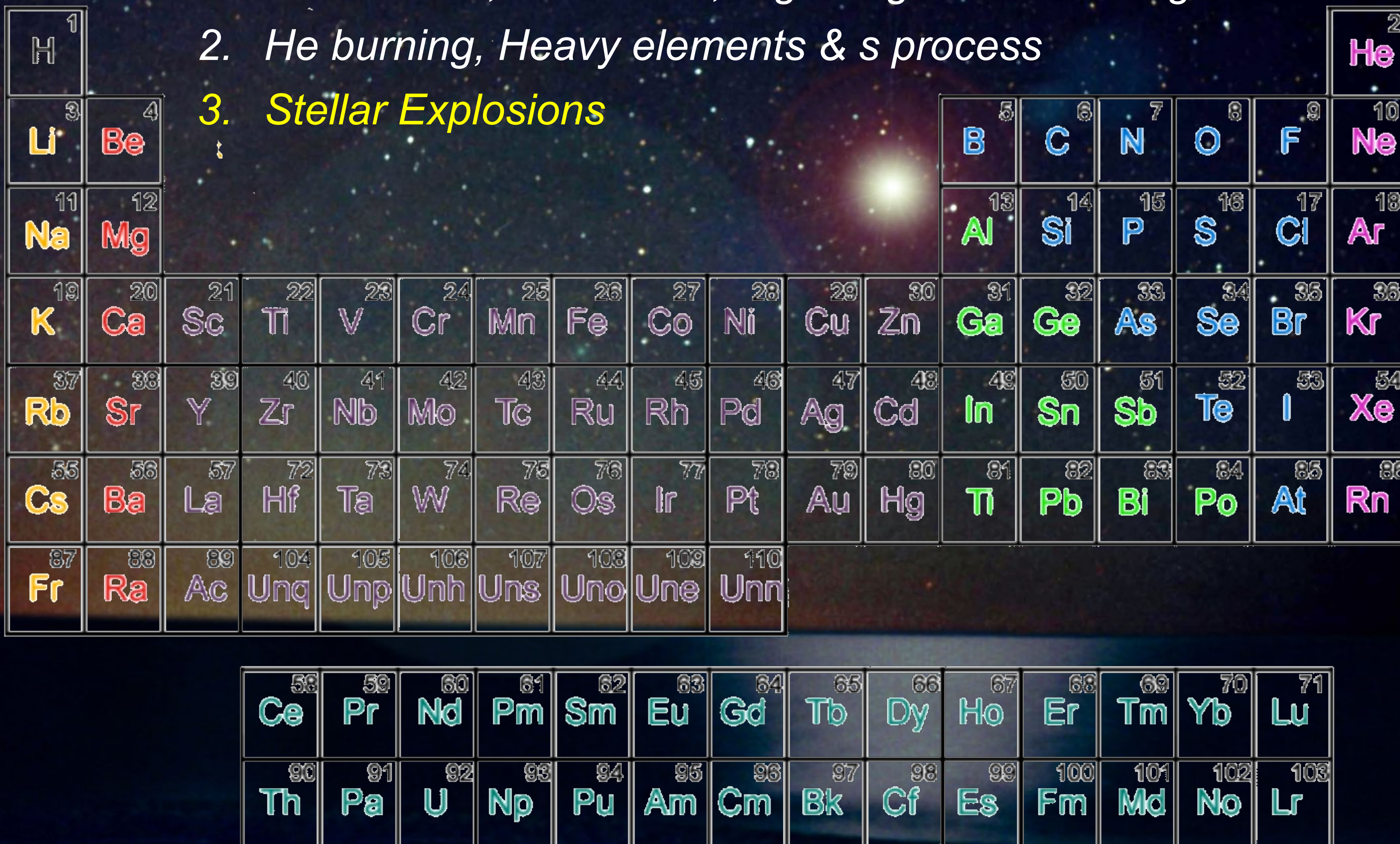
Nuclear Astrophysics

Jeff Blackmon (LSU)

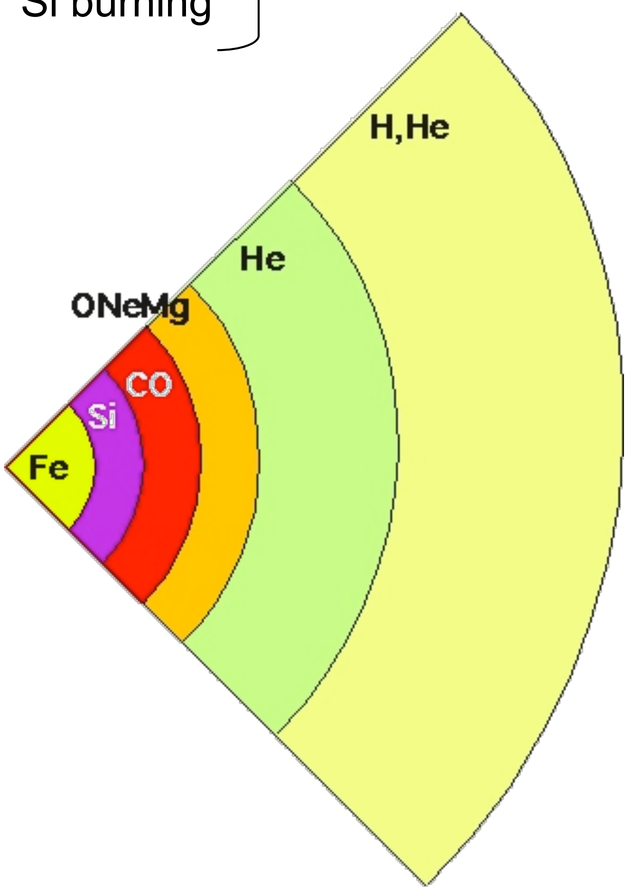
1. *Introduction, Formalism, Big Bang and H burning*
2. *He burning, Heavy elements & s process*
3. *Stellar Explosions*

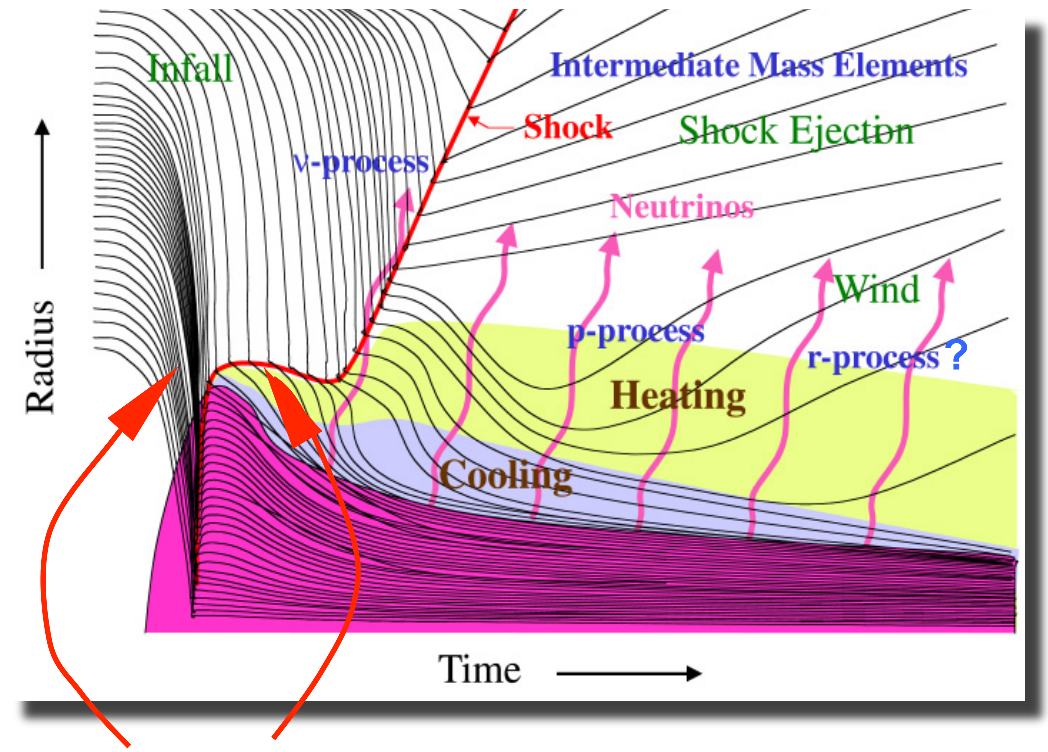


Core-Collapse Supernovae

Stars > 10 solar masses
- Higher gravity
- Faster burning stages
- Less mass loss

C burning
O burning
Si burning
} In rapid succession

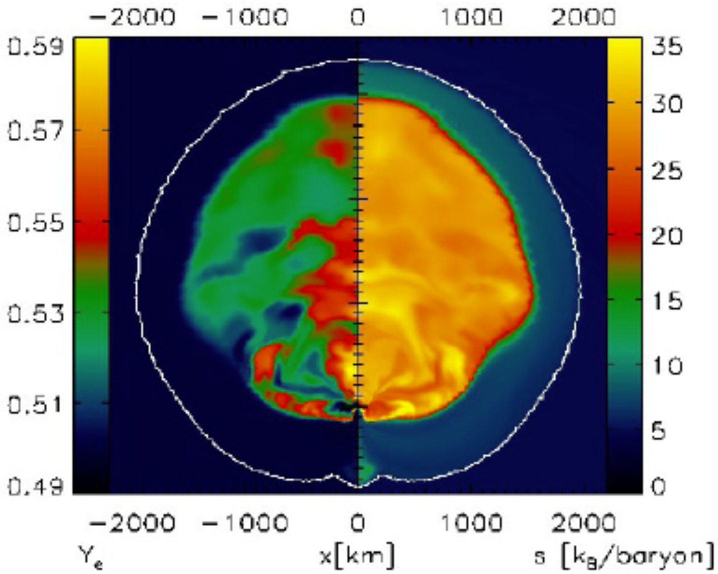




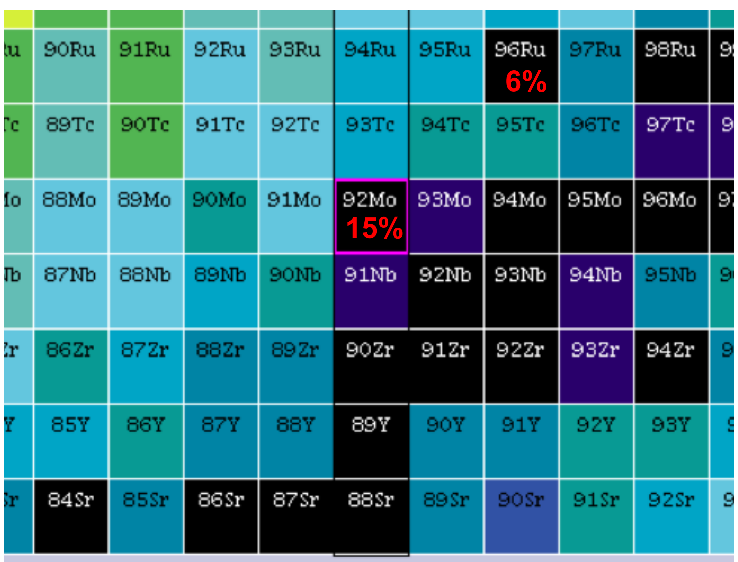
Weak interaction plays an important role

- ➢ Electron capture affects formation of shock wave.
- ➢ Neutrino interactions help drive the explosion.
- ➢ Neutrino induced reactions alter nucleosynthesis.
- ➢ Weak rates are not well understood:
  - GT strength distributions
  - First-forbidden contribution

Calculations favor ***proton-rich*** ejecta



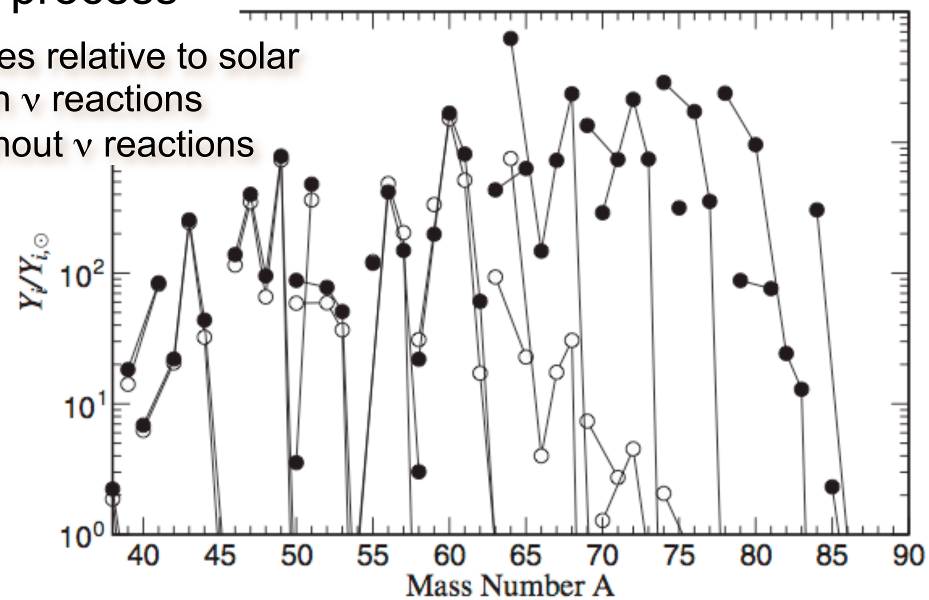
Müller, Janka et al.



