Beyond the Standard Model

Symmetry-Magazine

Why is BSM physics interesting?

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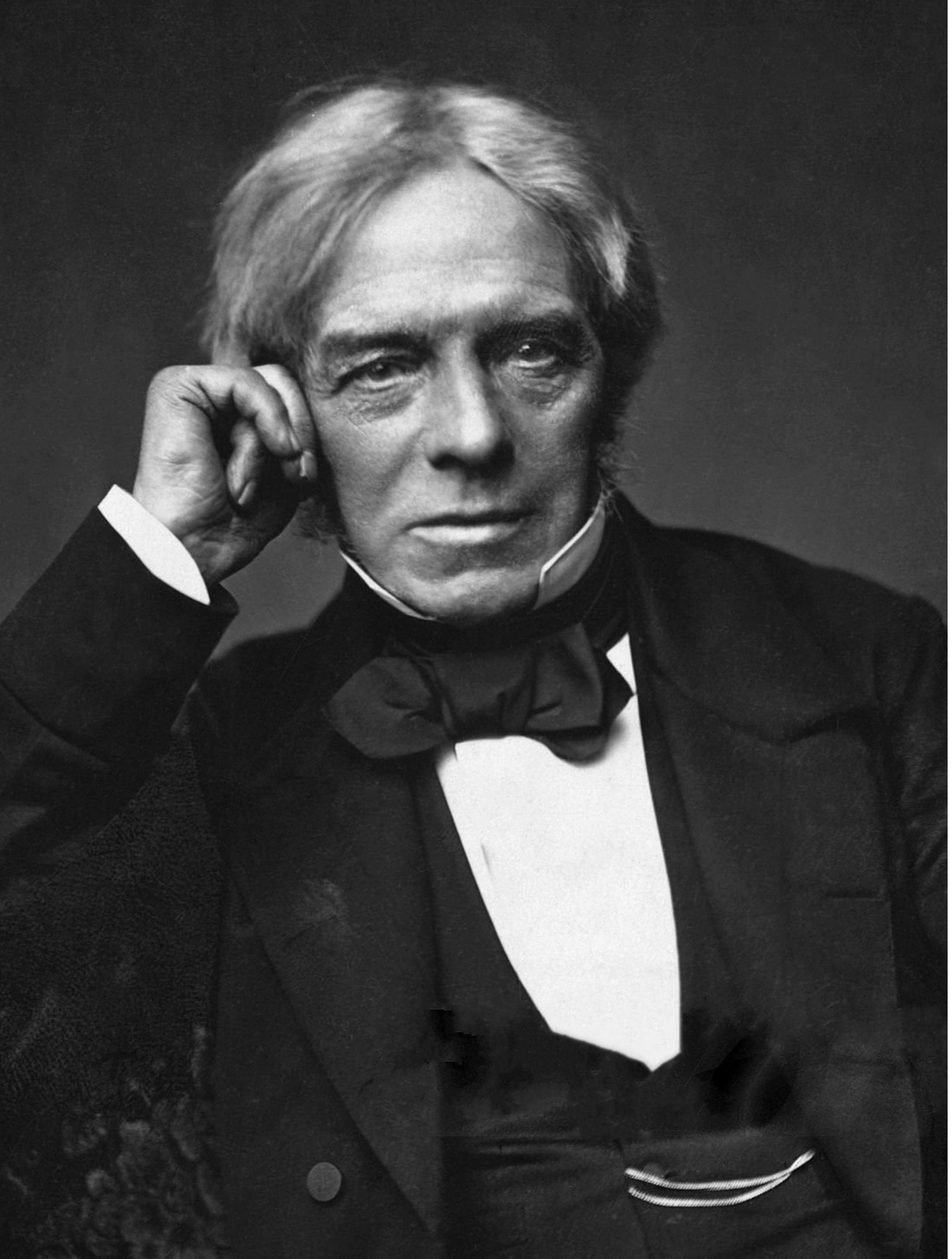

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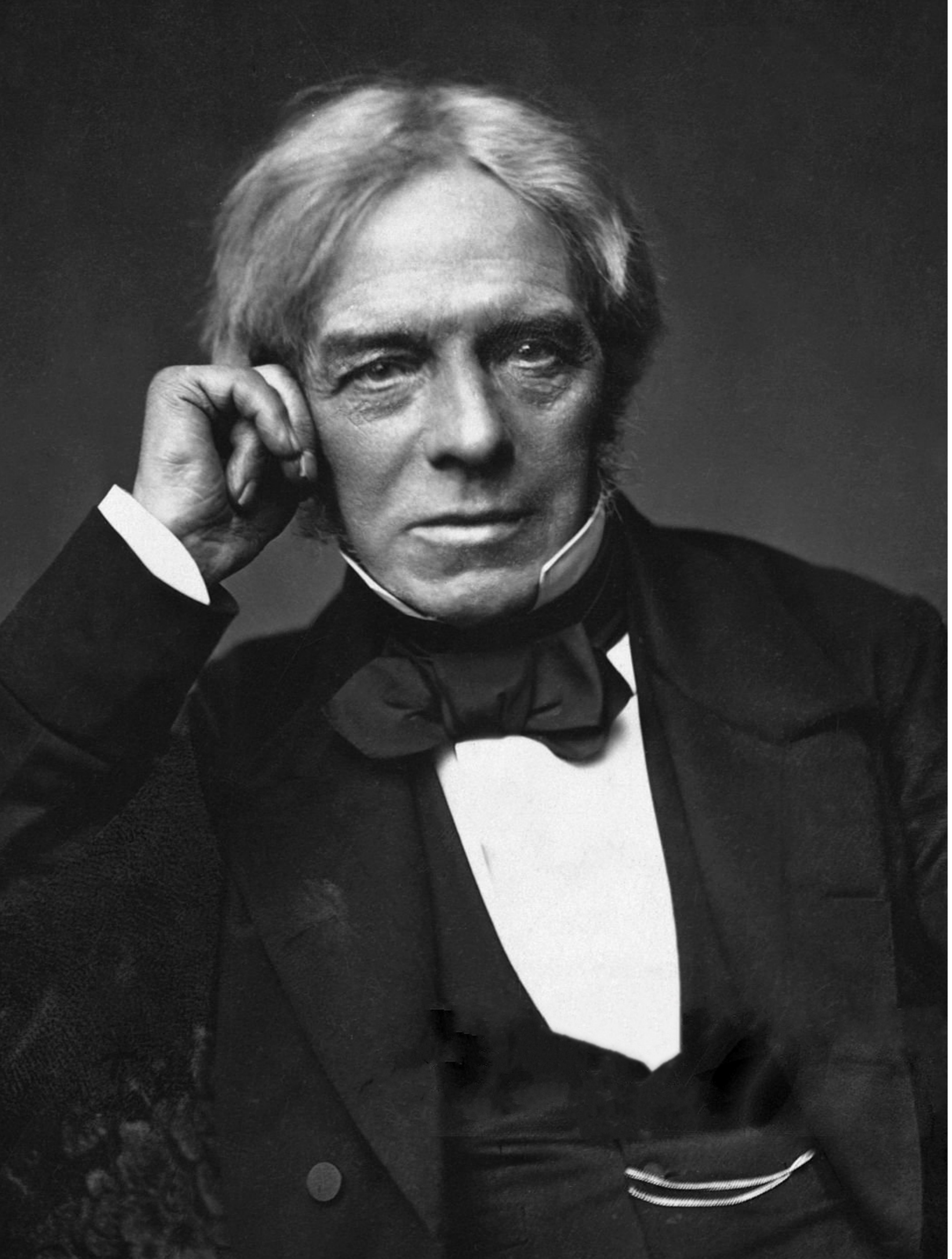

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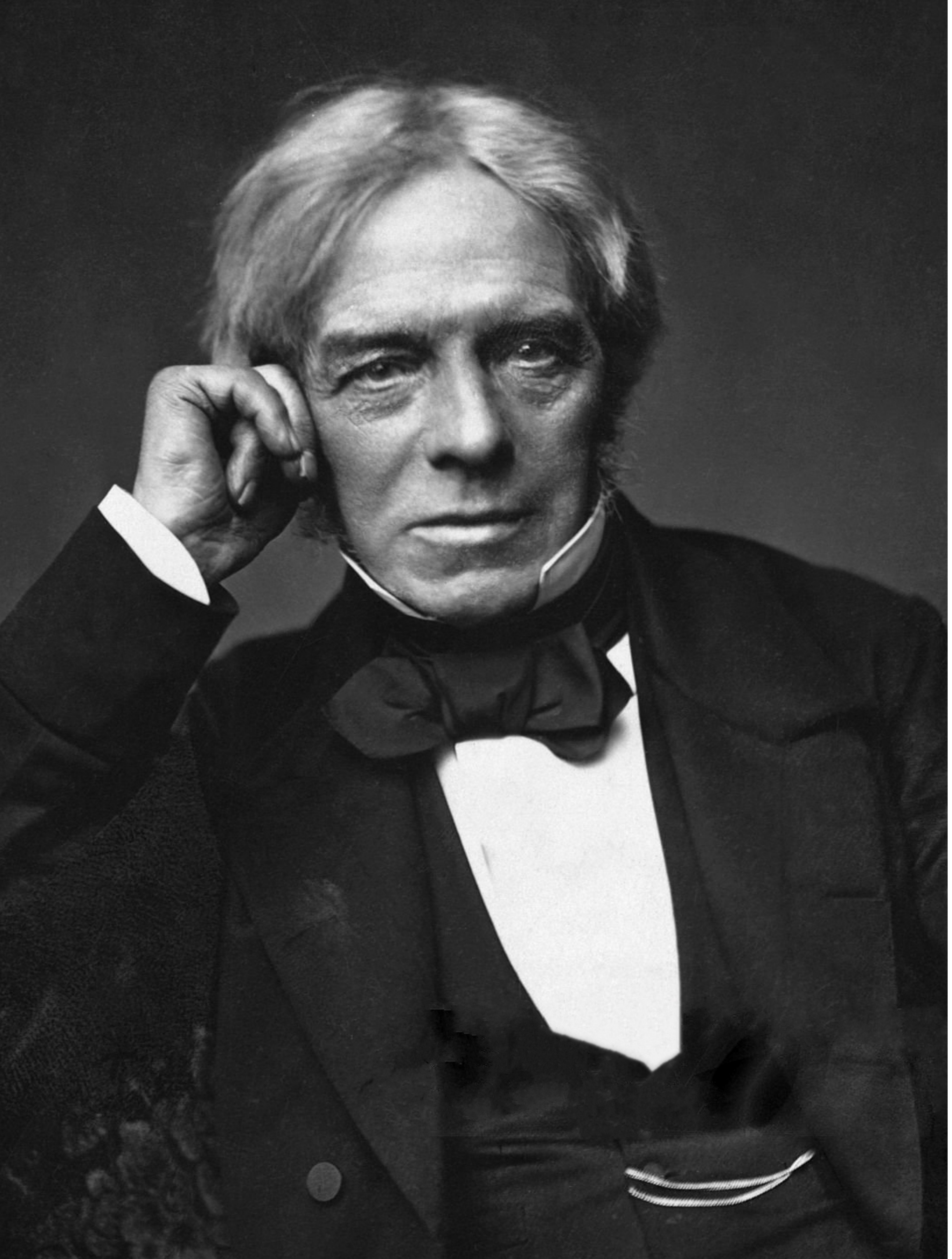

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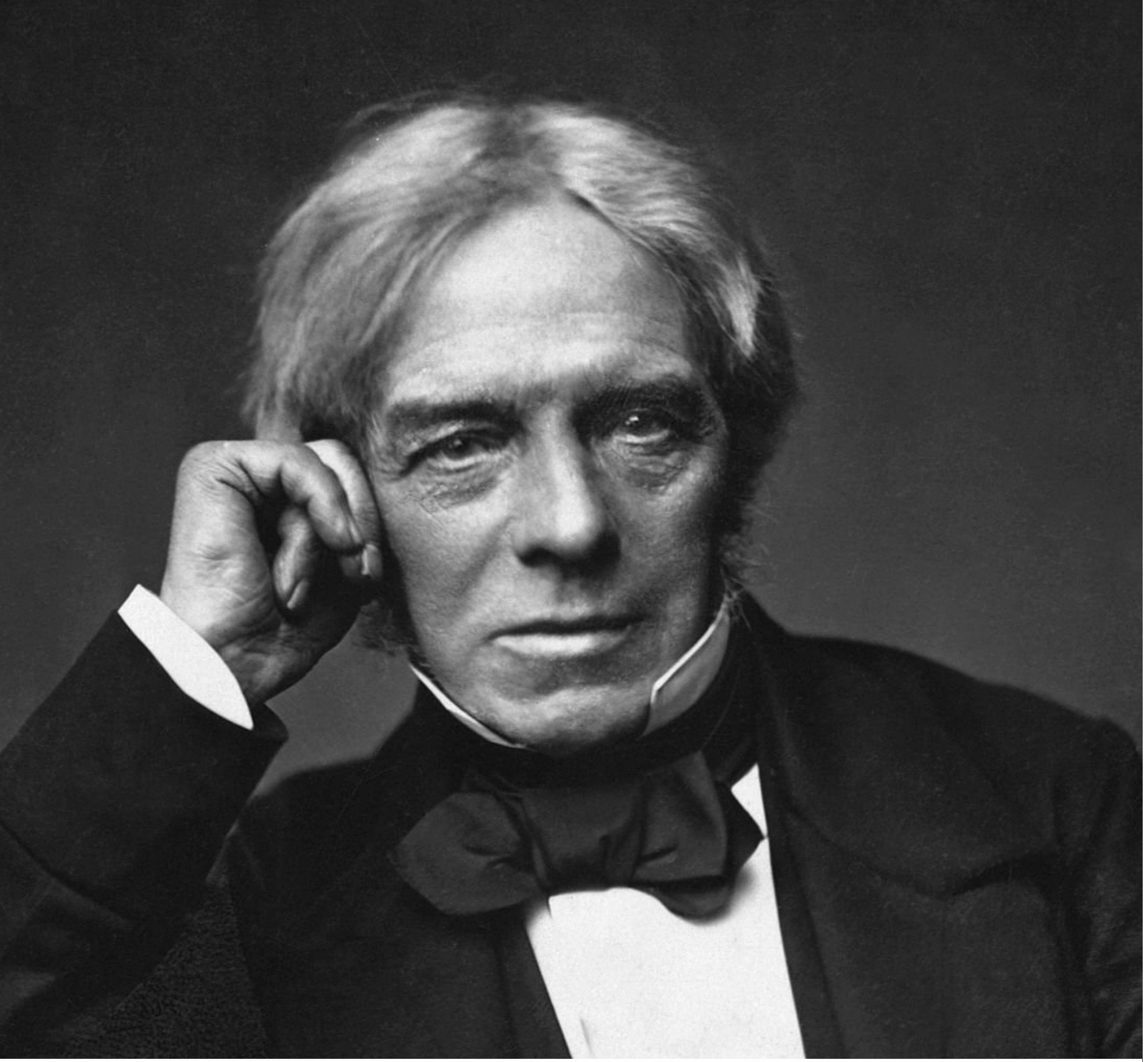

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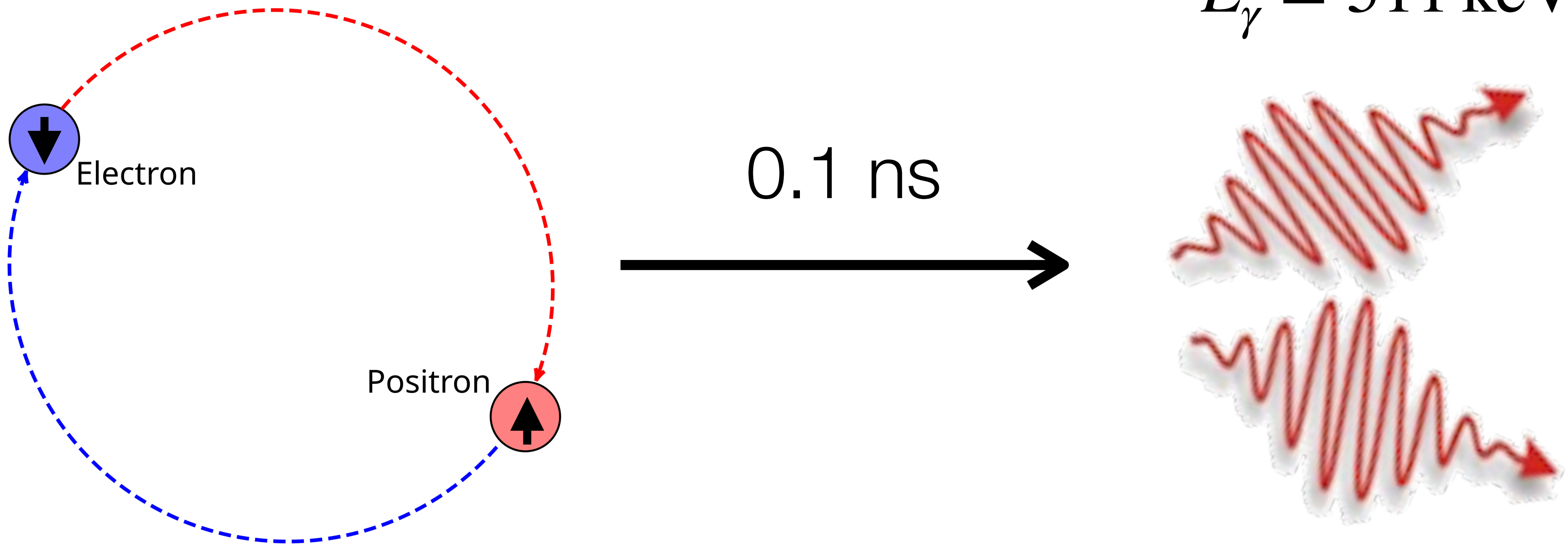
A modern example: the Positronium

If an electron (e^-) meets a positron (e^+) they can form **Positronium**

Two kinds of Positronium:

- **Para-positronium**: anti-parallel spin

$E_\gamma = 511\,\mathrm{keV}$



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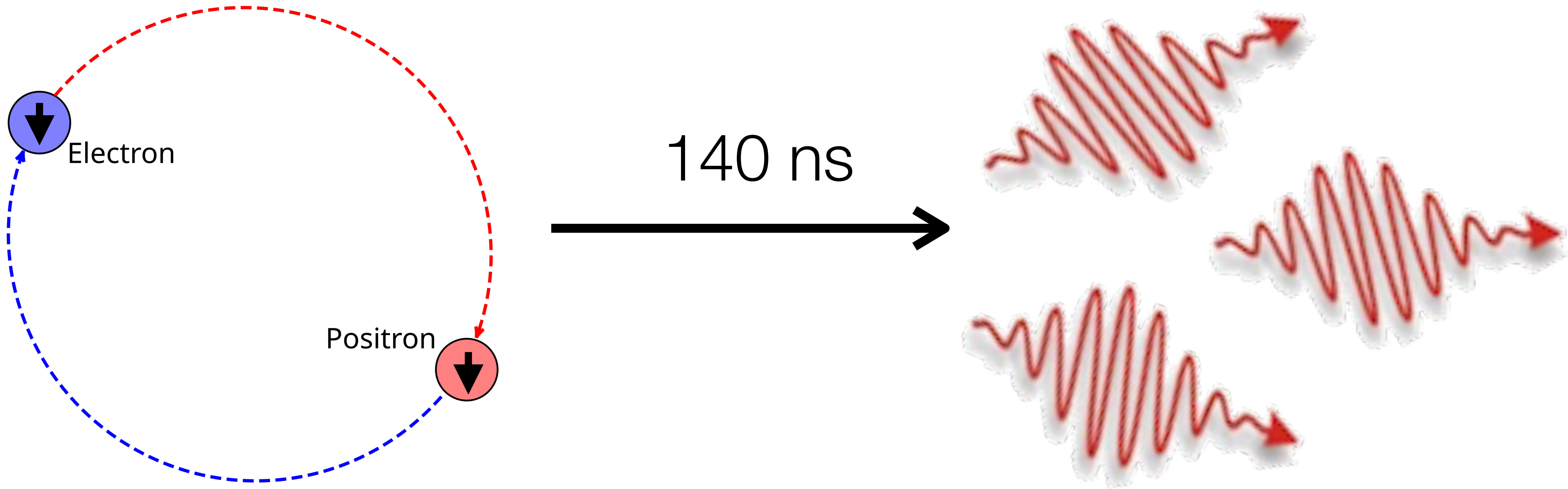

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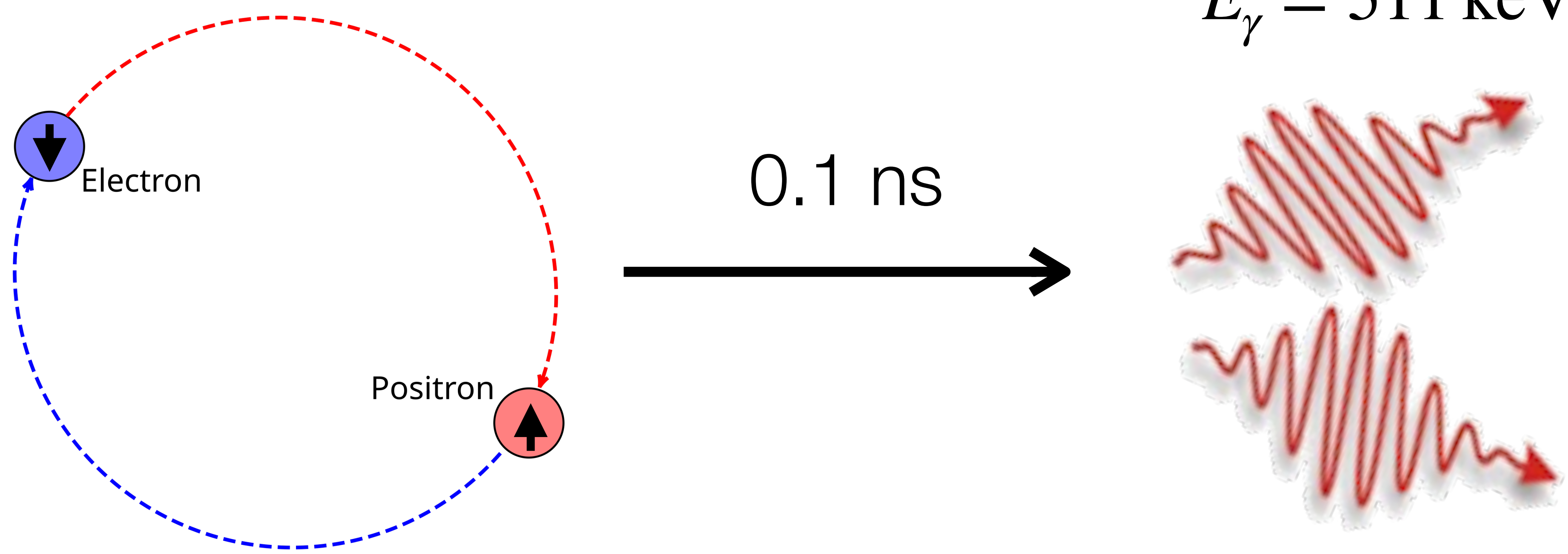

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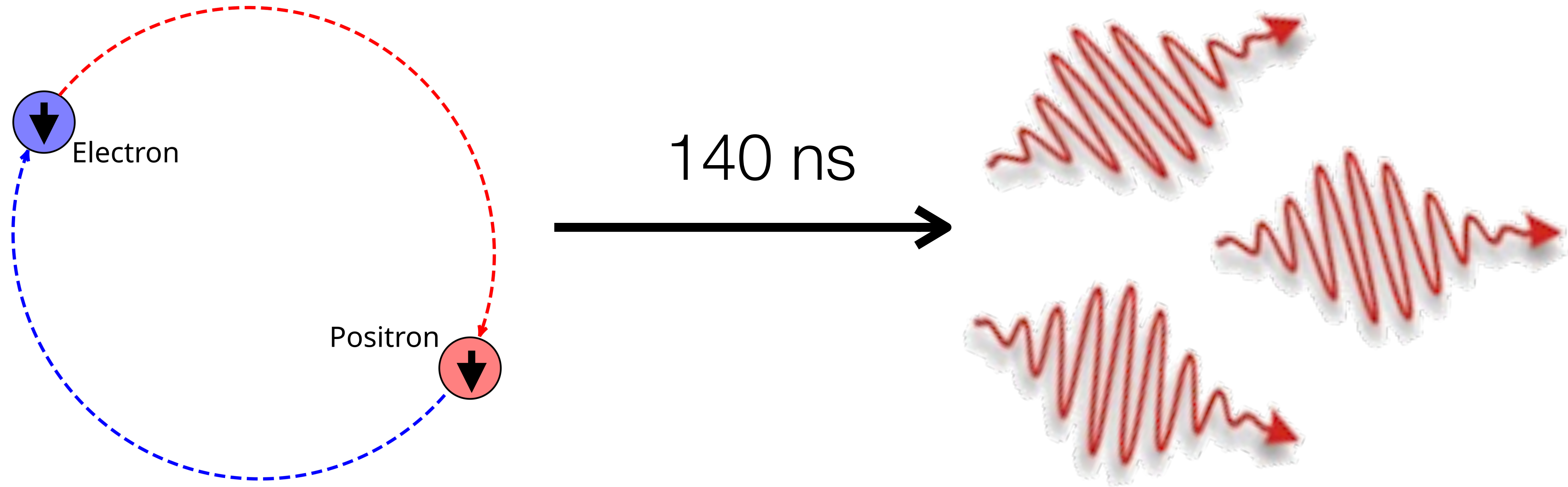

1 eV := energy acquired by electron in 1 V potential

$$E = qV = 1.6 \cdot 10^{-19}\mathrm{C} \times 1\mathrm{V} = 1.6 \cdot 10^{-19}\mathrm{C} \times \frac{\mathrm{J}}{\mathrm{C}} = 1\,\mathrm{eV}$$

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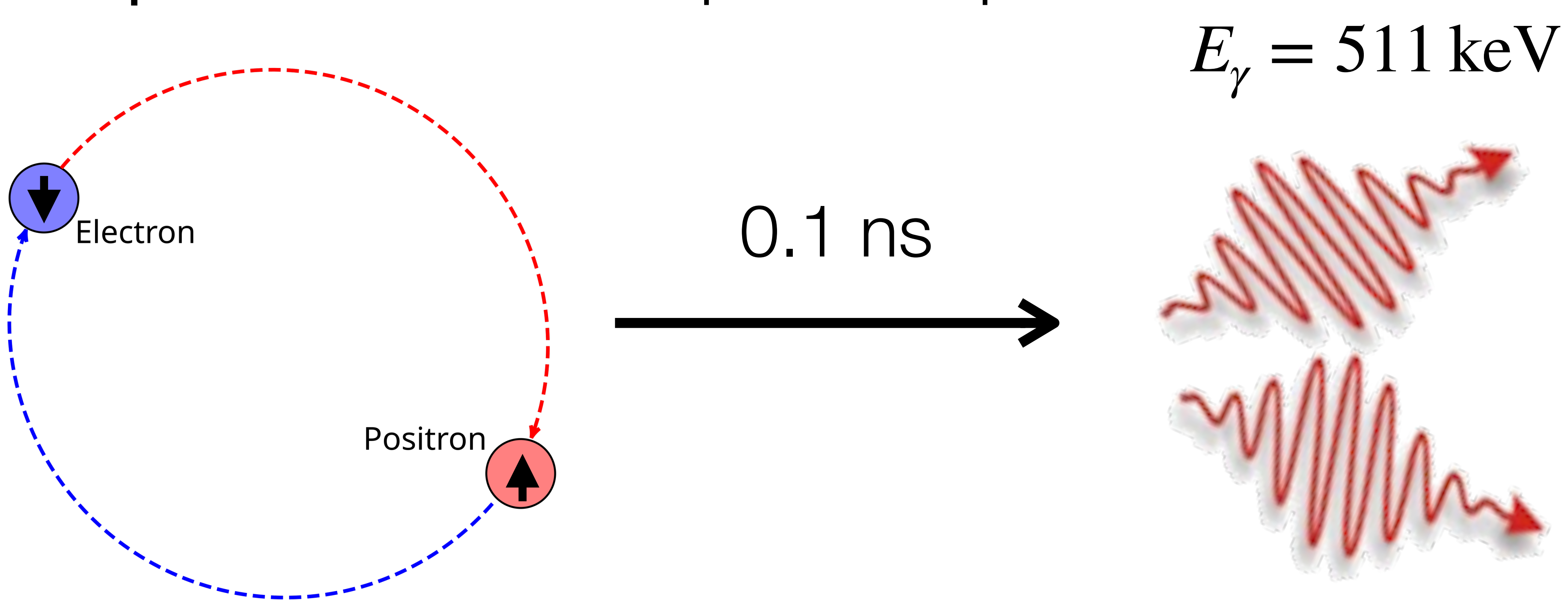

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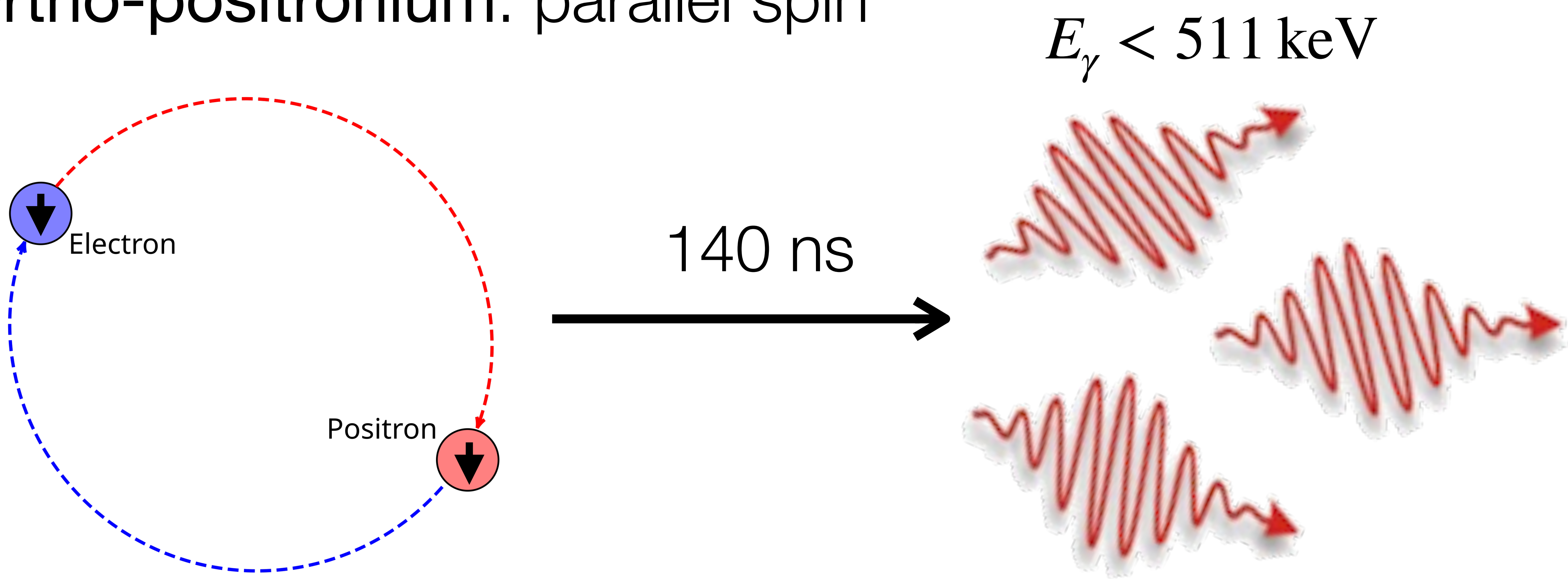

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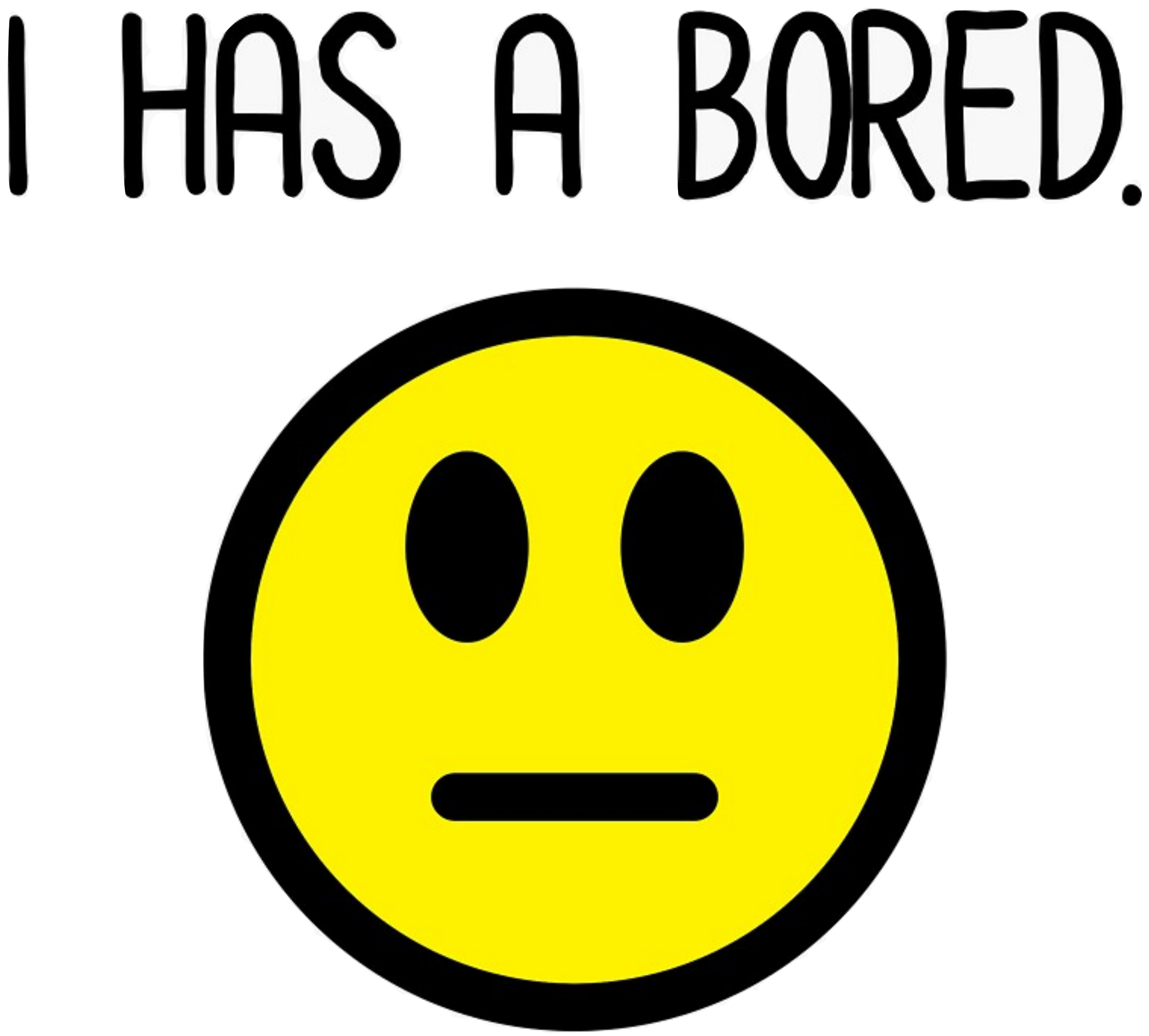

A futuristic example:
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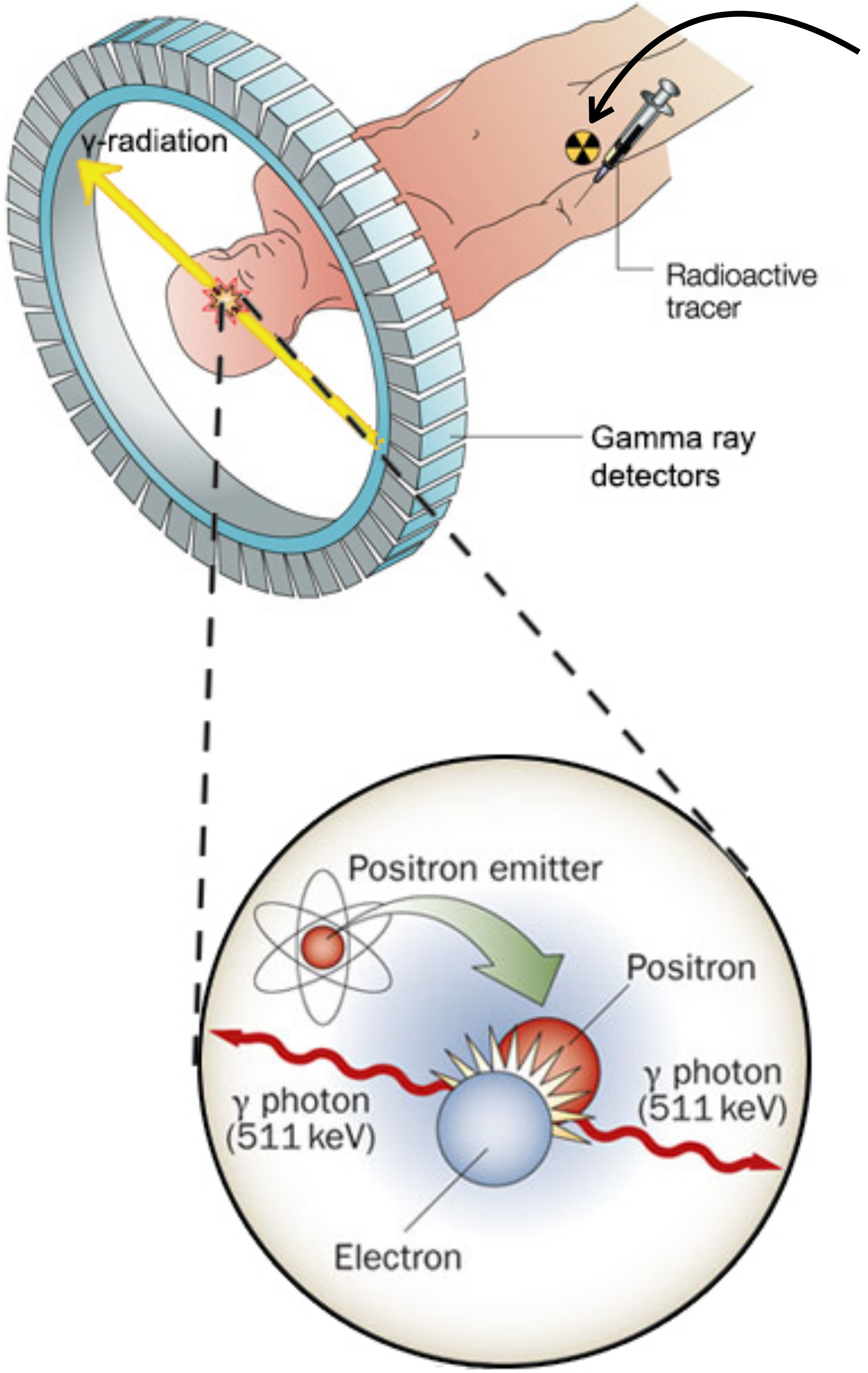

A radioactive source of e^+ is injected in the patient

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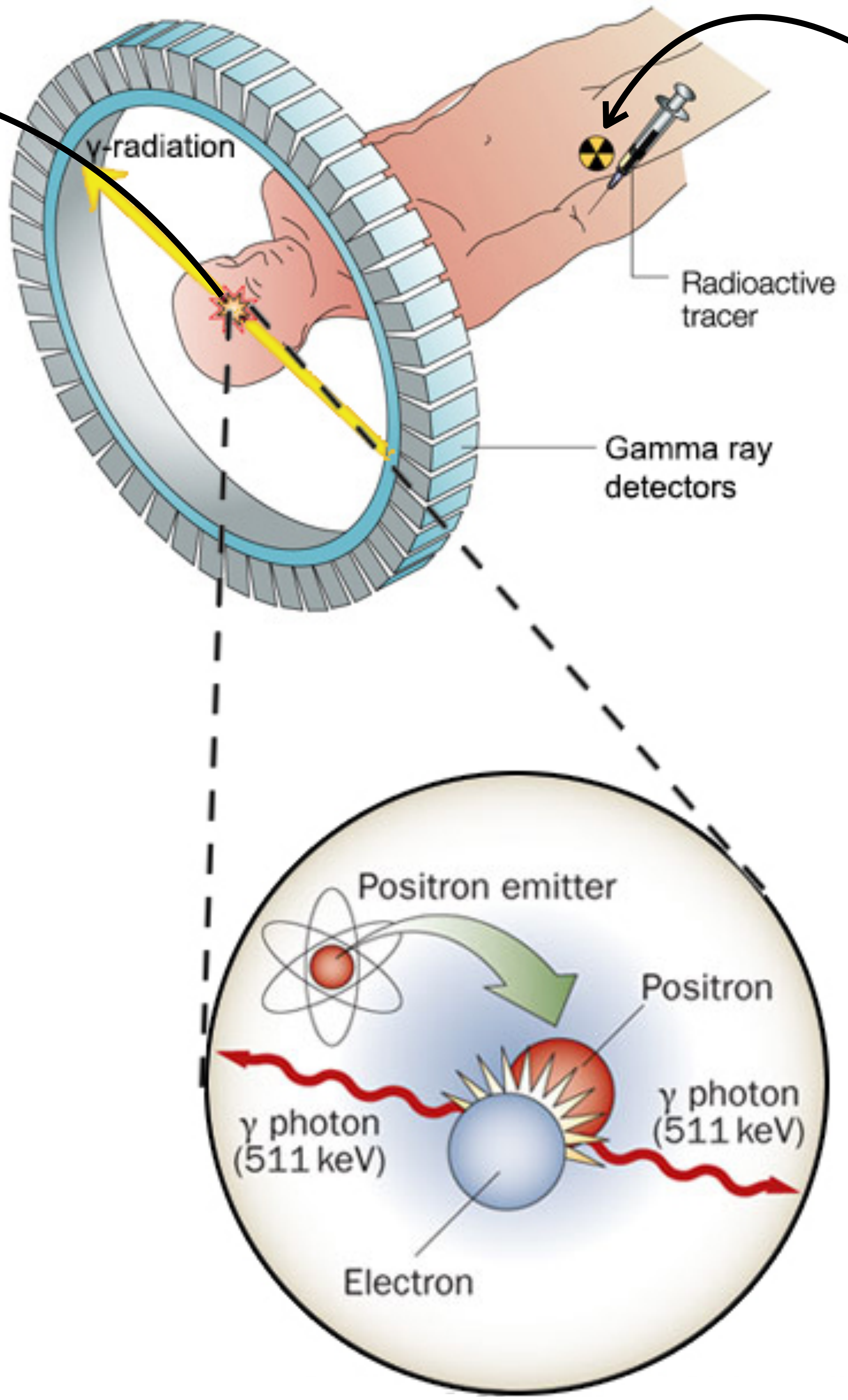
Different radioactive source bonds with different parts of the body (e.g. **tumours**, bones, blood)



