The Frontiers of Nuclear Physics

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October 12, 2017

Working Group 9 Mandate

•Maintain a compendium of facilities existing or developing worldwide; include the science issues in NP for next decade

•Show a mapping of facilities onto the scientific questions

•Identify missing components that are needed to provide a comprehensive network of international facilities

•Explore mechanisms to enhance international collaboration

•Identify R/D projects that could benefit from international effort

•Serve as a source of expert advice for governmental or inter-governmental organizations

•Serve as a forum for the discussion of future directions of nuclear science in the broadest sense – Nuclear Science Symposium

•Cross disciplinary impact of Nuclear Physics and of nuclear facilities and identify mechanisms for expanding (fostering) cross disciplinary research

Major Questions in Nuclear Physics (from the IUPAP WG.9 Facilities report)

- Can the structure and interactions of hadrons be understood in terms of QCD?
- What is the structure of nuclear matter?
- What are the phases of nuclear matter?
- What is the role of nuclei in shaping the evolution of the universe?
- What physics is there beyond the Standard Model?

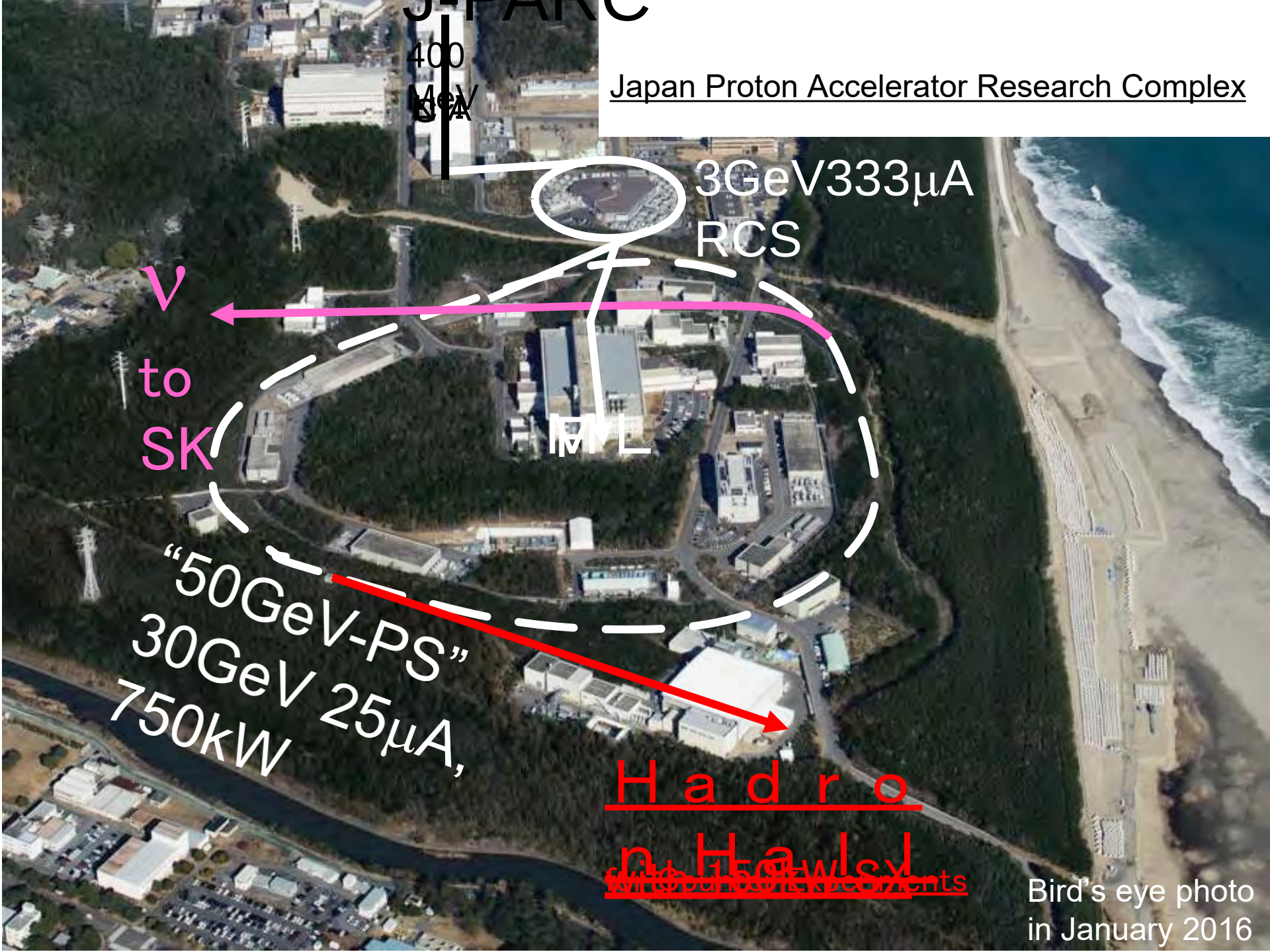
Can the structure and interactions of hadrons be understood in terms of QCD?

