Nuclear Astrophysics
Summary from Fall 2012 Town Meeting
H. Schatz

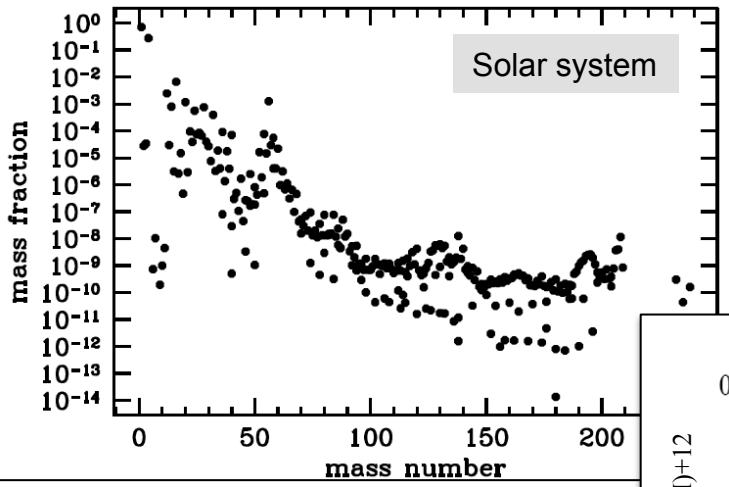
Detroit, Fall 2012

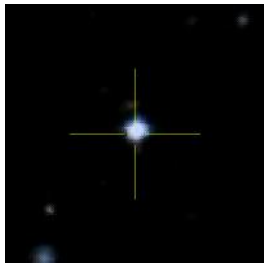
- 150 Participants from **Nuclear Physics, Astrophysics, and Astronomy**
- 22 Plenary Talks, 13 2h working groups

Approach:

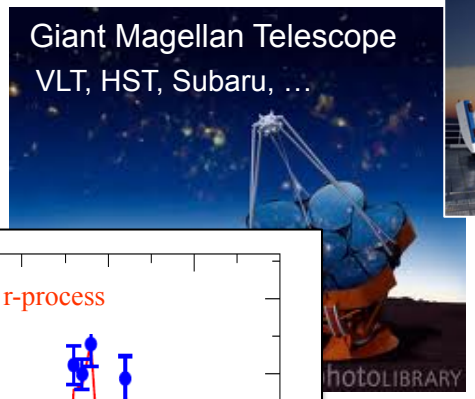
- Use White Paper draft at https://extwiki.nscl.msu.edu/astrotown2012 as starting point for new white paper for LRP process.
- Advantage: we have input from astrophysics/astronomy
- This Town Meeting
  - Discuss improvements, additions, and updates (working groups)
  - Discuss conclusions and recommendations

