Exploring the largest and smallest scales of the universe: a day in the life of a National Lab

Natalie Roe
Physics Division Director
Lawrence Berkeley National Laboratory

CUWiP, Oregon State University
January 16, 2016
Outline

• National Labs: what, where, why?
• Focus on Lawrence Berkeley National Lab
• My research career: from quarks to quasars
  – CP Violation studies with quarks
  – Dark Energy studies with galaxies and quasars
• Q&A
DOE National Lab System

• The 17 DOE laboratories comprise a preeminent federal research system, providing the Nation with strategic scientific and technological capabilities.
• They develop unique, often multidisciplinary, scientific capabilities beyond the scope of academic and industrial institutions, to benefit the Nation’s researchers and national strategic priorities;
• They develop and sustain critical scientific and technical capabilities to which the government requires assured access; and
• They execute long-term government scientific and technological missions, often with complex security, safety, project management, or other operational challenges.
DOE Lab Internships

• SULI program
  – Science Undergraduate Laboratory Internships
  – encourages undergraduate students to pursue science, technology, engineering, and mathematics (STEM) careers by providing research experiences at the Department of Energy (DOE) laboratories.
  – Selected students participate as interns appointed at one of 17 participating DOE laboratories/facilities.
  – They perform research, under the guidance of laboratory staff scientists or engineers, on projects supporting the DOE mission.

• There is also a Community College Internship program (CCI)

• Got to http://science.energy.gov/wdts/ for more information about SULI and CCI
NIST, NASA

• Dept of Commerce operates the National Institute of Standards and Technology
  – 2 locations in Boulder, CO and Gaithersburg, MD
  – Basic research in many fields of physics

• NASA operates a number of laboratories and facilities focused on aerospace, astronomy, astrophysics and space science
Career Opportunities at the National Labs

• National labs offer a great environment to pursue a career in scientific research
  – Focus is on research, basic and applied, often in multi-disciplinary teams. Labs hire technical staff as well as research staff.
  – Provide exceptional engineering and computing resources to tackle big problems, and world-class user facilities
  – National labs recognize the need to improve diversity and are implementing more enlightened policies
    • Providing demographic data: admitting there is a problem
    • Establishing women in science and engineering groups to provide advice to management and establish support networks
    • Day care, lactation rooms, paid maternity/paternity leave
    • Efforts to accommodate two-career couples
Diversity & Inclusion at Berkeley Lab

Vision Statement

Berkeley Lab has a tradition of multidisciplinary teams working together to bring science solutions to the world. Fostering a diverse workforce—in experience, perspective and background—and culture of inclusion are key to attracting and engaging the brightest minds and furthering our record of scientific excellence and groundbreaking innovations.

Director’s Q&A

Erika Lindquist
JGI Sequencing QA/QC Group Lead
California Army National Guard Veteran

Berkeley Lab Veterans Share Their Stories
LBNL Demographic Data by Ethnicity and Gender

Gender Data by Job Category
E. O. Lawrence Berkeley National Lab
Established in 1931

E. O Lawrence and the 184” cyclotron (circa 1940).

The small seed from which Big Science grew.
Today Berkeley Lab is home to 16 scientific divisions organized in six research areas.
World-Class User Facilities at Berkeley Lab Today

- Advanced Light Source
- Joint Genomics Institute
- Molecular Foundry
- National Center for Electron Microscopy (NCEM)
- National Energy Research Scientific Computing Center (NERSC)
- Energy Sciences Network (ESNet)
- 88" Cyclotron
Berkeley Lab Scientific Areas

Energy Sciences

Earth and Environmental Sciences

Energy Technologies

Computational Science

Biosciences

Physical Sciences
LBNL Physics Division Program

• Addressing Big Questions in Particle Physics & Cosmology:
  – Energy Frontier:
    • What is the origin of matter?
    • Is there new physics waiting to be discovered at LHC?
  – Cosmic Frontier:
    • What is Dark Matter?
    • What is Dark Energy?
  – Intensity Frontier:
    • Understanding neutrino oscillations
    • Rare decays to probe for new physics
Recent Scientific Highlights

• Discovery of Higgs boson!

