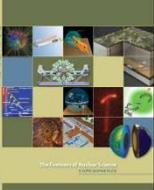


# Long Range Plans for Nuclear Science

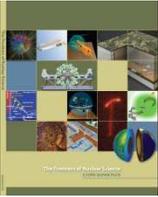
W.A. Zajc  
Columbia University

National User Facility Organization Annual Meeting  
June 7-9, 2010, Brookhaven National Laboratory



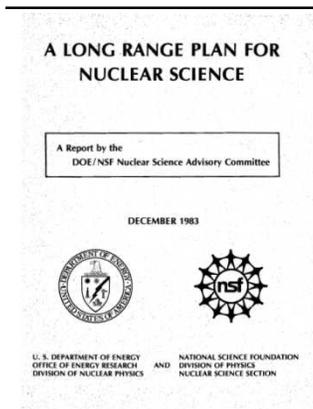
# Outline

- Very brief overview of long-range planning process in nuclear science
- A guided introduction to nuclear physics in the context of the current Long Range Plan for Nuclear Science.

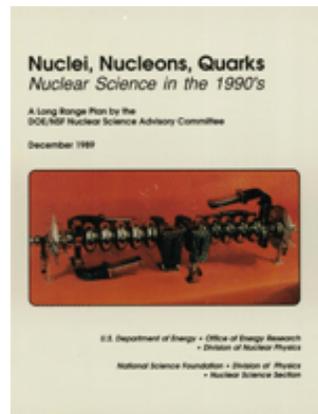


# Long Range Planning in Nuclear Science

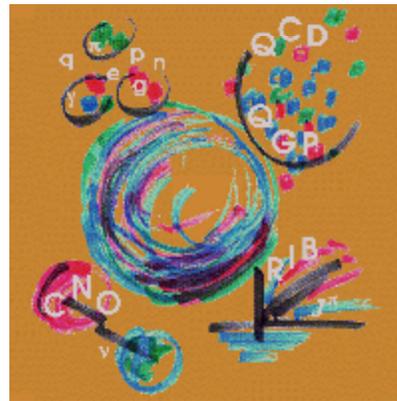
- A source of considerable community pride
- Something we're good at
- The plans are 'resource burdened'
- We've been at it for a long time:



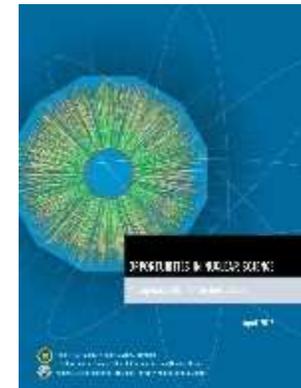
1983



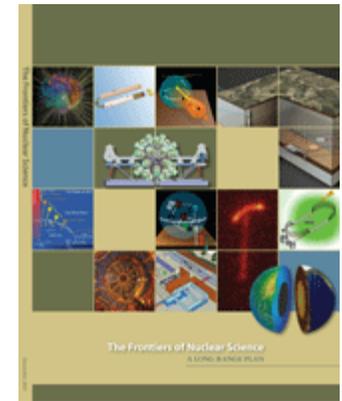
1989



1996



2002

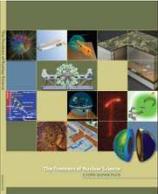


2007



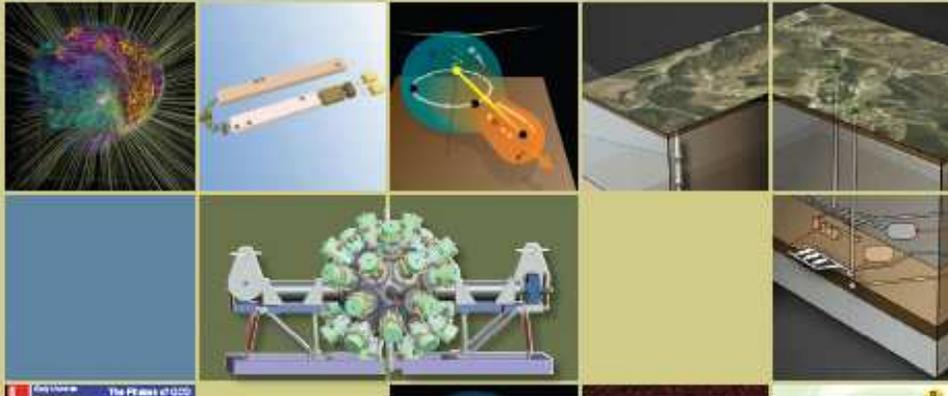
## We're Good at It and Have Been For a Long Time

- A case in point –  
the Relativistic Heavy Ion Collider (RHIC)
- 1983 Plan:
  - ▶ *“We identify a relativistic heavy ion collider as the highest priority for the next major facility to be constructed, with the potential for addressing a new scientific frontier of fundamental importance.”*
- 2000: RHIC begins operations
- 2005: Announcement of major discoveries  
at RHIC

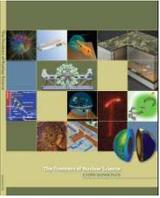


# The 2007 Plan

The Frontiers of Nuclear Science

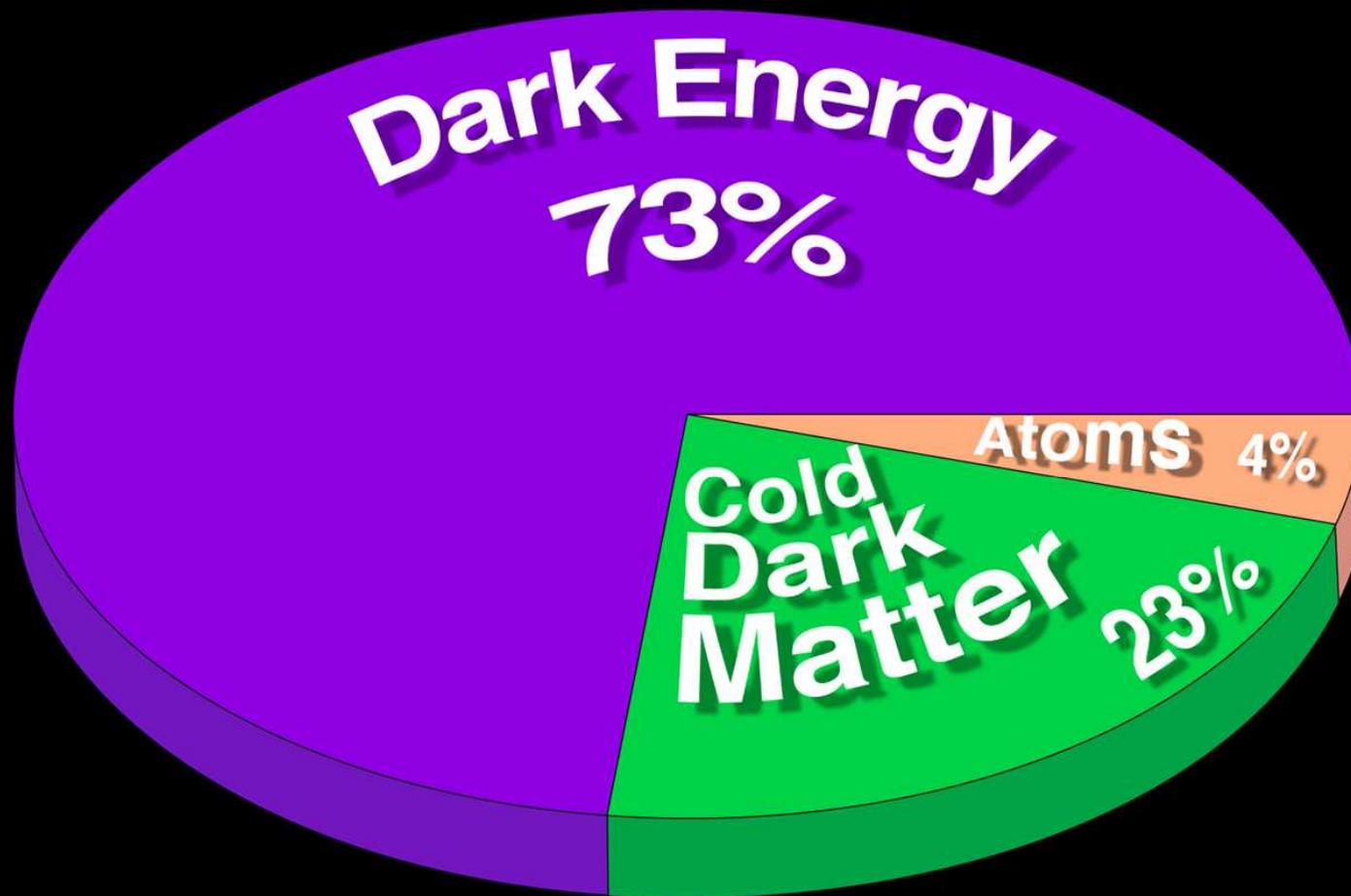


- More than a year in the making
- A community-wide effort
- Input from 6 multi-day “town meetings” spanning the field
- 59-member group attends week-long “resolution meeting”

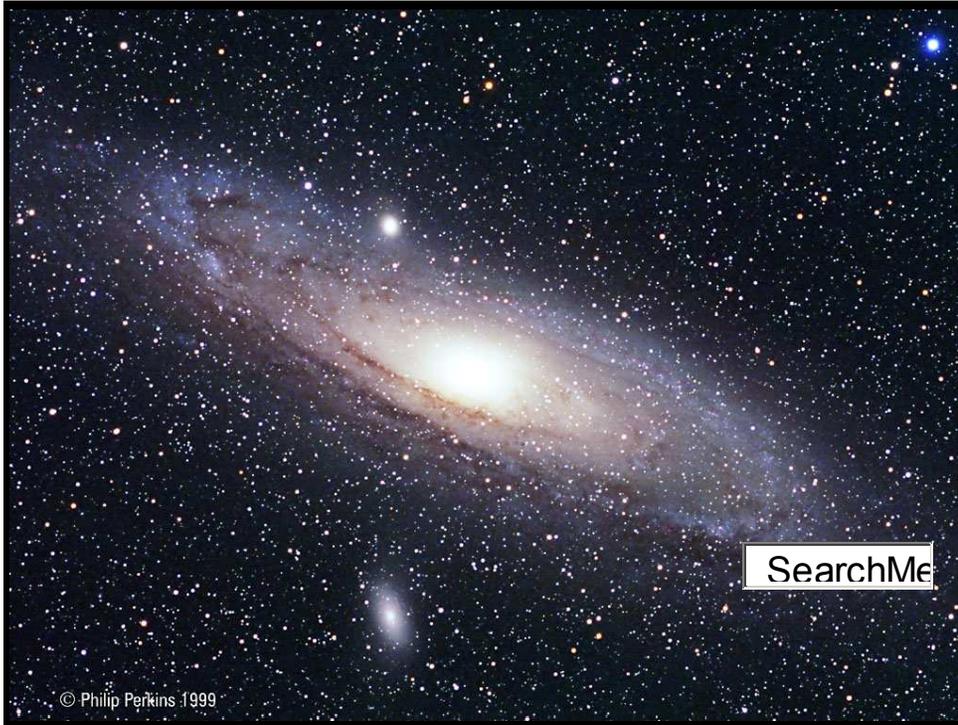


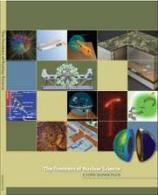
# The Frontiers of Nuclear Science

## A Long Range Plan



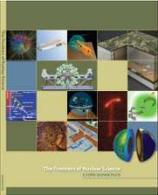
**Atoms 4%**





# The Central Truths of Nuclear Physics

- We are nothing
- We are dust
- We don't matter

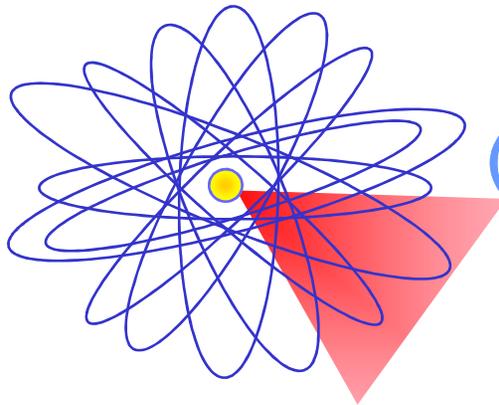


# We are nothing (c. 1900)

Most of “us” is (nearly) empty space

- ▶ 99.9% of the mass of atoms is contained in the nucleus
- ▶ The volume of the nucleus is (much) less than one-trillionth (  $1/1,000,000,000,000$  ) the atom's.

