Nuclear Structure and Reactions - VI

Brad Sherrill

Chief Scientist Facility for Rare Isotope Beams

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MICHIGAN STATE UNIVERSITY

U.S. DEPARTMENT OF ENERGY | Office of Science

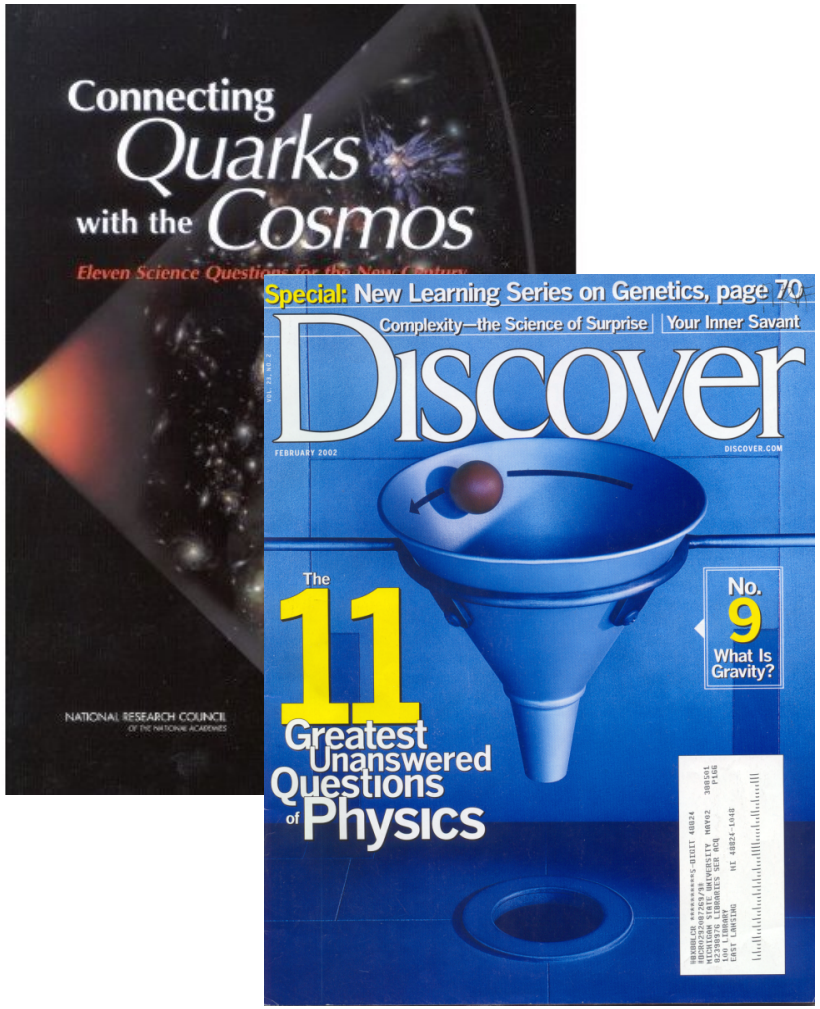
Outline of my six lectures

- One of HUGS goals is to introduce students to “topics of interest in nuclear physics”. My lectures will attempt to describe what is interesting in the study of nuclei.
- Lecture 1: Search for the limits of nuclear binding and production of new isotopes
- Lecture 2: Attempts to model atomic nuclei I
- Lecture 3: Attempts to model atomic nuclei II
- Lecture 4: Nuclear Reactions
- Lecture 5: The origin of atoms – Nuclear Astrophysics I
- **Lecture 6: The origin of atoms – Nuclear Astrophysics II**

The Origin of the Elements

- One of 11 Science Questions for the 21st century

- **How were the elements from iron to uranium made?**
  - Where and how does the r-process occur?



Nuclear Process in the Universe

rp-process in X-ray bursts/Novae/ Supernovae
- Direct reaction rates (SECAR)
- Indirect reaction rate studies
- Masses and p-drip line

s-process in AGB stars
- Harvesting of targets for n-capture on branchpoints

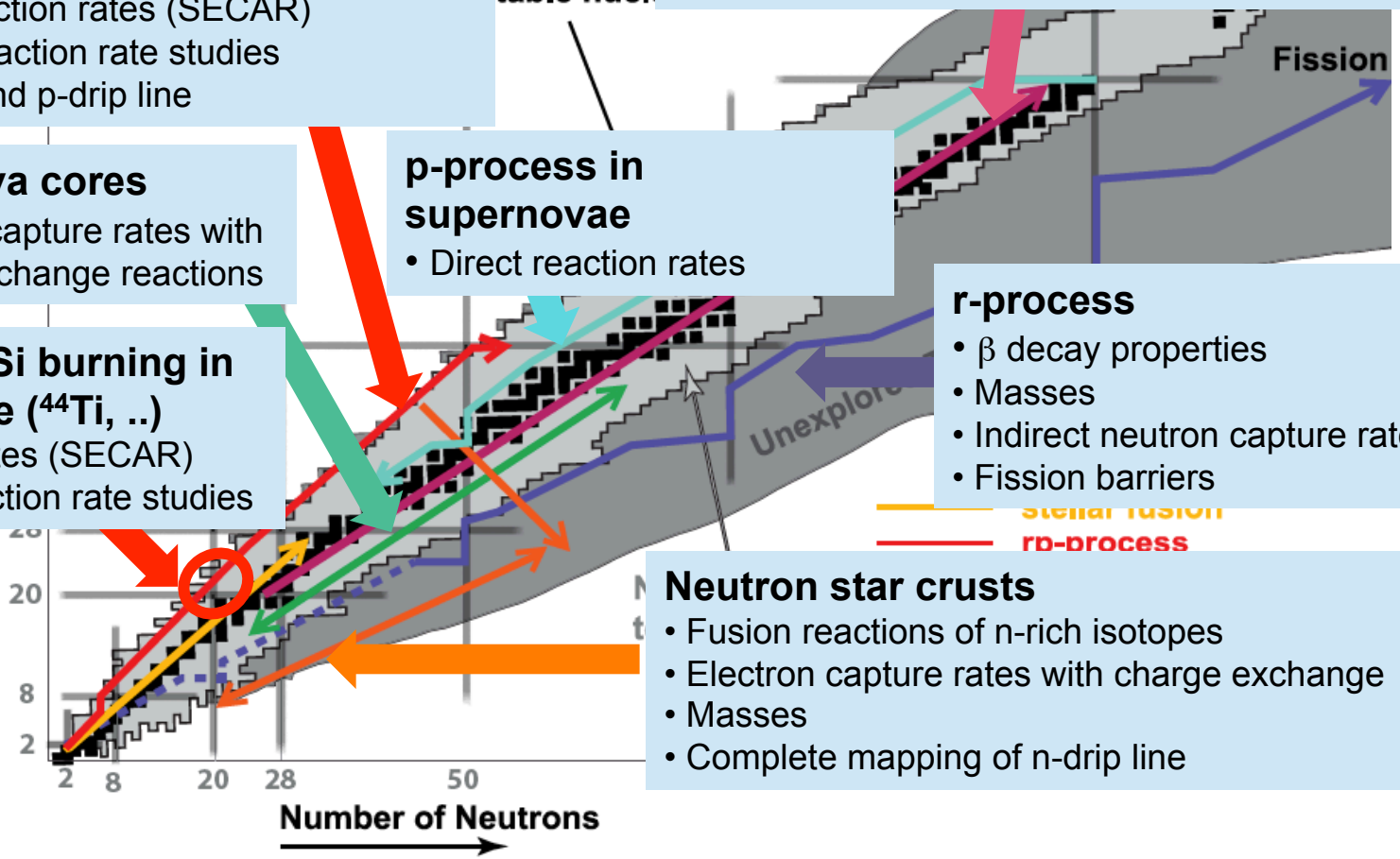
Supernova cores
- Electron capture rates with charge exchange reactions

p-process in supernovae
- Direct reaction rates

Explosive Si burning in supernovae (^{44}Ti, ..)
- Reaction rates (SECAR)
- Indirect reaction rate studies

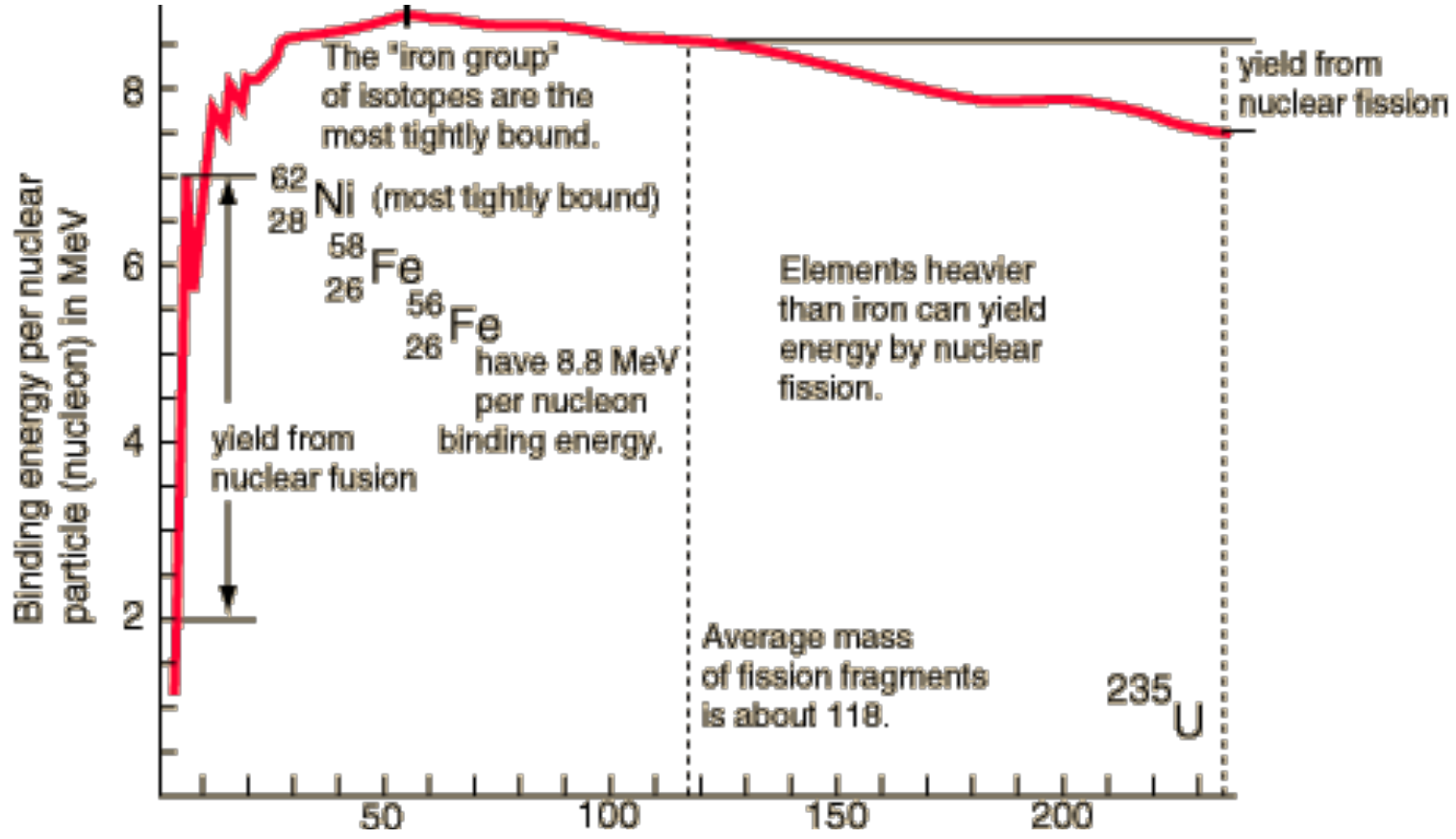
r-process
- β decay properties
- Masses
- Indirect neutron capture rate studies
- Fission barriers

Neutron star crusts
- Fusion reactions of n-rich isotopes
- Electron capture rates with charge exchange
- Masses
- Complete mapping of n-drip line



