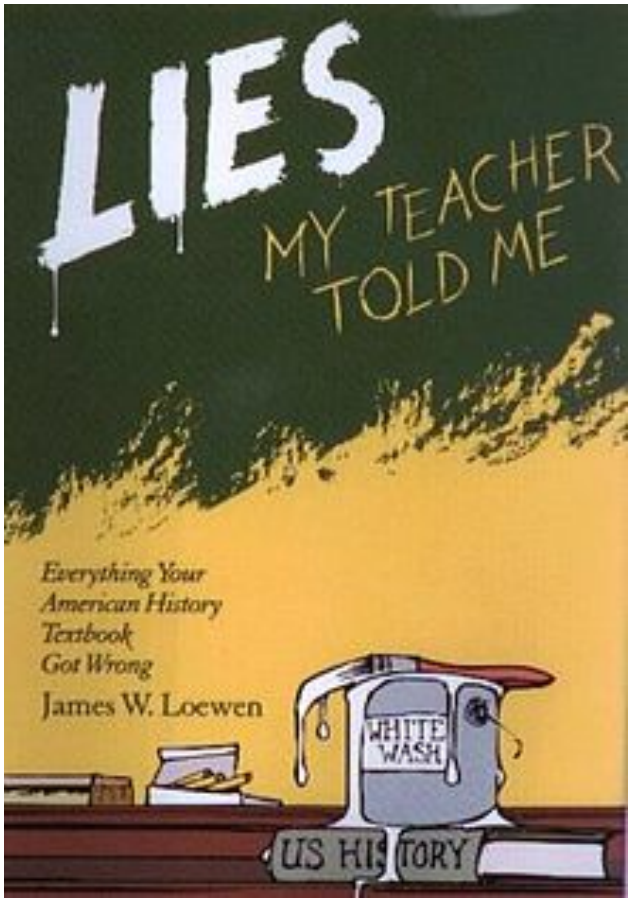
Progress and Challenges in Understanding Nuclear Reactions in Astrophysical Environments

Jeff Blackmon, Louisiana State University

There has recently been progress in many areas:

- Hydrogen Burning
- Helium Burning
- Carbon burning and Type Ia
- Novae
- X-ray bursts
- Weak interactions
- Decay properties
- Masses
- p process

But significant challenges remain

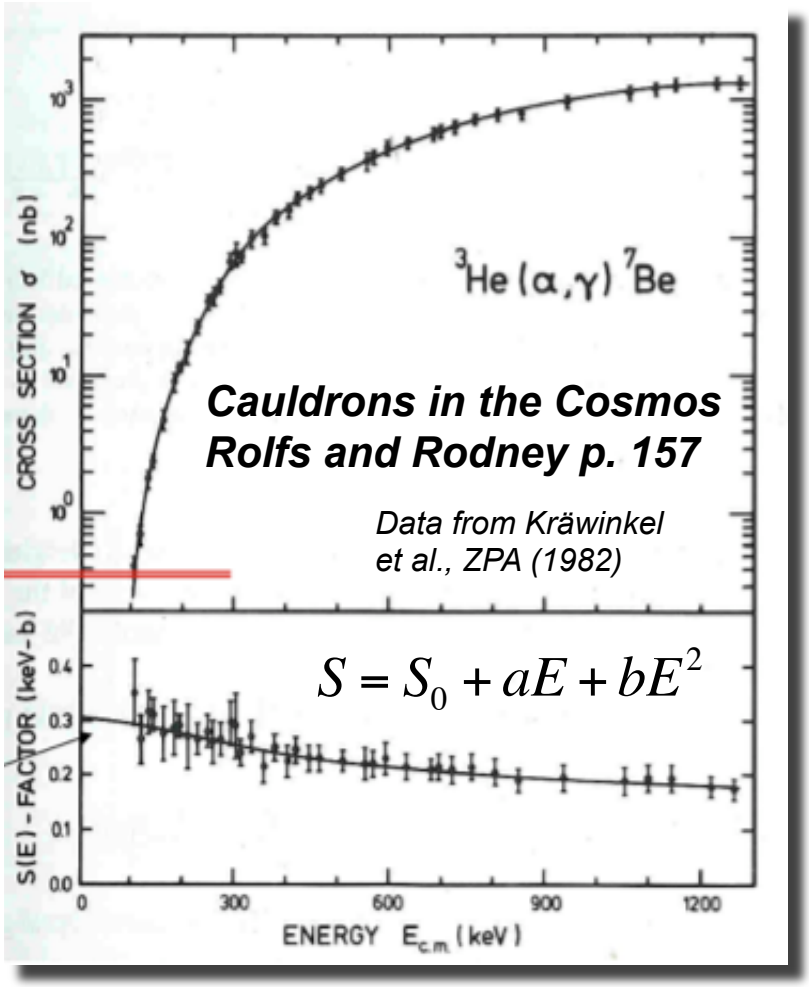


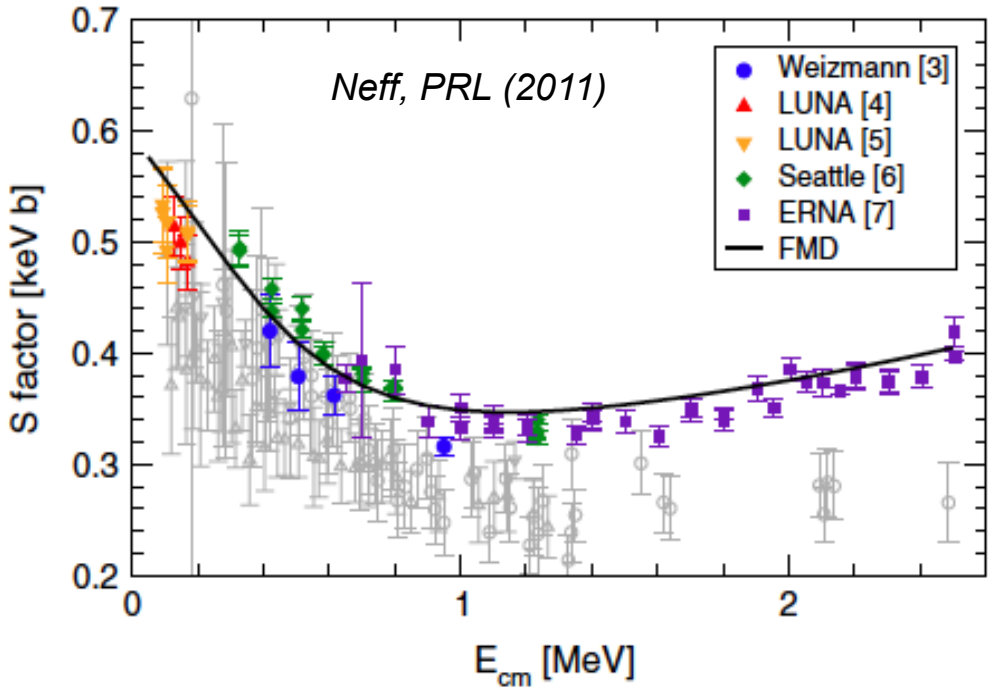
Globular clusters form from a SSP.

Type Ia SN are standard candles.

The r process occurs in core-collapse supernovae.

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

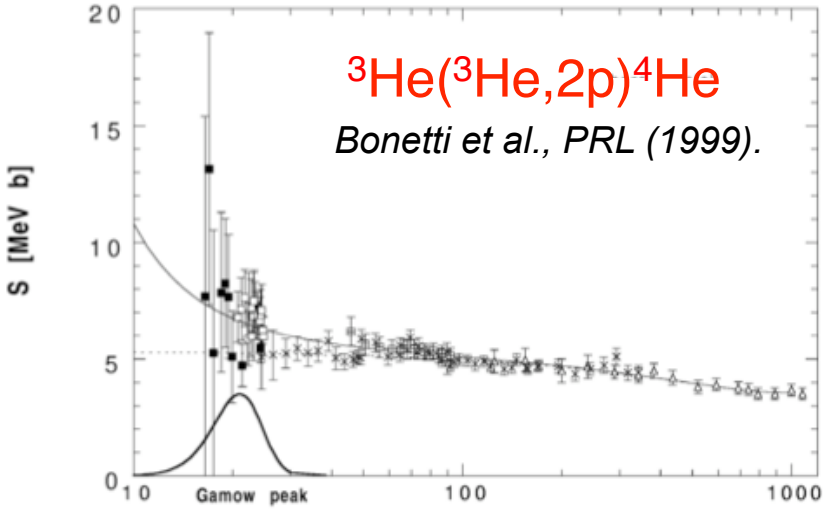


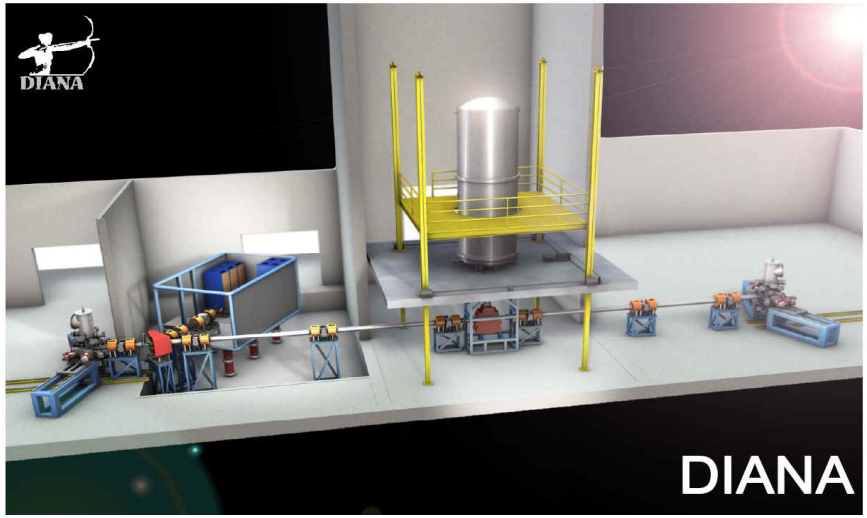


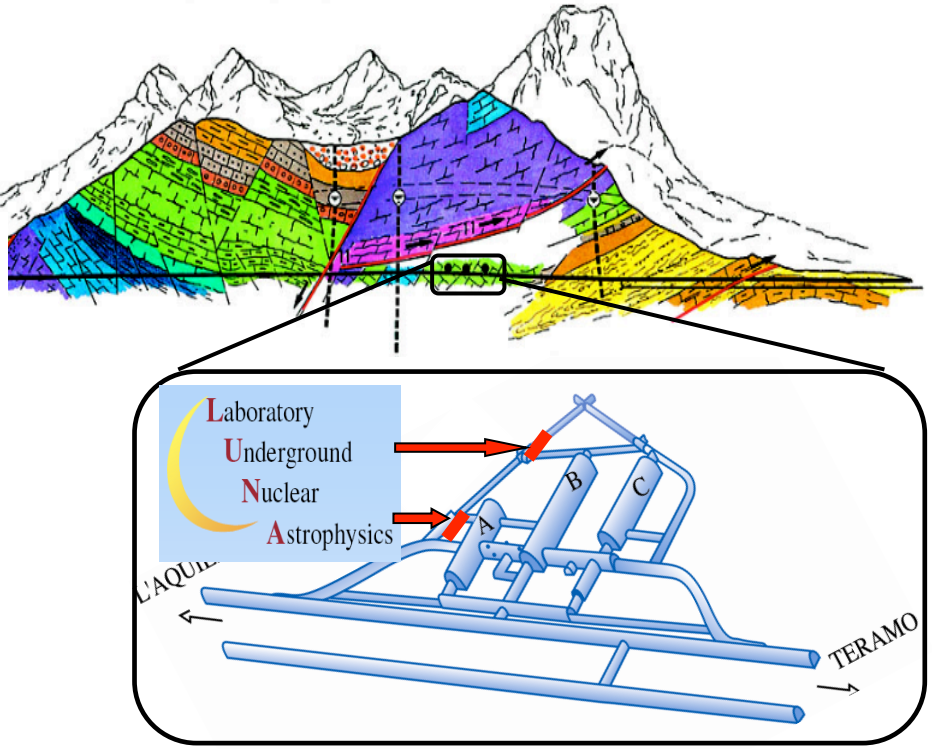
- Measurements using *complementary techniques* over a broad energy range are crucial
- Microscopic calculations are a new paradigm

Low Energies

First measurement at stellar energies







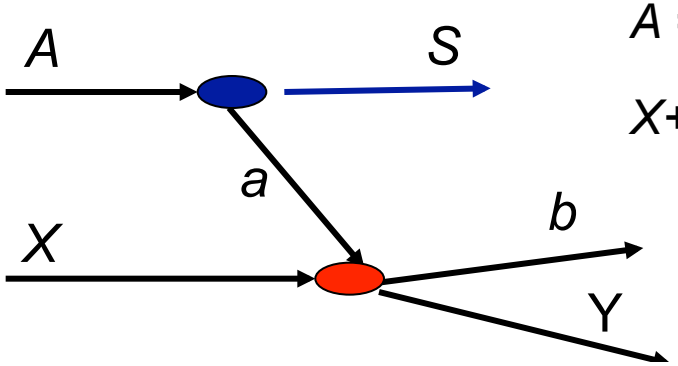
Imbriani – Recent results (Wednesday)

