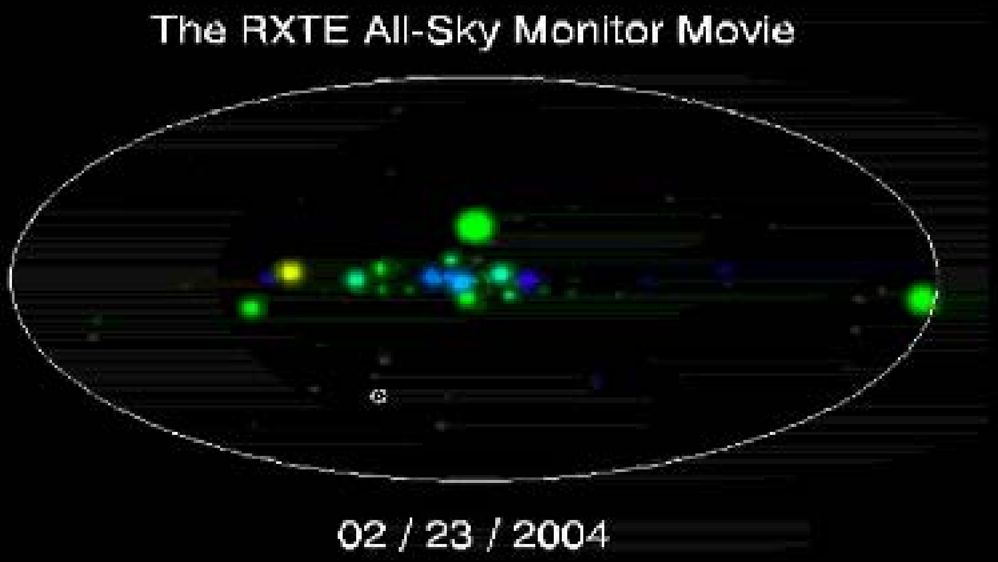
Nuclear Astrophysics

Lecture III: Stellar explosions

Jeff Blackmon, Physics Division, Oak Ridge National Laboratory



http://heasarc.gsfc.nasa.gov/xte_weather/

- Radioactive nuclei play an important role in stellar explosions
  - Novae, t ~ 10 minutes
  - X-ray bursts, t ~ minute
  - Supernovae, t ~ few seconds → source of the heavy elements

thermonuclear events

Nuclear astrophysics

A survey in 6 parts

Jeff Blackmon, Physics Division, ORNL

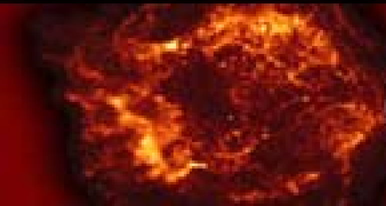
Nuclear physics plays an important role in astrophysics:

$$\left.\begin{array}{l}\text{Energy generation}\\ \text{Synthesis of elements}\end{array}\right\}\ \text{astronomical observables}$$

1. Introduction
2. Big Bang
3. Stellar structure & solar neutrinos
4. Stellar evolution & s process

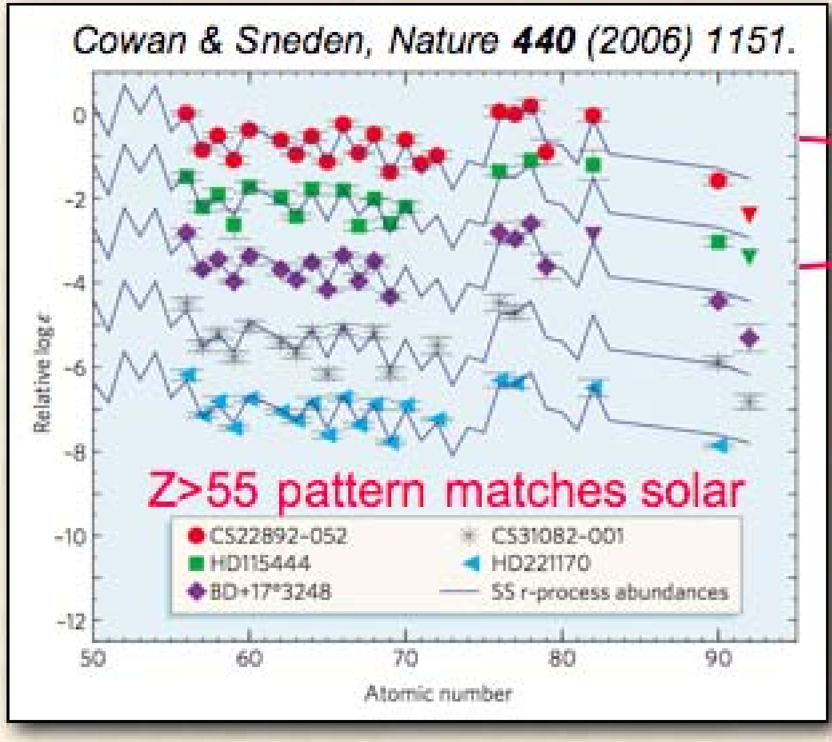
→ 5. Supernovae & r process

6. Binary systems



Creation of elements in the early Galaxy

Now many observations of unmixed supernova nucleosynthesis in the Galactic halo



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

Z>55 pattern matches solar

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

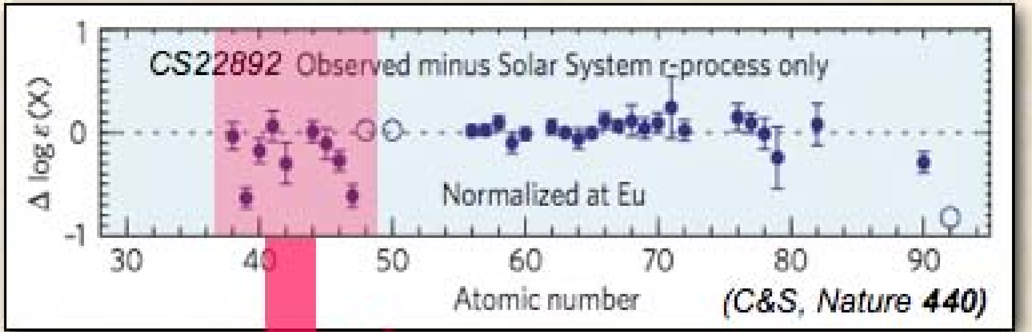
Expect ~ 1% with Fe/H < 0.001solar

~36 known r process stars

11 with r/Fe > 10 solar

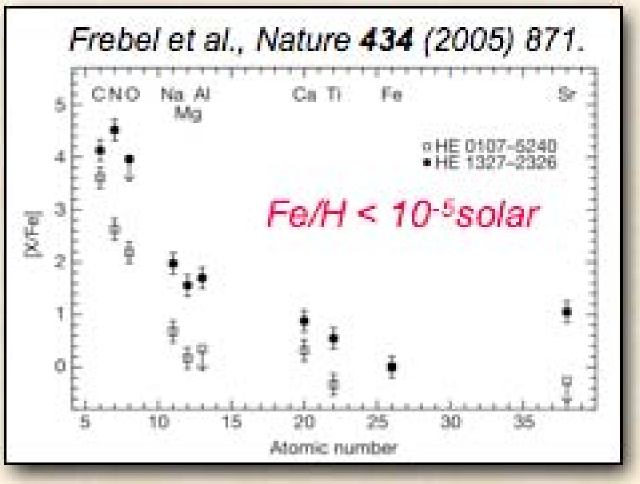
Distribution Fe/H puzzling

Lowest Fe/H stars intriguing



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

Z<50 abundances vary



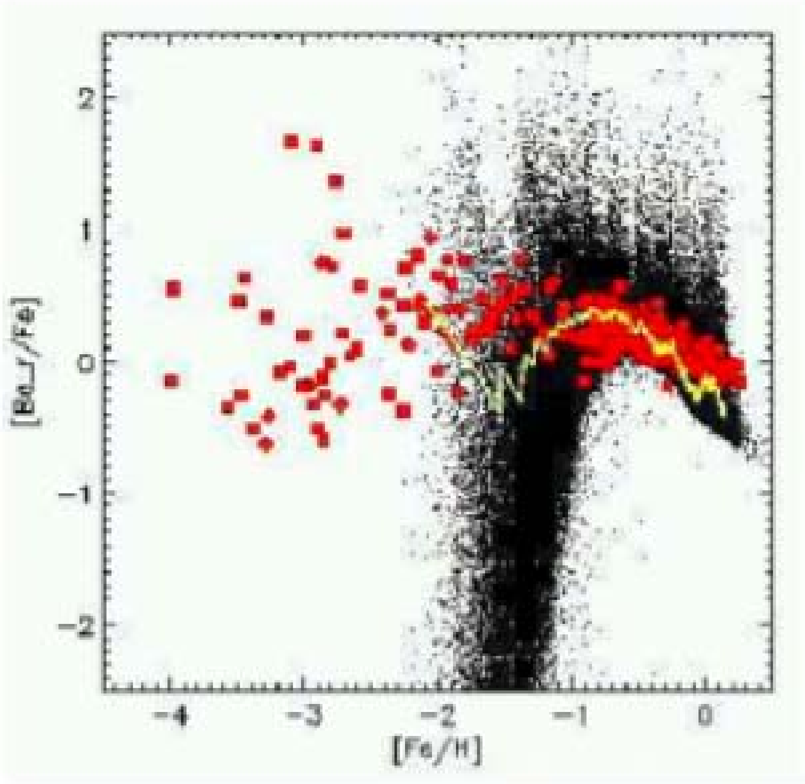
Frebel et al., Nature ***434*** *(2005) 871.*

Fe/H < 10^{-5}solar

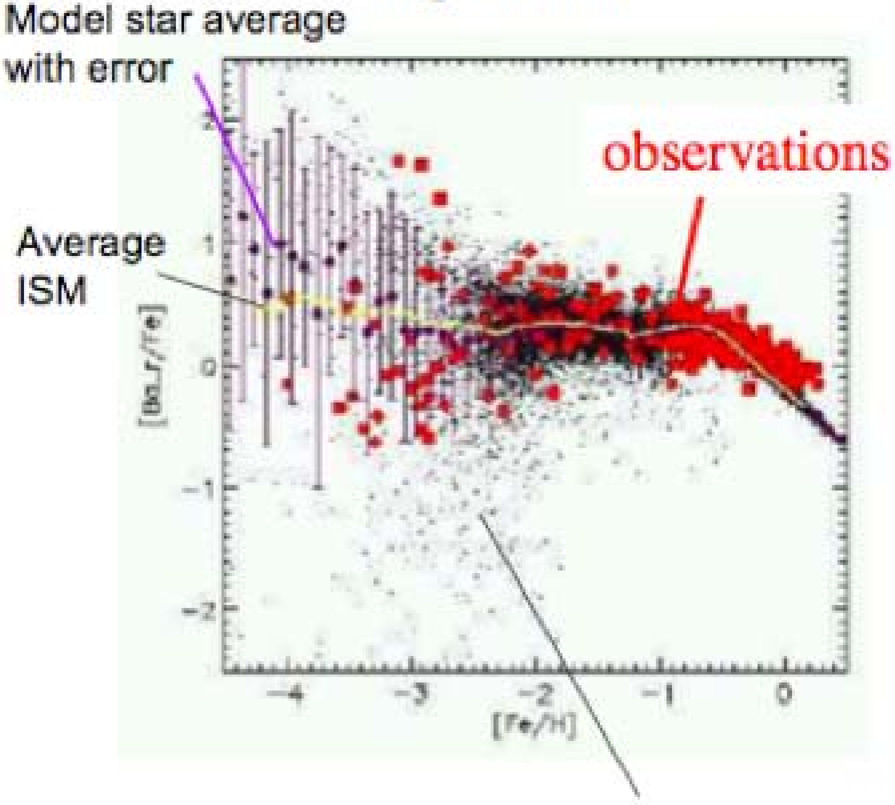
The r process site

Galactic chemical evolution arguments favor supernovae as the dominant source for elements early in the history of the Galaxy → an r process

NS mergers



Supernovae



Model star average with error

Average ISM

observations

Dots: model stars

Argast et al., A&A 416 (2004) 997.

Core-collapse supernovae

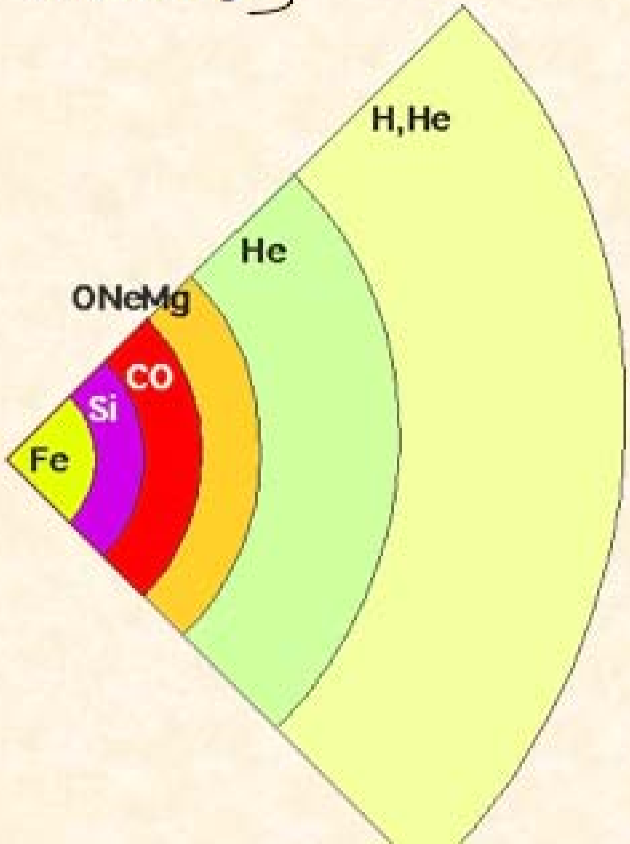
Stars > 10 solar masses

  Higher gravity

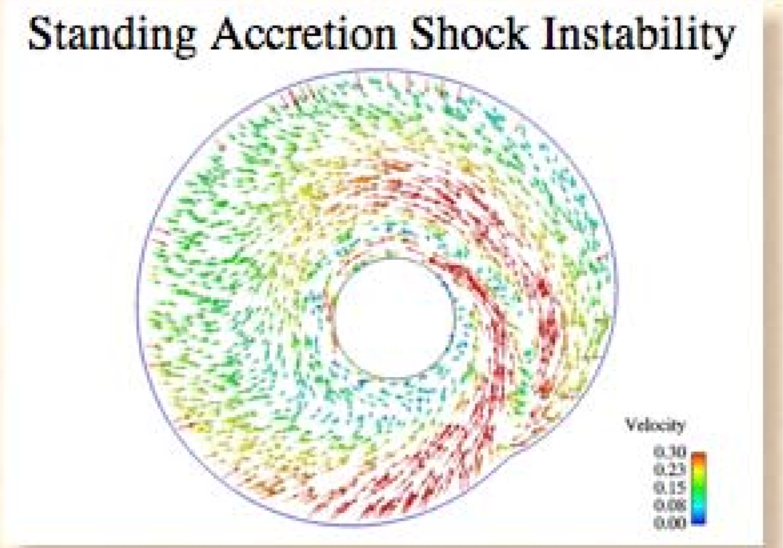
  Faster burning stages

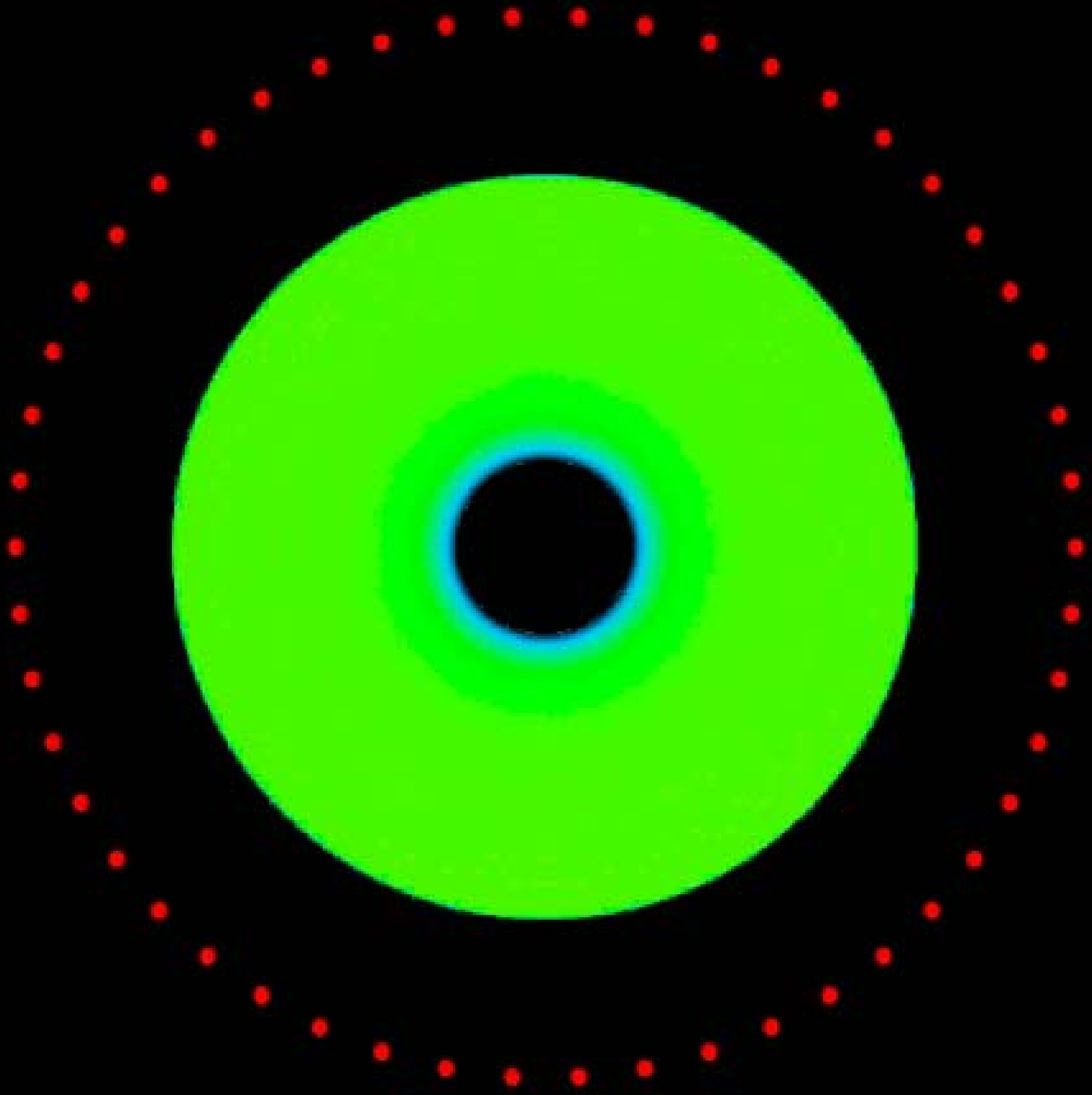
  Less mass loss

C burning
O burning
Si burning
} In rapid succession

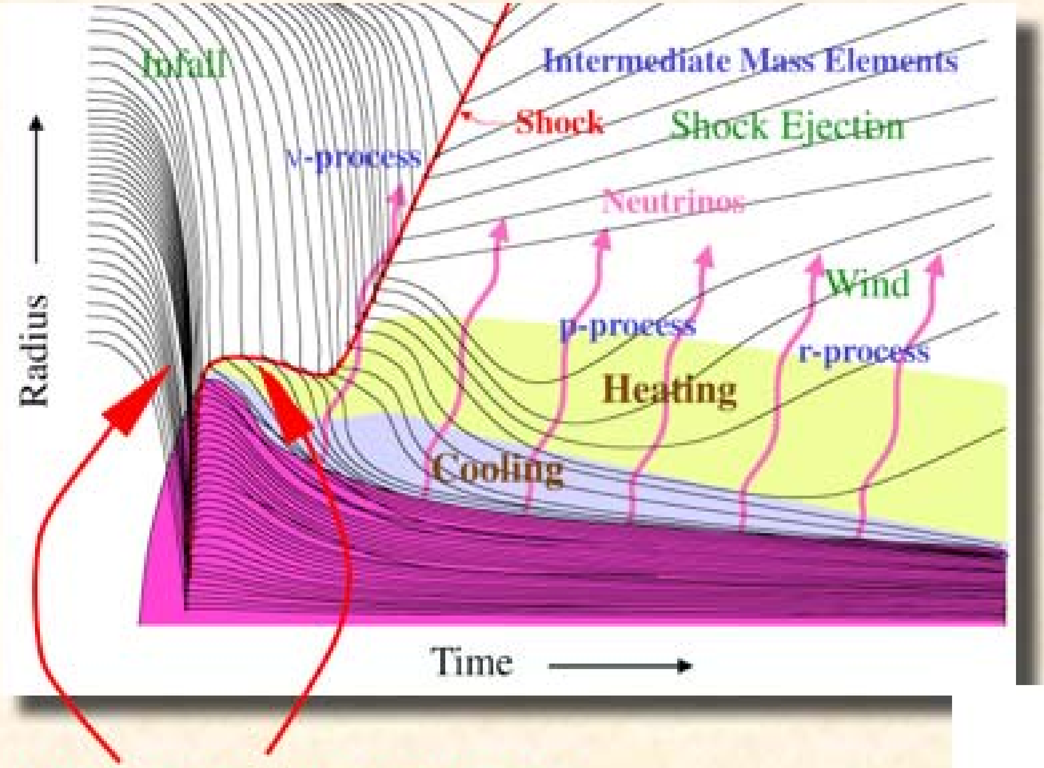


- Fermi degeneracy initially supports core
- Shell Si burning increases core size of
- Electron capture on nuclei in core begins to reduce pressure support
- Core undergoes runaway collapse
- Reaches supernuclear densities & shock rebounds -- EOS important
- Mechanism involves interplay of hydrodynamics and nuclear physics
- Spherical models fail to explode
- Multidimensional effects important?
- Influence of nuclear reactions on dynamics?


