

Nuclear Astrophysics

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

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	104 Unq	105 Unp	106 Unh	107 Uns	108 Uno	109 Une	110 Unn								

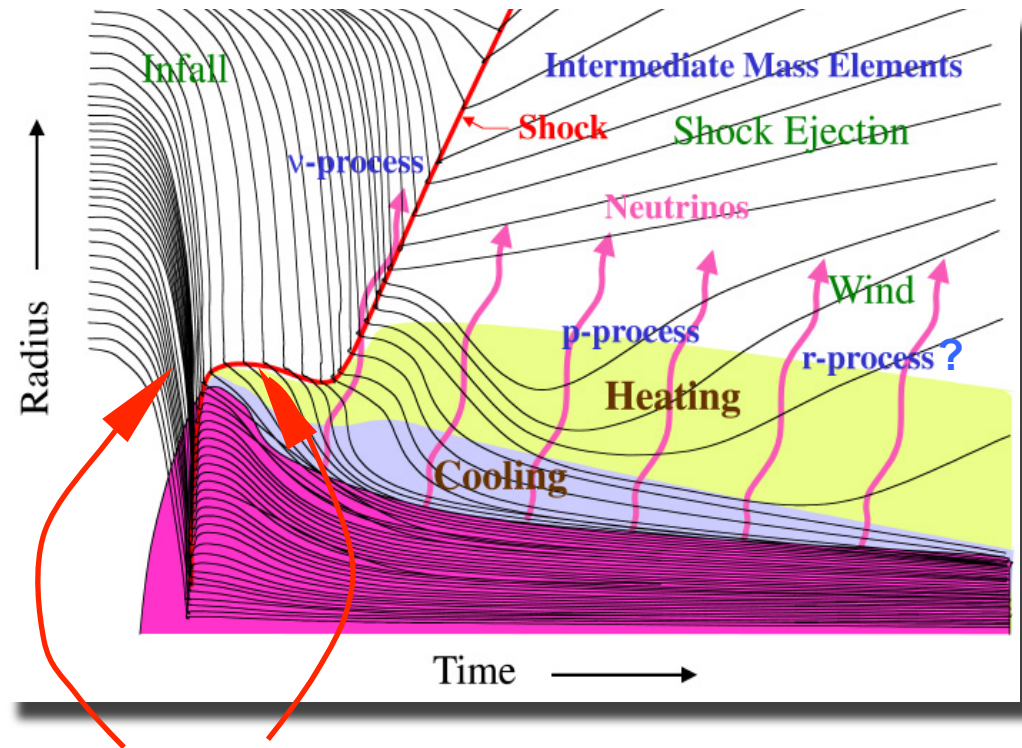
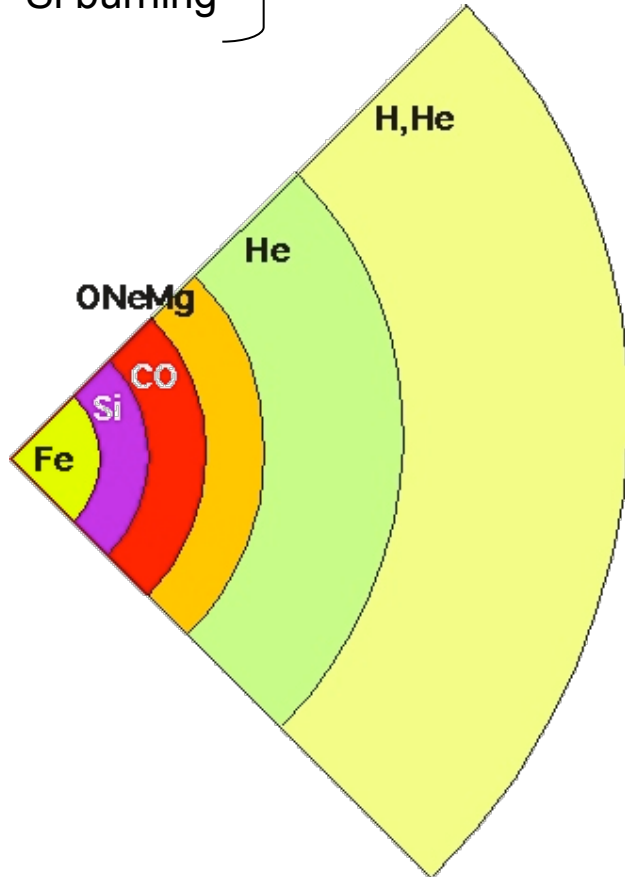
58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Core-Collapse Supernovae

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

C burning
 O burning
 Si burning

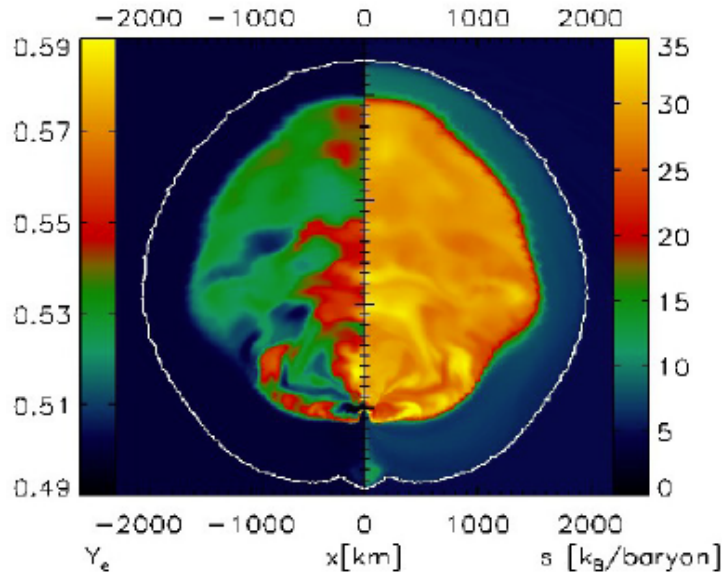
In rapid succession



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.

Ru	90Ru	91Ru	92Ru	93Ru	94Ru	95Ru	96Ru	97Ru	98Ru	99Ru
Tc	89Tc	90Tc	91Tc	92Tc	93Tc	94Tc	95Tc	96Tc	97Tc	98Tc
Mo	88Mo	89Mo	90Mo	91Mo	92Mo	93Mo	94Mo	95Mo	96Mo	97Mo
Nb	87Nb	88Nb	89Nb	90Nb	91Nb	92Nb	93Nb	94Nb	95Nb	96Nb
Zr	86Zr	87Zr	88Zr	89Zr	90Zr	91Zr	92Zr	93Zr	94Zr	95Zr
Y	85Y	86Y	87Y	88Y	89Y	90Y	91Y	92Y	93Y	94Y
Sr	84Sr	85Sr	86Sr	87Sr	88Sr	89Sr	90Sr	91Sr	92Sr	93Sr

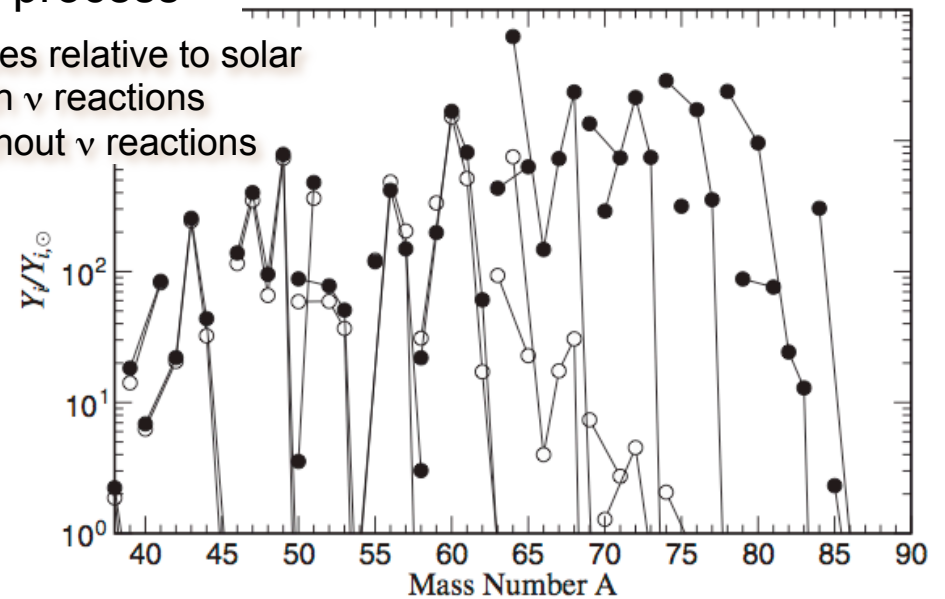
- Nuclear statistical equilibrium favors production of ^{56}Ni
- Weak interactions can produce neutrons boosting masses produced

➤ νp process

Fröhlich et al., PRL (2006).

Abundances relative to solar

- with ν reactions
- without ν reactions



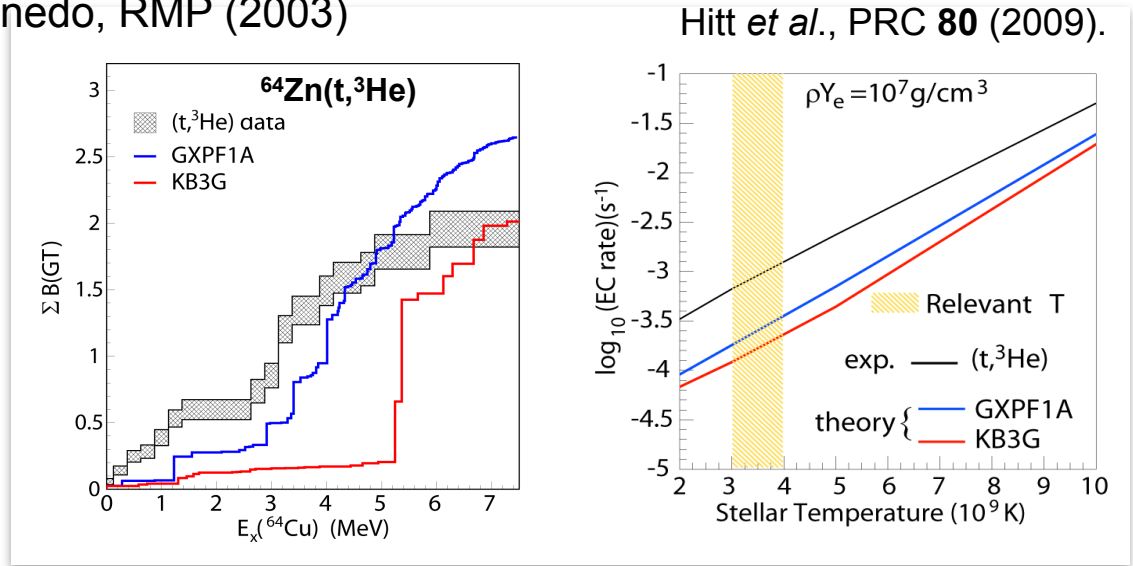
- Possible additional source for intermediate mass elements?
- Contributes to anomalous abundance of light “p” isotopes?

