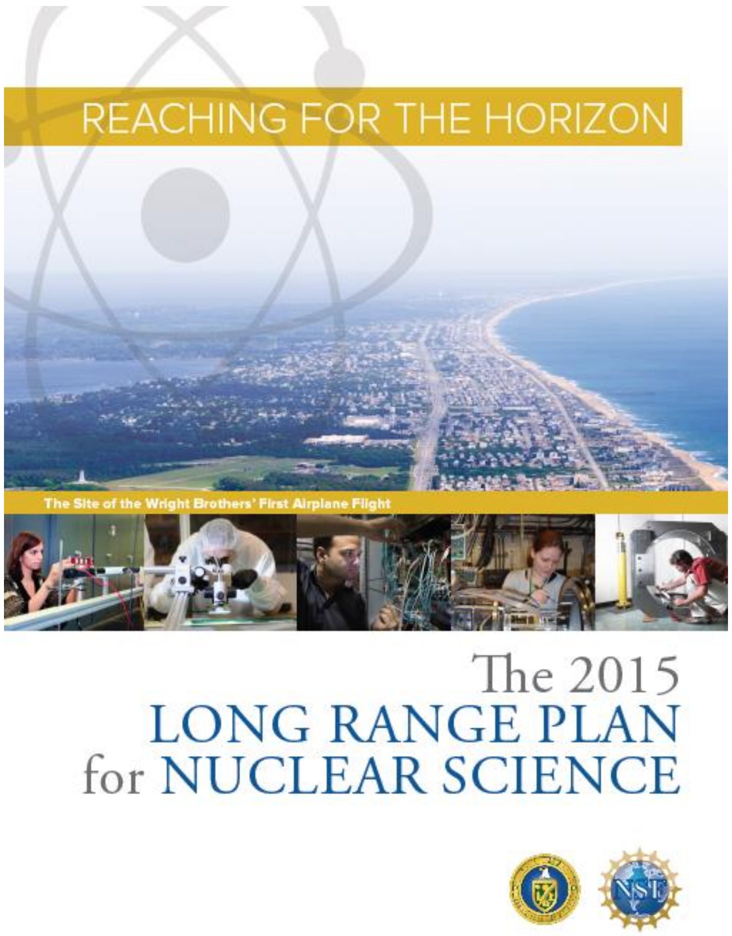
Summary from US Nuclear Astrophysics Town Meetings Leading up to the 2015 NSAC Long Range Plan

H. Schatz
NSCL
Department of Physics and Astronomy
JINA Center for the Evolution of the Elements
Michigan State University

2015 US NSAC Nuclear Science Long Range Plan
Nuclear Astrophysics

http://science.energy.gov/np/nsac/



2014 Town meetings on each major section:

- Low energy nuclear physics
- **Nuclear Astrophysics**

joint

- Hadron and Heavy Ion QCD
- Fundamental Symmetries and Neutrinos
- Education and Innovation

→ Nuclear Astrophysics is a major subfield of Nuclear science

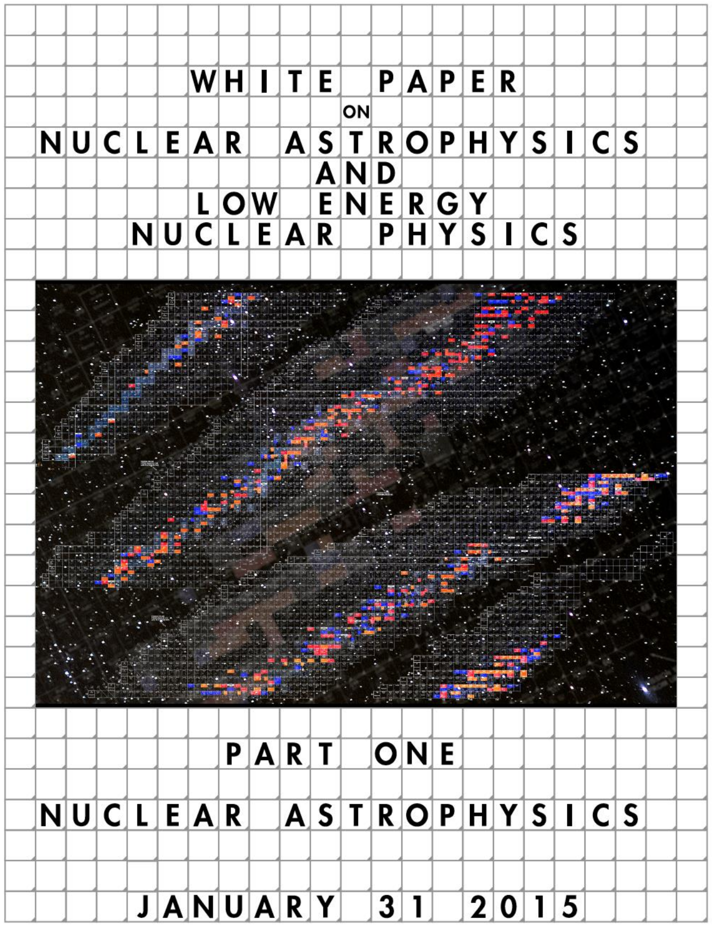
2012 Town meeting on Nuclear Astrophysics

→ Organized by Joint Institute for Nuclear Astrophysics (JINA)

→ Brought together 150 Nuclear scientists astrophysicists, and astronomers in wake of NP2010 and Astro2010 Decadal Surveys: **unique perspective**

Input: Nuclear Astrophysics White Paper based on 2012 and 2014 Town Meetings

http://www.lecmeeting.org/whitepapers/NAP_White_Paper.pdf

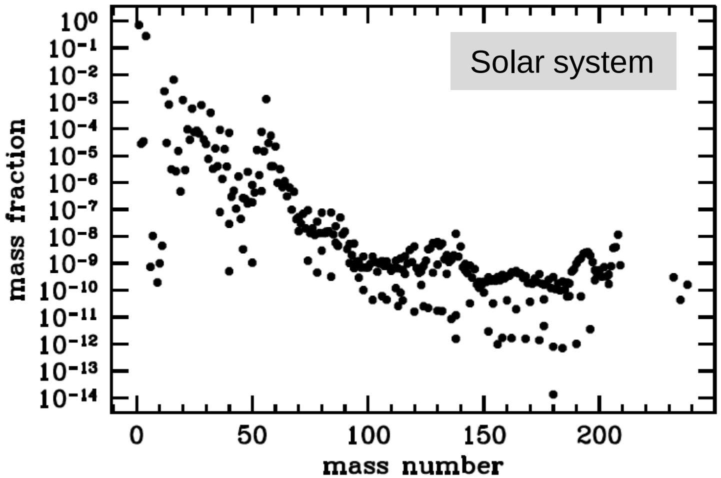


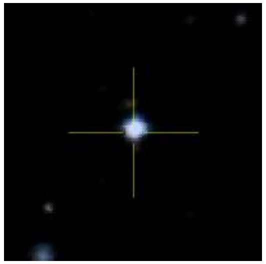
Edited by: H. Schatz, M. Wiescher

Other text contributors:

Almudena Arcones
Dan Bardayan
Lee Bernstein
Timothy Beers
Alex Brown
Edward Brown
Carl Brune
Jeff Blackmon
Art Champagne
Alessando Chieffi
Aaron Couture
Pawel Danielewicz
Roland Diehl
Mounib El Eid
Jutta Escher
Brian Fields
Carla Fröhlich
Falk Herwig
Raph Hix
Christian Illiadis
Bill Lynch
Brad Meyer
Gail McLaughlin
Bronson Messer
Tony Mezzacappa
Filomena Nunes
Brian O'Shea
Madappa Prakash
Boris Pritychenko
Ernst Rehm
Sanjay Reddy
Grischa Rogachev
Bob Rutledge
Michael Smith
Tod Strohmayer
Ingrid Stairs
Andrew Steiner
Frank Timmes
Dean Townsley
Remco Zegers
Vladimir Zelevinsky
Michael Zingale

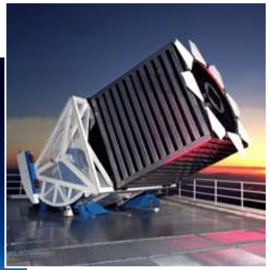
Observations of Stars have Revolutionized Nuclear Astrophysics





The largest telescopes

Large surveys:
Millions of stars



SDSS/APOGEE
AEGIS
LAMOST
GAIA
GALAH

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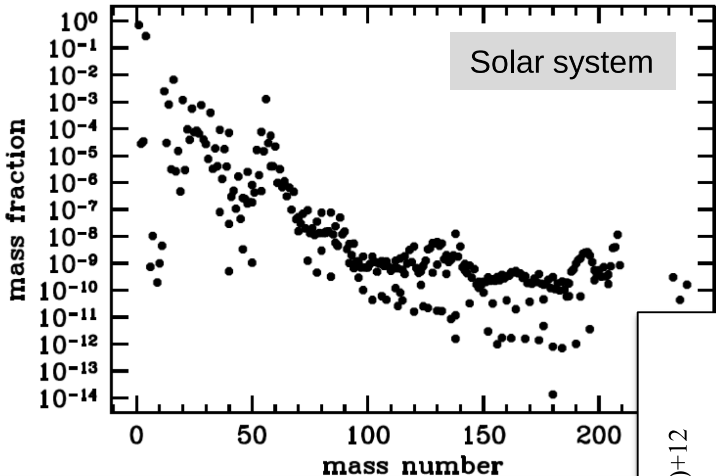

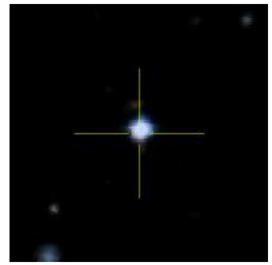

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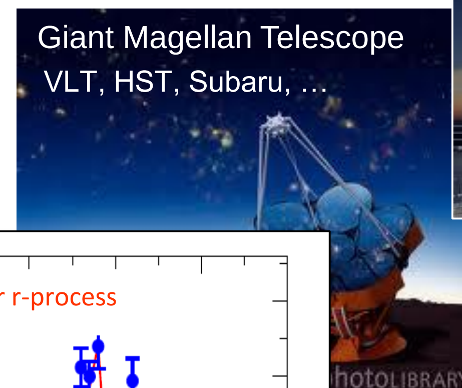

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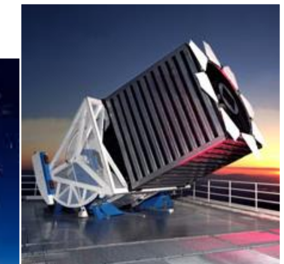

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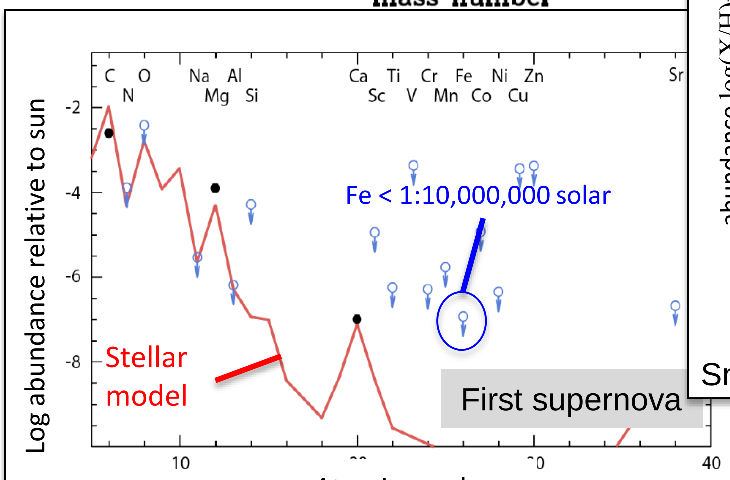
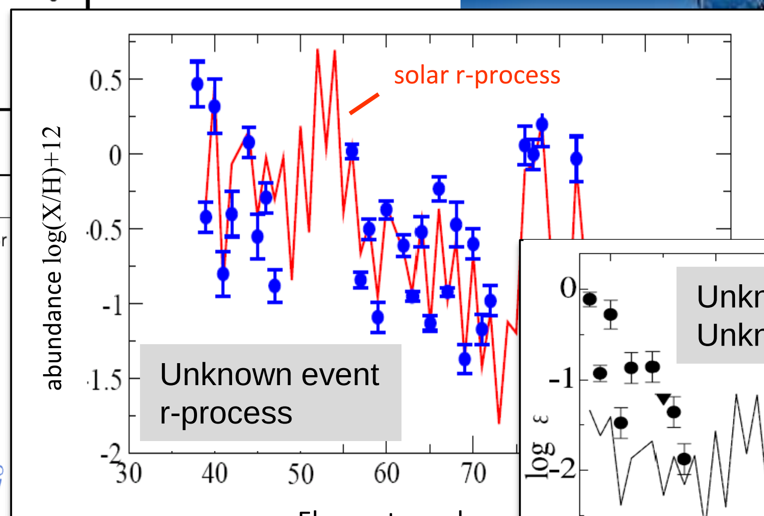
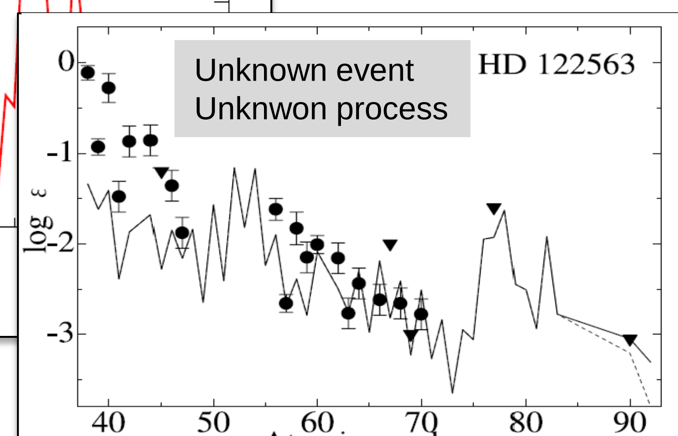


Keller 2014

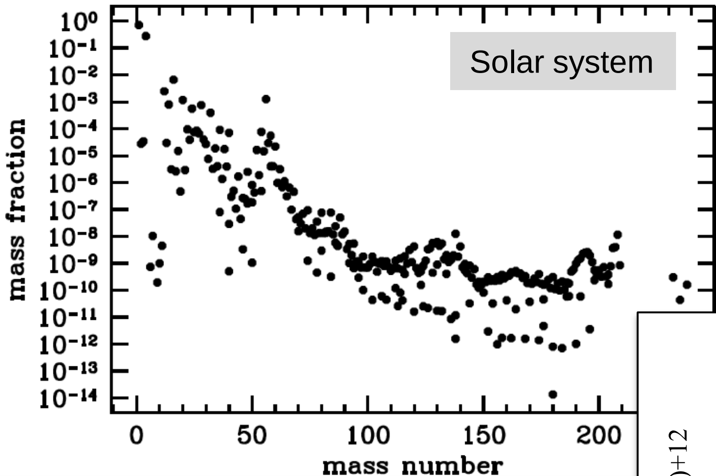


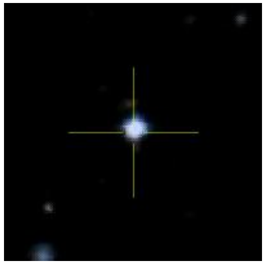
Sneden 2009



Honda 2009

Observations of Stars have Revolutionized Nuclear Astrophysics





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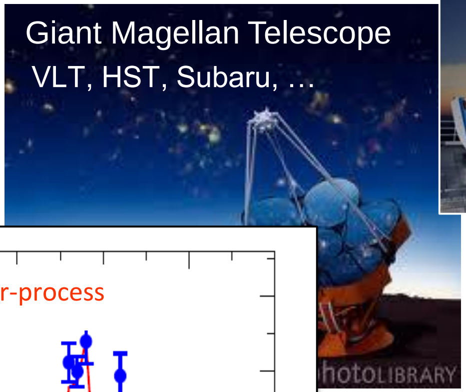

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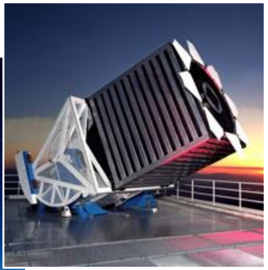

