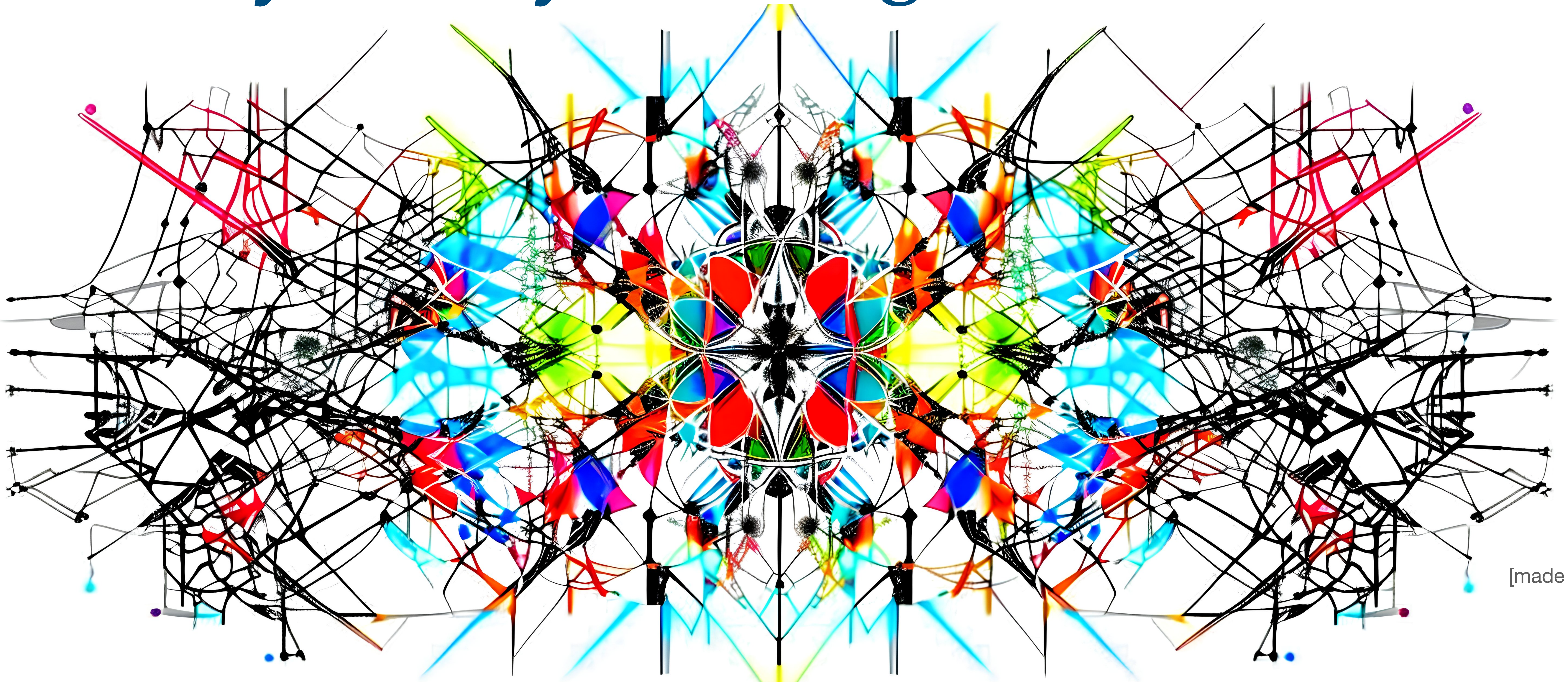
Imprints of Electro-Weak Symmetry Breaking at Colliders



[made with stablecog]

Andreas Papaefstathiou

National Science Foundation

Kennesaw State University, GA, USA

@ Georgia State University [September 26th 2023]

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Today's Plan:

Today's Plan:

1 High Energy Physics

2 Open Questions,

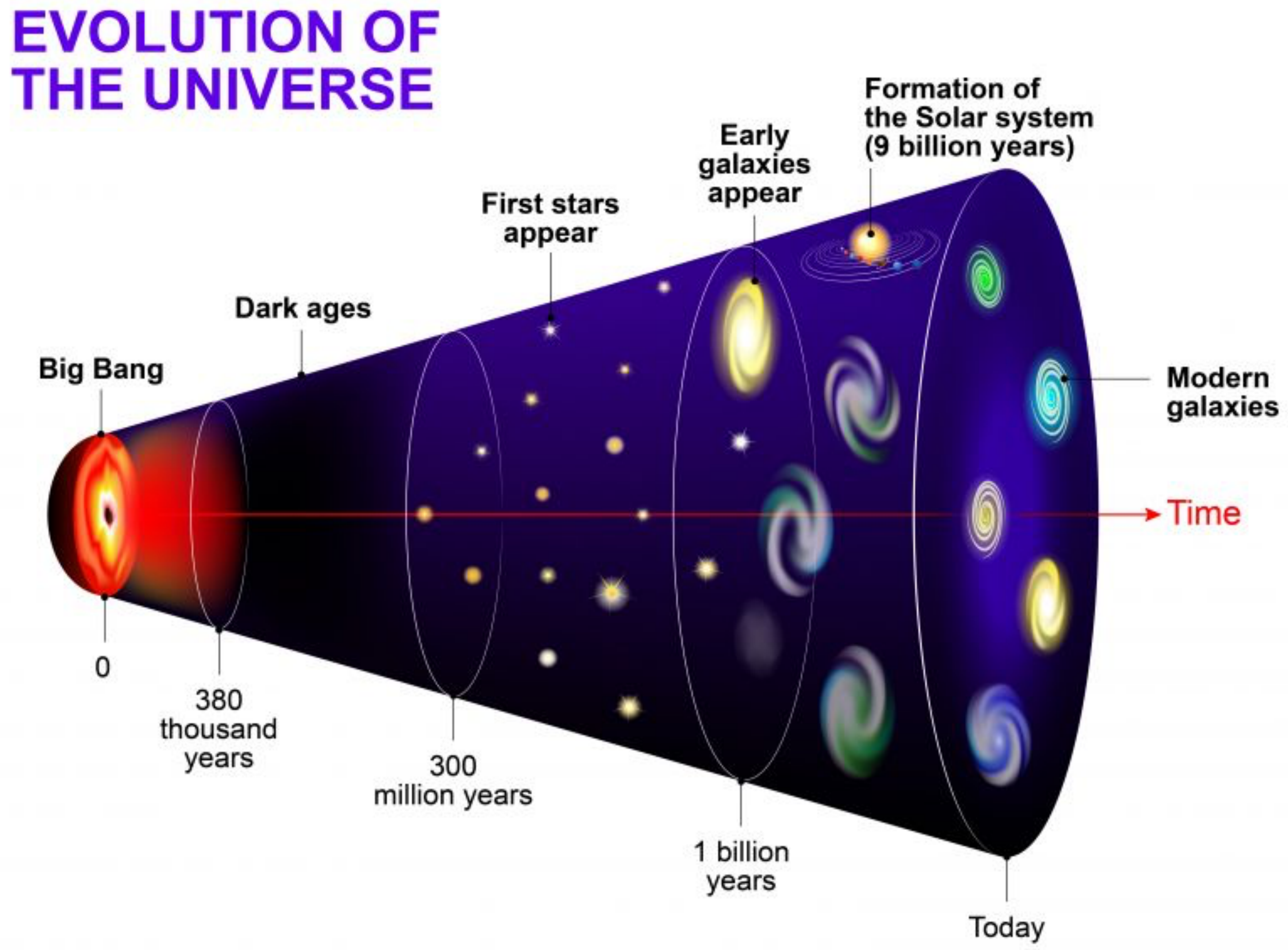
3 ➜ the Breaking of Symmetry,

4 Extended Scalar Sectors.

1 What is High Energy Physics?

What is High Energy Physics?

Aim: Smash particles together to "emulate" conditions <u>closer</u> to the Big Bang! ("Particle Archaeology")



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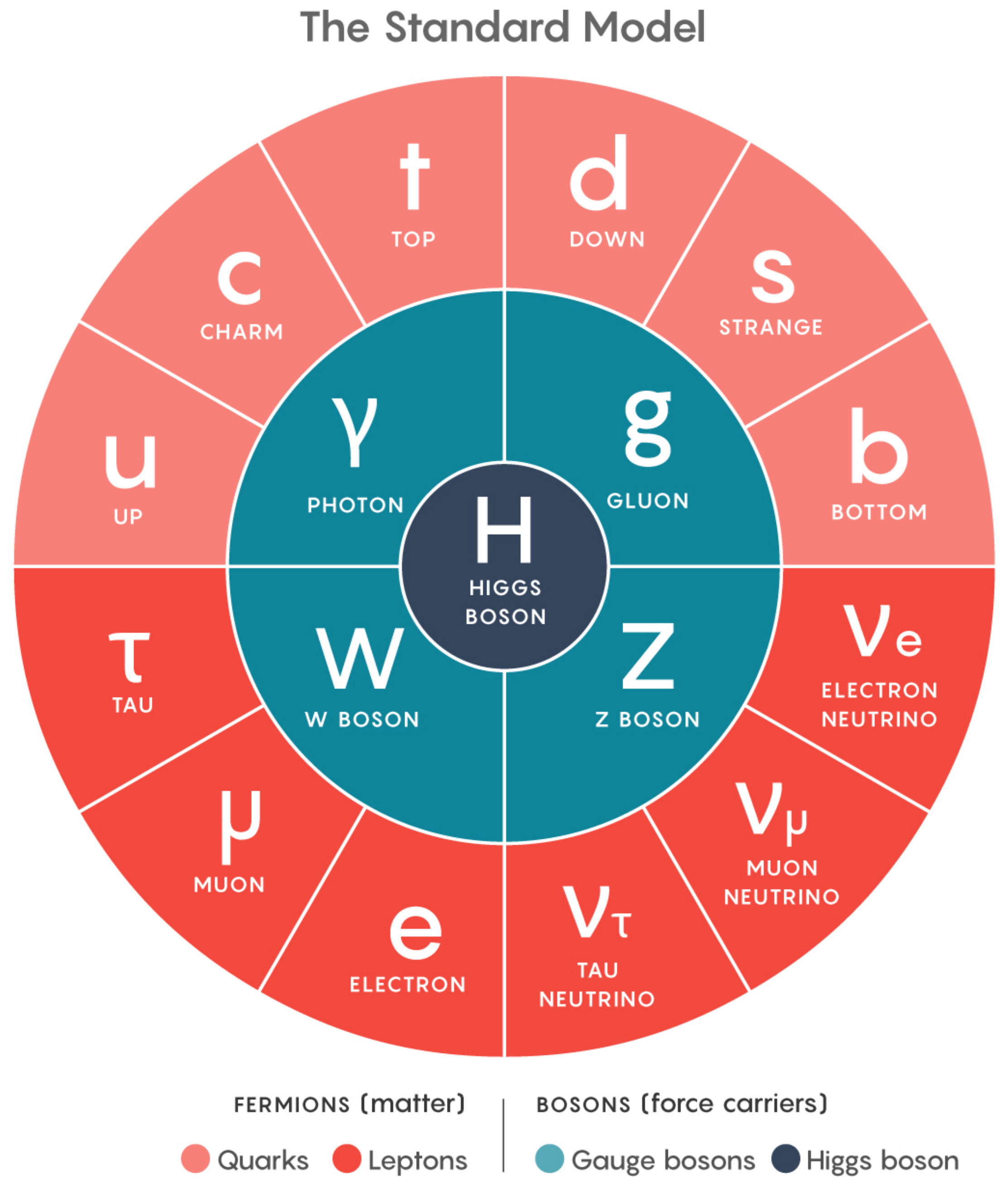
understand
particle interactions:
e.g. **The "Standard Model" (SM)**



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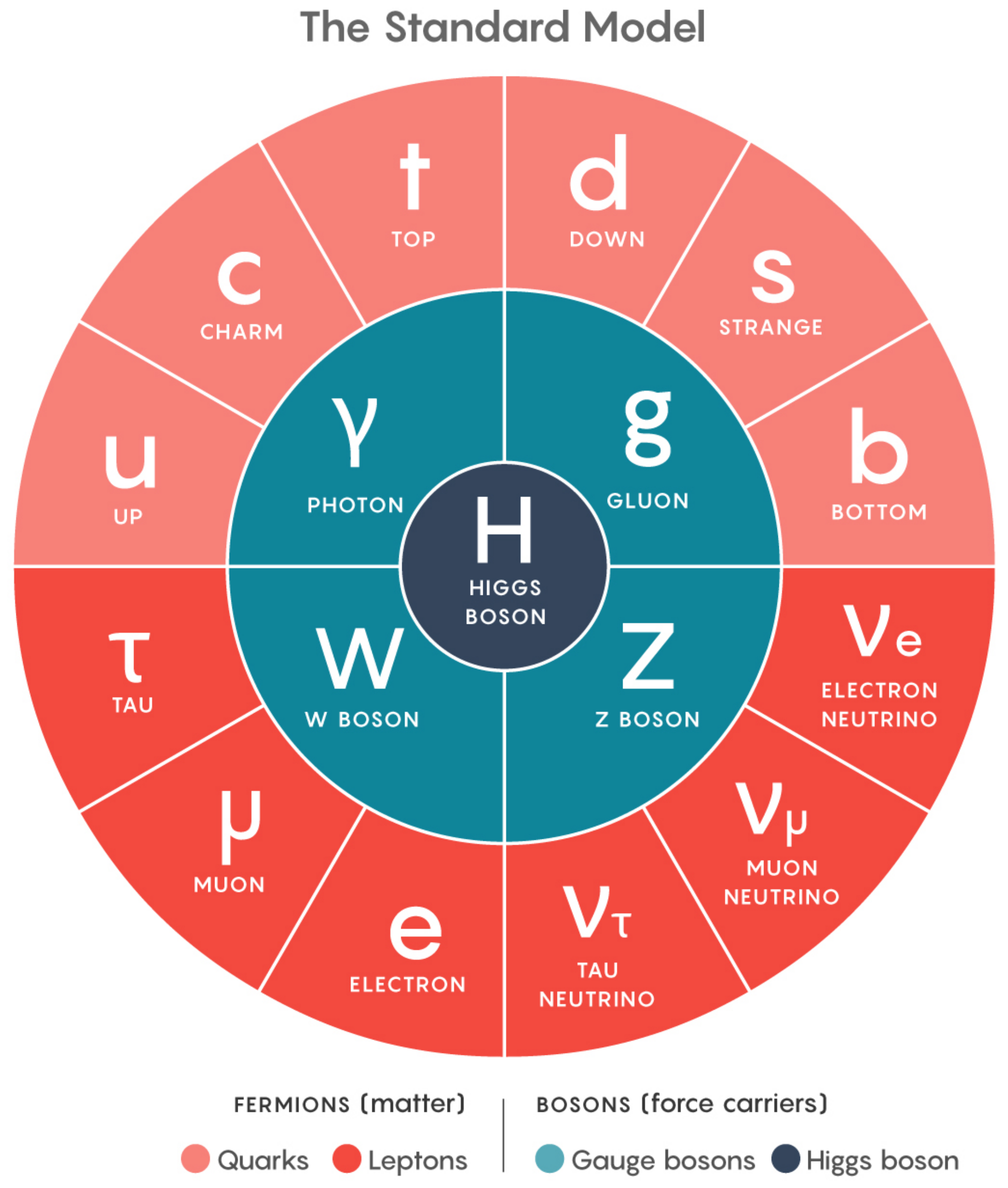

and discover **exotic** phenomena!