Weak interaction rates

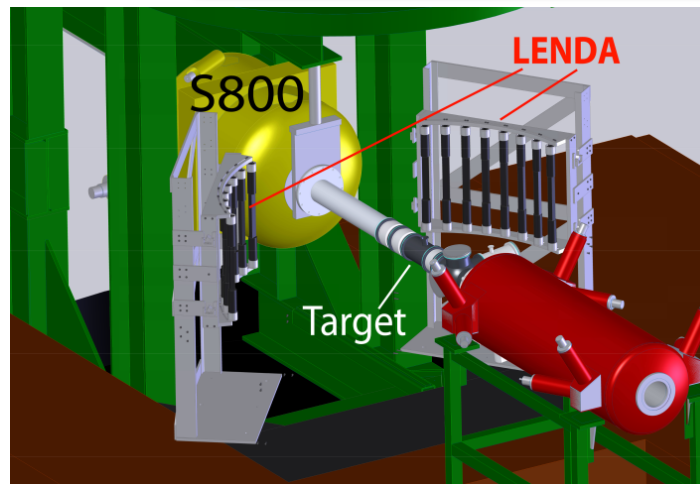
- Great improvements in weak rates from theory (nuclear shell model calculations)

See Langanke & Martinez-Pinedo, RMP (2003)

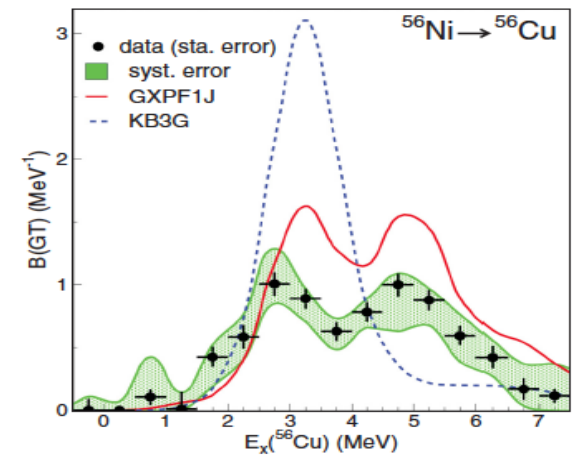
- Gamow-Teller strengths can be determined from charge exchange reactions
- (p,n) or (n,p) measurements test shell model predictions and effective interactions
- Some studies so far with stable nuclei



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

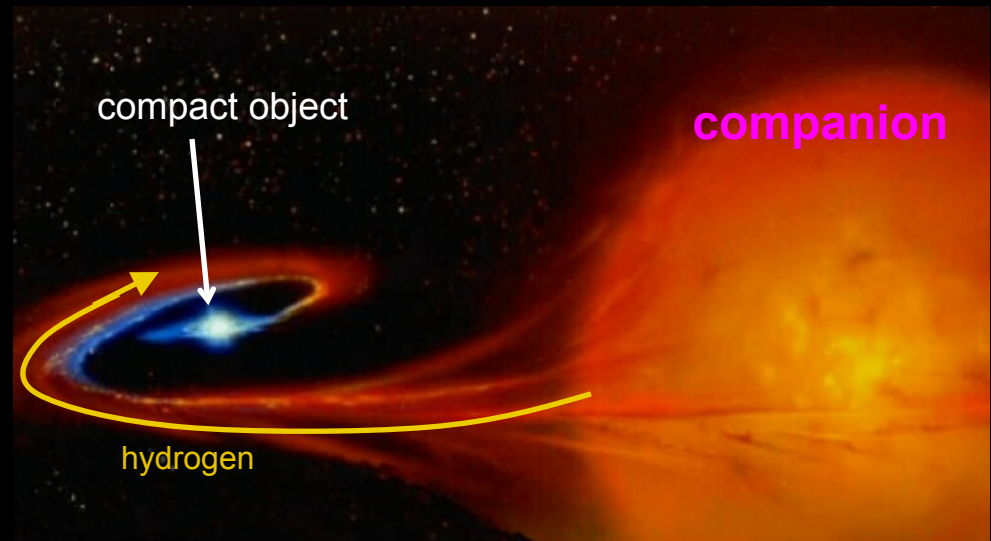


Sasano *et al.*, PRL 107 (2011).



Stellar Explosions in Binary Systems

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



➡ Novae

- White dwarf
- ~40/yr in our Galaxy
- Recurrence times?

➡ X-ray bursts

- On surface of neutron star
- Frequently recur (hours → days)
- Influences evolution of system

➡ Type Ia Supernovae

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

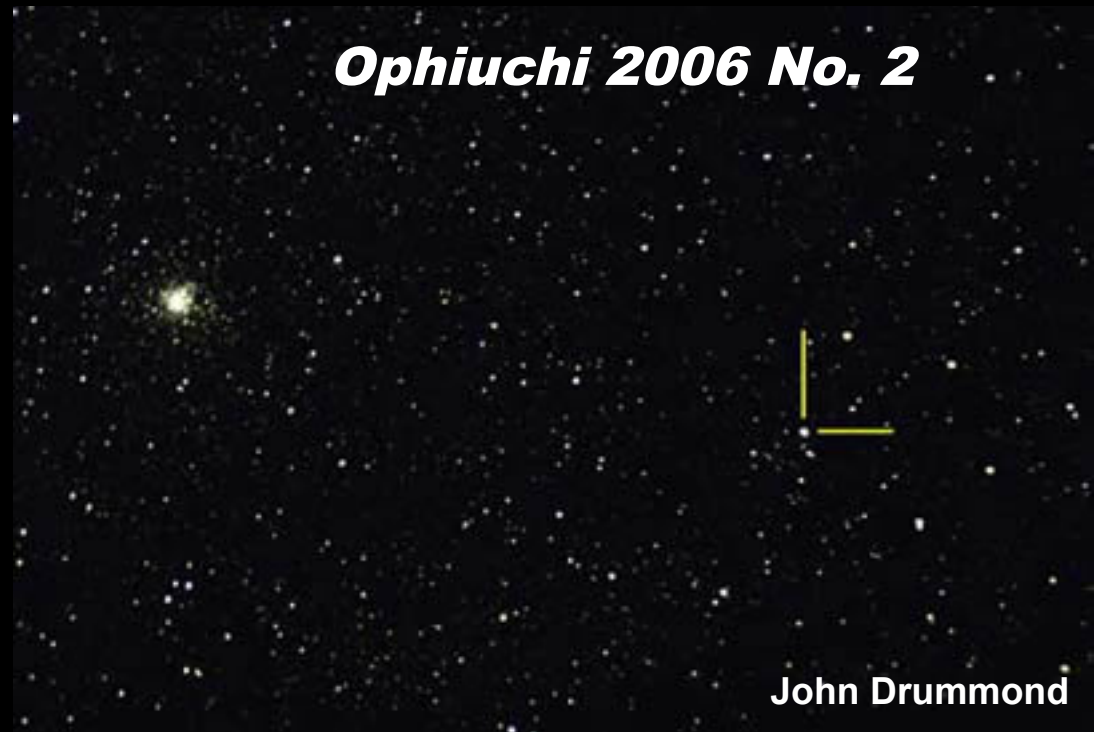
Discovering Novae

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

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

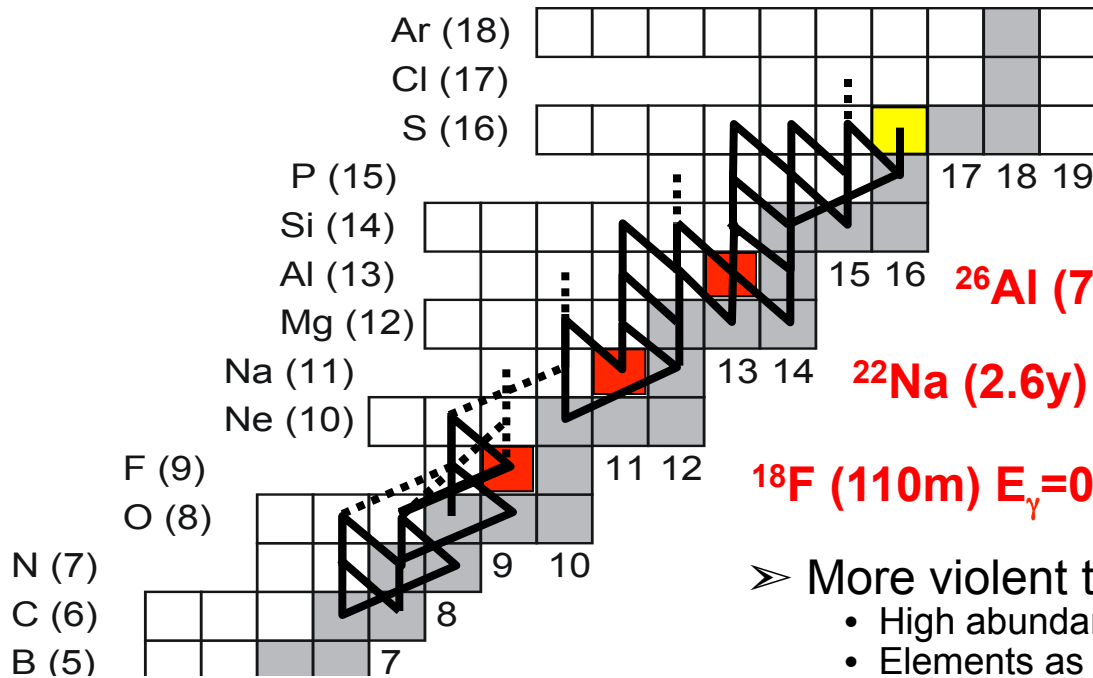
- Nova Ophiuchi 2006 No. 2

- Discovered April 6, 2006
- Peter Williams, Sydney Australia
- Visual discovery (Magnitude 10)
- Peak brightness 9.2
- Confirmation:
 - William Liller (Chile)
 - Tom Krajci (US)
 - Jaciej Reszelski (Poland)



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

Nova nucleosynthesis



➤ Many ejecta substantially enriched in S

^{26}Al ($7 \times 10^5 \text{y}$) $E_\gamma = 1.275 \text{ MeV}$

^{22}Na (2.6y) $E_\gamma = 1.809 \text{ MeV}$

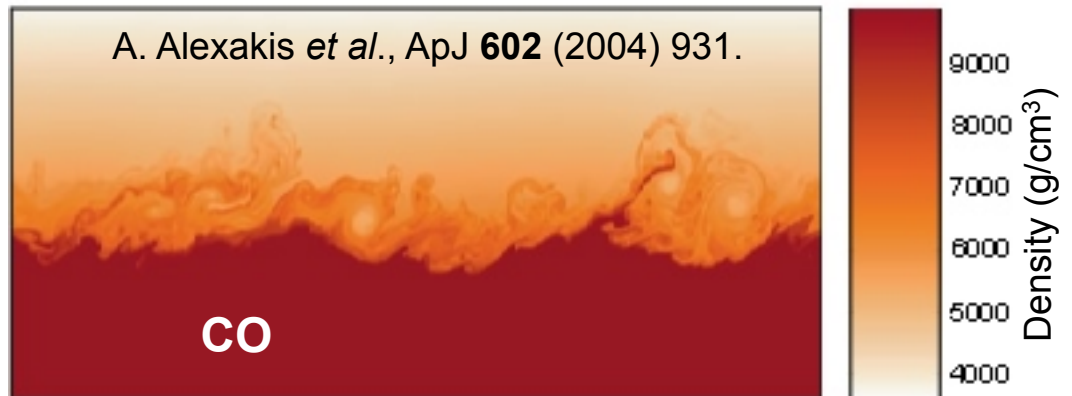
^{18}F (110m) $E_\gamma = 0.511 \text{ MeV}$

