Designing the next generation of materials for rare-event searches: high-strength, ultra-pure Cu-based alloys

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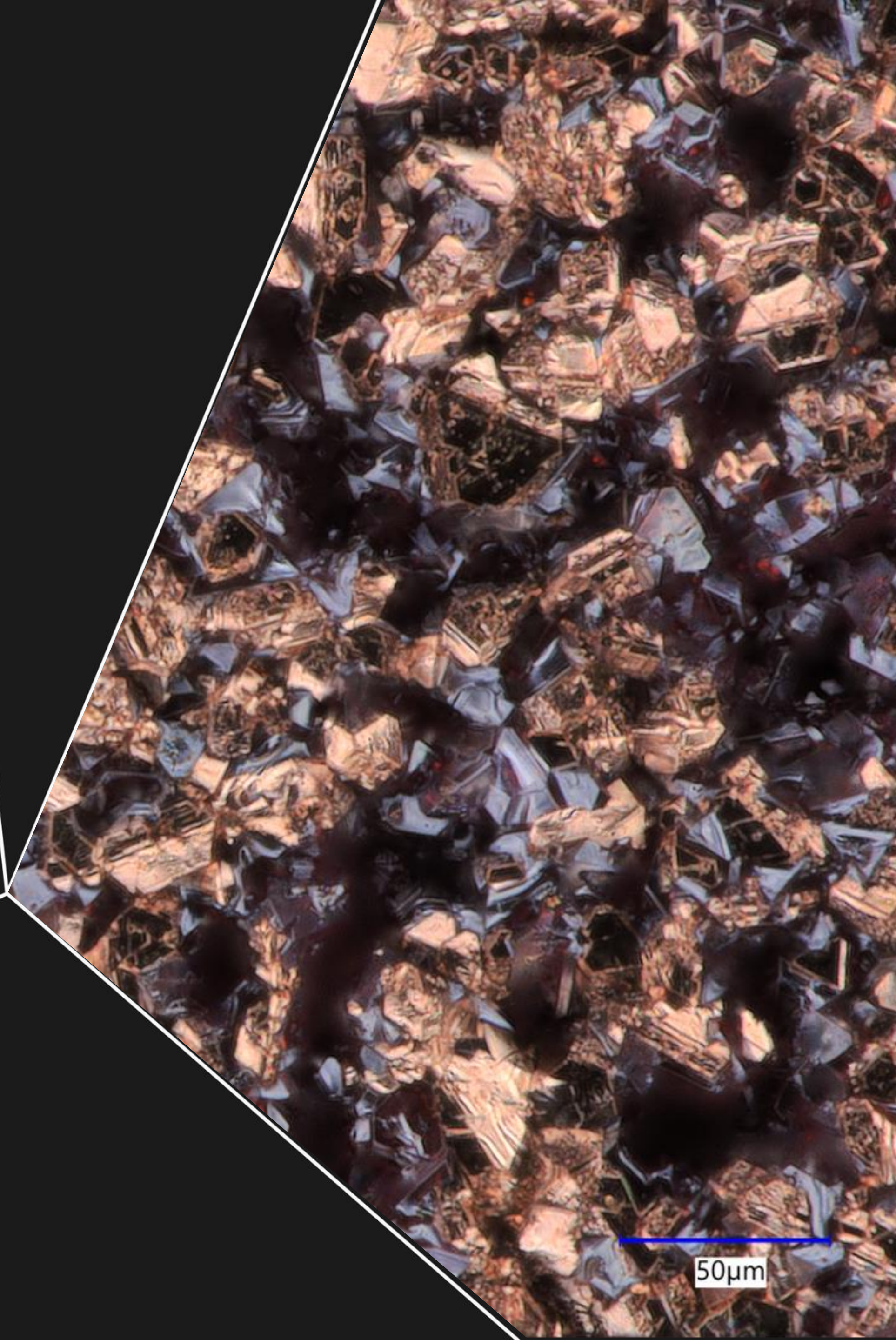
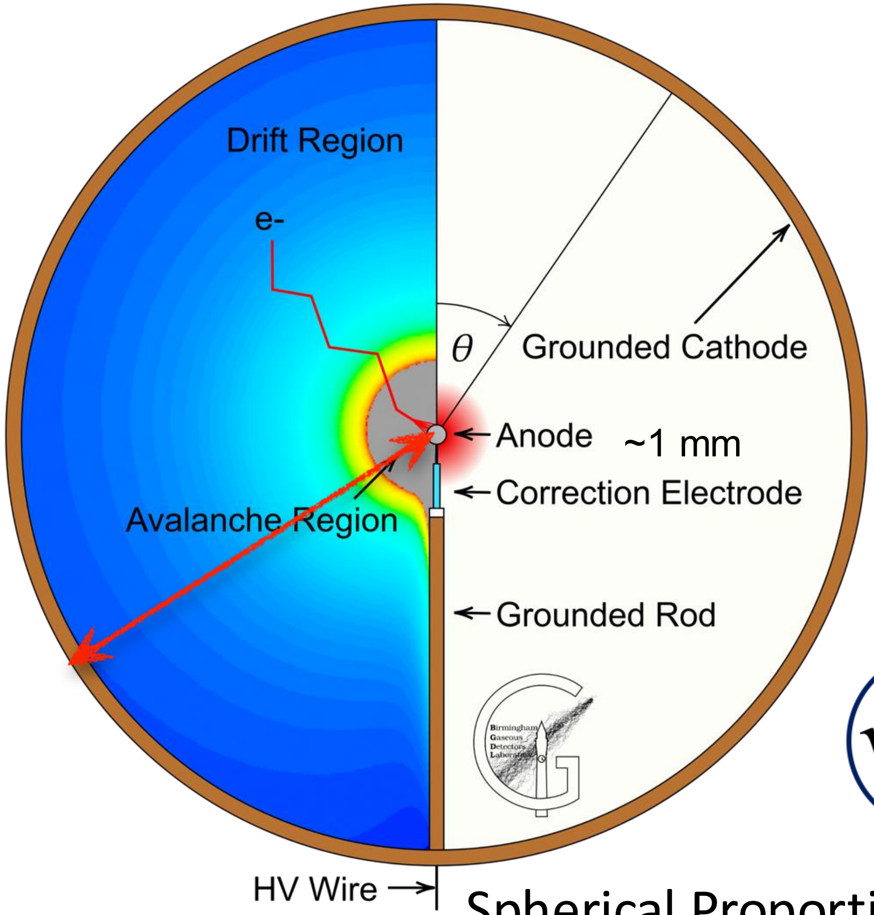
UK Research and Innovation

Horizon Europe

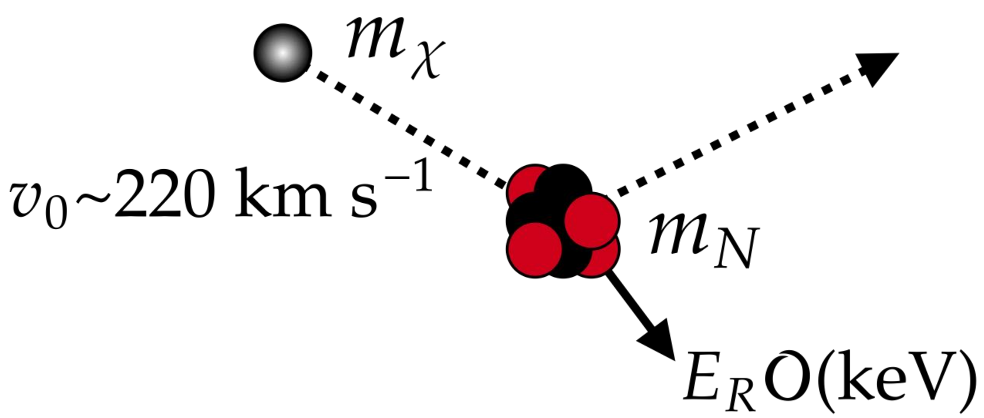
UNIVERSITY OF BIRMINGHAM



Motivation: Dark Matter Direct detection



Spherical Proportional Counter (SPC)