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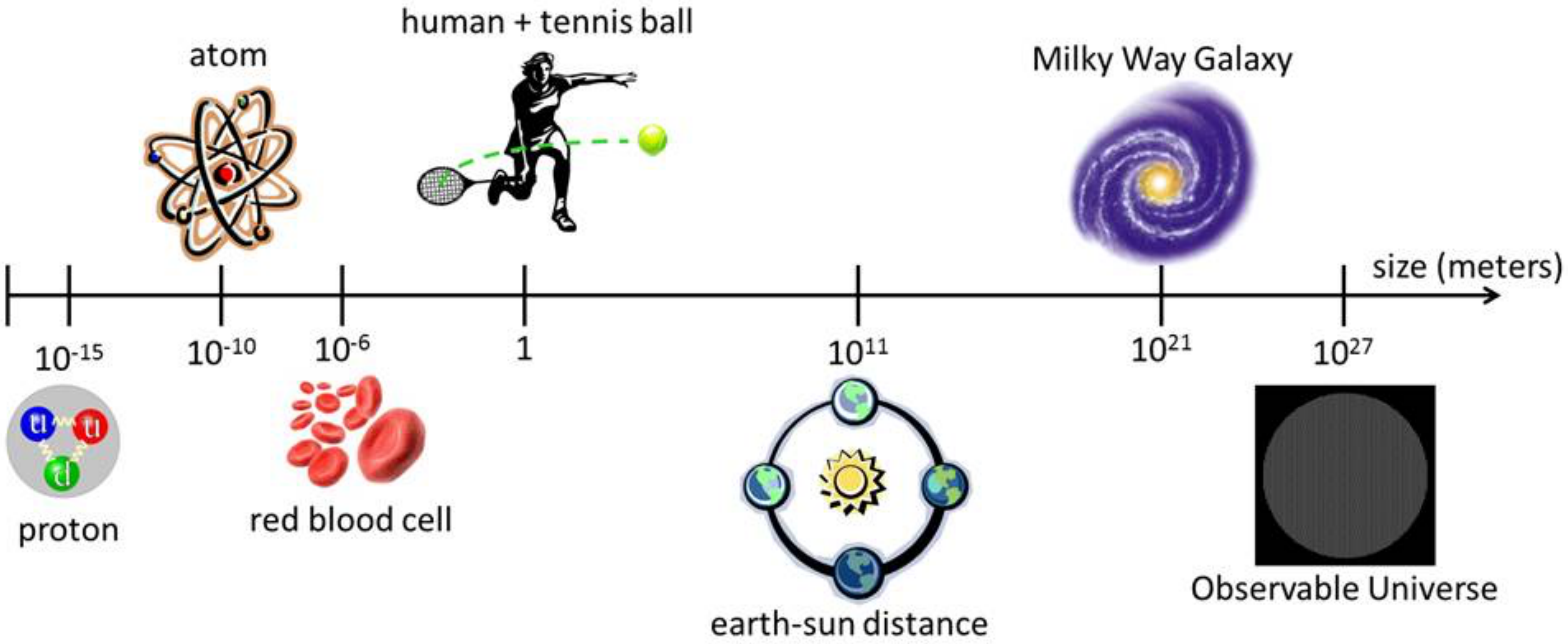
What is High Energy Physics?

Rule: Higher Energy $\Longleftrightarrow$ Smaller Scales!



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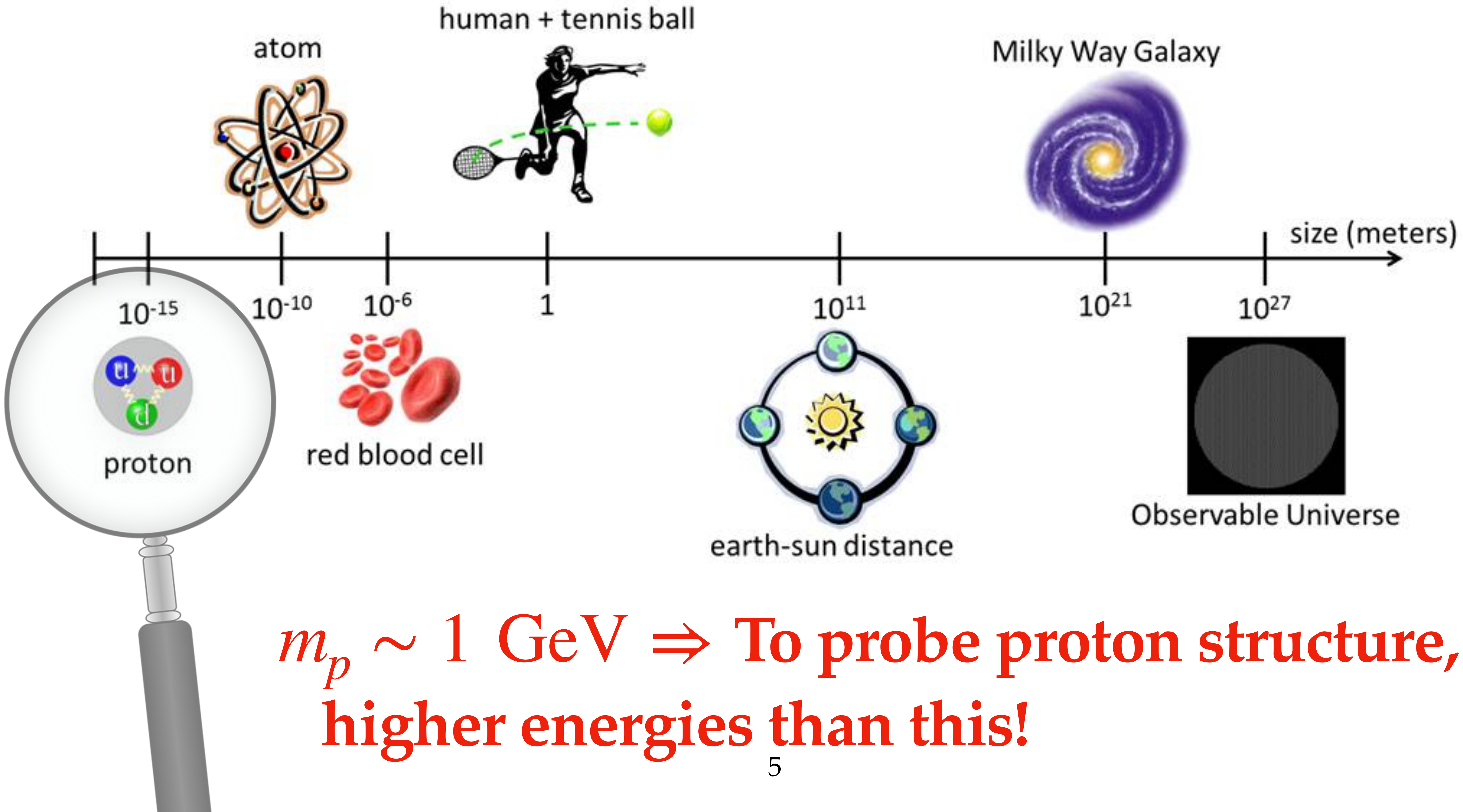


$m_p \sim 1$ GeV $\Rightarrow$ **To probe proton structure, go to higher energies than this!**

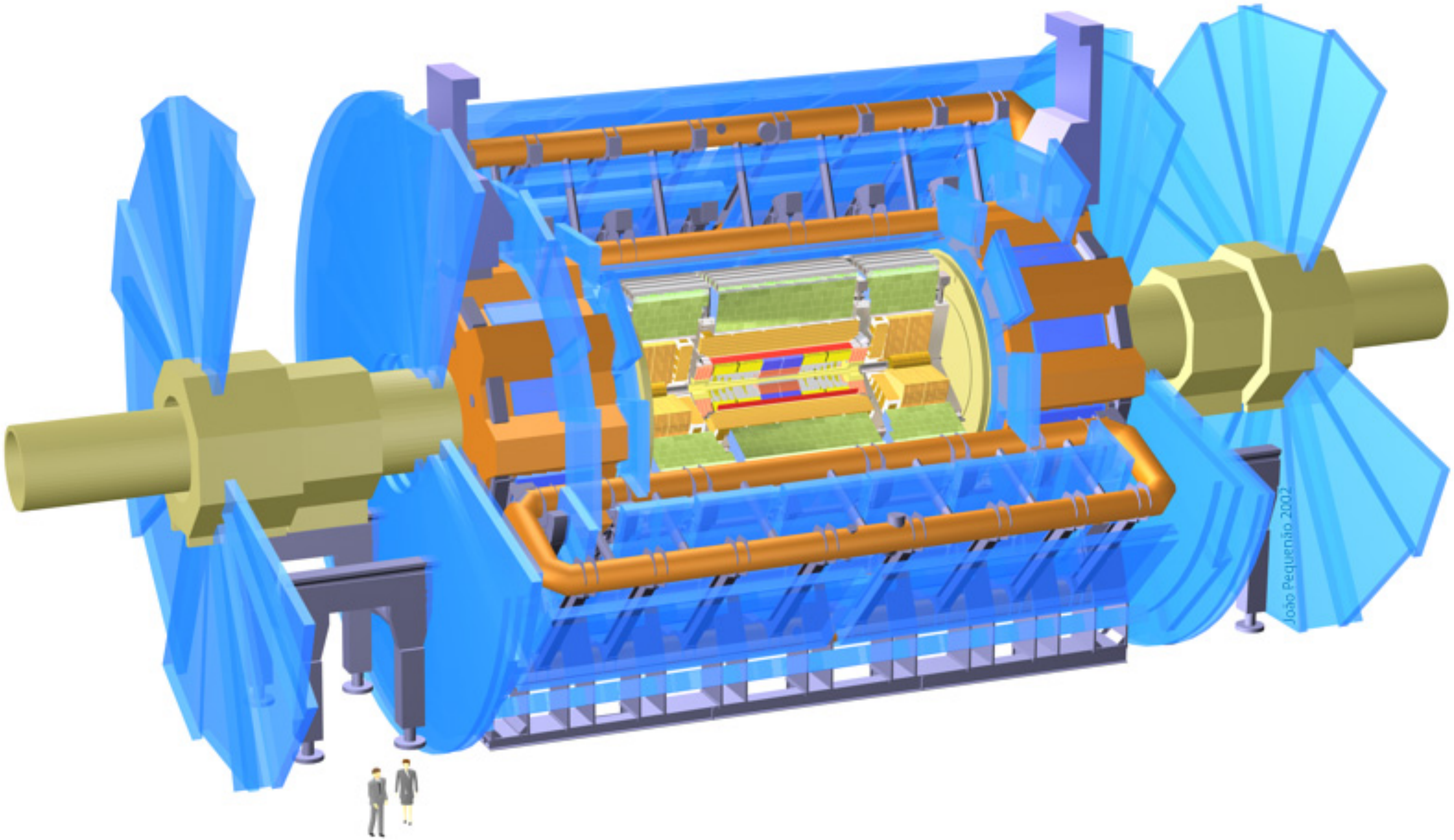
High Energy Particle Colliders

Large Hadron Collider
@ CERN
in Geneva, Switzerland

Center-of-mass energy:
13,600 GeV = 13.6 TeV

High Energy Particle Colliders

High Energy Particle Colliders



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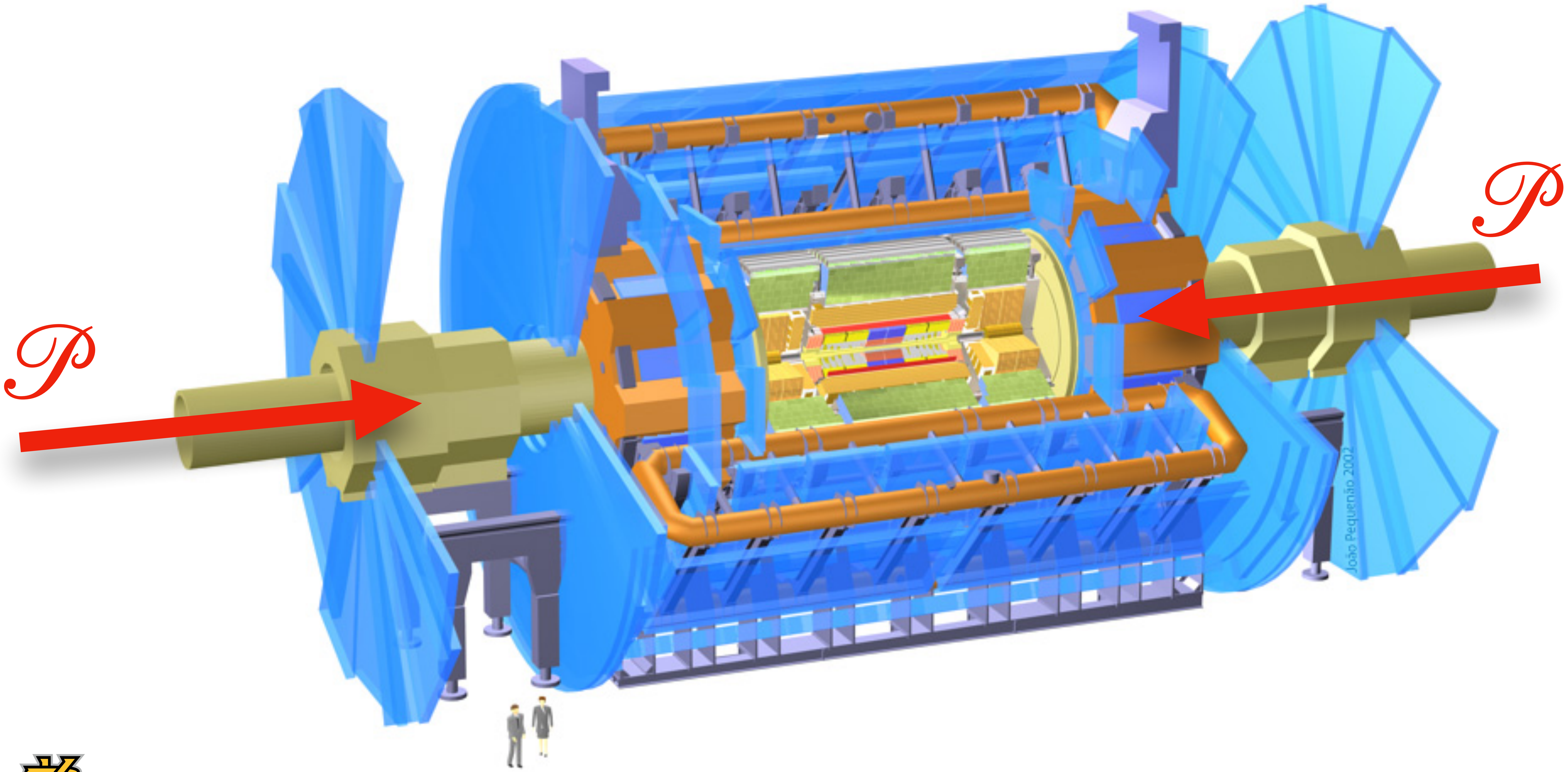

