Nuclear Astrophysics Measurements with Radioactive Beams

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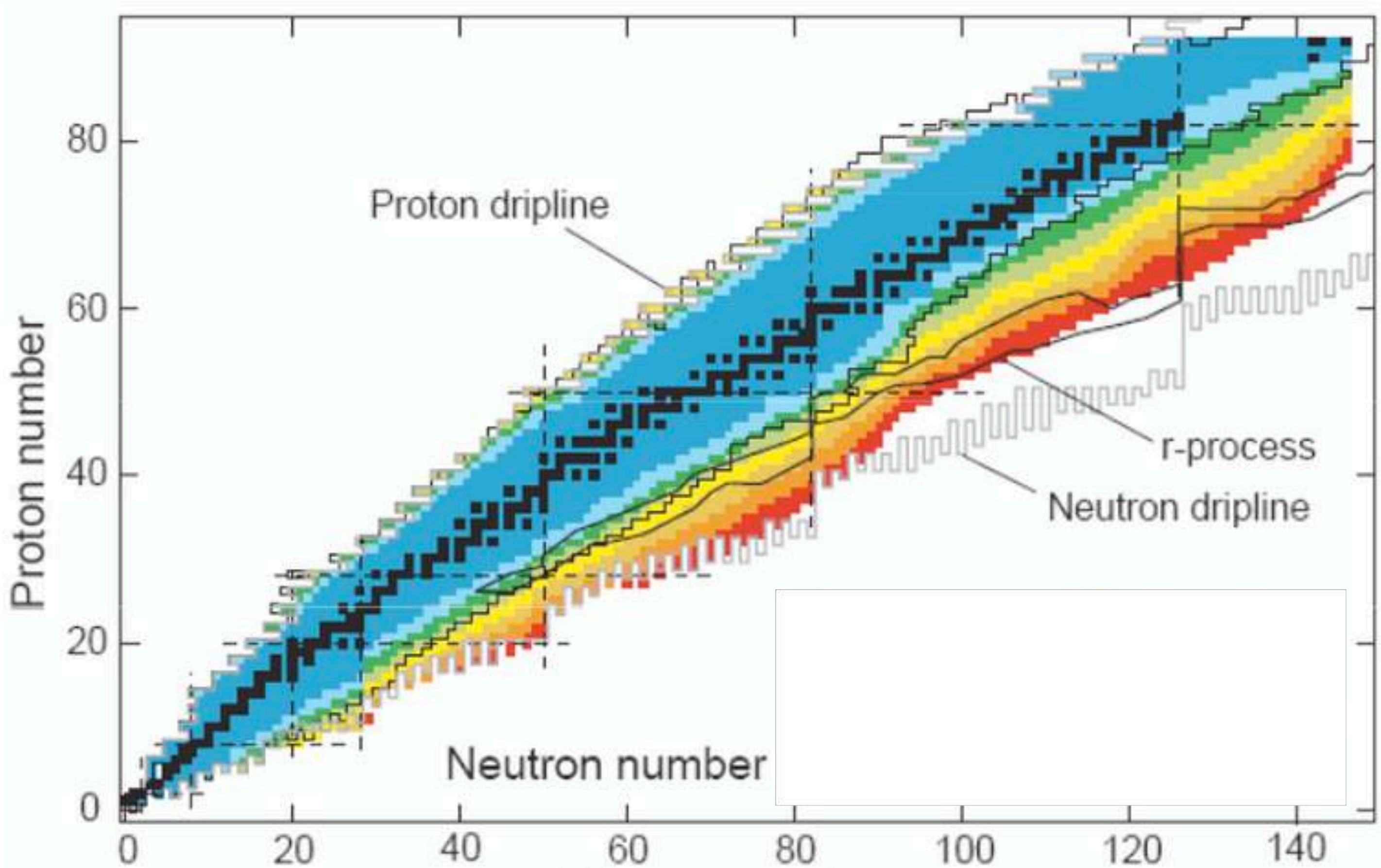
Promise of Radioactive Beams

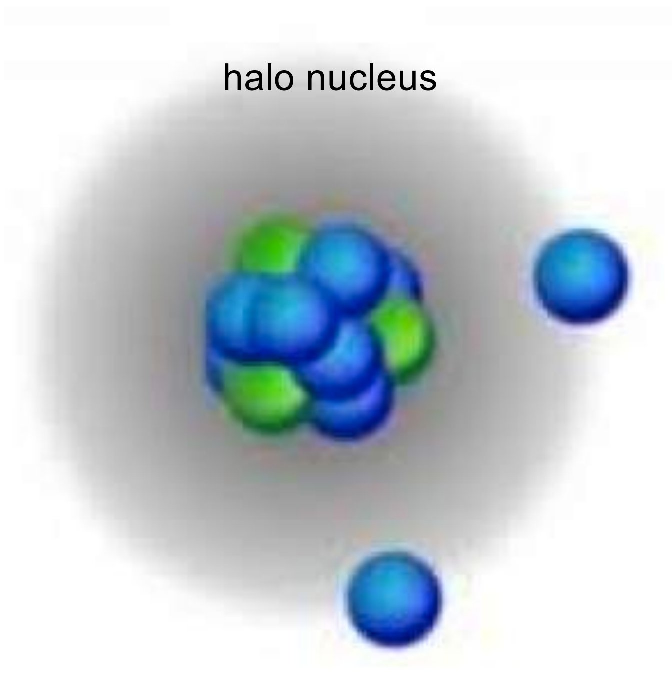
- *radioactive beam facilities enable nuclear scientists to study some of the most fascinating phenomena in nature*

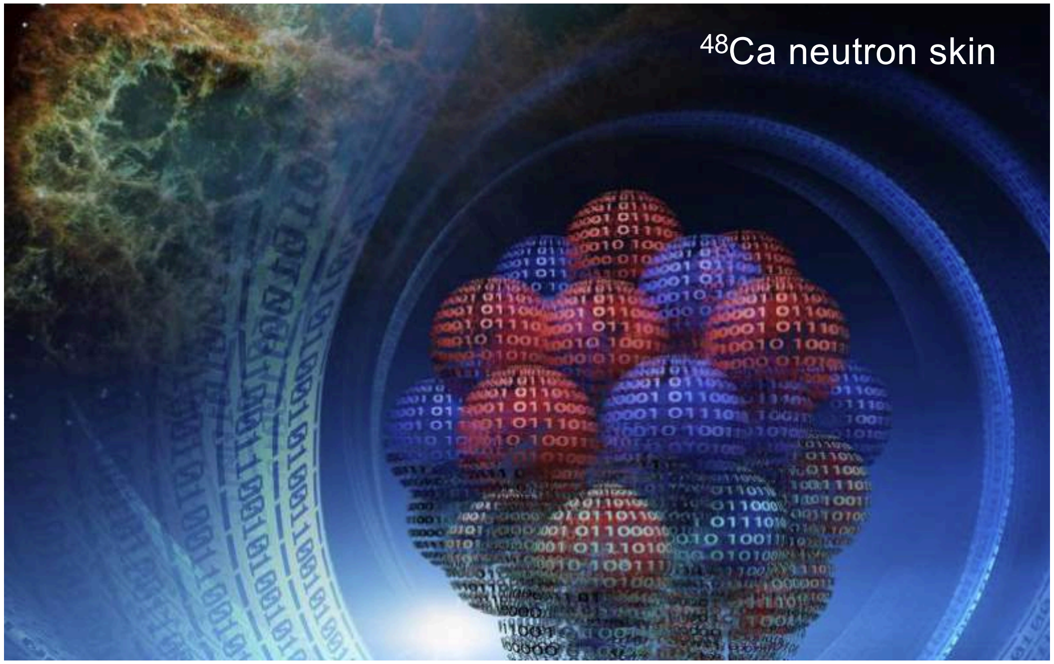
Promise of Radioactive Beams



- *find limits of nuclear stability & determine structure of "extreme" nuclei*

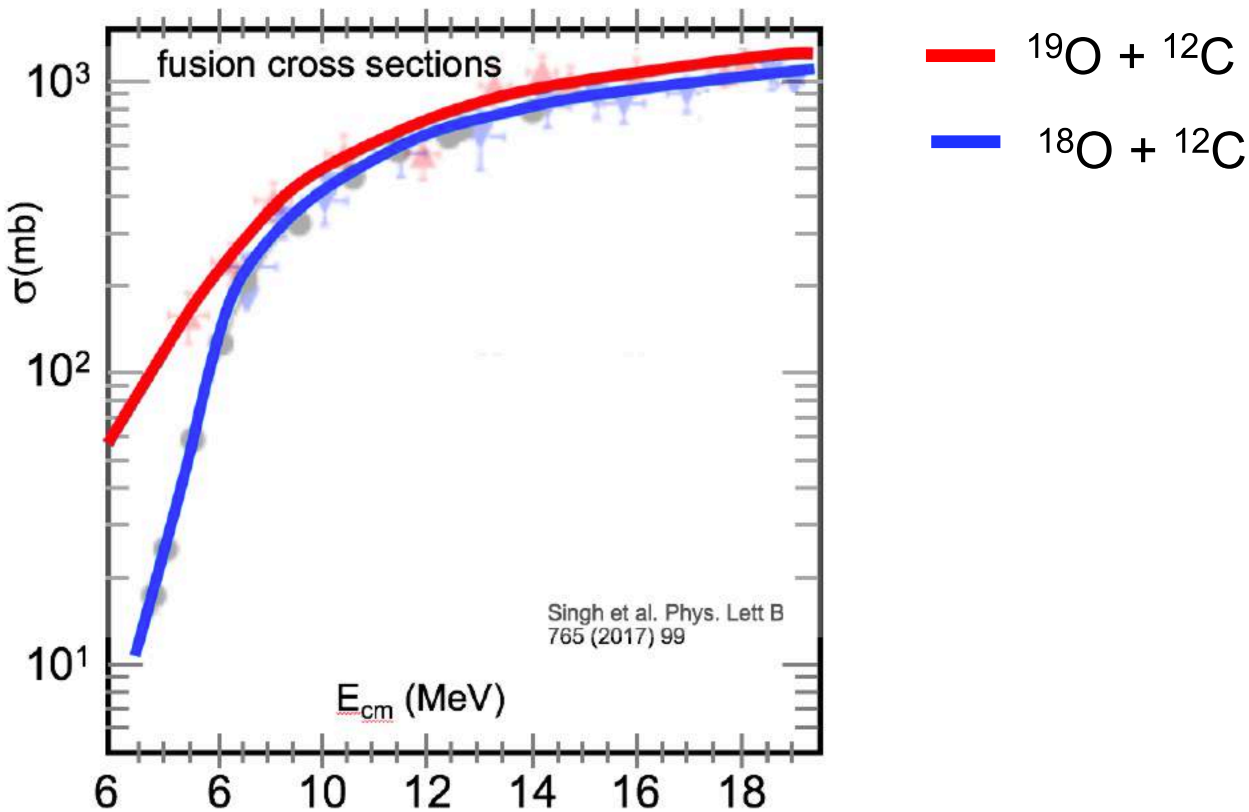
Promise of Radioactive Beams





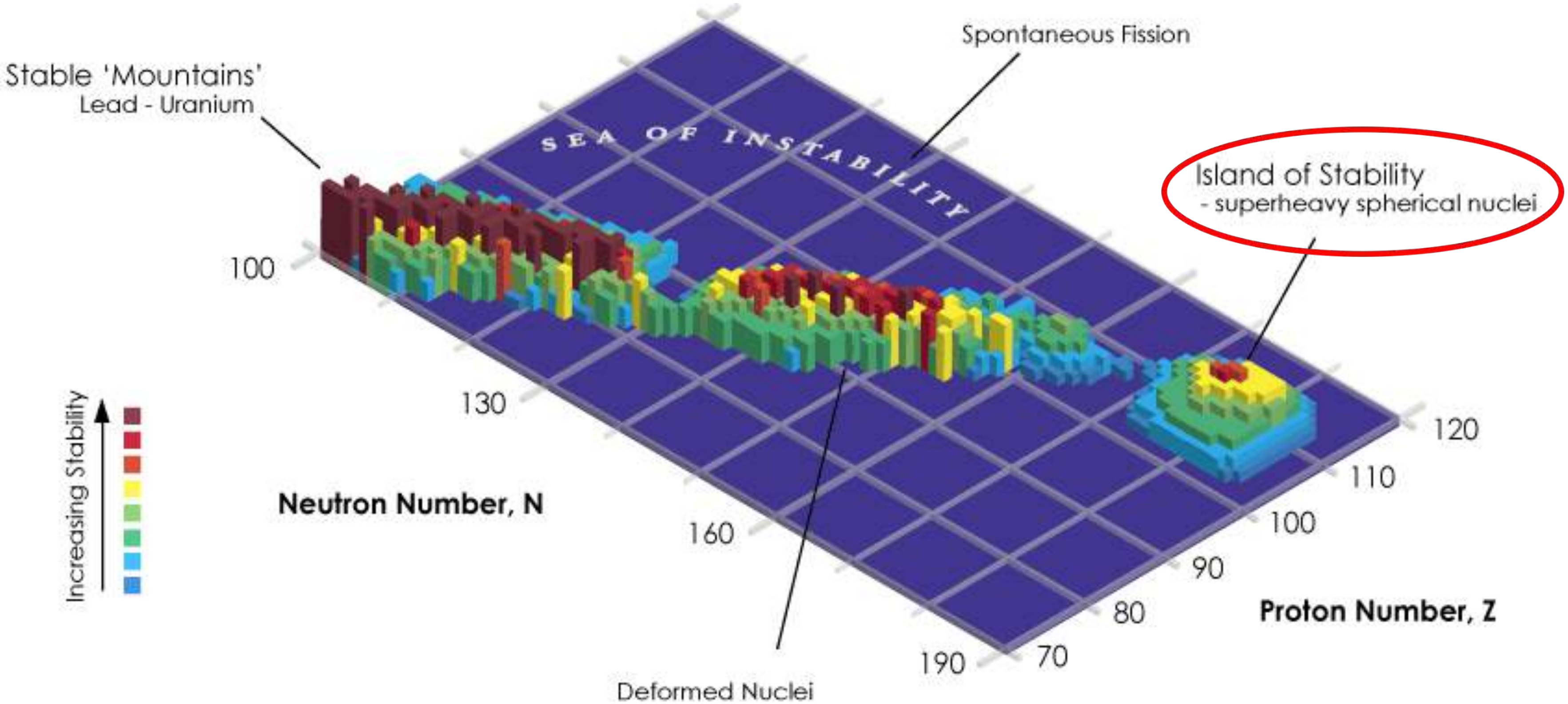
- *use this information to determine predictive models of subatomic nuclei*

Promise of Radioactive Beams



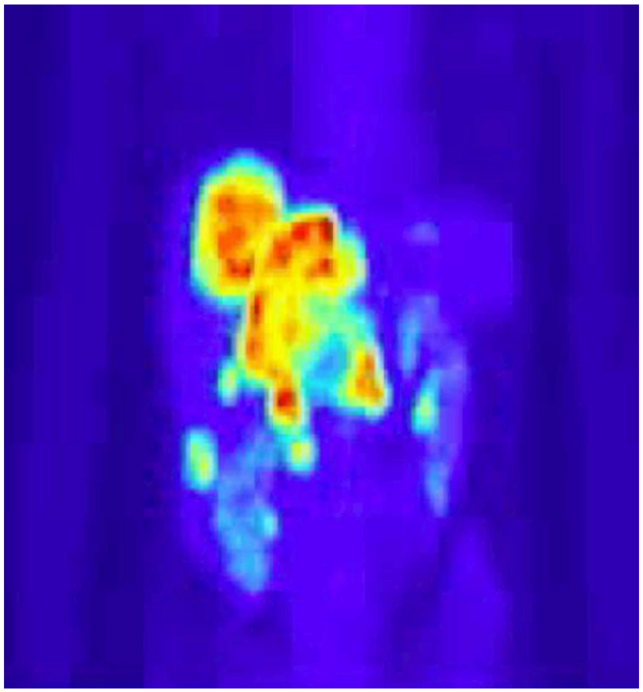
- *improve our understanding of nuclear reactions*

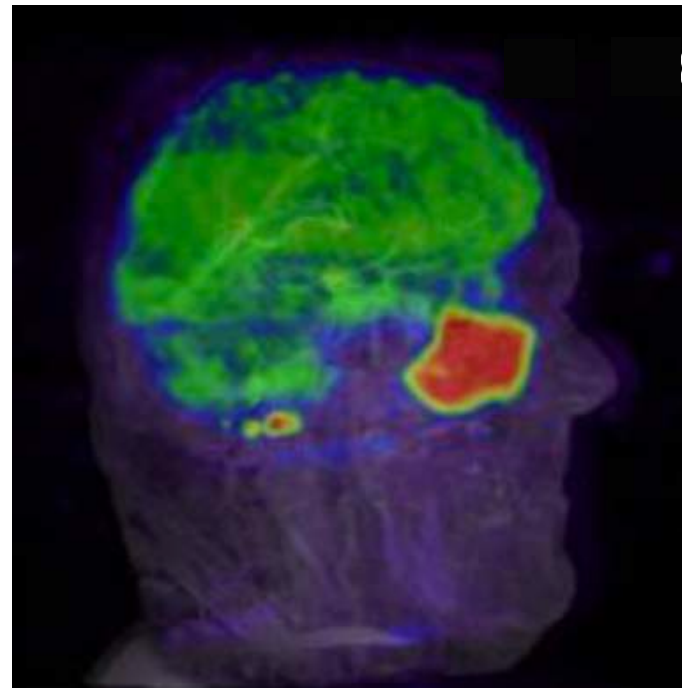
Promise of Radioactive Beams



- *discover a new pathway to synthesize superheavy nuclei*

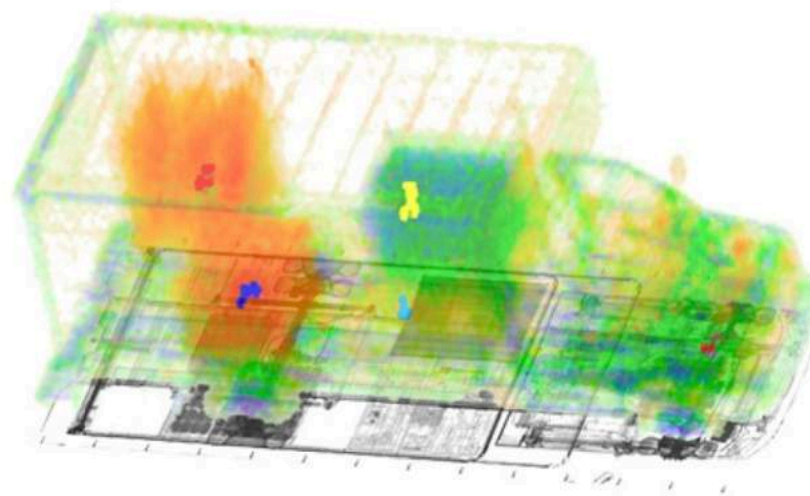
Promise of Radioactive Beams





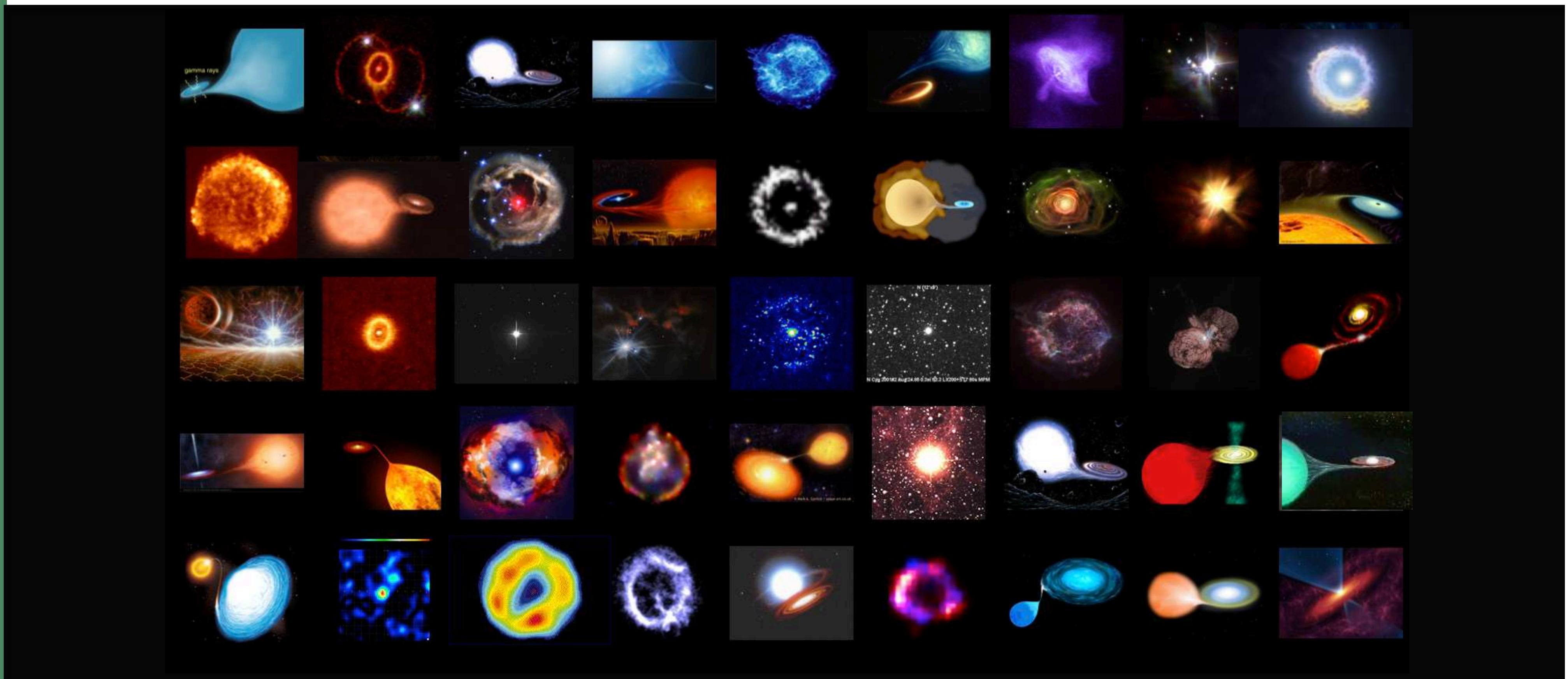
- *produce new isotopes for imaging and treating cancer*

Promise of Radioactive Beams



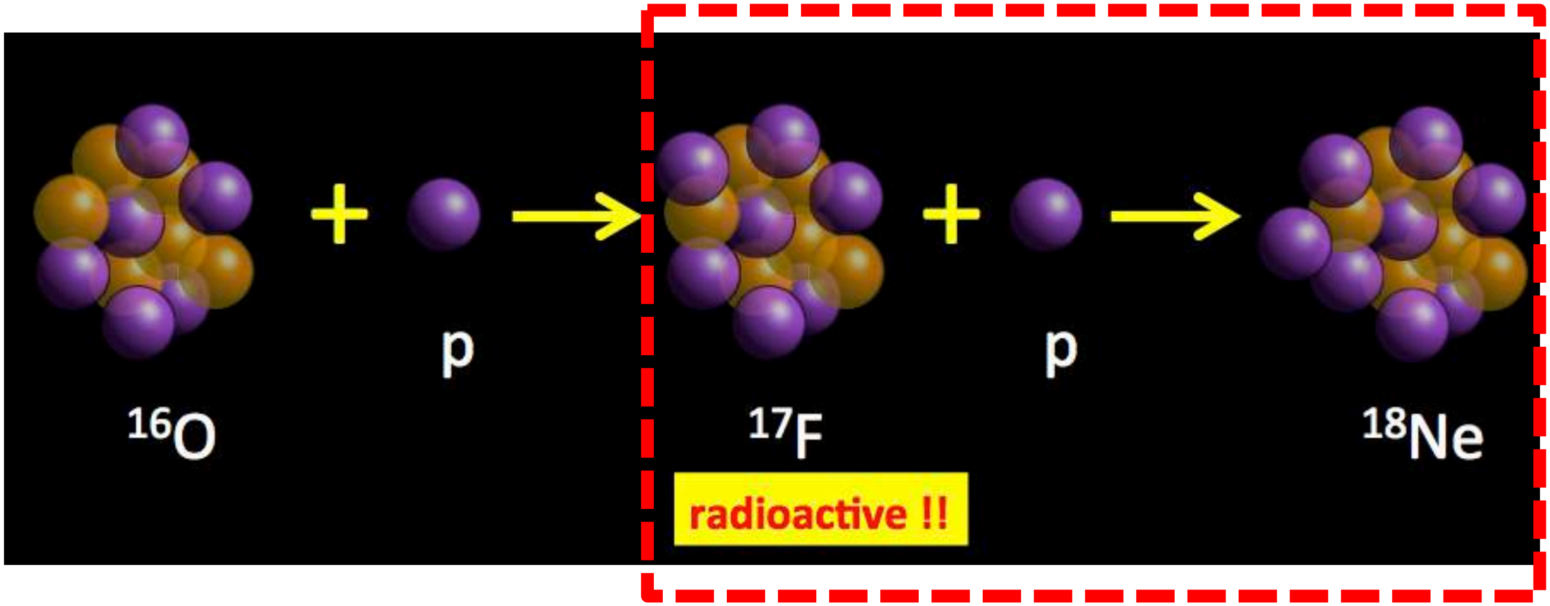
- *help improve international nuclear security*

