Energy Critical Elements

More precious than gold

supported by

APS
AMERICAN PHYSICAL SOCIETY

MITei

R. L. Jaffe
MIT

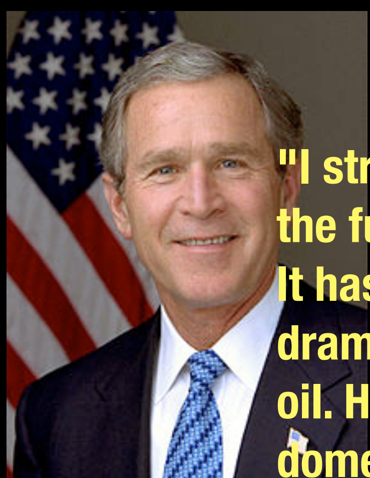
Lake Geneva 1974

Lake Geneva 1974

Frustration at low level of public discourse

Frustration at low level of public discourse

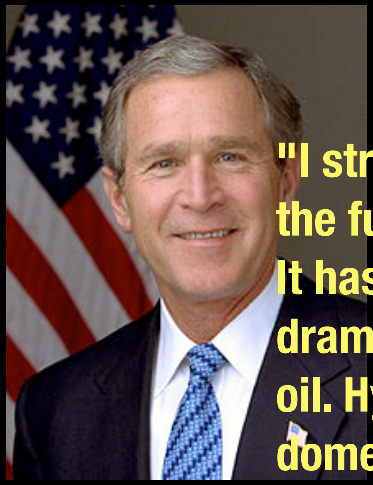
Frustration at low level of public discourse



"I strongly believe hydrogen is the fuel of the future. That's what we're talking about. It has the potential -- a vast potential to dramatically cut our dependence on foreign oil. Hydrogen is clean, hydrogen is domestically produced, and hydrogen is the way of the future."

Frustration at low level of public discourse

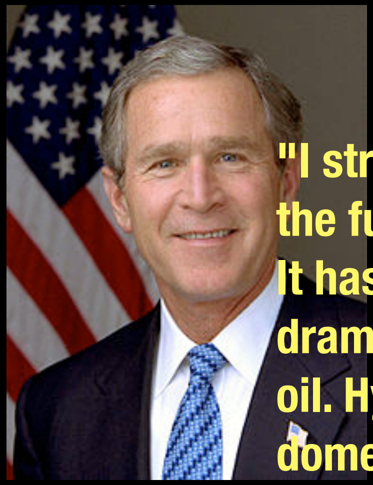
+



"I strongly believe hydrogen is the fuel of the future. That's what we're talking about. It has the potential -- a vast potential to dramatically cut our dependence on foreign oil. Hydrogen is clean, hydrogen is domestically produced, and hydrogen is the way of the future."

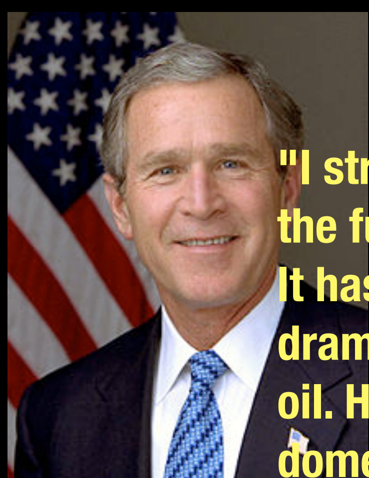
Frustration at low level of public discourse

+

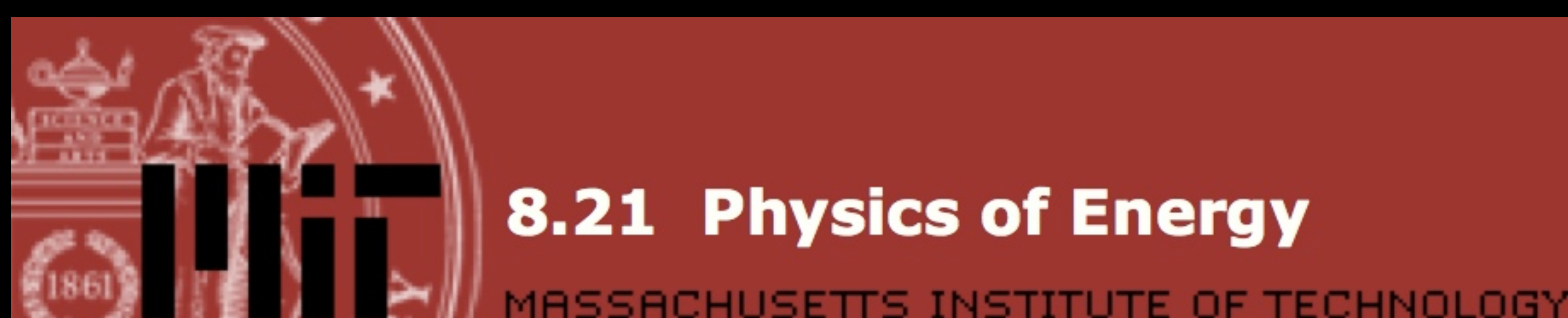


"I strongly believe hydrogen is the fuel of the future. That's what we're talking about. It has the potential -- a vast potential to dramatically cut our dependence on foreign oil. Hydrogen is clean, hydrogen is domestically produced, and hydrogen is the way of the future."

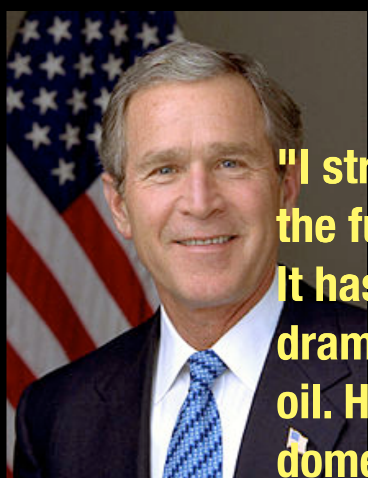
Frustration at low level of public discourse



"I strongly believe hydrogen is the fuel of the future. That's what we're talking about. It has the potential -- a vast potential to dramatically cut our dependence on foreign oil. Hydrogen is clean, hydrogen is domestically produced, and hydrogen is the way of the future."



Frustration at low level of public discourse



"I strongly believe hydrogen is the fuel of the future. That's what we're talking about. It has the potential -- a vast potential to dramatically cut our dependence on foreign oil. Hydrogen is clean, hydrogen is domestically produced, and hydrogen is the way of the future."

8.21 Physics of Energy

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

RLJ & Wati Taylor

8.21 Physics of Energy

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

8.21 Physics of Energy

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

2	Mechanical energy (RJ)
3	Electromagnetic energy (RJ)
4	Heat and thermal energy (RJ)
5	Heat transfer (RJ)
6	Quantum Mechanics I: Intro to quantum, energy quant
7	Quantum Mechanics: Discussion (RJ)
8	Entropy and temperature (RJ)
9	Entropy and the second law discussion (RJ)
10	Energy in matter (RJ)
11	Thermal energy conversion (IC)
12	Internal combustion engines (IC)
13	Phase change energy conversion (IC)
14	Thermal power and heat extraction cycles (IC)

8.21 Physics of Energy

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

2	Mechanical energy (RJ)
3	Electromagnetic energy (RJ)
4	Heat and thermal energy (RJ)
5	Heat transfer (RJ)
6	Quantum Mechanics I: In
7	Quantum Mechanics: Dis
8	Entropy and temperatur
9	Entropy and the second
10	Energy in matter (RJ)
11	Thermal energy conversi
12	Internal combustion engi
13	Phase change energy con
14	Thermal power and heat

15	Fundamental forces in the universe (RJ)
16	Quantum Mechanics II: Quantum mechanics relevant for nuc
17	Nuclear I: An overview of nuclear energy (RJ)
18	Nuclear II: Structure, properties, and decays of nuclei (RJ)
19	Nuclear III: Nuclear energy processes: fission and fusion (RJ)
20	Nuclear IV: Physics of nuclear fission reactors (RJ)
21	Energy in the universe & solar energy (WT)
22	No class (Hurricane)
23	Solar I: Overview, light & matter, and solar heating (IC)
24	Solar II: Concentrating solar power (IC)
25	Solar III: Photovoltaics (IC)
26	Nuclear V: Nuclear reactors -- design, operation, and safety
27	Wind I: Overview, power in the wind, nature and scale of th

8.21 Physics of Energy

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

2	Mechanical energy (RJ)
3	Electromagnetic energy (RJ)
4	Heat and thermal energy (RJ)
5	Heat transfer (RJ)
6	Quantum Mechanics I: In
7	Quantum Mechanics: Dis
8	Entropy and temperatur
9	Entropy and the second l
10	Energy in matter (RJ)
11	Thermal energy conversi
12	Internal combustion engi
13	Phase change energy con
14	Thermal power and heat

15	Fundamental forces in the universe (RJ)
16	Quantum Mechanics II: Quantum mechanics relevant for nuc
17	Nuclear I: An overview of nuclear energy (RJ)
18	Nuclear II: Structure, properties, and decays of nuclei (RJ)
19	Nuclear III: Nuclear energy processes: fission and fusion (RJ)
20	Nuclear IV: Physics of nu
21	Energy in the universe &
22	No class (Hurricane)
23	Solar I: Overview, light
24	Solar II: Concentrating s
25	Solar III: Photovoltaics (
26	Nuclear V: Nuclear reac
27	Wind I: Overview, powe

28	Wind II: Fluids mechanics, wind turbines, and utilization
29	Energy from moving water (IC)
30	Biological Energy (IC)
31	Geothermal energy (IC)
32	Energy and climate I (WT)
33	Energy and climate II (WT)
34	Energy and climate III (WT)
35	Ionizing radiation, nuclear fuel cycles, waste and prolifera
36	Energy storage (RJ)
37	Electricity generation and transmission: the grid (RJ)
38	Energy conservation (RJ)

8.21 Physics of Energy

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

2 Mechanical energy (RJ)
3 Electromagnetic energy (RJ)
4 Heat and thermal energy (RJ)
5 Heat transfer (RJ)
6 Quantum Mechanics I: In
7 Quantum Mechanics: Dis
8 Entropy and temperatur
9 Entropy and the second l
10 Energy in matter (RJ)
11 Thermal energy conversi
12 Internal combustion engi
13 Phase change energy con
14 Thermal power and heat

15 Fundamental forces in the universe (RJ)
16 Quantum Mechanics II: Quantum mechanics relevant for nuc
17 Nuclear I: An overview of nuclear energy (RJ)
18 Nuclear II: Structure, properties, and decays of nuclei (RJ)
19 Nuclear III: Nuclear energy processes: fission and fusion (RJ)
20 Nuclear IV: Physics of nu
21 Energy in the universe &
22 No class (Hurricane)
23 Solar I: Overview, light
24 Solar II: Concentrating s
25 Solar III: Photovoltaics (
26 Nuclear V: Nuclear reac
27 Wind I: Overview, powe

28 Wind II: Fluids mechanics, wind turbines, and utilization
29 Energy from moving water (IC)
30 Biological Energy (IC)
31 Geothermal energy (IC)
32 Energy and climate I (WT)
33 Energy and climate II (WT)
34 Energy and climate III (WT)
35 Ionizing radiation, nuclear fuel cycles, waste and prolifera
36 Energy storage (RJ)
37 Electricity generation and transmission: the grid (RJ)
38 Energy conservation (RJ)

Appointment to APS Panel on Public Affairs (POPA)

→

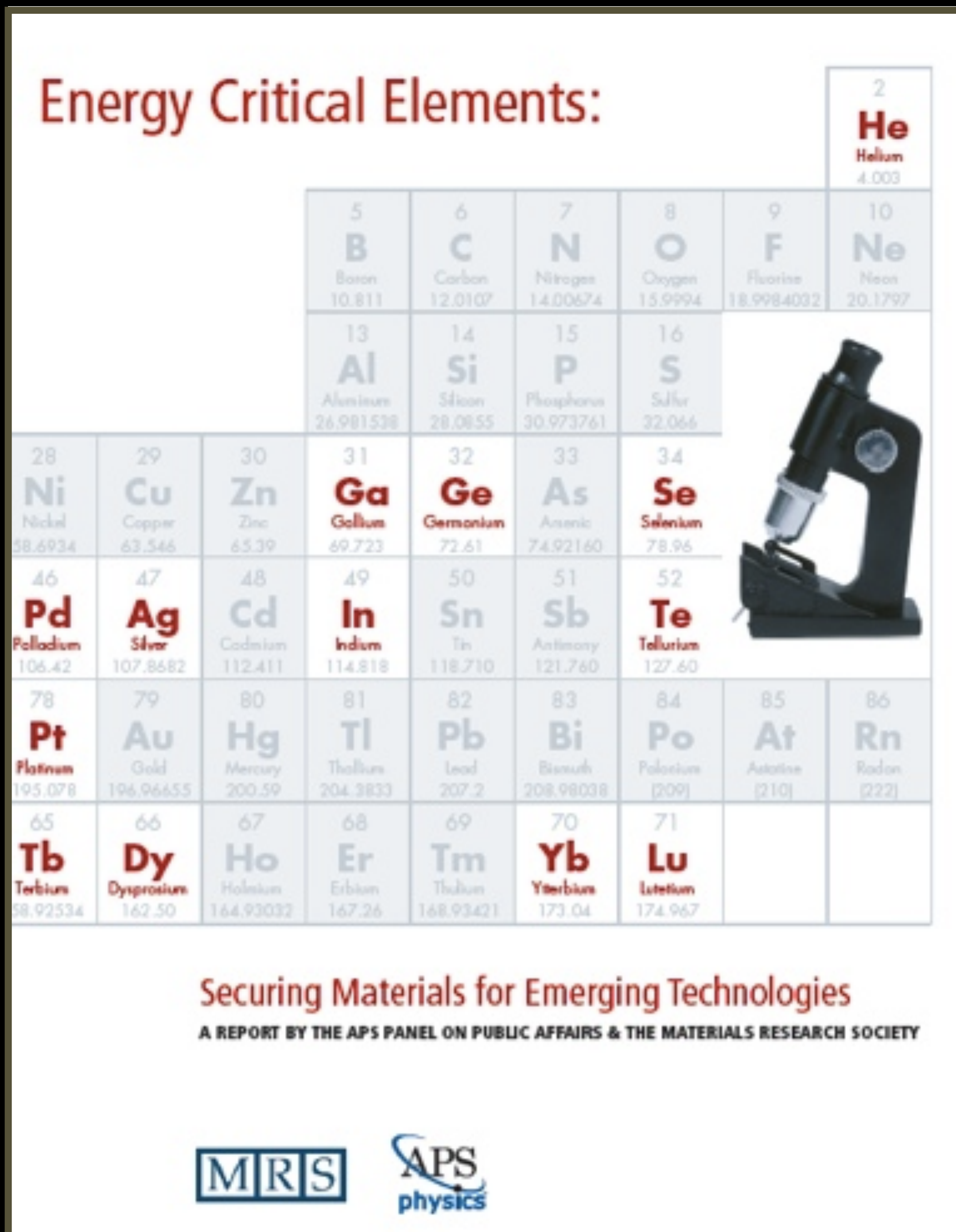
Appointment to APS Panel on Public Affairs (POPA)

Appointment to APS Panel on Public Affairs (POPA)

→ + →

February 2011 APS(POPA)/MRS/MITEI Study

Energy Critical Elements



http://www.aps.org/about/pressreleases/elementsreport.cfm

APS physics

MRS MATERIALS RESEARCH SOCIETY

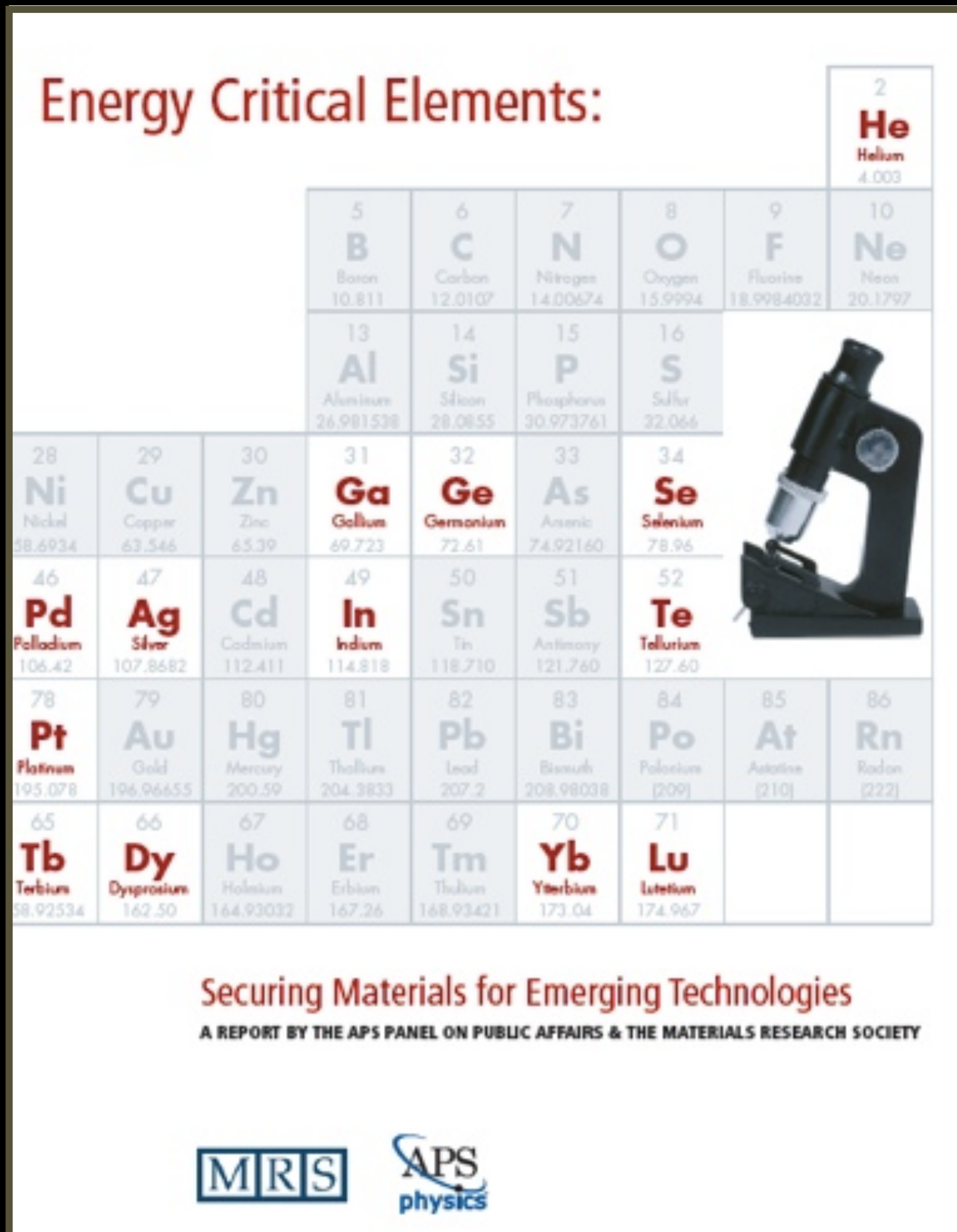
MITei

APS-POPA Studies

- Fast
- Focused
- Policy oriented
- Follow up

February 2011 APS(POPA)/MRS/MITEI Study

Energy Critical Elements



http://www.aps.org/about/pressreleases/elementsreport.cfm

APS physics

MRS MATERIALS RESEARCH SOCIETY

MITei

APS-POPA Studies

- Fast
- Focused
- Policy oriented
- Follow up

Gerbrand Ceder (MIT) ---Material Science

Rod Eggert (Colorado School of Mines) ------------------------------Economics / economic geology

Thomas Graedel (Yale) ---Industrial ecology

Karl Gschneidner (Iowa State/Ames Lab) ---Material science

Murray Hitzman (Colorado School of Mines) ------------------------------------Economic geology

Frances Houle (InVisage Technologies, Inc.) ------------------------------------Physical chemistry

Alan Hurd (LANL) --Material science

Robert Jaffe (MIT) Chair -- --Physics

Alex King (Ames Lab) ---Material science

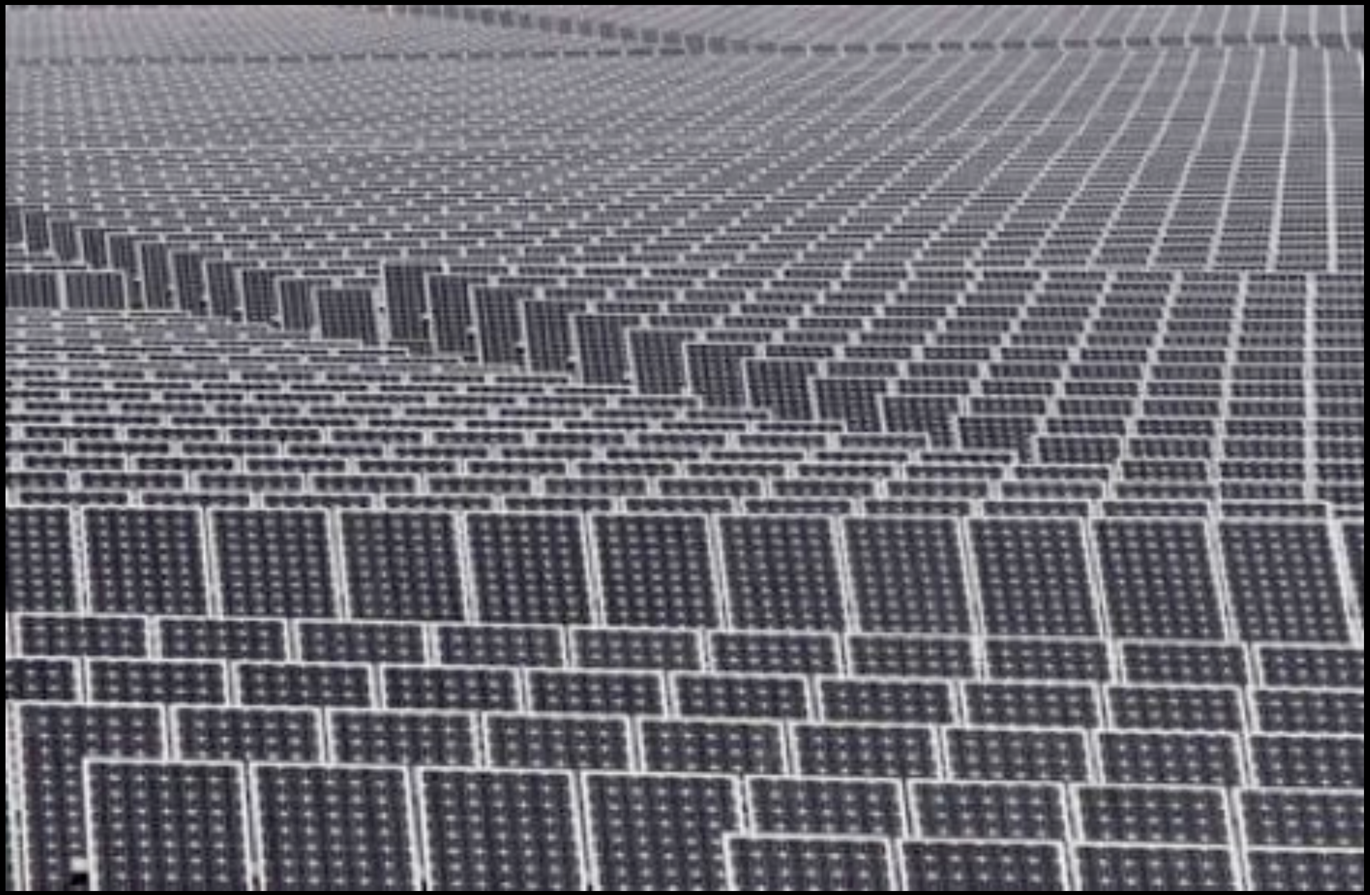
Delia Milliron (Lawrence Berkeley Lab) --- Physical chemistry

Jonathan Price (University of Nevada, Reno) Co-chair --------------------Geology/mineral resources

Professor, State Geologist of Nevada and Director, Nevada Bureau of Mines

Brian Skinner (Yale) ---Geology

Energy critical elements?

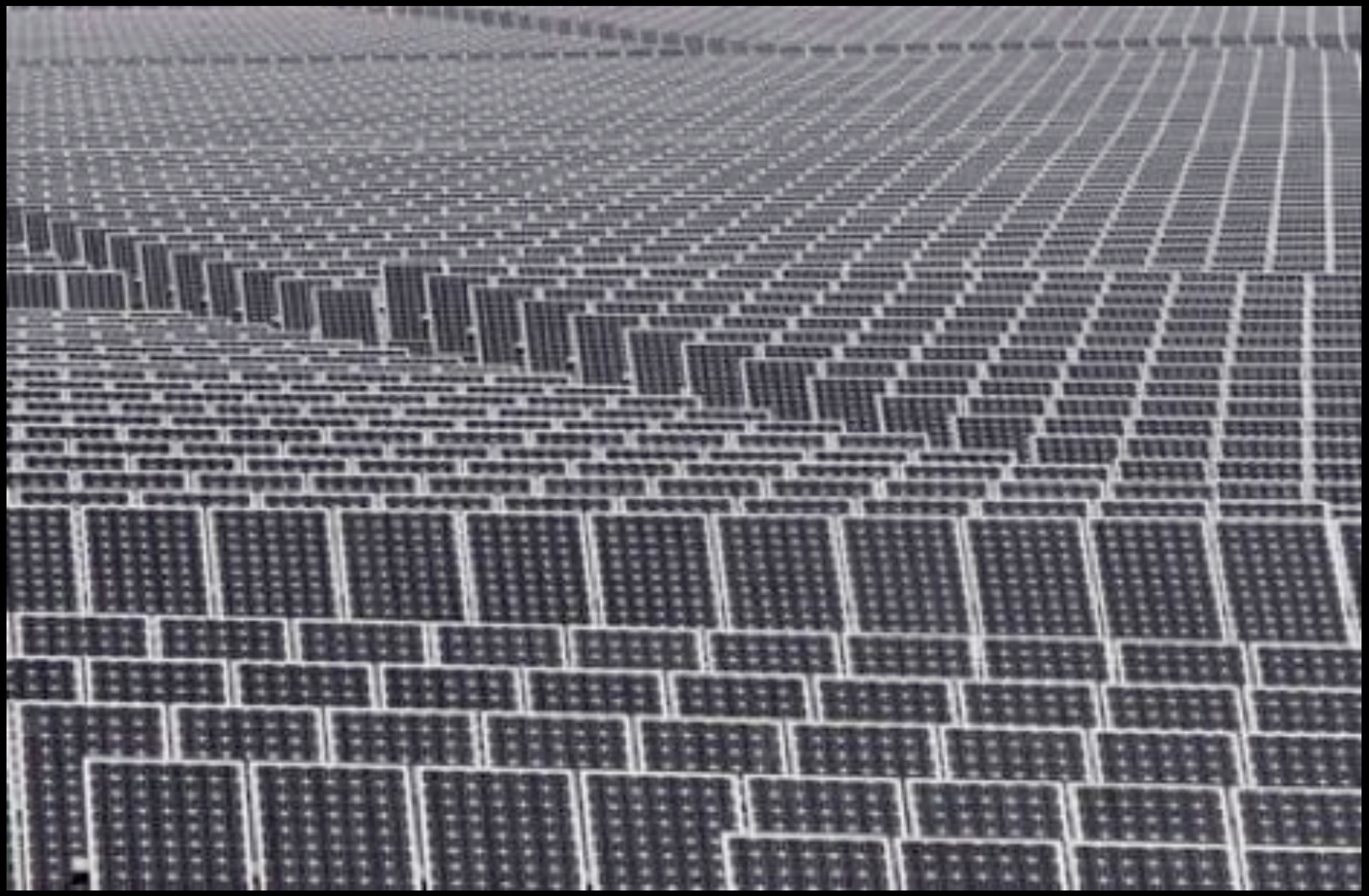


- Energy technologies:
  Deployment at massive scale
  Materials intensive

Power ∝ Area ∝ Material

(Especially since renewable energy is typically diffuse)

Energy critical elements?



- **Energy technologies:**
  Deployment at massive scale
  Materials intensive

Power ∝ Area ∝ Material

(Especially since renewable energy is typically diffuse)

Grand challenge problems for the 21st century

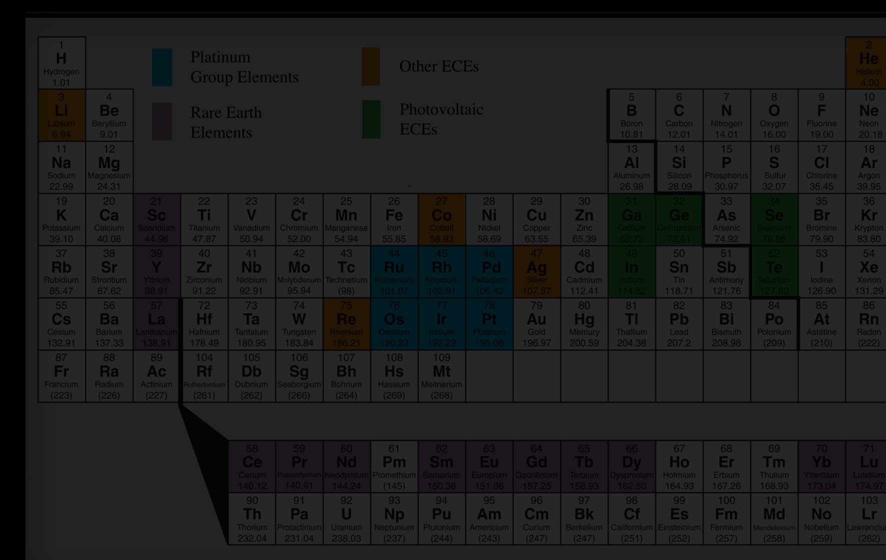
- Increasing demand for energy
- Anthropogenic climate change
- Resouce exhaustion

Research community → new ideas for

Harvesting, Storing, Transmitting, Transforming, Using Energy

- Search the periodic table
- Superb technical solutions
- Usually without regard to availability

And there’s the rub...



Grand challenge problems for the 21st century

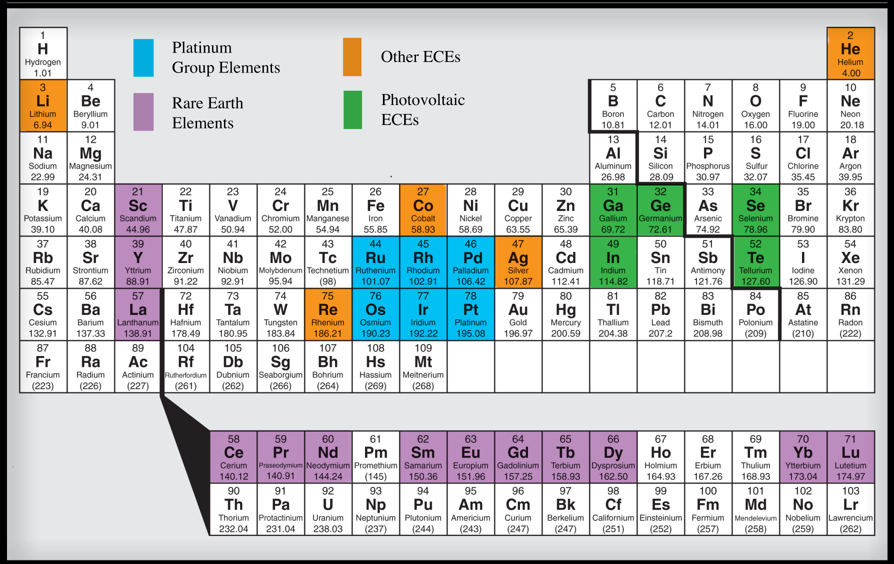
- Increasing demand for energy
- Anthropogenic climate change
- Resouce exhaustion

Research community → new ideas for

Harvesting, Storing, Transmitting, Transforming, Using Energy

- Search the periodic table
- Superb technical solutions
- Usually without regard to availability

And there's the rub...



