Experimental Nuclear Astrophysics

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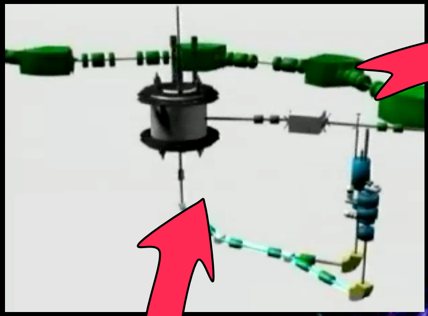
➢ Nuclear reactions and nuclear properties determine:
  - Energy generation
  - Nucleosynthesis
    - →Origin of the elements
    - →Test between models and observations

2010 National Nuclear Physics Summer School & TRIUMF Summer Institute

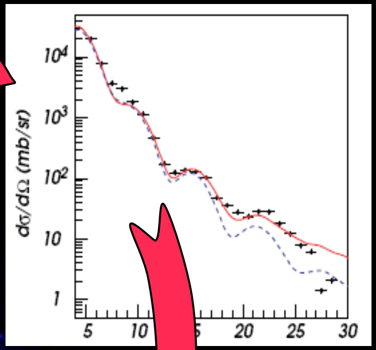
Interdisciplinary research
New tools drive progress

Laboratory measurements

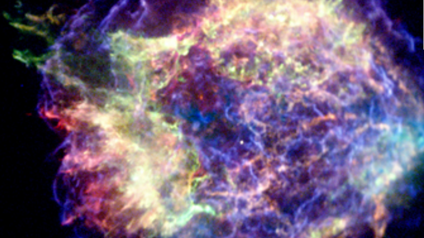


New beams & experimental techniques

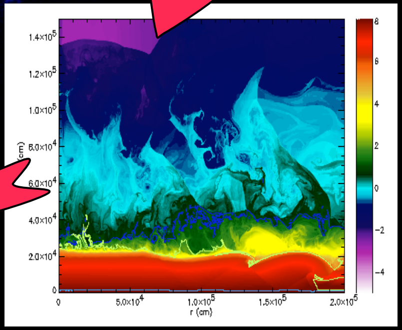
Nuclear theory and data



Improved reaction theory, large-scale shell model calc, & reaction rate libraries

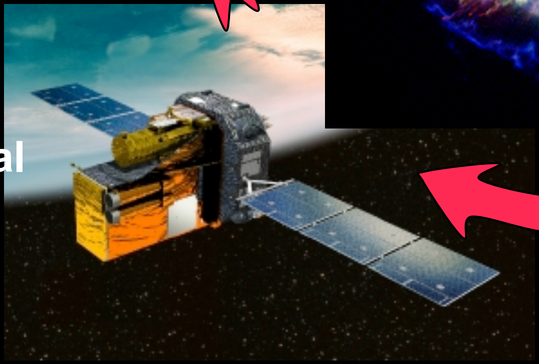


Astrophysics



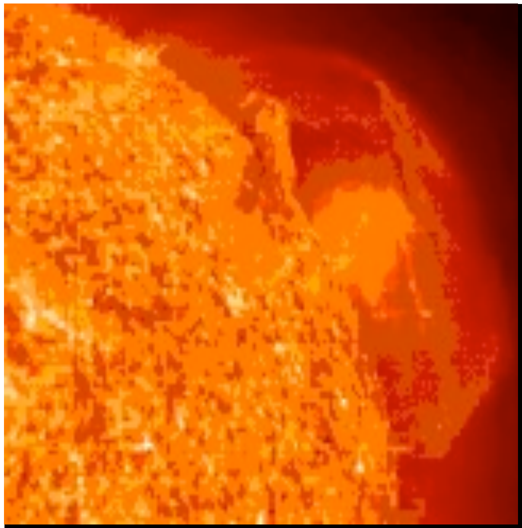
Advancing computing power →more realistic simulations

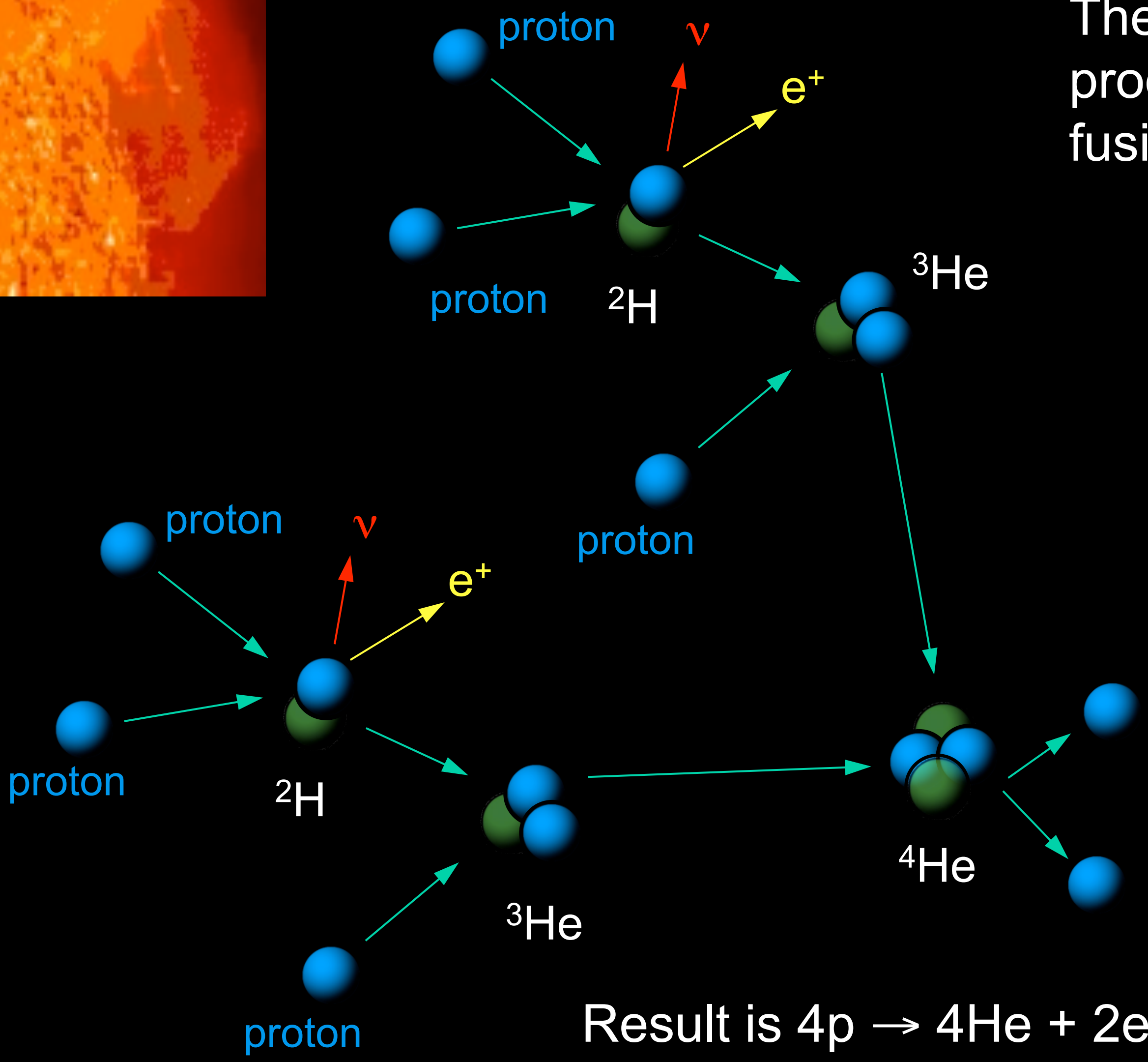
Observations



New orbiting instruments, increased optical power, presolar grains

Solar fusion





The sun's energy is produced by nuclear fusion in its core

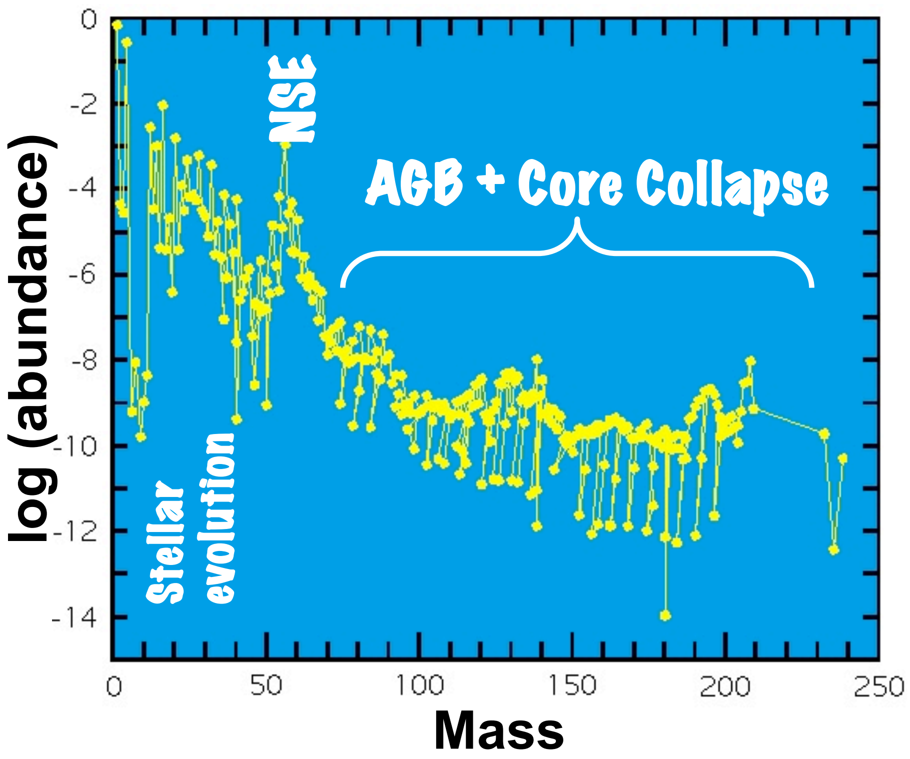
T(core)=15 MK

T(surf)=5800 K

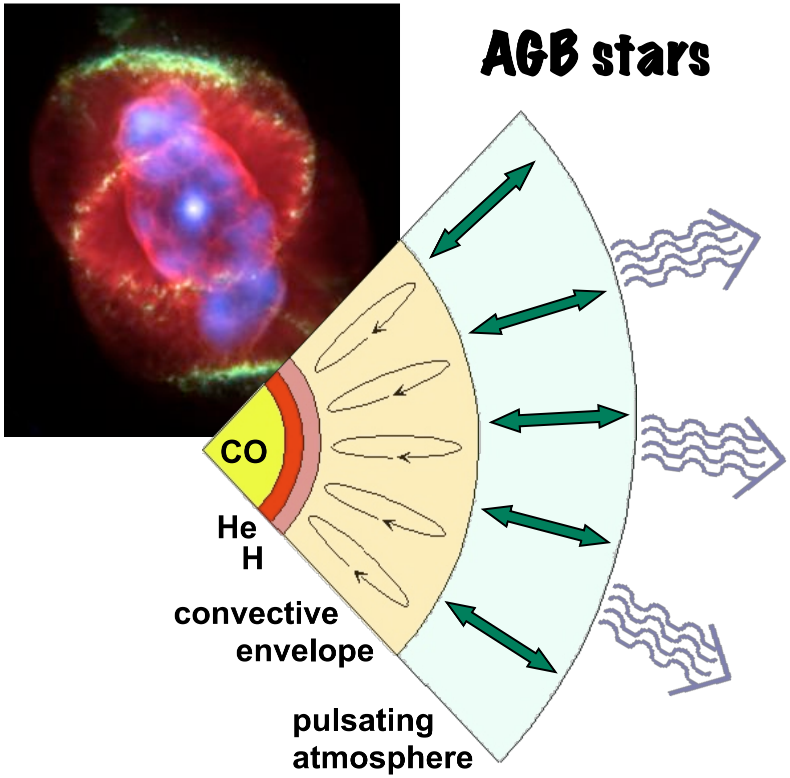
Result is $4p \rightarrow 4He + 2e^{+} + 2\nu + 27$ MeV

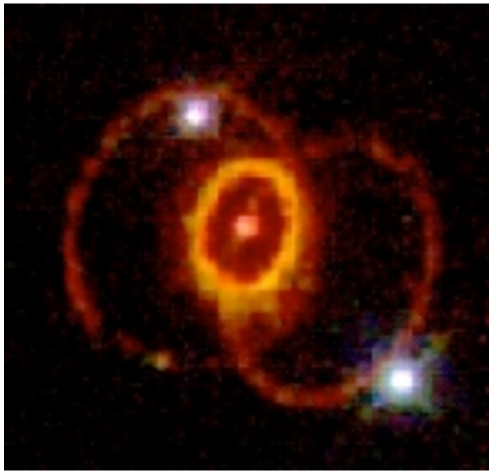
$27 \text{ MeV} = 4 \times 10^{-12} \text{ J}$ $* \; 10^{38}$ fusions/s $= 4 \times 10^{26}$ Watts

What are the origins of the elements?



AGB stars

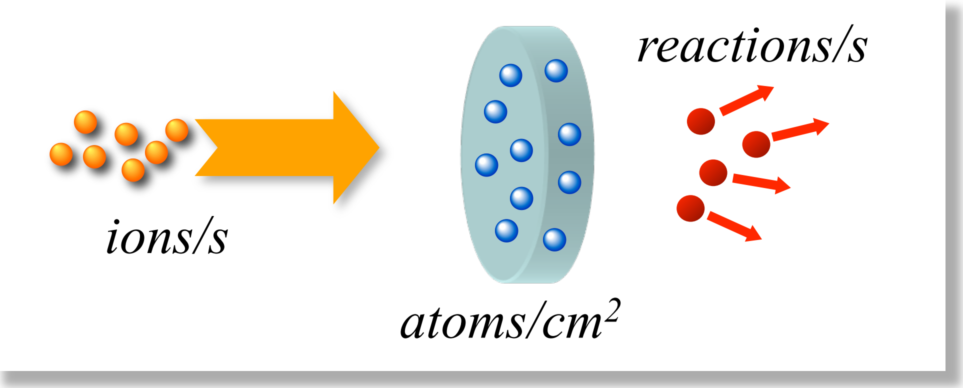




Core-collapse Supernovae

Nuclear reactions in the lab & in space

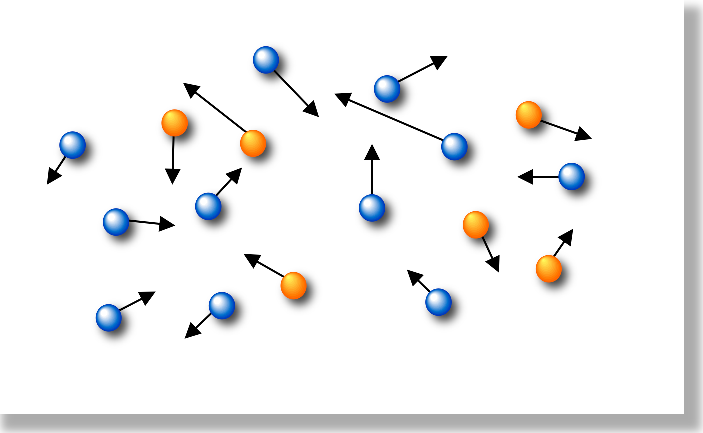
What you are used to in the lab:



cross section

$$\frac{reactions}{s} = \frac{ions}{s}\,\frac{atoms}{cm^2}\,\sigma$$

In astrophysical environments:



reaction rate

$$\frac{reactions}{cm^3 s} = \int \frac{n_x}{cm^3}\,\frac{n_y}{cm^3}\, v\sigma(v)\phi(v)\,dv$$

$$\phi(v) = 4\pi v^2 \left(\frac{\mu}{2\pi kT}\right)^{3/2} \exp\left(-\frac{\mu v^2}{2kT}\right)$$

$$\frac{reactions}{cm^3 s} = \frac{n_x}{cm^3}\,\frac{n_y}{cm^3}\,\langle \sigma v \rangle$$

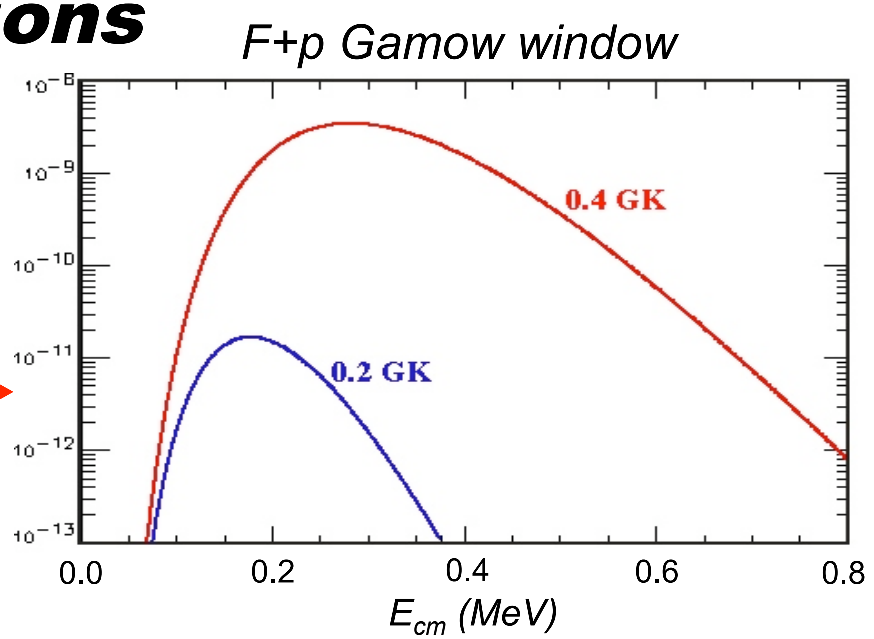
$$\langle \sigma v \rangle = \sqrt{\frac{8}{\pi\mu}}\,(kT)^{3/2} \int_0^\infty \sigma E e^{-E/(kT)}\,dE$$