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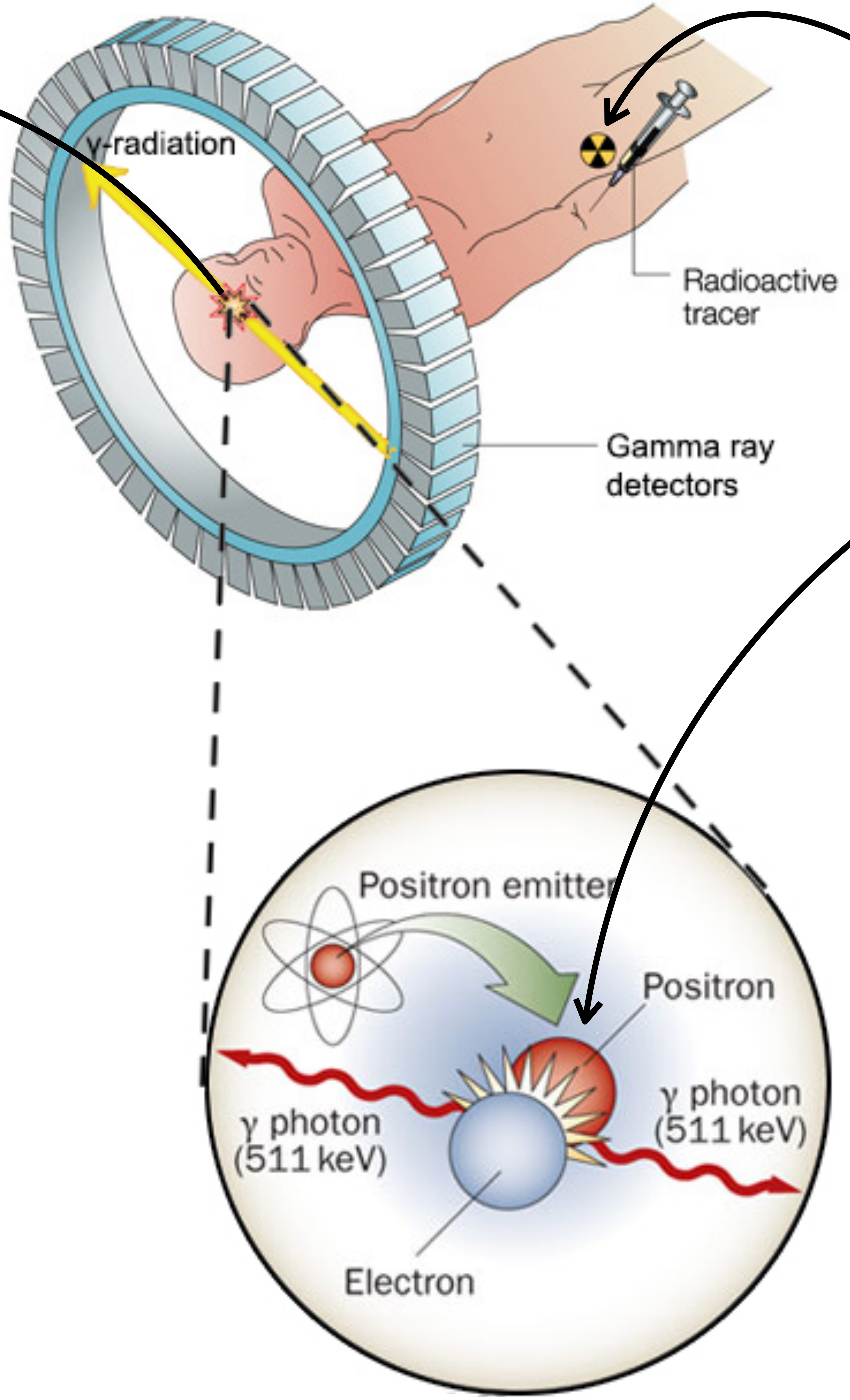

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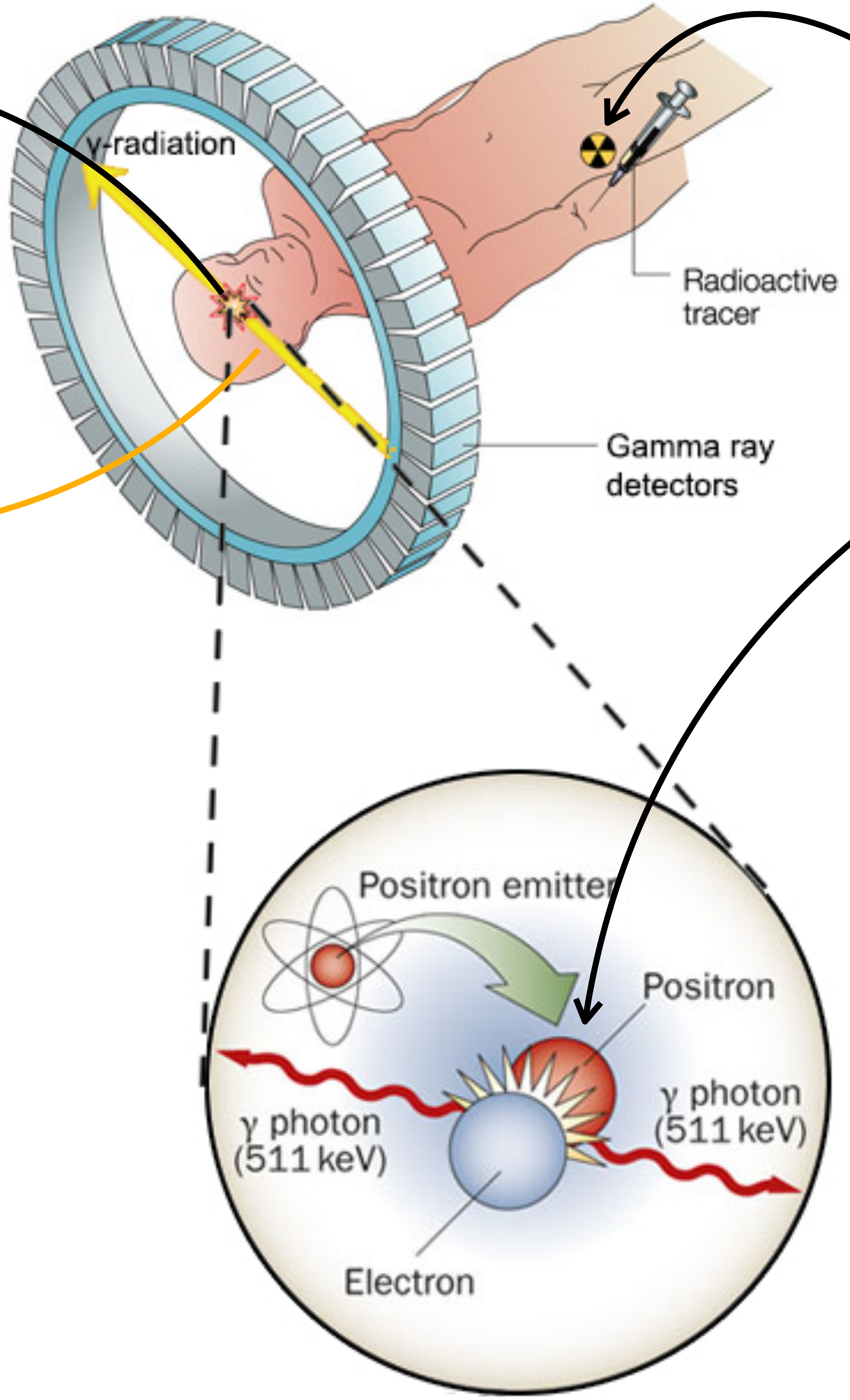

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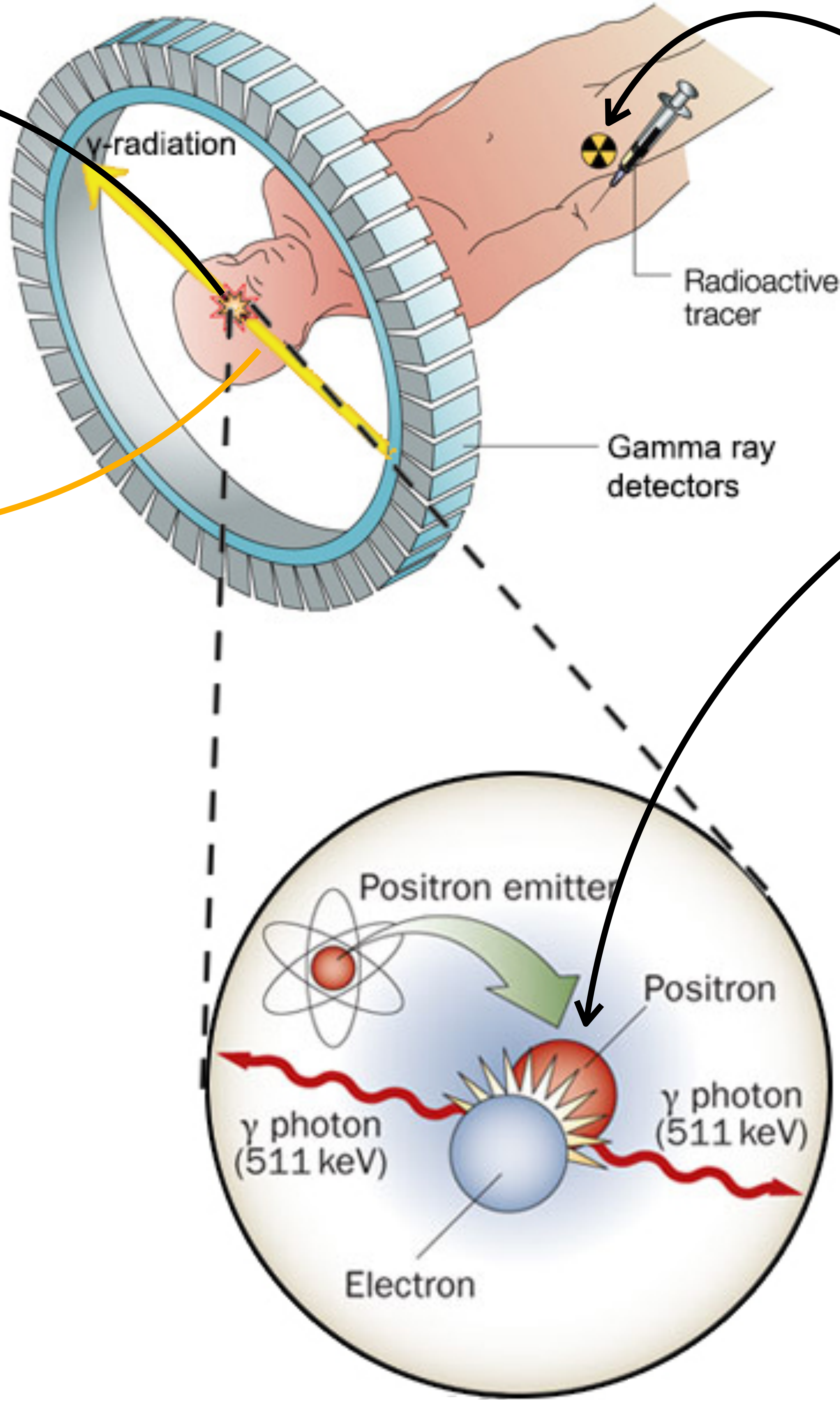
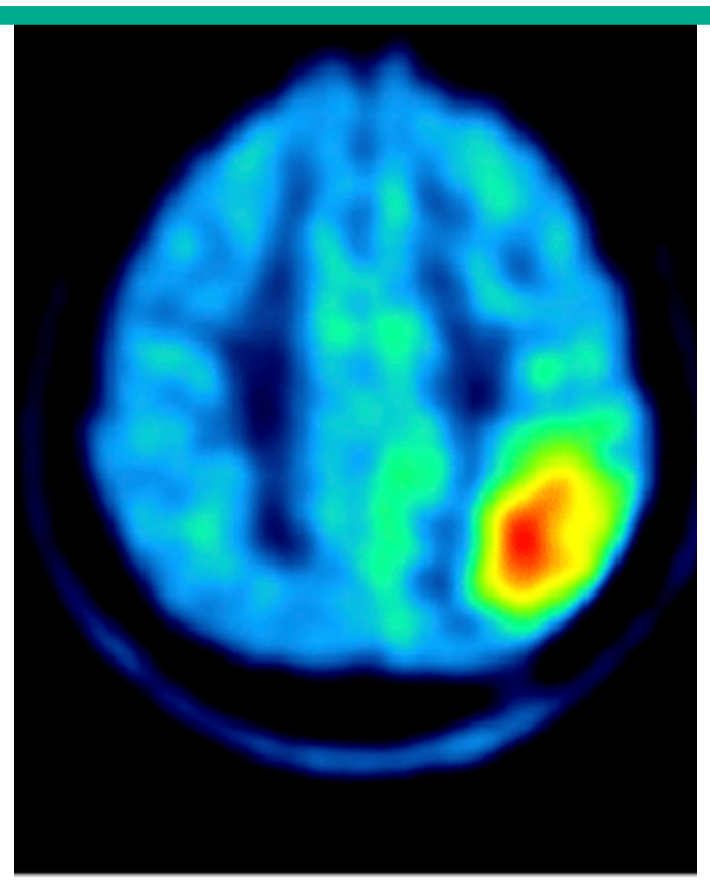


PET image of tumour



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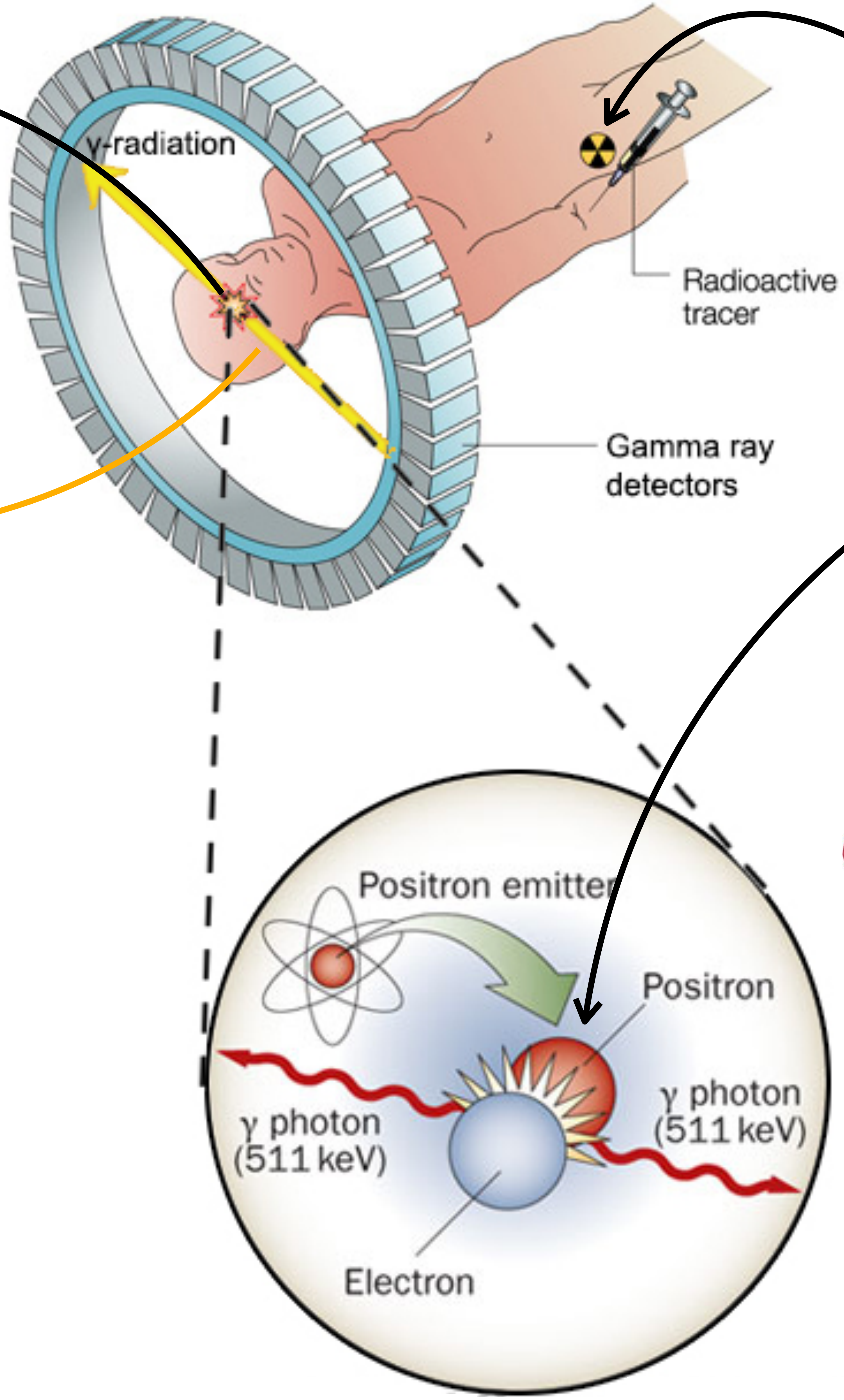

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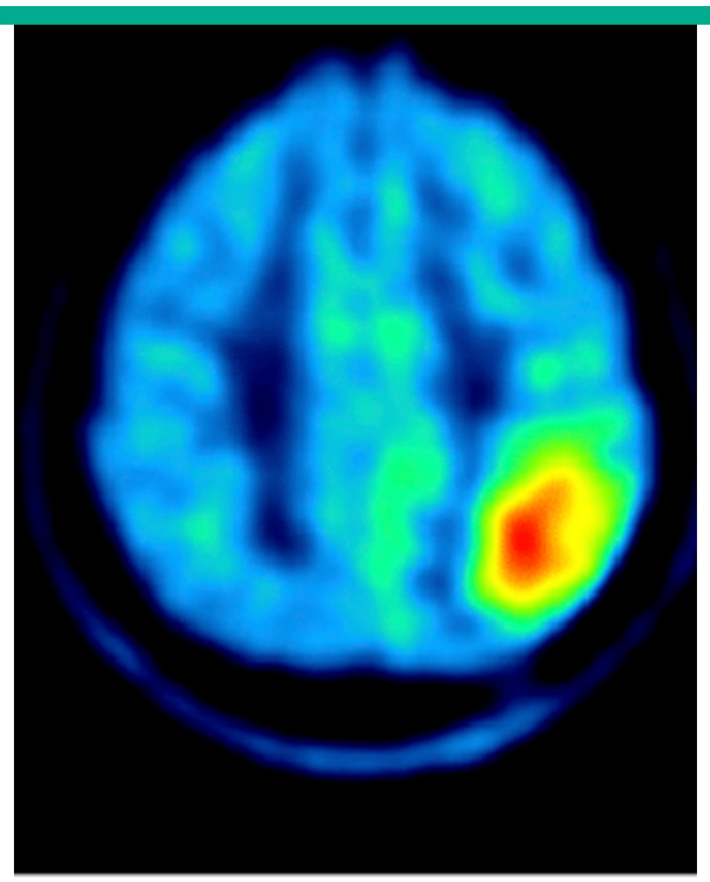

New PET scans could use Positronium, more information as Positronium production rate depends on environment!

Do we need to go Beyond the Standard Model?

Plato's allegory of the cave

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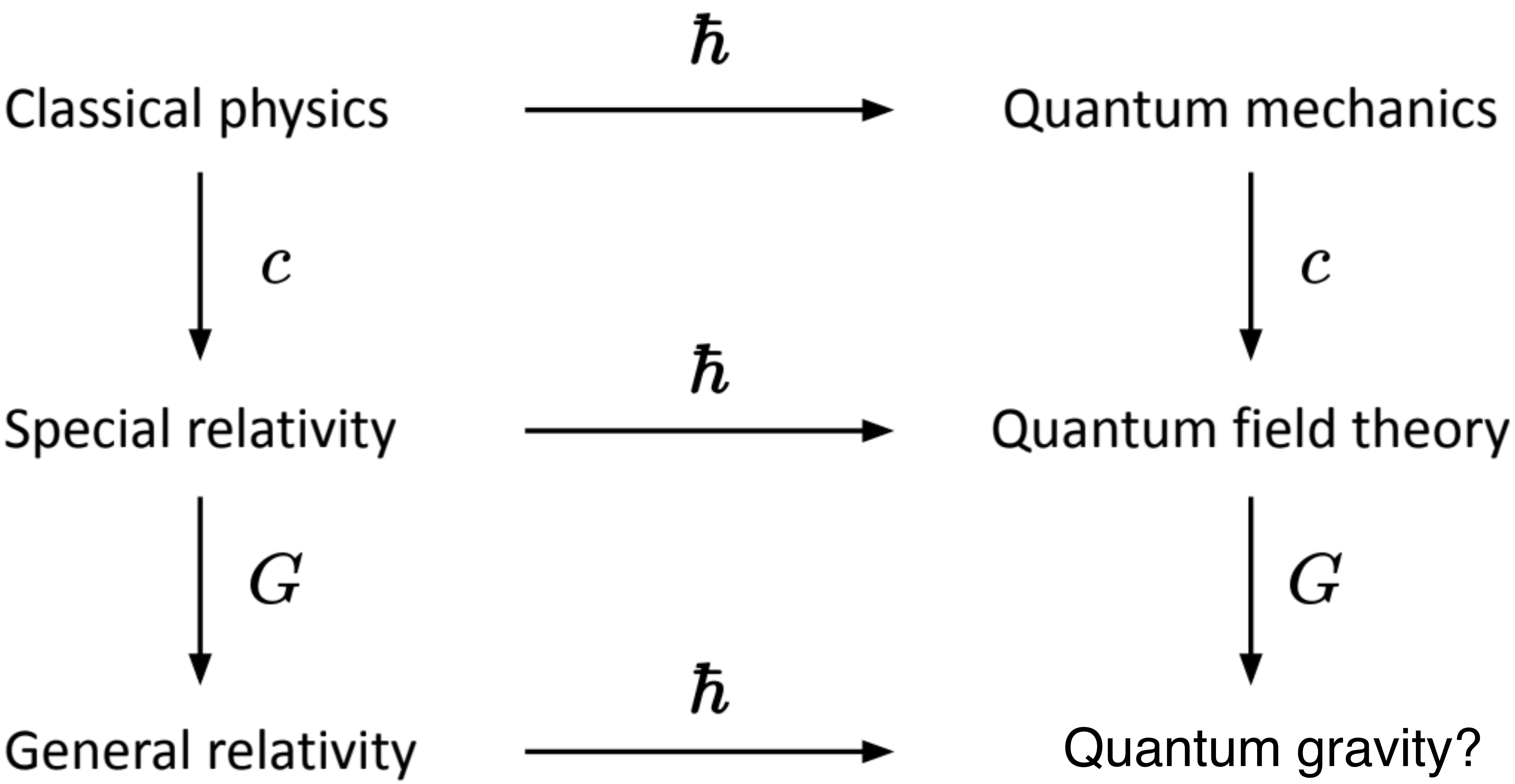
Our experience of reality is tied to what we can access
and how we perceive it

→ our description of reality is limited by definition

Plato’s prisoner in modern physics:

A revised Bronstein Cube

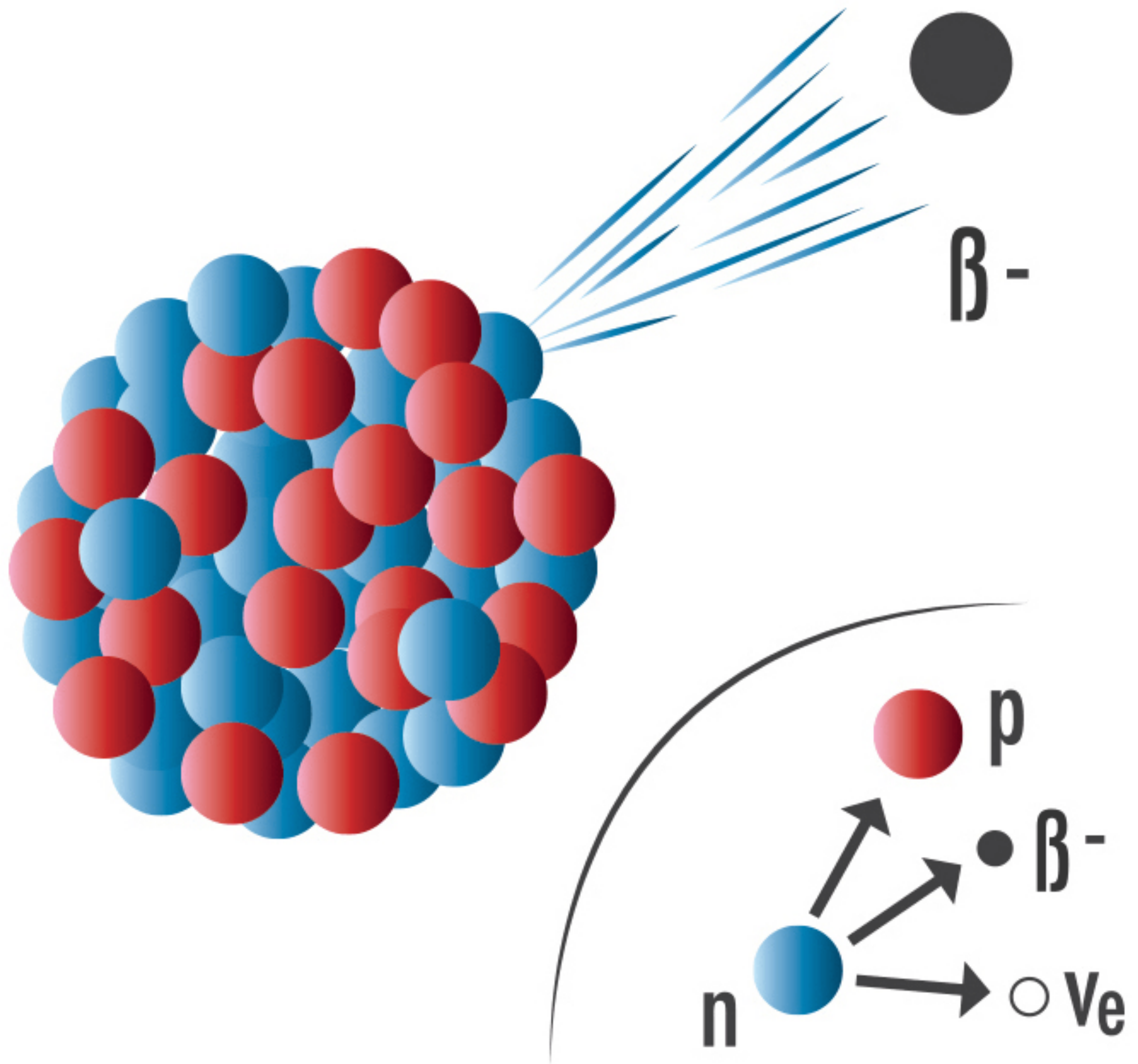
A model is
accurate (≠ true)
at a given scale



Missing piece #1:
Gravity

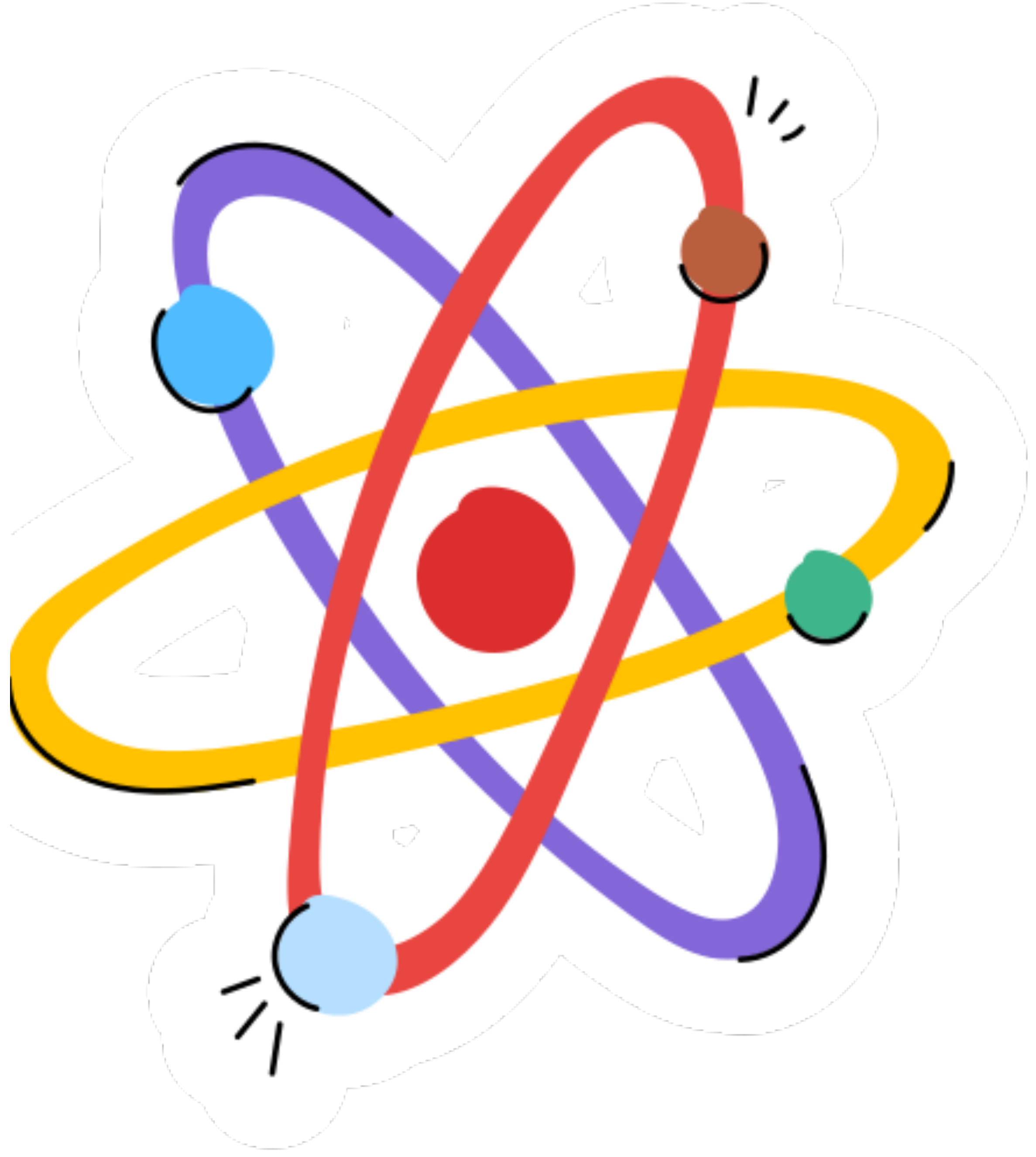
Weak force:

$\beta^{\pm}$ decays



Electromagnetic force:

Binding atoms together



Strong force:

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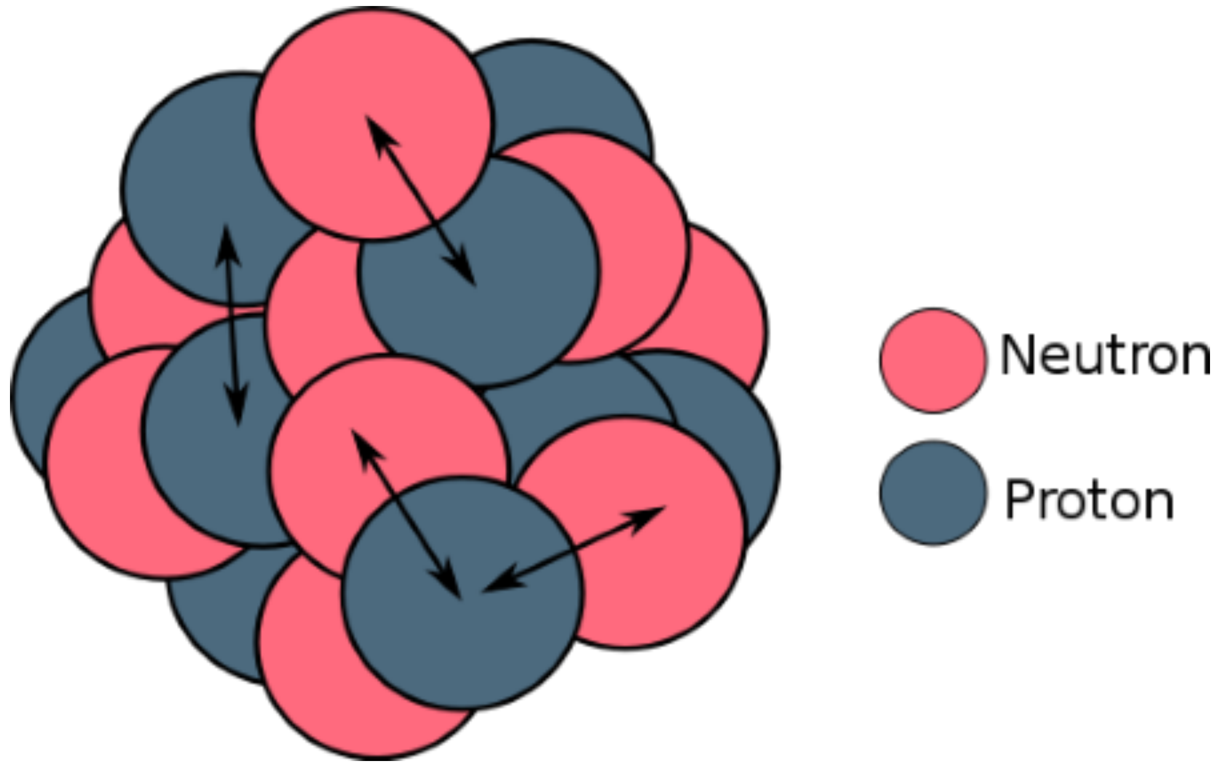

Gravitational force:

Binding solar system together

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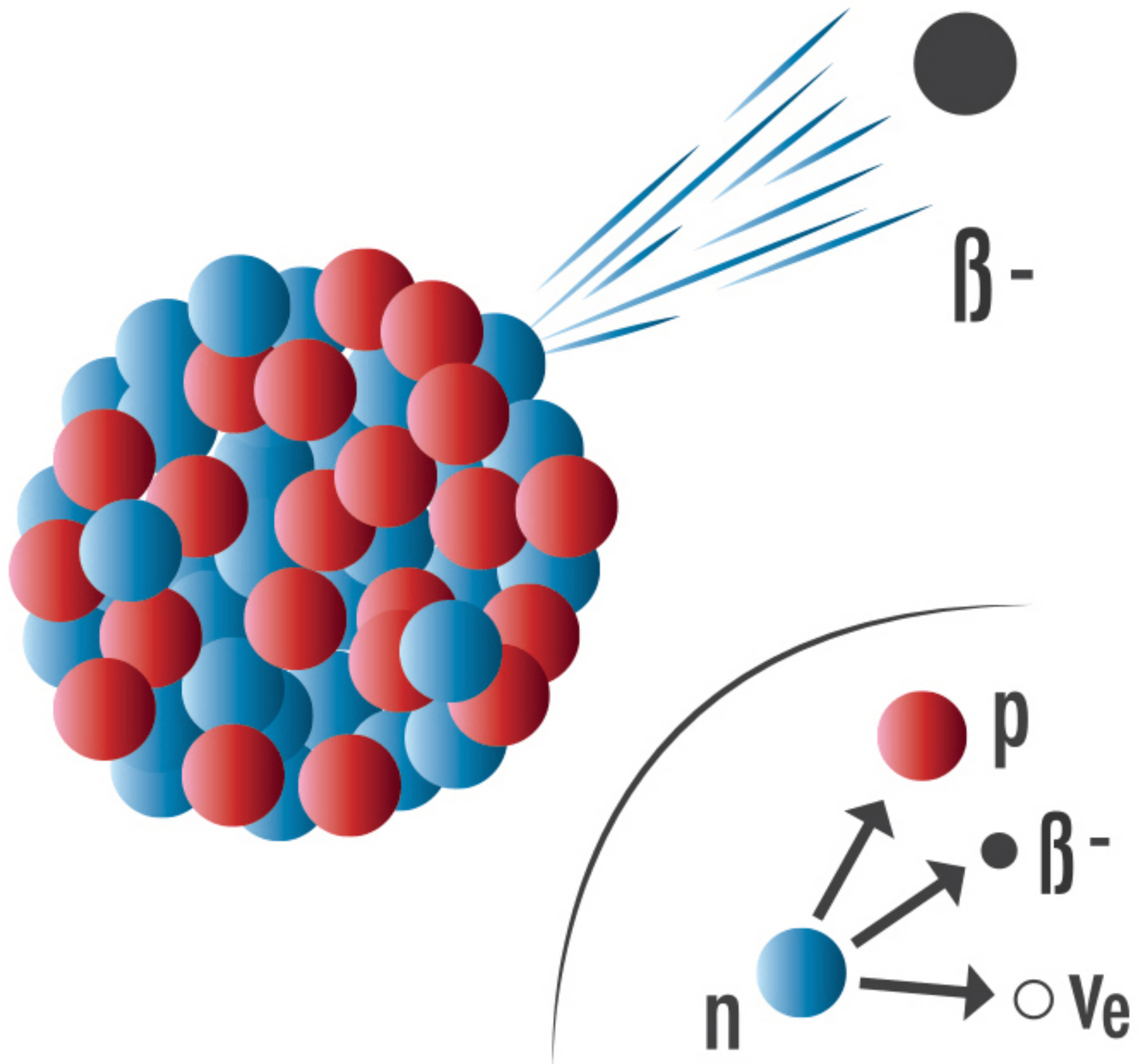

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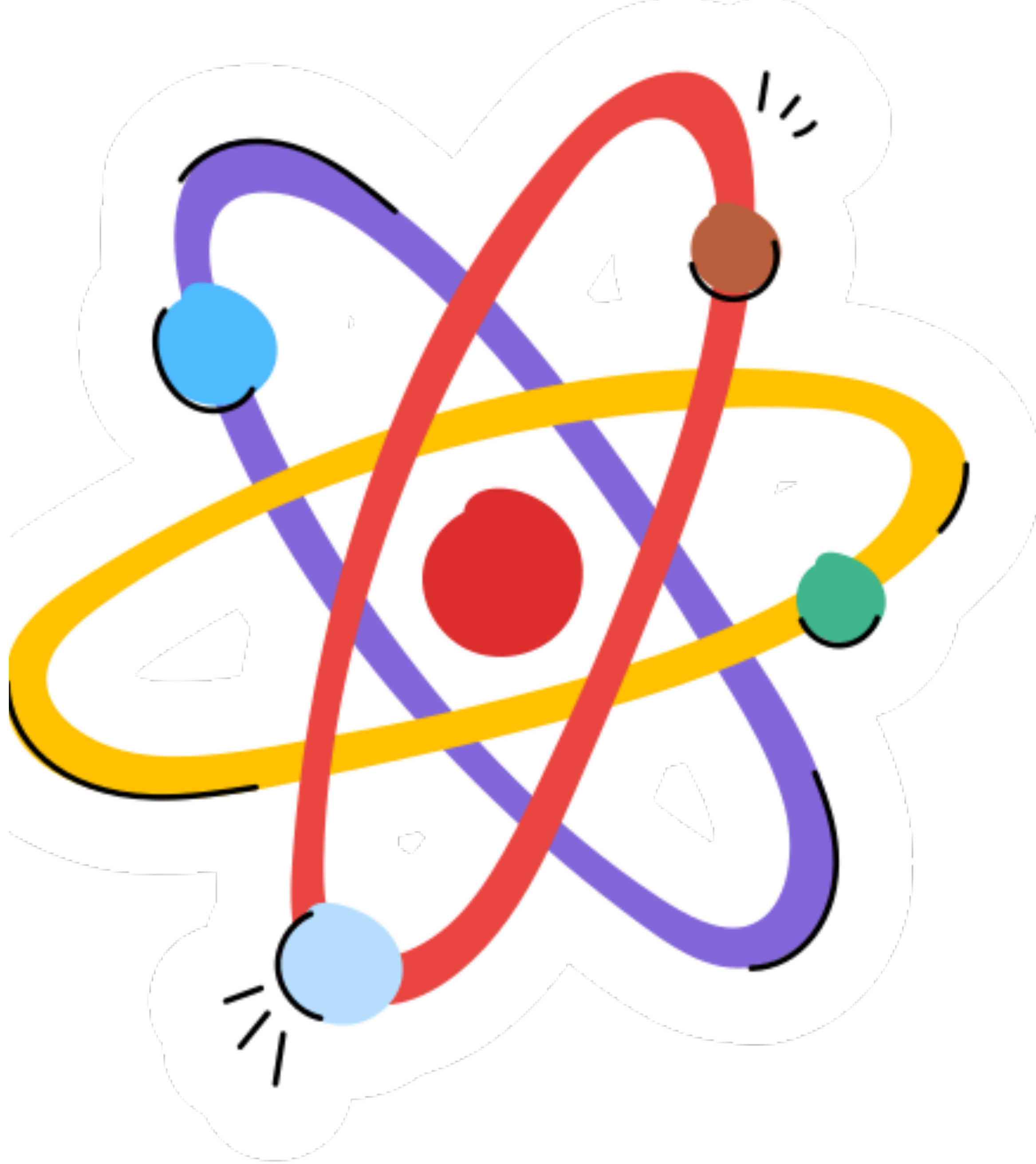

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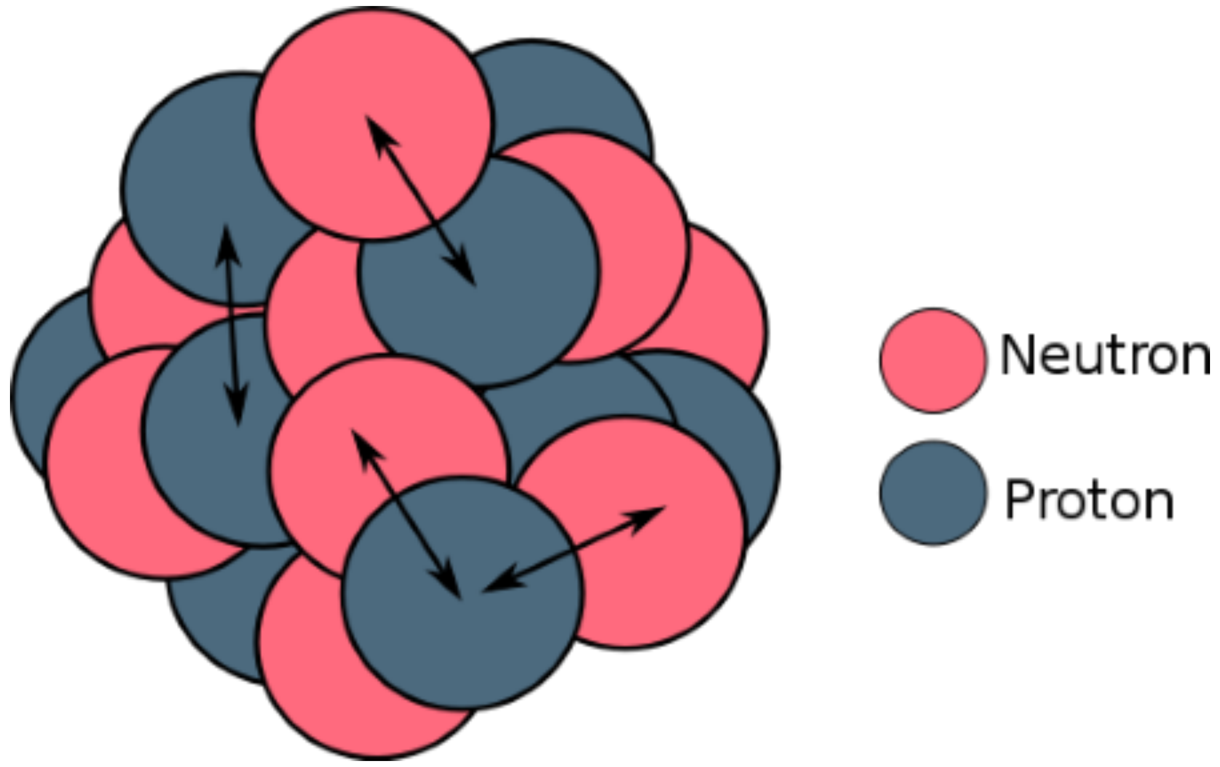

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Included in the SM Lagrangian!

