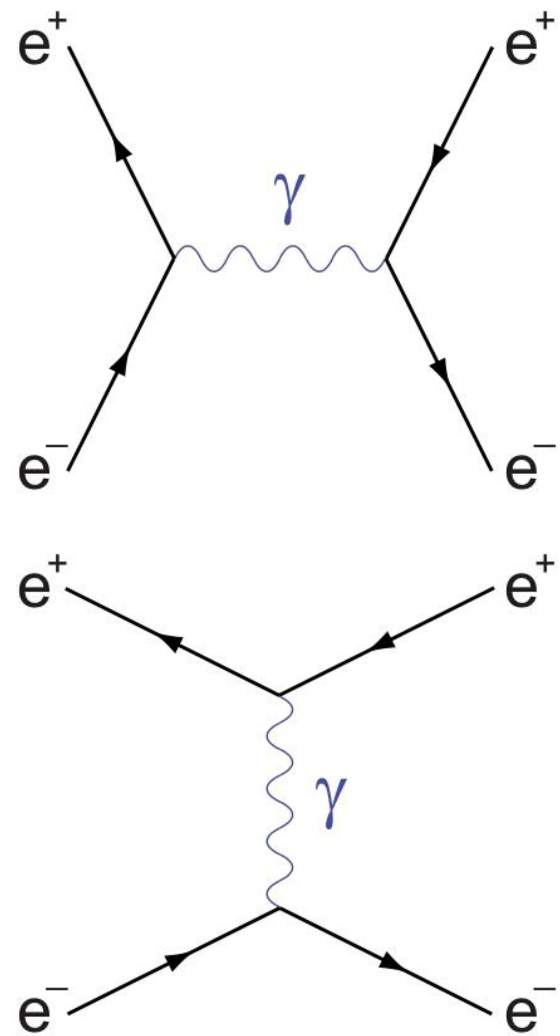
Measured and predicted magnetic moment of an electron agree within 0.3 parts per trillion accuracy



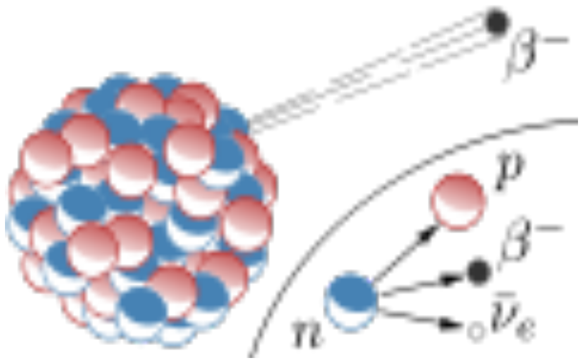
Electromagnetic force between two electrons mediated by "photon" exchange

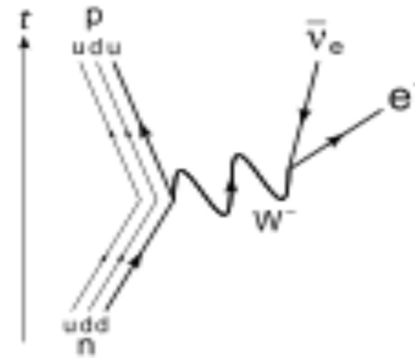
Homi Bhabha
electron-positron scattering





Weak Nuclear Decay





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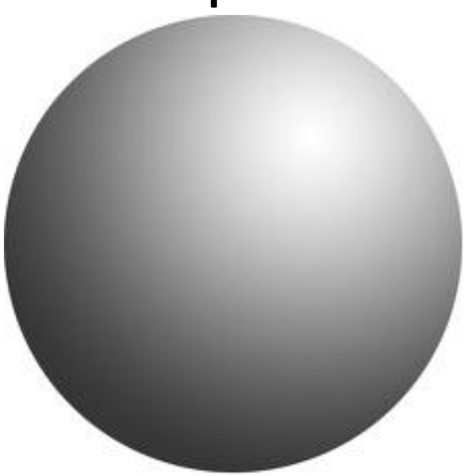
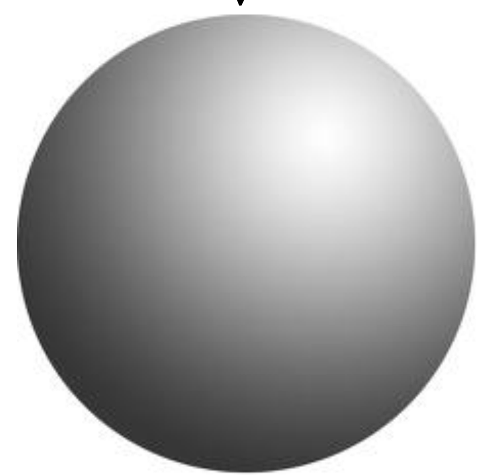


n

The force causing this interaction is described by particles making transitions on a "mathematical sphere"

ν



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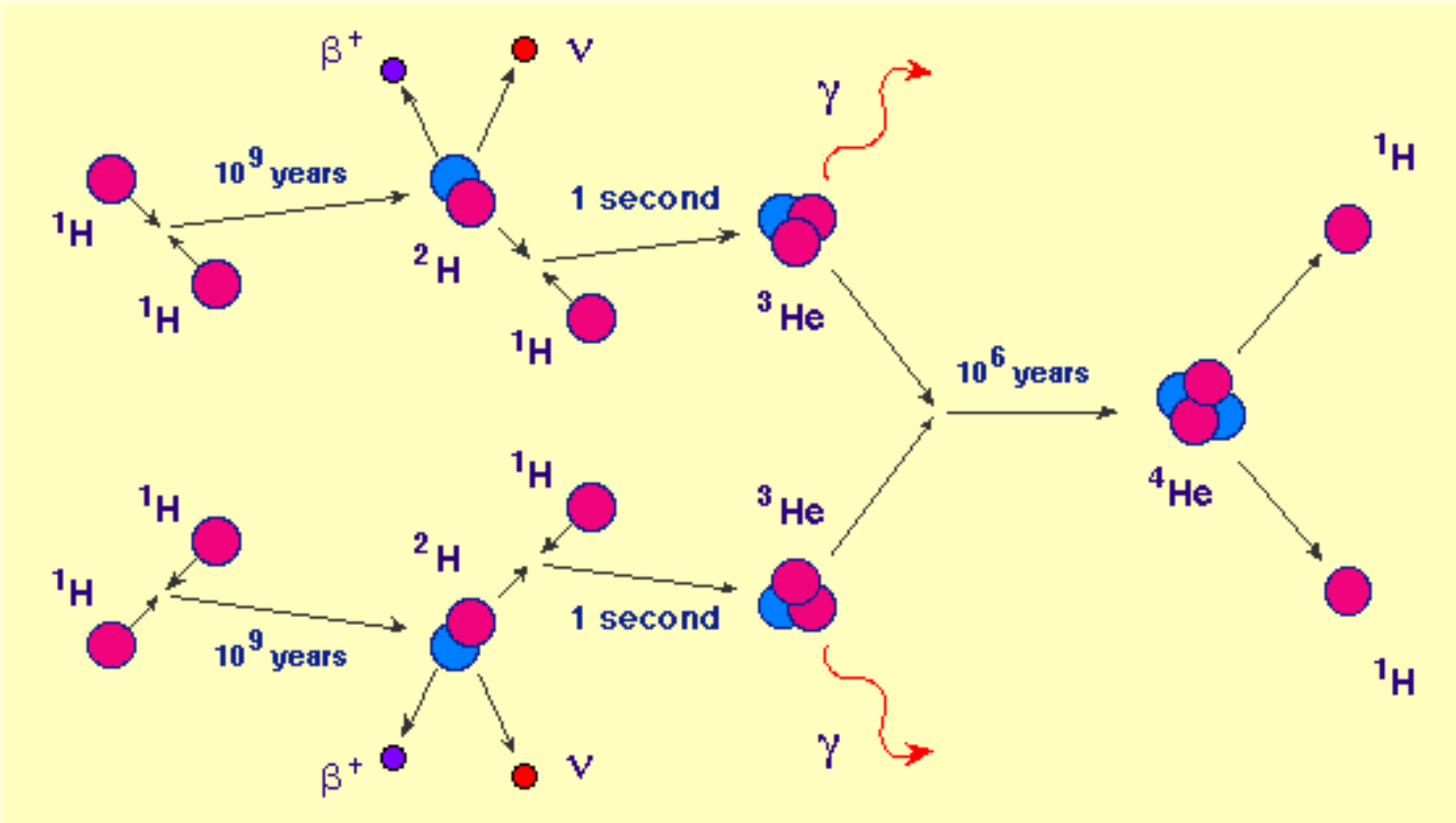
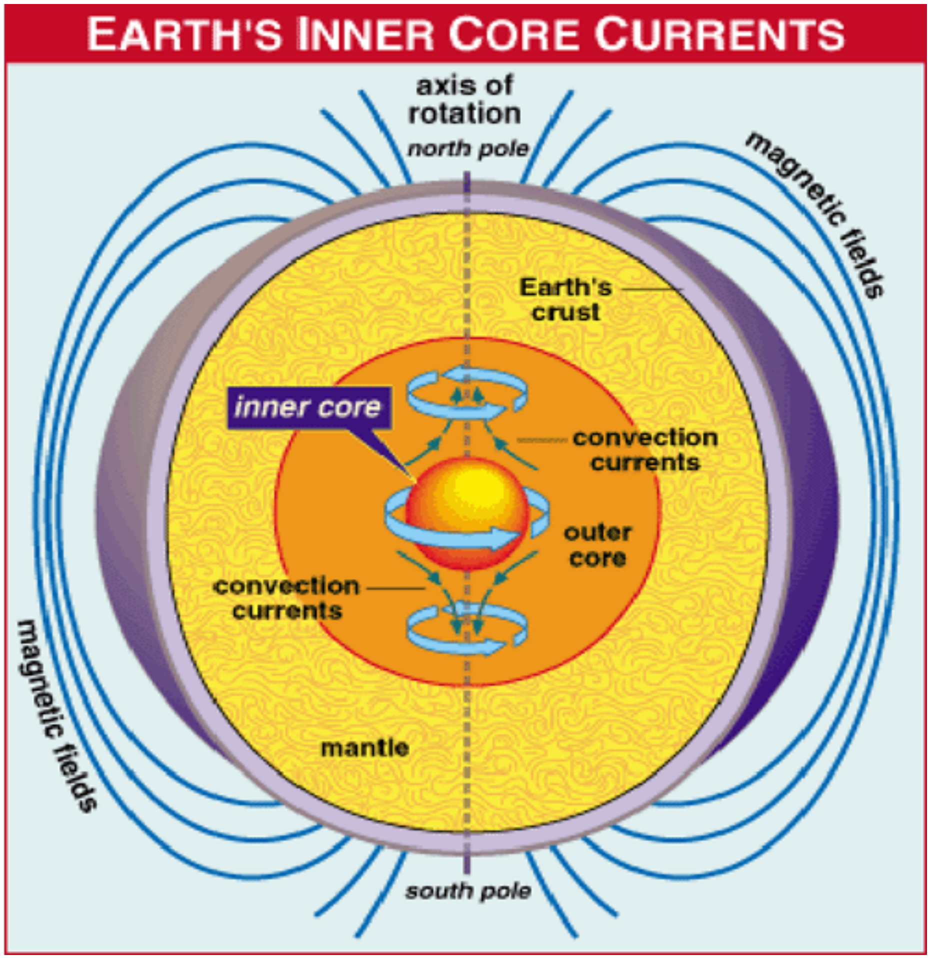
Nuclear Fusion in Sun's Core

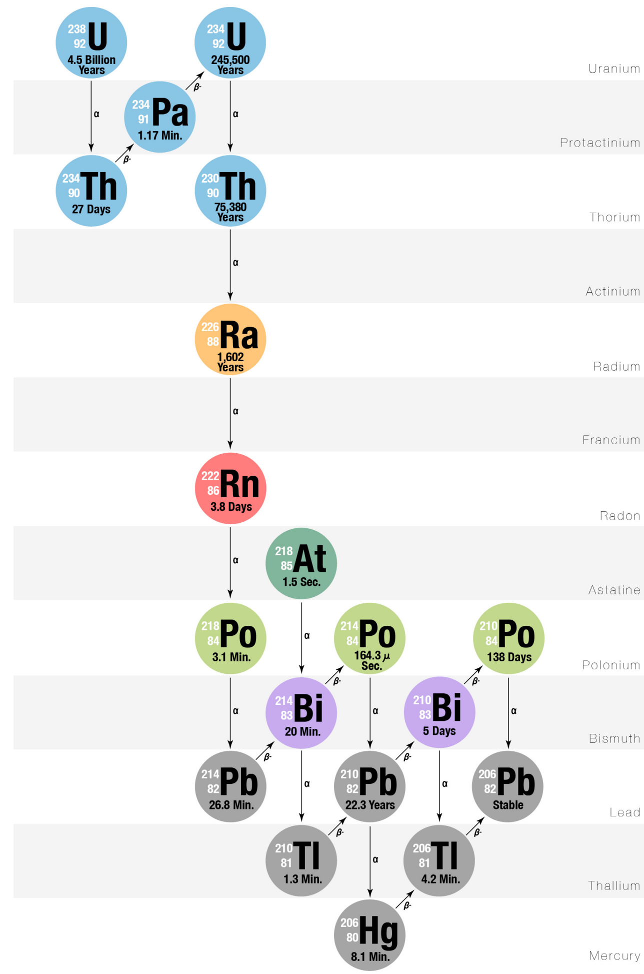


Main branch of the proton–proton chain.

Crucial role of W boson in hydrogen -> helium fusion in Sun's core

What Keeps the Earth's Core Molten?





Crucial role of W boson in keeping Earth core molten and generate protective magnetic shield against harmful solar radiation

E. C. George Sudarshan

Sudarshan
SEVEN SCIENCE QUESTS

I V-A: Universal Theory of Weak Interaction

In the mid-fifties nuclear beta decay was characterized by scalar and tensor interactions. But with this, no universal Fermi Interaction governing nuclear beta decay, muon decay and muon capture would be possible. After the discovery of parity violation in beta decay there was renewed interest, but no satisfactory solution was forthcoming.

$$H_{int} = g\overline{\Psi}_1\gamma_\mu\left(1+\gamma_5\right)\Psi_2\overline{\Psi}_4\gamma_\mu\left(1+\gamma_5\right)\Psi_3$$

In his graduate research under Robert Marshak, Sudarshan studied these questions. He recognized that not all experimental results were consistent and so some of them must be wrong. By a comprehensive and detailed analysis of the results of all the weak decay data he came to the far reaching conclusion that a V-A structure of weak interaction could explain all but four crucial experiments. Marshak and Sudarshan

SEVEN SCIENCE QUESTS SYMPOSIUM NOV. 6-7, 2006

- Curriculum Vitae
- **Seven Science Quests**
  - **V-A: Universal Theory of Weak Interaction**
  - Symmetry
  - Spin Statistics
  - Quantum Optical Coherence: Sudarshan Representation
  - Quantum Zeno Effect
  - Theory of Tachyons
  - Quantum Mechanics of Open Systems

Crucial contributions of the pre-eminent Indian theoretical physicist, including the prediction of a vital aspect of the weak nuclear force

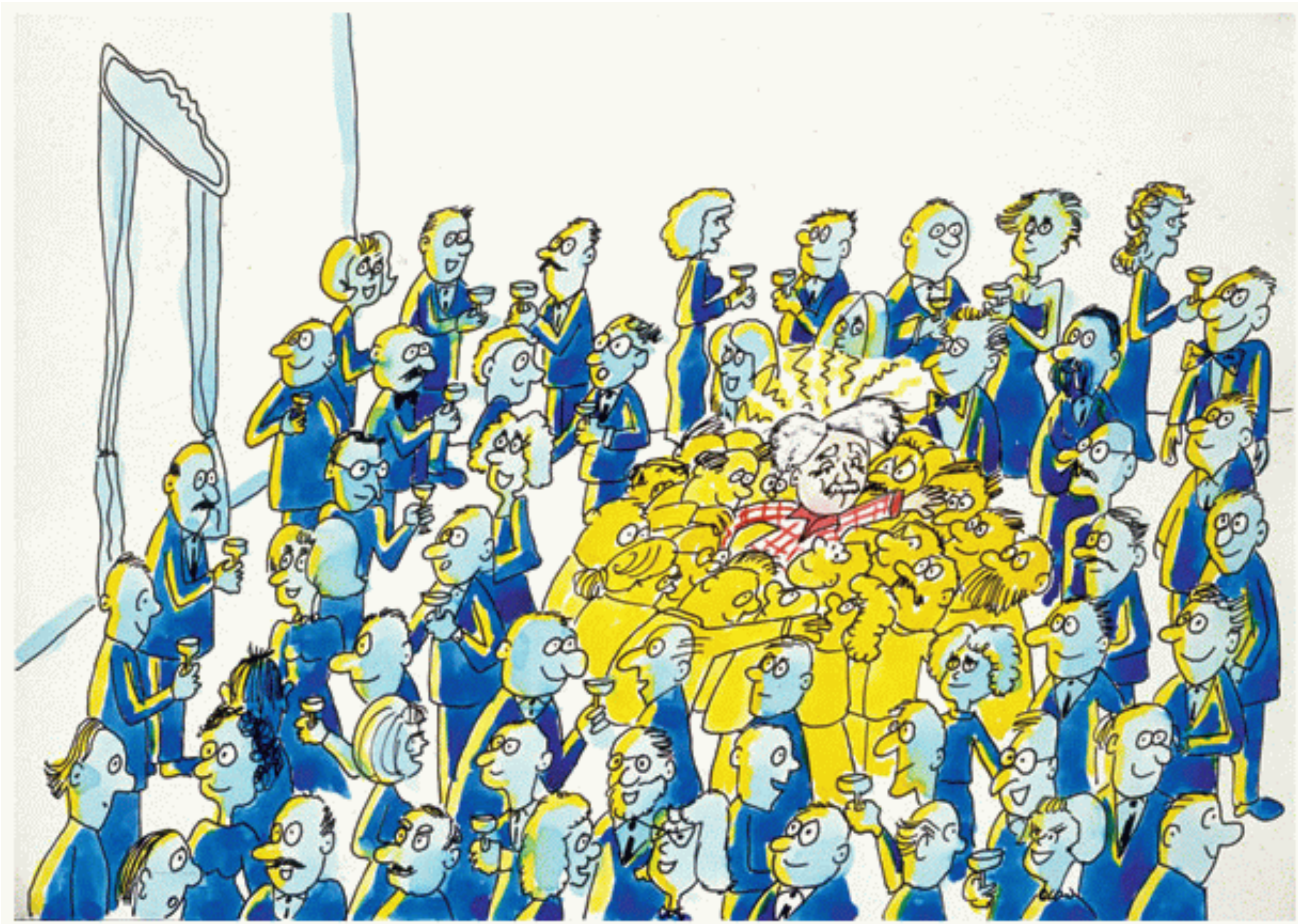
Success and Problem of Force Theory

- Success: correct mathematical description of all properties of electromagnetic force and the weak nuclear force
- Another prediction: force-mediating particles must be massless
- Correct prediction for photon – mediator particle of electric and magnetic forces and all electromagnetic waves: radio, light, microwave, x-rays described by massless photons
- Problem: for the weak nuclear force causing nuclear beta-decay, the mediator particle, "W boson" is very heavy
- Question: How can we preserve the original theory and simultaneously impart mass to the W boson?

How does the W boson Acquire Mass?

- Fill all of space with "Higgs" field
- Particles propagating through "empty space" actually propagating though Higgs field
- Interaction of particles with Higgs field slows down the particle ⇔ imparting the property of mass to it

The “Sticky” Higgs Field



Implications of Higgs Discovery

- Empty space is not really empty
- Filled with the Higgs
- All fundamental particles interacting with the Higgs field “slow down”
  – appear to be massive

Light versus Heavy Particles –
like moving through water

Streamlined
⇒ Moves fast through water
⇒ analogous to light particle

Not streamlined
⇒ Moves slowly through water
⇒ analogous to heavy particle

How did we confirm the existence of the Higgs?

- Create ripples in the Higgs field

Ripples ⇔ Higgs boson

A Century of Particle Physics

- Success # 1: discovery of 6 quarks and 6 leptons
- 12 fundamental fermions: matter particles (and their antimatter counterparts) derived by combining quantum mechanics and special relativity

Quarks

$$\mathrm{u} < 1\ \mathrm{GeV} \quad \mathrm{c} \sim 1.5\ \mathrm{GeV} \quad \mathrm{t} \sim 175\ \mathrm{GeV}$$
$$\mathrm{d} < 1\ \mathrm{GeV} \quad \mathrm{s} < 1\ \mathrm{GeV} \quad \mathrm{b} \sim 4.5\ \mathrm{GeV}$$

But the intriguing pattern of mass values is not explained – just blamed on Higgs boson interactions

Leptons

$$\nu_e < 1\ \mathrm{eV} \quad \nu_\mu < 0.17\ \mathrm{MeV} \quad \nu_\tau < 24\ \mathrm{MeV}$$
$$\mathrm{e}\ 0.5\ \mathrm{MeV} \quad \mu\ 106\ \mathrm{MeV} \quad \tau\ 1.8\ \mathrm{GeV}$$

A Century of Particle Physics

- Success # 2: principle of gauge invariance for *predicting* the nature of fundamental forces
  - matter particles (quarks and leptons) transform in *curved* internal spaces
  - The equations of motion predict terms that describe particle interactions with force fields

Gauge sector $$L = i\bar{\psi}\gamma^{\mu}D_{\mu}\psi - \frac{1}{2}F_{\mu\nu}F^{\mu\nu}$$

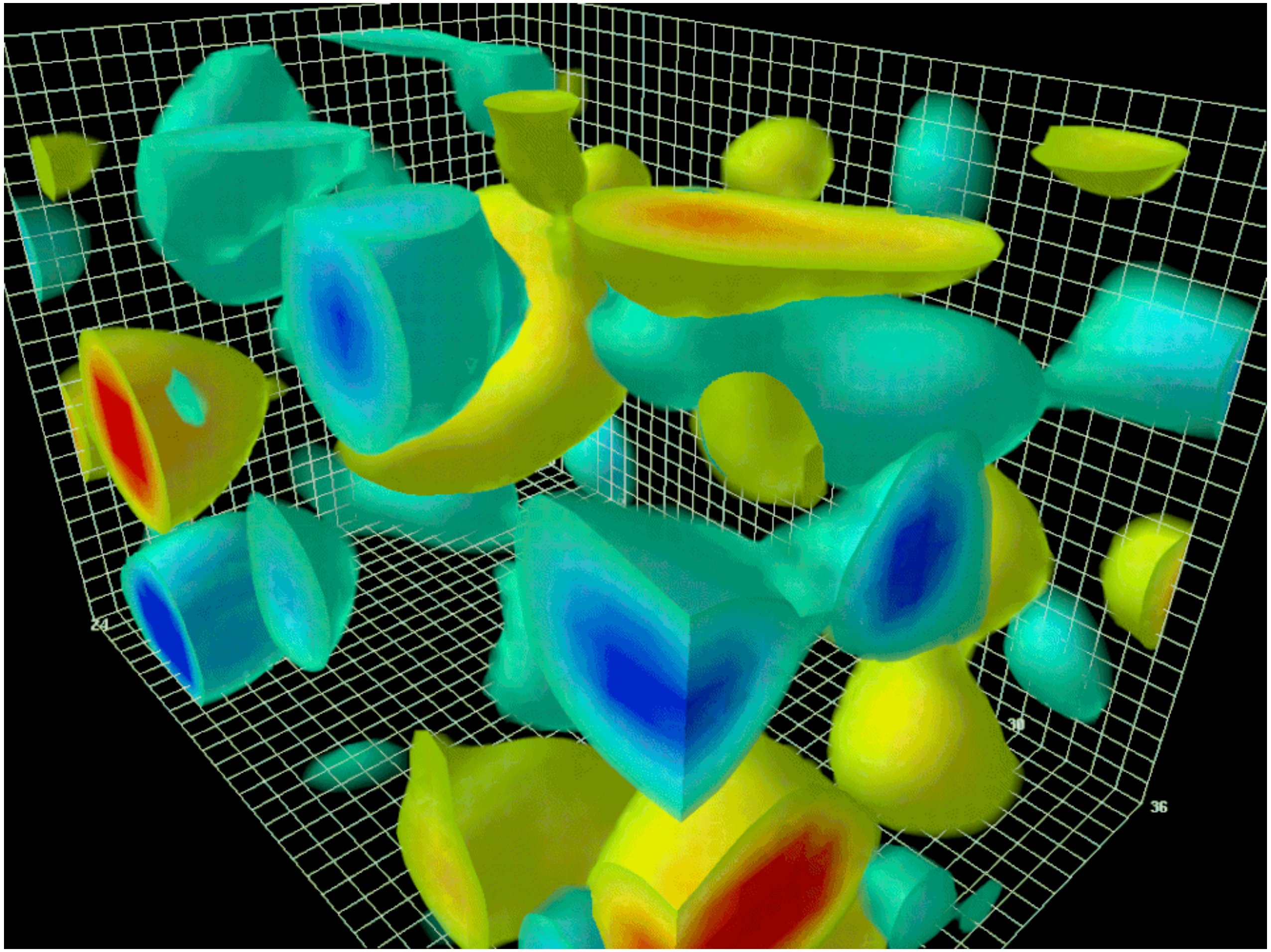
The Vacuum is a Quantum Foam

Implication of Heisenberg Uncertainty Principle

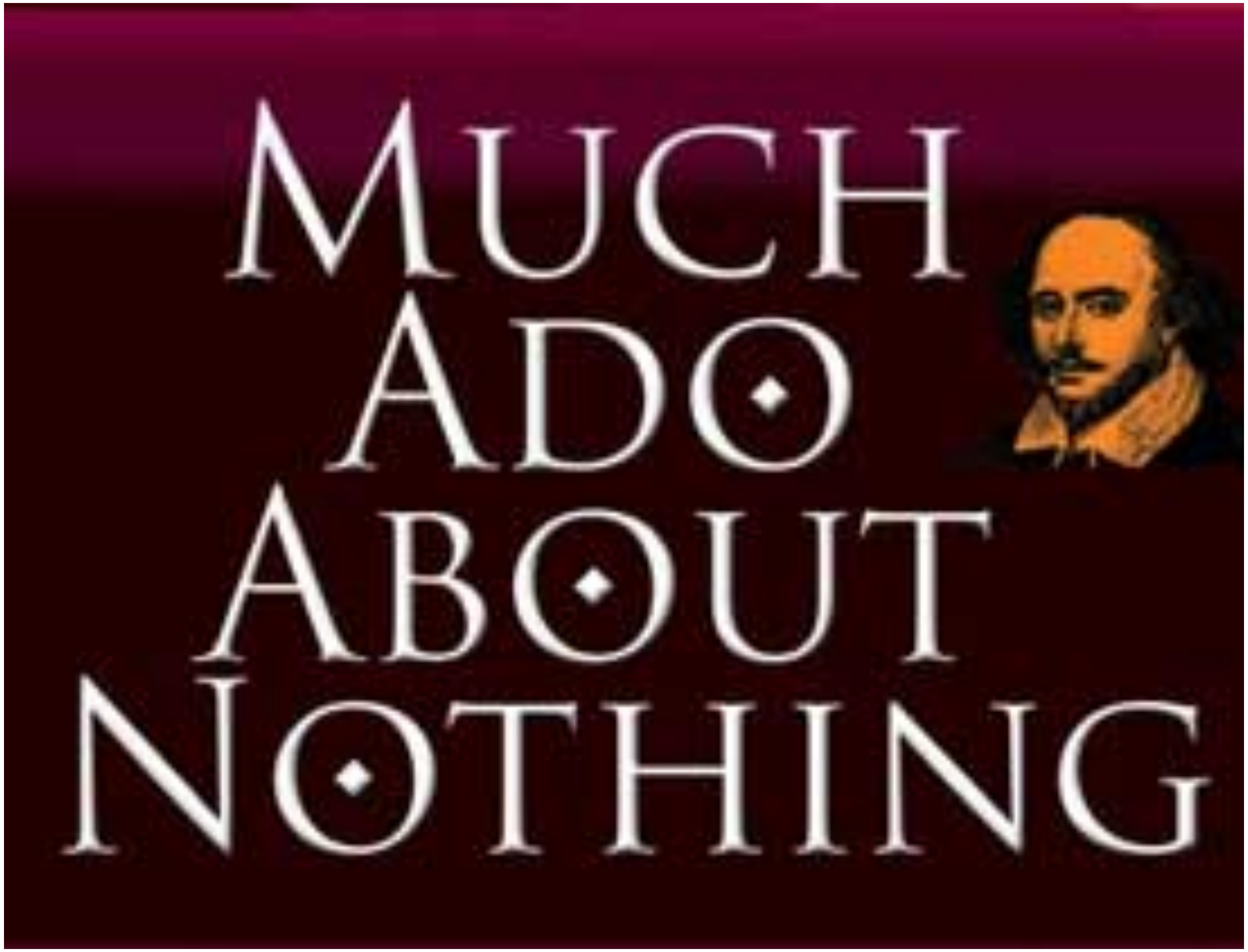
$$\Delta E \sim h / \Delta t$$

- Nature can "borrow" energy of amount ΔE for a short time Δt
- The shorter the time period of this "energy loan", the larger the amount of the loaned energy that is available
- Therefore the vacuum is a bubbling foam with high-energy particles popping up and disappearing

