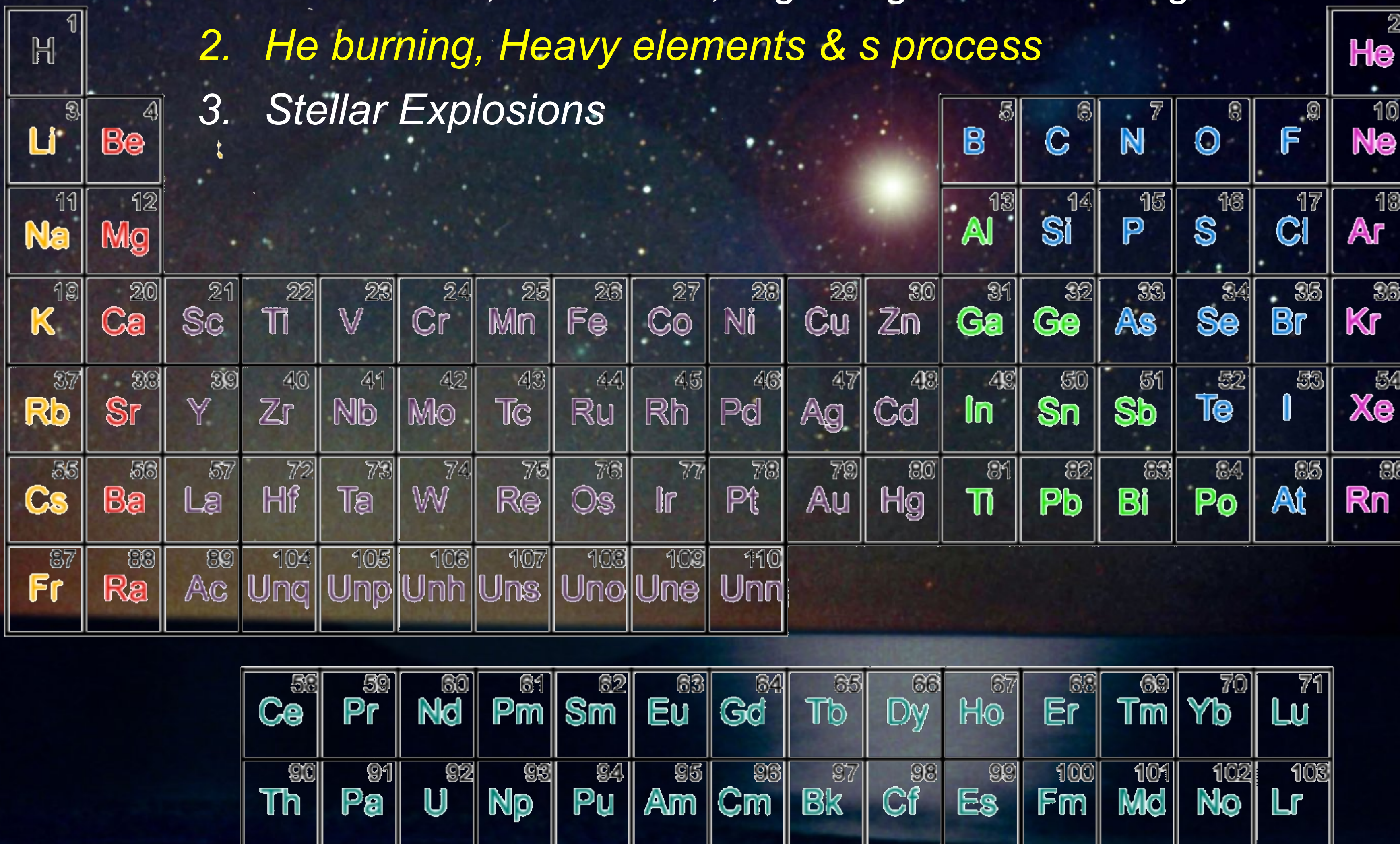
Nuclear Astrophysics

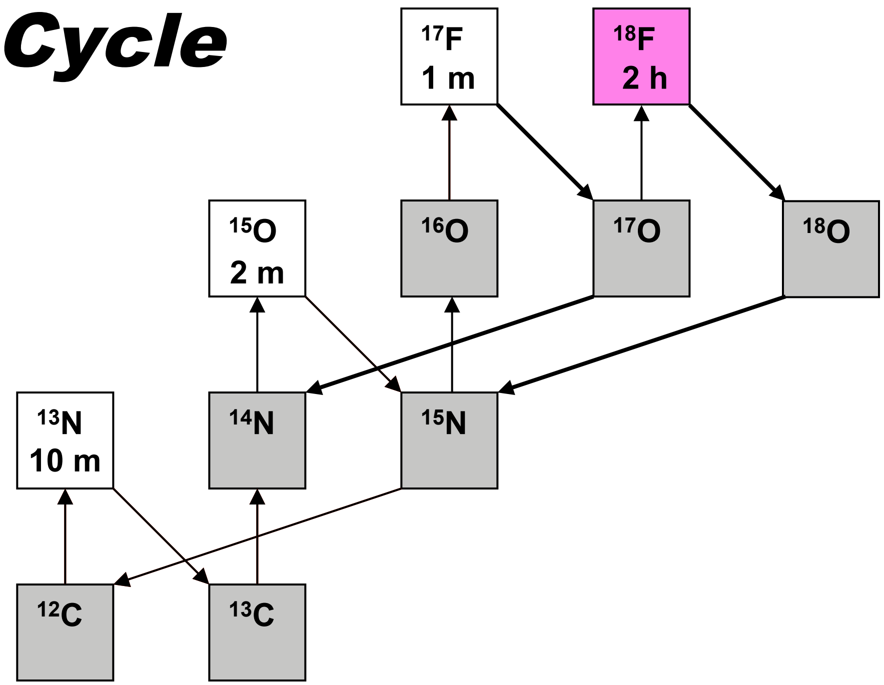
Jeff Blackmon (LSU)

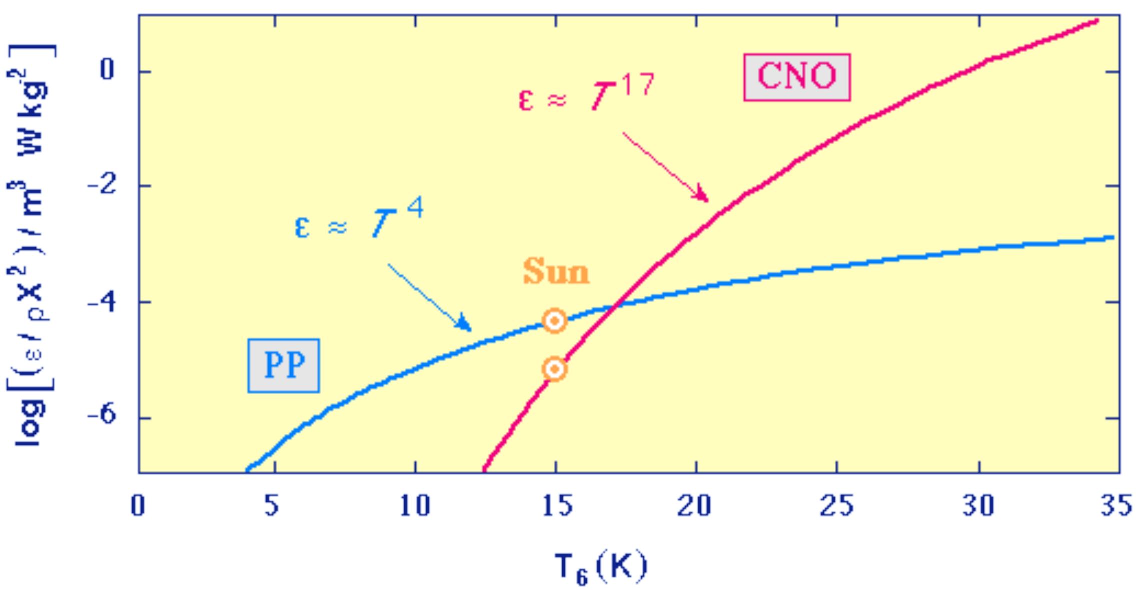
1. *Introduction, Formalism, Big Bang and H burning*
2. *He burning, Heavy elements & s process*
3. *Stellar Explosions*



CNO Cycle

- Dominant source of energy generation in stars heavier than the sun
- What is CNO contribution to energy production in the sun? Few% ?
- CNO abundances in sun uncertain
- Stellar photospheric metallicity disagrees with helioseismology

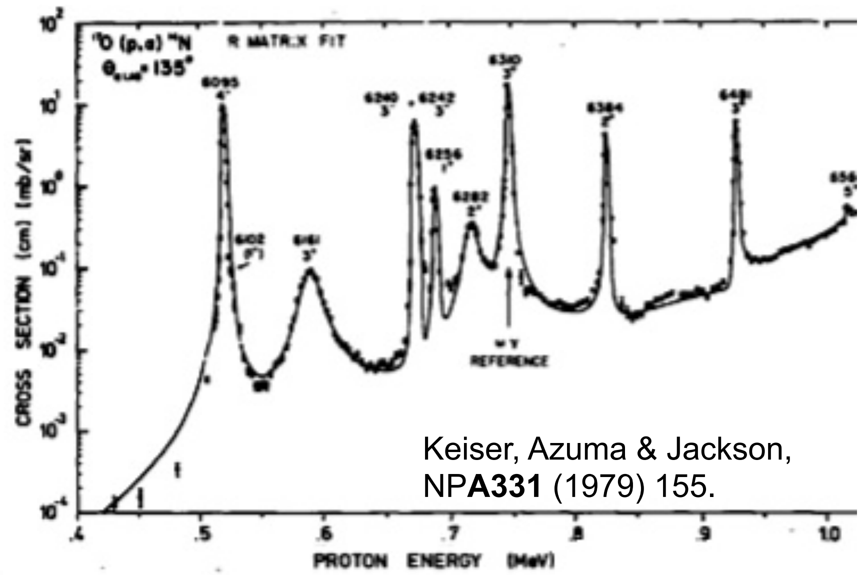




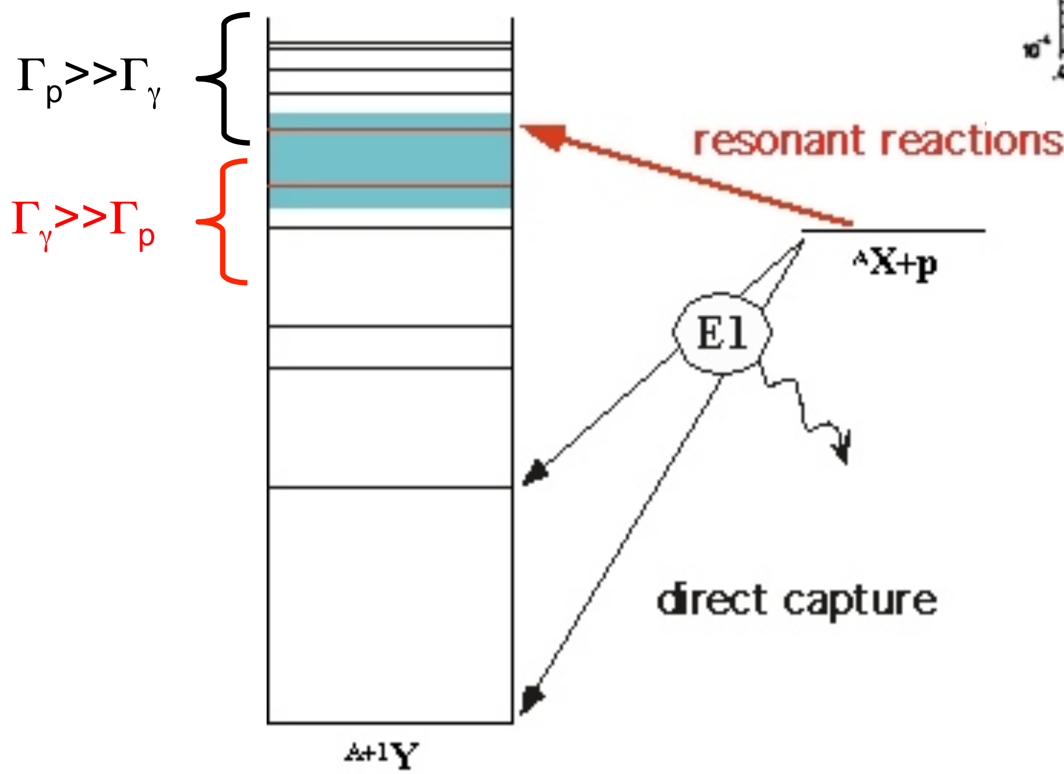
Resonances are important

$$\langle \sigma v \rangle = \sqrt{\frac{8}{\pi\mu}}(kT)^{3/2} \int_0^\infty \sigma E e^{-E/(kT)} dE$$

$$\sigma(E) = \pi \lambda\!\!\!^{-2} \frac{2J+1}{(2J_x+1)(2J_y+1)} \frac{\Gamma_x \Gamma_y}{(E-E_r)^2 + (\Gamma/2)^2}$$



Keiser, Azuma & Jackson, NP**A331** (1979) 155.



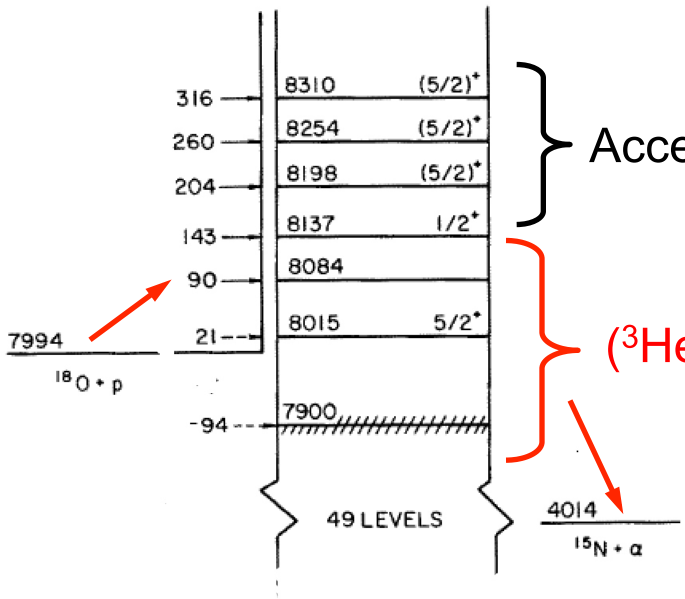
If resonance is narrow

$$\langle \sigma v \rangle = \left(\frac{2\pi}{\mu} kT\right)^{3/2} \hbar^2 (\omega\gamma) e^{-E_r/kT}$$

$$\omega\gamma = \frac{2J+1}{(2J_x+1)(2J_y+1)} \frac{\Gamma_x \Gamma_y}{\Gamma}$$

"resonance strength"

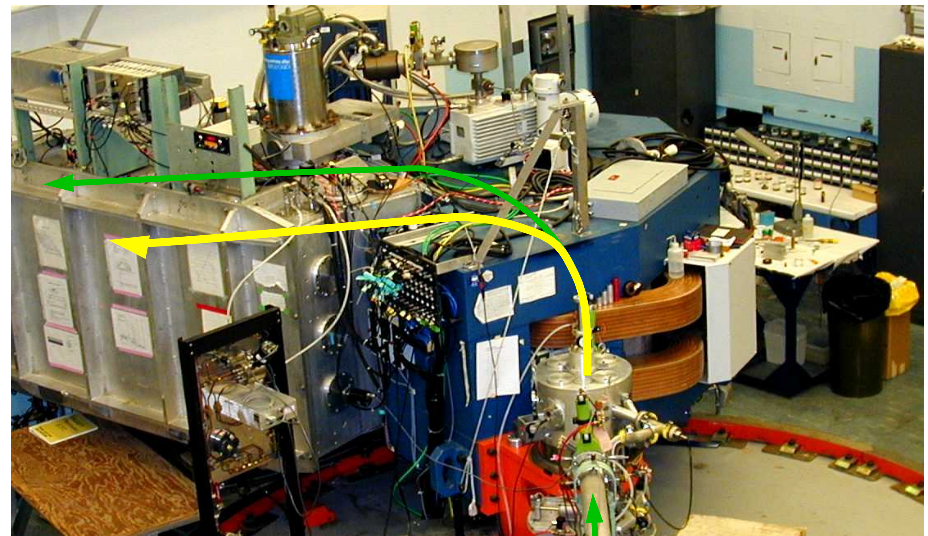
Example: $^{18}O(p,\alpha)^{15}N$



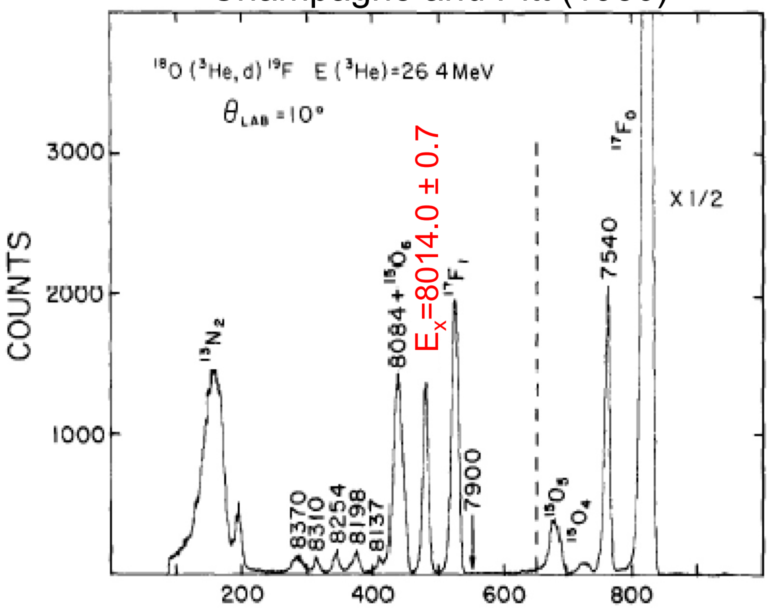
Accessible with high intensity proton beams

(^{3}He,d)

