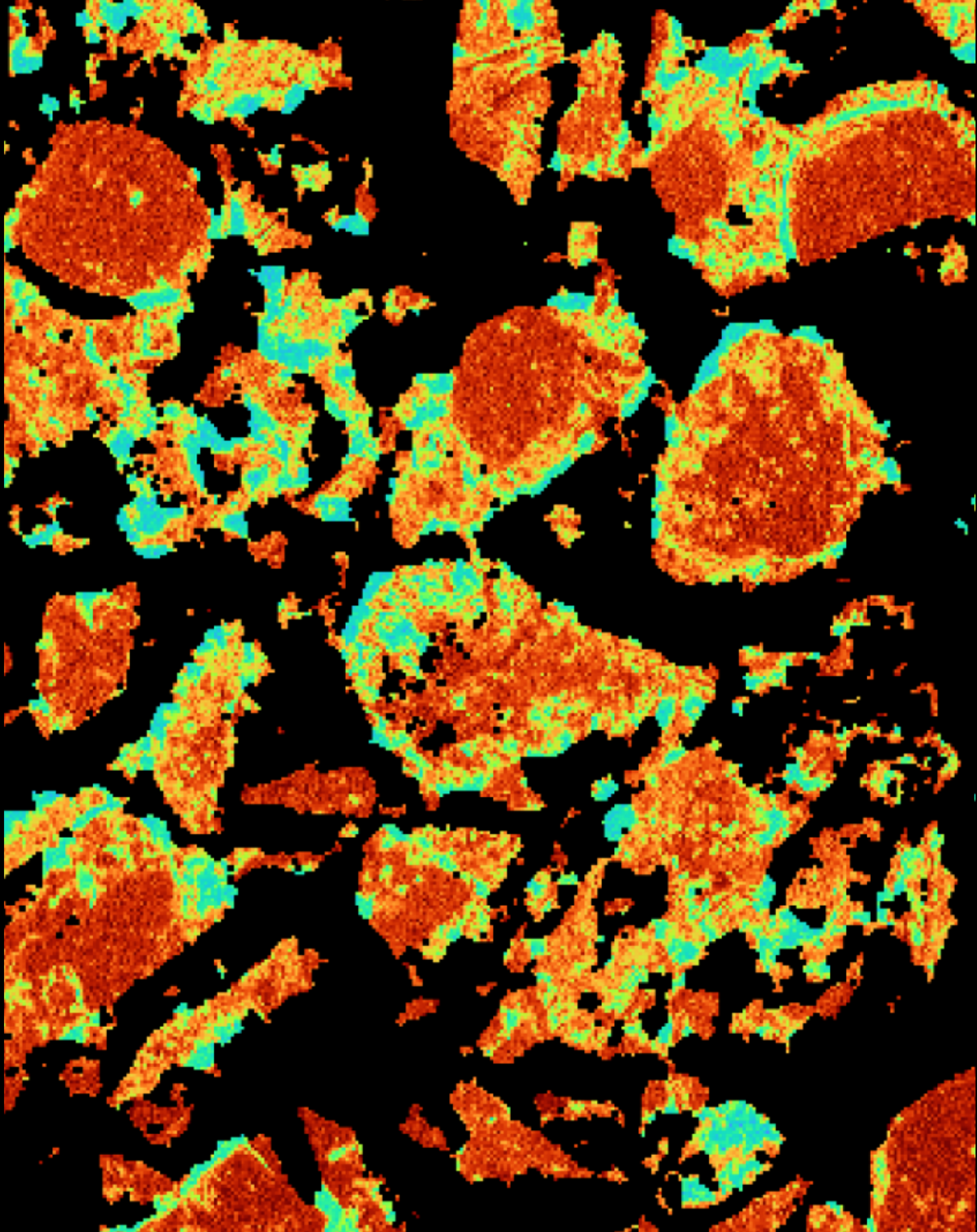
Antoine Allanore
Professor of Metallurgy
MIT - Materials Science & Engineering
allanore@mit.edu

Sustainable metal recovery using sulfur



$\$/t_{metal}$

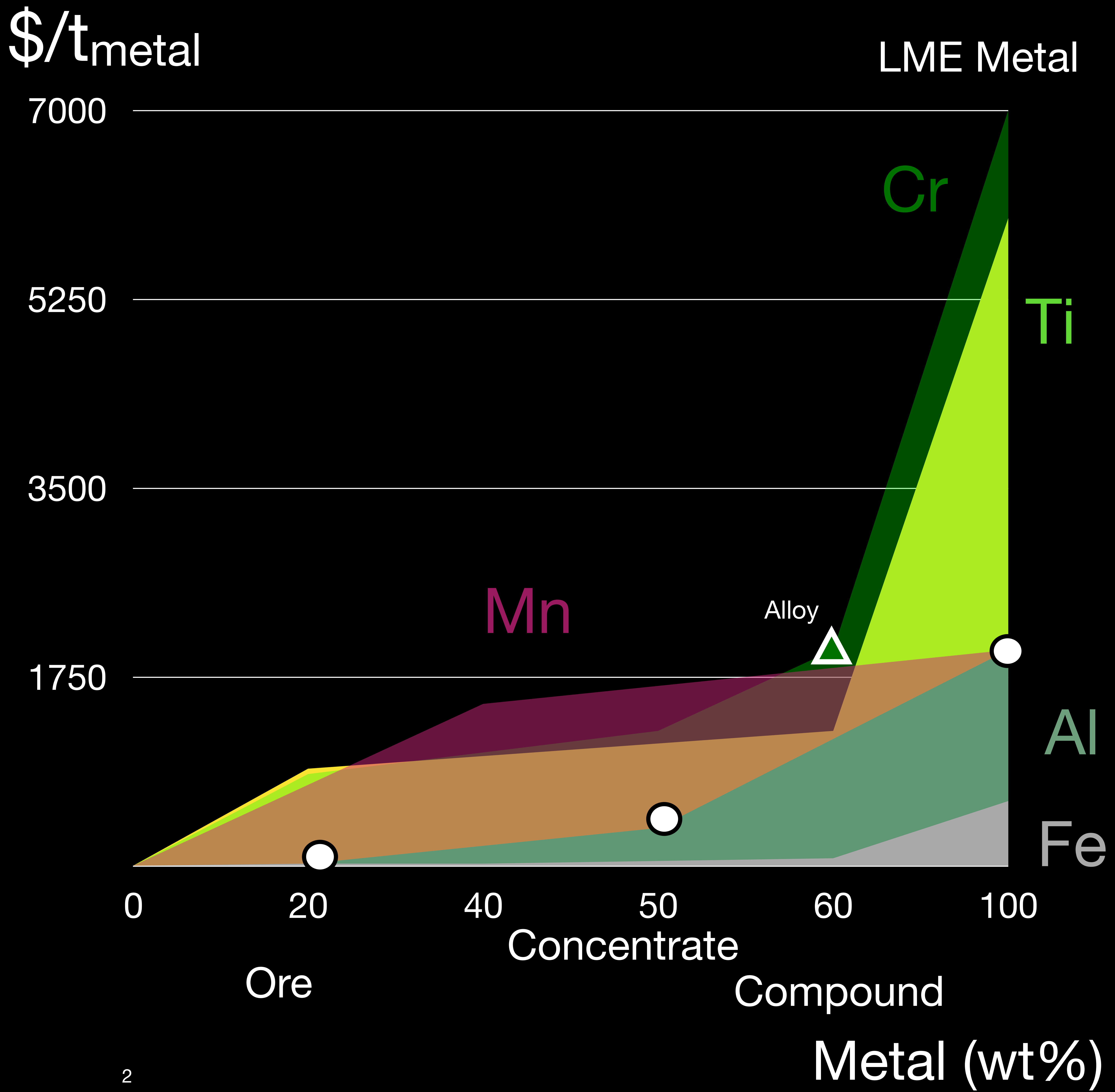
Supply chain (1)