- All hadrons are composites made of quarks and gluons

- Quantum Chromo Dynamics (QCD) is the theoretical framework to describe the interactions between quarks and gluons but it is enormously complicated to solve

- Experimenters working at multiple major facilities are providing input to help develop and confirm the theoretical tools that also are being developed to understand hadronic structure

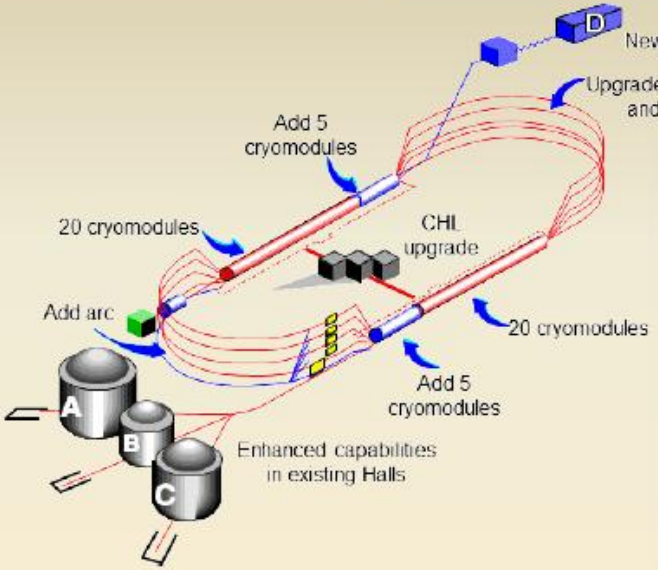
Major Facilities for Hadron Structure



Japan Proton Accelerator Research Complex

JLab 12 GeV Upgrade – Path to Completion

Completion of the 12 GeV CEBAF Upgrade was ranked the highest priority in the 2007 NSAC Long Range Plan.



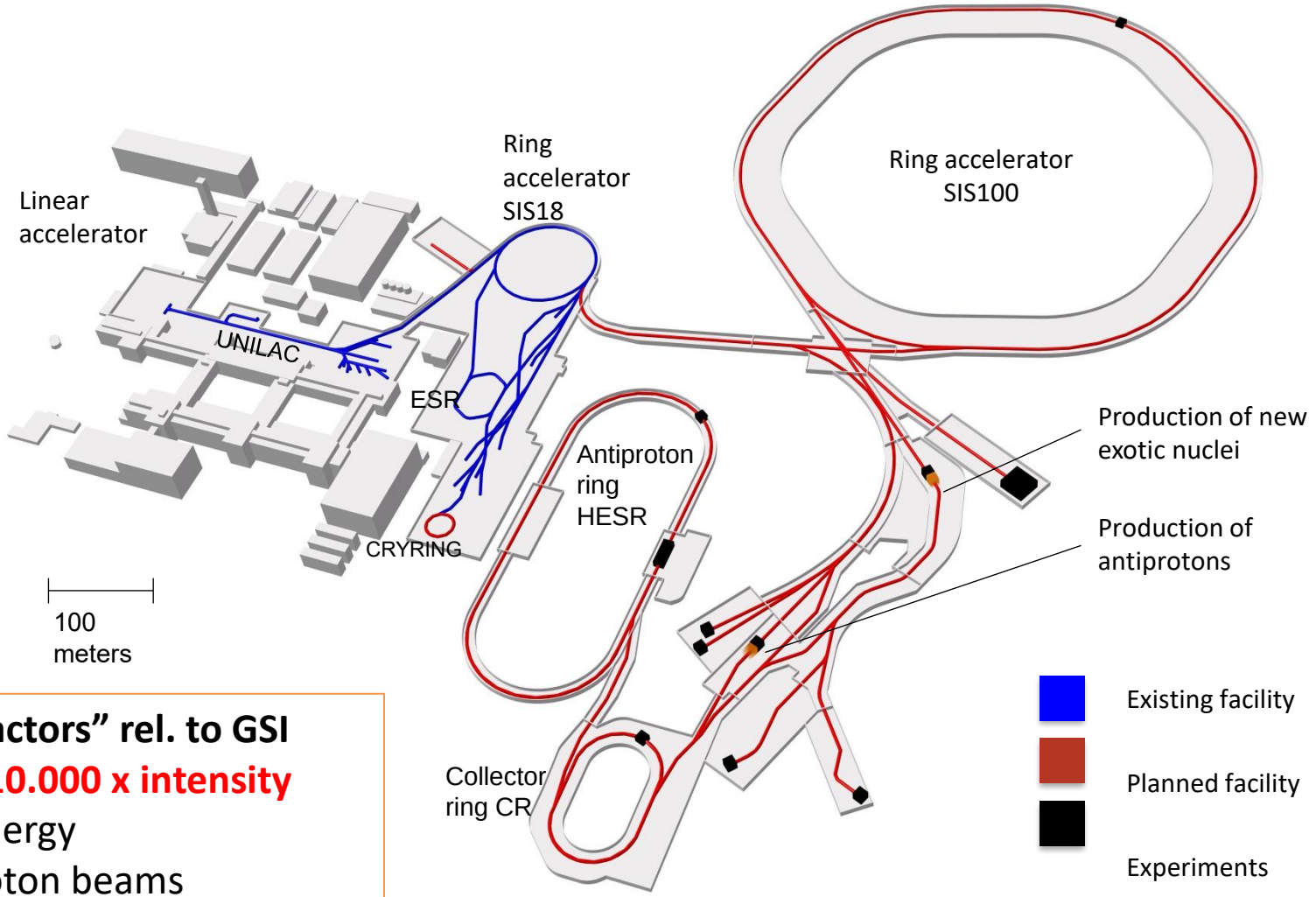
Total Project Cost = $338M
Estimate to Complete = $1.2M