Magnetic Spectrograph

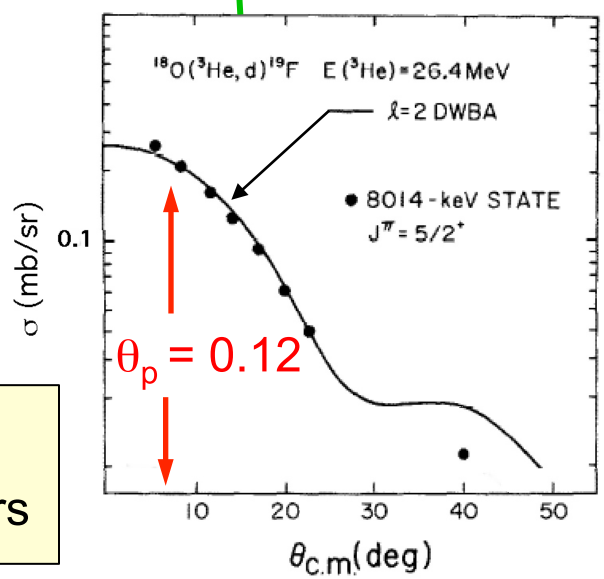


Champagne and Pitt (1986)



- Accurate E_x
- ℓ, J^{π} inferred

$$\Gamma_p = 2\left(\frac{\hbar^2}{\lambda \mu R}\right)\left(\frac{\theta_p^2}{F_\ell^2 + G_\ell^2}\right)$$

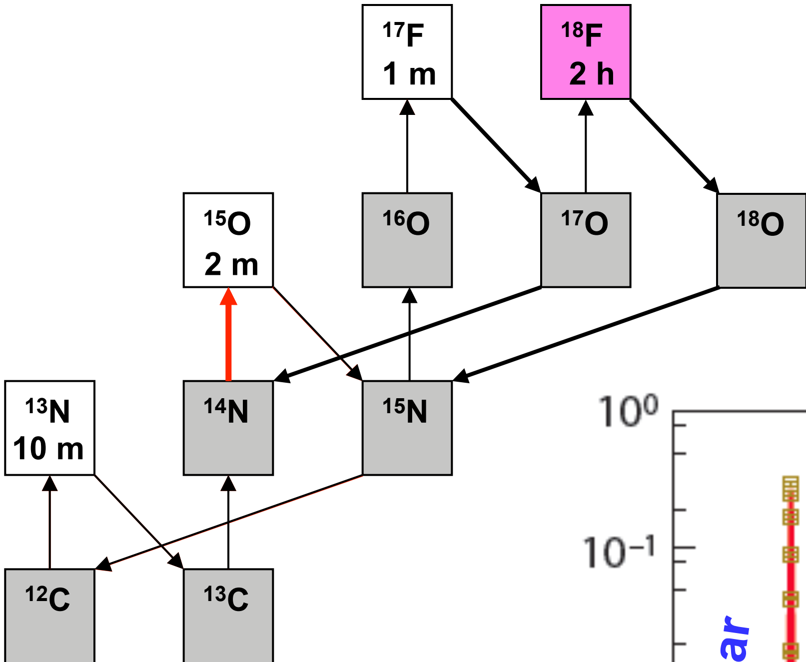


with 1 mA p + ^{18}O

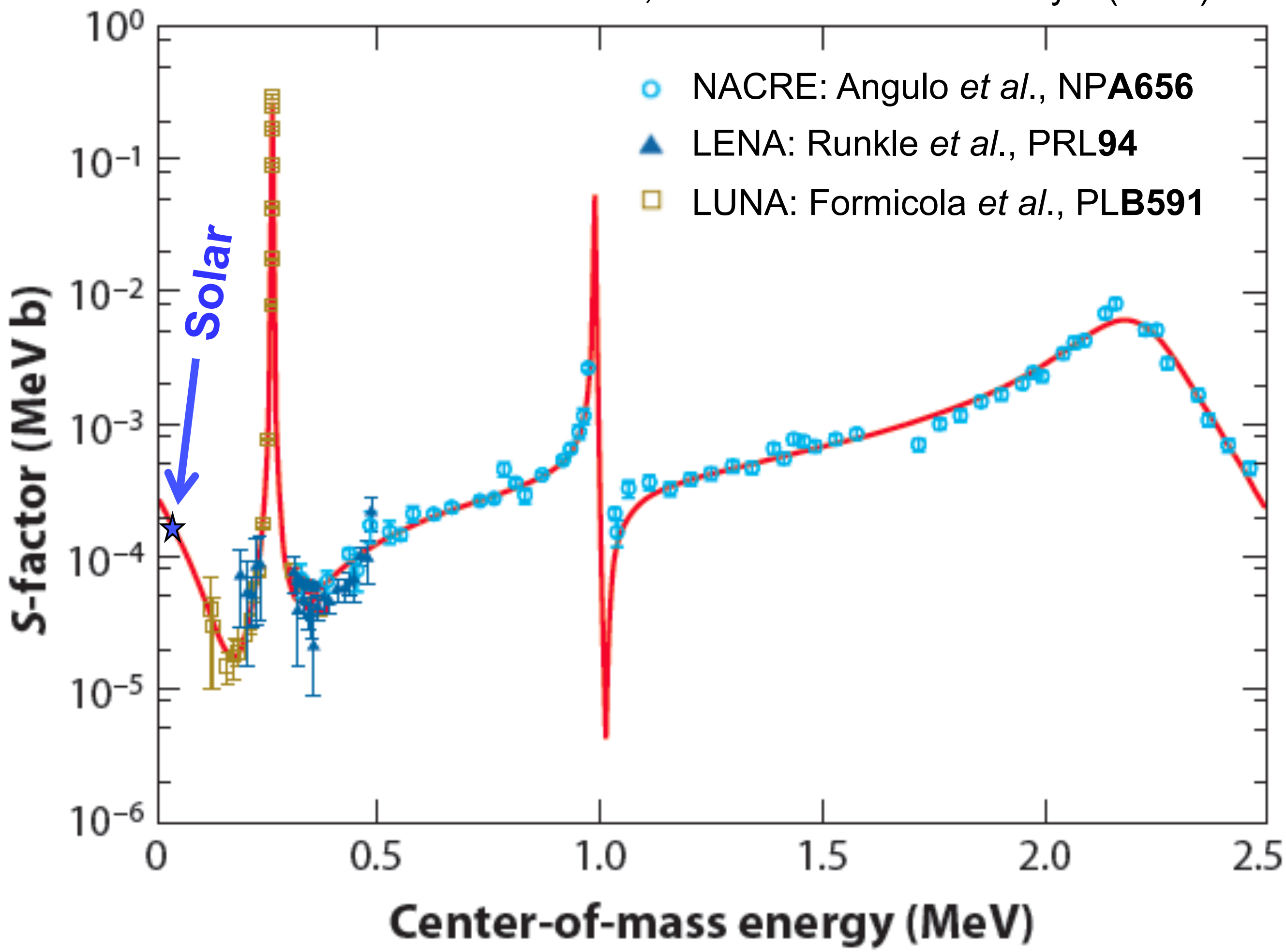
1 event / 3x10^{5} years

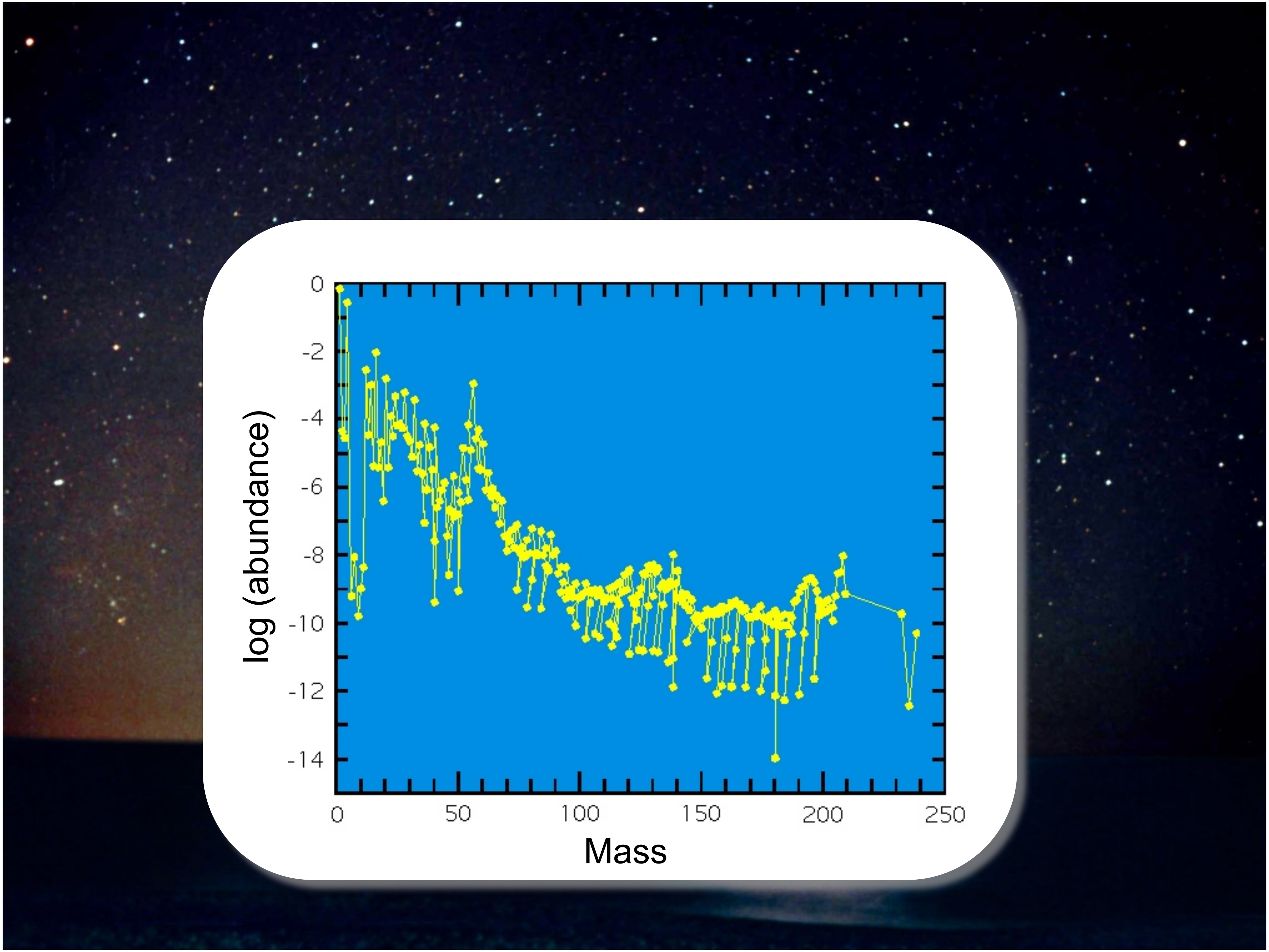
$^{14}N(p,\gamma)^{15}O$

- Slowest reaction in CN cycle
- Determines rate of energy generation and relative abundances



From Wiescher *et al*., Ann. Rev. Nucl. Part. Phys. (2010)





log (abundance)
Mass
0
-2
-4
-6
-8
-10
-12
-14
0
50
100
150
200
250

Can the sun synthesize heavier elements?

$^{4}He + p \rightarrow ?$

$^{4}He + {}^{4}He \rightarrow ?$

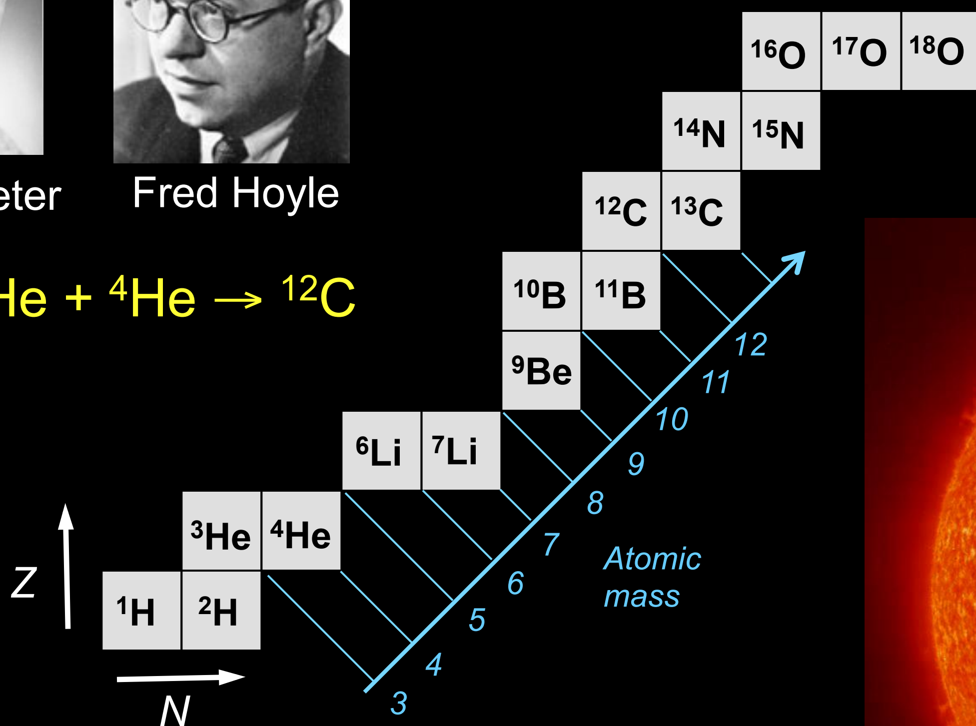
No atoms exist in nature with an A = 5 or 8

^{8}Be lifetime ~ 10^{-16} s

Edwin Salpeter

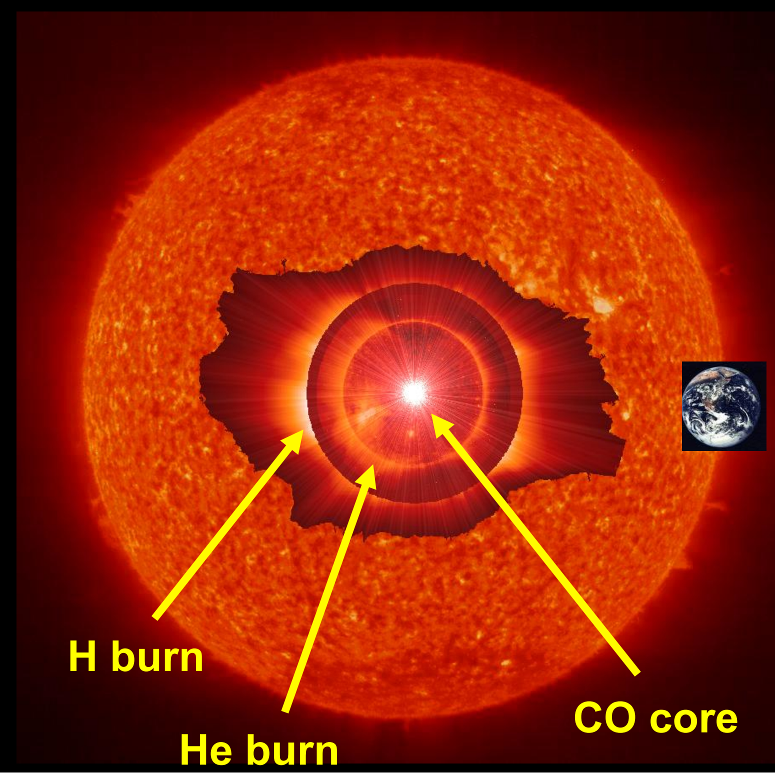
Fred Hoyle

$^{4}He + {}^{4}He + {}^{4}He \rightarrow {}^{12}C$



Only possible if ^{12}C has a very large resonance at perfect energy

Red Giant Star



He burning & the "Hoyle" state

$t_{1/2}(^{8}Be) = 9.7x10^{-17}$ s

$^{8}Be \leftrightarrows \alpha + \alpha$

$$\frac{N(^{8}B)}{N(\alpha)} \approx 5 \times 10^{-10}$$

0^+ resonance near the Gamow energy was predicted by Hoyle

Phys Rev 92 (1953) 1095.

