李政道研究所
TSUNG-DAO LEE INSTITUTE

Muon Science Frontier and Technological Applications

One particle, two industries, three numbers

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High Energy Physics and Astrophysics
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How this lecture works

I will stop six times. Each time, you answer before I do.

You will be wrong at least twice. That is the design — a question everyone gets right has taught nobody anything.

Nothing here is graded. I will not call on anyone by name, and I will never ask anyone to speak to the room unless they want to.

All I need is that you commit to an answer before you hear mine. Guessing — on purpose, in public, badly — is how you find out what you actually believe.

THE RITUAL

1 VOTE

Select/calculate your answer. Keep it to yourself for now.

2 PAIR

60 seconds with one neighbour. Argue.

3 VOTE AGAIN

Change your mind if they convinced you.

4 THEN I ANSWER

And you find out who moved.

STOP 1 · NO PHONES

First, a number to hold

How many cosmic muons pass through your body every second?

You get one fact and your own body. Work it out with the person beside you.
I want an order of magnitude, not a calculation.

```
At sea level:   ≈ 1 muon per cm²  per minute
You:            ≈  ?  cm²  facing the sky
```

60

SECONDS

PAIR

ESTIMATE

COMMIT

THE ANSWER

About ten. Every second. Always.

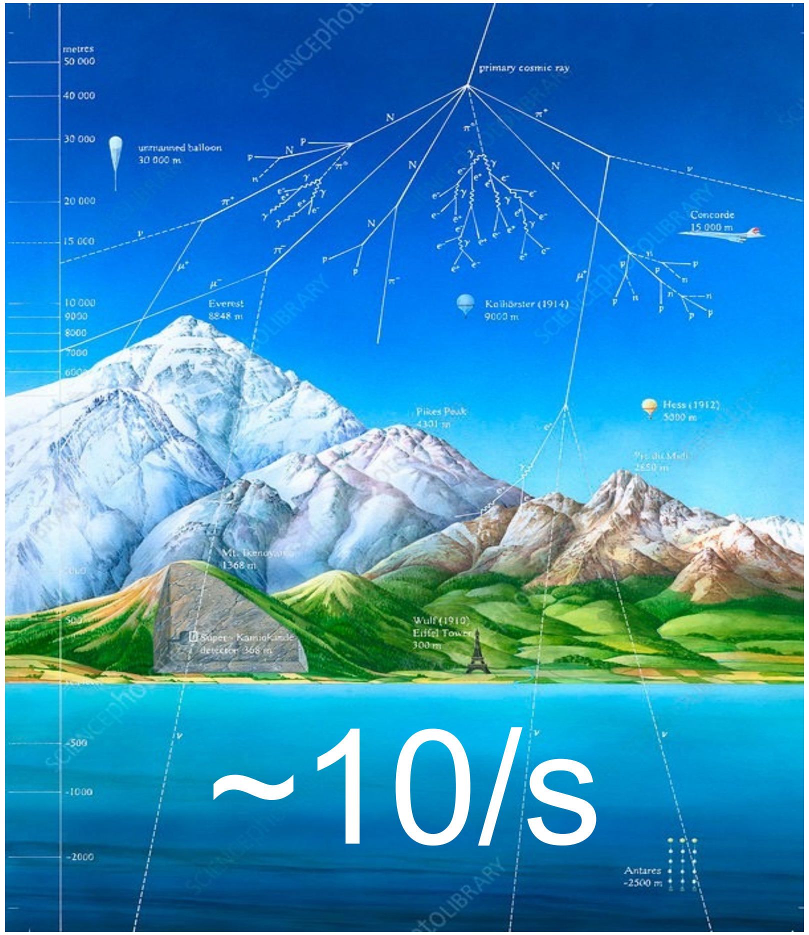
$$1/\text{cm}^2/\text{min} \times 600\ \text{cm}^2 \approx 600/\text{min}$$
$$\approx 10/\text{second}$$

- **Two facts, no detector, ninety seconds.**

Nobody here could have looked that up faster than they just estimated it. That is the skill — not the muon.

- **And they should not be here at all.** In 2.2 μs even light travels 660 m. They are born ~10 km up. Only time dilation gets them down: every muon is a relativity experiment.

Free, everywhere, unstoppable.
That is the whole business case for muography.



A cosmic-ray air shower. The source is the sky, and nobody has to pay for it.

Where we are going

I

The particle

Three numbers that decide everything a muon can do.

II

The instrument

Detectors — and the equation that sets your budget.

III

Seeing inside

Muography, MIXE, μSR, and a fusion that doesn't pay.

IV

The frontier

g−2, and the anomaly that vanished.

Five more stops. One of them puts you on your feet, and the last one is the most interesting thing that has happened in this field in twenty years.

The muon particle

Three numbers, and what each one buys

The muon in four numbers

MASS	LIFETIME	SPIN & CHARGE	g-FACTOR
105.66	**2.1970**	**½ , ±e**	**2.00233….**
MeV/c^2 · ~207 m_e	**microseconds**	**a spin-½ lepton**	**not quite 2 …**
Penetration through rock — and sensitivity to new physics that goes as mass².	Long enough to steer, store, implant. Short enough to watch it decay.	The decay points along the spin. The muon reports its own state.	One number containing every quantum fluctuation there is.