Nuclear Binding Energy

http://hyperphysics.phy-astr.gsu.edu/hbase/nucene/nucbin.html

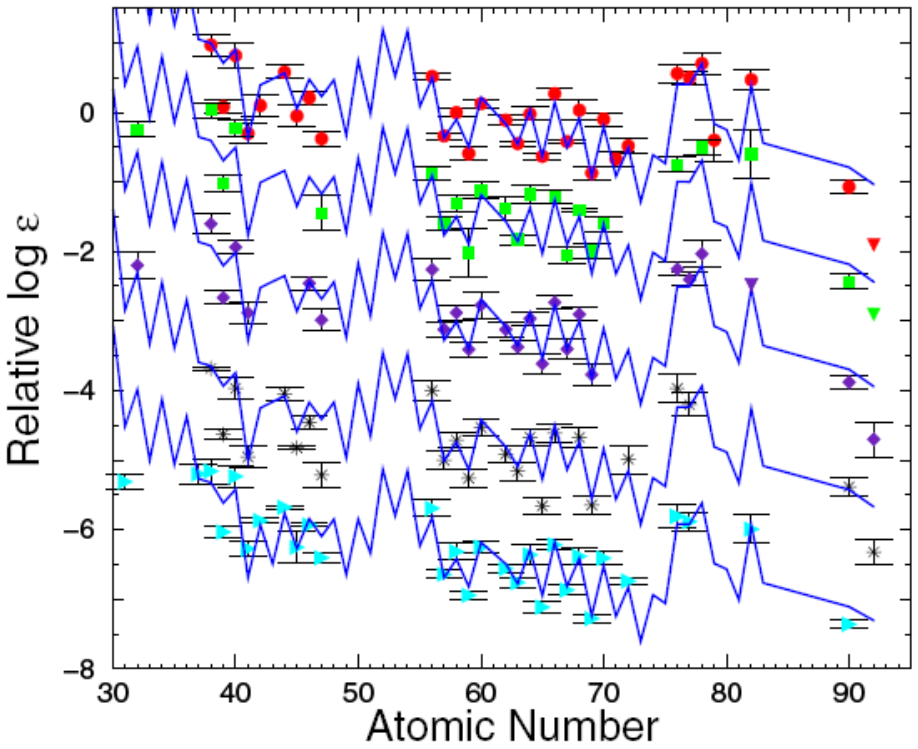


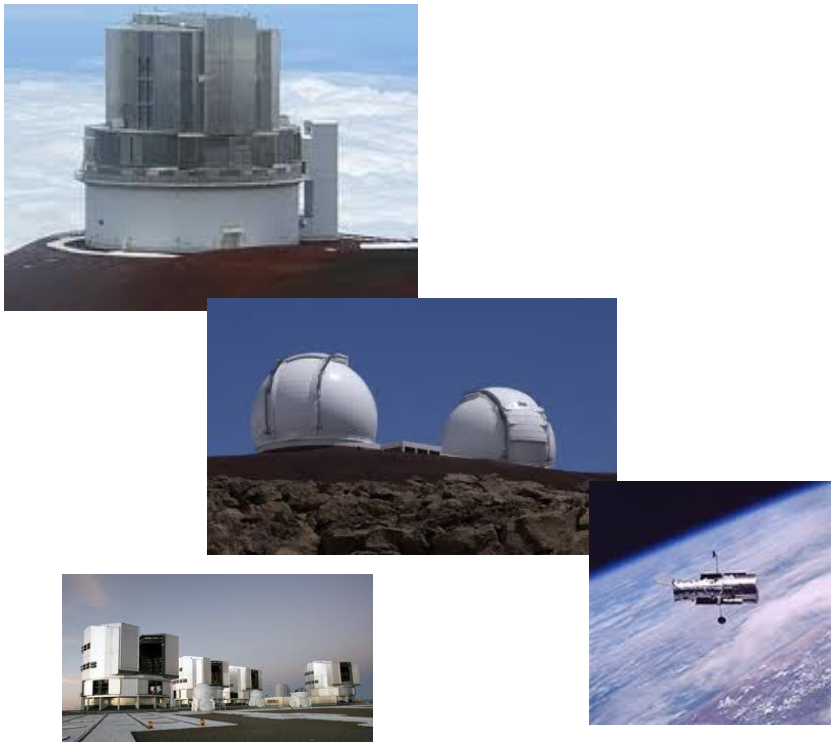
Example: Where do gold atoms come from? More than half of Z>28 from an r-process

- E. M. Burbidge, G. R. Burbidge, W. A. Fowler, and F. Hoyle. (1957). "Synthesis of the Elements in Stars". Rev Mod Phy 29: 547, must be an r-procees (10% of gold from s-process)
- We know they must be made in a neutron-rich environment $T > 10^9$ K, $\rho_{neutron} \approx 10^{20\text{-}28}$ cm^{-3} , that lasts for about 1 second; called the rapid-neutron capture process, r-process
- Type II supernovae are a possible site (variants)
  - Neutrino driven shock wave, however models do not produce the entropy and neutron flux needed to match abundance data (although we can't say that for sure)
  - Shock waves in C-O layers
  - Magnetic outflows
- Colliding neutron stars would also work, but there does not seem to be enough of these in the early universe to explain how much heavier elements we see
- Once the underlying physics is known, we can infer information of the site from observational data

Breakthrough in Astronomy

- We now understand what nuclei various types of r-processes make

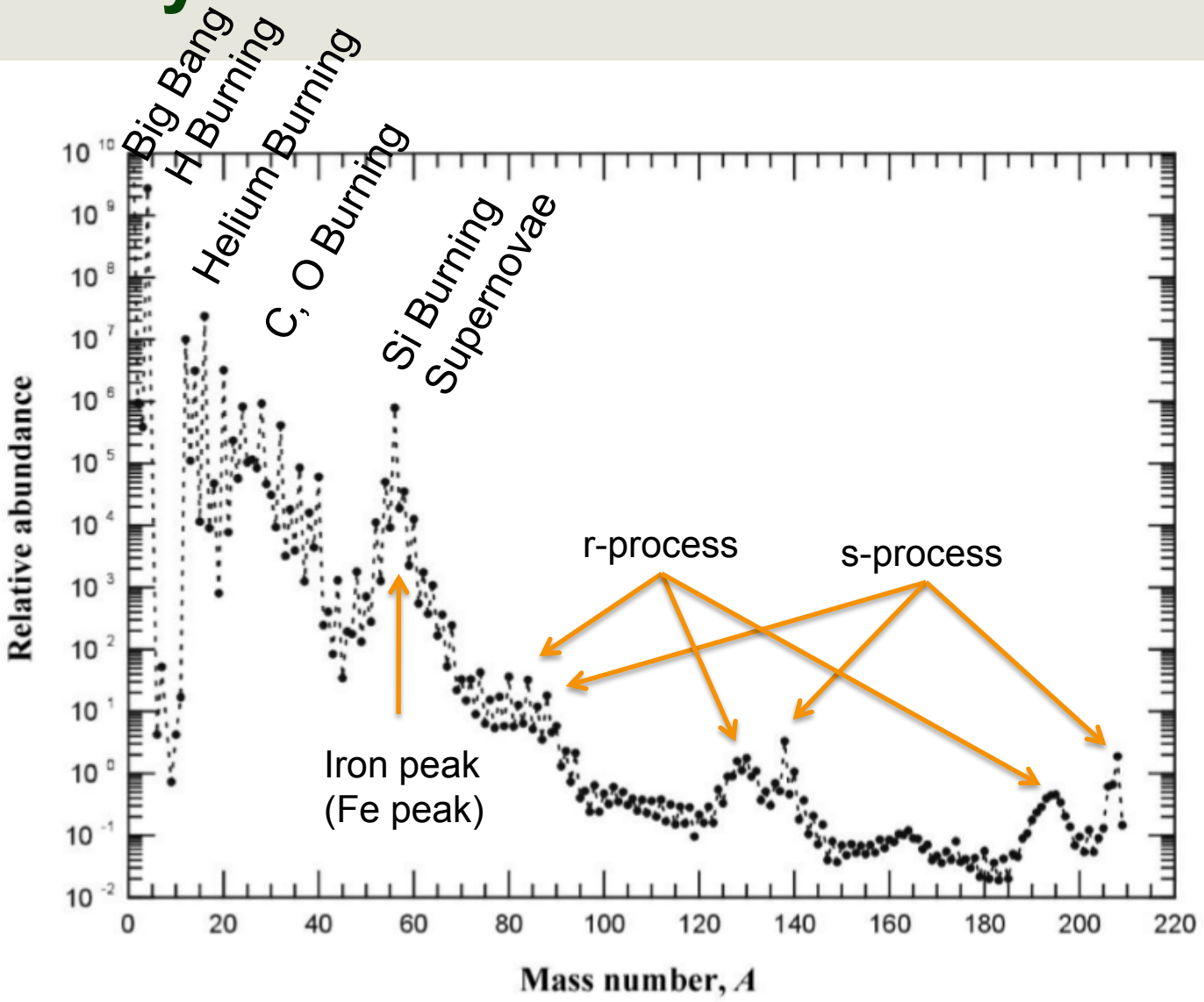




Major astronomy effort with largest telescopes

Solar System Abundances

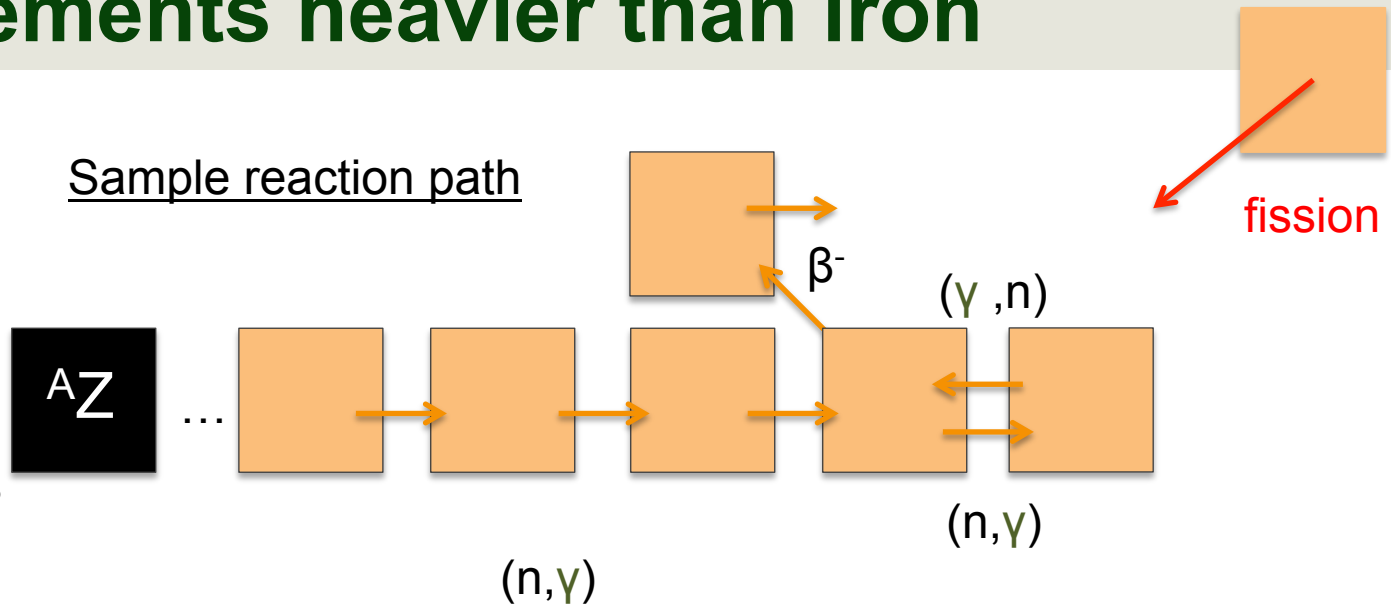
- The pattern plotted versus mass number shows the origin of some of the processes more clearly
- For clarity, not all process contributing to element synthesis are listed



Neutron-capture processes leading to elements heavier than iron

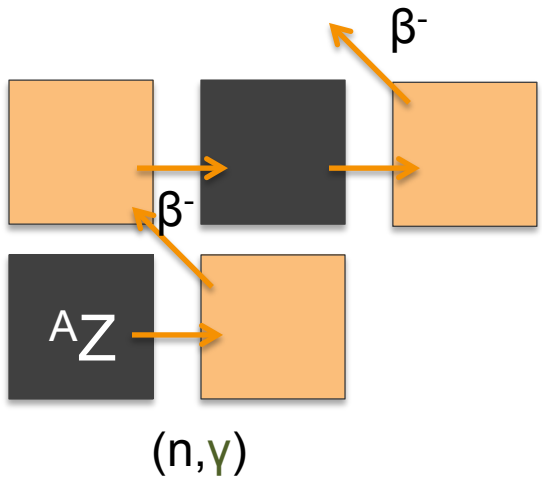
r-process

- Fast, few s
- $10^{20\text{-}28}$ n/cm^3
- Runs out to where (n,γ) and (γ,n) are similar in rate
- Adds 30-40 neutrons
- Site unknown



