nuclear astrophysics experiments

exotic beam studies

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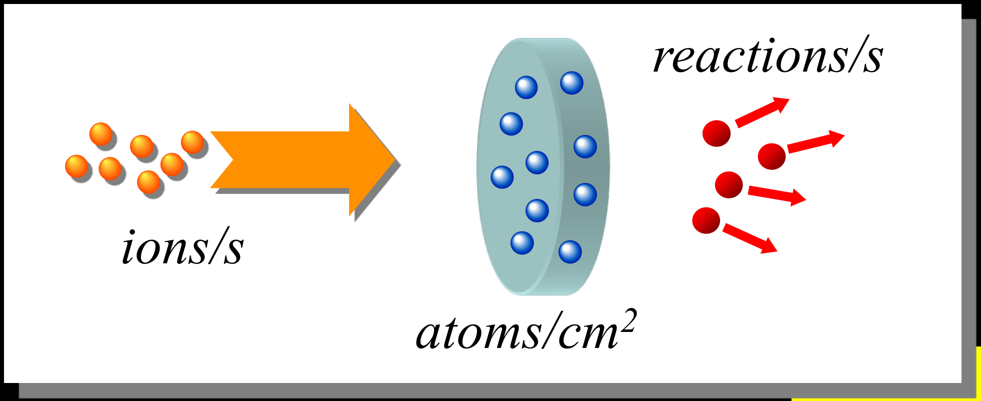
1st RIA Summer School - 2002

Outline

- Quick Review
- Astrophysics that primarily depends upon exotic nuclei
- Proton-induced reactions on exotic nuclei
- Nuclear physics measurements for the r-process

velocity averaged cross section

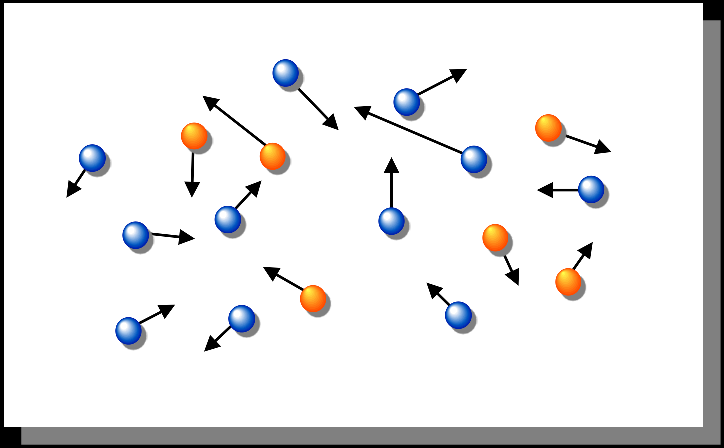
What you are used to in the lab:



cross section

$$\frac{reactions}{s} = \frac{ions}{s}\frac{atoms}{cm^2}\sigma$$

In astrophysical events:



reaction rate

$$\frac{reactions}{cm^3 s} = \int \frac{n_x}{cm^3}\frac{n_y}{cm^3} v\sigma(v)\phi(v)dv$$

$$\phi(v) = 4\pi v^2 \left(\frac{\mu}{2\pi kT}\right)^{3/2} \exp\left(-\frac{\mu v^2}{2kT}\right)$$

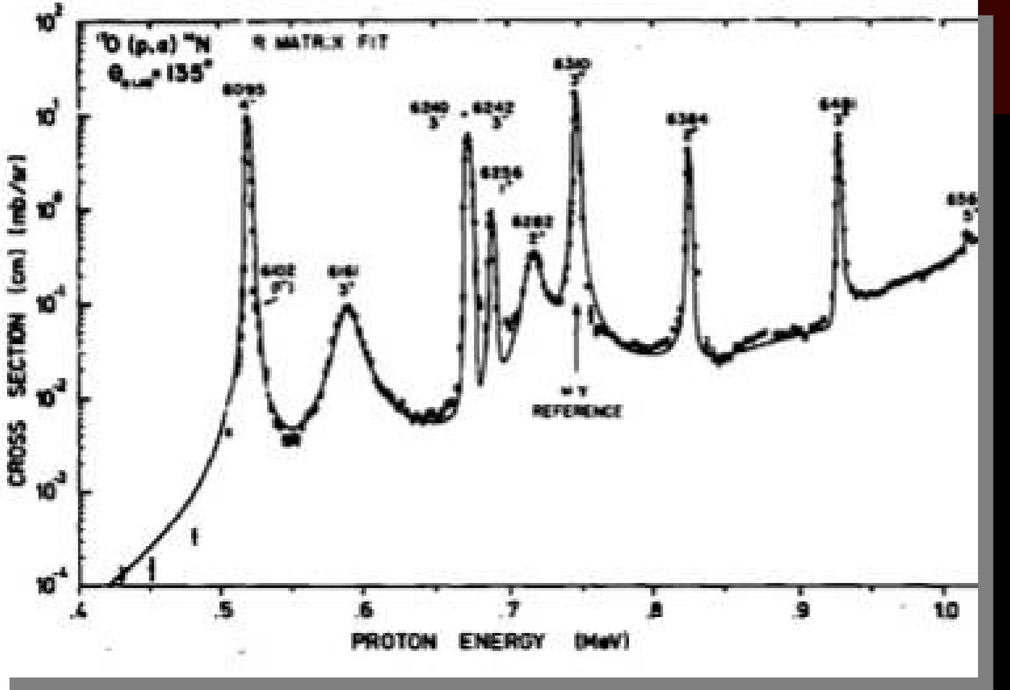
$$\frac{reactions}{cm^3 s} = \frac{n_x}{cm^3}\frac{n_y}{cm^3}\langle\sigma v\rangle$$

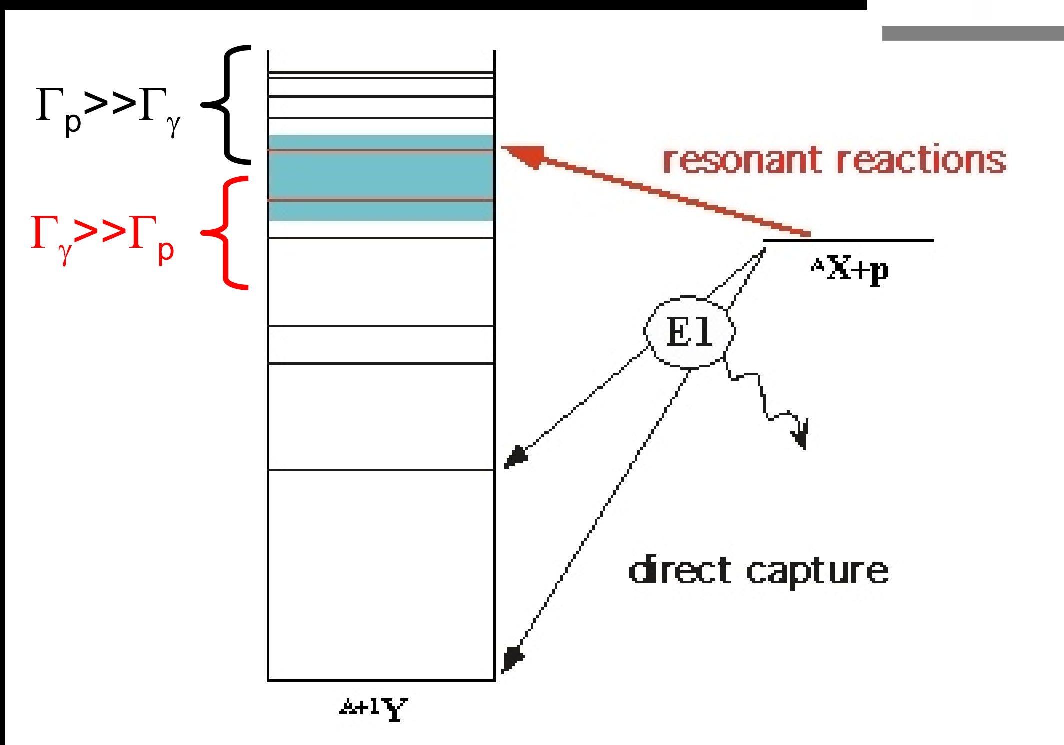
$$\langle\sigma v\rangle = \sqrt{\frac{8}{\pi\mu}}(kT)^{-3/2}\int_0^\infty \sigma E e^{-E/(kT)} dE$$

resonance reaction rates

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

$$\sigma(E) = \pi \lambda\!\!\!^{-2} \frac{2J+1}{(2J_x+1)(2J_y+1)} \frac{\Gamma_x \Gamma_y}{(E-E_r)^2 + (\Gamma/2)^2}$$





If resonance is narrow

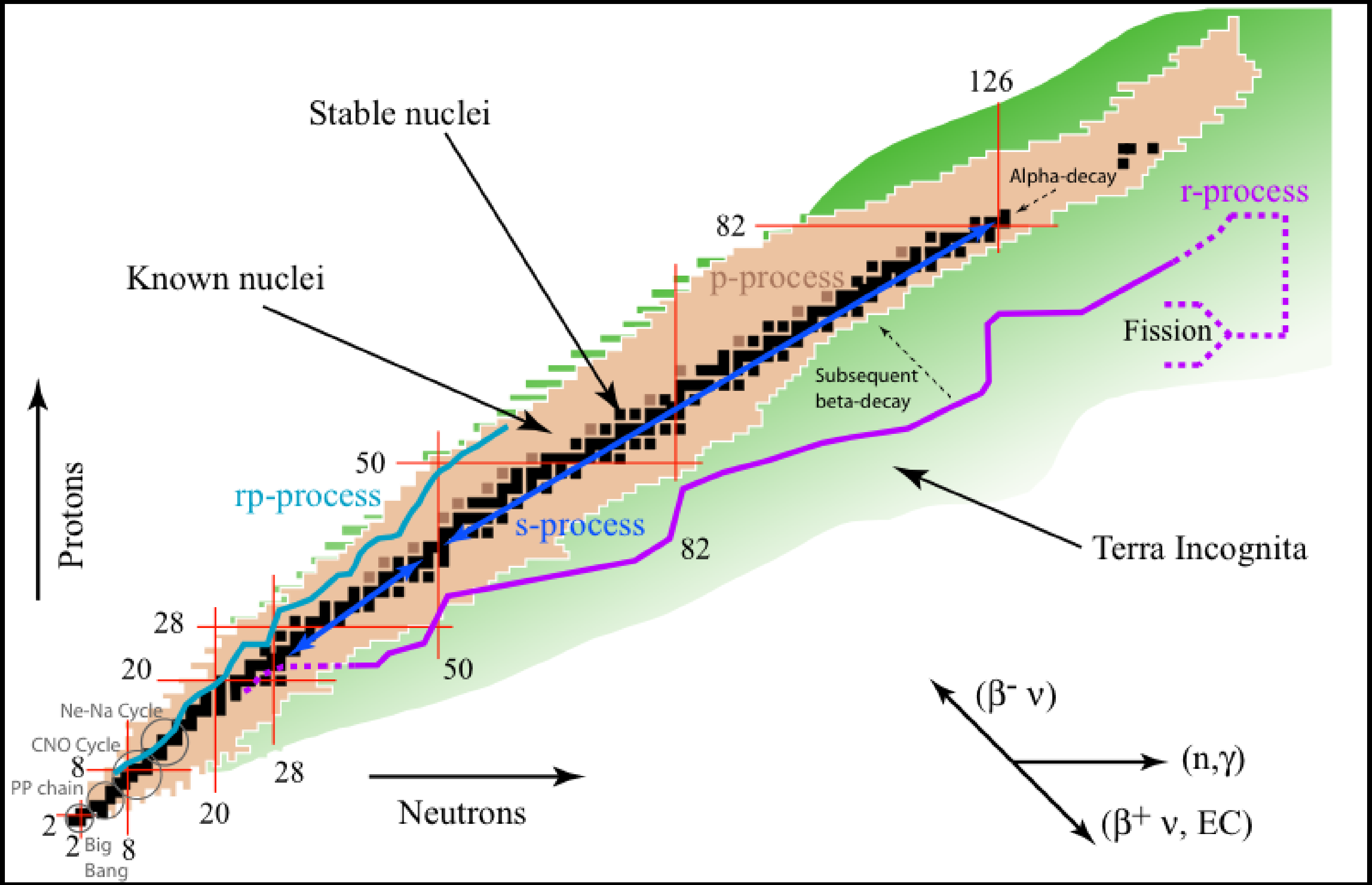
$$\langle \sigma v \rangle = \left(\frac{2\pi}{\mu} kT \right)^{-3/2} \hbar^2 (\omega\gamma) e^{-E_r/kT}$$

E_r & J^π are most important

$$\omega\gamma = \frac{2J+1}{(2J_x+1)(2J_y+1)} \frac{\Gamma_x \Gamma_y}{\Gamma}$$

“resonance strength”

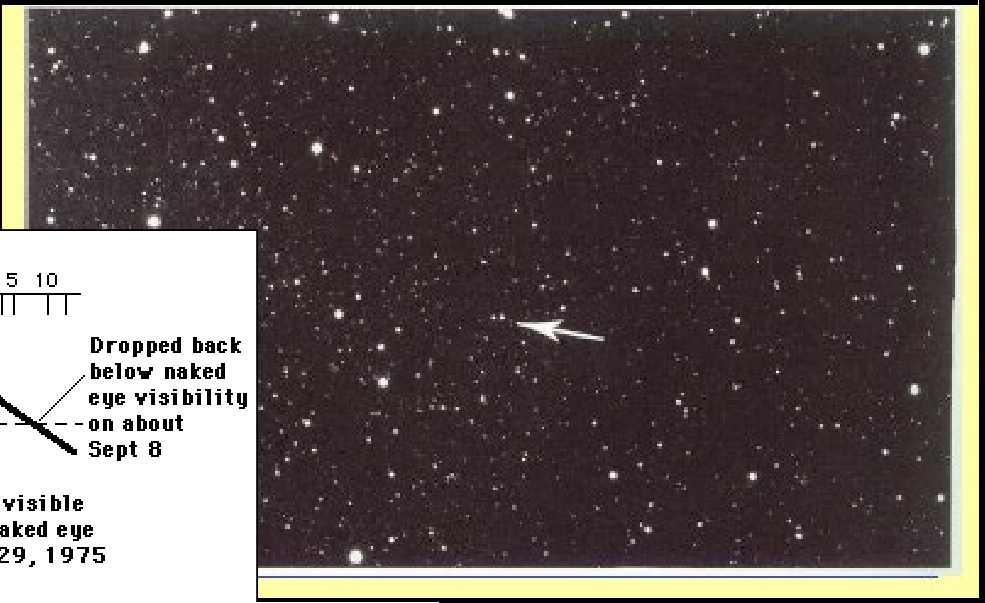
what processes typically involve exotic nuclei?

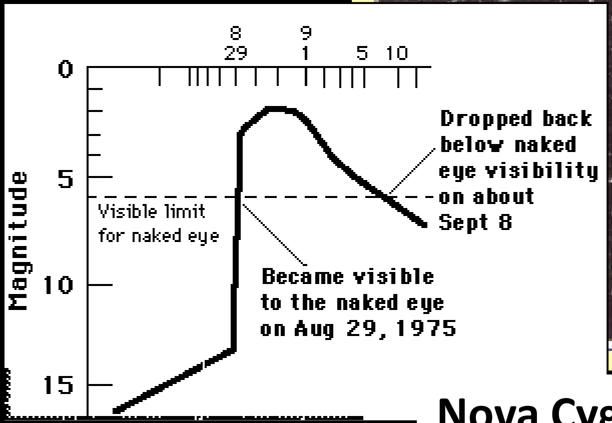


major goal of nuclear astrophysics is to explain the cosmic origin of the elements:

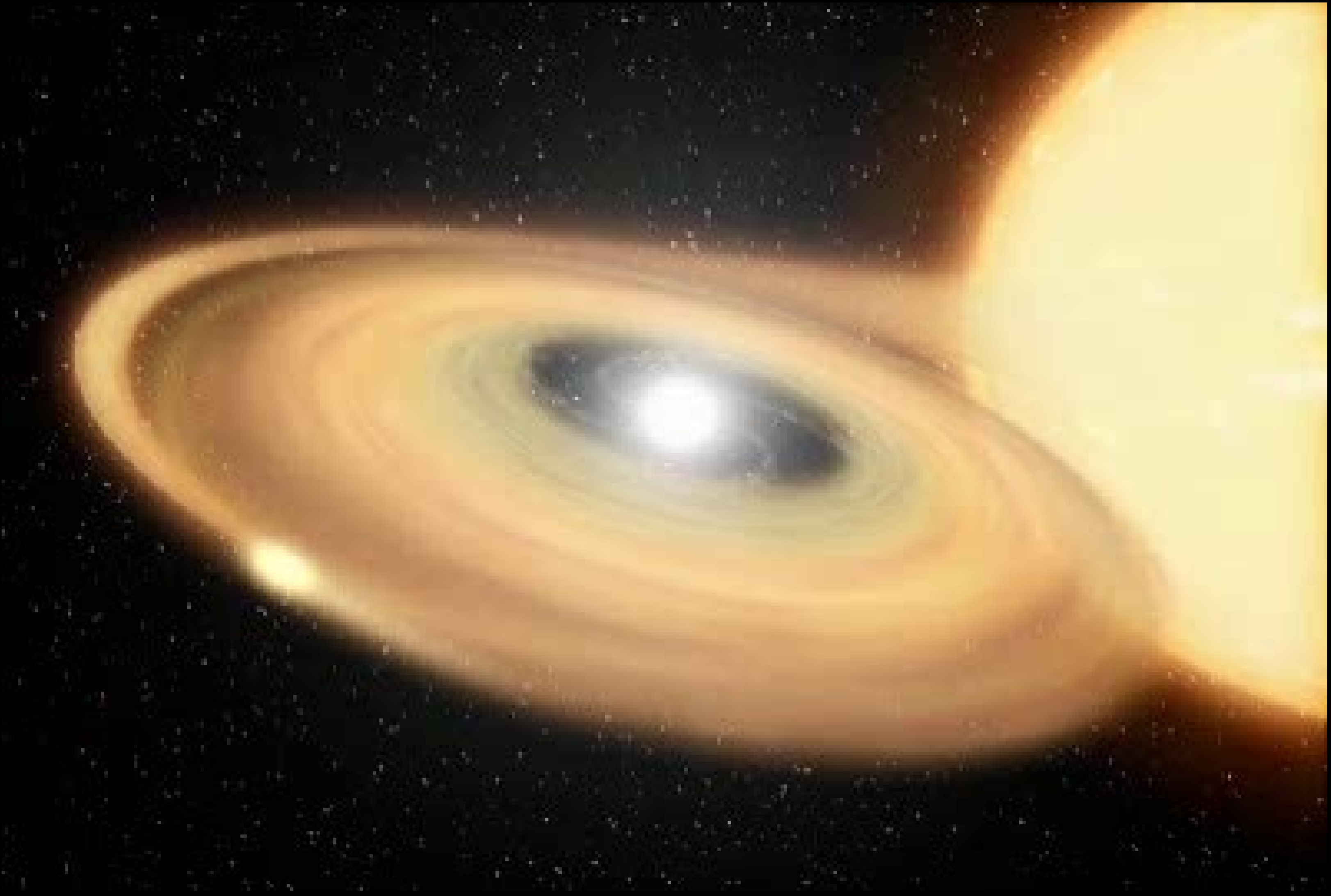
at what astrophysical sites are each of the nuclides produced ? how ?