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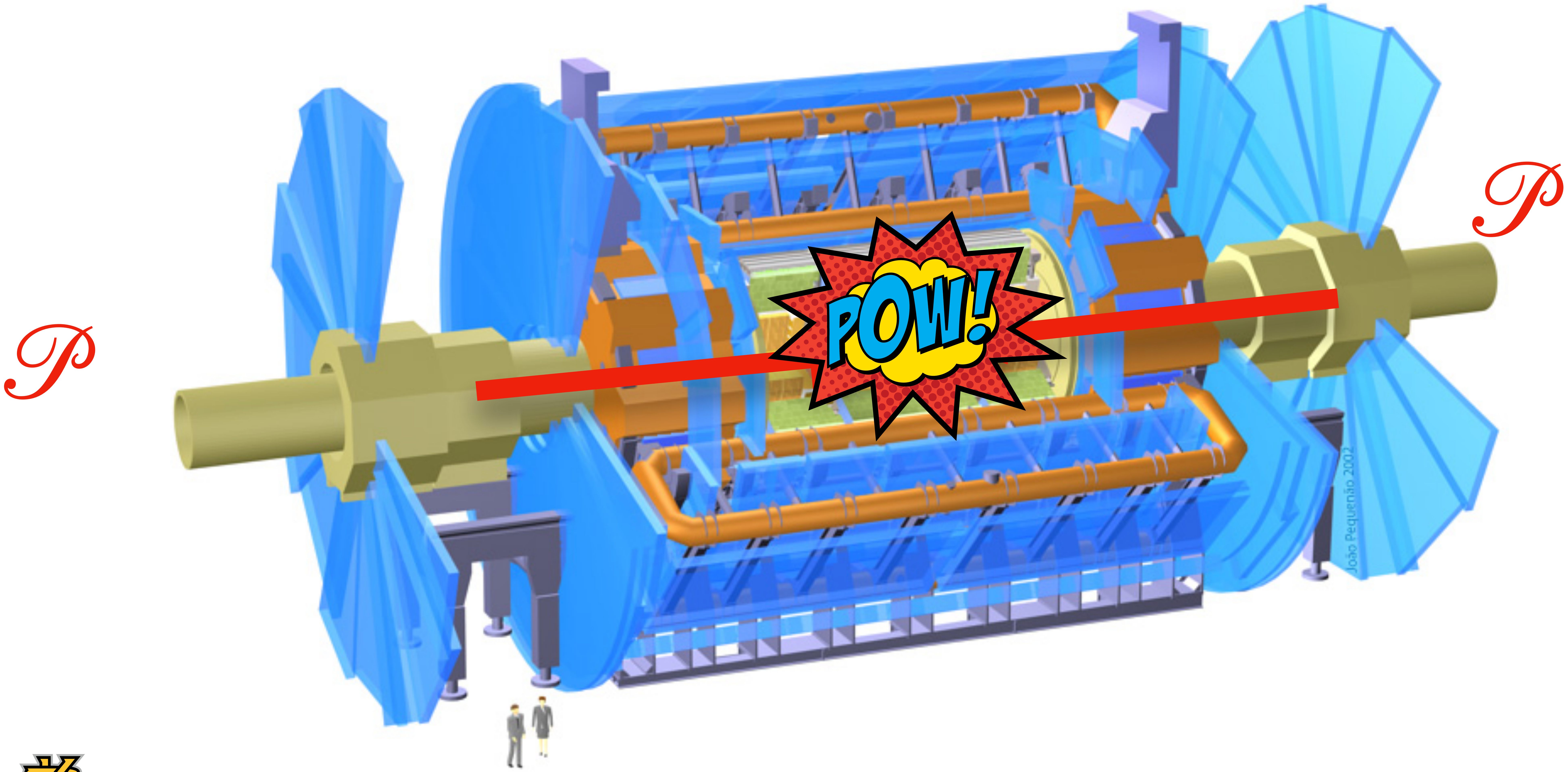
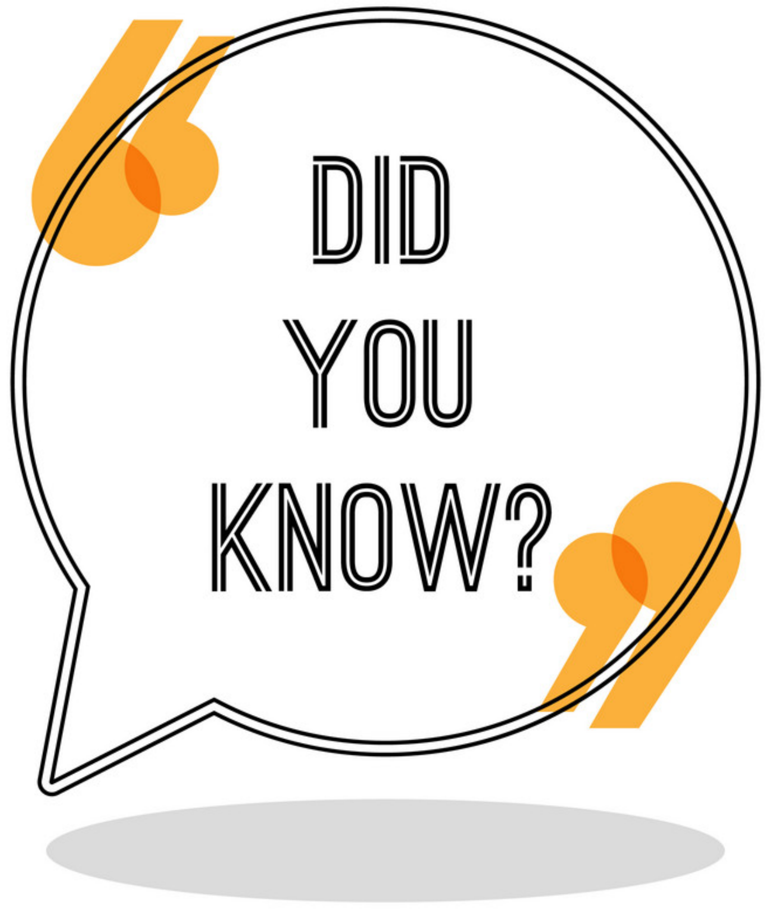
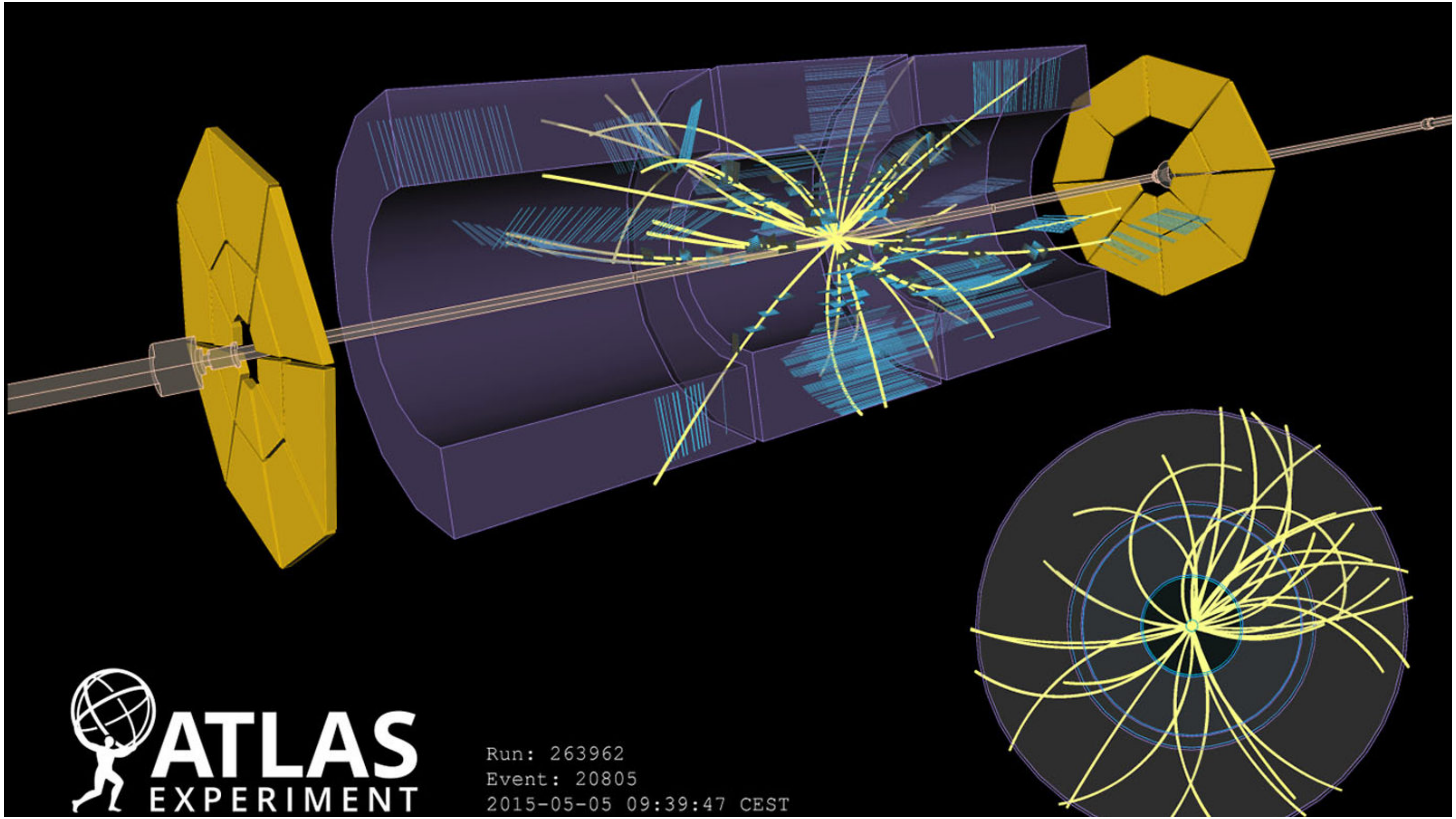


LHC: Fun Facts



- Circumference of **27 km** (17 miles).
- Lies **100 m** (330 feet) underground.
- Produces **hundreds of millions of particle collisions/ second** (="events").
- **Energy stored** in particle beam = Energy of **1000 kg car @ 3000 km/h** (~1900 mph)!
- The data recorded can fill around **100,000 DVDs each year**!

This is a real “event”!



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How do we make sense of it all?

Pictured: Richard Feynman playing the bongos.

How do we make sense of it all?

$$
\begin{aligned}
\mathcal{L} = &-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\Psi}\not{D}\Psi \\
&+ \Psi_i y_{ij}\Psi_j + \text{h.c.} \\
&+ |D_\mu\Phi|^2 - V(\Phi)
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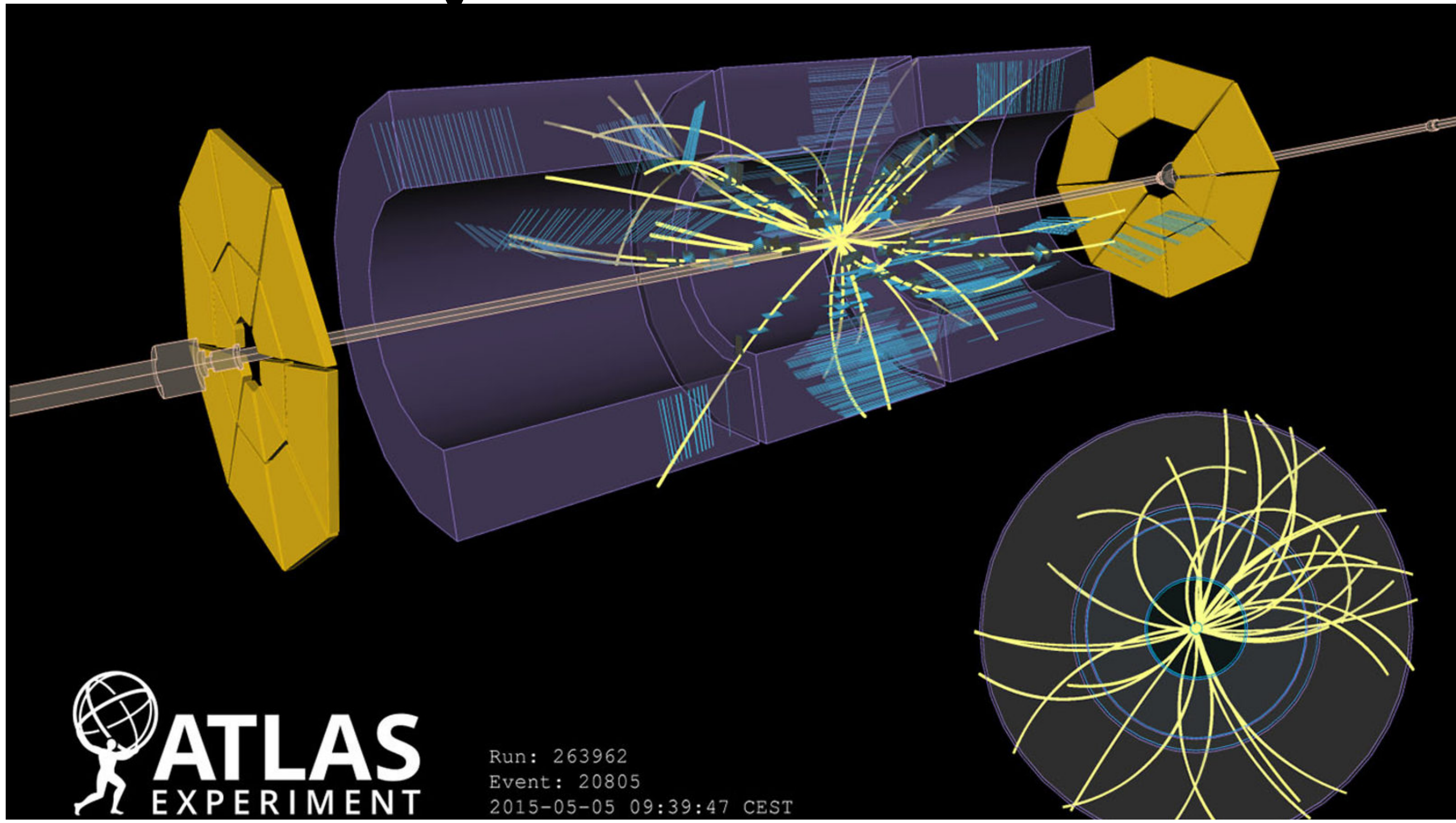
Experiment



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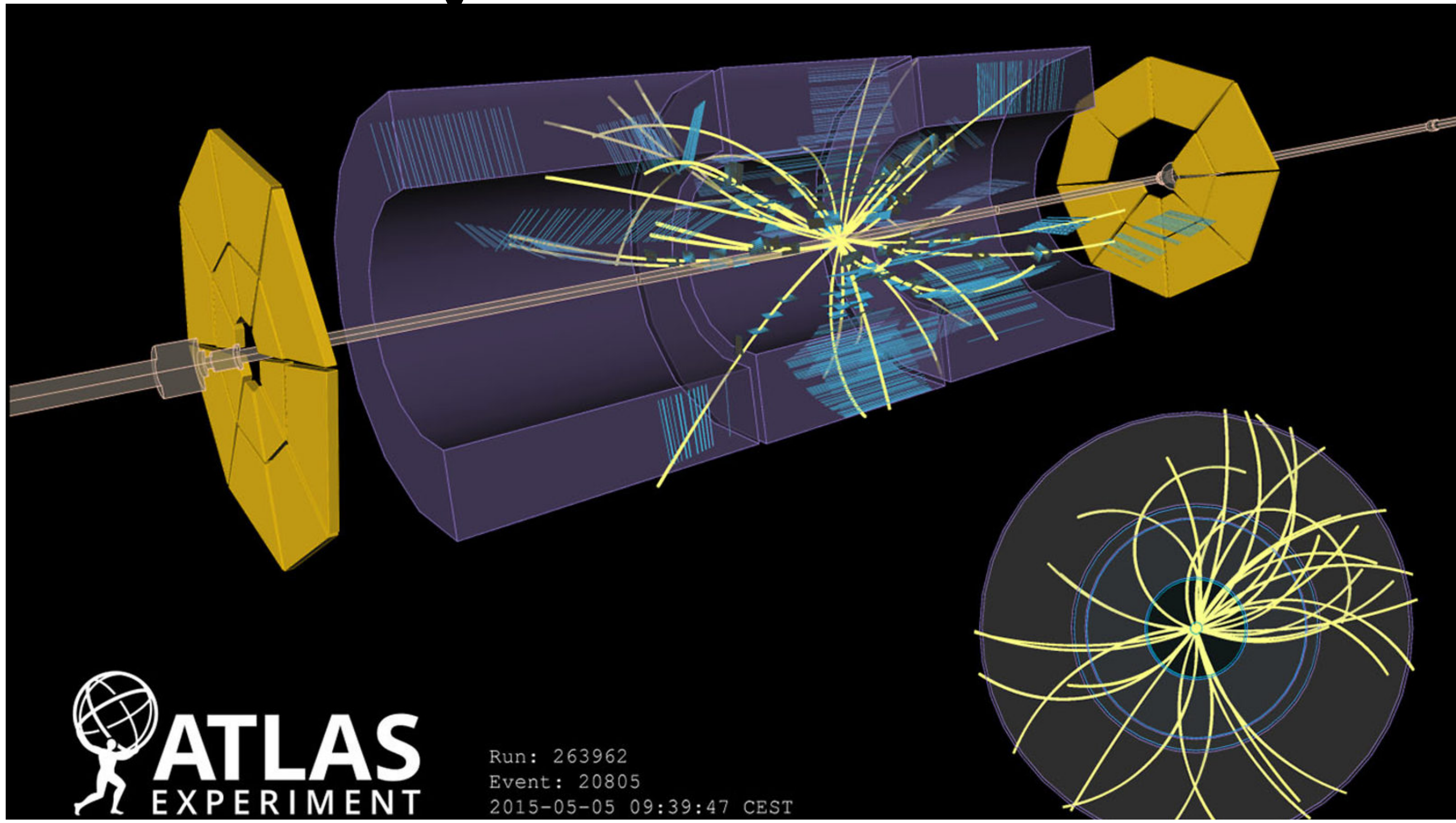
???

Experiment



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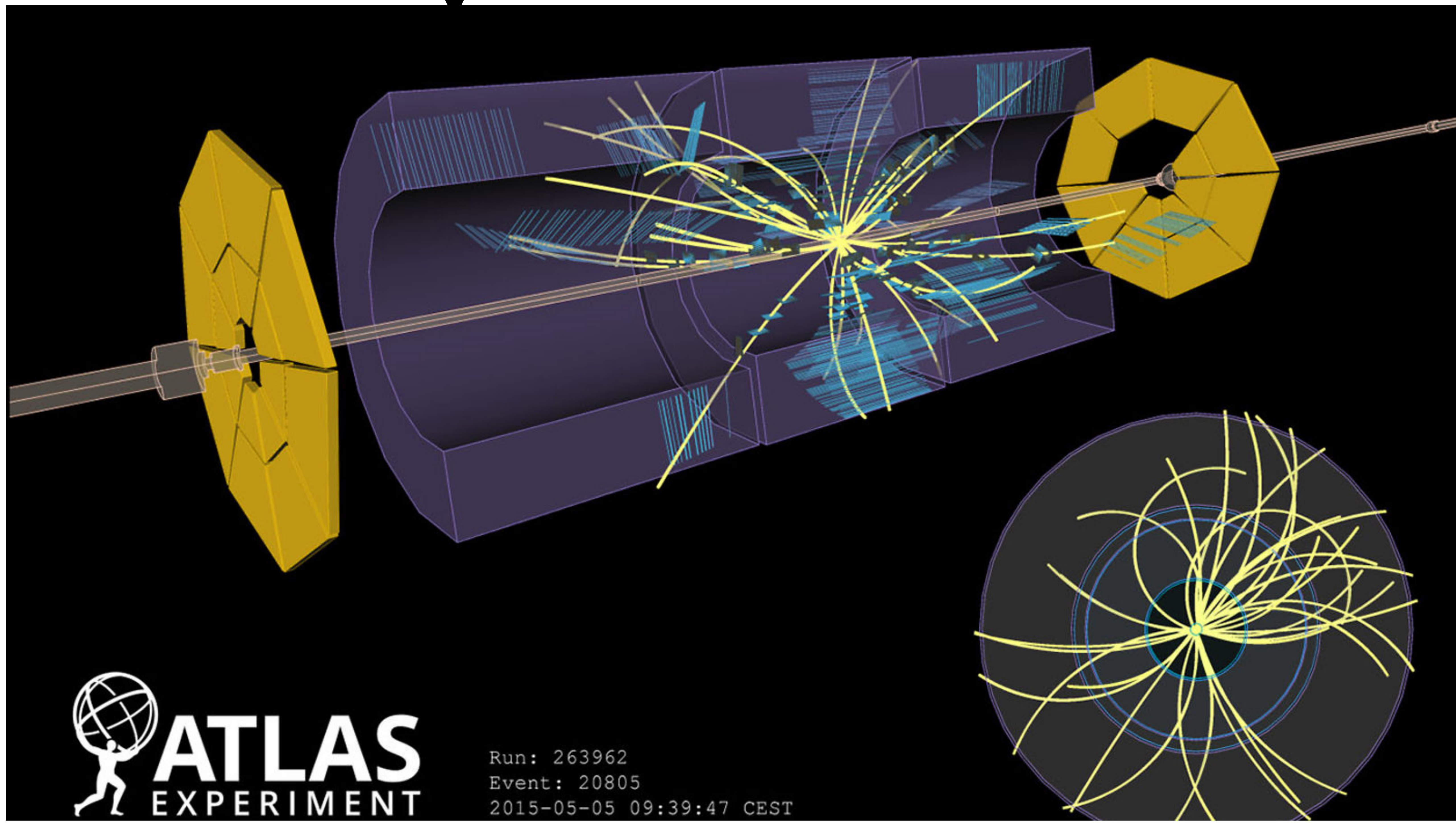
How do we make sense of it all?