New energy technologies

- Efficient
- Clean, renewable
- CO_2 neutral or negative

New energy technologies

- Efficient
- Clean, renewable
- CO2 neutral or negative

Neodymium
Dysprosium
Praseodymium
Cobalt
Samarium

New energy technologies

- Efficient
- Clean, renewable
- CO2 neutral or negative

Neodymium Dysprosium

Praseodymium

Cobalt Samarium

Rhenium

New energy technologies

- Efficient
- Clean, renewable
- CO2 neutral or negative

Neodymium

Dysprosium

Praseodymium

Cobalt

Samarium

Rhenium

Europium

Terbium

New energy technologies

- Efficient
- Clean, renewable
- CO2 neutral or negative

Neodymium Dysprosium

Praseodymium

Cobalt Samarium

Rhenium

Europium

Terbium

Palladium

Platinum

Ruthenium

New energy technologies

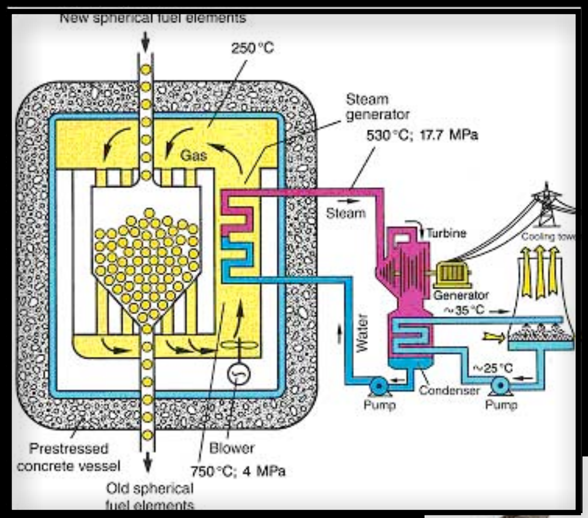
- Efficient
- Clean, renewable
- CO2 neutral or negative

Neodymium Dysprosium

Praseodymium

Cobalt Samarium

Rhenium



Palladium

Platinum

Ruthenium

Helium

Europium

Terbium

New energy technologies

- Efficient
- Clean, renewable
- CO2 neutral or negative

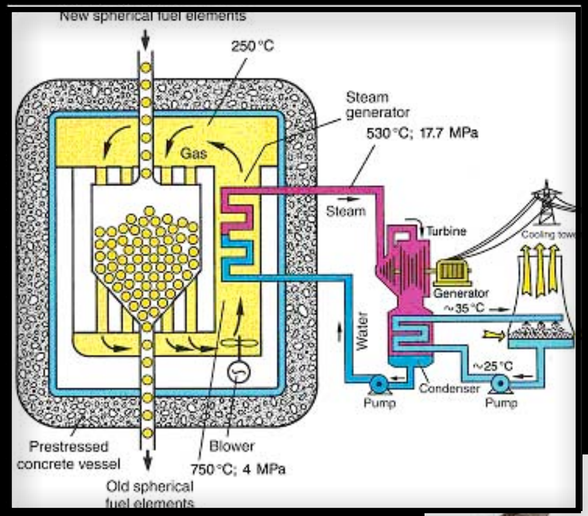
Neodymium Dysprosium

Praseodymium

Cobalt Samarium

Lithium

Rhenium



Helium

Palladium

Platinum

Ruthenium

Lanthanum

Europium

Terbium

New energy technologies

- Efficient
- Clean, renewable
- CO2 neutral or negative

Neodymium Dysprosium

Tellurium Gallium Silver

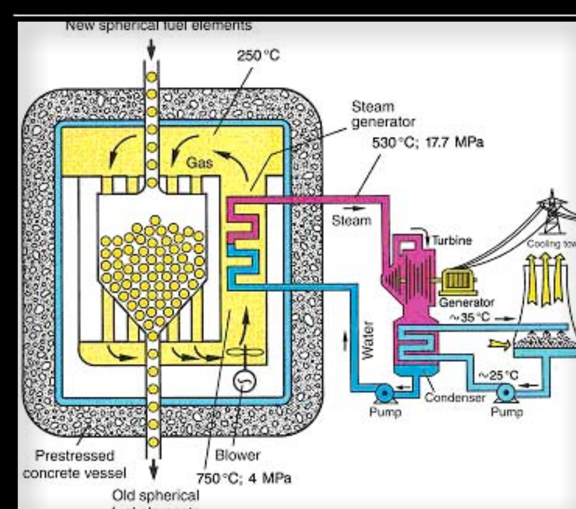
Praseodymium

Selenium Indium Germanium

Cobalt Samarium

Rhenium

Lithium



Palladium

Platinum

Ruthenium

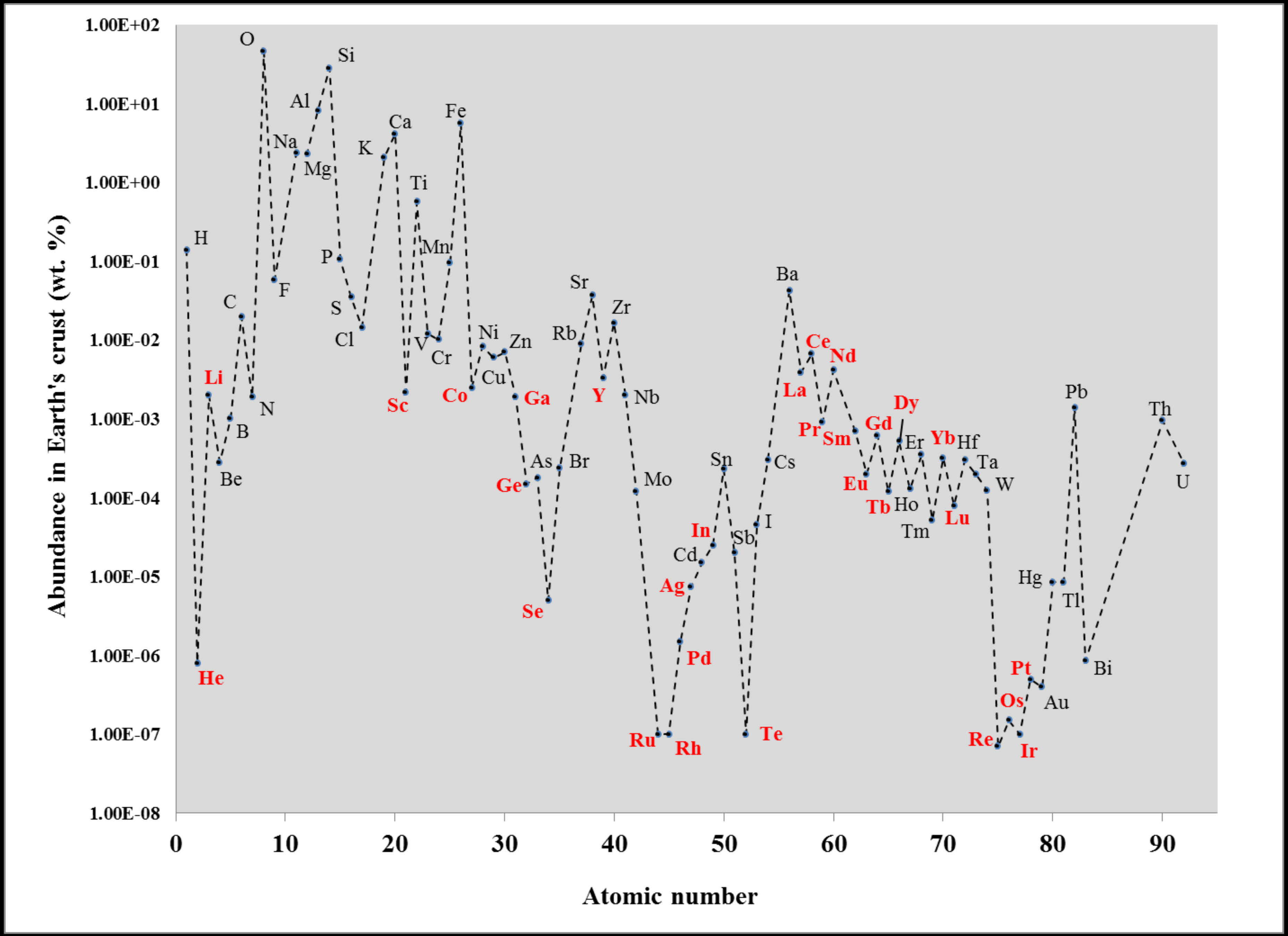
Helium

Lanthanum

Europium

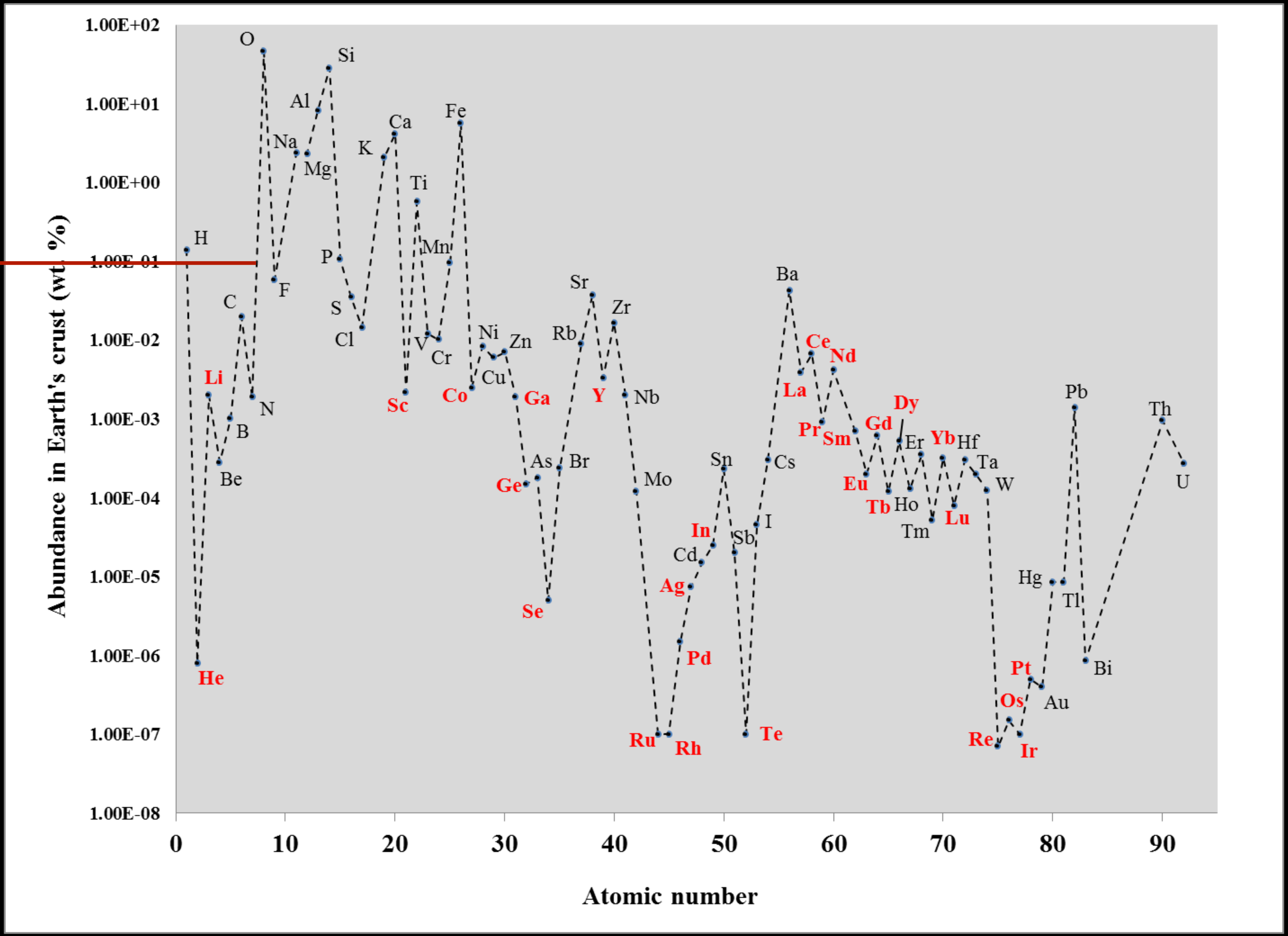
Terbium

- **Novel energy technologies:**
  Unfamiliar and uncommon chemical elements



● **Novel energy technologies:**
Unfamiliar and uncommon chemical elements

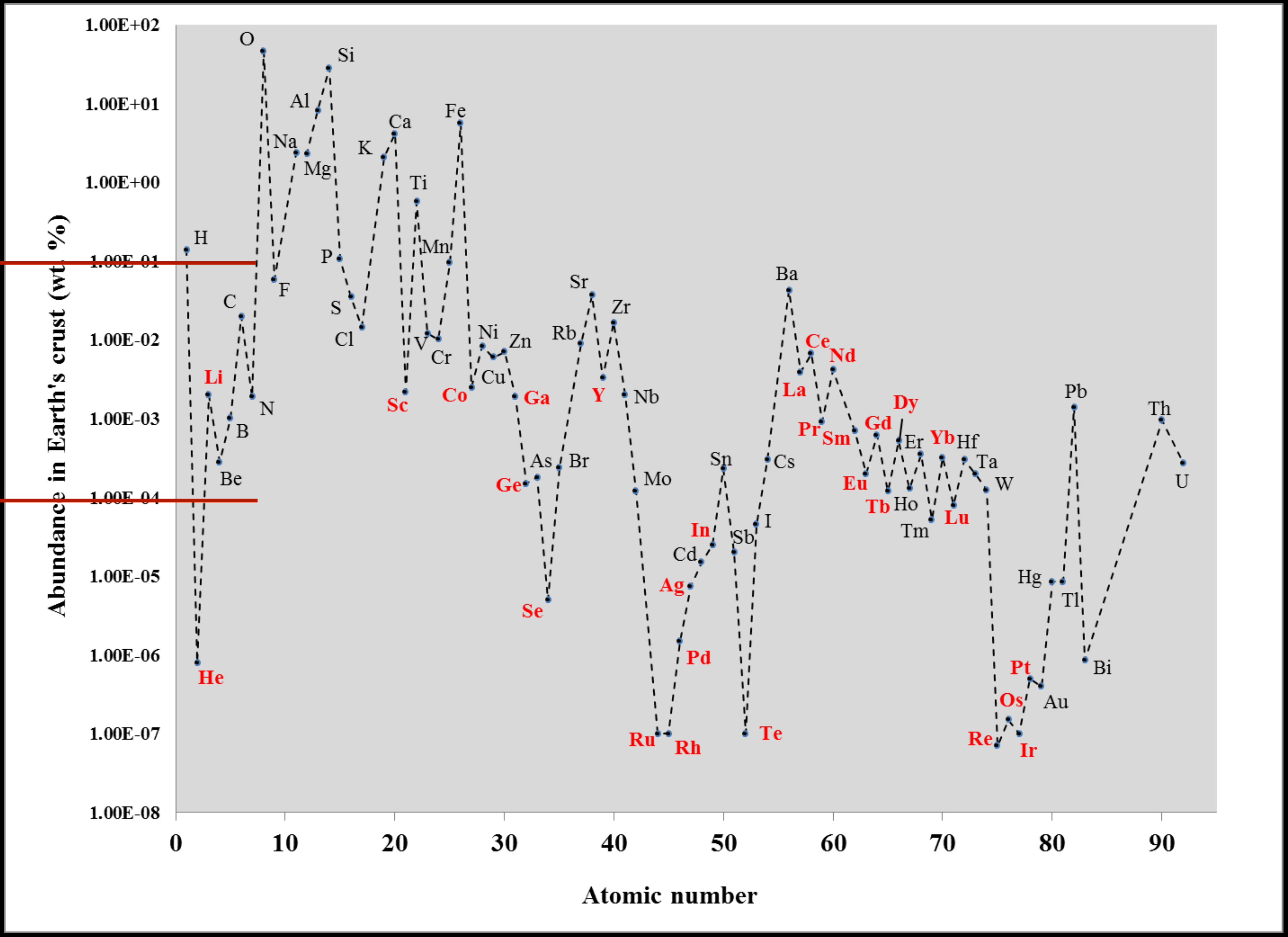
1 ‰



● Novel energy technologies:
Unfamiliar and uncommon chemical elements

1 ‰

1 ppm

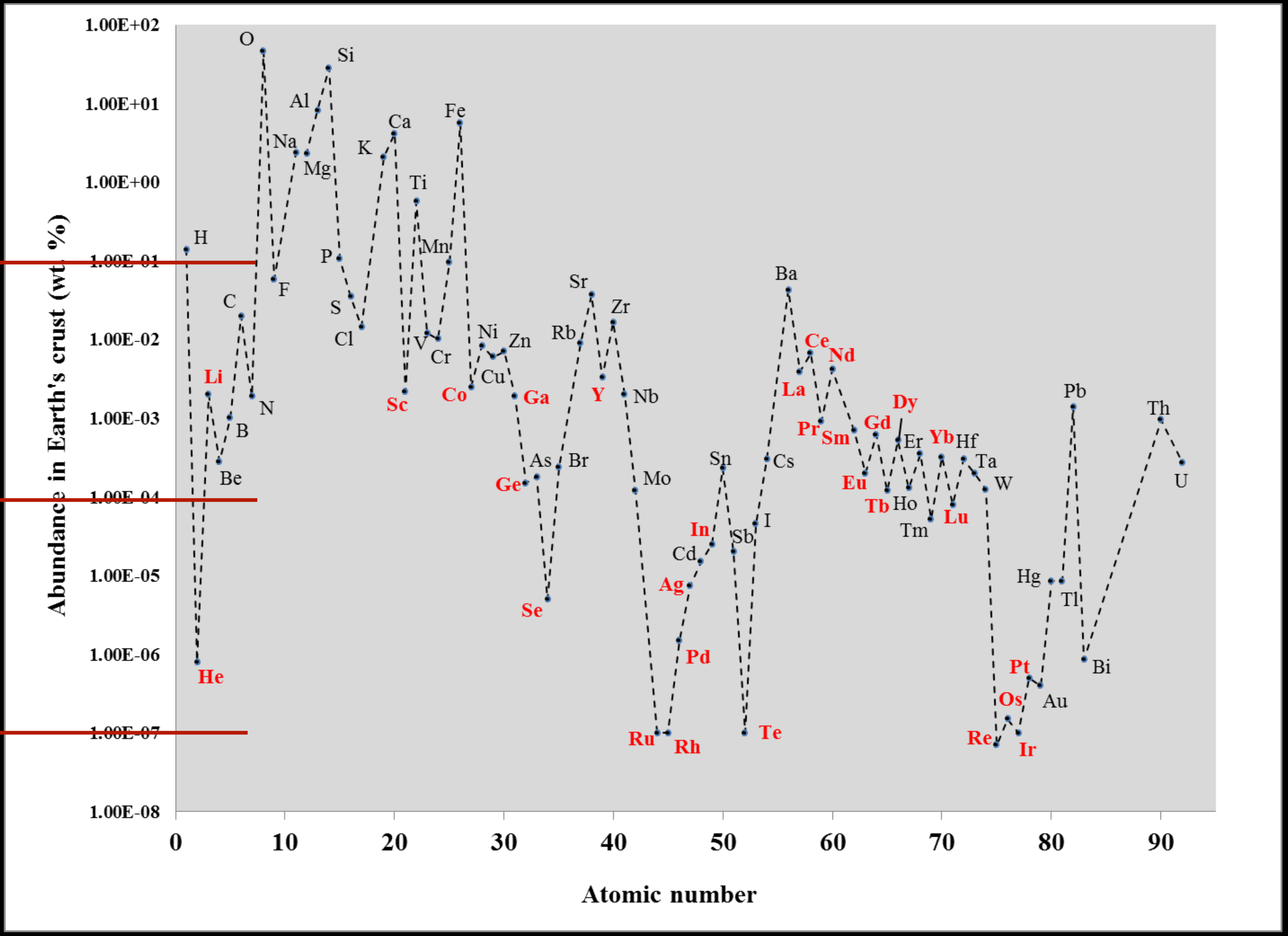


- **Novel energy technologies: Unfamiliar and uncommon chemical elements**

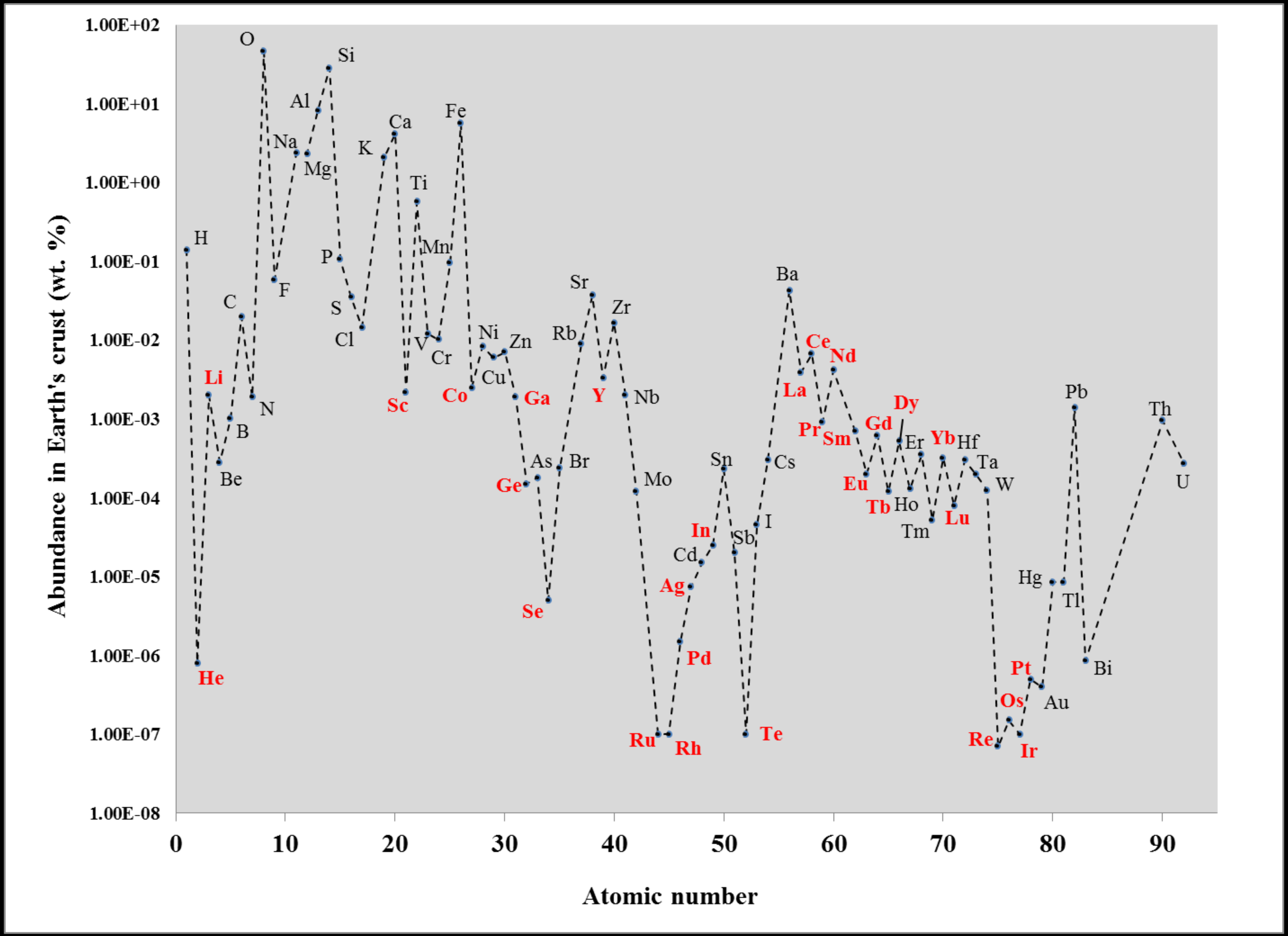
1 ‰

1 ppm

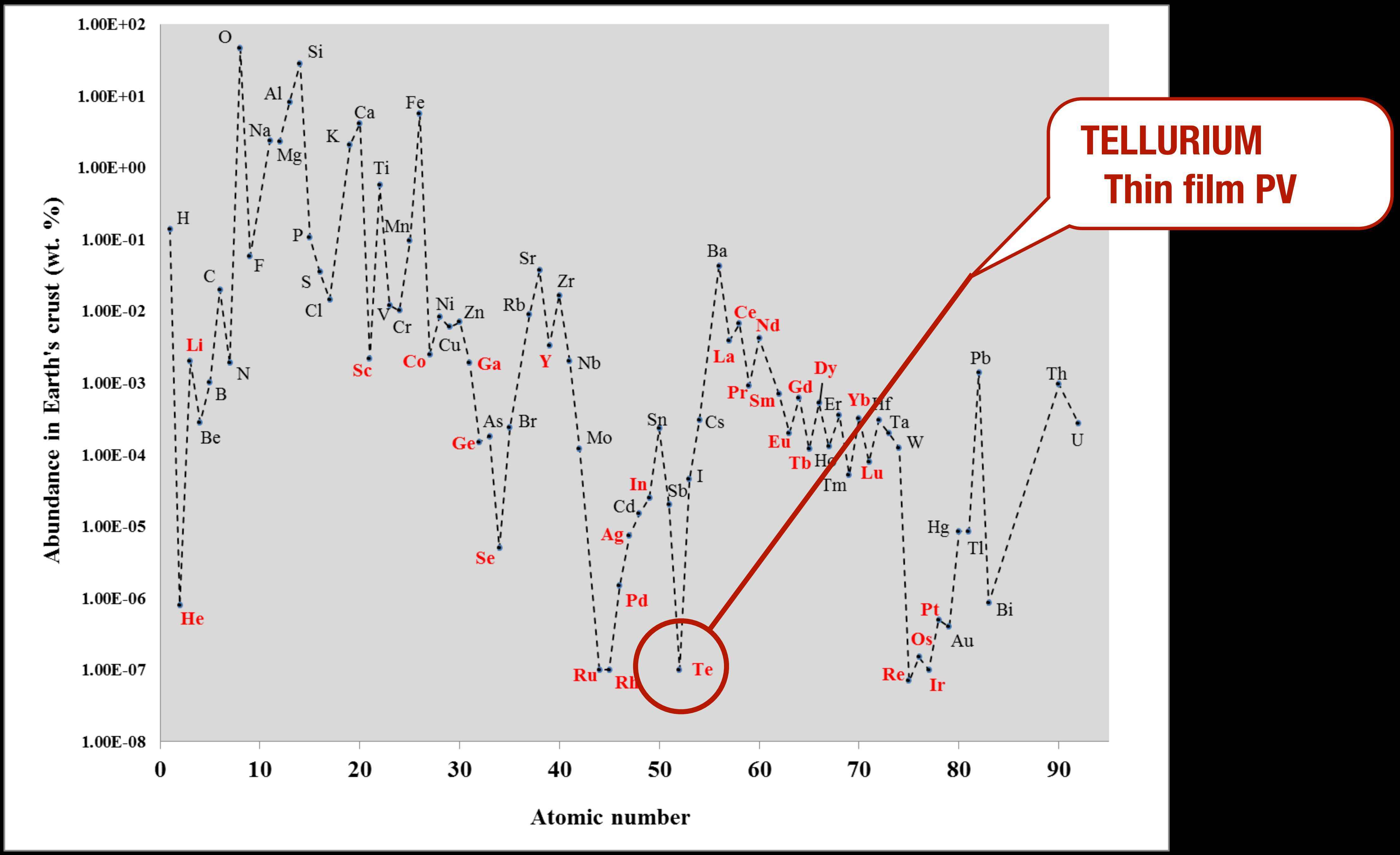
1 ppb



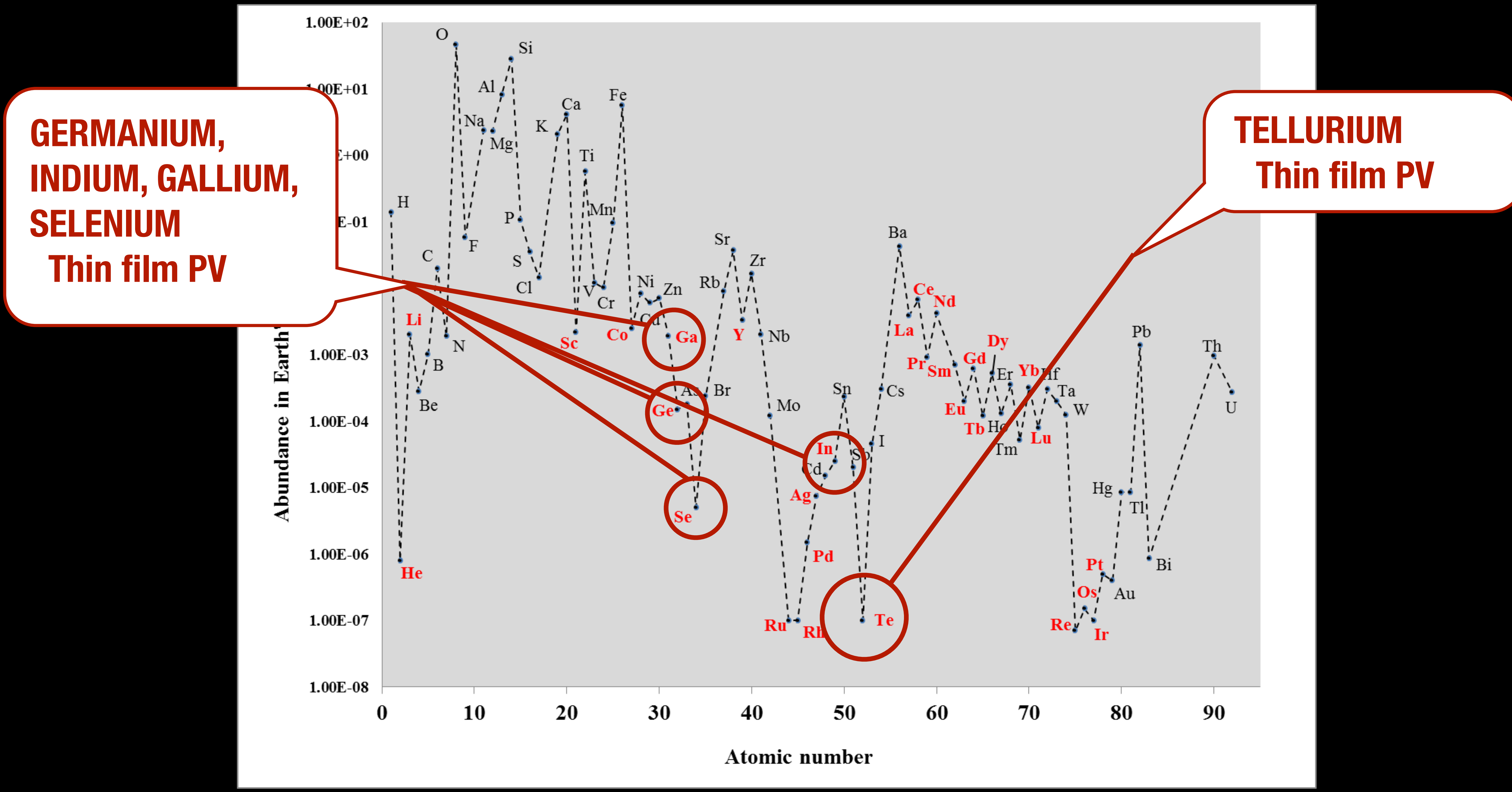
- Novel energy technologies:
  Unfamiliar and uncommon chemical elements



