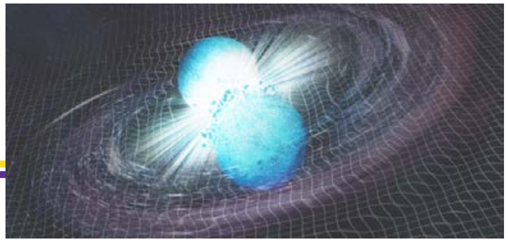
Nuclear Astrophysics

Jeff Blackmon (LSU)

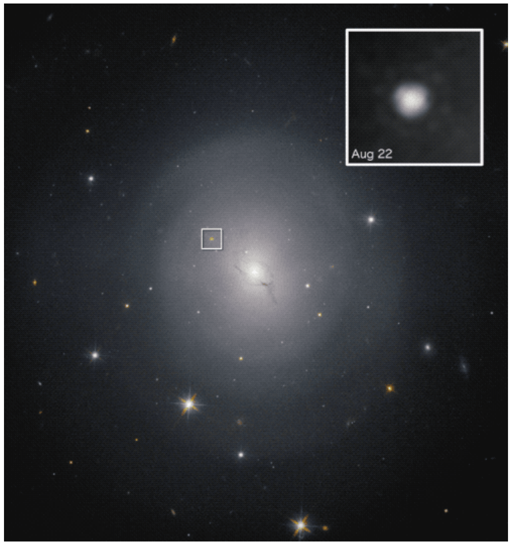
1. *Introduction, BBN & charged-particle reactions*
2. *Stellar evolution, heavy elements & neutrons*
3. *Stellar explosions & neutron stars*

GW170817 = AT2017gfo

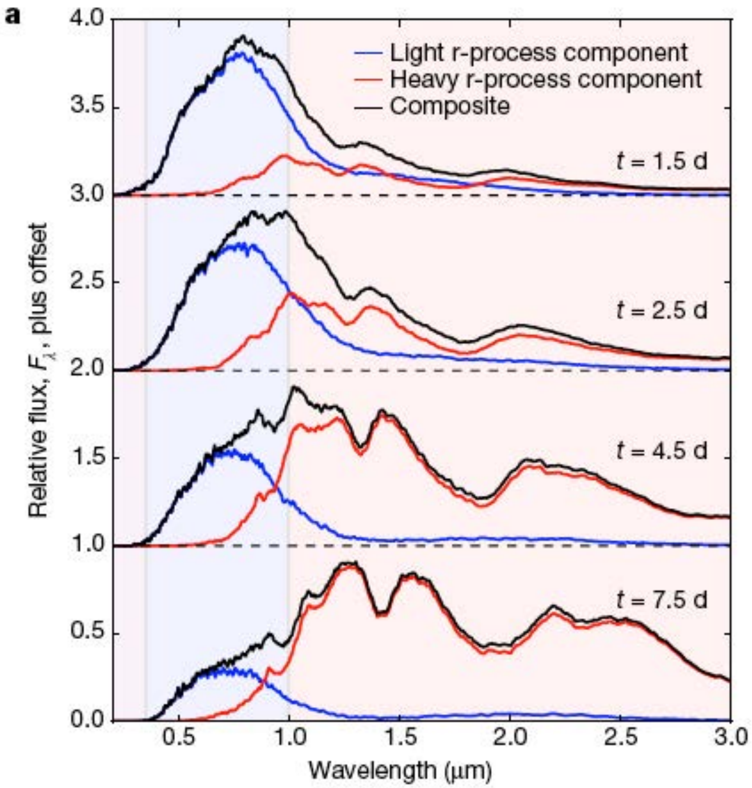


- Multiwavelength (optical, infrared, x-ray, . . .) obserations of kilonova → GW170817

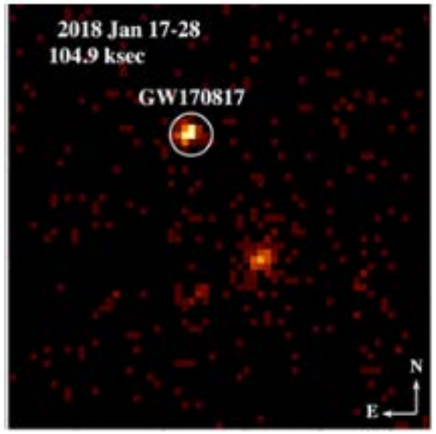
Hubble Timelapse (NASA STSci)



Kasen *et al.*, Nature, Nov. 2017



Pooley *et al.*, Ap. J. Lett, May 2018
Analysis of Chandra observations



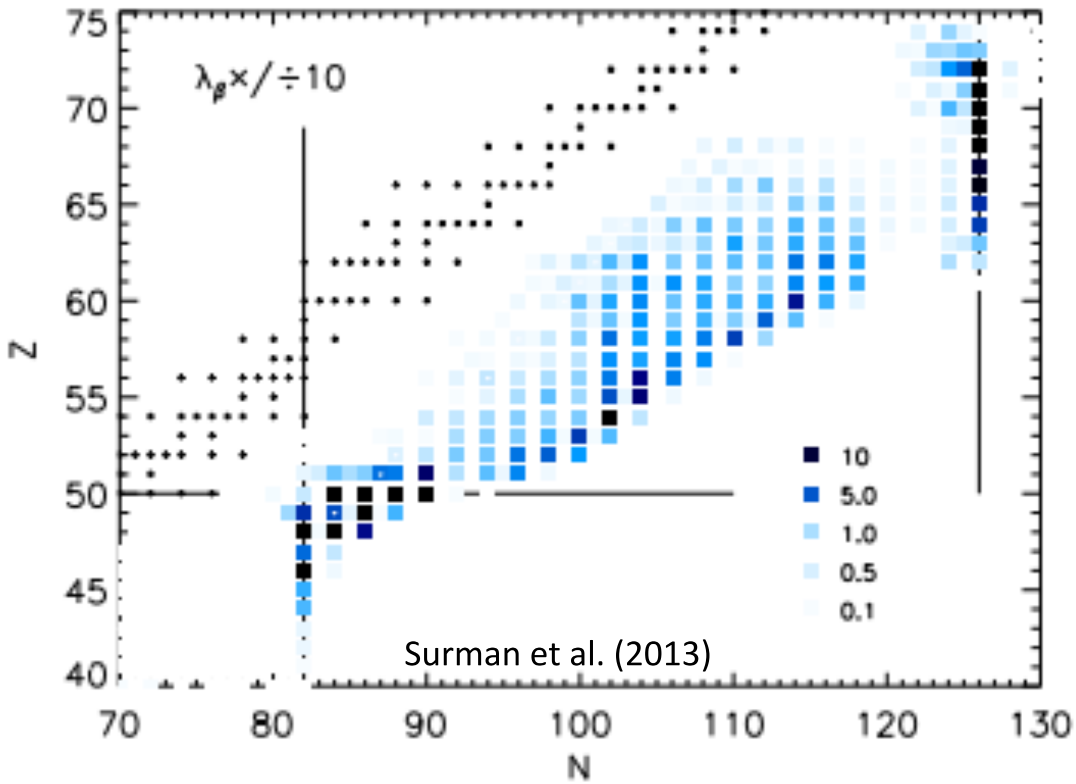
- “Smoking gun” evidence for robust r process in n star mergers

Beta decay properties and the r process

- Decay properties (half-lives) and neutron emission probabilities affect the abudances in the r process
- Few measurements possible thus far
- Efficient techniques are needed to push far away from stability

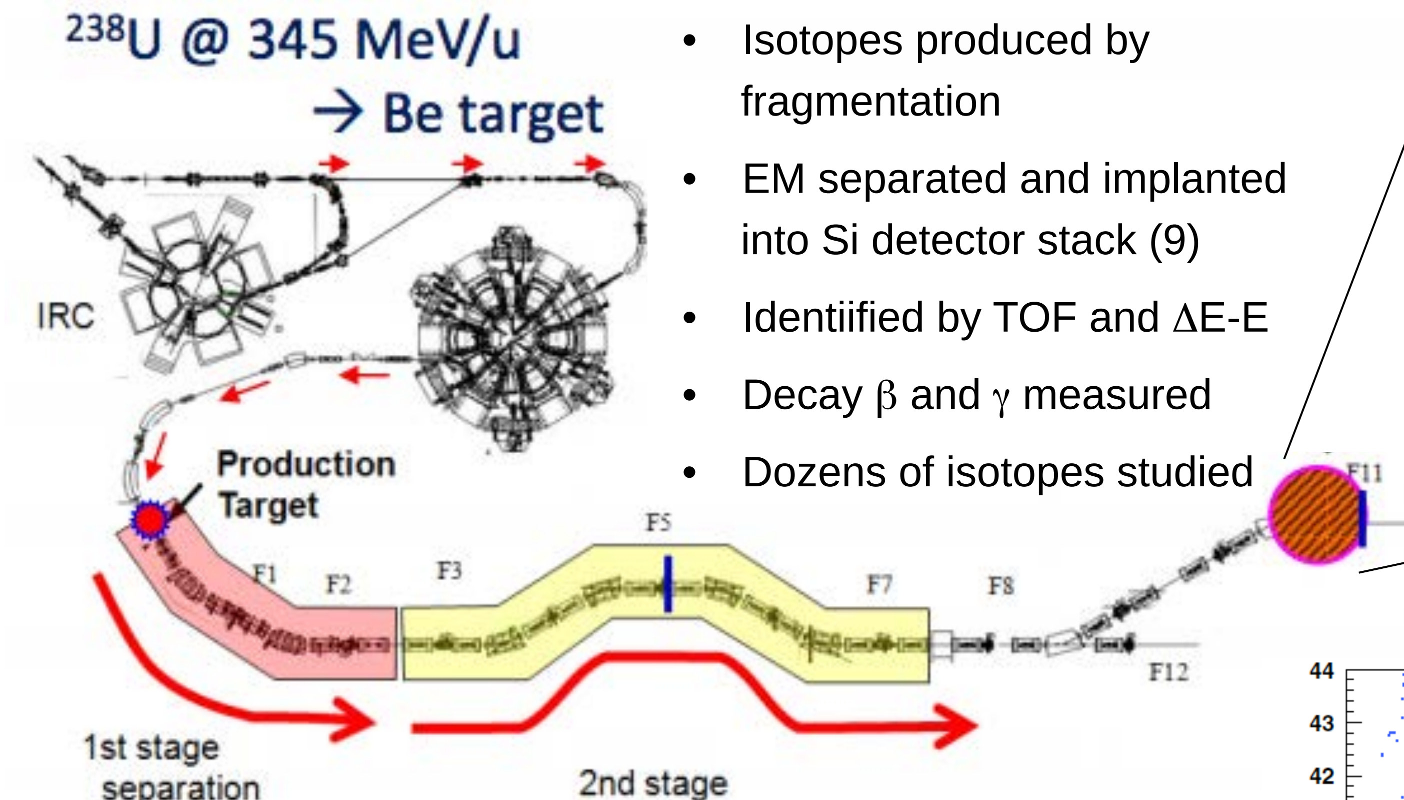
- Almost all nuclei along the r process path are important

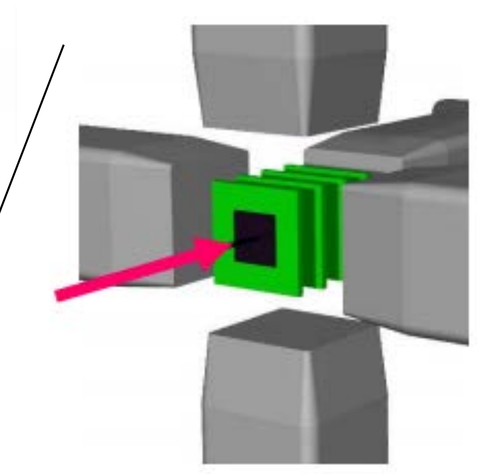
- It is crucial to produce and study these nuclei

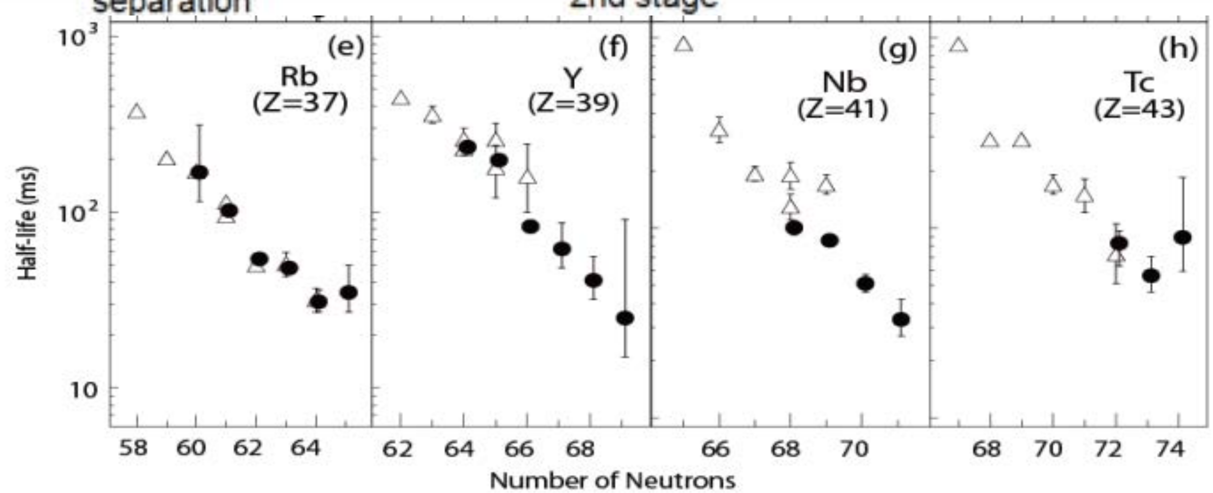


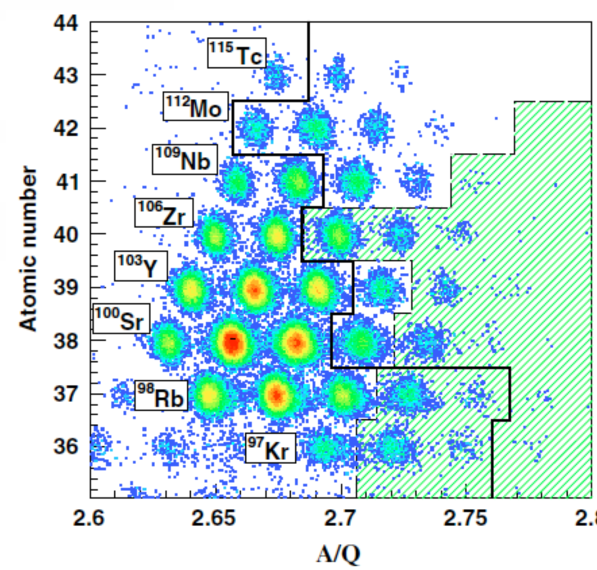
Beta Decay Example: RIBF @ RIKEN

- Isotopes produced by fragmentation
- EM separated and implanted into Si detector stack (9)
- Identiified by TOF and ΔE-E
- Decay β and γ measured
- Dozens of isotopes studied