NEWS-G S140 in SNOLAB

Radiopure Cu for rare event searches

- <u>Cu</u>: common material for rare event searches experiments

✓ Electrically conductive

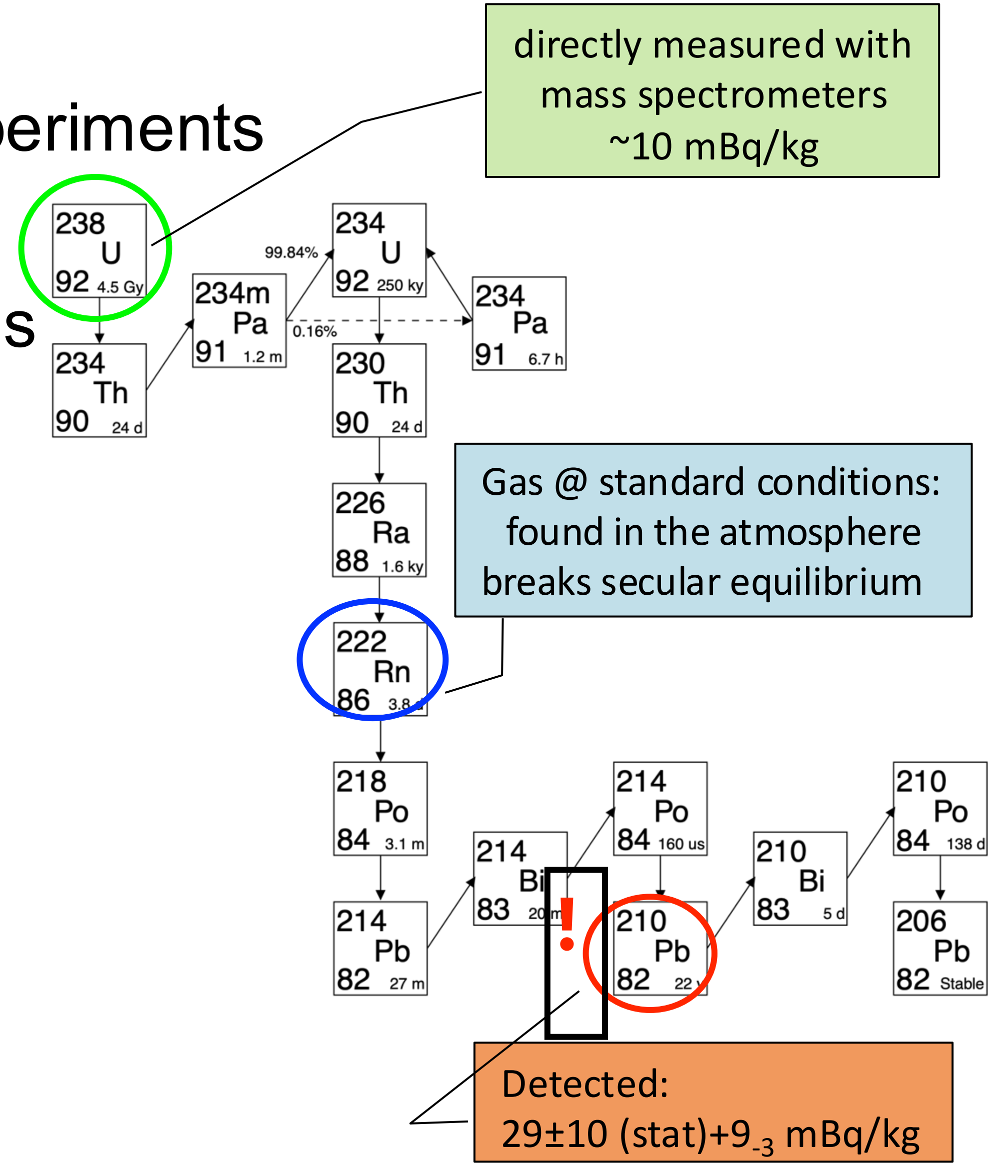
✓ Strong enough to build low-pressure gas vessels

✓ No long-lived isotopes (^{67}Cu $t_{1/2}$=62h)

✓ Low cost/commercially available at high purity

- <u>Backgrounds</u>

1. Cosmogenic: $^{63}Cu(n,\alpha)^{60}Co$ from fast neutrons
2. Contaminants: $^{238}U/^{232}Th$ decay chains



Dimitra Spathara l d.spathara@bham.ac.uk l July 2026

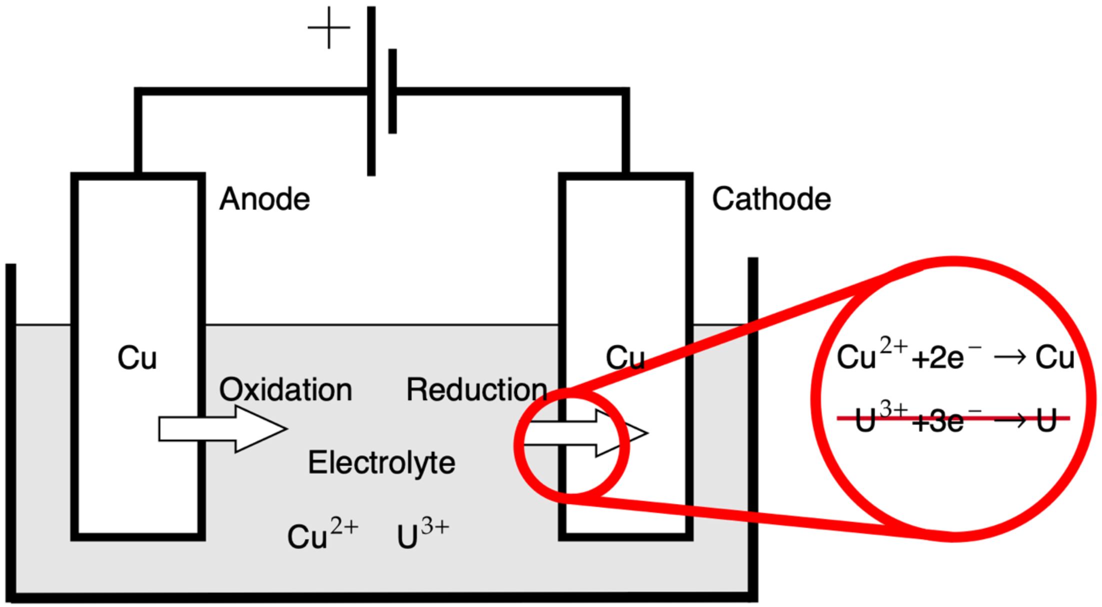
Electroformed Cu (EFCu) for rare event searches

Reduction potential for copper and possible radiocontaminants.

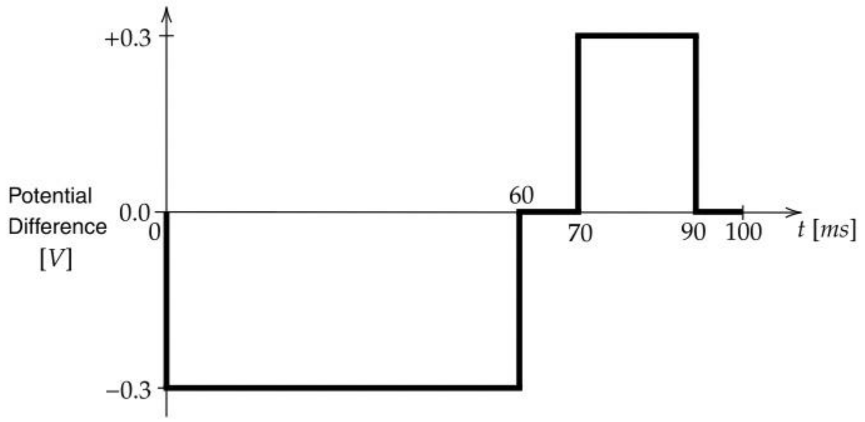
Reductants		Oxidants	E^0 (V)
$Cu^{2+} + 2e^-$	$\leftrightharpoons$	Cu	+0.34
$Pb^{2+} + 2e^-$	$\leftrightharpoons$	Pb	−0.13
$U^{3+} + 3e^-$	$\leftrightharpoons$	U	−1.80
$Th^{4+} + 4e^-$	$\leftrightharpoons$	Th	−1.90
$K^+ + e^-$	$\leftrightharpoons$	K	−2.93

Cu '**high reduction** potential' → preferentially deposited

→ Additive-free, electroforming



NIMA 988 (2021) 164844



rare event searches:
e.g. LEGEND, NEWS-G, ANAIS, Majorana, nEXO, DarkSPHERE

Ultra-pure Cu electroforming

Majorana Demonstrator

#	Material	Method	K (10^{-9} g/g)	^{232}Th (10^{-12} g/g)	^{238}U (10^{-12} g/g)
	Metals				
1	Cu Electroformed Stock Sample	ICPMS		<0.17	
2	Cu Electroformed Stock Sample	ICPMS		0.011±0.005	0.017±0.003
3	Cu Electroformed Stock Sample	GDMS	<2.2	<50	<70
4	Cu Electroformed Stock Sample	ICPMS		<0.029	<0.008
5	Cu Electroformed Stock Sample	ICPMS		<0.029	<0.009
6	Cu Electroformed Stock Sample	ICPMS		<0.029	<0.008
7	Cu Electroformed Stock Sample	ICPMS		<0.030	<0.009
8	Cu Electroformed, machined part, guide clip	ICPMS		0.330 ± 0.022	0.123 ± 0.005
9	Cu Electroformed, machined part, guide clip	ICPMS		0.112 ± 0.009	0.078 ± 0.002
10	Cu Electroformed, machined part, guide clip	ICPMS		0.170 ± 0.008	0.087 ± 0.002
11	Cu Electroformed, machined part, spring clip	ICPMS		0.215 ± 0.009	0.130 ± 0.010
12	Cu Electroformed, machined part, hex bolt	ICPMS		0.118 ± 0.011	0.035 ± 0.004
13	Cu Electroformed, machined part, hex bolt	ICPMS		0.119 ± 0.014	0.041 ± 0.003
14	Cu Electroformed, machined part, hex bolt	ICPMS		0.148 ± 0.021	0.051 ± 0.002
15	Cu, C10100 cake stock, (source for Rows 16,17)	ICPMS		0.46 ± 0.06	0.21 ± 0.06
16	Cu, C10100 2.5" plate stock, exterior sample	ICPMS		0.27±0.05	0.10±0.02
17	Cu, C10100 2.5" plate stock, interior sample	ICPMS		0.27±0.05	0.12±0.02
18	Cu, C10100 1" plate stock, saw cut (same stock Row 19)	ICPMS		10.2 ± 1.0	6.62 ± 0.58
19	Cu, C10100 1" plate stock, machined surfaces	ICPMS		1.88 ± 0.45	3.11 ± 0.39
20	Cu, C10100 1" x 2" bar stock, machined surfaces	ICPMS		2.12 ± 0.39	2.25 ± 0.15
21	Cu, C10100 1" plate stock	ICPMS		<0.029	0.013 ± 0.002
22	Cu, C10100 2.5" plate stock	ICPMS		<0.030	0.017 ± 0.003
23	Cu, C10100 2.5" plate stock	ICPMS		0.049 ± 0.010	0.061 ± 0.006
24	Cu, C10100 0.5" plate stock	ICPMS		<0.030	0.009 ± 0.001

