nuclear astrophysics theory and FRIB

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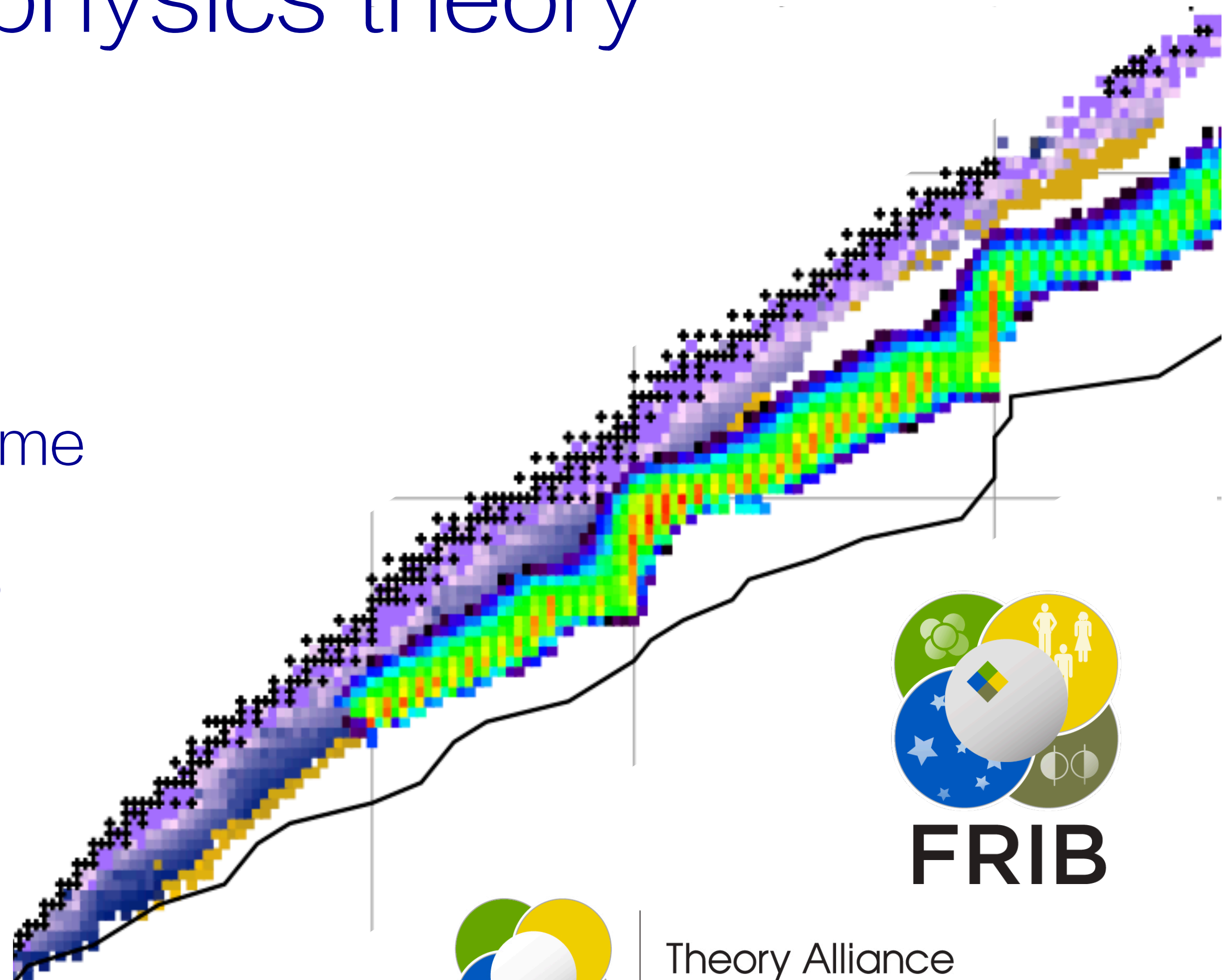
University of Notre Dame

FRIB Day 1 Workshop
LECM 2017

Argonne National Lab
2 August 2017



FRIB

Theory Alliance
FACILITY FOR RARE ISOTOPE BEAMS

U.S. DEPARTMENT OF ENERGY | Office of Science

JINA-CEE

overview of FRIB theory

Topic	Theory development needed
Forces	Effective field theory (EFT) constants from LQCD; Improved optimization of chiral forces, with and without Δ; Consistent operators and power counting for chiral EFT.
Nuclear structure	Connect realistic nuclear forces to shell model and DFT; Microscopic optical potential that incorporates many-body correlations.
Medium mass nuclei	Properties of nuclei with validated ab-initio techniques; Shell-model effective interactions and operators derived and/or constrained from microscopic interactions, with controlled uncertainties; Unified treatment of structure and reactions.
Heavy nuclei	DFT constrained by rare isotope data and ab-initio theory; Beyond-DFT treatment of open shell systems; calculations of Schiff and anapole moments. Improved DFT-based adiabatic models of the large-amplitude collective motion; Implementation of TDDFT and multi-reference DFT approaches; Effective field theory for collective nuclear phenomena based on powerful existing phenomenology. Implementation of proton-neutron, symmetry-projected multi-reference DFT and large-scale shell model to compute nuclear matrix elements for double-beta decay. Masses and beta-decay rates, calculated from DFTs and combined with experiment.
Neutron stars	Controlled calculations of the nuclear equation of state for all relevant densities including extrapolations to high densities with known uncertainties; Improve constraints on nuclear EOS by identifying observables most sensitive to the high-density behavior of nuclear symmetry energy; Calculate structure in neutron star crust at various densities (ground state and response functions).
Reactions	Ab-initio reaction theory, consistent with nuclear structure, with quantified uncertainties, adequate for many domains of experimental interest, including radiative capture, transfer, charge-exchange, breakup of dripline nuclei and superheavy synthesis to estimate production of nuclei at and beyond the dripline and to extract structural information. Microscopic theory of spontaneous and neutron-induced fission; Ab-initio theory for light-ion fusion. Reaction theory for compound nucleus formation consistent with structure. Reliable transport theory with quantified errors, including a quantum formulation with correlations, for heavy-ion reactions from low to intermediate energies.
Astrophysics	Advanced simulations of compact objects; supernova, binary neutron star mergers and related explosive phenomena; Nucleosynthesis and chemical evolution simulations with up-to-date nuclear input; Neutrino interactions with nuclei in hot and dense nuclear matter, including neutrino oscillations; Hydrodynamics and neutrino transport in stars; Screening in stellar plasma consistent with reaction theory.