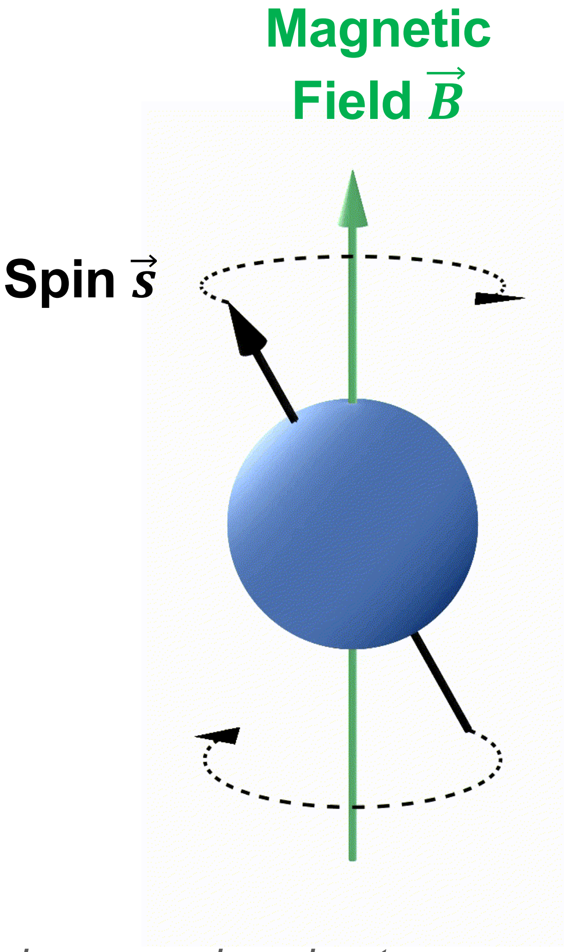
Do not memorise this. Just notice that the mass column does most of the work — and hold on to it, because you will need it twice today.

PDG values; a_μ from the Muon g−2 Collaboration final result (2025).

Three numbers, three capabilities

- **Heavy — 207×.** It punches through hundreds of metres of rock. And it is $207^2 \approx 43{,}000\times$ more sensitive to heavy new physics than the electron.
- **Long-lived — 2.2 μs.** Long enough to make a beam, bend it, store it, implant it. Short enough that the whole decay fits in your data.
- **It reports back.** The decay is parity-violating: the positron comes out along the spin. The muon tells you its own state — no external polarimeter, ever.

Everything else today
is one of these three properties, put to work.



Spin precessing about a magnetic field — the readout behind both μSR and g−2.

The made beam

- **Protons on a target, and you harvest the pions' children.**

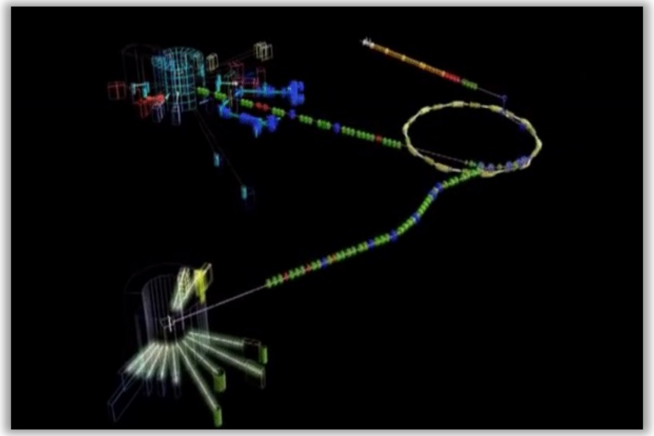
Surface muons — from π^+ decaying at rest in the target skin — come out ~100 % spin-polarised at 29.8 MeV/c, and stop inside a thin sample.

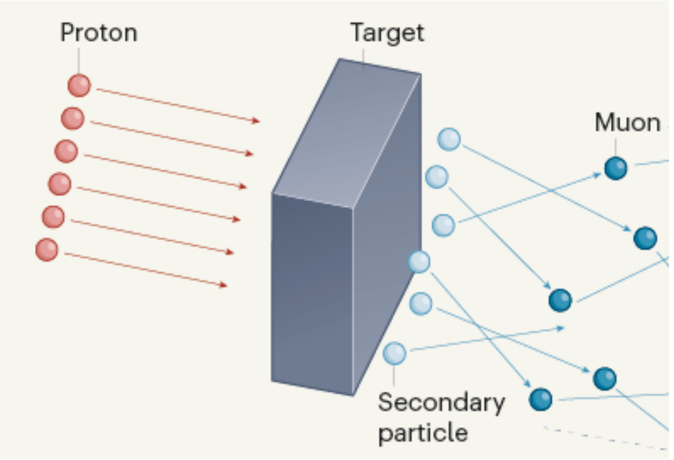
- **Nobody engineered that polarisation.**

It falls straight out of parity violation. It is a gift, and it is the reason μSR and g−2 exist at all.

> **Cosmic muons are free but faint.**
> An accelerator costs you a facility and buys you intensity, timing and polarisation. Which you need depends entirely on what you are trying to see.

Learn from the Nature





Natural and artificial production — protons make pions, and the pions hand you muons.

The instrument

From here on, you are the engineer

What a muon detector has to do

- **Track it.** Two positions give the direction. Your angular resolution is your image resolution — nothing downstream can recover it.
- **Time it.** Nanoseconds. Coincidence is what kills the real enemy: accidentals, and muons arriving from the wrong side.

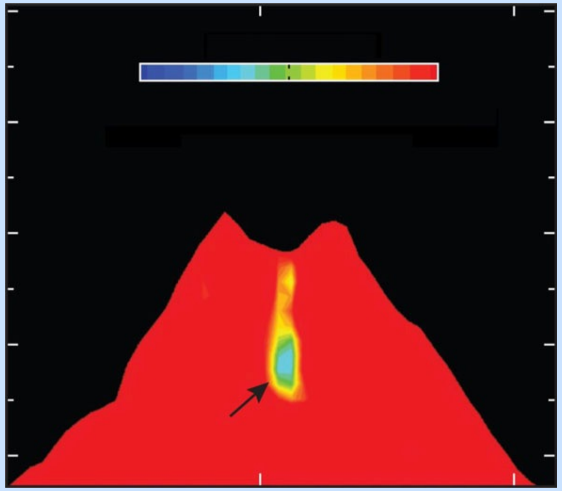
And notice what is NOT on that list.
Speed. A 1 m² telescope sees about ten muons a second. Muon detectors are never rate-limited — they are limited by staying alive, and staying calibrated, for months.

