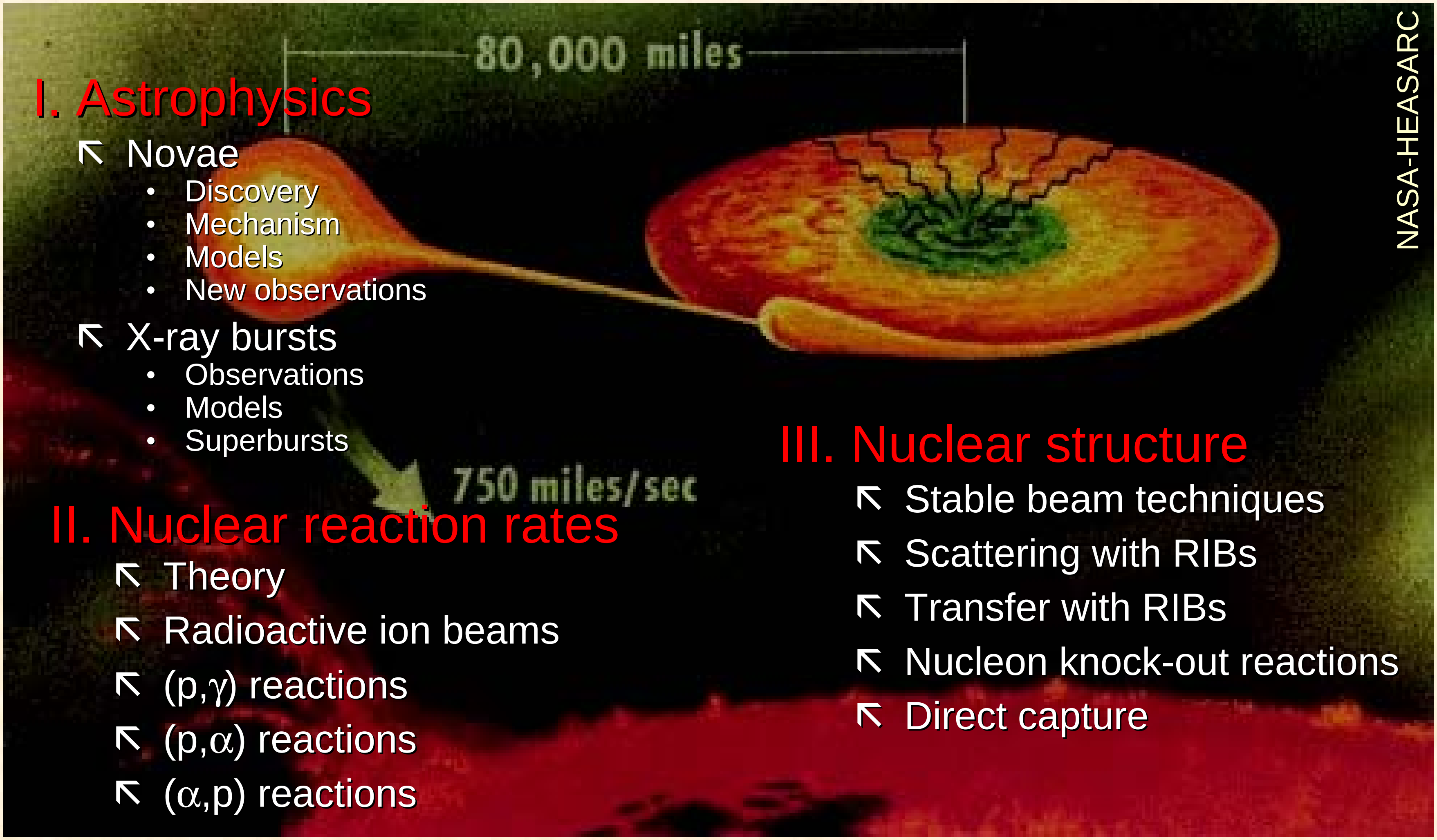
Cataclysmic variables

Jeff Blackmon, Physics Division, Oak Ridge National Lab



NASA-HEASARC

I. Astrophysics

- Novae
  - Discovery
  - Mechanism
  - Models
  - New observations
- X-ray bursts
  - Observations
  - Models
  - Superbursts

II. Nuclear reaction rates

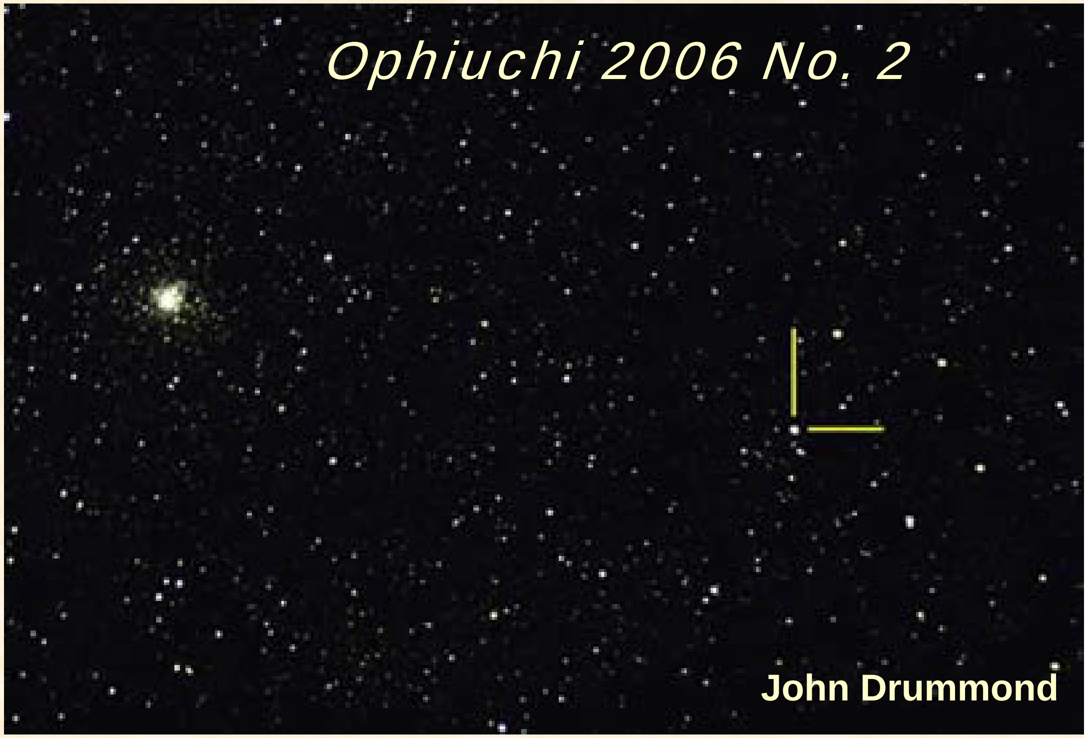
- Theory
- Radioactive ion beams
- (p,γ) reactions
- (p,α) reactions
- (α,p) reactions

III. Nuclear structure

- Stable beam techniques
- Scattering with RIBs
- Transfer with RIBs
- Nucleon knock-out reactions
- Direct capture

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)

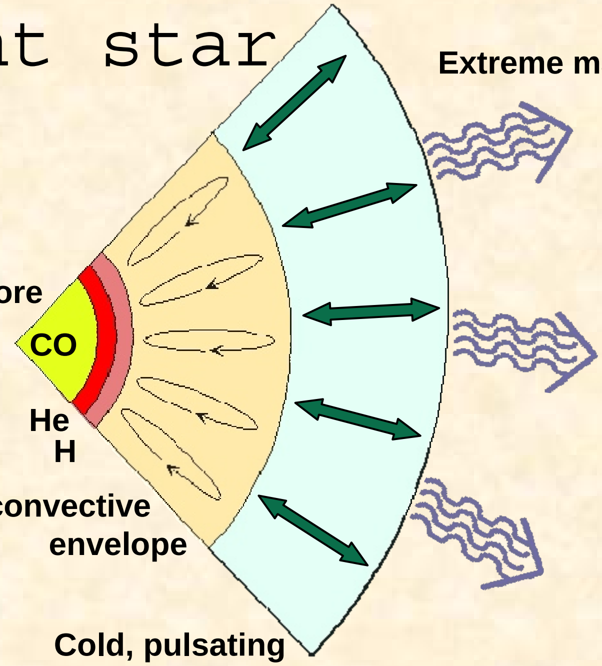


Ophiuchi 2006 No. 2

John Drummond

Giants and dwarves

Giant star



Extreme mass loss

Degenerate core

CO

He

H

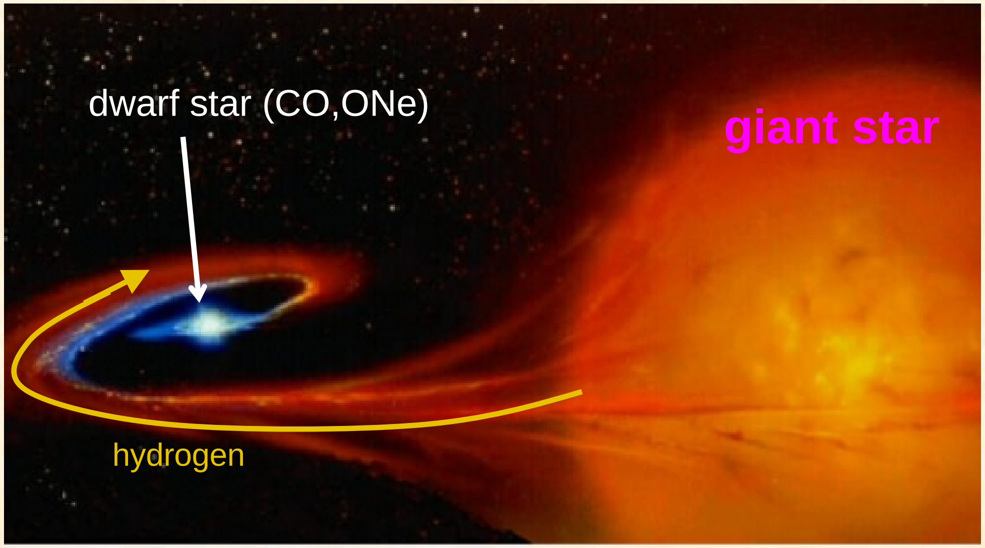
convective envelope

Cold, pulsating atmosphere

Harrington & Borkowski- STSci

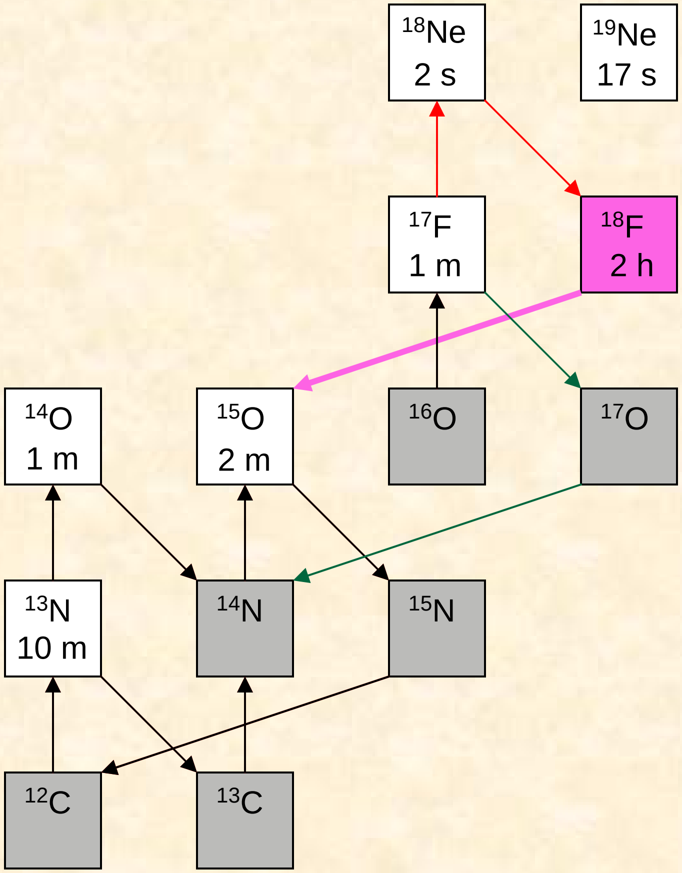
- Most stars are in multiple-star systems
- Some are close enough to interact

Novae mechanism



- Hydrogen-rich gas from main sequence or giant star accretes onto white dwarf and burns via ***hot-CNO cycle***
- Pressure support by electron degeneracy

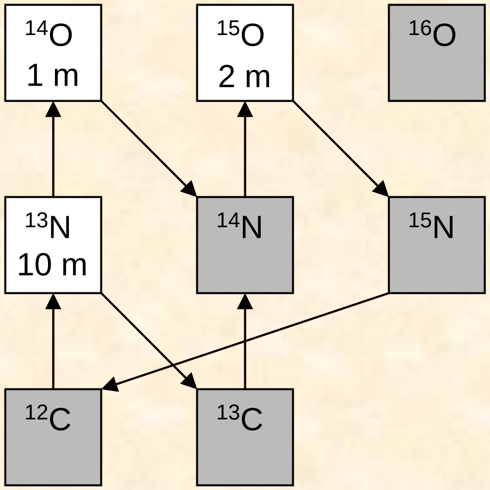
- Thermonuclear runaway
- Driven by nuclear physics
- Rates of nuclear reactions are important for understanding energy generation and nucleosynthesis
- Source for ^{13}C, ^{15}N, ^{17}O, …

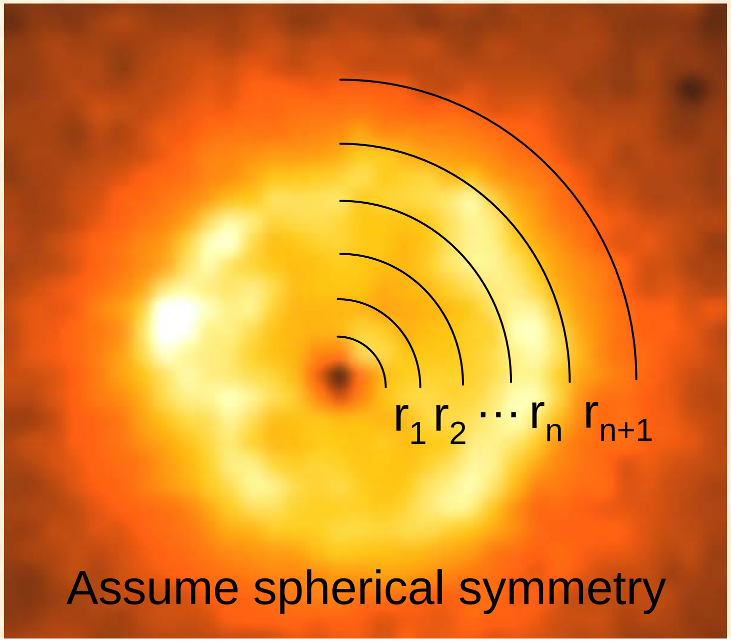


^{18}Ne 2 s
^{19}Ne 17 s
^{17}F 1 m
^{18}F 2 h
^{14}O 1 m
^{15}O 2 m
^{16}O
^{17}O
^{13}N 10 m
^{14}N
^{15}N
^{12}C
^{13}C

Thermonuclear events

- Difficult problem
  $t_{\mathrm{nuclear}} \sim t_{\mathrm{hydro}}$
- Simple example: 1D - CN cycle





Assume spherical symmetry

Reaction network

$$\frac{dN_{12C}}{dt} = N_{15N} N_p \langle \sigma v \rangle_{15Np} - N_{12C} N_p \langle \sigma v \rangle_{12Cp}$$

$$\frac{dN_{13N}}{dt} = N_{12C} N_p \langle \sigma v \rangle_{12Cp} - N_{13N} N_p \langle \sigma v \rangle_{13Np} - \lambda_{13N} N_{13N}$$

$$\frac{dN_{13C}}{dt} = \lambda_{13N} N_{13N} - N_{13C} N_p \langle \sigma v \rangle_{13Cp}$$

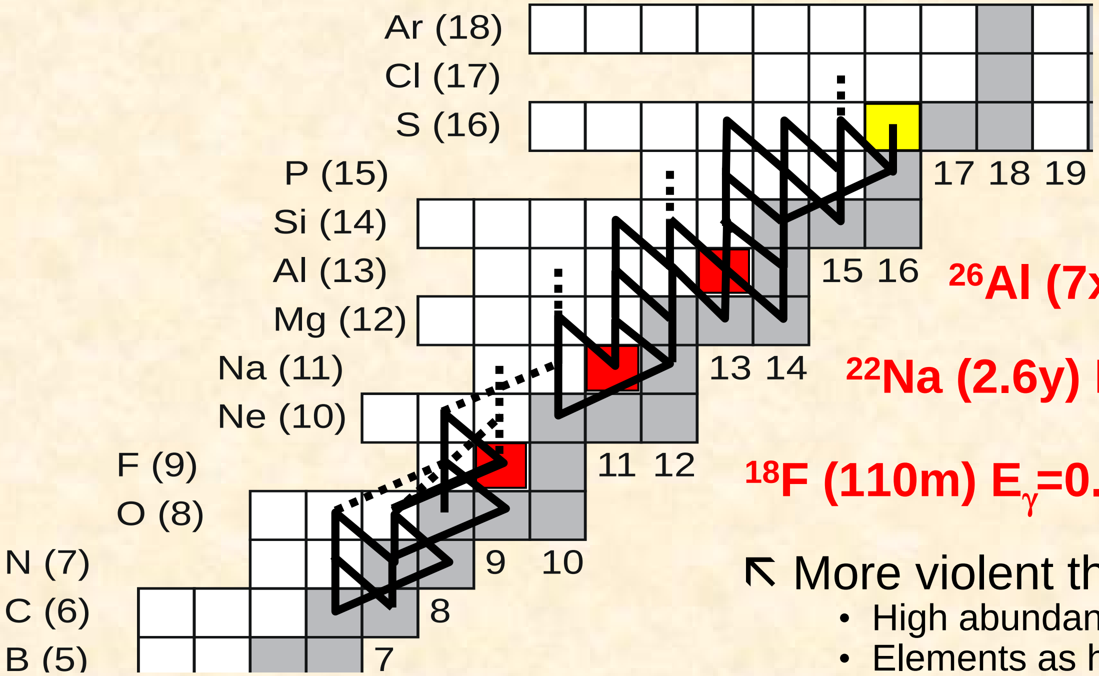
$$\frac{dN_{14O}}{dt} = N_{13N} N_p \langle \sigma v \rangle_{13Np} - \lambda_{14O} N_{14O}$$

$$\frac{dN_{14N}}{dt} = N_{13C} N_p \langle \sigma v \rangle_{13Cp} + \lambda_{14O} N_{14O} - N_{14N} N_p \langle \sigma v \rangle_{14Np}$$

$$\frac{dN_{15O}}{dt} = N_{14N} N_p \langle \sigma v \rangle_{14Np} - \lambda_{15O} N_{15O}$$

$$\frac{dN_{15N}}{dt} = \lambda_{15O} N_{15O} - N_{15N} N_p \langle \sigma v \rangle_{15Np}$$

Complex, multidimensional problem



↖ Many ejecta substantially enriched in S

^{26}Al (7x10^5y) E_γ=1.275 MeV

^{22}Na (2.6y) E_γ=1.809 MeV

^{18}F (110m) E_γ=0.511 MeV

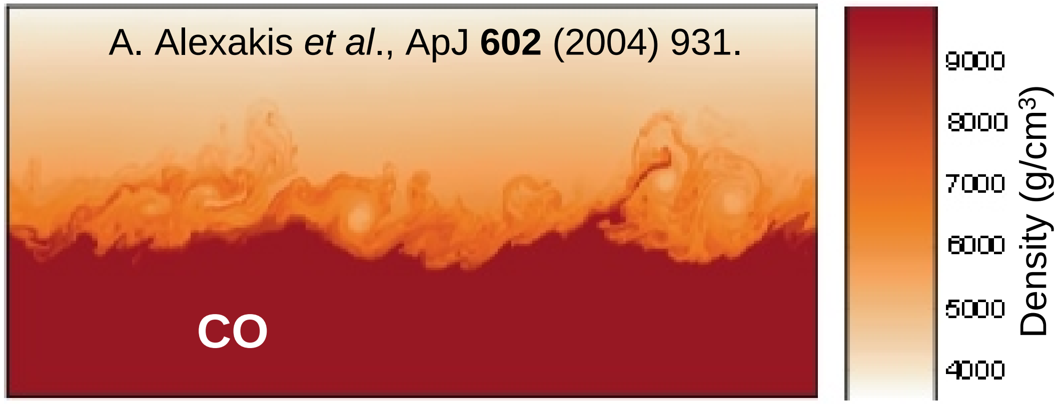
↖ More violent than expected

- High abundance of heavier elements
- Elements as heavy as sulfur
- High ejected mass

→ Substantial mixing of accreted material with core?

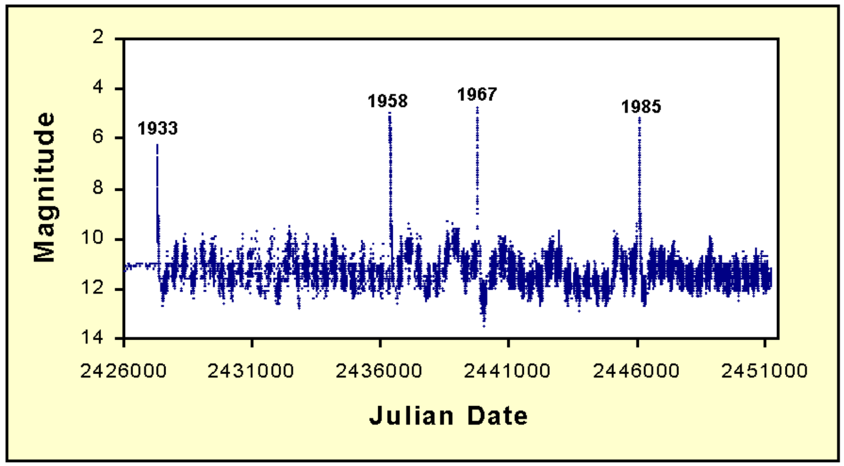
↖ Complex hydrodynamical models required

- 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.

RS Ophiuchi

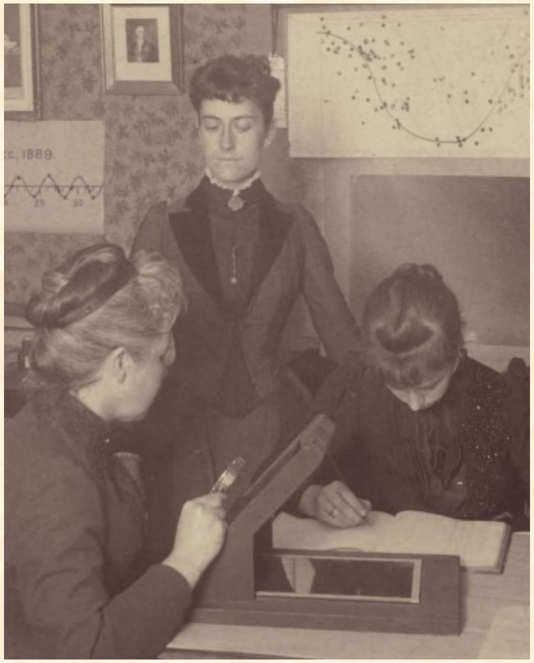
- "Recurrent Nova" (one of few known)




Guido & Sostero

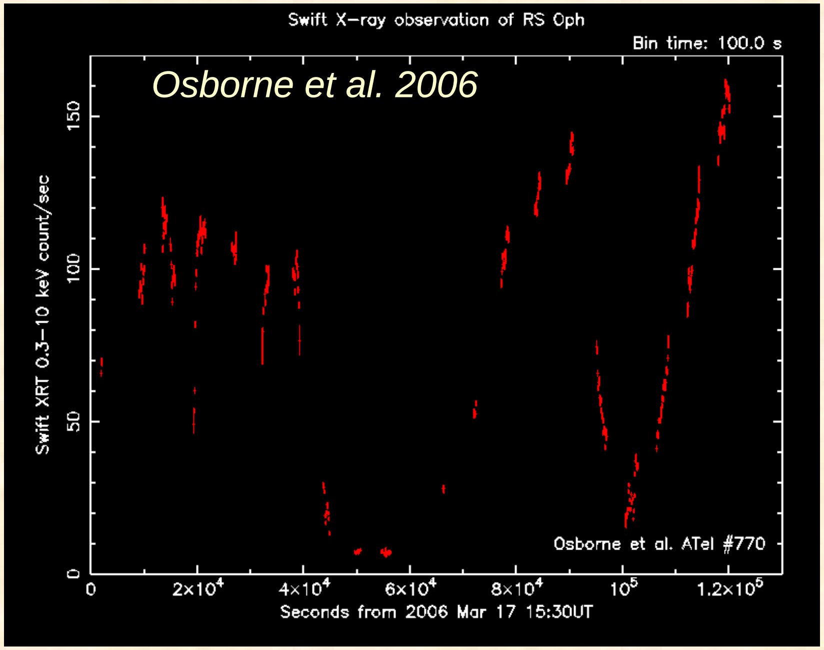
Recurrent Nova RS Ophiuchi in outburst; 2006 February 14.49

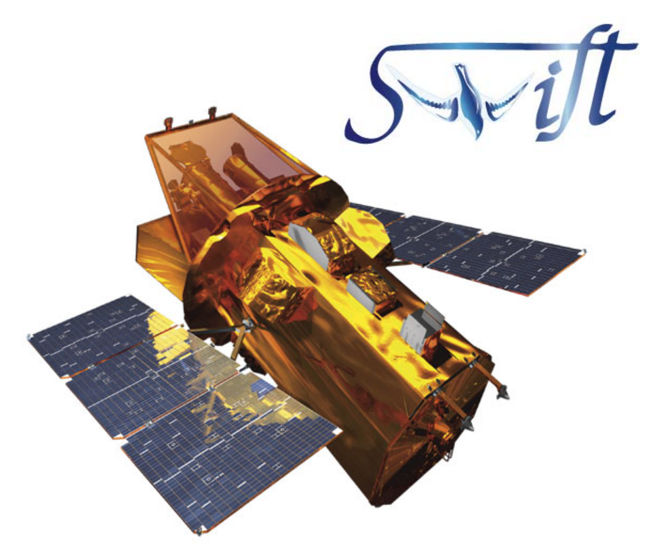
Takahashi Epsilon, D= 0.25m, f/3.4 + SBIG-ST8XE
Remotely from the "New Mexico Skies Observatory"
E. Guido and G. Sostero (AFAM, Remanzacco)
http://www.afamweb.com


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)