Strieder – LUNA-MV (this afternoon)

Still only a few measurements in Gamow window

- DIANA now under development in U.S.
- Site selection just completed (SURF)

Complementary techniques

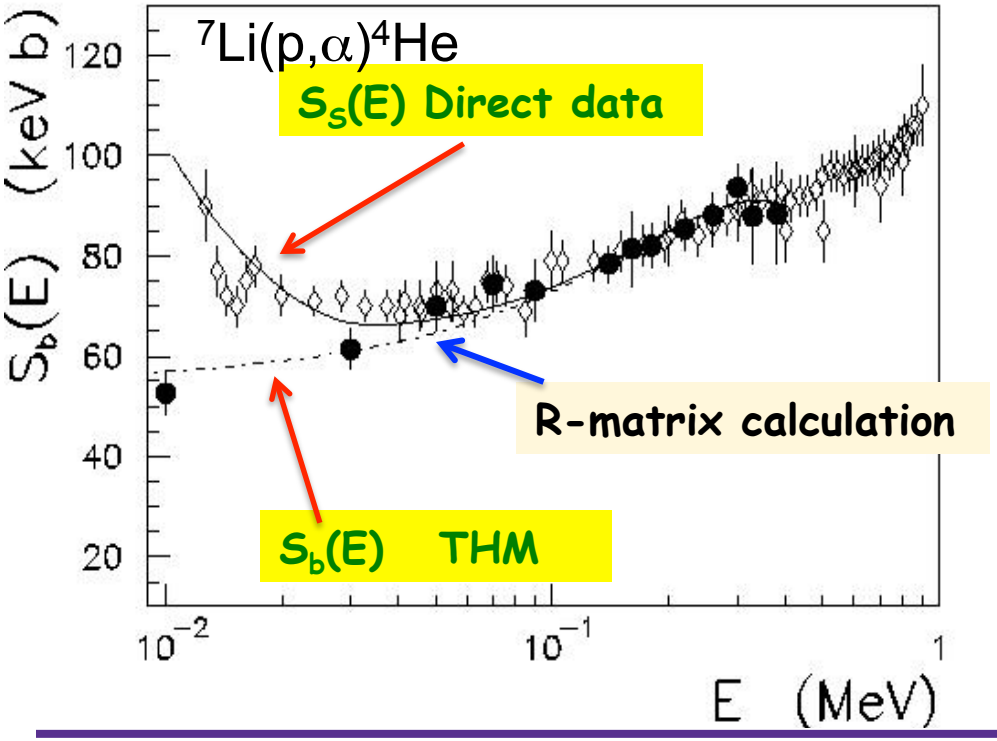


$A = S+a$

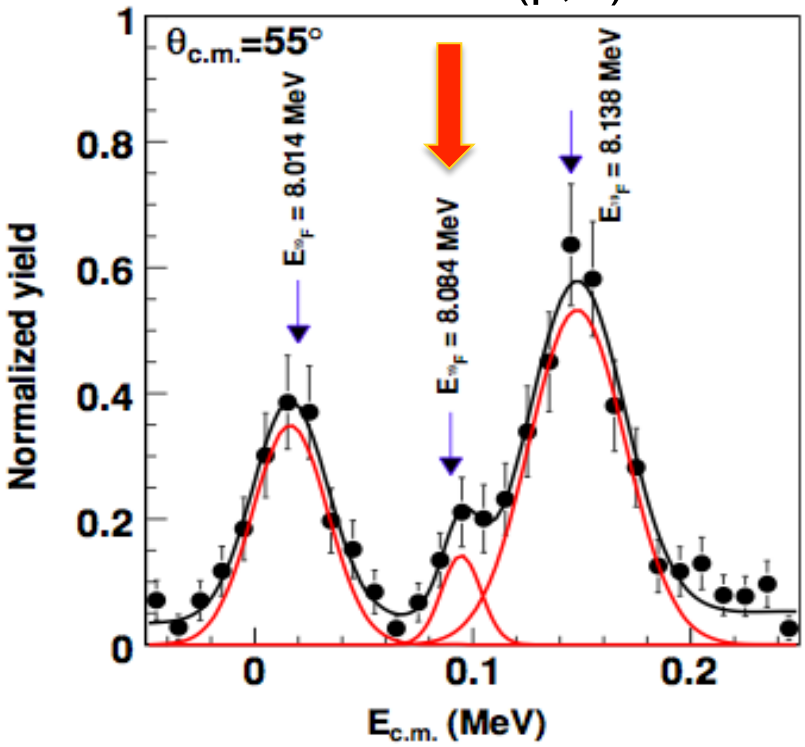
$X+A \rightarrow Y+b+S$ with $\vec{p}_A \approx \vec{p}_S$

3 body final state
Phase space cuts select low momentum transfer to spectator

"Trojan Horse"
See Cognata
(this afternoon)



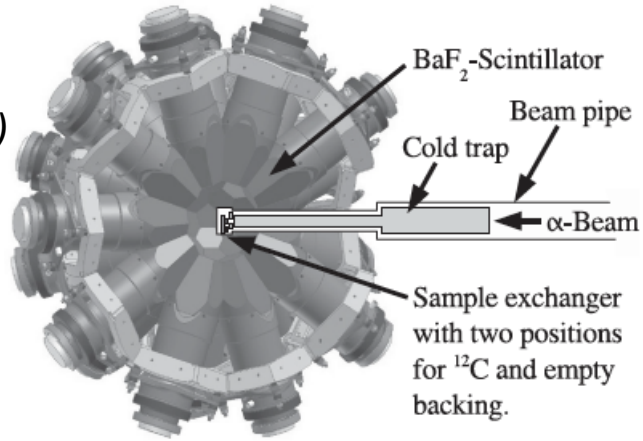
^{18}O(p,α)^{15}N

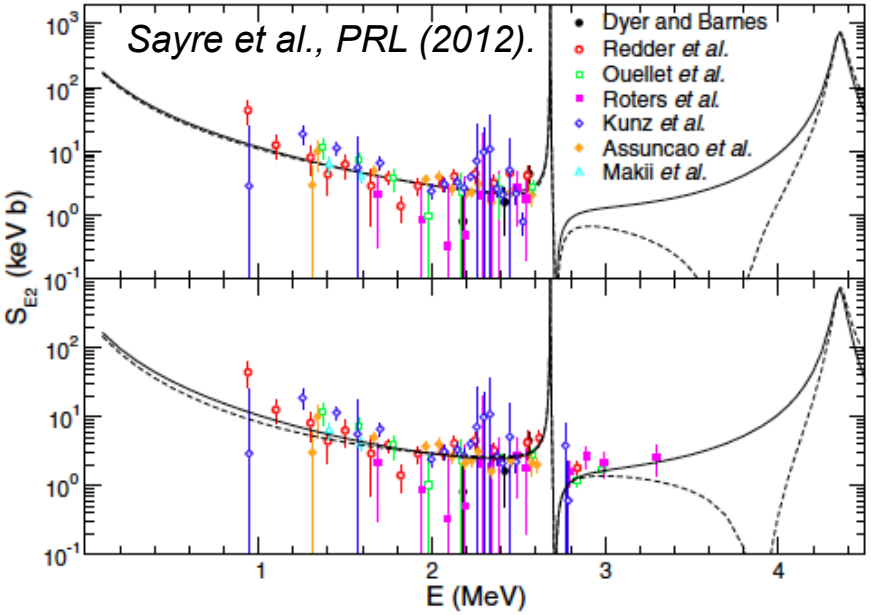


$^{12}C(\alpha,\gamma)^{16}O$

- Promising new techniques

Plag et al, PRC (2012)





- New measurements of transfer reactions

Oulebsir et al., PRC (2012)

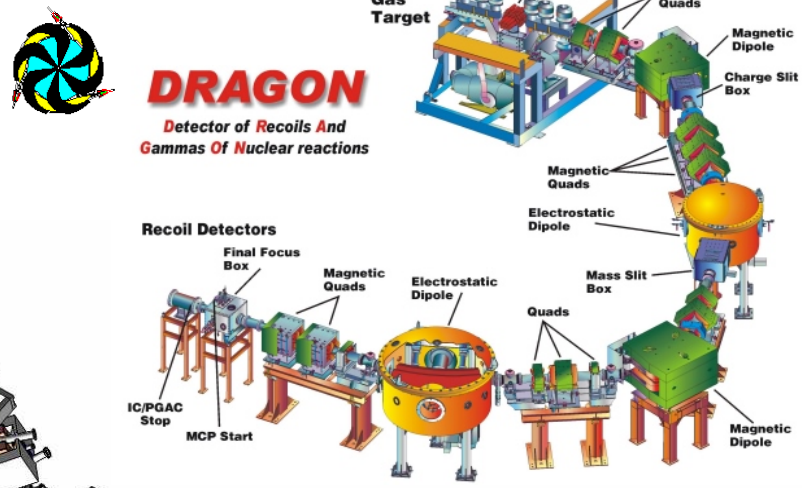
Experiment	S_{E1} (0.3 MeV) (keV b)	S_{E2} (0.3 MeV) (keV b)	S_{total} (0.3 MeV) (keV b)
This work	100 ± 28	50 ± 19	175^{+63}_{-62}
Brune [25]	101 ± 17	44^{+19}_{-23}	170^{+52}_{-55}
Belhout [8]	80^{+17}_{-16}	—	—
Tischauser [26]	—	53 ± 13	—
Tang [34]	84 ± 21	—	—
Azuma [35]	79 ± 21	—	—
Hammer [36]	77 ± 17	81 ± 22	183^{+55}_{-54}
Kunz [28]	76 ± 20	85 ± 30	186^{+66}_{-65}
NACRE [5]	79 ± 21	120 ± 60	224^{+97}_{-96}
Ouellet [29]	79 ± 16	36 ± 6	140^{+38}_{-37}
Rotters [31]	95 ± 44	—	—
Mean value	83 ± 6	43 ± 5	151^{+27}_{-26}

- New measurements in region of 2.6 MeV resonance constrain sign of interference E1-E2 interference

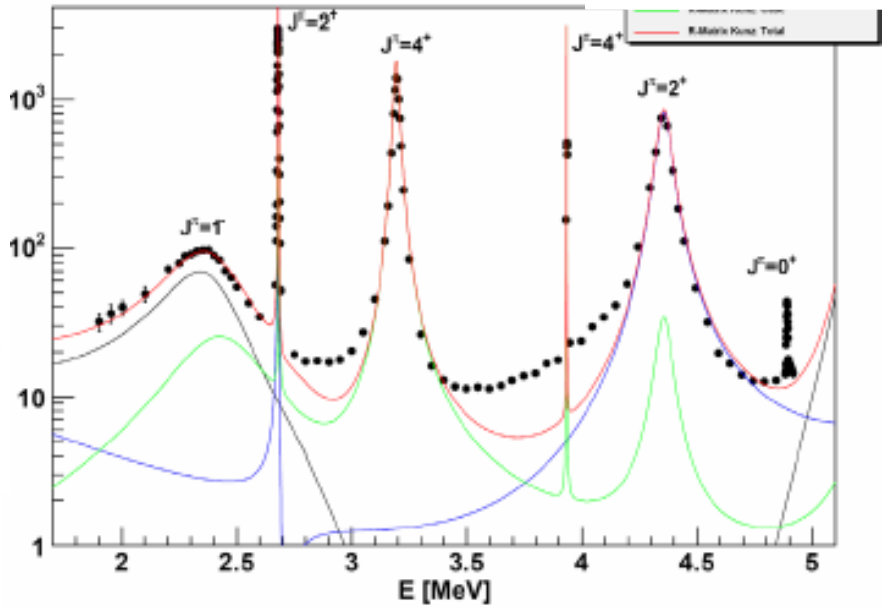
$S_{E2}(300\ \text{keV}) = 62^{+9}_{-6}$ keV•b

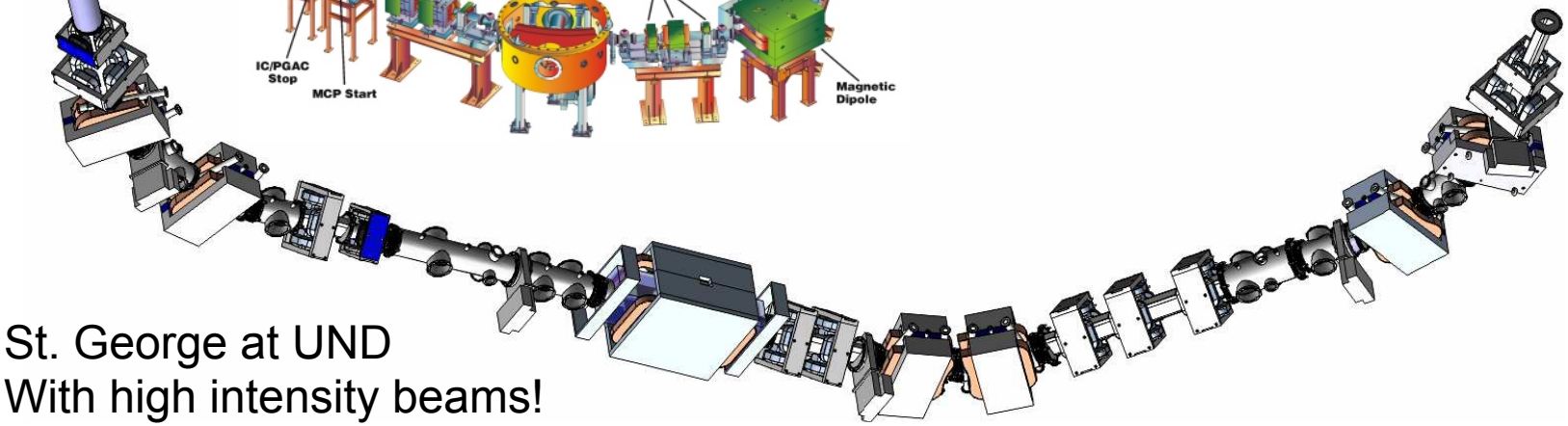
Total cross section thru recoils

- Detect recoiling heavy nuclei (instead of or in addition to) gamma rays
- Proven approach
  DRAGON, ERNA, DRS . . .