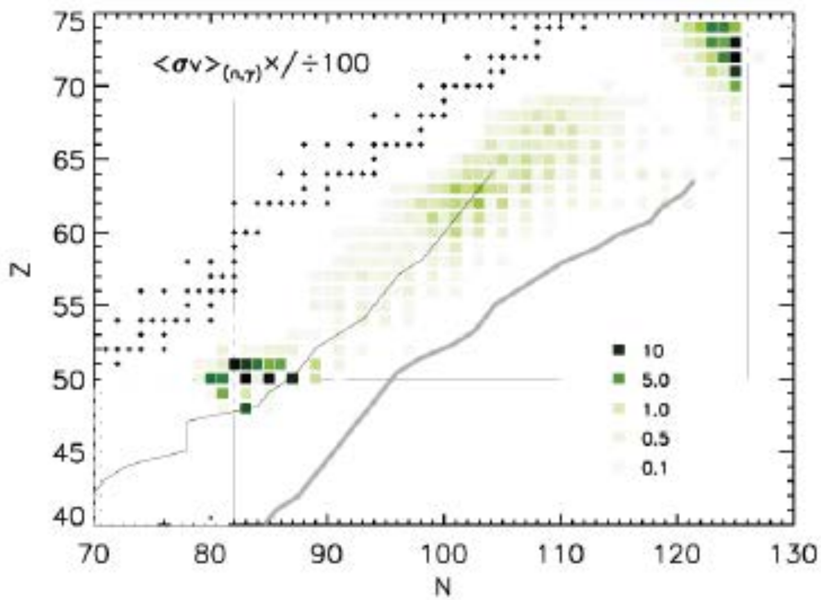


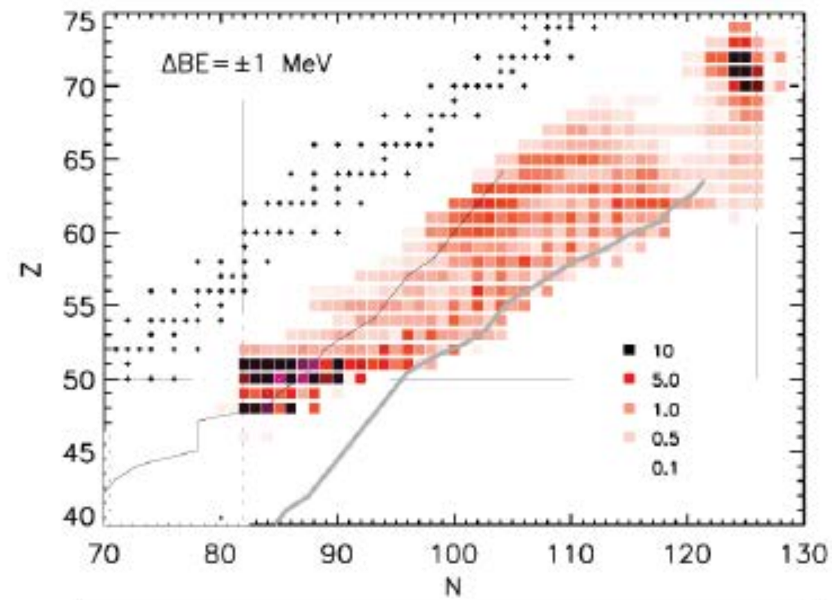




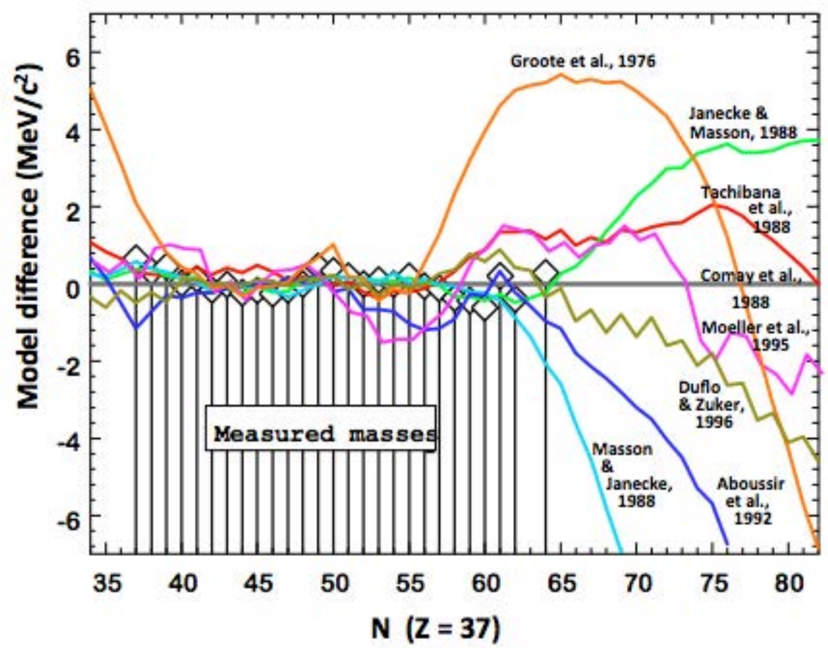
S. Nishimura *et al*., PRL **106**, 052502 (2011).

r process: masses and reaction rates



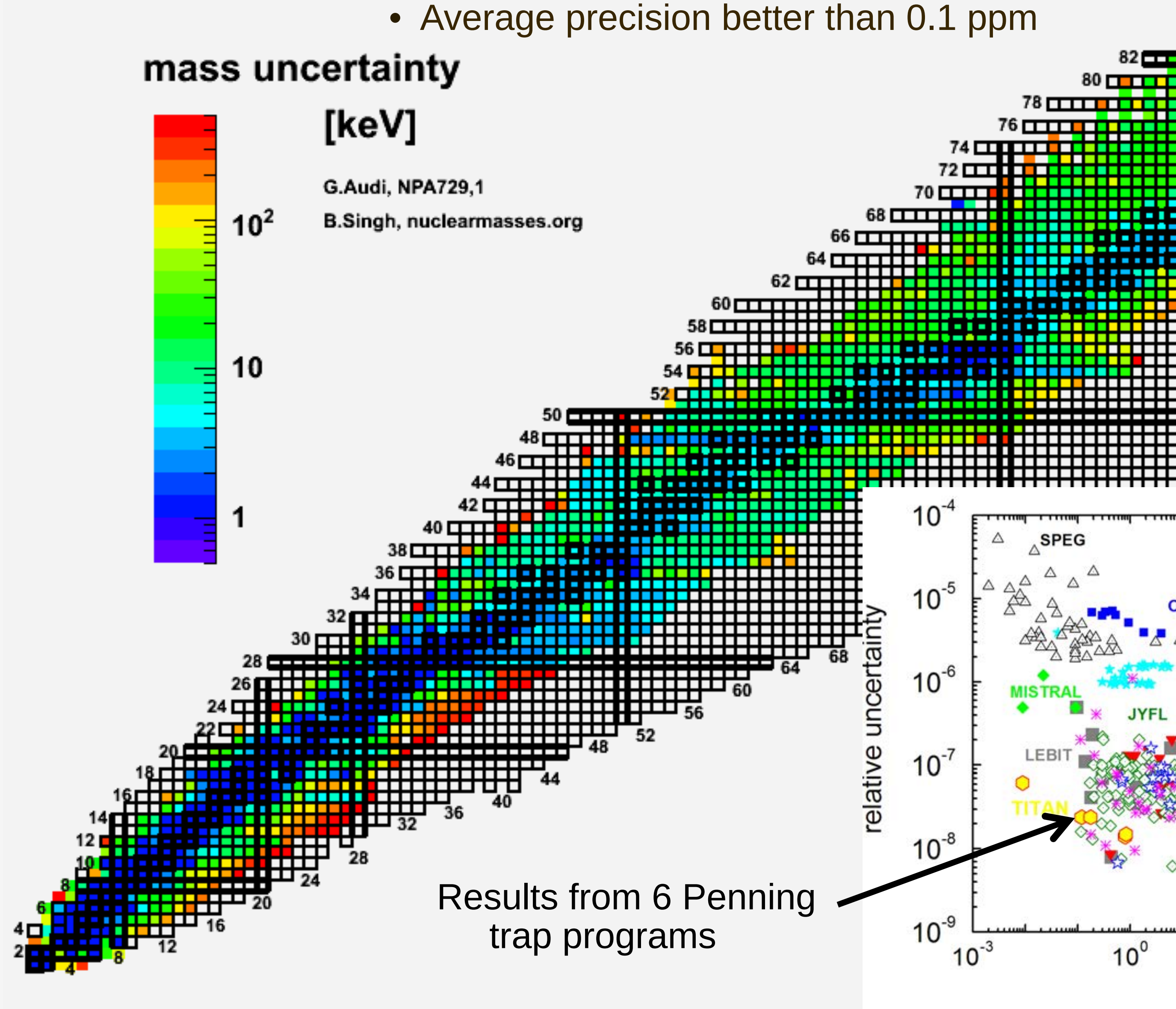


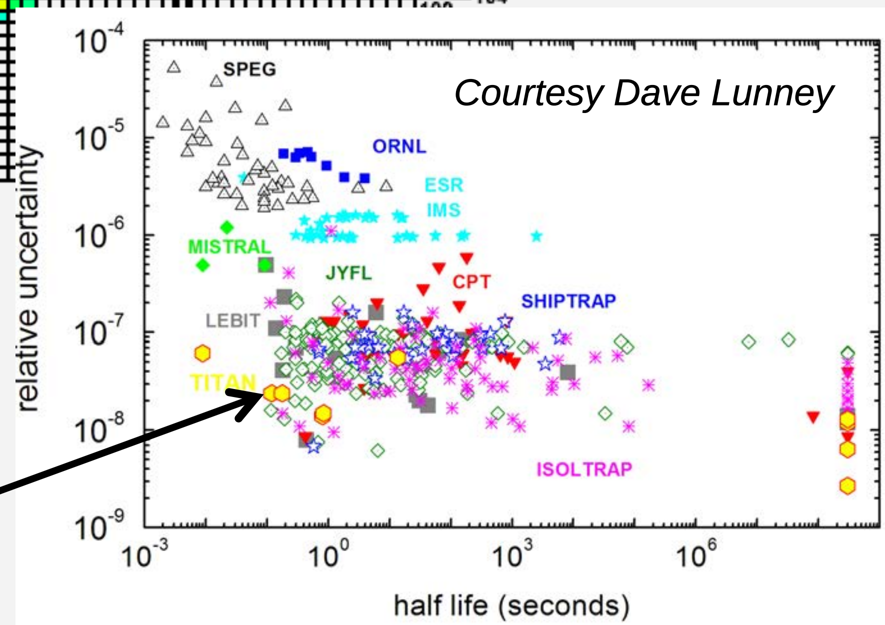
- Some (n,γ) capture rates are important
- Abundances are very sensitive to most atomic masses and becay properties
- Most mass models do not reliably extrapolate away from stability
- Need measurements of nuclear properties in neutron-rich nuclei



Atomic masses

- About 2400 isotopes have measured masses
- Average precision better than 0.1 ppm





Penning Traps: In a Nutshell

Trap electrodes in a hyperboloid geometry ($r_0/z_0 \approx 1.16$)

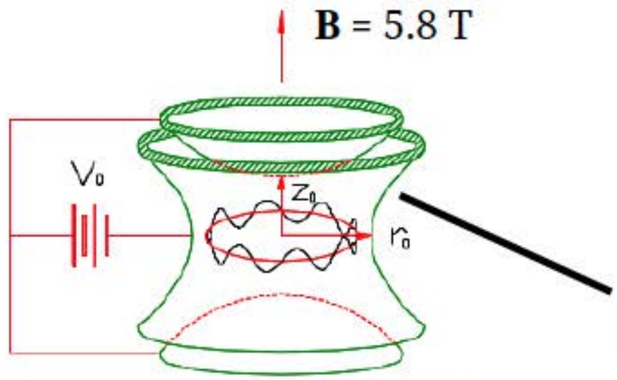
Placed inside uniform magnetic field

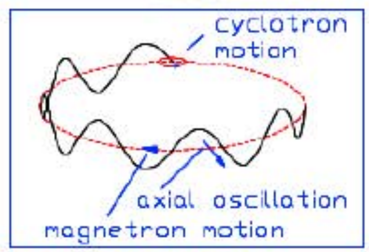
Three types of motion:
- Axial (ω_z)
- Reduced cyclotron (ω_+)
- Magnetron motion (ω_-)

Drive trapped ions into an excitation using RF signal

Ions are ejected from the trap and measure their time-of-flight to a detector

Resonant enhancement at the ion cyclotron frequency: ω_c

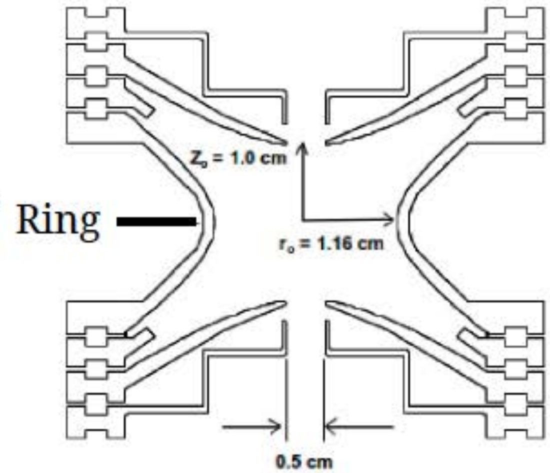




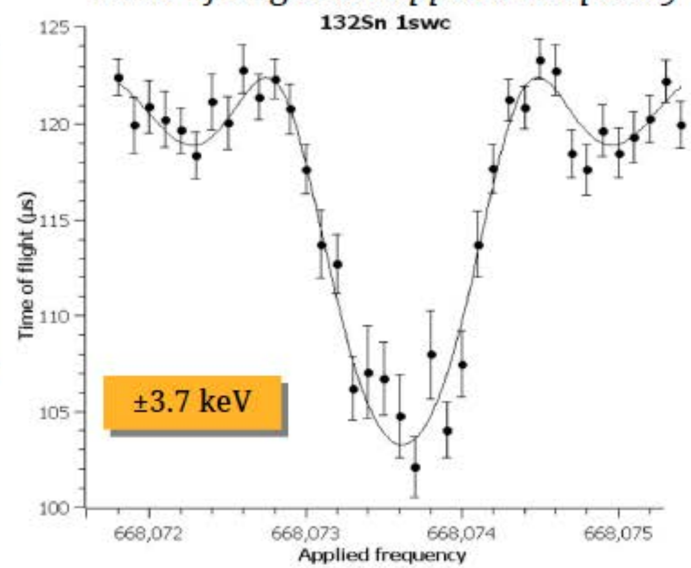
The mass of the trapped ions are measured *indirectly* by determining the cyclotron frequency:

$$\omega_c = qB/m$$

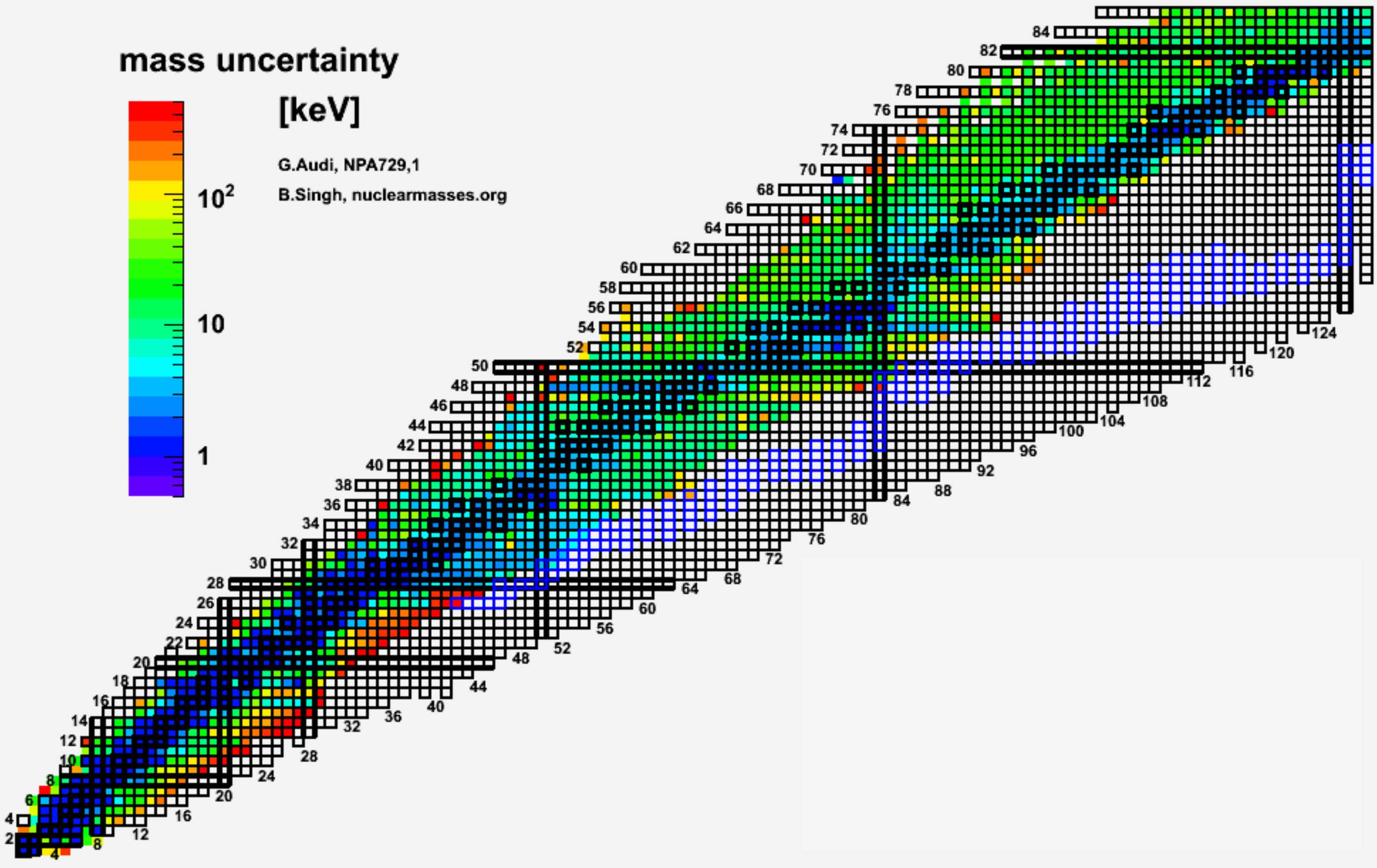
Cross section of CPT



Time-of-Flight vs. Applied Frequency

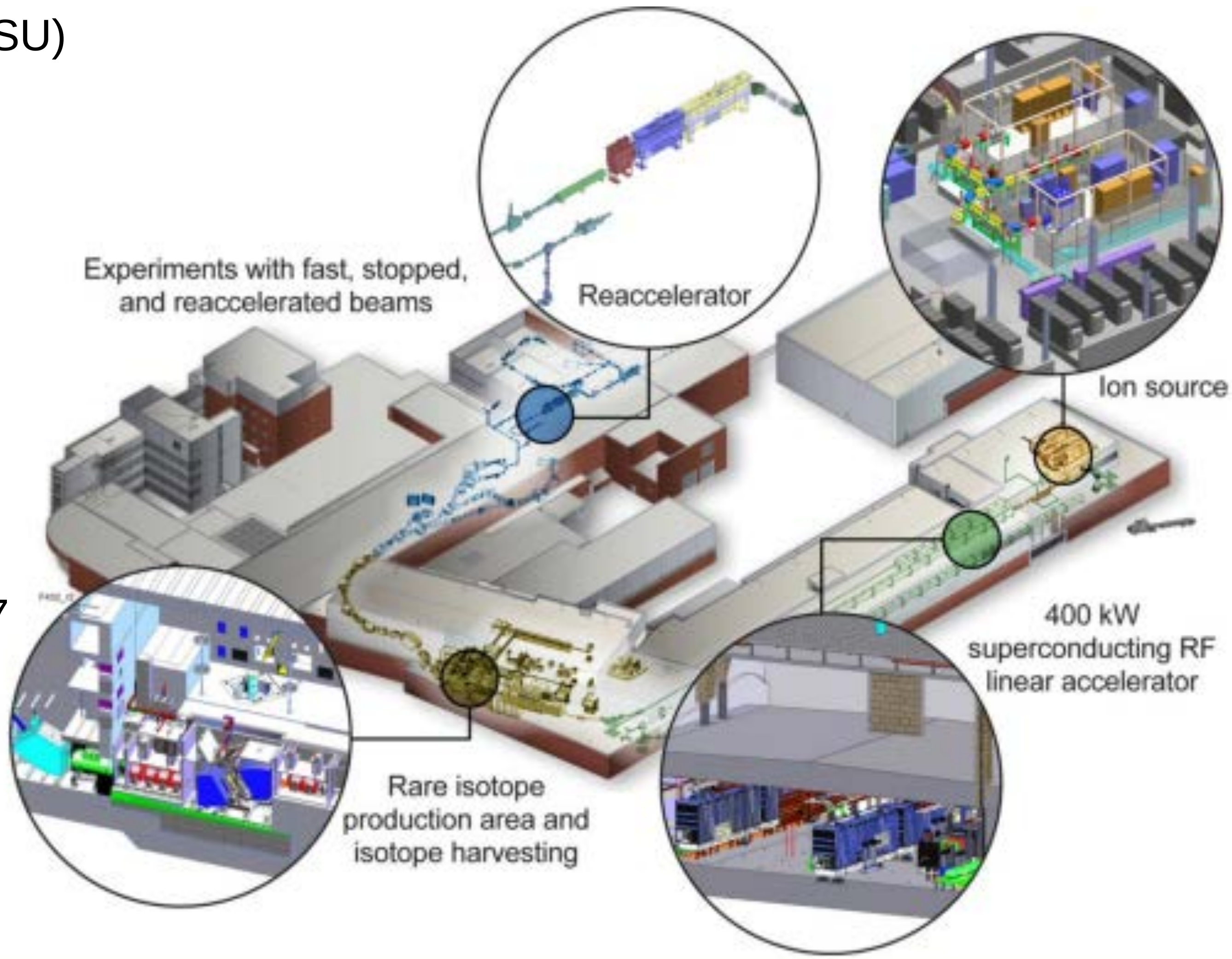


The r process

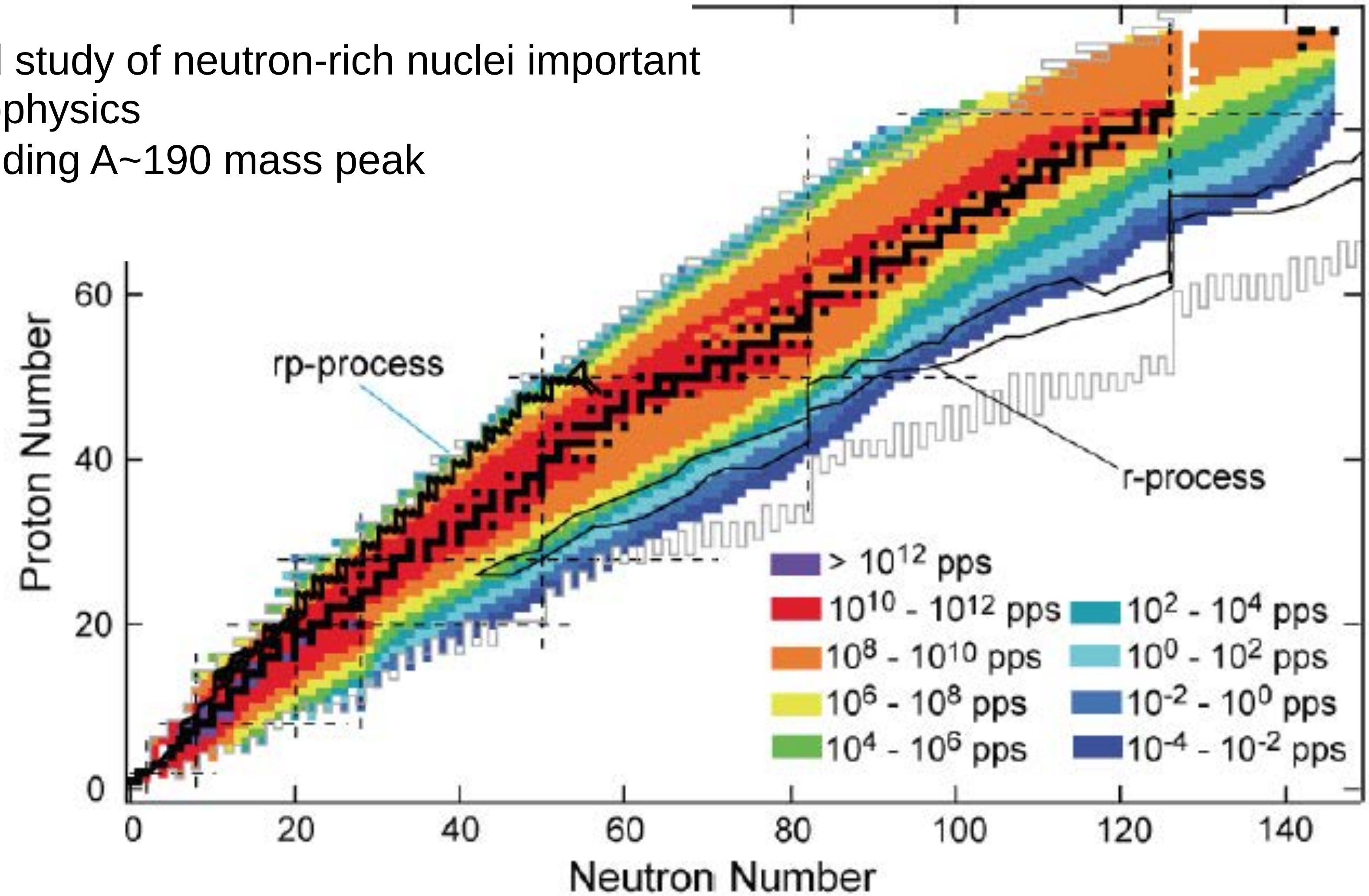


FRIB Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science
Michigan State University

- Under construction on existing NSCL Site (MSU)
- New gas stopping technology + post accelerator
- New Powerful driver LINAC
  → 200 MeV/u for U
  → 400 kW
- TPC $720M
- Civil construction completed March 2017
- CD-4 ~FY2021



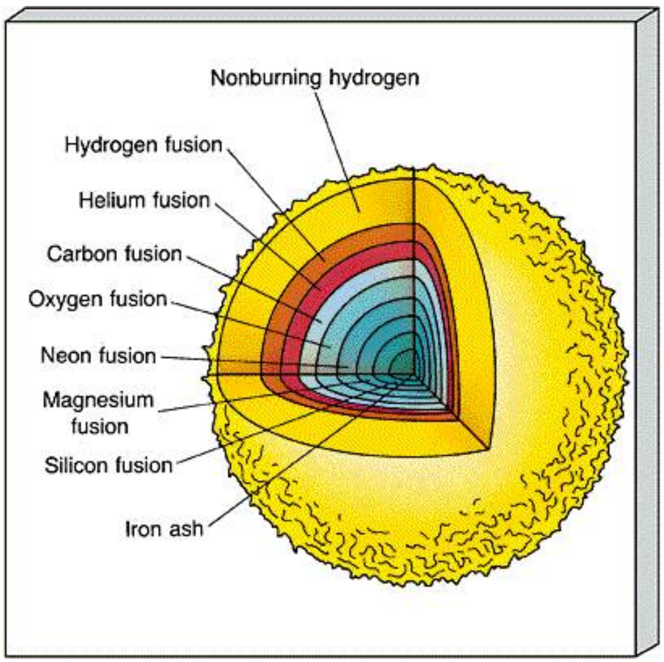
- Detailed study of neutron-rich nuclei important for astrophysics
  - Including A~190 mass peak