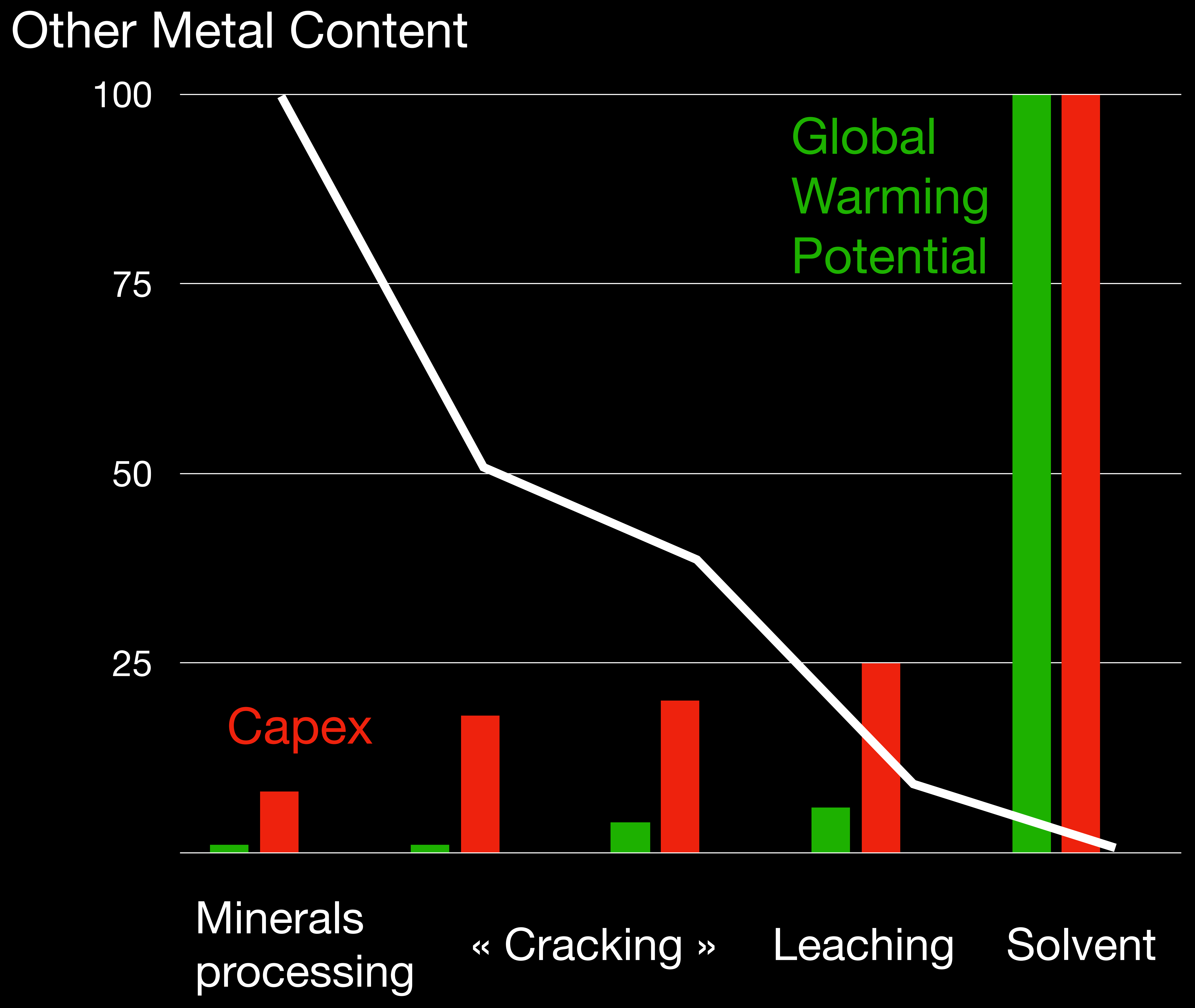
Upstream low value added inherent to the sector, makes incremental solutions unlikely to mitigate the environmental impact while maintaining the highest standards.

Metal (wt%)

Supply chain (1)

Upstream low value added inherent to the sector, makes incremental solutions unlikely to mitigate the environmental impact while maintaining the highest standards.





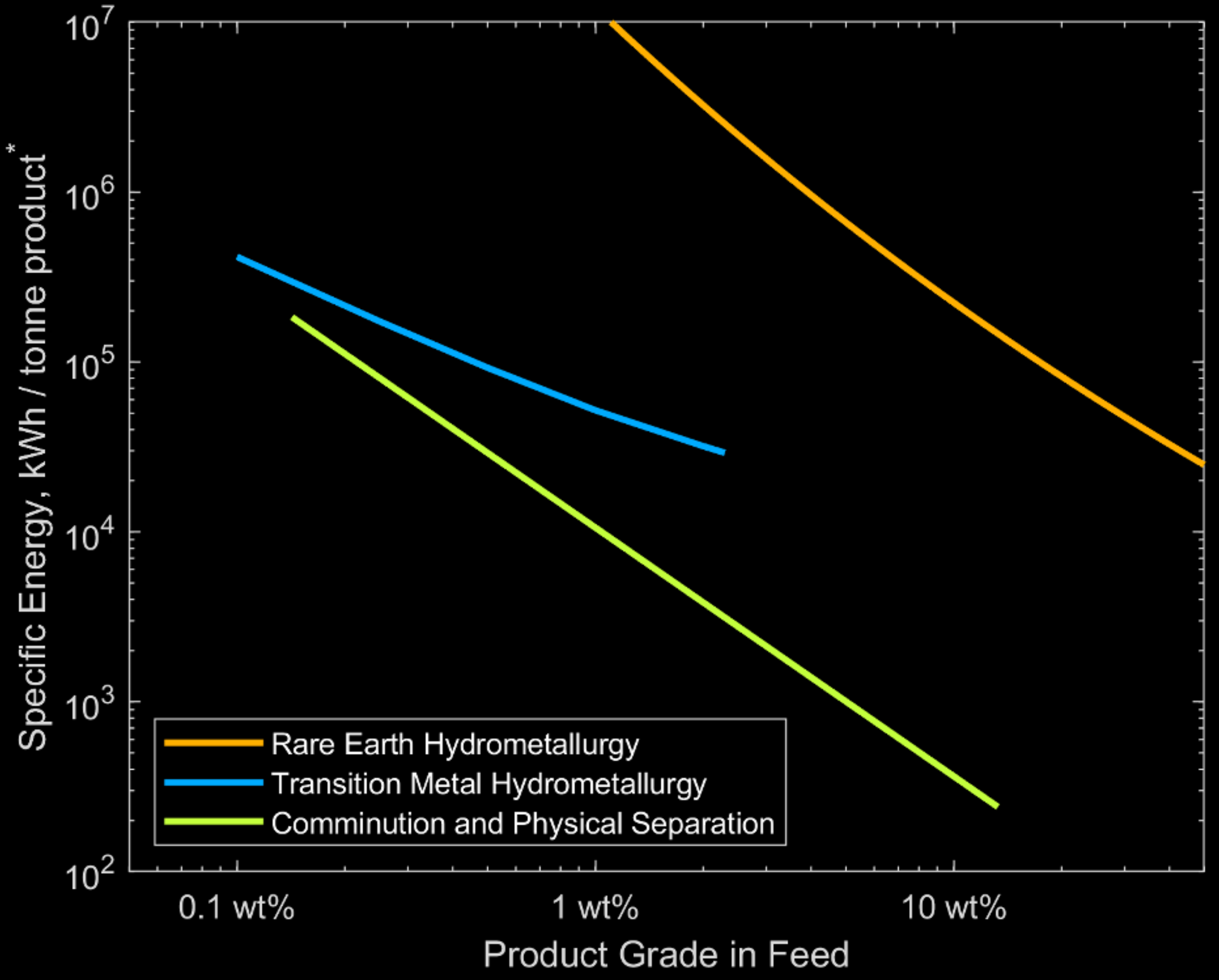
Supply chain(2)

Process Technology Bottleneck

Processes based on hydrometallurgy and organic solvents are the most expensive and questionable from a sustainability standpoint