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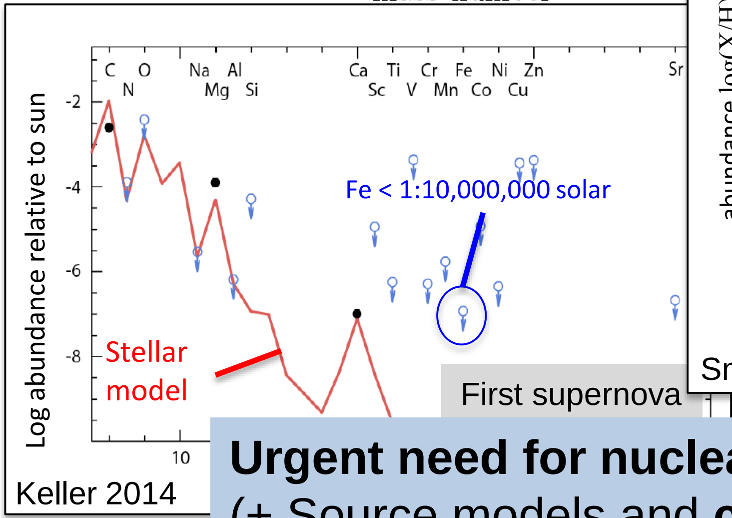
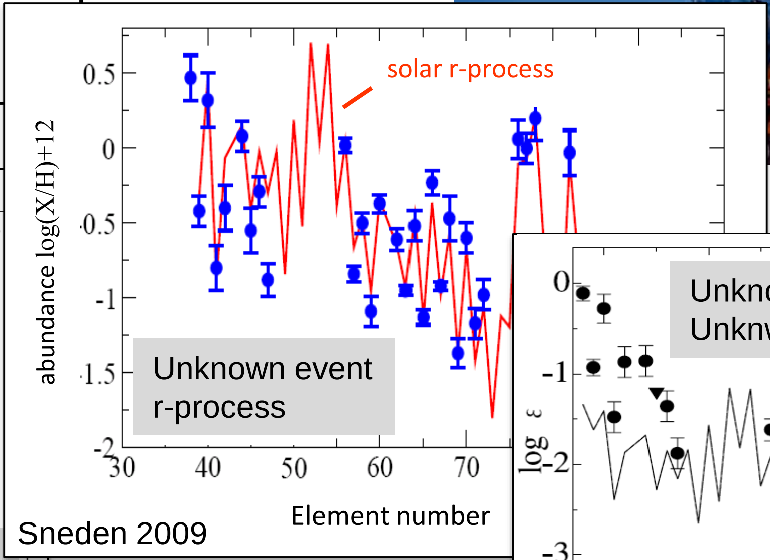
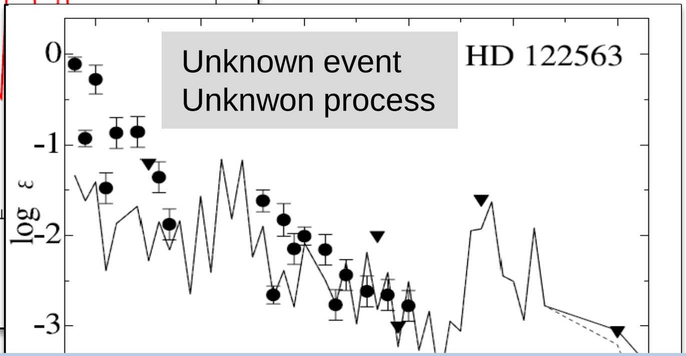
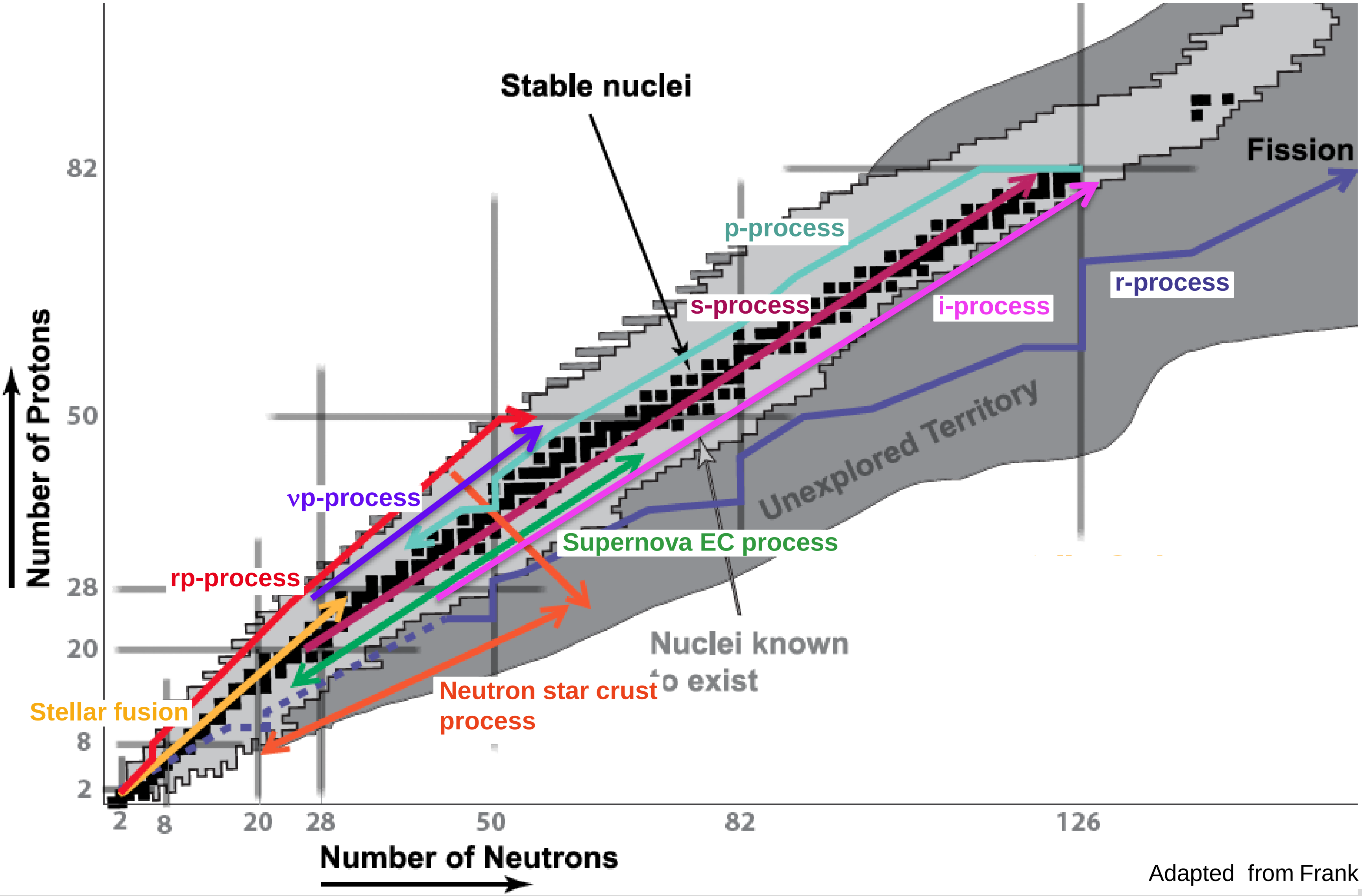






Urgent need for nuclear physics to explain all this
(+ Source models and **chemical evolution** to link to full body of observations)
→ Opportunity to unravel the origin of the elements

Nuclear Physics Discoveries
Are an Essential Part of this Revolution

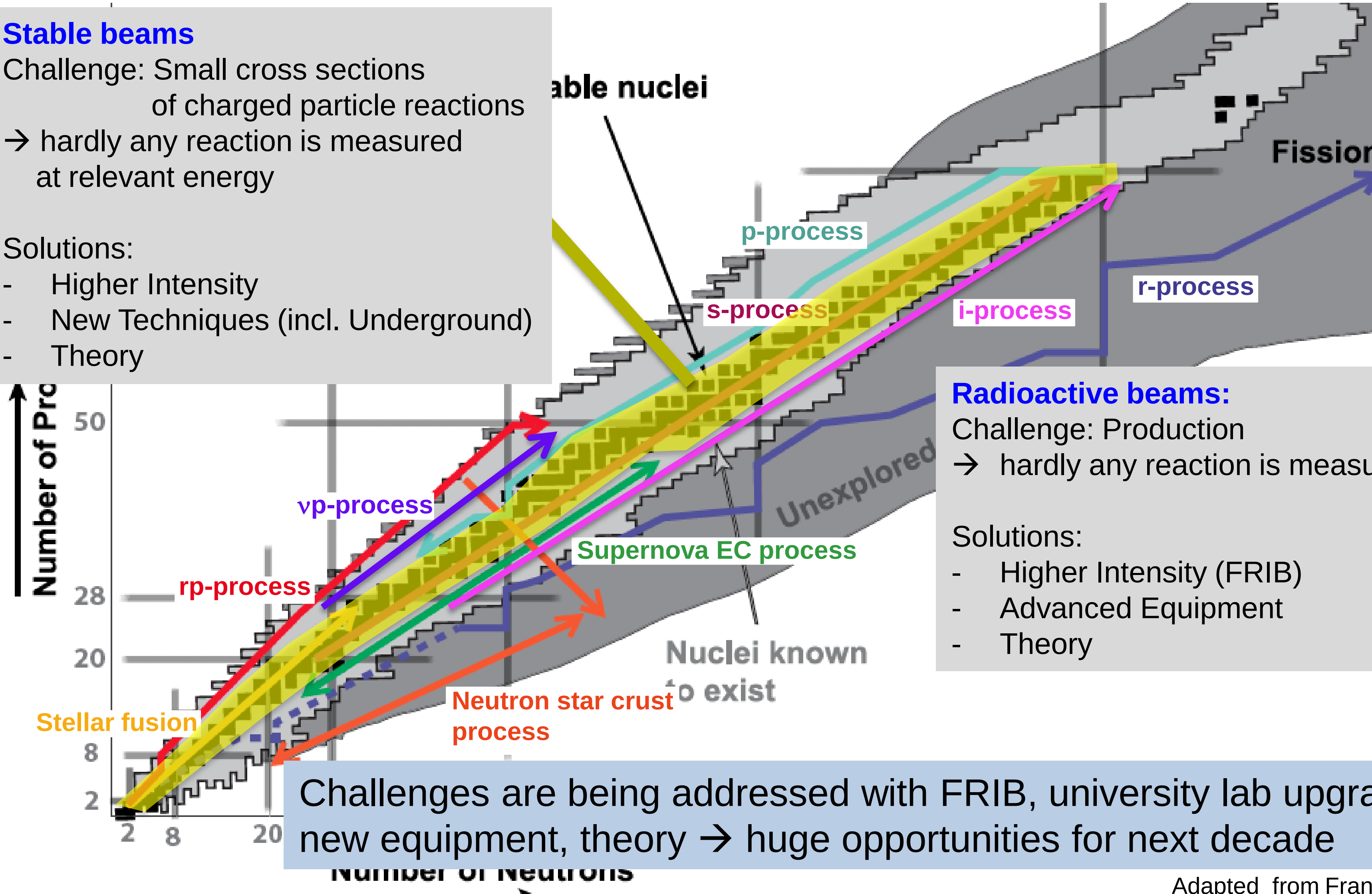


Adapted from Frank Timmes

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

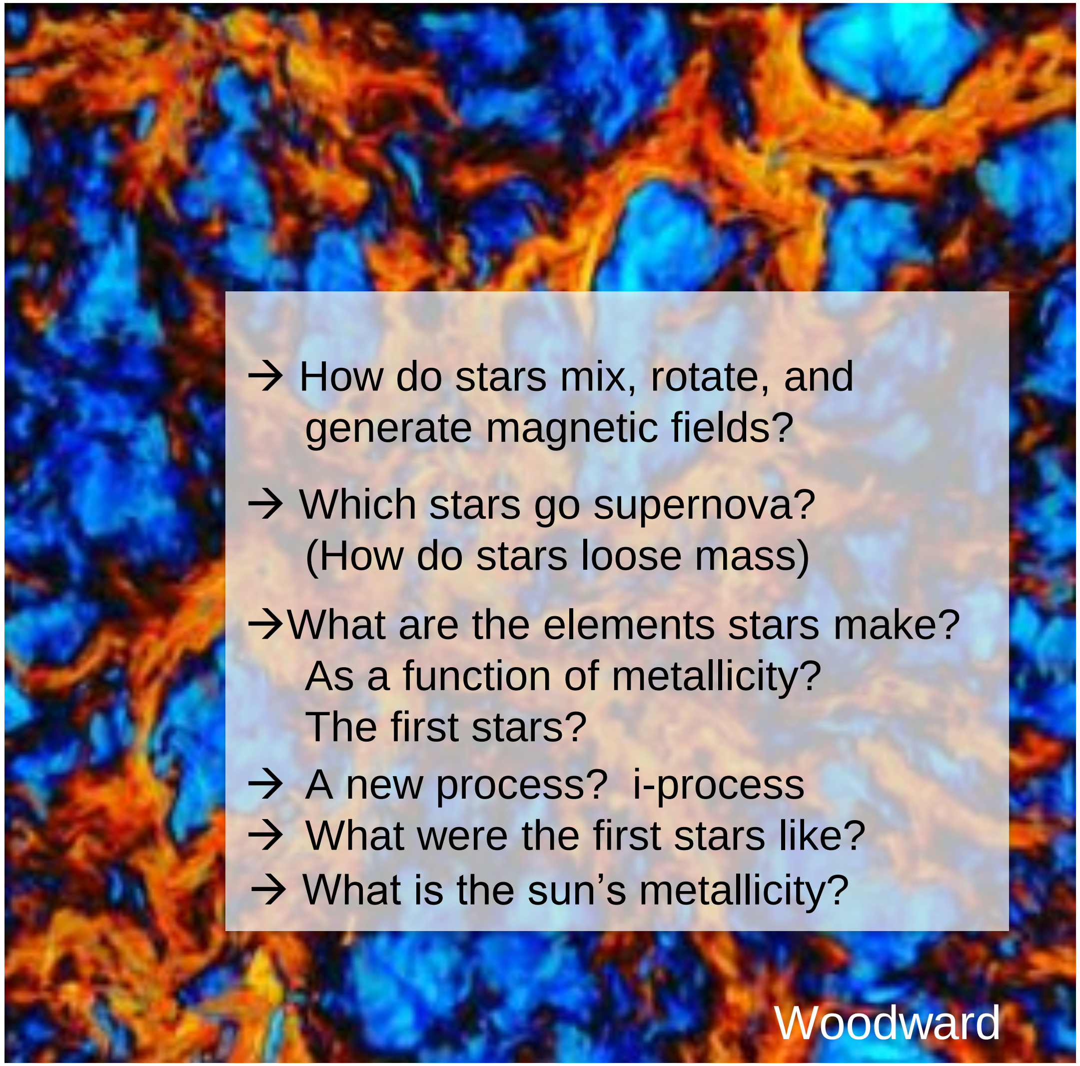
Solutions:
- Higher Intensity (FRIB)
- Advanced Equipment
- Theory

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

Theme: Validation of Advanced Models



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

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

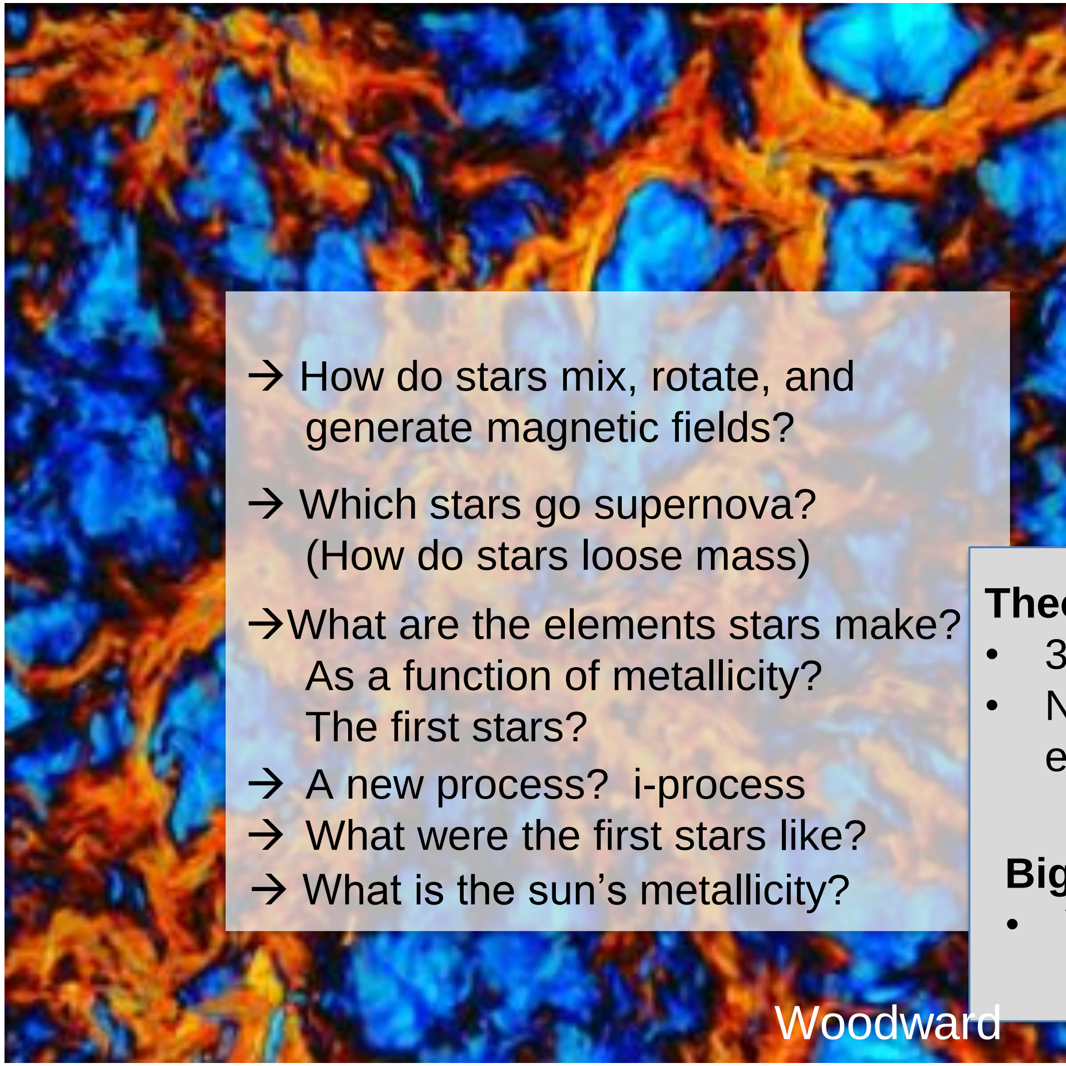
→ What are the elements stars make?
As a function of metallicity?
The first stars?