Charged-particle reactions

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

$$\sigma \equiv \frac{S}{E}e^{-\sqrt{E_G/E}} \qquad E_G \equiv \frac{2\mu}{\hbar^2}\left(\pi Z_1 Z_2 e^2\right)^2$$

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


F+p Gamow window

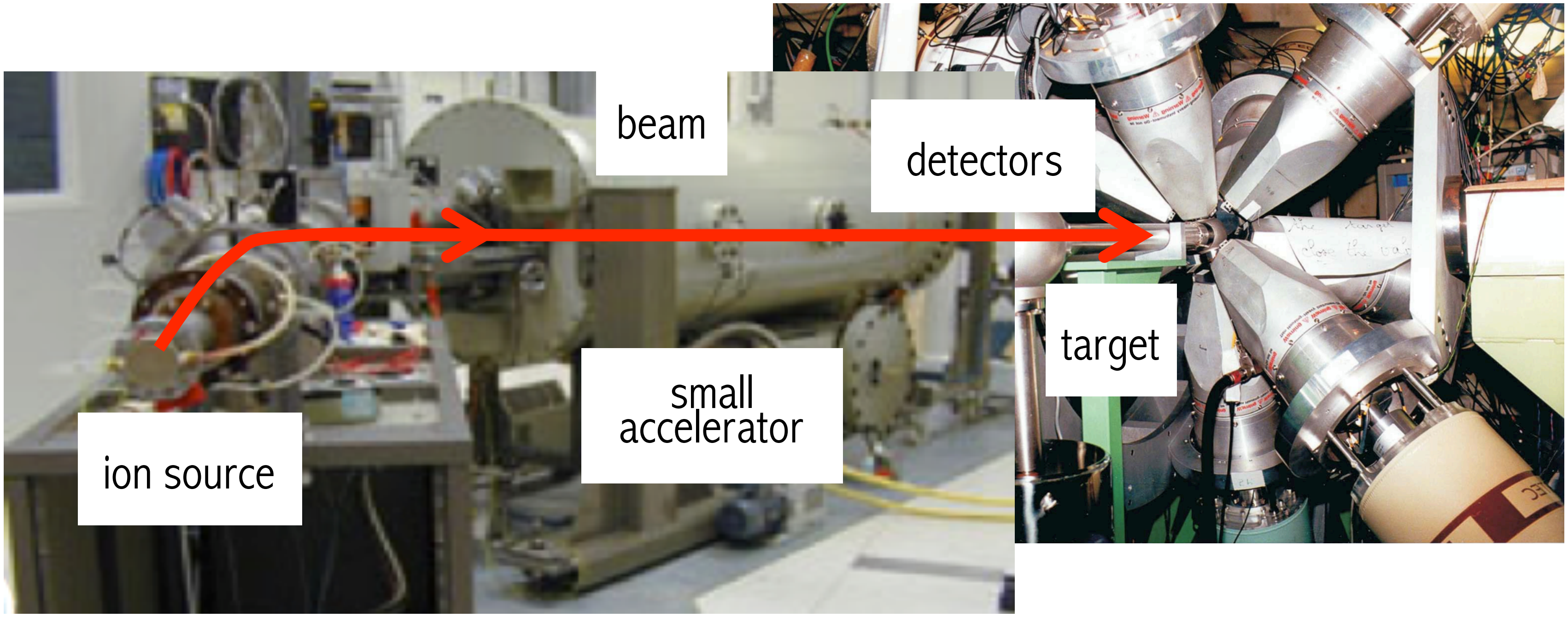
Reaction	site	T (10^6 K)	kT (keV)	r_{turn} (fm)	r (fm)	E_0 (keV)
p+p	sun	15	1.3	1100	2.5	6
p+^{14}N	CNO	30	2.6	3900	4.3	42
α+^{12}C	red giant	190	16	1060	4.8	300
p+^{17}F	nova	300	26	500	4.5	230
α+^{30}S	x-ray burst	1000	86	500	5.9	1800
^{3}He+^{4}He	big bang	2000	170	33	3.8	580

We have a fairly good understanding of hydrogen fusion in stable stars

Good observations (e.g. sun)

The astrophysical environment is not too complicated

We have directly measured most of the reactions in the laboratory



The S-factor

Example: $^3He(\alpha,\gamma)^7Be$

Important for:

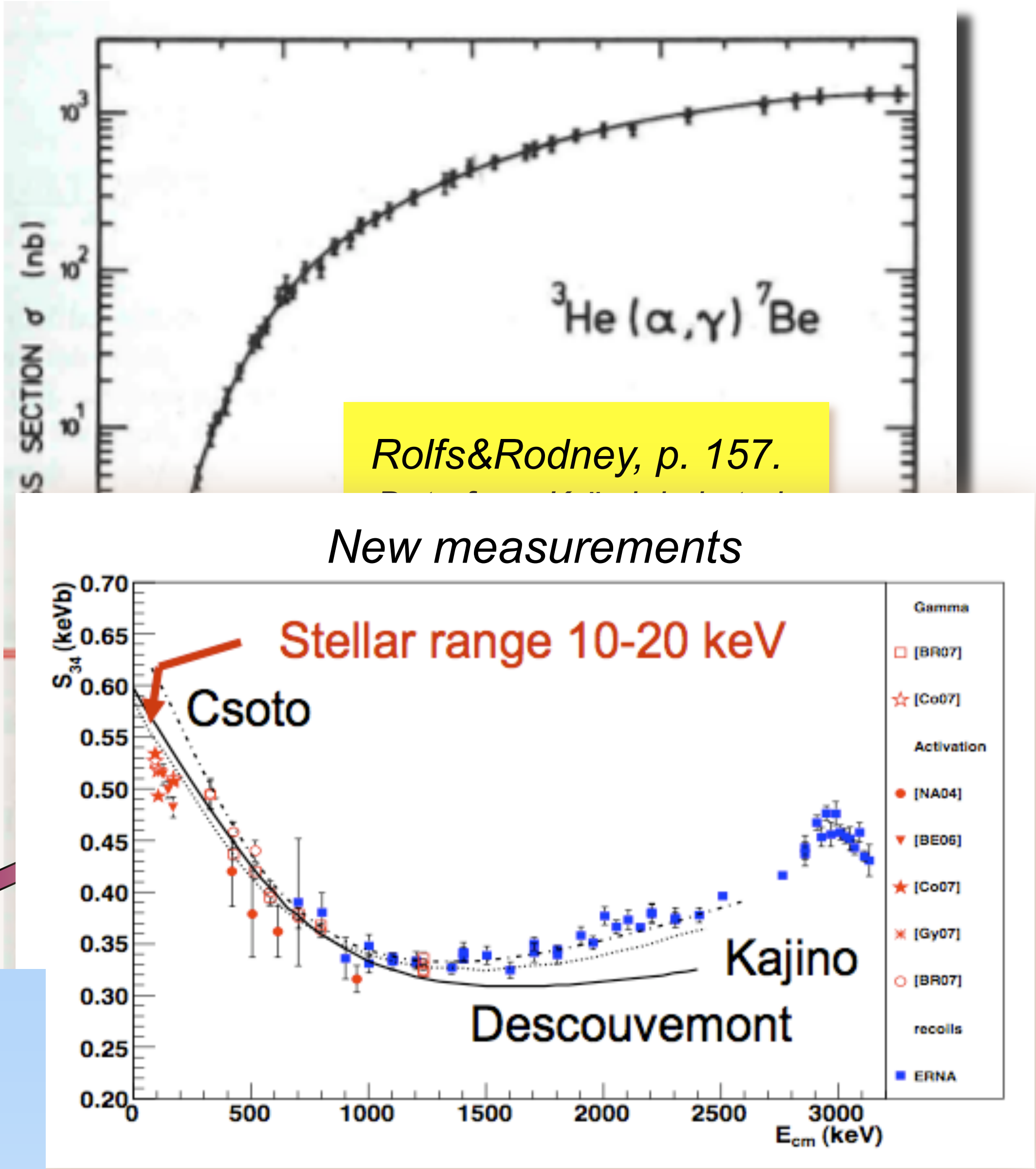
The sun (ν production)

Big Bang (Li production)

$$\sigma \equiv \frac{S}{E} e^{-\sqrt{E_G / E}}$$

Previous experimental limit

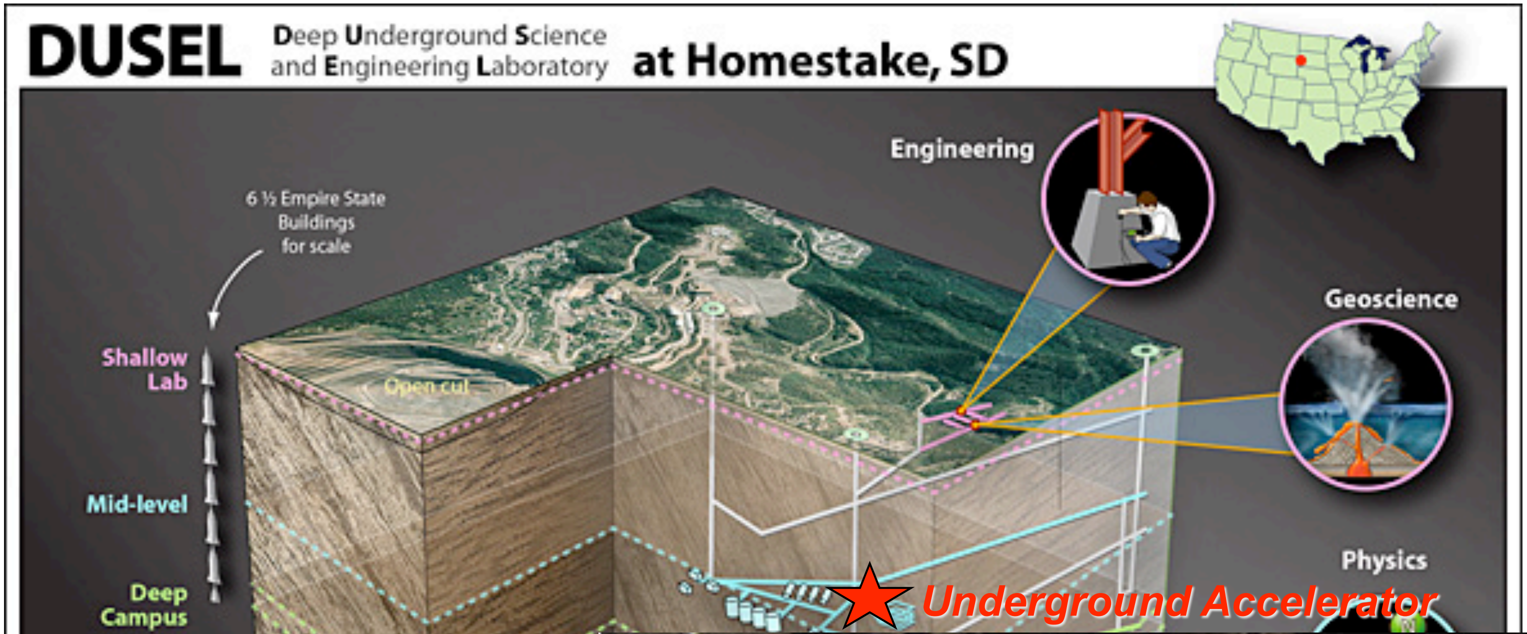
Need σ here for sun

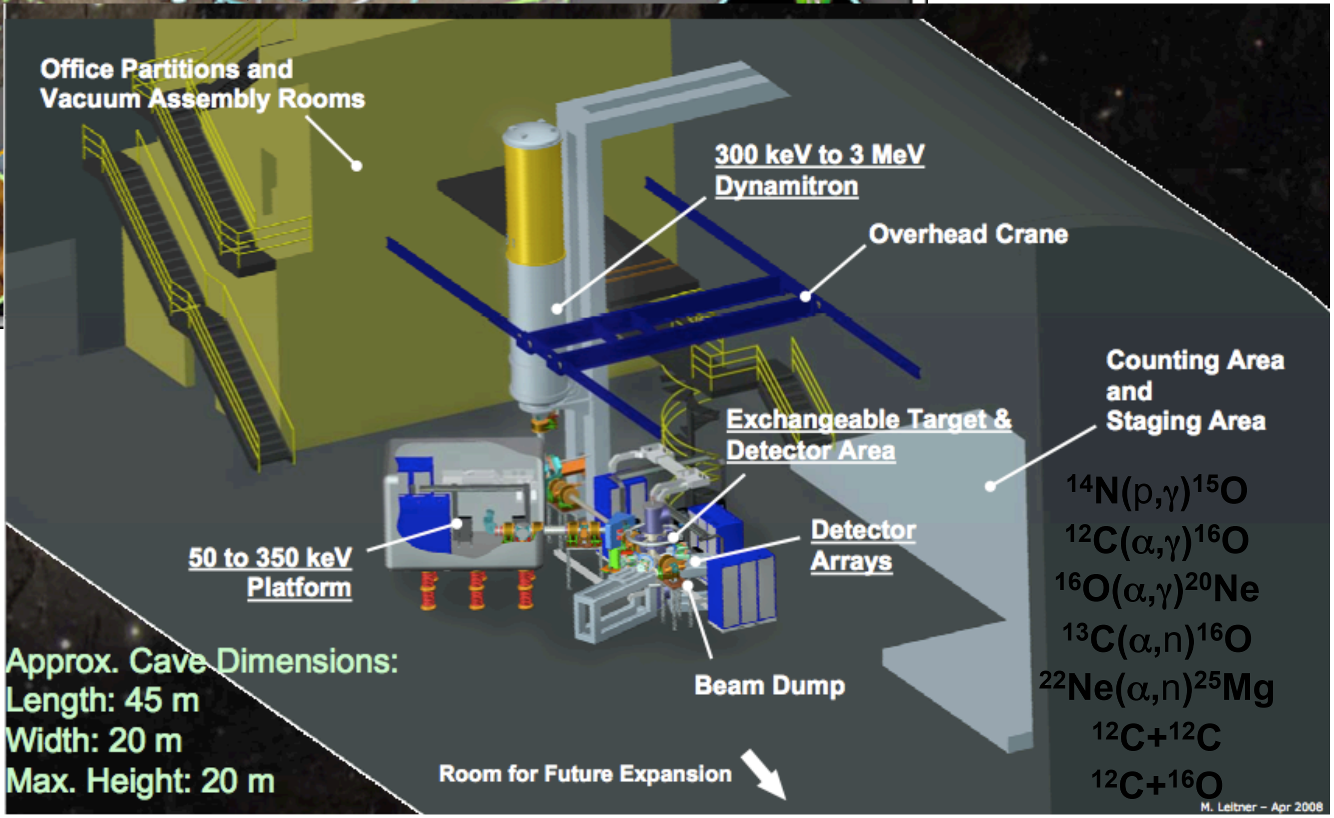


Rolfs&Rodney, p. 157.

