LINAC 16

28TH LINEAR ACCELERATOR CONFERENCE

East Lansing, MI USA
25-30 September

Worldwide Direction on Nuclear Science and Application

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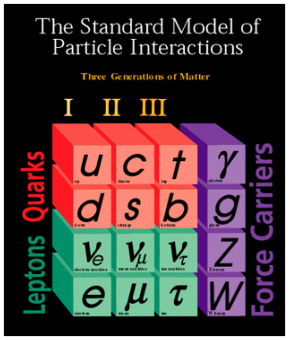
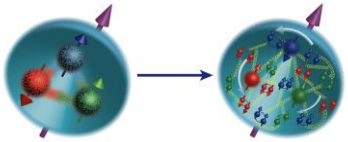
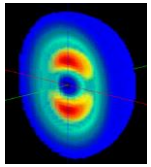
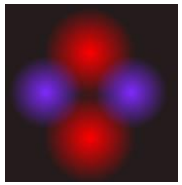
21st Century Nuclear Science

Probing nuclear matter in all forms and exploring applications



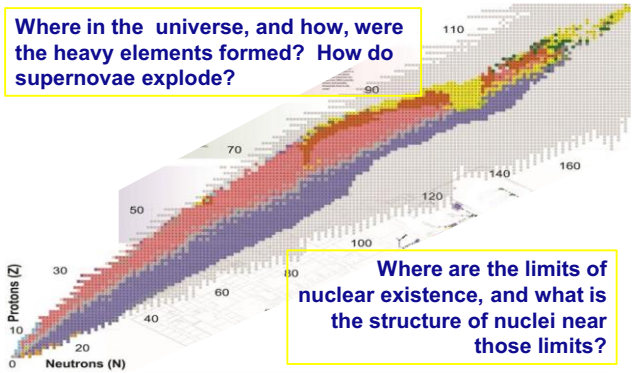




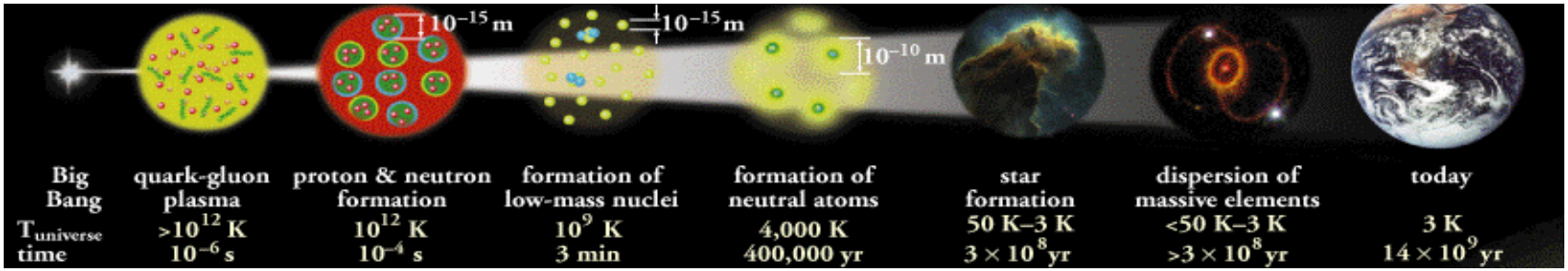


How are the properties of protons and neutrons, and the force between them, built up from quarks, antiquarks and gluons? What is the mechanism by which these fundamental particles materialize as hadrons?

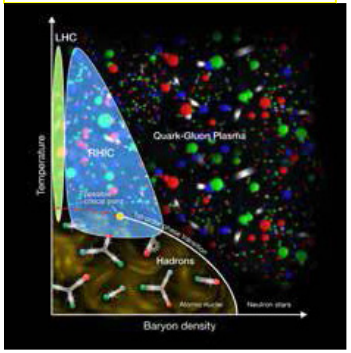
Where in the universe, and how, were the heavy elements formed? How do supernovae explode?



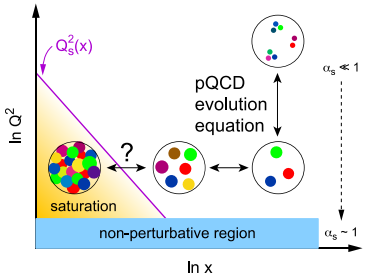
Where are the limits of nuclear existence, and what is the structure of nuclei near those limits?



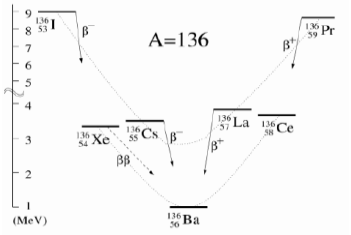
What is the nature of the different phases of nuclear matter through which the universe has evolved?



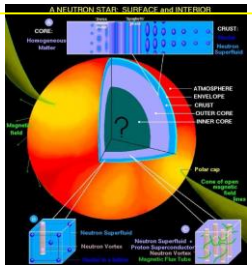
Do nucleons and all nuclei, viewed at near light speed, appear as walls of gluons with universal properties?



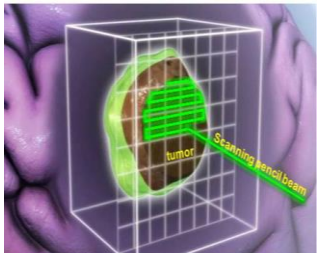
How can the properties of nuclei be used to reveal the fundamental processes that produced an imbalance between matter and antimatter in our universe?



How are the nuclear building blocks manifested in the internal structure of compact stellar objects, like neutron stars?



How can technologies developed for basic nuclear physics research be adapted to address society's needs?

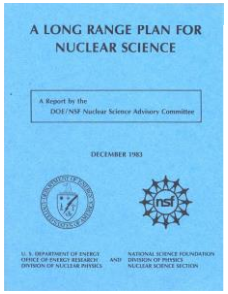


Nuclear Scientists Articulate Accelerator Needs Based on Science Drivers

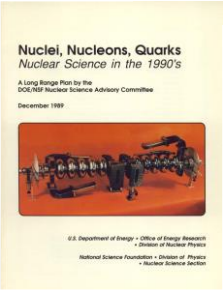
- NuPECC – working on the next long range plan now, town meetings coming up. 2010 LRP report recommended many LINAC projects
  - FAIR, SPIRAL2, HIE-ISOLDE, SPES, Superconducting LINAC for superheavy element at GSI, Future facilities: EURISOL, ISOL@MYRRHA
- Canadian Five-Year Plan 2017-2021 Recommendations
  - TRIUMF ISAC ARIEL, SNOLAB, ATLAS, T2K
- LINAC plans in Japan, South Korea, China, …
- US –Long Range Plan published in 2015
  - 12 GeV, FRIB, EIC

1979

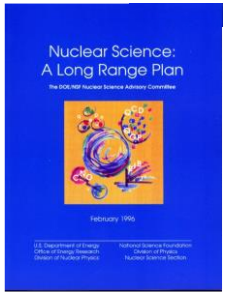
1983



1989



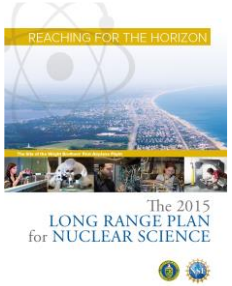
1996



2002

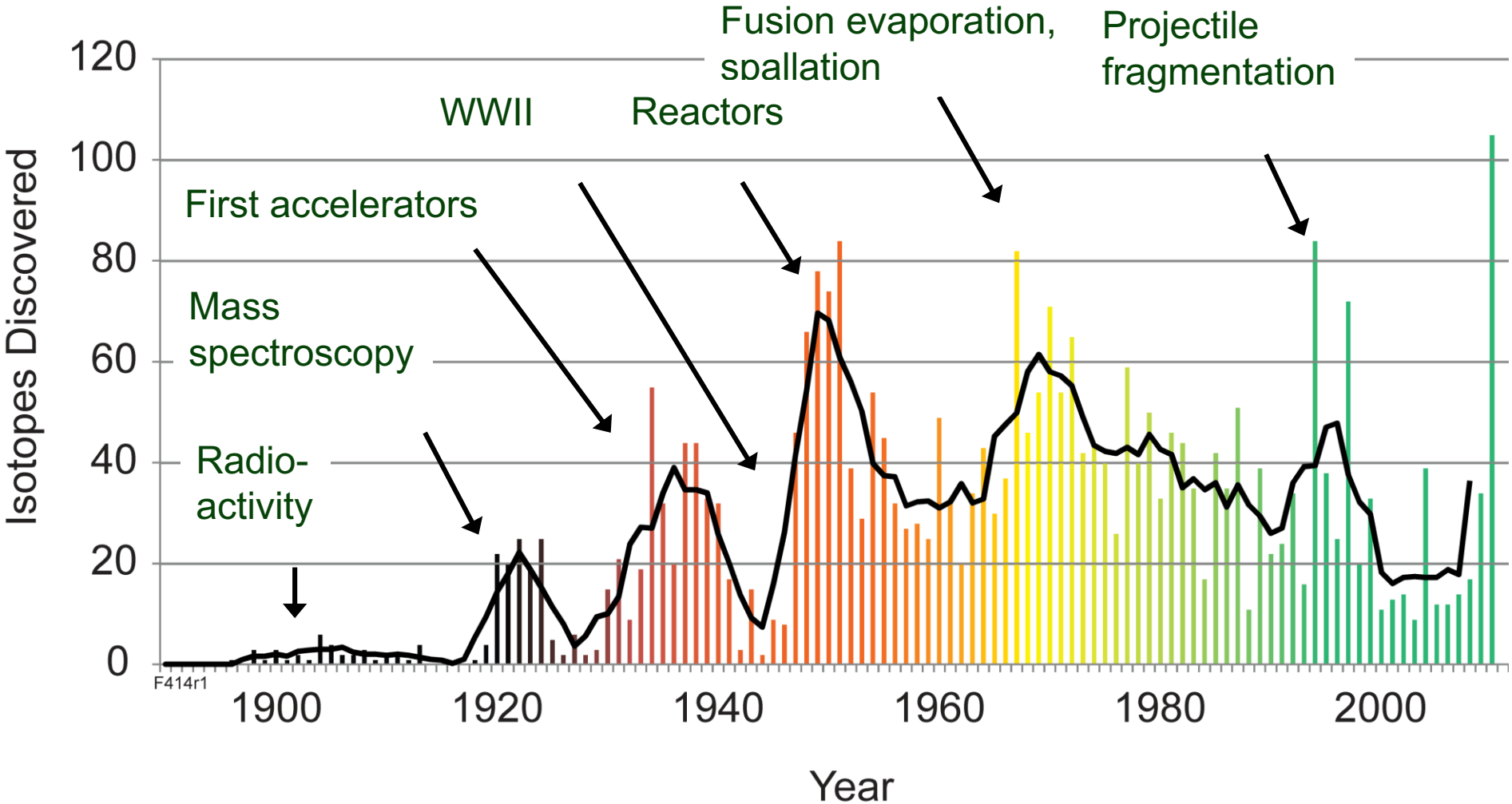
2007

2015



- Science drives machine development ↔ Machine capability drives scientific discoveries

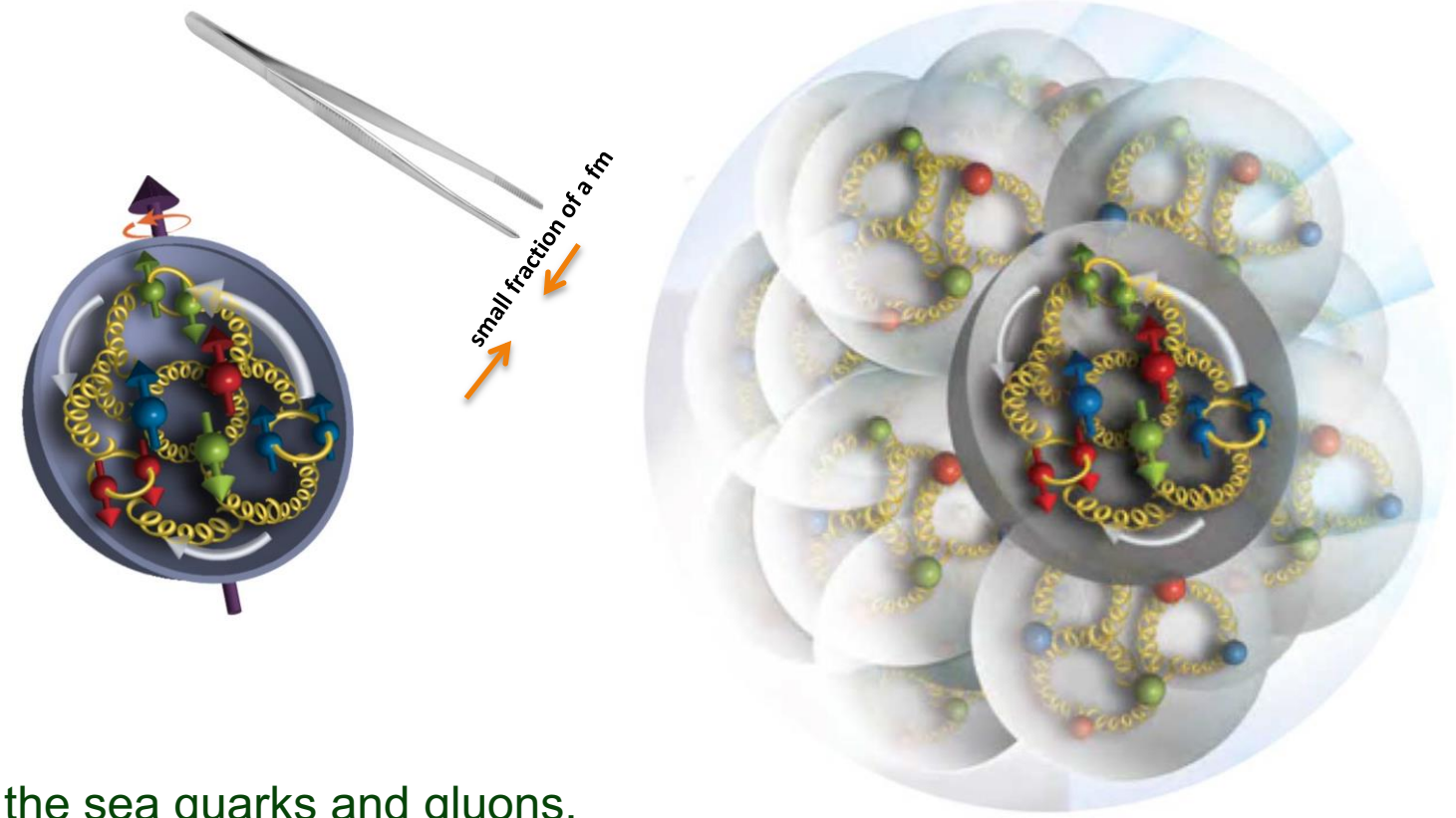
Machine capability drives discoveries:
New Isotope Discoveries Facilitated by Accelerators