Schürmann, EPJA (2005) - $^{12}C(\alpha,\gamma)$ w/ ERNA





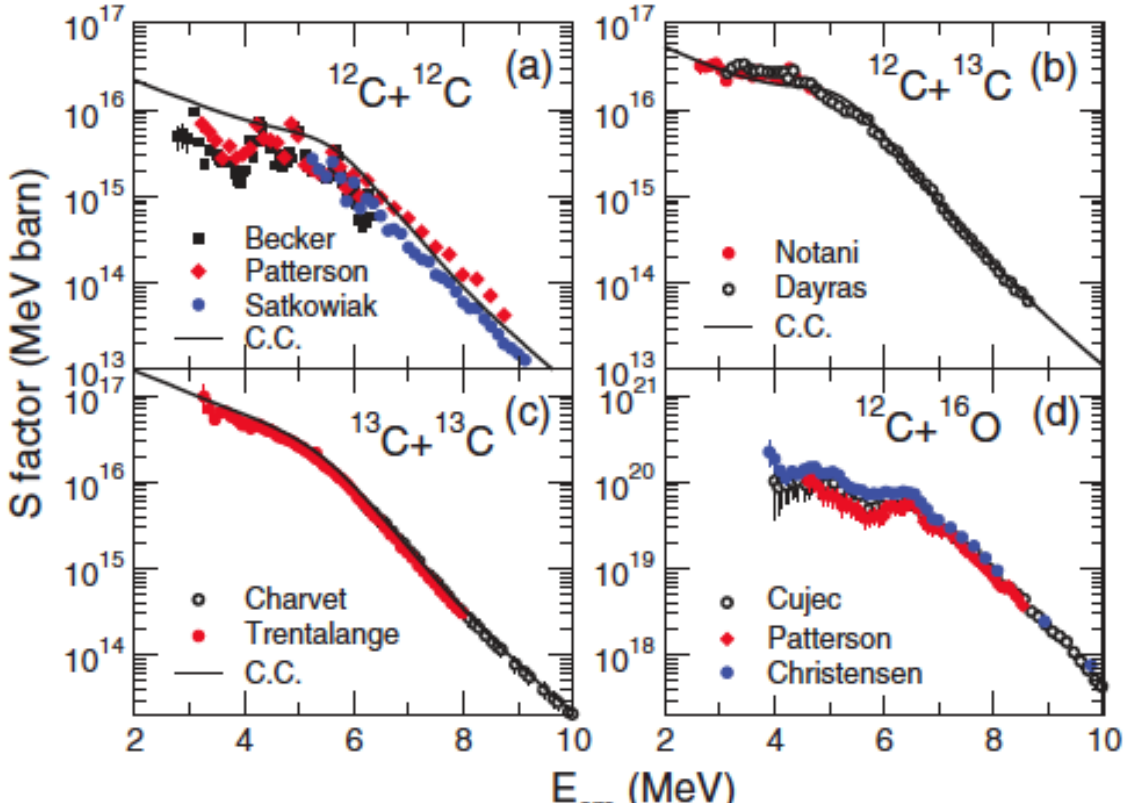
St. George at UND
With high intensity beams!

Carbon Burning

See Soic (next)

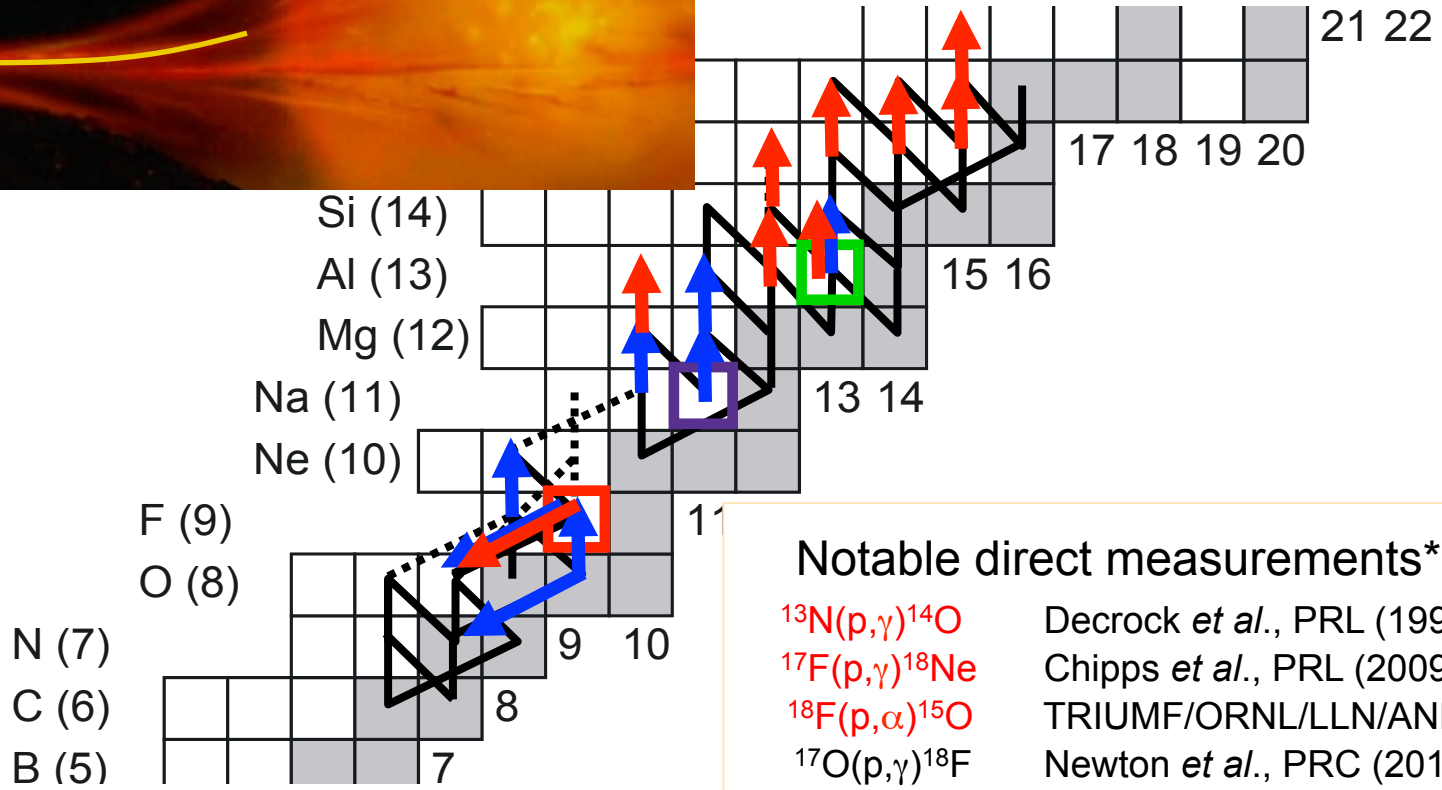
Jiang et al., PRL (2013)

- $^{12}C+^{12}C$ is special
- Discrete resonances in ^{24}Mg are important
- Not well known or easily predicted
- New measurements are important for SN



System	Q (MeV)	E_g (MeV)	U_g (MeV)	V_c (MeV)	$(\Gamma/D)_c$
$^{12}C + ^{12}C$	13.934	7.3	21.2	6.66	0.7
$^{12}C + ^{13}C$	16.318	−1.1	15.2	6.56	120
$^{13}C + ^{13}C$	22.465	−8.5	14.0	6.48	2210
$^{12}C + ^{16}O$	16.765	1.8	8.5	8.45	12
$^{16}O + ^{16}O$	16.542	0.8	17.3	10.76	94

Novae



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

Notable direct measurements*

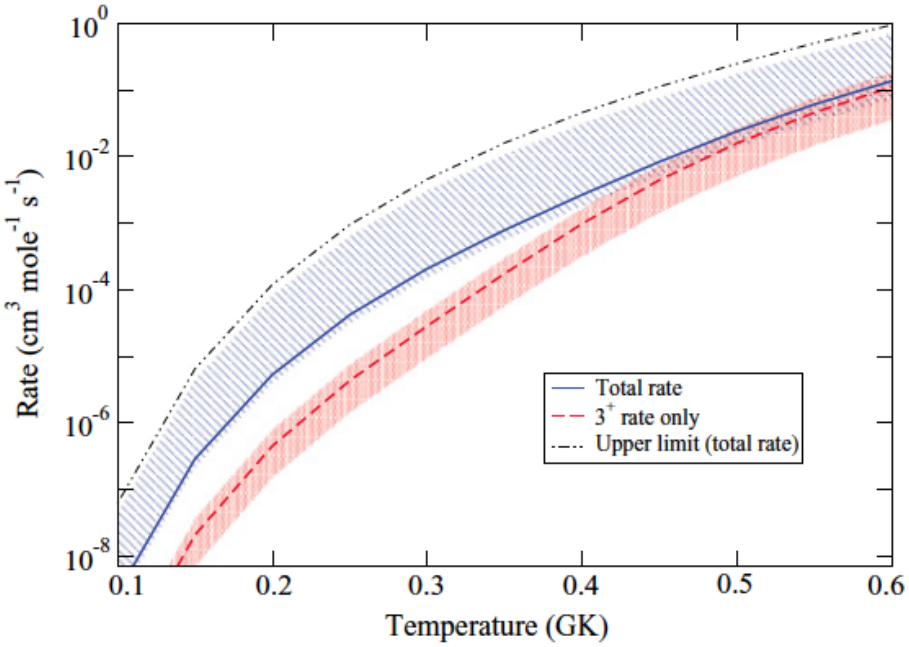
$^{13}N(p,\gamma)^{14}O$	Decrock *et al.*, PRL (1991)
$^{17}F(p,\gamma)^{18}Ne$	Chipps *et al.*, PRL (2009)
$^{18}F(p,\alpha)^{15}O$	TRIUMF/ORNL/LLN/ANL
$^{17}O(p,\gamma)^{18}F$	Newton *et al.*, PRC (2010).
$^{21}Na(p,\gamma)^{22}Mg$	D'Auria *et al.*, PRC (2004).
$^{22}Na(p,\gamma)^{23}Mg$	Sallaska *et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

Direct measurements

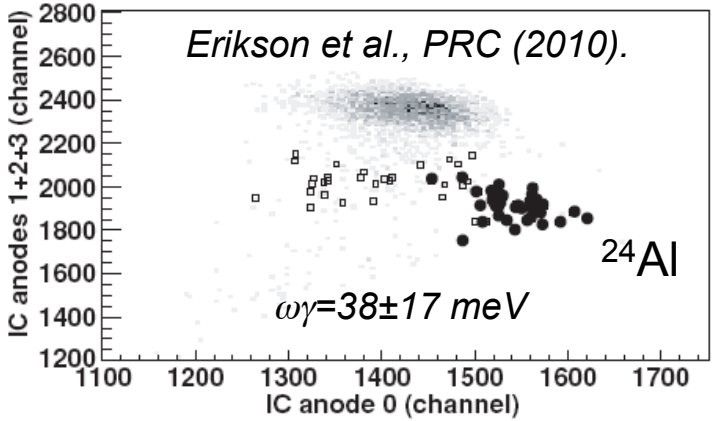
- Intense low-energy beam (ISOL)
- Windowless H_2 gas target
- EM recoil separator
  → DRAGON: Coincident γ-rays

$^{17}F(p,\gamma)^{18}Ne$: $^{16}O+p \rightarrow {}^{17}F \rightarrow$?

