The Birth, Life, and Death of Stars

The Osher Lifelong Learning Institute
Florida State University

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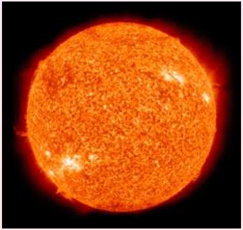
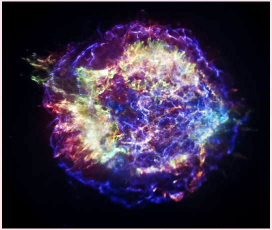
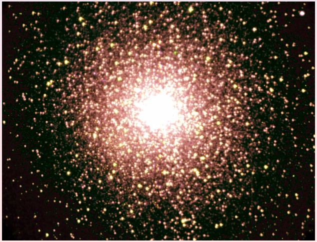
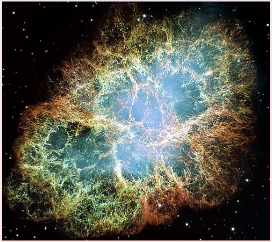
Schedule:	September 29 – November 3
Time:	11:30am – 1:30pm
Location:	Pepper Center, Broad Auditorium





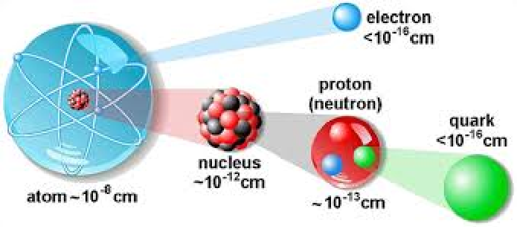
Ten Compelling Questions

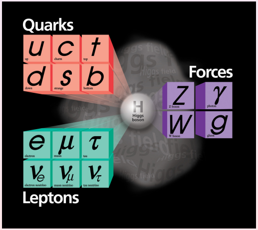
- What is the raw material for making stars and where did it come from?
- What forces of nature contribute to energy generation in stars?
- How and where did the chemical elements form? ⋆
- How long do stars live?
- How will our Sun die?
- How do massive stars explode? ⋆
- What are the remnants of such stellar explosions?
- What prevents all stars from dying as black holes?
- What is the minimum mass of a black hole? ⋆
- What is role of FSU researchers in answering these questions?

Particle Physics: The Physics of the Very Small

- What are the fundamental building blocks of matter?
  Six quarks and six leptons – arranged in 3 families/generations
- What are the interactions between them?
  Electromagnetic (photon) – physics of charges, magnets, light
  Weak ($W^{\pm}$ and Z) – physics of radioactive decays
  Strong (gluons) – physics that binds quarks inside protons/neutrons
  Gravitation (graviton?) – physics that binds "massive" objects
- How do particles acquire mass?
  Via the "Higgs mechanism" – Discovery announced July 4, 2012

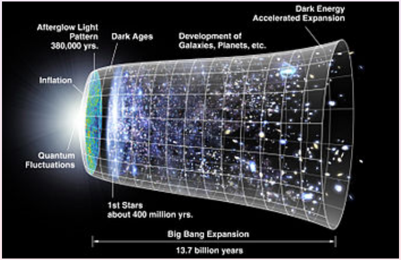


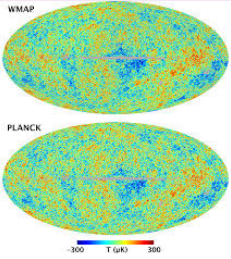


The 2013 Nobel Prize in Physics was awarded to Englert and Higgs

Astrophysics: The Physics of the Very Big

- The Universe was created about 13.7 billion years ago
- *"Big Bang Theory"* has been enormously successful:
  "Hubble's Law" – distance to a galaxy correlated to its recessional velocity
  "First Three Minutes" – Hydrogen, Helium, and traces of light nuclei formed
  "CMB" – Afterglow light when Universe was 380,000 years old
- Stars and galaxies form from H and He clouds about 1 billion years after Big Bang
- Giant molecular clouds become fertile ground for stellar nurseries and star formation
- Meteorites and radioactive dating suggest that our Sun is about 4.6 billion years old
- Our Sun is (most likely) a 3rd generation star containing small traces of O,C,Ne,Fe