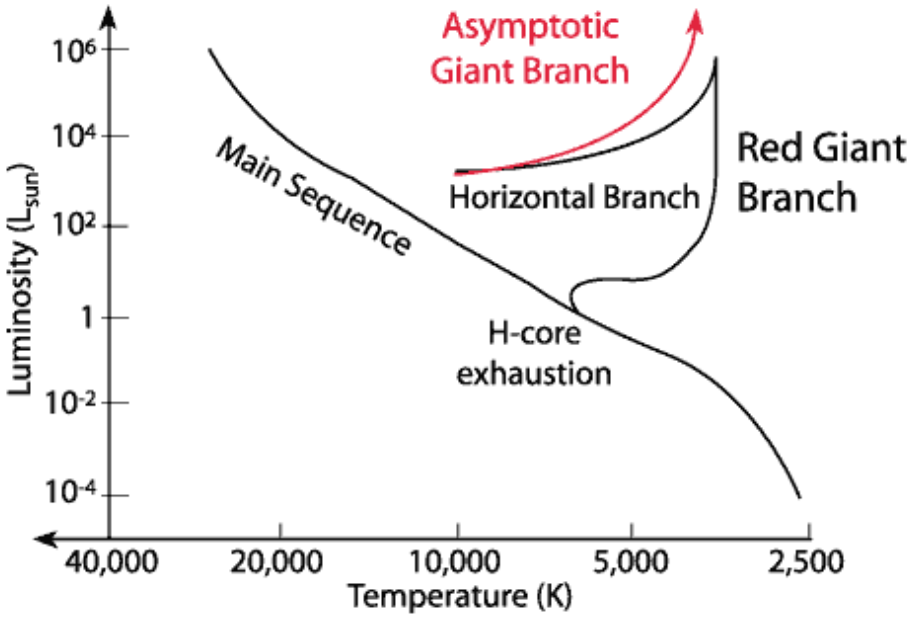
s-process

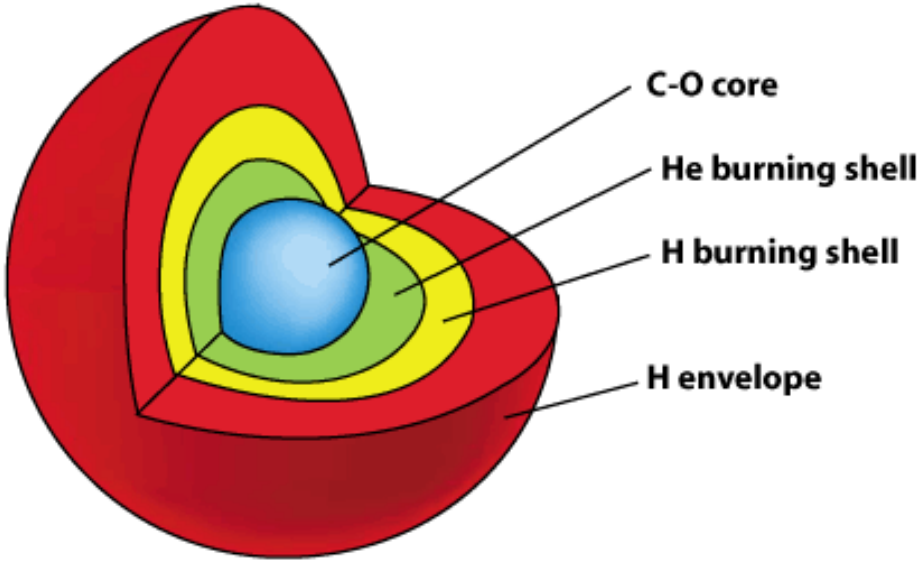
- Occurs over a time of hundreds of thousands of years
- Technetium observed in red giant stars
- Occurs in AGB Stars (C,O core; He and H fusion shells)



Asymptotic Giant Branch Stars

- Technetium found in AGB stars. Since the half life is 4.2 My and the stars are much older, it must be made there.



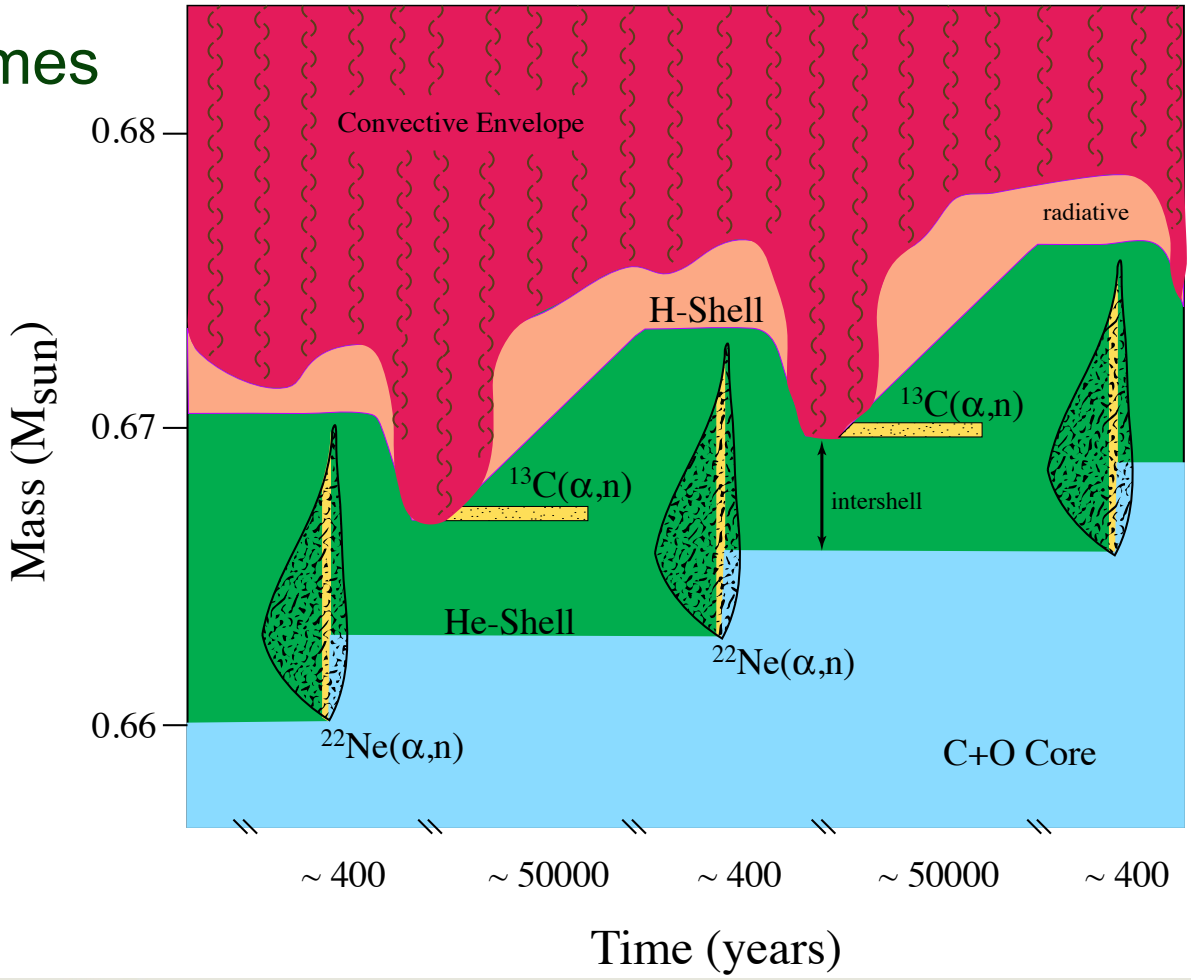


http://www.noao.edu

Model of the s-process

http://cococubed.asu.edu/index.html

F. Timmes



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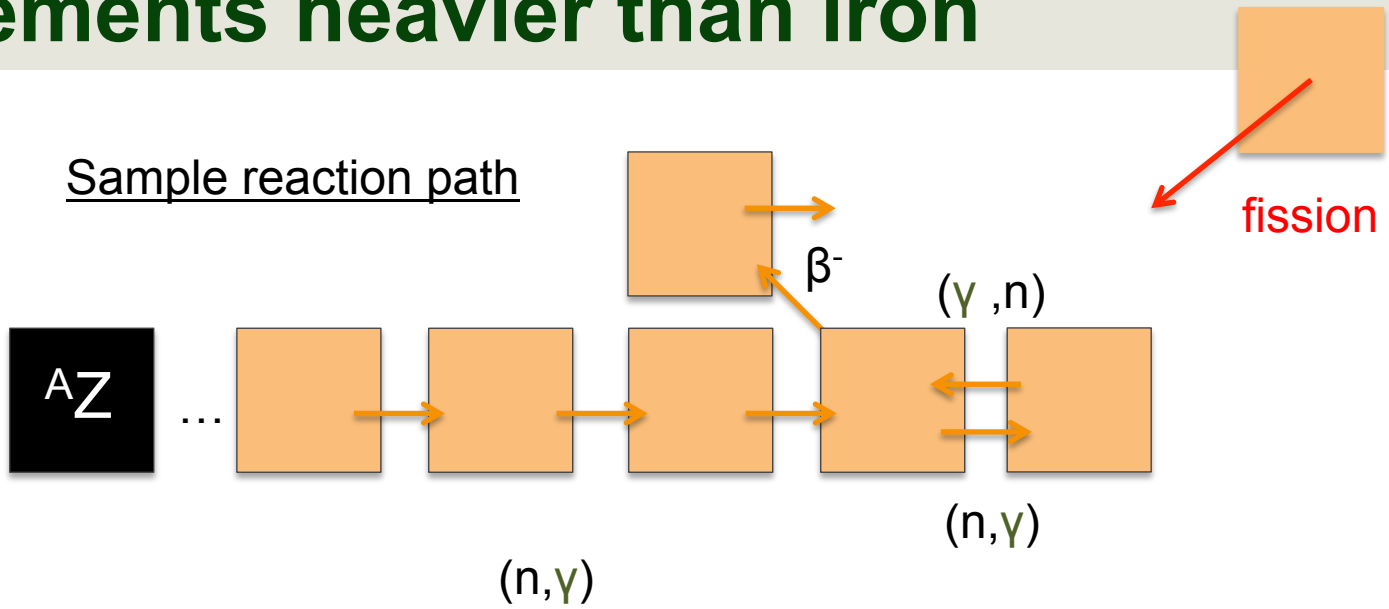

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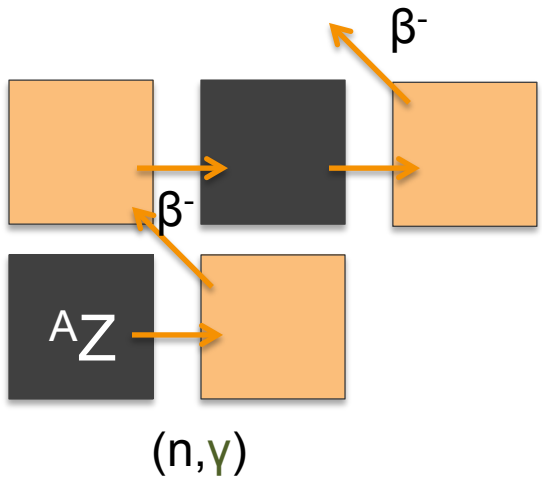
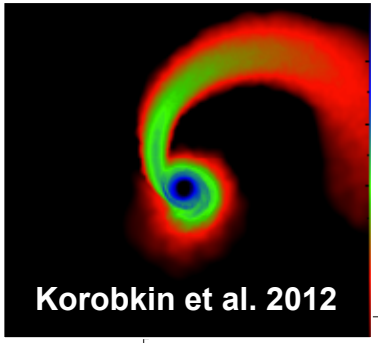
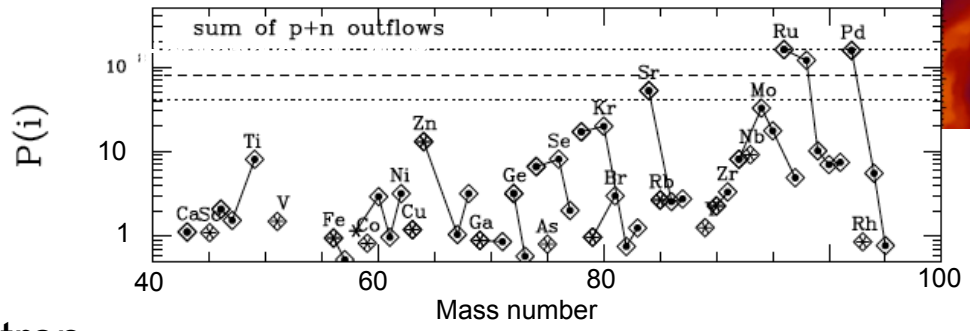


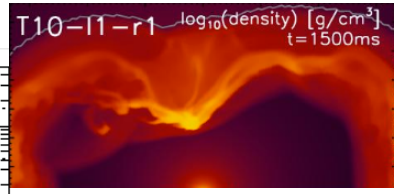
Advances in Theoretical Astrophysics

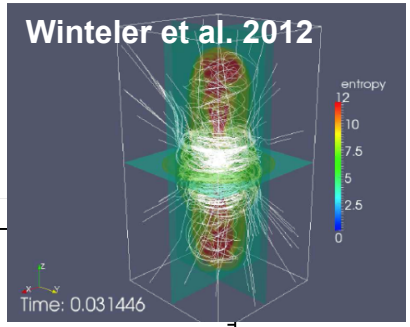
- We now have several robust, self-consistent r-process models; to test them against observations, we need nuclear data