Chipps *et al.*, PRC (2010).



$^{23}Mg(p,\gamma)^{24}Al$: NeNa→MgAl ?

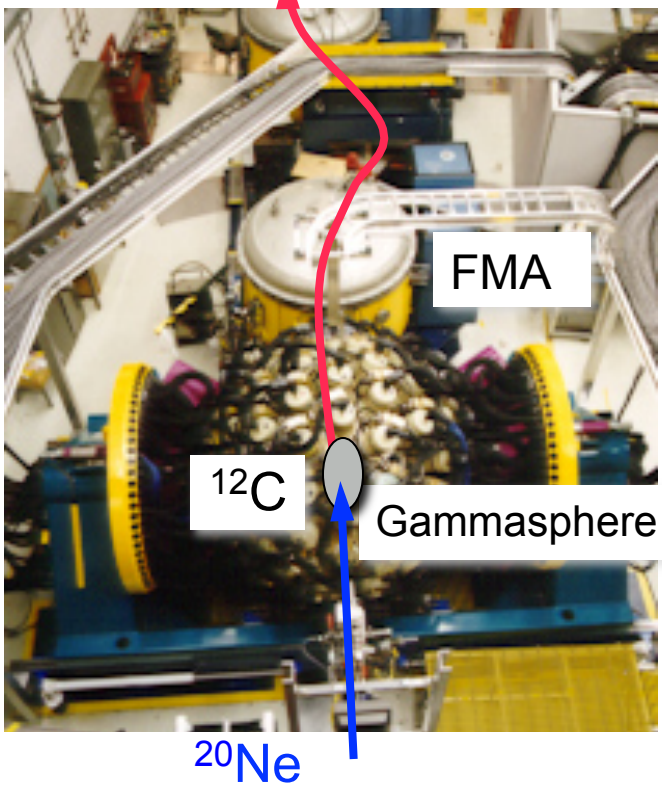


Indirect approaches – Gammas

Use Fusion-evaporation or knock-out reactions to populate states in nuclei of interest

Detect γ-rays from decay of states and tag with recoiling heavy ions

$^{30}P(p,\gamma)^{31}S$ rate at Argonne



Jenkins et al., PRC (2006)

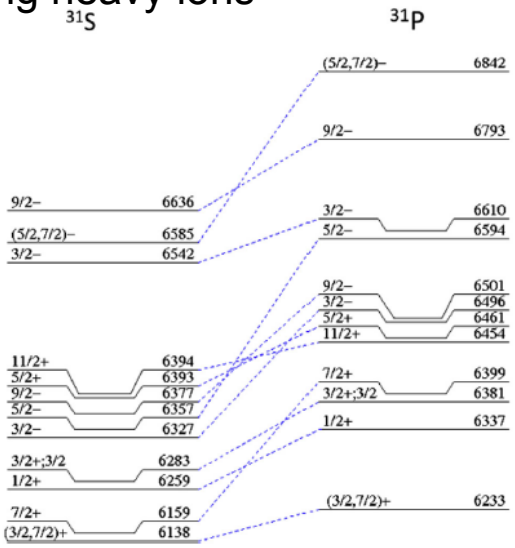
New measurements

$^{28}Si(\alpha,n)^{31}S$

Gammasphere only

New J^{π} assignments

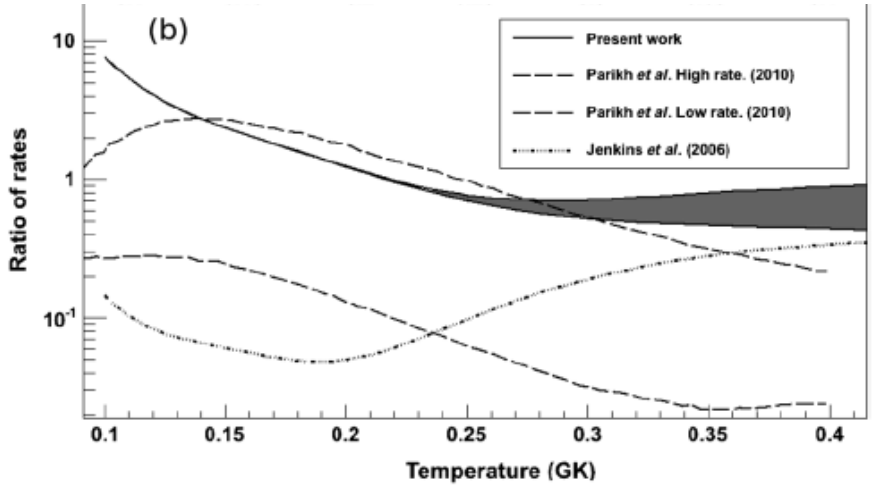
Doherty et al., PRL (2012)



But

Should be confirmed

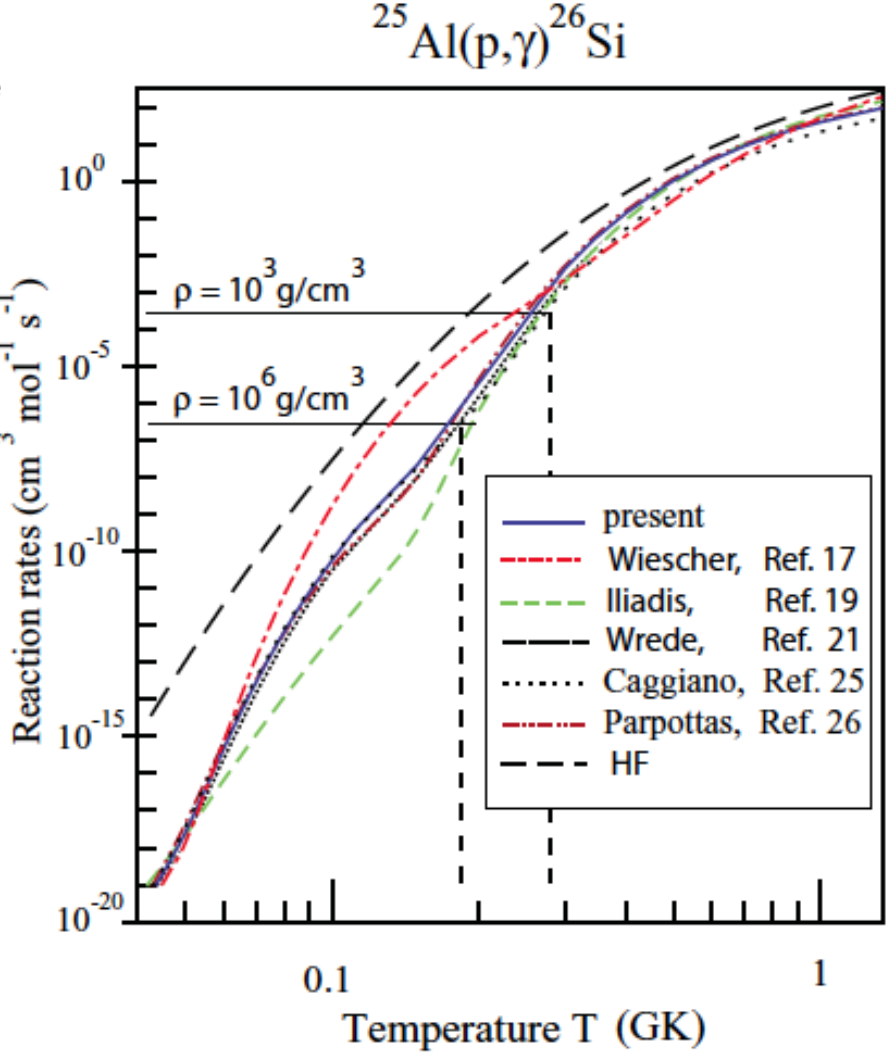
Resonance strengths?



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

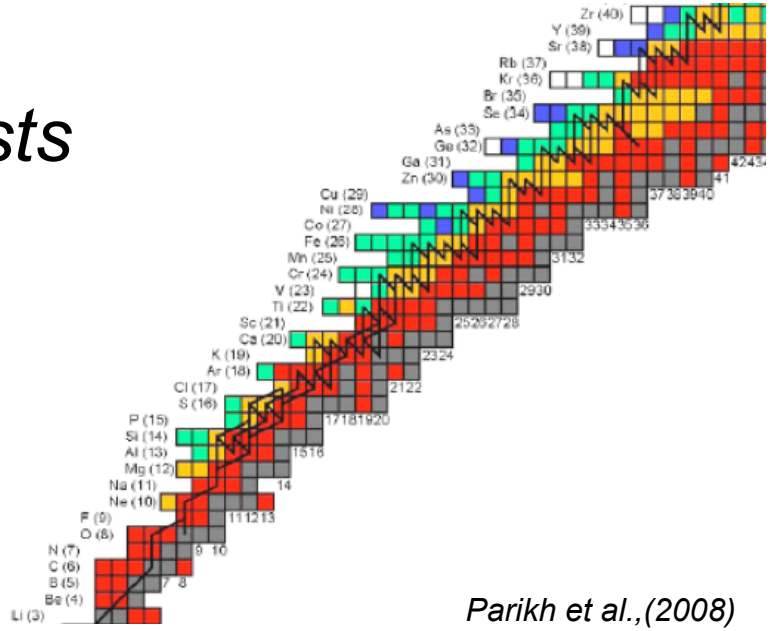
- One of most important rates for understanding ^{26}Al in novae
  - Rates depends on properties of low-lying s-wave resonances (2^+ and 3^+ states in ^{26}Si)

$^{25}Al(p,p)^{25}Al$	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)



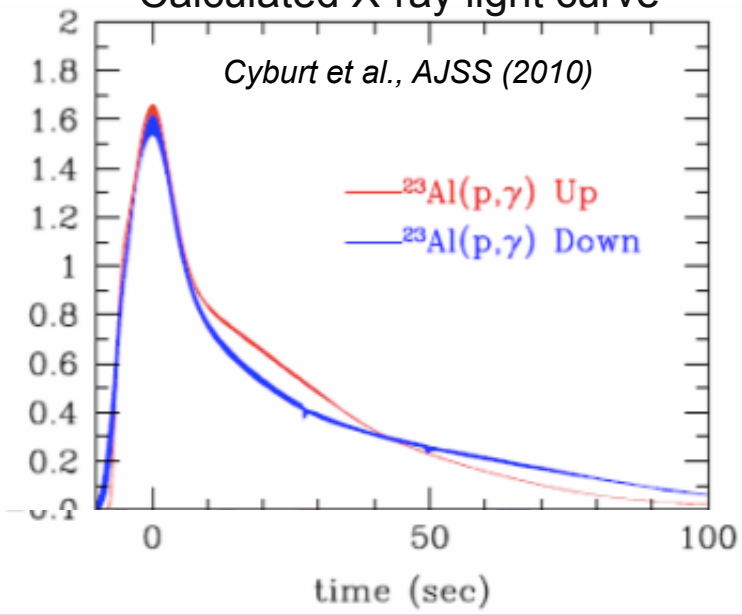
X-ray bursts

- Nuclear reactions 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.,(2008)

Calculated X-ray light curve

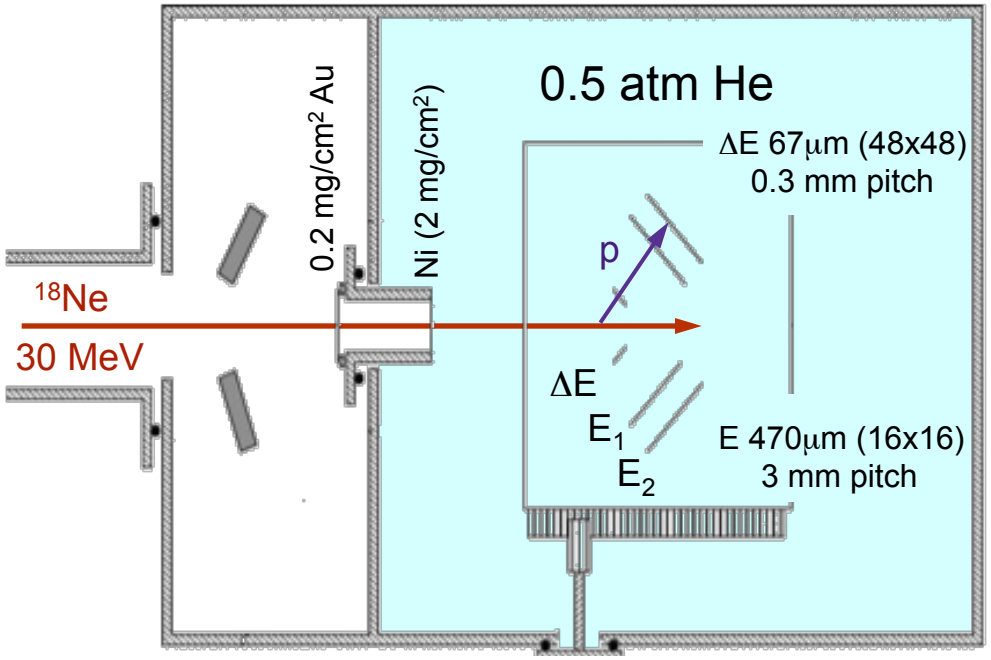


Reaction	Models affected
$^{15}O(\alpha,\gamma)^{19}Ne^{a}$	K04, K04-B1, K04-B6
$^{18}Ne(\alpha,p)^{21}Na^{a}$	K04-B1, K04-B6
$^{22}Mg(\alpha,p)^{25}Al$	F08
$^{23}Al(p,\gamma)^{24}Si$	K04-B1
$^{24}Mg(\alpha,p)^{27}Al^{a}$	K04-B2
$^{26g}Al(p,\gamma)^{27}Si^{a}$	F08
$^{28}Si(\alpha,p)^{31}P^{a}$	K04-B4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

$^{18}Ne(\alpha,p)^{21}Na$ studies

$^{18}Ne(\alpha,p)^{21}Na$ at LLN

Groombridge et al., PRC (2002).

