Planetary & Terrestrial Mining Sciences Symposium 2013

Electrostatic Placer Deposits of **GOLD!!**

A POTENTIALLY LUCRATIVE LUNAR RESOURCE

Abstract:

LRO-LAMP detected a reported 2σ upper limit of up to 0.3% (3,000 g/t) of gold (along with surprising concentrations of several other metals) within the LCROSS impact plume composed of material from within a permanently shaded region (PSR). We discuss a possible transport mechanism whereby dust particles of native gold are preferentially transported by the Moon's electrical environment to areas in PSRs where electrical forces are nil. Empirical support is found in Apollo 12 samples where pristine rocks averaged 5 ppb Au concentrations, whereas core samples of regolith only averaged 2 ppb. Assuming the missing 3 ppb Au was concentrated within the PSRs and the PSR/total lunar surface area ratio is ~10^{-4}, then 30 ppm (30 g/t) would be a reasonable, minimum estimate of Au concentrations within the PSRs. However, according to Farrell et al. (2010) strong electrical fields caused by solar wind exist in PSRs. Metallic dust particles could form a "current of last resort". Small but deep polar craters may experience low ion erosion allowing mass accumulation. PSR erosion and subsequent concentration of gold dust could increase Au concentrations by another order of magnitude to ~300 ppm.

Electrostatic Placer Deposits

WHAT ARE THEY?!?

- Similar to placer deposits formed by differential water or wind transport
- Electrostatic placer deposits caused by differential electrostatic dust transport

GOLD: A Killer App for the Moon?

- Requirements of a killer app:
  - Doesn't require an "ecosystem" of revenue streams
  - A single revenue stream that can produce ≥ **$10B/year**

- Potential contenders:
  - Propellant: No one can afford to pay $10B/year for rocket fuel
  - PGMs: Total market < $10B/year; oversupply would crash price
  - Gold: Large market can absorb 200 mT/year without disruption
  - The traditional target since the days of Columbus, '49, Klondike…

Outlook for **Gold:**

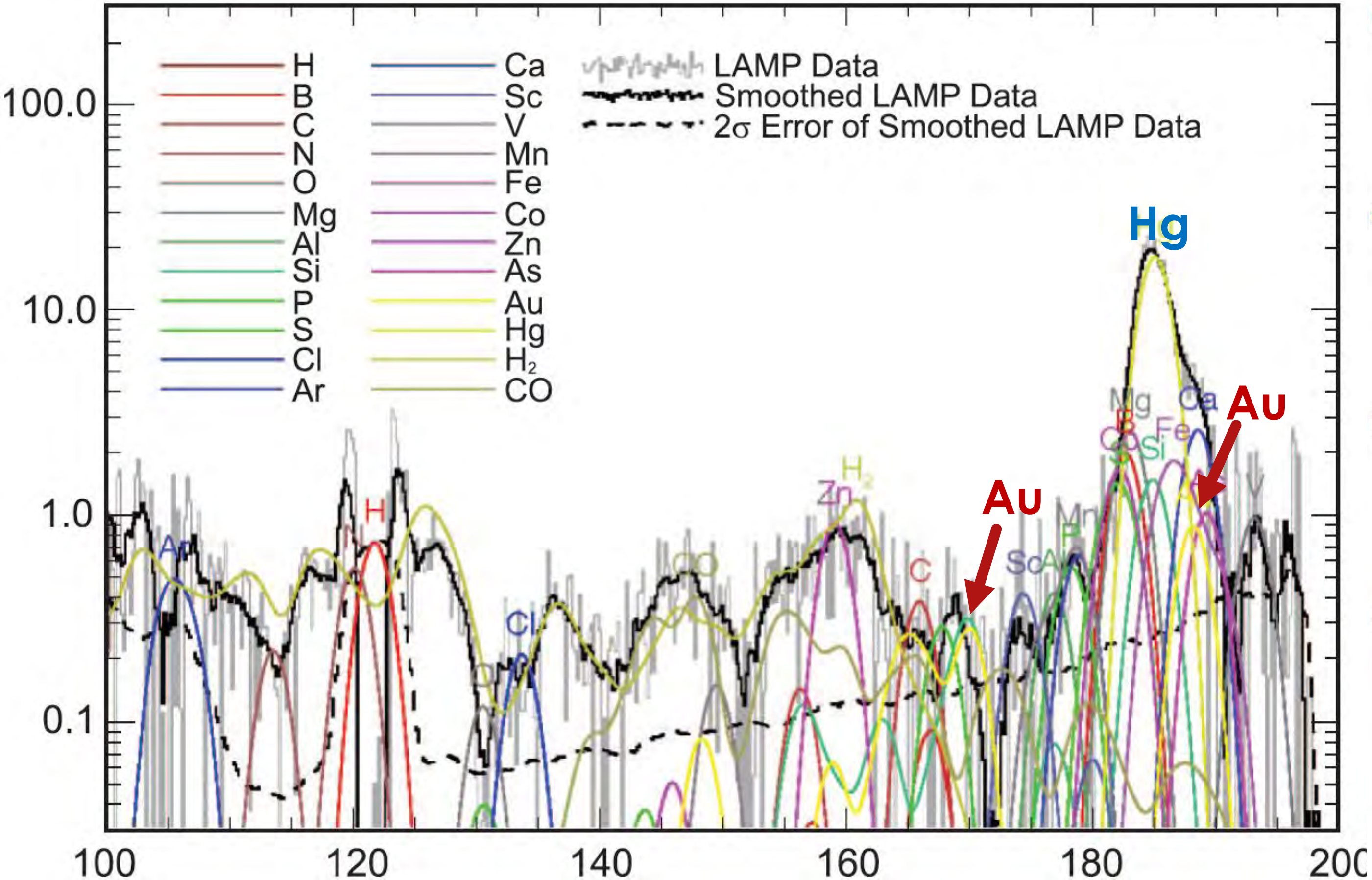
- Precious **Au** was an Inflation hedge: now a currency + hedge
- Moves with unknown political issues, not cycles
- Economic malaise will extend unknown "bull" market

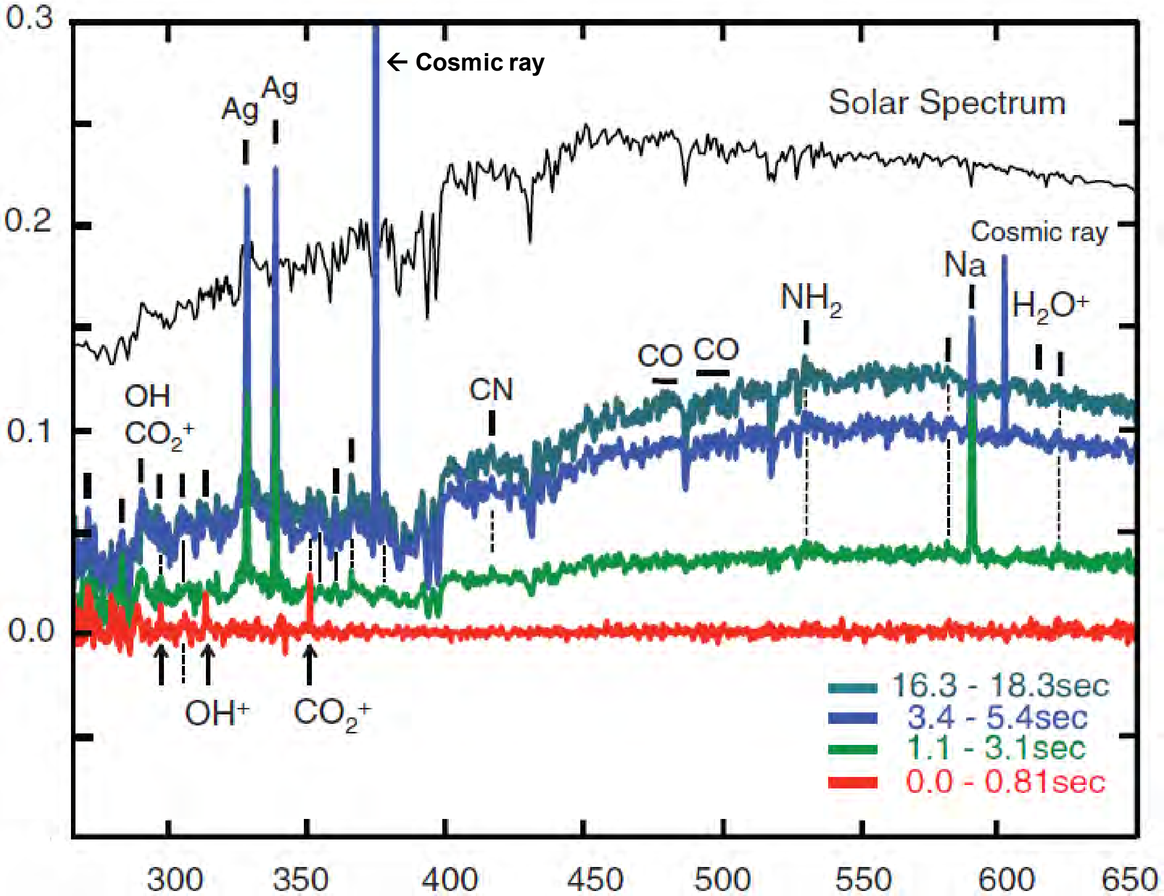
Source: CIM 2013 convention

- Peak Gold???
- Yes, there has been record production of **Au** in recent years. However …
- Production of gold declining practically everywhere except China
- Discovery of new **Au** reserves not keeping pace with production
- New high quality deposits of **Au** practically impossible to find
- Survey of 71 Canadian gold companies: reserves < 1 gram/tonne (g/t ≡ ppm)
- Main effect of Lunar **Au** would be to offset declining production on Earth