→ A new process? i-process

→ What were the first stars like?

→ What is the sun's metallicity?

Stars – Still a Mystery
Theme: Validation of Advanced Models



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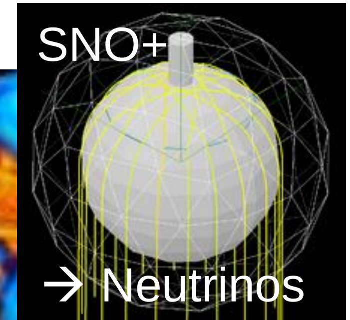
Theory:
- 3D Modeling
- Nuclear cross section extrapolation

Big Theme:
- Validation

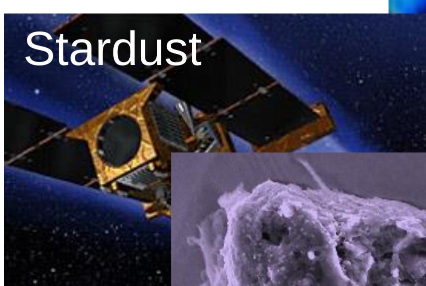
Stars – Still a Mystery

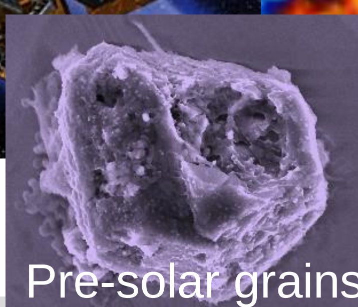
Theme: Validation of Advanced Models

Multi-messenger Observations



Samples of stars





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Validation: Growing need for nuclear physics

Woodward

Theory:
- 3D Modeling
- Nuclear cross section extrapolation

Big Theme:
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Stars – Still a Mystery

Theme: Validation of Advanced Models

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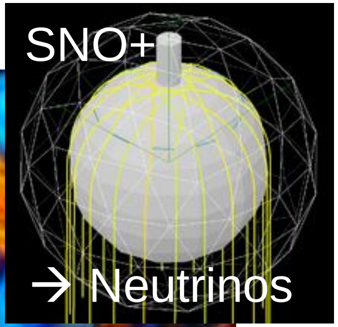

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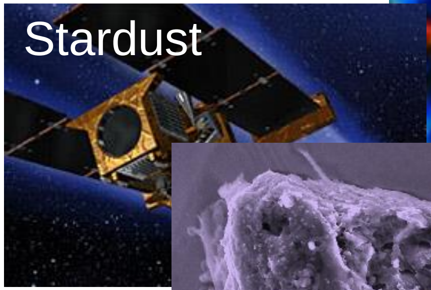

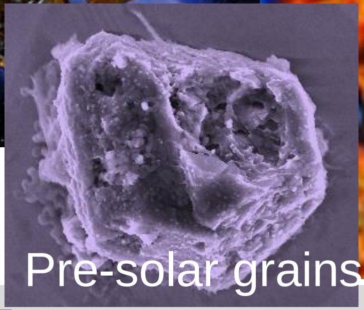

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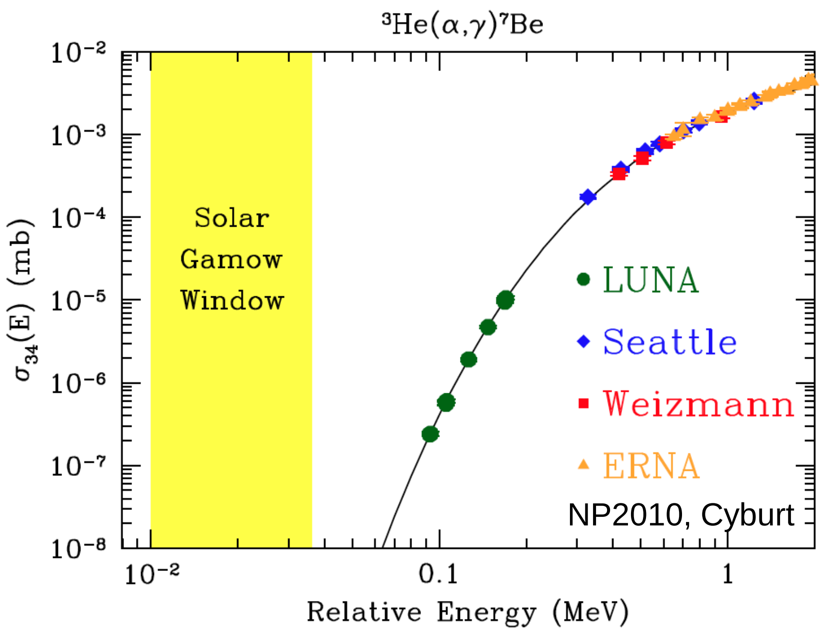
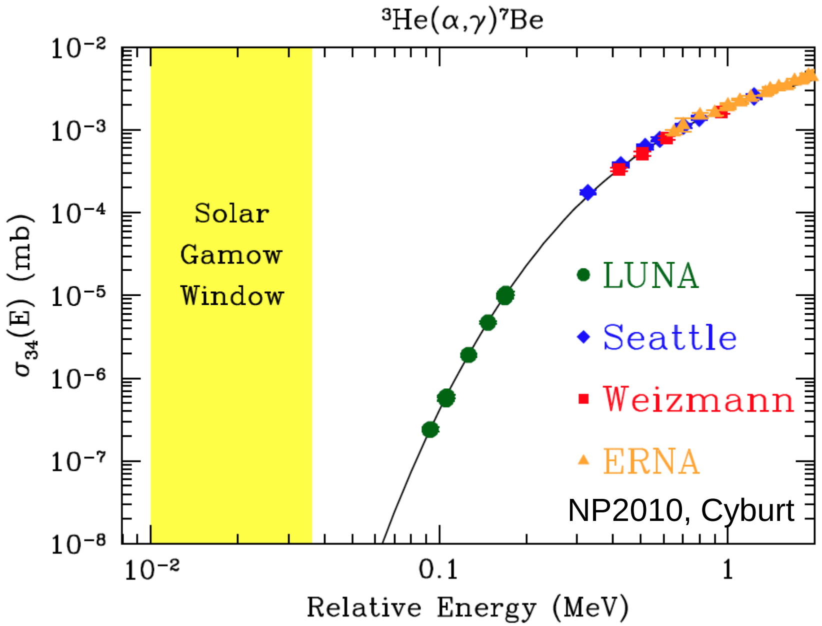
The Quest Towards Stellar Cross Sections Measurements



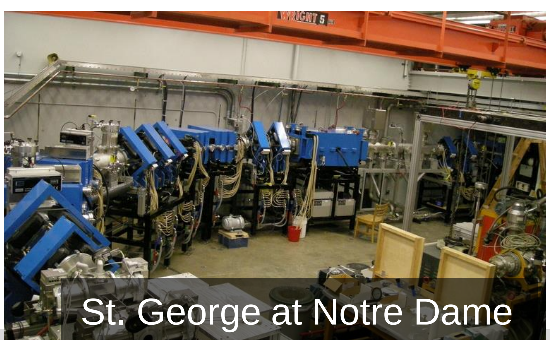
Stable beam experiments
are essential to understand stars

The Quest Towards Stellar Cross Sections Measurements

Approach: Underground



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: Higher Intensity

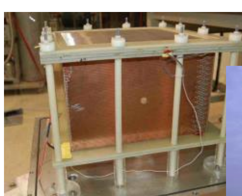
LENA upgrade
at TUNL

New St Ana accelerator
at Notre Dame

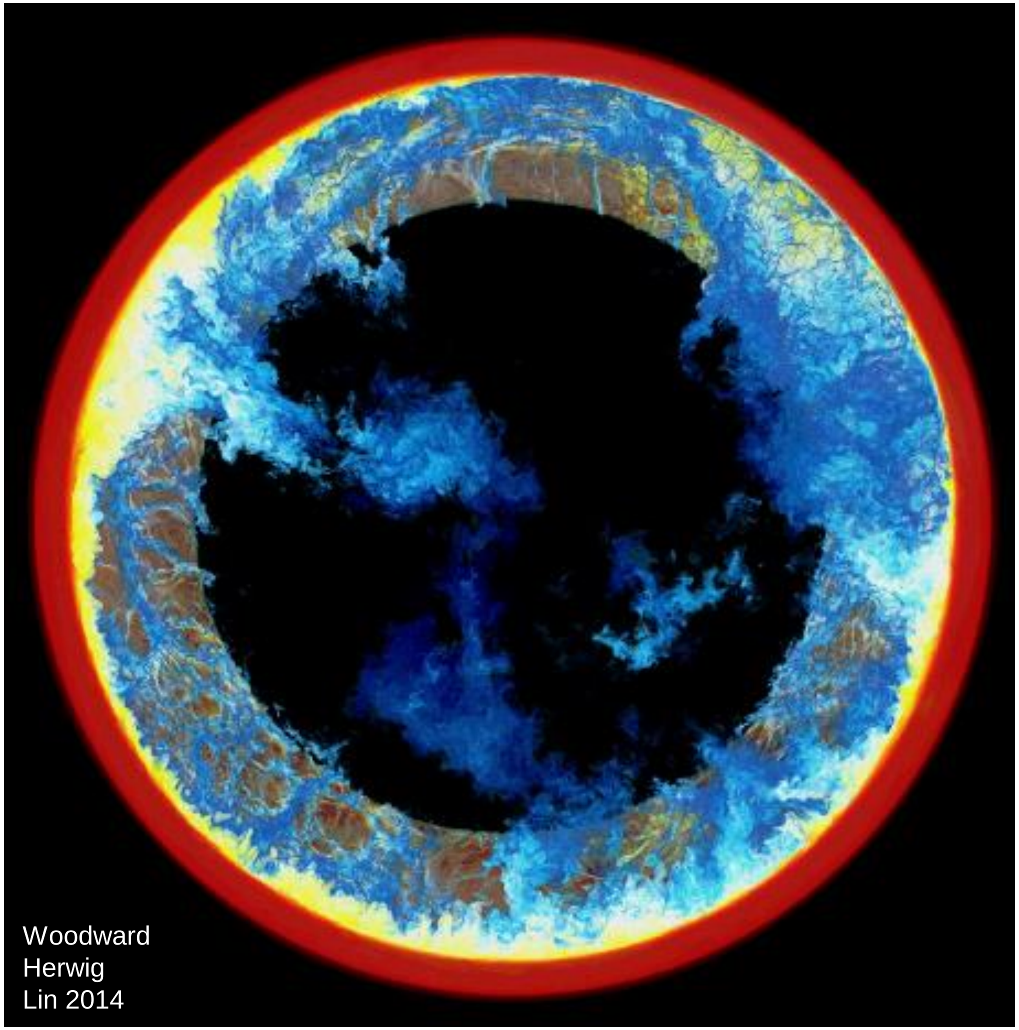
LANSCE
And planned HIγS upgrades

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: i,s processes



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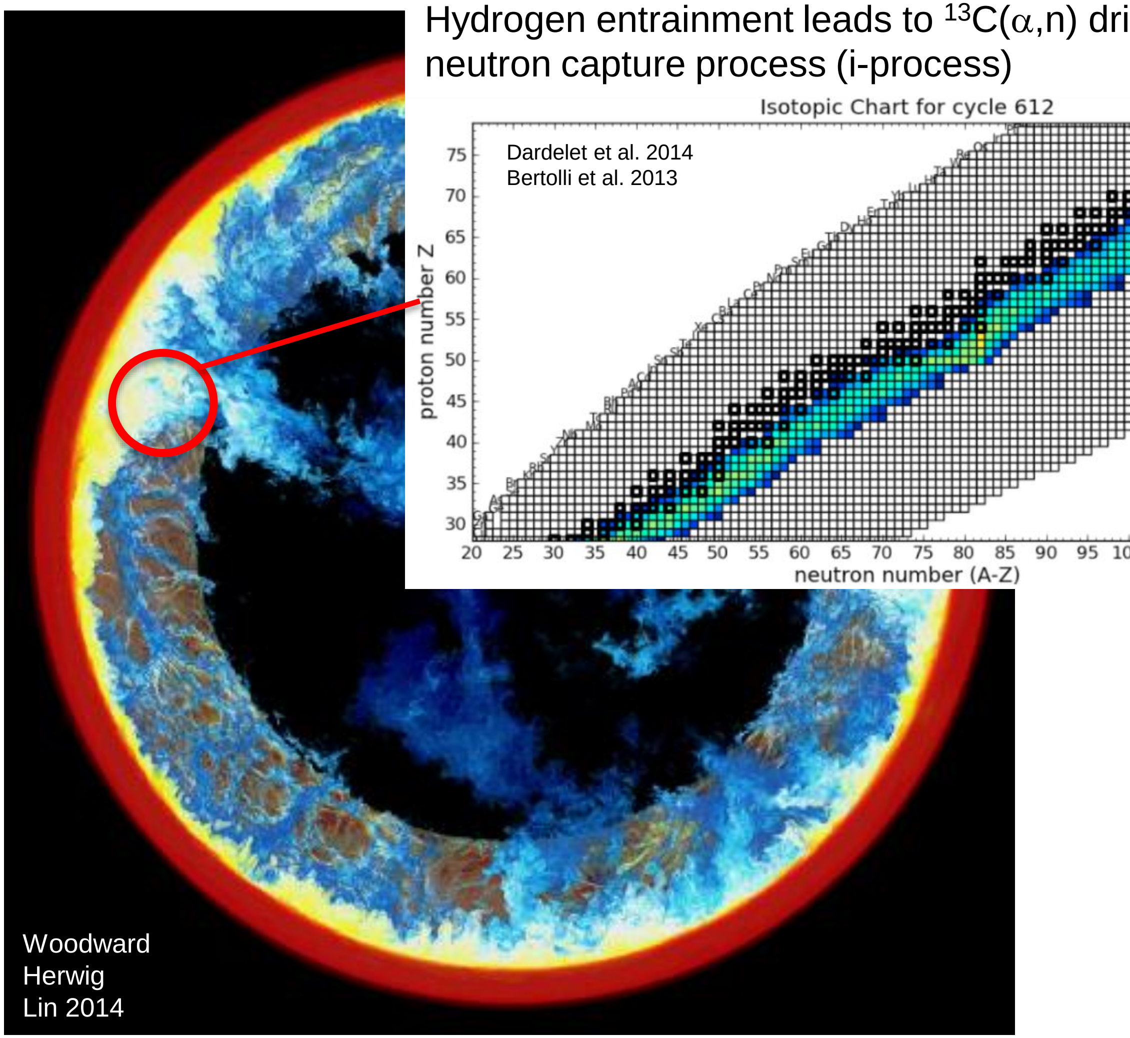
Hydrogen entrainment leads to $^{13}C(\alpha,n)$ driven neutron capture process (i-process)



