A practical approach to nuclear astrophysics: activation method studies on $^{86}Kr(\alpha, n)$ and its connection to weak r-process

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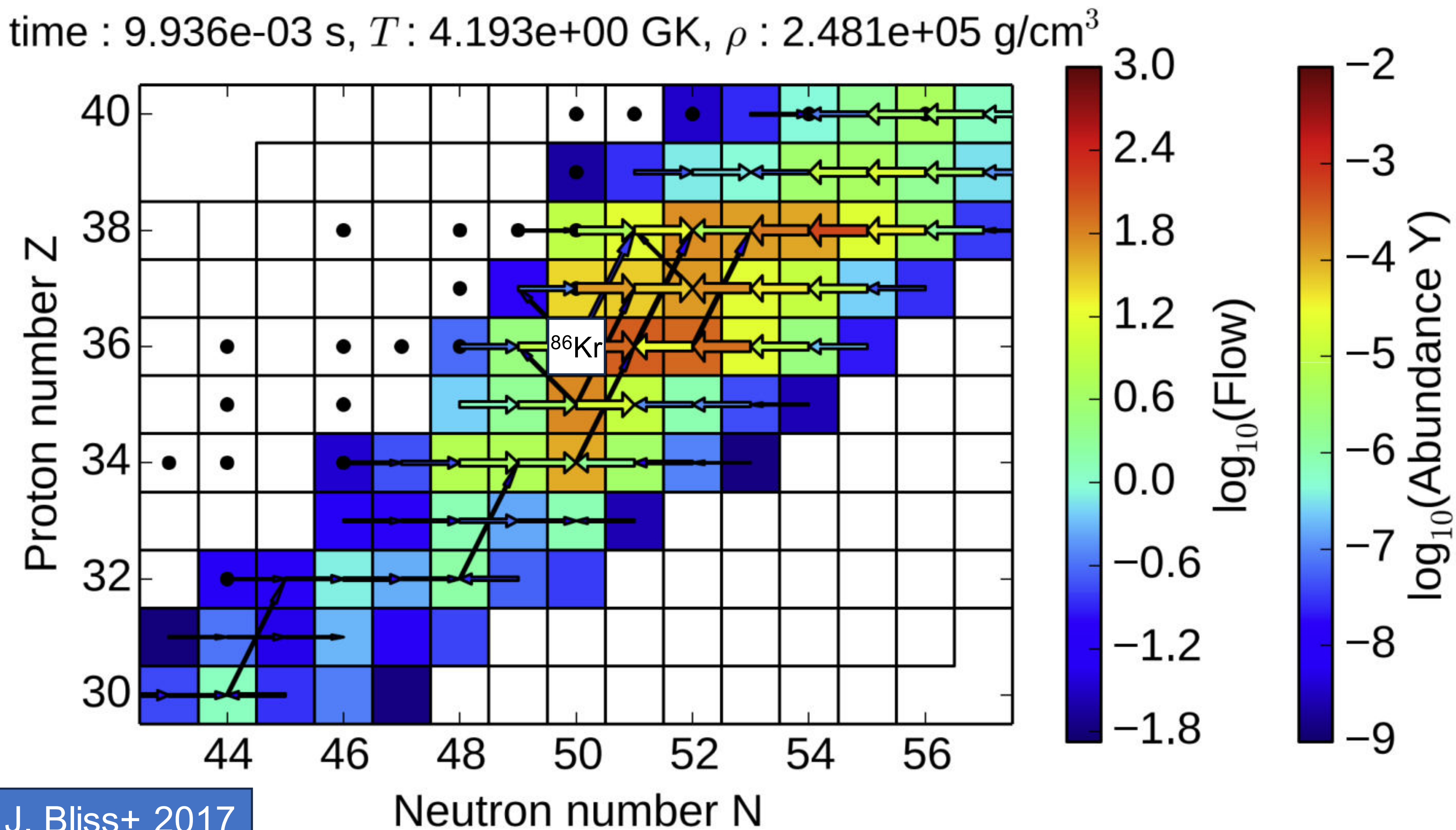
Reaction networks

Weak r-process: $Y_n/Y_{seed} \leq 10^{-2}$ → close to stability → slow β-decay → $(\alpha,\gamma), (\alpha,n), (p,\gamma), (p,n)$ reactions move matter toward higher Z



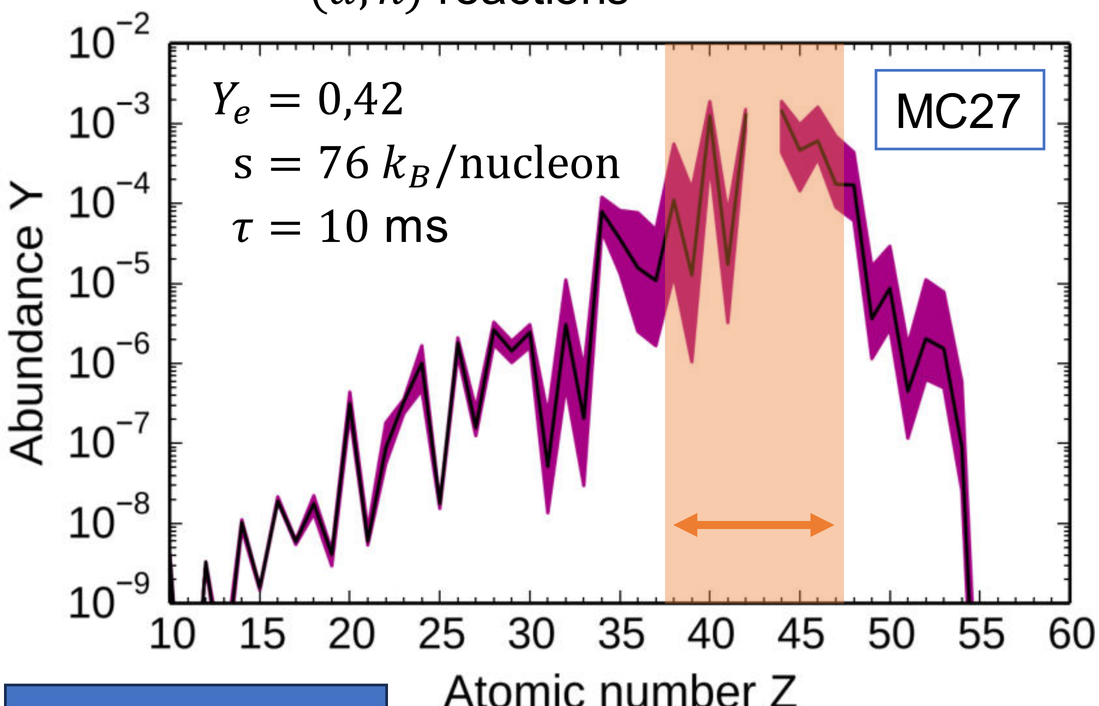
J. Bliss+ 2017

Effect of (α,n)