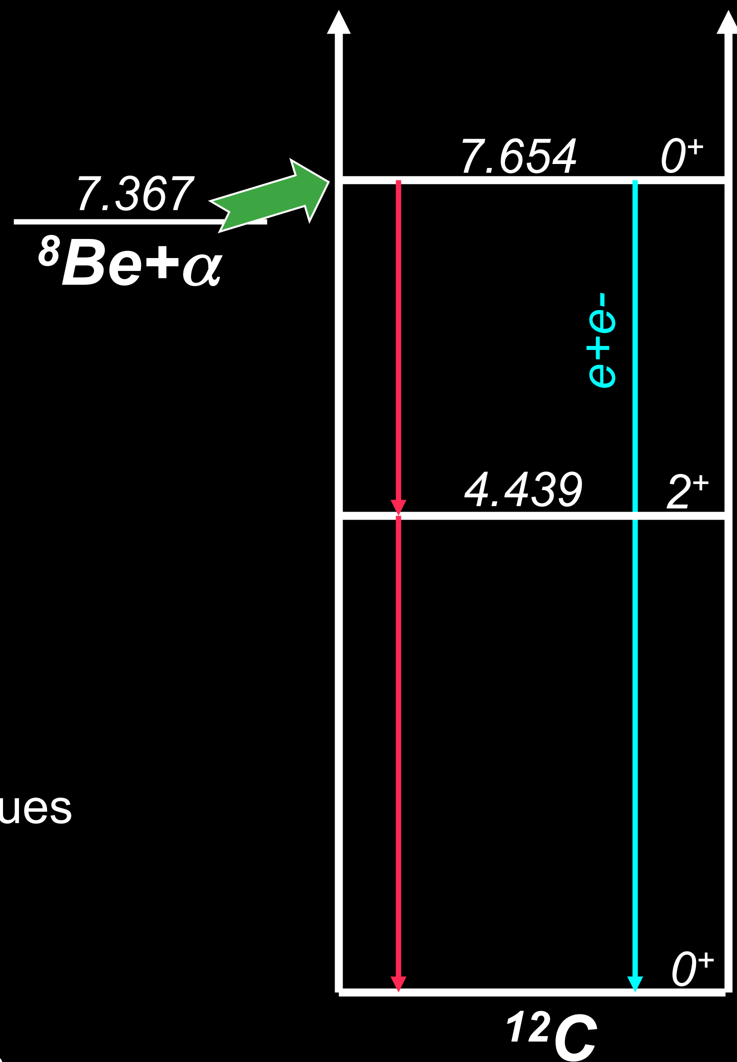
Numerous complementary techniques

$^{12}C(p,p')^{12}C^*$

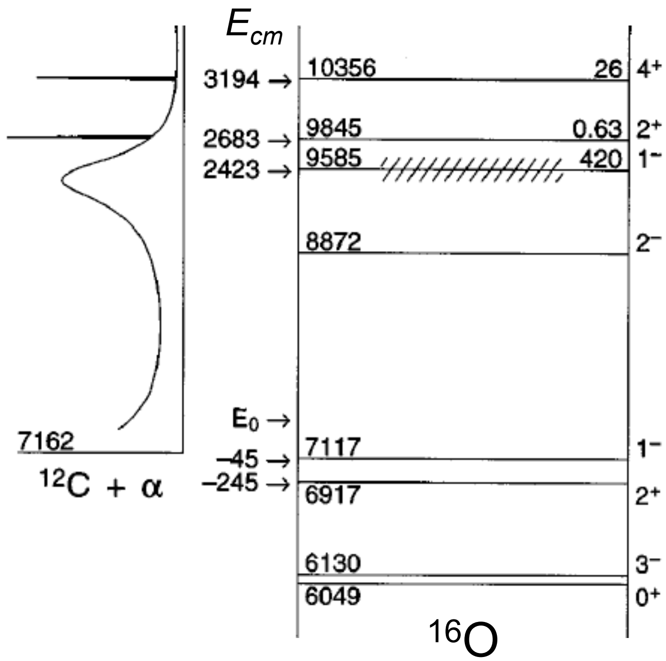
$^{13}C(^{3}He,\alpha)^{12}C^*$

→ $\gamma\gamma$, 3α, e^+e^-

Largest uncertainty Γ_{ee}~12%



$^{12}C(\alpha,\gamma)^{16}O$

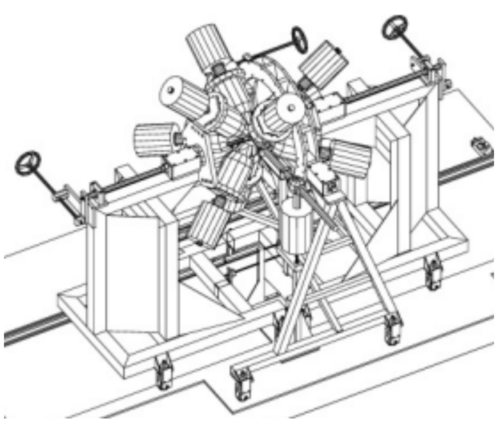


- The $^{12}C(\alpha,\gamma)^{16}O$ reaction rate fixes ratio of $^{12}C/^{16}O$ following helium burning
  ➨ Abundance ratio of $^{12}C/^{16}O$
- The $^{12}C/^{16}O$ ratio governs subsequent evolution of the star:
  ➨ Size of Fe core & supernova dynamics

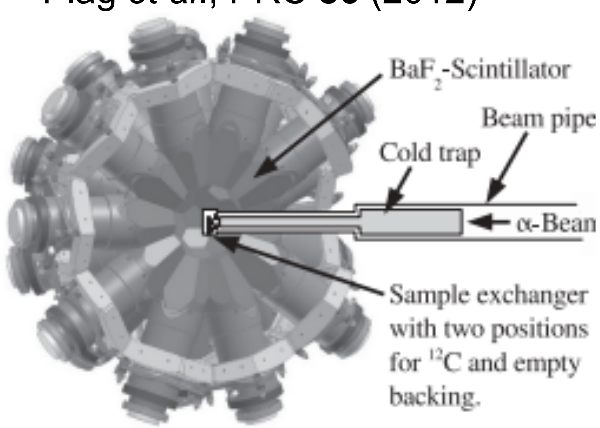
Subthreshold states influence → uncertain interference with other states

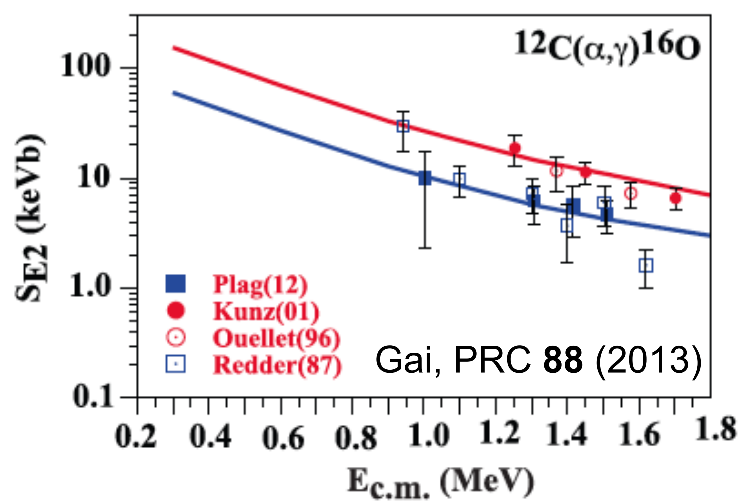
- Contribution of both E1 and E2 contributions are important → need to measure angular distributions

Stuttgart: Eurogam (HPGe)
Assuncão *et al.*, PRC **73** (2006)



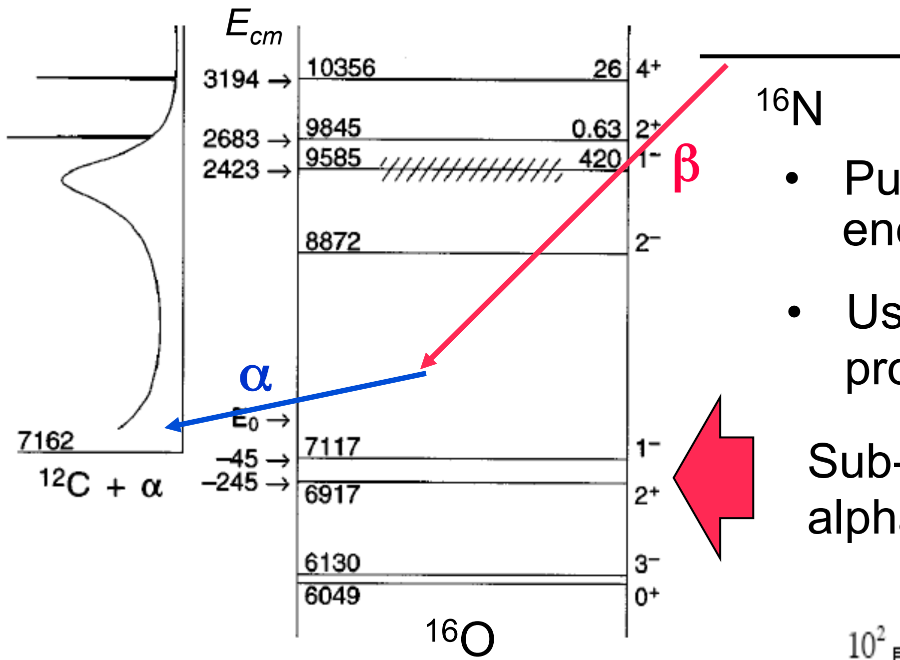
Karlsruhe: BaF_2
Plag *et al.*, PRC **86** (2012)





Gai, PRC **88** (2013)

$^{12}C(\alpha,\gamma)^{16}O$

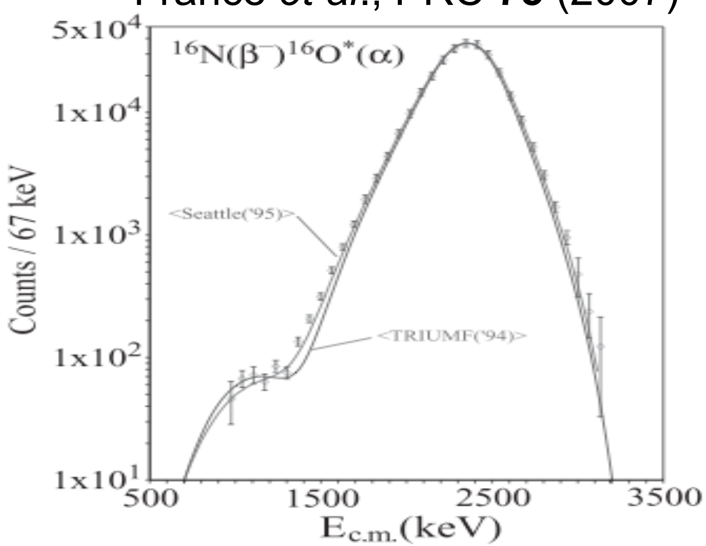


Inverse reaction studied from ^{16}N beta-delayed alpha emission

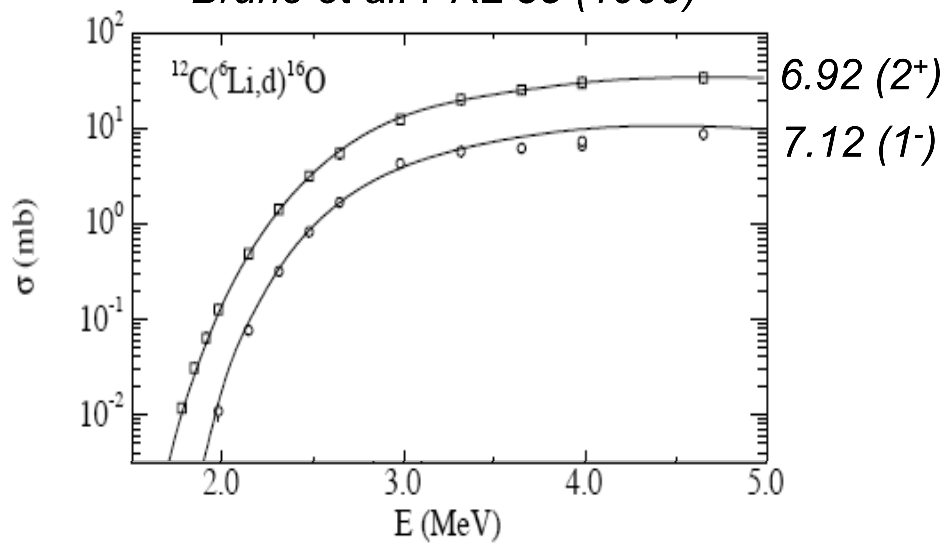
- Pushing direct measurements to lower energies is crucial but challenging
- Use indirect techinques to study properties of subthreshold states

Sub-Coulomb alpha transfer determines alpha-like part of asymptotic wavefunction

France *et al*., PRC **75** (2007)



Brune et al. PRL ***83*** *(1999)*



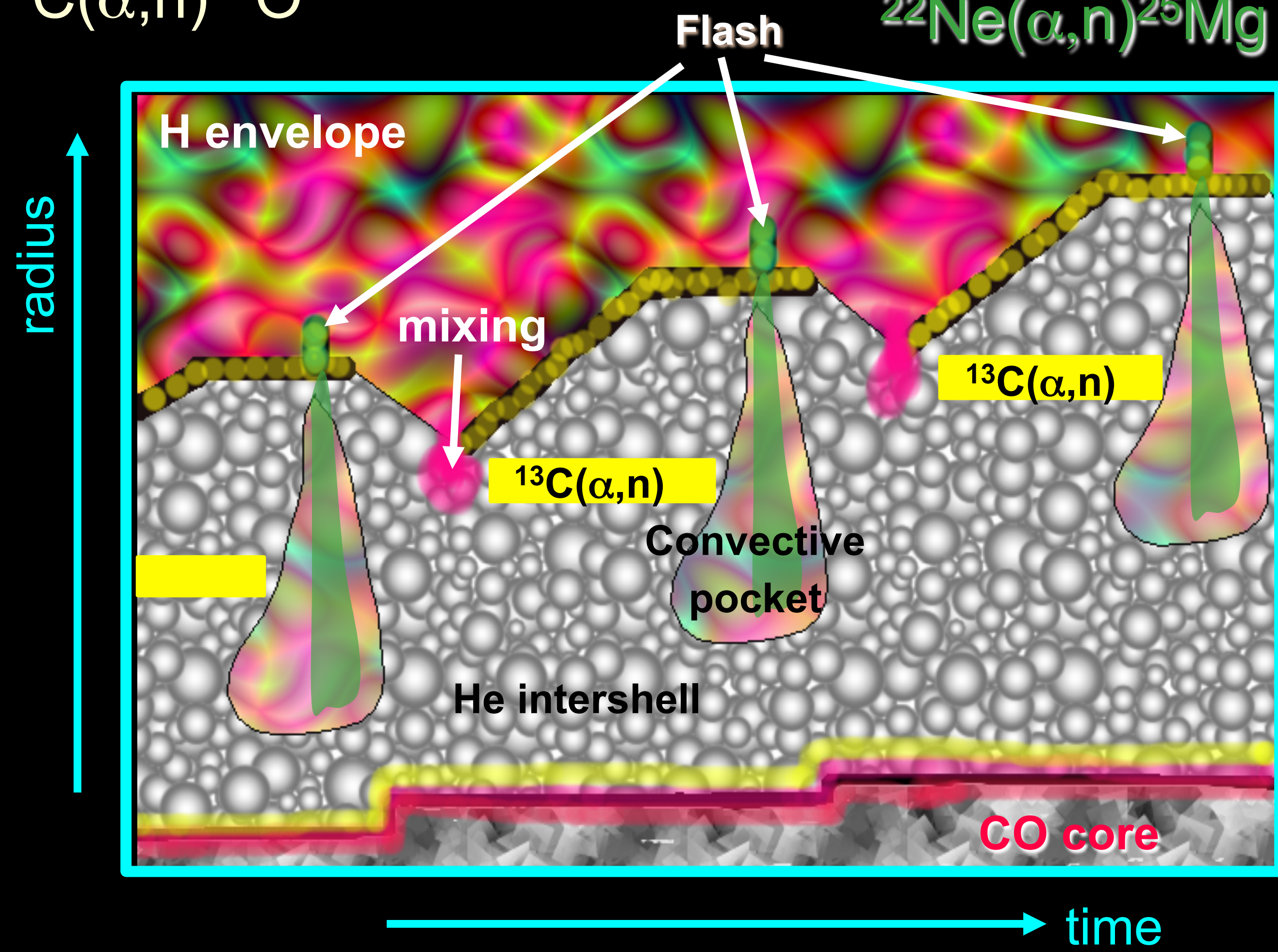
$$S_{E2}(300keV) = 40 \pm 20 keV \cdot b$$

AGB Stars – Fate for $M < 8\ M_\odot$

Thermally unstable: mixing, convection, mass loss → nebulae

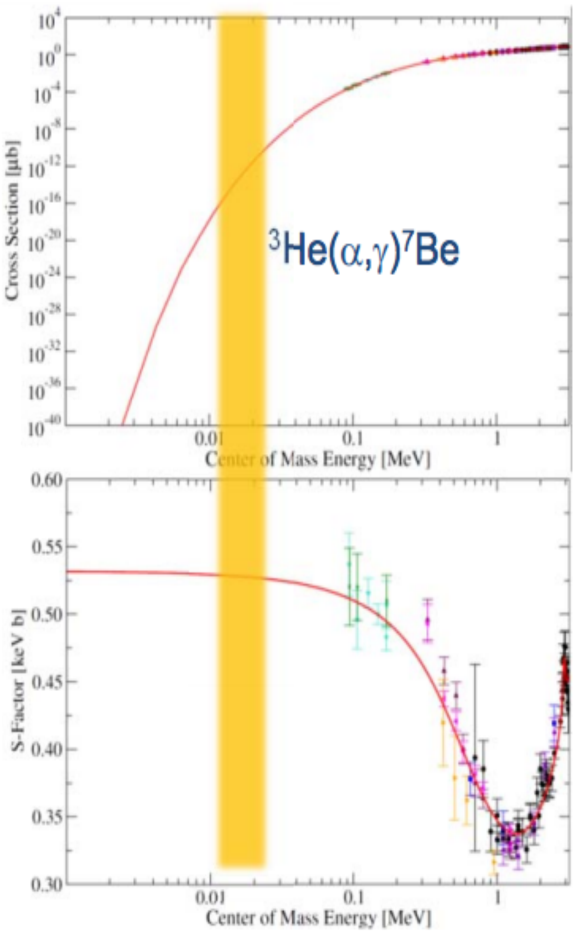
$^{12}C(p,\gamma)^{13}N(\beta\nu)^{13}C(\alpha,n)^{16}O$

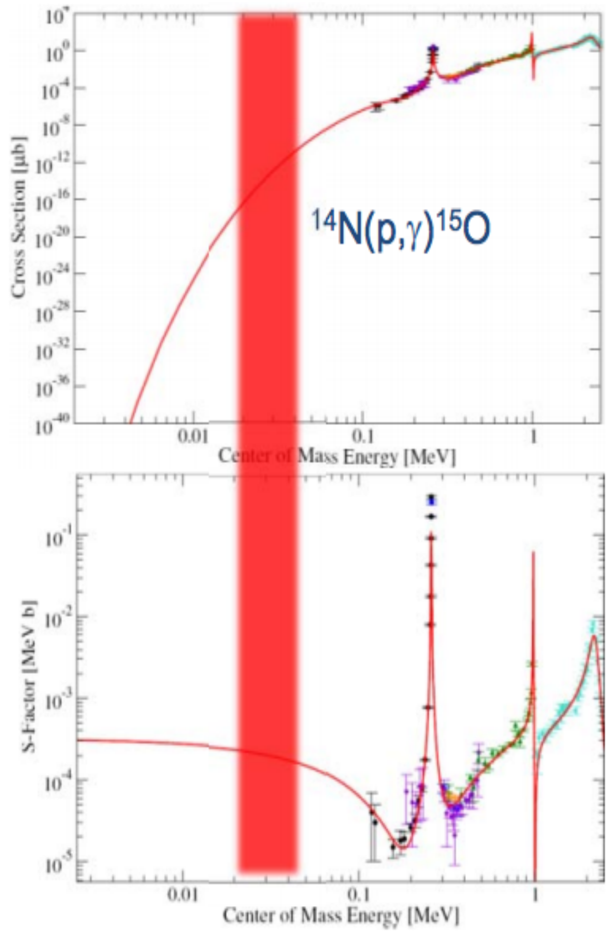
Neutrons drive synthesis of heavy elements