Observations of Stars have Revolutionized Nuclear Astrophysics

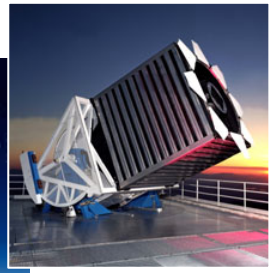




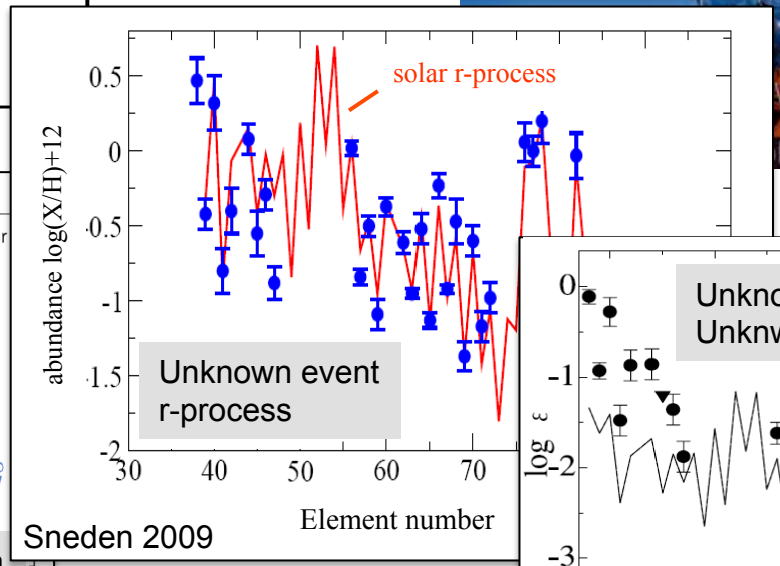
The largest telescopes

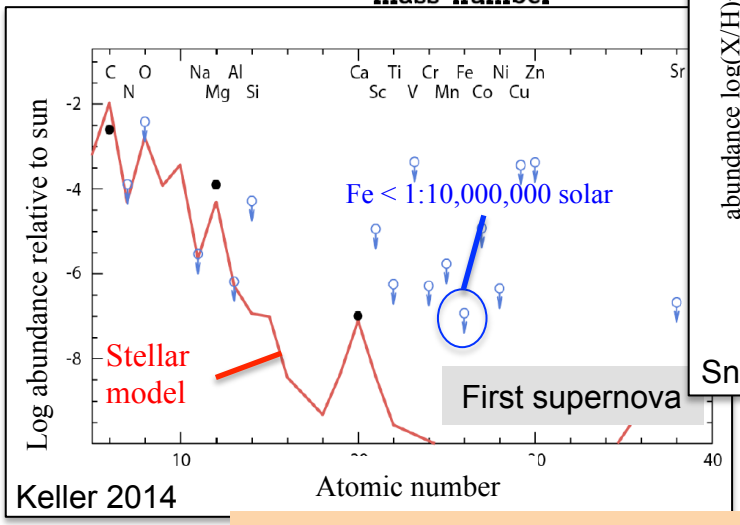


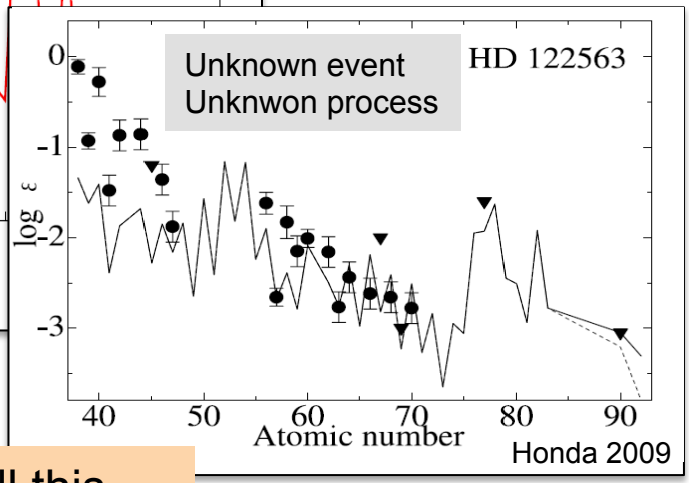
Large surveys:
Millions of stars



SDSS/APOGEE
AEGIS
LAMOST
GAIA
GALAH





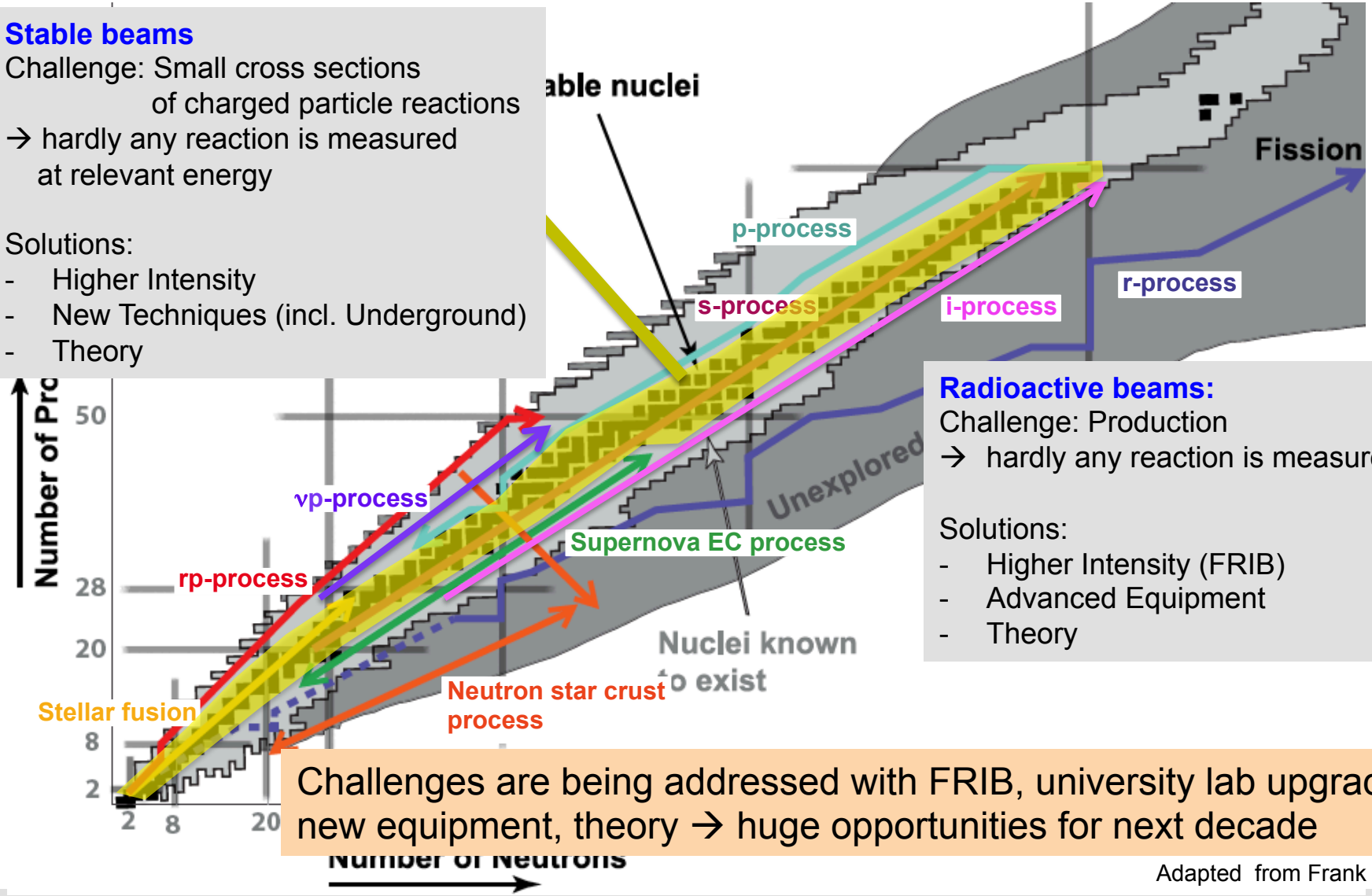


Urgent need for nuclear physics to explain all this
→ Opportunity to unravel the origin of the elements

Nuclear Physics Discoveries Are an Essential Part of this Revolution

Stable beams
Challenge: Small cross sections
of charged particle reactions
→ hardly any reaction is measured
at relevant energy

Solutions:
- Higher Intensity
- New Techniques (incl. Underground)
- Theory



Radioactive beams:
Challenge: Production
→ hardly any reaction is measured

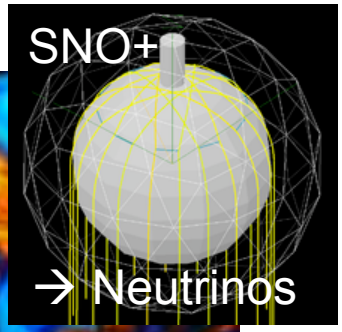
Solutions:
- Higher Intensity (FRIB)
- Advanced Equipment
- Theory

Challenges are being addressed with FRIB, university lab upgrades, new equipment, theory → huge opportunities for next decade

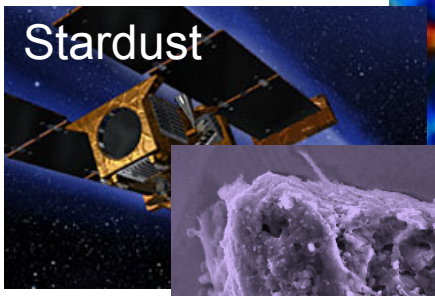
Adapted from Frank Timmes

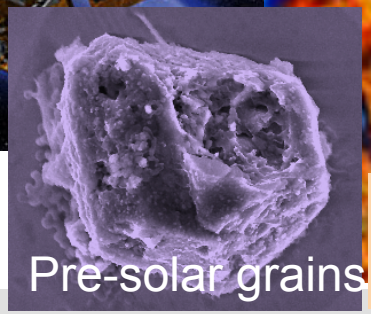
Stars – Still a Mystery

Multi-messenger Observations



Samples of stars





→ How do stars mix, rotate, and generate magnetic fields?

→ Which stars go supernova? (How do stars loose mass)

→What are the elements stars make? As a function of metallicity? The first stars?

→ A new process? i-process

→ What is the sun's metallicity?