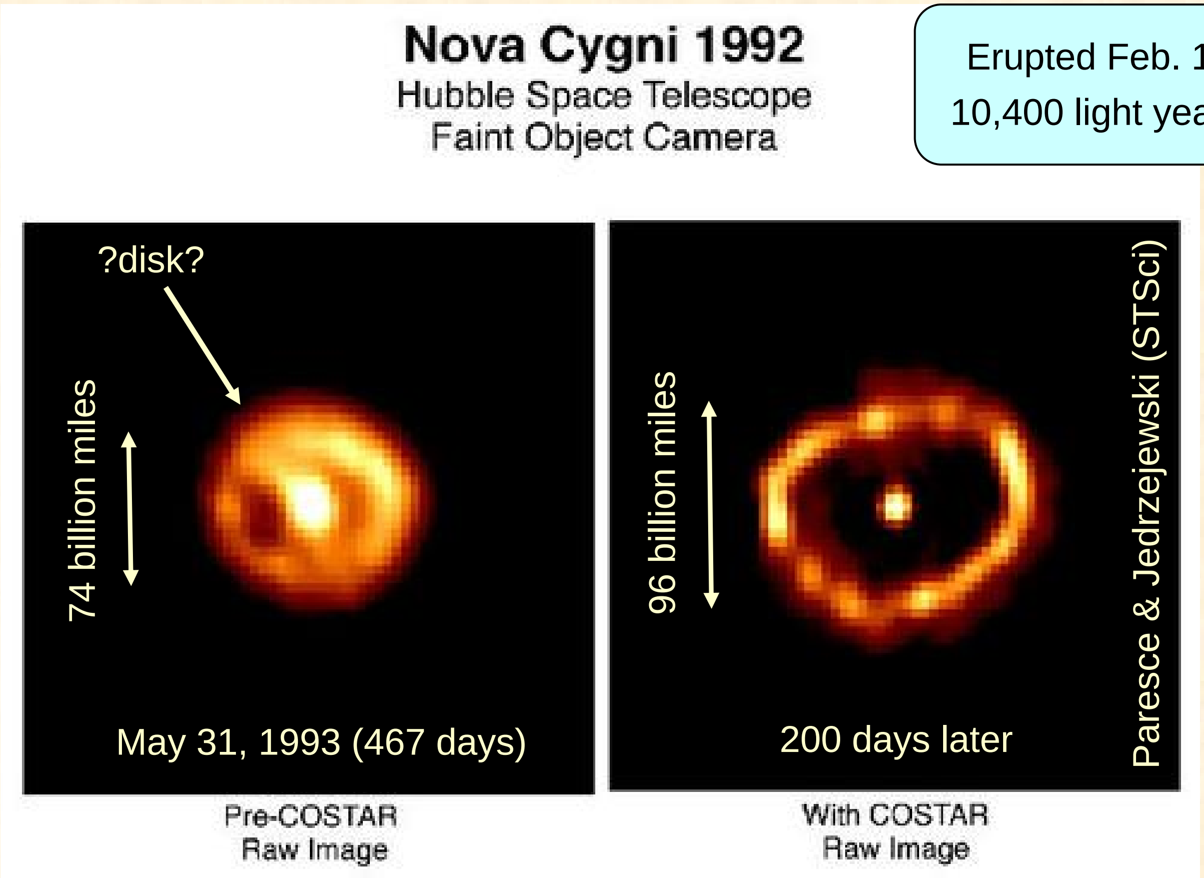
New observational techniques





- Observations of RS Oph
  - White dwarf mass near maximum
  - Red giant experiencing extremely high mass loss
  - Laboratory for studying interactions ejecta with nebula
  - Rise in X-ray emissions observed as white dwarf is “unveiled”
  - Oscillations in X-ray emission not understood
  - Gamma ray line observations not yet correlated with novae

Hubble Space Telescope



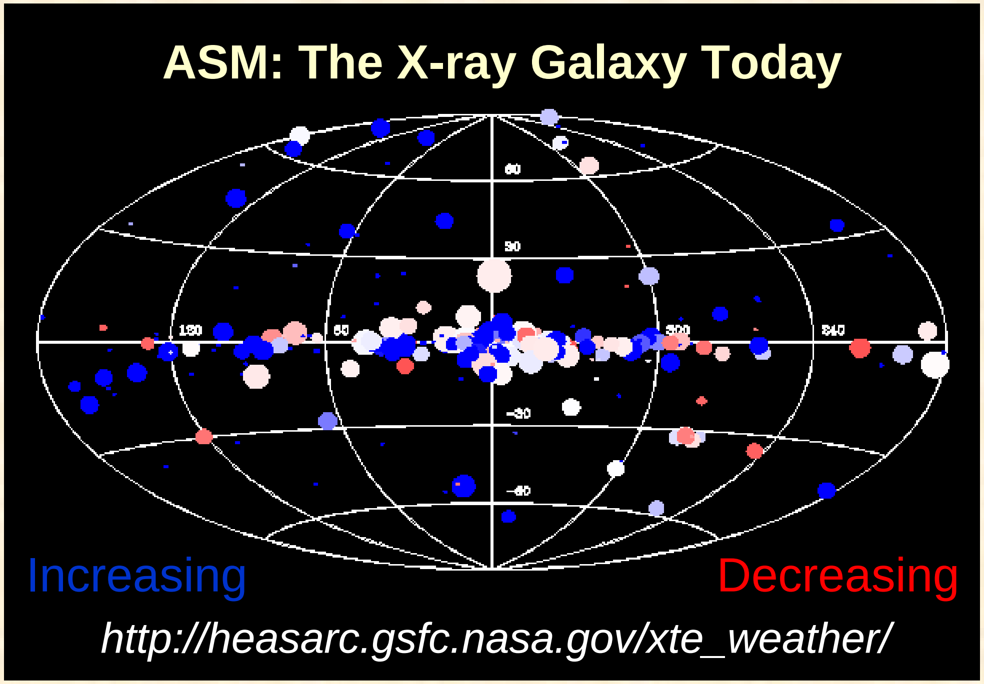
Erupted Feb. 19, 1992
10,400 light years away

- Now more than a dozen observations of the expansion of nova shell ejecta over time
  - C.D. Gill and T.J. O’Brien, MNRAS **314** (2000) 175.

X-ray vision

RXTE

Rossi X-ray Timing Explorer



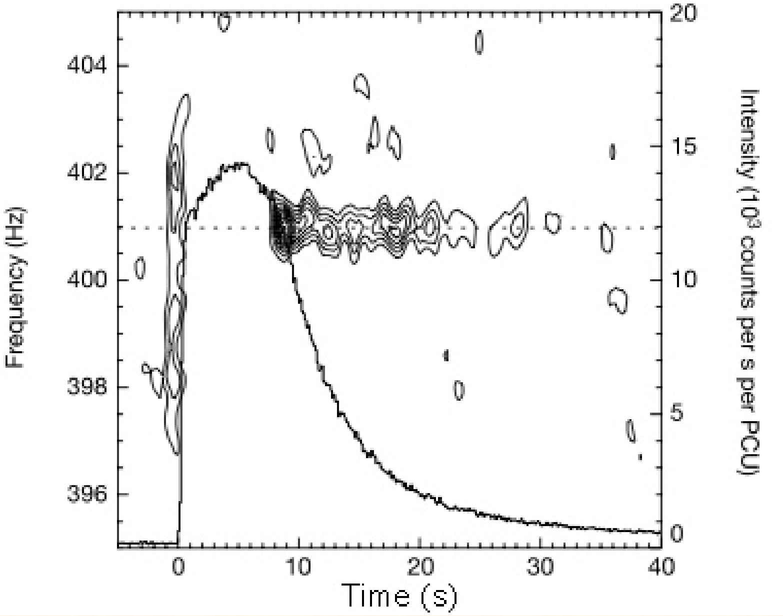
ASM: The X-ray Galaxy Today

Increasing

Decreasing

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

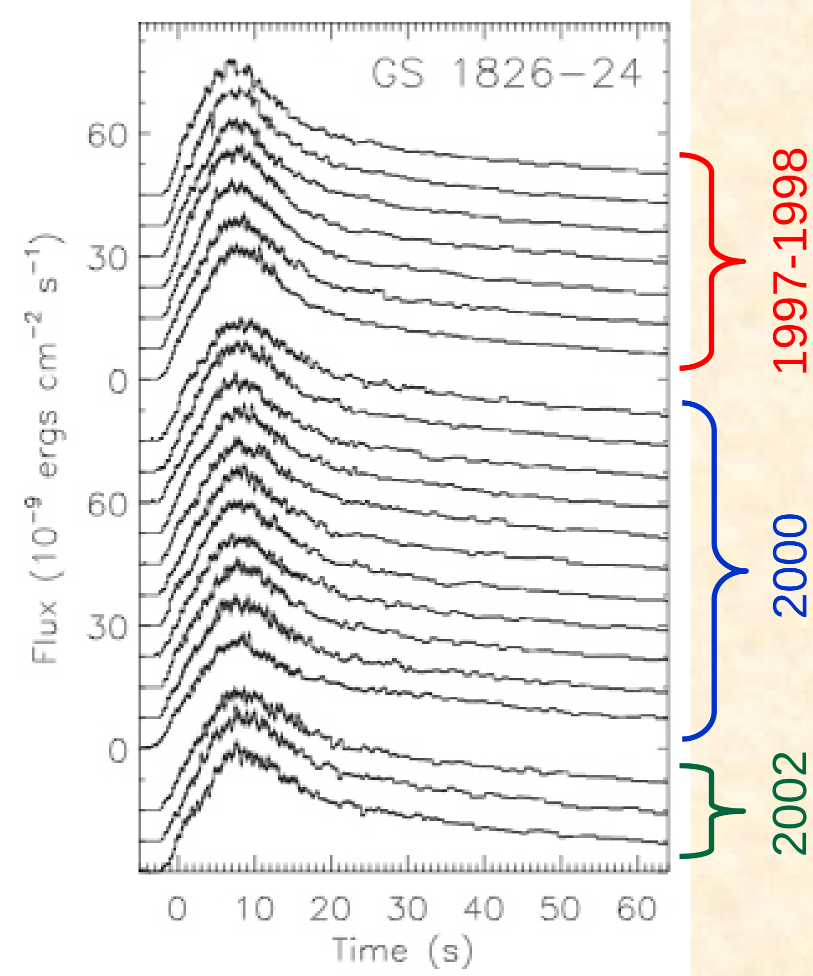
D. Chakrabarty *et al*., Nature **424** (2003) 42.

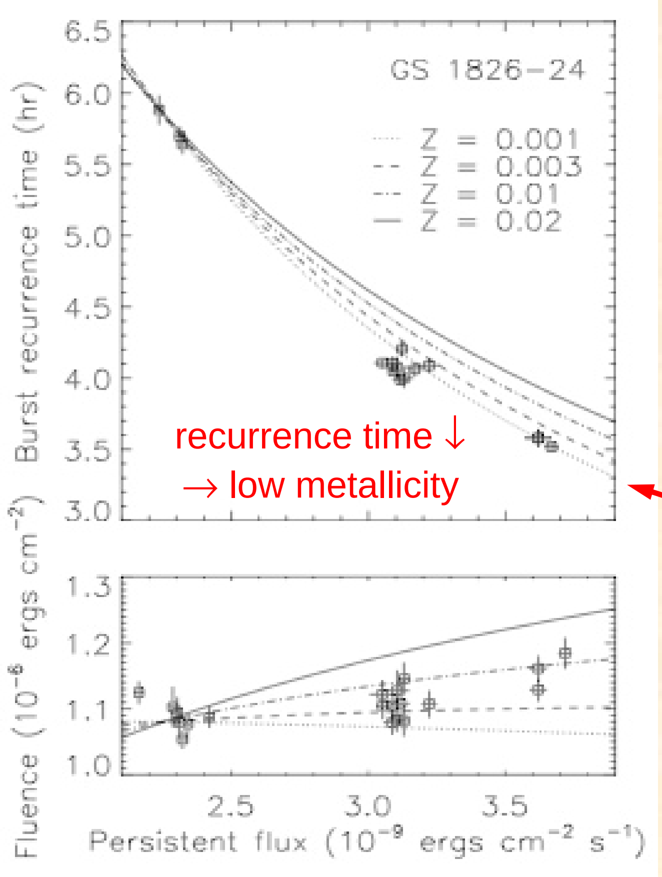


- Over 100 sources ***in the Milky Way***
  - Do not confuse with Gamma ray-bursts
- Recur on a semi-regular time scale
- Thermonuclear explosion on surface of a neutron star
- Observations provide crucial insights into neutron star properties
  - Spin limited by gravitational radiation

Classic example: Ginga 1826

RXTE Observations: D. K. Galloway *et al*., ApJ **601** (2004) 466.



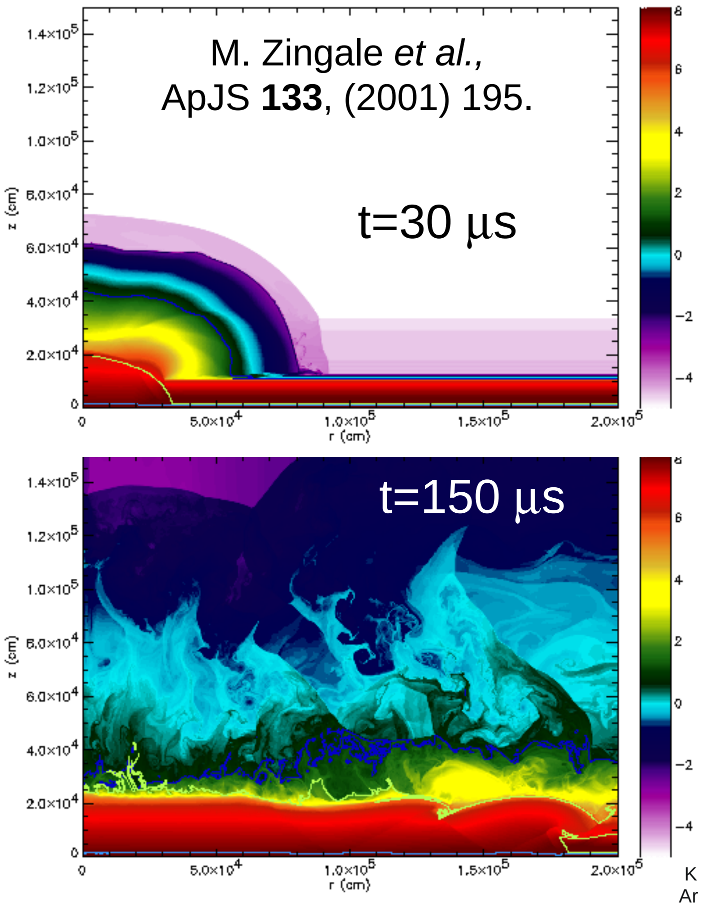


recurrence time ↓
→ low metallicity

↸ Regular bursts
↸ Similar light curves

↸ Recurrence time decreasing
↸ X-ray flux increasing
↸ Burst energetics
- Hydrogen burning between bursts
- Increasing flux
- → ~solar metallicity?

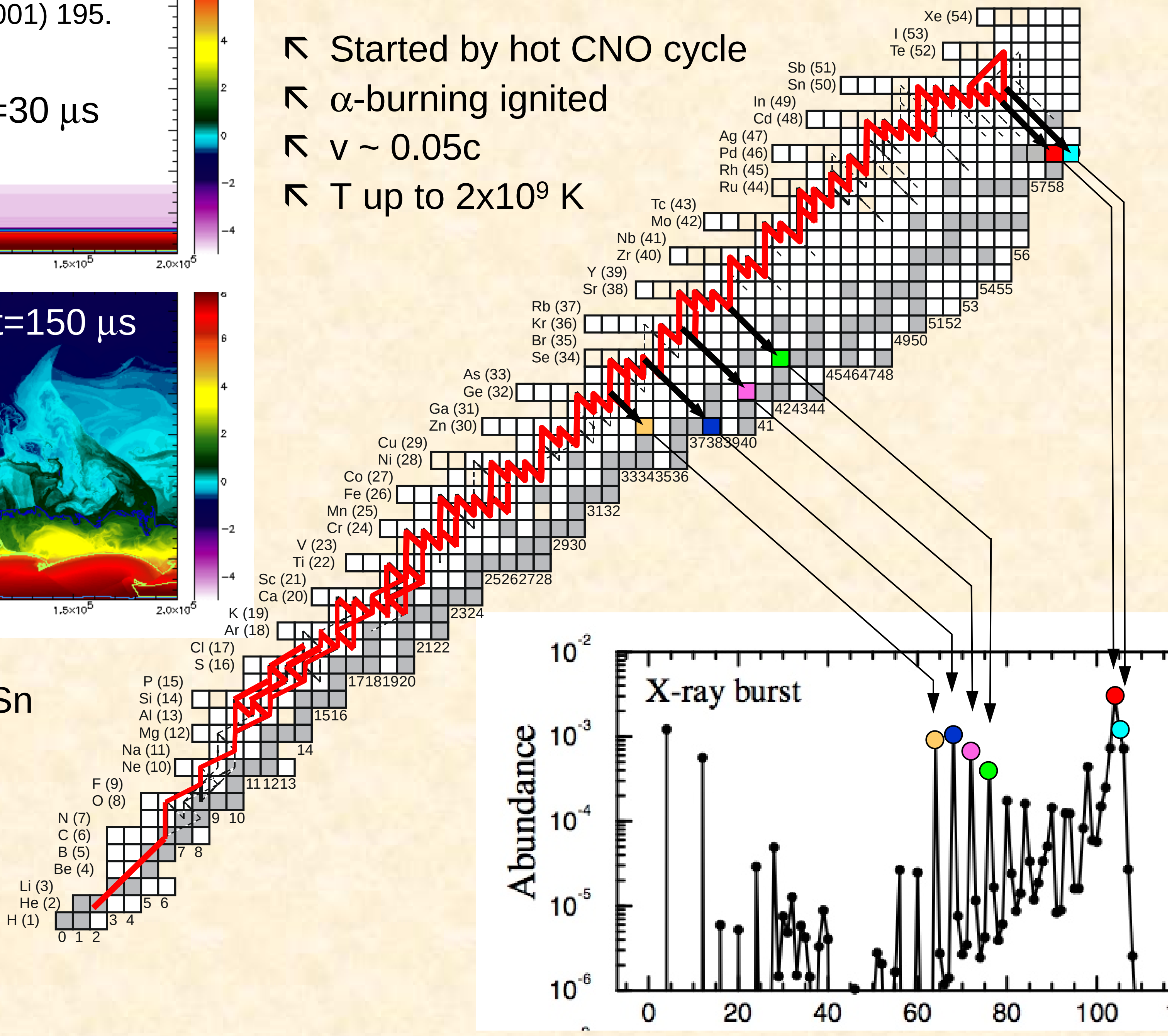
?



M. Zingale *et al.*,
ApJS **133**, (2001) 195.

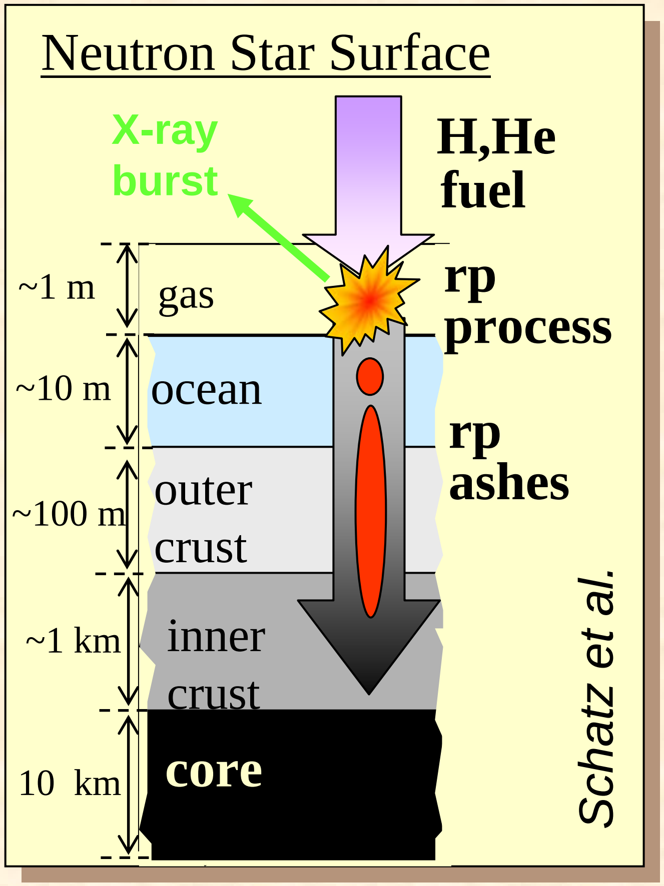
H. Schatz et al., PRL **86** (2001) 3471.

- Started by hot CNO cycle
- α-burning ignited
- v ~ 0.05c
- T up to 2x10^9 K



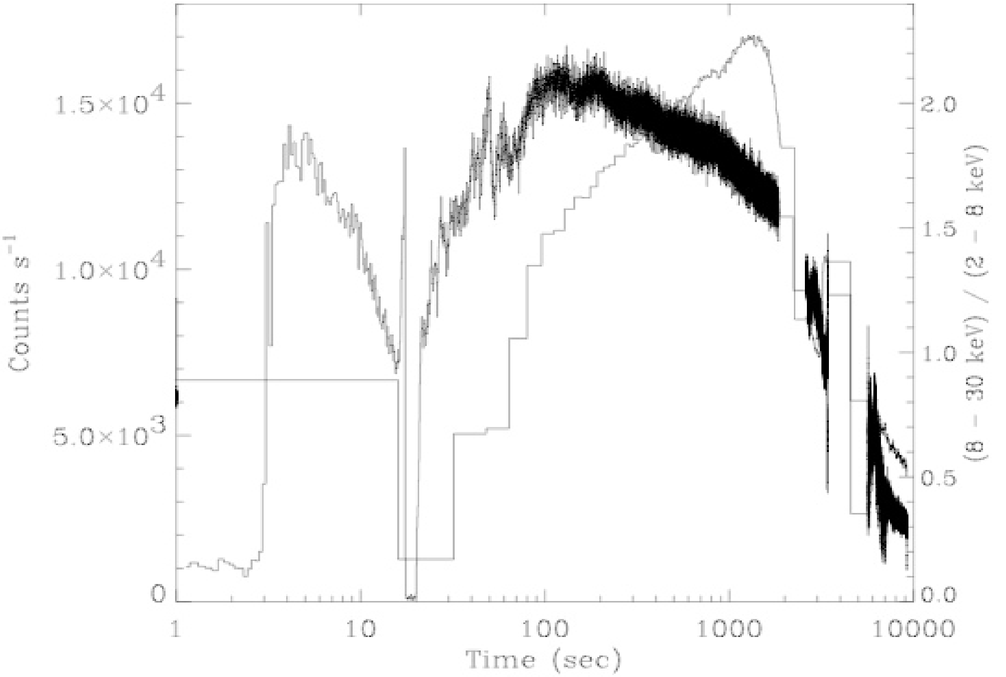
- Nuclei up to Sn
- N=Z waiting points crucial
  - ^{64}Ge
  - ^{68}Se
  - ^{72}Kr
  - ^{76}Sr

Superbursts



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

"A remarkable 3 hour thermonuclear burst from 4U 1820-30"



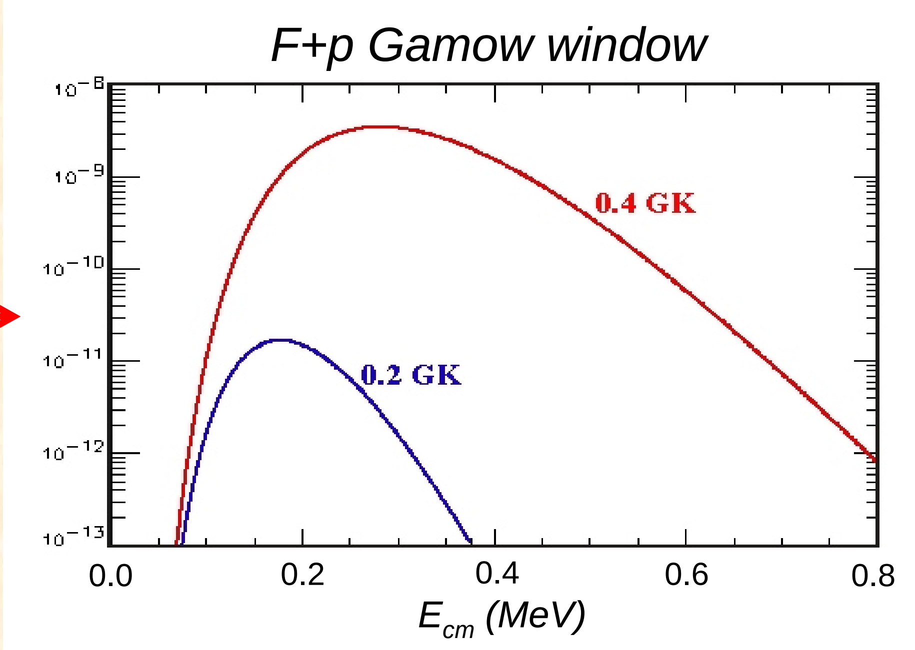
- Ignition of the unburned ashes from previous bursts
- Probably ignited by carbon burning
- Photodisintegration may provide major energy source
  - Schatz, Bildsten and Cumming, ApJ **583** (2003) L87.
- Composition of rp process ashes is important

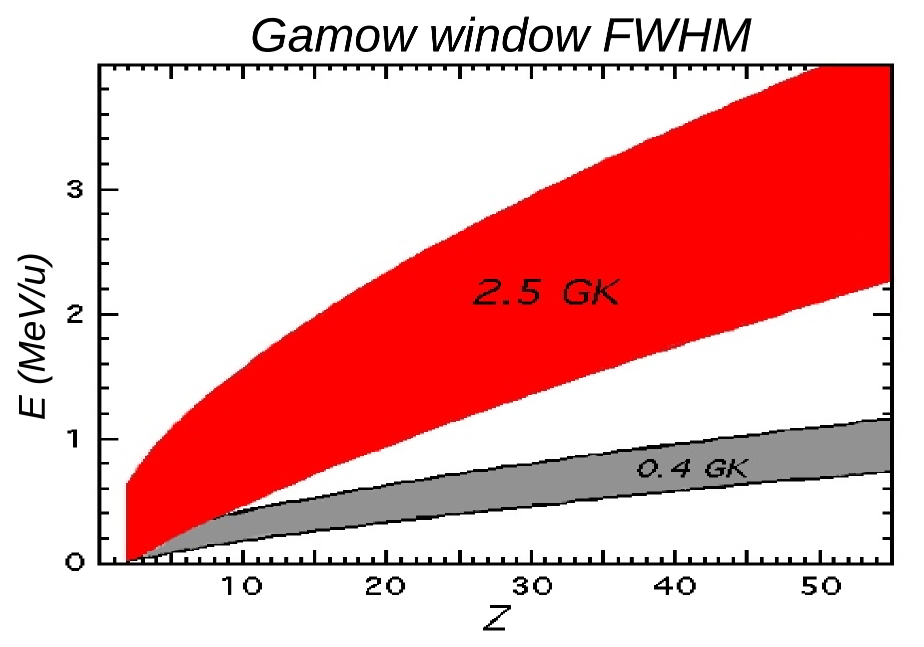
Nuclear reaction rates

- The rates of nuclear reactions are important for understanding novae and X-ray bursts.