- Nuclear statistical equilibrium favors production of ^{56}Ni
- Weak interactions can produce neutrons boosting masses produced
- νp process

Fröhlich *et al*., PRL (2006).

Abundaces relative to solar
- ● with ν reactions
- ○ without ν reactions



- Possible additional source for intermediate mass elements?
- Contributes to anomalous abundance of light "p" isotopes?

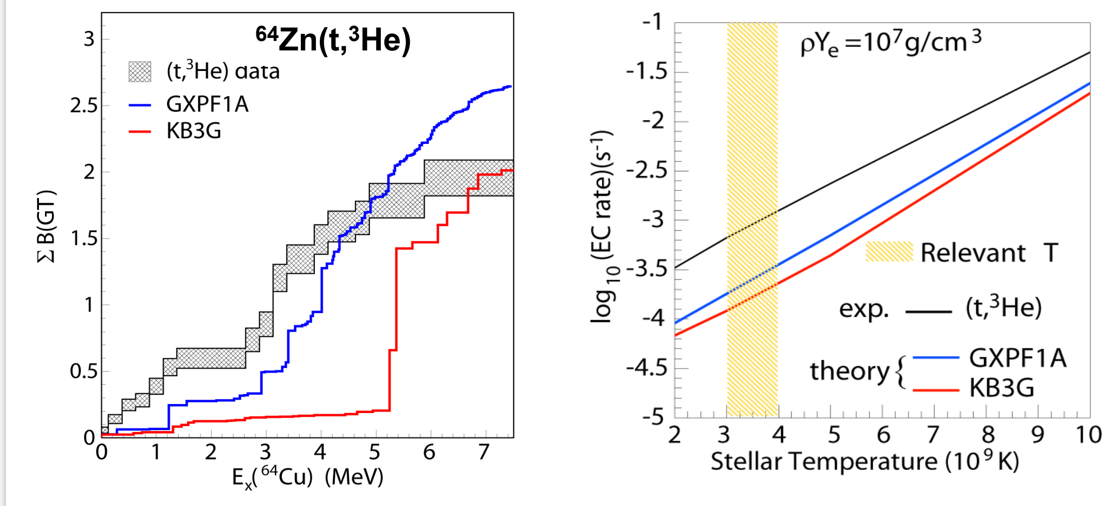
Weak interaction rates

- Great improvements in weak rates from theory (nuclear shell model calculations)

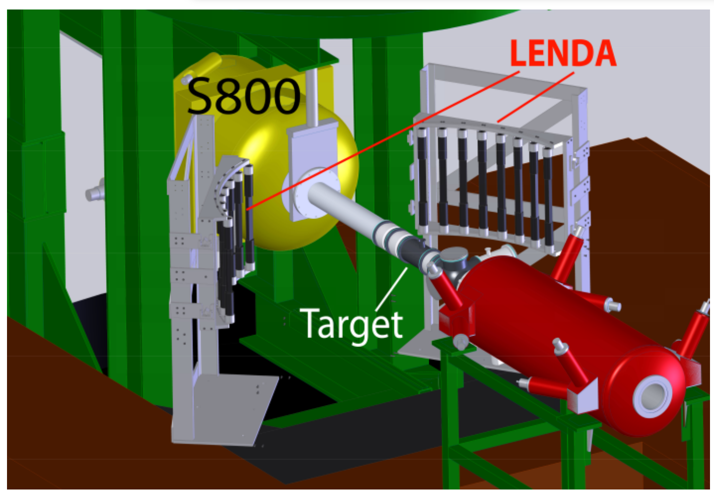
  See Langanke & Martinez-Pinedo, RMP (2003)

- Gamow-Teller strengths can be determined from charge exchange reactions
- (p,n) or (n,p) measurements test shell model predictions and effective interactions
- Some studies so far with stable nuclei

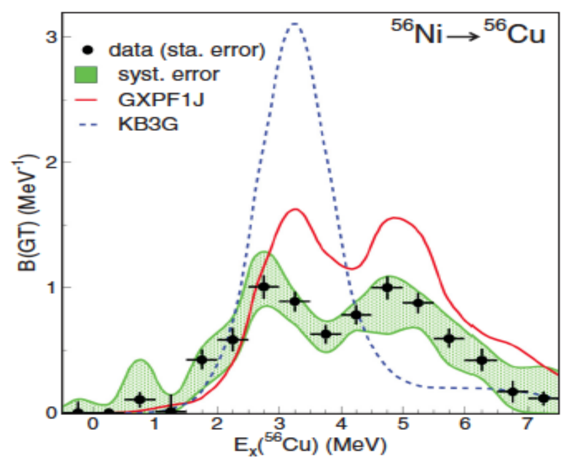
Hitt *et al.*, PRC **80** (2009).



- **First measurements now with radioactive nuclei**
- (p,n) measurements using Low-Energy Neutron Detector (LENDA) developed with the S800 and radioactive beams.

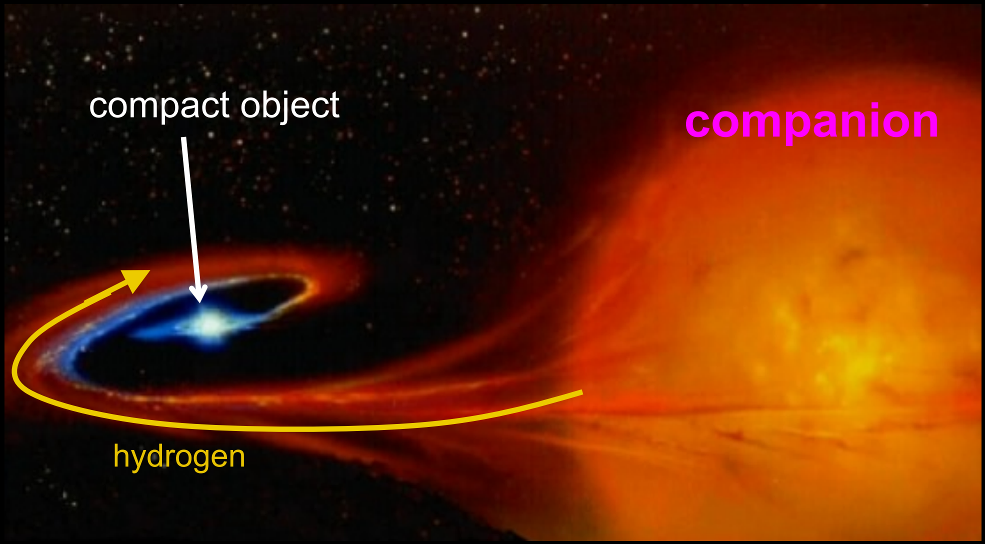


Sasano *et al.*, PRL **107** (2011).



Stellar Explosions in Binary Systems

- Most stars are in binary systems
  - Some close enough to interact (transfer mass)
- Thermonuclear explosions can occur in such systems
- Driven by nuclear reactions on stable and proton-rich nuclei
- Higher T → higher σ



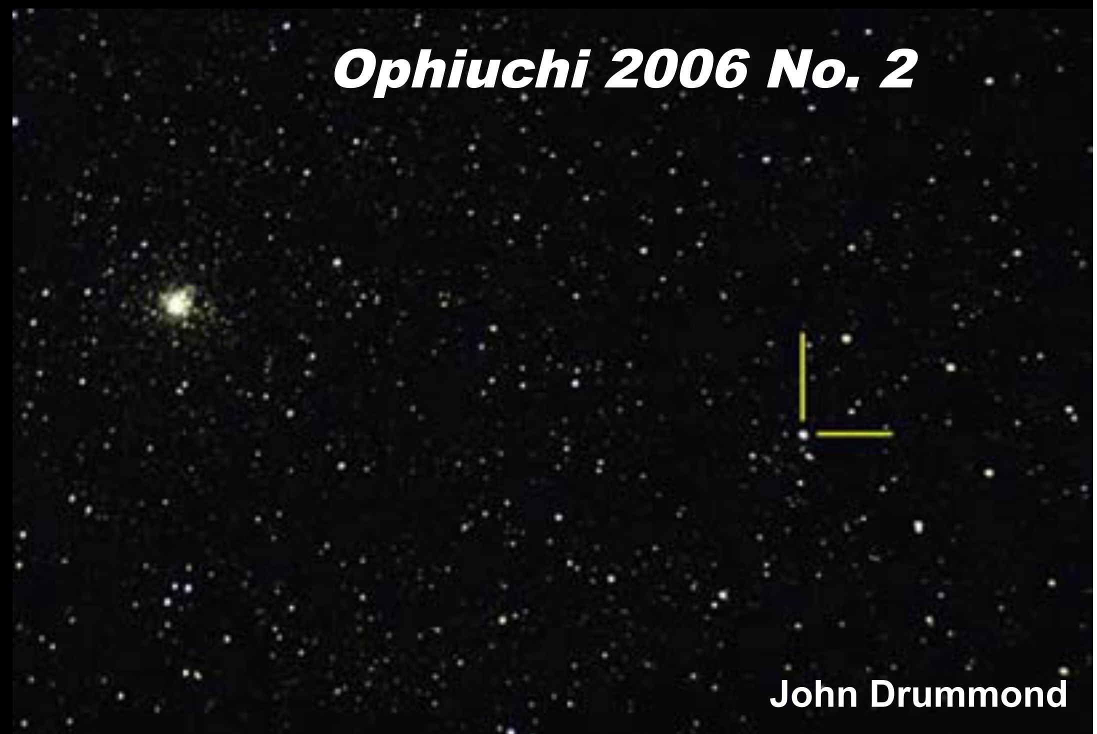
- Novae
  - White dwarf
  - ~40/yr in our Galaxy
  - Recurrance times?
- X-ray bursts
  - On surface of neutron star
  - Frequently recur (hours → days)
  - Influences evolution of system
- Type Ia Supernovae
  - White dwarf + ?
  - SD? DD? Both?!
  - Star completely destroyed
  - Fe-group production in Galaxy (late times)