from the FRIB Theory Alliance proposal

nuclear astrophysics: role of theory

astrophysical conditions
dense matter properties
neutrino physics

nuclear physics inputs:
masses, halflives, reaction rates,
fission yields

astrophysical
simulations
+
nuclear network
calculations

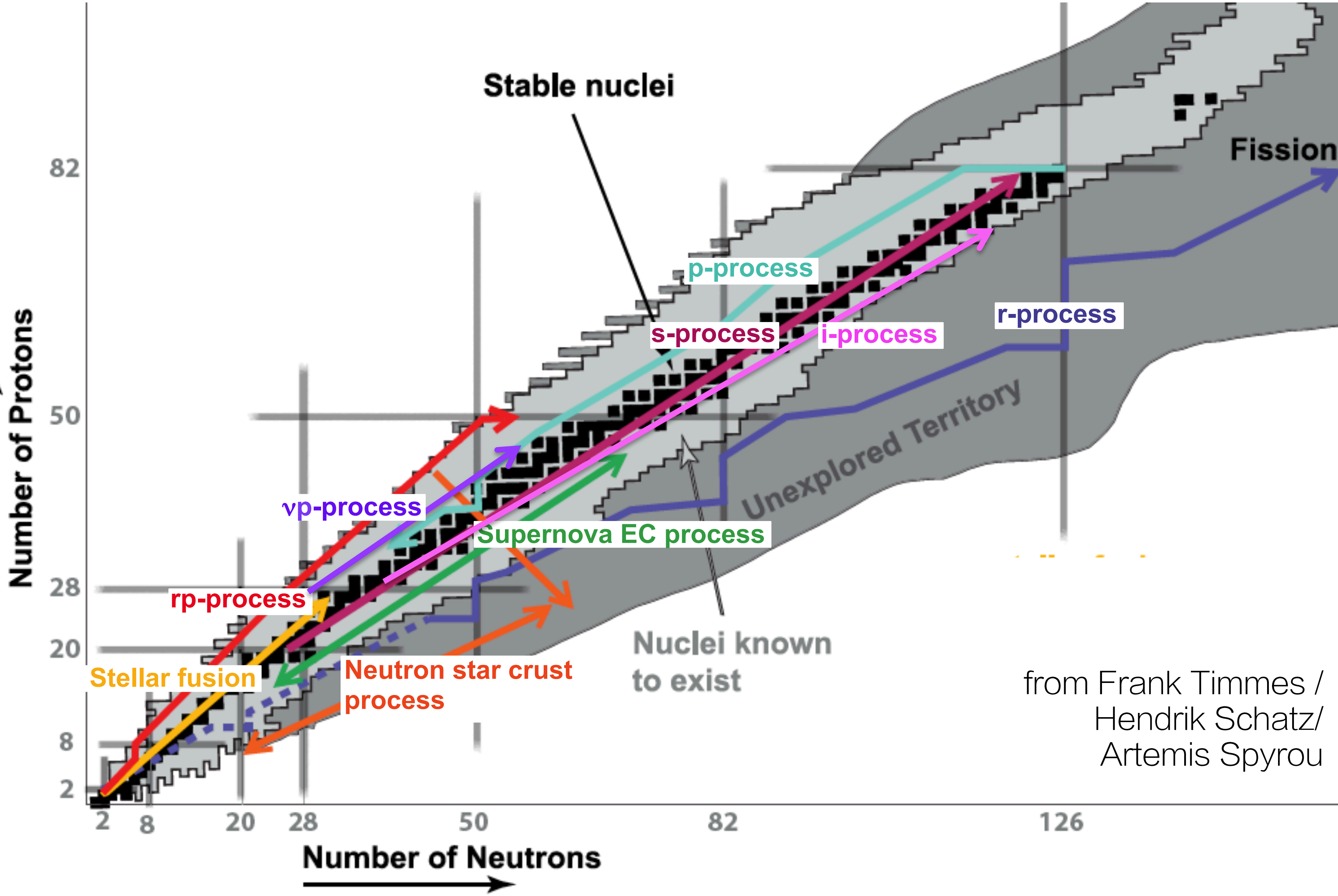
Neutron stars
Astrophysics

contributions from
Nuclear structure
Medium mass nuclei
Heavy nuclei
Reactions

abundance pattern predictions

comparison to astrophysical
observables

overview of nuclear astrophysical processes

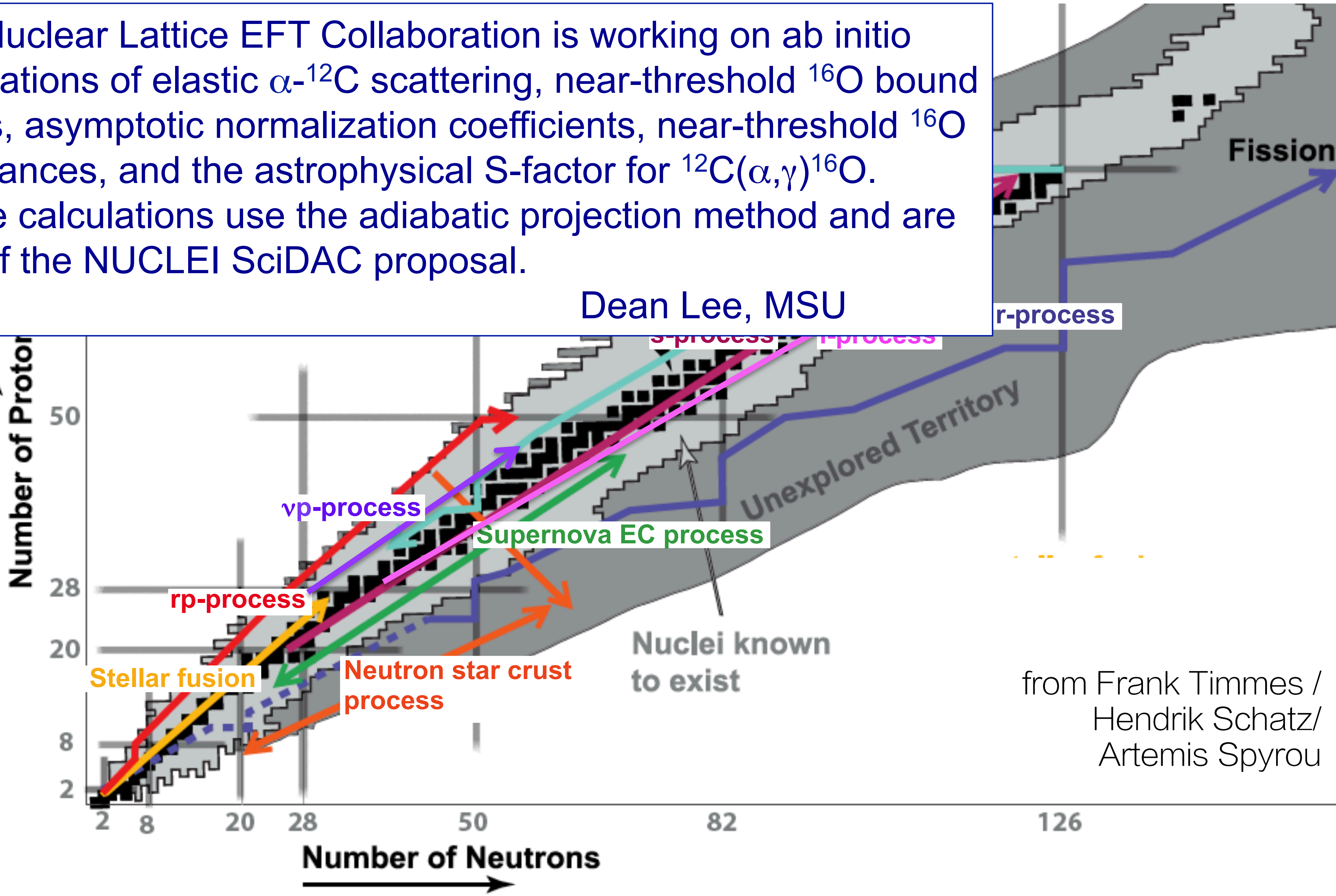


from Frank Timmes / Hendrik Schatz/ Artemis Spyrou

overview of nuclear astrophysical processes

The Nuclear Lattice EFT Collaboration is working on ab initio calculations of elastic α-^{12}C scattering, near-threshold ^{16}O bound states, asymptotic normalization coefficients, near-threshold ^{16}O resonances, and the astrophysical S-factor for $^{12}C(\alpha,\gamma)^{16}O$. These calculations use the adiabatic projection method and are part of the NUCLEI SciDAC proposal.