**Atom**

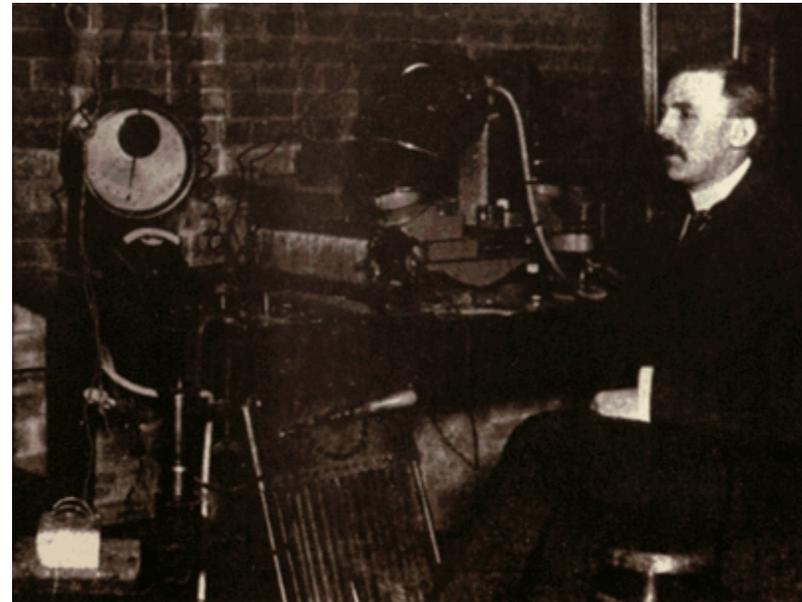
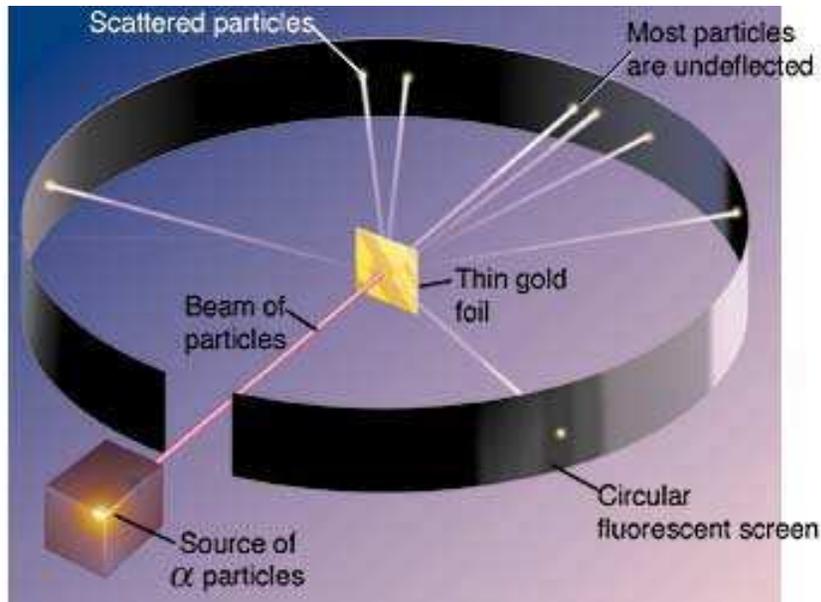


**Nucleus**  
(“ion” when alone)



# Rutherford's Invention (1911)

- Investigate the nucleus with *scattering* .



- That remains our fundamental technique –
- Scaled up by a factor of (1-10) thousand



# Recommendation 1

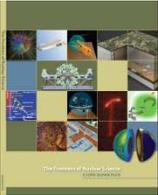
☞ We recommend completion of the  
**12 GeV CEBAF Upgrade** at Jefferson Lab.

The Upgrade will enable new insights into the structure of the nucleon, the transition between the hadronic and quark/gluon descriptions of nuclei, and the nature of confinement.



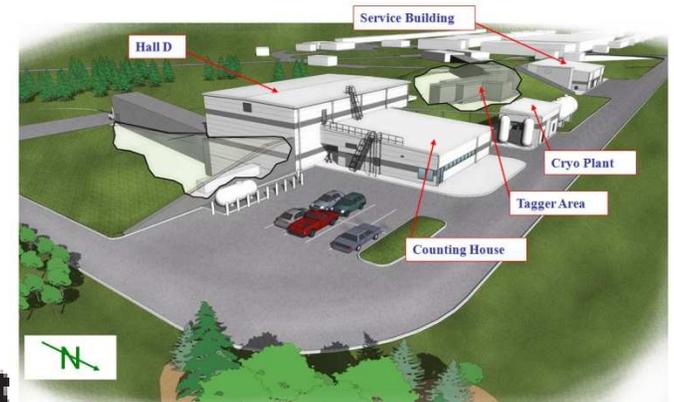
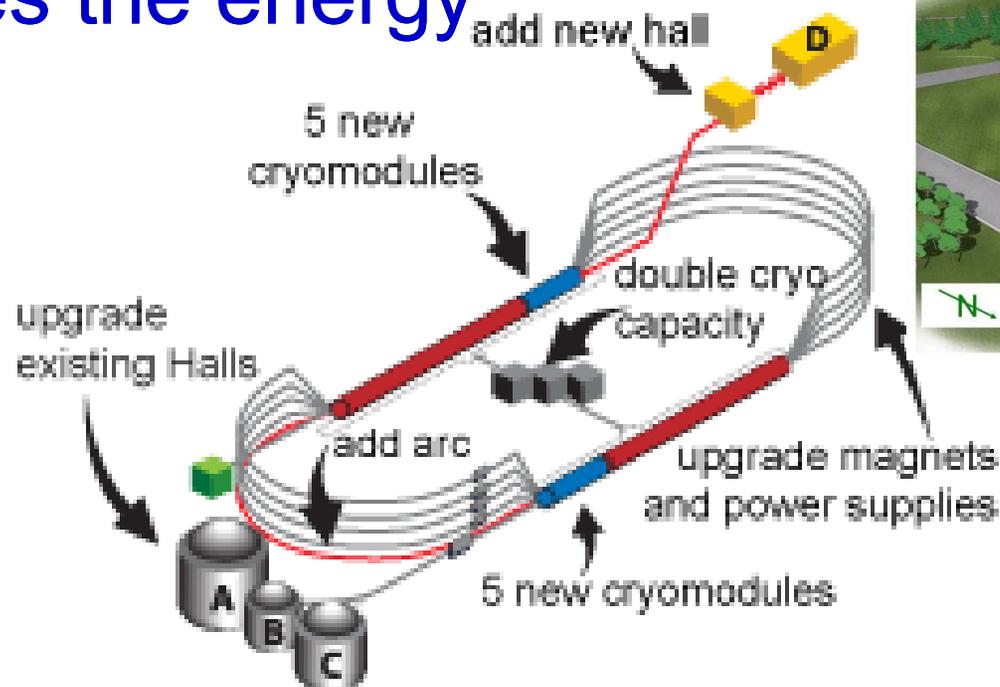
# Jefferson Lab (JLab)



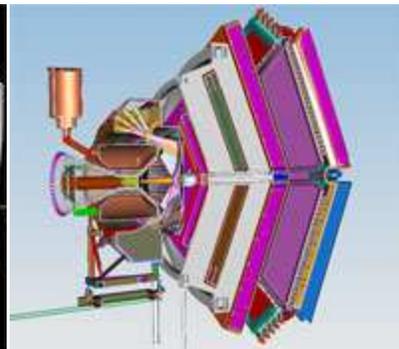
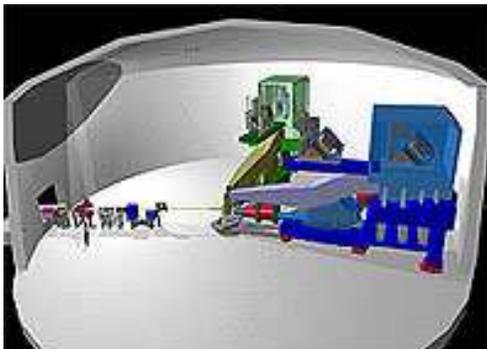


# The JLab 12 GeV Upgrade

- Doubles the energy



- Upgrades the halls, adds new hall





# The Ties That Bind

- With the 12 GeV Upgrade
  - ▶ Understand the unique nature of the “flux-tubes” formed by gluons
  - ▶ Perform “tomography” on the proton
  - ▶ Understand spin and orbital angular momentum components of proton spin