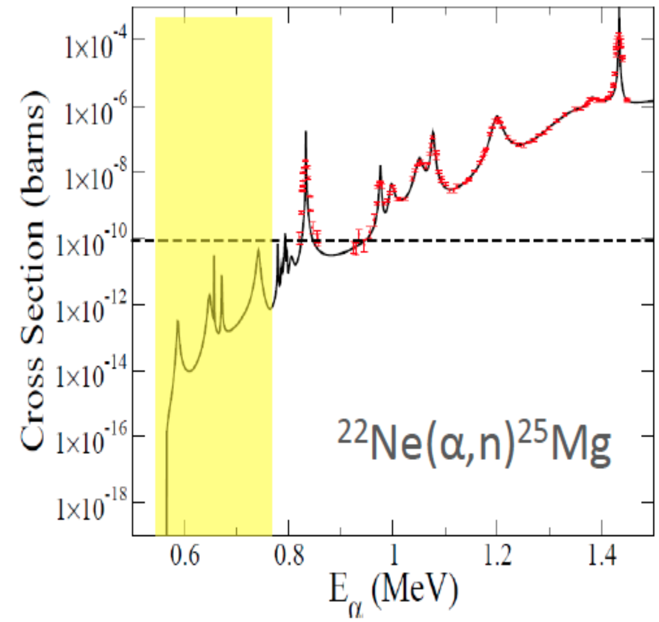


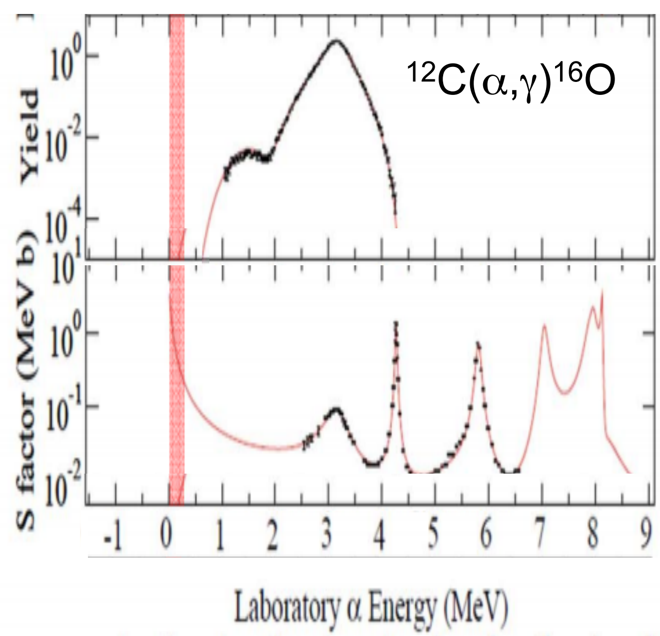
CO core remnant (white dwarf)

Challenging measurements at lower energies needed to understand important reaction rates

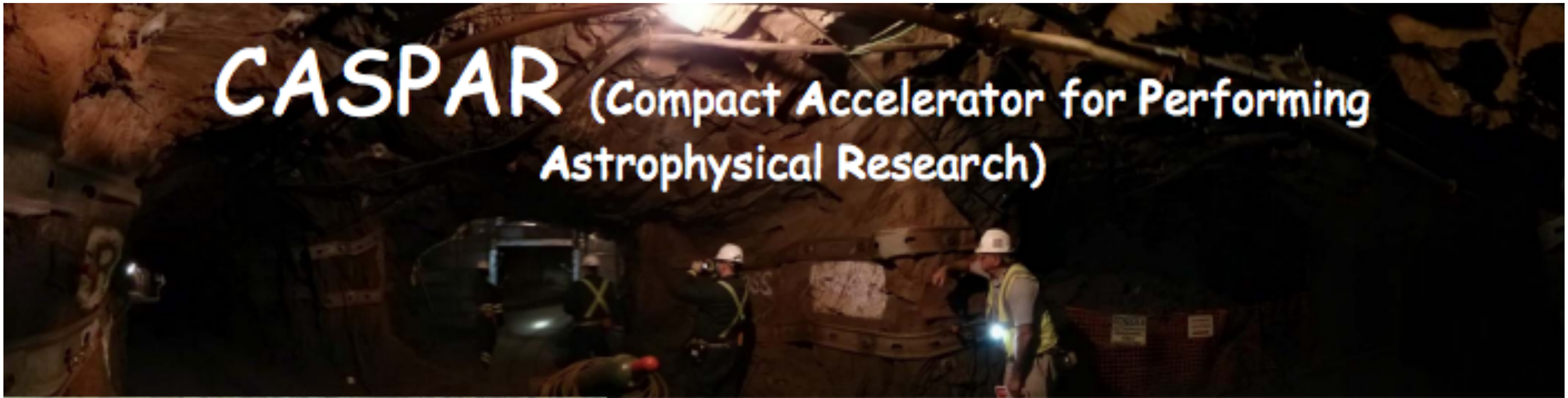


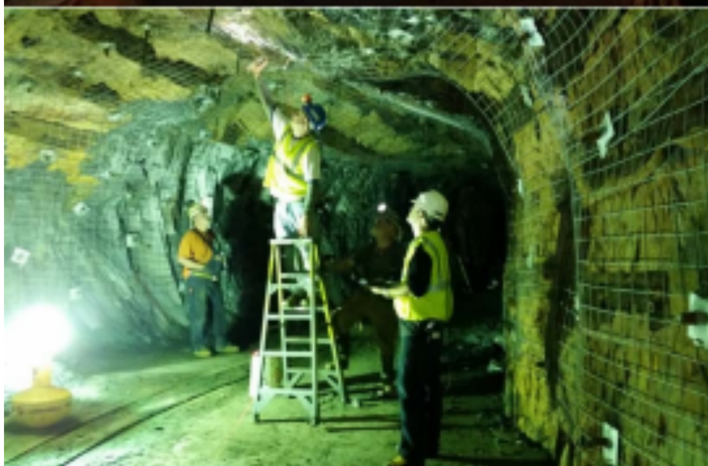






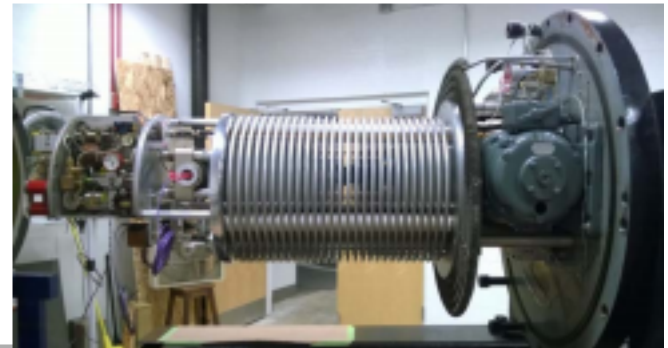
CASPAR (Compact Accelerator for Performing Astrophysical Research)

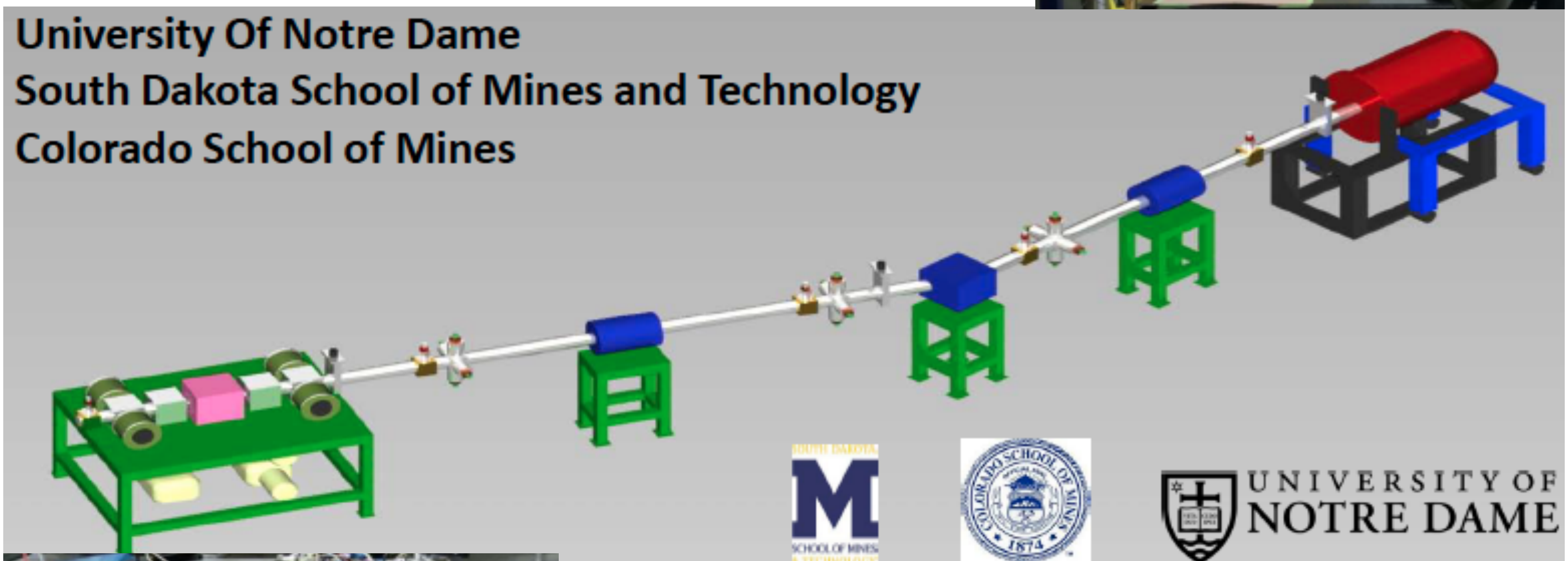




Sanford Underground Facility
in Homestake Mine, South Dakota

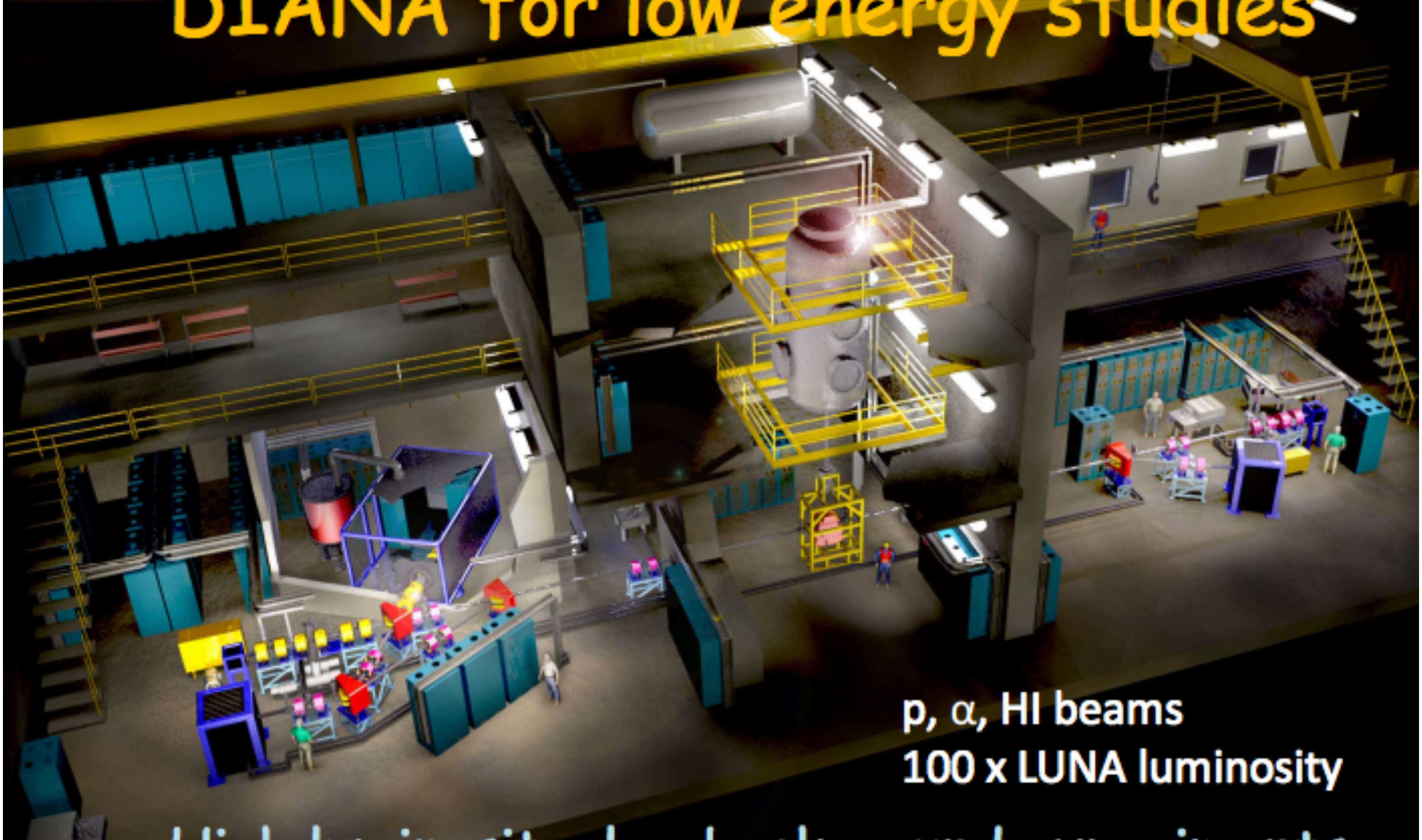
High current JN accelerator





Windowless gas target

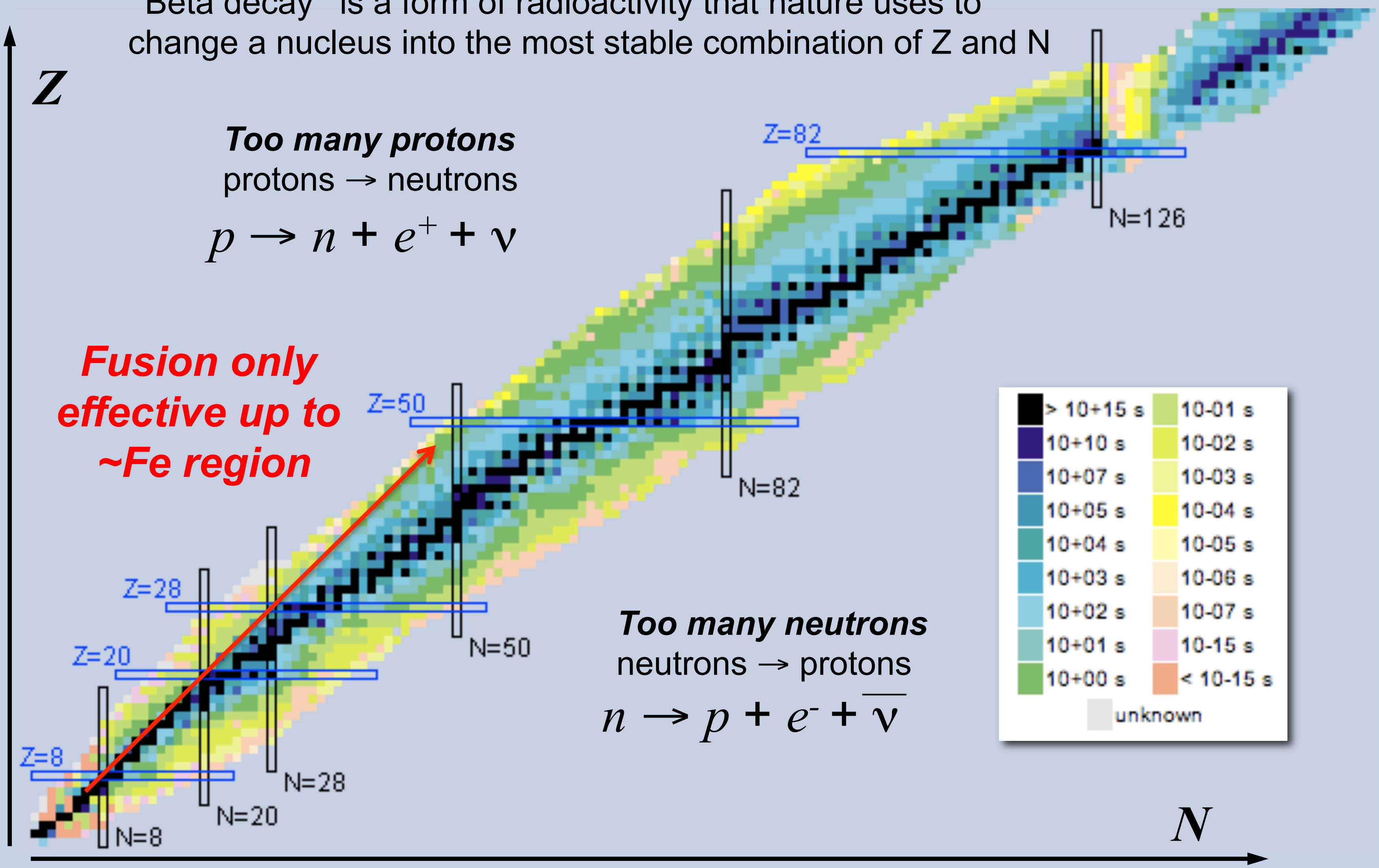
Underground accelerator project DIANA for low energy studies