Theory:
- 3D Modeling
- Nuclear cross section extrapolation

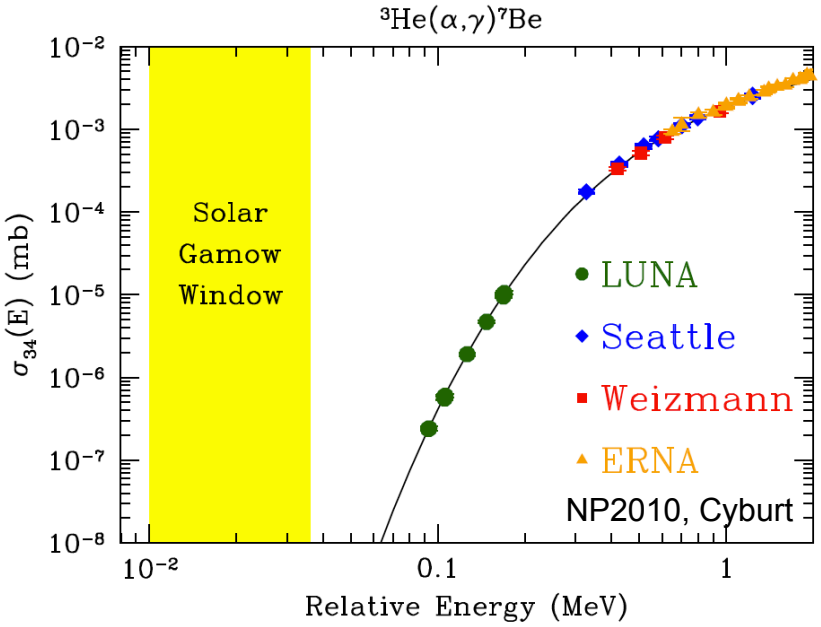
Big Theme:
- Validation

Validation: Growing need for nuclear physics

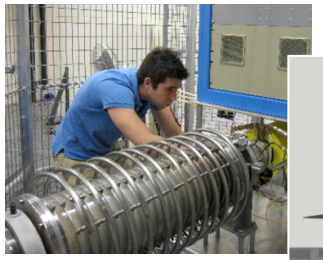
Woodward

The Quest Towards Stellar Cross Sections Measurements

Approach: Underground



Approach: Higher Intensity



LENA upgrade
at TUNL

New St Ana accelerator
at Notre Dame

LANSCE
And planned HIγS upgrades

Approach: Recoil Separator

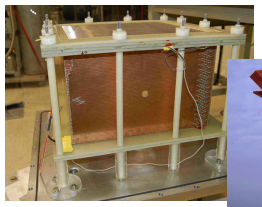
Theory:

- Reaction theory to analyze data and extrapolate
- Ab-initio based rate predictions

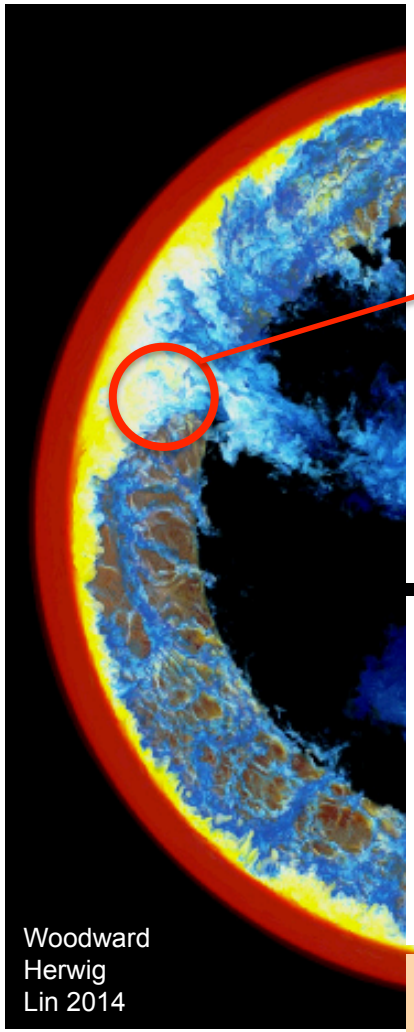
Stable beam experiments
are essential to understand stars

Approach: New Techniques

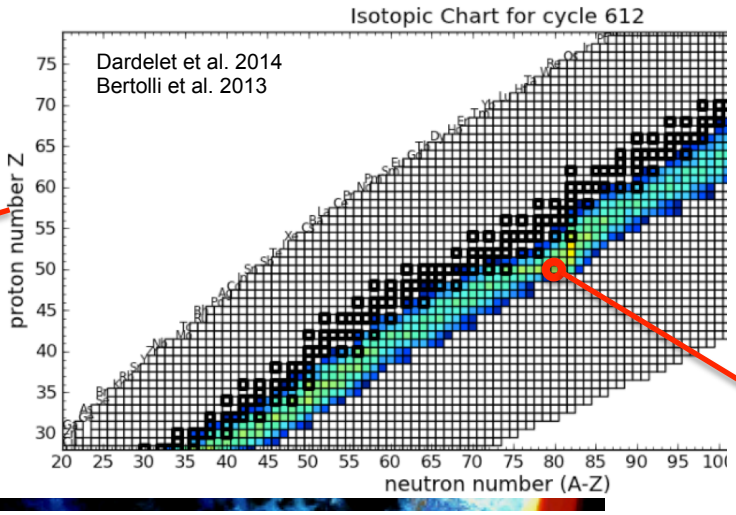
- Summing/Coincidence Detection (SUN@NSCL, LENA@TUNL)
- Optical TPC at HIγS
- STAR Bubble Chamber at ANL (JLab)
- Trojan Horse Technique



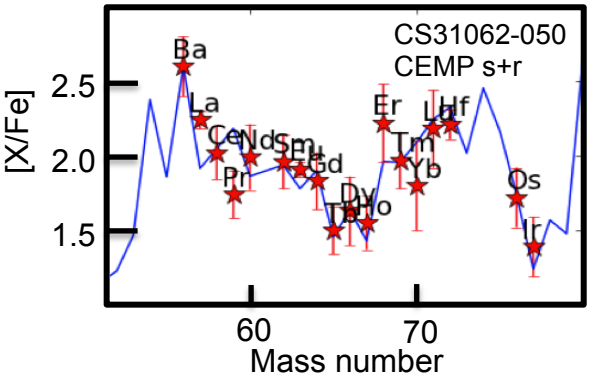
New Nuclear Challenges in Stars from Multi-D Model Approaches



Hydrogen entrainment leads to $^{13}C(\alpha,n)$ driven neutron capture process (i-process)



Explains abundance signatures?