Mineralogical barrier and energy consumption

TMS 2022

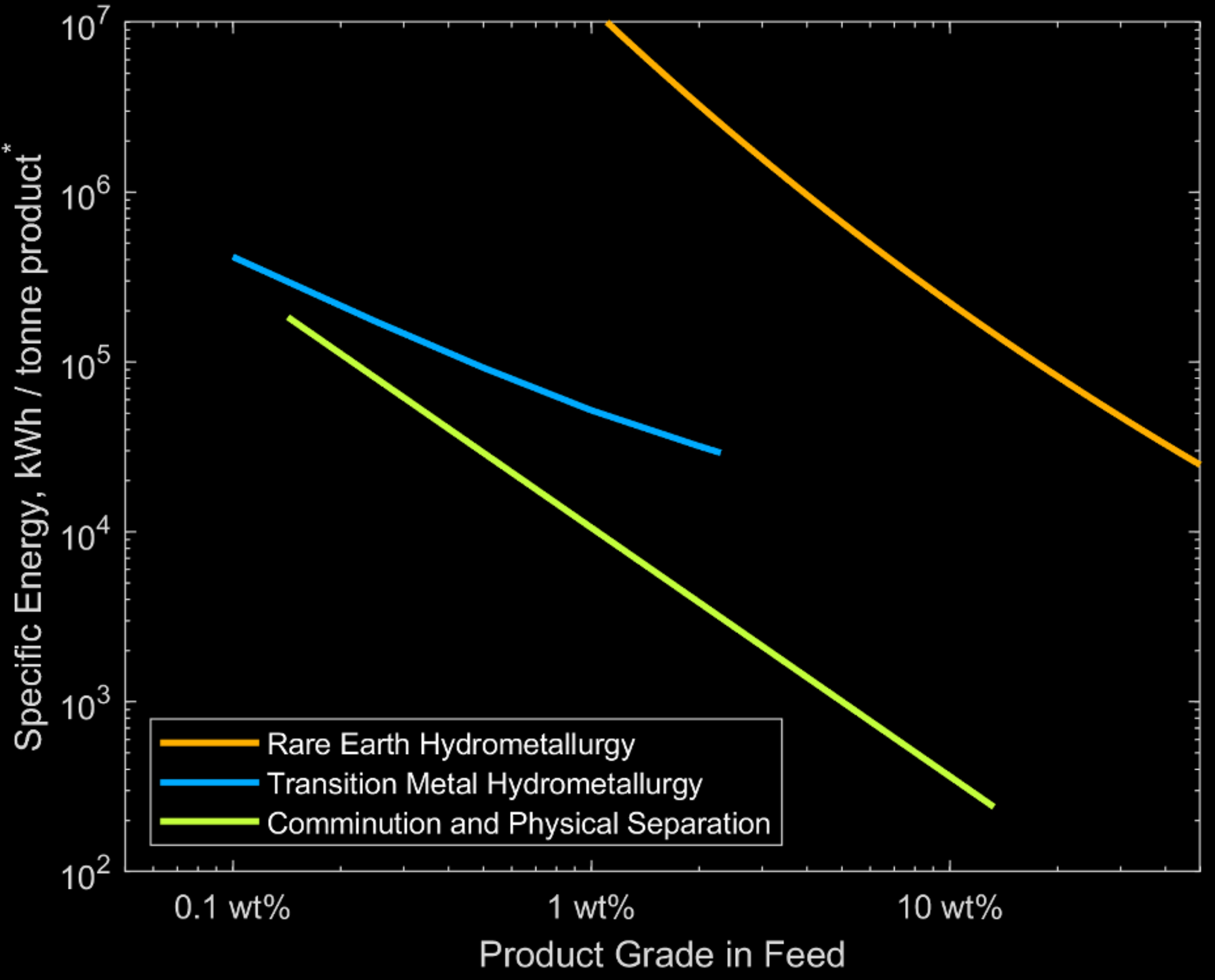


Mineralogical barrier and energy consumption

TMS 2022

- The volume of material handled is larger in aqueous than solid-state separations.

- Processes converge at low feedstock grades.



Materials Processing - directions

HIGHER RECOVERY

- increase liberation size
  - coarsening
  - partial melting
  - new phase

  → high temperature

- enhance separation
  - density
  - magnetic

  sulfides (~5.5) vs oxides (~7.3) → sulfur chemistry

Materials Processing - directions

HIGHER RECOVERY

- increase liberation size { coarsening, partial melting, new phase } → high temperature
- enhance separation { density, magnetic } — sulfides (~5.5) vs oxides (~7.3) → sulfur chemistry

BETTER SELECTIVITY

- change chemistry — sulfides vs oxides → sulfur chemistry
- change state of matter — liquid vs solid → high temperature

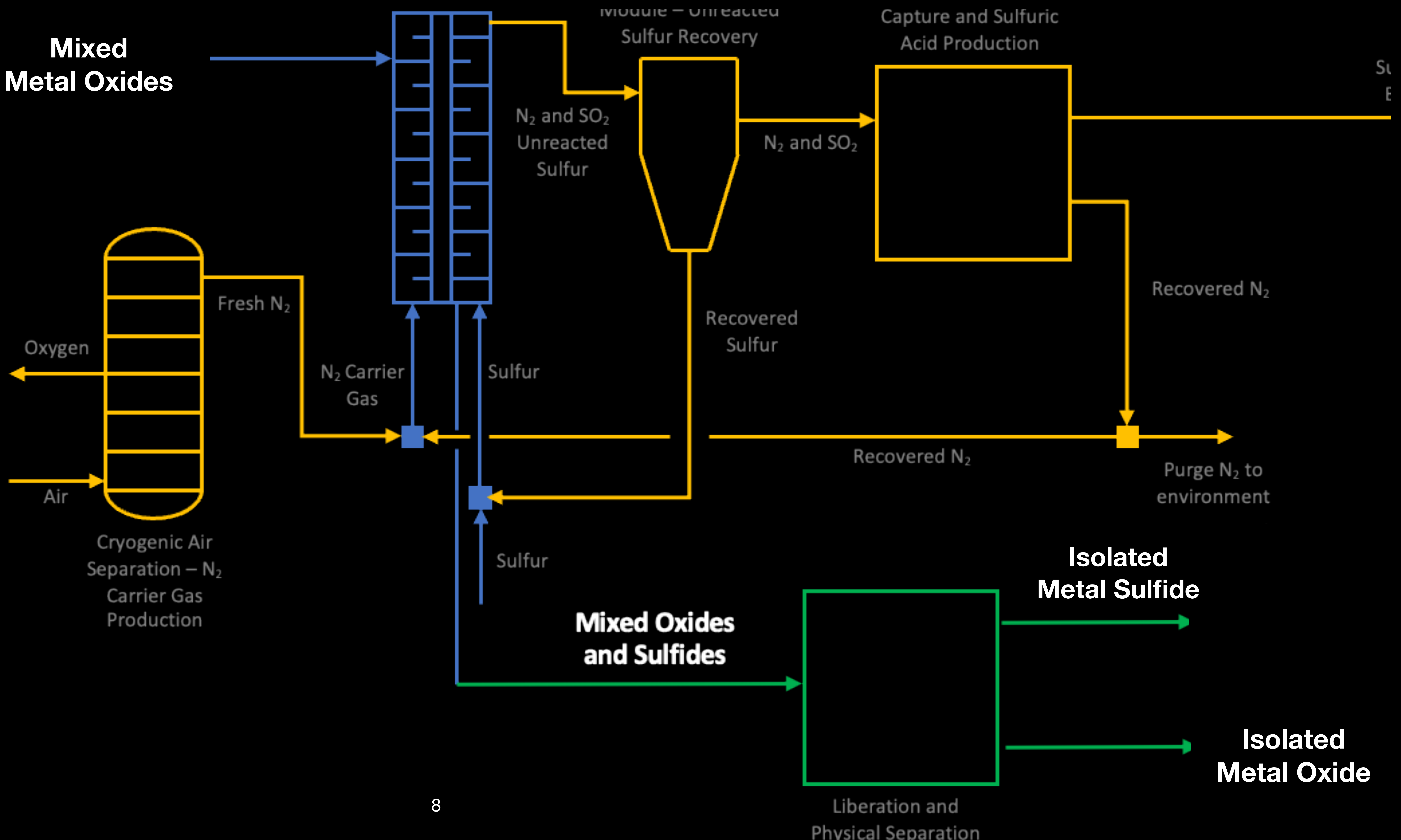
Selective sulfidation flow-sheet

Stinn and Allanore, *Nature*, 2022

Gas

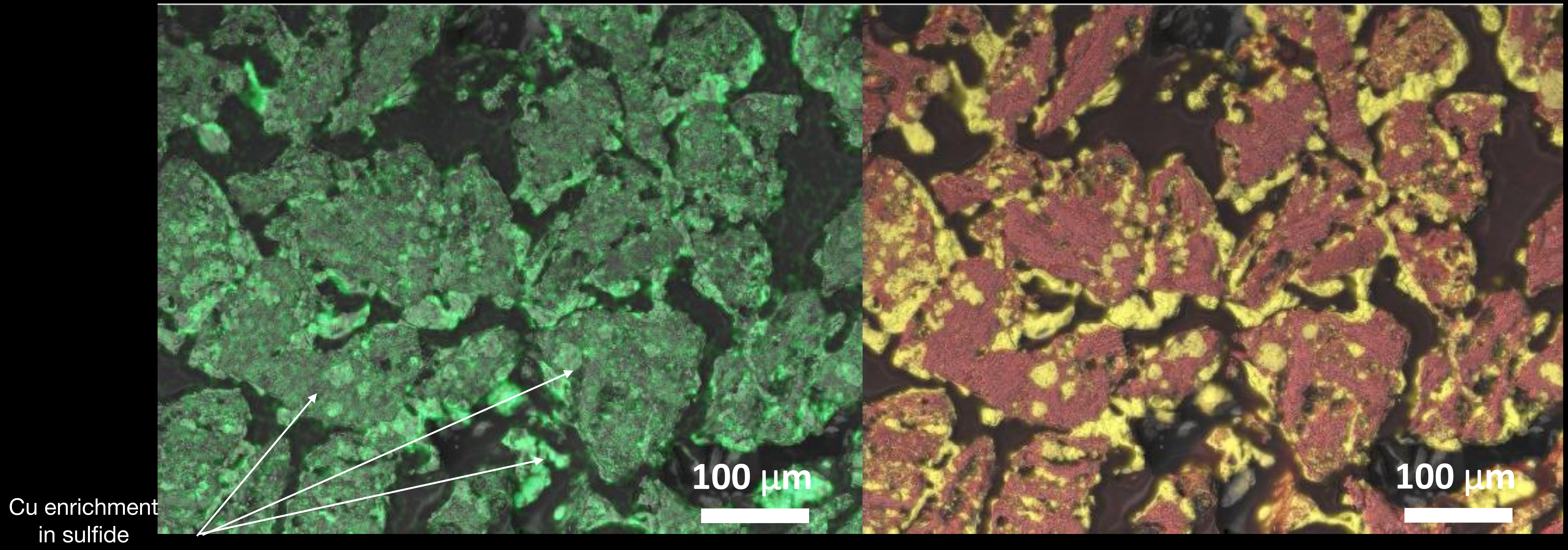
Chem

Physical



Sulfidation of copper slag (“fayalite”+Cu)