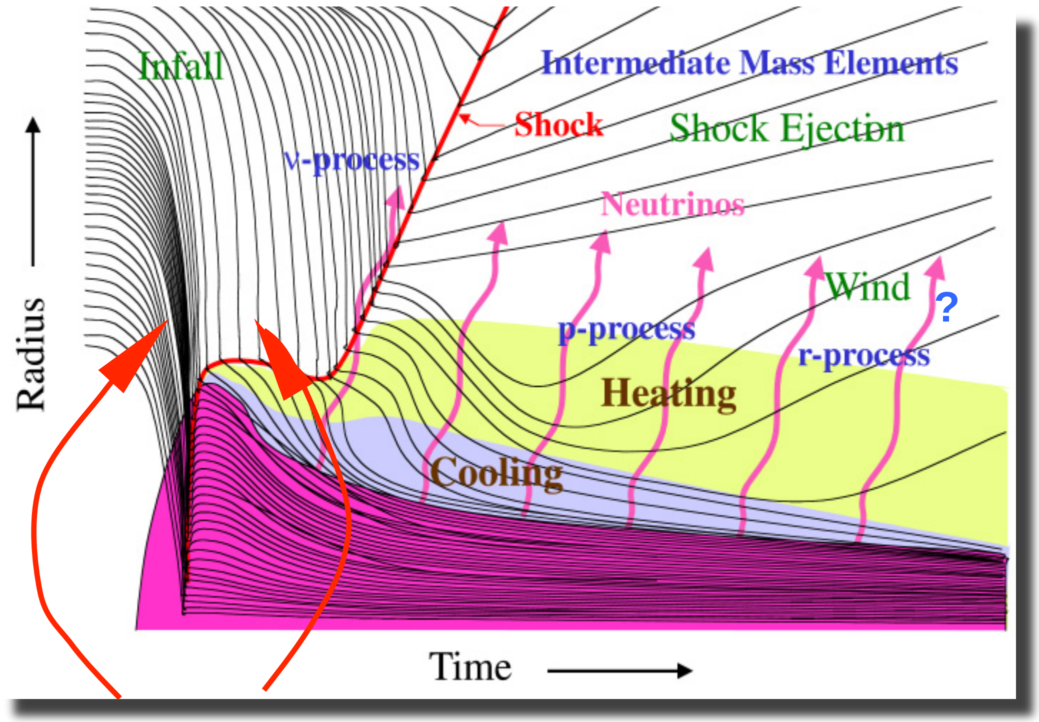


Core-Collapse Supernovae

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

C burning
O burning
Si burning
} In rapid succession

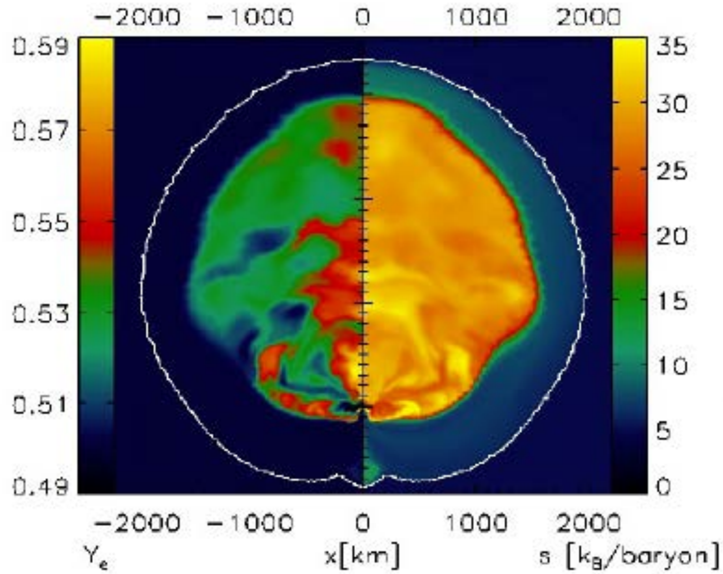




Weak interaction plays an important role

- 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



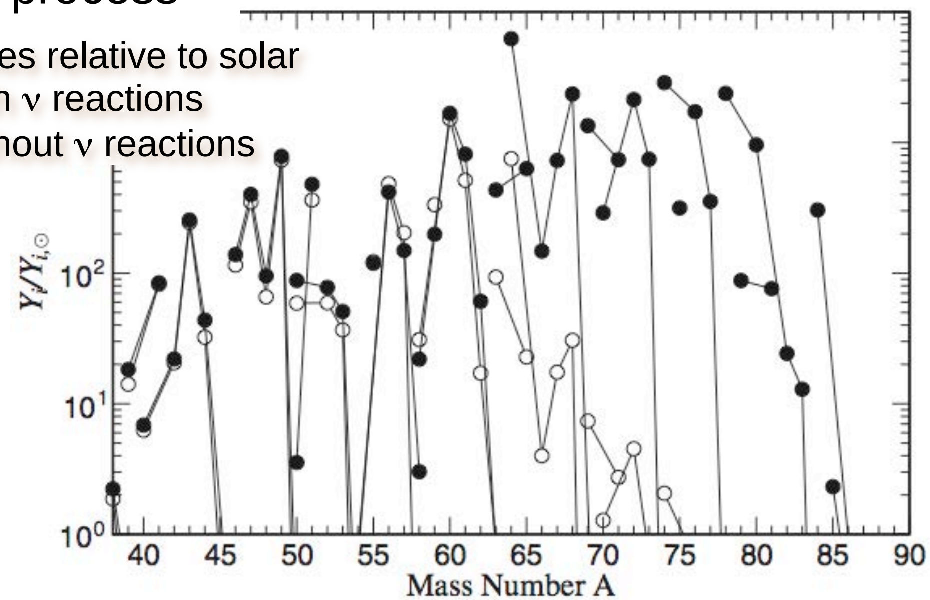
Müller, Janka et al.

- 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?

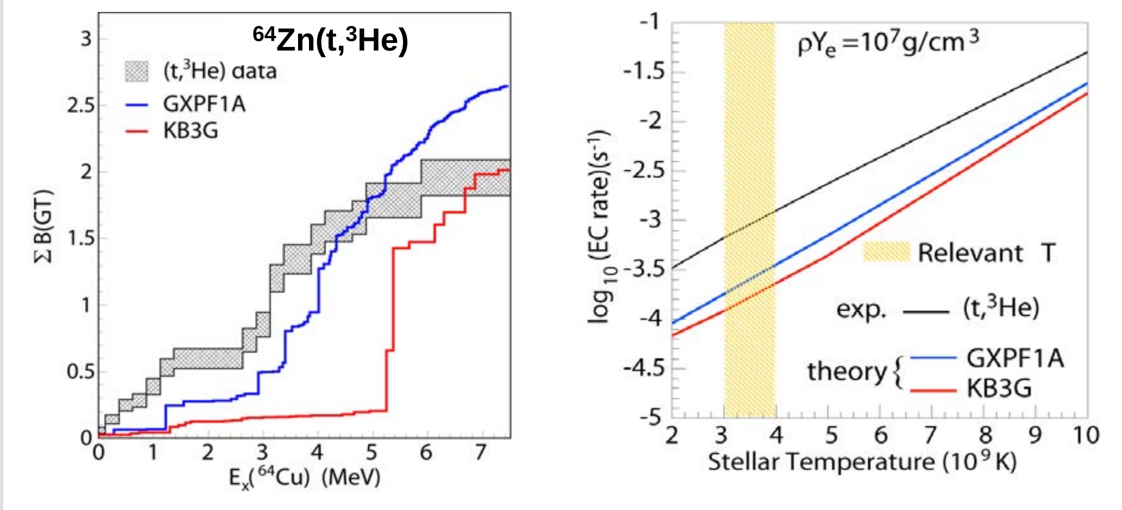
Weak interaction rates

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

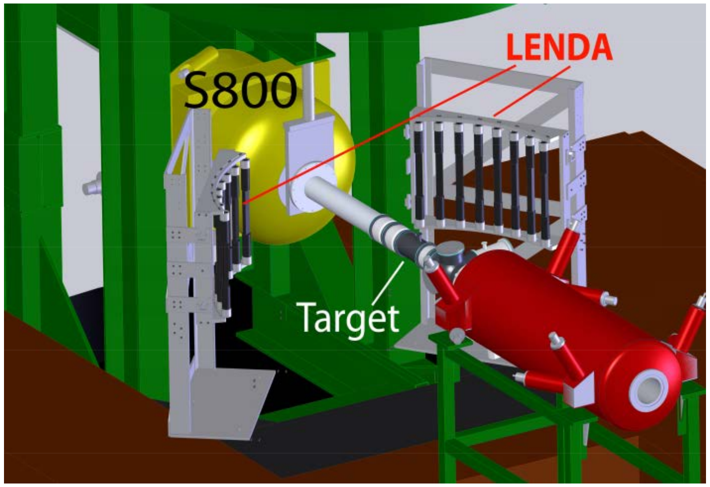
  See Langanke & Martinez-Pinedo, RMP (2003)

- 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

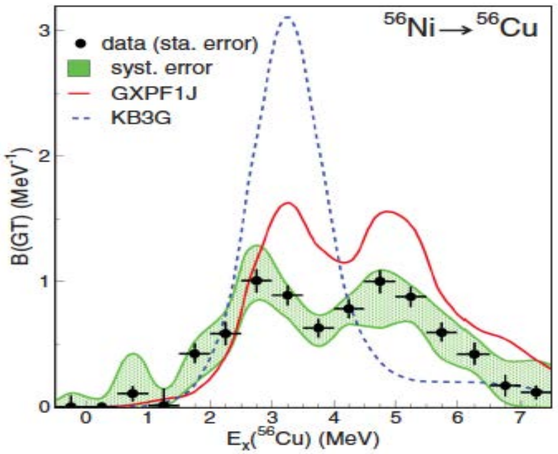
Hitt *et al*., PRC **80** (2009).



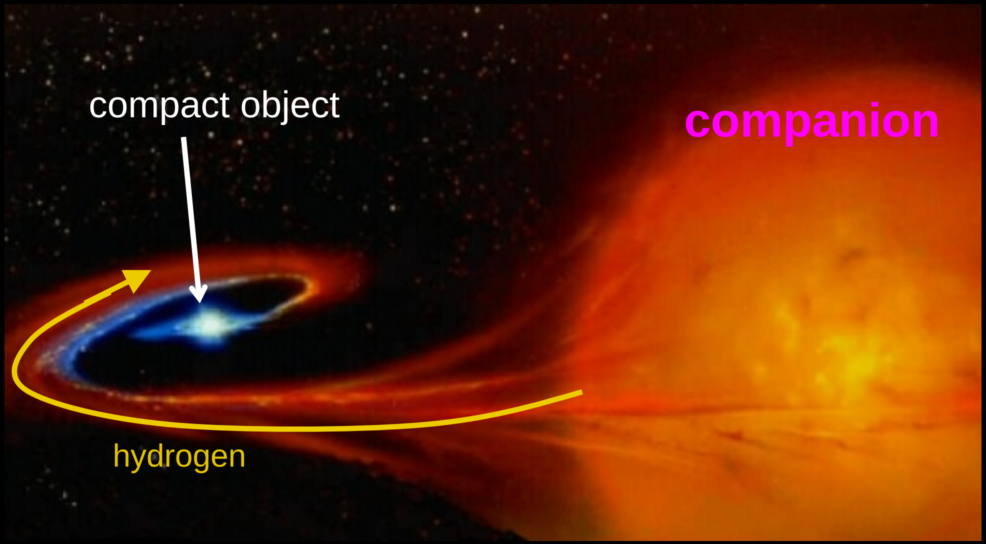
- **First measurements now with radioactive nuclei**
- (p,n) measurements using Low-Energy Neutron Detector (LENDA) developed with the S800 and radioactive beams.



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



Stellar Explosions in Binary Systems



- ➢ Most stars are in binary systems
  - ➨ Some close enough to interact (transfer mass)
- ➢ Most common thermonuclear explosions are 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

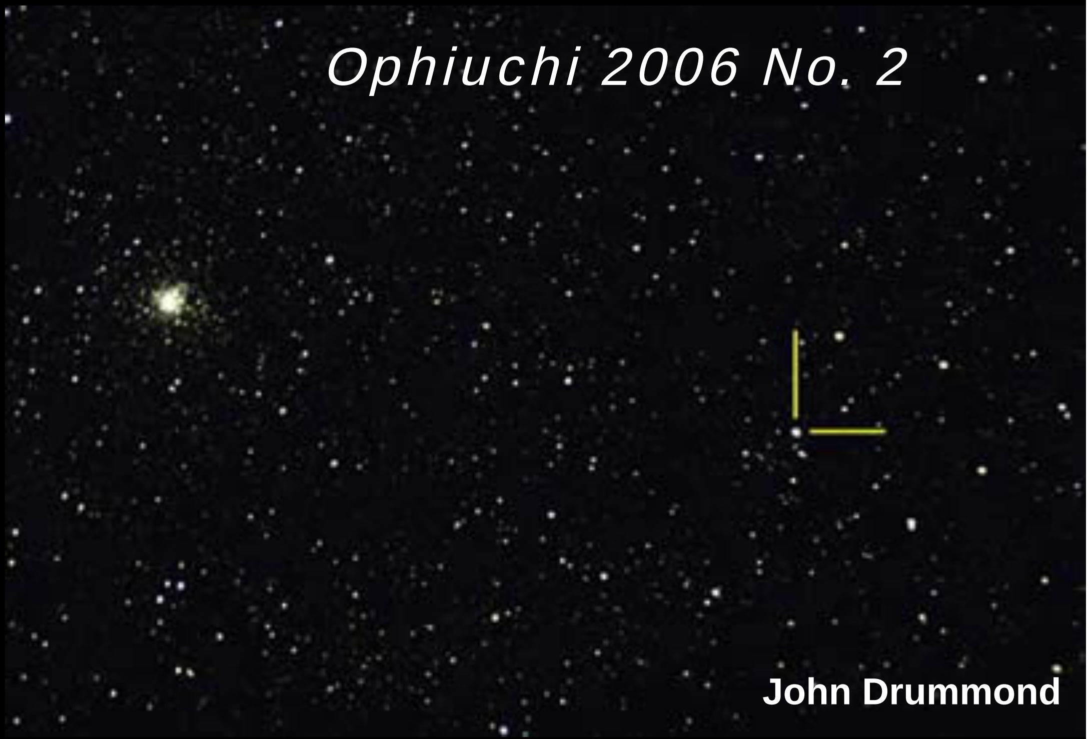
➨ Type Ia Supernovae
- White dwarf + ?
- SD? DD? Both?!
- Star completely destroyed
- Fe-group production in Galaxy (late times)

Discovering Novae

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

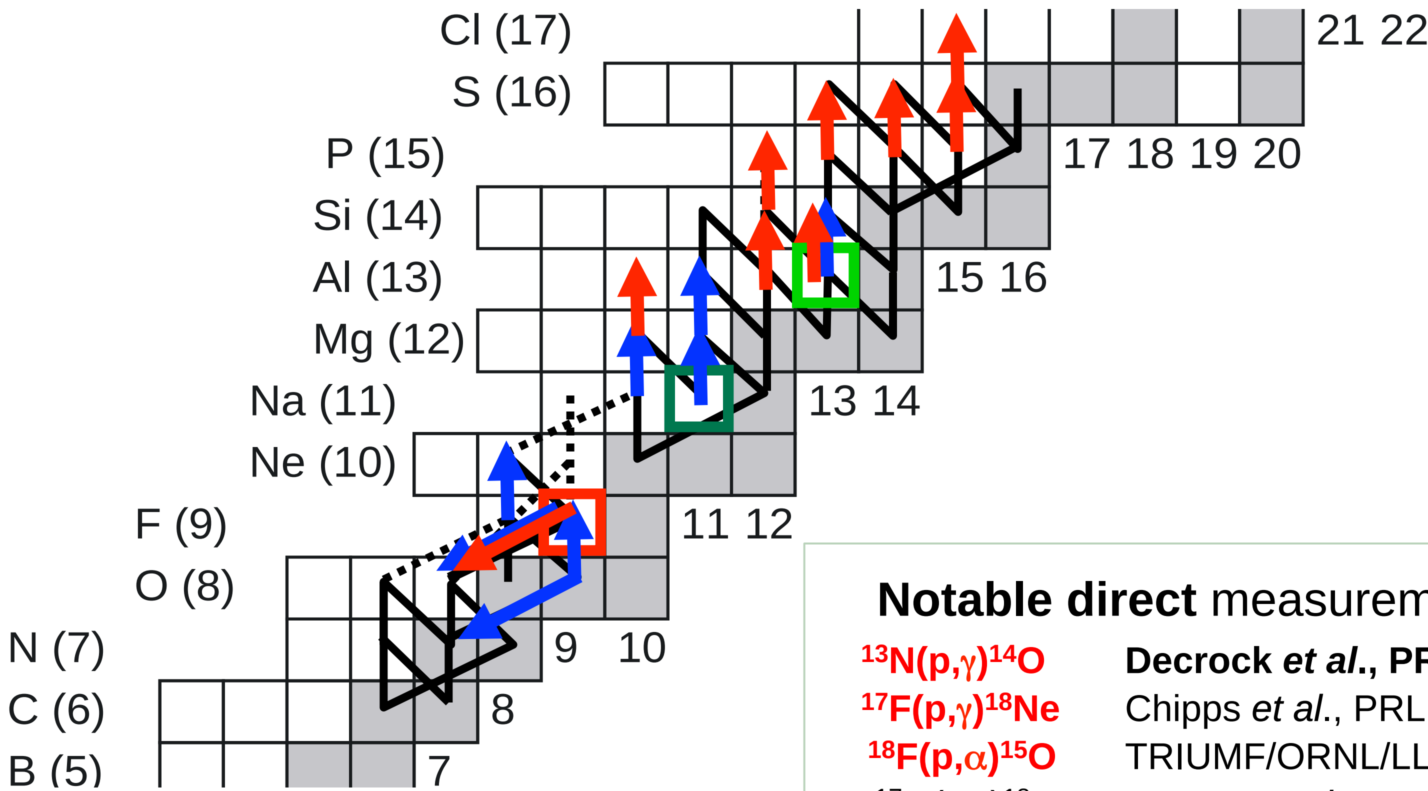
- Characterized by increase in brightness of 8-15 magnitudes (10^3-10^6 times)
  - Peak reached in < 24 h
  - Much slower decay (weeks)
  - Recur after t >1000 yr ?
  - Discovered by amateurs
  - 100's observers networking around the world
  - Usually discovered photographically