New measurements

Laboratory
Underground
Nuclear
Astrophysics





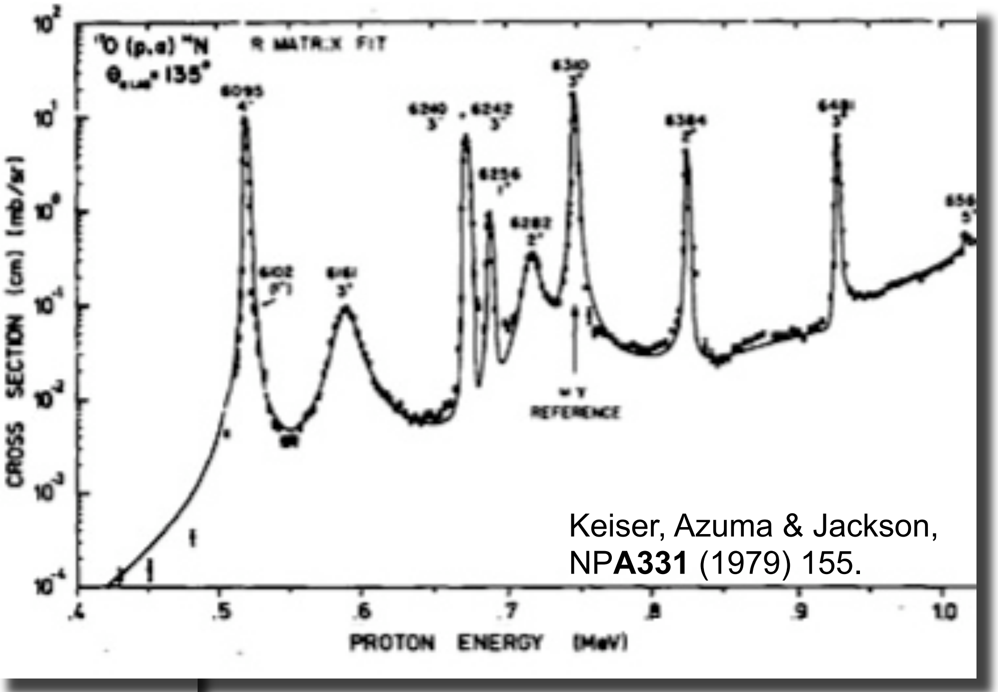
"S4" Proposal Funded

Initial suite of experiments for DUSEL

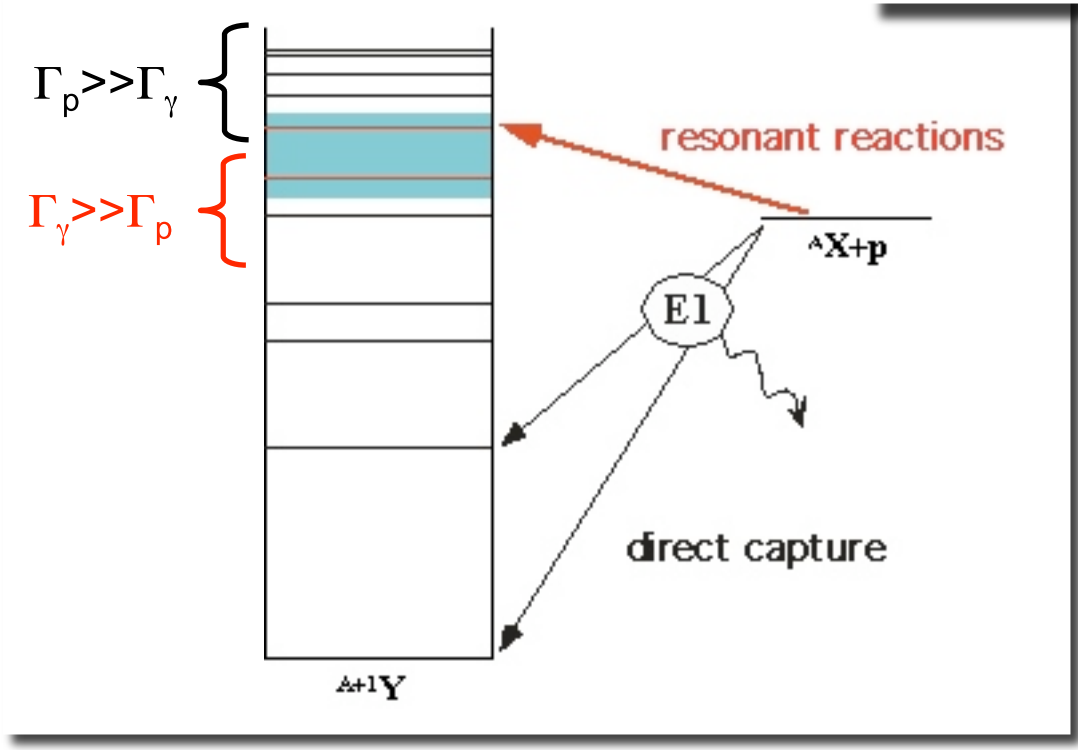
Resonances

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

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



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



If resonance is narrow

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

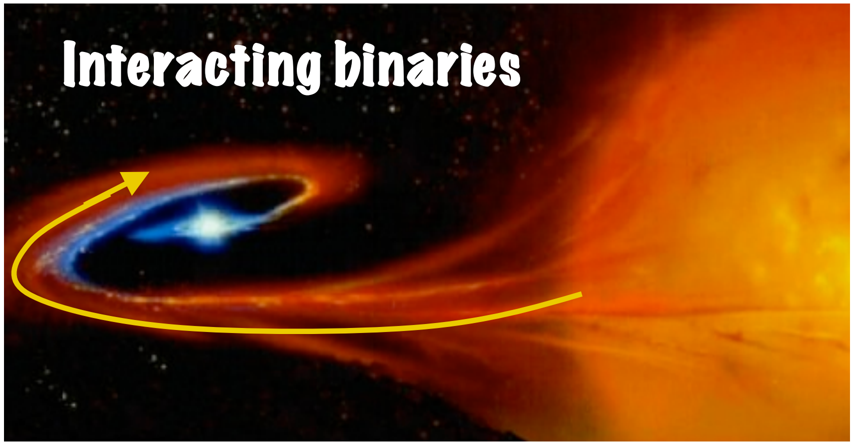
E_r & J^π are most important

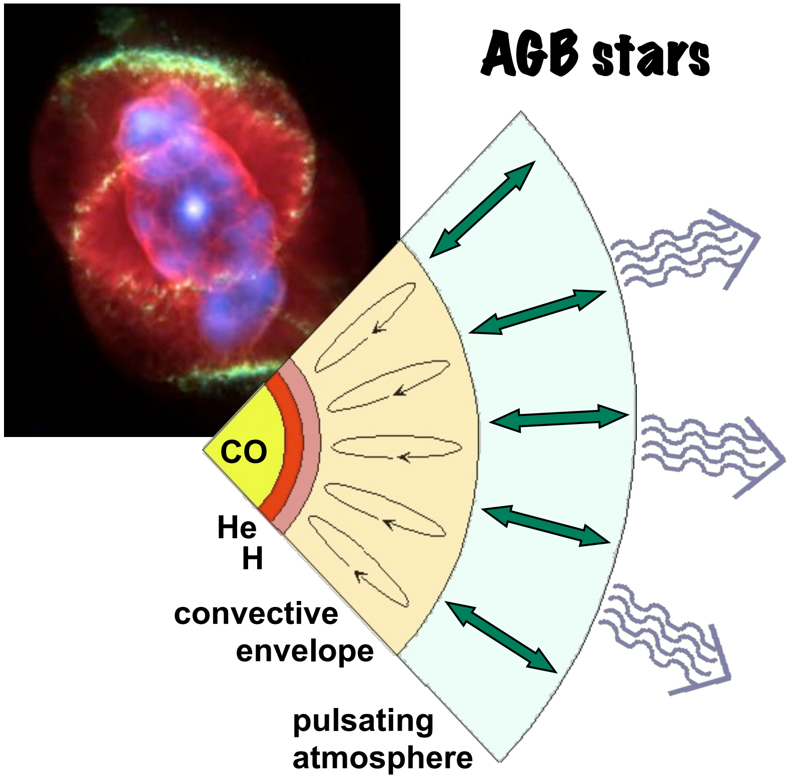
$$\omega\gamma = \frac{2J+1}{(2J_x+1)(2J_y+1)} \frac{\Gamma_x \Gamma_y}{\Gamma}$$

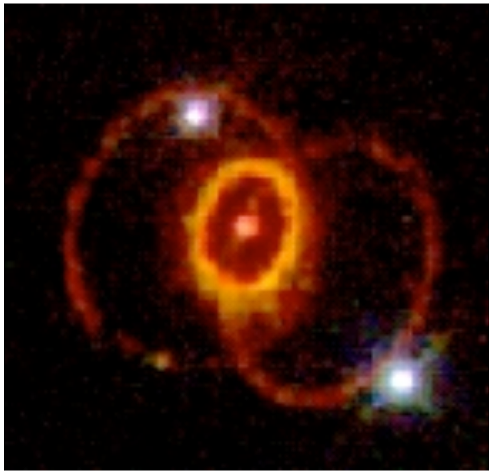
“resonance strength”

The cataclysmic death of a star

- ➢ Interacting binaries
  - Novae, X-ray bursts, Type Ia Sne
  - Most common stellar explosions
  - Thermonuclear events
- ➢ Core-collapse Supernovae
  - Site for the r process?
  - p process νp process?
- ➢ Asymptotic Giant Branch (AGB) stars
  - Site for s process
  - Source of ~half the heavy elements
- ➢ Others?







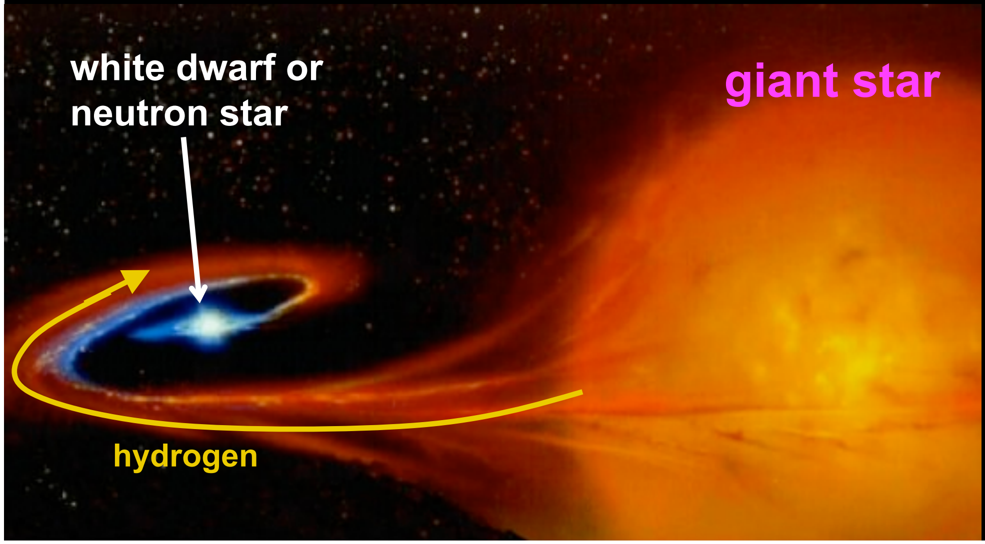
Novae and X-ray bursts

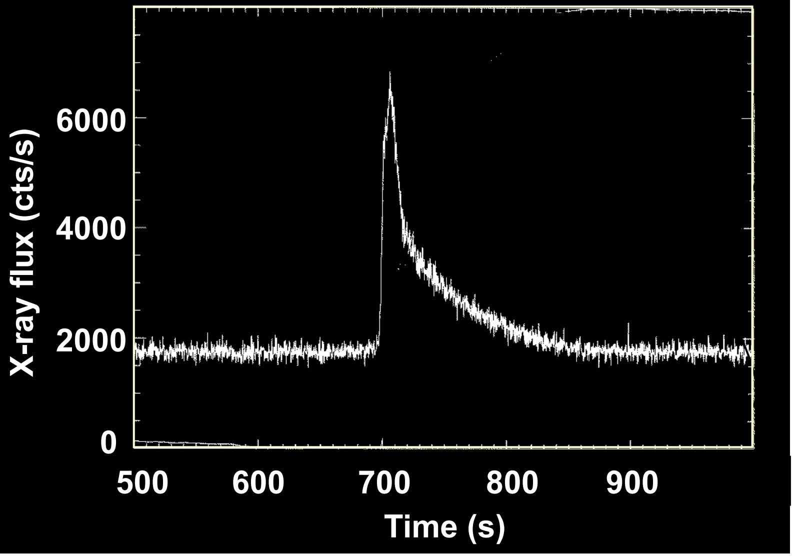
- The most common stellar explosions in the Galaxy
  - Thermonuclear events
  - About 3 dozen novae/year in Milky Way
  - Over 100 known Type 1 X-ray bursts

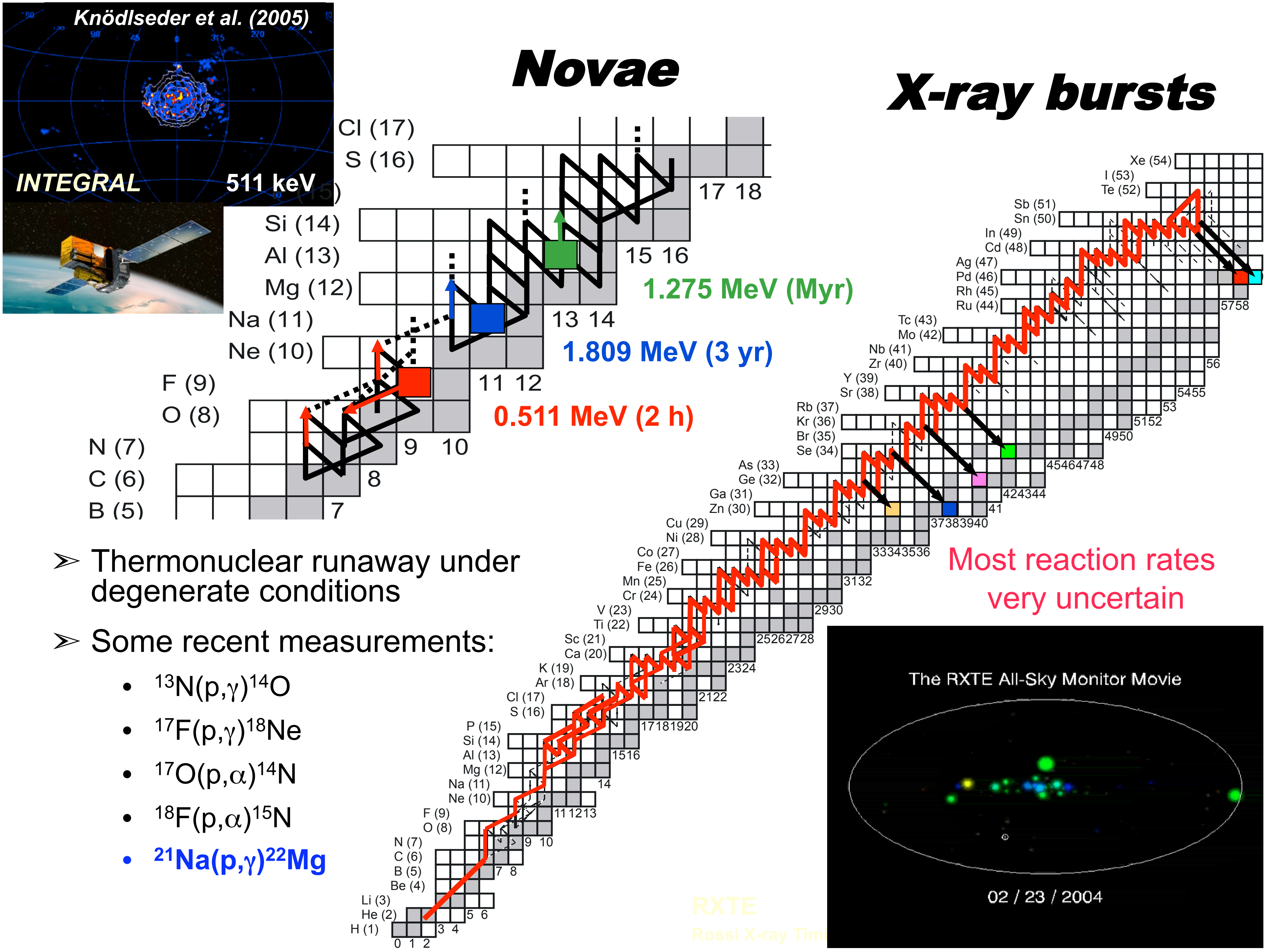
- Novae:
  - Recur after t >>1000 yr
  - Increase in brightness by 10^3-10^6 times
  - Usually discovered by amateurs
  - Explosion on white dwarf

- X-ray bursts:
  - Recur on scale from hours to months
  - Don't confuse with gamma-ray bursts


Ophiuchi 2006 No. 2







Novae

X-ray bursts

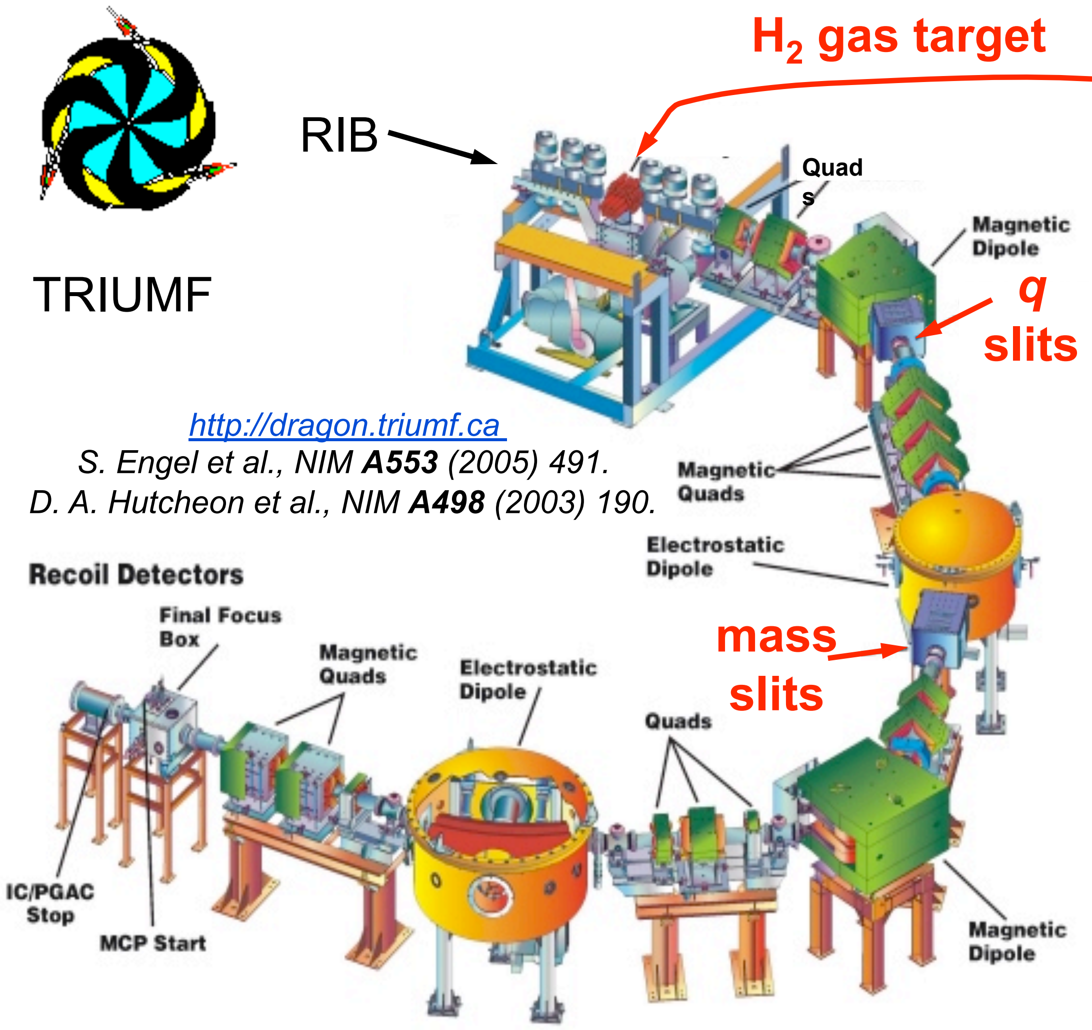
Most reaction rates very uncertain

- ➢ Thermonuclear runaway under degenerate conditions
- ➢ Some recent measurements:
  - $^{13}N(p,\gamma)^{14}O$
  - $^{17}F(p,\gamma)^{18}Ne$
  - $^{17}O(p,\alpha)^{14}N$
  - $^{18}F(p,\alpha)^{15}N$
  - **$^{21}Na(p,\gamma)^{22}Mg$**