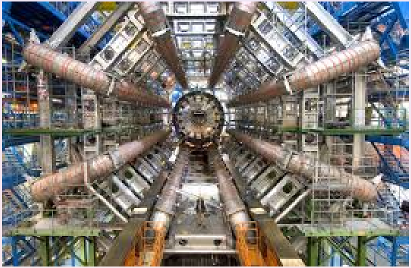


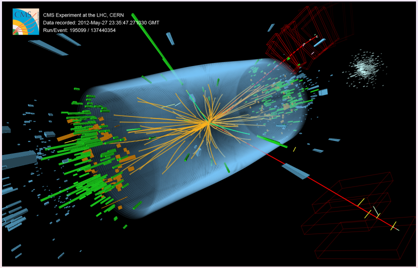


Stars embody a unique synergy between the very small and the very big!

The Large Hadron Collider at CERN

- Located at the Franco-Swiss border near Geneva
- A mammoth 27 kilometer-ring particle accelerator
- The Higgs particle discovered on July 4, 2012
- Hope to elucidate the nature of dark matter

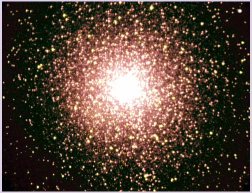




Now sit down, relax and let us watch a 5-minute movie courtesy of the LHC on the very small and the very big!

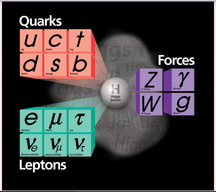
A Star is Born: Synergy between the very small and the very big!

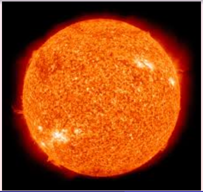
- Star-forming regions "Stellar Nurseries" form in the interstellar space
  Giant molecular clouds develop from gravitational attraction
- Gravitational (potential) energy is converted into thermal (kinetic) energy
- A protostar achieves stardom when the core temperature reaches 10 million K
  Protons overcome their Coulomb repulsion and fuse



$$p + p \to d + e^{+} + \nu_e$$
$$p + d \to {}^3He + \gamma$$
$${}^3He + {}^3He \to {}^4He + p + p$$

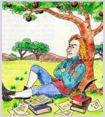
- The ubiquitous proton-proton chain: converting 4 protons into ^{4}He
  $4M_p - M_{^4He} = (6.690 - 6.644) \times 10^{-27}\mathrm{kg} \to E = Mc^2$
- All 4 fundamental interactions (G, EM, W, and S) essential to achieve stardom





The Gravitational Interaction

- The oldest and the most evident of the four fundamental forces
- Isaac Newton (1643) view: $F = G\frac{mM}{r^2}$ $\quad (g \equiv GM_{\oplus}/R_{\oplus}^2 = 9.81 \mathrm{m/s^2})$



- Always attractive!
- Proportional to the product of the masses
- Inversely proportional to the square of their separation
- Explains the behavior of planets, stars, and galaxies
- Breaks down when $v_{\rm esc} = \sqrt{\frac{2GM}{R}} \lesssim c$

- Albert Einstein (1879) view: $G_{\mu\nu} + g_{\mu\nu}\Lambda = \frac{8\pi G}{c^4} T_{\mu\nu}$

- Always attractive! (although there is Λ)
- Gravity is a property of spacetime; not of masses!
- Even massless objects will interact gravitationally
  Confirmed by Eddington in 1919 during solar eclipse
- Predicts the existence of black holes
- Essential for the study of neutron stars and black holes

Without gravity, interstellar material would not "clump"
Hence, no stars, no planets, and no life!

The Electromagnetic Interaction

- Together with gravity, it has a clear manifestation in every day life
  Physics of charges and magnets instead of masses
- Charles-Augustin de Coulomb (1736) view: $F = \frac{qQ}{r^2}$

  - Attractive(Repulsive) between opposite(like) charges
  - Proportional to the product of the charges
  - Inversely proportional to the square of their separation
  - Gravity irrelevant for elementary particles:

    $$F_{\rm G}/F_{\rm EM} = \frac{Gm_e^2}{\hbar c\alpha} = \frac{m_e^2}{\alpha m_{\rm P}^2} \approx 10^{-42} \text{ (at all distances)}$$

- James-Clerk Maxwell (1831) view: $\partial_\mu F^{\mu\nu} = \frac{4\pi}{c} J^\nu$