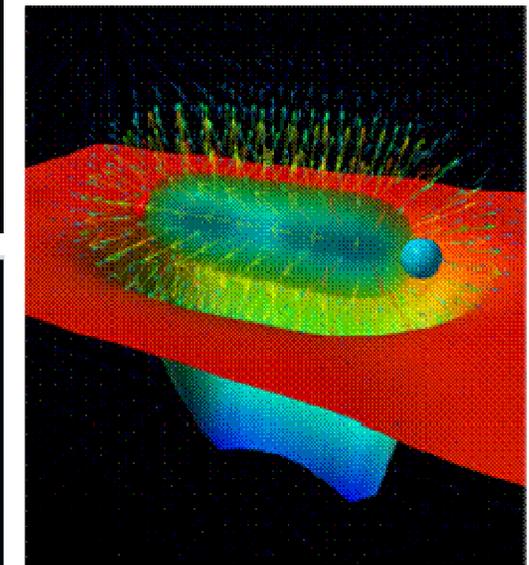
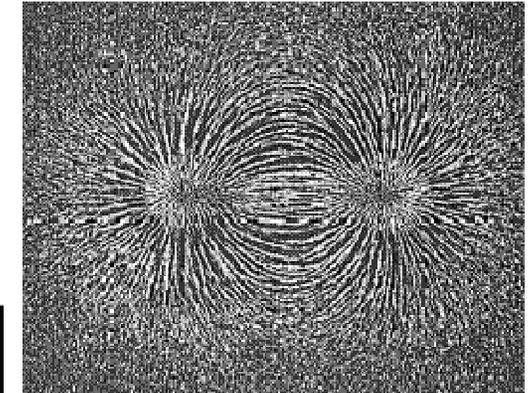
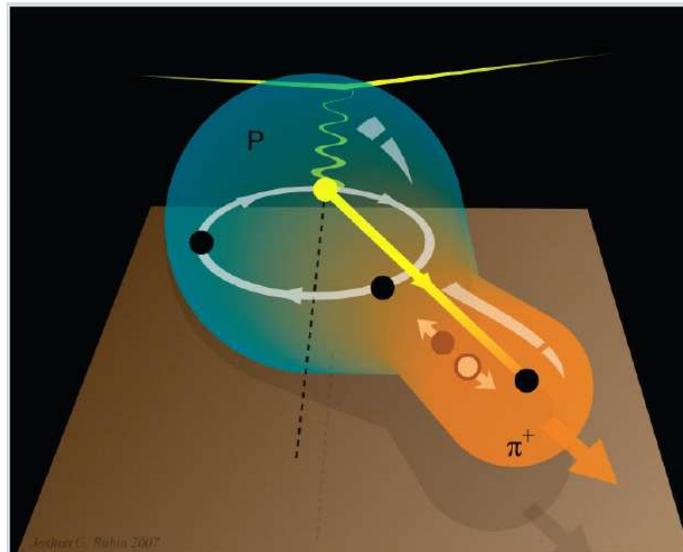
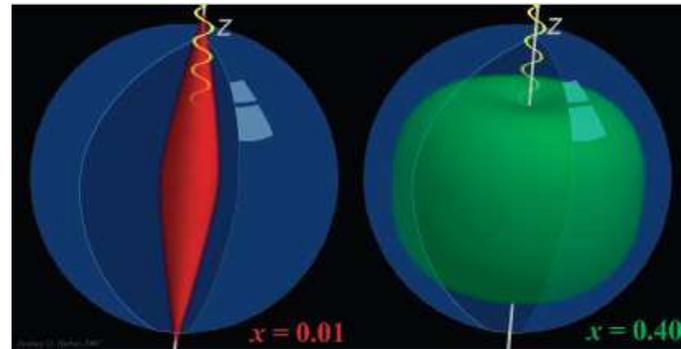
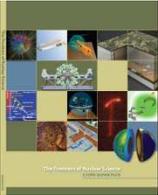


Fig.2. Faraday lines of the electromagnetic field obeying the Coulomb law, in the left panel. A string-like structure - the collimated flux tube of QCD chromoelectric field - that binds a quark-antiquark pair in a meson, in the right panel (lattice simulation by **Leinweber**).



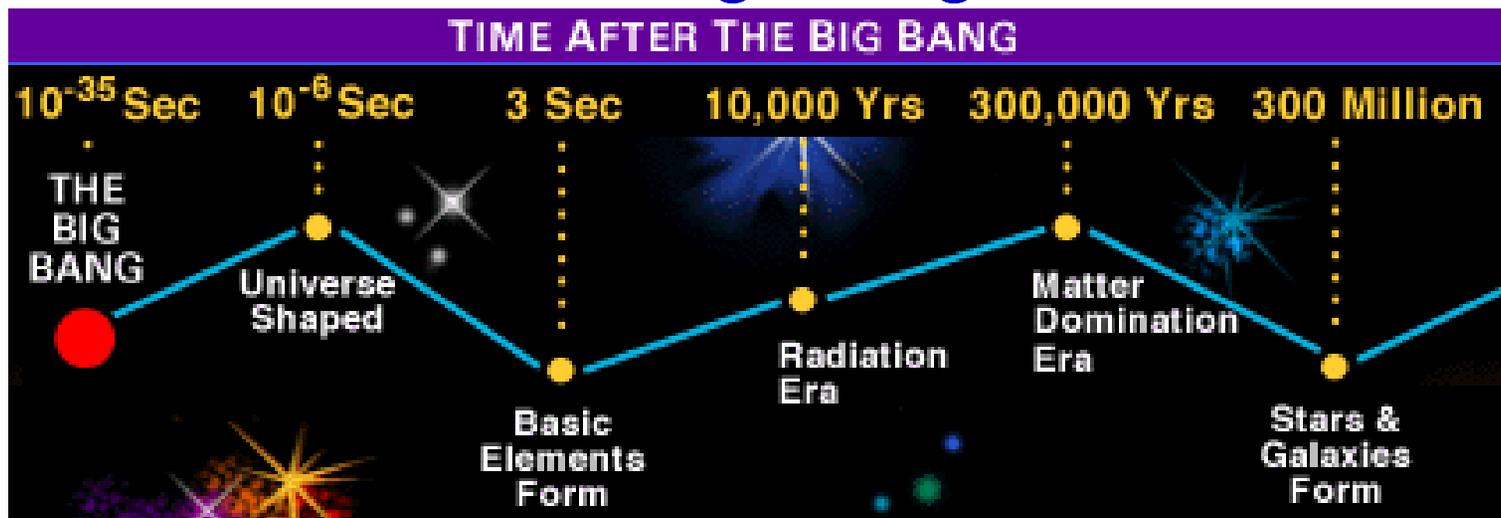
# The Central Truths of Nuclear Physics

- We are nothing
- **We are dust**
- We don't matter



# We are (star) dust (c. 1950)

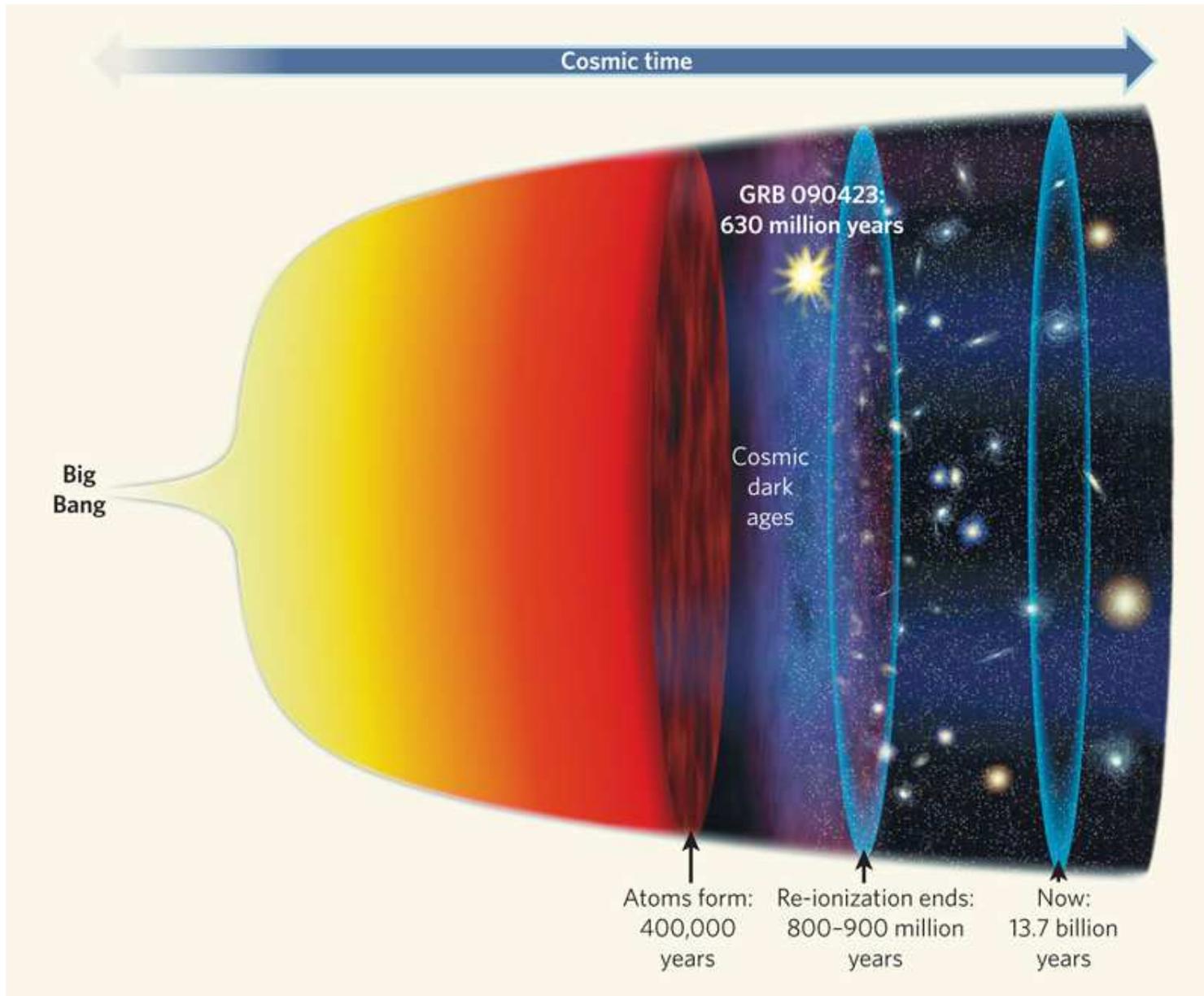
- Only the lightest elements (Hydrogen, Helium) were created in the Big Bang



- The rest of “us” is literally stardust
  - ▶ All heavy elements (like the Carbon and Nitrogen we’re made of) were “cooked” together inside stars
  - ▶ Explosions of those (early) stars spread the heavier elements throughout the universe.