Thoennessen and Sherrill, Nature 473 (2011) 25
www.nscl.msu.edu/~thoennes/isotopes/

Electron Ion Collider Physics Program

Exploration and 3D mapping of nucleons in terms of quarks and gluons



- How are the sea quarks and gluons,
  and their spins, distributed in space and momentum inside the nucleon?
- What is the role of the orbital motion of sea quarks and gluons in building the nucleon spin?
- Where does the saturation of gluon densities set in?
- How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei?

Electron Ion Collider (U.S. version)

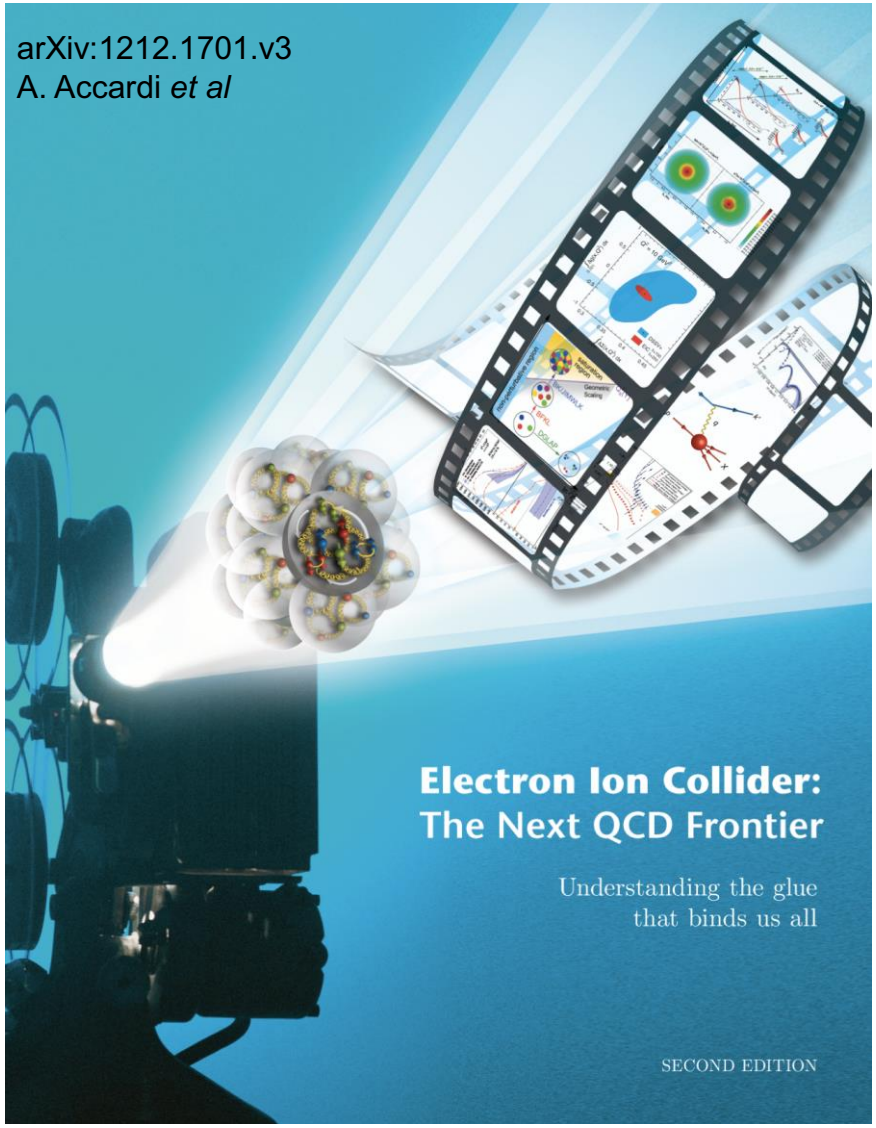
For e-N collisions at the EIC:

- ✓ Polarized beams: e, p, d/^{3}He
- ✓ e-beam 3-10(20) GeV
- ✓ Luminosity $L_{ep} \sim 10^{33\text{-}34}$ cm^{-2}sec^{-1}
  100-1000 times HERA
- ✓ 20-~100 (140) GeV variable CoM

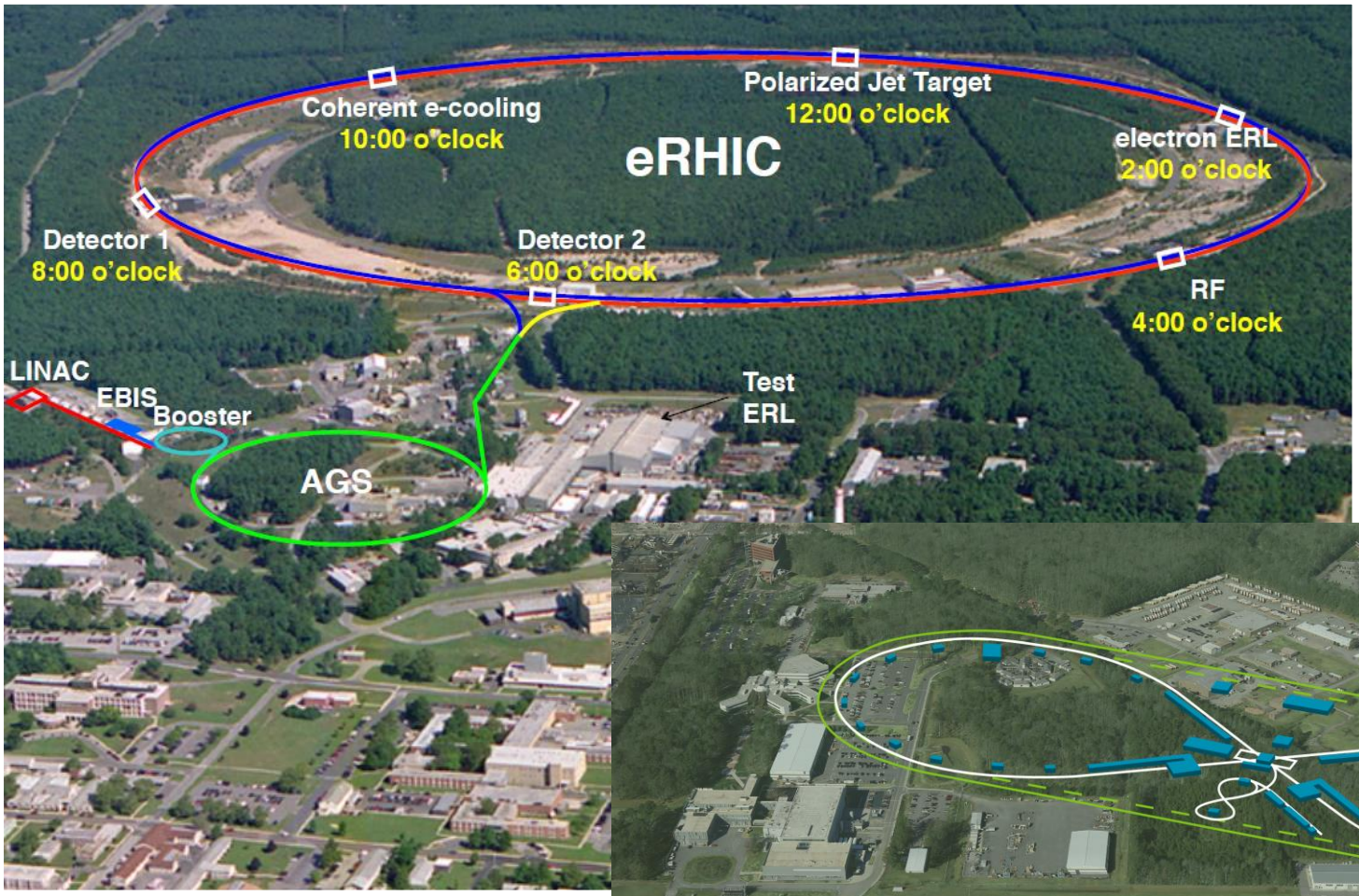
For e-A collisions at the EIC:

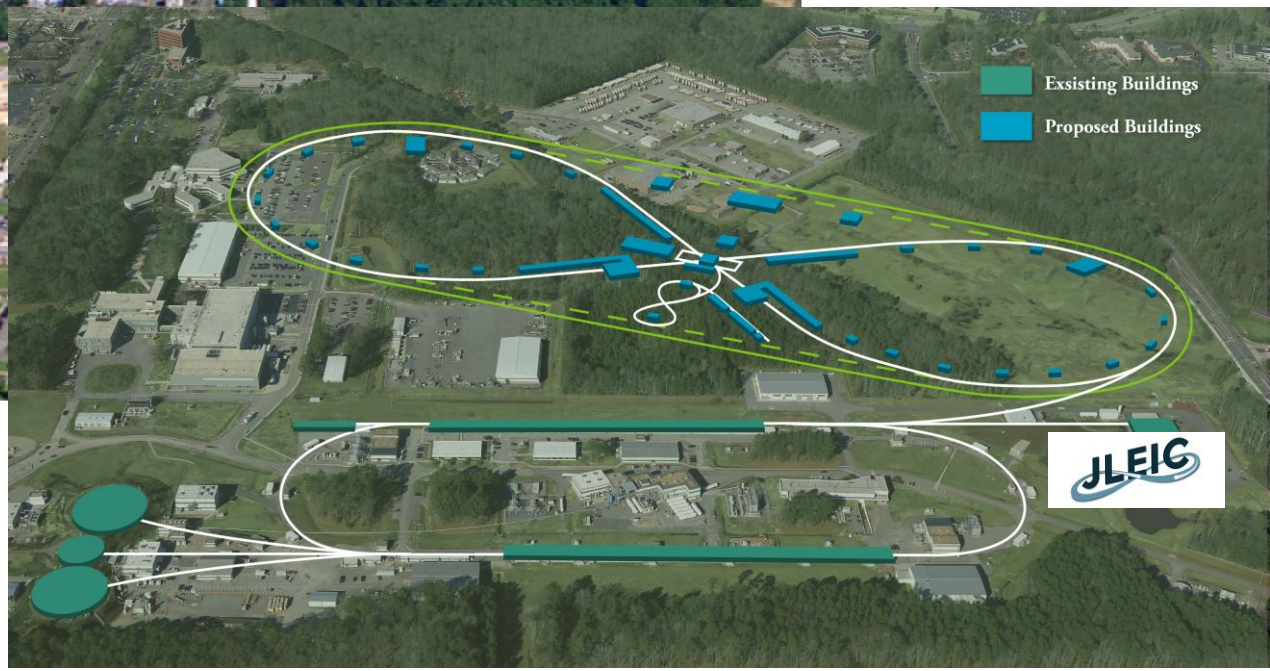
- ✓ **Wide range in nuclei**
- ✓ Luminosity per nucleon same as e-p
- ✓ Variable center of mass energy

