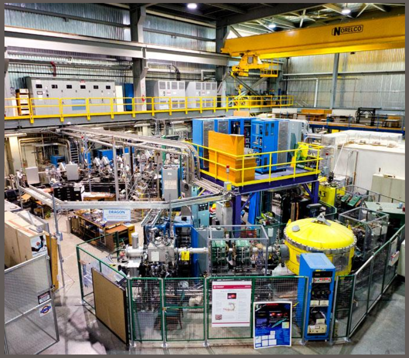
TRIUMF

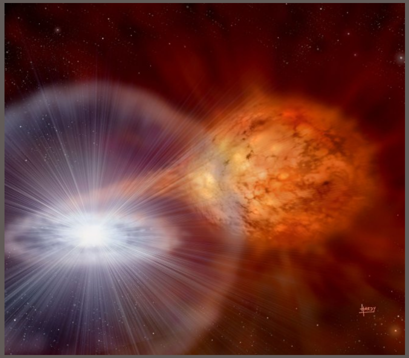
Canada’s national laboratory for particle and nuclear physics
Laboratoire national canadien pour la recherche en physique nucléaire et en physique des particules

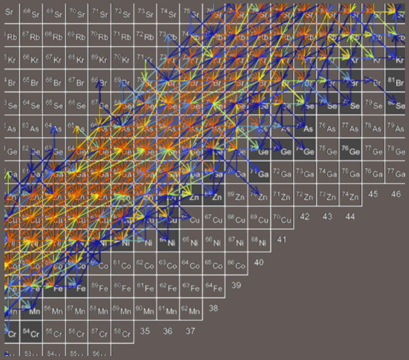
Nuclear Astrophysics at TRIUMF-ISAC

@ DRAGON, TUDA, DSL, EMMA, …

Chris Ruiz | Research Scientist | TRIUMF







Accelerating Science for Canada
Un accélérateur de la démarche scientifique canadienne

"TRIUMF" Nuclear Astrophysics Group People

TRIUMF

Experiment: Barry Davids, Iris Dillmann, Reiner Krücken, Chris Ruiz
Theory: Petr Navratil

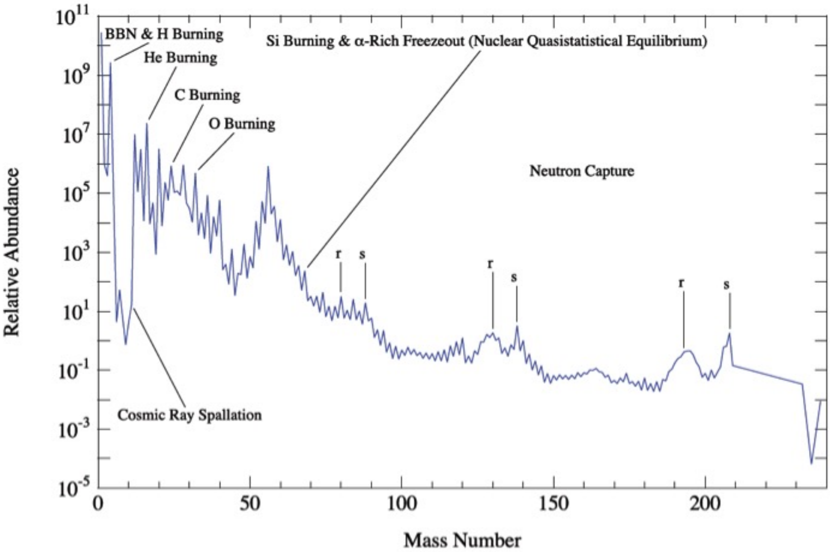
McMaster University

Prof. Alan Chen (Experiment)

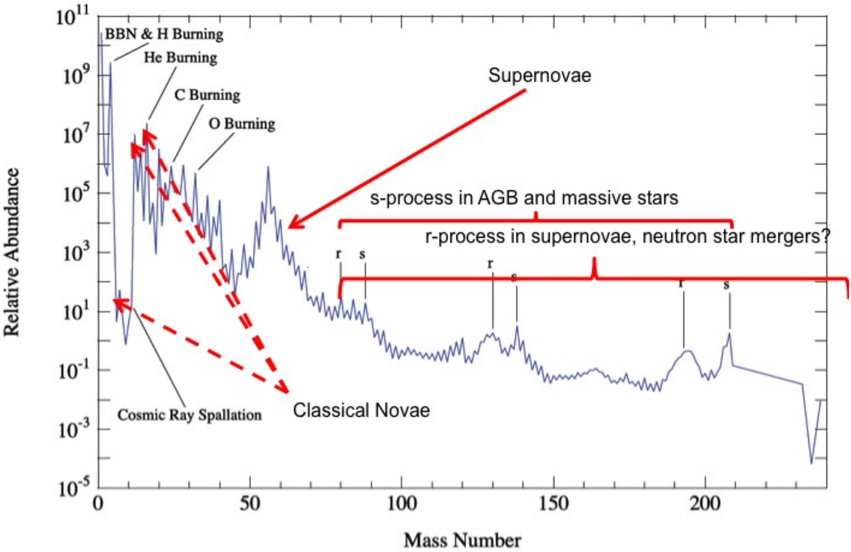
University of Victoria

Prof. Falk Herwig and Dr. Pavel Denissenkov (Theory)
(+ JINA & NuGrid connection)
(+ Astronomy Research Centre)