Sulfidation of copper slag (“fayalite”+Cu)



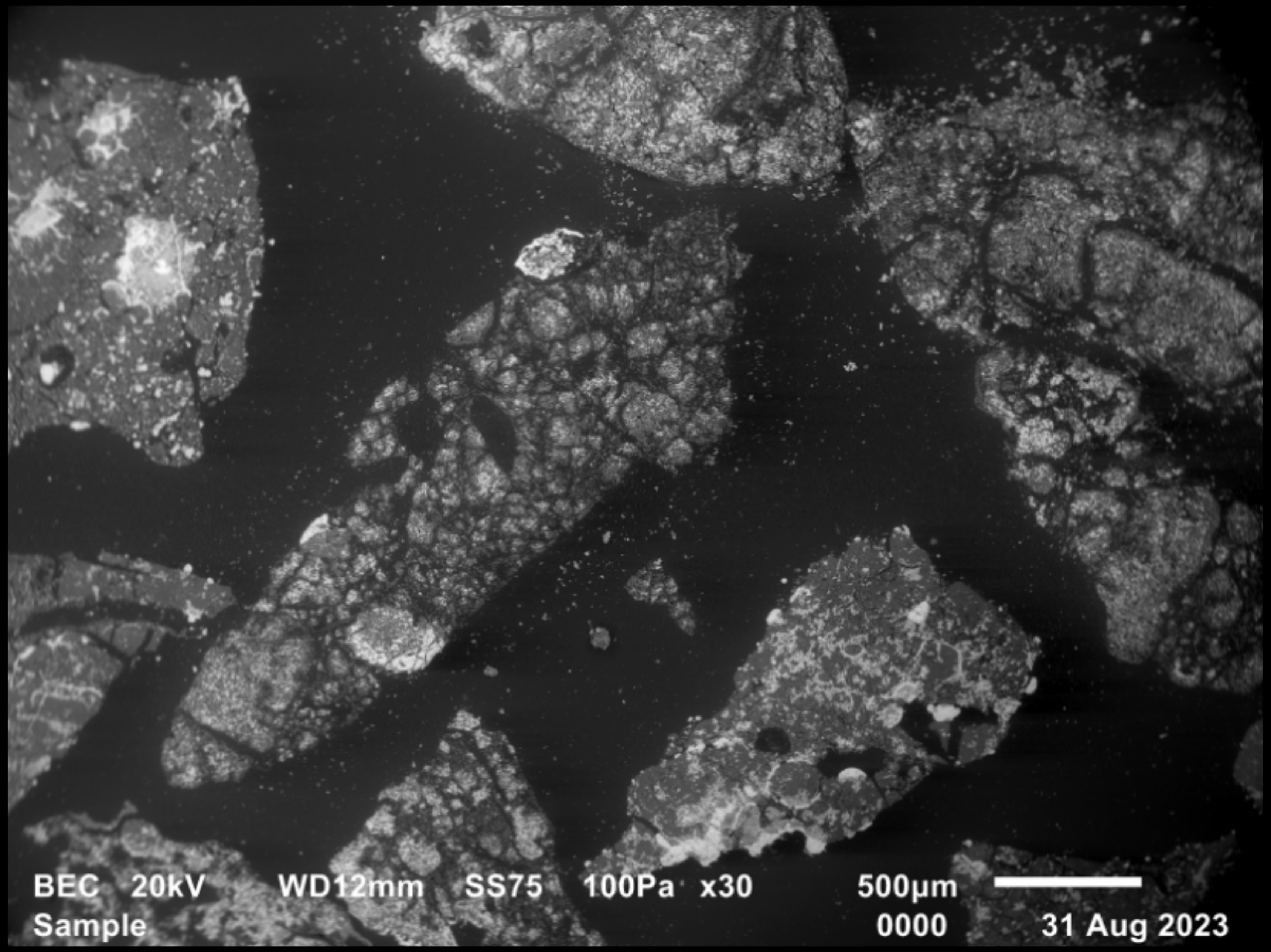
possible formation of new Cu and Fe sulfides from copper oxide slag

Sulfidation of bauxite

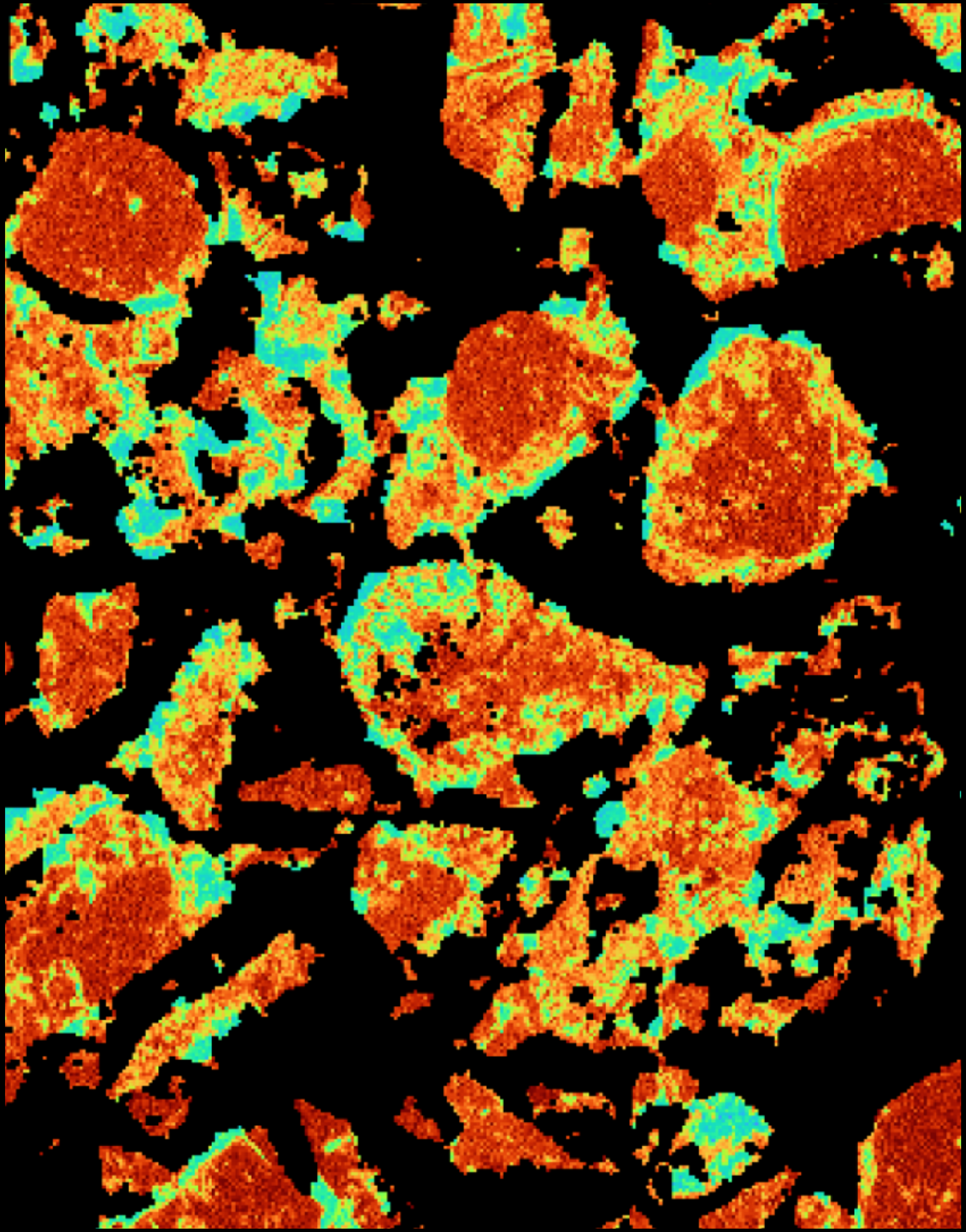
Bauxite

Crushed
(5cm OD, 2cm deep)