Promise of Radioactive Beams



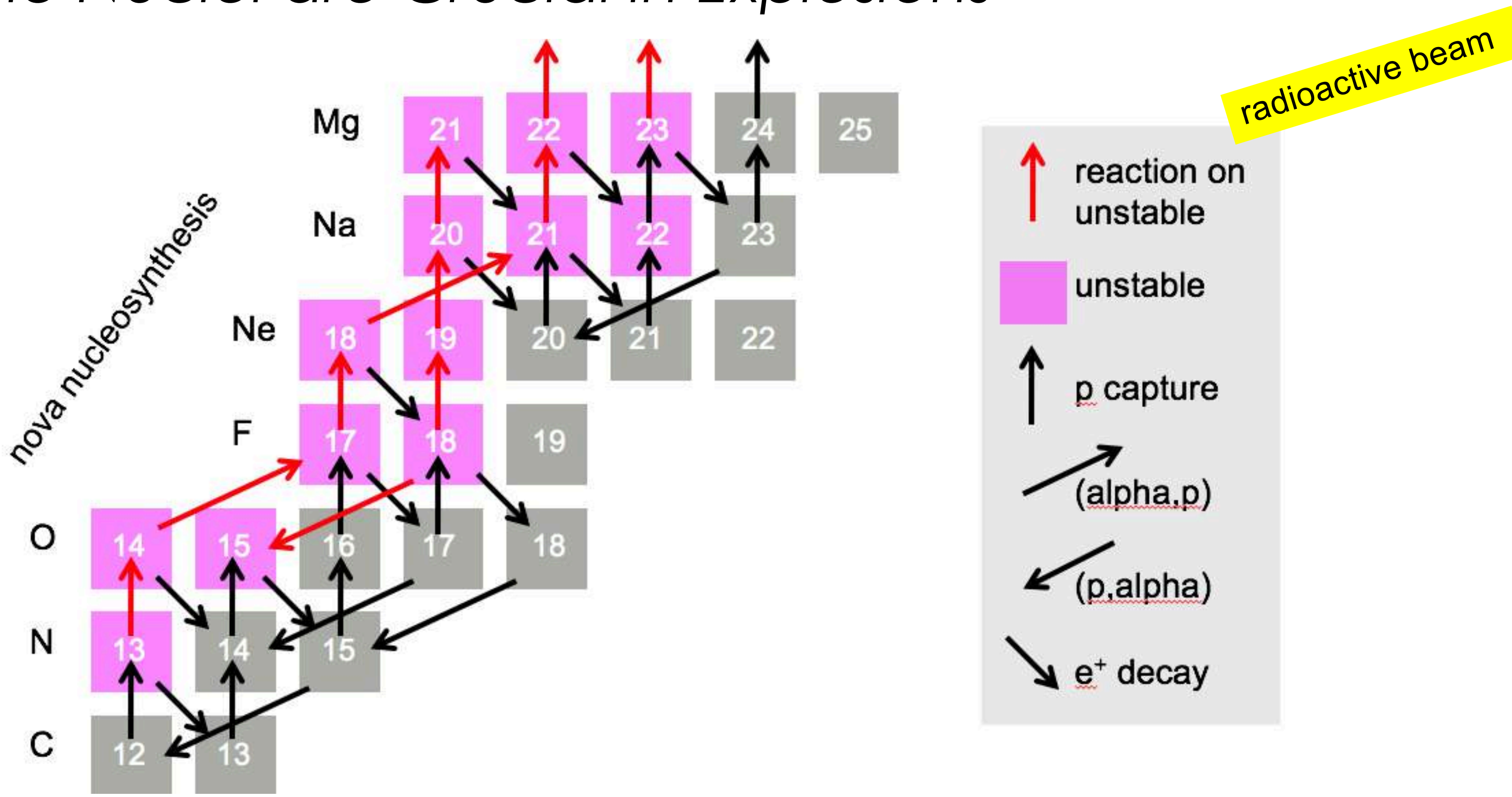
- *provide an **empirical foundation** for understanding **exploding stars***

Unstable Nuclei are Crucial in Explosions



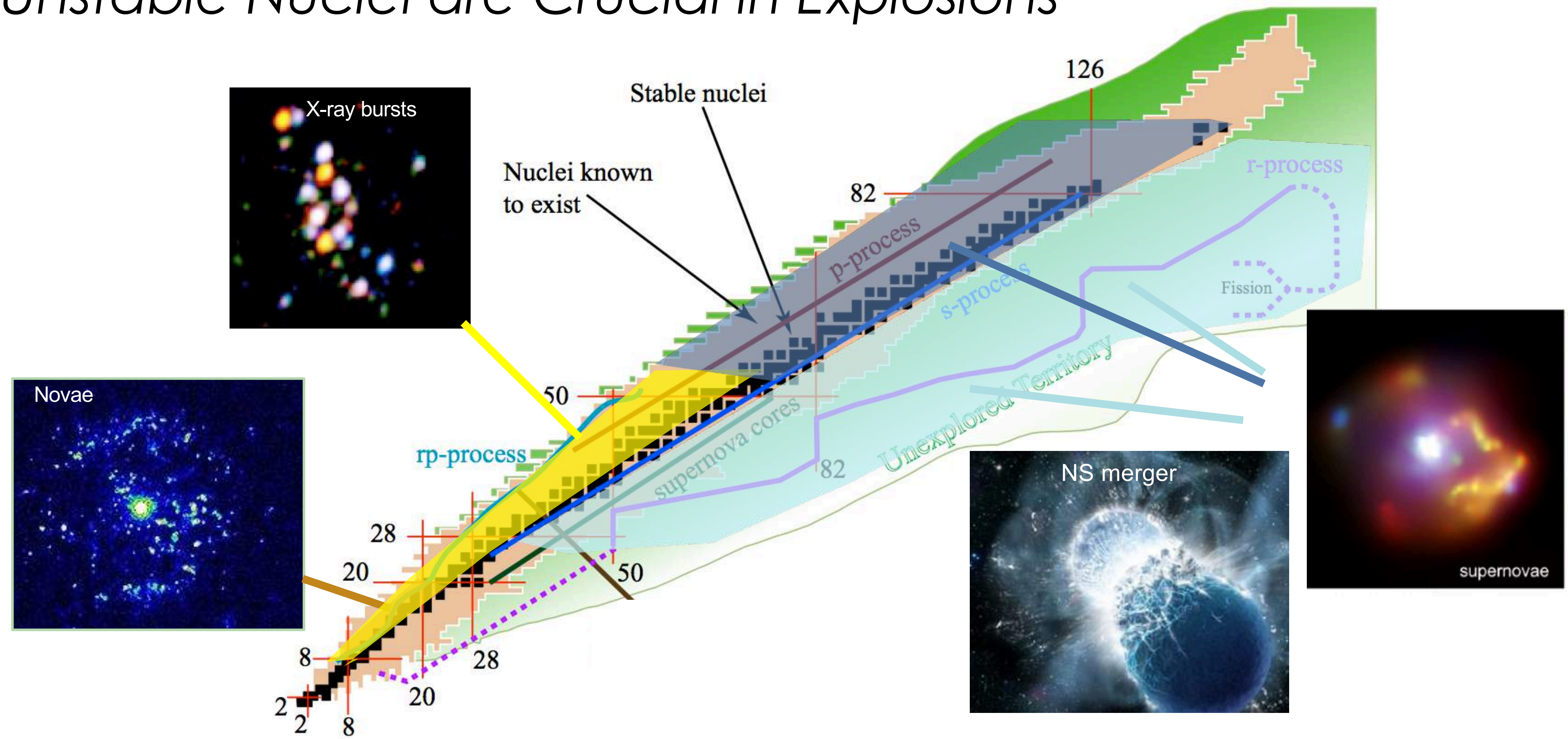
- *in exploding stars, extreme temperatures & densities cause unstable nuclei to be formed and have* ***subsequent reactions before decay***

Unstable Nuclei are Crucial in Explosions



- ***sequences** of reactions on **unstable isotopes** occur in explosions*

Unstable Nuclei are Crucial in Explosions



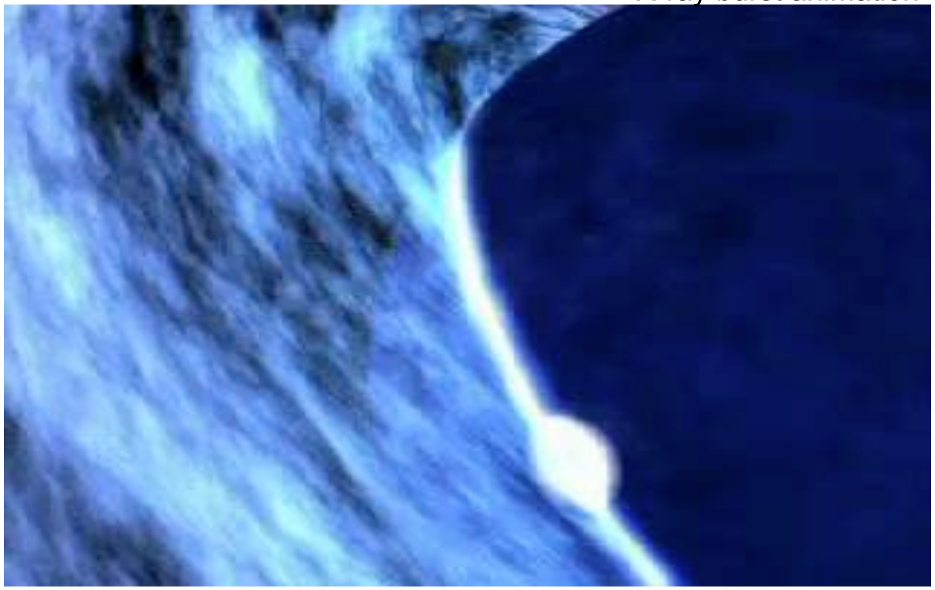
- *these reaction sequences play a critical role in element creation*

Unstable Nuclei are Crucial in Explosions

- *radioactive beam facilities* ***enable measurements*** *that form an* ***empirical foundation*** *for our understanding of stellar explosions*

Science Goals in Nuclear Astrophysics with Unstable Beams

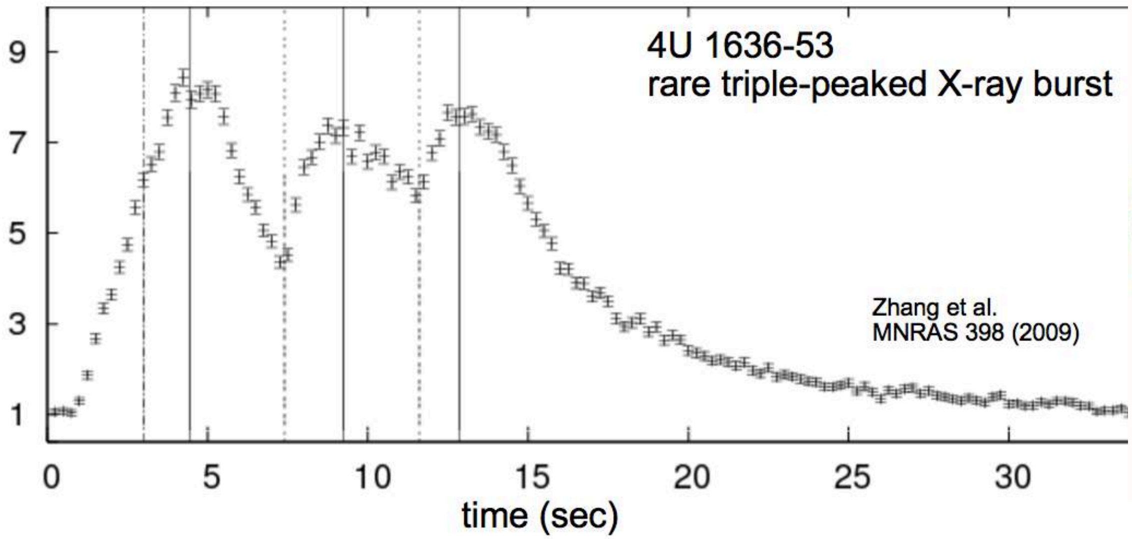
X-ray burst animation

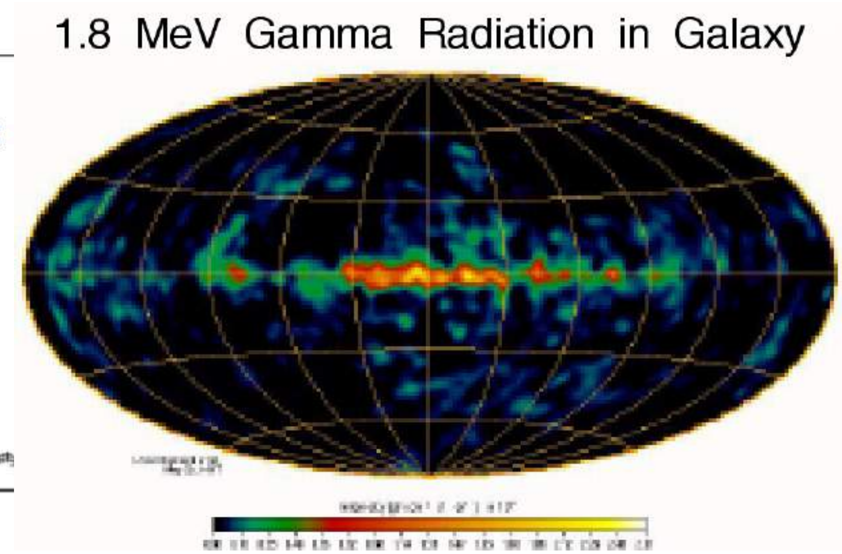


Core collapse supernova animation

- *understand the energy generation and element creation in stellar explosions*

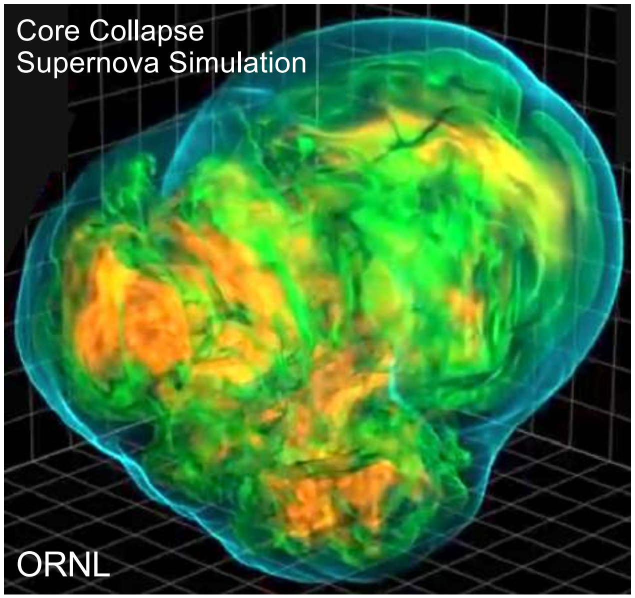
Science Goals in Nuclear Astrophysics with Unstable Beams

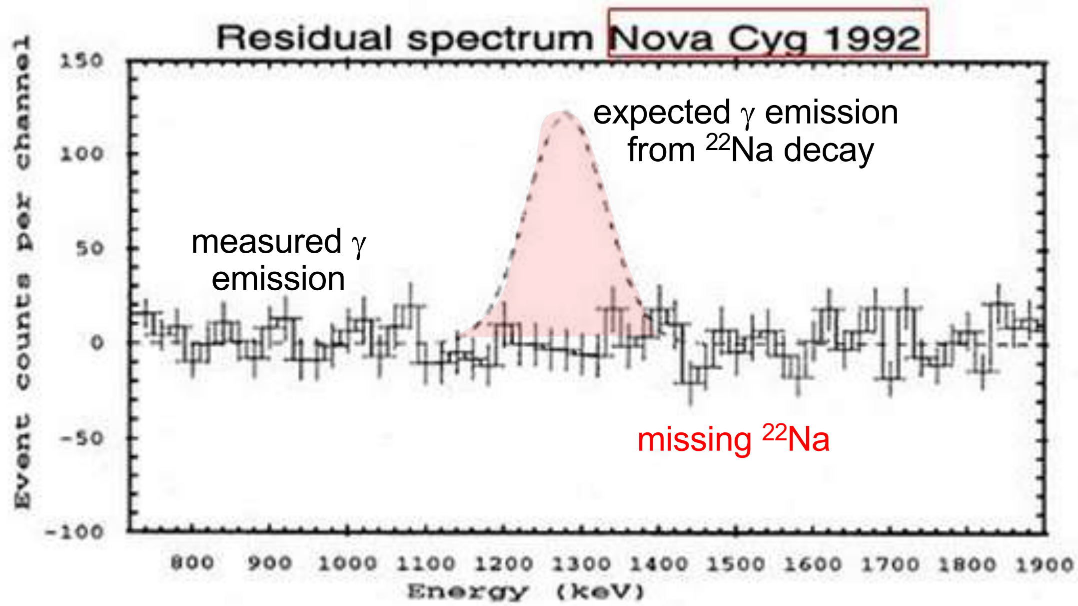




- *understand the energy generation and element creation in stellar explosions*
- *help decipher explosion observables*

Science Goals in Nuclear Astrophysics with Unstable Beams





- *understand the energy generation and element creation in stellar explosions*
- *help decipher explosion observables*
- *address important unanswered puzzles about exotic cosmic events*

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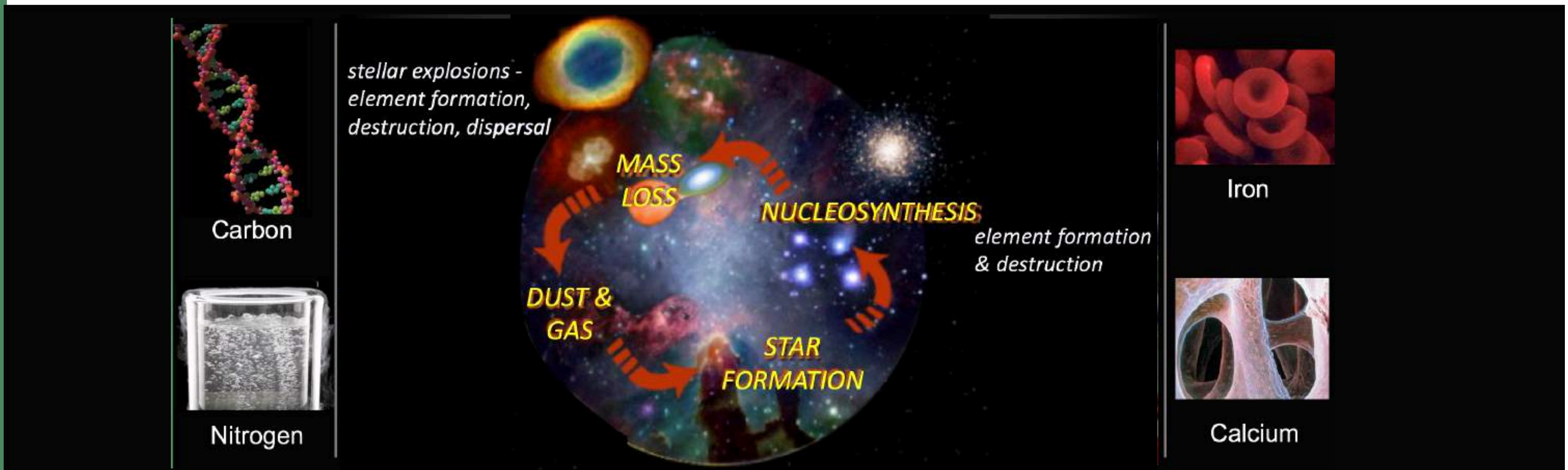
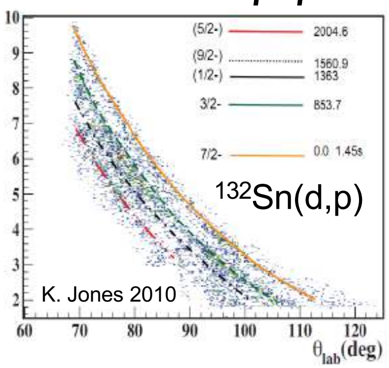
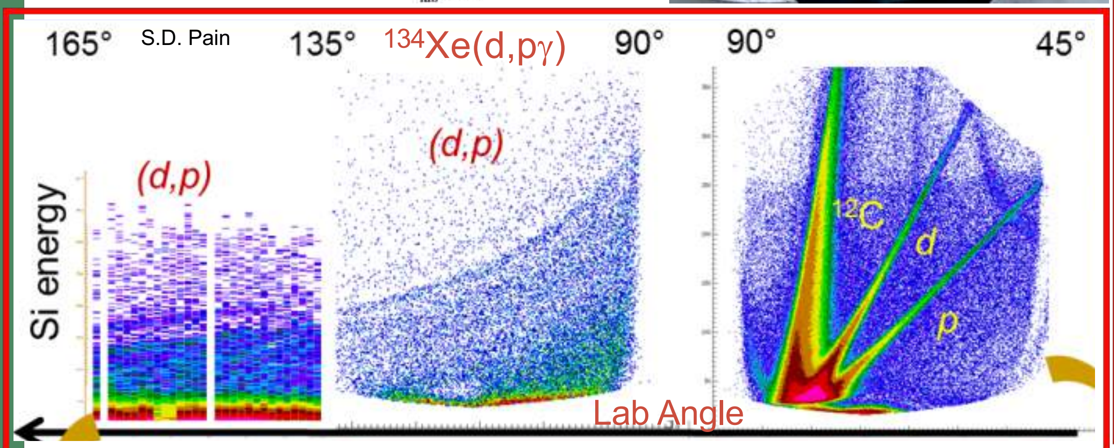
Science Goals in Nuclear Astrophysics with Unstable Beams

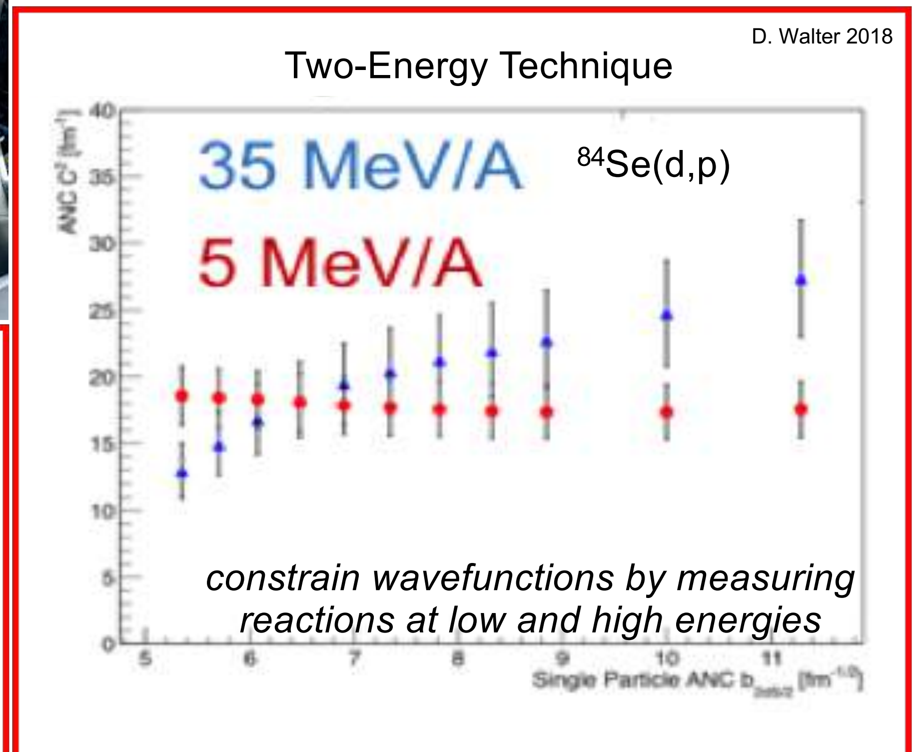


- *understand the energy generation and element creation in stellar explosions*
- *help decipher explosion observables*
- *address important unanswered puzzles about exotic cosmic events*
- *probe the chemical evolution of the galaxy*

Overall Approach

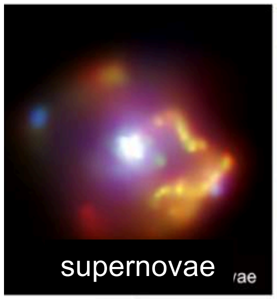


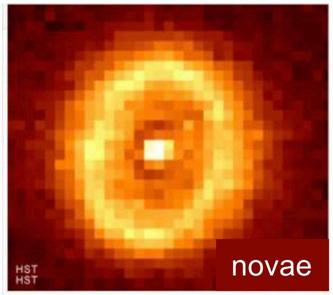


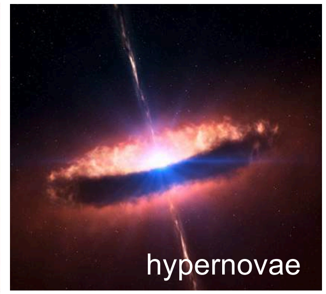


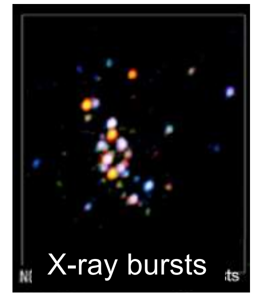
- *closely couple **radioactive beam measurements** with the **development** of advanced **detectors** & **techniques** needed to make these measurements*