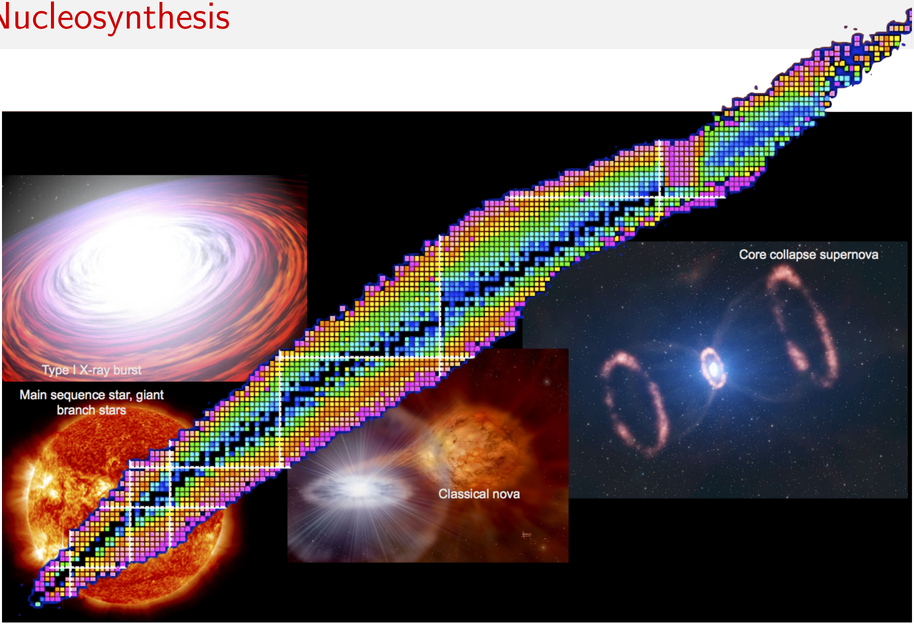
Origin of the Elements



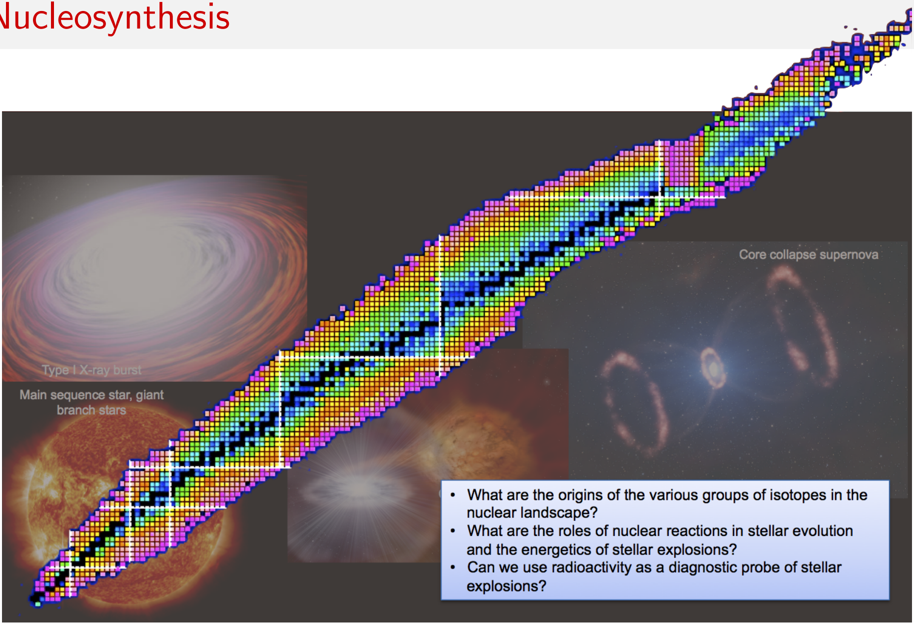
Origin of the Elements



Nucleosynthesis

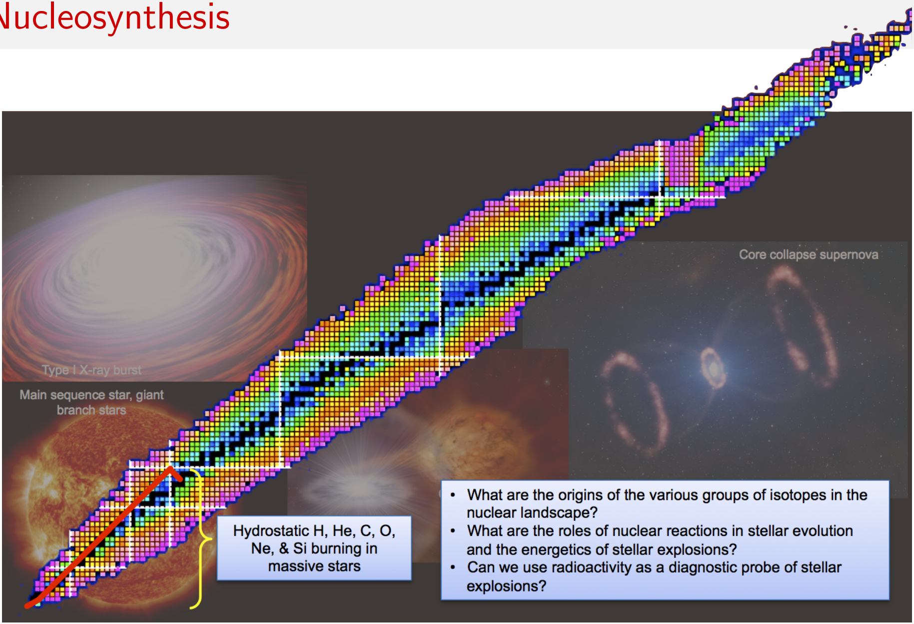


Nucleosynthesis



- What are the origins of the various groups of isotopes in the nuclear landscape?
- What are the roles of nuclear reactions in stellar evolution and the energetics of stellar explosions?
- Can we use radioactivity as a diagnostic probe of stellar explosions?

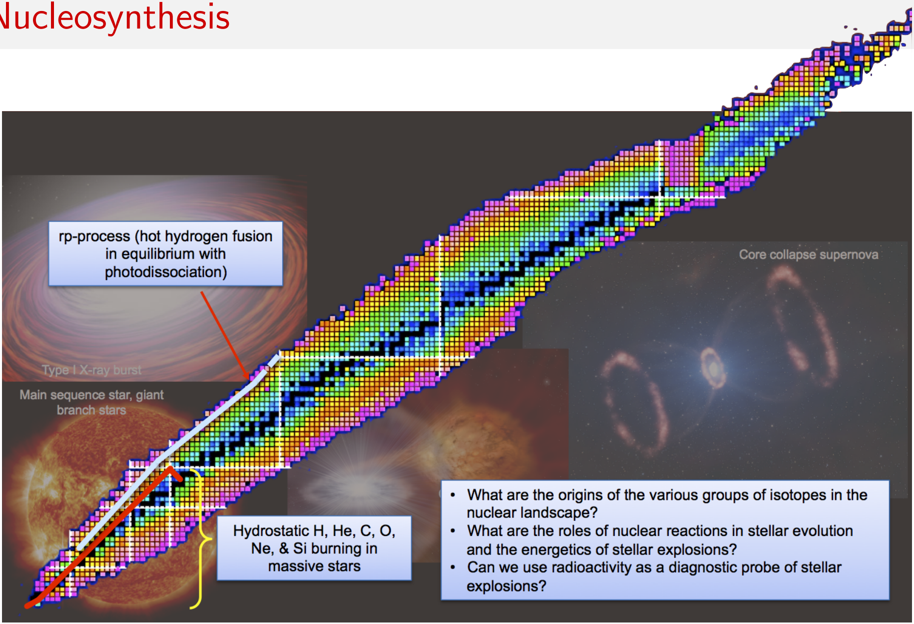
Nucleosynthesis



Hydrostatic H, He, C, O, Ne, & Si burning in massive stars

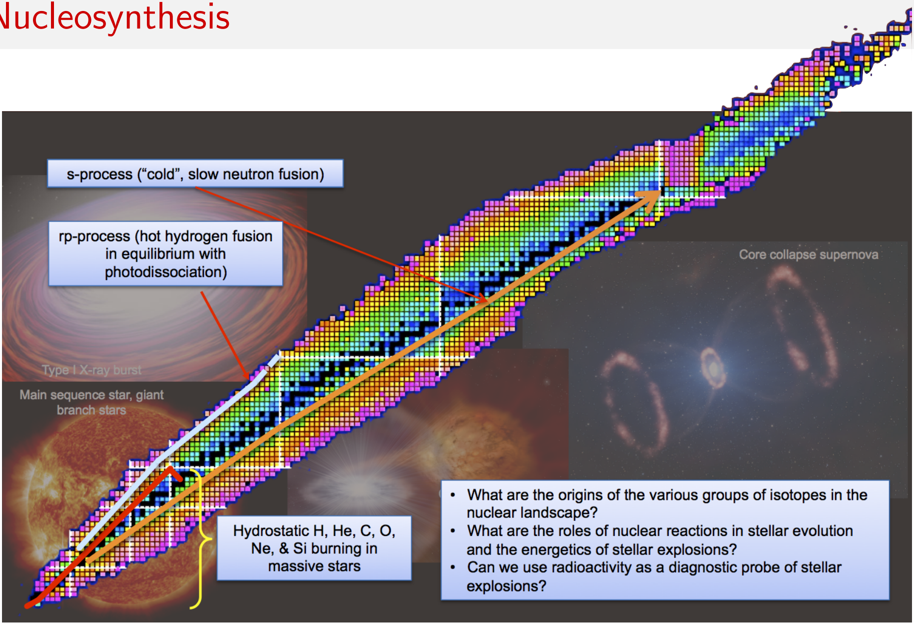
- What are the origins of the various groups of isotopes in the nuclear landscape?
- What are the roles of nuclear reactions in stellar evolution and the energetics of stellar explosions?
- Can we use radioactivity as a diagnostic probe of stellar explosions?