➤ More violent than expected

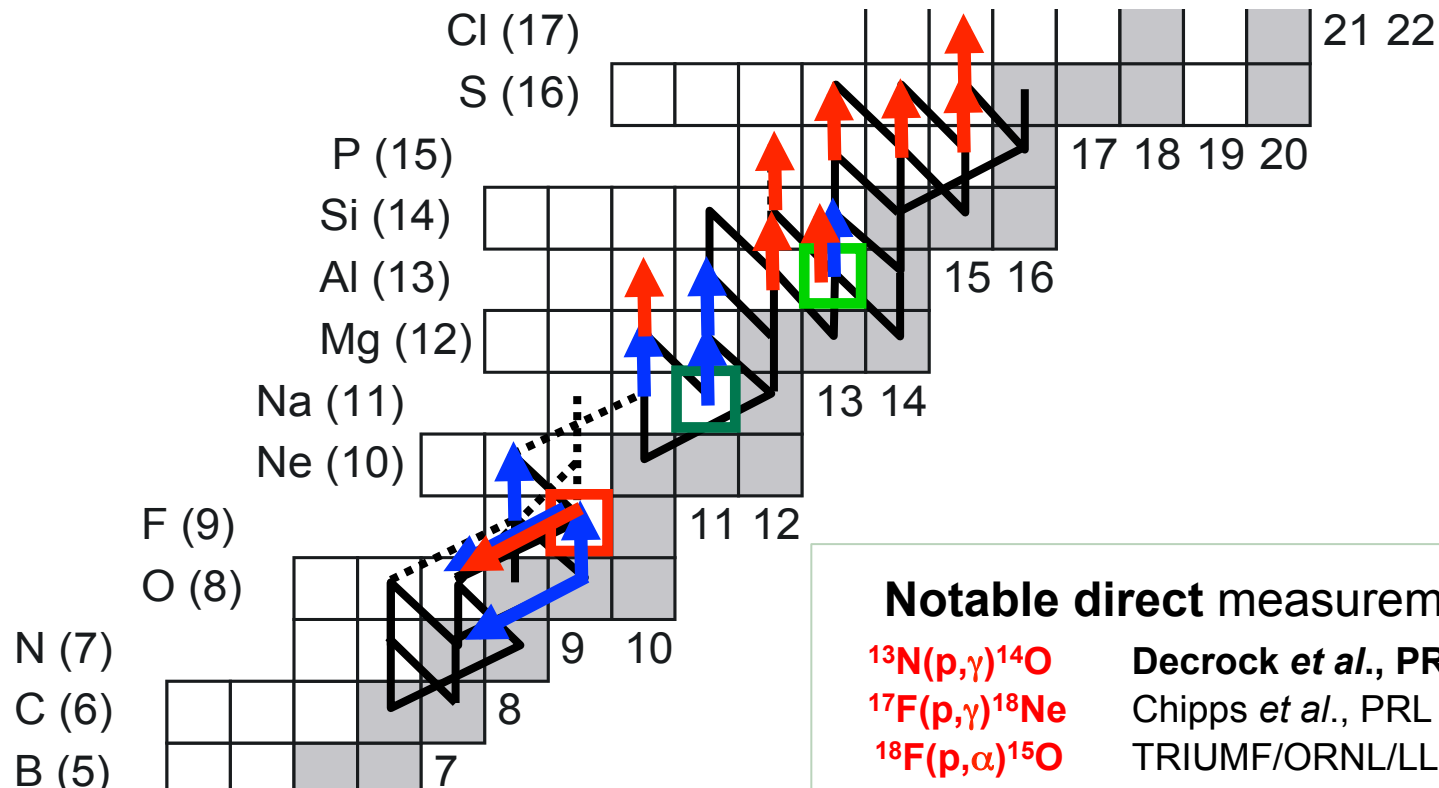
- High abundance of heavier elements
- Elements as heavy as sulfur
- High ejected mass
- Substantial mixing of accreted material with core?

➤ Complex hydrodynamical models required


- Multidimensional models using adaptive coordinate mesh
- Nuclear physics typically decoupled or simplified
- Nucleosynthesis tracked in detail in a post-processing approach
- Frontier is now coupling of better nuclear physics with more realistic hydrodynamical models



Many nova reactions have been recently determined

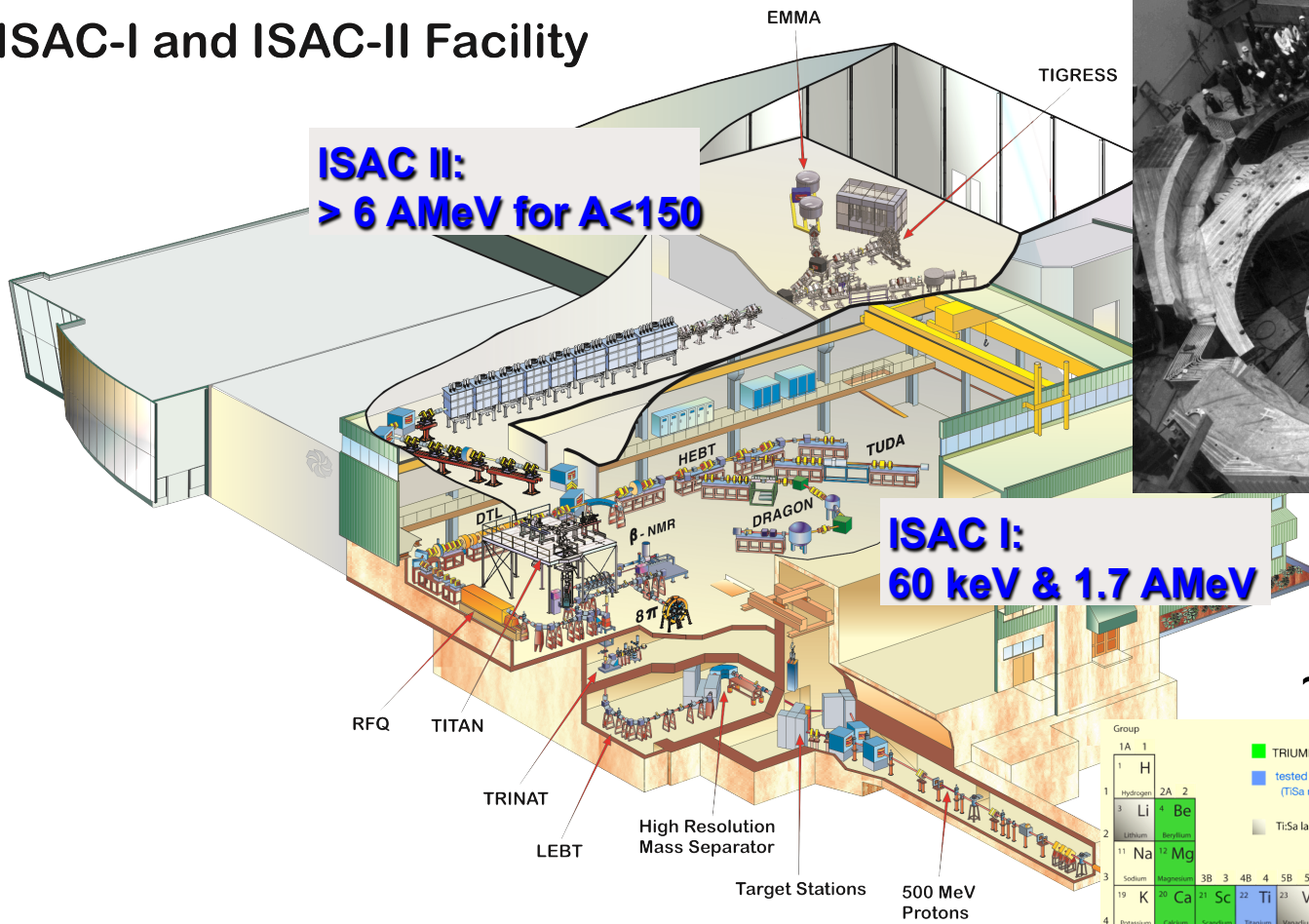


Others: $^{18}\text{F}(p,\gamma)^{19}\text{Ne}$,
 $^{19}\text{Ne}(p,\gamma)^{20}\text{Na}$, . . .

Notable direct measurements* 

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

ISAC-I and ISAC-II Facility



~3500 RIB hours /yr

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

Group 1

■ TRIUMF RILIS isotopes on-line status: 05/2012
 ■ tested TiSa laser schemes status: 01/2012 (TiSa network: Mainz, TRIUMF, GANIL, HRIBF, JYFL, ISOLDE)
 ■ TiSa laser ionization schemes on paper (theory)