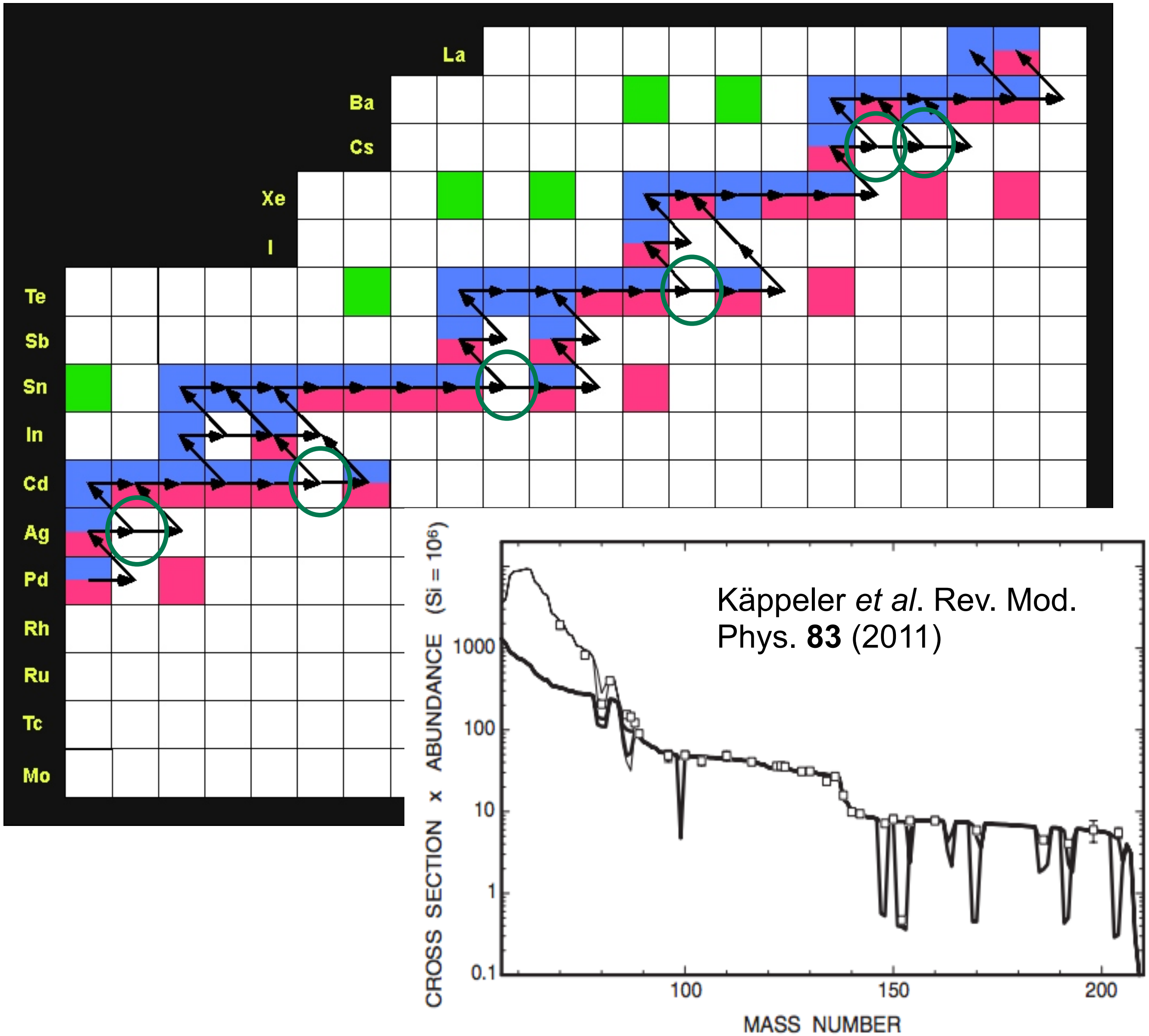
High luminosity, low background experiments

Generally only one combination of protons and neutrons is stable for each A (smallest mass)

"Beta decay" is a form of radioactivity that nature uses to change a nucleus into the most stable combination of Z and N



Slow neutron capture (s) process



- s process
  - Produces about half of matter that is heavier than iron
  - Series of slow neutron captures
  - Pattern of isotopes produced is generally well understood
  - Most σ' s measured

(n,γ) cross sections for the s process

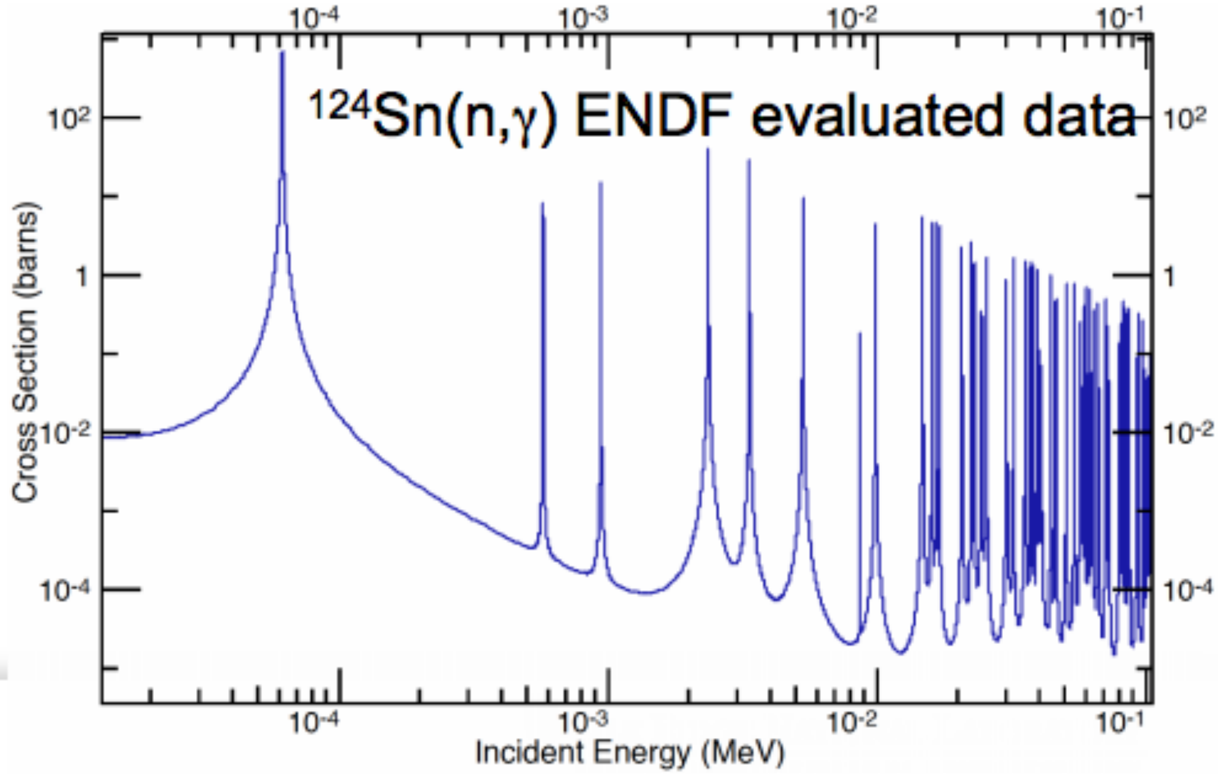
Good data on most stable isotopes

Spallation n sources

TOF techniques

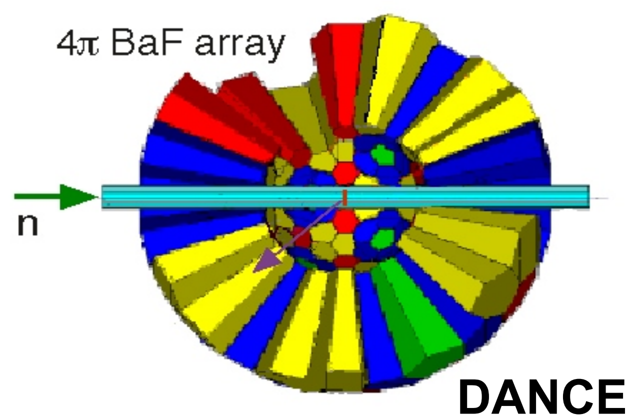
Good energy resolution

Usually high level densities



Some outstanding issues

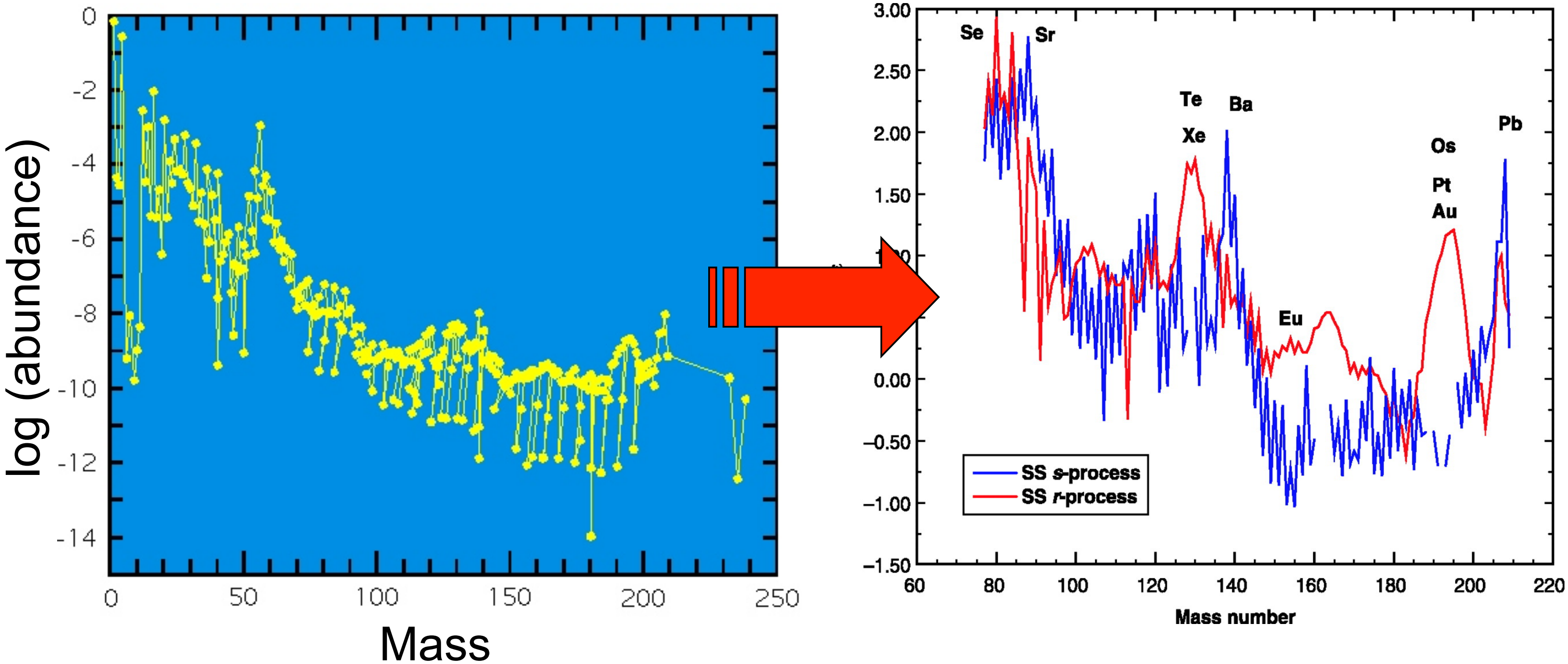
- Influence of low-energy levels at low temp
- Direct capture near closed shells
- Effect of thermal excitations in stellar environmen
- Branch point isotopes
- Lighter elements – “weak s process”



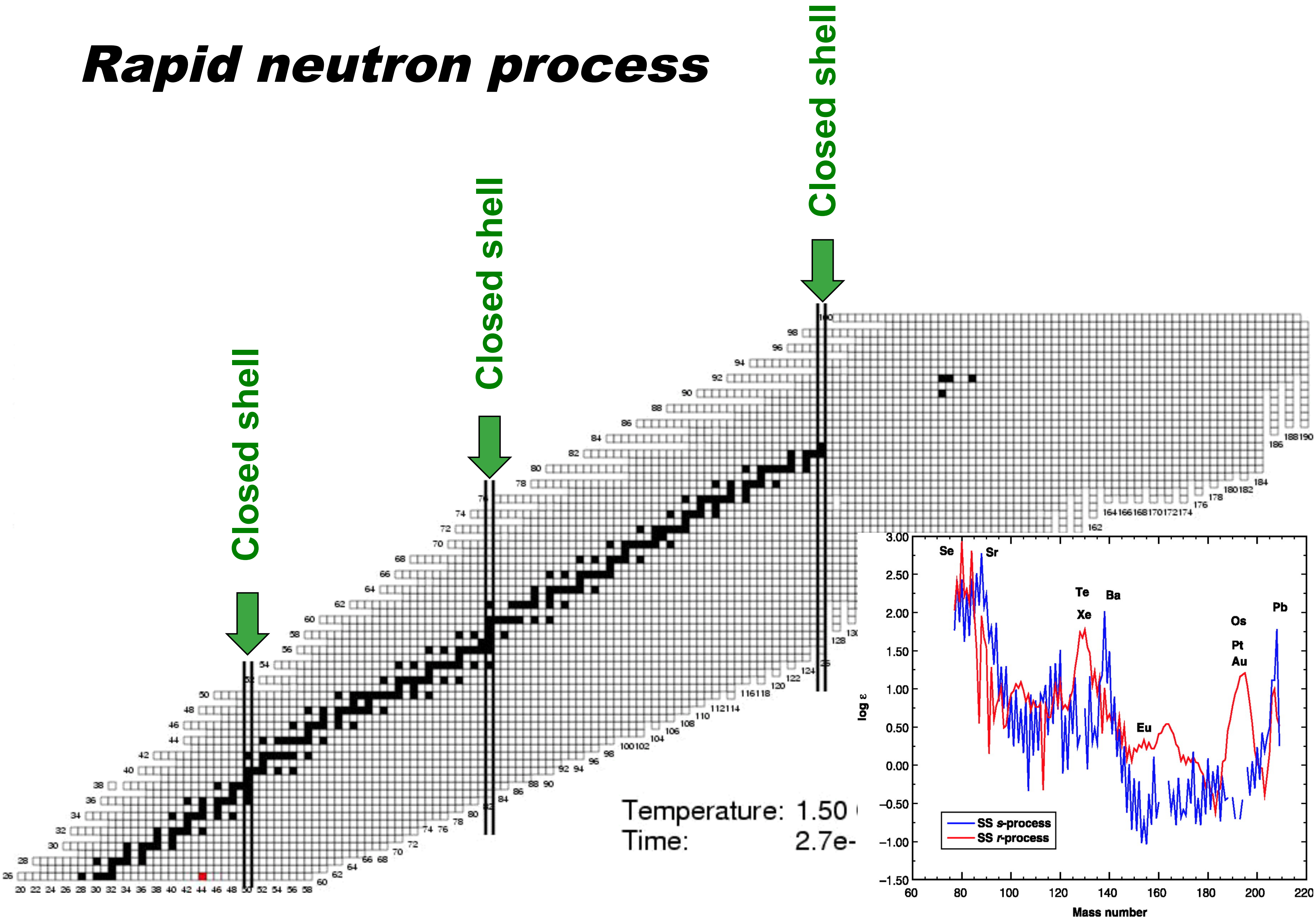
What can AGB stars produce?

Relative abundances of s process isotopes well understood

Subtract s abundances from solar system to get remainder

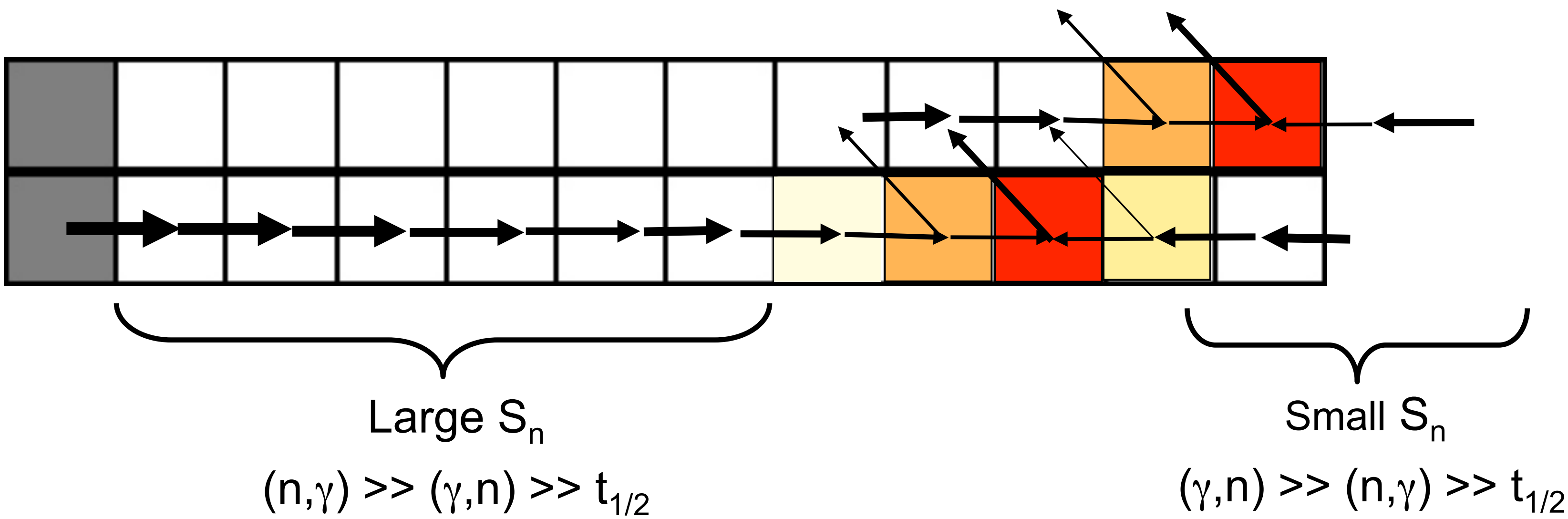


Rapid neutron process



Cartoon r process

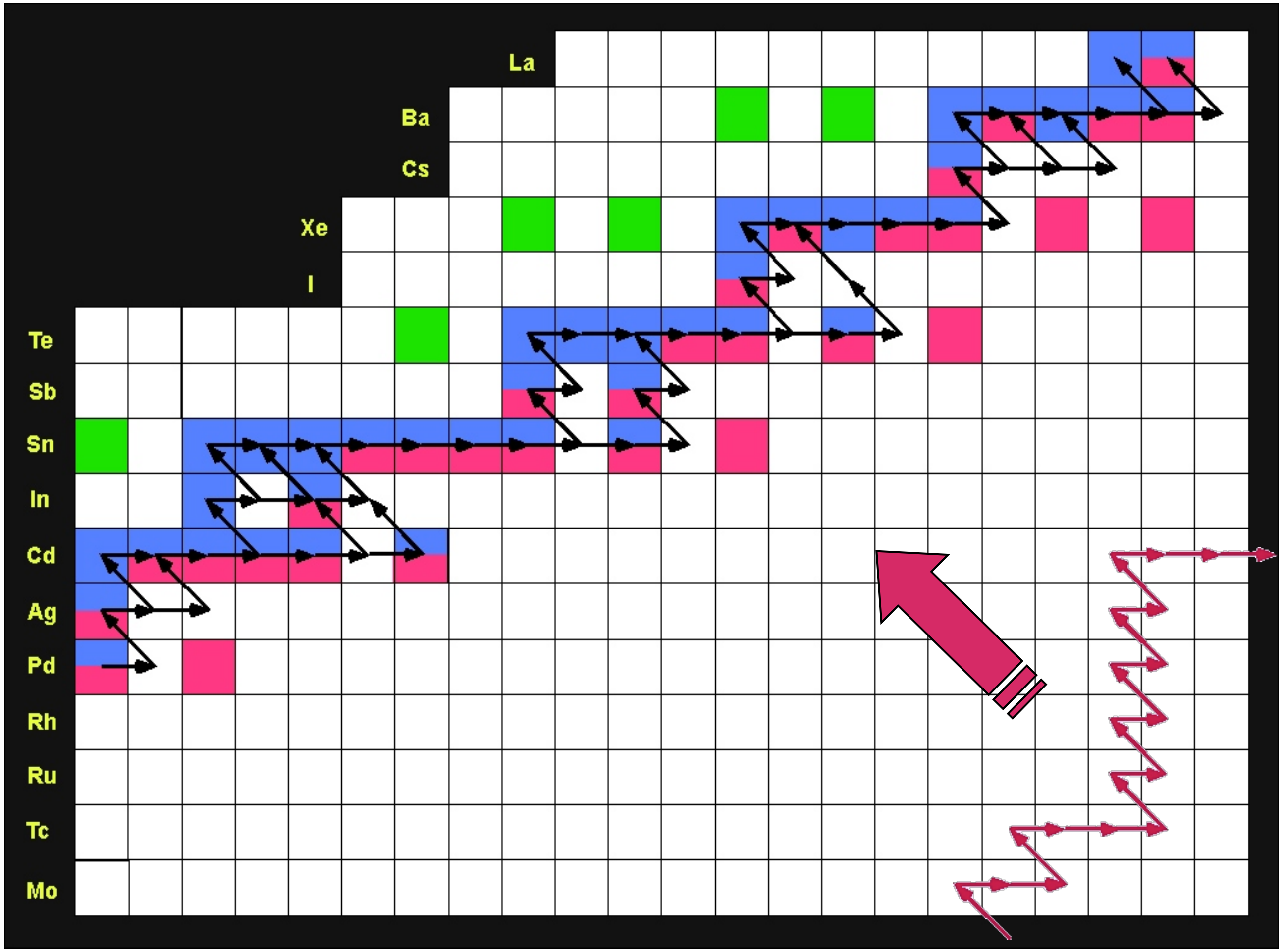
$$\frac{Y(A+1)}{Y(A)} \approx \frac{1}{2}\left(\frac{2\pi\hbar^2}{m_u kT}\right) n_n e^{S_n/(kT)}$$