Nucleosynthesis



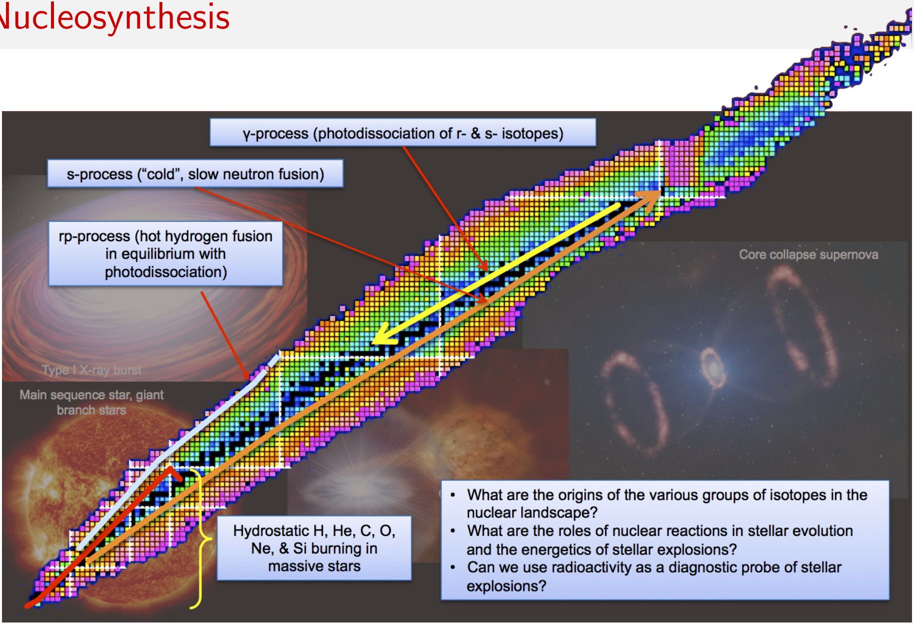
- What are the origins of the various groups of isotopes in the nuclear landscape?
- What are the roles of nuclear reactions in stellar evolution and the energetics of stellar explosions?
- Can we use radioactivity as a diagnostic probe of stellar explosions?

Nucleosynthesis

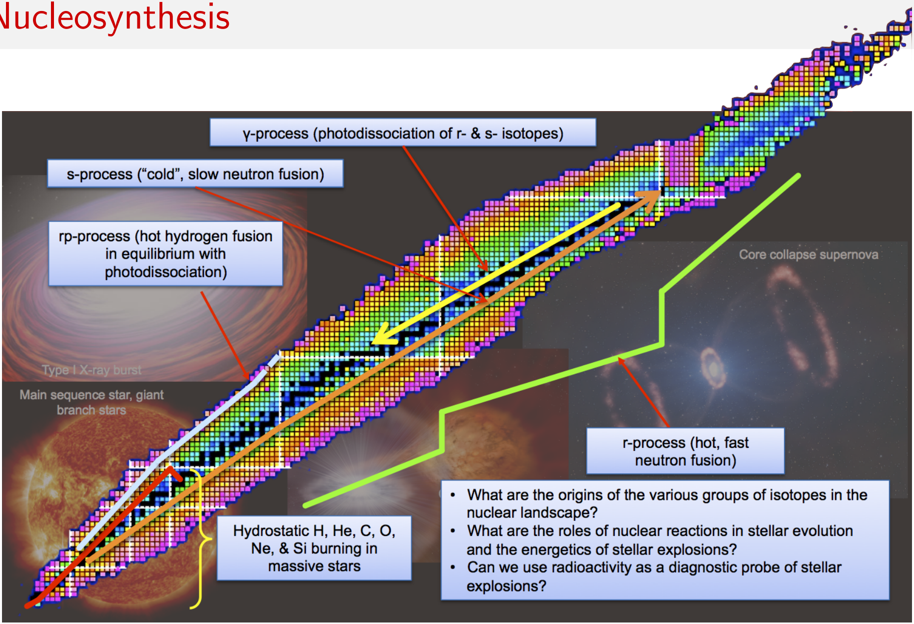


- What are the origins of the various groups of isotopes in the nuclear landscape?
- What are the roles of nuclear reactions in stellar evolution and the energetics of stellar explosions?
- Can we use radioactivity as a diagnostic probe of stellar explosions?

Nucleosynthesis

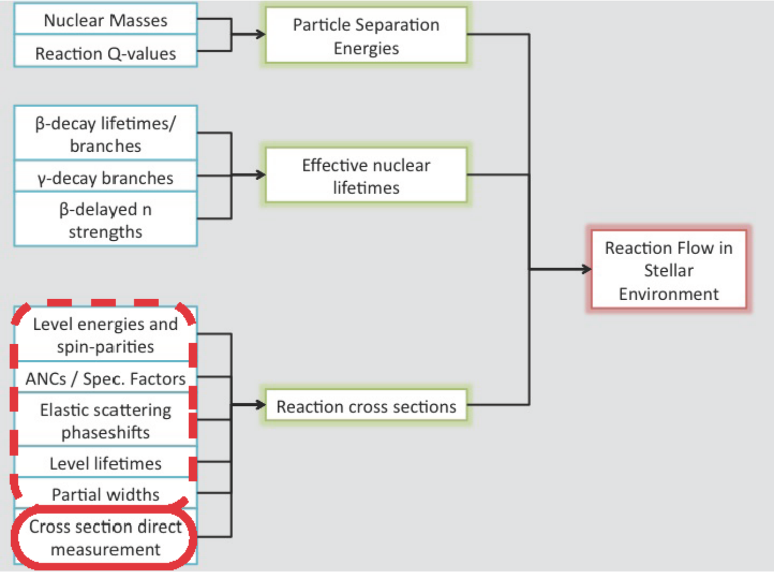


Nucleosynthesis



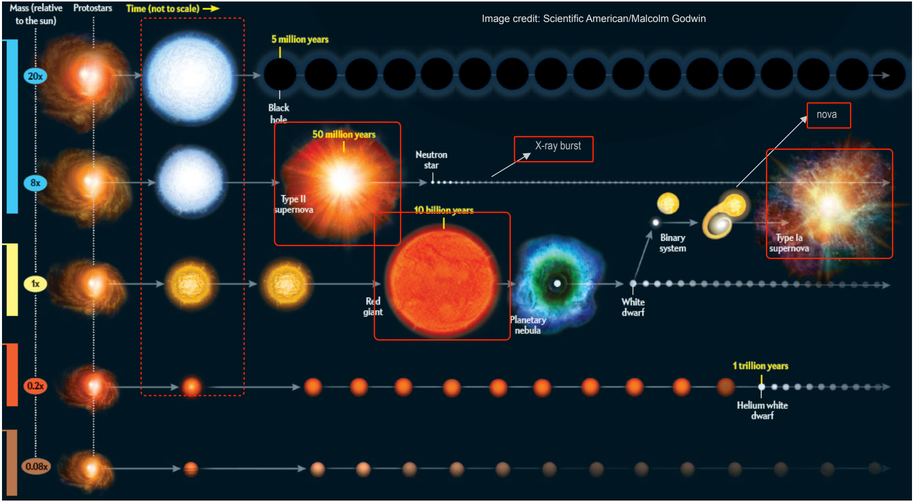
- What are the origins of the various groups of isotopes in the nuclear landscape?
- What are the roles of nuclear reactions in stellar evolution and the energetics of stellar explosions?
- Can we use radioactivity as a diagnostic probe of stellar explosions?

Data Needs:

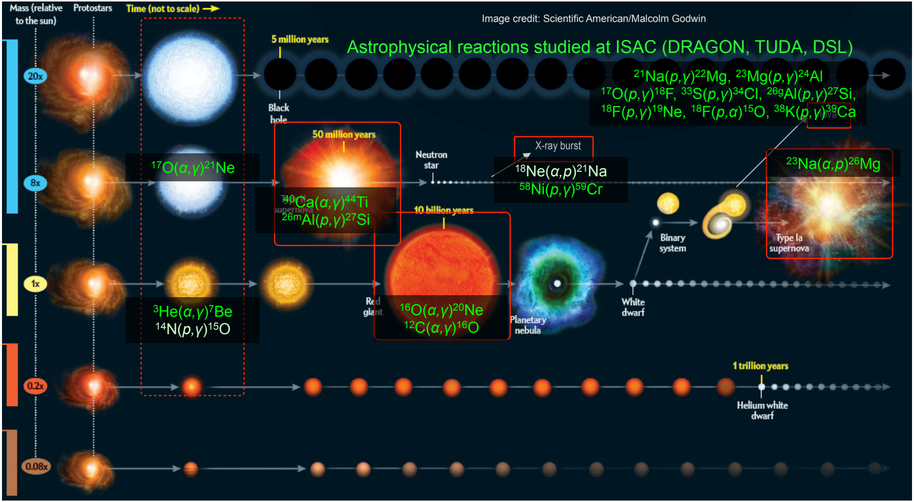


Nuclear Masses
Reaction Q-values
Particle Separation Energies
β-decay lifetimes/ branches
γ-decay branches
β-delayed n strengths
Effective nuclear lifetimes
Level energies and spin-parities
ANCs / Spec. Factors
Elastic scattering phaseshifts
Level lifetimes
Partial widths
Cross section direct measurement
Reaction cross sections
Reaction Flow in Stellar Environment

Through the lives of stars...