First polarized electron-proton/light ion and electron-Nucleus collider



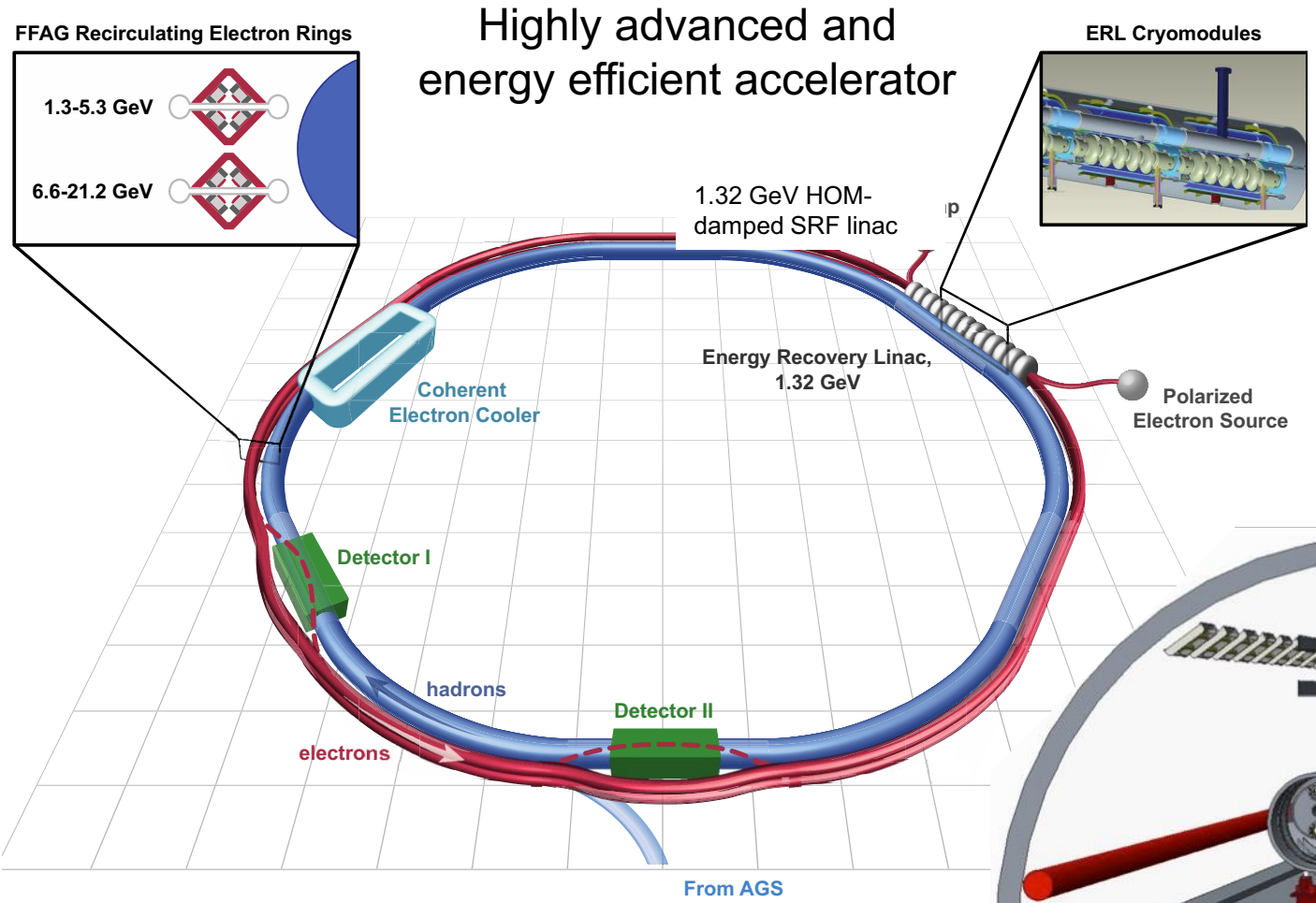
US-Based EIC Proposals

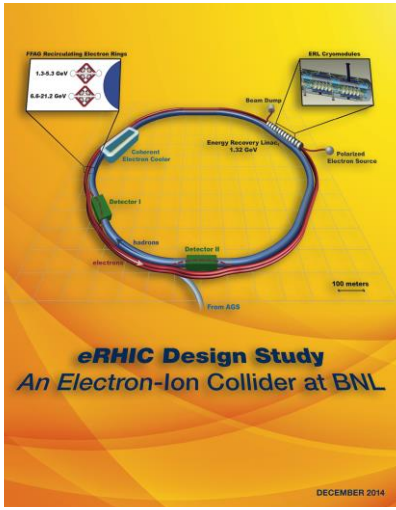


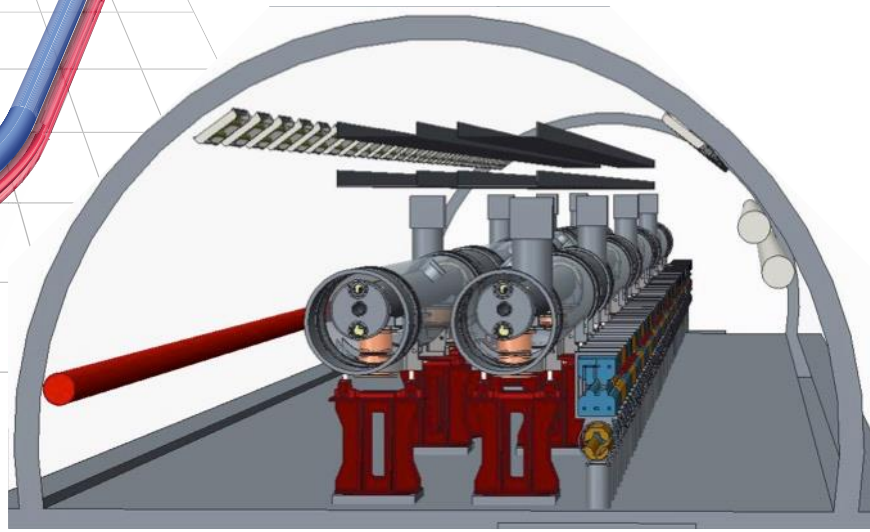


eRHIC Baseline Design at Brookhaven National Laboratory

arXiv:1409.1633

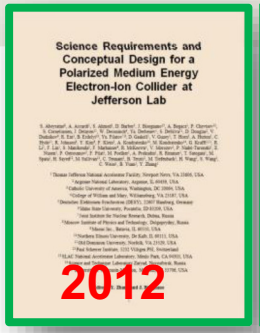


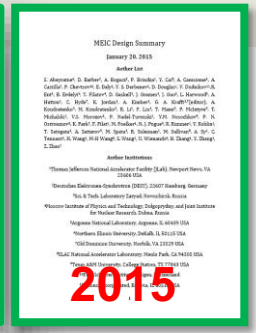




- Peak luminosity 2×10^{34} cm^{-2} s^{-1} for $\sqrt{s}$ ~ 70-105 GeV (250 GeV p↑)
  - Low-risk luminosity ~ $5\text{-}9 \times 10^{32}$ cm^{-2} s^{-1}

JLEIC Baseline Design at Jefferson Laboratory





arXiv:1209.0757 arXiv:1504.07961

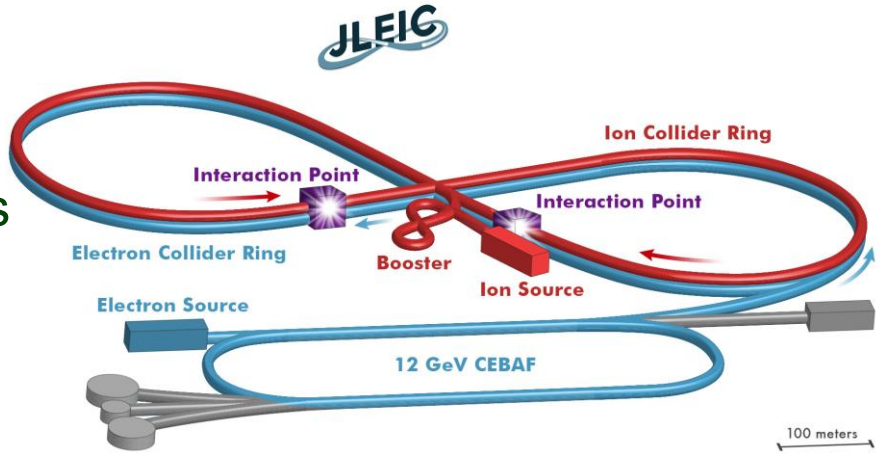
Features:

- Collider ring circumference: ~2100 m
- Electron collider ring and transfer lines : PEP-II magnets, RF (476 MHz) and vacuum chambers
- Ion collider ring: super-ferric magnets (3T)
- Booster ring: super-ferric magnets
- SRF ion linac

- Low-risk luminosity ~ 5-10 × 10^{33} cm^{-2} s^{-1}
  √s ~ 20-65 GeV (100 GeV p↑)

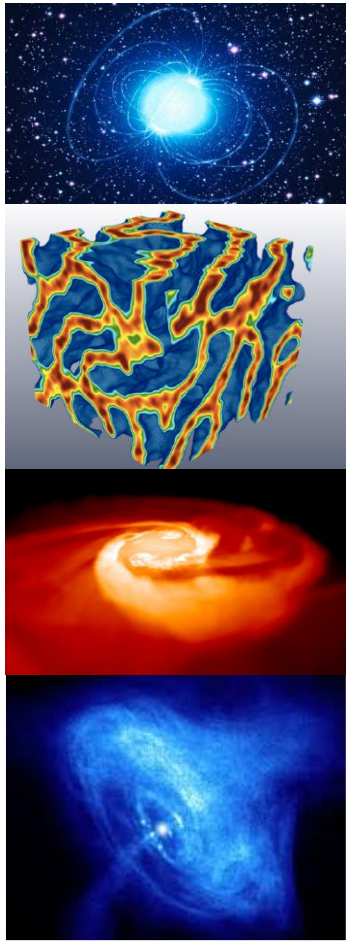
Goals:

- Balance of civil construction versus magnet costs and risks
- Aim overall for low technical risks



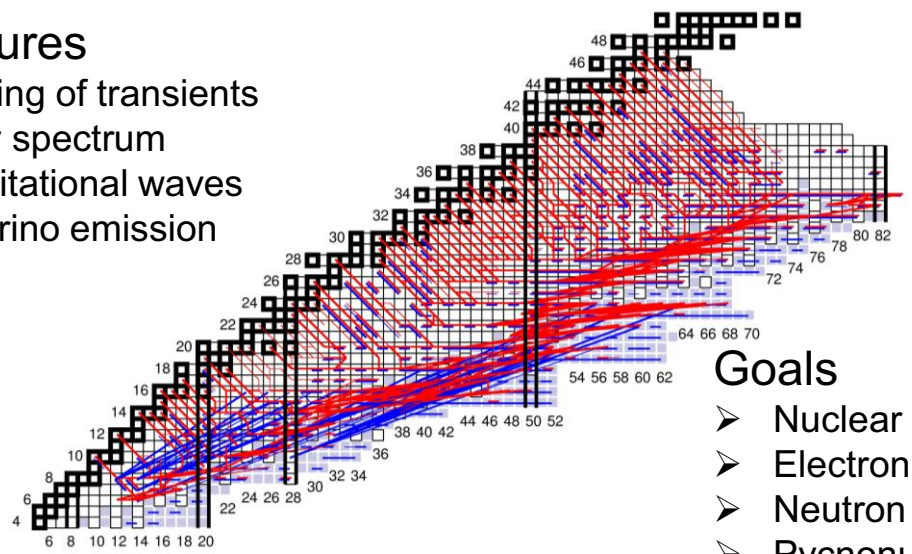
What is the Nature of Dense Matter?

- What is the equation of state for neutron star matter
- Transition from nuclei to nuclear pasta
- What is its effect on isolated neutron stars, thermonuclear bursts, superbursts, neutron star mergers, and supernova observables?
- How can we address the question using accreting neutron star observations, Advanced LIGO results and FRIB experiments?



Signatures

- Cooling of transients
- x-ray spectrum
- Gravitational waves
- Neutrino emission

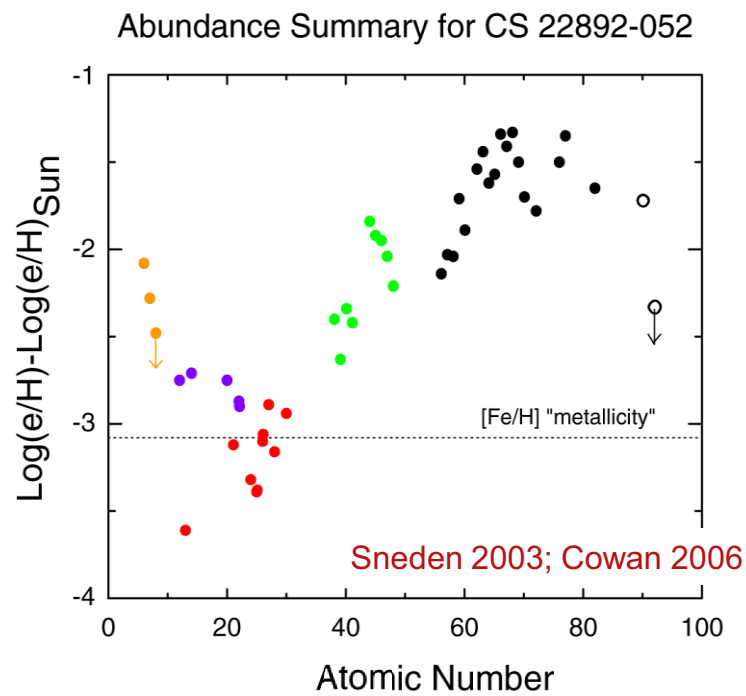


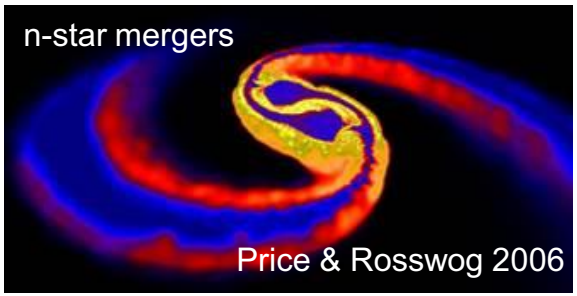
Goals

- Nuclear reactions far of stability
- Electron capture and decay processes
- Neutron capture and photodisintegration
- Pycnonuclear fusion

What are the Nuclear Reactions that Drive Stars and Stellar Explosions?