- Free parameters n_n, kT, t
- freezeout relatively fast & decay back to stability

➡ **Most important: masses, $t_{1/2}$, and P_n**

Synthesis of heavy elements

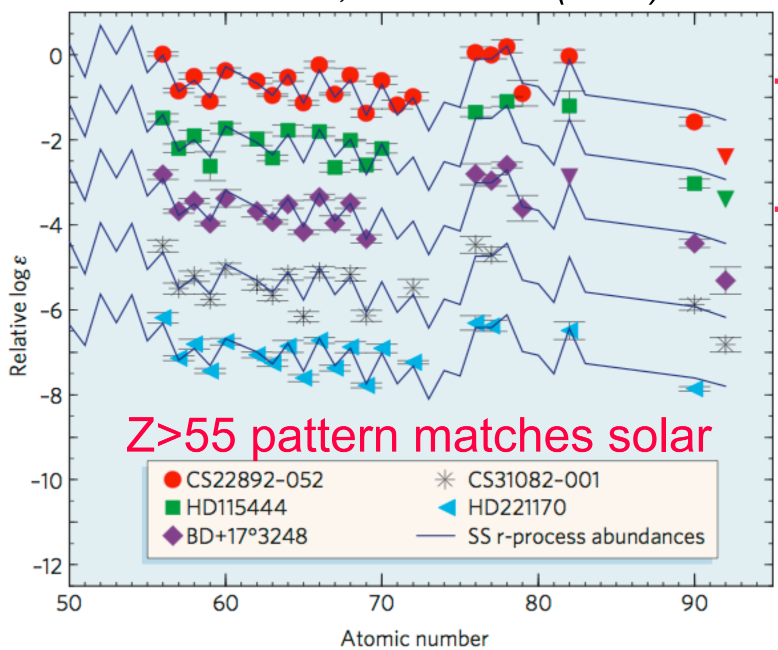


- s process
- r process
  - Produces about half of matter heavier than iron
  - High neutron flux
  - Reactions on unstable isotopes
  - Site unknown

r process in the early Galaxy

New observations of unmixed abundances early in the Galactic halo

Cowan & Sneden, Nature ***440*** *(2006) 1151.*



CS22892-052

Fe/H = (8x10^{-4}) solar = very old

r/Fe = 50 solar

Only 2 known in 2000

Now extensive surveys

e.g. see Frebel et al., ApJ ***652*** *(2006) 1585*

SEGUE (Sloan DSS)

Spectra of >2x10^{5} selected halo stars

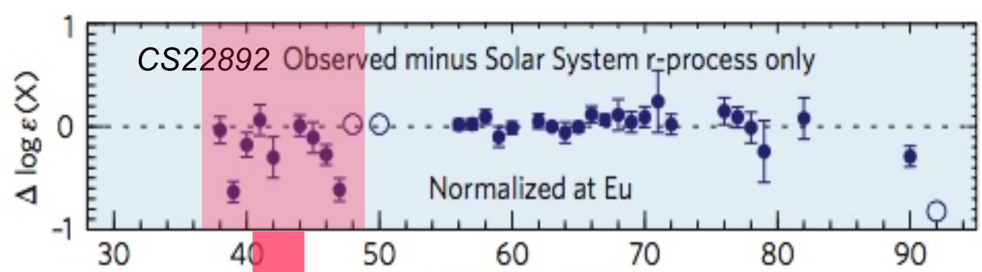
Expect ~ 1% with Fe/H < 0.001solar

~36 known r process stars

11 with r/Fe > 10 solar

Distribution Fe/H puzzling

Lowest Fe/H stars intriguing



(C&S, Nature ***440****)*

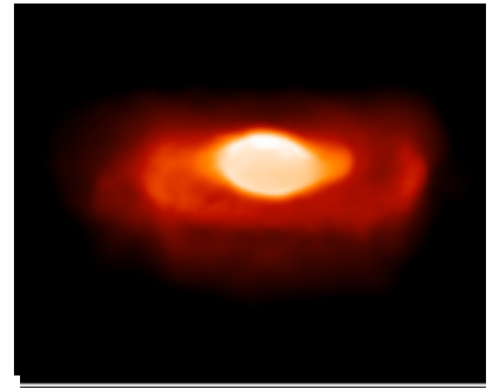
Z<50 abundances vary

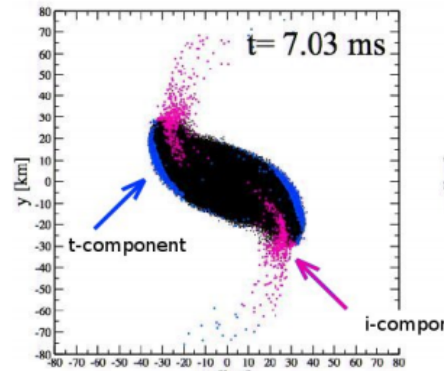
An additional process (besides r/s) must contribute significantly to elements from Fe-Sn

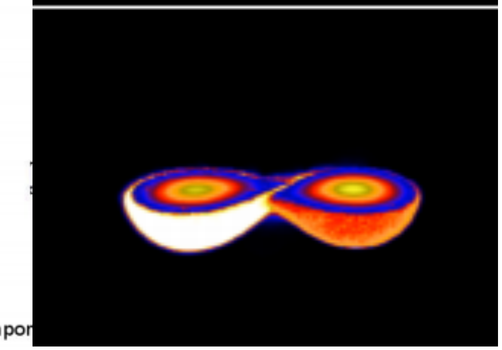
r process, where?

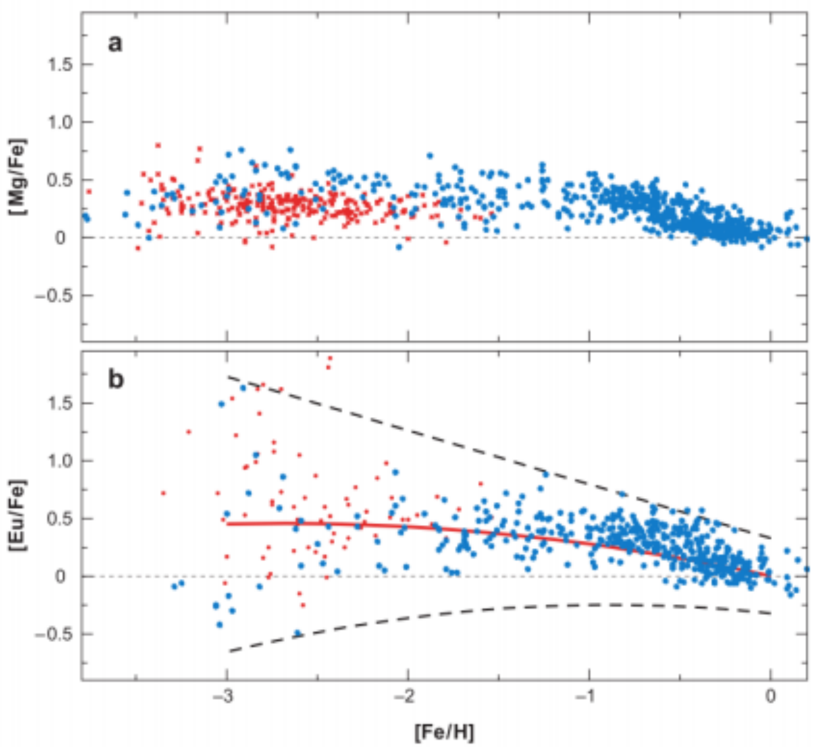
Neutron star mergers?

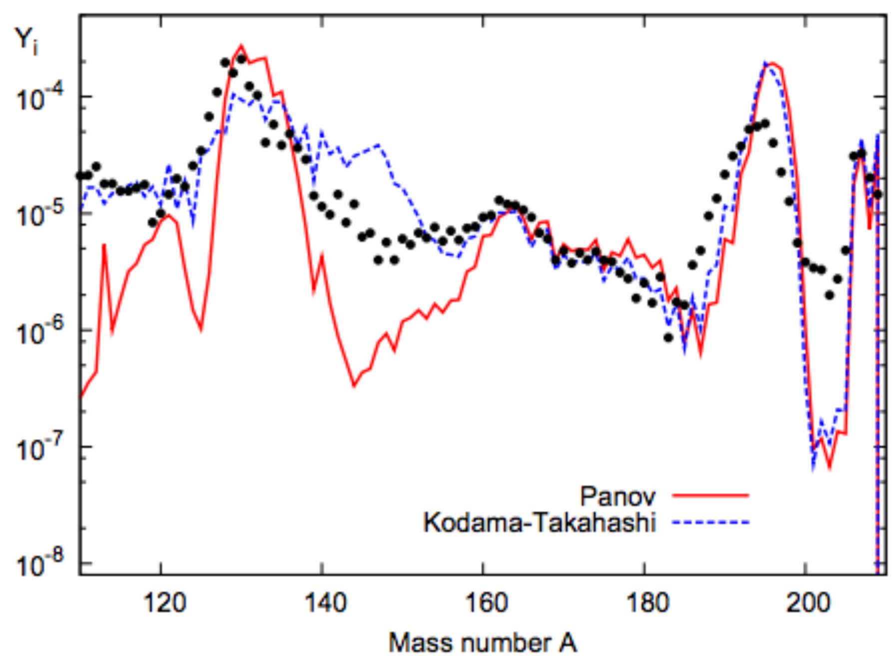
- 10 systems known in our Galaxy
- Believed to be origin of gamma-ray bursts
- Potentially explains dispersion in Eu
- High output in rare event
- Calculations produce a robust r process
- Huge uncertainties due to nuclear data