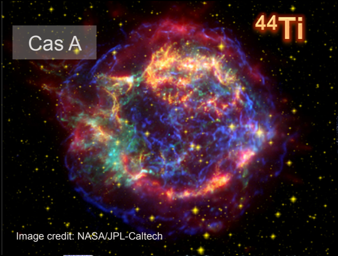


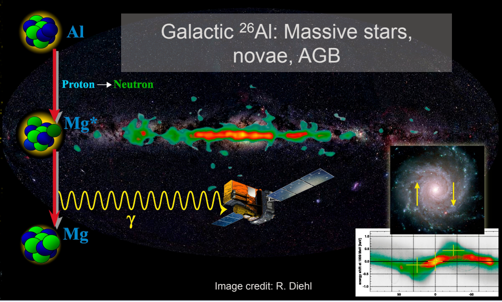
Through the lives of stars...

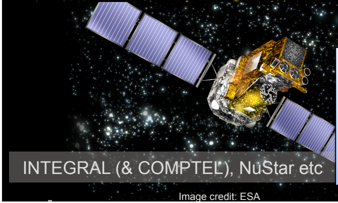


Observables - γ rays and grains

- Experiments intimately linked to observations via models:

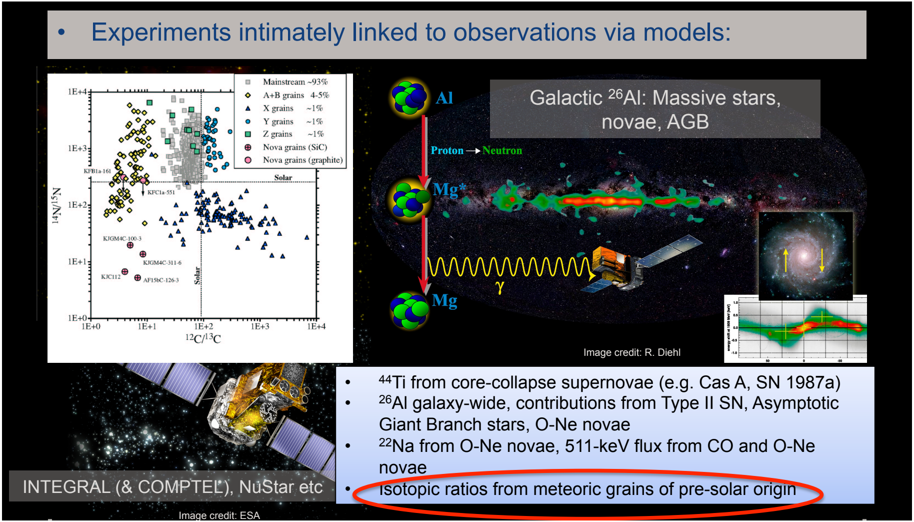




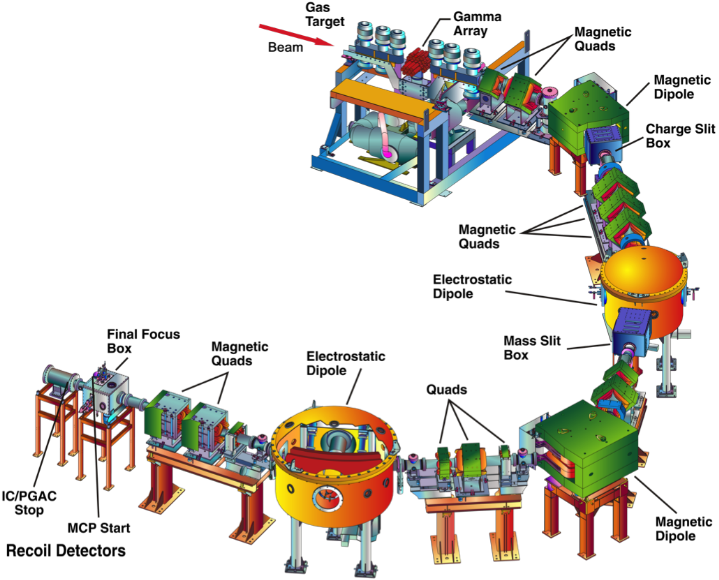


- ^{44}Ti from core-collapse supernovae (e.g. Cas A, SN 1987a)
- ^{26}Al galaxy-wide, contributions from Type II SN, Asymptotic Giant Branch stars, O-Ne novae
- ^{22}Na from O-Ne novae, 511-keV flux from CO and O-Ne novae
- Isotopic ratios from meteoric grains of pre-solar origin