Novel energy technologies:
Unfamiliar and uncommon chemical elements

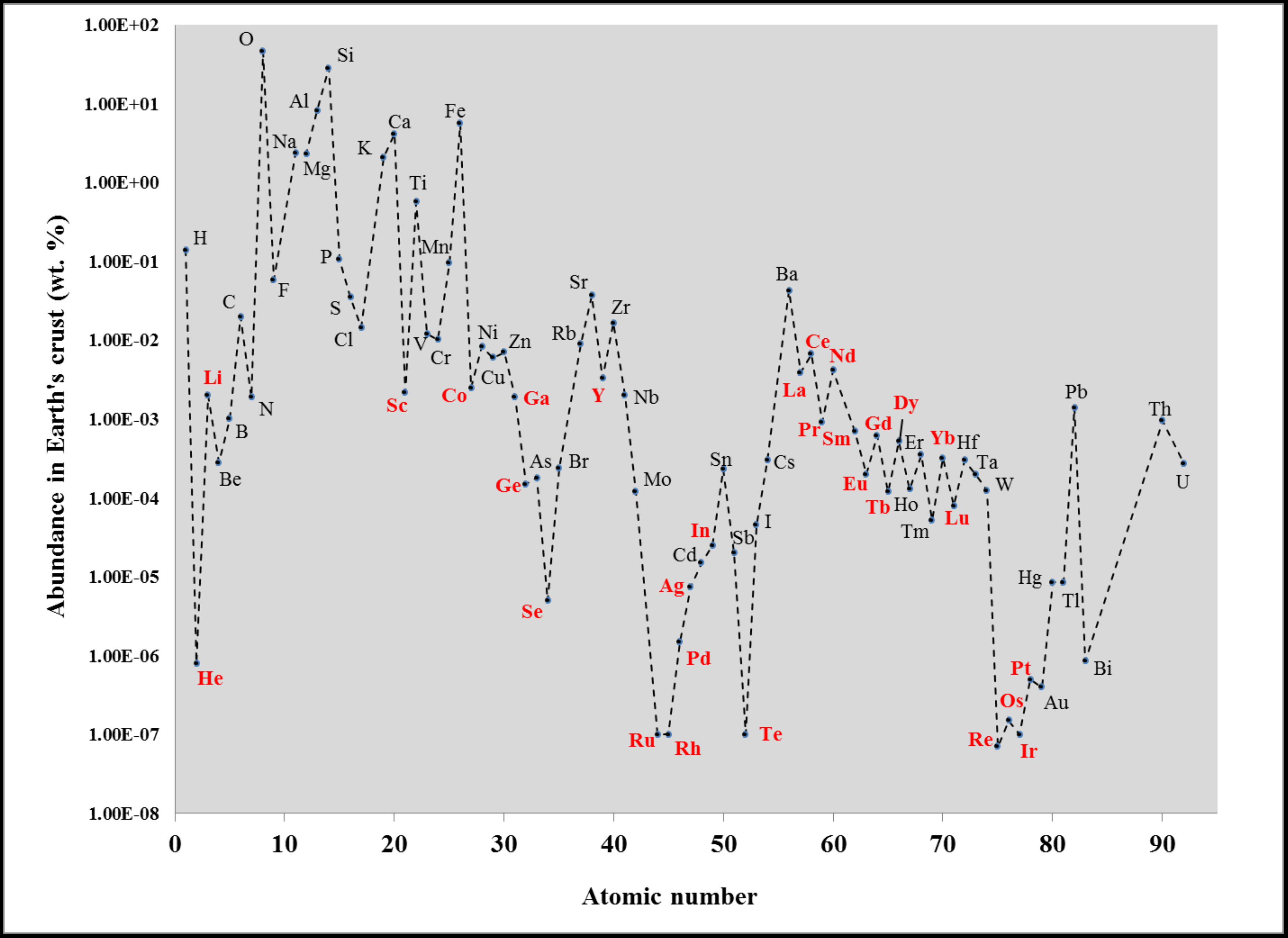


- **Novel energy technologies: Unfamiliar and uncommon chemical elements**

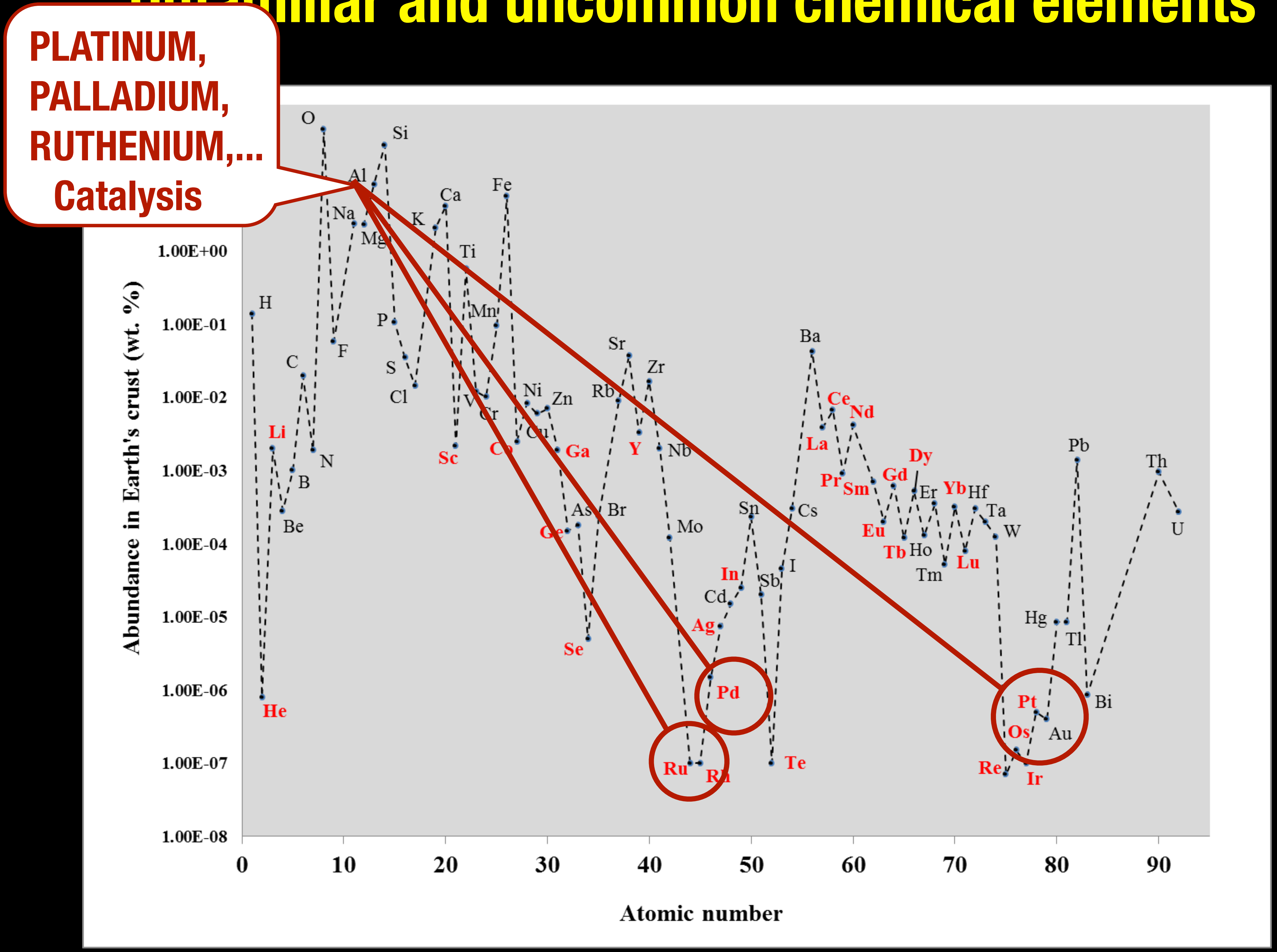


- **Novel energy technologies:**

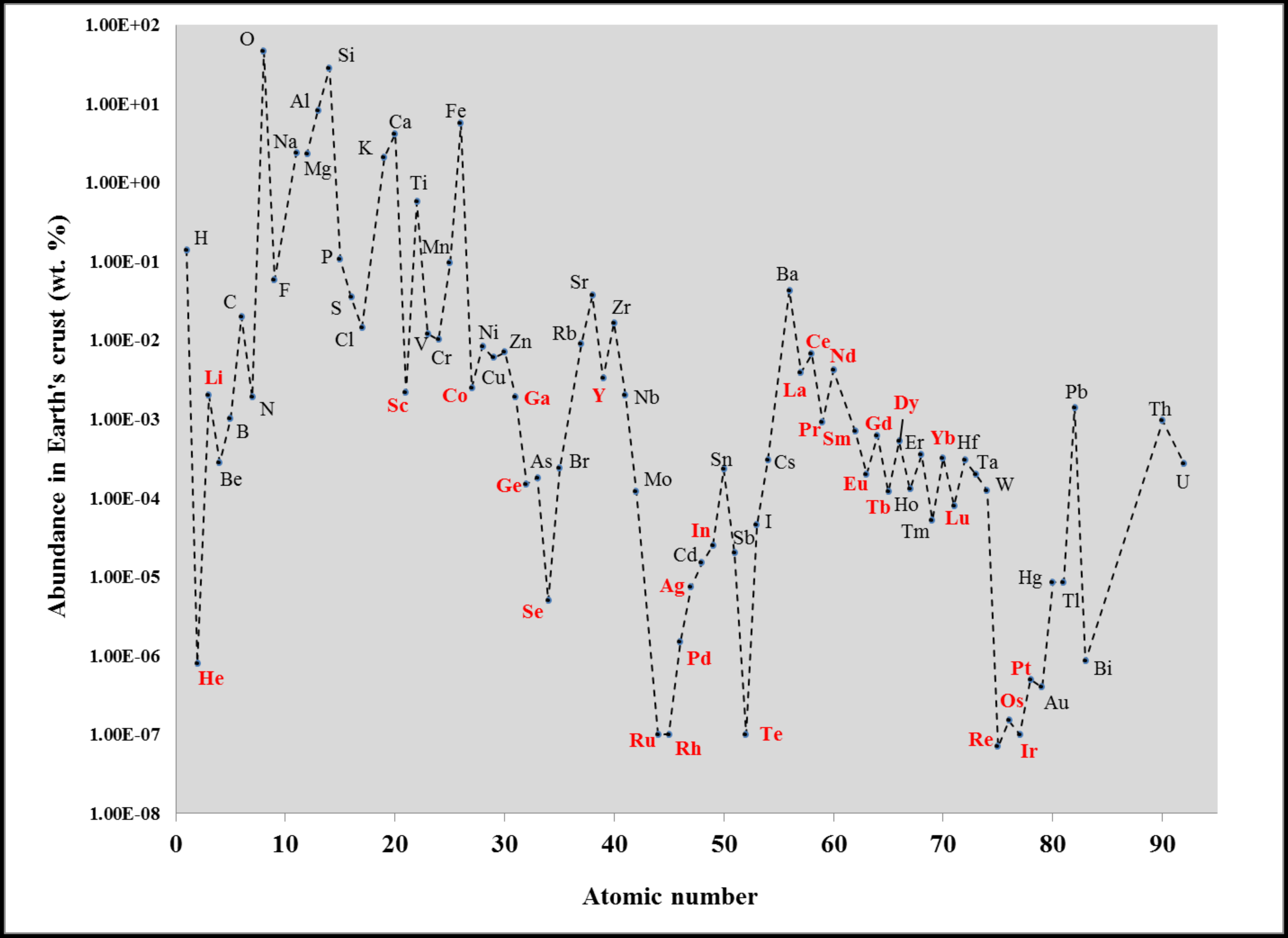
  Unfamiliar and uncommon chemical elements



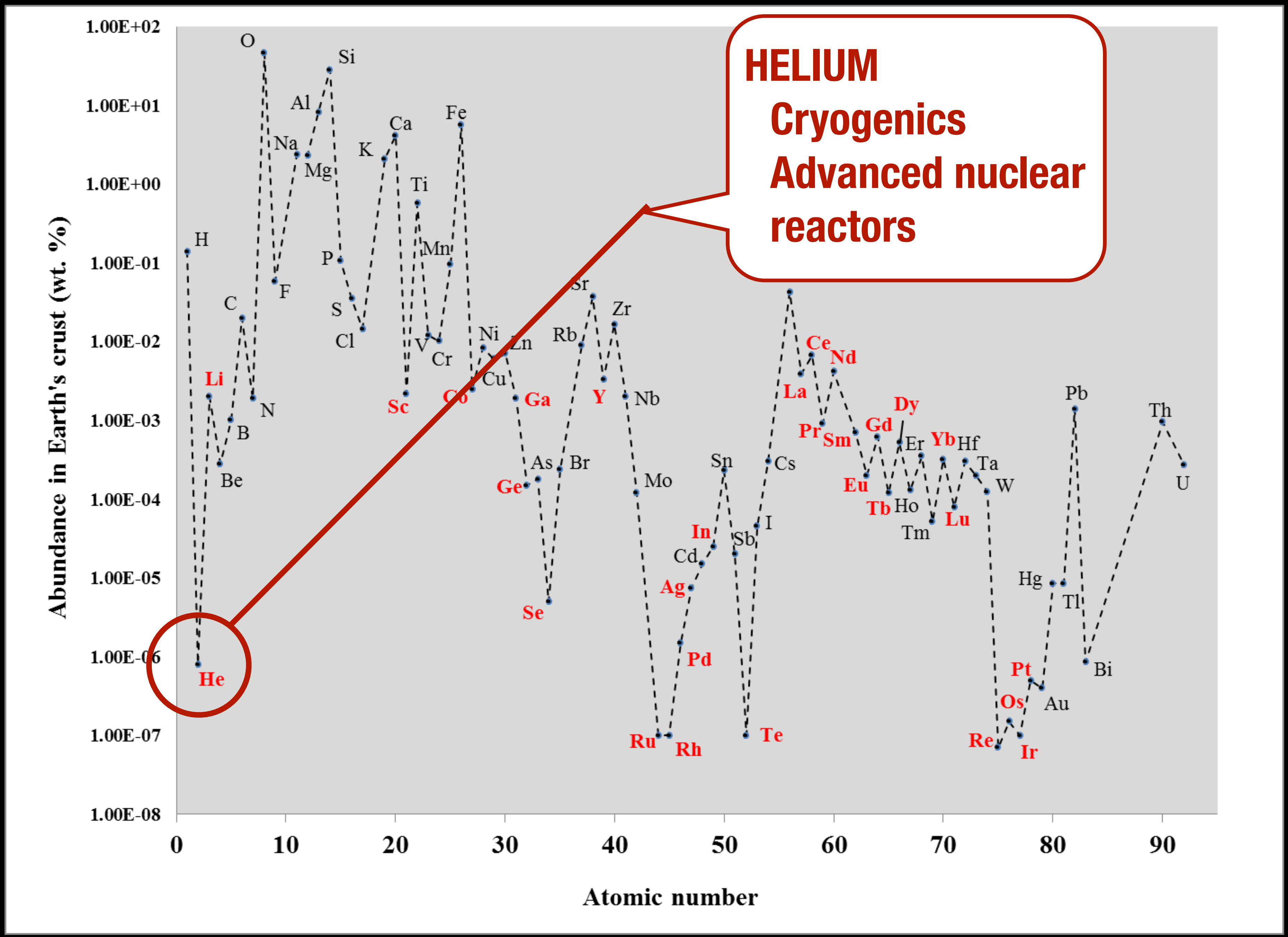
- **Novel energy technologies:**
  Unfamiliar and uncommon chemical elements



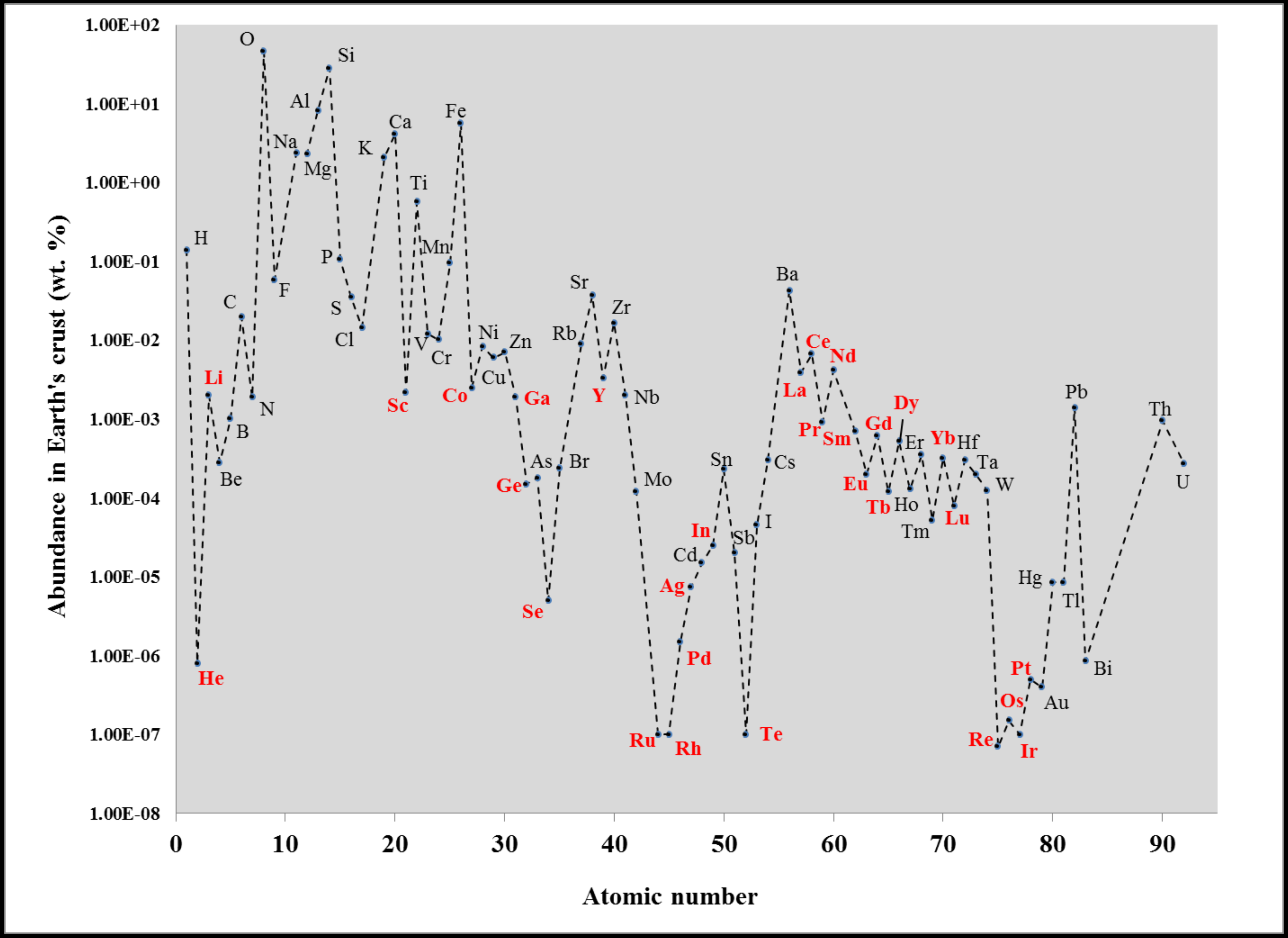
- **Novel energy technologies:**
  Unfamiliar and uncommon chemical elements



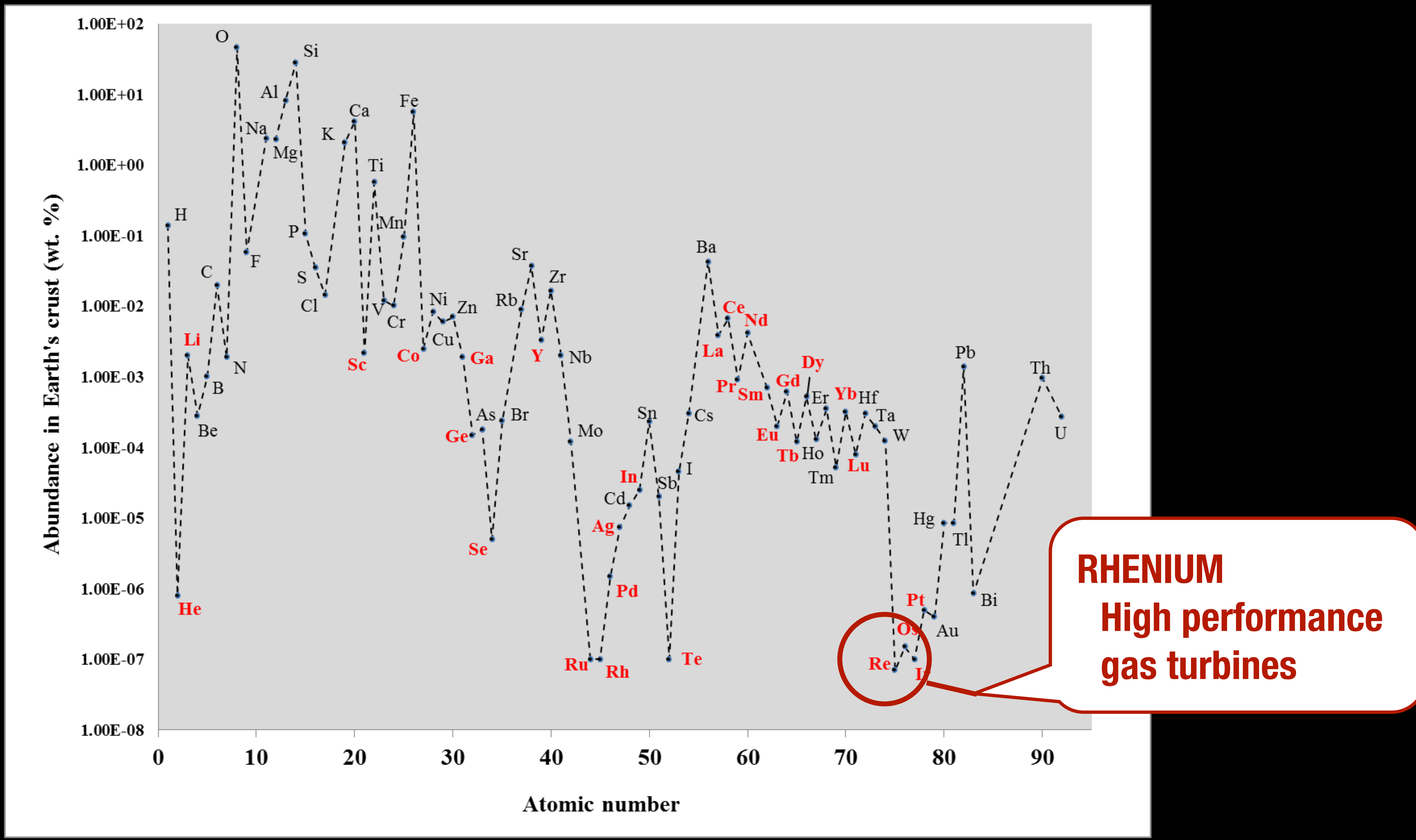
● Novel energy technologies:
Unfamiliar and uncommon chemical elements



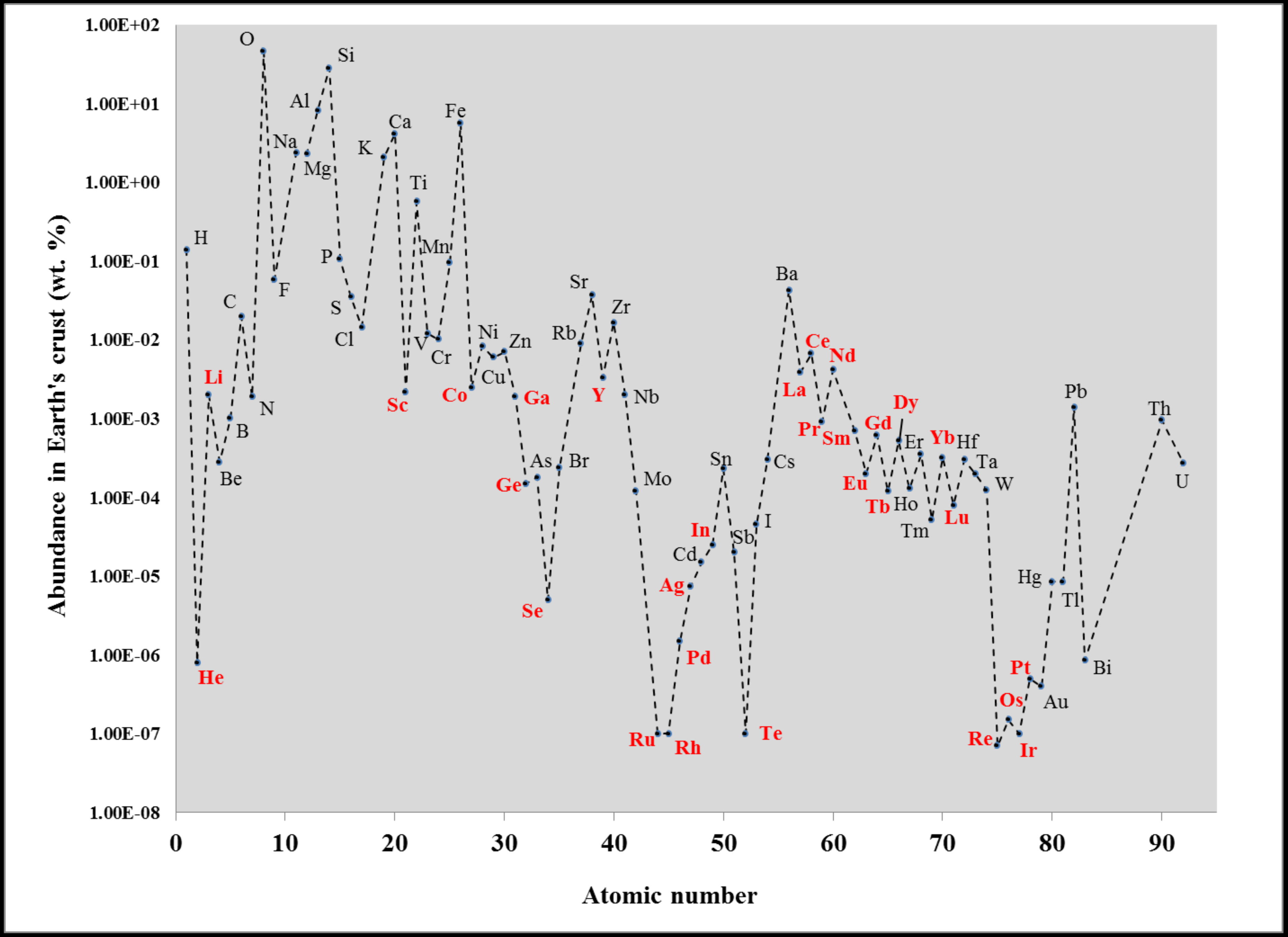
- **Novel energy technologies: Unfamiliar and uncommon chemical elements**



Novel energy technologies:
Unfamiliar and uncommon chemical elements

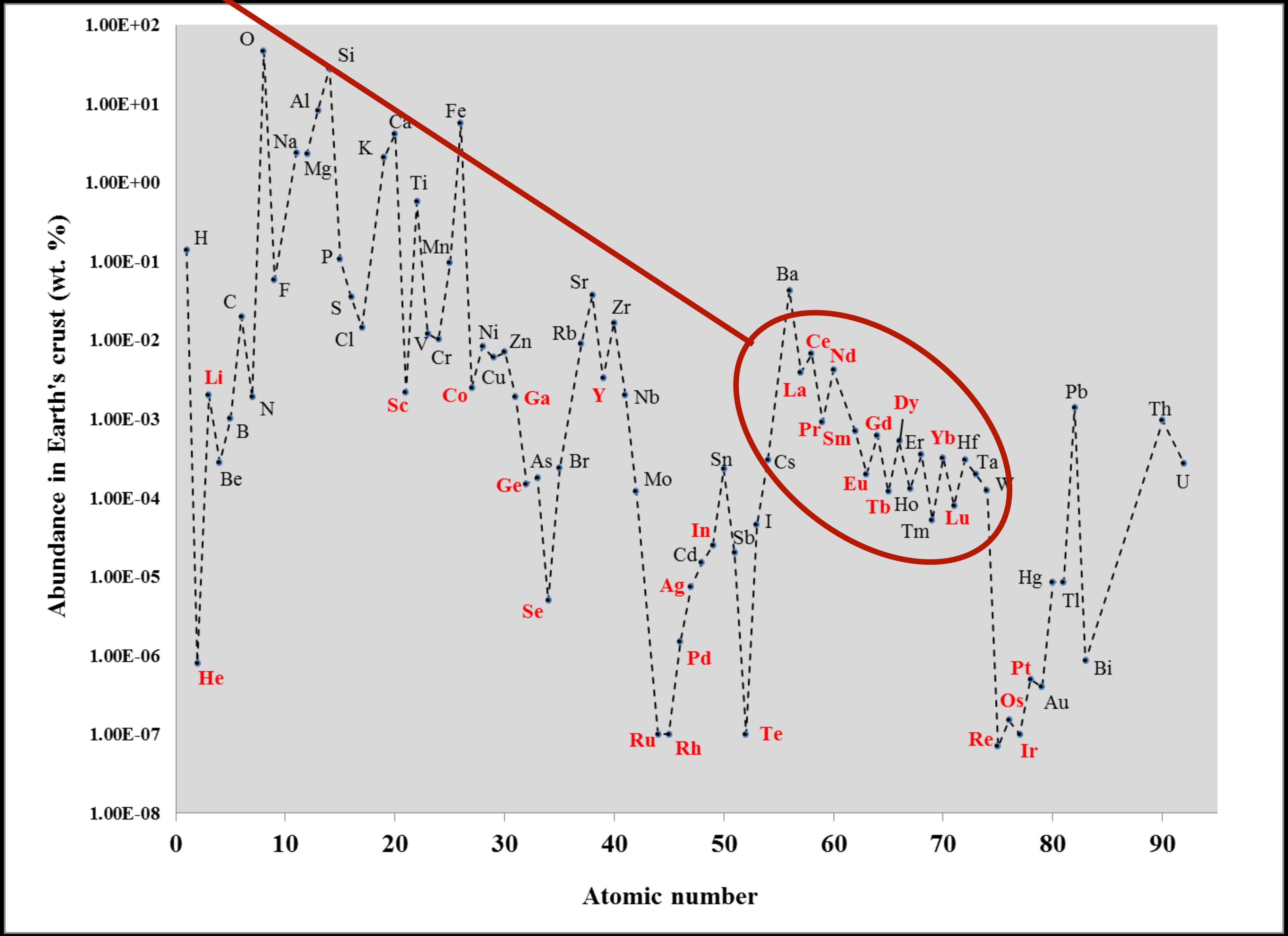


- **Novel energy technologies:**
  Unfamiliar and uncommon chemical elements

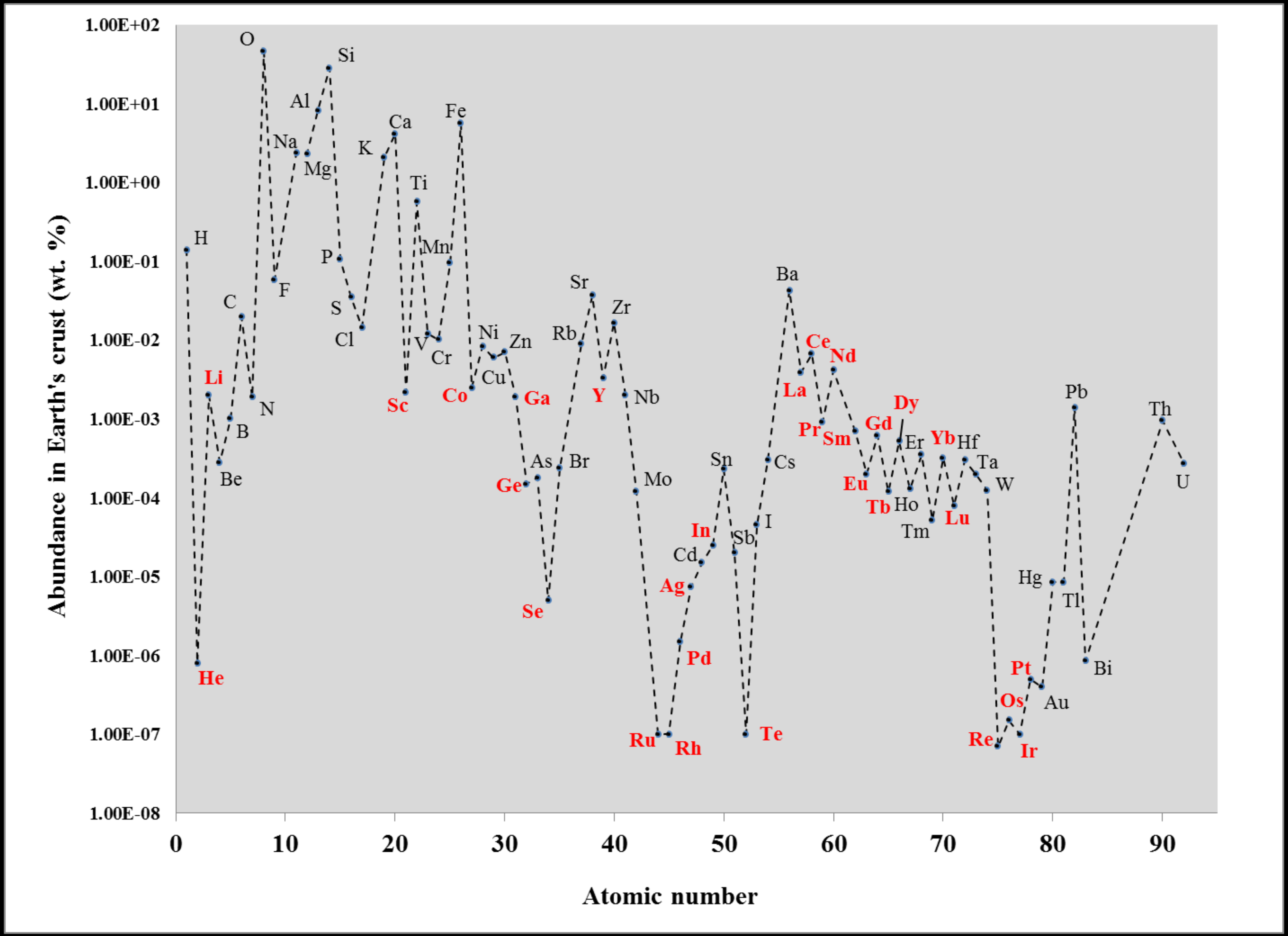


RARE EARTHS
Magnets
Phosphors
Catalysts

el energy technologies:
Unfamiliar and uncommon chemical elements

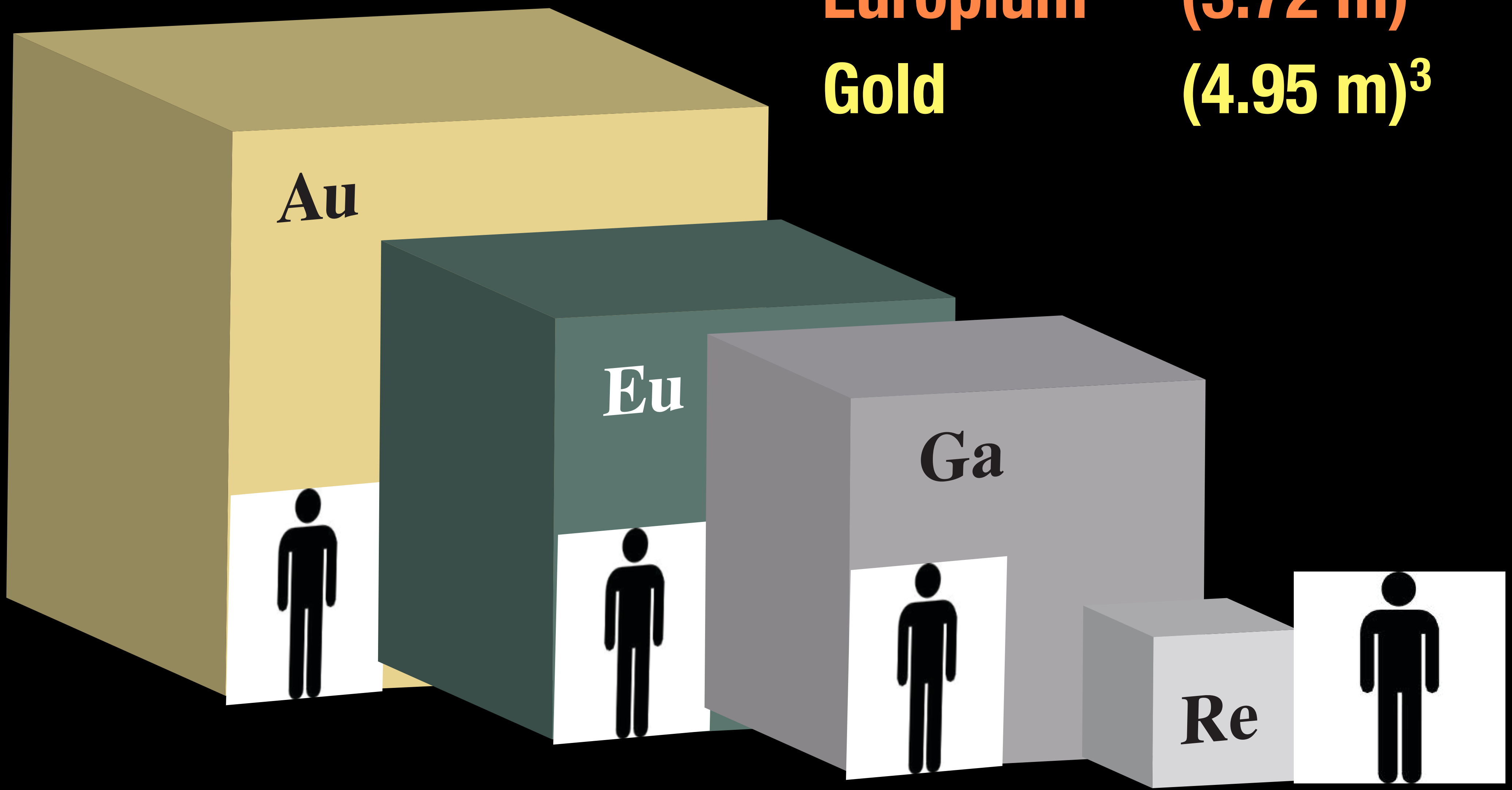


- **Novel energy technologies:**
  Unfamiliar and uncommon chemical elements



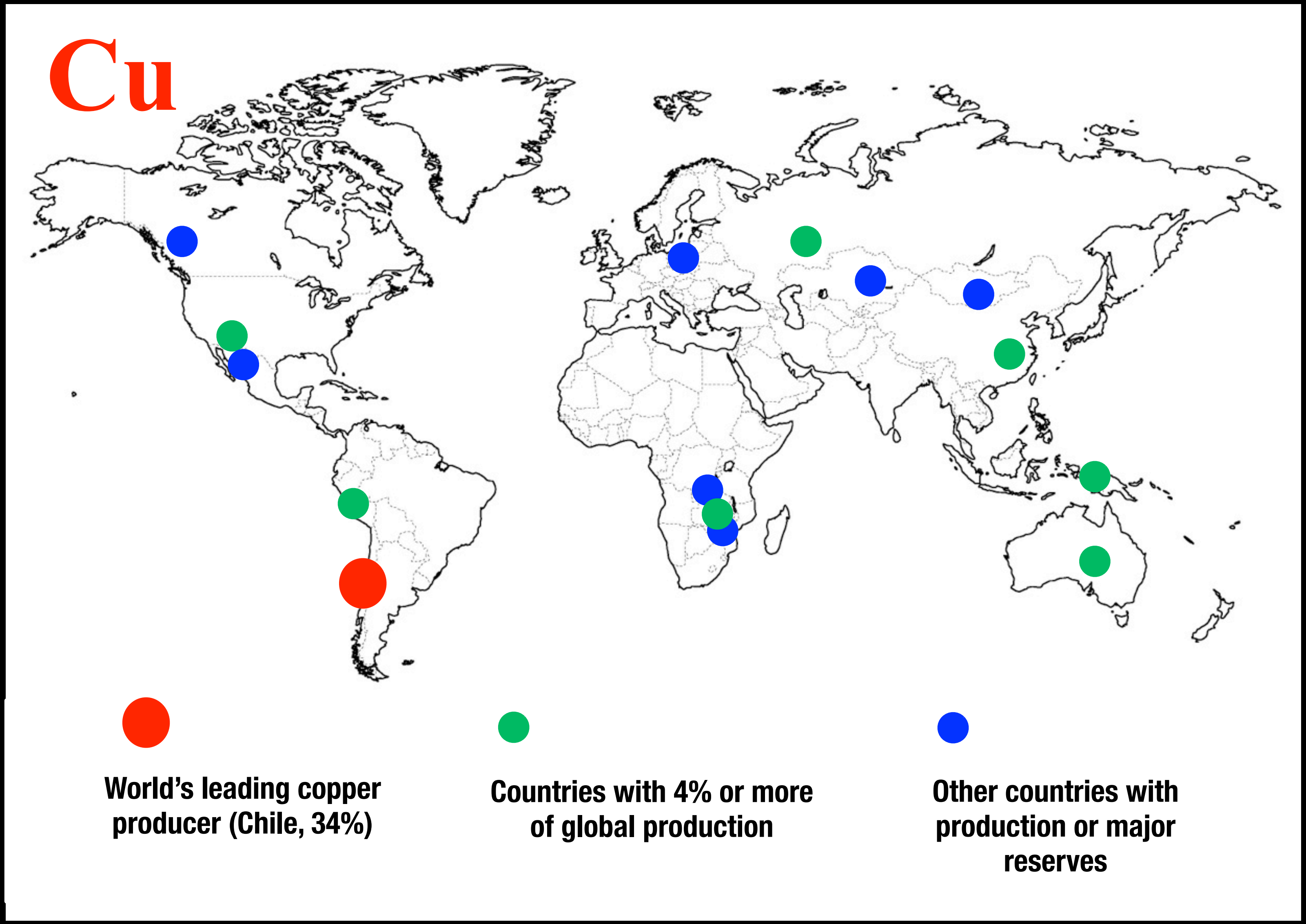
Often exquisitely small production

Rhenium	$(1.32\ m)^3$	MCS(2012)
Gallium	$(3.32\ m)^3$	MCS(2012)
Europium	$(3.72\ m)^3$	Lifton (2010)
Gold	$(4.95\ m)^3$	Lifton (2010)