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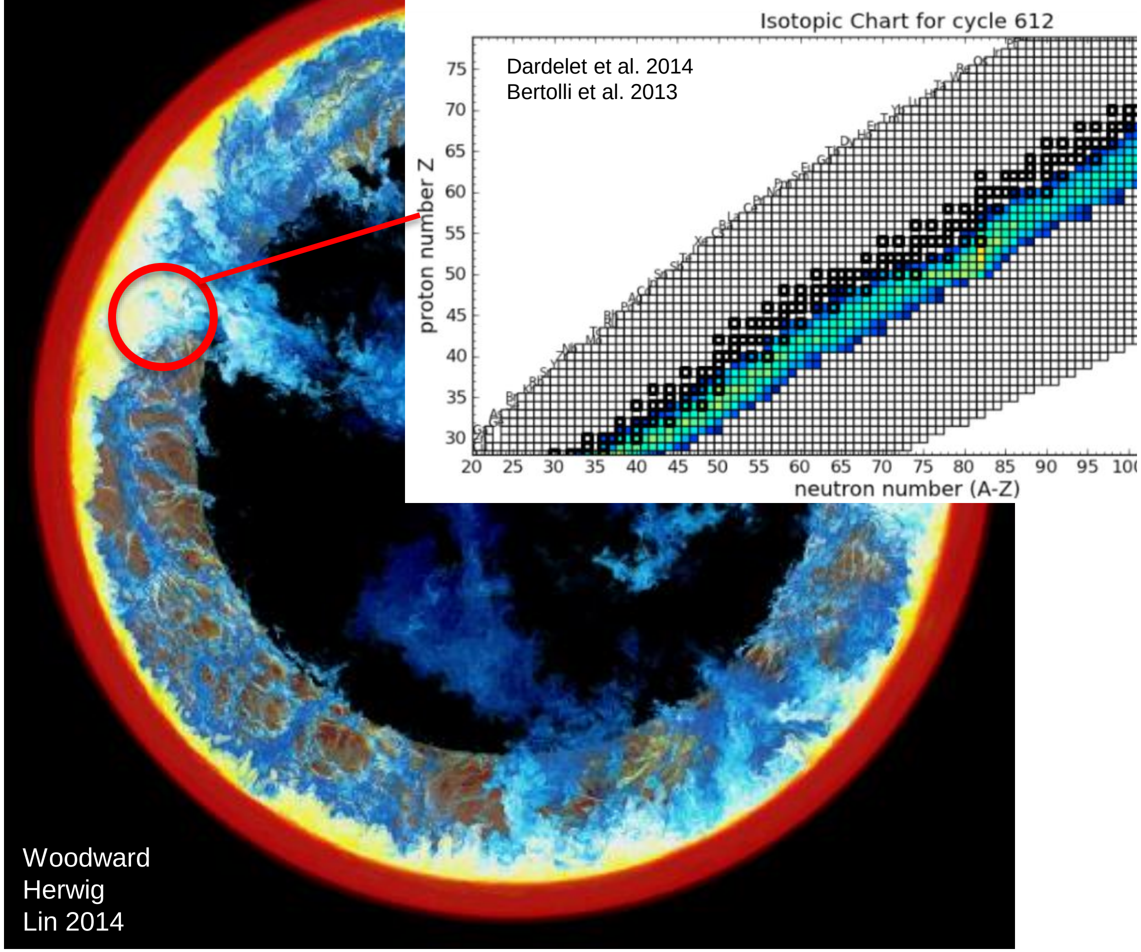
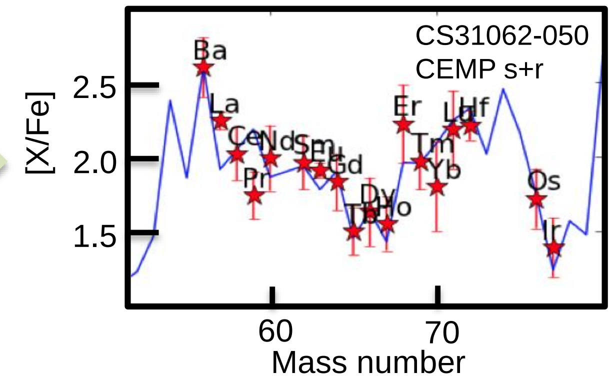


Explains abundance signatures?



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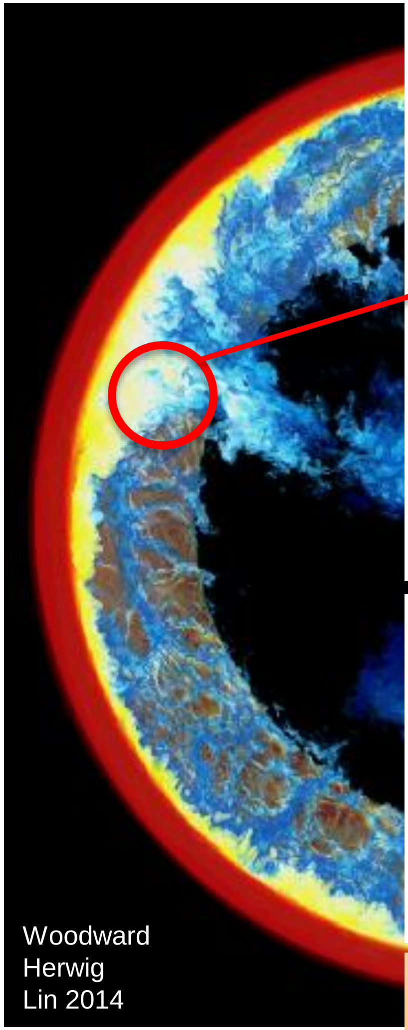

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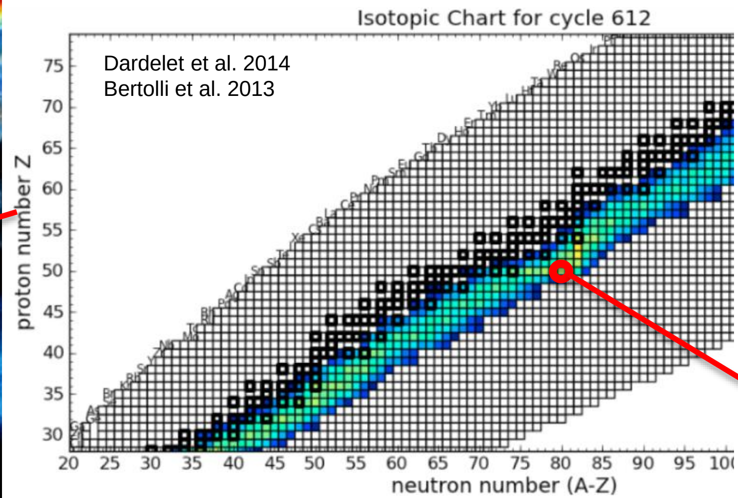

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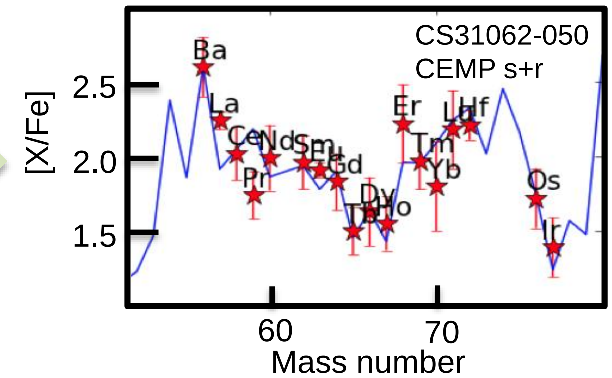
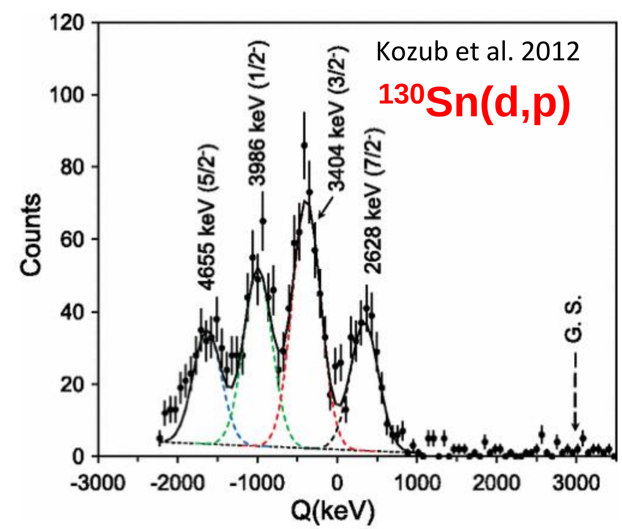


Nuclear physics for s/i processes:

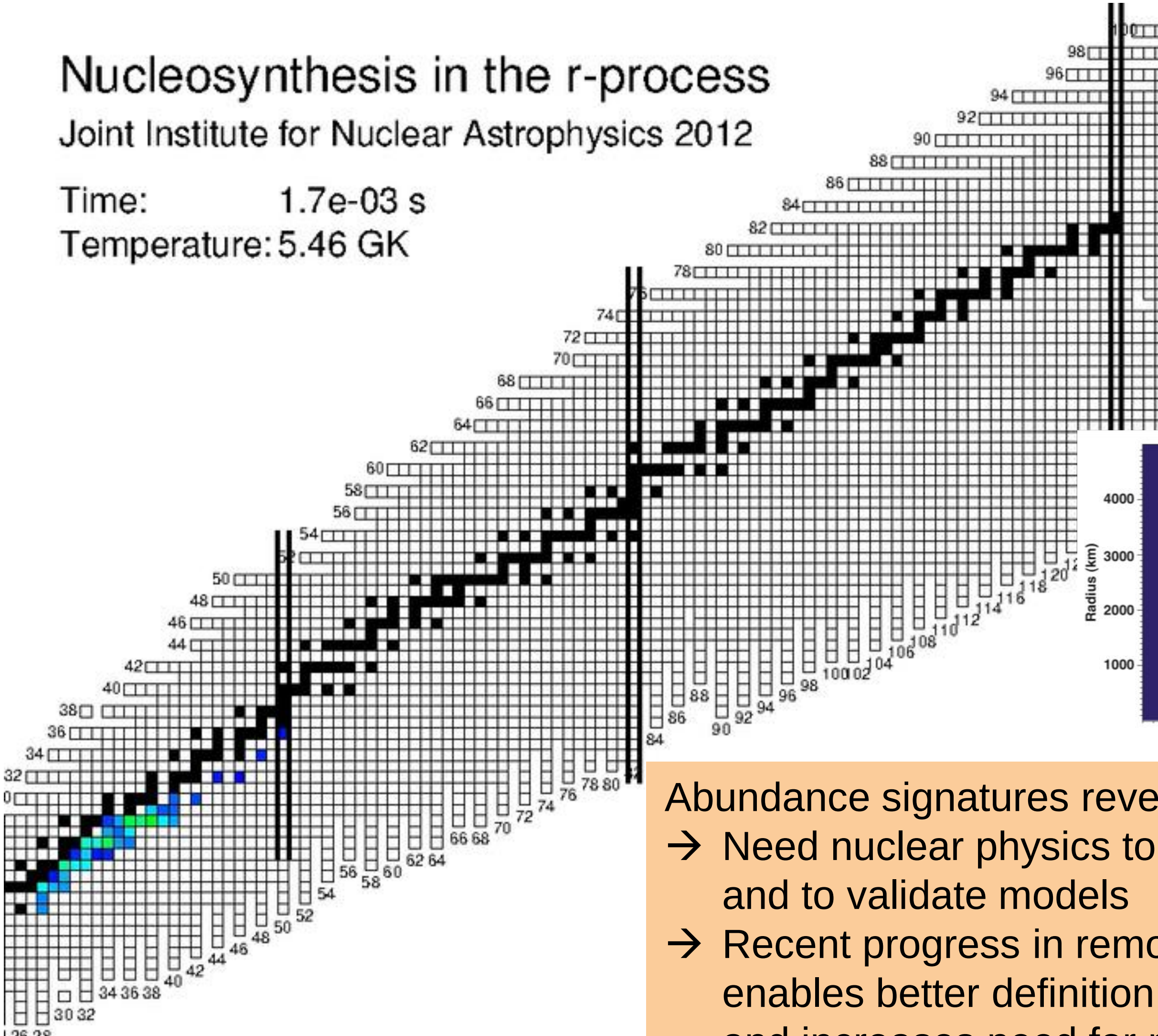
- (α,n) rates (stable beam experiments)
- n-captures on stable nuclei: LANSCE
- n-capture rates 1-6 units from stability
  - Develop (d,p) and other surrogate techniques
  - NEED REACTION THEORY !!

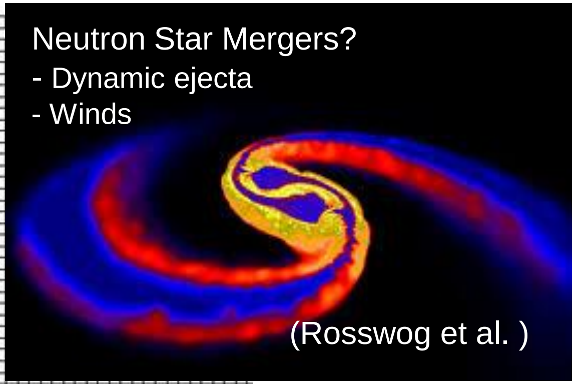
Need a multi-facility approach (stable beams, neutron beams, and radioactive beams, FRIB 6-12 MeV)

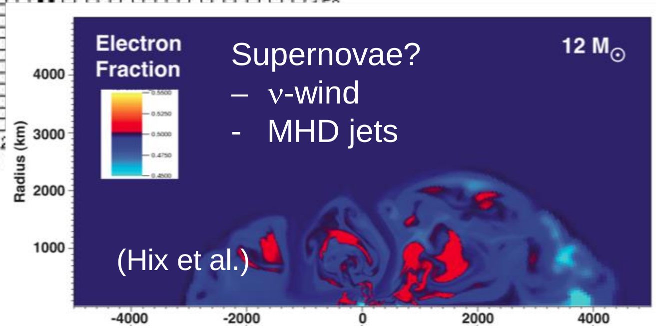
Pioneering (d,p) work at HRIBF



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





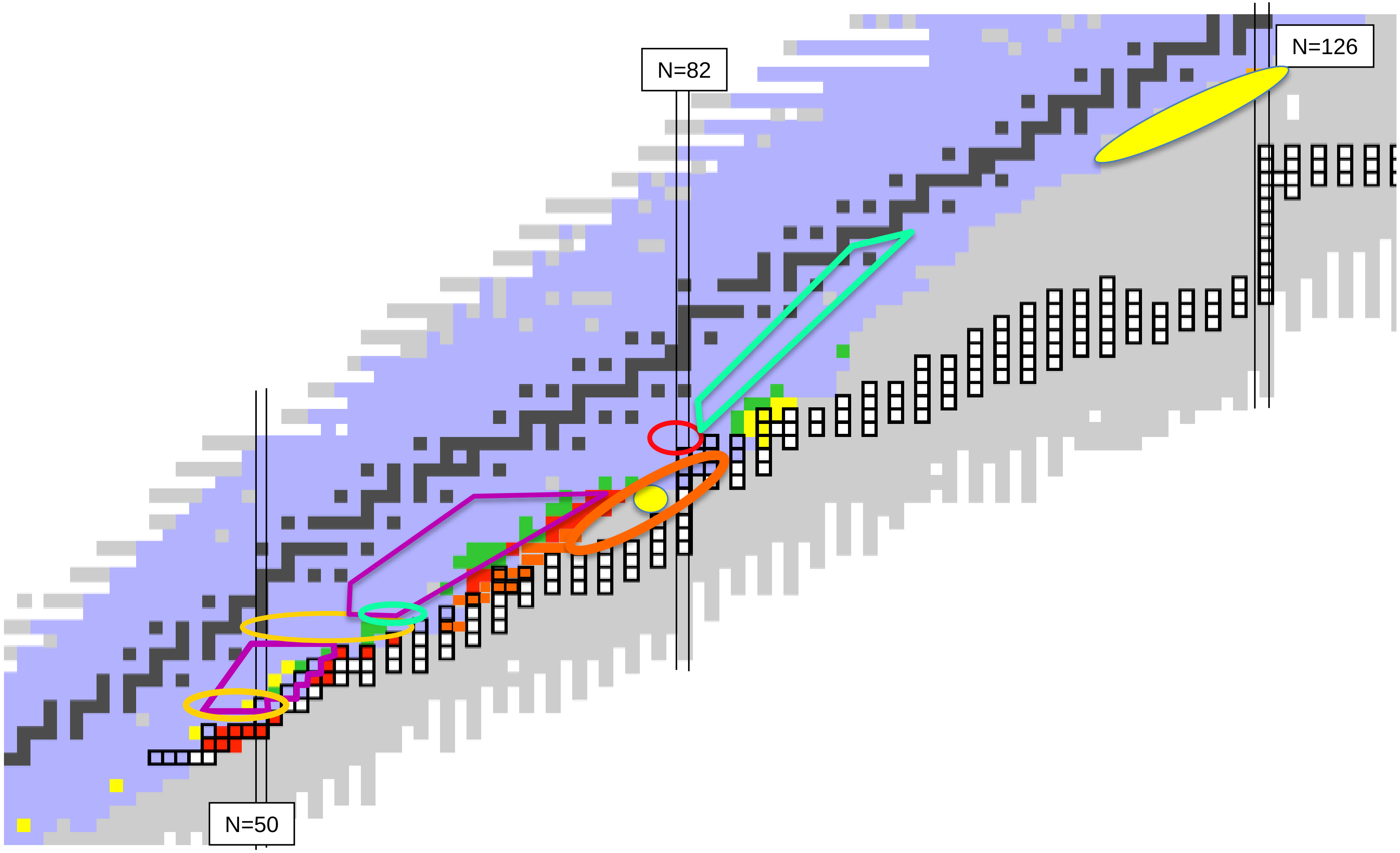


Abundance signatures reveal astrophysical environment

→ Need nuclear physics to extract that information and to validate models

→ Recent progress in removing astrophysical ambiguity enables better definition of required nuclear physics and increases need for nuclear data to test ideas