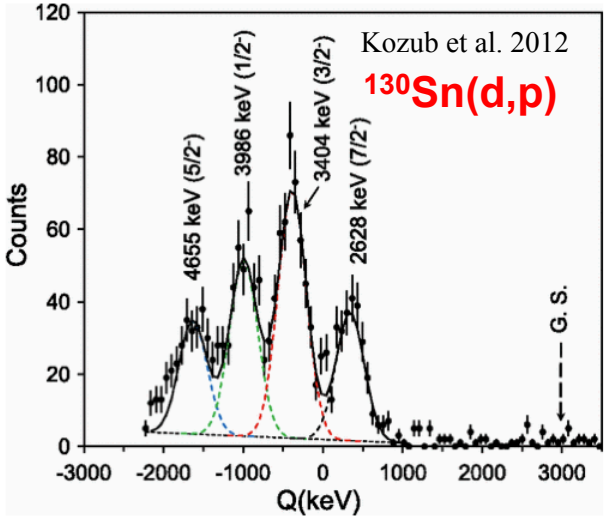


Nuclear physics needs:

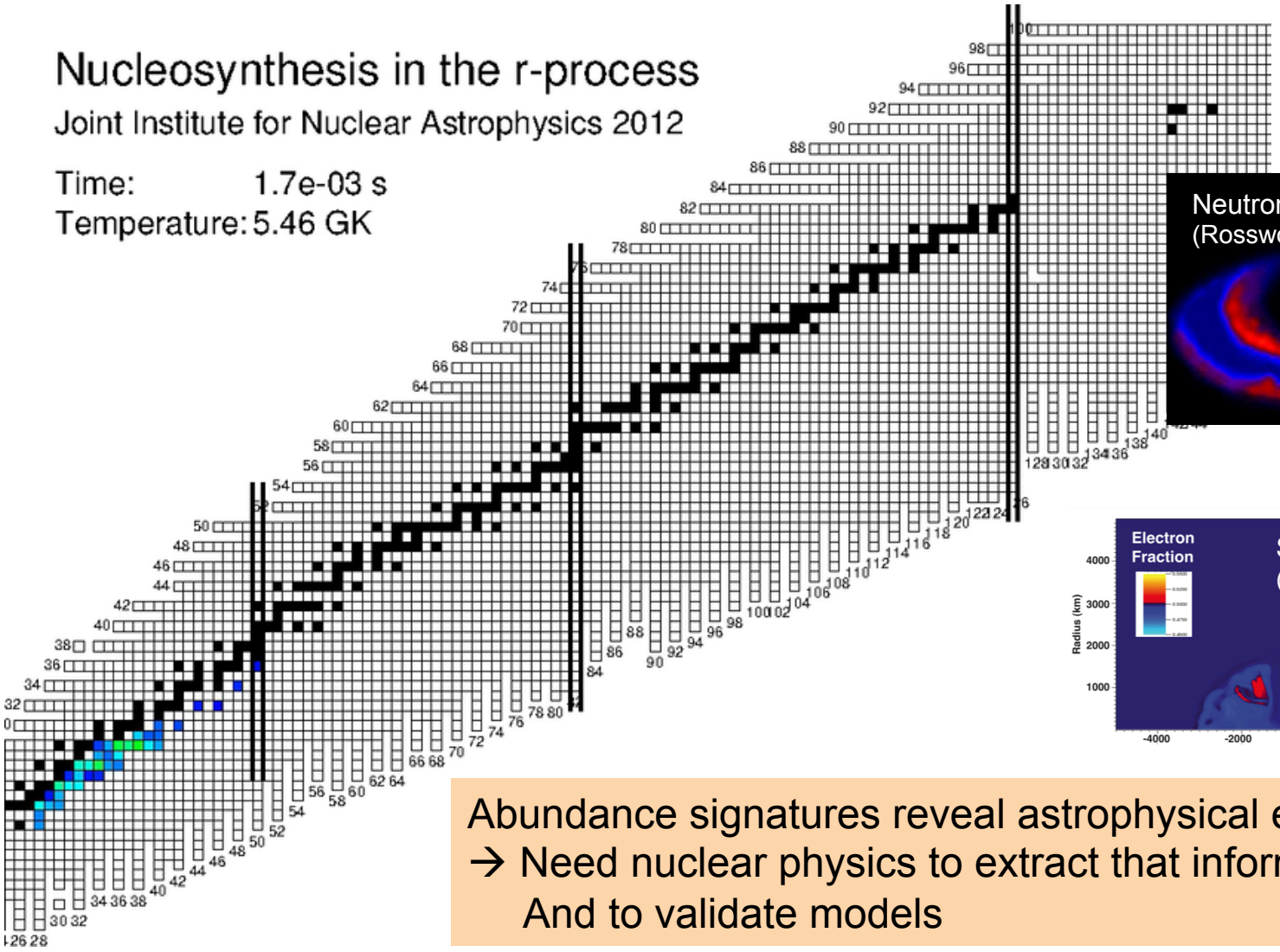
- (α,n) rates (stable beam experiments)
- n-captures on stable nuclei: LANSCE
- n-capture rates 1-6 units from stability
  - Develop (d,p) and other surrogate techniques
  - NEED REACTION THEORY !!

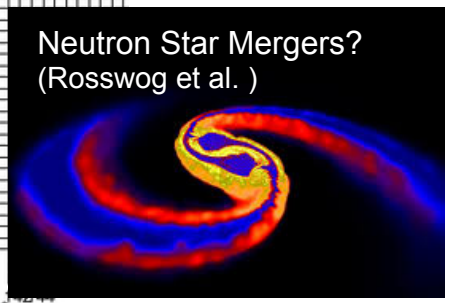
Need a multi-facility approach
(stable beams, neutron beams,
and radioactive beams, FRIB 6-12 MeV)

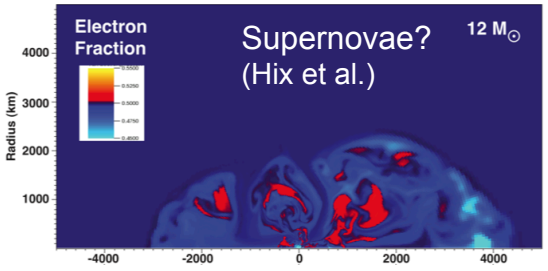
Pioneering (d,p) work at HRIBF



What is the Origin of Elements Beyond Selenium? What is (are) the r-process (es)

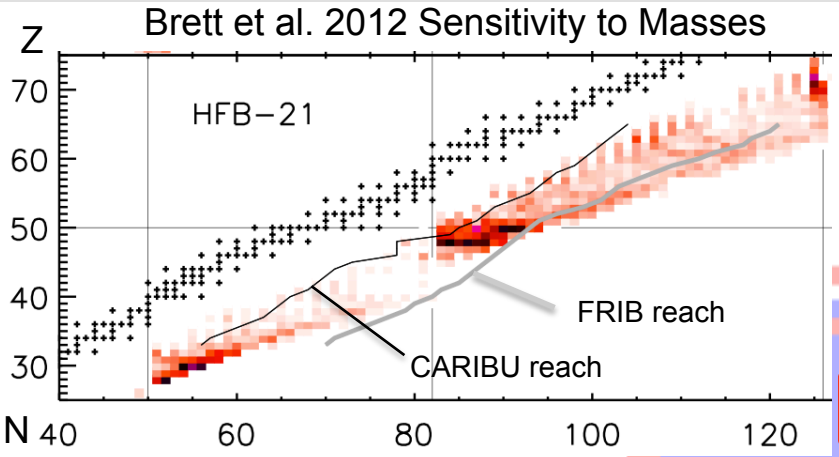






Abundance signatures reveal astrophysical environment
→ Need nuclear physics to extract that information
And to validate models