The Vacuum as a Quantum Foam

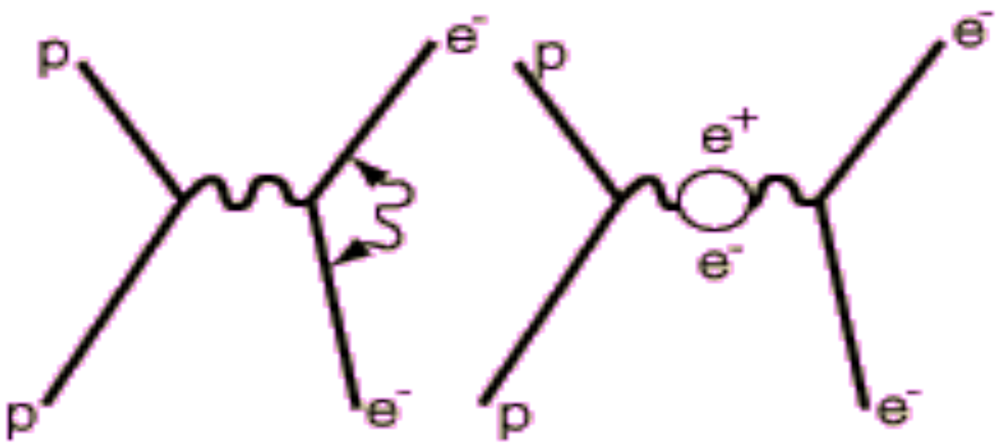


Alternate title of my talk:

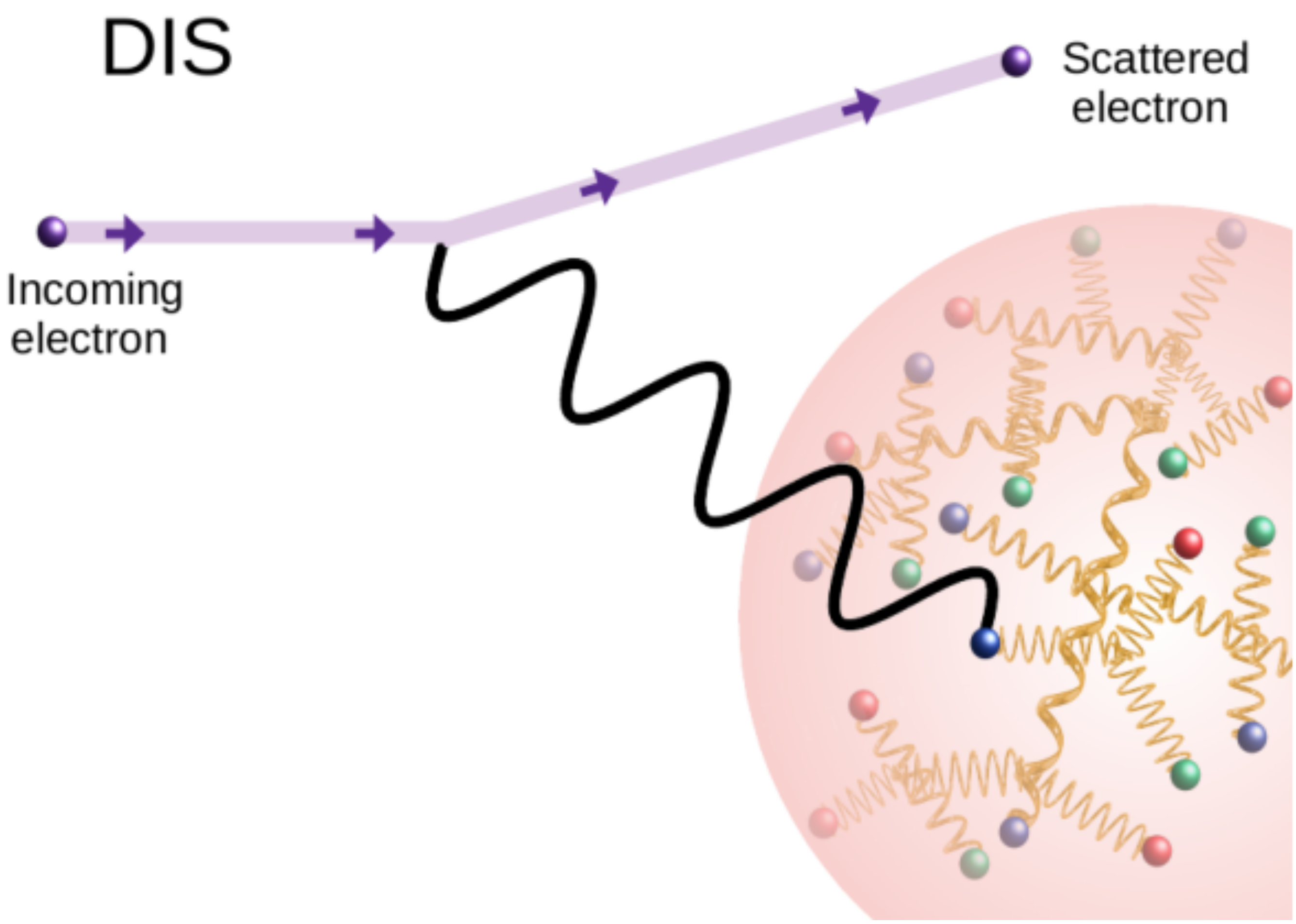


Detecting New Physics through Precision Measurements

- Willis Lamb (Nobel Prize 1955) measured the difference between energies of $^2S_{1/2}$ and $^2P_{1/2}$ states of hydrogen atom
  - Observed one part per million difference in their energies
  - States should have the same energy in the absence of vacuum fluctuations
- Harbinger of vacuum fluctuations to be calculated by Feynman diagrams containing quantum fluctuations
  - Modern quantum field theory of electrodynamics followed (Nobel Prize 1965 for Schwinger, Feynman & Tomonaga)

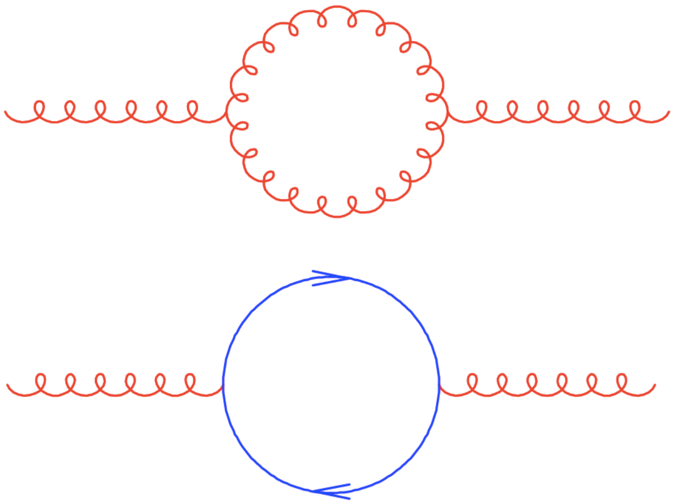


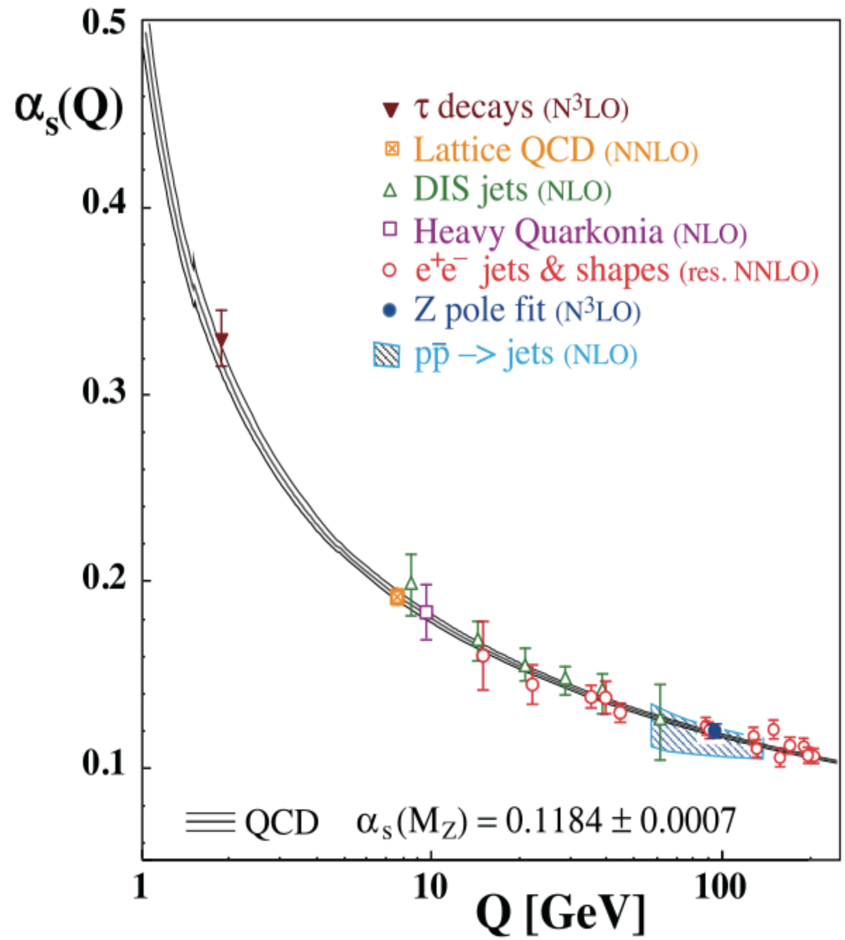
From Atoms to Quarks



DIS = Deep Inelastic Scattering

Test of Quantum Fluctuations at High Energy

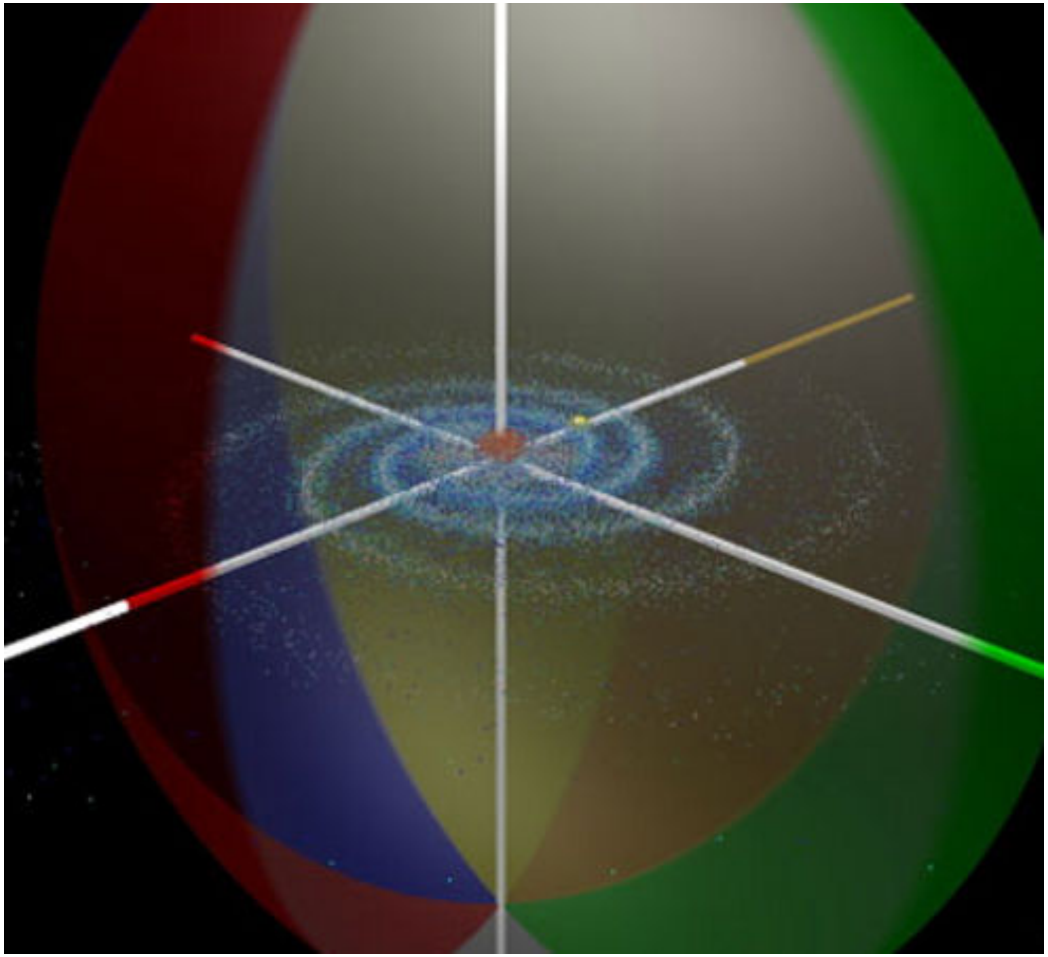




Changing strength of the strong force with energy has been confirmed experimentally

Dark Matter, Galaxy Formation and the Quantum Foam

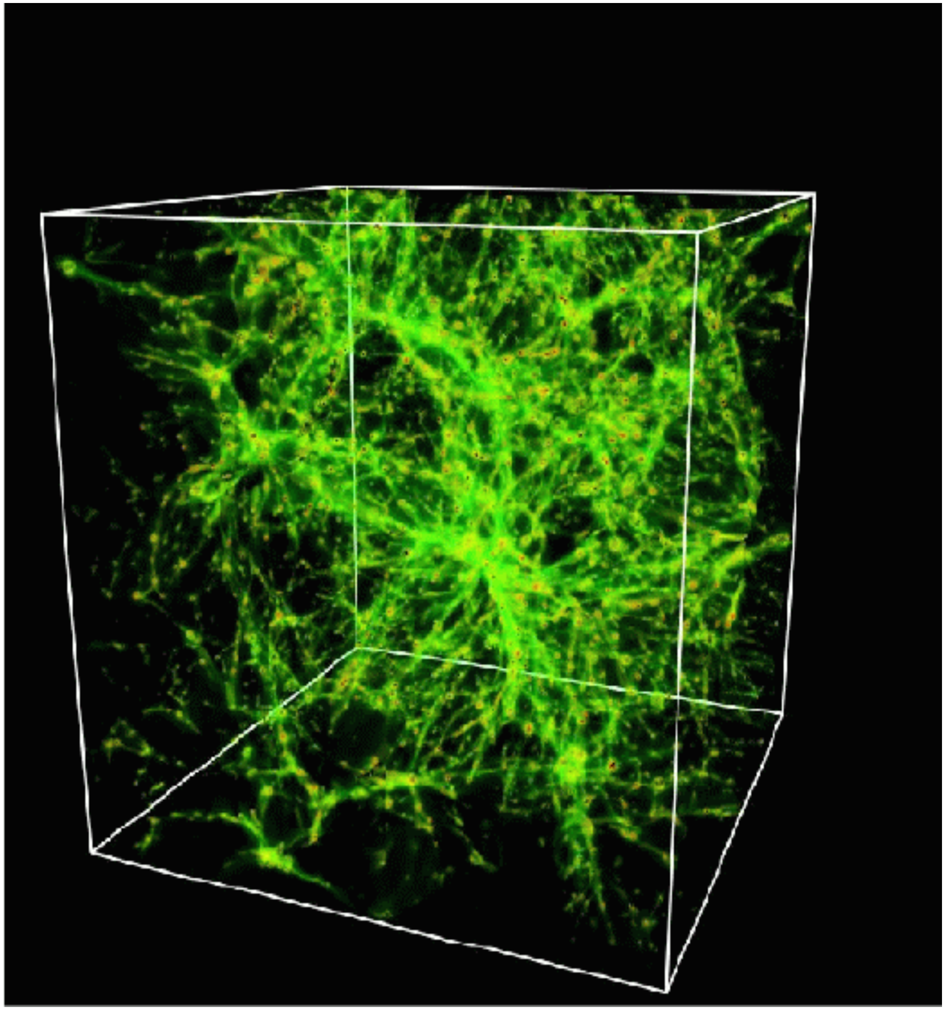
Halo of Invisible Dark Matter around Galaxies



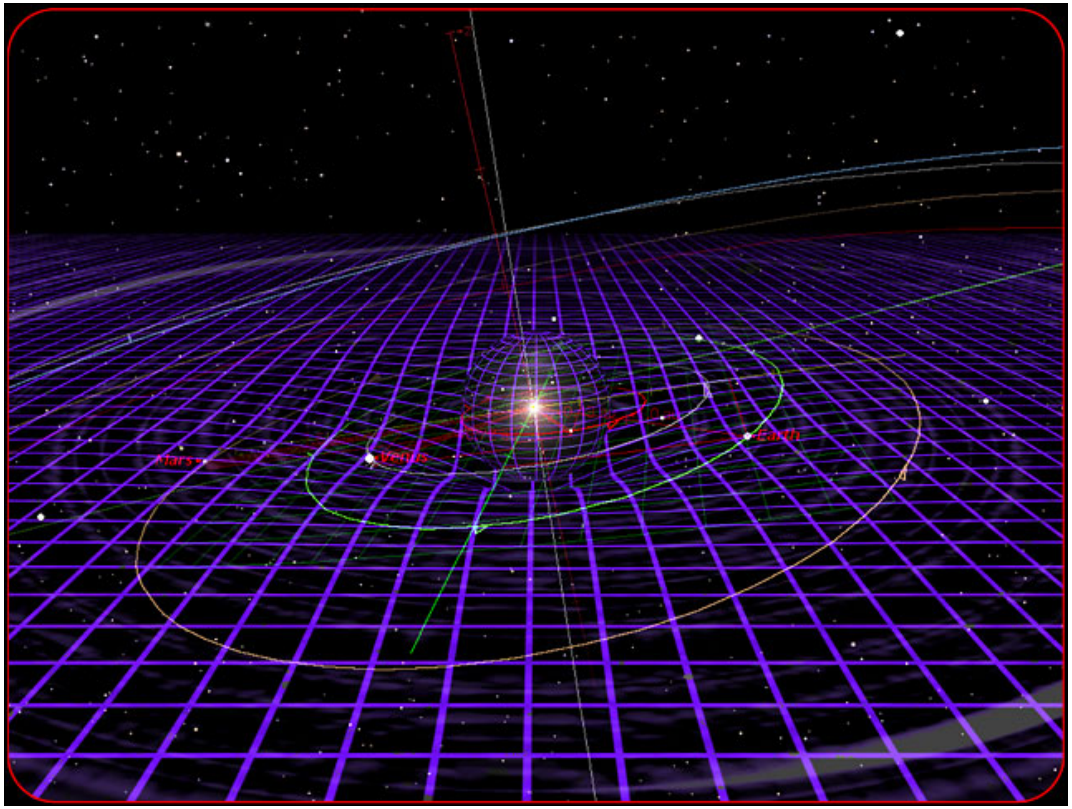
Four times as much dark matter as visible matter

Mapping out the Dark Matter

- *A lot* of dark matter is required to hold galaxies together
- It cannot all be made of protons
- It must be neutral, stable, heavy
- It must be some new form of matter – new fundamental particles



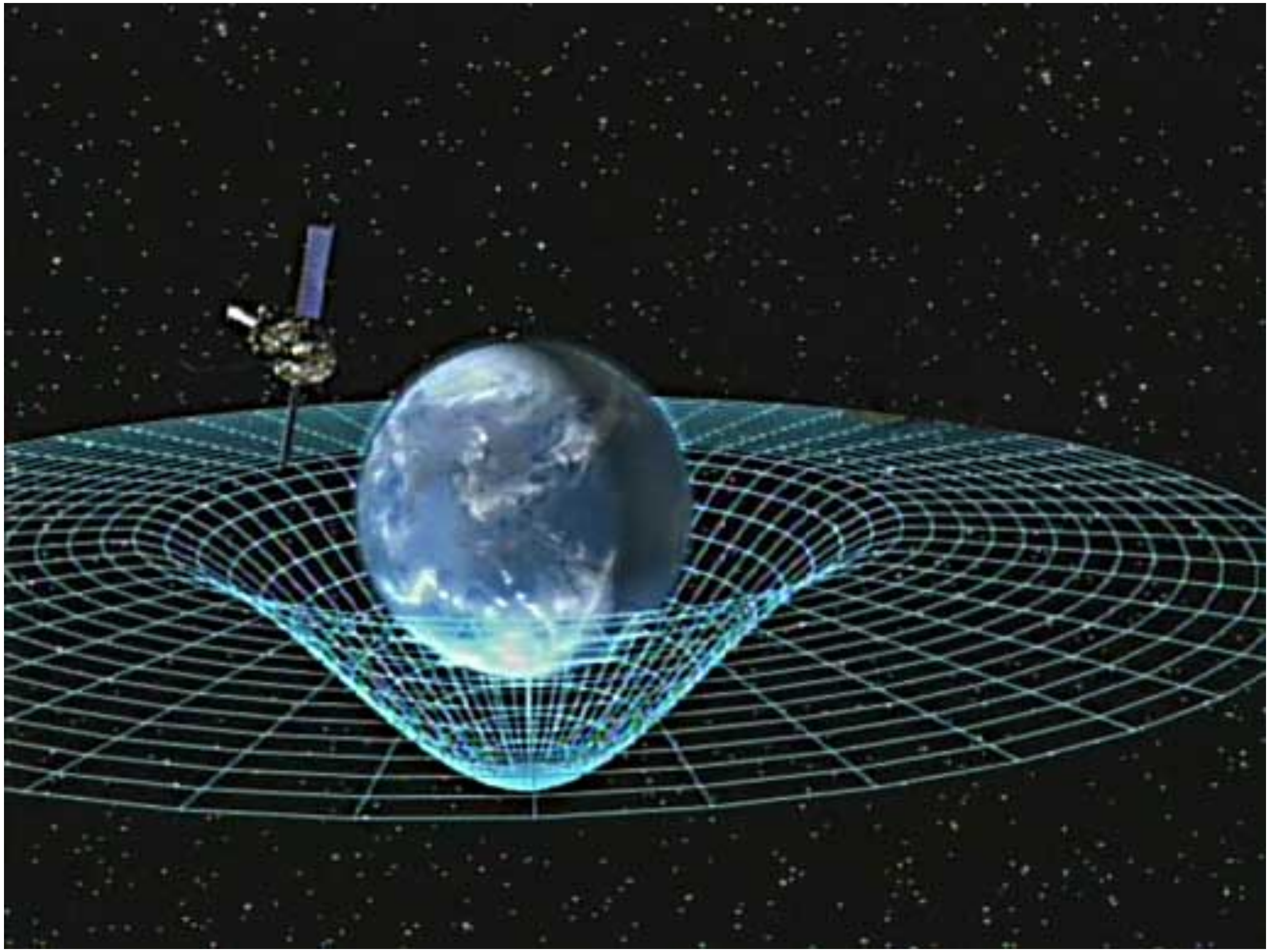
Albert Einstein



1915: Spacetime is active: curves, expands, shrinks, …

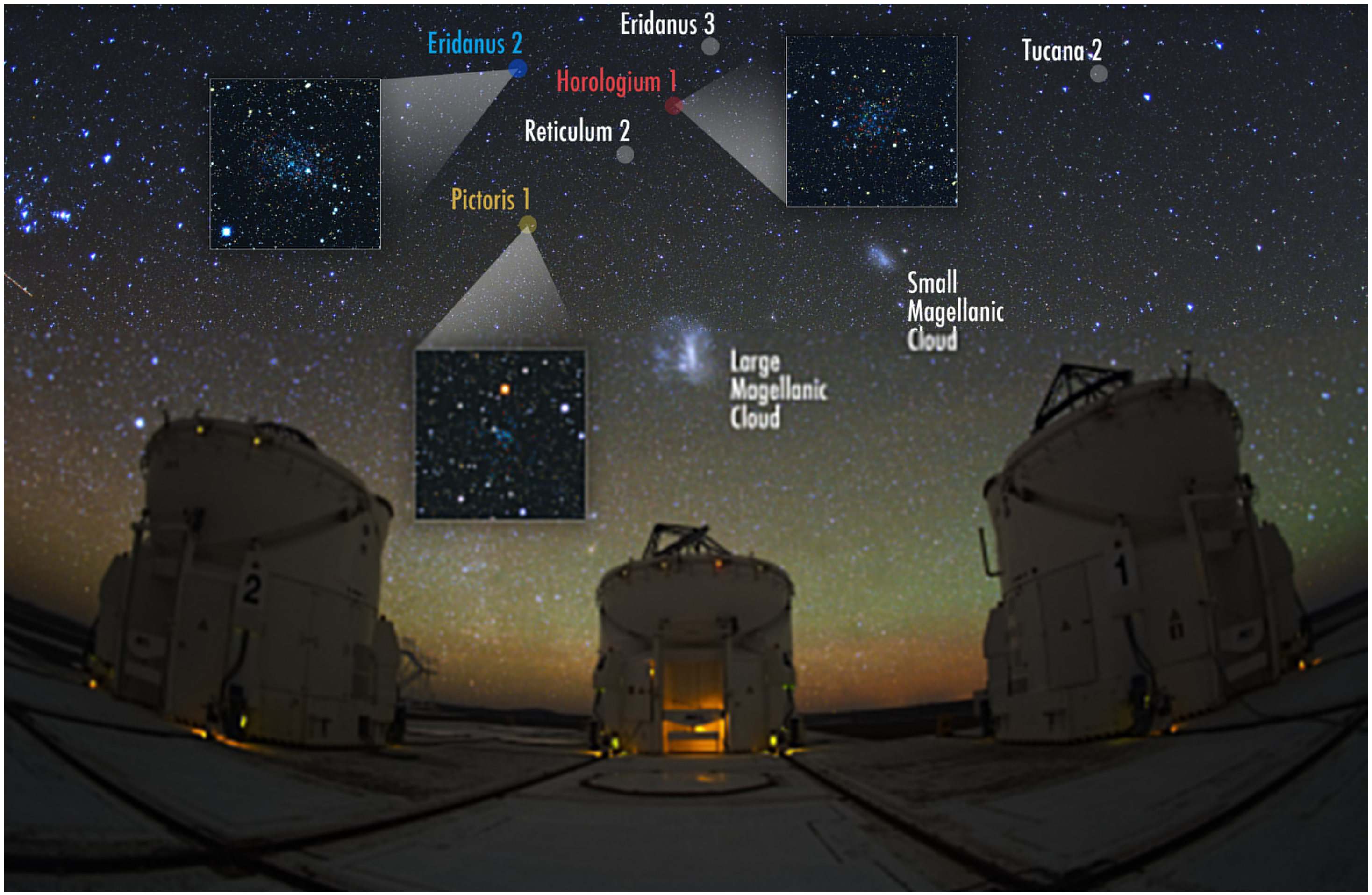
3-space directions and time direction are combined into a single 4-dimensional spacetime