Standing Accretion Shock Instability



The weak interaction in supernovae



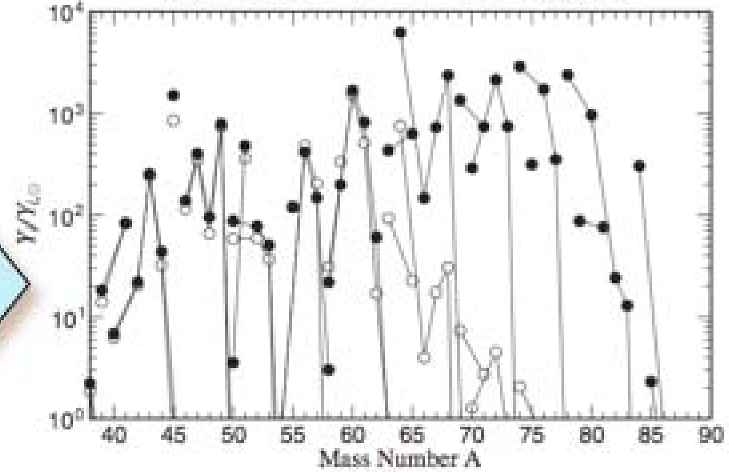
- Electron capture rates affect formation of shock wave.
- Neutrino interactions play a role in driving the explosion.
- Neutrino induced reactions alter nucleosynthesis.
- Weak rates in this mass region are not well understood:
  - GT strength distributions
  - first-forbidden contribution

Weak interaction plays an important role in dynamics

Abundaces relative to solar

- ● with ν reactions
- ○ without ν reactions

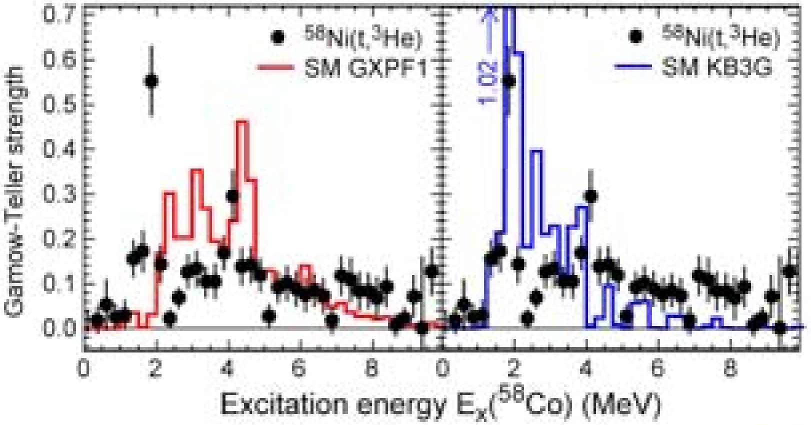
Fröhlich *et al.*, PRL **96** (2006)



Cole *et al.*, PRC **74** (2006) 034333.

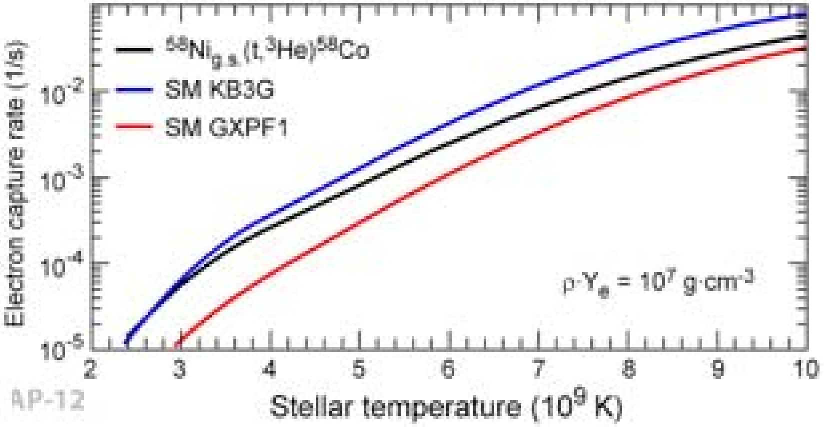
Charge exchange reactions with fast beams at the NSCL

Charge exchange reactions such as (t,^{3}He) are sensitive probes for GT strength at 100 – 200 MeV/u



Needed for

- core collapse supernova models
- type Ia supernova models
- neutron star crust processes

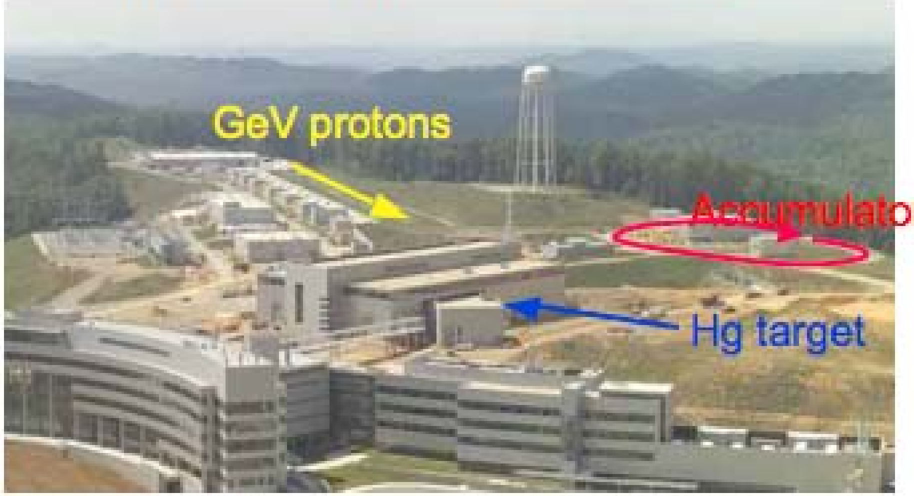


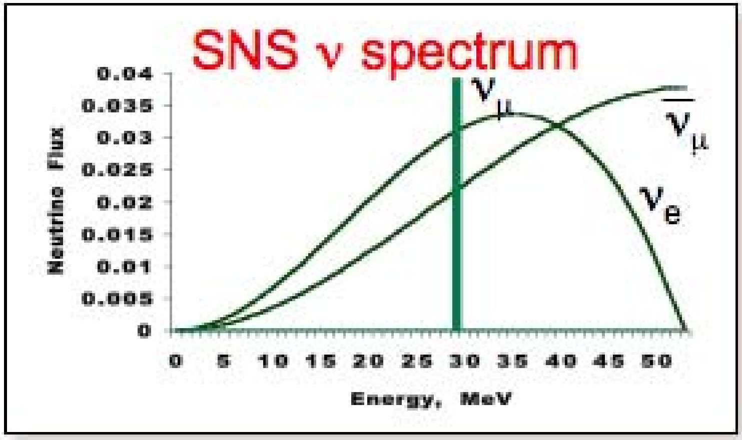
Special case or systematic issue? Need systematic measurements for entire relevant range (especially beyond fp shell where nuclear models become much simpler)

→can help decide which theoretical model to use and can help to improve theoretical models for supernova usage

→Need to develop technique for inverse kinematics and radioactive beams http://www.phy.ornl.gov/nusns

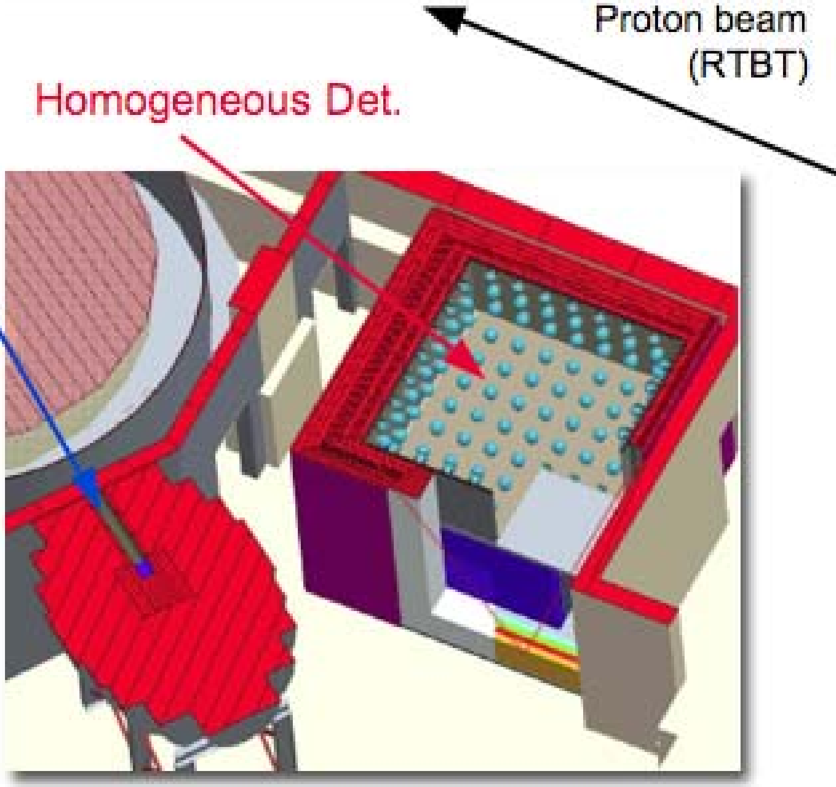
- A proposal has been submitted to DOE to construct a facility for neutrino reaction measurements at the Spallation Neutron Source.





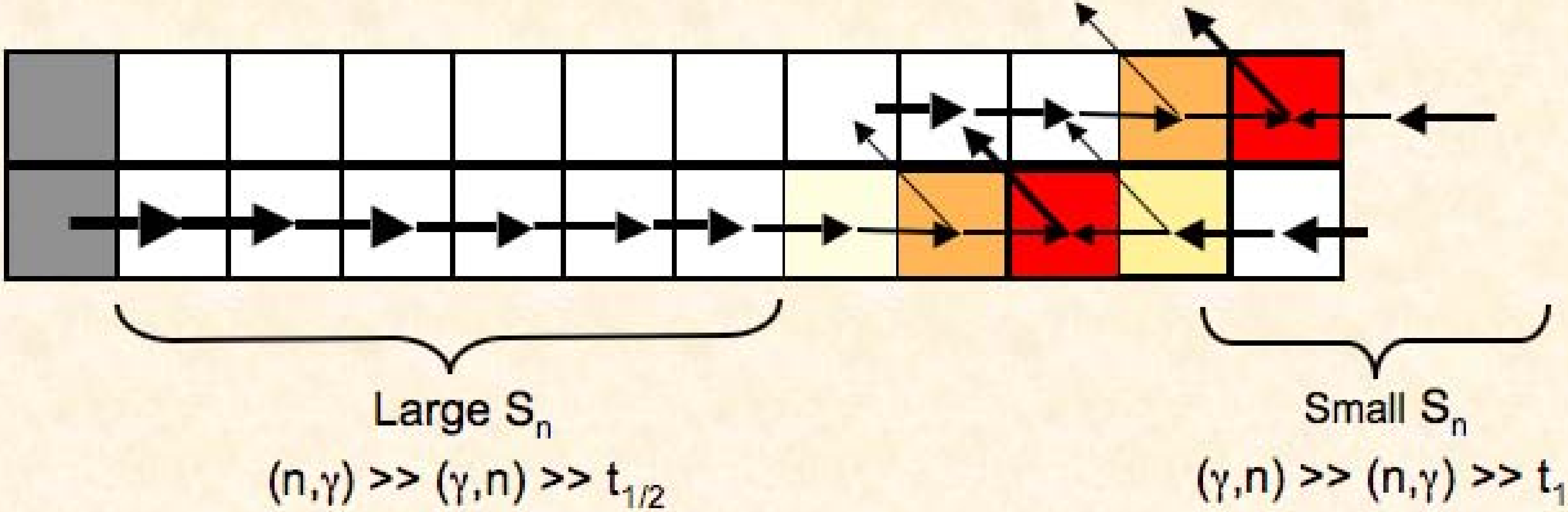
15 ton (fiducial) target/detector
20 m from SNS spallation target

ν_e+O→F+e^- (450 events/yr)
ν_e+Fe→Co+e^- (1100 events/yr)
ν_e+Al→Si+e^- (1100 events/yr)
ν_e+Pb →Bi+e^- (4900 events/yr)



Cartoon r process

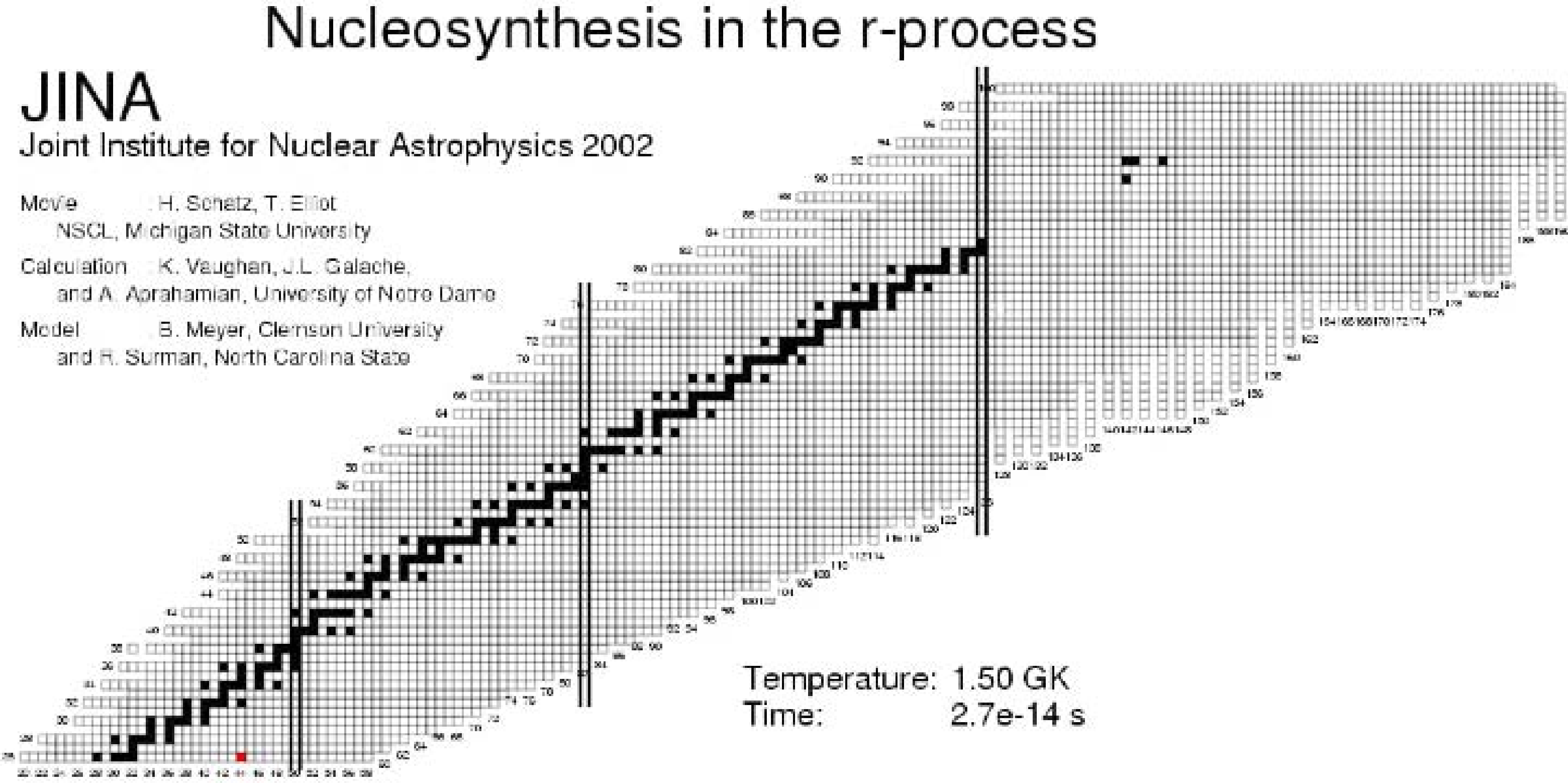
$$\frac{Y(A+1)}{Y(A)} \approx \frac{1}{2}\left(\frac{2\pi\hbar^2}{m_u kT}\right) n_n e^{S_n/(kT)}$$



- ➢ Free parameters n_n, kT, t
- ➢ Instantaneous freezeout & decay to stability

➡ Only masses, $t_{1/2}$, and P_n needed

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

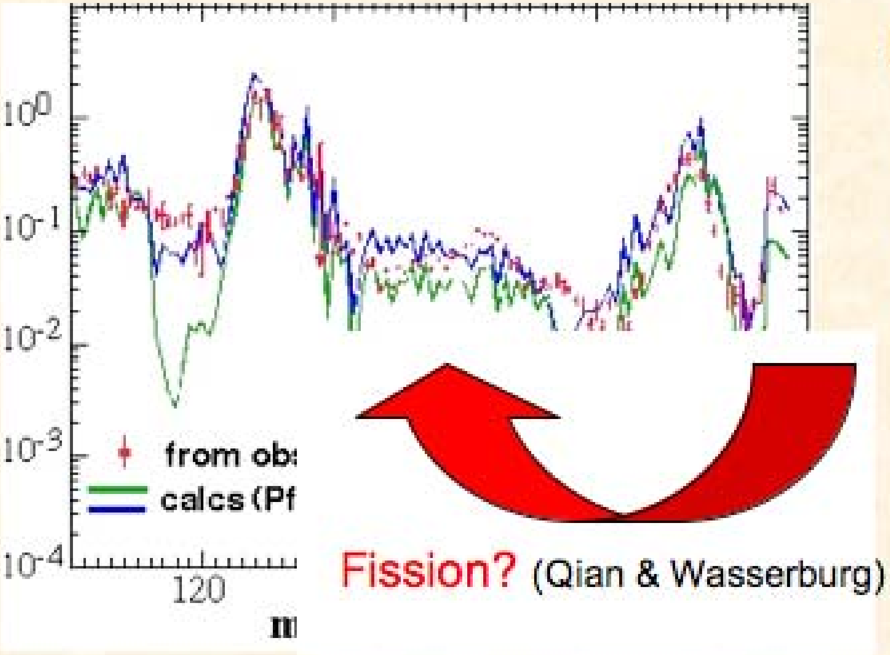
Model : B. Meyer, Clemson University
and R. Surman, North Carolina State

Temperature: 1.50 GK
Time: 2.7e-14 s

Results of r process calculations

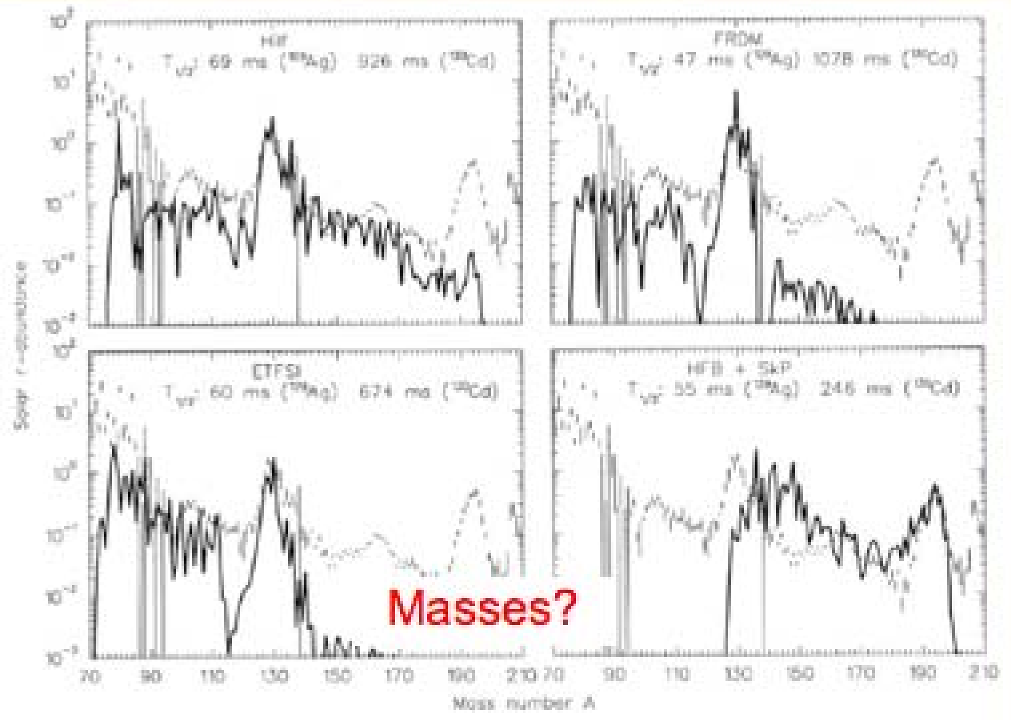
- Many different n densities needed
- Reasonable fits to A=130,190 peaks
- Not so nice reproduction of intermediate nuclei

Evidence for quenching of the shell gaps? (Kratz et al.)

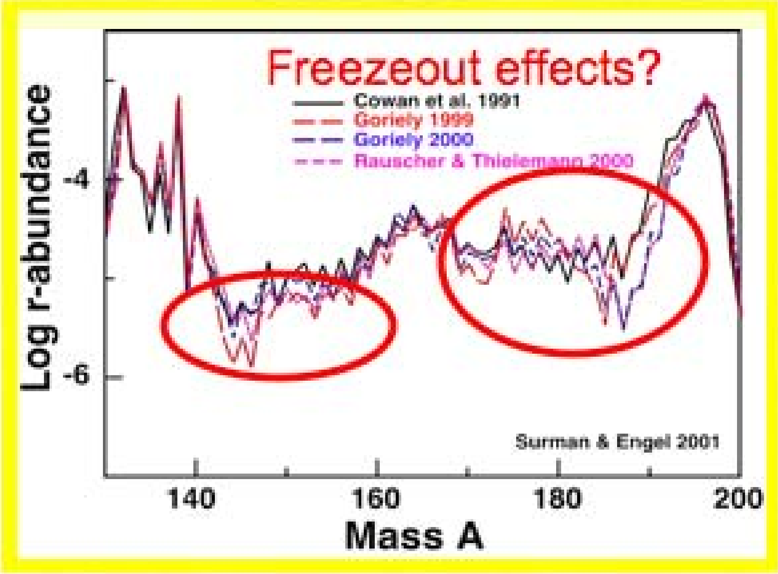


Fission? (Qian & Wasserburg)

Astrophysical environment?



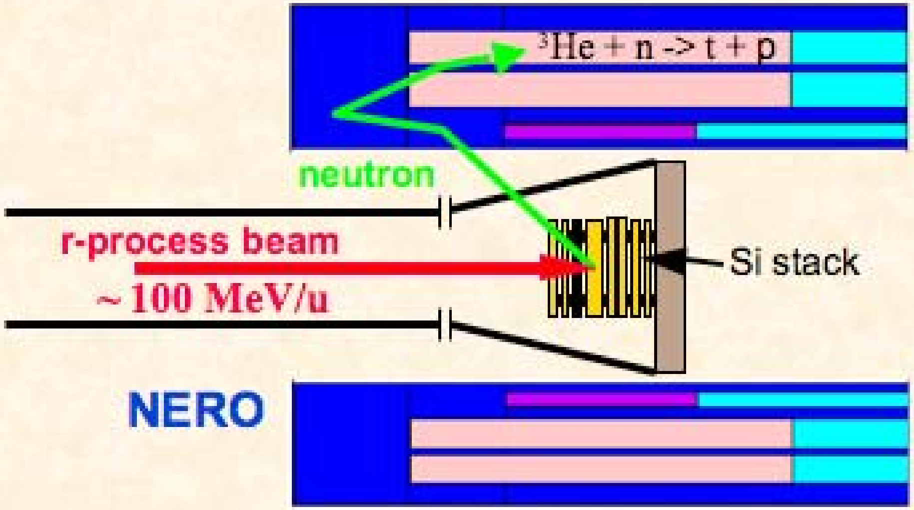
Masses?

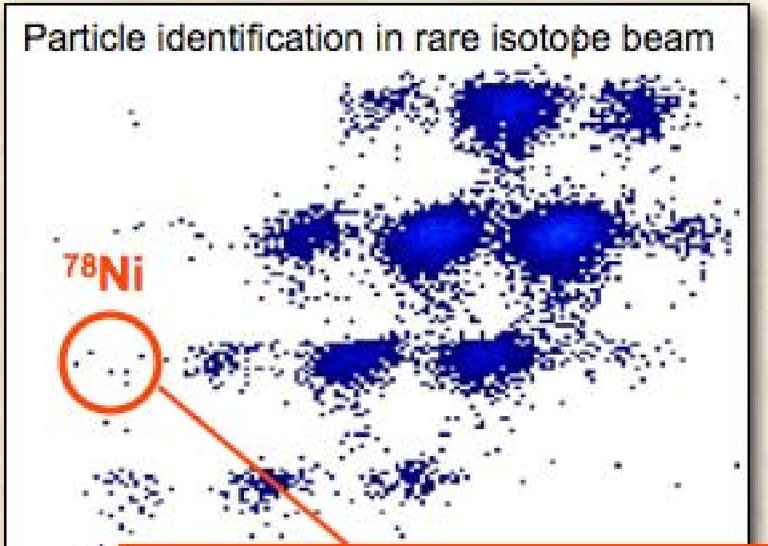


Freezeout effects?