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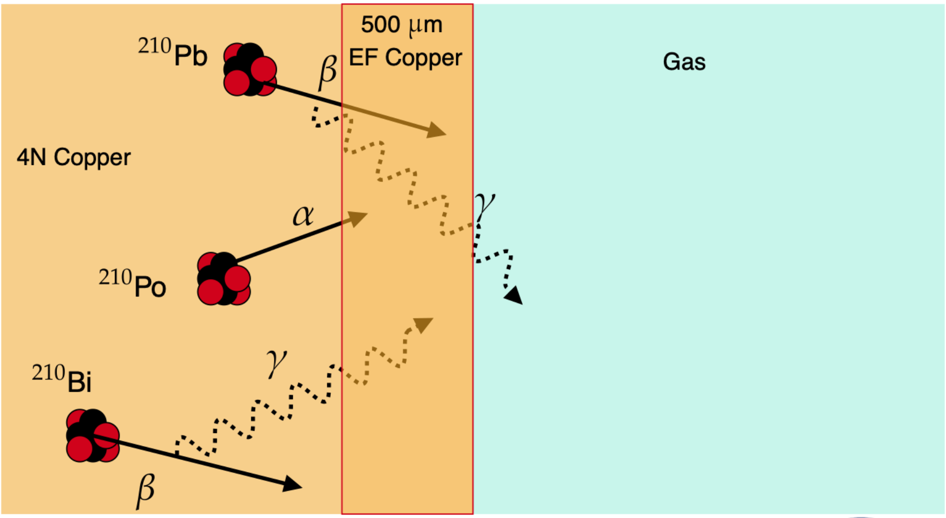
NEWS-G EFCu coating



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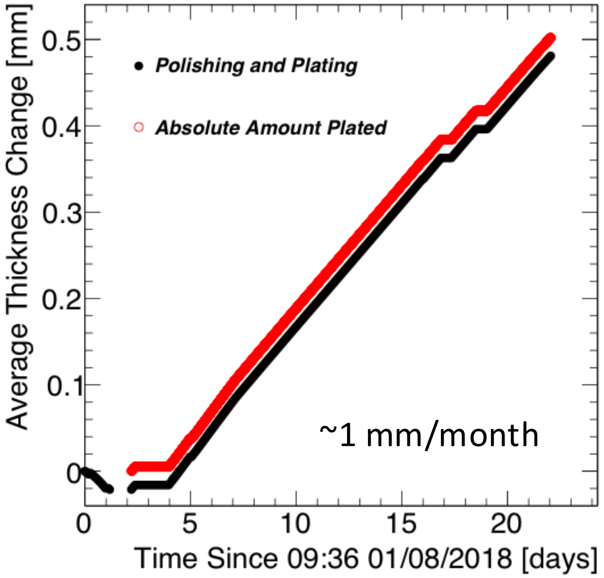
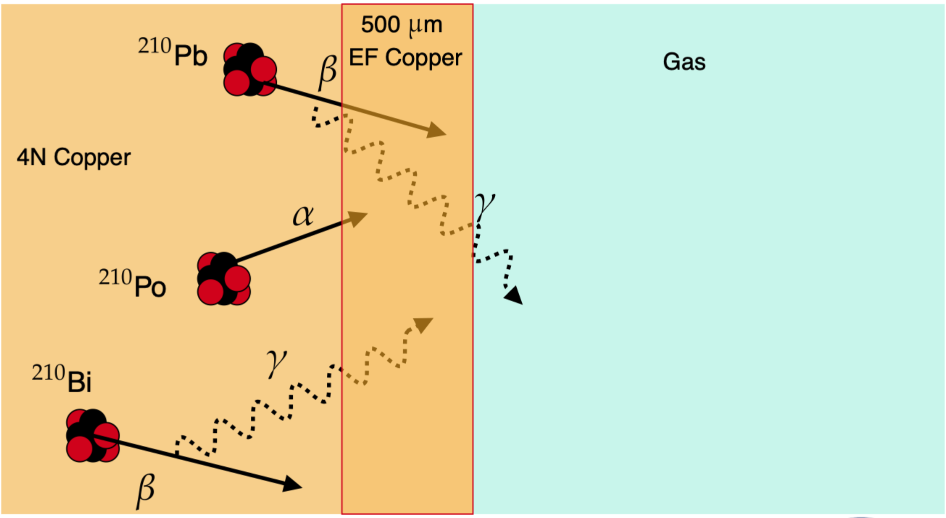
- ✓ 500 μm electroplated layer to NEWS-G detector inner surface
- ✓ Demonstrated potential to electroform full detector on feasible time scale

Ultra-pure Cu electroforming



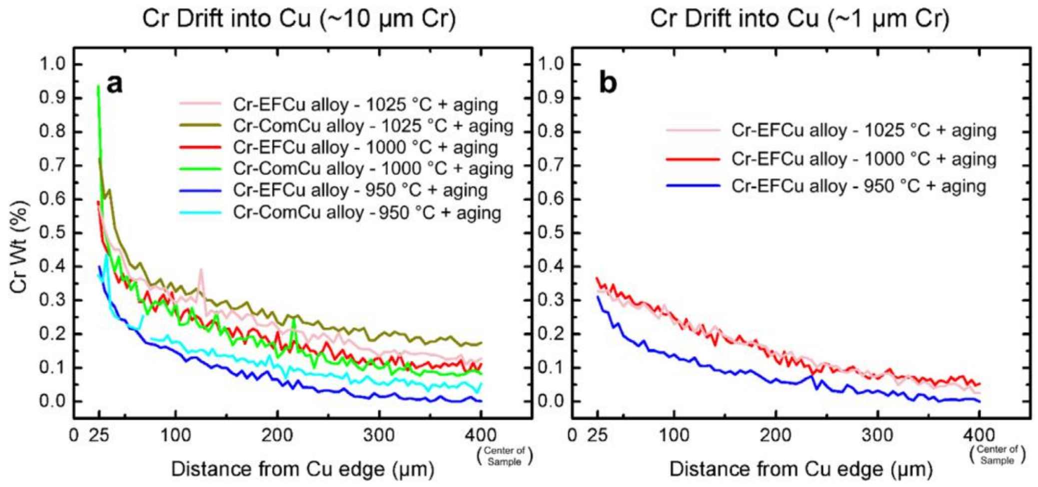
Sample	Weight [g]	^{232}Th [µBq kg^{-1}]	^{238}U [µBq kg^{-1}]
C10100 Cu (Machined)	-	8.7 ± 1.6	27.9 ± 1.9
Cu Electroformed	-	<0.119	<0.099
Hemisphere 1	0.256	<0.58	<0.26
Hemisphere 2	0.614	<0.24	<0.11



NIMA 988 (2021) 164844

- ✓ 500 µm electroplated layer to NEWS-G detector inner surface
- ✓ Demonstrated potential to electroform full detector on feasible time scale

Motivation of ultra-pure, high-strength Cu-based alloys

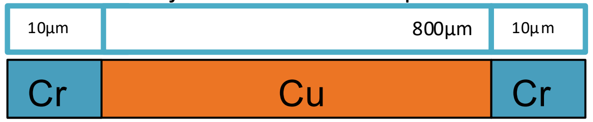


- ✓ Retain EFCu capabilities for rare event searches
- ✓ Option for stronger material compared to EFCu
- ✓ Scale up the current geometries for gas vessels (i.e. maximising the physics potential in DM experiments)

Alloying EFCu with Cr additions

1. Cr and Cu layers from separate solutions
2. Solution heat treatment at **1000ºC** (homogenisation)
3. Aging at **400ºC – 12 hours** (precipitation strengthening)

adjacent diffusion couples



~70% harder

Sample	[Th] pgTh/gSample	±sd	[U] pgU/gSample	±sd
EFCu	0.011	0.005	0.017	0.003
Cr	8.72	0.32	2.37	0.61
Cu-Cr(0.585wt%) projection	0.062	0.007	0.031	0.007