- Use observational data to infer conditions at the site
- Accurate modeling requires
  - that we make the same isotopes that participate in astrophysical environments
  - reproduce the nuclear reactions that occur in those environments
- The hard part is that nature produces isotopes in environments like the r-process with $T > 10^9$ K, $\rho_{neutron} \approx 10^{20\text{-}28}$ cm^{-3}

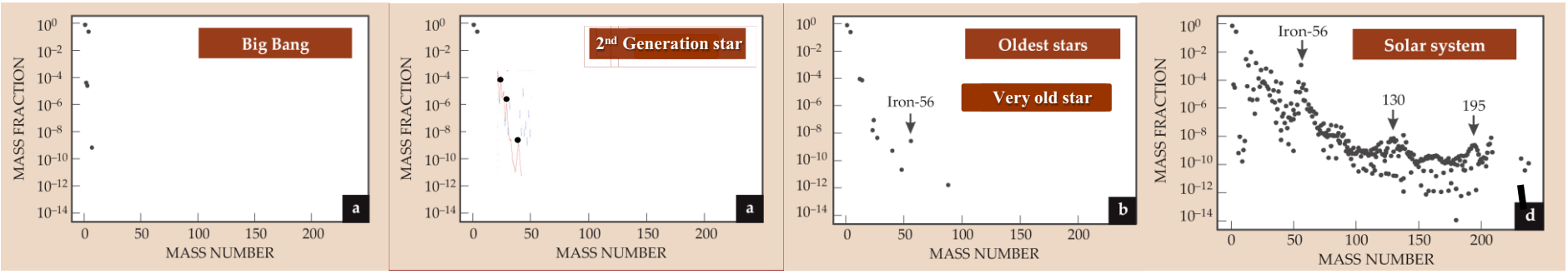


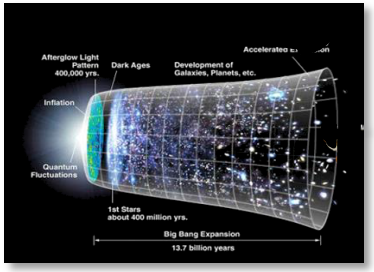


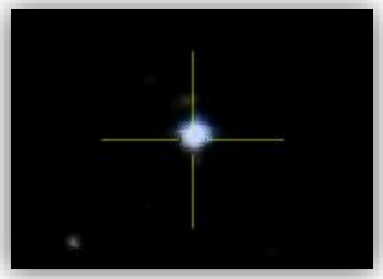
Crab Nebula

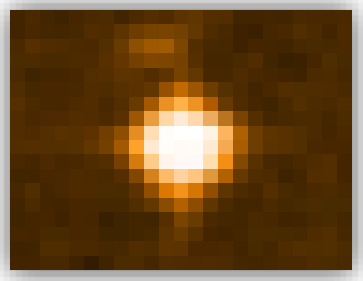
What is the Origin of the Elements?

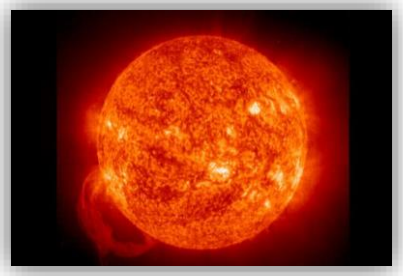
- What nuclear processes contribute to the origin of elements
- How did the chemical composition of the universe evolve?







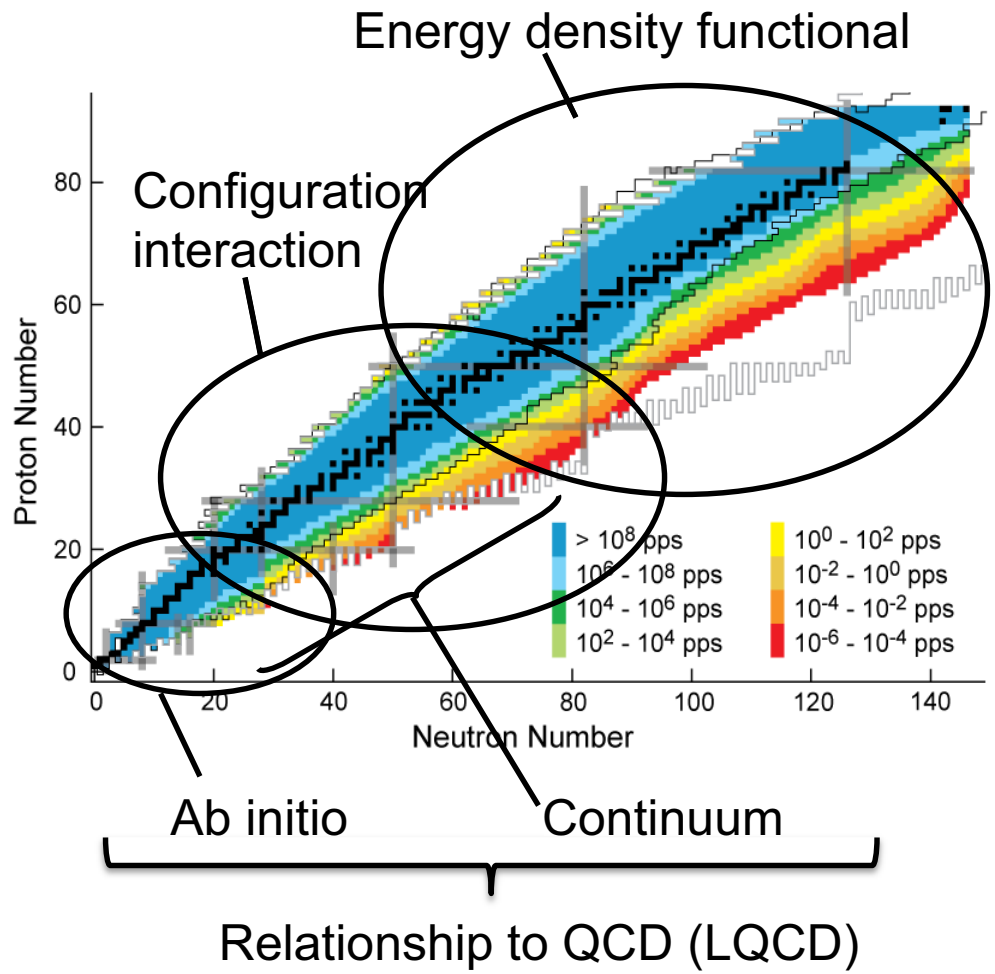




Big Bang – Li Problem – what is primordial abundance?
Early Stars – dynamic nucleosynthesis – how are C and O formed?
Quiescent burning and seed material – what are burning and ignition conditions
r-process, s-process, p-process, i-process and the origin of the heavy materials
Weak interaction and neutrino physics in Big Bang, core collapse, and dense objects

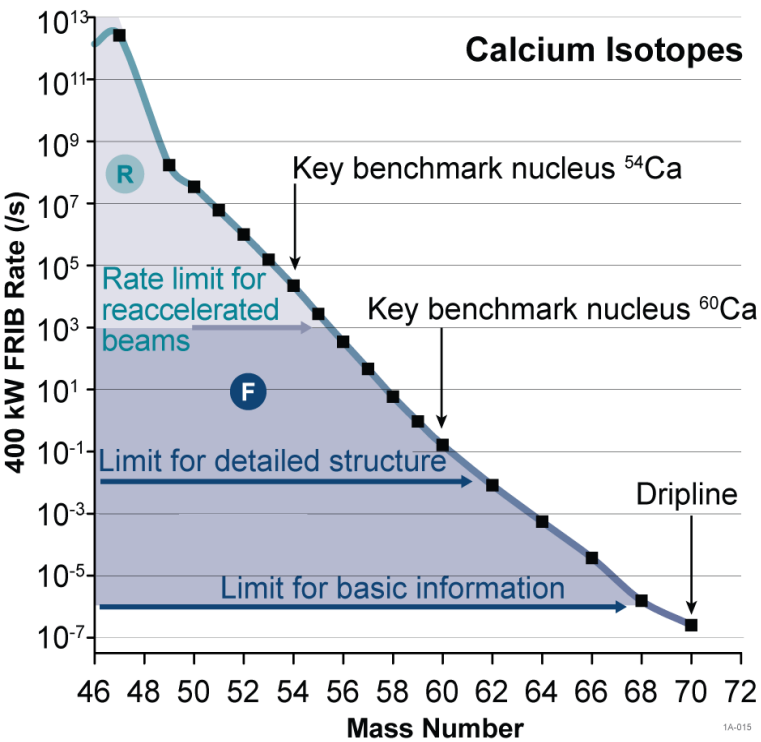
What is the Nature of the Nuclear Force that Binds Protons and Neutrons?

- Theory Road Map – comprehensive description of the atomic nucleus
  - Ab initio models – study of neutron-rich, light nuclei helps determine force to use in models (measurement of sensitive properties for N = 14,16 nuclei)
  - Configuration-interaction theory; study of shell and effective interactions (study of key nuclei such as ^{54}Ca, ^{60}Ca)
  - The universal energy density functional (DFT) – determine parameters (broad view of mass surface, BE(2)s, BE(4)s, fission barrier surface, etc.)
  - The role of the continuum and reactions and decays of nuclei (halo studies up to A ~100)
- IMPORTANT: Understand and select the most sensitive measurements (role for theory)



Fast, Stopped, and Reaccelerated Rare Isotope Beams Afford Different Probes

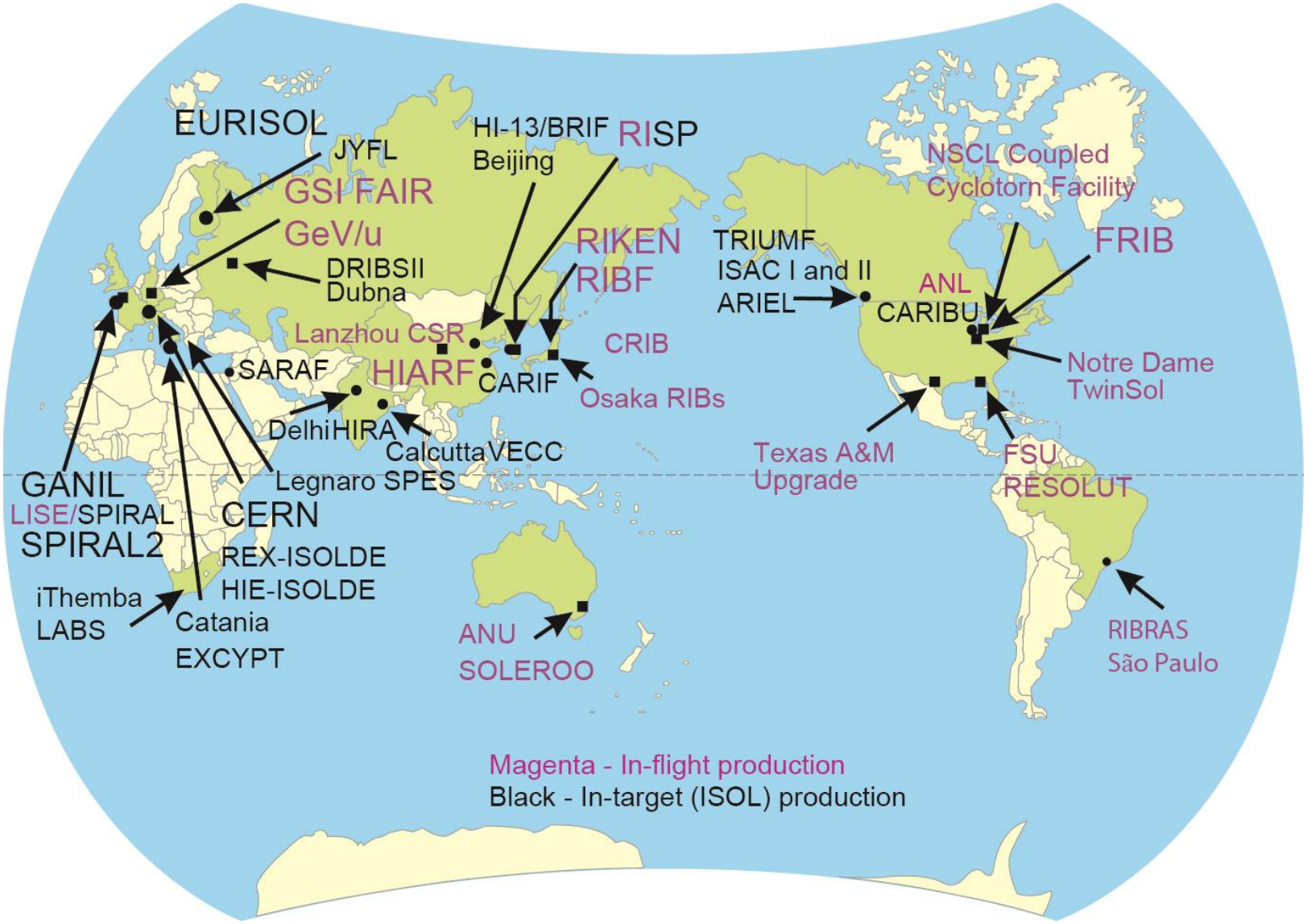
- Fast beams (>100 MeV/u)
  - Farthest reach from stability, nuclear structure, limits of existence, EOS of nuclear matter
- Stopped beams (0-100 keV)
  - Precision experiments – masses, moments, symmetries
- Reaccelerated beams (0.2-20 MeV/u)
  - Detailed nuclear structure studies, high-spin studies
  - Astrophysical reaction rates