Shut up and Calculate!

???

Experiment



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(Shut up and Calculate) Using Quantum Field Theory

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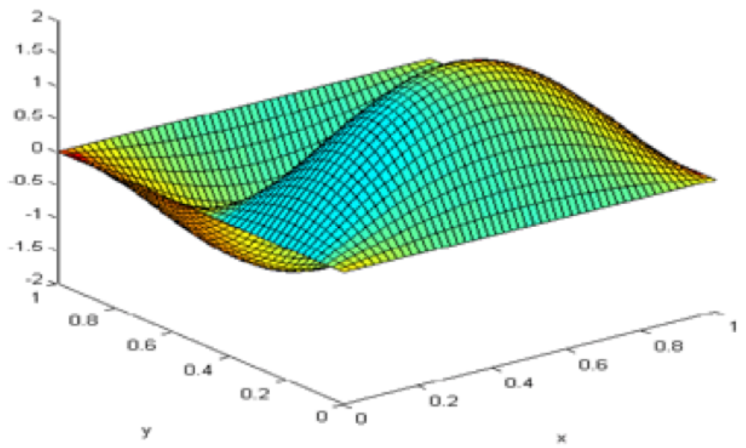
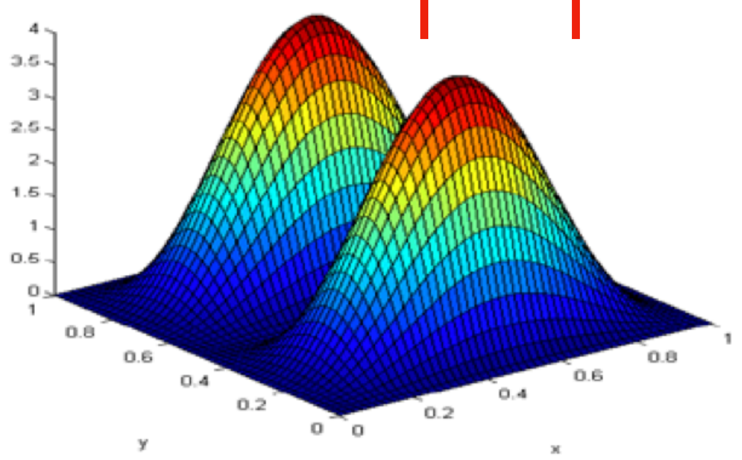
Ψ



$|\Psi|^2$



→ Calculate Ψ,

⇒ <u>Probability</u> to find particle somewhere $\propto |\Psi|^2$

[Ψ is called the "wave function"]

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(Shut up and Calculate) Using Quantum Field Theory

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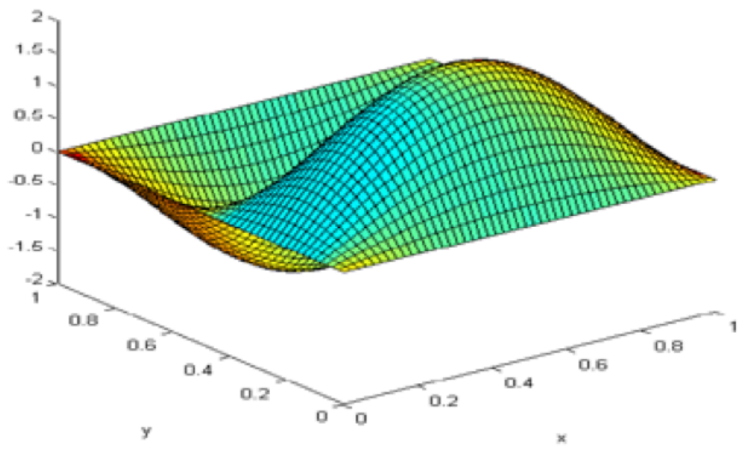
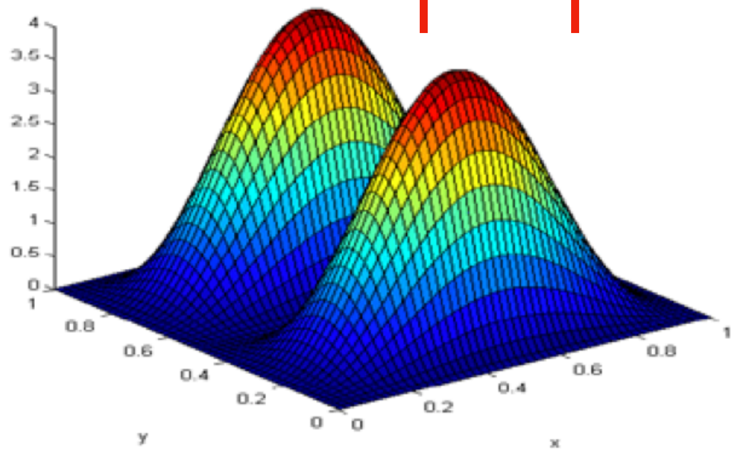
Ψ 

$|\Psi|^2$ 

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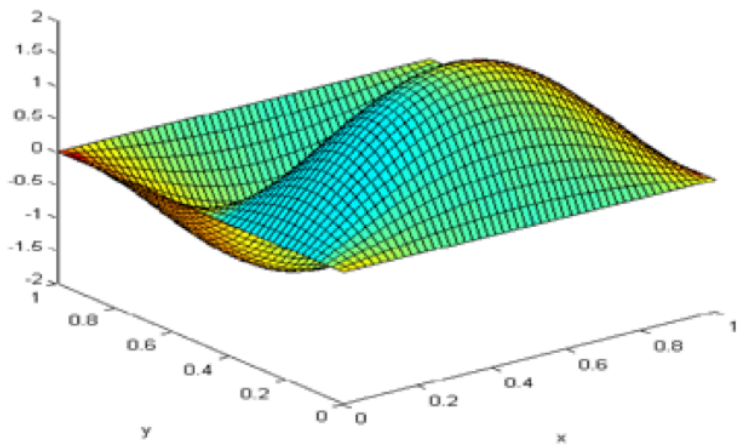

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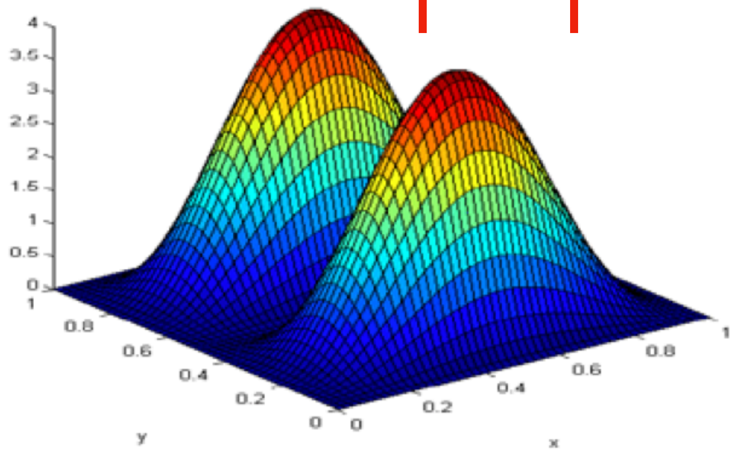

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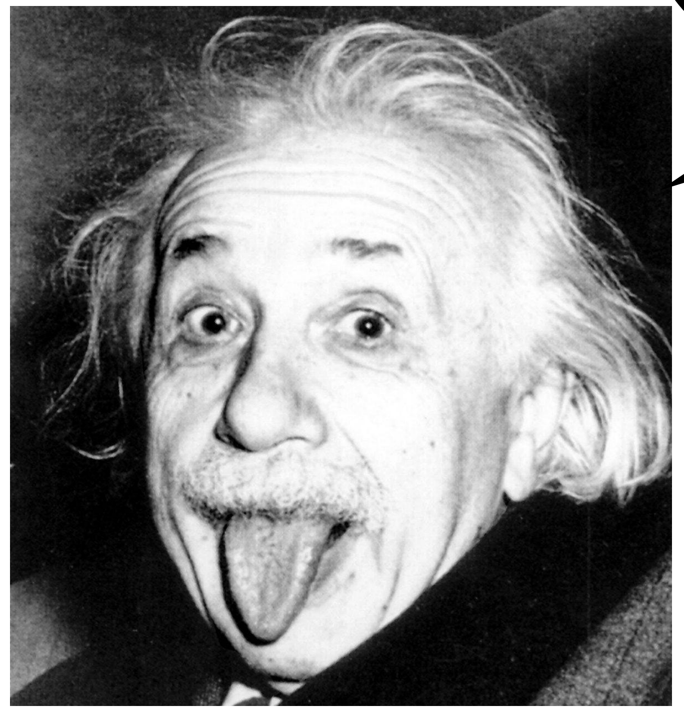

$E = mc^2$

(Shut up and Calculate) Using Quantum Field Theory

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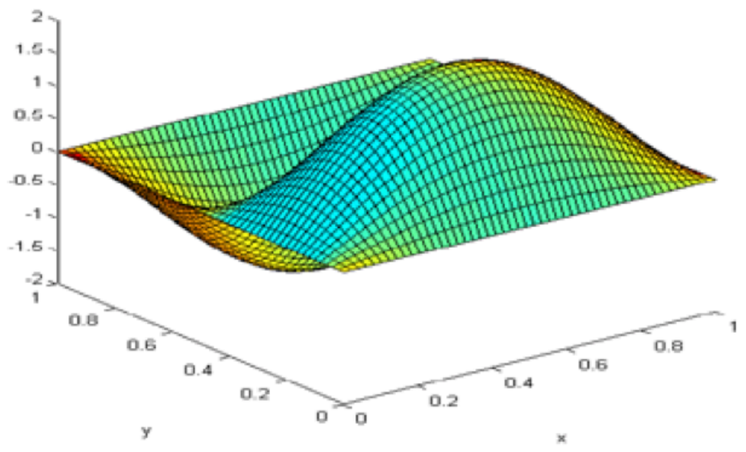

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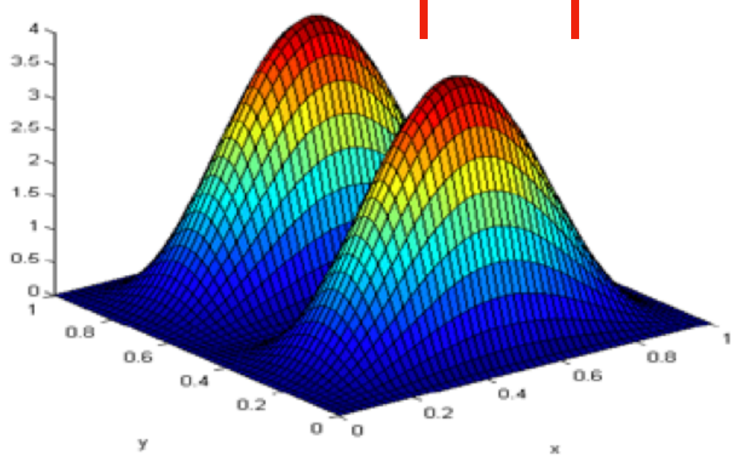

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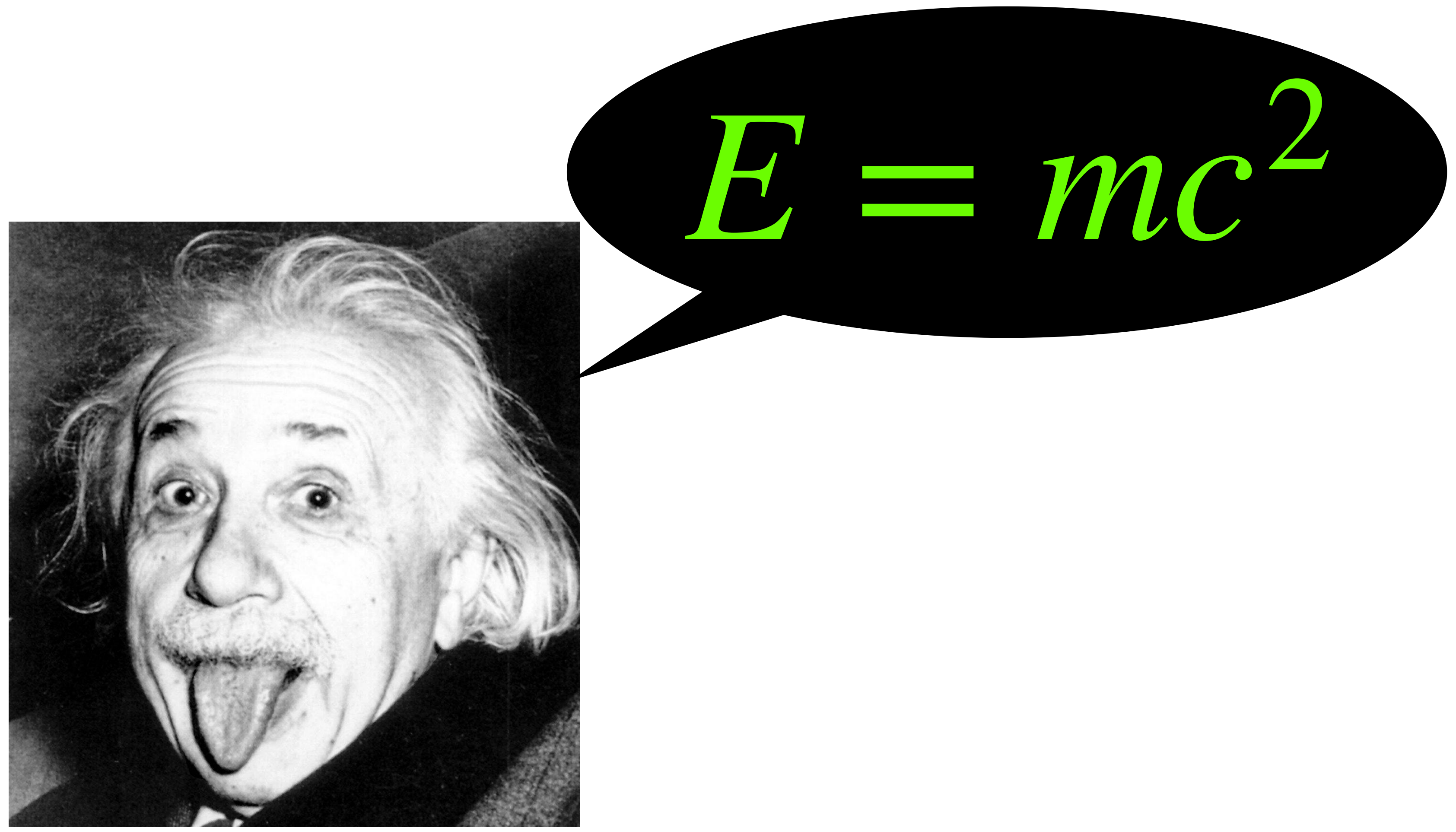

→ Mass and Energy are equivalent!

⇒ You can exchange one for the other!

⇒ Particle creation from Energy!