The Quest for r-process Nuclear Physics



N=82

N=126

ANL Trap @ CARIBU

ORNL (d,p)

GSI ESR Ring

Jyvaskyla Trap

TRIUMF Trap

CERN/ISOLDE Trap

NSCL TOF

^{9}Be(γ,n) HIγS

N=50

ORNL $T_{1/2}$ P_n

NSCL $T_{1/2}$ P_n

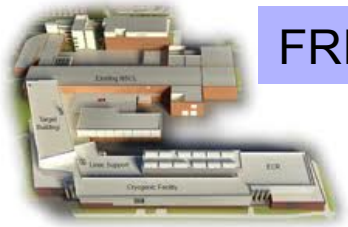
RIKEN $T_{1/2}$

GSI/Mainz $T_{1/2}$ P_n

CERN/ISOLDE $T_{1/2}$ P_n

Theory:
- Guides Experiment
- Provide less critical data
- Provide data out of reach
- Environmental corrections

+ Neutrino Physics
+ Nuclear Matter EOS
+ Fission

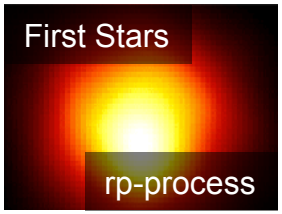


FRIB

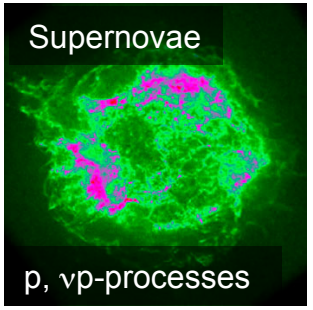
FRIB Reach
FRIB is a Game Changer

H/He induced Stellar Reactions on Unstable Neutron Deficient Nuclei

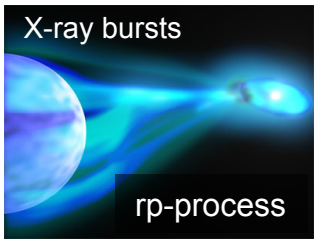
- Do they exist?
- What are their abundance signatures?

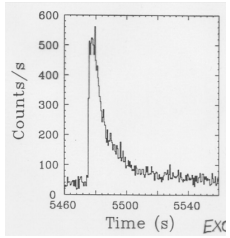


- What were their properties?
- What are their abundance signatures? (→ Massive Surveys)
- How much did they contribute to re-ionization of the cosmos?

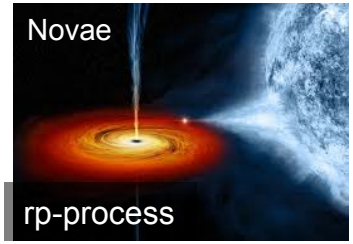


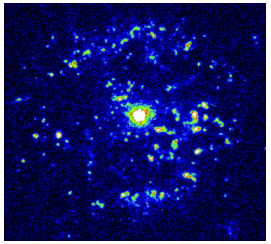
- What is the contribution to the origin of the elements?
- Why do observations disagree with models?





- What do 3000 bursts in MINBAR archive tell us about neutron star?
- How can we understand the wide variety of burst behaviors



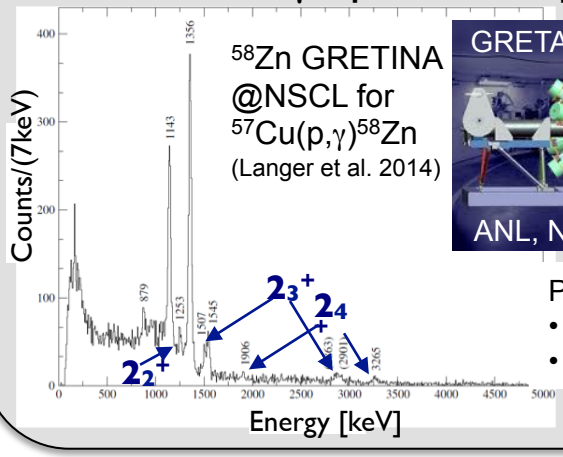


- How much radioactivity do they eject?
- How is white dwarf matter mixed in?
- Are there exotic types of explosions? (→ LLST)

The Quest to Measure Reaction Rates of Unstable p-rich Nuclei

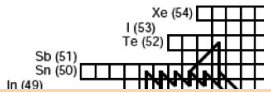
Fast Beams

Indirect: γ-spectroscopy

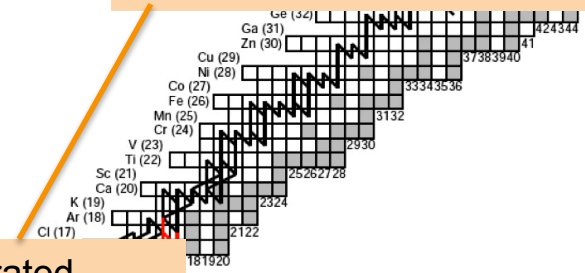


^{58}Zn GRETINA @NSCL for ^{57}Cu(p,γ)^{58}Zn (Langer et al. 2014)

Past Achievements:
- Gammasphere
- SeGA



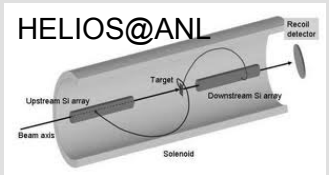
FRIB will provide
vastly expanded rp-process reach
for all these approaches
(Lower rp-process: stable beam opportunities)

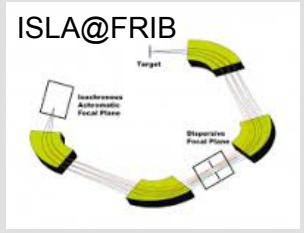


Reaccelerated Beams <6-12 MeVu

Reaccelerated Beams <3 MeV/u

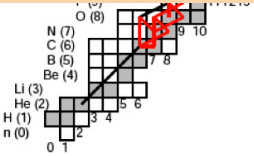
Indirect: particle-spectroscopy





Transfer reactions:
- JENSA Gas Jet (CSM)
- TWINSOL@Notre Dame
- (d,n)@RESOLUT FSU
- Spectrometer plans:
  - TUNL Tandem
  - FSU
- ANASEN (FSU, LSU)
- AT-TPC@NSCL