Wilson's cloud chamber, 1911. From this to a SiPM array, the job has never changed: make the muon leave a mark you can read.

You are the engineer

A volcano observatory wants its magma conduit imaged.

Your detector sits in a hut on the flank for eight months. No mains power, no road, and nobody goes up there in winter. Which technology do you take?



- **A** Nuclear emulsion — sub-micron resolution. No power at all.
- **B** Gas RPC — 0.1 mm resolution. Needs high voltage and a gas bottle.
- **C** Scintillator + SiPM — 10 mm resolution. A few watts.
- **D** Whichever is cheapest per square metre.

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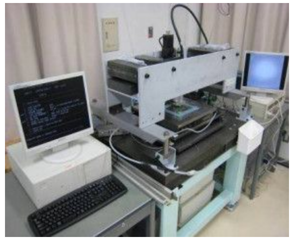
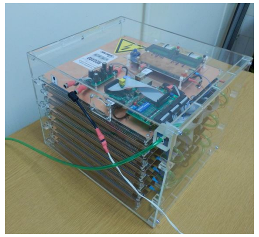
SECONDS

VOTE

PAIR

VOTE AGAIN

Choose for the environment


	NUCLEAR EMULSION	GAS RPC / MPGD	SCINTILLATOR + SiPM	DRIFT TUBES
RESOLUTION	< 1 µm	0.1 – 1 mm	**5 – 20 mm**	~1 mm
TIMING	none	~1 ns	**~1 ns**	~ns
SERVICES	no power at all	HV + gas supply	a few watts	HV + gas
WHERE IT WINS	Pyramids — but offline	Large area, high resolution	Rugged, real-time, unattended	Scattering muography, cargo

A had the best resolution and needed no power — and it is what ScanPyramids used (1/3).
It loses on a volcano application because it has no clock, and no data until somebody goes there.

STOP 3

How long is the campaign?

A mining company suspects a void 100 m under rock.

They want it confirmed. Your detector is 1 m^2. You need 1 % statistical uncertainty in the direction that matters. How long do you sit there?

A A weekend.

B Two weeks.

C Four months.

D Ten years.

60

SECONDS

VOTE

PAIR

VOTE AGAIN

Statistics is the schedule

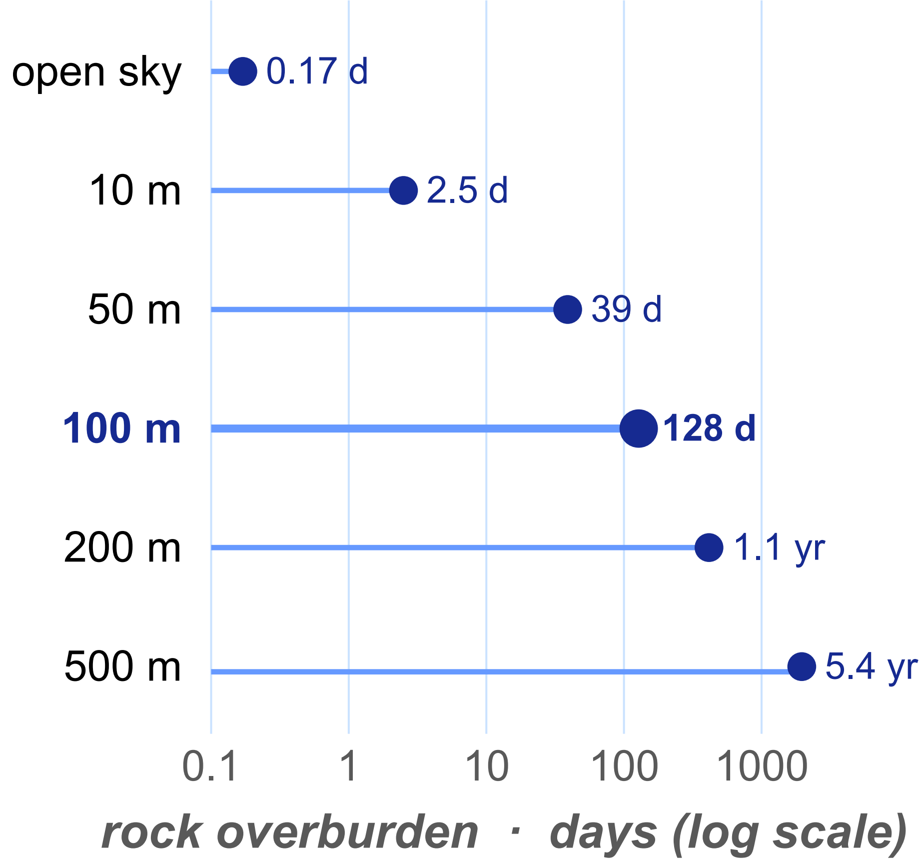
$N = \Phi(>E_{min}) \cdot A \cdot \Omega \cdot t$

$\Phi(>E) \propto E^{-1.7}$ $E_{min} \approx 0.5$ GeV/m of rock

Now the real question.
Your client will only pay for three weeks. What do you change? Thirty seconds, with your neighbour.

You cannot touch Φ.
The sky is not negotiable. You have A, Ω and t — so you buy area, or you accept a coarser pixel. That is the economics of this industry.

DAYS OF EXPOSURE FOR 1 % STATISTICS IN ONE PIXEL



Order of magnitude: $I(>E) \propto E^{-1.7}$, E_min ≈ 0.5 GeV per metre of standard rock, 1 m^2 detector, 10 msr pixel, 10^4 muons for 1 %.

Seeing inside

And one experiment that found nothing

Two ways to image with a muon

TRANSMISSION

Count the survivors.

Contrast comes from absorption: thick, dense rock removes muons. One detector, under or beside the object.

Pyramids, volcanoes, tunnels, blast furnaces, ore bodies.

SCATTERING

Measure the deflection.

Multiple scattering grows with Z, so uranium and lead scream out of a steel background. Needs detectors on both sides.