$^{86}Kr(\alpha,n)^{89}Sr$

Z	Trajectories
38-42, 44, 45, 47	4, 5, 7, 8, 13, 14, 15, 16, 20, 24, 25, 33, 34, 35

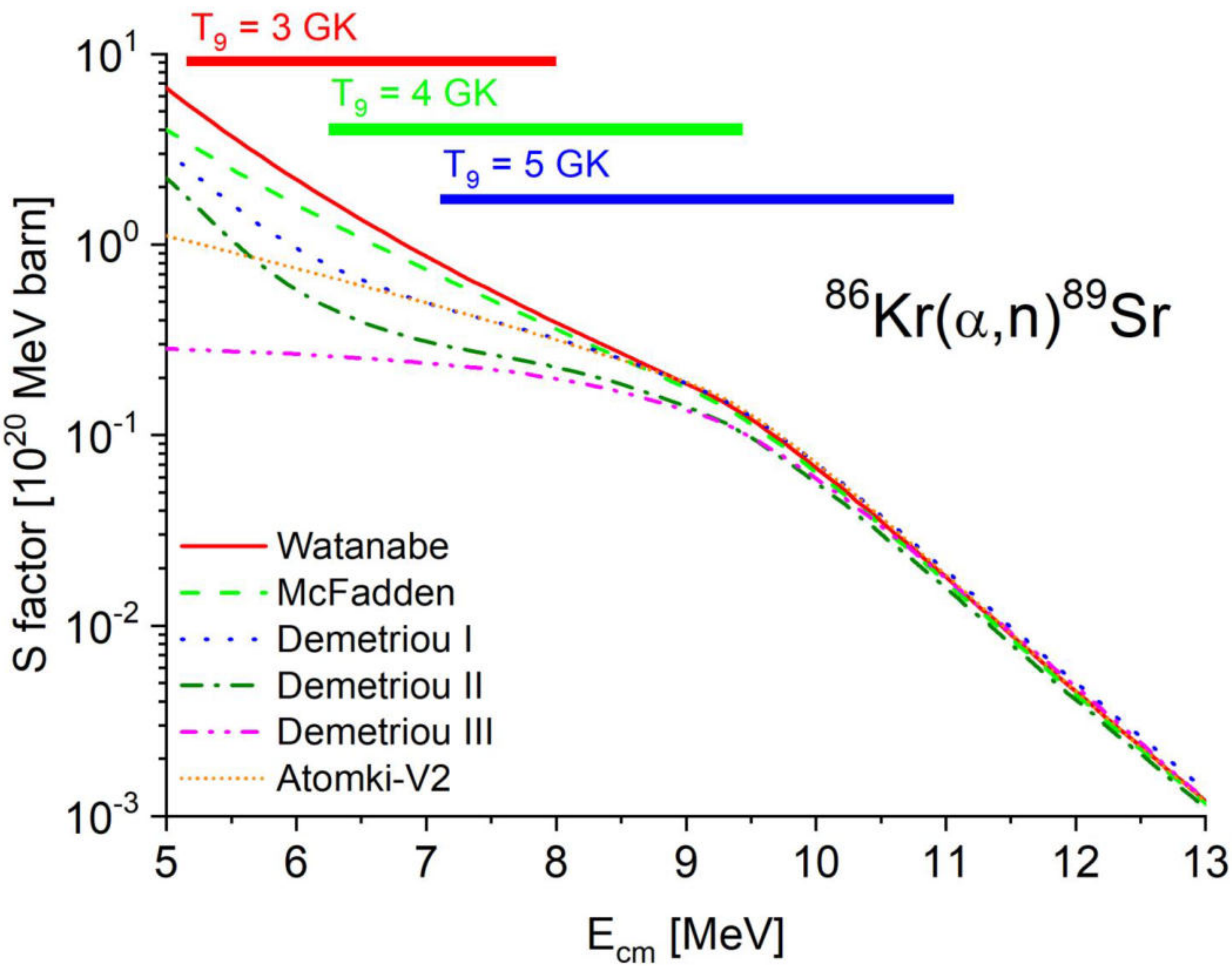
2σ uncertainties due to (α,n) reactions



J. Bliss+ (2020)

Trajectory	Y_e	Entropy k_B/nuc	Expansion time ms
MC1	0.42	129	11.7
MC2	0.45	113	11.9
MC3	0.45	122	10.3
MC4	0.44	66	19.2
MC5	0.43	66	34.3
MC6	0.4	56	63.8
MC7	0.47	96	11.6
MC8	0.43	78	35
MC9	0.40	73	28.1
MC10	0.40	54	31
MC11	0.44	104	13.2
MC12	0.48	85	9.7
MC13	0.43	64	35.9
MC14	0.45	46	14.4
MC15	0.48	103	20.4
MC16	0.49	126	15.4
MC17	0.46	132	12.4
MC18	0.45	131	21.4
MC19	0.41	75	9.8
MC20	0.41	42	59.3
MC21	0.41	31	22.2
MC22	0.40	40	46.7
MC23	0.41	48	37.5
MC24	0.43	56	16.2
MC25	0.46	96	20.9
MC26	0.40	84	36.2
MC27	0.42	76	10
MC28	0.46	113	11.9
MC29	0.41	66	41.4
MC30	0.43	79	26.3
MC31	0.43	71	11.4
MC32	0.42	103	12.7
MC33	0.49	175	14.2
MC34	0.40	34	58.7
MC35	0.44	48	13
MC36	0.40	32	63.4