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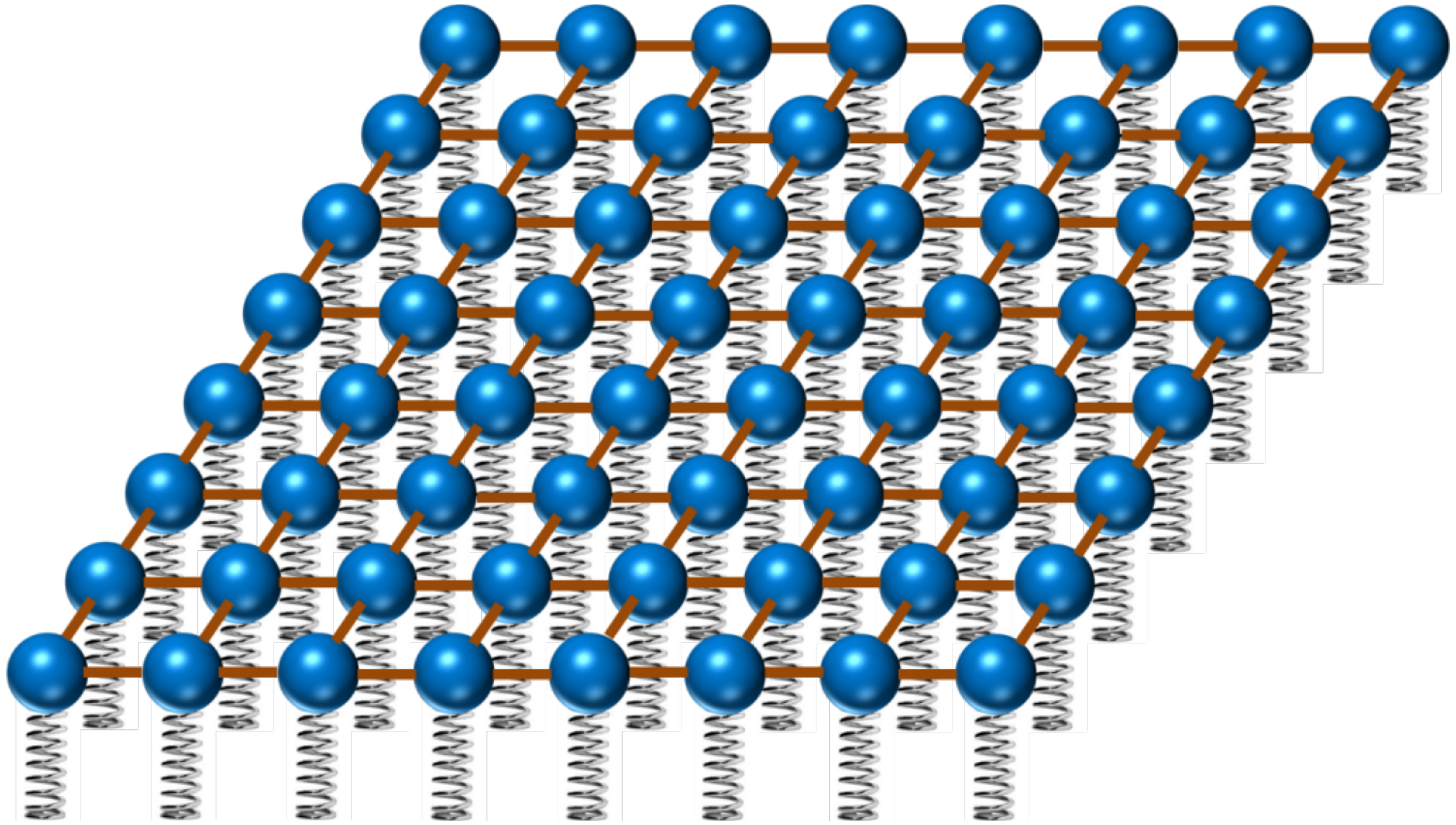
Quantum Mechanics + Special Relativity ≈ **Quantum Field Theory**



From Theory to Experiment and Back Again

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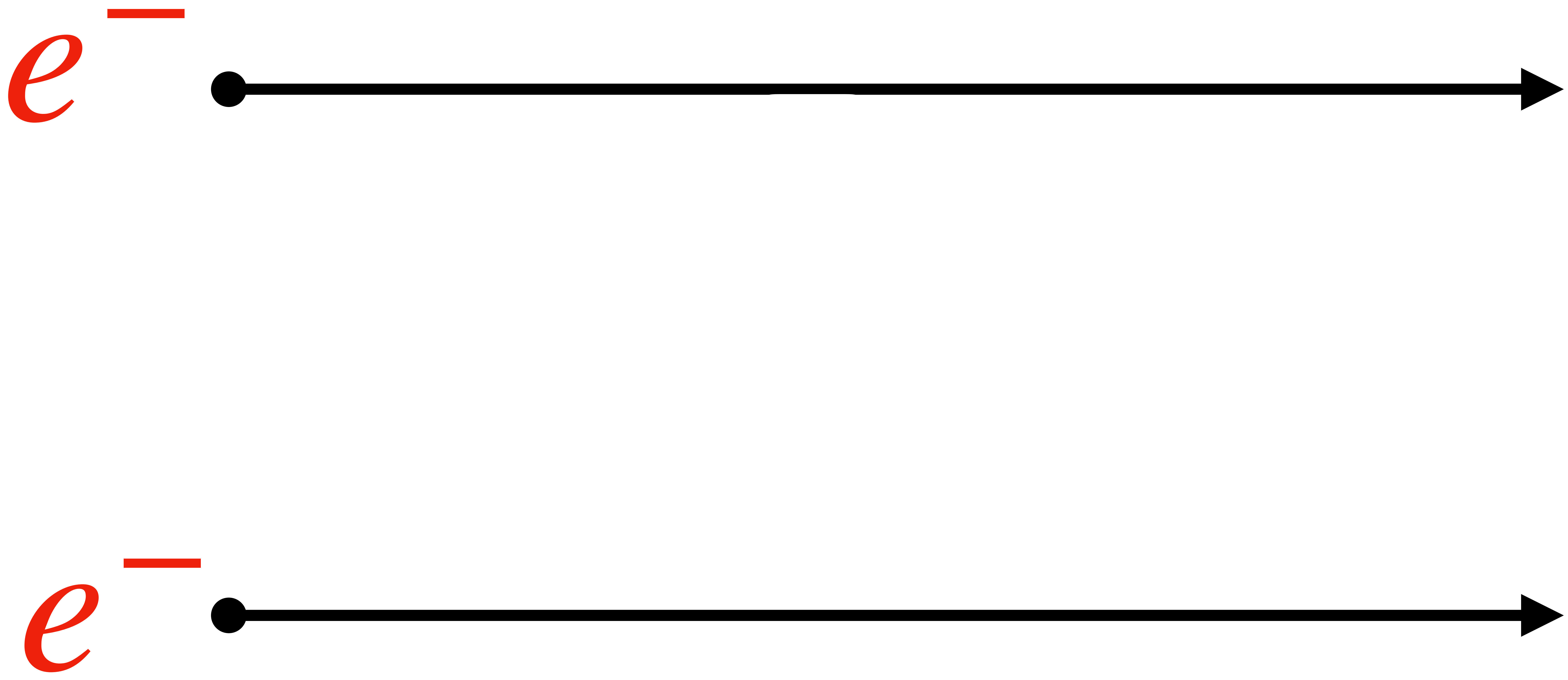

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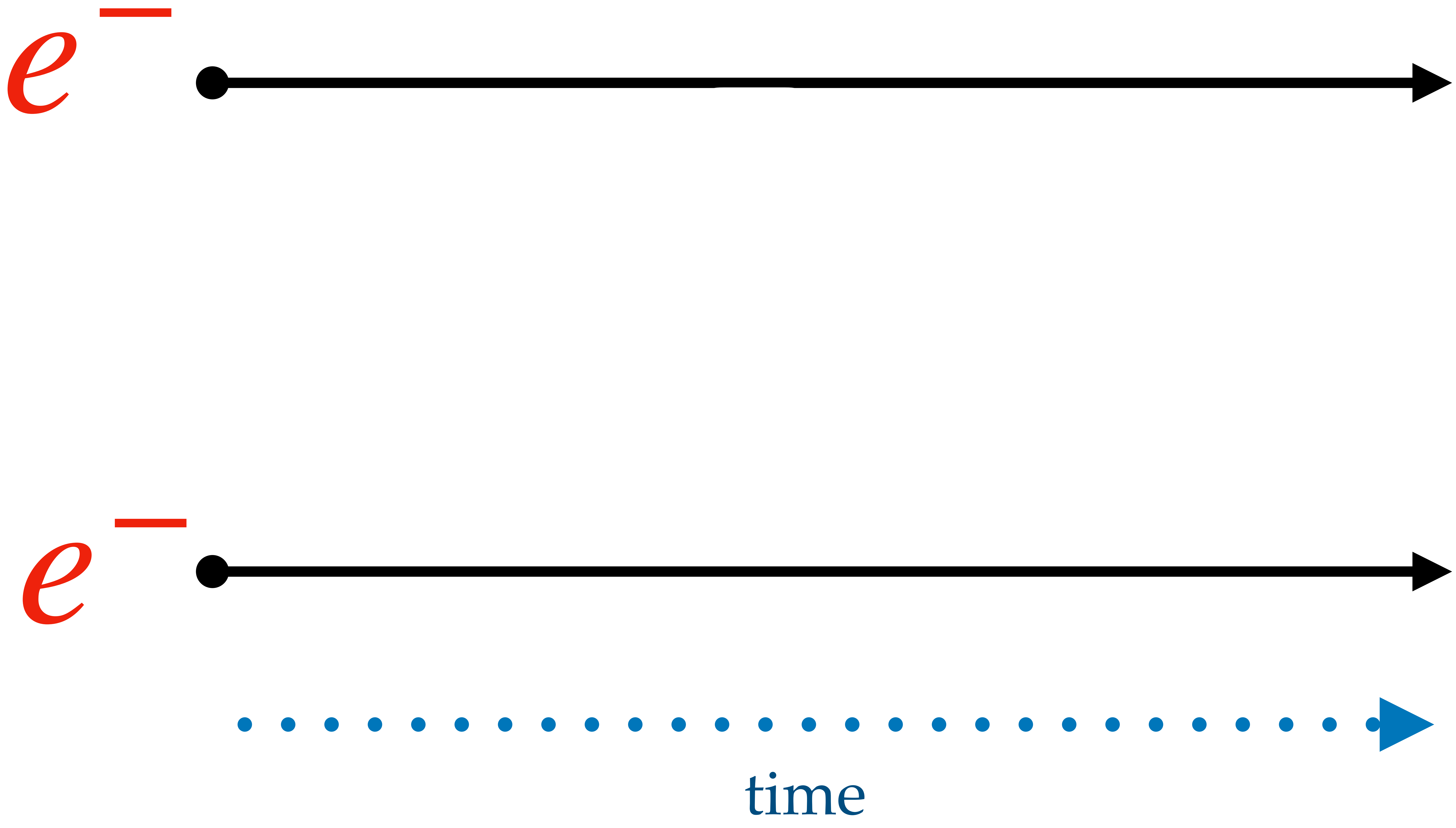

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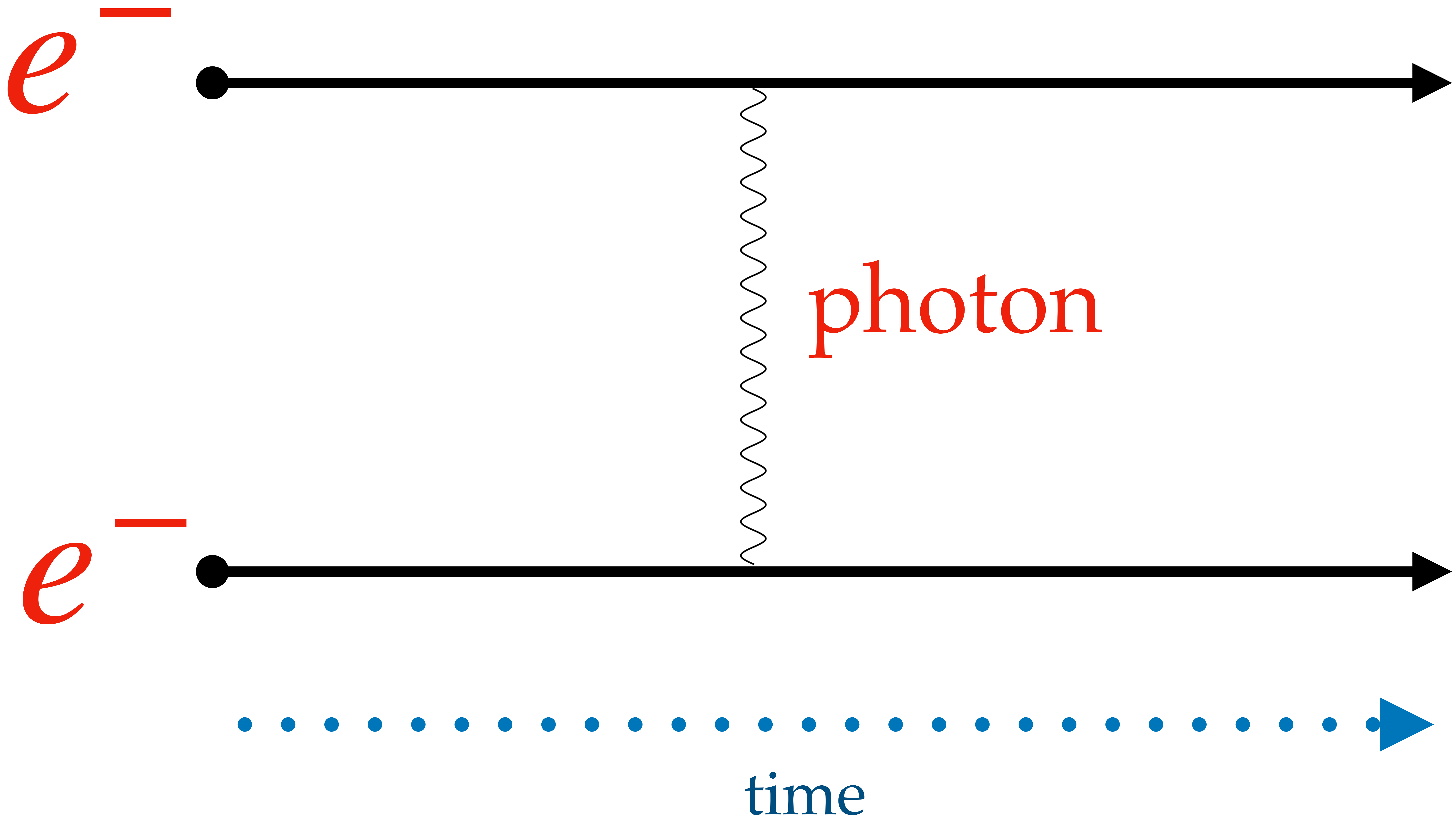

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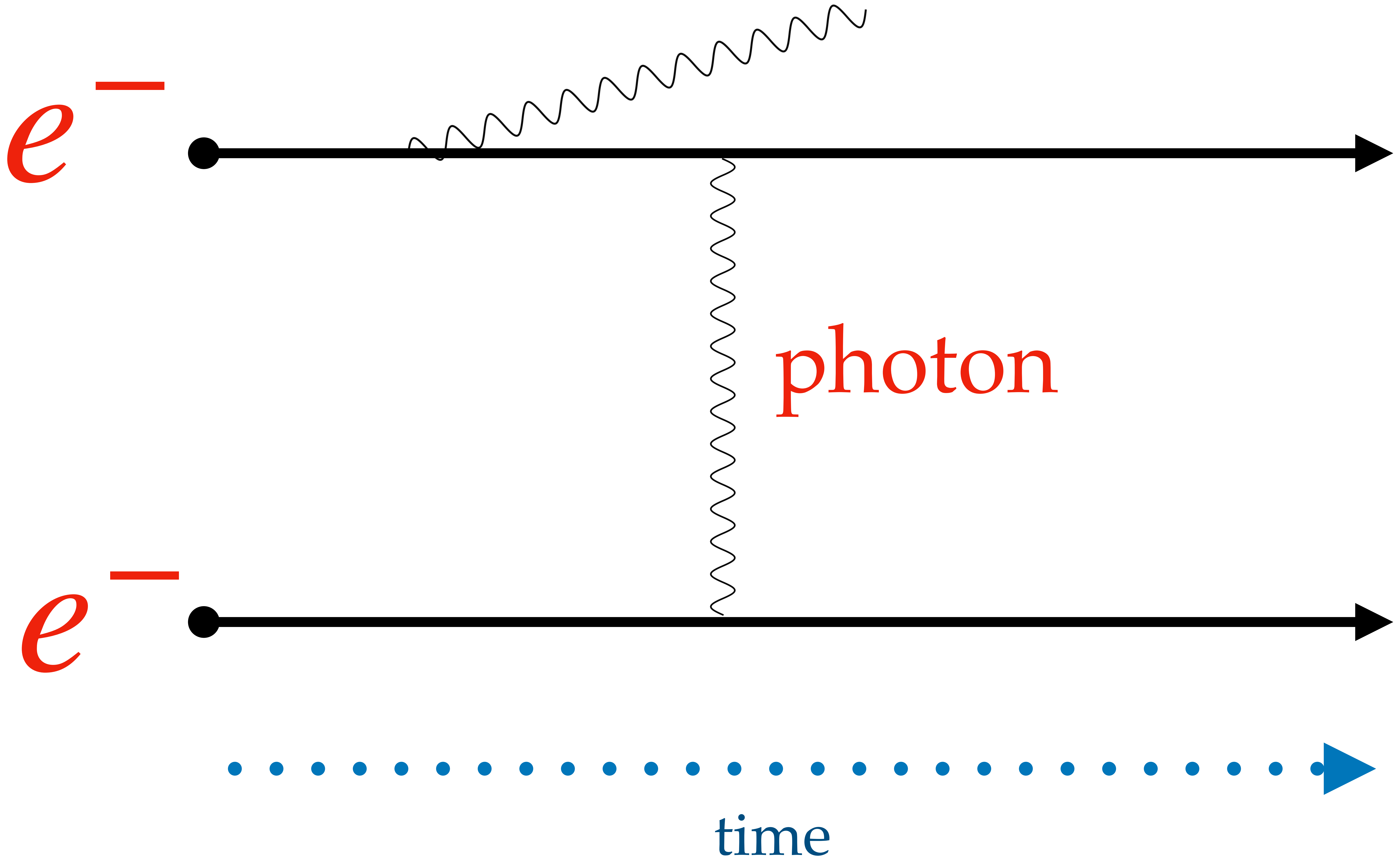