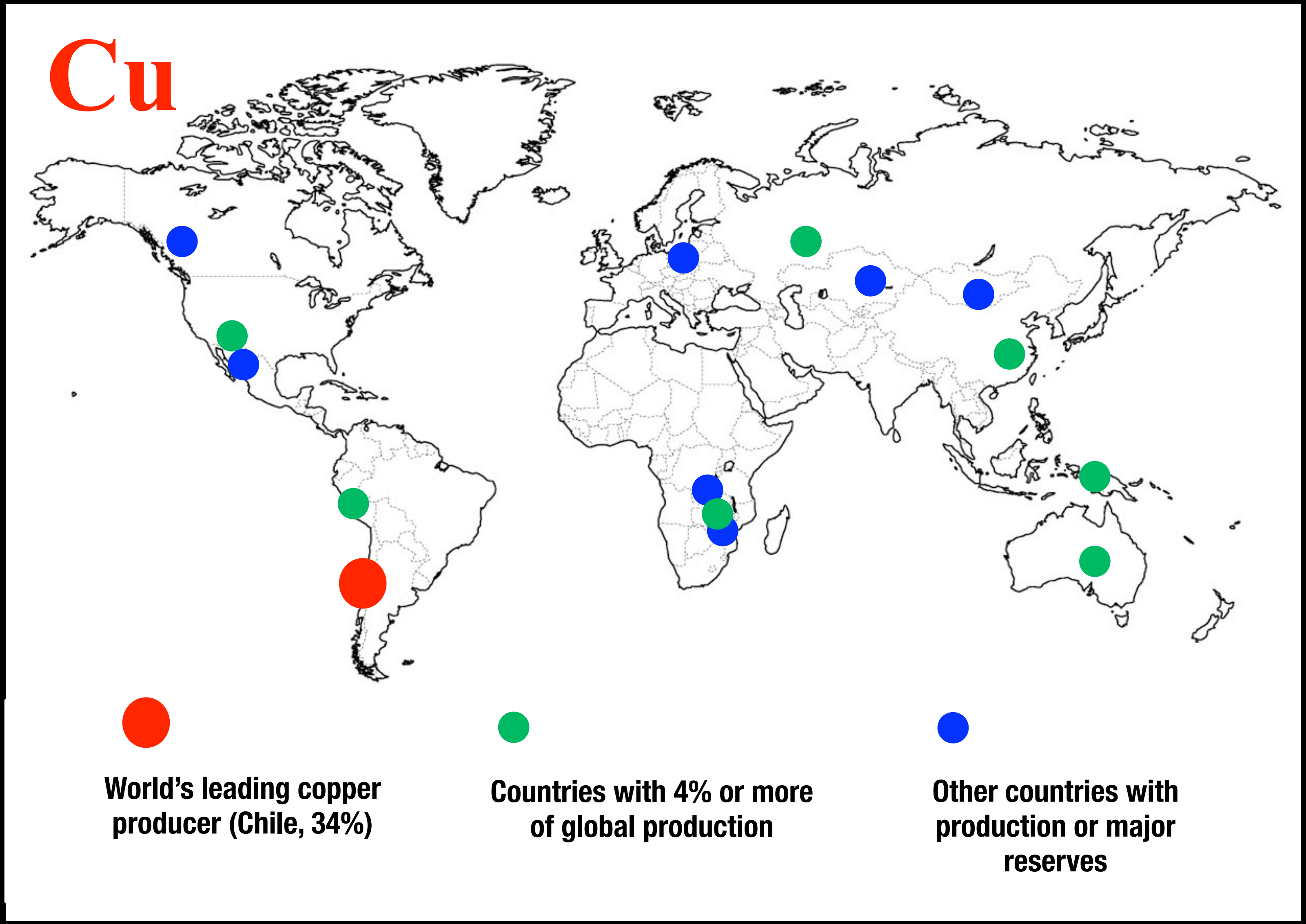
Why not copper (Al, Fe, Zn, Mn, Si, ...)?

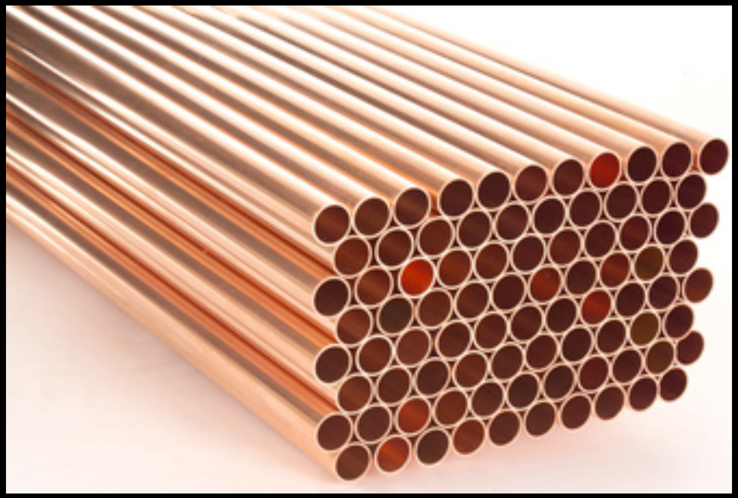
- resources are broadly distributed
- markets are well developed
- many substitutions from non-critical uses



Why not copper (Al, Fe, Zn, Mn, Si, ...)?

- resources are broadly distributed
- markets are well developed
- many substitutions from non-critical uses





Lab ⇒ Pilot ⇒ Massive Deployment

Not been widely extracted, traded, or utilized in the past

Not the focus of well-established, robust markets.

Obstructions to availability? ⇒ Inhibit, derail, otherwise potentially game changing technologies

"Energy critical elements"

Lab ⇒ Pilot ⇒ Massive Deployment

Not been widely extracted, traded, or utilized in the past

Not the focus of well-established, robust markets.

Obstructions to availability? ⇒ Inhibit, derail, otherwise potentially game changing technologies

“Energy critical elements”

ENERGY SCALE

Findings: Constraints on availability

I Absolute abundance & concentration (GERMANIUM...)

Some intrinsically rare. Only the ~15 most abundant "rock forming" elements typically form mineral ores. The rest usually exist in "solid solution" in silicate rock --obtainable only at great energy (and €/$) -- or rarely in ores.

II Geopolitical risks (REE & PLATINUM GROUP)

- Law of small numbers: one or two large or relatively rich deposits with great comparative economic advantage
- Geology, history and politics have led to dominance of a single or small number of countries, allowing market manipulation and raising political issues.

III Risks of joint production (INDIUM, GALLIUM, TELLURIUM...)

Historically low demand → Recovery as by-products → Artificially low cost/price – Raises a host of economic issues

IV Environmental and social concerns (REEs, ...)

Developed world will not accept environmental disruption. Countries willing to tolerate environmental degradation for short term gain can dominate markets. Rising environmental consciousness renders this unstable.

V Response times in development & extraction (battery paradigm – Li/La?)

It takes 5-15 years to bring new sources online and/or research and develop substitutes.

I Absolute abundance & concentration (GERMANIUM...)

★ II Geopolitical risks (REE & PLATINUM GROUP)

★ III Risks of joint production (INDIUM, GALLIUM, TELLURIUM...)

★ IV Environmental and social concerns (REEs, ...)

V Response times in development & extraction (battery paradigm – Li/La?)

GEOPOLITICS

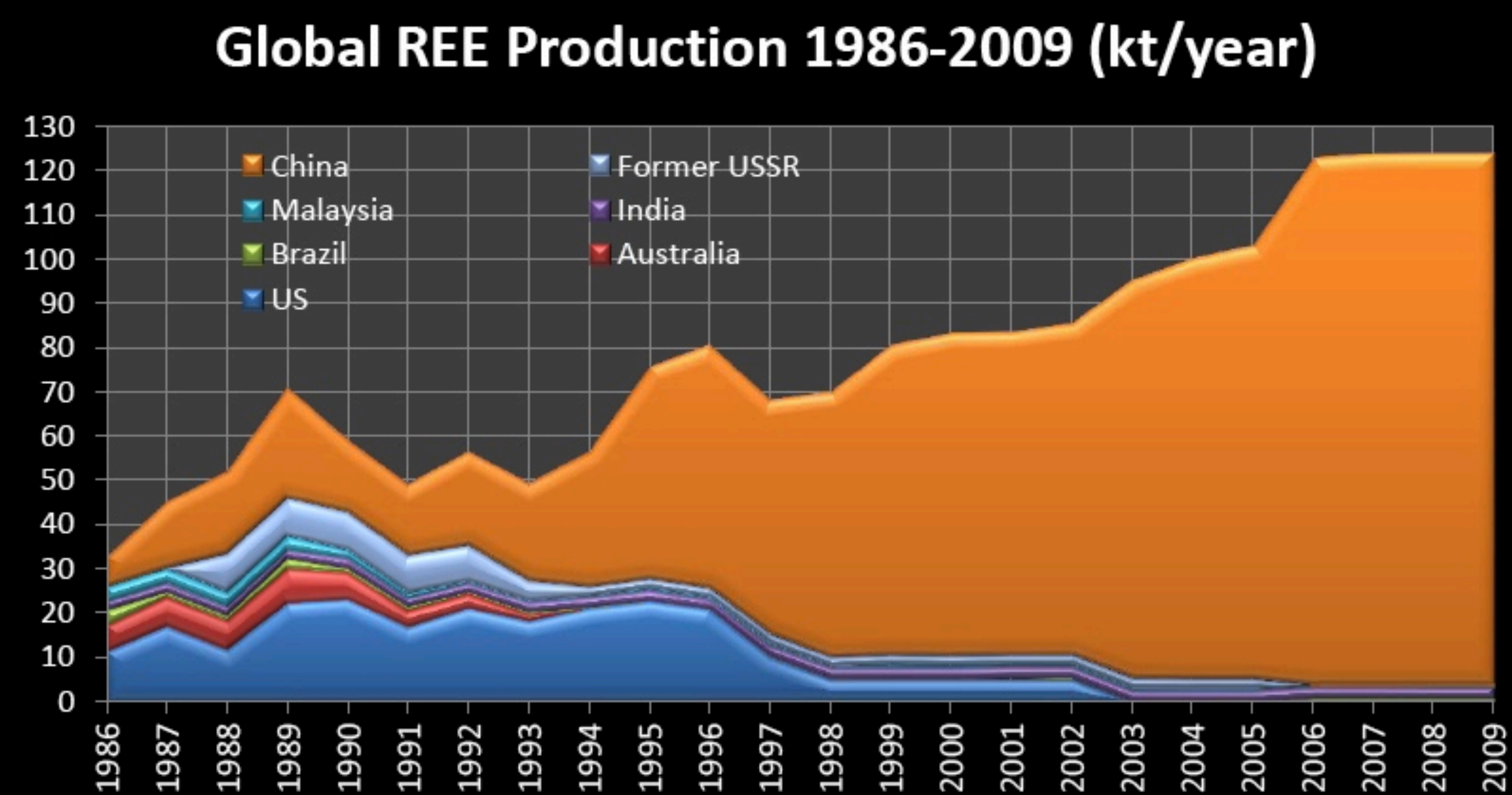
- Reliance on imports is not a priori bad > efficient markets & comparative advantage
- US, for example, relies on imports for over 90% of most ECEs
- Problems arise when happenstance or monopoly economic policies concentrate production in one or a very few countries
- Platinum & palladium: World's reserves are overwhelmingly concentrated in SA (Bushveld complex). Production dominated by SA and Russia.

Rare earth elements

0.007 -- 0.00005%, 130 Kt/yr

95% produced in China, including all HREE

Eamon Keane BE, ME September 2010



GEOPOLITICS (CONT'D)

GEOPOLITICS (CONT'D)

BAYAN OBO IRON/REE MINE
MONGOLIA

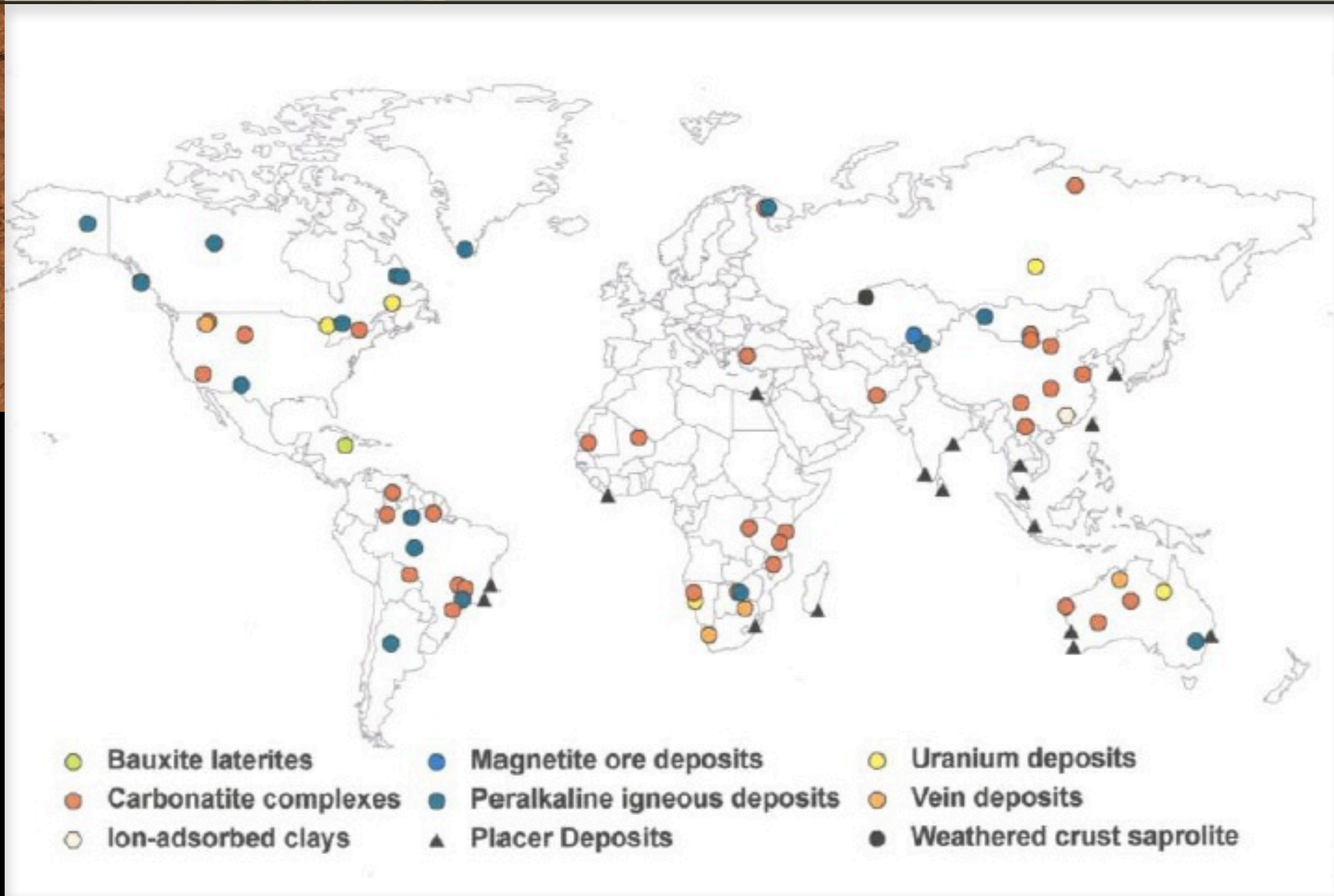
GEOPOLITICS (CONT'D)

1987年6月，改革开放的总设计师邓小平同志，在分析内蒙古的经济发展时，预言内蒙古发展起来很可能“走在前列”。这是1992年1月，他在南巡讲话中指出：“中东有石油，中国有稀土。”

'In June of 1987, Comrade Deng Xiaoping, the architect of reform and opening, speaking on the subject of the economic development of Inner Mongolia ... “The Middle East has its oil, China has rare earth.”

GEOPOLITICS (CONT'D)

济发
他在

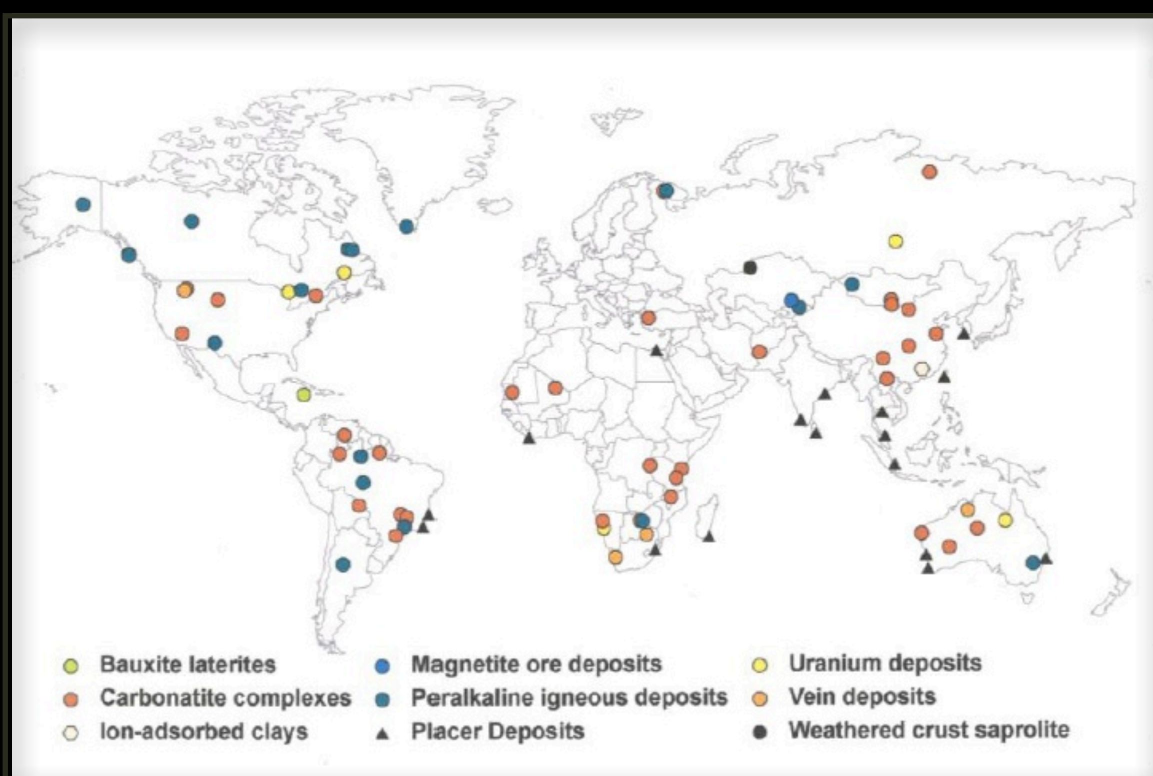


A. Mariano, private communication

GEOPOLITICS (CONT'D)

1987年6月，改革开放的总设计师邓小平同志，在分析内蒙古的经济发展时，预言内蒙古发展起来很可能“走在前列”。这是1992年1月，他在南巡讲话中指出：“中东有石油，中国有稀土。”

'In June of 1987, Comrade Deng Xiaoping, the architect of reform and opening, speaking on the subject of the economic development of Inner Mongolia ... “The Middle East has its oil, China has rare earth.”



- Thank you, China, for the wake-up call
- Many plans afoot for re-opening old and new mines
- Mountain Pass, California
- Mt. Weld, Australia
- But see discussion of co-production and environmental/social issues.

II. Coproduction economics

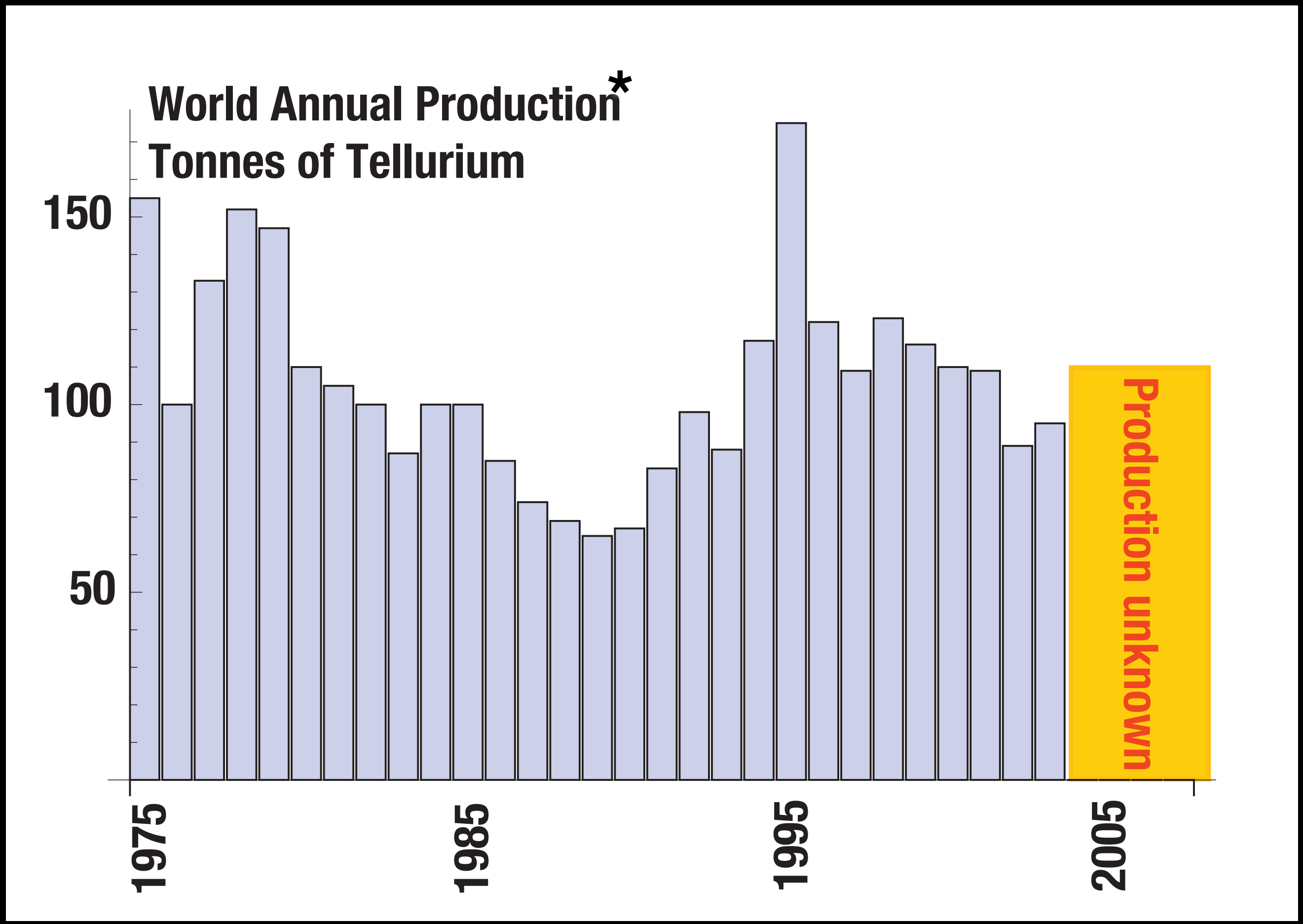
- Many (most) ECE's are now produced entirely as by-products of the refining of major metals.
- Tellurium (copper), indium & germanium (zinc), gallium (aluminum), rhenium (molybdenum), rare earths (iron)
- Prices are artificially low (economy of scope) until the coproduction saturates. By-product does not drive production of main product. Price demand inelasticity.

Example: Tellurium

- 0.0000001% of earth's crust (compare gold -- 0.0000004%)
- Key in CdTe thin-film photovoltaics
- 3μ thick & 11% efficiency → 80 mg(Te)/W_p or 80 tonnes/GW_p(capacity)[1]
- ÷ 20 - 25% capacity factor → 320 tonnes(Te)/GW(delivered) [2]

[1]Capacity – assumes 1000 W/m² constant insolation

[2]Delivered – assumes 250 W/m² average insolation



- World electric consumption (2011) ~ 2000 GW †
- Te "Reserves" (Cu) ~ 24,000 tonnes* → ~75 GW

† USEIA
* USGS Mineral Commodity Summary

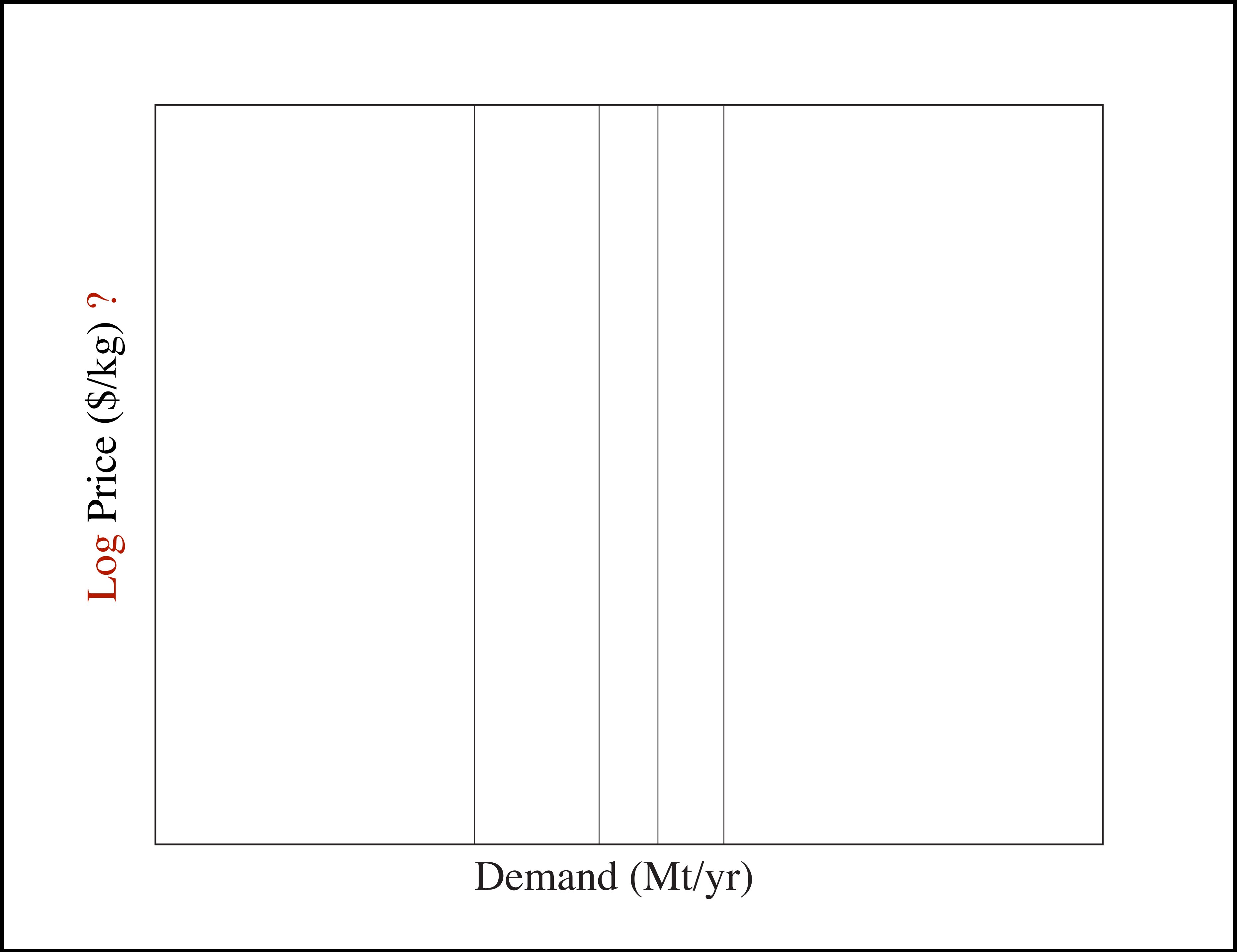
Take tellurium, for example...