(p,γ) cross section measurements

Very powerful experimental techniques have been developed to allow measurements of the weakest rates with minimum incident beam intensity

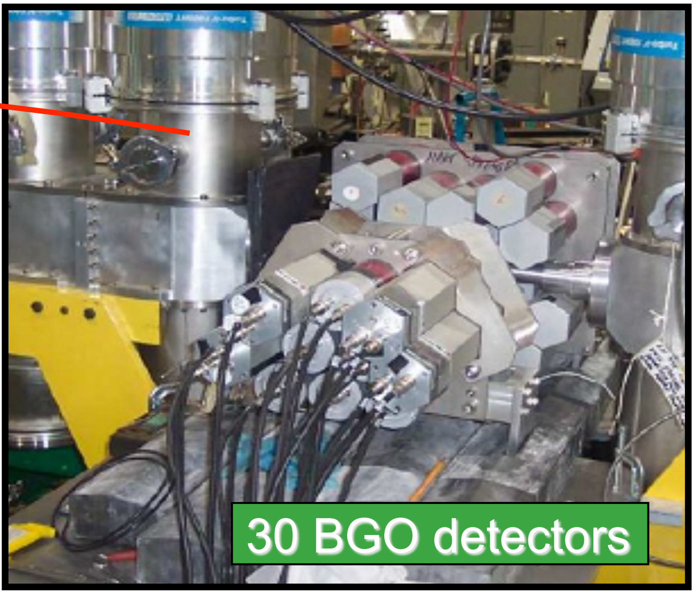
TRIUMF



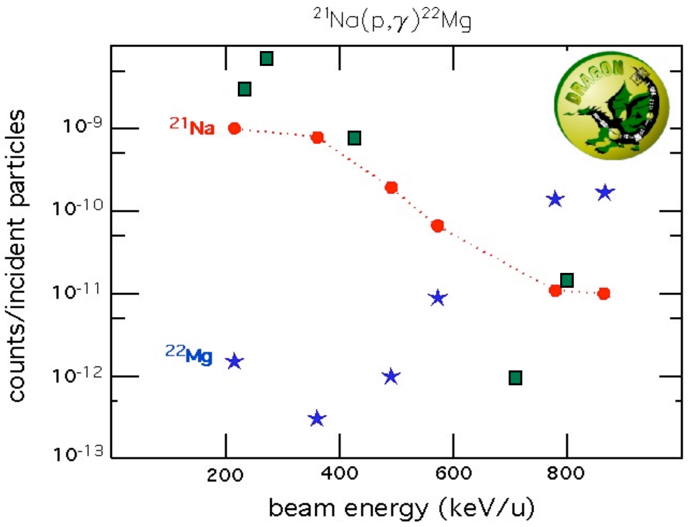
http://dragon.triumf.ca

S. Engel et al., NIM ***A553*** *(2005) 491.*

D. A. Hutcheon et al., NIM ***A498*** *(2003) 190.*

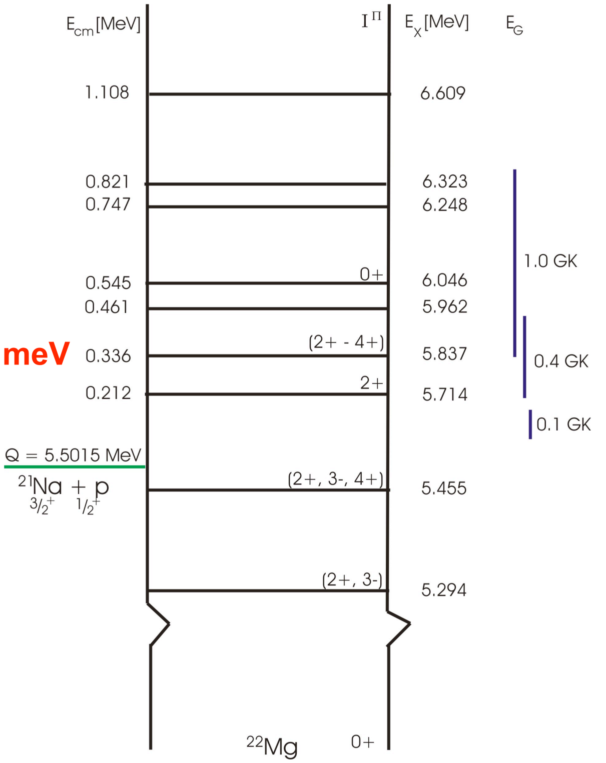


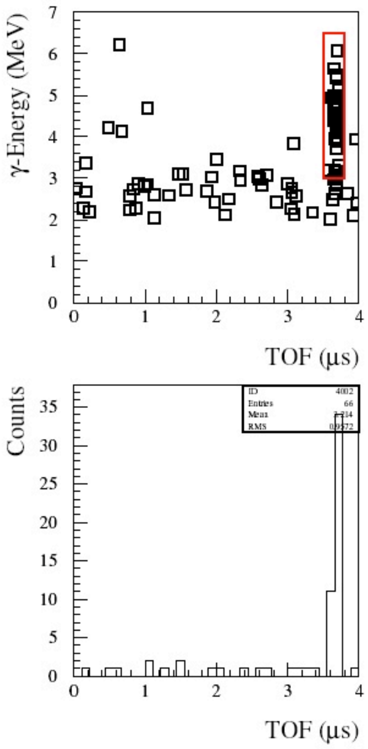
30 BGO detectors

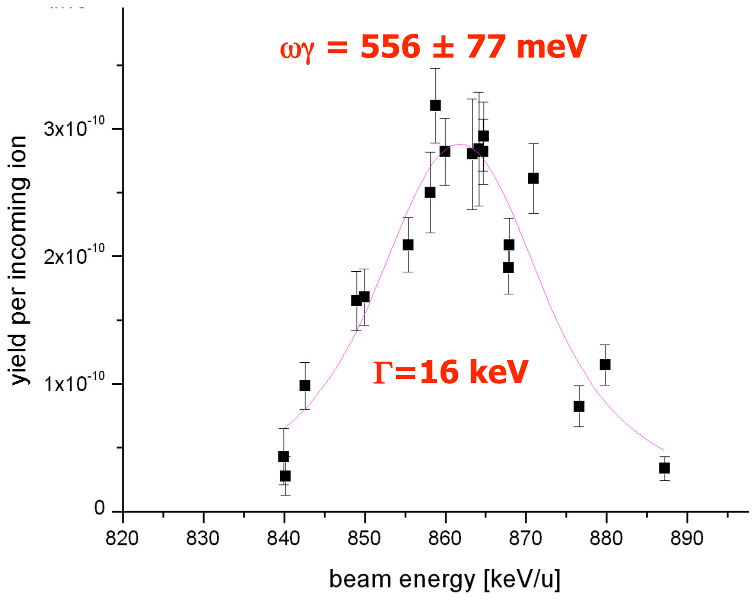


^{21}Na(p,γ)^{22}Na with DRAGON

<0.3 meV



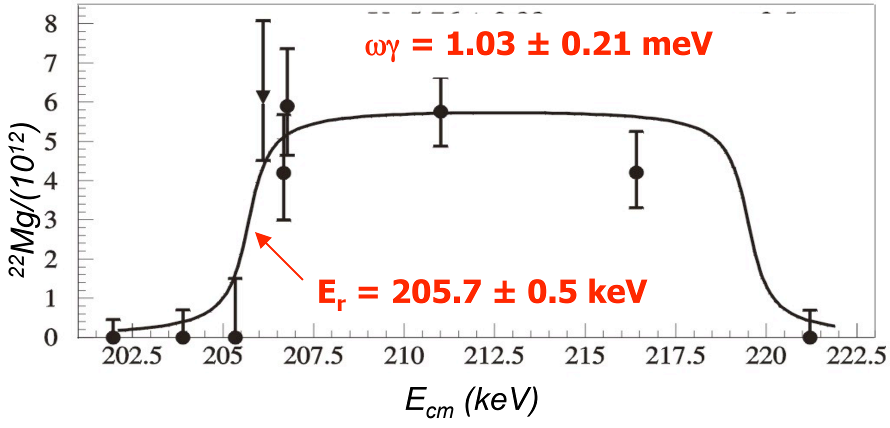



ωγ = 556 ± 77 meV

Γ=16 keV

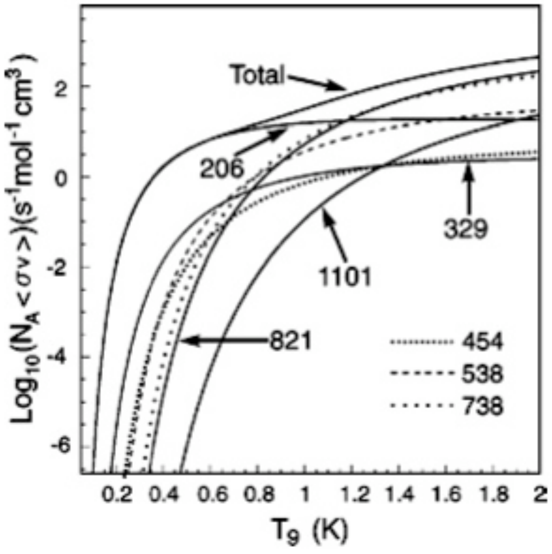
*J. D'Auria et al., PRC **69** (2004) 065803.*

*S. Bishop et al., PRL **90** (2003) 162501.*


ωγ = 1.03 ± 0.21 meV

E_r = 205.7 ± 0.5 keV

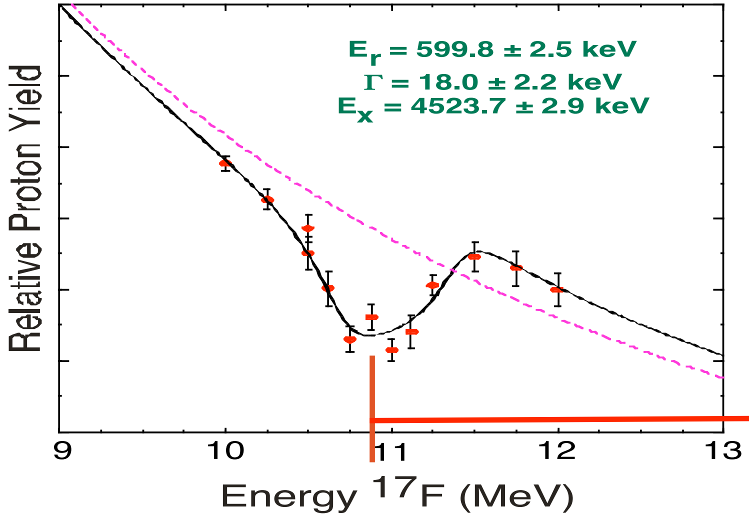
^{21}Na(p,γ)^{22}Mg
uncertainty
now only 20%

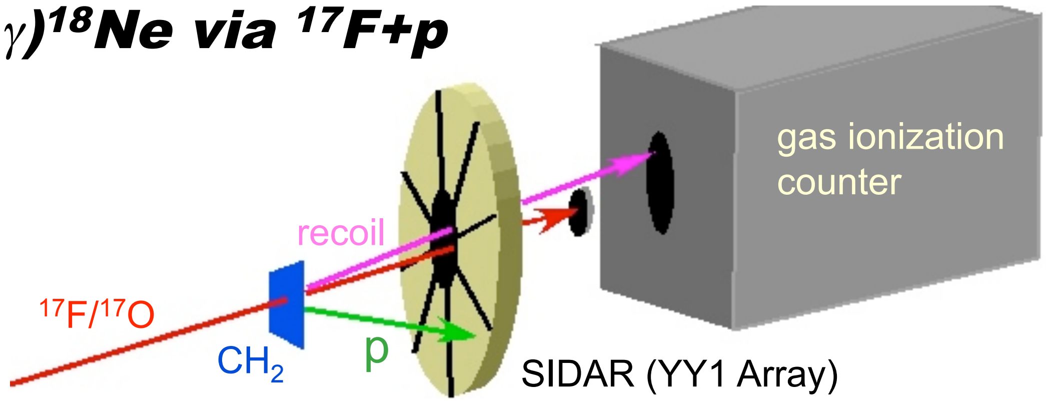


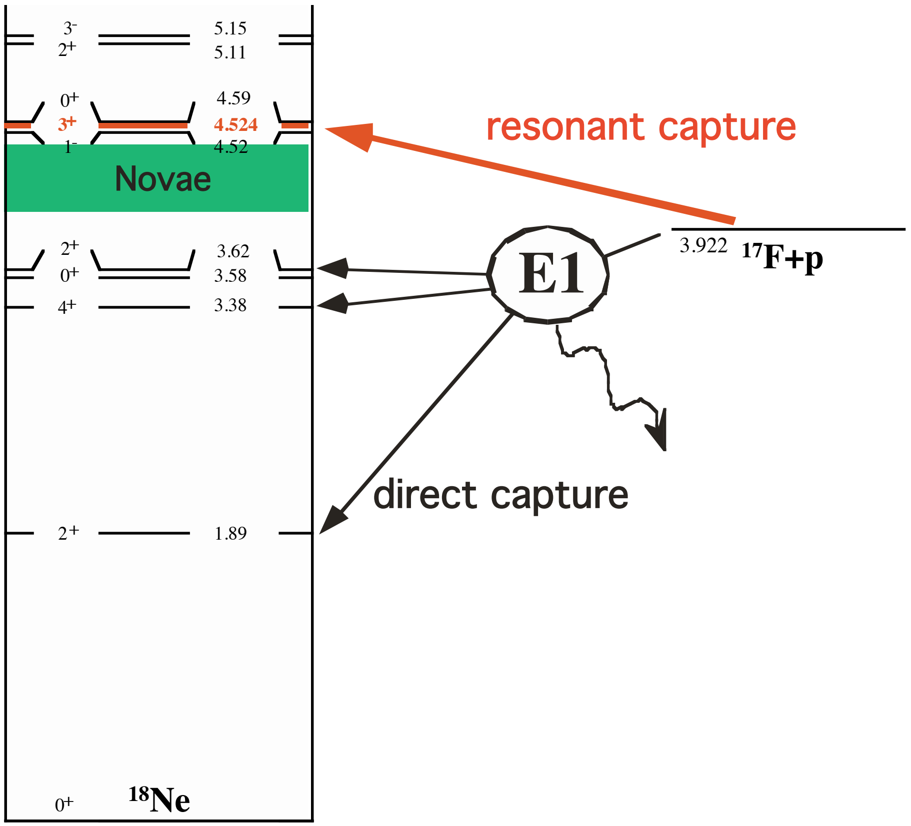
Where are the resonances?

$^{17}F(p,\gamma)^{18}Ne$ via $^{17}F+p$

Bardayan *et al.*, PRC**62** (2000) 055804.