Problem at astrophysically relevant energies

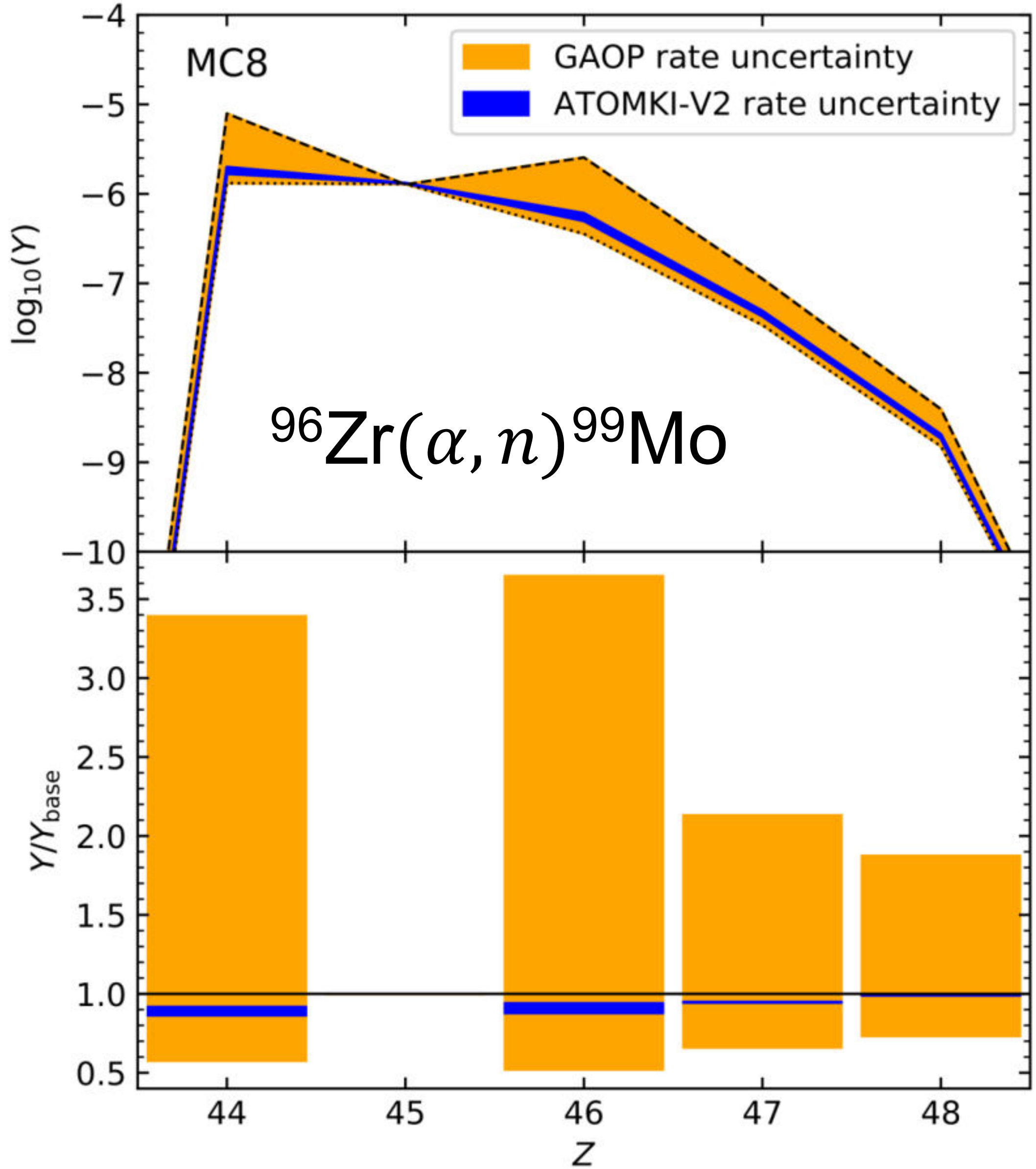


Experimental solution?

$^{96}Zr(\alpha, n)^{99}Mo$ measurements → ATOMKI-V2 potential

We need a LOT of measurements:

- on relevant **energies**
- on relevant **isotopes**



G. G. Kiss+ (2021)

Relevant isotopes

Reaction	Z	MC tracers
$^{59}Fe(\alpha,n)^{62}Ni$	39 – 42, 45	34, 36
$^{68}Fe(\alpha,n)^{71}Ni$	36, 37	3
$^{63}Co(\alpha,n)^{66}Cu$	39–42, 45	20, 34, 36
$^{71}Co(\alpha,n)^{74}Cu$	36, 37	3
$^{74}Ni(\alpha,n)^{77}Zn$	36–42	2, 3, 17, 18, 32
$^{76}Ni(\alpha,n)^{79}Zn$	36–42	2, 3, 18, 32
$^{67}Cu(\alpha,n)^{70}Ga$	47	35
$^{77}Cu(\alpha,n)^{80}Ga$	37	3
$^{72}Zn(\alpha,n)^{75}Ge$	39–42	36
$^{76}Zn(\alpha,n)^{79}Ge$	36, 37–42	2, 3, 17, 18, 32
$^{78}Zn(\alpha,n)^{81}Ge$	36, 37–42	2, 3, 17, 18, 32
$^{79}Zn(\alpha,n)^{82}Ge$	36, 37–42	2, 3, 18, 32
$^{80}Zn(\alpha,n)^{83}Ge$	36, 37, 39–42	2, 3, 18, 32
$^{81}Ga(\alpha,n)^{84}As$	36, 38, 39, 41	17, 32
$^{78}Ge(\alpha,n)^{81}Se$	39–42	36
$^{80}Ge(\alpha,n)^{83}Se$	36–39, 42	28, 33, 36
$^{82}Ge(\alpha,n)^{85}Se$	36–39, 41	11, 17, 19, 27, 28, 33
$^{83}As(\alpha,n)^{86}Br$	36, 37, 41	11, 26, 27, 28, 33
$^{84}Se(\alpha,n)^{87}Kr$	36–42, 44, 45	2, 6, 7, 8, 9, 10, 11, 18, 19, 20, 22, 23, 24, 26, 27, 28, 29, 30, 31, 33, 34, 36
$^{85}Se(\alpha,n)^{88}Kr$	36–42, 44, 45	2, 6, 7, 8, 9, 10, 11, 18, 19, 22, 23, 24, 26, 27, 28, 29, 30, 31
$^{85}Br(\alpha,n)^{88}Rb$	37–39	6, 7, 8, 9, 10, 22, 23, 24, 26, 28, 29, 30, 31
$^{87}Br(\alpha,n)^{90}Rb$	37, 39	6, 9, 10, 29, 31
$^{88}Br(\alpha,n)^{91}Rb$	39	26
$^{86}Kr(\alpha,n)^{89}Sr$	38–42, 44, 45, 47	4, 5, 7, 8, 13, 14, 15, 16, 20, 24, 25, 33, 34, 35
$^{87}Kr(\alpha,n)^{90}Sr$	38–42, 45	4, 5, 7, 8, 13, 16, 20, 24, 25, 28, 30, 33, 34
$^{88}Kr(\alpha,n)^{91}Sr$	37–42, 44, 45	2, 4, 5, 6, 7, 8, 9, 11, 13, 16, 17, 18, 19, 20, 22, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34
$^{89}Kr(\alpha,n)^{92}Sr$	39, 40, 42, 44, 45	2, 6, 11, 17, 18, 19, 26, 27, 28, 29, 30, 32
$^{90}Kr(\alpha,n)^{93}Sr$	37–42, 44–46	2, 3, 6, 9, 10, 11, 17, 18, 19, 22, 26, 27, 28, 29, 30, 31, 32
$^{87}Rb(\alpha,n)^{90}Y$	41, 45	14, 15
$^{89}Rb(\alpha,n)^{92}Y$	41, 42	5, 7, 13, 20, 34
$^{88}Sr(\alpha,n)^{91}Zr$	42, 44	14, 15
$^{89}Sr(\alpha,n)^{92}Zr$	42	14, 15
$^{90}Sr(\alpha,n)^{93}Zr$	42, 44–47	4, 5, 12, 13, 14, 15, 16, 20, 35
$^{91}Sr(\alpha,n)^{94}Zr$	44, 45	5, 12, 13, 16
$^{92}Sr(\alpha,n)^{95}Zr$	38, 42, 44–47	4, 5, 6, 7, 8, 11, 12, 13, 16, 20, 21, 22, 23, 24, 25, 28, 29, 30, 31, 34
$^{93}Sr(\alpha,n)^{96}Zr$	42, 44 – 47	6, 7, 9, 10, 11, 22, 26, 27, 28, 29, 30, 31
$^{94}Sr(\alpha,n)^{97}Zr$	37–42, 44–47	2, 6, 7, 8, 9, 10, 11, 18, 19, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32
$^{94}Y(\alpha,n)^{97}Nb$	45	4, 8, 16, 21, 23, 24, 25
$^{95}Y(\alpha,n)^{98}Nb$	45, 46	8, 23, 24, 25, 30
$^{94}Zr(\alpha,n)^{97}Mo$	44, 45	14, 15, 35
$^{95}Zr(\alpha,n)^{98}Mo$	45–47	5, 12, 13, 35
$^{96}Zr(\alpha,n)^{99}Mo$	44–47	4, 5, 6, 7, 8, 12, 13, 16, 20, 21, 22, 23, 24, 25, 29, 30, 35
$^{97}Zr(\alpha,n)^{100}Mo$	44, 46, 47	4, 5, 6, 7, 8, 21, 22, 23, 24, 25, 29, 30
$^{98}Zr(\alpha,n)^{101}Mo$	44, 46, 47	6, 7, 8, 22, 23, 24, 25, 29, 30
$^{97}Nb(\alpha,n)^{100}Tc$	45, 46, 47	12, 13, 14, 15, 35

Experimental solution?