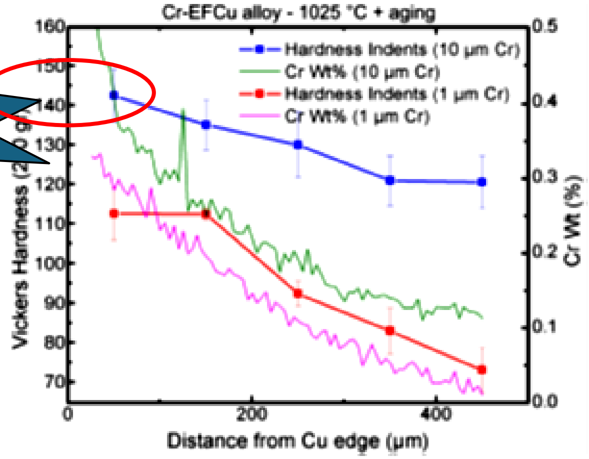
Cr and Cu layers

EFCu	72 HV
Cu-0.585Cr	121 HV

Homogenisation 24h:
950ºC
1000ºC
1025ºC

Aging:
500ºC – 12 hours

~100% harder

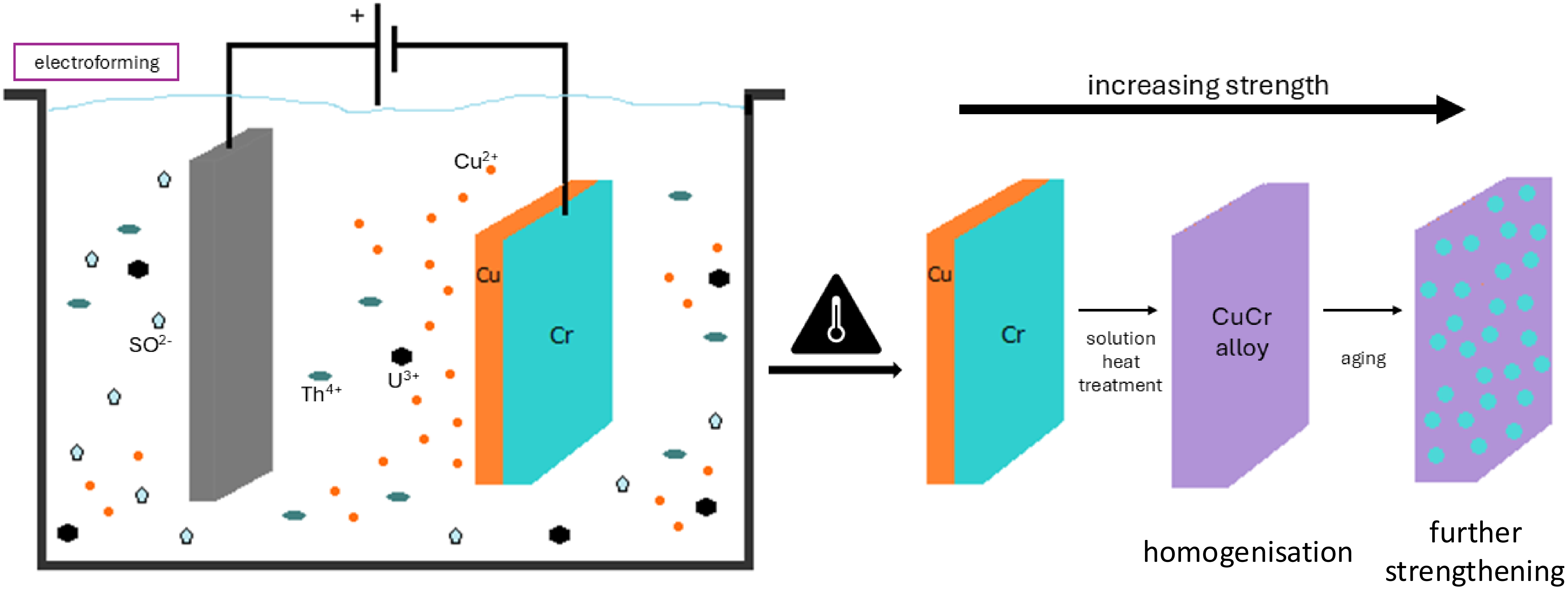


Suriano et al. AIP Conf Proc 1921, 1003 (2018) 080001

A. Vitale et al. NIMA 1003 (2021) 165291

Designing using CALPHAD-based tools

Proposed manufacturing process for radiopure Cu-based alloys



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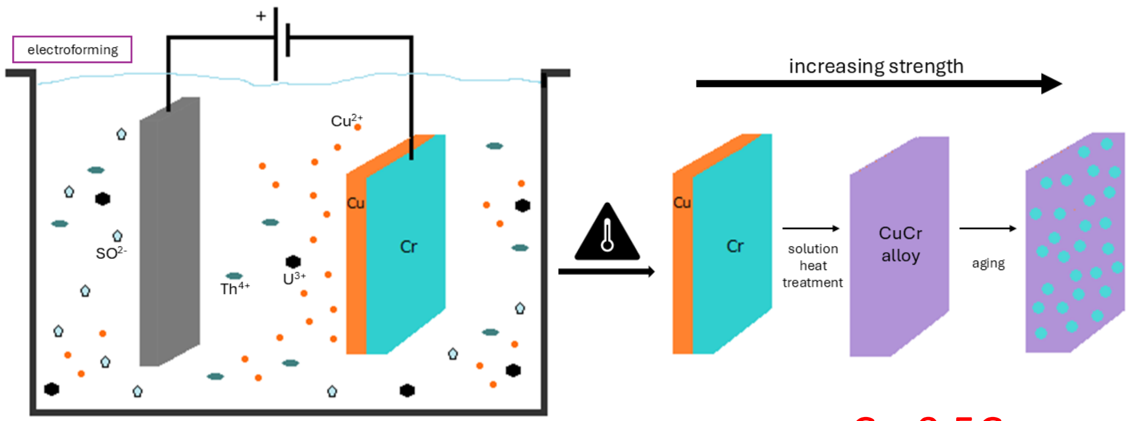
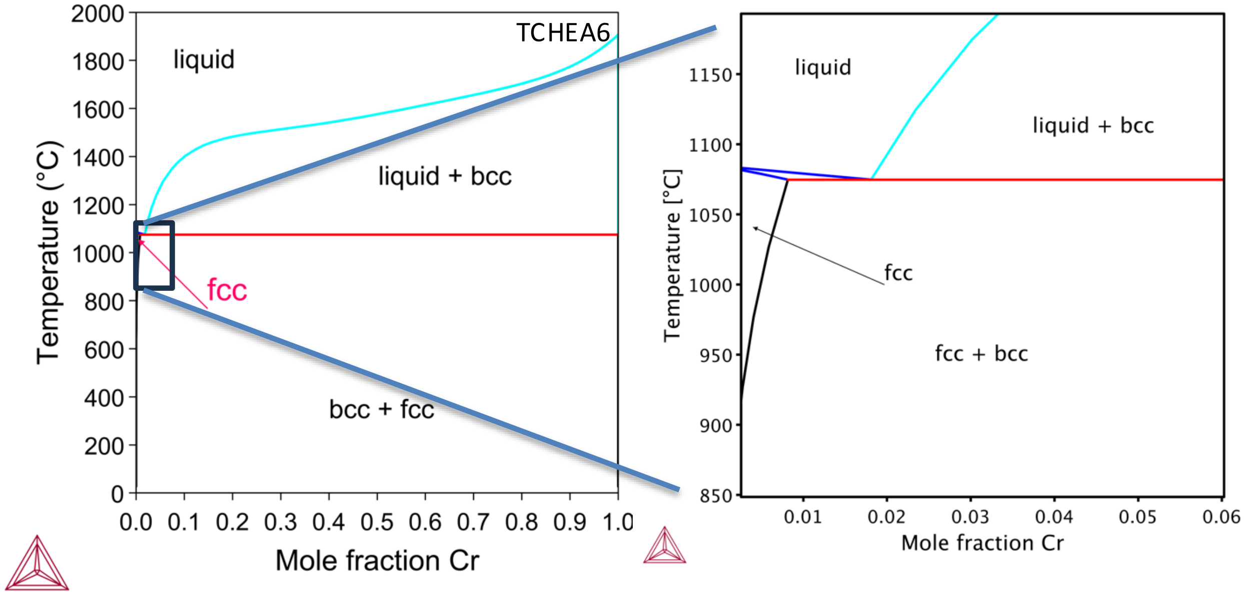
Modelling solution heat treatment and aging

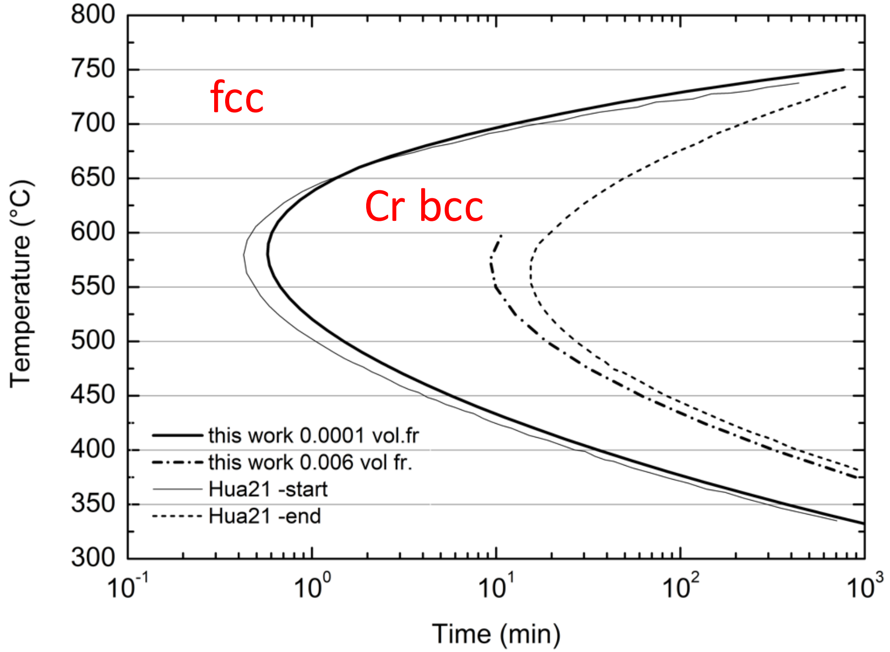


Cu-0.5Cr

Cu-Cr phase diagram



Calculated TTT diagram using TC-PRISMA



TCHEA6 - MOBHEA3

Compared with
TCCU3 - MOBCU3

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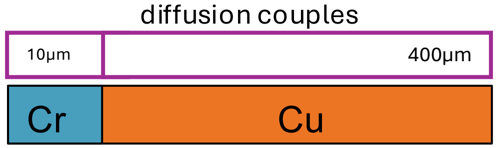
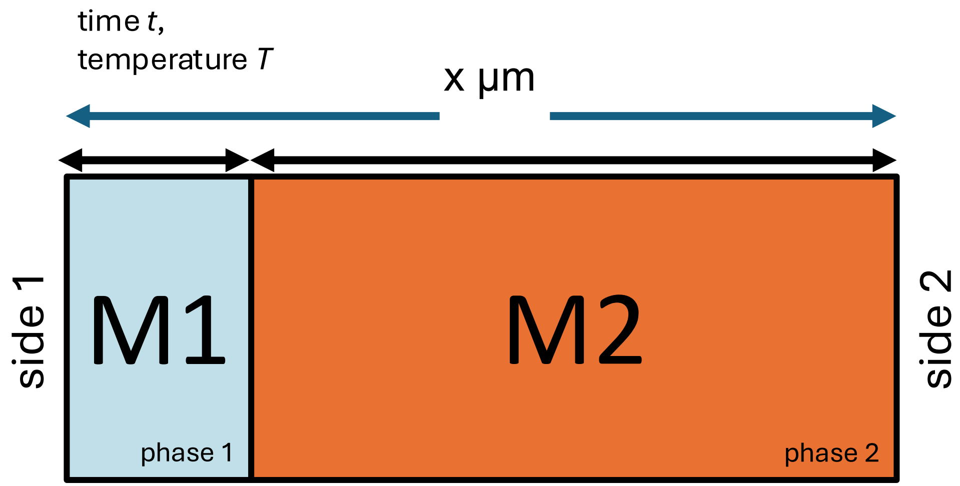
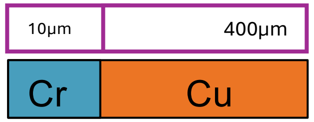
Modelling solution heat treatment using DICTRA



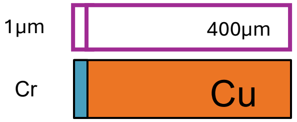
Optimise *T* and *t* for solution heat treatment