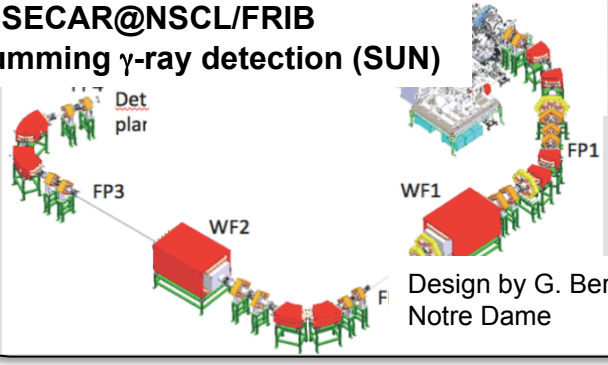
Beta decay:
- β-p at TAMU and NSCL



Direct measurements (p,γ)

Recoil separators:
- DRAGON/HRIBF DRS …
- **SECAR@NSCL/FRIB**

Summing γ-ray detection (SUN)



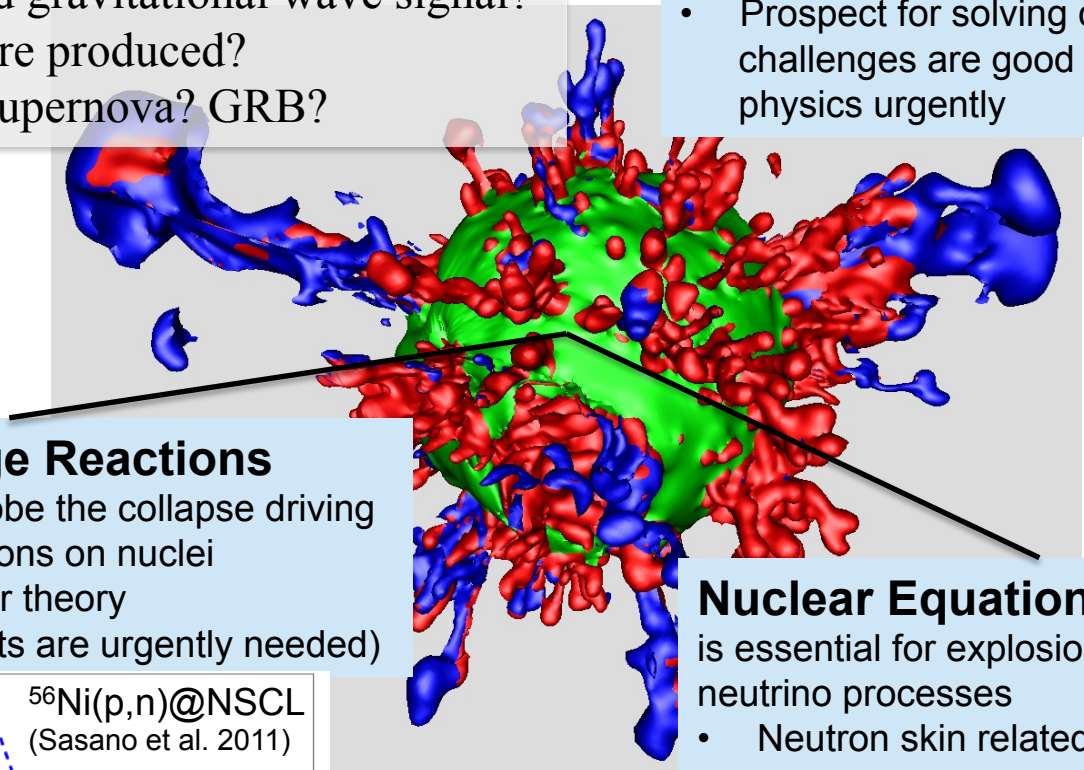
Design by G. Berg
Notre Dame

How do Core Collapse Supernovae explode?

→ What is the supernova mechanism?
→ What is the ν and gravitational wave signal?
→ What elements are produced?
→ Which stars go supernova? GRB?

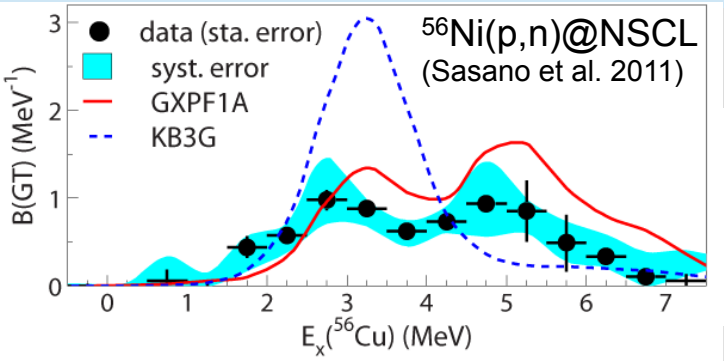
Astrophysical Models

- 3D Modeling Seems Essential
- Prospect for solving computational challenges are good → need nuclear physics urgently



Charge Exchange Reactions

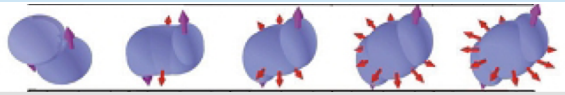
at ~100 MeV/u can probe the collapse driving electron capture reactions on nuclei
→ Can validate nuclear theory
(theory developments are urgently needed)



Nuclear Equation of State

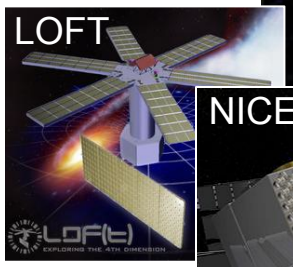
is essential for explosion mechanism and neutrino processes

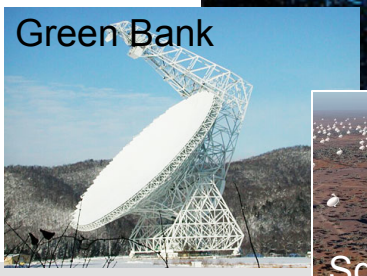
- Neutron skin related measurements
- Nuclear masses
- Heavy Ion Collisions
- Nuclear Theory