Most novae discovered by amateur astronomers

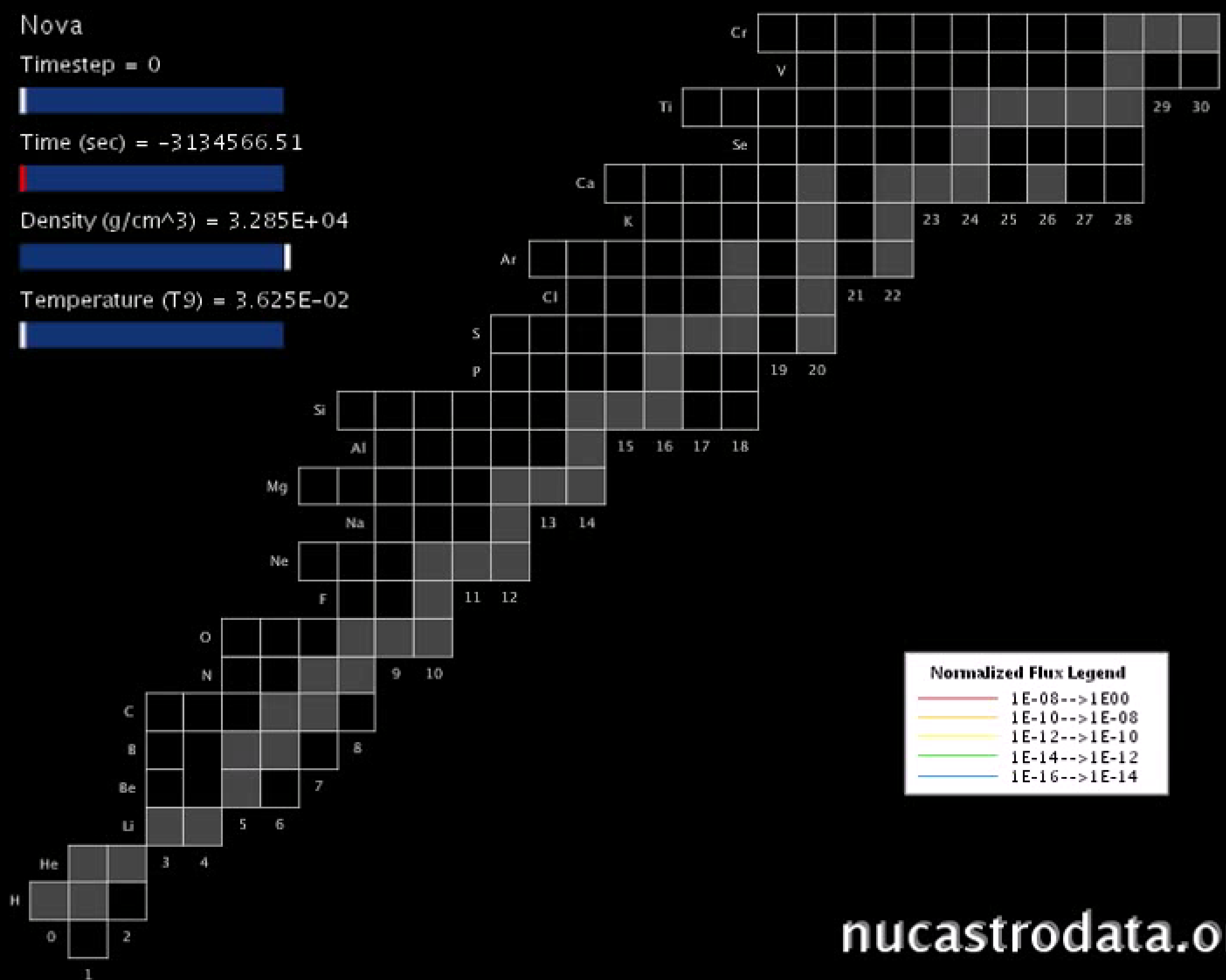




Nova Cygni 1975

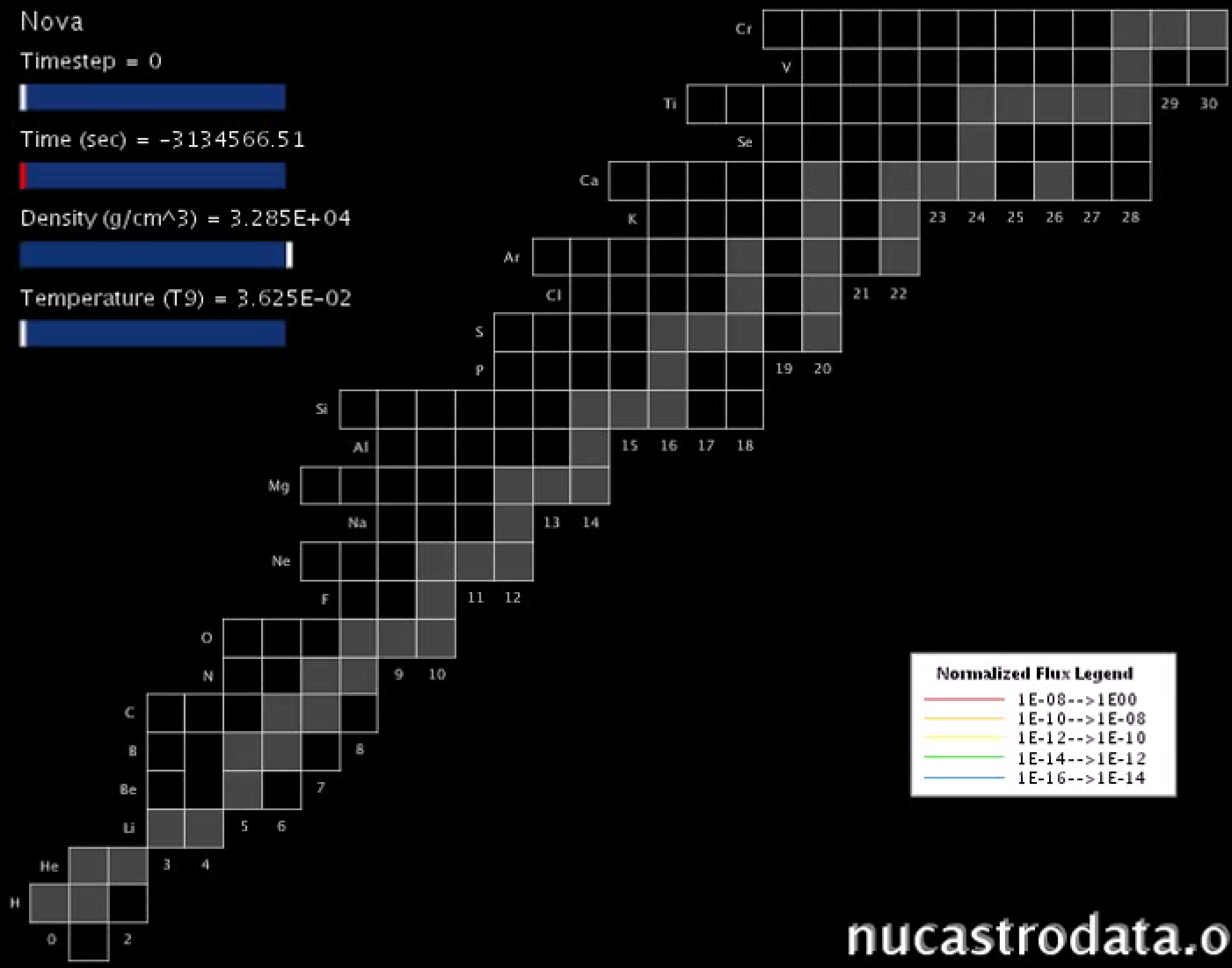


Nuclear reactions produce exotic nuclei



nucastrodata.org

Nuclear reactions produce exotic nuclei

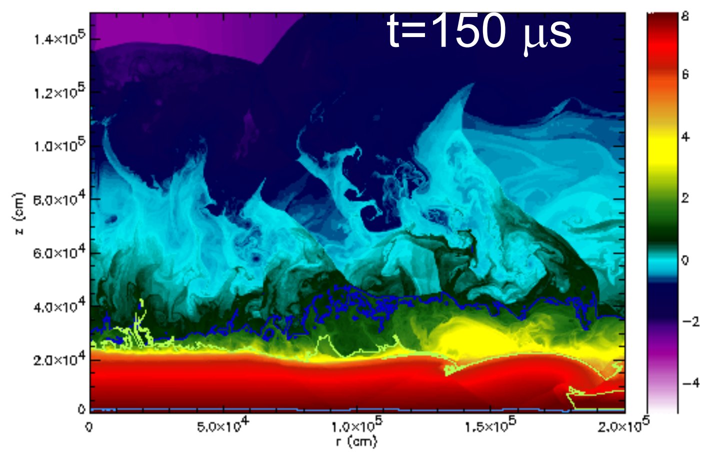


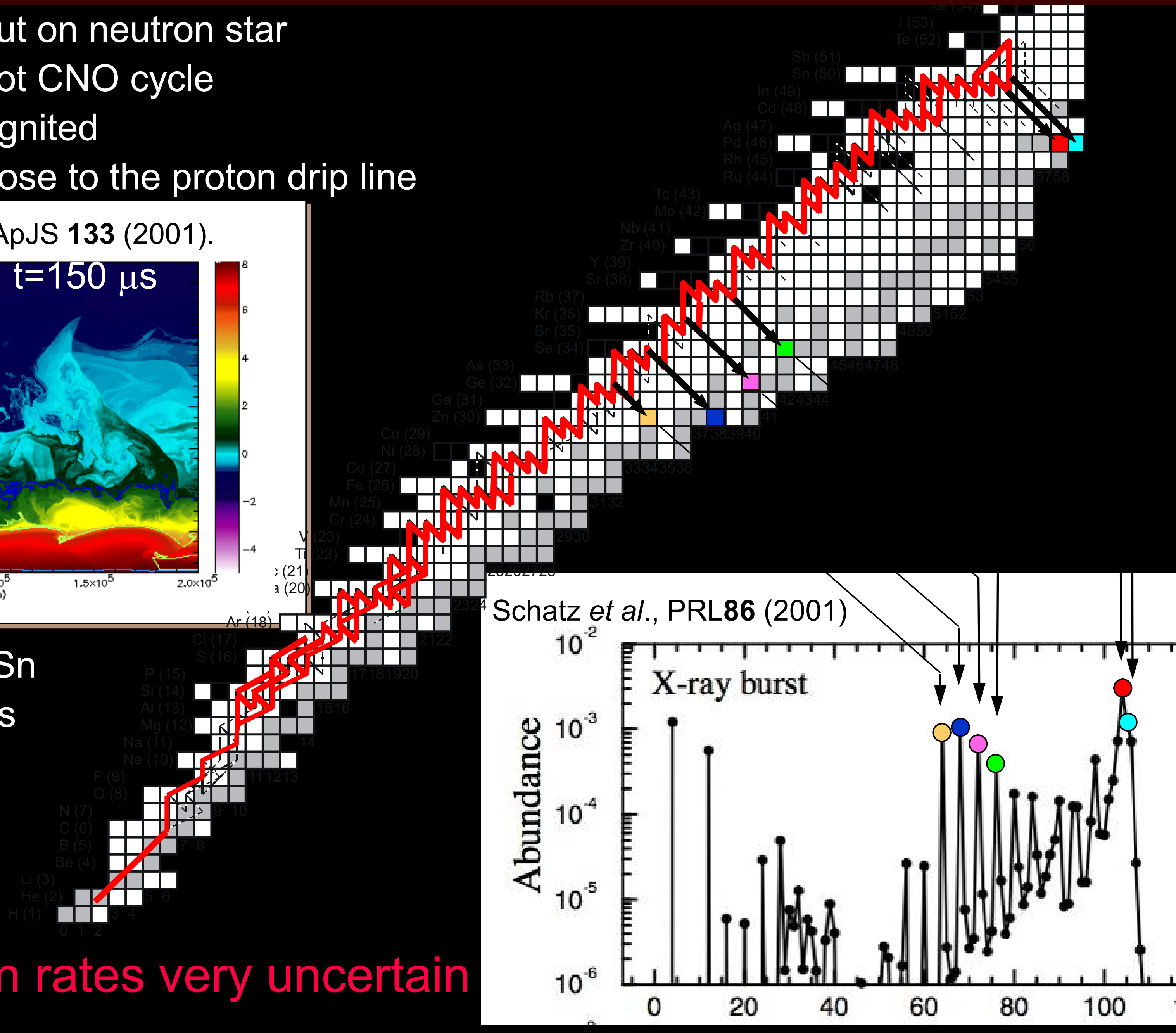
nucastrodata.org

x-ray bursts

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

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





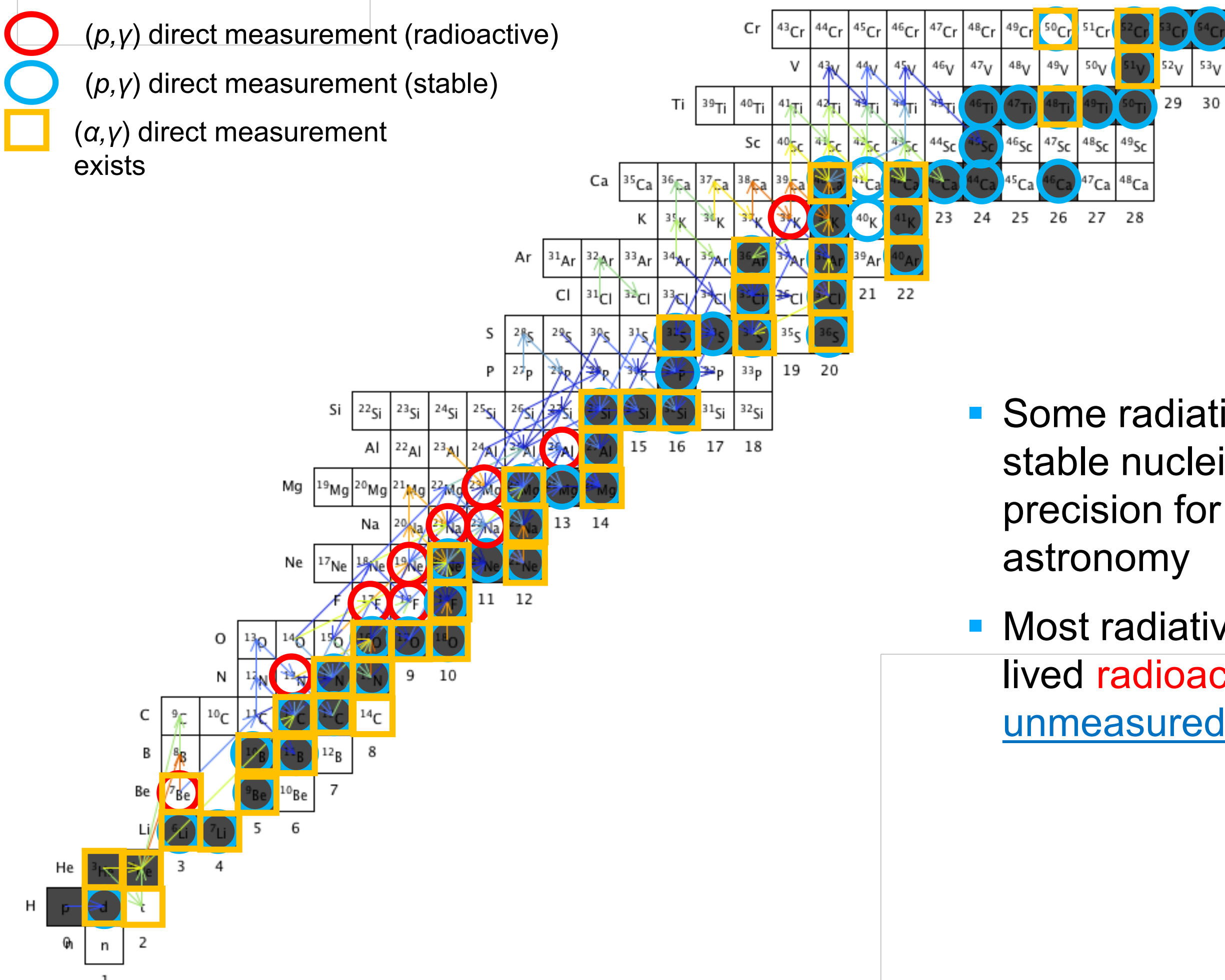
- Nuclei up to Sn
- Waiting points crucial
  - ^{64}Ge
  - ^{68}Se
  - ^{72}Kr
  - ^{76}Sr

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

Most reaction rates very uncertain

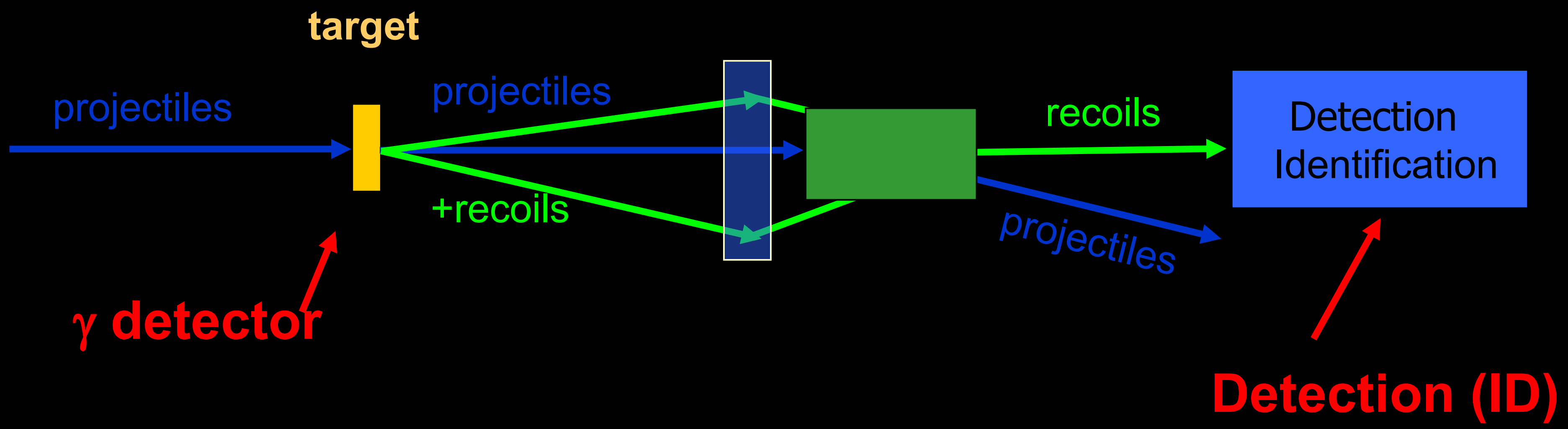
nuclear measurements for novae and x-ray bursts