Dean Lee, MSU



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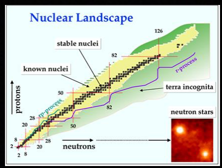
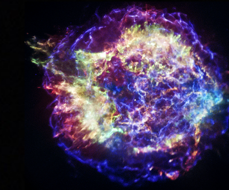
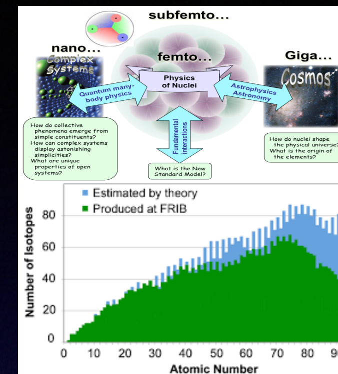


Neutron-rich Matter in Heaven and Earth



Measurements of large neutron skins of exotic nuclei at FRIB will have a dramatic impact on our understanding of the structure and composition of neutron stars



- Laboratory Experiments

  Neutron skins highly sensitive to the EOS of neutron-rich matter

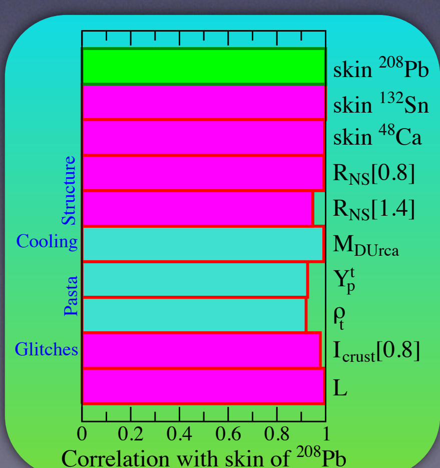
- Observations of neutron star radii

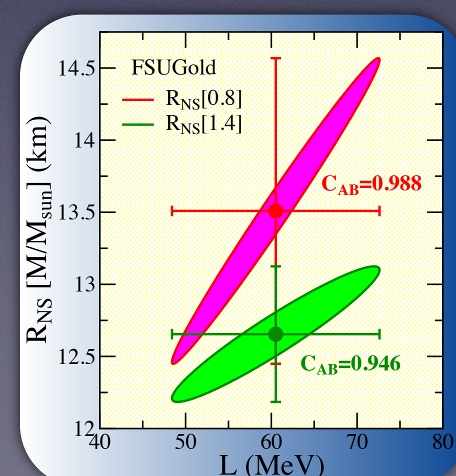
  Measurements of stellar radii sensitive to EOS around $2\rho_0$

- Neutron-Star Mergers and gravitational waves

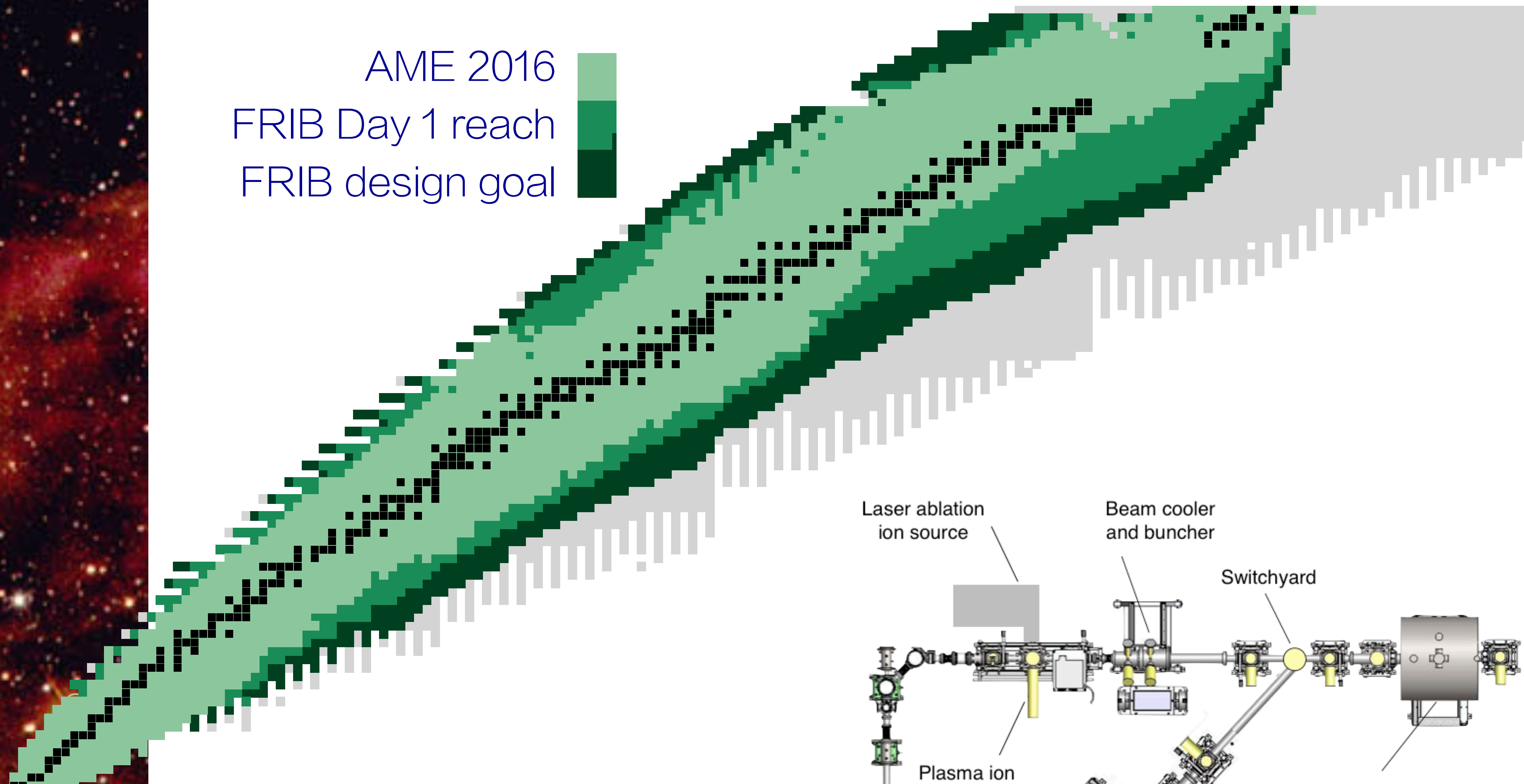
  May constrain neutron-star radii to better than 1km