The Quest for r-process Nuclear Physics



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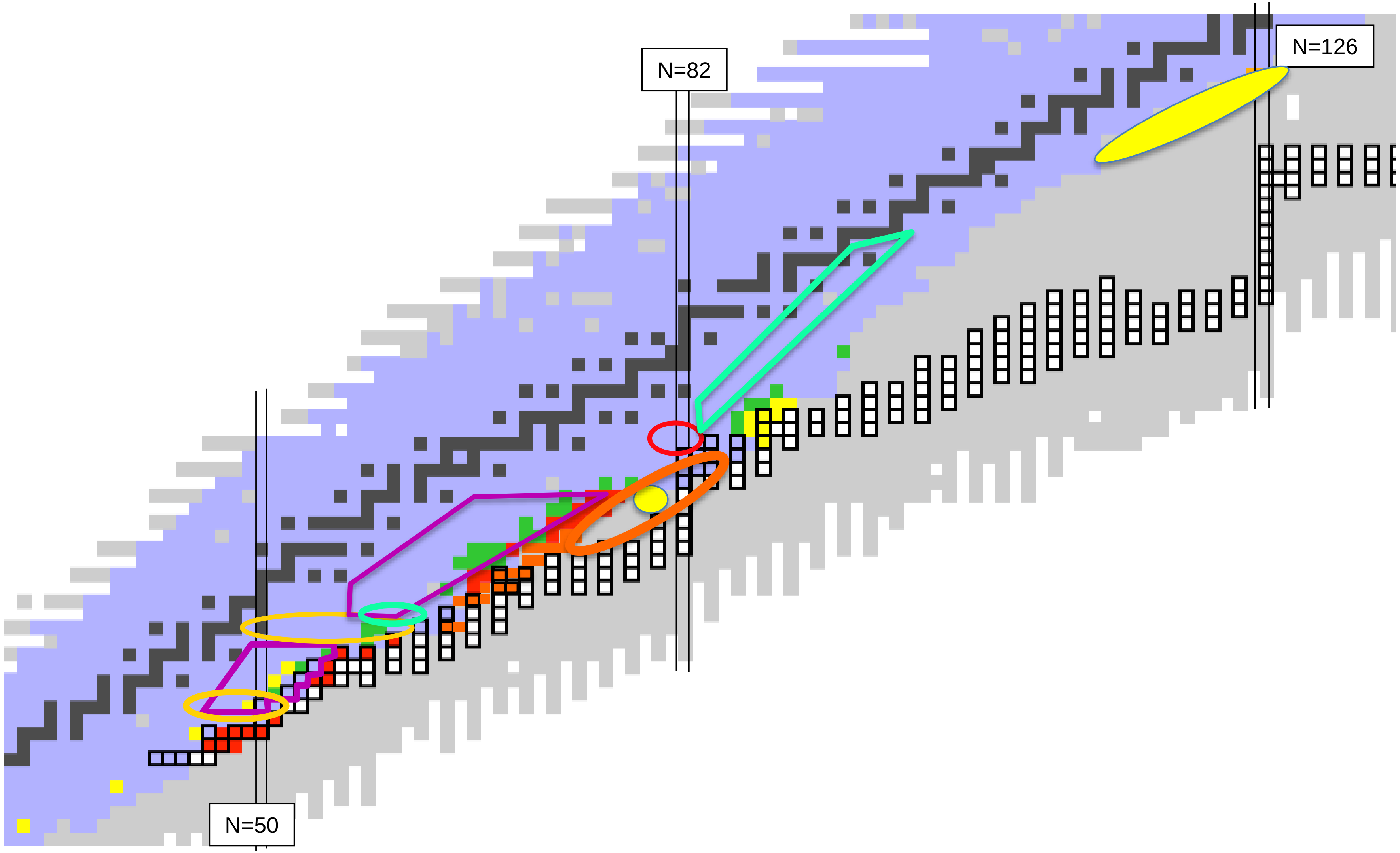

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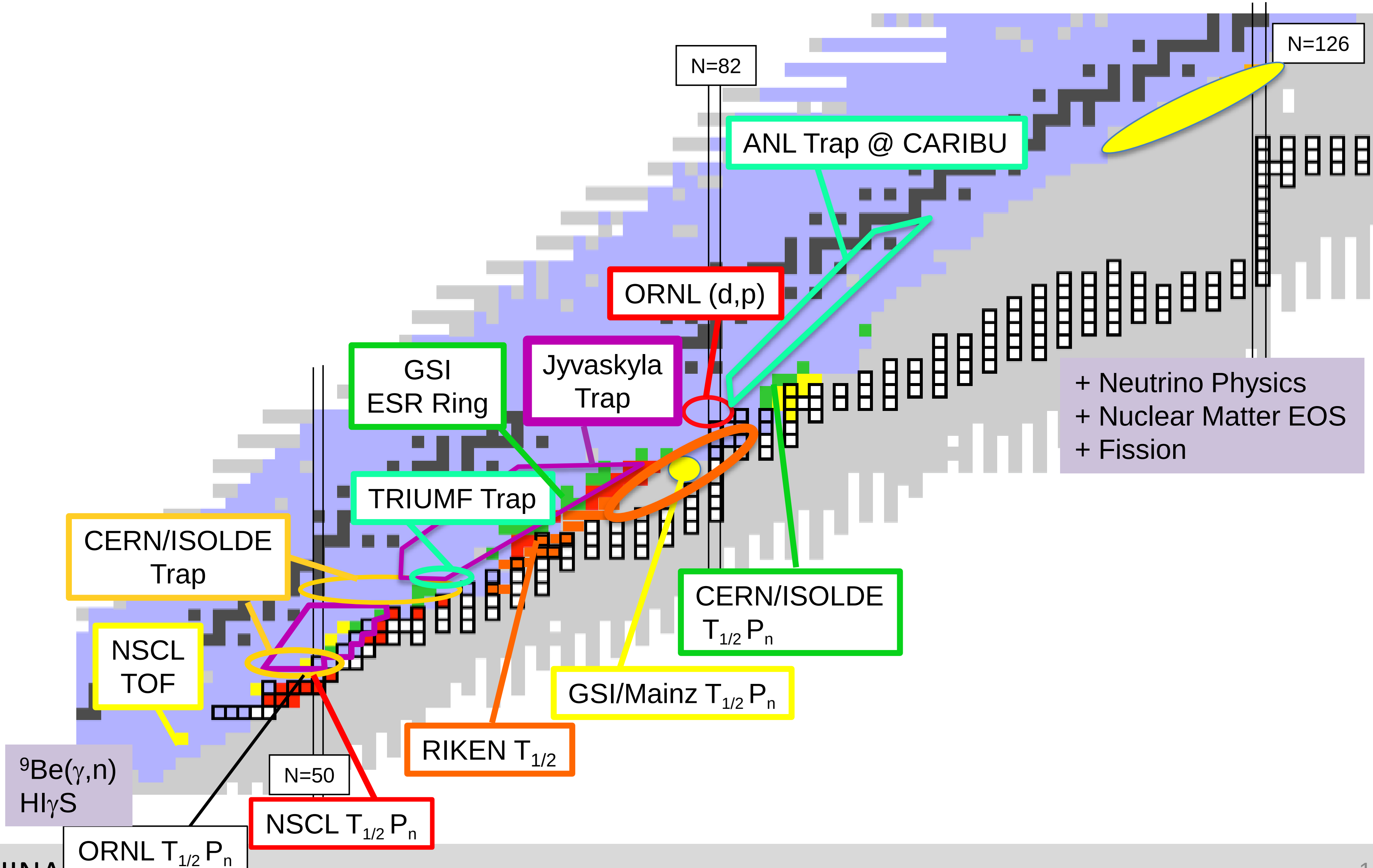
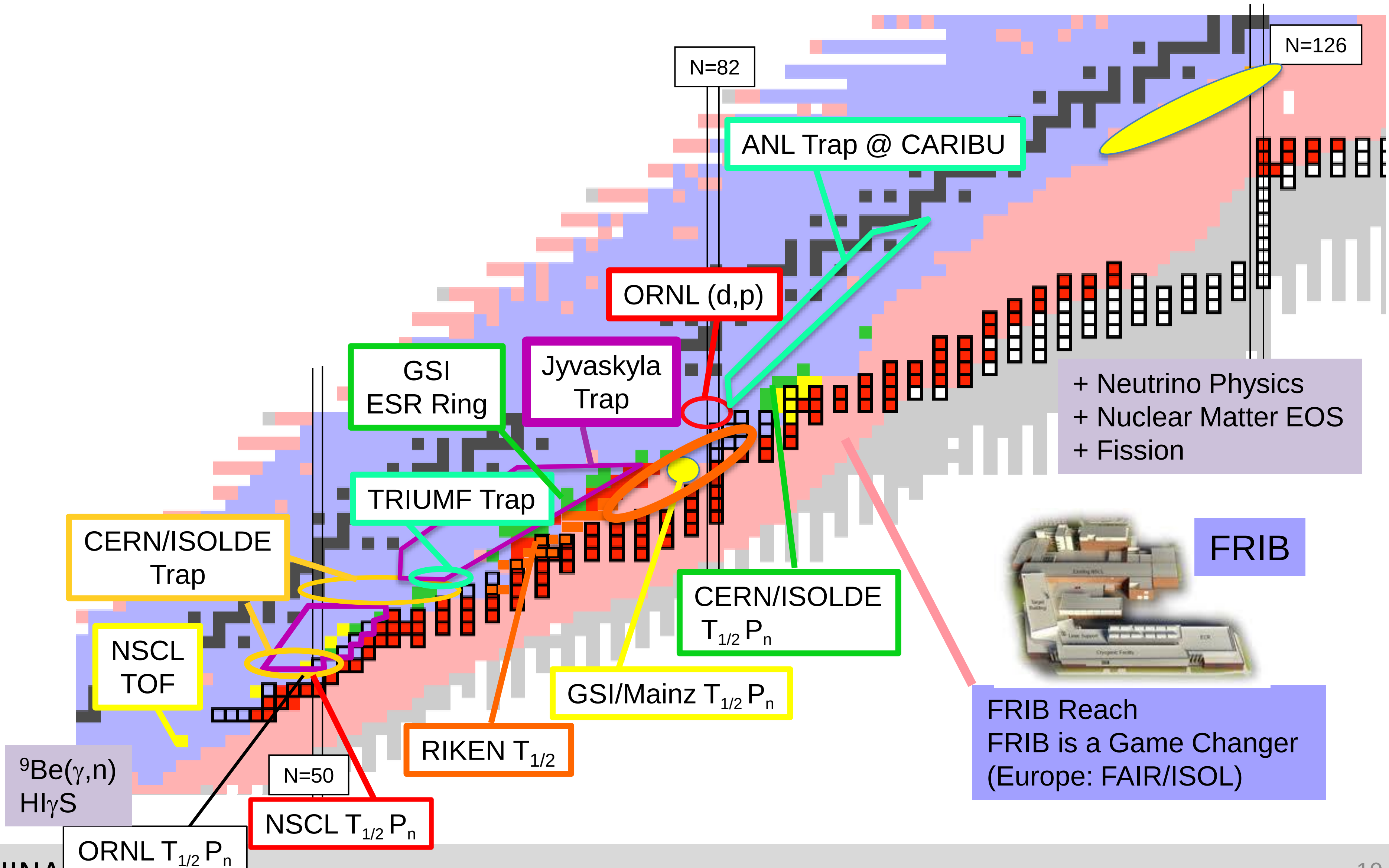


+ Neutrino Physics
+ Nuclear Matter EOS
+ Fission

The Quest for r-process Nuclear Physics



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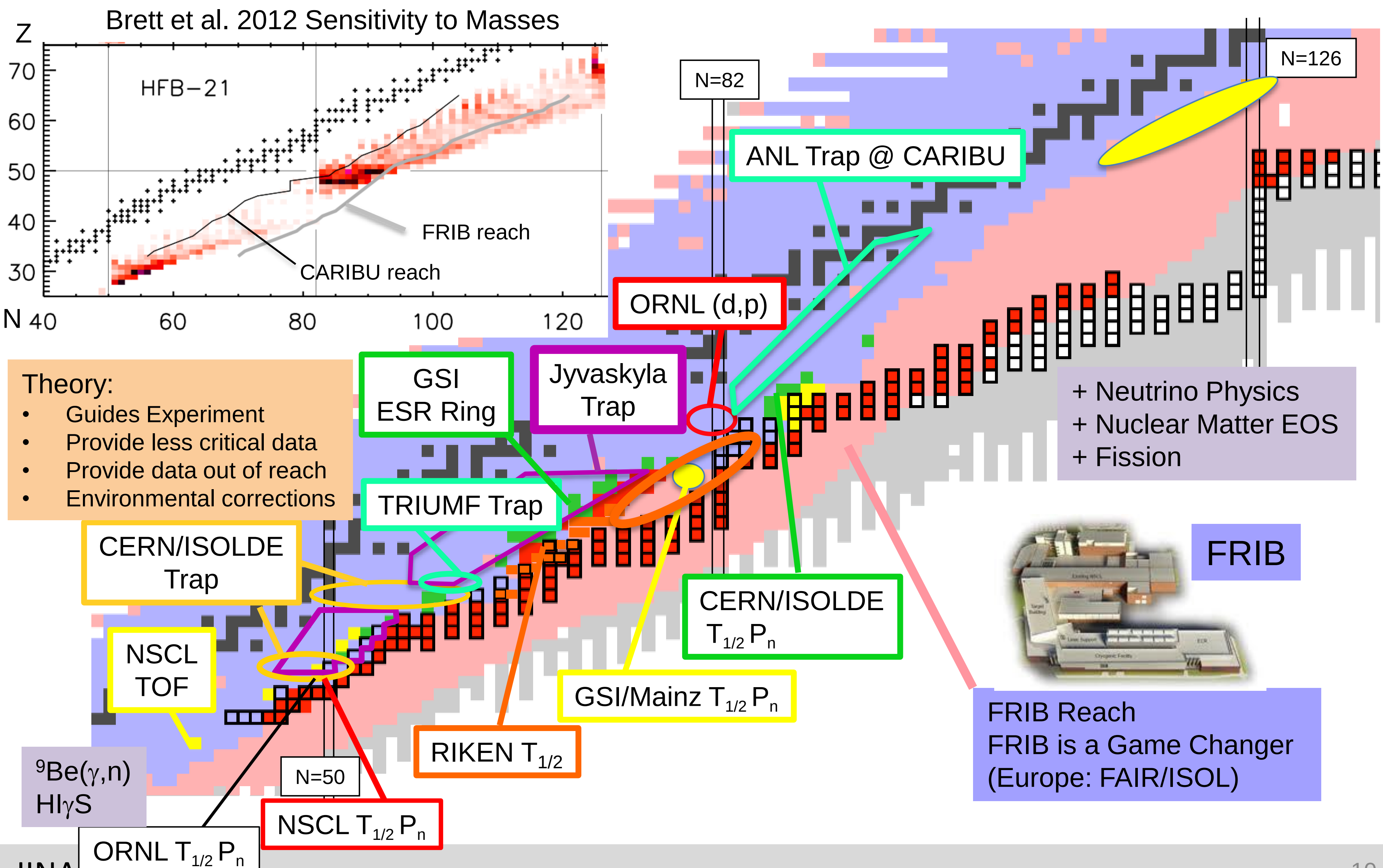
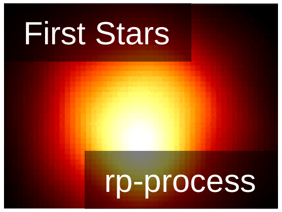