Project now complete!

Project (99.7% complete):

- Doubling the accelerator beam energy – DONE
- Civil construction including utilities – DONE
- New experimental Hall D and beam line – DONE
- Upgrade to Experimental Hall C – DONE
- Upgrade to Experimental Hall B – 99%
  - Solenoid magnet only remaining scope

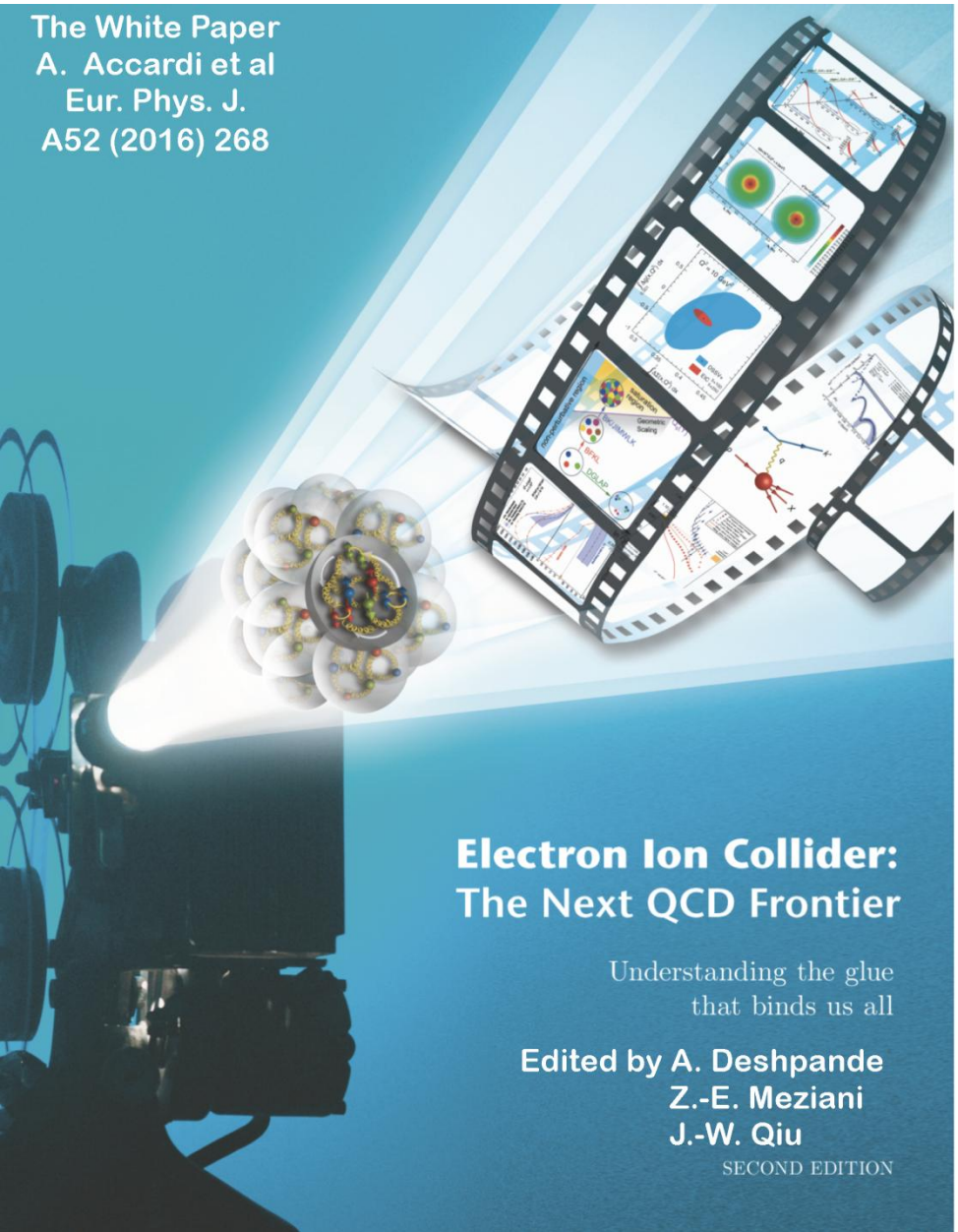
FAIR – The Facility

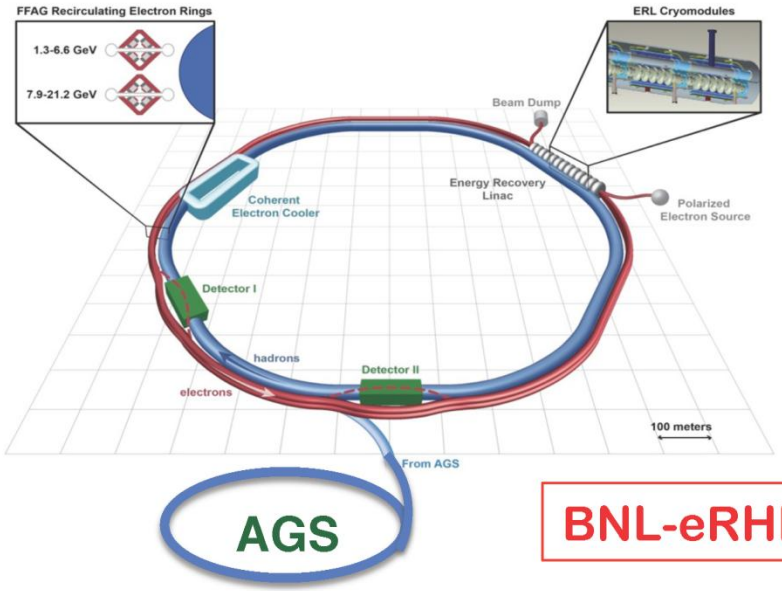


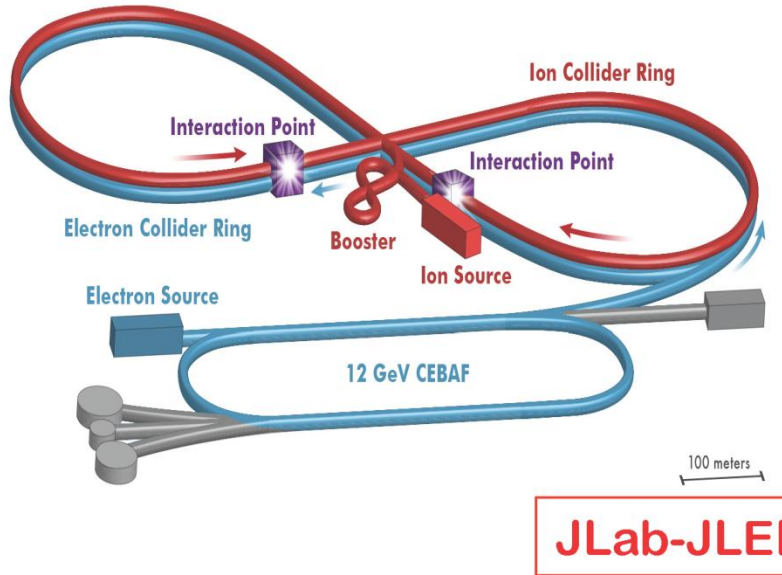
“Gain factors” rel. to GSI

- **100 – 10.000 x intensity**
- 10 x energy
- antiproton beams

The Future – an Electron Ion Collider