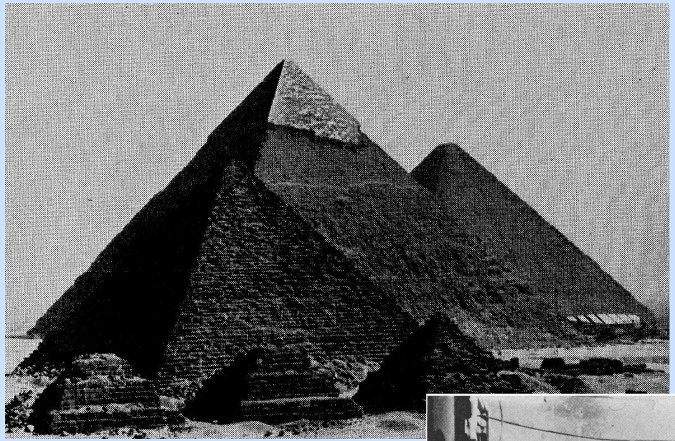
Cargo, casks, and the fuel debris at Fukushima.

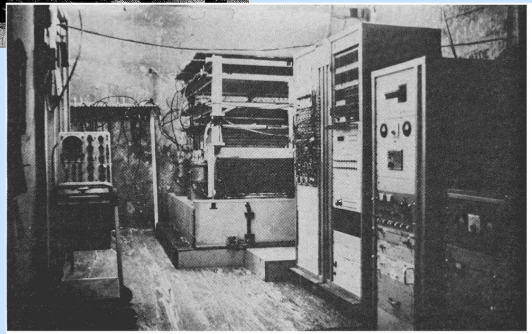
$$\theta_0 \approx (13.6\ \text{MeV} / \beta c p) \cdot \sqrt{(x / X_0)}$$

The scattering angle is the fingerprint

One is a shadow. The other is a fingerprint. Transmission tells you how much; scattering tells you what.

Was it a wasted experiment?





1969. Alvarez puts spark chambers under the Pyramid of Chephren.

He is hunting for a hidden burial chamber. After months of running, he finds none. Nothing. An empty result.

L. W. Alvarez et al. Science 167 (1970) 832

↑ STAND UP — it was worth doing.

• STAY SEATED — it wasted a Nobel laureate's time.

30

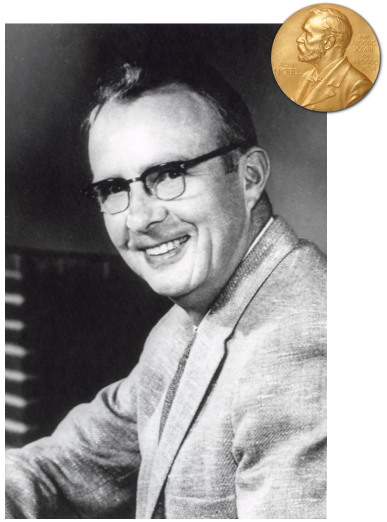
SECONDS EACH

STAND OR SIT

FIND SOMEONE

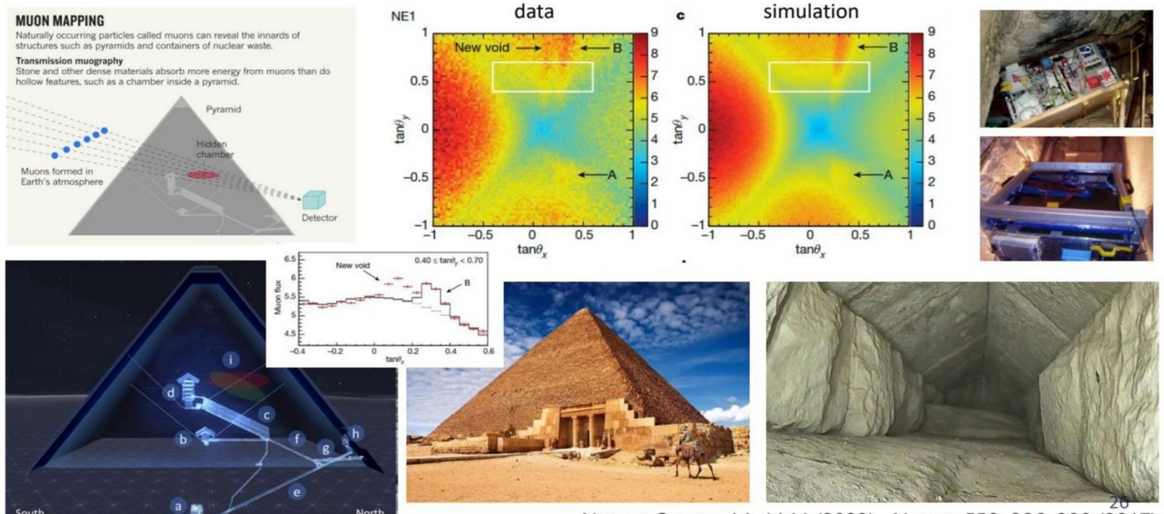
WHO DID NOT

He did not find nothing



Alvarez, 1969.

He established, to his sensitivity, that there was no chamber in the volume he scanned. That is not nothing. A limit is a measurement.



Nature Comm. 14, 1144 (2023) , Nature 552, 386–390 (2017)

ScanPyramids, 2017.

Three independent technologies, one excess above the Grand Gallery of Khufu. A void of at least 30 m. Same physics — a better instrument.

One more, for the walk home:

"no signal" and "no sensitivity" look identical in the data. How would you tell them apart?

He did not find nothing

Chephren pyramid: Finding something in finding nothing

The Quick Study by Giulio Saracino and Cristina Cârloganu (PHYSICS TODAY, December 2012, page 60) correctly identifies Luis Alvarez and collaborators as the first to use cosmic-ray muons to explore terrestrial structures by constructing a muon telescope in the Chephren pyramid's Belzoni chamber to search for undiscovered chambers. However, the authors' statement that Alvarez and coworkers "found nothing" is incorrect. What the Alvarez team found was that there were no undiscovered chambers. That is a distinction with a difference.