  - Unification of Electricity/Magnetism: Electromagnetism
  - Predicts the existence of electromagnetic waves: Light!
    Light are EM waves traveling trough vacuum at c
  - Ideal framework for Einstein's theory of special relativity
  - Every object in the Universe emits EM waves

Electromagnetic waves are the language of the stars!
Without them we could not communicate with the Universe

The Weak Interaction

- Unlike gravity and EM, it has no clear manifestation in every day life
  Range of the interaction is only 10^{-18} m
- Responsible for radioactive decays ($n \to p + e^- + \bar{\nu}_e$)
  Only interaction that can transform one particle into another
  Only interaction – besides gravity – that neutrinos participate in
- Glashow (1932), Salam (1926), and Weinberg (1933):

  - Shared 1979 Nobel Prize in Physics
    For unifying electromagnetic and weak interactions
  - Interaction mediated by 3 very massive particles
    $W^{\pm}$ and Z; about 90 times the proton mass
  - The Higgs mechanism essential for EW unification
- Rubbia (1934) and van der Meer (1925):

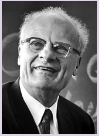
  - Shared 1984 Nobel Prize in Physics
    For discovering the "communicator" of the weak force
  - As the Higgs boson, discovery was done at CERN!

Without the weak interaction, stars would not shine!

The Strong Interaction

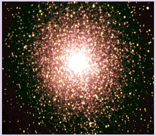
- Unlike gravity and EM, it has no clear manifestation in every day life
  Range of the interaction is only 10^{-15} m
- Responsible for binding protons and neutrons inside atomic nuclei
- The strongest of all 4 fundamental forces
  Must overcome enormous Coulomb repulsion
- Gross (1941), Politzer (1949), and Wilczek (1951):

  - Shared 2004 Nobel Prize in Physics
    For elucidating the theory of the strong interaction
  - Fundamental theory between quarks and gluons
    Only quarks participate in the strong interaction
    Interaction mediated by 8 massless gluons
  - Neither quarks nor gluons exist in isolation
    Permanently confined within protons/neutrons
  - Strong force between nucleons is a "residual" force
- Hans Bethe (1906):

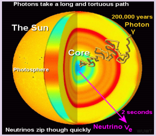


  - 1967 Nobel Prize in Physics
    For elucidating the role of nuclear reactions
    in energy production in stars

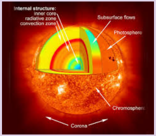
The proton-proton chain revisited ...



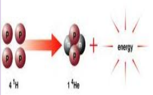
- Gravitational Interaction
  Gravity promotes clumping of primordial *H* and *He*
  Gravitational energy converted into thermal energy
  Core temperature must at least reach 10 million K



- Weak Interaction: $(p + p \to d + e^{+} + \nu_e)$
  p convert to n – which bind into deuterons
  Neutrinos powerful probes of the stellar interior
  Solar neutrinos triggered a revolution in Physics



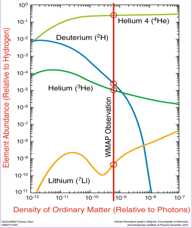
- Electromagnetic Interaction: $(p + d \to {}^{3}He + \gamma)$
  Unlike neutrinos, photons interact many times
  It takes a very long time for photons to leave the Sun
  Solar spectrum suggests a surface T of 5,778K



- Strong Interaction: $({}^{3}He + {}^{3}He \to {}^{4}He + p + p)$
  By far the strongest of all four fundamental forces
  Responsible for energy generation in stars
  Million times more energy to break ${}^{4}He$ than *H*-atom

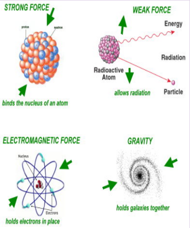
Answer to 2 of the 10 Compelling Questions

- What is the raw material for making stars and where did it come from?



  – Primordial Hydrogen and Helium (and ...)
  – Created 3 minutes after the Big Bang
  (*"The First Three Minutes"* by Steven Weinberg)

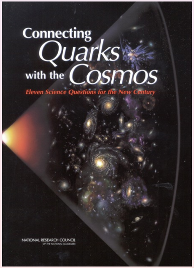
- What forces of nature contribute to energy generation in stars?