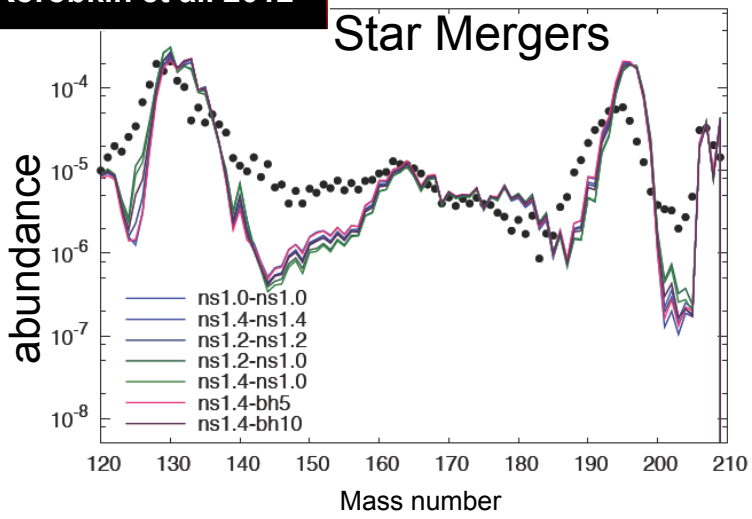
Neutrino Driven Wind



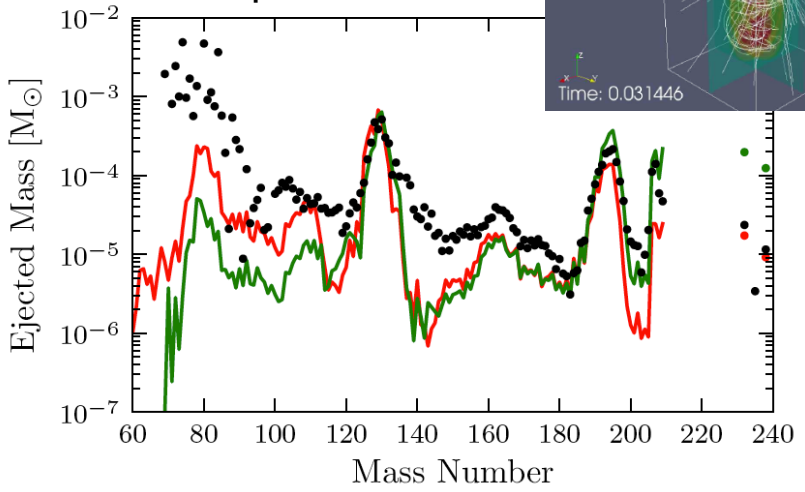




Neutron Star Mergers

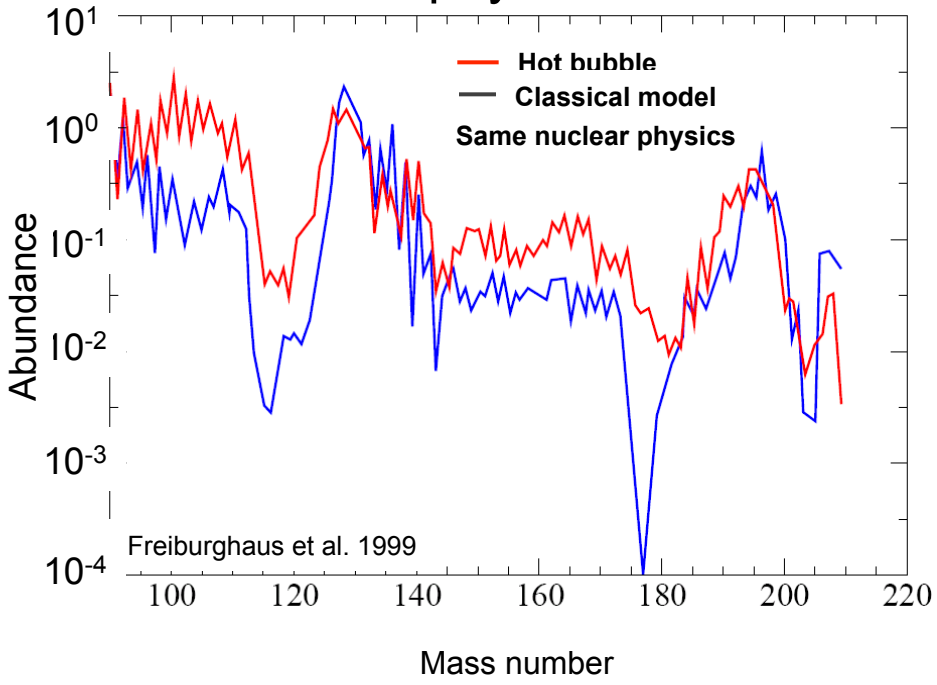


MHD Supernova Jets

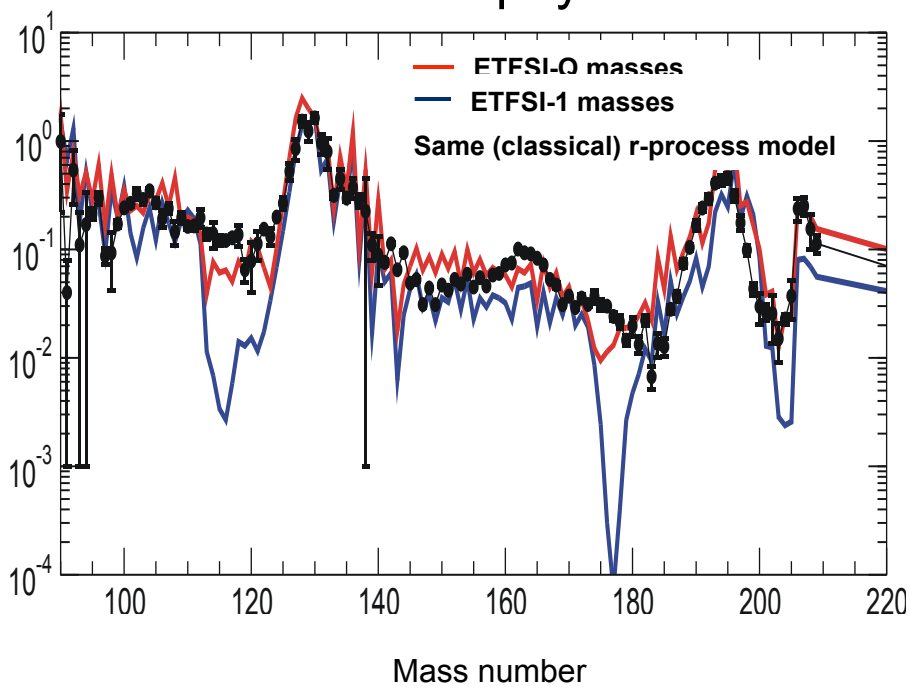


Uncertainty between models and nuclear properties

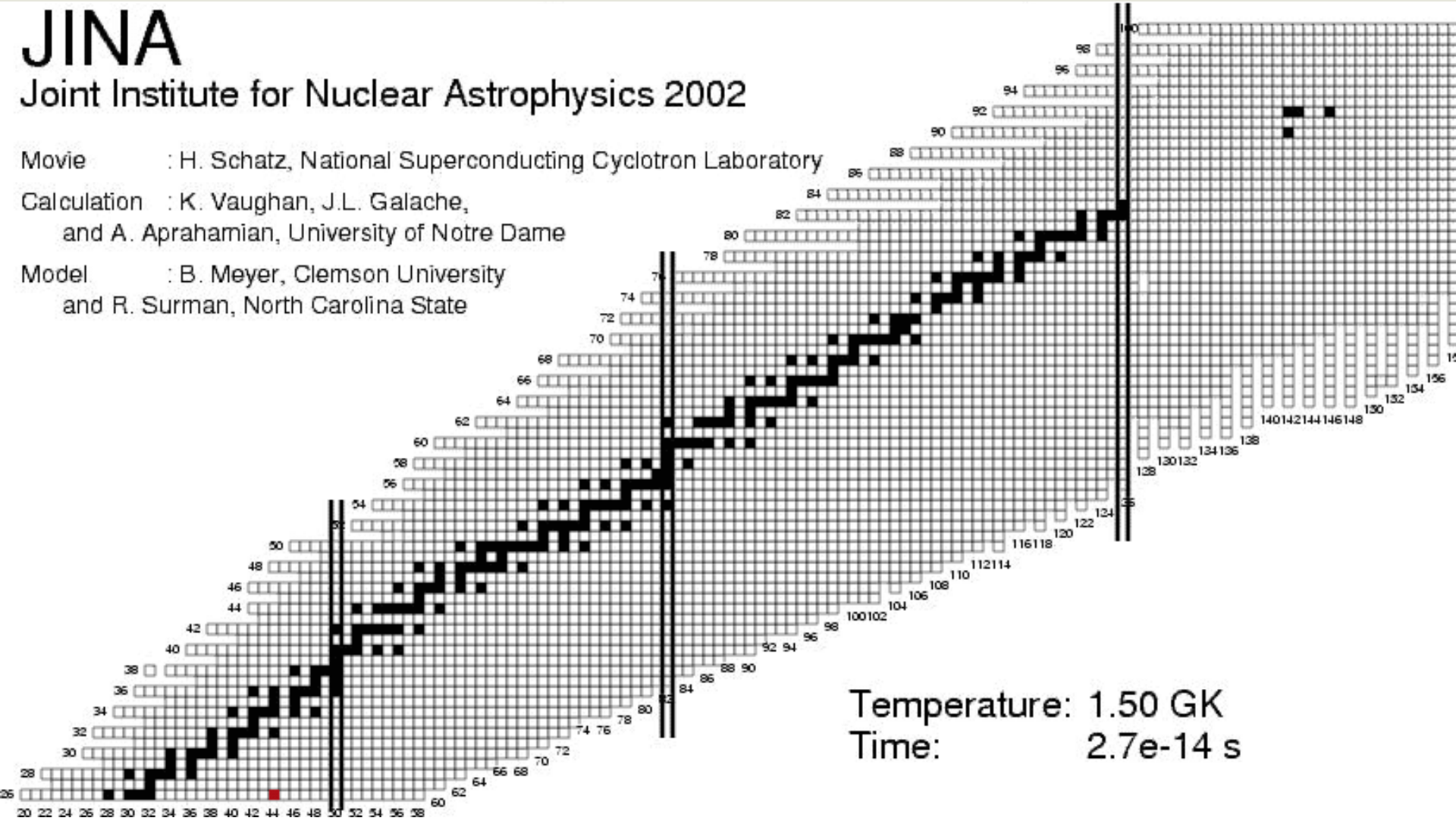
Astrophysics



Nuclear physics

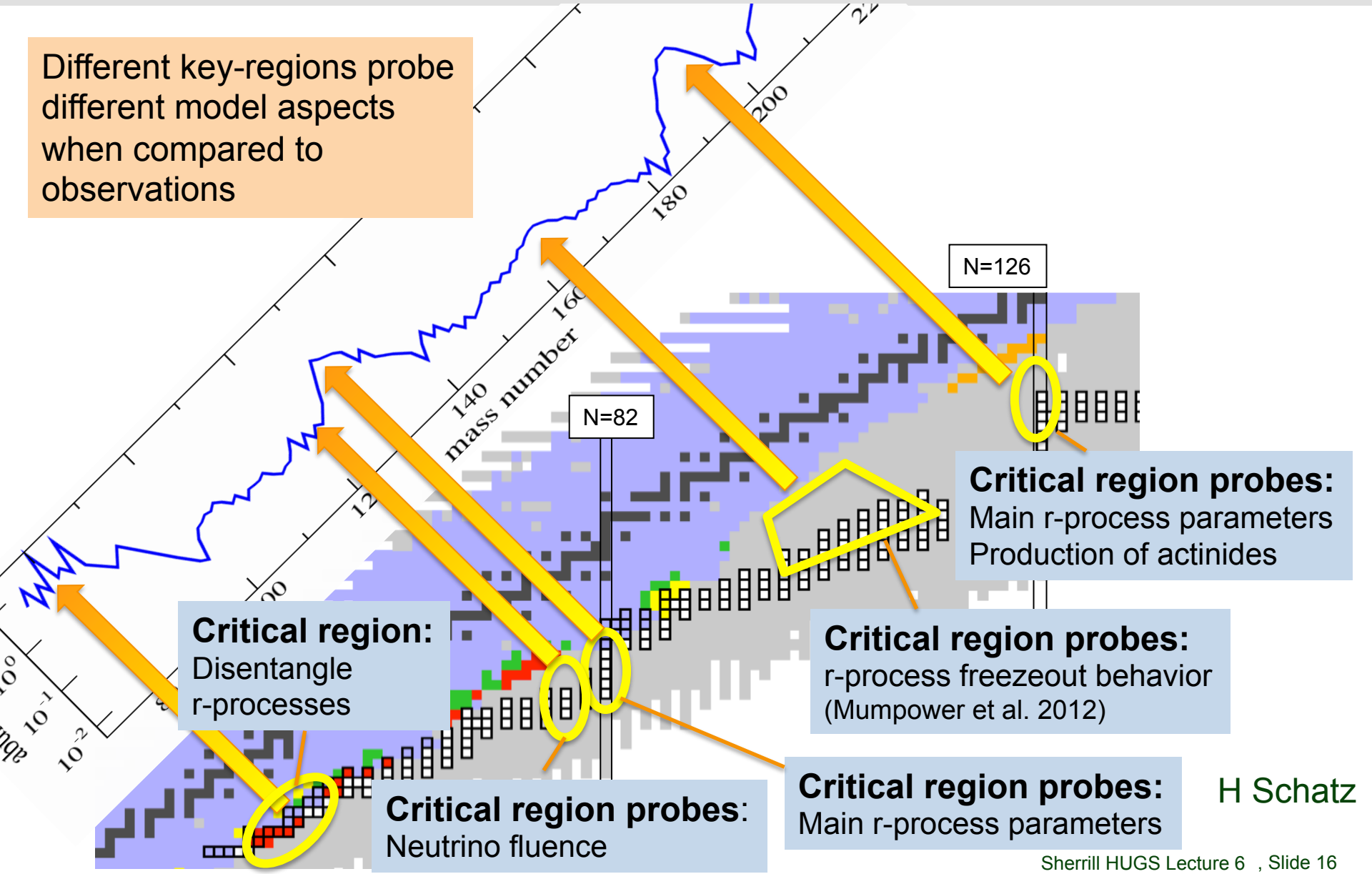


About Half of Heavier Elements must be made in an r-Process



New Facilities will Enable the Needed Breakthrough in Nuclear Physics

Different key-regions probe different model aspects when compared to observations