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

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


F+p Gamow window


Gamow window FWHM

- Narrow range of relatively low energies are important in novae
- Energy range increases substantially with temperature and with atomic number
- Resonances in or near the Gamow window are crucial

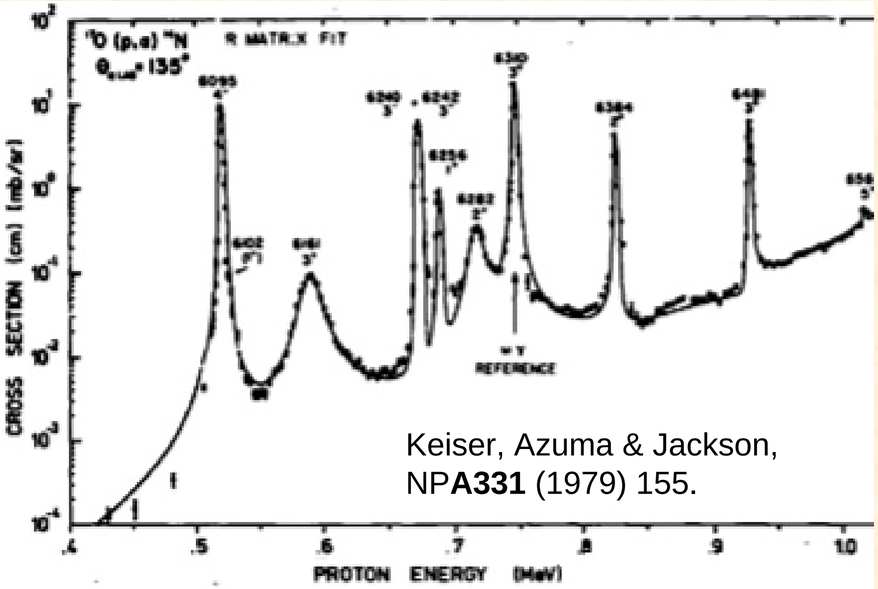
Resonant properties

Narrow resonance approximation

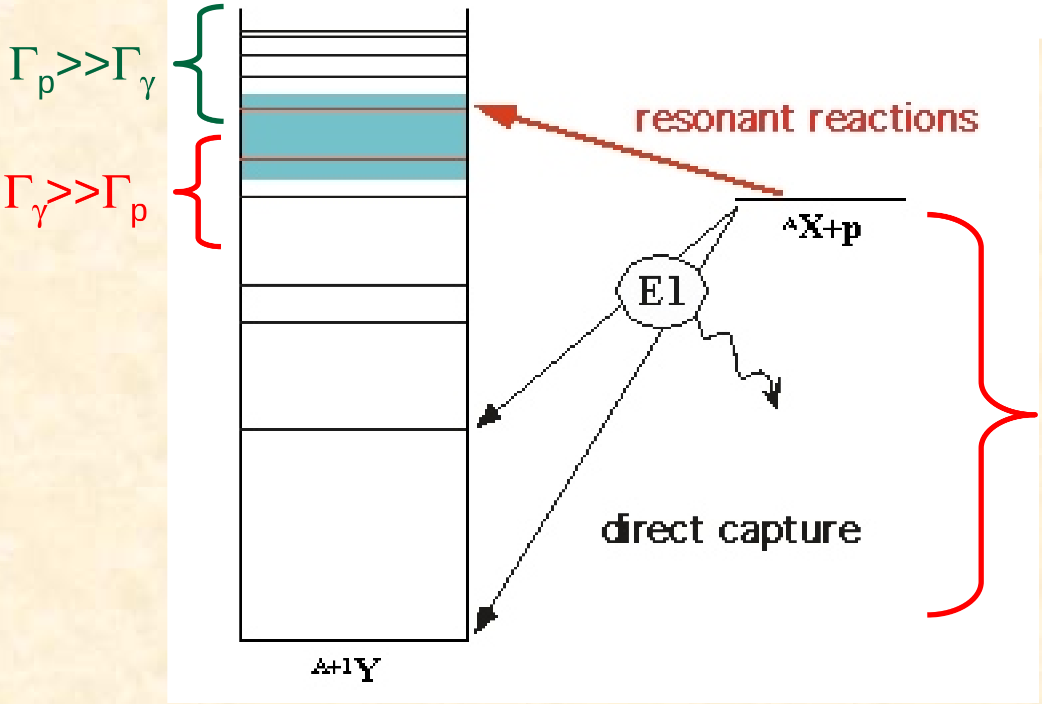
$$\langle \sigma v \rangle \approx \hbar^2 \left(\frac{2\pi}{\mu kT} \right)^{3/2} (\omega\gamma)_r e^{-E_r/(kT)}$$

$$(\omega\gamma)_r = \frac{2J+1}{(2J_p+1)(2J_t+1)} \frac{\Gamma_{in}\Gamma_{out}}{\Gamma} = \text{“resonance strength”}$$

→ $E_x, J^\pi, \Gamma_{in}, \Gamma_{out}, \Gamma$



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

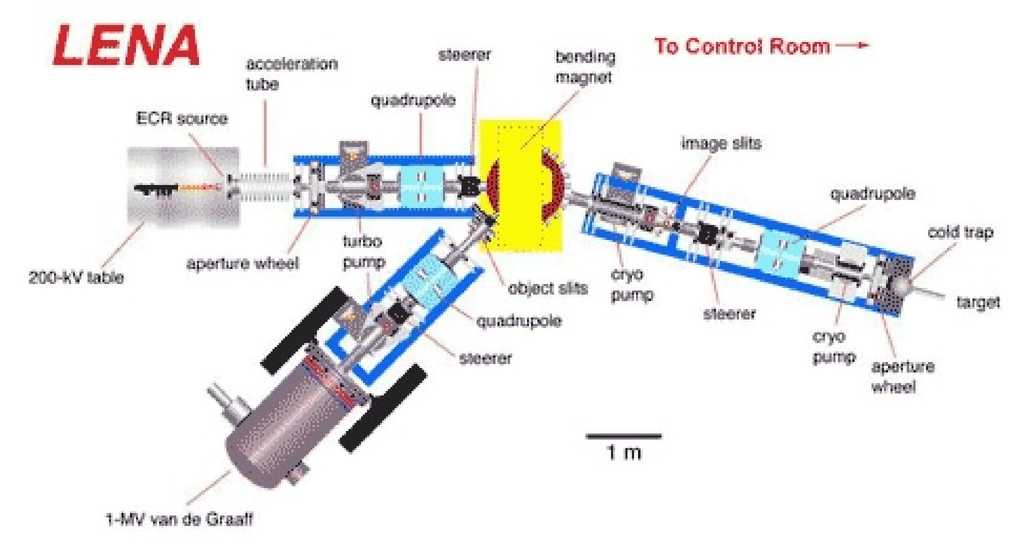


$$\Gamma_p = 2 \left(\frac{\hbar^2}{\lambda \mu R} \right) \left(\frac{\theta_p^2}{F_\ell^2 + G_\ell^2} \right)$$

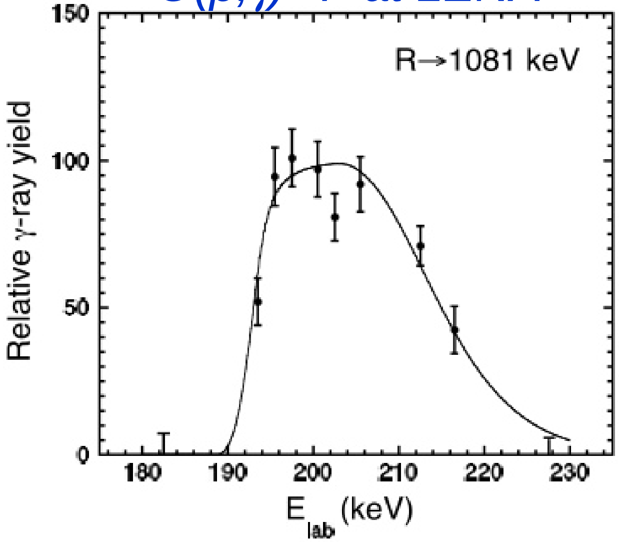
- Lower binding energy for radioactive nuclei
  - Lower level density
  - Fewer resonances
  - Broad states
- Direct capture can sometimes play an important role

Reactions on stable isotopes

- Good direct measurements with high intensity proton/alpha beams in the energy regime for explosion nucleosynthesis



$^{17}O(p,\gamma)^{18}F$ at LENA



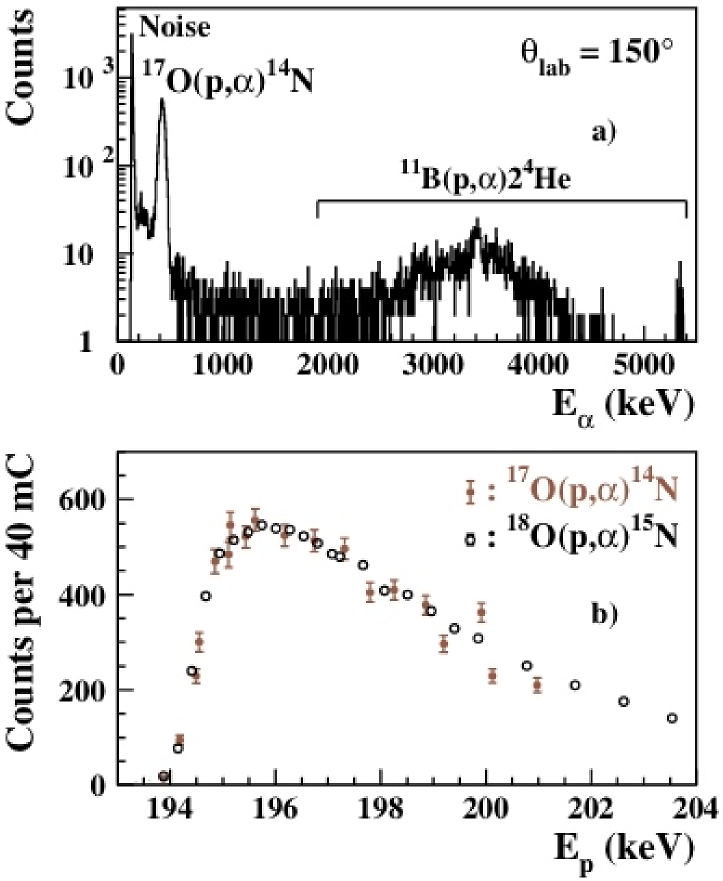
Fox *et al.*, PRC **71** (2005) 055801.

$^{17}O(p,\alpha)^{14}N$ rate increased by ~100 times

$$\frac{(p,\alpha)}{(p,\gamma)} \approx 700$$

^{18}F production reduced by ~3-8 times in novae

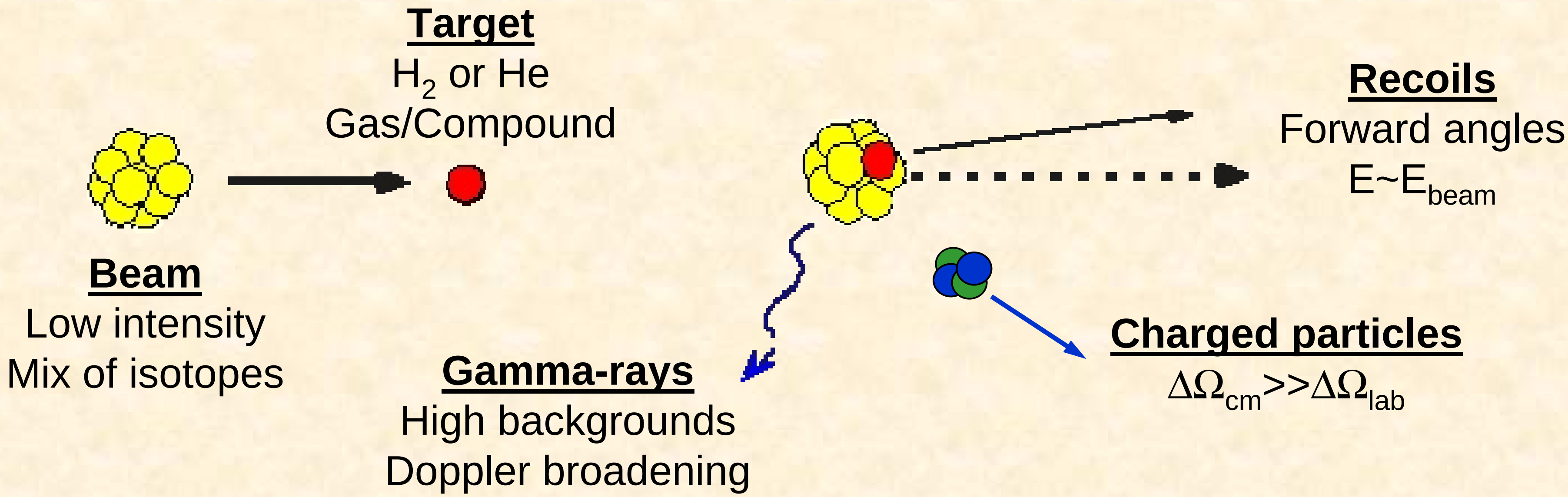
$^{17}O(p,\alpha)^{14}N$ at CSNSM-Orsay



Chafa et al., PRL **95** (2005) 031101.

Reactions with radioactive ions

- Many reactions involving radioactive isotopes play an important role in novae and X-ray binaries, but reaction rates generally have substantial uncertainties owing to a lack of experimental data.
- Radioactive Ion Beams (RIBs) are now allowing measurements that are significantly improving nuclear reaction rates.
- Very different experimental techniques are required for measurements with RIBs.



Target
H_2 or He
Gas/Compound

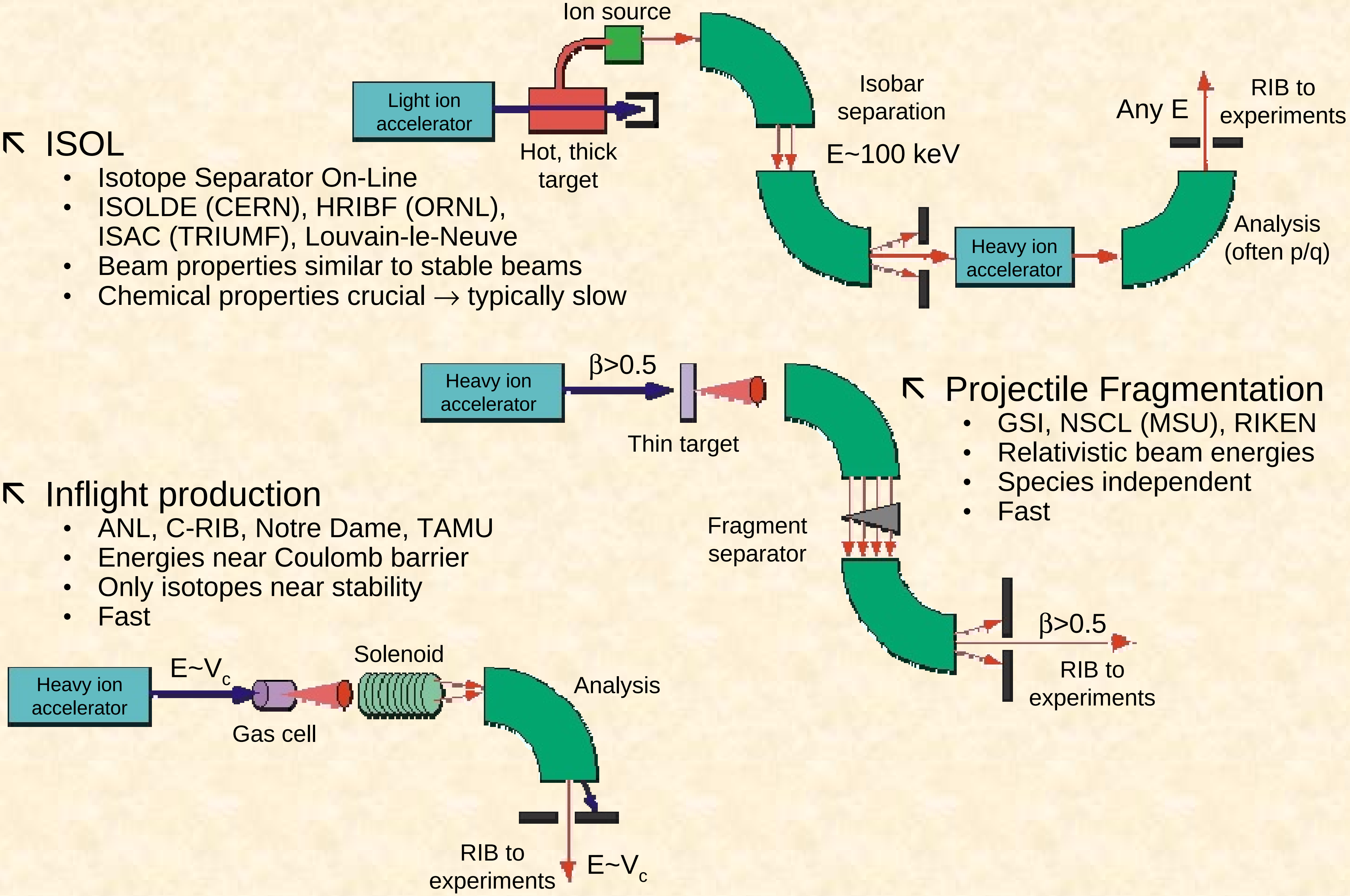
Recoils
Forward angles
$E \sim E_{beam}$

Beam
Low intensity
Mix of isotopes

Gamma-rays
High backgrounds
Doppler broadening

Charged particles
$\Delta\Omega_{cm} >> \Delta\Omega_{lab}$

Radioactive Ion Beam (RIB) production



↖ ISOL

- Isotope Separator On-Line
- ISOLDE (CERN), HRIBF (ORNL), ISAC (TRIUMF), Louvain-le-Neuve
- Beam properties similar to stable beams
- Chemical properties crucial → typically slow

↖ Projectile Fragmentation

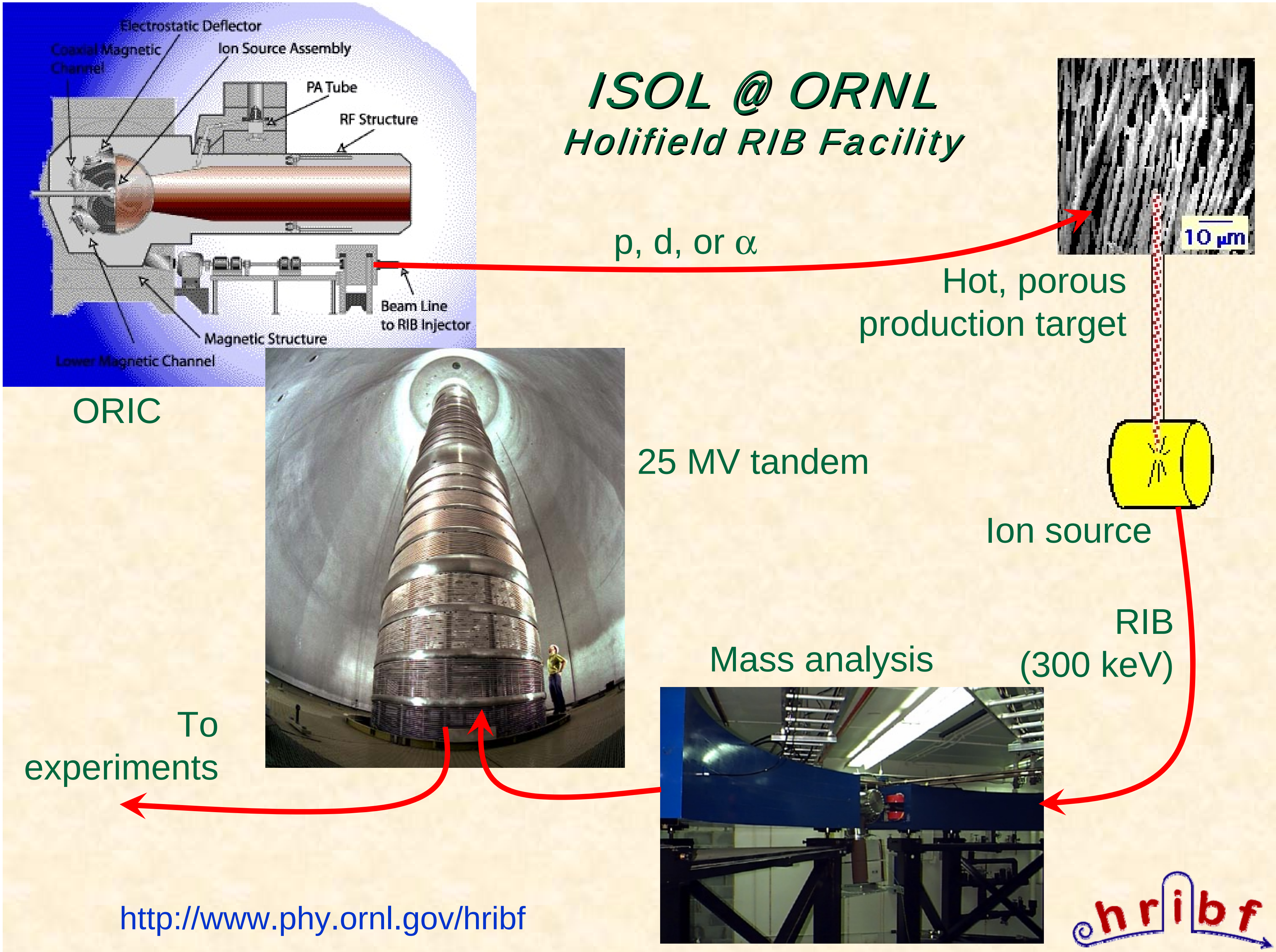
- GSI, NSCL (MSU), RIKEN
- Relativistic beam energies
- Species independent
- Fast

↖ Inflight production

- ANL, C-RIB, Notre Dame, TAMU
- Energies near Coulomb barrier
- Only isotopes near stability
- Fast

ISOL @ ORNL

Holifield RIB Facility



ORIC

p, d, or α

Hot, porous production target

Ion source

RIB
(300 keV)

Mass analysis

25 MV tandem

To experiments

http://www.phy.ornl.gov/hribf

hribf

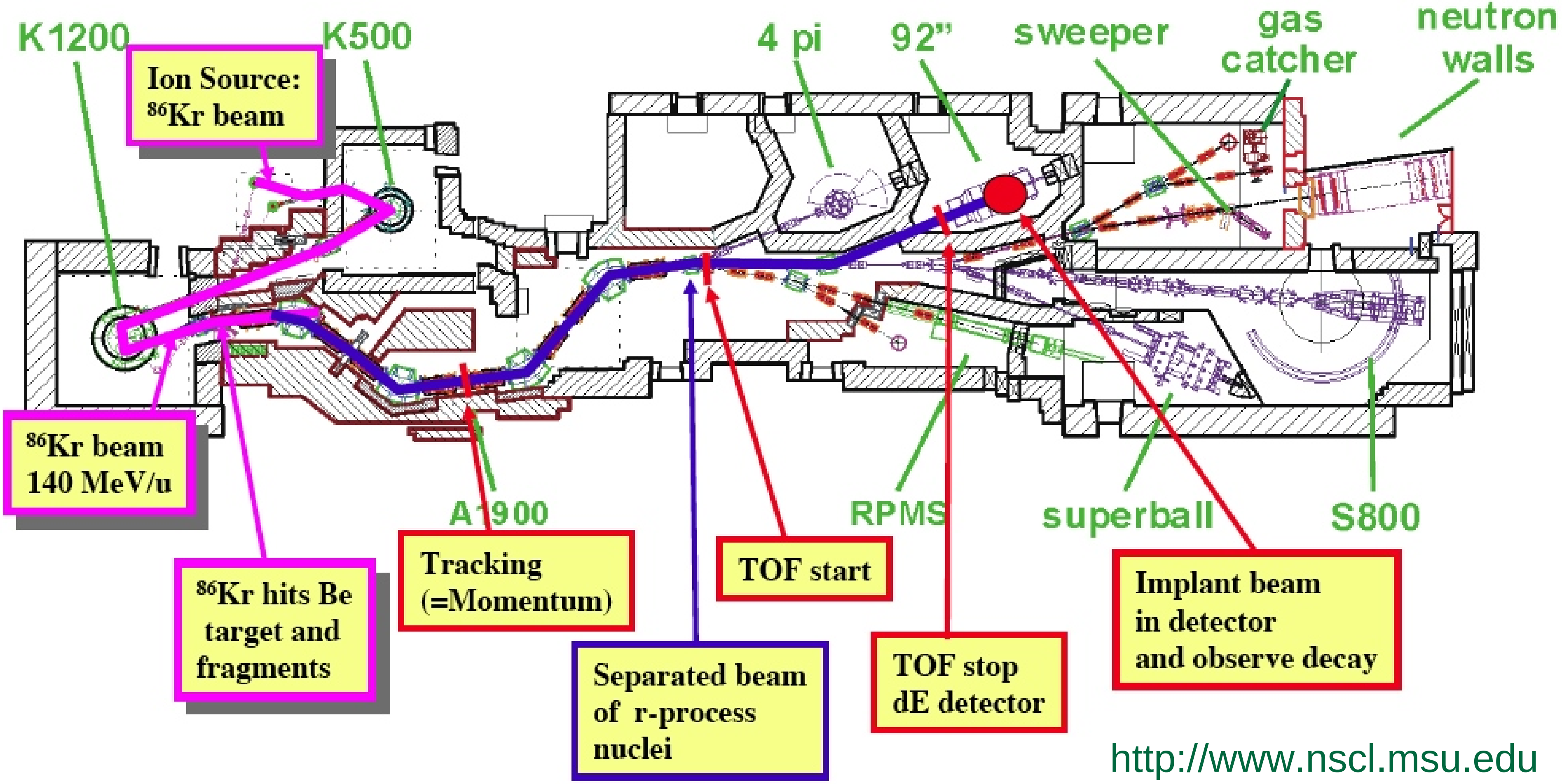
Projectile Fragmentation @ the NSCL

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

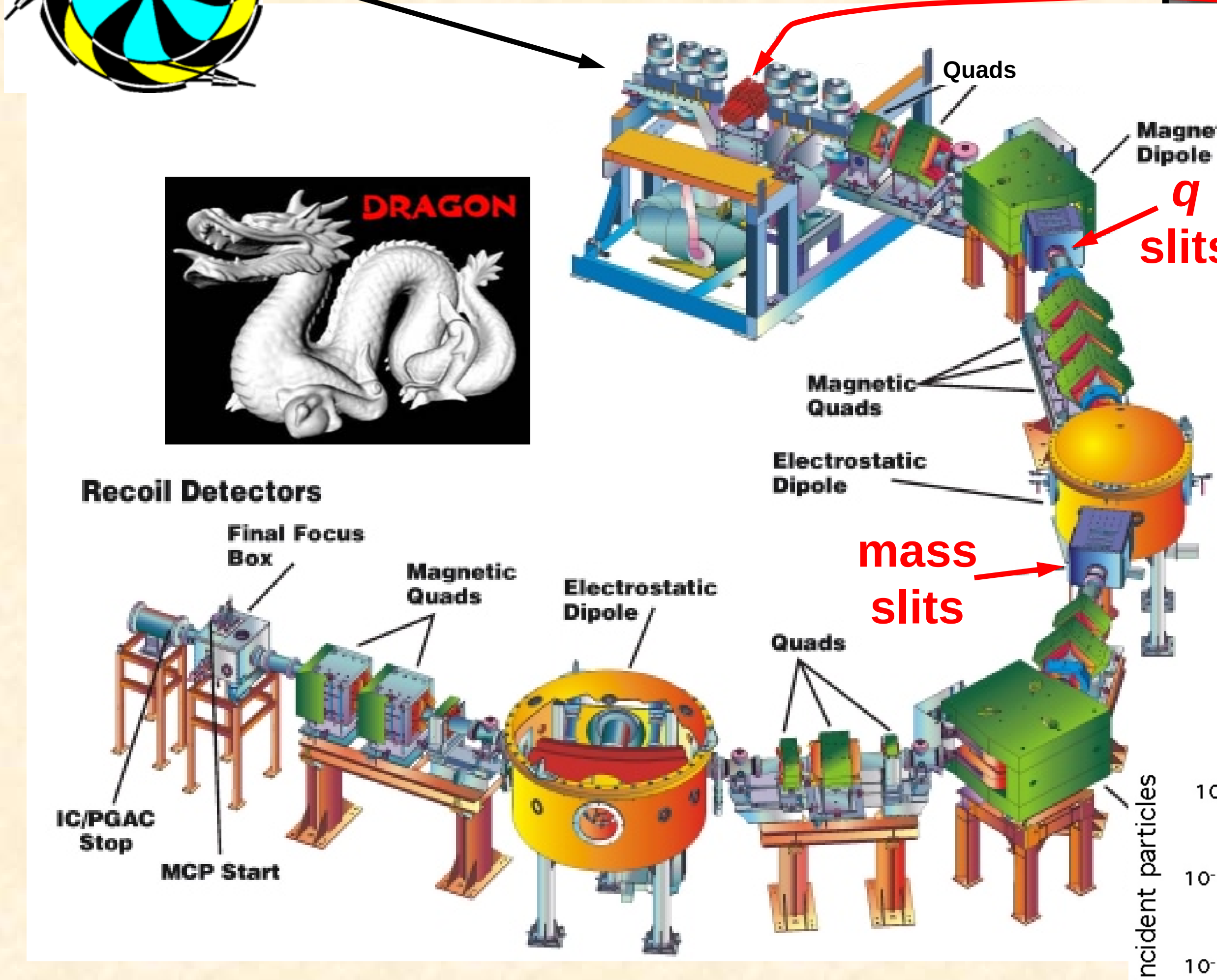
Implant beam in detector and observe decay

http://www.nscl.msu.edu

(p,γ) at ISAC

RIB

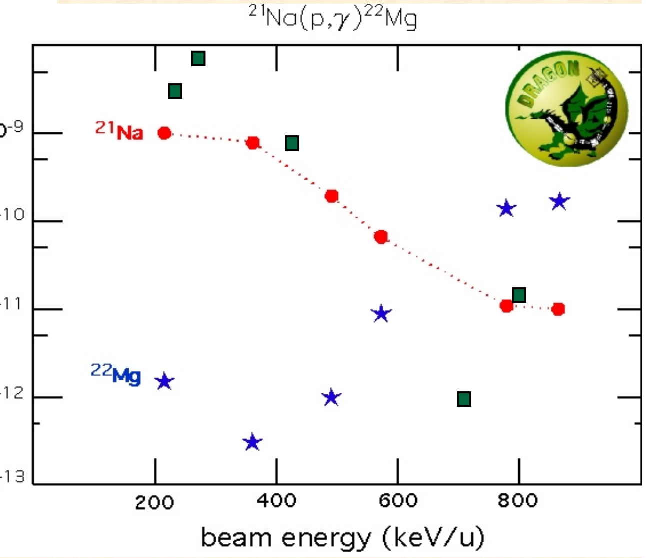
H_2 gas target



q slits

mass slits

recoil+γ coincidences provide sensitive selection of events

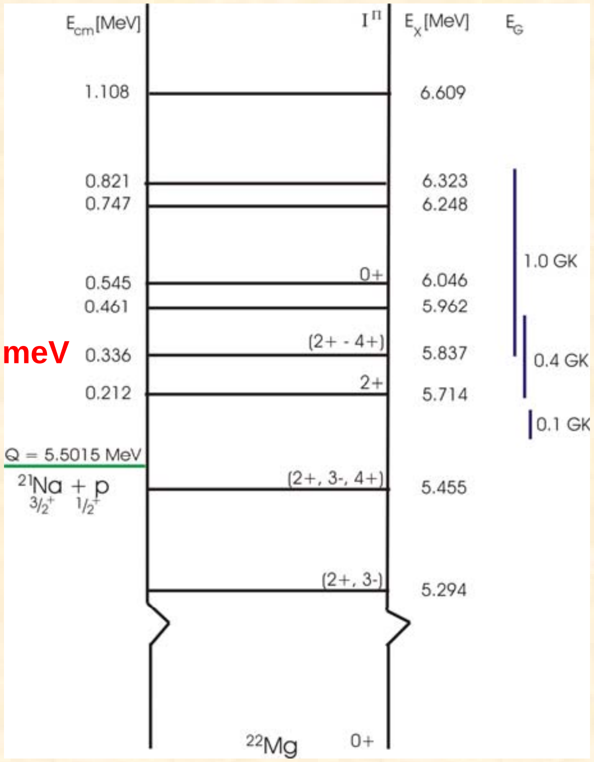


http://dragon.triumf.ca

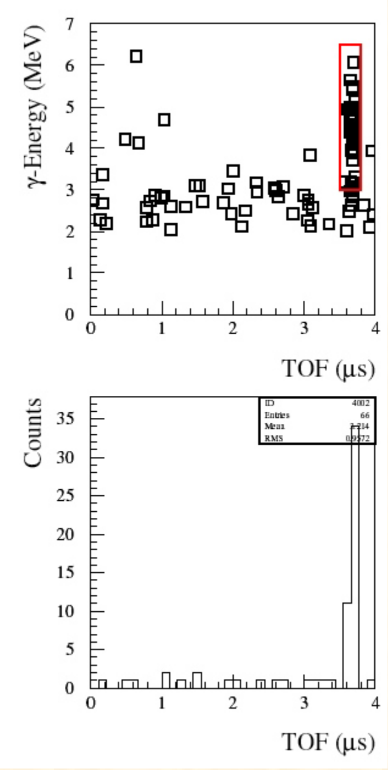
*S. Engel et al., NIM **A553** (2005) 491.*