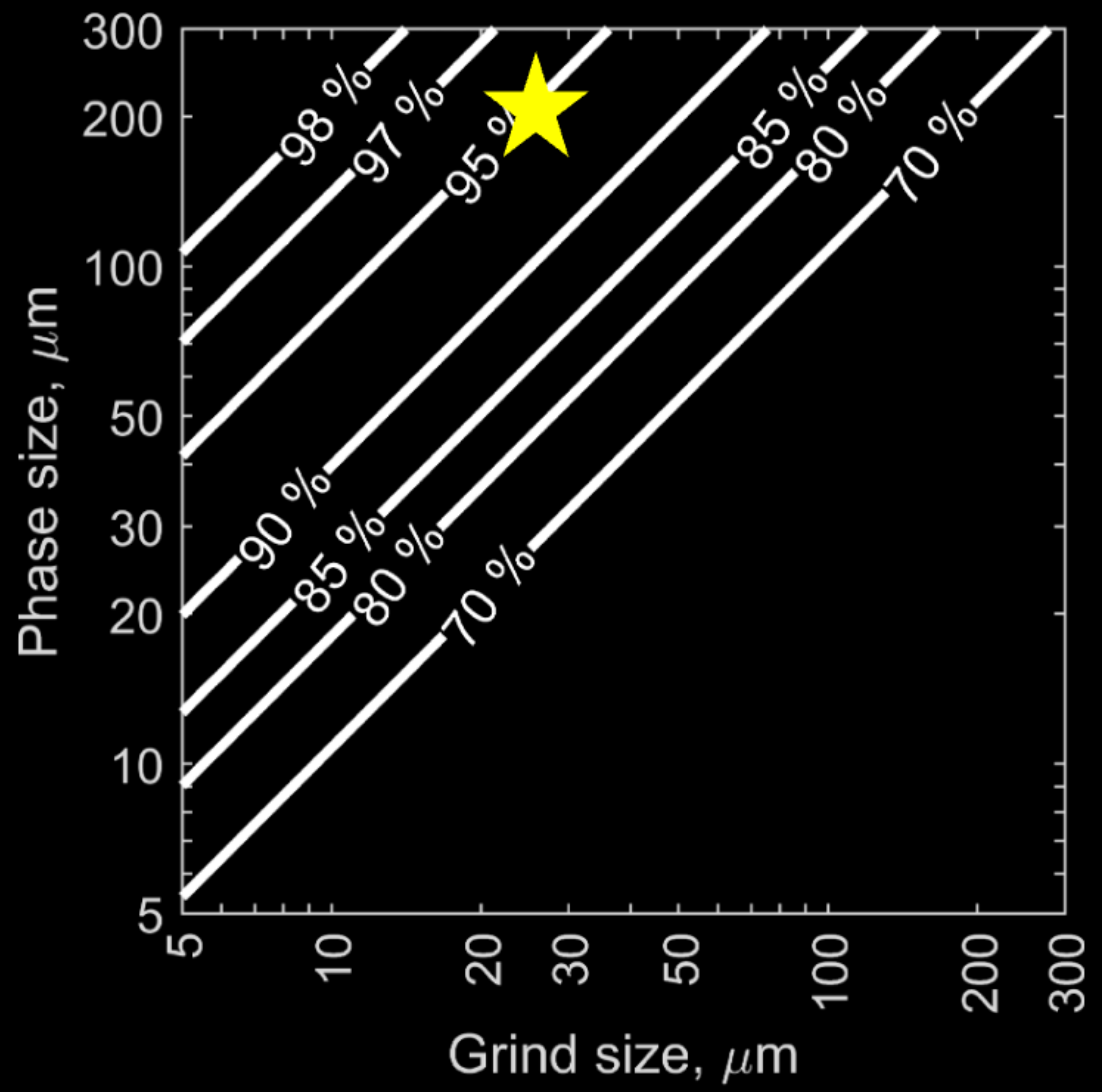
Sulfidized



Light phases: Fe-rich sulfide
Dark phases: Al-rich oxide



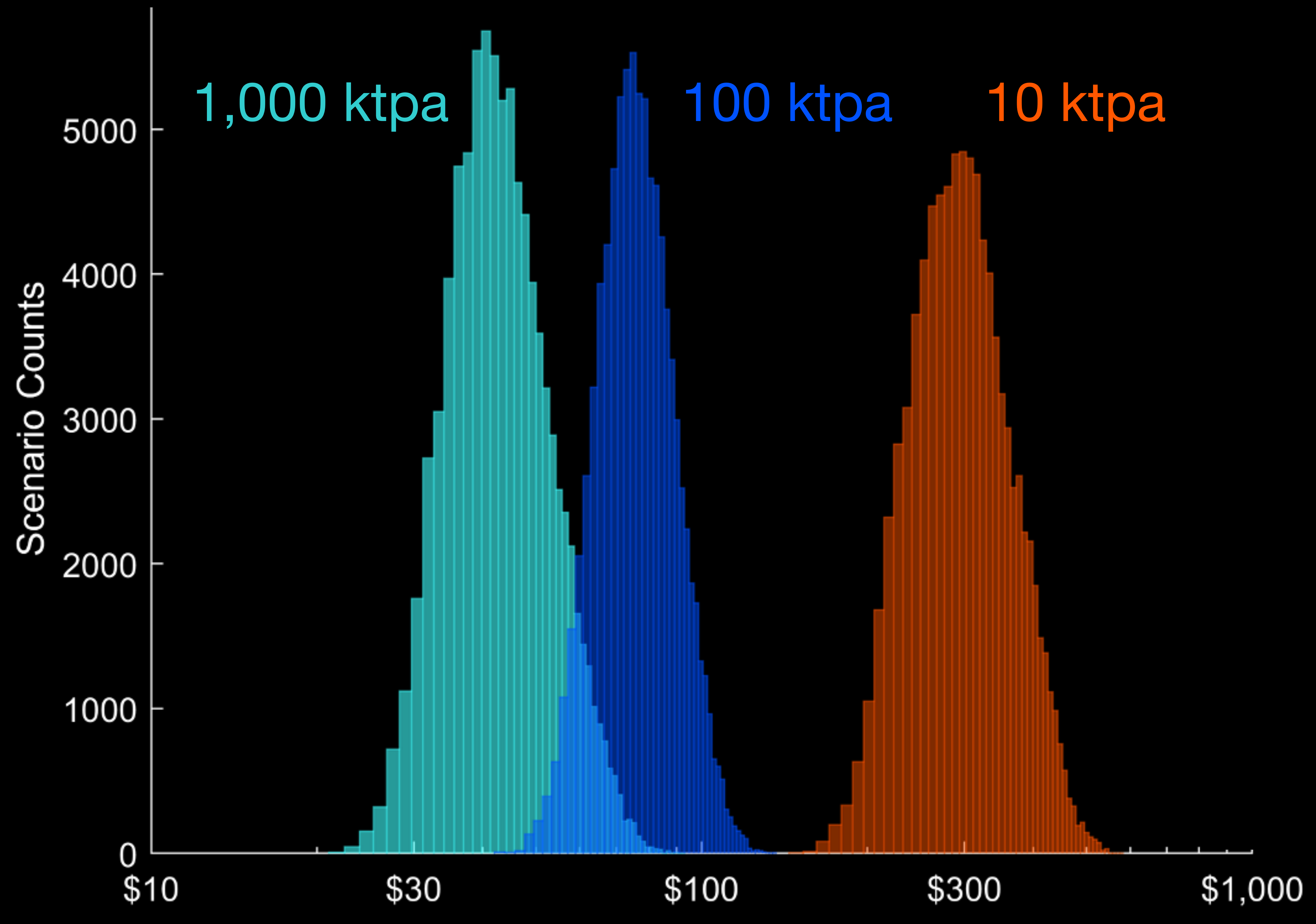
Sulfidation of bauxite



- From Finch and Petruk's solution to the King liberation model:
  - >95% of 200 µm sulfide phases can be liberated from oxides at a grind size of 25 µm
  - Recoverable via physical separation