  – All 4 fundamental forces are essential (Gravitational, EM, Weak, and Strong)

From the Very Small to the Very Large

The Very Small	The Very Large
$m_e = 9.109 \times 10^{-31}$ kg $m_p = 1.672 \times 10^{-27}$ kg $R_p = 0.877 \times 10^{-15}$ m	$M_\oplus = 5.972 \times 10^{24}$ kg $M_\odot = 1.988 \times 10^{30}$ kg $R_\odot = 6.995 \times 10^{8}$ m
$1\,\mathrm{fm} = 10^{-15}$ m $1\,\mathrm{eV} = 1.602^{-19}$ J	$1\,\mathrm{pc} = 3.26\,\mathrm{ly} = 3.086 \times 10^{16}$ m $1\,\mathrm{J} = 1\,\mathrm{Joule} = 2.39 \times 10^{-4}$ kcal
$m_p c^2 \approx 10^9$ eV	$GM_\odot^2/R_\odot \approx 10^{41}$ J
$(4m_p - {}^4\mathrm{He})c^2 = 2.771 \times 10^5$ eV	$M_\odot/m_p = 1.189 \times 10^{57}$



The Solar Luminosity

$L_\odot = 3.846 \times 10^{26}$ W (J/s)

The Sun: Our Own Star

- $M_\odot = 1.988 \times 10^{30}\,\mathrm{kg} \approx 300,000\, M_\oplus$
- $R_\odot = 6.995 \times 10^{8}\,\mathrm{m} \approx 100\, R_\oplus$
- $T_\odot = 5,778\, K \; (T_{\mathrm{core}} = 15\,\mathrm{million}\, K)$
- $d_\odot = 1.496 \times 10^{11}\,\mathrm{m} \equiv 1\,\mathrm{AU} \approx 8\, lm$
- $L_\odot = 3.846 \times 10^{26}$ W (J/s)

What Powers the Sun?

- Electromagnetic Energy ("Chemistry" – TNT: 4.7×10^6 J/kg)

$$\mathrm{Lifetime} = \frac{\mathrm{Chemical\ Energy}}{\mathrm{Luminosity}} = \frac{(4.7 \times 10^6)(1.988 \times 10^{30})\,\mathrm{J}}{3.846 \times 10^{26}\,\mathrm{J/s}} \approx 770\ \mathrm{years}\ (\times)$$

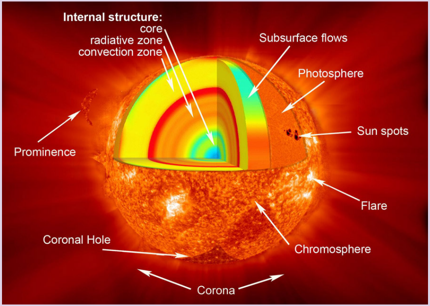
- Gravitational Energy ("Contraction" – $GM_\odot^2/R_\odot$)

$$\mathrm{Lifetime} = \frac{\mathrm{Gravitational\ Energy}}{\mathrm{Luminosity}} = \frac{3.769 \times 10^{41}\,\mathrm{J}}{3.846 \times 10^{26}\,\mathrm{J/s}} \approx 30\ \mathrm{million\ years}\ (\times)$$

- Nuclear Energy ("Thermonuclear Fusion (core)" – 0.7% of $0.1 M_\odot c^2$)

$$\mathrm{Lifetime} = \frac{\mathrm{Nuclear\ Energy}}{\mathrm{Luminosity}} = \frac{1.252 \times 10^{44}\,\mathrm{J}}{3.846 \times 10^{26}\,\mathrm{J/s}} \approx 10\ \mathrm{billion\ years}\ (\surd)$$

The Solar (Stellar) Thermostat



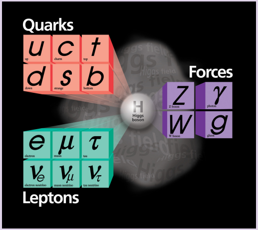
Our Sun shines because equilibrium is reached between gravity – that tends to compress the star – and the pressure from thermonuclear fusion that halts the collapse.

Such equilibrium is maintained for billions of years!

- Temperature decreases ⇒ Fusion Rate decreases ⇒ Stellar Core contracts ⇒ Temperature increases and equilibrium is restored!
- Temperature increases ⇒ Fusion Rate increases ⇒ Stellar Core expands ⇒ Temperature decreases and equilibrium is restored!