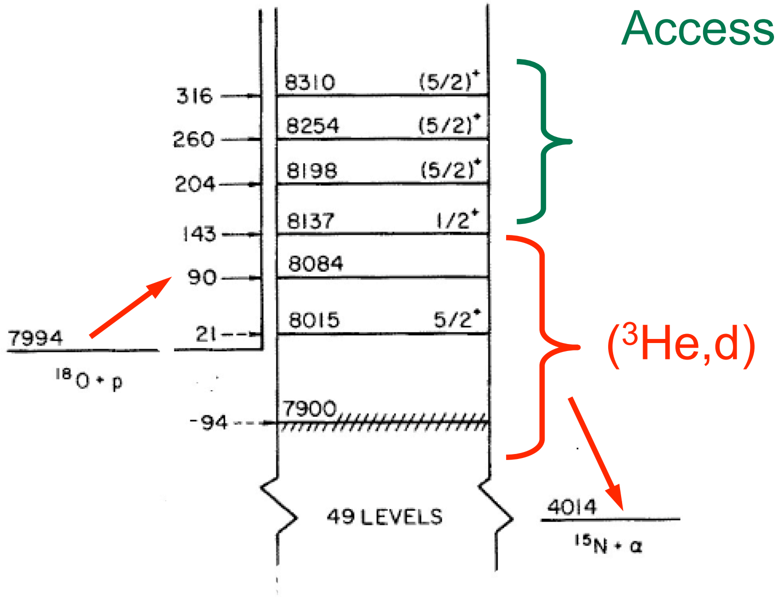


- ➢ 3$^+$ state expected from mirror symmetry, but not observed in transfer reactions
  - ^{20}Ne(p,t)^{18}Ne
  - ^{16}O(^{3}He,n)^{18}Ne
- ➢ Resonance energy and width accurately determined from ^{17}F+p elastic scattering

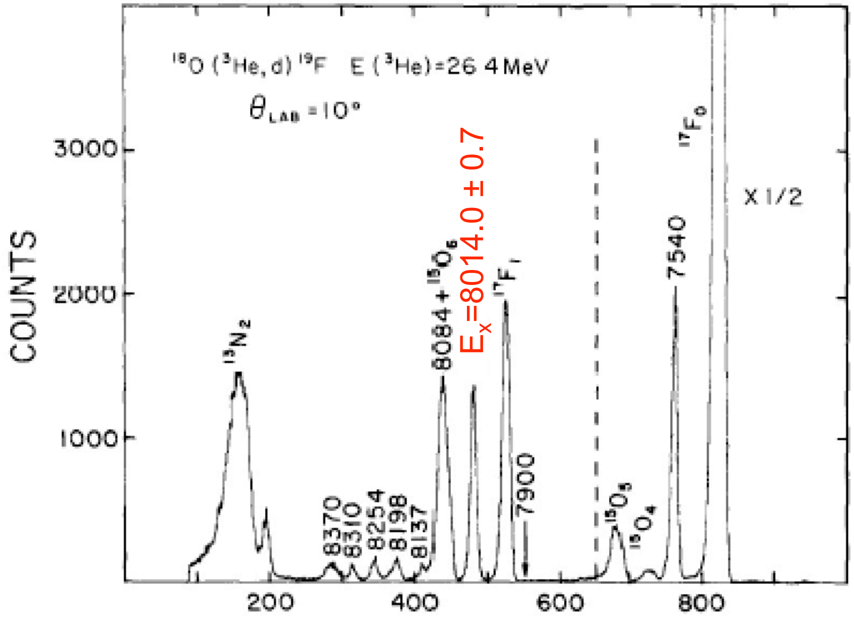
  Only ***s-wave*** resonances have strong signatures at low energies

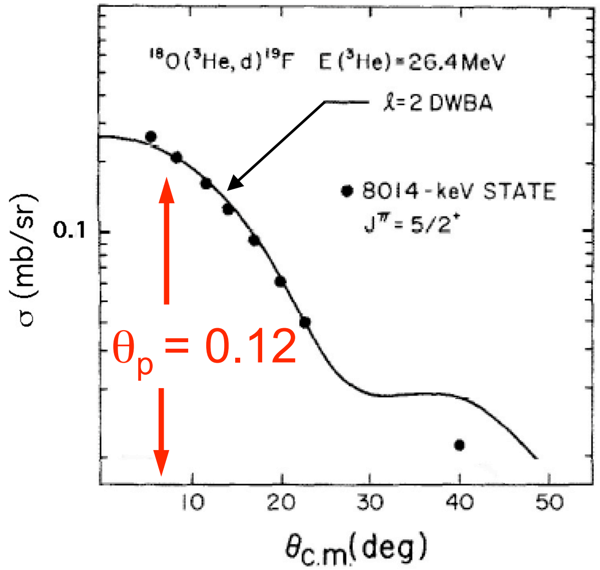
Classic Example: $^{18}O(p,\alpha)^{15}N$ via (^{3}He,d)

Accessible with high intensity proton beams



Champagne and Pitt (1986)



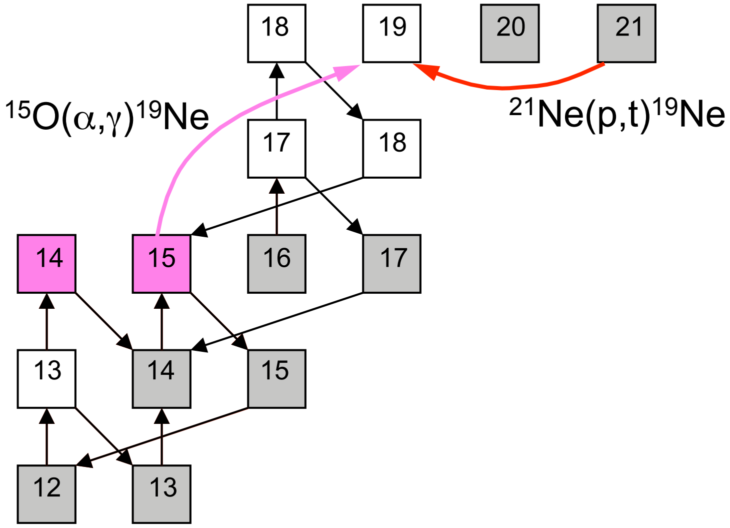


$$\Gamma_p = 2\left(\frac{\hbar^2}{\lambda\mu R}\right)\left(\frac{\theta_p^2}{F_\ell^2+G_\ell^2}\right) \Longrightarrow \Gamma_p = 2\text{x}10^{-19}\ \text{eV}$$

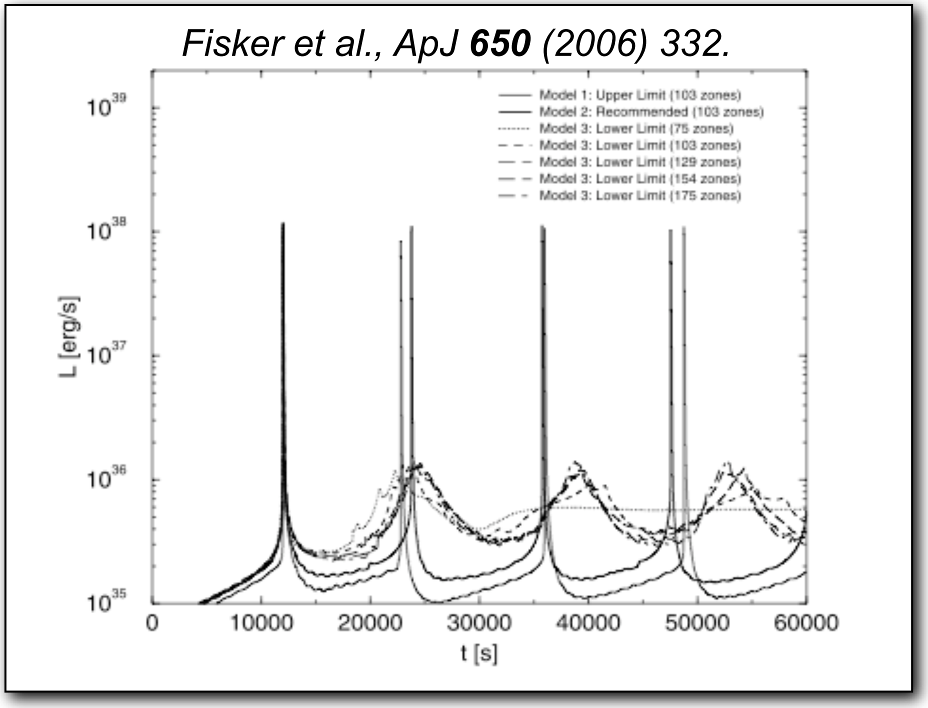
1 mA p + ^{18}O → 1 event / 3x10^5 years

- ➢ Accurate E_x
- ➢ Unambiguous ℓ, J^π inferred
- ➢ Γ if broad
- ➢ Γ_x sometimes, but can be model dependent

Recent example: $^{15}O(\alpha,\gamma)^{19}Ne$ reaction

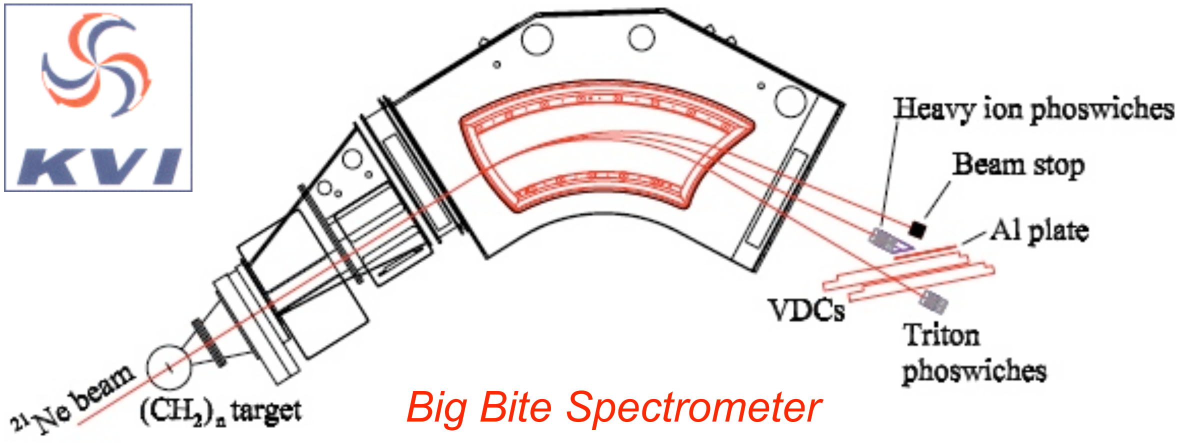


- ➢ The $^{15}O(\alpha,\gamma)^{19}Ne$ reaction rate produces substantial qualitative changes in the X-ray burst light curve

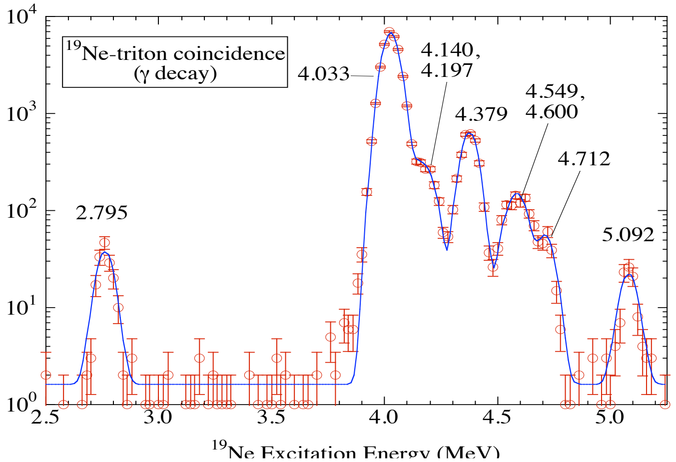

Fisker et al., ApJ ***650*** *(2006) 332.*

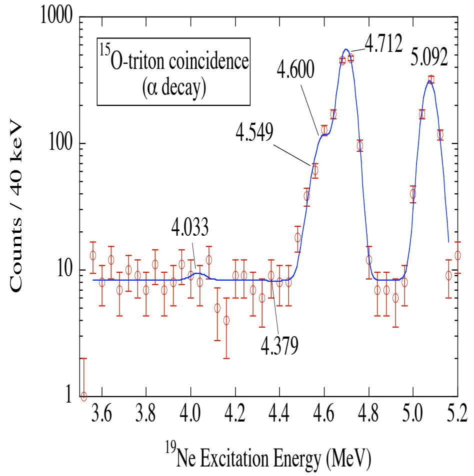
- ➢ Direct measurement of the $^{15}O(\alpha,\gamma)^{19}Ne$ rate would require ~μA beam intensities
- ➢ Crucial quantities are Γ_α's of resonances, particularly state at E_x=4.03 MeV
- ➢ Populate state using another reaction and measure B_α

$$B_\alpha = \frac{\Gamma_\alpha}{\Gamma}$$



Big Bite Spectrometer





*Davids et al., PRC **67** (2003) 065808.*

$B_\alpha < 4\times10^{-4}$

E_x (MeV)	Γ_α/G
4.033	< 0.0004
4.379	< 0.004
4.549	0.16±0.04
4.6	0.32±0.04
4.712	0.85±0.04

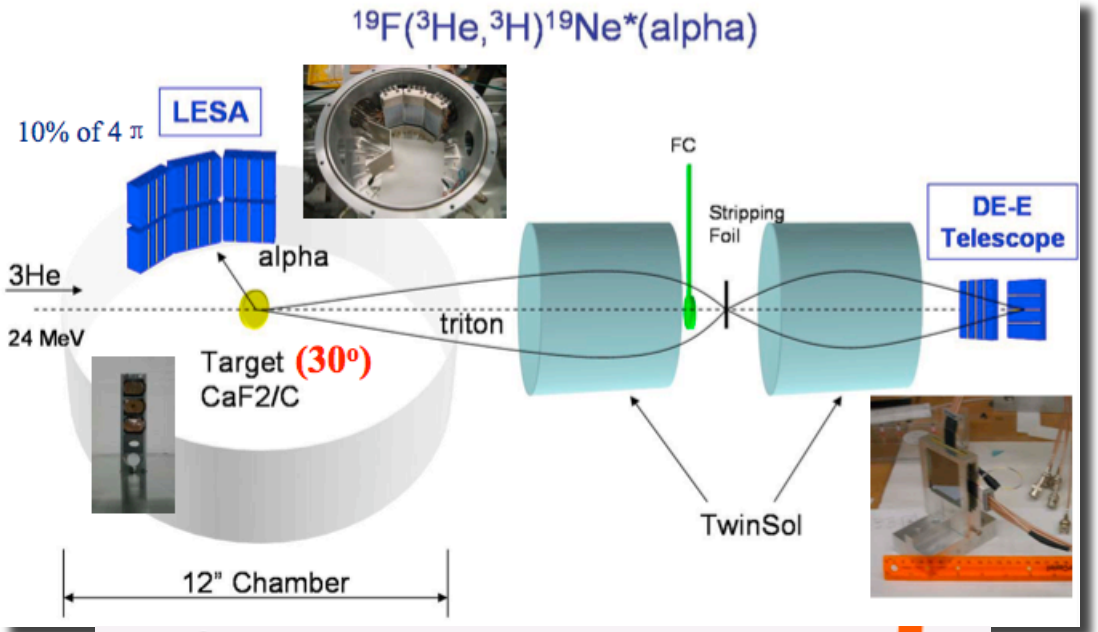
- Somewhat similar measurement about the same time at ANL using the Enge splitpole:

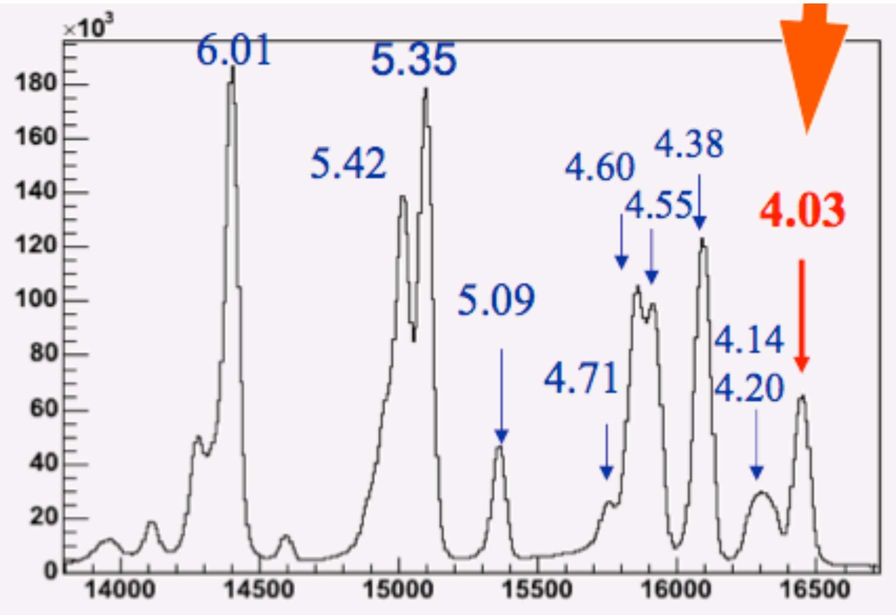
*Rehm et al., PRC **67** (2003) 065809.*

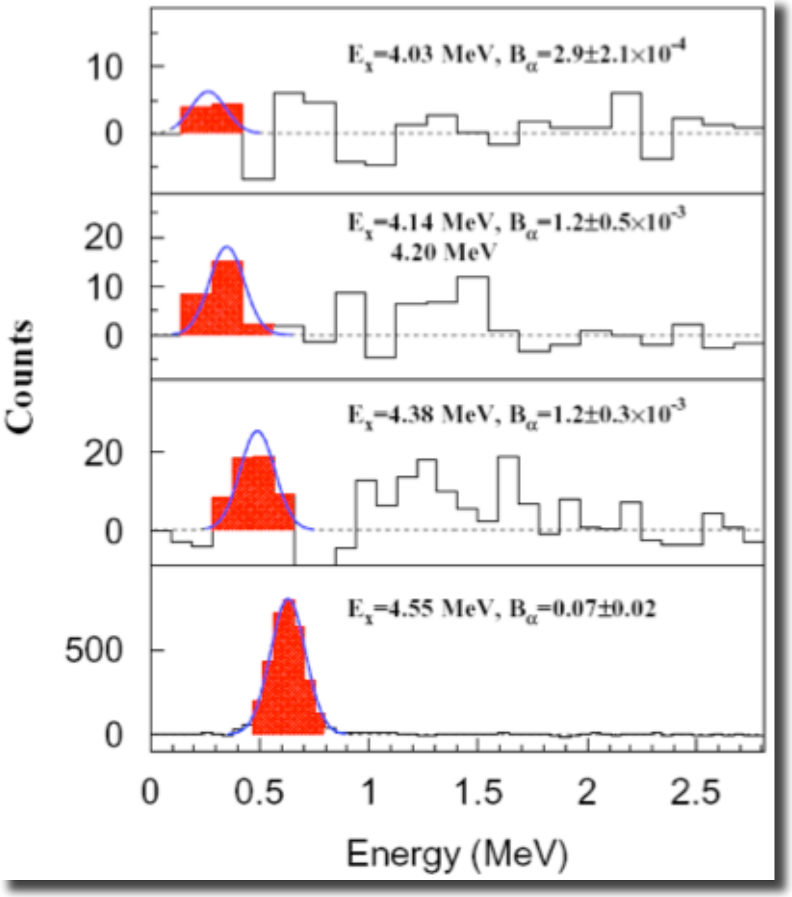
^{3}He(^{20}Ne,α)^{19}Ne$\rightarrow$^{15}O+ α

$B_\alpha < 6\times10^{-4}$

3rd reaction







Tan *et al.*, PRL **98** (2007) 242503.