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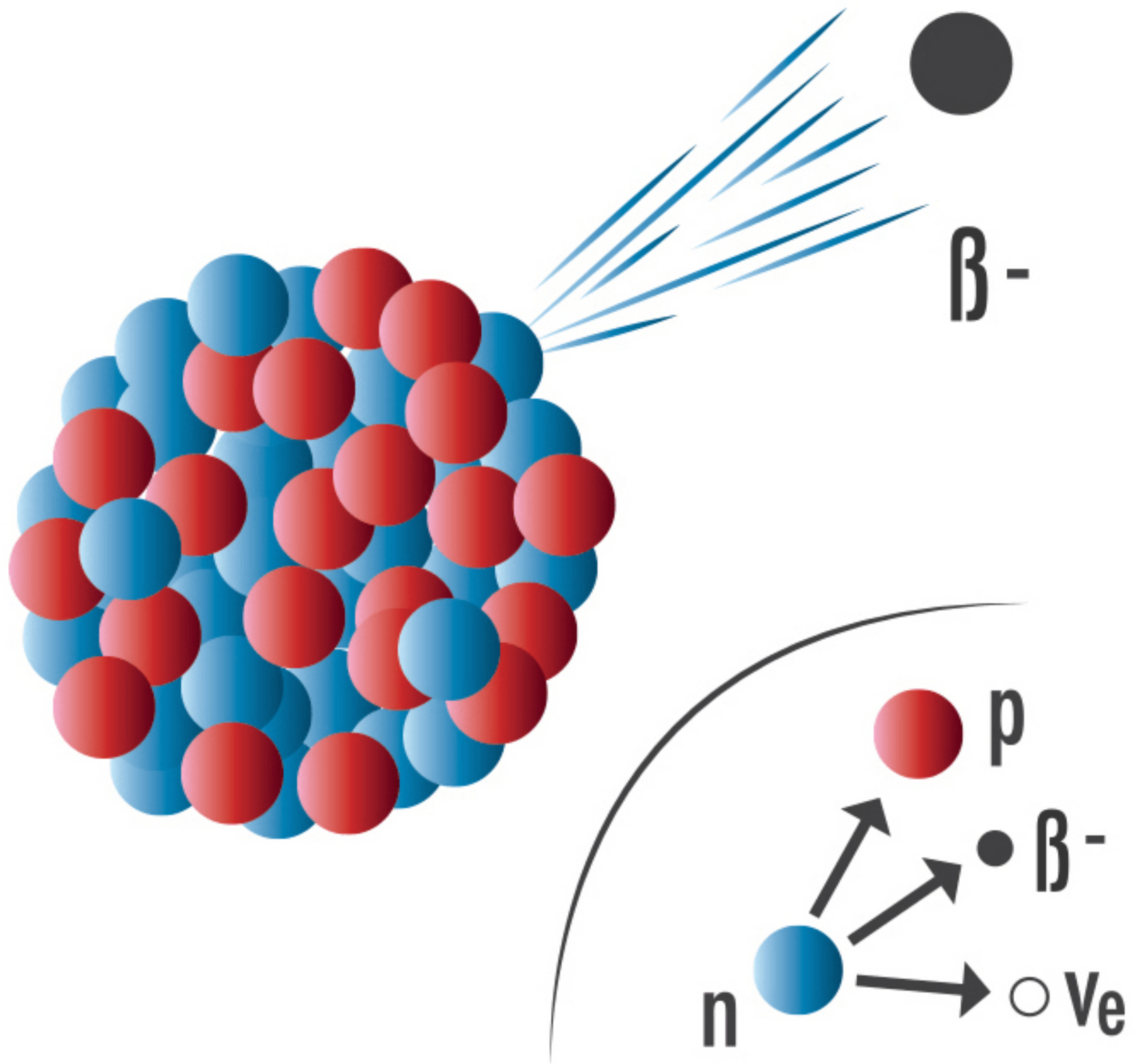

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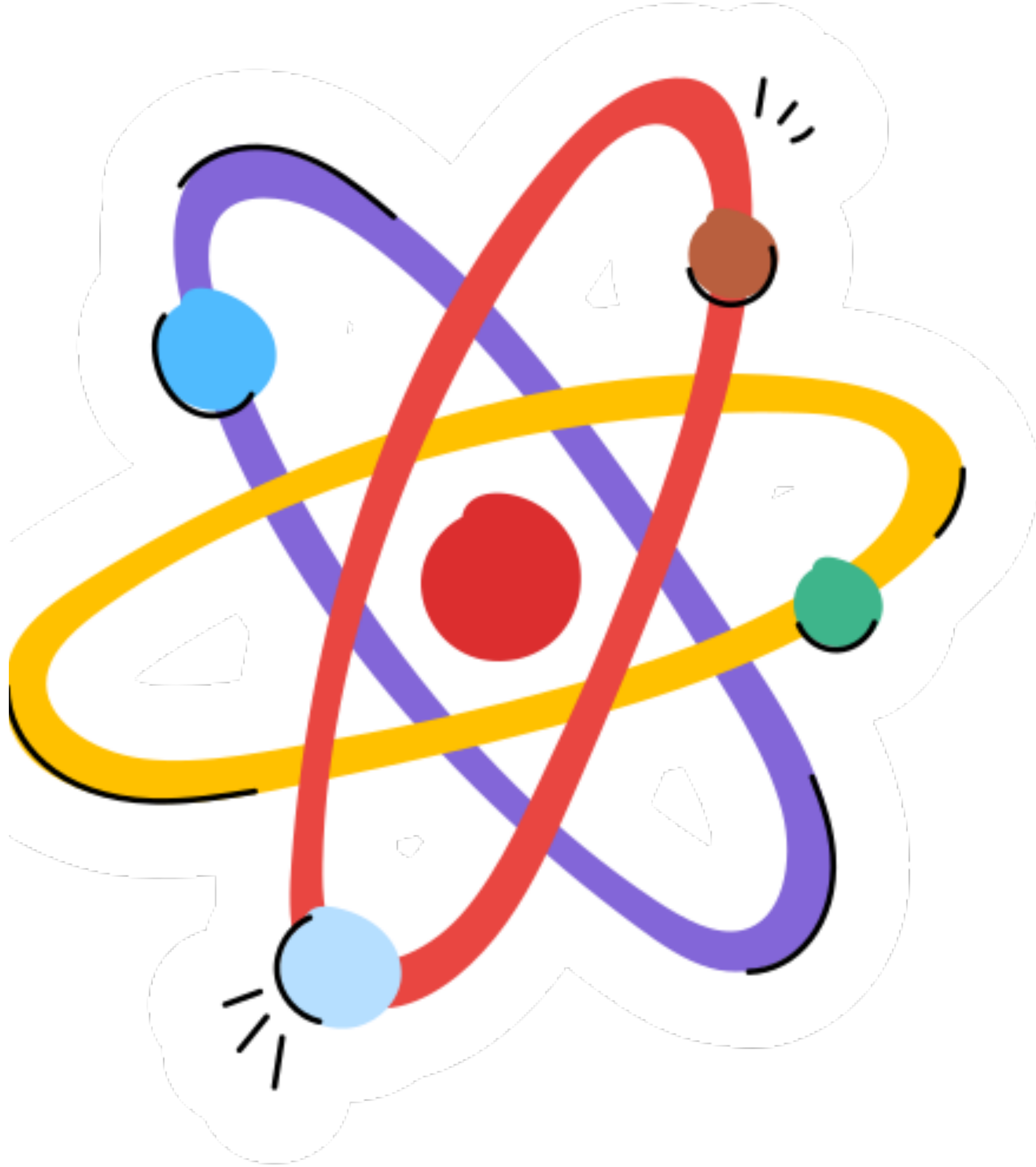

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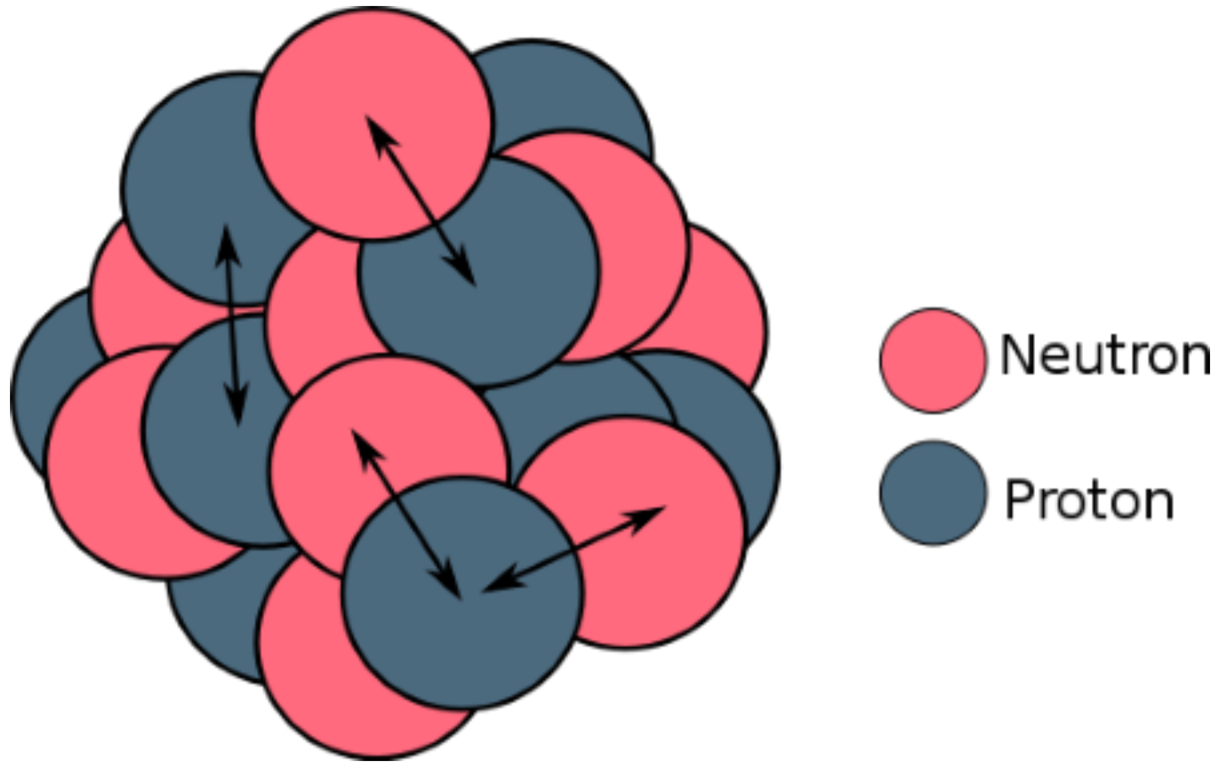

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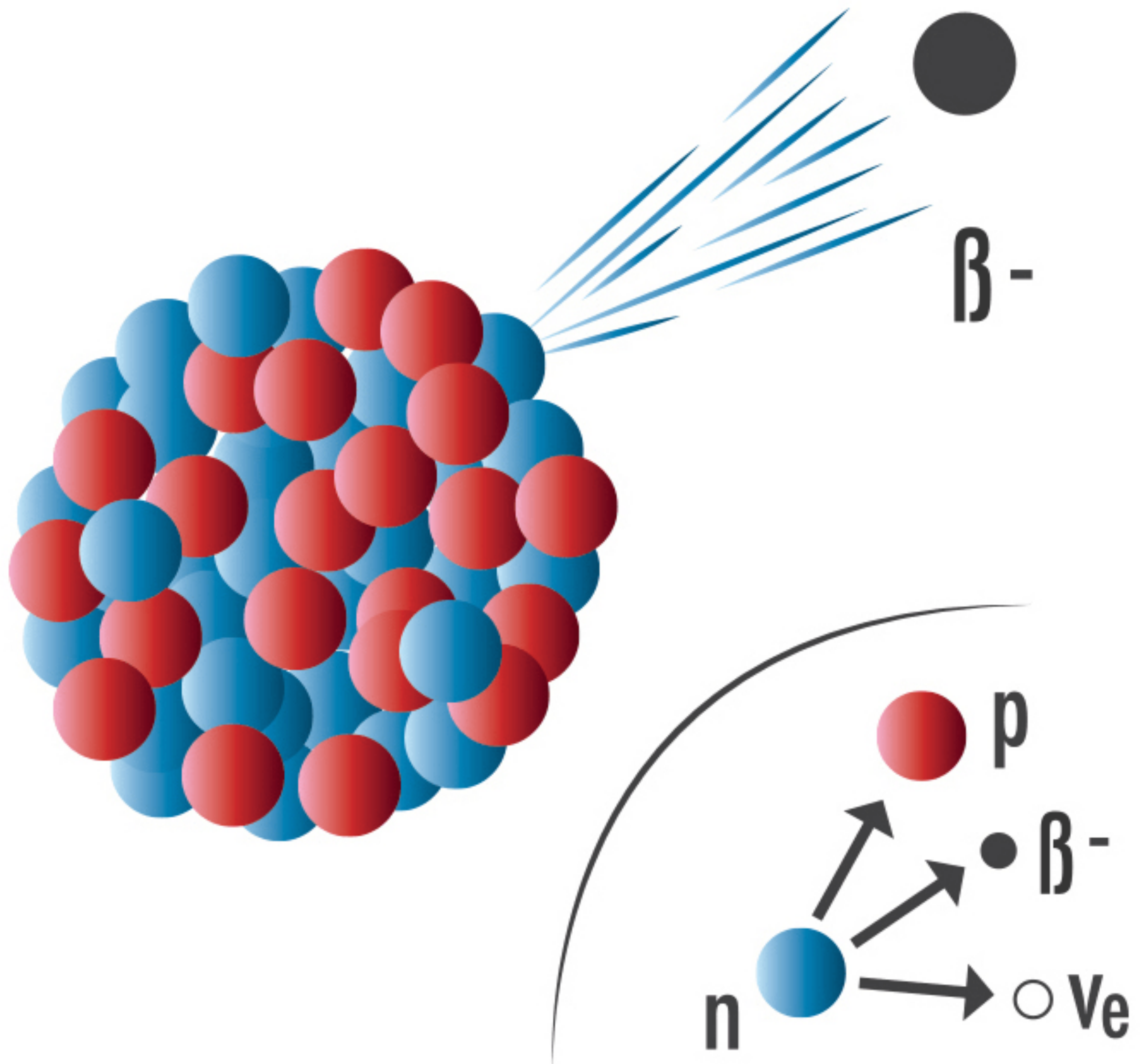

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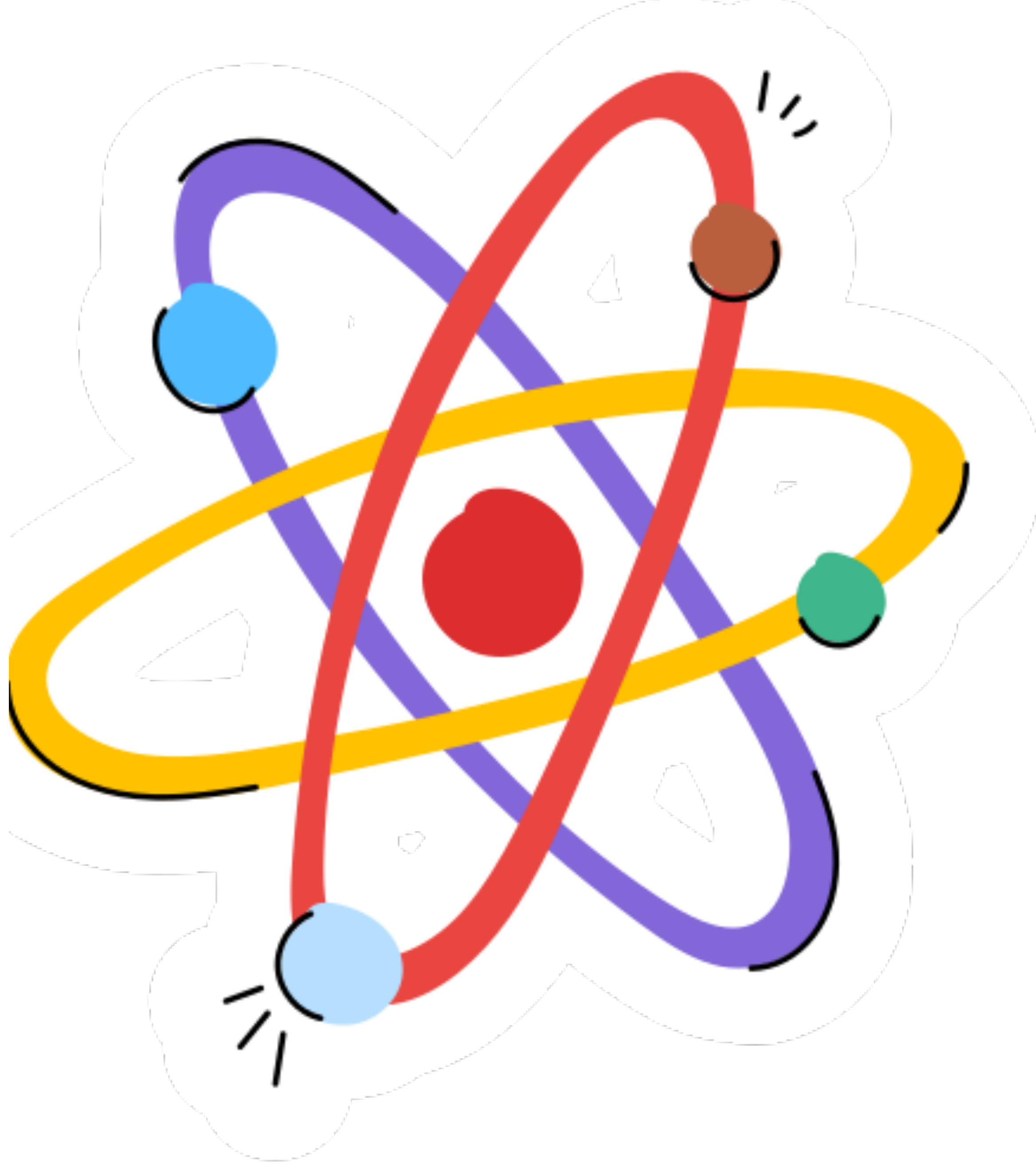

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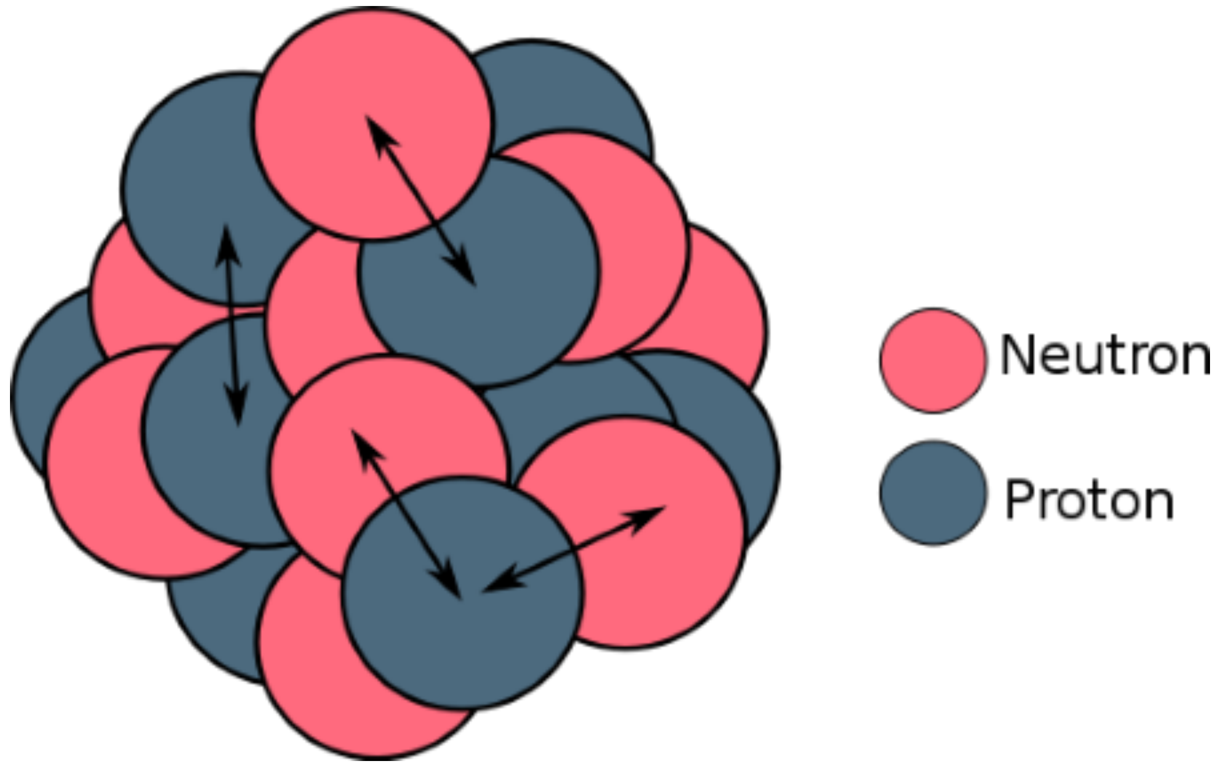
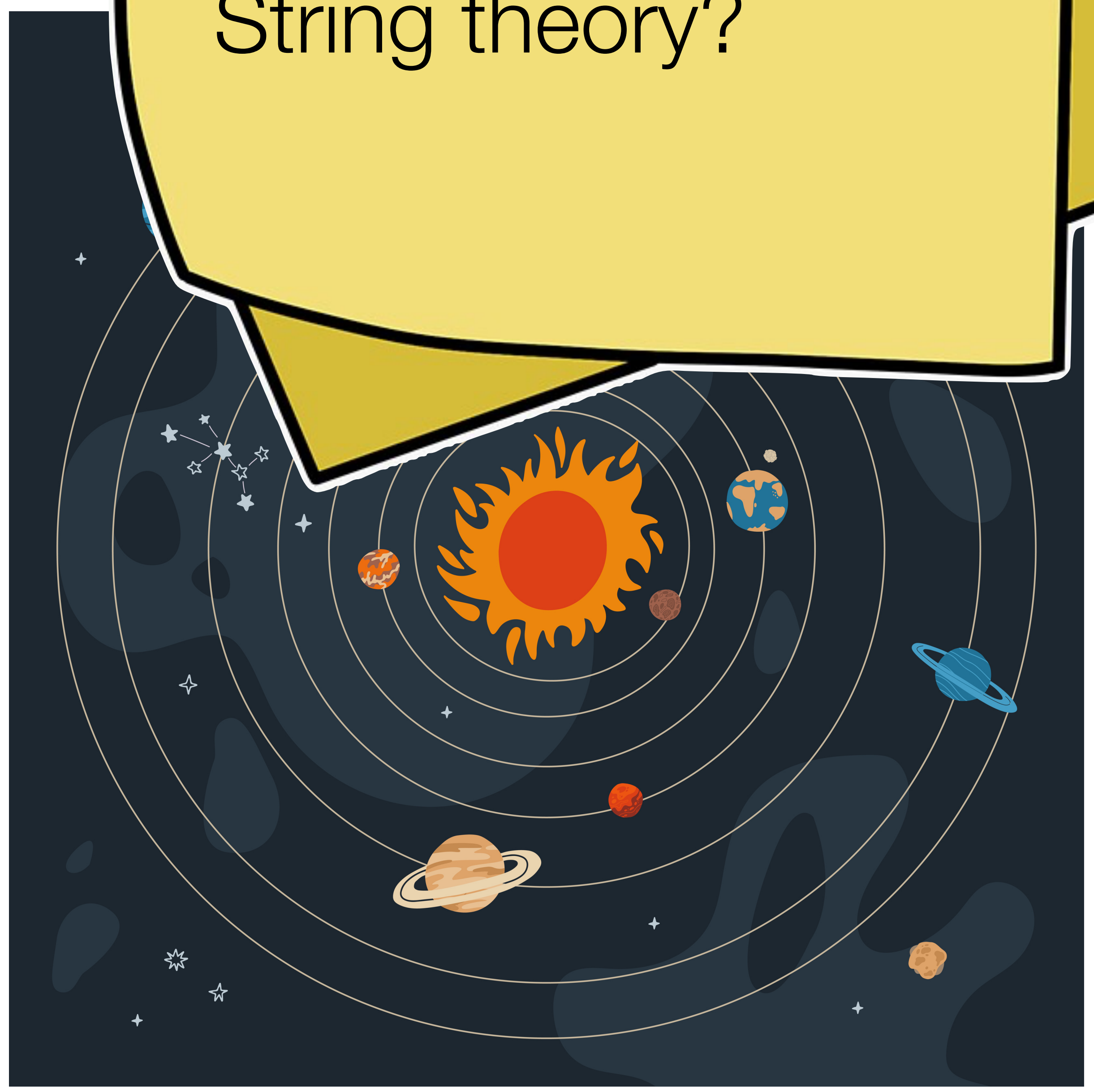


Quantum gravity?

String theory?



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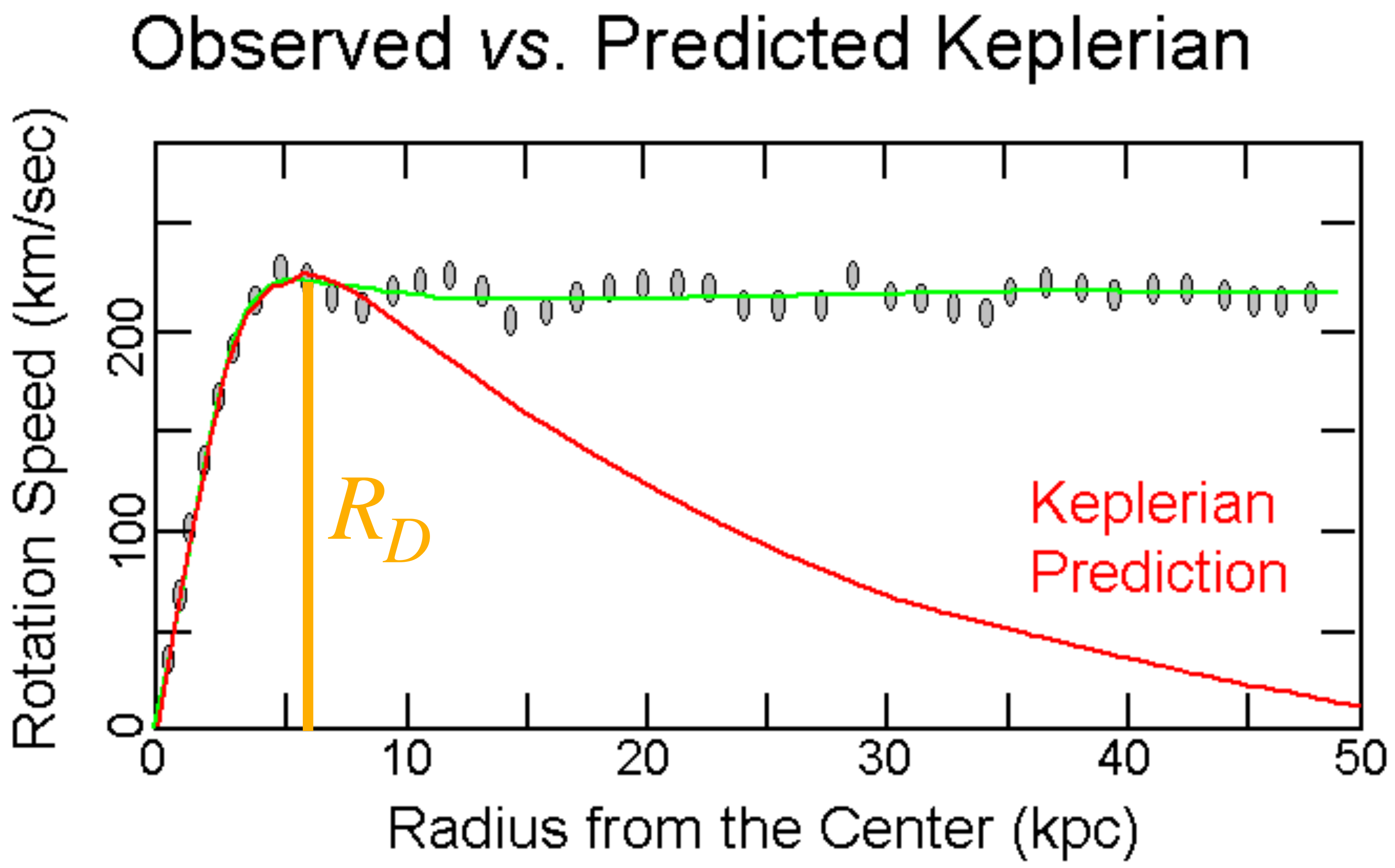
Missing piece #2:
Dark matter

Evidence of additional non-luminous mass in the Universe from gravitational effects at different scales



Galaxy speed outside galactic disk:

$$v_{r>R_D} \propto \frac{M}{r^{1/2}}$$

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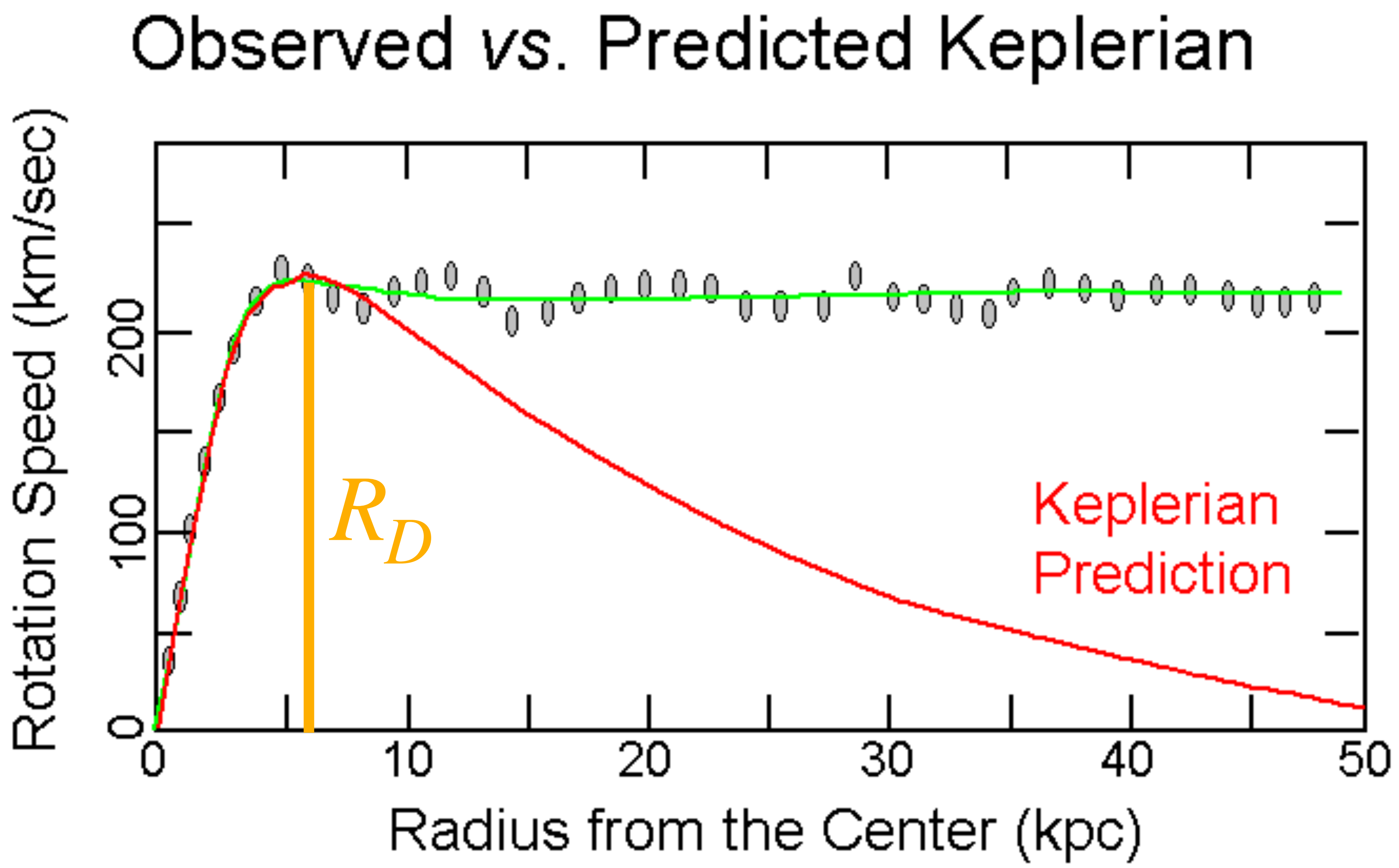

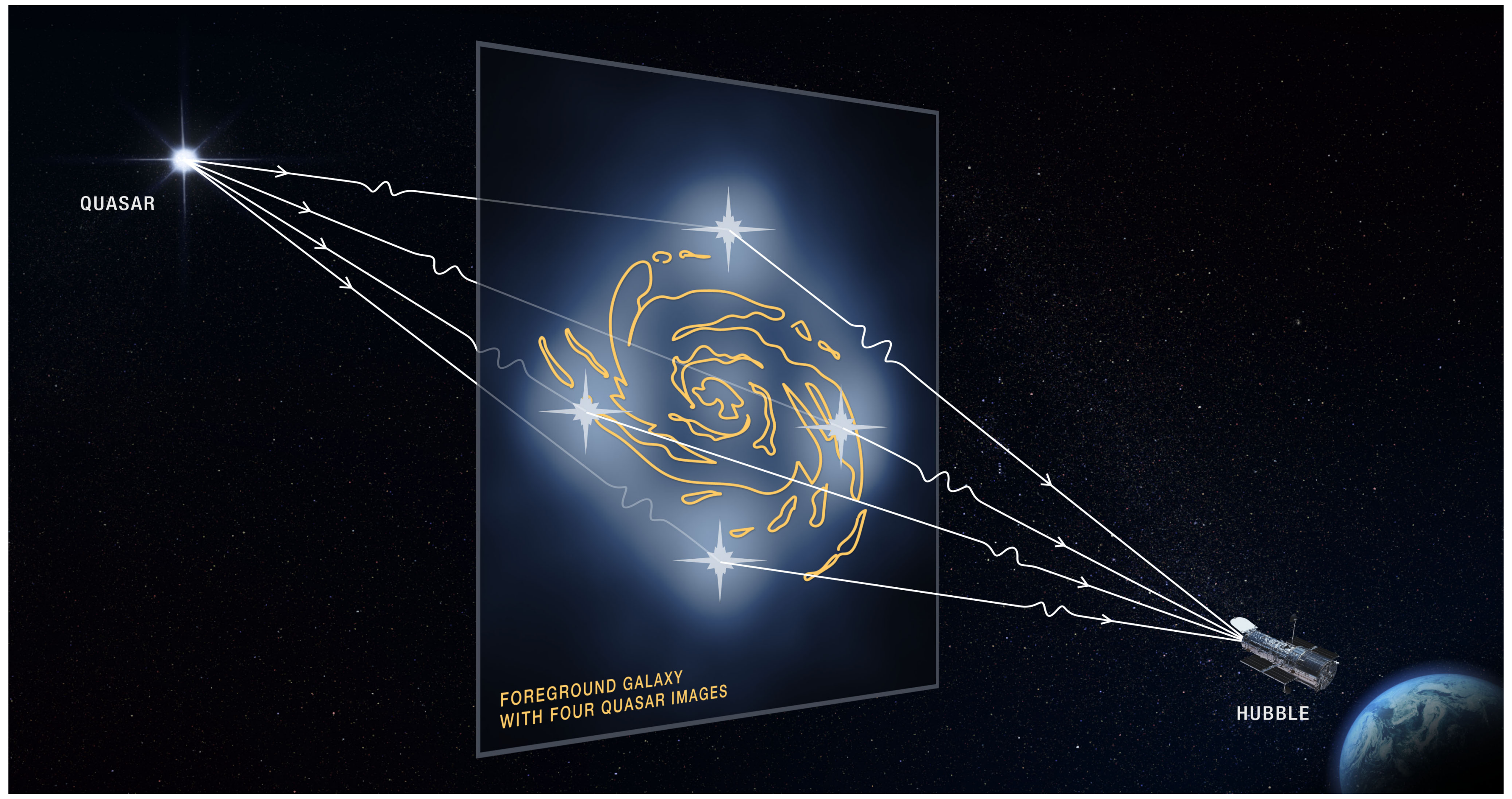

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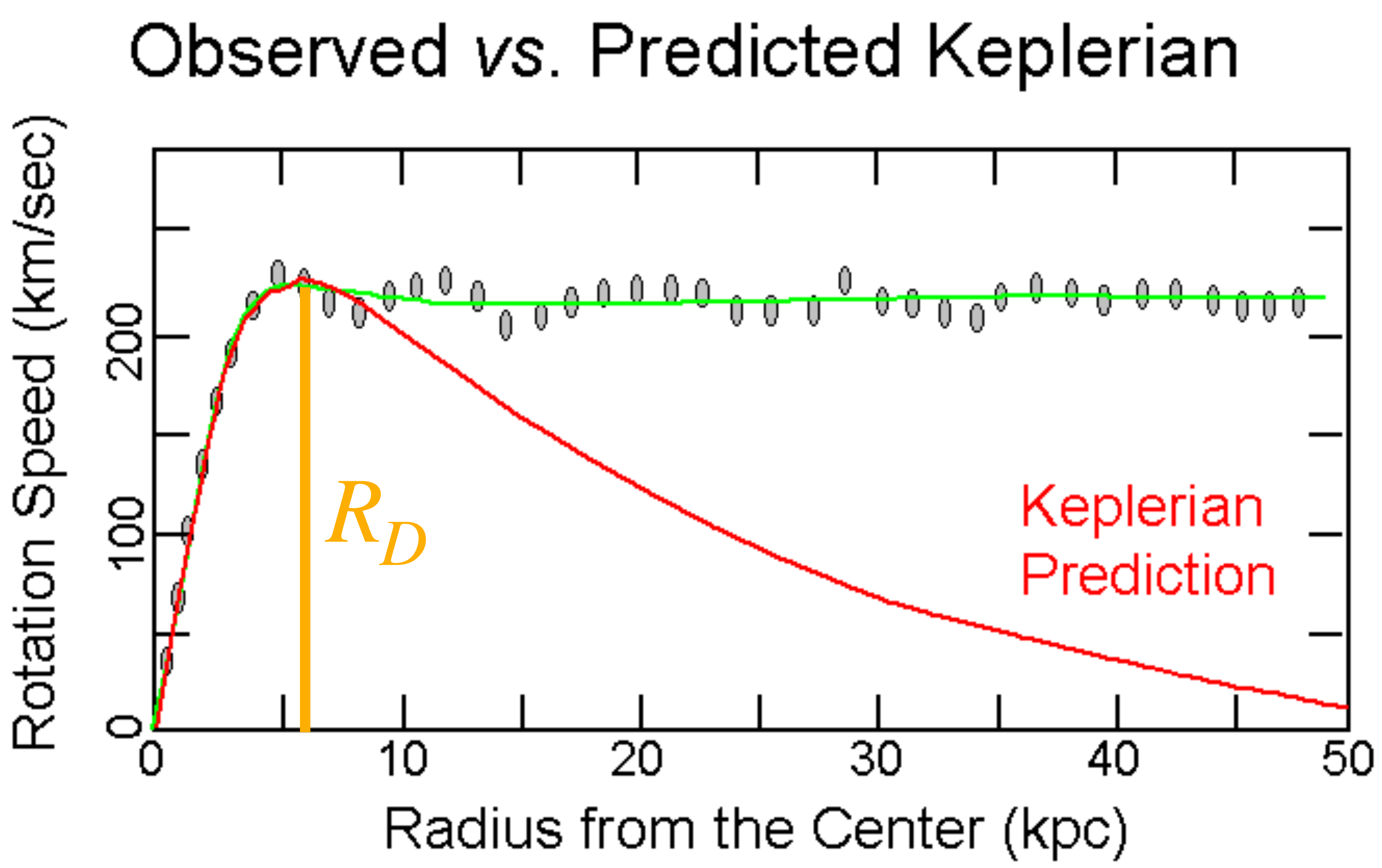