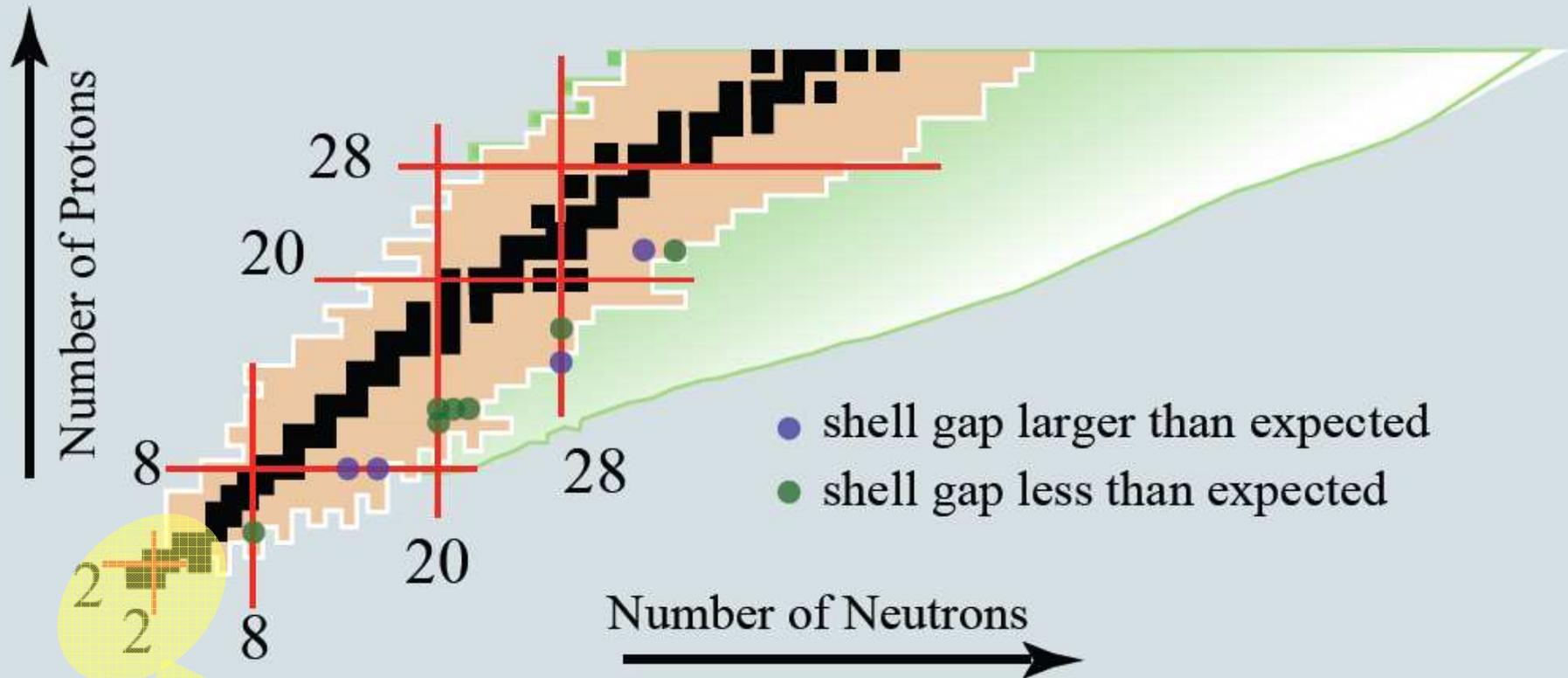


# Emerging From the Dark Ages





# A Starter Universe

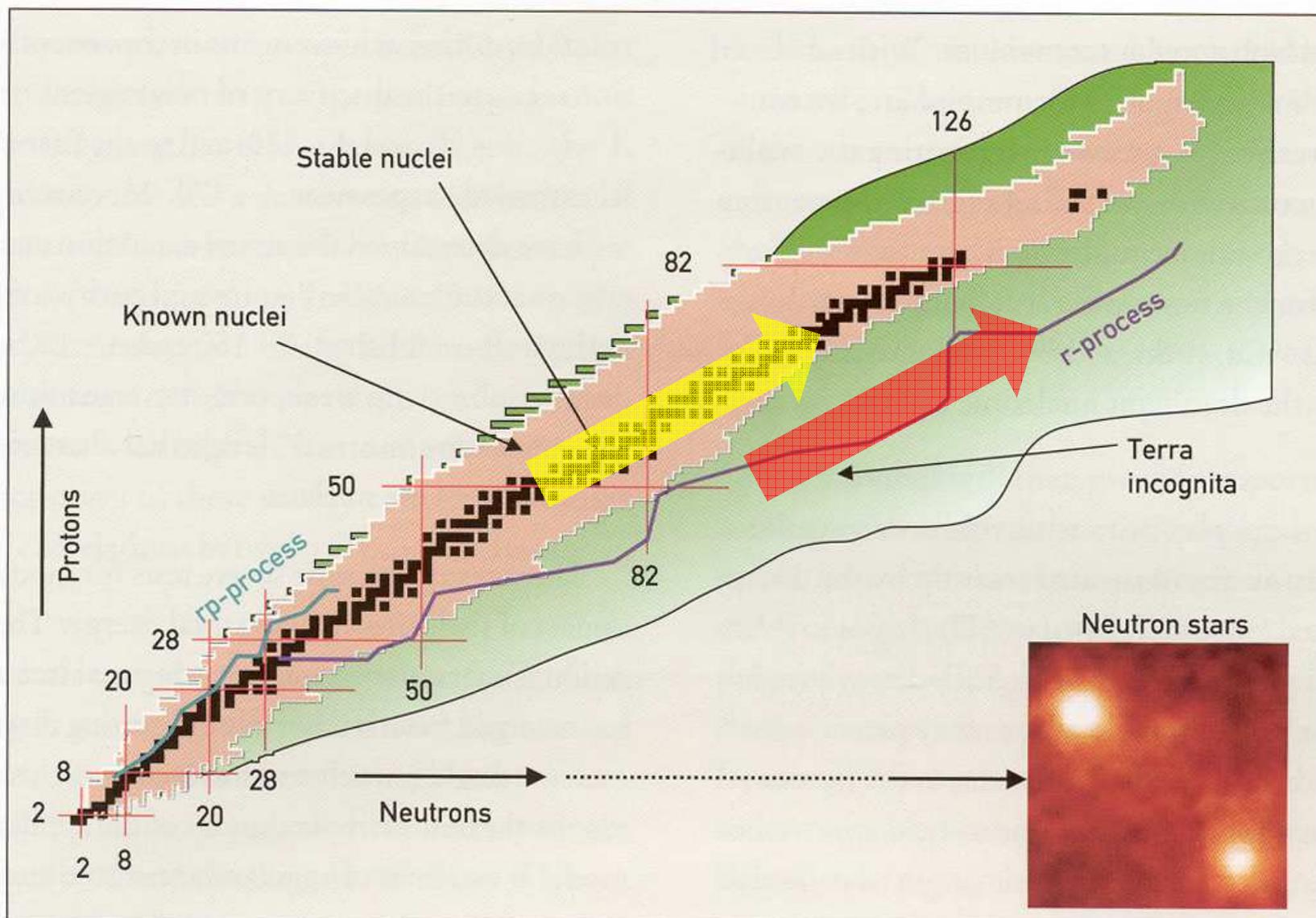


Shell structure of the lighter nuclei. Shown are the original magic numbers (solid red lines) and blue and green dots indicating measurements that point to changes in magic numbers in the neutron-rich nuclei.