Matter and Energy Curves Space

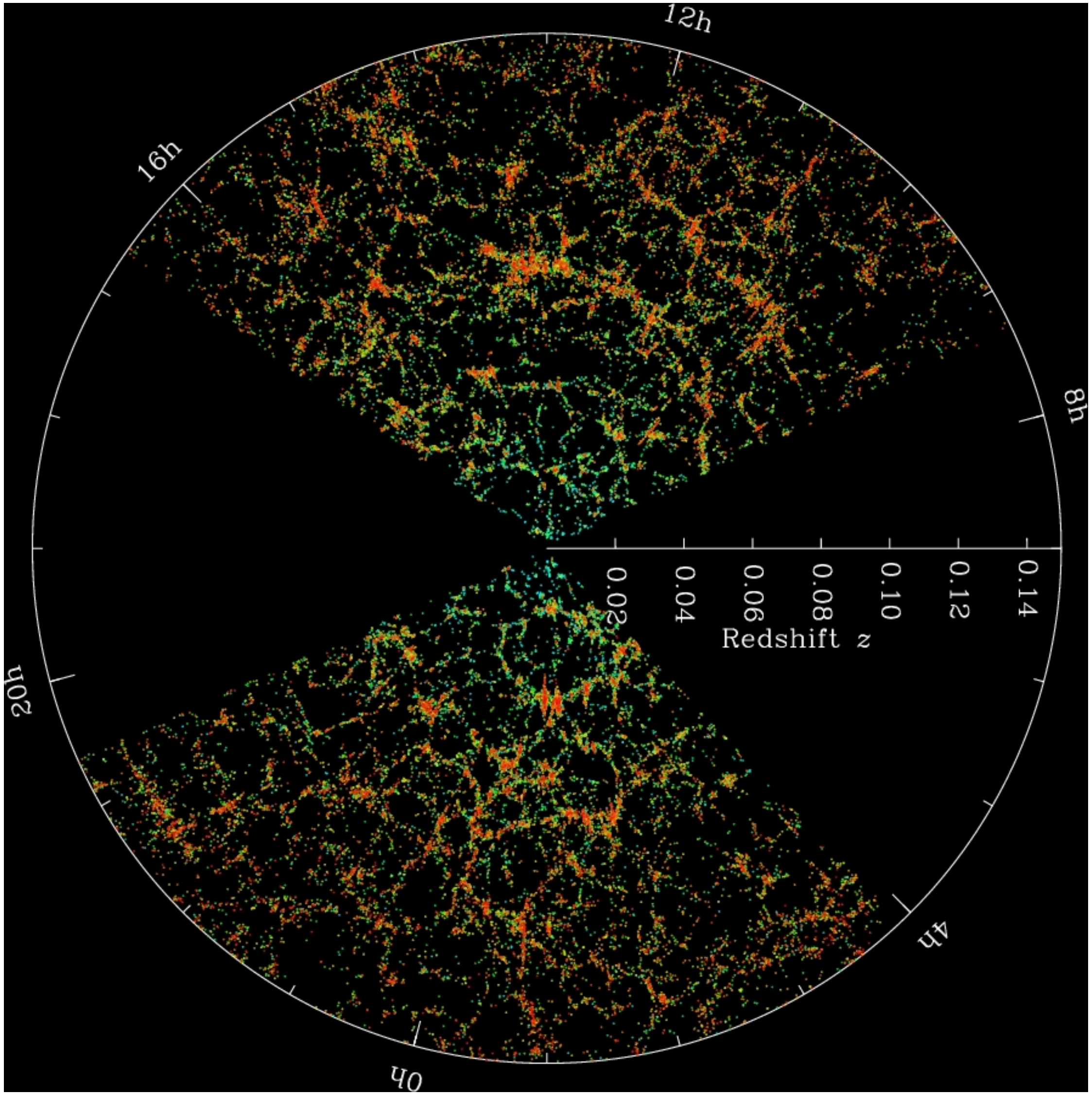


Light bends in curved space

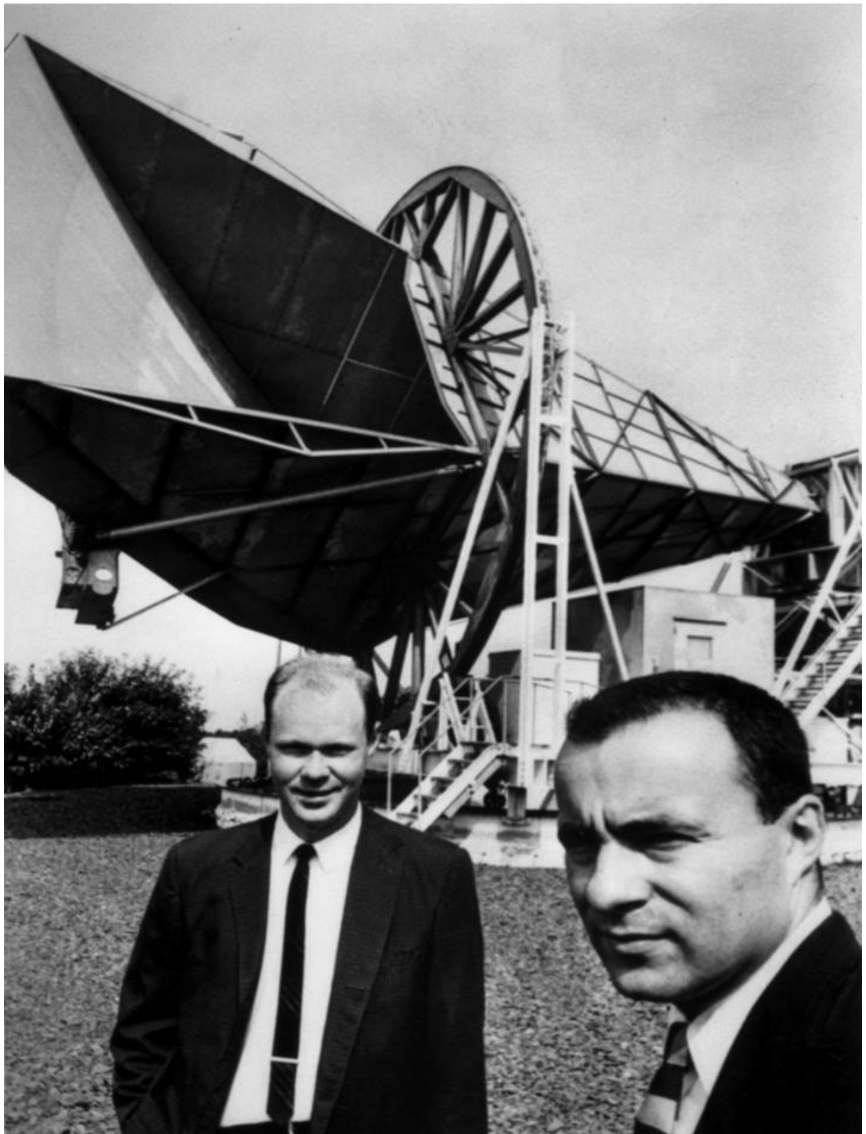
Newly Discovered Dark Matter Galaxies



3D Distribution of Galaxies



Cosmic Microwave Background

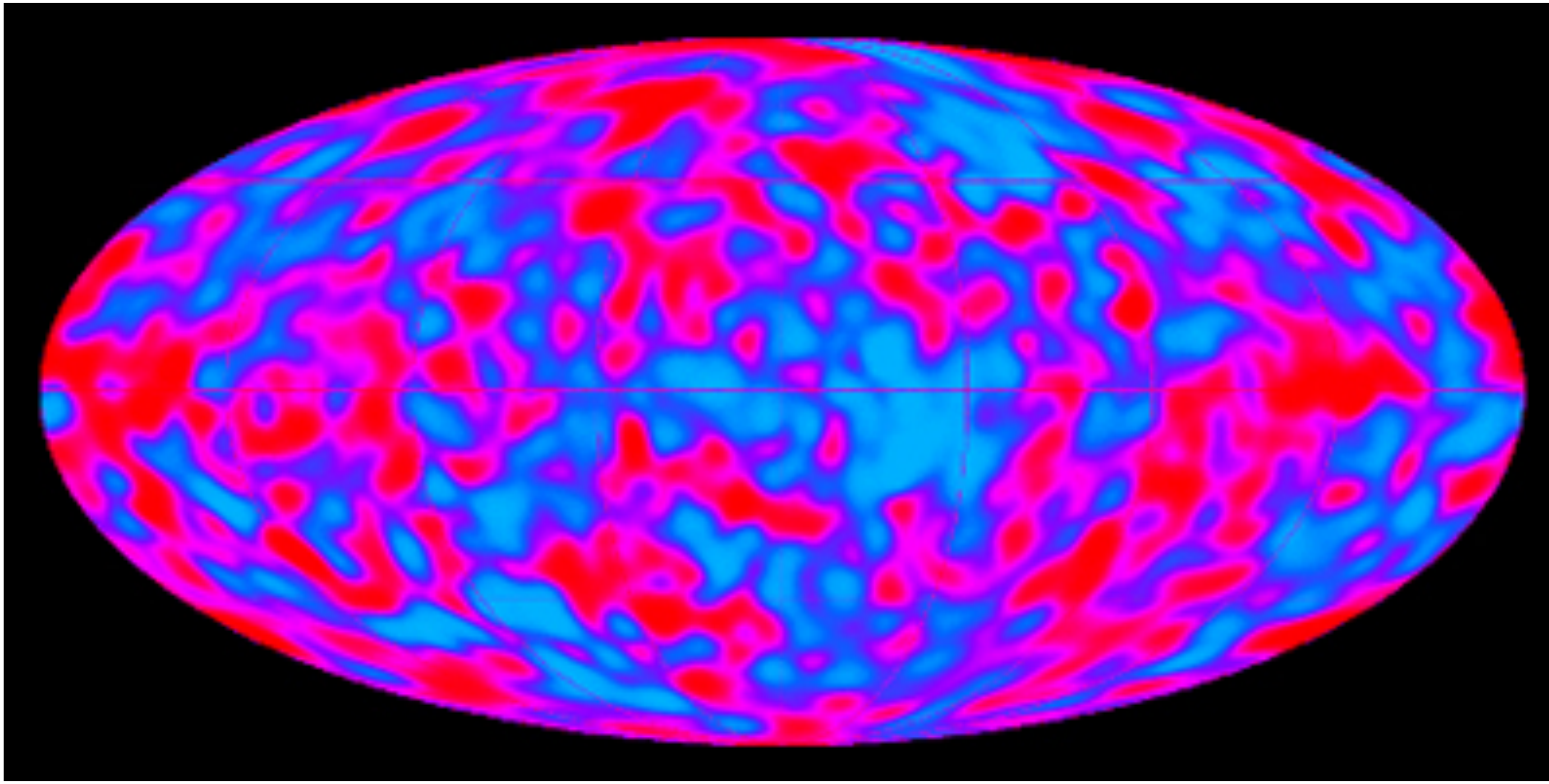


Penzias and Wilson (Bell Labs) discovered in 1964 a constant microwave radiation coming uniformly from all points in the sky

This radiation was emitted at the beginning of the Universe

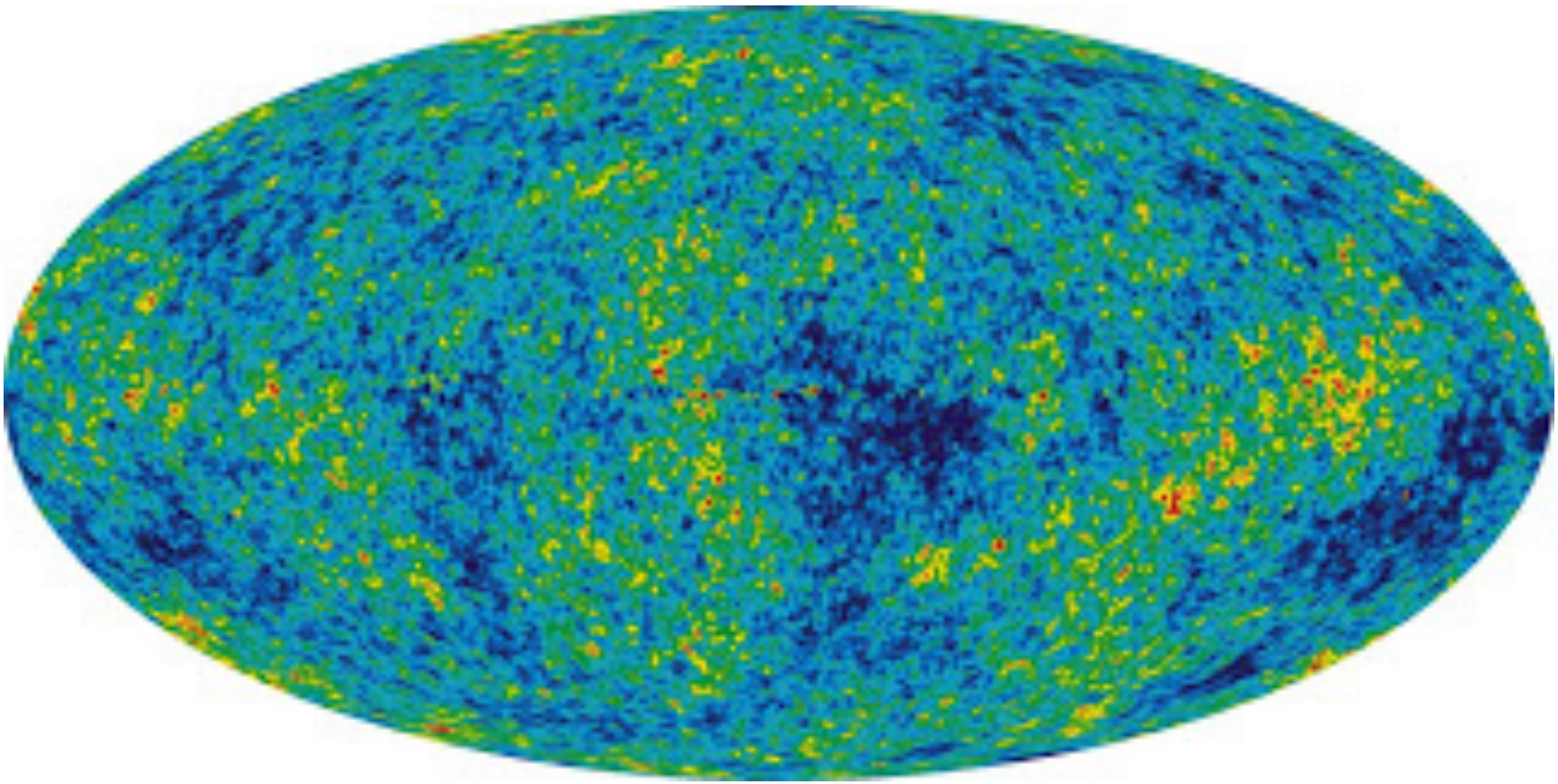
Nobel-prize winning discovery

Cosmic Microwave Background Fluctuations



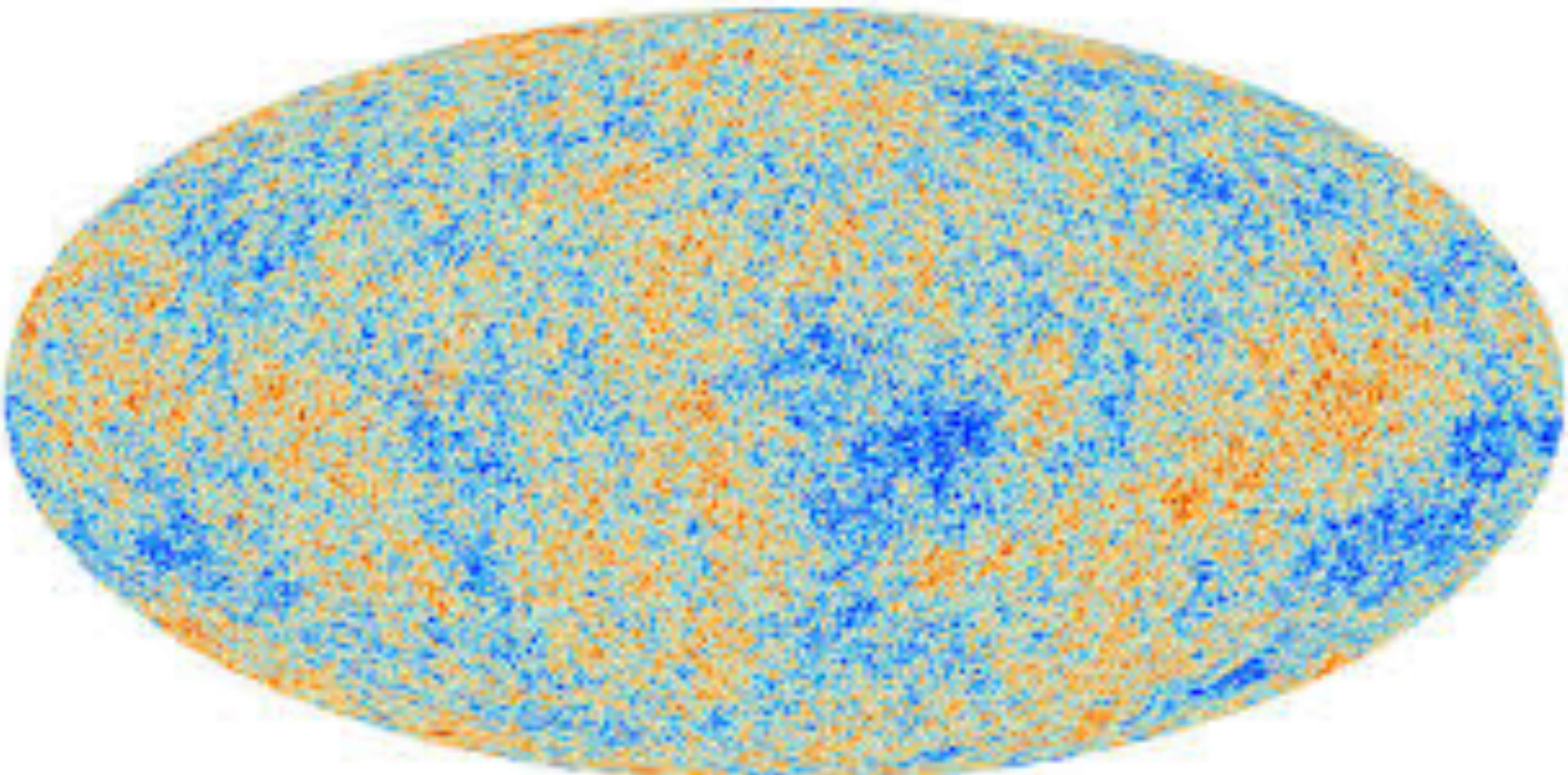
Full sky measurement of variation of microwave radiation
0.001% variation with direction in sky, measured by COBE satellite
(Nobel-prize winning discovery)

Cosmic Microwave Background Fluctuations



Full sky measurement of variation of radiation
Improved direction precision measured by WMAP satellite

Cosmic Microwave Background Fluctuations

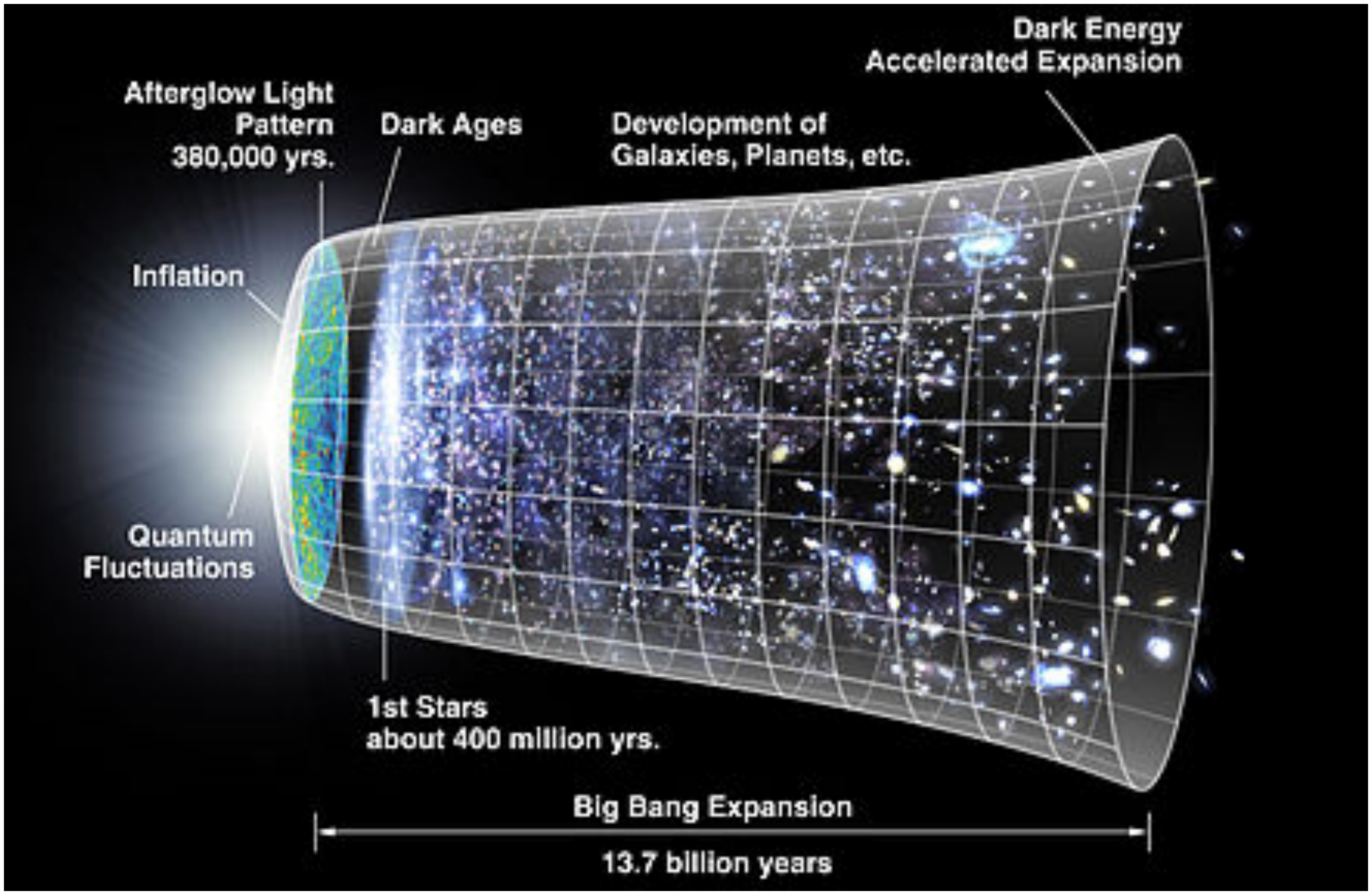


Full sky measurement of variation of radiation
Further improved direction precision measured by PLANCK satellite

Origin of Galaxies Requires Dark Matter

- Quantum fluctuations at the Big Bang cause density variations
  - We are seeing the imprint of these density variations on the earliest light
- Density variations seeded the accretion of dark matter
- Dark matter accretion causes accretion of visible matter
  - Leading to galaxies we see today