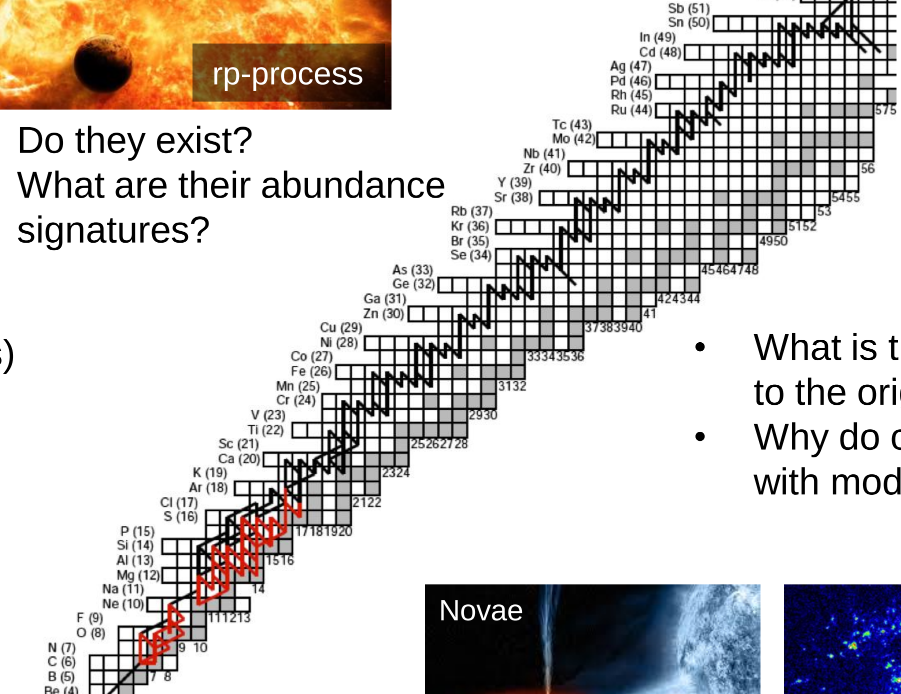
Theory:
- Guides Experiment
- Provide less critical data
- Provide data out of reach
- Environmental corrections

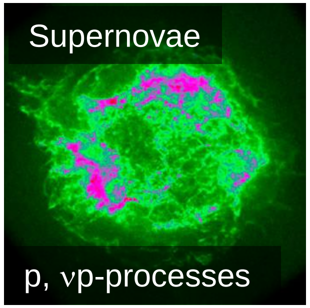
H/He induced Stellar Reactions on Unstable Neutron Deficient Nuclei

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

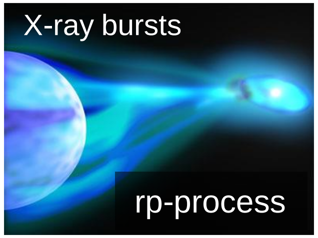


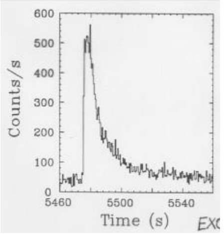
- What were their properties?
- What are their abundance signatures? (→ Massive Surveys)
- How much did they contribute to re-ionization of the cosmos?



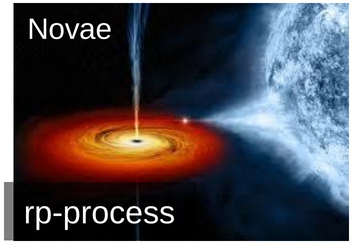


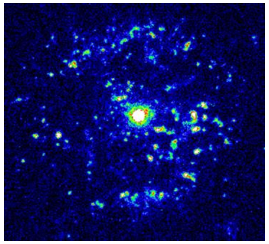
- What is the contribution to the origin of the elements?
- Why do observations disagree with models?





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

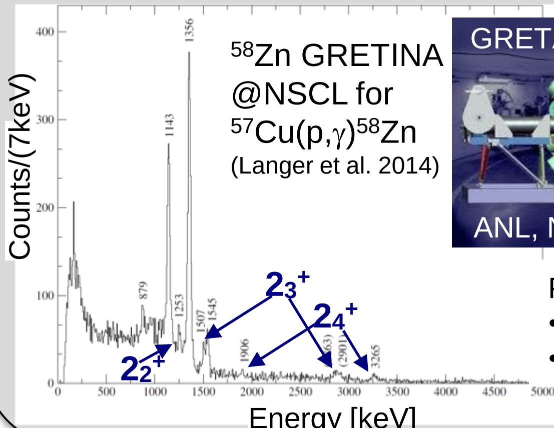




- How much radioactivity do they eject?
- How is white dwarf matter mixed in?
- Are there exotic types of explosions? (→ LLST)

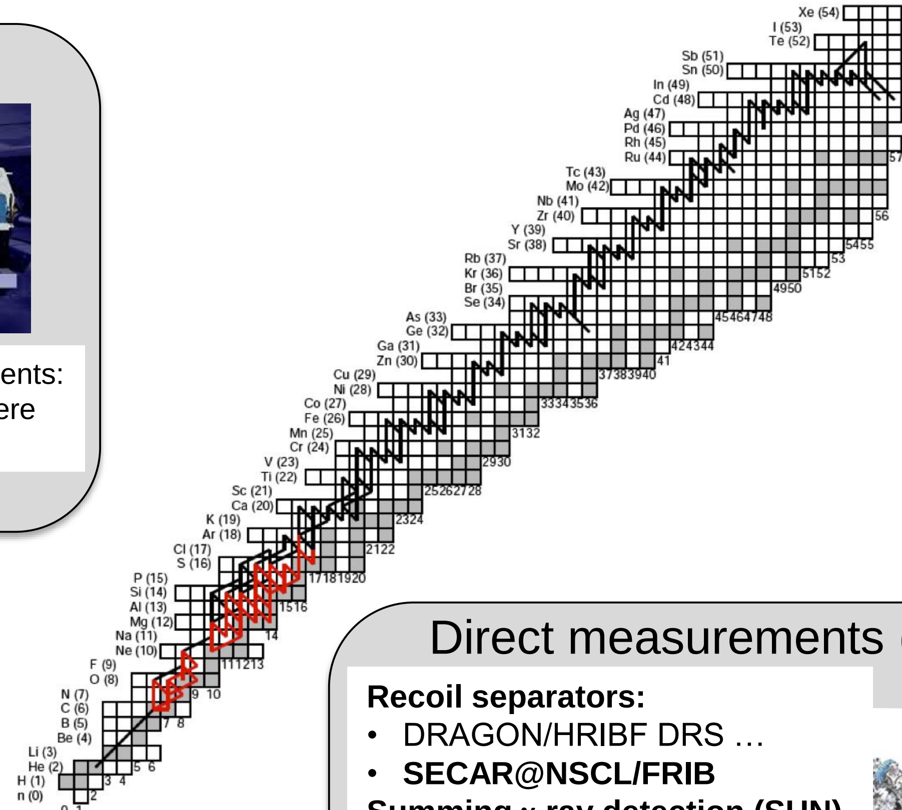
The Quest to Measure Reaction Rates of Unstable p-rich Nuclei

Indirect: γ-spectroscopy

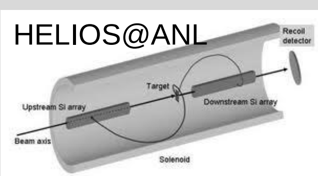


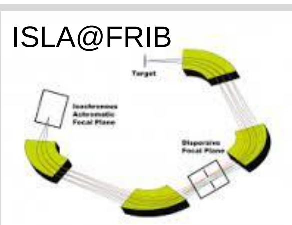
^{58}Zn GRETINA @NSCL for ^{57}Cu(p,γ)^{58}Zn (Langer et al. 2014)

Past Achievements:
- Gammasphere
- SeGA



Indirect: particle-spectroscopy





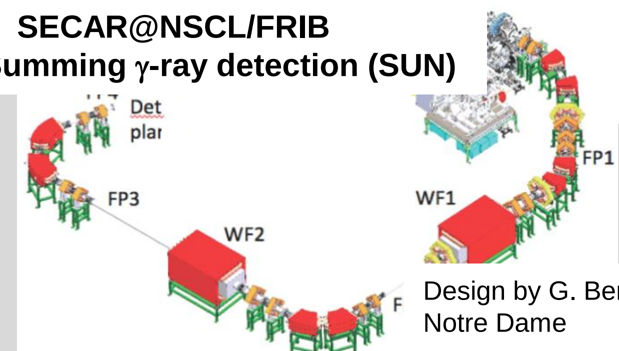
Transfer reactions:
- JENSA Gas Jet (CSM)
- TWINSOL@Notre Dame
- (d,n)@RESOLUT FSU
- Spectrometer plans:
  - TUNL Tandem
  - FSU
- ANASEN (FSU, LSU)
- AT-TPC@NSCL

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

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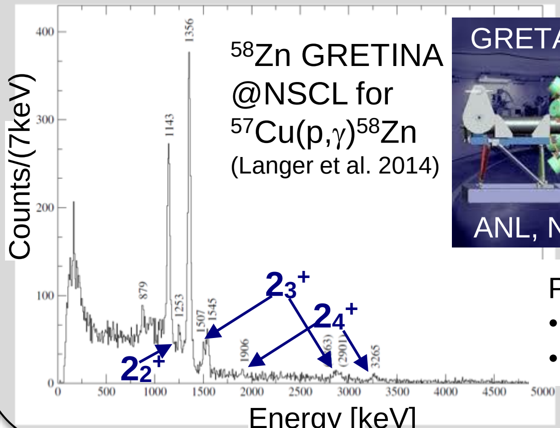

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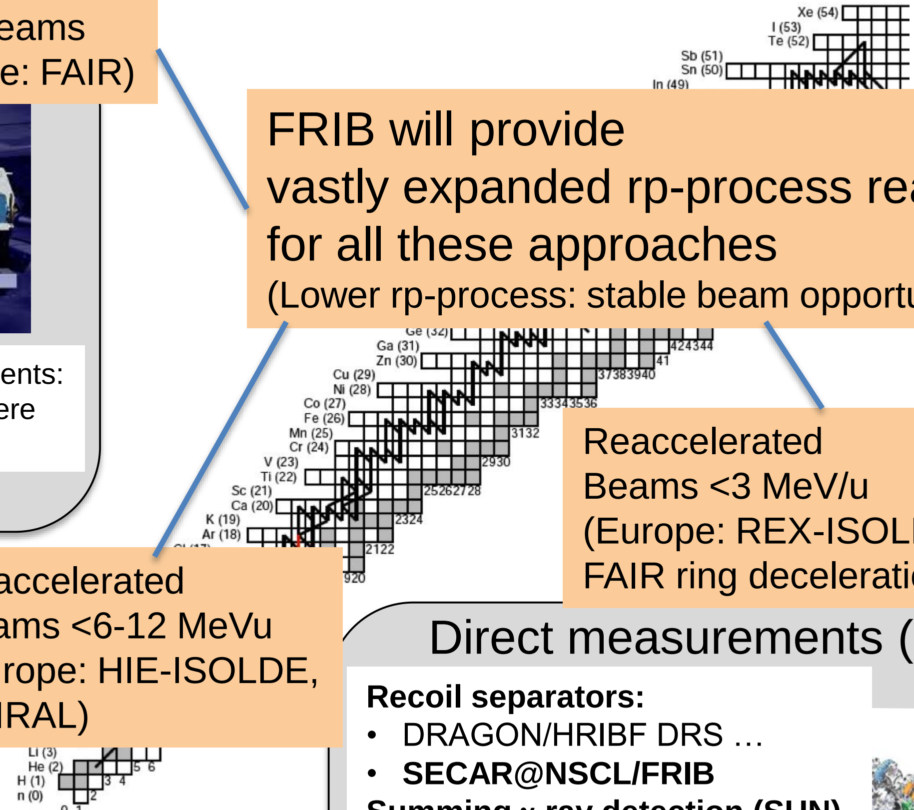
Fast Beams
(Europe: FAIR)



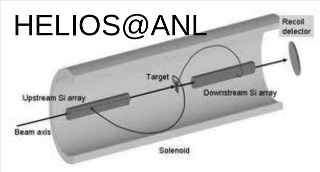
FRIB will provide
vastly expanded rp-process reach
for all these approaches
(Lower rp-process: stable beam opportunities)

Reaccelerated
Beams <3 MeV/u
(Europe: REX-ISOLDE, TSR
FAIR ring deceleration)

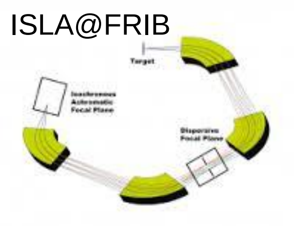
Reaccelerated
Beams <6-12 MeVu
(Europe: HIE-ISOLDE,
SPIRAL)

Indirect: particle-spectroscopy

HELIOS@ANL



ISLA@FRIB



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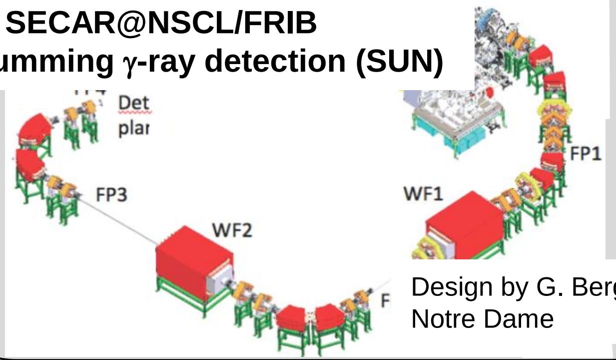

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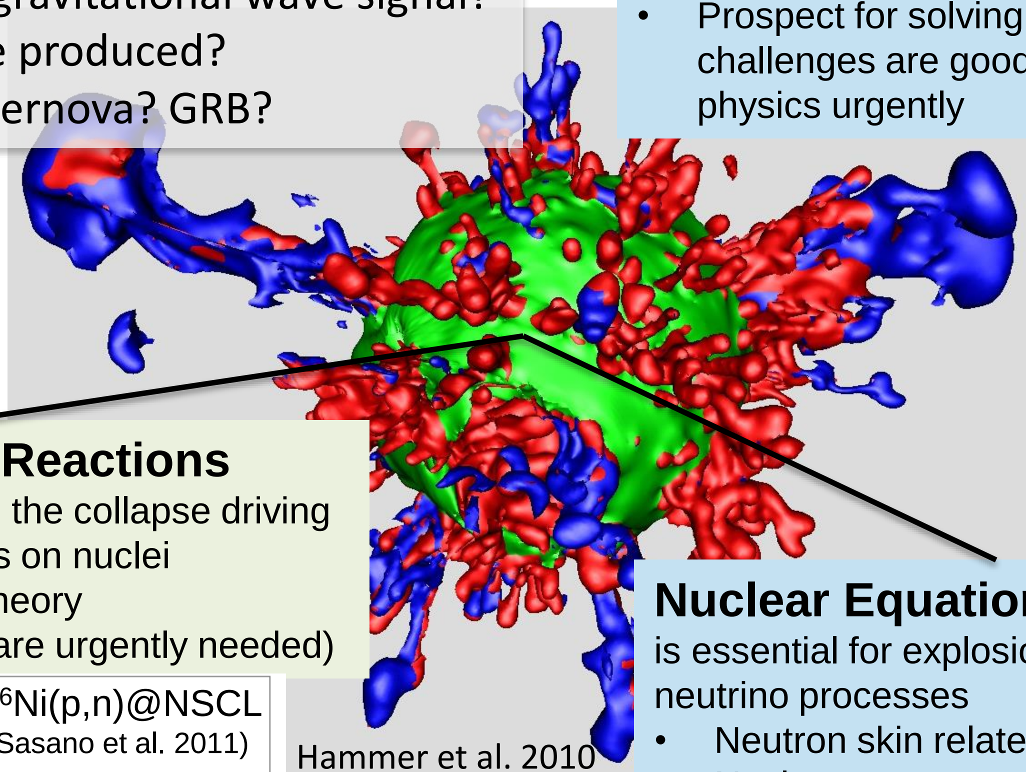
How do Core Collapse Supernovae explode?

