TRIUMF

^{86}Kr(α,n)^{89}Sr and the Weak r-process

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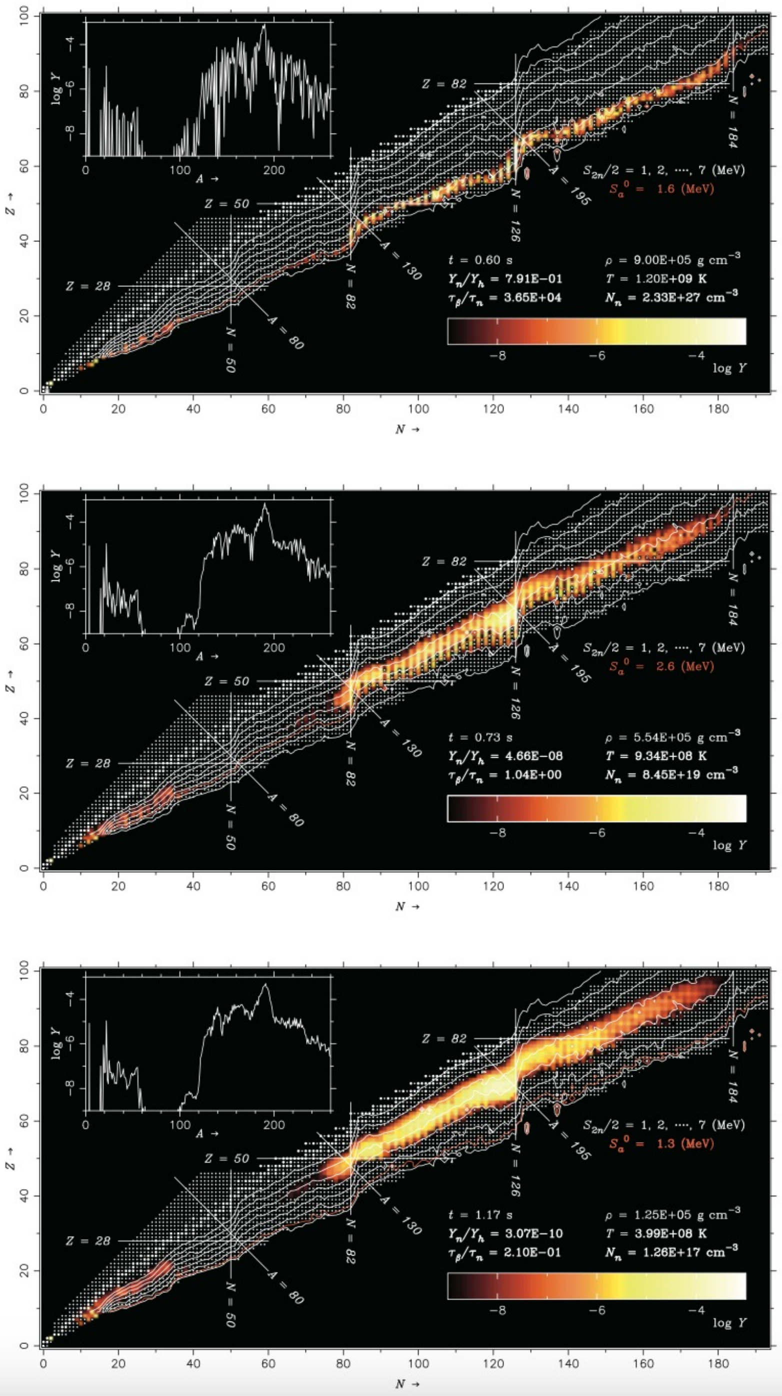
Discovery, accelerated

‘Main’ r-process

- ‘rapid’ neutron-capture process
- Responsible for producing ~50% of heavier-than-iron elements
- Currently thought to take place in neutron star mergers (GW170817)
- Primary process



Wanajo *et al.* (2004) ApJ.

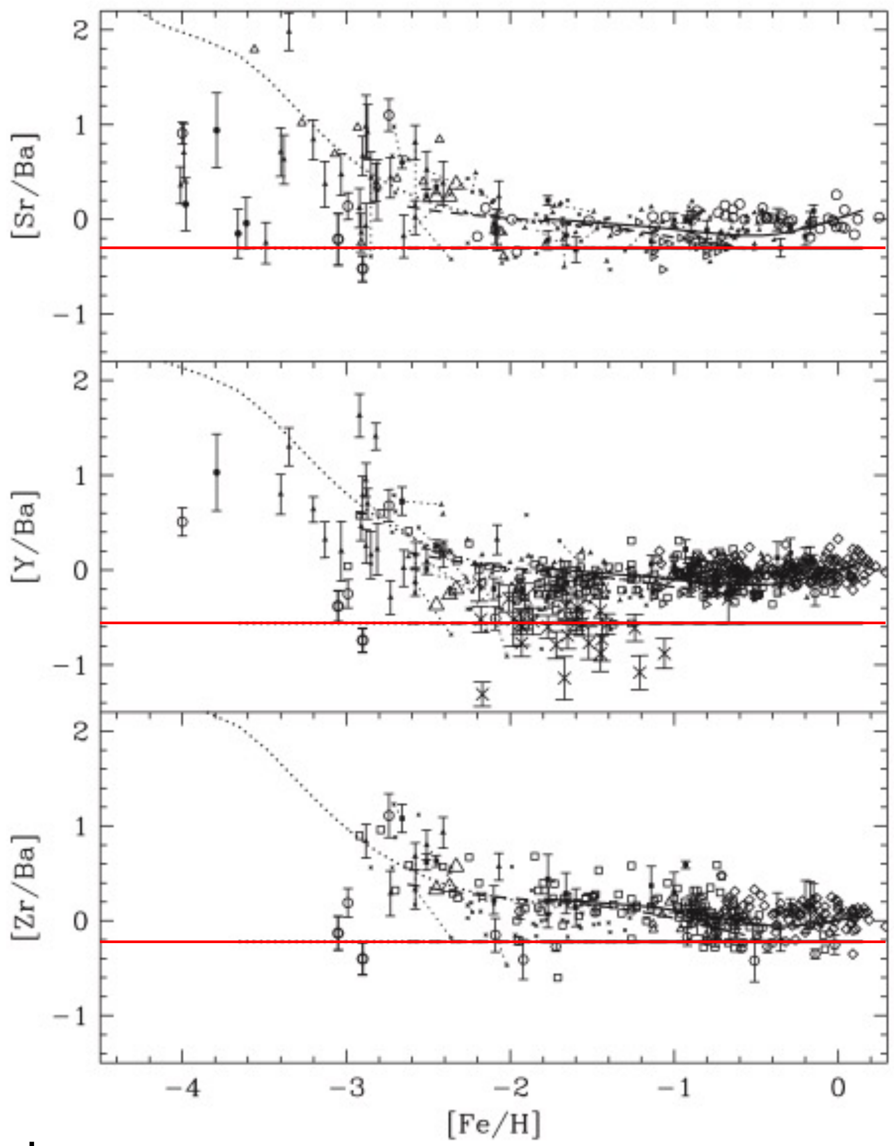
The r-process in Ultra Metal Poor stars

- r-process is the dominant source of heavier-than-iron elements at early times
- Abundance predictions can be compared to UMP abundances
- Observations *mostly* in agreement with theoretical r-process abundance predictions