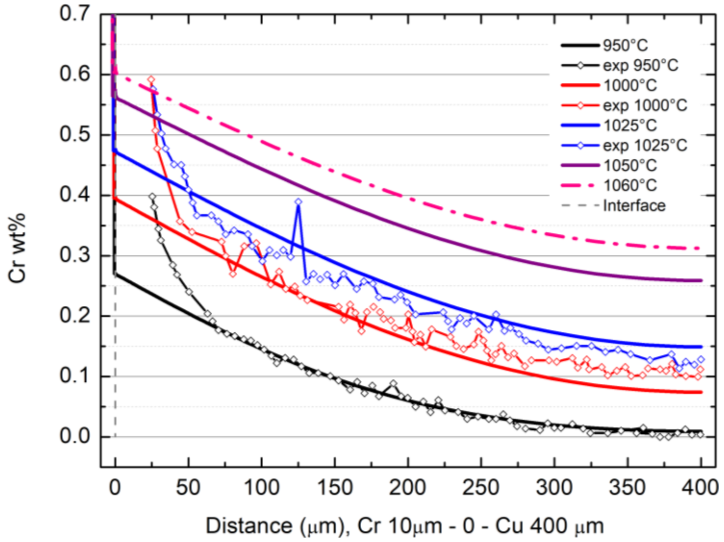


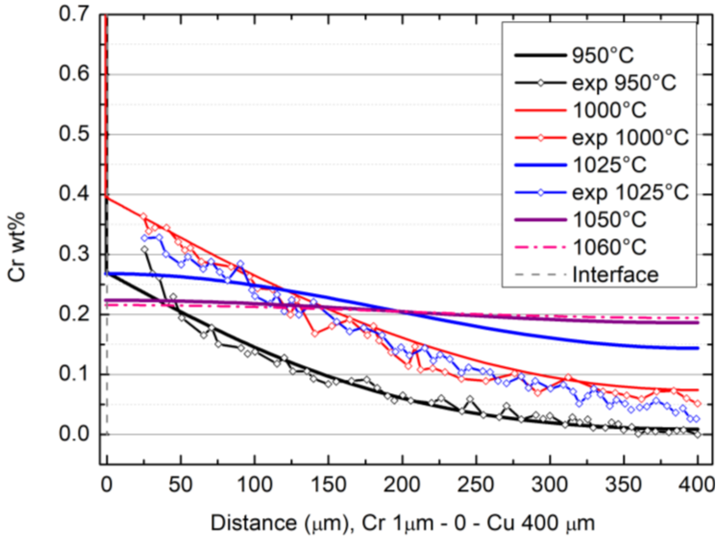
D. Spathara et al. Metall Trans A (2018)



Thermo-Calc databases
TCHEA6 - MOBHEA3
24h isothermals







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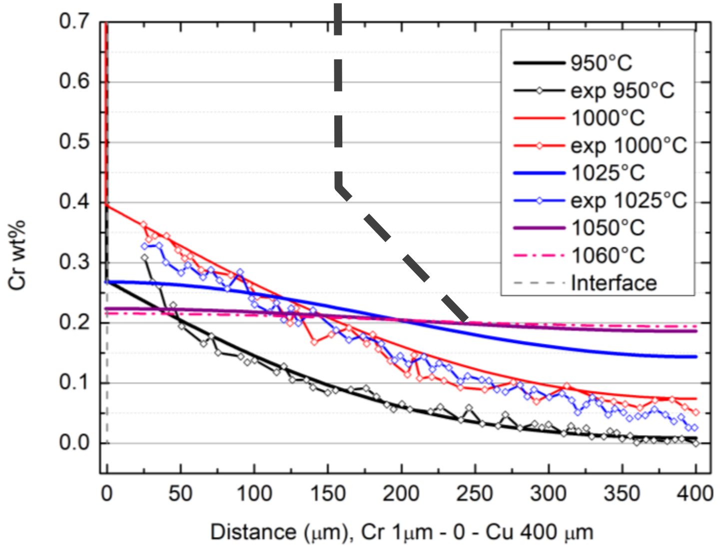
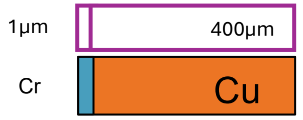
Modelling solution heat treatment using DICTRA

Cu-0.2Cr
1060°C or more than 24h





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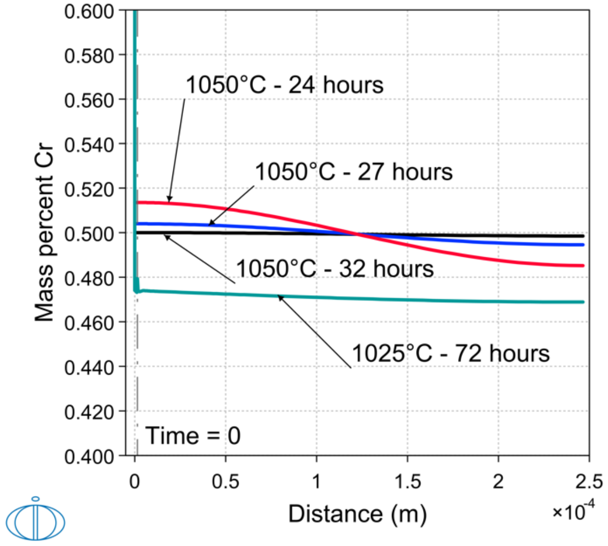
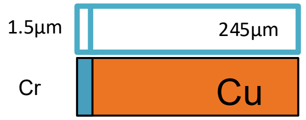
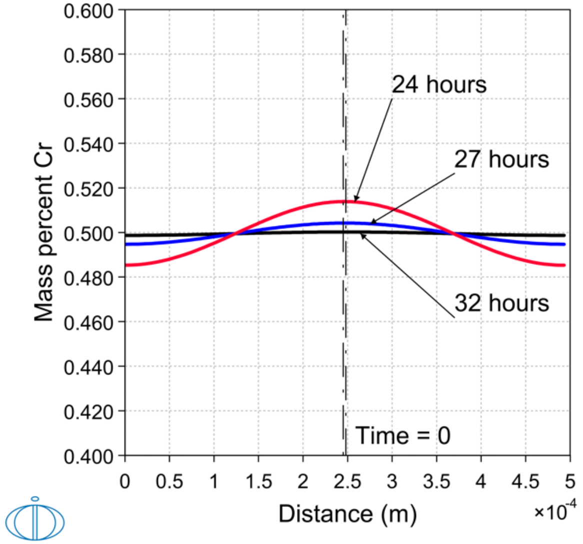
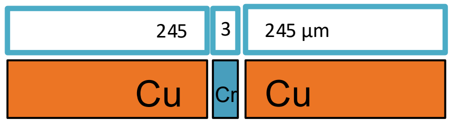
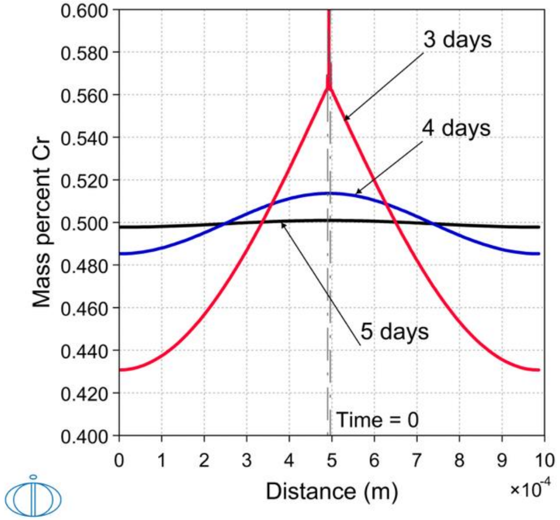
Solution heat treatment → Cu-0.5Cr

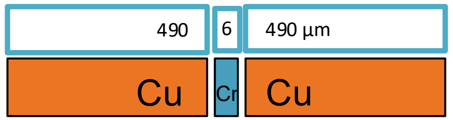












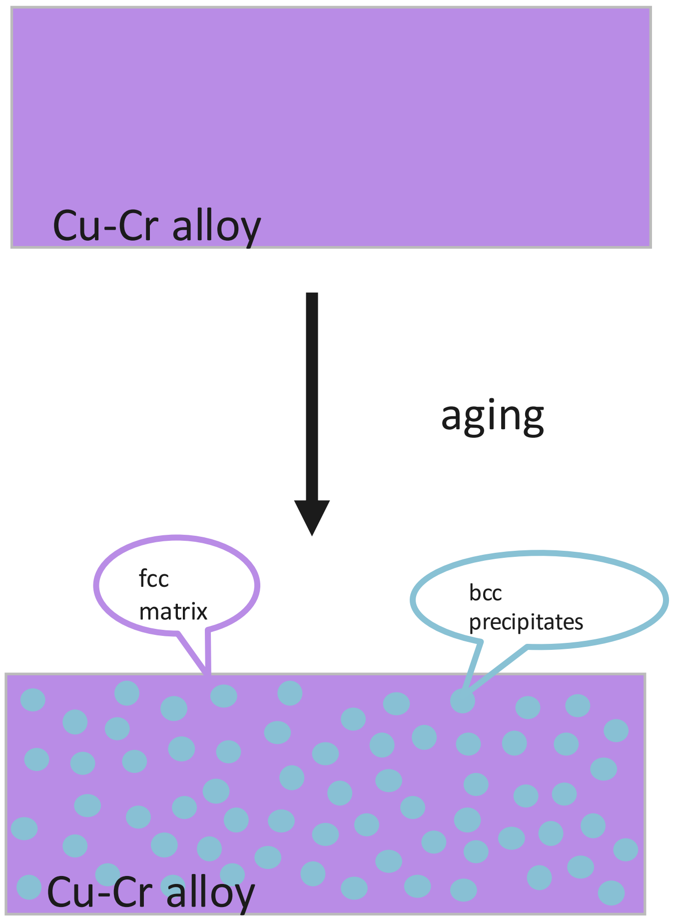
D. Spathara et al. Commun Phys (2025)