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

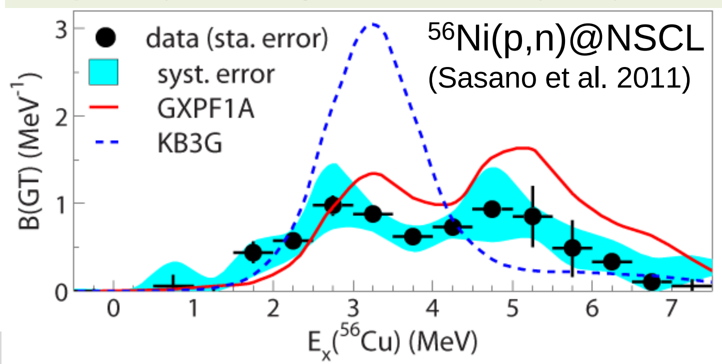
Astrophysical Models

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



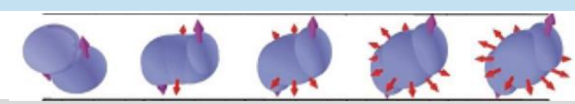
Hammer et al. 2010

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

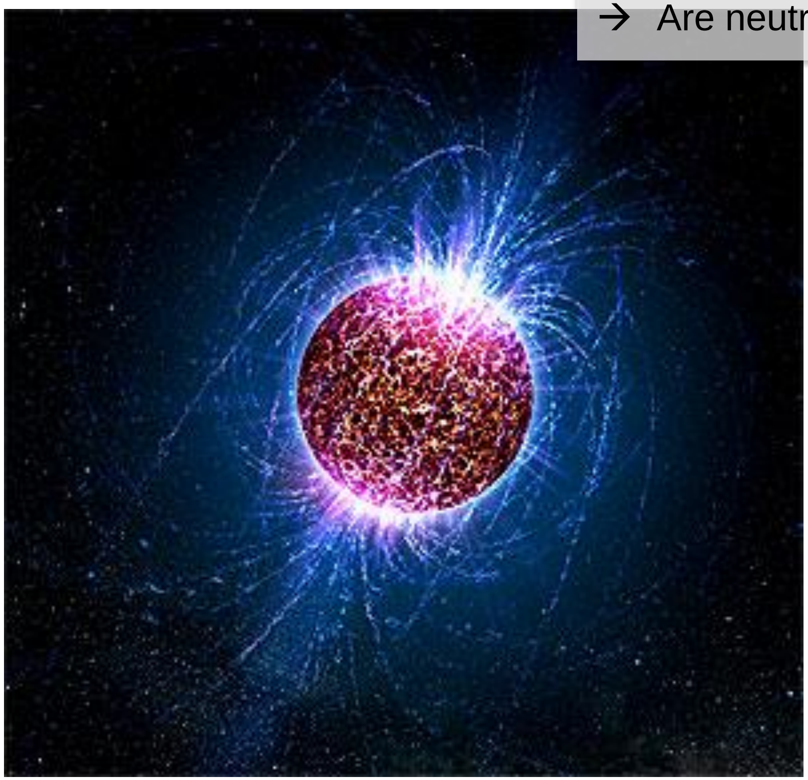
- Neutron skin related measurements
- Nuclear masses
- Heavy Ion Collisions
- Nuclear Theory



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?



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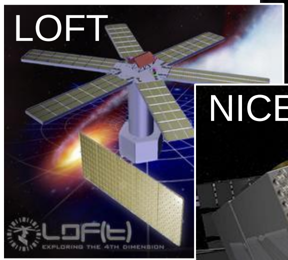

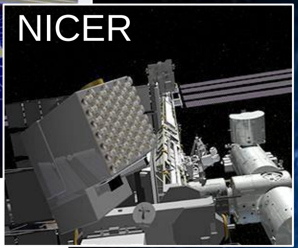

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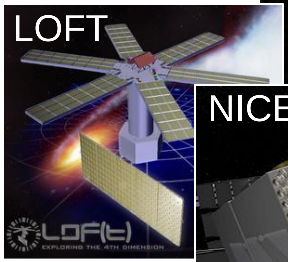

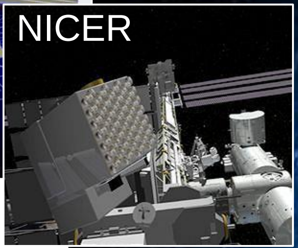

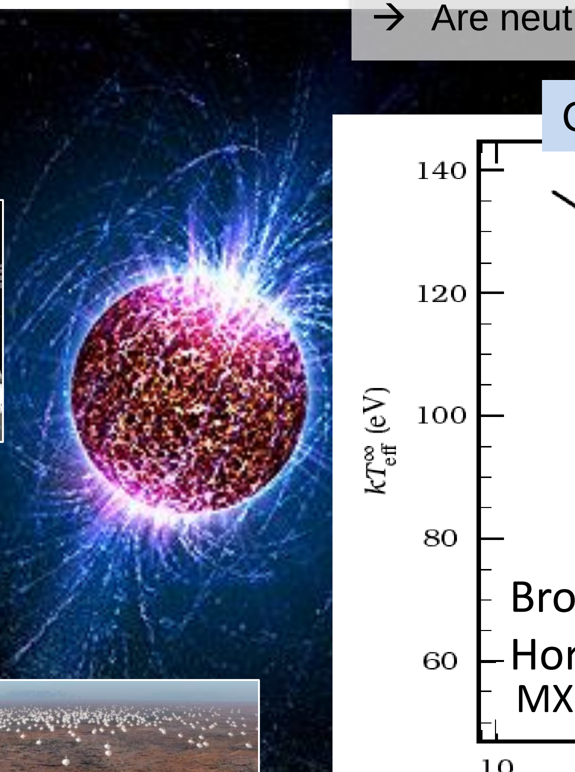

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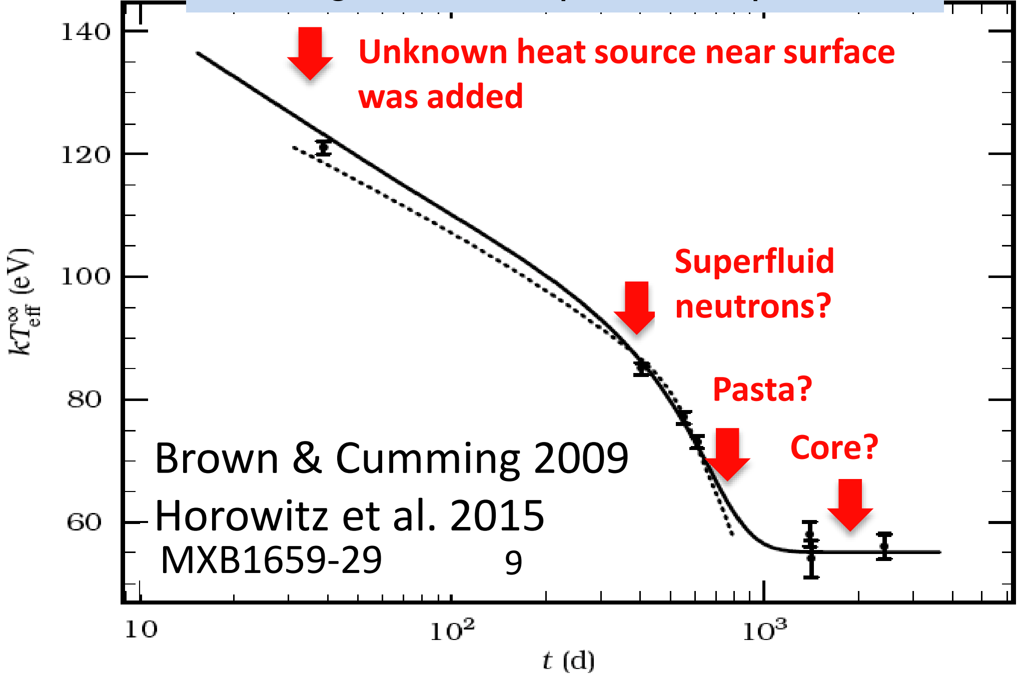
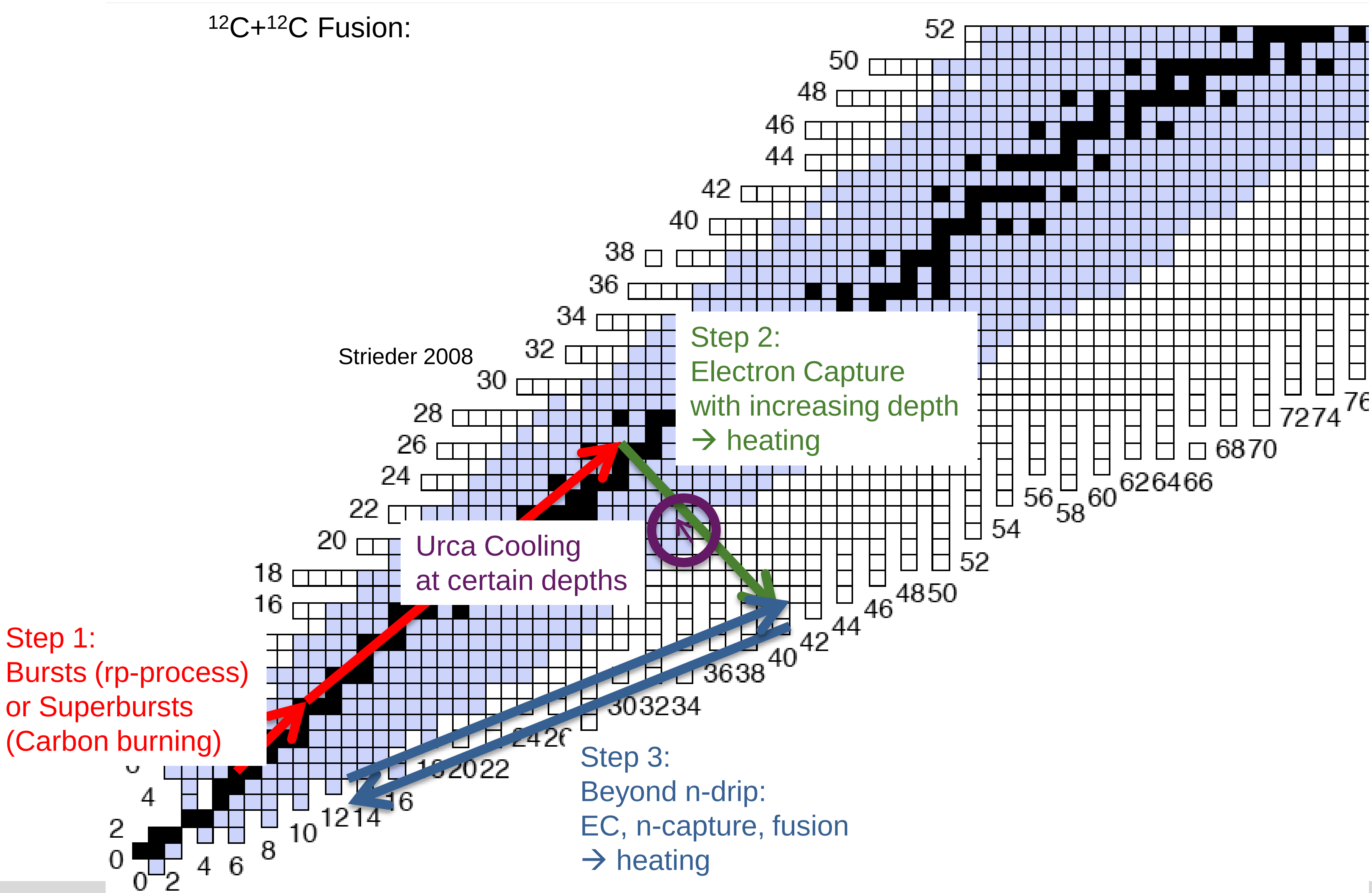
Cooling transients probe deeper crust



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



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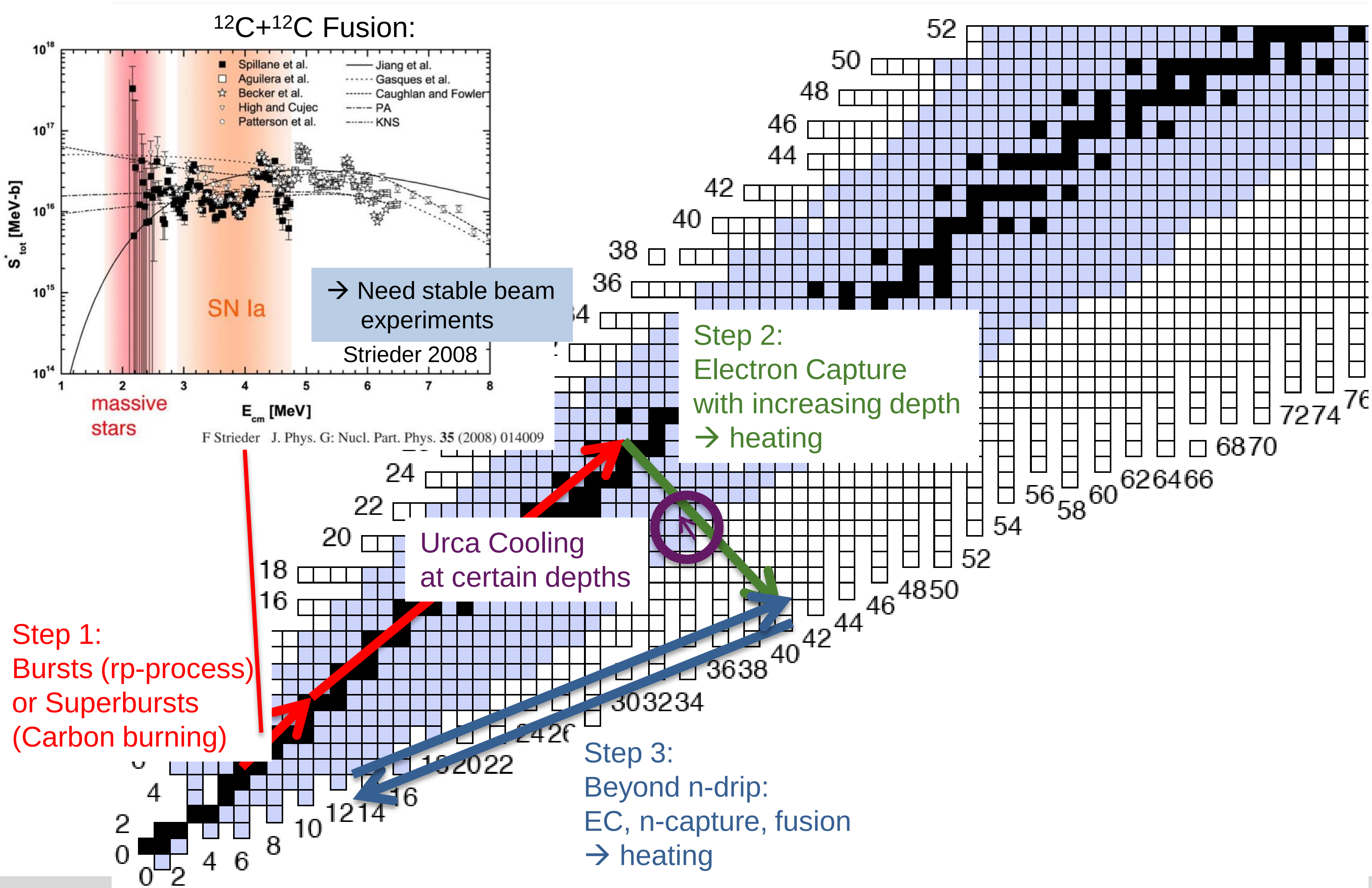