1	2A	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120	121	122	123	124	125	126	127	128	129	130	131	132	133	134	135	136	137	138	139	140	141	142	143	144	145	146	147	148	149	150	151	152	153	154	155	156	157	158	159	160	161	162	163	164	165	166	167	168	169	170	171	172	173	174	175	176	177	178	179	180	181	182	183	184	185	186	187	188	189	190	191	192	193	194	195	196	197	198	199	200	201	202	203	204	205	206	207	208	209	210	211	212	213	214	215	216	217	218	219	220	221	222	223	224	225	226	227	228	229	230	231	232	233	234	235	236	237	238	239	240	241	242	243	244	245	246	247	248	249	250	251	252	253	254	255	256	257	258	259	260	261	262	263	264	265	266	267	268	269	270	271	272	273	274	275	276	277	278	279	280	281	282	283	284	285	286	287	288	289	290	291	292	293	294	295	296	297	298	299	300	301	302	303	304	305	306	307	308	309	310	311	312	313	314	315	316	317	318	319	320	321	322	323	324	325	326	327	328	329	330	331	332	333	334	335	336	337	338	339	340	341	342	343	344	345	346	347	348	349	350	351	352	353	354	355	356	357	358	359	360	361	362	363	364	365	366	367	368	369	370	371	372	373	374	375	376	377	378	379	380	381	382	383	384	385	386	387	388	389	390	391	392	393	394	395	396	397	398	399	400	401	402	403	404	405	406	407	408	409	410	411	412	413	414	415	416	417	418	419	420	421	422	423	424	425	426	427	428	429	430	431	432	433	434	435	436	437	438	439	440	441	442	443	444	445	446	447	448	449	450	451	452	453	454	455	456	457	458	459	460	461	462	463	464	465	466	467	468	469	470	471	472	473	474	475	476	477	478	479	480	481	482	483	484	485	486	487	488	489	490	491	492	493	494	495	496	497	498	499	500	501	502	503	504	505	506	507	508	509	510	511	512	513	514	515	516	517	518	519	520	521	522	523	524	525	526	527	528	529	530	531	532	533	534	535	536	537	538	539	540	541	542	543	544	545	546	547	548	549	550	551	552	553	554	555	556	557	558	559	560	561	562	563	564	565	566	567	568	569	570	571	572	573	574	575	576	577	578	579	580	581	582	583	584	585	586	587	588	589	590	591	592	593	594	595	596	597	598	599	600	601	602	603	604	605	606	607	608	609	610	611	612	613	614	615	616	617	618	619	620	621	622	623	624	625	626	627	628	629	630	631	632	633	634	635	636	637	638	639	640	641	642	643	644	645	646	647	648	649	650	651	652	653	654	655	656	657	658	659	660	661	662	663	664	665	666	667	668	669	670	671	672	673	674	675	676	677	678	679	680	681	682	683	684	685	686	687	688	689	690	691	692	693	694	695	696	697	698	699	700	701	702	703	704	705	706	707	708	709	710	711	712	713	714	715	716	717	718	719	720	721	722	723	724	725	726	727	728	729	730	731	732	733	734	735	736	737	738	739	740	741	742	743	744	745	746	747	748	749	750	751	752	753	754	755	756	757	758	759	760	761	762	763	764	765	766	767	768	769	770	771	772	773	774	775	776	777	778	779	780	781	782	783	784	785	786	787	788	789	790	791	792	793	794	795	796	797	798	799	800	801	802	803	804	805	806	807	808	809	810	811	812	813	814	815	816	817	818	819	820	821	822	823	824	825	826	827	828	829	830	831	832	833	834	835	836	837	838	839	840	841	842	843	844	845	846	847	848	849	850	851	852	853	854	855	856	857	858	859	860	861	862	863	864	865	866	867	868	869	870	871	872	873	874	875	876	877	878	879	880	881	882	883	884	885	886	887	888	889	890	891	892	893	894	895	896	897	898	899	900	901	902	903	904	905	906	907	908	909	910	911	912	913	914	915	916	917	918	919	920	921	922	923	924	925	926	927	928	929	930	931	932	933	934	935	936	937	938	939	940	941	942	943	944	945	946	947	948	949	950	951	952	953	954	955	956	957	958	959	960	961	962	963	964	965	966	967	968	969	970	971	972	973	974	975	976	977	978	979	980	981	982	983	984	985	986	987	988	989	990	991	992	993	994	995	996	997	998	999	1000
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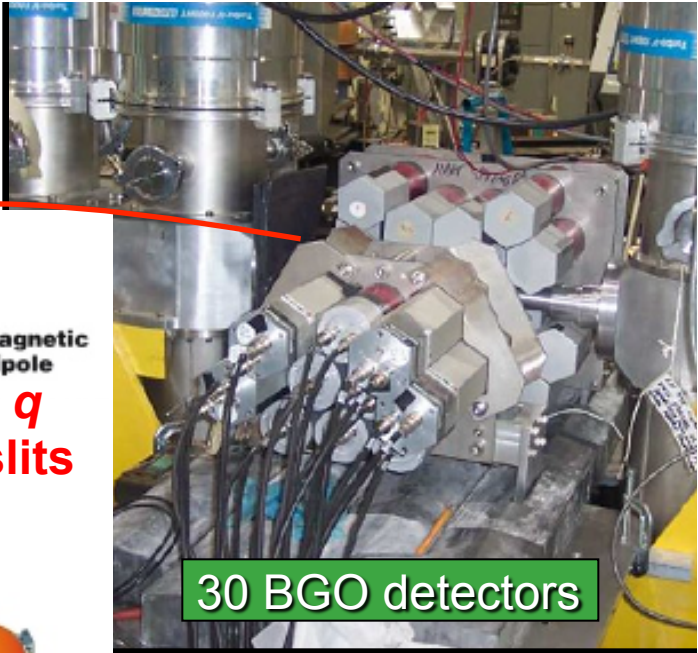
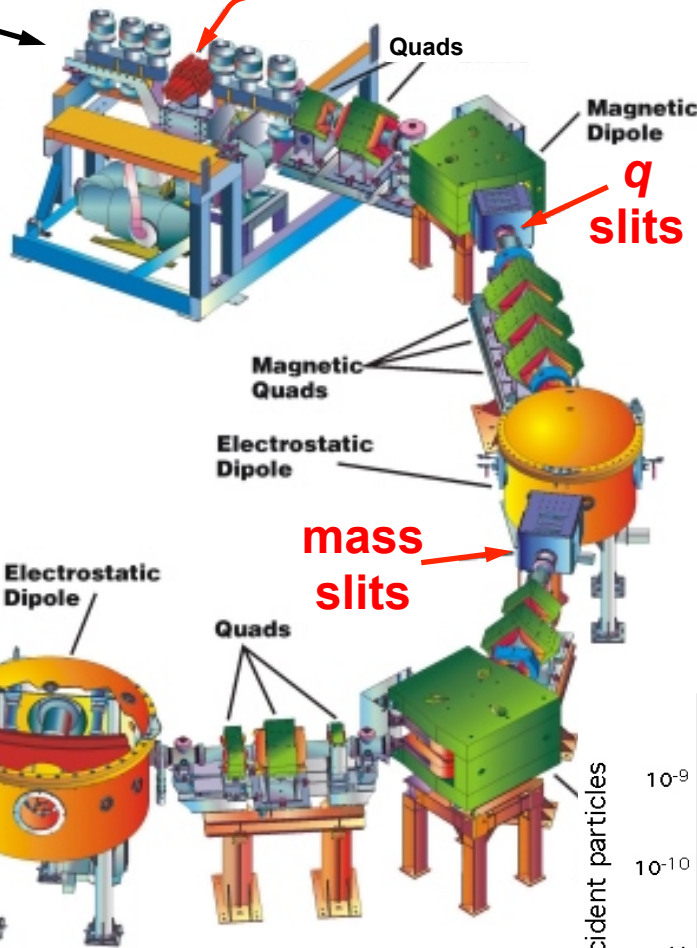
Jens Lassen TRI LIS status: 05/2012



(p, γ) at ISAC

RIB

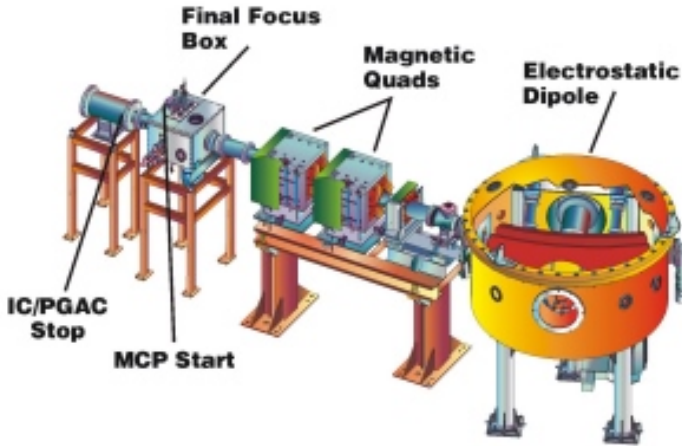
H_2 gas target



30 BGO detectors

recoil+ γ coincidences provide sensitive selection of events

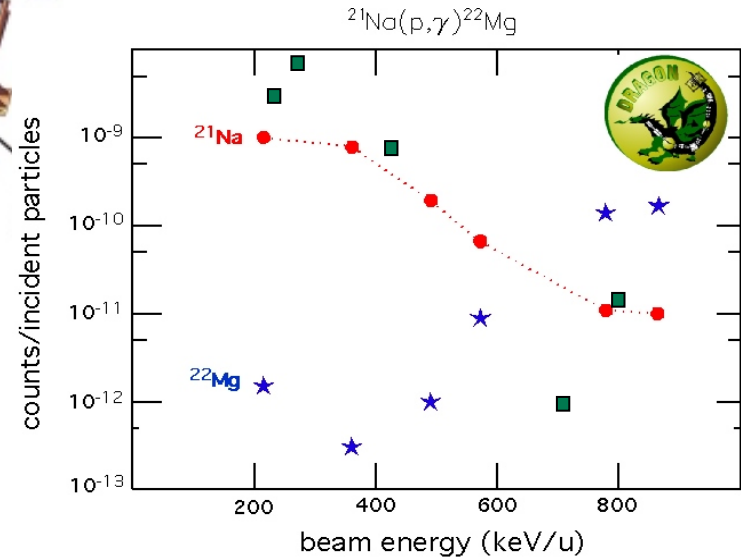
Recoil Detectors



mass slits

<http://dragon.triumf.ca>

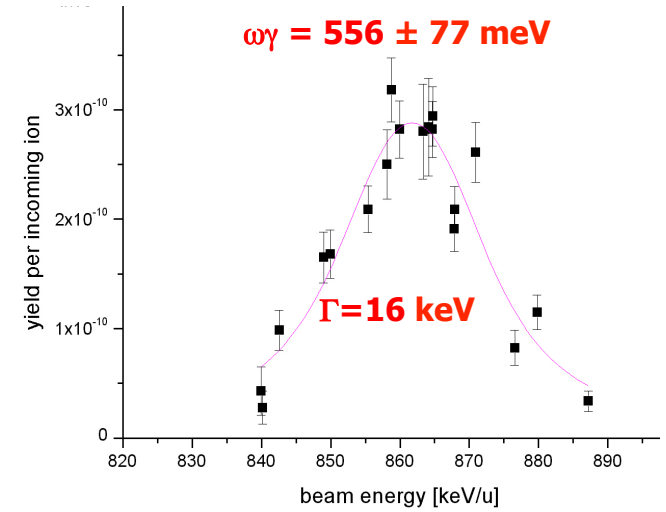
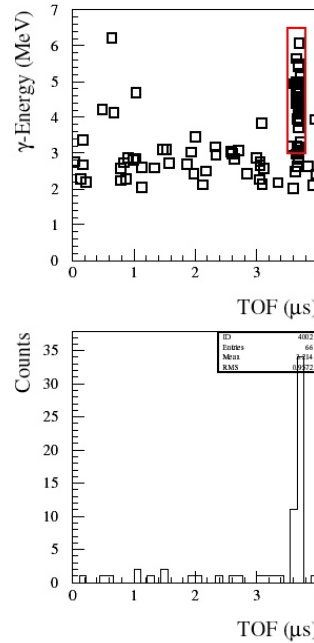
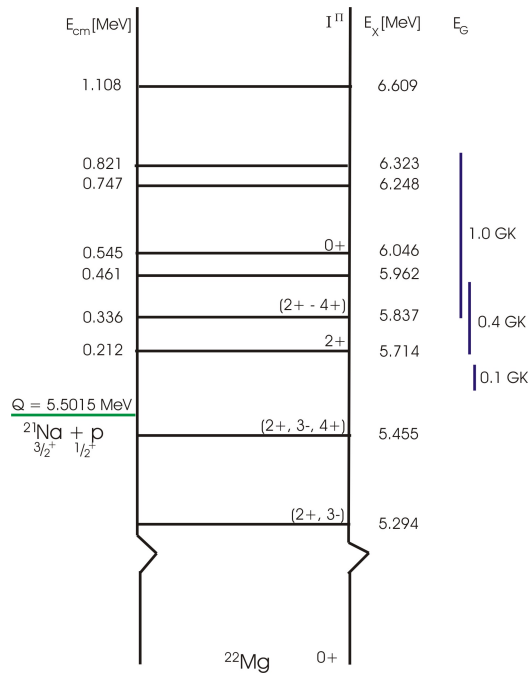
S. Engel et al., NIM A553 (2005) 491.
D. A. Hutcheon et al., NIM A498 (2003) 190.