	Main product	Byproduct
	Cu	Te
Global production (metric tons)	16,200,000	< 200 -- 500 ?
Price ($/kg)	$7.50	$135
Value of global production ($)	$122 x 10^9	~$70 x 10^6
Ratio of global value to Cu		1750:1

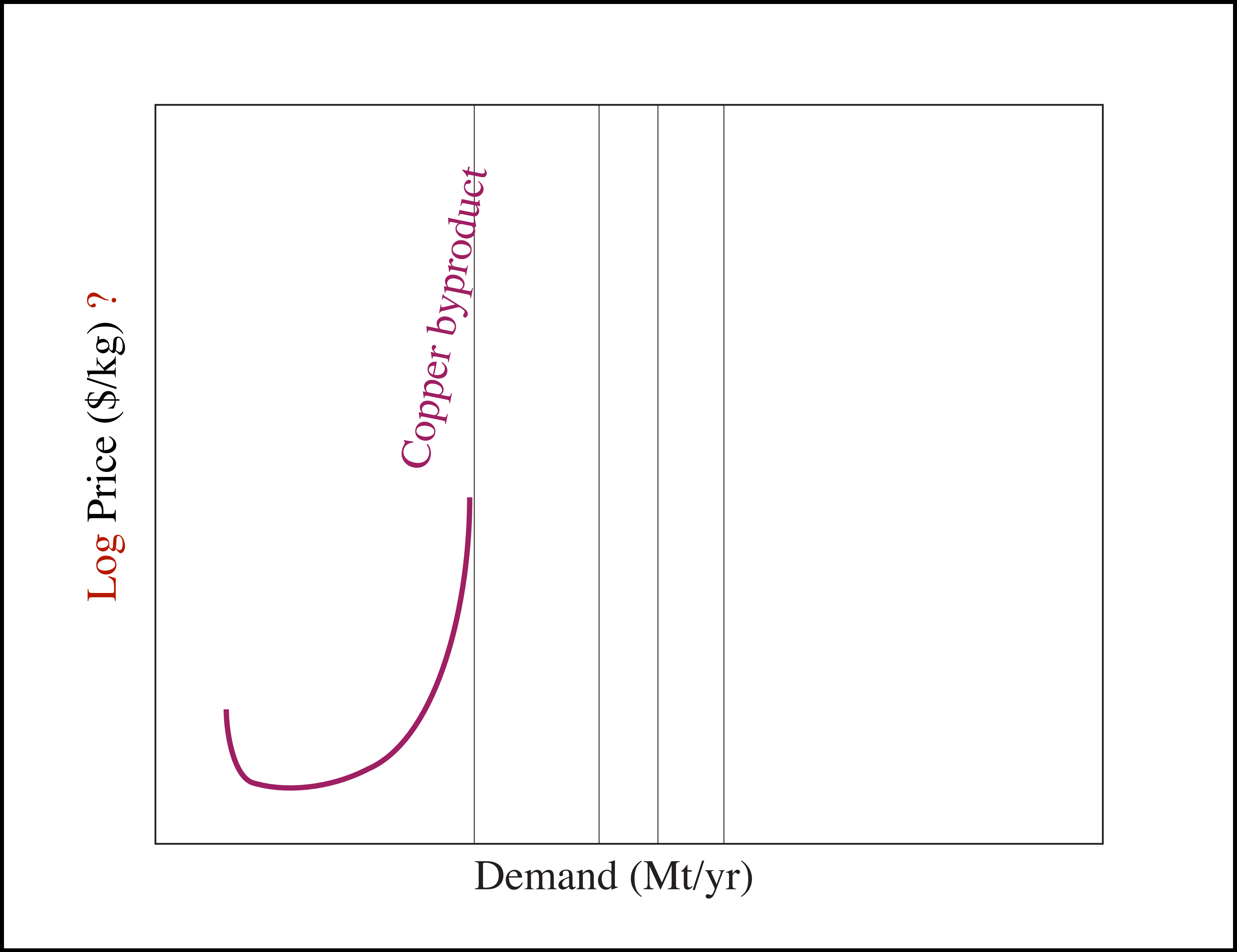
Take tellurium, for example...

	Main product	Byproduct
	Cu	Te
Global production (metric tons)	16,200,000	< 200 -- 500 ?
Price ($/kg)	$7.50	$135
Value of global production ($)	$122 x 10^9	~$70 x 10^6
Ratio of global value to Cu		1750:1

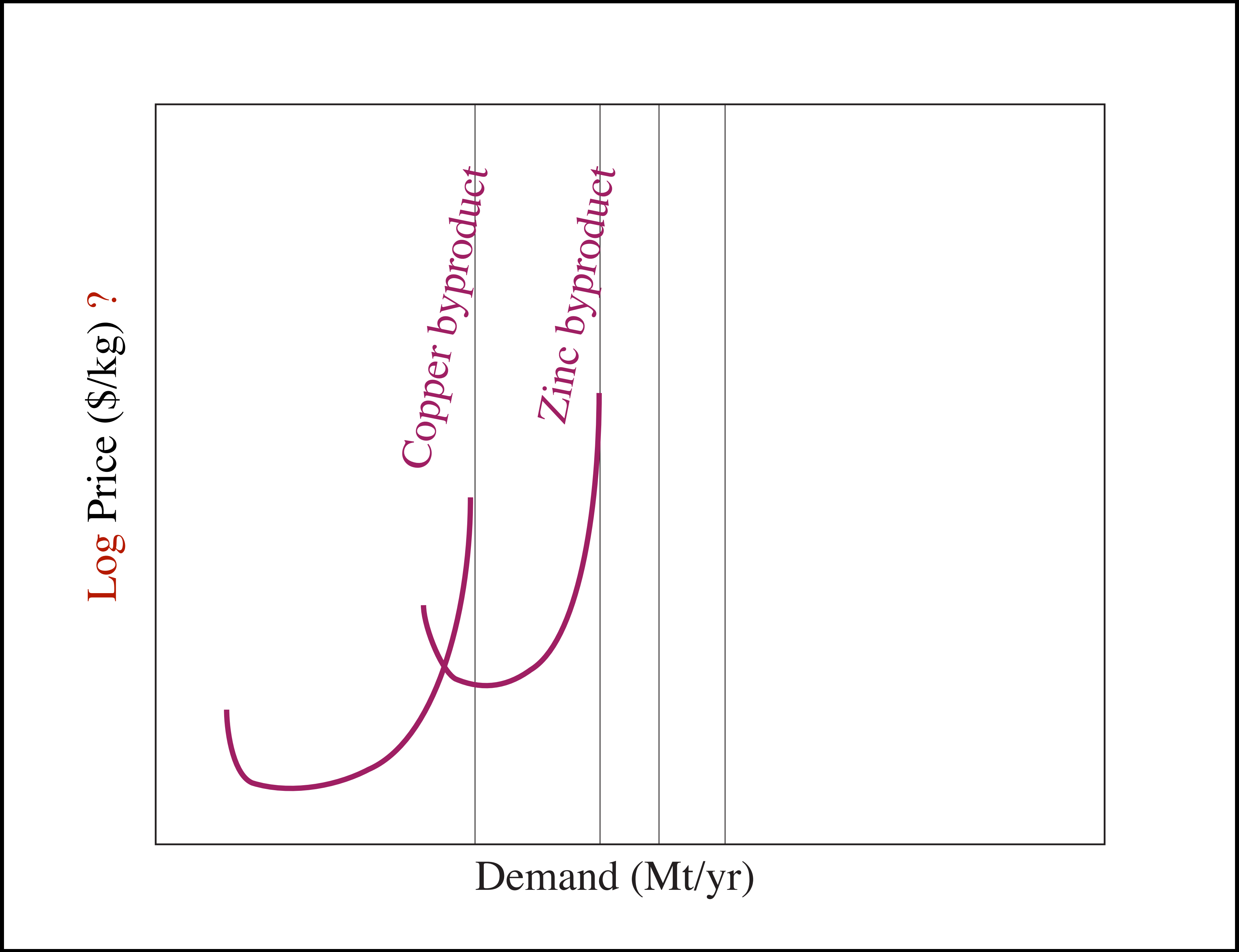
Cartoon of a price/demand curve for tellurium in a massive deployment scenario



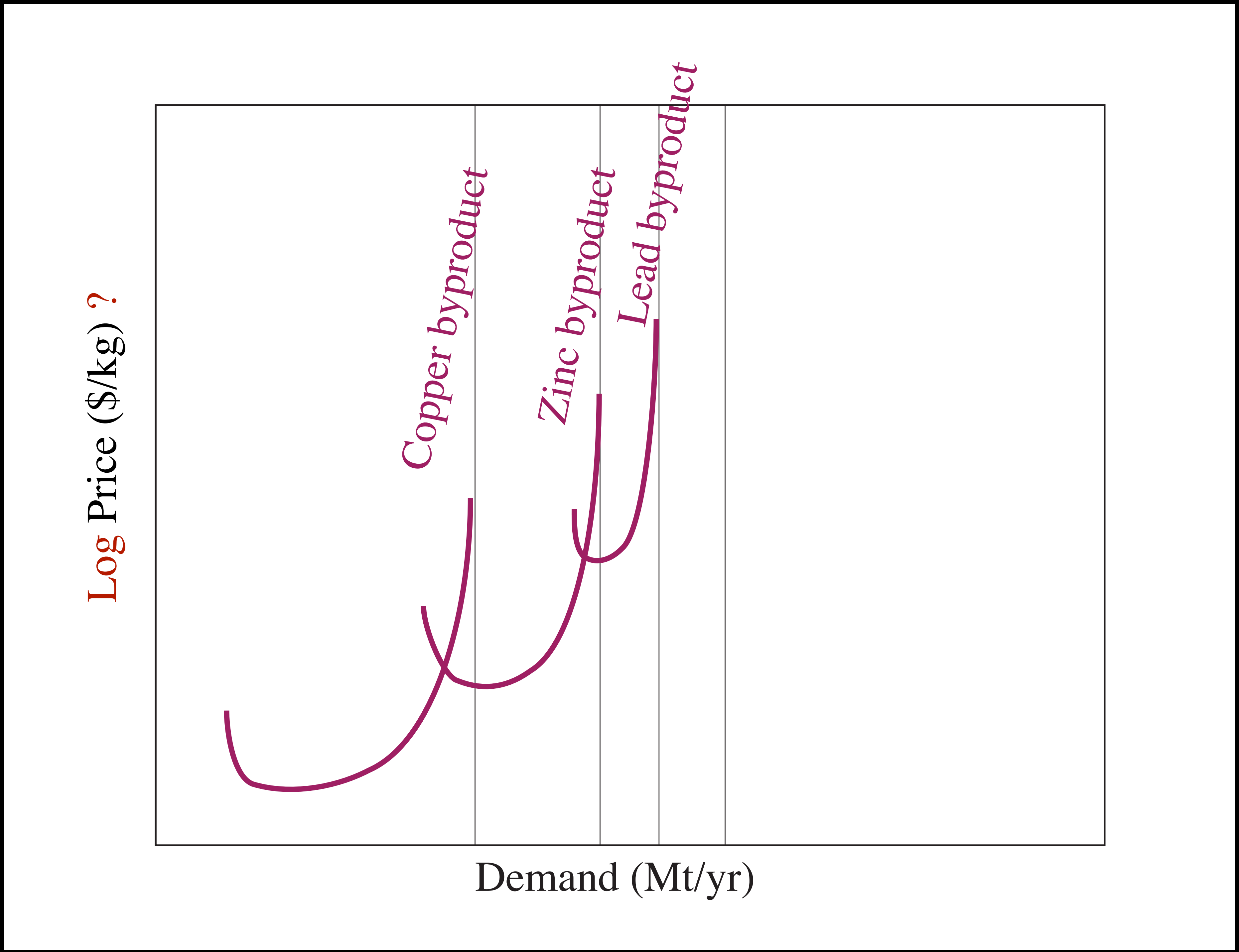
Cartoon of a price/demand curve for tellurium in a massive deployment scenario



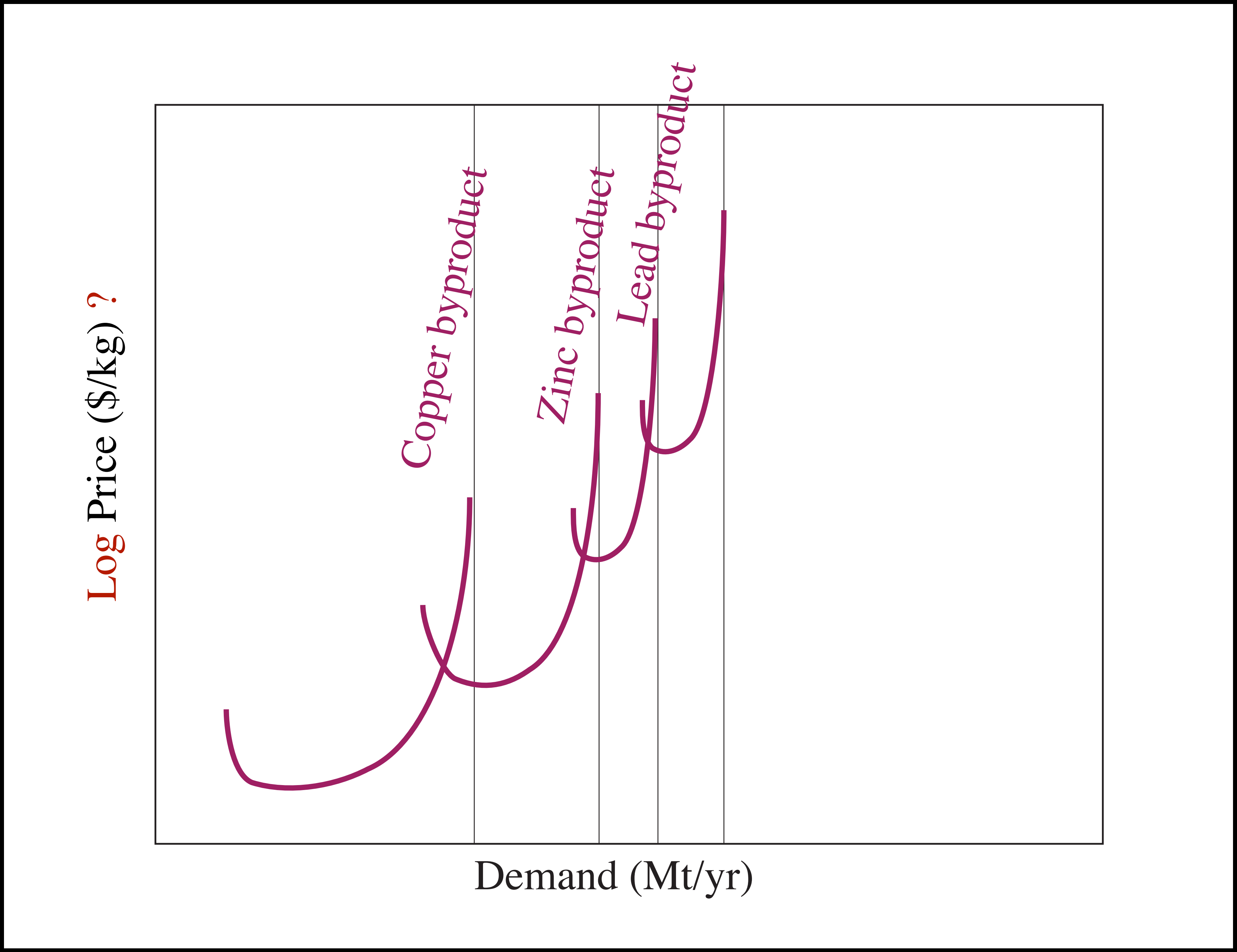
Cartoon of a price/demand curve for tellurium in a massive deployment scenario



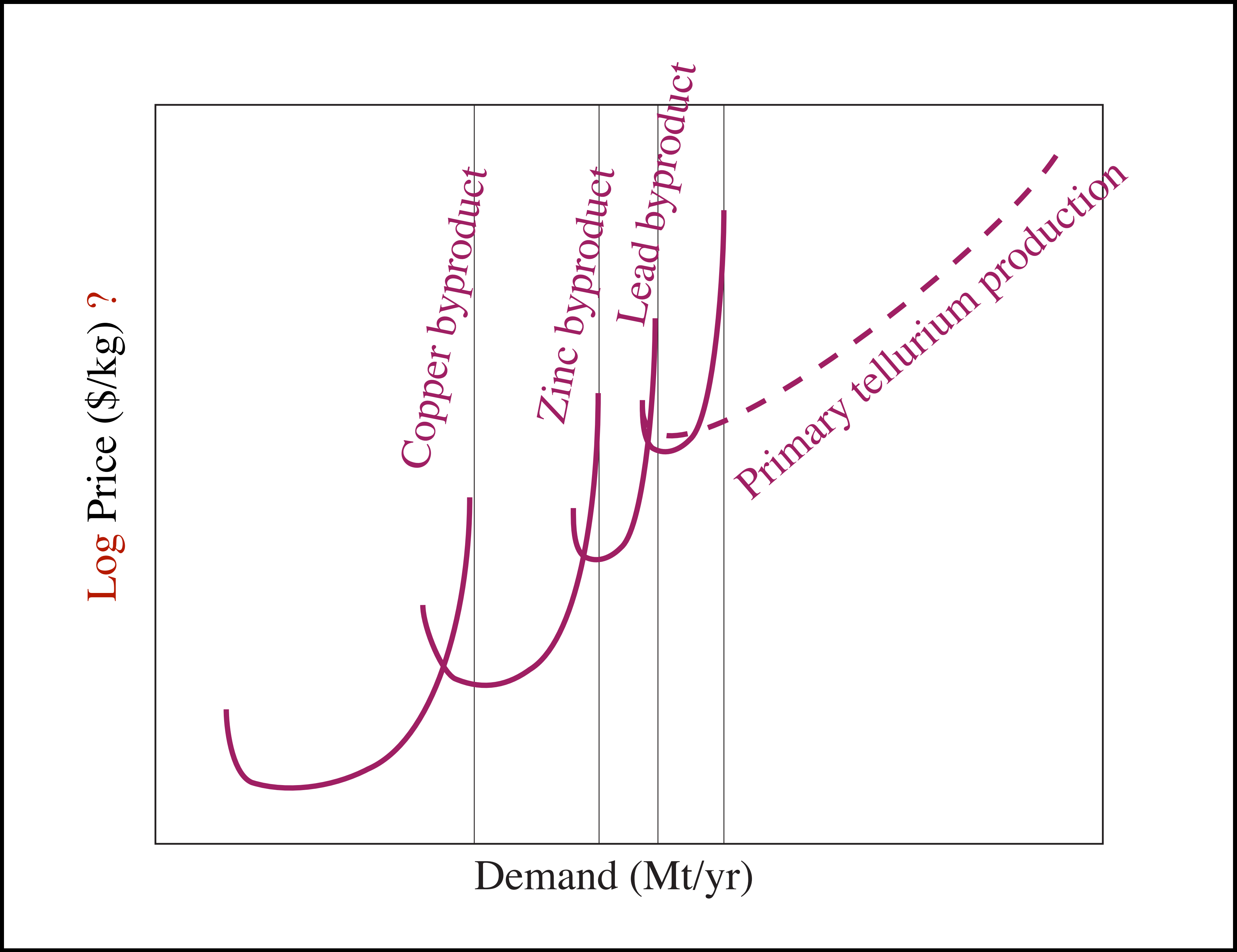
Cartoon of a price/demand curve for tellurium in a massive deployment scenario



Cartoon of a price/demand curve for tellurium in a massive deployment scenario



Cartoon of a price/demand curve for tellurium in a massive deployment scenario



ENVIRONMENTAL AND SOCIAL CONCERNS

ENVIRONMENTAL AND SOCIAL CONCERNS

- Decades of increasing vigilance w.r.t. externalities, esp. environmental and social.
- Developed world exports environmentally/socially destructive extraction overseas.
- Worldwide rising standard: International Council on Mining and Minerals (ICMM) and International Finance Corp (IFC) (World Bank) have set social and environmental sustainability standards.

Environmental and Social Concerns

- Decades of increasing vigilance w.r.t. externalities, esp. environmental and social.
- Developed world exports environmentally/socially destructive extraction overseas.
- Worldwide rising standard: International Council on Mining and Minerals (ICMM) and International Finance Corp (IFC) (World Bank) have set social and environmental sustainability standards.

Example 1: HREE mining in South China clays, almost the exclusive present source for HREE

ENVIRONMENTAL AND SOCIAL CONCERNS

- Decades of increasing vigilance w.r.t. externalities, esp. environmental and social.
- Developed world exports environmentally/socially destructive extraction overseas.
- Worldwide rising standard: International Council on Mining and Minerals (ICMM) and International Finance Corp (IFC) (World Bank) have set social and environmental sustainability standards.

Example 1: HREE mining in South China clays, almost the exclusive present source for HREE

Environmental and Social Concerns

- Decades of increasing vigilance w.r.t. externalities, esp. environmental and social.
- Developed world exports environmentally/socially destructive extraction overseas.
- Worldwide rising standard: International Council on Mining and Minerals (ICMM) and International Finance Corp (IFC) (World Bank) have set social and environmental sustainability standards.

Example 1: HREE mining in South China clays, almost the exclusive present source for HREE

ENVIRONMENTAL AND SOCIAL CONCERNS

- **Decades of increasing vigilance w.r.t. externalities, esp. environmental and social.**
- **Developed world exports environmentally/socially destructive extraction overseas.**
- **Worldwide rising standard: International Council on Mining and Minerals (ICMM) and International Finance Corp (IFC) (World Bank) have set social and environmental sustainability standards.**

Example 1: HREE mining in South China clays, almost the exclusive present source for HREE

Example 2: Cobalt mining in the Congo

ENVIRONMENTAL AND SOCIAL CONCERNS

- Decades of increasing vigilance w.r.t. externalities, esp. environmental and social.
- Developed world exports environmentally/socially destructive extraction overseas.
- Worldwide rising standard: International Council on Mining and Minerals (ICMM) and International Finance Corp (IFC) (World Bank) have set social and environmental sustainability standards.

Example 1: HREE mining in South China clays, almost the exclusive present source for HREE

Example 2: Cobalt mining in the Congo

Environmental and Social Concerns

- Decades of increasing vigilance w.r.t. externalities, esp. environmental and social.
- Developed world exports environmentally/socially destructive extraction overseas.
- Worldwide rising standard: International Council on Mining and Minerals (ICMM) and International Finance Corp (IFC) (World Bank) have set social and environmental sustainability standards.

Example 1: HREE mining in South China clays, almost the exclusive present source for HREE

Example 2: Cobalt mining in the Congo

ENVIRONMENTAL AND SOCIAL CONCERNS

- Decades of increasing vigilance w.r.t. externalities, esp. environmental and social.
- Developed world exports environmentally/socially destructive extraction overseas.
- Worldwide rising standard: International Council on Mining and Minerals (ICMM) and International Finance Corp (IFC) (World Bank) have set social and environmental sustainability standards.

Example 1: HREE mining in South China clays, almost the exclusive present source for HREE

Example 2: Cobalt mining in the Congo

Example 3: Thorium contamination of rare earth ores

ENVIRONMENTAL AND SOCIAL CONCERNS

- Decades of increasing vigilance w.r.t. externalities, esp. environmental and social.
- Developed world exports environmentally/socially destructive extraction overseas.
- Worldwide rising standard: International Council on Mining and Minerals (ICMM) and International Finance Corp (IFC) (World Bank) have set social and environmental sustainability standards.

Example 1: HREE mining in South China clays, almost the exclusive

Example 2: Cobalt mining in the Congo

Example 3: Thorium contamination of rare earth ores

	Bastnaesite Mt. Pass	Monazite Australia	Xenotime Malaysia	Monazite Australia
La_2O_3	26.06	11.55	1.75	13.46
CeO_2	36.81	25.66	4.22	27.20
Pr_6O_{11}	3.02	2.98	0.51	2.98
Y_2O_3	0.04	0.83	30.86	1.17
ThO_2	0.09	5.73	1.26	6.5

ENVIRONMENTAL AND SOCIAL CONCERNS

- Decades of increasing vigilance w.r.t. externalities, esp. environmental and social.
- Developed world exports environmentally/socially destructive extraction overseas.
- Worldwide rising standard: International Council on Mining and Minerals (ICMM) and International Finance Corp (IFC) (World Bank) have set social and environmental sustainability standards.

Example 1: HREE mining in South China clays, almost the exclusive present source for HREE

Example 2: Cobalt mining in the Congo

Example 3: Thorium contamination of rare earth ores

	Bastnaesite Mt. Pass	Monazite Australia	Xenotime Malaysia	Monazite Australia
La_2O_3	26.06	11.55	1.75	13.46
CeO_2	36.81	25.66	4.22	27.20
Pr_6O_{11}	3.02	2.98	0.51	2.98
Y_2O_3	0.04	0.83	30.86	1.17
ThO_2	0.09	5.73	1.26	6.5

Policy recommendations from studies

I. COORDINATION

Complex, multi-dimensional issue: OSTP should coordinate federal response.

II. INFORMATION

Ask me offline!

High quality information is extremely valuable, promotes transparency. from discovered and potential resources, to production, use, trade, disposal, and recycling. Model ~ EIA (USGS & DOE?)

III. RESEARCH, DEVELOPMENT, AND WORKFORCE

Federal R&D: focused on energy-critical elements and possible substitutes. Across the materials life-cycle from extraction to recycling

III. RECYCLING

More precious than gold. Research on technical issues. Consumer awareness

Case study: ECEs for photovoltaics

Case study: ECEs for photovoltaics

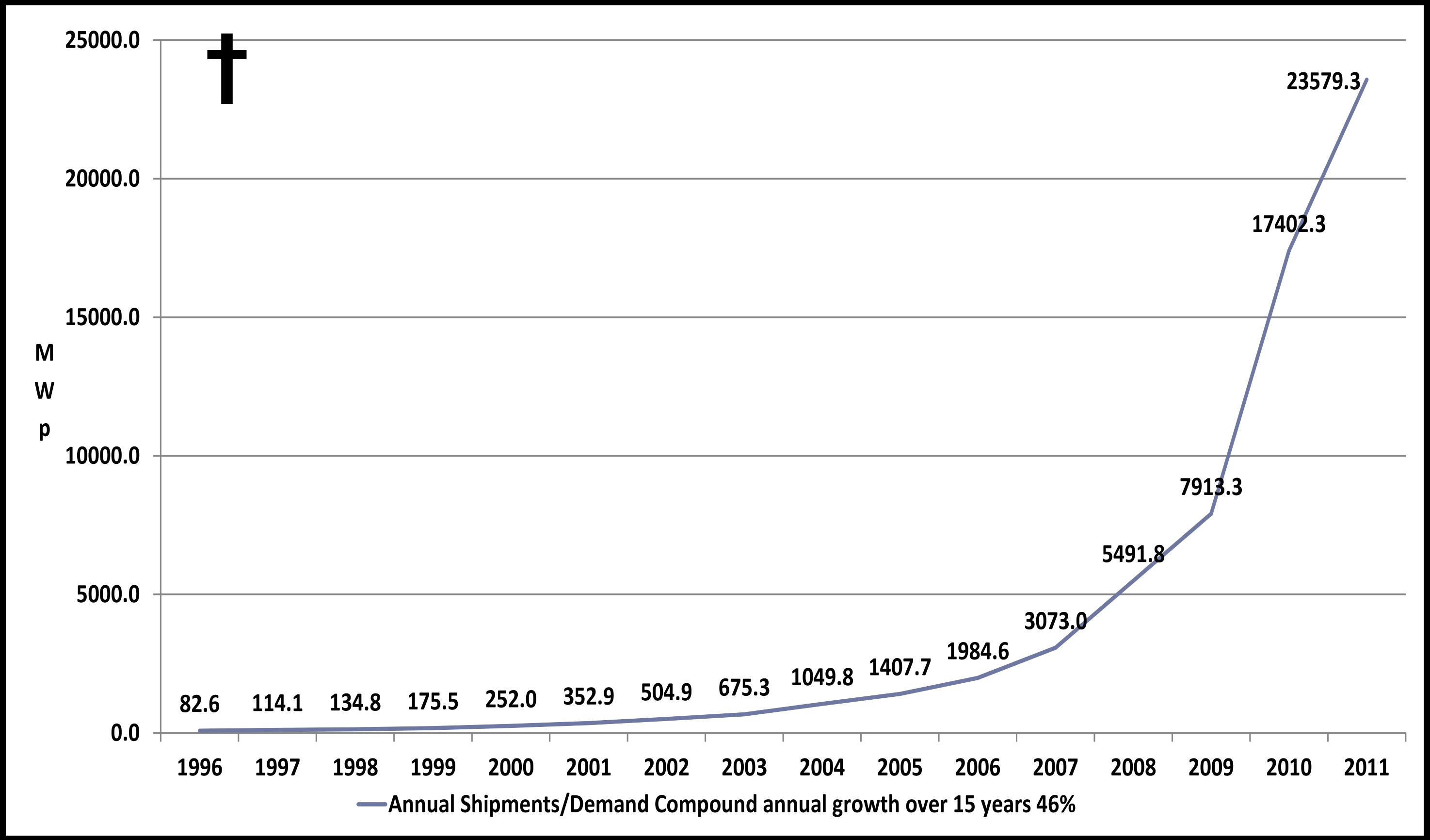
For MITEI Solar Study

Tonio Buonassissi (MIT)
Riley Brandt (MIT)
Jessika Trancik (MIT)
RLJ (MIT)

Case study: ECEs for photovoltaics

- What impact can photovoltaics have on world electricity use.
- Potential for large scale deployment?
- Given its ~<u>20% capacity factor</u>, it would require 250 GW_p/y of PV deployment to match growth in world electricity consumption in 2012; growing to 680 GW_p/y in 2050

For MITEI Solar Study
Tonio Buonassissi (MIT)
Riley Brandt (MIT)
Jessika Trancik (MIT)
RLJ (MIT)

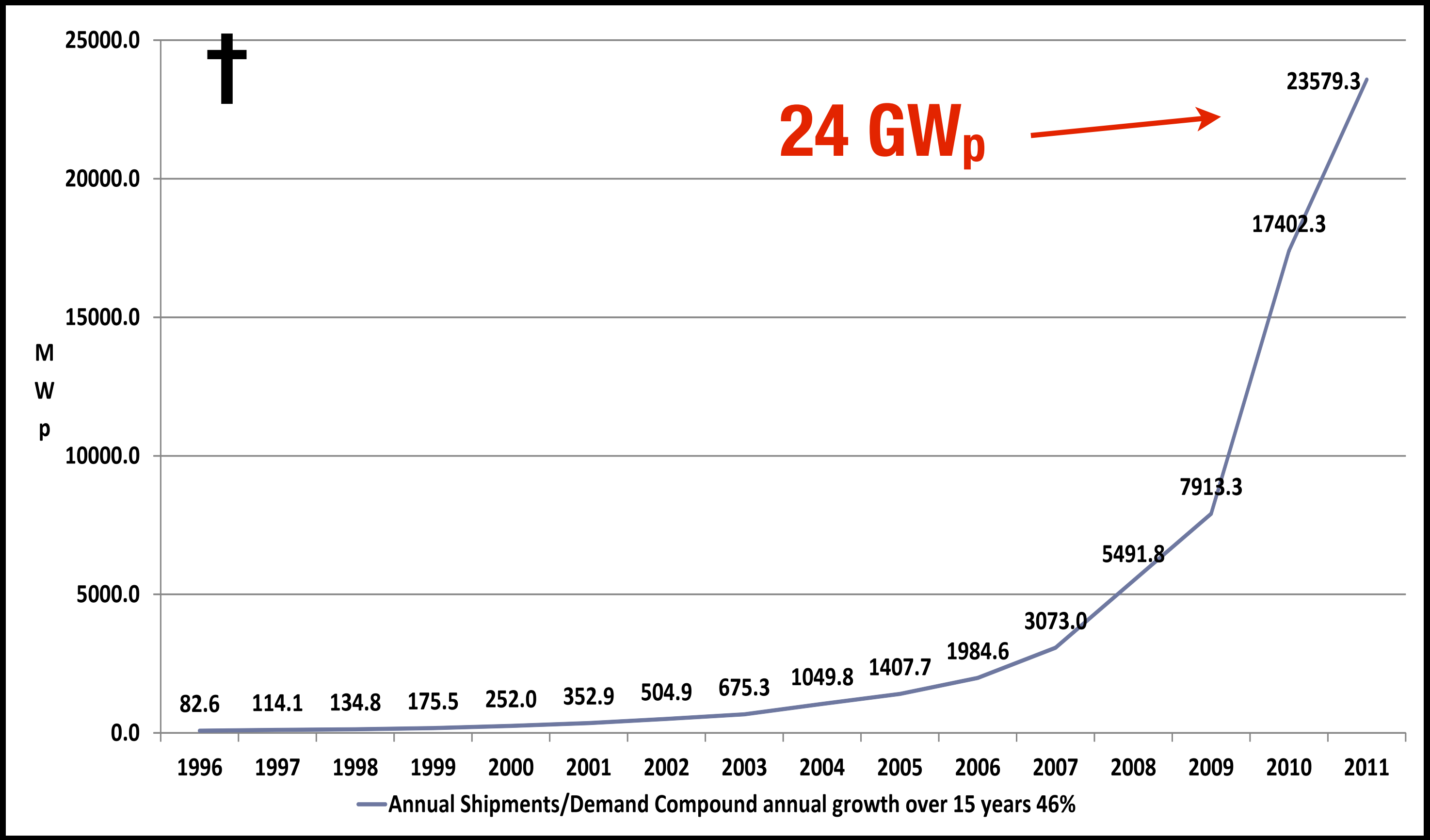


†Paula Mints DOE May 2012
Navigant Consulting

Case study: ECEs for photovoltaics

- What impact can photovoltaics have on world electricity use.
- Potential for large scale deployment?
- Given its ~<u>20% capacity factor</u>, it would require 250 GW_p/y of PV deployment to match growth in world electricity consumption in 2012; growing to 680 GW_p/y in 2050

For MITEI Solar Study
Tonio Buonassissi (MIT)
Riley Brandt (MIT)
Jessika Trancik (MIT)
RLJ (MIT)



†Paula Mints DOE May 2012
Navigant Consulting

POTENTIAL ECEs AMONG PHOTOVOLTAIC MATERIALS

- x-Si and p-Si (Generation I) remain dominant, but manufacturing costs are relatively expensive (!)

  Silver(!)

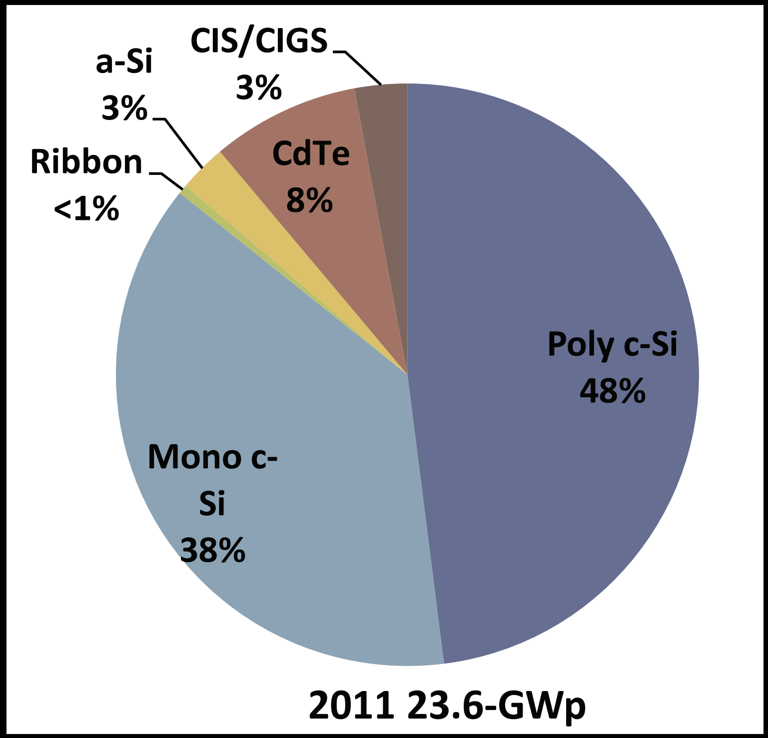
- Thin films (Generation II) are significant, with manufacturing advantages

  CdTe – Tellurium

  CIGS – Indium, Gallium, Selenium

- Note: economies of scale are key to lowering cost of new energy technologies like PVs

But cost of rare materials do not benefit from economies of scale! In fact they are most likely anticorrelated with scale



†Paula Mints DOE May 2012 Navigant Consulting

POTENTIAL ECEs AMONG PHOTOVOLTAIC MATERIALS

- x-Si and p-Si (Generation I) remain dominant, but manufacturing costs are relatively expensive (!)