Accelerators – Drivers to Initiate the Production of Rare Isotopes

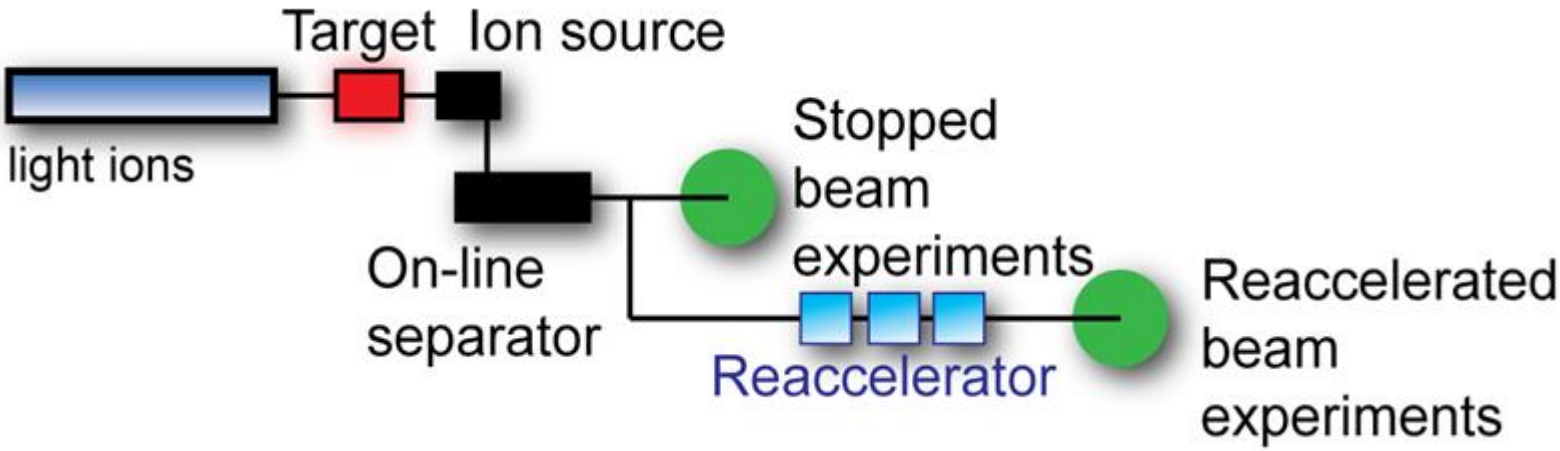
- The particle accelerator used for production is often called the “driver” accelerator
- Technologies
  - Cyclotron (NSCL, GANIL, TRIUMF (protons), RIKEN RIBF (heavy ions)
  - Synchroton (GSI, FAIR – GSI)
  - LINAC (LINear ACcelerator) (ATLAS – ANL, SPIRAL2, FRIB, RAON, HIAF)
- Features
  - Maximum Energy (e.g. FRIB will have 200 MeV/u uranium ions)
  - Particle type (e.g. TRIUMF cyclotron accelerates hydrogen, hence is used for spallation)
  - Beam Intensity (1 pμA = 6.25×10^{12} /s from 1 W = 6.25×10^{18} eV/s)
  - Power = Beam Intensity x Beam Energy = pμA x Beam Energy (in GeV)
    - » Note
      - 400 kW protons at 1 GeV beam energy is 400 pμA (or 2.4×10^{15} protons/s)
      - 400 kW protons at 50 GeV beam energy is 8 pμA (or 4.8×10^{13} protons/s)

Rare Isotope Beams Facilities Based on Accelerators



Rare Isotopes Complementary Rare Isotope Production Methods

- Isotope Separation Online (ISOL) – Light beam breaks up heavy target



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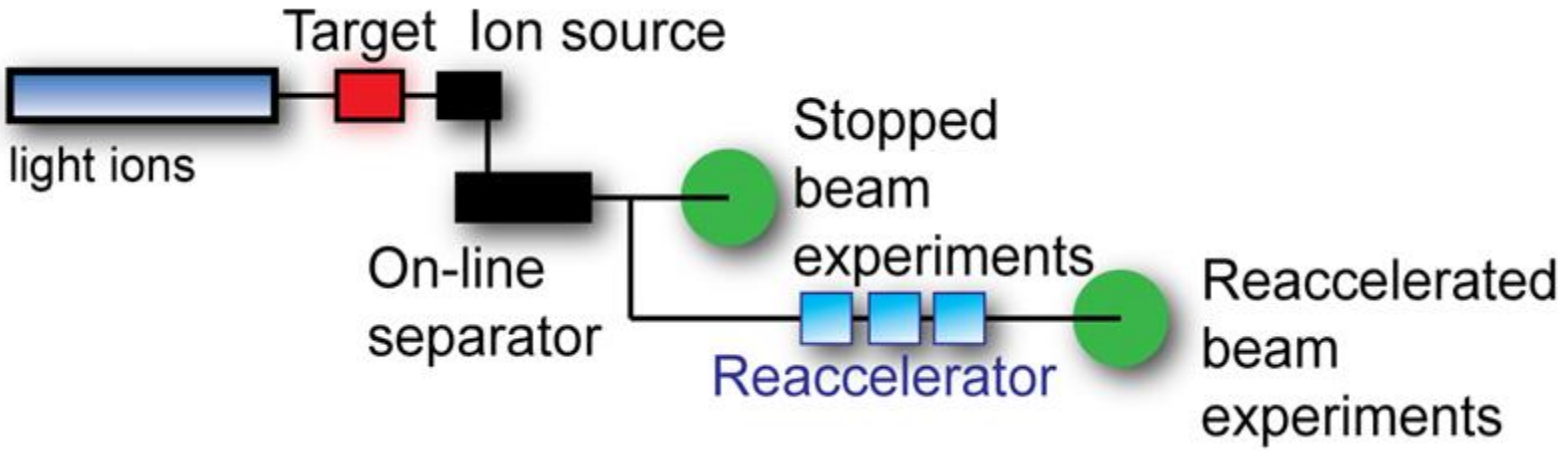
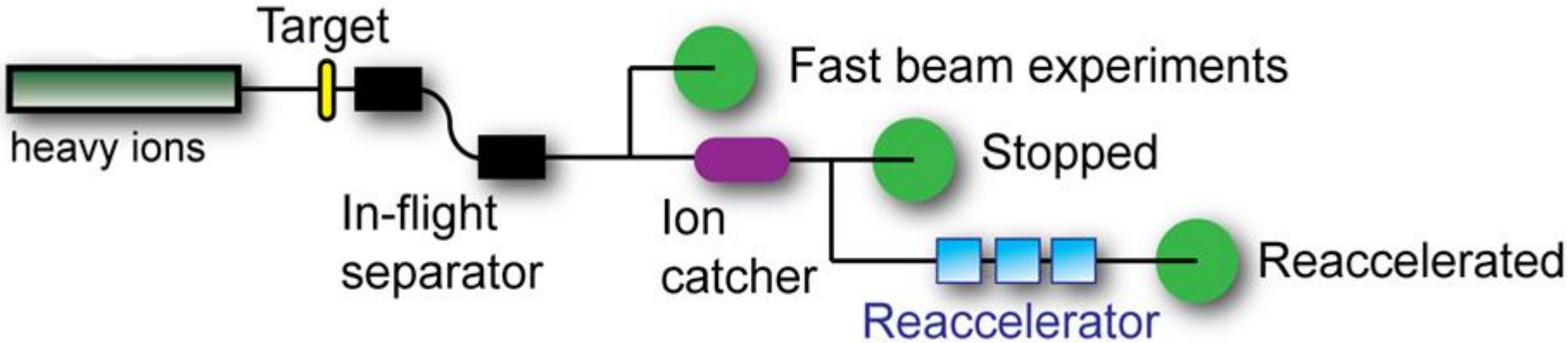
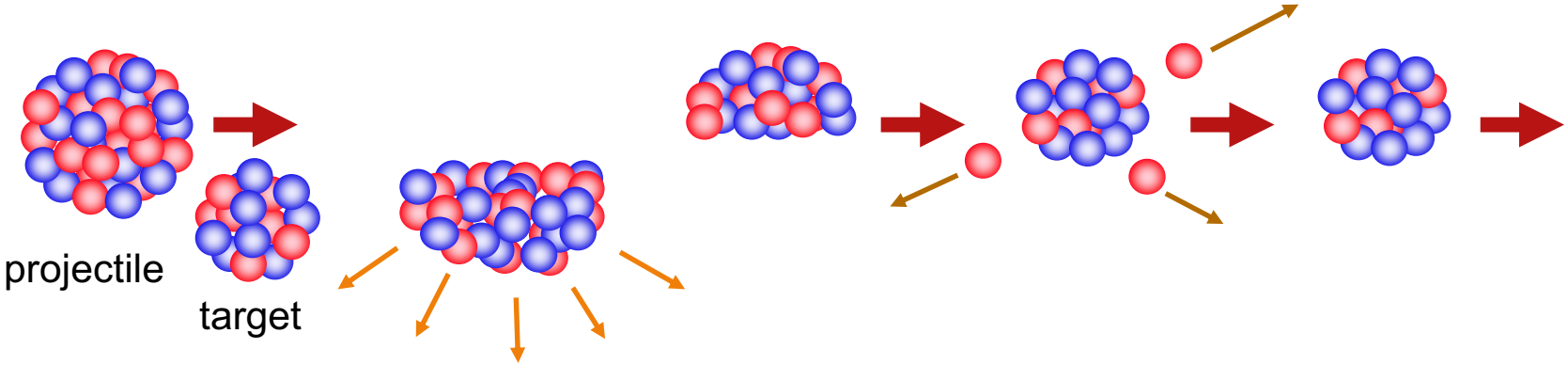


- In-flight Production – Heavy beam interacts with light target



In-flight Isotope Production Scheme

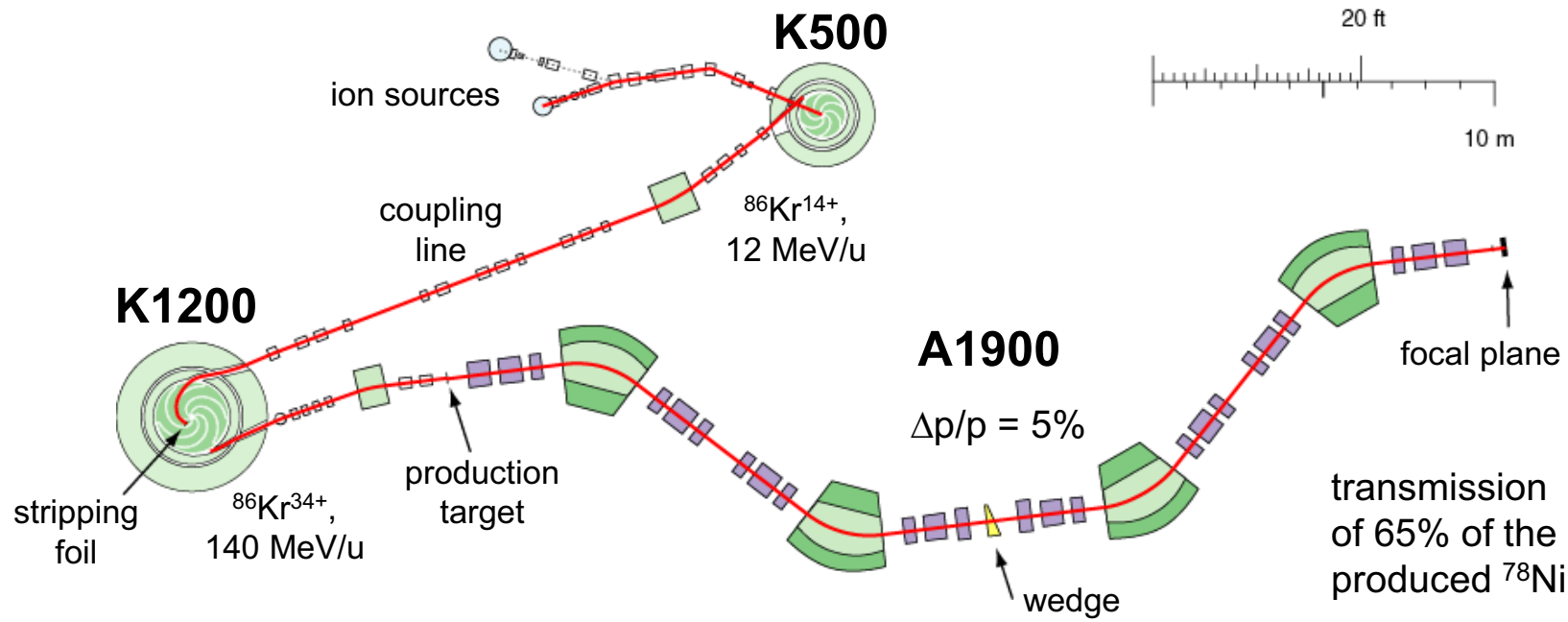
- Projectile fragmentation or fission (Coulomb breakup, transfer, …)