Outline

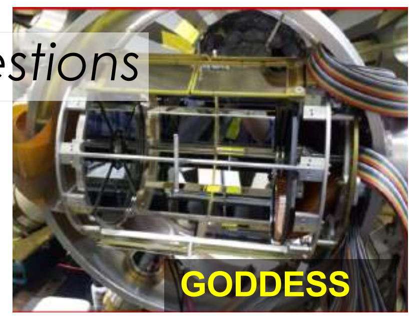


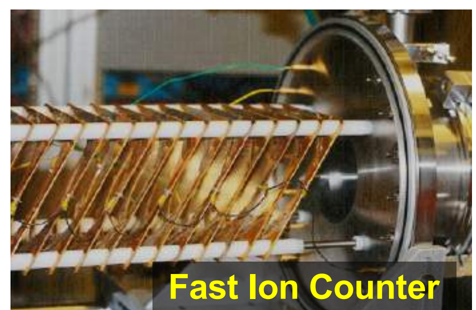




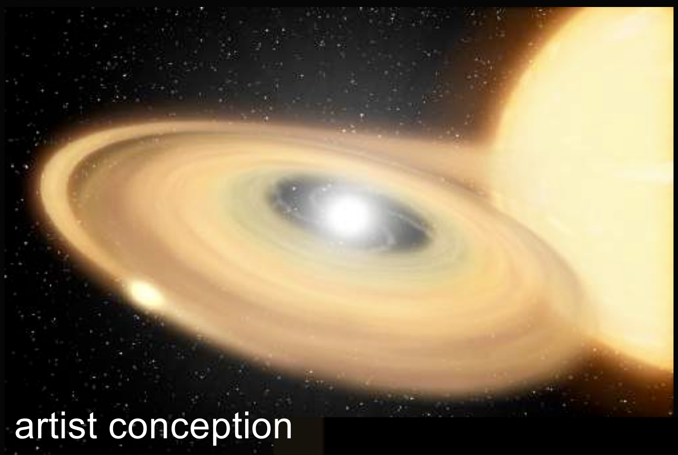


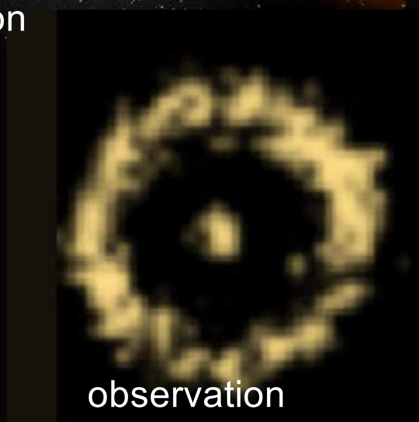
- *Astrophysical Sites & Open Questions*
- *Experimental Approaches*
- *Challenges*
- *Recent Highlights*
- *Future Plans*

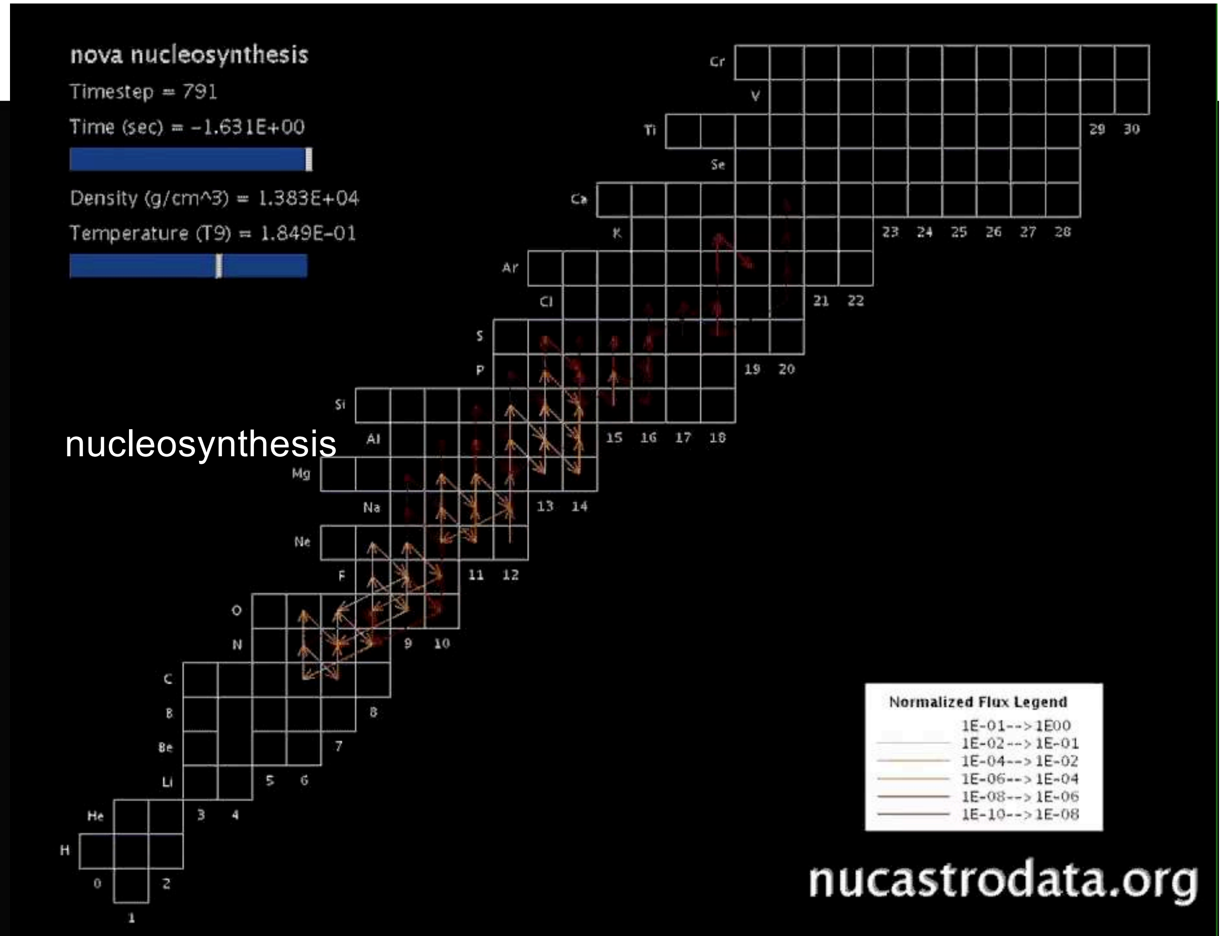




Nova Explosions

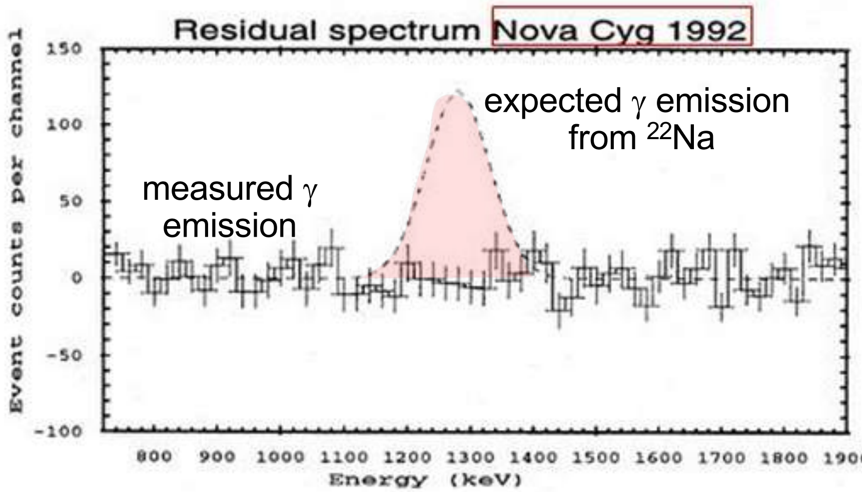

artist conception

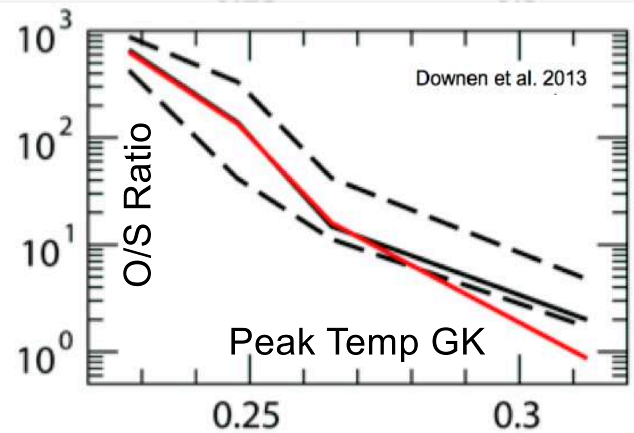

observation



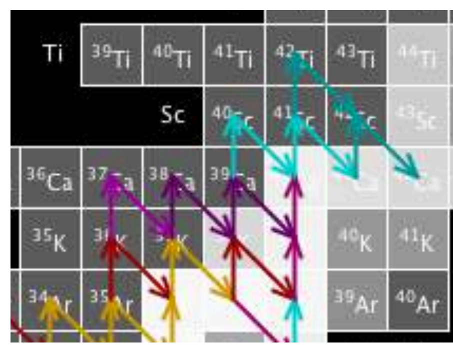
- *thermonuclear outburst on the surface of an accreting white dwarf star*

Nova Explosions – Open Questions

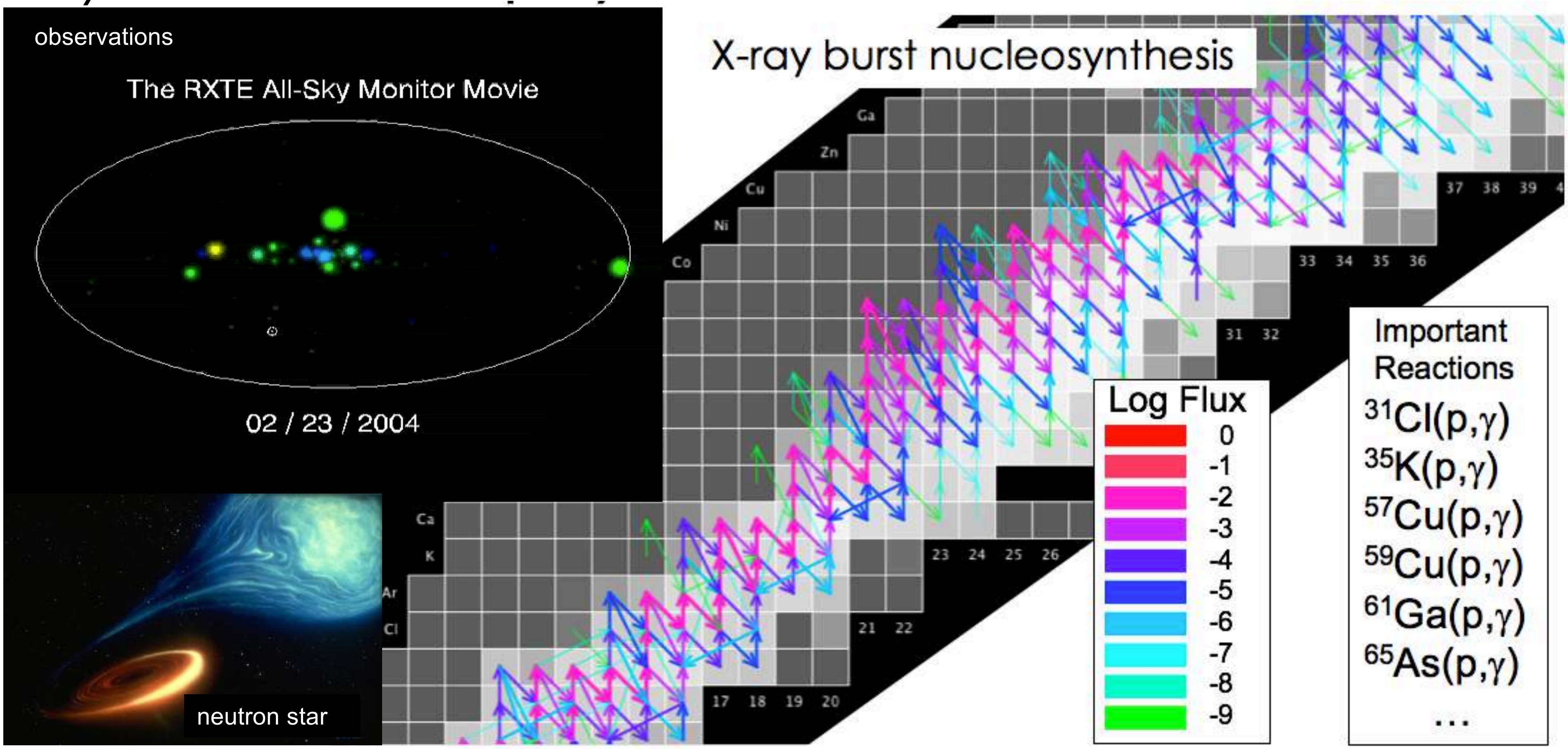




- *explain nova observables from meteorites & satellites*
- *what triggers the outburst?*
  - *Mixing of WD material with accreted layer?*
- *highest peak temperatures?*
  - *Possible new class of high-temperature novae*
  - *Isotopic ratios that are "thermometers"*
- *heaviest masses synthesized?*

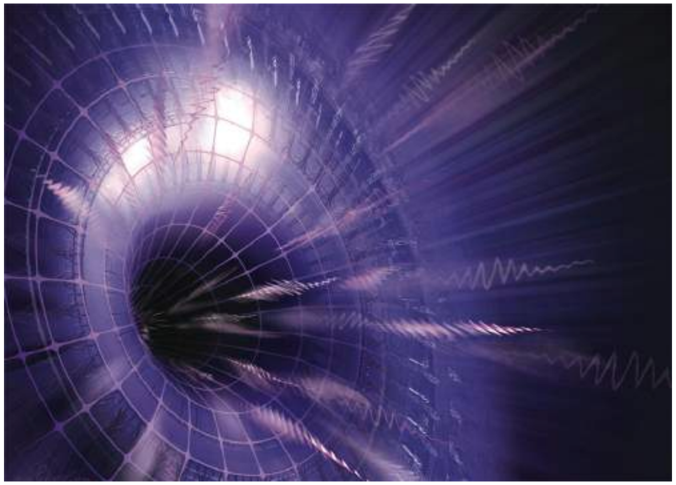


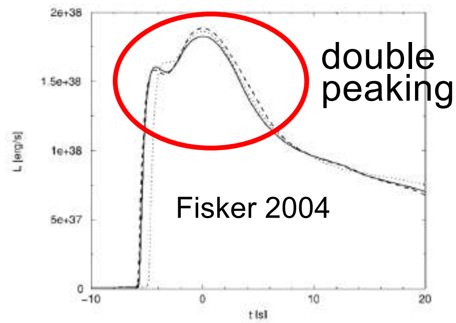
X-ray Bursts

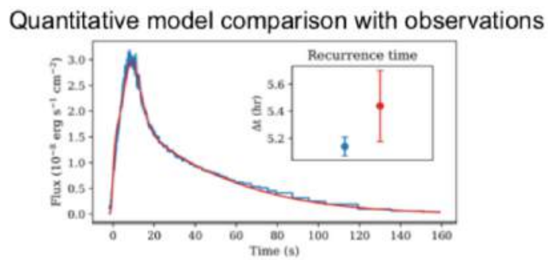


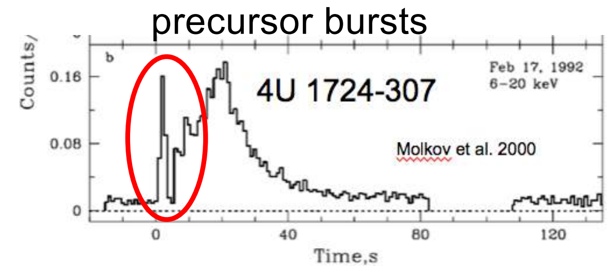
- *thermonuclear outburst on the surface of an accreting neutron star*

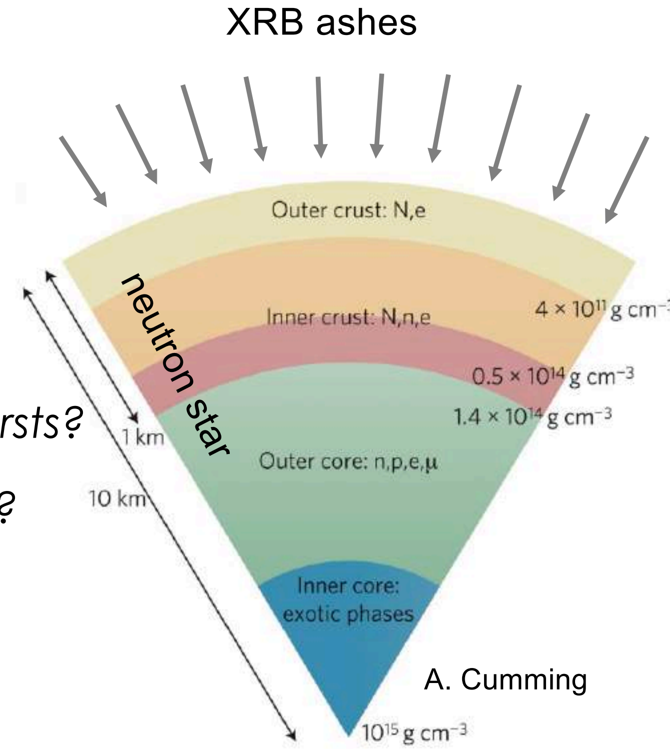
X-ray Bursts – Open Questions





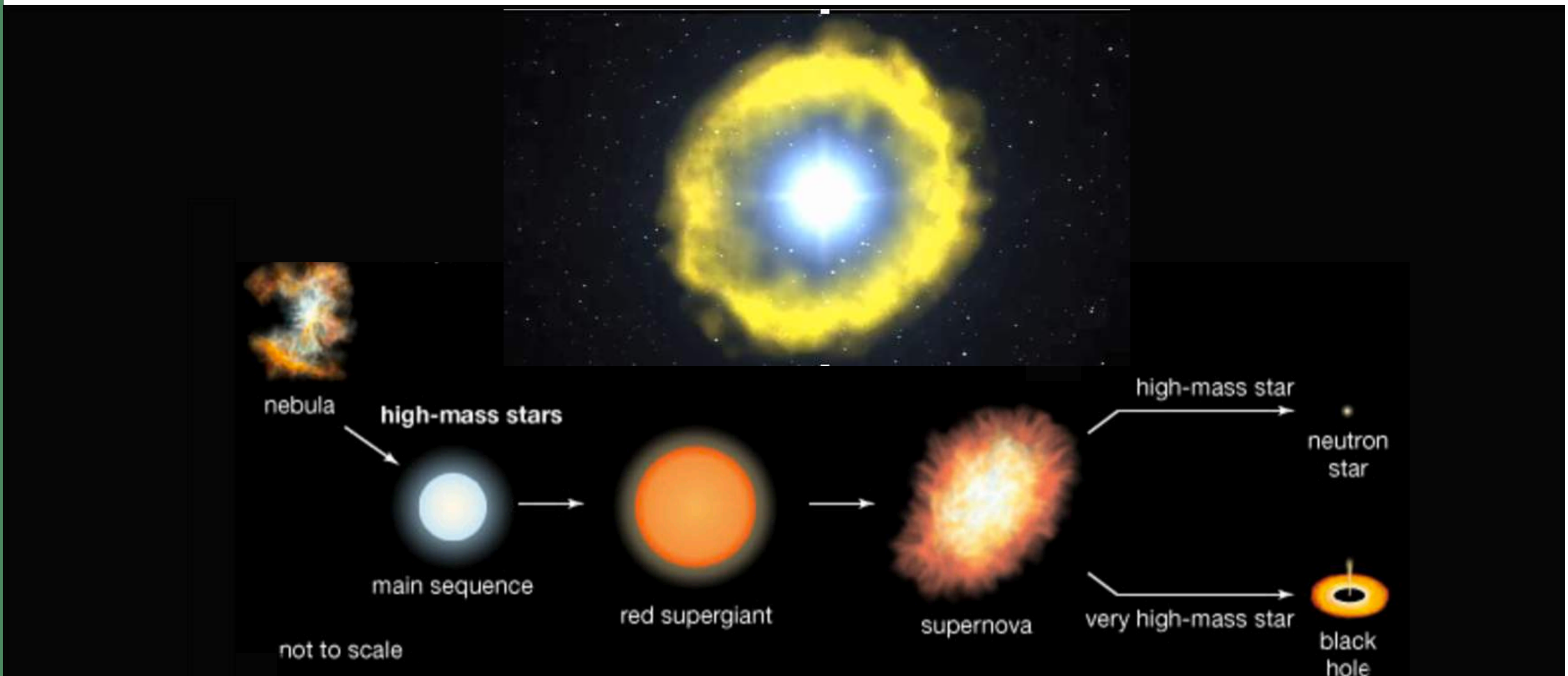






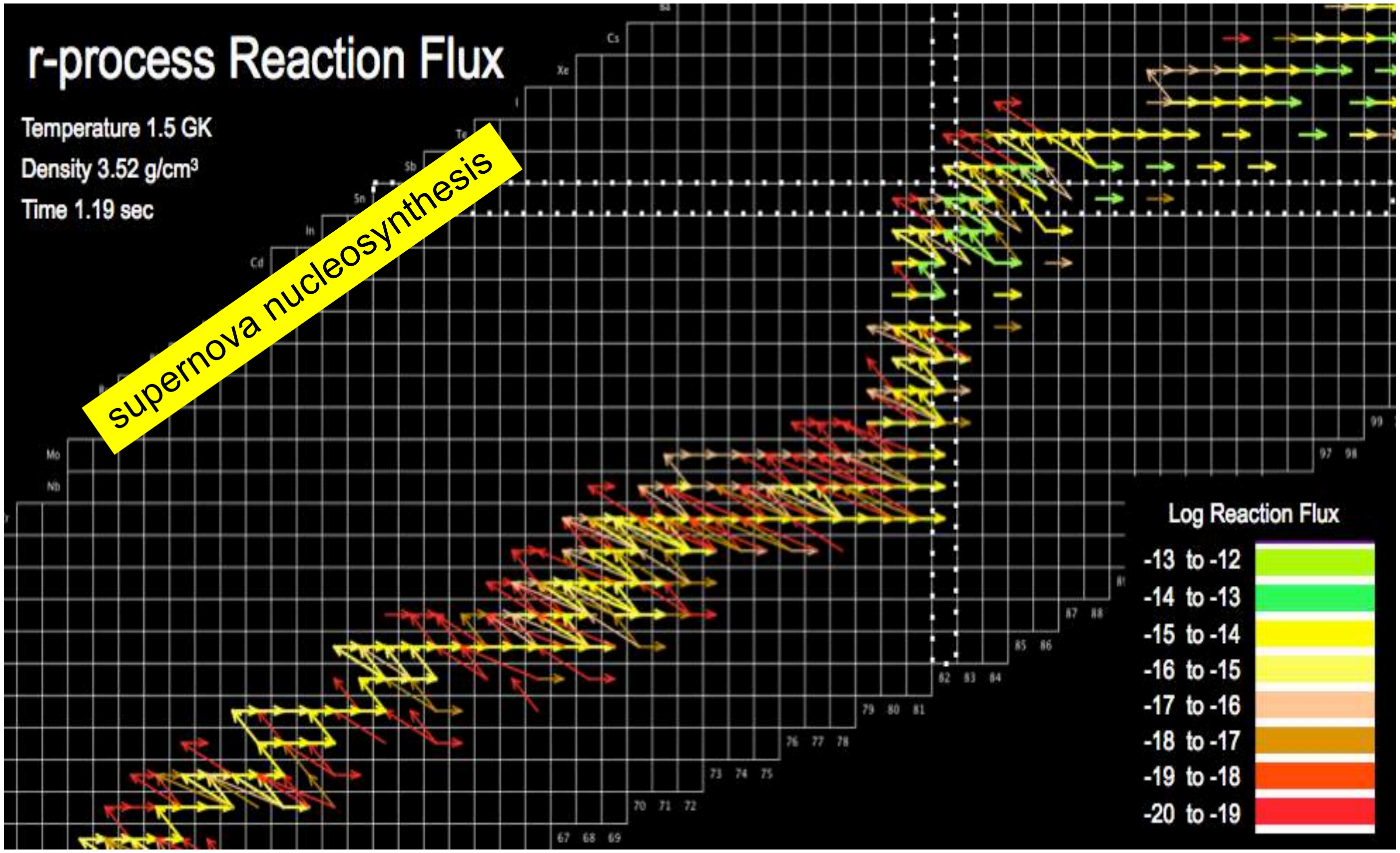
- *radius expansion bursts and possible* ***ejection*** *of material*
- *short recurrence time bursts, double peaking, precursor bursts?*
- ***termination*** *via hydrogen exhaustion or cooling expansion?*
- *highest masses synthesized and peak temperatures?*
- *ash composition & influence on* ***neutron star evolution***