- Best approach is to directly measure cross sections for the reactions of interest
  - (p,γ), (α,p), (p,α) mostly
  - only a handful or exotic beam measurements
  - Radioactive ion beams on hydrogen & helium targets at low energies
  - typically data of limited statistical significance
- Direct measurements are difficult, and we must exploit indirect techniques to some degree in nearly all cases
  - Measurements with both stable and radioactive ion beams are important
  - Information we can obtain is often incomplete
  - Results can be model dependent



- Some radiative capture reactions on stable nuclei remain unknown to sufficient precision for stellar evolution or astronomy
- Most radiative capture reactions on short-lived radioactive nuclei in stars remain unmeasured

Principles



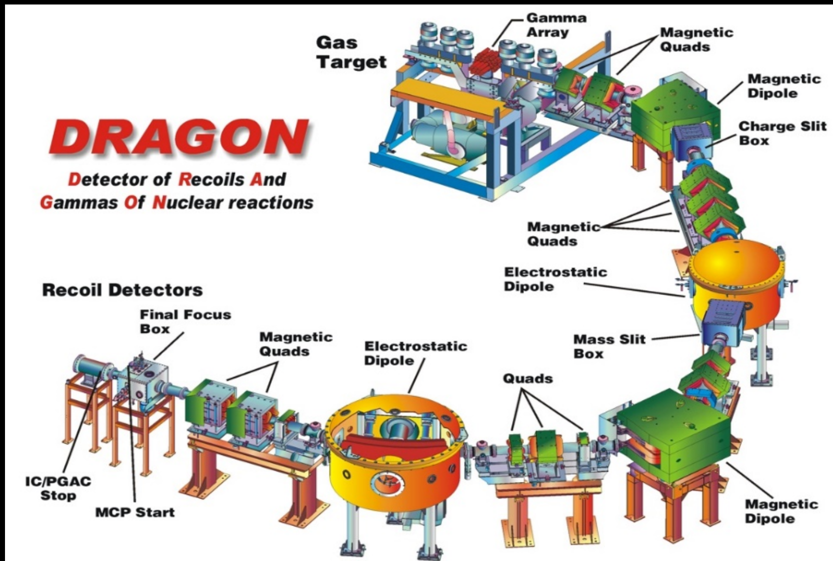
$$E_{lab} = E_{cm}\frac{M_t + M_b}{M_t}$$

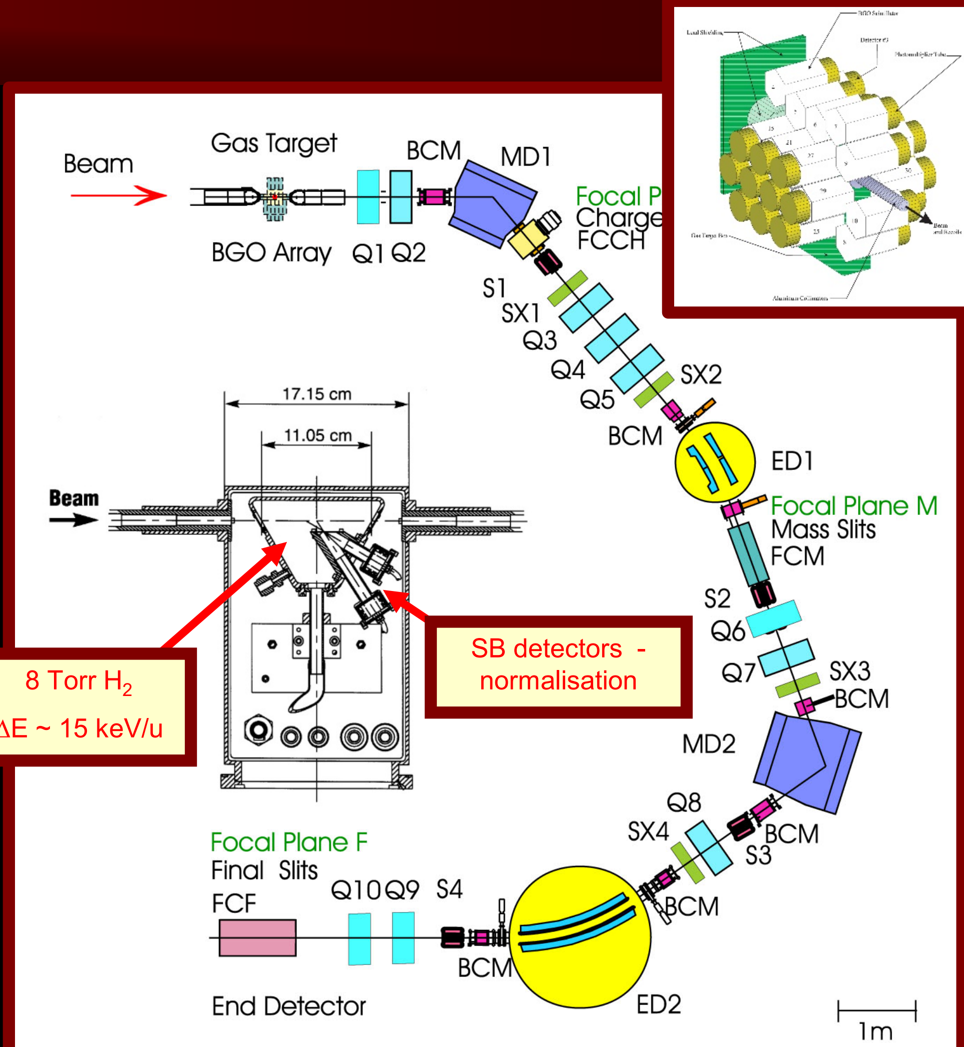
Background suppression
and identification

Diagnostic
High power stopper

Drawings from D. Schürmann

DRAGON



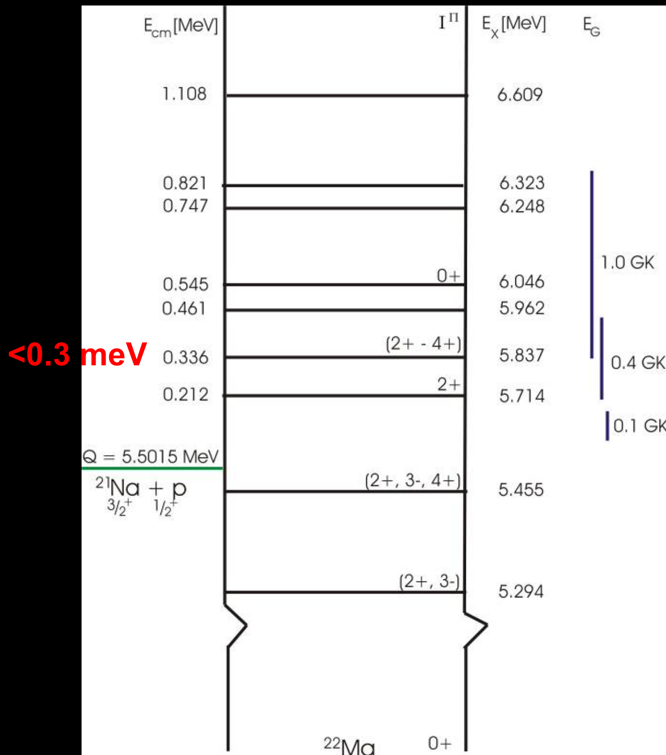


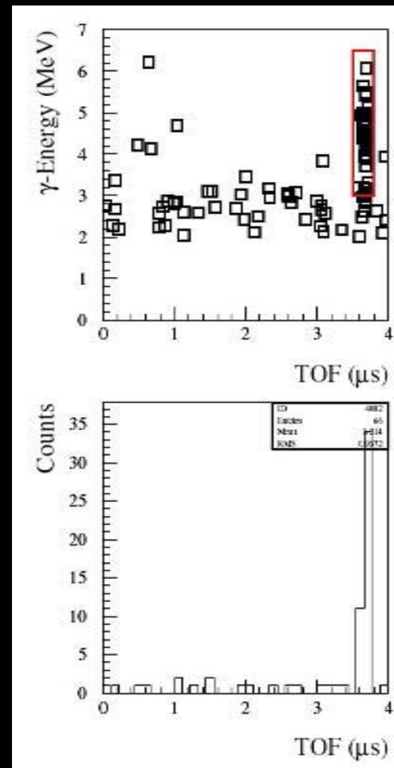
8 Torr H_2

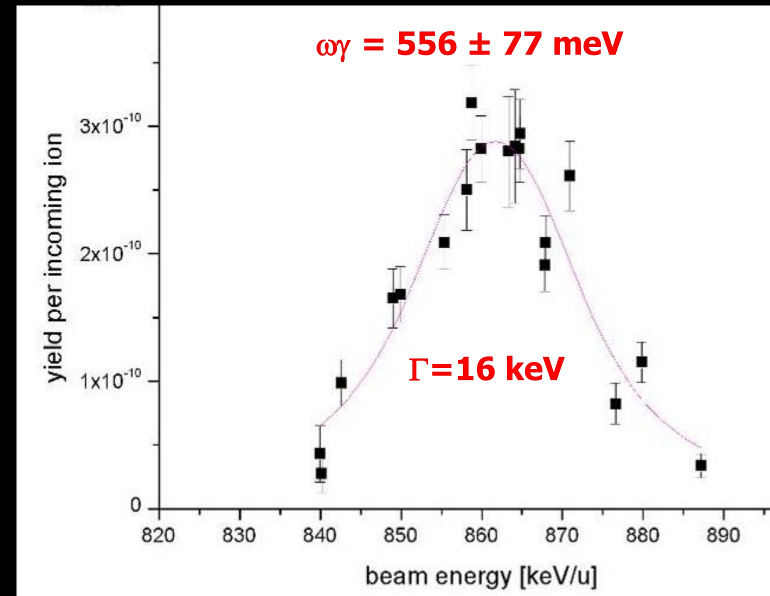
$\Delta E \sim 15$ keV/u

SB detectors - normalisation

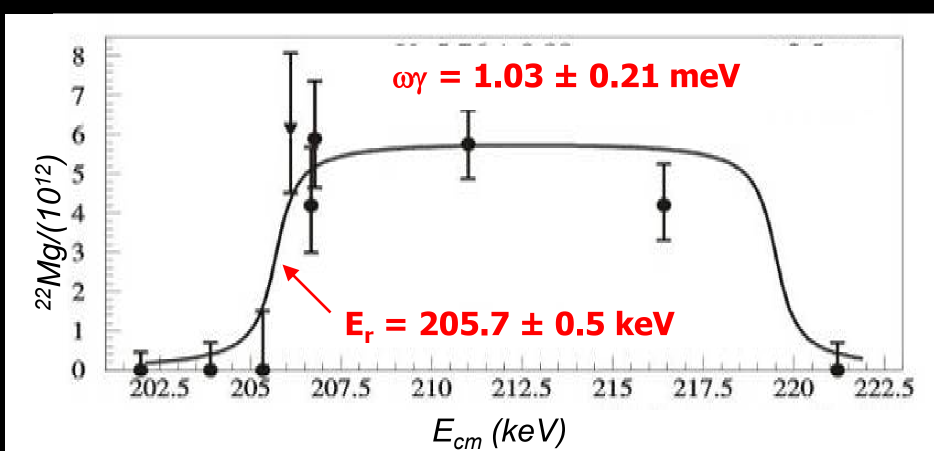
$^{21}Na(p,\gamma)^{22}Mg$ with DRAGON



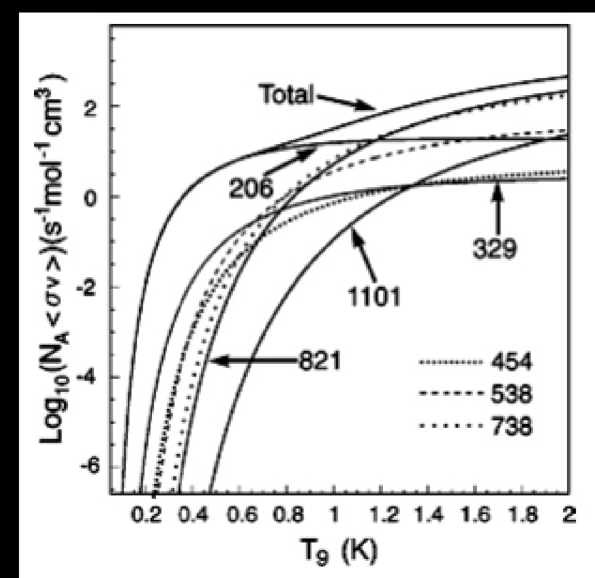




*J. D'Auria et al., PRC **69** (2004) 065803.*
*S. Bishop et al., PRL **90** (2003) 162501.*

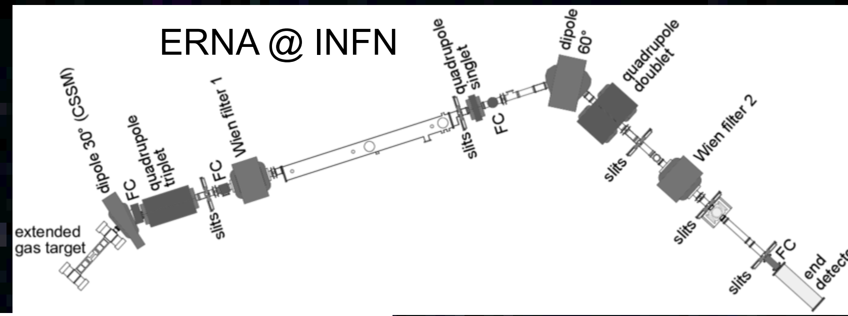


$^{21}Na(p,\gamma)^{22}Mg$ uncertainty now only 20%

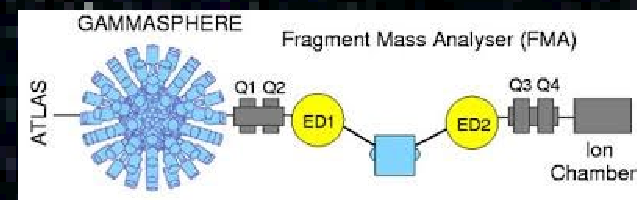


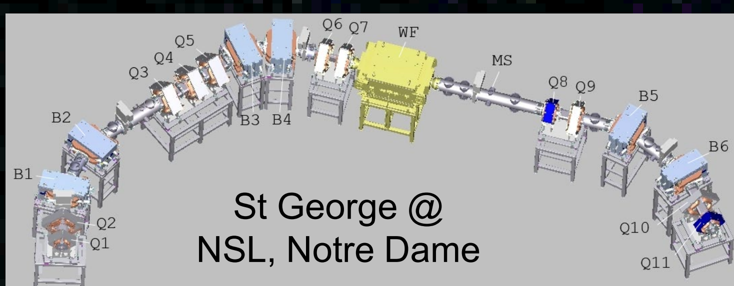
Recoil Separators Worldwide

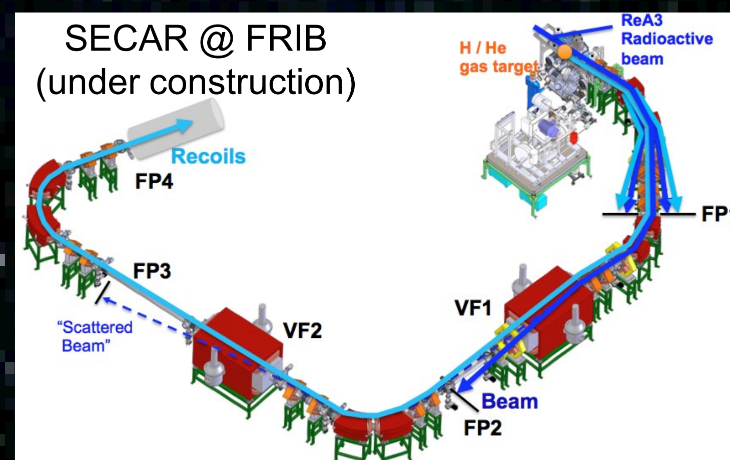
+ Caltech
NABONA @ Napoli
ARES @ LLN
DRS @ ORNL



Reaction	Year	Location
$^{13}N(p,\gamma)^{14}C$	1991	CRC (Louvain-la-Neuve)
$^{7}Be(p,\gamma)^{8}B$	2000,2009	Nabona (Naples), DRS (HRIBF)
$^{21}Na(p,\gamma)^{22}Mg$	2001-2003	DRAGON (TRIUMF)
$^{26g}Al(p,\gamma)^{27}Si$	2004-2005	DRAGON (TRIUMF)
$^{17}F(p,\gamma)^{18}Ne$	2008	DRS (HRIBF)
$^{23}Mg(p,\gamma)^{24}Al$	2009	DRAGON (TRIUMF)
$^{18}F(p,\gamma)^{19}Ne$	2011	DRAGON (TRIUMF)
$^{26m}Al(p,\gamma)^{27}Si$	2012	DRAGON (TRIUMF)
$^{38}K(p,\gamma)^{39}Ca$	2014	DRAGON (TRIUMF)