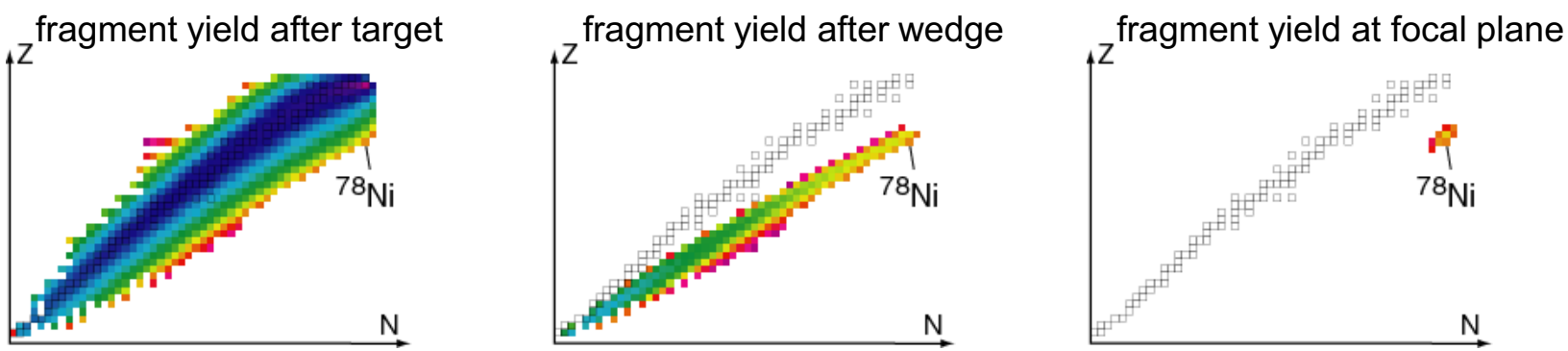


- Kinematic focusing of rare isotope beam
- To produce a key nucleus like ^{122}Zr the production cross section (from ^{136}Xe) is estimated to be 2×10^{-18} b (2 attobarns, 2×10^{-46} m^2)
- Probability 1 in 10^{18}: One ^{122}Zr for each 10^{18} ^{136}Xe projectiles
- With a ^{136}Xe beam of 8×10^{13} ion/s (400 kW at 200 MeV/u) a few atoms per week (10^5 s) can be made and studied

Example: In-Flight Production of ^{78}Ni at NSCL

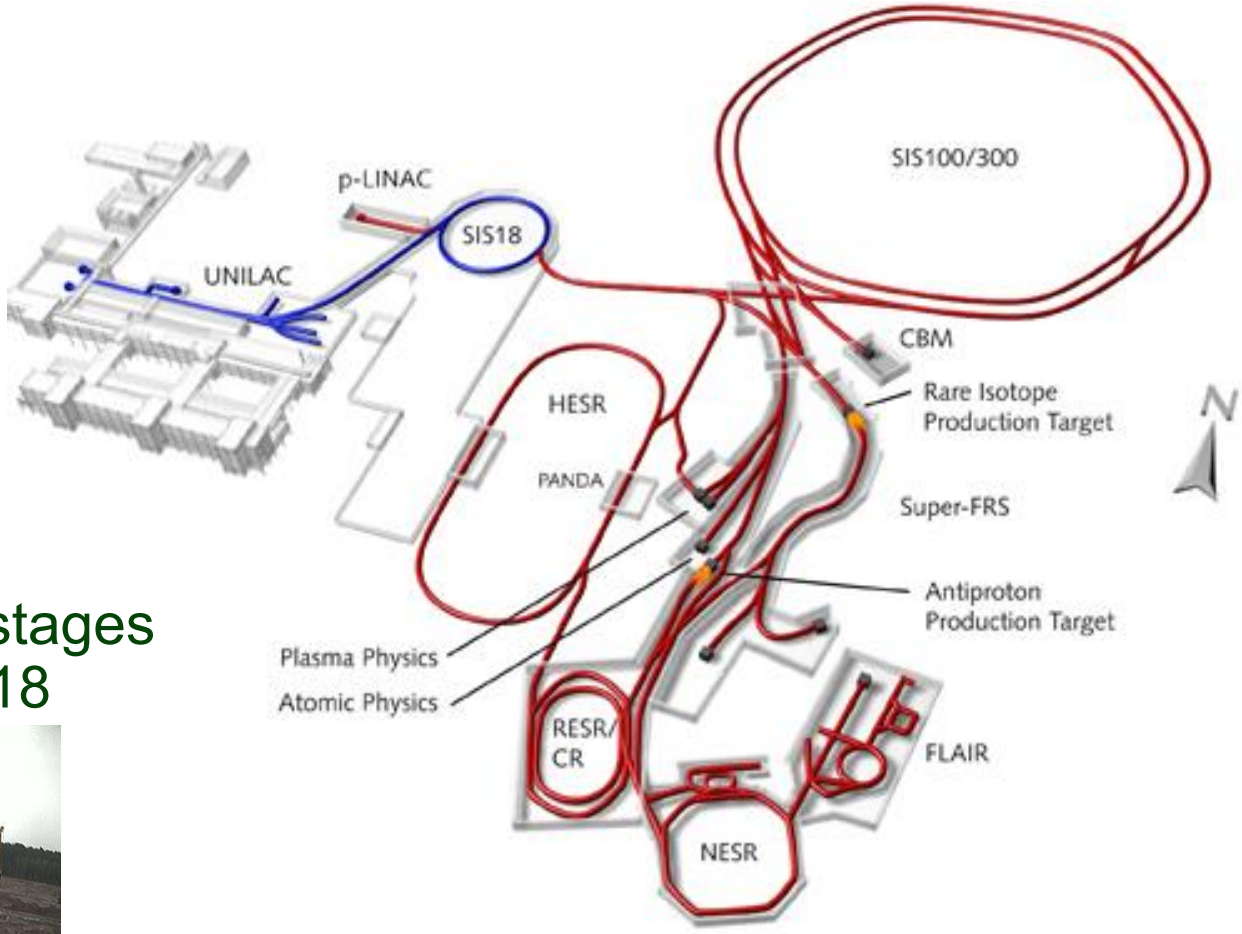
D.J. Morrissey, B.M. Sherrill, Philos. Trans. R. Soc. Lond. Ser. A. Math. Phys. Eng. Sci. 356 (1998) 1985.





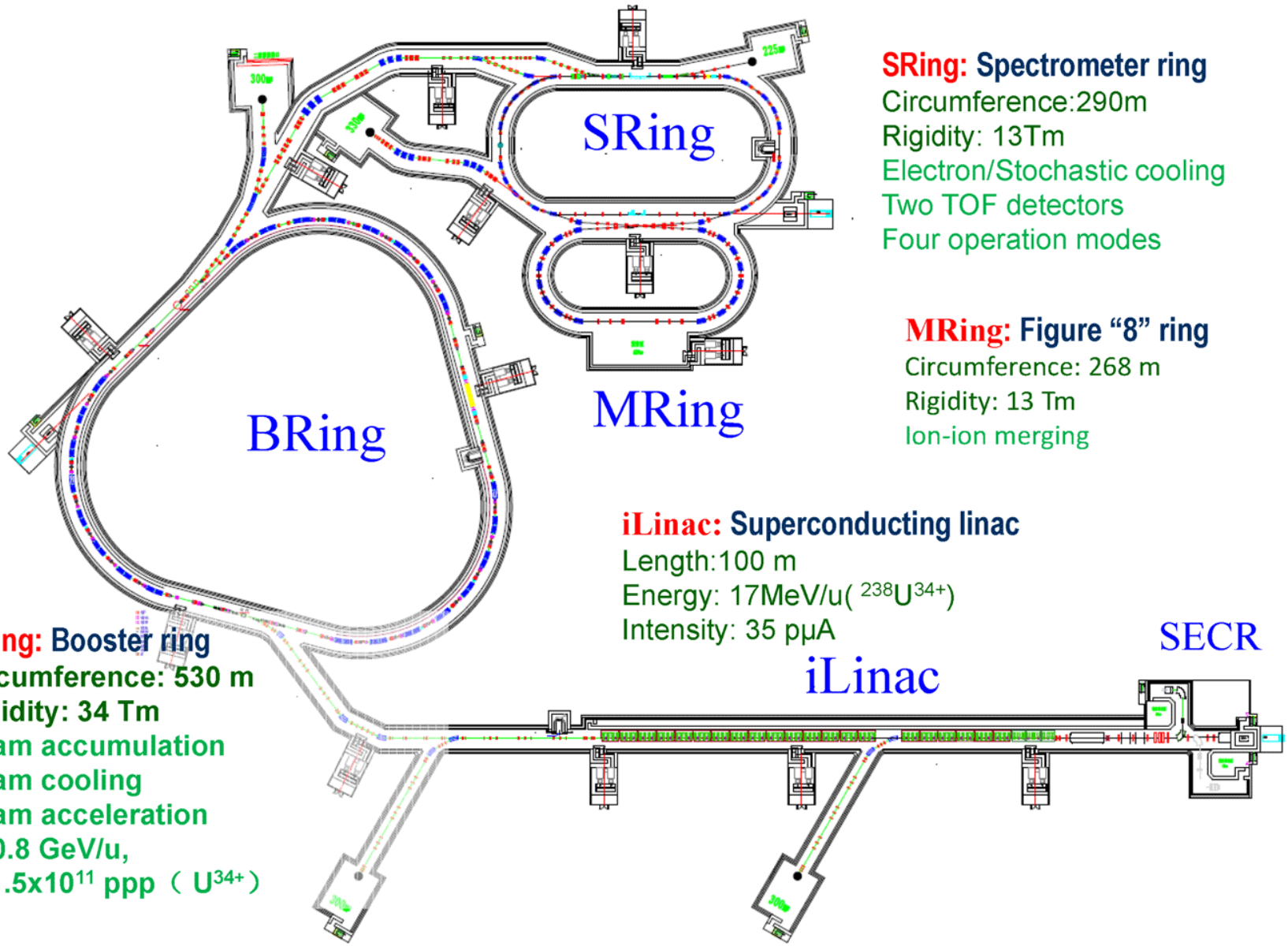
Facility for Antiproton and Ion Research at GSI in Germany under Construction

- Beams at 1.5 GeV/u
- 10^{12}/s Uranium
- Research
  - Compressed matter
  - Rare isotopes
  - Antiproton
  - Plasma
  - Atomic physics
- Completion of the first stages are planned around 2018



www.fair-center.de/index.php?id=1

High Intensity Heavy Ion Accelerator Facility (HIAF) in China being Designed and R&D



SRing: Spectrometer ring
Circumference:290m
Rigidity: 13Tm
Electron/Stochastic cooling
Two TOF detectors
Four operation modes