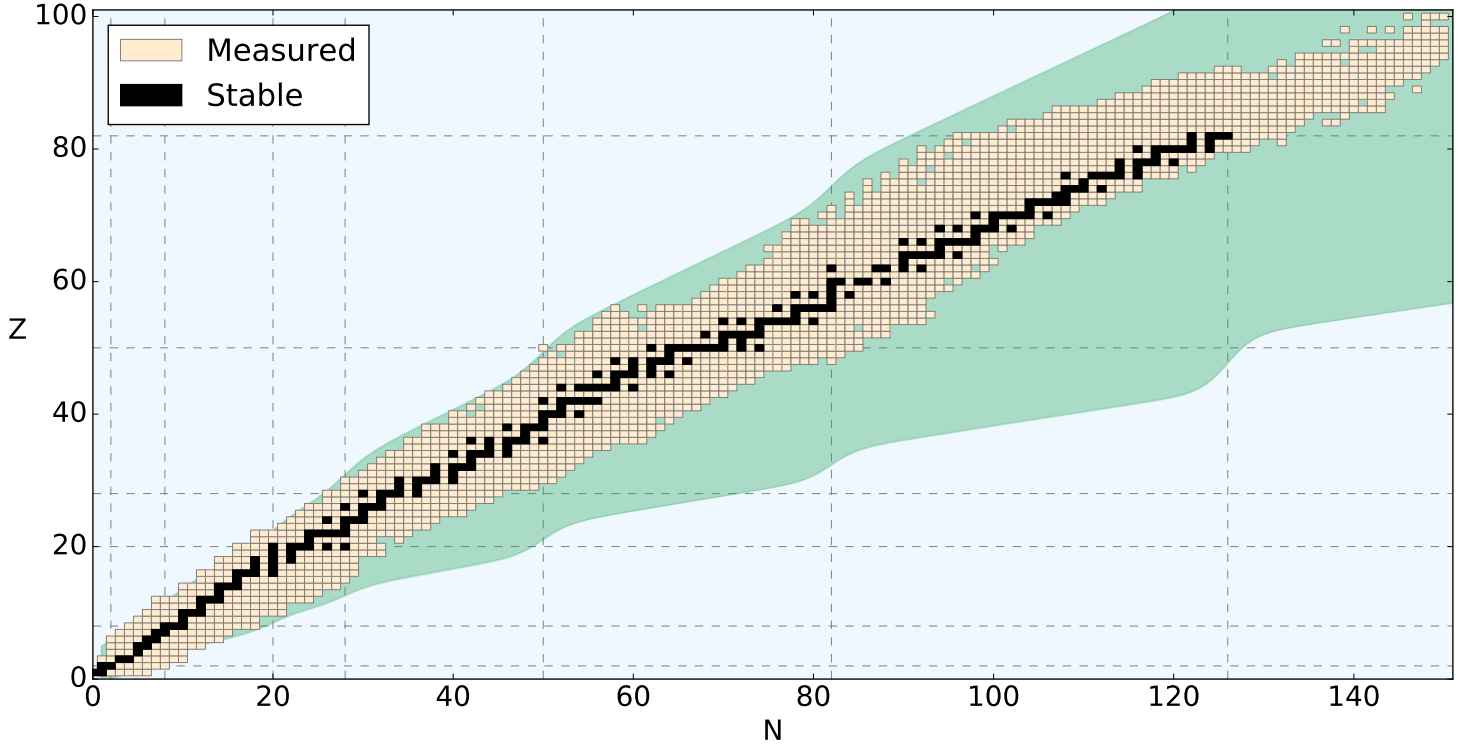






What is the structure of nuclear matter?

•Predicting properties of nuclei across the full nuclear landscape is a long-standing problem



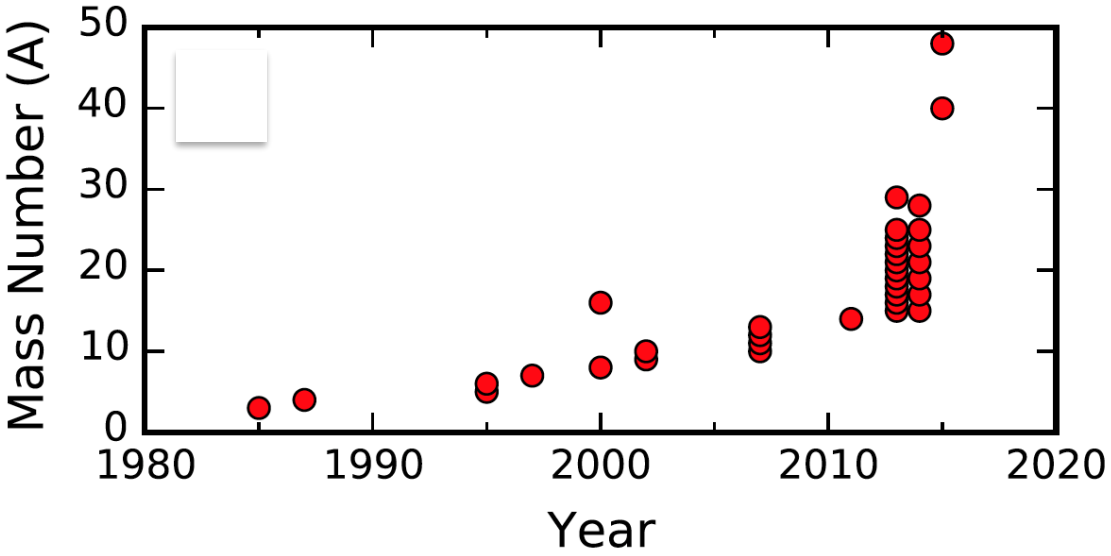
Chronological Reach of Ab Initio Many-Body Methods