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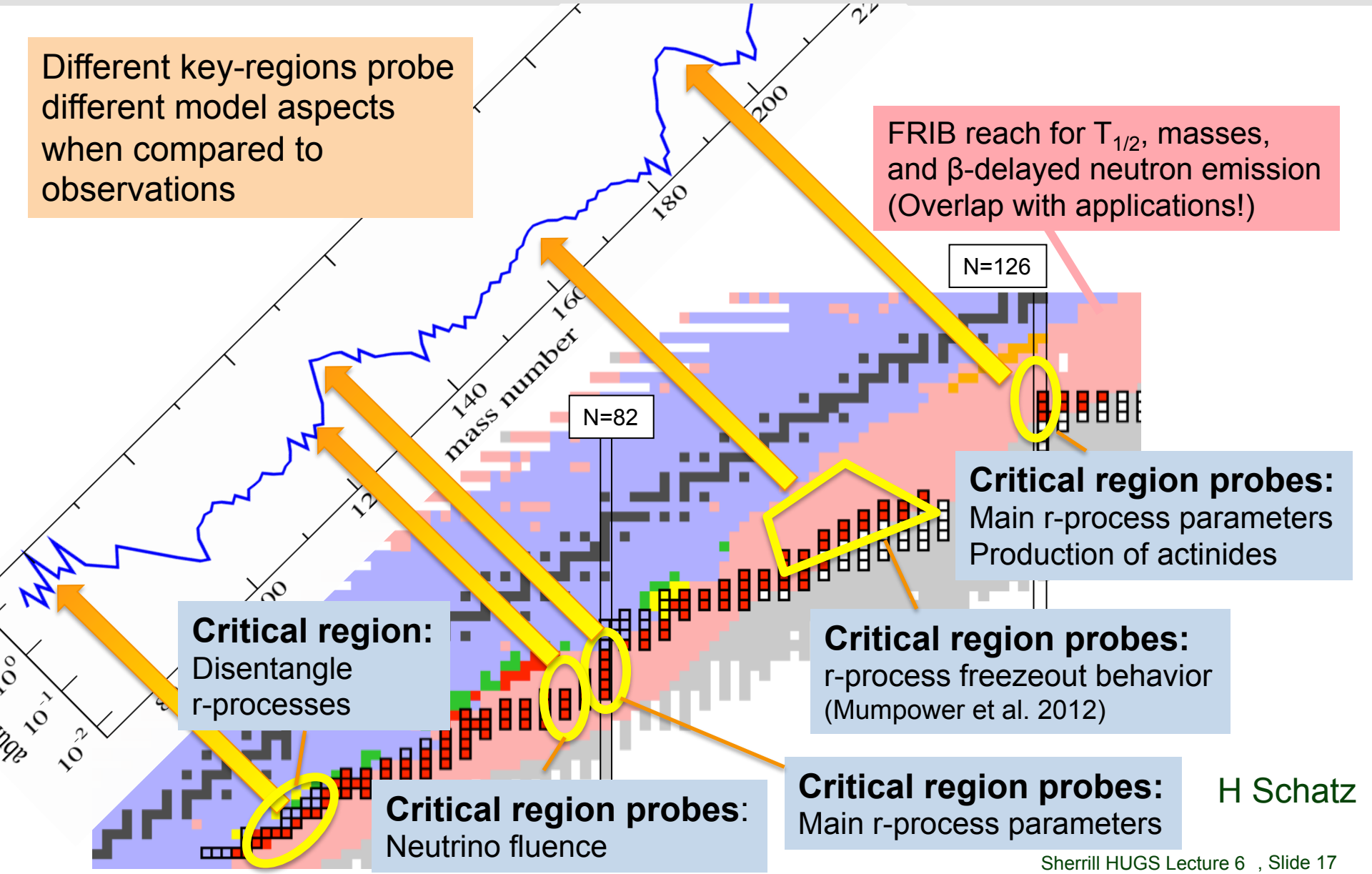

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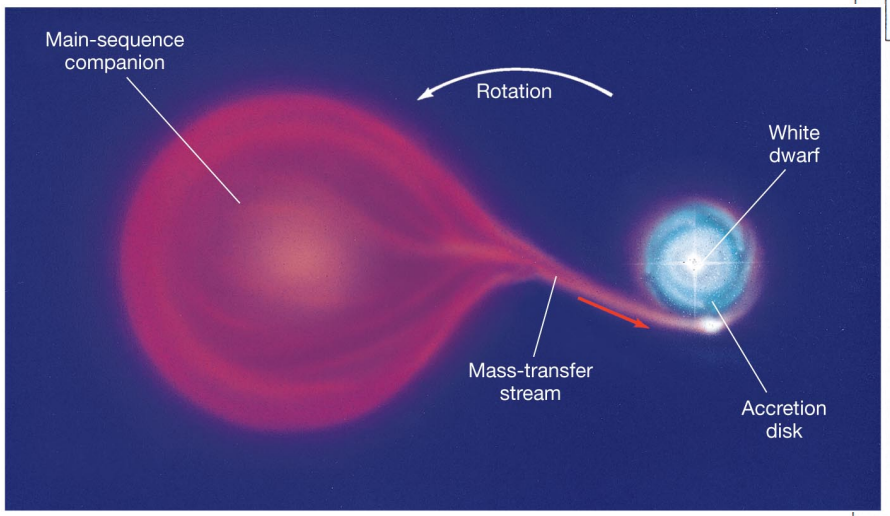
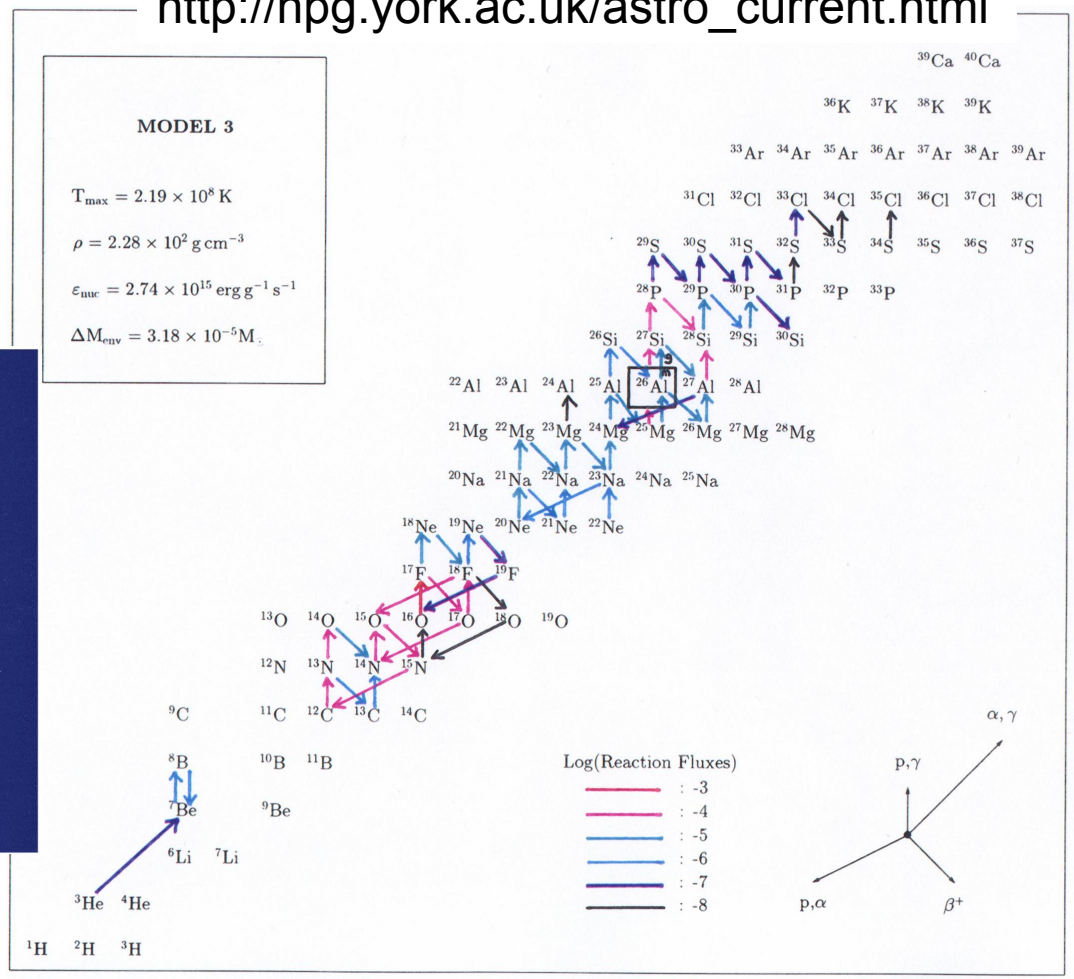
Novae Nucleosynthesis