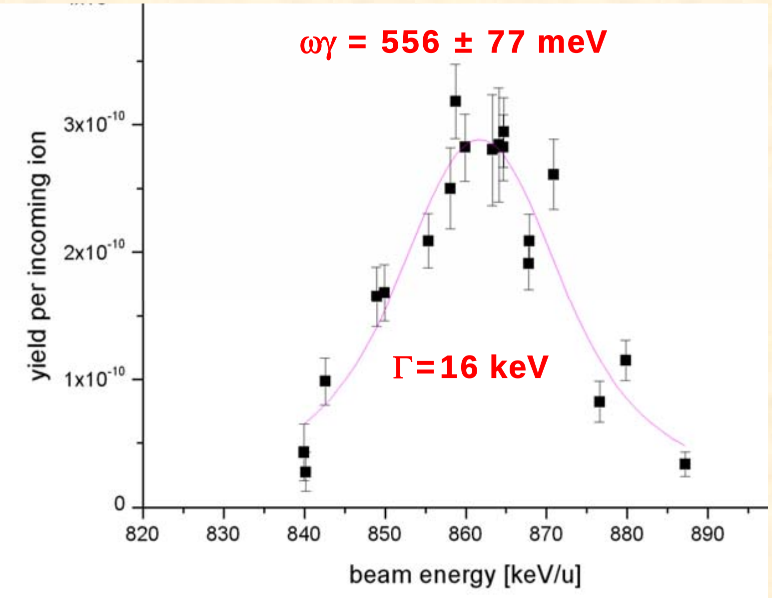
*D. A. Hutcheon et al., NIM **A498** (2003) 190.*

^{21}Na(p,γ)^{22}Na with DRAGON



<0.3 meV

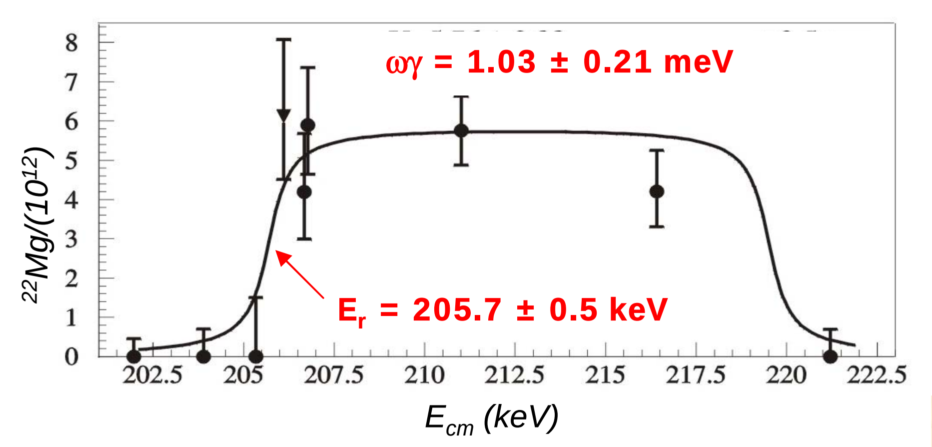




ωγ = 556 ± 77 meV

Γ=16 keV

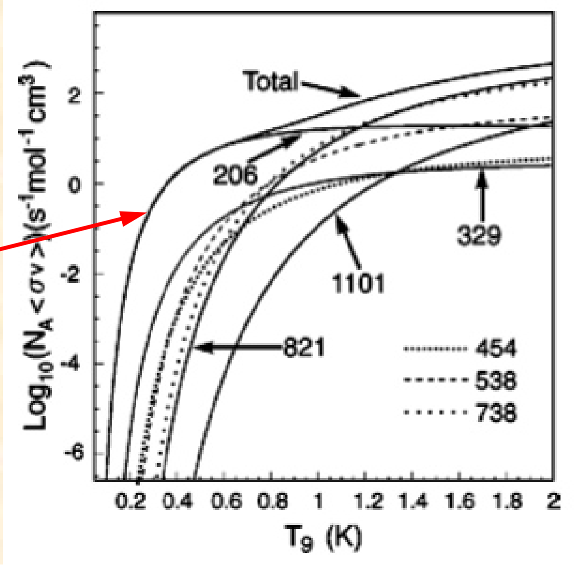
*J. D'Auria et al., PRC **69** (2004) 065803.*
*S. Bishop et al., PRL **90** (2003) 162501.*



ωγ = 1.03 ± 0.21 meV

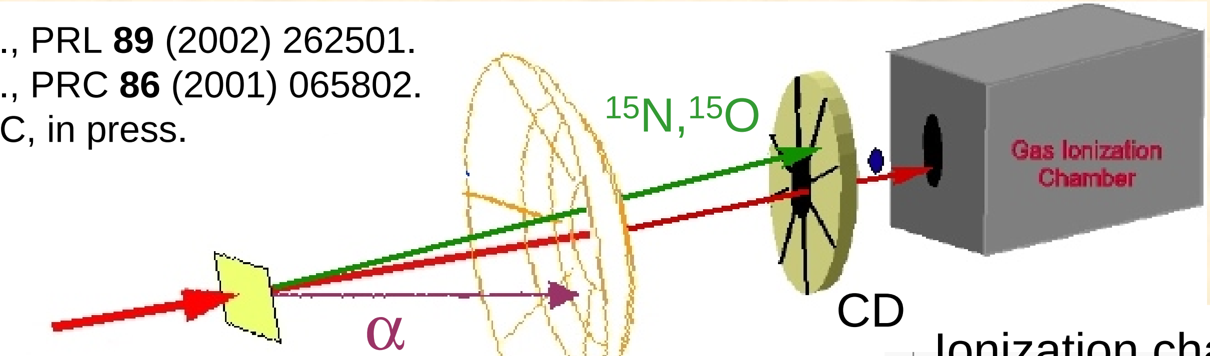
E_r = 205.7 ± 0.5 keV

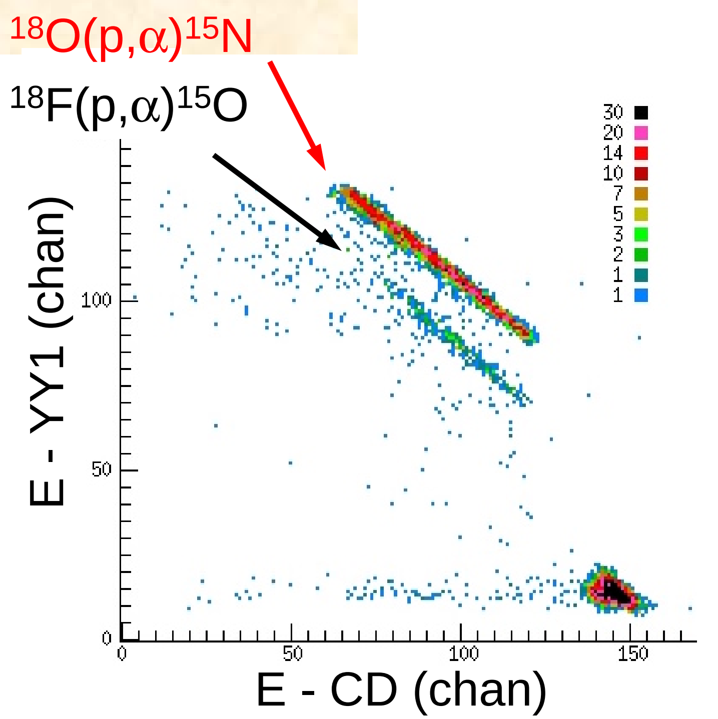
Higher rate for
206 keV
resonance
→ ~25% less
^{22}Na

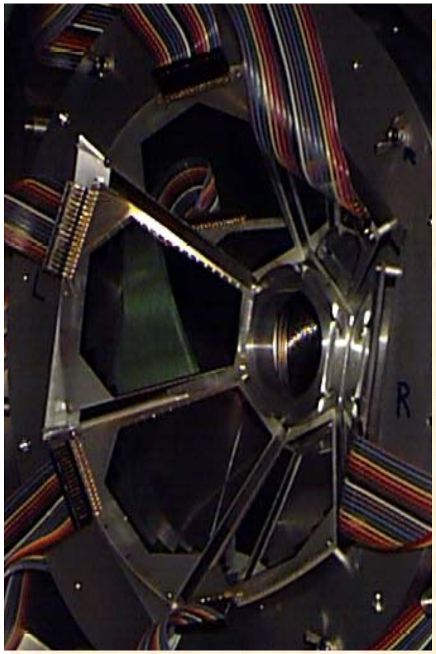


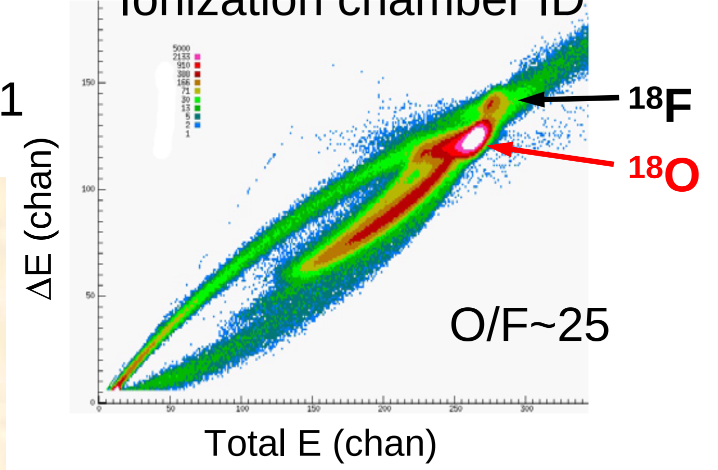
$^{18}F(p,\alpha)^{15}O$ at the HRIBF

D.W. Bardayan *et al.*, PRL **89** (2002) 262501.
D.W. Bardayan *et al.*, PRC **86** (2001) 065802.
K.Y. Chae *et al.*, PRC, in press.



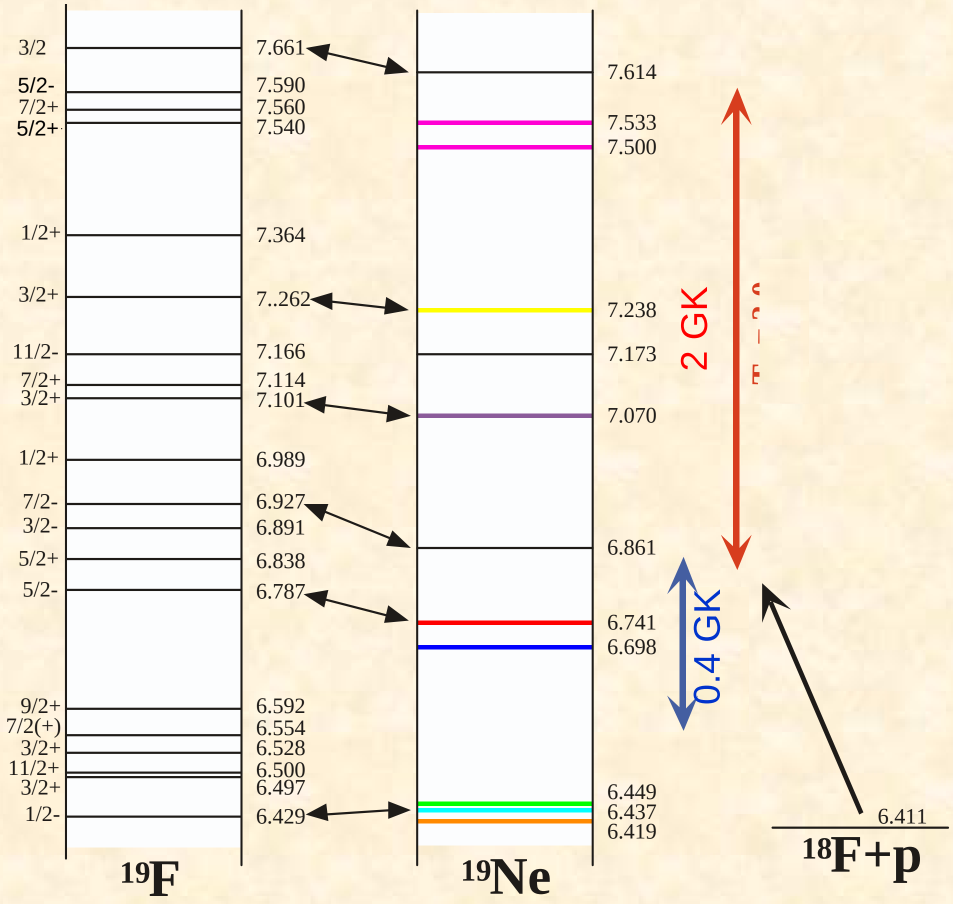


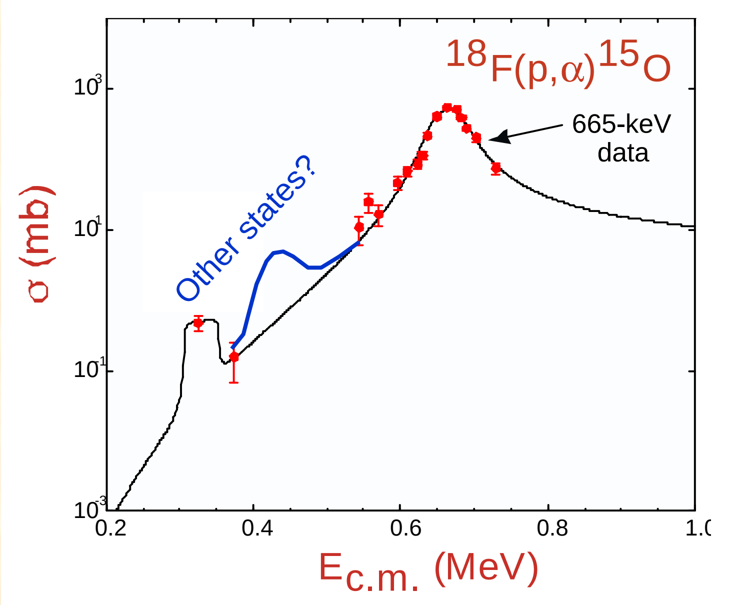


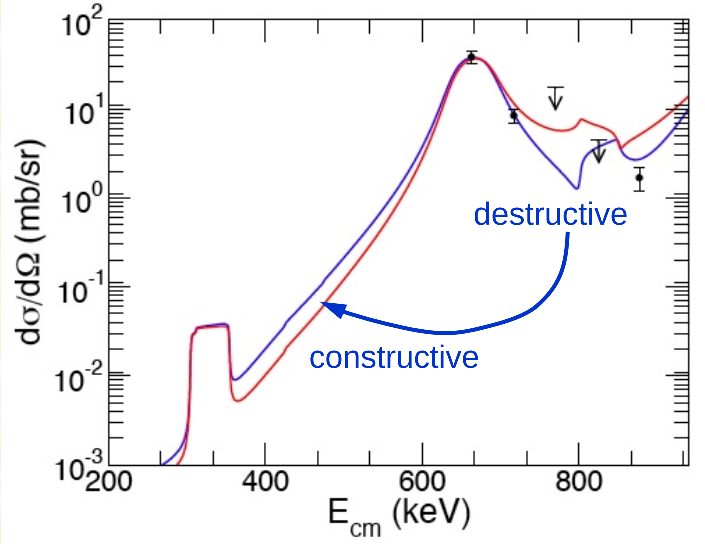


↖ Coincidence allows clean measurement even with highly contaminated beam.

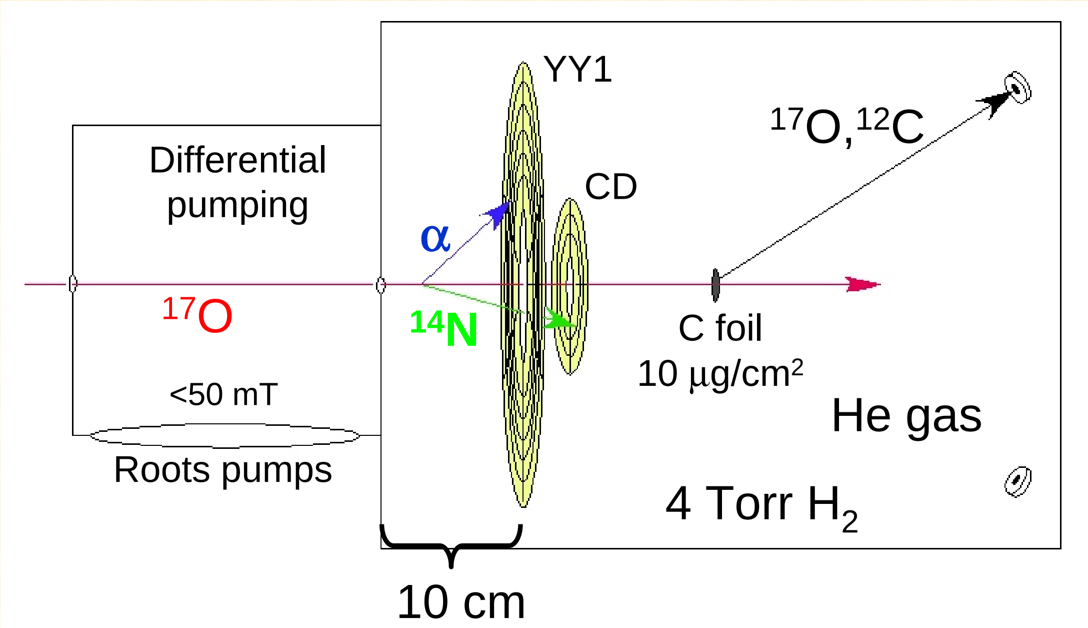
HRIBF results so far

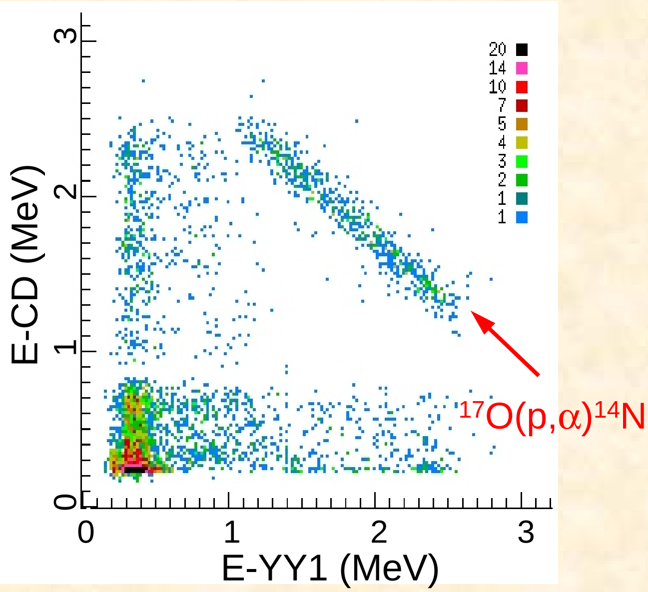






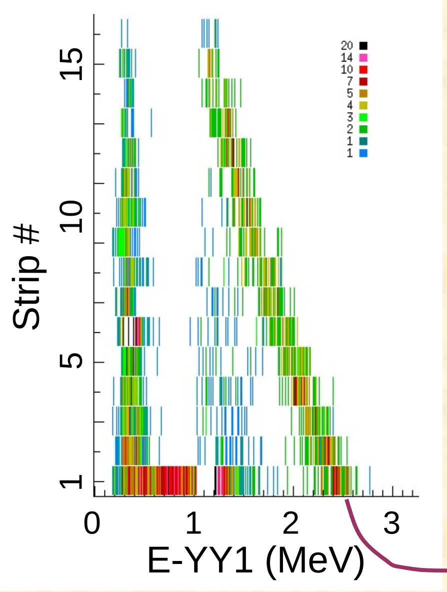
Novel approach to (p,α) reactions

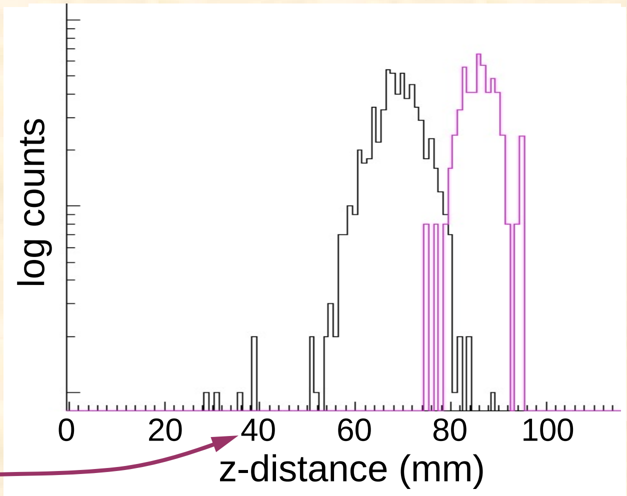


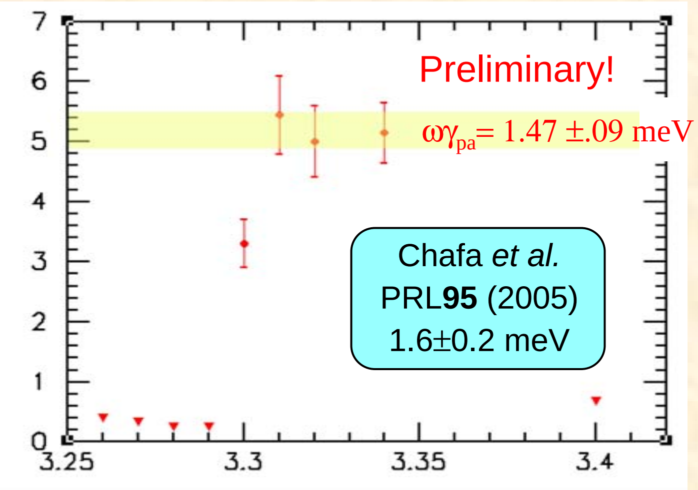


↖ High sensitivity to narrow resonances, especially with contaminated beams

$E_\alpha \otimes$ strip # → vertex







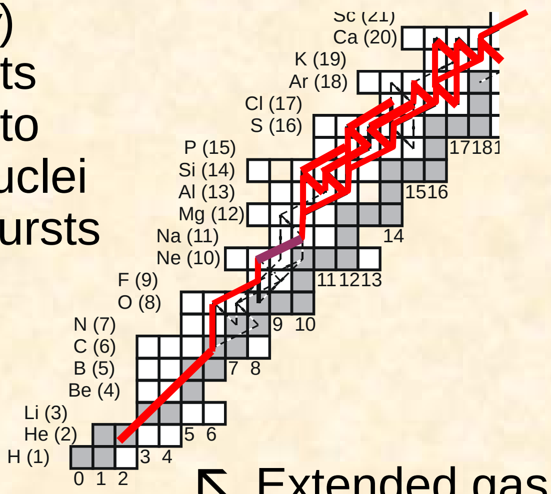
↖ Well-suited to (α,p) reactions

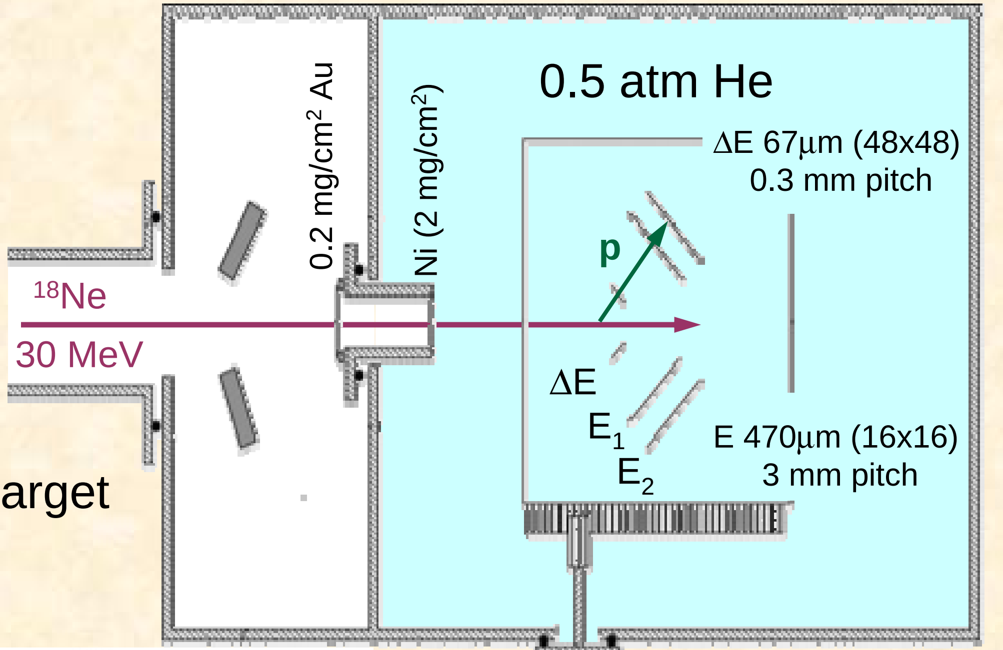
(α,p) at CRC at Louvain-le-Neuve

D. Goombridge *et al.*, PRC **66** (2002) 055802.

http://www.cyc.ucl.ac.be/

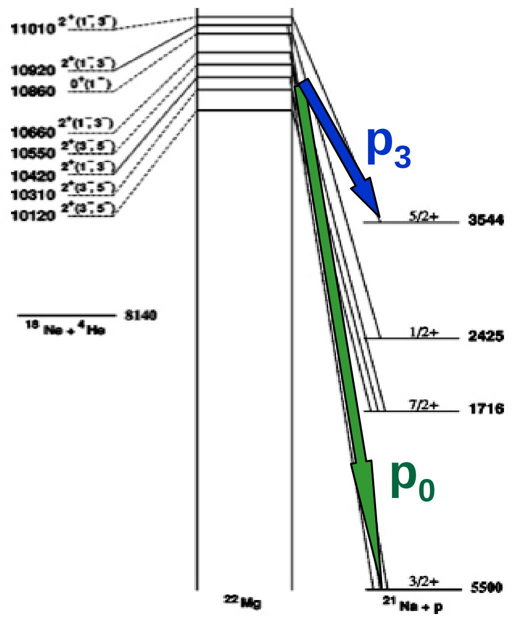
↖ (α,p)-(p,γ) chain starts transition to heavier nuclei in X-ray bursts