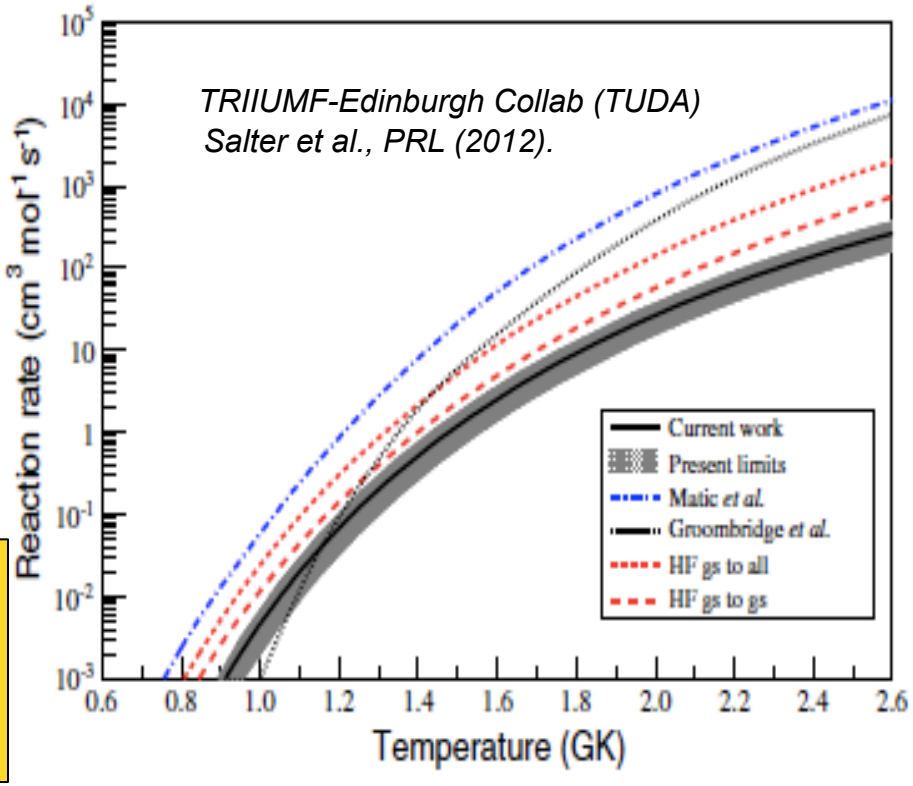


Indirect studies: e.g. $^{24}Mg(p,t)^{22}Mg$

Matic et al., PRC (2009).

$^{21}Na(p,\alpha)^{18}Ne_{gs}$

Up to 25x smaller σ than Groombridge



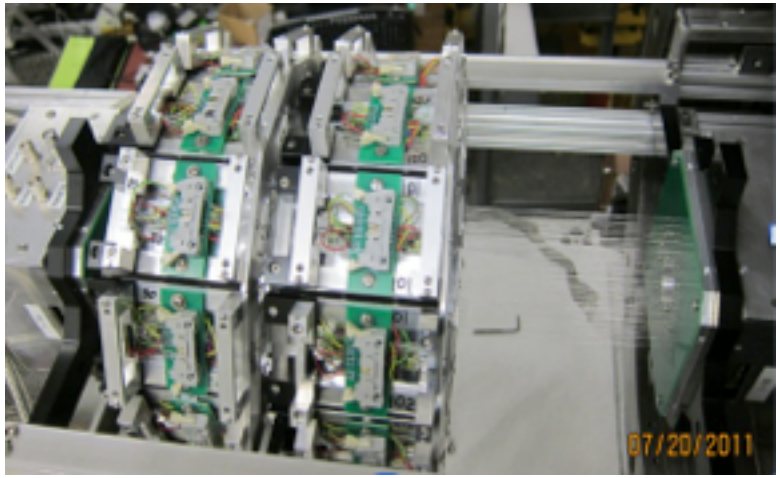
- Large discrepancies/uncertainties
- Only upper limits below E_{cm}=1.7 MeV
- Statistical model reliability questionable

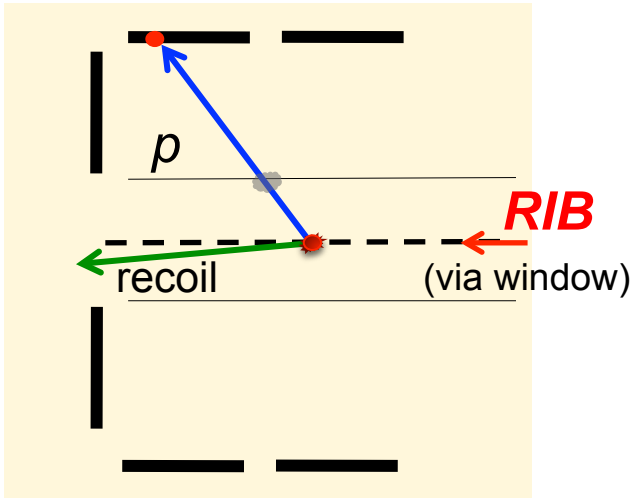
Array for Nuclear Astrophysics and Structure with Exotic Nuclei: *ANASEN*

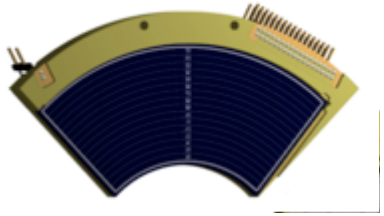
Extended active gas target/detector

- Cylindrical proportional counter (PC) surrounding beam axis
  - *19 anodes 7-μm* diameter carbon fiber → High Gain
- Over 1000 cm^2 of Si-strip detectors (28) with CsI scintillators
- 600+ channels of ASIC electronics (Wash. U.)

19 Anode PC







New QQQ

24x Super-X3

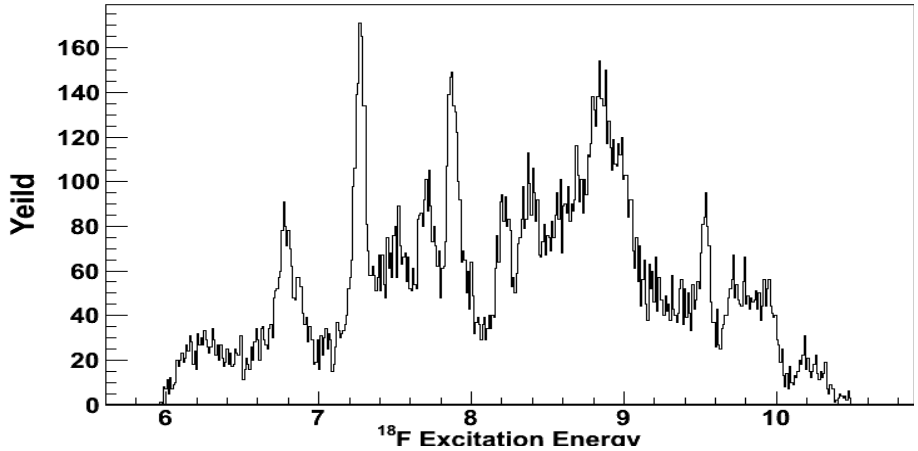
1. ΔE in PC → particle identification
2. Position Si + Position PC → θ_{lab}
3. Energy Si + θ_{lab} → E_{cm}

Entire excitation function simultaneously measured

Macon *et al.*

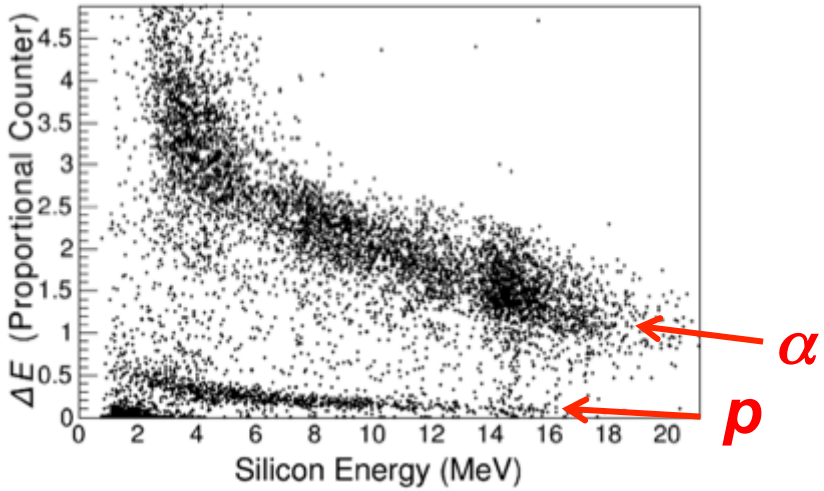
(α,p) with ANASEN

$^{14}N(\alpha,p)^{17}O$



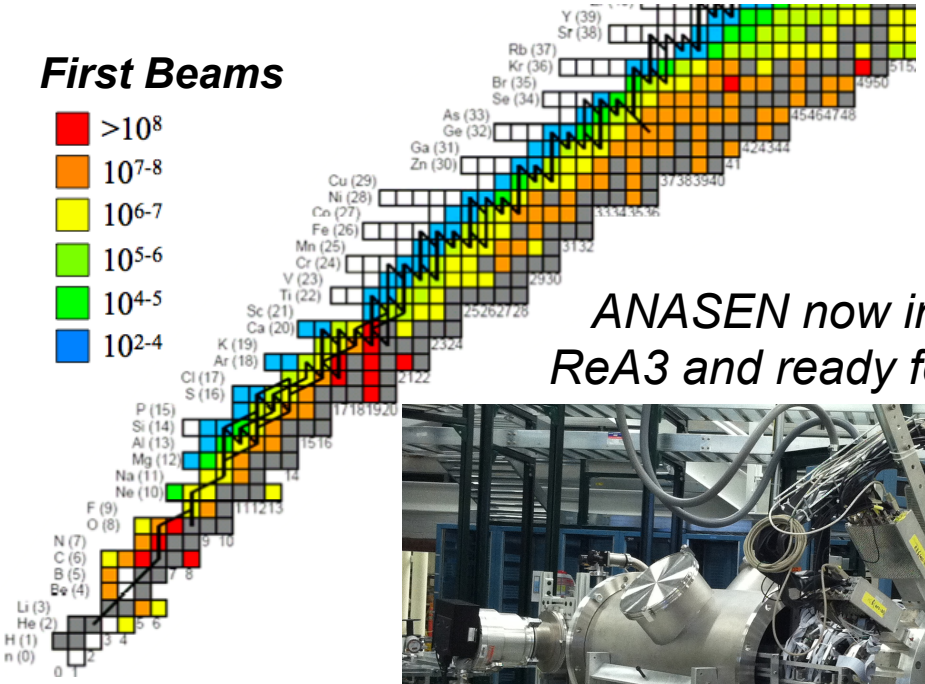
- 2012 Successful stable beam test:
- Clean identification of channel
- Low background (w/o heavy ion tag!)
- ~100 keV$_{cm}$ energy resolution

- Feb-Mar 2013: ***$^{18}Ne(\alpha,p)^{21}Na$***
- Large discrepancies between previous (α,p), transfer studies, and H.F.
- 56-MeV ^{18}Ne beam from ^{3}He(^{16}O,^{18}Ne)*n* using RESOLUT
- ~10^4 ^{18}Ne/s with 6% purity
- Clean tag of ^{18}Ne
  - — TOF with RF and scintillating foil
- Protons cleanly detected up to E_p~10 MeV
- But
  - — Will not reach most of Gamow window
  - — Fusion-evaporation backgorund on CO_2 quenching gas (5%) needs investigation