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

NSCL fast beam r-process campaign

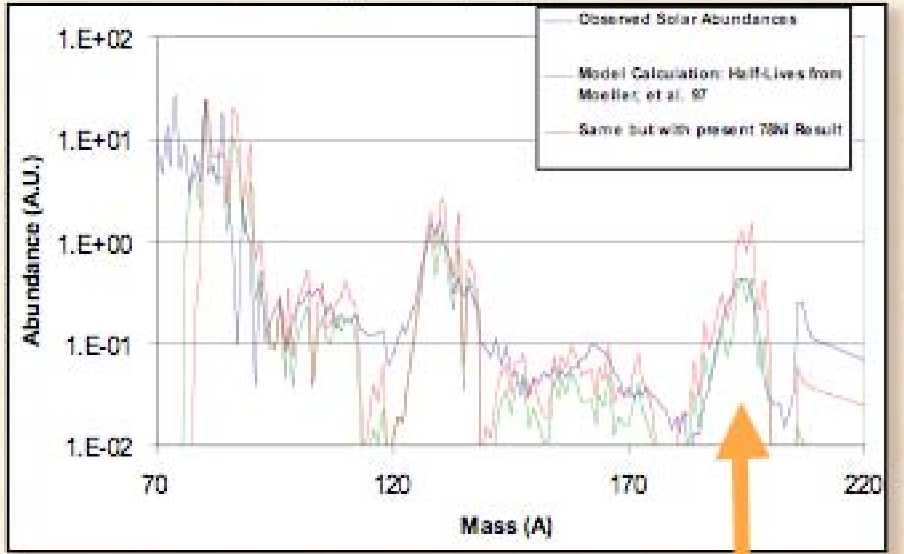



Particle identification in rare isotope beam

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

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

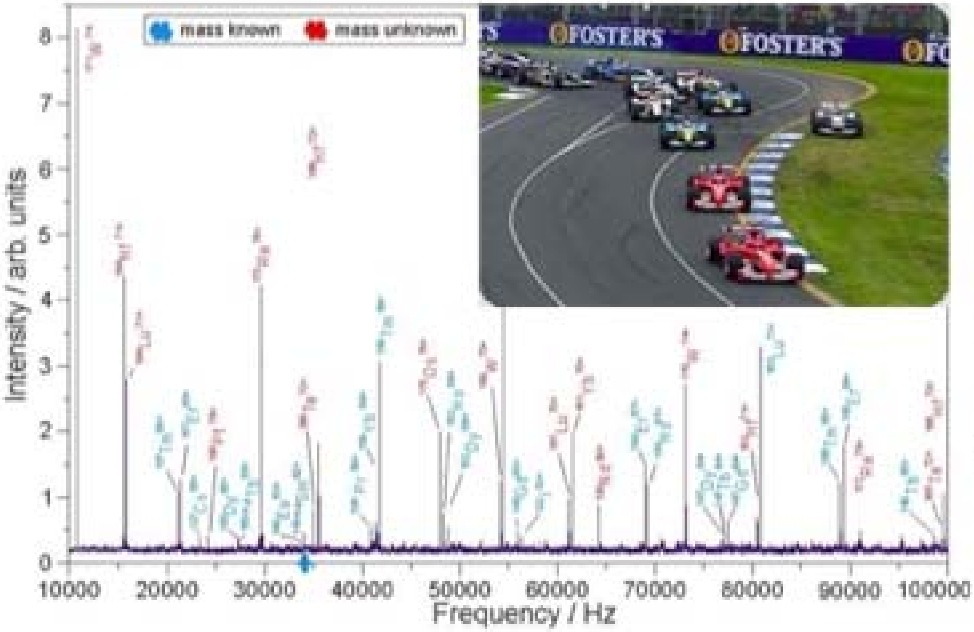
Effect of new $t_{1/2}$ on r process abundances



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

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

Mass measurements



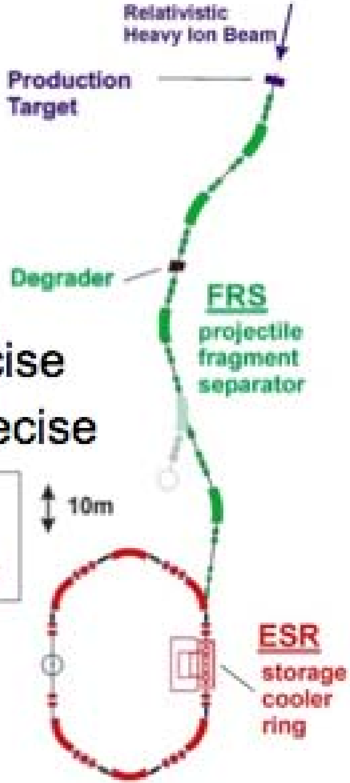
<u>2 modes</u>:

Schottky - slow, more precise

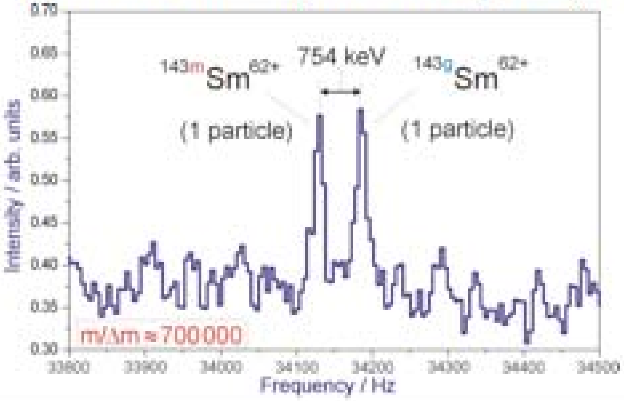
isochronous - fast, less precise

Experimental Storage Ring:

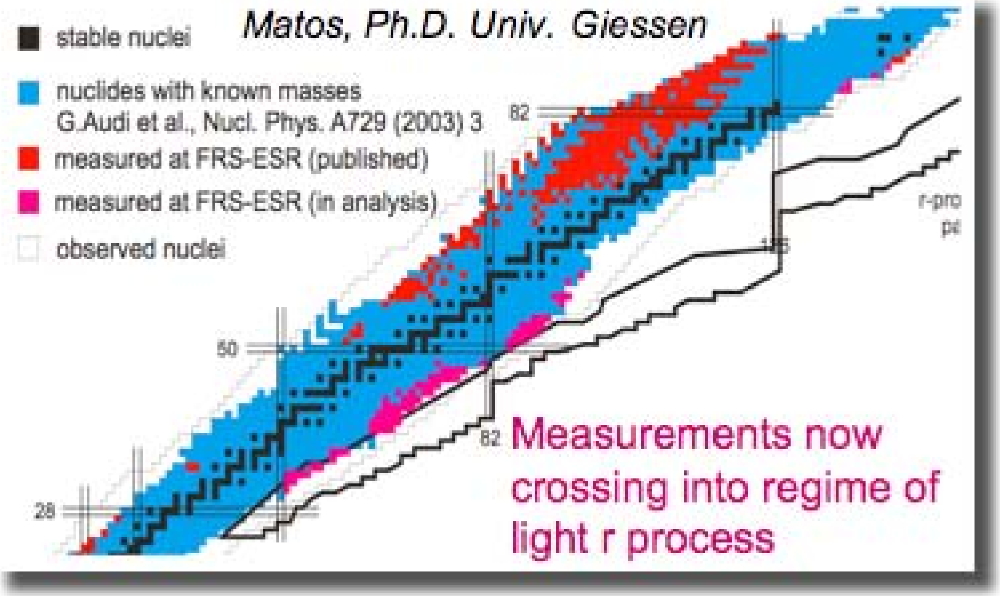
$$\Delta m/m = \gamma_t^2\ \Delta f/f + (\gamma_t^2 - \gamma^2)\ \Delta v/v$$



*Yu. Litvinov et al., NPA**756** (2005) 3.*

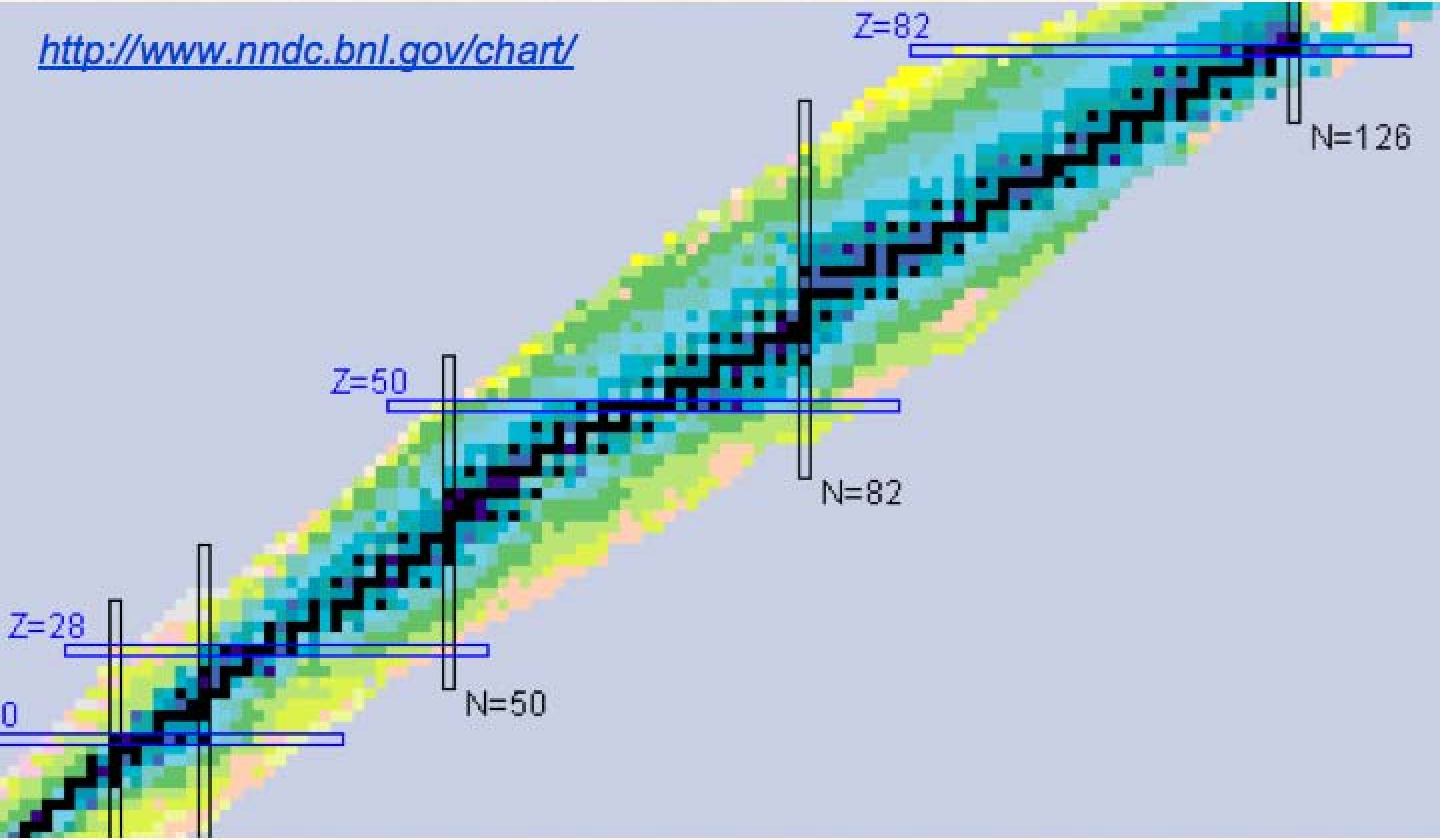


Matos, Ph.D. Univ. Giessen



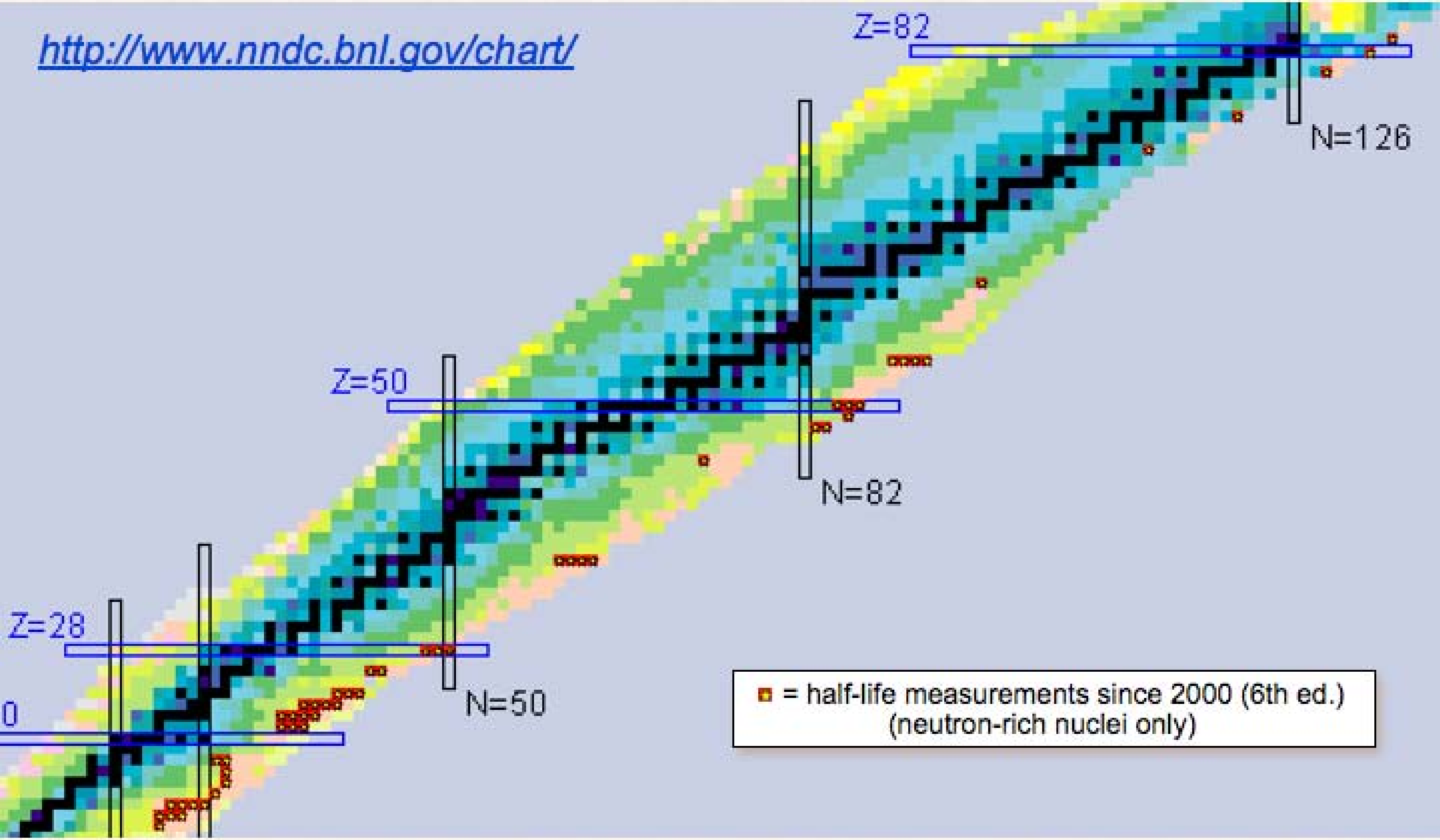
Measurements now crossing into regime of light r process

The Chart of the Nuclides

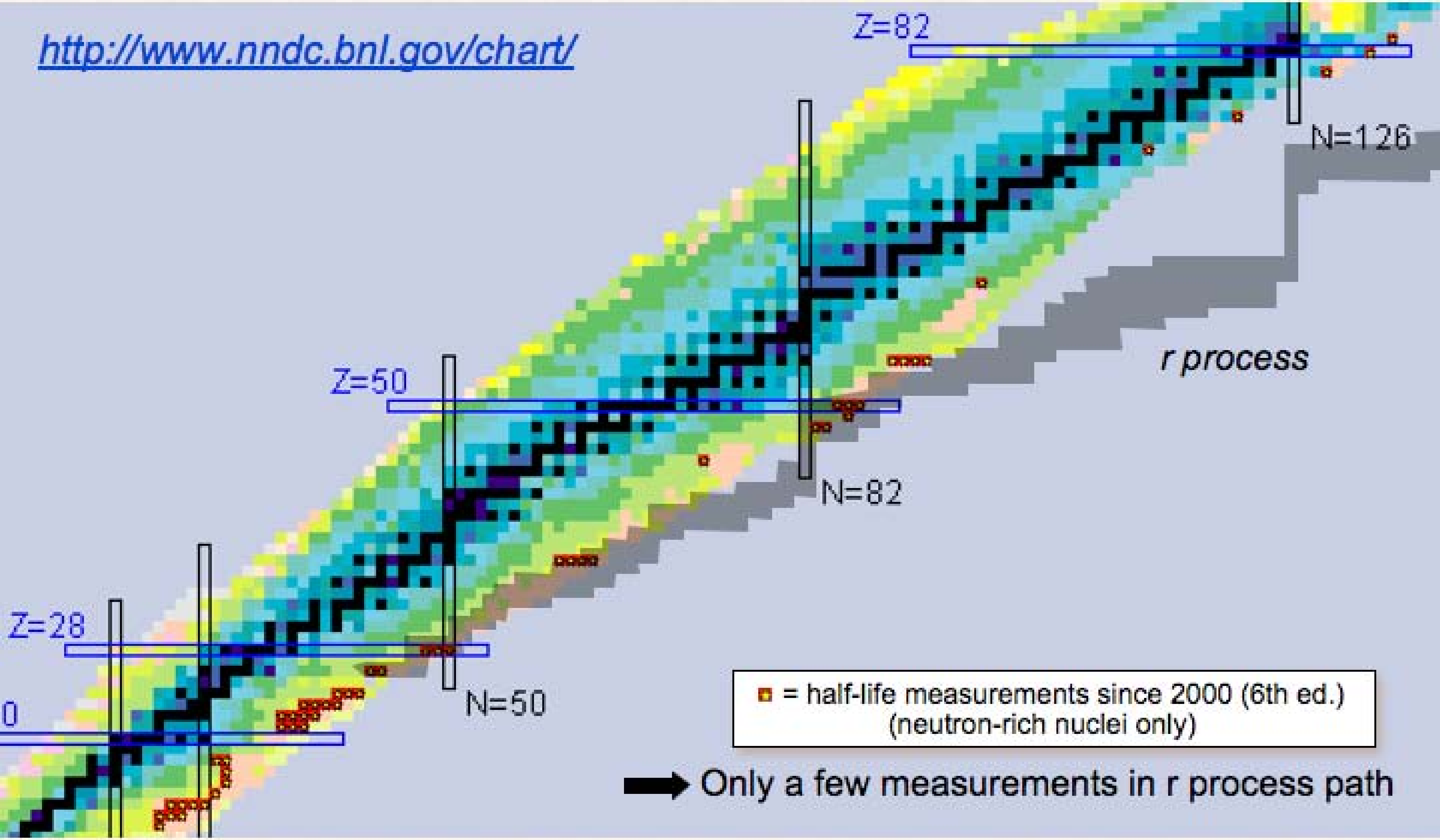


The Chart of the Nuclides

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



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

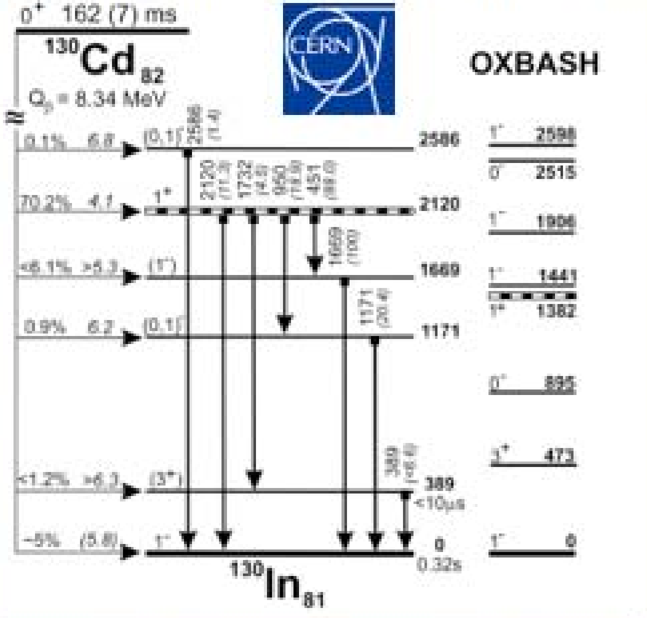
Structure n-rich nuclei and the r process

Masses, half-lives and P_n are crucial ➡ direct impact on r process abundances.

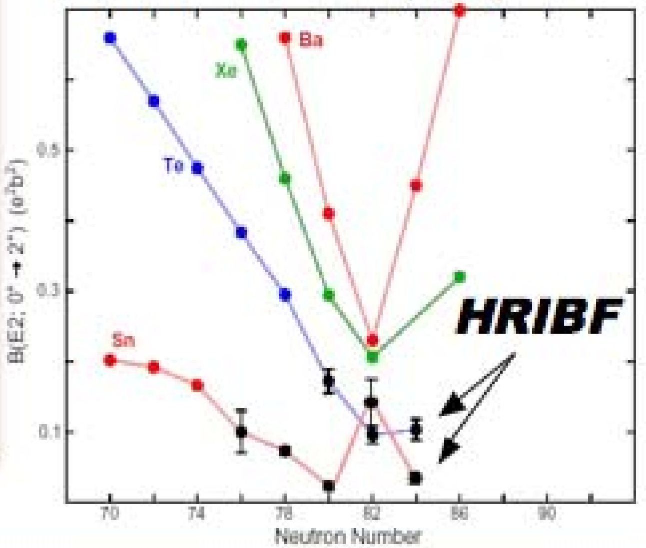
Must rely on theory.

Properties like level energies and B(E2) values provide some direct benchmarks.