Discovering Novae

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

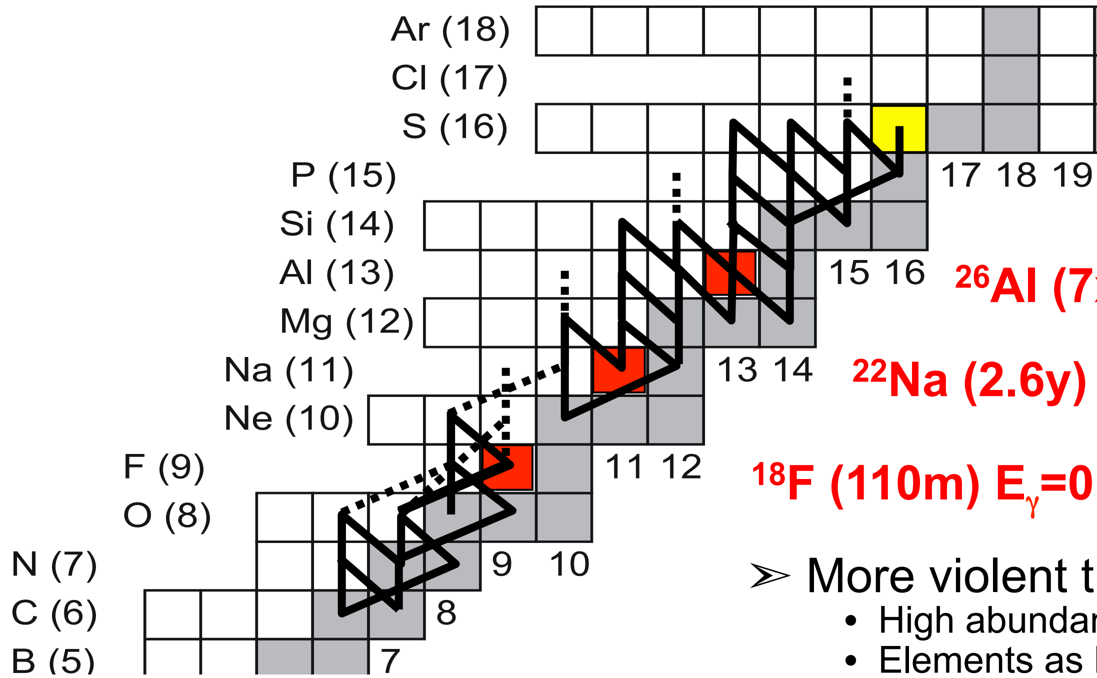
- Characterized by increase in brightness of 8-15 magnitudes (10^3-10^6 times)
  - Peak reached in < 24 h
  - Much slower decay (weeks)
  - Recur after t >1000 yr ?
  - Discovered by amateurs
  - 100's observers networking around the world
  - Usually discovered photographically

- 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)



- RS Oph is a *recurrent* novae.
  - Few observed but many more possible.
  - Distribution of recurrence times unknown

Nova nucleosynthesis



➢ Many ejecta substantially enriched in S

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

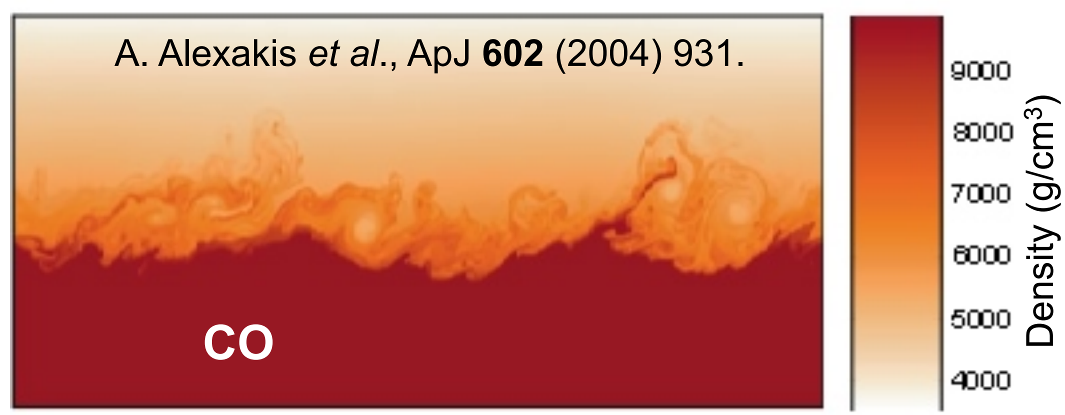
^{22}Na (2.6y) E$_{\gamma}$=1.809 MeV

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

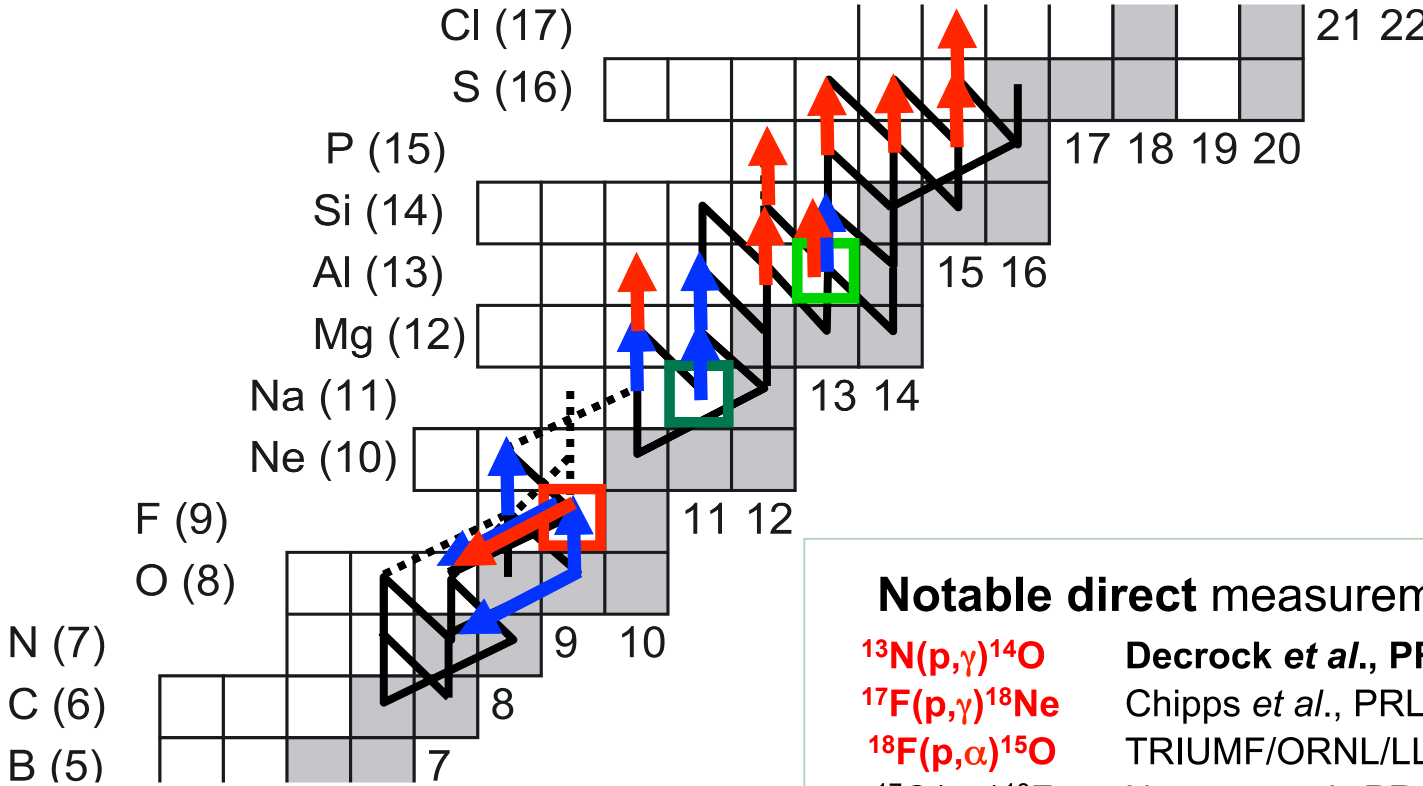
➢ More violent than expected
- High abundance of heavier elements
- Elements as heavy as sulfur
- High ejected mass

→ 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



Many nova reactions have been recently determined

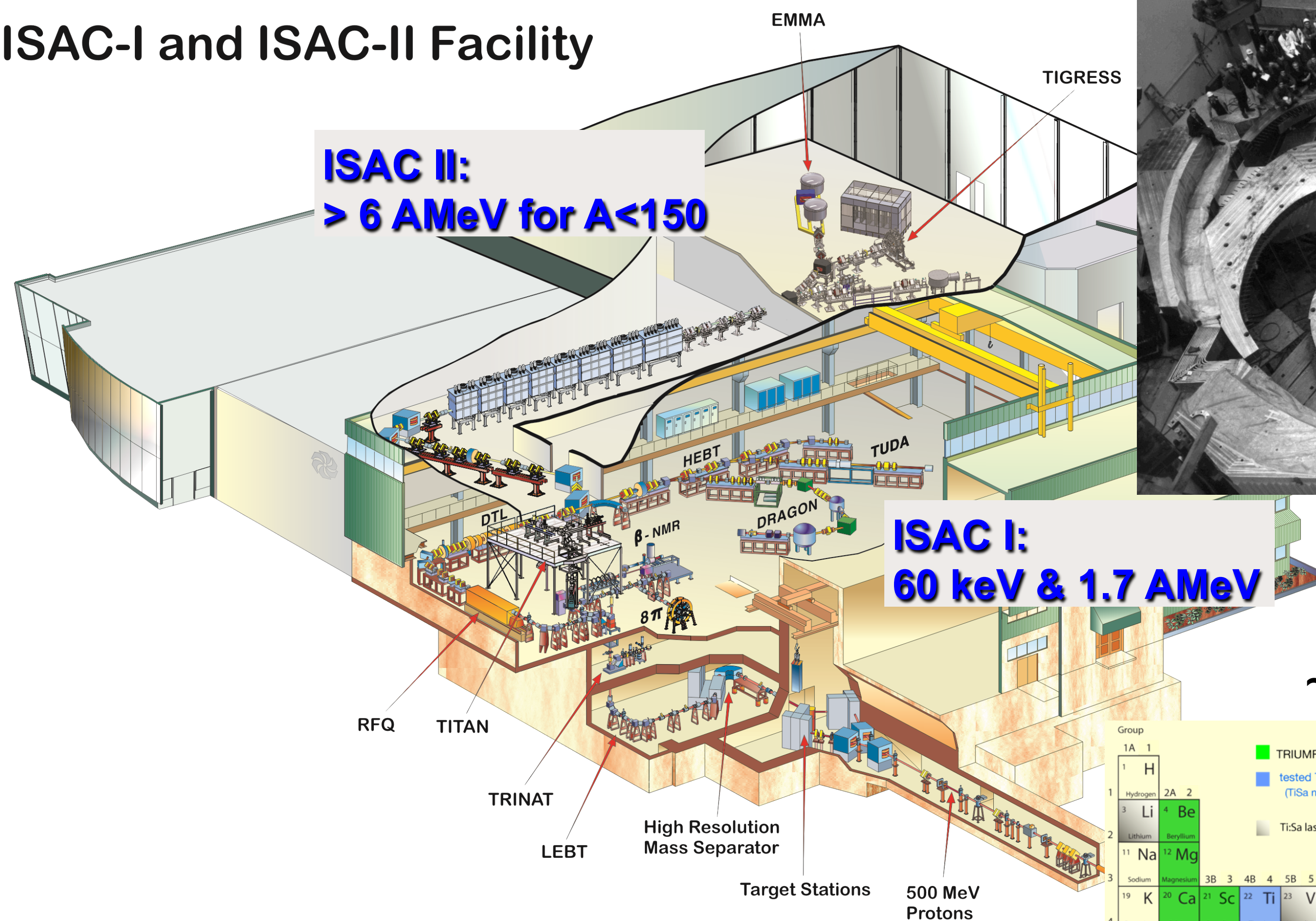


Notable direct measurements*

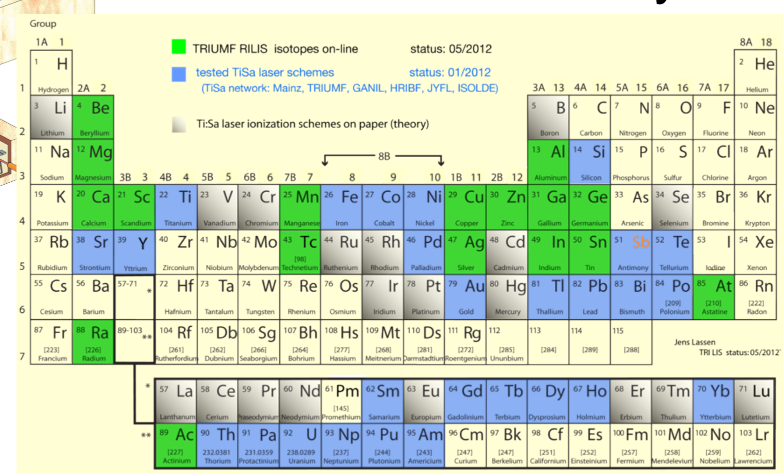
$^{13}N(p,\gamma)^{14}O$	**Decrock *et al.*, PRL (1991)**
$^{17}F(p,\gamma)^{18}Ne$	Chipps *et al.*, PRL (2009)
$^{18}F(p,\alpha)^{15}O$	TRIUMF/ORNL/LLN/ANL
$^{17}O(p,\gamma)^{18}F$	Newton *et al.*, PRC (2010).
$^{21}Na(p,\gamma)^{22}Mg$	D'Auria *et al.*, PRC (2004).
$^{22}Na(p,\gamma)^{23}Mg$	Sallaska *et al.*, PRL (2010).
$^{23}Mg(p,\gamma)^{24}Al$	Erikson *et al.*, PRC (2010).
$^{26}Al(p,\gamma)^{27}Si$	Ruiz *et al.*, PRL (2006).