Neutron stars and cold dense nuclear matter

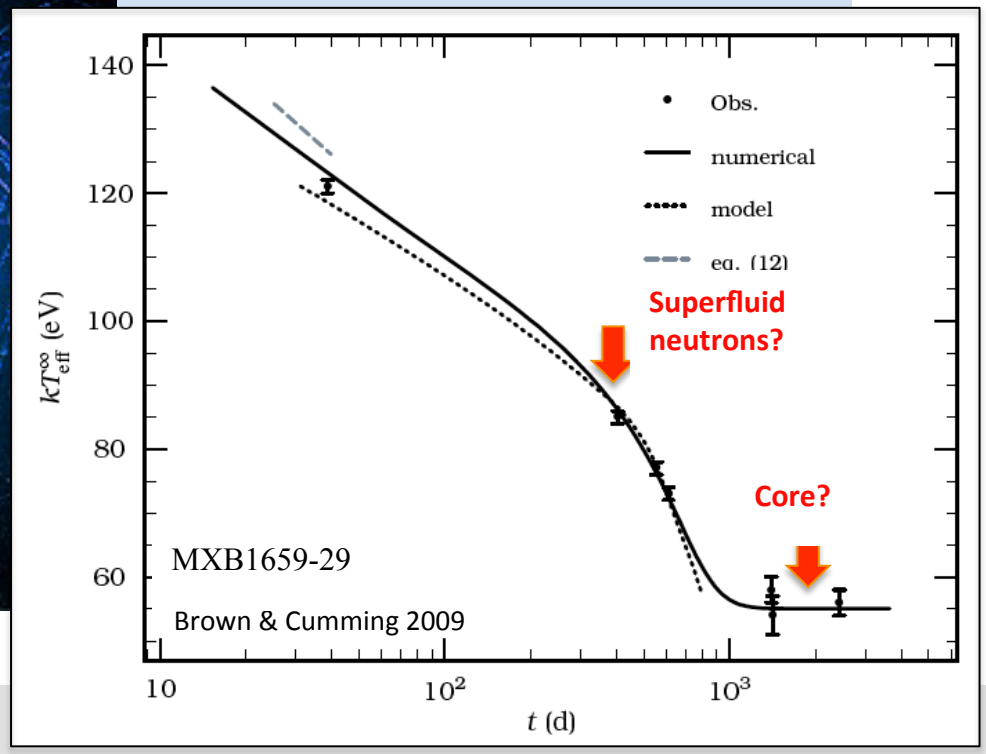
Multi-Messenger Observations





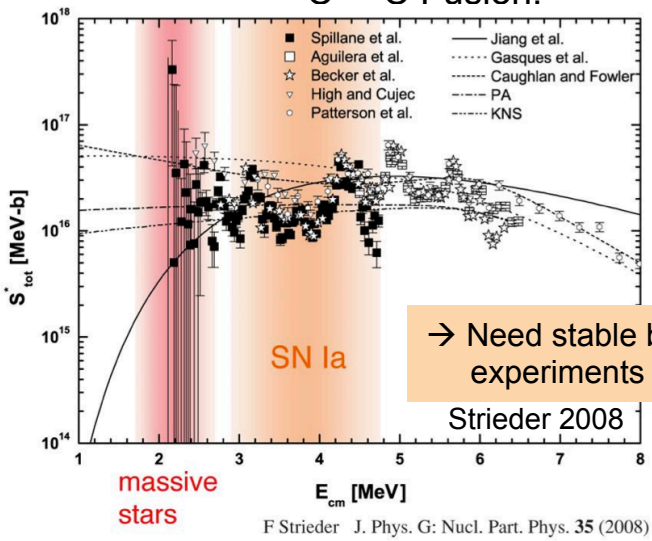
- What are the properties of cold dense matter? What is its maximum density?
- How can we determine radii, masses, and crust properties of neutron stars from observations?
- What powers superbursts?
- Origin of burst oscillations?
- Are neutron star mergers GRBs? r-process site?

Cooling transients probe deeper crust



Accreting neutron stars are powerful probes but require broad range of nuclear physics

$^{12}C+^{12}C$ Fusion:



F Strieder J. Phys. G: Nucl. Part. Phys. **35** (2008) 014009

→ Need stable beam experiments

Strieder 2008

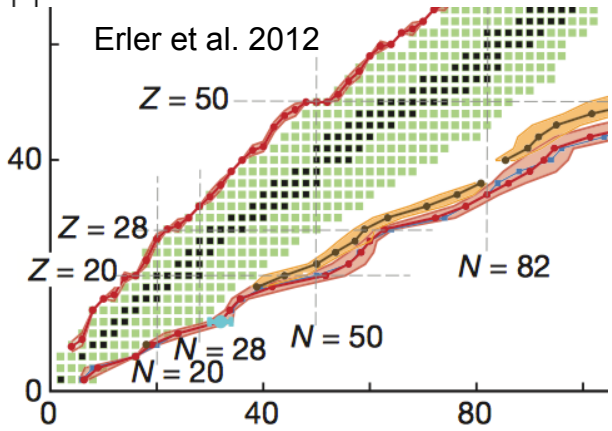
Need for neutron rich A=12-108 nuclei
→ Masses
→ Neutron drip
→ EC/β strengths
→ Fusion reactions
Need FRIB with HRS
Need nuclear theory for n-rich nuclei with uncertainties!