Thermo-Calc databases
TCHEA6 - MOBHEA3

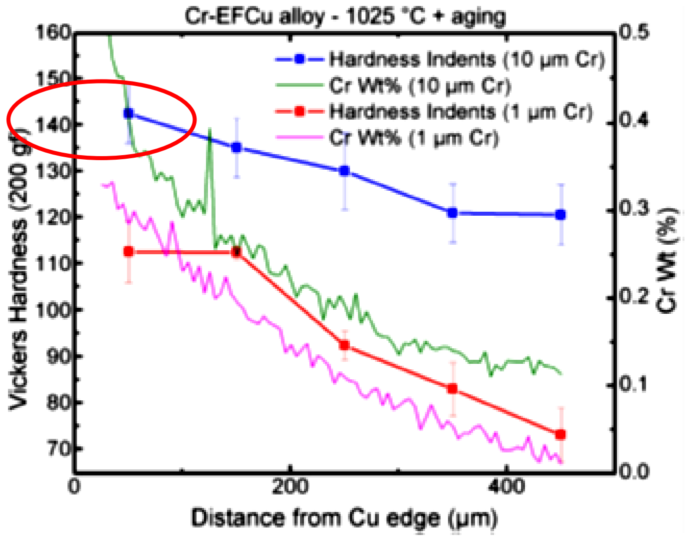
Strengthening mechanism during aging

Optimise *T* and *t* for aging

homogeneous alloy



500°C – 12 hours



Cu-0.4Cr	140 HV

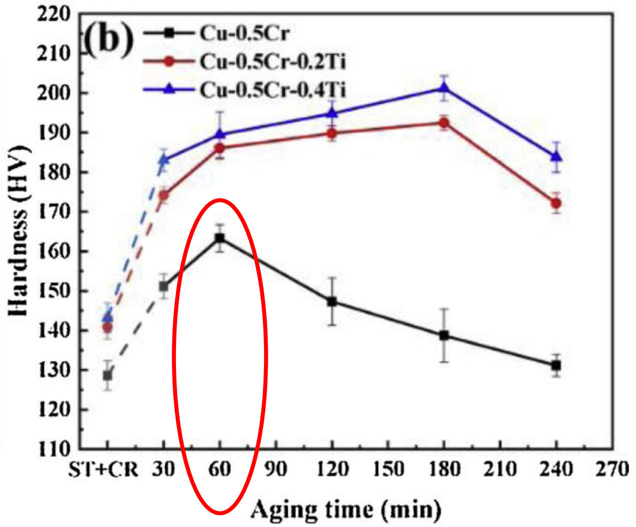
Vitale et al. 2021

400°C – 12 hours

EFCu	72 HV
Cu-0.585Cr	121 HV

Suriano et al. 2018

450°C – 60 min



Cu-0.5Cr	150 HV
Cu-0.5Cr0.2Ti	230 HV
Cu-0.5Cr0.4Ti	280 HV

Huang et al. 2021

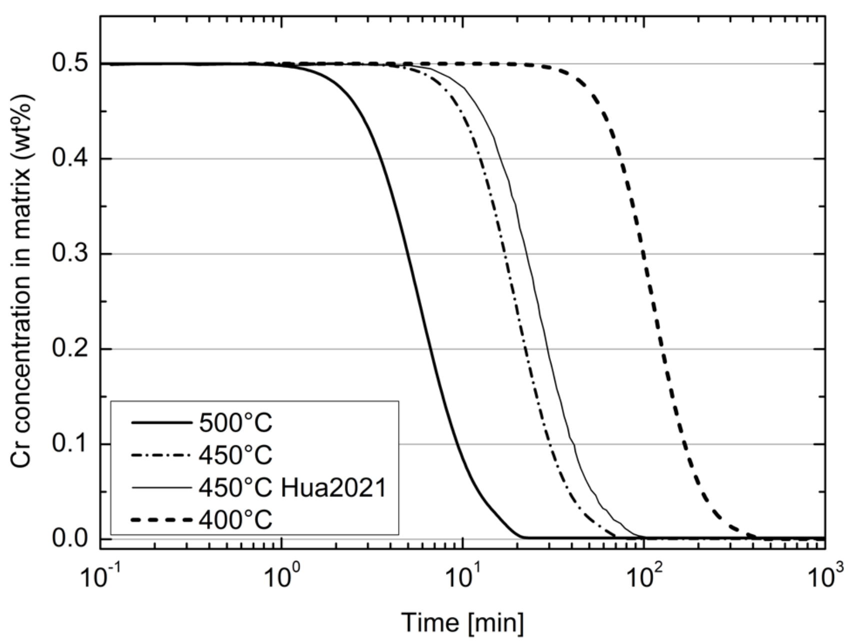
Predicting strengthening during aging using TC-PRISMA