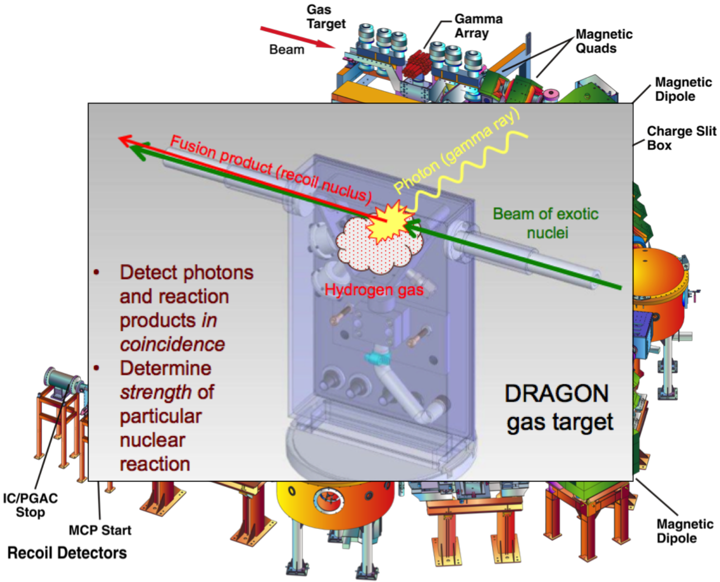
Observables - γ rays and grains



DRAGON: recoil separator

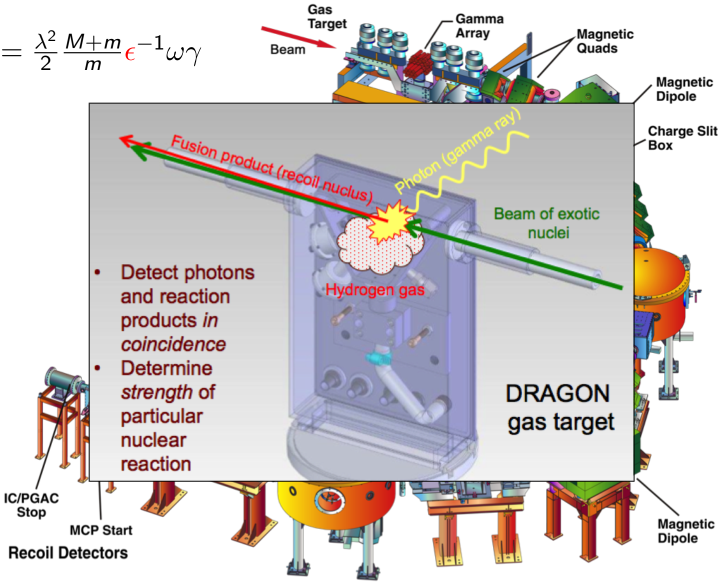


DRAGON: recoil separator

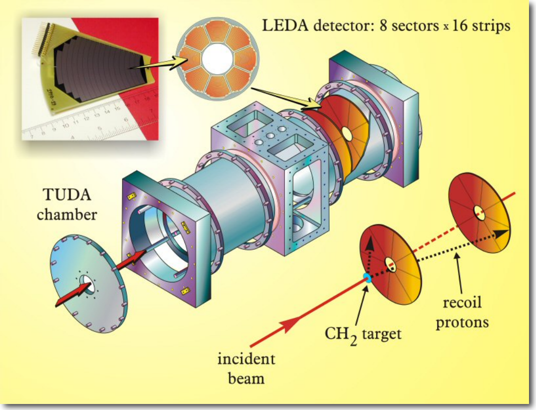


DRAGON: recoil separator

$$Y(\infty) = \frac{\lambda^2}{2}\frac{M+m}{m}\epsilon^{-1}\omega\gamma$$

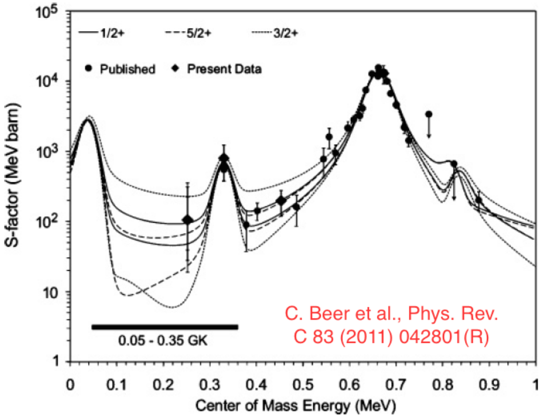


TUDA: charged particle reactions & scattering



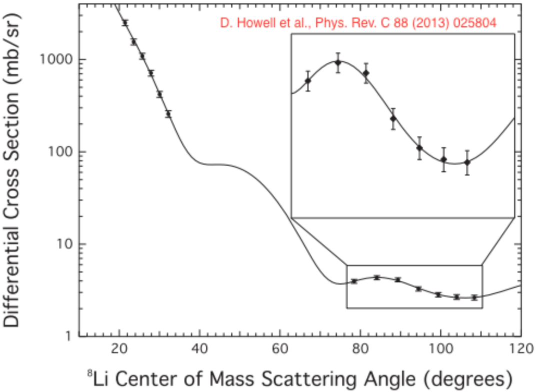
- Direct cross-section measurements of charged particle reactions e.g. $^{18}\mathrm{F}(p,\alpha)^{15}\mathrm{O}$, $^{21}\mathrm{Na}(p,\alpha)^{18}\mathrm{Ne}$, $^{18}\mathrm{Ne}(\alpha,p)^{21}\mathrm{Na}$
- Elastic Scattering e.g. $^{20,21}\mathrm{Na}(p,p)$, $^{18}\mathrm{F}(p,p)$, $^{7}\mathrm{Li}(^{8}\mathrm{Li},^{7}\mathrm{Li})^{8}\mathrm{Li}$
- Indirect e.g. transfer $\rightarrow$ ANC, spectroscopy

TUDA: charged particle reactions & scattering



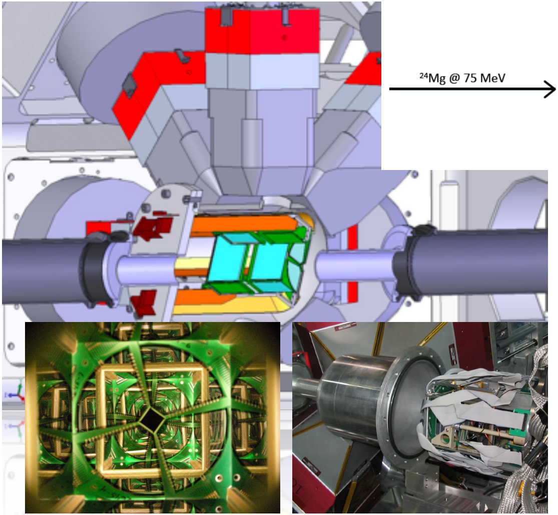
- Direct cross-section measurements of charged particle reactions e.g. ^{18}F(p, α)^{15}O, ^{21}Na(p, α)^{18}Ne, ^{18}Ne(α, p)^{21}Na
- Elastic Scattering e.g. ^{20,21}Na(p, p), ^{18}F(p, p), ^{7}Li(^{8}Li,^{7}Li)^{8}Li
- Indirect e.g. transfer $\rightarrow$ ANC, spectroscopy

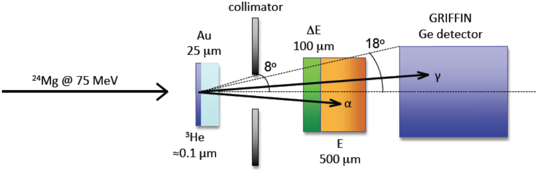
TUDA: charged particle reactions & scattering

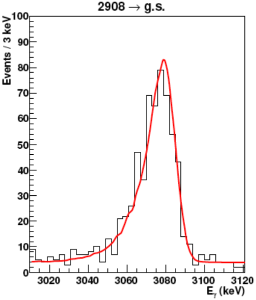


- Direct cross-section measurements of charged particle reactions e.g. $^{18}F(p,\alpha)^{15}O$, $^{21}Na(p,\alpha)^{18}Ne$, $^{18}Ne(\alpha,p)^{21}Na$
- Elastic Scattering e.g. $^{20,21}Na(p,p)$, $^{18}F(p,p)$, $^{7}Li(^{8}Li,^{7}Li)^{8}Li$
- Indirect e.g. transfer $\rightarrow$ ANC, spectroscopy

DSL and SHARC-TIGRESS: nuclear lifetimes, Coulex, transfer

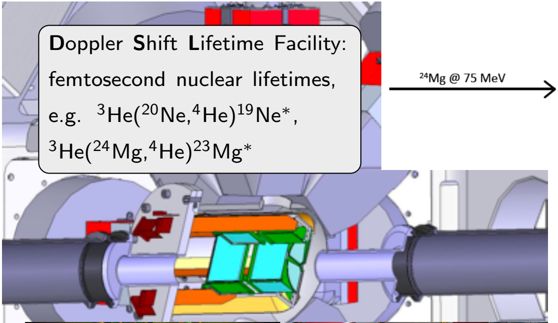


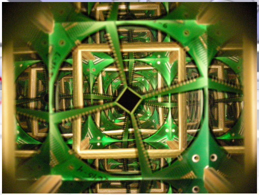


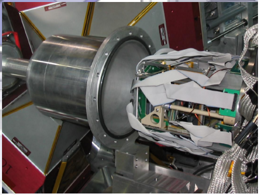


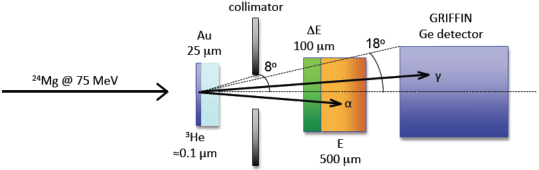
DSL and SHARC-TIGRESS: nuclear lifetimes, Coulex, transfer

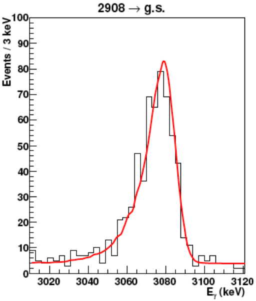
Doppler **S**hift **L**ifetime Facility: femtosecond nuclear lifetimes, e.g. $^{3}He(^{20}Ne,^{4}He)^{19}Ne^{*}$, $^{3}He(^{24}Mg,^{4}He)^{23}Mg^{*}$