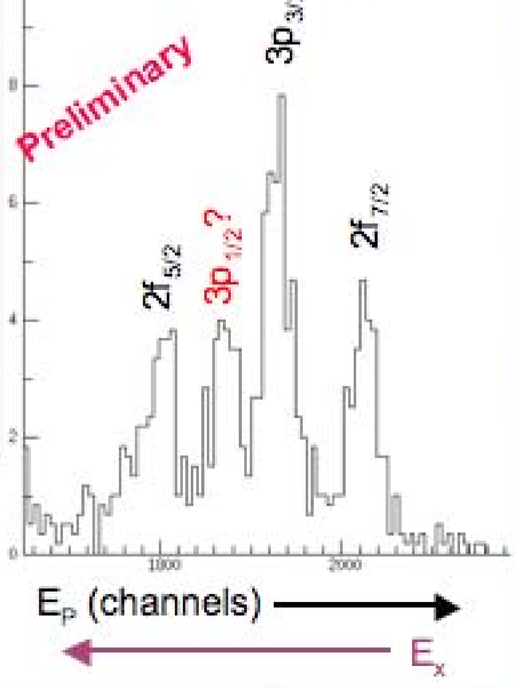
Dillman et al., PRL ***91*** *(2003) 162503.*



Radford et al., PRL ***88*** *(2002) 222501.*
Varner et al., EPJ ***25*** *(2005) 391.*

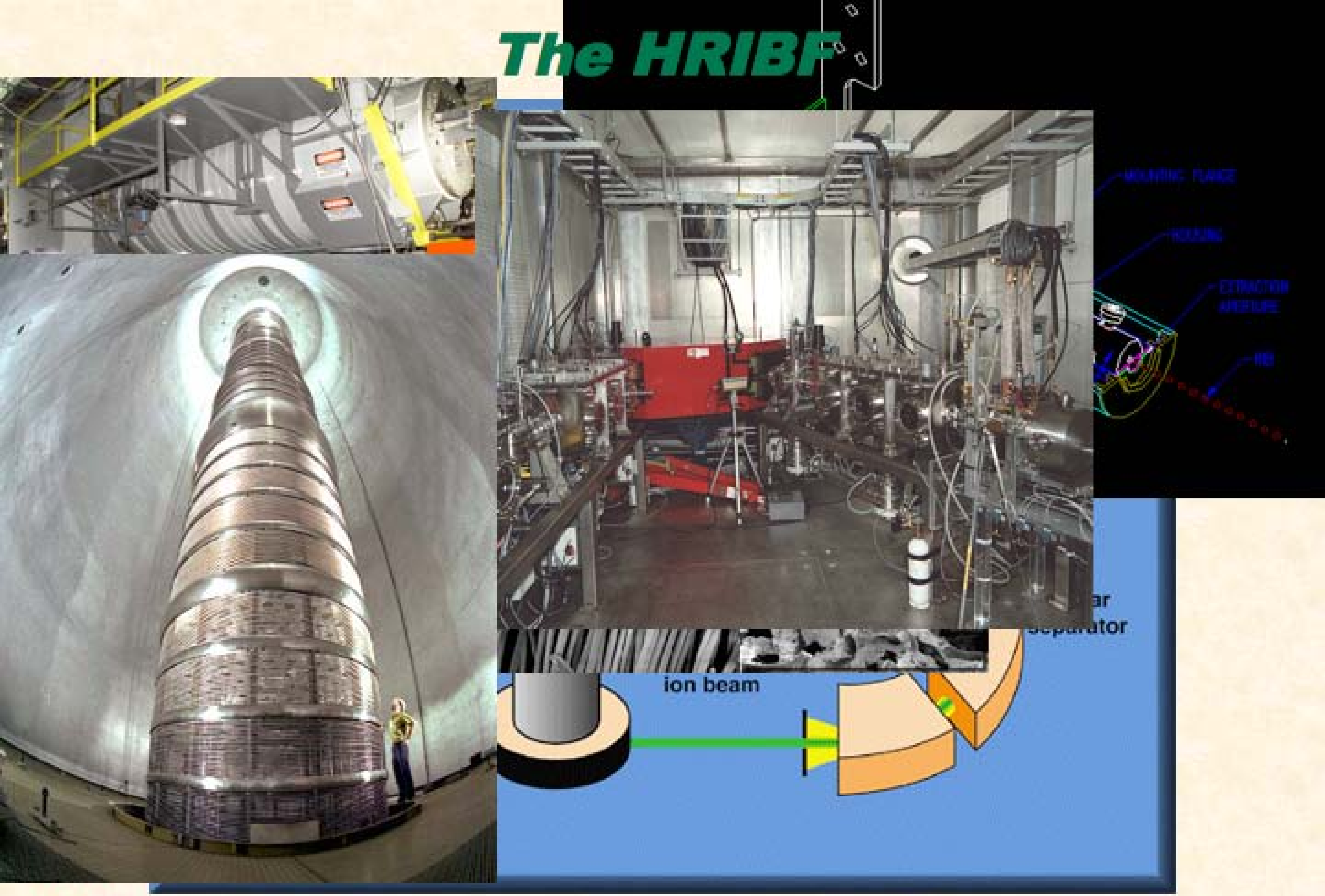


$^{132}Sn(d,p)^{133}Sn$ @ HRIBF
Jones et al.



Understanding the structure of neutron-rich nuclei is crucial to improving extrapolations to more neutron-rich (unmeasured nuclei).

The HRIBF



OAK RIDGE National Laboratory

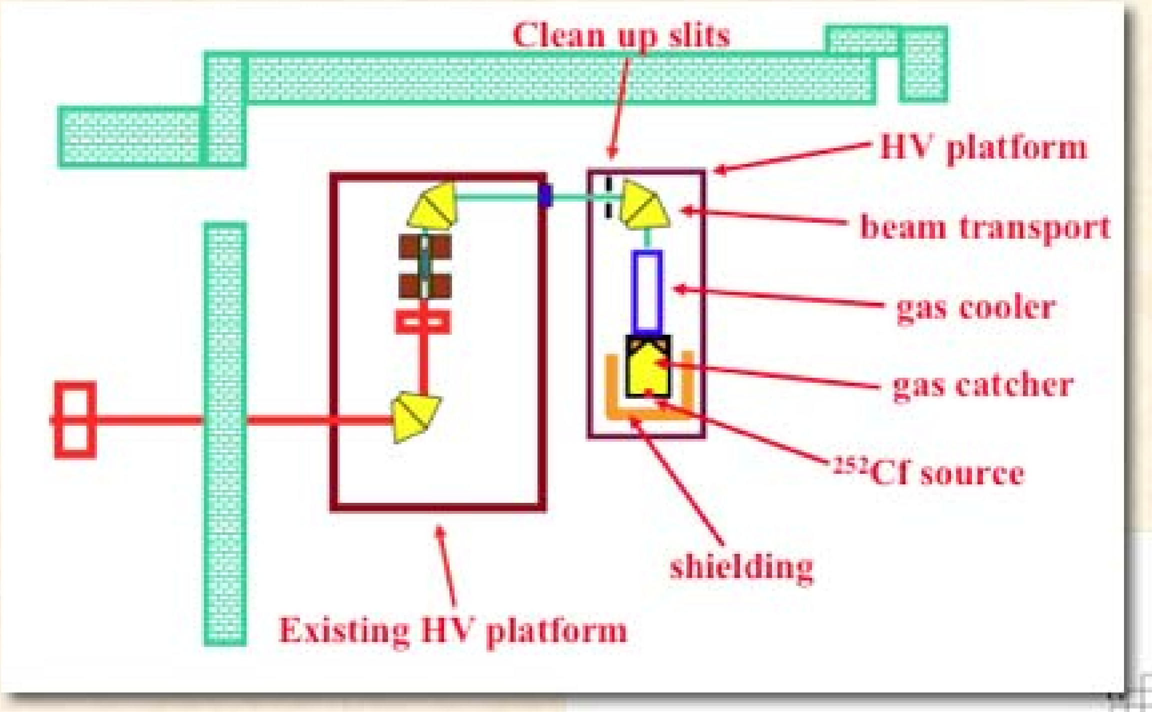
Office of Science U.S. DEPARTMENT OF ENERGY

Office of Nuclear Physics

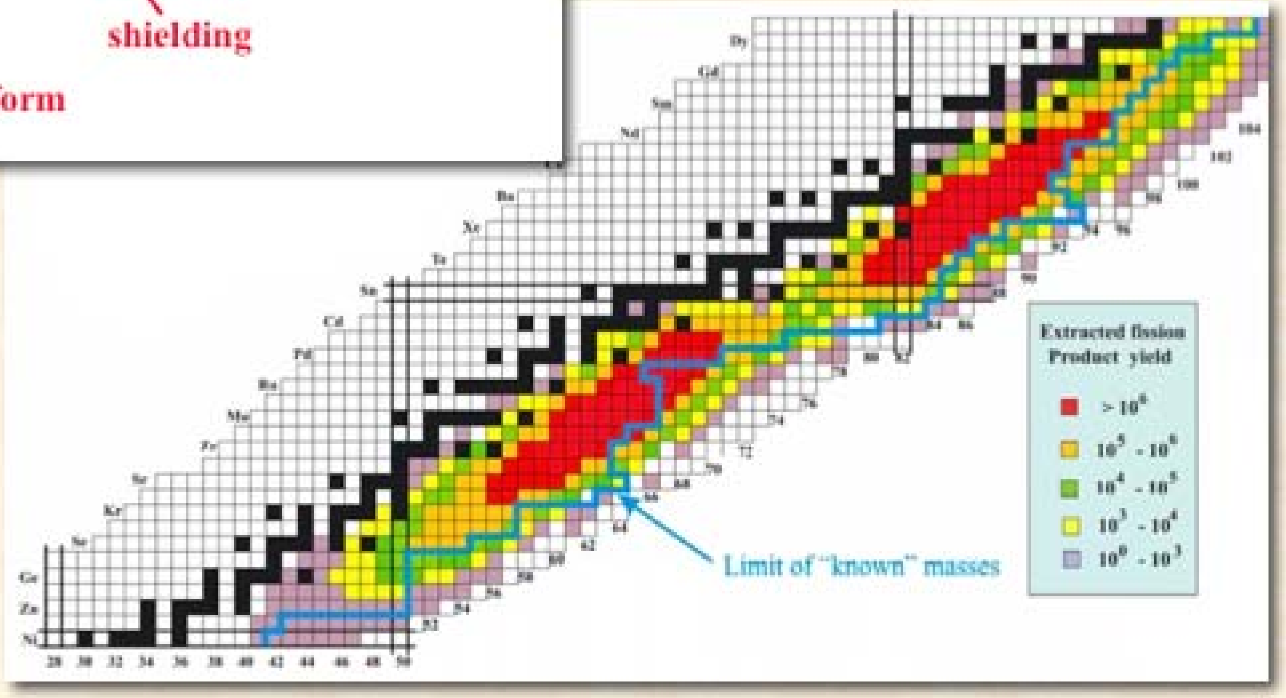
hribf

UT-BATTELLE

CARIBU

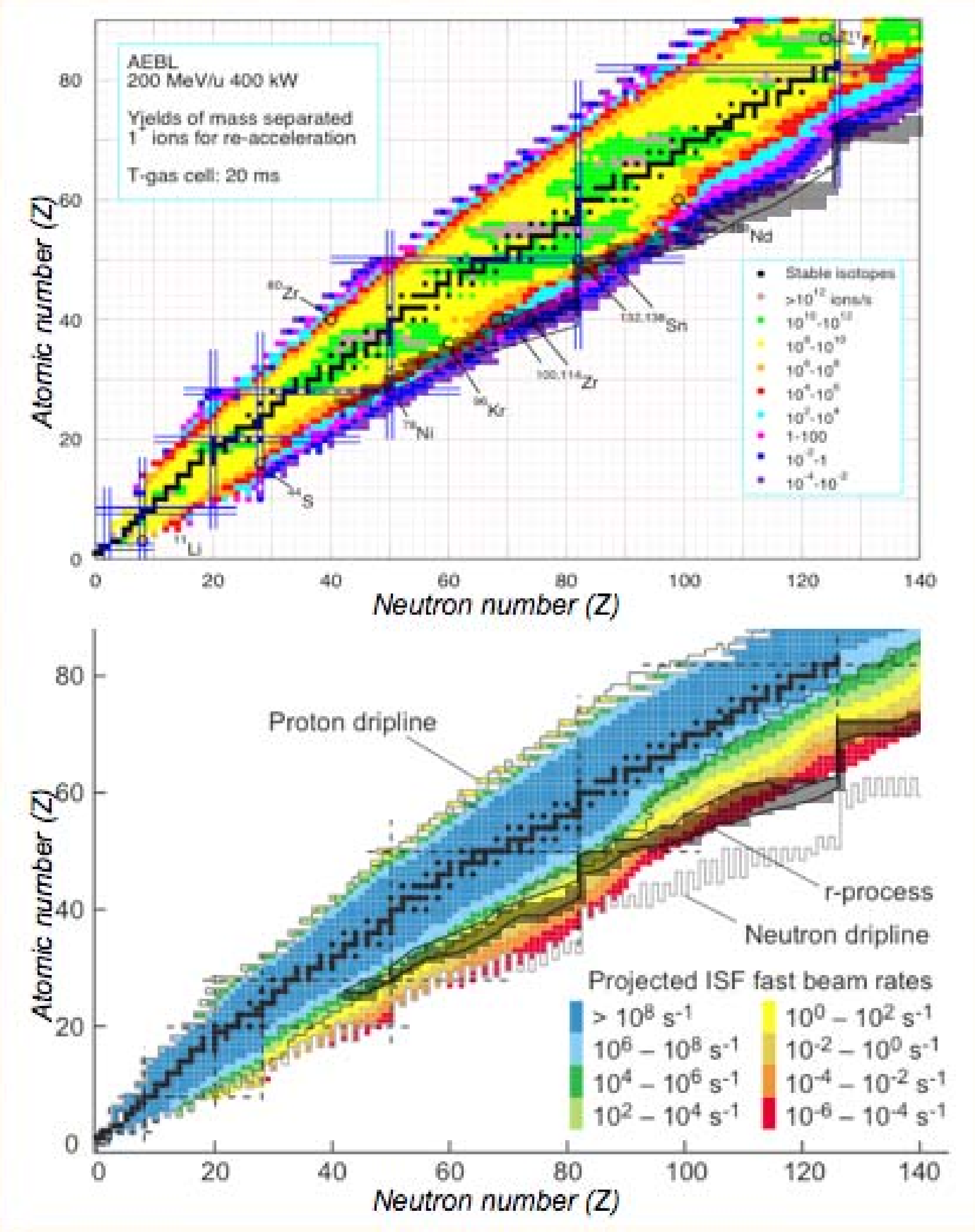


- Intense ^{252}Cf fission source under construction at ATLAS
- Gas stopping technology
- Neutron-rich RIBs will push the boundaries of our knowledge
- Different region on nuclei → complementary to HRIBF



- CPT measurements of very neutron-rich nuclei
- Intense beams and high energy will allow unique structure studies, e.g. (p,t)

Next-generation RIB Facilities



RIBF (RIKEN), FAIR (GSI), SPIRAL-II (GANIL), RIA (USA)

Ground state properties of nearly all r process nuclei up to the A=190 peak can be measured

Nuclear structure studies far from stability will greatly improve our ability to extrapolate to the unknown

Understanding observations of the oldest stars and the origin of the heavy elements in our Galaxy

Recommendations of 2007 NSAC LRP

- We recommend completion of the 12 GeV Upgrade at Jefferson Lab. The Upgrade will enable new insights into the structure of the nucleon, the transition between the hadronic and quark/gluon descriptions of nuclei, and the nature of confinement.
- We recommend construction of the Facility for Rare Isotope Beams, FRIB, a world-leading facility for the study of nuclear structure, reactions and astrophysics. Experiments with the new isotopes produced at FRIB will lead to a comprehensive description of nuclei, elucidate the origin of the elements in the cosmos, provide an understanding of matter in the crust of neutron stars, and establish the scientific foundation for innovative applications of nuclear science to society.
- We recommend a targeted program of experiments to investigate neutrino properties and fundamental symmetries. These experiments aim to discover the nature of the neutrino, yet unseen violations of time-reversal symmetry, and other key ingredients of the new standard model of fundamental interactions. Construction of a Deep Underground Science and Engineering Laboratory is vital to US leadership in core aspects of this initiative.
- The experiments at the Relativistic Heavy Ion Collider have discovered a new state of matter at extreme temperature and density—a quark-gluon plasma that exhibits unexpected, almost perfect liquid dynamical behavior. We recommend implementation of the RHIC II luminosity upgrade, together with detector improvements, to determine the properties of this new state of matter.

Nuclear astrophysics

A survey in 6 parts

Jeff Blackmon, Physics Division, ORNL

Nuclear physics plays an important role in astrophysics:

Energy generation
Synthesis of elements
} astronomical observables

1. Introduction
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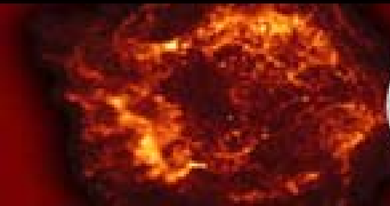
3. Stellar structure & solar neutrinos
4. Stellar evolution & s process
5. Supernovae & r process
6. → Binary systems



Discovering Novae

- The most common stellar explosion
  - About 3 dozen per year in Milky Way

- Characterized by increase in brightness of 8-15 magnitudes (10^3-10^6 times)
  - Peak reached in < 24 h
  - Much slower decay (weeks)
  - Recur after t >1000 yr ?
  - Discovered by amateurs
  - 100's observers networking around the world
  - Usually discovered photographically

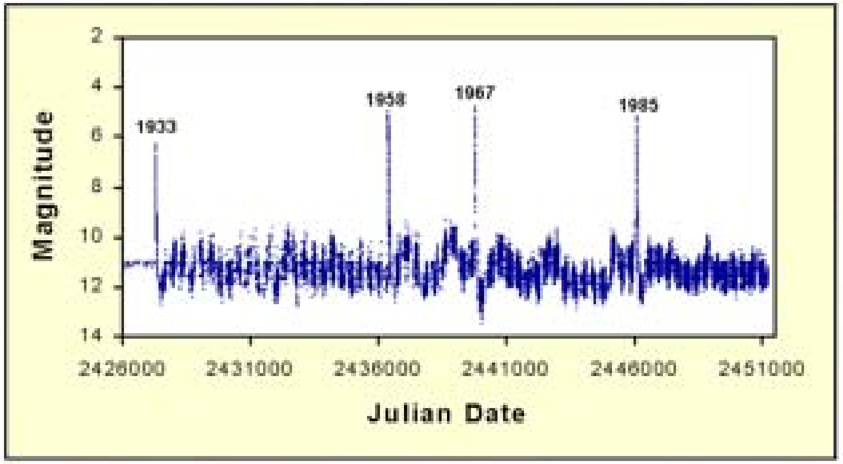
- Nova Ophiuchi 2006 No. 2
  - Discovered April 6, 2006
  - Peter Williams, Sydney Australia
  - Visual discovery (Magnitude 10)
  - Peak brightness 9.2
  - Confirmation:
    - William Liller (Chile)
    - Tom Krajci (US)
    - Jaciej Reszelski (Poland)

Ophiuchi 2006 No. 2

John Drummond

RS Ophiuchi

- "Recurrent Nova" (one of few known)




Guido & Sostero

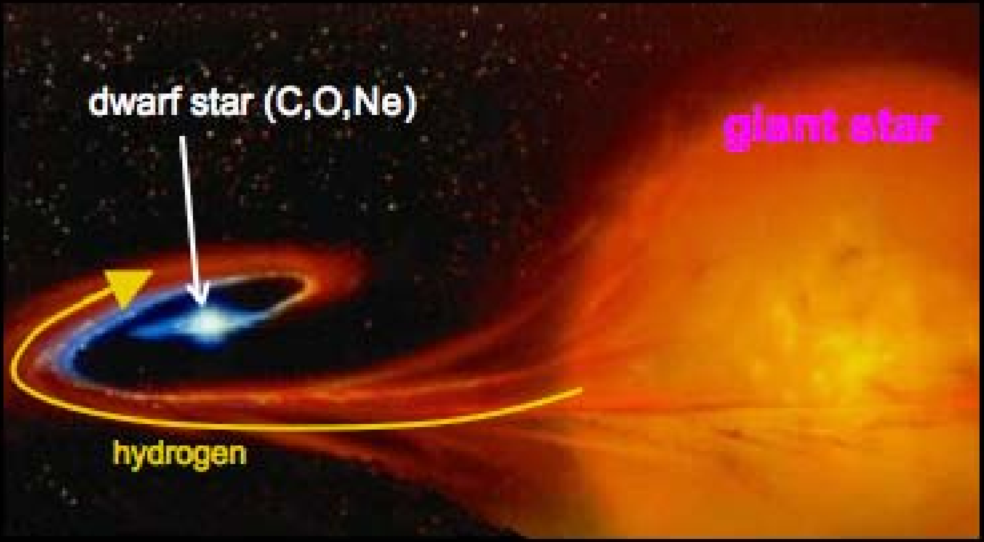
Recurrent Nova RS Ophiuchi in outburst; 2006 February 14.49

Takahashi Epsilon, D= 0.25m, f/3.4 + SBIG-ST8XE
Remotely from the "New Mexico Skies Observatory"
E. Guido and G. Sostero (AFAM, Remanzacco)
http://www.afamweb.com


Harvard University Archives

- Feb. 12, 2006
- Reached Magnitude 4.8
- Swift observations began less than 3 days after onset (observations only after 3 weeks in 1985)
- Observed by 4 space observatories and variety of ground based instruments on the same day (Feb. 26)
- First observed in 1898
  - Williamina Stevens Flemming (1857-1911)

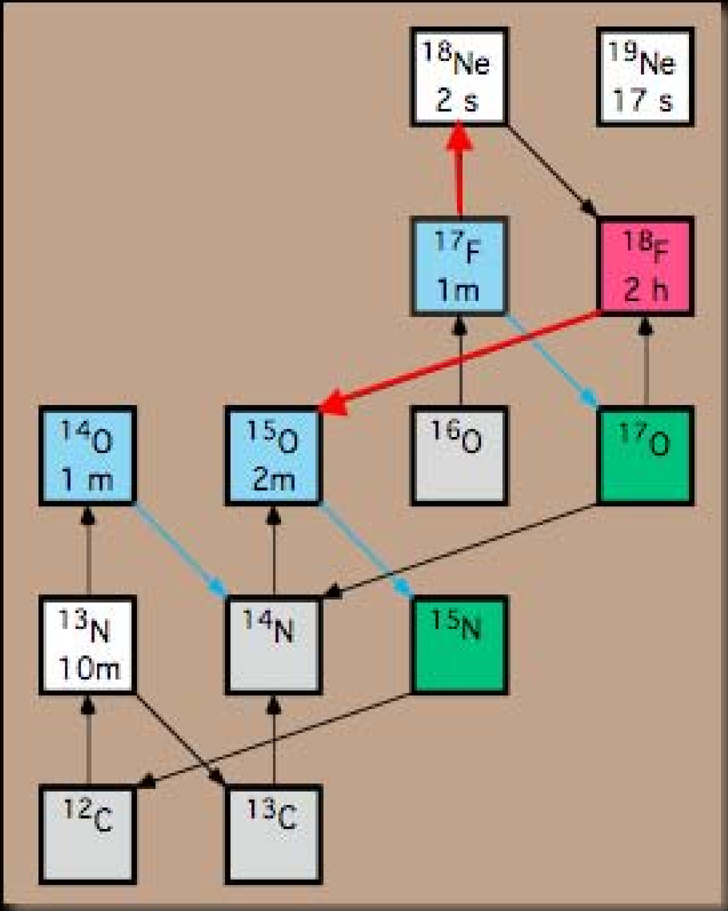
Novae mechanism



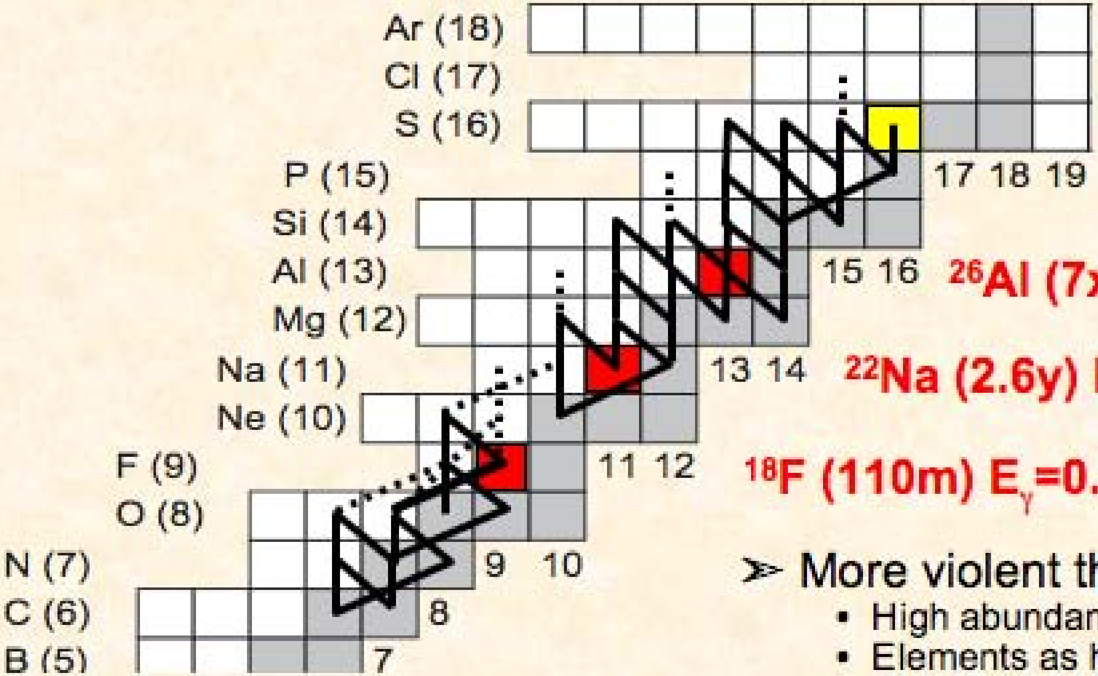
- Hydrogen-rich gas from companion accretes onto white dwarf & burns: ***hot-CNO cycle***
- Electron degeneracy → pressure
- Thermonuclear runaway