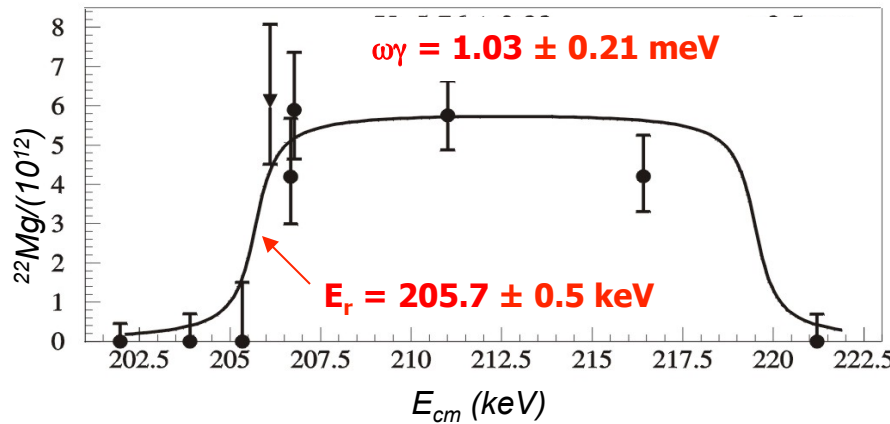
$^{21}\text{Na}(p,\gamma)^{22}\text{Na}$ with DRAGON

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

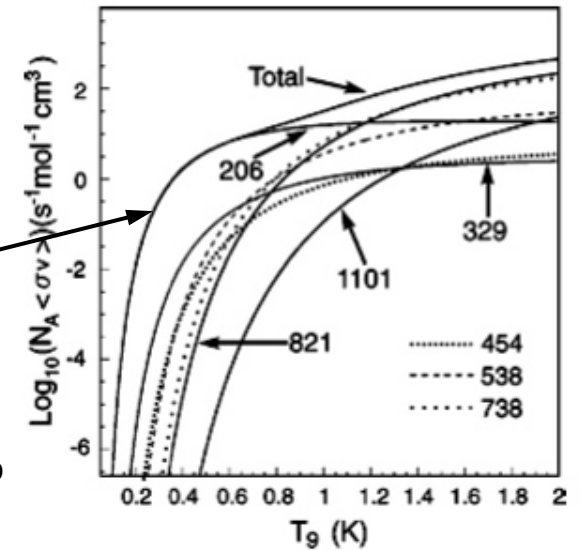
In 1999: $^{21}\text{Na}(p,\gamma)^{22}\text{Mg}$ rate uncertain by $>10^5\times$ (Jose, Coc, Hernanz, *ApJ*520.)



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

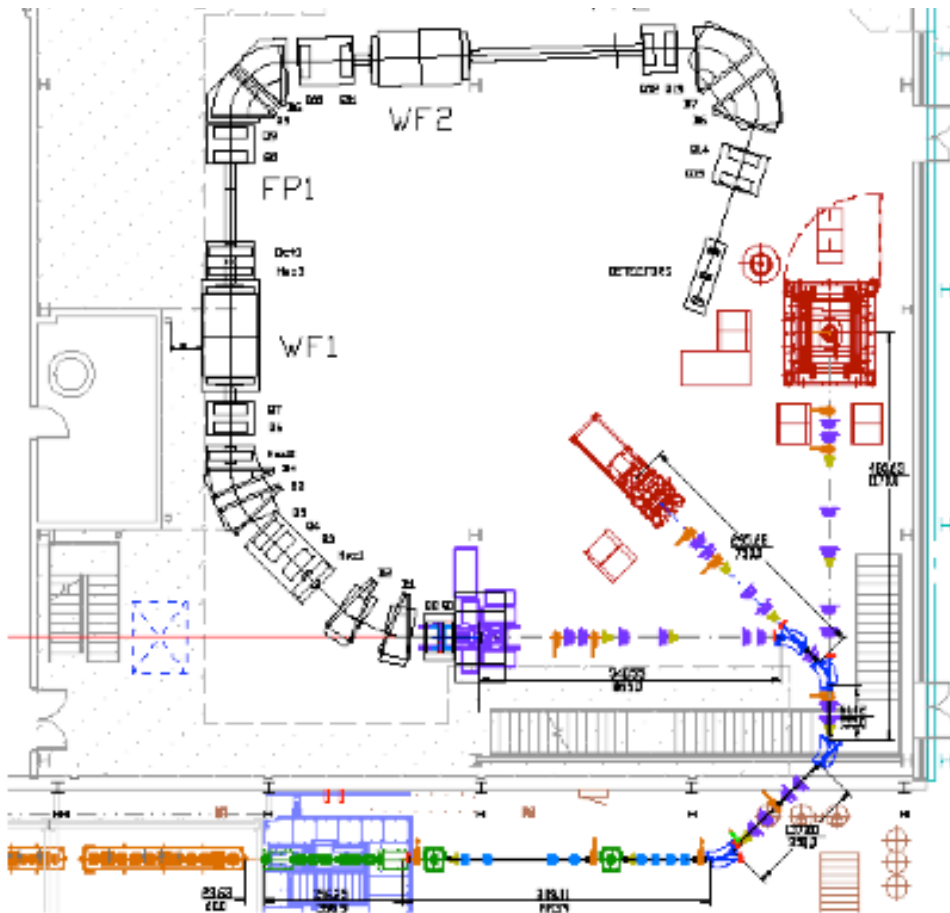


Higher rate for
206 keV
resonance
→ ~25% less
 ^{22}Na
Uncertainty ~25%



SEparator for CApture Reactions (SECAR)

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

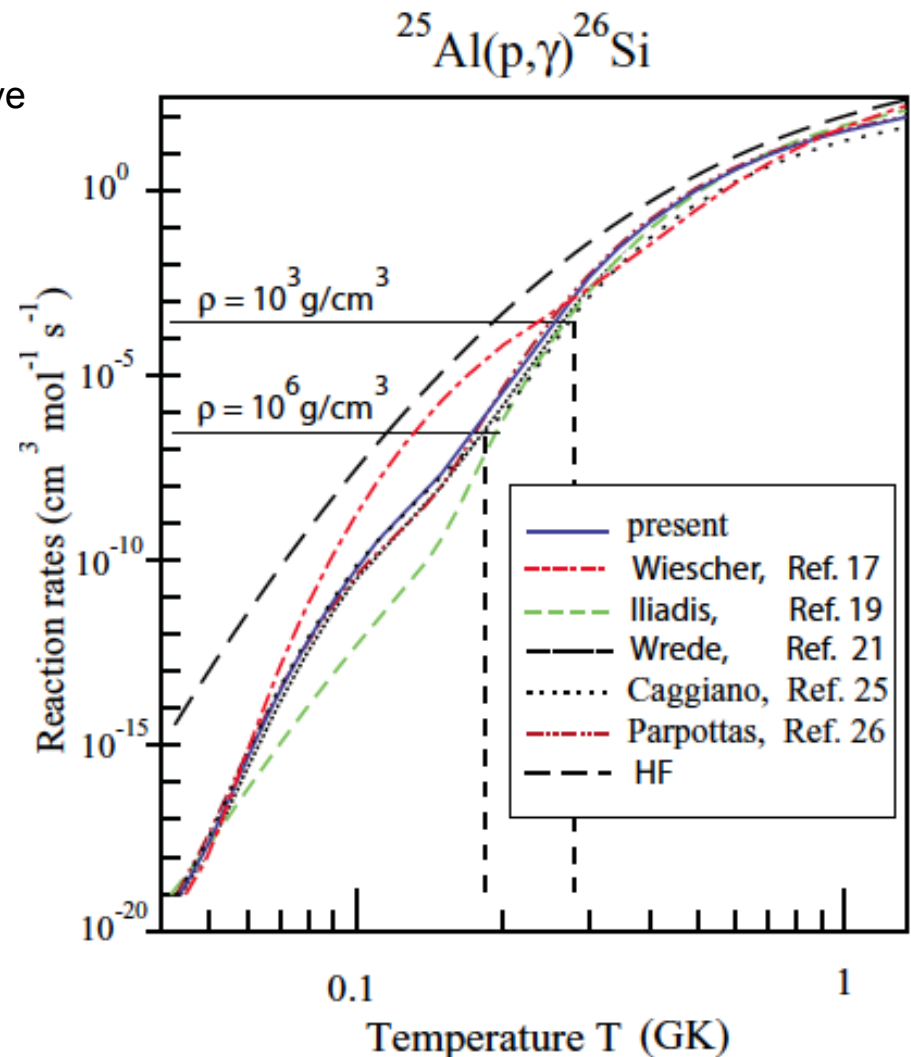


- Next-generation EM separator for direct measurements of capture reactions at ReA3/FRIB
- Two Wien filter design provides high mass resolution and suppression of scattered beam
 - Phased approach proposed that allows for initial experiments at reduced cost
 - 2nd WF required for higher mass beams –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

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

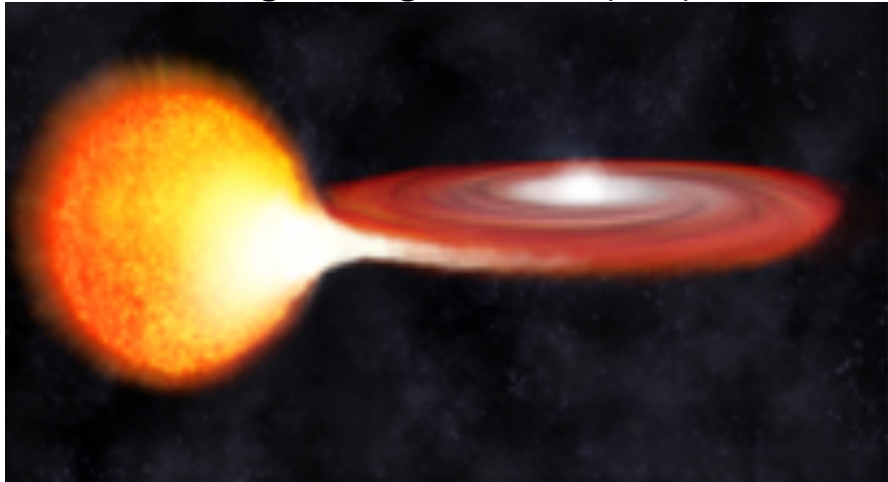
- One of most important rates for understanding ^{26}Al in novae
 - Rates depends on properties of low-lying s-wave resonances (2^+ and 3^+ states in ^{26}Si)