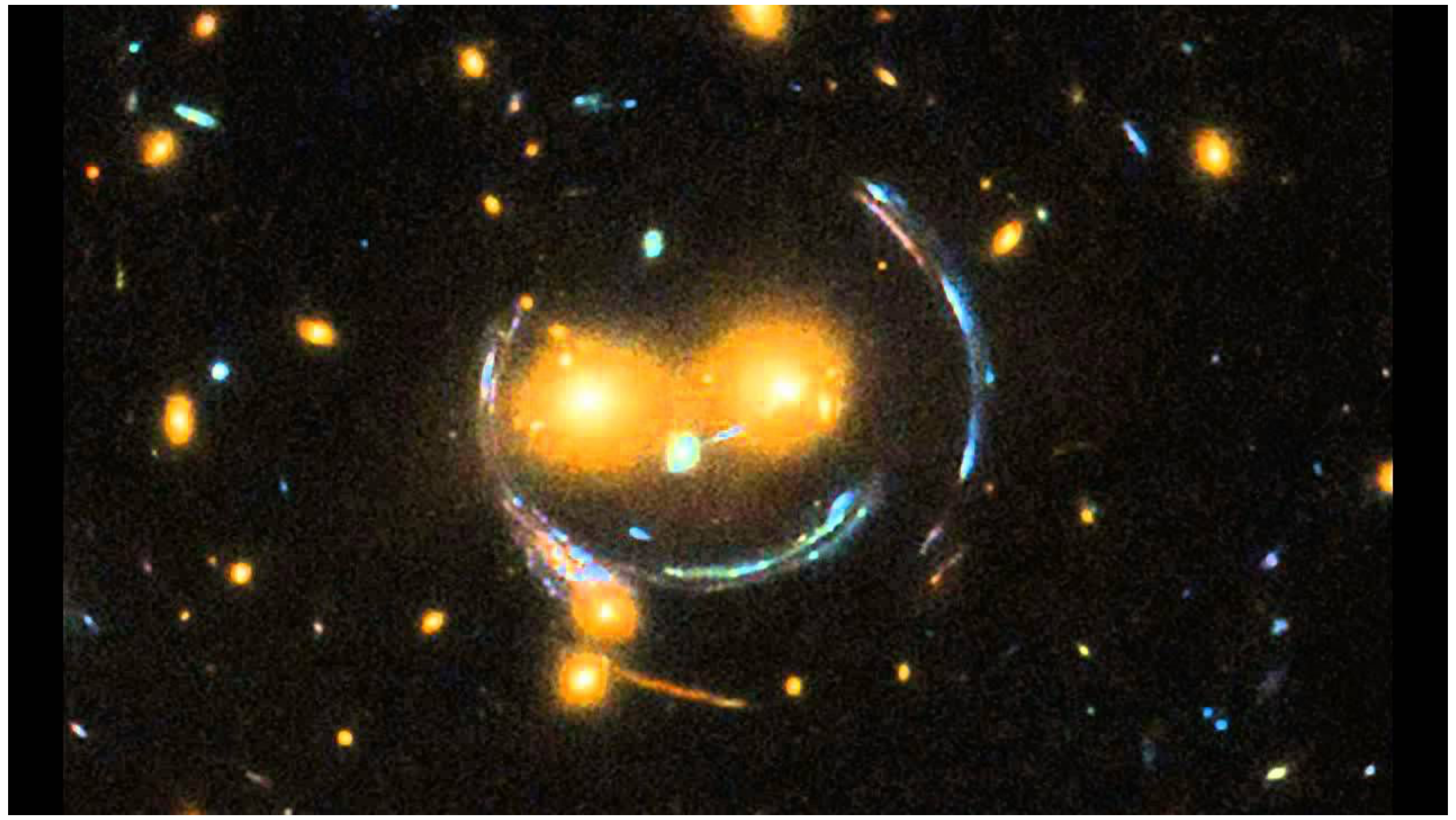

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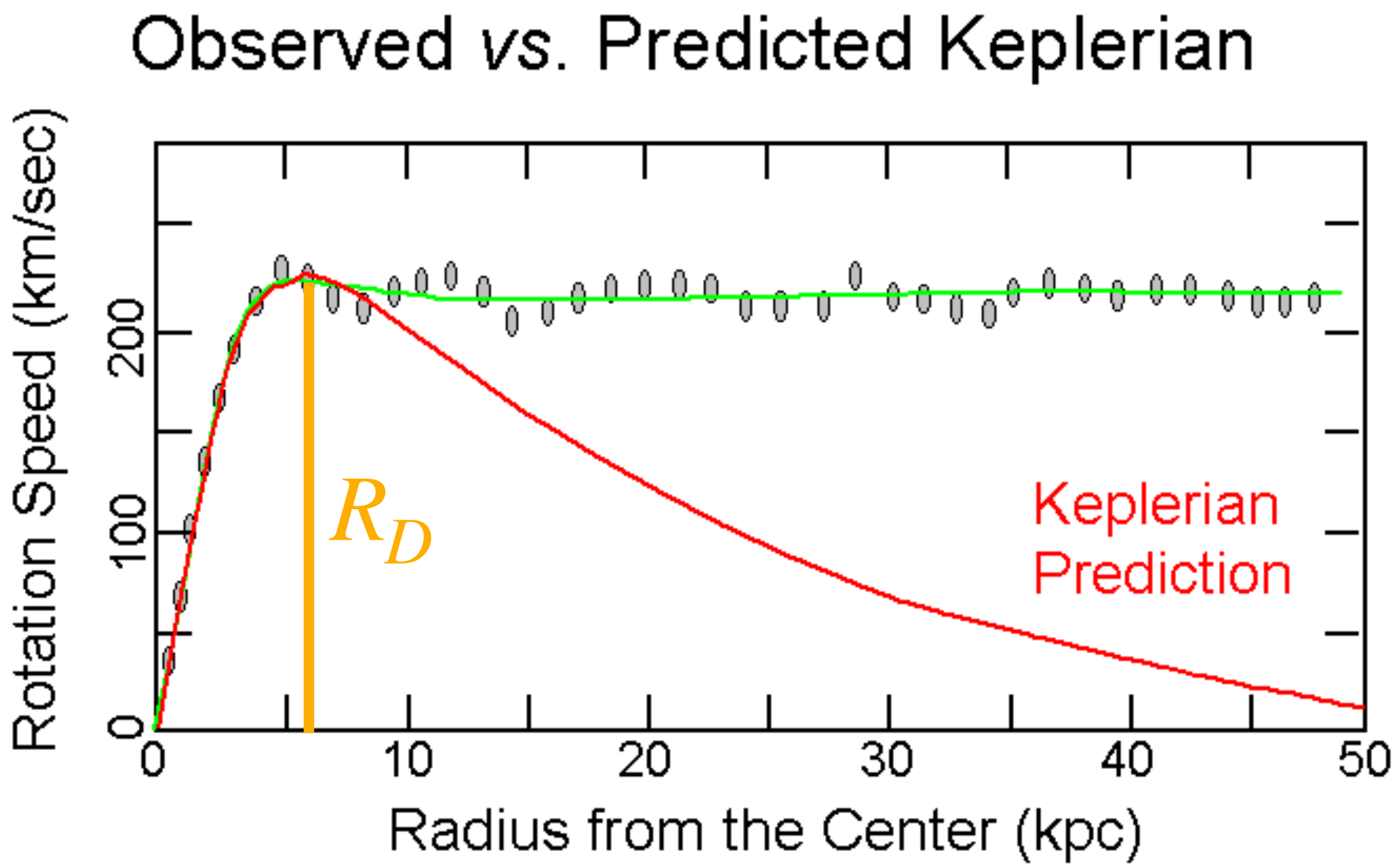

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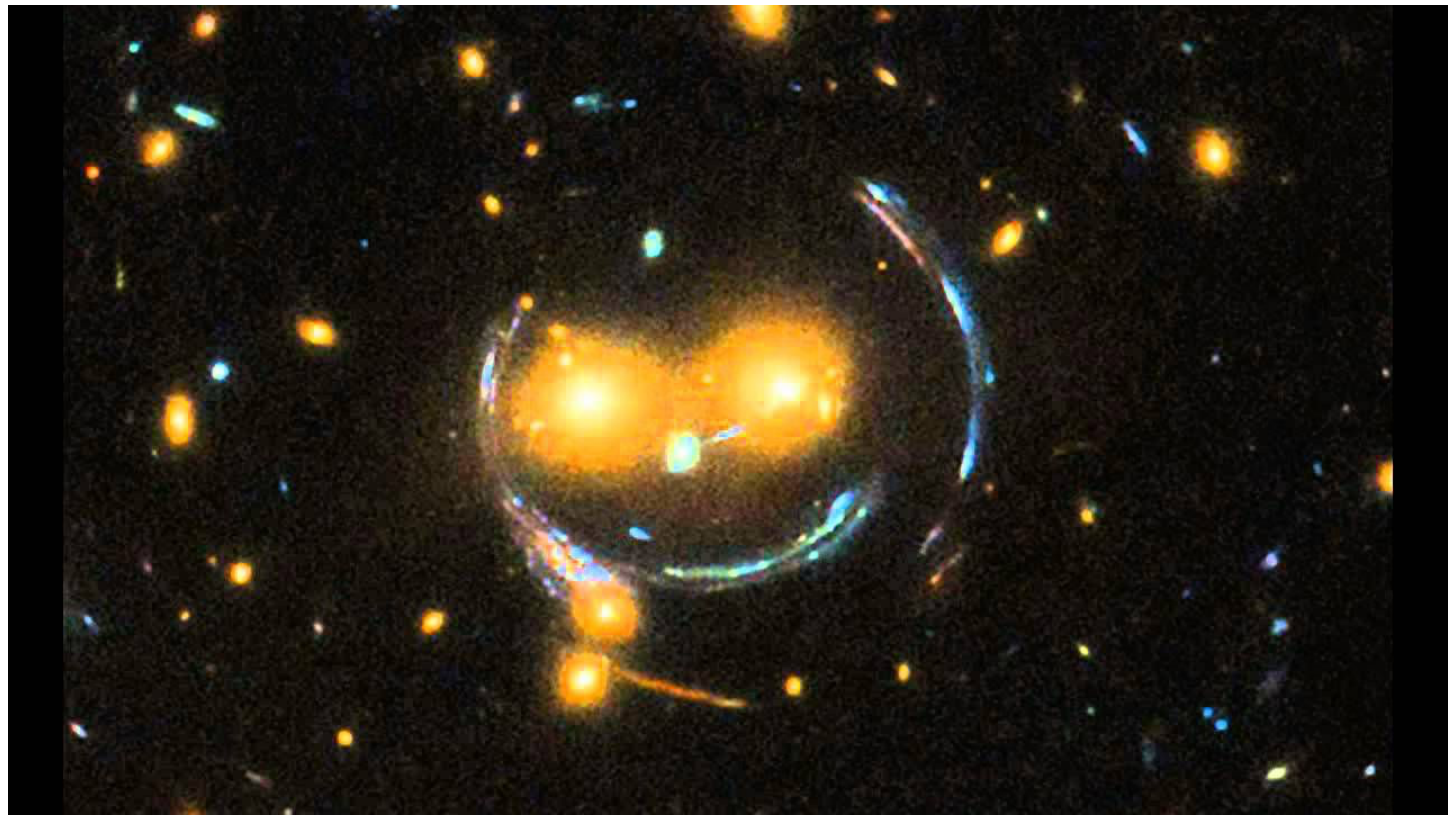

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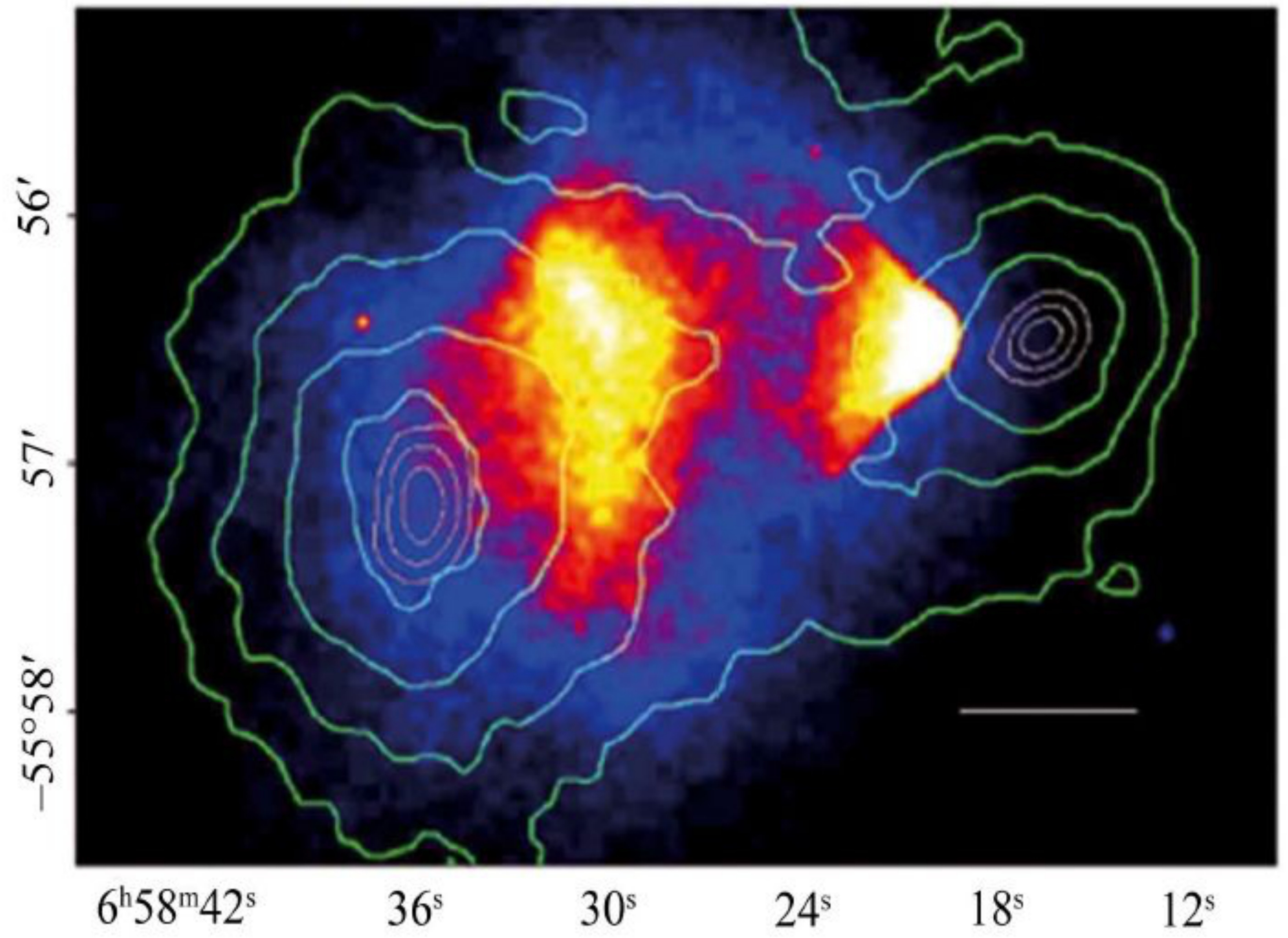

Lensing measurement → additional mass in the cluster of galaxy

Missing piece #2: Dark matter

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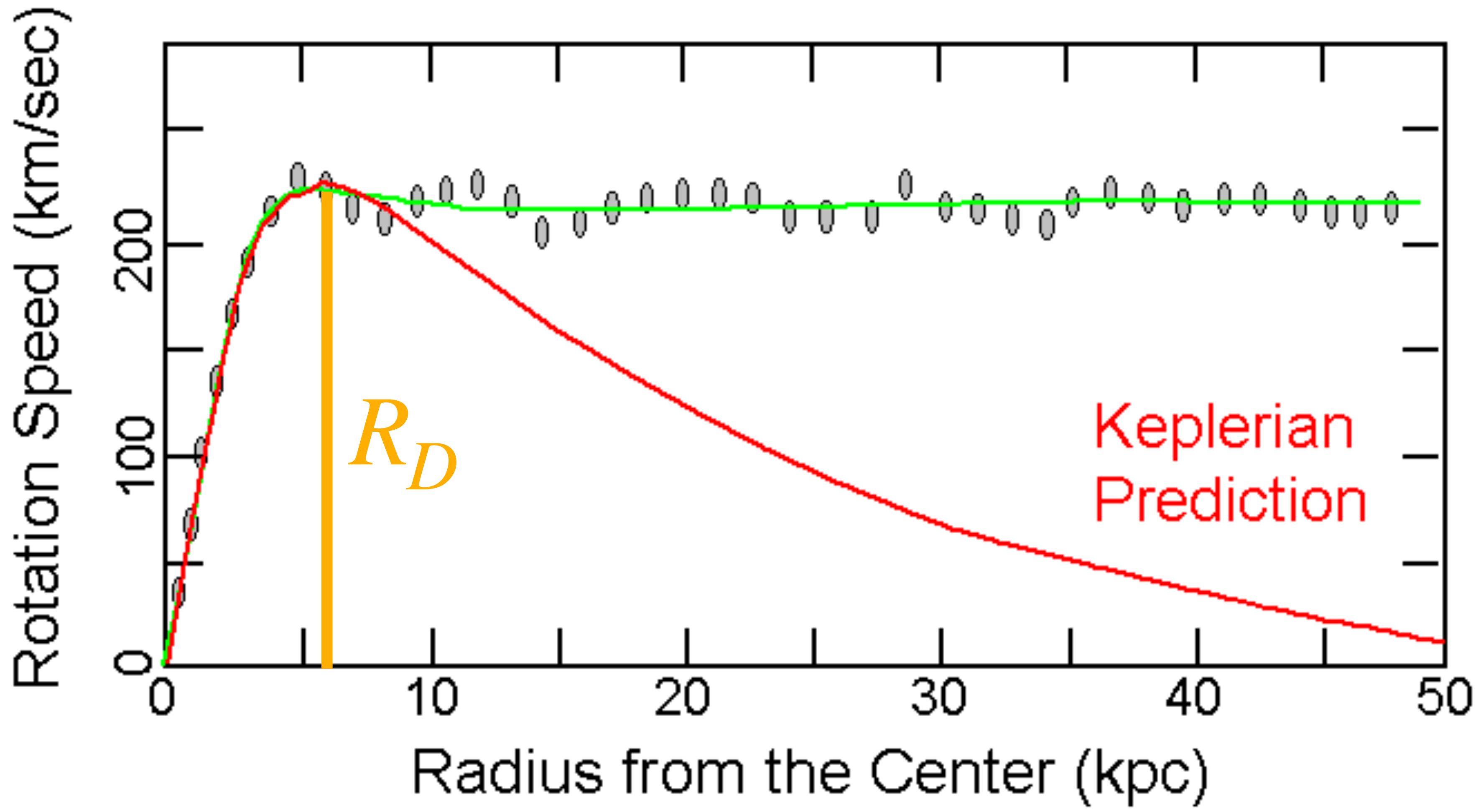
Modified gravity?

Weakly Interactive Massive Particles?

New Dark Sectors?

Observed *vs.* Predicted Keplerian



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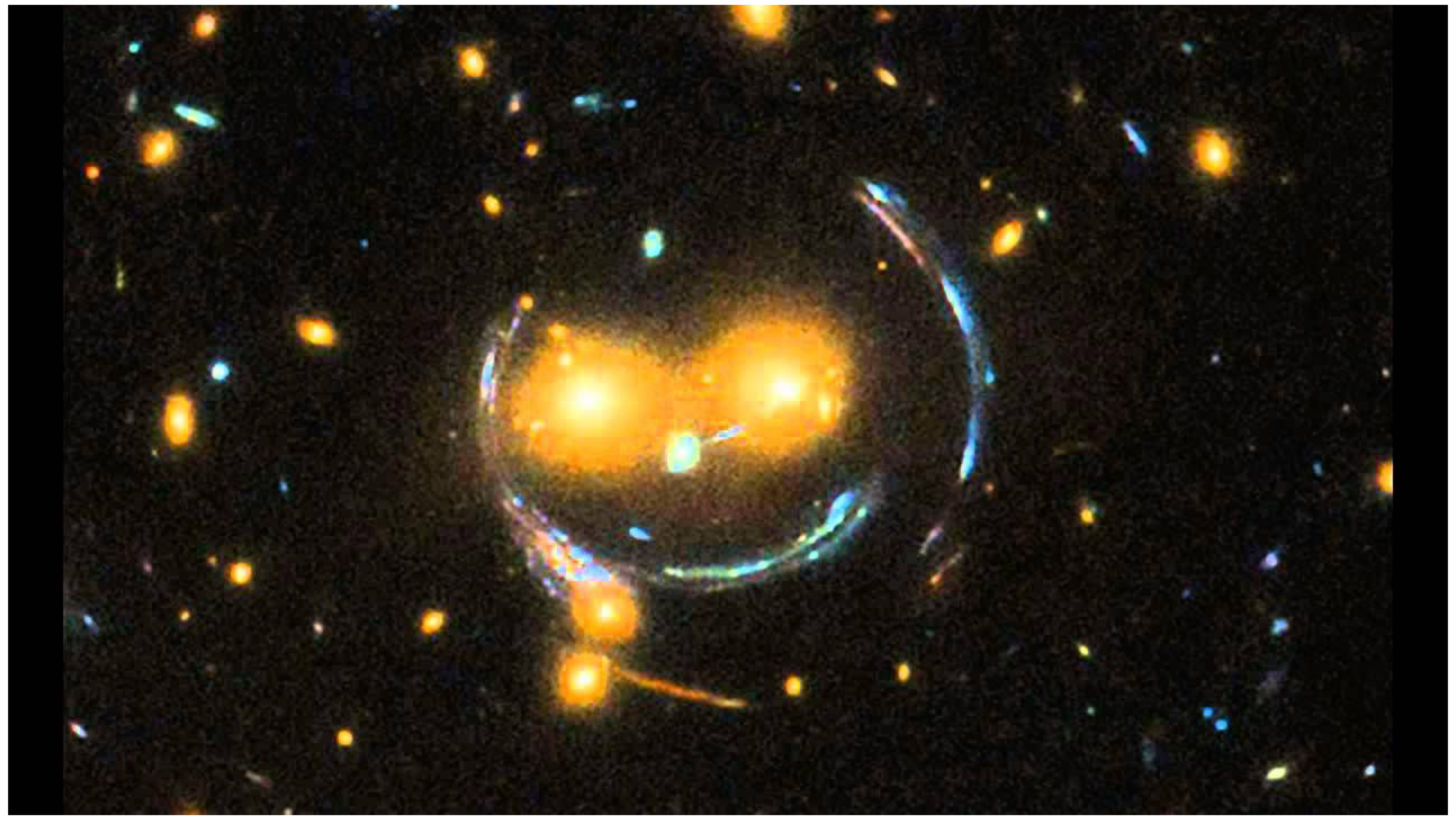

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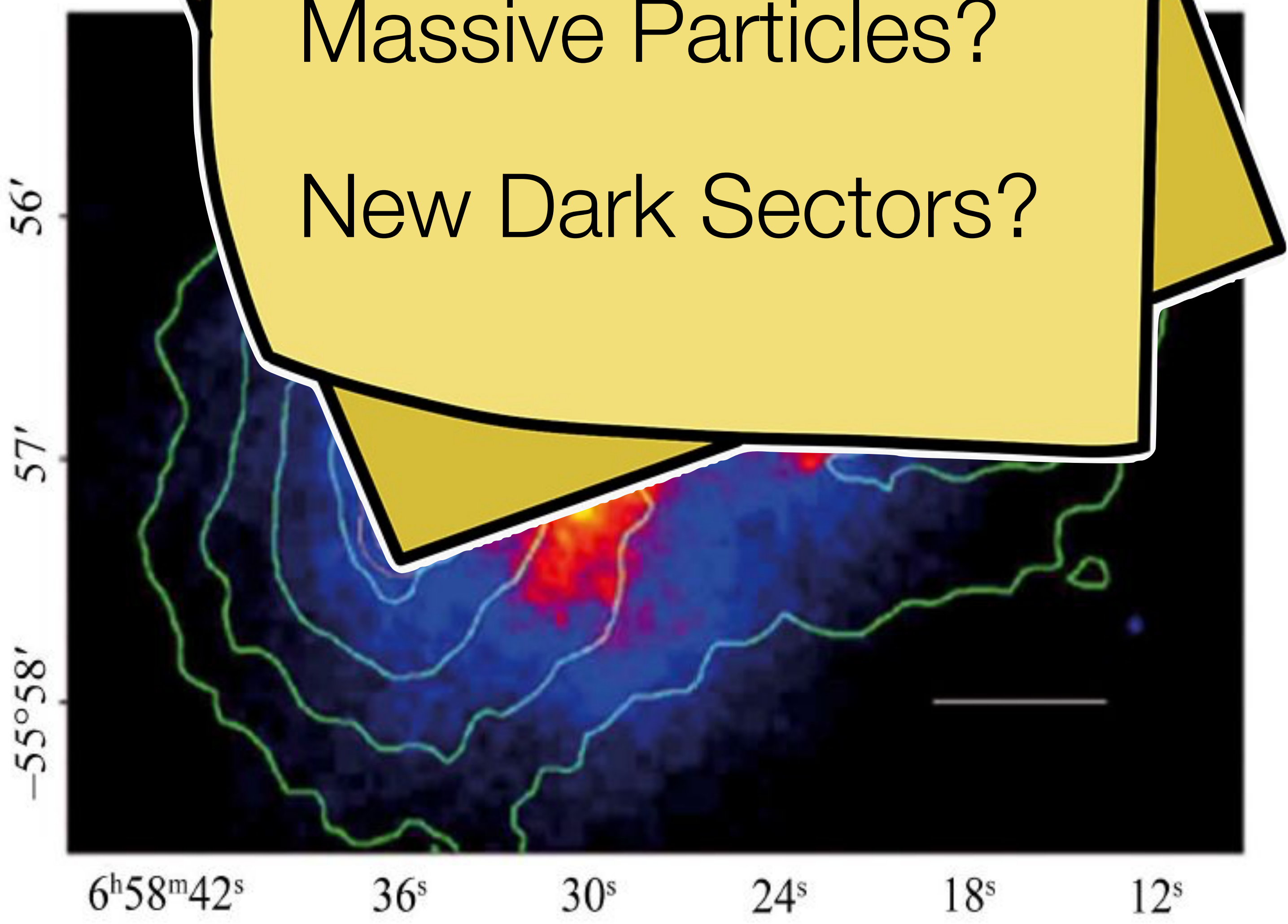

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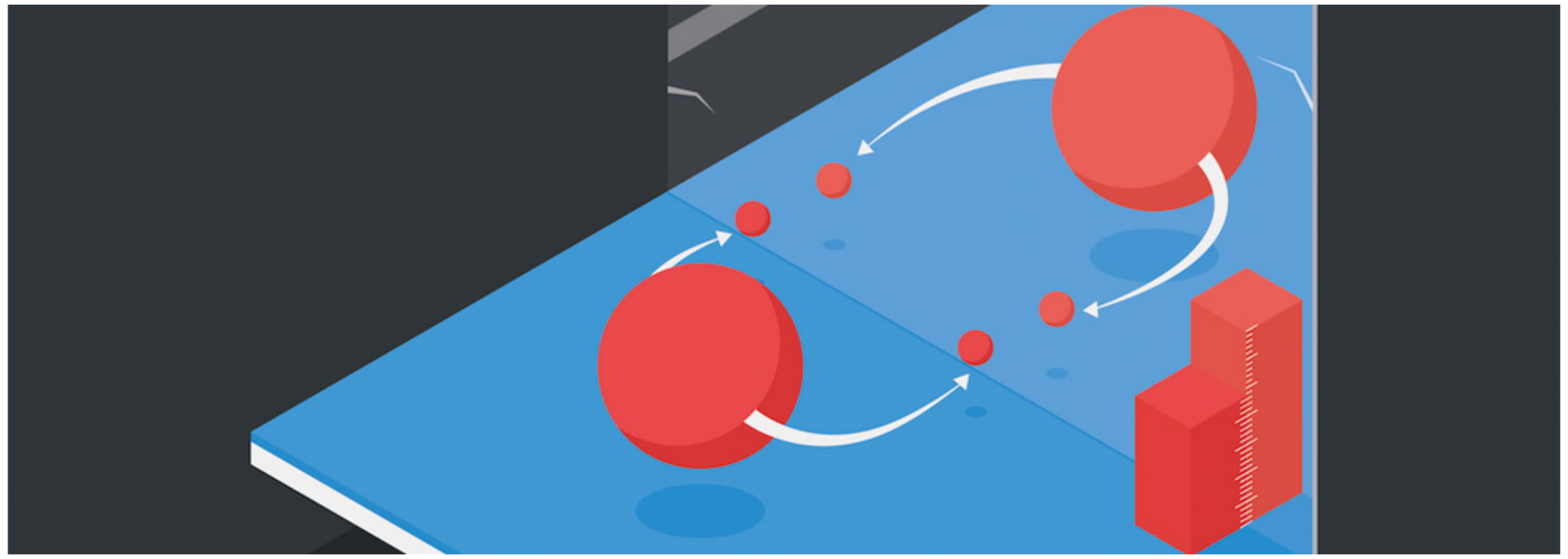
Anti-matter is twin of matter:

Same spin, mass but opposite charge



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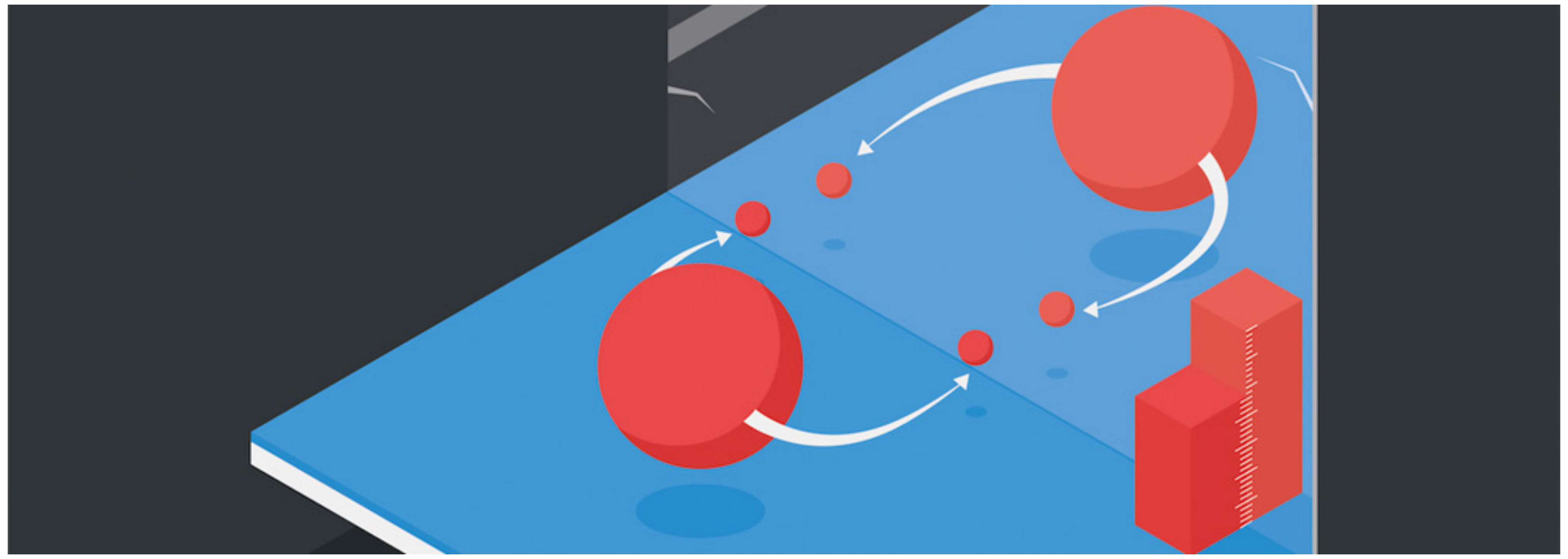
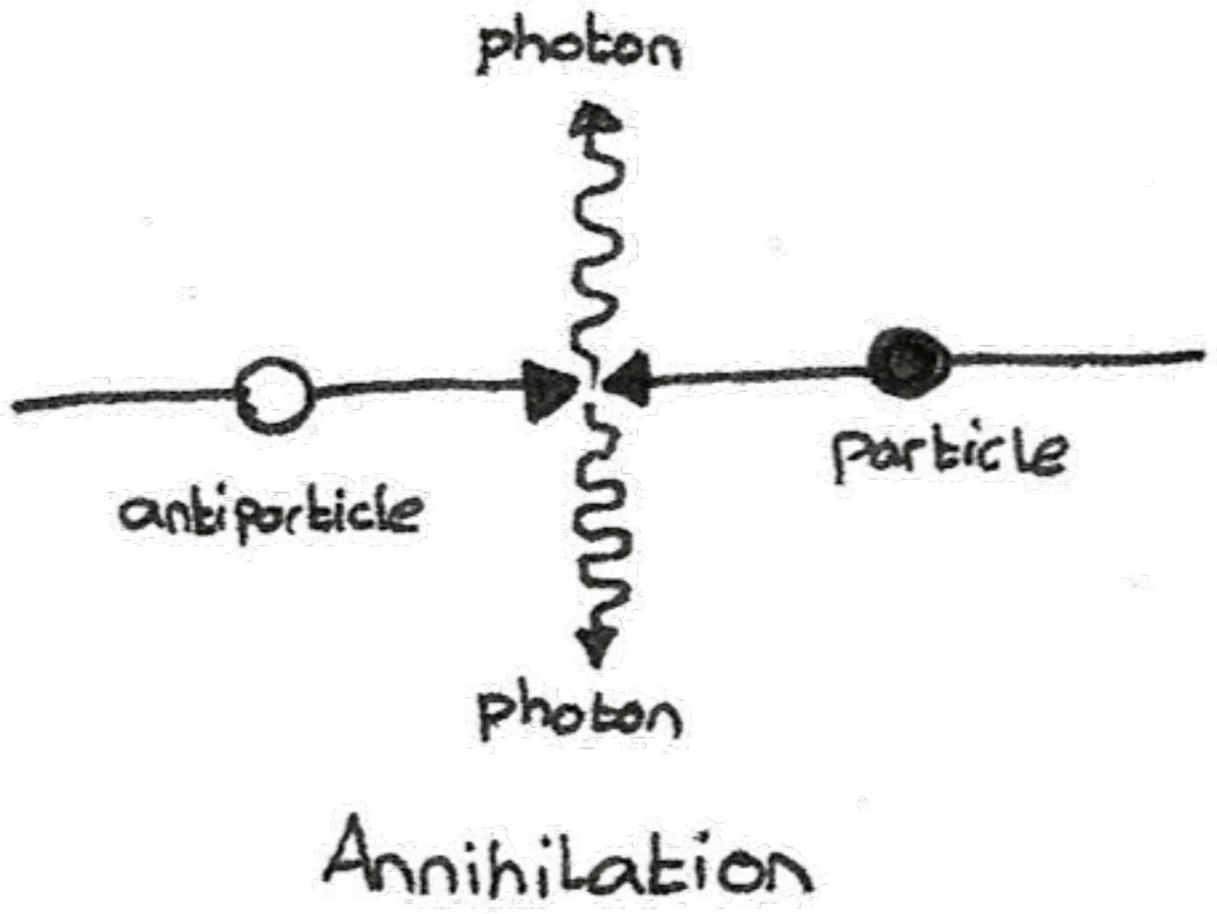


In interaction between particle and its antiparticle the annihilate, releasing energy!



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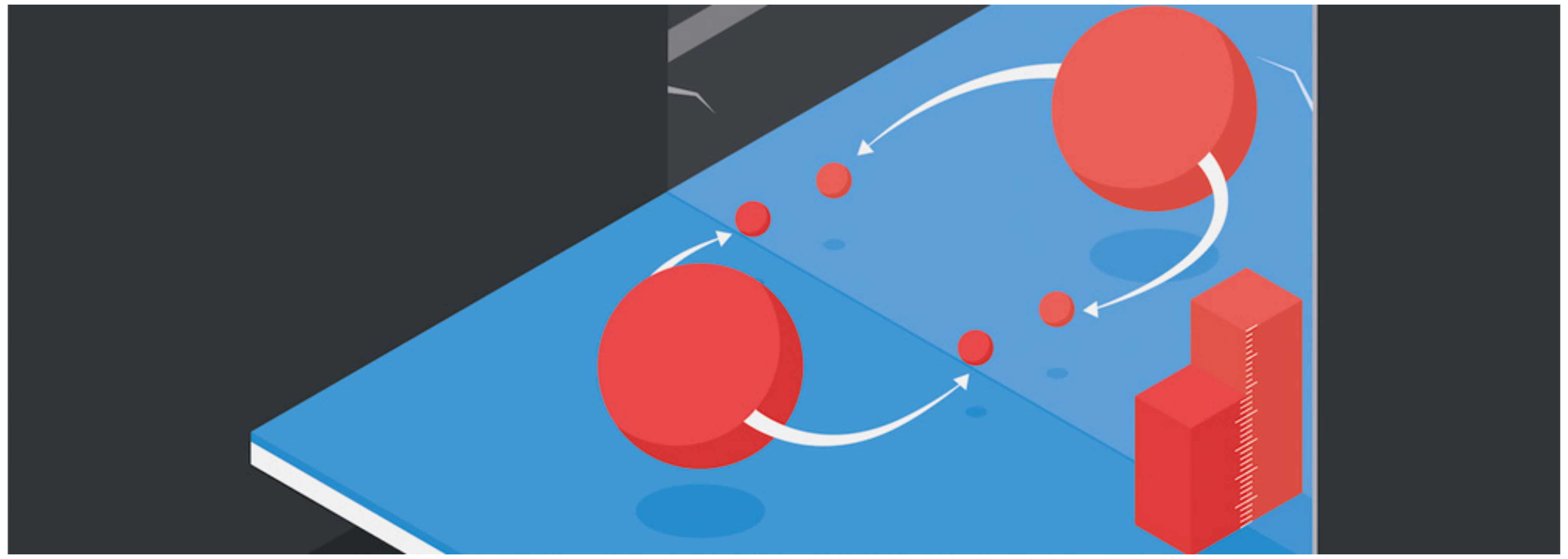

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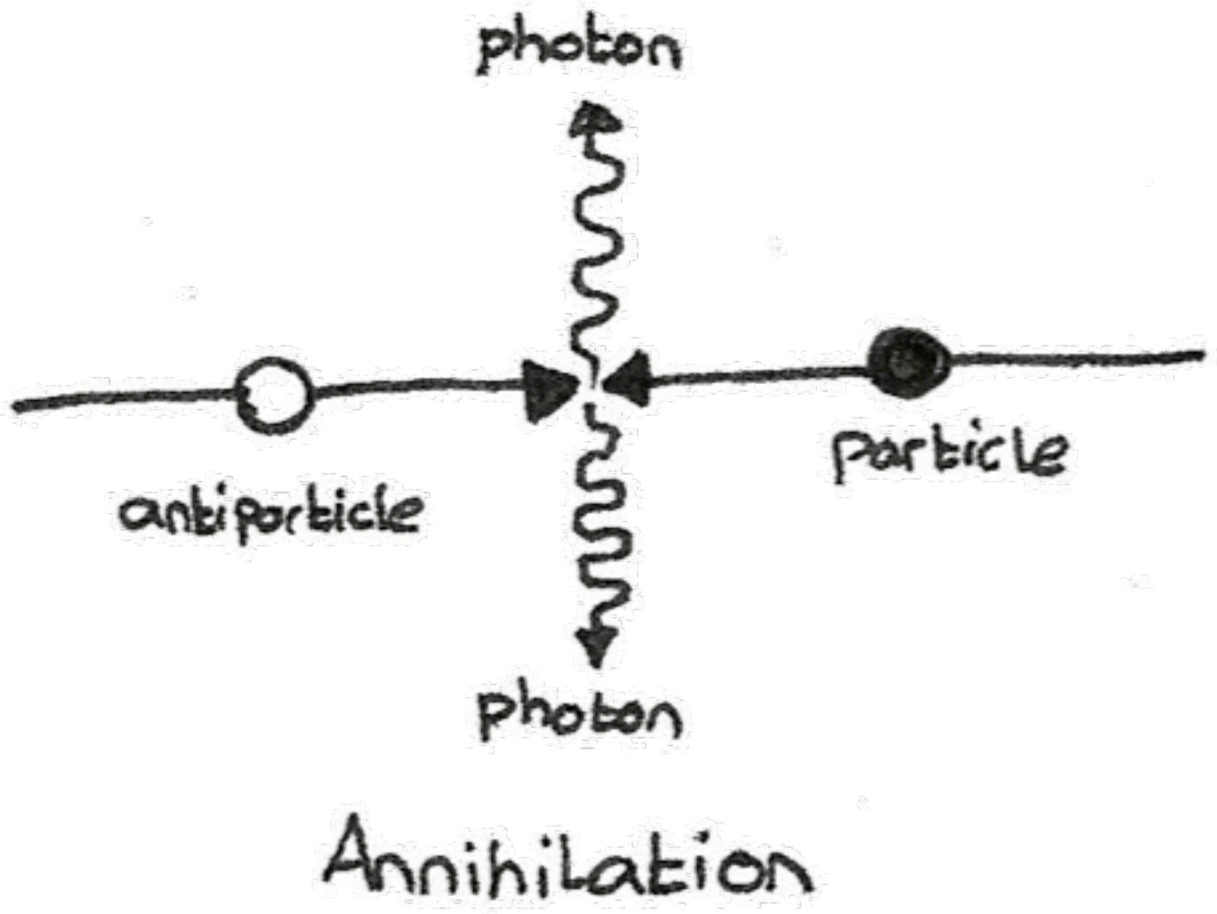
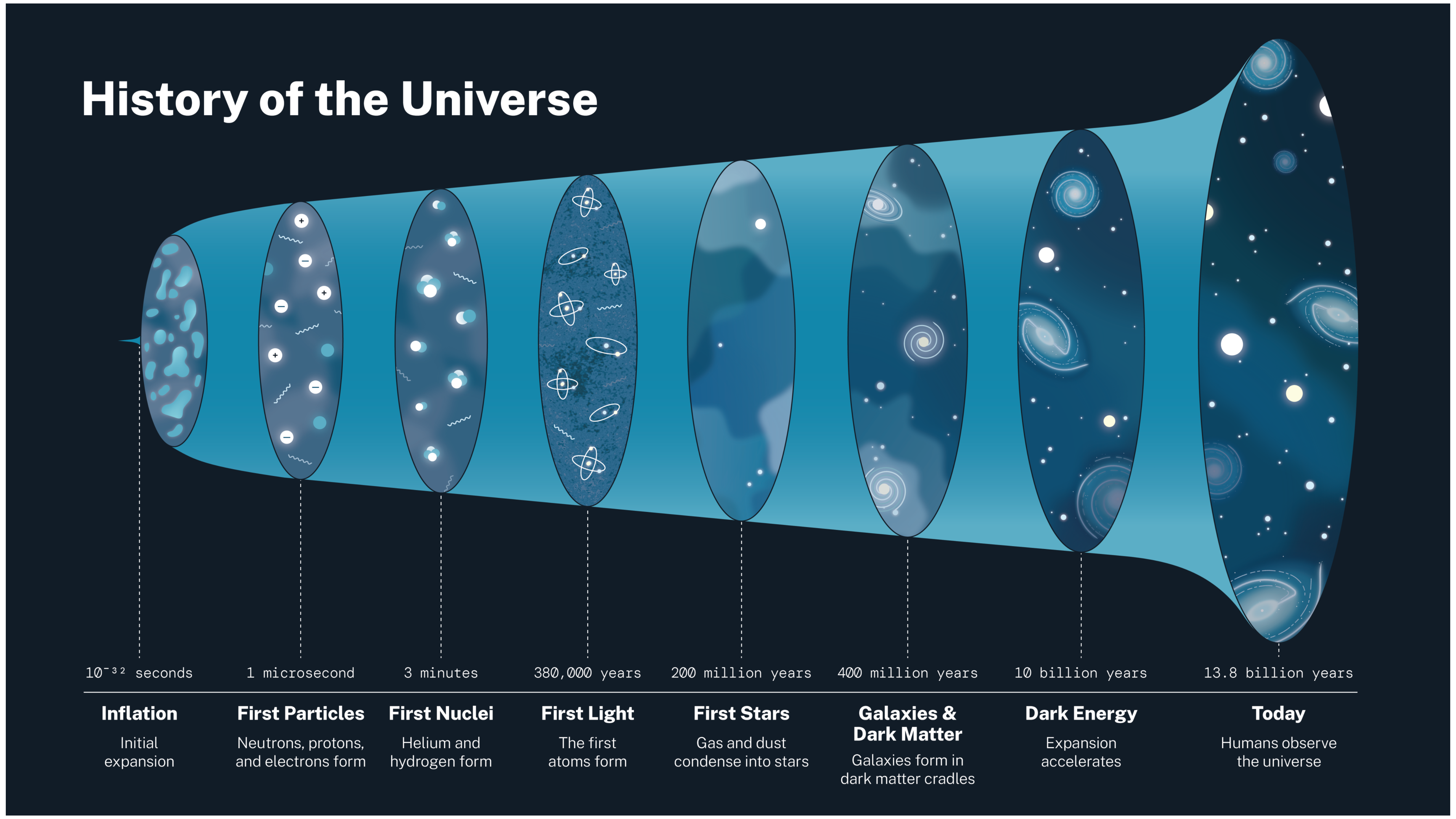


Our existence poses a question: where is antimatter?