LCROSS Evidence For Lunar Gold:

- Main gold peaks at **170** and **188** nm
- Not easy to see, but **Au**, **Ag**, & **Hg** tend to be found together
- Mercury peak unmistakable at **185** nm
- Silver peaks unmistakable at **328** and **338** nm
- Zinc, manganese, magnesium, iron, cobalt, arsenic, vanadium also reported





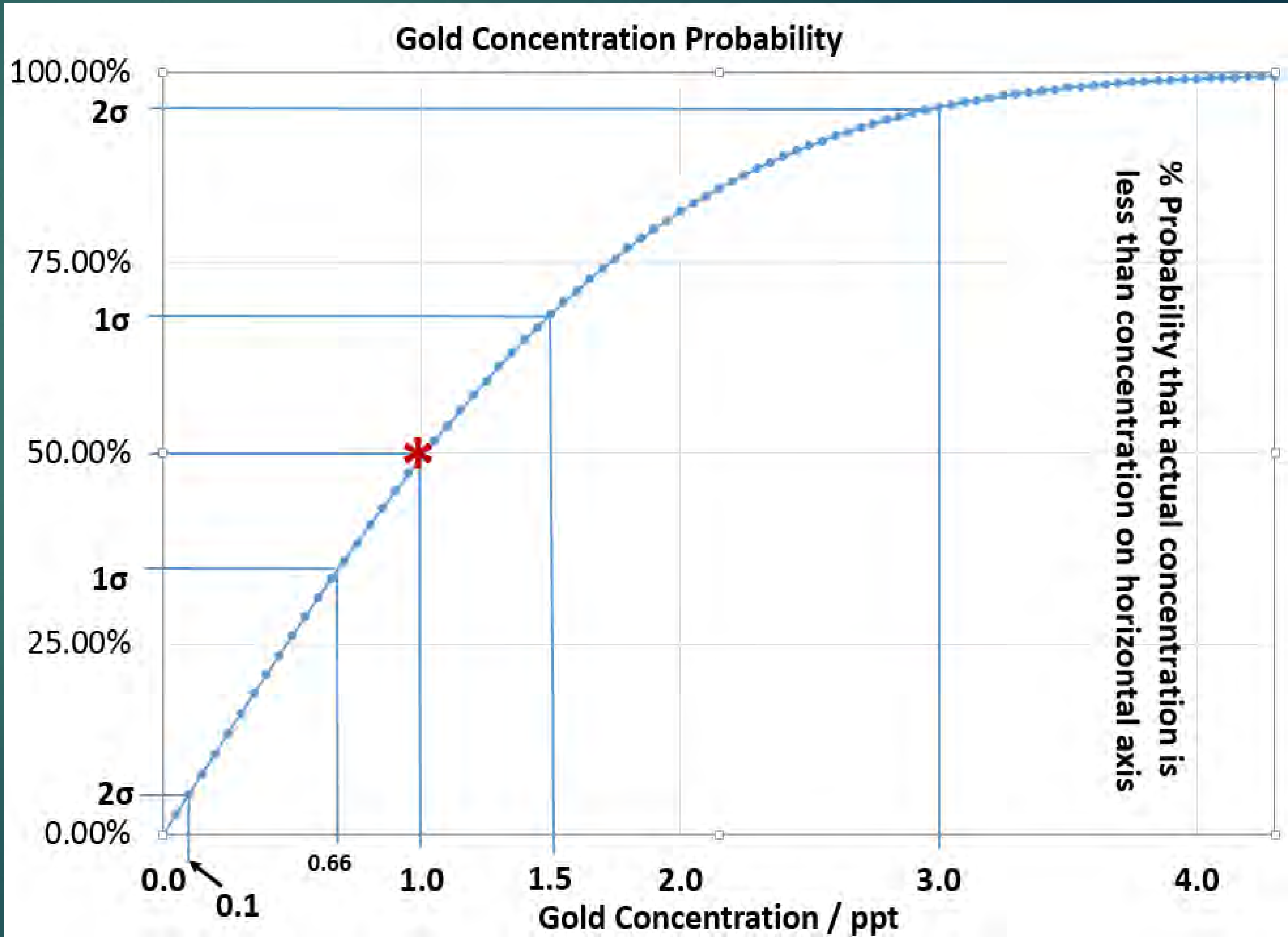
Interpreting the LCROSS results

- LCROSS reported 2-sigma upper limit gold concentration of 3 ppt = ***3 kg/t!***
- Actual concentration "could be anything less than that, as far as we can tell."

  --Randy Gladstone, personal communication
- However, very tight error bars given for **Hg** and **Mg**
- Gold and silver spectra probably not result of contamination
- Source of **Ag** in the Centaur, sufficient to produce emission lines not been identified
- **Ag** lines did not appear immediately, indicating it was below the surface
- Hardly any **Al** (a major spacecraft component) detected
  - **Al** extremely common on the Moon, but exists almost totally in oxidized form

Estimate of expected concentration

- Since 2σ upper lim = 3 ppt conservative estimate of σ = 1.5 ppt
- Apply error function to derive expected value:
- erf [conc / σ sqrt(2)]
- Yields expected value of **~1 ppt (1 kg / tonne)**
- **But HOW ?!?**



How to achieve concentration in PSRs

- George Warren Reed, Jr. predicted heavy **Hg** concentrations in PSRs
- Basis: volatility of **Hg** and deficit of **Hg** in pristine rocks versus regolith
- Got to within an order of magnitude or two of LCROSS reported concentration

- However: **Au** not volatile at typical lunar temperatures

Report

Don't drink the water

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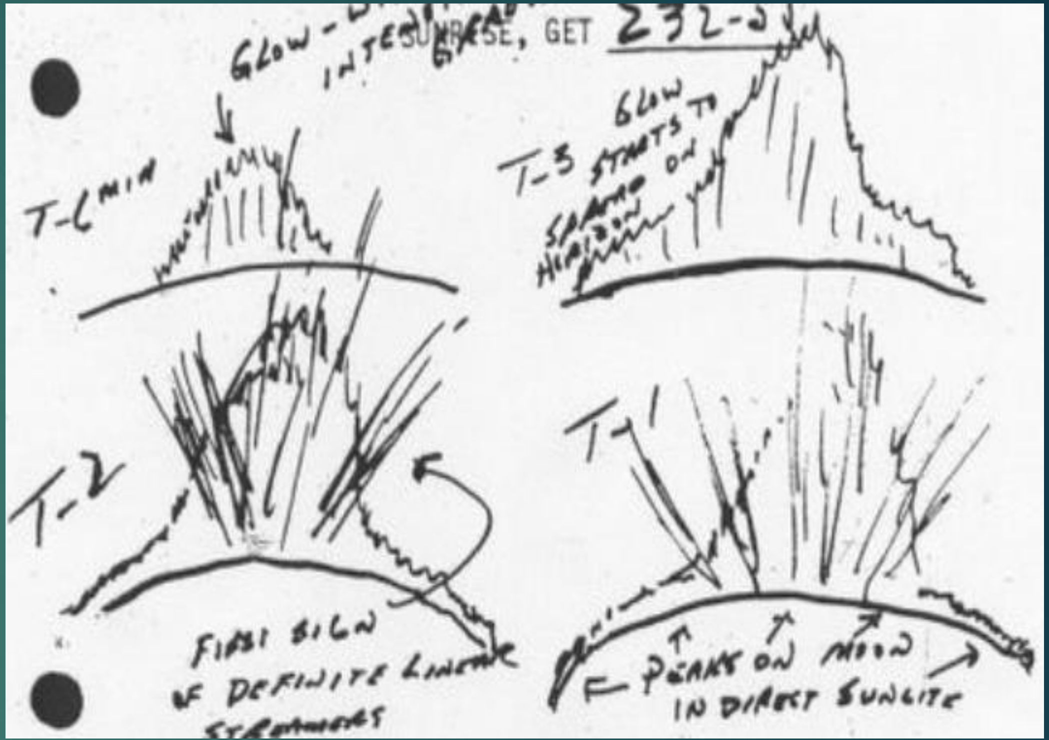
HOW GOLD GETS CONCENTRATED