- **First stars: Mostly hydrogen, helium, (lithium)**

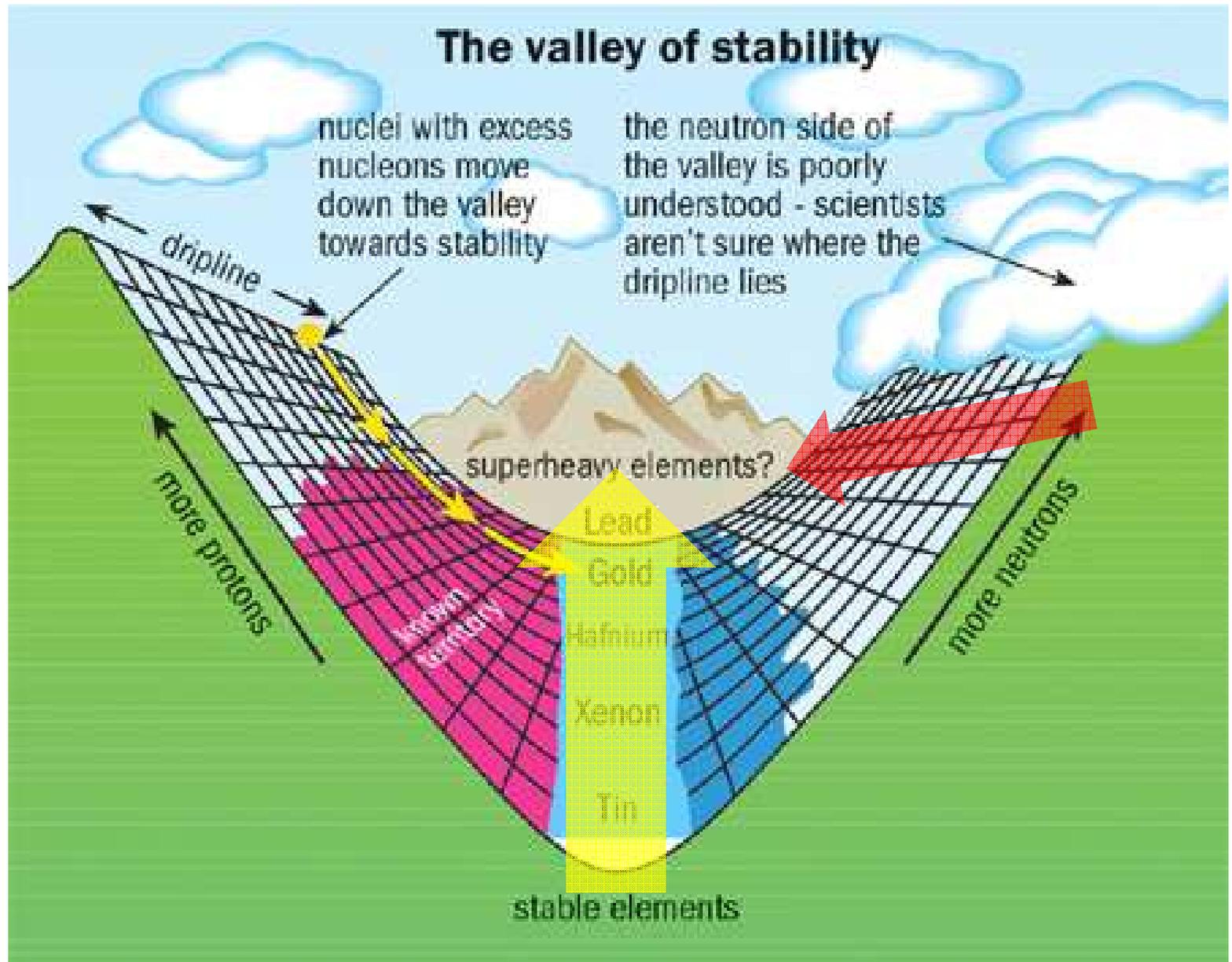


# The Origin of the Species





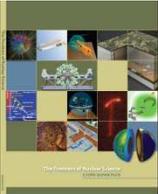
# Climbing the Walls





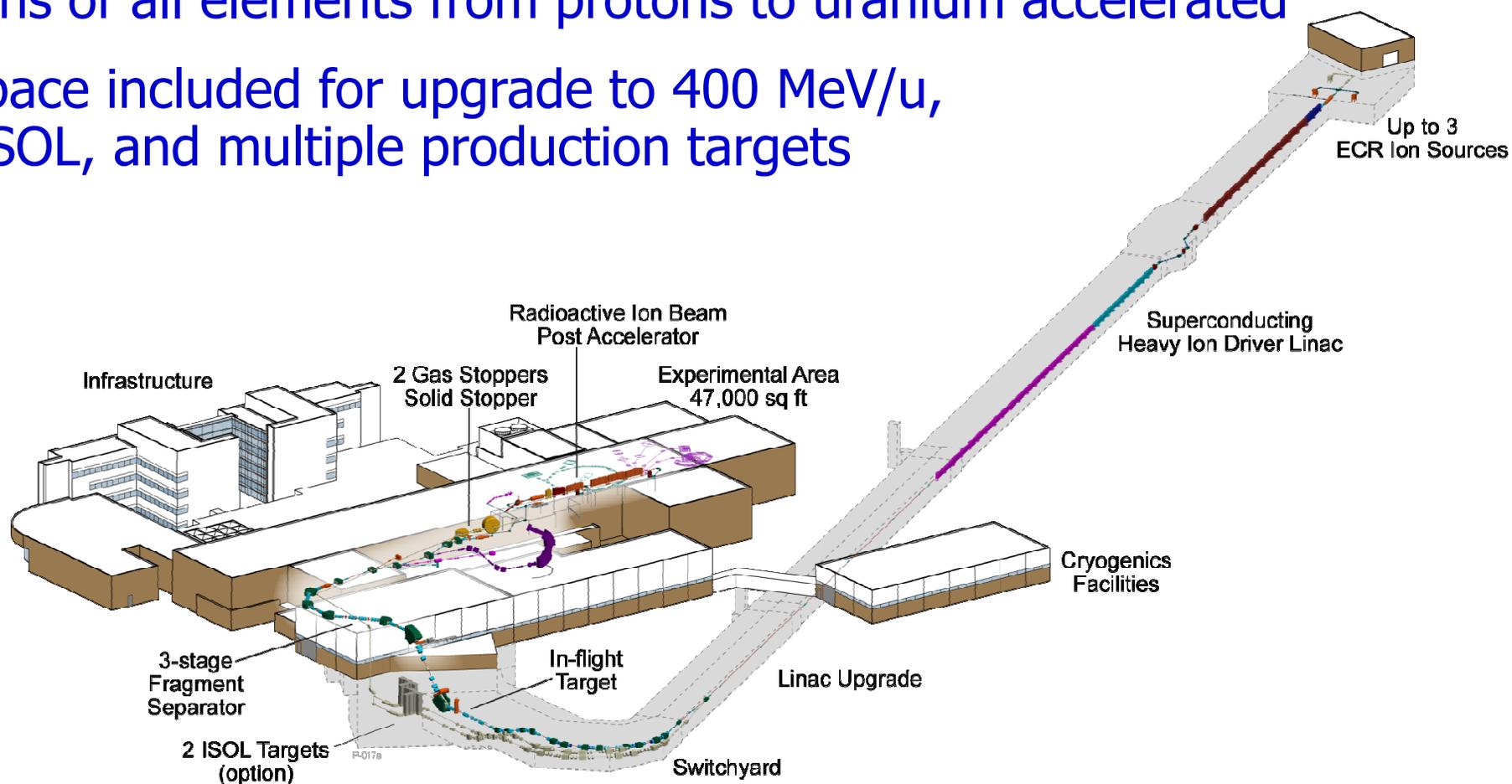
## Recommendation 2

- ☞ We recommend construction of the **Facility for Rare Isotope Beams (FRIB)**, a world-leading facility for the **study of nuclear structure, reactions, and astrophysics**.
- Experiments with the new isotopes produced at FRIB will lead to a comprehensive description of nuclei, elucidate the origin of the elements in the cosmos, provide an understanding of matter in the crust of neutron stars, and establish the scientific foundation for innovative applications of nuclear science to society.



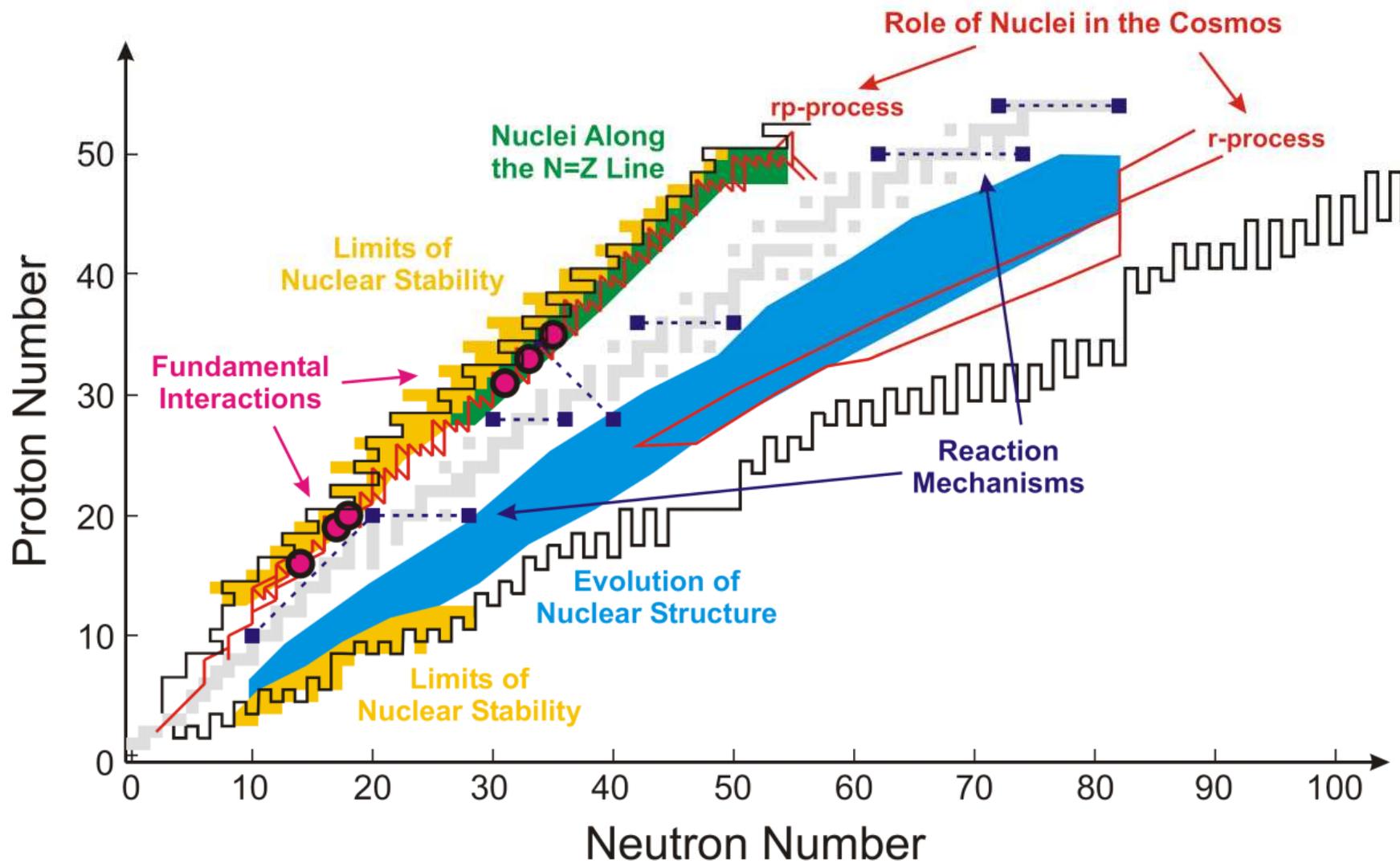
# FRIB: Facility for Rare Isotope Beams

- Driver linac with 400 kW and greater than 200 MeV/u for all ions
- Ions of all elements from protons to uranium accelerated
- Space included for upgrade to 400 MeV/u, ISOL, and multiple production targets





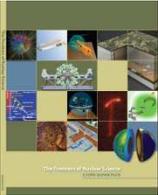
# FRIB Physics Reach





# The Central Truths of Nuclear Physics

- We are nothing
- We are dust
- **We don't matter**



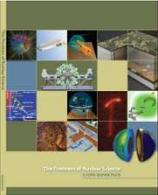
# We don't matter (c. 2000)

- More accurately:  
*Our “matter” barely matters to the universe*
- Ordinary “stuff” is a billion-to-one shot in the composition of the universe.
- This is literally true – in some sense  
*anti-particles ‘balanced’ particles*  
in the early universe to within a part per billion

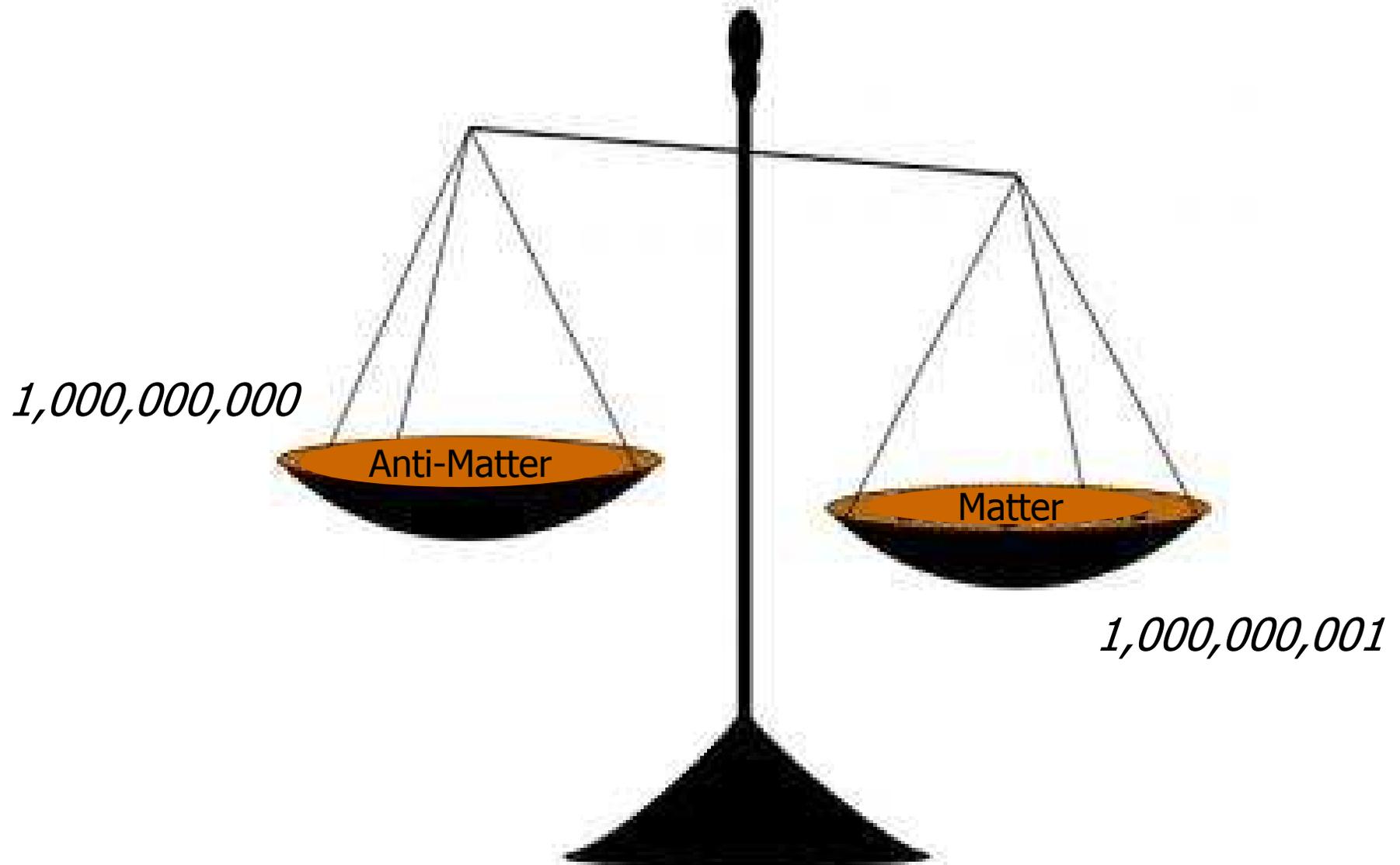


# Life in the Balance





# Life in the Balance





# A Vote for Matter

- The ‘balance-breaker’ responsible for
  - ▶ the 1 in a billion asymmetry
  - ▶ (and us!)

is referred to as ‘CP Violation’

- Understanding CP violation is an important goal of the nuclear physics effort in *neutrinos and fundamental symmetries* .