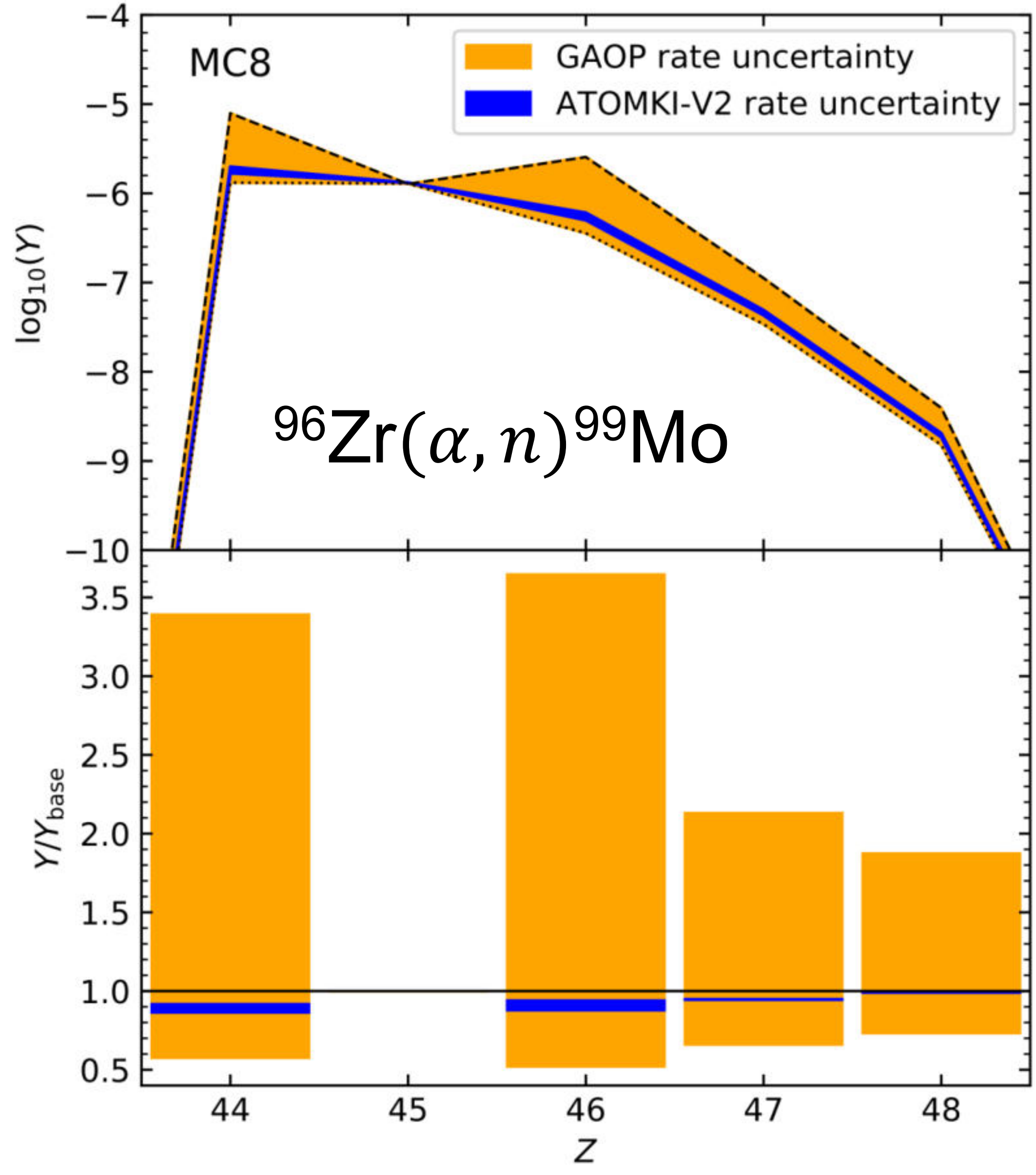
$^{96}Zr(\alpha, n)^{99}Mo$ measurements → ATOMKI-V2 potential

We need a LOT of measurements:

- on relevant **energies**
- on relevant **isotopes**

Ongoing experiments:

- NSCL
- ANL
- Triumph
- ATOMKI



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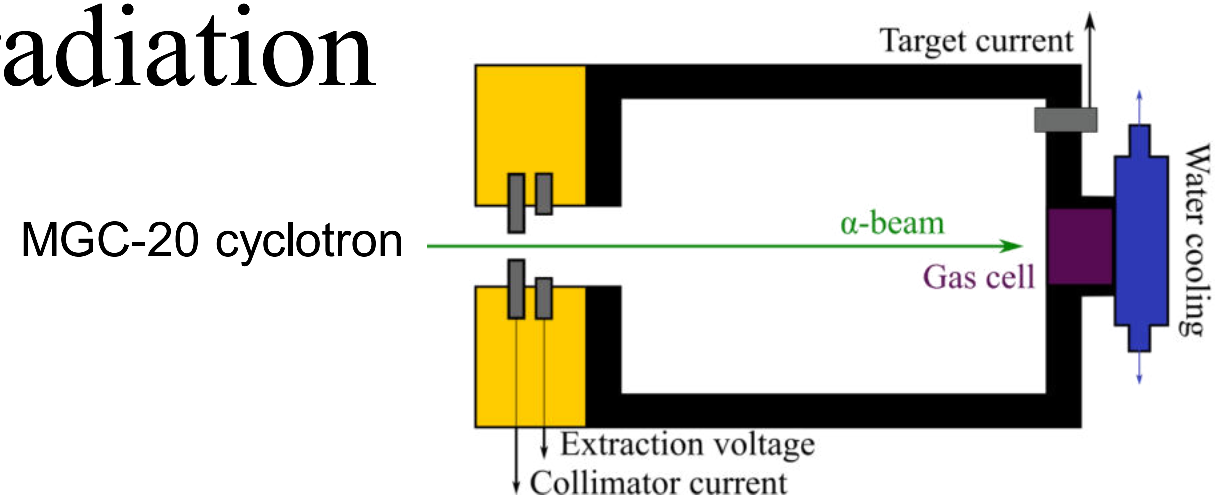
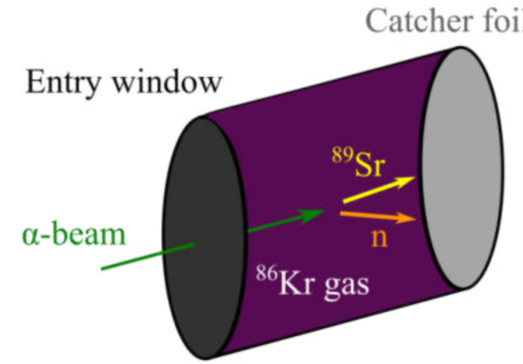
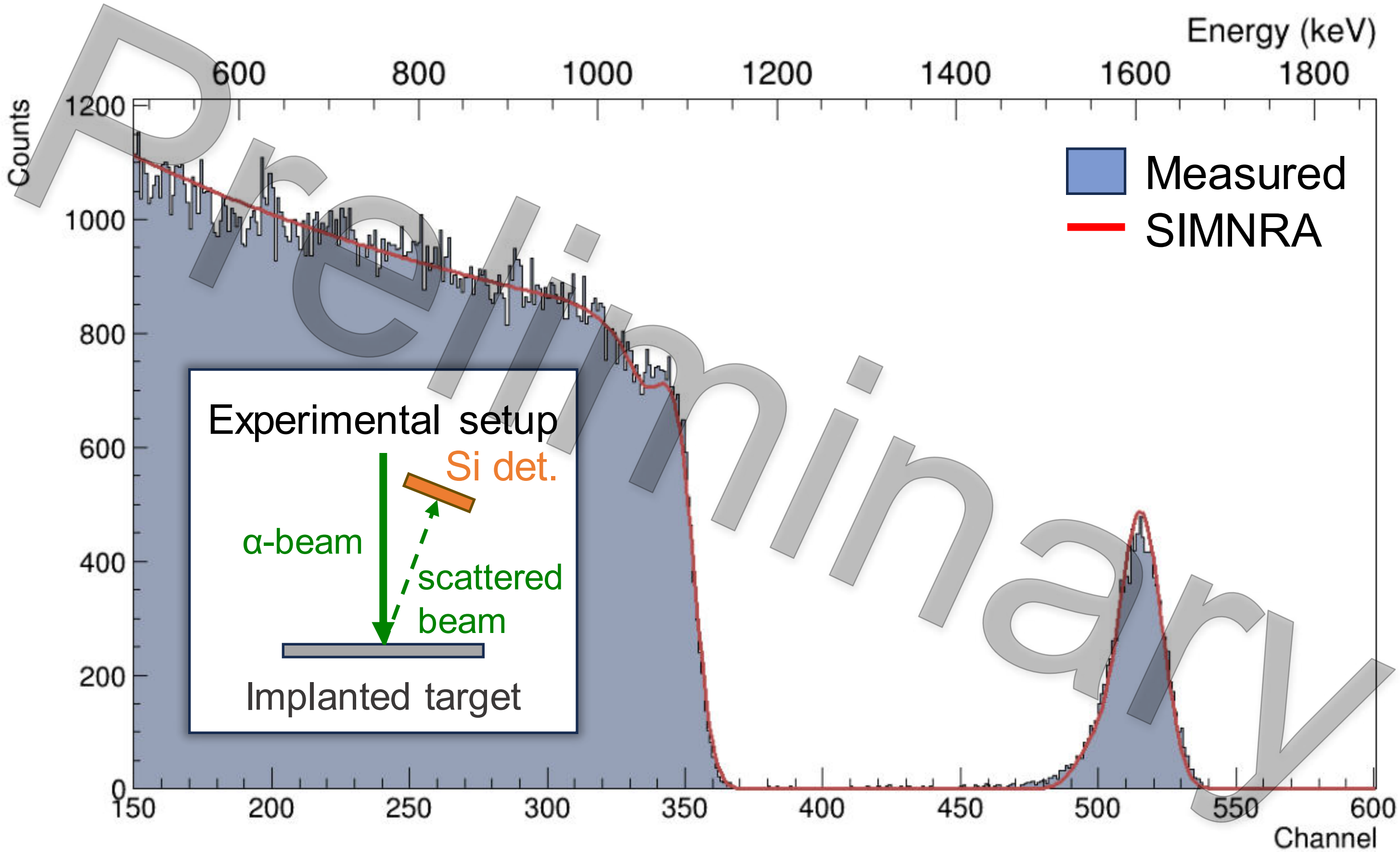
Irradiation