- **THE THEORY:**
- **<u>Electrostatic Dust Transport</u>**

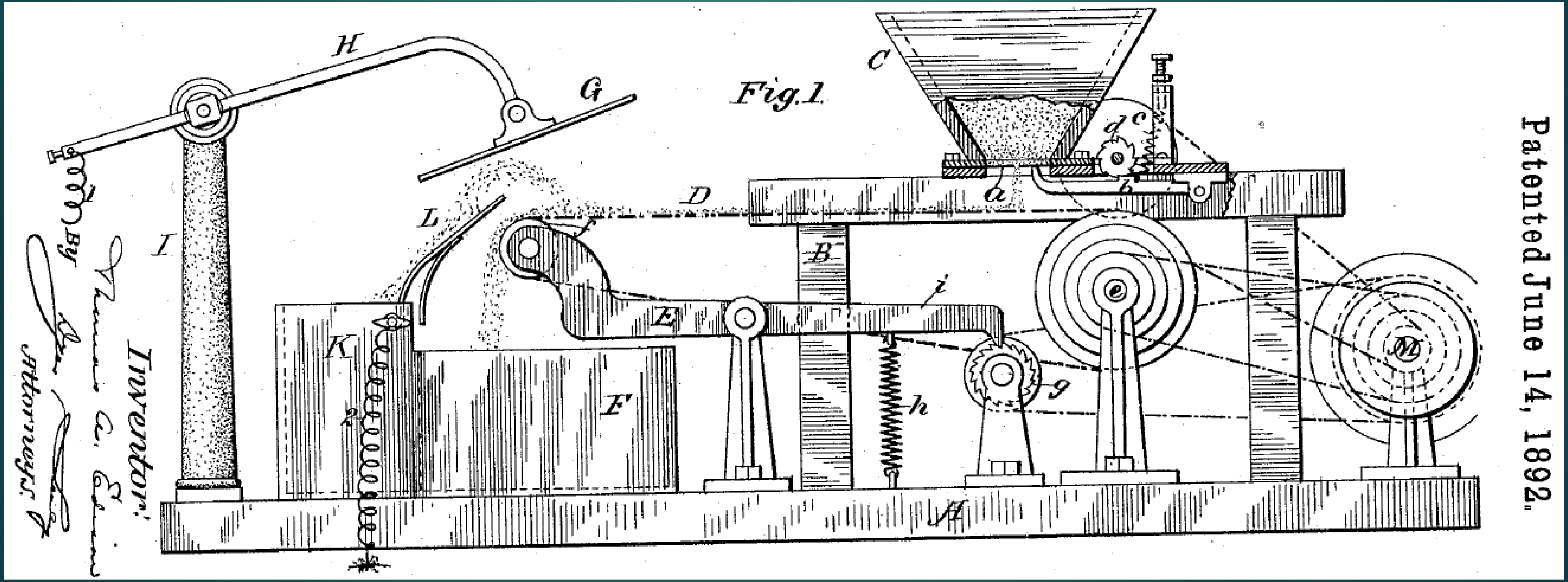
- First discovered as a result of Apollo missions
- During daytime positive charges build up due to photoemission of electrons
- During nighttime solar wind electron clouds cause negative charging
- Strong electric fields can result in electrostatic levitation of dust particles
- Native metals will collect in areas lacking electrostatic forces (PSRs)

But why expect concentration?

- Electrostatic separation (including **gold**) happens: it is an everyday industrial process
- General principle of geology that **any** transport mechanism will result in separation and concentration based on physical properties of grains
- Numerical simulations
- Empirical data

Electrostatic separation:

- First invented by Thomas Edison for separating New Mexico desert gold
- Used for separating metals from gangue, rocks from dried beans, recyclables
- Should not be surprised to find analogues in nature



It is a general principle of geology that *ANY* transport process—including electrostatic dust transport--will result in separation and concentration based on properties of grains.

- Density: favors ordinary dust over dense gold
- Photoelectric efficiency: decisively favors gold
- Capacitance: gold will often have higher effective capacitance
- Work Function: will cause gold to want to donate electrons

Numerical Simulations

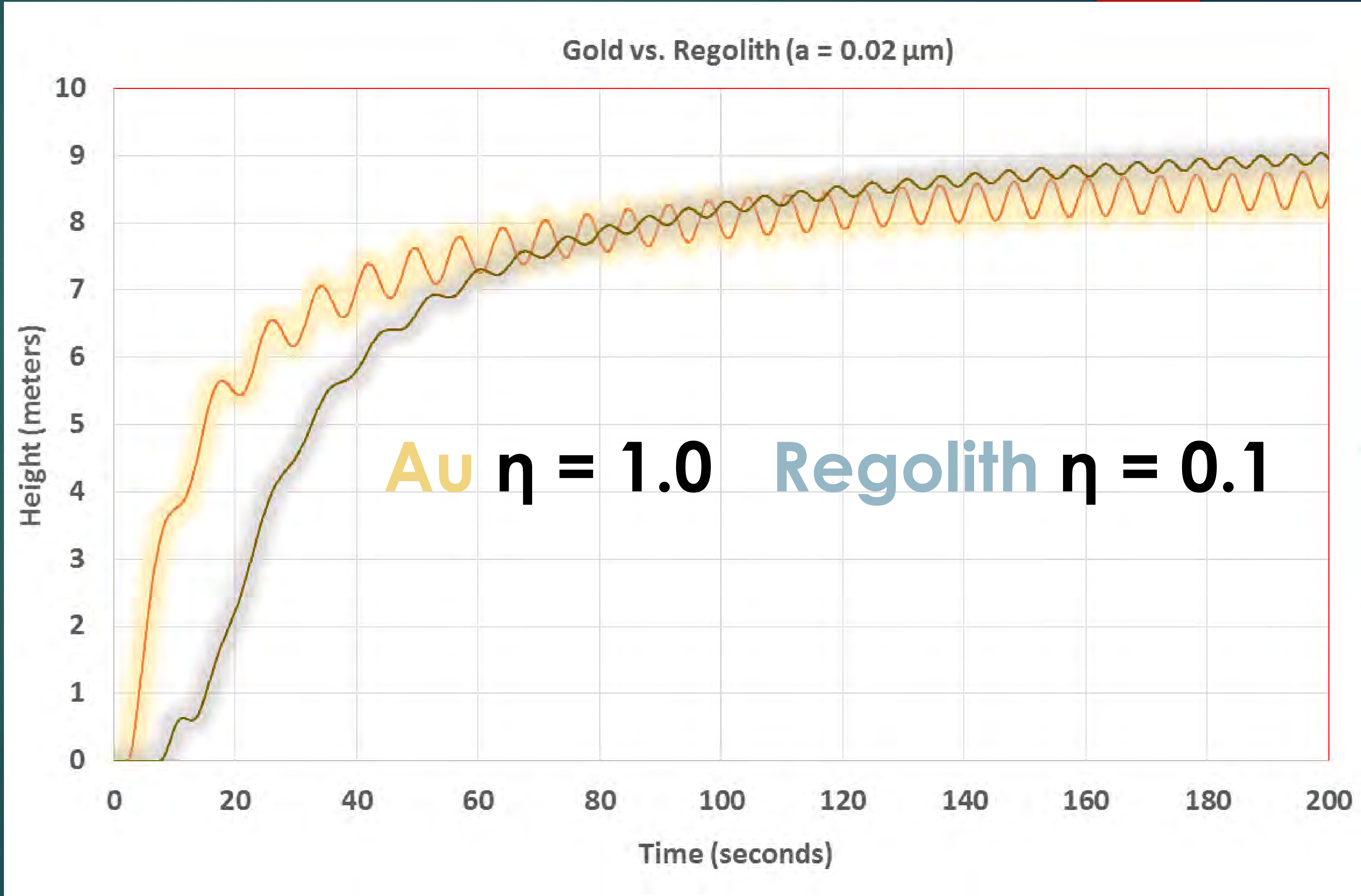
- I attempted to simulate noontime conditions on the Moon
- Environmental parameters taken from Andrew Poppe's Ph.D. thesis (2011) based on particle in cell (PIC) simulations
- Test particle approach: 1-dimension (z)

- Findings:
  - Higher photoelectric efficiency **η** of gold makes up for higher density
  - <u>Using realistic PEs, submicron-sized regolith particles **cannot** levitate</u>

Numerical Simulation Test Particle Results:

Traditional mathematical treatments assume regolith photoelectric efficiency η = 0.1

No qualitative difference between gold and ordinary regolith observed with regolith dust η = 0.1