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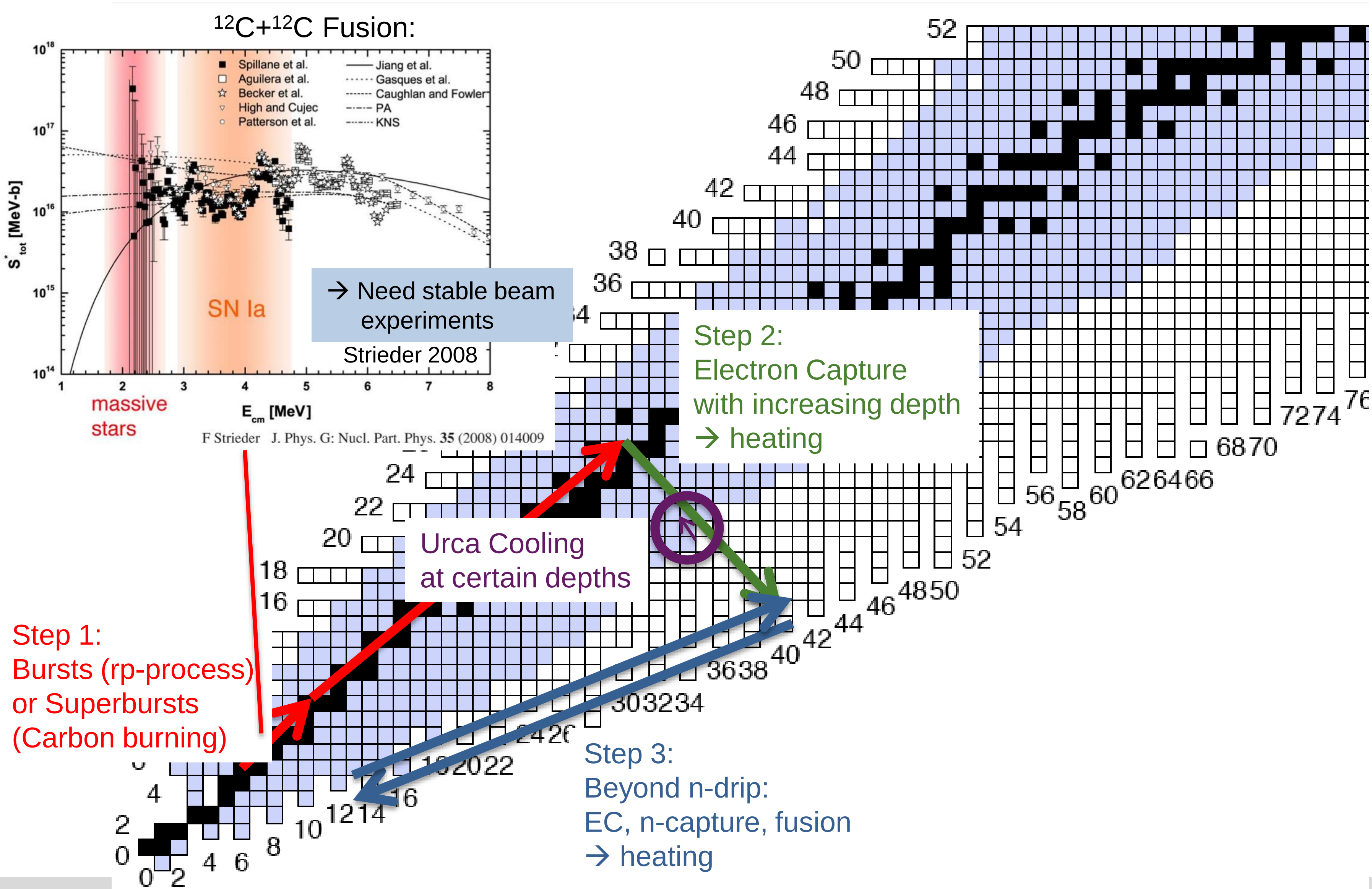

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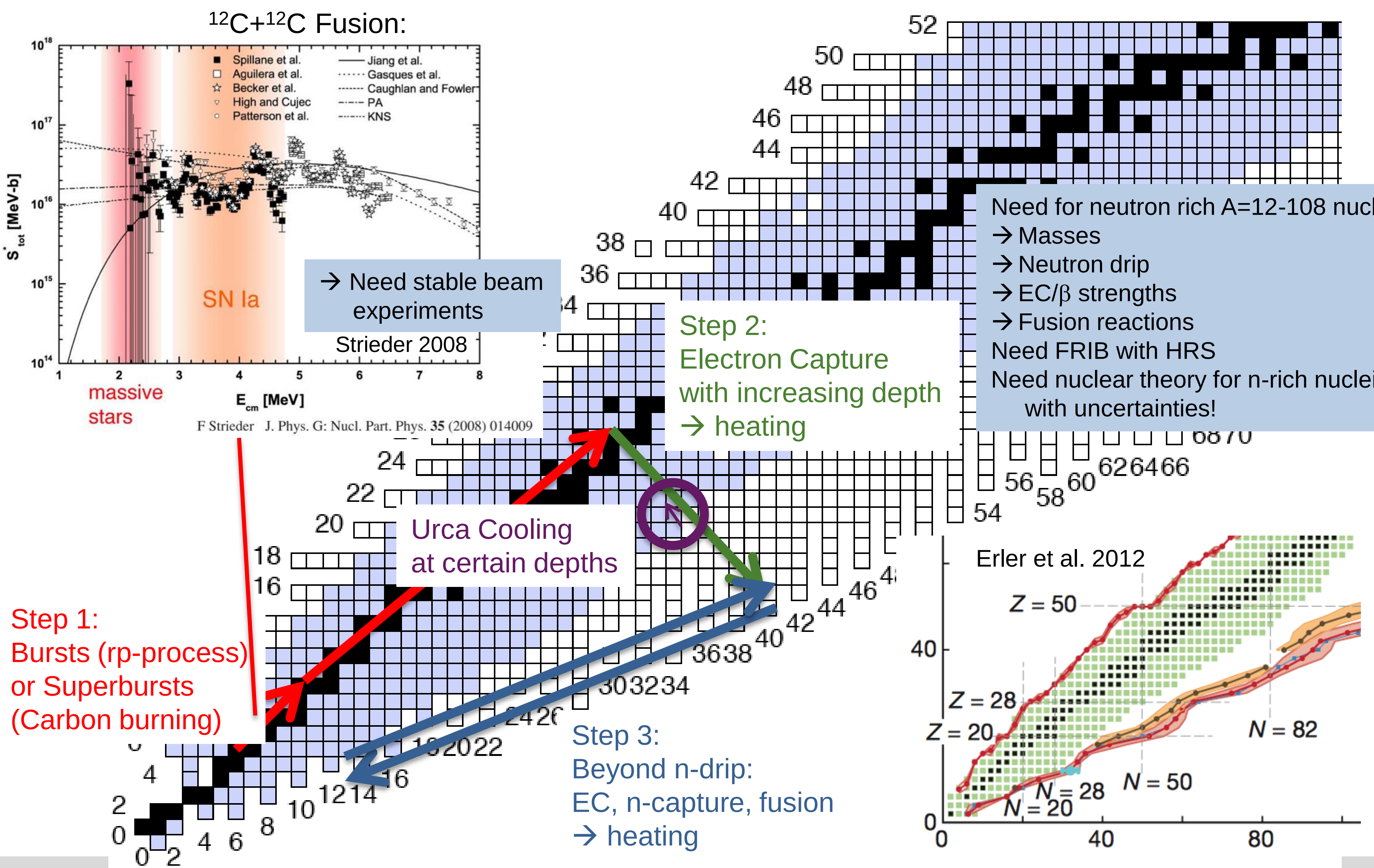
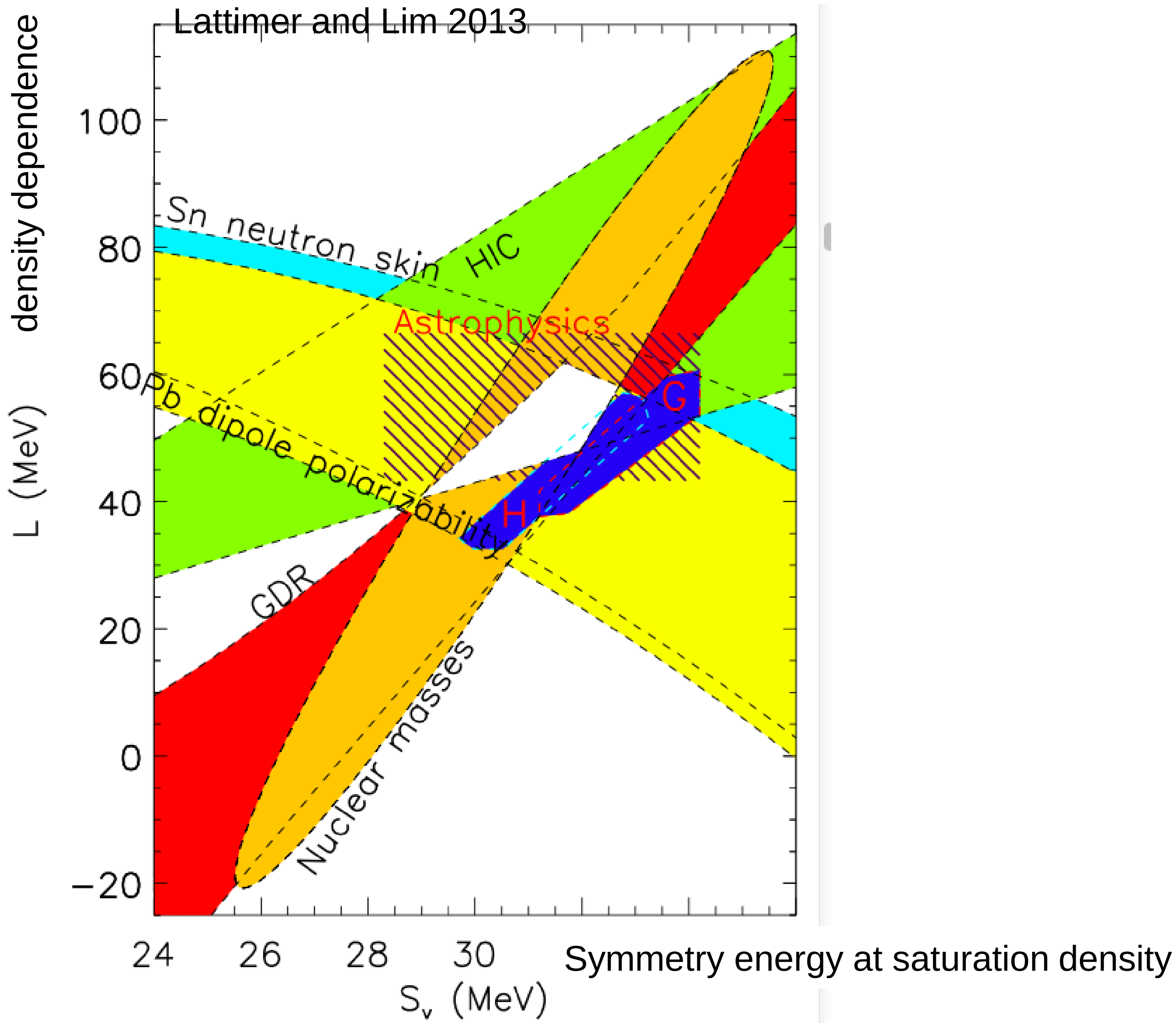


Probing the Nuclear Equation of State



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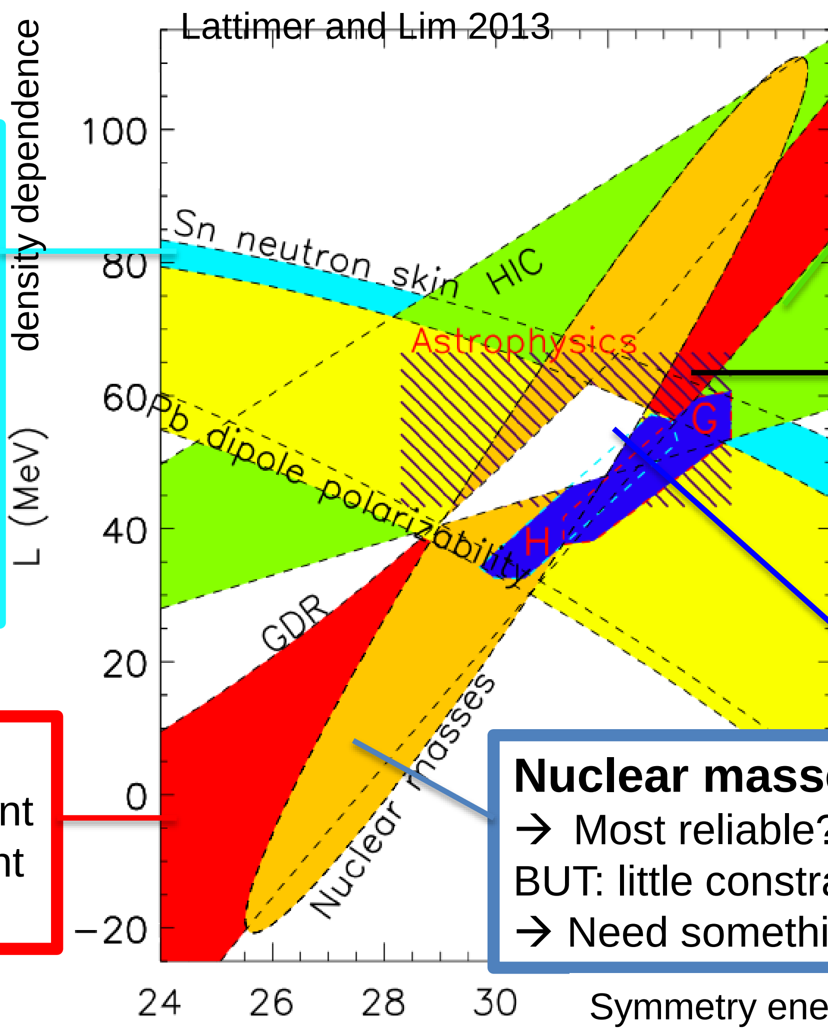


Symmetry energy at saturation density

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

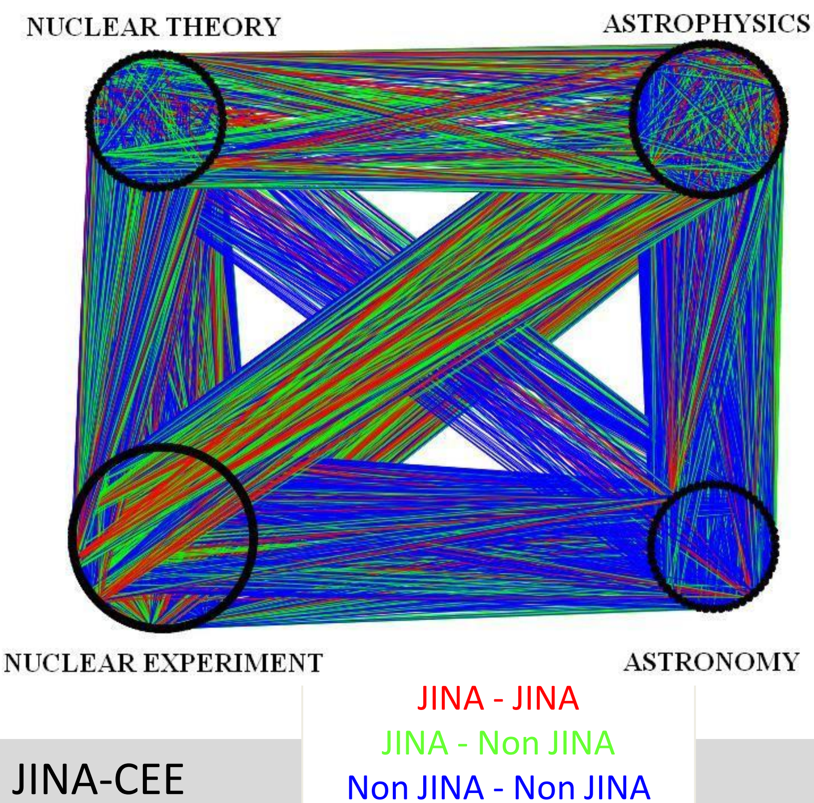
→ Need something else

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

Important Topics Skipped

- Type Ia Supernovae
- Plasma Physics Opportunities
- Links to particle physics: neutrino physics, dark matter

Nuclear Astrophysics Recommendations (abbreviated summary)

1. FRIB
   - Timely completion
   - Development of key nuclear astrophysics equipment (SECAR, GRETA, HRS)
2. Broad program and theory
   - Effective utilization of the available nuclear physics facilities, in particular university-based laboratories
   - Strong theory support, FRIB theory center
   - Focused multi-institutional collaborations that take advantage of new opportunities created by increased computing capabilities and large data science.
3. Underground accelerator facility: construction and operation
4. Interdisciplinary centers
   - Support for JINA,
   - Support for data centers and compilation efforts
5. Education and Innovation

Summary

- **Exciting new open questions driven by observations:**
  - Era of large scale spectroscopic surveys
  - Time domain capabilities – LLST, LIGO, Asteroseismology
  - Unprecedented amount of X-ray data
- **Exciting developments in nuclear physics**
  - Next generation RIB facilities
  - New approaches to enable stellar reaction measurements (Underground, Sensitive techniques, new neutron facilities)
  - Microscopic theory, uncertainty estimates
- **Exciting developments in modeling:**
  - Towards 3D modeling: Validation will become critical
  - Increased need for precise nuclear physics!
- **Field has important questions to address:**
  - What is the origin of the elements?
  - How do stars explode?
  - What do the stars teach us about dense matter?