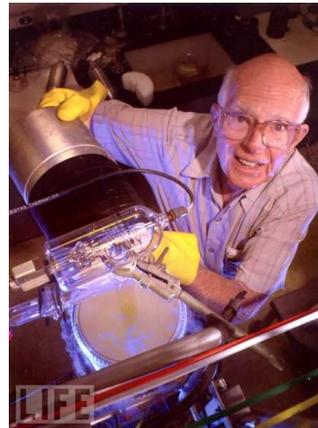


## Recommendation 3

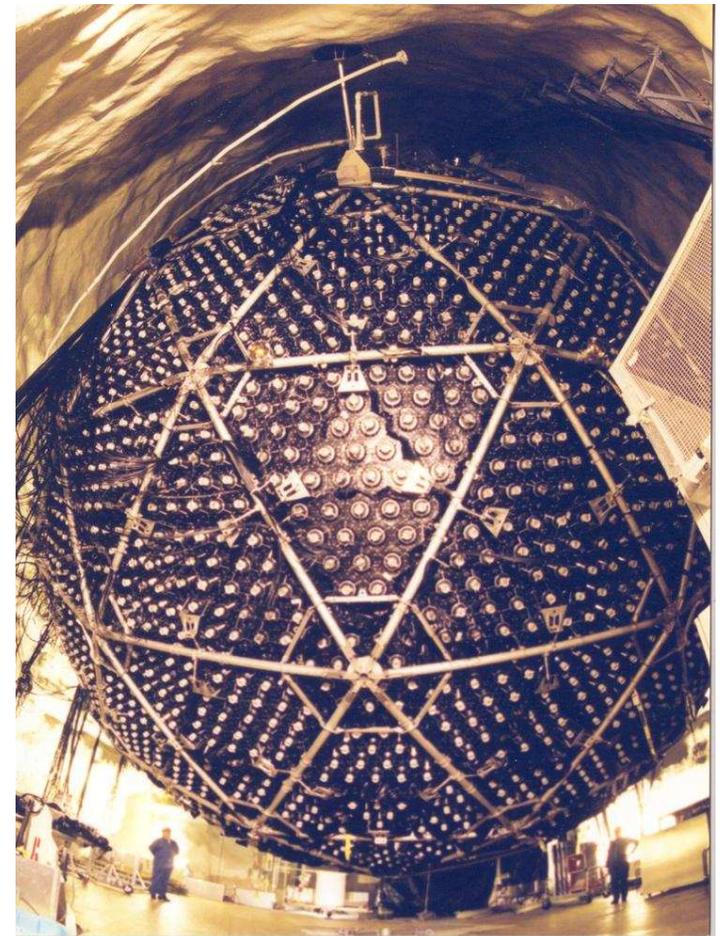
-  We recommend a targeted program of experiments to investigate **neutrino properties and fundamental symmetries**.
- These experiments aim to discover the nature of the neutrino, yet-unseen violations of time-reversal symmetry, and other key ingredients of the New Standard Model of fundamental interactions.
  - Construction of a Deep Underground Science and Engineering Laboratory is vital to U.S. leadership in core aspects of this initiative.

# Neutrinos

- Underground study pioneered by BNL's Ray Davis in Homestake mine (South Dakota)
- Extraordinary work at SNO in Sudbury, CA establishes that neutrino's "mix".



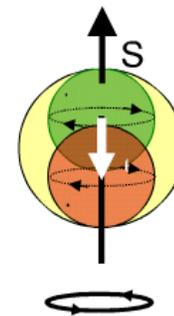
TBA



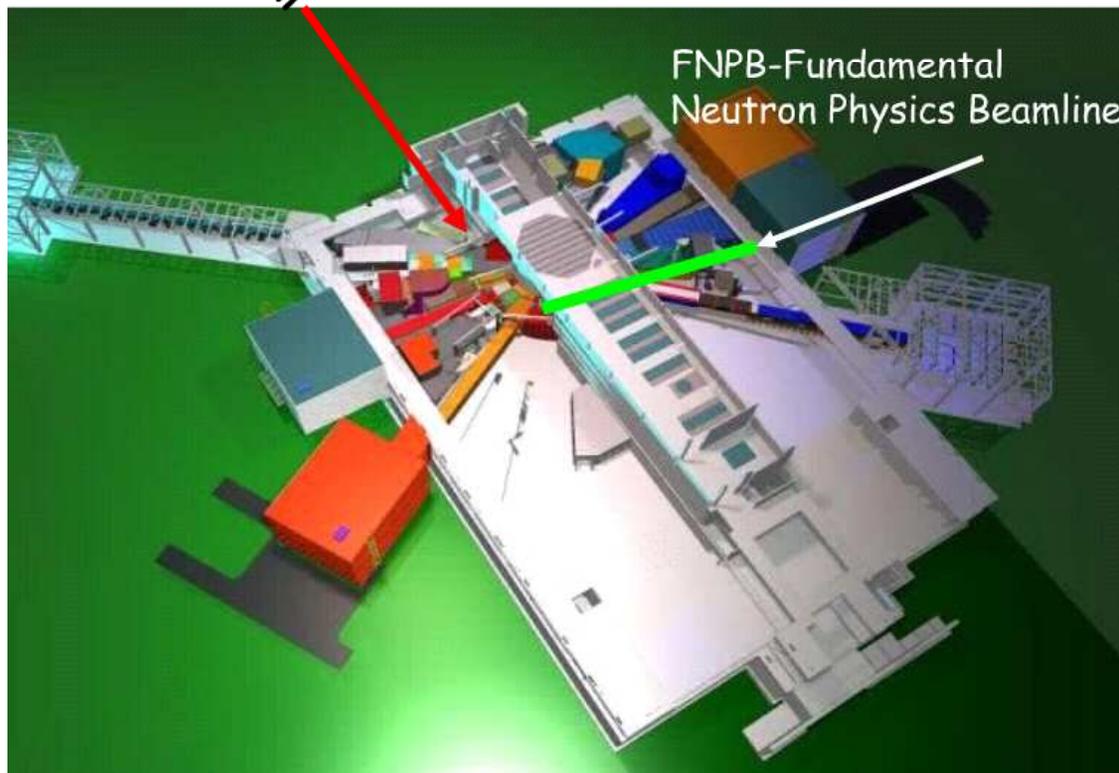


“These experiments aim to discover ... yet-unseen violations of time-reversal symmetry”

- The neutron cannot have an “electric dipole moment” if time-reversal symmetry is exact.
- Use BES’s Spallation Neutron Source SNS Target Hall



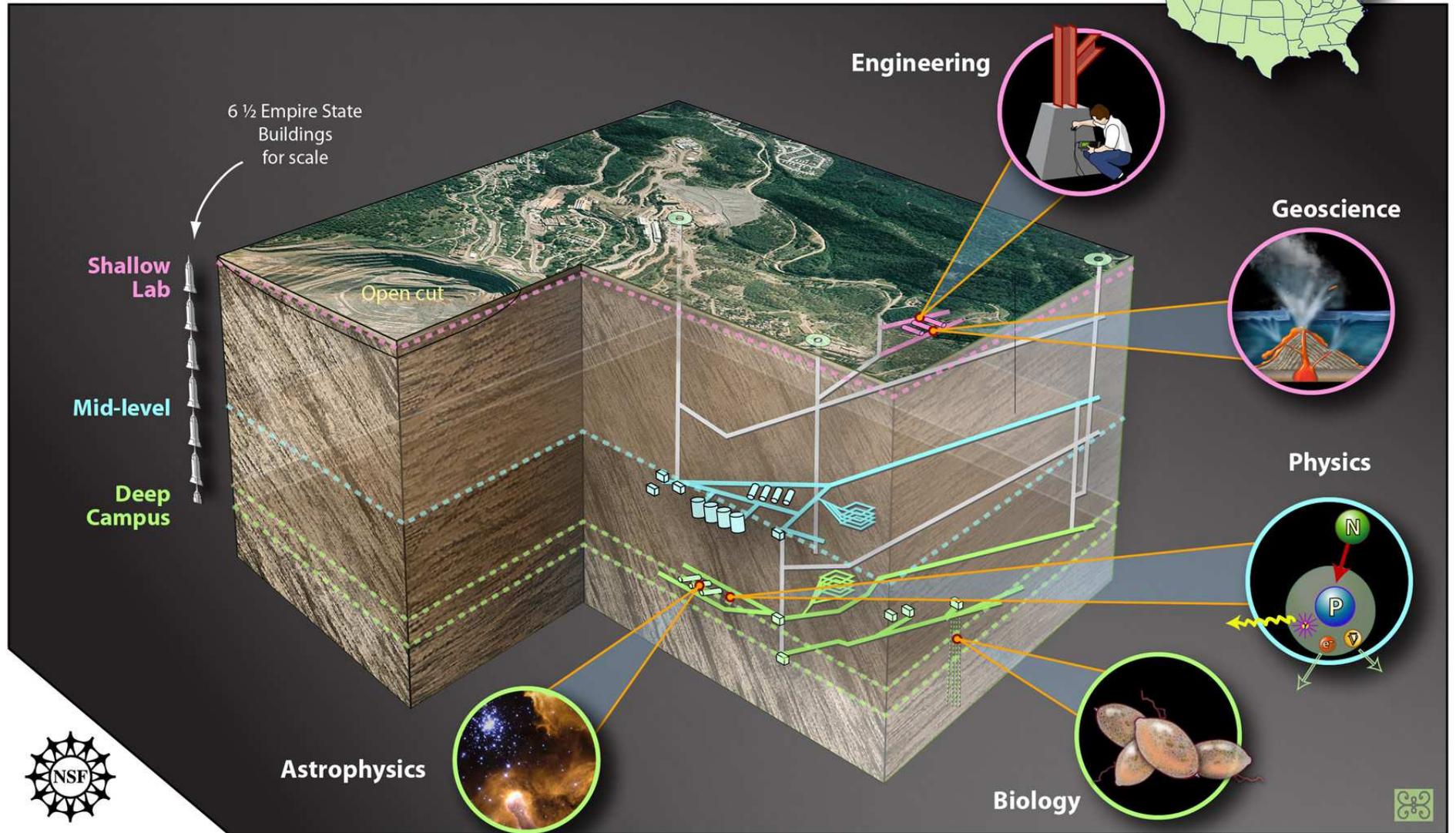
p beam





“Construction of a Deep Underground Science and Engineering Laboratory is vital to U.S. leadership in core aspects of this initiative.”