  Silver(!)

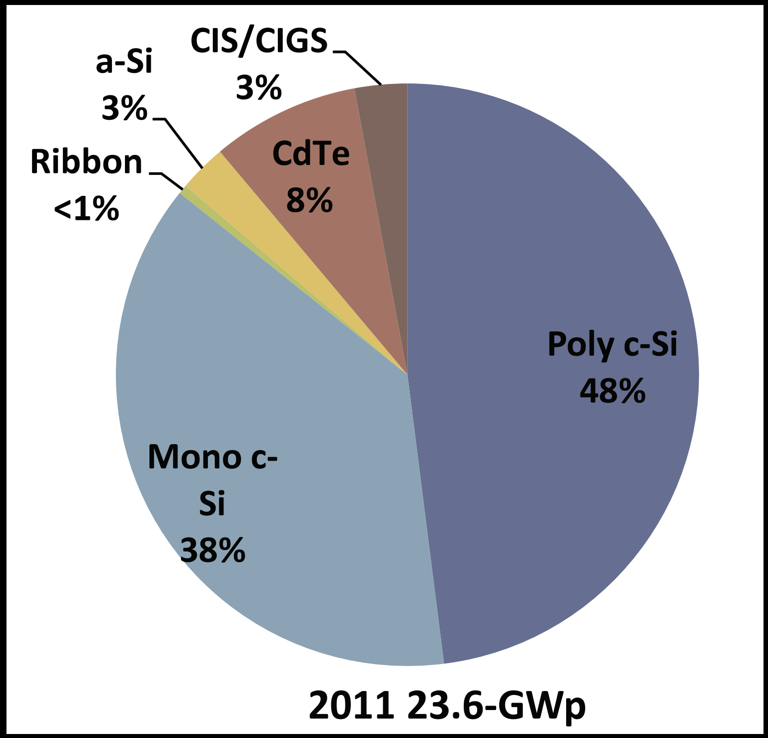
- Thin films (Generation II) are significant, with manufacturing advantages

  CdTe – Tellurium

  CIGS – Indium, Gallium, Selenium

- Note: economies of scale are key to lowering cost of new energy technologies like PVs

But cost of rare materials do not benefit from economies of scale! In fact they are most likely anticorrelated with scale

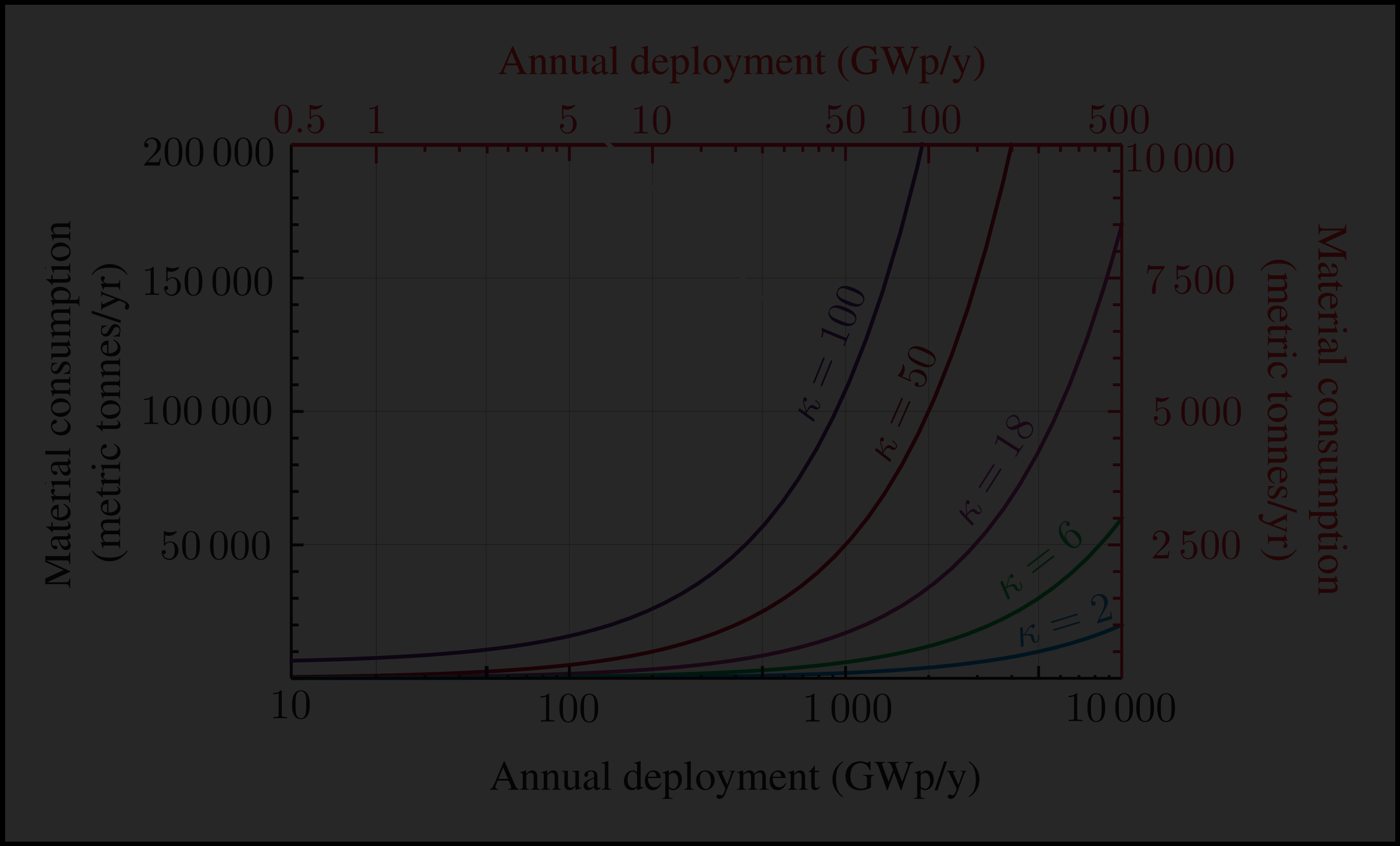


†Paula Mints DOE May 2012
Navigant Consulting

THE MATHEMATICS (NOT STRING THEORY)

- For a given material intensity κ (t/GW$_p$), how much material M (t/y) is required for a proposed deployment D (GW$_p$/y).

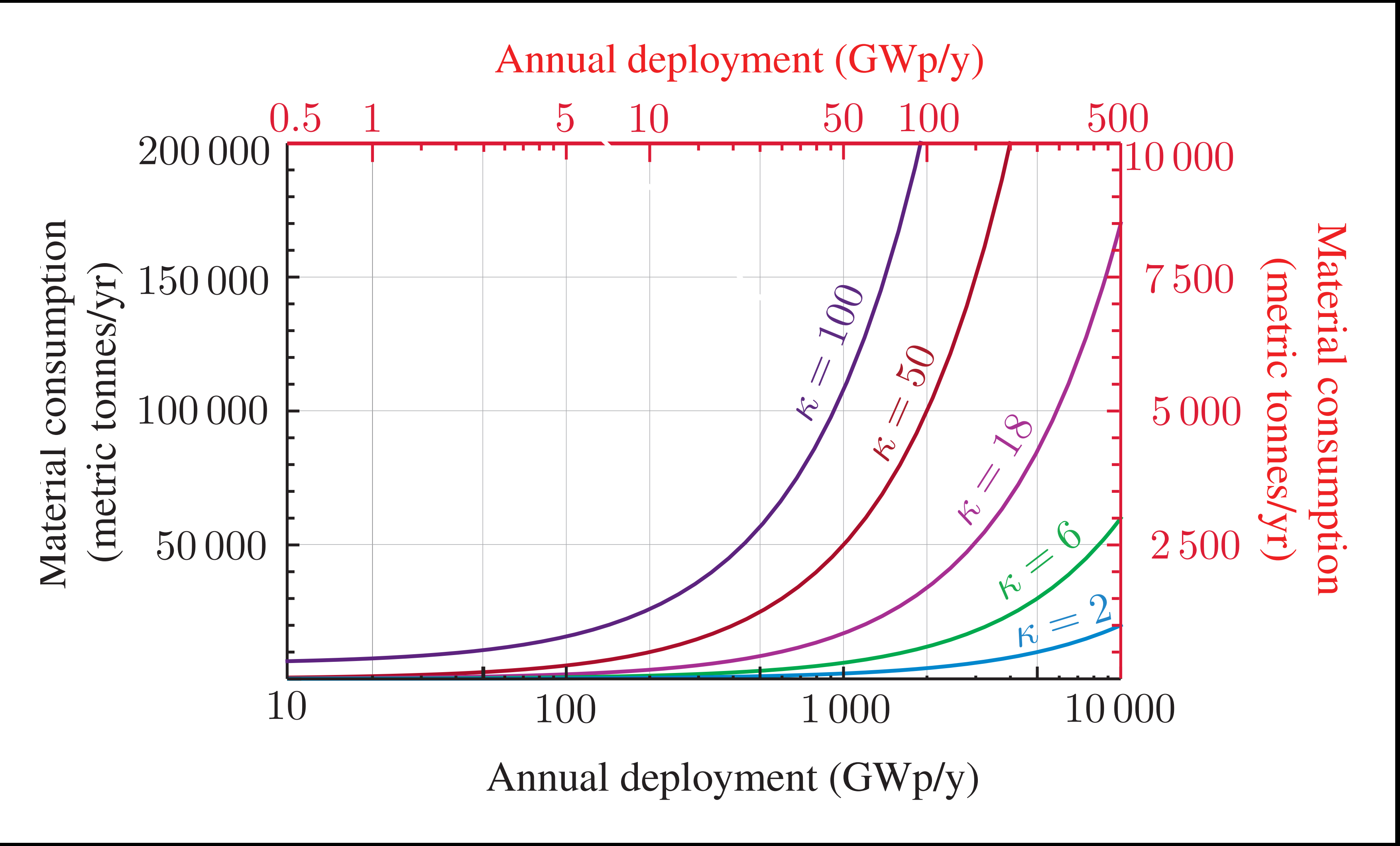
$$M = \kappa D$$



THE MATHEMATICS (NOT STRING THEORY)

- For a given material intensity κ (t/GW_p), how much material M (t/y) is required for a proposed deployment D (GW_p/y).

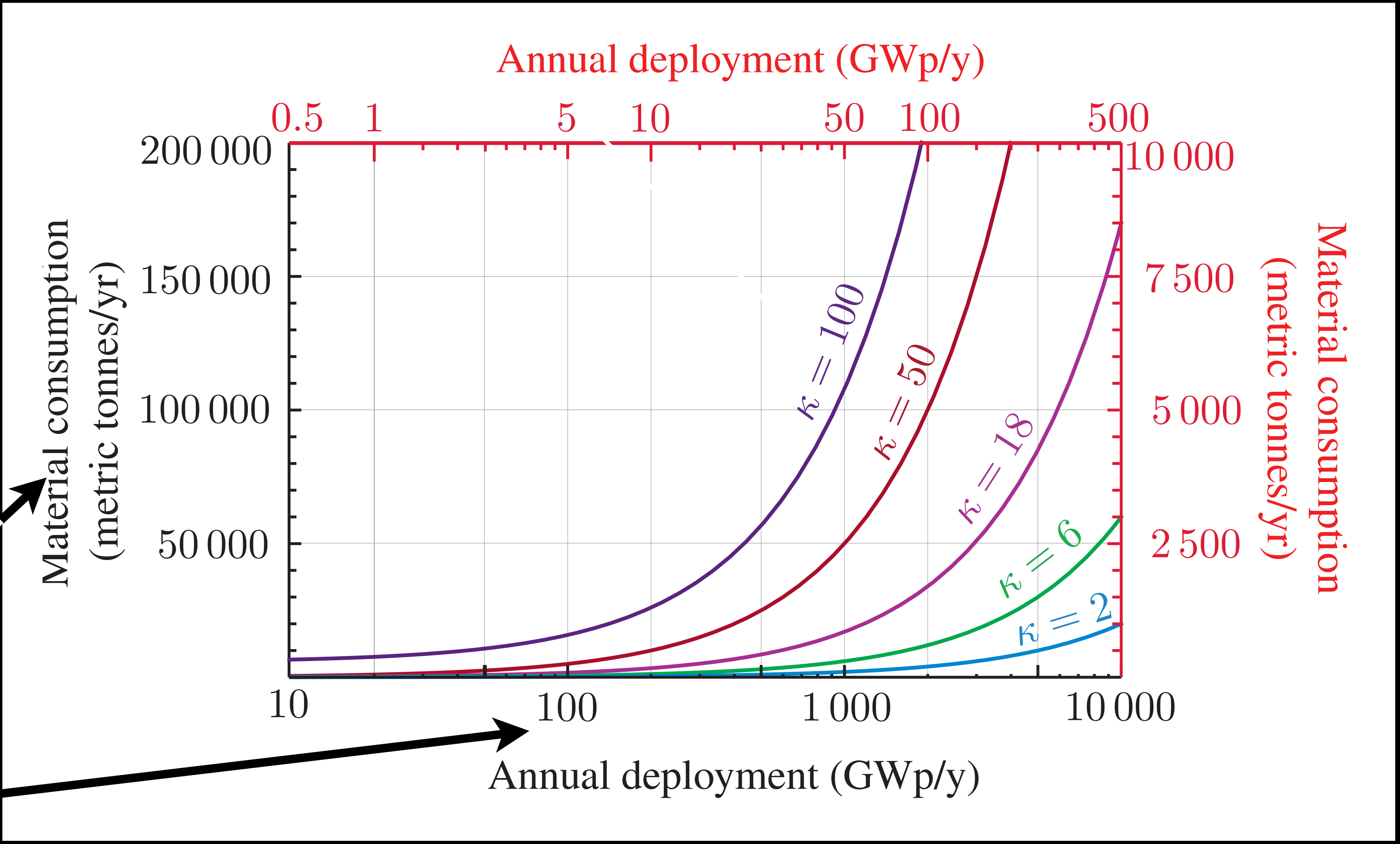
$$M = \kappa D$$



The mathematics (not string theory)

- For a given material intensity κ (t/GW$_p$), how much material M (t/y) is required for a proposed deployment D (GW$_p$/y).

$$M = \kappa D$$

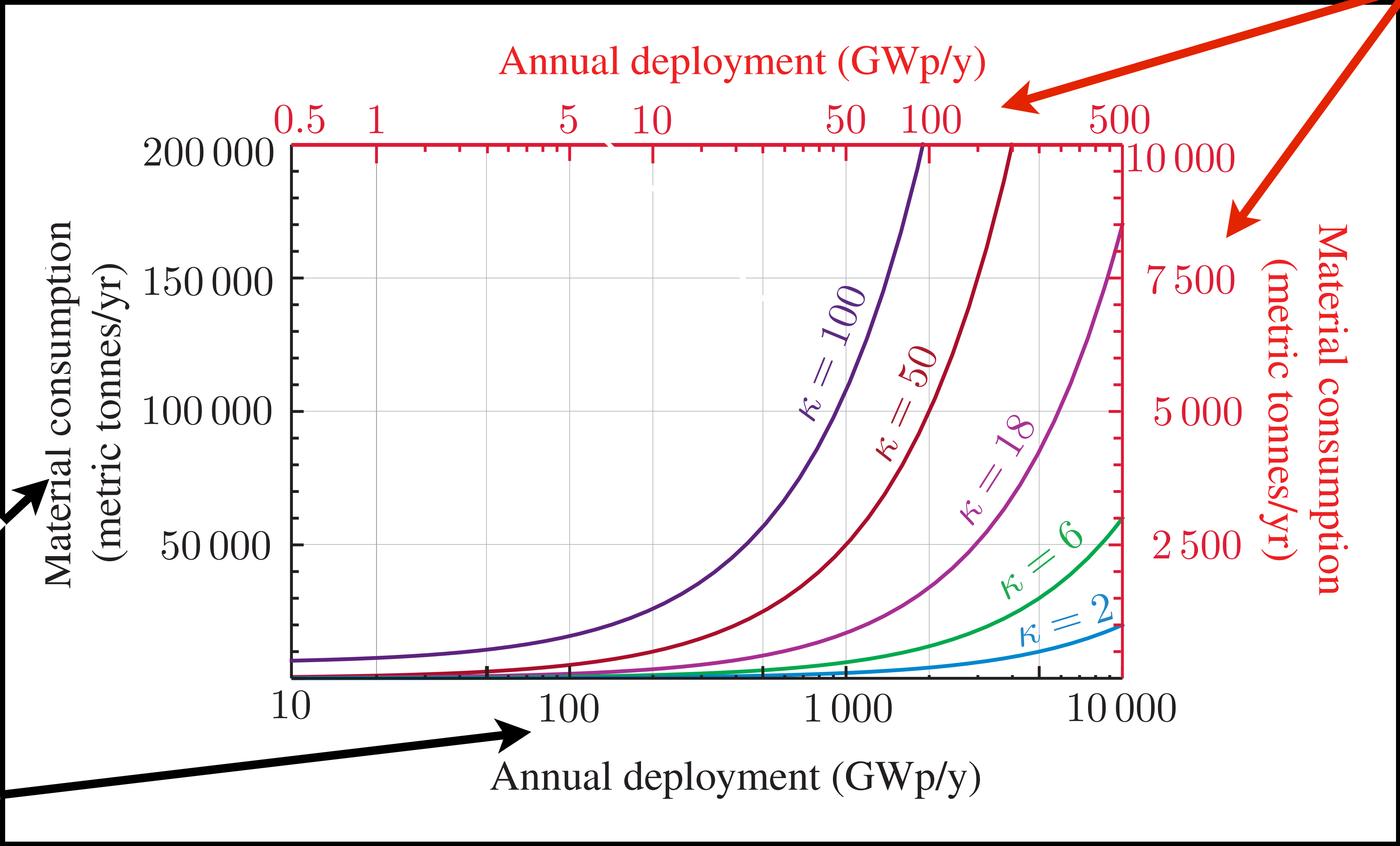


high impact regime

THE MATHEMATICS (NOT STRING THEORY)

- For a given material intensity κ (t/GW$_p$), how much material M (t/y) is required for a proposed deployment D (GW$_p$/y).

$$M = \kappa D$$



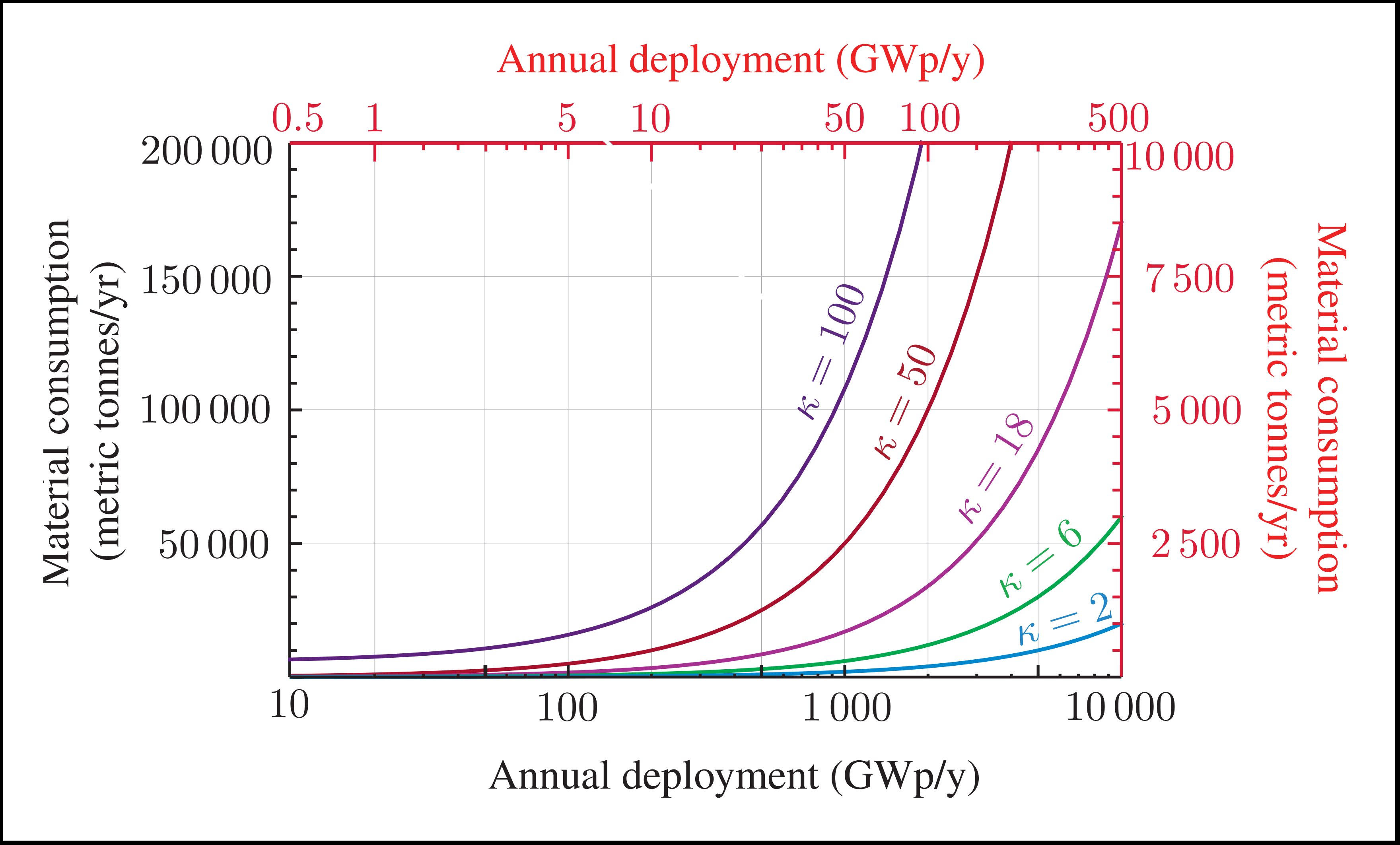
boutique regime

high impact regime

THE MATHEMATICS (NOT STRING THEORY)

- For a given material intensity κ (t/GW_p), how much material M (t/y) is required for a proposed deployment D (GW_p/y).

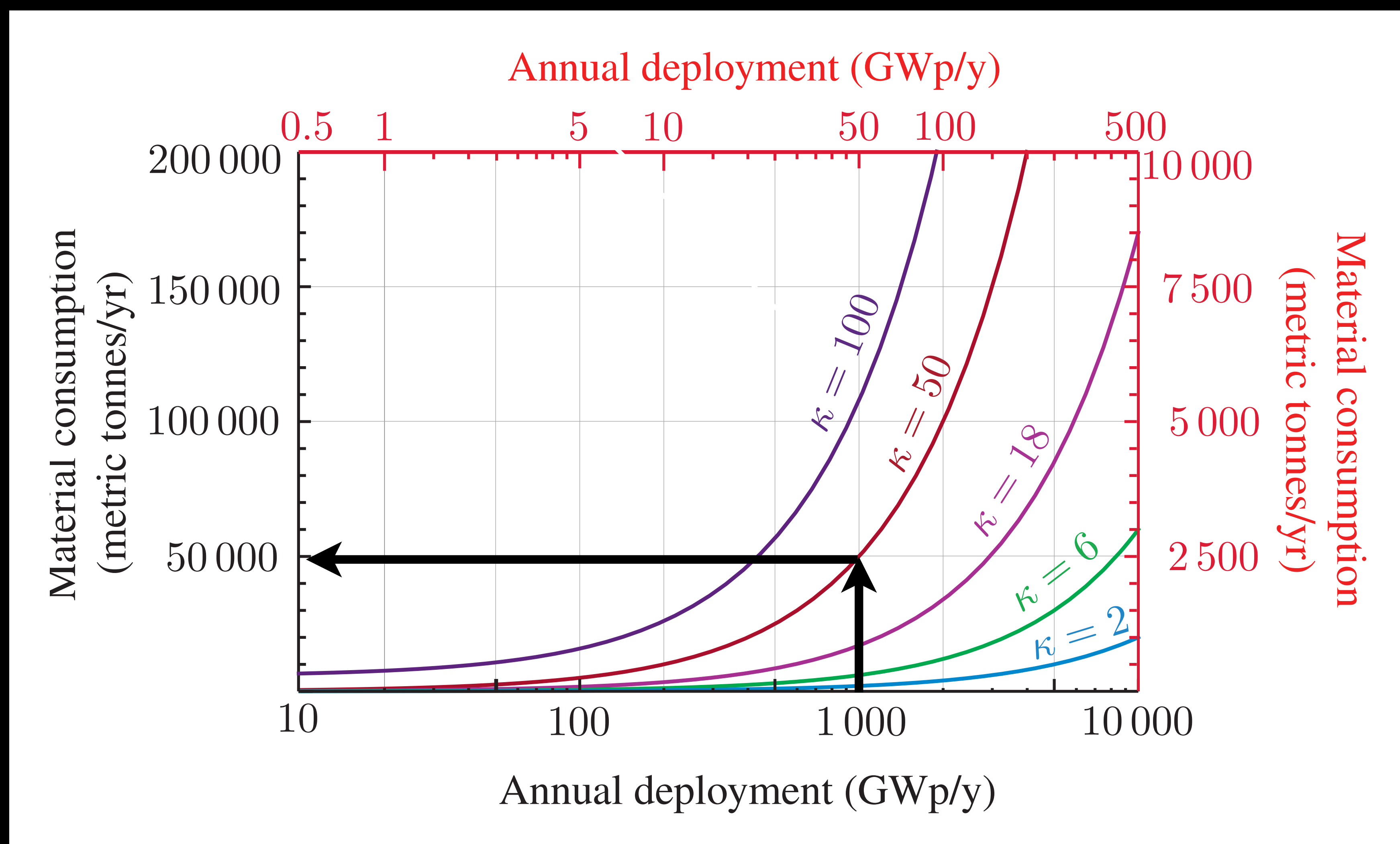
$$M = \kappa D$$



THE MATHEMATICS (NOT STRING THEORY)

- For a given material intensity κ (t/GW$_p$), how much material M (t/y) is required for a proposed deployment D (GW$_p$/y).

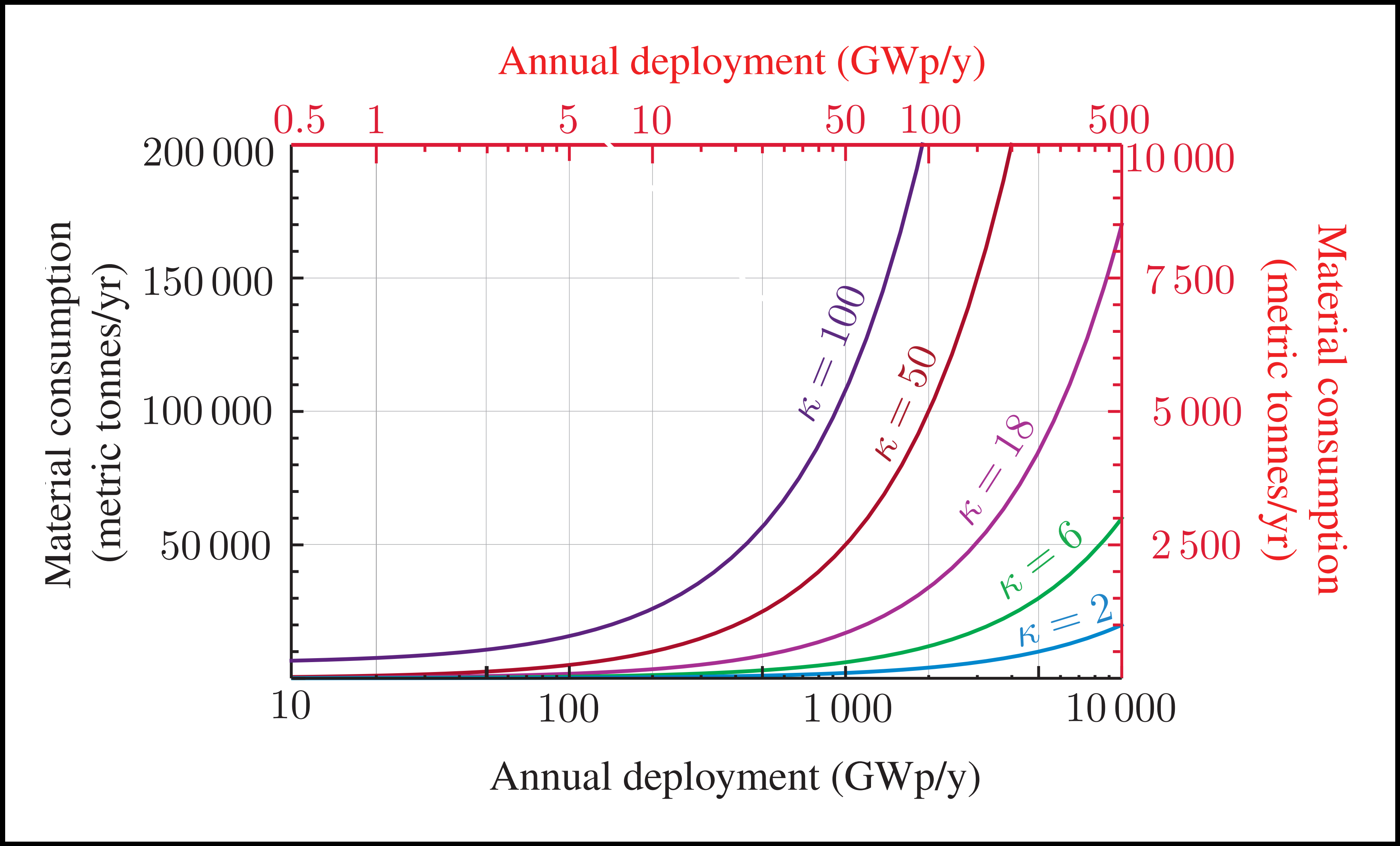
$$M = \kappa D$$



The mathematics (not string theory)

- For a given material intensity κ (t/GW_p), how much material M (t/y) is required for a proposed deployment D (GW_p/y).

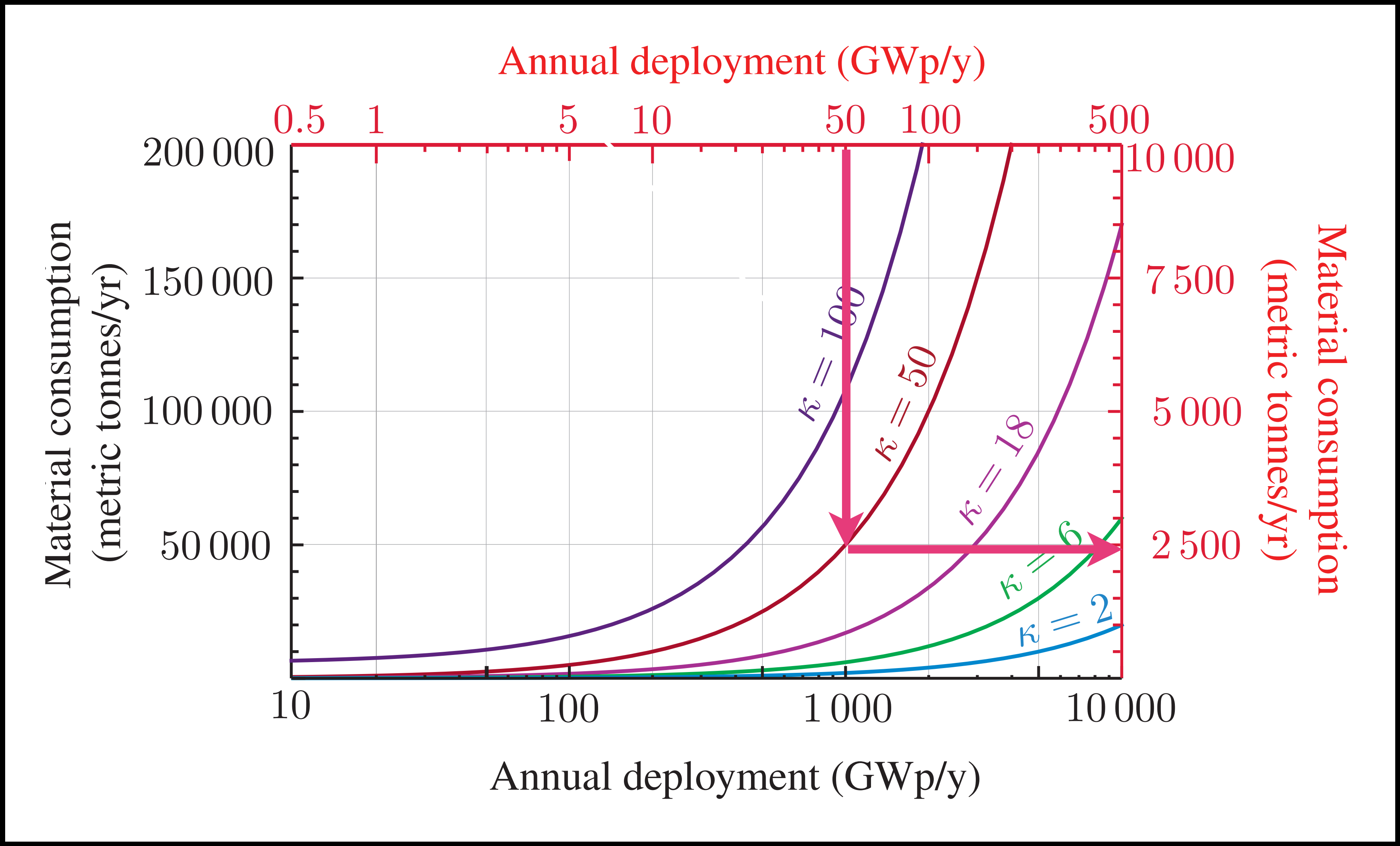
$$M = \kappa D$$



THE MATHEMATICS (NOT STRING THEORY)

- For a given material intensity κ (t/GW$_p$), how much material M (t/y) is required for a proposed deployment D (GW$_p$/y).