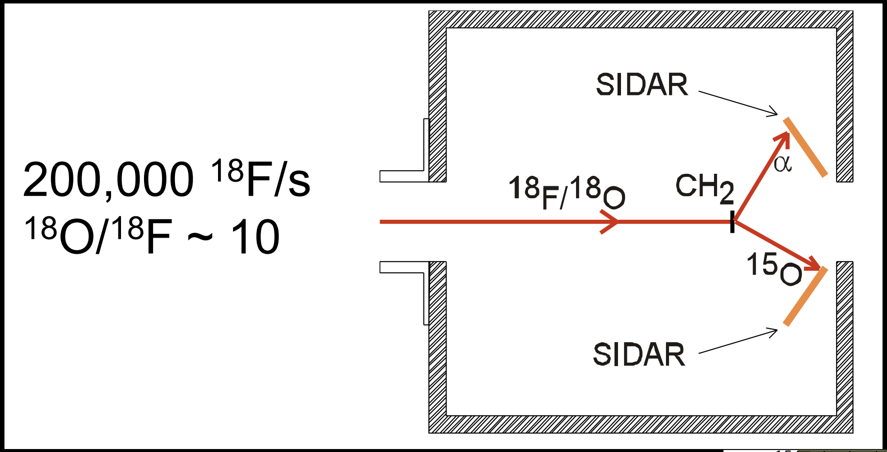


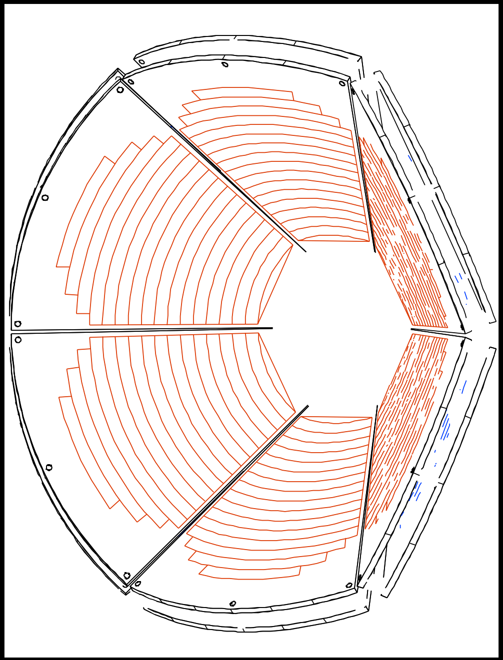




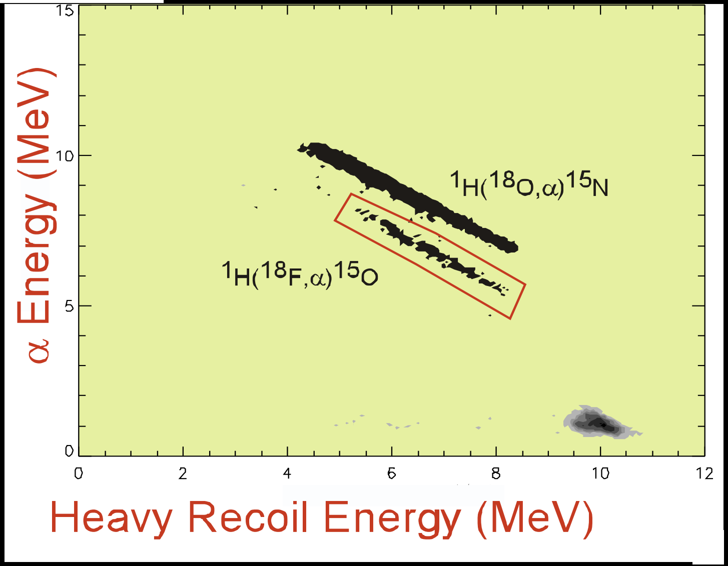
$^{18}F(p,\alpha)^{15}O$

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



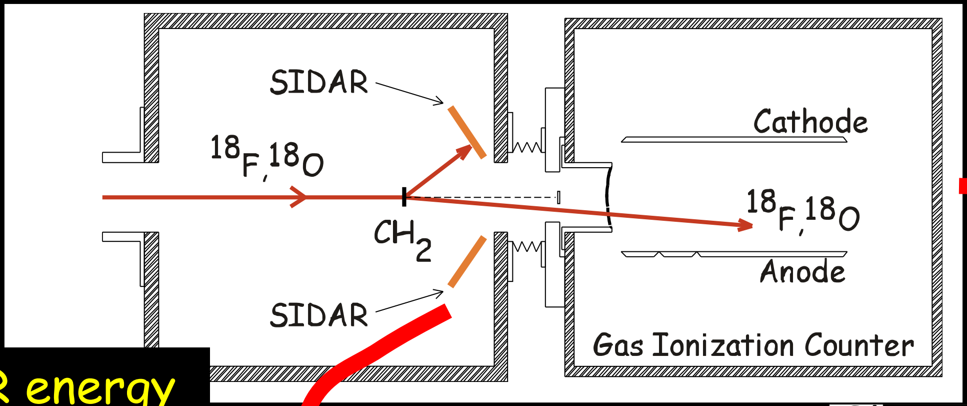


SIDAR in lampshade configuration

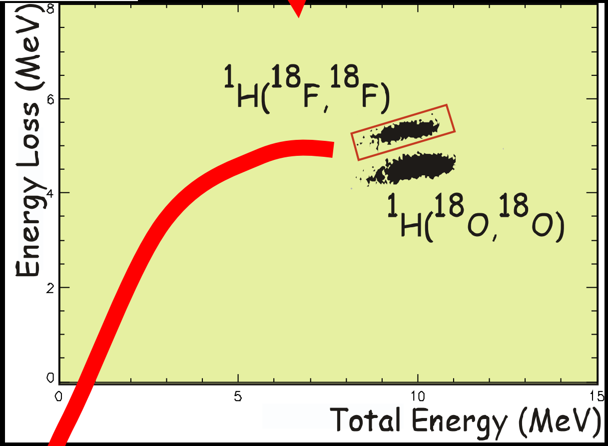


$^{18}F(p,p)^{18}F$ at 665 keV

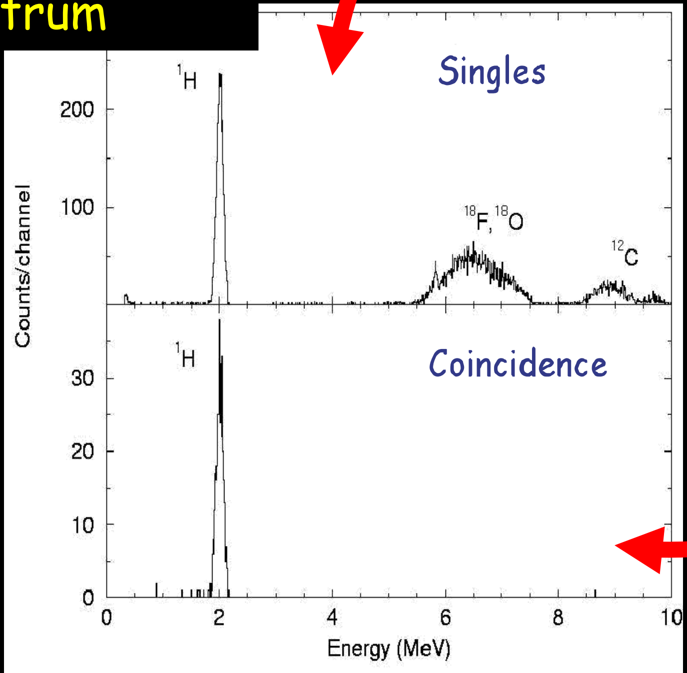
D. W. Bardayan et al., Phys. Rev. C62, 042802 (R) (2000).



Z – identification of recoils

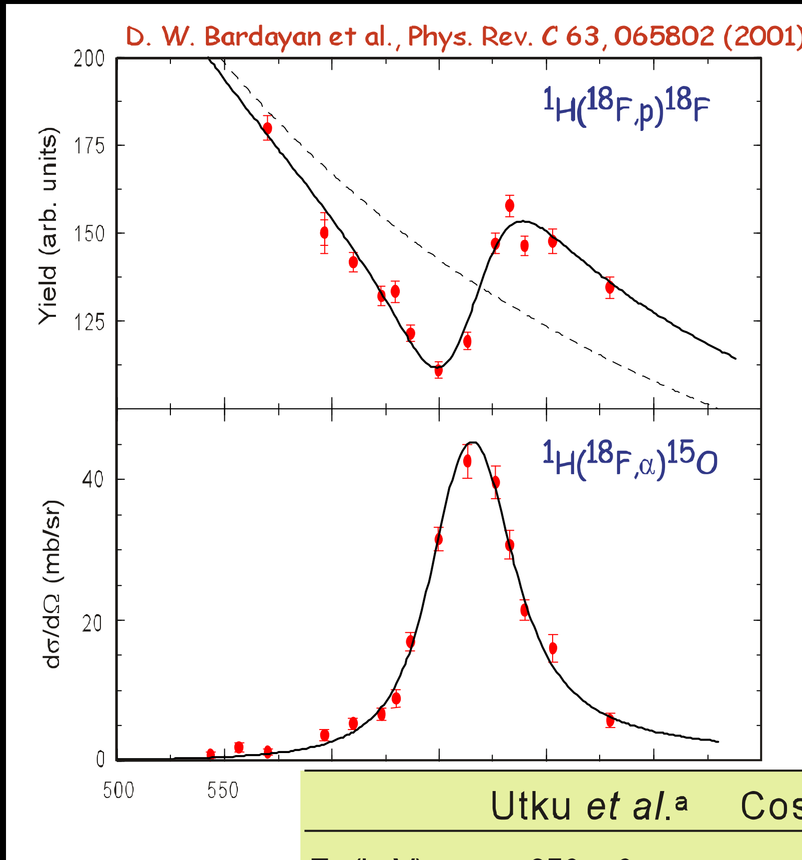


SIDAR energy spectrum



Coincidence provides clean separation of events of interest.

^{18}F+p excitation functions

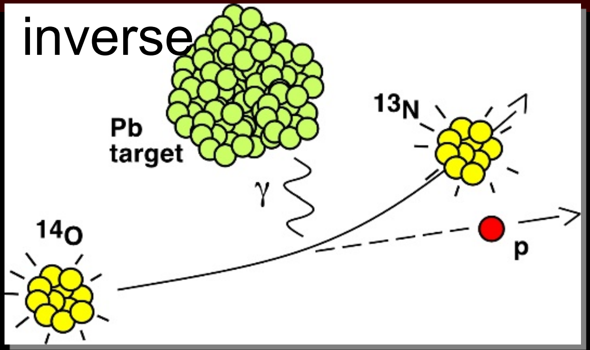


	Utku *et al.*[a]	Coszach *et al.*[b]	Rehm *et al.*[c]	This Work
E_r (keV)	659 ± 9	638 ± 15	652 ± 4	664.7 ± 1.6
Γ (keV)	39 ± 10	37 ± 5	13.6 ± 4.6	39.0 ± 1.6
Γ_p/Γ	0.37 ± 0.04	0.4 - 0.6	0.37[d]	0.39 ± 0.02

[a]Utku *et al.*, Phys. Rev. C57, 2731 (1998). [b]Coszach *et al.*, Phys. Lett. B353, 184 (1995).
[c]Rehm *et al.*, Phys. Rev. C53, 1950 (1996). Rehm *et al.*, Phys. Rev. C52, R460 (1995).
[d]From Utku *et al.*

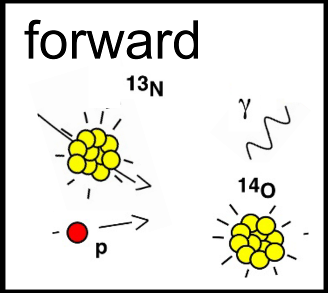
indirect measurements

inverse reactions



measure the time inverse of the reaction of interest

use detailed balance to get forward reaction rate



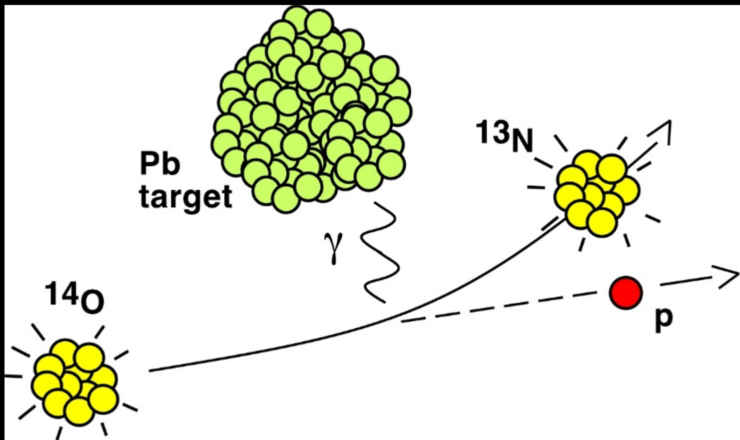
necessary when beam for forward reaction is not available

includes

- Inverses of (p,α) or (α,p) reactions
- Coulomb dissociation - use virtual photons to measure inverse of (p,γ)

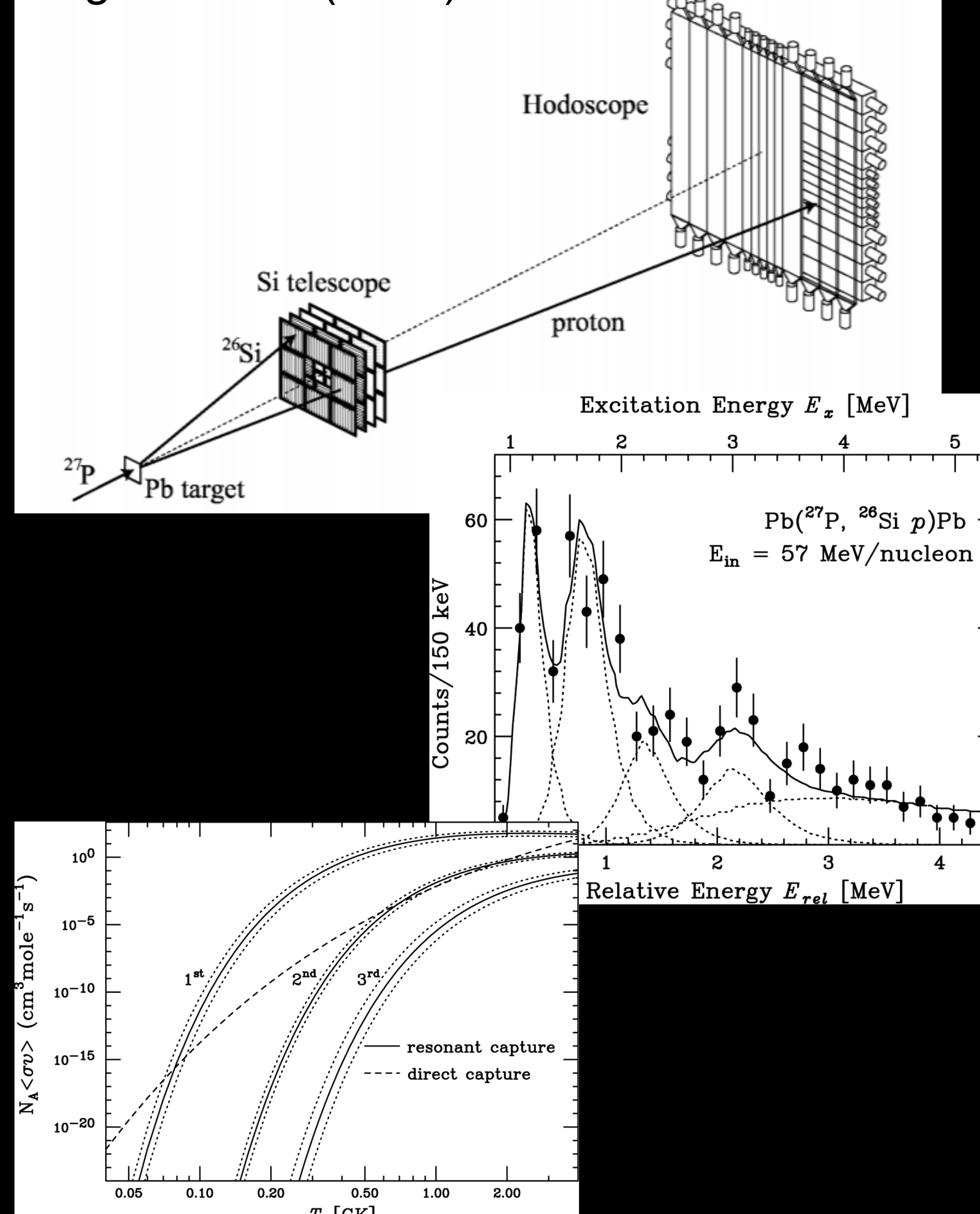
indirect measurements

coulomb dissociation



- determine (p,γ) by measuring time inverse reaction (γ,p) using virtual photons from Coulomb field
- orders of magnitude enhancement in cross sections (can do measurements with 10^3 pps as compared to 10^8 pps for direct measurement)
- technique very successful for cases with isolated resonances (e.g., $^{14}O(\gamma,p)^{13}N$, …)

Togano et al. (2008)