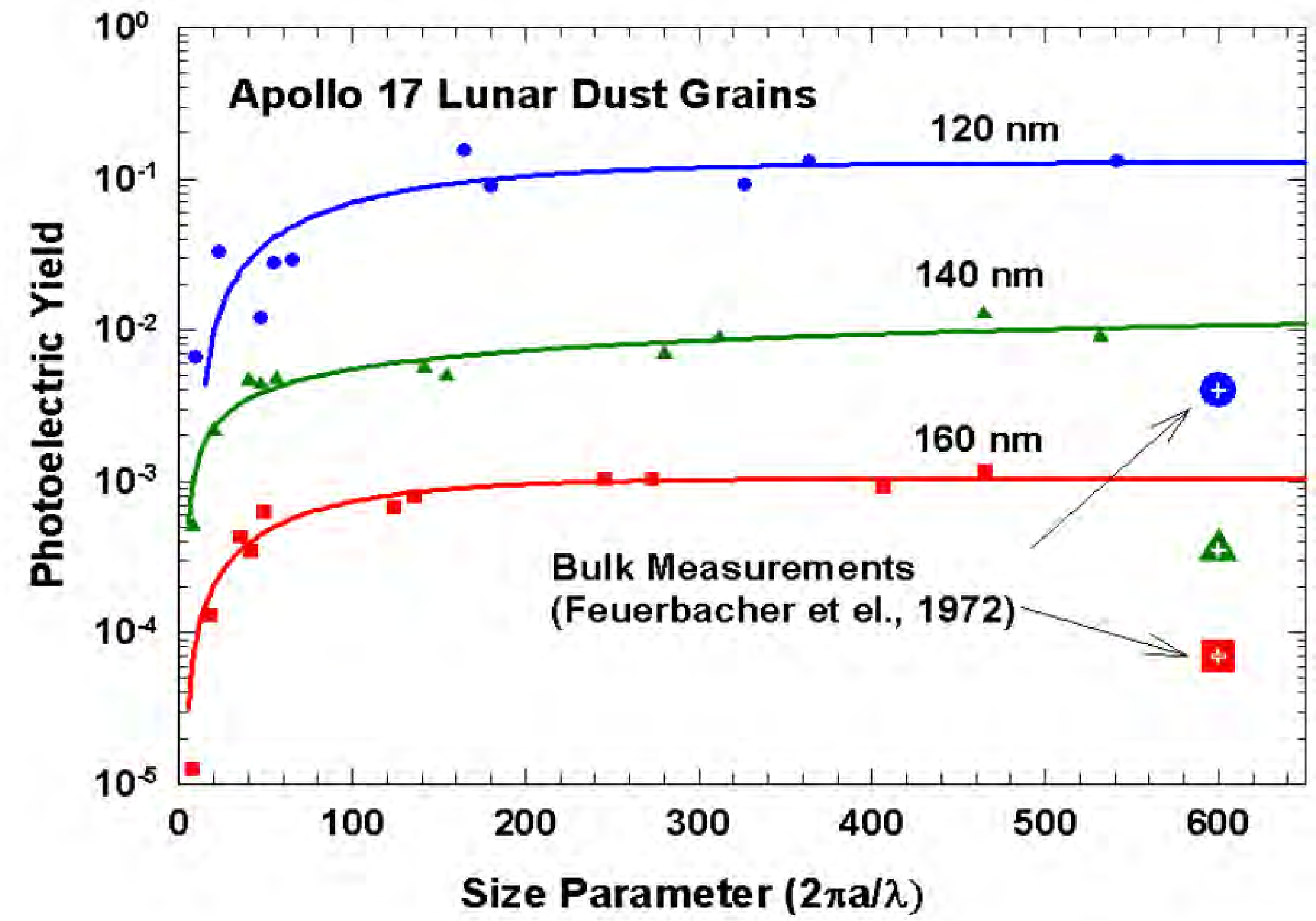
Empirical determinations of η

HOWEVER:

Actual empirical measurements of photoelectric efficiency **η** of actual Apollo 17 regolith demonstrate extreme size dependence at submicricon sizes

Empirical photoelectric efficiencies **η** at submicron sizes range from $\mathbf{10^{-2}}$ to $\mathbf{10^{-5}}$

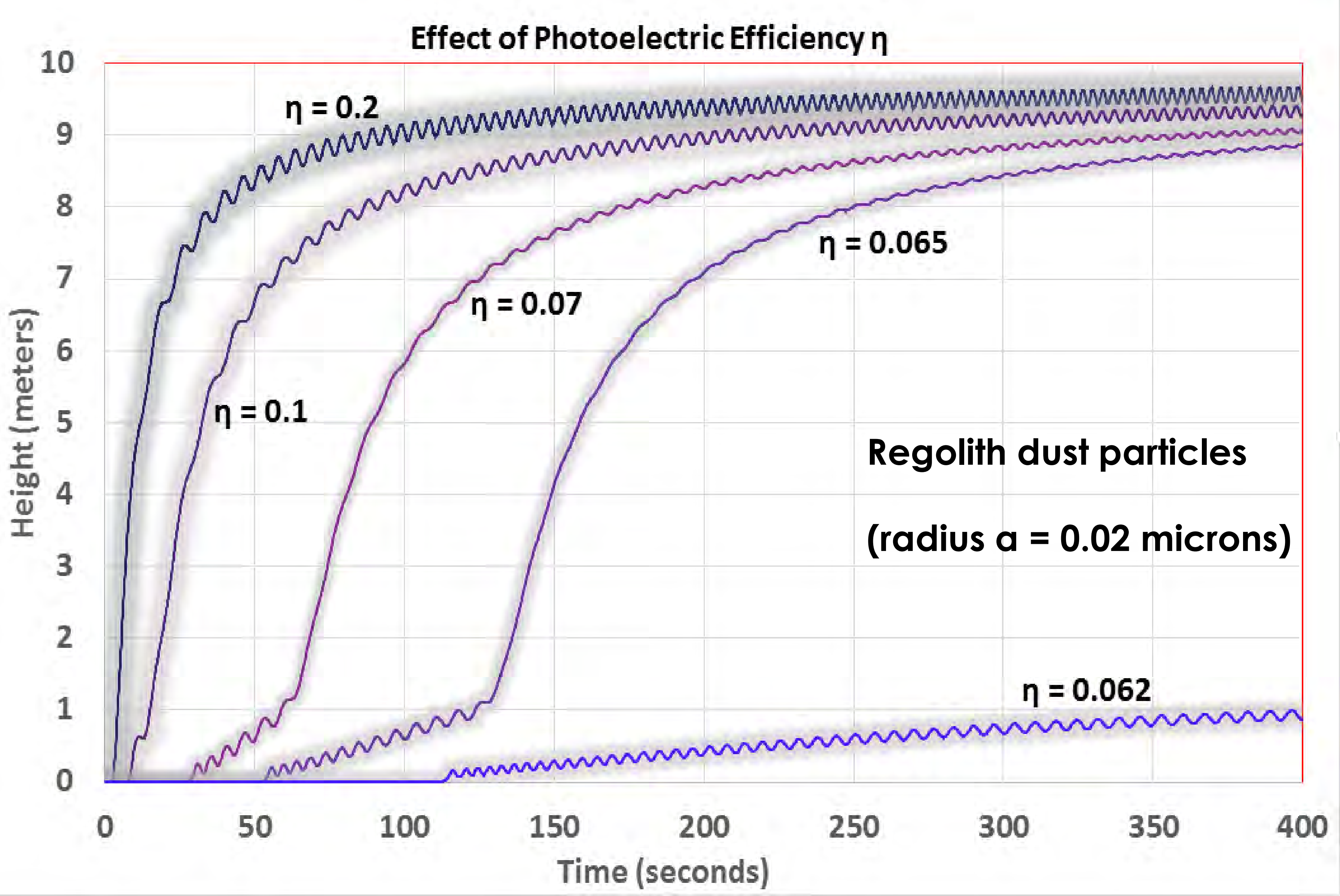
NOT $\mathbf{10^{-1}}$



Source: Abbas et al. (2007)

Levitation ceased when **η** ≤ 0.06

- Simulation reran with more realistic photoelectric efficiencies **η** for regolith dust particles
- Ability to levitate highly dependent on PE **η**
- Ability to levitate ceased altogether when **η** = 0.06 or less
- PE **η** = 0.06 many times higher than 0.01 to 0.00001
- **Therefore, <u>ONLY</u> gold (and other native metals) was able to be levitated at Lunar noontime conditions when realistic PEs used**



Empirical Evidence for Concentration

- LCROSS: A careful study whose surprising results deserve to be taken seriously
- No Eros-like dust ponds on the Moon:
  - Wholesale transport of lunar dust would result in huge polar dust ponds
  - Instead, polar craters tend to have rugged interiors

The Apollo 12 core…

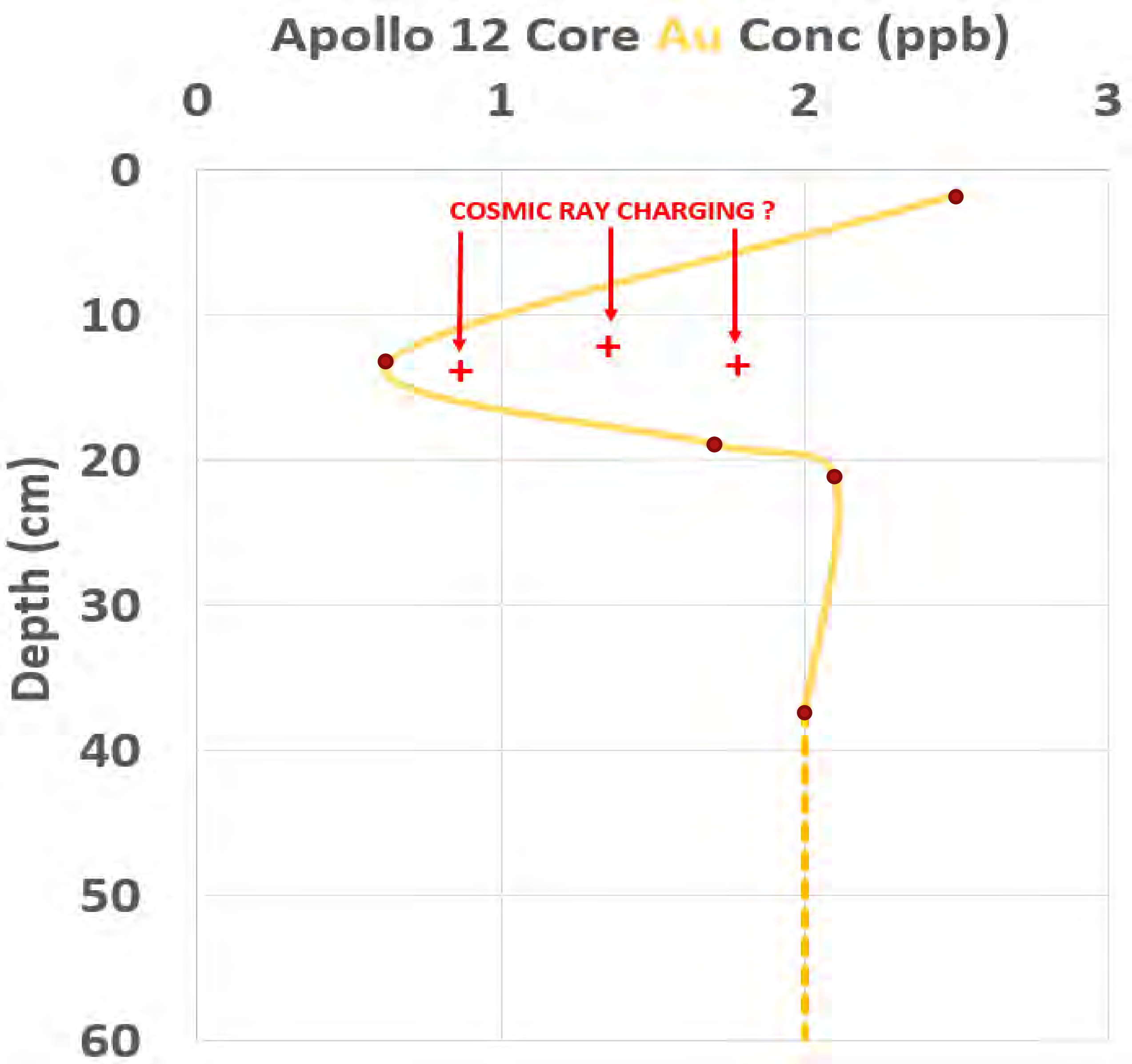
- Top layer enriched: consistent with population of **Au** particles moving about surface