- Rates of nuclear reactions determine energy generation and nucleosynthesis
- Source for ^{13}C, ^{15}N, ^{17}O
- ^{18}F: largest source of 511 keV γ–rays
- Most important nuclear physics problems
  - $^{13}N(p,\gamma)^{14}O$ CRC-Louvain-le-Neuve
  - $^{17}F(p,\gamma)^{18}Ne$
  - $^{17}O(p,\alpha)^{14}N$
  - $^{18}F(p,\alpha)^{15}N$
  - ^{22}Na TRIUMF-ISAC

Part of initial HRIBF Program



Complex, multidimensional problem



- Many ejecta substantially enriched in S

^{26}Al (7x10^{5}y) E$_\gamma$=1.275 MeV

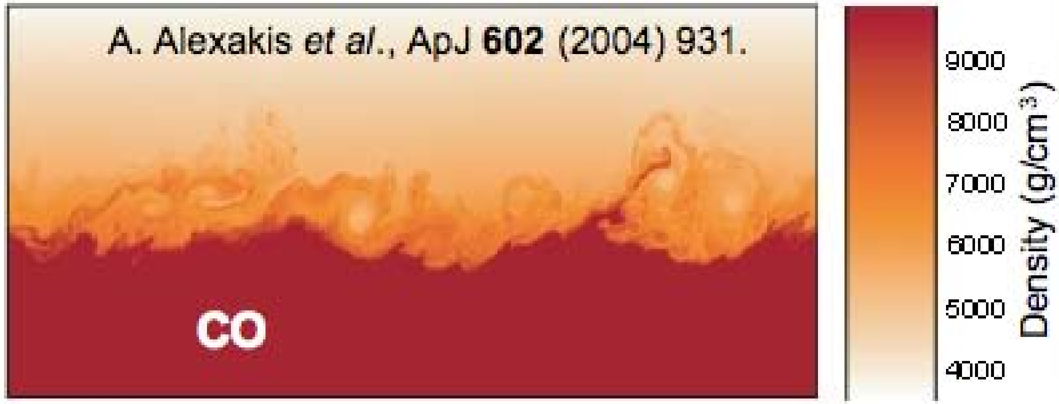
^{22}Na (2.6y) E$_\gamma$=1.809 MeV

^{18}F (110m) E$_\gamma$=0.511 MeV

- More violent than expected
  - High abundance of heavier elements
  - Elements as heavy as sulfur
  - High ejected mass

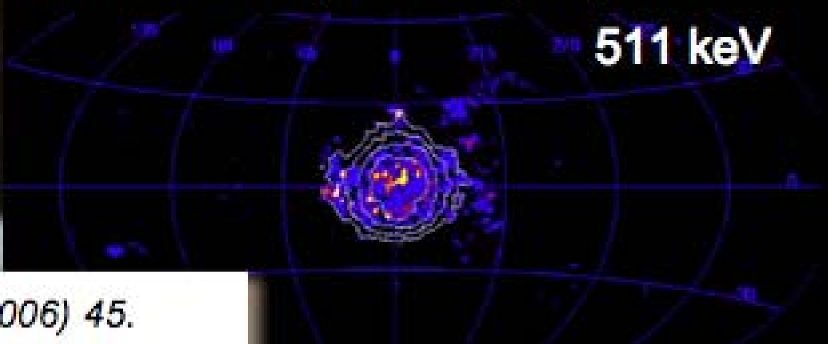
  → Substantial mixing of accreted material with core?

- Complex hydrodynamical models required
  - Mulitdimensional models using adaptive coordinate mesh
  - Nuclear physics typically decoupled or simplified
  - Nucleosynthesis tracked in detail in a post-processing approach
  - Frontier is now coupling of better nuclear physics with more realistic hydrodynamical models

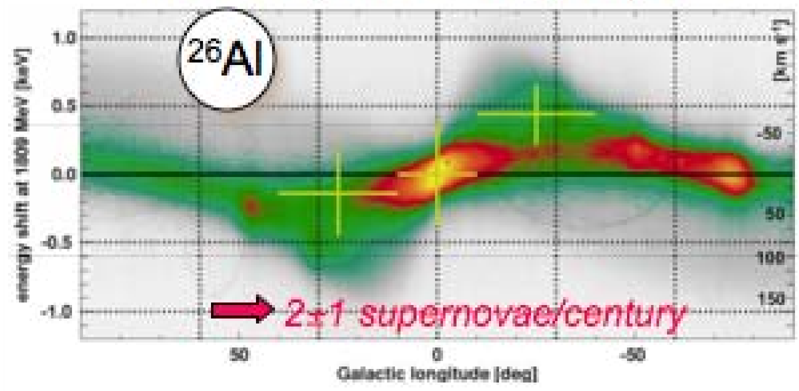

A. Alexakis *et al*., ApJ **602** (2004) 931.

Advances in observation

*Knödlseder et al., A&A **441** (2005) 513.*



*Diehl et al., Nature **439** (2006) 45.*

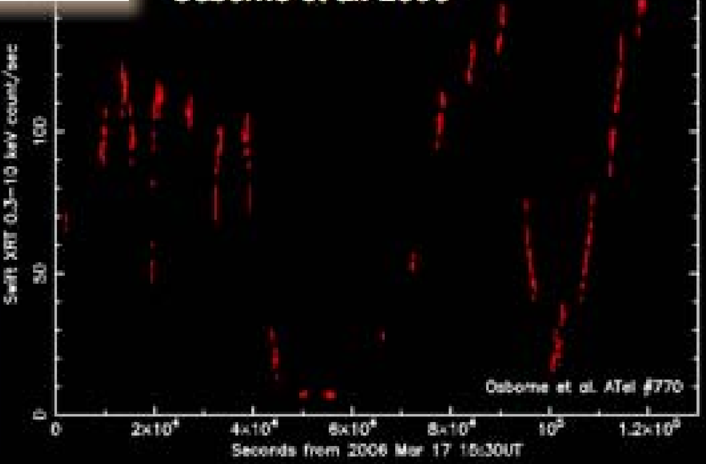


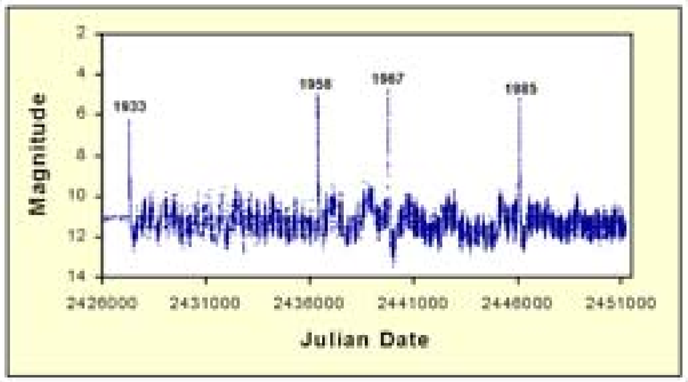
→ *2±1 supernovae/century*

RS Ophiuchi

Feb. 12, 2006

Osborne et al. 2006

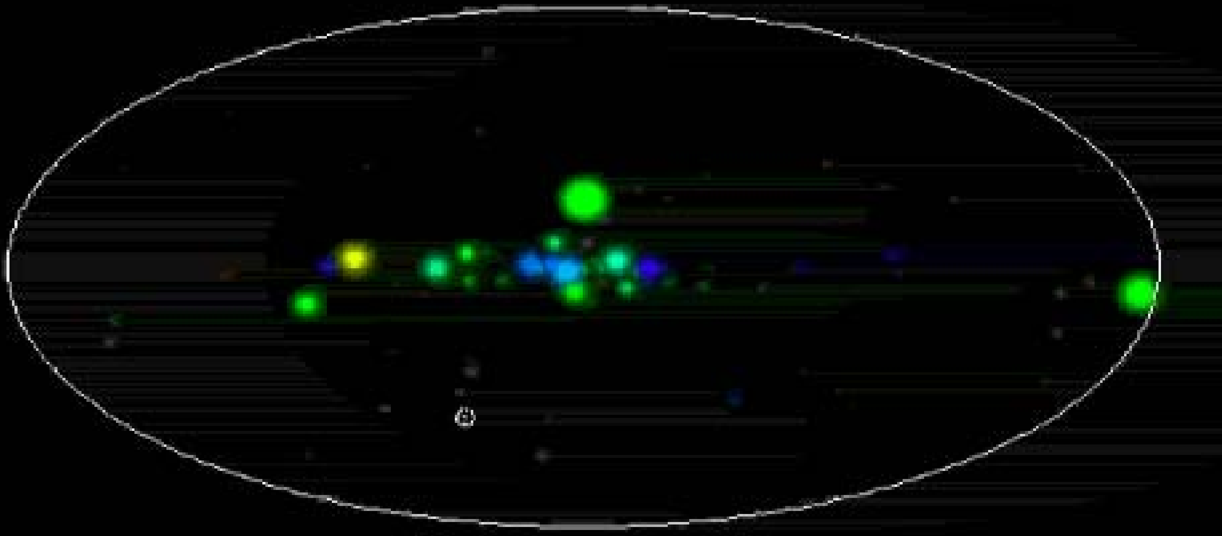




X-ray vision

RXTE
Rossi X-ray Timing Explorer

The RXTE All-Sky Monitor Movie



02 / 23 / 2004

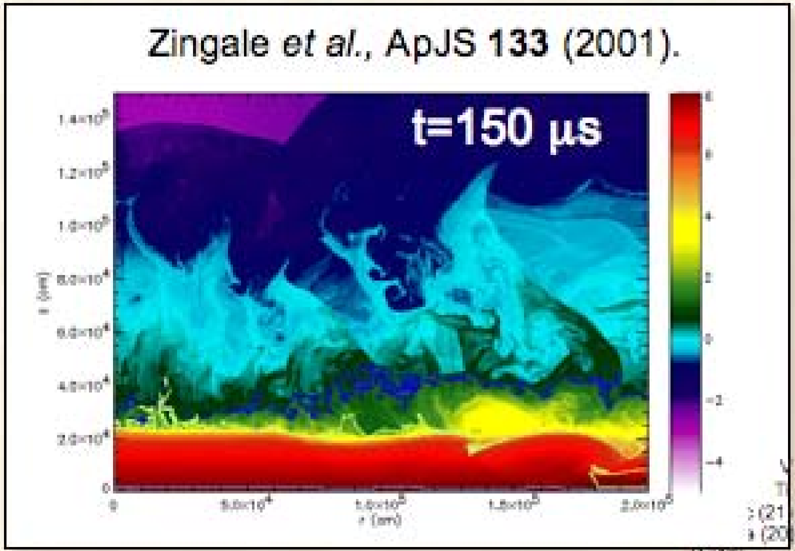
http://heasarc.gsfc.nasa.gov/xte_weather/

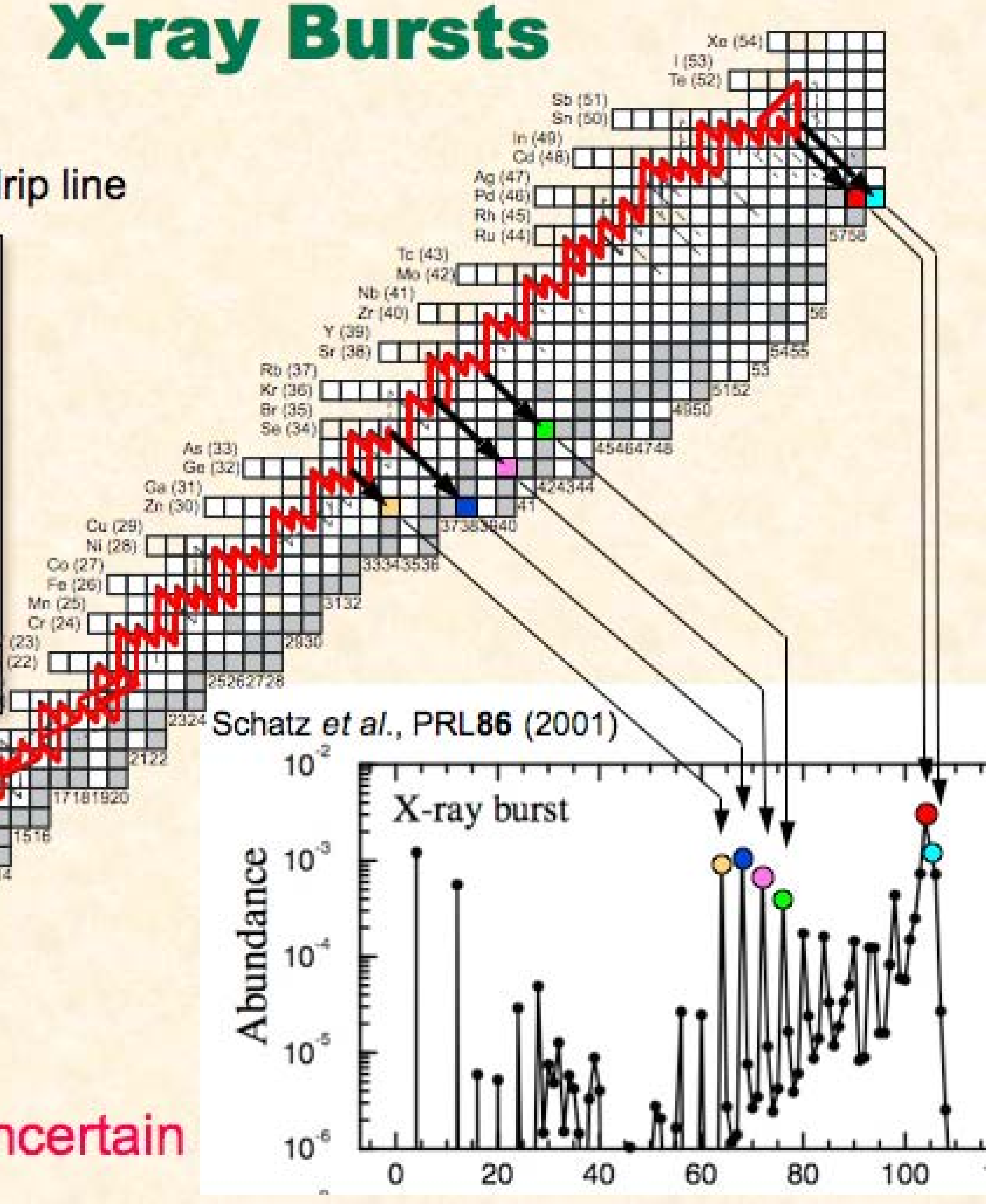
- Over 100 sources ***in the Milky Way***
  - Do not confuse with Gamma ray-bursts
- Recur on a semi-regular time scale
- Thermonuclear explosion on surface of a neutron star
- Observations provide crucial insights into neutron star properties

X-ray Bursts

- Like nova, but on neutron star
- Started by hot CNO cycle
- α-burning ignited
- Reactions close to the proton drip line

Zingale *et al.*, ApJS **133** (2001).



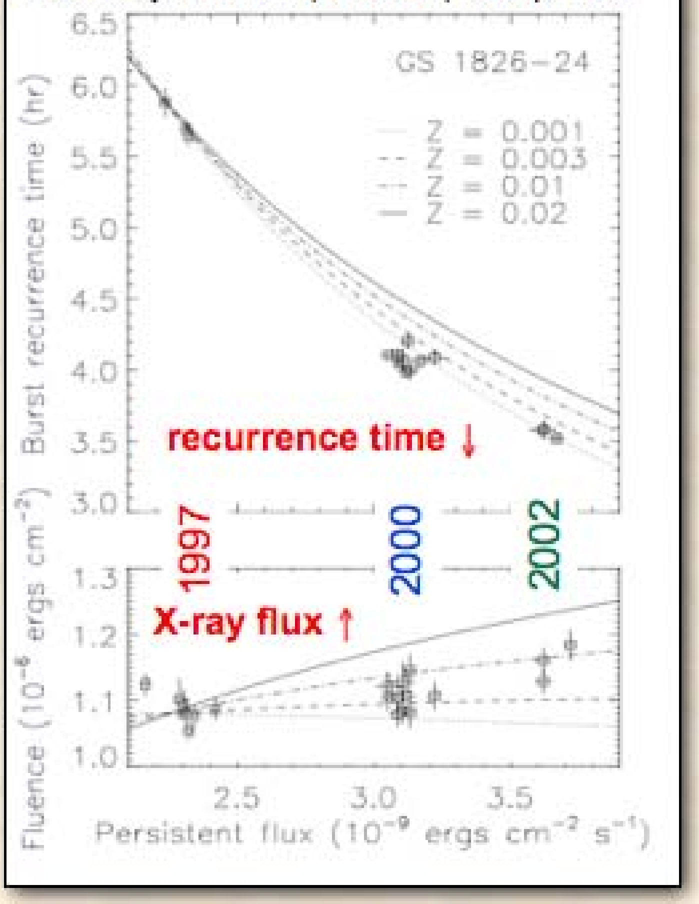


- Nuclei up to Sn
- Waiting points crucial
  - ^{64}Ge
  - ^{68}Se
  - ^{72}Kr
  - ^{76}Sr

Most reaction rates very uncertain

X-ray Bursts & Superbursts

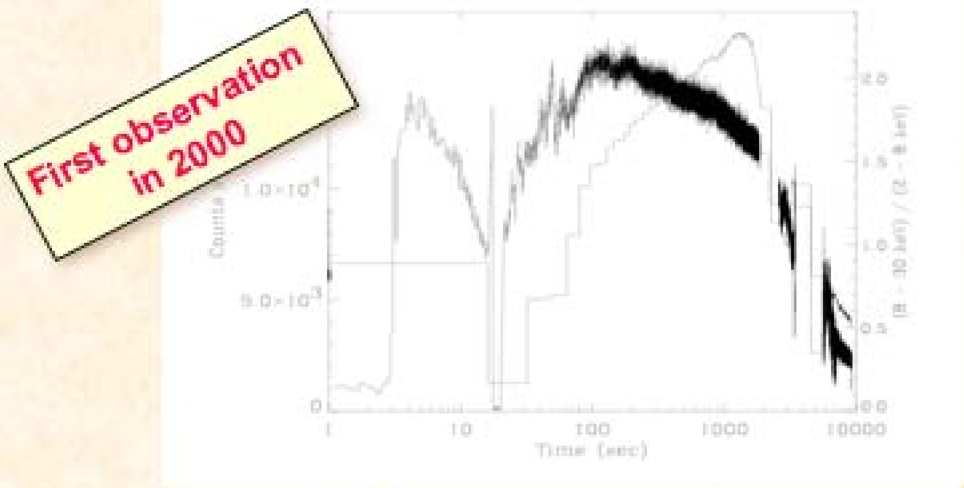
Galloway et al., ApJ **601** (2004) 466.



Ginga 1826 over 5 years

- More frequent and intense bursts
- Increasing burning between pulses
- Trends not fit with consistent models

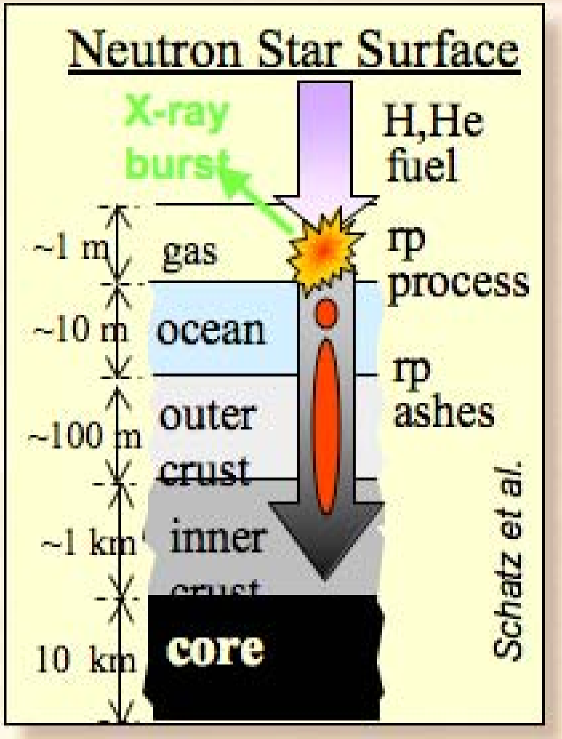
Strohmayer and Brown, ApJ **556** (2002) 1045.