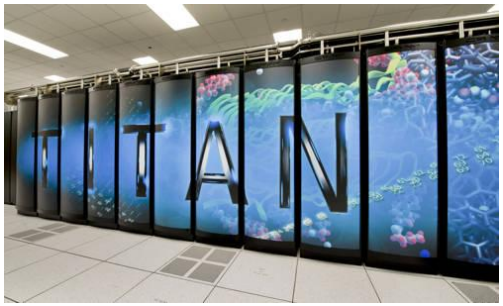
Moore's law: exponential growth in computing pow

2017: A>100

Methods for light nuclei (QMC, NCSM) scale exponentially with mass

Mid 2000's **polynomial scaling methods developed** (coupled cluster, in-medium SRG,…)
Explosion in limits of ab initio theory





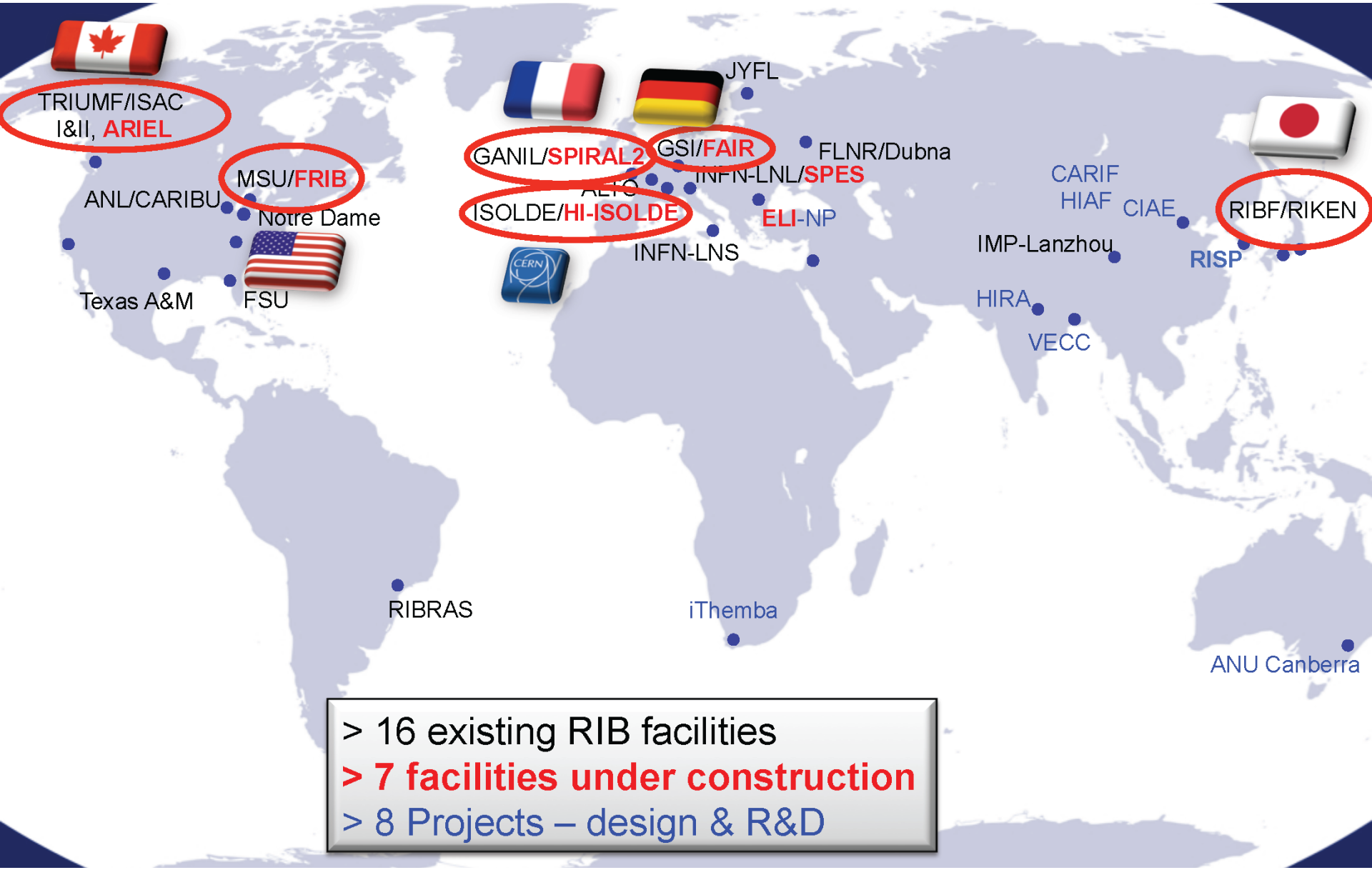
What is the structure of nuclear matter?