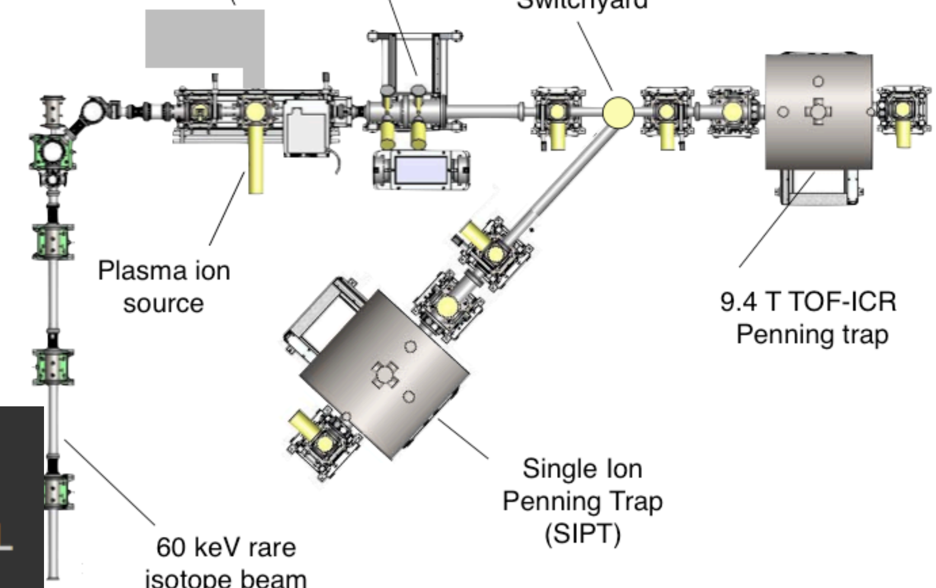
Jorge Piekarewicz
FSU





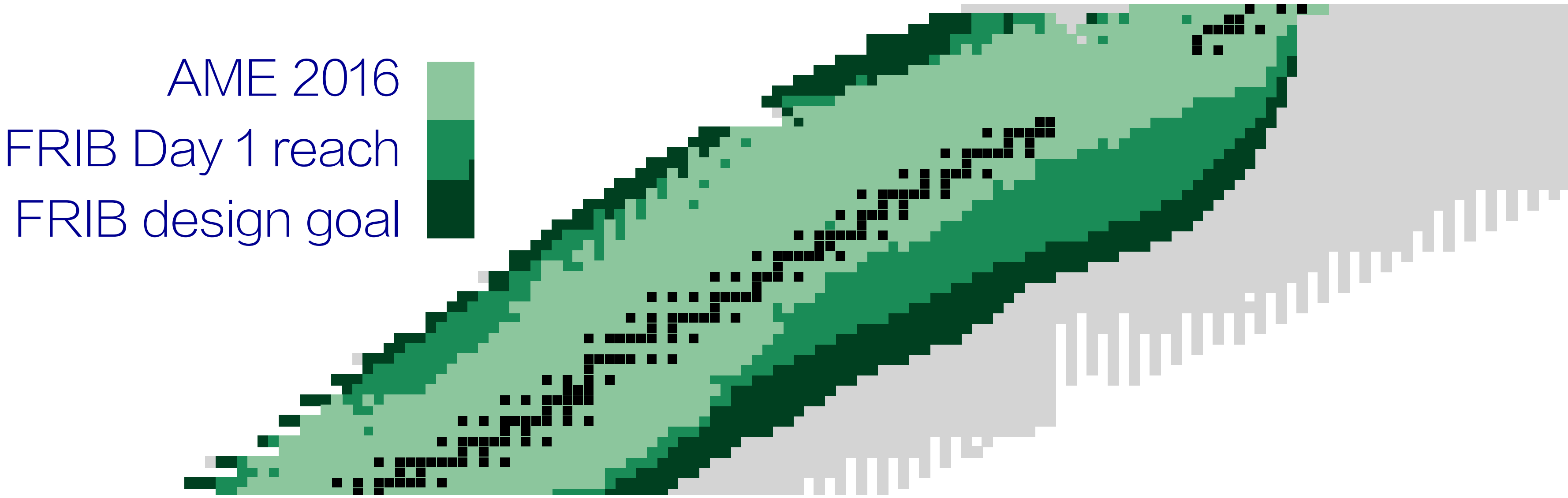
experimental prospects at FRIB: masses

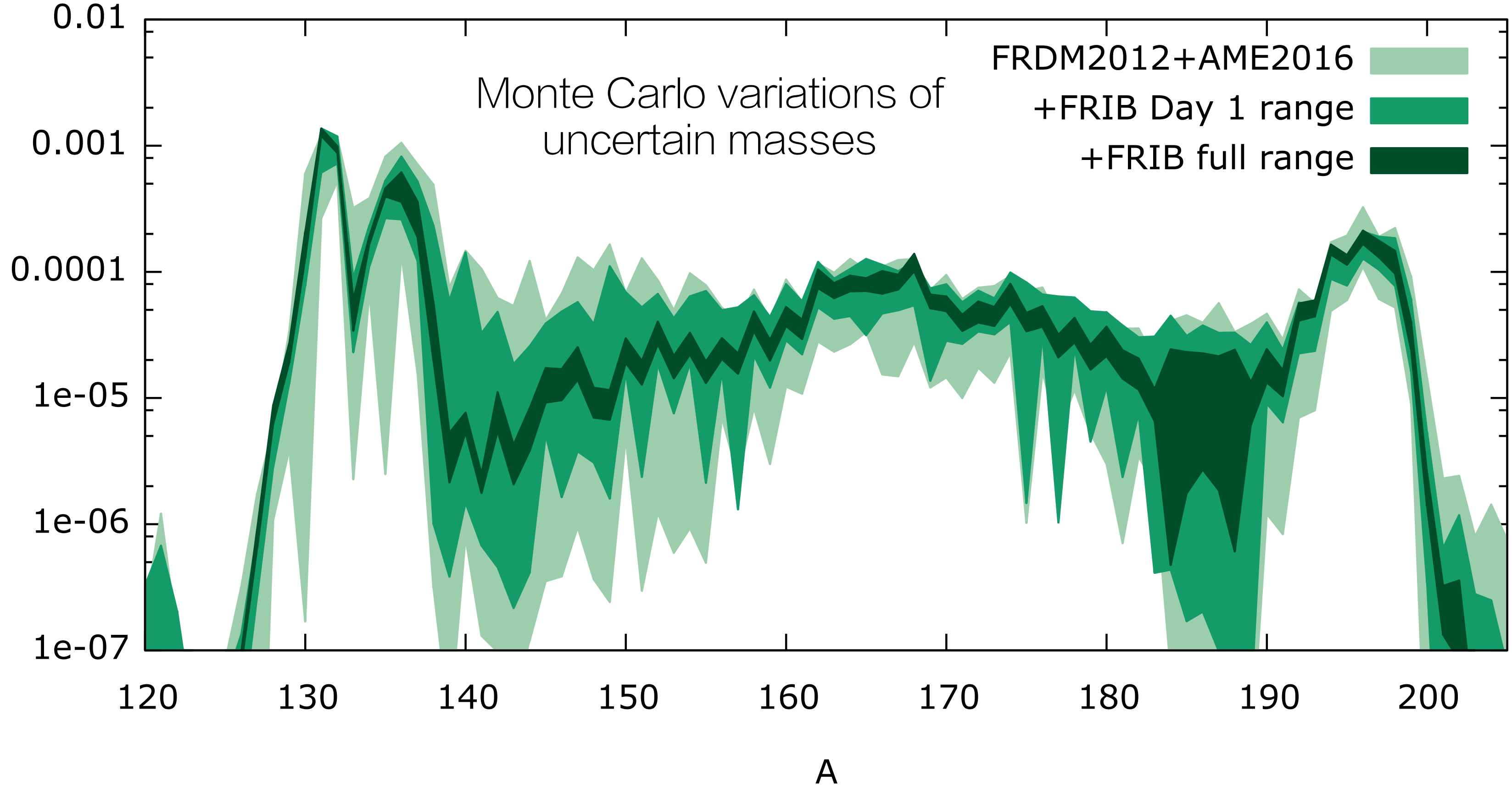




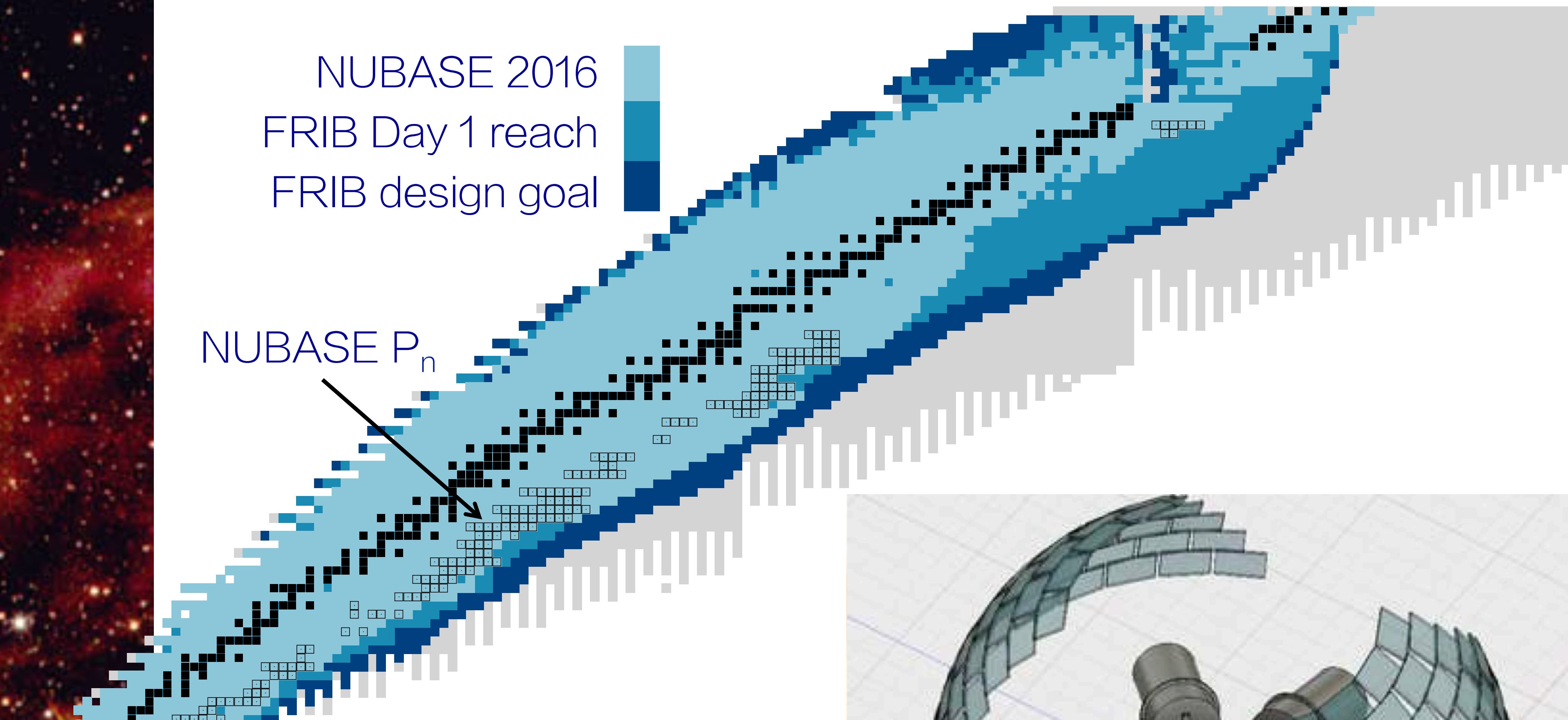
The LEBIT Group
Penning trap mass spectrometry at the NSCL