Orders of magnitude greater energy release and duration

Ignition of carbon from unburned ashes of previous bursts

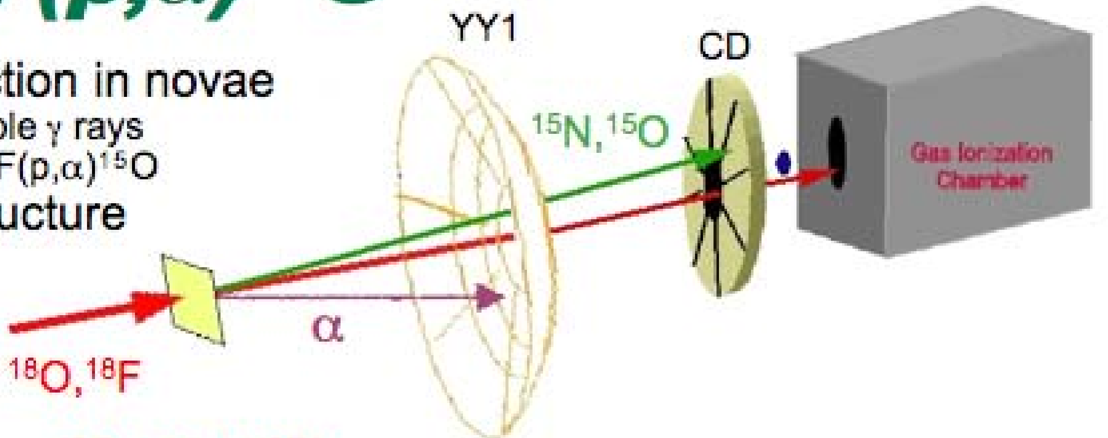
Composition of rp process ashes is very important



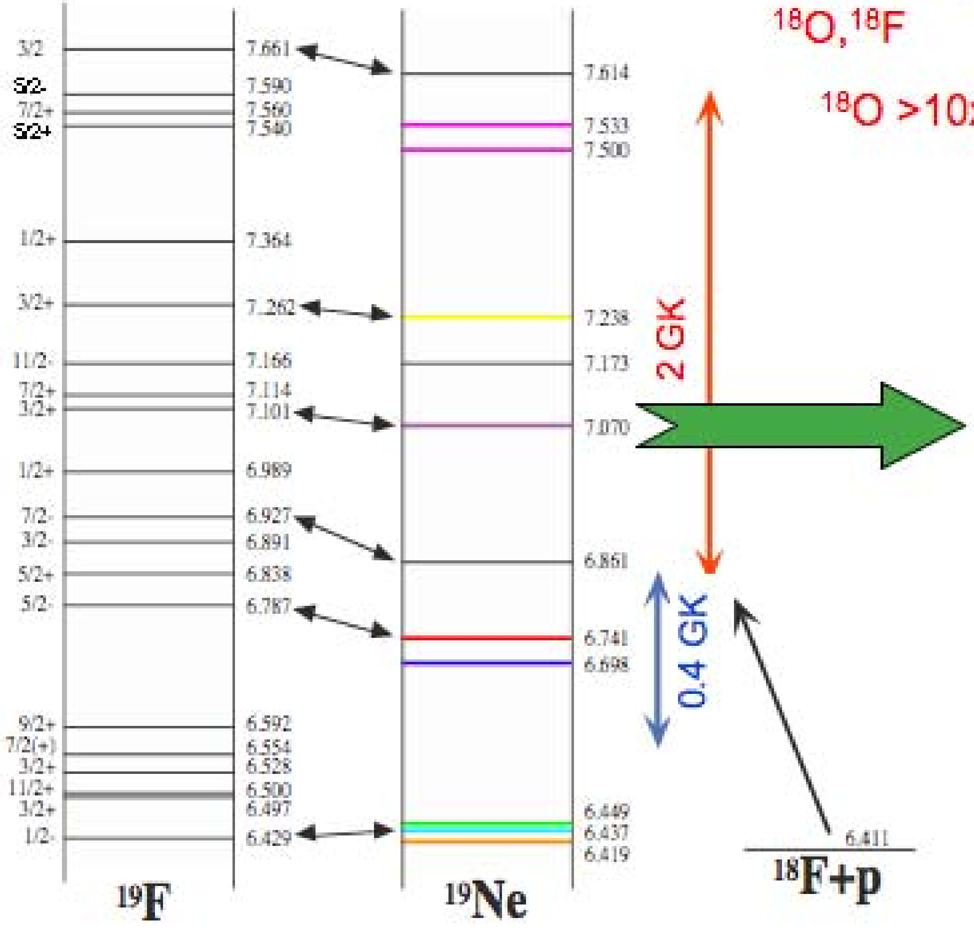
Schatz et al.

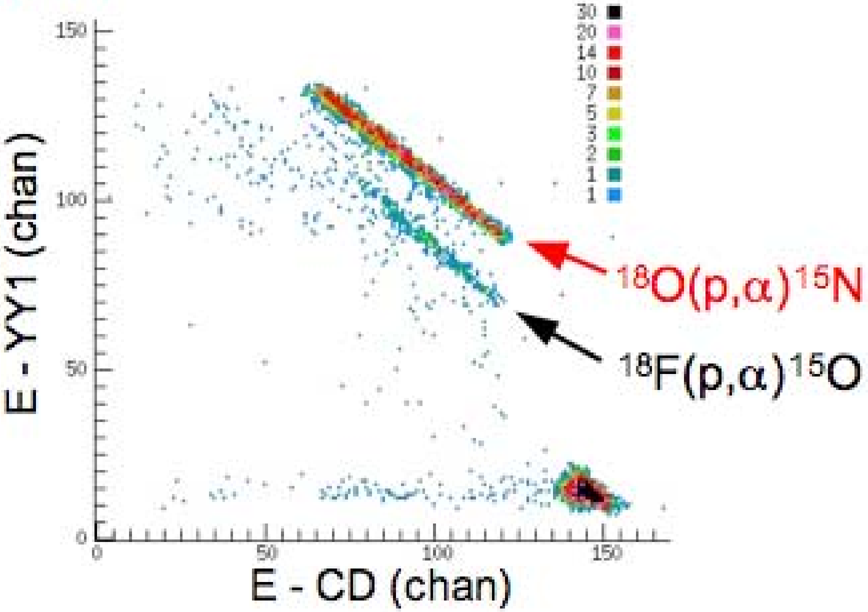
$^{18}F(p,\alpha)^{15}O$

- Largest uncertainty in ^{18}F production in novae
  - Largest source of potentially observable γ rays
  - Flux uncertain by ~300x just due to $^{18}F(p,\alpha)^{15}O$
- Complicated (uncertain) level structure



^{18}O >10x (^{18}F)



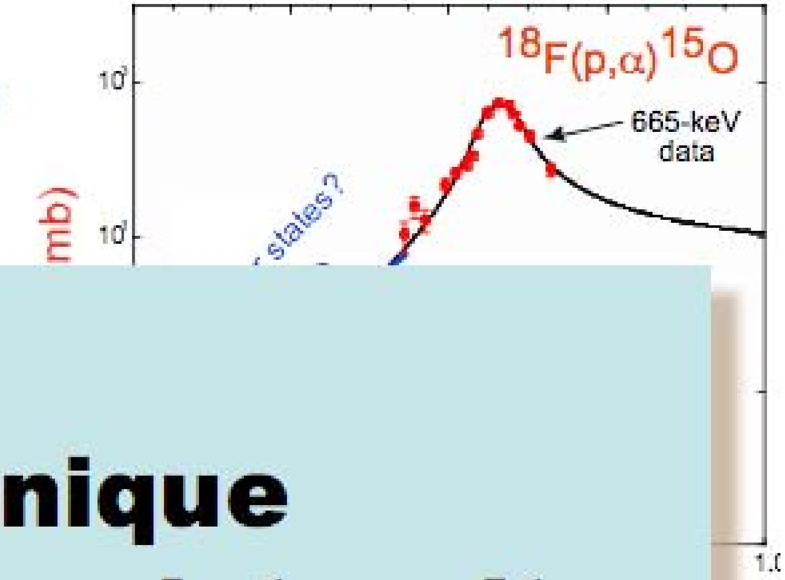


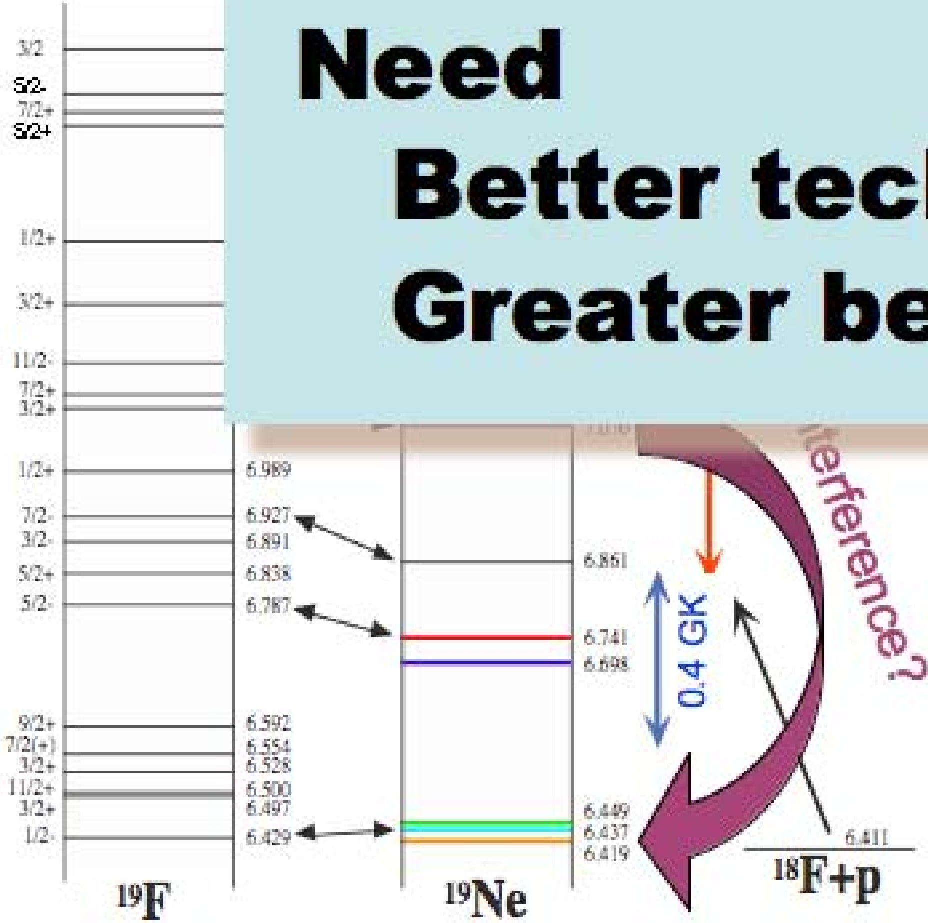
- Coincidence allows reaction to be distinguished with highly contaminated beam.

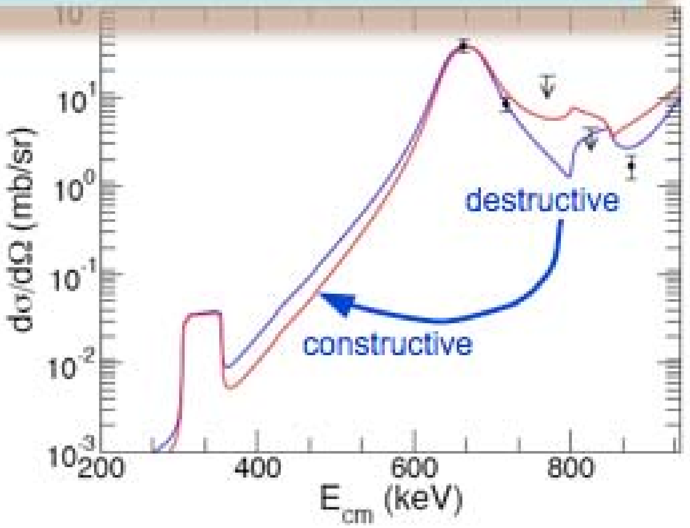
Results

Bardayan et al., PRL **89** (2002)
& PRC **63** (2001)

- Significant progress …
  … but 3 significant outstanding issues







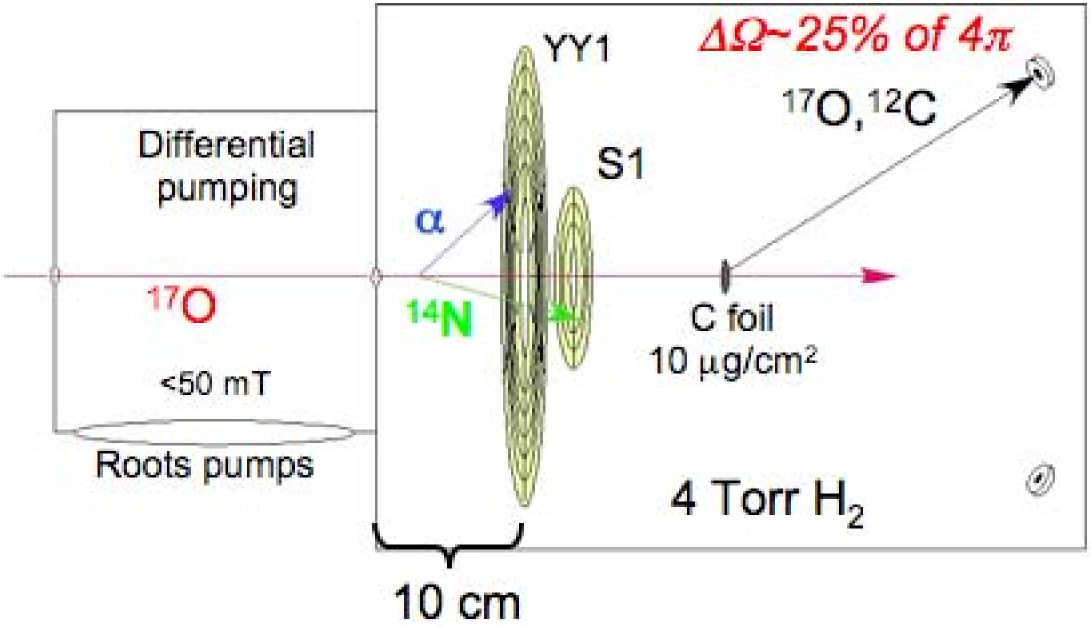
Need

Better technique

Greater beam intensity

New technique developed with $^{17}O(p,\alpha)^{14}N$

Moazen et al., Phys Rev C ***601*** *(2004) 466.*



- Extended windowless hydrogen gas target
- Reaction yield increased by 3x relative to using CH_2
- Target thickness matched to resonance width by pressure

  ➡ reduced background

  Narrow states → low P

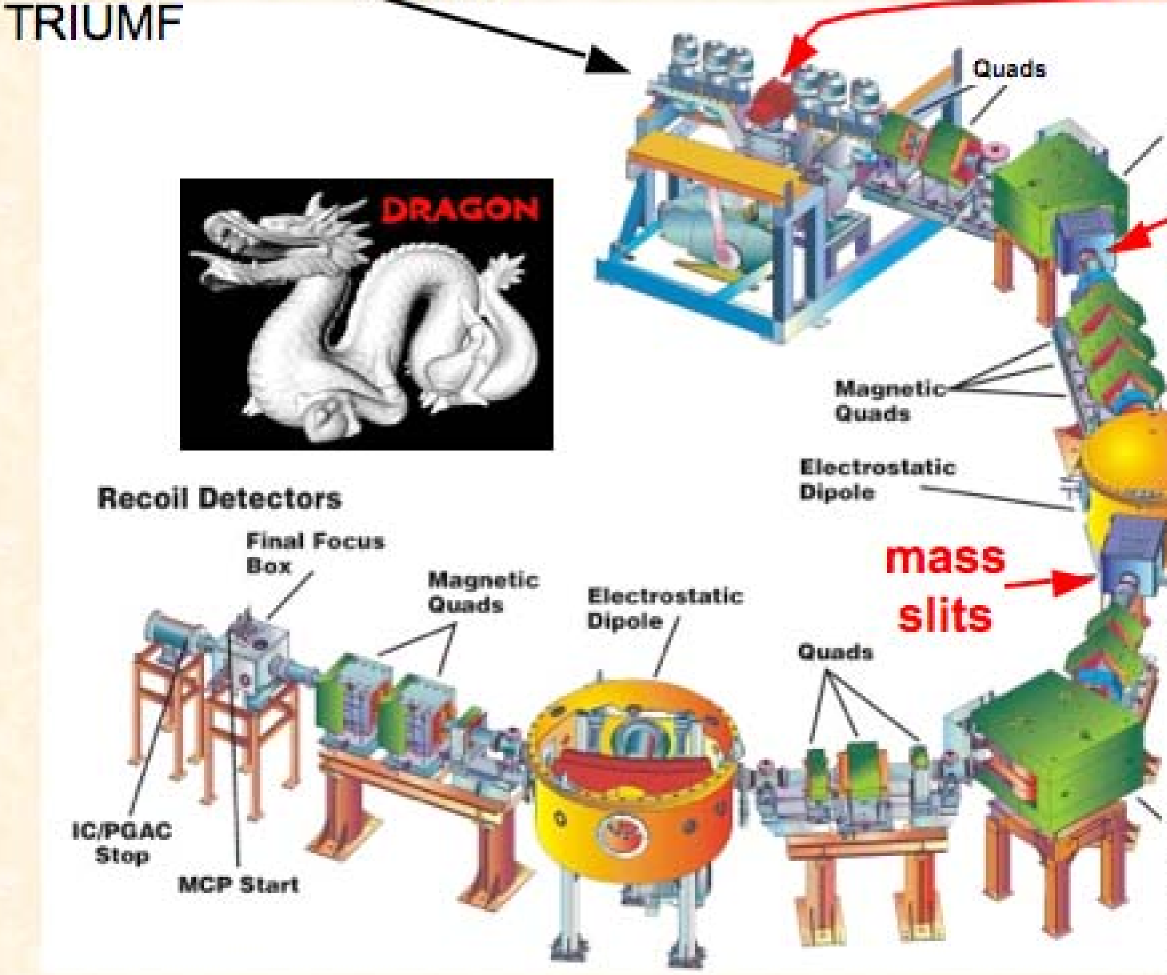
183-keV resonance in $^{17}O(p,\alpha)^{14}N$ reaction measured with an accuracy of 9%

Measurement of $^{18}F(p,\alpha)^{15}O$ approved by HRIBF PAC

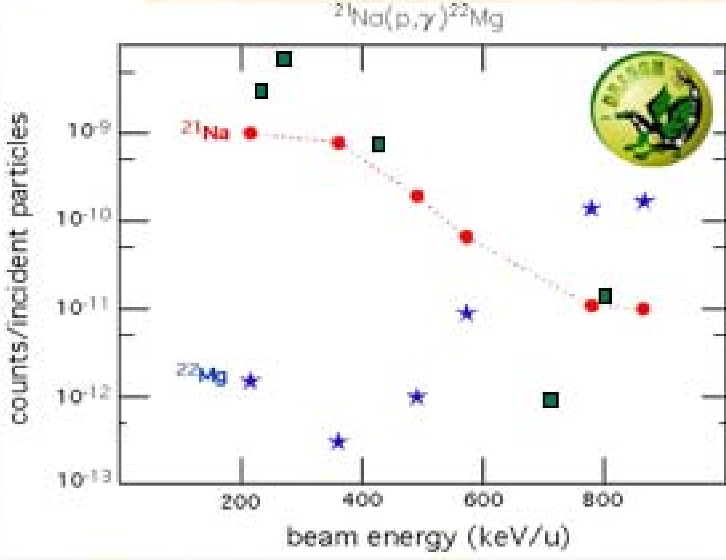
See talk by B. Moazen, Thursday July 19

(p,γ) at ISAC

TRIUMF



recoil+γ coincidences provide sensitive selection of events



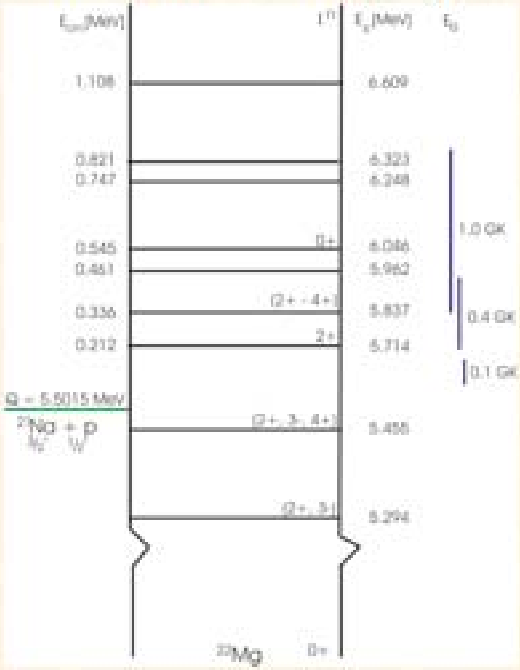
http://dragon.triumf.ca

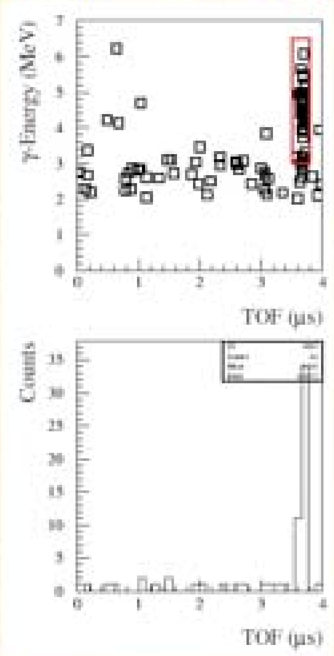
*S. Engel et al., NIM **A553** (2005) 491.*
*D. A. Hutcheon et al., NIM **A498** (2003) 190.*

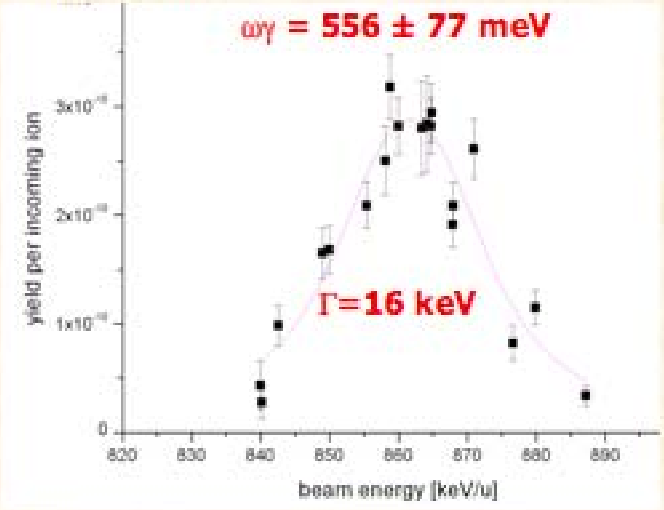
^{21}Na(p,γ)^{22}Na with DRAGON

2.6 yr half-life and 1.27 MeV gamma ray make ^{22}Na a prime observational target

In 1999: ^{21}Na(p,γ)^{22}Mg rate uncertain by >10^5x *(Jose, Coc, Hernanz, ApJ520).)*

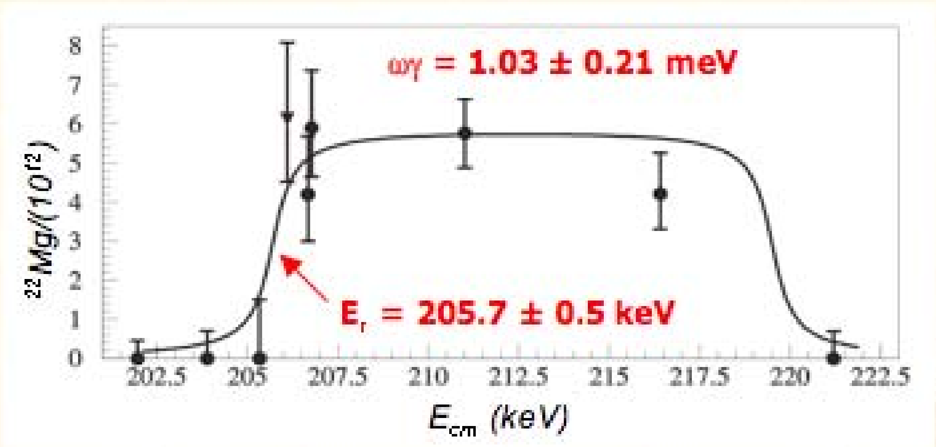






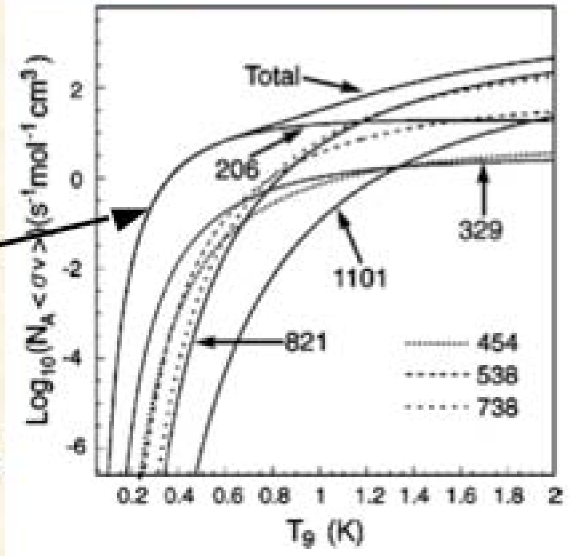
J. D'Auria et al., PRC ***69*** *(2004) 065803.*

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



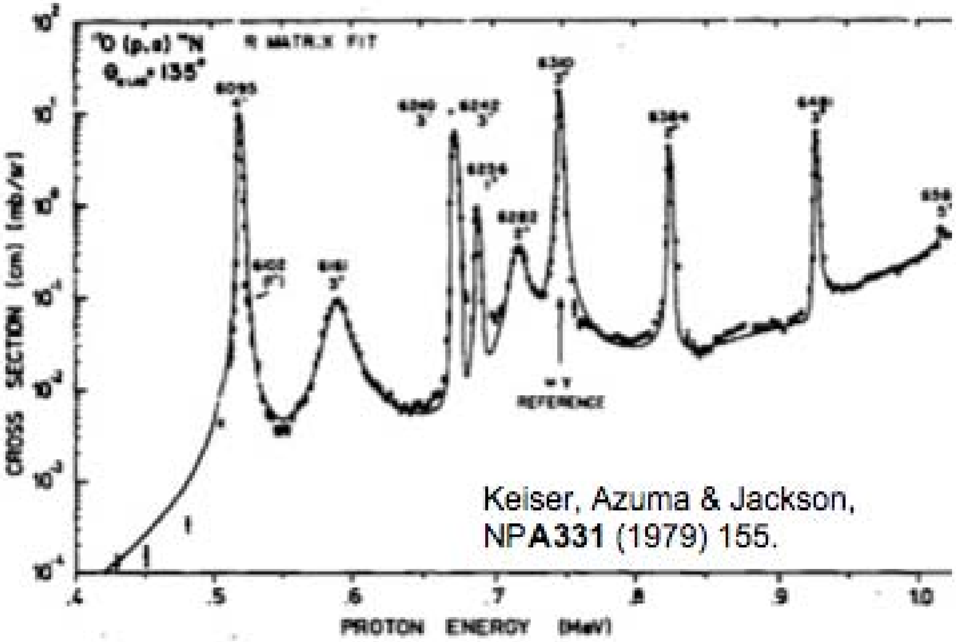
Higher rate for
206 keV
resonance
→ ~25% less
^{22}Na

Uncertainty~25%



That's great, but ...