- Predicting properties of nuclei across the full nuclear landscape is a long-standing problem
- Effective field theories are making significant progress
- A comprehensive, predictive theory of complex nuclei is a key goal of the field – nuclei off of stability now known to be critical for this

Many Regional Facilities Being Built

or Upgraded to produce Radioactive Ion Beams

Existing and next-generation RIB Facilities



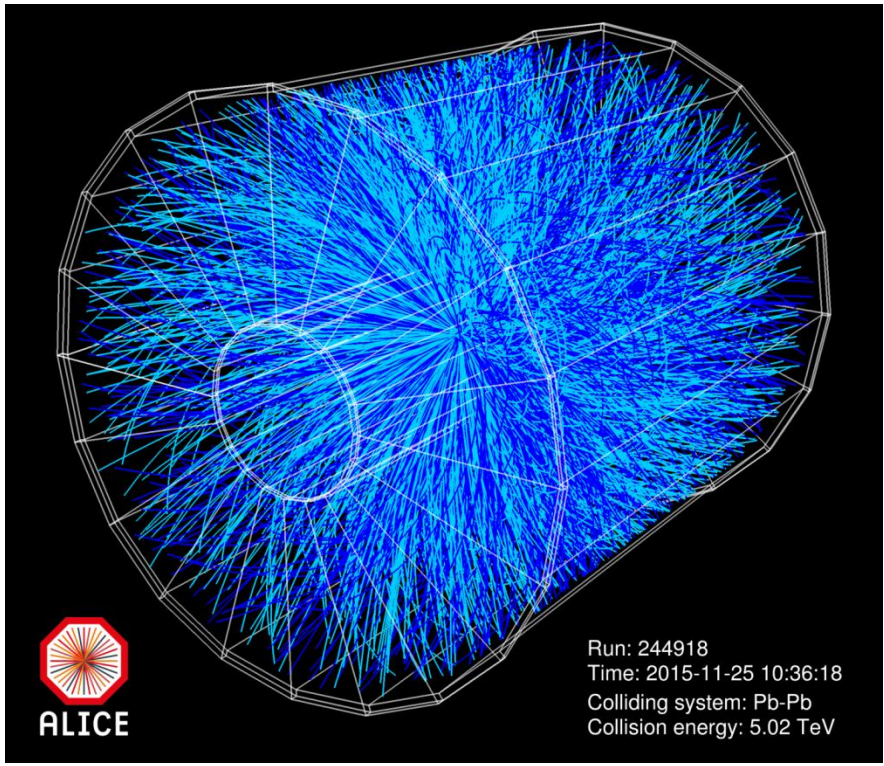
> 16 existing RIB facilities
> **7 facilities under construction**
> 8 Projects – design & R&D

$4-5 Billion worldwide investment

What are the phases of nuclear matter?

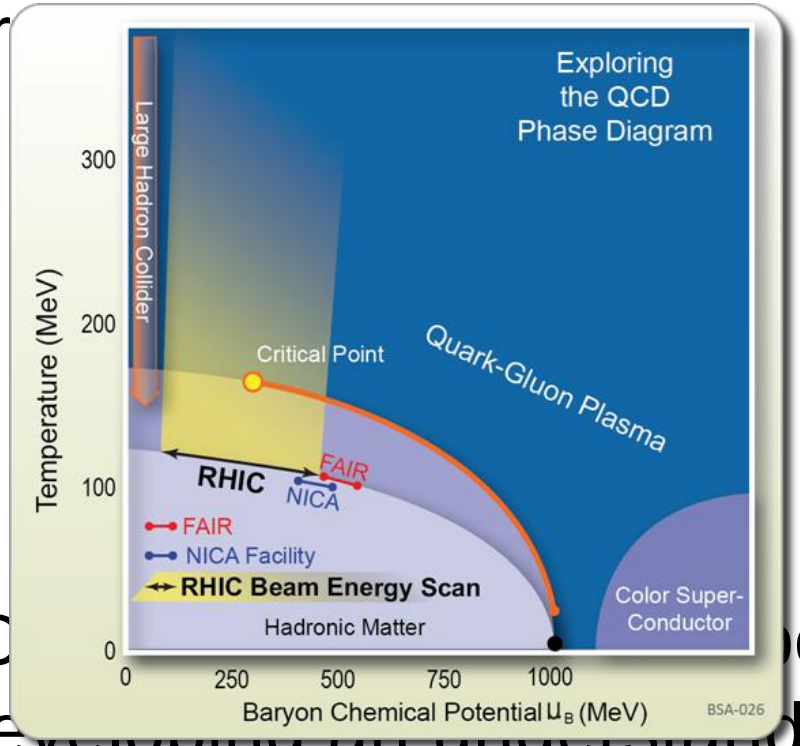
- The quark-gluon plasma phase now known to be liquid with an entropy density near quantum limit from RHIC at BNL and LHC