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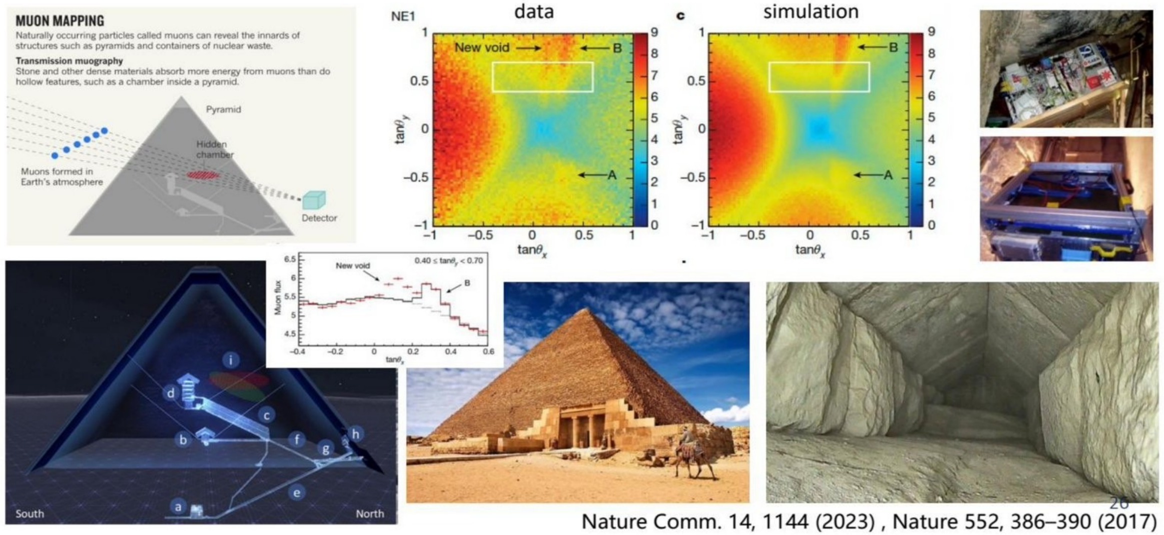


Nature Comm. 14, 1144 (2023) , Nature 552, 386–390 (2017)

ScanPyramids. 2017.

/e the Grand Gallery
a better instrument.

ı apart?

Where muography earns its keep

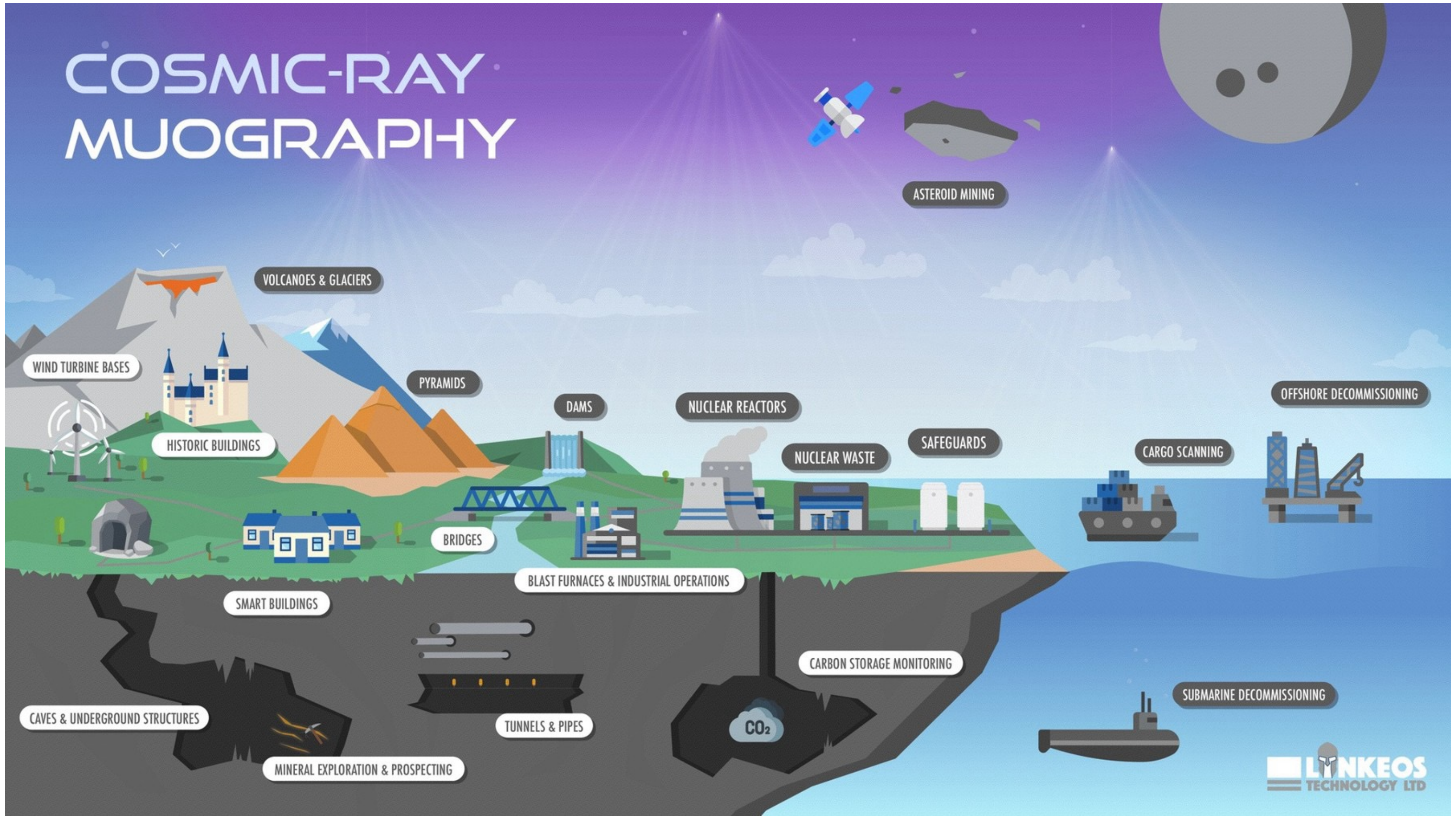
Volcanoes
Magma conduits, eruption forecasting