Image credit: NASA, ESA, J. Hester, A. Loll (ASU)

Light Element Primary Process

- Predictions for heavy element abundances agree with observations
- Intermediate-mass elements are more abundant than expected (26<Z<45)
- Additional source of nucleosynthesis operating at early times?



Travaglio *et al.* (2004) ApJ.

The Weak r-process

- Site: Core-collapse Supernovae
- Neutrino-driven winds that drives the shock
    - Neutrinos released from cooling proto-neutron star
- Simulations suggest nucleosynthesis viable for $A < 130$

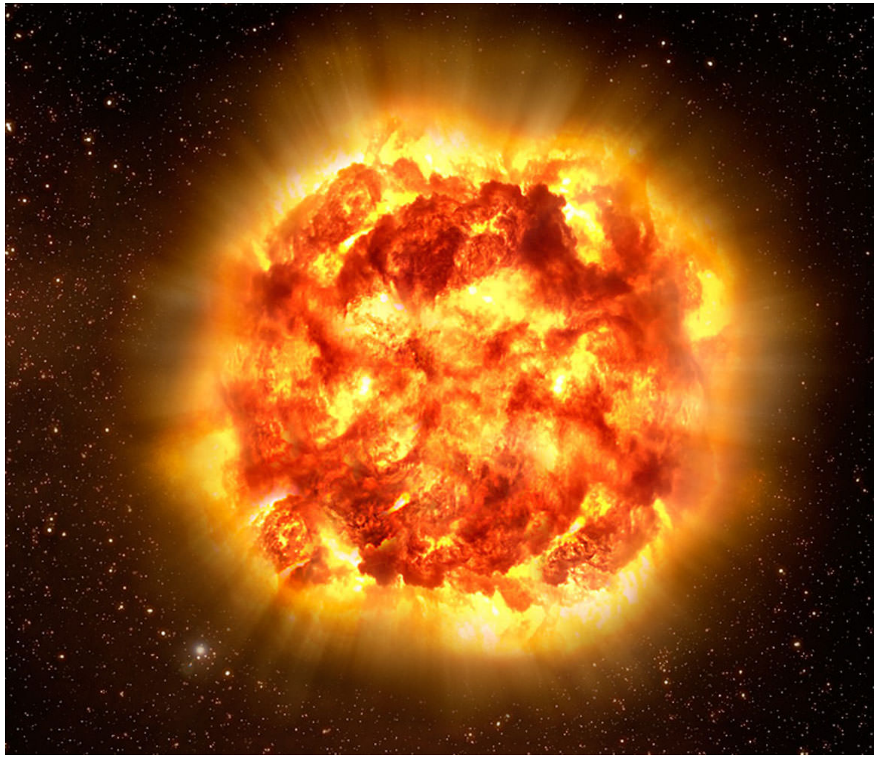
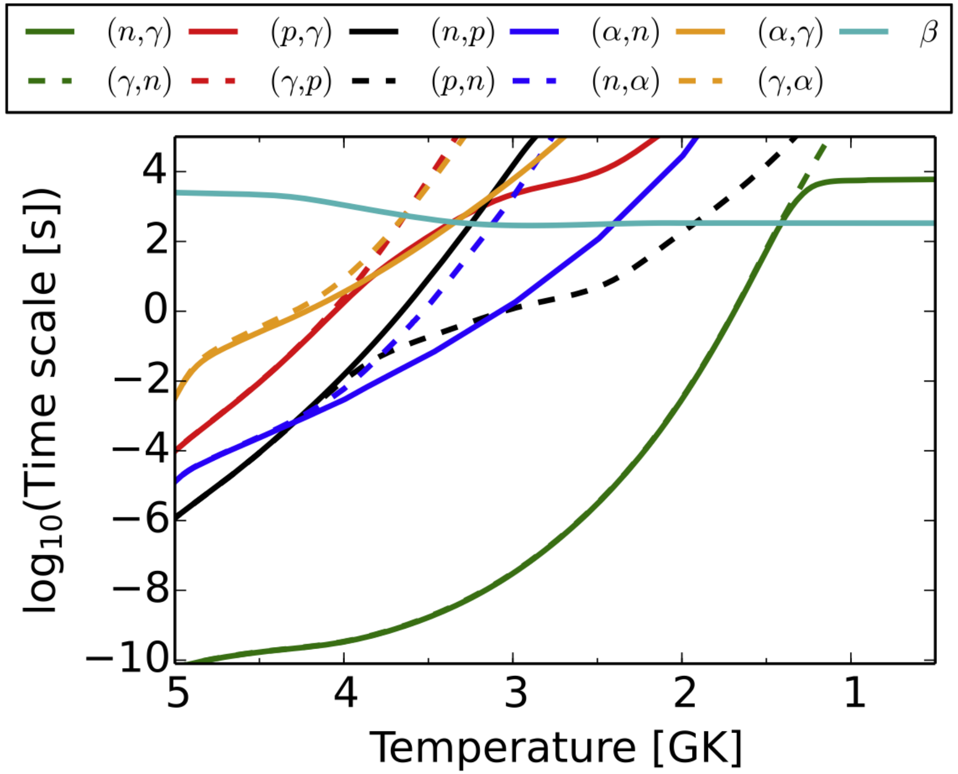
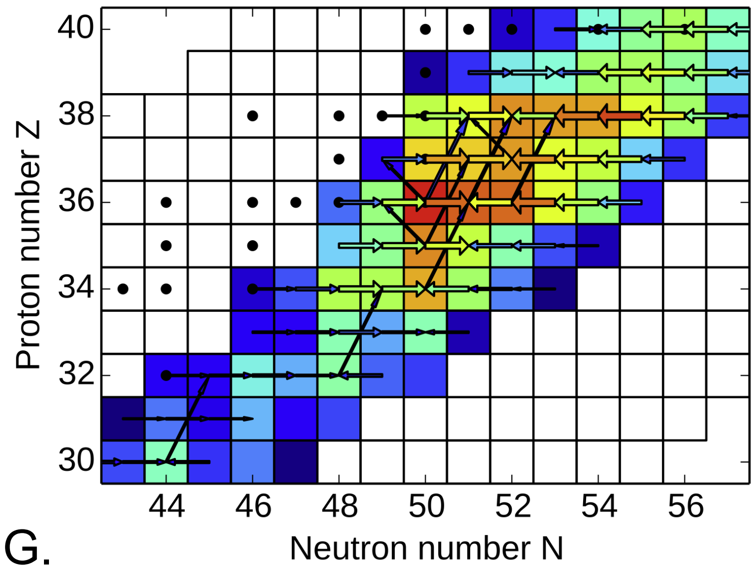