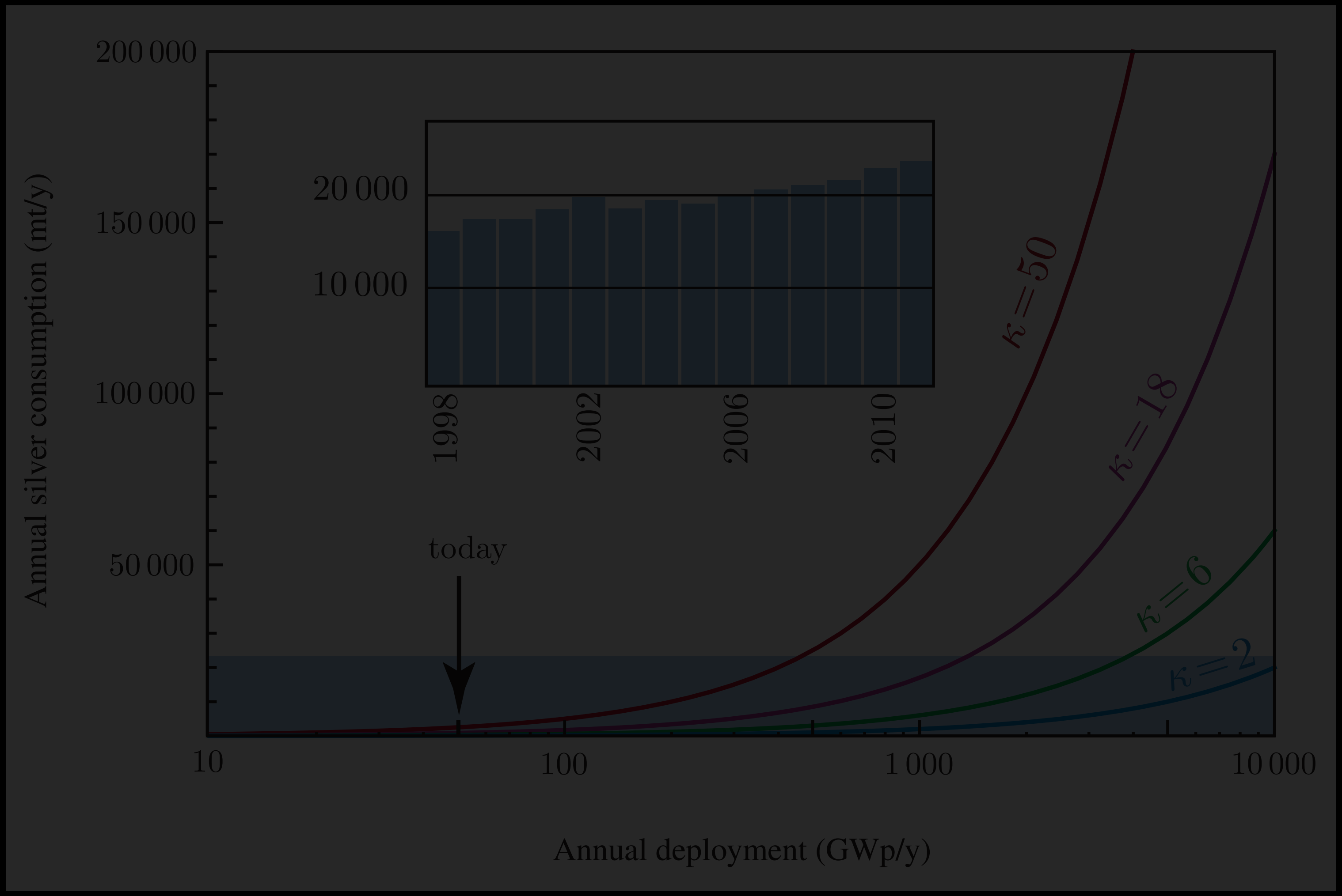
$$M = \kappa D$$



SILVER IN (POLY) CRYSTALLINE PVS

- Used for front contact material (paste/ink)
- 2012: ~10% of all new silver production
- 2012: ~$0.09/W$_p$
- Significant constraint for large scale deployment

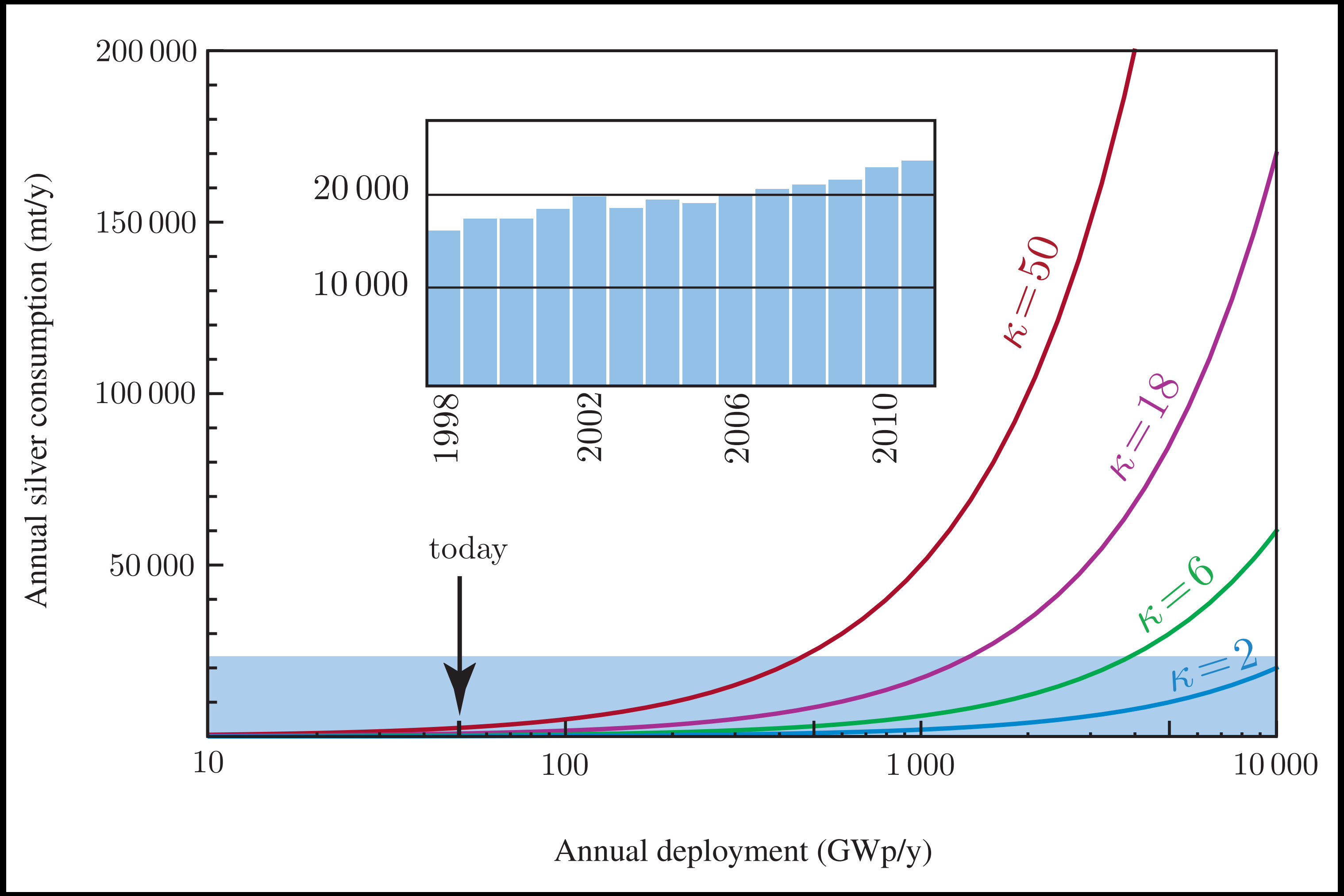
2012 material intensity
κ(Ag) ~ 65 - 80 gm/Wp



SILVER IN (POLY) CRYSTALLINE PVs

- Used for front contact material (paste/ink)
- 2012: ~10% of all new silver production
- 2012: ~$0.09/W$_p$
- Significant constraint for large scale deployment

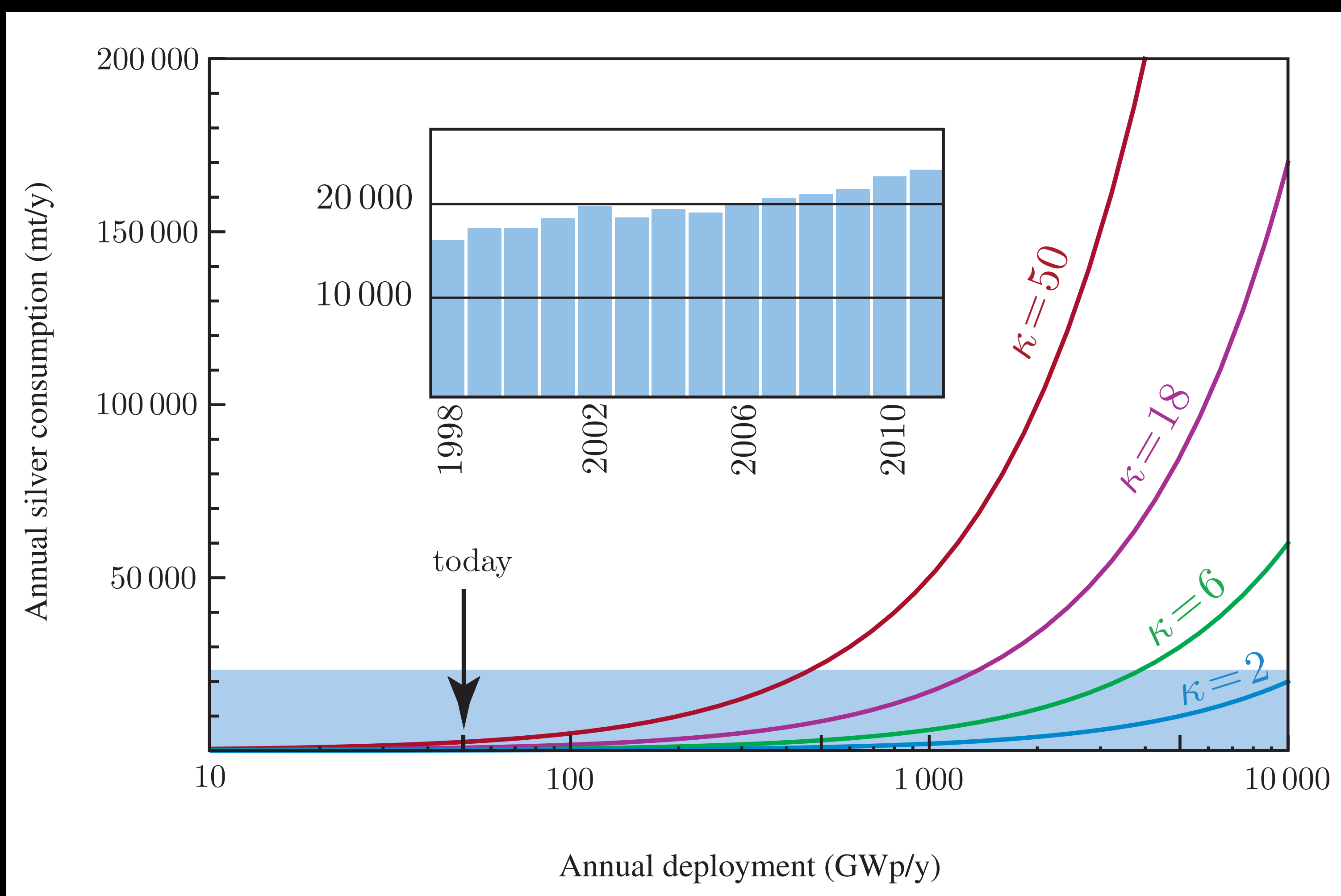
2012 material intensity
κ(Ag) ~ 65 - 80 gm/Wp

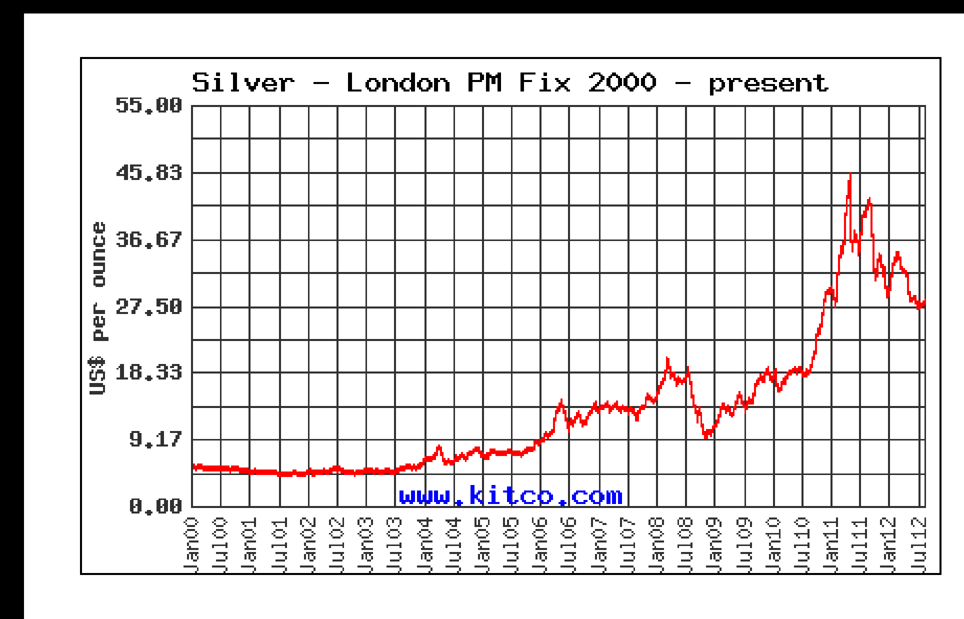


SILVER IN (POLY) CRYSTALLINE PVs

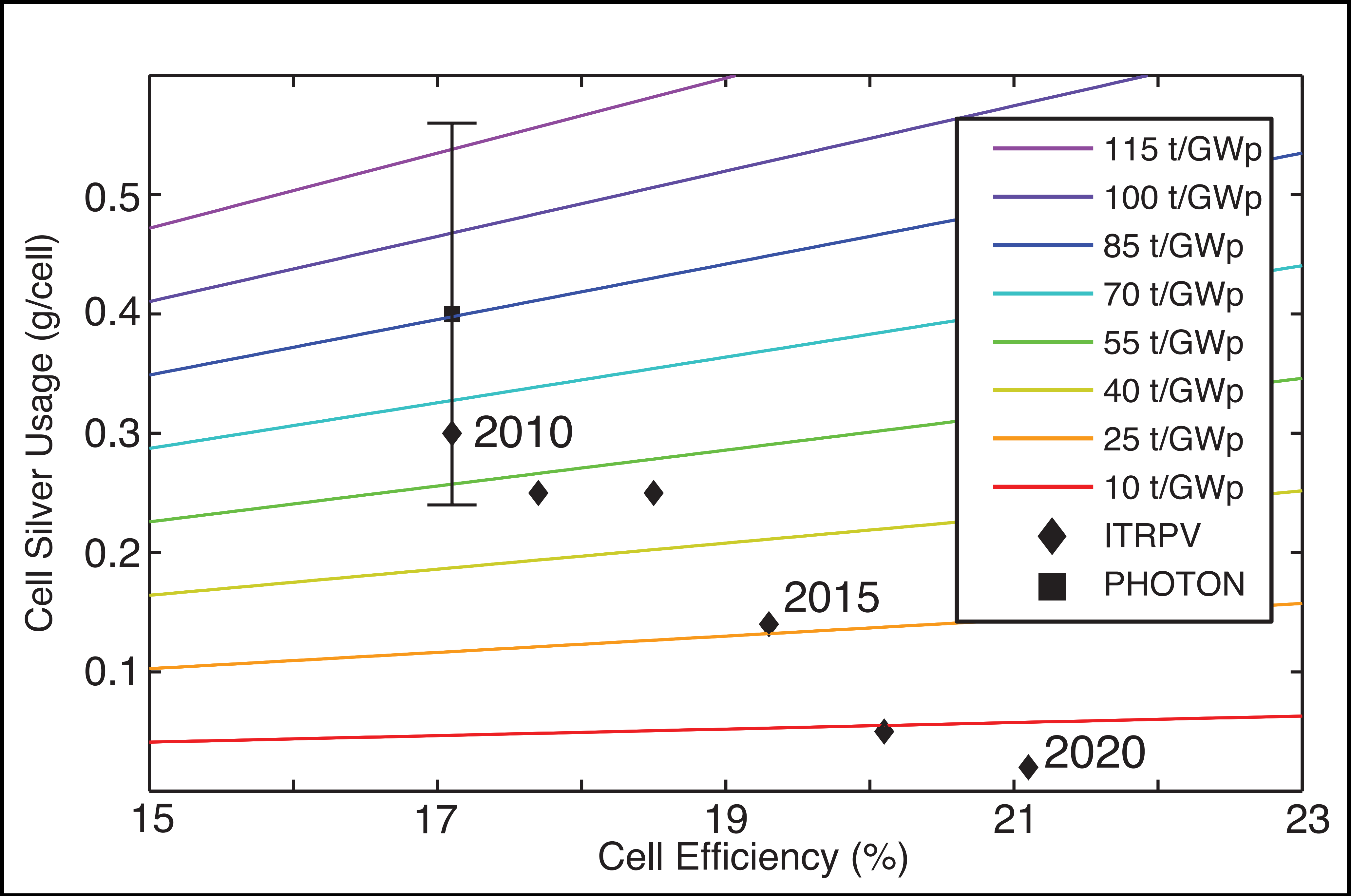
- Used for front contact material (paste/ink)
- 2012: ~10% of all new silver production
- 2012: ~$0.09/W$_p$
- Significant constraint for large scale deployment

2012 material intensity
κ(Ag) ~ 65 - 80 gm/Wp

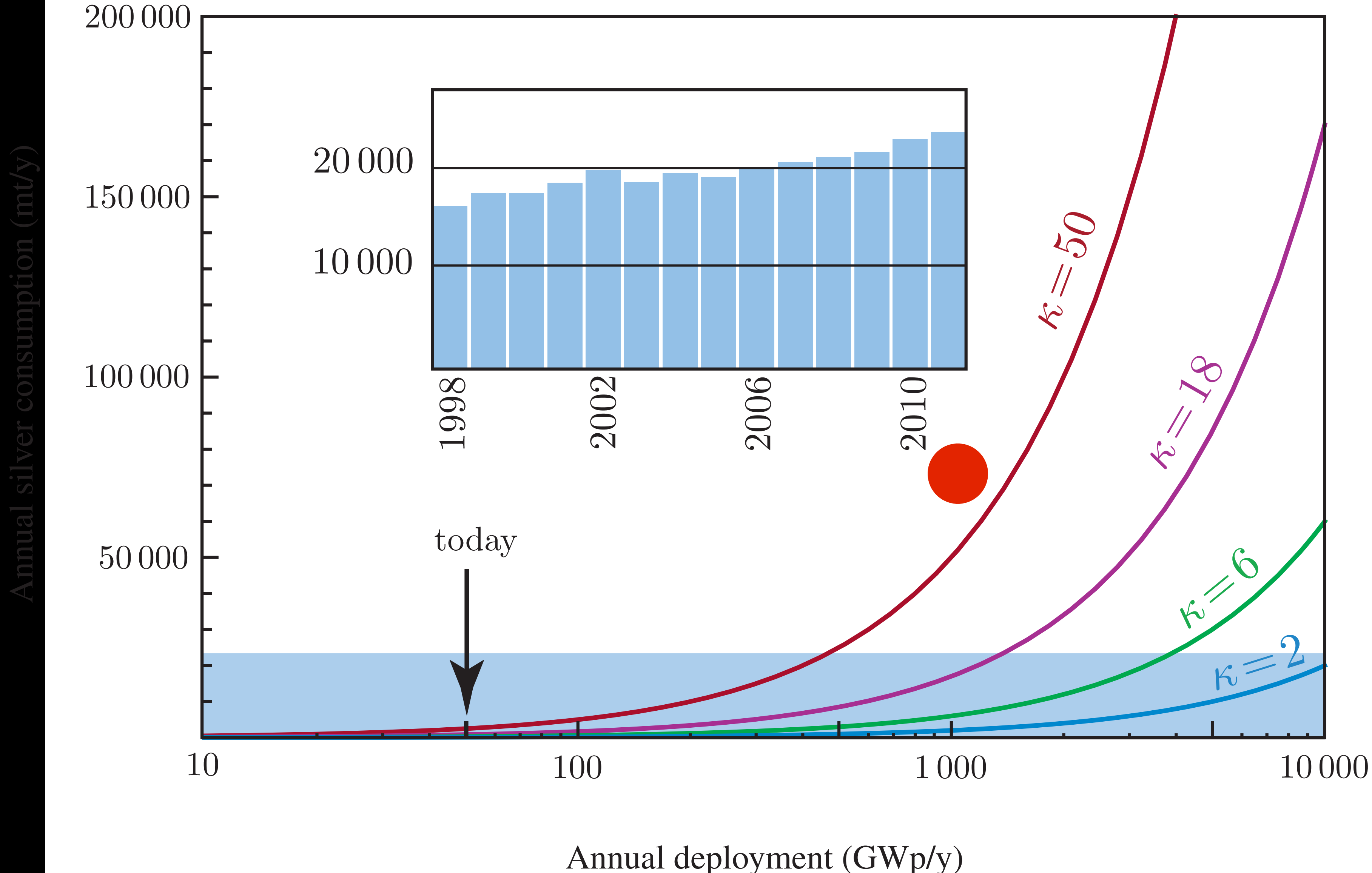


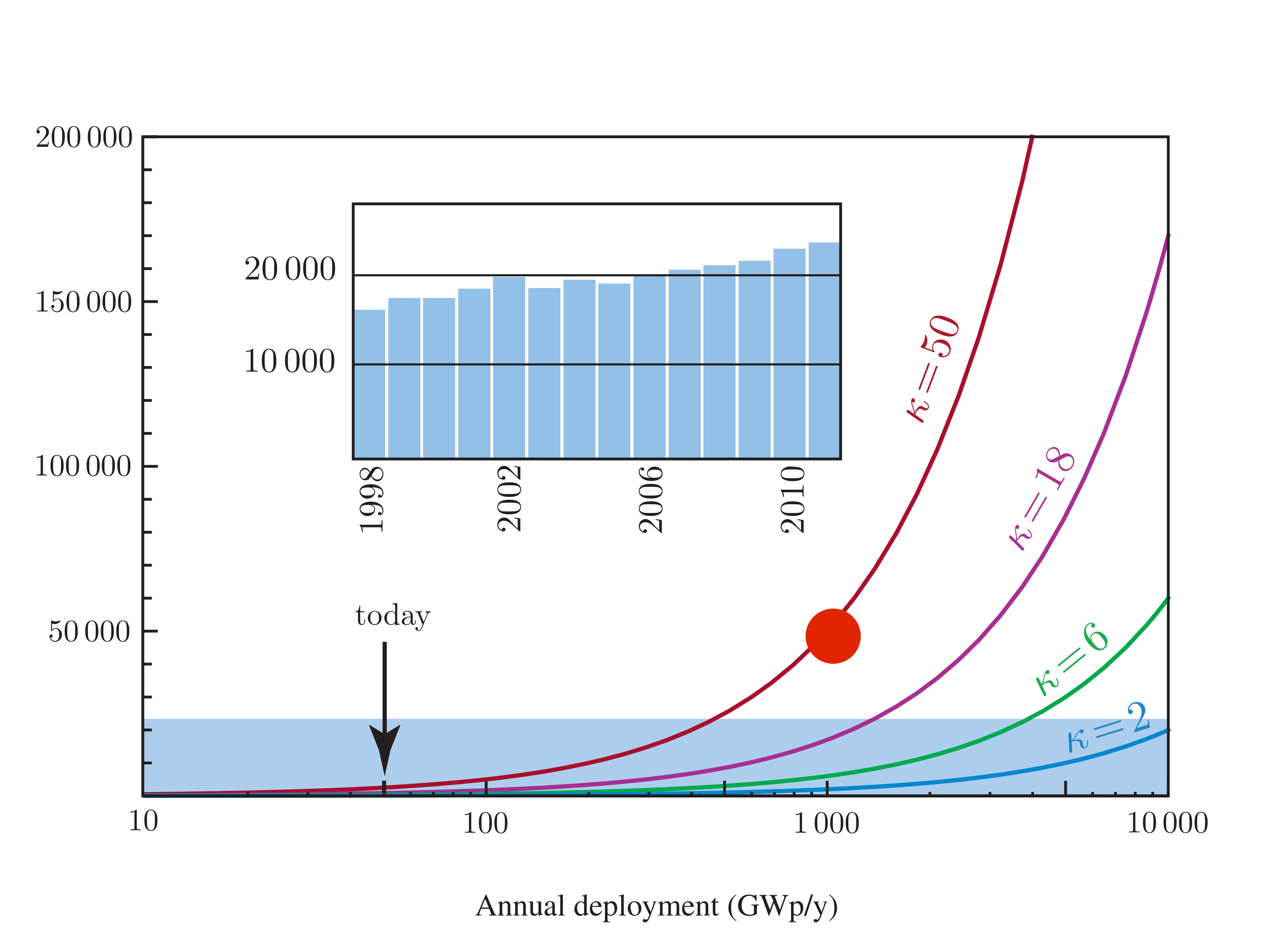


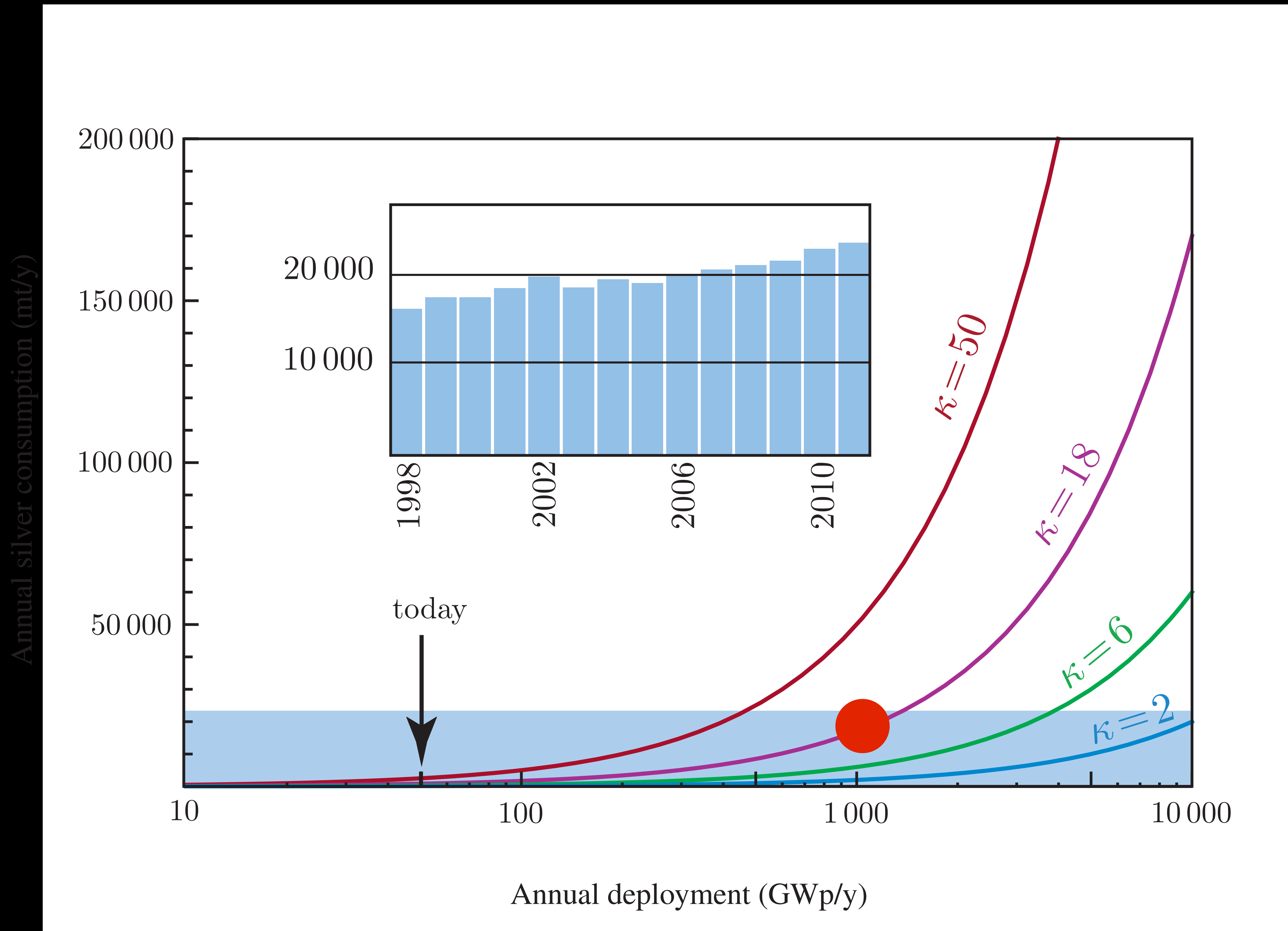
Roadmap for improvement in silver material intensity κ(Ag)

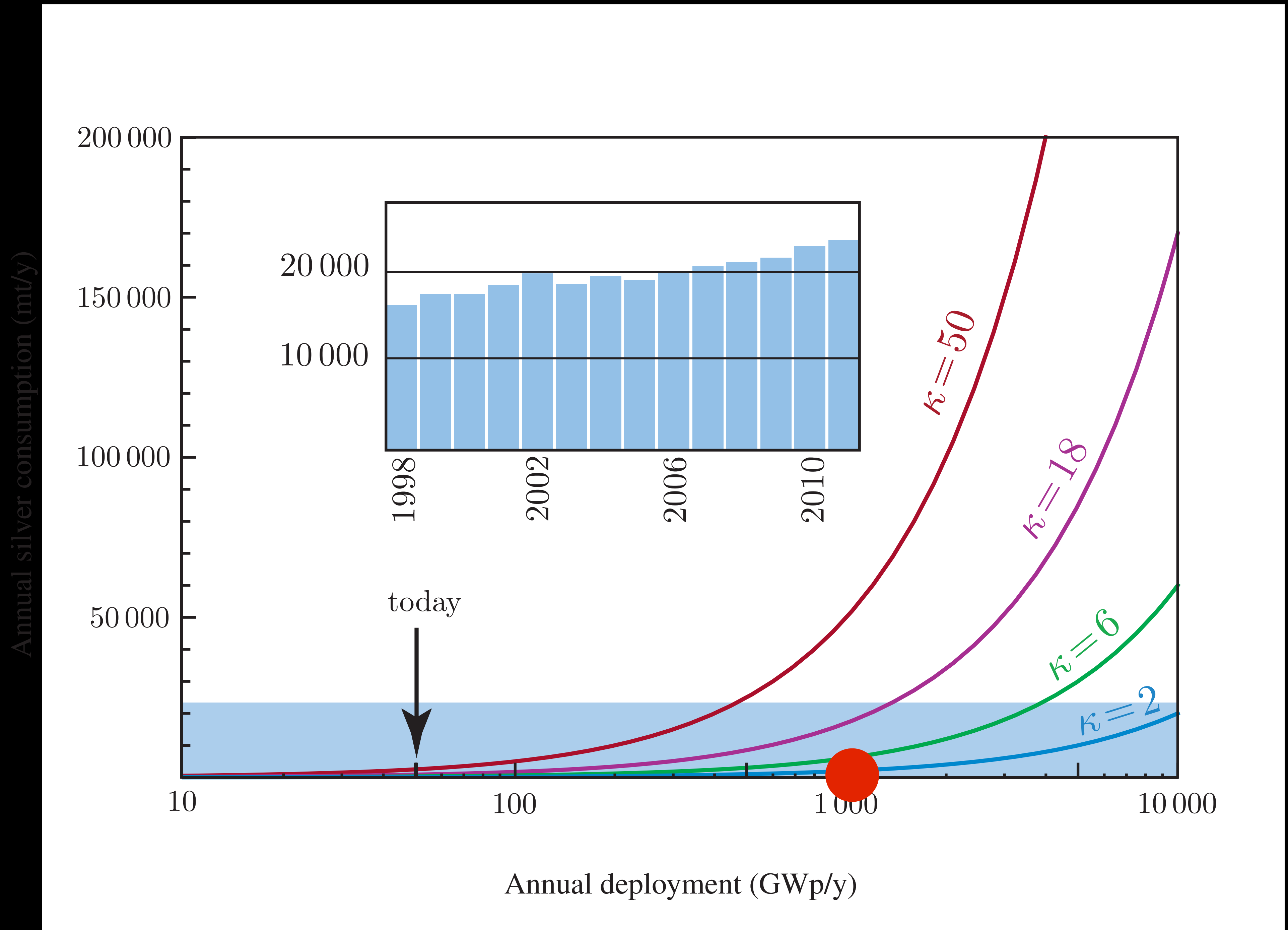


†International Technology Roadmap for Photo Voltaics


200 000
150 000
100 000
50 000
Annual silver consumption (mt/y)
20 000
10 000
1998
2002
2006
2010
κ=50
κ=18
κ=6
κ=2
today
10
100
1 000
10 000
Annual deployment (GWp/y)