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

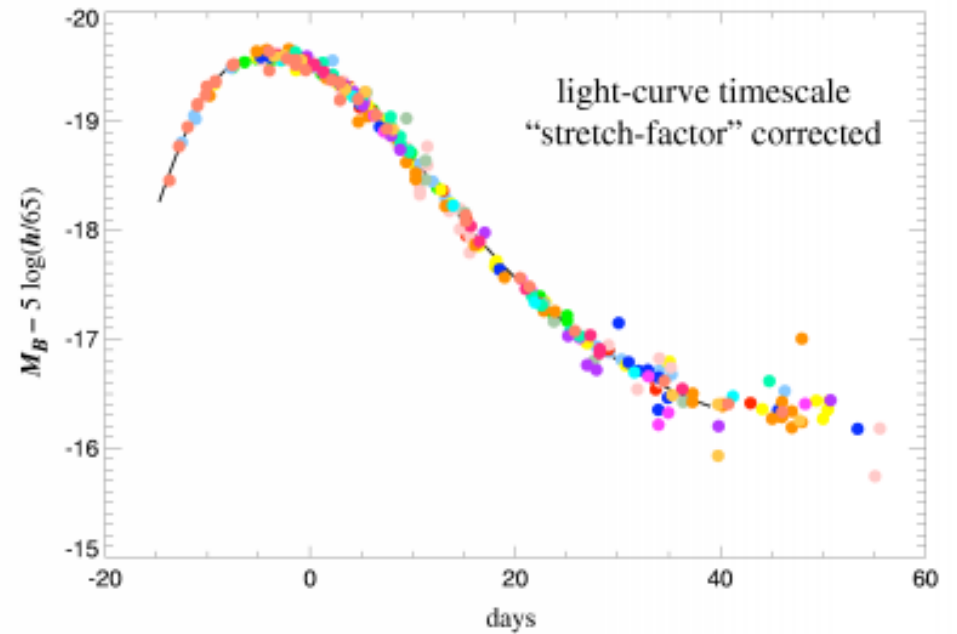
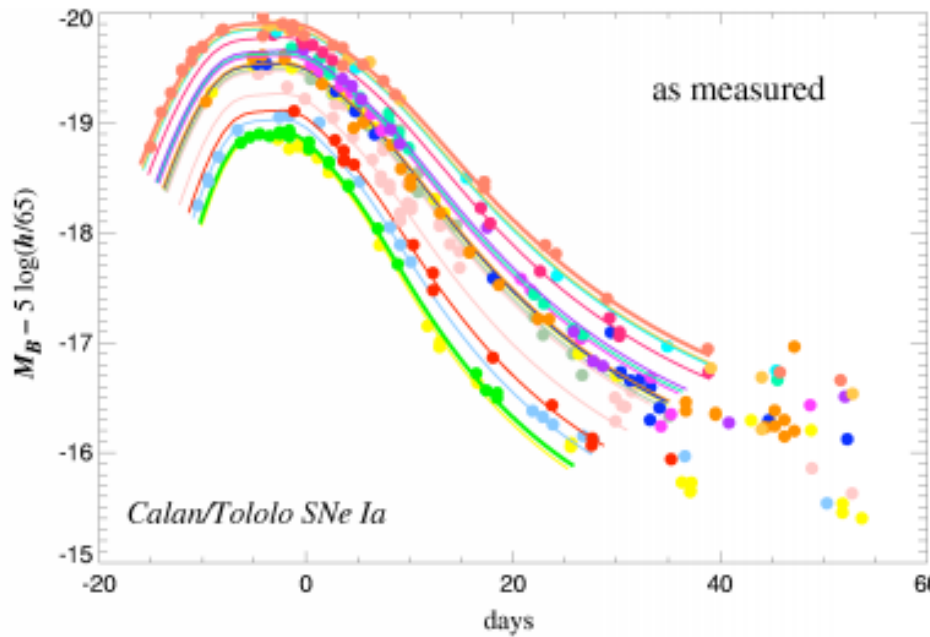


Type Ia Supernovae

Single Degenerate (SD)



Double Degenerate (DD)



Nuclear physics of Type Ia

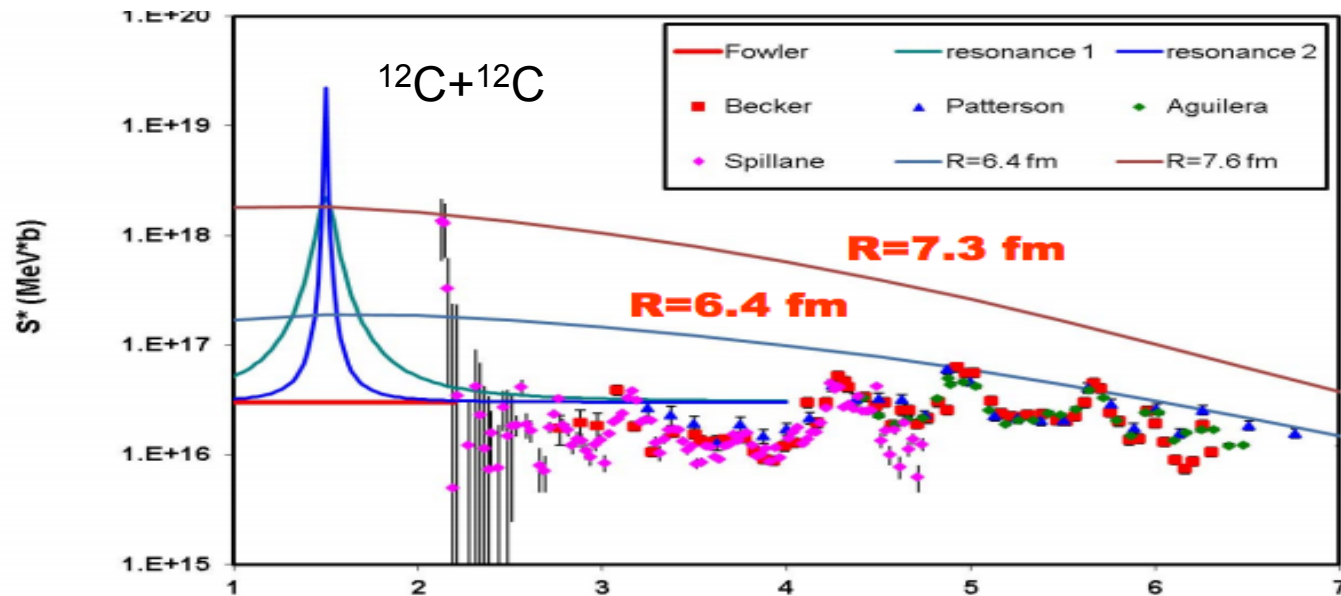
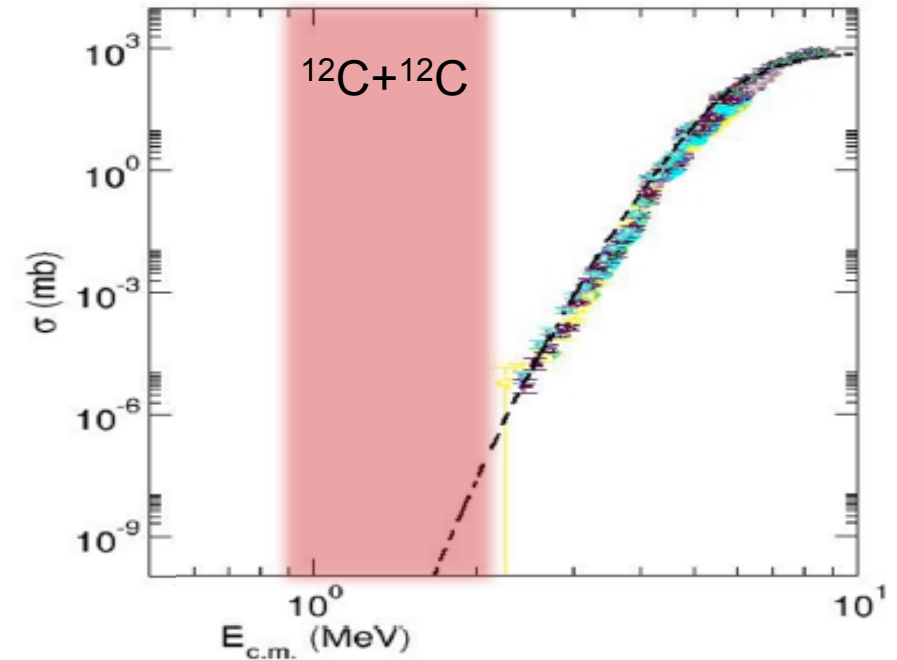
➤ Most important nuclear physics is fusion of C,O, Ne nuclei