Cu-0.5Cr

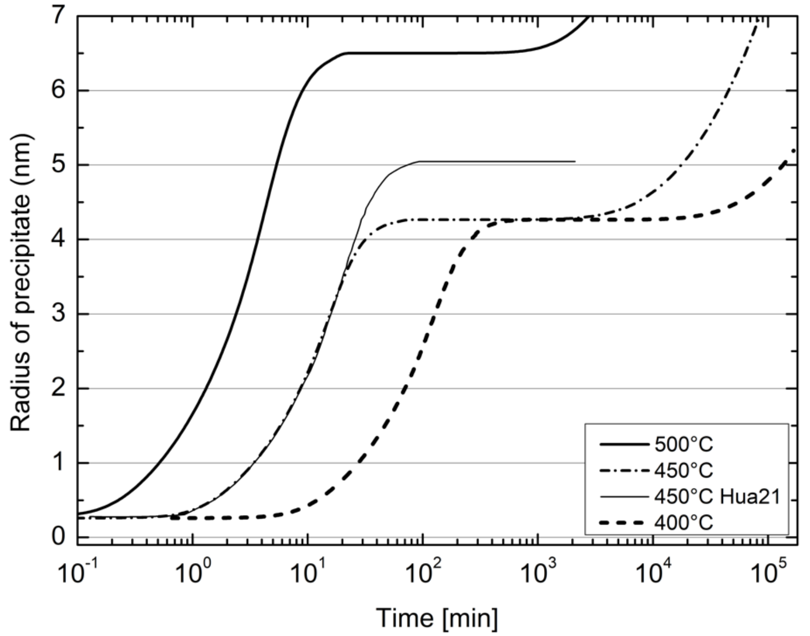
Thermo-Calc databases

TCHEA6 - MOBHEA3

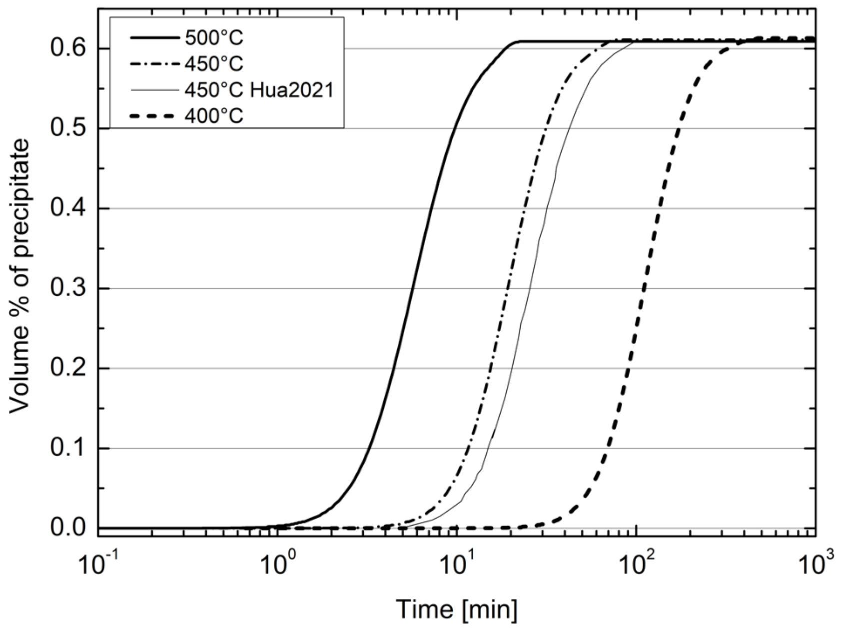
Cr concentration in the matrix



mean radius of precipitates



Volume of Cr precipitate



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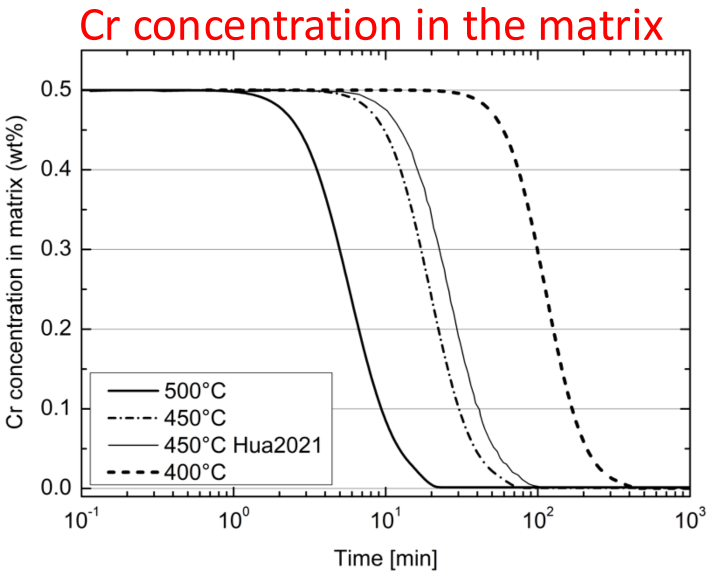
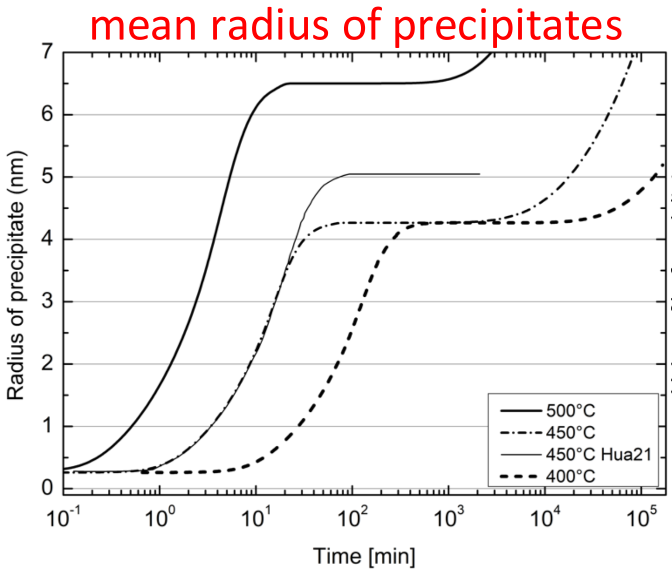
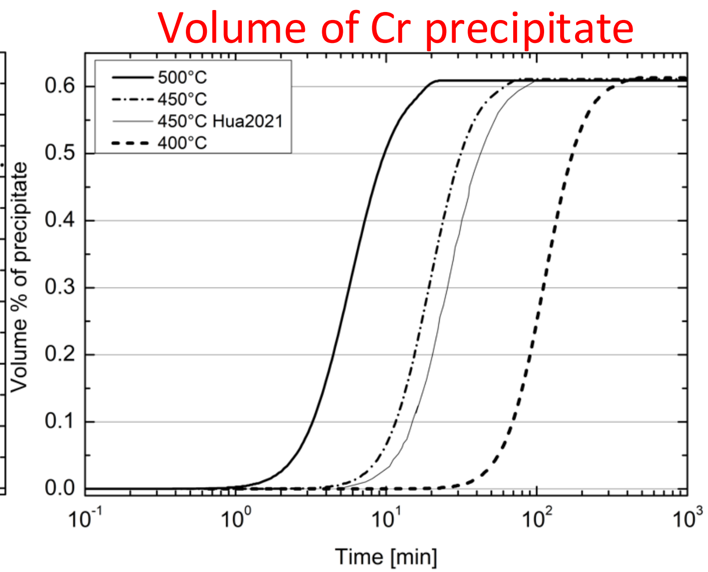
Predicting strengthening during aging using TC-PRISMA







Cu-0.5Cr

Thermo-Calc databases
TCHEA6 - MOBHEA3

solid solution strengthening

$$\Delta\sigma_{ss} = G(|\delta| + \frac{1}{20}|\eta|)^{3/2}\sqrt{\frac{\chi_{Cr}}{3}}$$

precipitation strengthening

$$\Delta\sigma_{os} = \frac{0.81\ G\ b}{2\pi(1-\nu)^{1/2}}\frac{ln(2r/b)}{(\lambda - 2r)}$$

$$\lambda = \left(\sqrt{\frac{2\pi}{3f}} - 1.63\right)r$$

Parameter	Value
Shear modulus $G(Cu)$	46 GPa
Factor δ	0.0435
Factor η	0.1492
Burgers factor b	0.2556 nm
Poisson's ratio ν	0.34
Cr atomic frac. χ_{Cr}	Calculated (at%)
Mean radius of precip. r	Calculated (nm)
Precipitate volume fraction f	Calculated

Huang et al. 2021

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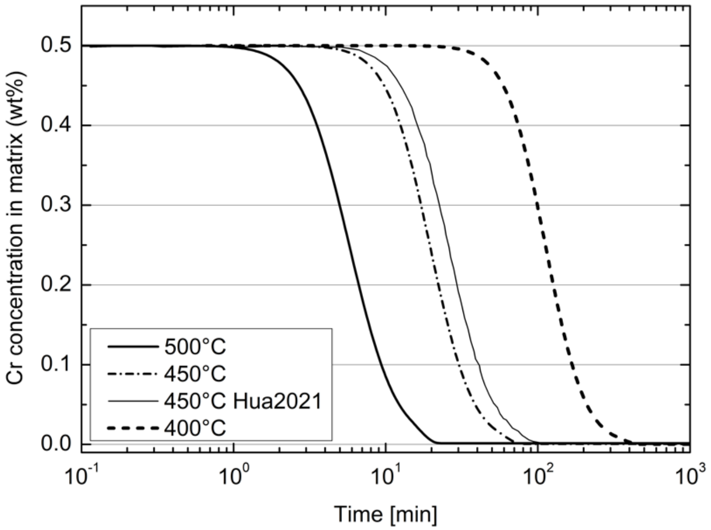
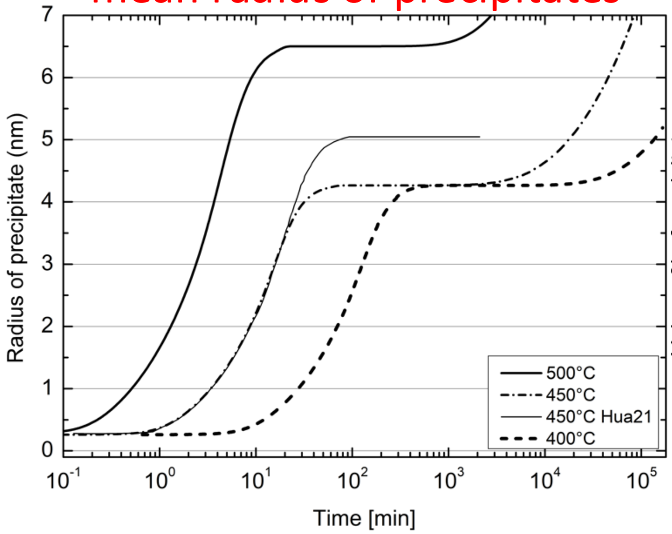
Predicting strengthening during aging using TC-PRISMA