- 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

Many nova reactions have been recently determined



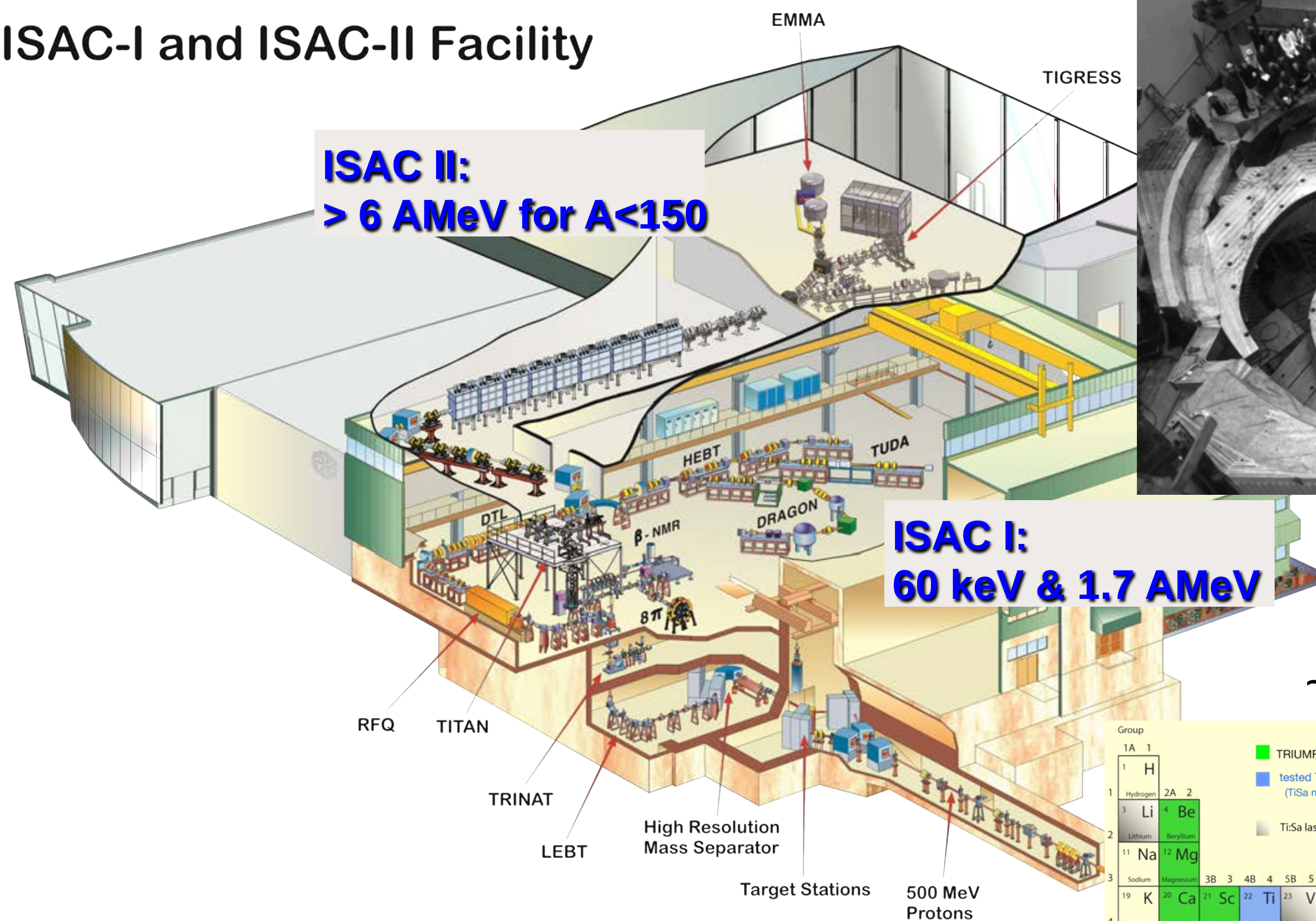
Others: ^{18}F(p,γ)^{19}Ne, ^{19}Ne(p,γ)^{20}Na, . . .

Notable direct measurements*

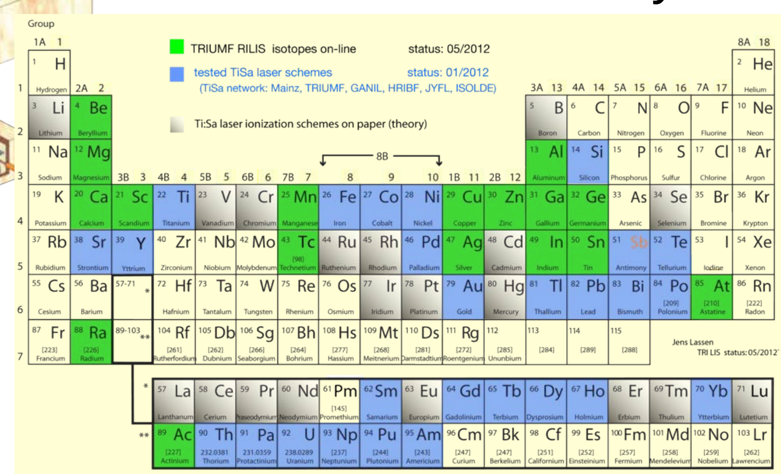
^{13}N(p,γ)^{14}O	**Decrock *et al*., PRL (1991)**
^{17}F(p,γ)^{18}Ne	Chipps *et al*., PRL (2009)
^{18}F(p,α)^{15}O	TRIUMF/ORNL/LLN/ANL
^{17}O(p,γ)^{18}F	Newton *et al*., PRC (2010).
^{21}Na(p,γ)^{22}Mg	D'Auria *et al*., PRC (2004).
^{22}Na(p,γ)^{23}Mg	Sallaska *et al*., PRL (2010).
^{23}Mg(p,γ)^{24}Al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

TRIUMF

ISAC-I and ISAC-II Facility



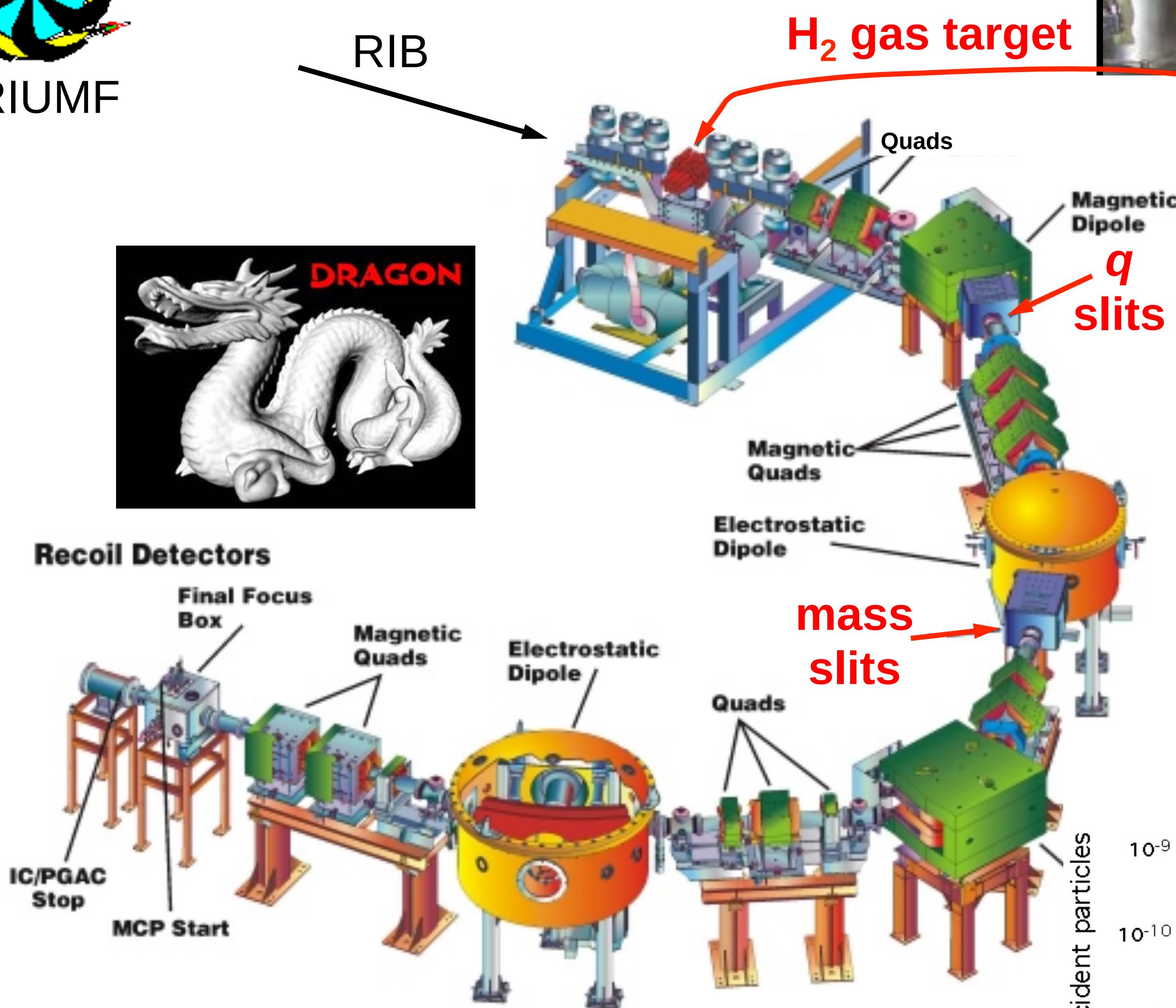
~3500 RIB hours /yr

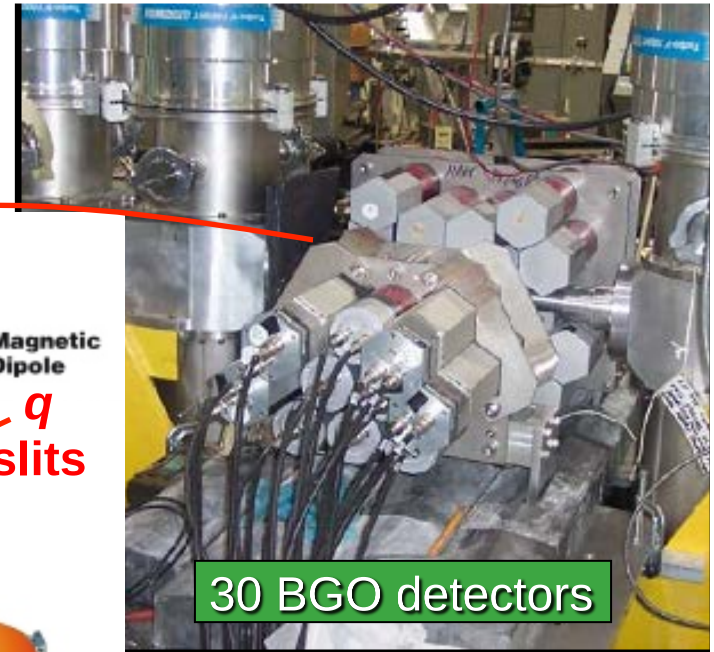


- ISOL facility with highest primary beam intensity (100 µA, 500 MeV protons)
- Now adding high intensity electron driver (ARIEL)

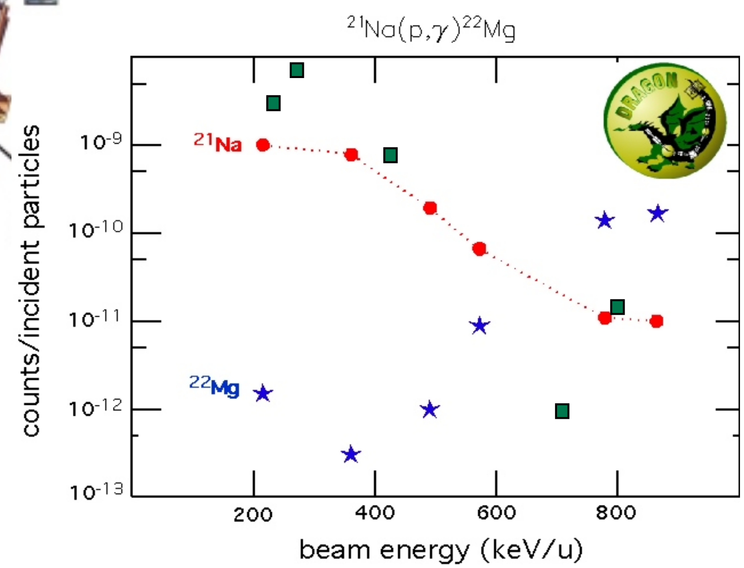
(p,γ) at ISAC

TRIUMF





recoil+γ coincidences provide sensitive selection of events



http://dragon.triumf.ca

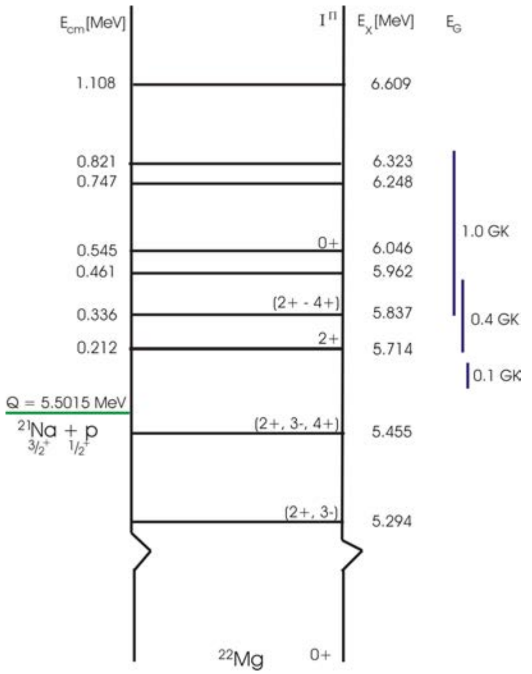
S. Engel et al., NIM ***A553*** *(2005) 491.*