Image credit: ESO

(α,n) reactions

- Initially, the ejecta is in nuclear statistical equilibrium
- $\mathrm{T} = 2 - 5\mathrm{GK}$
- Pathway close to stability, in contrast to the 'main' r-process
- Most (α,n) reactions on the intermediate-mass elements do not have measured cross sections…

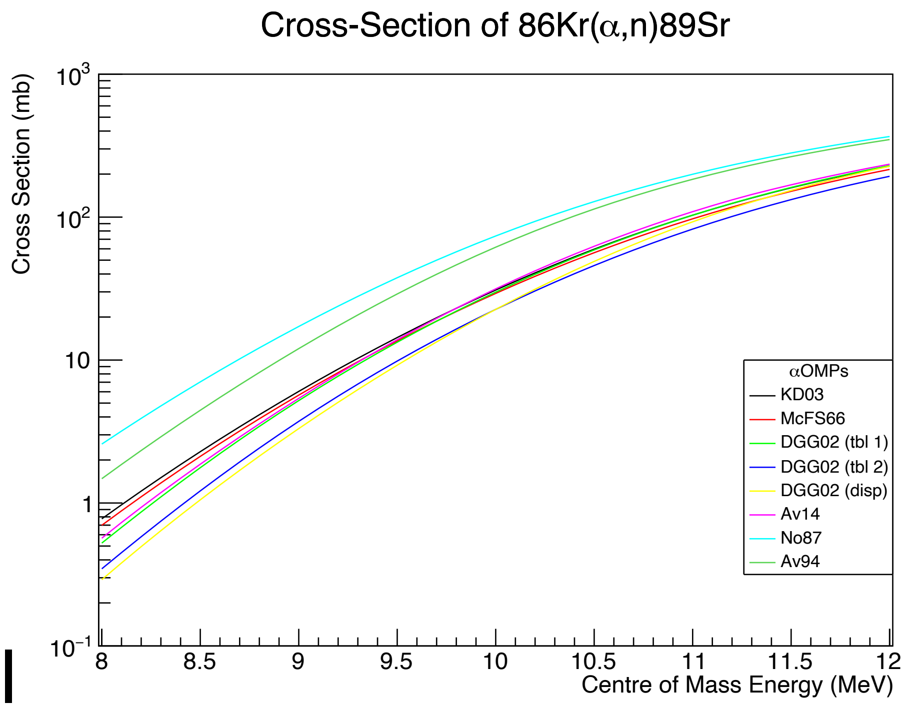




Bliss *et al.* (2017) J. Phys. G.

Hauser-Feshbach Predictions

- Nucleosynthesis models rely on Hauser-Feshbach theory for (α,n) cross sections
- Statistical averaging over many energy levels
- Significant uncertainties in abundance predictions arising from choice of α-Optical Model Potential



Experiment(s)

- Reactions
  - $^{86}Kr(\alpha,n)^{89}Sr$
    - Studied in 3 parts
  - $^{94}Sr(\alpha,n)^{97}Zr$

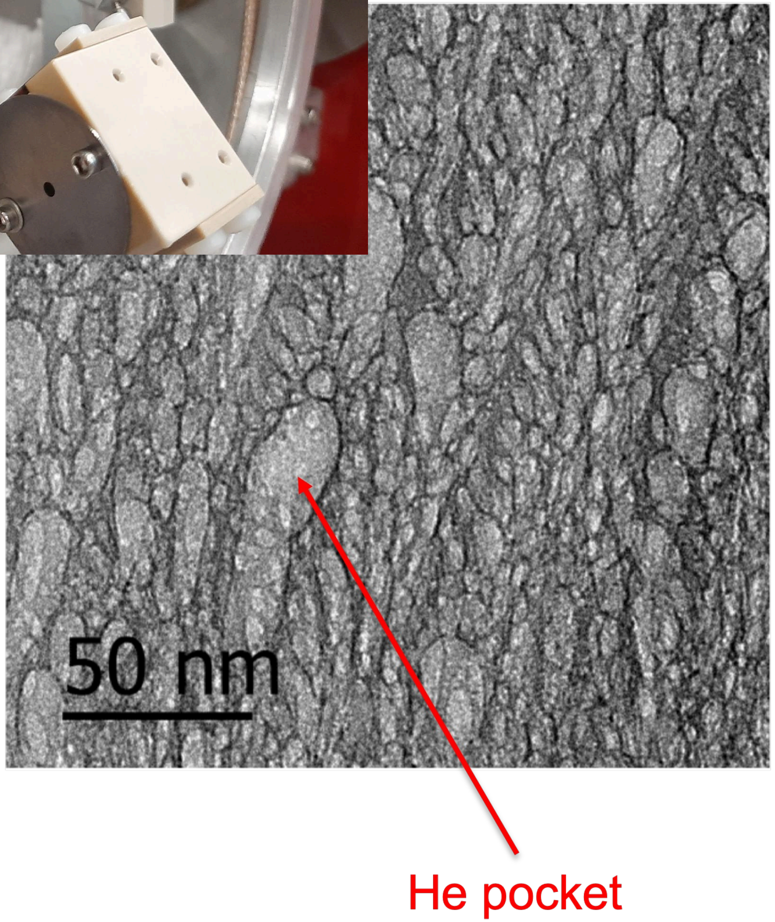
"*affecting many astrophysical abundances under many astrophysical conditions*" – Bliss *et al.* (2020)