Core Collapse Supernovae



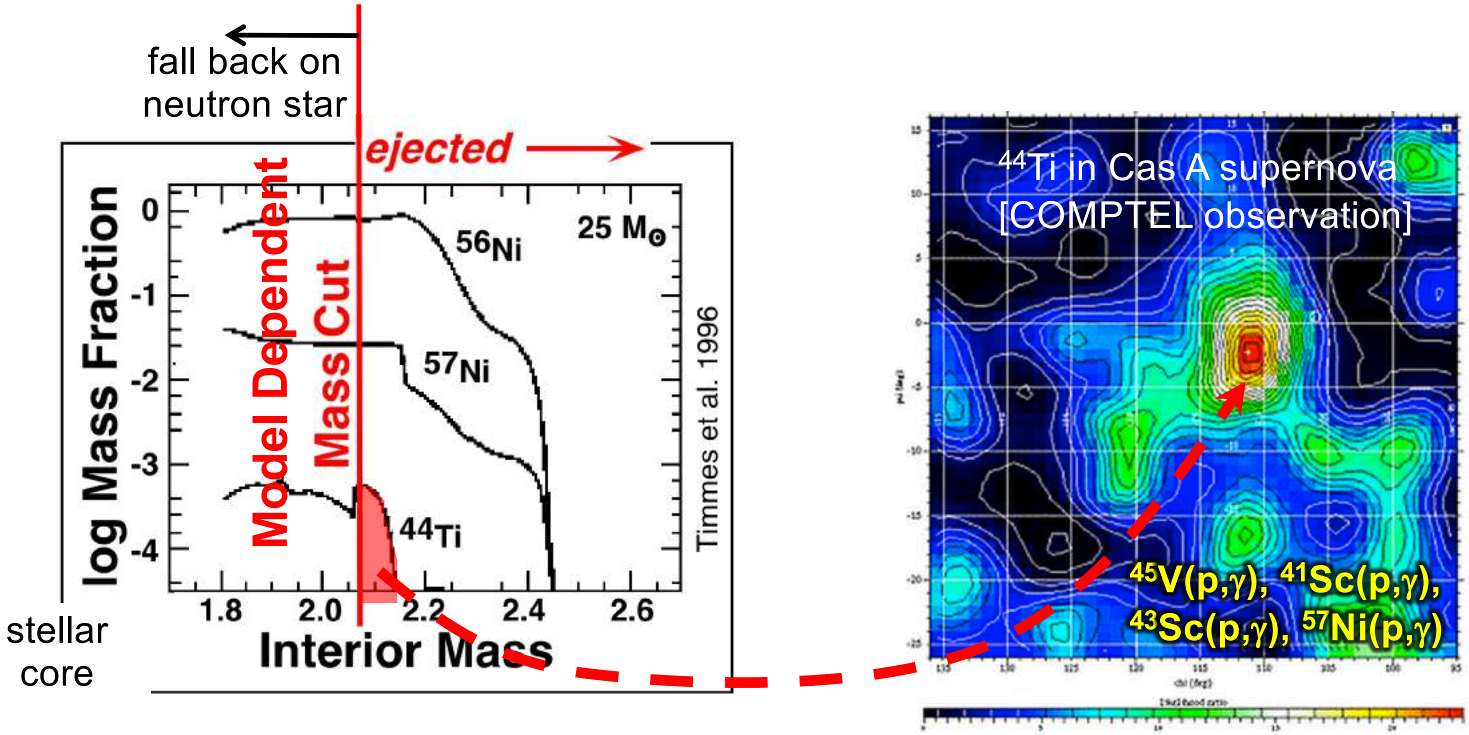
- *collapse of a massive star forming a neutron star or black hole*

Core Collapse Supernovae – Open Questions



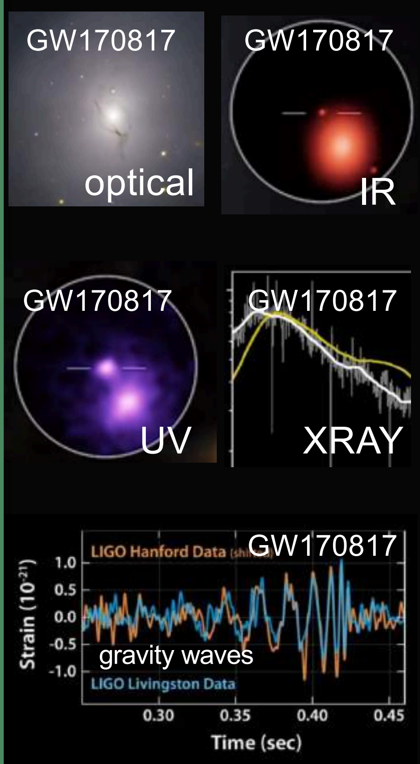
- *what fraction of the elements heavier than iron are synthesized in supernovae?*

Core Collapse Supernovae – Open Questions



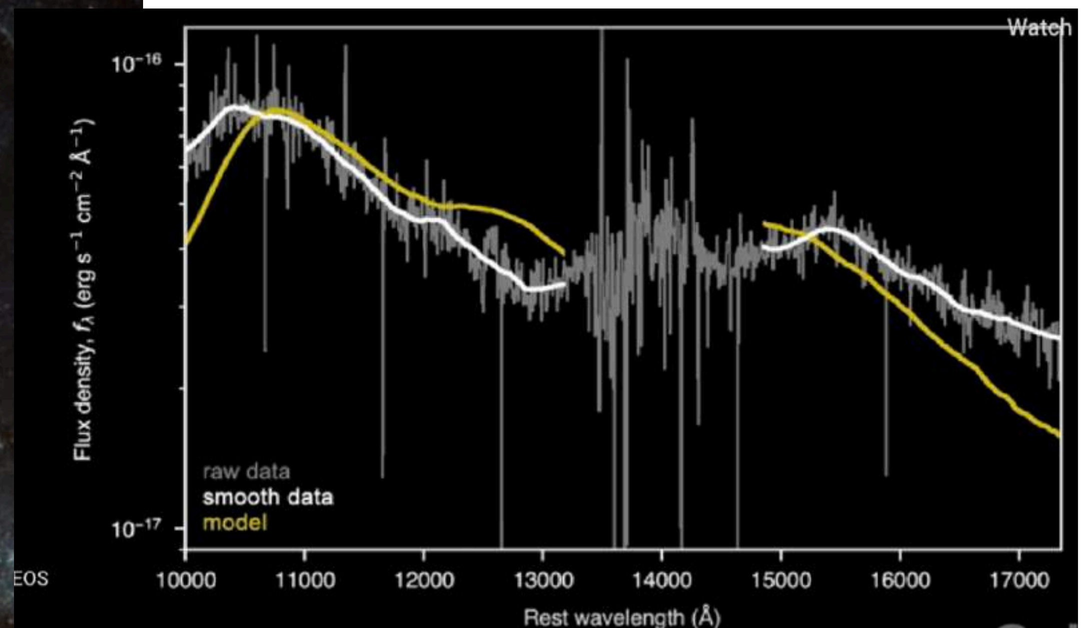
- *production of radionuclides ^{44}Ti, ^{26}Al, others influenced by (p,γ) rates*
- *location of "mass cut" can be constrained with help of better rates*

Neutron Star Mergers



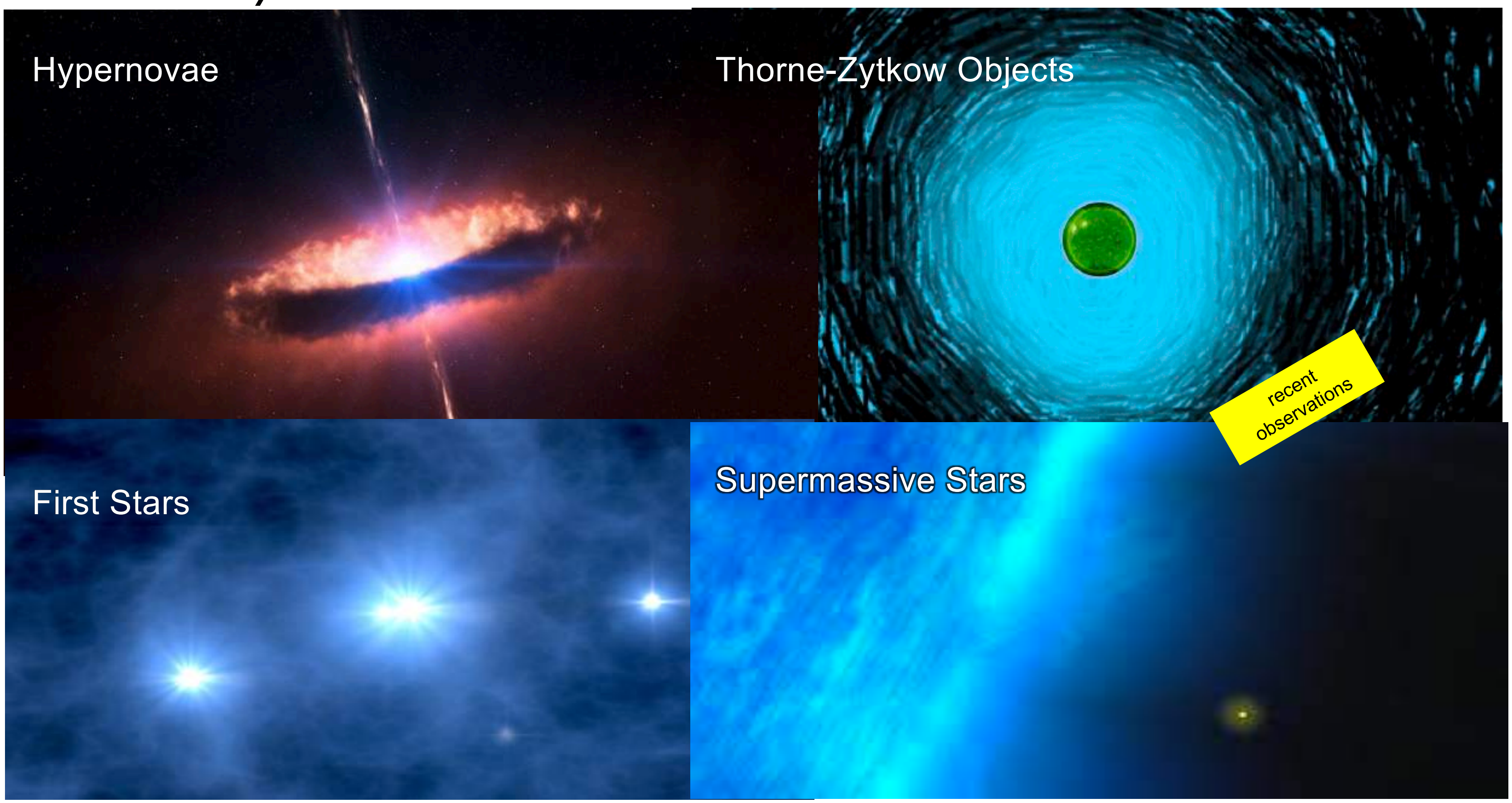
- *merger of 2 neutron stars forming a kilonova*

Neutron Star Mergers – Open Questions



- *can we understand the nucleosynthesis in the kilonova?*
- *can we predict robust observational signatures of NSMs?*
- *what percentage of r-process material is formed in mergers?*

Other Exotic Systems



- *these exotic systems feature unusual thermonuclear burning*

Experimental Approaches

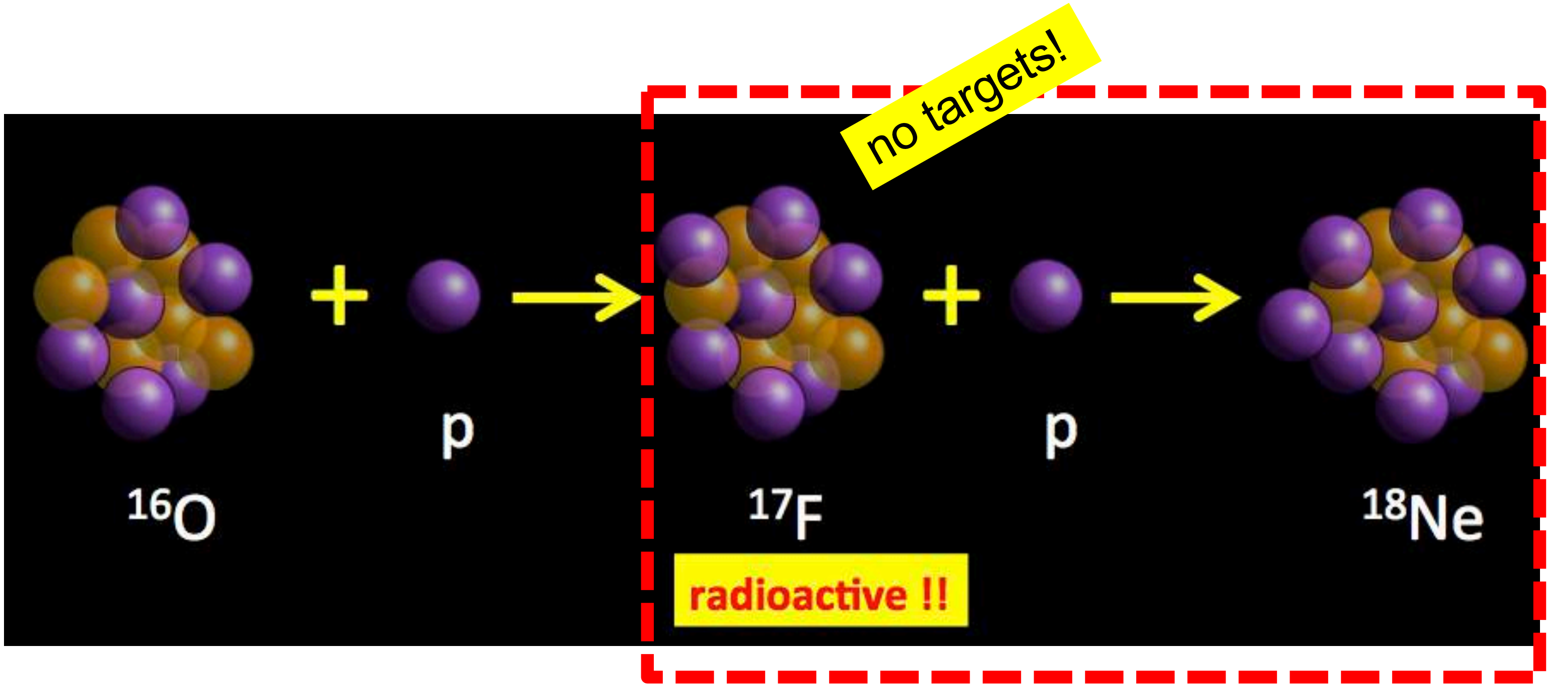
Annu. Rev. Nucl. Part. Sci. 2001. 51:91–130

NUCLEAR ASTROPHYSICS MEASUREMENTS WITH RADIOACTIVE BEAMS*

Michael S. Smith[1] and K. Ernst Rehm[2]

CONTENTS

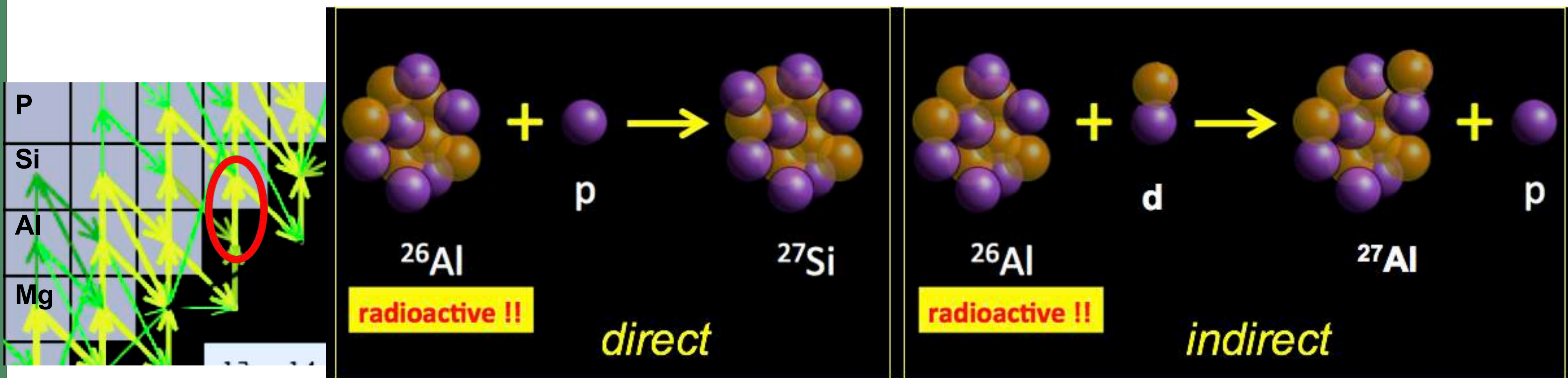
Experimental Approaches – Inverse Kinematics



- *cannot make a target out of the heavy radioactive nuclei*
- *measurements therefore utilize an* ***inverse kinematics*** *approach – radioactive* ***heavy beam bombarding a light target***

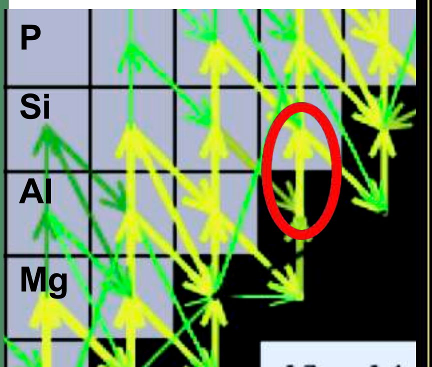
challenging!

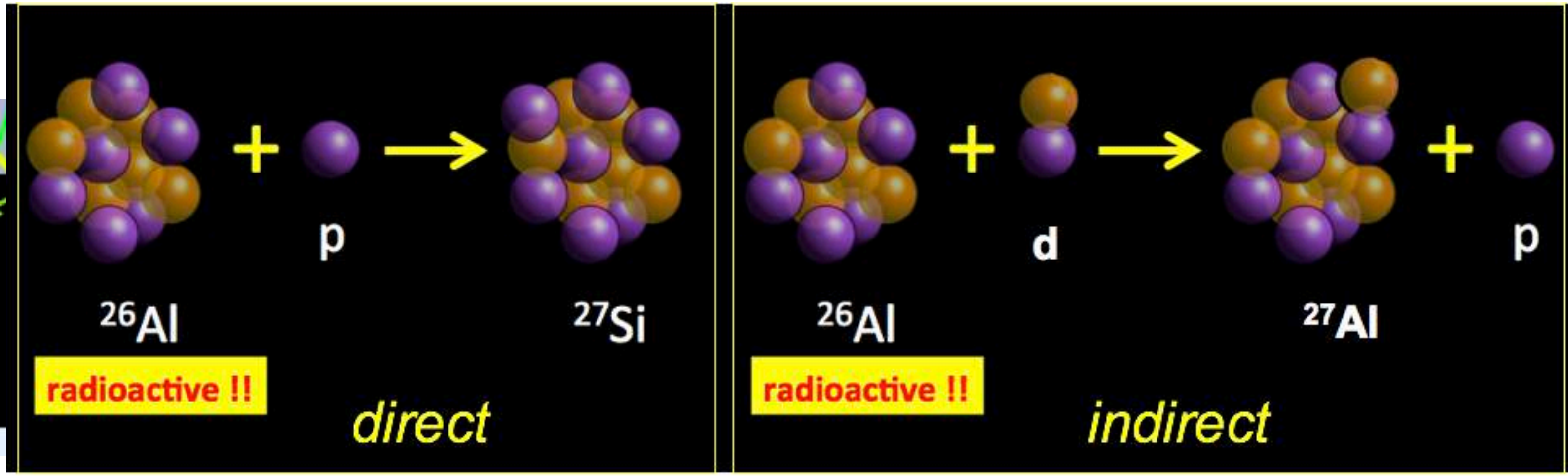
Experimental Approaches



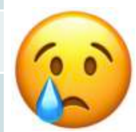
- *direct studies – measure reaction in lab that occurs in star*
- *indirect studies – measure different reaction for relevant structure / reaction information*

Experimental Approaches

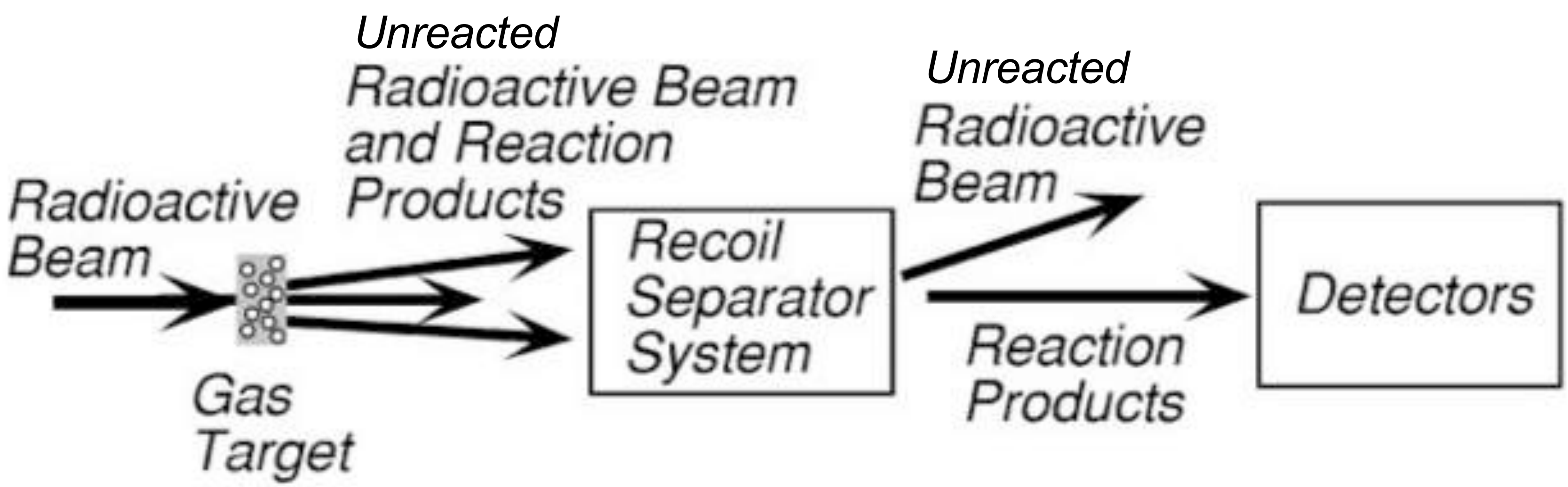




	Direct Studies	Indirect Studies
beam	one choice	multiple choices
equipment	few choices / expensive	wide variety of types/cost
yields	very low (~ event/day)	~10^5 times higher
results	low ambiguity	higher ambiguity
data analysis	relatively straightforward	can be very complex

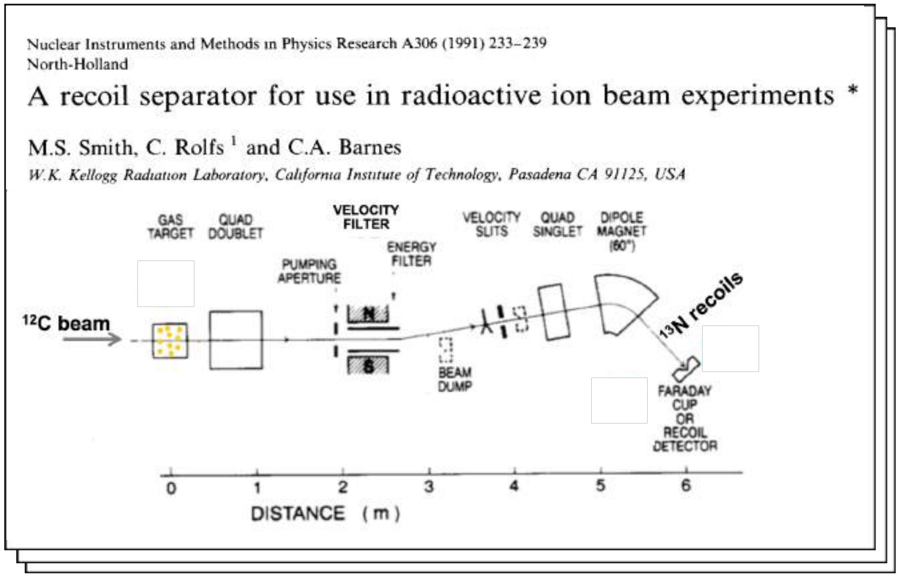


Direct Measurements – capture reactions



- *recoil separator is positioned along the beam axis*
- *its purpose is to* ***separate*** *all* ***unreacted beam particles*** *from fusion reaction products that are* 10^{10} *–* 10^{17} *times less intense*
- *usually employs a combination of components that deflect charged particles (dipole magnet, velocity filter, electrostatic deflectors …)*

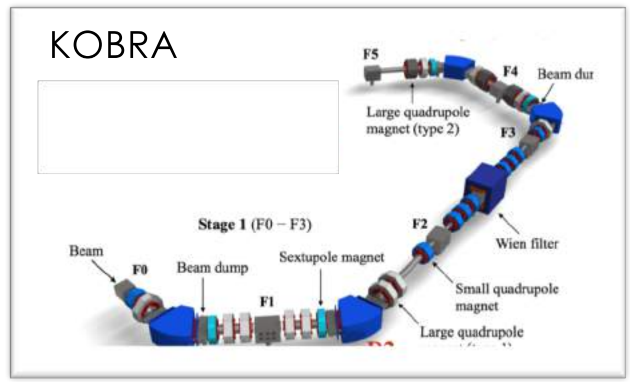
Direct Measurements – capture reactions

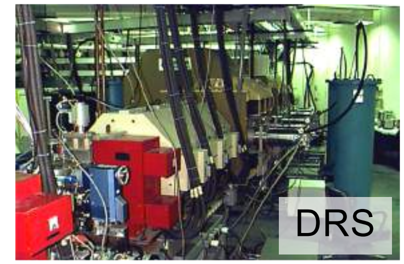

Nuclear Instruments and Methods in Physics Research A306 (1991) 233–239
North-Holland

A recoil separator for use in radioactive ion beam experiments *

M.S. Smith, C. Rolfs [1] and C.A. Barnes

W.K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena CA 91125, USA





- *approach pioneered in 1991*
- *now popular approach at numerous labs*
- *SECAR system at FRIB under construction / commissioning*
- *KOBRA at RAON has promise for these measurements*

Yield Determinations

$$\text{Yield (counts/sec)} = I\left(\frac{\text{beam particles}}{\text{sec}}\right)\cdot N_t\left(\frac{\text{target particles}}{\text{cm}^2}\right)\cdot$$

$$\frac{d\sigma}{d\Omega}\left(\frac{\text{cm}^2}{\text{sr}}\,\frac{\text{reactant particle}}{\text{beam particle} \;\; \text{target particle}}\right)\cdot \Delta\Omega\,(\text{sr})\cdot \varepsilon\left(\frac{\text{counts}}{\text{reactant particle}}\right)$$

beam current

target density

cross section

solid angle

detector efficiency

Yield Determinations

Typical example...