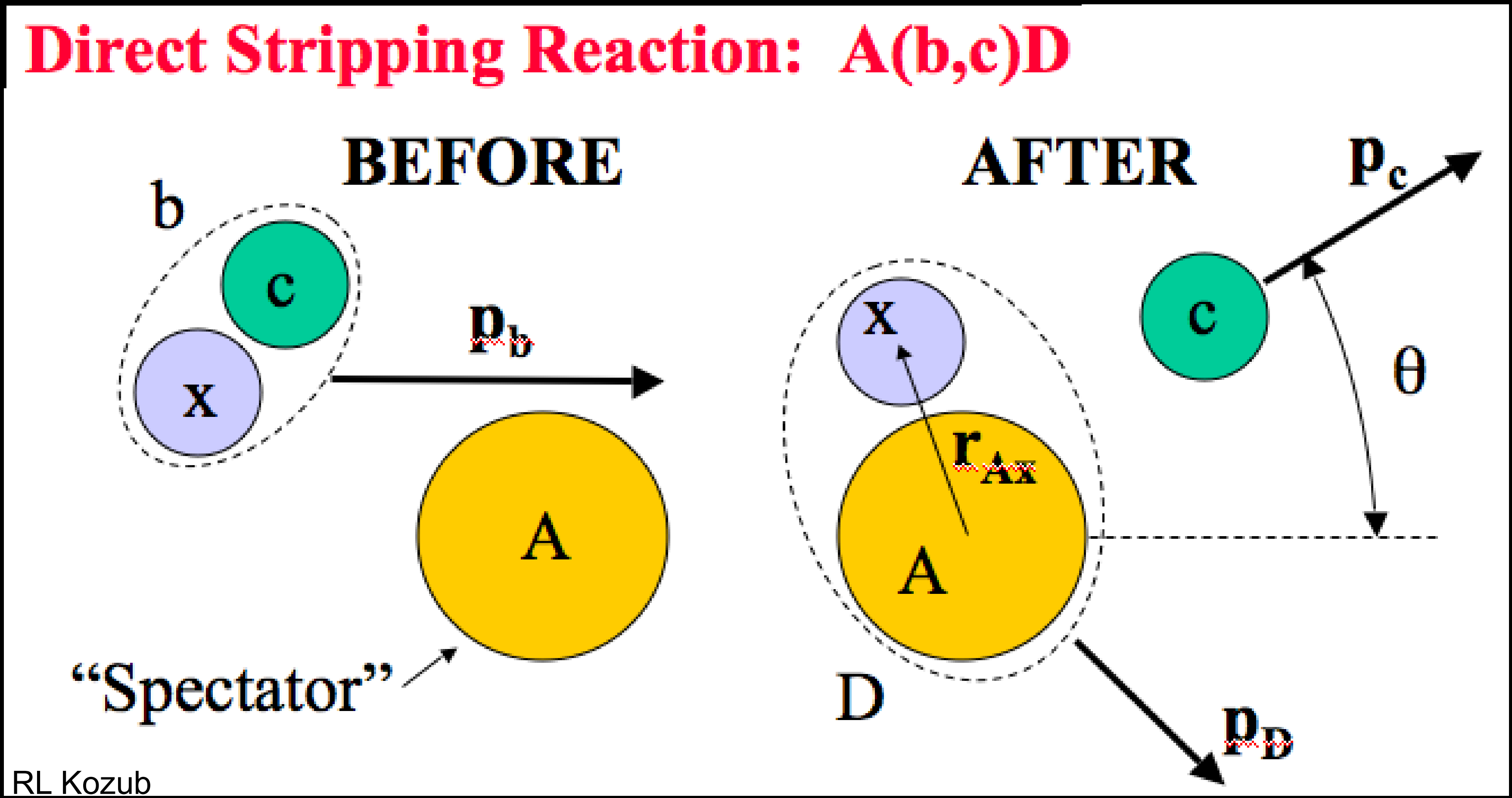


indirect measurements

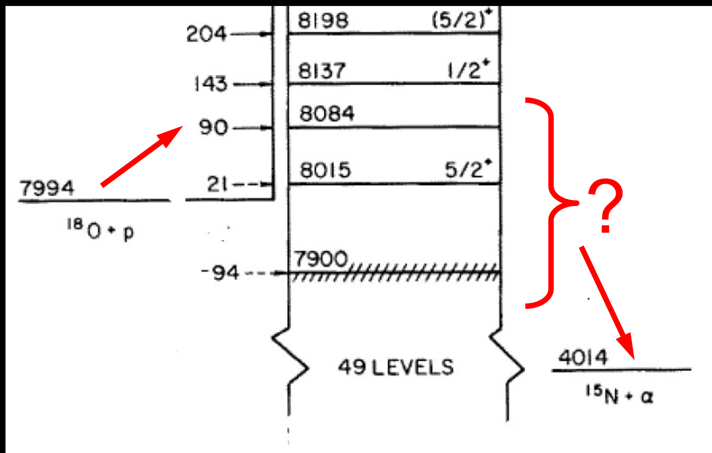
transfer reactions

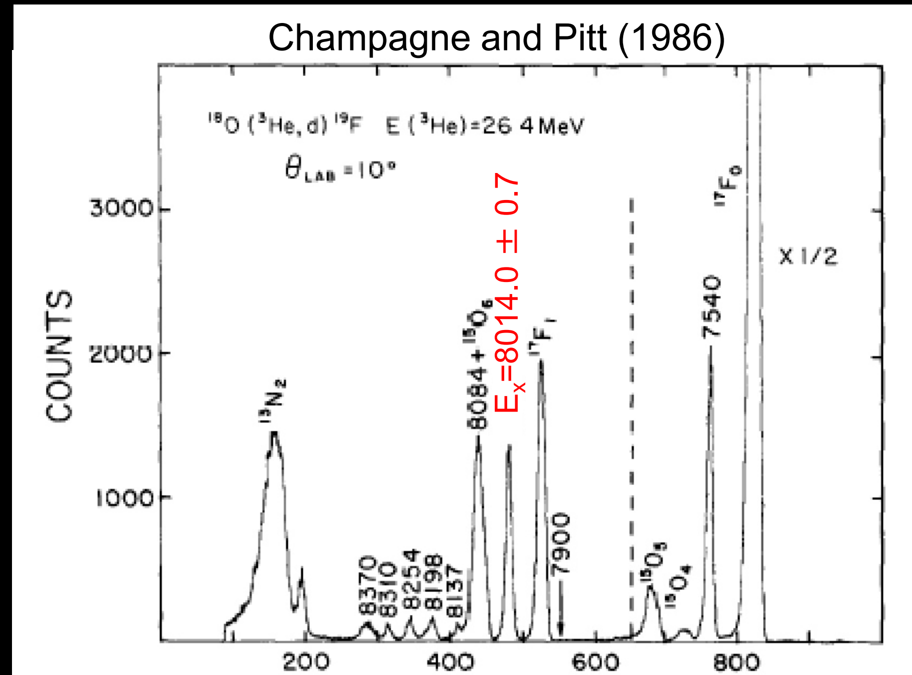
surrogate reactions, stripping, pickup, knockout …

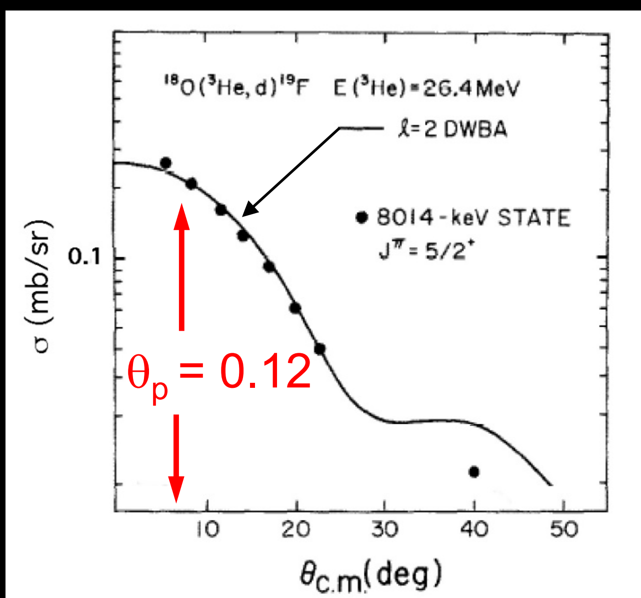
- reactions where nucleon(s) jump (“transfer”) from on reactant to the other



(^{3}He,d) on stable targets to determine (p,γ) rates







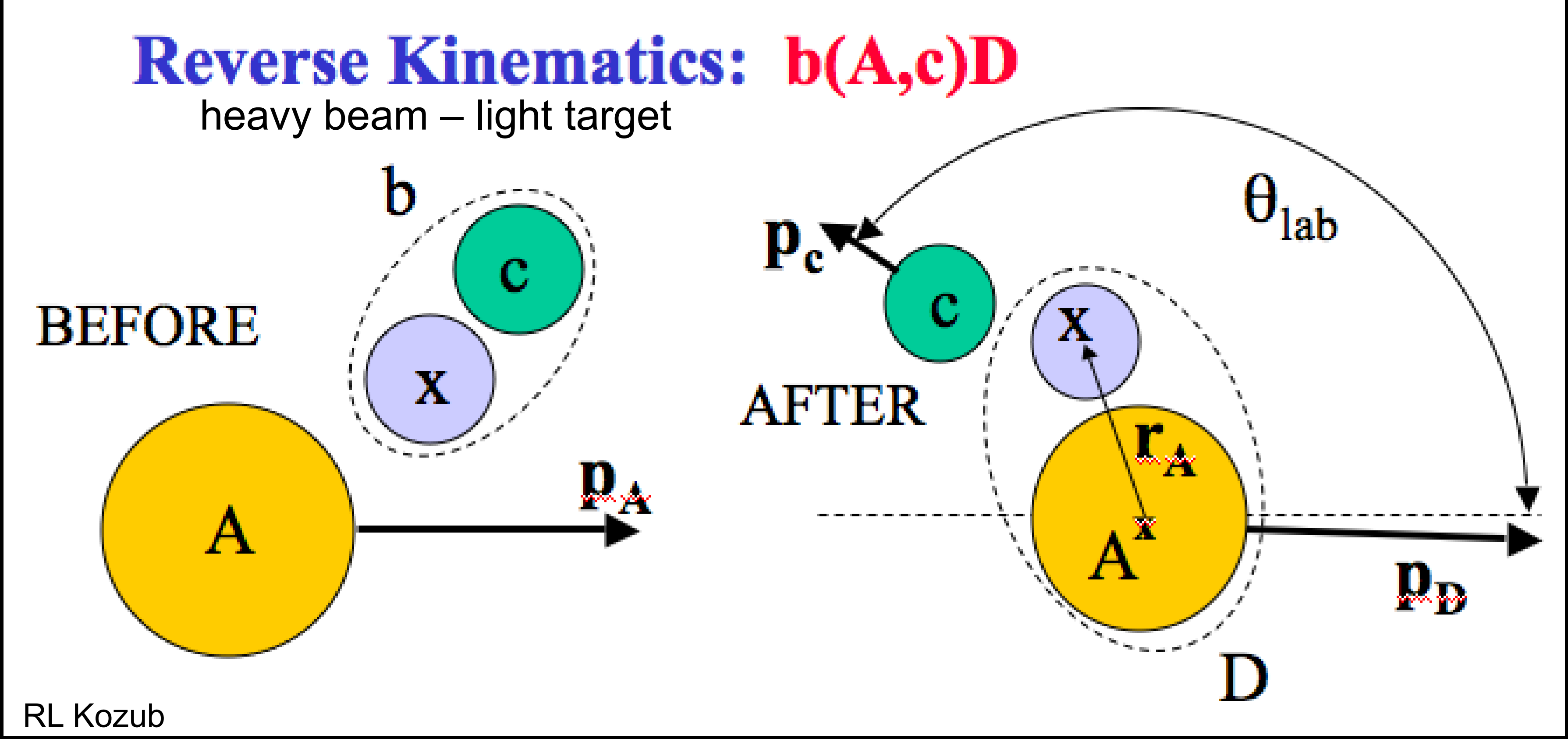
$$\Gamma_p = 2\left(\frac{\hbar^2}{\lambda \mu R}\right)\left(\frac{\theta_p^2}{F_\ell^2 + G_\ell^2}\right) \rightarrow \Gamma_p = 2\times10^{-19}\ \text{eV}$$

1 mA p + ^{18}O $\rightarrow$ 1 event / 3x10^5 years

transfer reactions

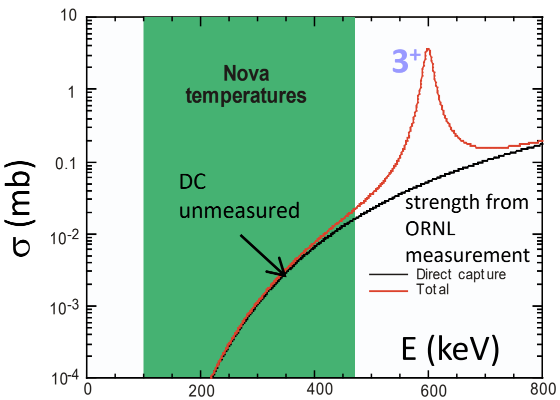
surrogate reactions, stripping, pickup, knockout …

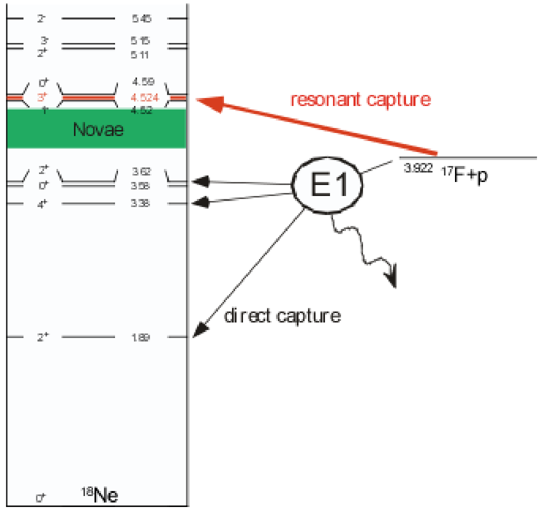
- reactions where nucleon(s) jump ("transfer") from on reactant to the other



$^{17}F(d,n)^{18}Ne$ at Notre Dame

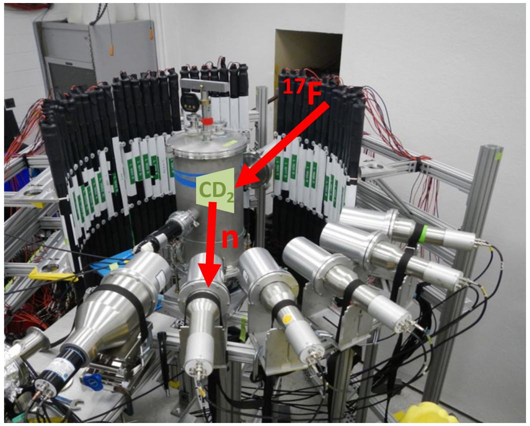
$^{17}F(p,\gamma)^{18}Ne$ in novae strongly affected by unmeasured DC rate.

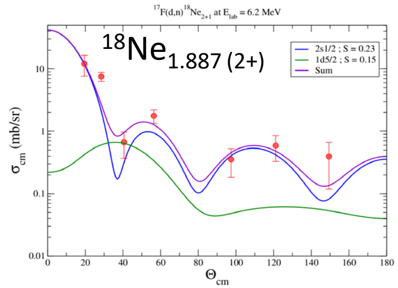




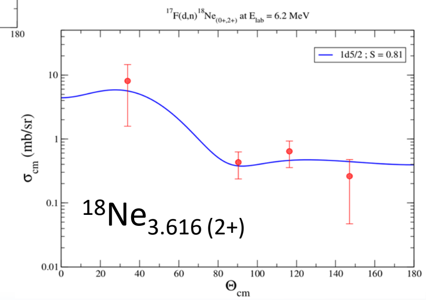
Direct capture populates bound 2^+ and 4^+ ^{18}Ne levels. Can constrain direct capture via measurements of (d,n) transfer on ^{17}F.

^{17}F beam from TwinSol bombarded CD_2 target. Neutrons detected in VANDLE and Michigan Deuterated Benzene detectors.





Neutron angular distributions under analysis to extract spectroscopic strengths.



P. D. O'Malley, D. W. Bardayan, et al.

indirect measurements

determining nuclear structure

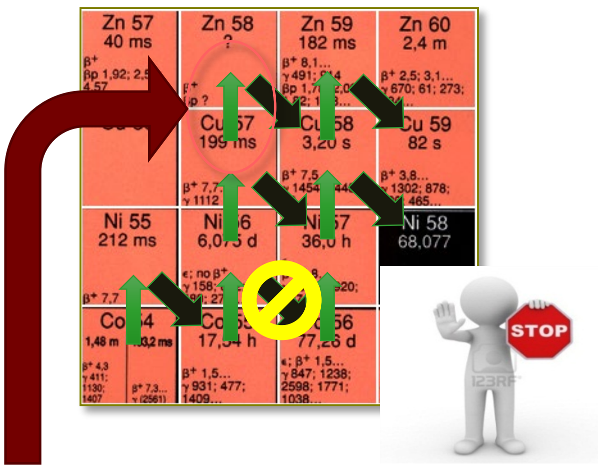
measuring γ-rays after reaction or β decay particularly productive

- want to produce same compound nucleus through some alternative method
- resonance energies determined once level scheme constructed
- γ-rays can provide precise level energies

- typically need some external signature that compound nucleus of interest has been populated
- Doppler shifts can limit resolution in reactions
- beam contaminants can be problem in β-decay studies
- Need efficient γ-ray detector

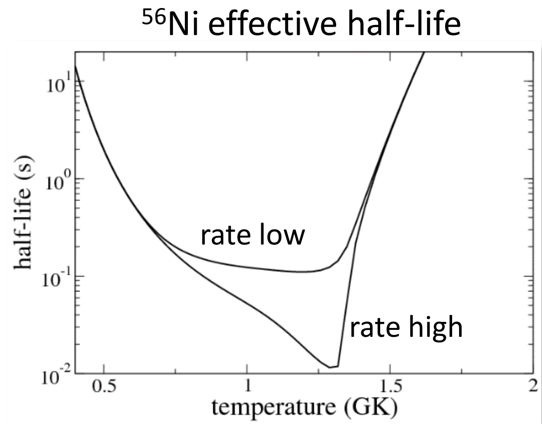
Excitation Energies in ^{58}Zn

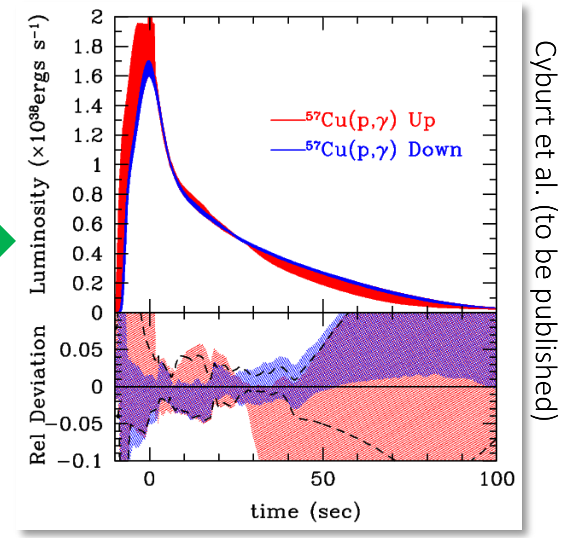
Important ^{58}Zn Excitation Energies for rp-Process