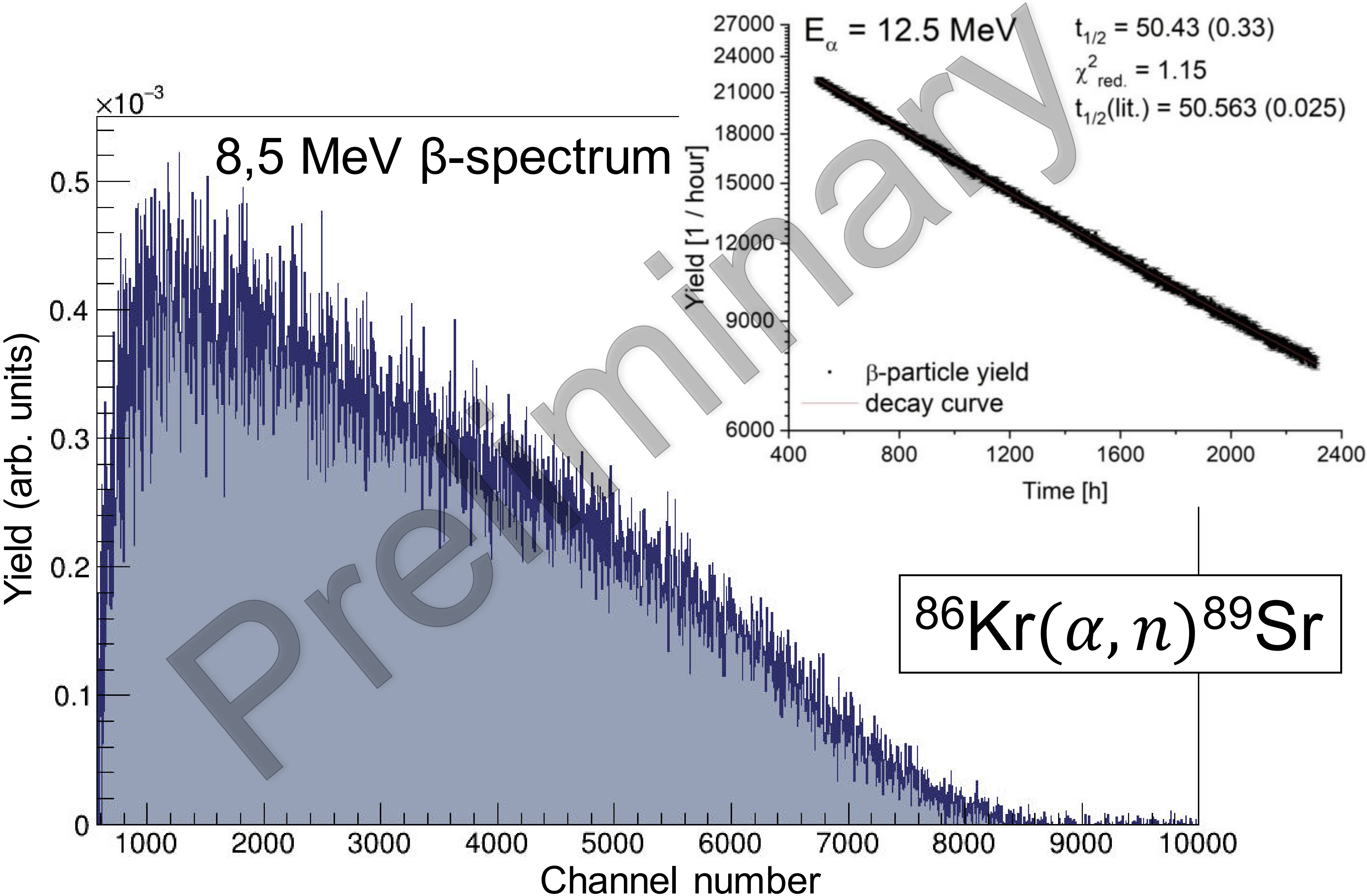




Alternative:

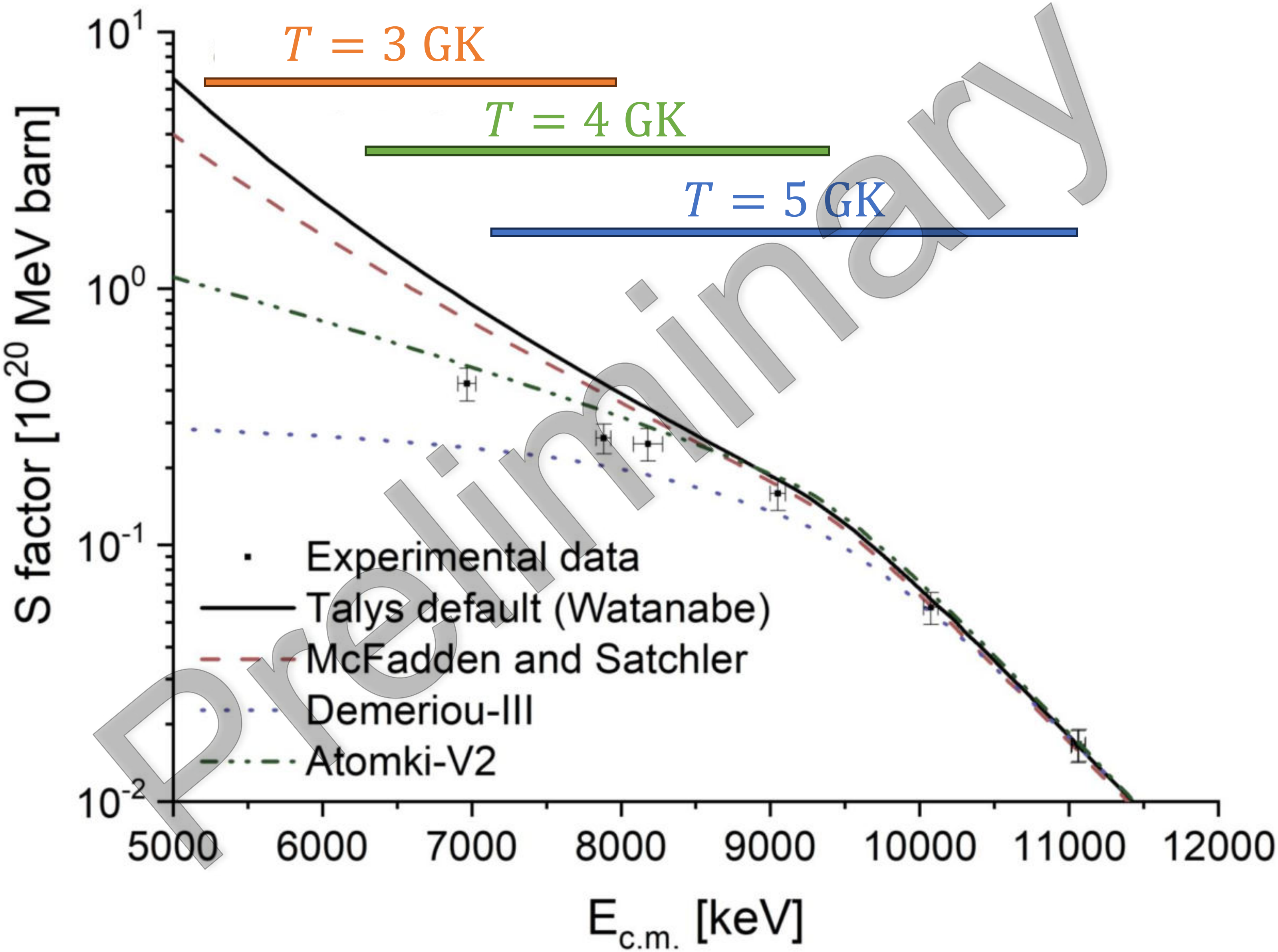
implanted target

Activity measurement



$^{86}Kr(\alpha,n)^{89}Sr$

Results and astrophysical analysis



Summary

Weak r-process

- Charged particle captures $(\alpha,n),(p,n),(\alpha,\gamma),(p,\gamma)$
- ^{86}Kr(α,n) key reaction ⟷ Cross section uncertain from theory

Activation method:

- Gas target
- Implanted target
- Current measurement
- β-decay

$^{86}\mathrm{Kr}(\alpha,n)^{89}\mathrm{Sr}$

Results and astrophysical implications:

Factor of 10 uncertainty from theory → constrained uncertainty

Thank you!