$I \sim 10^{7}\ \frac{\text{beam particles}}{\text{sec}}$

excellent current for an unstable beam!

$N_t \sim 10^{18}\ \frac{\text{target particles}}{\text{cm}^2}$

gas jet target

$\frac{d\sigma}{d\Omega} \sim 10^{-29}\ \frac{\text{cm}^2}{4\pi\ \text{sr}}\ \frac{\text{reactant particle}}{\text{beam particle}\ \ \text{target particle}}$

10 μb is typical

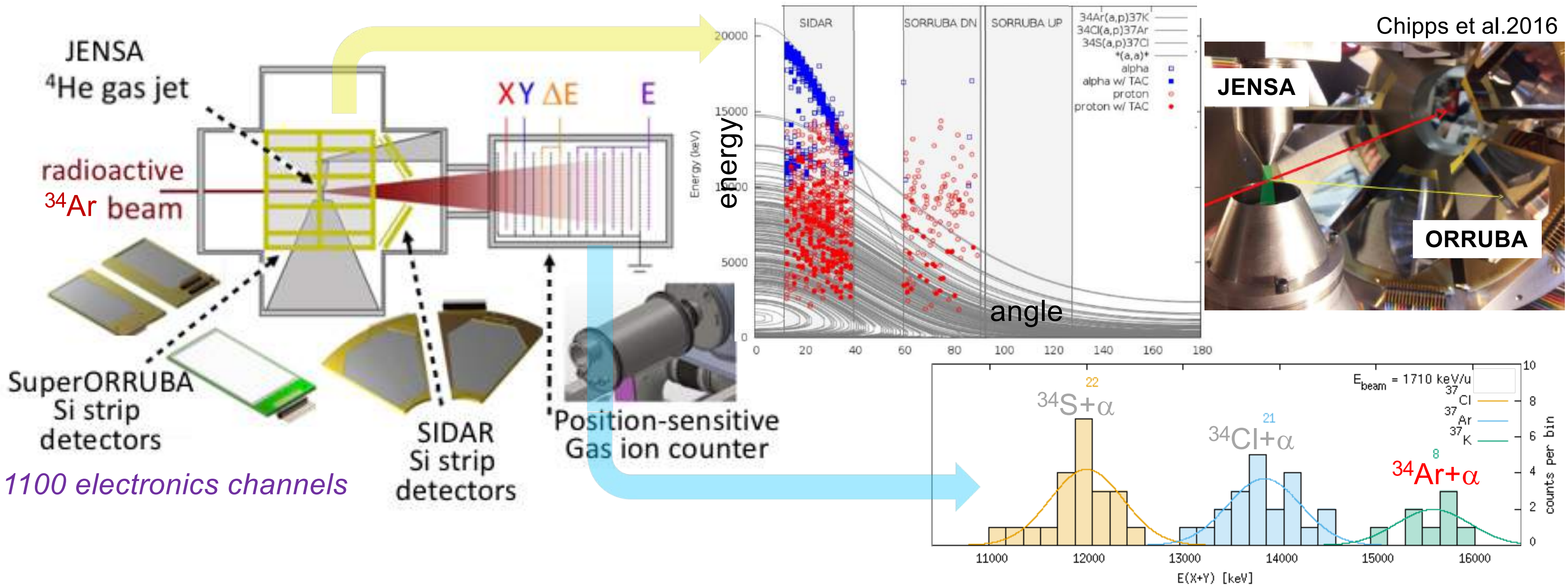
$\Delta\Omega \sim 0.1 \bullet 4\pi\ \text{sr}$

$\varepsilon \sim 0.8\ \frac{\text{counts}}{\text{reactant particle}}$

Yield ~ $0.8 \bullet 10^{-5}$ reactant particles/sec

~ 0.7 reactant particles/day

Direct Measurements – other reactions

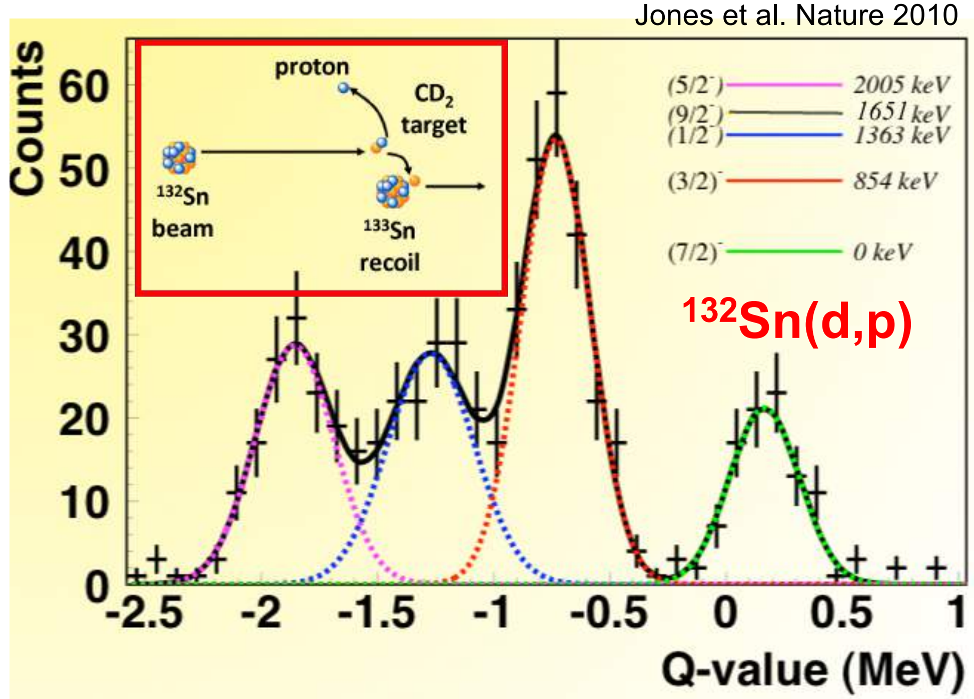


- *(p,α) and (α,p) reactions are often measured directly with Si strip detectors*

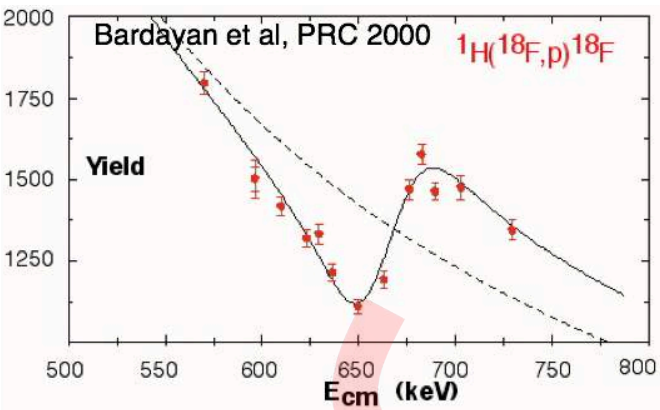
Indirect Approaches

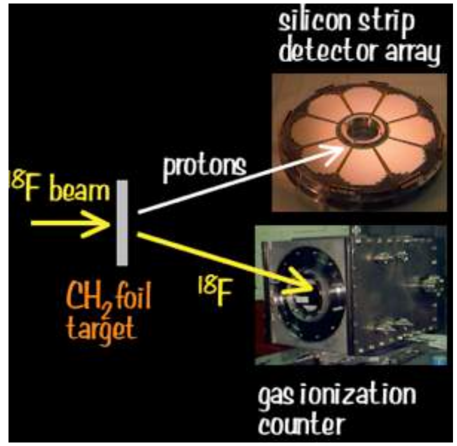
- *(p,p) to locate resonances*
- *(p,p') for branching ratios*
- *(d,n), (^{3}He,d), (α,t) to simulate (p,γ)*
- ***(d,p) to simulate (n,γ)***
- *surrogate reactions*
- *Trojan horse methods*
- *inverse reactions for ground state transitions*
- *Coulomb dissociation (γ,p)*
- *multinucleon transfer for structure info (mass, lifetimes, decay branches, level densities, beta-delayed particle emission…)*

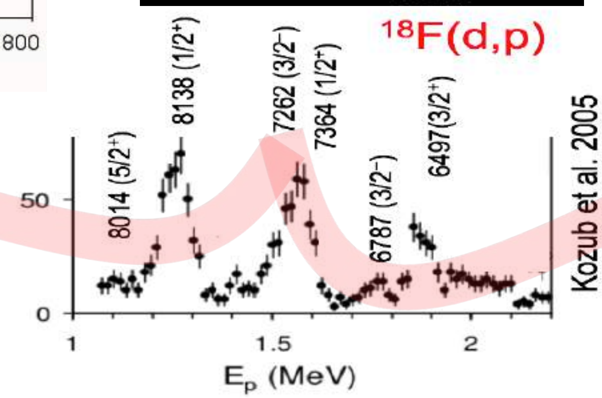
Jones et al. Nature 2010

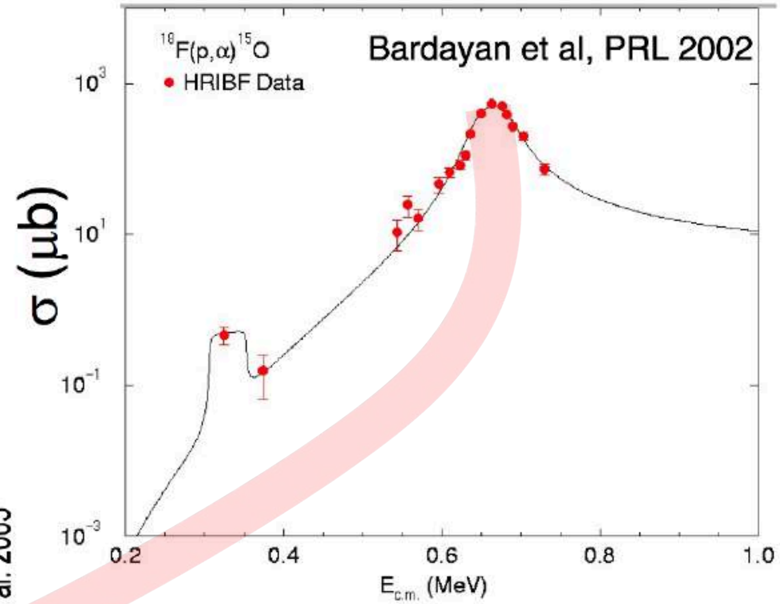


Combined Approach



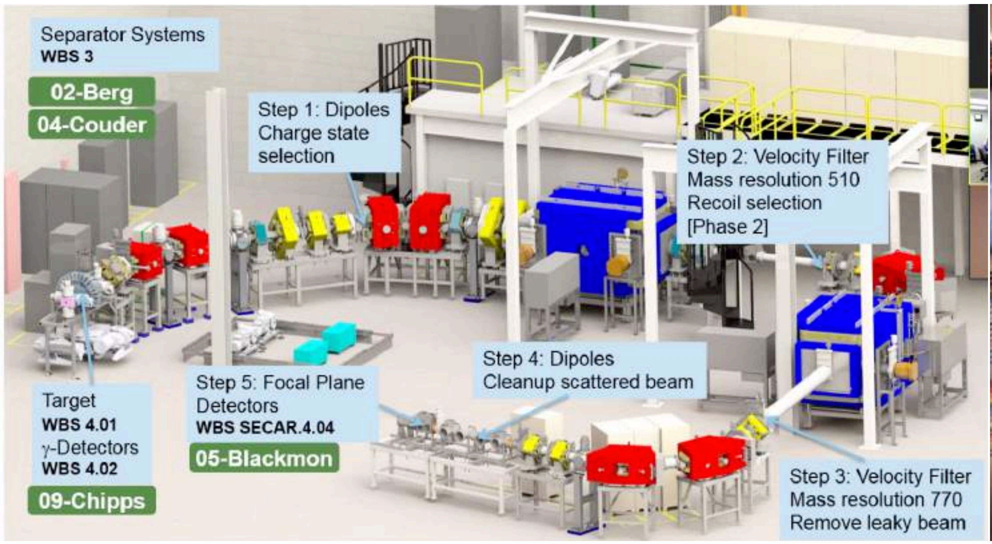


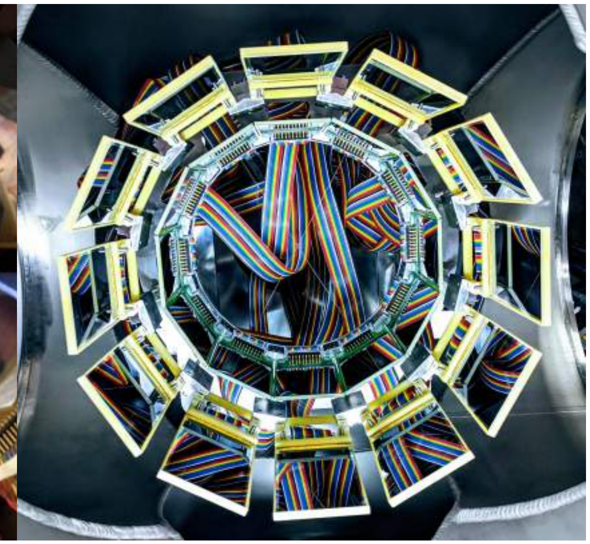




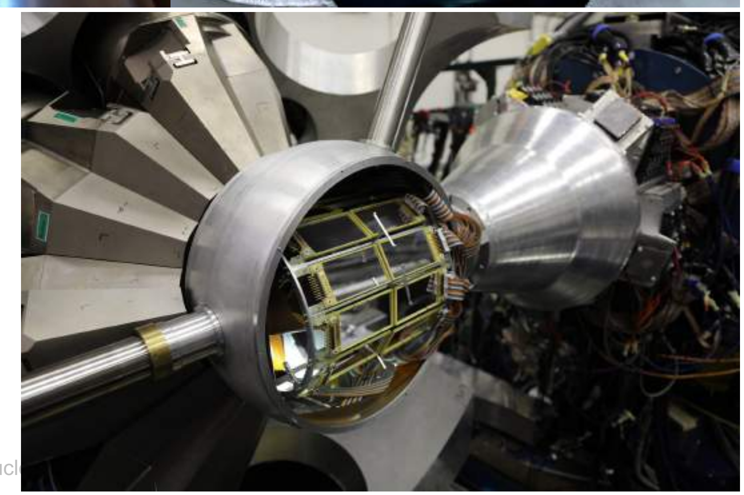
- *first measure scattering to locate resonances [beam ~10^3 pps]*
- *follow up with transfer to measure spectroscopic factors [~10^4 – 10^5 pps]*
- *finish with direct measurements on strongest resonances [~10^5 – 10^7 pps]*

Equipment

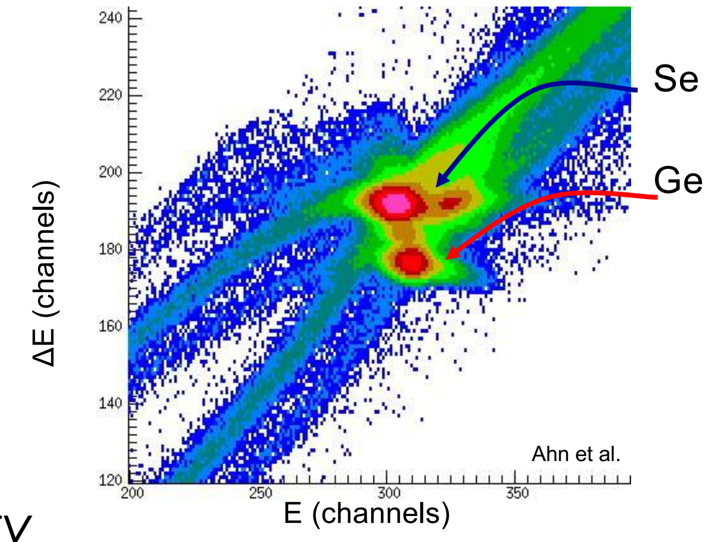


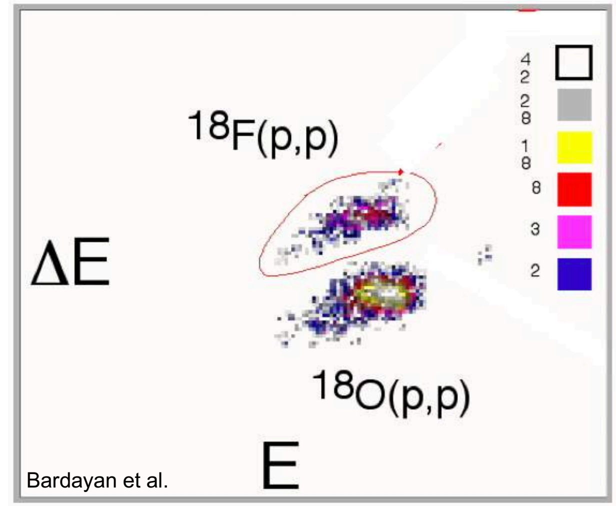


- *recoil separators for capture measurements*
- *gas targets for capture and (p,α),(α,p)*
- *Si strip arrays for charged-particle detection*
- *gamma arrays for coincidence measurements*

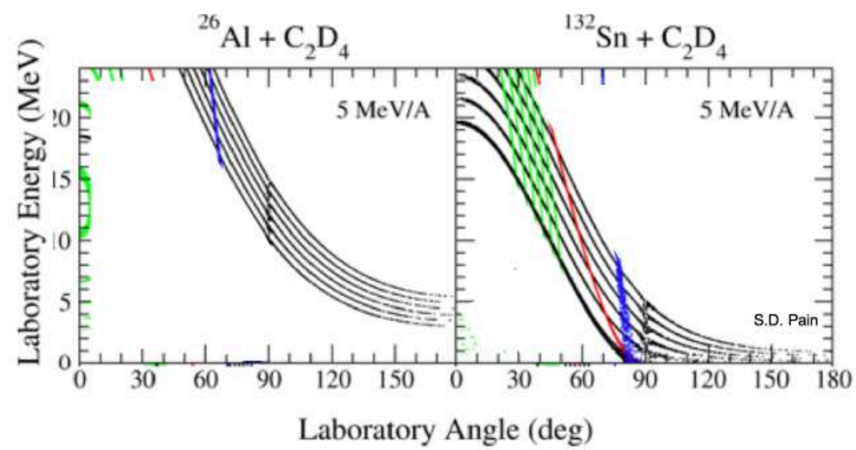


Challenges

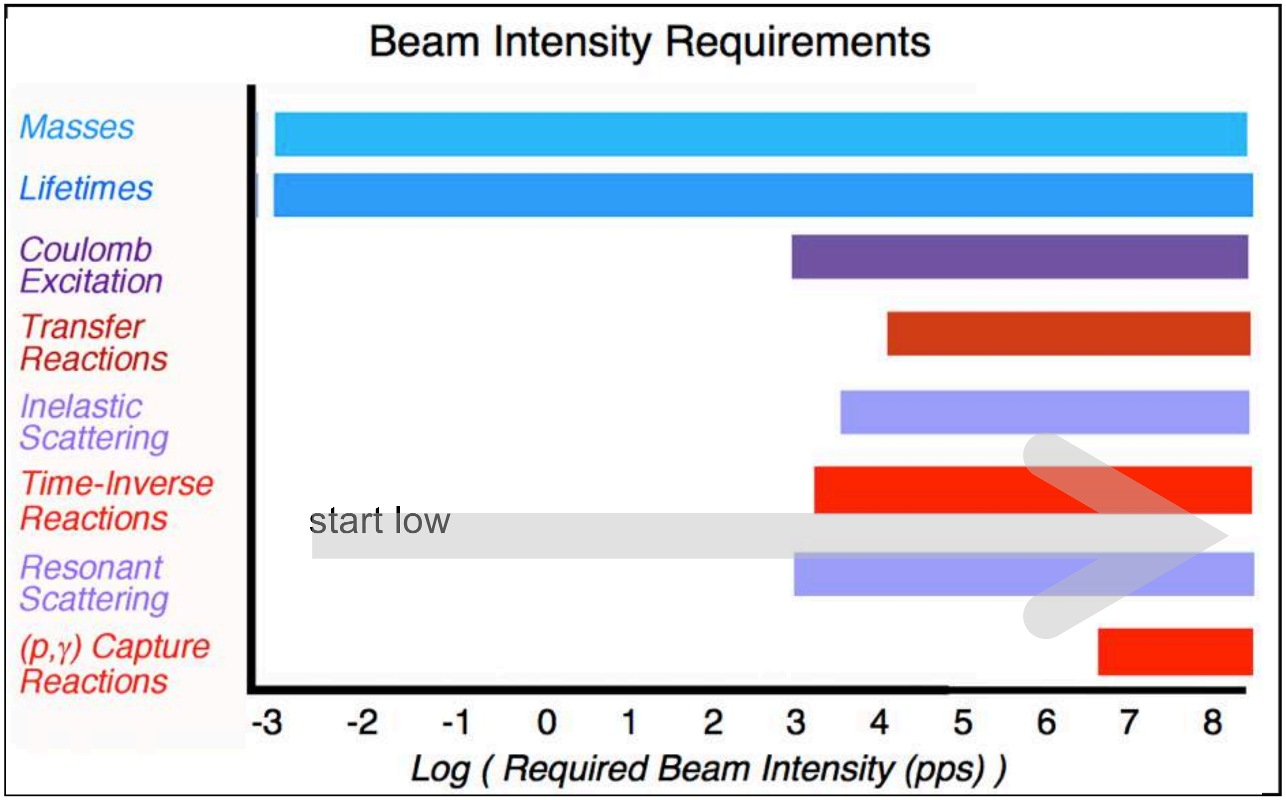




- *low beam intensity*
- *low beam purity/isobaric contaminants*
- *poor energy resolution & emittance*
- *limited species*
- *kinematic compression*
- *limited beamtime*

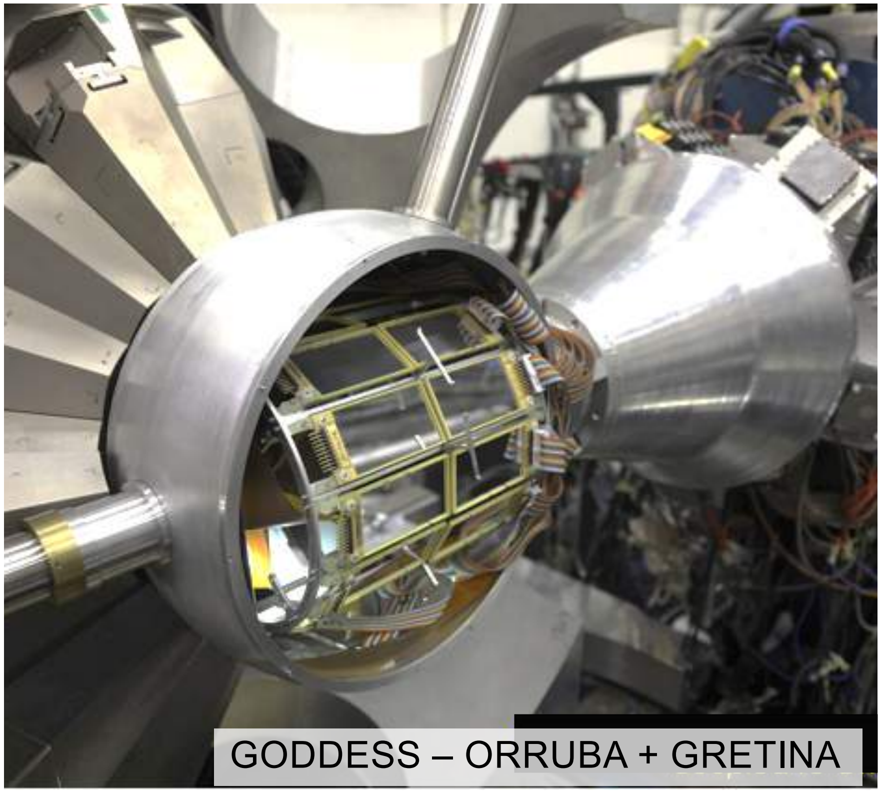


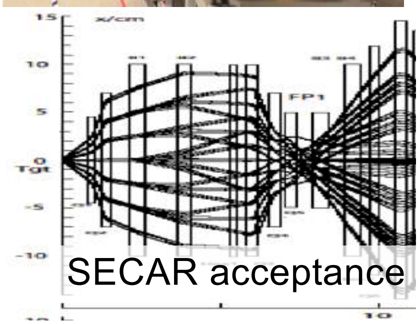
Challenges – Low Intensity

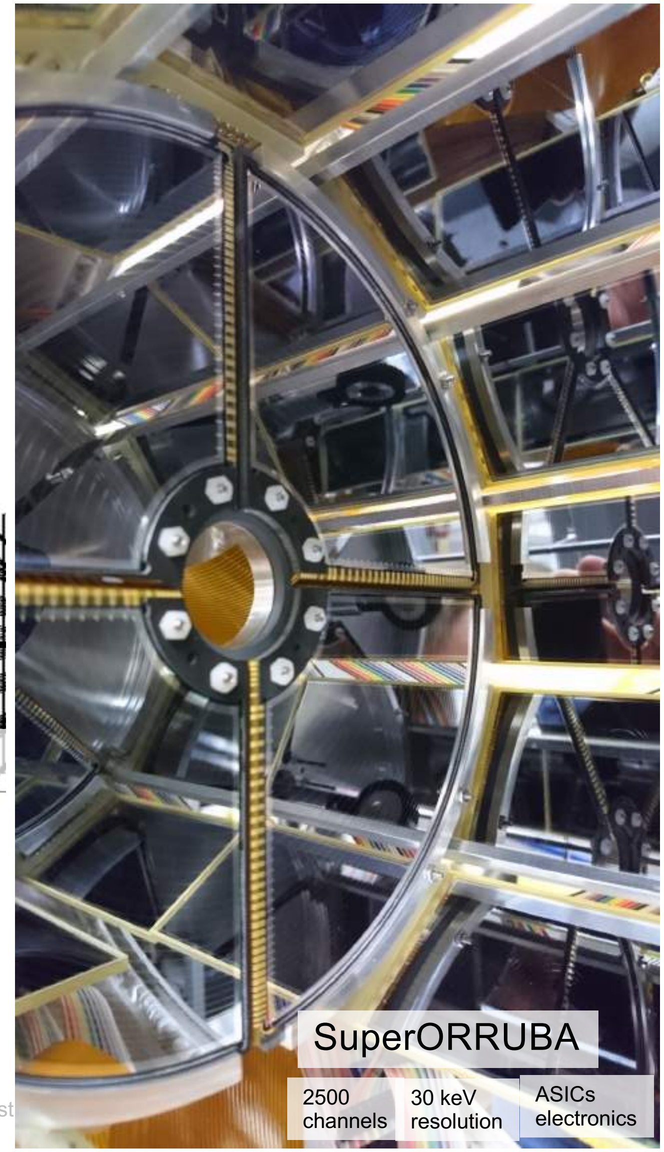


- *careful choice of reaction channel*
- *design experiments with lower-than-expected beam intensities*