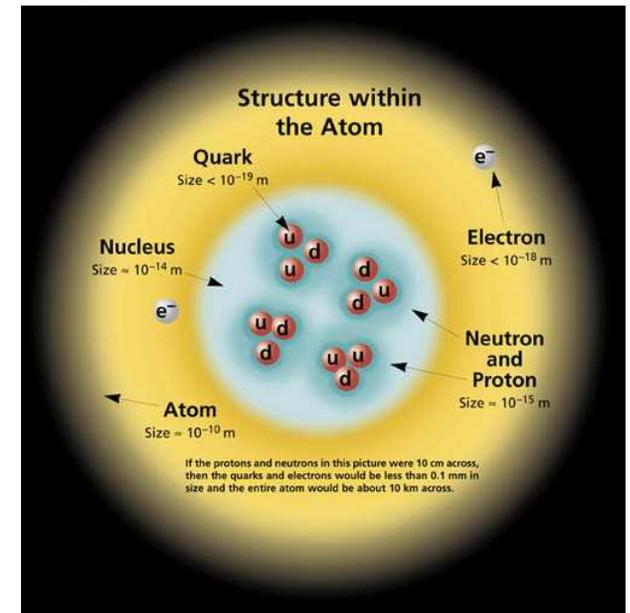
# DUSEL Deep Underground Science and Engineering Laboratory at Homestake, SD

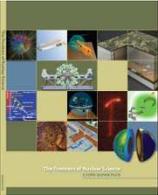




# We don't matter (c. 2000)

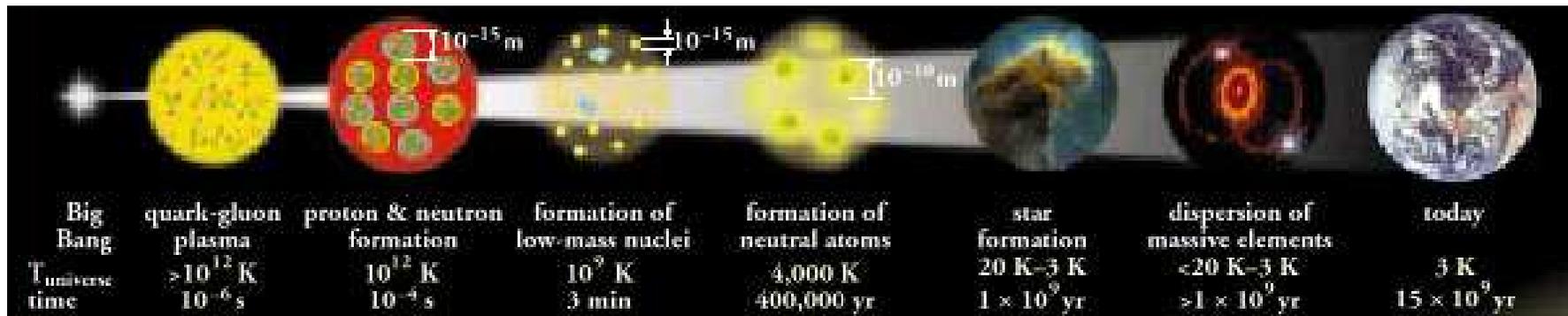
- More accurately: *We're not matter*
- 99.9% of the mass of each atom is concentrated in the nucleus:
  - ▶ Each nucleus consists of neutrons and protons
  - ▶ Each neutron and proton consists of 3 quarks
  - ▶ Each quark has less than 1% of the proton or neutron mass, totaling to  $< 2\%$
  - ▶ The *rest of the mass* of protons and neutrons (and hence our mass) is “*frozen energy*” from the Big Bang :  $m = E / c^2$  .





# Phase Transitions

- The “great freeze” took place about 10 millionths of a second after the Big Bang

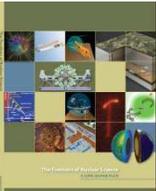


- General name for such phenomena:  
*Phase transition*

Examples:

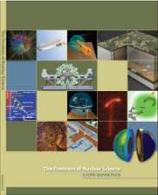
Steam to water to ice

(Free quarks and gluons) to (protons and neutrons) to nuclei



# RHIC = Relativistic Heavy Ion Collider

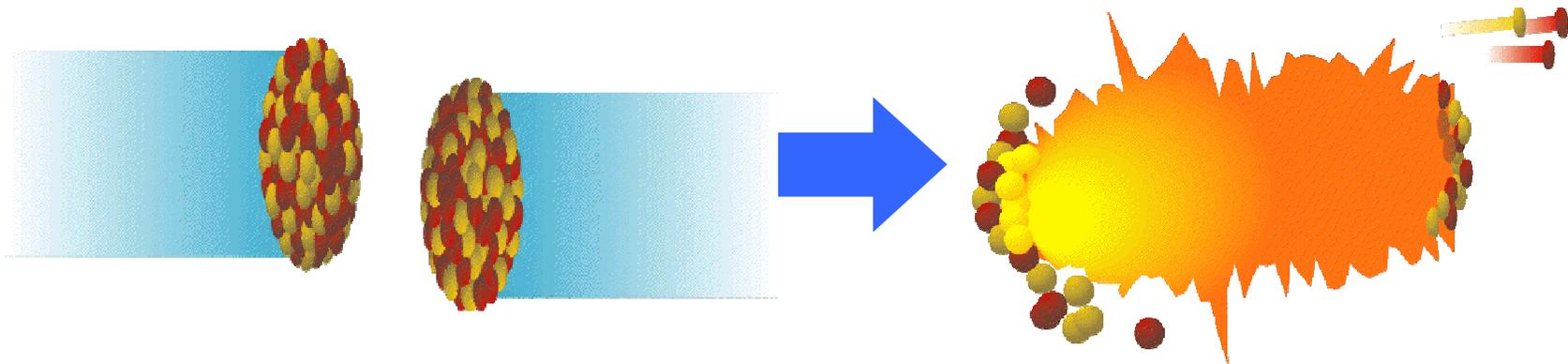




# Boiling Neutrons and Protons

- Fundamental Method:

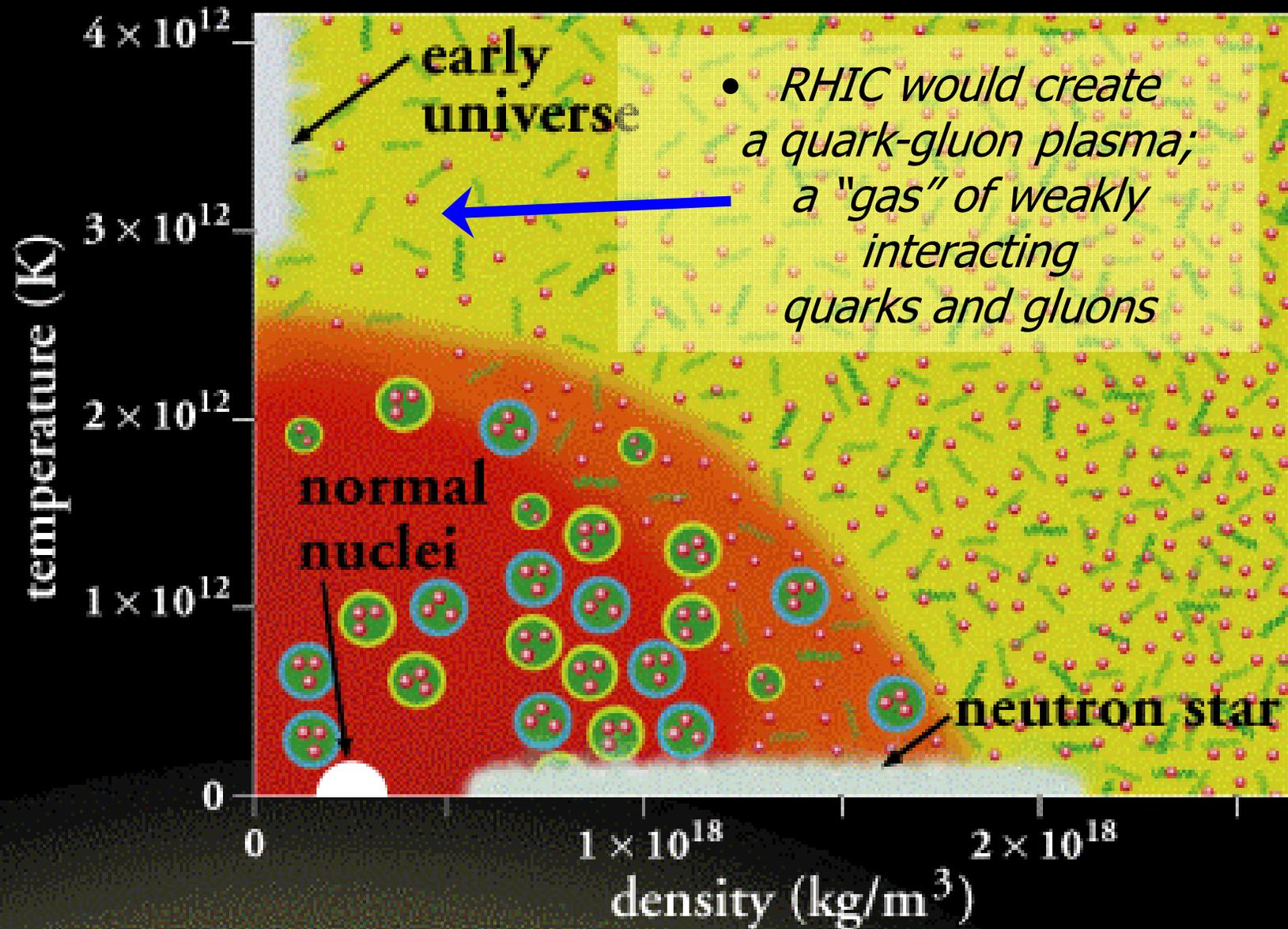
Collide heavy nuclei at the highest possible energies:

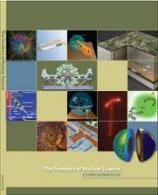


- Fundamental Goals:

- ▶ Create (new) dense forms of nuclear matter
- ▶ Create a *quark-gluon plasma*

# Expectations circa 2000





# The Quark-Gluon Plasma is Not a Gas

- Prejudice circa 2000:

- ▶ Protons and neutrons would 'sublimate' to a gas of quarks and gluons
- ▶ Much like dry ice

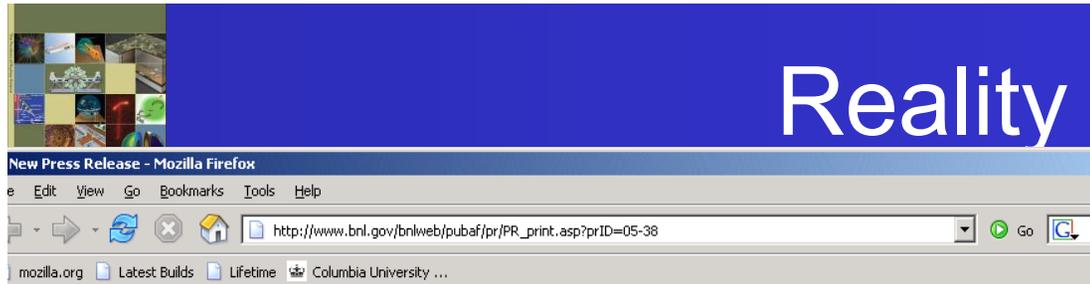


- Discovery circa 2005

- ▶ The quark-gluon plasma is a nearly perfect liquid
- ▶ Something like regular ice to water



# Reality 2005



## Hunting the Quark Gluon Plasma

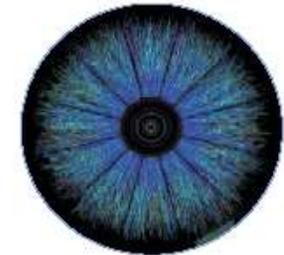
RESULTS FROM THE FIRST 3 YEARS AT RHIC

ASSESSMENTS BY THE EXPERIMENTAL COLLABORATIONS

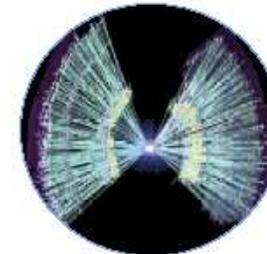
April 18, 2005



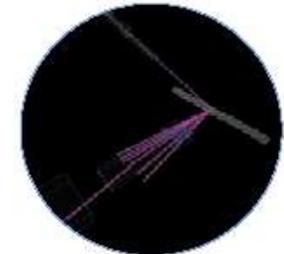
PHOBOS



STAR



PHENIX



BRAHMS

Relativistic Heavy Ion Collider (RHIC) • Brookhaven National Laboratory, Upton, NY | 1974-5000



Contact: Karen McNulty Walsh, (631) 344-8350 or Mona S. Rowe, (631) 344-5056

## RHIC Scientists Serve Up "Perfect" Liquid

New state of matter more remarkable than predicted -- raising many new questions

April 18, 2005

TAMPA, FL -- The four detector groups conducting research at the [Relativistic Heavy Ion Collider](#) (RHIC) -- a giant atom "smasher" located at the U.S. Department of Energy's Brookhaven National Laboratory -- say they've created a new state of hot, dense matter out of the quarks and gluons that are the basic particles of atomic nuclei, but it is a state quite different and even more remarkable than had been predicted. In [peer-reviewed papers](#) summarizing the first three years of RHIC findings, the scientists say that instead of behaving like a gas of free quarks and gluons, as was expected, the matter created in RHIC's heavy ion collisions appears to be more like a *liquid*.