Gábor Kiss

Peter Mohr

Fernando Montes

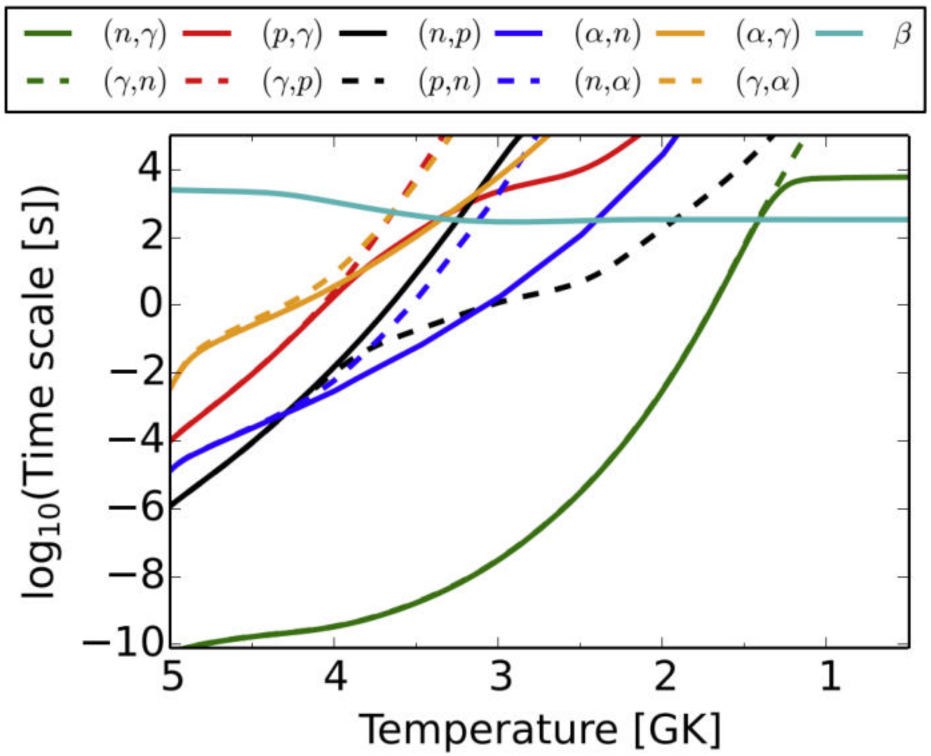
Arcones Almudena

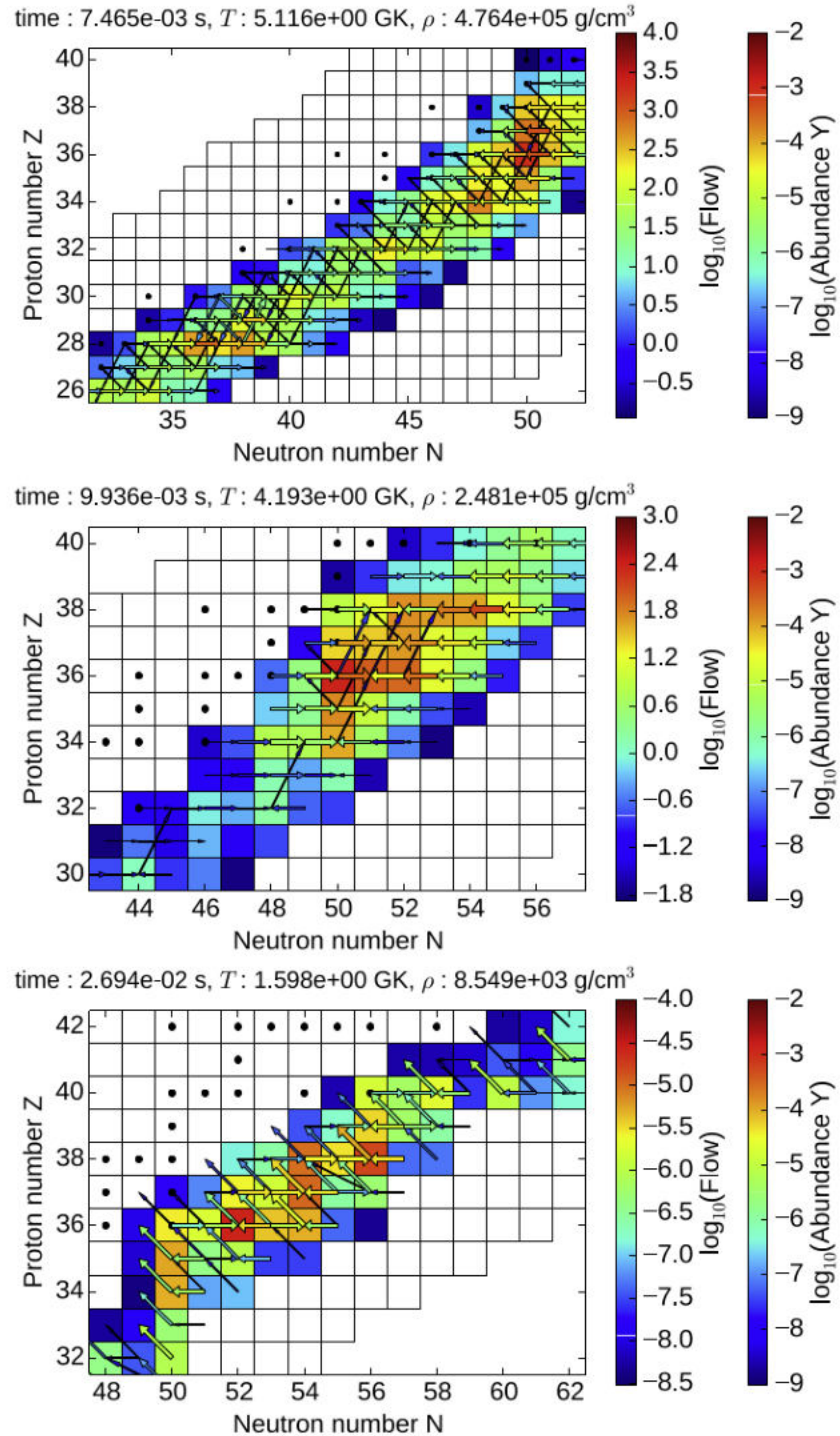
Fig.1: J. Bliss, A. Arcones, F. Montes and J. Pereira, J. Phys. G: Nucl. Part. Phys. **44** (2017) 054003: 10.1088/1361-6471/aa63bd

Fig. 2, Tab. 1, Tab. 2: J. Bliss, A. Arcones, F. Montes and J. Pereira, PRC **101** (2020) 055807: 10.1103/PhysRevC.101.055807

Fig. 4: G. G. Kiss et. al, APJ **908**, (2021) 202: 10.3847/1538-4357/abd2bc

Temperature dependence





J. Bliss+ 2017