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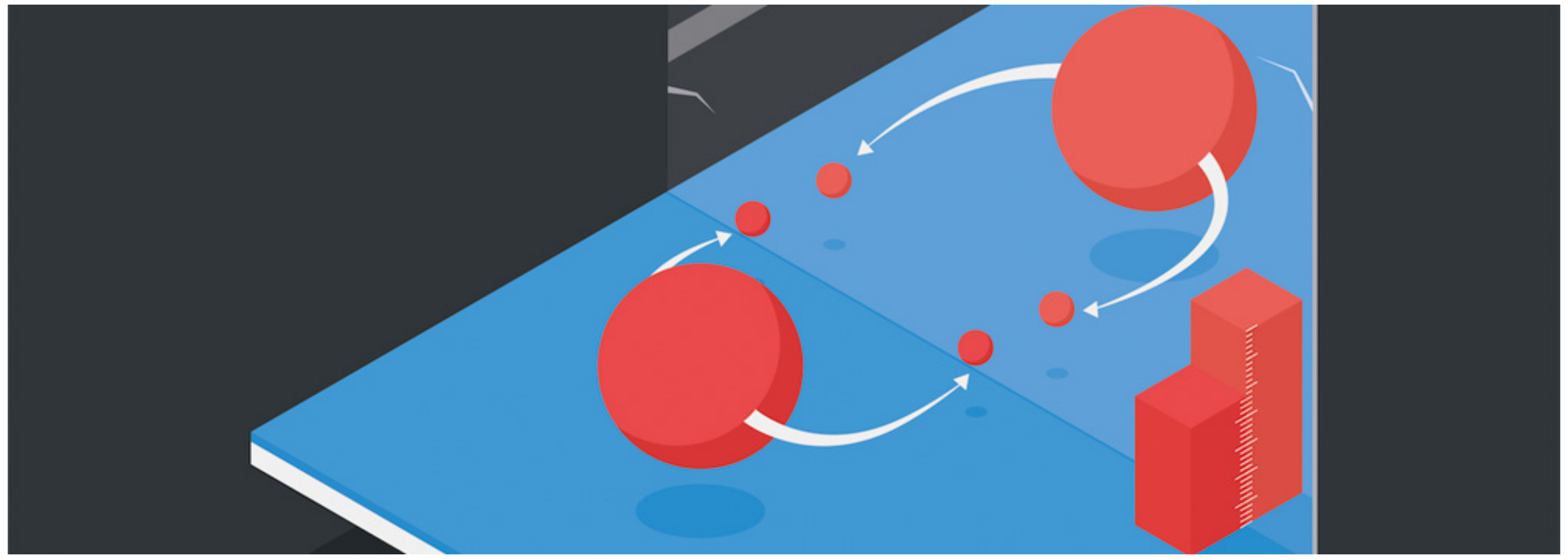

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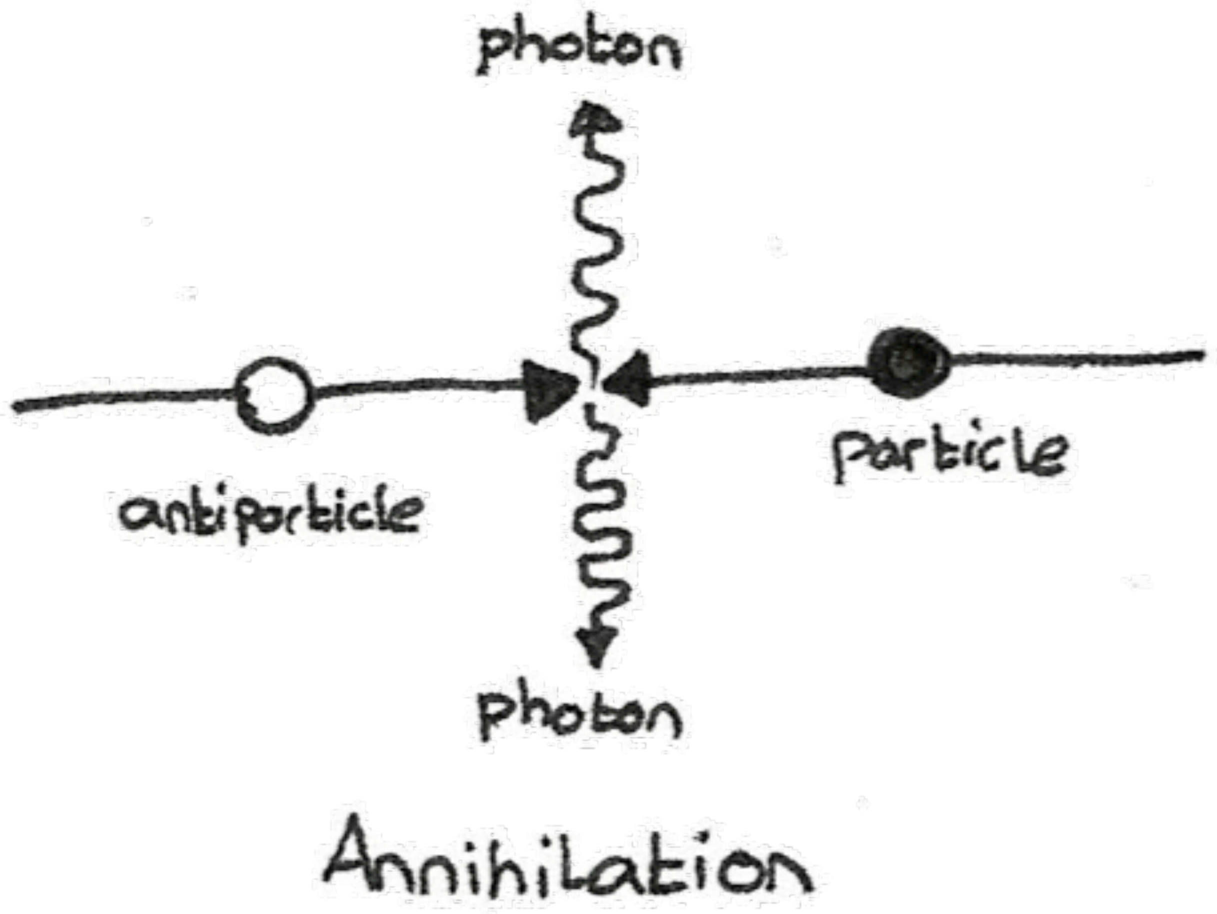

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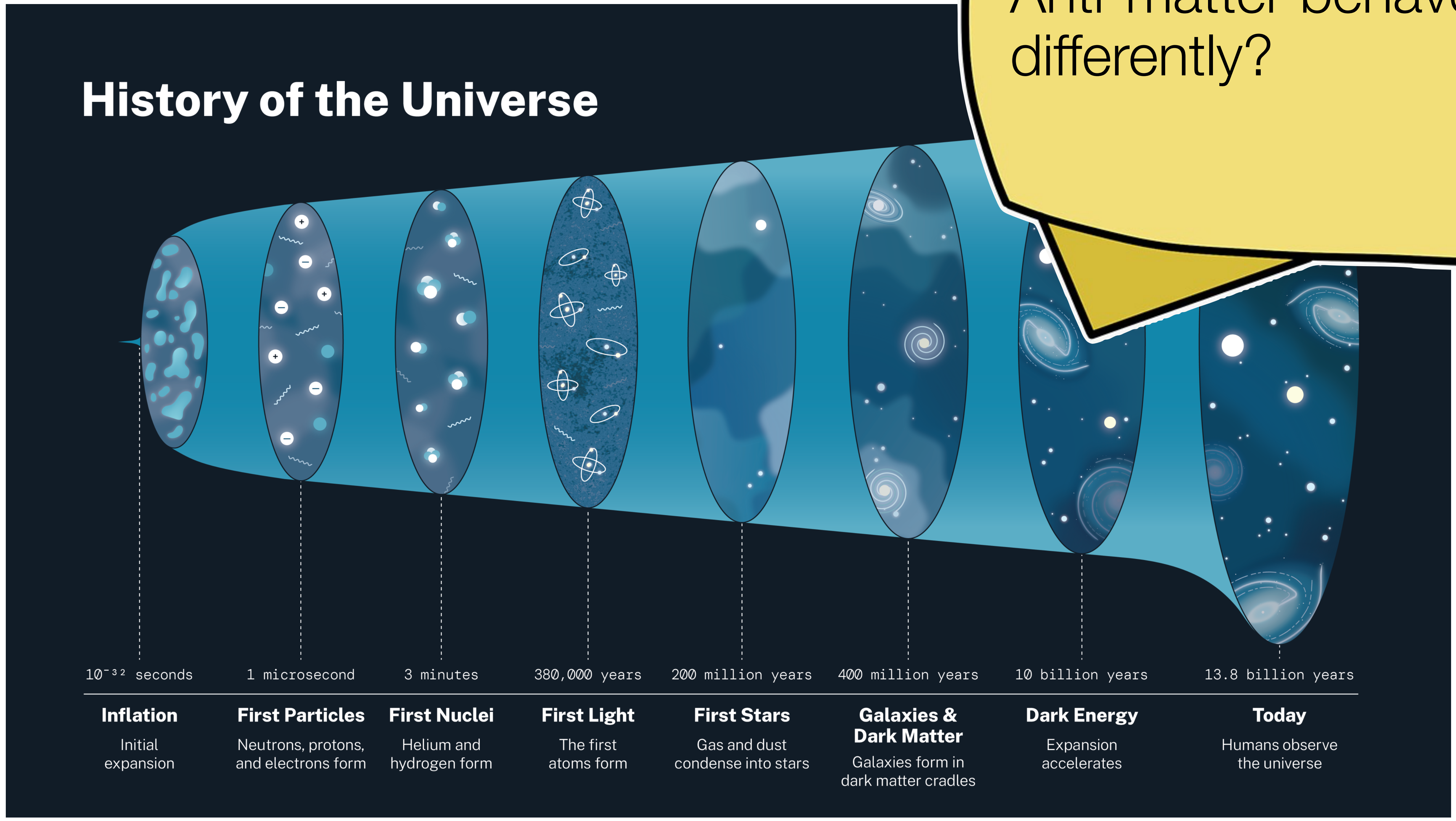

Anti-matter produced in different quantity?

Anti-matter behaves differently?

Missing piece #4: Neutrino mass puzzle

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi} \not{D} \psi + h.c. + \psi_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

All particles (ψ) acquire their mass through interaction with Higgs field (ϕ)

The mass term is composed of Left-handed and Right-handed chiral particles

For very energetic particles this means:

Right-handed neutrinos don't exist, but they are massive → how do they acquire their mass? Why are they so light?

Missing piece #4: Neutrino mass puzzle

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi} \not{D} \psi + h.c. + \psi_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

All particles (ψ) acquire their mass through interaction with Higgs field (ϕ)

The mass term is composed of Left-handed and Right-handed chiral particles

For very energetic particles this means:

Right-handed neutrinos don't exist, but they are massive → how do they acquire their mass? Why are they so light?

Heavy Neutral Leptons?

Dirac Neutrinos?

Majorana Neutrinos?

Missing piece #5:
The naturalness/hierarchy/potential stability problem

Higgs boson mass much smaller than gravity energy scale (10^{17}, one hundred billiard, times smaller) → **hierarchy problem**

Higgs mass extremely small → some specific mathematics (cancellations) happening →fine-tuning or **naturalness problem**

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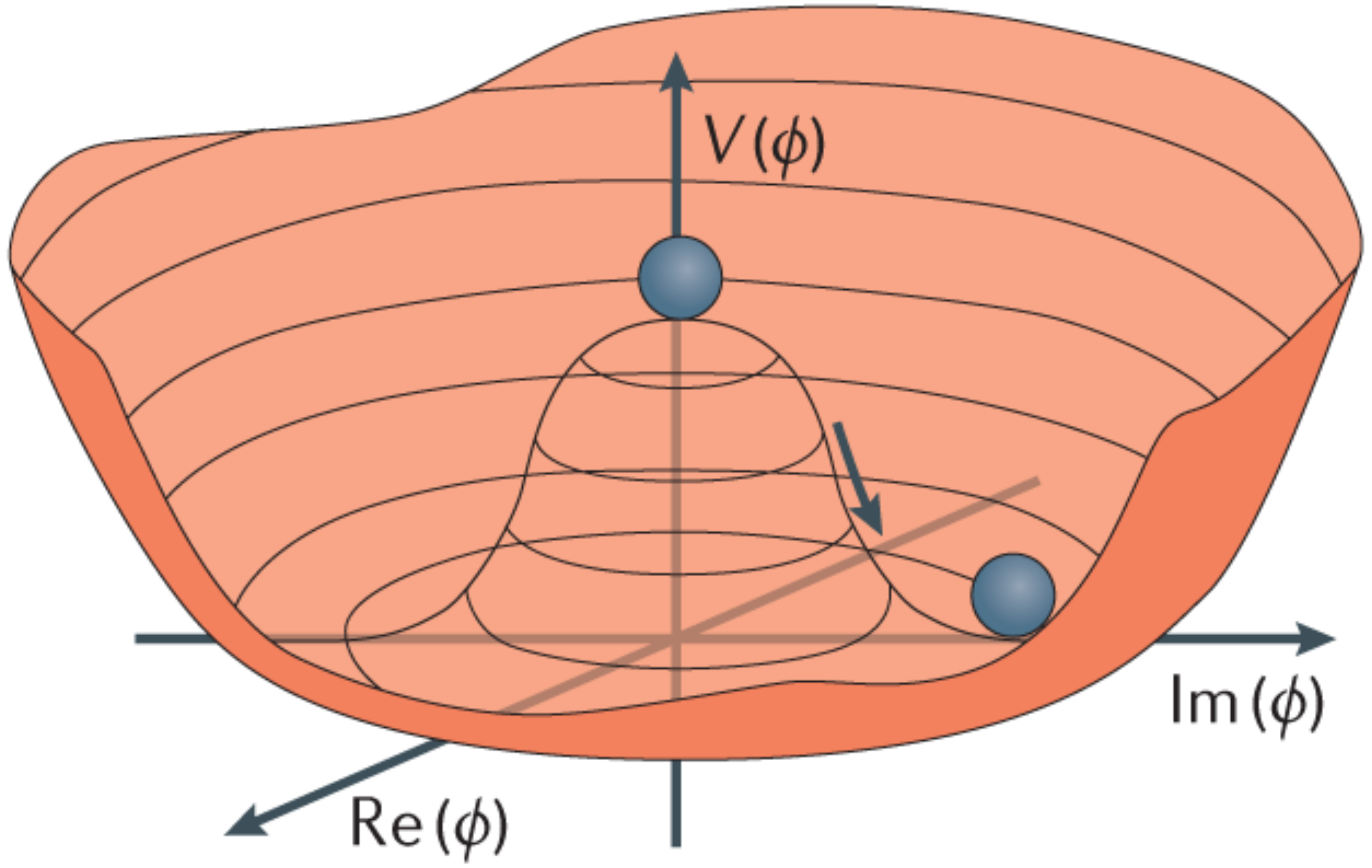

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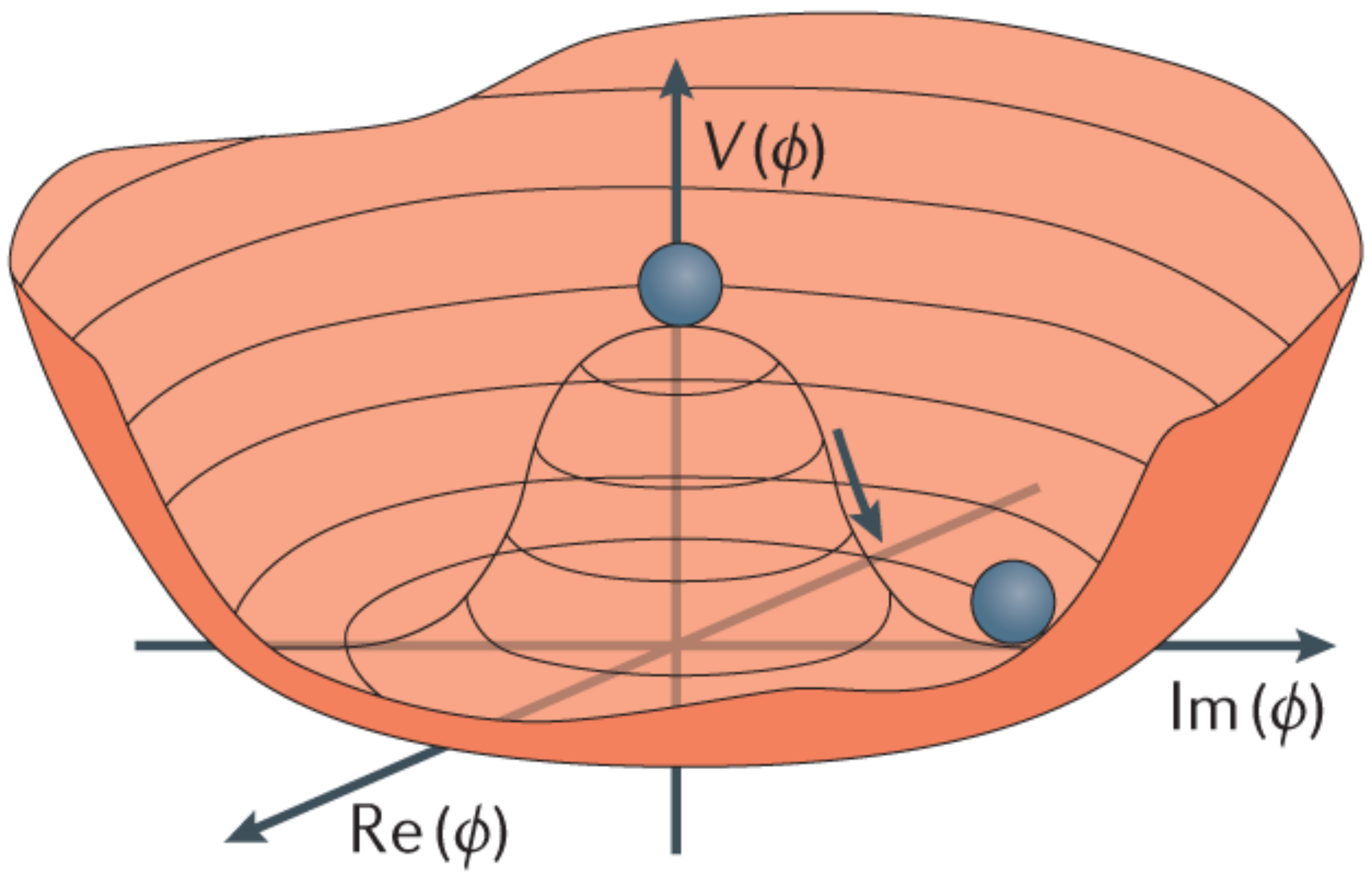

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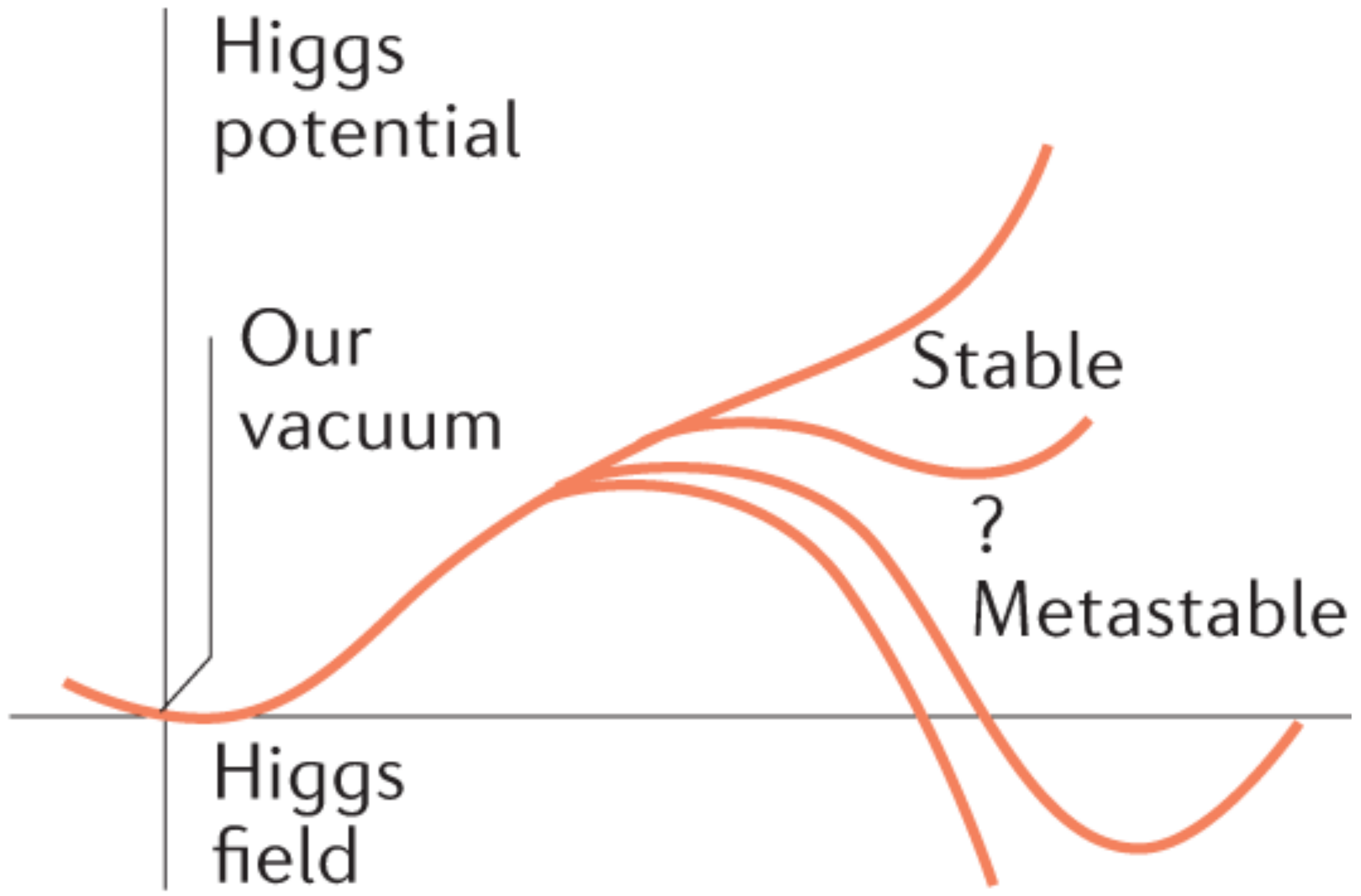

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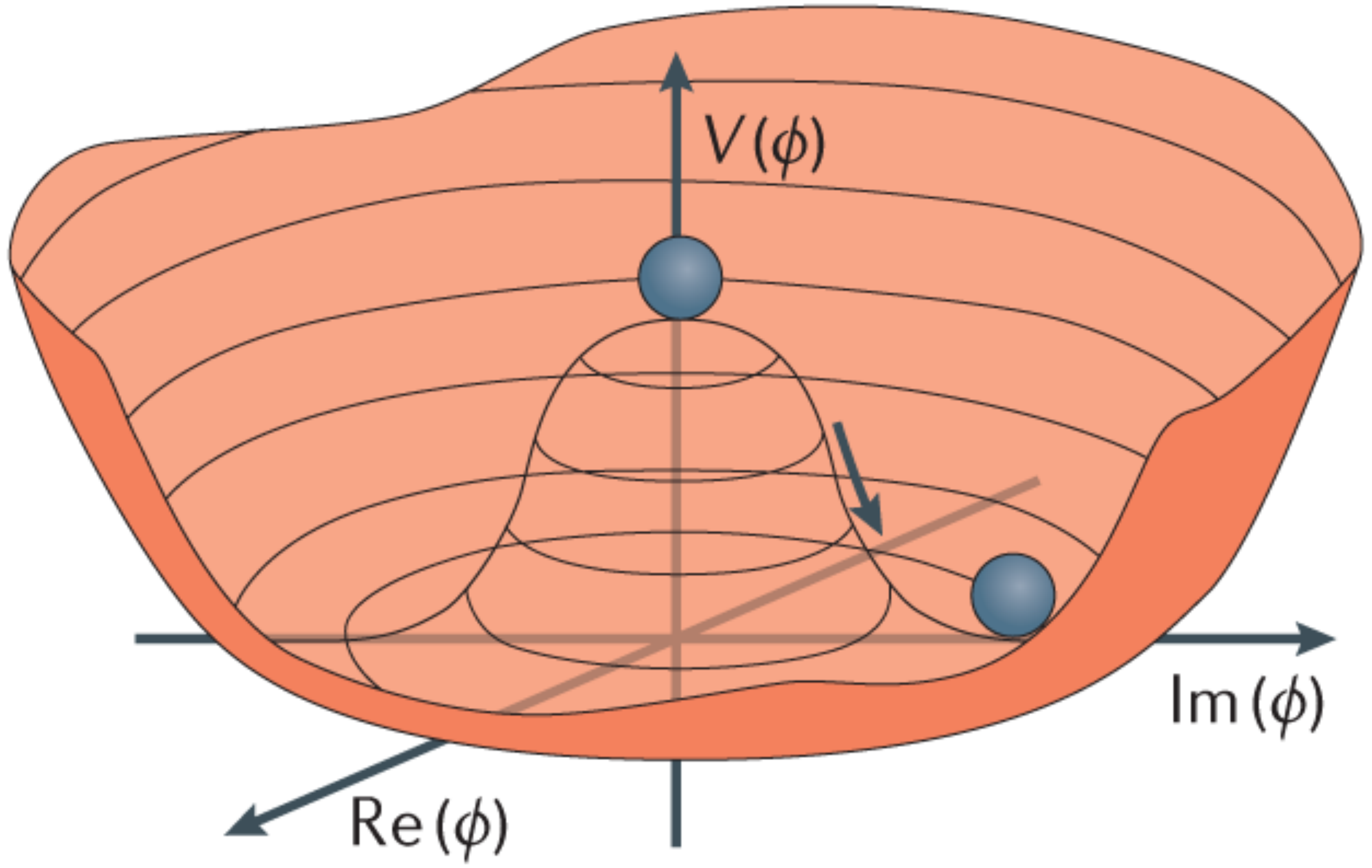

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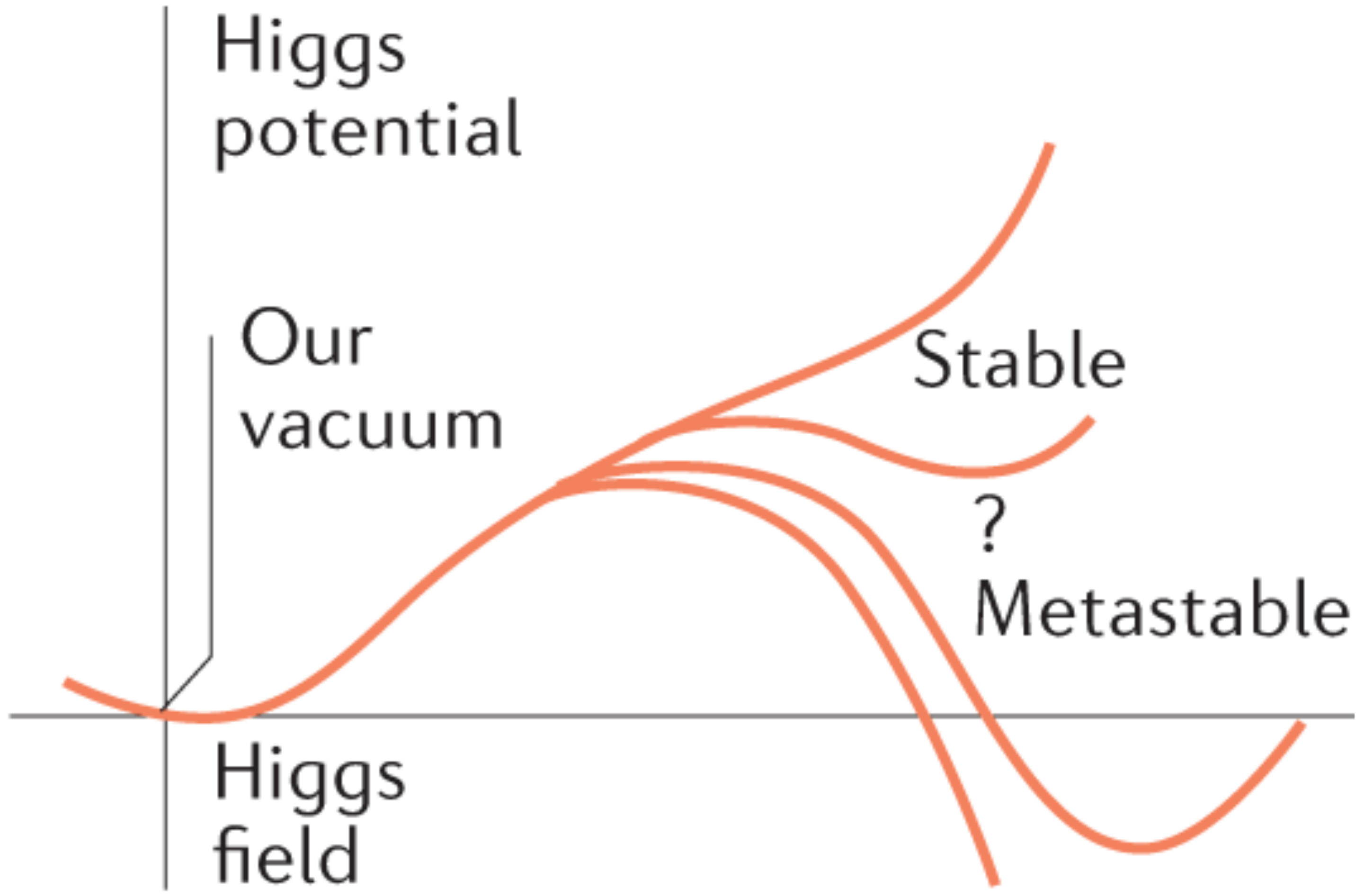

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Missing piece #5:
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SUperSYmmetry?

Extra dimensions?

Twin Higgs?

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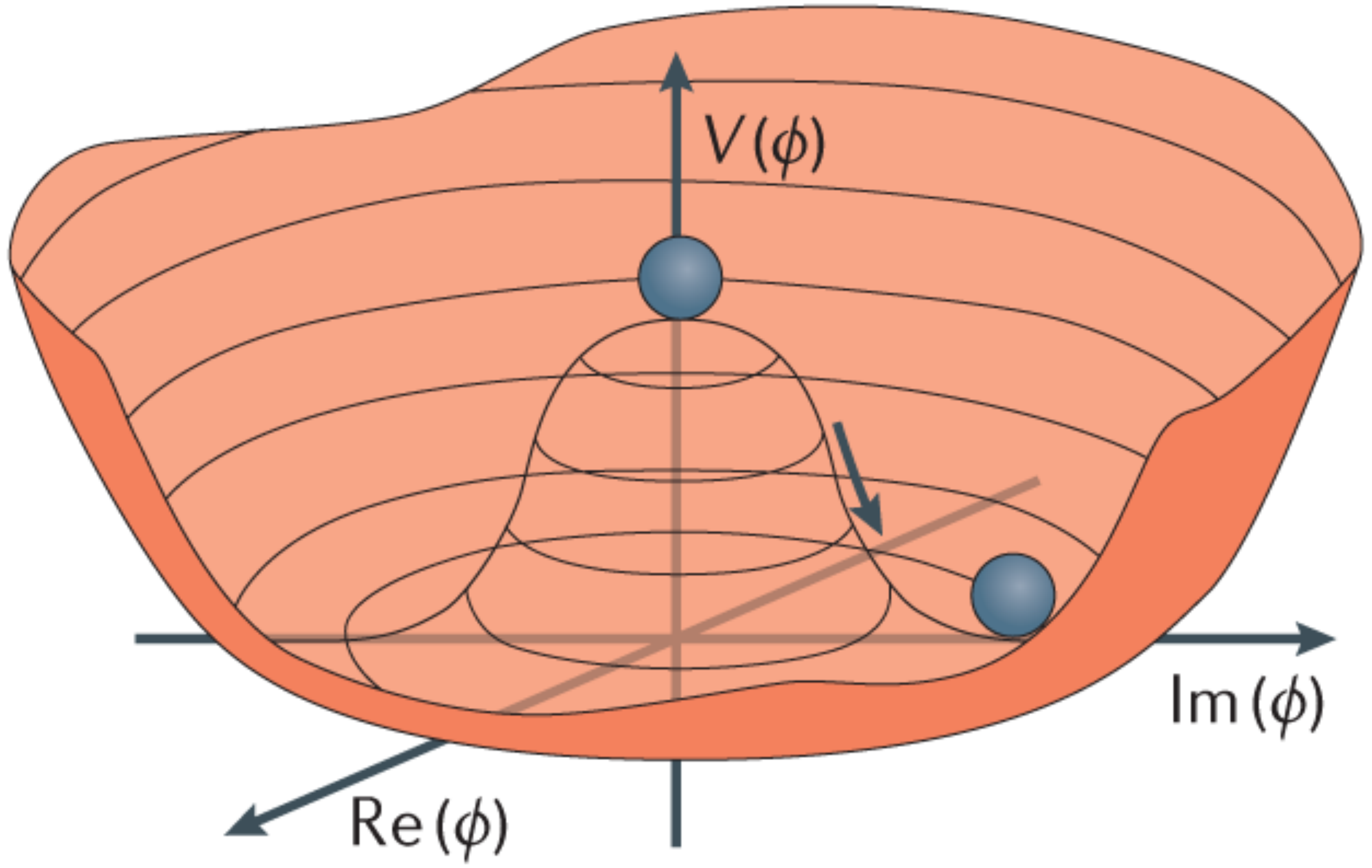

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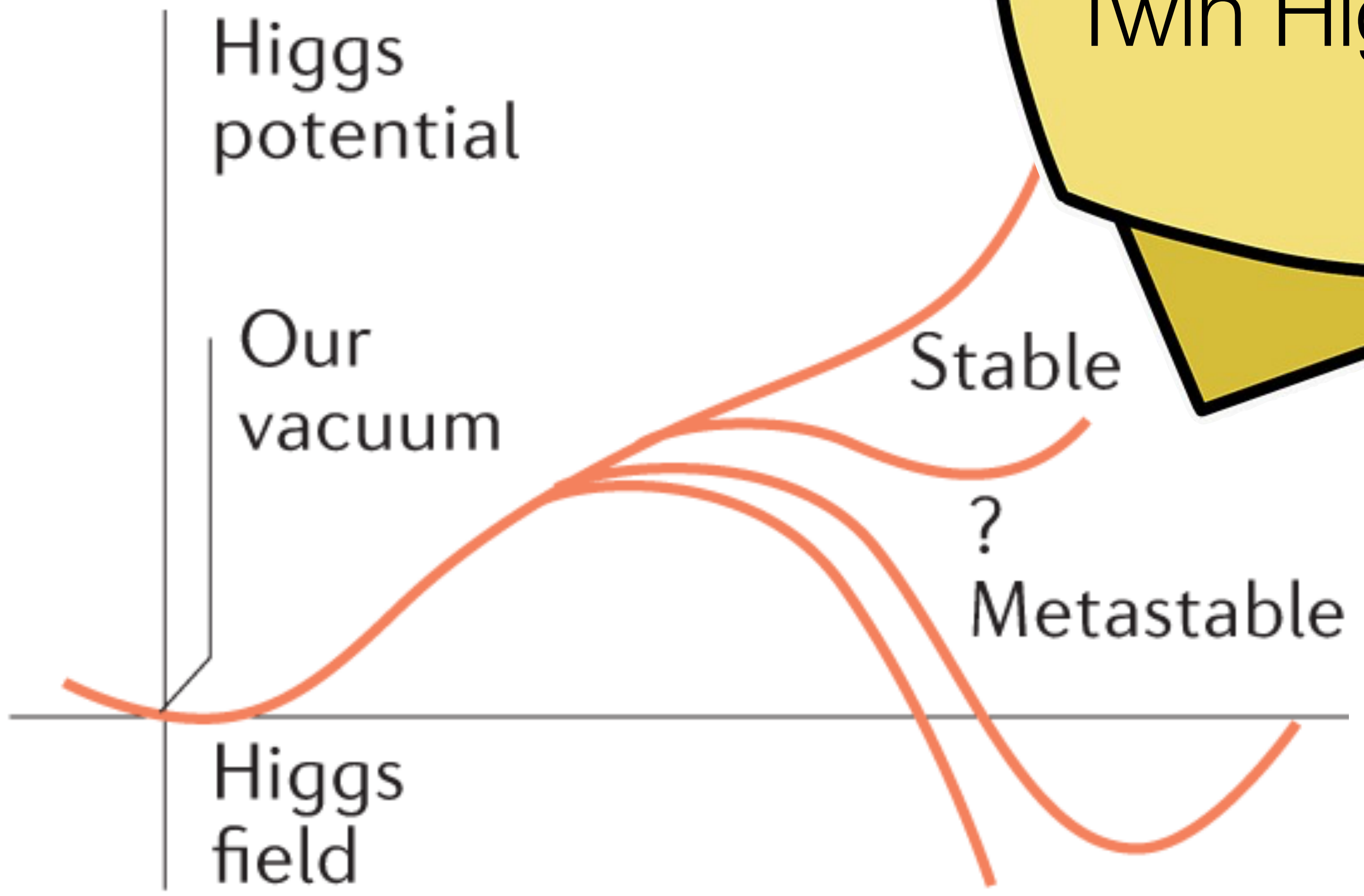

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The strong CP problem

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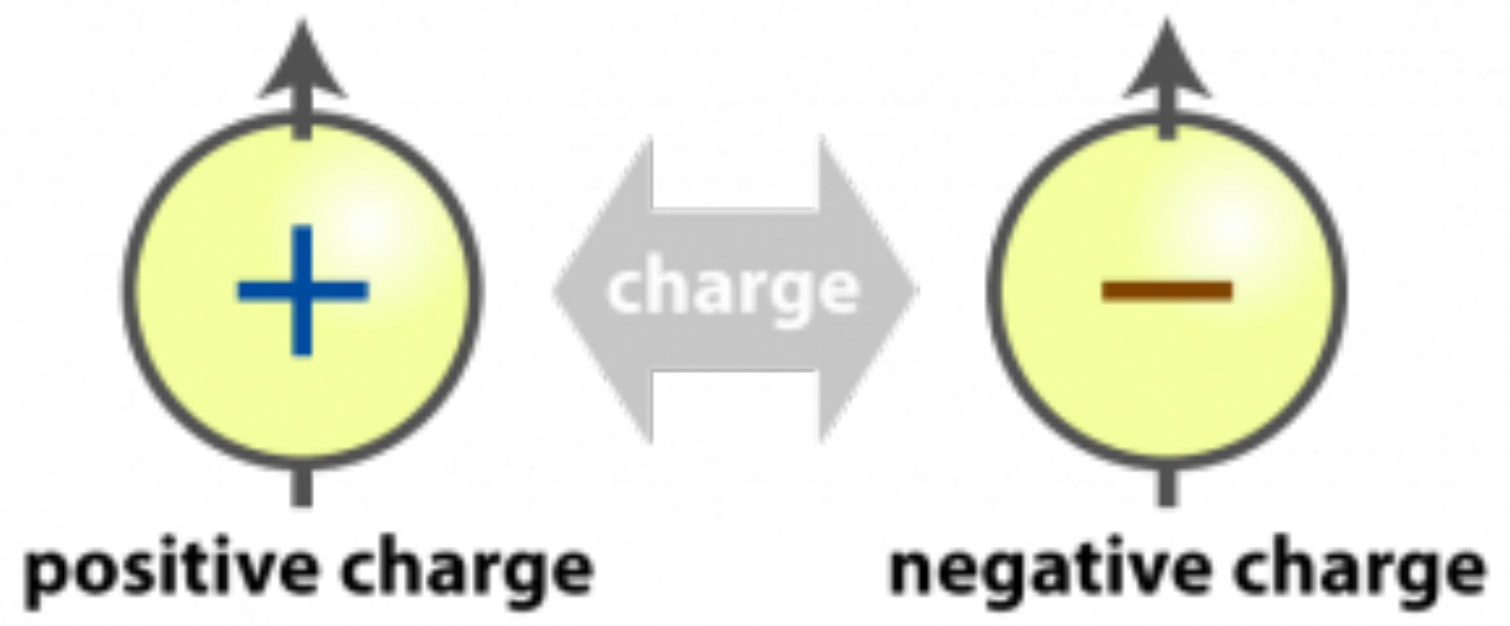

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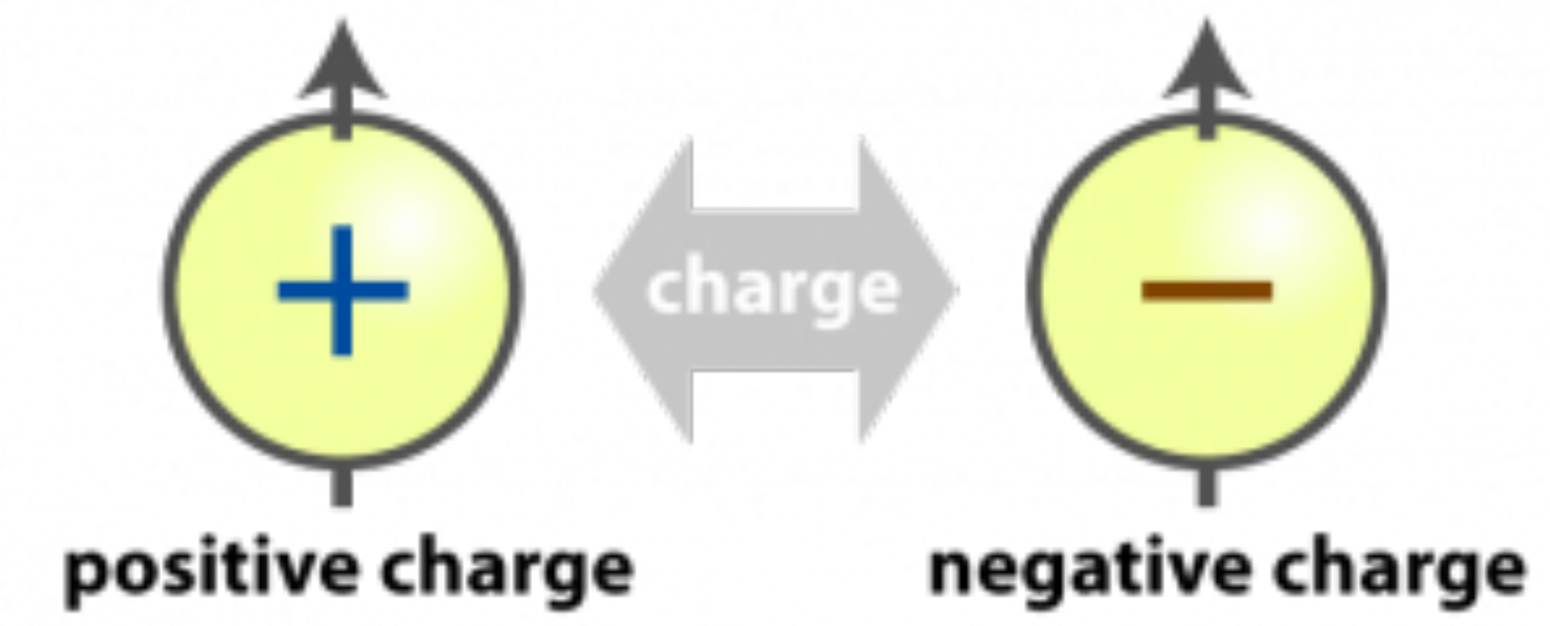

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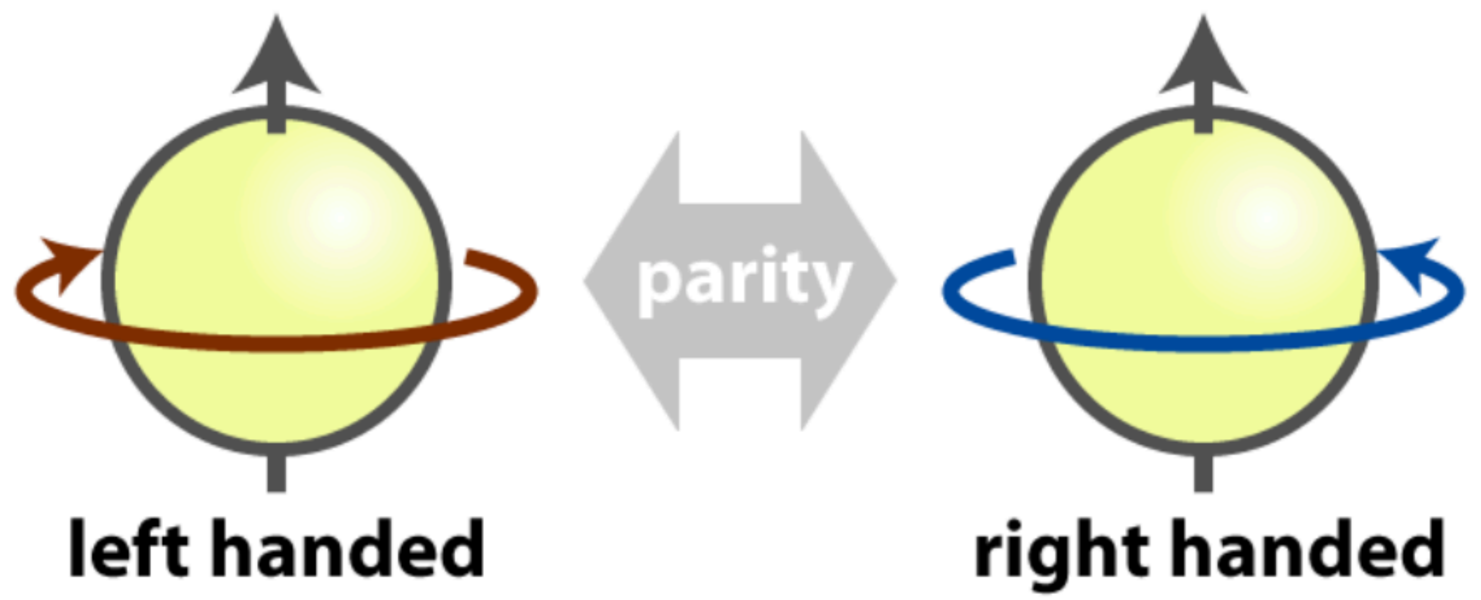