$B_\alpha = (2.9 \pm 2.1) \times 10^{-4}$

Exercise for the student: $^{15}O(\alpha,\gamma)^{19}Ne$

The $^{15}O(\alpha,\gamma)^{19}Ne$ reaction is one of the most important reactions in X-ray binaries. The $^{15}O(\alpha,\gamma)^{19}Ne$ reaction rate is dominated by the contribution from a single 4.03 MeV (E_{cm}=504 keV, $J^{\pi}=3/2^{+}$) resonance in ^{19}Ne. Plot the density as a function of temperature where the $^{15}O(\alpha,\gamma)^{19}Ne$ rate is equal to the beta decay rate. Use the narrow-resonance approximation for the $^{15}O(\alpha,\gamma)^{19}Ne$ reaction rate:

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

The number of alpha particles/cm^3, N_α, is given by:

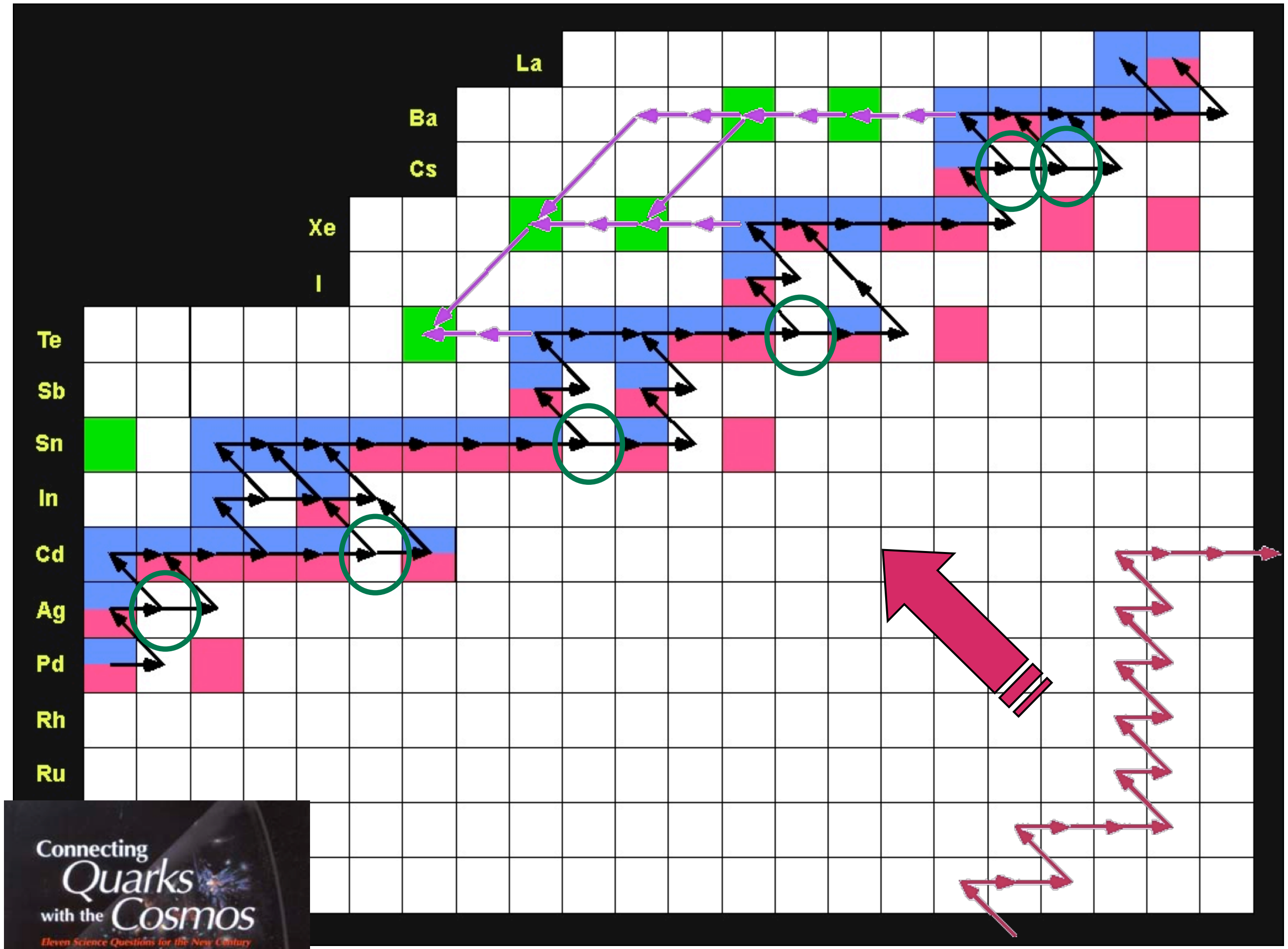
$$N_\alpha = \rho X_\alpha \frac{A}{w_\alpha}$$

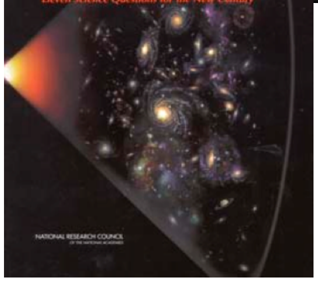
where ρ is the density (*g/cm*^{3}), A is Avogadro's number, and w_α is the molecular weight of helium (4 g/mole). Take the mass fraction of ^4He, X_α, *to be 25%*

Assume the alpha-decay branching ratio of the 4.03 MeV resonance to be 4×10^{-4}, about the current upper limit. The ^{15}O ground state has $J^{\pi}=1/2^{-}$. What is the orbital angular momentum of the captured alpha particle?

The maximum temperature and density in nova explosions is 4×10^{8} K and 10^{5} g/cm^3. Is this reaction important in novae?

Synthesis of elements heavier than iron





“What is the origin of the heavy elements?”
One of the top 11 questions

- **s process**
  - ~ 80% of isotopes
  - Most (n,γ) rates known
  - Branch points crucial
- **r process**
  - ~ 70% of isotopes
  - Far from stability
  - Supernovae?
- **p process**
  - ~ 10% of isotopes
  - Very low abundance
  - Secondary process

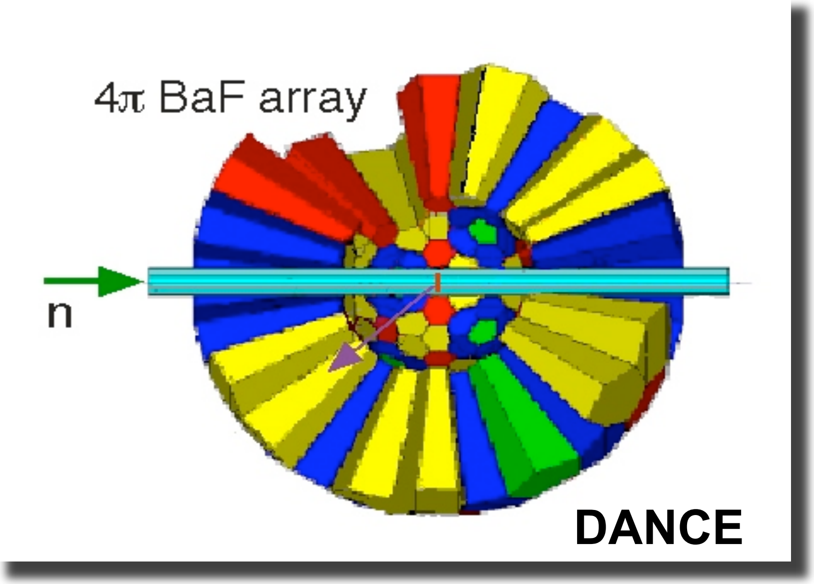
Neutron capture on long-lived nuclei

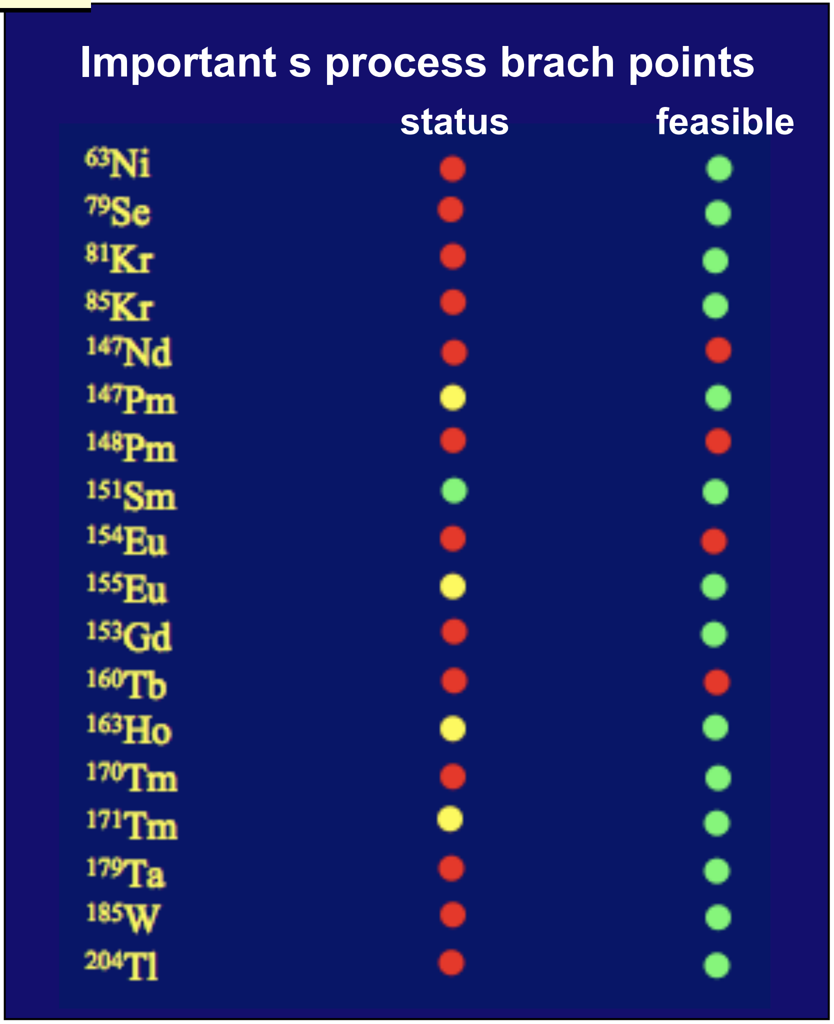
Source	***ORELA***	***Lujan***	***n TOF***	***SNS***
flight path (m)	40	20	180	20
resolution (ns/m)	0.2	6.2	0.05	18
power (kW)	8	64	45	2000
flux (n/s/cm^2)	2×10^4	5×10^6	3×10^5	2×10^8
FOM (n/s/cm^2)	5×10^5	6×10^9	5×10^8	9×10^{10}

Experiments now possible with samples of only ~ 10^{16} atoms/cm^2.

High efficiency detector arrays

High segmentation to handle rate from radioactive sources

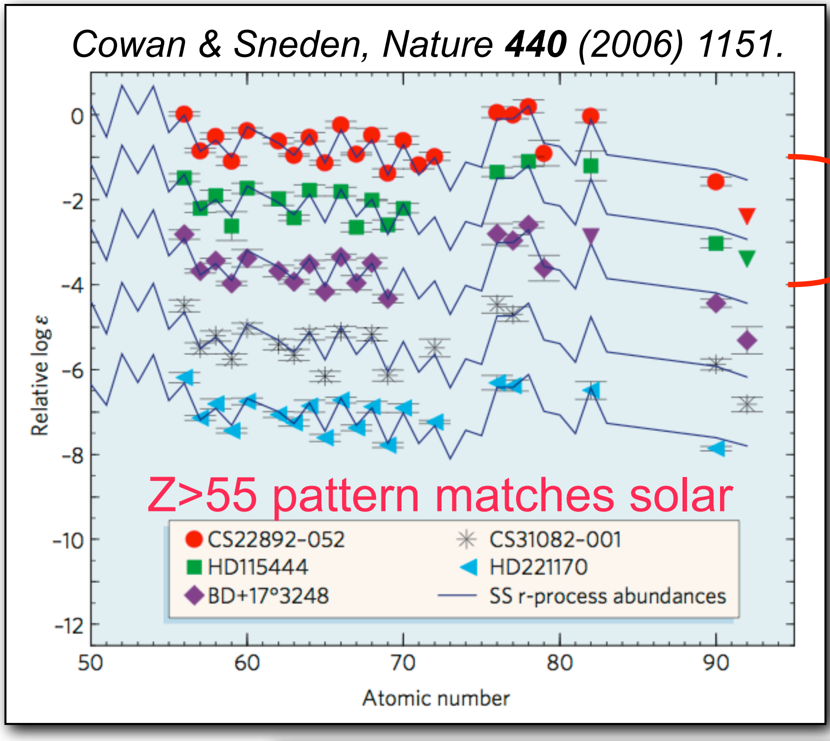




Important s process brach points

	status	**feasible**
^{63}Ni	🟥	🟩
^{79}Se	🟥	🟩
^{81}Kr	🟥	🟩
^{85}Kr	🟥	🟩
^{147}Nd	🟥	🟥
^{147}Pm	🟨	🟩
^{148}Pm	🟥	🟥
^{151}Sm	🟩	🟩
^{154}Eu	🟥	🟥
^{155}Eu	🟨	🟩
^{153}Gd	🟥	🟩
^{160}Tb	🟥	🟥
^{163}Ho	🟨	🟩
^{170}Tm	🟥	🟩
^{171}Tm	🟨	🟩
^{179}Ta	🟥	🟩
^{185}W	🟥	🟩
^{204}Tl	🟥	🟩

New observations are allowing us to study the early evolution of the heavy elements in the Galactic halo



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

Z>55 pattern matches solar

Stars with:

Fe/H < (0.001) solar → very old

heavy/Fe = 50 solar

Only 2 known in 2000

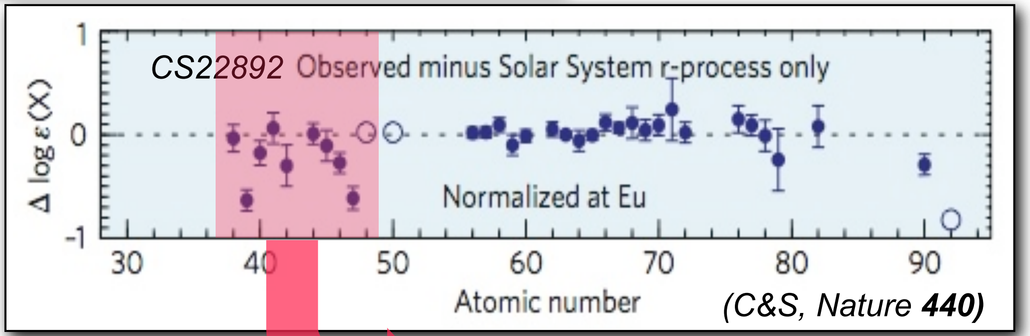
Now extensive surveys

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

SEGUE (Sloan DSS)

Spectra of >2x10^5 selected halo stars

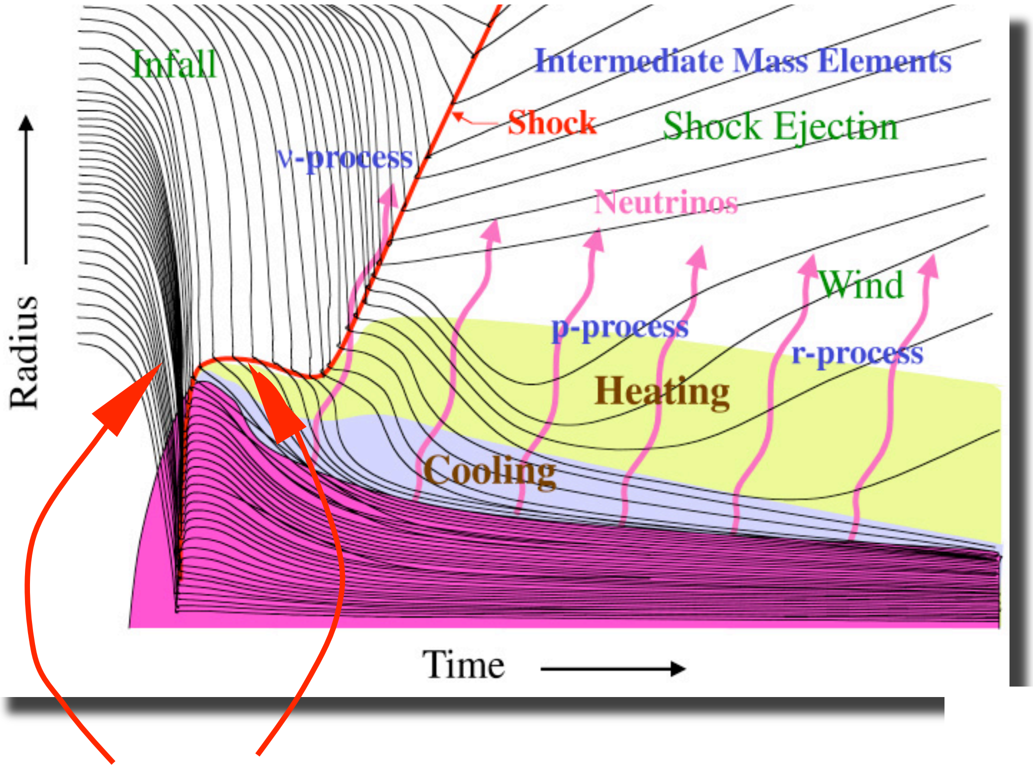
Expect ~ 1% with Fe/H < 0.001solar



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

Z<50 abundances vary

Usual suspect: Core collapse supernovae



- ➢ Explosion mechanism is not well understood.
- ➢ Electron capture rates affect formation of shock wave.
- ➢ Neutrino interactions play a role in dynamics and nucleosynthesis.
- ➢ Weak rates in this mass region are not well understood:
  - GT strength distributions
  - first-forbidden contribution