Nuclear
Fukushima fuel debris, waste casks

Heavy industry
Blast furnaces — BLEMAB, ArcelorMittal

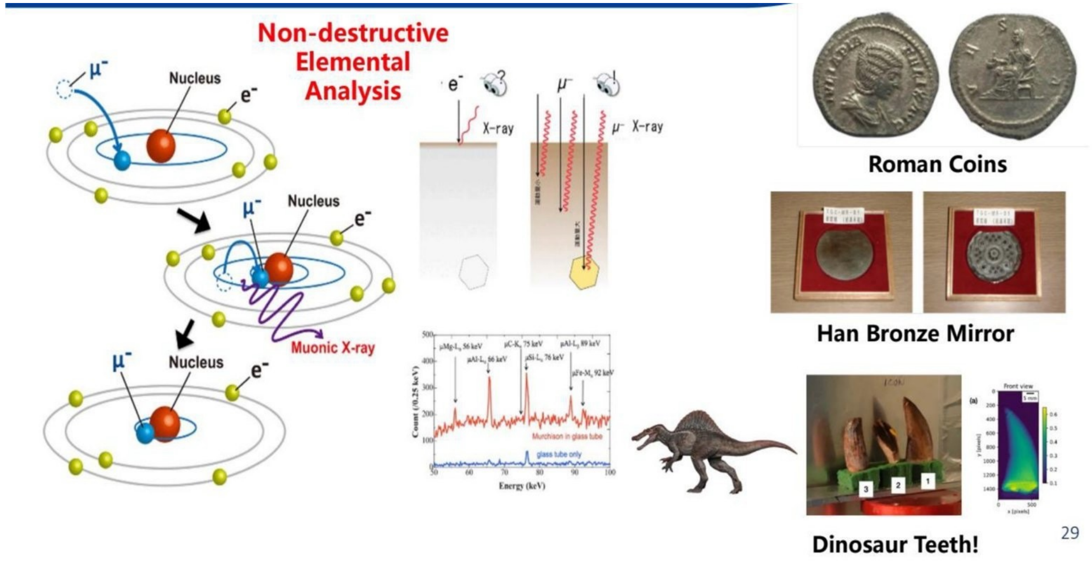
Mining
Ore bodies under thick cover

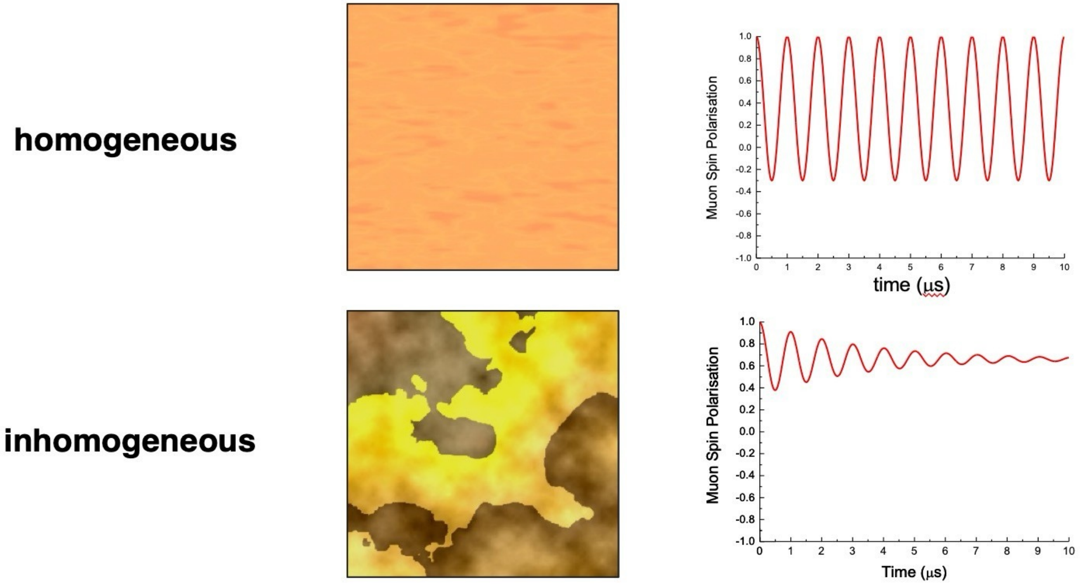
Civil & heritage
Tunnels, dams, voids under roads



Tanaka et al., Nature Rev. Methods Primers (2023) · Procureur et al., Sci. Adv. 9, eabq8431 (2023) · Muographers 2026.

Two more instruments, one trick





MIXE — what is it made of?

Stop a negative muon and it cascades into a muonic atom, emitting X-rays unique to each element — 200× more energetic, so they escape from deep inside. Tune the momentum, tune the depth. Roman coins, Han bronzes, working batteries.

μSR — a magnetometer inside the sample

Implant a polarised muon; its spin precesses in the local field; the decay positron reports where the spin was pointing. A uniform field gives clean oscillations; a disordered one damps them. The shape IS the magnetic order.

Both of these are the third bullet from slide 8, cashed in. The muon reports its own state.

Kill it, or fund it

Muon-catalysed fusion is real, and it runs at room temperature.