- EMMA+TIGRESS at the TRIUMF-ISAC facility

- Inverse Kinematics with novel He-containing targets

He:Si Targets

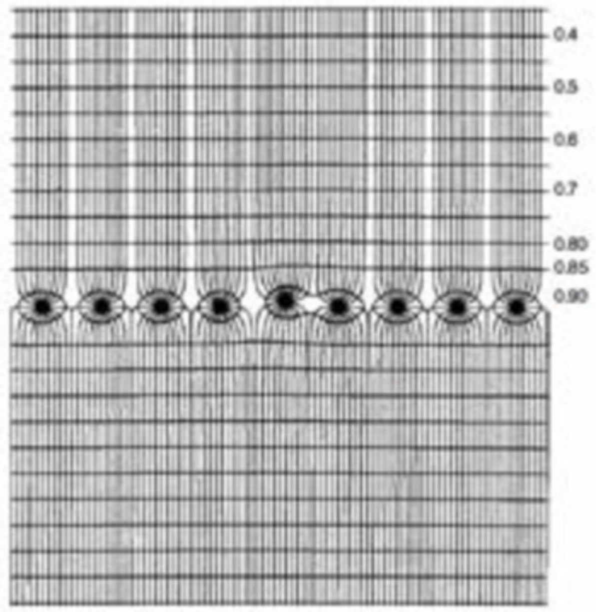
- Novel target design
- Magnetron-sputtered Si
- Traps pockets of He
- He density ~ $3.3 - 5.4 \times 10^{18}$ atoms cm^{-2}
  - Comparable to windowless gas-targets

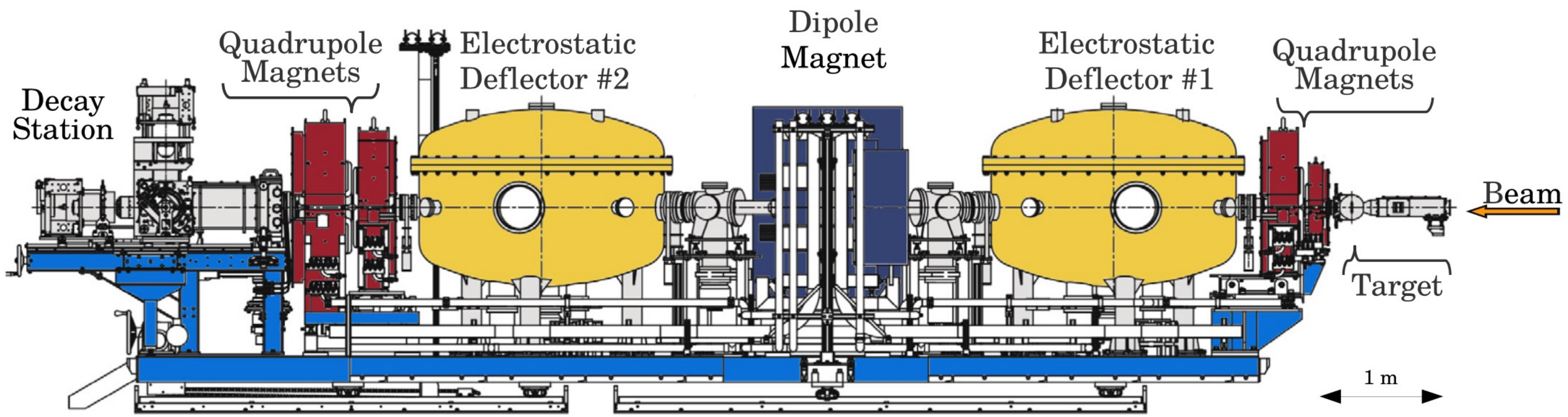


Godinho *et al.* (2016) ACS Omega

ElectroMagnetic Mass Analyser

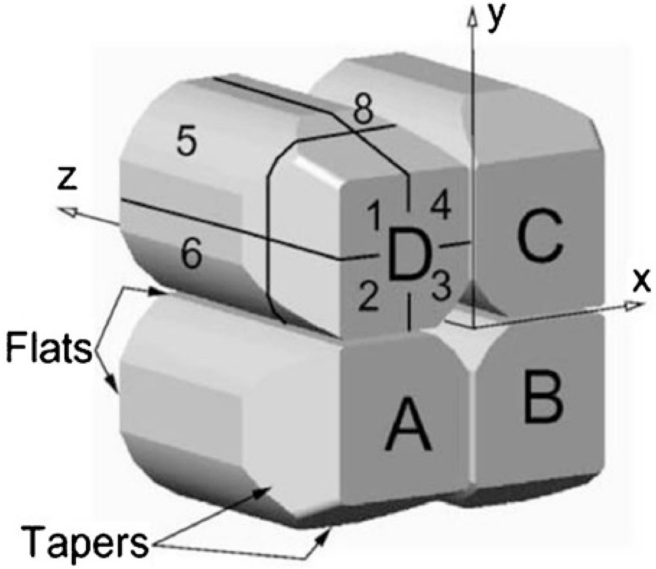
- Recoil mass spectrometer
- Separates ions by M/q ratio
- 3 detectors at focal plane
  - PGAC, Ionization Chamber + Si detector
  - PGAC gives position sensitivity

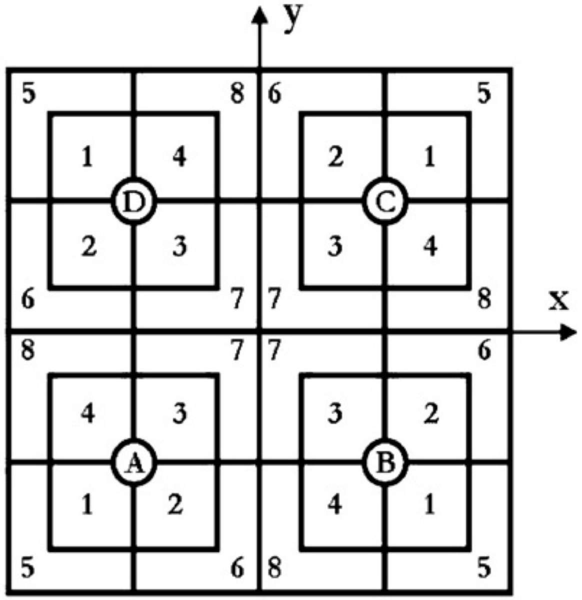




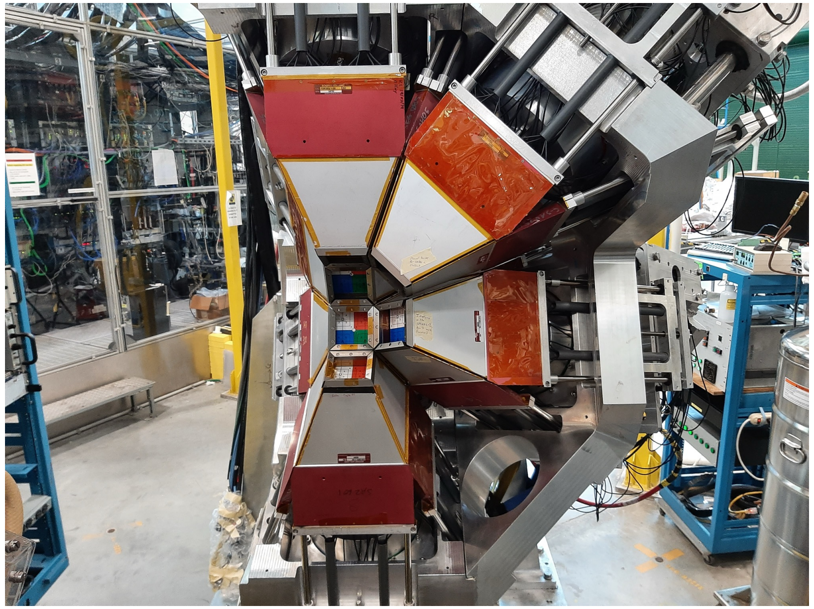
Davids *et al.* (2019), NIM.A.