- **Au** depleted in intermediate layer indicating upward movement
- Possibly result of cosmic ray charging
- Lower layers plateau at ~2 ppb

- **Pristine rocks averaged ~5 ppb Au** (crustal average on Earth also ~5 ppb)

- **<u>Thus 3 ppb Au unaccounted for</u>**

- Conservation of matter requires that the gold had to go somewhere….



Back Of The Envelope Calculation:

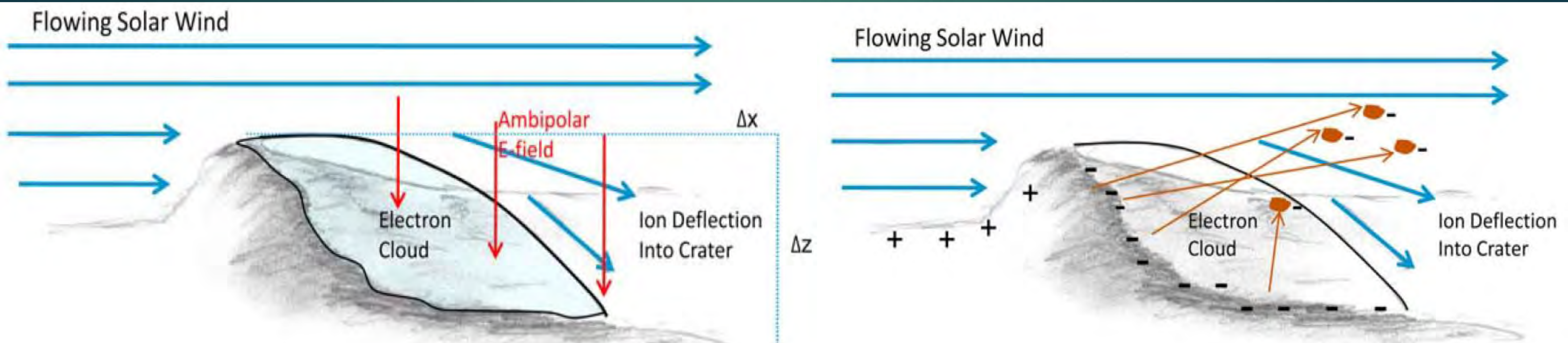
- **Assumptions:**
- Regolith depth in PSRs is basically the same as elsewhere (e.g., no massive dust ponds in polar craters)
- Total area of PSRs is 1/10,000th of Moon's surface area (Reed 1999)
- No **Au** lost to space

▶ 3 ppb x 10,000 = 30 ppm (g/t)

- Assuming 10 m average regolith depth: ~2 million mT **Au** "reserve"
- Total worth **$100 TRILLION** @ $50K/kg

BUT WAIT! THERE'S MORE!

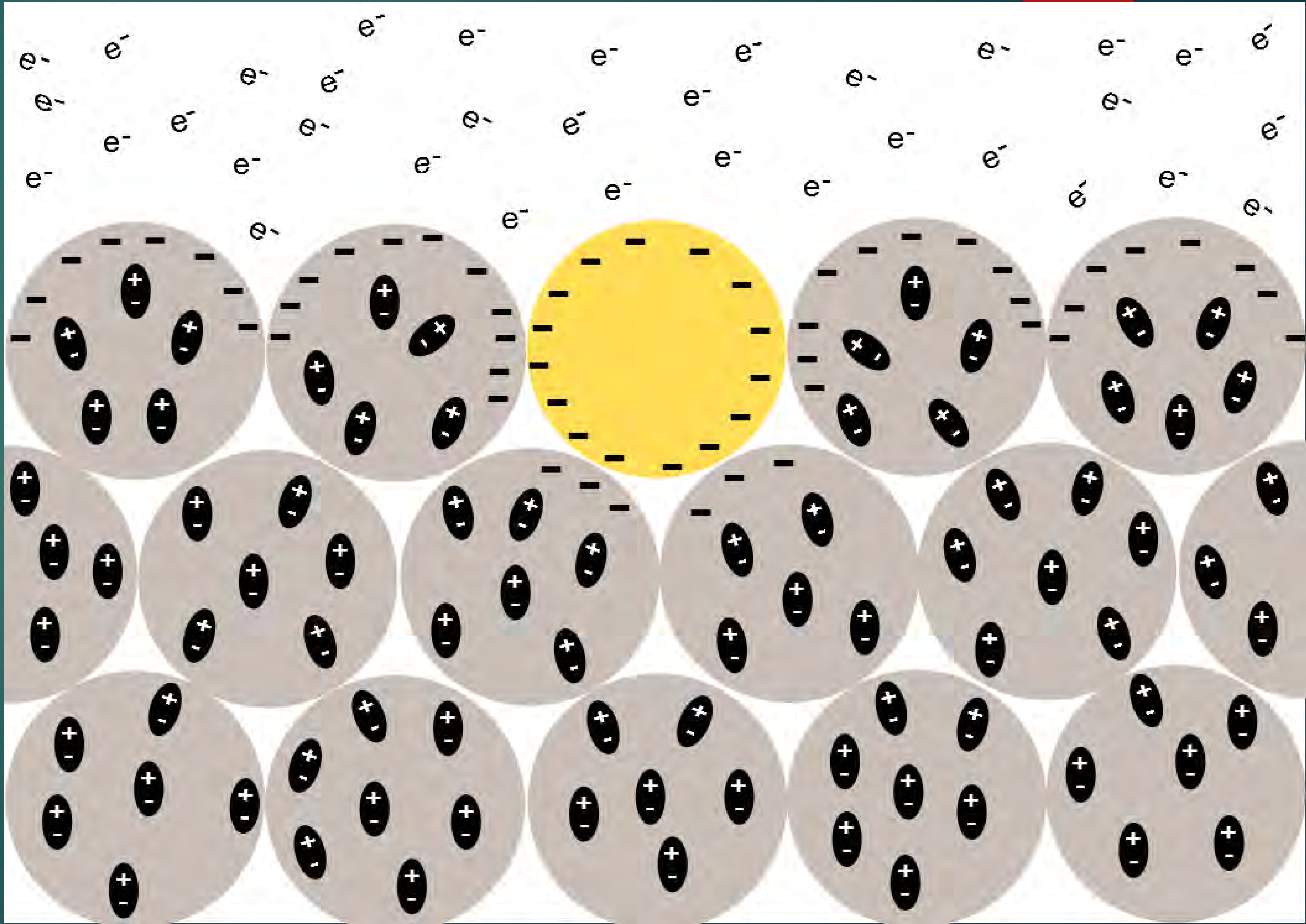
- Farrell et al. (2010) predict that strong ambipolar electric fields will be set up in most PSRs
- High thermal velocity of solar wind electrons cause electron clouds leeward of crater walls
- Charged dust particles may form "current of last resort"
- Deflected ion beams expected to cause sputtering and erosion of volatiles
- It is possible that native metal particles may in fact provide the "current of last resort"
- Small, deep craters < 30 km experience least erosion, thus may be zones of concentration



Source: Farrell et al. (2010)