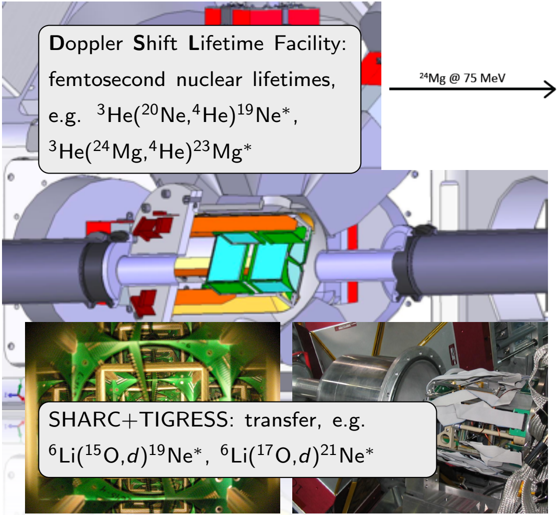






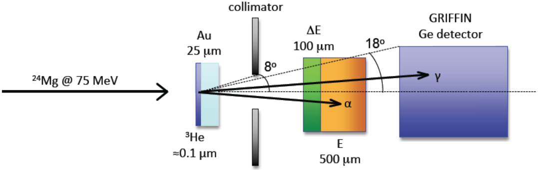


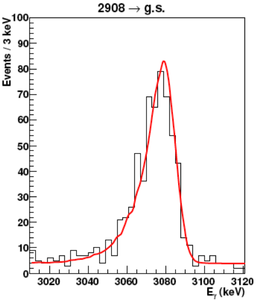
DSL and SHARC-TIGRESS: nuclear lifetimes, Coulex, transfer



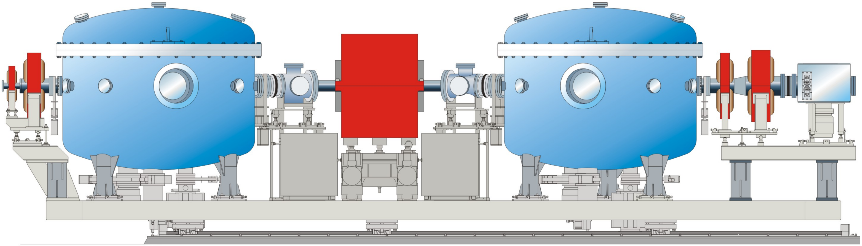
Doppler **S**hift **L**ifetime Facility: femtosecond nuclear lifetimes, e.g. ^{3}He(^{20}Ne,^{4}He)^{19}Ne*, ^{3}He(^{24}Mg,^{4}He)^{23}Mg*

SHARC+TIGRESS: transfer, e.g. ^{6}Li(^{15}O,d)^{19}Ne*, ^{6}Li(^{17}O,d)^{21}Ne*



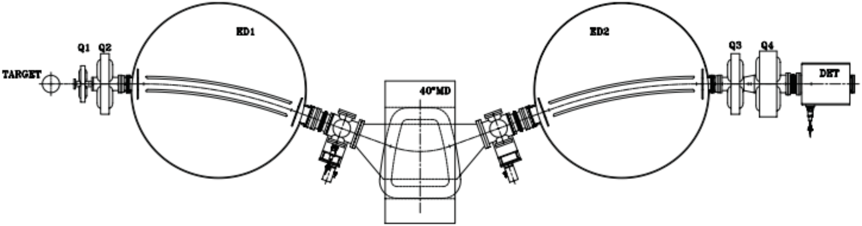


EMMA



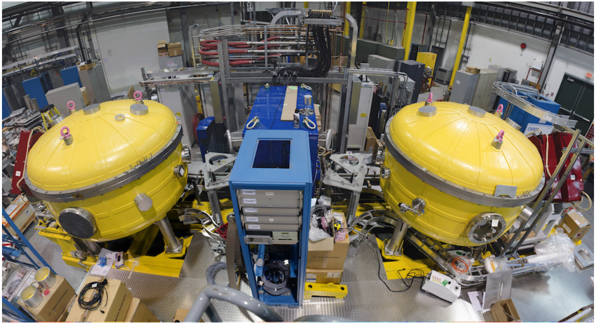
- **E**lectro**M**agnetic **M**ass **A**nalyzer for structure & astrophysical reactions
- Will measure (d,p), (p,γ), (d,n) and (p,n) reactions
- ^{88}Rb$(d,p)^{89}$Rb for r-process ^{88}Rb$(n,\gamma)^{89}$Rb
- ^{83}Rb$(p,\gamma)^{84}$Sr for *p*-process in core-collapse supernovae
- ^{135}I$(d,p)^{136}$I for "*i*-process"

EMMA



- **E**lectro**M**agnetic **M**ass **A**nalyzer for structure & astrophysical reactions
- Will measure (d,p), (p,γ), (d,n) and (p,n) reactions
- ^{88}Rb$(d,p)^{89}$Rb for r-process ^{88}Rb$(n,\gamma)^{89}$Rb
- ^{83}Rb$(p,\gamma)^{84}$Sr for p-process in core-collapse supernovae
- ^{135}I$(d,p)^{136}$I for "i-process"

EMMA



- **E**lectro**M**agnetic **M**ass **A**nalyzer for structure & astrophysical reactions
- Will measure (d,p), (p,γ), (d,n) and (p,n) reactions
- ^{88}Rb$(d,p)^{89}$Rb for r-process ^{88}Rb$(n,\gamma)^{89}$Rb
- ^{83}Rb$(p,\gamma)^{84}$Sr for *p*-process in core-collapse supernovae
- ^{135}I$(d,p)^{136}$I for "*i*-process"

Program successes: DRAGON

Reaction	Motivation	Intensity (s^{-1})	Purity (desired:contaminant)
^{21}Na$(p,\gamma)^{22}$Mg	1.275 MeV line emission in ONe novae	5×10^{9}	100%
^{12}C$(\alpha,\gamma)^{16}$O	Helium burning in red giants	3×10^{11}	
^{26g}Al$(p,\gamma)^{27}$Si	Nova contribution to galactic ^{26}Al	3×10^{9}	30,000:1
^{12}C$(^{12}\mathrm{C},\gamma)^{24}$Mg	Nuclear cluster models	3×10^{11}	
^{40}Ca$(\alpha,\gamma)^{44}$Ti	Production of ^{44}Ti in SNII	3×10^{11}	10,000:1 - 200:1
^{12}C$(^{16}\mathrm{O},\gamma)^{28}$Si	Nuclear cluster models	3×10^{11}	
^{23}Mg$(p,\gamma)^{24}$Al	1.275 MeV line emission in ONe novae	5×10^{7}	1:20 - 1:1,000
^{17}O$(\alpha,\gamma)^{21}$Ne	Neutron poison in massive stars	1×10^{12}	
^{18}F$(p,\gamma)^{19}$Ne	511 keV line emission in ONe novae	2×10^{6}	100:1
^{33}S$(p,\gamma)^{34}$Cl	S isotopic ratios in nova grains	1×10^{10}	
^{16}O$(\alpha,\gamma)^{20}$Ne	Stellar helium burning	1×10^{12}	
^{17}O$(p,\gamma)^{18}$F	Explosive H burning in novae	1×10^{12}	
^{3}He$(\alpha,\gamma)^{7}$Be	Solar neutrino spectrum	5×10^{11}	
^{58}Ni$(p,\gamma)^{59}$Cu	High mass tests (p-process, XRB)	6×10^{9}	
^{26m}Al$(p,\gamma)^{27}$Si	SNII contribution to galactic ^{26}Al	2×10^{5}	1:10,000
^{38}K$(p,\gamma)^{39}$Ca	Ca/K/Ar production in novae	2×10^{7}	1:1

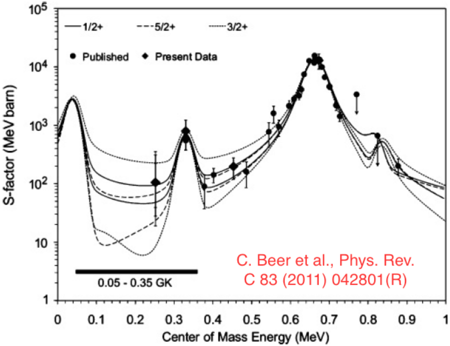
Program successes: DRAGON

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)

- Textbook radiative capture measurement in inverse kinematics: $^{21}Na(p,\gamma)^{22}Mg$
- Weakest resonance strength ever measured using most intense RIB ever: $^{26g}Al(p,\gamma)^{27}Si$
- First measurement of radiative capture using isomeric beam: $^{26m}Al(p,\gamma)^{27}Si$
- Highest mass RIB for radiative capture: $^{38}K(p,\gamma)^{39}Ca$

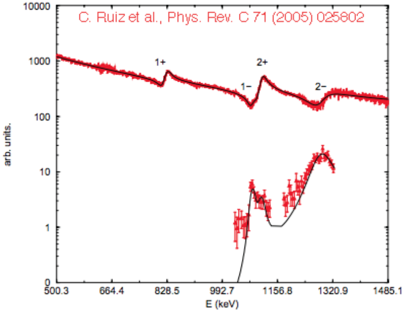
Program successes: TUDA, DSL, ...