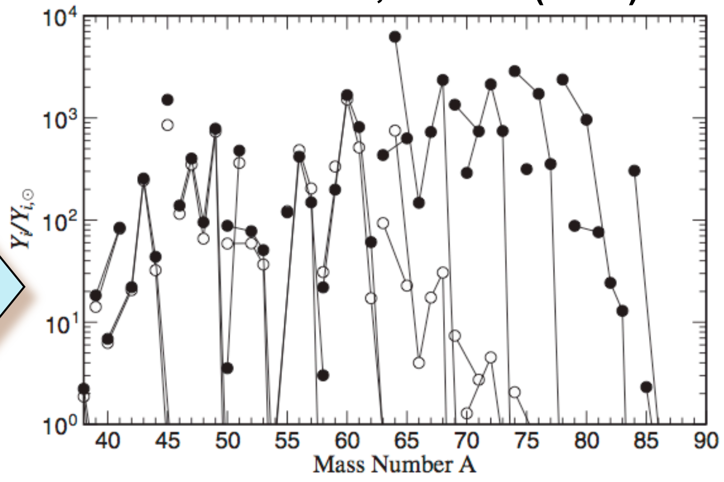
Weak interaction plays an important role in

Abundaces relative to solar

● with ν reactions

○ without ν reactions

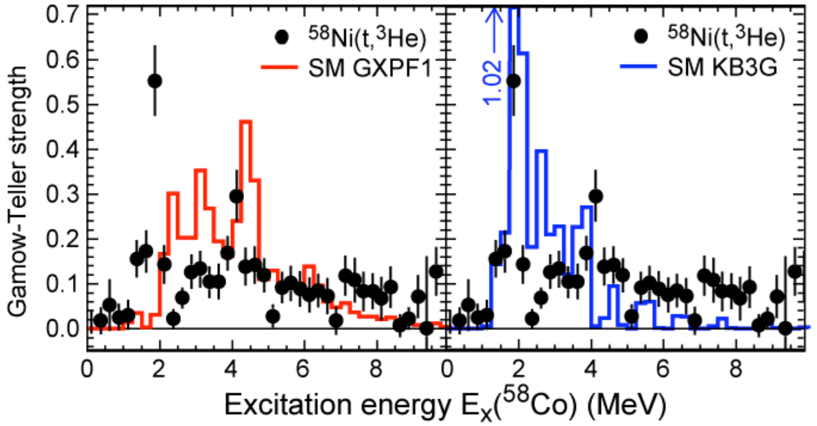
Fröhlich *et al.*, PRL 96 (2006)



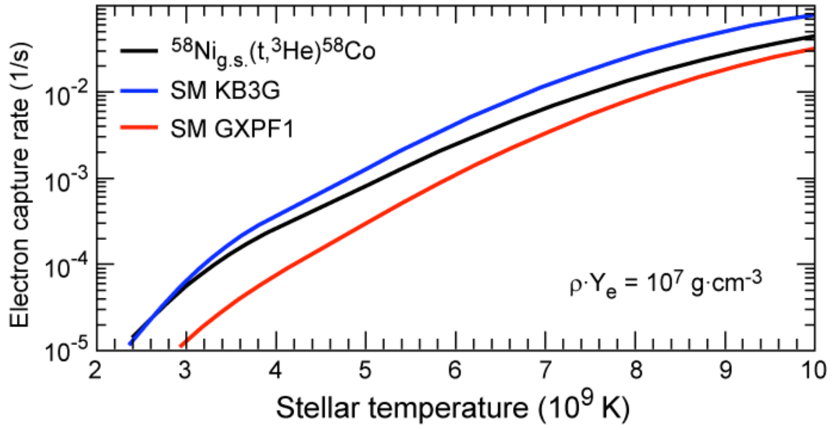
Zegers *et al.*

Charge exchange reactions with fast beams at the NSCL

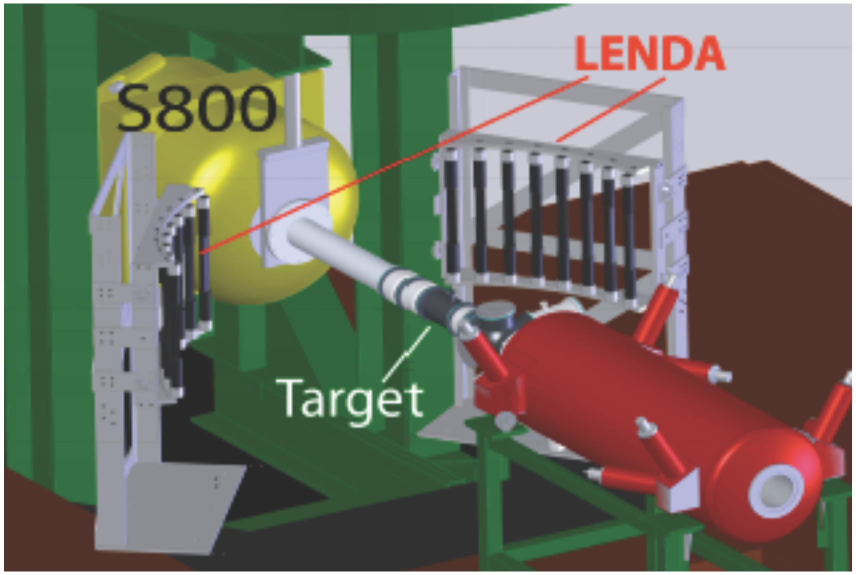
Charge exchange reactions such as (t,^{3}He) and (p,n) have been measured on some stable nuclei and provide sensitive probes of Gamow-Teller strength at 100 – 200 MeV/u.



Shell model calculations using the best interactions do not do an adequate job in predicting electron capture rates

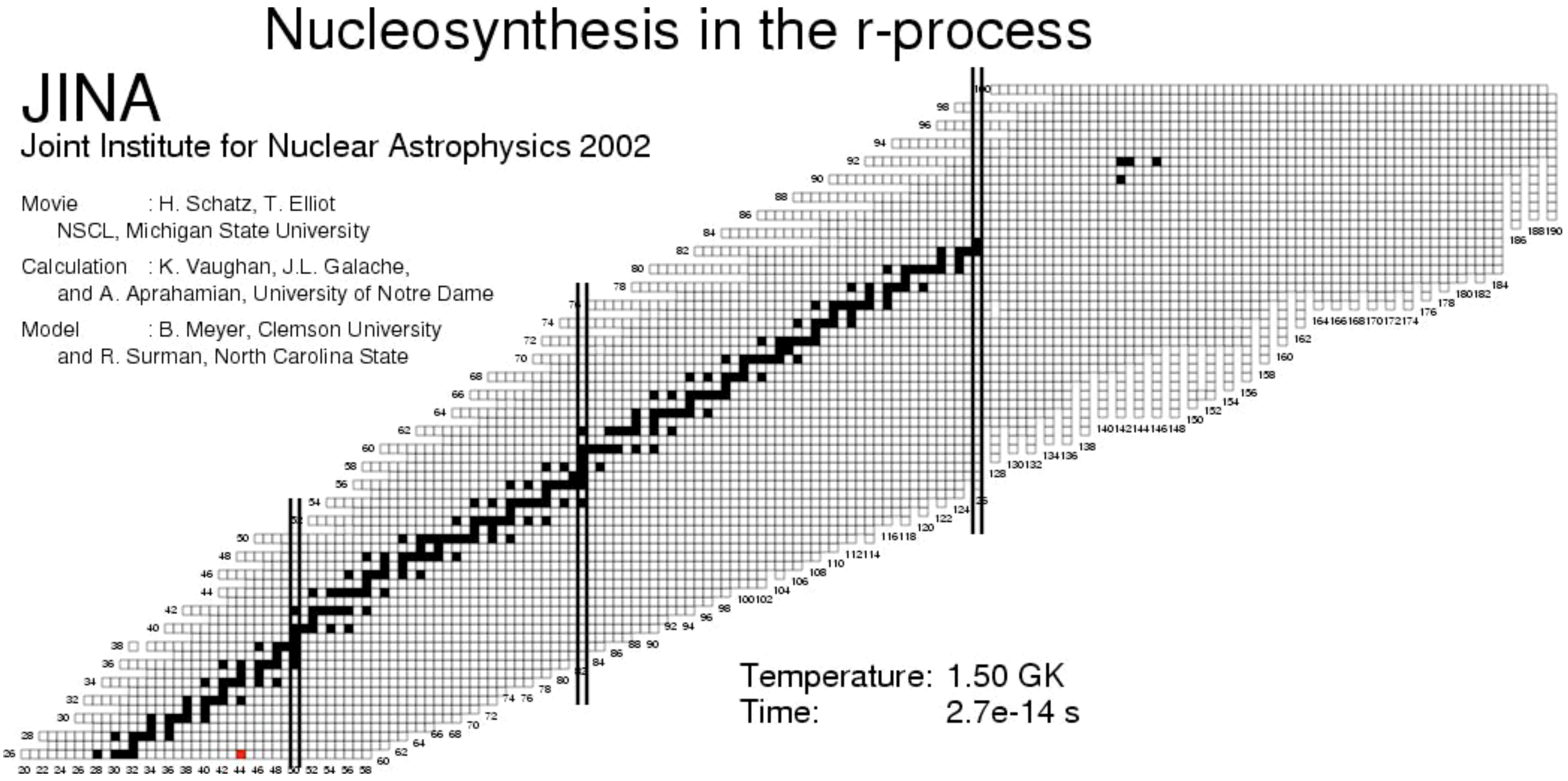


Measurements on radioactive nuclei are very important, but require new experimental techniques



The LENDA neutron detector array is being developed at the NSCL for measurements of the (p,n) reaction in inverse kinematics

Calculated r process



Nucleosynthesis in the r-process

JINA

Joint Institute for Nuclear Astrophysics 2002

Movie : H. Schatz, T. Elliot
NSCL, Michigan State University

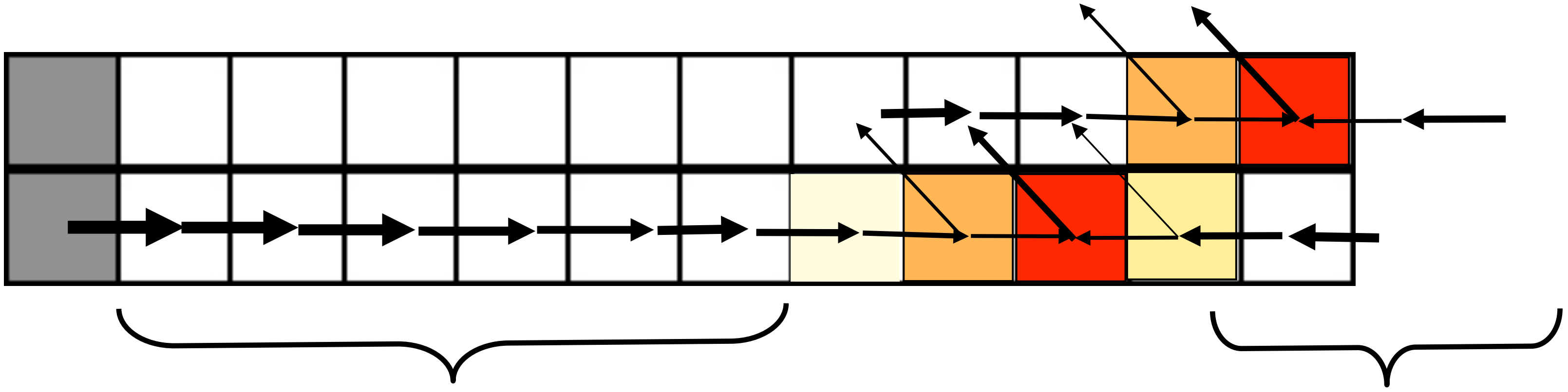
Calculation : K. Vaughan, J.L. Galache,
and A. Aprahamian, University of Notre Dame

Model : B. Meyer, Clemson University
and R. Surman, North Carolina State

Temperature: 1.50 GK
Time: 2.7e-14 s

r process cartoon

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



Large S_n

$(n,\gamma) >> (\gamma,n) >> t_{1/2}$

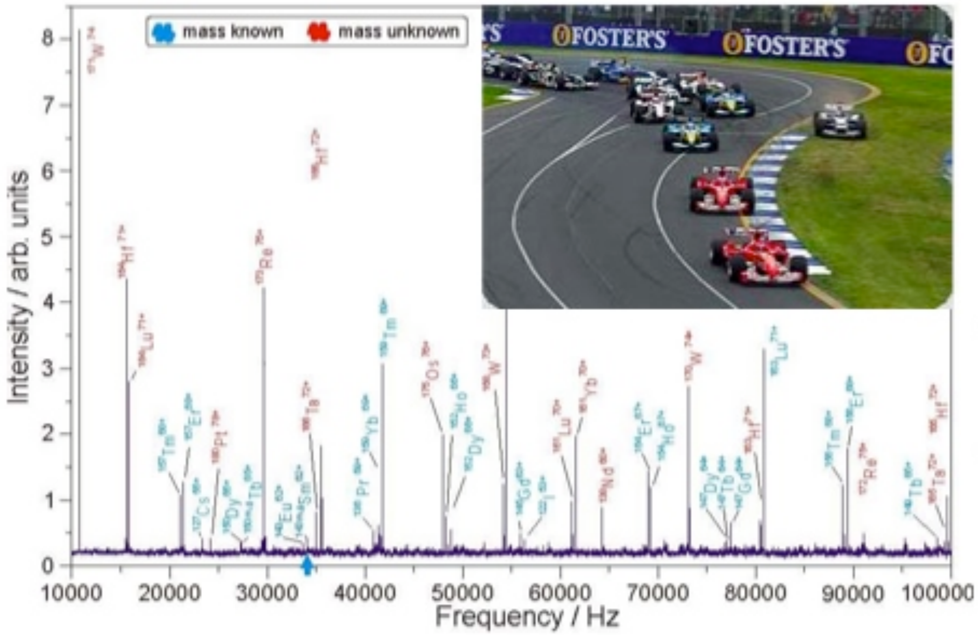
Small S_n

$(\gamma,n) >> (n,\gamma) >> t_{1/2}$

- ➢ Dynamics: n_n, kT, t from astrophysical model
- ➢ Freezeout is relatively fast, followed by decay to stability

Masses, $t_{1/2}$, and P_n are crucial

Mass measurements



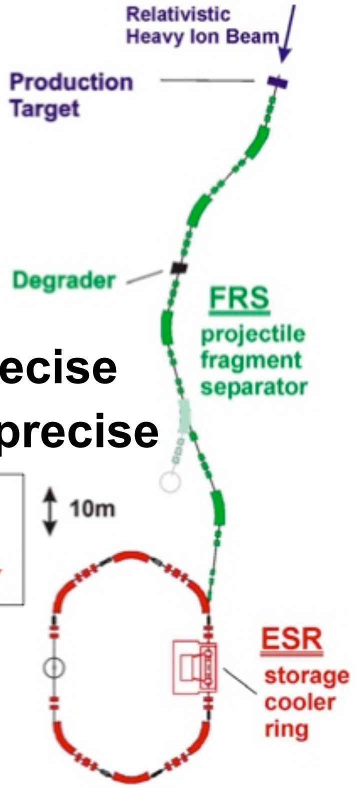
2 modes:

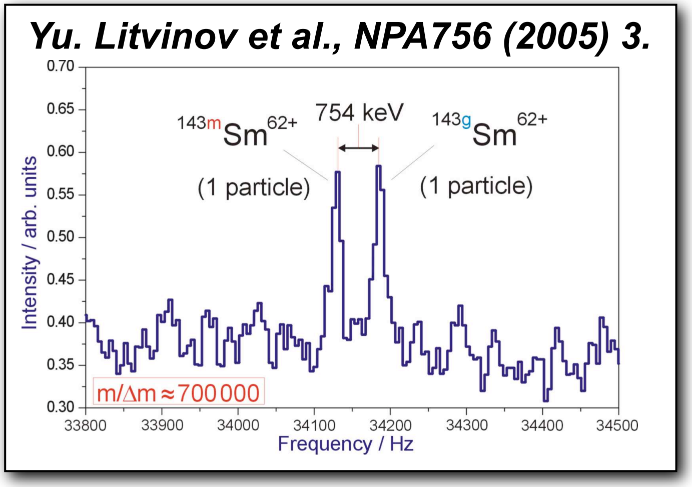
Schottky - slow, more precise

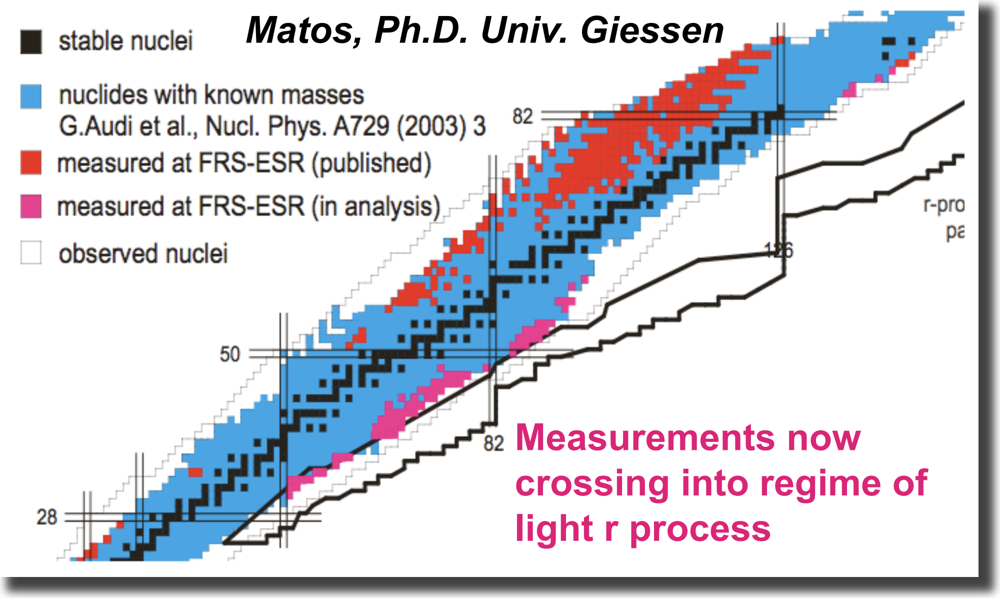
isochronous - fast, less precise

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.