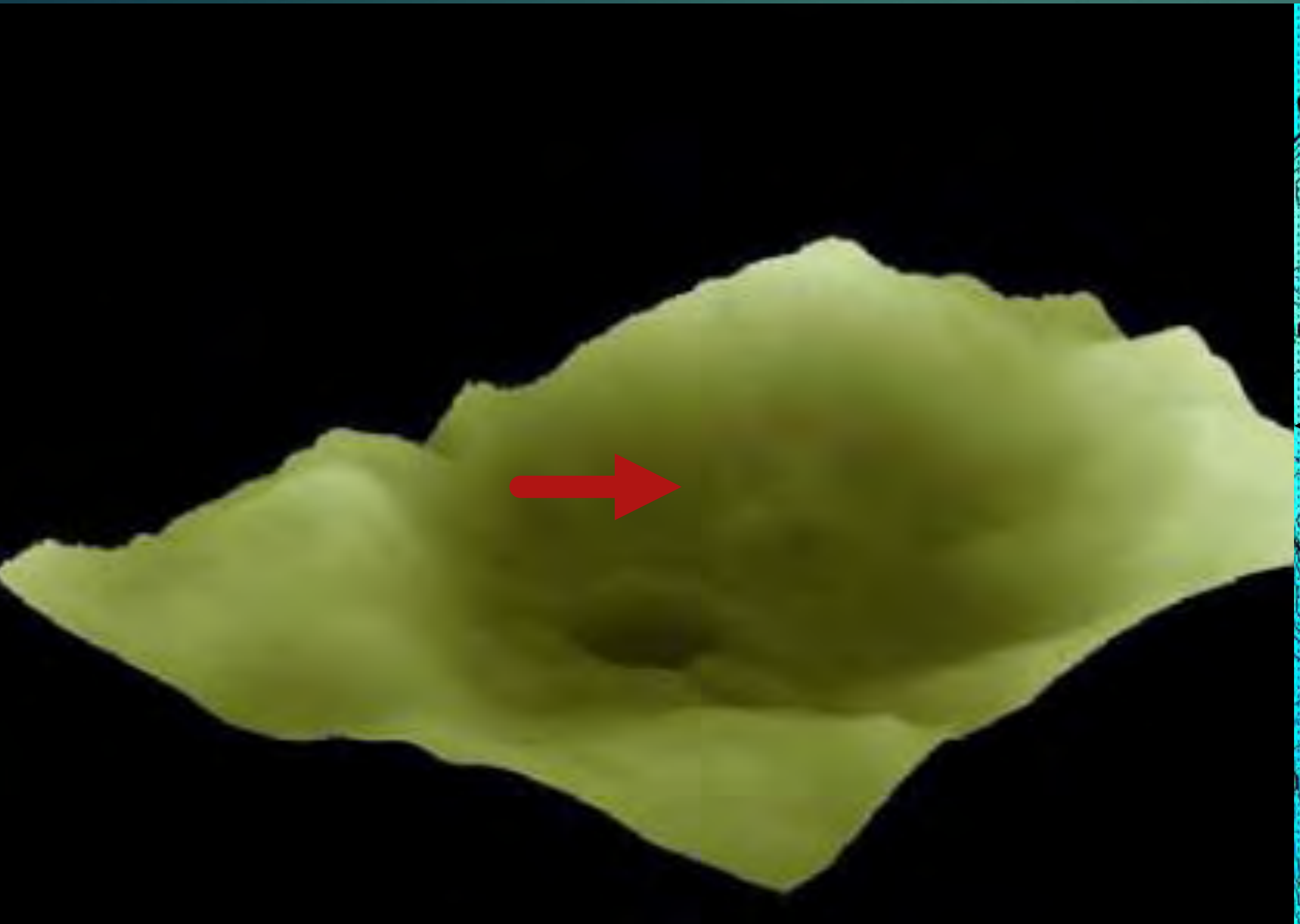
Effect of electron cloud

- Electrons cannot flow through dielectric particles
- Induced polarization will tend to increase adhesive forces
- Lower work function of gold will cause it to donate electrons
- Increased negative local potential will tend to repel gold particles

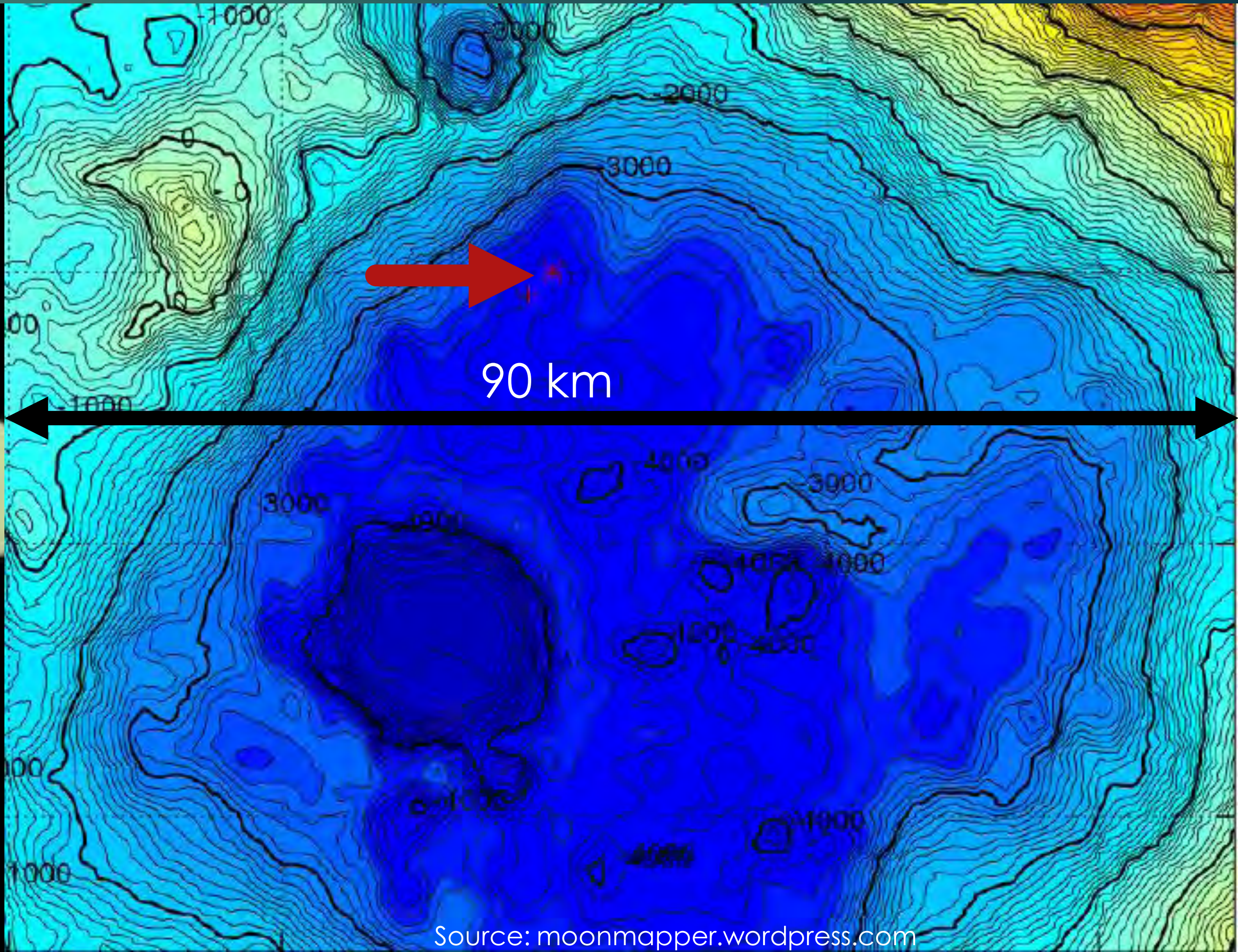


LCROSS site crater within Cabeus Crater

- Smaller subcrater nestled within side of main crater
- Reasonable to expect hyperconcentration to occur



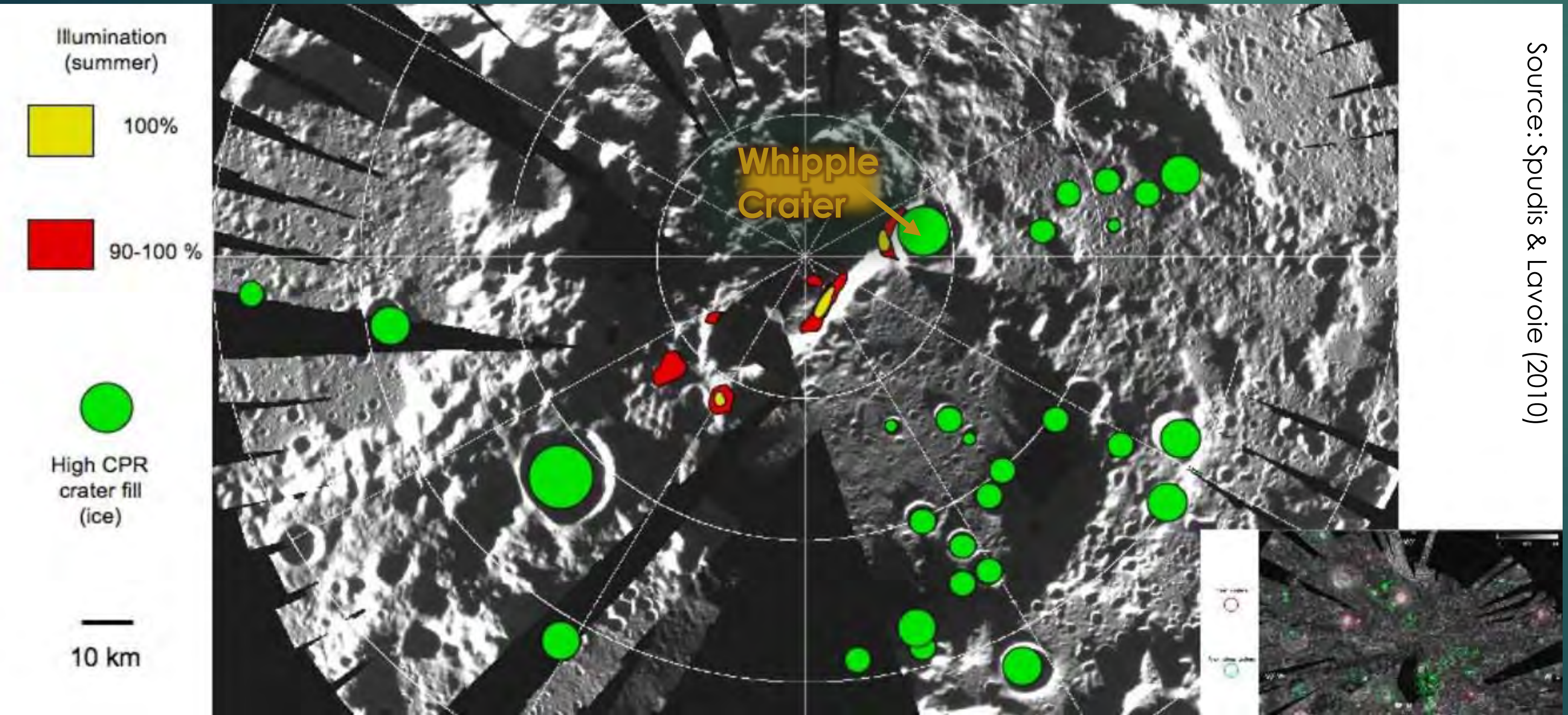
Source: Kozlova & Lazarev (2010)