Others: $^{18}F(p,\gamma)^{19}Ne$, $^{19}Ne(p,\gamma)^{20}Na$, . . .

ISAC-I and ISAC-II Facility



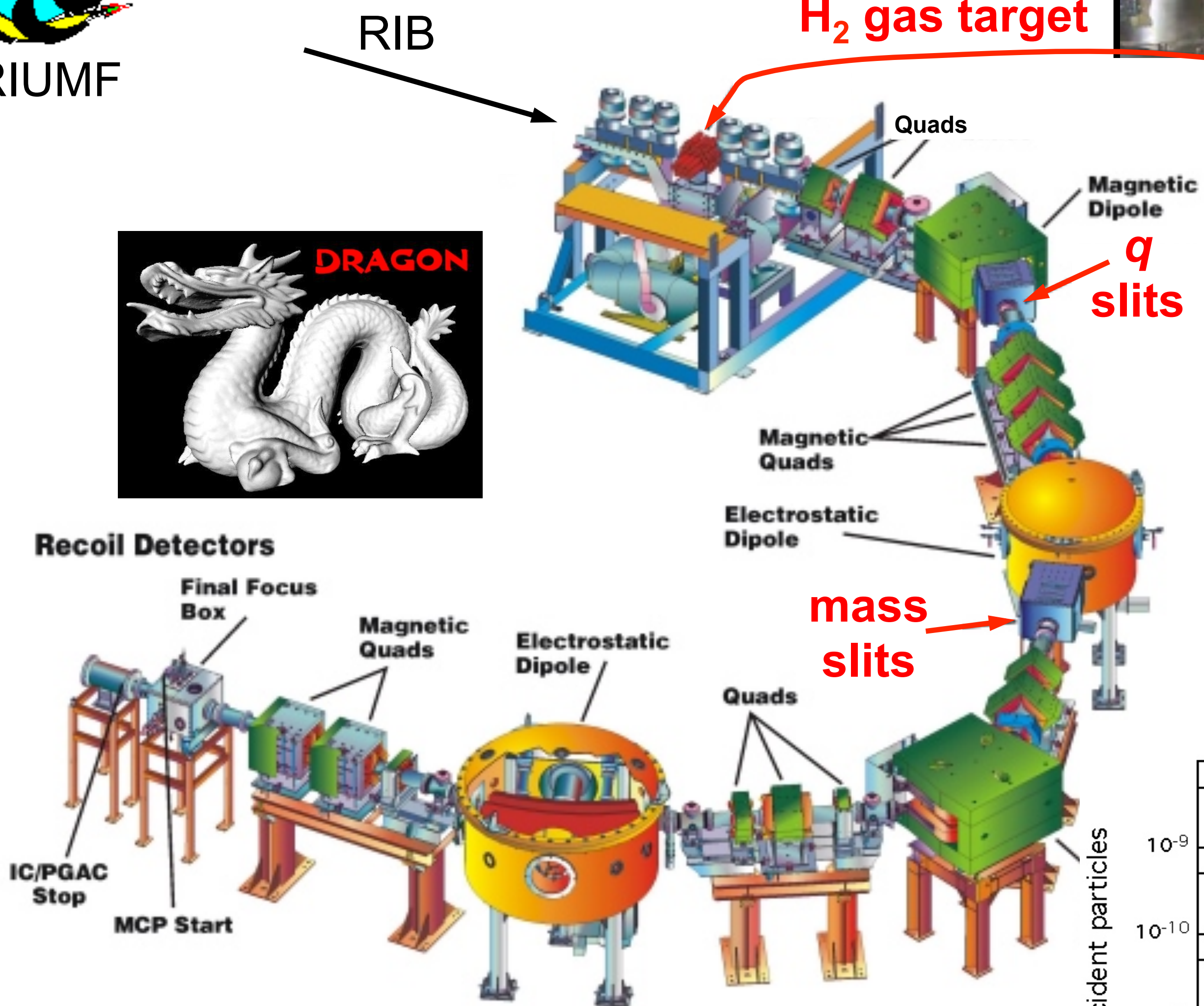
~3500 RIB hours /yr

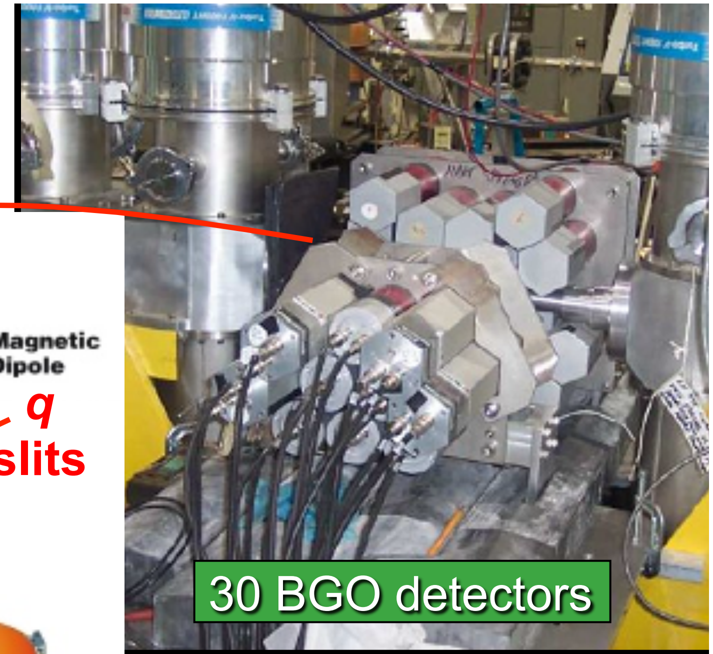


- ISOL facility with highest primary beam intensity (100 μA, 500 MeV protons)
- Now adding high intensity electron driver (ARIEL)

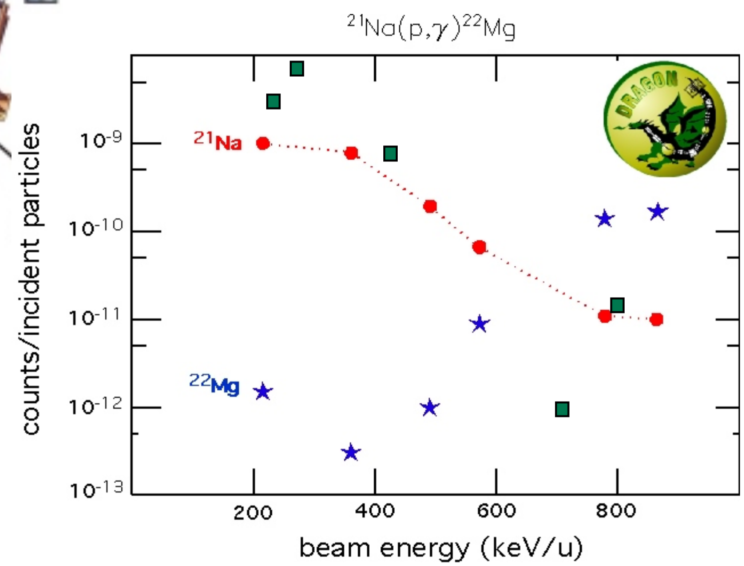
(p,γ) at ISAC

TRIUMF





recoil+γ coincidences provide sensitive selection of events



http://dragon.triumf.ca

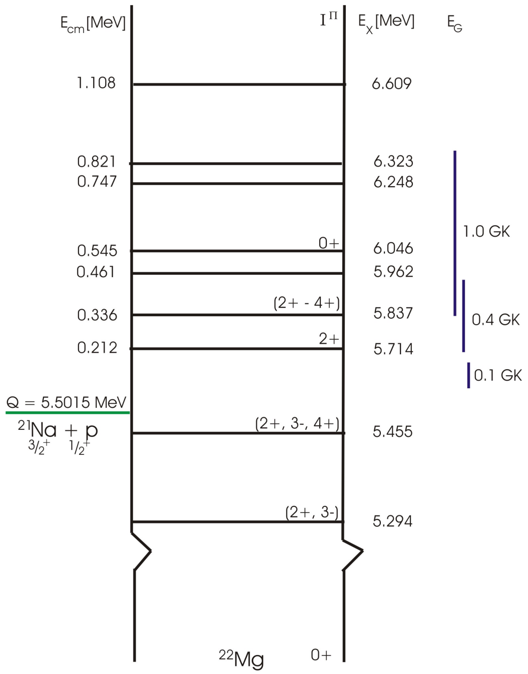
*S. Engel et al., NIM **A553** (2005) 491.*

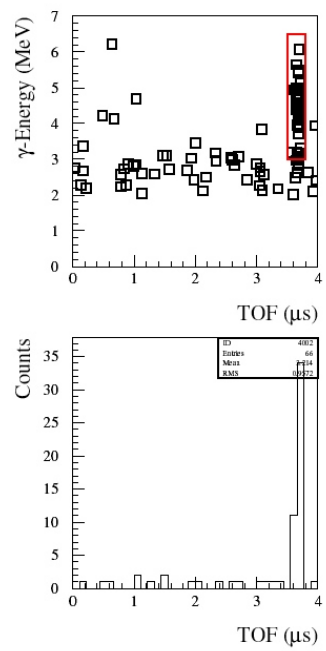
*D. A. Hutcheon et al., NIM **A498** (2003) 190.*