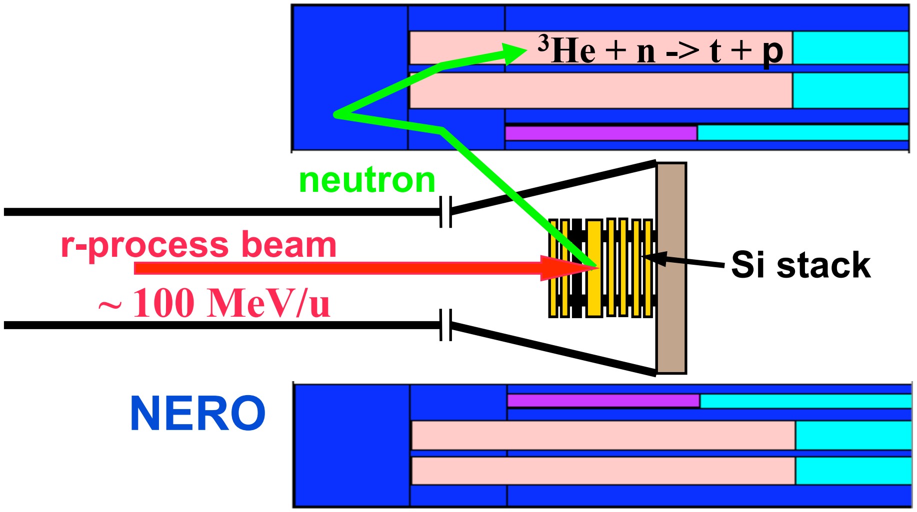

Matos, Ph.D. Univ. Giessen

Measurements now crossing into regime of light r process

The Joint Institute for Nuclear Astrophysics

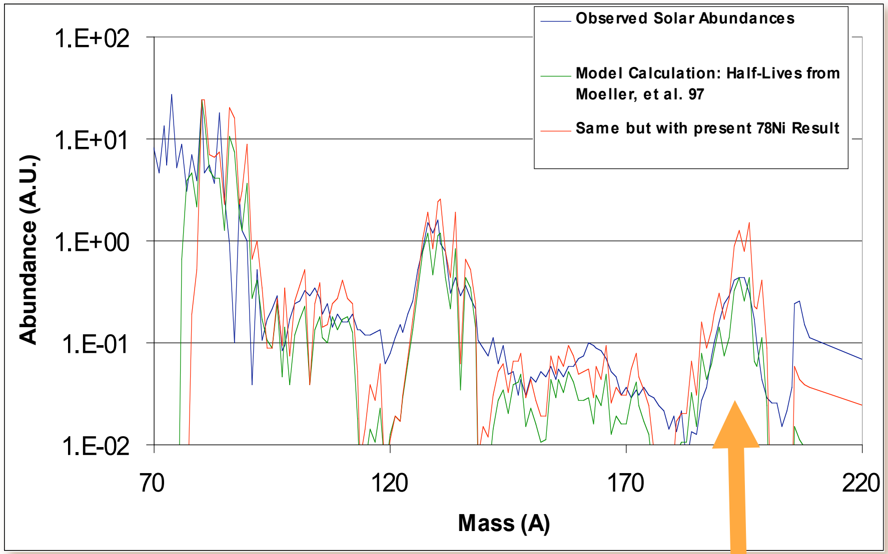
P. Hosmer et al. PRL 94 (2005) 112501.

NSCL fast beam r-process campaign: the half-life of ^{78}Ni



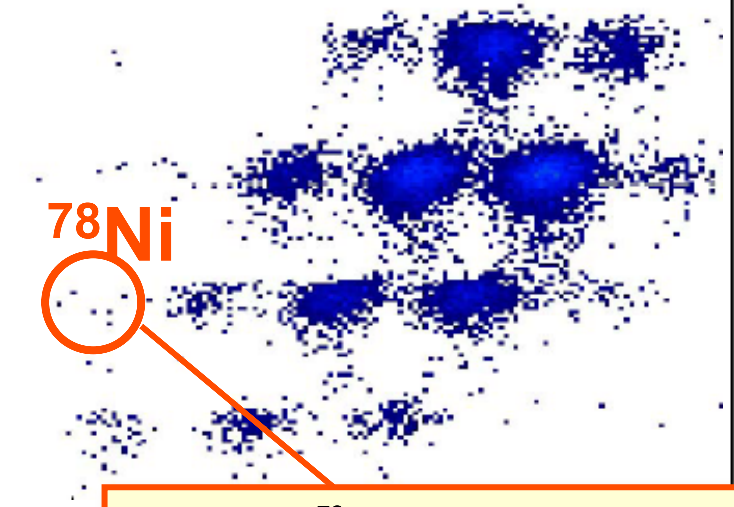
$t_{1/2}(^{78}Ni)$: 110 $^{+100}_{-60}$ ms

Effect of new $t_{1/2}$ on r process abundances



Shorter ^{78}Ni half-life leads to greater production of A=190 peak

Particle identification in rare isotope beam

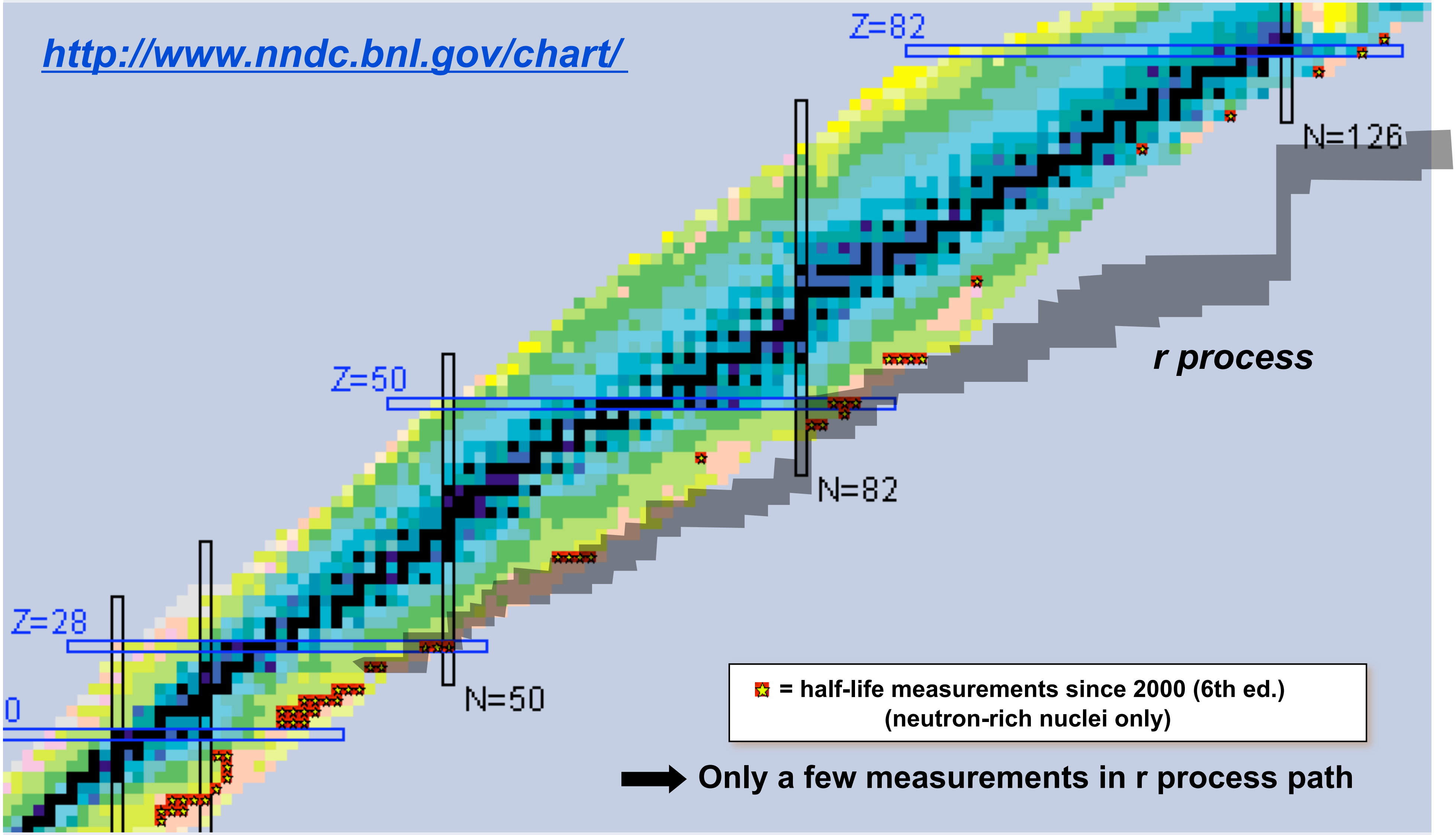


Half-life of ^{78}Ni measured with 11 events.

The properties of neutron-rich nuclei are crucial for understanding the site(s) of the r process and the chemical history of the Galaxy

The Chart of the Nuclides

http://www.nndc.bnl.gov/chart/

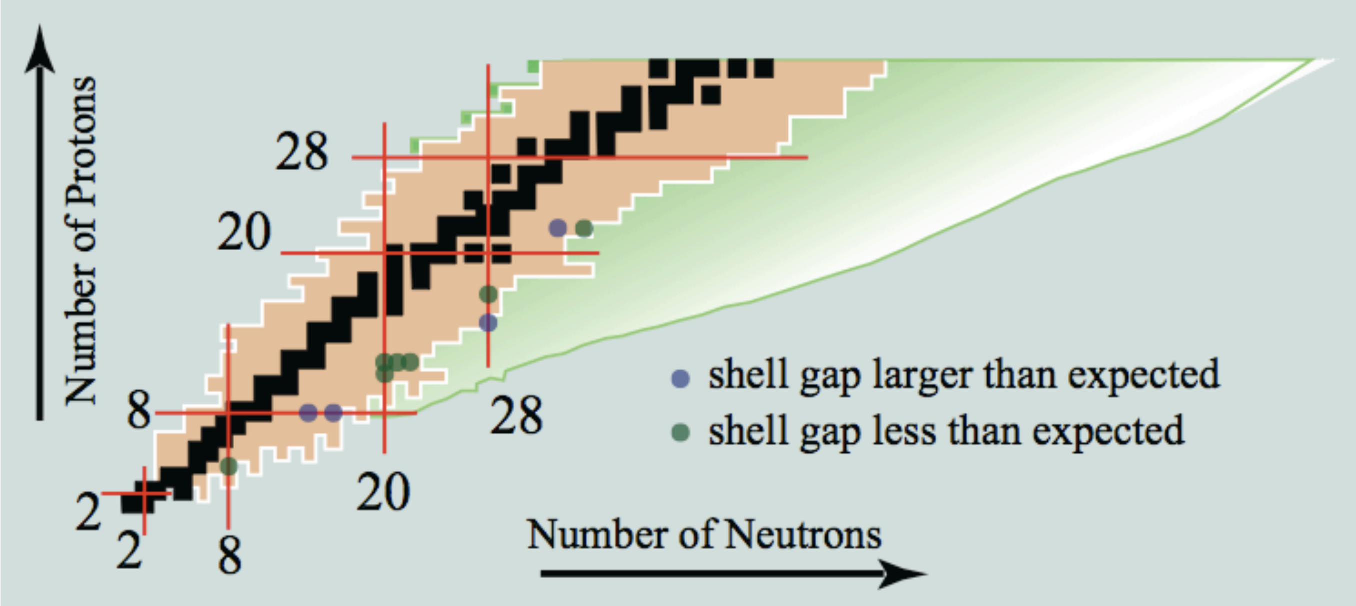


★ = **half-life measurements since 2000 (6th ed.)**
(neutron-rich nuclei only)

➡ **Only a few measurements in r process path**

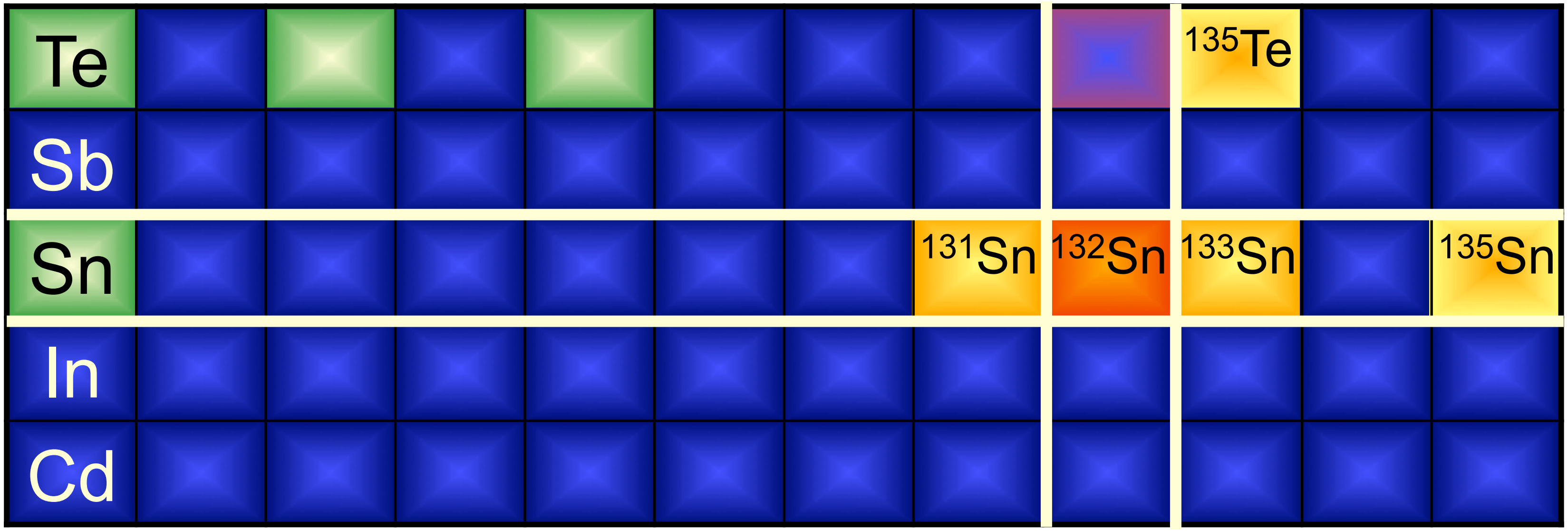
Nuclear structure and astrophysics

- Not all masses and half-lives can/will be measured.
- Our understanding of the synthesis of nuclei in the r process must depend upon nuclear theory.
- Measurements of light isotopes have shown surprises, including modifications to the magic numbers.
- What is expected in heavier nuclei near the r process?
- Nuclear structure studies are crucial to improving the reliability with which nuclear models can extrapolate to more neutron-rich isotopes

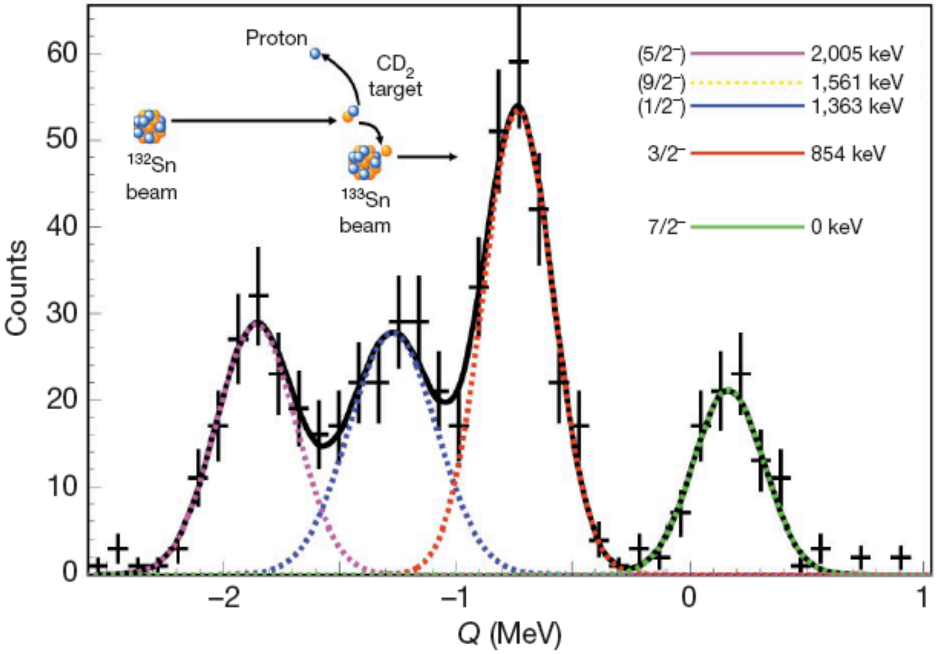


Structure around ^{132}Sn

K.L. Jones et al. Nature 465 (2010) 454.



- States populated using the (d,p) neutron-transfer reaction in inverse kinematics at the HRIBF.
- Angular distributions of protons measured in coincidence with recoiling heavy ions.
- States in ^{133}Sn found to be strongly single-particle in nature, showing that ^{132}Sn is a good “doubly-magic” nucleus.



The current frontiers of experimental nuclear astrophysics

- Direct measurements of cross sections with intense stable ion beams deep underground
- Direct measurements of charged particle induced reactions using proton-rich radioactive ion beams
- Innovative indirect approaches using both stable and radioactive ion beams
- Mass and decay property measurements of the most neutron-rich nuclei
- Nuclear structure studies to improve our understanding of the evolution of nuclear structure with isospin
- ***New capabilities*** to produce a much larger variety of isotopes are required