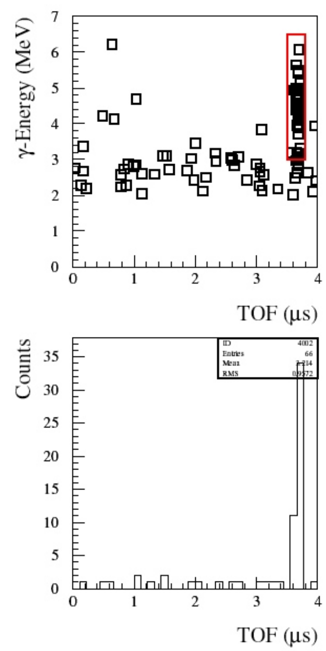
D. A. Hutcheon et al., NIM ***A498*** *(2003) 190.*

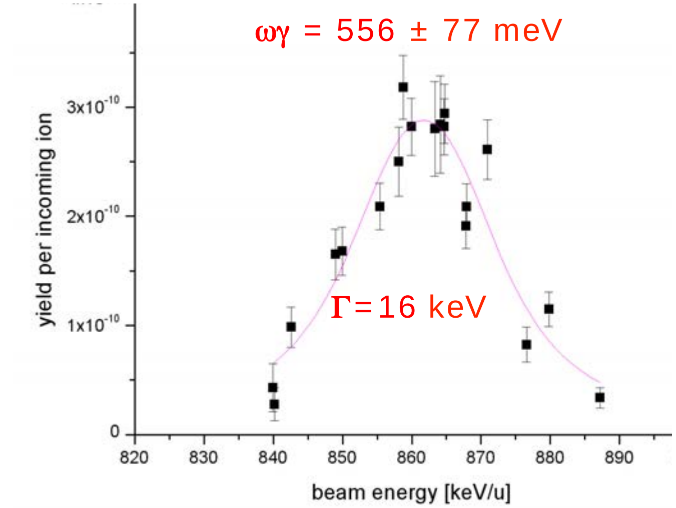
$^{21}Na(p,\gamma)^{22}Na$ with DRAGON

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

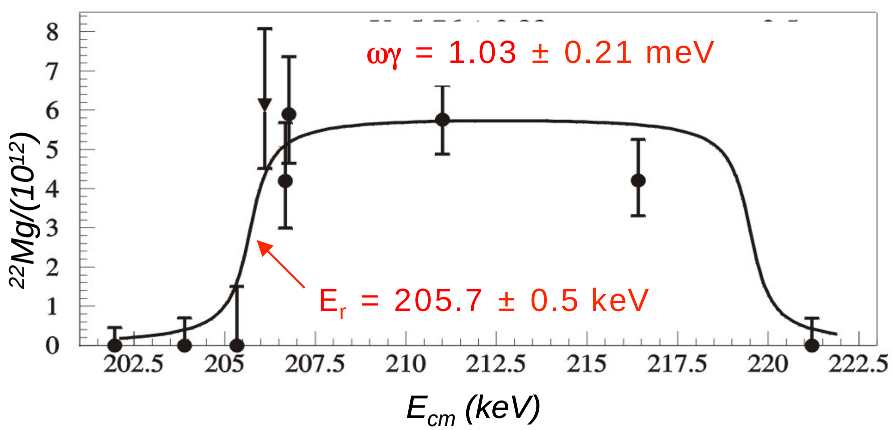
In 1999: $^{21}Na(p,\gamma)^{22}Mg$ rate uncertain by $>10^5$x *(Jose, Coc, Hernanz, ApJ520).)*





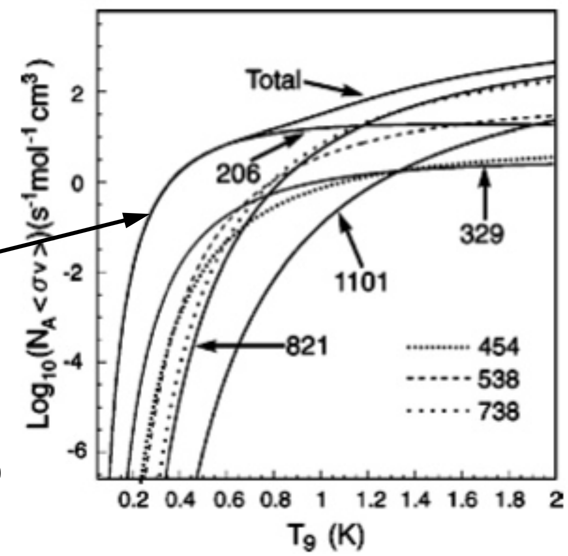


J. D'Auria et al., PRC ***69*** *(2004) 065803.*
S. Bishop et al., PRL ***90*** *(2003) 162501.*



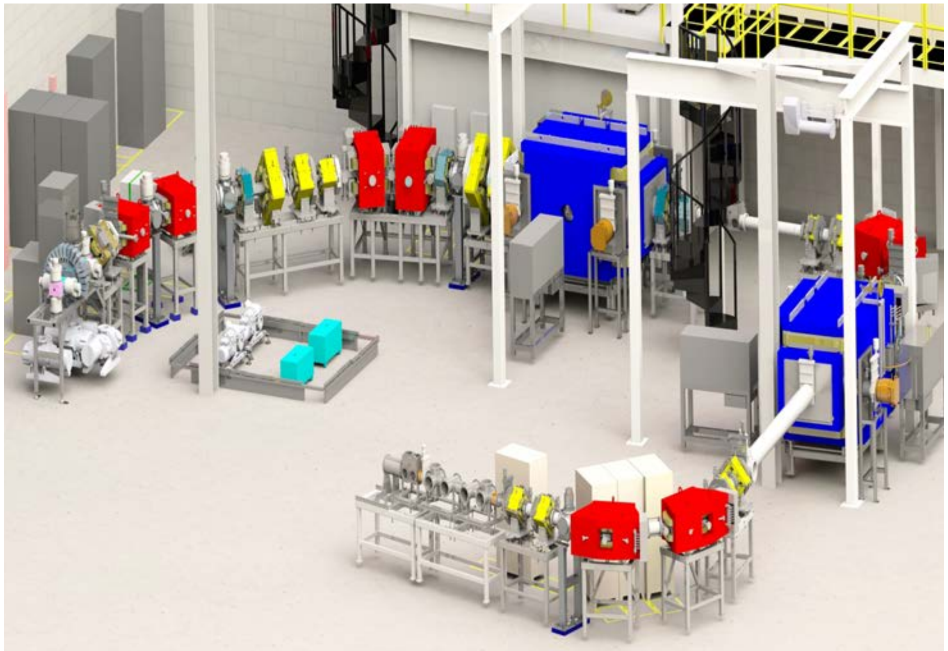
Higher rate for 206 keV resonance → ~25% less ^{22}Na

Uncertainty~25%



SEparator for CApture Reactions (SECAR)

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

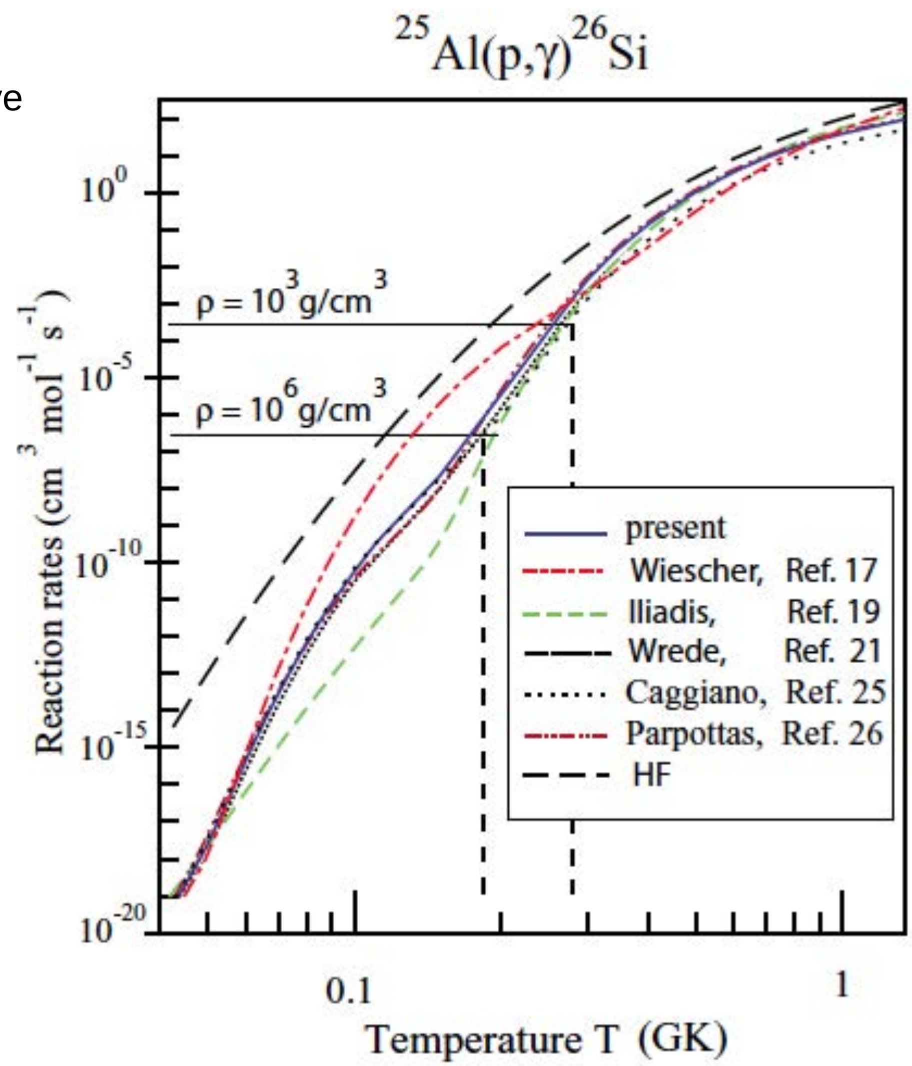


- Next-generation EM separator for direct measurements of capture reactions at FRIB
- Two Wien filter design provides high mass resolution and suppression of scattered beam
- Current under construction (DOE/NSF)
- SECAR to be commissioned in 2020
  - Will be ready for first experiments at FRIB

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

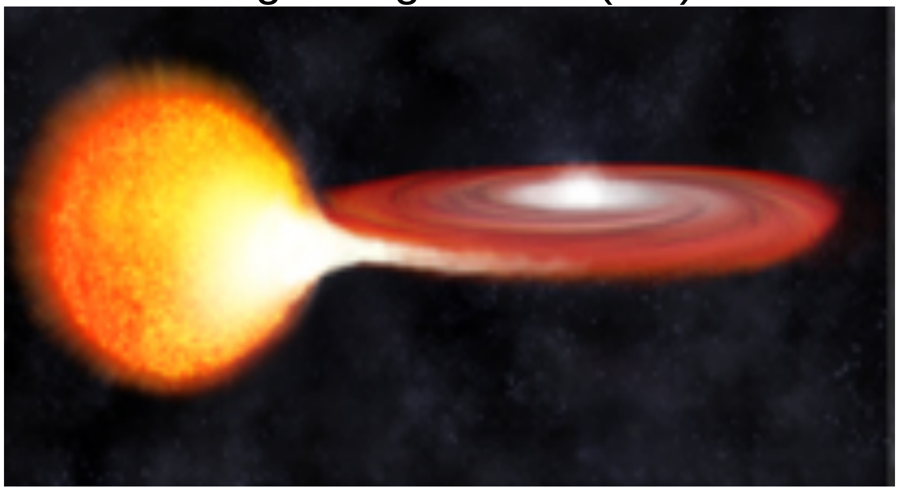
- One of most important rates for understanding ^{26}Al in novae
  - Rates depends on properties of low-lying s-wave resonances (2^+ and 3^+ states in ^{26}Si)

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

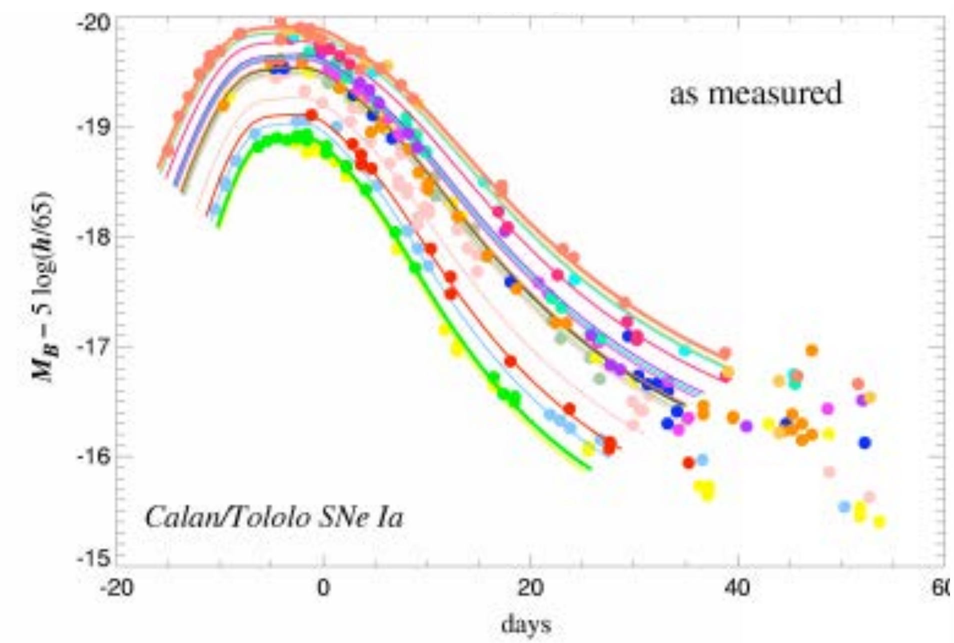


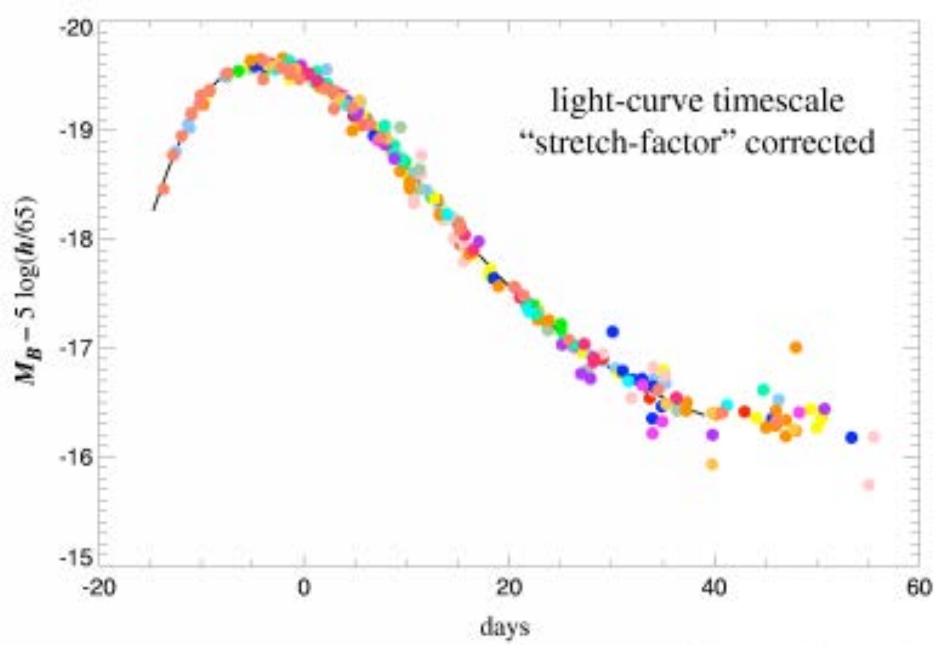
Type Ia Supernovae

Single Degenerate (SD)