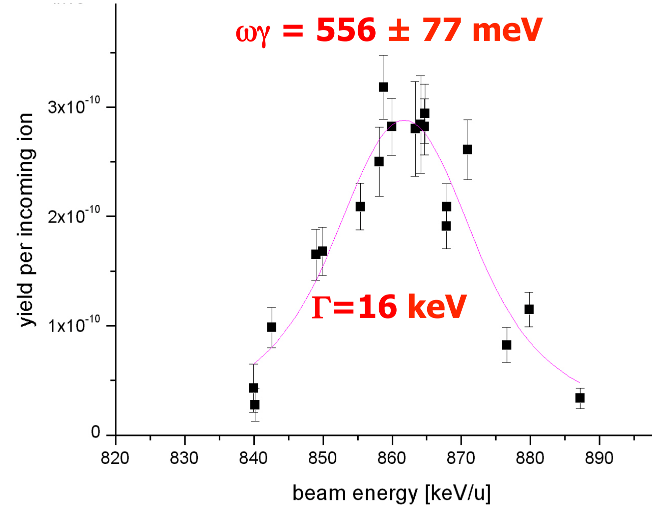
^{21}Na(p,γ)^{22}Na with DRAGON

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

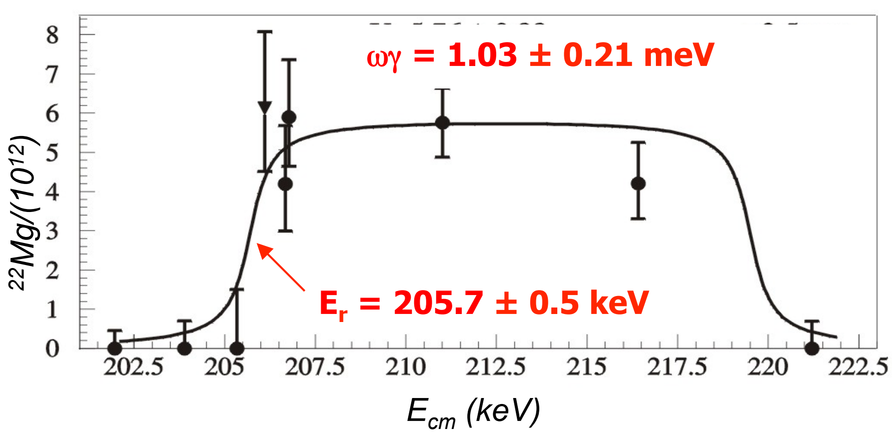
In 1999: ^{21}Na(p,γ)^{22}Mg rate uncertain by >10^5x *(Jose, Coc, Hernanz, ApJ520).)*





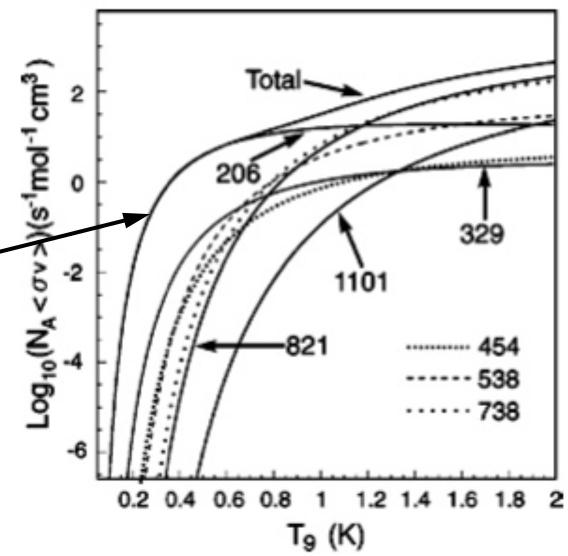


J. D'Auria et al., PRC ***69*** *(2004) 065803.*
S. Bishop et al., PRL ***90*** *(2003) 162501.*



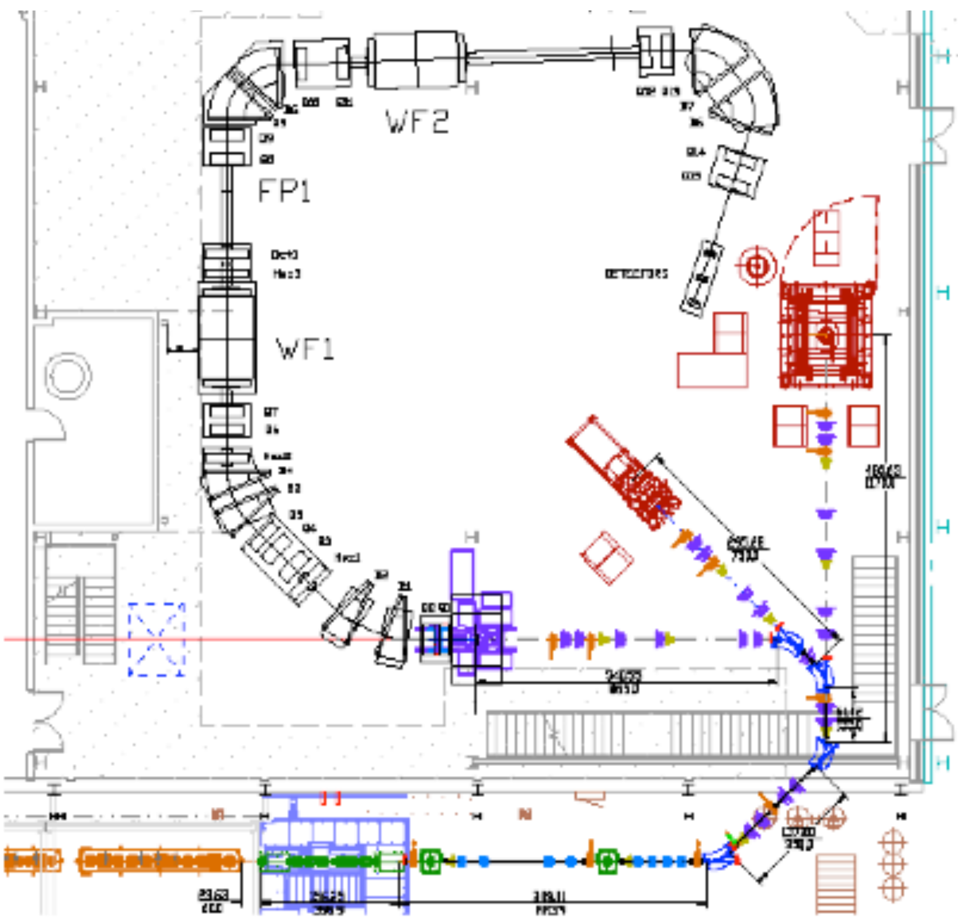
Higher rate for
206 keV
resonance
→ ~25% less
^{22}Na

Uncertainty~25%



SEparator for CApture Reactions (SECAR)

Being developed for NSCL/FRIB by MSU, Notre Dame, ORNL, LSU, Mines, . . .

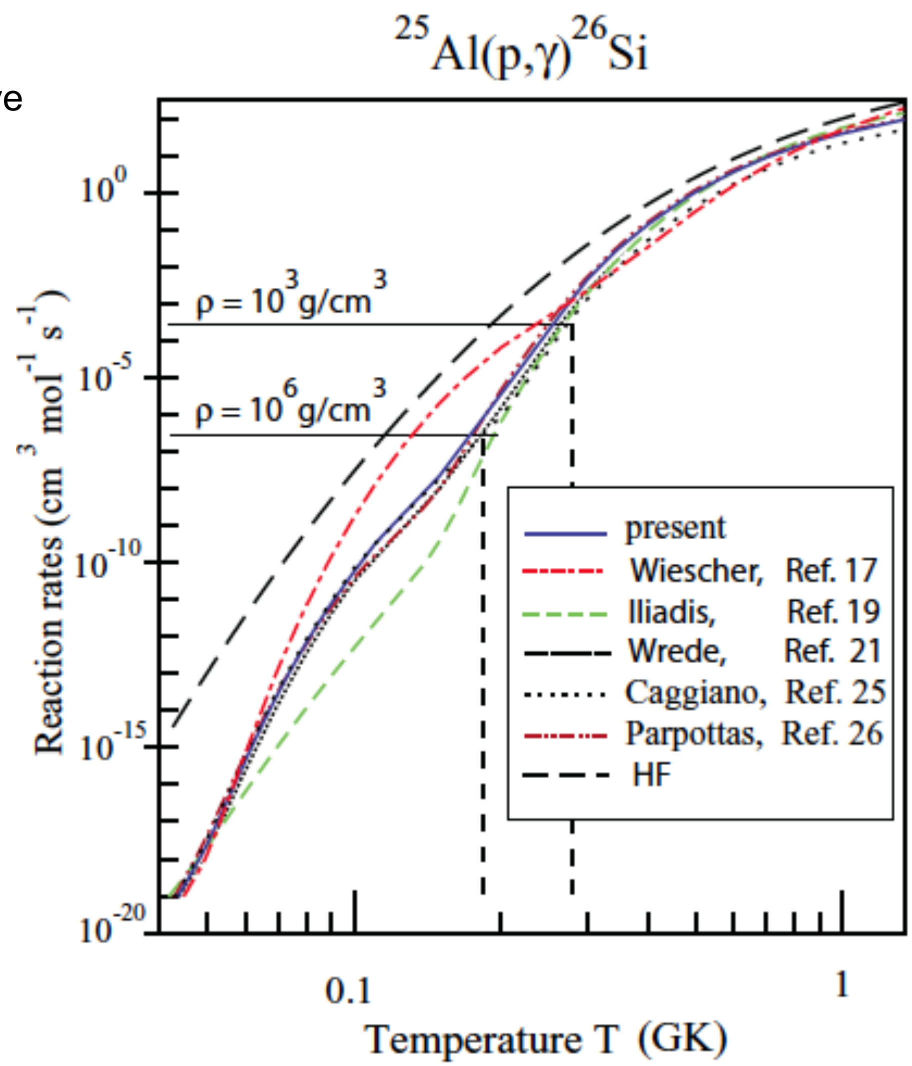


- Next-generation EM separator for direct measurements of capture reactions at ReA3/FRIB
- Two Wien filter design provides high mass resolution and suppression of scattered beam
  - Phased approach proposed that allows for initial experiments at reduced cost
  - 2^{nd} WF required for higher mass beams – to be proposed to NSF
- Long development time
  - Must start soon to be ready for initial experiments at FRIB

Indirect approaches – $^{25}Al(p,\gamma)^{26}Si$

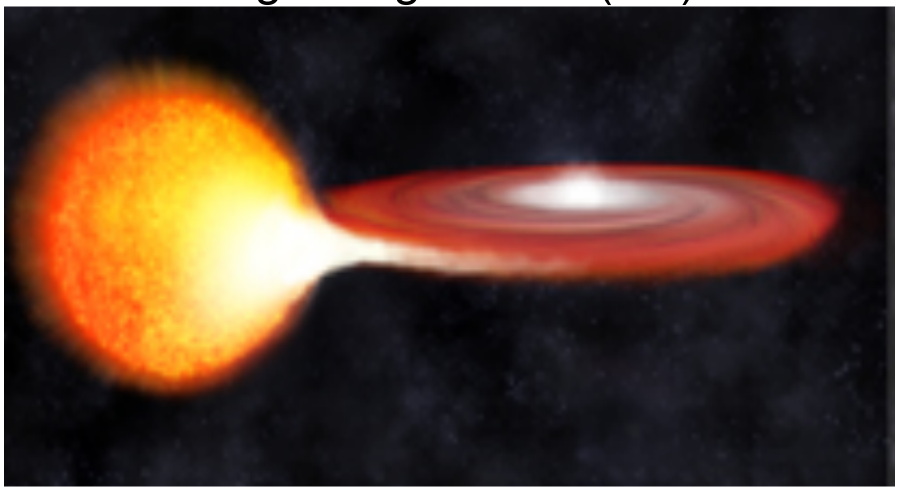
- One of most important rates for understanding ^{26}Al in novae
  - Rates depends on properties of low-lying s-wave resonances (2^+ and 3^+ states in ^{26}Si)

$^{25}Al(p,p)^{25}Al$	**Chen *et al*., PRC (2012)**
$^{27}Si(p,d)^{26}Si$	Chen *et al*., PRC (2012)
$^{28}Si(p,t)\,^{26}Si$	**Matic *et al*., PRC (2011)**
$^{28}Si(p,t)\,^{26}Si$	**Chipps *et al*., PRC (2010)**
$^{28}Si(p,t)\,^{26}Si$	**Matic *et al*., PRC (2010)**
$^{25}Al(d,n)^{26}Si$	**Peplowski *et al*., PRC (2009)**
$^{28}Si(\alpha,^{6}He)\,^{26}Si$	**Kwon *et al*., JKPS (2008)**
$^{12}C(^{16}O,2n)^{26}Si$	Seweryniak et al., PRC (2007)
$^{28}Si(p,t)^{26}Si$	**Bardayan *et al*., PRC (2006)**
$^{28}Si(p,t)^{26}Si$	**Parikh *et al*., PRC (2005)**
$^{24}Mg(^{3}He,n)^{26}Si$	**Parpottas *et al*., PRC (2004)**
$^{28}Si(p,t)^{26}Si$	**Bardayan *et al*., PRC (2002)**
$^{29}Si(^{3}He,^{6}He)^{26}Si$	Caggiano *et al*., PRC (2002)