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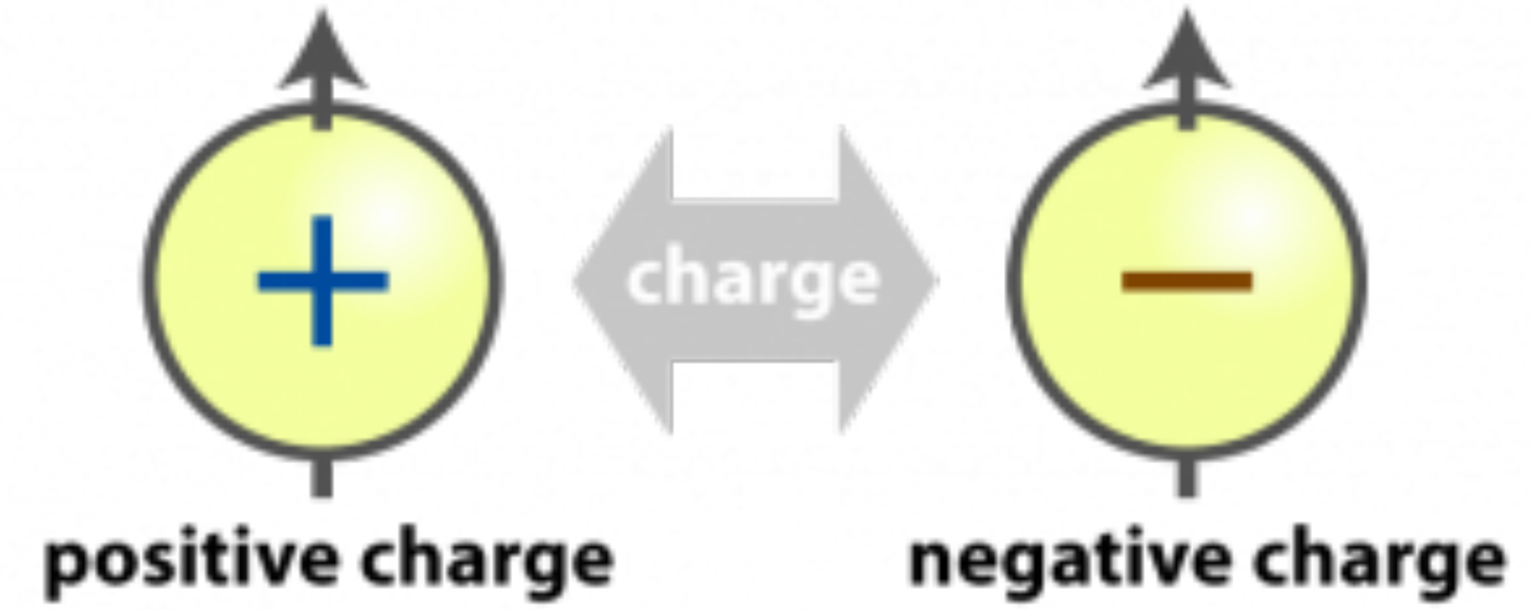

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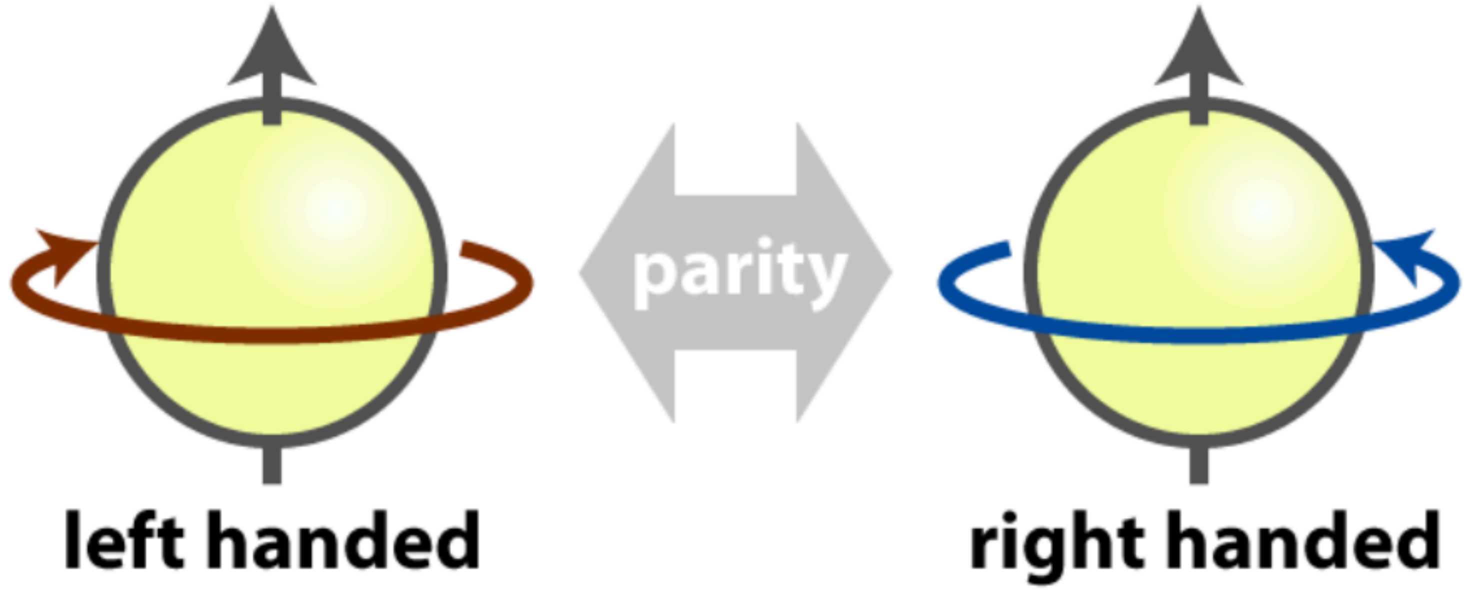

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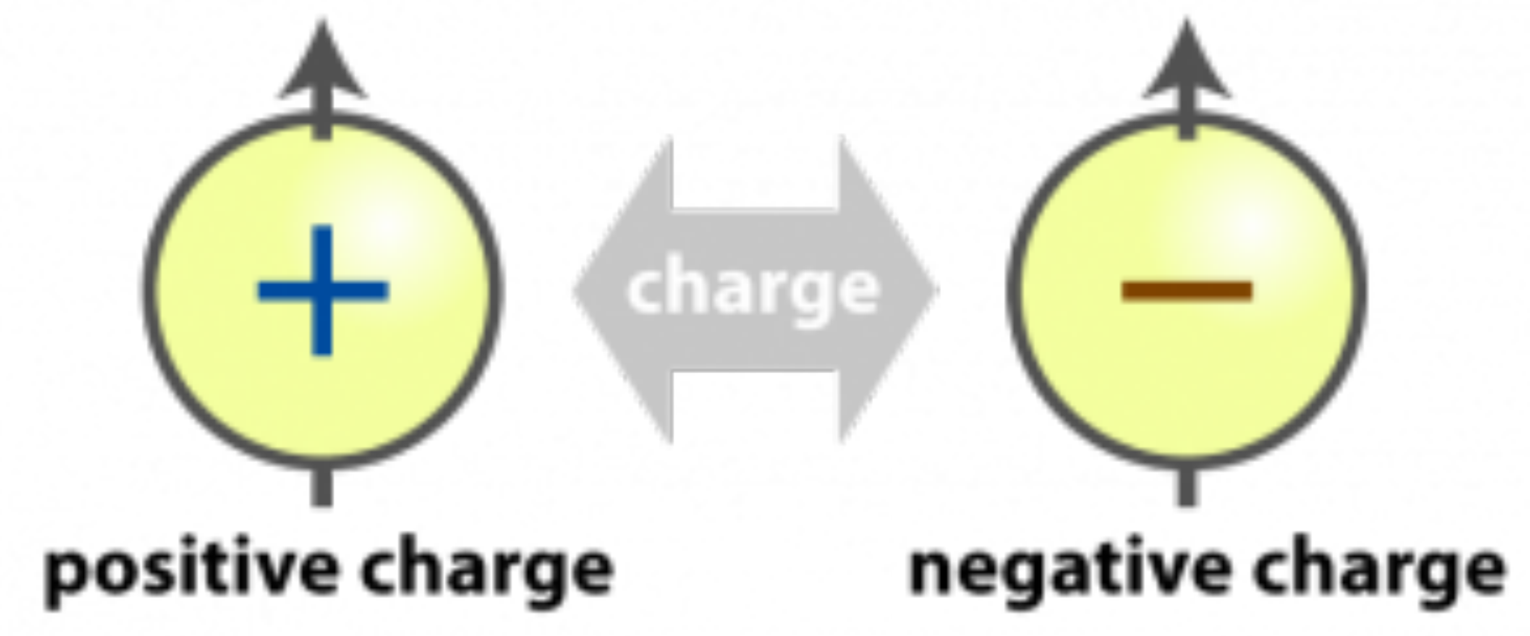

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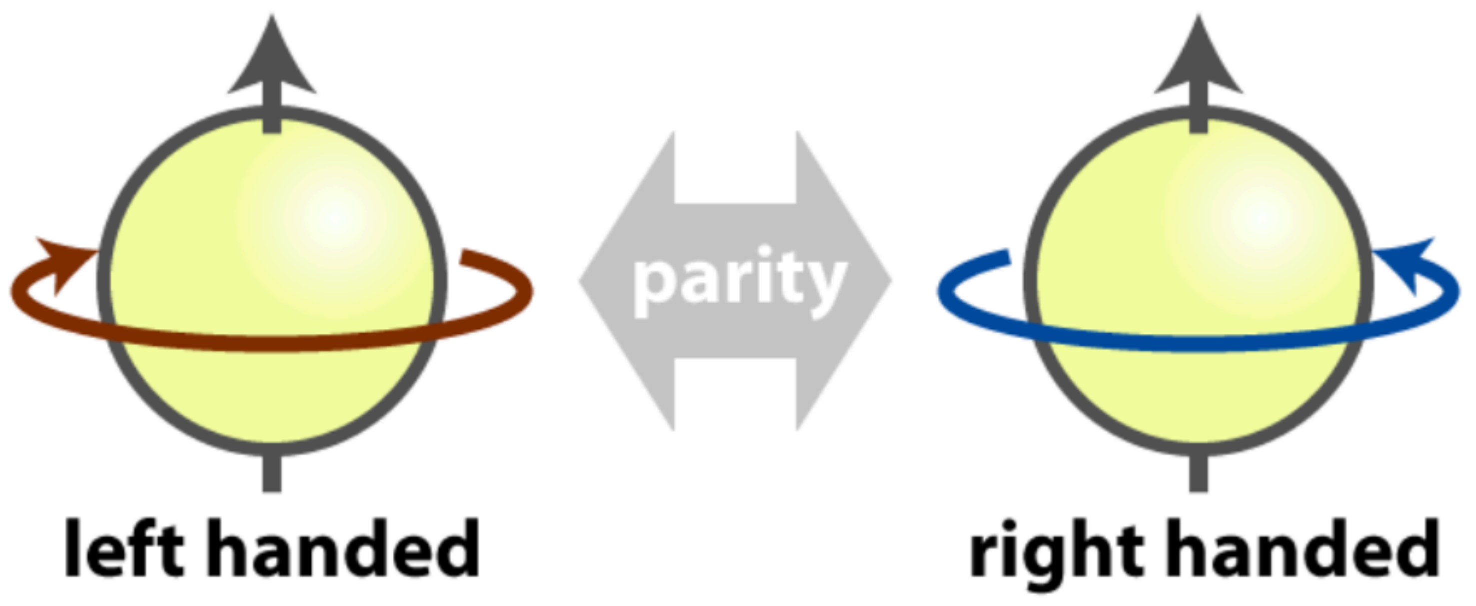
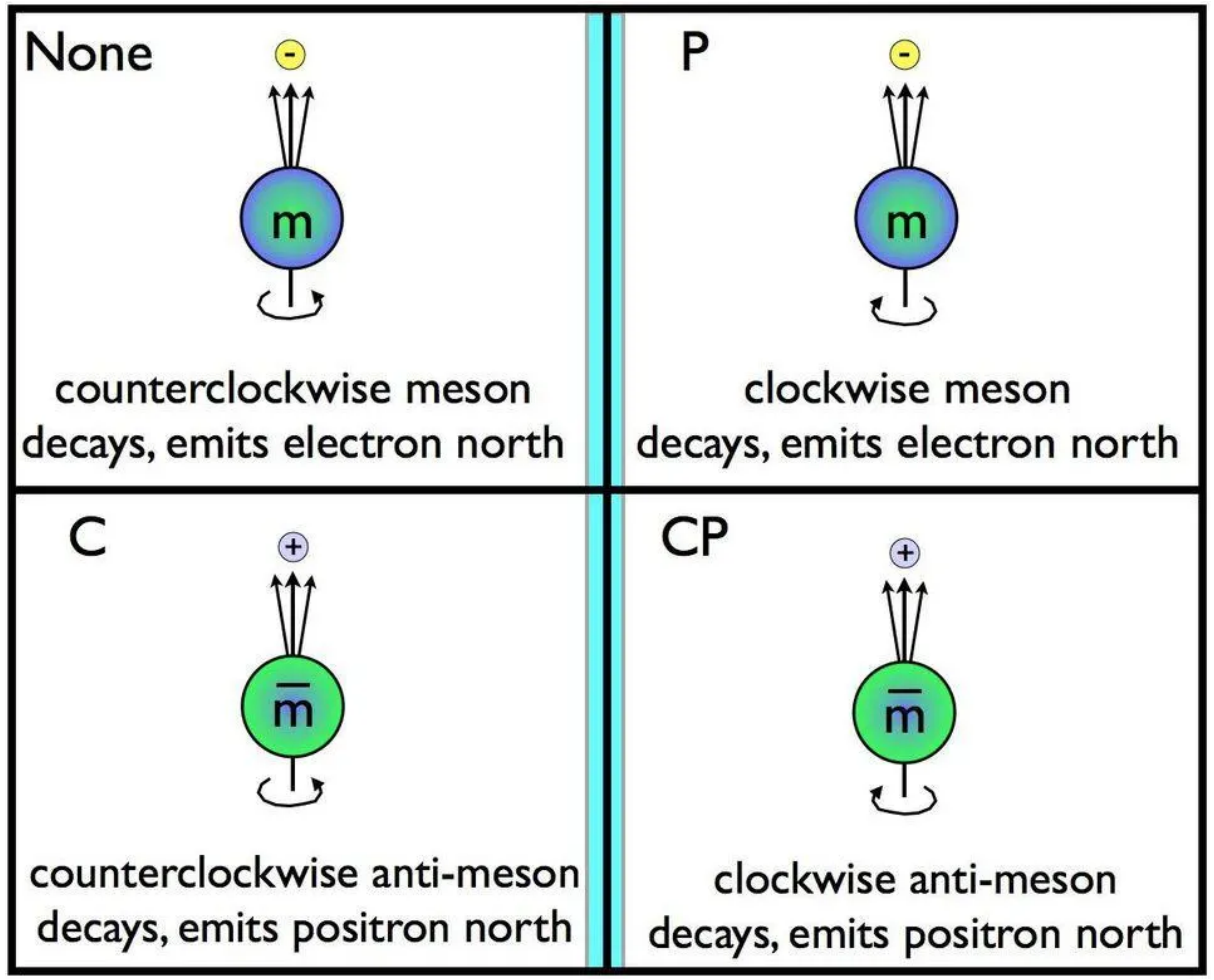


Charge+Parity transformation:

Example of CP symmetry into action:

Meson decays (integer spin hadrons)



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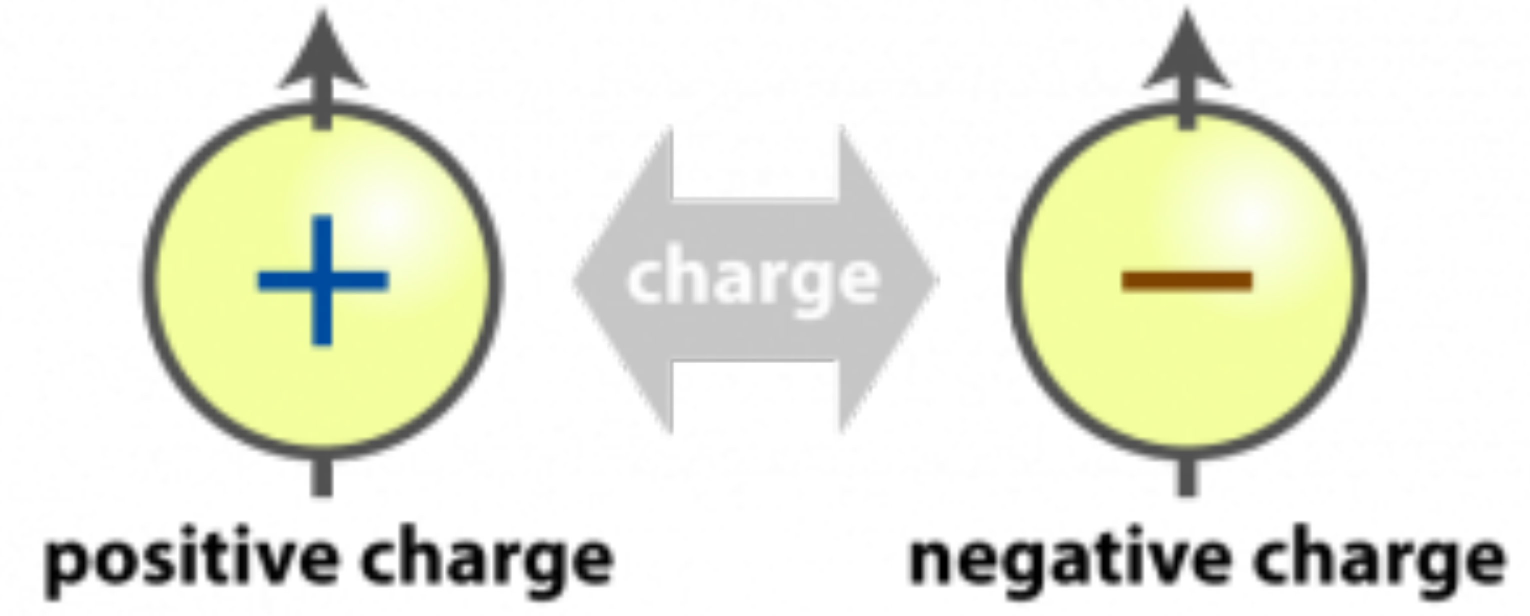

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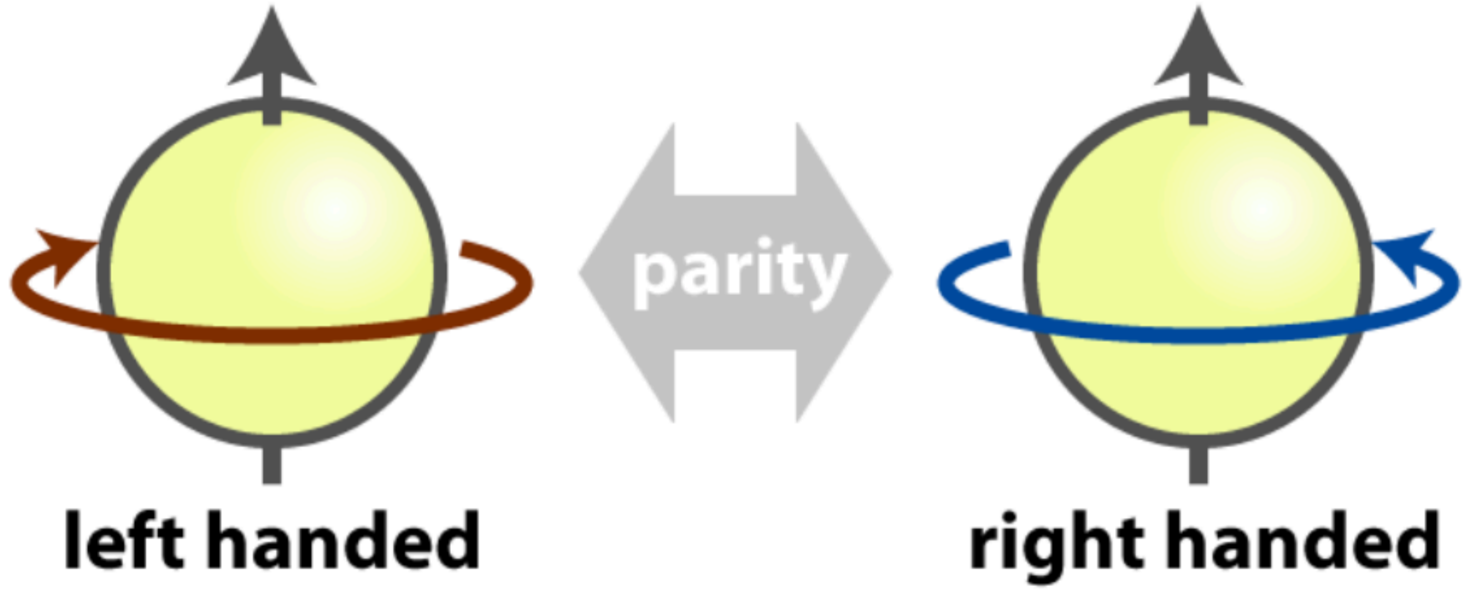

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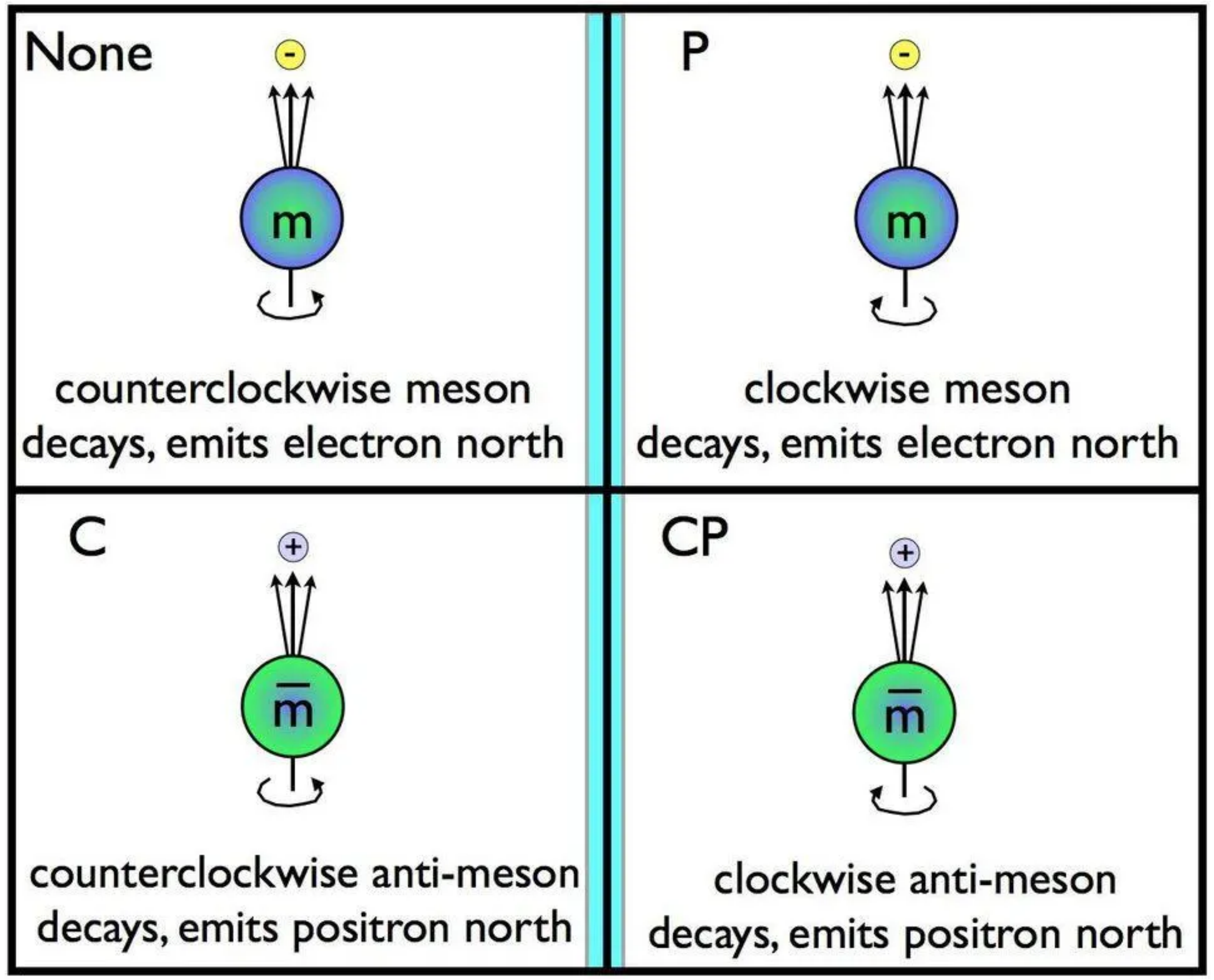

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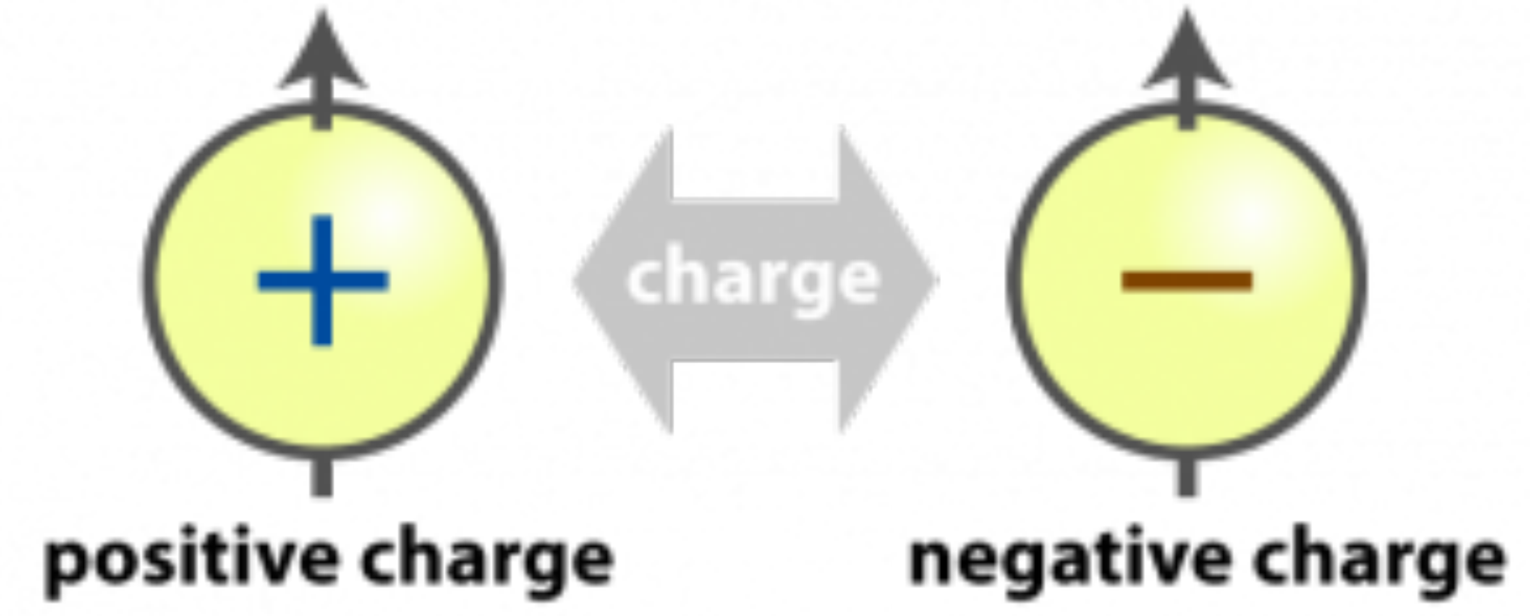

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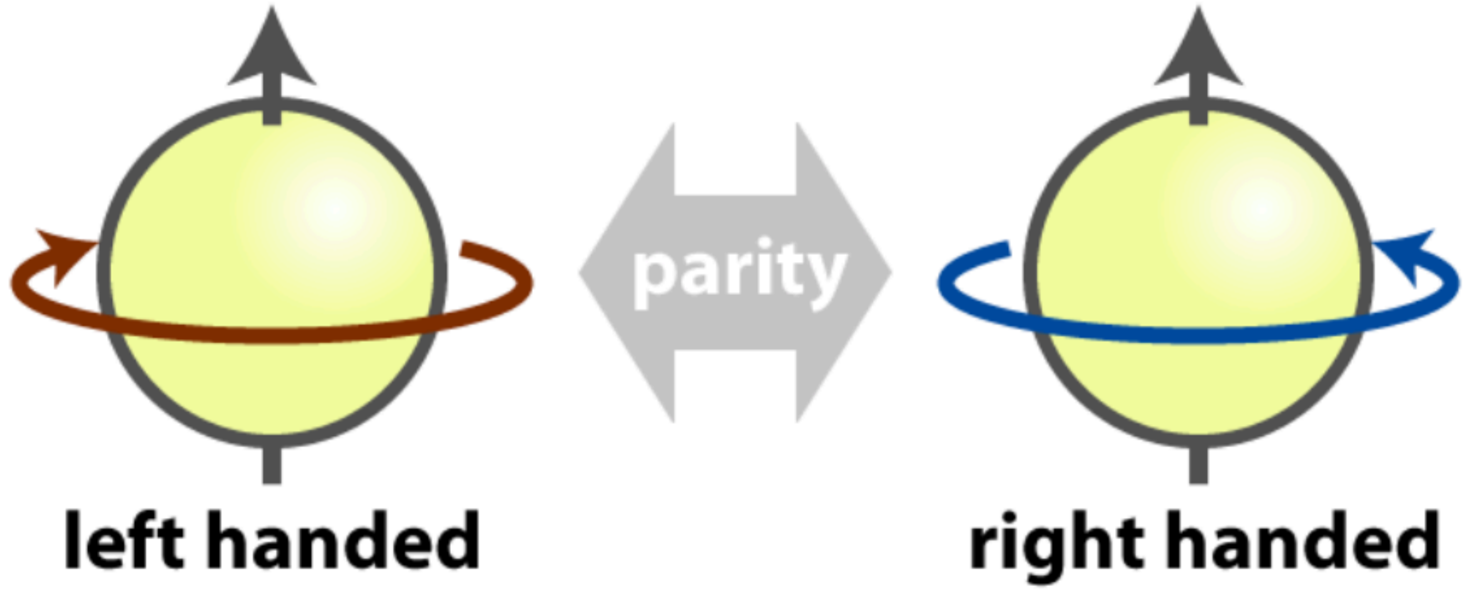

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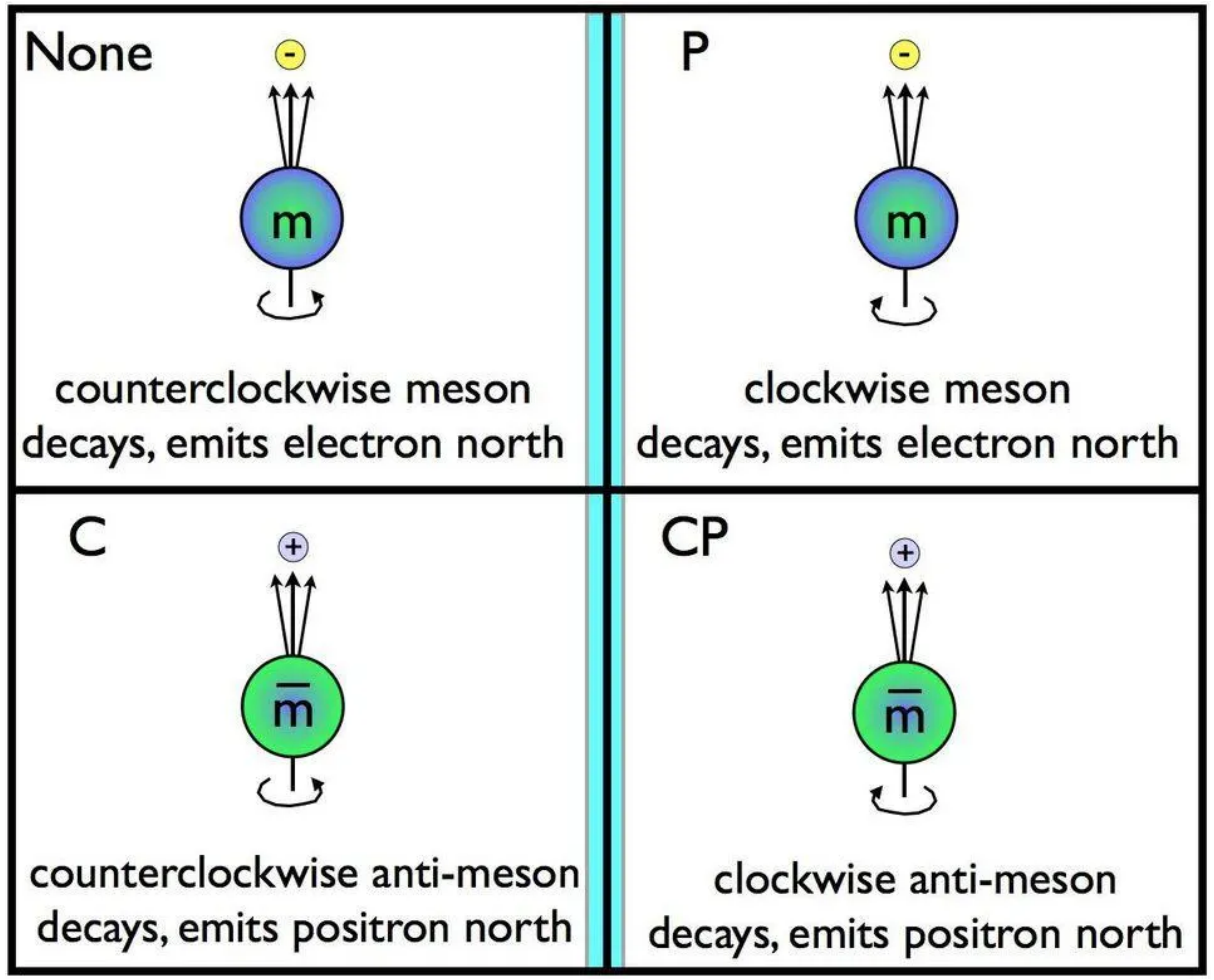

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"Everything that is not forbidden is compulsory!"

Murray Gell-Mann

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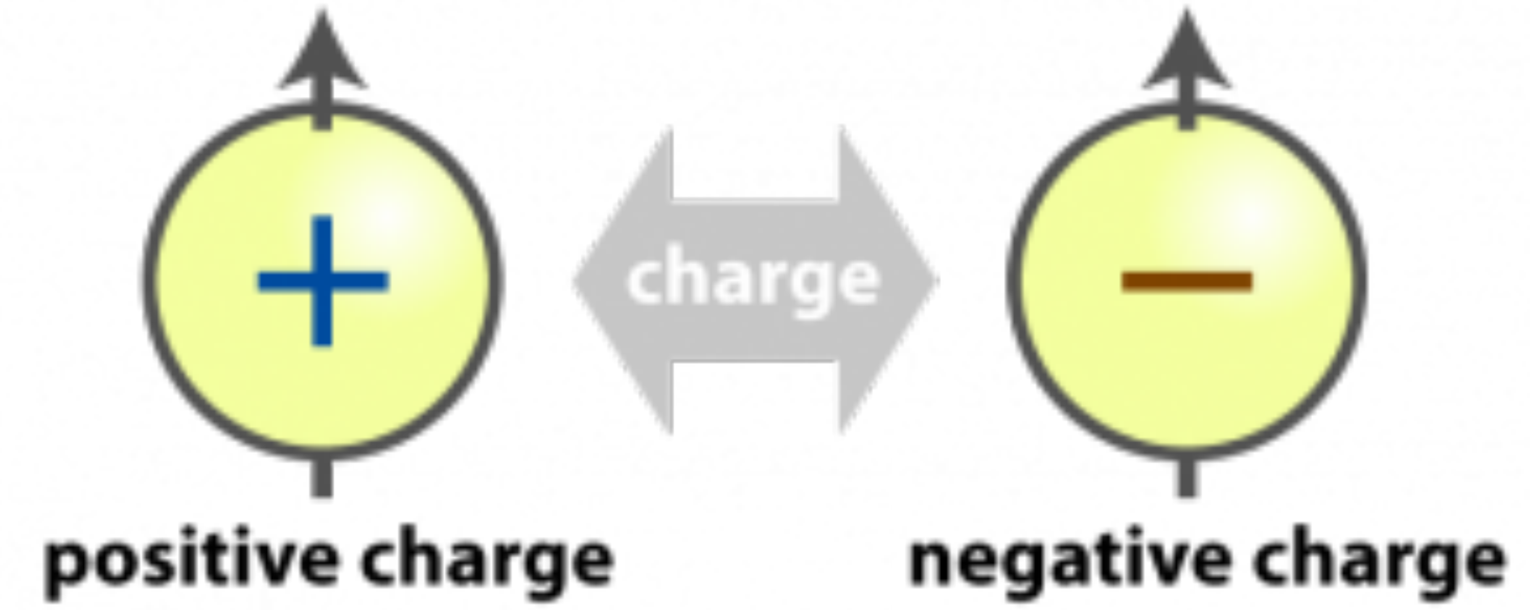

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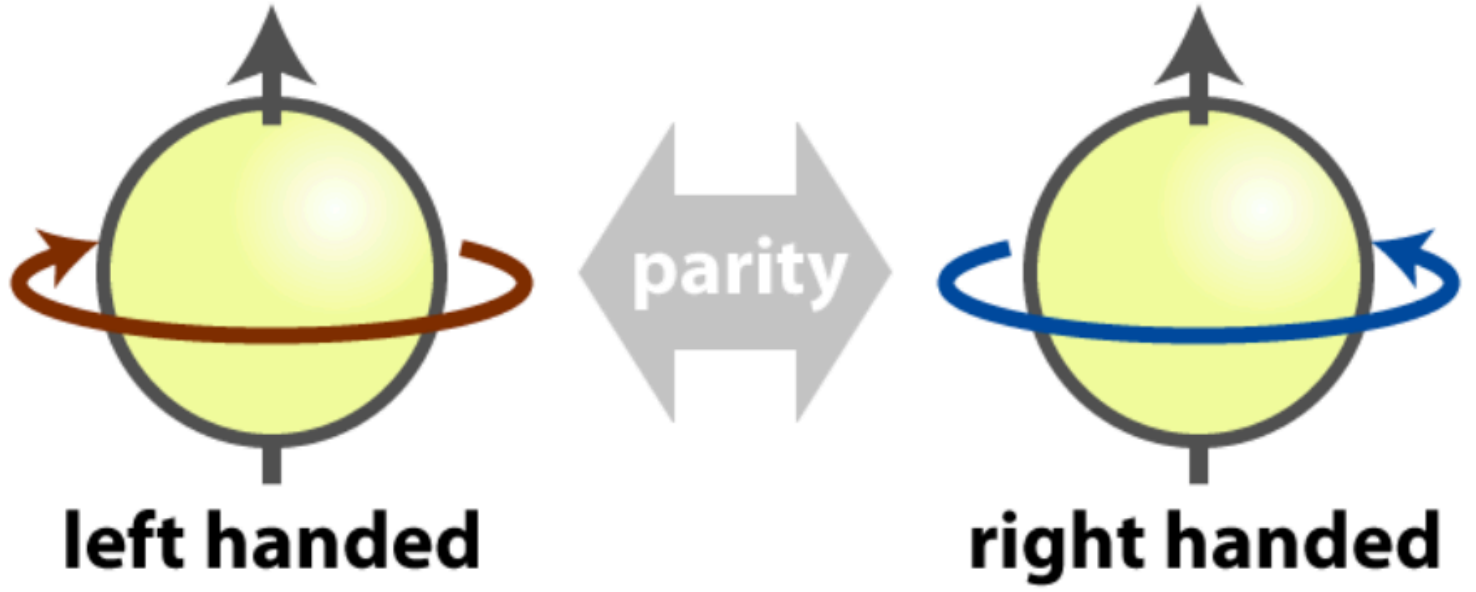

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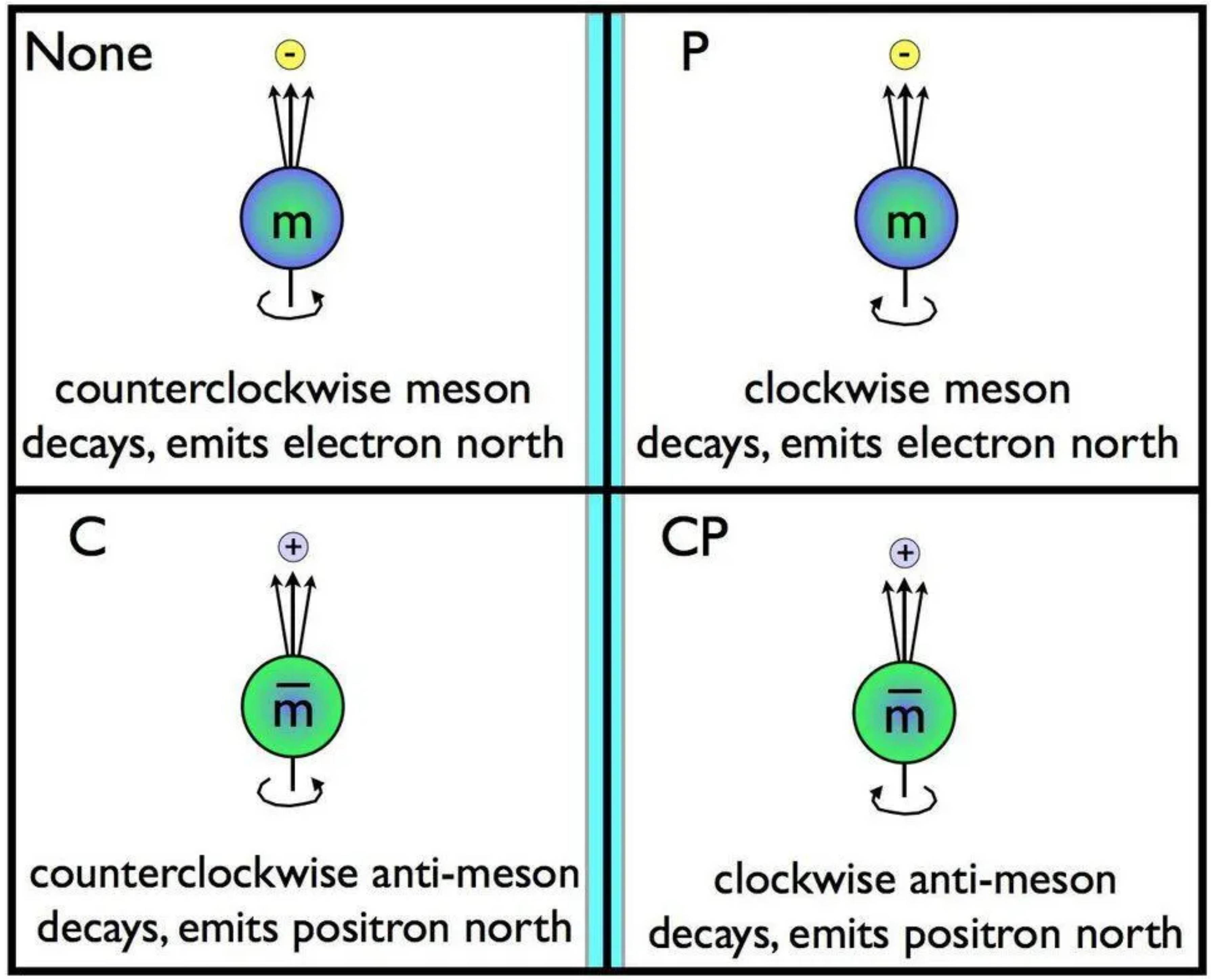

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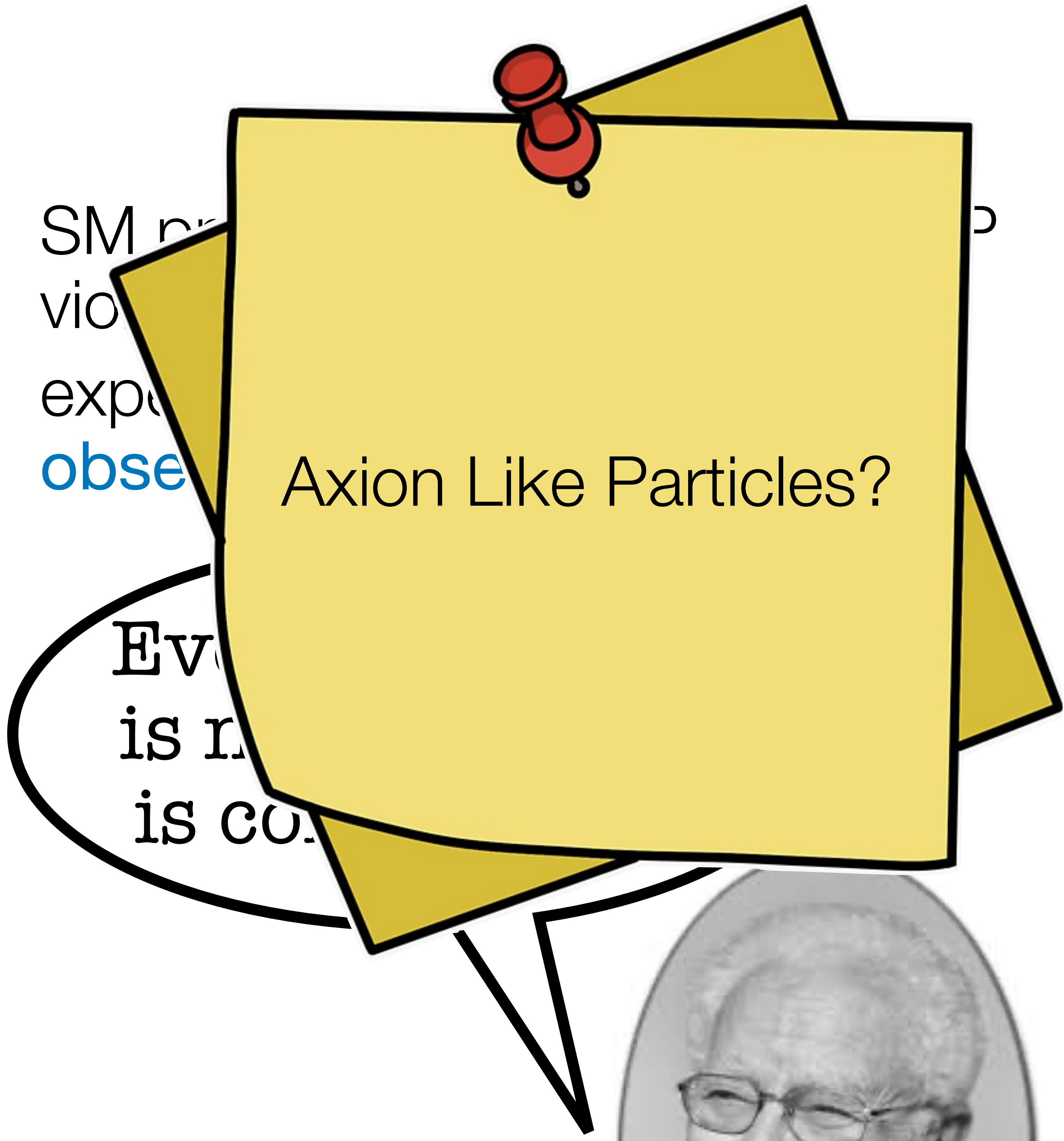

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How to search for physics Beyond the Standard Model?