http://npg.york.ac.uk/astro_current.html

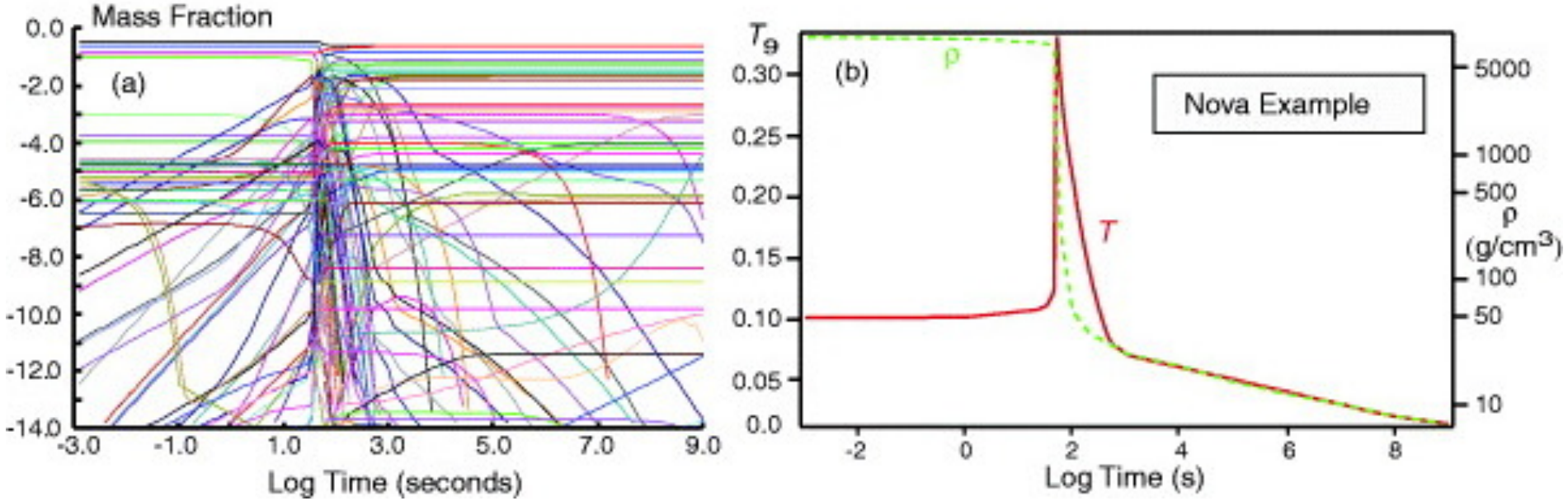




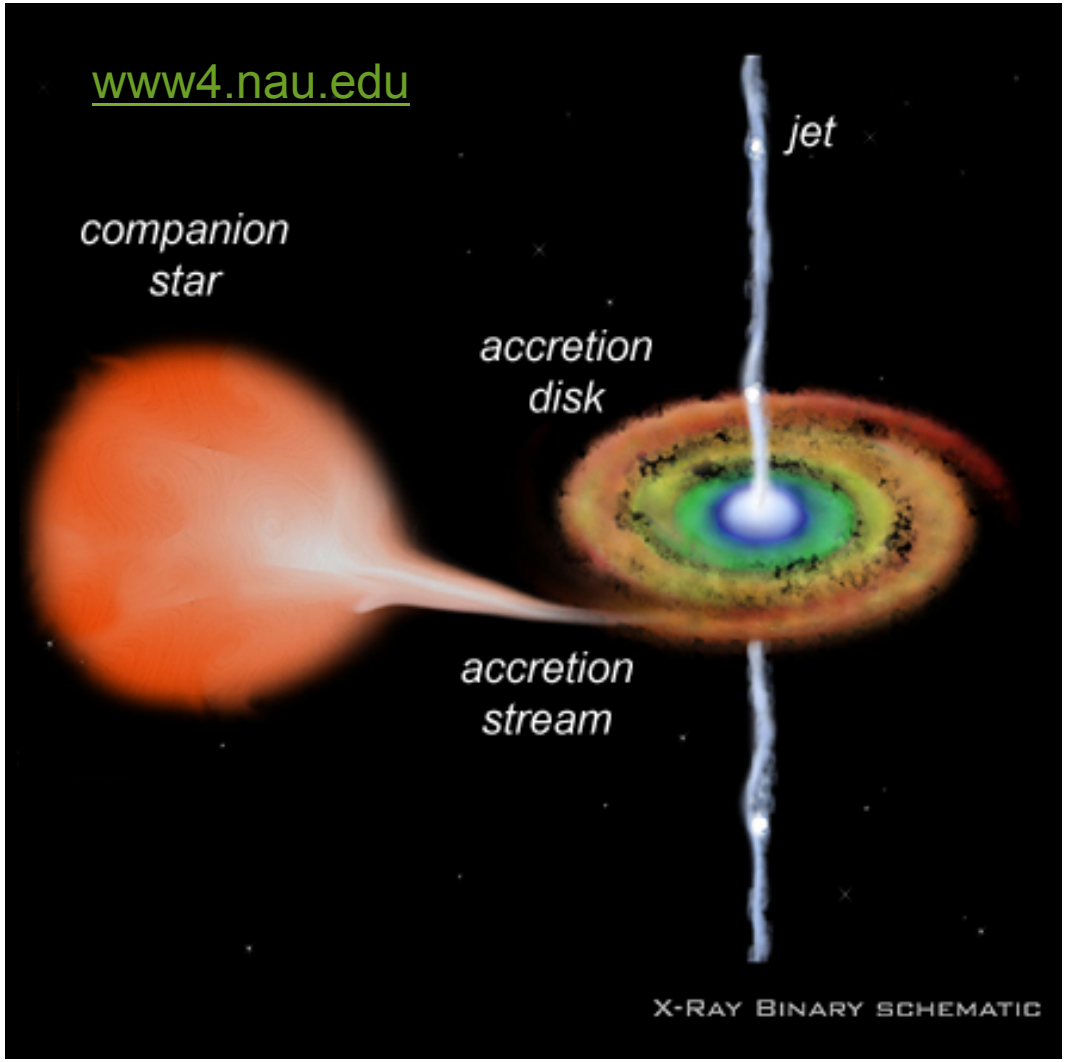
Novae Nucleosynthesis Calculation Sample

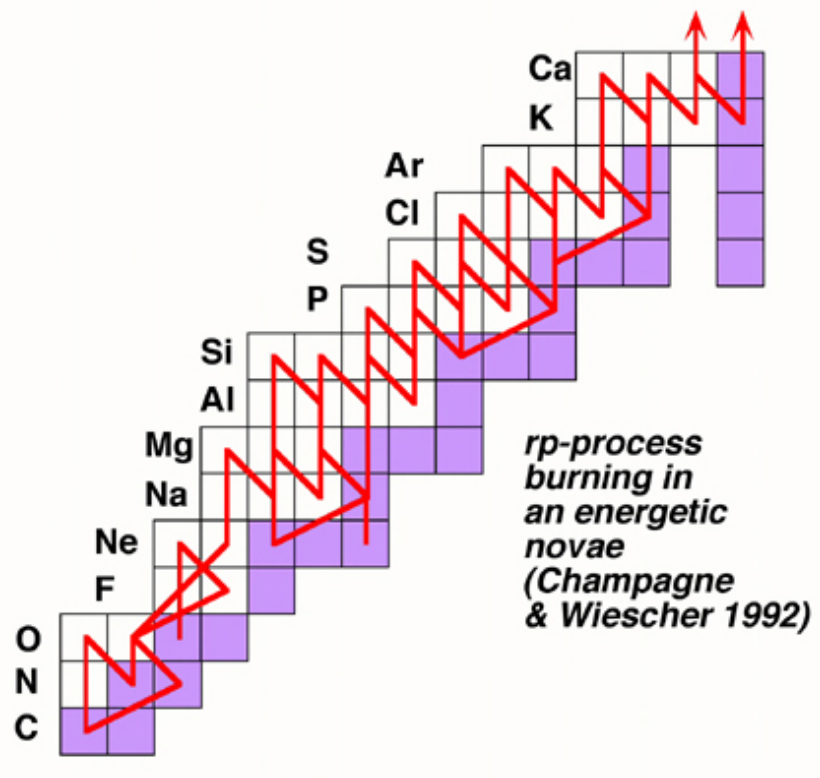
Light Curve

Figure 7 from M W Guidry and J A Harris 2013 Comput. Sci. Disc. 6 015002



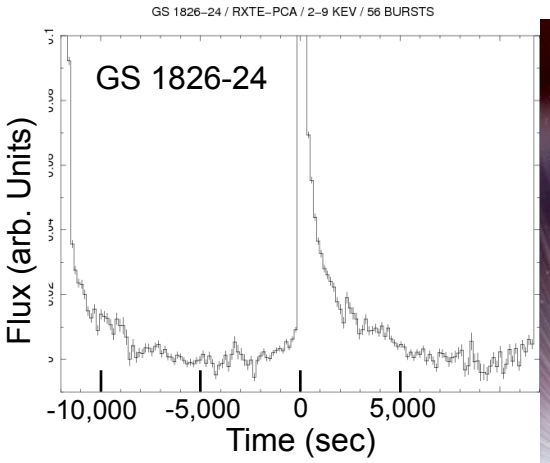
Model for X-ray Bursts



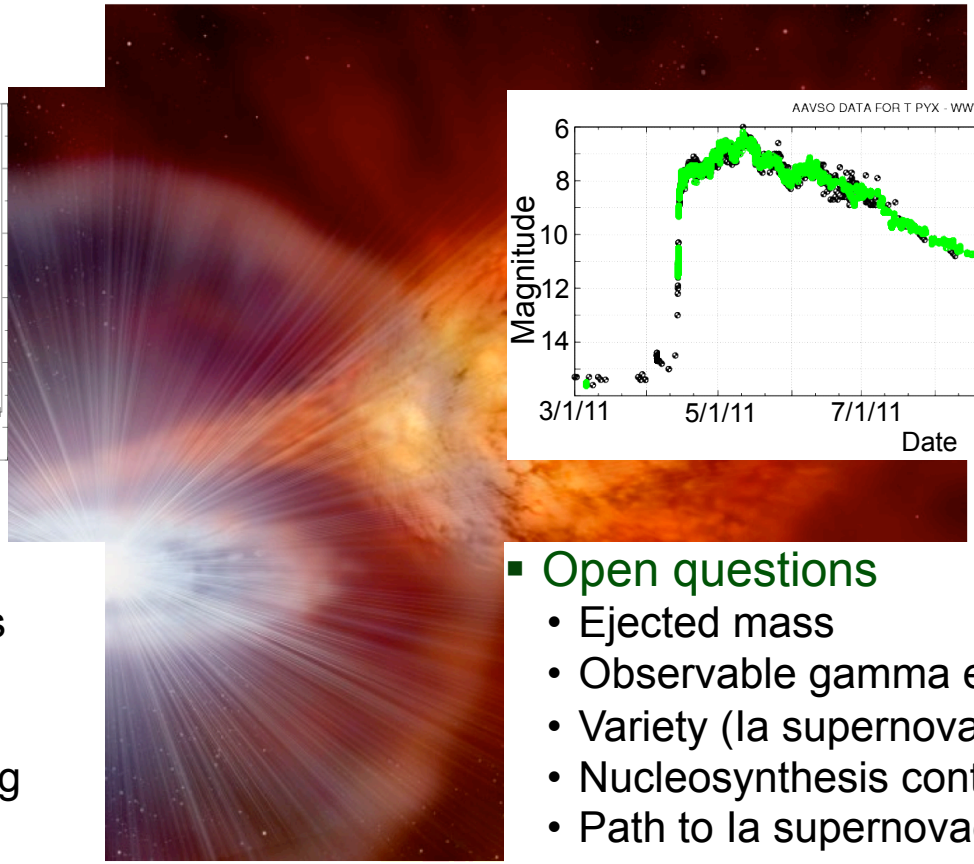


Stellar Hydrogen Explosions: Common and Not Understood

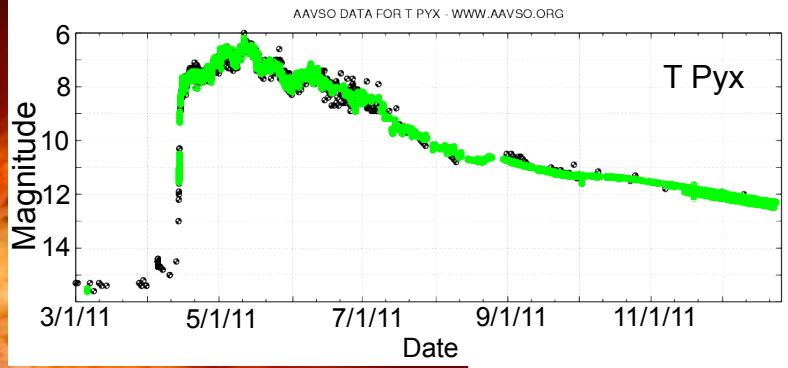
- X-ray bursts on neutron stars quired to answe
  - Most common explosions (~100 per day)



- Open questions
  - Neutron star compactness
  - Short burst intervals
  - Multiple peaked bursts
  - Transition to stable burning
  - Nature of superbursts



- Classical novae on white dwarfs
  - ~30 per year



- Open questions
  - Ejected mass
  - Observable gamma emitters
  - Variety (Ia supernovae, …)
  - Nucleosynthesis contribution
  - Path to Ia supernovae

Making Sense of X-ray Burst Observations

- Major progress in observations
  - MINBAR archive: 5000 widely varying bursts
- Need nuclear data on rare isotopes to create reliable model templates to analyze observations

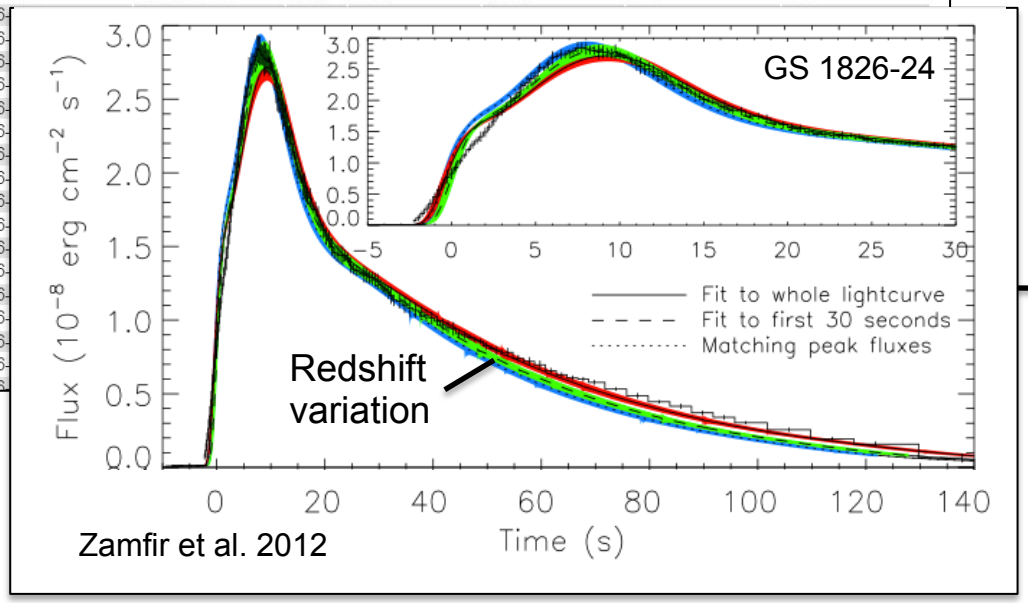
Multi-INstrument Burst ARchive

Galloway et al.

70 bursts of H 1636-536. View observations.