Challenges – Low Intensity

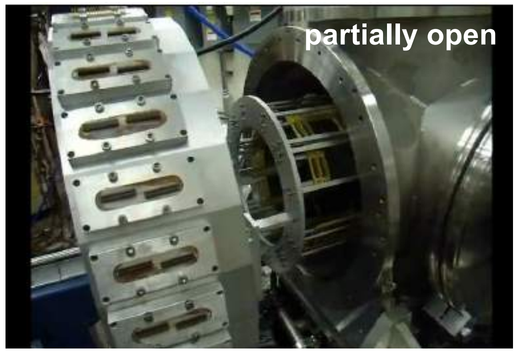






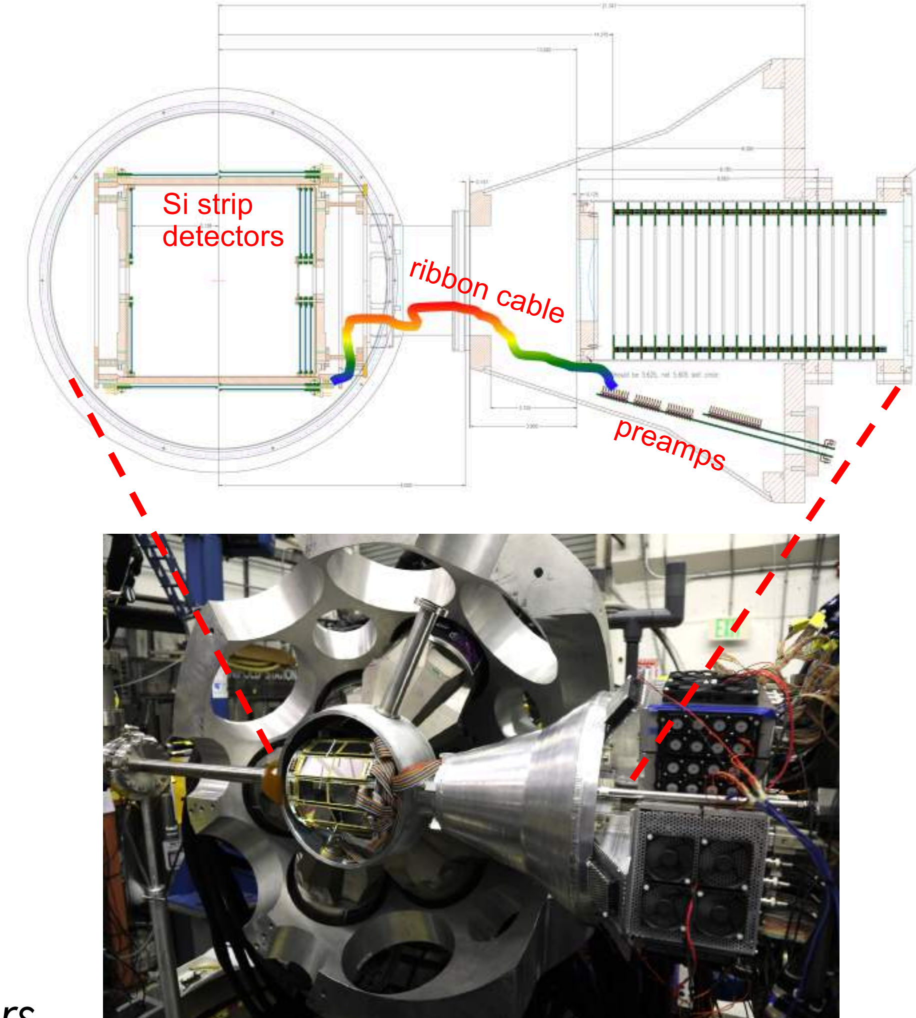
- *high efficiency detection schemes*
- *large acceptance detection schemes*

Challenges – Low Intensity



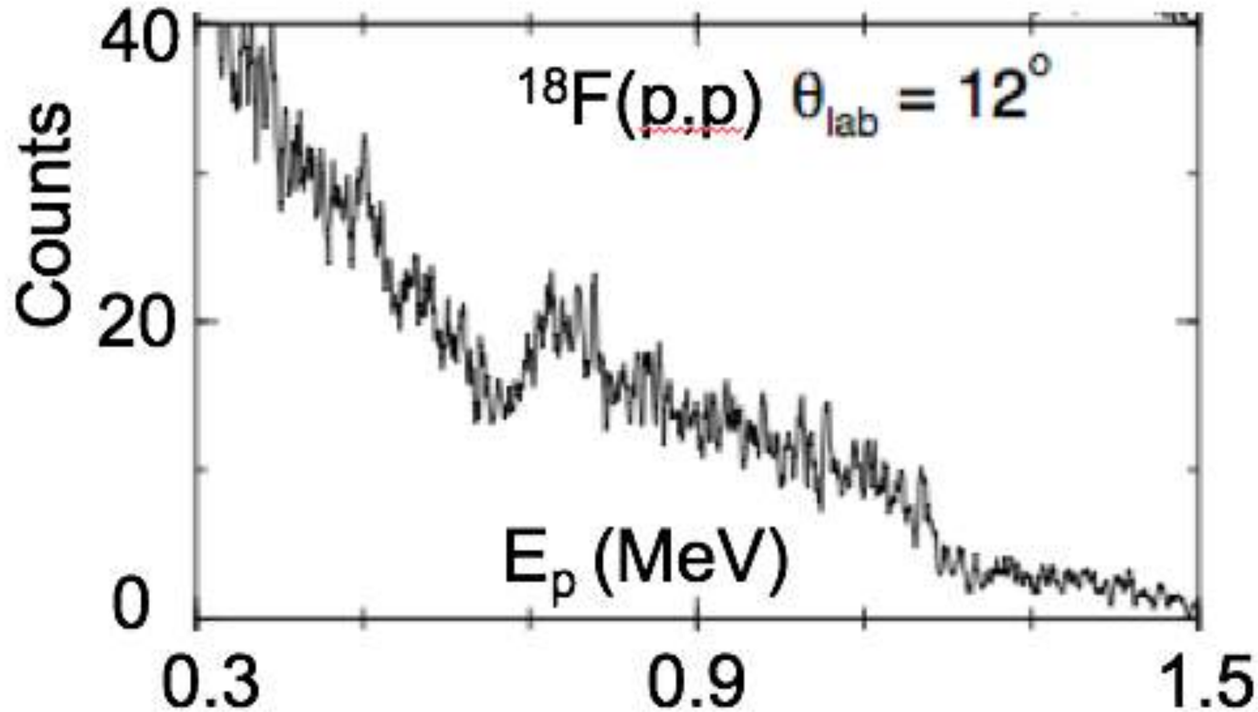
Si strip
detectors

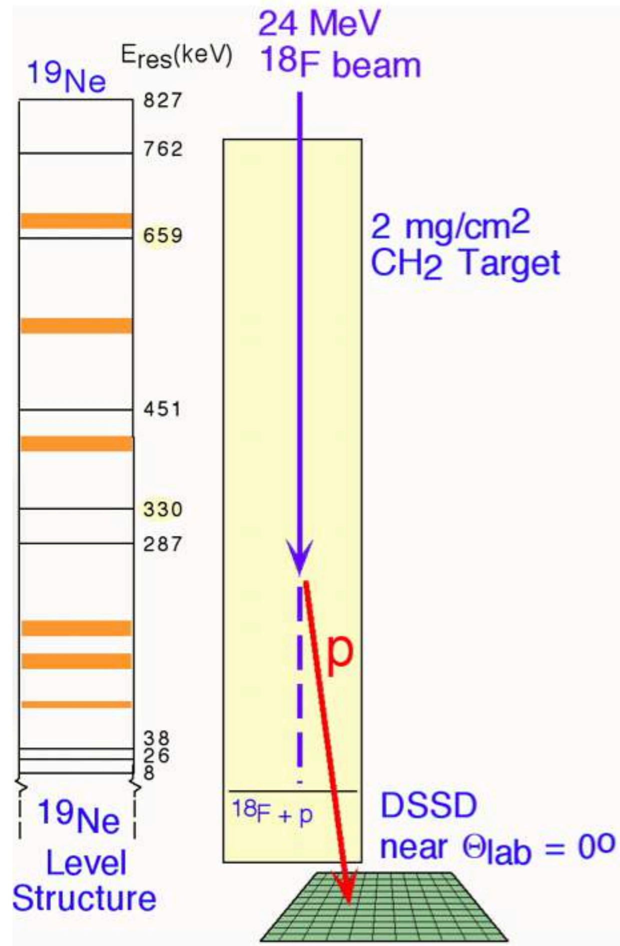
preamps



- *maximize signal – to – noise by closely connecting preamps to Si strip detectors*

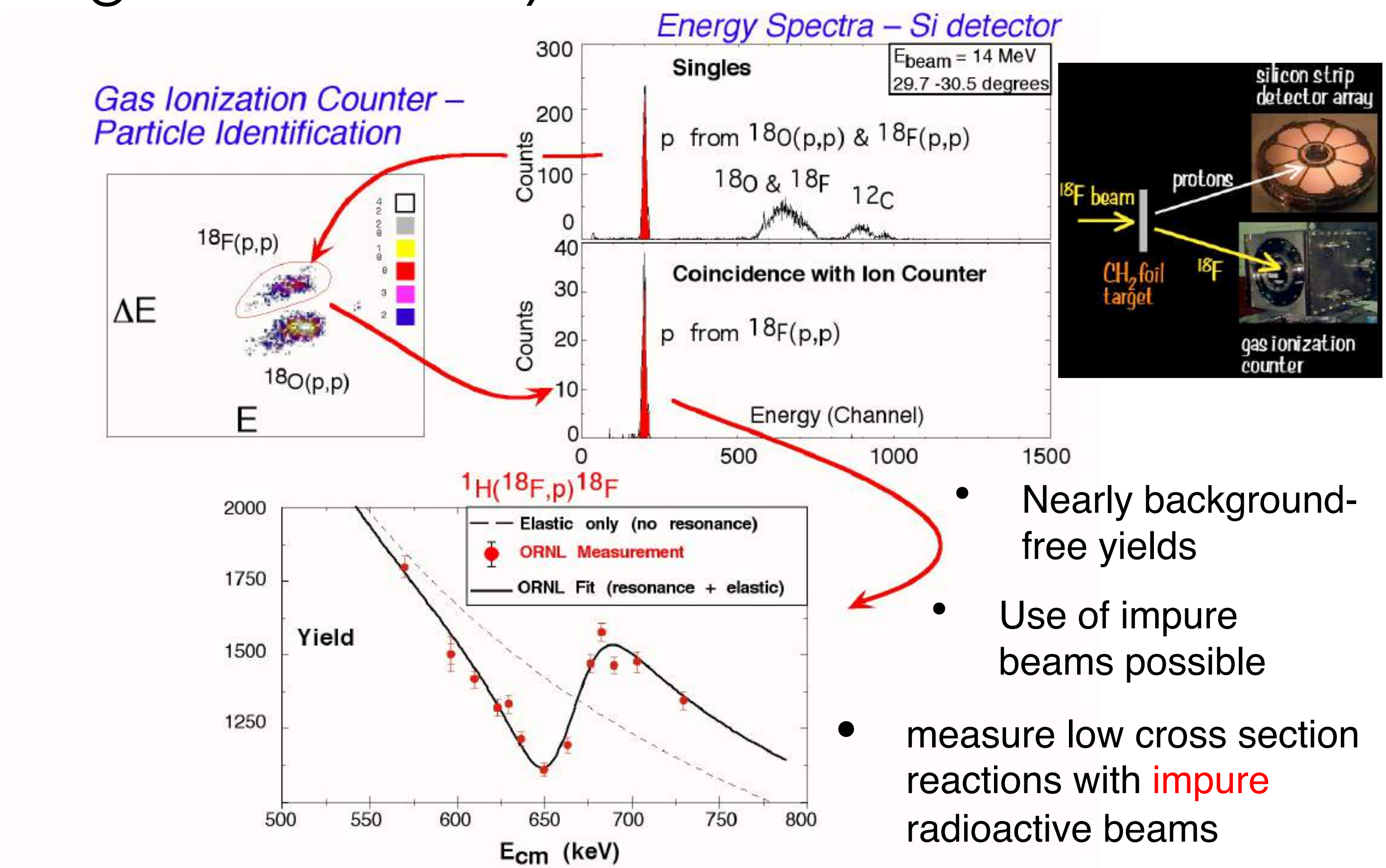
Challenges – Low Intensity





- *thick target yields to measure entire excitation functions at once*

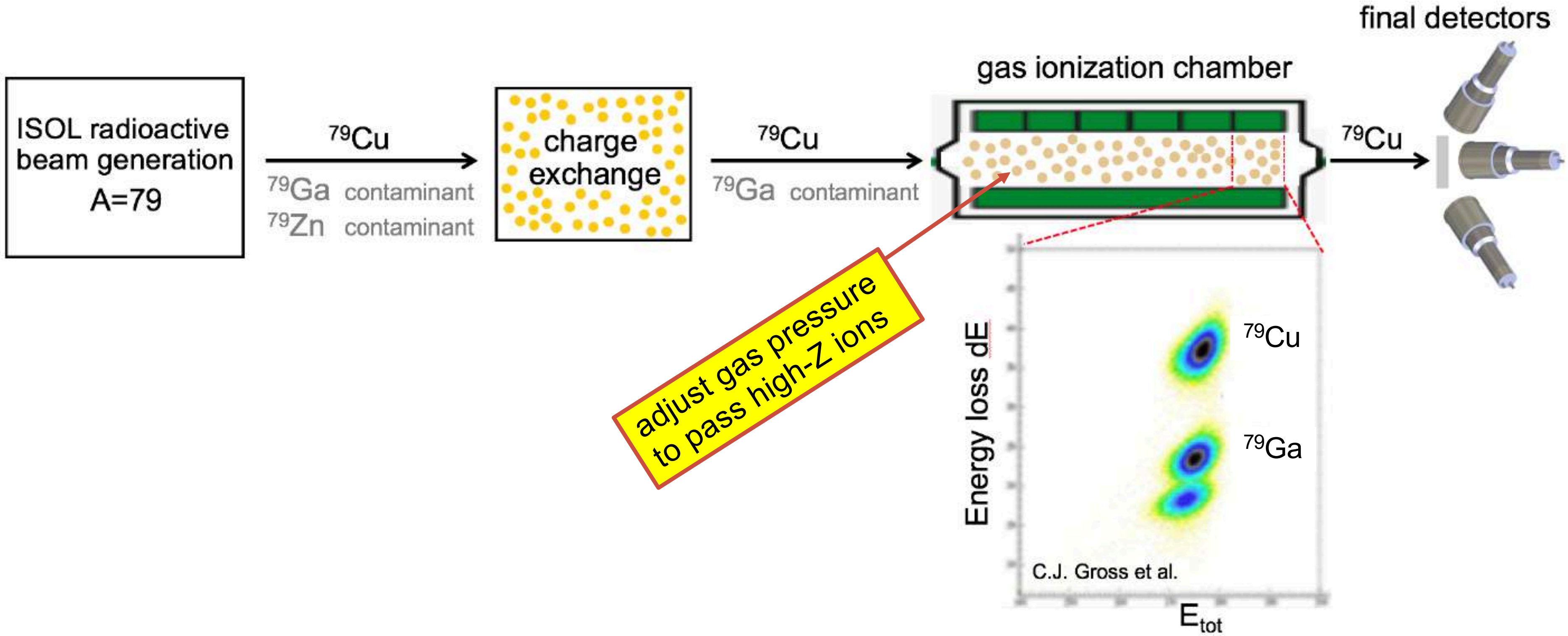
Challenges – Low Purity



- Nearly background-free yields
- Use of impure beams possible
- measure low cross section reactions with impure radioactive beams

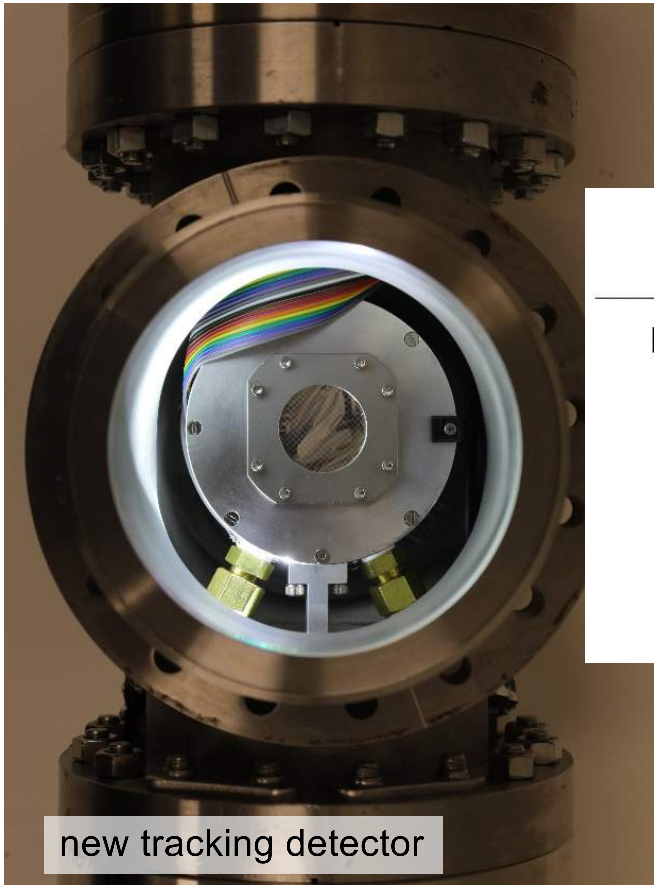
- *coincidence measurements*

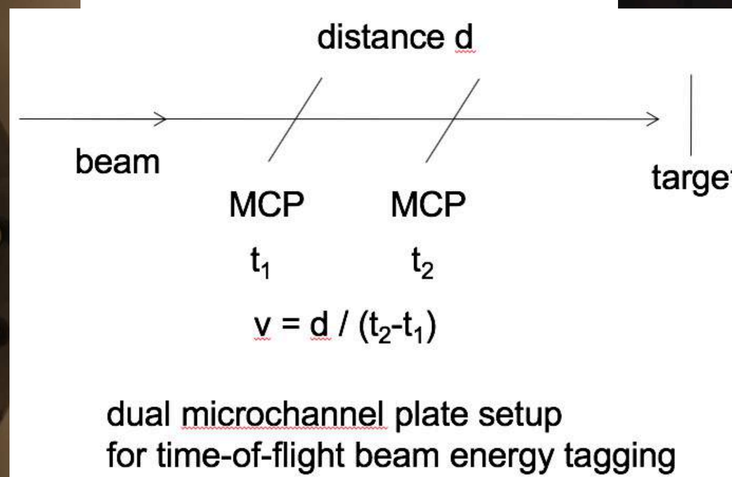
Challenges – Low Purity

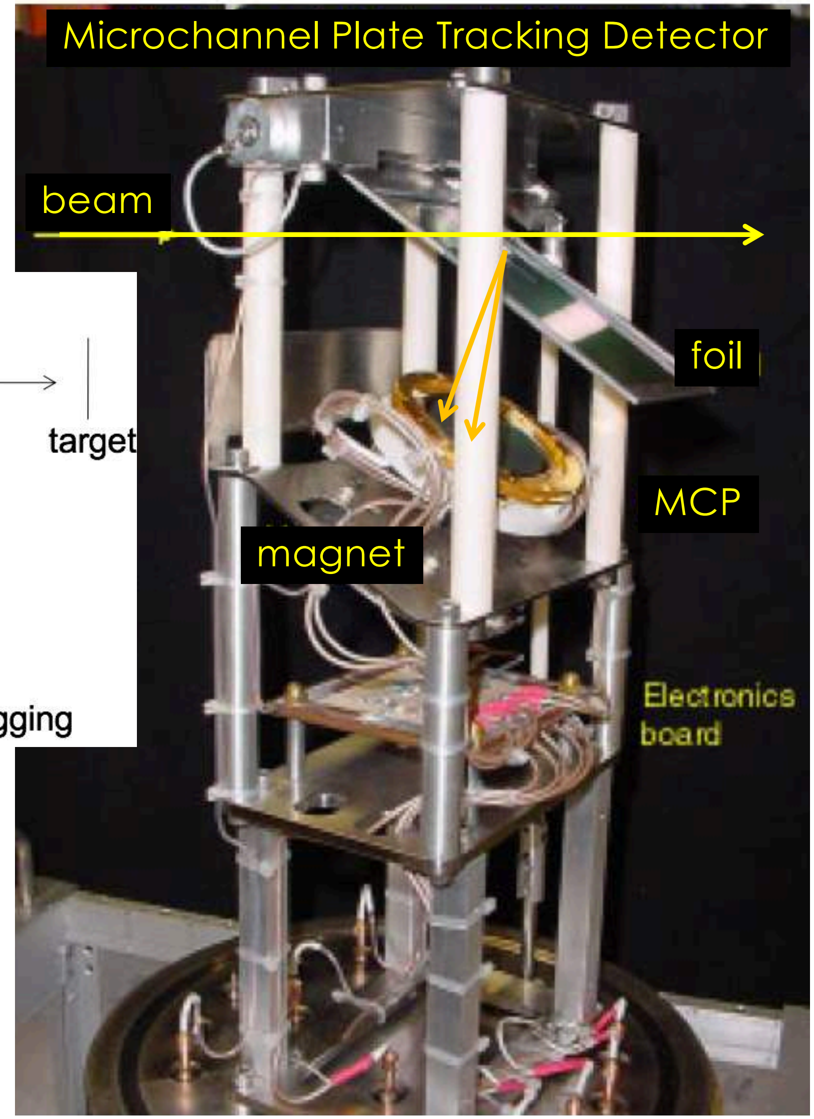


- *ranging out techniques use gas volumes to selectively filter out contaminant isotopes based on different energy losses*