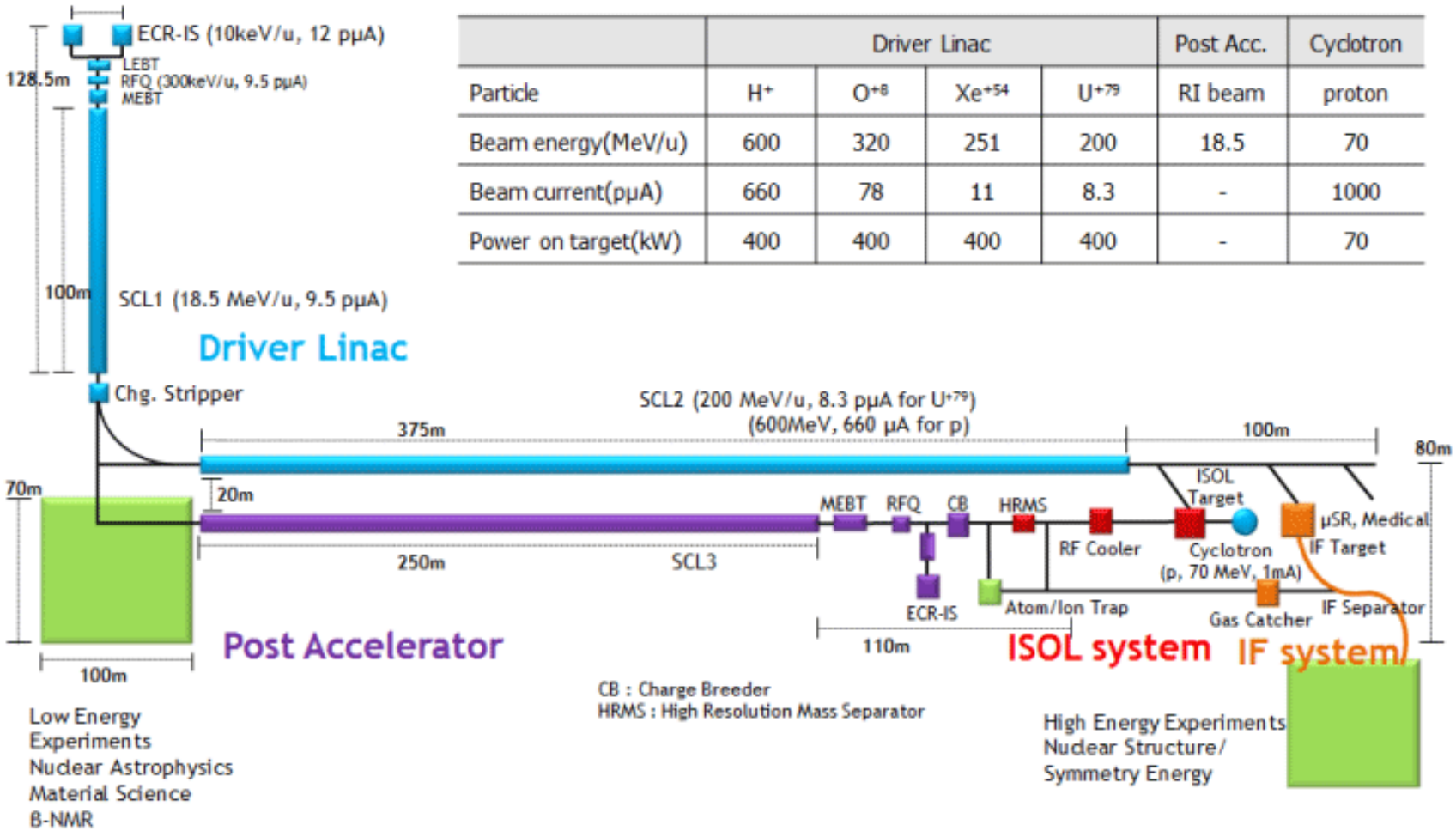
MRing: Figure "8" ring
Circumference: 268 m
Rigidity: 13 Tm
Ion-ion merging

iLinac: Superconducting linac
Length:100 m
Energy: 17MeV/u($^{238}U^{34+}$)
Intensity: 35 pμA

BRing: Booster ring
Circumference: 530 m
Rigidity: 34 Tm
Beam accumulation
Beam cooling
Beam acceleration
E=0.8 GeV/u,
I= 1.5x10^{11} ppp（ U^{34+}）

RAON Accelerator In South Korea's RISP Project

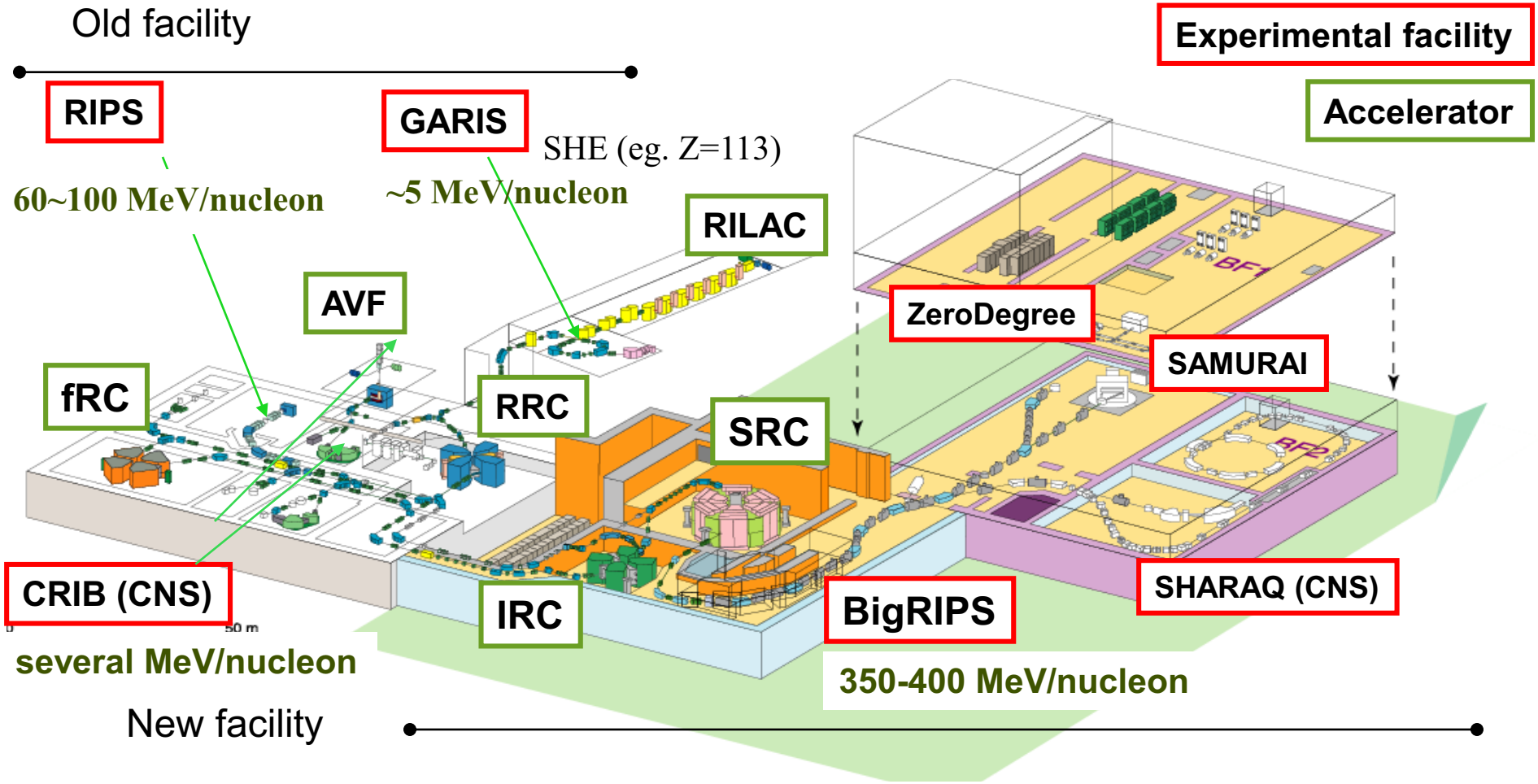
	Driver Linac				Post Acc.	Cyclotron
Particle	H^{+}	O^{+8}	Xe^{+54}	U^{+79}	RI beam	proton
Beam energy(MeV/u)	600	320	251	200	18.5	70
Beam current(pμA)	660	78	11	8.3	-	1000
Power on target(kW)	400	400	400	400	-	70



www.risp.re.kr/eng/orginfo/intro_project.do

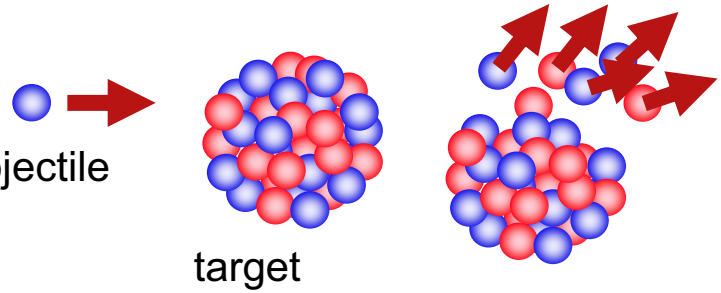
RI Beam Factory (RIBF) at RIKEN in Japan

www.nishina.riken.jp/RIBF/



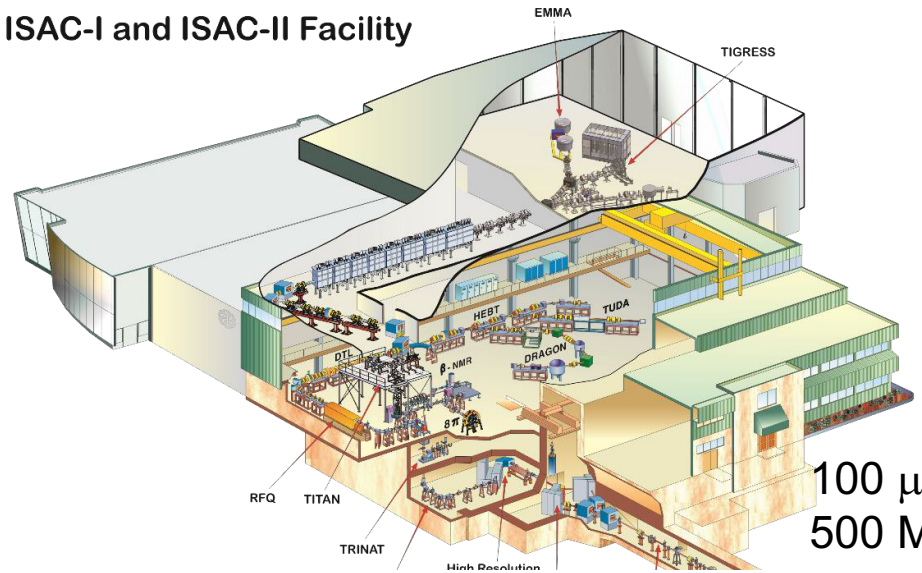
Intense heavy ion beams (up to U) up to 345*A*MeV at SRC
Fast RI beams by projectile fragmentation and U-fission at BigRIPS
In operation since 2007

ISAC and ARIEL at TRIUMF in Canada

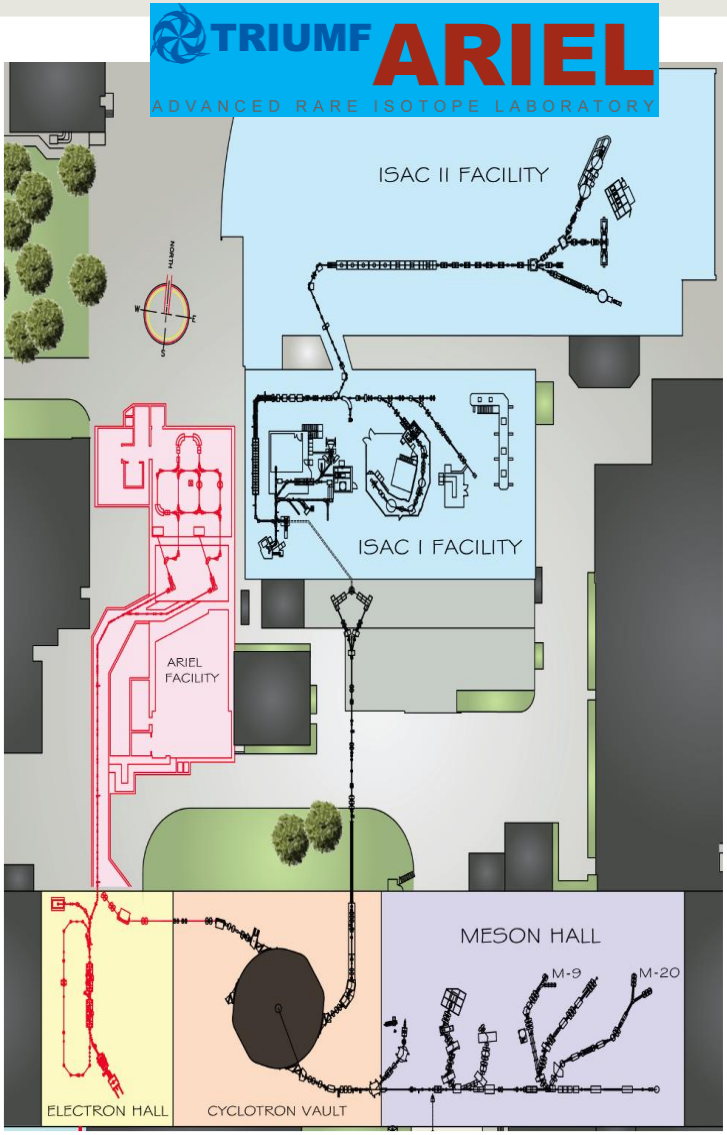


Isotope
Separation
On-Line ISOL

- Highest power ISOL facility: >50 kW
- Programs in nuclei, astrophysics, symmetry condensed matter, medical isotopes