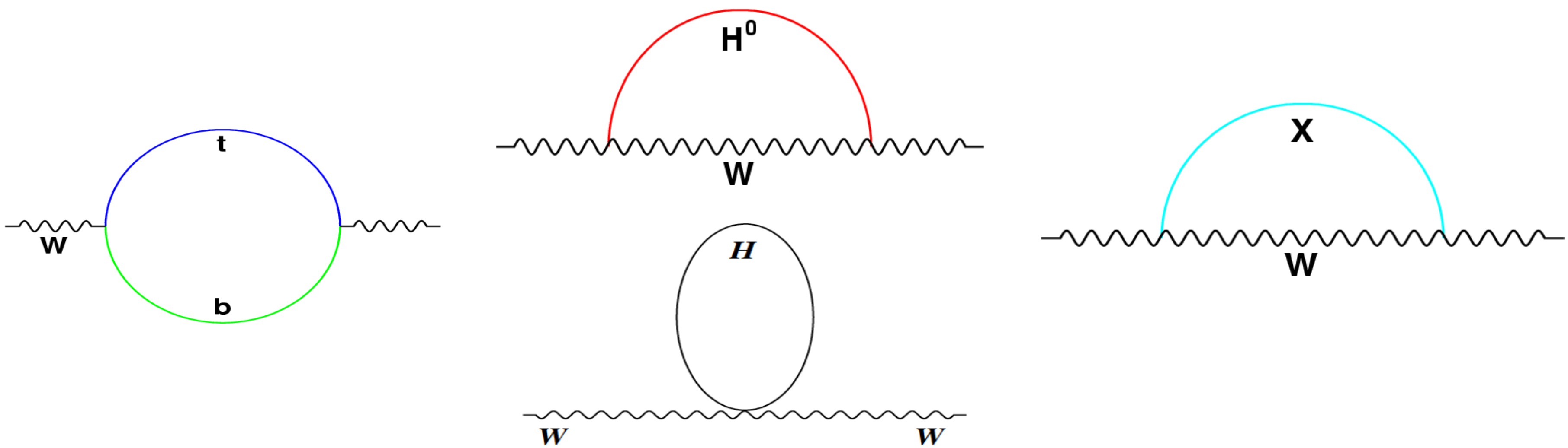
Origin of Galaxies Requires Dark Matter and Quantum Foam at Big Bang



The Vacuum Quantum Foam and the W boson Mass

Motivation for Precision Measurement of W boson Mass

- Quantum fluctuations due to top quark and Higgs boson and (potentially) undiscovered particles



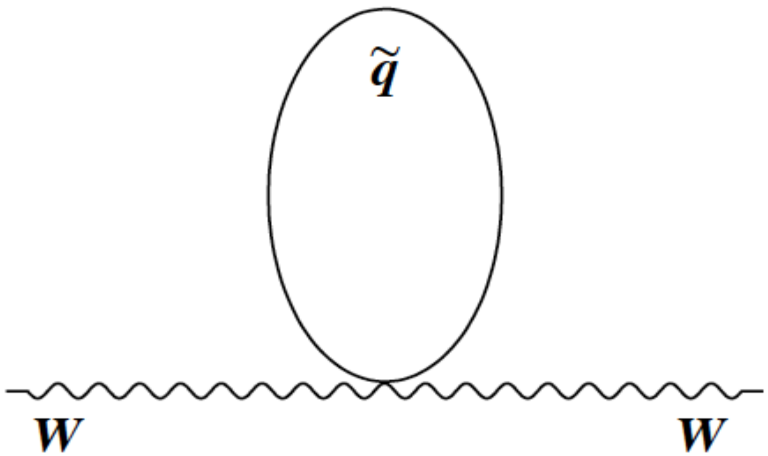
Standard Model calculation of the quantum fluctuations:

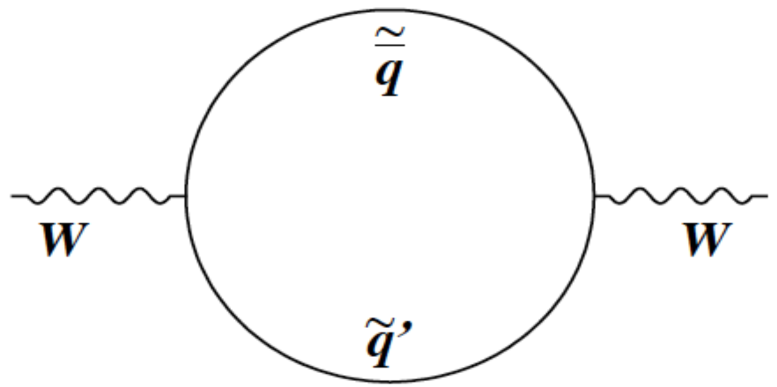
- Since we know top quark and Higgs boson masses, comparing measured and calculated values of W boson mass tells us about new particles "X" beyond the Standard Model

Motivation for Precision Measurement of W boson Mass

- The mass of the W boson is precisely calculable in Standard Model theory
  - The Higgs boson was the last missing component of the model
- The W boson mass is calculated to accuracy of 0.01%
  - Standard Model expectation
  - $M_W = 80{,}357 \pm 4_{\text{inputs}} \pm 4_{\text{theory}}$ MeV
  - A target for comparison to experimental measurement

Quantum Fluctuations from Supersymmetric Particles

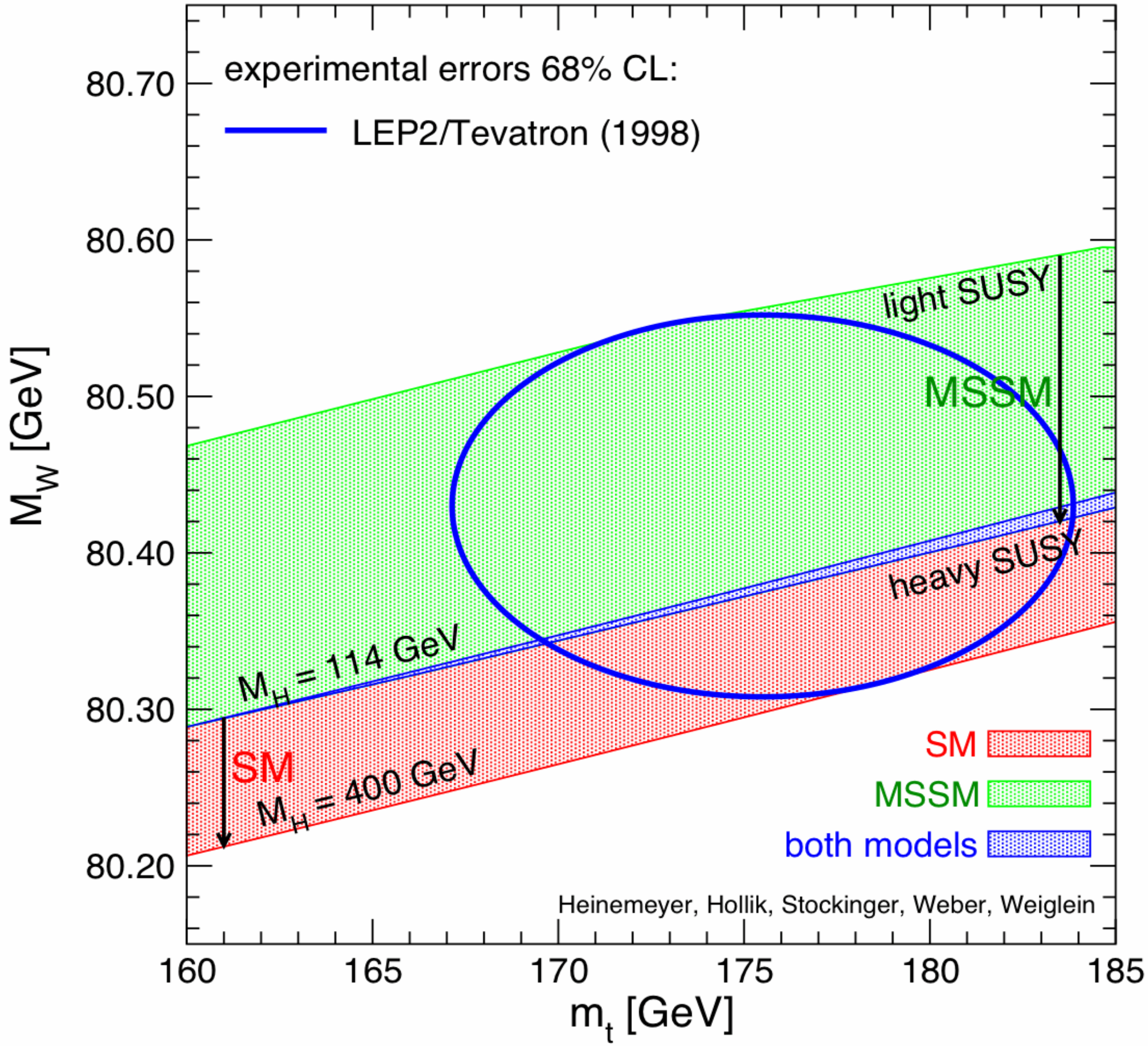




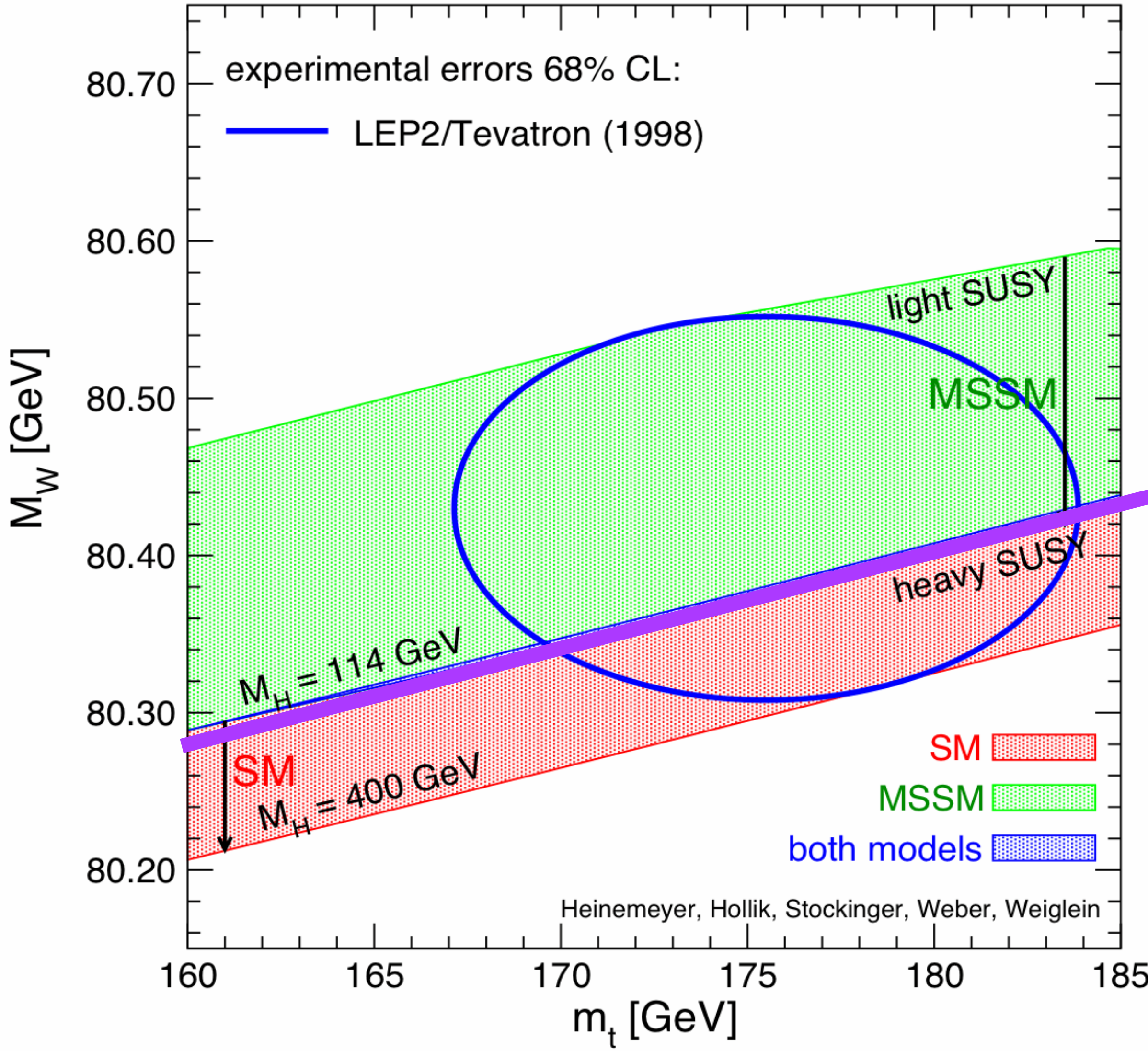
- Quantum fluctuations involving supersymmetric particles contribute to the W boson mass

- Supersymmetric particle could constitute dark matter

1998 Status of M_W *vs* M_{top}

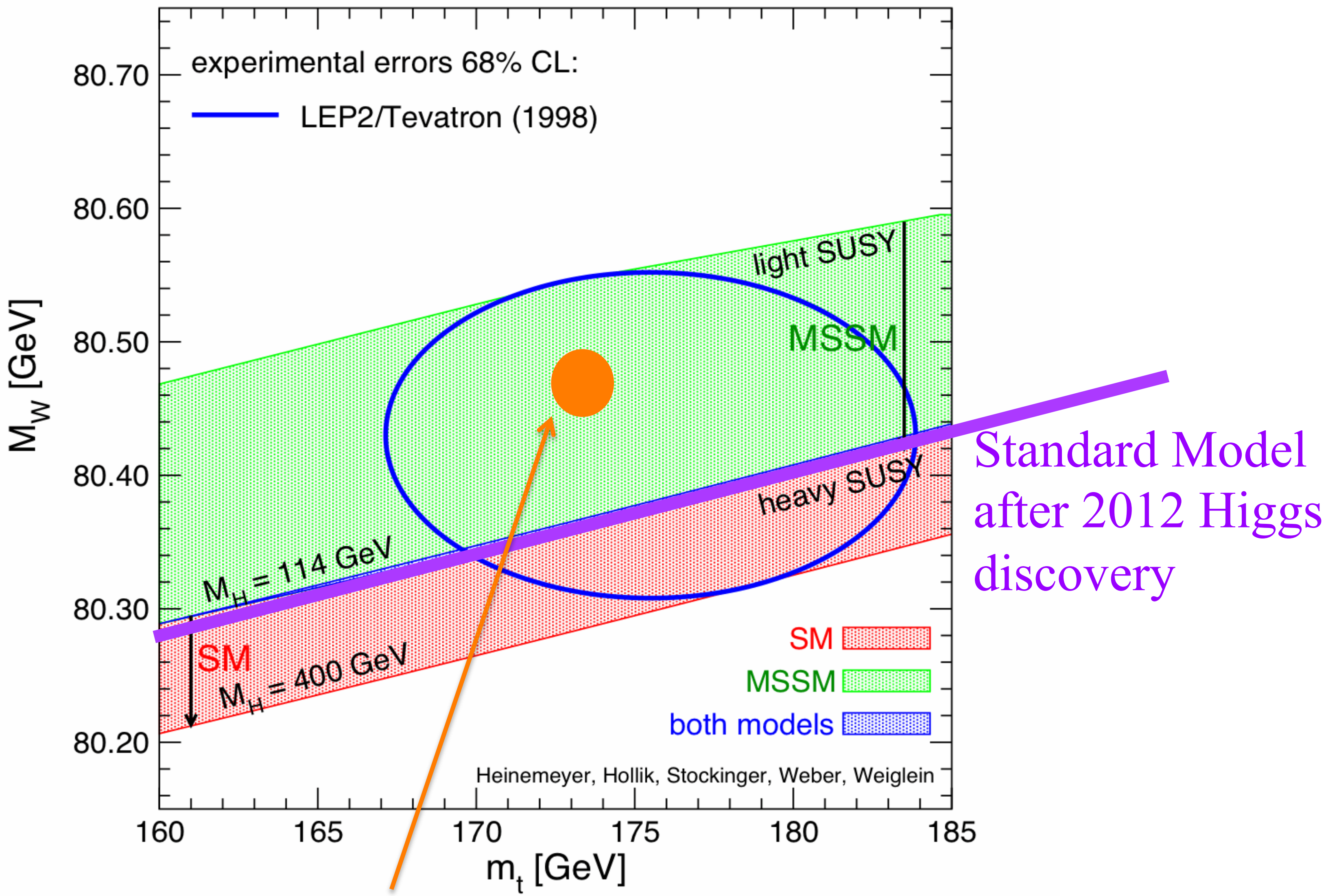


1998 Status of M_W *vs* M_{top}



Standard Model after 2012 Higgs discovery

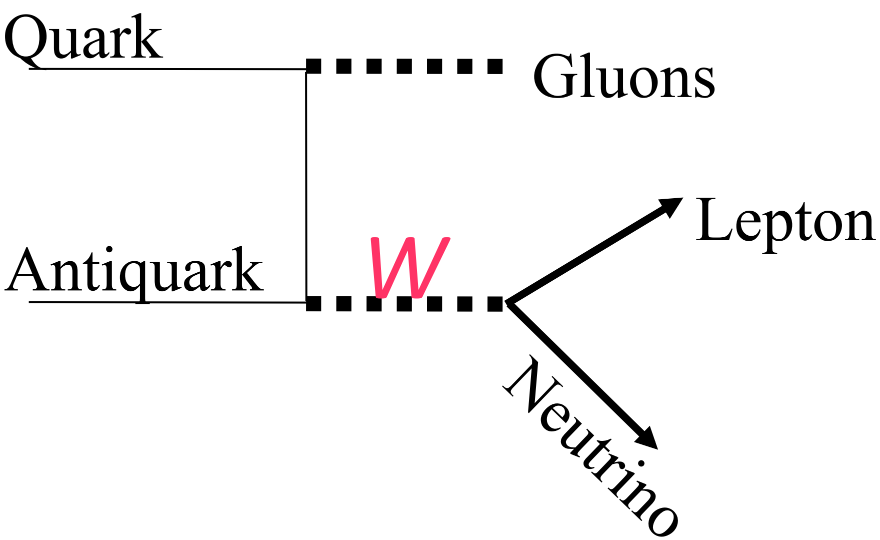
2022 Status of M_W *vs* M_{top}

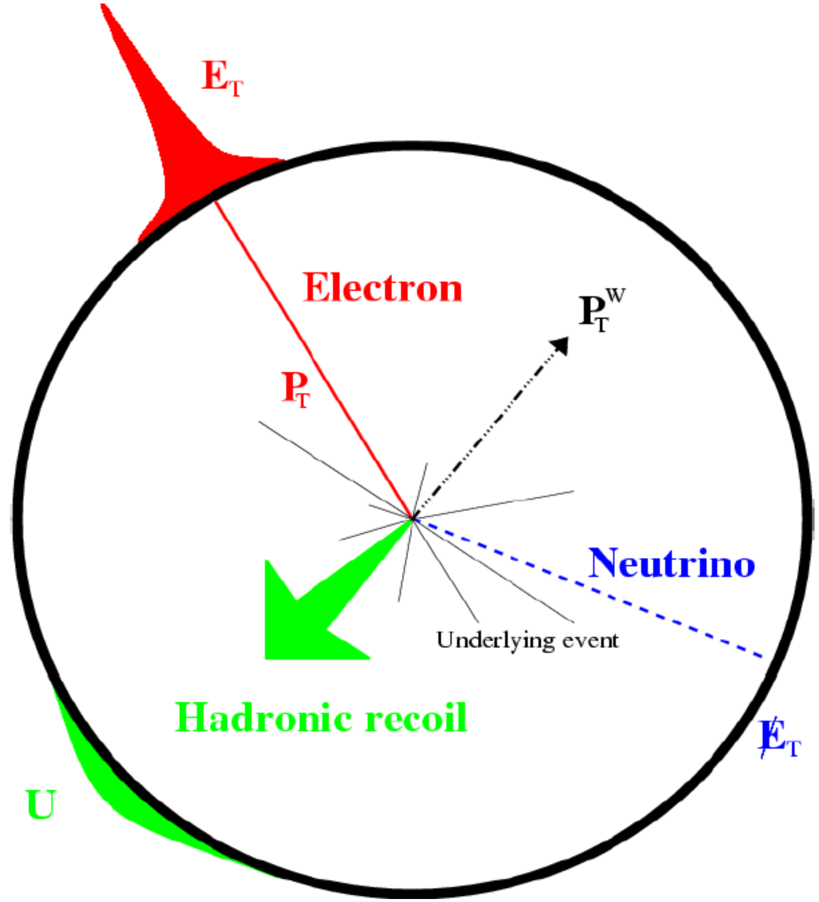


Science **376**, 170 (April 7, 2022); DOI: 10.1126/science.abk1781

How to Measure the W boson Mass to 0.01% accuracy

W Boson Production in Proton-Antiproton Collisions





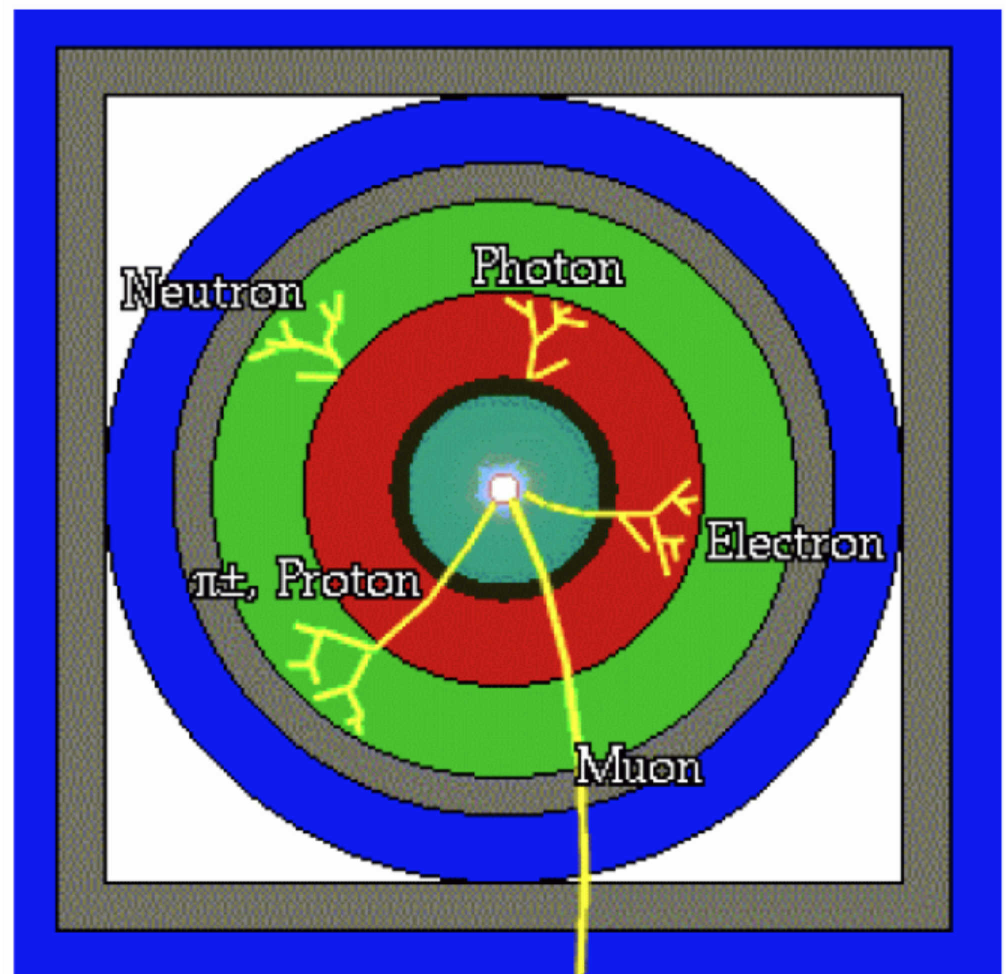
Quark-antiquark annihilation produces W boson

W boson decays to neutrino, accompanied by electron or muon

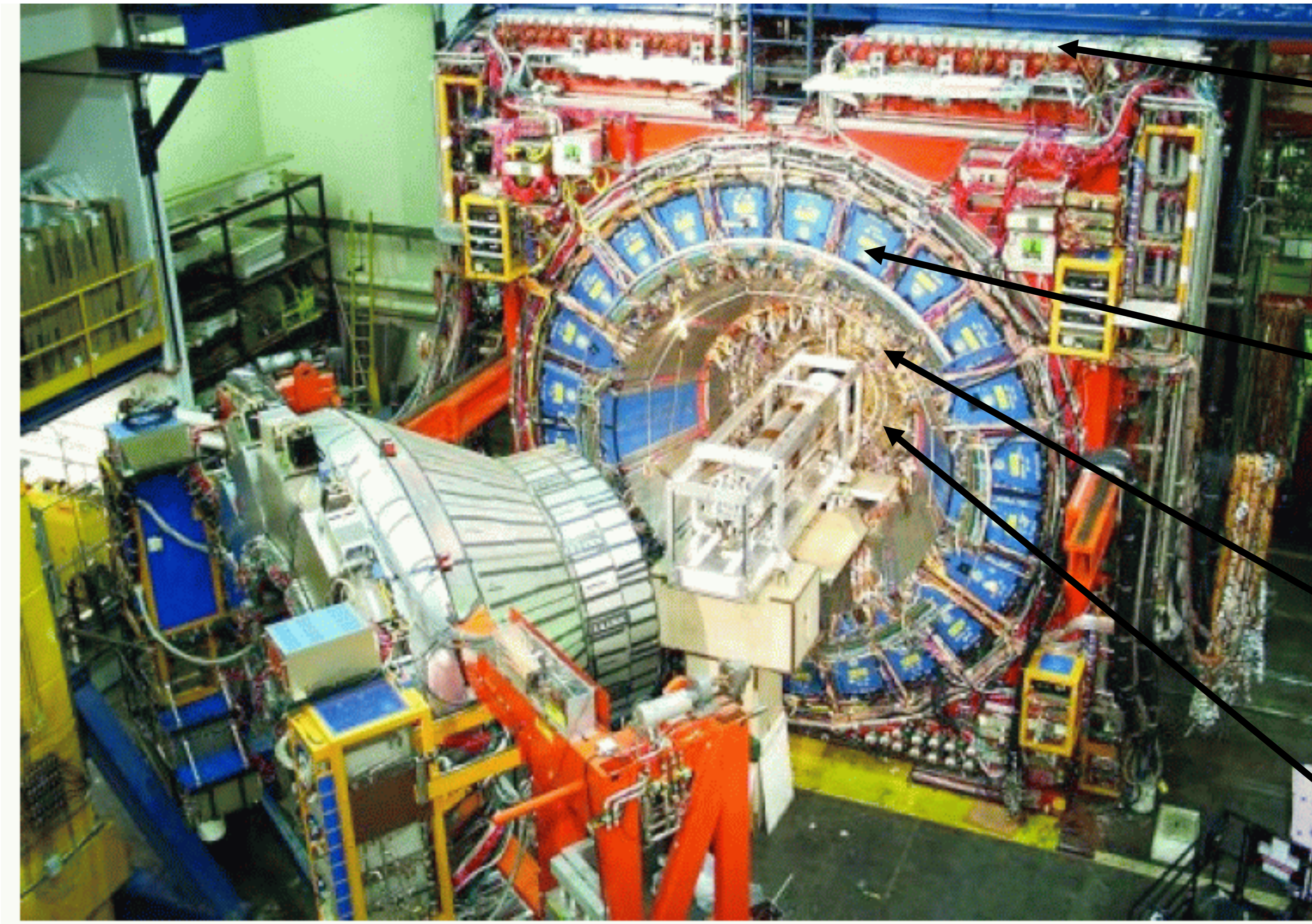
Lepton (electron or muon) momentum carries most of *W* mass information, can be measured precisely (achieved 0.004%)