Triumf-Isac Gamma-Ray Escape Suppressed Spectrometer





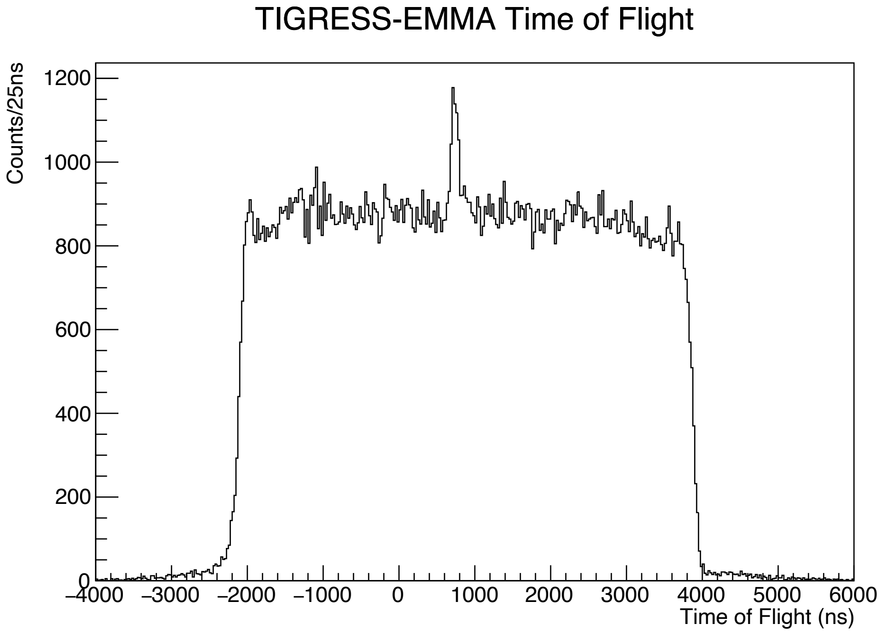
- Gamma-ray detector coupled to EMMA
- 12 HPGe clovers surrounded by BGO scintillators for Compton suppression
- Segmented readouts give high angular resolution



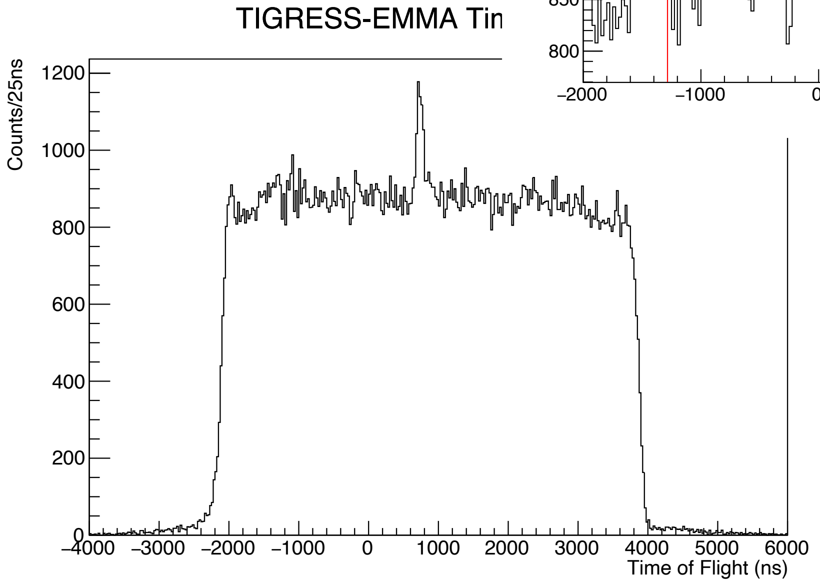
Svensson *et al.* (2005) *J. Phys. G.* **31**, S1663-S1668