Solar activity – such as sunspots, solar flares, and prominences – are associated with the complex nature of the magnetic field (Wikipedia)

The Solar Neutrino "Problem"



- Three families of neutrinos (ν_e, ν_μ, ν_τ)
- Very weakly interacting particles
  carry neither electric nor "color" charge
  unlike photons, they are free streaming
- Very sensitive probes of the solar interior
  $p + p \rightarrow d + e^+ + \nu_e$
  $^7Be + e^- \rightarrow {}^7Li + \nu_e$
  $^8B \rightarrow {}^8Be + e^- + \nu_e$ (highest energy ν_e)

Synergy between the very small and the very big!

- The standard solar model made a definite prediction about the solar neutrino flux
- Painstaking experiments were designed to measure the predicted flux
  J.N. Bahcall and R. Davies (2002 Nobel Prize)
- R. Davies detected a deficit of neutrinos relative to the predicted number
- First "explanations" suggested experiment and/or theory were wrong!
- Subsequent experiments vindicated both Bahcall and Davies

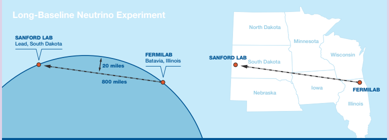
Neutrino Oscillations: transformation among the 3 neutrino families!

The Future of Neutrino Research: LBNE

May 2013

Long-Baseline Neutrino Experiment (LBNE)

A new particle physics experiment, planned to take place at Fermilab and the Sanford Lab, aims to transform our understanding of neutrinos and their role in the universe.



The proposed Long-Baseline Neutrino Experiment would send neutrinos straight through the earth from Batavia, Illinois, to Lead, South Dakota. No tunnel would be necessary for this 800-mile-long trip.

Mysterious neutrinos

Neutrinos are among the most abundant particles in the universe, a billion times more abundant than the particles that make up stars, planets and people. Each second, a trillion neutrinos from the sun and other celestial objects pass through your body. Although neutrinos are all around us, they interact so rarely with other matter that they are very difficult to observe.

The latest developments in particle accelerator and detector technology make possible promising new experiments in neutrino science. A collaboration of more than 350 scientists from five countries has proposed to build a world-leading neutrino experiment that would involve construction at both Fermi National Accelerator Laboratory (Fermilab), located in Batavia, Illinois, and the Sanford Underground Research Facility (Sanford Lab) in Lead, South Dakota.

Why are neutrinos important?

Neutrinos may provide the key to answering some of the most fundamental questions about the nature of our universe. The discovery that neutrinos have mass, contrary to what was previously thought, has revolutionized our understanding of neutrinos in the last two decades while raising new questions about matter, energy, space and time. Neutrinos may play a key role in solving the mystery of how the universe came to consist of matter rather than antimatter. They could also unveil new, exotic physical processes that have so far been beyond our reach.

Facts about neutrinos

Neutrinos are elementary particles that have no electric charge. They are among the most abundant particles in the universe.

They are very light. A neutrino weighs at least a million times less than an electron, but the precise mass is still unknown.

In nature, they are produced in great quantities in the sun and in smaller quantities in the Earth. In the laboratory, scientists can make neutrino beams with particle accelerators.

Neutrinos pass harmlessly right through matter, and only very rarely do they collide with other matter particles.

There are three types of neutrinos: electron neutrinos, muon neutrinos and tau neutrinos.

The laws of quantum mechanics allow a neutrino of one type to turn into another one as the neutrino travels long distances. And they can transform again and again. This process is called neutrino oscillation.

Understanding neutrino oscillations is the key to understanding neutrinos and their role in the universe.

The distance between Fermilab and the Sanford Lab is 800 miles. It is ideal for measuring neutrino oscillations with the proposed Long-Baseline Neutrino Experiment.

U.S. DEPARTMENT OF ENERGY   Fermilab   Sanford Underground Research Facility

- Nu's provide the key to some of the most fundamental questions about our universe
- Contrary to previously believed, Nu's have mass
- Nu's may help solve the mystery of a matter dominated universe
- Nu's for the next decade:
  - What is the origin of ν mass?
  - What are the ν masses?
  - Do ν and $\bar{\nu}$ oscillate differently?
  - Are ν their own antiparticles?
  - Are there additional neutrinos?

... and it all started in the Sun!