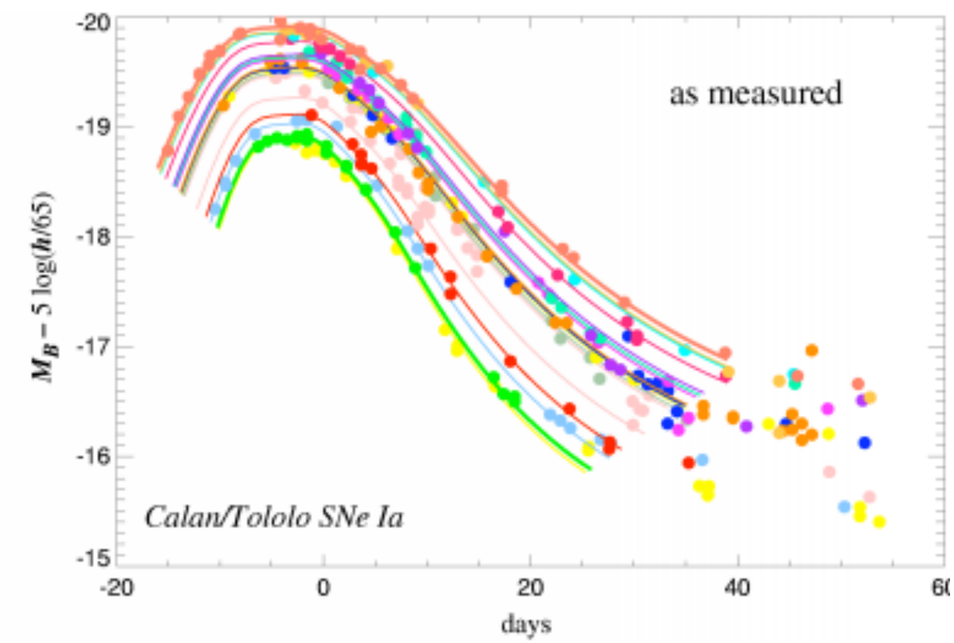


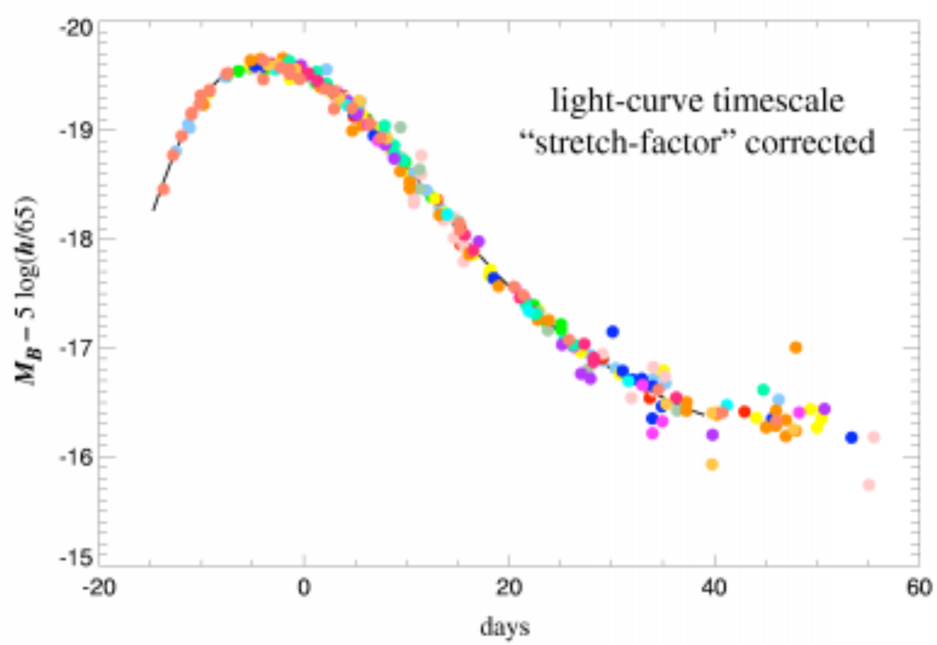
Type Ia Supernovae

Single Degenerate (SD)



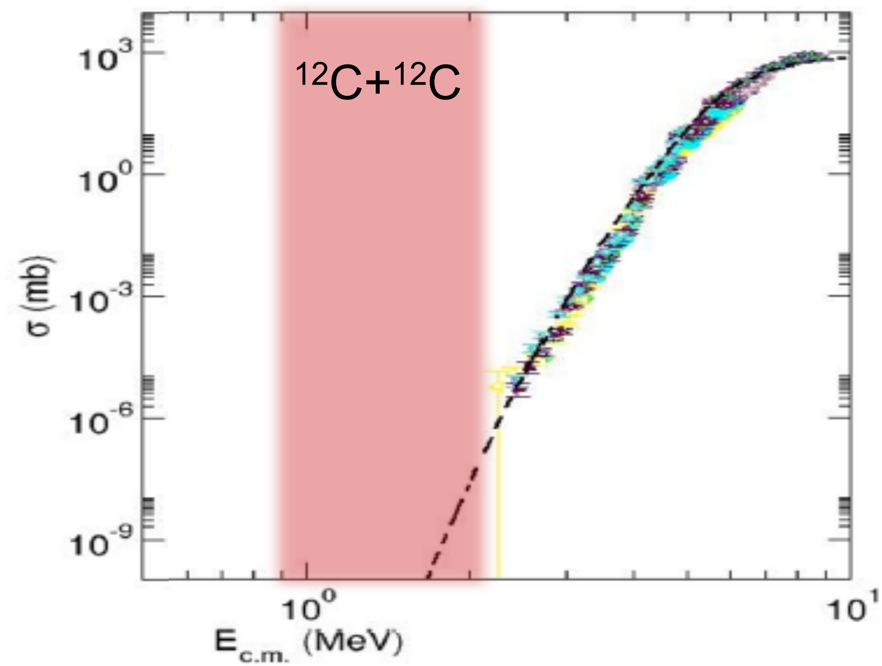
Double Degenerate (DD)

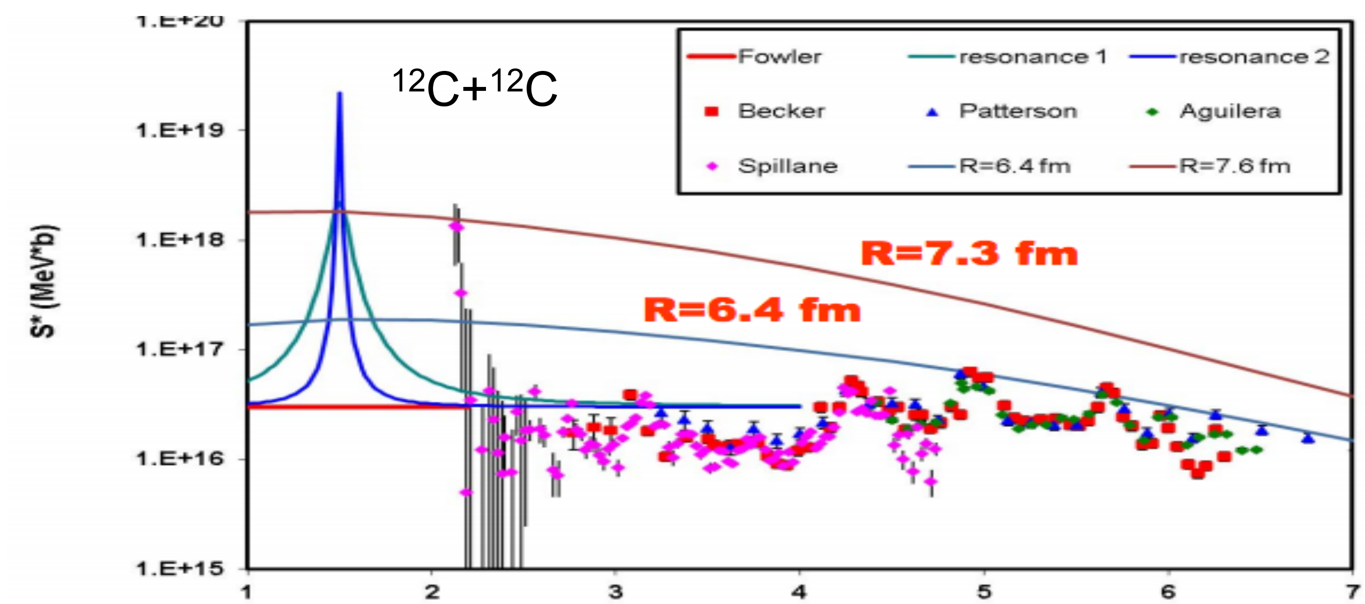




Nuclear physics of Type Ia

- ➢ Most important nuclear physics is fusion of C,O, Ne nuclei
  - ➢$^{12}C+^{12}C \rightarrow$
  - ➢$^{12}C+^{16}O \rightarrow$
- ➢Measurements needed to lower energies
- ➢Resonances could contribute in a few cases