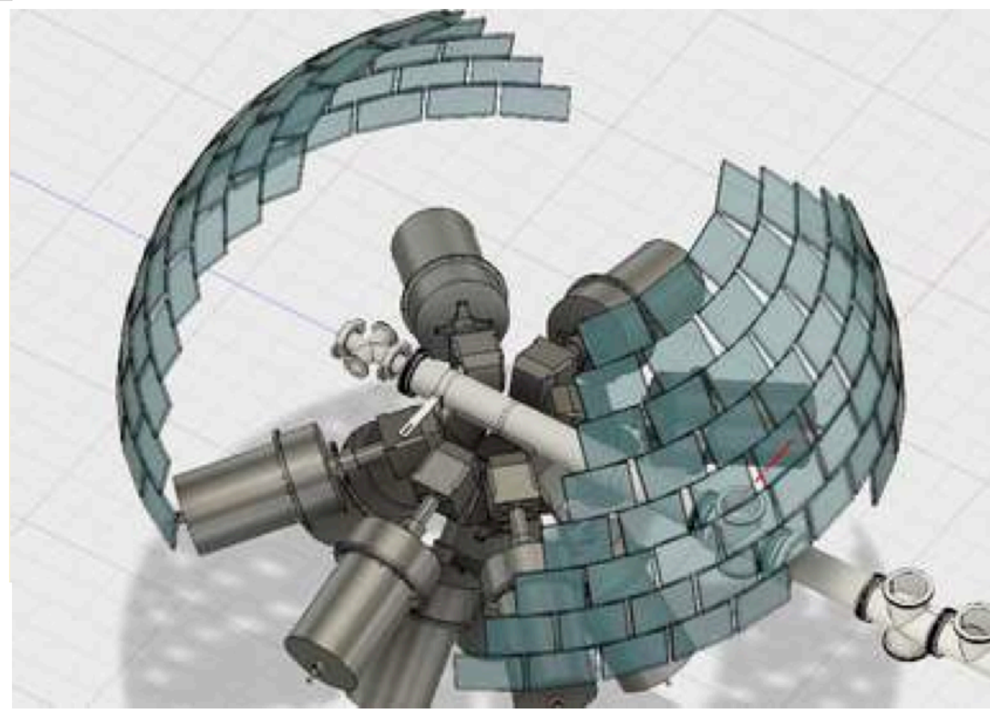
experimental prospects at FRIB: masses





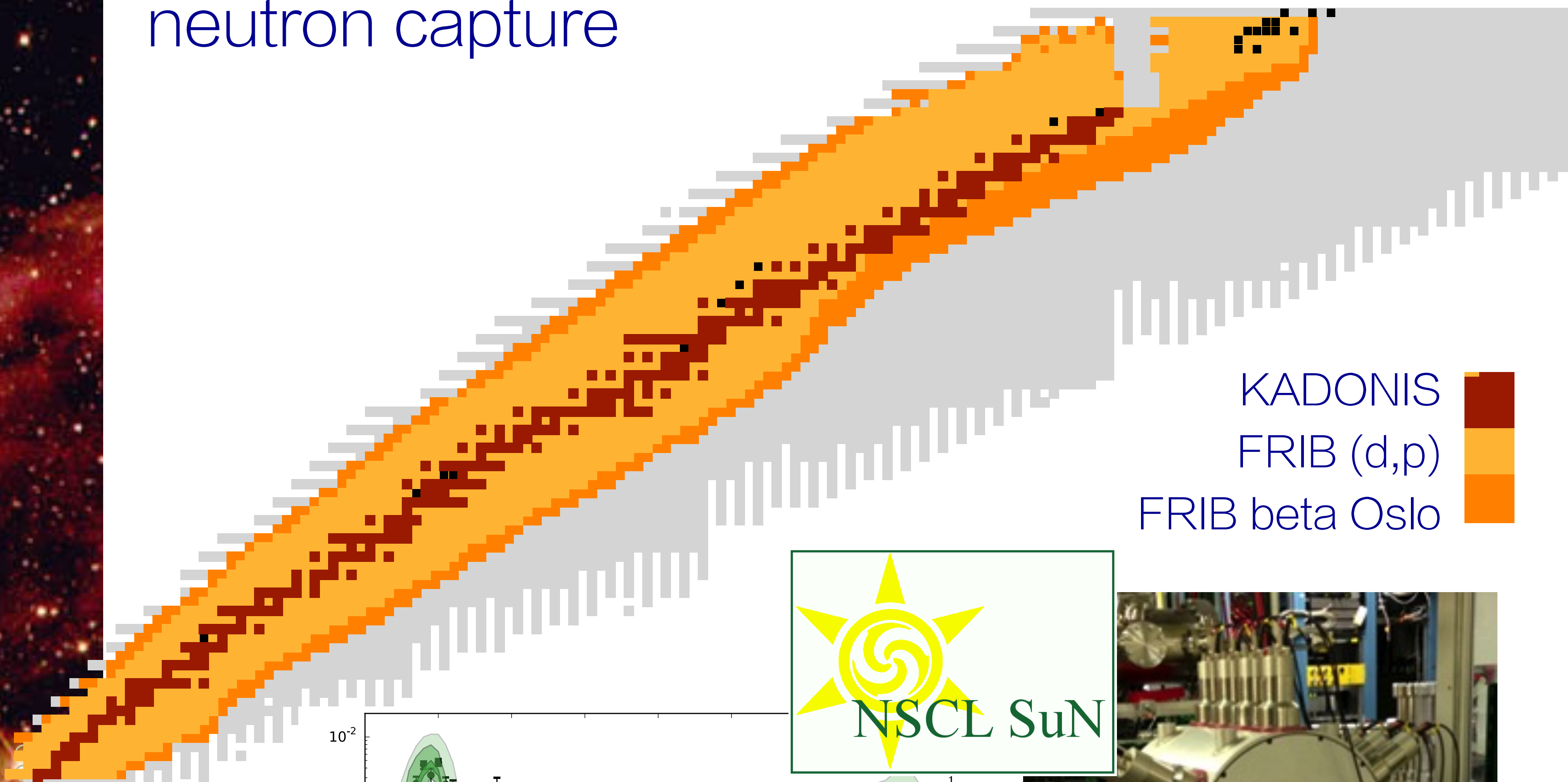
experimental prospects at FRIB: beta decay