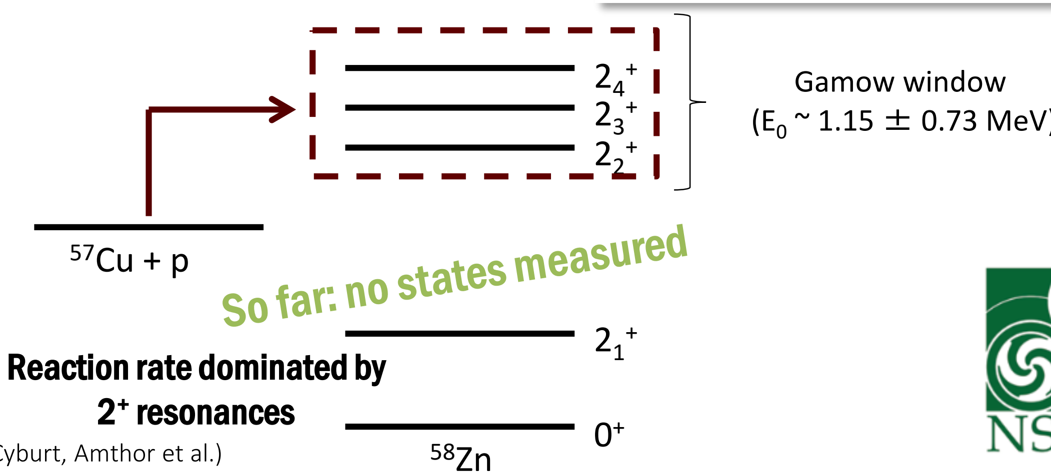


Large-scale sensitivity study with single-zone X-ray burst model:

Among the *top 20 reactions* influencing the burst light curve







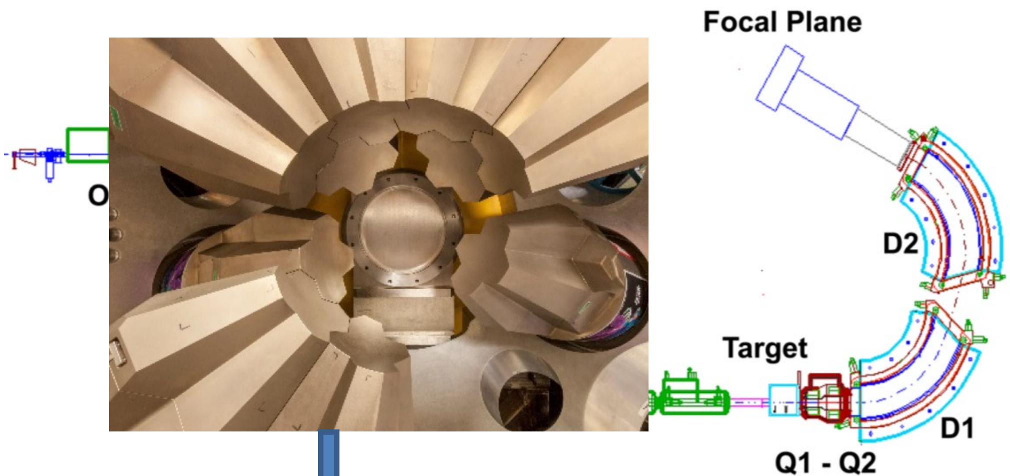
So far: no states measured

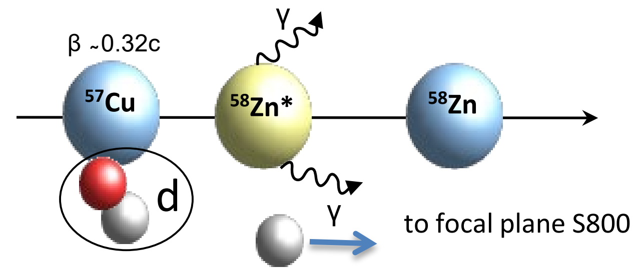
Reaction rate dominated by 2^+ resonances

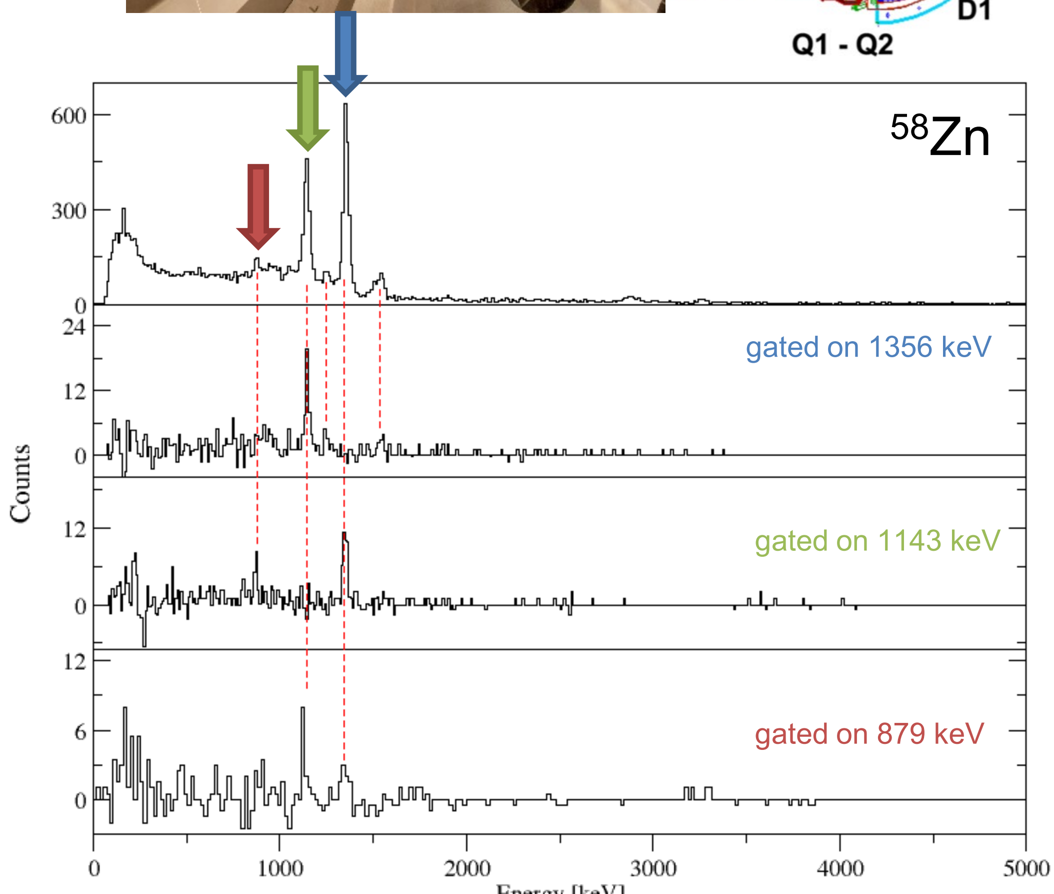
(K. Smith et al. http://adsabs.harvard.edu/abs/2008nuco.confE.178S Cyburt, Amthor et al.)

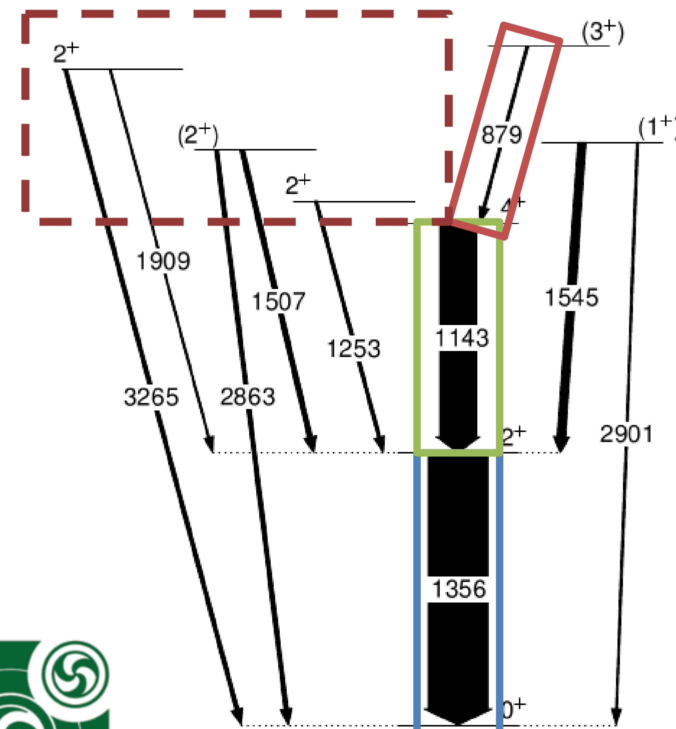
Resonance energies with GRETINA+S800 – 56Ni case

Langer et al (2014)



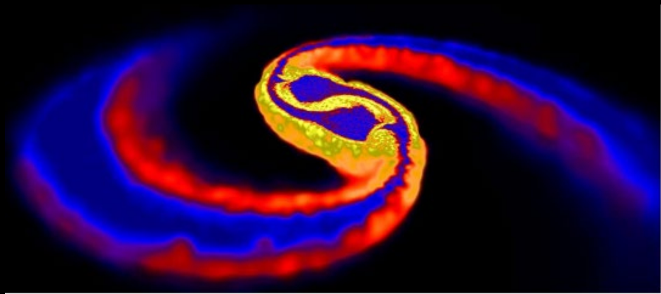


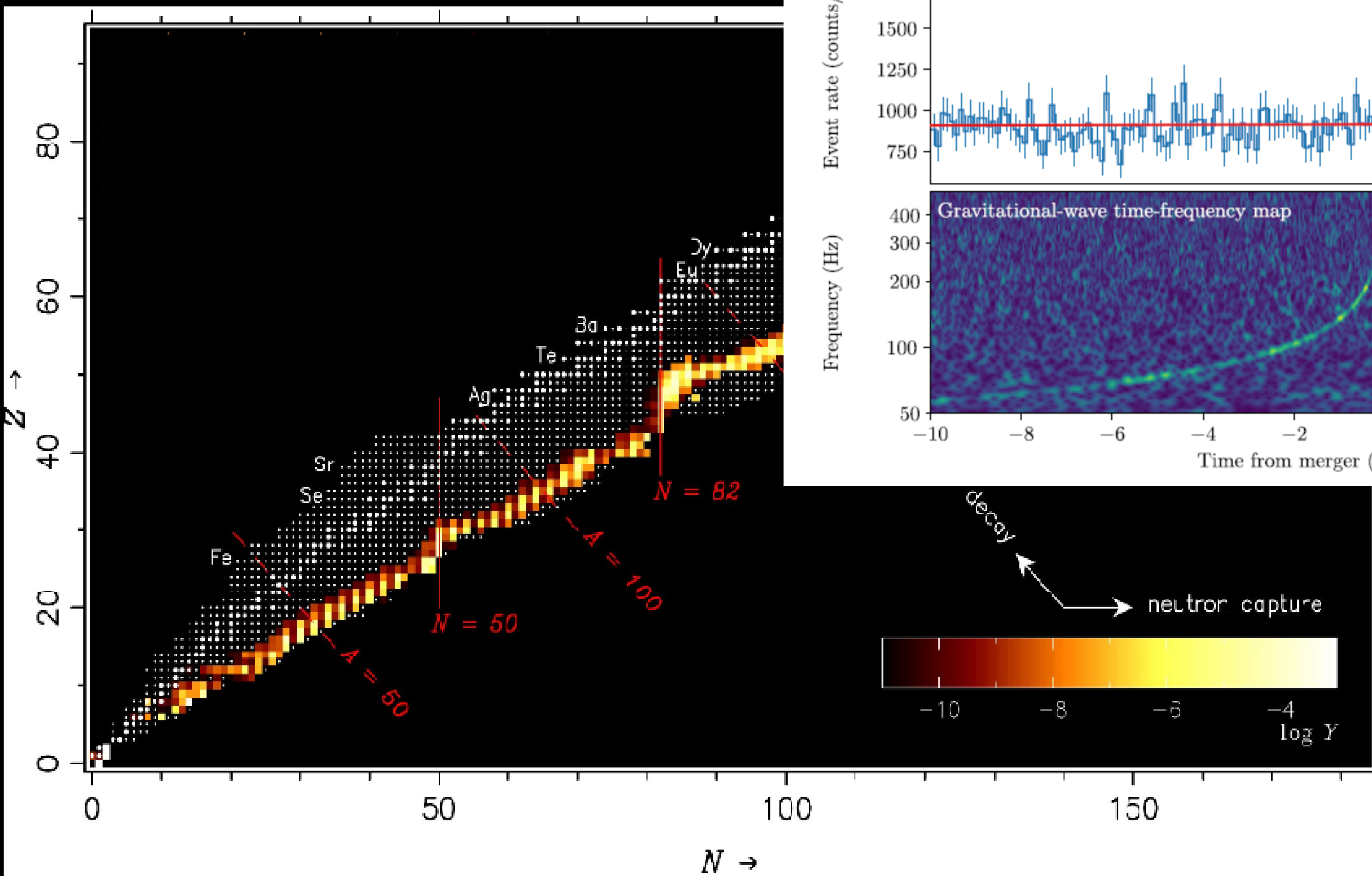


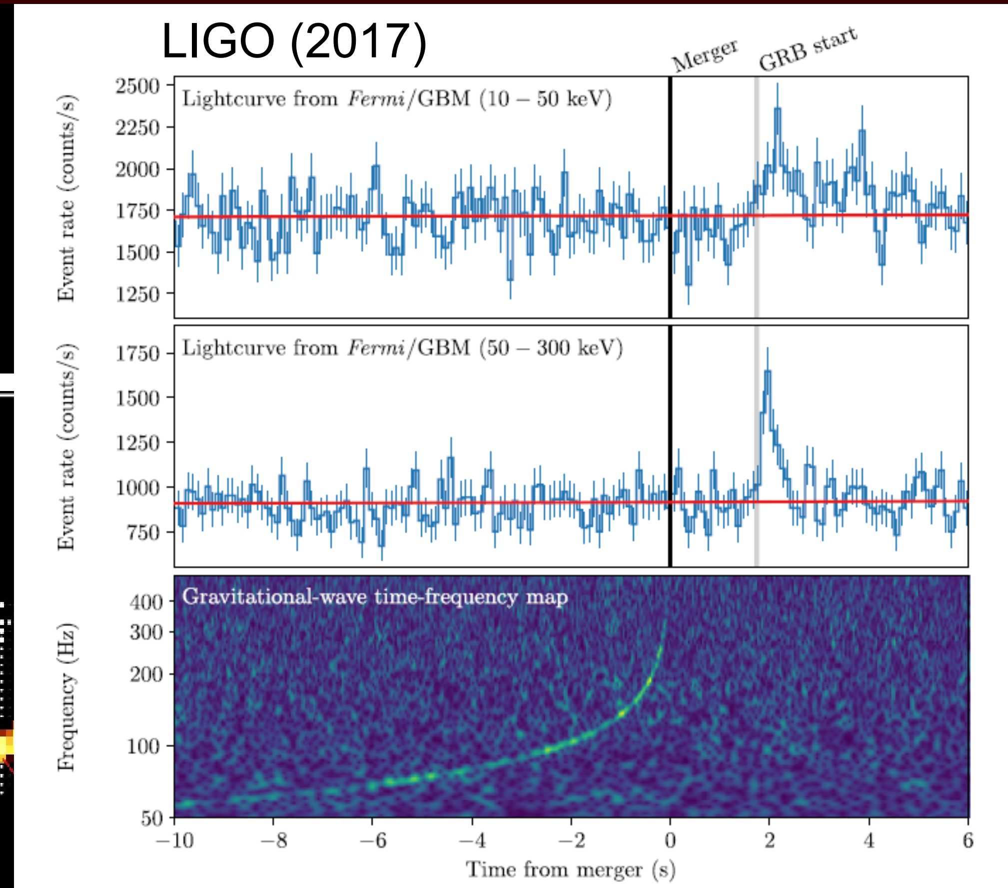


58Zn

r-process involves thousands of exotic neutron-rich nuclei





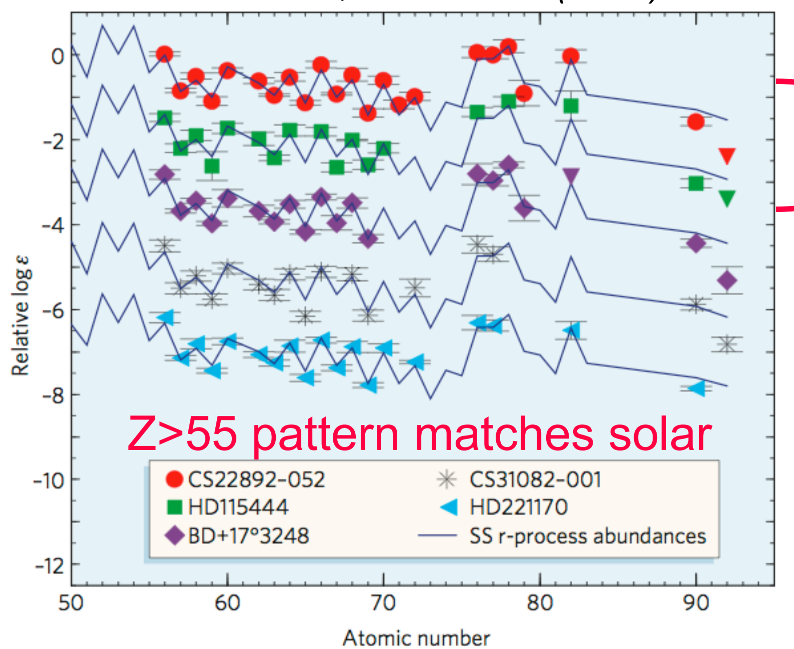


100 Earth Masses of Gold synthesized

observed r-process abundances

Now many observations of early, unmixed nucleosynthesis in the Galactic halo

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



CS22892-052

Fe/H = ($8x10^{-4}$) solar = very old

r/Fe = 50 solar

Only 2 known in 2000

Now extensive surveys

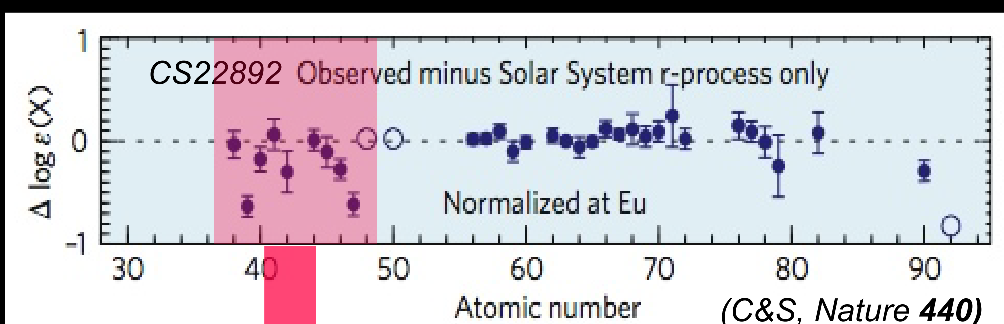
e.g. see Frebel et al., ApJ ***652*** *(2006) 1585*

SEGUE (Sloan DSS)