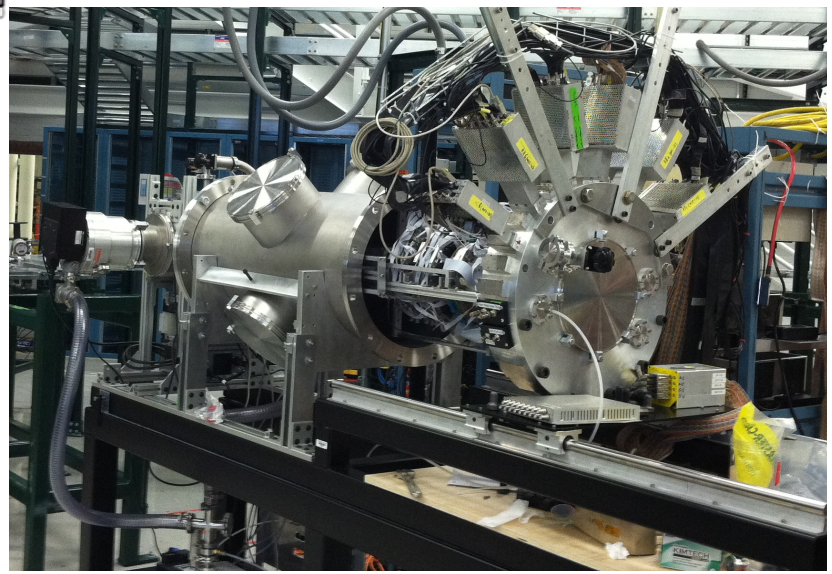


ANASEN at ReA3

Gas stopping and first stage of reacceleration ready for first beams to 1.5 MeV/u



ANASEN now installed at ReA3 and ready for first beam



Physicists' Spring Break Road Trip 2013

First ANASEN experiments at NSCL starting July 18

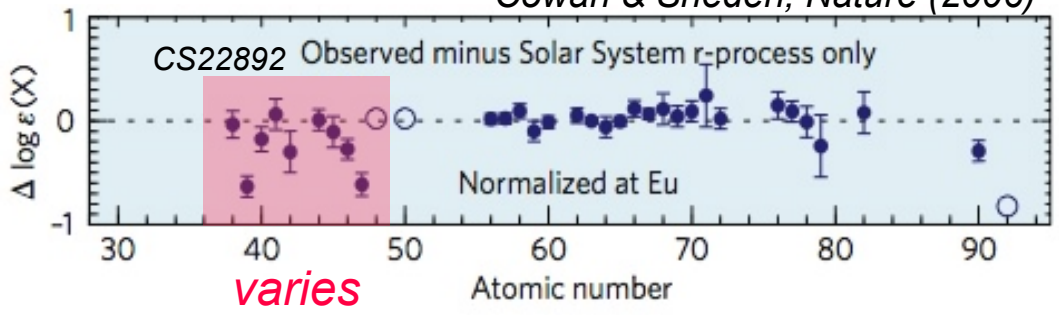
$^{38}K+\alpha \rightarrow {}^{41}Ca+p$?

Heavy elements - where?

- *s process*
  → Nuclear physics ok except for branch points (nTOF & DANCE)

- *r process & LEPP*
  - Abundances sensitive to uncertain nuclear physics
    → *Masses*
    → *Decay properties*
    → Few reactions (Surman PRC 2009)

Cowan & Sneden, Nature (2006)



r process

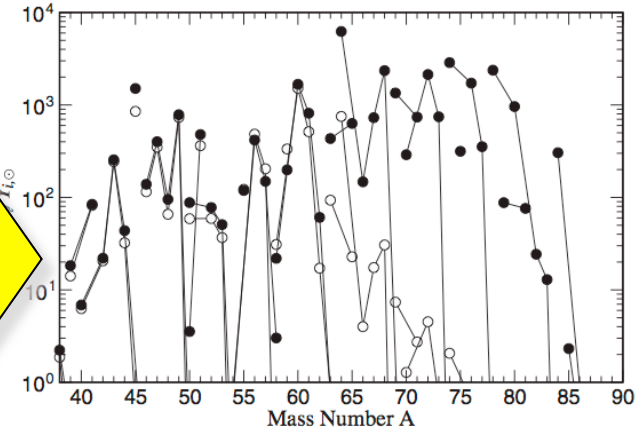
- Supernovae?
  →Hydrodynamics don't match
  →Explosions?
  →Many uncertainties
- Neutron star mergers?
  →Difficult to produce in early Galaxy

LEPP

- Low neutron flux environment
  → Site early in Galaxy?
- Supernovae?
  → Proton-rich?

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

Fröhlich *et al.*, PRL (2006).



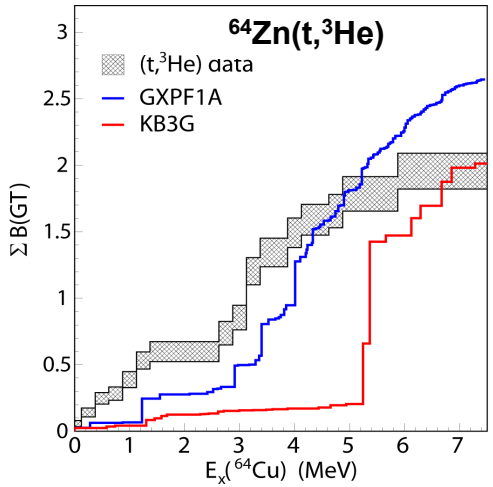
Weak interaction rates

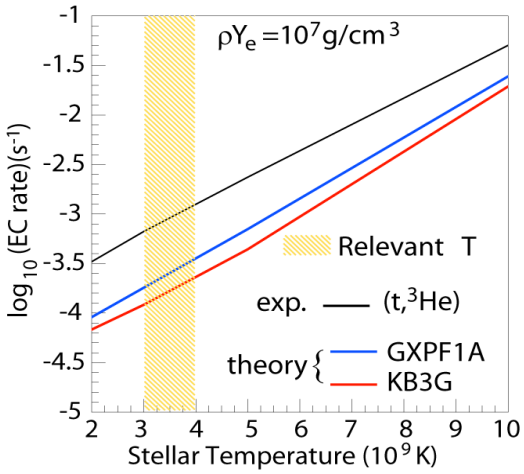
- Great improvements in weak rates from theory (nuclear shell model calculations)

  See Langanke & Martinez-Pinedo, RMP (2003)

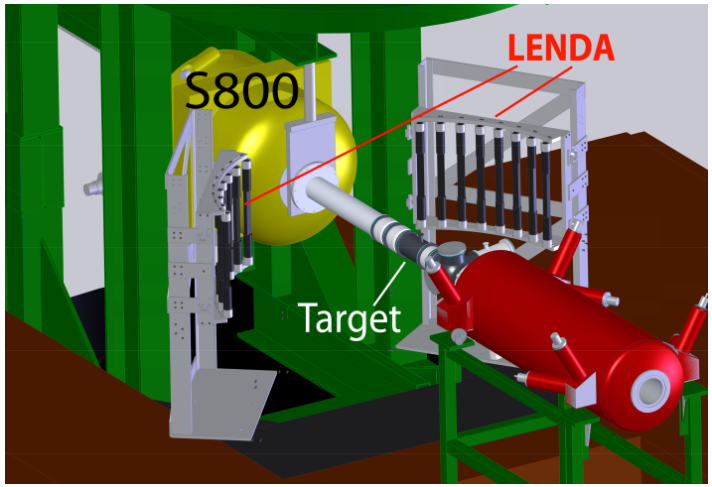
- Gamow-Teller strengths can be determined from charge exchange reactions
- (p,n) or (n,p) measurements test shell model predictions and effective interactions

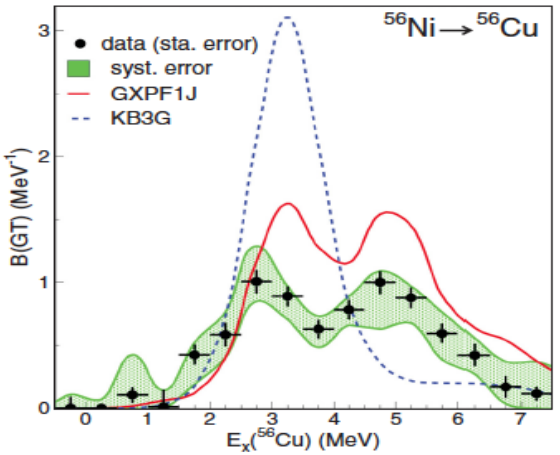
Hitt *et al.*, PRC 80 (2009).





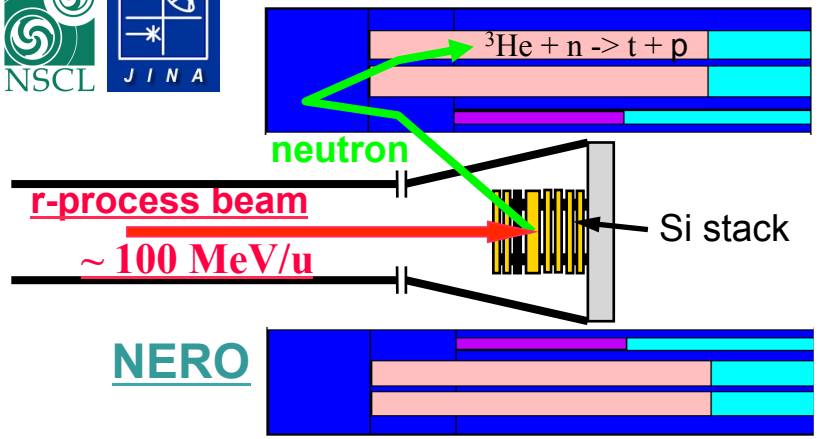
- Challenging tests with radioactive nuclei
- Low-Energy Neutron Detector (LENDA) developed for (p,n) measurements with the S800 and radioactive beams.

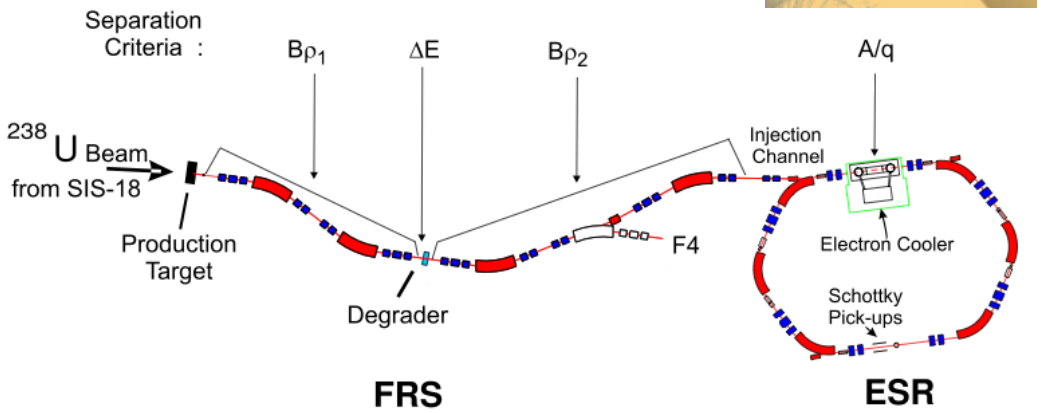




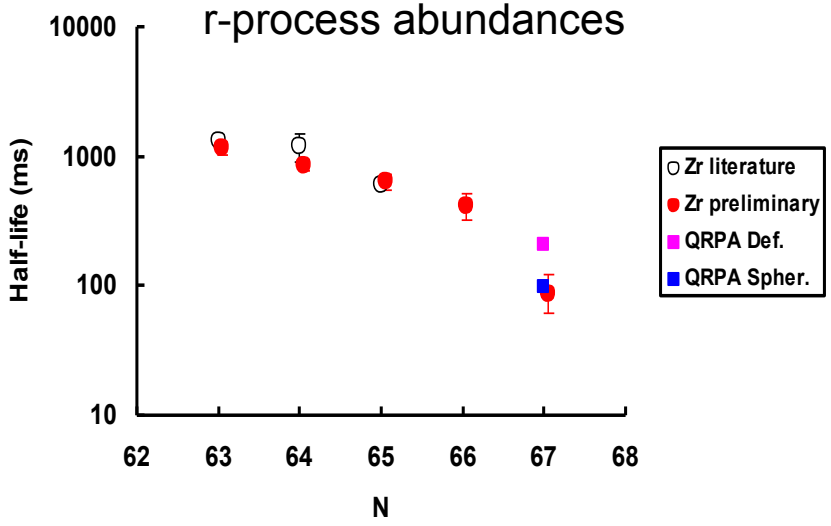
Decay properties

Quinn et al., PLC (2012).