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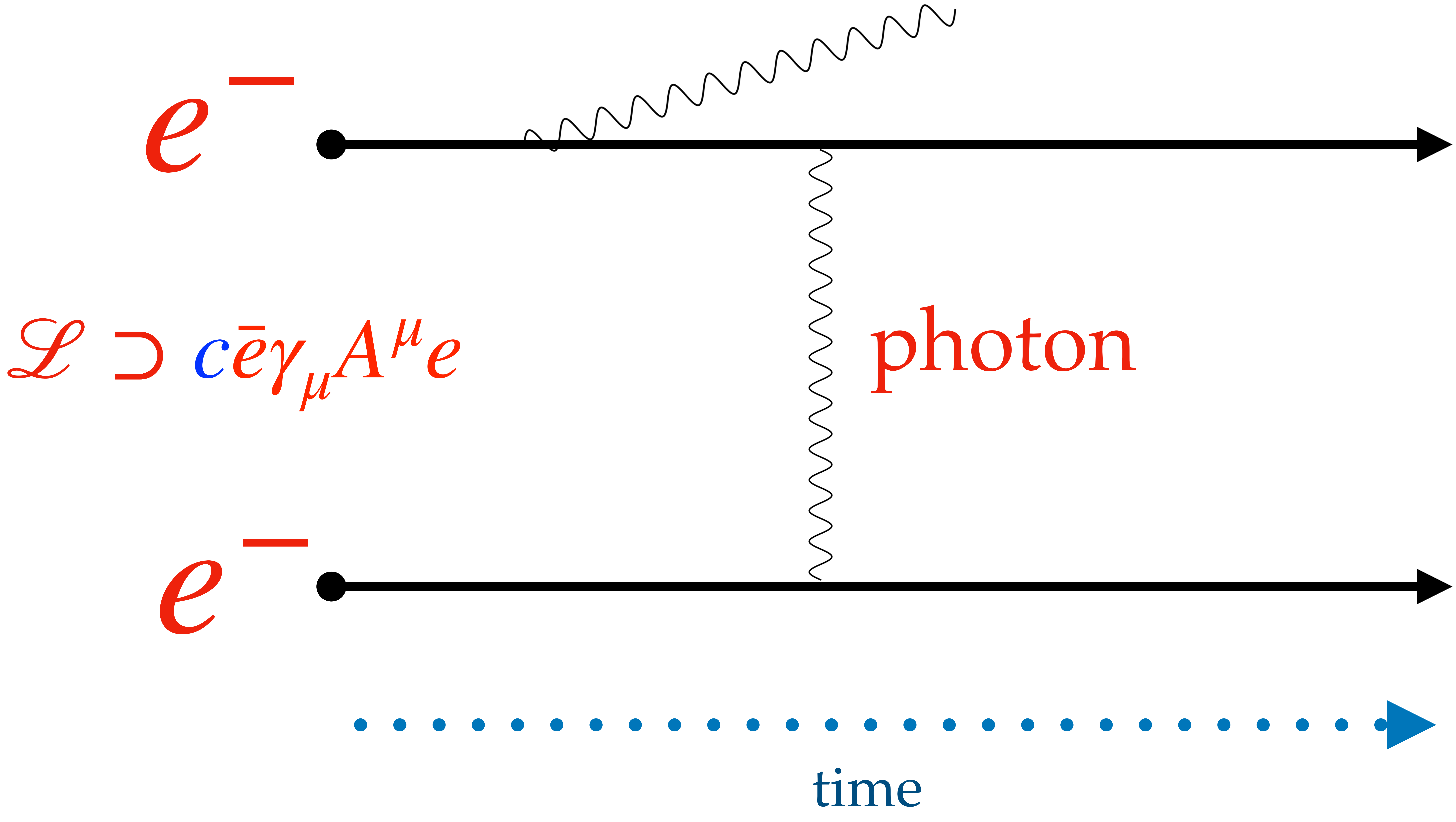

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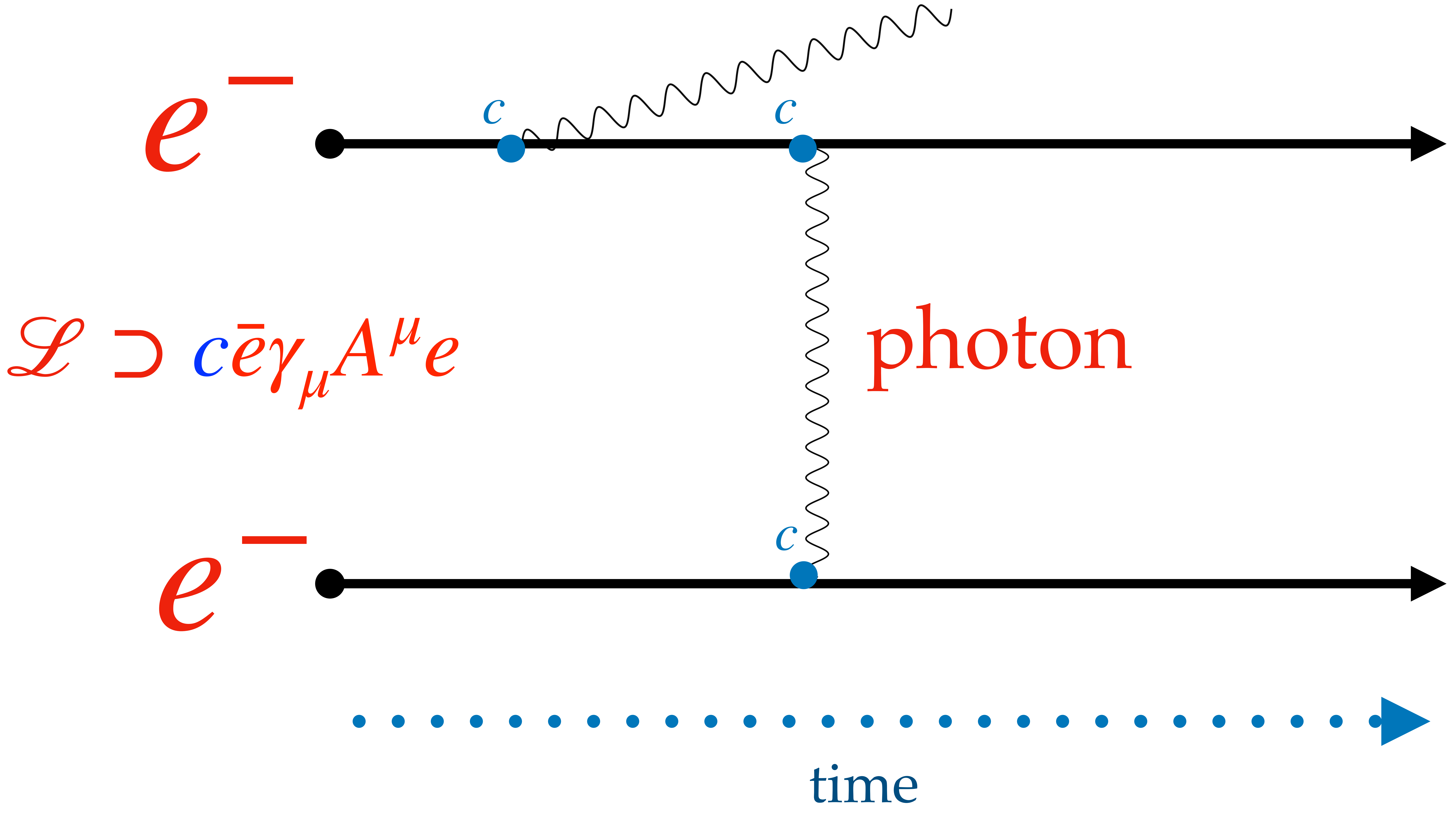

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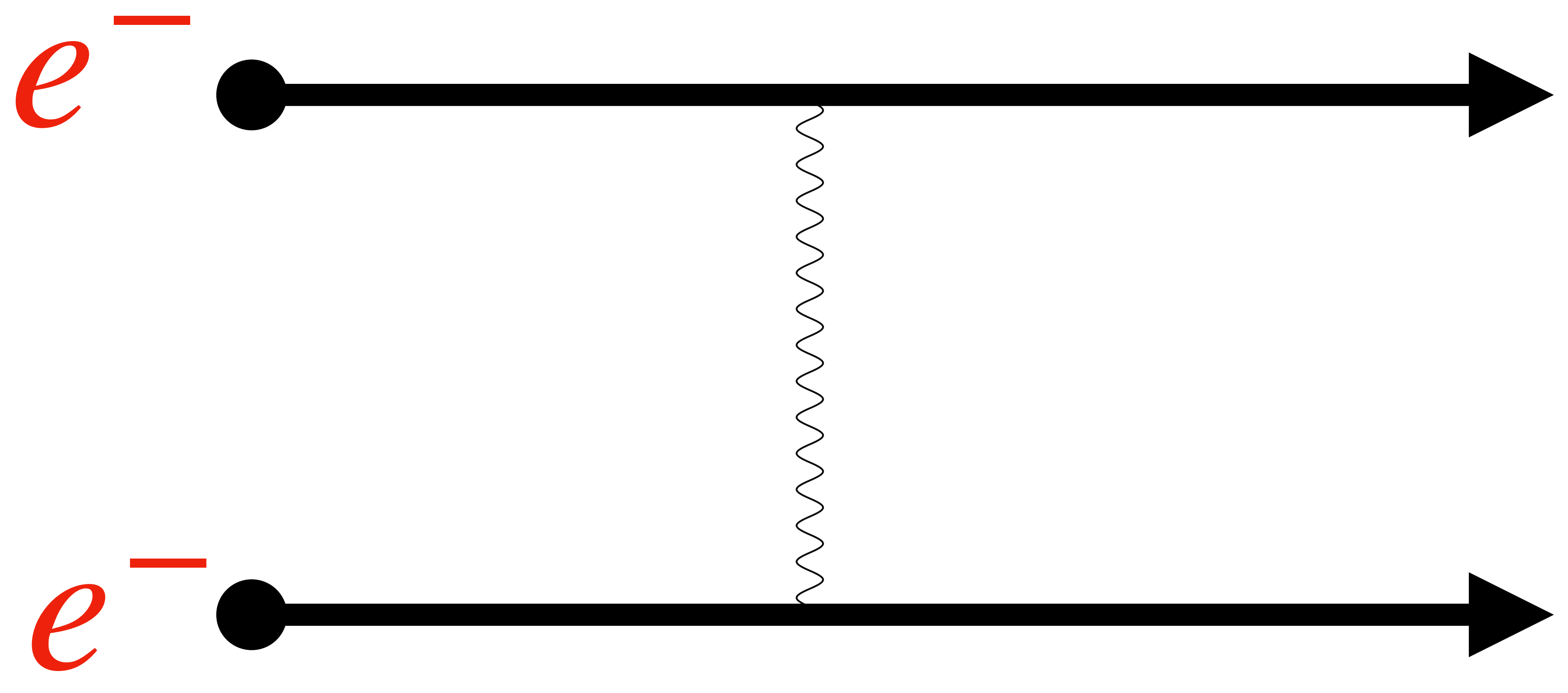
From Theory to Experiment and Back Again

time

From Theory to Experiment and Back Again



time

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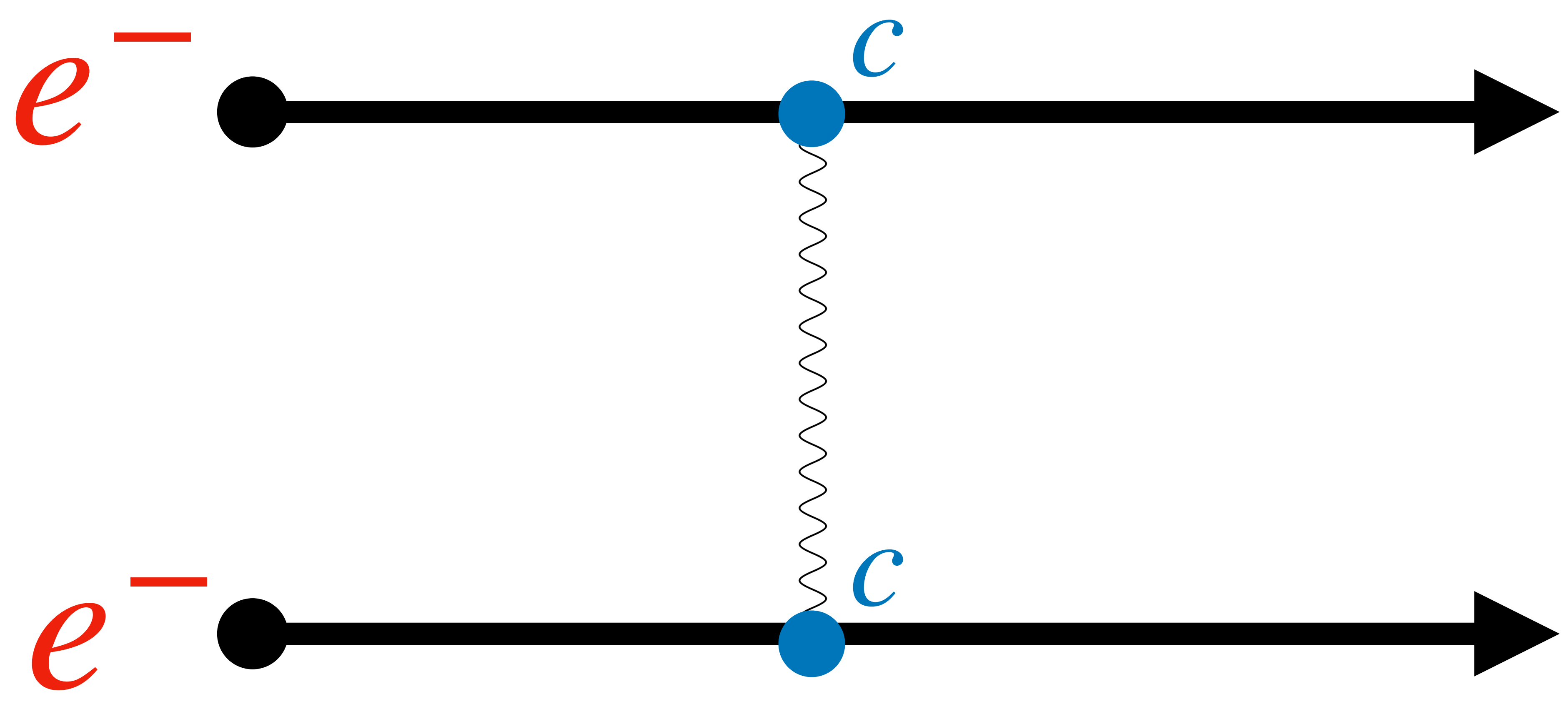