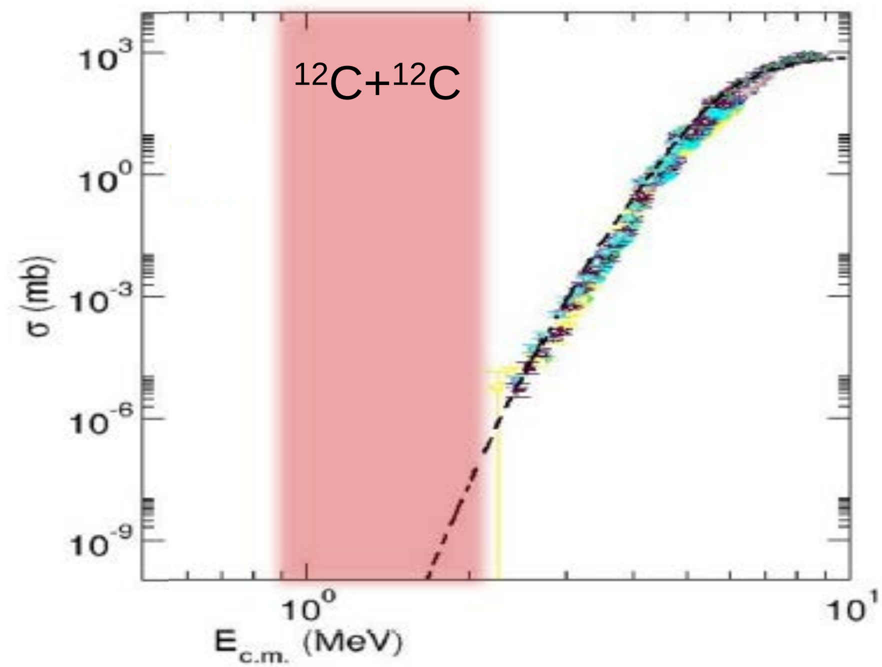
Double Degenerate (DD)

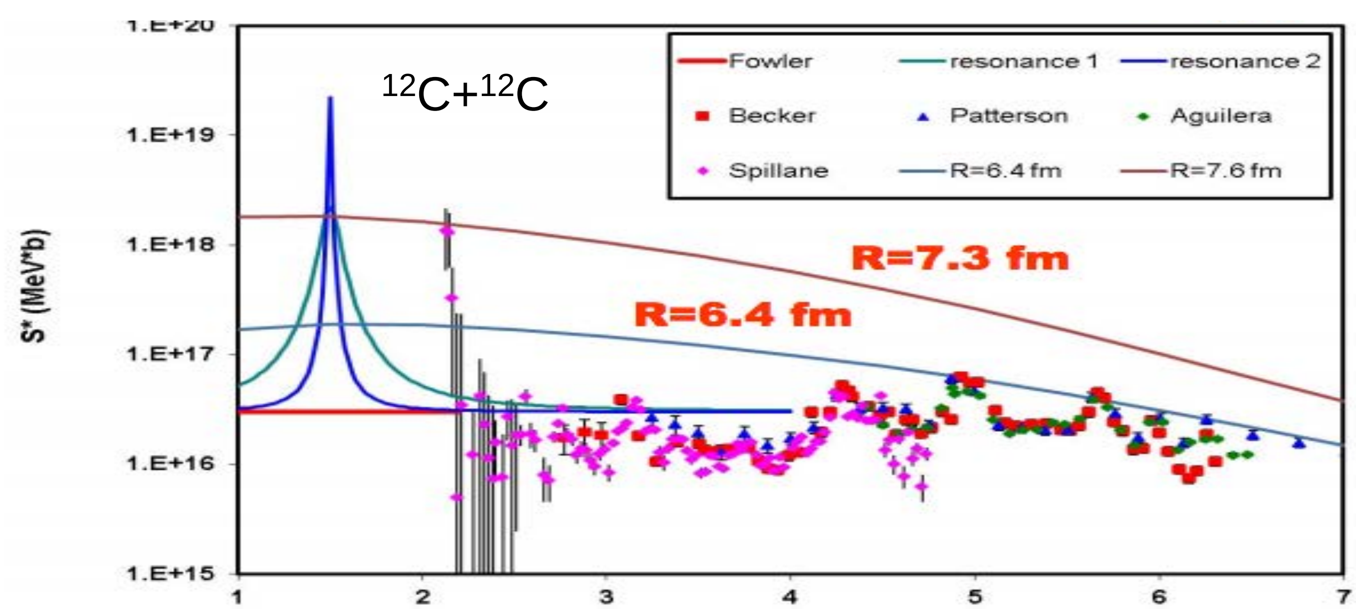




Nuclear physics of Type Ia

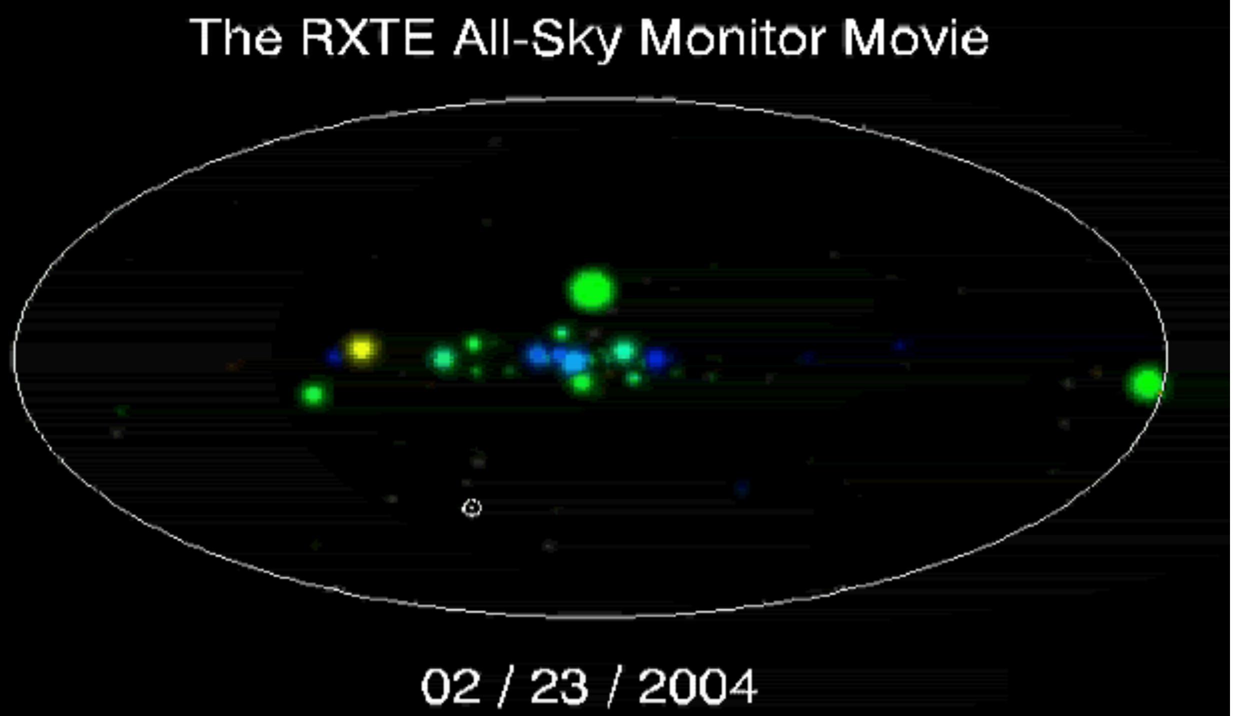
- Most important nuclear physics is fusion of C,O, Ne nuclei
    - $^{12}C+^{12}C \rightarrow$
    - $^{12}C+^{16}O \rightarrow$
- Measurements needed to lower energies
- Resonances could contribute in a few cases





X-ray vision

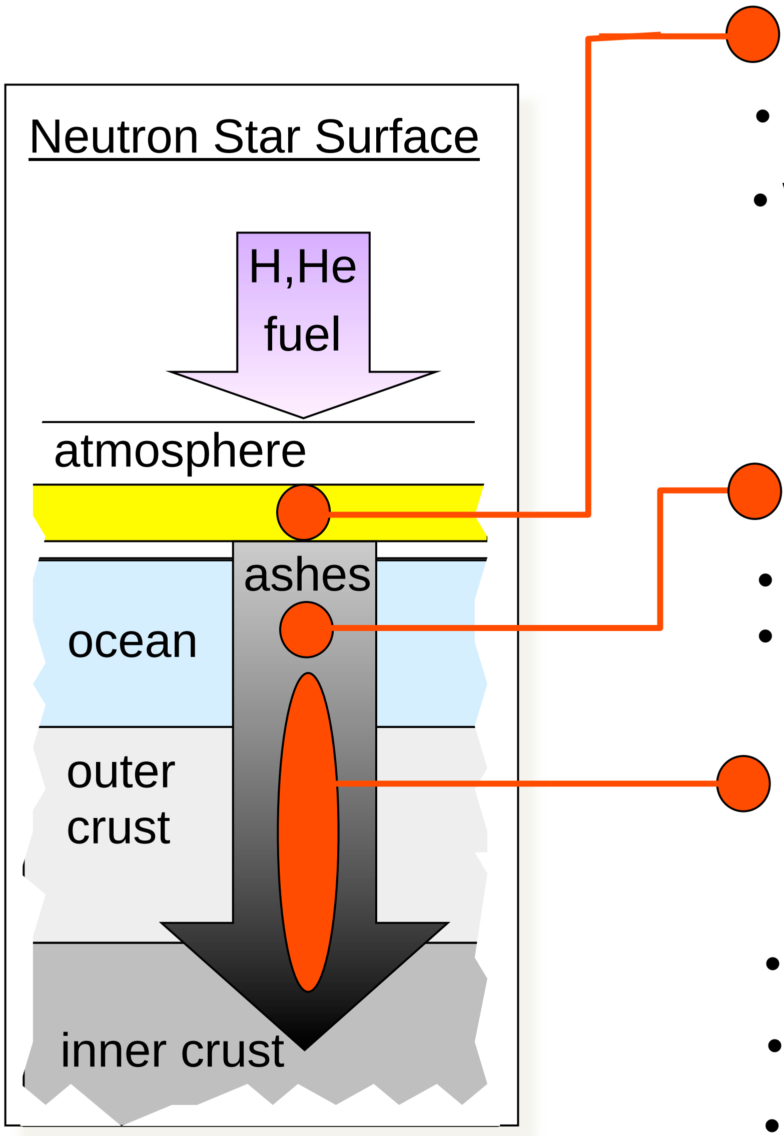
RXTE
Rossi X-ray Timing Explorer



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

Neutron star reactions



- Why do burst durations vary ? (10s – min)
- What nuclei are made in the explosion ?
  - Galactic nucleosynthesis contribution ?
  - Start composition for deeper processes ?

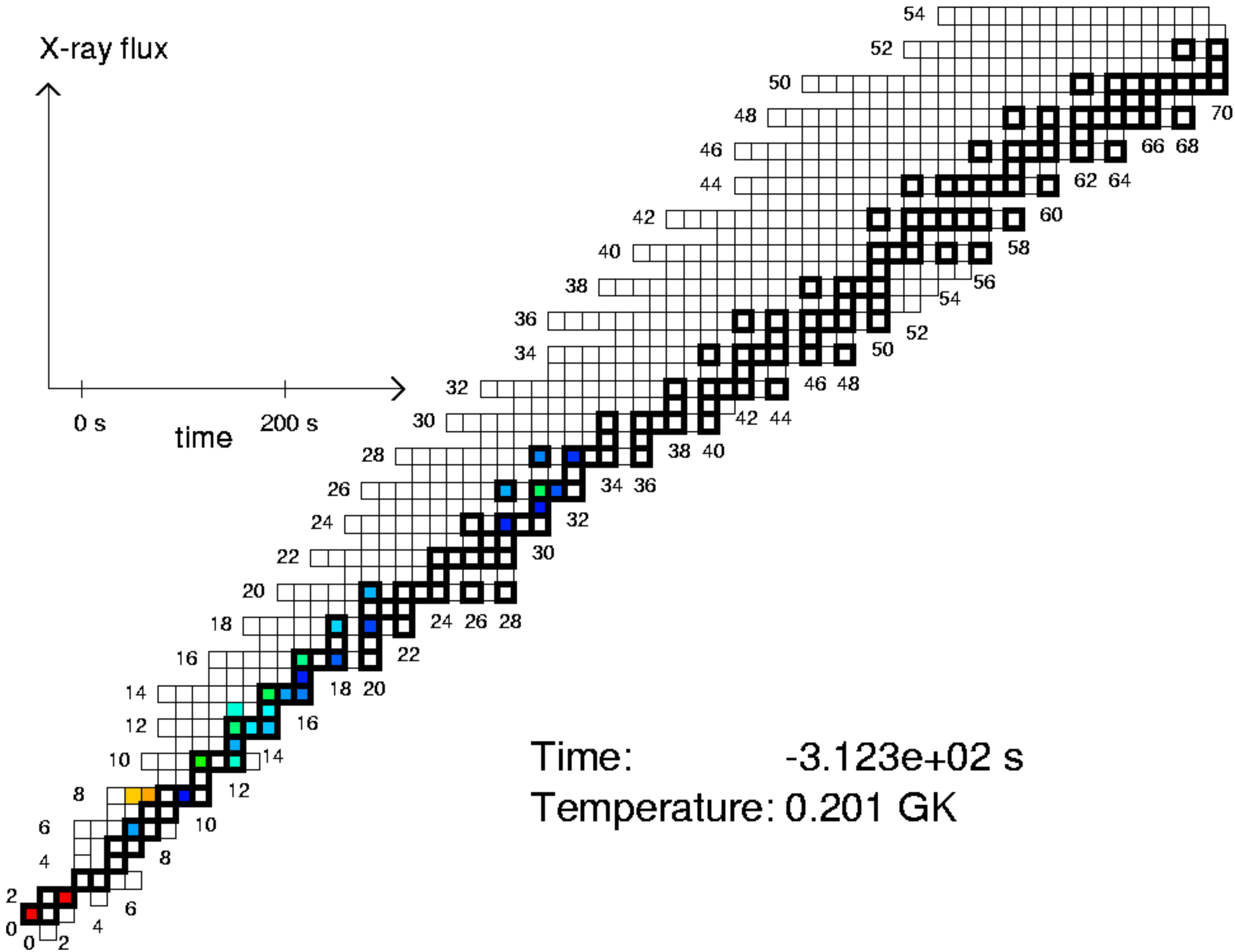
Deep H, C, … burning

- Origin of Flares ?
- Origin of Superbursts ?