Challenges – Poor Emittance

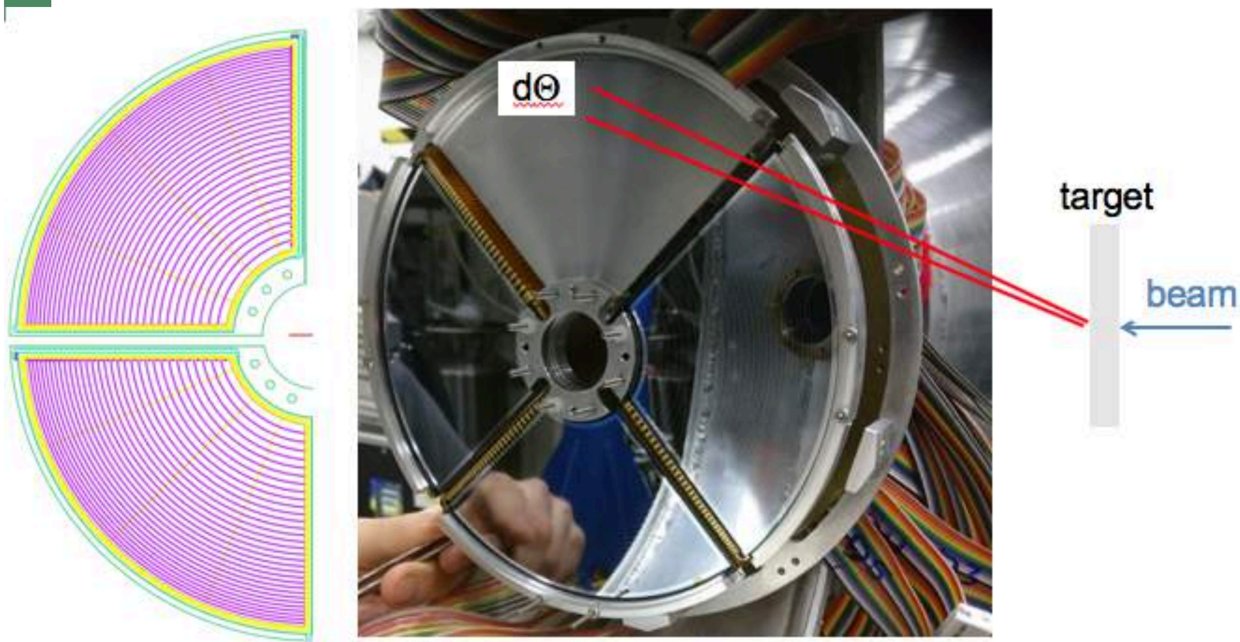


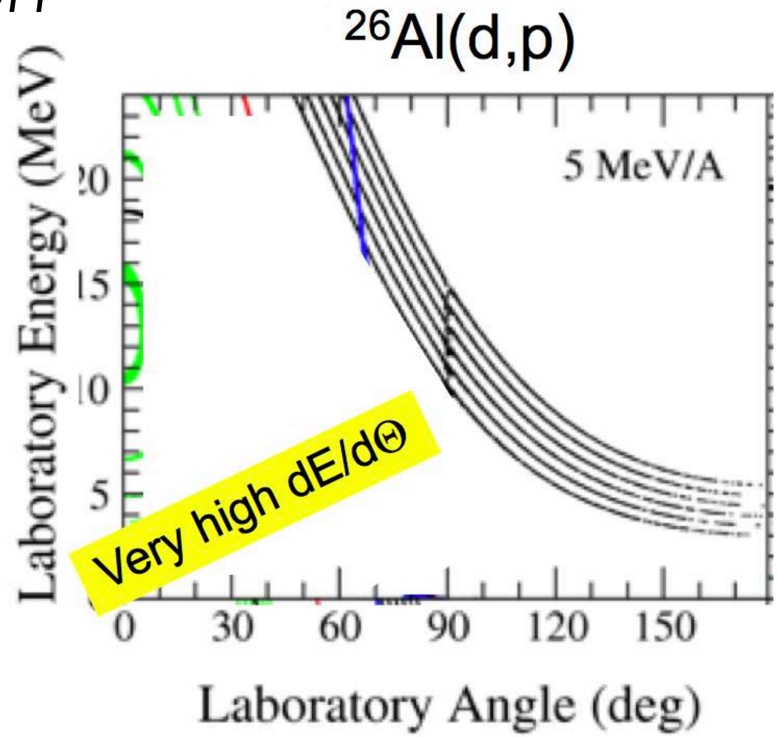




- *beam particle tracking*

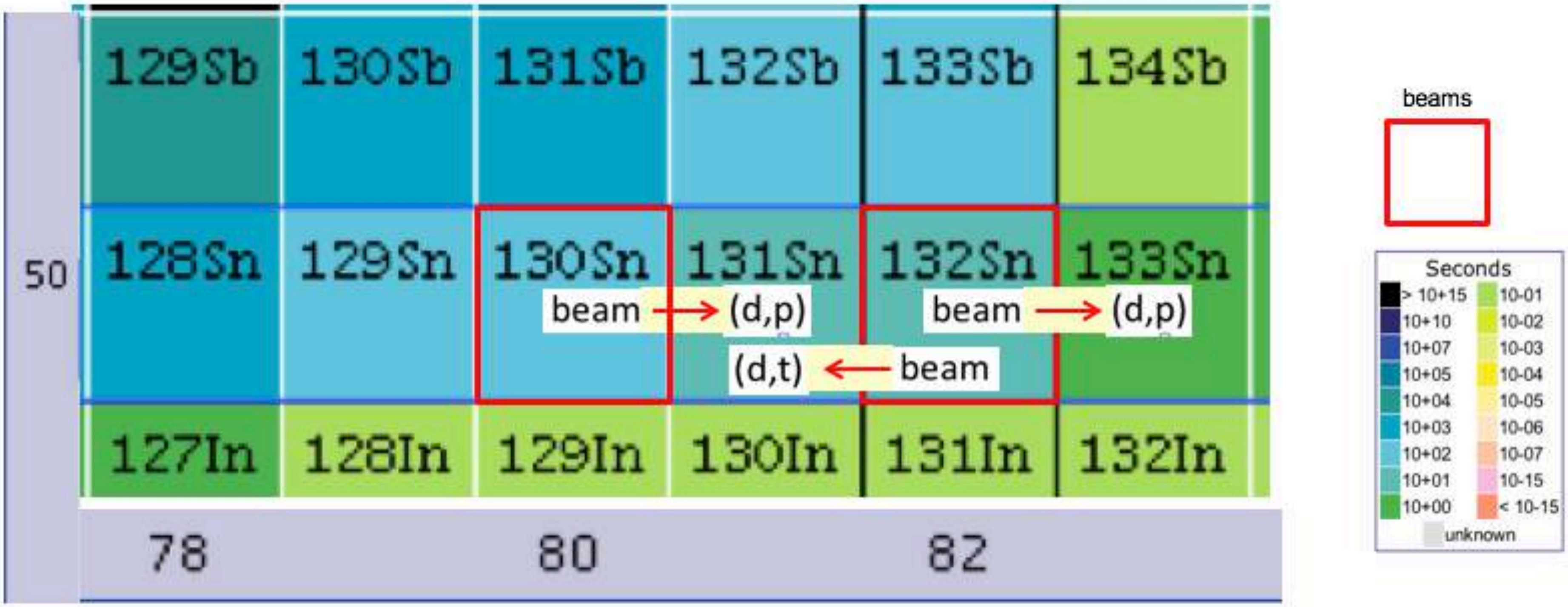
Challenges – Kinematic Compression





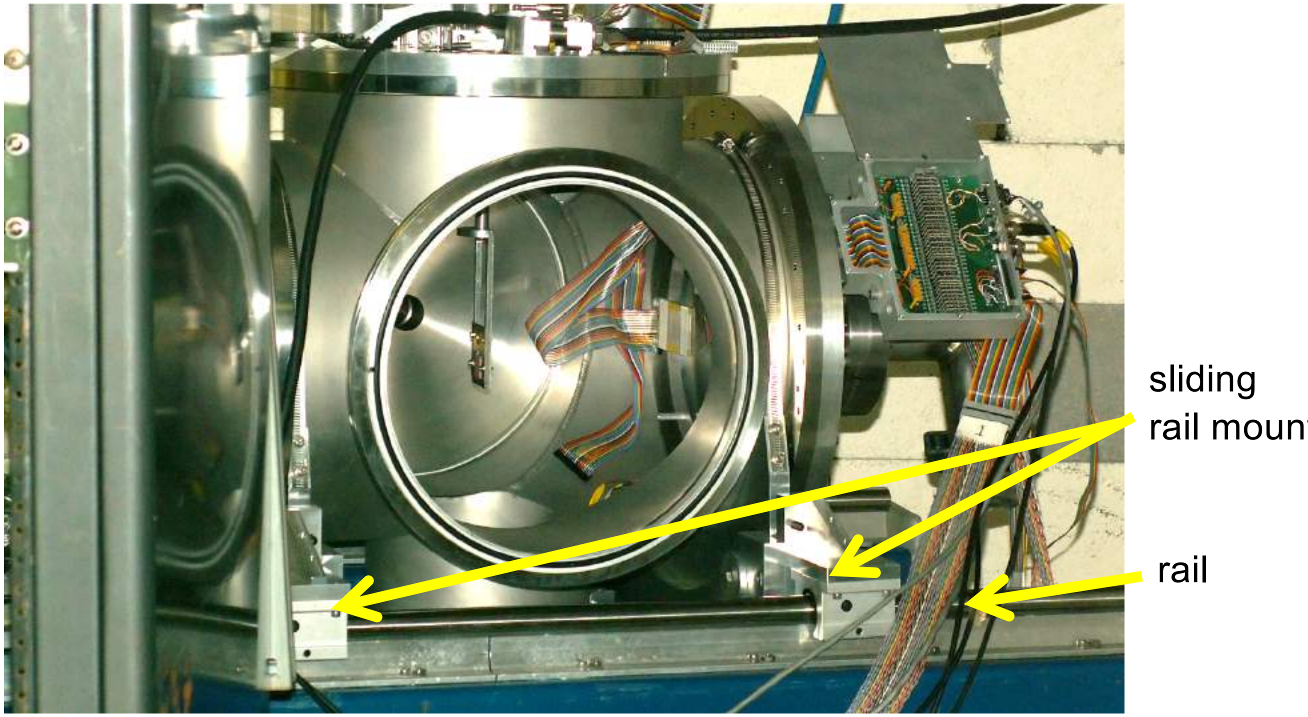
- *use detectors with higher pixellation (lower* ***dΘ****)*
- *use thinner targets (lower dE)*
- *careful choice of beam energies*

Challenges – Limited Species



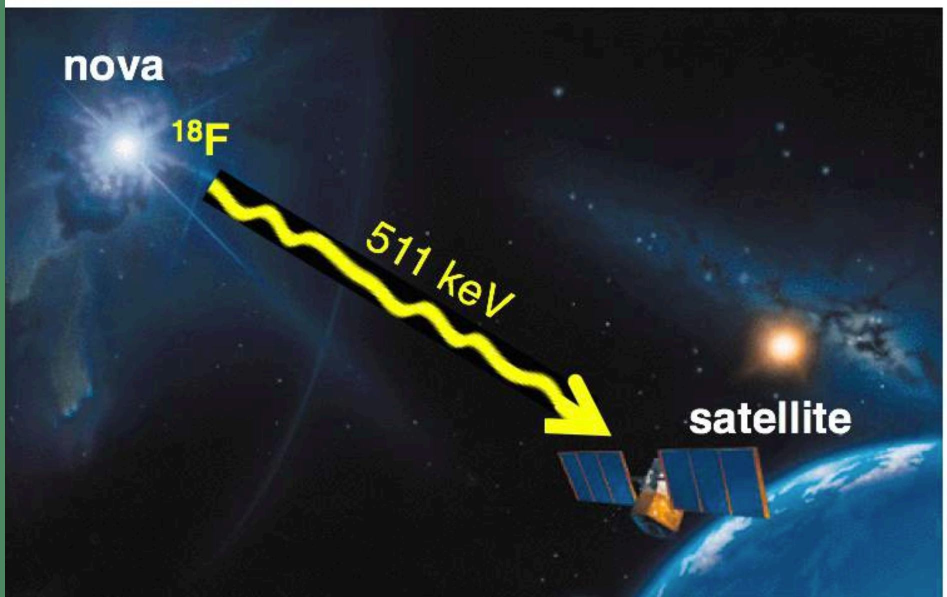
- *use multiple reaction channels*
- *run as many experiments per beam as possible*

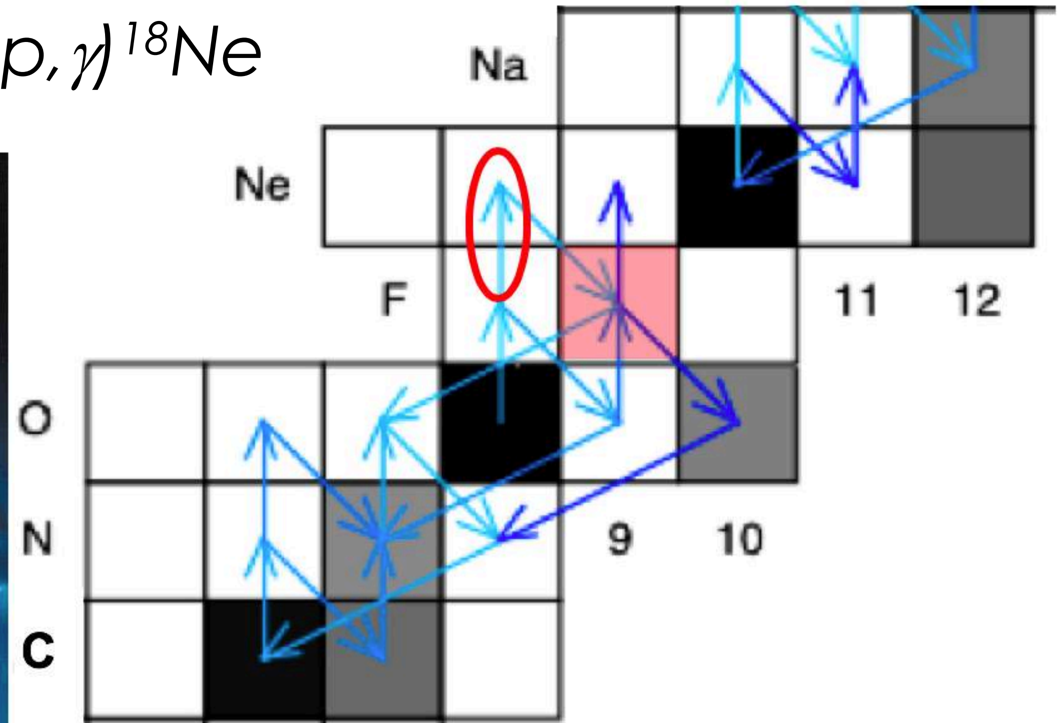
Challenges – Limited Beamtime



- *assume detector configurations may change between runs*
- *use rail mounting systems for quick changes without alignments*

Direct Measurement of $^{17}F(p,\gamma)^{18}Ne$

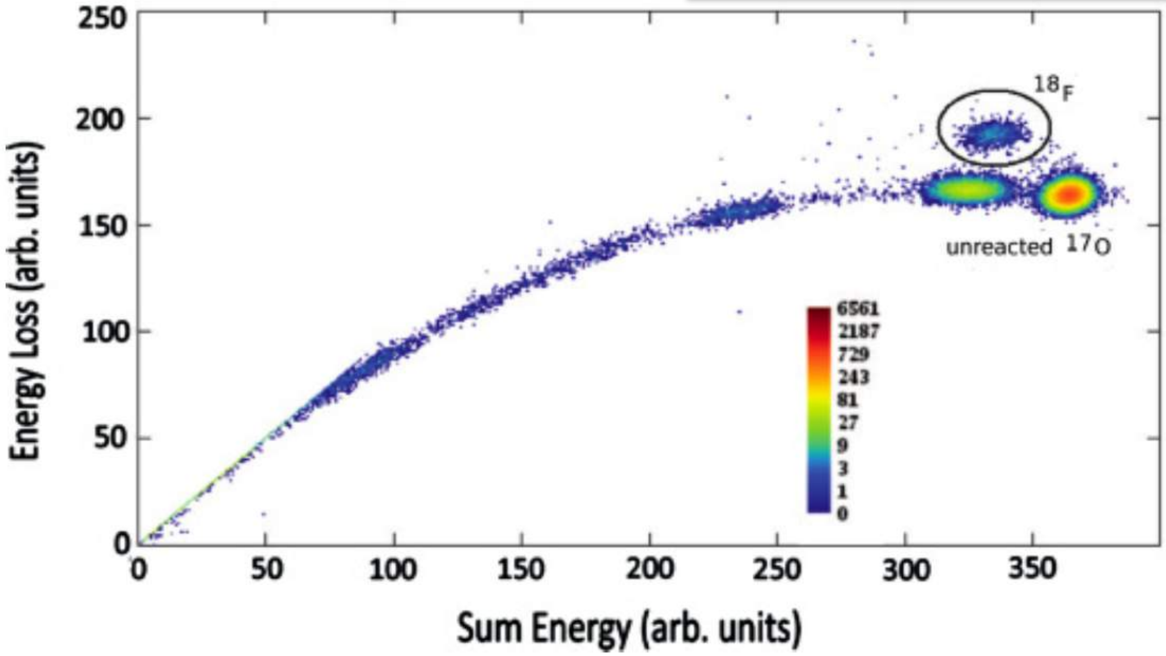




- *reaction important for synthesizing ^{18}F in novae – possible observable*
- *we used a recoil separator to make the first and only direct measurement of $^{17}F(p,\gamma)^{18}Ne$*

Direct Measurement of $^{17}F(p,\gamma)^{18}Ne$

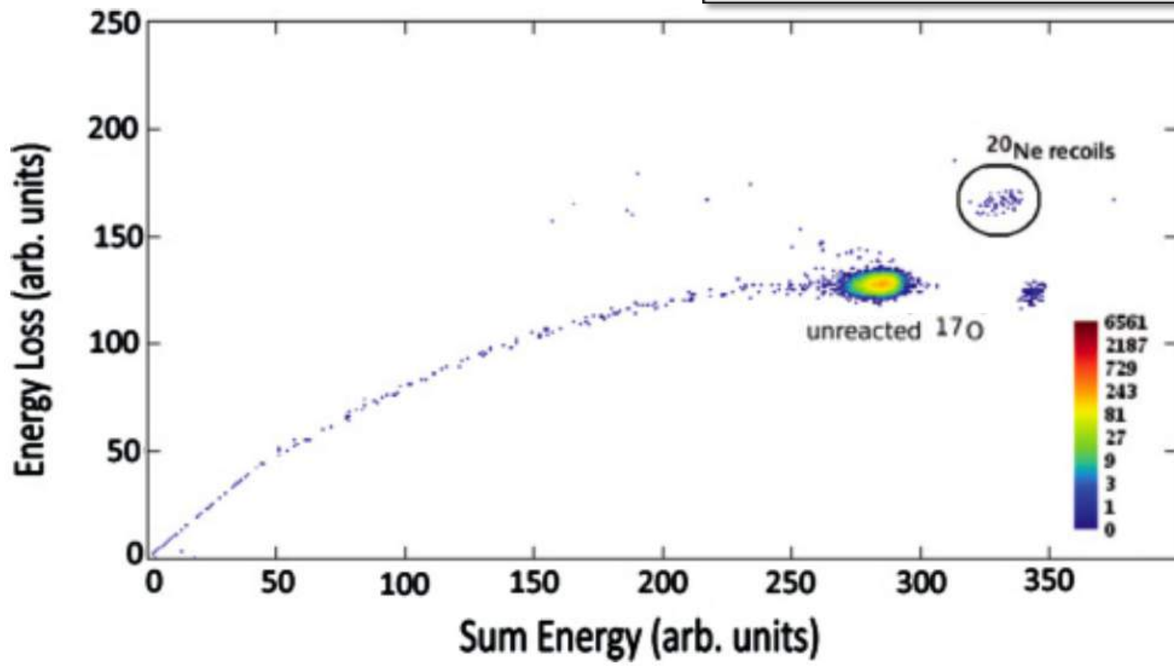
FIG. 4. (Color online) Energy loss versus total energy from the ionization chamber for the 557 keV resonance in $^{17}O(p,\gamma)^{18}F$.



- *measured ^{17}O + p capture to calibrate system & method*

Direct Measurement of $^{17}F(p,\gamma)^{18}Ne$

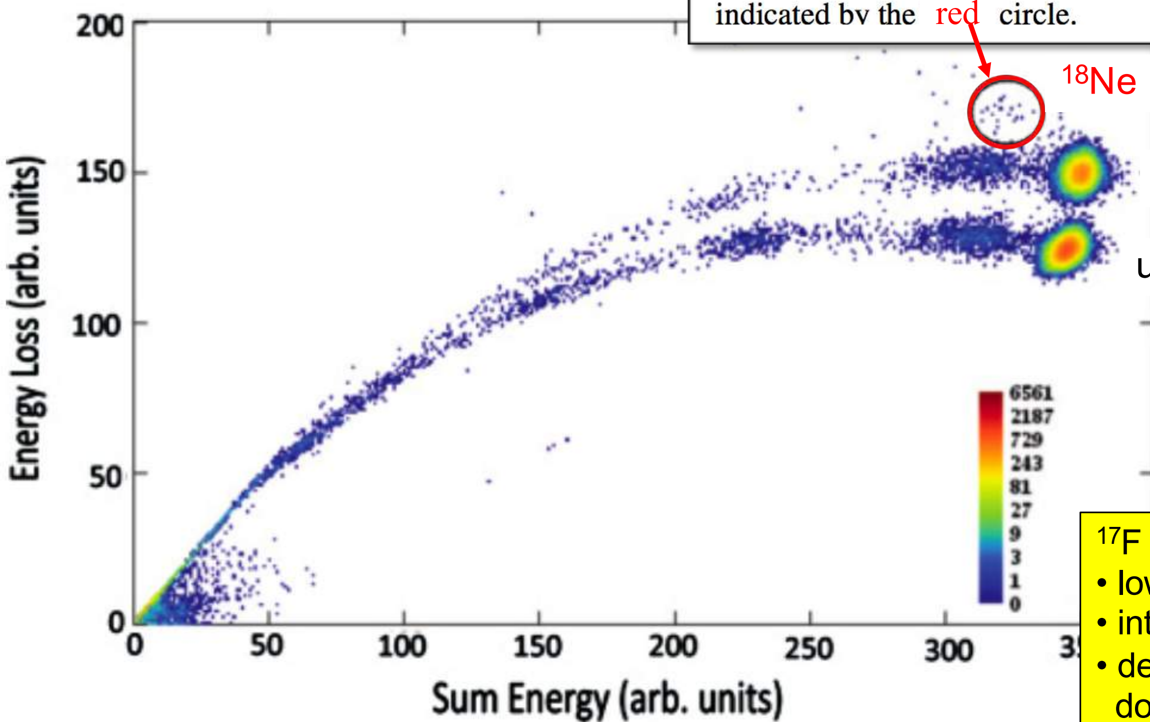
FIG. 5. (Color online) Ionization chamber spectrum for the $^{17}O + ^{20}Ne$ scattering measurement with Ne recoils indicated; performed to verify the location of ^{18}Ne recoils during the $^{17}F(p,\gamma)^{18}Ne$ experiment.



- *measured $^{17}O + ^{20}Ne$ capture to show where Ne recoils should be*

Direct Measurement of $^{17}F(p,\gamma)^{18}Ne$

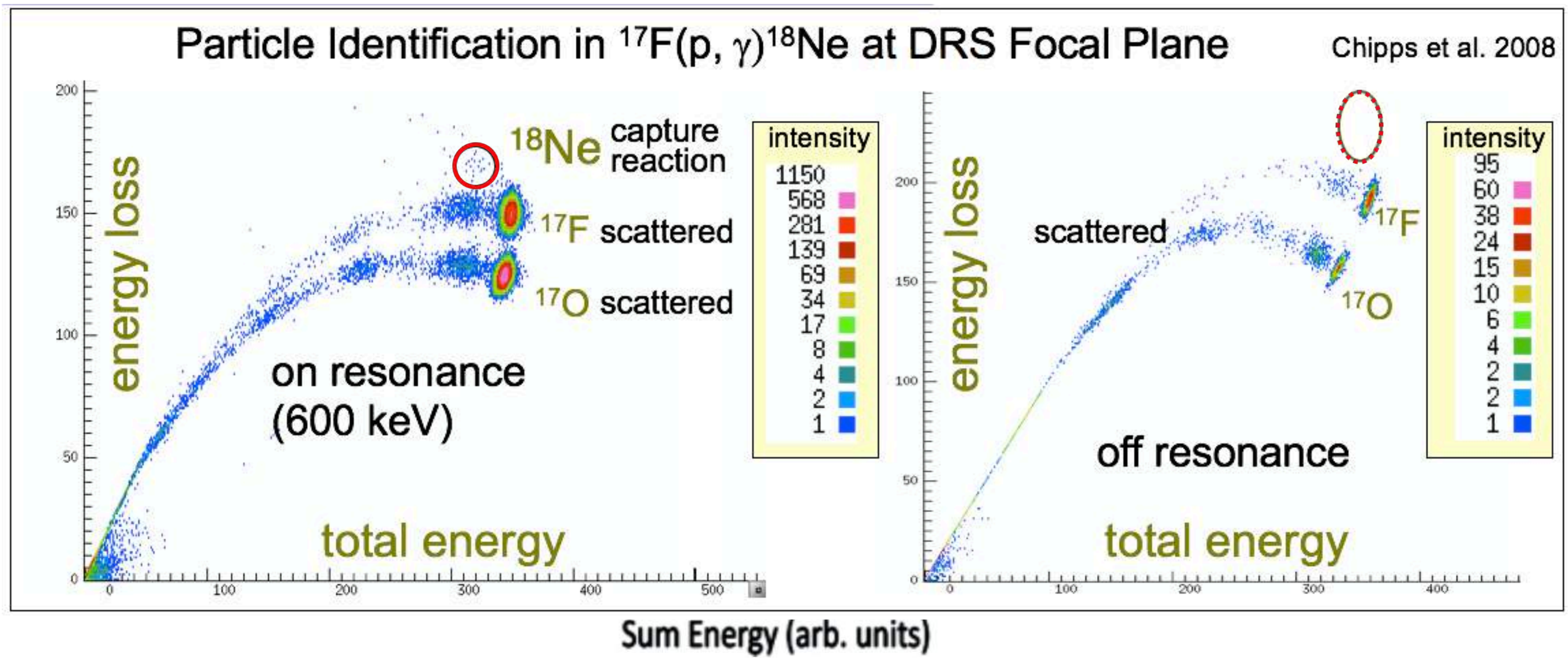
FIG. 6. (Color online) Energy loss versus total energy from the ionization chamber for the 599.8 keV resonance; ^{18}Ne recoils are indicated bv the red circle.