• Daya Bay experiment measures electron neutrino oscillations

• BOSS measures expansion history of Universe to new precision

• LBNL was a major player in all three
My Career in Physics

• Undergraduate Physics Major
  – Began doing research with Prof. Carlo Rubbia at Harvard
  – After graduation, spent 1 year at CERN in Geneva working on the experiment which discovered the W and Z bosons

• Graduate school in Physics at Stanford/SLAC
  – Thesis research was a search for super-symmetric particles
  – Met my future husband on a ski trip (and Janet!)

• Postdoc in LBNL Physics Division
  – Studied W boson production at the Fermilab Tevatron collider; had my first child around this time
  – Began working on a new proposal to study CP violation using B mesons, and went on to lead the construction of the Silicon Vertex Tracker for the BaBar detector
• Staff Scientist => Senior Scientist at LBNL
  – Studied CP Violation using B Factory data; had second child around this time
  – In 2003 I switched to cosmology and took over the leadership of the LBNL MicroSystems Lab making CCDs for cosmology experiments
  – Led upgrade of spectrographs for the Sloan Digital Sky Survey BOSS project and the fabrication of the CCDs for the 500 Megapixel Dark Energy Camera, now installed on a telescope in Chile
  – Currently working on a new dark energy experiment
  – Physics Division Director as of March 2012
High Energy Physics Goals

- Understand the fundamental nature of Matter and Force
- Understand the history and evolution of the Universe
Big Questions in Particle Physics

• Why three families of quarks & leptons?
• Are there additional particles or extra dimensions?
• What happened to all the anti-matter created in the Big Bang?
• How can gravity be included in the Standard Model?
• Are neutrinos their own anti-particles?
• What is the nature of dark matter?
• What is the nature of dark energy?
Outstanding Questions in Particle Physics

• Why three families of quarks & leptons?
• Are there additional particles or extra dimensions?
• What happened to all the anti-matter created in the Big Bang?
• How can gravity be included in the Standard Model?
• Are neutrinos their own anti-particles?
• What is the nature of dark matter?
• What is the nature of dark energy?
Matter and Anti-matter

- 3 families of quarks and leptons make up all matter
  - Proton = 2 up + 1 down quarks
  - Neutron = 1 up + 2 down quarks
- The mass of particles is determined by their coupling to the Higgs Boson
- All particles have anti-particle partners

The Standard Model particles
Matter and Energy

- Einstein first realized the equivalence of matter and energy
- When matter and antimatter meet, they annihilate into energy

\[ e^- \rightarrow \gamma \]
\[ e^+ \rightarrow \gamma \]

- Energy can also materialize as particle-antiparticle pairs

\[ \gamma \rightarrow e^- \]
\[ \gamma \rightarrow e^+ \]

- This is what we believe happened in the "Big Bang"
- What happened to the anti-particles?
Particles meet Anti-particles and annihilate....
Particles meet Anti-particles and annihilate.....

but somehow 1 particle in $10^{10}$ survives. This tiny remnant will form stars, galaxies, planets and eventually.... life
CP Violation

C: Charge conjugation: particle → antiparticle

P: Parity (mirror reflection): x → -x

CP together change matter to antimatter. A difference between matter and antimatter is evidence for CP Violation.
PEP-II Asymmetric B Factory

Stanford Linear Accelerator Center, Stanford, California
The BaBar Detector

The BaBar collaboration: ~550 physicists from 76 institutions and 9 different countries
Silicon Vertex Tracker (SVT)

5 layers of double-sided silicon strip detectors, ~150K channels of custom rad-hard IC readout
BaBar observed CP violation

BaBar result: \( \sin 2\beta = 0.741 \pm 0.067 \pm 0.034 \)

Matter – Anti-matter asymmetry observed in B meson decays

Measurement of decay vertices using SVT was crucial to detect this difference and make a precise measurement.
The BaBar result agrees perfectly with the prediction of the Standard Model.