The nuclei sit 200× closer and tunnel straight through the barrier.
Three numbers — does it power your home?

```
one muon catalyses       ≈ 150 fusions
each fusion releases     =  17.6 MeV
making one muon costs    ≈    5 GeV
```

60

SECONDS

MULTIPLY

COMPARE

DECIDE

You just killed a technology

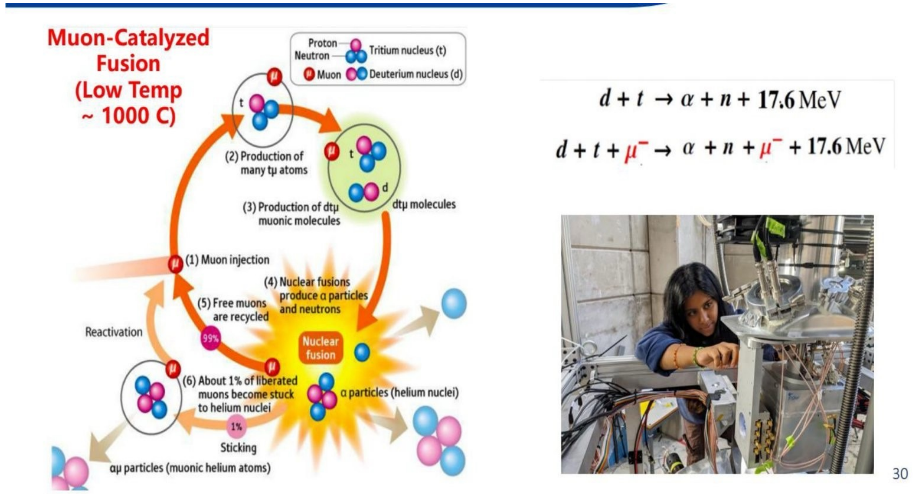
150 × 17.6 MeV		≈	2.6 GeV	out
one muon		≈	5.0 GeV	in

- **It fails by a factor of two.**

Break-even needs ~300 fusions per muon; a real plant needs closer to 900. The muon sticks to the helium about 1 % of the time, and that is what caps it.

- **Nobody has closed that gap in fifty years.** Not for want of trying, and not because the physics is wrong.

Do this arithmetic before you write the grant,
not after.



The muon-catalysed fusion cycle. Everything works except the balance sheet.

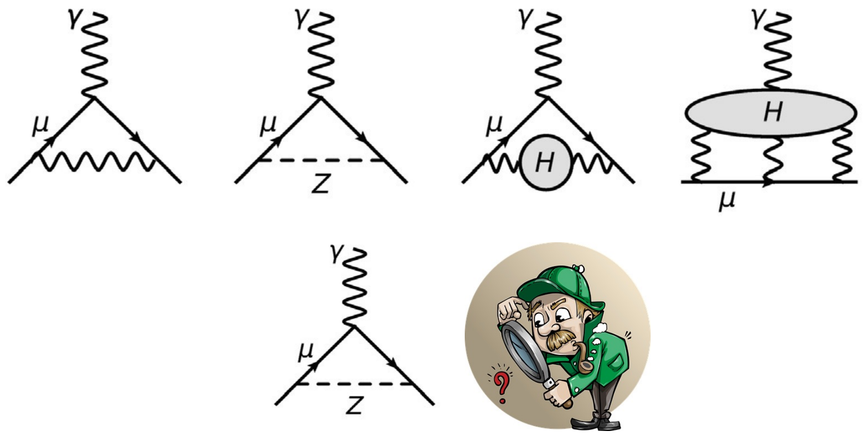
The frontier

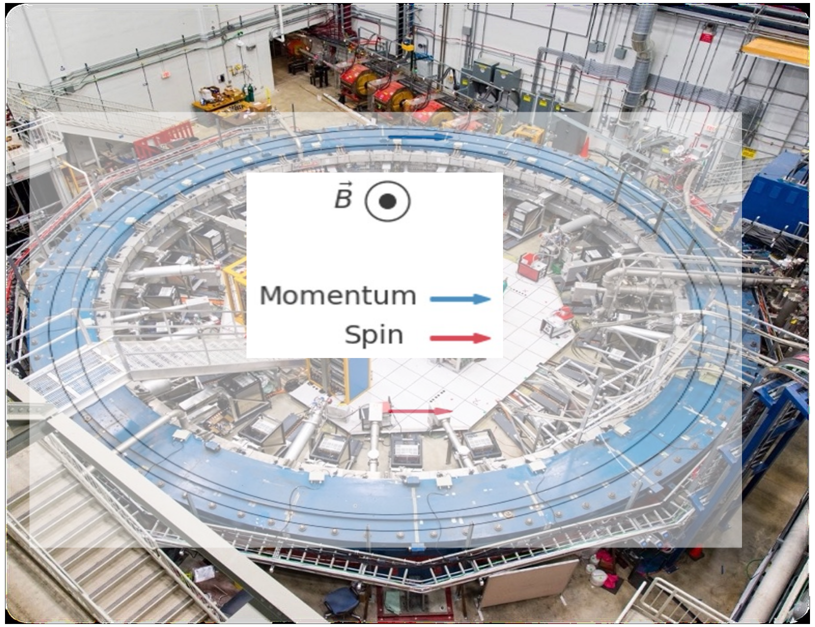
And the anomaly that vanished

What "anomaly" really means

- **Dirac says g = 2, exactly.** But a real muon is never bare. It is dressed in virtual particles, and every one of them nudges g upward.
- **So $a_\mu = (g - 2)/2$ is a census.** Of everything that exists — including whatever we have not found yet. And the muon's 207× mass buys 43,000× the electron's reach.
- **The whole experiment is one frequency.** Store muons in a 14 m ring, watch the spin outrun the momentum, count positrons. Never measure anything but frequency.