Source: moonmapper.wordpress.com

Anomalous Craters

- Reported by Spudis et al. (2009)
- High CPR on the inside; Low CPR on the outside
- Thought to represent "relatively pure" ice deposits
- Tend to be small (< 15 km diam.) and relatively deep
- Surrogate for calculating area immune to solar wind wake erosion
- Area of anomalous craters is 1/10th to 1/12th of total PSR area
- Could result in another order of magnitude **Au** concentration **(300 ppm)!**



Source: Spudis & Lavoie (2010)

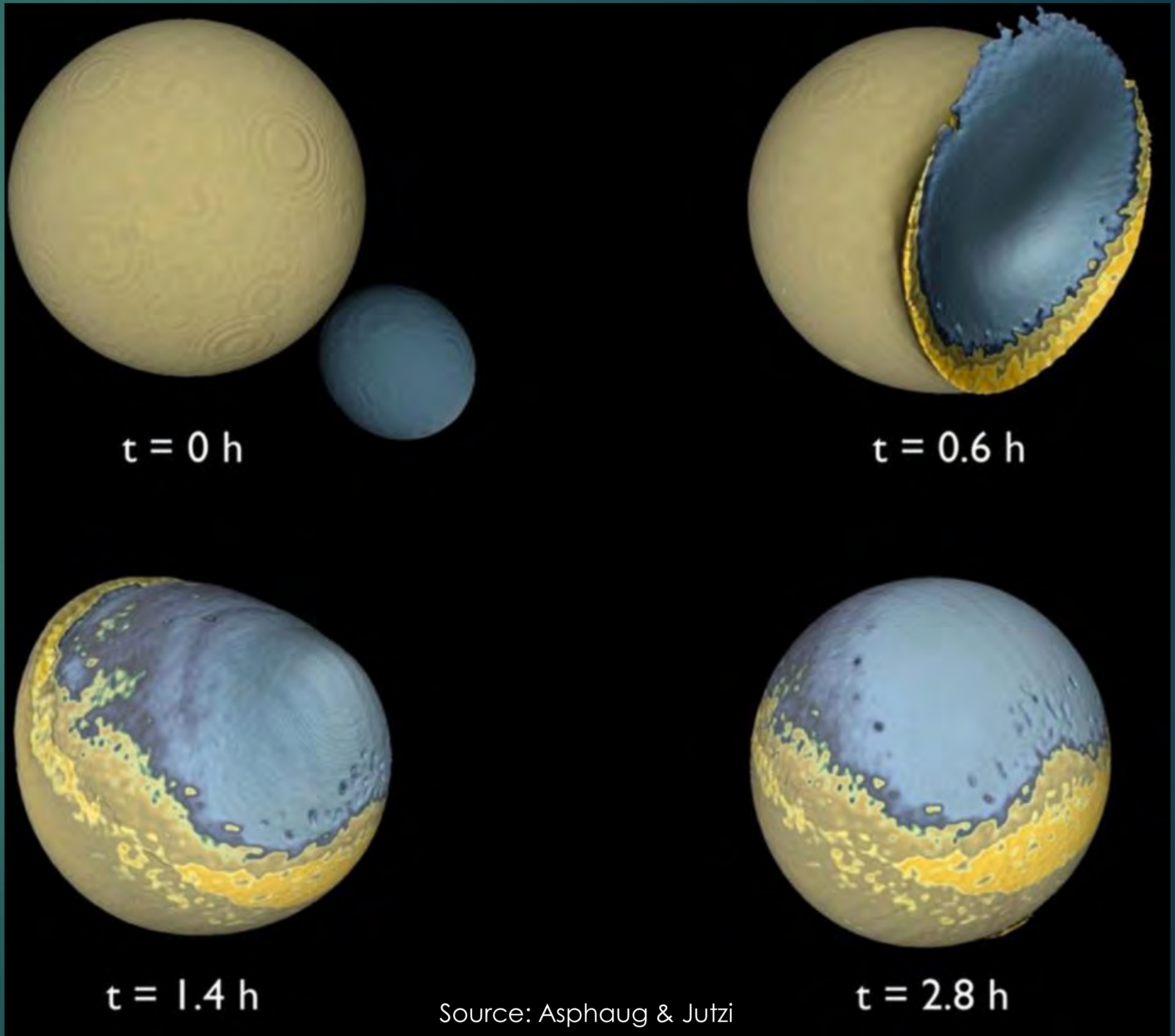
30 ppm

X 10 =

300 ppm

If true, “Big Splat” theory could result in even higher concentrations

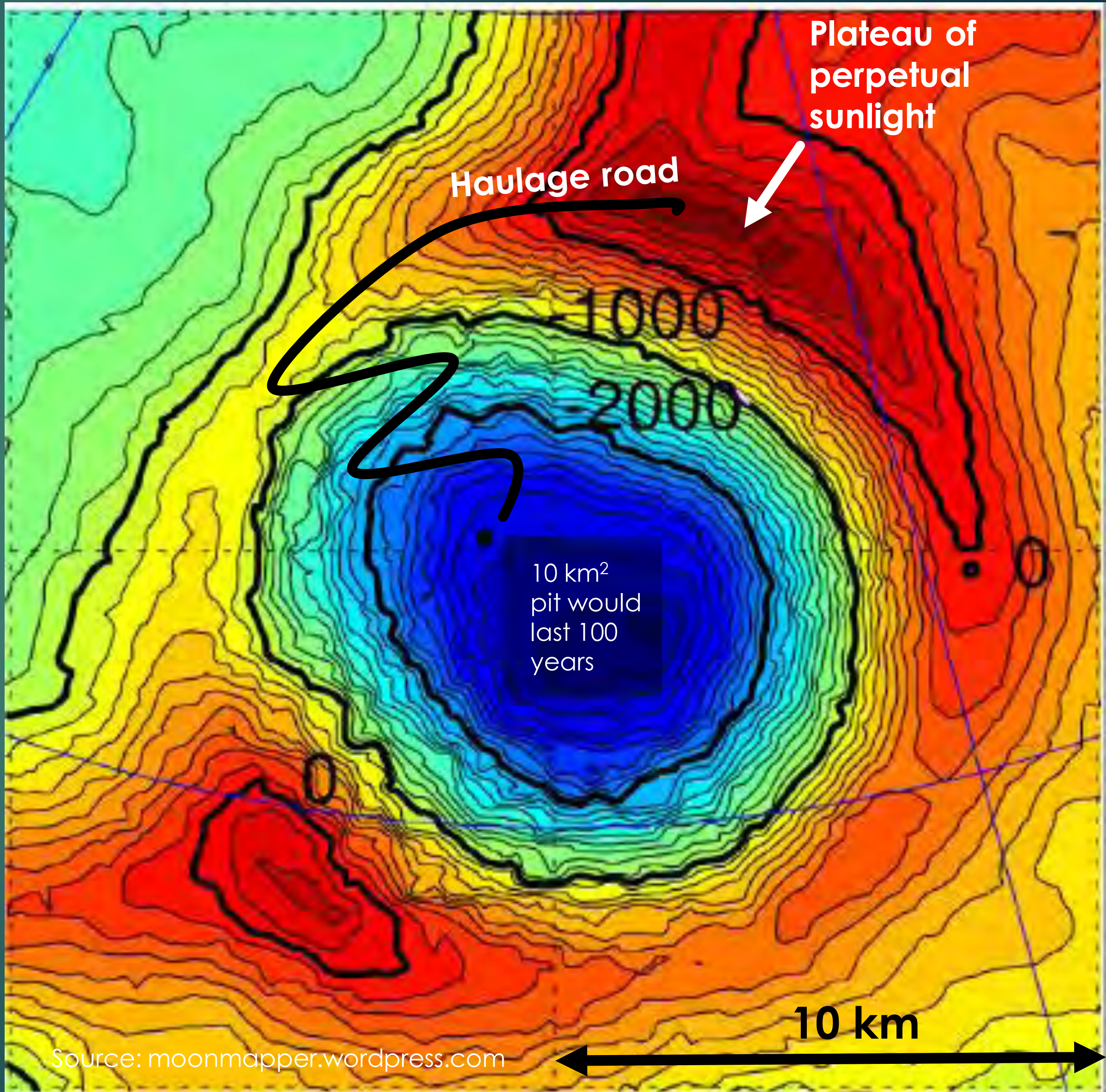
- Theory is that “sister” moonlet formed at same time The Moon
- Moonlet thought to have impacted at low velocity; resulting carapace formed Lunar farside highlands
- Farside has never been sampled for gold
- If impactor happened to have bulk Earth concentration of **Au**, then Lunar concentrations in PSRs would be increased by an order of magnitude