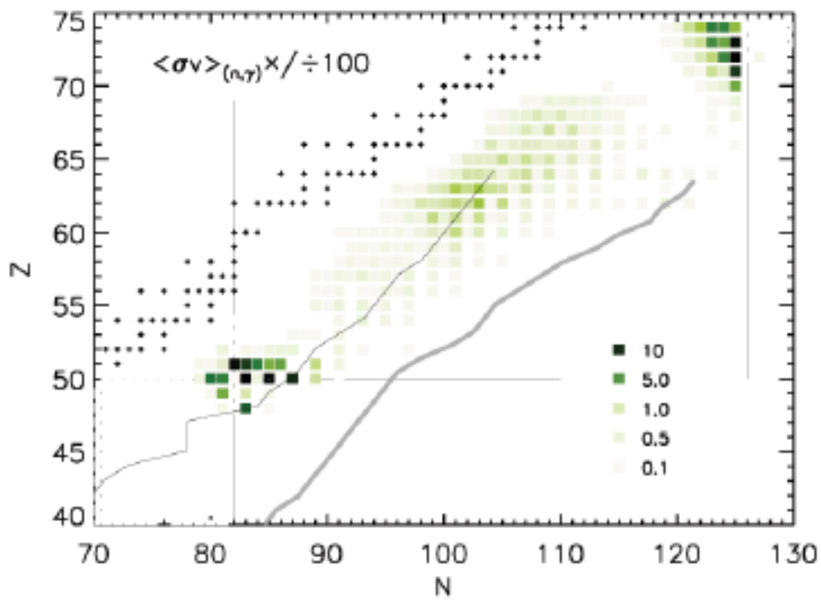


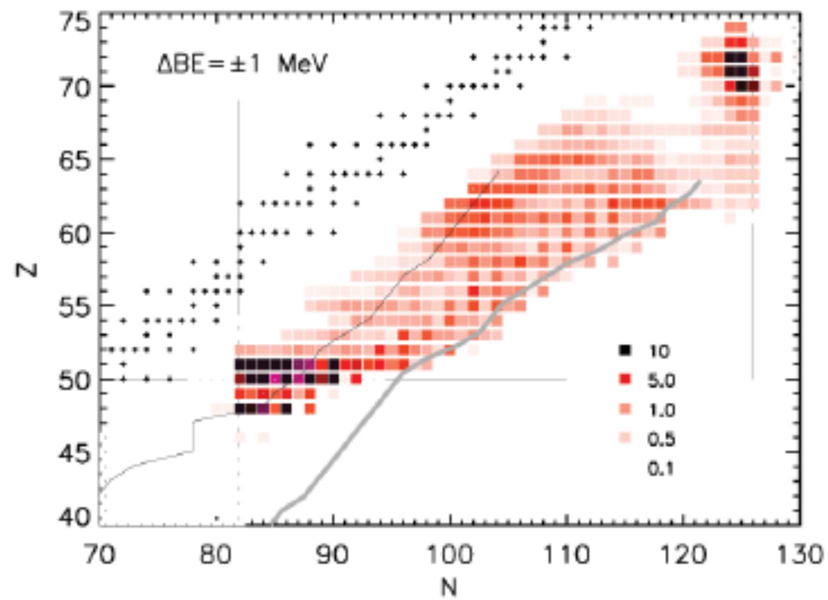




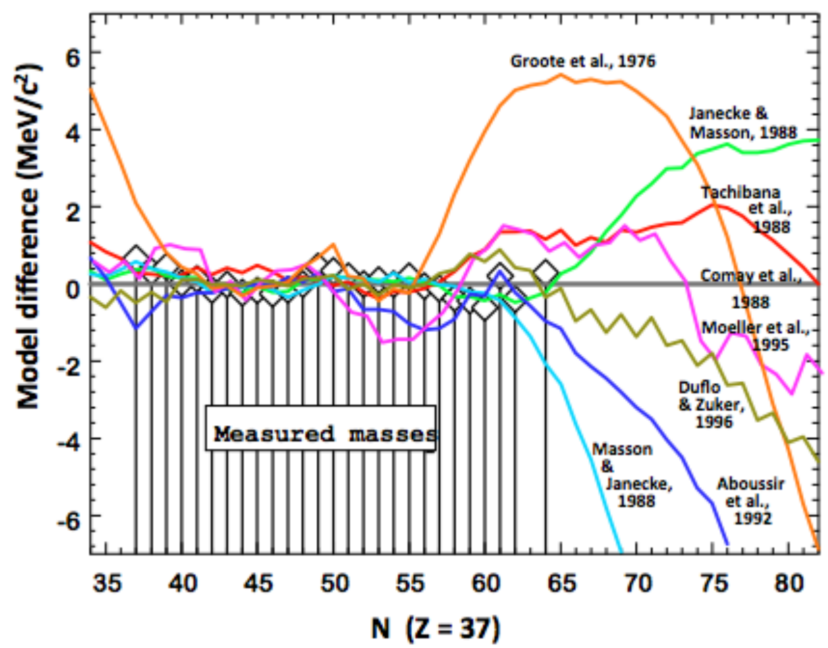


r process: masses and reaction rates



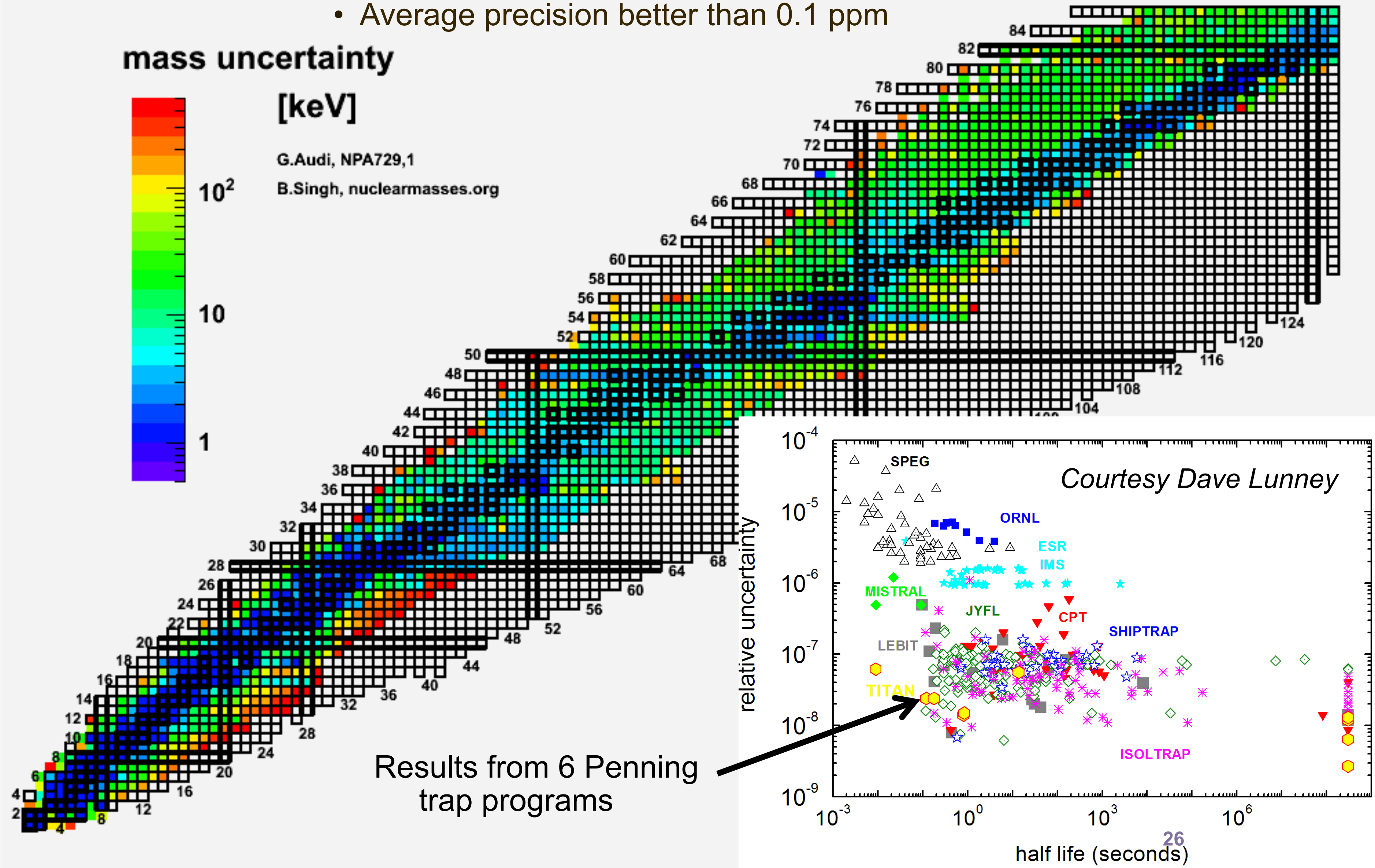


- Some (n,γ) capture rates are important
- Abundances are very sensitive to most atomic masses and becay properties
- Most mass models do not reliably extrapolate away from stability
- Need measurements of nuclear properties in neutron-rich nuclei



Atomic masses

- About 2400 isotopes have measured masses
- Average precision better than 0.1 ppm



Results from 6 Penning trap programs

Penning Traps: In a Nutshell

Trap electrodes in a hyperboloid geometry ($r_0/z_0 \approx 1.16$)

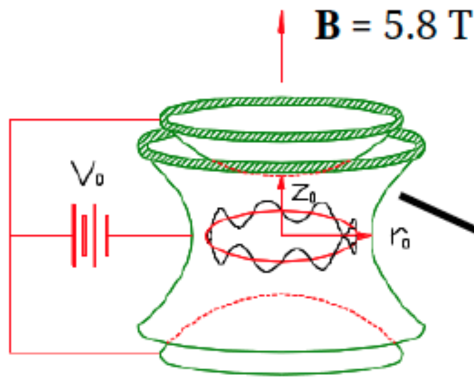
Placed inside uniform magnetic field

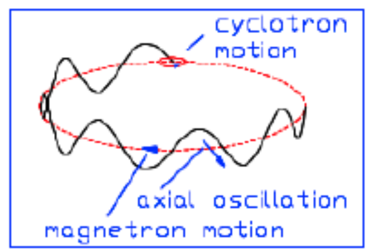
Three types of motion:
- Axial (ω_z)
- Reduced cyclotron (ω_+)
- Magnetron motion (ω_-)

Drive trapped ions into an excitation using RF signal

Ions are ejected from the trap and measure their time-of-flight to a detector

Resonant enhancement at the ion cyclotron frequency: ω_c

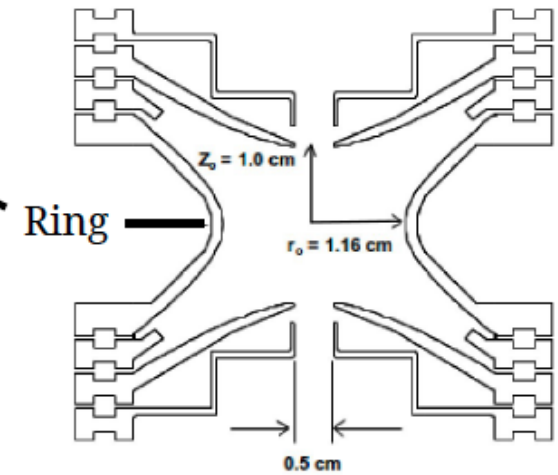




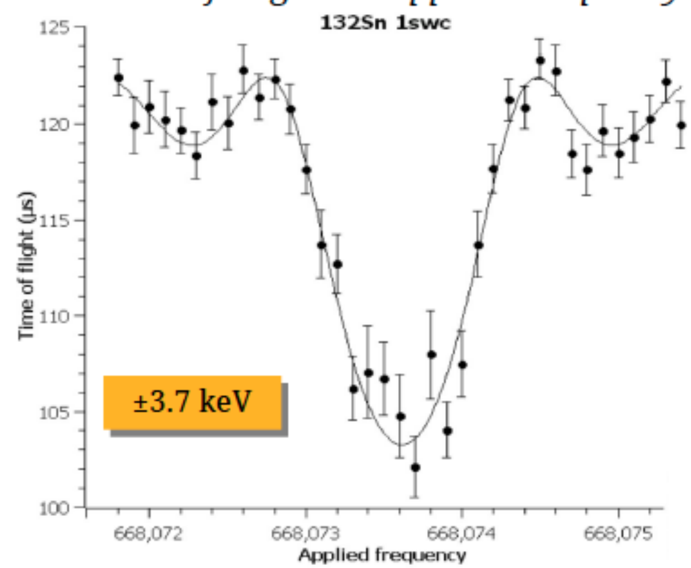
The mass of the trapped ions are measured *indirectly* by determining the cyclotron frequency:

$$\omega_c = qB/m$$

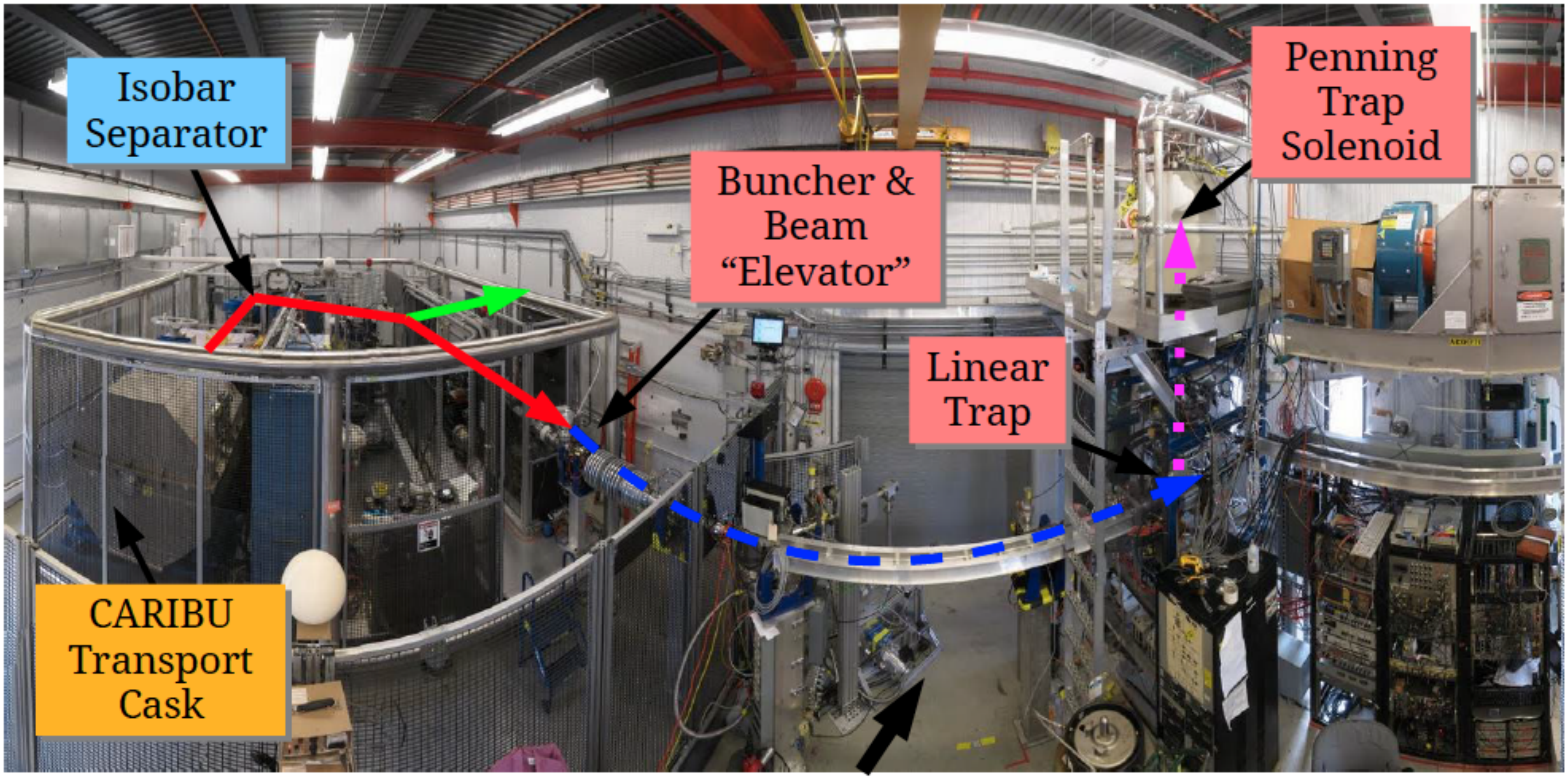
Cross section of CPT



Time-of-Flight vs. Applied Frequency



Canadian Penning Trap
Argonne National Laboratory
ATLAS Accelerator Facility



Precision Mass Measurements

$$\textit{Precision} = \frac{\Delta m}{m} \propto \frac{m}{TqB\sqrt{N}}$$

Conversion Time
Time spent exciting the ion in the trap.
Limited by isotope half-life!!!

Ion Charge State
Typically q=1^+
For some isotopes q=2^+; More precise measurement

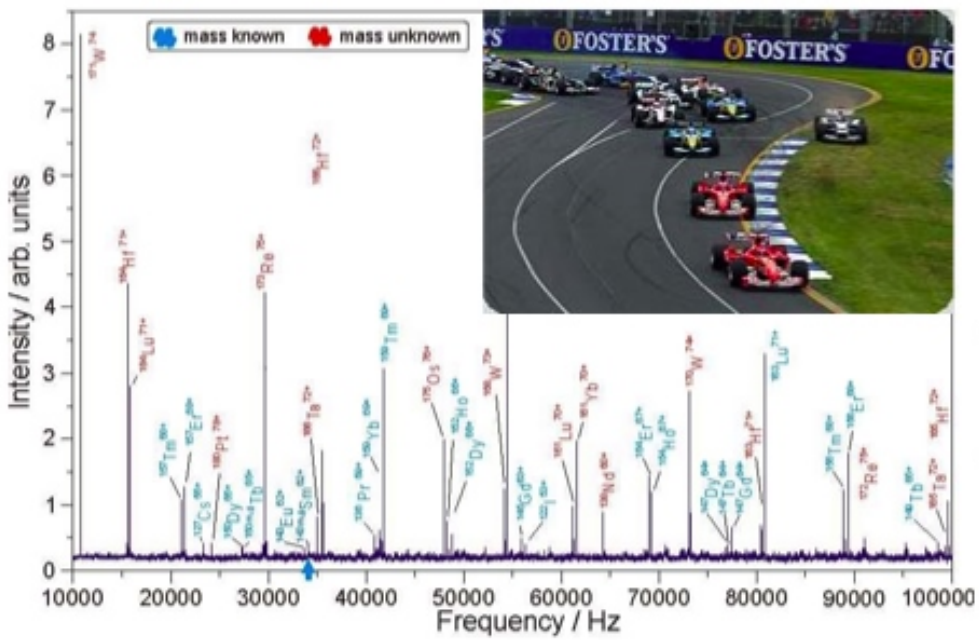
Magnetic Field
Measured with a reference ion ($^{133}Cs^+$) of known mass in between mass measurements

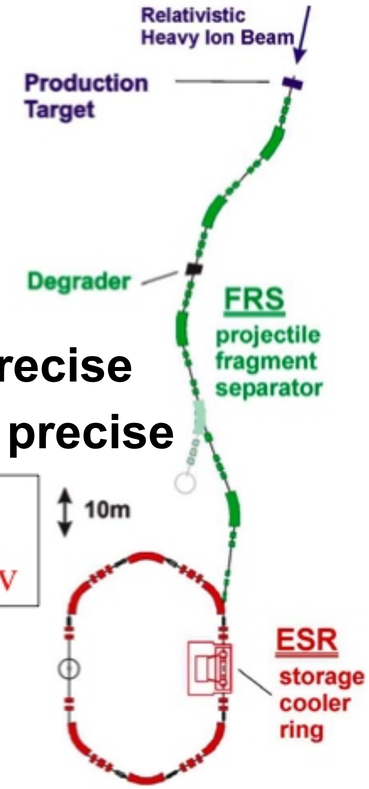
Statistics
The longer you acquire data, the better the measurement.
CARIBU transport efficiency!

Many of the most neutron-rich nuclei produced at CARIBU have short half lives (≤150 ms) as well as small fission branches from ^{252}Cf ($\leq 10^{-4}$ %)

Improvements in both CARIBU and the CPT systems are required to perform mass measurements of influential *r*-process nuclei to $\Delta m/m \leq 10^{-7}$

Mass measurements – storage rings





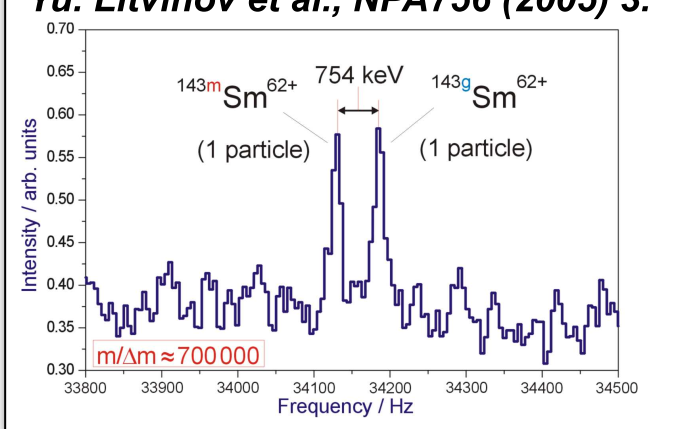
<u>2 modes</u>:

Schottky - slow, more precise

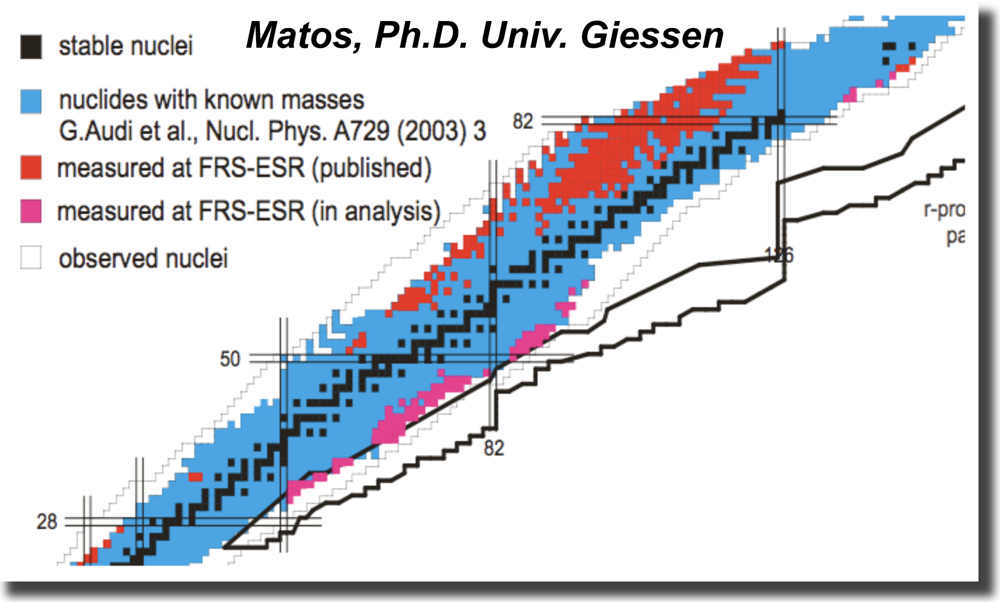
isochronous - fast, less precise

Experimental Storage Ring:

$$\Delta m/m = \gamma_t^2\ \Delta f/f + (\gamma_t^2 - \gamma^2)\ \Delta v/v$$



Yu. Litvinov et al., NPA756 (2005) 3.