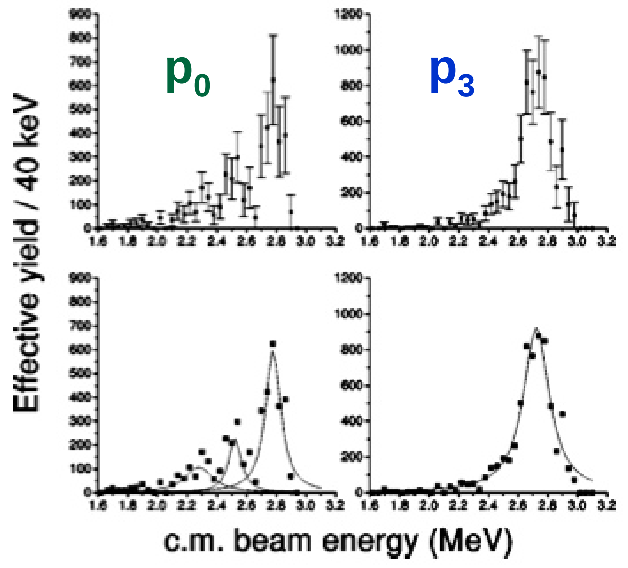


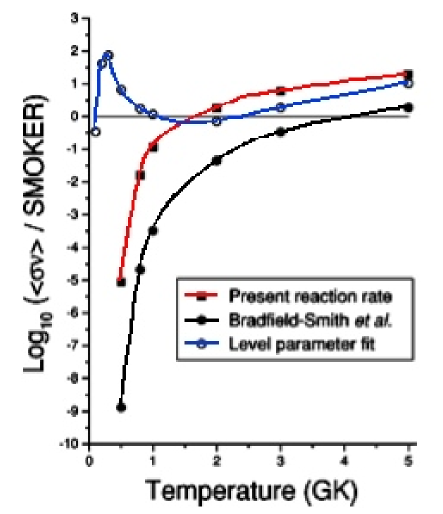


↖ Extended gas target

↖ $\theta_p \rightarrow E_{cm}$

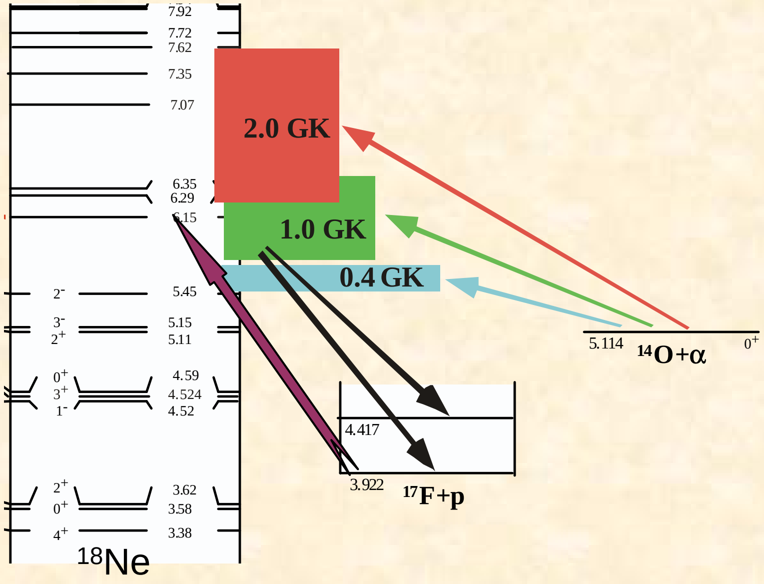






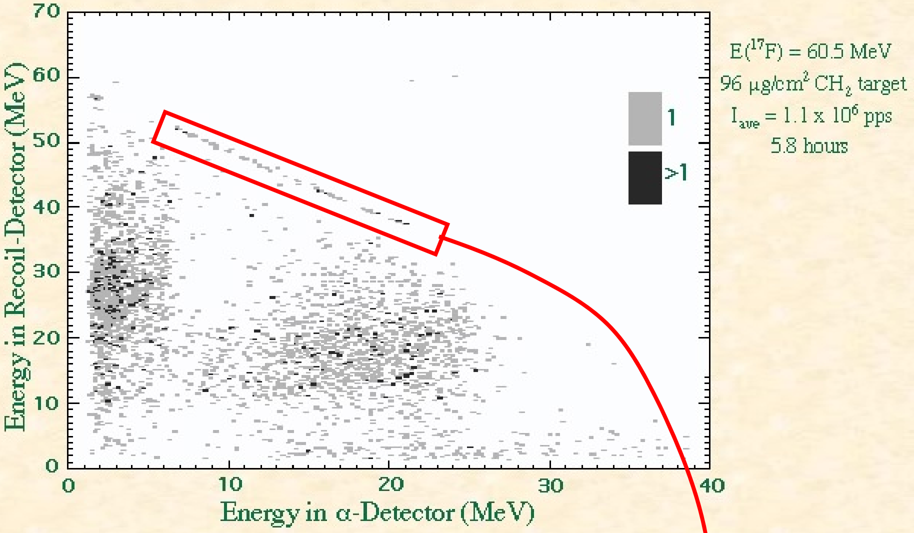
(α,p) via the inverse (p,α) reaction

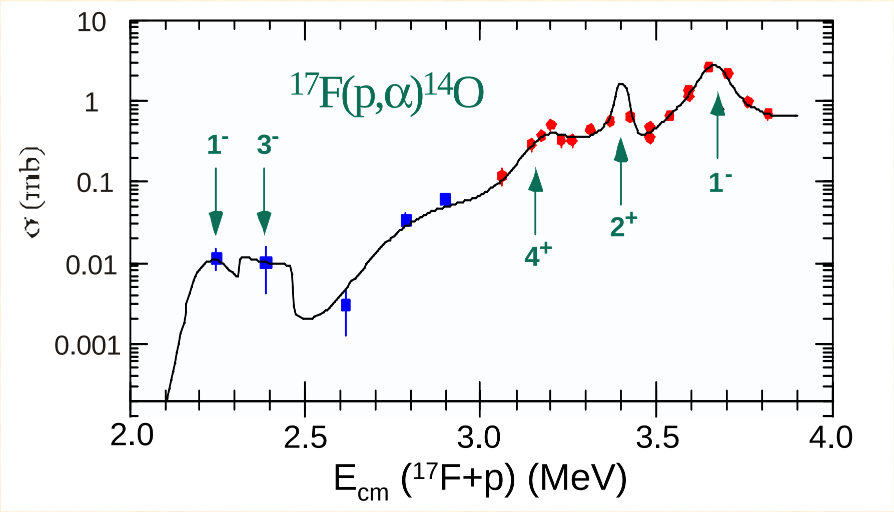
J.C. Blackmon *et al.*, NP**A688** (2001) 142.

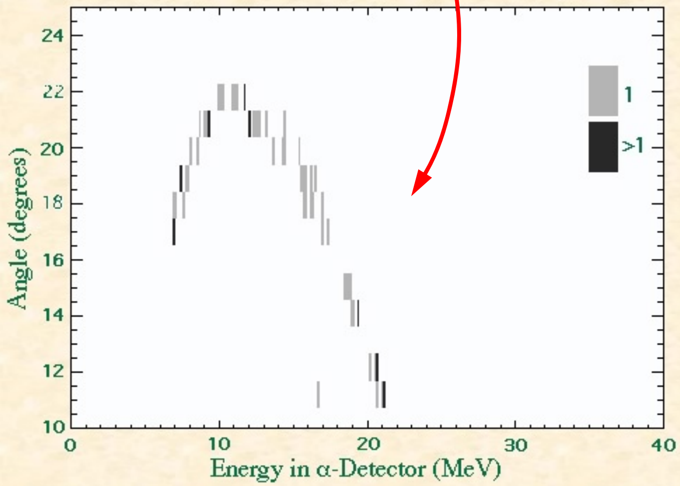


↖ (p,α) → (α,p) by detailed balance

$$\frac{\sigma_{12}}{\sigma_{34}} = \frac{m_3 m_4}{m_1 m_2}\,\frac{E_{34}}{E_{12}}\,\frac{(2J_3+1)(2J_4+1)}{(2J_1+1)(2J_2+1)}$$



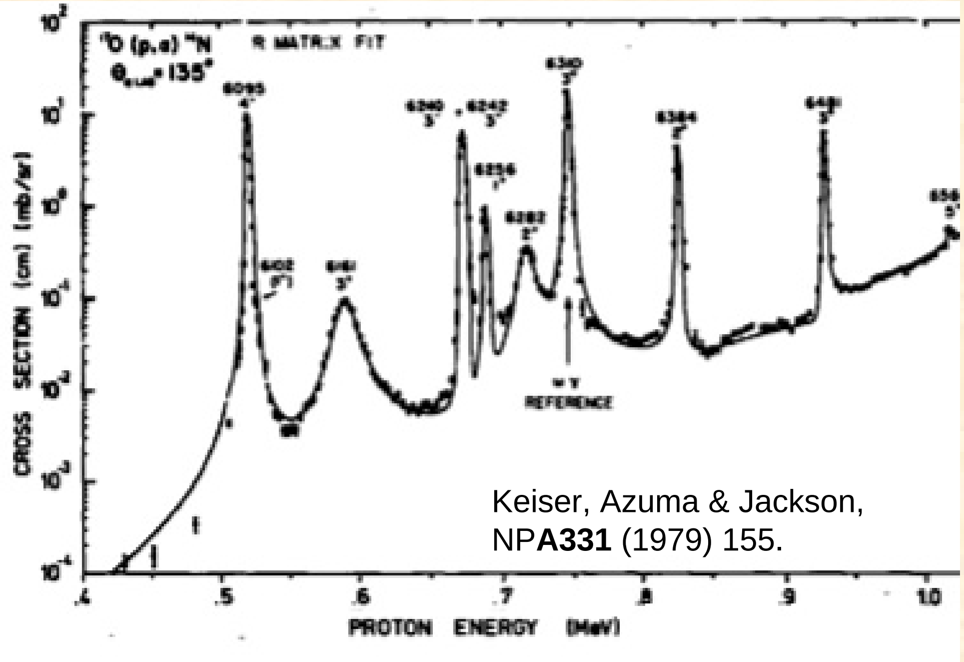




↖ Ground state → ground state only

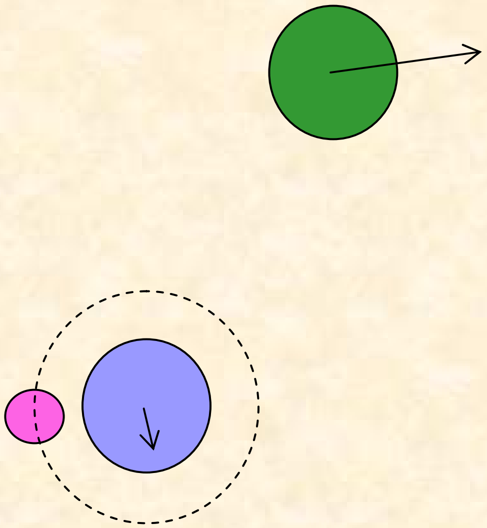
That's great, but ...

- Radioactive ion beam intensities are typically very low.
  - Expensive to produce
  - Beam time limited
- Cross sections for reactions of interest are low:
  - (p,γ) $\sigma < \mu b$
  - (p,α) $\sigma < mb$
- 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.

Transfer Reactions → Resonant properties



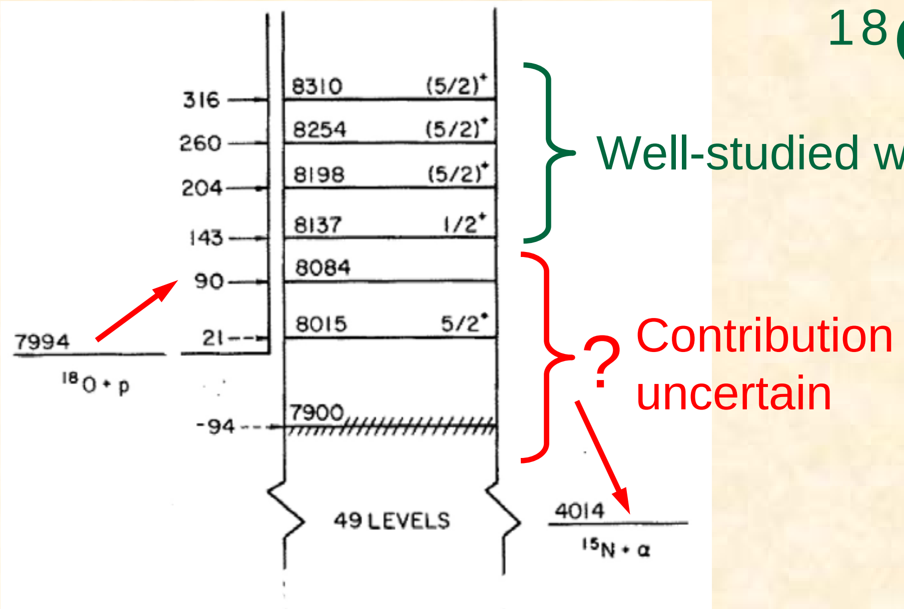
- A nucleon or “cluster” of nucleons (no internal degrees of freedom) is transferred from one nucleus to another.
- Populates “valence” states in the final nucleus.
- The core nuclei are unperturbed.
- E_x, ℓ-transfer, sometimes widths.

$$T_{DWBA} = \left\langle \varphi_{Ax}\chi_{bB}^{-} \middle| V_{xb} \middle| \chi_{aA}^{+}\varphi_{bx} \right\rangle$$

$$\left(\frac{d\sigma}{d\Omega}\right)_{\exp} = C^2S\left(\frac{d\sigma}{d\Omega}\right)_{DWBA}$$

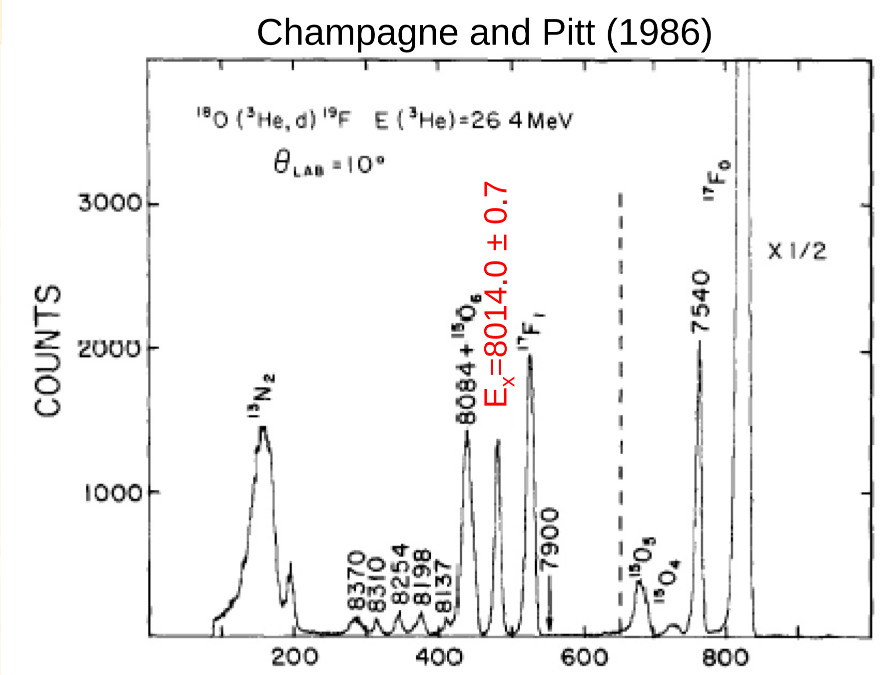
$$C^2S = \frac{\Gamma_p}{\Gamma_{sp}}$$

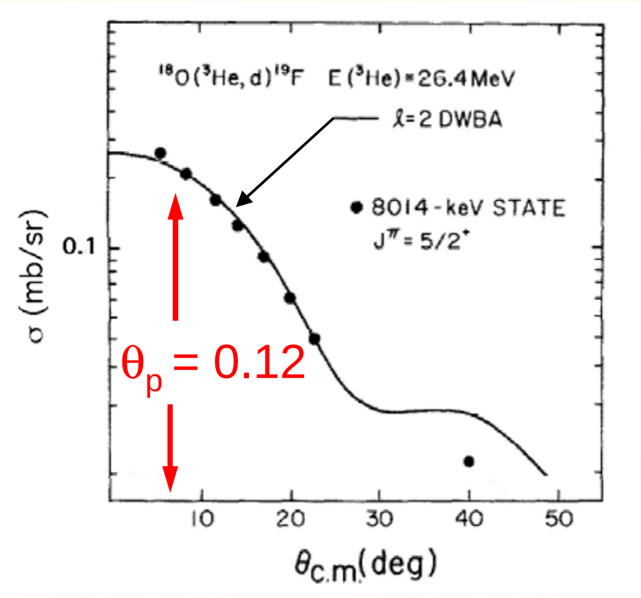
^{18}O(p,α)^{15}N via (^{3}He,d)



Well-studied with high intensity proton beams

Contribution uncertain


Champagne and Pitt (1986)



θ_p = 0.12

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

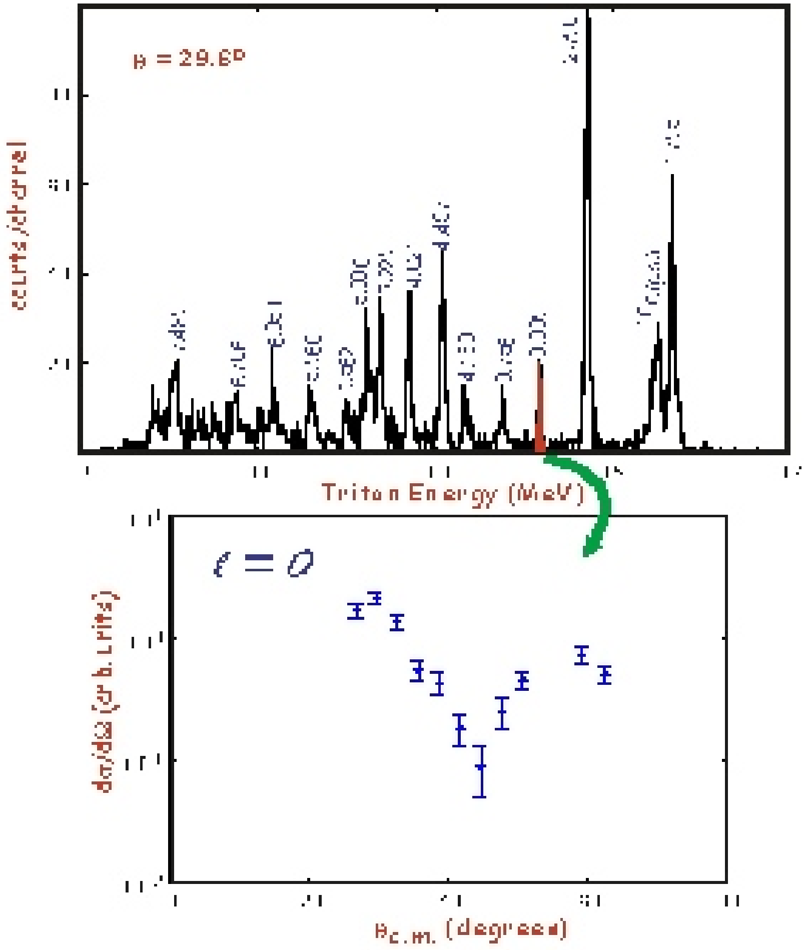
1 mA p + ^{18}O → 1 event / 3x10^{5} years

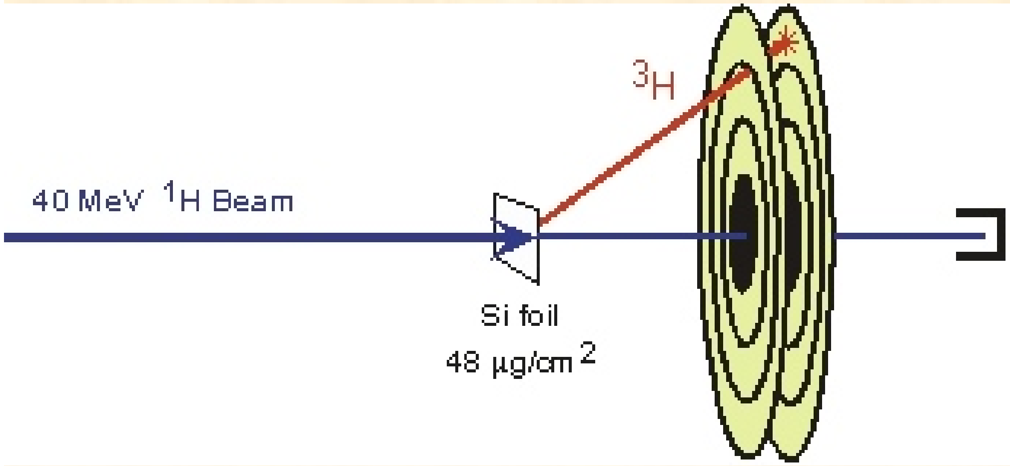
↸ Accurate E$_x$
↸ Unambiguous ℓ, J$^{\pi}$ inferred
↸ Γ if broad
↸ Γ$_x$ sometimes, but model dependent

Stable measurements → RIB reaction rates

- Transfer of multiple nucleons can probe properties of nuclei away from stability.
- E_x
- In some cases J^π
- Example: (p,t)
  - Removal of 2 neutrons
  - S=0, no relative orbital angular momentum
  - ℓ transfer is indicative of nucleon pair

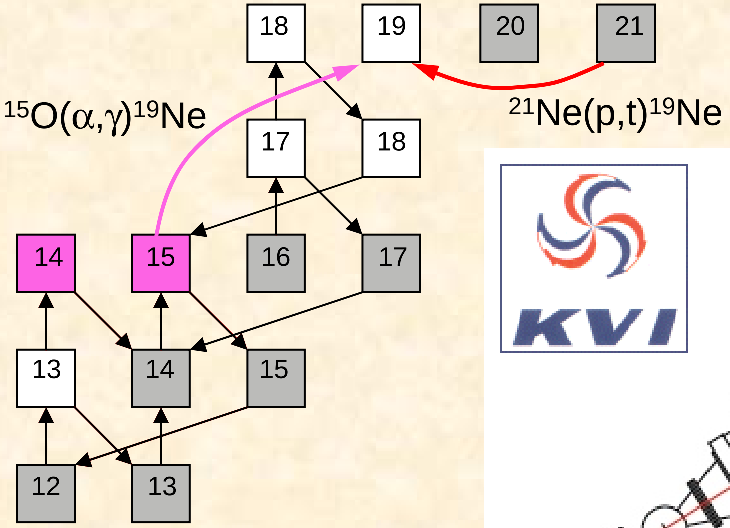
D.W. Bardayan *et al.*, PRC **65** (2002) 032801.