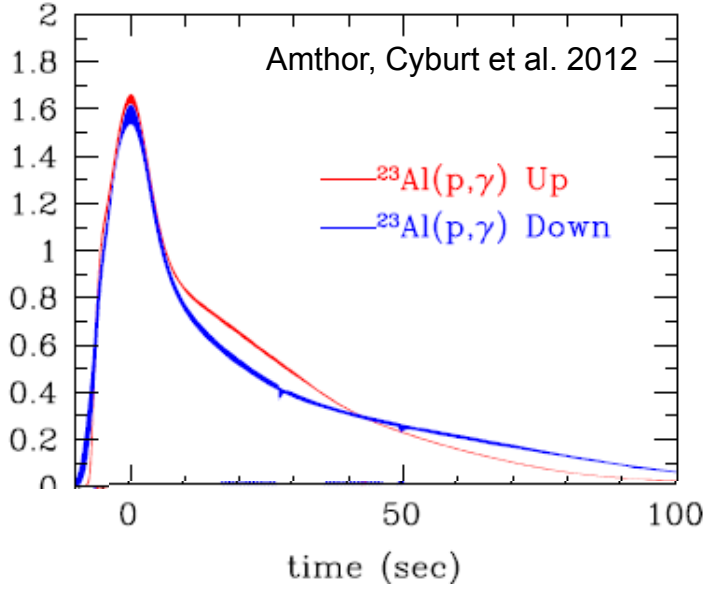
Source: H 1636-536 (All sources) Fields: name,time,instr,bpflux,nh (Add a field) Output: Webpage Show Reset

Likely source origin	Start time (MJD)	Instr.	Bol. peak flux	Error peak flux	nH @max 10^22	Error nH @max
H 1636-536	50349.93782	SW2	382.92	281.78	0.25	0.00
H 1636-536	51766.42301	SW2	130.90	18.89	0.25	0.00



Zamfir et al. 2012

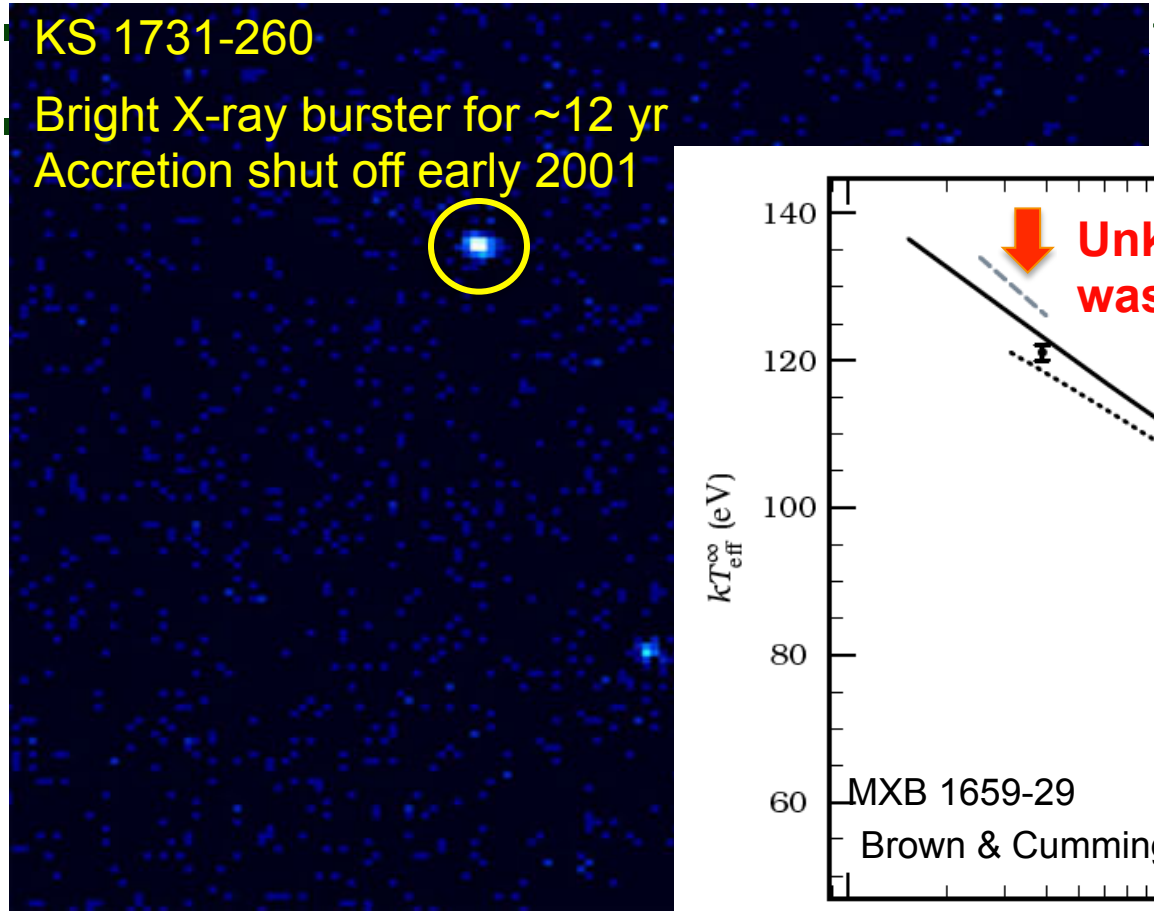
Burst profiles depend on nuclear rates



With accurate model templates

- Absolute peak flux, distance
- H/He composition
- Redshift + color correction (distance and anisotropy independent) → neutron star compactness

Transiently Accreting Neutron Stars Allow the Study of Dense Matter



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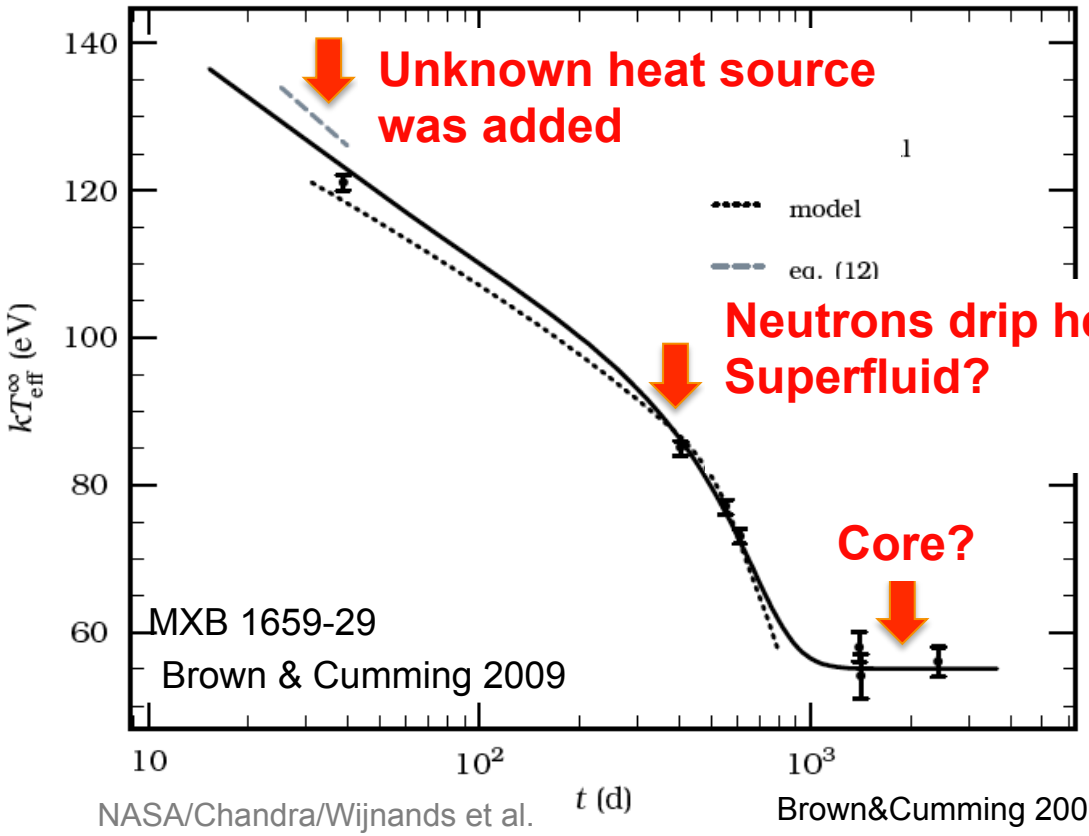
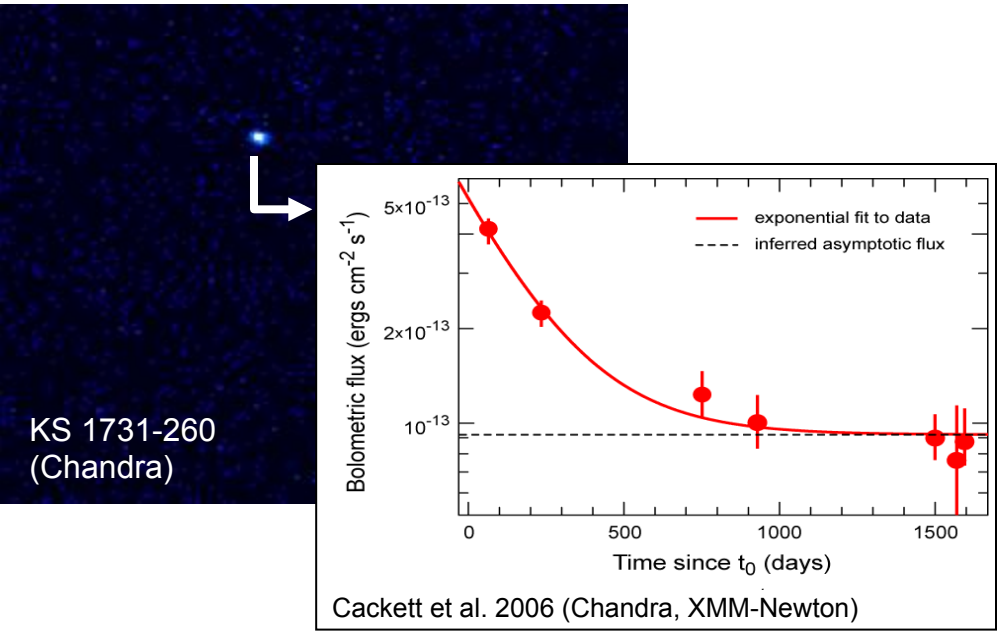
Cooling probes crust

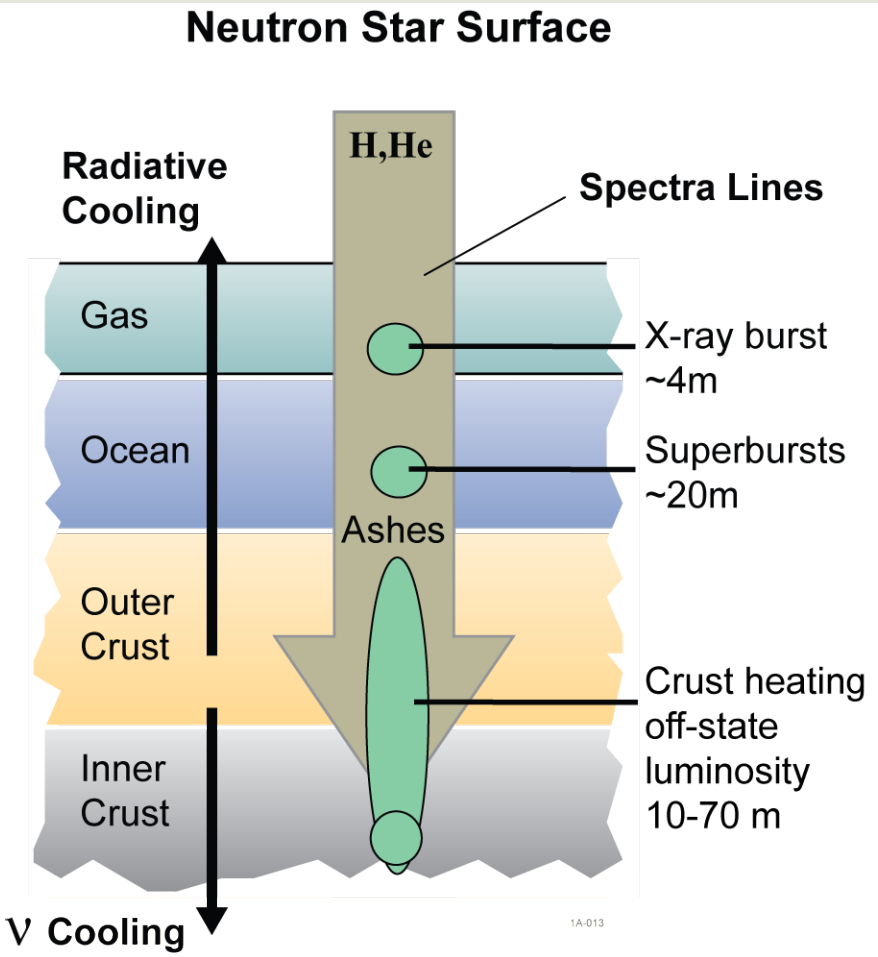


NASA/Chandra/Wijnands et al.