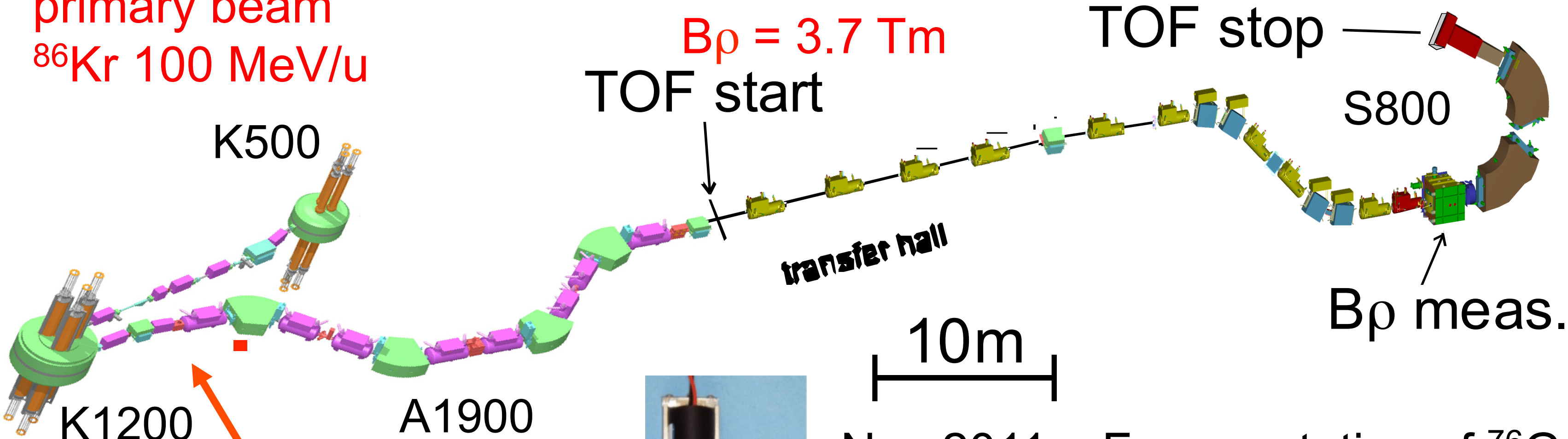


Matos, Ph.D. Univ. Giessen

NSCL

TOF-Bρ Mass Measurements

primary beam
^{86}Kr 100 MeV/u



production target
Be 51 and 94 mg/cm^2

$$B\rho = \frac{m}{q} v$$

⇒ ***mass***

No dependence on lifetime!

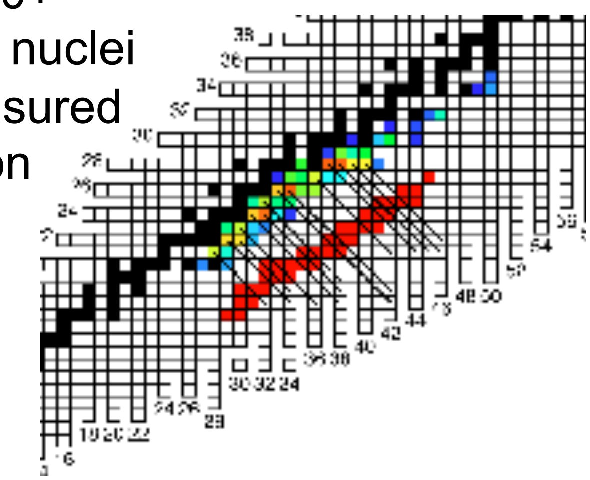
Path length ~ 58m

Time resolution ~ 30ps

Nov 2011 – Fragmentation of ^{76}Ge

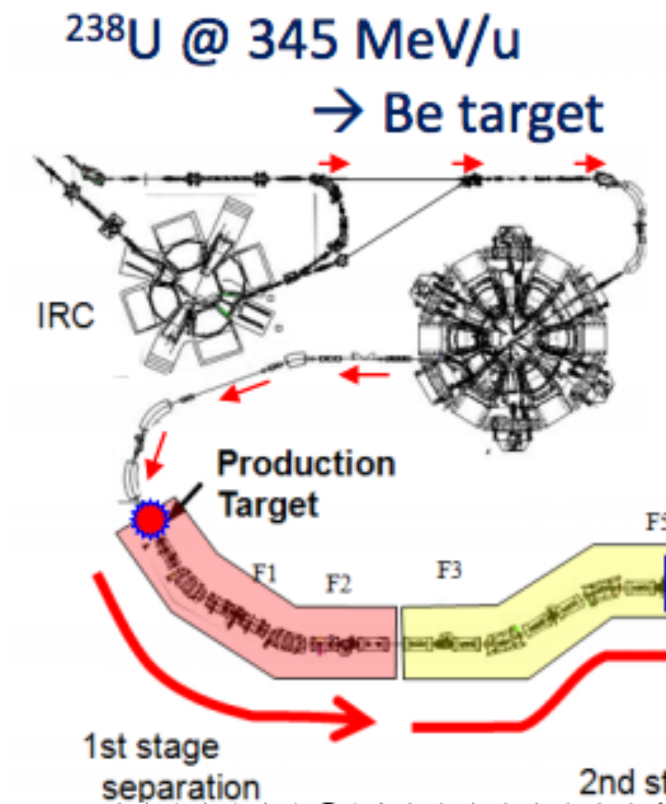
Estrade, George, Matos, Schatz *et al.*

Masses of 30+ neutron-rich nuclei near Ni measured with precision better than 1:200,000

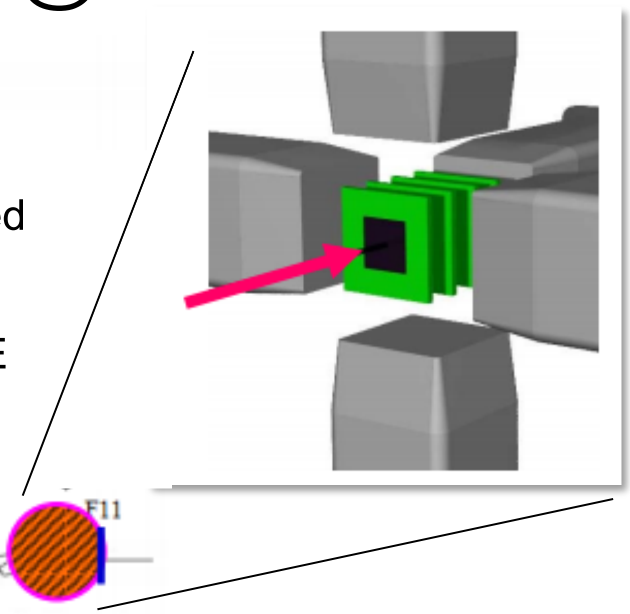


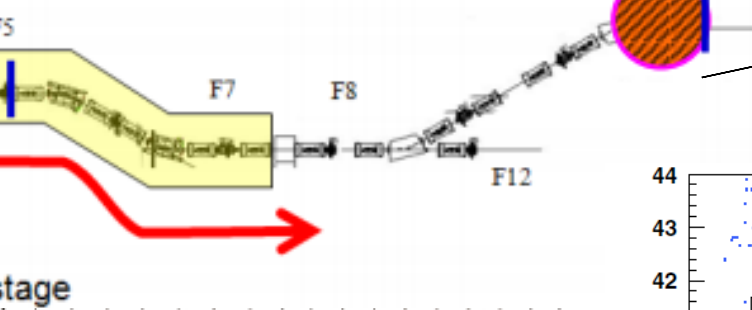
New approved exp.
Fragmentation of ^{124}Sn

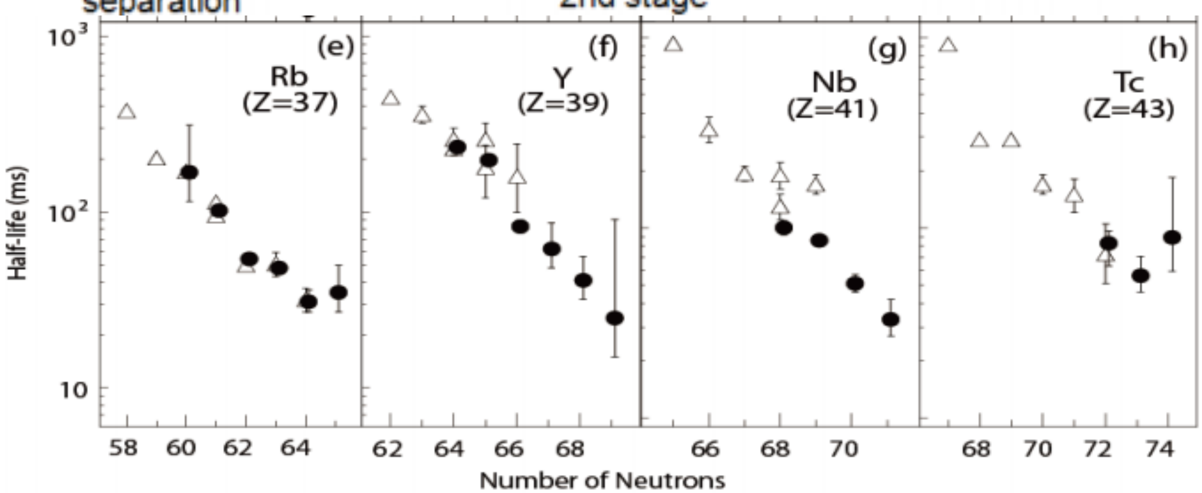
Beta Decay Example: RIBF @ RIKEN

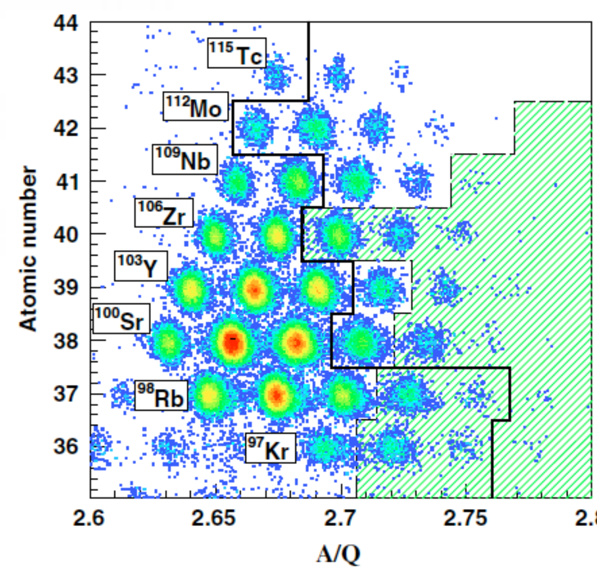


- Isotopes produced by fragmentation
- EM separated and implanted into Si detector stack (9)
- Identiified by TOF and ΔE-E
- Decay β and γ measured
- Dozens of isotopes studied



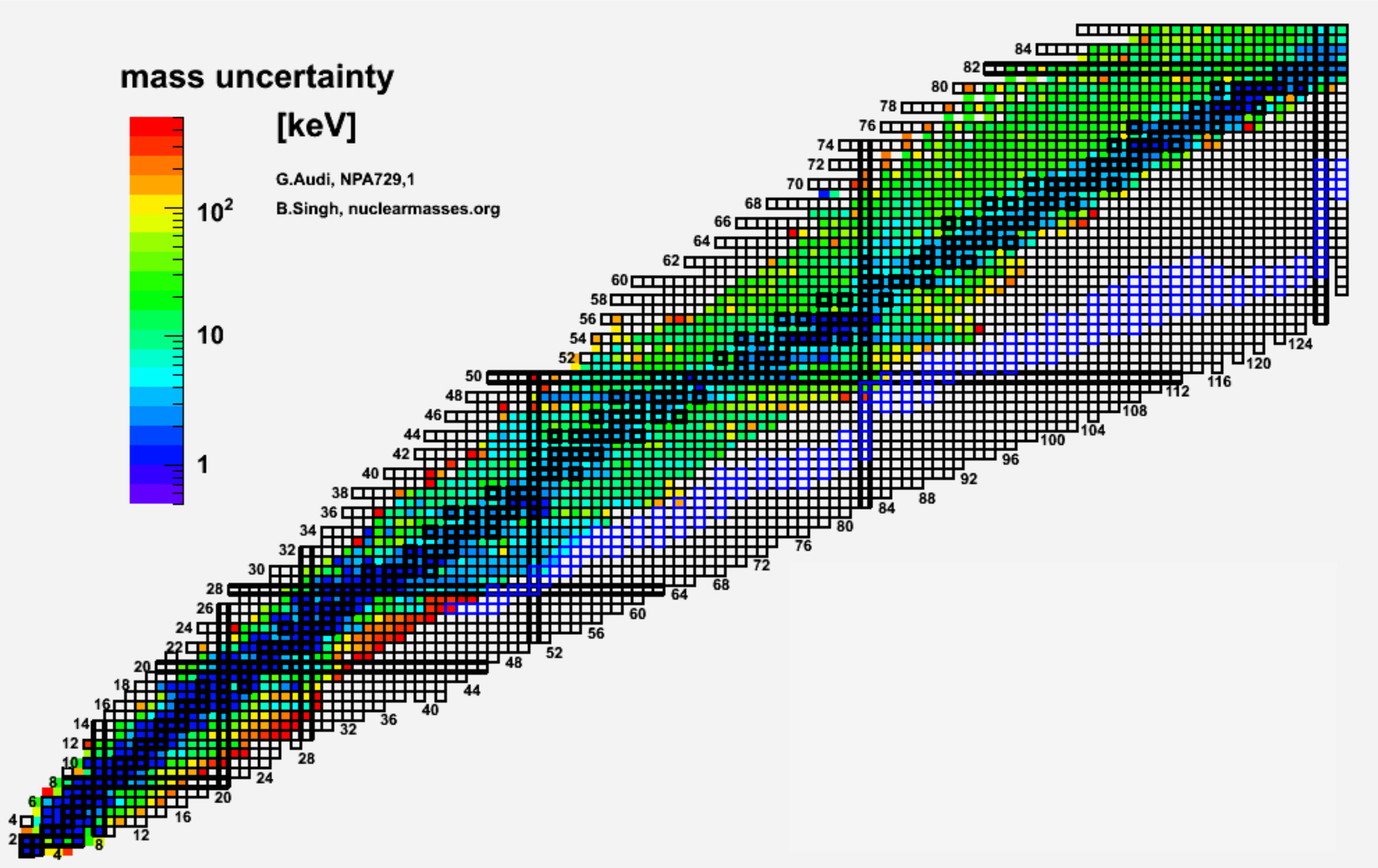






S. Nishimura *et al*., PRL **106**, 052502 (2011).

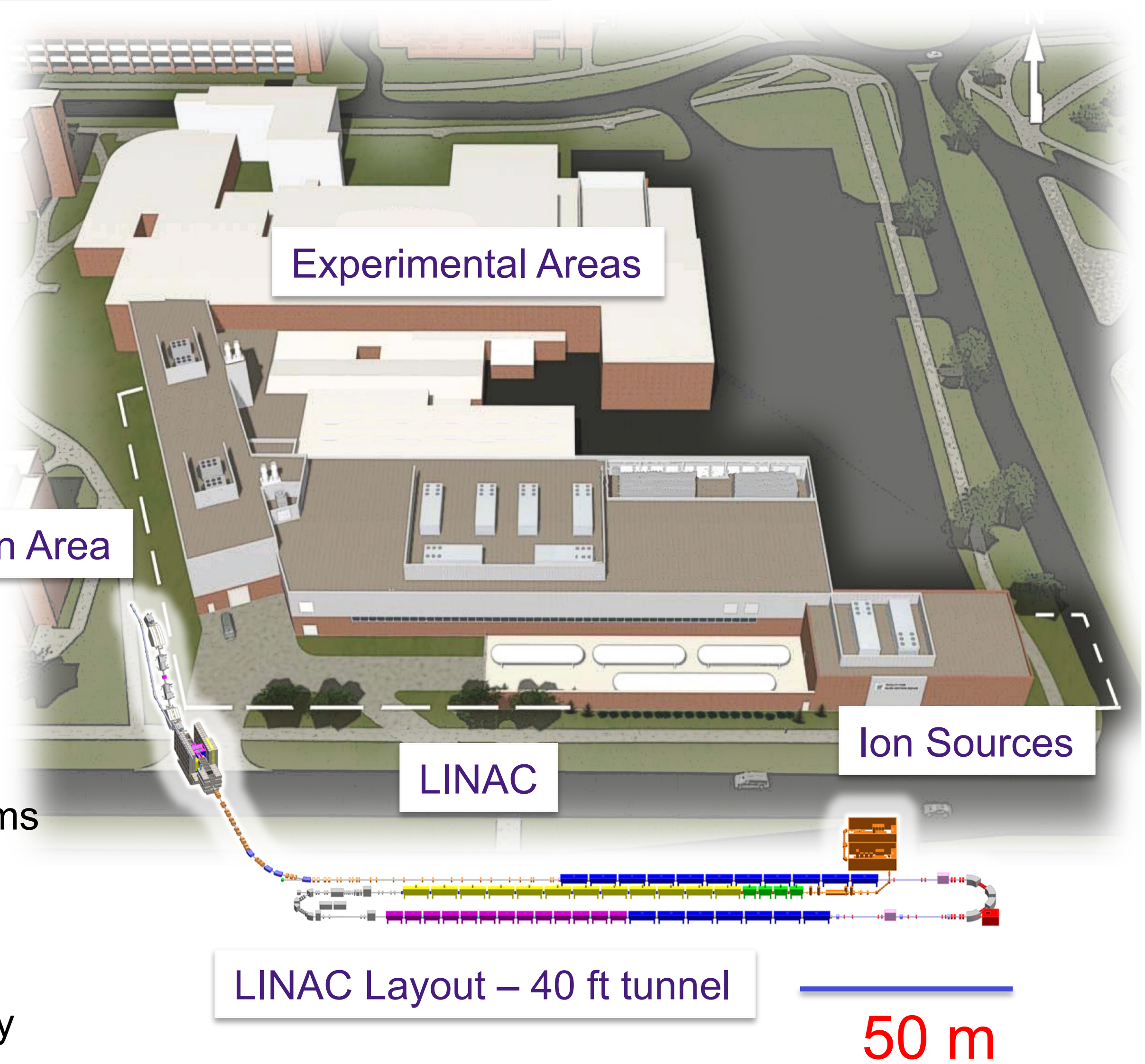
The r process



FRIB Facility for Rare Isotope Beams

U.S. Department of Energy Office of Science
Michigan State University

- On existing NSCL Site
- New gas stopping technology + post accelerator
- New Powerful driver LINAC
  → 200 MeV/u for U
  → 400 kW
- 9/01/10 CD-1
  → $614M TPC
  → $520 DOE
- CD-4 ~FY2020



- Wide ***variety*** of ***intense*** beams at ***low energies***
- First access to many of the *r process* isotopes
- Direct measurements of many reactions for the first time

FRIB Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science
Michigan State University

- Detailed study of all neutron-rich nuclei important for astrophysics possible up to Sn
- Masses and half-lives possible for most nuclei
  - Including A~190 mass peak
  - Pin down r process site