Source: Asphaug & Jutzi

Whipple Crater Mining Project

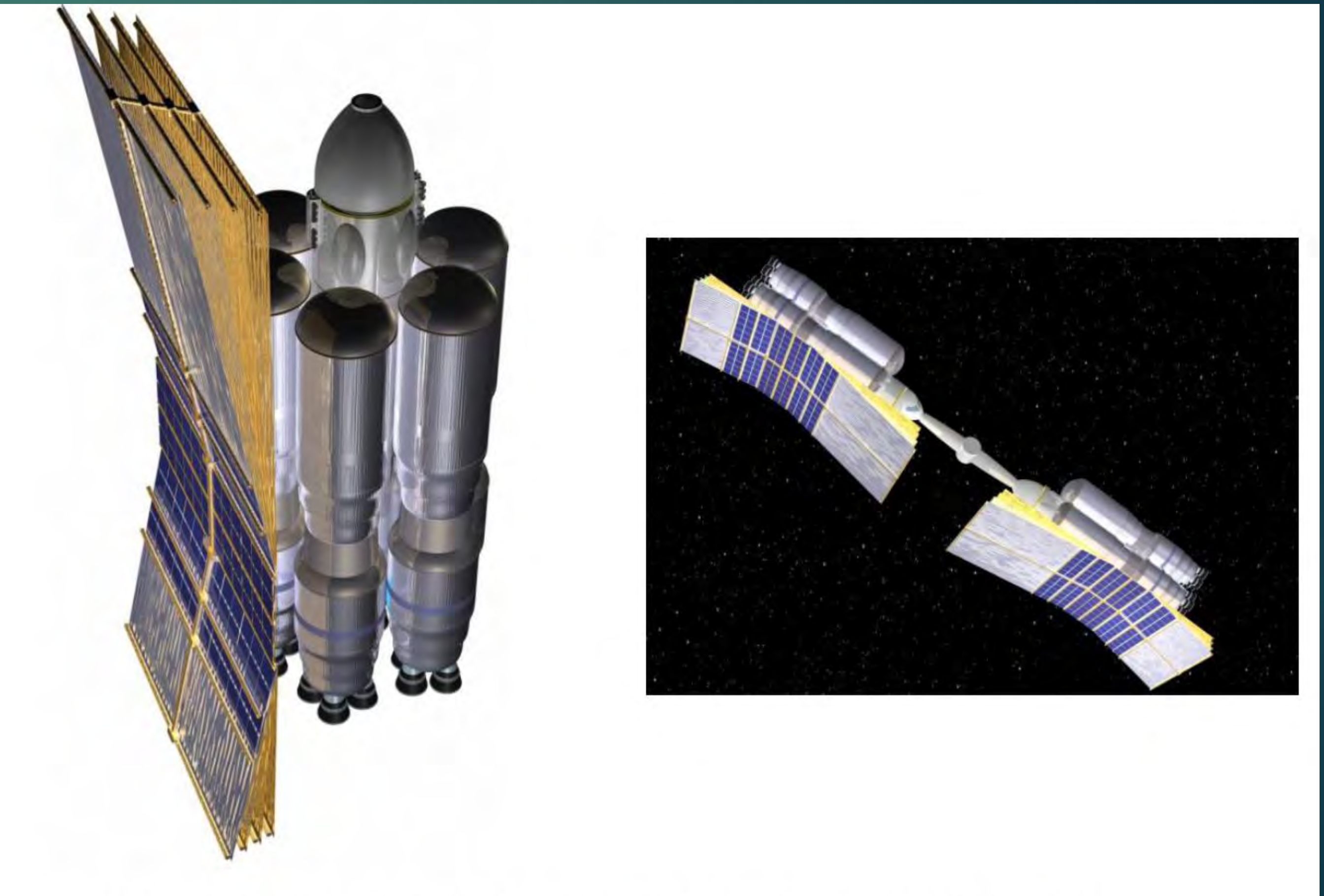
- Propellant required to send back to Earth found in same ore body
- $10B/year requires 200 mT @ $50K/kg
- @ 0.5 kg/mT, 400,000 mT of regolith to be excavated
- 10 hectares/year (2 meter shelf): 10 km^2 pit would last 100 years: **<u>100 years X $10B/year = $1 trillion</u>**
- Down mass to start: 400 to 600 mT
- Power requirements: 10's of megaWatts; SBSP?
- Produced water: 24,000 mT @ 5% concentration
- LH2/LO2: ~13,000 mT/year (mass ratio 5)
- Propellant required for mine: ~5,000 mT/year
- Surplus: 8,000 mT/year LH2/LO2



Surplus propellant secondary revenue stream worth $3B+/year

- 8,000 mT on Lunar surface translates to 3,000 mT surplus at L2 depot
- Would enable "abundant chemical", fully reusable Mars architecture

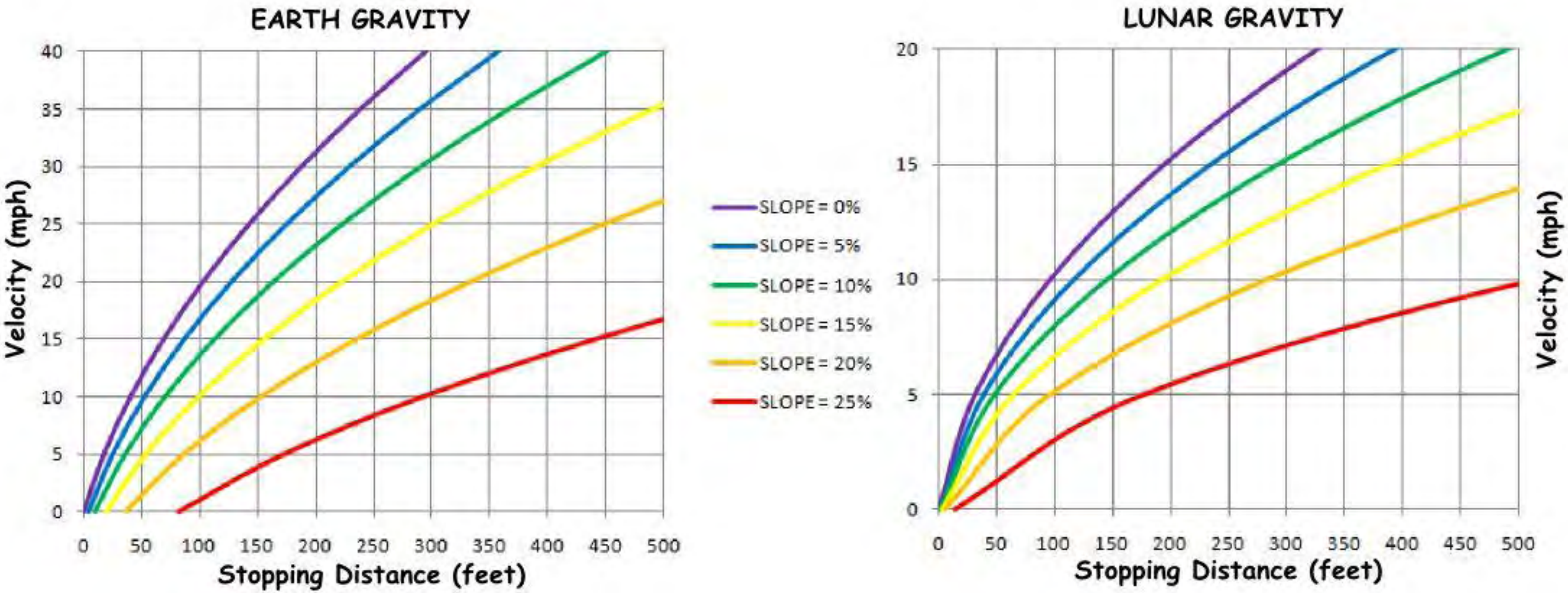
- Fully propulsive, reusable Mars Transfer Vehicle envisioned by ULA engineers
- Would require over 720 mT of LH2/LO2 to fill up
- They propose sending two at a time
- Capable of 11 km/sec delta v
- If refueled in LMO, transit time could be shortened to 90 – 100 days
- LH2 best radiation protection we know



Source Zegler & Kutter (2010)

Figure 7. ACES 121 Depots Clustered for Delivery of 16 Crew Transfer Habitat to Mars.

Lunar Stopping Distances:
Are about twice that on Earth



Excavation / Haulage requirements

- Interesting trade shows that haulage road grade of 20% most efficient time-wise

grade	miles	mph	hr:min
05%	36	14	2:34
10%	18	12	1:30
15%	12	10	1:12
20%	9.0	8.0	1:07
25%	7.2	5.5	1:19
30%	6.0	1.0	5:30

- Excavation rate of 100 m^3 normal for Earth-based equipment
- 2,000 hours of digging required (167 12 hour days)
- 40 mT per load haulage trucks would be doable
- Would take 10,000 truck trips/year
- Would need about 5 40 mT-capacity trucks for a Whipple Crater mine
- Might be better to look for smaller crater for first mine…

Bottom Line:
THERE'S **GOLD** IN THEM THAR CRATERS!!!