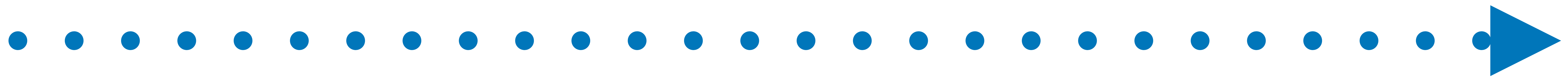

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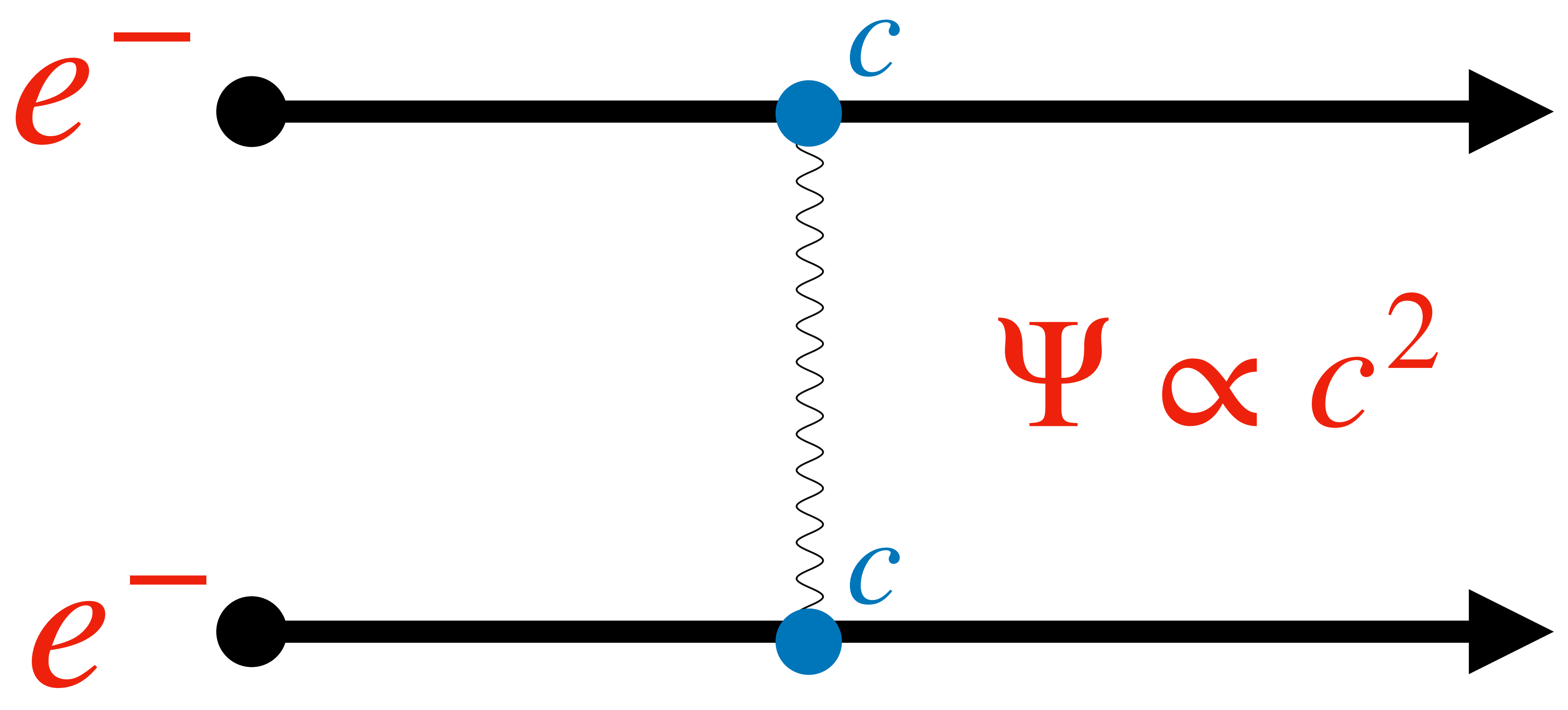

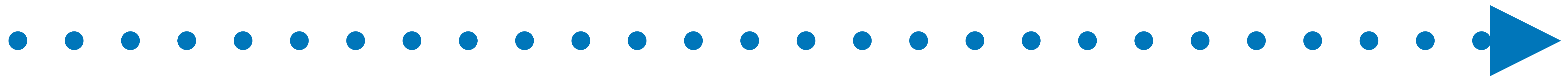

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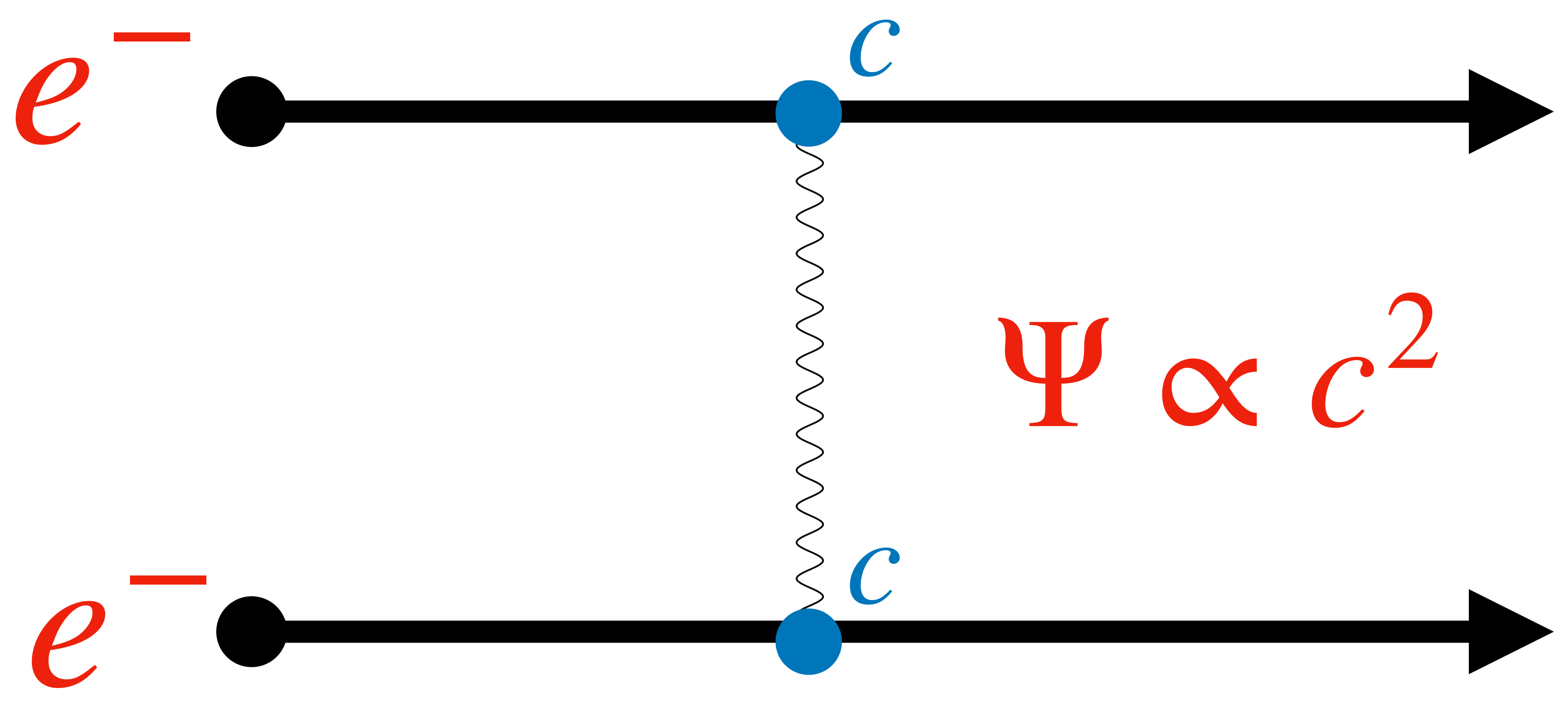

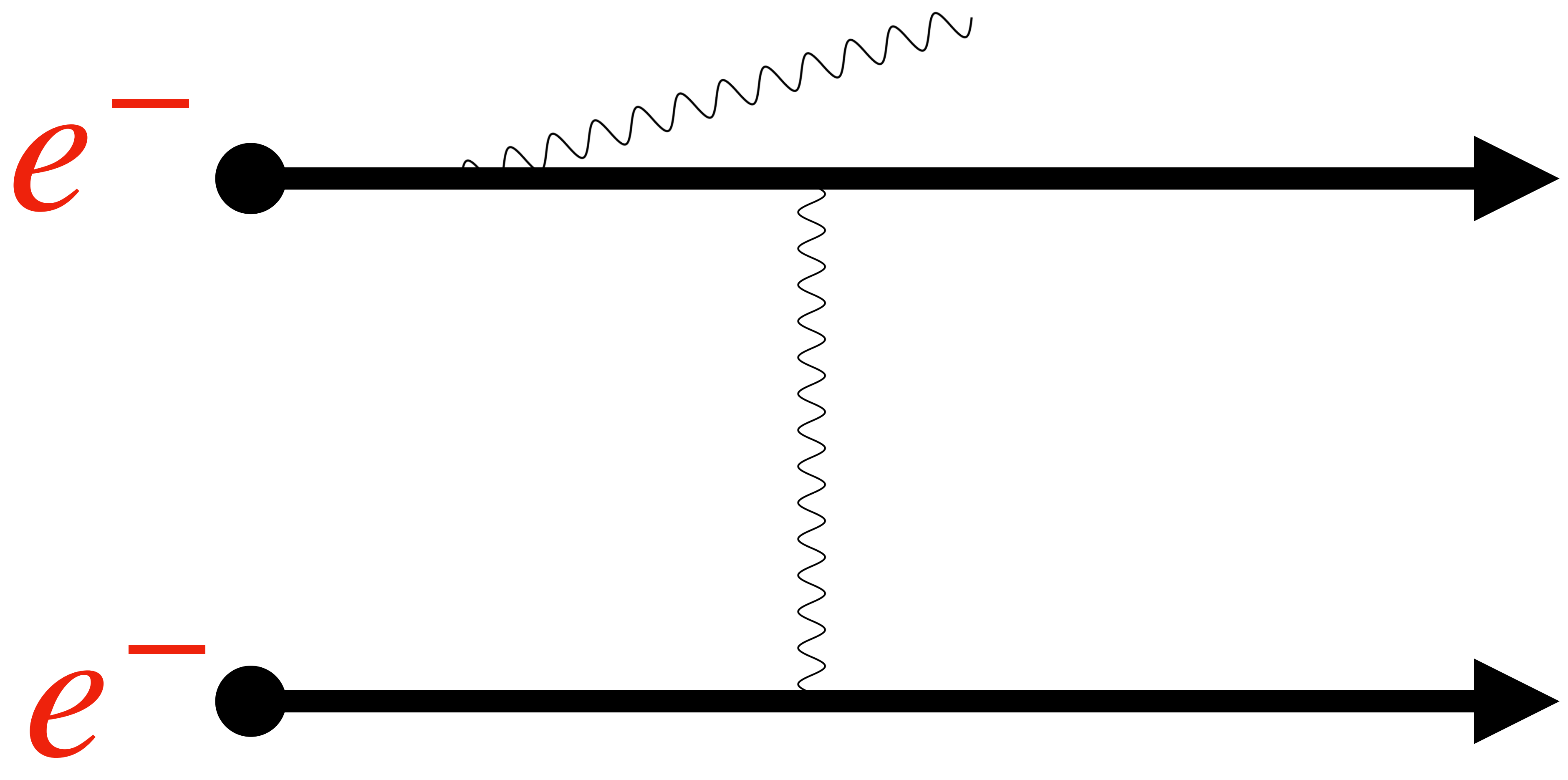

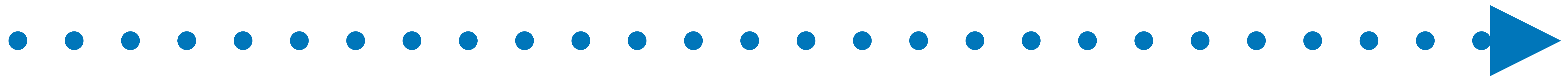

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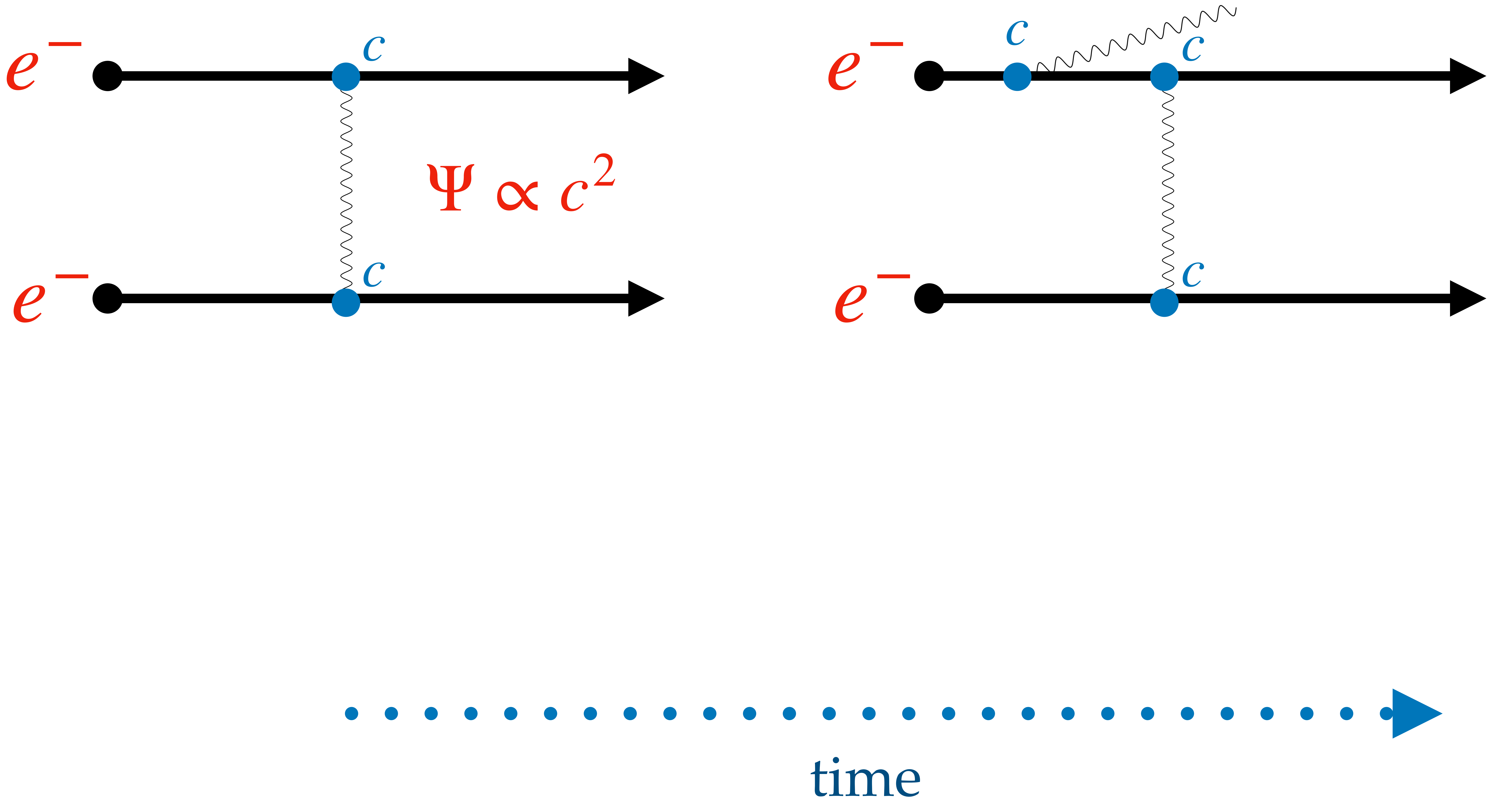

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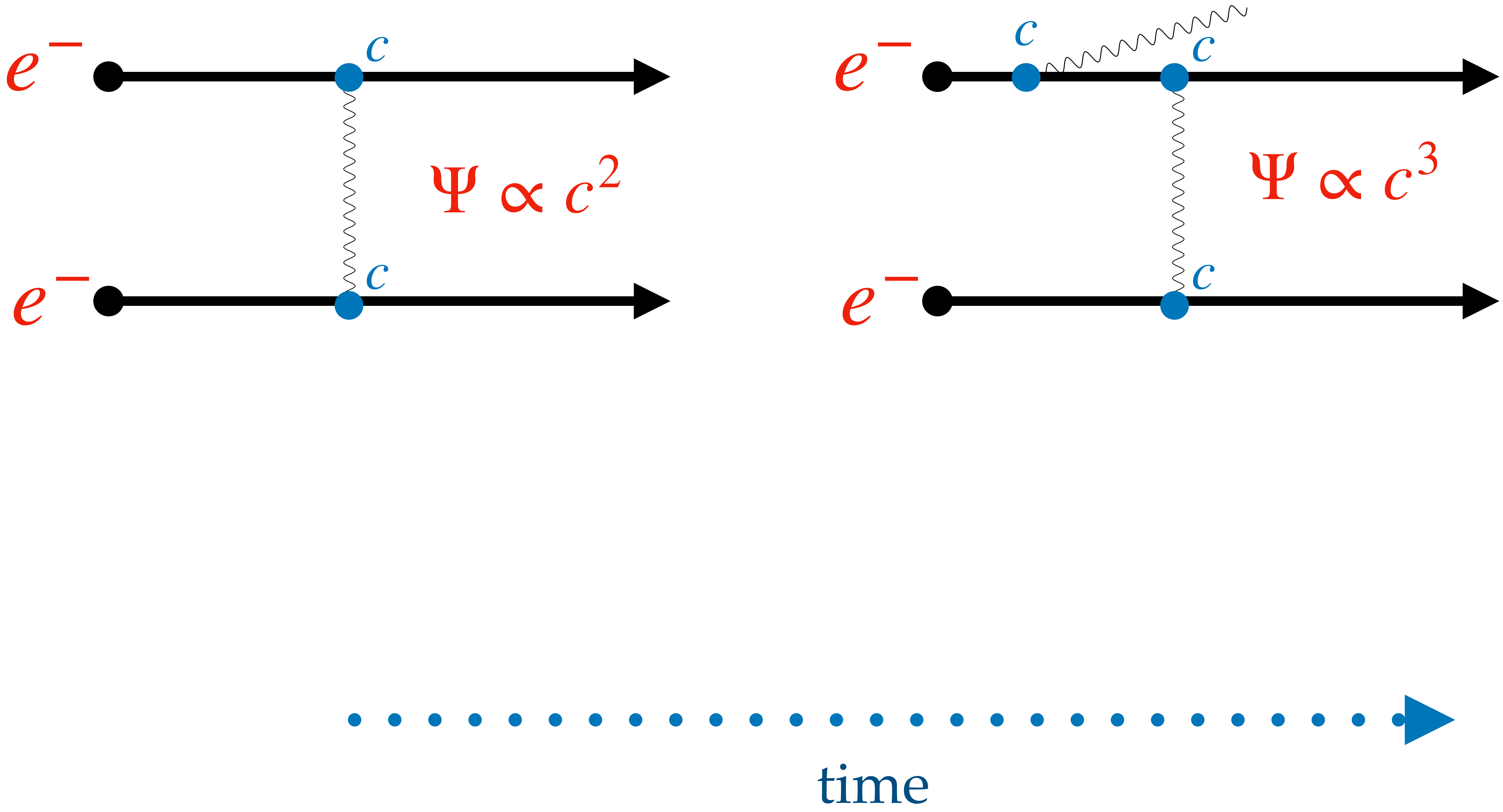