>500 papers published, but no sign of new physics
Outstanding Questions in Particle Physics

• Why three families of quarks & leptons?
• Are there additional particles or extra dimensions?
• What happened to all the anti-matter created in the Big Bang?
• How can gravity be included in the Standard Model?
• Are neutrinos their own anti-particles?
• What is the nature of dark matter?
• What is the nature of dark energy?
Energy budget of Universe

Composition of the Cosmos

Dark Energy: ~70%

Dark Matter: ~25%

Heavy elements: 0.03%

neutrinos: 0.3%

Stars: 0.5%

Free hydrogen and helium: 4%

Dark matter: ~25%

Dark energy: ~70%
Dark Energy

• First discovered by Saul Perlmutter in 1998
  – Used supernovae as standard candles to find that the expansion of the Universe is accelerating
  – Don’t understand it – so we call it “dark energy”

• What can dark energy be?
  – not a particle or dark matter
  – Einstein’s cosmological constant?
  – a breakdown of General Relativity?
  – something even stranger – a new field with negative pressure filling the Universe?

• Need more experimental data on expansion history of Universe to test different possibilities
Another technique to measure distance – the standard ruler

Standard candles have known brightness, so observed brightness is a proxy for distance

Standard rulers have known size, so observed size is a proxy for distance
Baryon Acoustic Oscillations: A Standard Ruler from Early Universe Physics

- Small fluctuations in the hot plasma of the early Universe create over dense regions.
- Photon pressure produces a spherical wave, travelling at 57% c.
- As universe expands and cools, atoms form; photons are no longer coupled to matter; the wave stalls.
- Over dense regions seed the formation of galaxies.
- Result: A preferred separation of 150 Mpc. (500 million light years!)
- This effect is called Baryon Acoustic Oscillations (BAO).
How to detect this (huge) ruler?

• Baryon acoustic oscillations (BAO) can be detected in the distribution of galaxies.
• Need an enormous number of galaxies covering a large volume to detect the preferred separation at 150 Mpc = 500 million light years.
• Requires a galaxy redshift survey – acquiring spectra of many many thousands of galaxies.
Sloan Telescope
Apache Point, NM
BAO Peak Detected by Sloan Digital Sky Survey

4% distance scale measurement at z=0.35

Eisenstein et al. 2005
BOSS experiment at SDSS
Spectrograph Upgrade 2007 – 2009
Survey 2009 - 2014

Spectrograph

1000 small-core fibers

Galaxy spectrum

LBL CCDs
Recent Results from BOSS

BAO peak at $z=0.57$

1% distance measurement from BOSS
DESI – Dark Energy Spectroscopic Instrument

Kitt Peak 4-m (Mayall) at Kitt Peak, Arizona in 6 years

- 5000 fiber positioners on 1-m focal plane
- Corrector lenses
  3° FOV

SDSS-inspired:
  simple, high-throughput

- 5000 fibers
- 10 spectrographs
  × 3 channels each
Measuring the accelerating Universe

Alternative Universes for constant $w$, $\Omega_m = 0.27$, and $\Omega_\Lambda = 0.73$
DESI discriminates between DE models

Alternative Universes for constant $w$, $\Omega_m = 0.27$, and $\Omega_{\Lambda} = 0.73$

past ← today → future
Conclusions

• Particle physics and cosmology have many exciting questions and answers may be near
  – Nature of dark energy and dark matter
  – Properties of Higgs Boson
  – Neutrino oscillations and CP violation
  – Search for new physics and new types of particles

• LBNL is a wonderful place to pursue research in particle physics & cosmology, and many other areas of research as well

• Consider the National Labs in your career search!