Precision measurements (and not only!)

Precision measurements

Precision measurements are one of the way to tackle BSM physics.

Idea: measure quantity predicted by the SM → if not-compatible with SM new Physics!

Ingredients:

1 cup of precision in the measurement

1 cup of precision in the prediction

Procedure:

1. Perform theoretical calculation with smallest possible uncertainty

2. Perform measurement with smallest possible uncertainty

Notes :

Best results obtained via collaboration of theorists and experimentalists

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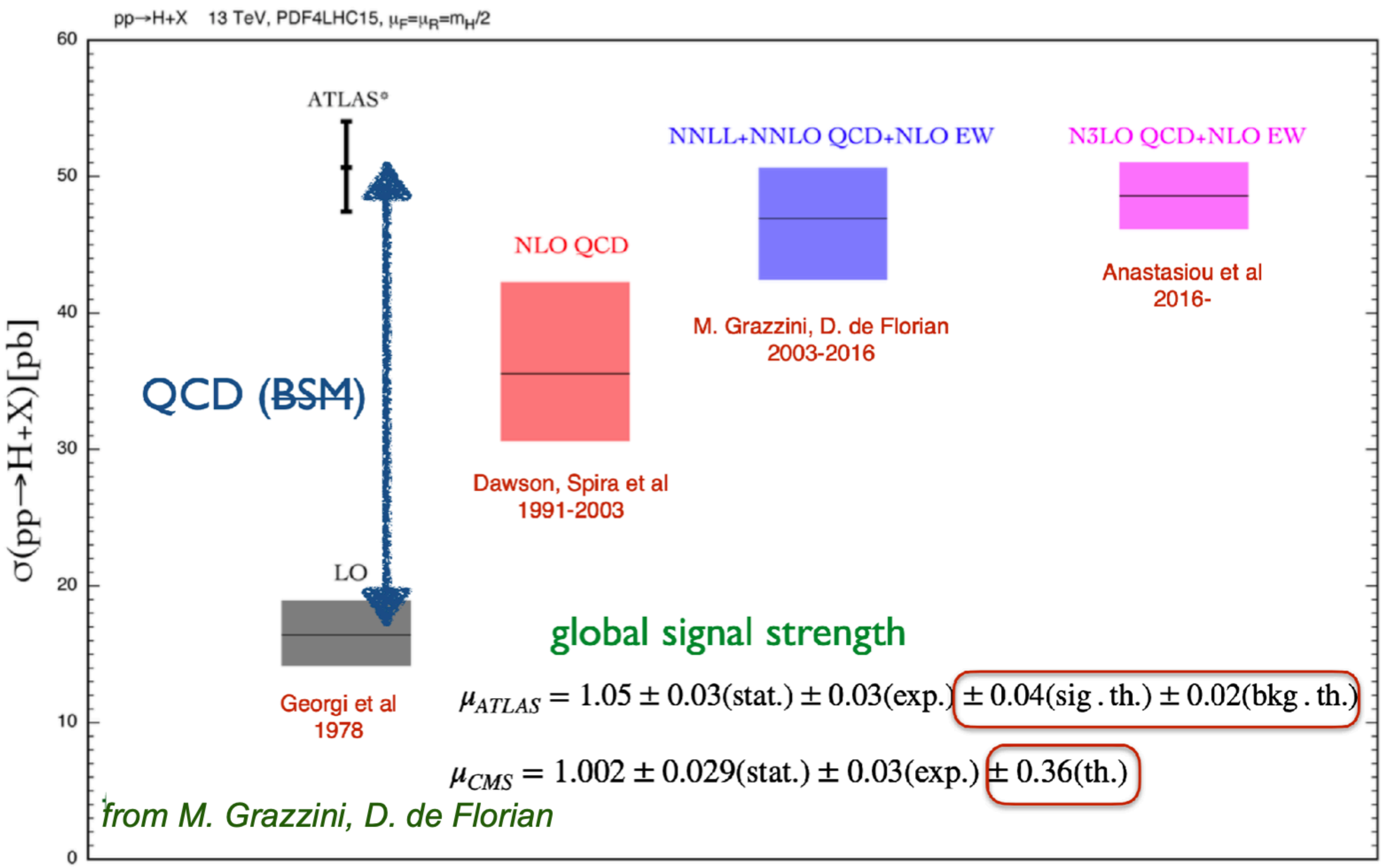
An example:

The measurement of the Higgs boson production cross section



An example of precision measurement: the Higgs decay width

Heisenberg uncertainty principle:
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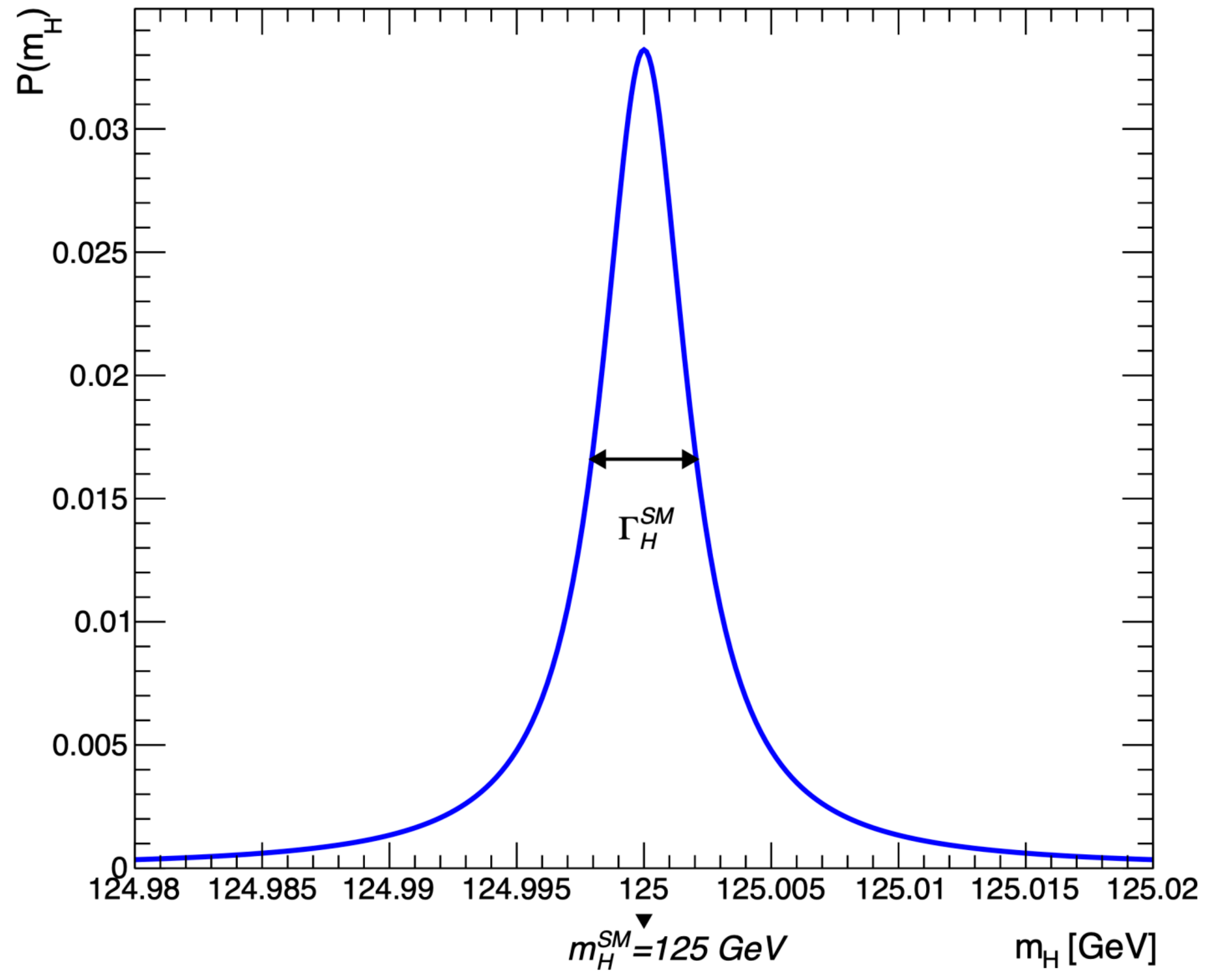

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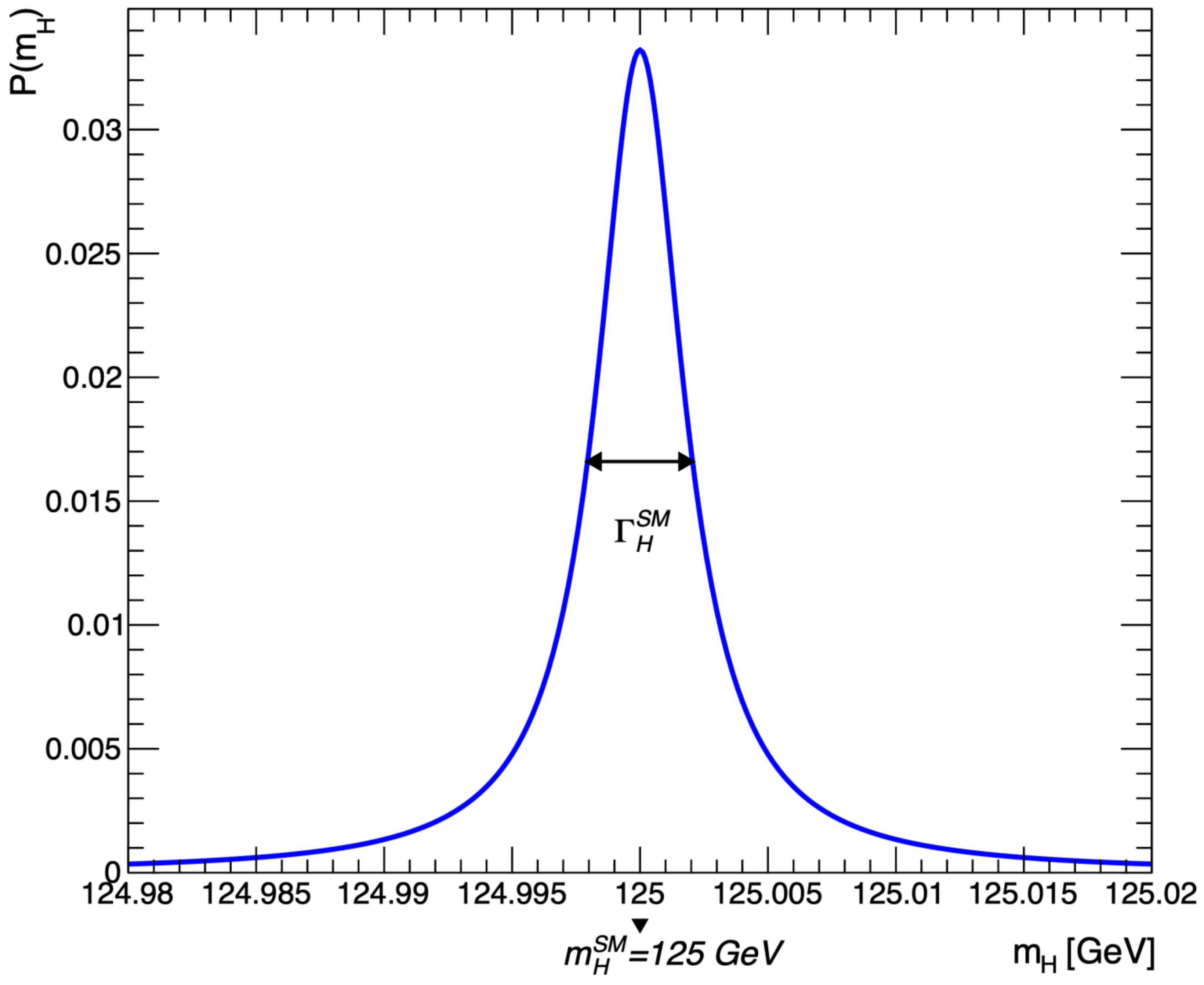

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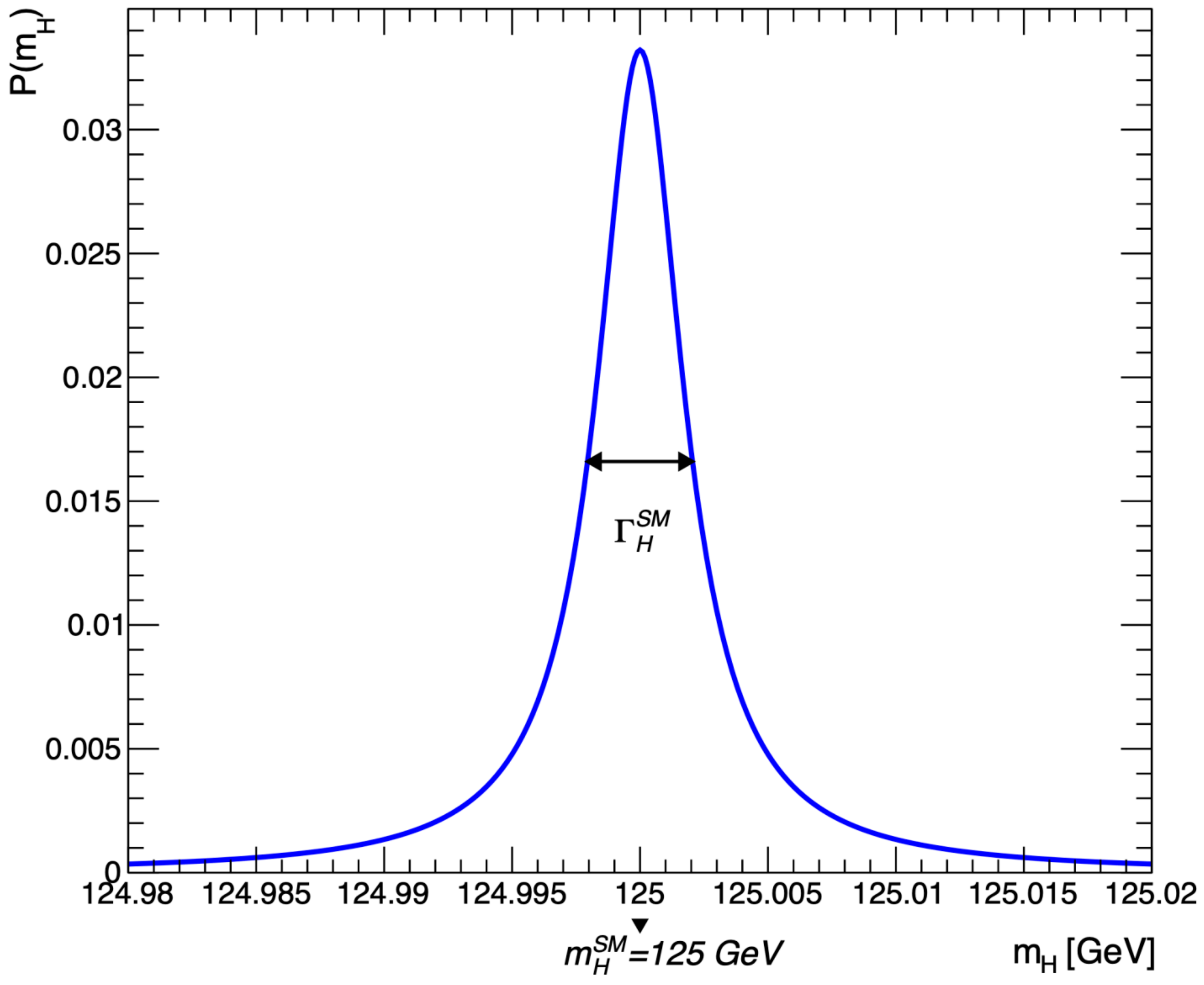

- $\Gamma_H^{obs} > \Gamma_H^{SM}$ → Higgs boson decays into BSM states →DM?
- $\Gamma_H^{obs} < \Gamma_H^{SM}$→multiple Higgs boson exist→naturalness problem?

New Physics searches

~~Finding~~ Looking for a needle in a haystack!

e.g. @ LHC:

$\sim 10^{10}$ collisions produced per run (~6h) to look at!

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New Physics searches: Dark Matter & detection

From gravitational effects

→ DM can be a particle with:

- Lifetime ~ Universe age
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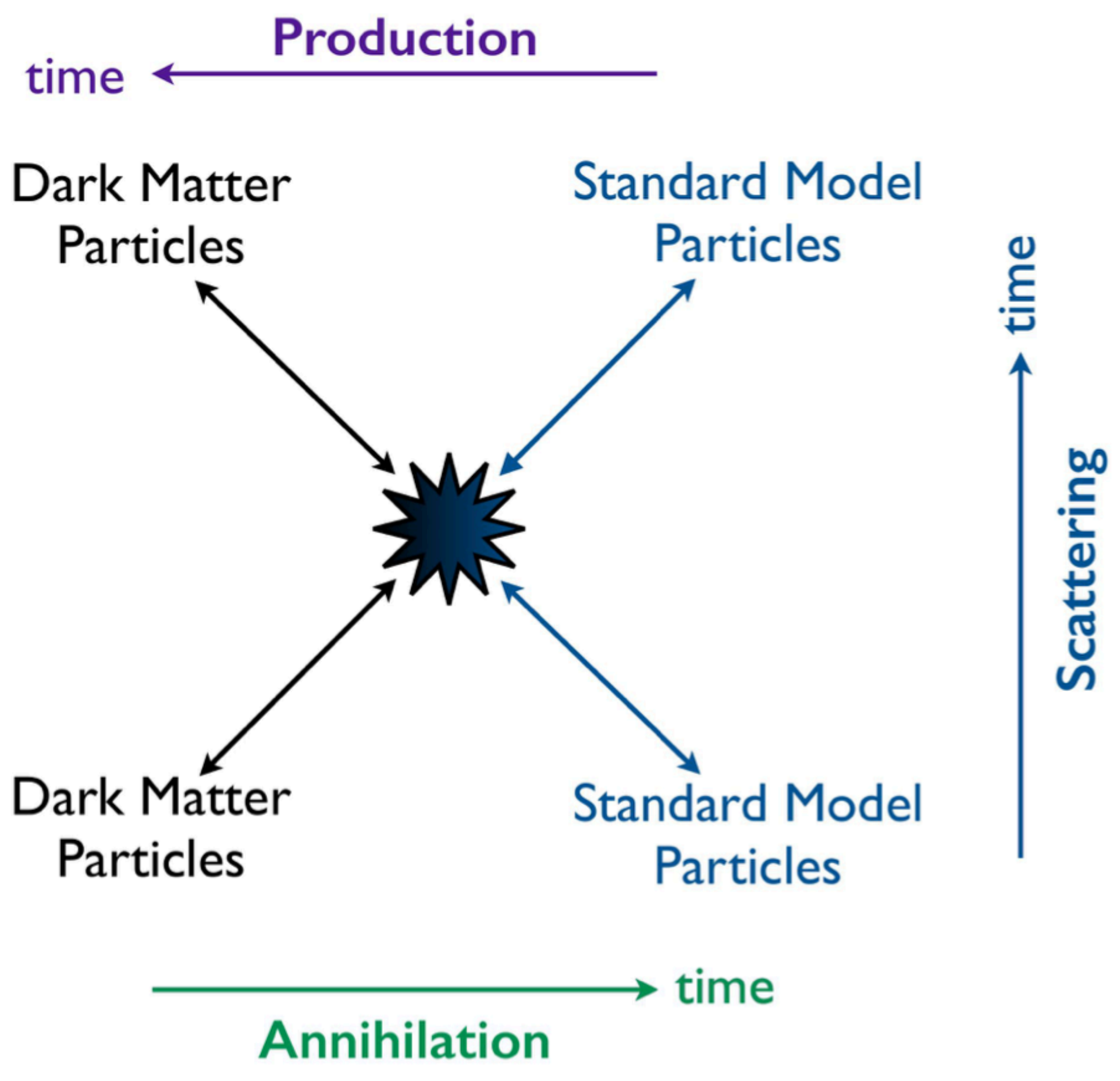
- Very small self-interaction

Can be observed via:

- Scattering
- Production
- Annihilation



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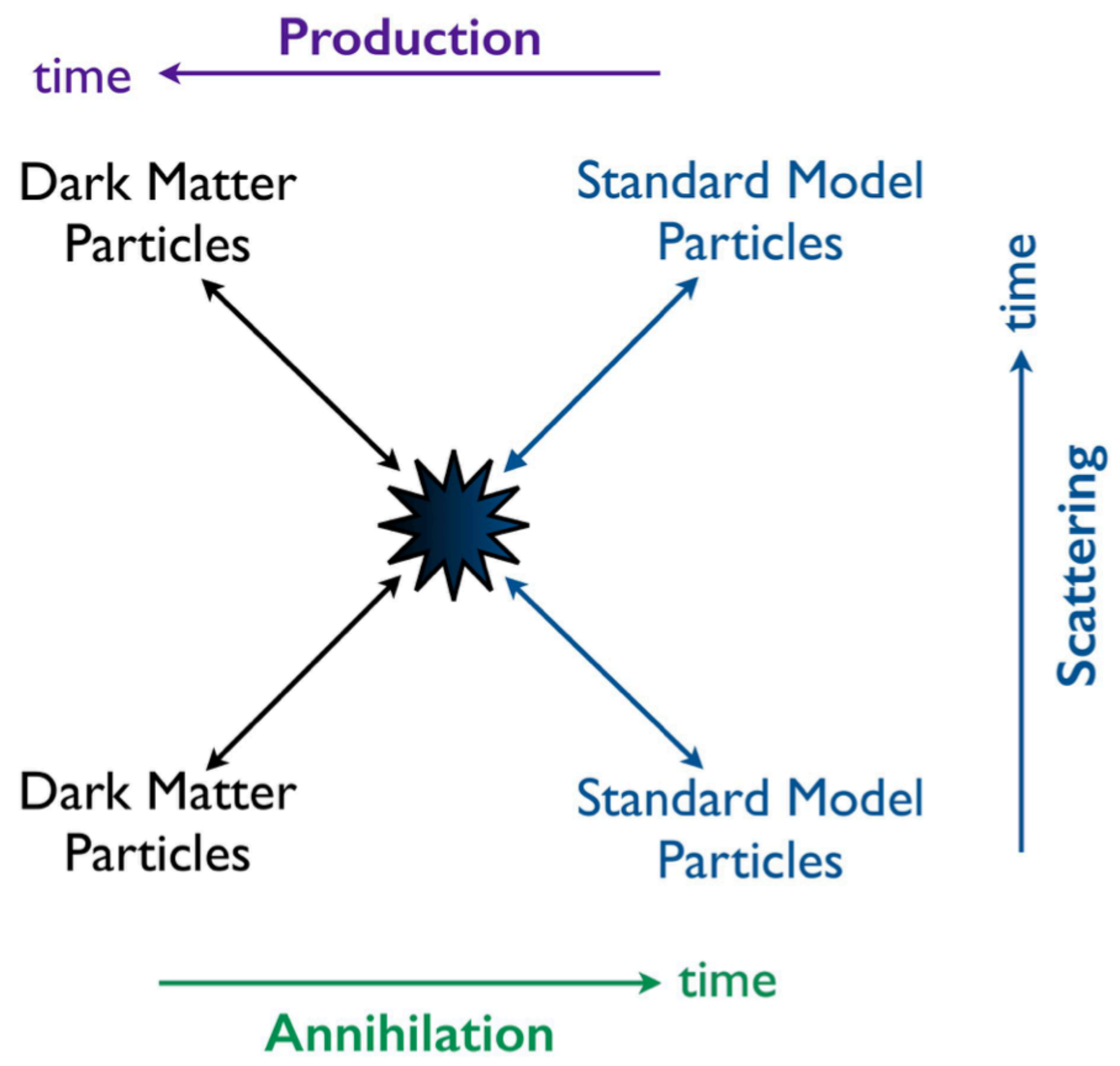

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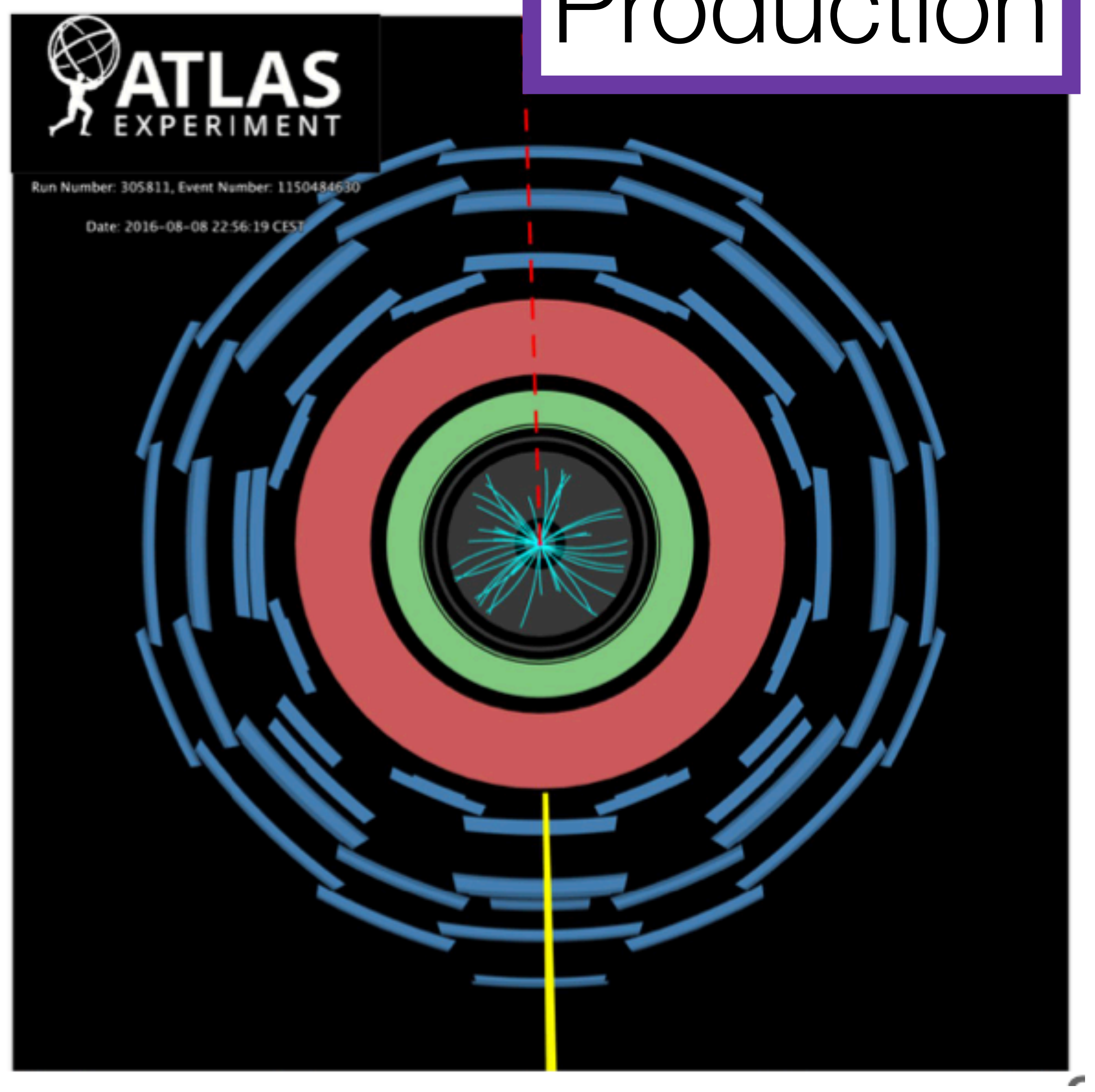

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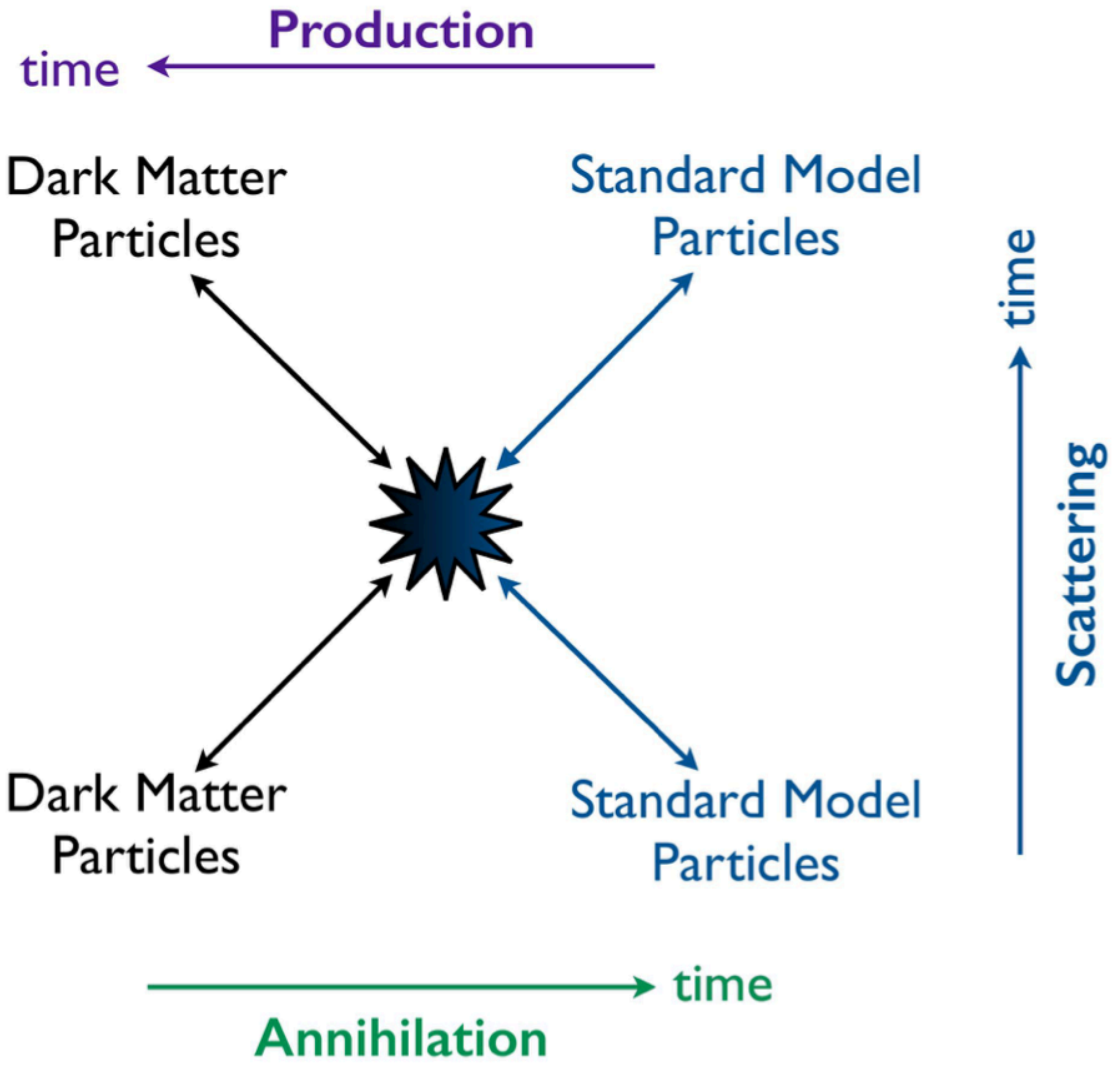

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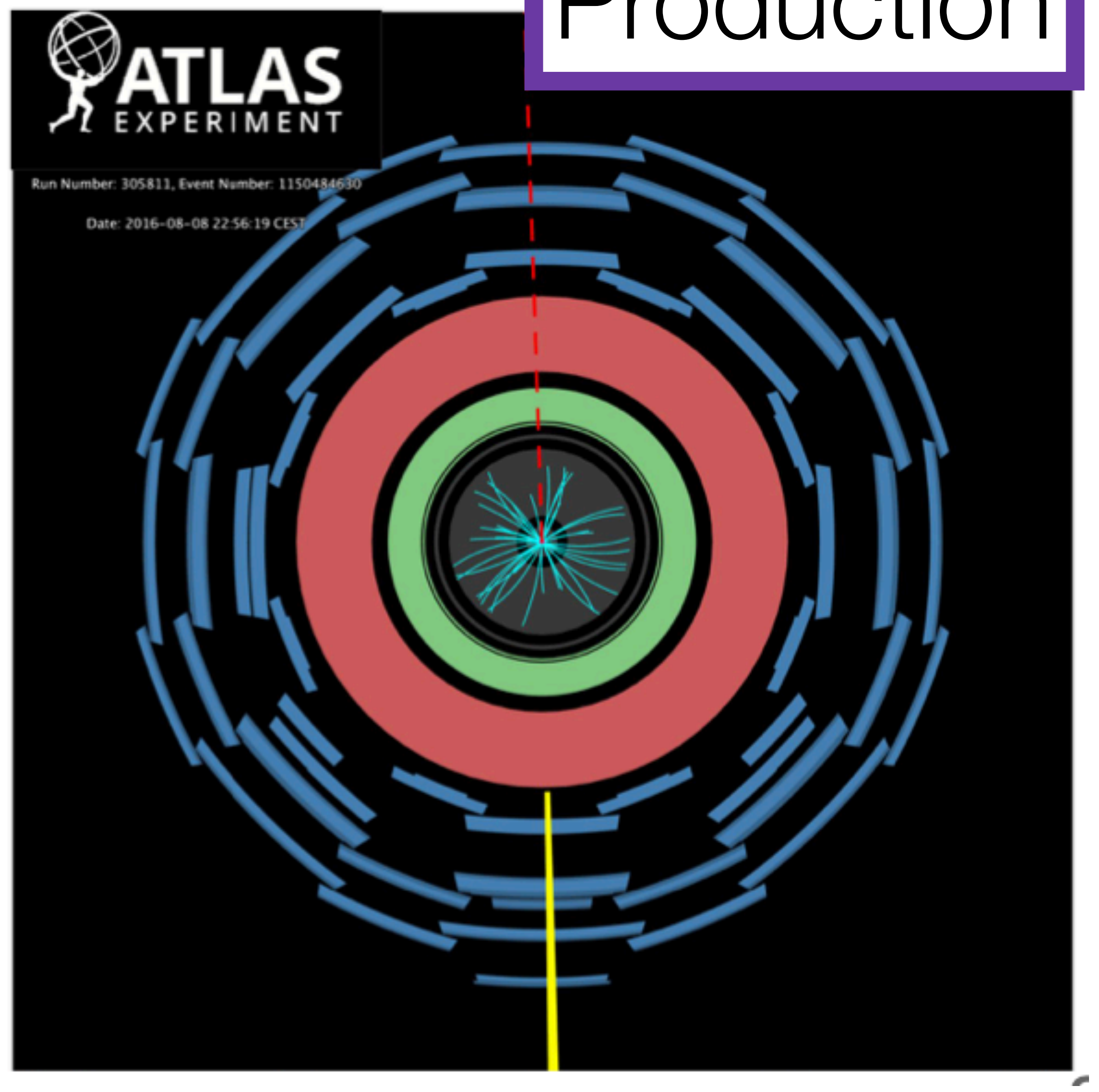

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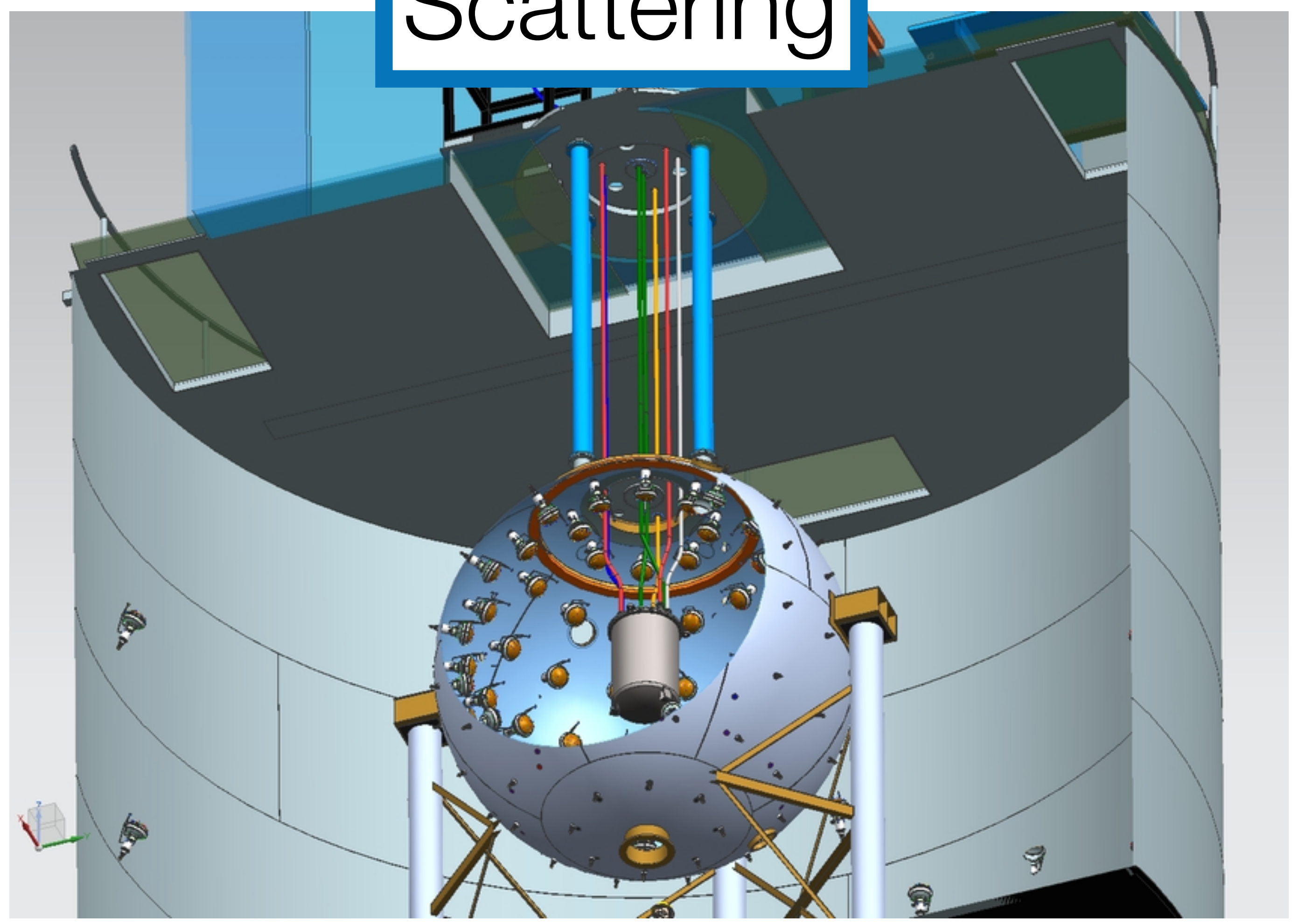