Sustainable? - example rare-earth

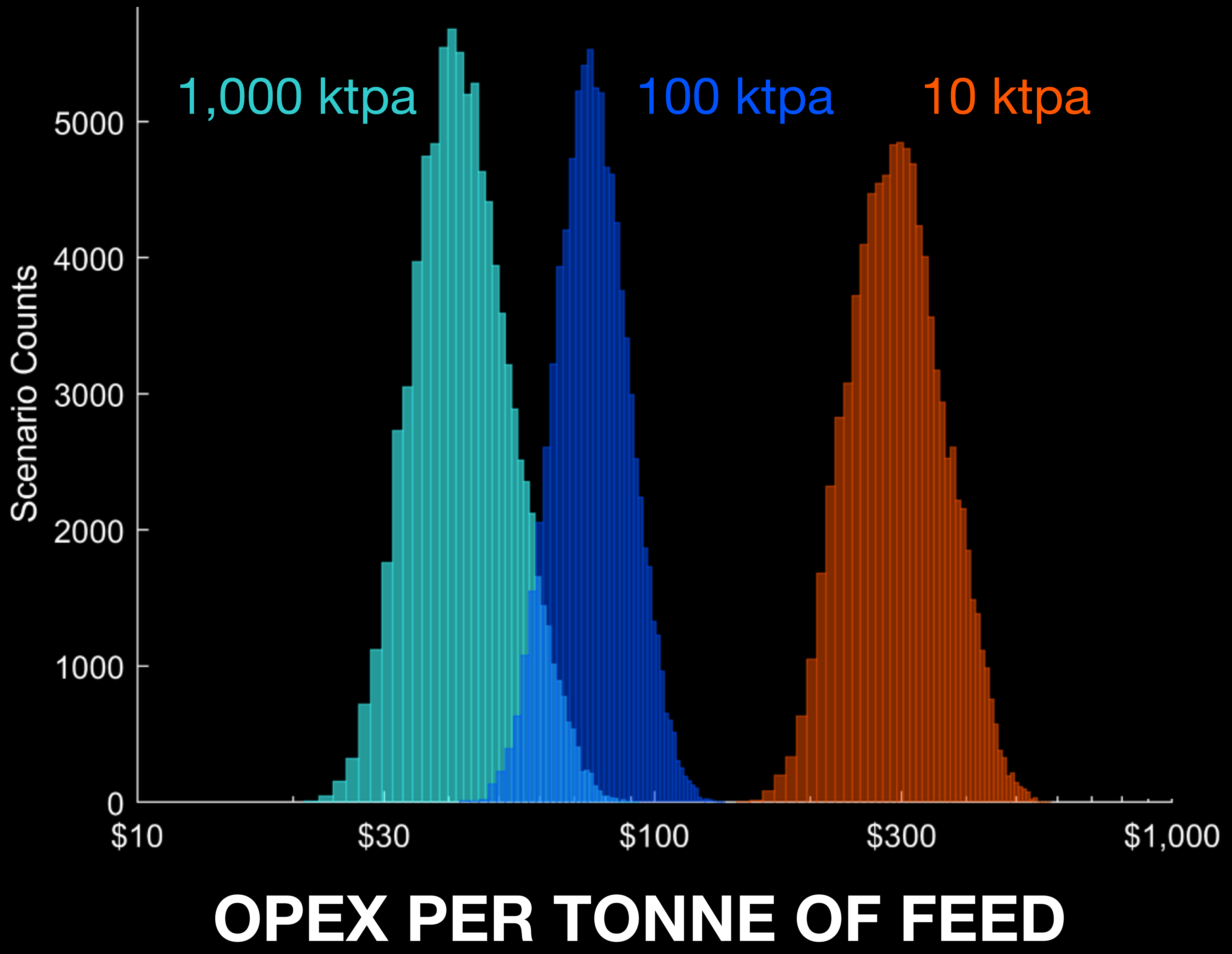
Stinn and Allanore, *Nature*, 2022

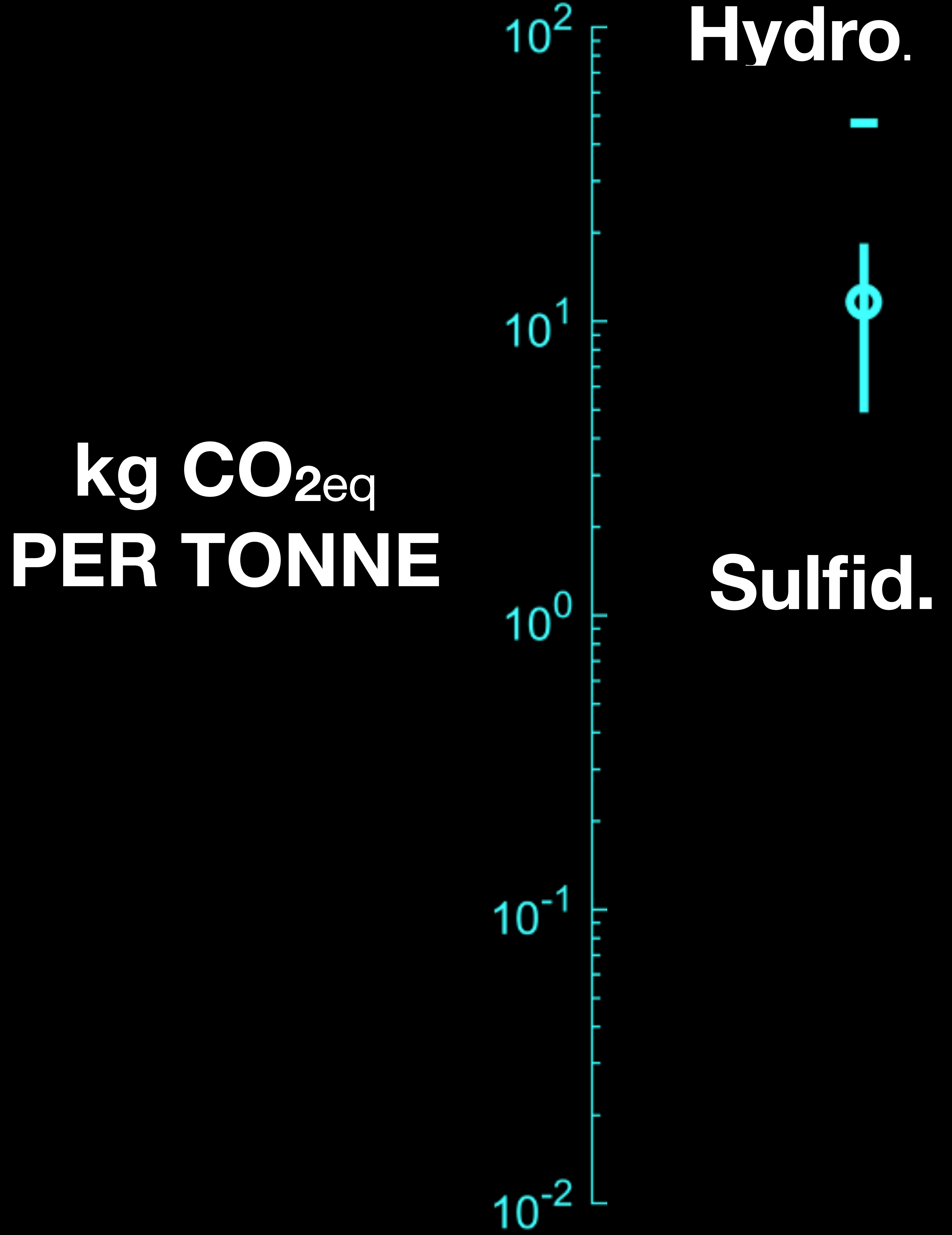


OPEX PER TONNE OF FEED

Sustainable? - example rare-earth

Stinn and Allanore, *Nature*, 2022

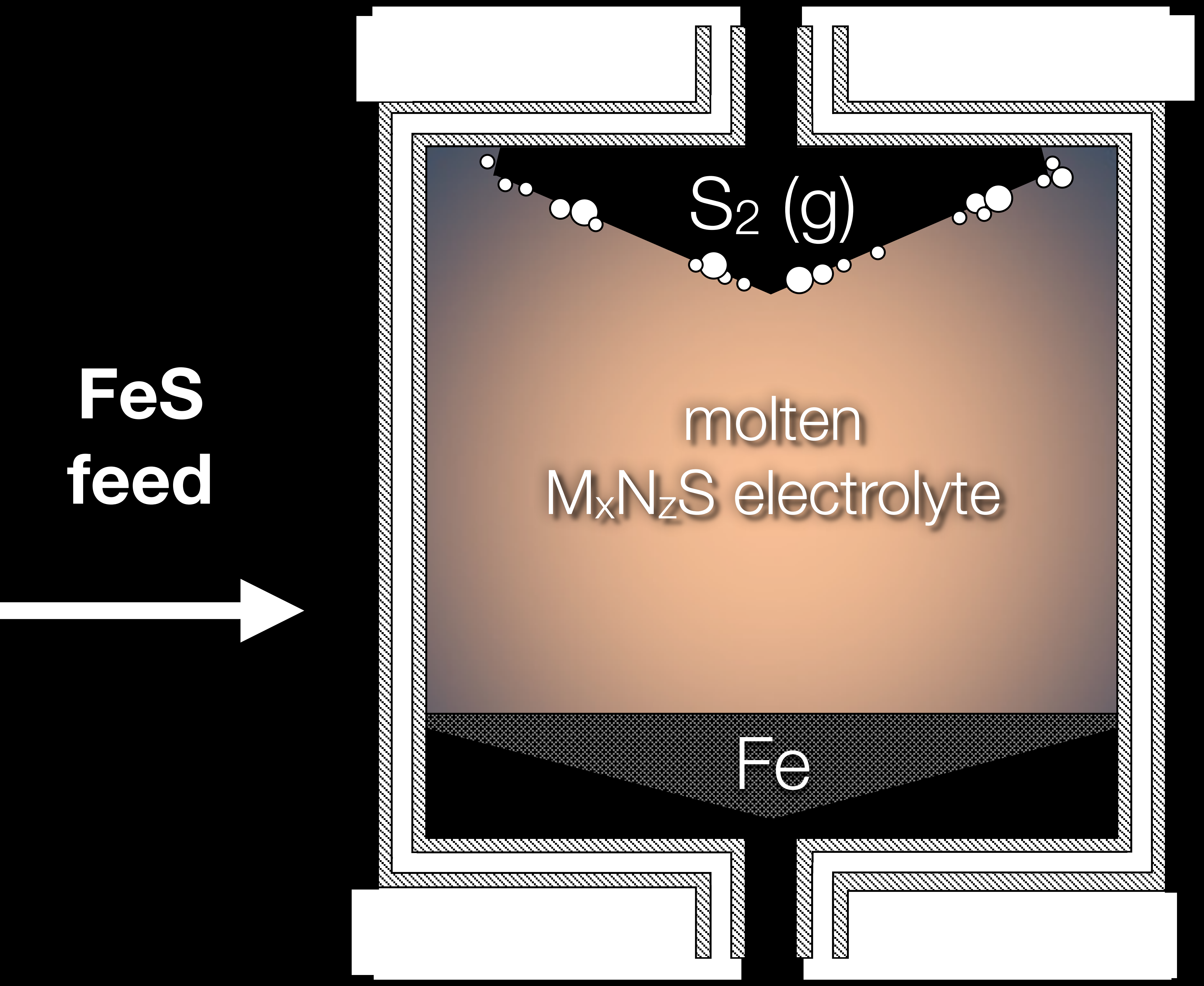




GHG-free production of metal from sulfide

Sulfides processing in absence of oxygen

FeS feed

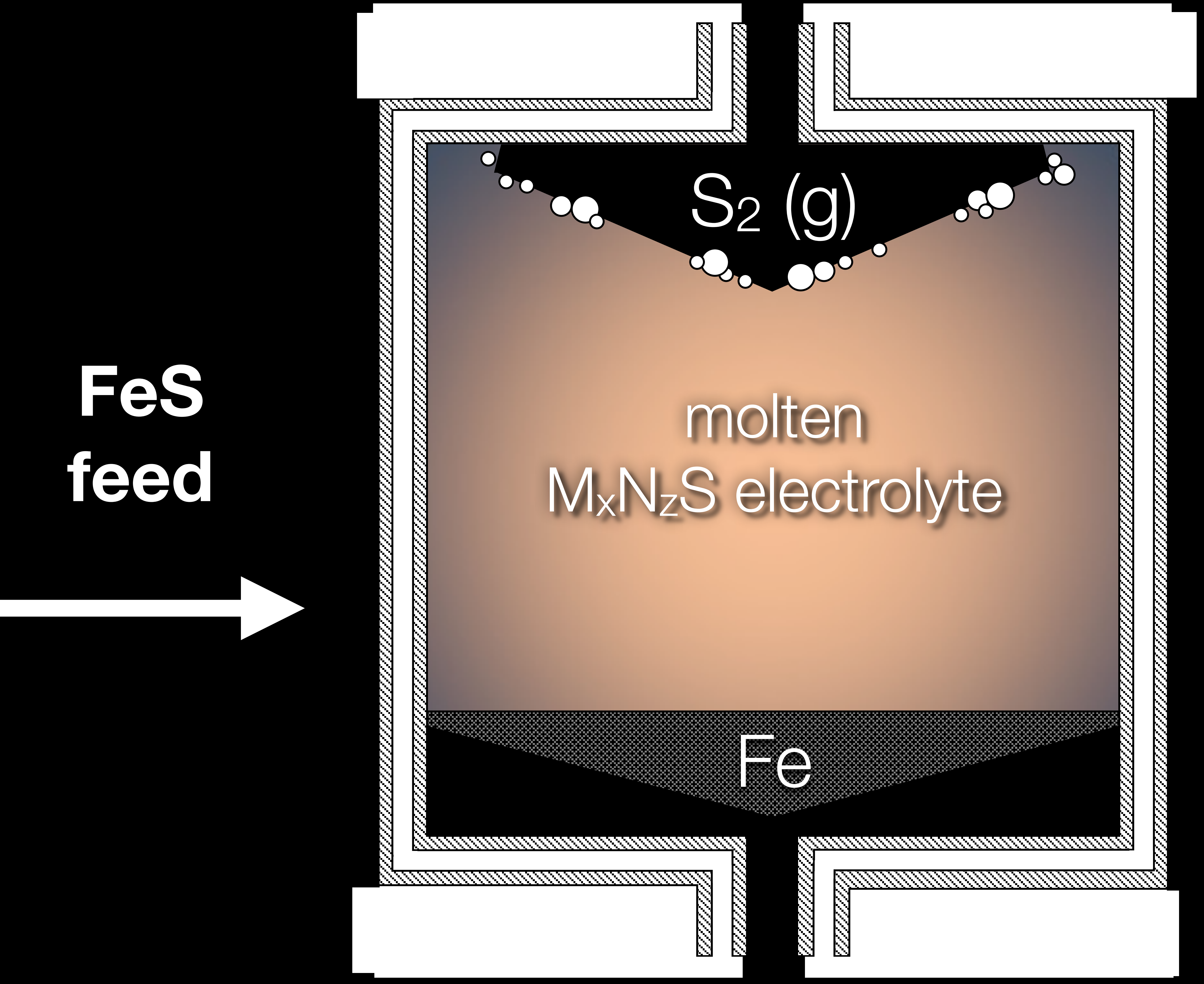


$$\text{FeS} \rightarrow \text{Fe} + \frac{1}{2}\text{S}_2(g)$$

GHG-free production of metal from sulfide

Sulfides processing in absence of oxygen

FeS feed

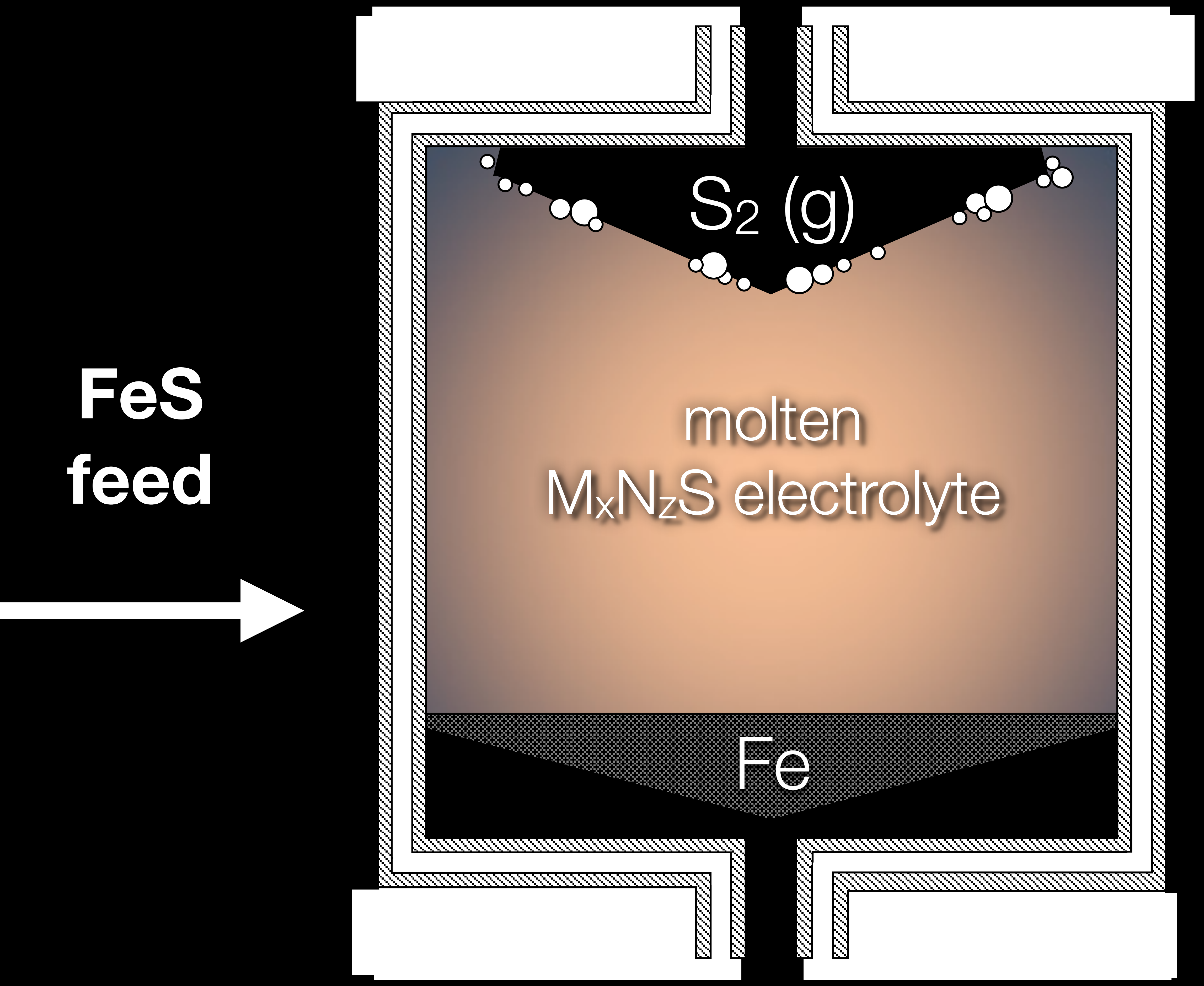


$$FeS \rightarrow Fe + \frac{1}{2}S_2(g)$$