Electron captures

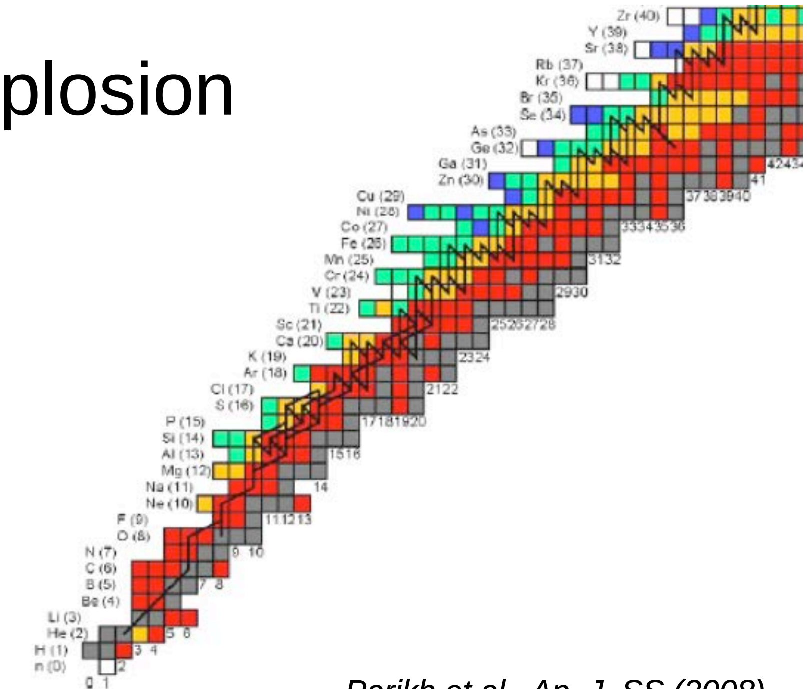
Pycnonuclear reactions

- Gravitational wave emission ?
- Crust heating ?
- Dissipation of magnetic fields ?


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

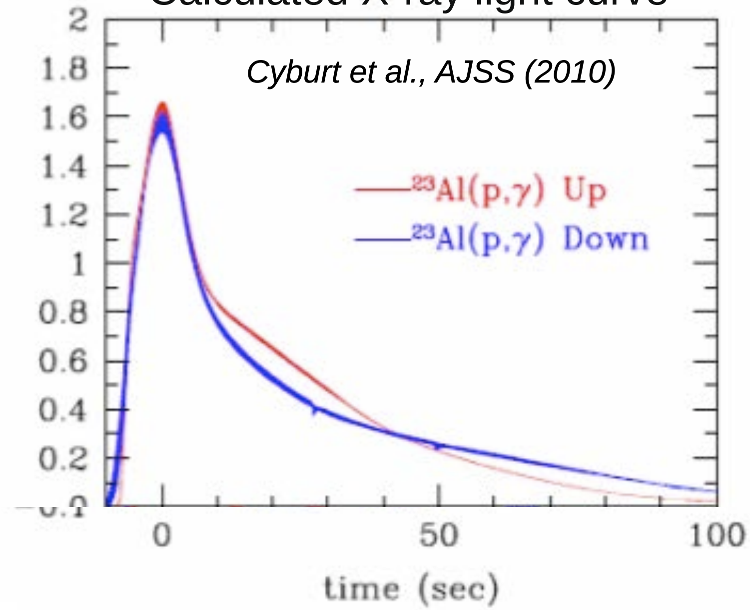
Nuclear reactions drive explosion

- 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

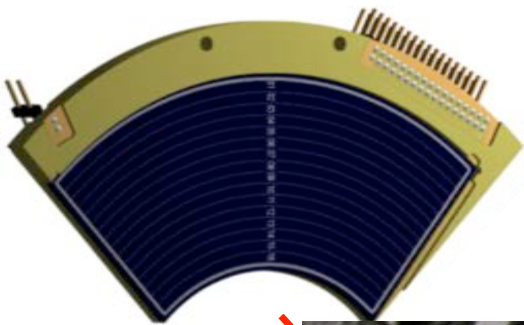


Reaction	Models affected
^{15}O(α, γ)^{19}Ne[a]	K04, K04-B1, K04-B6
^{18}Ne(α, p)^{21}Na[a]	K04-B1, K04-B6
^{22}Mg(α, p)^{25}Al	F08
^{23}Al(p, γ)^{24}Si	K04-B1
^{24}Mg(α, p)^{27}Al[a]	K04-B2
^{26g}Al(p, γ)^{27}Si[a]	F08
^{28}Si(α, p)^{31}P[a]	K04-B4
^{30}S(α, p)^{33}Cl	K04-B4, K04-B5
^{31}Cl(p, γ)^{32}Ar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

(α,p) with active gas target

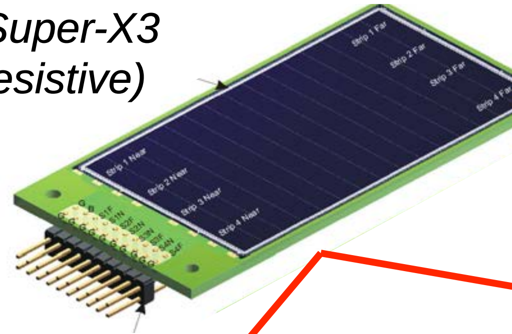
NSF MRI

Array for Nuclear Astrophysics and Structure with Exotic Nuclei

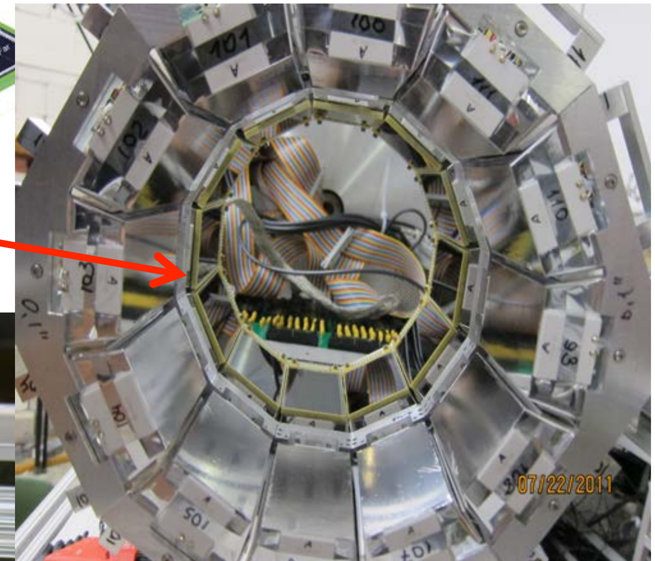


New QQQ (16x16)

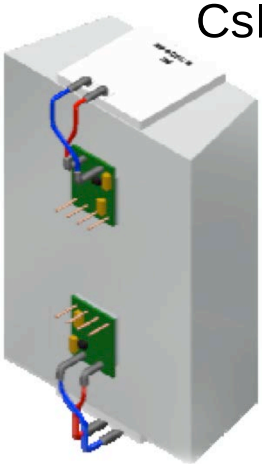
2x12 Super-X3 (4x4Resistive)

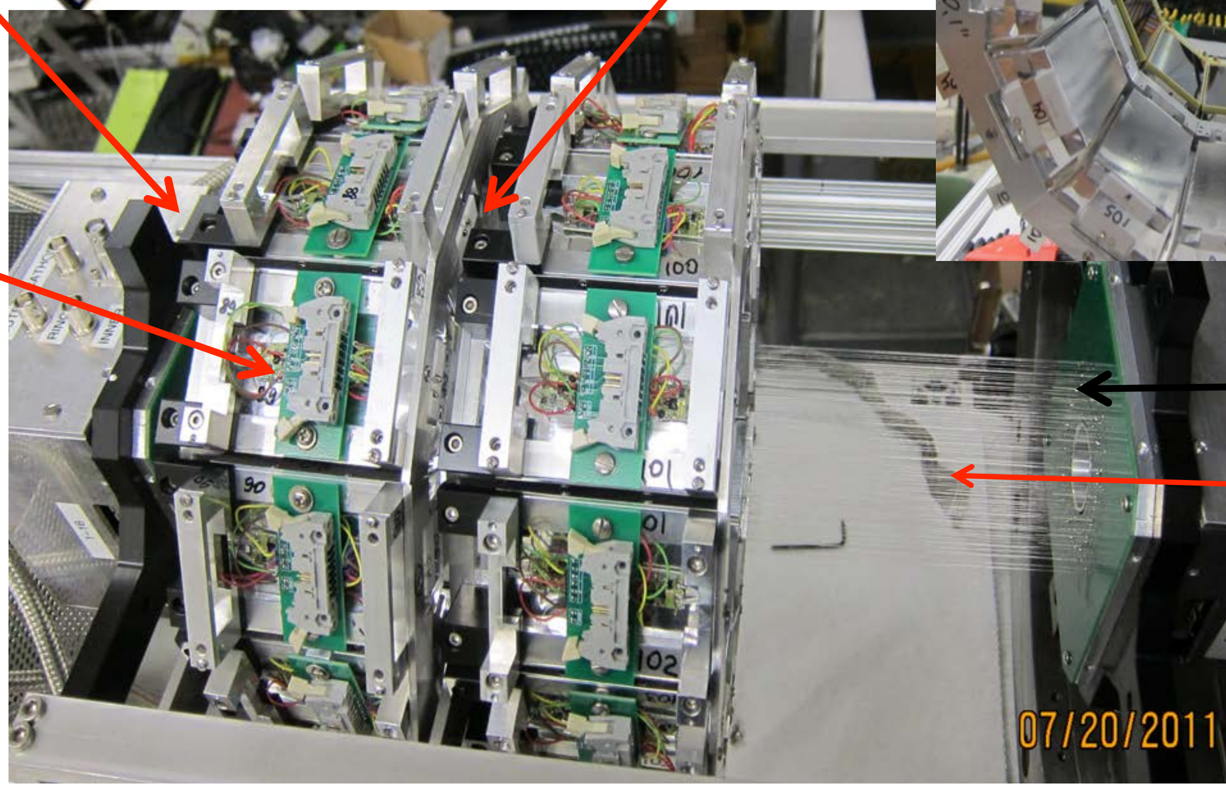


End View w/o PC



CsI





PC wires

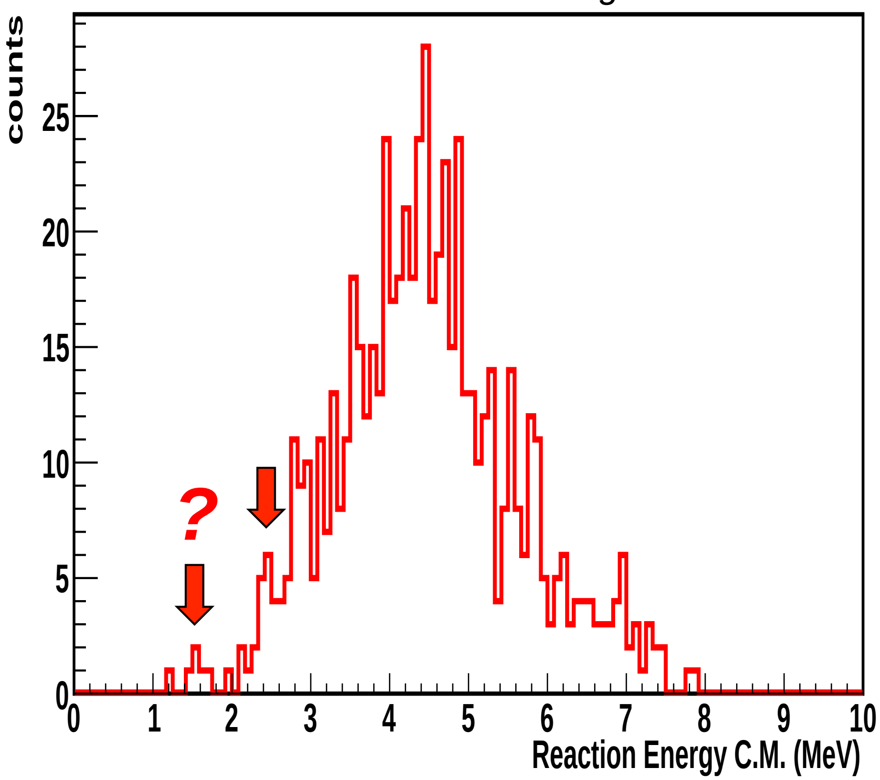
Beam

window

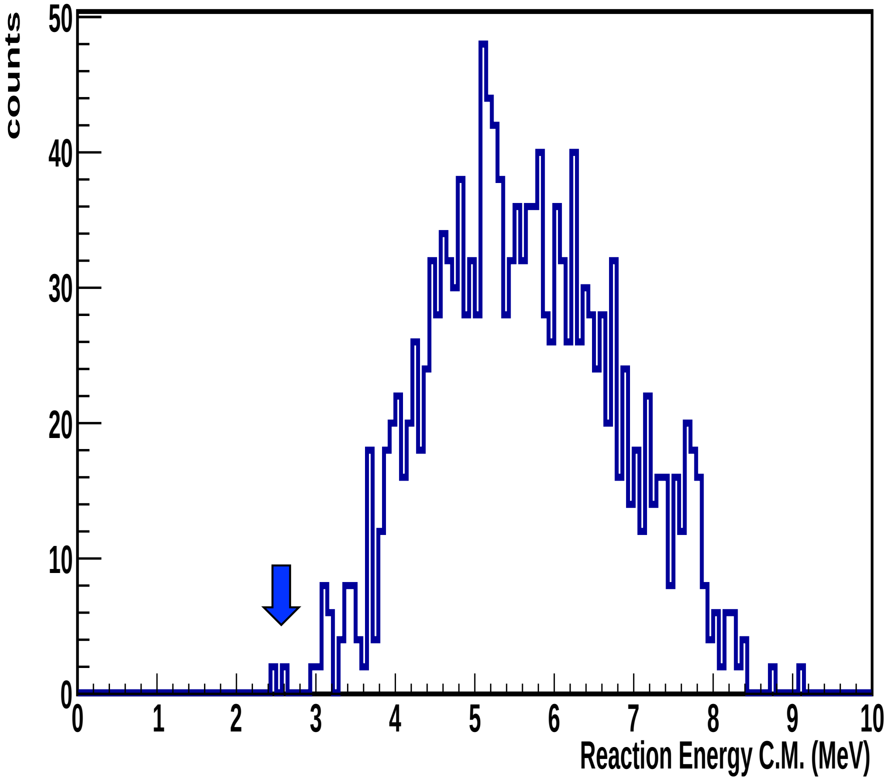
Side View

$^{18}Ne(\alpha,p)^{21}Na$ vs. $^{18}Ne(\alpha,2p)^{20}Ne$

$^{18}Ne(\alpha,p)^{21}Na_{gs}$



$^{18}Ne(\alpha,2p)^{20}Ne$



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