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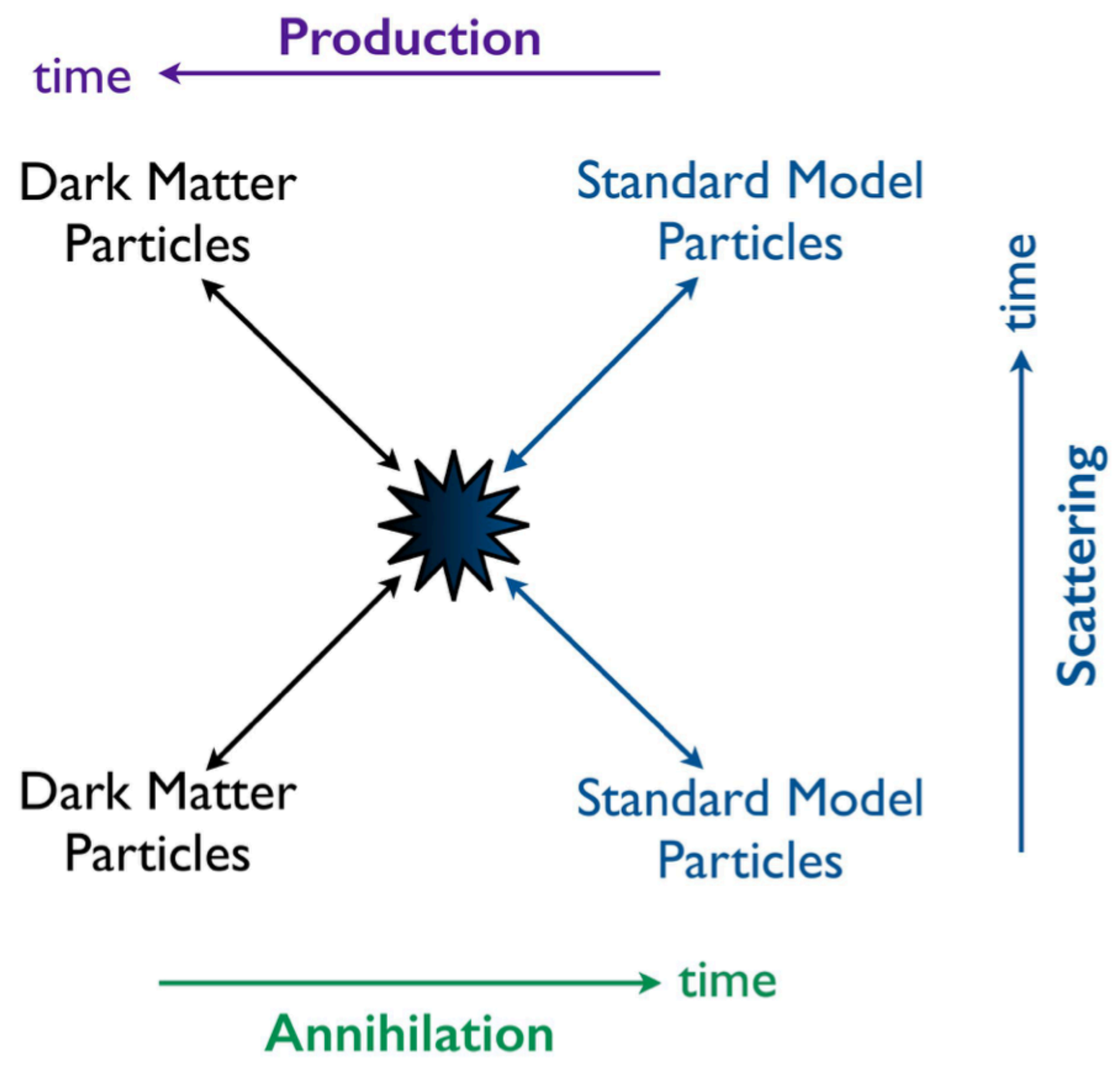

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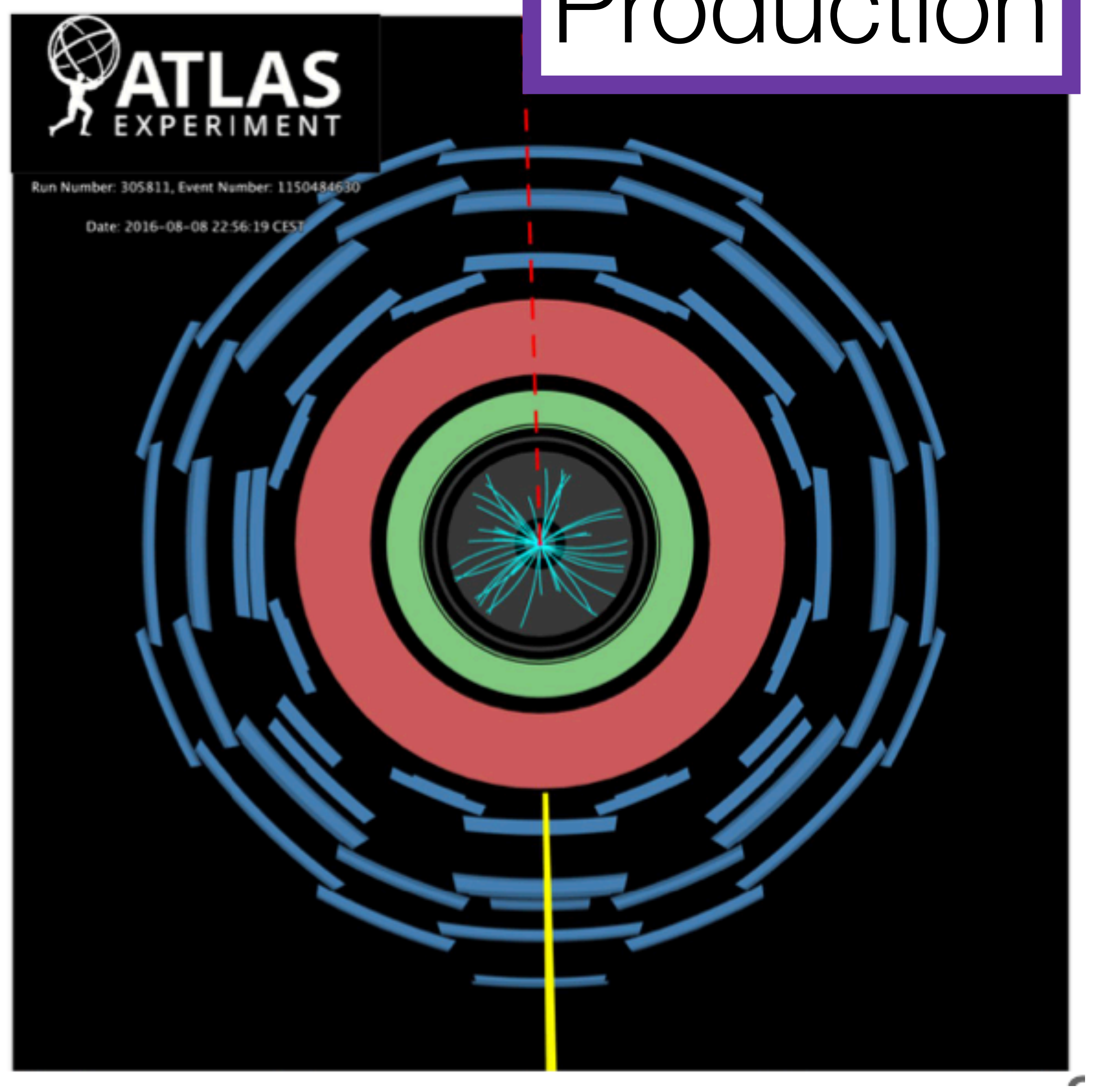

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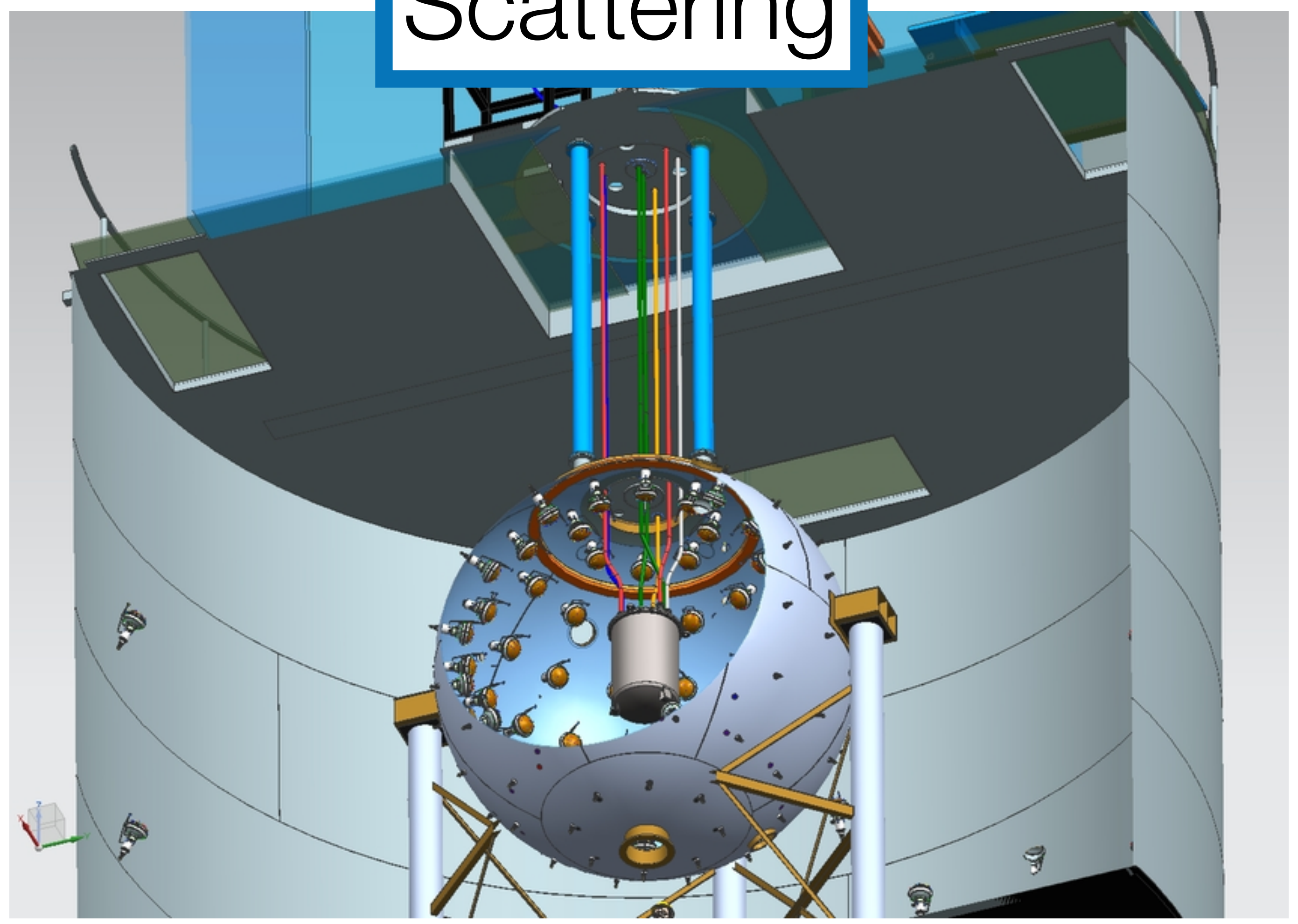
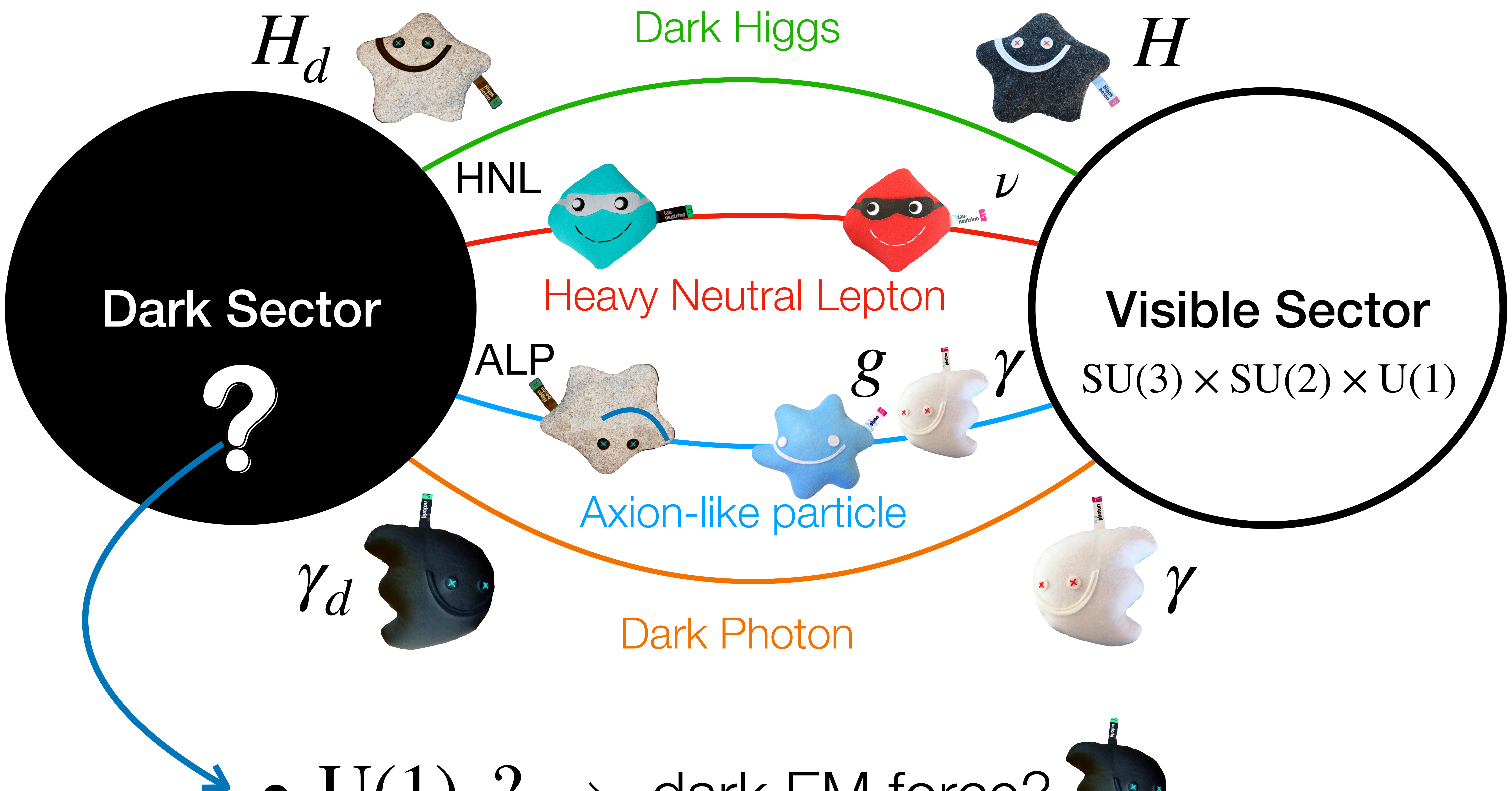


Annihilation

New Physics searches: Dark Sectors

Dark matter is one of the many particles present in so-called Dark Sector



Portal particles have very wide range of masses and lifetimes $\Rightarrow$ very different signatures in the detector!

- $U(1)_d$? $\rightarrow$ dark EM force?
- $SU(3)_d$? $\rightarrow$ dark strong force?

New Physics searches: SUSY

From Higgs naturalness and hierarchy problem

→ SUperSYmmetry!

Each particle has its own s-particle, completely equivalent but opposite under SUperSYmmetry.

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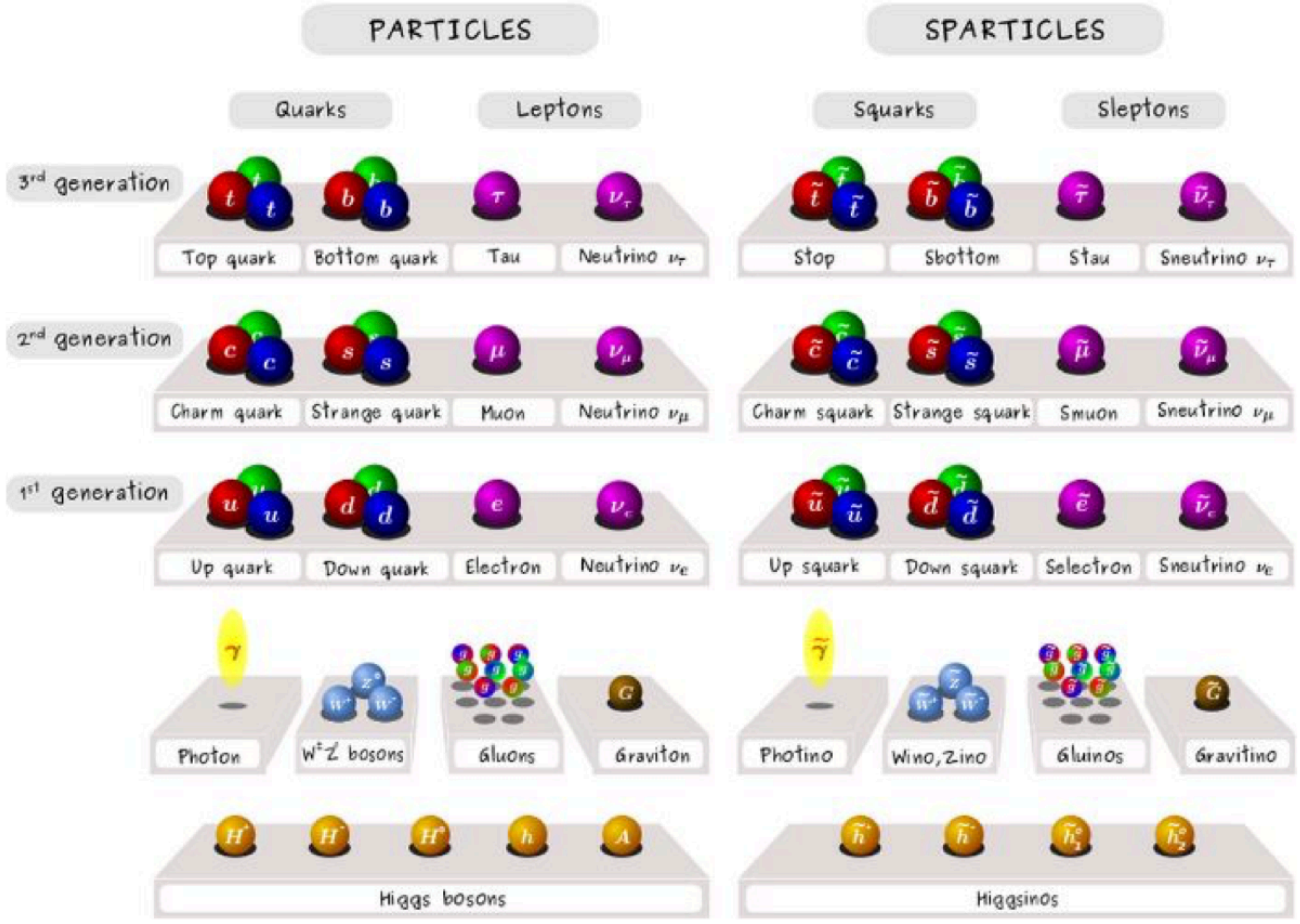
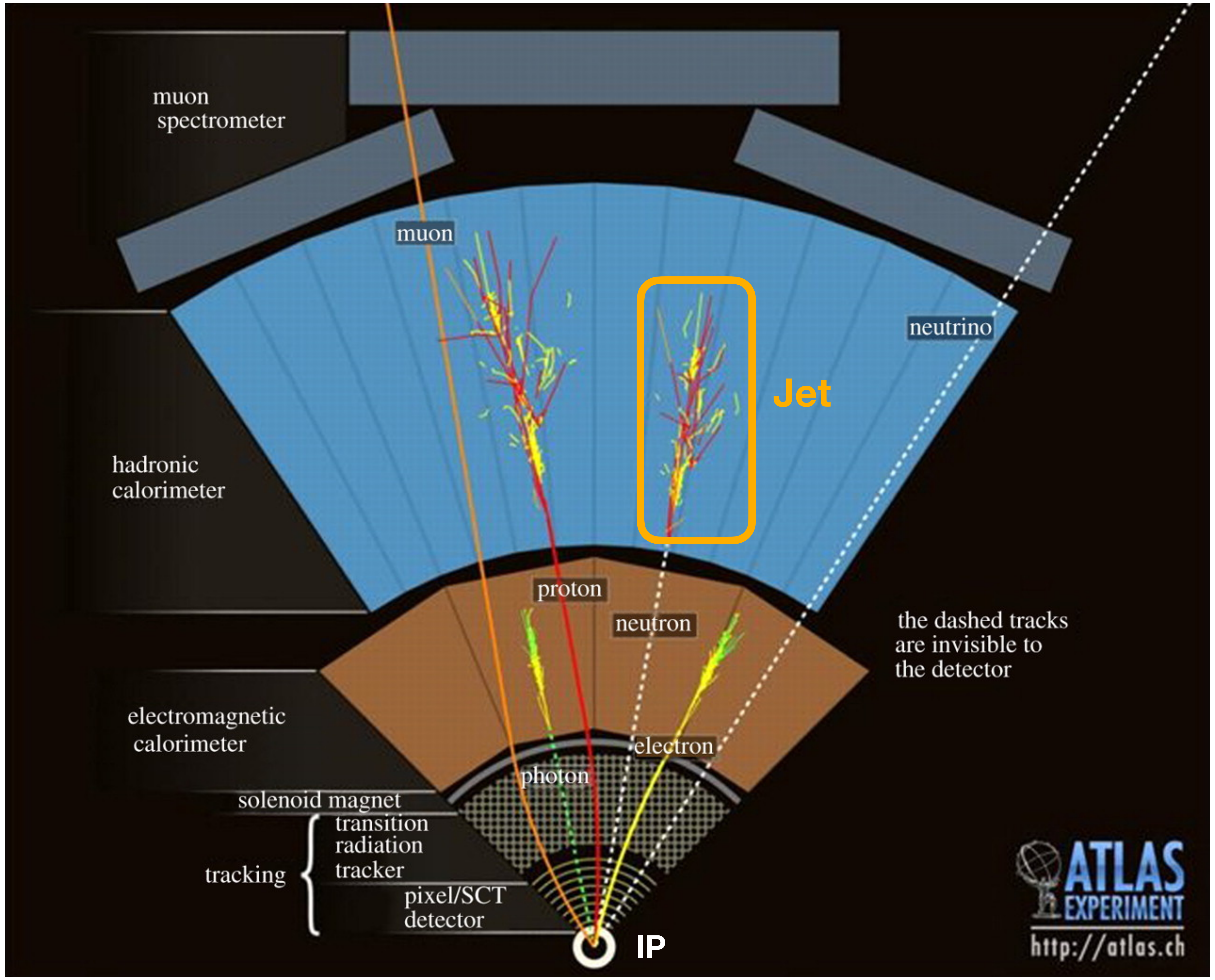
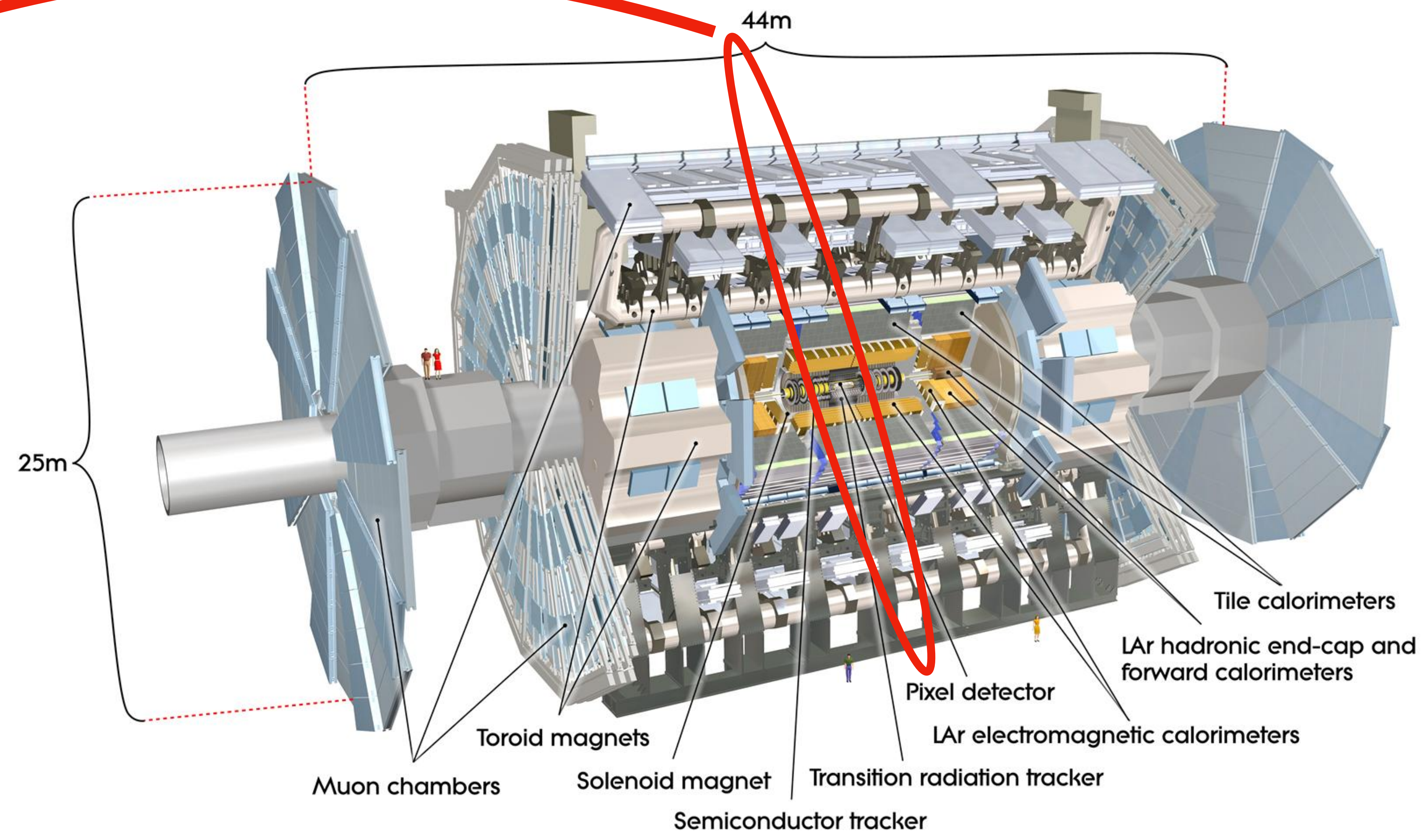


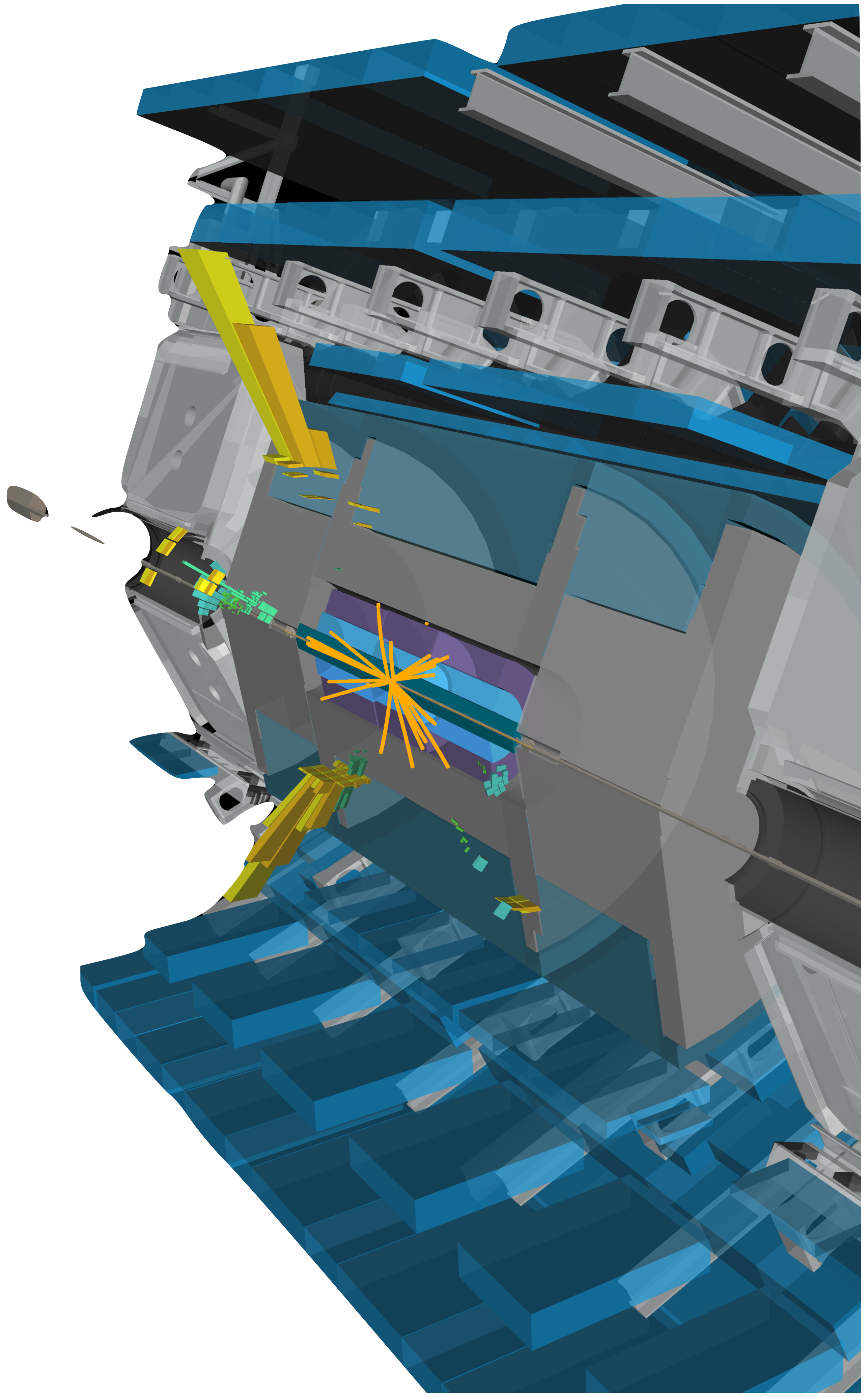
The ATLAS detector



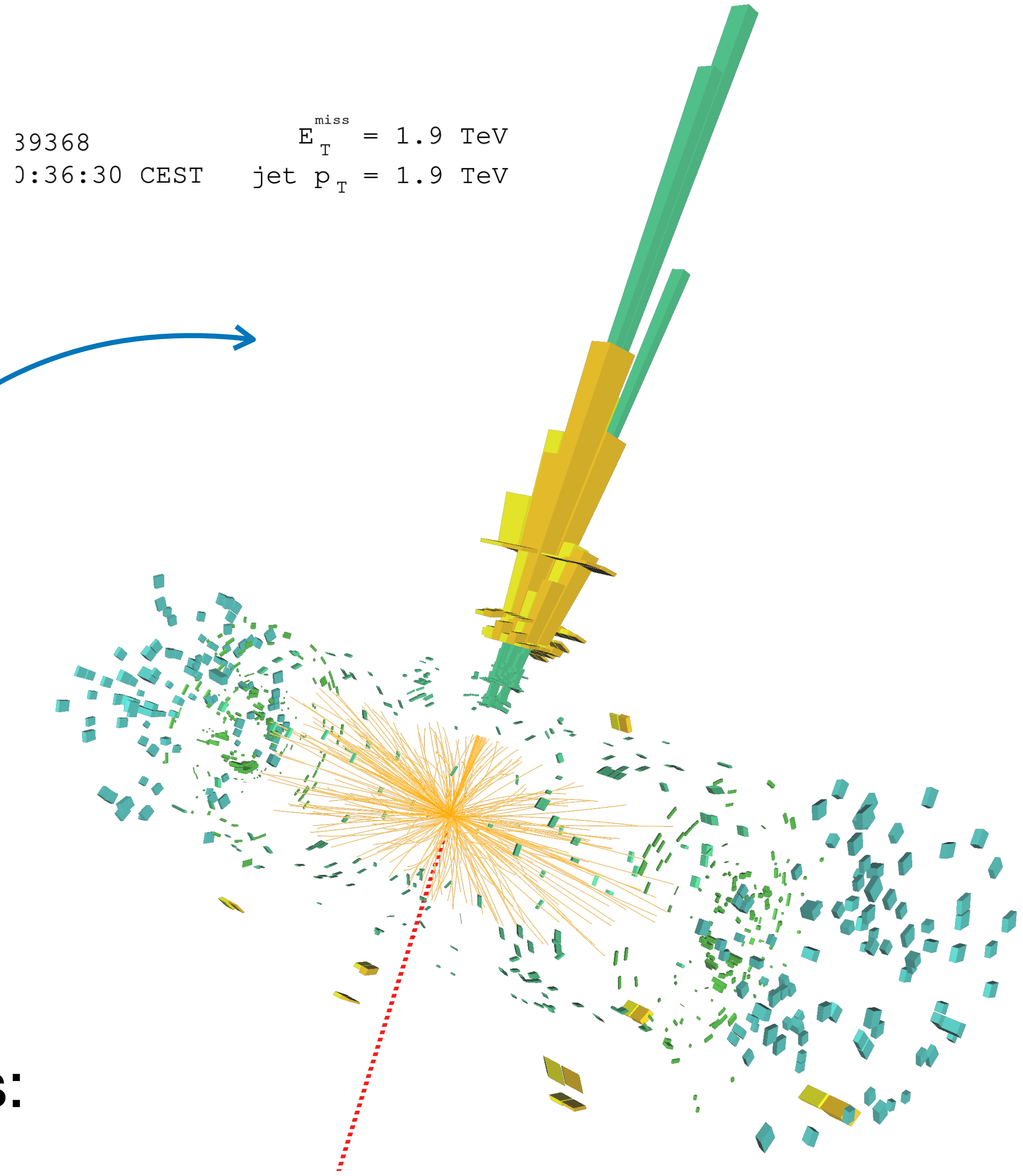


	ID	ECAL	HCAL	MS
p	✓	✓	✓	✗
n	✗	✓	✓	✗
e^-	✓	✓	✗	✗
γ	✗	✓	✗	✗
μ^-	✓	✓	✗	✓

New Physics at LHC



New Physics events may have very different signatures in the detector wrt standard events!



Long-Lived signatures:

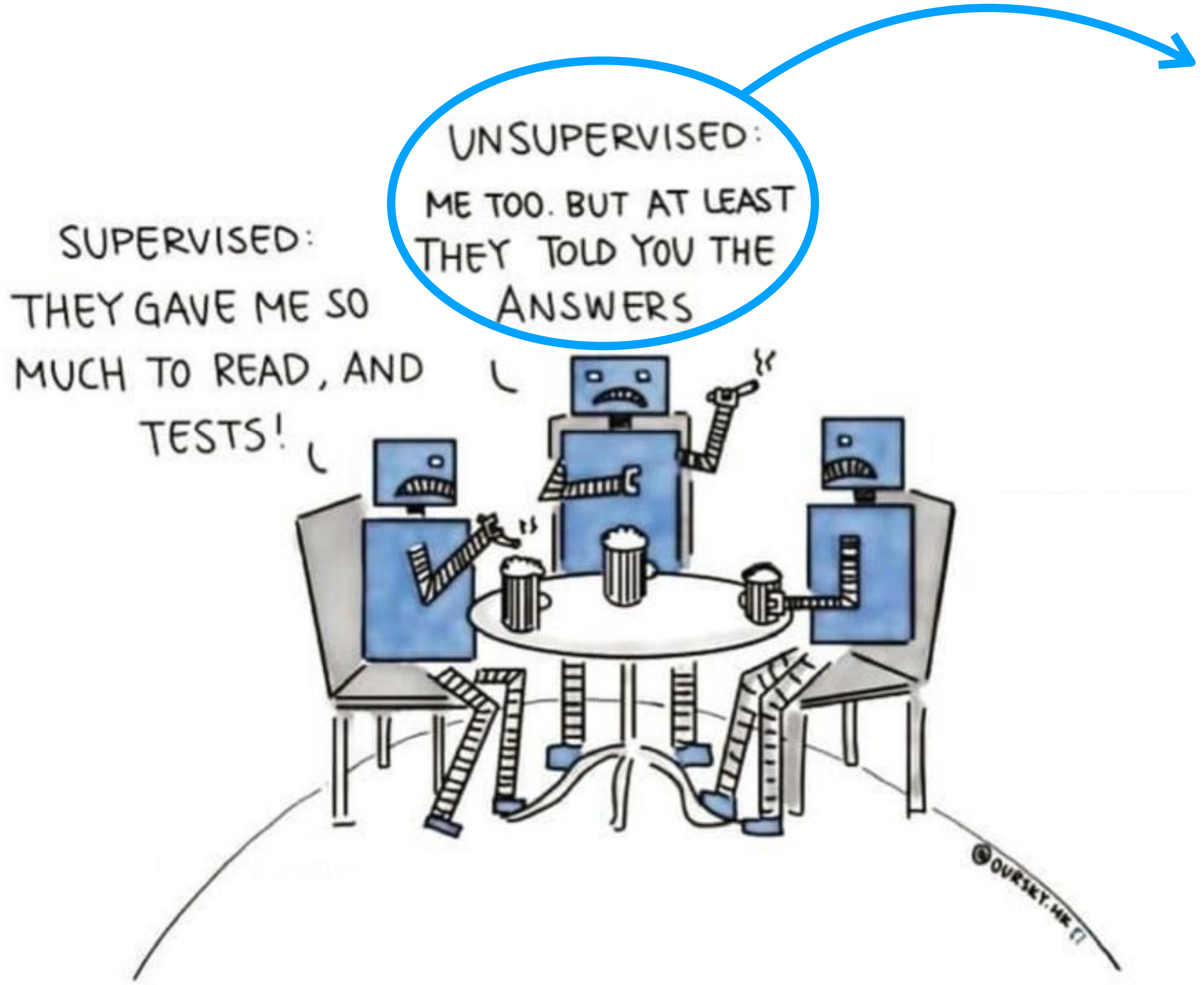
Particles “appears” at a certain point in the detector (here displaced jets)

Missing energy signatures:

Very long-lived or non-interactive BSM Particles are not detected → apparent missing energy!

Machine Learning for new Physics: Anomaly detection

Is one model more motivated than the other? Can we do better? Yes, with Machine Learning!



Anomaly detection:

ML trained on standard events, non-standard ones are reconstructed as anomalous!

The future

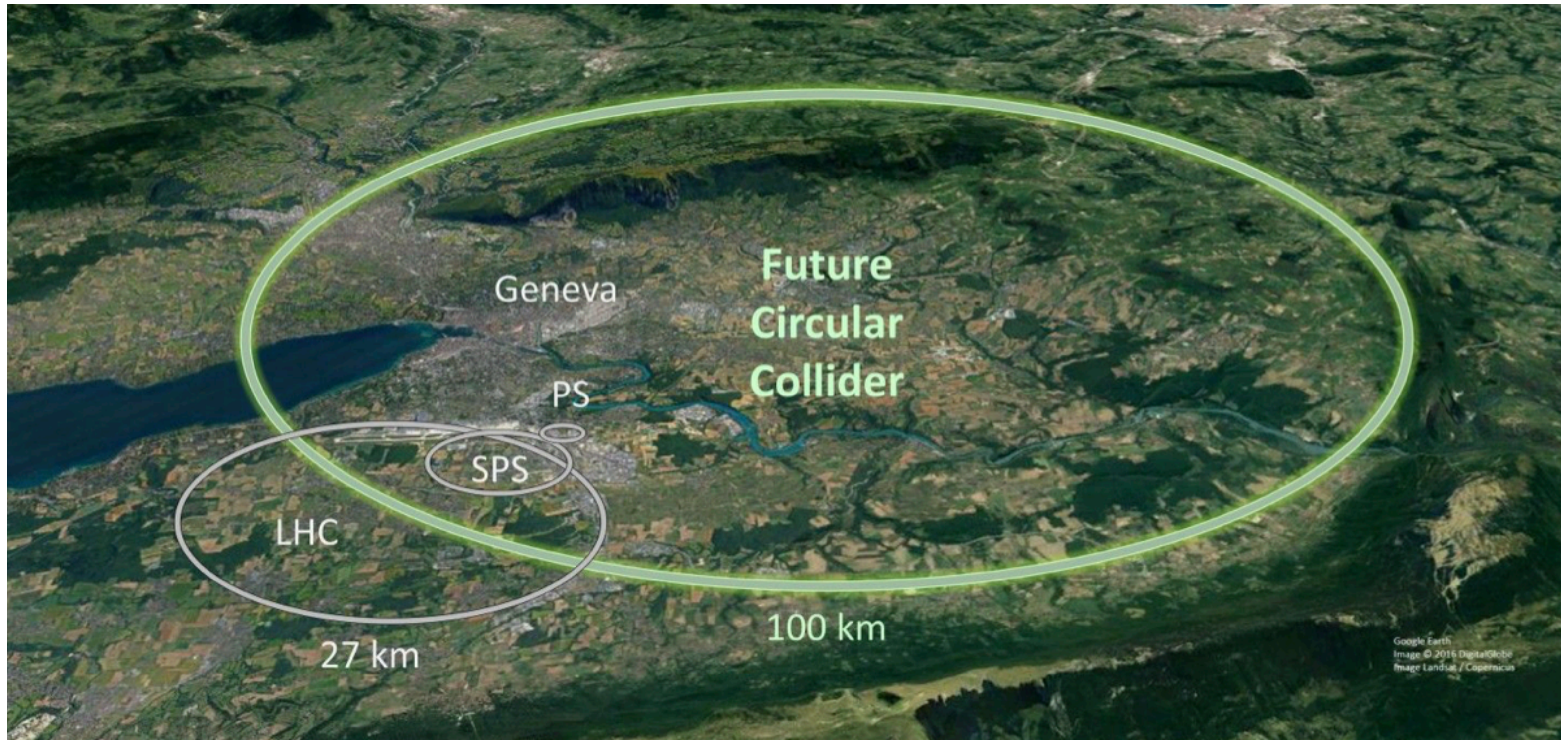
We are run in the third successful data-taking of LHC

Soon we will have a new run with improved detector and much more data to be analysed for many years

Probably new accelerator (FCC) will grant unprecedented energies!

A lot of things yet to be understood

⇒ it's your turn!



2020-2025	2027- 2028	2030-2031	2032- 2040	2041 – 2043	2060
~Now	HL-LHC starts, you are in your BSc		You finish your PhD	We find new physics?	You are a leading physicist
FCC feasibility Study	**Update of the European Strategy for Particle Physics**	**End of detailed studies. Presentation to CERN Council for decision**	**Civil engineering works**	**Start operation of FCC-ee collider**	**Start operation of FCC-hh collider**