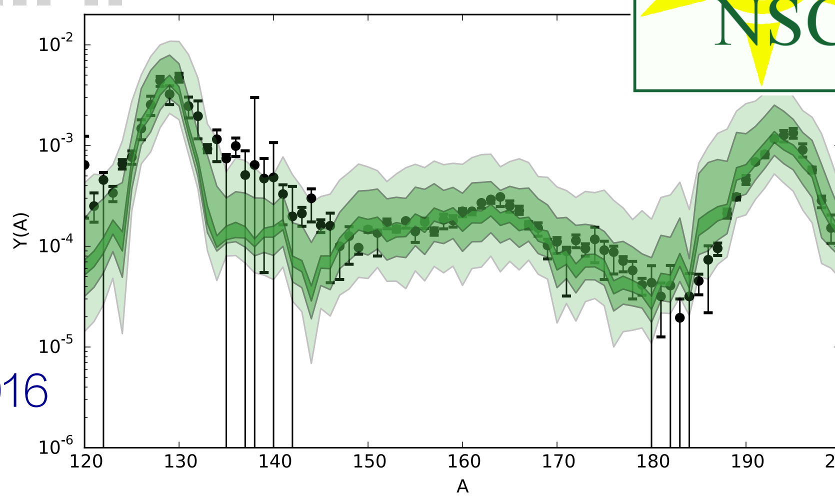


Decay Station at FRIB

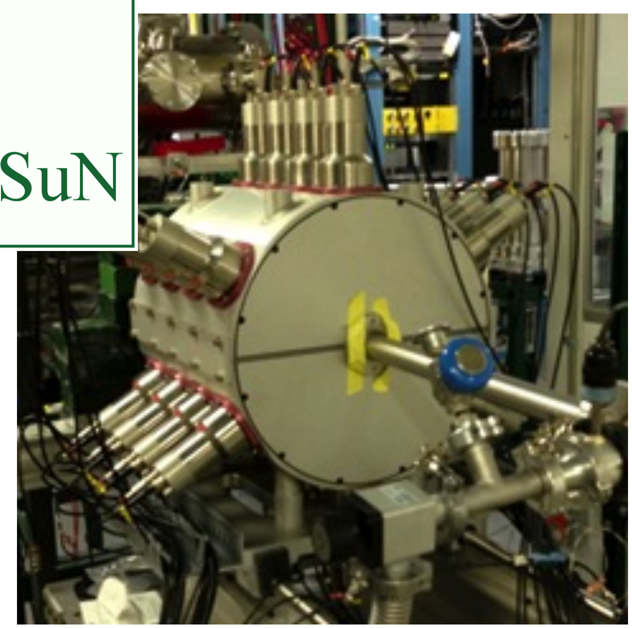
experimental prospects at FRIB: neutron capture



NSCL SuN

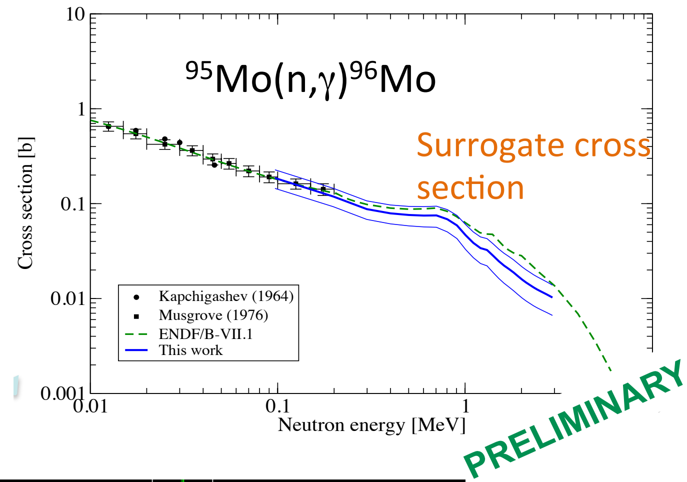


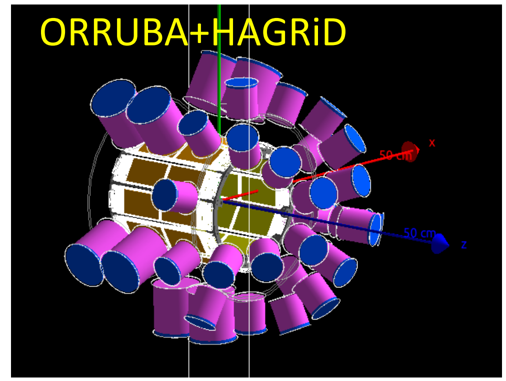
Liddick+2016



Transfer reactions to constrain neutron capture

- DSD n capture from spec. factor of bound states
- Benchmarking of (d,pγ) as surrogate for (n,γ)
  - ^{95}Mo(d,pγ)^{96}Mo measurement [normal kin]
  - CN spin distributions Potel *et al*, PRC **92** (2015)034611
  - HF calculations (J. Esher)
  - **Reproduce ^{95}Mo(n,γ)^{96}Mo cross sections**
- Inverse kinematics techniques under development with GODDESS

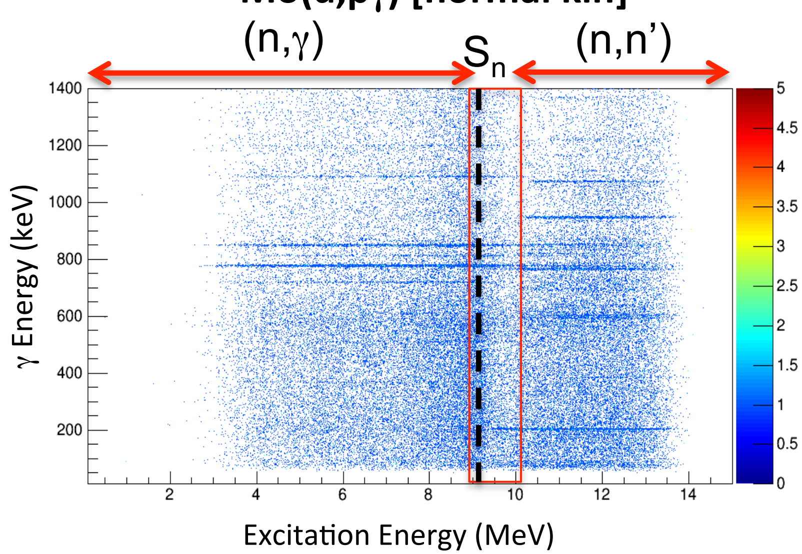




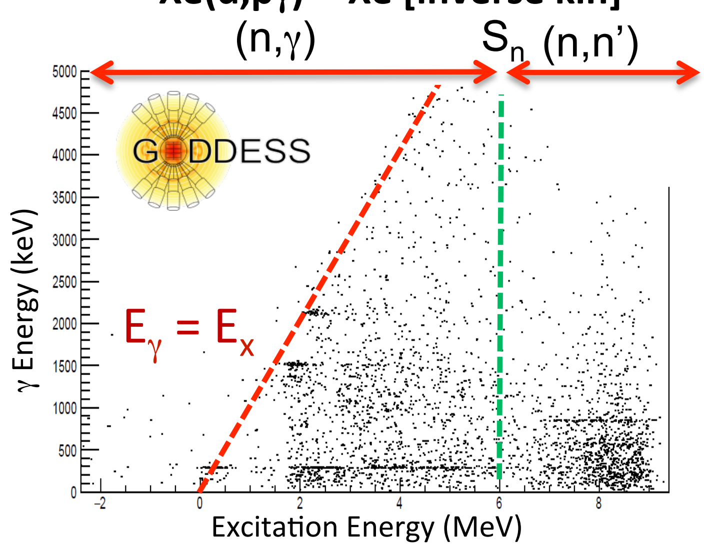
- FRIB
  - •ORRUBA+GRETINA/GRETA coupling
  - •ORRUBA + HAGRiD coupling ($LaBr_3$ array)