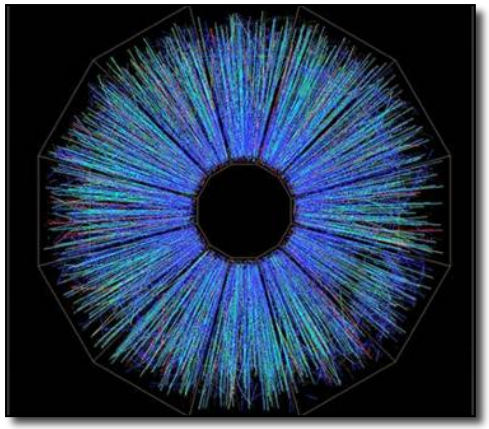
RHIC complex



What are the phases of nuclear matter?

•The transition from hadrons to quarks and gluons forms a phase diagram with properties like or





STAR Collaboration

•D oint is next step in developing an understanding of phase diagram for hadronic matter

What is the role of nuclei in shaping the evolution of the universe?

- Transition in early universe from QGP to protons and small amounts of He, and Li
- Coalescence into first stars started nucleosynthesis

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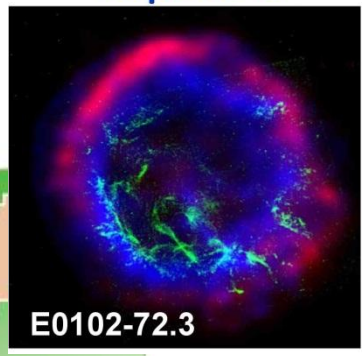
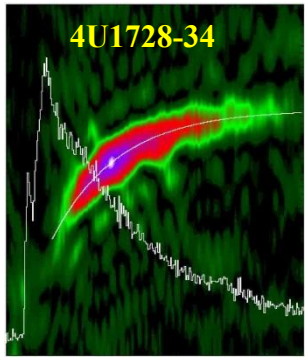
- **Many processes occur in stellar evolution**

The Nuclear Landscape in the Cosmos

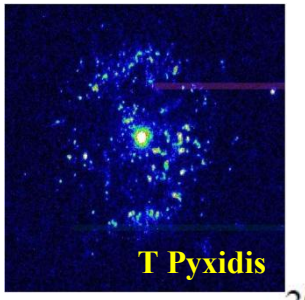
Supernova



X-ray burst



Nova



Neutron star

Hydrogen and helium burning in stars

What is the role of nuclei in shaping the evolution of the universe?

- Transition in early universe to protons and small amounts of He, and Li
- Coalescence into first stars started nucleosynthesis
- Many processes occur in stellar evolution
- **For lighter nuclei, full understanding of evolution requires reaction rates of unstable nuclei**
- **For the heaviest nuclei, must understand the r-process, which requires knowledge of neutron-rich nuclei**

The Tools for Nuclear Astrophysics

- New RIB facilities for radioactive beams and access to very neutron-rich nuclei
- High-intensity light ion beams at low energy for direct measurements
- Accelerators in underground facilities for very-low cross section reactions
- Extensive modeling and network calculations

What physics is there beyond the Standard Model?

- Standard Model has been remarkably resilient when pitted against experiments since its introduction more than 5 decades ago
- Issues that suggest physics beyond it
  - The matter-antimatter asymmetry in the universe
  - The complicated neutrino sector
  - The expectation that other forces existed in the early universe that we no longer see
- Both nuclear and particle/high-energy physics efforts aimed at searching for SM breakdown

(Mostly) Nuclear Physics Efforts

- Low-energy processes in β and μ decay
  - –RIB facilities, TRIUMF, J-PARC, . . .
- Searches for an Electric Dipole Moment in neutron and nuclei (T-reversal)
  - –Spallation Neutron Source, Reactors, . . .
- Precision measurement of anomalous moment (g-2) of muon
  - –Fermilab, J-PARC
- Parity violating electron scattering for ‘running’ of $\sin^2\theta_W$
  - –JLab
- Symmetries in antimatter (antihydrogen)
  - –CERN, GSI/FAIR

The Vibrant Field of Nuclear Physics

- Wide range of problems being attacked to understand the interactions that govern the evolution of the universe
- Multi-billion $ investments being made around the world in new capabilities
- The field continues to have many applications, e.g. in areas such as medicine, accelerators for industry and power