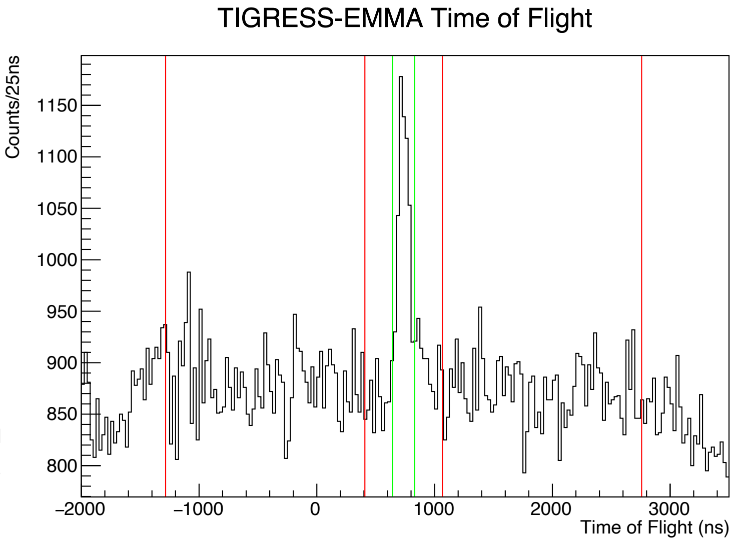
EMMA + TIGRESS

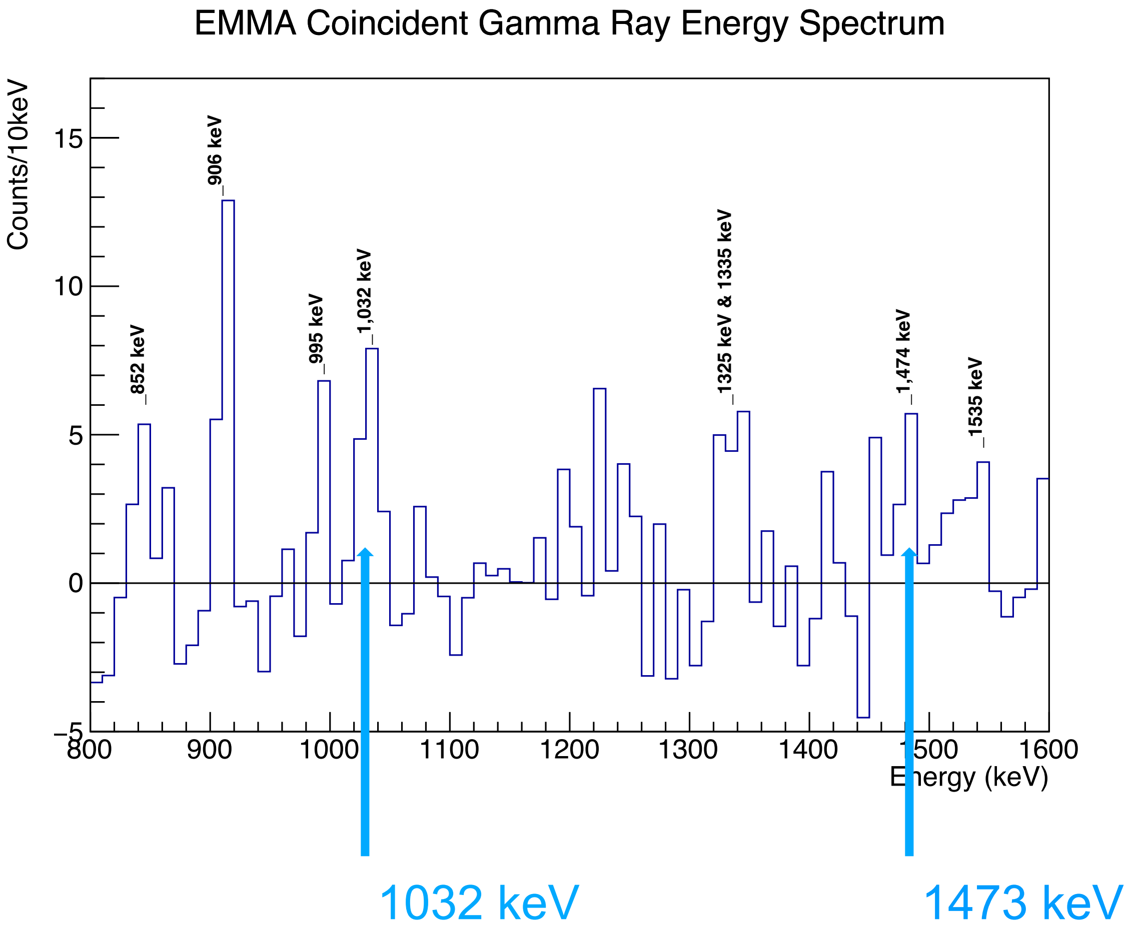
- EMMA measures recoiling ^{89}Sr ions
- TIGRESS measures gamma rays from reactions
- Coupling allow allow coincidence measurements



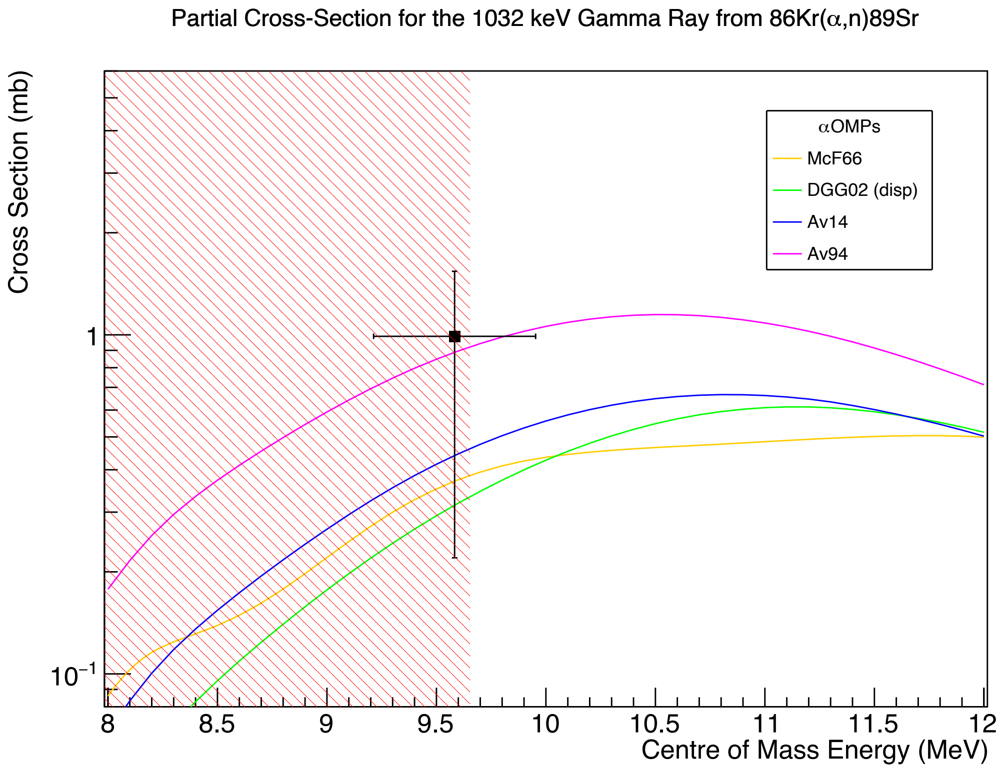
Results from $^{86}Kr(\alpha,n)^{89}Sr$ – part 1