- current flow generates heat

GHG-free production of metal from sulfide

Sulfides processing in absence of oxygen

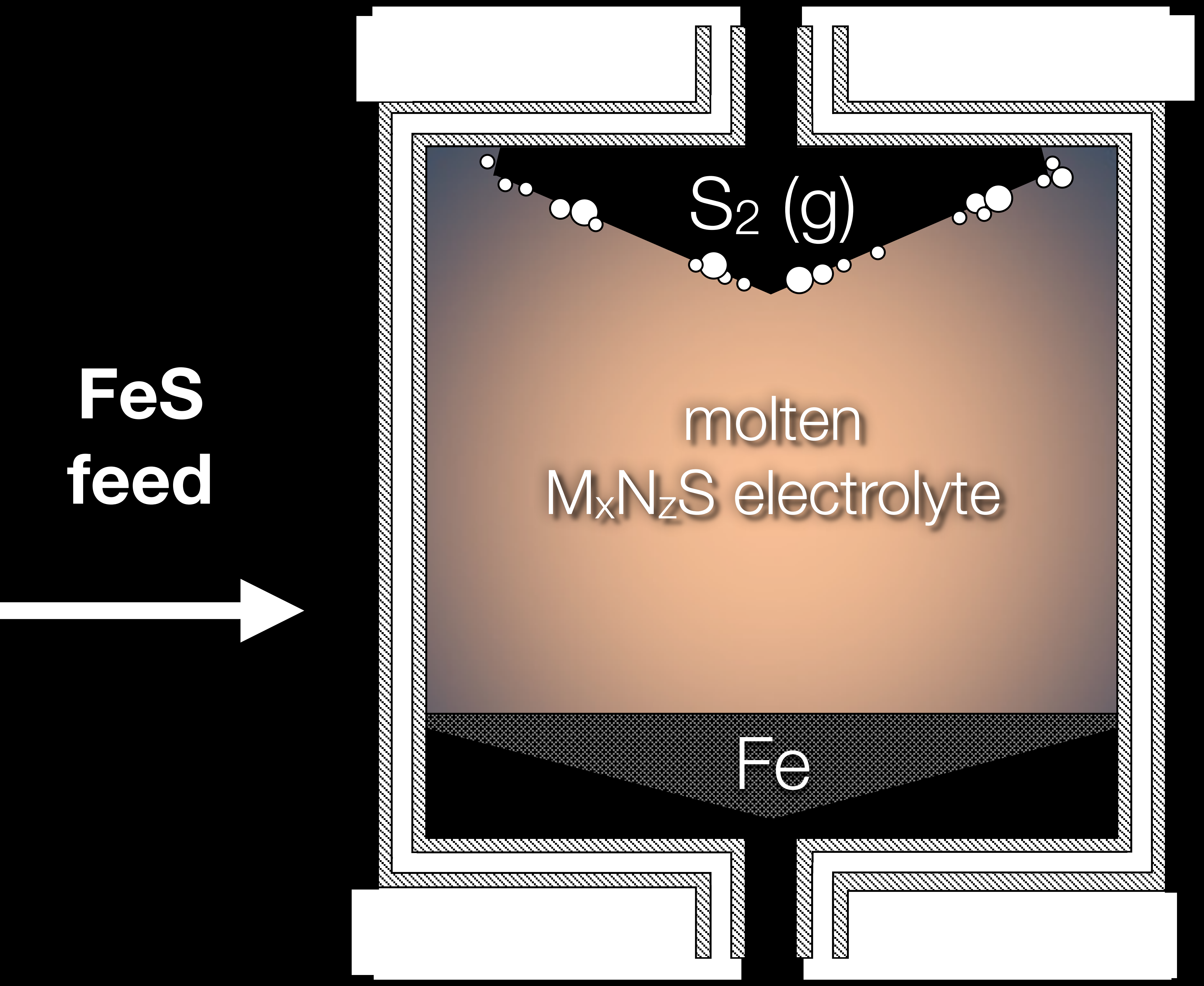


$$\mathrm{FeS} \rightarrow \mathrm{Fe} + \frac{1}{2}\mathrm{S}_2(g)$$

- current flow generates heat
- 66% of energy needed vs oxide

GHG-free production of metal from sulfide

Sulfides processing in absence of oxygen



$$FeS \rightarrow Fe + \frac{1}{2} S_2(g)$$

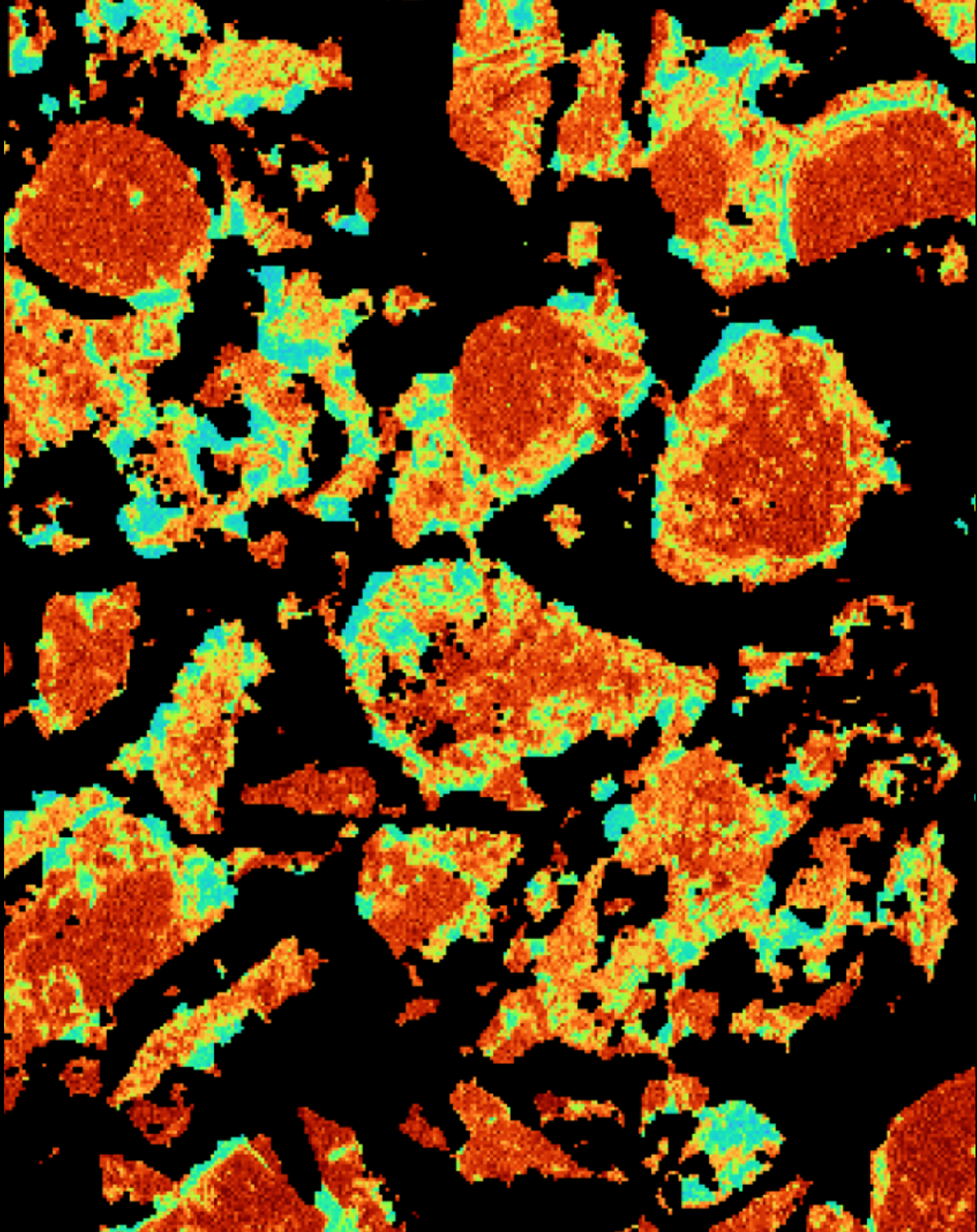
- current flow generates heat
- 66% of energy needed vs oxide
- proven possible for Cu, Zn, Pb, Au, Ag, Mo, Re, Ni, …

Prior Findings (DOE-AMO, $CuFeS_2$ electrolysis)

Iron production stage

- 300g/h scale
- High Faradaic efficiency
- Low cell voltage
- High current density
- Ability to produce “hot metal”, i.e. iron with up to 4% C

- Sulfur is an extremely efficient mediator for redistribution and new phase growth from natural minerals
- The prior-art at scale shows the path toward energy and cost efficient usage of sulfur
- Several features known to metallurgy (sulfuric acid, power generation, …)
- Opportunity for GHG-free reduction approach, e.g. using electricity.
- At MIT, we have kilogram scale capabilities, working now on the tonne scale.



“It does not mean a thing if it ain’t got that swing…”

Duke Ellington/Irving Mills