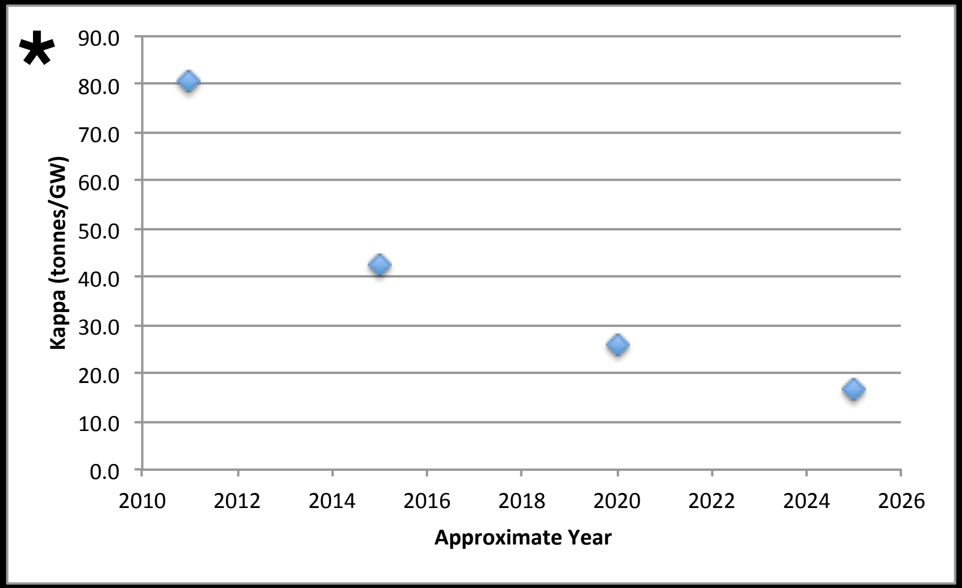

200 000
150 000
100 000
50 000
Annual silver consumption (mt/y)
20 000
10 000
1998
2002
2006
2010
κ=50
κ=18
κ=6
κ=2
today
10
100
1 000
10 000
Annual deployment (GWp/y)

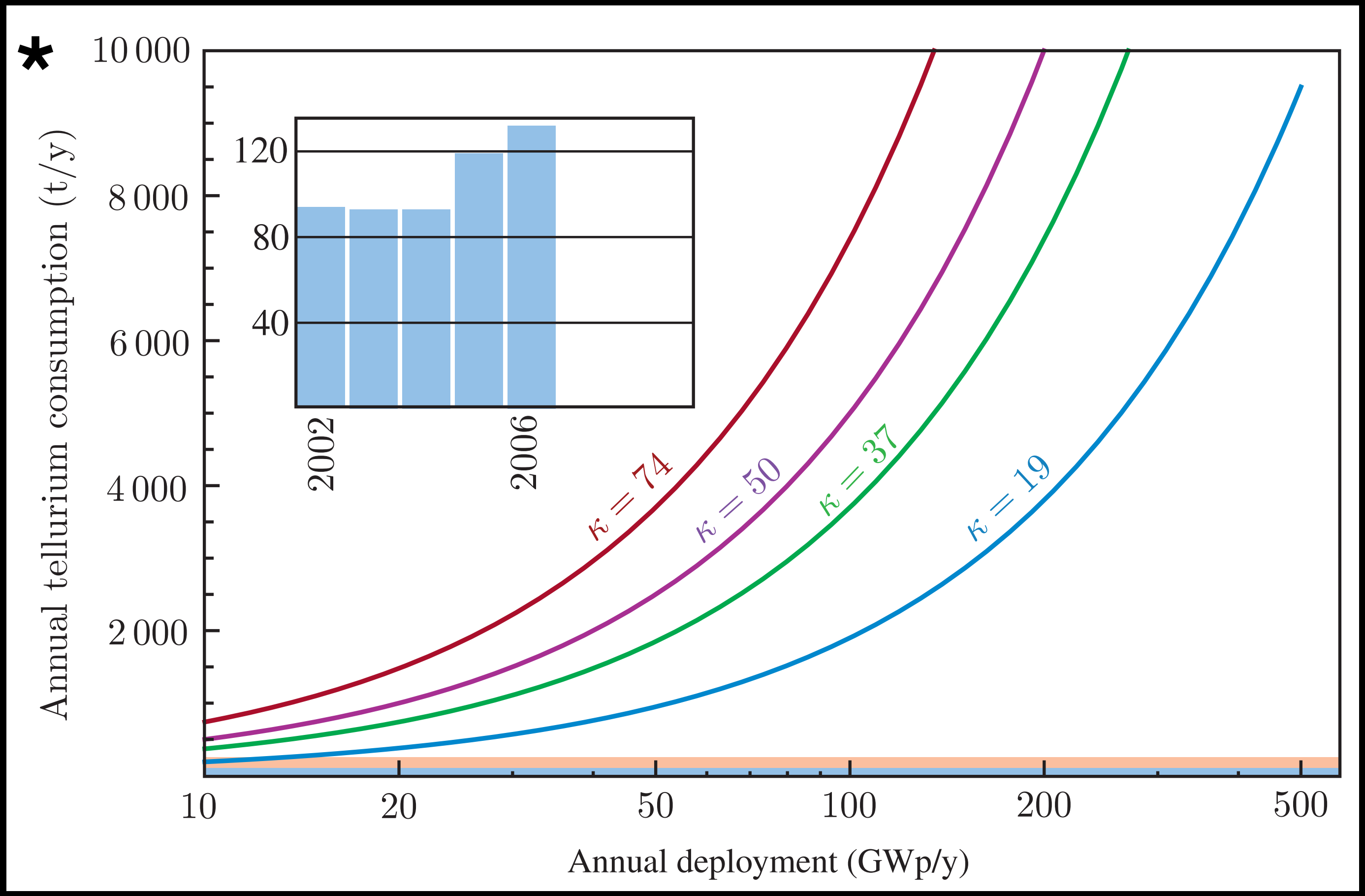

200 000
150 000
100 000
50 000
Annual silver consumption (mt/y)
20 000
10 000
1998
2002
2006
2010
κ=50
κ=18
κ=6
κ=2
today
10
100
1 000
10 000
Annual deployment (GWp/y)


Annual silver consumption (mt/y)
200 000
150 000
100 000
50 000
20 000
10 000
1998
2002
2006
2010
κ = 50
κ = 18
κ = 6
κ = 2
today
10
100
1 000
10 000
Annual deployment (GWp/y)

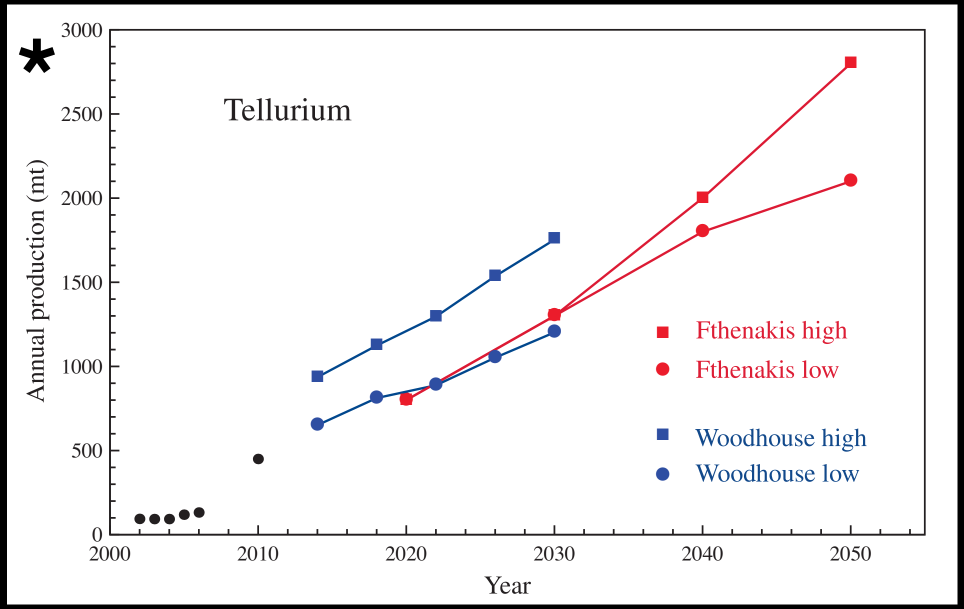
Te in CdTe PV

Materials efficiency?
Production expansion?





* From ongoing MITEI Solar Energy Study



Constraints depend on the goal:

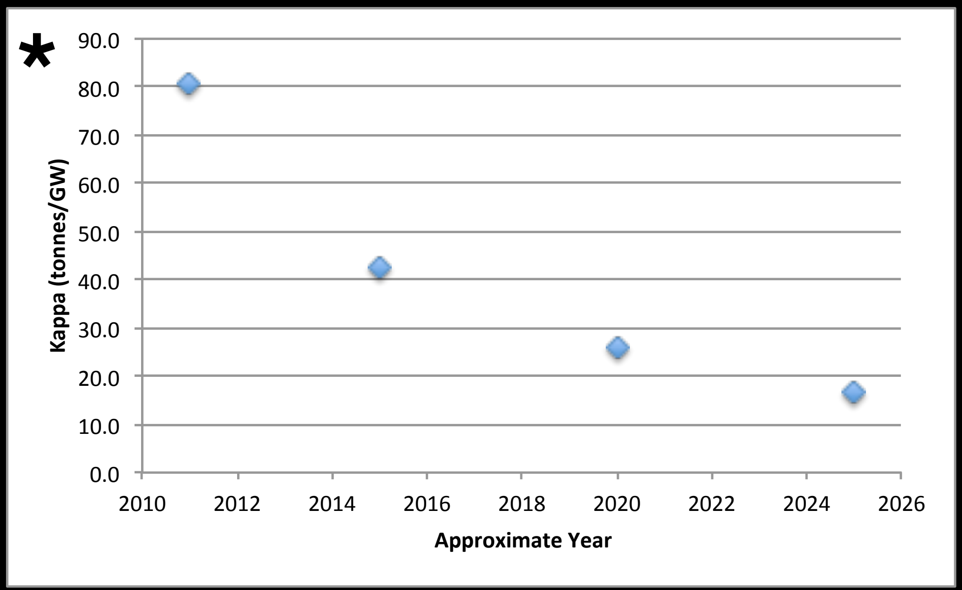
i) Company producing ~10's GW_p/yr

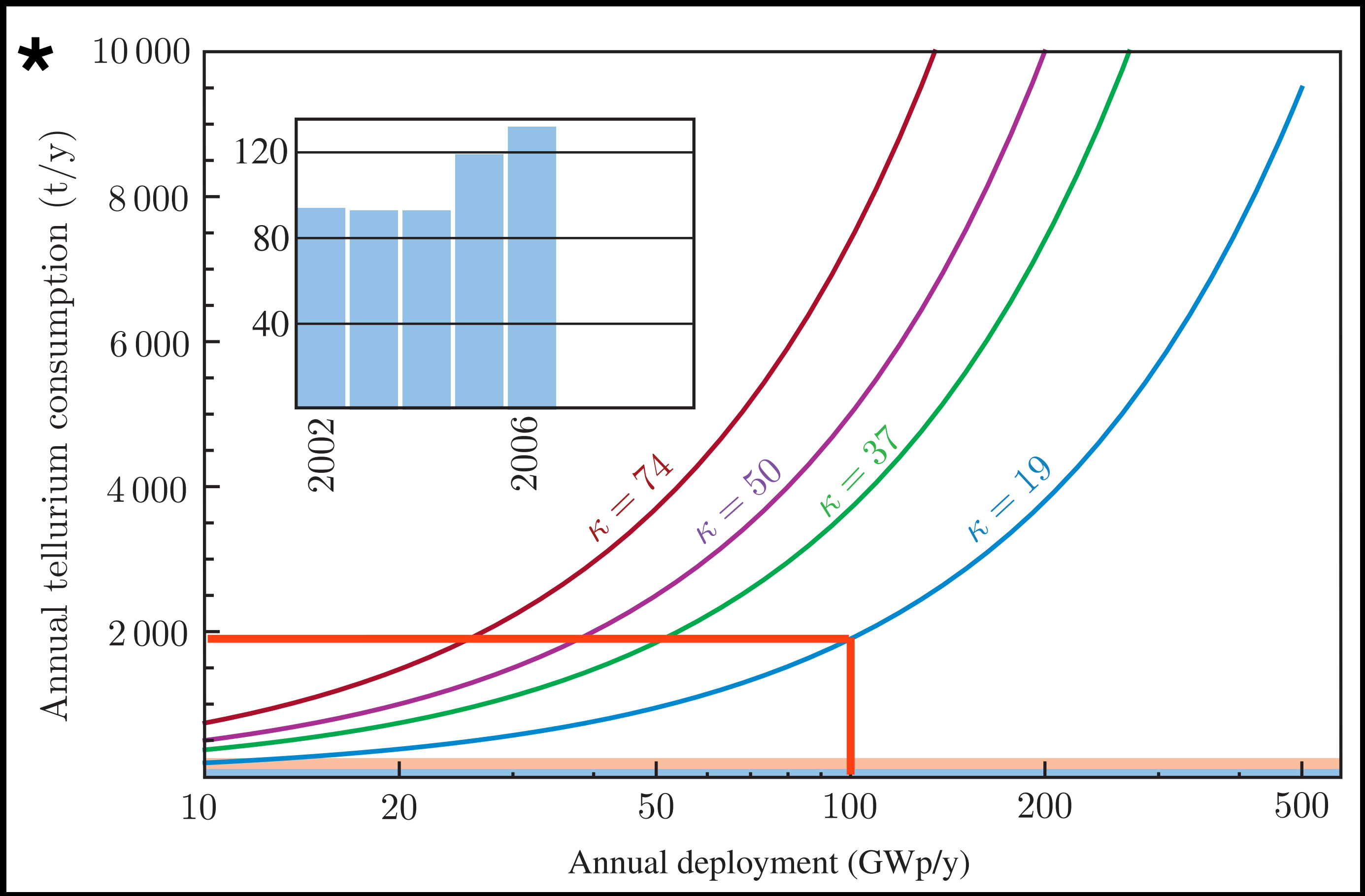
ii) Bridge to future ~100 GW_p/yr

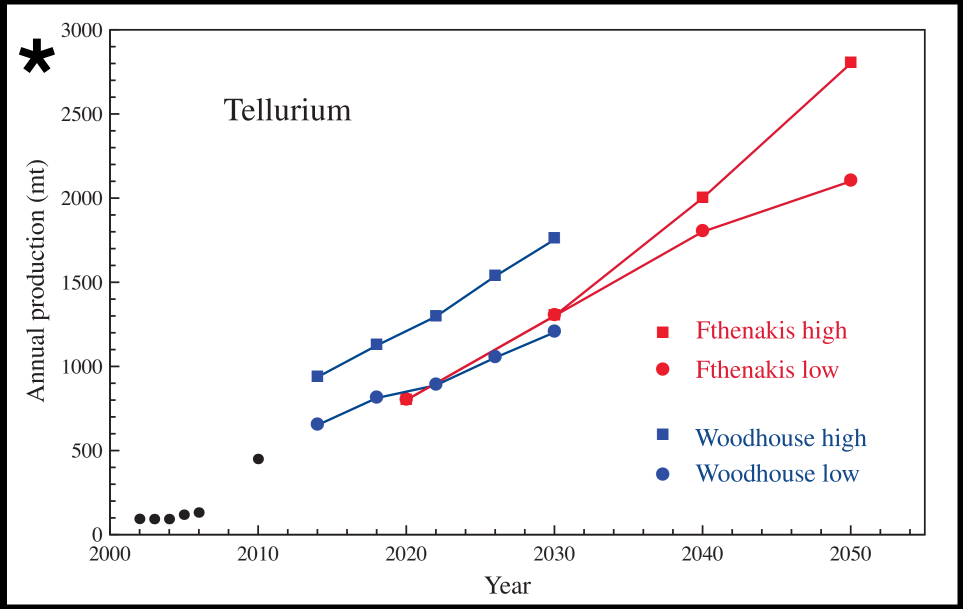
iii) The future? ~ 1000 GW_p/yr

Te in CdTe PV

Materials efficiency?
Production expansion?







* From ongoing MITEI Solar Energy Study

Constraints depend on the goal:

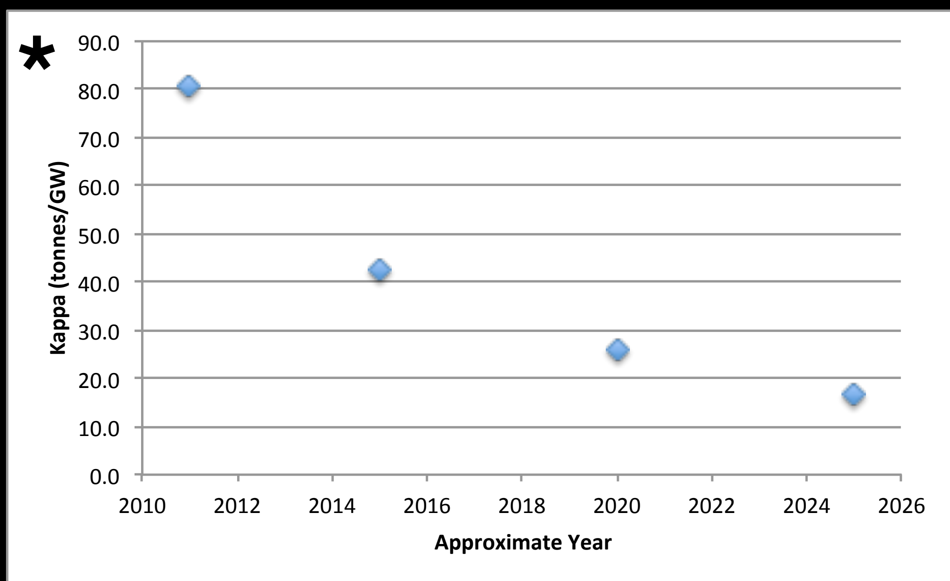
i) Company producing ~10's GW_p/yr

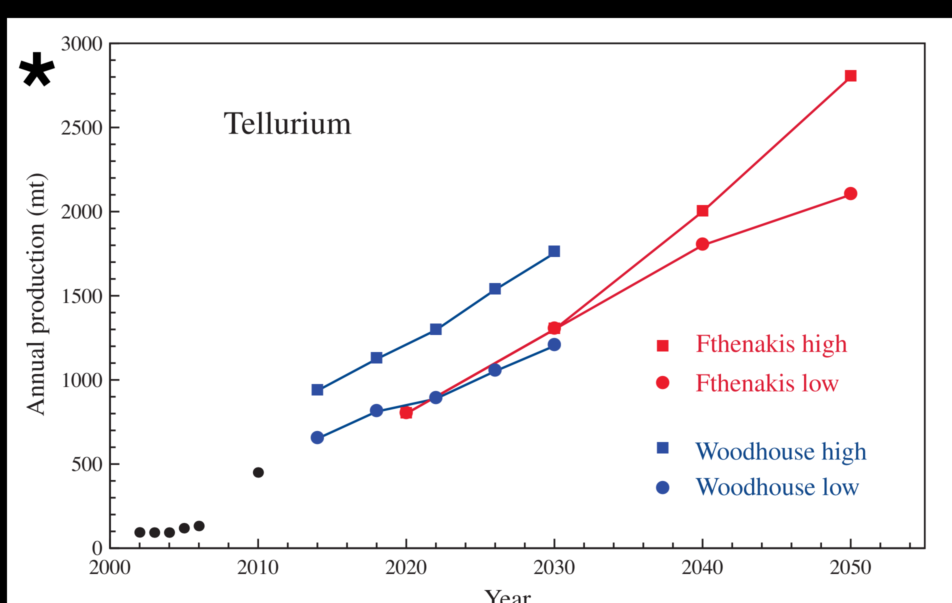
ii) Bridge to future ~100 GW_p/yr

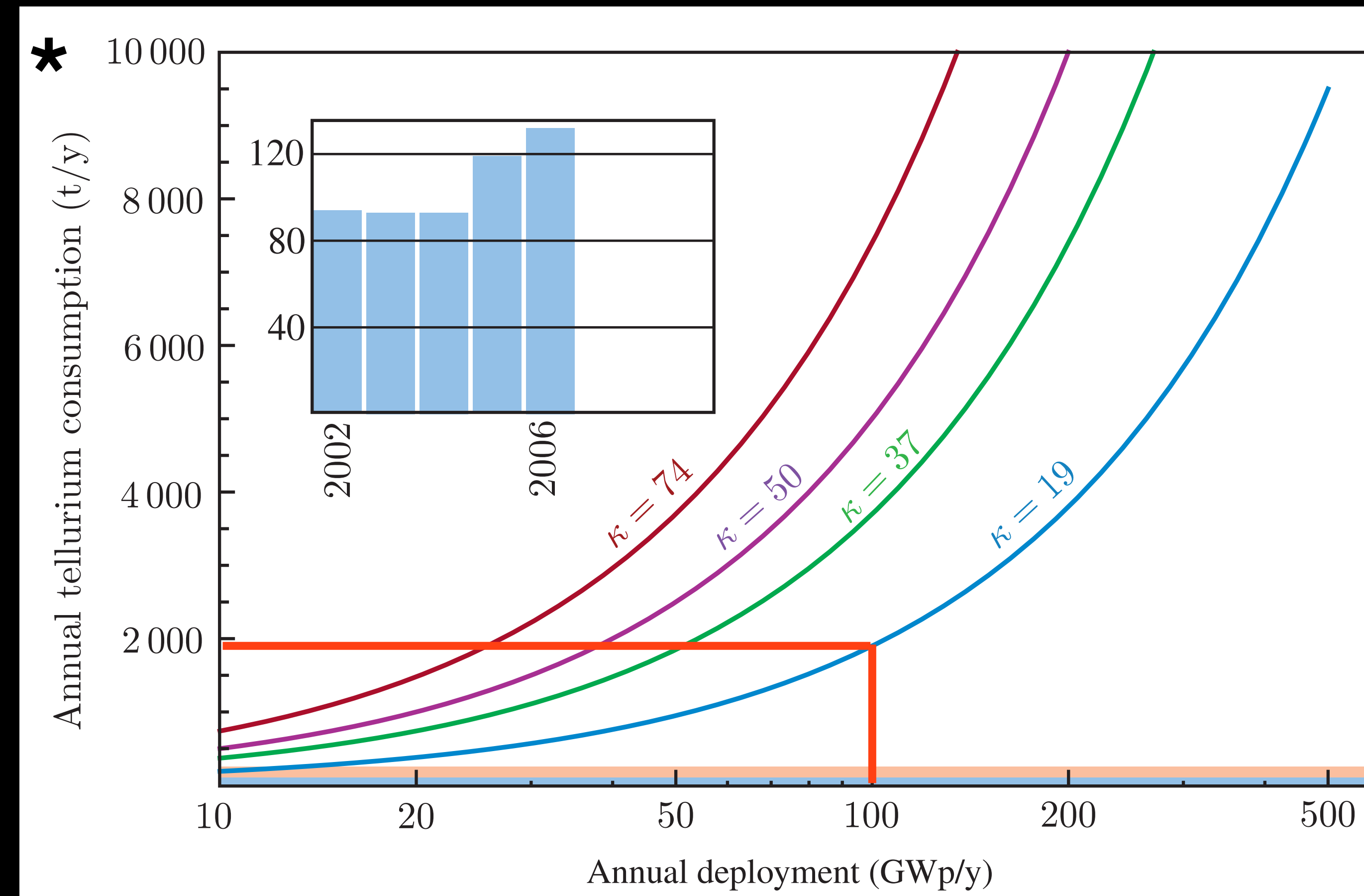
iii) The future? ~ 1000 GW_p/yr

Te in CdTe PV

Materials efficiency?
Production expansion?







* From ongoing MITEI Solar Energy Study

Constraints depend on the goal:

i) Company producing ~10’s GW_p/yr

ii) Bridge to future ~100 GW_p/yr

iii) The future? ~ 1000 GW_p/yr

Principal take aways

- Energy Critical Elements – the periodic table is the playing field
- Constraints on available may/will derail potentially game changing technologies.
- Rare Earths are/were the Flavor of the Month. Next year/decade it may be tellurium, indium, helium, rhenium, platinum, ...
- Materials criticality is an emerging research field at the intersection of economics, material science, geology, ... Especially important for Energy Critical Elements

Platinum Group Elements

Other ECEs

Rare Earth Elements

Photovoltaic ECEs

1 H Hydrogen 1.01																	2 He Helium 4.00
3 Li Lithium 6.94	4 Be Beryllium 9.01											5 B Boron 10.81	6 C Carbon 12.01	7 N Nitrogen 14.01	8 O Oxygen 16.00	9 F Fluorine 19.00	10 Ne Neon 20.18
11 Na Sodium 22.99	12 Mg Magnesium 24.31											13 Al Aluminum 26.98	14 Si Silicon 28.09	15 P Phosphorus 30.97	16 S Sulfur 32.07	17 Cl Chlorine 35.45	18 Ar Argon 39.95
19 K Potassium 39.10	20 Ca Calcium 40.08	21 Sc Scandium 44.96	22 Ti Titanium 47.87	23 V Vanadium 50.94	24 Cr Chromium 52.00	25 Mn Manganese 54.94	26 Fe Iron 55.85	27 Co Cobalt 58.93	28 Ni Nickel 58.69	29 Cu Copper 63.55	30 Zn Zinc 65.39	31 Ga Gallium 69.72	32 Ge Germanium 72.61	33 As Arsenic 74.92	34 Se Selenium 78.96	35 Br Bromine 79.90	36 Kr Krypton 83.80
37 Rb Rubidium 85.47	38 Sr Strontium 87.62	39 Y Yttrium 88.91	40 Zr Zirconium 91.22	41 Nb Niobium 92.91	42 Mo Molybdenum 95.94	43 Tc Technetium (98)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.91	46 Pd Palladium 106.42	47 Ag Silver 107.87	48 Cd Cadmium 112.41	49 In Indium 114.82	50 Sn Tin 118.71	51 Sb Antimony 121.76	52 Te Tellurium 127.60	53 I Iodine 126.90	54 Xe Xenon 131.29
55 Cs Cesium 132.91	56 Ba Barium 137.33	57 La Lanthanum 138.91	72 Hf Hafnium 178.49	73 Ta Tantalum 180.95	74 W Tungsten 183.84	75 Re Rhenium 186.21	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.97	80 Hg Mercury 200.59	81 Tl Thallium 204.38	82 Pb Lead 207.2	83 Bi Bismuth 208.98	84 Po Polonium (209)	85 At Astatine (210)	86 Rn Radon (222)
87 Fr Francium (223)	88 Ra Radium (226)	89 Ac Actinium (227)	104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (266)	107 Bh Bohrium (264)	108 Hs Hassium (269)	109 Mt Meitnerium (268)									

58 Ce Cerium 140.12	59 Pr Praseodymium 140.91	60 Nd Neodymium 144.24	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.96	64 Gd Gadolinium 157.25	65 Tb Terbium 158.93	66 Dy Dysprosium 162.50	67 Ho Holmium 164.93	68 Er Erbium 167.26	69 Tm Thulium 168.93	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.97
90 Th Thorium 232.04	91 Pa Protactinium 231.04	92 U Uranium 238.03	93 Np Neptunium (237)	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (262)

Platinum Group Elements

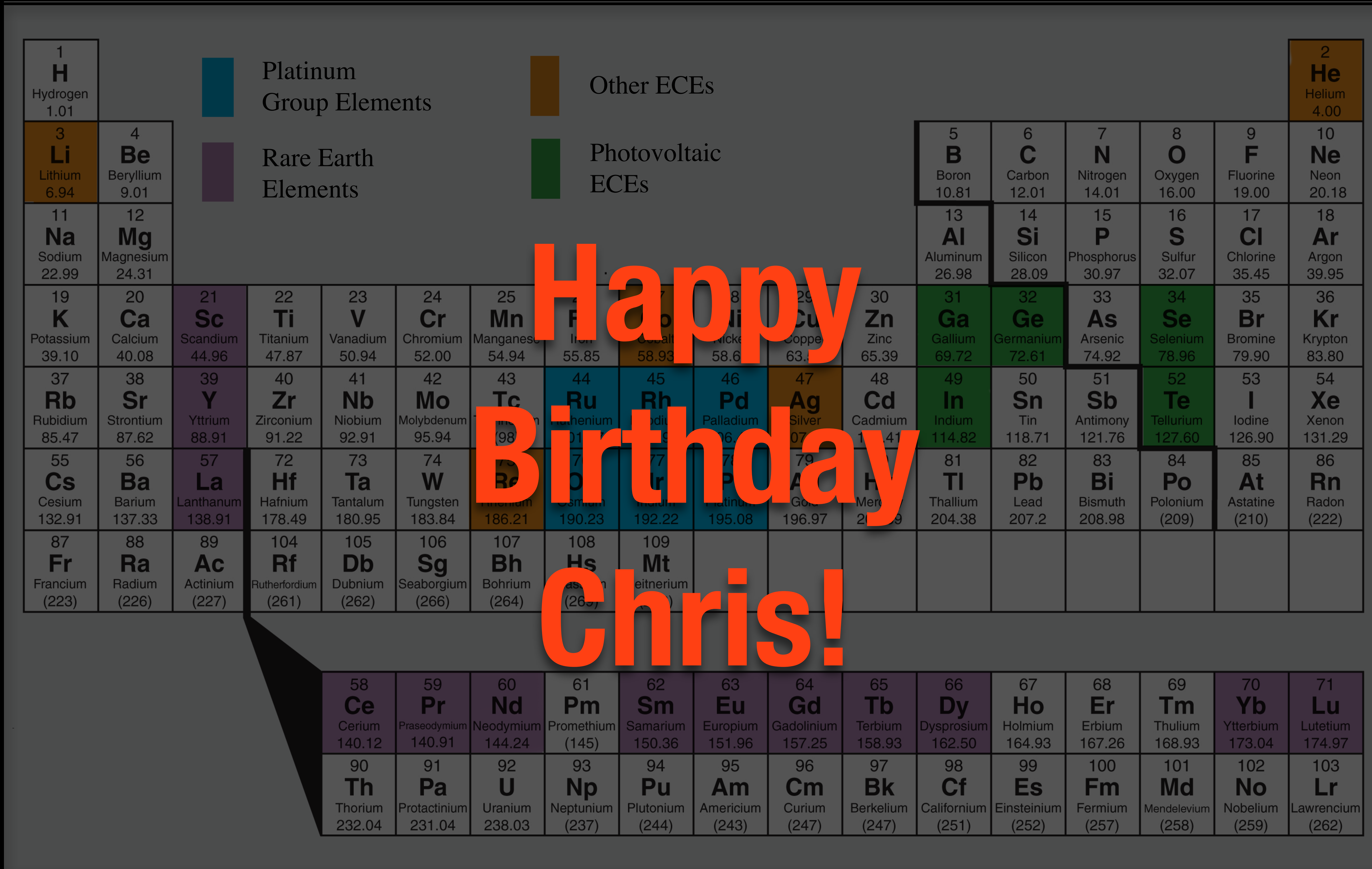
Rare Earth Elements

Other ECEs

Photovoltaic ECEs

1 H Hydrogen 1.01																	2 He Helium 4.00
3 Li Lithium 6.94	4 Be Beryllium 9.01											5 B Boron 10.81	6 C Carbon 12.01	7 N Nitrogen 14.01	8 O Oxygen 16.00	9 F Fluorine 19.00	10 Ne Neon 20.18
11 Na Sodium 22.99	12 Mg Magnesium 24.31											13 Al Aluminum 26.98	14 Si Silicon 28.09	15 P Phosphorus 30.97	16 S Sulfur 32.07	17 Cl Chlorine 35.45	18 Ar Argon 39.95
19 K Potassium 39.10	20 Ca Calcium 40.08	21 Sc Scandium 44.96	22 Ti Titanium 47.87	23 V Vanadium 50.94	24 Cr Chromium 52.00	25 Mn Manganese 54.94	26 Fe Iron 55.85	27 Co Cobalt 58.93	28 Ni Nickel 58.69	29 Cu Copper 63.55	30 Zn Zinc 65.39	31 Ga Gallium 69.72	32 Ge Germanium 72.61	33 As Arsenic 74.92	34 Se Selenium 78.96	35 Br Bromine 79.90	36 Kr Krypton 83.80
37 Rb Rubidium 85.47	38 Sr Strontium 87.62	39 Y Yttrium 88.91	40 Zr Zirconium 91.22	41 Nb Niobium 92.91	42 Mo Molybdenum 95.94	43 Tc Technetium (98)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.91	46 Pd Palladium 106.42	47 Ag Silver 107.87	48 Cd Cadmium 112.41	49 In Indium 114.82	50 Sn Tin 118.71	51 Sb Antimony 121.76	52 Te Tellurium 127.60	53 I Iodine 126.90	54 Xe Xenon 131.29
55 Cs Cesium 132.91	56 Ba Barium 137.33	57 La Lanthanum 138.91	72 Hf Hafnium 178.49	73 Ta Tantalum 180.95	74 W Tungsten 183.84	75 Re Rhenium 186.21	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.97	80 Hg Mercury 200.59	81 Tl Thallium 204.38	82 Pb Lead 207.2	83 Bi Bismuth 208.98	84 Po Polonium (209)	85 At Astatine (210)	86 Rn Radon (222)
87 Fr Francium (223)	88 Ra Radium (226)	89 Ac Actinium (227)	104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (266)	107 Bh Bohrium (264)	108 Hs Hassium (269)	109 Mt Meitnerium (268)									

58 Ce Cerium 140.12	59 Pr Praseodymium 140.91	60 Nd Neodymium 144.24	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.96	64 Gd Gadolinium 157.25	65 Tb Terbium 158.93	66 Dy Dysprosium 162.50	67 Ho Holmium 164.93	68 Er Erbium 167.26	69 Tm Thulium 168.93	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.97
90 Th Thorium 232.04	91 Pa Protactinium 231.04	92 U Uranium 238.03	93 Np Neptunium (237)	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (262)


Platinum Group Elements
Other ECEs
Rare Earth Elements
Photovoltaic ECEs
Happy Birthday Chris!