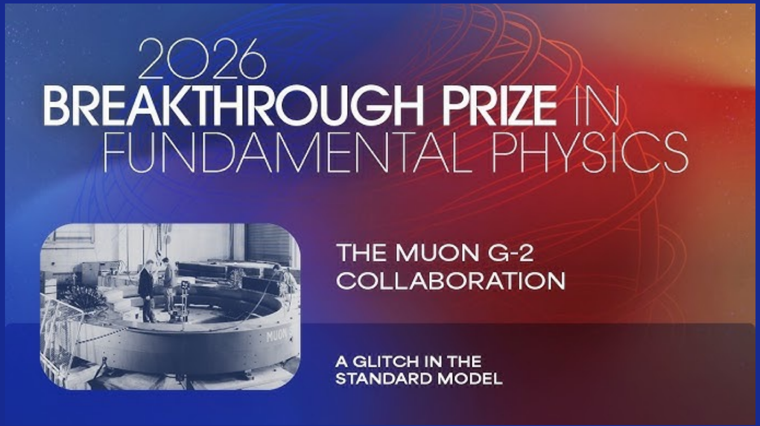
$$\omega_a = \omega_s - \omega_c = a_\mu \cdot e B / m$$





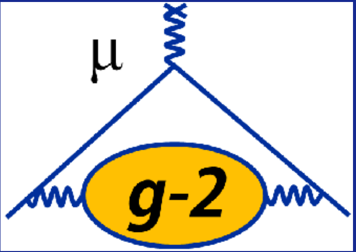
The Fermilab storage ring: 15 m across, 1.45 T, uniform to a few parts per million.

127 parts per billion



FERMILAB MUON g−2, FINAL RESULT · JUNE 2025

$$a_\mu = 0.001\,165\,920\,705\,(148)$$



Six runs. Six years. Four times better than Brookhaven.

98 ppb

statistical

78 ppb

systematic

10^{-10}

the last digit

We know how a muon wobbles in a magnetic field to better than one part in a billion.

(116 592 0705 ± 114 stat ± 91 syst ± 21 ext) × 10^{-11} · Muon g−2 Collaboration, Phys. Rev. Lett. 135, 101802 (2025).

Who was wrong?

2021: the muon g−2 anomaly stands at 4.2σ, and it is on the front page of every newspaper.

2025: it is gone. The experiment never changed its answer. So, who made the mistake?

60

SECONDS

- **A** The experimentalists.
- **B** The theorists.
- **C** Nobody.

VOTE

PAIR

VOTE AGAIN

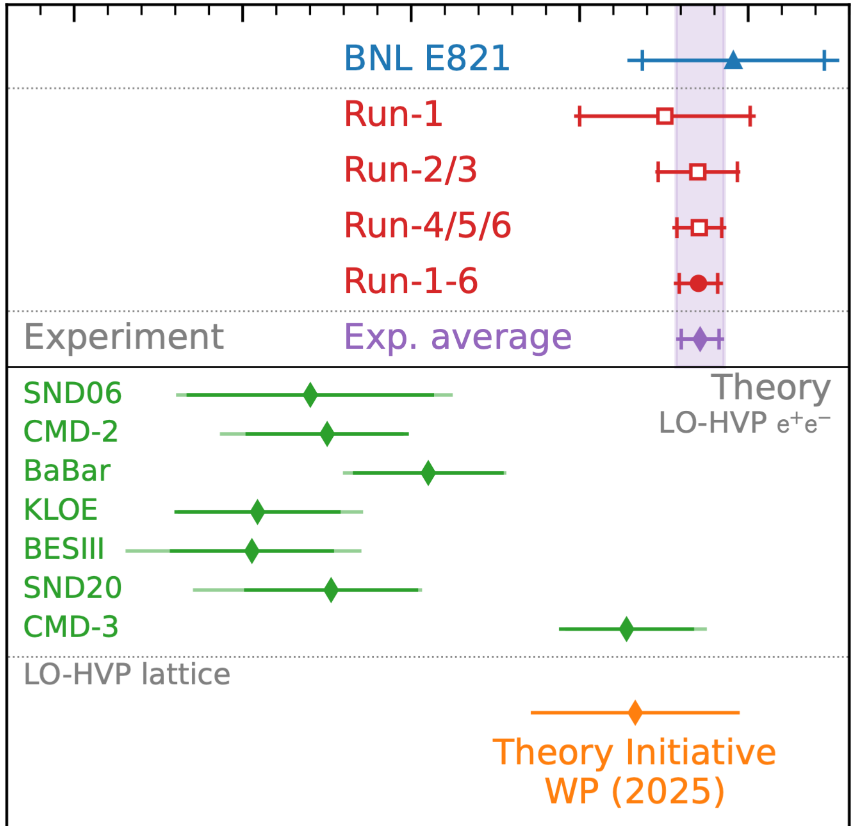
THE ANSWER · C

Nobody was wrong

- **The hadronic term was the hard part.** In 2020 the only way to get it was from $e^+e^- \to$ hadrons data. That is what gave the 4.2σ gap.
- **Then lattice QCD arrived.** BMW computed the same term from first principles, got a larger value, and moved the prediction toward the measurement. The 2025 White Paper now adopts it.
- **The anomaly dissolved because the calculation machinery got better.** That is not a scandal. That is the machine working exactly as designed — and you watched it happen live.

Your headline number is only as good

as the prediction you compare it to.



~ 100 authors
only 188 pages

One particle, two industries

The science frontier wants the muon because it is heavy and long-lived.

207× the electron's mass buys 43,000× the sensitivity to whatever is hiding above the electroweak scale.

The geologist/civil engineer wants the muon because it is free and irreplaceable.

The sky delivers ten thousand per square metre per minute, through concrete, rock and steel, for nothing.

Both run on the same three things:

a source you trust, a detector that survives, and an inference you can defend.

Thank you!

YOU ANSWERED SIX QUESTIONS TODAY. HERE ARE MORE FOR YOU TO EXERCISE.

- "No signal" and "no sensitivity" look identical in the data. How would you tell them apart?
- Which is the harder engineering problem — ten billion muons a second, or a detector that survives six months alone on a volcano?
- Where else could "measure a frequency instead" rescue a hard measurement?

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