➤ $^{12}\text{C}+^{12}\text{C} \rightarrow$

➤ $^{12}\text{C}+^{16}\text{O} \rightarrow$

➤ Measurements needed to lower energies

➤ Resonances could contribute in a few cases



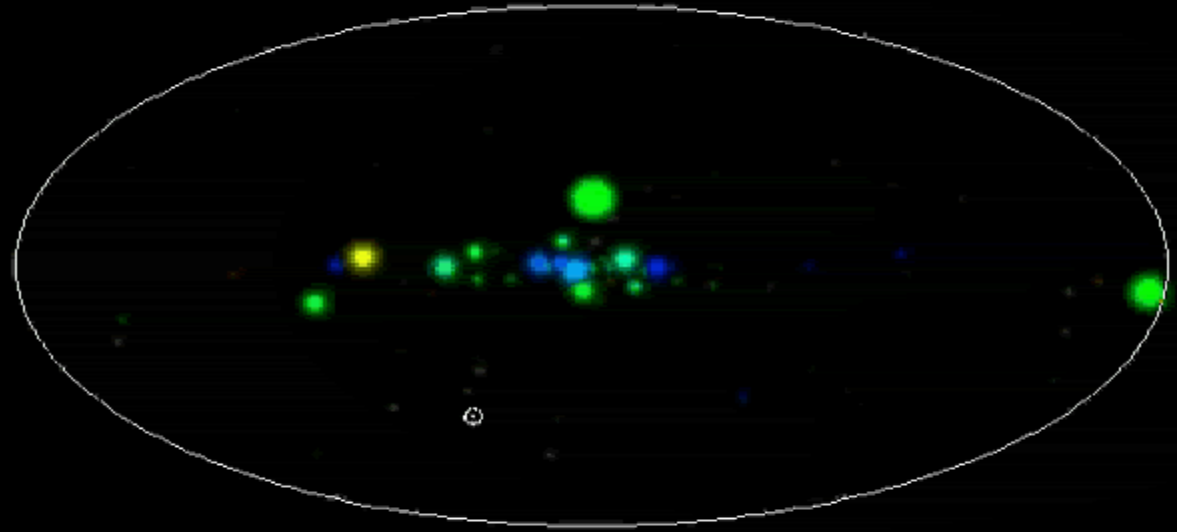
X-ray vision



RXTE

Rossi X-ray Timing Explorer

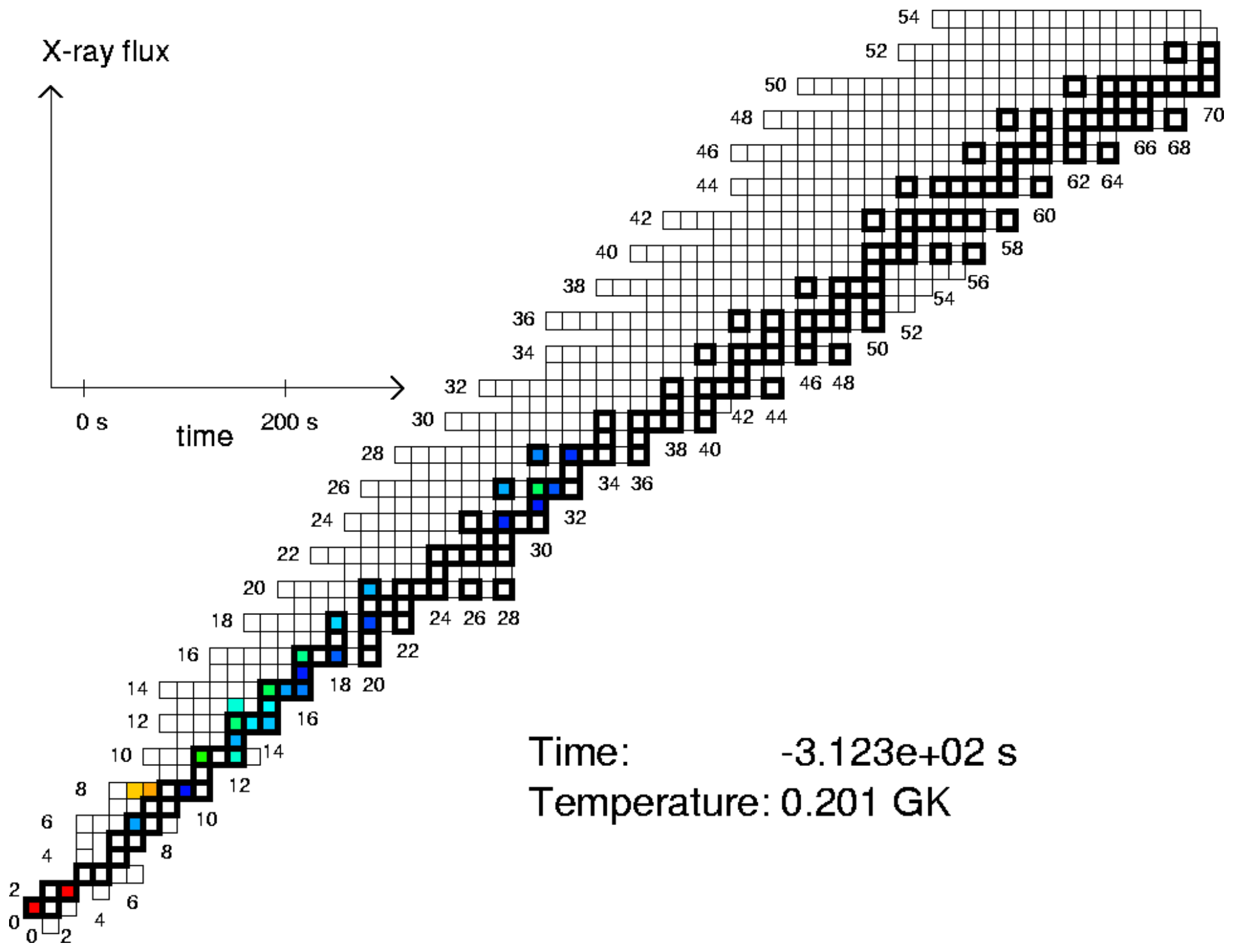
The RXTE All-Sky Monitor Movie



02 / 23 / 2004

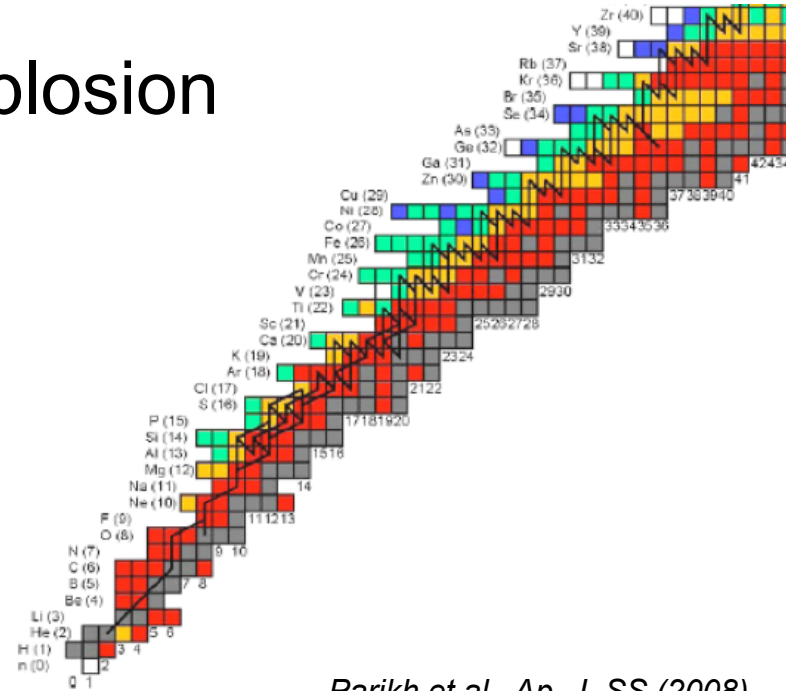
http://heasarc.gsfc.nasa.gov/xte_weather/

- Over 100 sources ***in the Milky Way***
 - Do not confuse with Gamma ray-bursts
- Recur on a semi-regular time scale
- Thermonuclear explosion on surface of a neutron star
- Observations provide crucial insights into neutron star properties

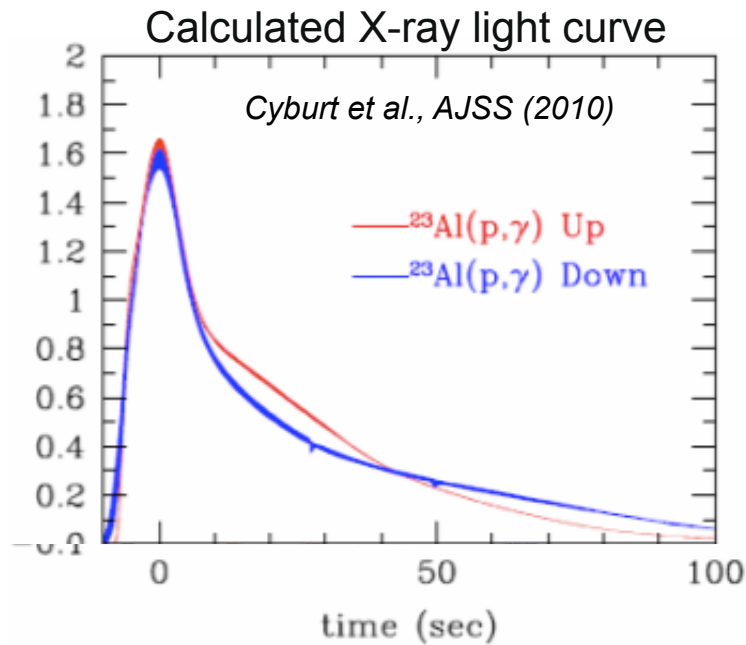


Nuclear reactions drive explosion

- 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)

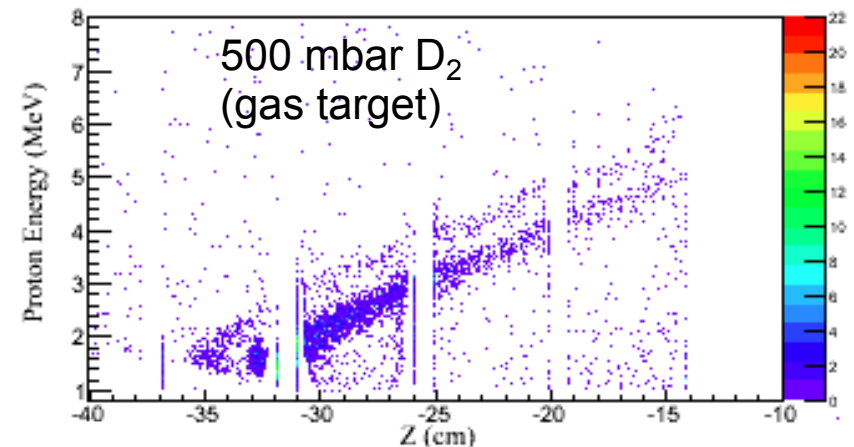
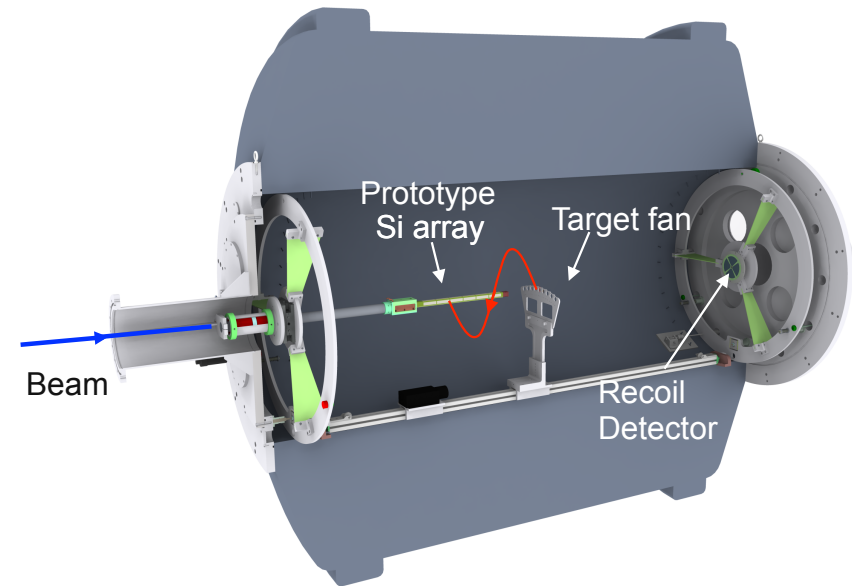


Reaction	Models affected
$^{16}\text{O}(\alpha, \gamma)^{19}\text{Ne}^a$	K04, K04-B1, K04-B6
$^{18}\text{Ne}(\alpha, p)^{21}\text{Na}^a$	K04-B1, K04-B6
$^{22}\text{Mg}(\alpha, p)^{25}\text{Al}$	F08
$^{23}\text{Al}(p, \gamma)^{24}\text{Si}$	K04-B1
$^{24}\text{Mg}(\alpha, p)^{27}\text{Al}^a$	K04-B2
$^{26}\text{Si}(\alpha, p)^{29}\text{S}^a$	F08
$^{28}\text{Si}(\alpha, p)^{31}\text{P}^a$	K04-B4
$^{30}\text{S}(\alpha, p)^{33}\text{Cl}$	K04-B4, K04-B5
$^{31}\text{Cl}(p, \gamma)^{32}\text{Ar}$	K04-B3
$^{32}\text{S}(\alpha, p)^{35}\text{Cl}$	K04-B2
$^{35}\text{Cl}(p, \gamma)^{36}\text{Ar}^a$	K04-B2
$^{56}\text{Ni}(\alpha, p)^{59}\text{Cu}$	S01
$^{59}\text{Cu}(p, \gamma)^{60}\text{Zn}$	S01
$^{65}\text{Zn}(\alpha, n)^{68}\text{Ga}$	K04, K04-B6, K04-B5