Spectra of >$2x10^5$ selected halo stars

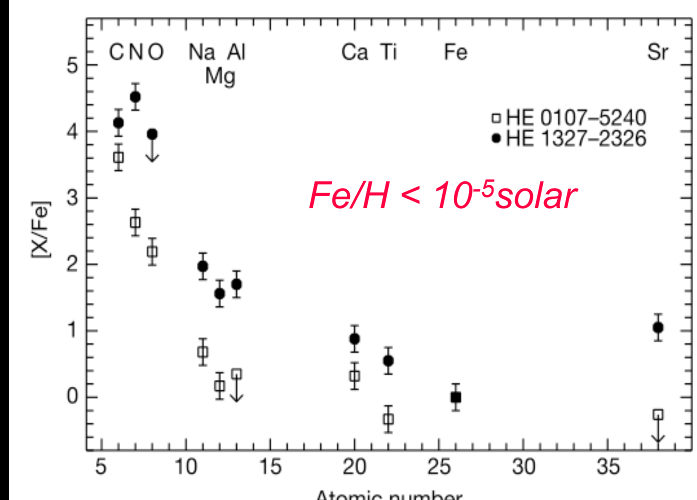
Expect ~ 1% with Fe/H < 0.001solar

Allowing us to trace nucleosynthesis throughout the history of the Galaxy



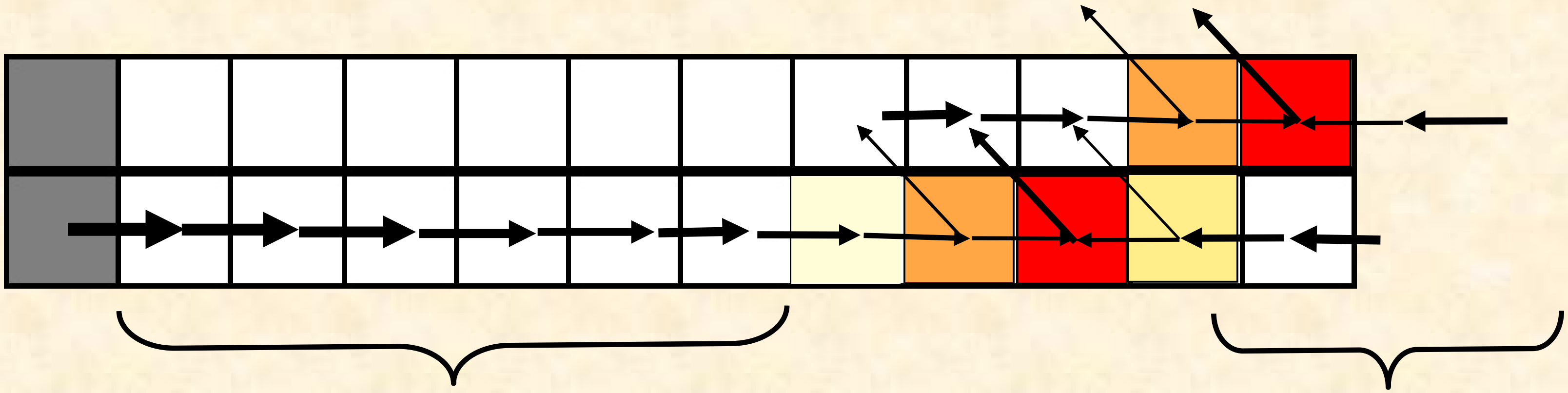
Z<50 abundances vary

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



waiting point approximation

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



Large S_n

$(n,\gamma) >> (\gamma,n) >> t_{1/2}$

Small S_n

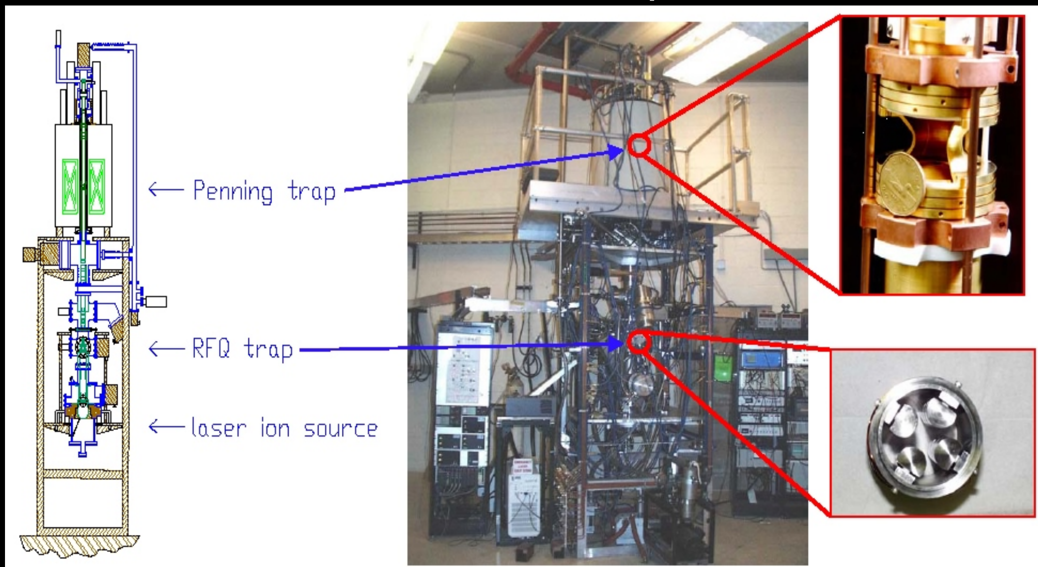
$(\gamma,n) >> (n,\gamma) >> t_{1/2}$

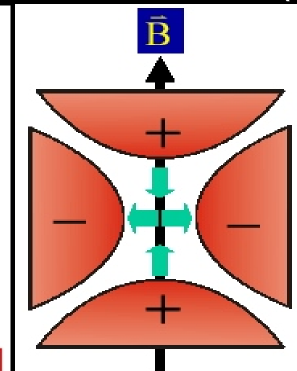
- Free parameters n_n, kT, t
- Instantaneous freezeout & decay to stability

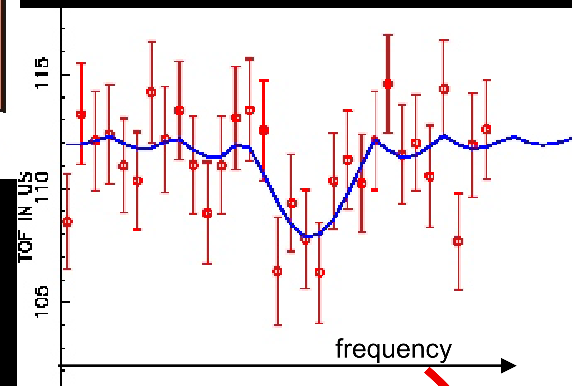
Only masses, $t_{1/2}$, and P_n needed

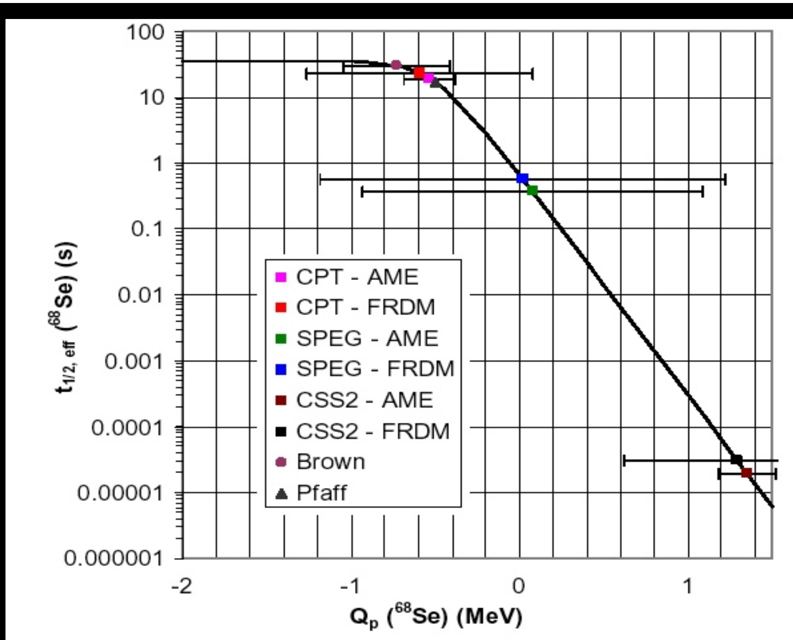
mass measurements with the CPT

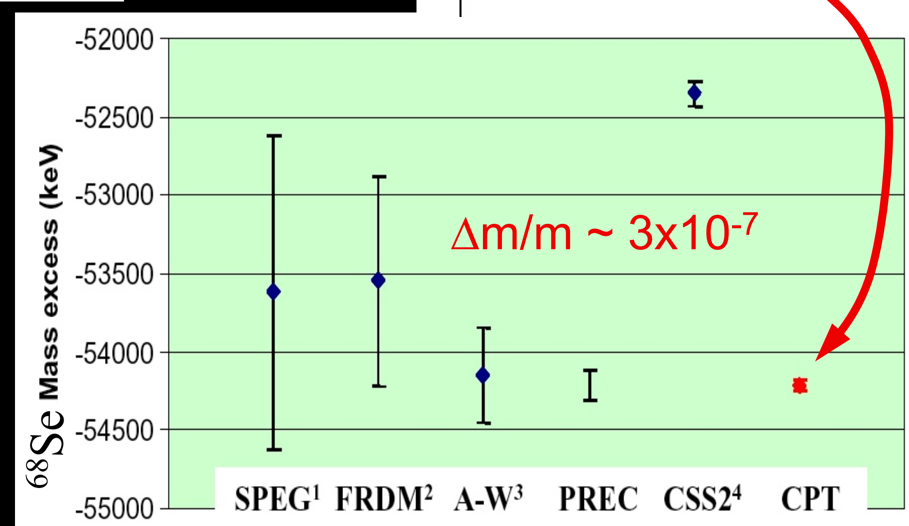
For example see: J. A. Clark *et al.*, PRL (2004)



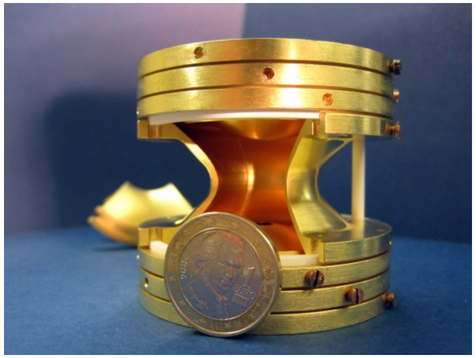






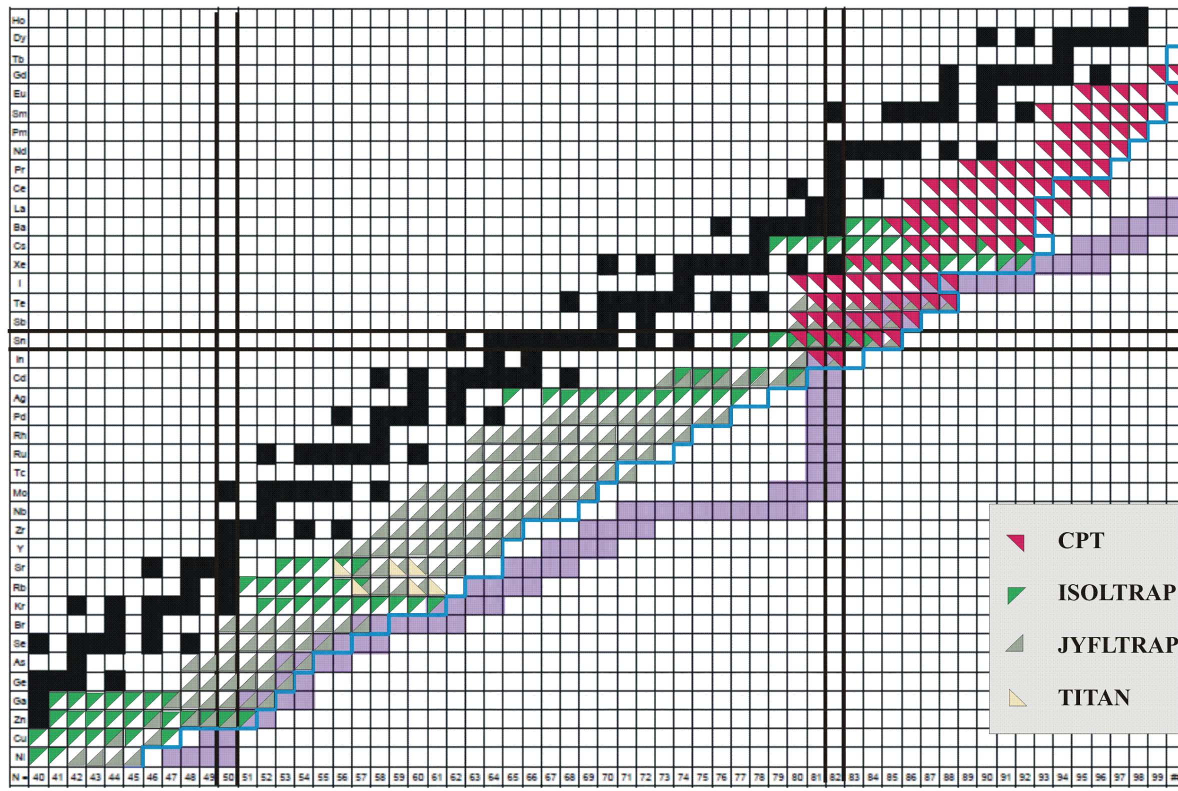


Mass measurements of neutron-rich nuclides



- **Masses determined via a measurement of the ions' cyclotron frequency**
- **Can measure the mass with a production rate of ~ 1 ion / s**
- **Mass precision ~ 10^{-7} to 10^{-8} (10 -100 keV/c^2) for masses approaching the *r* process**

- **Canadian Penning Trap (CPT) has measured more than 100 neutron-rich nuclides, including more than 70 from CARIBU (including 6 isomers)**
- **~ 20 had never been previously measured by any technique**
- **Currently reaching isotopes produced at the 10^{-6} fission branch level**
- **For some nuclei, no prior information on the nuclide existed!**



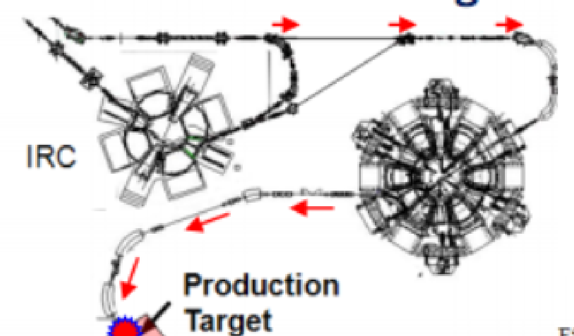
J. Van Schelt *et al.*, Phys. Rev. C **85**, 045805 (2012)

J. Van Schelt *et al.*, Phys. Rev. Lett. **111**,061102 (2013)

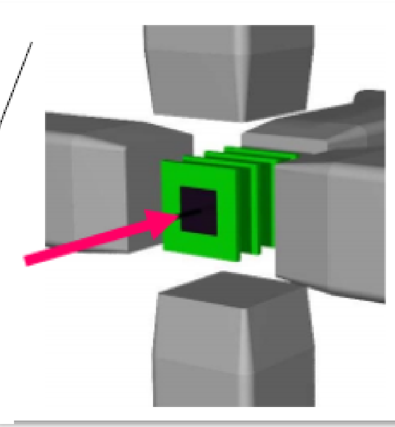
Beta Decay Example: RIBF @ RIKEN

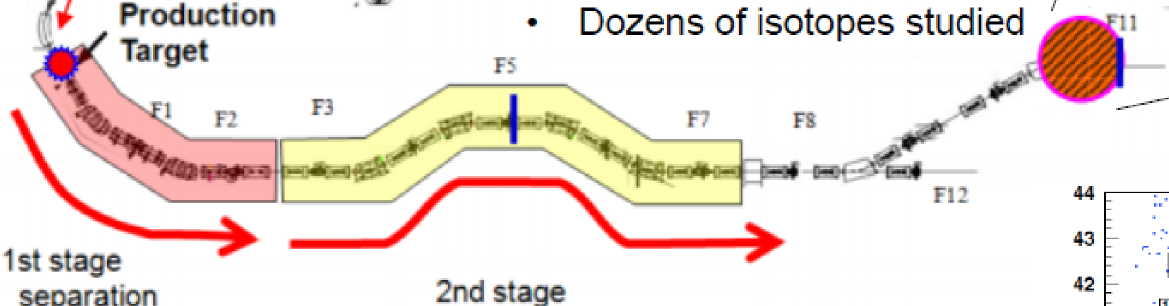
^{238}U @ 345 MeV/u

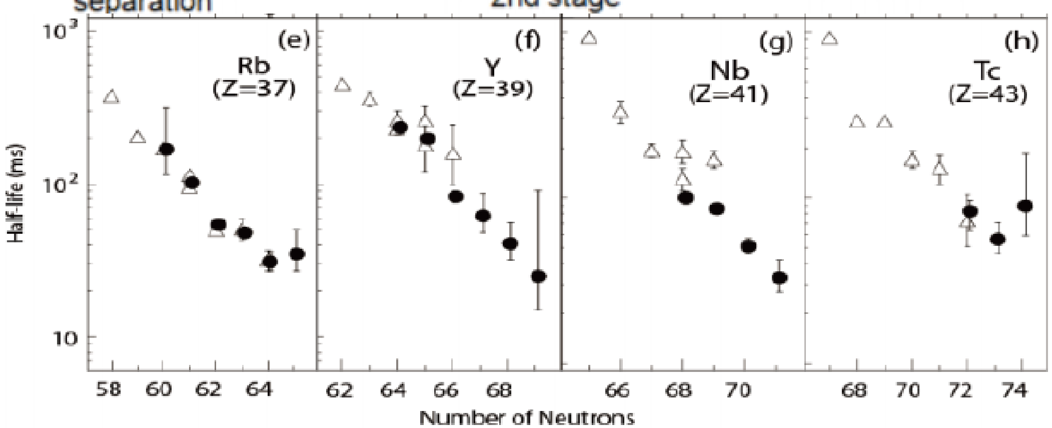
→ Be target

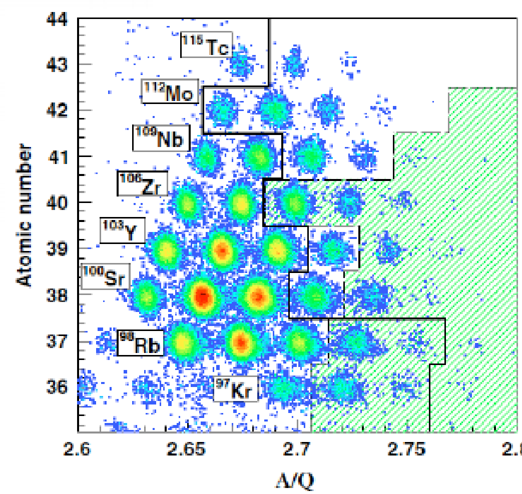


- Isotopes produced by fragmentation
- EM separated and implanted into Si detector stack (9)
- Identiified by TOF and ΔE-E
- Decay β and γ measured
- Dozens of isotopes studied