Particle Detector Design

- Concentric cylinders of different kinds of detector technologies
- Decay products of unstable particles identified



Collider Detector at Fermilab (CDF)



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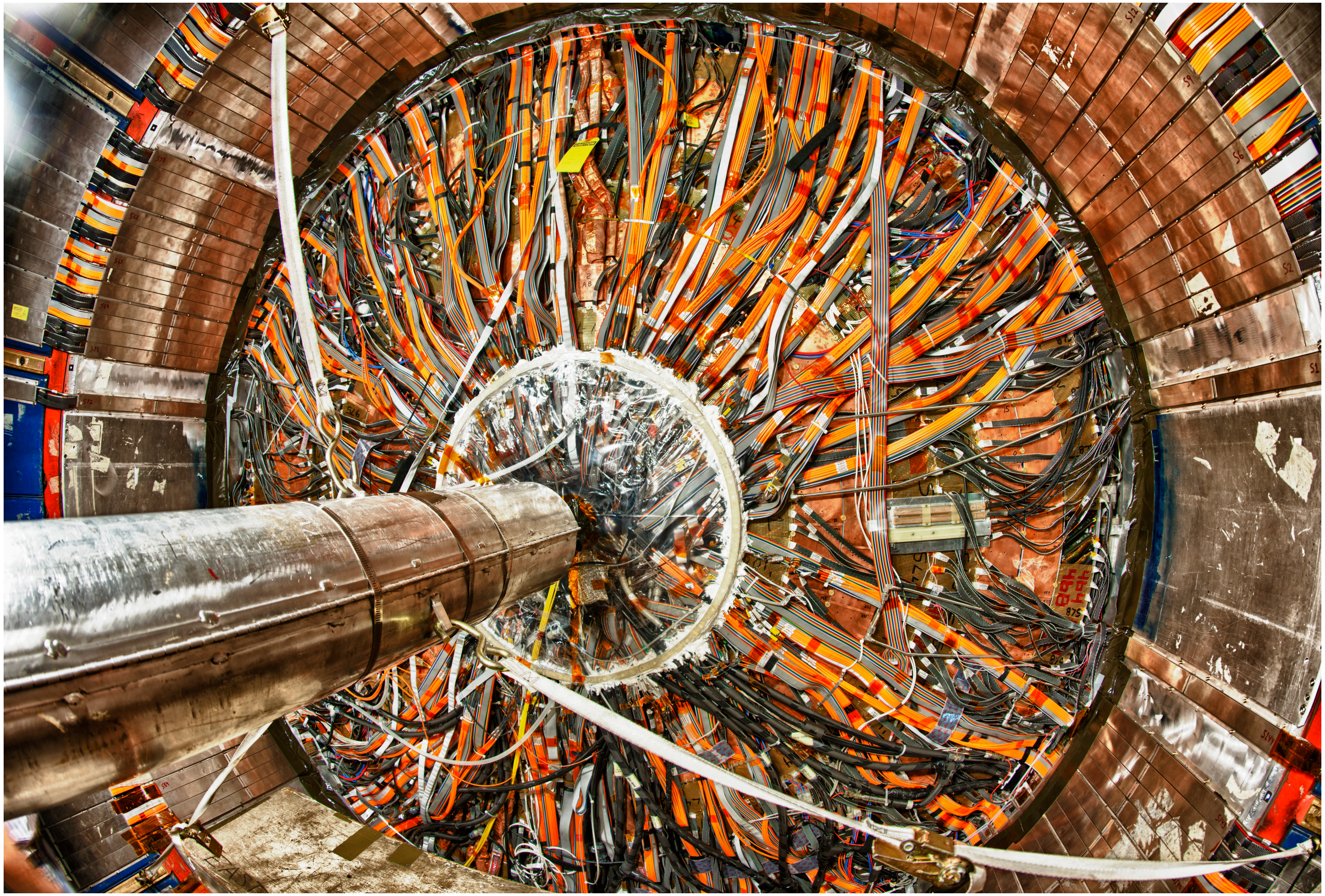
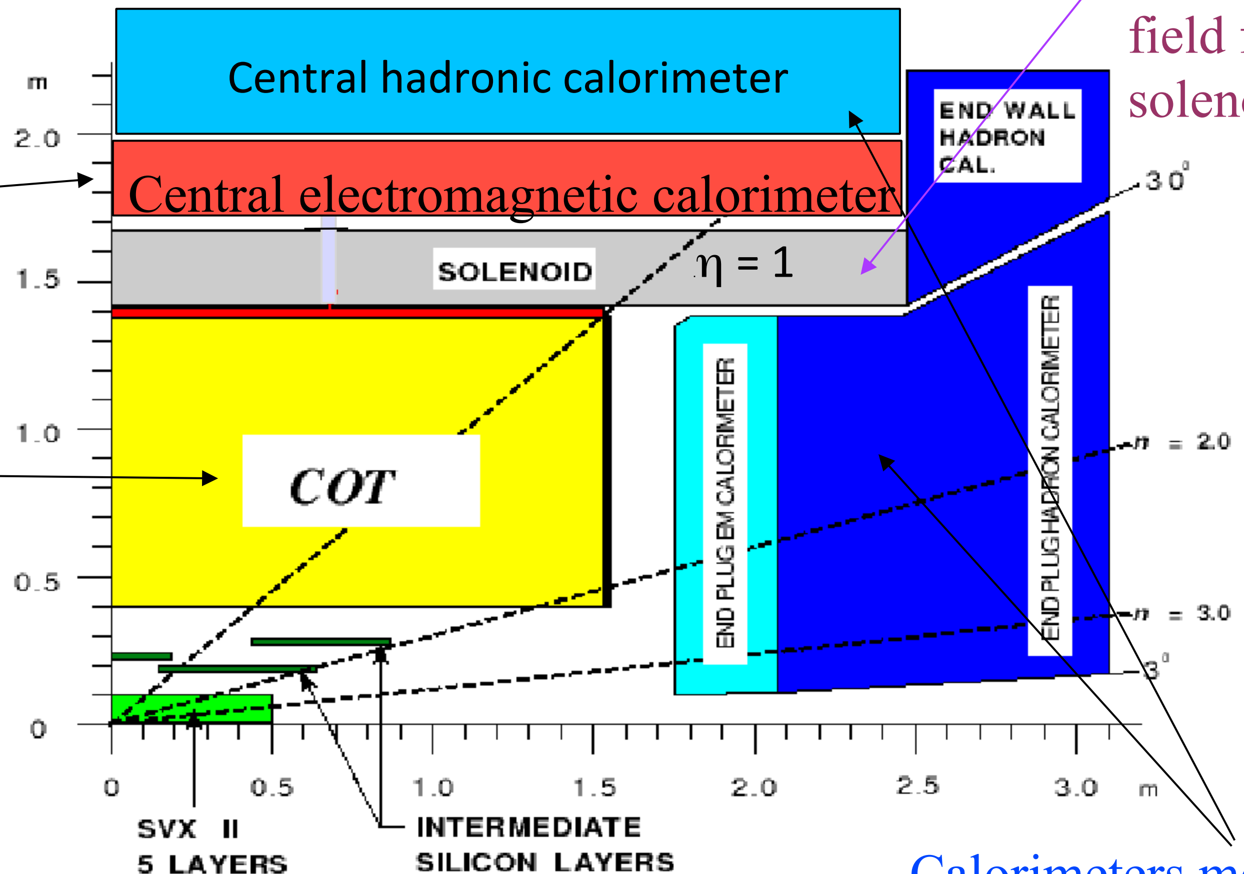


Quadrant of Collider Detector at Fermilab (CDF)

calorimeter provides precise electron energy measurement

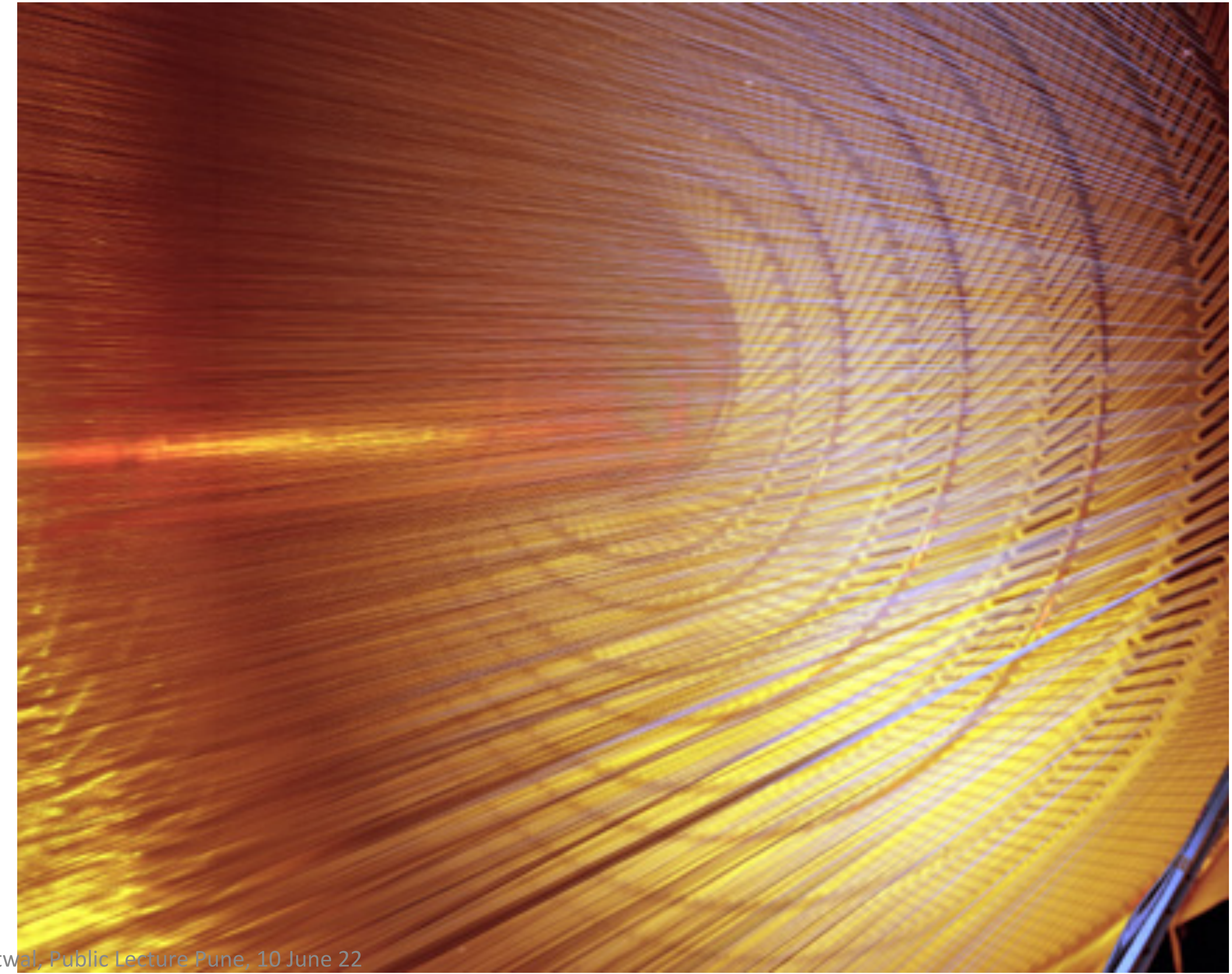
drift chamber provides precise particle momentum measurement

Axial magnetic field from solenoid

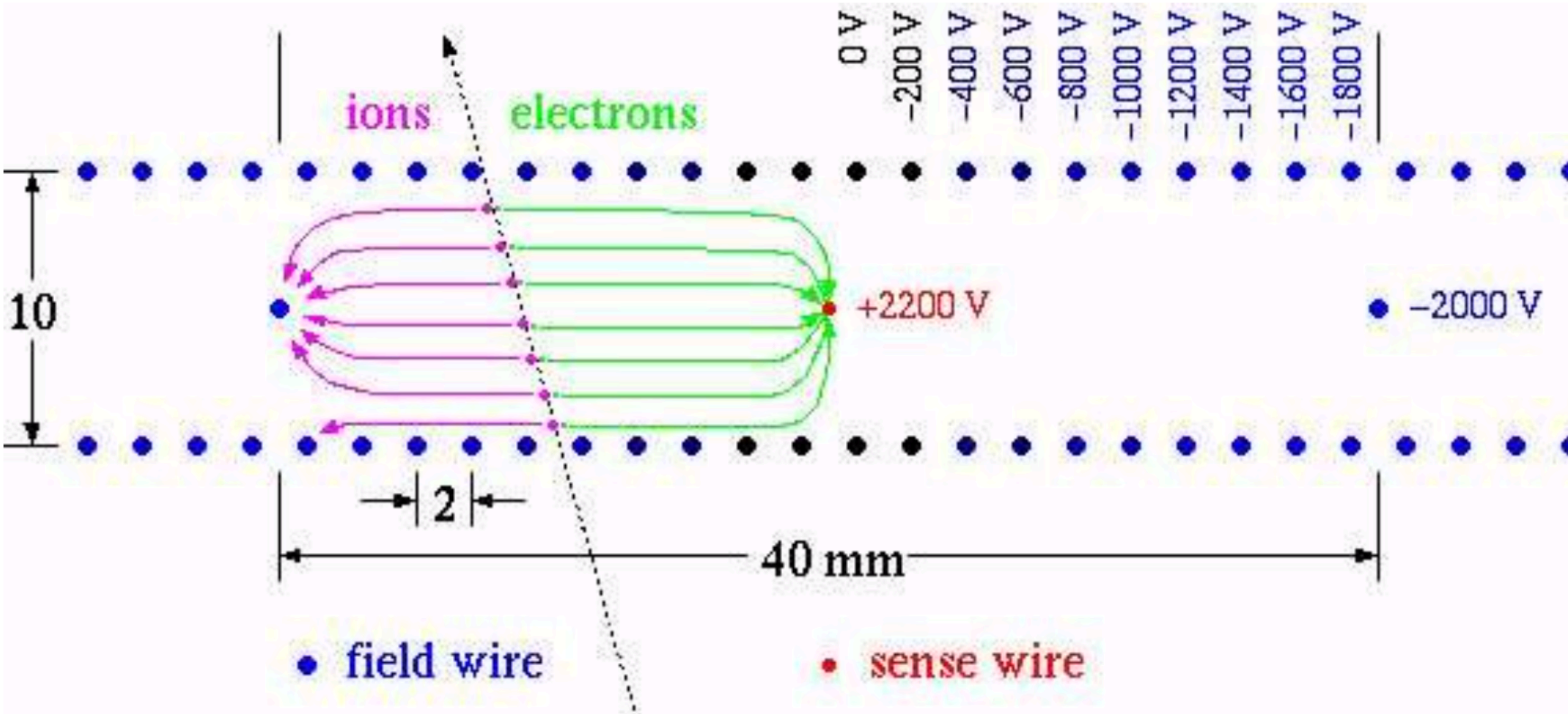


Calorimeters measure all other particles

CDF Particle Detector – Drift Chamber



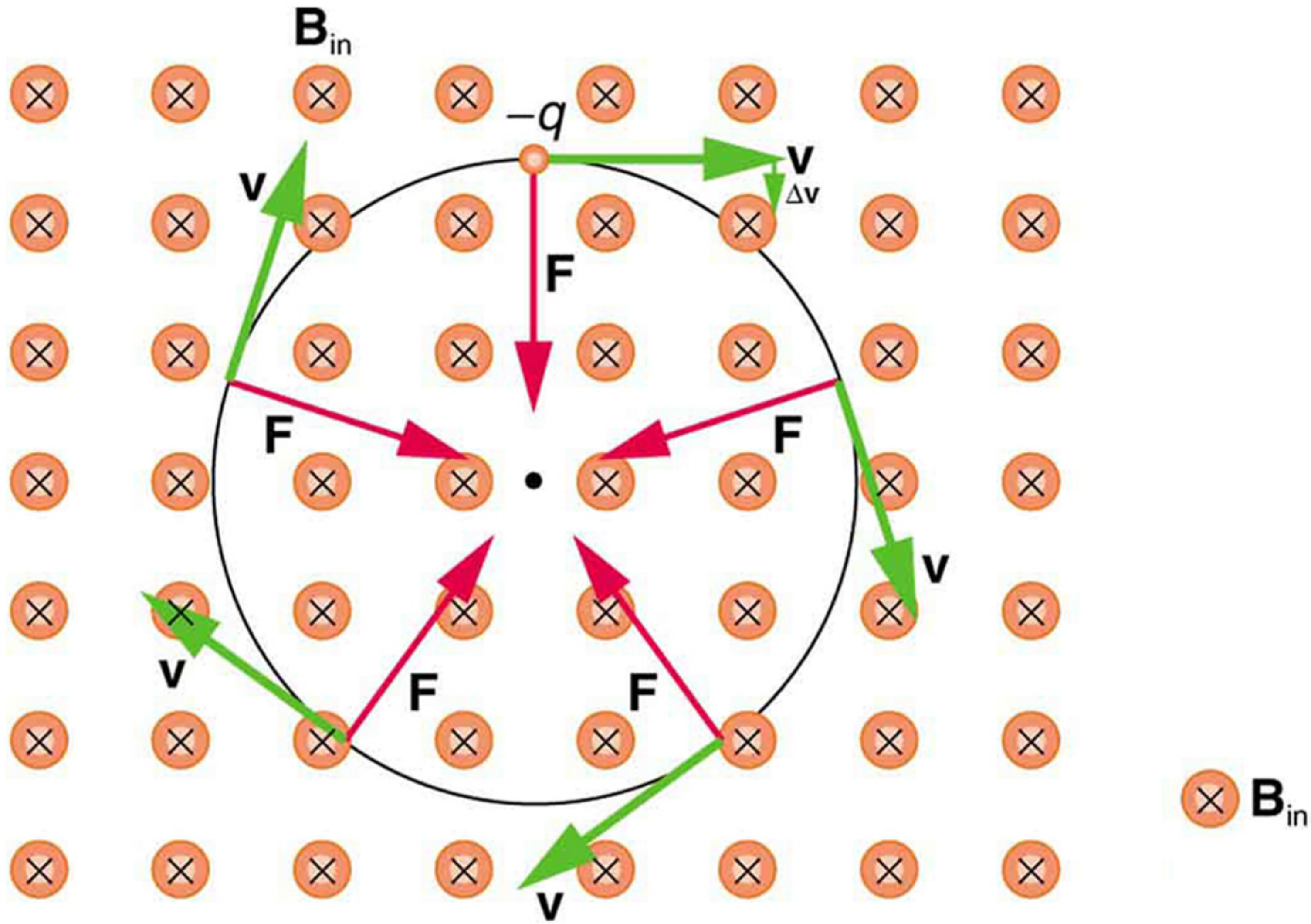
Drift Chamber Operation



Records the position of the charged particle as it passes near the high-voltage sense wire

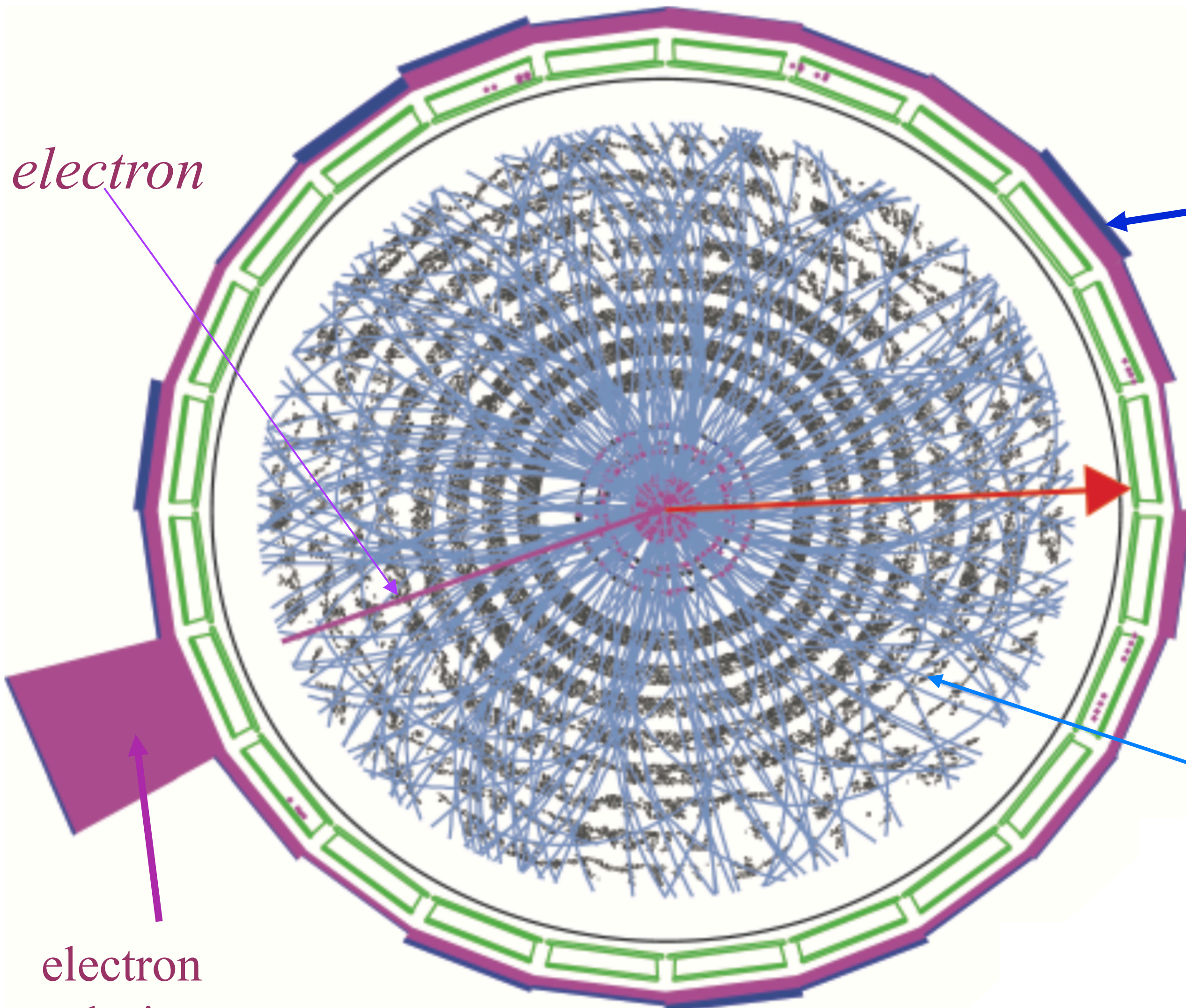
drift time x drift velocity = drift distance

Charged Particle in Magnetic Field



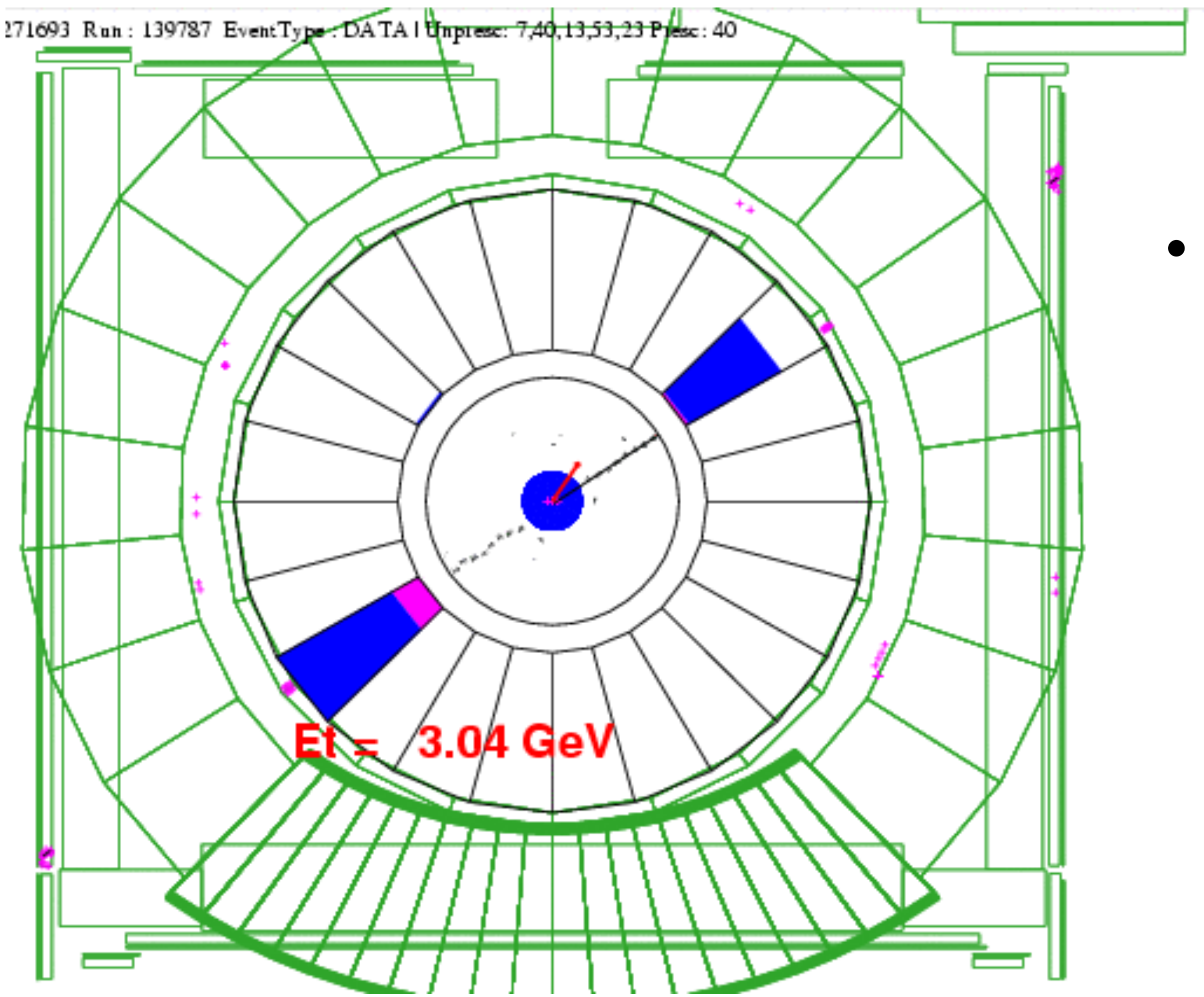
Circular trajectory of a charged particle in a perpendicular magnetic field