"Once again, the physics research sponsored by the Department of Energy is producing historic results," said Secretary of Energy Samuel Bodman, a trained chemical engineer. "The DOE is the principal federal funder of basic research in the physical sciences, including nuclear and high-energy physics. With today's announcement we see that investment paying off."



Secretary of Energy Samuel Bodman

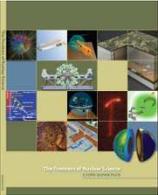
"The truly stunning finding at RHIC that the new state of matter created in the collisions of gold ions is more like a liquid than a gas gives us a profound insight into the earliest moments of the universe," said Dr. Raymond L. Orbach, Director of the DOE Office of Science.

Also of great interest to many following progress at RHIC is the emerging connection between the collider's results and calculations using the methods of string theory, an approach that attempts to explain fundamental properties of the universe using 10 dimensions instead of the usual three spatial dimensions plus time.

"The possibility of a connection between string theory and RHIC collisions is unexpected and exhilarating," Dr. Orbach said. "String theory seeks to unify the two great intellectual achievements of twentieth-century physics, general relativity and quantum mechanics, and it may well have a profound impact on the physics of the twenty-first century."



The papers, which the four RHIC collaborations ([BRAHMS](#), [PHENIX](#), [PHOBOS](#), and [STAR](#)) have been working on for nearly a year, will be published simultaneously by the journal *Nuclear Physics A*, and will also be compiled in a [special Brookhaven report](#), the Lab announced at the April 2005 meeting.



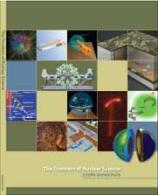
## Recommendation 4

- ☞ The experiments at the Relativistic Heavy Ion Collider have discovered a new state of matter at extreme temperature and density — a **quark-gluon plasma** that exhibits unexpected, almost **perfect liquid** dynamical behavior.
- We recommend implementation of the RHIC II luminosity upgrade, together with detector improvements, to determine the properties of this new state of matter.



# The Future RHIC Program

- “We recommend implementation of the RHIC II luminosity upgrade...
  - ▶ Underway! (technological breakthrough)
    - ~1/7 the cost
    - ~ 4 years early
- ...together with detector improvements ...
  - ▶ Underway
- ...to determine the properties of this new state of matter.”
  - ▶ Thermodynamics, equation of state of perfect liquid
  - ▶ Search for the critical point in its phase diagram



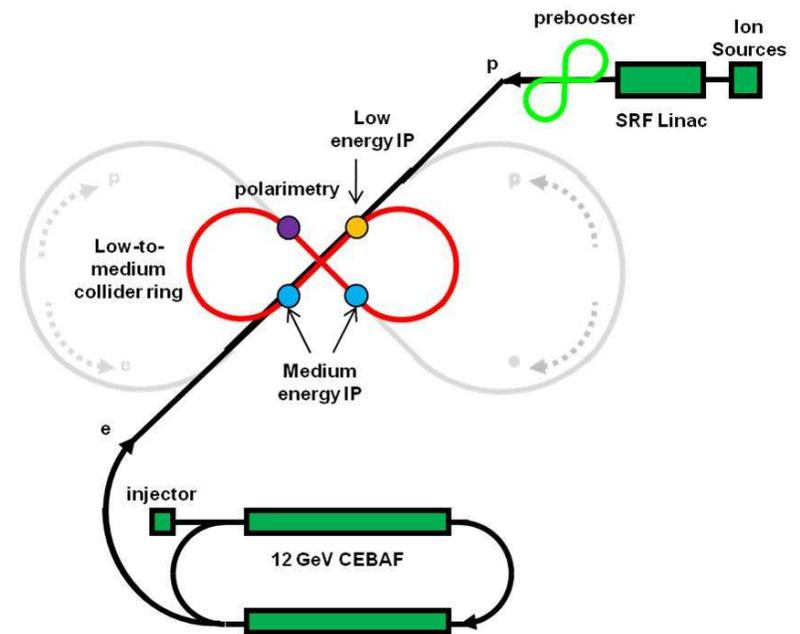
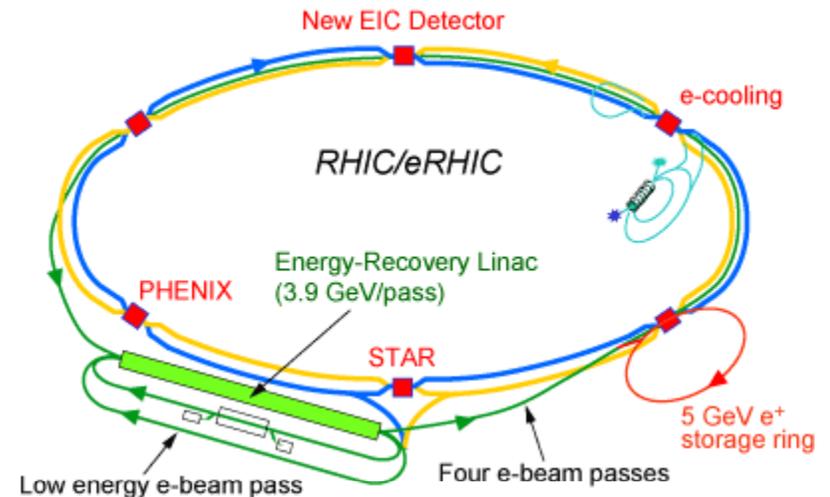
## Further Into The Future

- We recommend the allocation of resources to develop accelerator and detector technology necessary to lay the foundation for **a polarized Electron-Ion Collider.**
- The EIC would explore the new QCD frontier of strong color fields in nuclei and precisely image the gluons in the proton.



# Electron Ion Collider

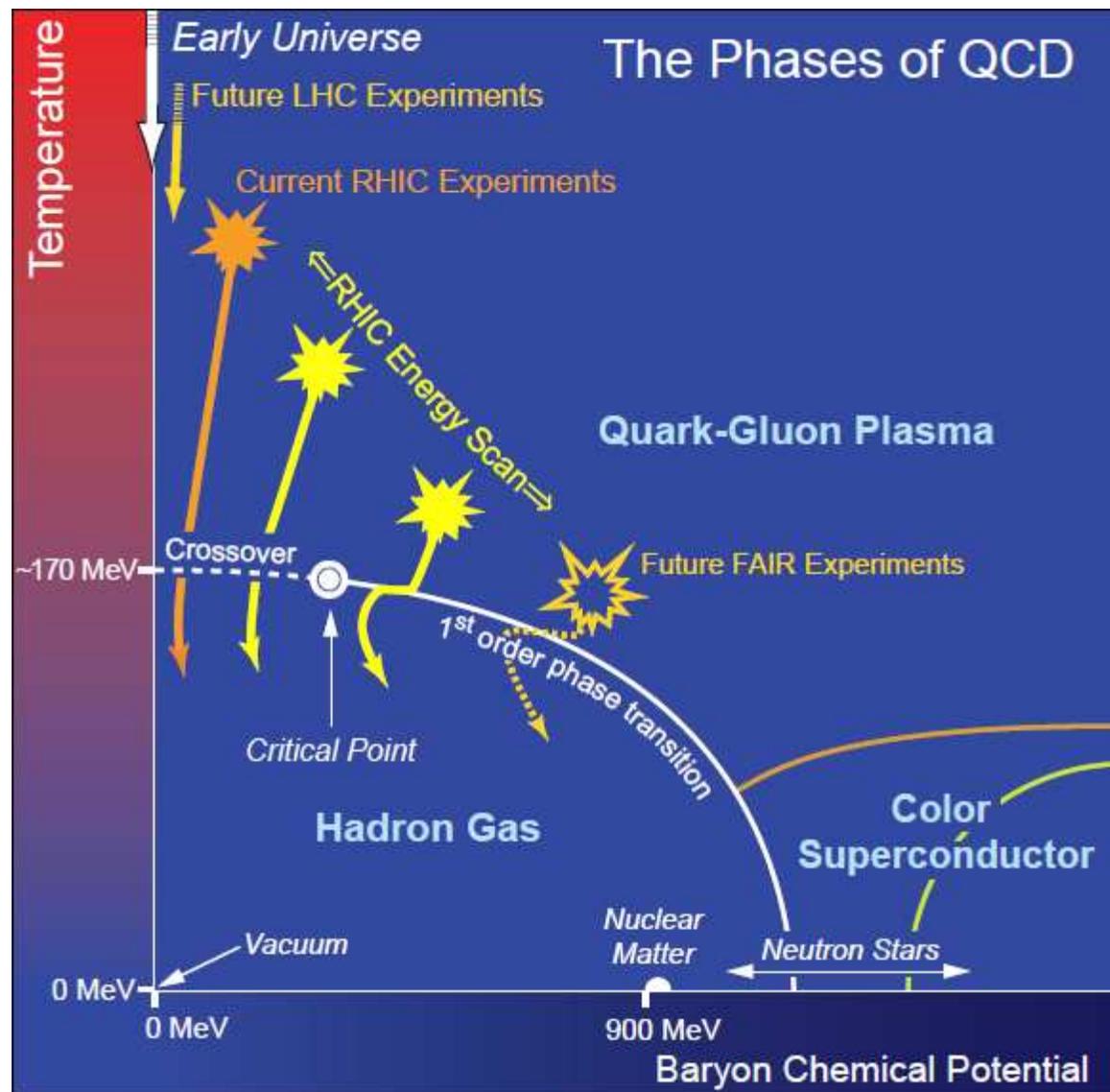
- Would greatly expand our understanding of the proton's spin.
  - ▶ Underway at RHIC
  - ▶ Underway at JLab
- Would allow study of the strongest force fields found in nature, deep inside the nucleus

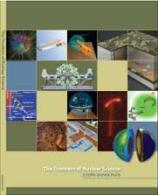




# Summary

- Long range planning has enabled extraordinary advances in nuclear science for more than a quarter-century
- Future plans provide for same in
  - ▶ The structure of strongly interacting particles
  - ▶ Nuclear structure and astrophysics
  - ▶ Neutrinos and fundamental symmetries
  - ▶ The phases of nuclear matter
- A rich, diverse scientific program for decades





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