- Radioactive ion beam intensities are typically very low.
  - Expensive to produce
  - Beam time limited
- Cross sections for reactions of interest are low:
  - $(p,\gamma)\ \sigma < \mu b$
  - $(p,\alpha)\ \sigma <$ mb
- Wide range of energies important in explosive environments.
- Measurement of complete excitation function over energy range of interest is usually not practical.
- Need alternative approaches to measure nuclear structure properties:
  - Stable beam measurements
  - Elastic scattering with RIBs
  - Direct reactions with RIBs

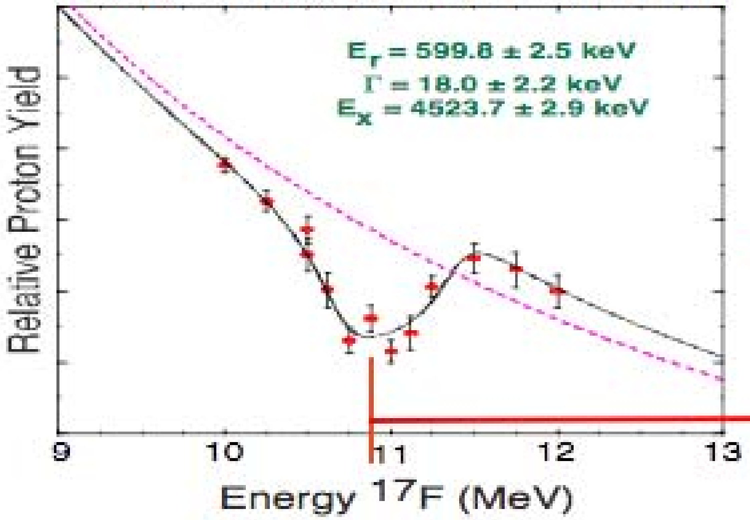


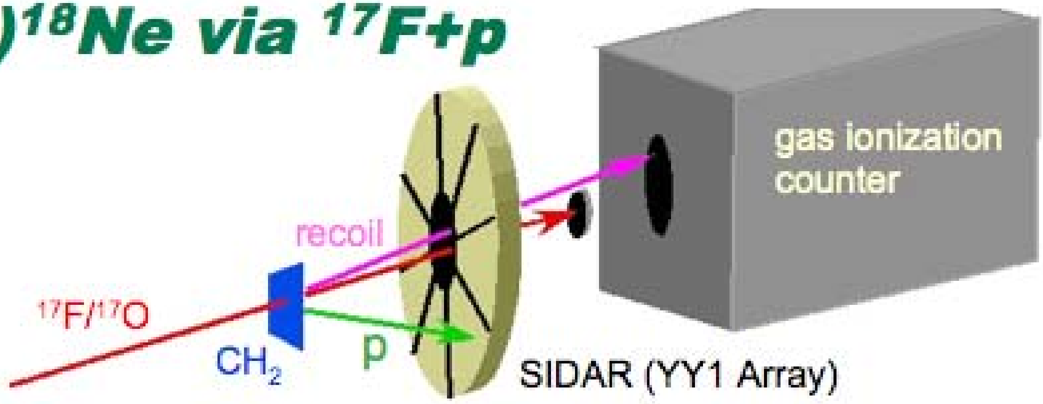
Keiser, Azuma & Jackson, NP**A331** (1979) 155.

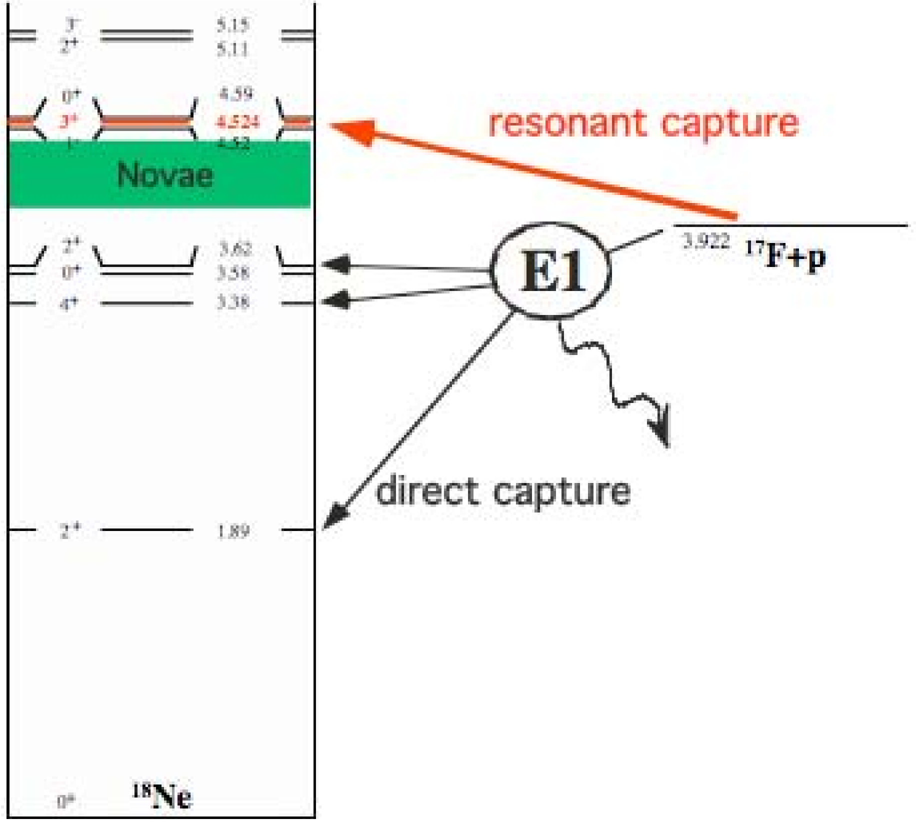
Elastic scattering with low energy beams

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

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







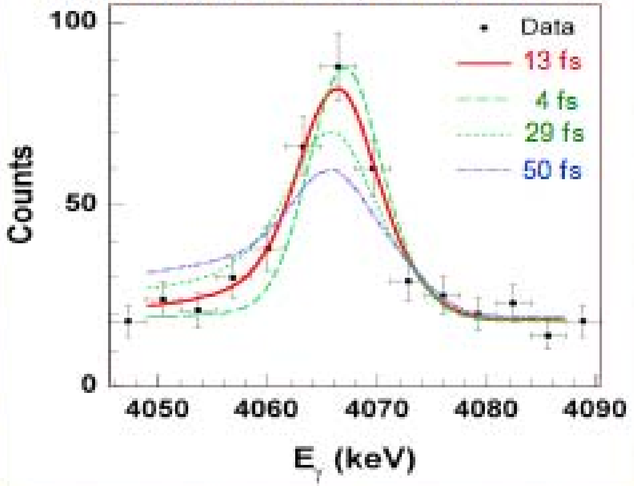
- ➢ 3^+ state predicted from mirror symmetry, but not observed in transfer reactions
  - $^{20}Ne(p,t)^{18}Ne$
  - $^{16}O(^3He,n)^{18}Ne$
- ➢ Discovered via $^{17}F+p$ elastic scattering to be too high in energy to contribute significantly at nova temperatures

The $^{15}O(\alpha,\gamma)^{19}Ne$ reaction & X-ray binaries

JINA

UNIVERSITY OF NOTRE DAME

*Tan et al., PRC **72** (2005) 041302.*



Lifetime of most important state (E_x=4.03 MeV) measured → Γ

ND

$^{17}O(^3He,n)^{19}Ne$

$\tau = 13^{+16}_{-9}$ fs (2σ)

TRIUMF

$^3He(^{20}Ne,\alpha)^{19}Ne$

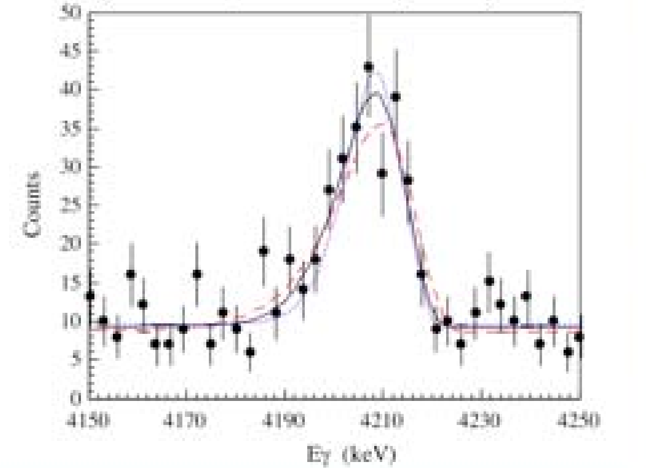
$\tau = 11^{+8}_{-7}$ fs (2σ)

Combined

$\tau = 12^{+7}_{-6}$ fs (2σ)

TRIUMF-ISAC

Kanungo et al., PRC 74 (2006) 045803.



Despite great efforts, only upper limit on Γ_α

Argonne NATIONAL LABORATORY

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

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

$B_\alpha < 6 \times 10^{-4}$

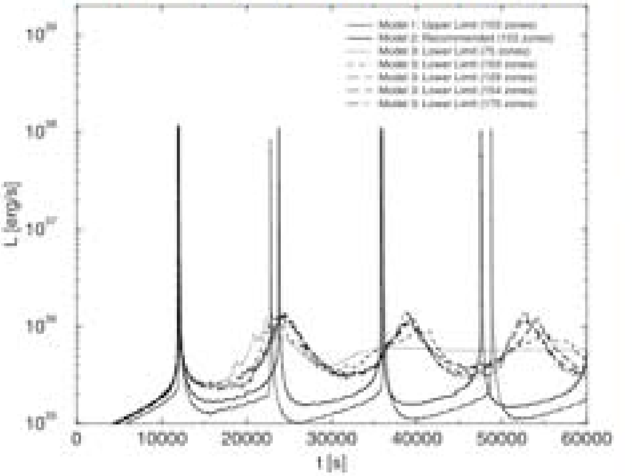
KVI

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

$^1H(^{21}Ne,t)^{19}Ne \rightarrow {}^{15}O + \alpha$

$B_\alpha < 4 \times 10^{-4}$

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

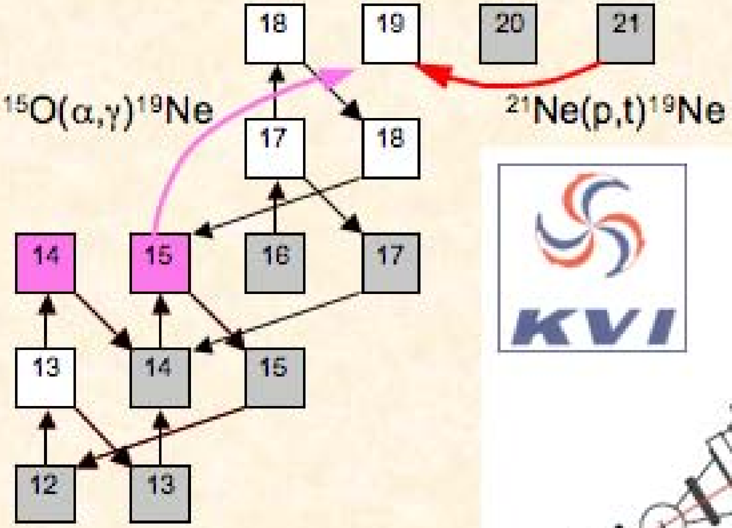


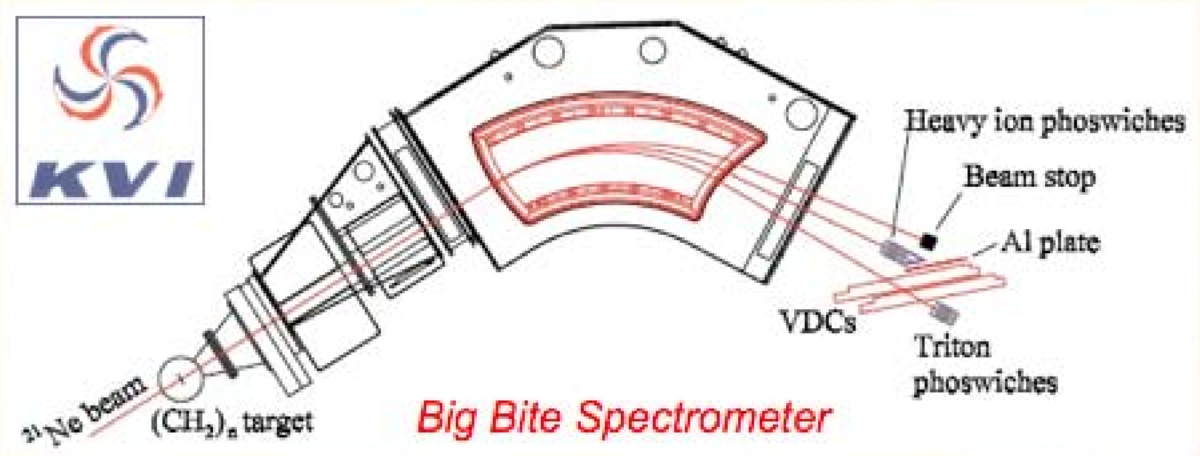
Uncertain lower limit on Γ_α results in substantial, qualitative changes in X-ray burst models

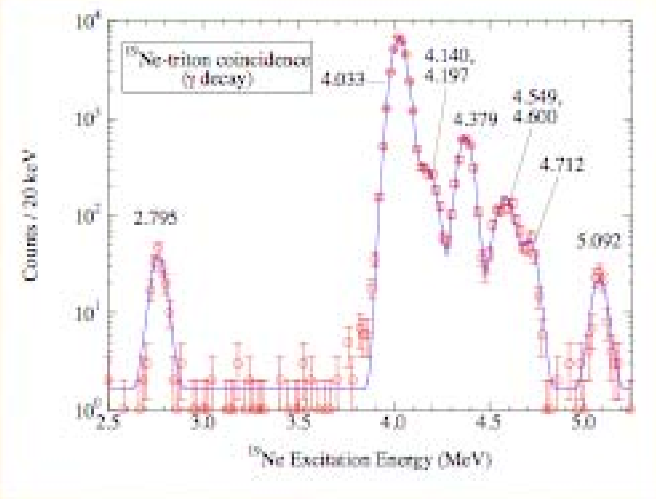
B. Davids *et al.*, PRC **67** (2003) 065808.

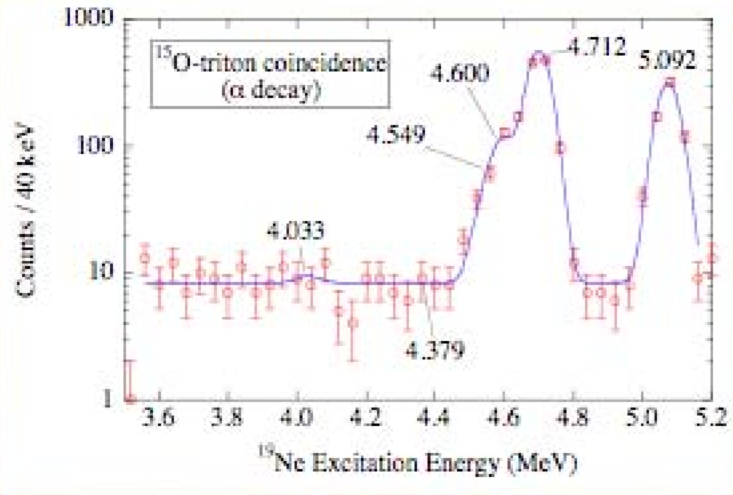
Measuring partial widths

- $^{15}O(\alpha,\gamma)^{19}Ne$ rate is important for "break-out" of CNO cycle and X-ray burst ignition → Γ_α's are major uncertainties



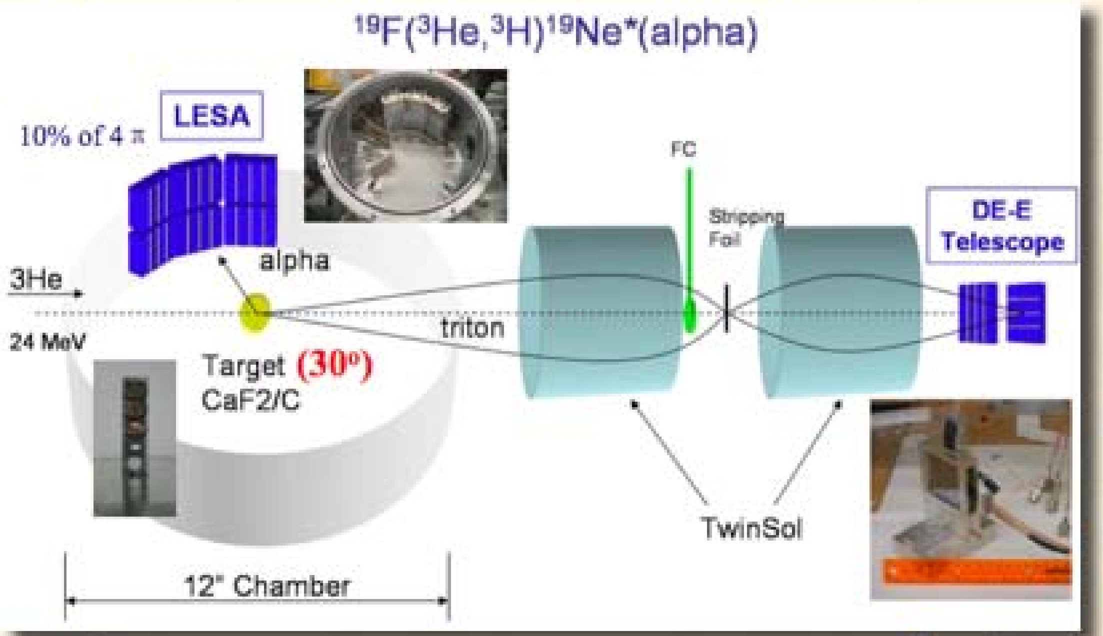




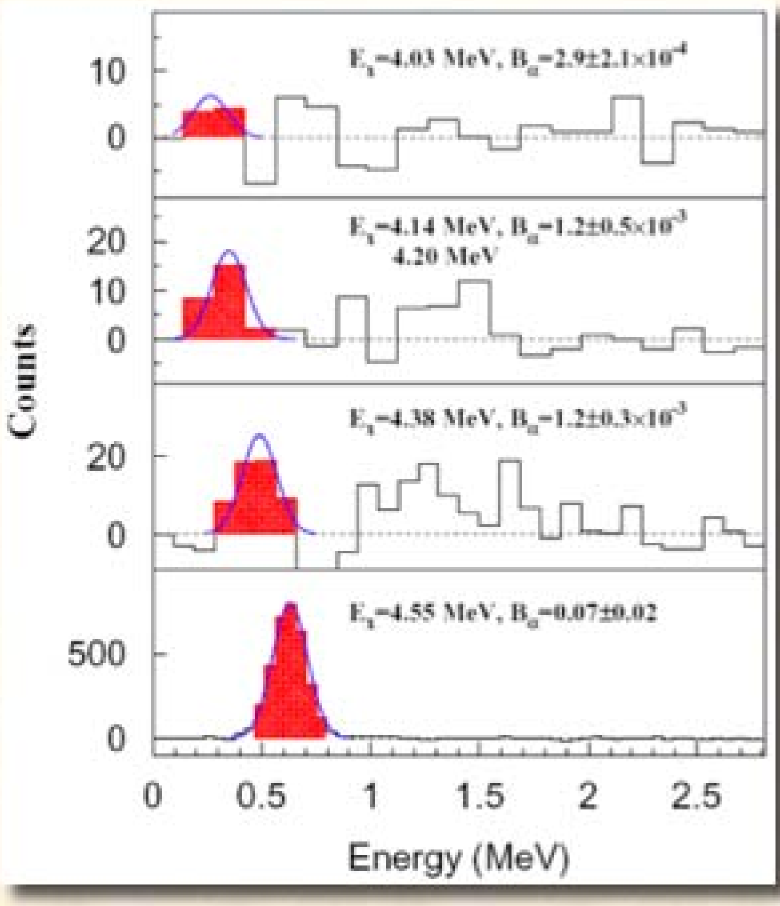


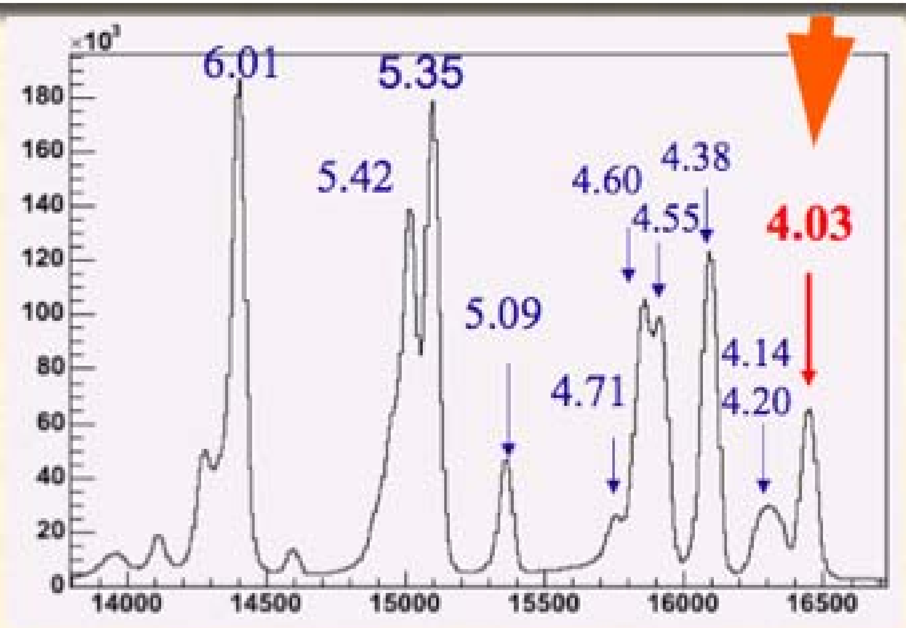
E_x (MeV)	Γ_α/G
4.033	< 0.0004
4.379	< 0.004
4.549	0.16±0.04
4.6	0.32±0.04
4.712	0.85±0.04

Recent Notre Dame Measurement



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





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

Homework problem - $^{15}O(\alpha,\gamma)^{19}Ne$

The $^{15}O(\alpha,\gamma)^{19}Ne$ reaction is one of the most important reactions in X-ray binaries (see Lecture #3). 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:

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

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 $4x10^{-4}$, the upper limit from Davids *et al.*, PRC **67** (2003). 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 $4x10^8$ K and 10^5 g/cm^3. Is this reaction important in novae?