Step 2:
Electron Capture
with increasing depth
→ heating

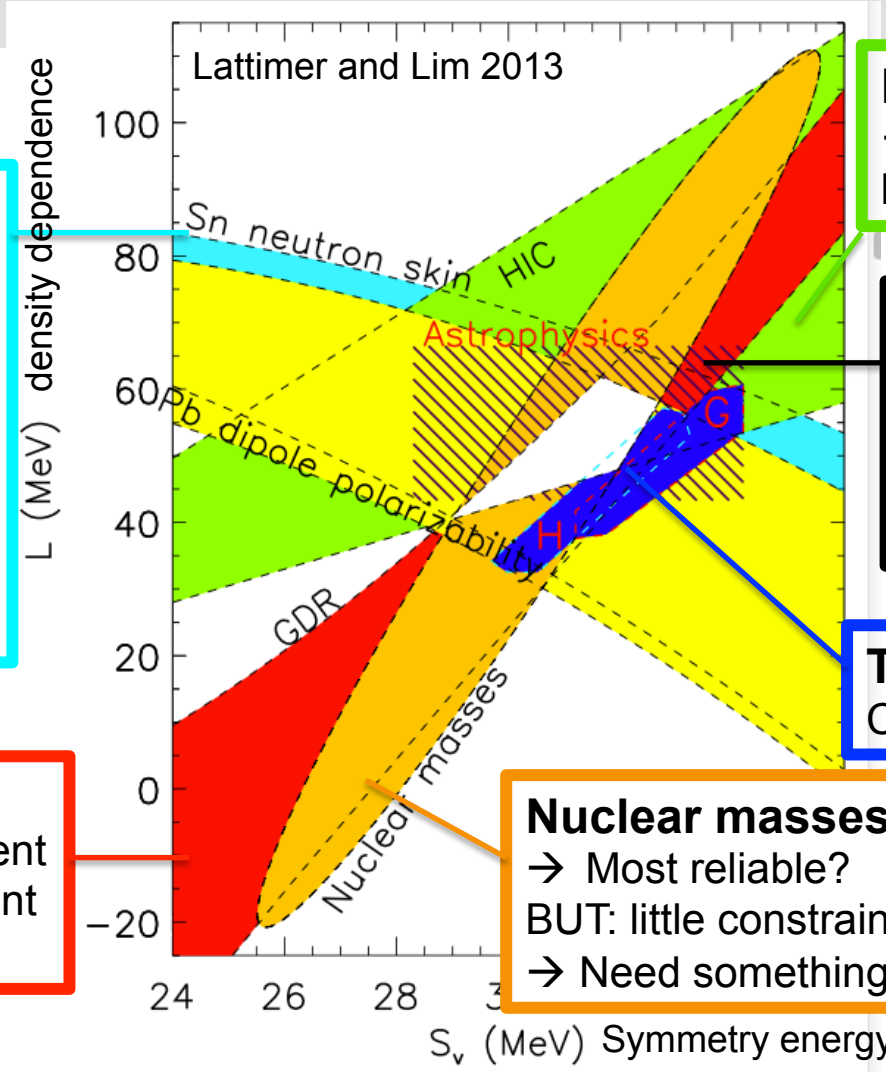
Urca Cooling
at certain depths

Step 1:
Superbursts
(Carbon burning)

Step 3:
Beyond n-drip:
EC, n-capture, fusion
→ heating



Probing the Nuclear Equation of State



Neutron Skin
→ **Important**
- Collective E/M modes (e.g. PDR, …)
- PREX
- Dipole polarizability
- Anti-protonic atoms
- Proton scattering

Heavy Ion Collisions
→ Model dependent but can get beyond ρ_0

Neutron Stars
→ Also depend on larger ρ
→ Use for concordance check, learn from discrepancies

Theoretical Constraints
Chiral Effective Field Theory

GDR
→ model dependent
→ similar constraint to masses

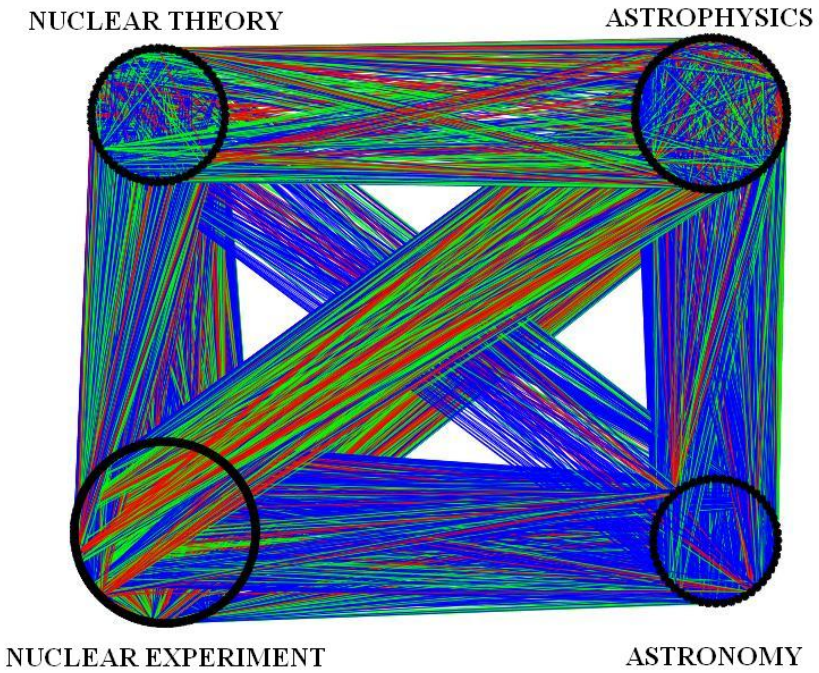
Nuclear masses
→ Most reliable?
BUT: little constraint in L
→ Need something else

Nice concordance – but what does it mean?
Need to understand systematic errors and model dependencies !!

Centers are important for interdisciplinary research

The Joint Institute for Nuclear Astrophysics (JINA)

- **Dedicated center for Nuclear Astrophyiscs**
- NSF Physics Frontiers Center since 2003; just renewed
- Bridges field boundaries
- International Research network, exchange, workshops, schools, data and codes

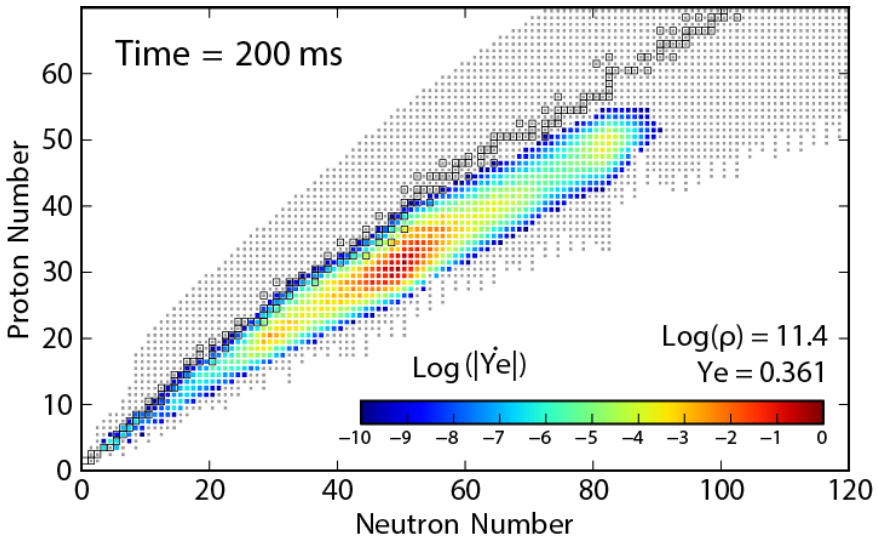


Institute for Nuclear Theory (INT)

- **Serves the nuclear theory community**
- DOE supported
- Focus on programs and summer schools
- Many programs in nuclear astrophysics
- Connects nuclear astrophysics with nuclear theory community

Summary

- **Exciting new open questions driven by observations:**
  - Era of large scale spectroscopic surveys, LLST, LIGO
  - Unprecedented amount of X-ray data
- **Towards 3D modeling: Validation will become critical**
  - Increased need for precise nuclear physics!
- **Broad Range of Accelerators, Equipment, and Theory needed**
- **Major advances on nuclear side within reach:**
  - FRIB is a game changer: finally most nuclei in the cosmos within reach
  - Need nuclear astrophysics equipment (SECAR, GRETA, HRS, …)
  - Unprecedented upgrades of stable/gamma/neutron beam facilities
  - Exciting interim RIB opportunities at ANL (CARIBU) and NSCL (fast/stopped/ReA3 beams)
  - Challenges in nuclear theory are being addressed:
    - reaction theory, EOS, structure of broad range of heavy nuclei
  - **International opportunities: FAIR, RIBF, LUNA, FRANZ, ….**
- Did not mention in detail: SN type Ia, s-process – they are important!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