Direct Studies of (α, p) Reactions



- (α, p) reactions can be studied directly:
 - radioactive ion beams
 - ^4He gas target
 - inverse kinematics techniques
- HELIOS with in-flight beams at ANL
 - gas target
 - high rate ionization chamber for coincidence measurement
- $^{14}\text{C}(d, p)^{15}\text{C}$ commissioning run with full setup:





NSF MRI

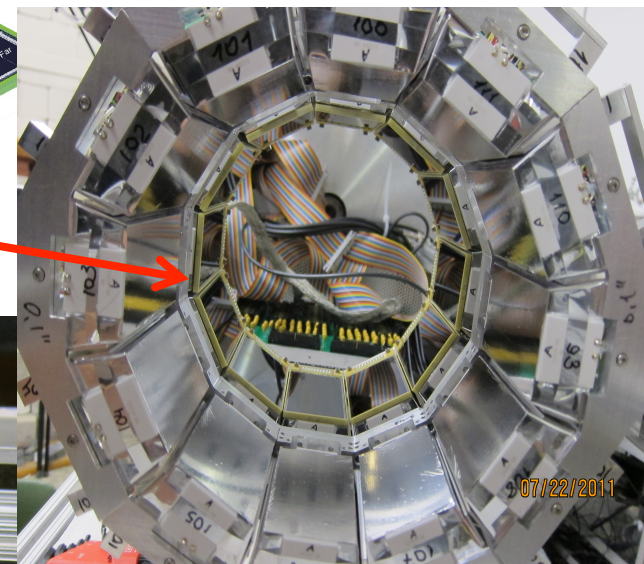
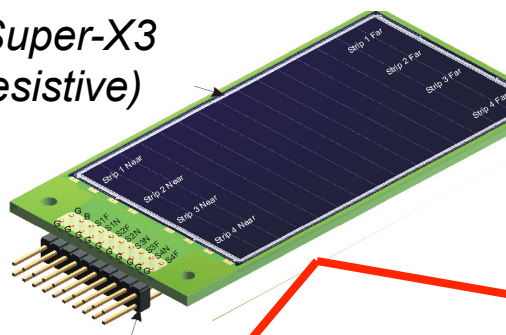
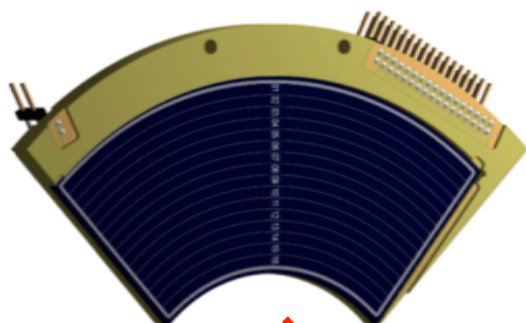
(α, p) with active gas target



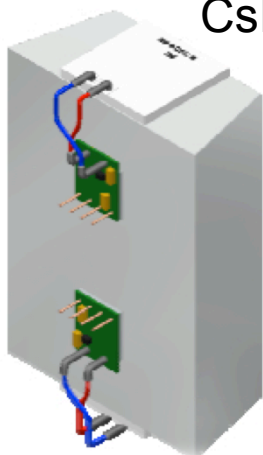
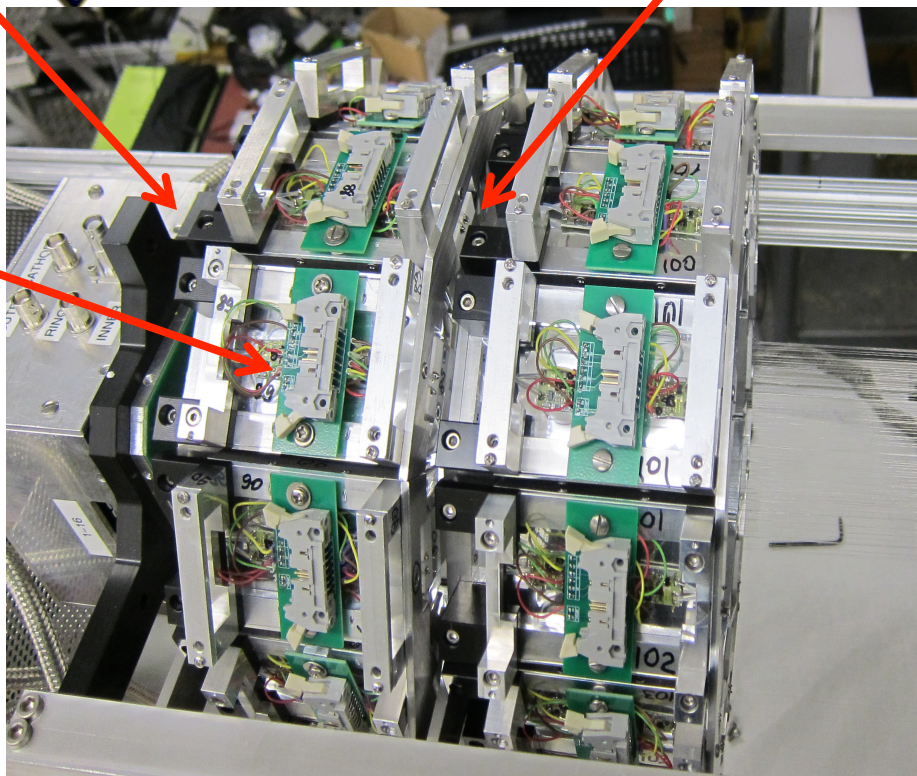
Array for Nuclear Astrophysics and Structure with Exotic Nuclei

2x12 Super-X3
(4x4 Resistive)

End View w/o PC



New QQQ
(16x16)



CsI

PC wires

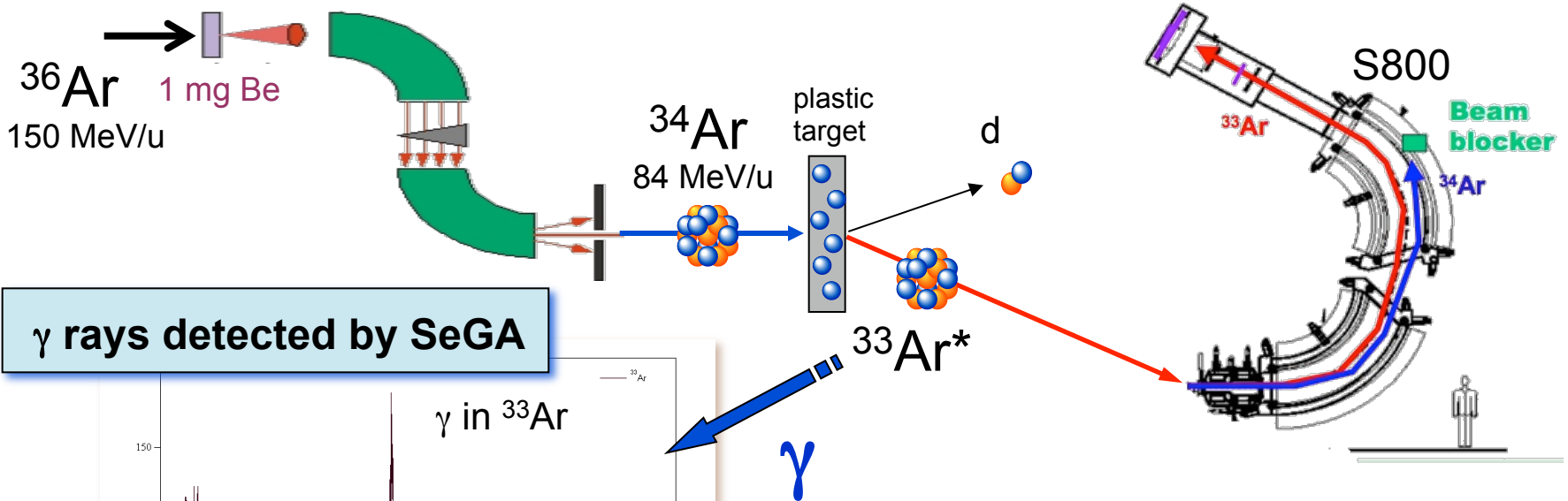
Beam window

Beam

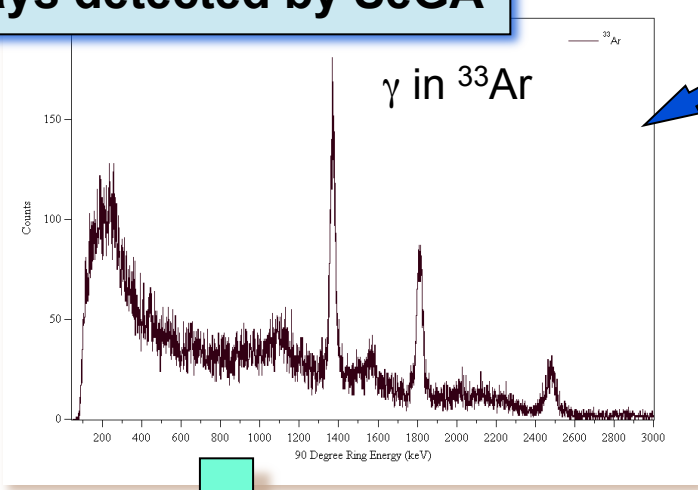
07/20/2011

Side View

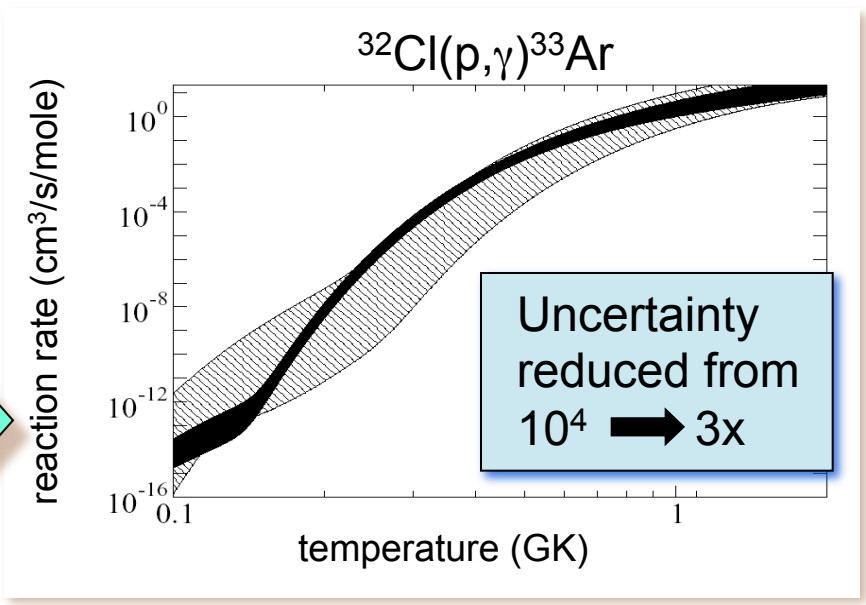
Resonance energies via (p,d) reactions & fast beams at NSCL



γ rays detected by SeGA



level energies in ^{33}Ar
 \rightarrow resonance energies
 in $^{32}\text{Cl}+p$



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