Homework solution

$$N_\alpha N_{15}\langle\sigma v\rangle = \lambda N_{15} \quad\Longrightarrow\quad \rho X_\alpha \frac{A}{w_\alpha}\langle\sigma v\rangle = \frac{\ln 2}{122s}$$

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

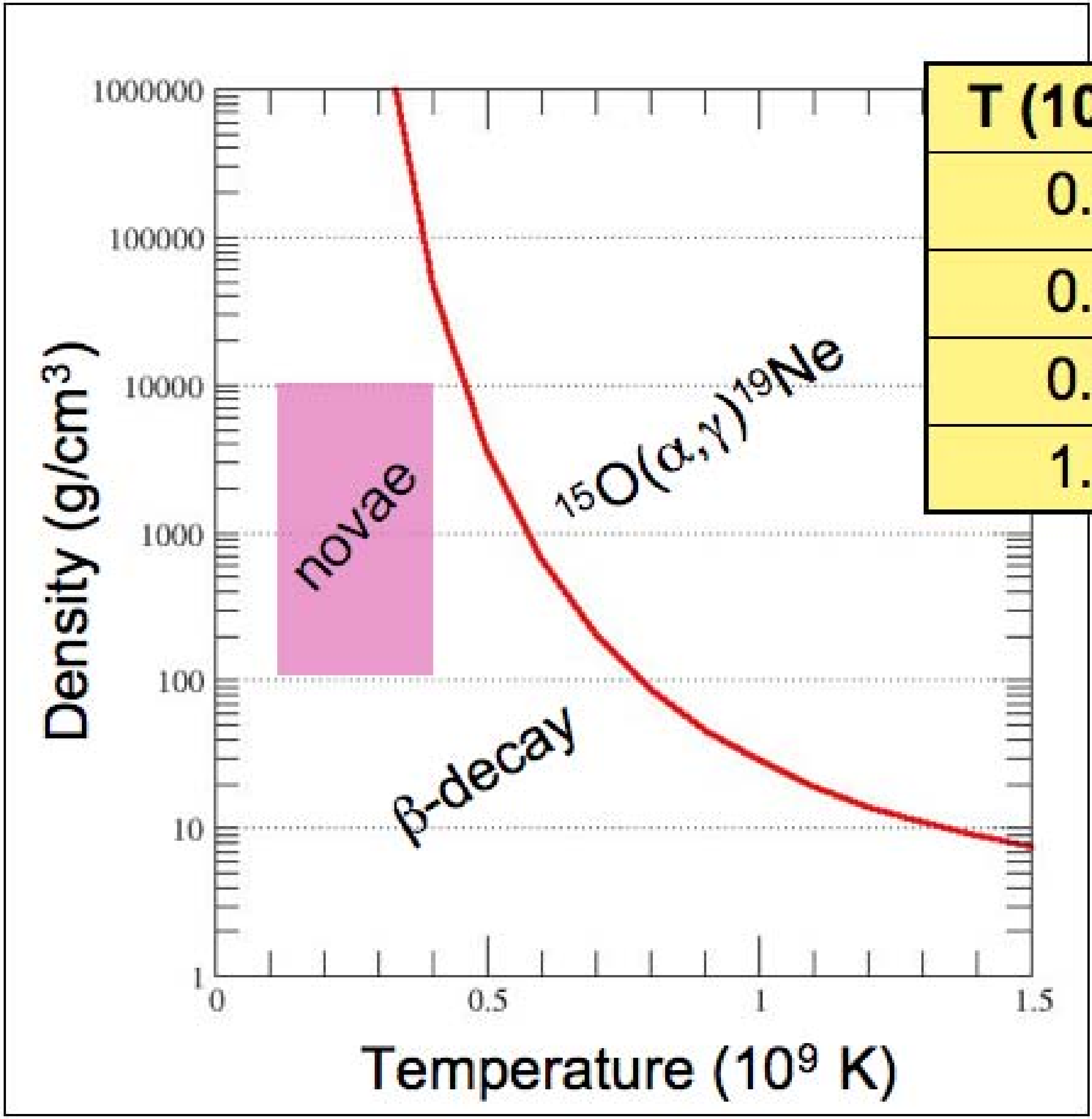
$$(\omega\gamma)_r = \frac{2J+1}{(2J_\alpha+1)(2J_{15}+1)}\frac{\Gamma_\alpha\Gamma_\gamma}{\Gamma} = \frac{2\frac{3}{2}+1}{(2\cdot 0+1)\left(2\frac{1}{2}+1\right)}\left(4\times10^{-4}\right)(50meV) = 4\times10^{-5}eV$$

$$\langle\sigma v\rangle \approx \left(6.6\times10^{-16}eV\cdot s\right)^2(2\pi)^{3/2}\left(\frac{19}{60\times0.931\times10^9 eV}\right)^{3/2}\left(3\times10^{10}cm/s\right)^3\left(4\times10^{-5}eV\right)(kT)^{-3/2}e^{-E_r/(kT)}$$

$$\langle\sigma v\rangle \approx 4.64\times10^{-17}(kT)^{-3/2}e^{-E_r/(kT)}cm^3/s$$ (with kT in eV)

$$\rho(0.25)\frac{6\times10^{23}}{4g}4.64\times10^{-17}(kT)^{-3/2}e^{-E_r/(kT)}cm^3/s = 0.0057/s$$

$$\rho = 3.3\times 10^{-9}\left(kT\right)^{3/2} e^{504000/(kT)} g/cm^{3}$$ With kT in eV



T (10^9 K)	ρ (g/cm^3)
0.1	6.5×10^{22}
0.2	3.7×10^{10}
0.5	3500
1.0	29

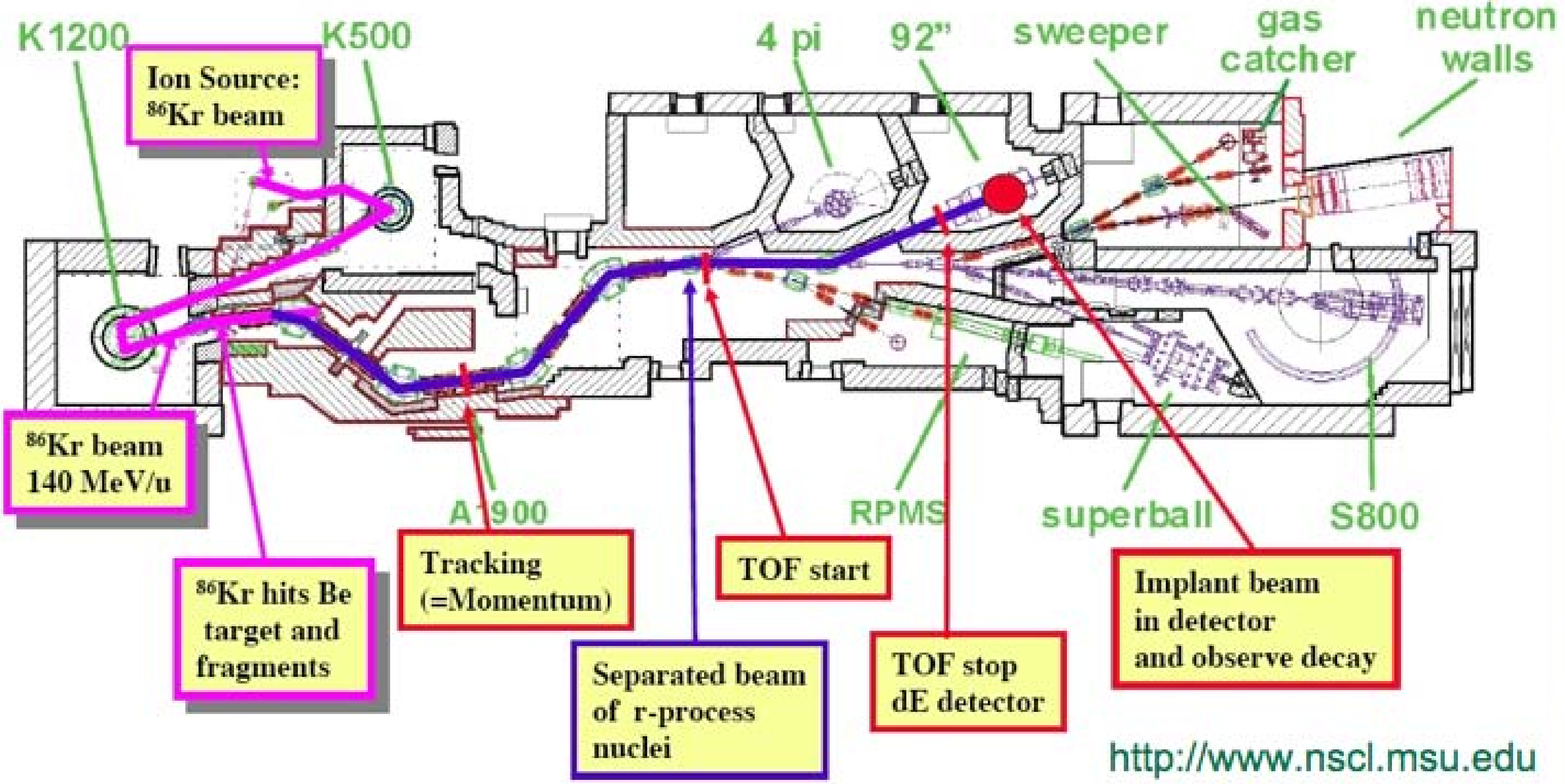
Projectile Fragmentation @ the NSCL

MICHIGAN STATE UNIVERSITY

Advancing Knowledge. Transforming Lives.

NSCL NATIONAL SUPERCONDUCTING CYCLOTRON LABORATORY AT MICHIGAN STATE UNIVERSITY

NSF



Ion Source: ^{86}Kr beam

^{86}Kr beam 140 MeV/u

^{86}Kr hits Be target and fragments

Tracking (=Momentum)

Separated beam of r-process nuclei

TOF start

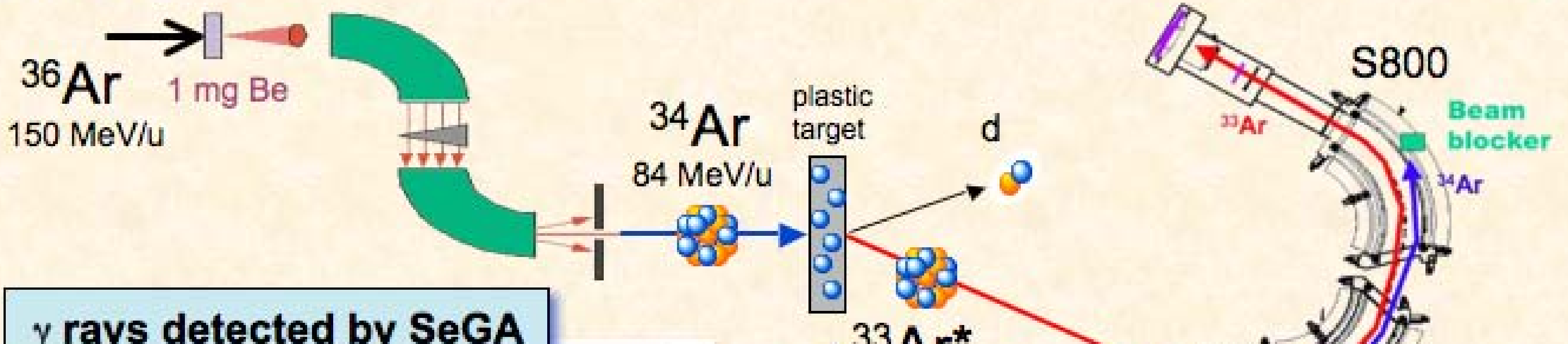
TOF stop dE detector

Implant beam in detector and observe decay

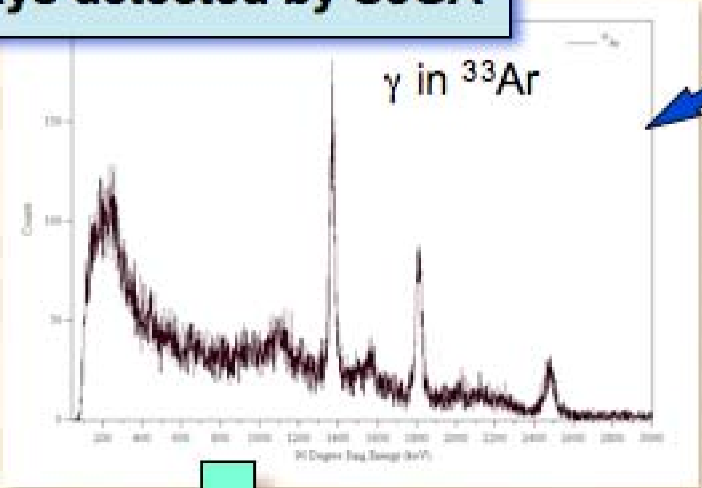
http://www.nscl.msu.edu

*R. Clement et al., PRL **92** (2004) 172502.*

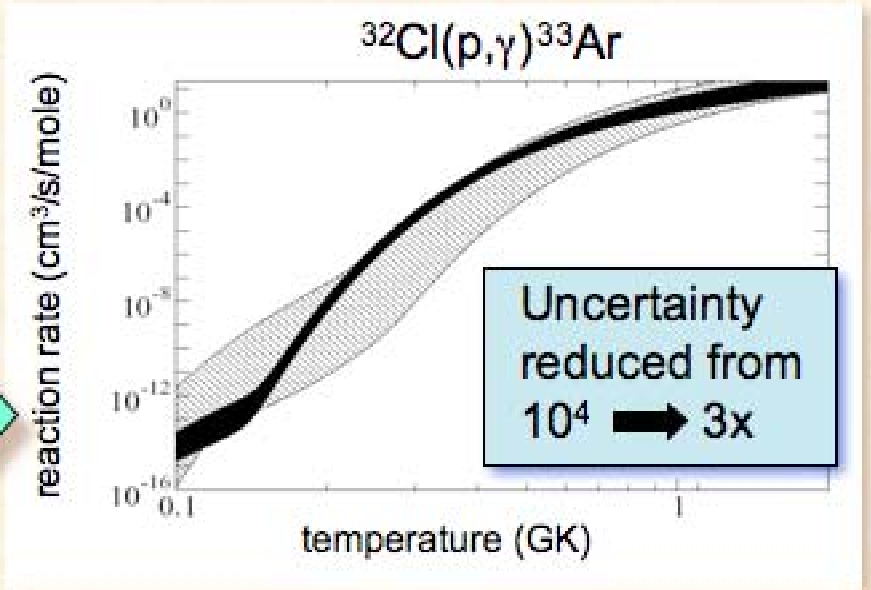
Resonance energies via (p,d) reactions & fast beams at NSCL



γ rays detected by SeGA



level energies in ^{33}Ar
➡ resonance energies in ^{32}Cl+p

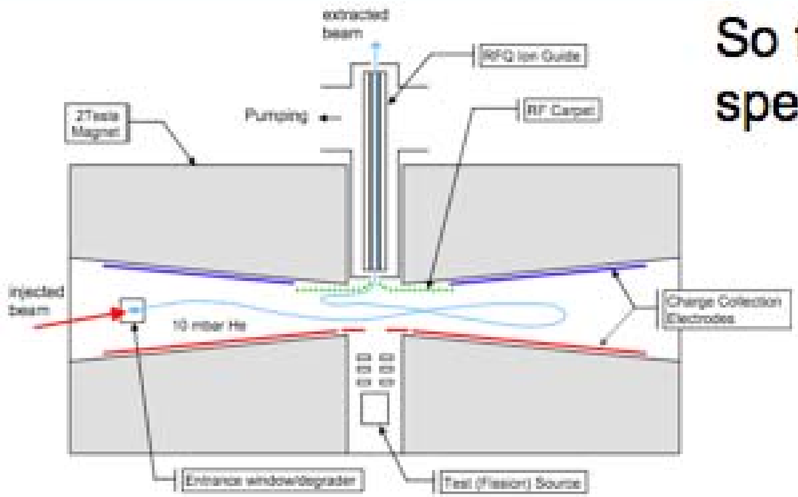


Uncertainty reduced from 10^4 ➡ 3x

MICHIGAN STATE UNIVERSITY

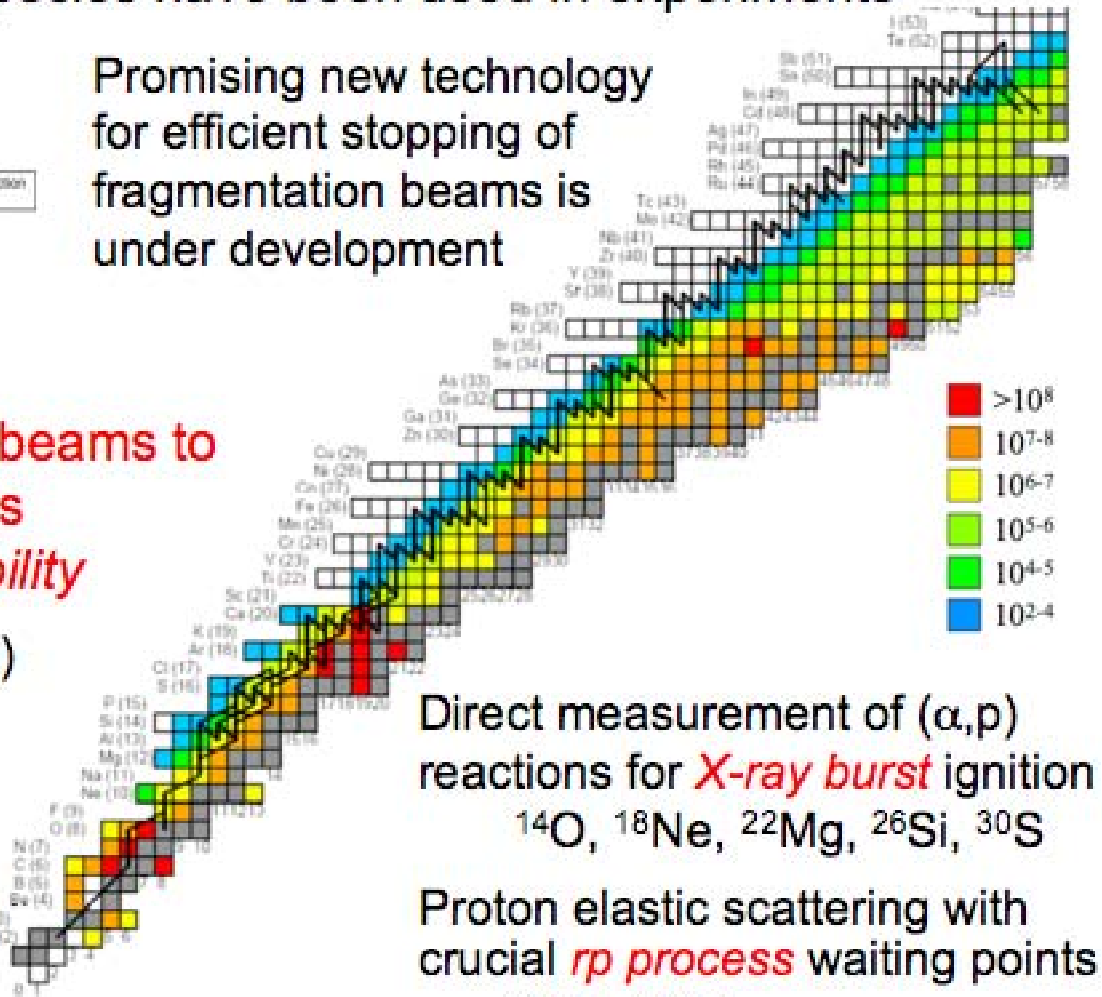
Reaccelerated beams at NSCL

Bollen, Morrissey, Shatz et al.



So far <10 proton-rich accelerated species have been used in experiments

Promising new technology for efficient stopping of fragmentation beams is under development



Would allow a broad range of beams to be accelerated for astrophysics measurements: *unique capability*

Direct measurement of many (p,γ) reactions important for *novae*

^{23}Mg, ^{25}Al, ^{30}P, ^{35}Ar, ^{38}K

Scattering & transfer reactions important for understanding iron-group nuclei in *supernovae*

^{44}Ti, ^{45}V, ^{46}Cr, ^{56}Ni

Direct measurement of (α,p) reactions for *X-ray burst* ignition

^{14}O, ^{18}Ne, ^{22}Mg, ^{26}Si, ^{30}S

Proton elastic scattering with crucial *rp process* waiting points

^{57}Cu, ^{68}Se

Conclusion

- Nuclear physics plays an important role in astrophysical objects.
- Nuclear astrophysics aims to supply nuclear data needed to help understand astrophysical objects, especially:
  - Energy generation
  - Nucleosynthesis
- Big bang nucleosythensis and stellar hydrogen burning are relatively well understood thanks to sensitive measurements, but there are important outstanding open questions. For example:
  - ^{7}Li production in Big Bang
  - Precise determination of neutrino production rates in sun
- The $^{12}C(\alpha,\gamma)^{16}O$ has a strong influence on all late stages of stellar evolution. Measurements (especially indirect approaches) have improved our understanding, but further work is very important.
- Measurements of (n,γ) reactions on radioactive s process branch points are important for understanding heavy element production.
- Measurements of nuclear reactions and nuclear structure properties using short-lived radioactive beams are beginning to provide data that is helping to improve our understanding of nucleosynthesis in stellar explosions, but next-generation radioactive ion beam facilities are needed.