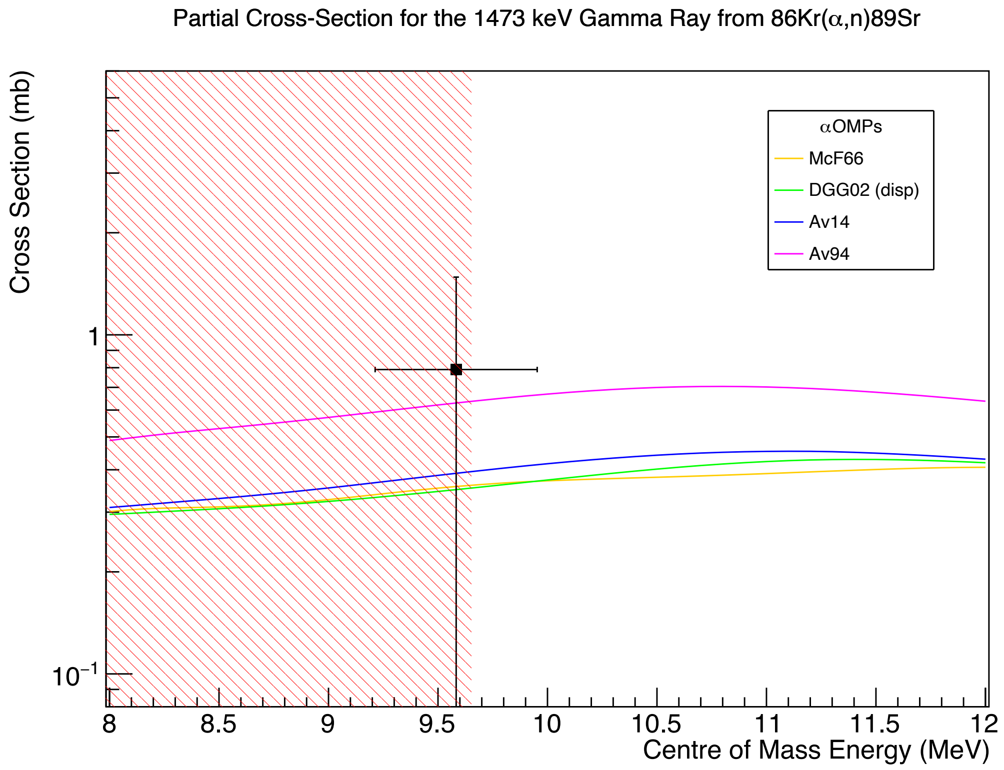




Results from $^{86}Kr(\alpha,n)^{89}Sr$ – part 1



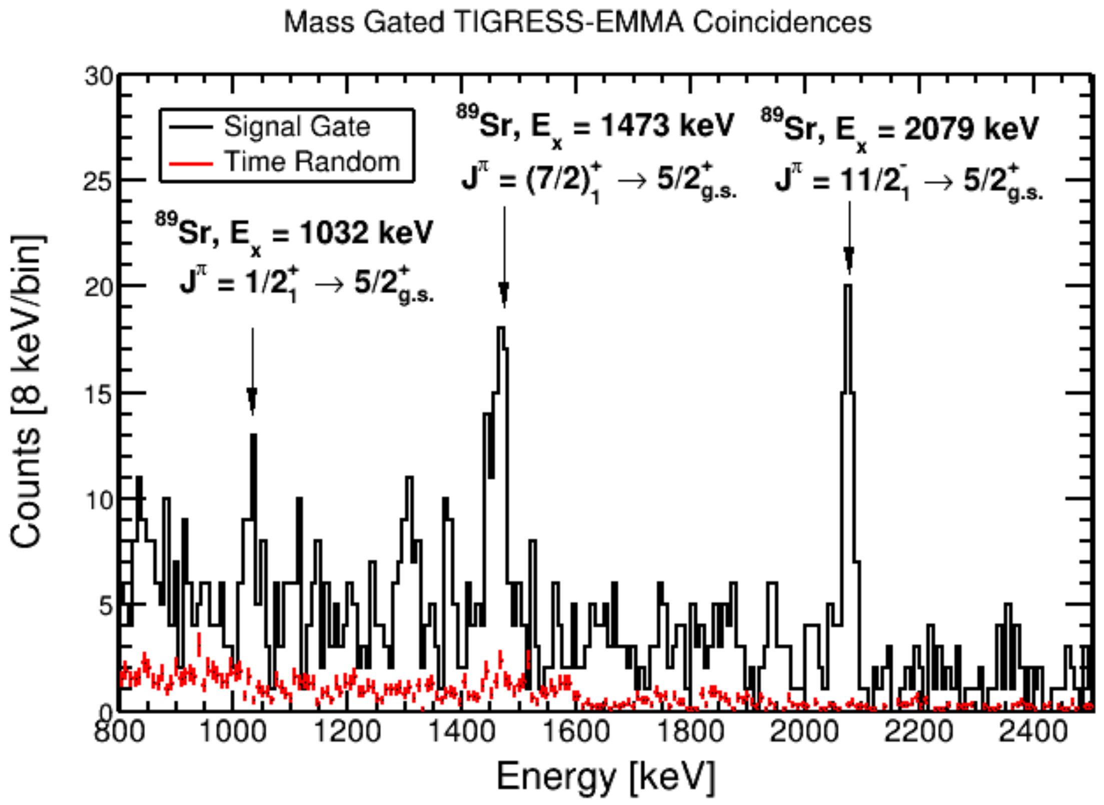
$$\sigma_{1032} = 1.0^{+0.6}_{-0.8}\ \text{mb}$$



$$\sigma_{1473} = 0.8^{+0.7}_{-0.8}\ \text{mb}$$

Future results

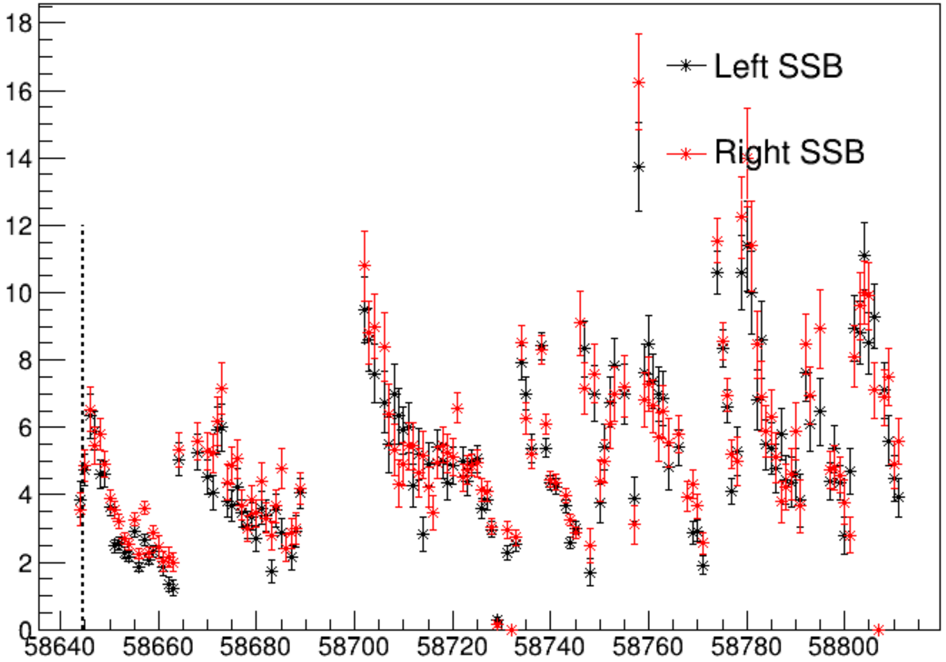
- Experiment was repeated with higher beam energy (and current)
- … and again with both ^{86}Kr and ^{94}Sr beams
  - Analysis underway by Dr. M. Williams (Surrey)