W boson Production Event



Measurement of Drift Chamber Wire Positions

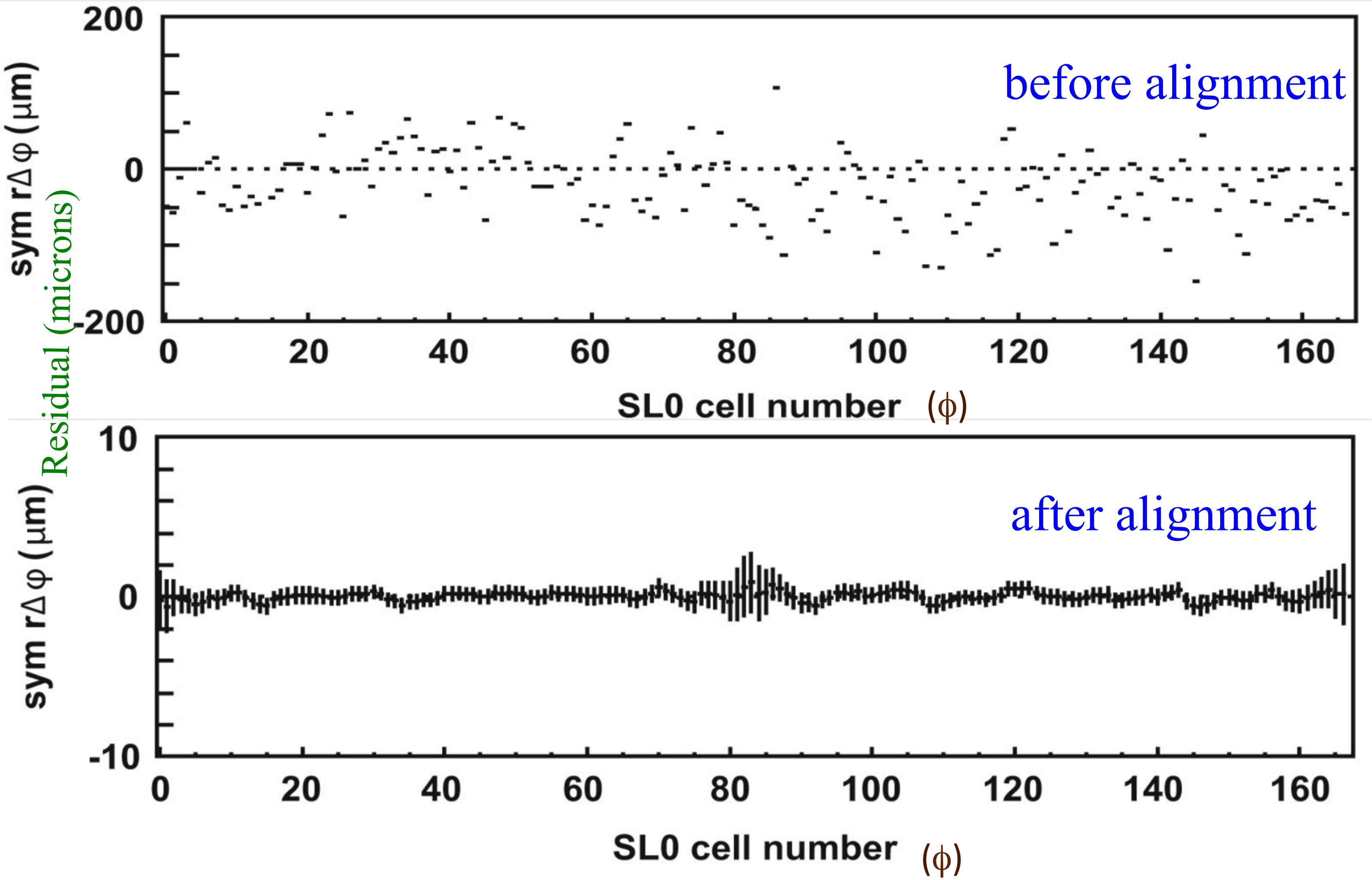
- Use cosmic rays for wire-by-wire position measurements



- Fit points on both sides simultaneously to a single helix
  (Ashutosh V. Kotwal , H. Gerberich and C. Hays, NIMA 506, 110 (2003)

Accuracy of Position Measurements

(Ashutosh V. Kotwal & Chris Hays, *NIM A* 762 (2014) pp 85-99)

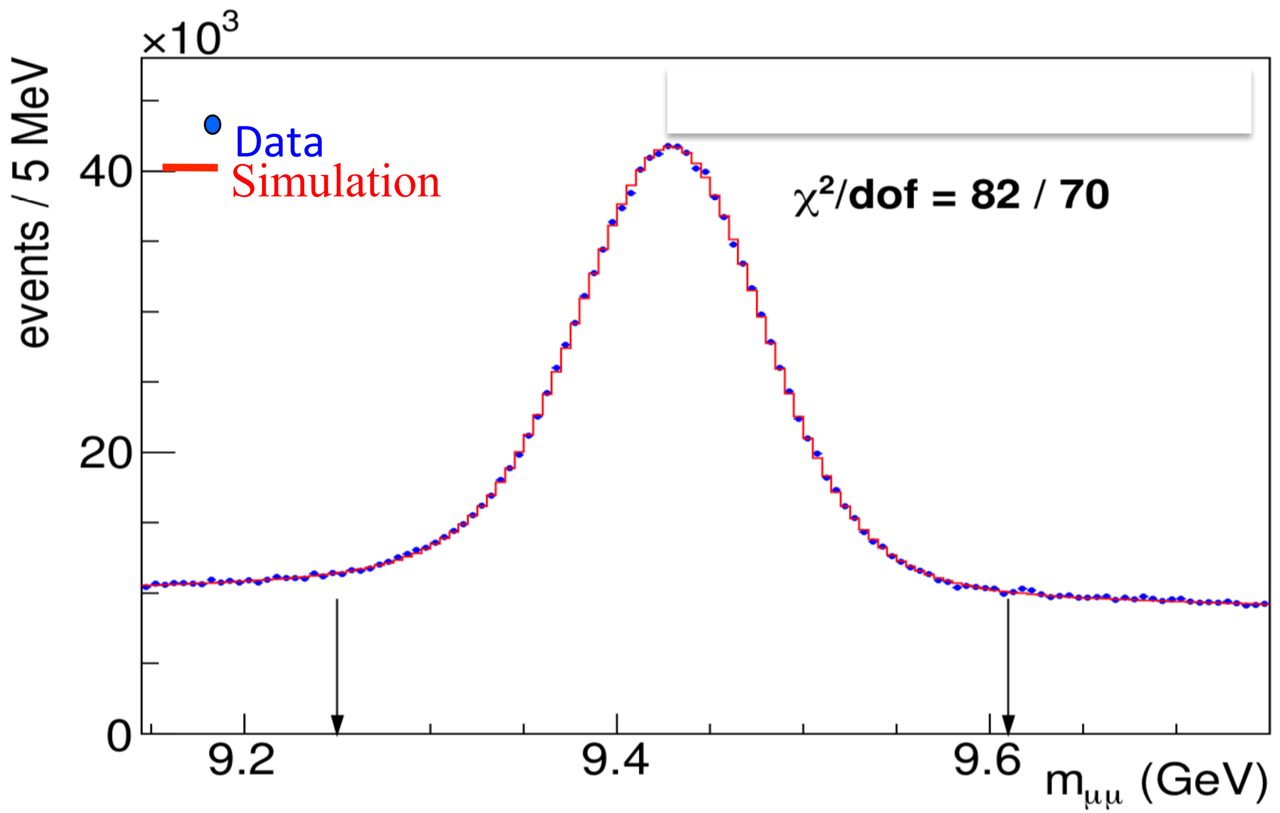


- Final position accuracy of 1 μm (initially 50 μm)

Momentum Calibration

- Well-known Υ (Upsilon) particle mass is measured and compared to previously known mass value

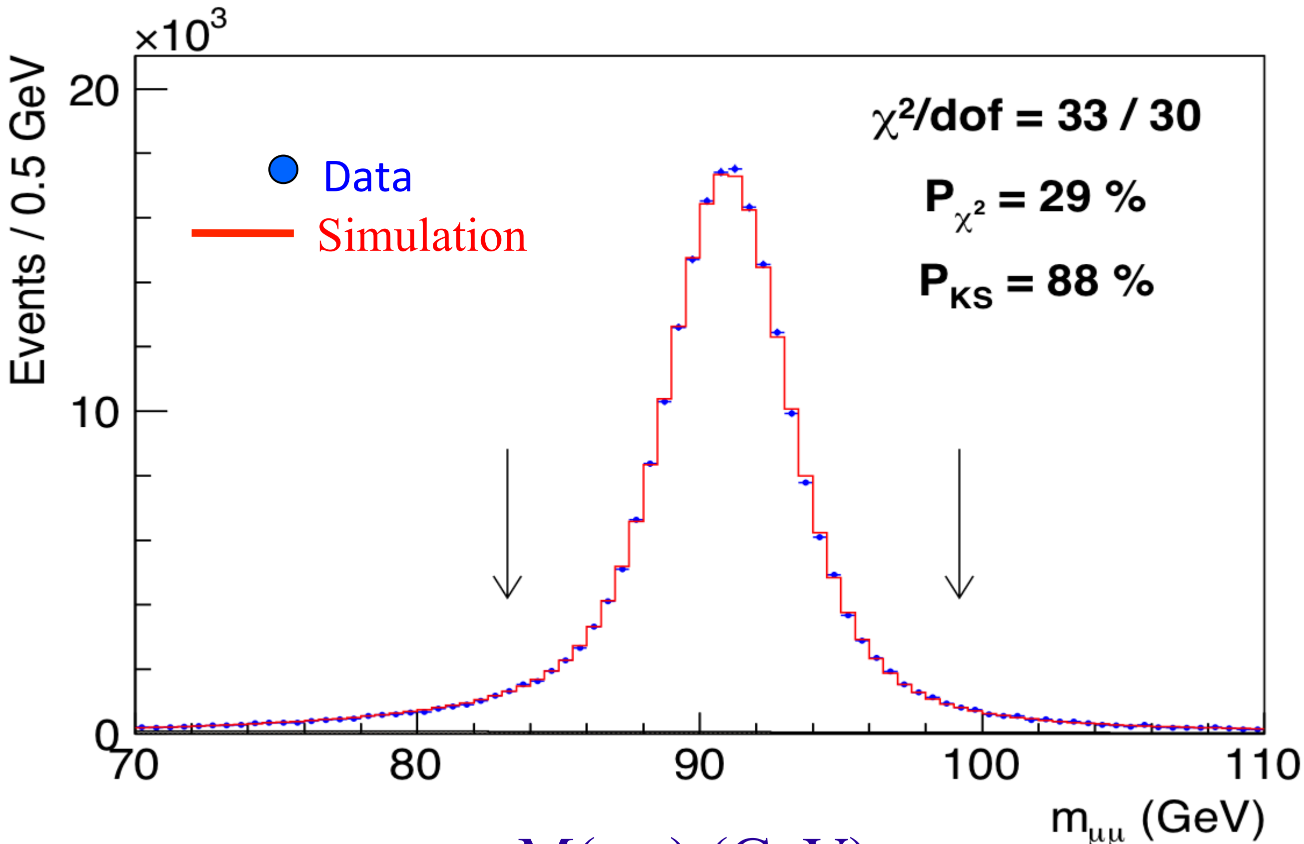
Achieved precision of 25 parts per million on momentum calibration



Proof of Momentum and Energy Calibration

- We measure the Z boson mass and it agrees with previous measurement of 91188 MeV from CERN electron-positron collider

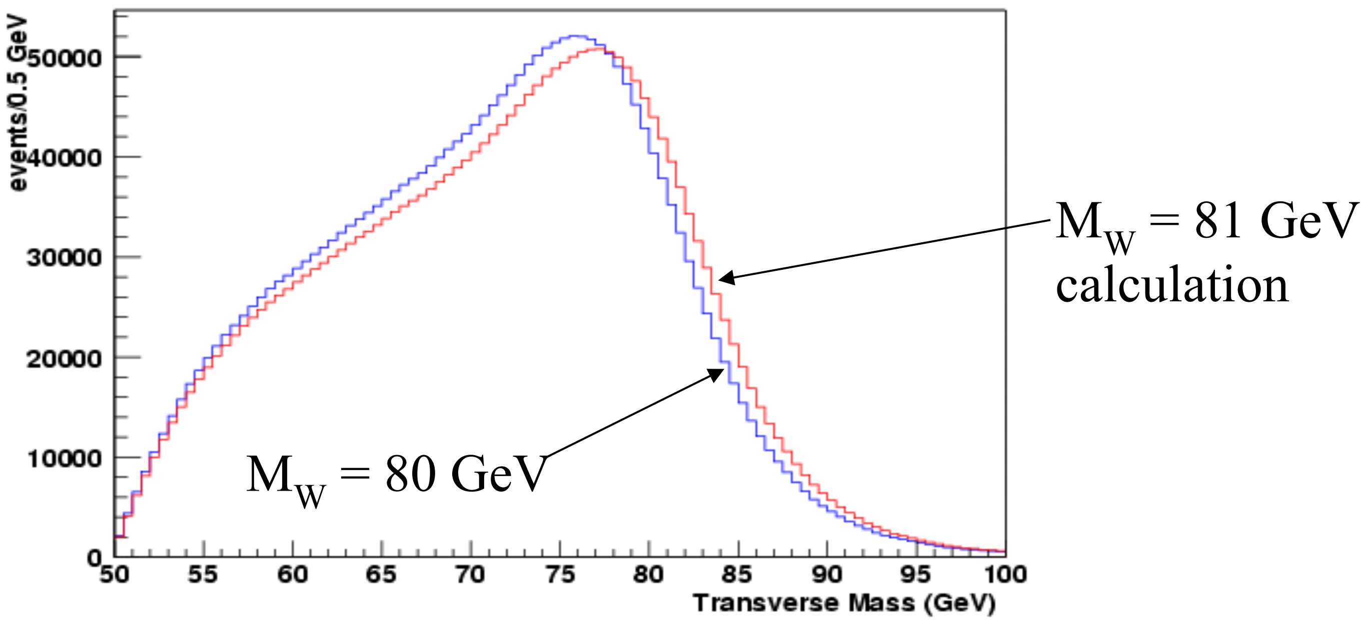
- We measure $M_Z = 91192.0 \pm 7.5_{stat}$ MeV



M(μμ) (GeV)

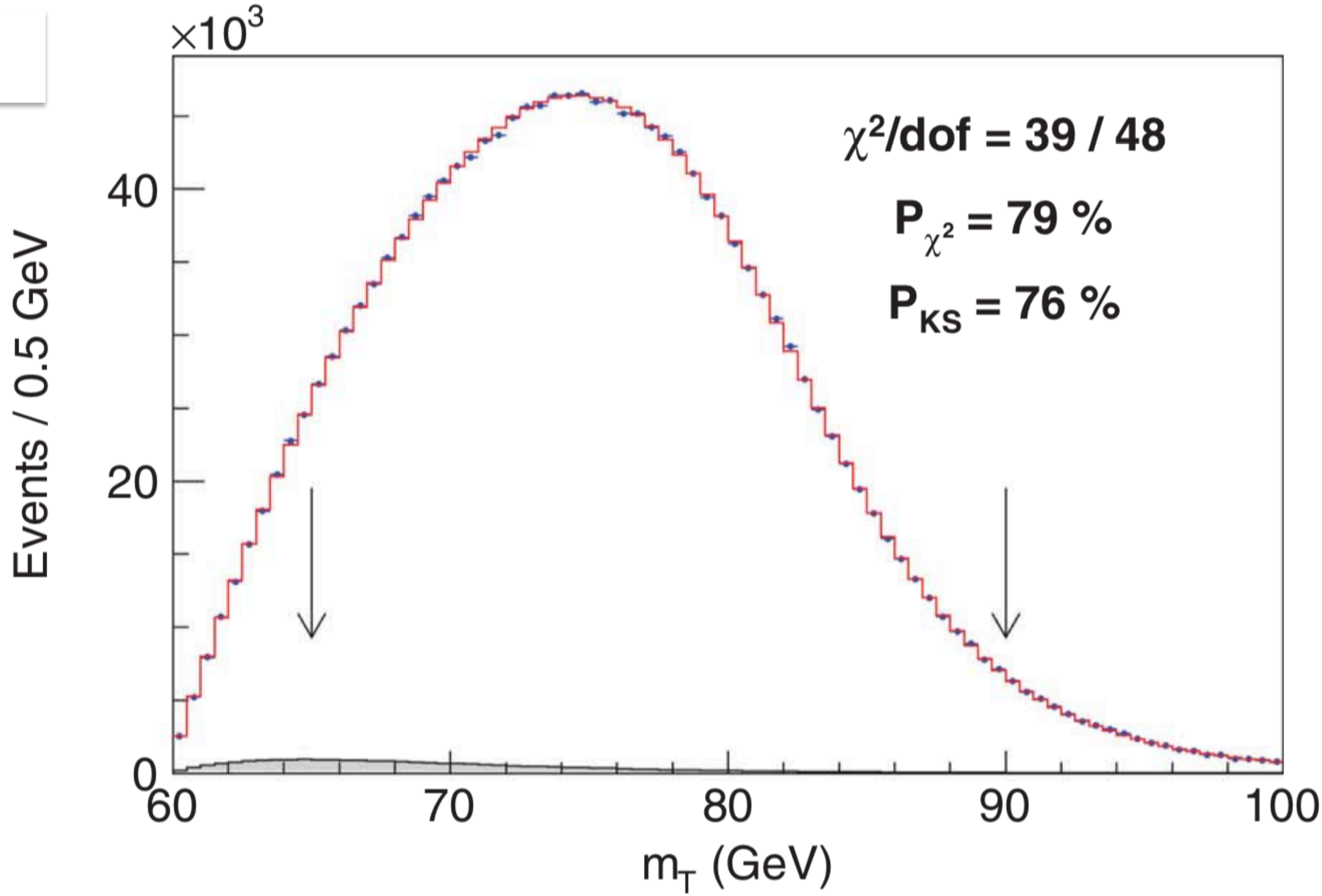
Matching Calculated and Observed Distributions

- We perform a very accurate calculation of the momentum of the electron or muon emanating from the W boson decay
- We perform a very accurate comparison of this momentum distribution between the observed data and the calculation

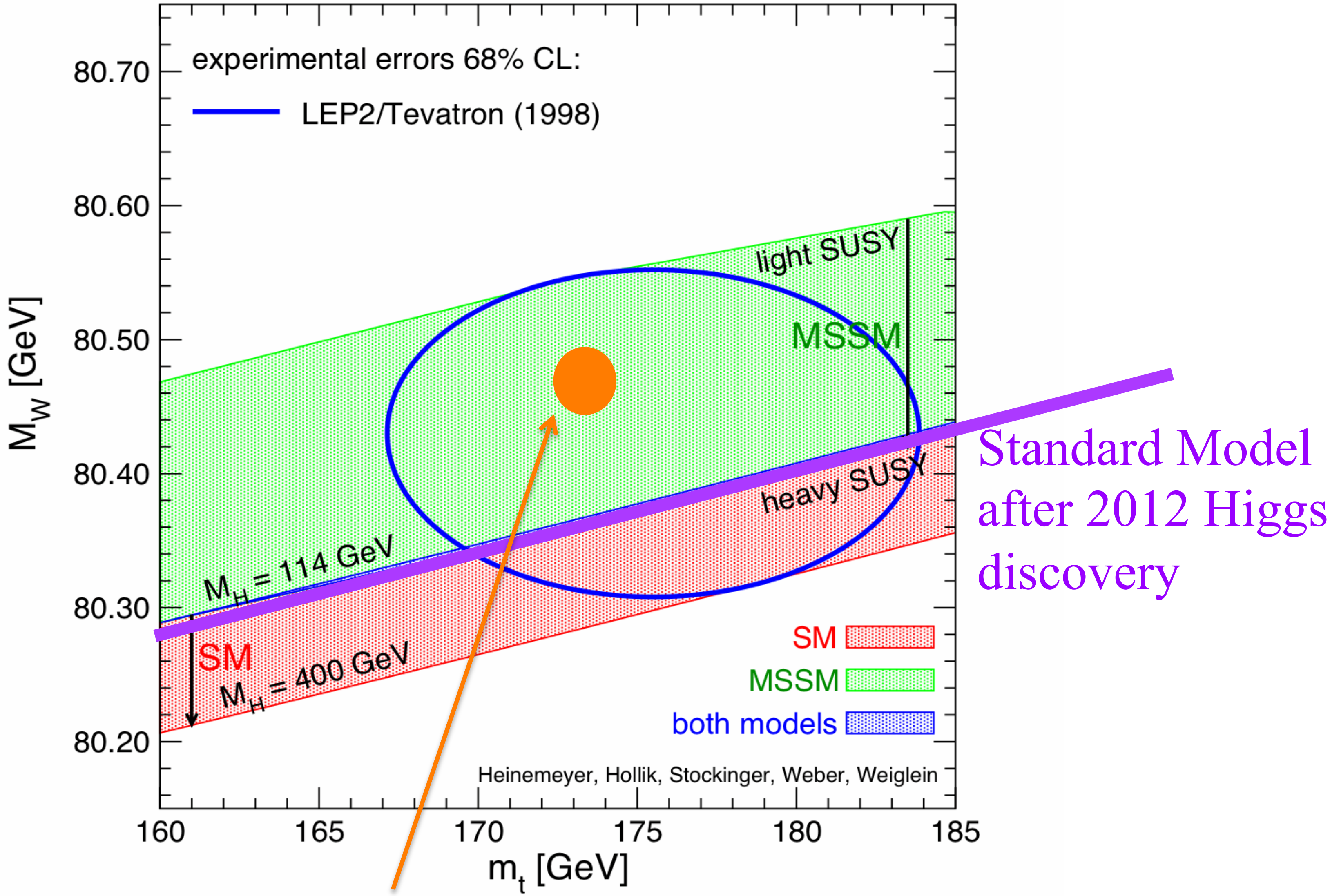


- We used advanced statistical methods to quantify this comparison and infer the W boson mass

Fit to Electron Momentum Distribution from *W* boson decay



2022 Status of M_W *vs* M_{top}

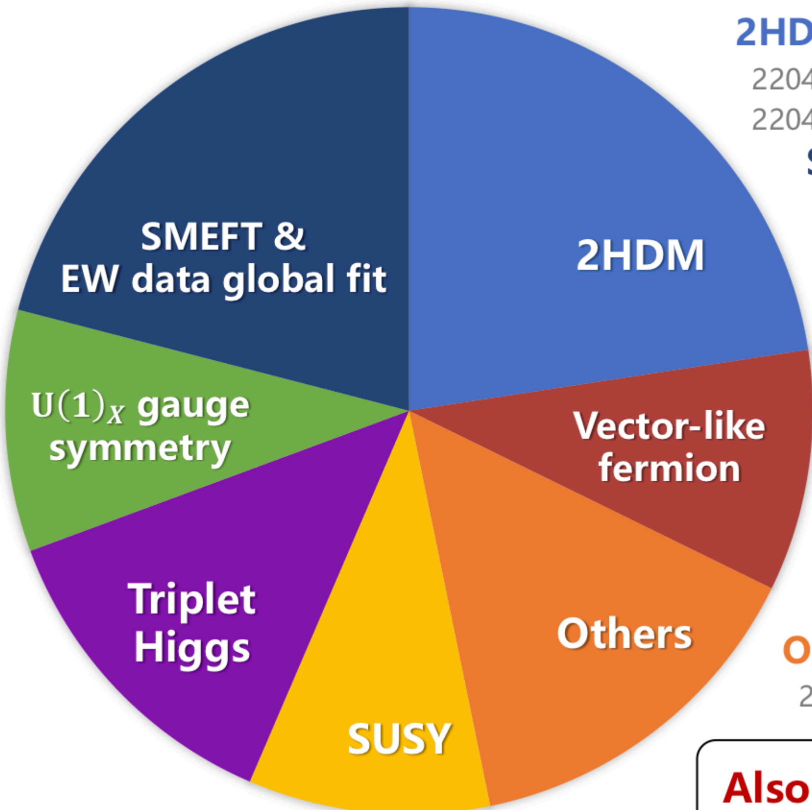


Science **376**, 170 (April 7, 2022); DOI: 10.1126/science.abk1781

Epilogue

Citations in 7 weeks since publication (April 8, 2022): 131

CDF W mass



Total number: 62*

2HDM: 14
2204.03693/03767/04834/04688/06485/05085/05269/05303
2204.05975/09001/05728/08406/08390/10338

SMEFT & EW data global fit: 13
2204.04805/05260/05284/05267/05992/05965/05965/08546
2204.08440/10130/04191/05283/04204

Triplet Higgs: 8
2204.05031/05760/07144/07511/07844/08266/10274/10315

SUSY: 6
2204.04286/04356/04202/05285/06541/07138

$U(1)_X$ gauge symmetry: 6
2204.07100/08067/09487/09024/09585/10156

Vector-like fermion: 6
2204.07022/07411/08568/09477/09671/05024

Others: 9 (Non-unitarity, leptoquark, singlet scalar, ...)
2204.04559/04672/04770/04514/05302/06327/03996/05942/09031

* Preprints as of April 25th are counted.

Also related to
dark matter, neutrino masses/seesaw, flavor violation,
muon g-2, flavor anomalies, gravitational waves, ...