^{17}F beam at ORNL
- low energy 0.6 MeV/u
- intensity $2 \cdot 10^7$ pps
- determined strength of dominant 599.8 keV resonance
- 50 events in 6 weeks of running

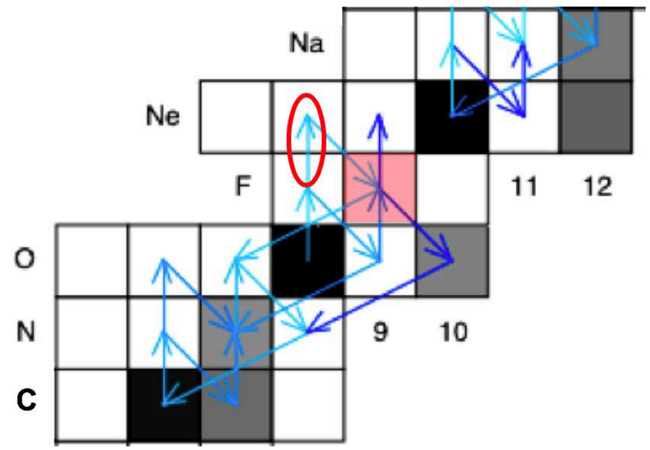
- *measured ^{17}F + p capture on resonance !*

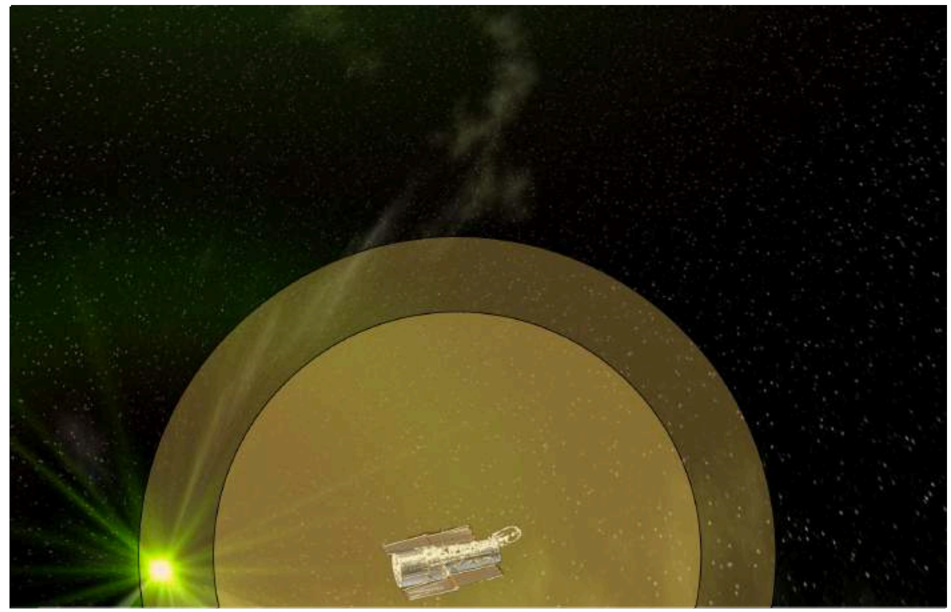
Direct Measurement of $^{17}F(p,\gamma)^{18}Ne$



- *measured ^{17}F + p capture on resonance !*

Direct Measurement of $^{17}F(p,\gamma)^{18}Ne$





- *implications for novae:*
  - *new fusion rate 2 - 3 times lower*
  - *in novae, new rate **increases** synthesis of ^{18}F by factor of 1.6 in some models, reduces uncertainties from factor of 15 to factor of ~ 2.5*
  - *more ^{18}F **survives** explosion –> volume scanned by billion dollar satellites increased by factor of 2*
- *implications for X-ray bursts: changes synthesis of ^{17}O by factor of 10, and reduces uncertainties (factor of 100 to factor of ~ 5)*

Systematic Measurements of (d,p) on exotic Sn isotopes

PHYSICAL REVIEW C **99**, 041302(R) (2019)

Rapid Communications

Informing direct neutron capture on tin isotopes near the $N = 82$ shell closure

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[10]*Department of Physics, Sungkyunkwan University, Suwon 440-746, Korea*
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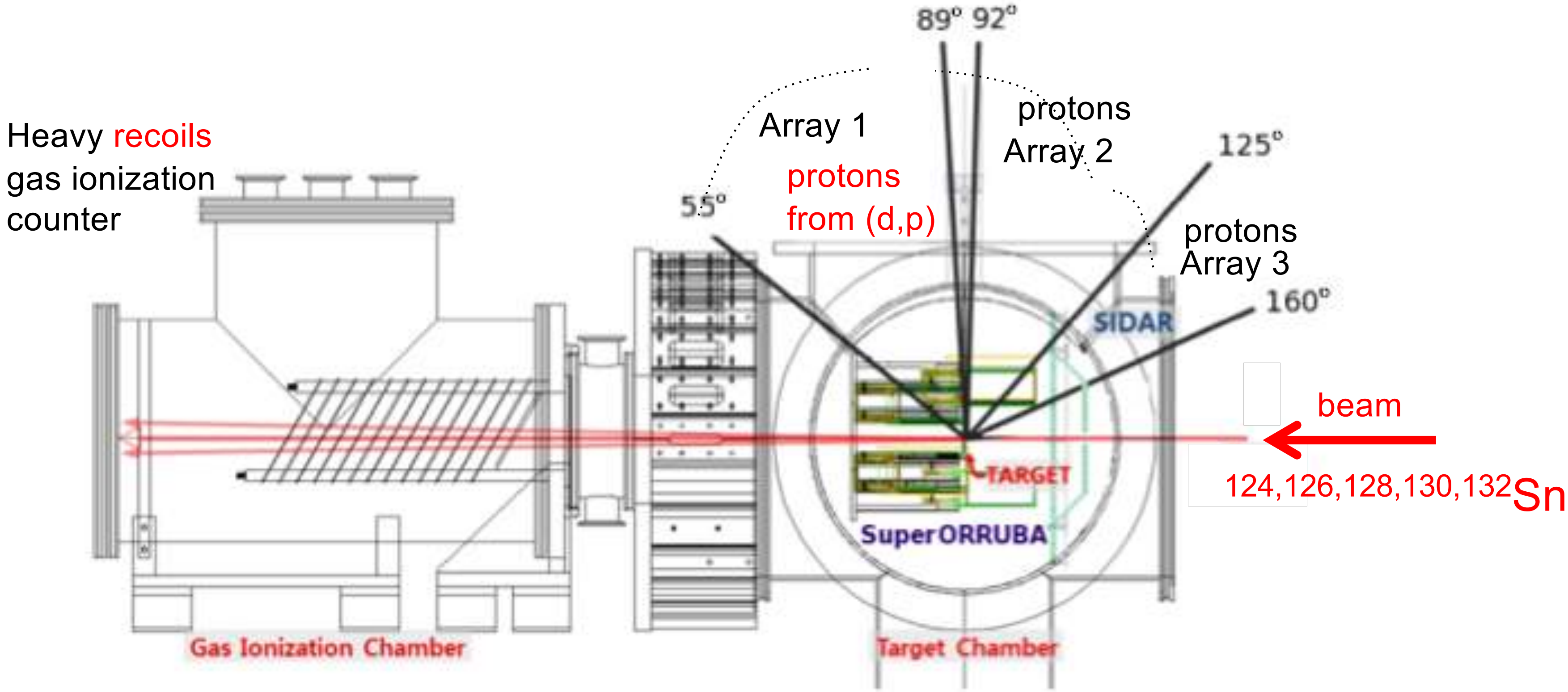
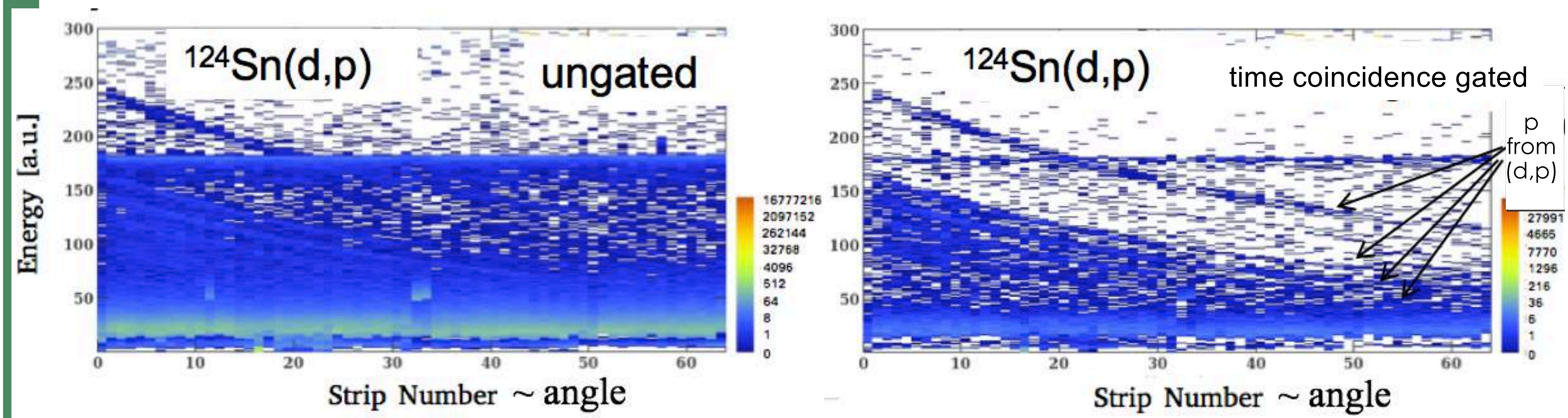
Systematic Measurements of (d,p) on exotic Sn isotopes



- *630 MeV ^{128}Sn beam (5 MeV/u) with > 99% purity*
- *Typical beam current 1 – 3 • 10^5 pps . . . 5 days data collection*
- *139 ± 17 μg/cm2 and 242 ± 39 μg/cm2 CD_2 targets*

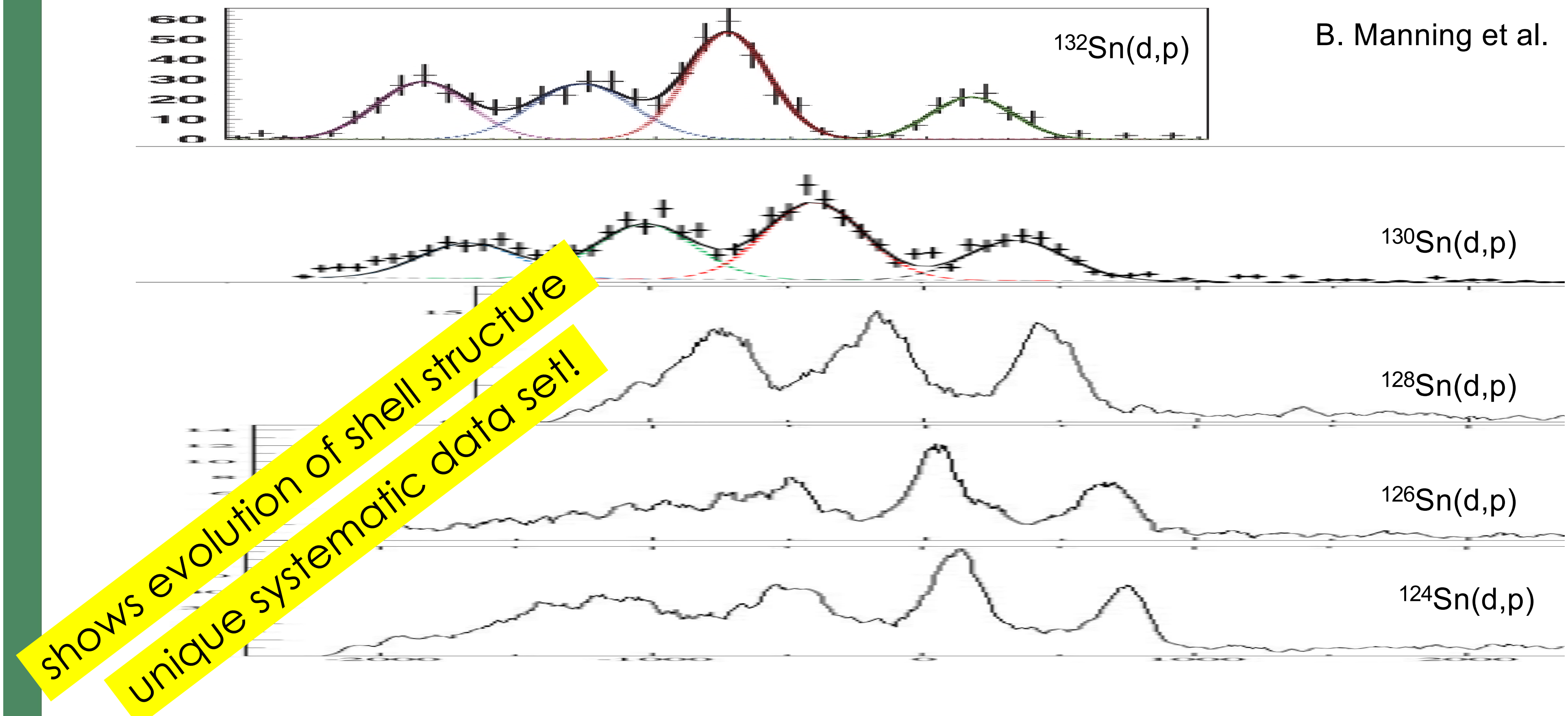
Systematic Measurements of (d,p) on exotic Sn isotopes



B. Manning et al.

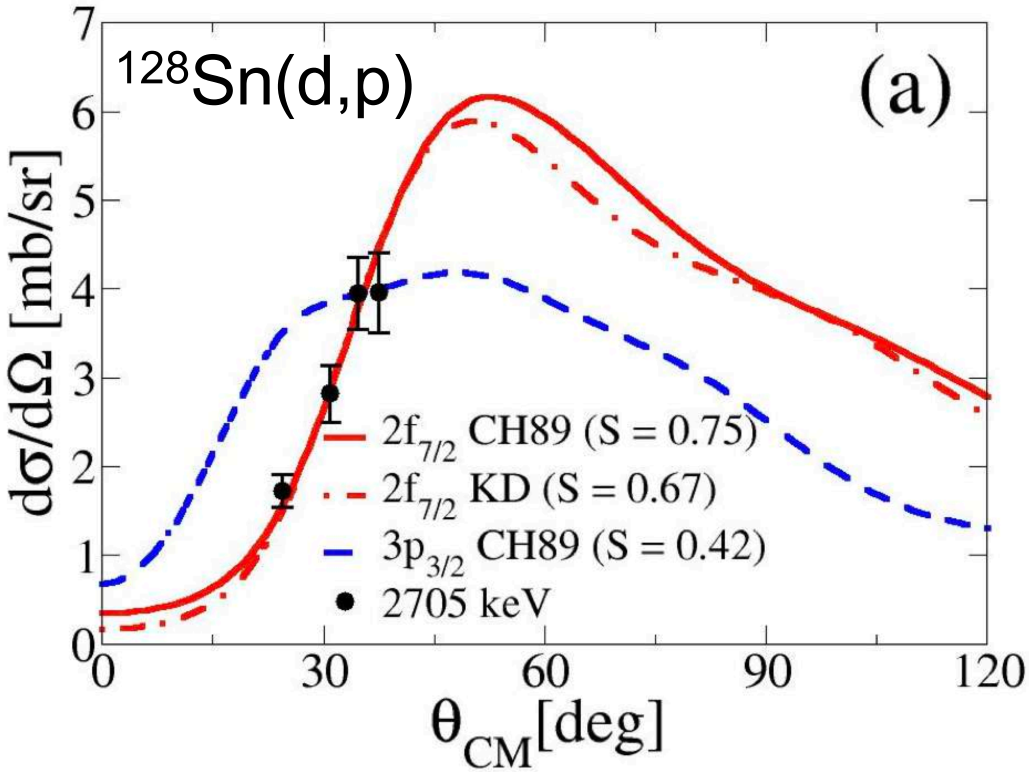
- *measured (d,p) energy-angle kinematic relationship*
- *gating on heavy – light particle time coincidence greatly reduces background*

Systematic Measurements of (d,p) on exotic Sn isotopes



- *Q-value spectra for (d,p) on Sn isotopes*

Systematic Measurements of (d,p) on exotic Sn isotopes



B. Manning et al.

- *highly-segmented detector arrays facilitate angular distribution measurements*
- *fit with FR-ADWA theory using CH89 and KD potentials and angular momentum transfers of 3 (red) or 1 (blue)*

Systematic Measurements of (d,p) on exotic Sn isotopes

B. Manning et al.

^{A}X	E_x (keV)	$n\ell j$	Spectroscopic Factors: DWBA	FR-ADWA-KD	FR-ADWA-CH
^{125}Sn	2769	$2f_{7/2}$	0.40 ± 0.03	0.36 ± 0.03	**0.39 ± 0.03**
	3385	$3p_{3/2}$	0.37 ± 0.04	0.24 ± 0.02	**0.29 ± 0.03**
	3998	$3p_{1/2}$	0.55 ± 0.07	0.34 ± 0.04	**0.42 ± 0.05**
^{127}Sn	2705	$2f_{7/2}$	0.51 ± 0.07	0.49 ± 0.07	**0.54 ± 0.08**
	3325	$3p_{3/2}$	0.35 ± 0.04	0.23 ± 0.03	**0.27 ± 0.03**
	3881	$3p_{1/2}$	0.70 ± 0.06	0.43 ± 0.04	**0.49 ± 0.04**
^{129}Sn	2705	$2f_{7/2}$	0.72 ± 0.09	0.67 ± 0.09	**0.75 ± 0.10**
	3317	$3p_{3/2}$	0.39 ± 0.05	0.24 ± 0.03	**0.29 ± 0.04**
	3913	$3p_{1/2}$	0.63 ± 0.09	0.44 ± 0.07	**0.46 ± 0.07**
^{131}Sn	2628	$2f_{7/2}$	0.75 ± 0.11	0.85 ± 0.11	**0.95 ± 0.13**
	3404	$3p_{3/2}$	0.75 ± 0.11	0.50 ± 0.11	**0.55 ± 0.08**
	3986	$3p_{1/2}$	1.00 ± 0.14	0.88 ± 0.14	**1.00 ± 0.14**
	4655	$2f_{5/2}$	0.89 ± 0.12	0.66 ± 0.12	**0.76 ± 0.11**
^{133}Sn	0	$2f_{7/2}$	0.86 ± 0.07	0.90 ± 0.07	**1.00 ± 0.08**
	854	$3p_{3/2}$	0.92 ± 0.07	0.87 ± 0.07	**0.92 ± 0.07**
	1363	$3p_{1/2}$	1.1 ± 0.2	1.3 ± 0.3	**1.3 ± 0.3**
	2005	$2f_{5/2}$	1.5 ± 0.3	1.1 ± 0.3	**1.3 ± 0.3**

low

high ~ 1.0
maximal

- *determined spectroscopic factors*

Systematic Measurements of (d,p) on exotic Sn isotopes

B. Manning et al.

			Spectroscopic Factors		
^{A}X	E_x (keV)	$n\ell j$	DWBA	FR-ADWA-KD	FR-ADWA-CH
^{125}Sn	2769	$2f_{7/2}$	0.40 ± 0.03	0.36 ± 0.03	**0.39 ± 0.03**
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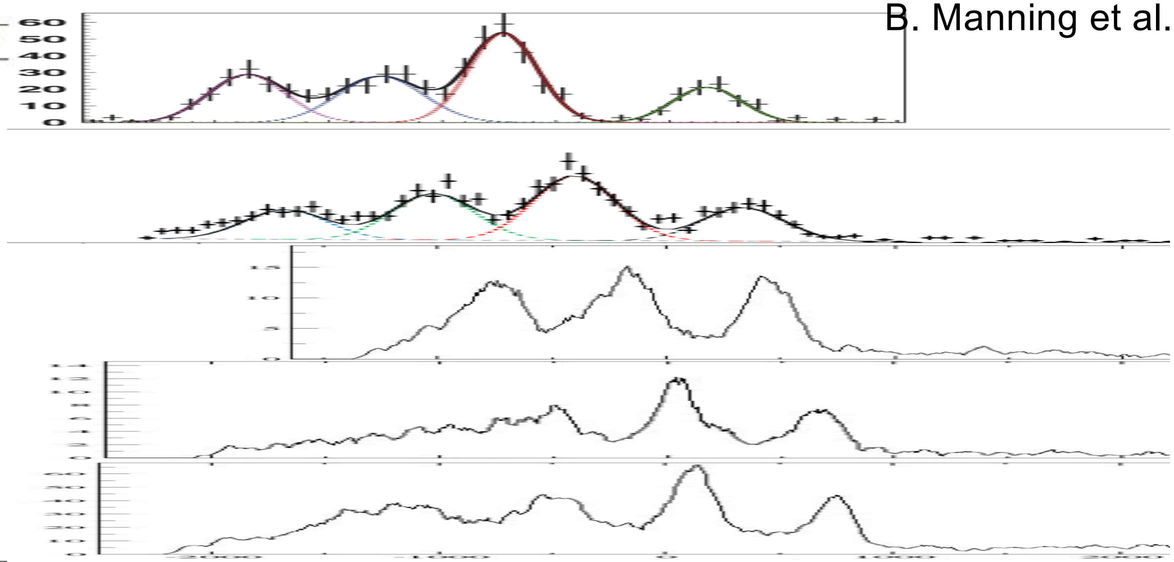
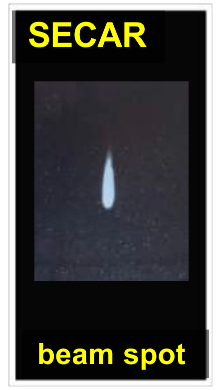
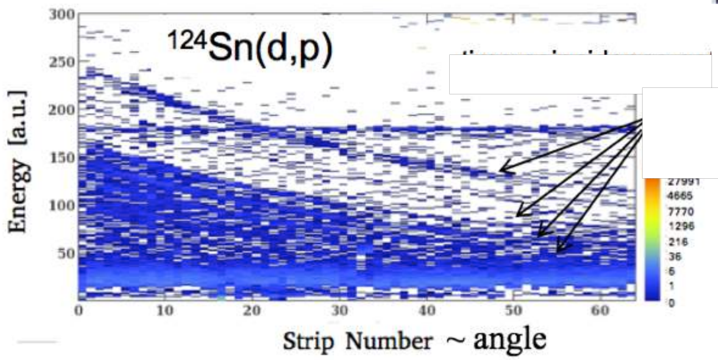
	3404	$3p_{3/2}$	0.75 ± 0.11	0.50 ± 0.11	**0.55 ± 0.08**
	3986	$3p_{1/2}$	1.00 ± 0.14	0.88 ± 0.14	**1.00 ± 0.14**
	4655	$2f_{5/2}$	0.89 ± 0.12	0.66 ± 0.12	**0.76 ± 0.11**
^{133}Sn	0	$2f_{7/2}$	0.86 ± 0.07	0.90 ± 0.07	**1.00 ± 0.08**
	854	$3p_{3/2}$	0.92 ± 0.07	0.87 ± 0.07	**0.92 ± 0.07**
	1363	$3p_{1/2}$	1.1 ± 0.2	1.3 ± 0.3	**1.3 ± 0.3**
	2005	$2f_{5/2}$	1.5 ± 0.3	1.1 ± 0.3	**1.3 ± 0.3**

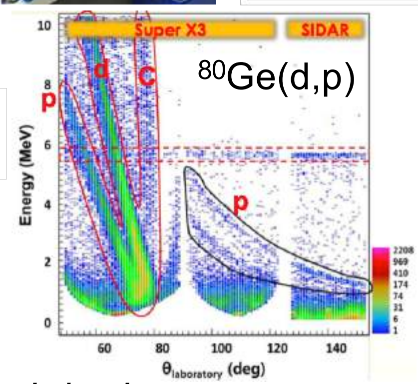


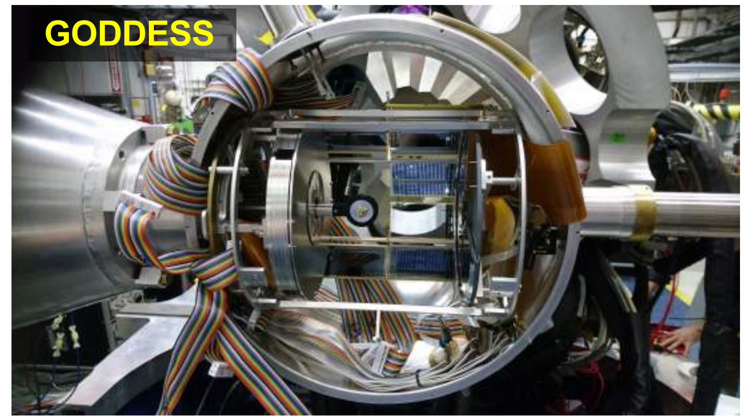
- *constrain spin-parity, determine spectroscopic factors from angular distributions*
- *best fits using DWBA and ADWA with different potentials*
- *used to constrain neutron capture cross sections in nuclei relevant for cold r-process models*
- *systematic info on single particle levels off stability provides challenge for theorists*

Future Plans



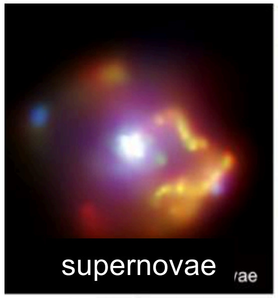


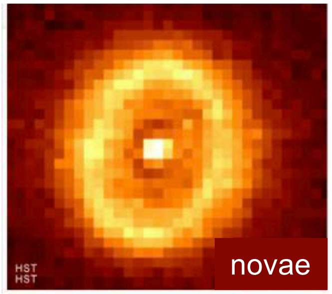


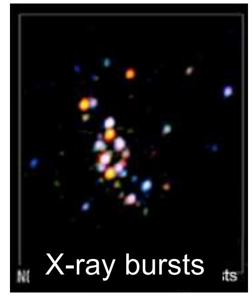


- *commissioning SECAR with stable beams*
- *measurements with p-rich and n-rich beams at FRIB*
- *further development of new techniques (2-energy approaches) & detectors*
- *measurements at RAON ☺ and other facilities*

Summary







- *measurements with radioactive beams have **tremendous potential** in nuclear astrophysics & other areas of nuclear science*
- *these measurements have many **special challenges** – low intensity, low purity, limited species, poorly defined energies …*
- *some approaches to try include*
  - *planning measurements with very LOW beam intensities (well below projected intensities)*
  - *combining direct & indirect measurements for valuable, complementary information on reactions and nuclei of interest*
  - *measuring kinematically complete (coincidence) reactions, measure multiple reaction channels, and tracking beam particles*
- *wish you **great success** with RISP / RAON !*