Brown&Cumming 2009

Rare Isotope Crusts of Accreting Neutron Stars





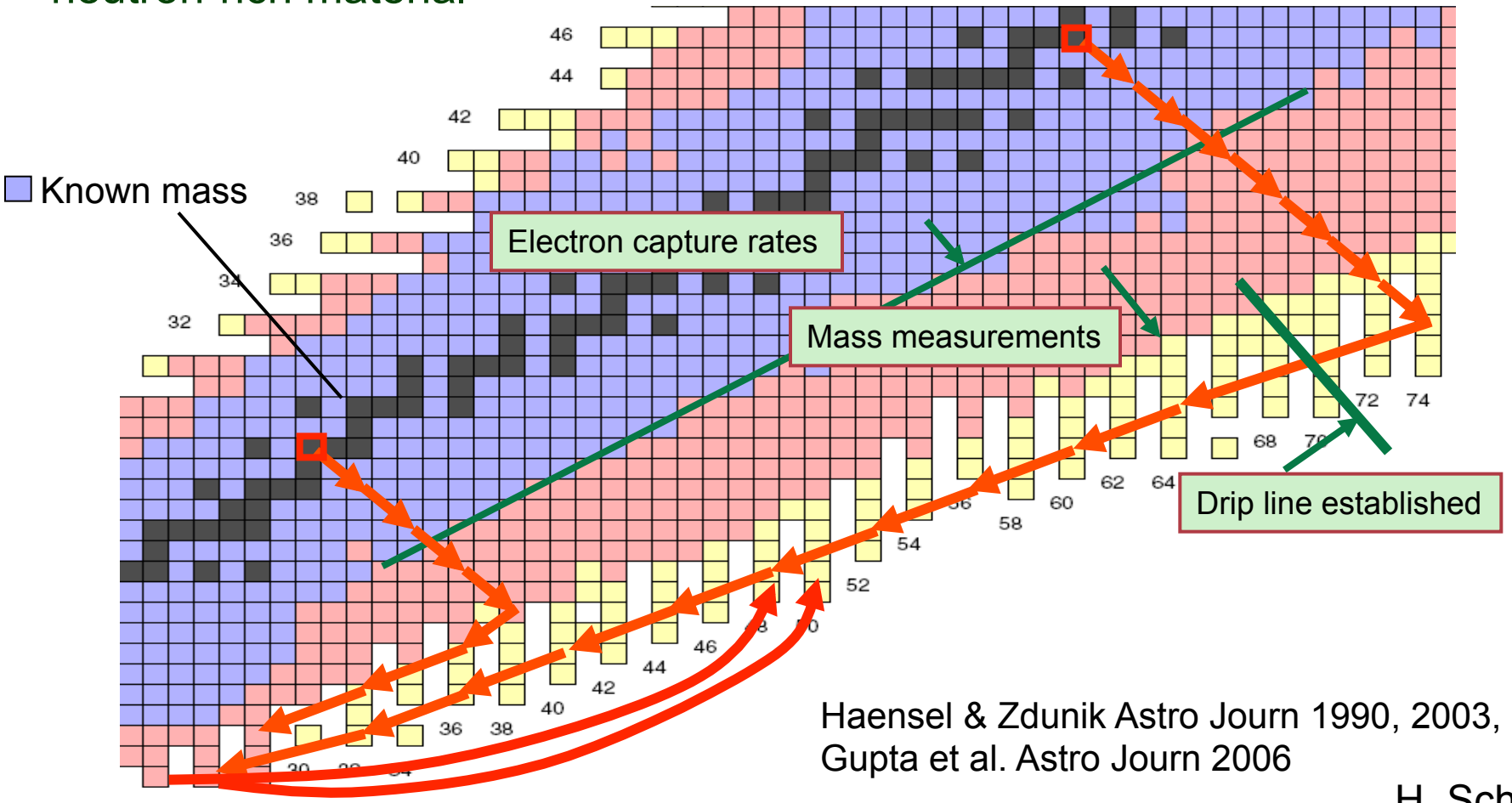
- Nuclear reactions in the crust set thermal properties
- Can be directly observed in transients
- Directly affects superburst ignition

Understanding of crust reactions offers possibility to constrain neutron star properties (core composition, neutrino emission…)

H. Schatz

FRIB Reach For Crust Processes

- Interesting set of reactions leading to proton-rich material converted to neutron-rich material



Haensel & Zdunik Astro Journ 1990, 2003, 2008
Gupta et al. Astro Journ 2006

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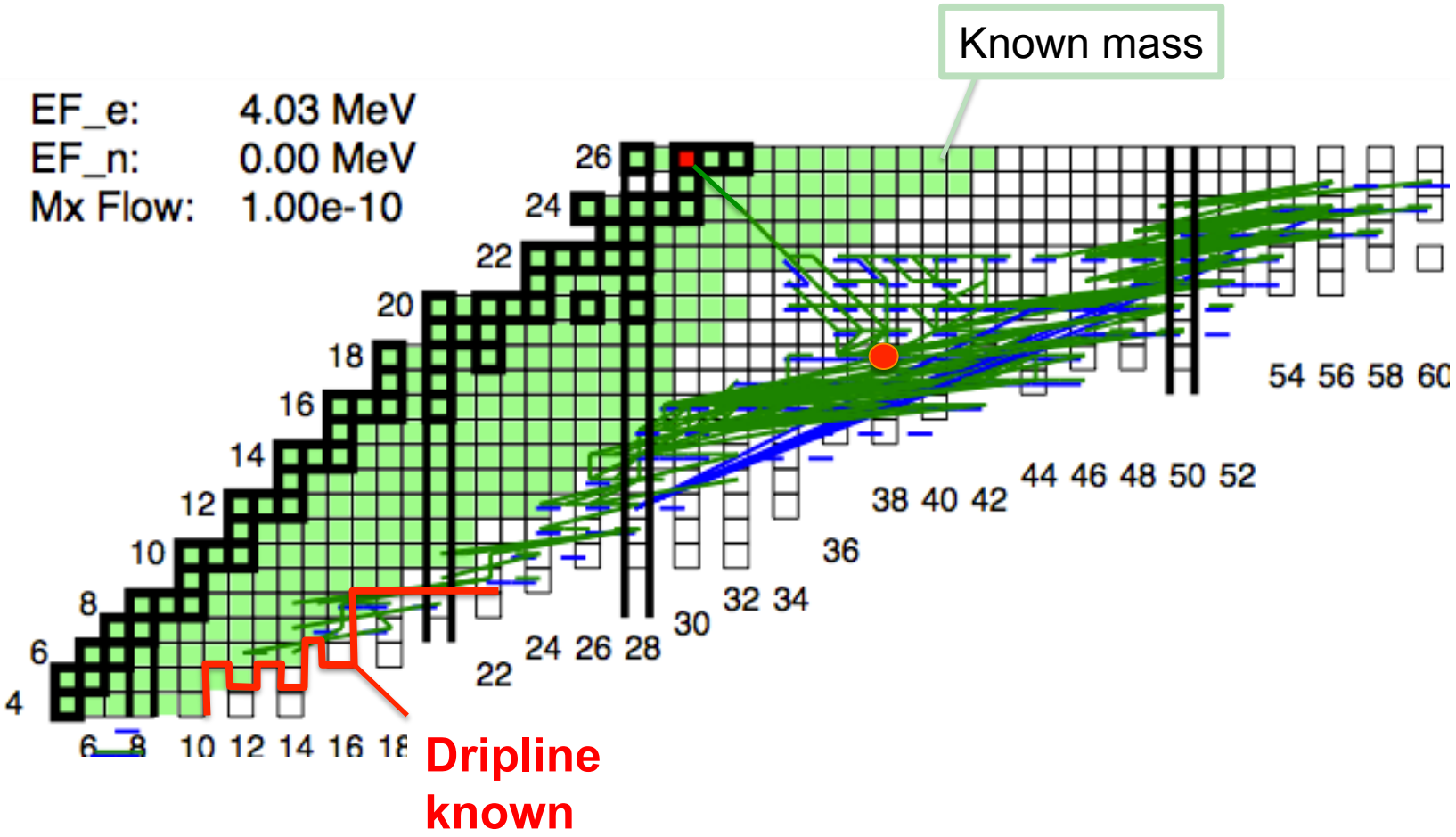
Where do Neutrons Drip?



K.-Y. Lau, M. Beard, P. Shternin, et al., to be published

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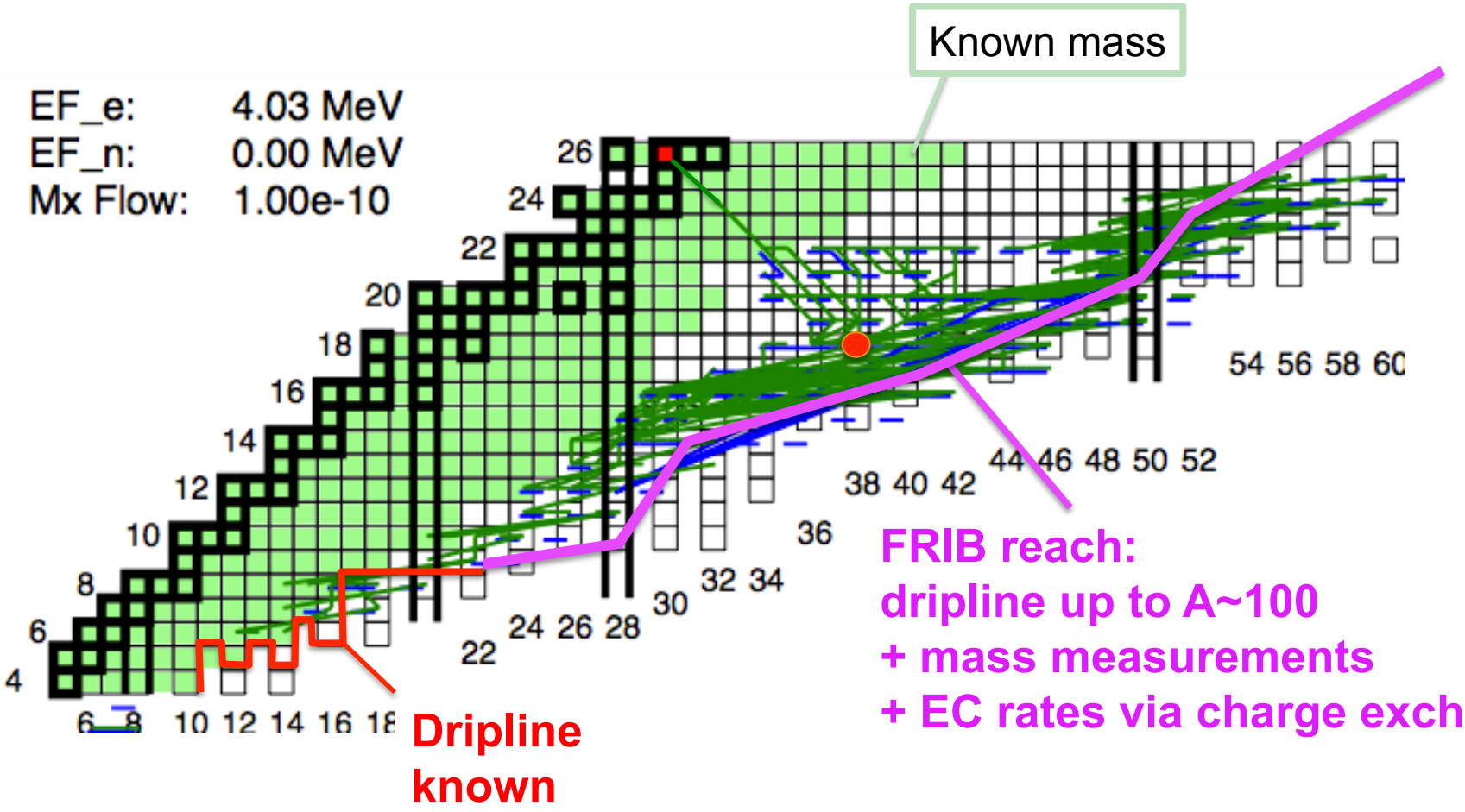

K.-Y. Lau, M. Beard, P. Shternin, et al., to be published

A Vision

"It is in my view that continued development and application of radioactive beam techniques could bring the most exciting results in laboratory astrophysics in the next decade"

Nobel Laureate Willy Fowler, 1984

Open Questions

- Where where the heavier elements made in nature?
- What is the history of our Sun?
- What were the first stars like? What does the abundance pattern in early stars tell us about the early Universe?
- What are the properties of neutron stars?

References

- General Nucleosynthesis - C. Iliadis, "Nuclear Physics of Stars", Wiley-VCH, 2007, ISBN 978-3-527-40602-9
- s-process - http://www.mpa-garching.mpg.de/lectures/ADSEM/WS0910_Goblirsch.pdf
- r-process – M. Arnould et al. Phys.Rept.450:97-213,2007
- Novae - http://www.jinaweb.org/events/SB05/Iliadis.pdf
- X-ray bursts – A. Cummings, http://www.phy.anl.gov/theory/ria06_pdf/cumming.pdf