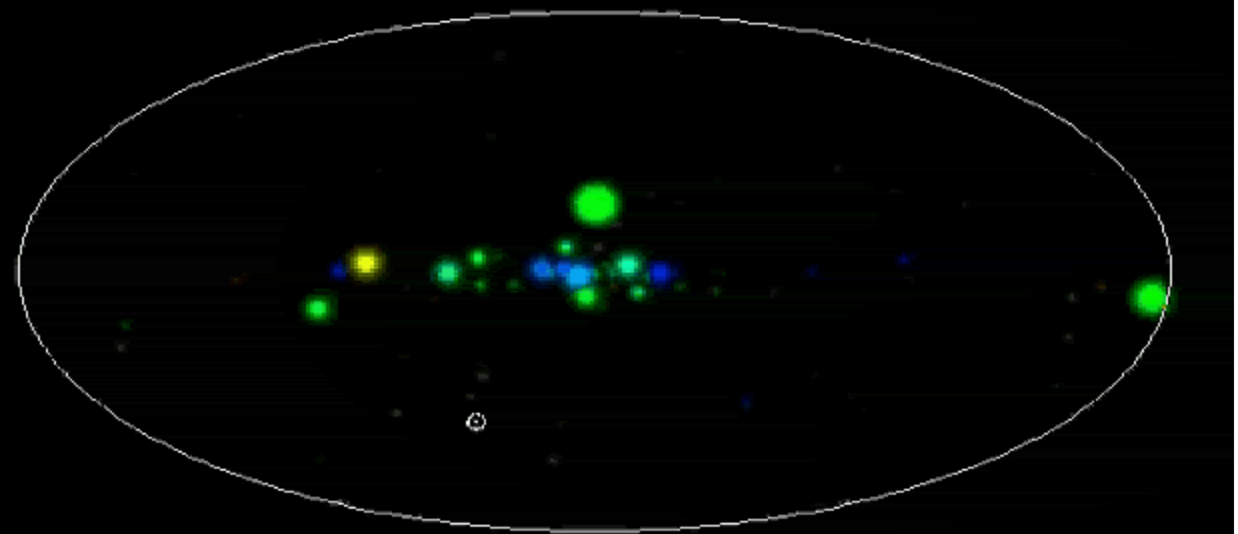




X-ray vision

RXTE
Rossi X-ray Timing Explorer

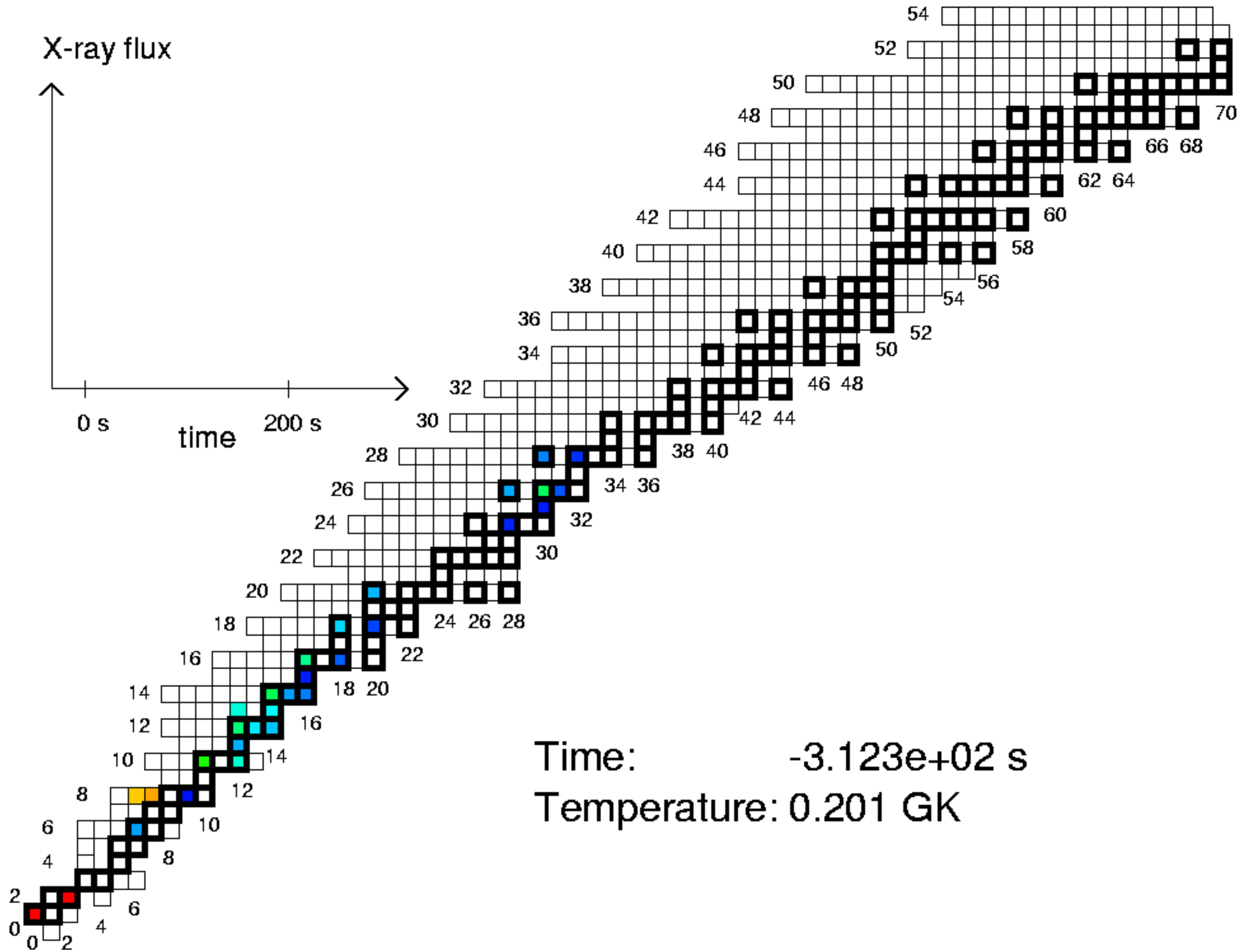
The RXTE All-Sky Monitor Movie



02 / 23 / 2004

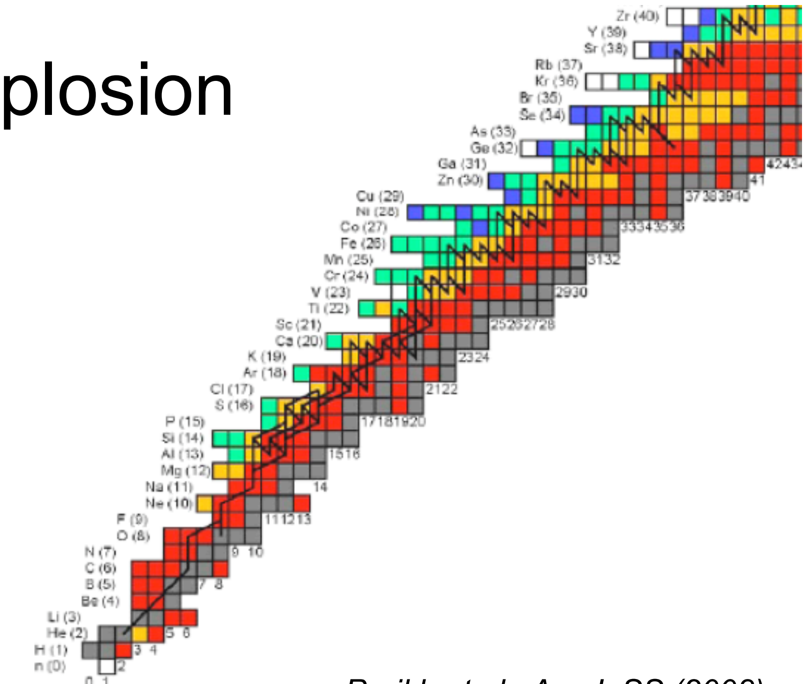
http://heasarc.gsfc.nasa.gov/xte_weather/

- 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 flux
time
0 s
200 s
Time: -3.123e+02 s
Temperature: 0.201 GK

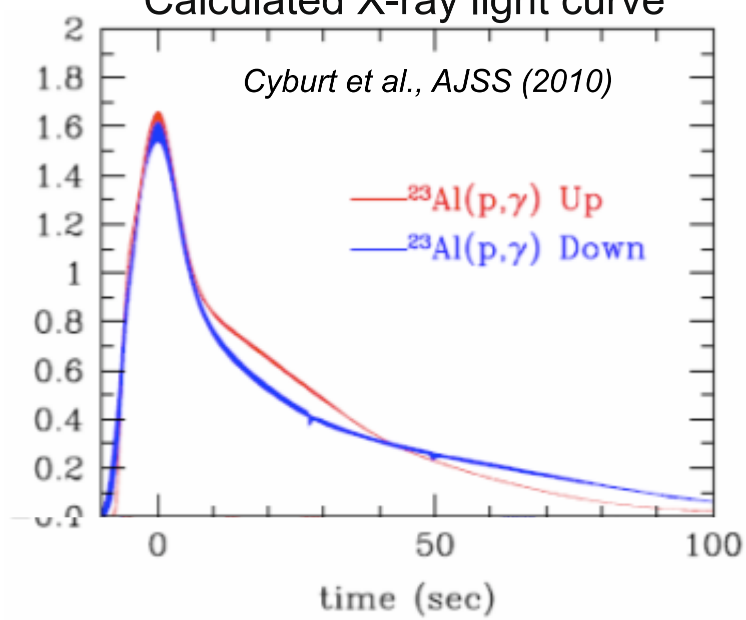
Nuclear reactions drive explosion

- Reaction rates are crucial
  - ***Thermonuclear* events**
  - Energy generation (light curve)
  - Abundances (spectra)
  - Evolution of system
  - (p,γ) and (α,p) reactions w/ large uncertainties
- Not all reactions are equally important
  - Sensitivity studies help to identify reactions that are likely most important
  - Caveat: Depends on assumptions of astrophysical model



Parikh et al., Ap. J. SS (2008)

Calculated X-ray light curve



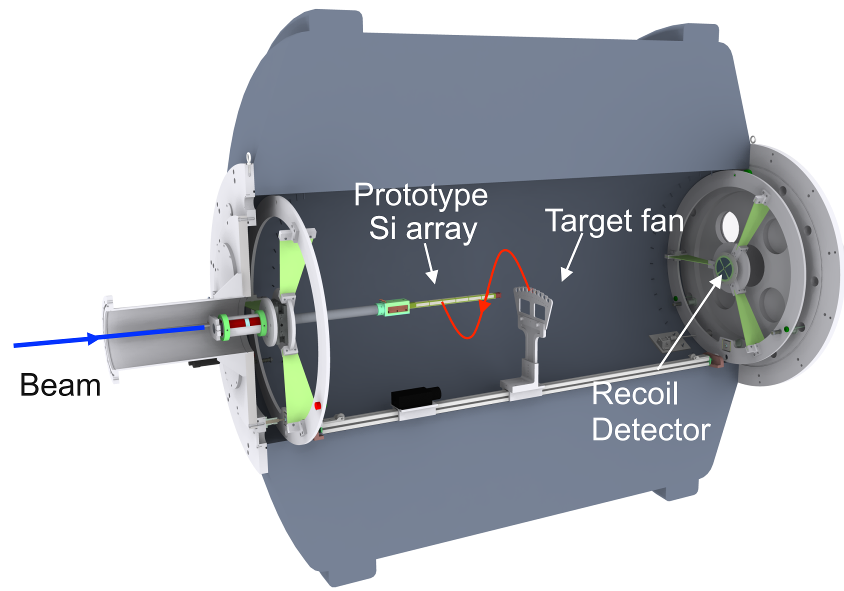
Reaction	Models affected
^{15}O(α, γ)^{19}Ne[a]	K04, K04-B1, K04-B6
^{18}Ne(α, p)^{21}Na[a]	K04-B1, K04-B6
^{22}Mg(α, p)^{25}Al	F08
^{23}Al(p, γ)^{24}Si	K04-B1
^{24}Mg(α, p)^{27}Al[a]	K04-B2
^{26g}Al(p, γ)^{27}Si[a]	F08
^{28}Si(α, p)^{31}P[a]	K04-B4
^{30}S(α, p)^{33}Cl	K04-B4, K04-B5
^{31}Cl(p, γ)^{32}Ar	K04-B3
^{32}S(α, p)^{35}Cl	K04-B2
^{35}Cl(p, γ)^{36}Ar[a]	K04-B2
^{56}Ni(α, p)^{59}Cu	S01
^{59}Cu(p, γ)^{60}Zn	S01
[illegible]	[illegible]

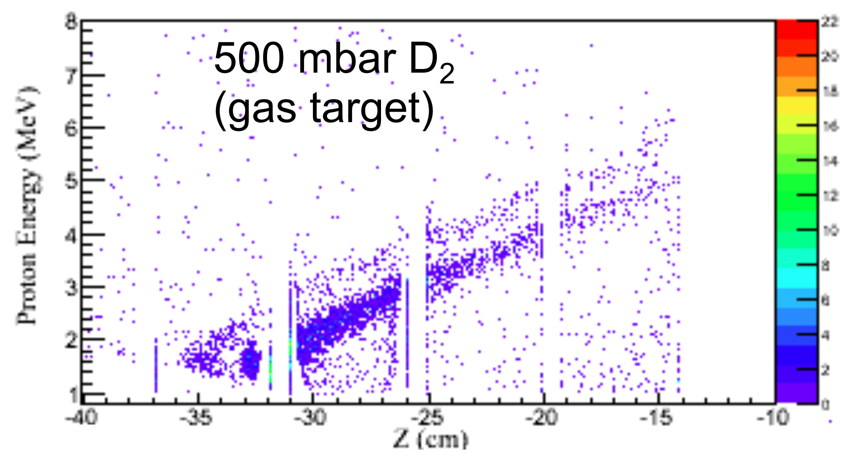
Direct Studies of (α,*p*) Reactions

- (α,*p*) reactions can be studied directly:
  - radioactive ion beams
  - ^{4}He gas target
  - inverse kinematics techniques

- HELIOS with in-flight beams at ANL
  - gas target
  - high rate ionization chamber for coincidence measurement