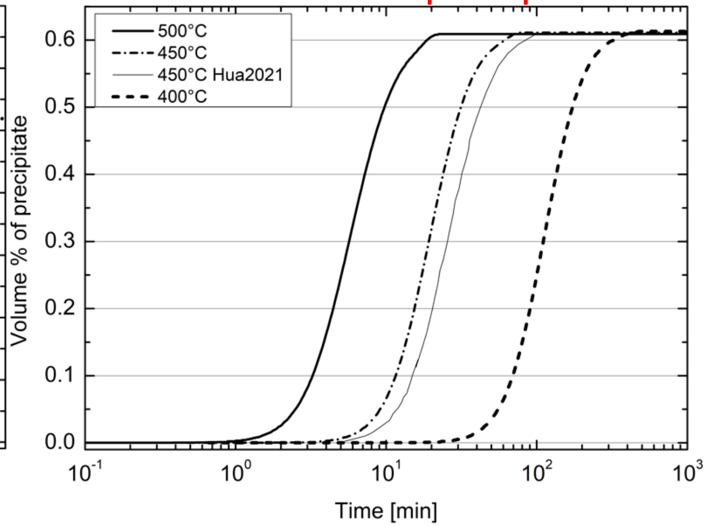
Cr concentration in the matrix



mean radius of precipitates



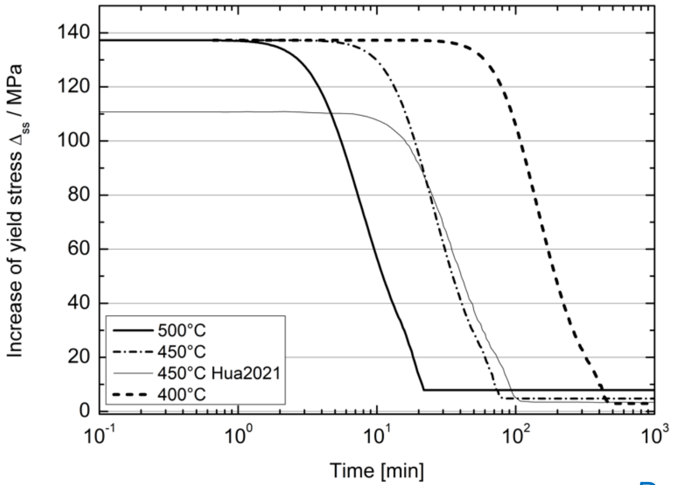
Volume of Cr precipitate



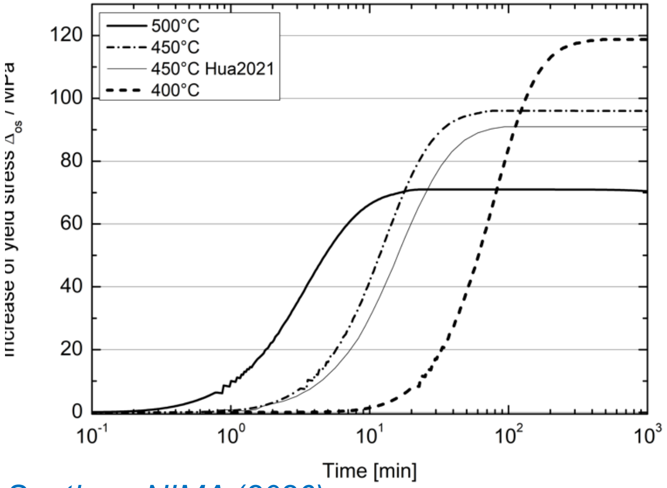
Cu-0.5Cr

Thermo-Calc databases
TCHEA6 - MOBHEA3

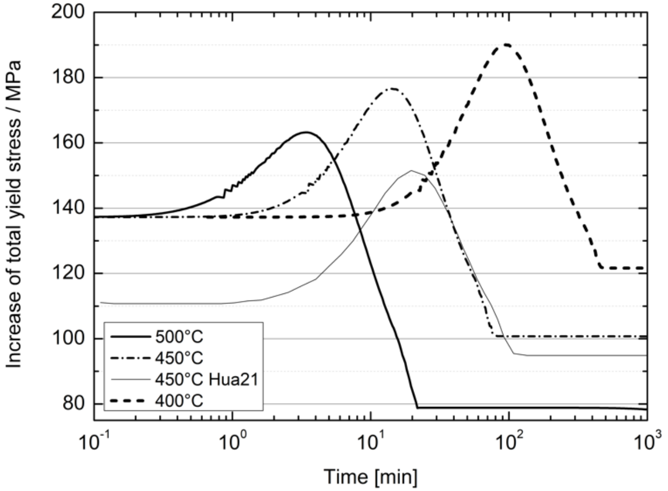
solid solution strengthening



precipitation strengthening



total strengthening



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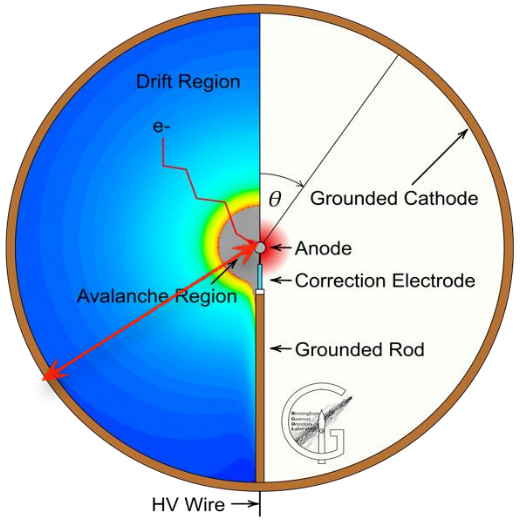
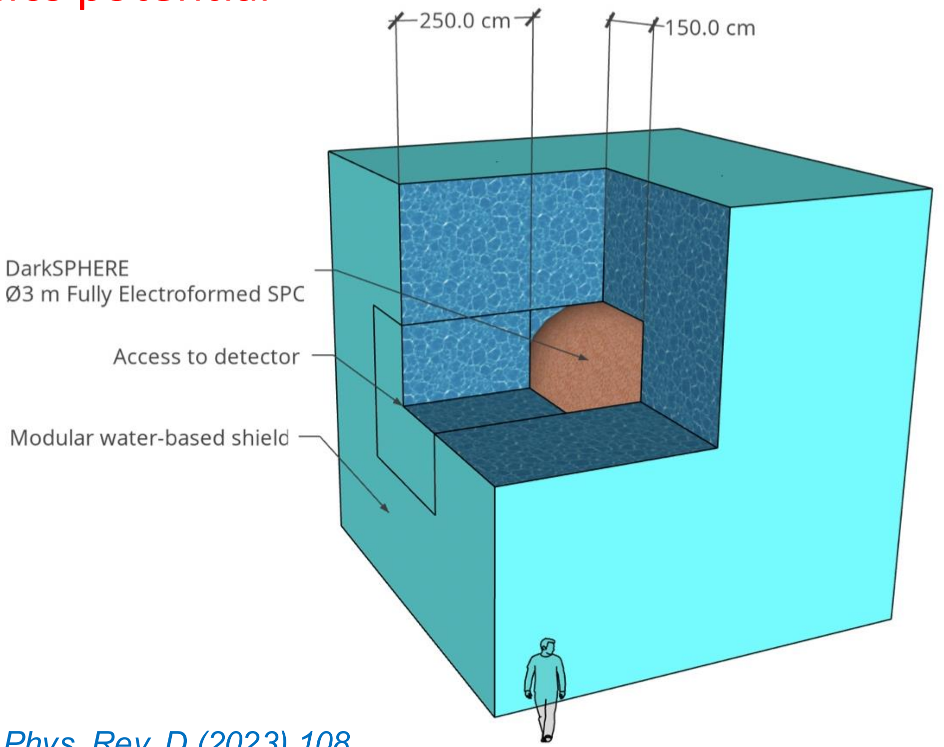
case study: DarkSPHERE

- ✓ Retain EFCu capabilities for rare event searches
- ✓ Option for stronger material compared to EFCu
- ✓ Scale up the current geometries for gas vessels (or gas pressure, wall thickness)
  → maximising the physics potential





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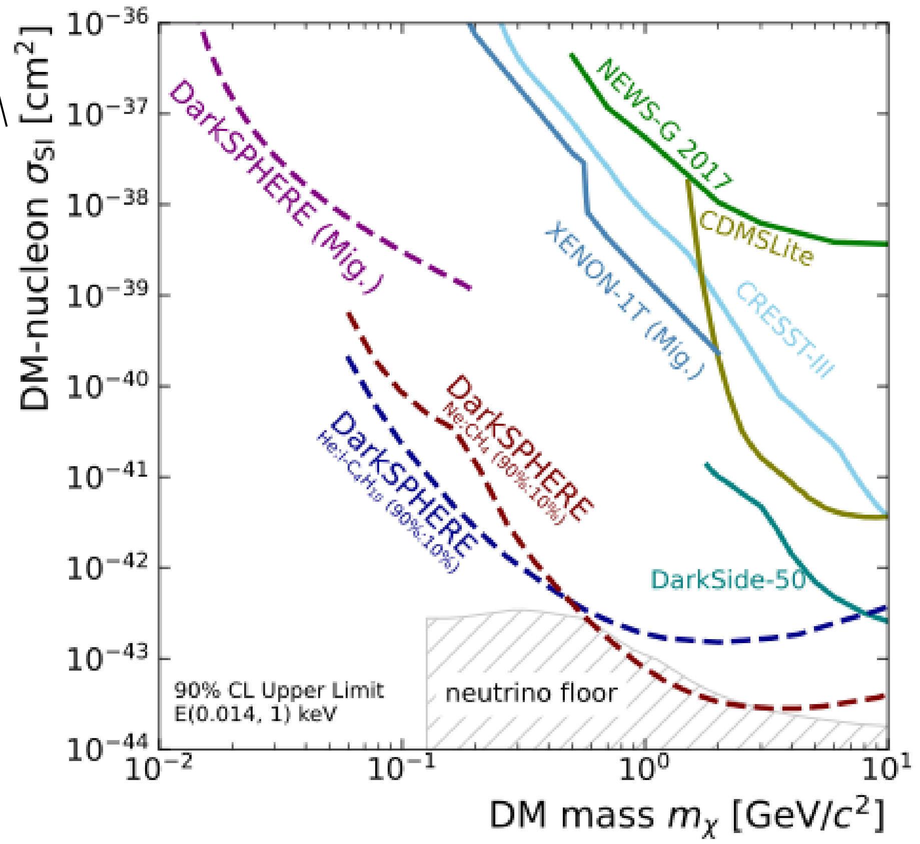
a high-purity CuCr alloy with double the strength over EFCu, would allow operation at 10 bar and reduce the required data collection time to 150 days.

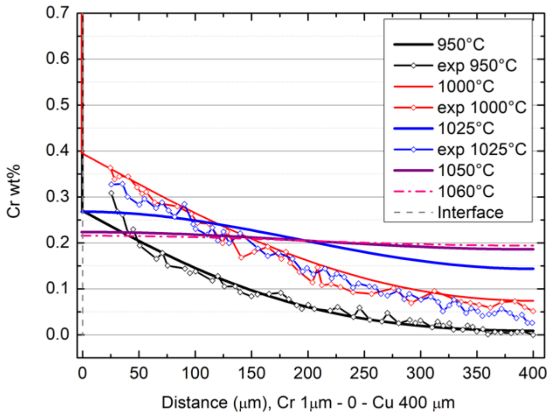


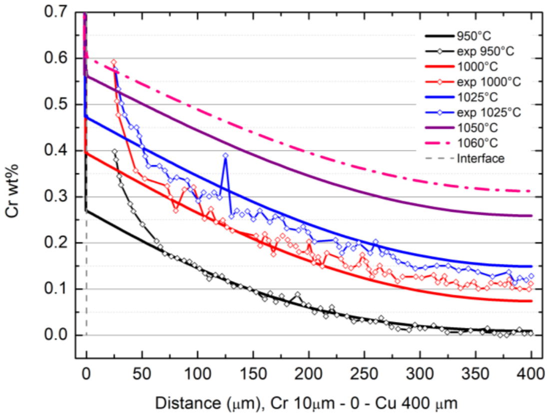
Commun Phys (2025)

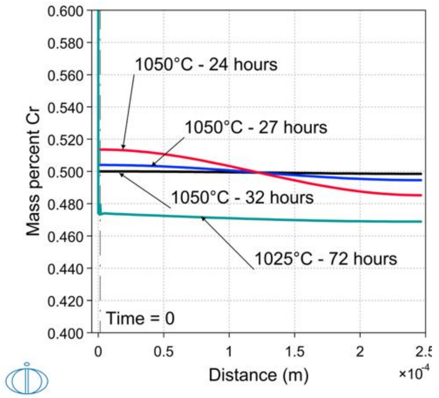
Beyond fundamental science

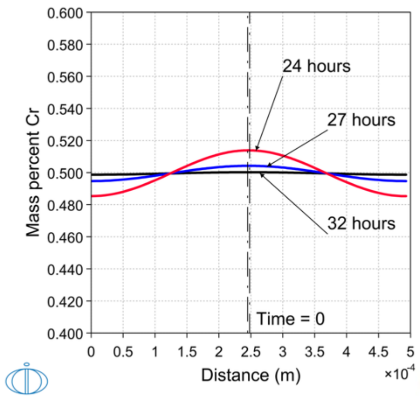
- Cu-based alloys used for **industrial applications** (electronics, rail…)
- **Sustainable use** of Cu (energy sector, AI infrastructure)
- **Clean energy** technologies (upcycling of Cu, etc.)
- Pure Cu and Cu-based alloys for **more accurate** thermodynamic and kinetic descriptions → **application-specific** databases

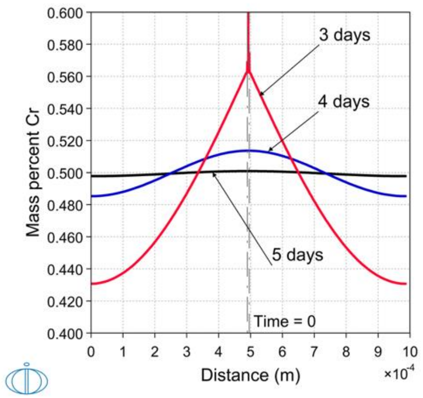
Thank you for your attention!











More on PureAlloys:
https://dematerializ.github.io/purealloys/

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