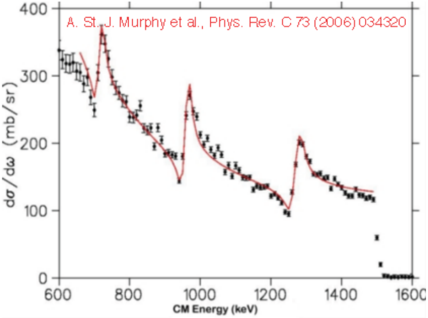
- Lowest energy measurement of $^{18}F(p,\alpha)^{19}Ne$
- Best quality RIB resonant elastic scattering data: $^{21,20}Na(p,p)^{21,20}Na$, $^{18}F(p,p)^{18}F$
- Spectroscopic quality RIB transfer data: $^{26g}Al(d,p)^{27}Al$



Program successes: TUDA, DSL, ...

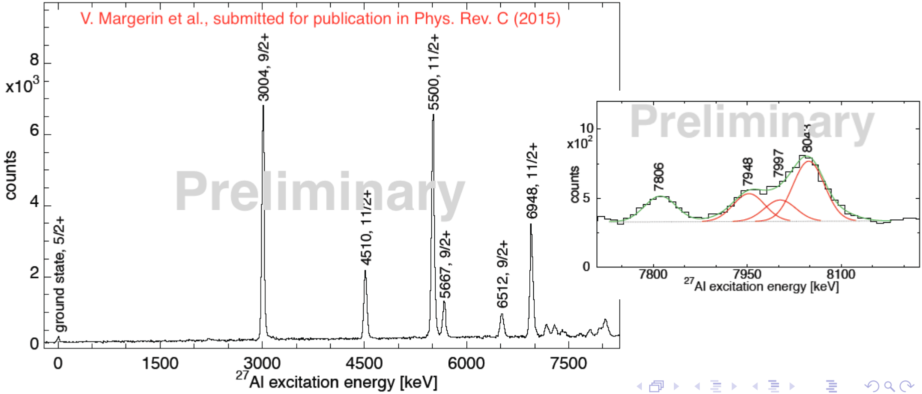
- Lowest energy measurement of $^{18}F(p,\alpha)^{19}Ne$
- Best quality RIB resonant elastic scattering data: $^{21,20}Na(p,p)^{21,20}Na$, $^{18}F(p,p)^{18}F$
- Spectroscopic quality RIB transfer data: $^{26g}Al(d,p)^{27}Al$





Program successes: TUDA, DSL, ...

- Lowest energy measurement of $^{18}F(p,\alpha)^{19}Ne$
- Best quality RIB resonant elastic scattering data: $^{21,20}Na(p,p)^{21,20}Na$, $^{18}F(p,p)^{18}F$
- Spectroscopic quality RIB transfer data: $^{26g}Al(d,p)^{27}Al$



Program successes: TUDA, DSL, ...

- TUDA direct measurement of ^{23}Na(α, p)^{26}Mg accepted for publication in Phys. Rev. Lett.†
- Best founded $^{15}O^{*}_{6.79\mathrm{MeV}}$ lifetime limit at DSL via ^{3}He(^{16}O,^{4}He)^{15}O* for ^{14}N(p, γ)^{15}O in oldest stars*
- Only absolute strength measurements of important ^{22}Na(p, γ)^{23}Mg resonances: implanted ^{22}Na at ISAC Implantation Station‡
- Implanted ^{26}Al targets for ^{26}Al(^{3}He,t/d) spectroscopic studies at Orsay, Munich, Florida State§

† J.R. Tomlinson *et al.*, Accepted for publication in Phys. Rev. Lett, June 2015

* N. Galinski *et al.*, Phys. Rev. C 90 (2014) 035803

‡ A. Sallaska *et al.*, Phys. Rev. Lett. 105 (2010) 152501

§ TRIUMF Experiments S1071/S1171

Program successes: TUDA, DSL, ...

- TUDA direct measurement of ^{23}Na(α, p)^{26}Mg accepted for publication in Phys. Rev. Lett.†
- Best founded $^{15}O^{*}_{6.79\mathrm{MeV}}$ lifetime limit at DSL via ^{3}He(^{16}O,^{4}He)^{15}O* for ^{14}N(p,γ)^{15}O in oldest stars*
- Only absolute strength measurements of important ^{22}Na(p,γ)^{23}Mg resonances: implanted ^{22}Na at ISAC Implantation Station‡
- Implanted ^{26}Al targets for ^{26}Al(^{3}He,t/d) spectroscopic studies at Orsay, Munich, Florida State§

† J.R. Tomlinson *et al.*, Accepted for publication in Phys. Rev. Lett, June 2015

* N. Galinski *et al.*, Phys. Rev. C 90 (2014) 035803

‡ A. Sallaska *et al.*, Phys. Rev. Lett. 105 (2010) 152501

§ TRIUMF Experiments S1071/S1171

Program successes: TUDA, DSL, ...

- TUDA direct measurement of $^{23}Na(\alpha, p)^{26}Mg$ accepted for publication in Phys. Rev. Lett.[†]
- Best founded $^{15}O^{*}_{6.79\mathrm{MeV}}$ lifetime limit at DSL via $^{3}He(^{16}O,^{4}He)^{15}O^{*}$ for $^{14}N(p,\gamma)^{15}O$ in oldest stars[*]
- Only absolute strength measurements of important $^{22}Na(p,\gamma)^{23}Mg$ resonances: implanted ^{22}Na at ISAC Implantation Station[‡]
- Implanted ^{26}Al targets for $^{26}Al(^{3}He,t/d)$ spectroscopic studies at Orsay, Munich, Florida State[§]

[†] J.R. Tomlinson *et al.*, Accepted for publication in Phys. Rev. Lett, June 2015

[*] N. Galinski *et al.*, Phys. Rev. C 90 (2014) 035803

[‡] A. Sallaska *et al.*, Phys. Rev. Lett. 105 (2010) 152501

[§] TRIUMF Experiments S1071/S1171

Program successes: TUDA, DSL, ...