- ^{14}C(*d*,*p*)^{15}C commissioning run with full setup:

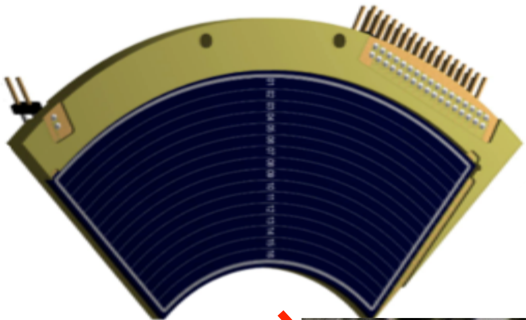




NSF MRI

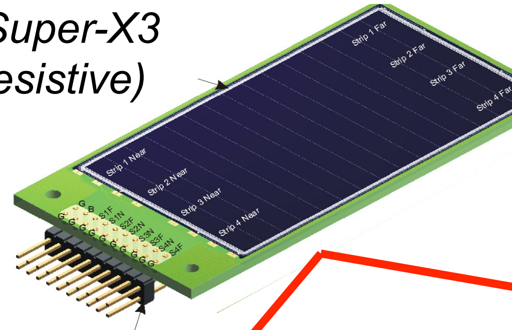
(α,p) with active gas target

Array for Nuclear Astrophysics and Structure with Exotic Nuclei

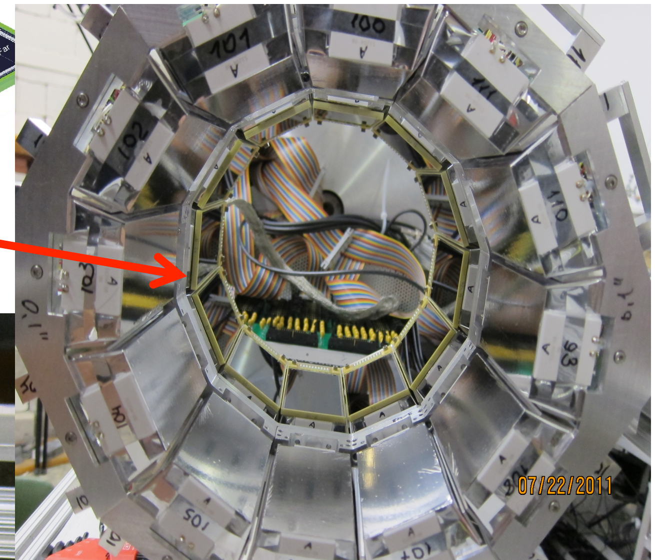


New QQQ (16x16)

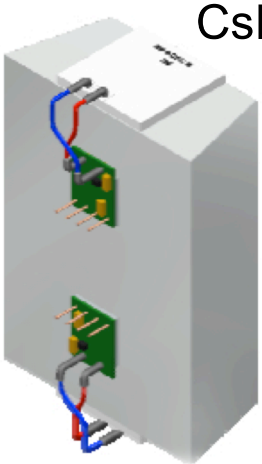
2x12 Super-X3 (4x4Resistive)

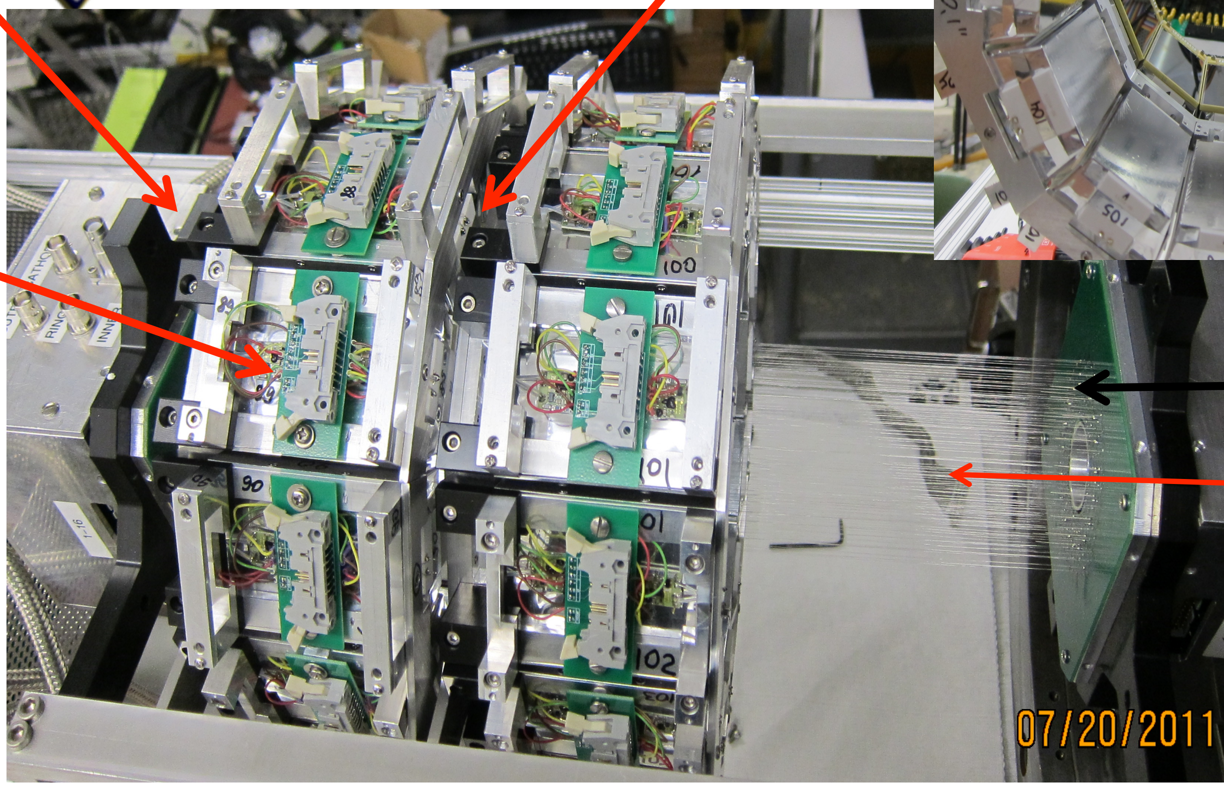


End View w/o PC



CsI





PC wires

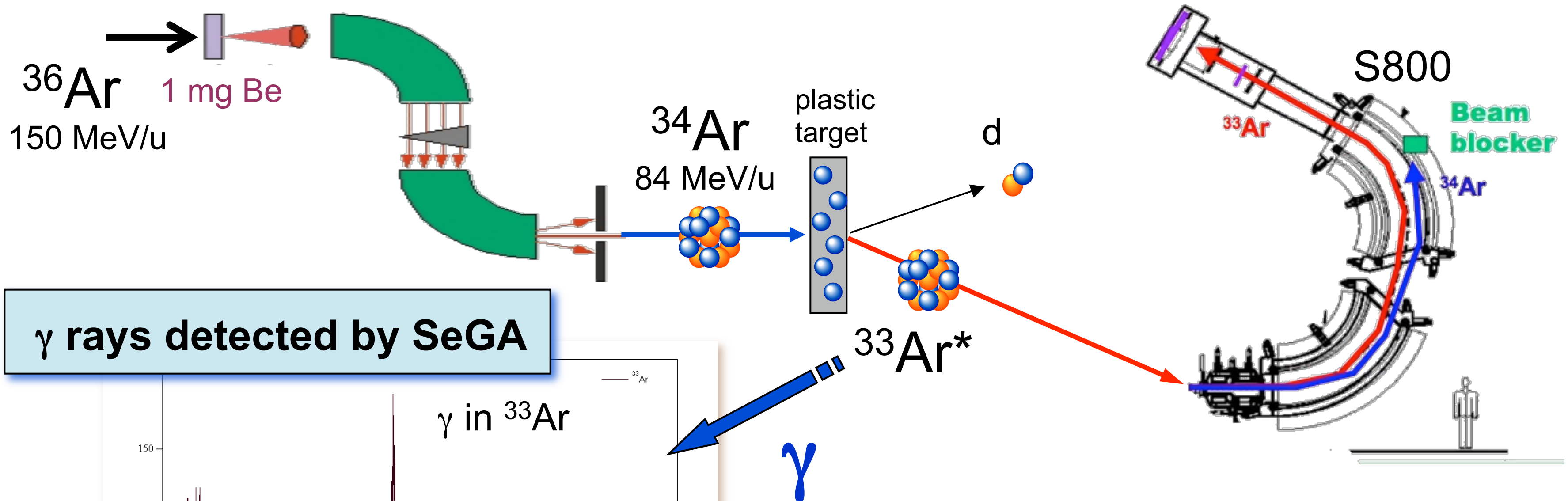
Beam

window

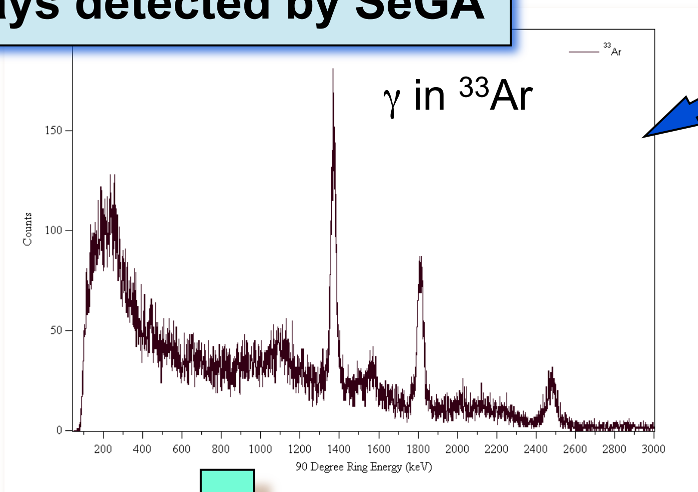
Side View

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

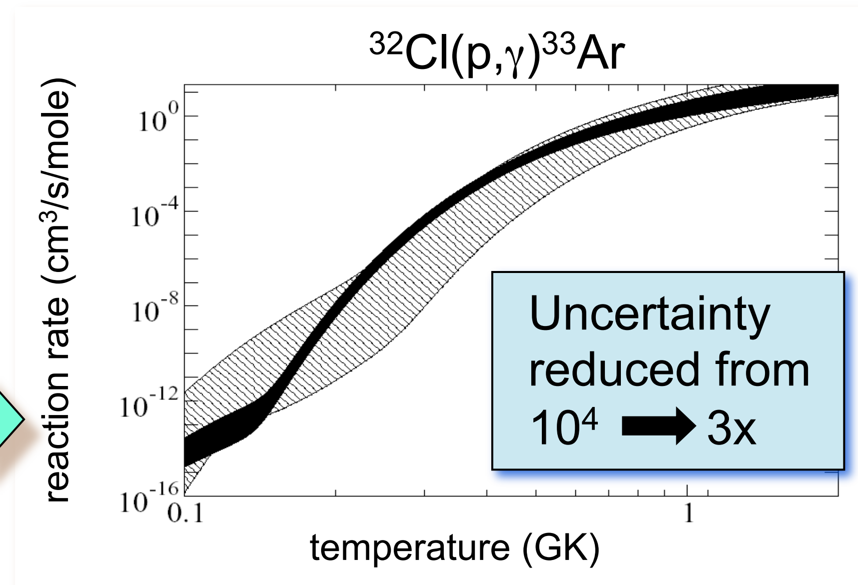
Resonance energies via (p,d) reactions & fast beams at NSCL



γ rays detected by SeGA



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



Uncertainty reduced from 10^4 ➡ 3x

Conclusion

Nuclear physics is central to answering some challenging questions related to astrophysics:

- What are the origins of the heavy elements?
- What are the progenitors of Type Ia supernovae?
- What is the mechanism involved in core collapse supernovae?
- What is the evolution of interacting binary systems?
- What are the properties of neutron stars?

New nuclear data and astrophysical observations are the keys to solving these cosmic questions