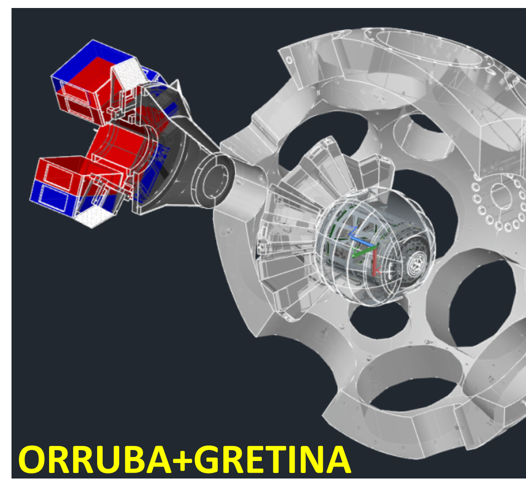
Beam energies ≥10 MeV/A **ReA12 + "fast" beam**

^{95}Mo(d,pγ) [normal kin]



^{134}Xe(d,pγ)^{135}Xe [inverse kin]

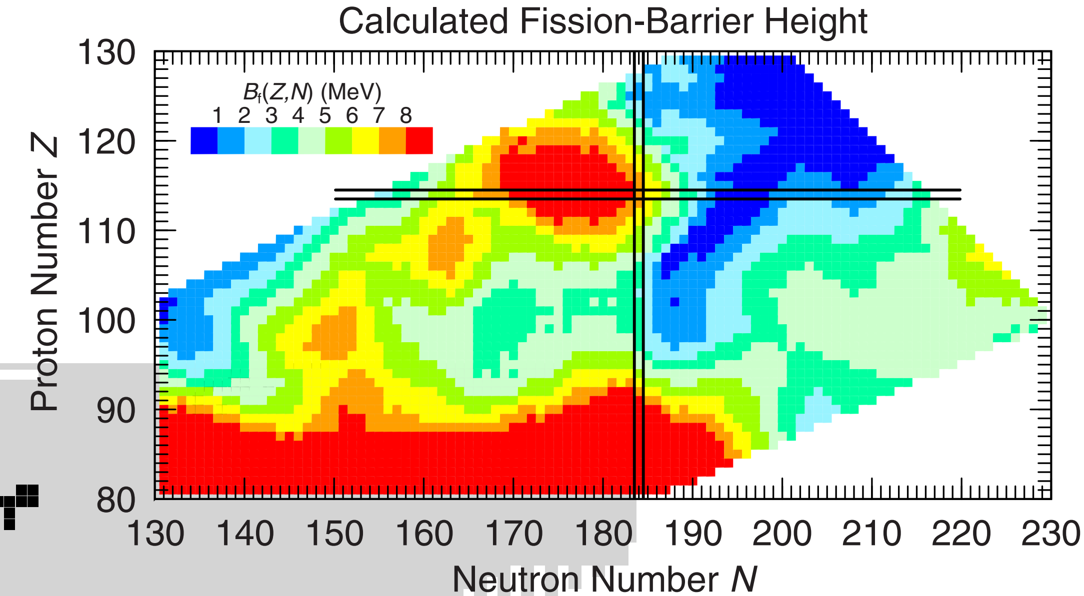




Steve Pain, ORNL

fission properties

Moller+2015

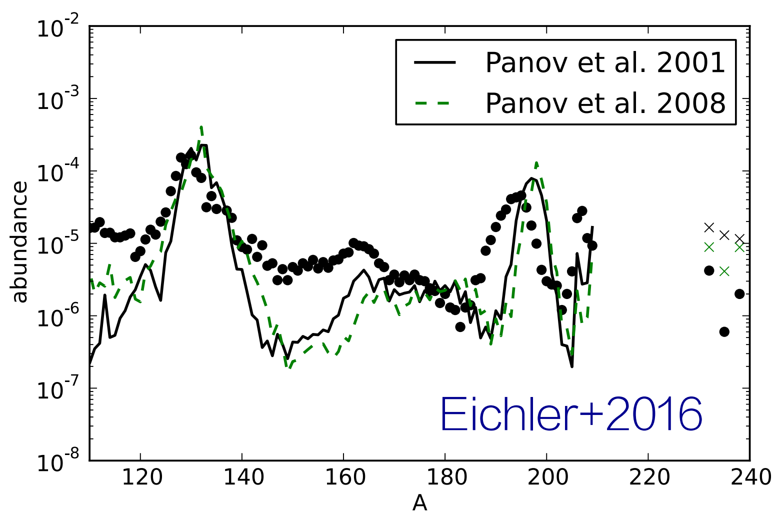


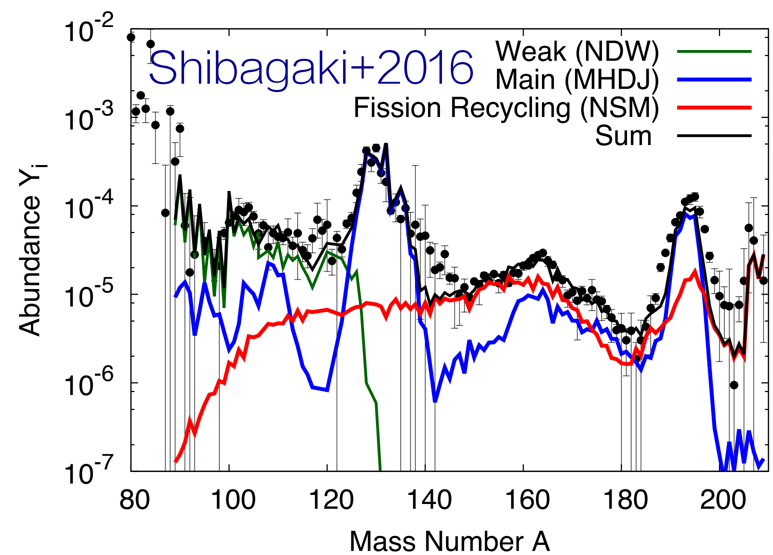
FIRE: Fission In R-process Elements
US DOE/NNSA
Topical Collaboration

fission rates

fission product distributions

some exp info anticipated from AT-TPC





R Surman
FRIB Day 1 Workshop
2 August 2017

Predictive, complete and consistent nuclear models of heavy nuclei are essential for nuclear astrophysics

- r-process simulations require basic (separation energies) and complex (neutron capture, decay rates, fission) nuclear data in heavy nuclei
- Density functional theory is currently the only available framework capable of providing the necessary microscopic, consistent set of nuclear data inputs
- Investments are needed in
  - Computational DFT for large-scale surveys – including decays
  - UQ methodology
  - Training of US-based workforce
- FRIB data will constrain DFT models
  - Masses and separation energies of neutron-rich nuclei
  - Low-energy spectra

Nicolas Schunck

FRIB Day-1 Science: nuclear astrophysics challenges

Priorities for FRIB theory

- Develop many-body theory that will unify nuclear structure and reactions
- Produce quantified global predictions of beta decays, neutron capture, and fission yields
- Develop predictive model of low-energy cross sections
- Explain properties of cluster structures around the reaction threshold

Ideas/needs for achieving them

- Development of spectroscopic-quality energy density functional for nuclei and neutron stars
- Beyond-DFT models of fission yield characteristics
- Beyond-DFT global models of beta decays, including forbidden transitions
- Beyond-DFT global models of level densities and low-energy multipole strength
- Reaction cross sections from the continuum shell model+RGM
- Advanced statistical tools for uncertainty quantification, model development, data selection, and identification of key experimental data needed
- Development of databases of theoretical results and open-source codes