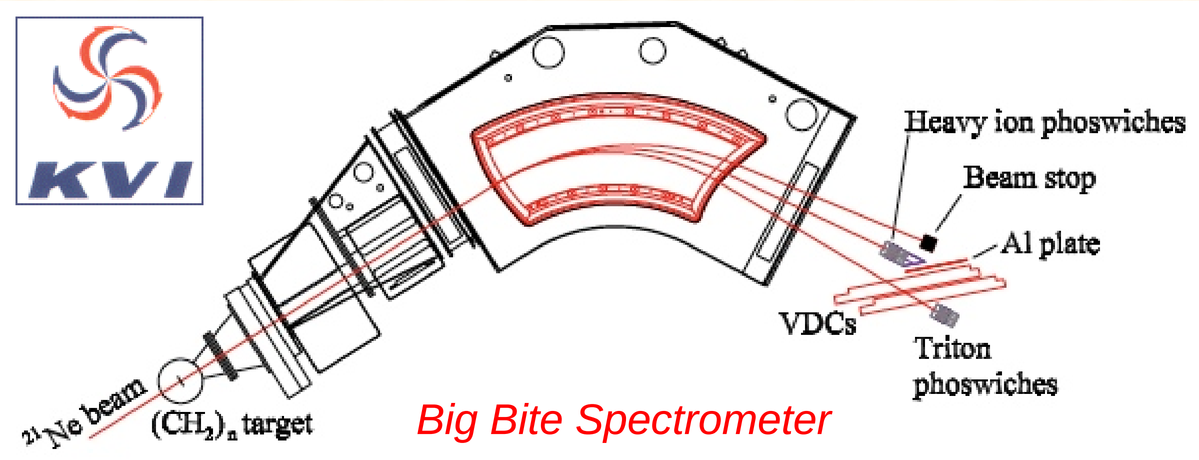


B. Davids *et al.*, PRC **67** (2003) 065808.

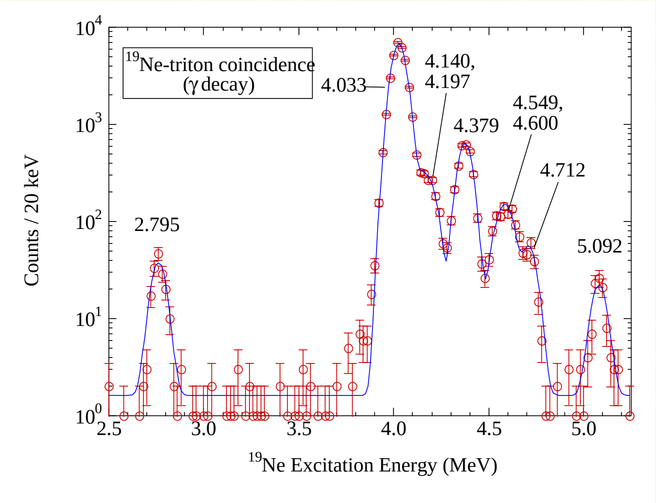
Measuring partial widths

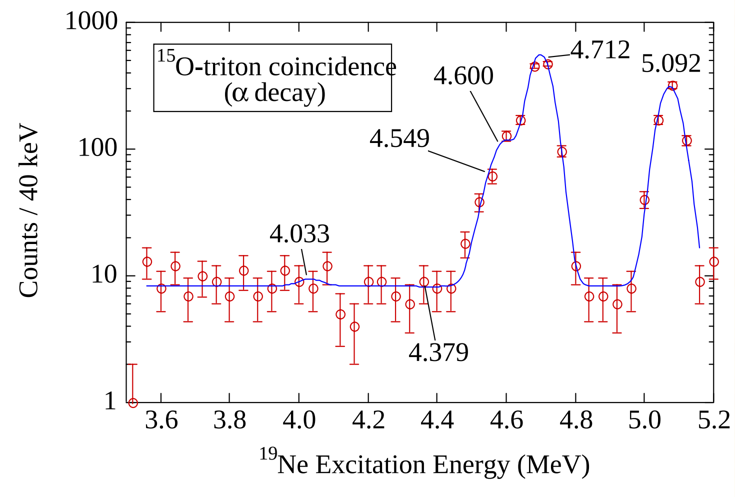


↖ ^{15}O(α,γ)^{19}Ne rate is important for "break-out" of CNO cycle and X-ray burst ignition → Γ_α's are major uncertainties



Big Bite Spectrometer





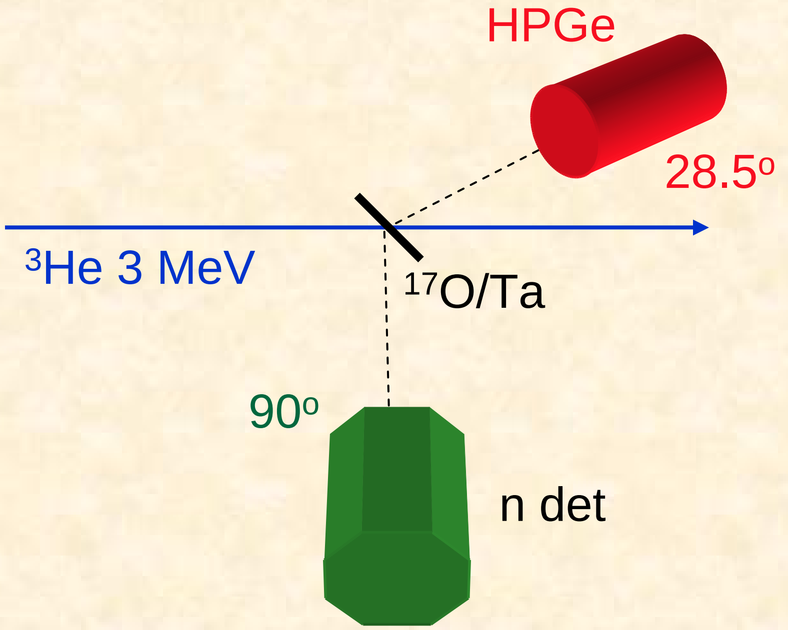
E_x (MeV)	Γ_α / G
4.033	< 0.0004
4.379	< 0.004
4.549	0.16±0.04
4.6	0.32±0.04
4.712	0.85±0.04

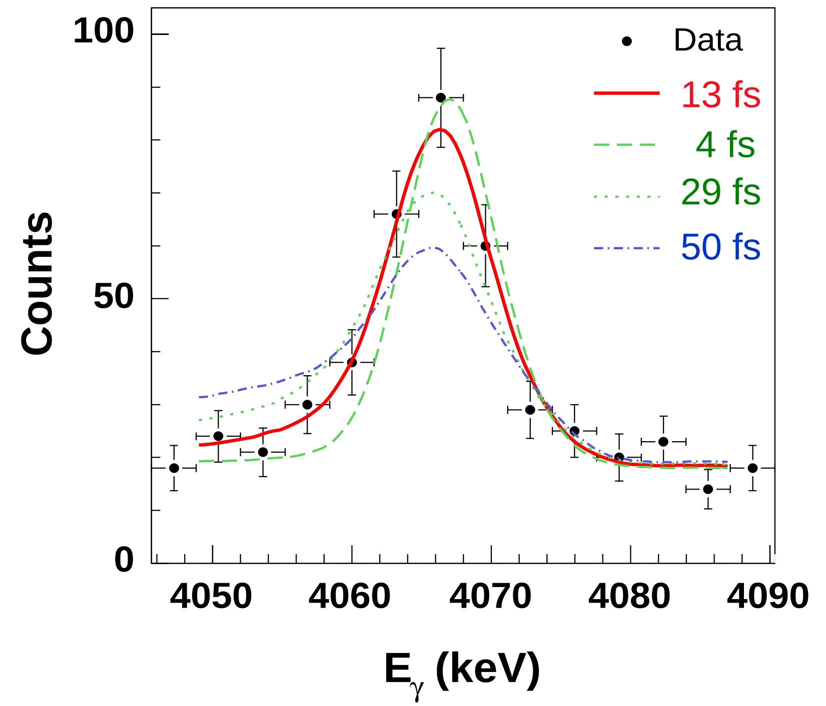
➡ Rate slow under nova conditions, but still uncertain for X-ray burst ignition

Gamma widths via Doppler-shift (DSAM)

W. Tan *et al.*, PRC, in press.

- Energy of γ from decay of recoiling heavy nucleus is shifted due to its relative motion.
- Nucleus slows down in target → range of shifts depending on lifetime.





- Detectors arranged to maximize effect.
- Line shape analysis.
- New lifetime for 4034 keV state in ^{19}Ne.

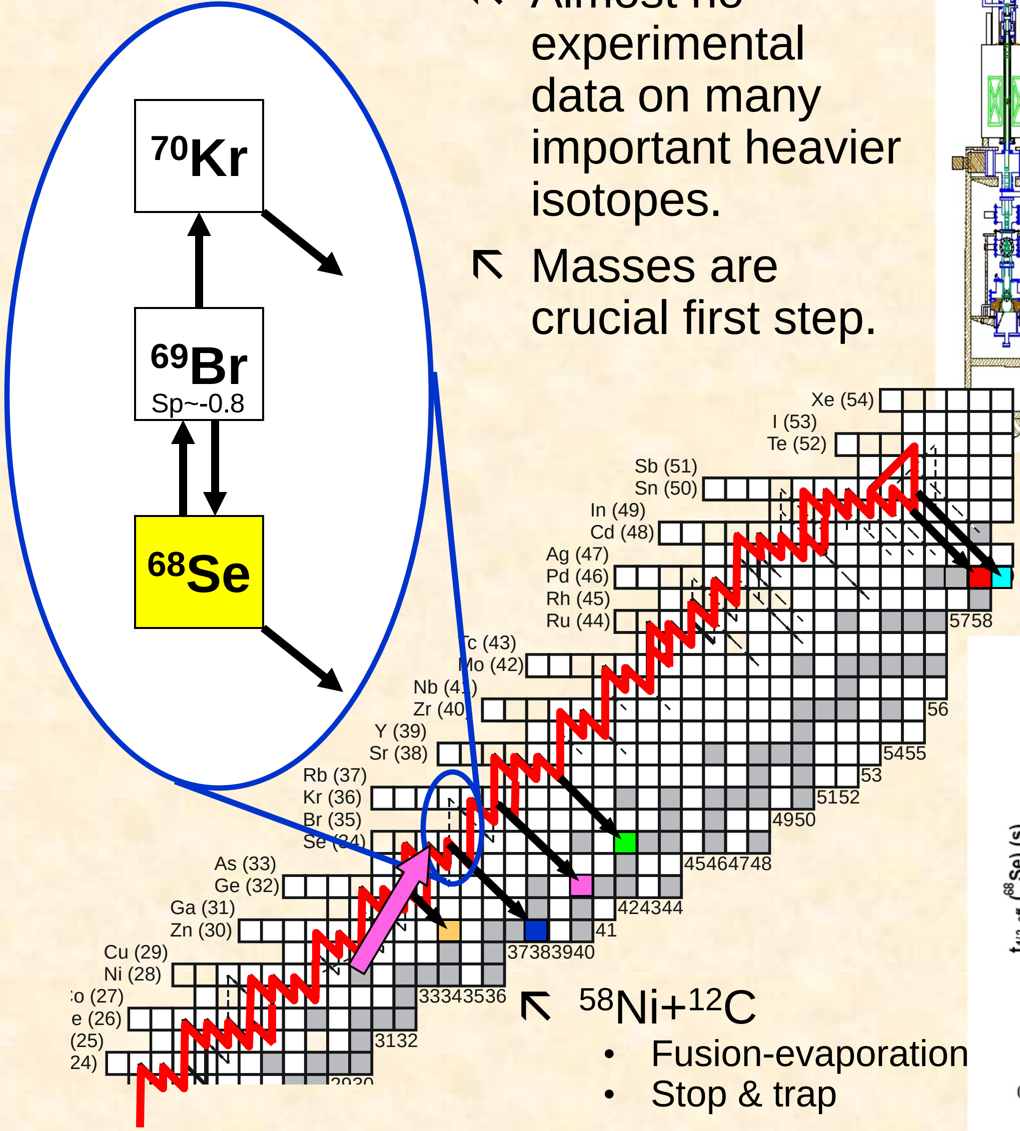
$$\tau = 13^{+9}_{-6}\ \text{fs} \rightarrow \Gamma = 51^{+43}_{-21}\ \text{meV}$$

Argonne NATIONAL LABORATORY Physics Division

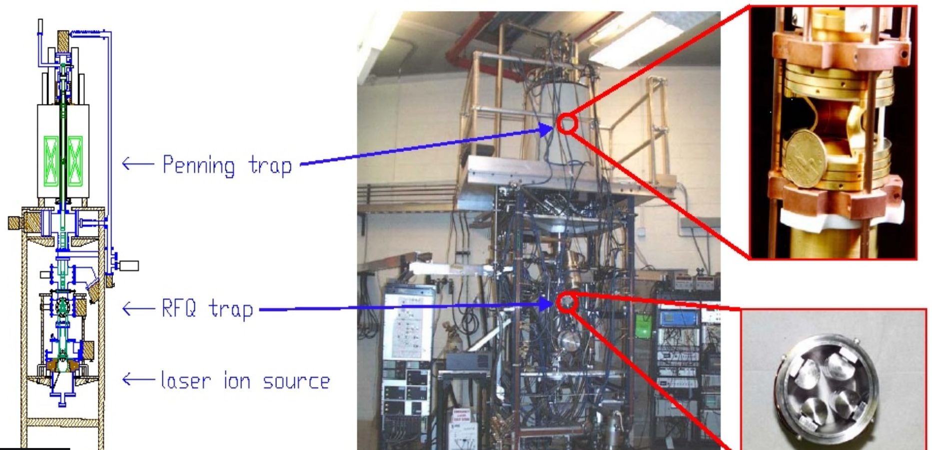
http://www.phy.anl.gov/atlas

Mass measurements

J. A. Clark *et al.*, PRL **92** (2004) 192501.

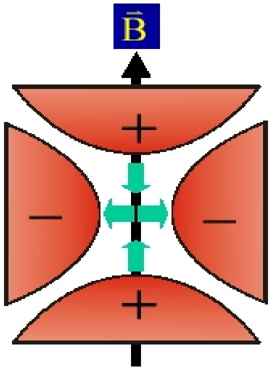


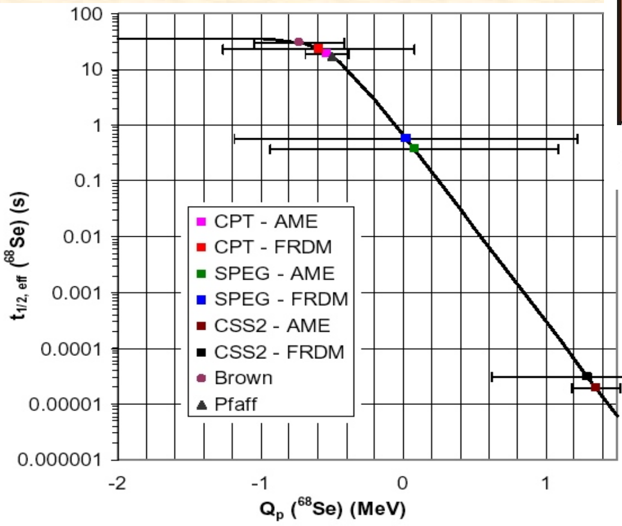
- ↖ Almost no experimental data on many important heavier isotopes.
- ↖ Masses are crucial first step.



$\Delta m/m \sim 3\times10^{-7}$

↖ ^{64}Ge & ^{68}Se



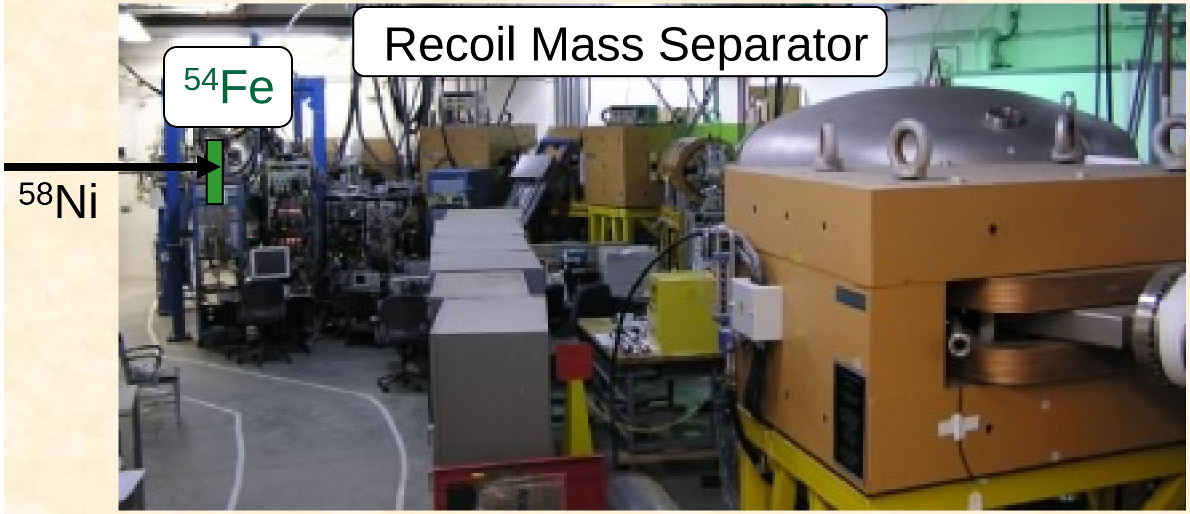


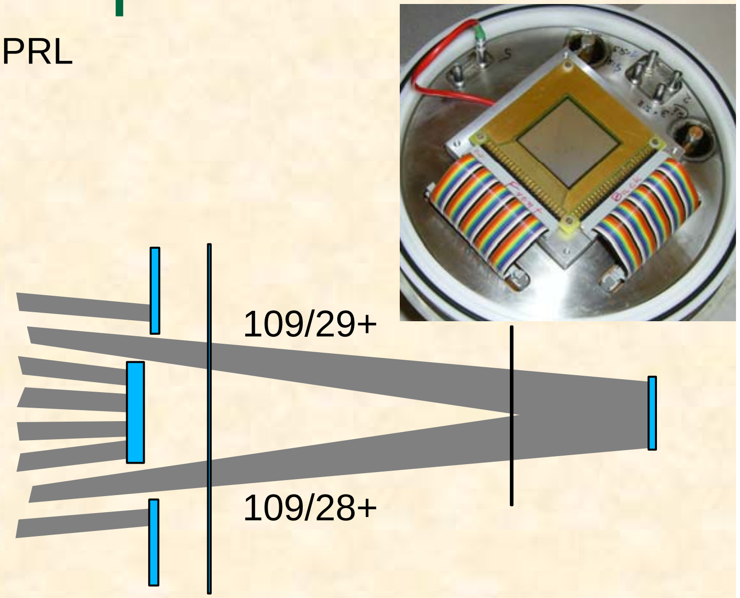
↖ ^{58}Ni+^{12}C

- Fusion-evaporation
- Stop & trap

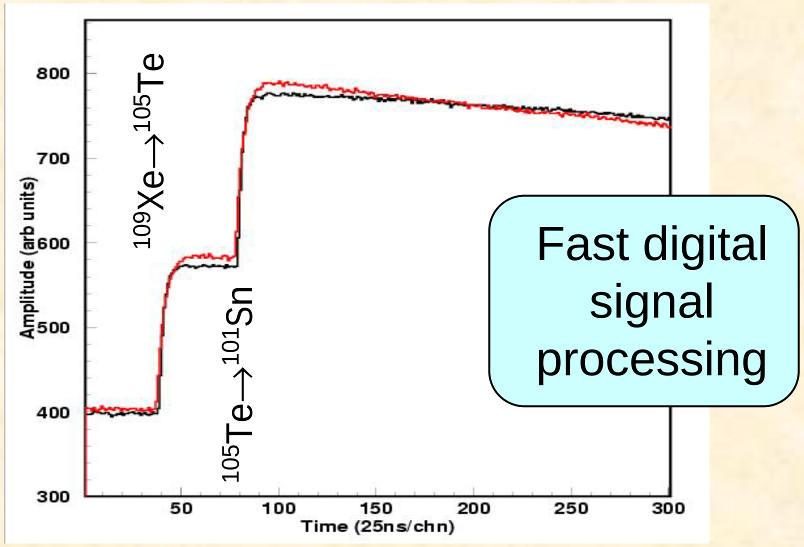
The rp process endpoint

S.N. Liddick *et al.*, submitted to PRL

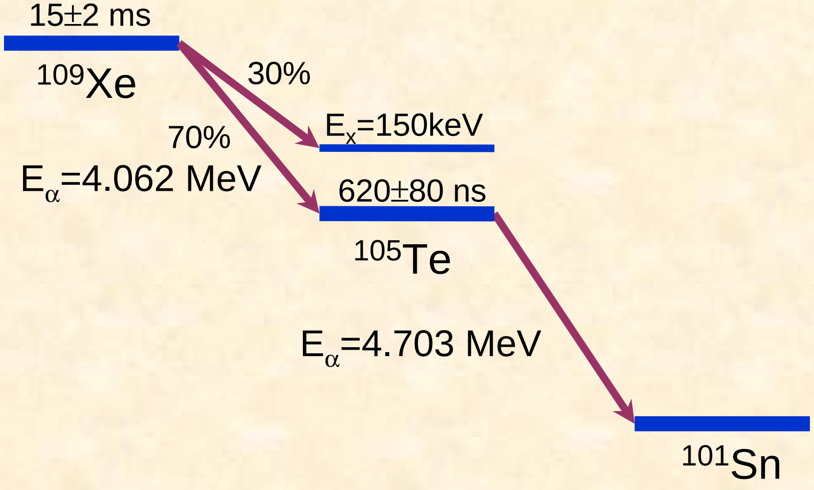




- Fusion evaporation reactions provide access to even the most heavy rp process nuclei.

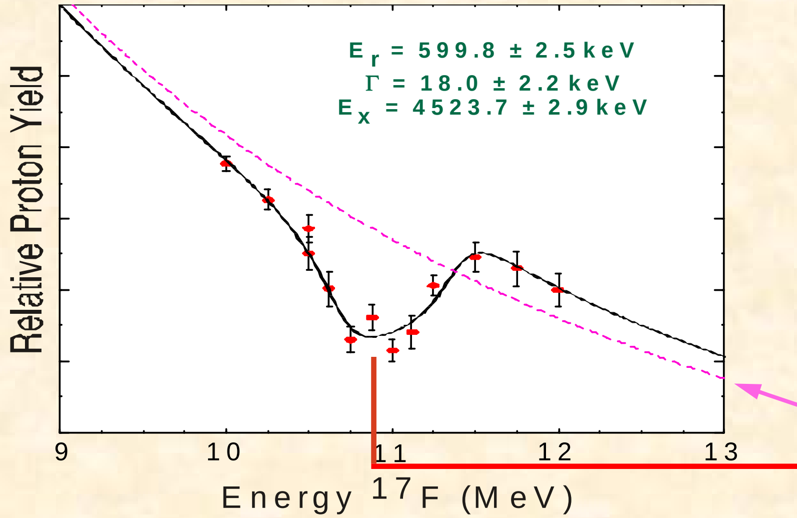


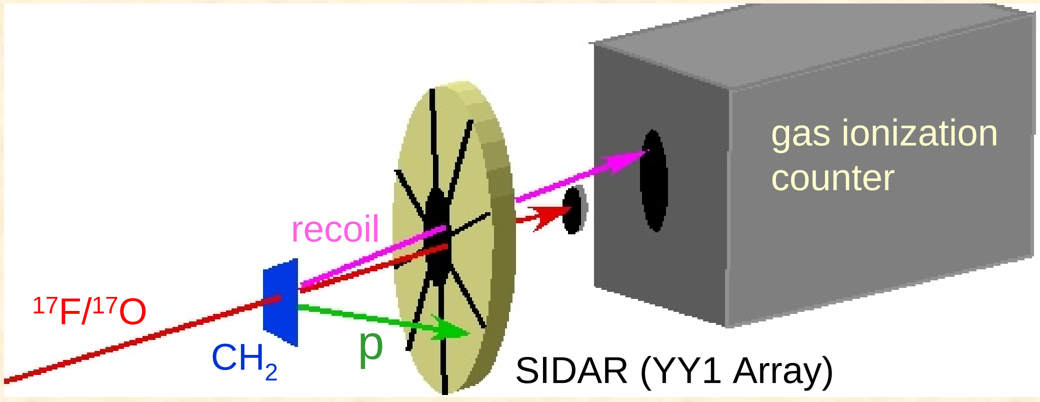
Fast digital signal processing

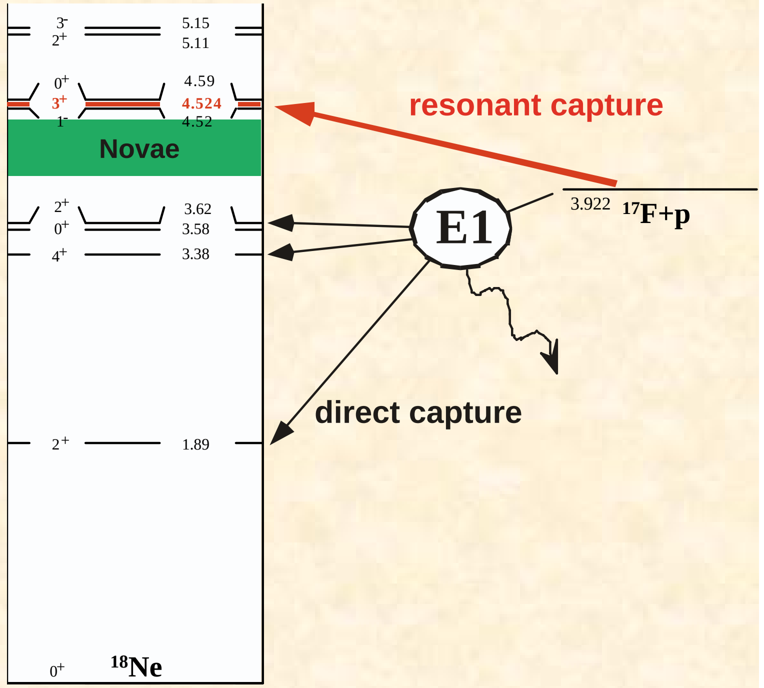


Proton elastic scattering - ^{17}F

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

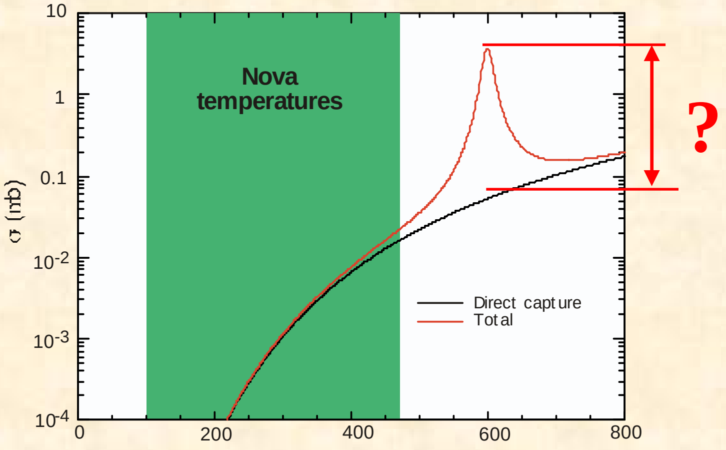






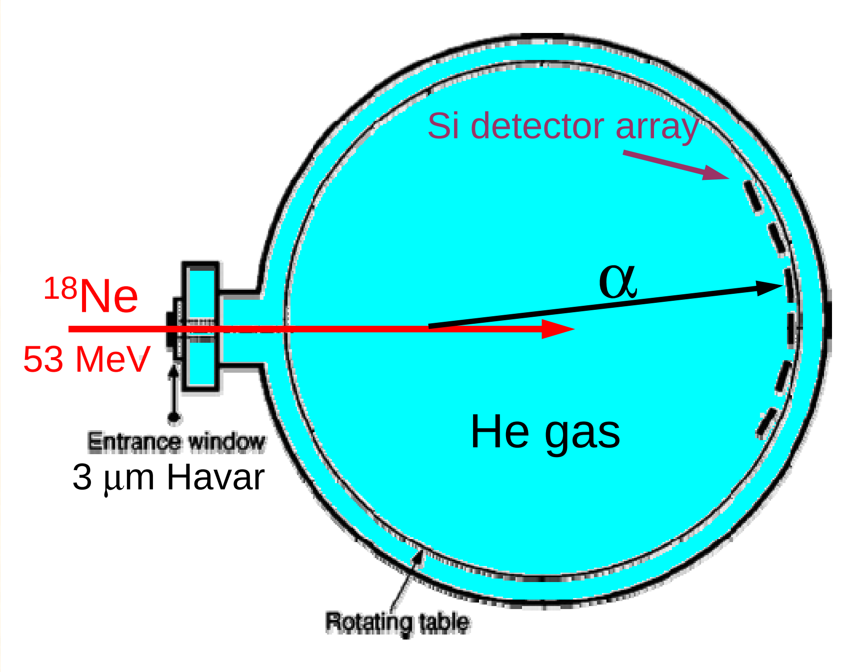
↖ 3^+ state predicted from mirror symmetry, but not observed in transfer reactions

- ^{20}Ne(p,t)^{18}Ne
- ^{16}O(^{3}He,n)^{18}Ne

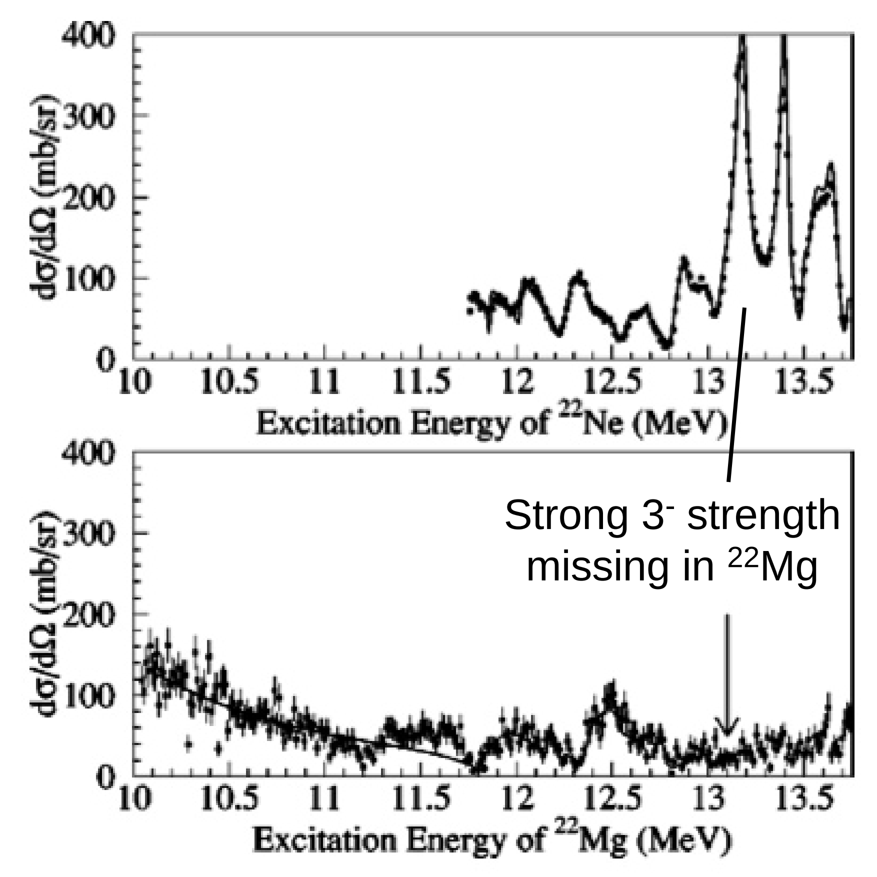


(α,α) at CRC at Louvain-le-Neuve

- Beam stopped in helium gas
- P ~ 300 Torr w/ Havar window
- Elastically scattered α detected by silicon array
- $E_\alpha \rightarrow E_{cm}$ of reaction
- Entire excitation function simultaneously measured



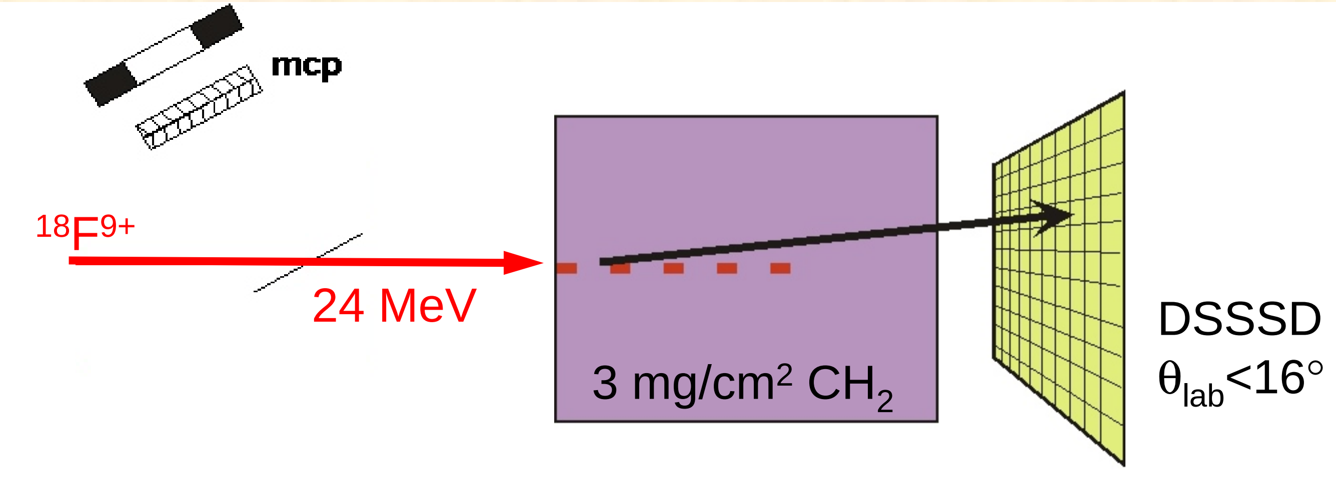
V.Z. Goldberg *et al.*, PRC **69** (2004) 024602.