- TUDA direct measurement of $^{23}Na(\alpha, p)^{26}Mg$ accepted for publication in Phys. Rev. Lett.[†]
- Best founded $^{15}O^*_{6.79\mathrm{MeV}}$ lifetime limit at DSL via $^{3}He(^{16}O,^{4}He)^{15}O^*$ for $^{14}N(p,\gamma)^{15}O$ in oldest stars[*]
- Only absolute strength measurements of important $^{22}Na(p,\gamma)^{23}Mg$ resonances: implanted ^{22}Na at ISAC Implantation Station[‡]
- Implanted ^{26}Al targets for $^{26}Al(^{3}He,t/d)$ spectroscopic studies at Orsay, Munich, Florida State[§]

[†] J.R. Tomlinson *et al.*, Accepted for publication in Phys. Rev. Lett, June 2015

[*] N. Galinski *et al.*, Phys. Rev. C 90 (2014) 035803

[‡] A. Sallaska *et al.*, Phys. Rev. Lett. 105 (2010) 152501

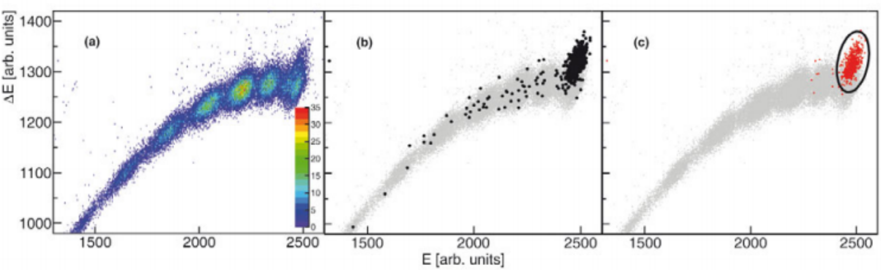
[§] TRIUMF Experiments S1071/S1171

What we need

- Continued support for DRAGON program
- Redoubled support for direct & indirect reactions program (TUDA, DSL, ...)
- Continued support for EMMA, starting of experimental program
- DRAGON High Mass Upgrade (see next slides)
- $LaBr_3$ Array for γ-tagging and fast timing at DRAGON & EMMA (see next slides)
- BEAMS! $\rightarrow$ alternate production methods for most difficult astrophysics RIB of high priority, e.g. ^{15}O, ^{18,19}Ne, ^{30}P, ^{44}Ti,...$\rightarrow$ **V.A.S.T evaporating liquid spallation ISOL targets e.g. salts, sulphur + advanced transport techniques**

DRAGON High Mass Upgrade

- Successful experiments ^{58}Ni(p, γ)^{59}Cu and ^{76}Se(α, γ)^{80}Kr show DRAGON capability far above A<30 design limit[¶]
- Prospect of p-process measurement program with limited RIB and high intensity stable beam $\rightarrow$ expanding reach
- Upgrades of electrostatics and magnet power supplies needed

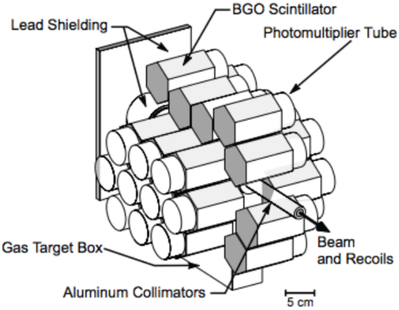


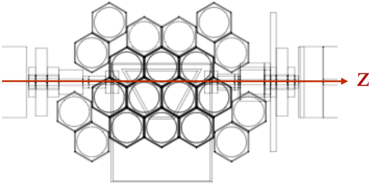
$$^{58}\text{Ni}(p,\gamma)^{59}\text{Cu: } \omega\gamma_{exp} = 0.687(96)\ \text{eV},\ \omega\gamma_{lit} = 0.63(10)\ \text{eV}$$

[¶] A. Simon *et al.*, Eur. Phys. J. A 49 (2013) 60; A. Simon *et al.*, Proc. Sci. 028 (2014)

BGO → $LaBr_3$

- 30-element $Bi_4Ge_3O_{12}$ array
- ∼40% - 80% efficiency, multiplicity & energy dependent

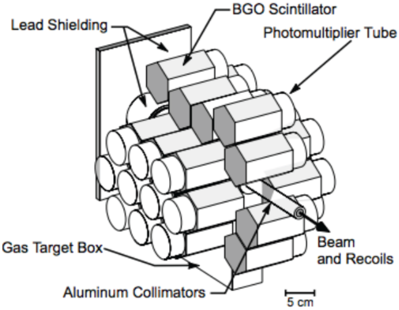


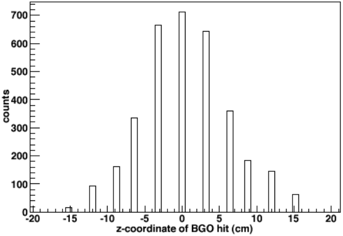


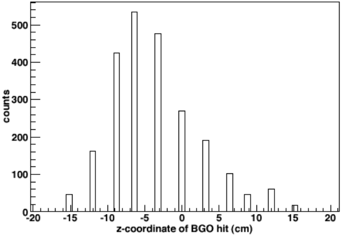
¶D. A. Hutcheon, C. Ruiz, J. Fallis *et al.*, Nucl. Inst. Meth. A **689** (2012) 70-74

BGO → $LaBr_3$

- 30-element $Bi_4Ge_3O_{12}$ array
- ∼40% - 80% efficiency, multiplicity & energy dependent



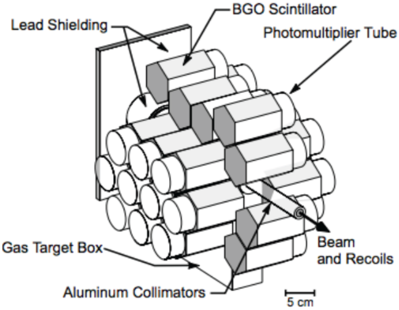


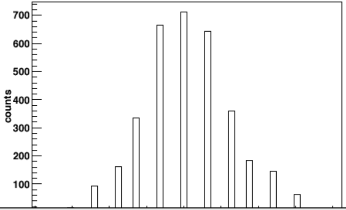


¶D. A. Hutcheon, C. Ruiz, J. Fallis *et al.*, Nucl. Inst. Meth. A **689** (2012) 70-74

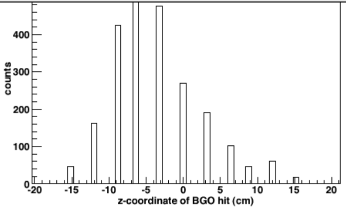
BGO → $LaBr_3$

- 30-element $Bi_4Ge_3O_{12}$ array
- ∼40% - 80% efficiency, multiplicity & energy dependent





E_{res} to 0.5% via this method (in limit of high statistics)



¶D. A. Hutcheon, C. Ruiz, J. Fallis *et al.*, Nucl. Inst. Meth. A **689** (2012) 70-74

BGO → $LaBr_3$

	BGO	$LaBr_3$(Ce)
Density [g·cm^2]	7.13	5.1
Hygroscopic	No	Yes
Light Yield [photons/keVγ]	8-10	63
Decay Const [ns]	300	16
σ_{662} [%]	10	2.9
σ_{2615} [%]	$\sim$ 6.5	1.6

- $LaBr_3$ → fast timing for high efficiency
- Buncher time focus at DRAGON + $LaBr_3$ → low-statistic resonance position measure
- Improved energy resolution → cascade transitions → much lower systematics
- γ-tagging at EMMA: same issues apply

Ask ($ CAD + ppl)

- Direct (DRAGON & TUDA) and Indirect (TUDA & DSL) Program (includes computational work): $380k/yr
- DRAGON Upgrades: $200k one-time cost
- $LaBr_3$ array for DRAGON & EMMA: $1M
- Total ask $3.1M over 5 years (minimum $1.9M)
- Increase Direct & Indirect program manpower (PDRA) by 2-3
- V.A.S.T. Likely to cost $900k for full implementation by 2019. NSERC component (personnel $ equipment based) originally estimated at ∼$500k

= Significant return on investment given likely program successes

The DRAGON & TUDA Collaborations:

- **TRIUMF:** Barry Davids, Iris Dillmann, Dave Hutcheon, Chris Ruiz
- **McMaster University:** Alan Chen
- **Simon Fraser University:** John D'Auria
- **University of Northern British Columbia:** Ahmed Hussein
- **Colorado School of Mines:** Uwe Greife
- **University of York:** Alison Laird, Brian Fulton
- **Michigan State University:** Ulrike Hager, Artemis Spyrou
- **Texas A&M:** Greg Christian
- **University of Edinburgh:** Tom Davinson, Alex Murphy, Marialuisa Aliotta, Phil Woods
- **University of Surrey:** G. Lotay
- **Polytechnic University of Catalunia:** Jordi José, Anuj Parikh
- **Notre Dame University:** James deBoer, Patrick O'Malley
- **Ohio University:** Carl Brune