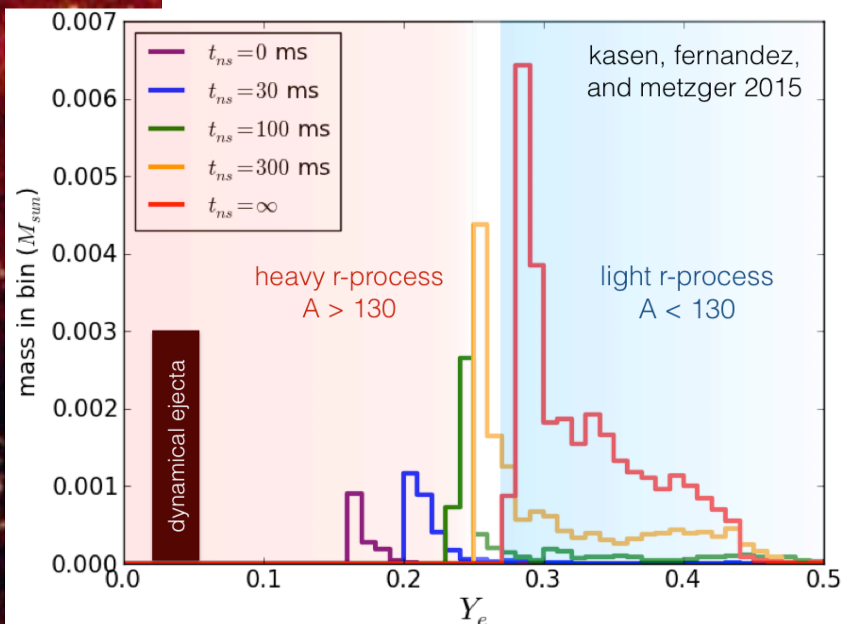
Impact on/alignment with the experimental effort. Experimental data needed.

- Key measurements: masses and beta-decays of neutron-rich nuclei; neutron capture rates; measurements of fission yields for neutron-rich heavy nuclei.

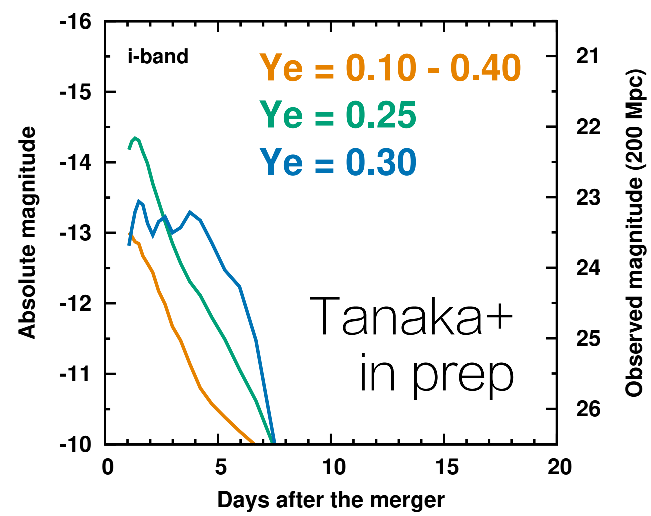
nuclear astrophysics: role of theory

astrophysical conditions
dense matter properties
neutrino physics

nuclear physics inputs:
masses, halflives, reaction rates,
fission yields



astrophysical simulations
+
nuclear network calculations



abundance pattern predictions

comparison to astrophysical observables

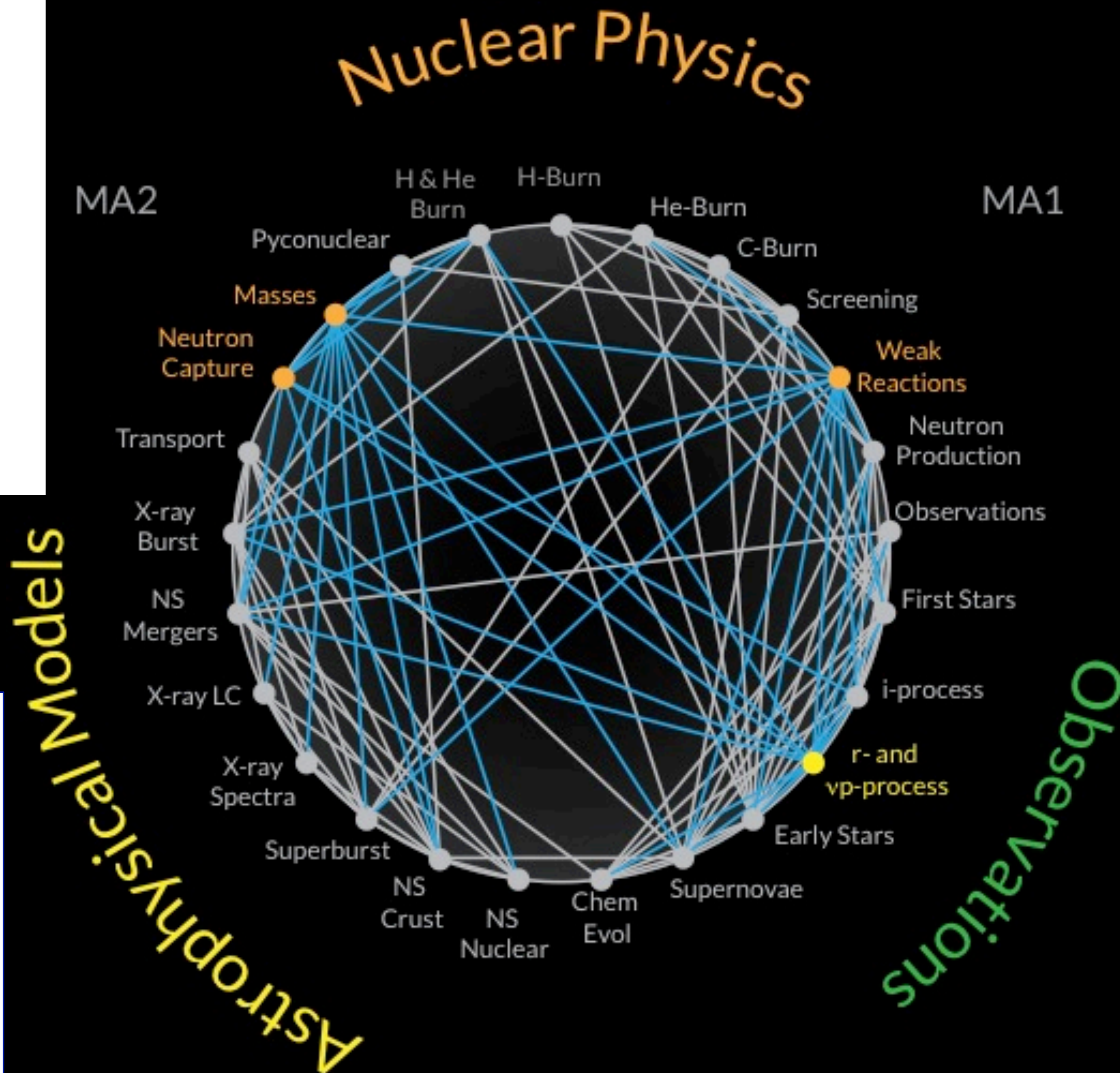
JINA-CEE

Center for the Evolution of the Elements

The *r*–process of nucleosynthesis: connecting FRIB to the cosmos

ICNT/JINA–CEE/ MSU/FRIB

June 2016



anticipating FRIB Day 1: nuclear astrophysics

- Produce reliable astrophysical simulations of candidate nucleosynthetic events with realistic microphysics
- Strive to improve key pieces of microphysics (e.g. equation of state in dense matter, neutrino opacities and oscillations) that influence conditions for element synthesis
- Identify the nuclear properties with the greatest leverage on abundance patterns and astronomical observables to recommend for detailed experimental or theoretical study
- Develop new ideas and fresh approaches to connect FRIB measurements to observations

FIRE

Fission In R-process Elements

The FIRE collaboration explores the role of fission in the rapid neutron capture or r-process of nucleosynthesis

N3AS

SciDAC proposal: TEAMS
lead P.I. R. Hix/ORNL

JINA-CEE

Center for the Evolution of the Elements

Impact on/alignment with the experimental effort. Experimental data needed.

- Key measurements: masses and beta-decay properties of neutron-rich nuclei; neutron capture rates; measurements of fission yields for neutron-rich heavy nuclei.