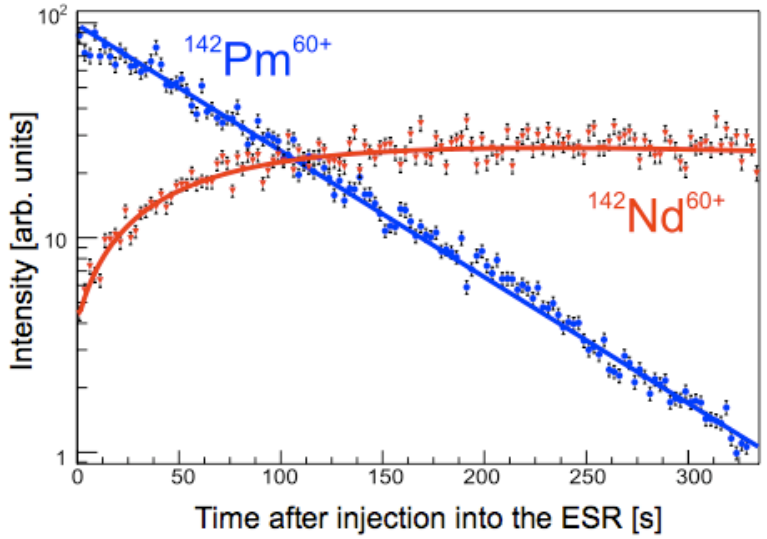




Shorter half-life of Se & Zr affects r-process abundances

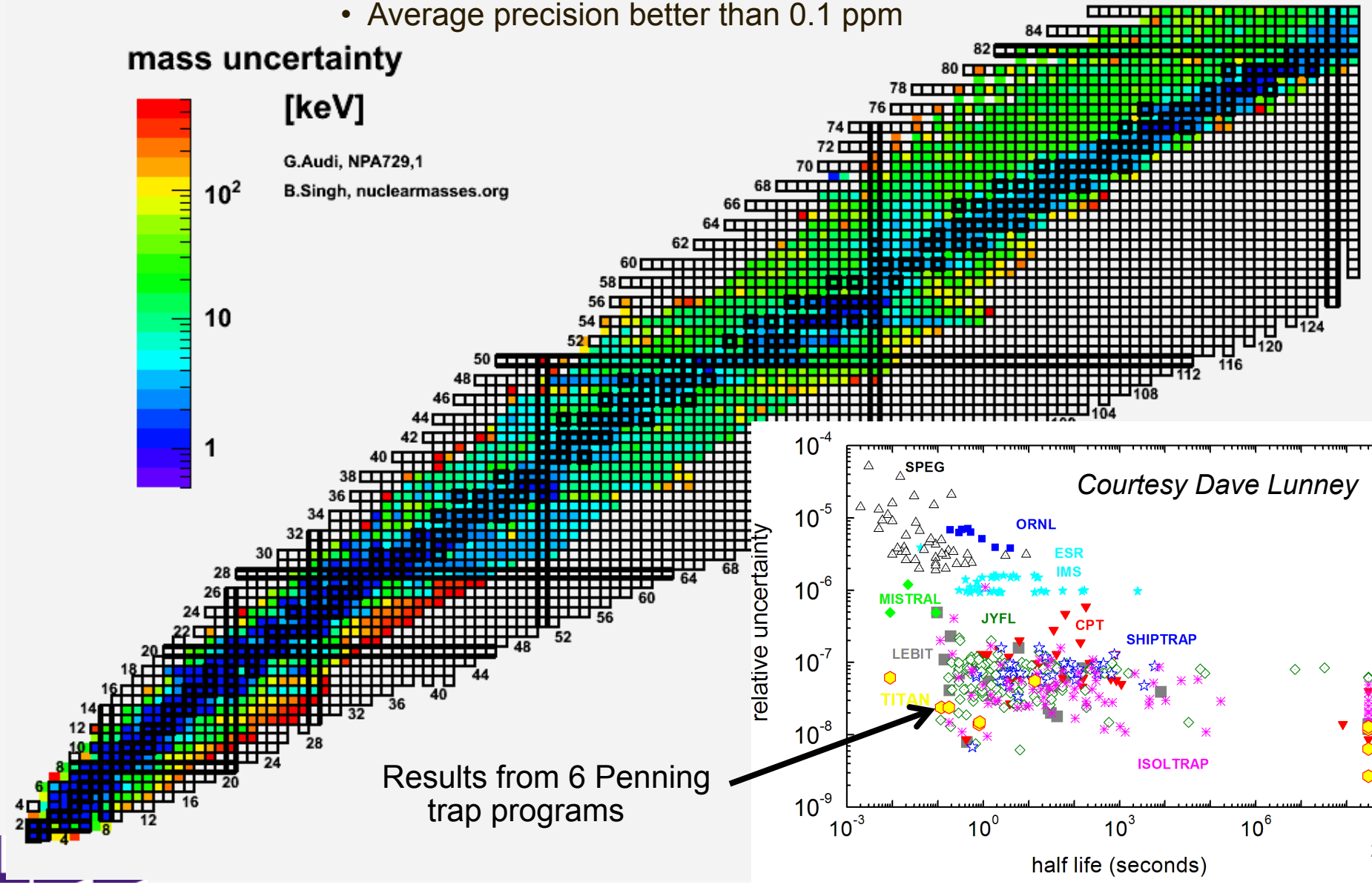


Chen et al., PLB (2010).
Litvinov et al., PLB (2008).



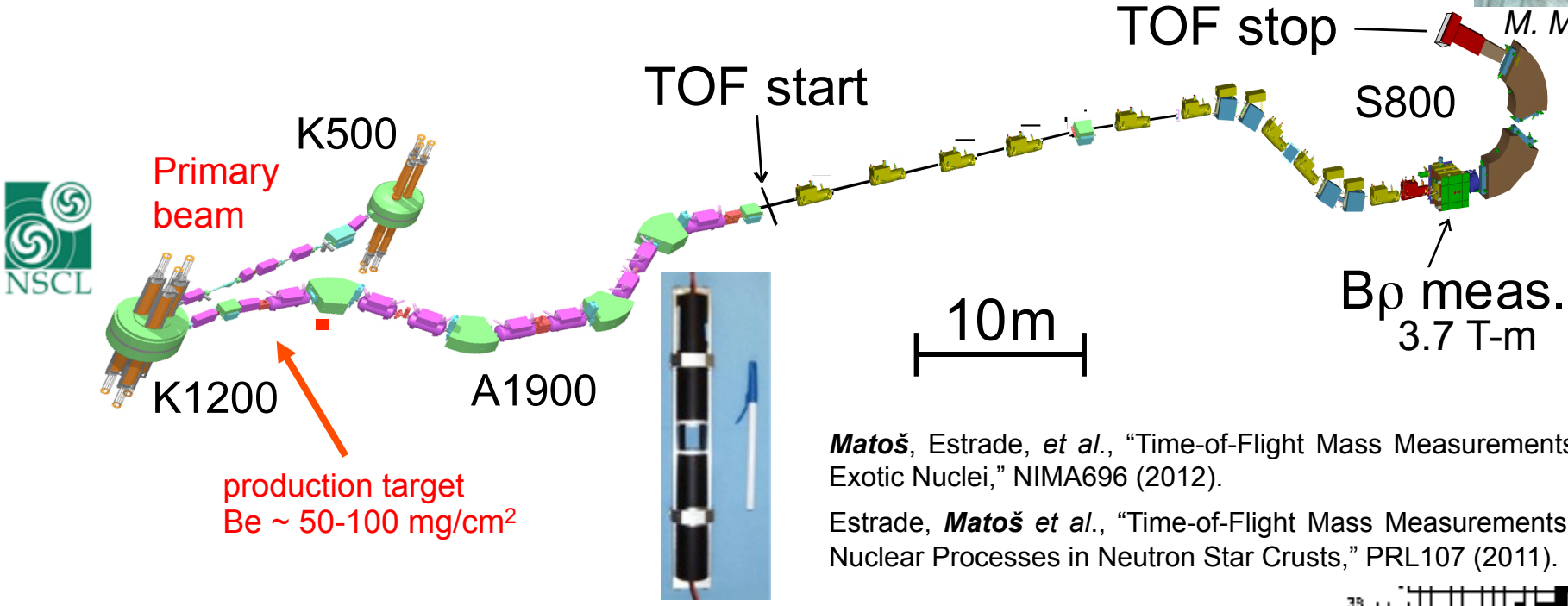
Atomic masses

- More than 2500 isotopes have measured masses
- Average precision better than 0.1 ppm



TOF-Bρ Mass Studies at NSCL

M. Matoš



Matoš, Estrade, *et al.*, "Time-of-Flight Mass Measurements of Exotic Nuclei," NIMA696 (2012).

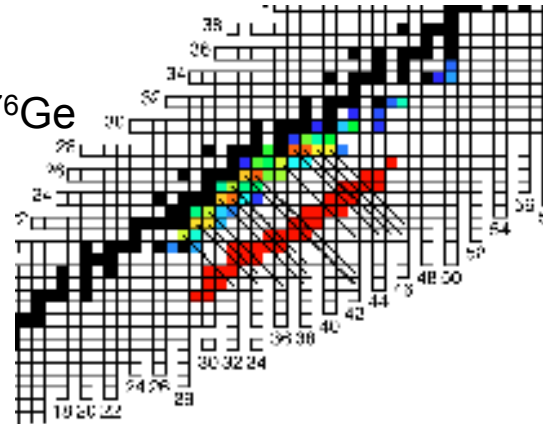
Estrade, ***Matoš*** *et al.*, "Time-of-Flight Mass Measurements for Nuclear Processes in Neutron Star Crusts," PRL107 (2011).