The Heavyweight W boson

&

The Mystery of the Missing AntiMatter

Matter-AntiMatter Symmetry

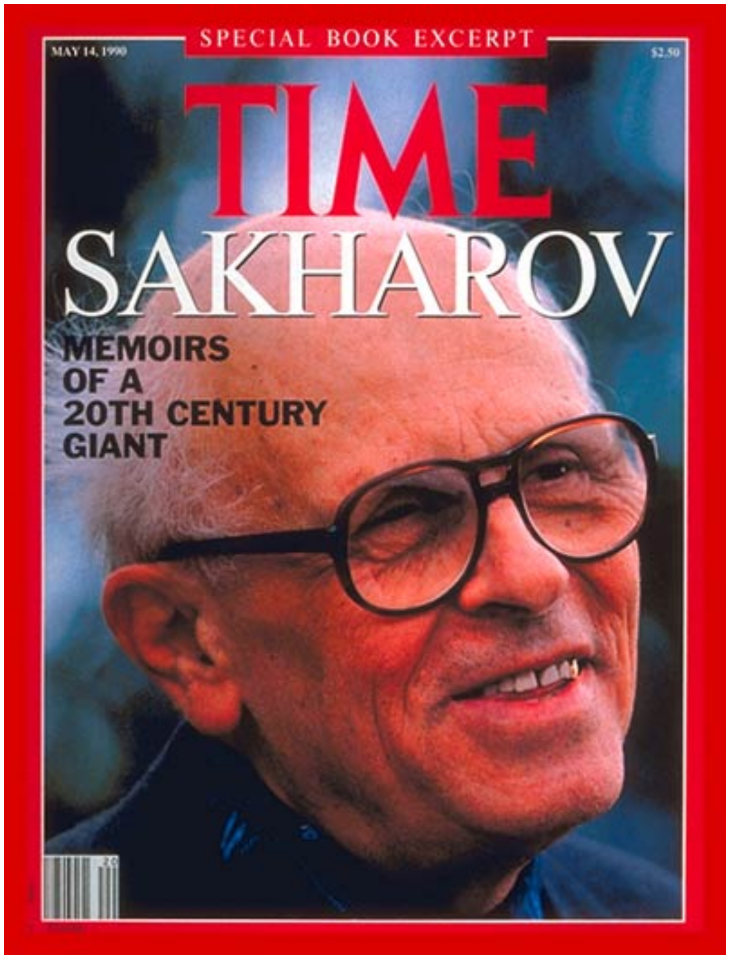
- Laws of nature have been proven to be (almost) exactly identical for matter and antimatter

- There should be equal amounts of matter and antimatter in the Universe

- Where is the *MISSING* antimatter?

- *WE* need an excess of matter over antimatter in order for galaxies, stars, planets and *us* to exist…

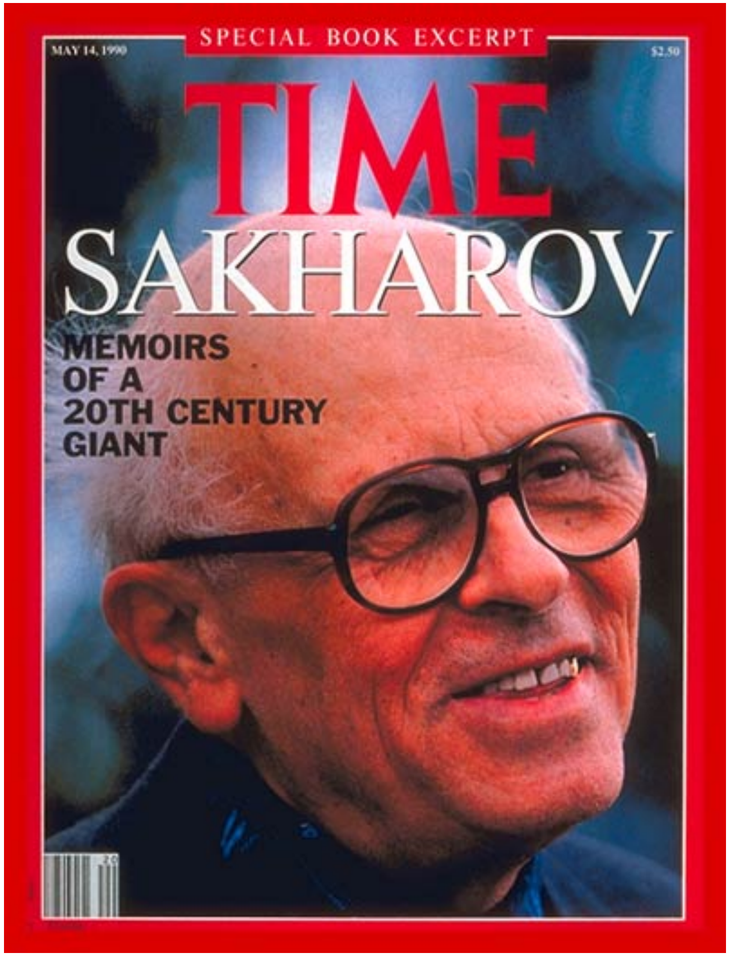
Sakharov Conditions for Matter Excess



Andrei Sakharov calculated three conditions that must exist in early Universe for creation of matter excess

The Standard Model of Particle Physics satisfies only one of these conditions

Sakharov Conditions for Matter Excess



If the Higgs boson had a partner

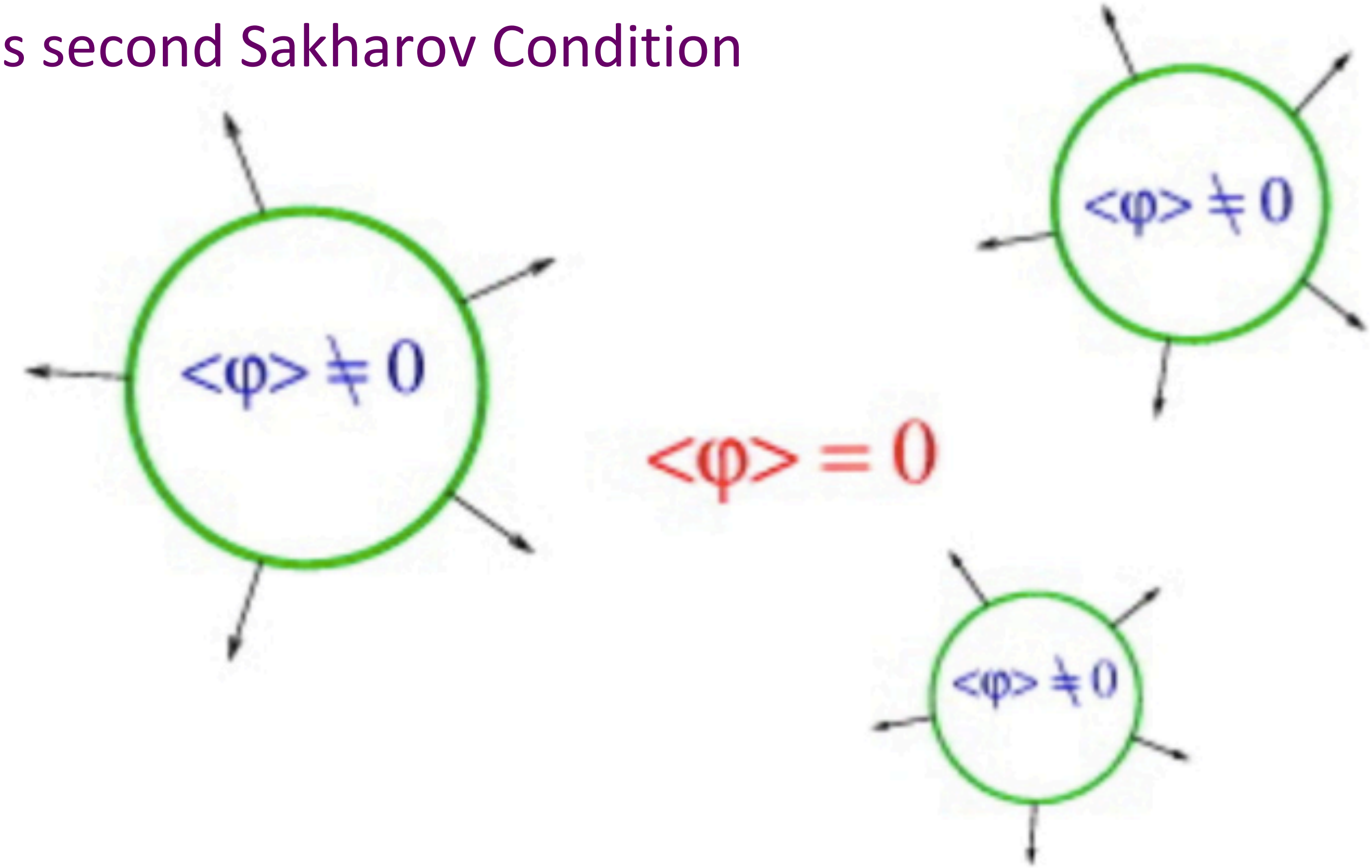
i.e. a second Higgs-like particle existed…

The second Sakharov condition can be satisfied !

Higgs Condensation after Big Bang
aided by Higgs-like Partner

Higgs droplets form and expand, filling the whole Universe

Satisfies second Sakharov Condition



Higgs Condensation after Big Bang
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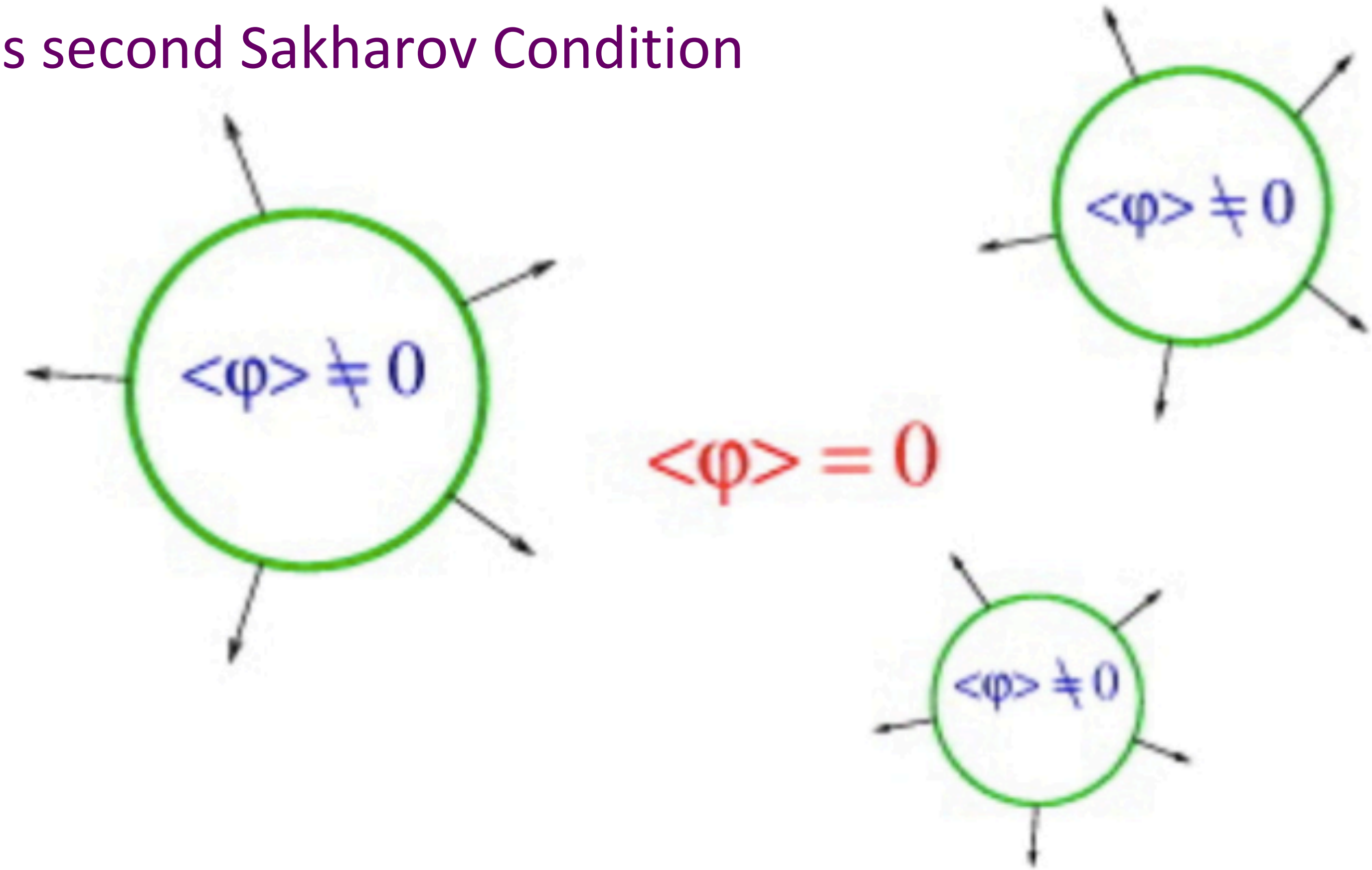


Higgs-like partner's existence increases the W boson mass by the observed 0.1%

Summary

- The *W* boson mass is sensitive to new laws of nature through quantum fluctuations

- New measurement is twice as precise as previous measurements

  - $M_W = 80433.5 \pm 9.4$ MeV

- Significant difference from Standard Model calculation of $M_W = 80{,}357 \pm 6$ MeV

  – significance of 7.0σ ($>5\sigma$ is considered scientific discovery)

Summary

- The *W* boson mass is sensitive to new laws of nature through quantum fluctuations

- New measurement is twice as precise as previous measurements

  - M_W = 80433.5 ± 9.4 MeV

- Significant difference from Standard Model calculation of M_W = 80,357 ± 6 MeV

  - significance of 7.0σ (>5σ is considered scientific discovery)
  - The Higgs boson is not the end of the story

Thank you for your attention !

Thank You!

Thank You!

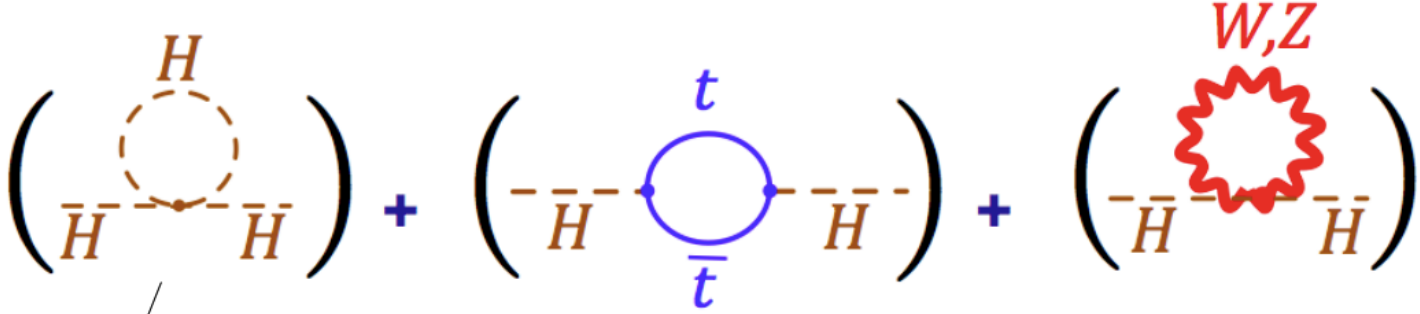
New CDF Result (8.8 fb^{-1})
Combined Fit Systematic Uncertainties

Source	Uncertainty (MeV)
Lepton energy scale	3.0
Lepton energy resolution	1.2
Recoil energy scale	1.2
Recoil energy resolution	1.8
Lepton efficiency	0.4
Lepton removal	1.2
Backgrounds	3.3
p_T^Z model	1.8
p_T^W/p_T^Z model	1.3
Parton distributions	3.9
QED radiation	2.7
W boson statistics	6.4
Total	9.4

Table 2

Next Big Question: Why is the Higgs Boson so Light?

$m_H^2 - m_{\text{bare}}^2 =$



$$\lambda \int^{\Lambda} d^4k \, (k^2 - m_H{}^2)^{-1} \sim \Lambda^2 \lambda$$

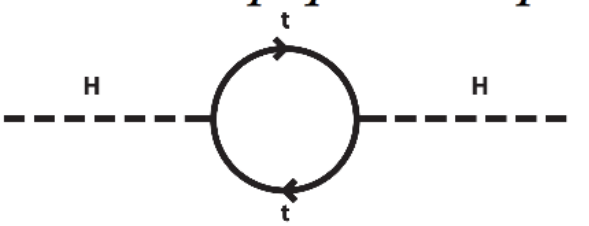
The Higgs boson ought to be a very heavy particle, naturally

However, observed $m_H << \Lambda$

Fine-tuning Problem of Higgs Boson Mass

- The divergent integral in this quantum loop must be regulated by a high-momentum cutoff, Λ, which could be the gravitational Planck energy scale $M_{planck} \sim 10^{19}$ GeV
    - Loop calculation gives Higgs boson mass correction $\sim M^2_{planck}$

Top quark loop



- physical Higgs boson mass ~ 125 GeV
- Therefore need extreme "fine-tuning" through renormalization

SuperSymmetry

- SuperSymmetry is a space-time symmetry introduced in particle physics in the 1970's

  A SuperSymmetry (SUSY) operator Q is defined by

  $$Q \,|\, j > \;=\; |\, j \pm 1/2 >$$

  ie. angular momentum of a quantum state is changed by ½ unit

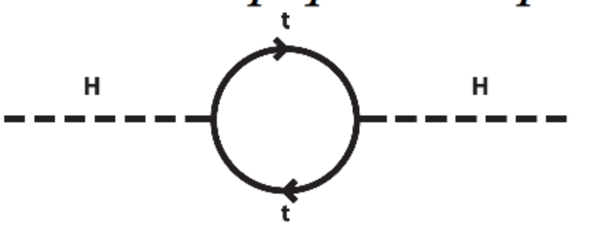
  - A (symmetry) operator linking fermions and bosons

- A minimal supersymmetric extension of the Standard Model (MSSM) has been constructed some time ago

SUSY to the Rescue

- The divergent integral in this quantum loop must be regulated by a high-momentum cutoff, **Λ**, which could be the gravitational Planck energy scale $M_{planck} \sim 10^{19}$ GeV
  - Loop calculation gives Higgs boson mass correction $\sim M^2_{planck}$

Top quark loop

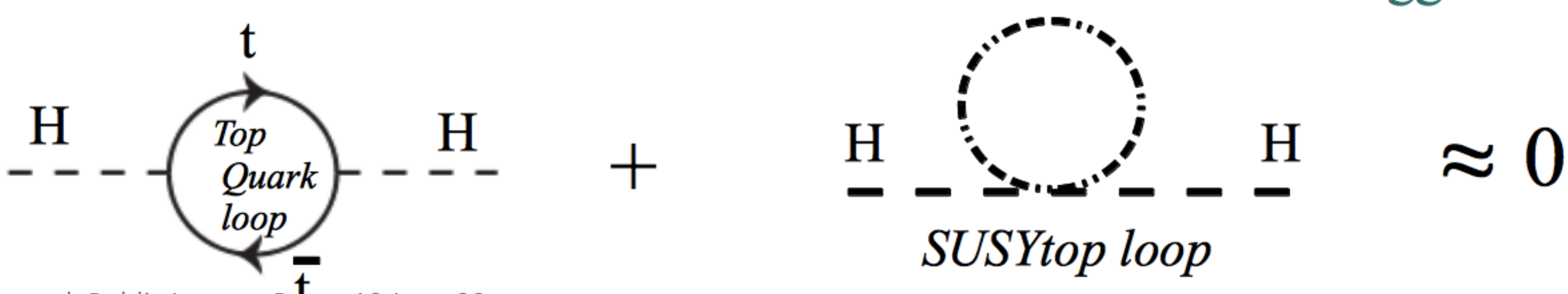


SUSY top loop

- physical Higgs boson mass ~ 125 GeV
- Therefore need extreme "fine-tuning" through renormalization
- SUSY vastly reduces fine-tuning requirement by introducing additional amplitudes containing fermion → boson loops and boson → fermion loops

SUSY to the Rescue

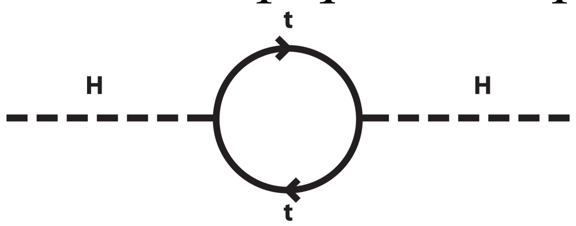
- SUSY adds bosonic (scalar) partners to fermions and fermionic partners to scalar and vector bosons
  - Higgs bosons ↔ Higgsino fermions
  - Top quark fermions ↔ supersymmetric top bosons
  - *W* and *Z* bosons ↔ Wino and Zino fermions
- By construction, all properties other than spin identical between super-partners
- Fermion loop with negative sign relative to boson loop, cancels exactly if SUSY was a exact symmetry
  - Eliminates uncontrolled radiative corrections in the Higgs sector



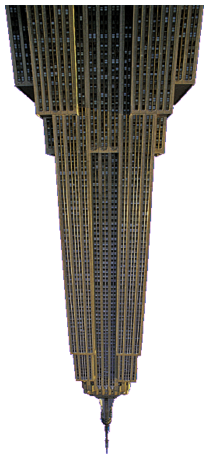
Fine-tuning Problem of Higgs Boson Mass

- The large quantum corrections must be regulated by some very high-energy physics such as energy associated with quantum gravity, $M_{planck} \sim 10^{19}$ GeV
  - Loop calculation gives Higgs boson mass correction $\sim M^2_{planck}$

Top quark loop



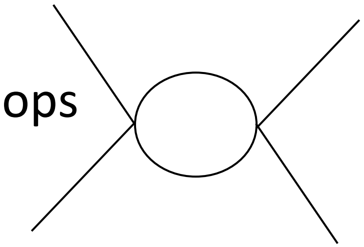
- physical Higgs boson mass ~ 125 GeV

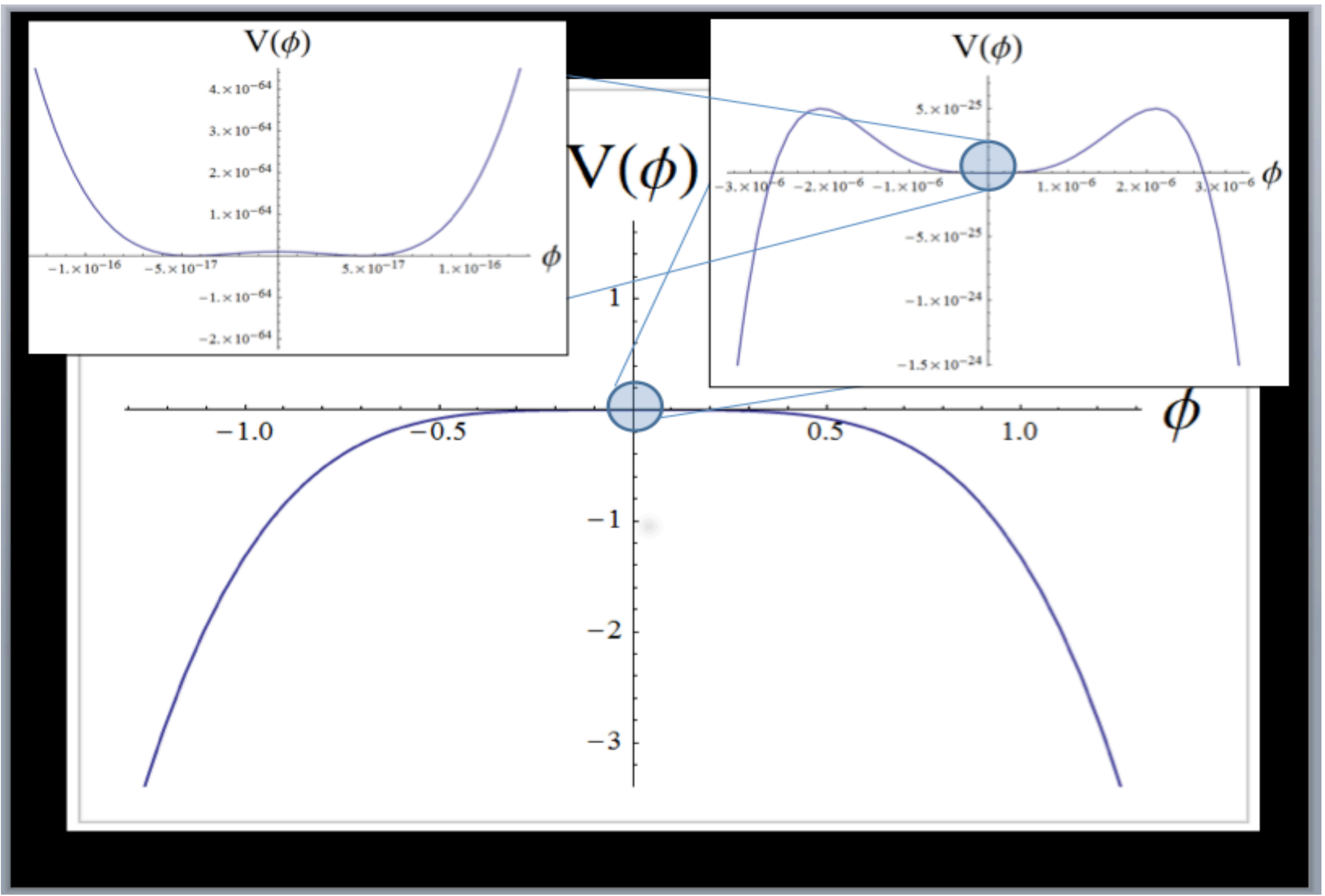


- Therefore need extreme "fine-tuning" of theoretical parameters at high energy
  - Conceptual weakness of Higgs theory as a quantum theory