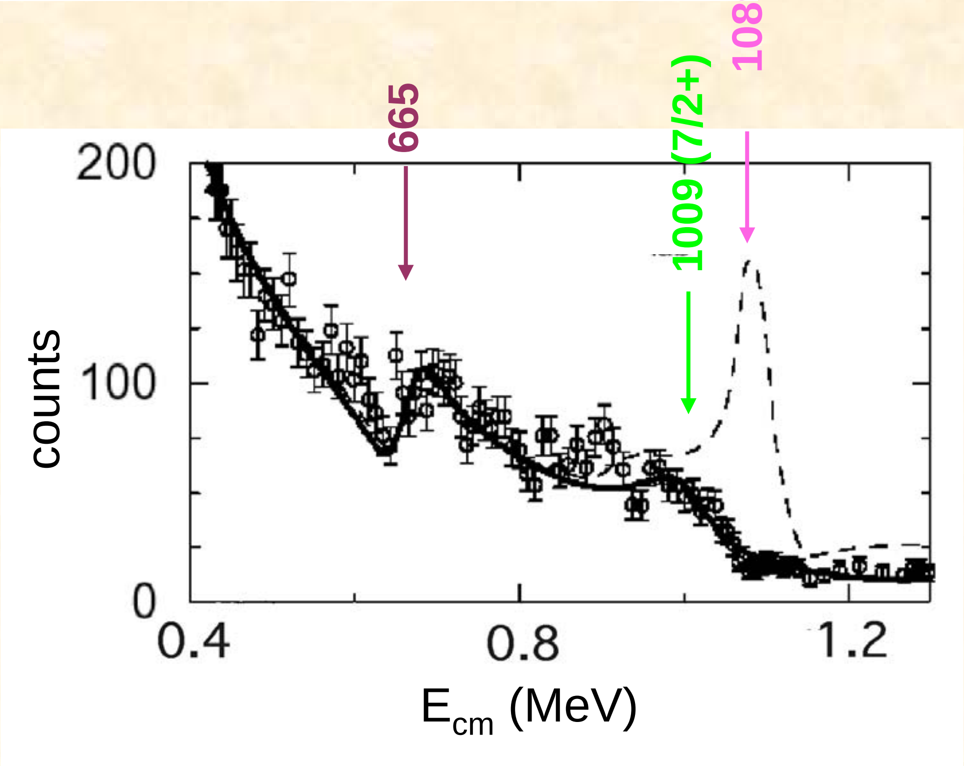
Strong 3^- strength missing in ^{22}Mg

Proton elastic scattering - ^{18}F

D.W. Bardayan et al., Phys. Rev.C 70 (2004).

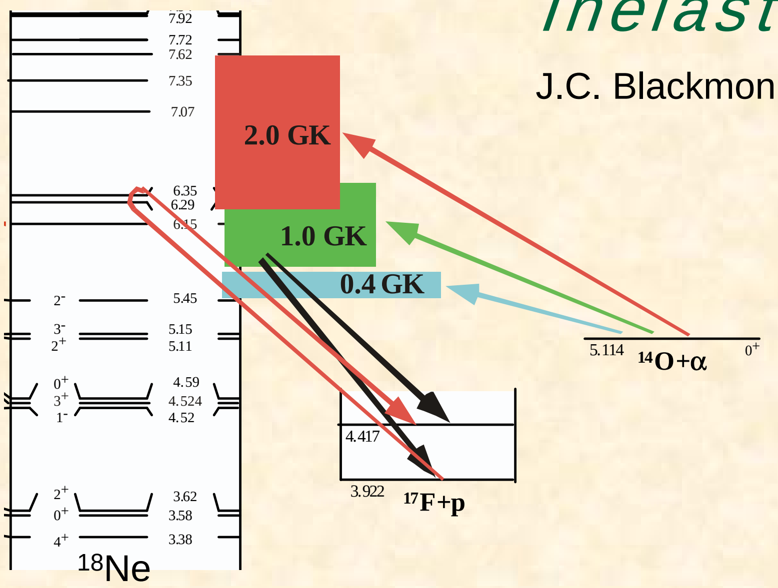


- Beam stopped in thick target
- Entire excitation function simultaneously measured
- E_p+angle → E_{cm} for event
- New resonance (7/2+) discovered at E_{cm}=1009 keV
- 665 keV and 1009 keV resonances dominate $^{18}F(p,\alpha)^{15}O$ rate at T>4x10^8 K

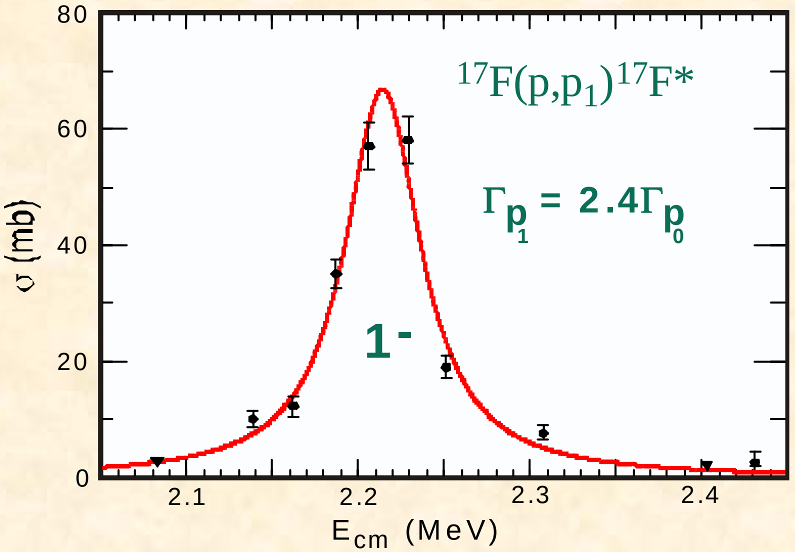


Inelastic scattering

J.C. Blackmon *et al.*, NP**A718** (2003) 127.

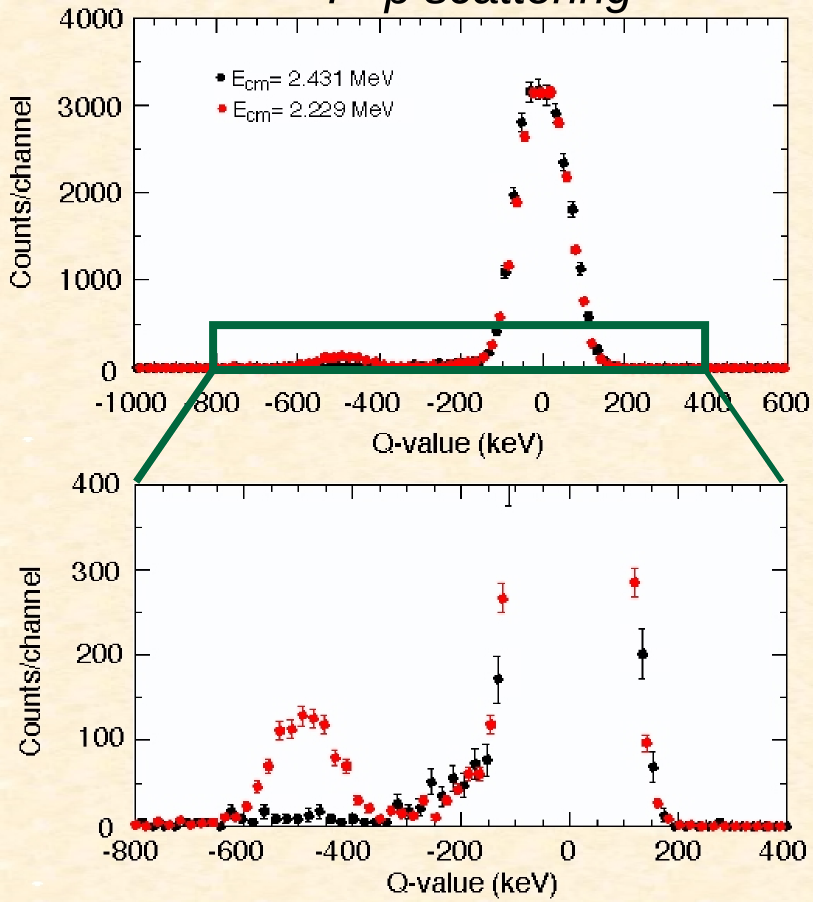


- Inelastic proton scattering can be a very useful probe in some cases
- High cross section
- Easily distinguished with thin target



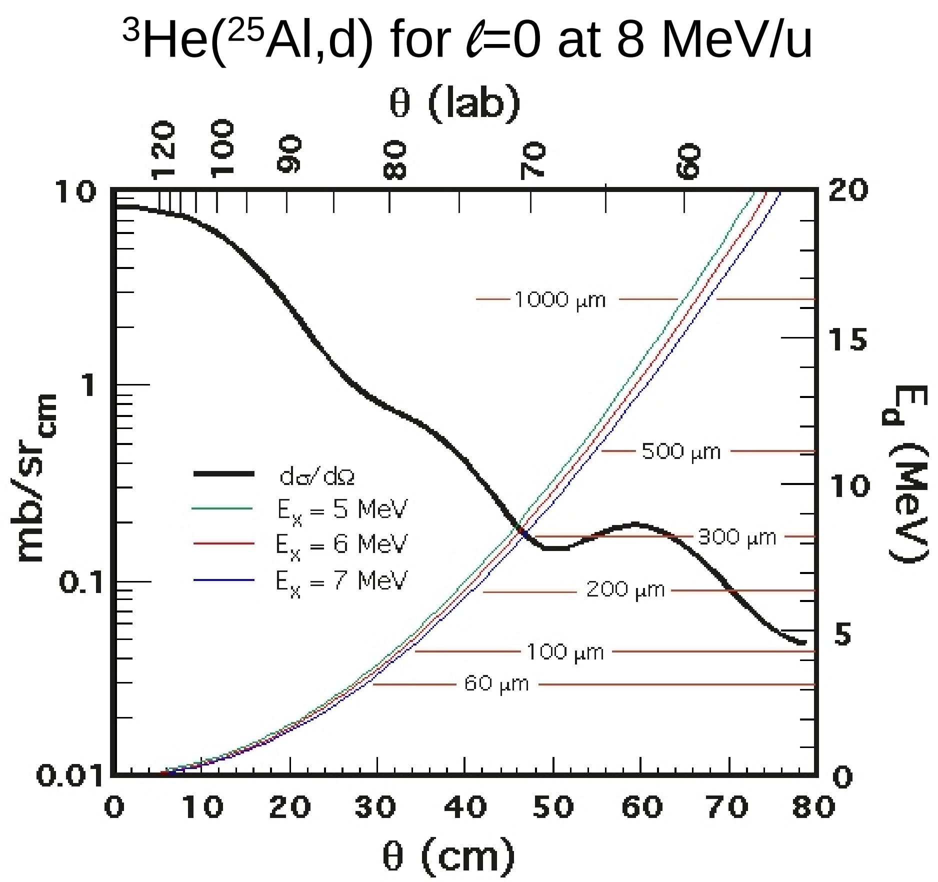
$\rightarrow$ $^{14}O(\alpha,p_1)^{17}F^* >> ^{14}O(\alpha,p_0)^{17}F$

$^{17}F+p$ *scattering*



(^{3}He,d) in inverse kinematics with RIBs

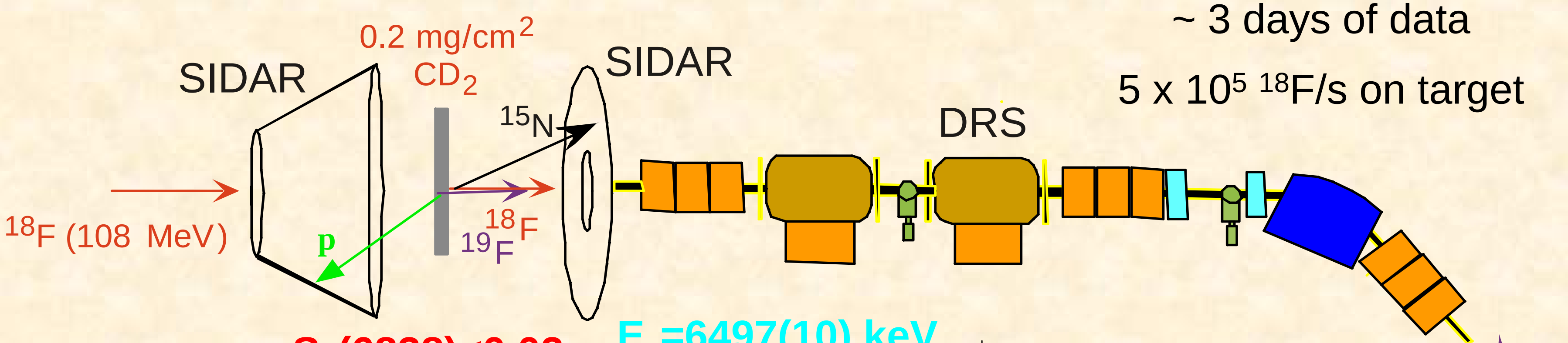
- Difficult → no measurements yet
- ^{3}He target
- Lab energy of d is low
- Need angles θ_{lab}~90°
- Need good resolution
  - Energy
  - Angle
- Gas jet target
- Look at alternatives


^{3}He(^{25}Al,d) for ℓ=0 at 8 MeV/u

(d,p) to improve mirror assignments

$^{18}F(d,p)^{19}F$ - Neutron single-particle strengths of mirror levels for $^{18}F(p,\alpha)^{15}O$.

*R.L. Kozub et al., PRC **71** (2005) 032801; and R.L. Kozub et al. PRC, in press.*



~ 3 days of data

5 x 10^5 ^{18}F/s on target

$S_n(6838)<0.02$

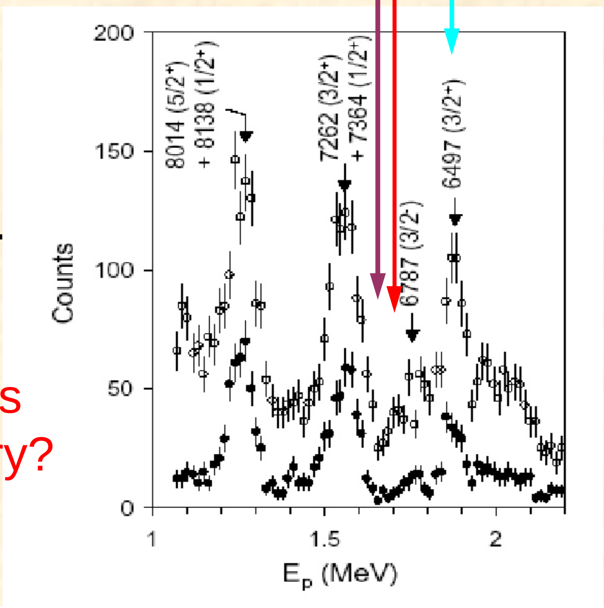
E_x=6497(10) keV

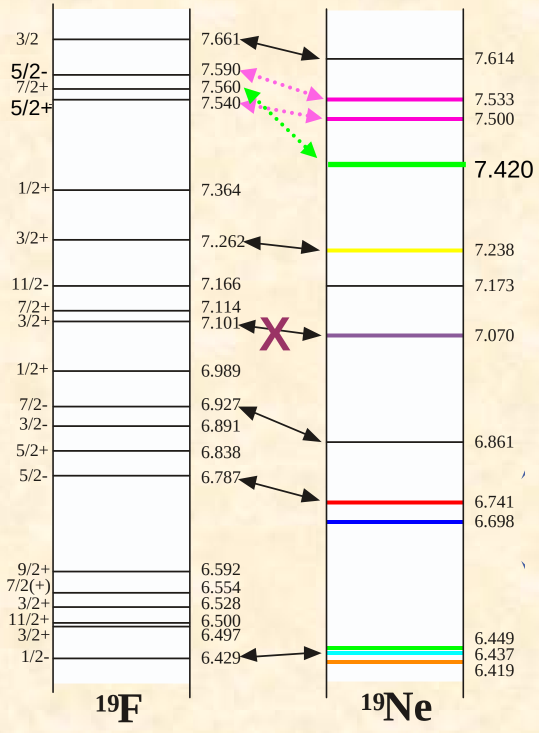
$S_n(6528)<0.04$

$S_n(7102)<0.02$

→ Significantly lower $^{18}F(p,\alpha)$ reaction rate …

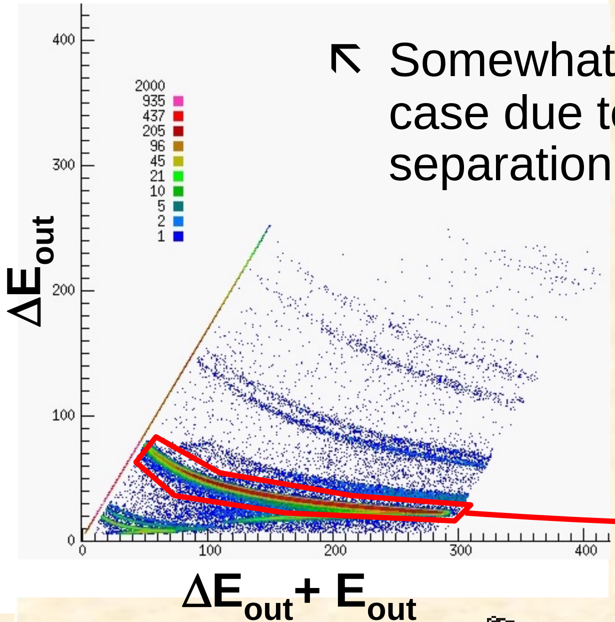
But how good is mirror symmetry?



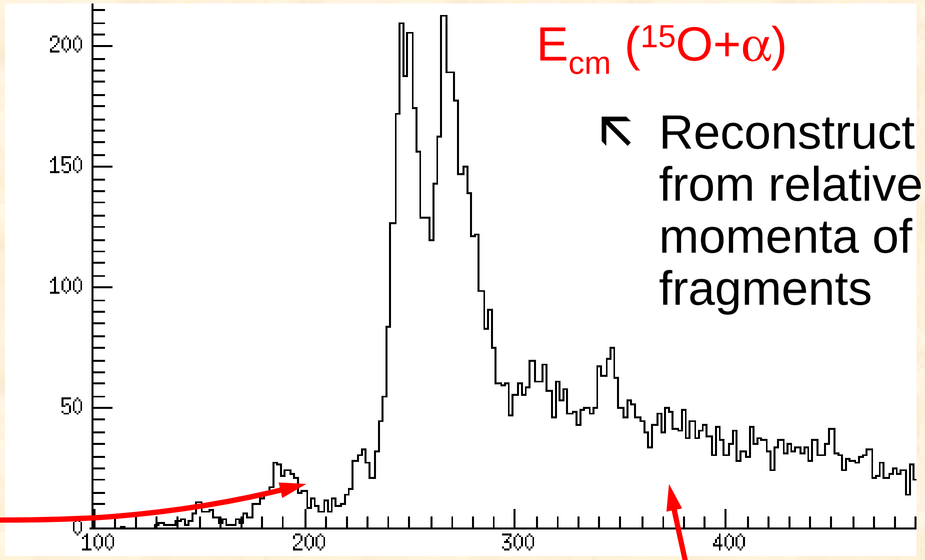


$^{2}H(^{18}F,n)^{19}Ne^{*}\rightarrow{}^{15}O+\alpha$

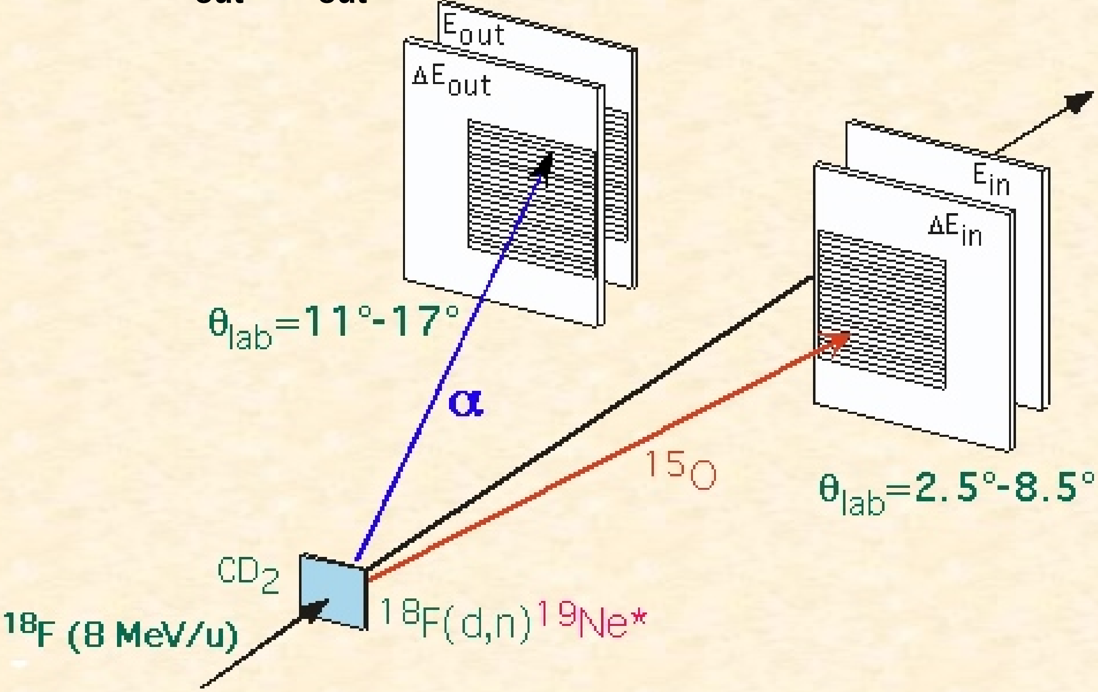
C. Brune, Ohio U., in prep.