226 MeV	265 MeV	213 MeV 247 MeV	259 MeV
^{86}Kr	^{86}Kr	^{86}Kr	^{94}Sr
Dec 2021	Aug 2022	Aug 2023	Dec 2023

Targets

- Measured scattering with SSBs in target chamber
- Have now tested self-supported, Au-backed and Al-backed



Summary

- The weak r-process is a potential source of intermediate-mass elements at early times in the universe
  - (a,n) reactions most important
- Model nucleosynthesis predictions rely on uncertain Hauser-Feshbach calculations for (a,n) reactions
- Partial cross sections measured for ^{86}Kr(α,n)^{89}Sr using EMMA and TIGRESS at TRIUMF
- Magnetron-sputtered He:Si targets are useful for nuclear astrophysics experiments

M. Williams[1], A. Andreyev[2], A. Arcones[11], S. S. Bhattacharjee[3], S. Buck[4], S. Chakraborty[1,2], B. Davids[1,5], C. Aa. Diget[2], D. Galaviz[12], S. Gillespie[1], C. Griffin[1], A. Fernandez[6], G. Hackman[1], K. Hudson[1,5], V. Karayonchev[1], Y. H. Kim[7], A.M. Laird[2], A. Lennarz[1], G. Lotay[13], K. Mashtakov[4], P. Machule[1], F. Montes[14,15], C. Natzke[8], K. Pak[7], J. Pereira[14], T. Psaltis[9], A. Radich[4], D. Rhodes[1], C. Ruiz[1], A. Simon[16], S. Upadhyayula[1], R. Wadsworth[2], J. Wiliams[1], D. Yates[1,10] & T. Zidar[4].

[1]TRIUMF, [2]University of York, [3]Czech Technical University Prague, [4]University of Guelph, [5]Simon Fraser University, [6]Universidad de Sevilla, [7]Hanyang University, [8]Colorado School of Mines, [9]Technische Universität Darmstadt, [10]University of British Columbia, [11]GSI, [12]Fisica Nuclear Liboa, [13]University of Surrey, [14]NSCL, [15]Michigan State University, [16]University of Notre Dame.

And thank you to the University of Seville for the targets!

TRIUMF

Thank you
Merci

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Discovery, accelerated

Spare Slides

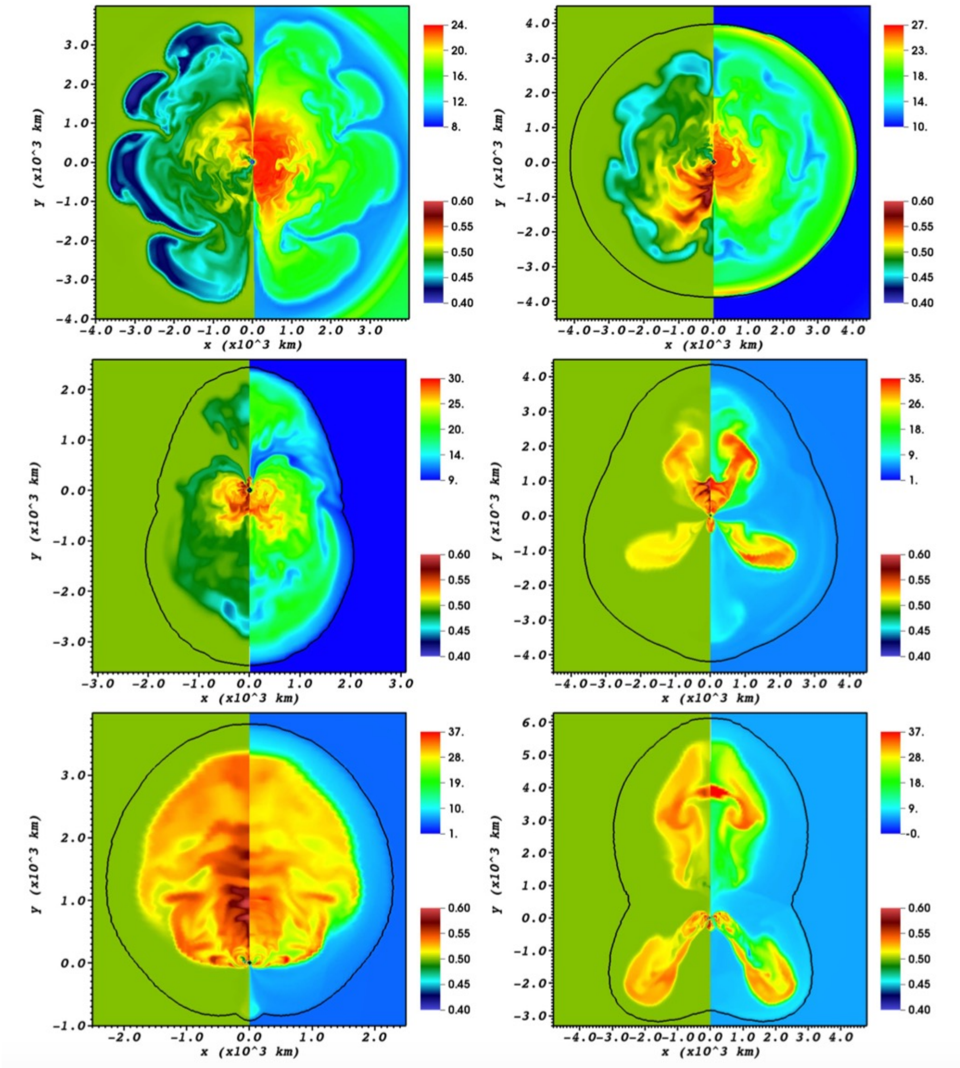
Neutrino-driven Winds

$$Y_e = \frac{N_p}{N_p + N_n}$$

- Expected to be proton-rich, but with significant slightly neutron-rich pockets

- $(\alpha$,n) reactions are most important for driving nucleosynthesis

- $T = 2 - 5$GK and $Y_e = 0.40 - 0.49$



Wanajo *et al*., (2018) ApJ.

Magnetron Sputtering

- He plasma forms a torus in the head
- Electric field accelerates He ions into Silicon surface
- Si atoms scattered into chamber
- Si deposits grow as a film on chosen substrate