Quantum Corrections to Higgs Self-Coupling

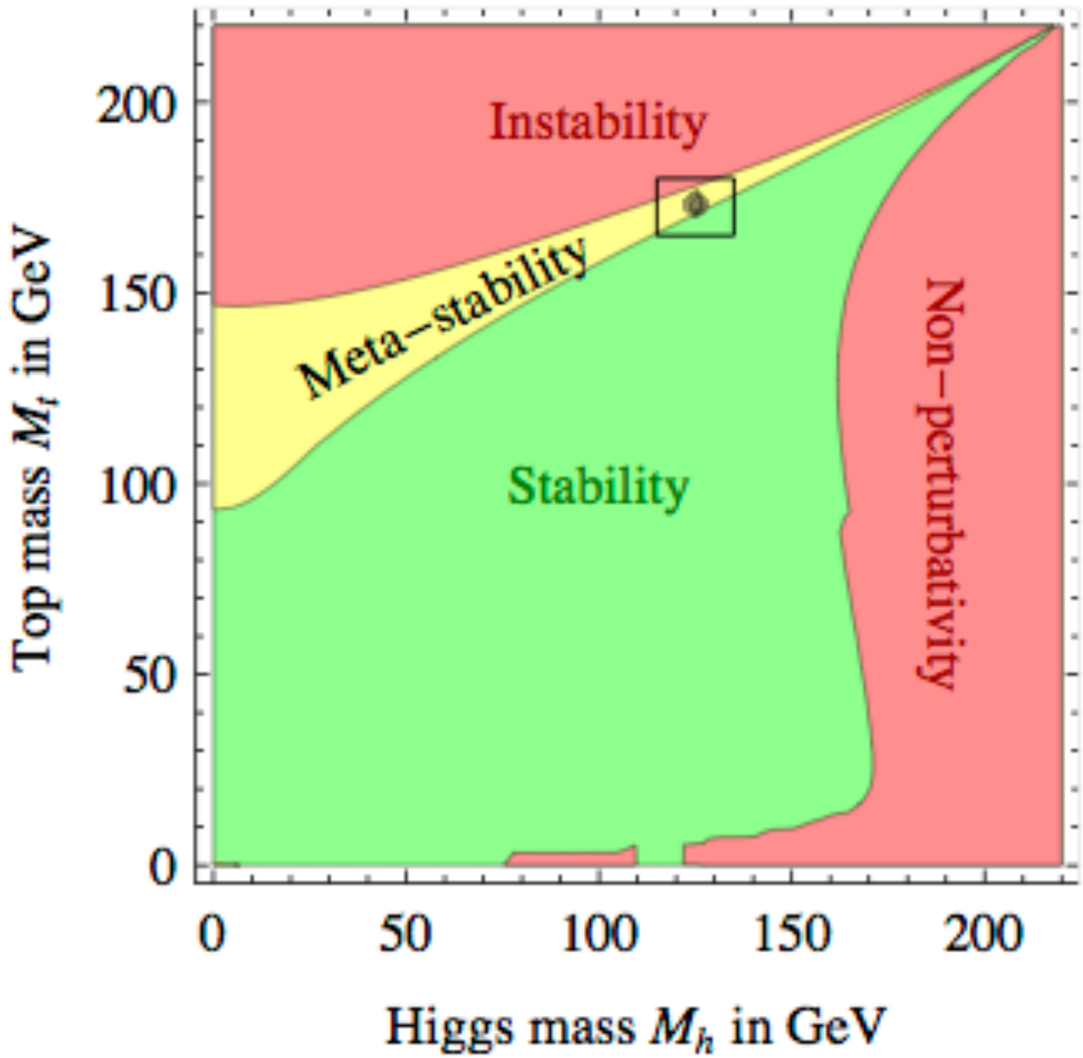
- $\lambda|\phi|^4$ receives quantum corrections from Higgs and top-quark loops



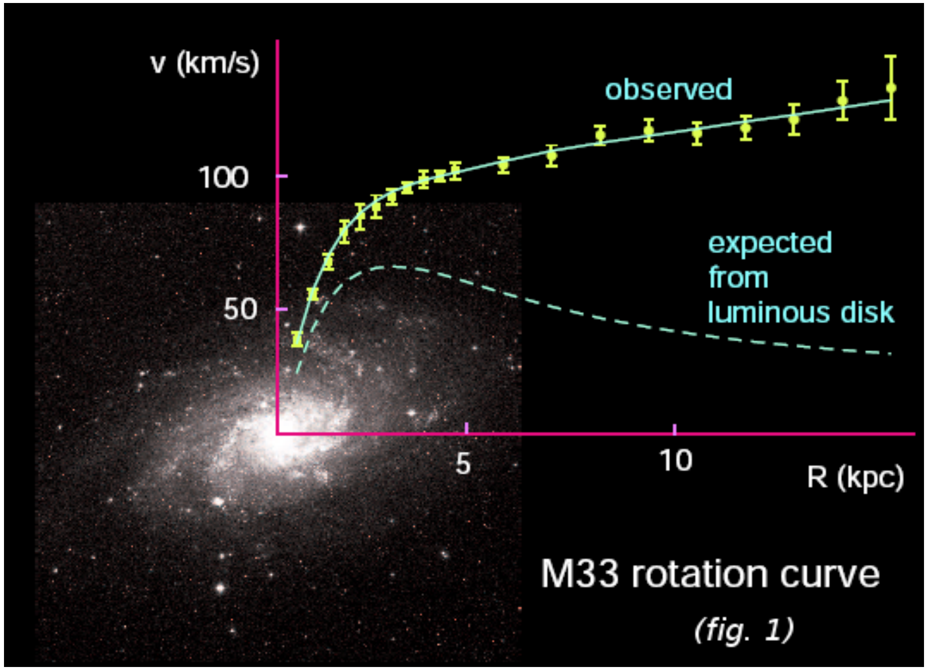


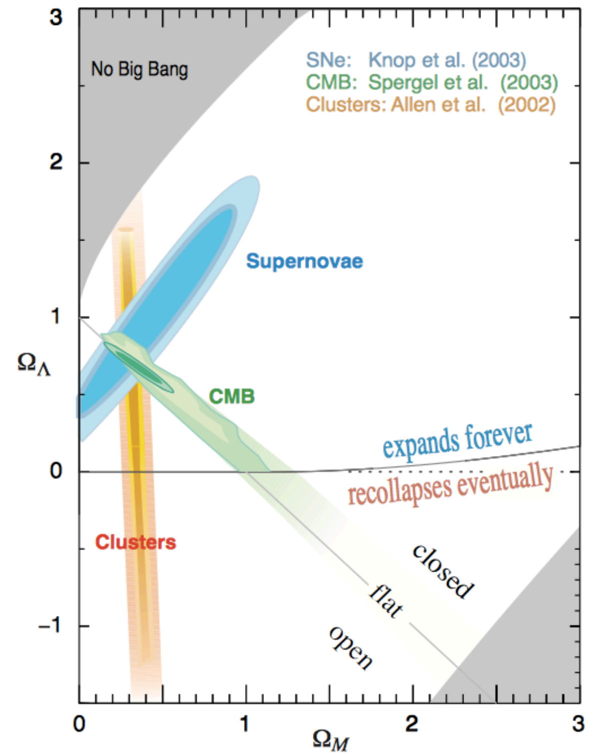
(from Paul Steinhardt)

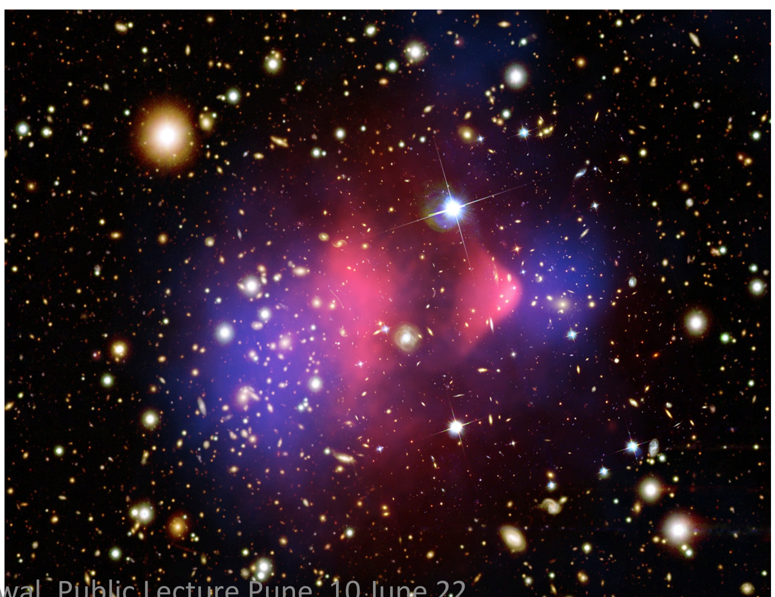
Stability of Vacuum Ground State



Dark Matter Particles







A consistent hypothesis is the existence of new particles beyond the Standard Model

Origin of Matter-Antimatter Asymmetry

POSSIBLE EXPLANATIONS...

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-9}$$ (from BBN)

⇨ **Baryogenesis at EW Scale** → **TESTABLE!**

⇨ ...

<u>SAKHAROV CONDITIONS</u> (for dynamical generation of baryon asymmetry)

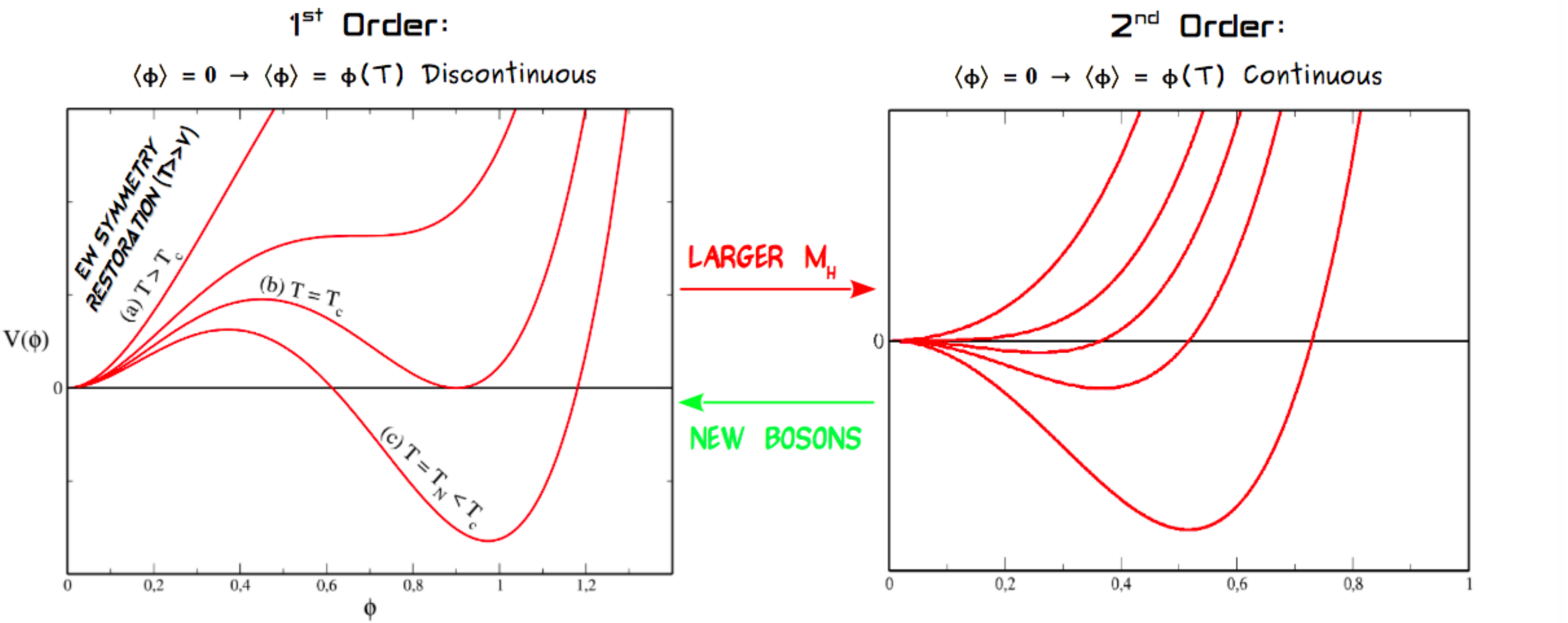
B Violation ✓ *Sphalerons*

*V. A. Kuzmin, V. A. Rubakov, M. Shaposhnikov, Phys. Lett. B**155** (1985) 36*

C/CP Violation ✗ *not enough*

Departure from Thermal Equilibrium ✗ *not enough*

Baryon Asymmetry and Higgs Phase Transition



In the SM (m_h = 125 GeV) EW Phase Transition Smooth CrossOver

K. Kajantie, M. Laine, K. Rummukainen, M. Shaposhnikov, Phys. Rev. Lett. **77** (1996) 2887

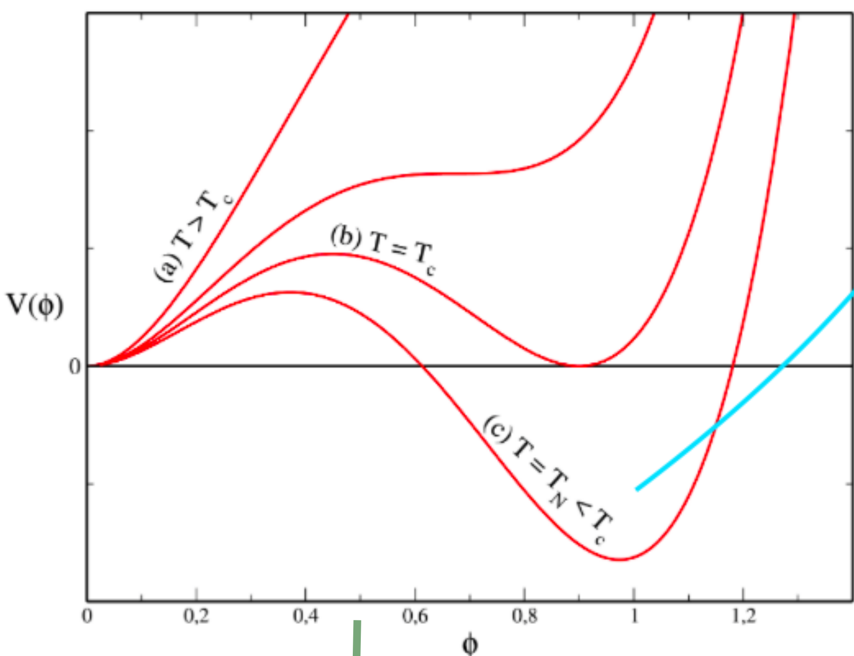
Beyond Standard Model physics needed to create matter excess

Standard Model cannot create matter excess

1st Order Electroweak Phase Transition Induced by Additional Higgs-like Particle

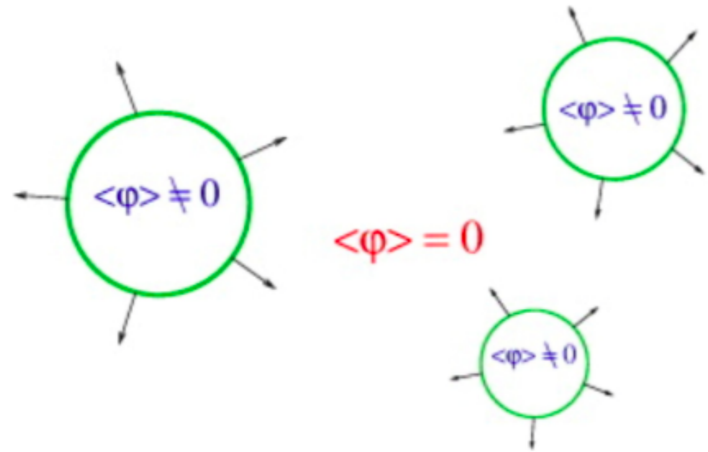
1st Order:

$\langle\phi\rangle = 0 \rightarrow \langle\phi\rangle = \phi(T)$ Discontinuous



Nucleation of True Vacuum Bubbles
(in False Vacuum Sea)

J. S. Langer, Ann. Phys. ***54*** *(1969) 258*
S. R. Coleman, Phys. Rev. D ***15*** *(1977) 2929*
A. D. Linde, Nucl. Phys. B ***216*** *(1983) 421*



SUDDEN CHANGE IN HIGGS VEV

Satisfies crucial Sakharov condition
for creating excess matter in the Universe

CDF M_W *vs* m_{top}

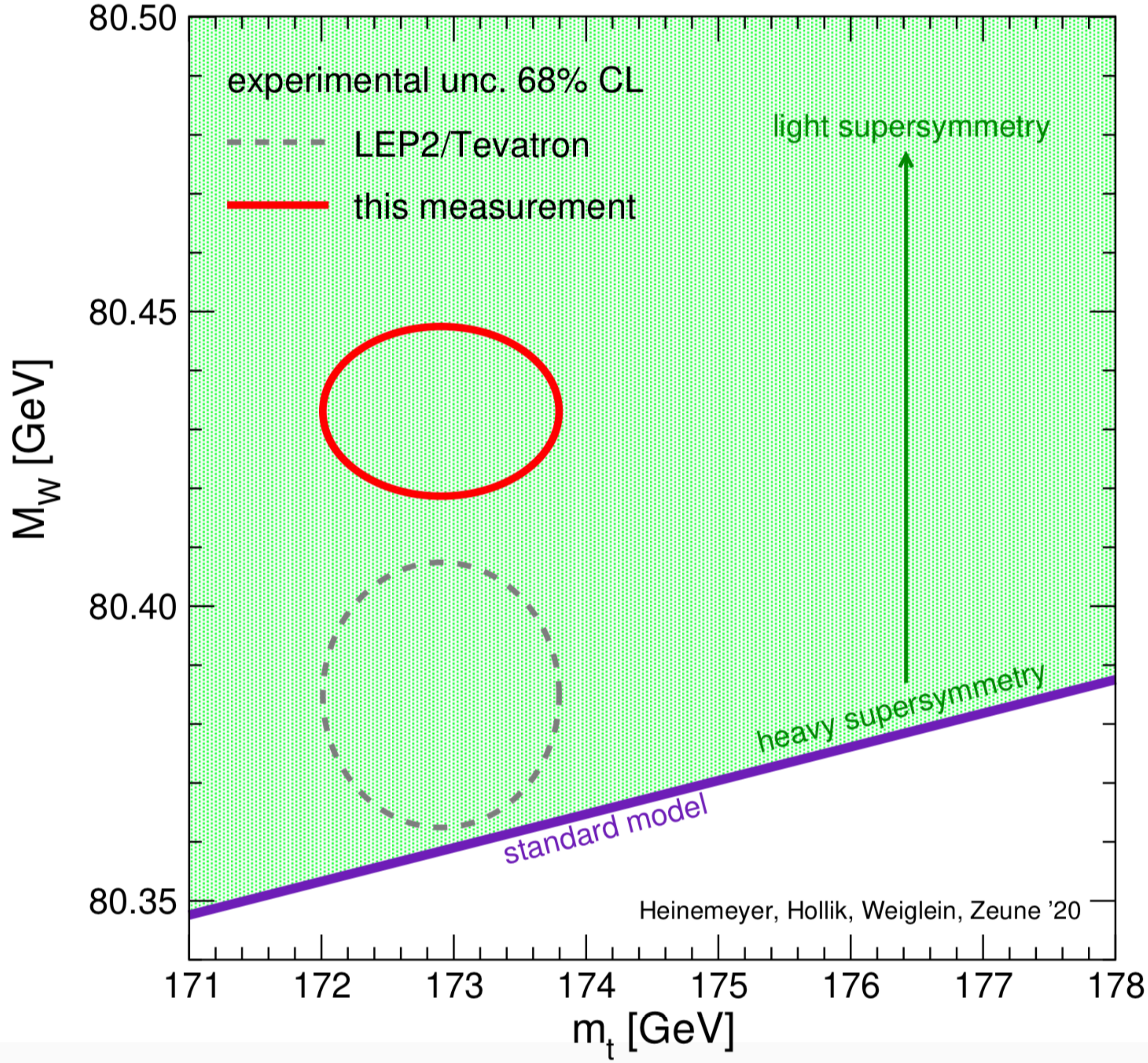
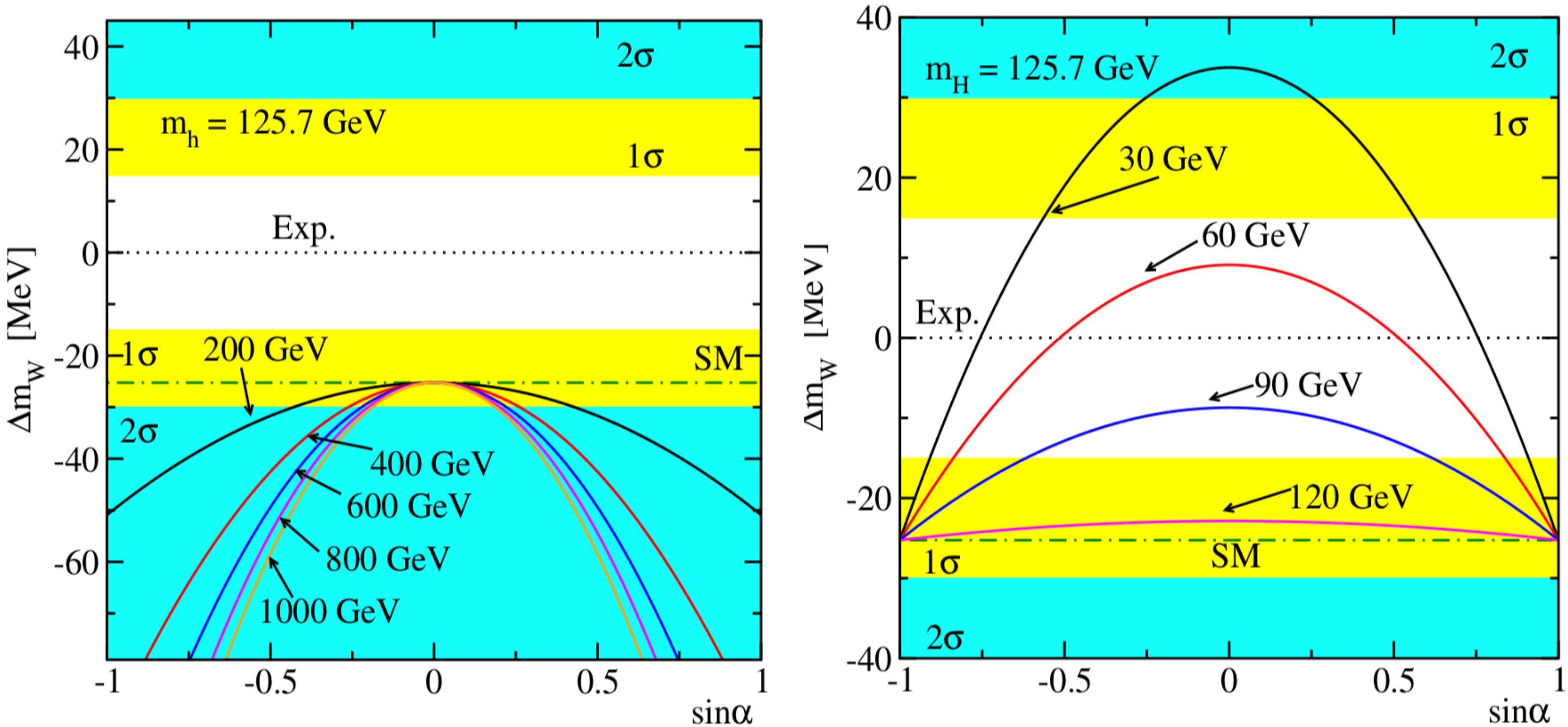


Fig. 1

Understanding Tevatron-LHC correlations and combination with ATLAS in progress

Single Scalar Extension of Higgs Sector

Inclusion of an additional scalar particle with no SM charges, which mixes with the Higgs boson



D. López-Val and T. Robens, Phys. Rev. D 90, 114018 (2014)

W Boson Mass Measurements from Different Experiments

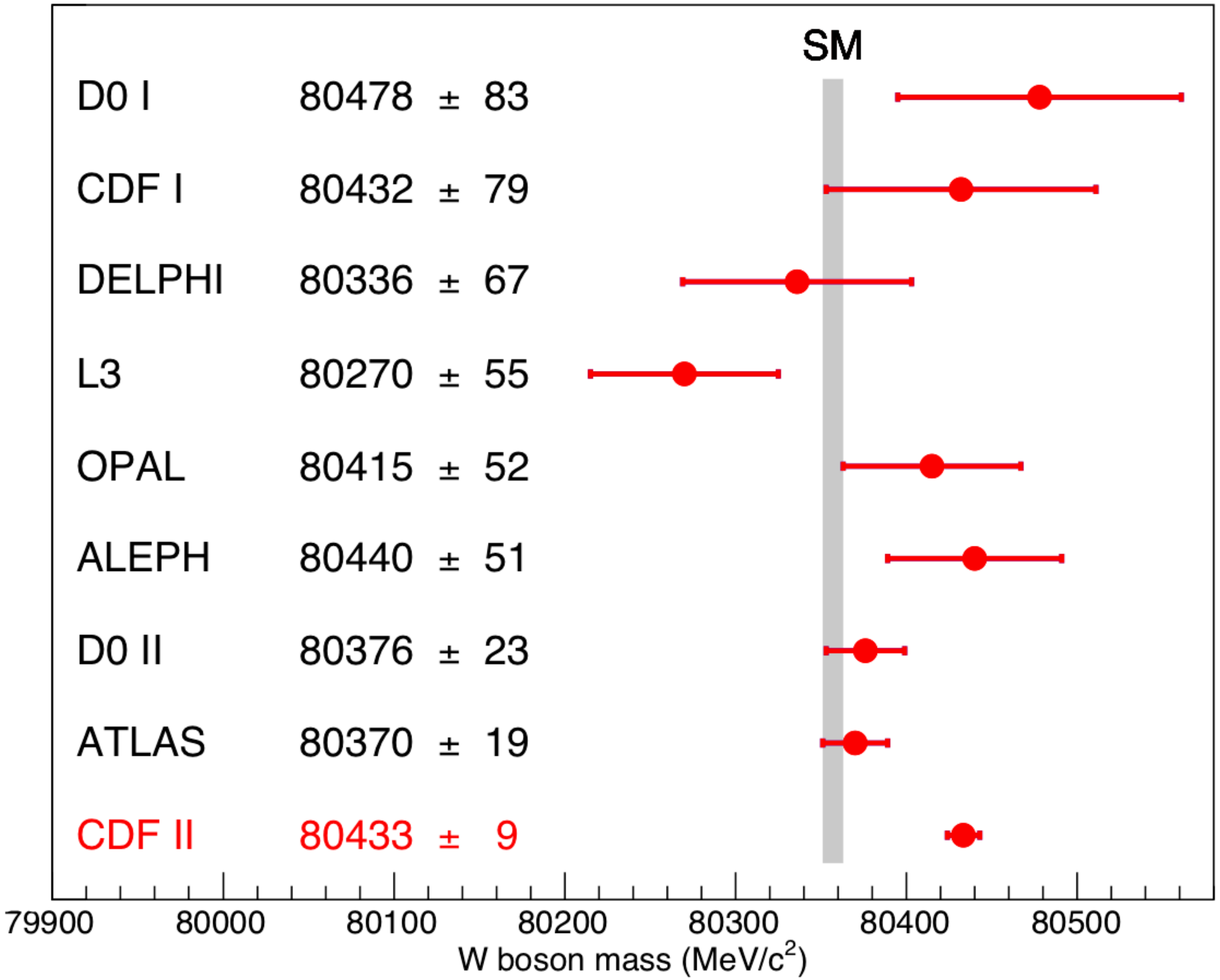


Fig. 5

SM expectation: $M_W = 80{,}357 \pm 4_{\text{inputs}} \pm 4_{\text{theory}}$