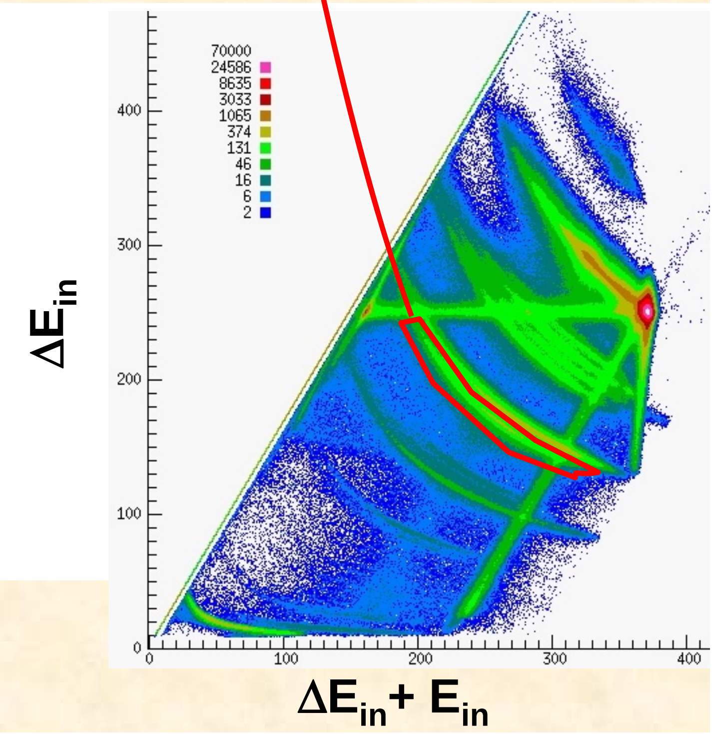


↖ Somewhat special case due to low α separation energy



↖ Reconstruct E_{cm} from relative momenta of fragments

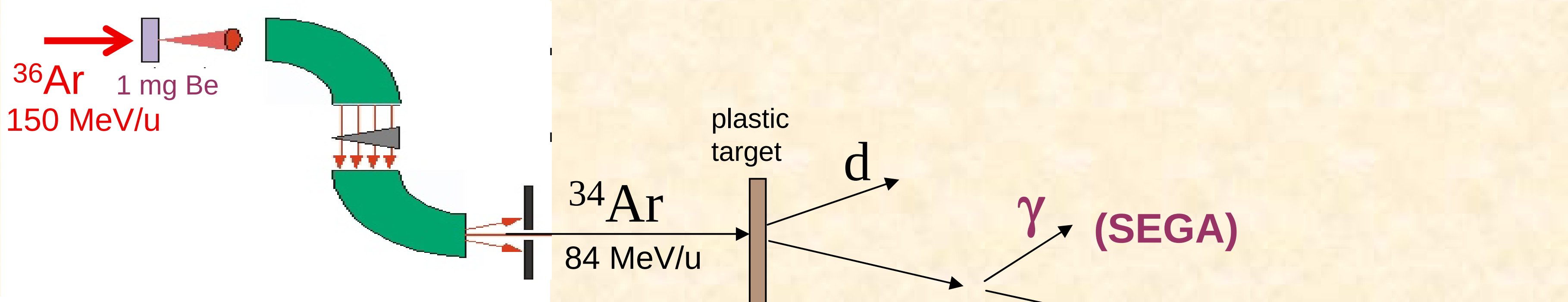




The Joint Institute for Nuclear Astrophysics

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

(p,d) in inverse kinematics at MSU/NSCL



^{36}Ar
150 MeV/u

1 mg Be

^{34}Ar
84 MeV/u

plastic target

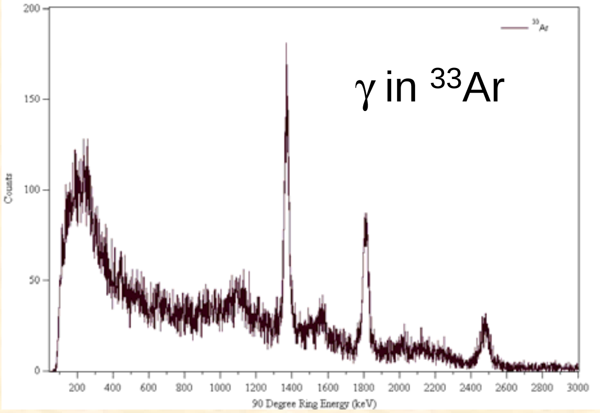
d

γ **(SEGA)**

^{33}Ar*

^{33}Ar

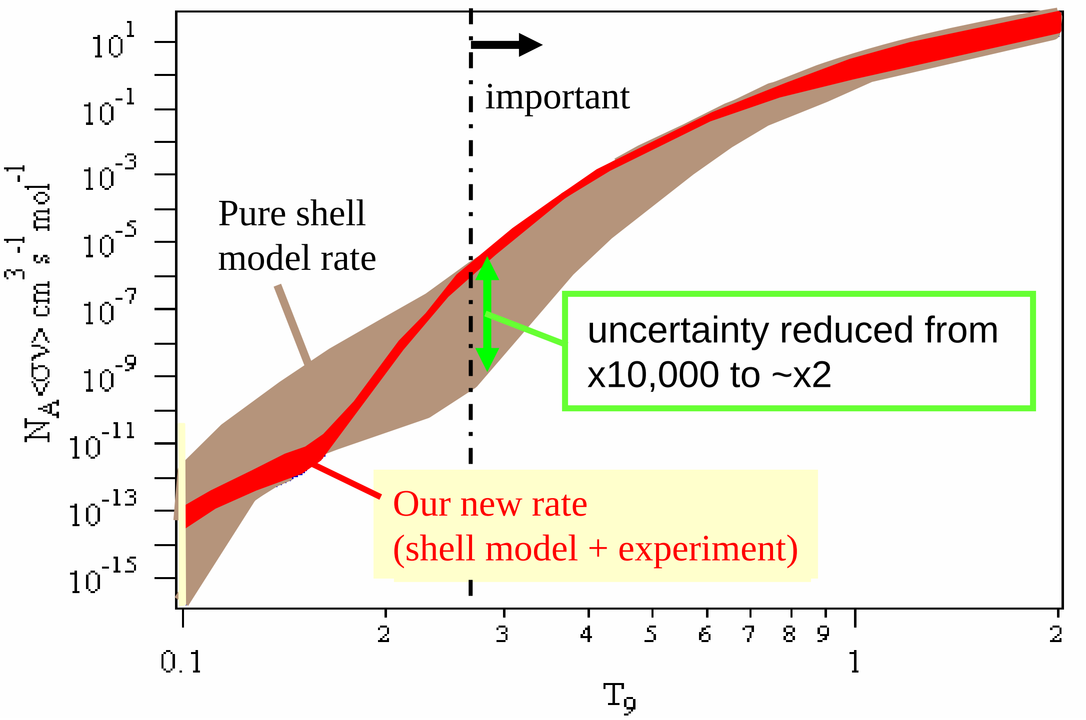
(S800 spectrometer)



γ in ^{33}Ar

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

New astrophysical ^{32}Cl(p,γ)^{33}Ar rate



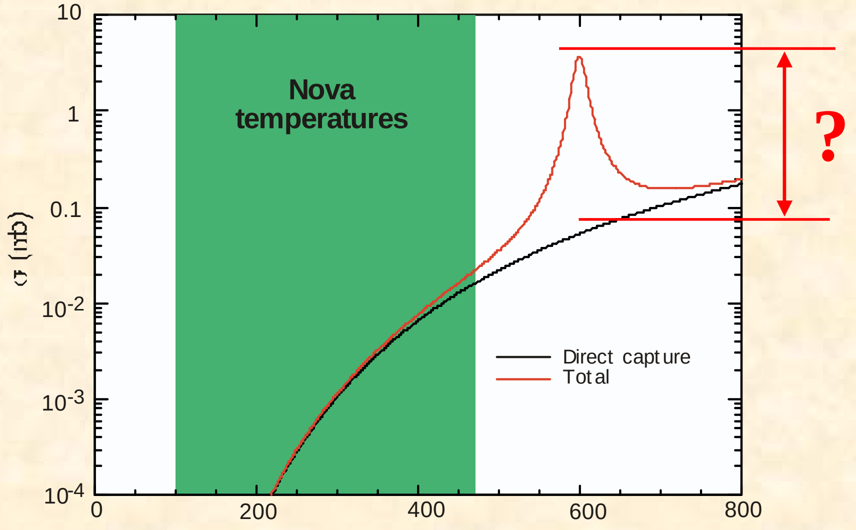
important

Pure shell model rate

uncertainty reduced from x10,000 to ~x2

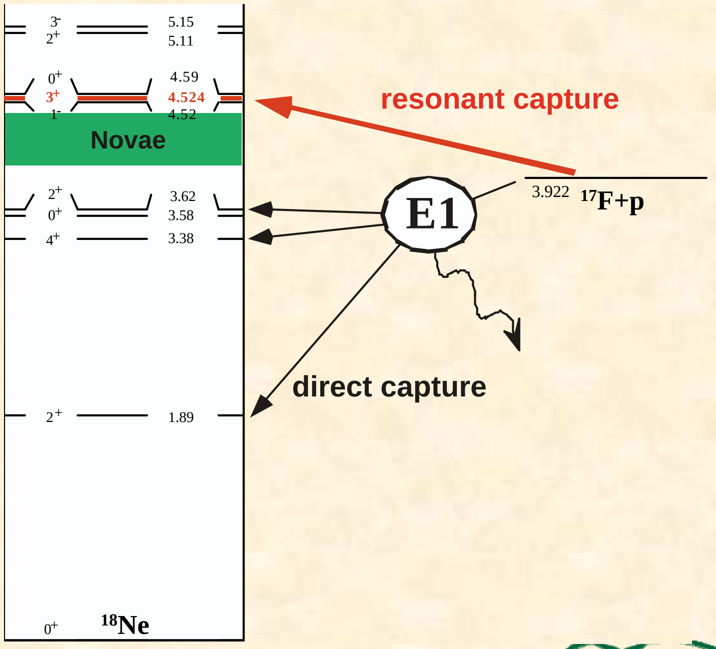
Our new rate (shell model + experiment)

Direct capture

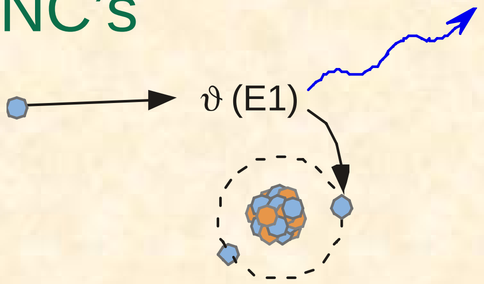


- Can be important in cases where the level density is very low → near drip line.
- $^{17}F(p,\gamma)^{18}Ne$ is a good example.
- Strength of 3^+ can be measured directly:
  - 10 events/day at 10^7 pps incident
- But direct capture is expected to dominate the rate at nova temperatures:
  - → 10^{10} pps incident needed

- Direct capture cross section is uncertain - based entirely on structure of mirror states in ^{18}O.
- Capture is expected to proceed primarily through a cascade via 2^+ and 4^+ excited states.
- Alternative techniques can be used to accurately determine the direct capture cross section.



Direct capture from ANC's

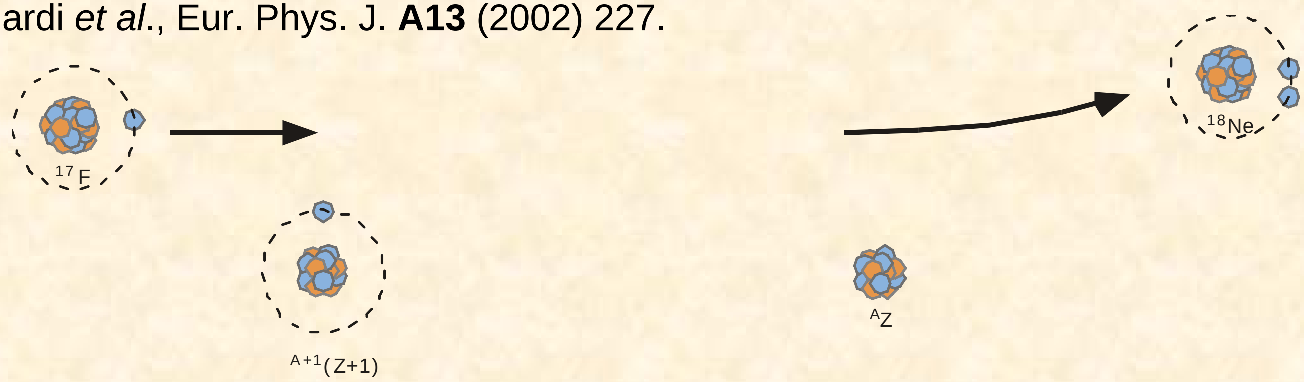


- Direct capture occurs via an electromagnetic transition at large radii.
- The cross section can be accurately calculated from the Asymptotic Normalization Coefficients (ANC's) with little model dependence.
- The ANC's can be determined by measuring the cross section for peripheral proton transfer reactions.
  - Mukhamedzhanov *et al*., PRC **56** (1997) 1302.
  - Gagliardi *et al*., PRC **59** (1999) 1149.
  - Gagliardi *et al*., Eur. Phys. J. **A13** (2002) 227.

$$\sigma_{DWBA} \sim \left|\langle \chi_\beta \psi_\beta | \vartheta | \chi_\alpha \psi_\alpha \rangle\right|^2$$

$$\psi \sim \left(\frac{C}{b}\right)\varphi \quad \text{and} \quad \varphi \xrightarrow[r \gg R_A]{} b\,\frac{W}{r}$$

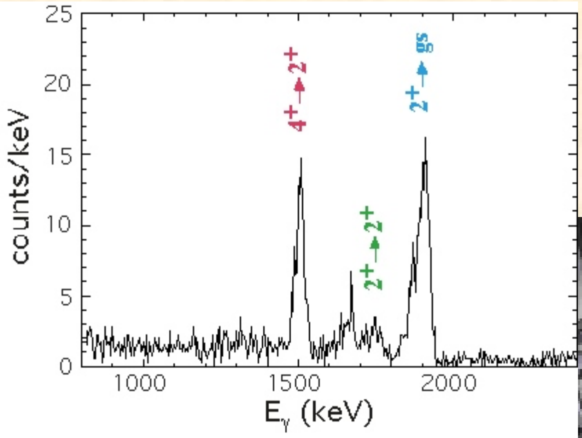
$$\frac{d\sigma}{d\Omega} = \frac{C_{Z+p}}{b_{Z+p}}\,\frac{C_{17F+p}}{b_{17F+p}}\,\sigma_{DWBA}$$

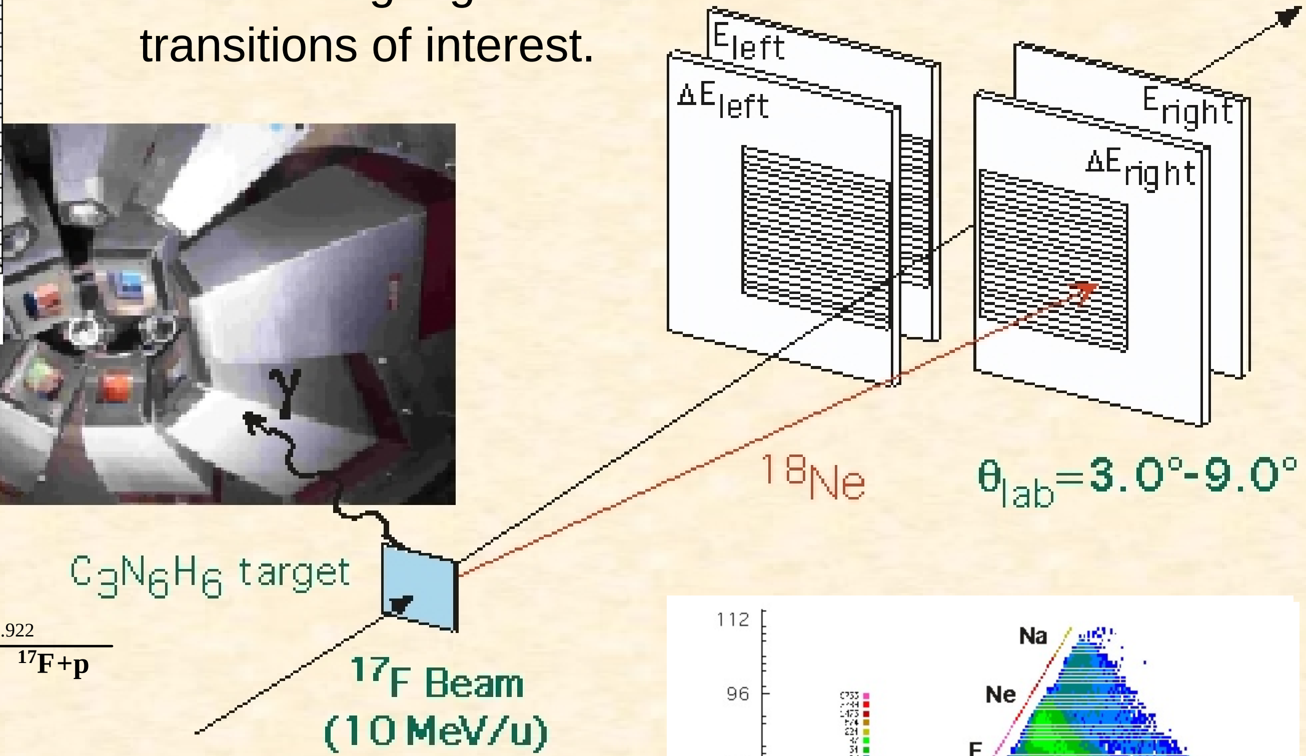


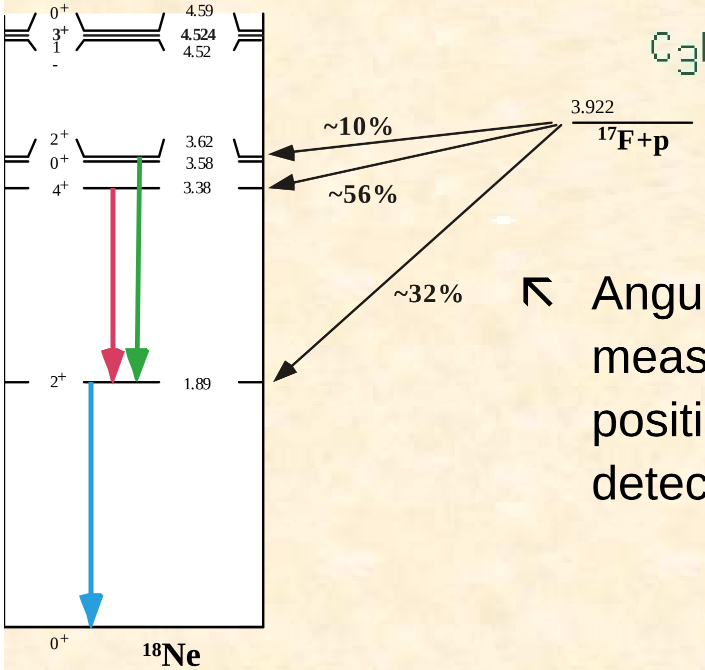
^{14}N(^{17}F,^{18}Ne*)^{13}C to determine ^{17}F+p ANC's

J.C. Blackmon *et al*., NP**A746** (2004) 365.

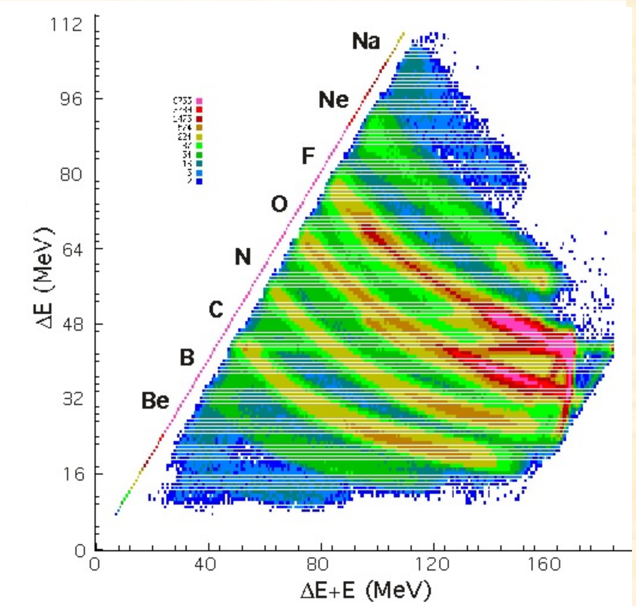
↸ Gamma-rag tag used to resolve transitions of interest.





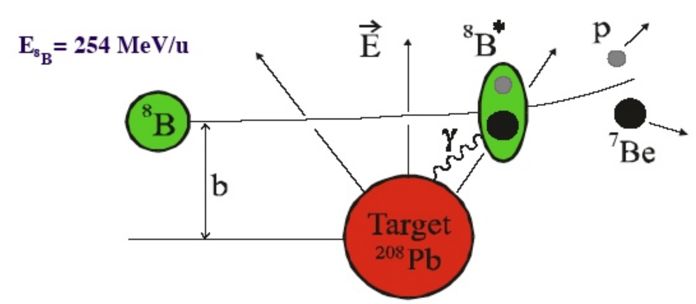


↸ Angular distributions of ^{18}Ne's measured at forward angles in position-sensitive Si-strip detectors.



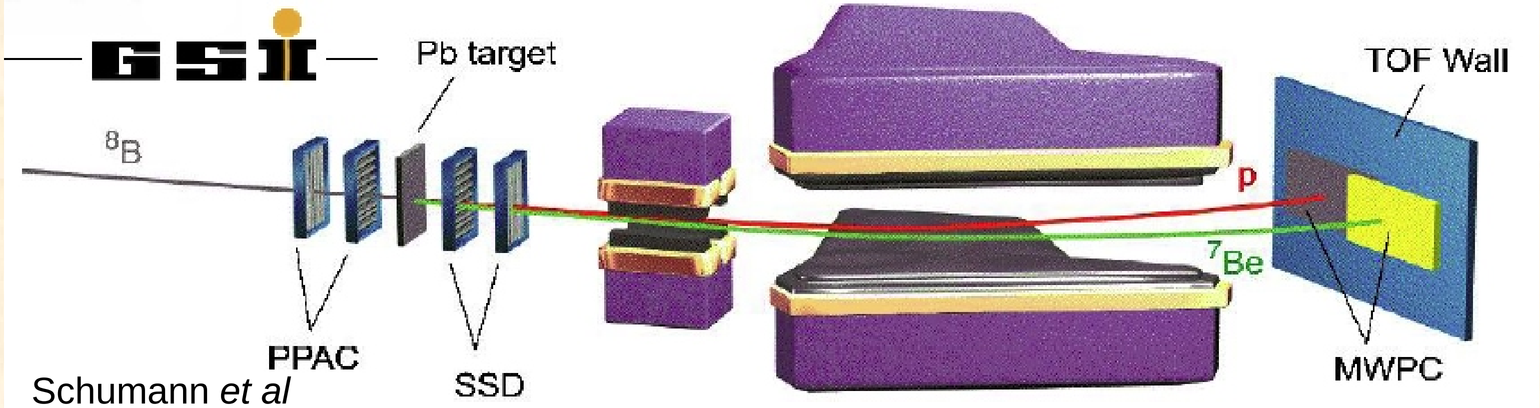
Coulomb dissociation

Schumann *et al*., PRL **90** (2003) 232501.
T. Motobayashi *et al*., Phys. Lett. **264B** (1991) 259.
J. Kiener et al., Nucl. Phys. **A552** (1993) 66

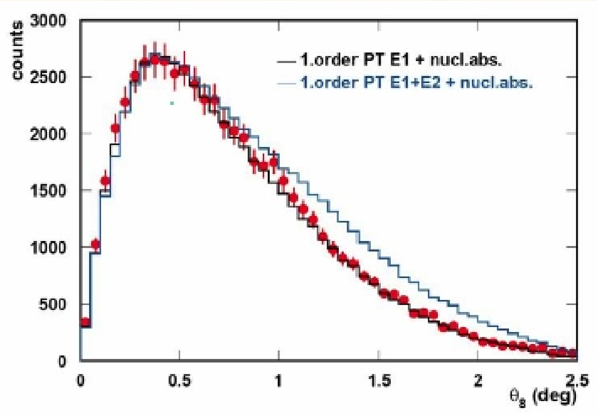


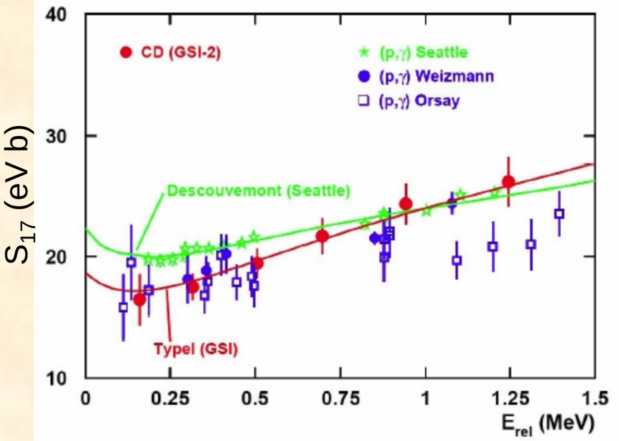
Measure inverse to capture reaction using RIB on a γ target.

Complications
  - multipolarities
  - nuclear contribution

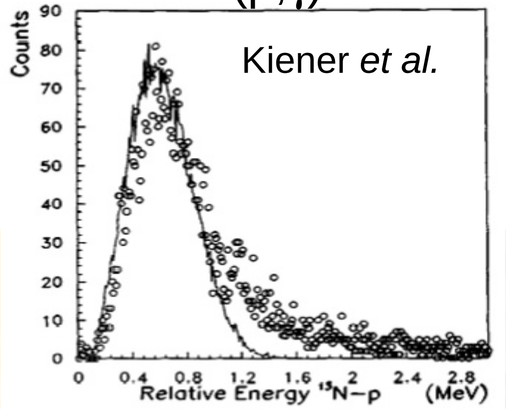


Schumann *et al*



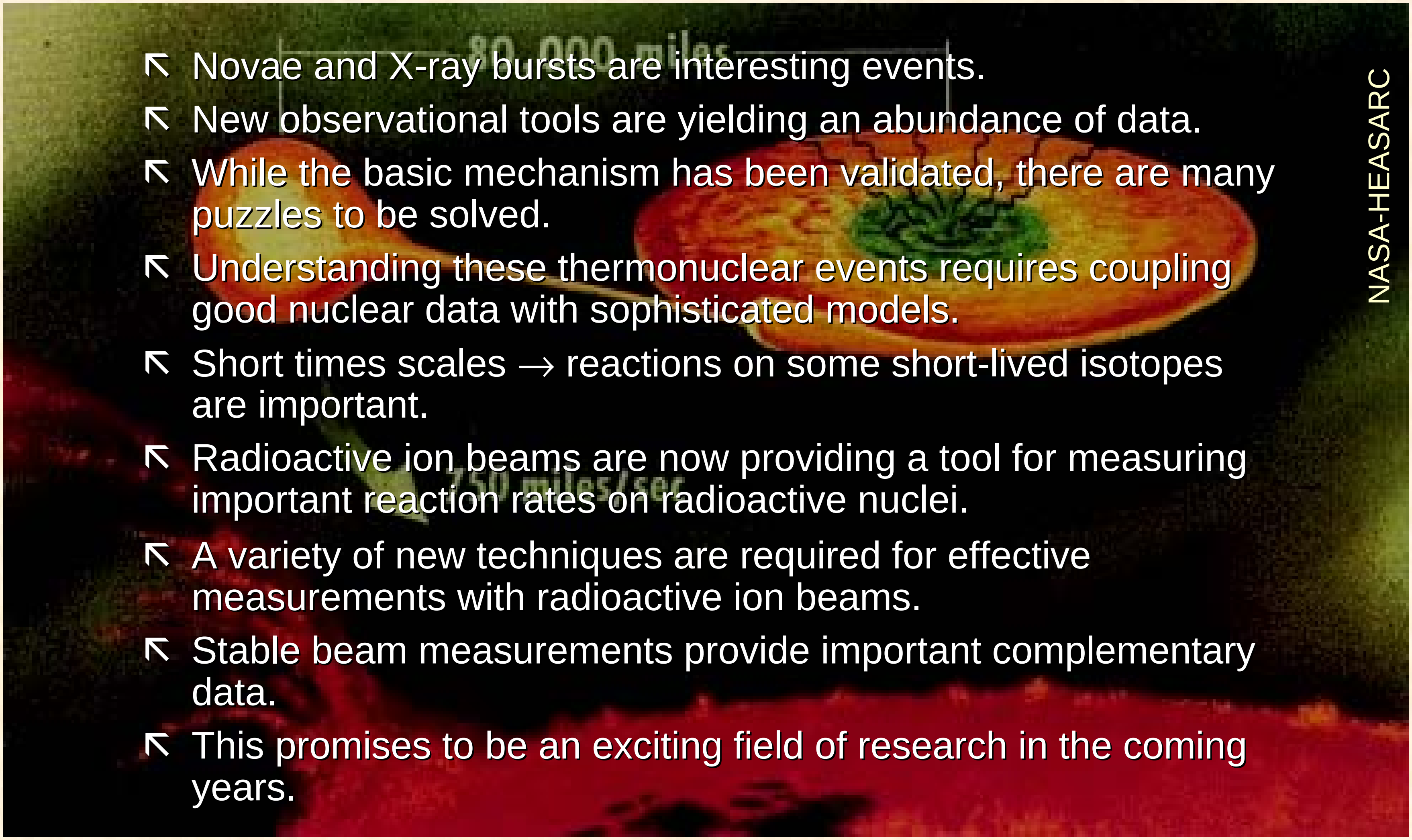


$^{13}N(p,\gamma)^{14}O$



Kiener *et al.*

Conclusion



NASA-HEASARC

- Novae and X-ray bursts are interesting events.
- New observational tools are yielding an abundance of data.
- While the basic mechanism has been validated, there are many puzzles to be solved.
- Understanding these thermonuclear events requires coupling good nuclear data with sophisticated models.
- Short times scales → reactions on some short-lived isotopes are important.
- Radioactive ion beams are now providing a tool for measuring important reaction rates on radioactive nuclei.
- A variety of new techniques are required for effective measurements with radioactive ion beams.
- Stable beam measurements provide important complementary data.
- This promises to be an exciting field of research in the coming years.