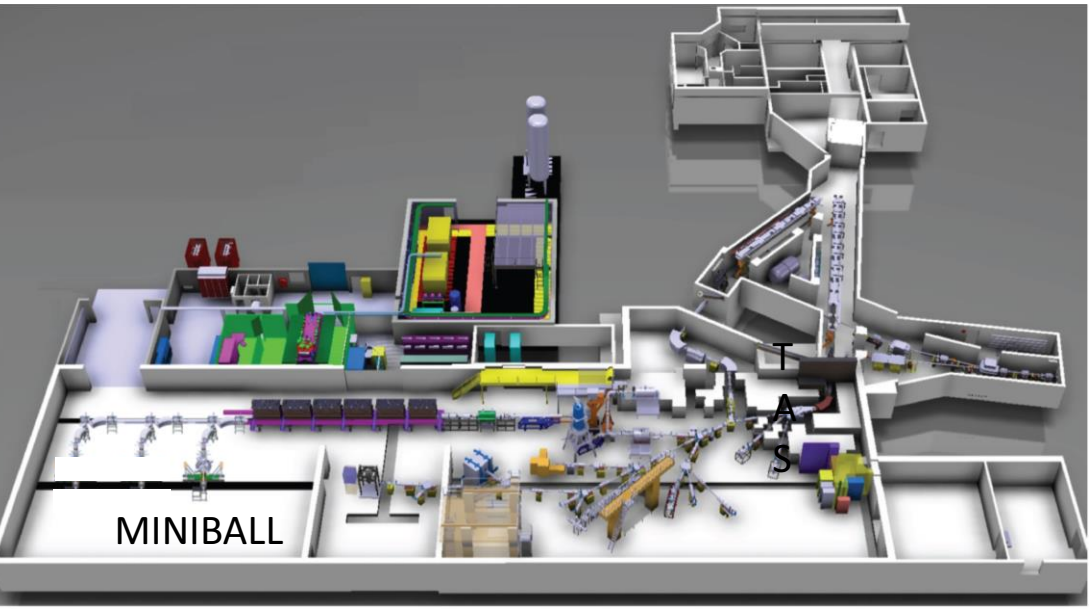
100 μA,
500 MeV, p

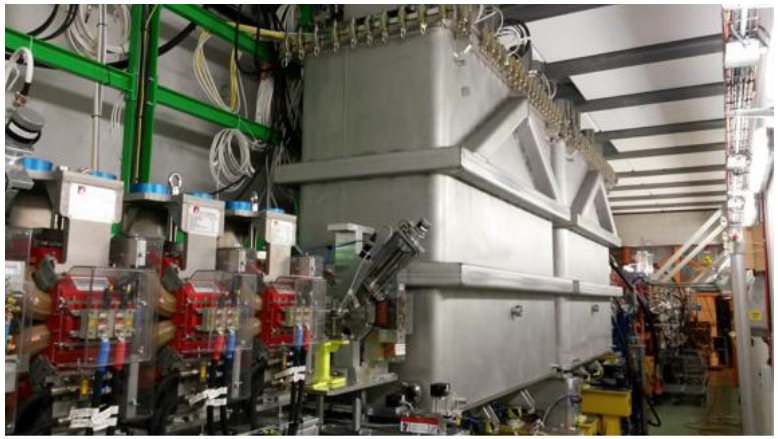


www.triumf.ca/research/research-facilities/isac-facilities-for-rare-isotope-beams

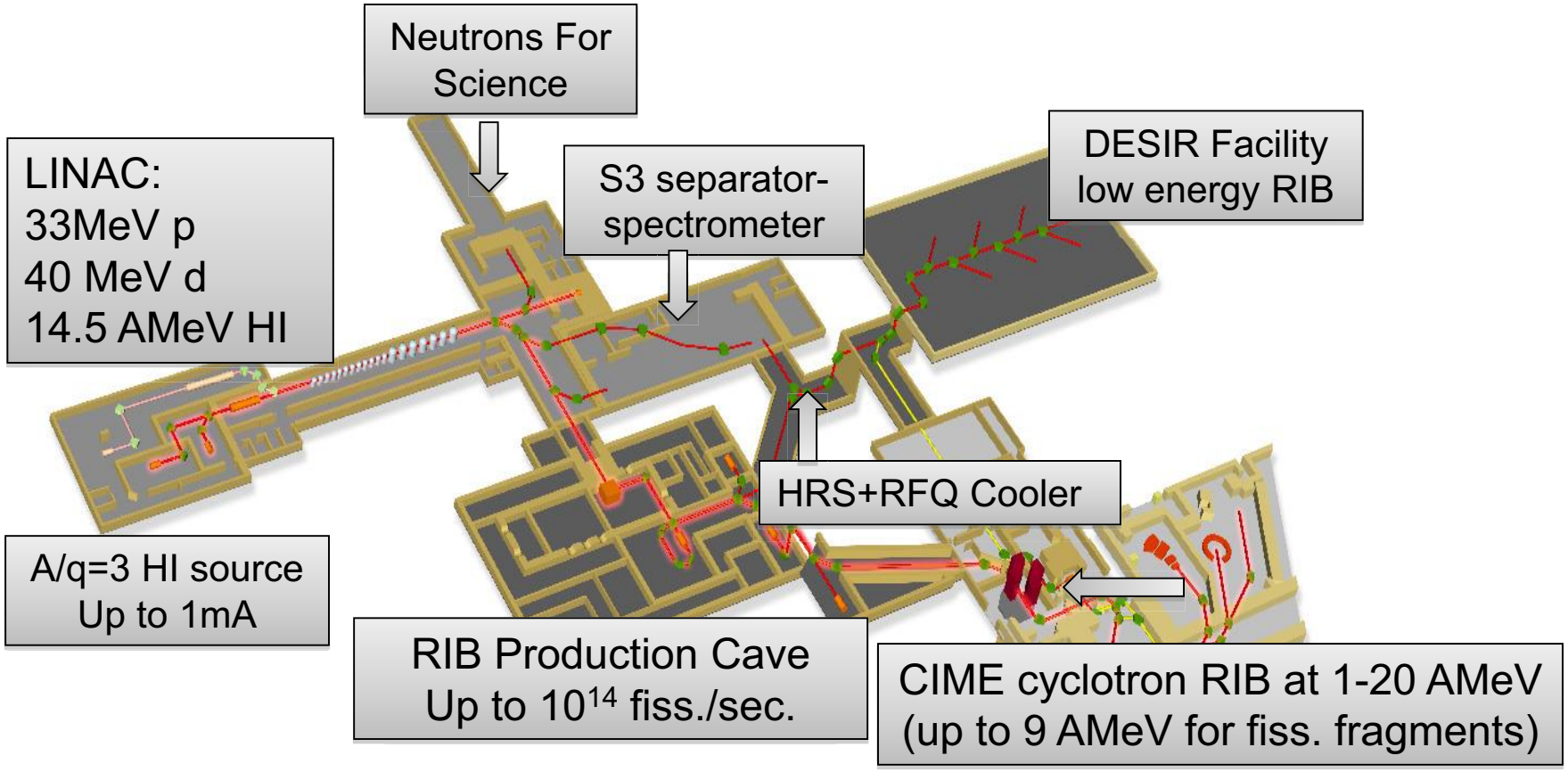
HIE-ISOLDE Facility at CERN

- ISOLDE can now run experiments at up to 5.5 MeV/u
- First experiment in September
- By Spring 2018 four cryomodules expected with energy up to 10 MeV/u





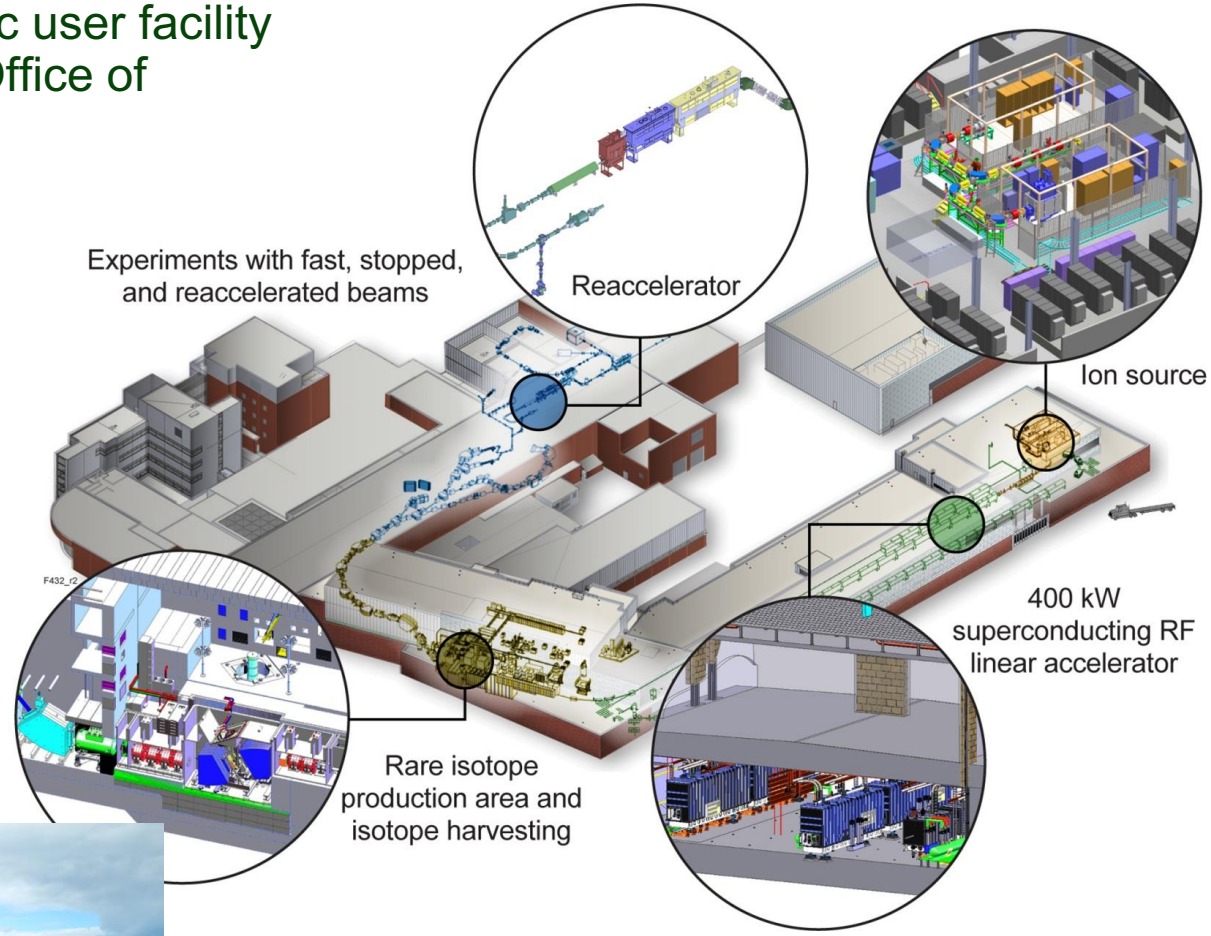
SPIRAL2 at GANIL in France



pro.ganil-spiral2.eu/spiral2

Facility for Rare Isotope Beams at MSU under Construction

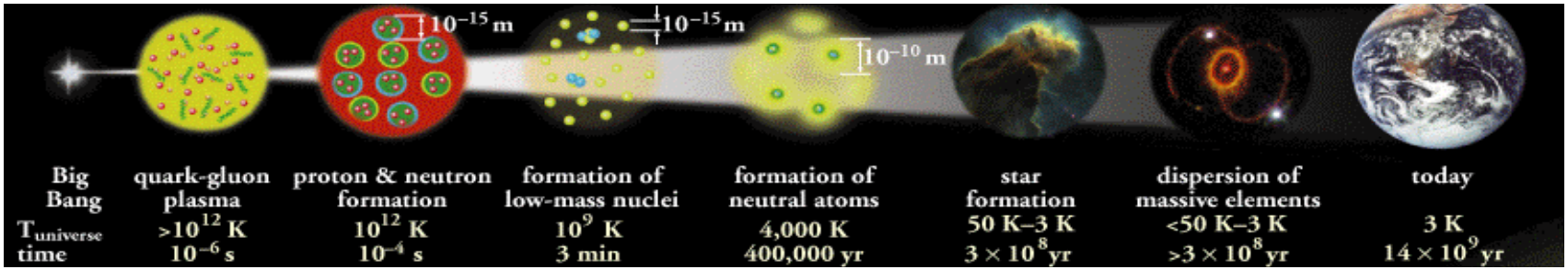
- DOE Office of Science scientific user facility supporting the mission of the Office of Nuclear Physics
- Key Feature is 400 kW beam power (5 x10^{13} ^{238}U/s)
- Separation of isotopes in-flight
  - Fast development time for any isotope
  - Suited for all elements and short half-lives
  - Fast, stopped, and reaccelerated beams
- CD-4 June 2022, managing to early completion in FY2021



www.frib.msu.edu

Summary

- Particle accelerators are key to realizing nuclear science discovery potential
  - Machine capability drives scientific discoveries ↔ Science drives machine development



- Vibrant world-wide effort
- Major facilities under construction in Asia, Europe and North America will enable new discoveries
- I hope you enjoyed LINAC 16 and hope to see you at the FRIB tour this afternoon