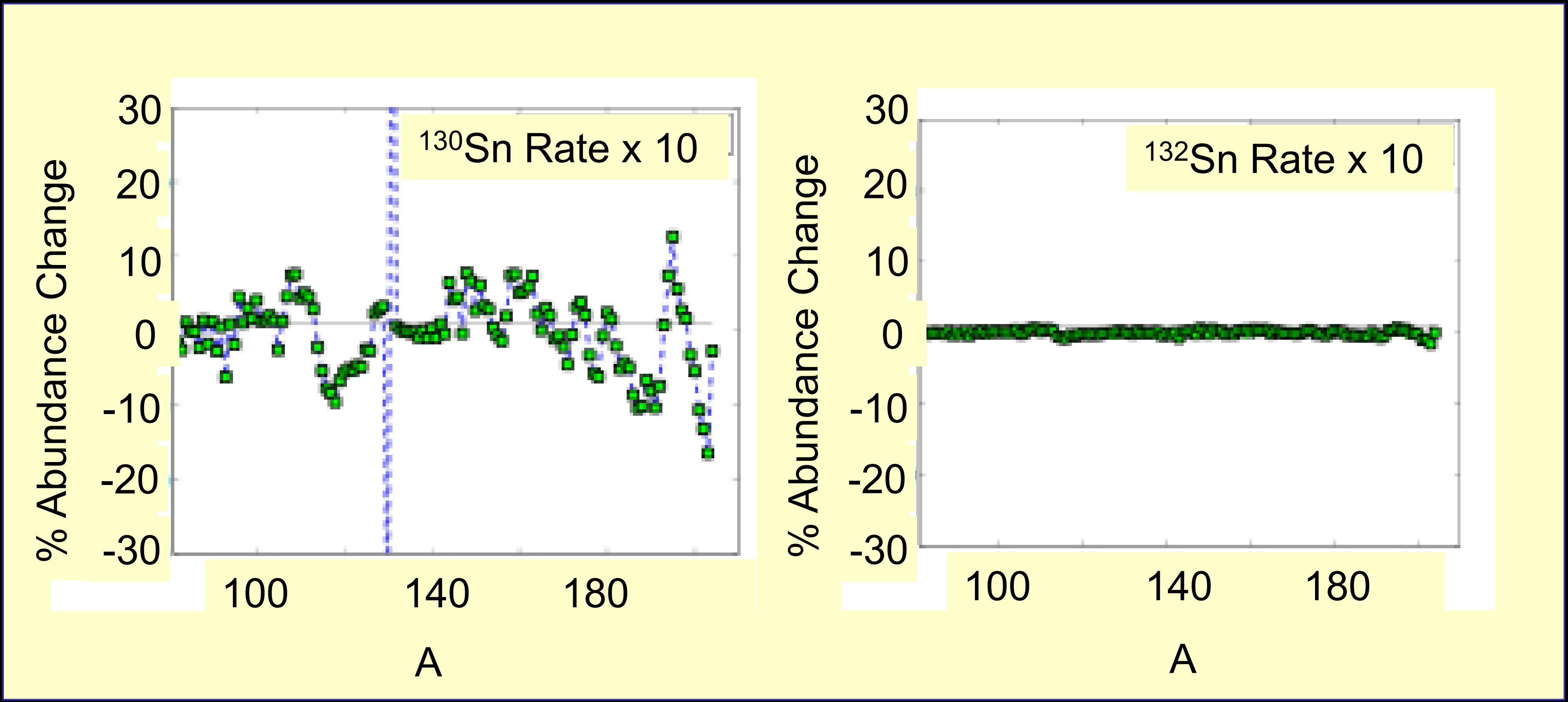






S. Nishimura *et al.*, PRL **106**, 052502 (2011).

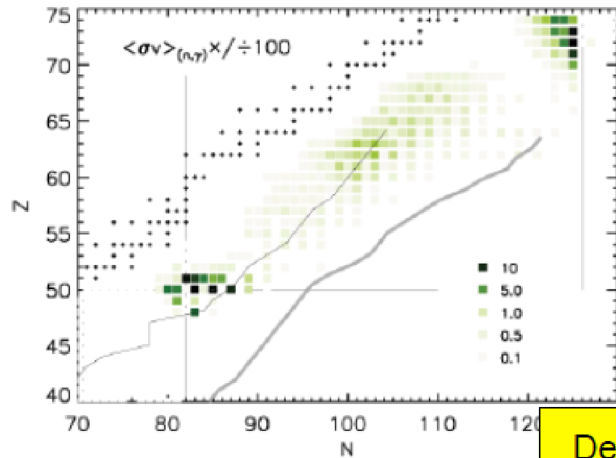
not so simple – (n,γ) cross sections also matter - sometimes



Simulations of the r-process show **global** sensitivity to the ^{130}Sn(n,γ) rate, in contrast to the ^{132}Sn(n,γ) rate.

From Surman, Beun, McLaughlin, Hix, PRC 79, 045809 (2009).

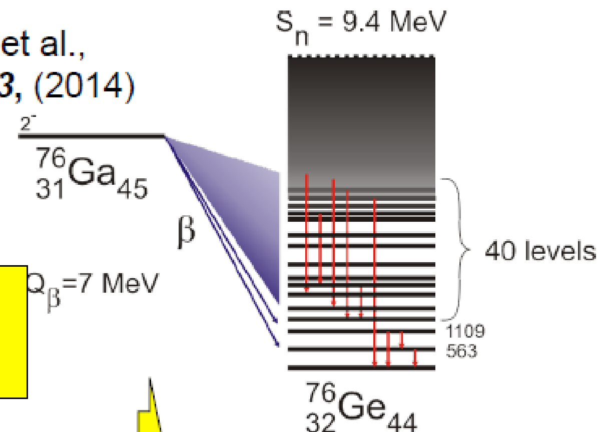
Neutron capture rates



- Indirect (statistical) approaches needed:
  - Nuclear level densities
  - Gamma strength functions

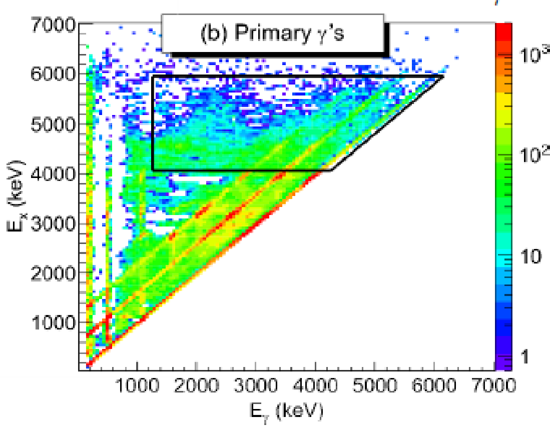
^{75}Ge(n,γ) "Beta-Oslo" test:

Spyrou et al.,
PRL ***113***, (2014)

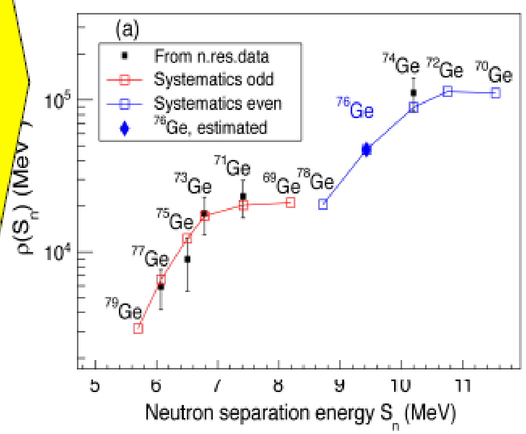


Developing approach away from stability

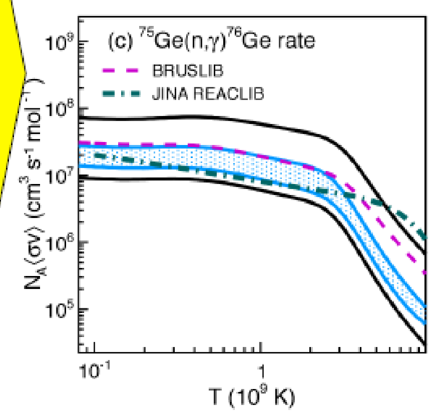
Unfold primary E_γ vs. E_x
→ *relative* $\rho(E_x)$ & $f(E_\gamma)$



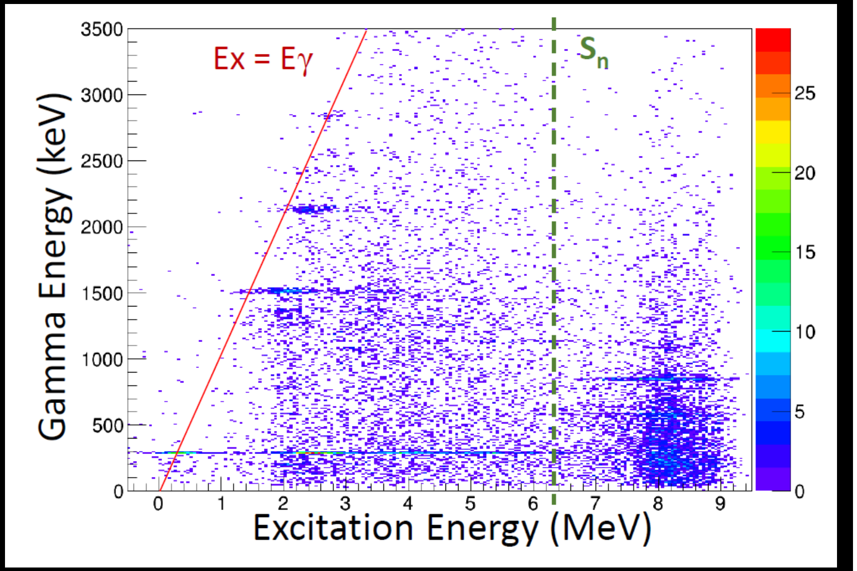
Normalize w/ systematics



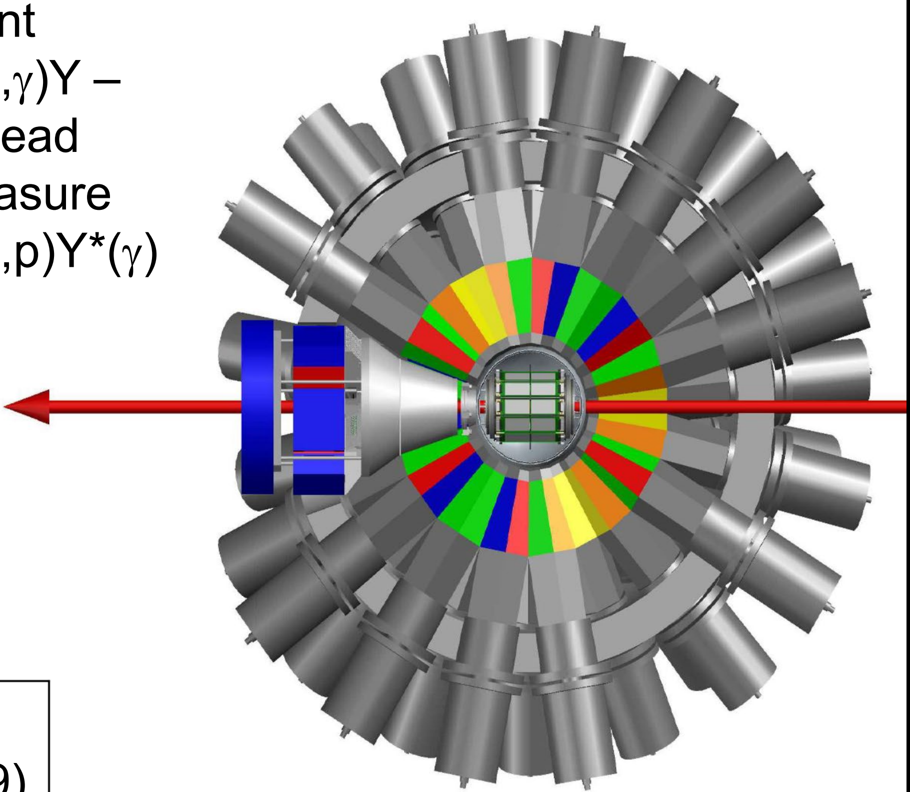
Statistical (n,γ) rate

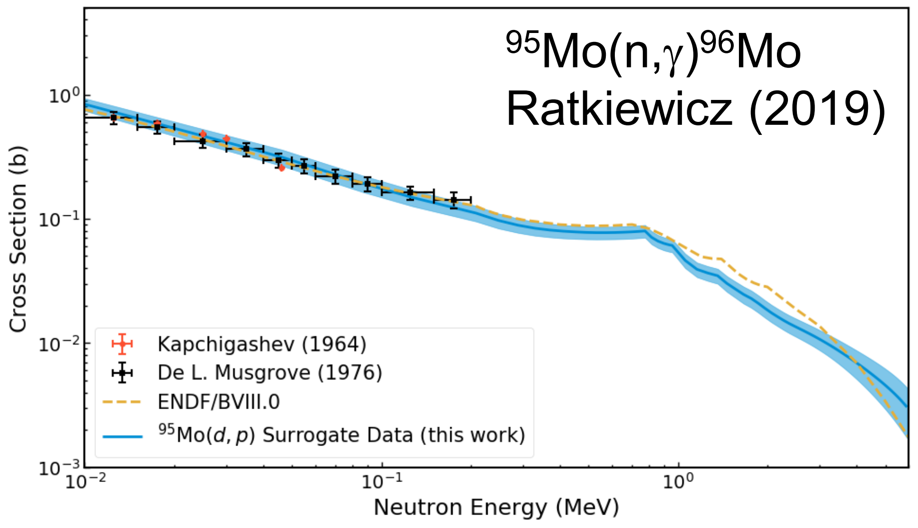


Surrogate Technique

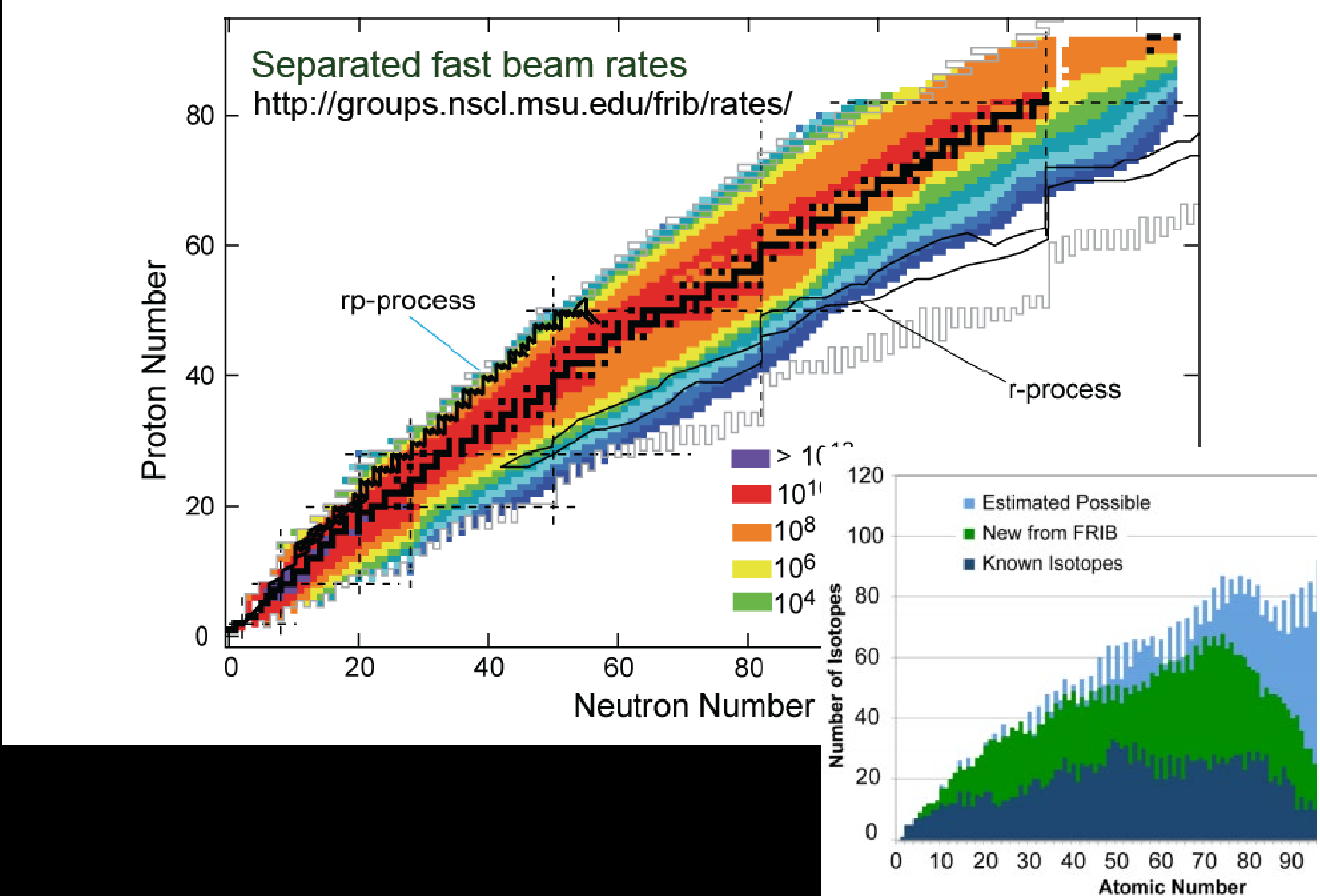


Want X(n,γ)Y – instead measure d(X,p)Y*(γ)





the reach of FRIB



exciting time for nuclear astrophysics

- incredible array of observations and precise data becoming available for a variety of astrophysical objects
- first pioneering measurements with exotic beams have been made but only a handful so far
- next generation of tools and facilities coming online in the next 10 years
- computational power allowing detailed multi-dimensional hydrodynamic nucleosynthesis calculations to be made
- wonderful time to be entering this field!