$$B\rho = \frac{m}{q}v$$ ⇒ *mass*

No dependence on lifetime!
Path length ~ 58 m
Time resolution ~ 30 ps

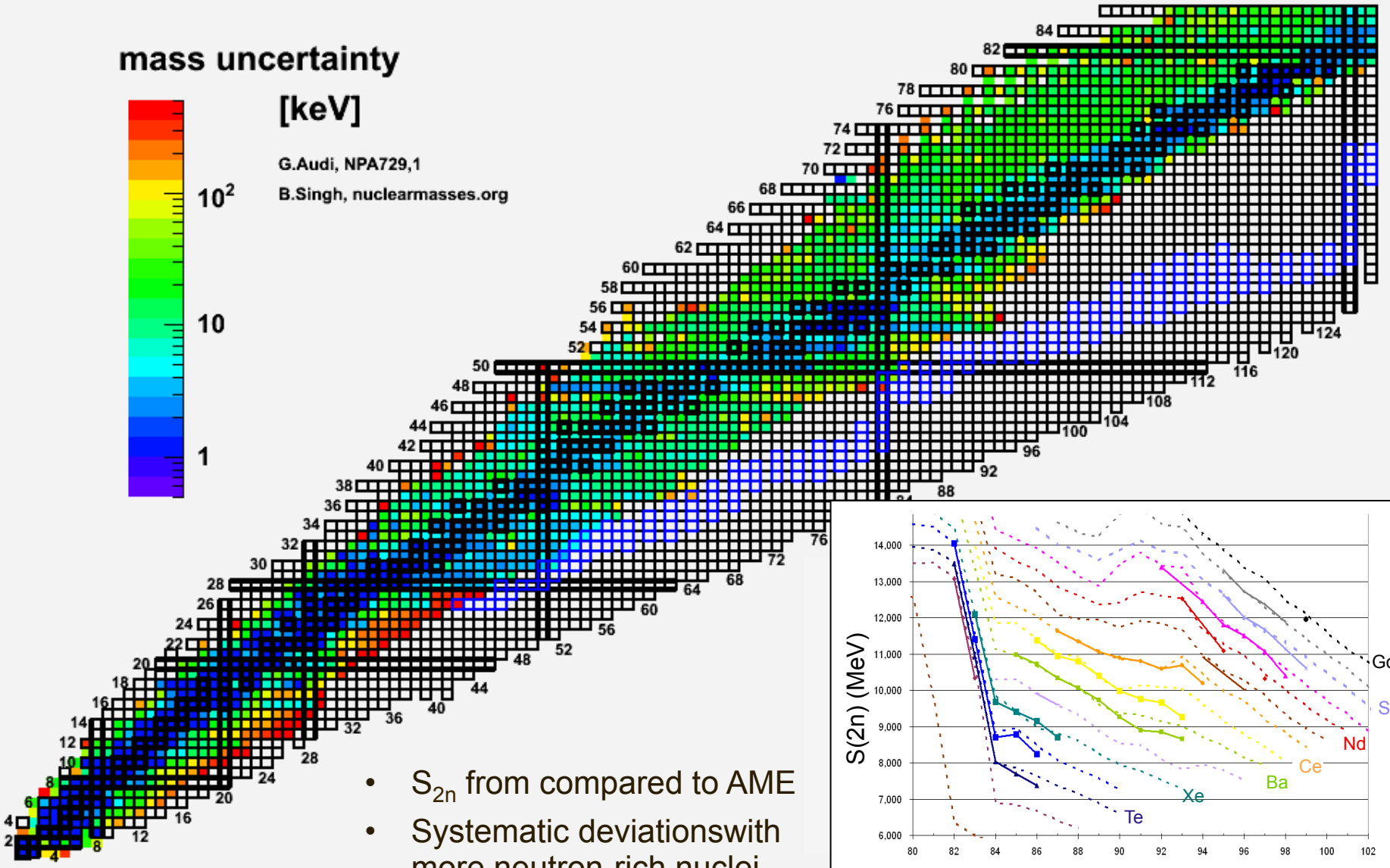
Nov 2011 – Fragmentation of ^{76}Ge

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

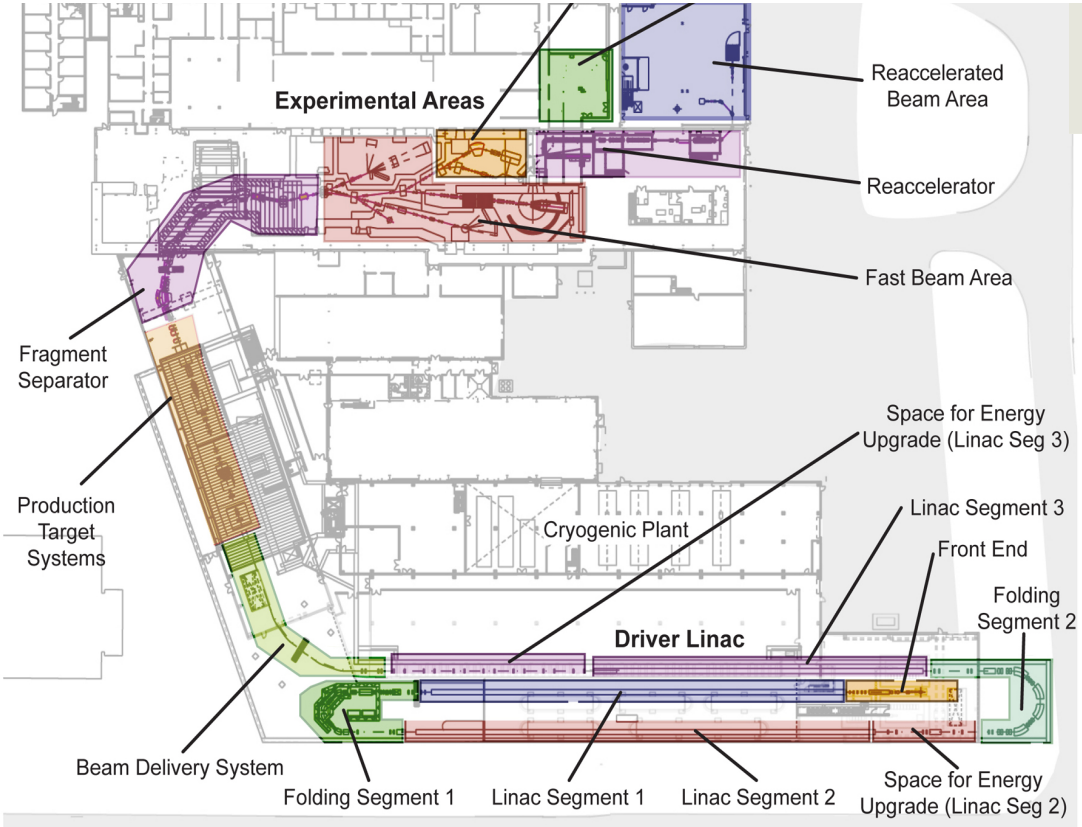


Next: Fragmentation of ^{124}Sn

The r process

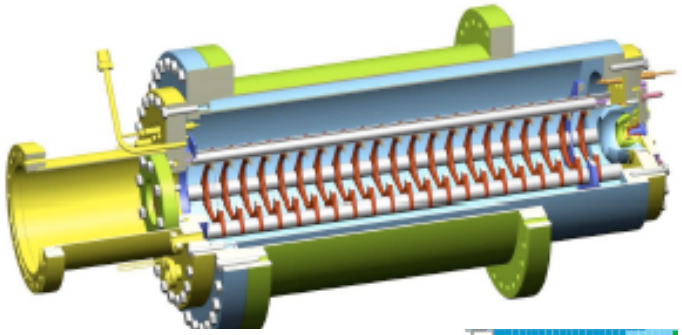


- S_{2n} from compared to AME
- Systematic deviationswith more neutron-rich nuclei

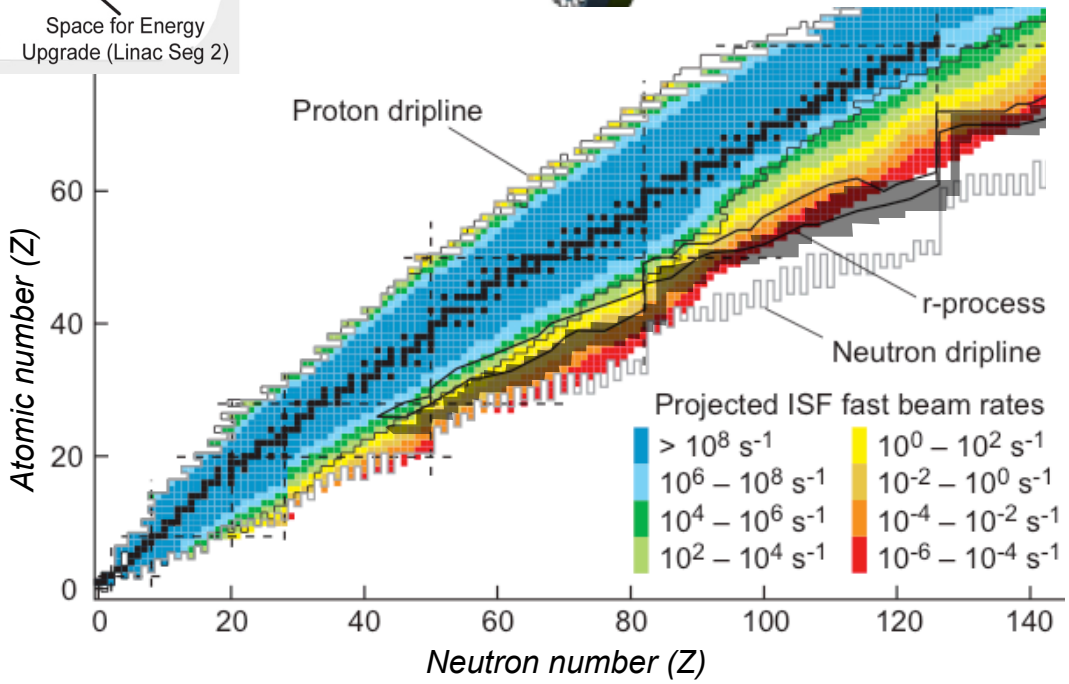


FRIB Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science
Michigan State University

- Being constructed at Michigan State Univ (~$550M)
  - Fragmention
    - → 200 MeV/u for U
    - → 400 kW

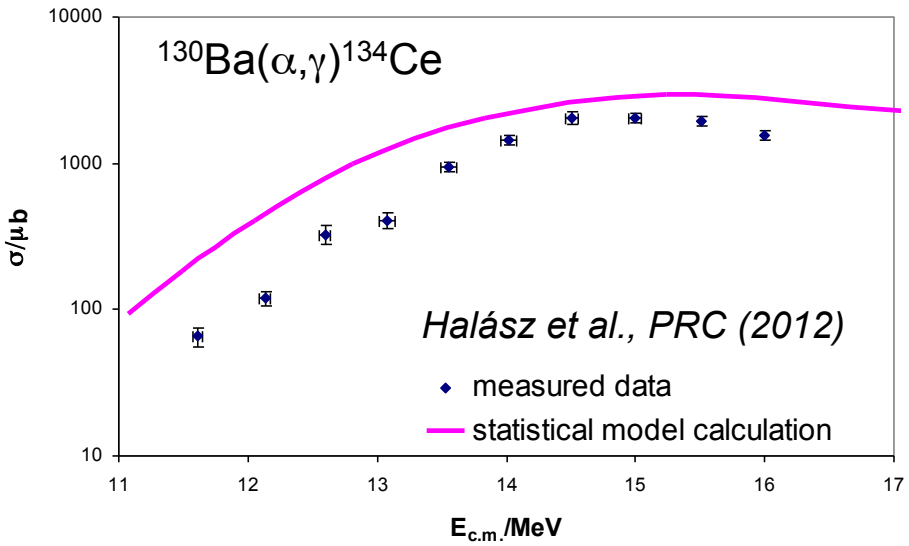


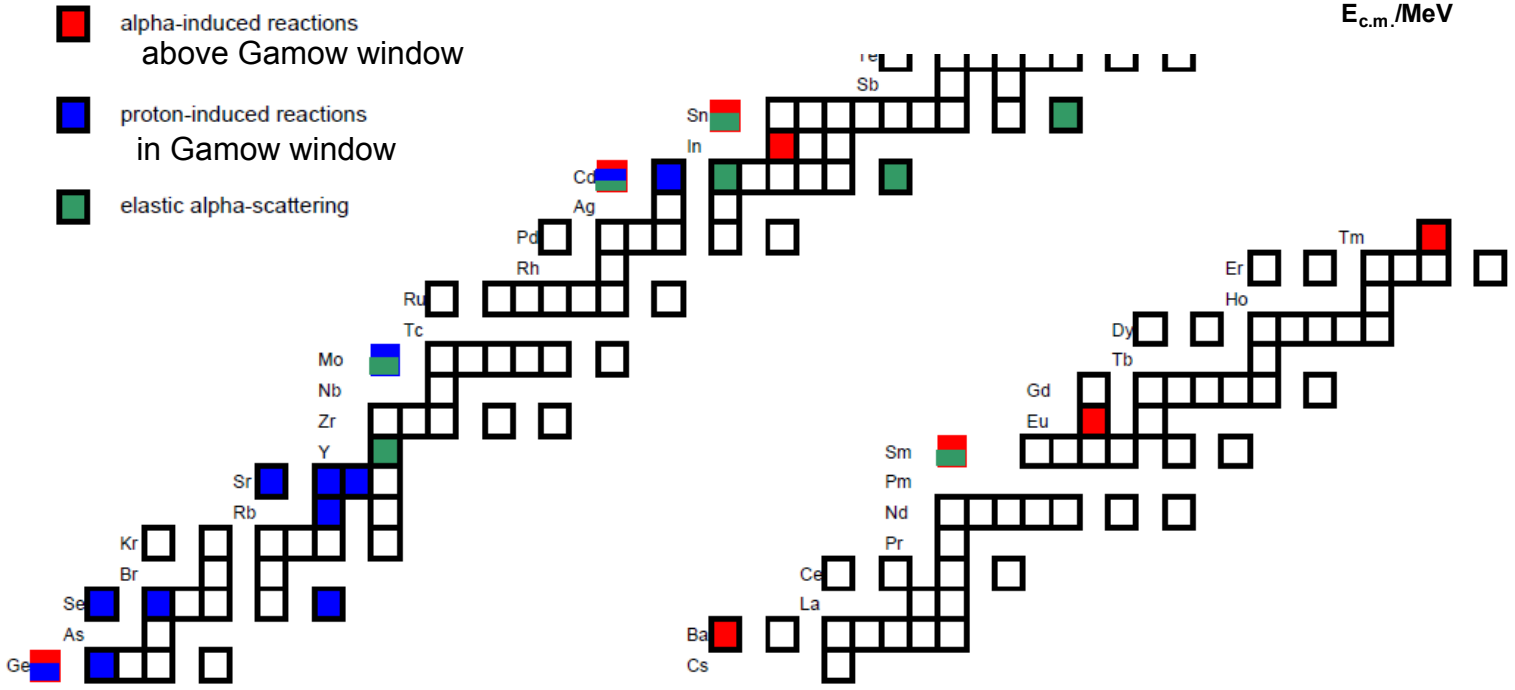
- Wide ***variety*** of ***intense*** beams at ***low energies***
- First access to many of the *r process* isotopes beyond Sn
- Direct measurements of many reactions important in stellar explosions for the first time
- Operational in ~2019



p process

- p and α reactions (ATOMKI)
- n induced reactions (Karlsruhe)
  e.g. Dillman et al., PRC (2010)





Conclusion

- **There has been much progress in nuclear physics**
  - → More realistic theoretical approaches
  - → Measurements closer to astrophysical energies
  - → Many reactions important for novae and the p process
  - → First measurements near the r process path

- **But there remains much to do**
  - → X-ray bursts
  - → Weak rates with radioactive nuclei
  - → r process – masses, half-lives, βn, nuclear structure
  - → LEPP

- **We should be careful with the "lies" we tell**
  - → The details do matter

- **Thanks for your attention!**