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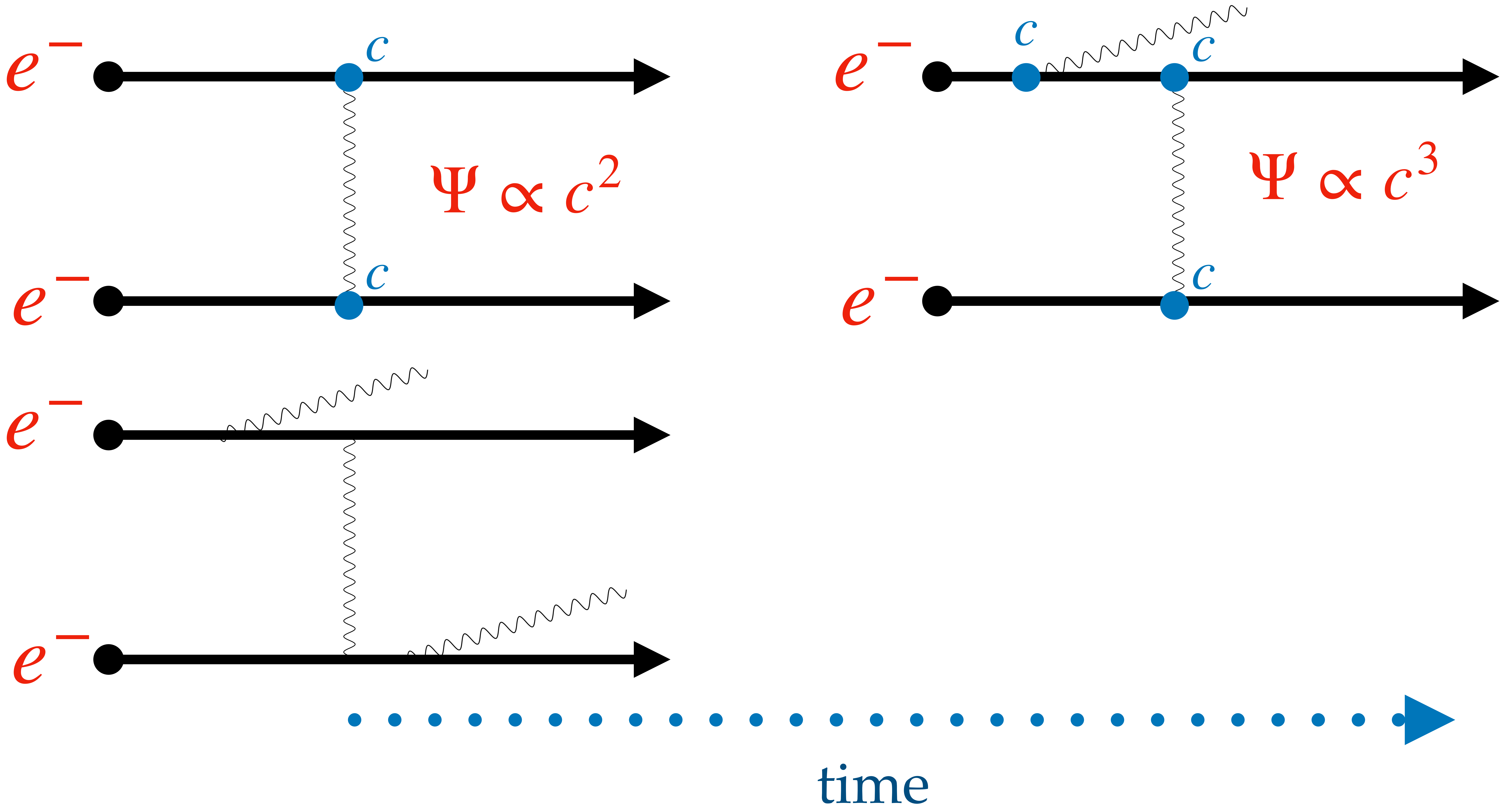

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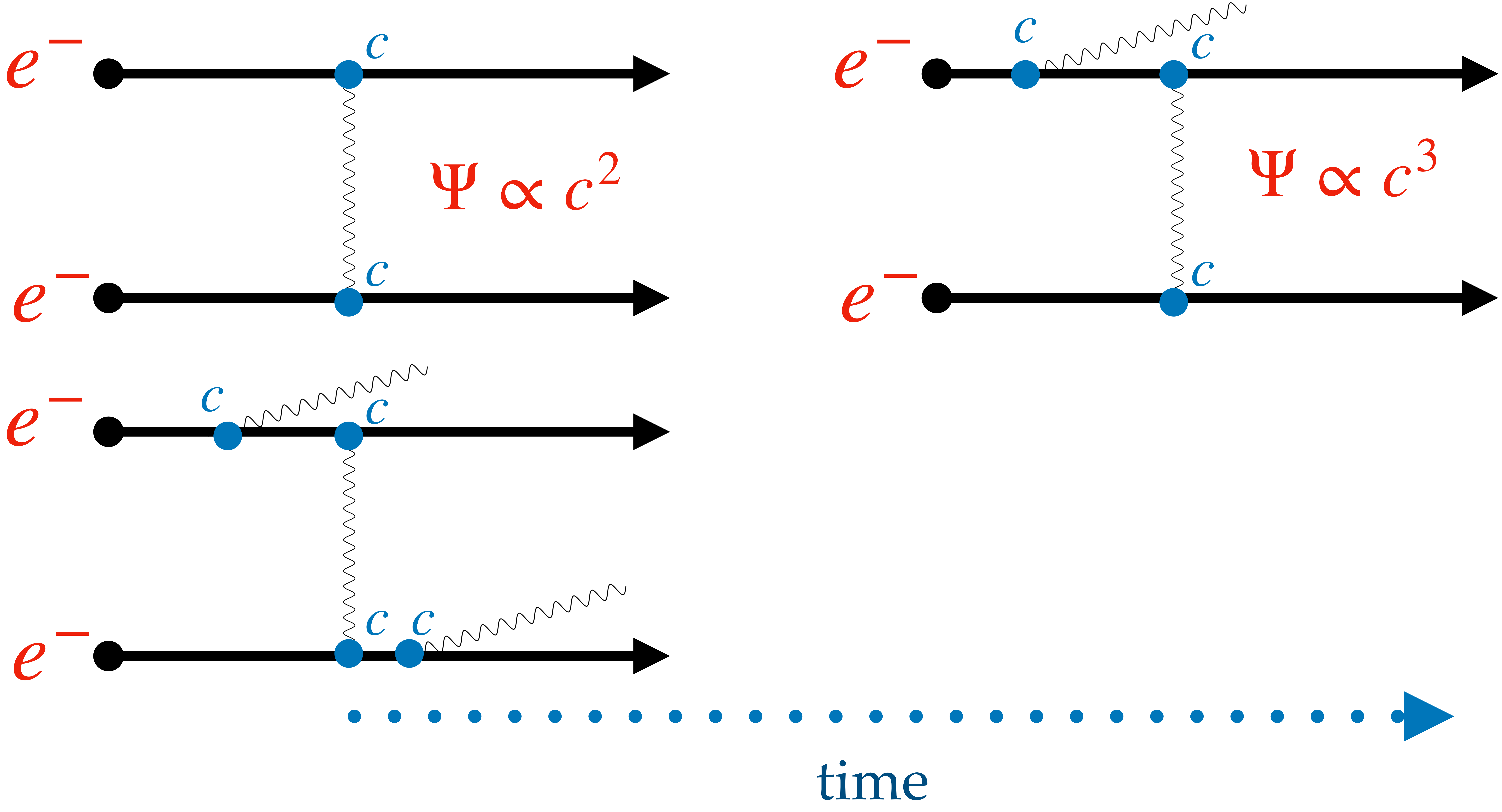

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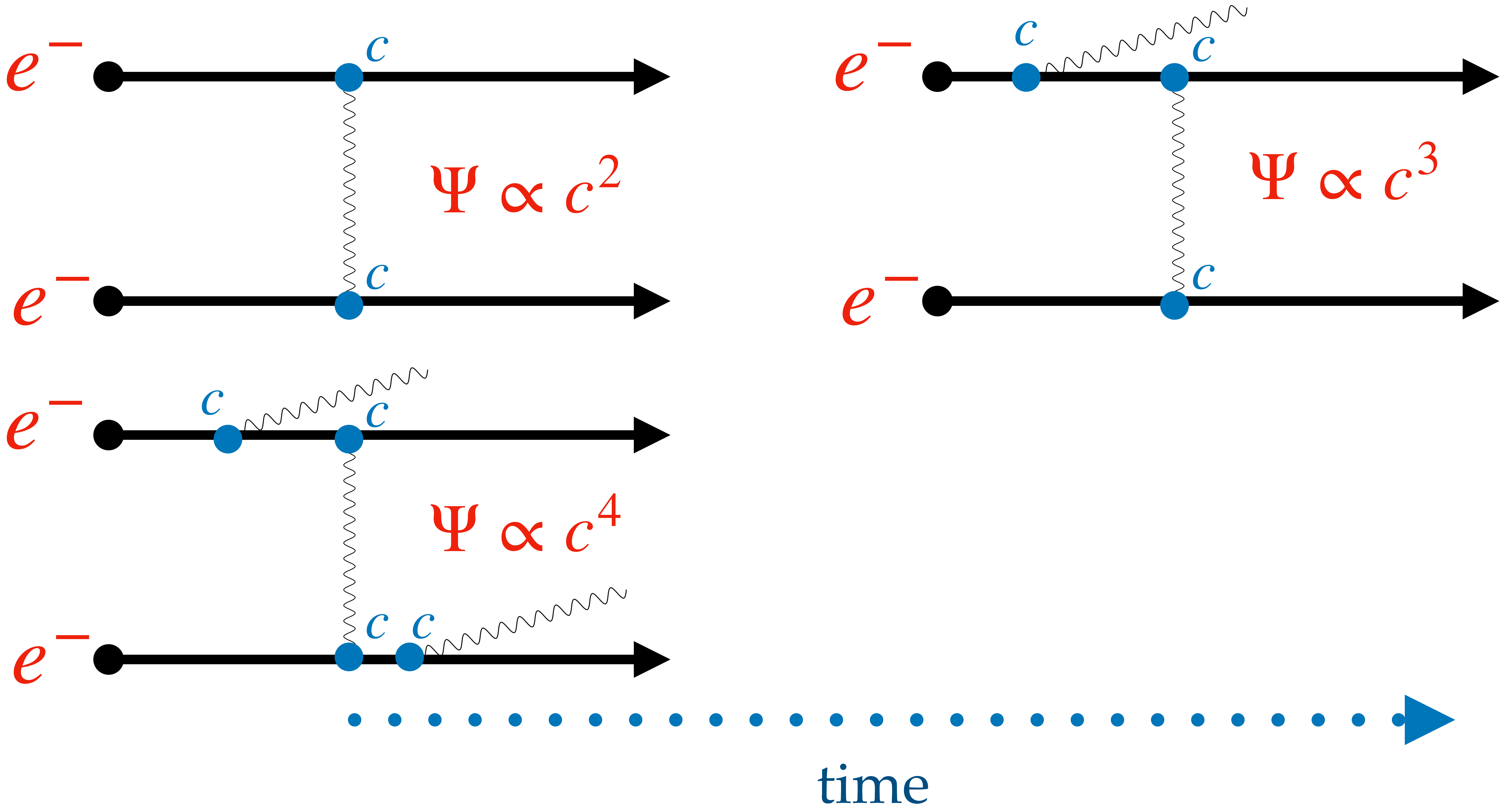

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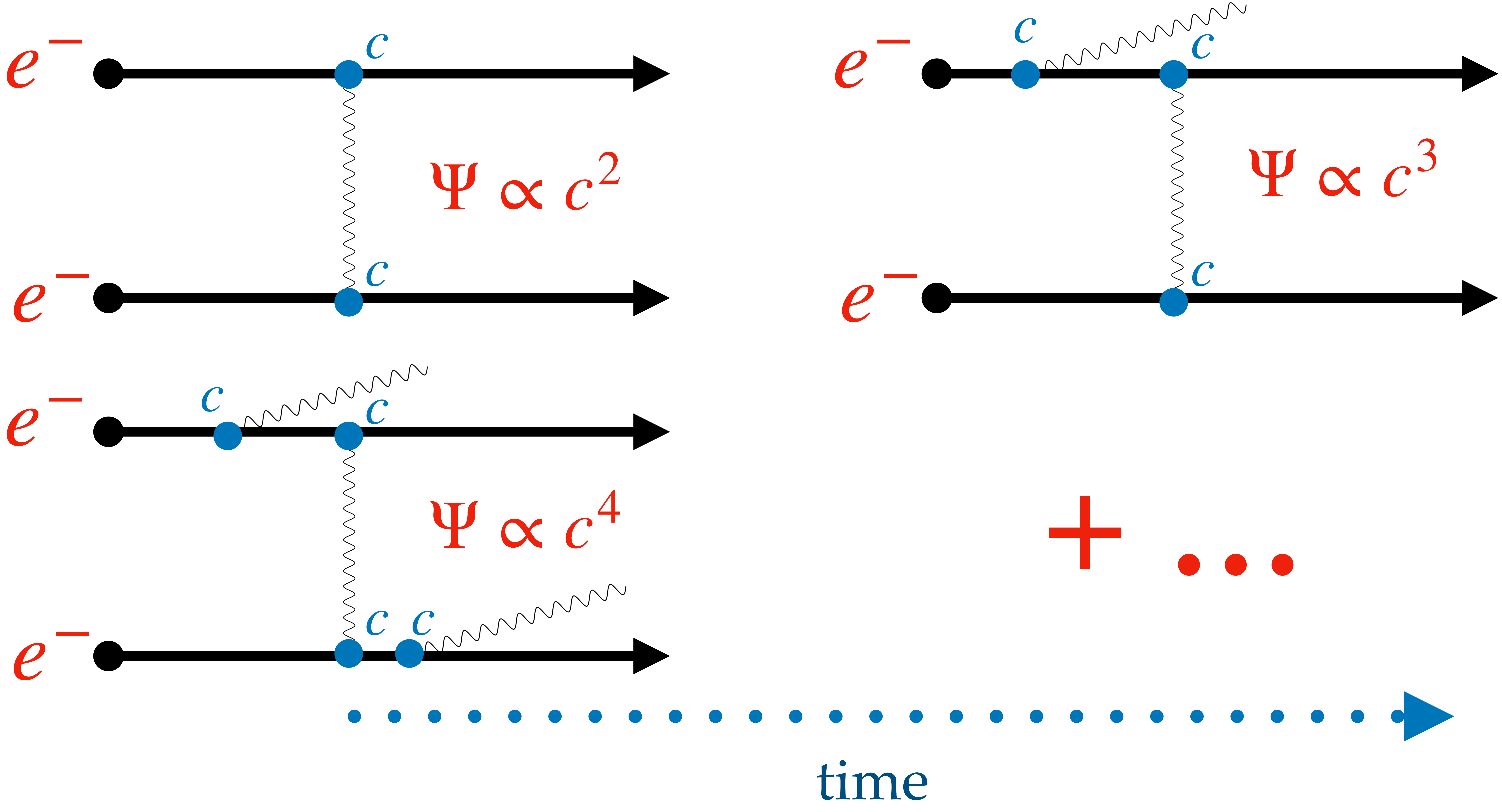

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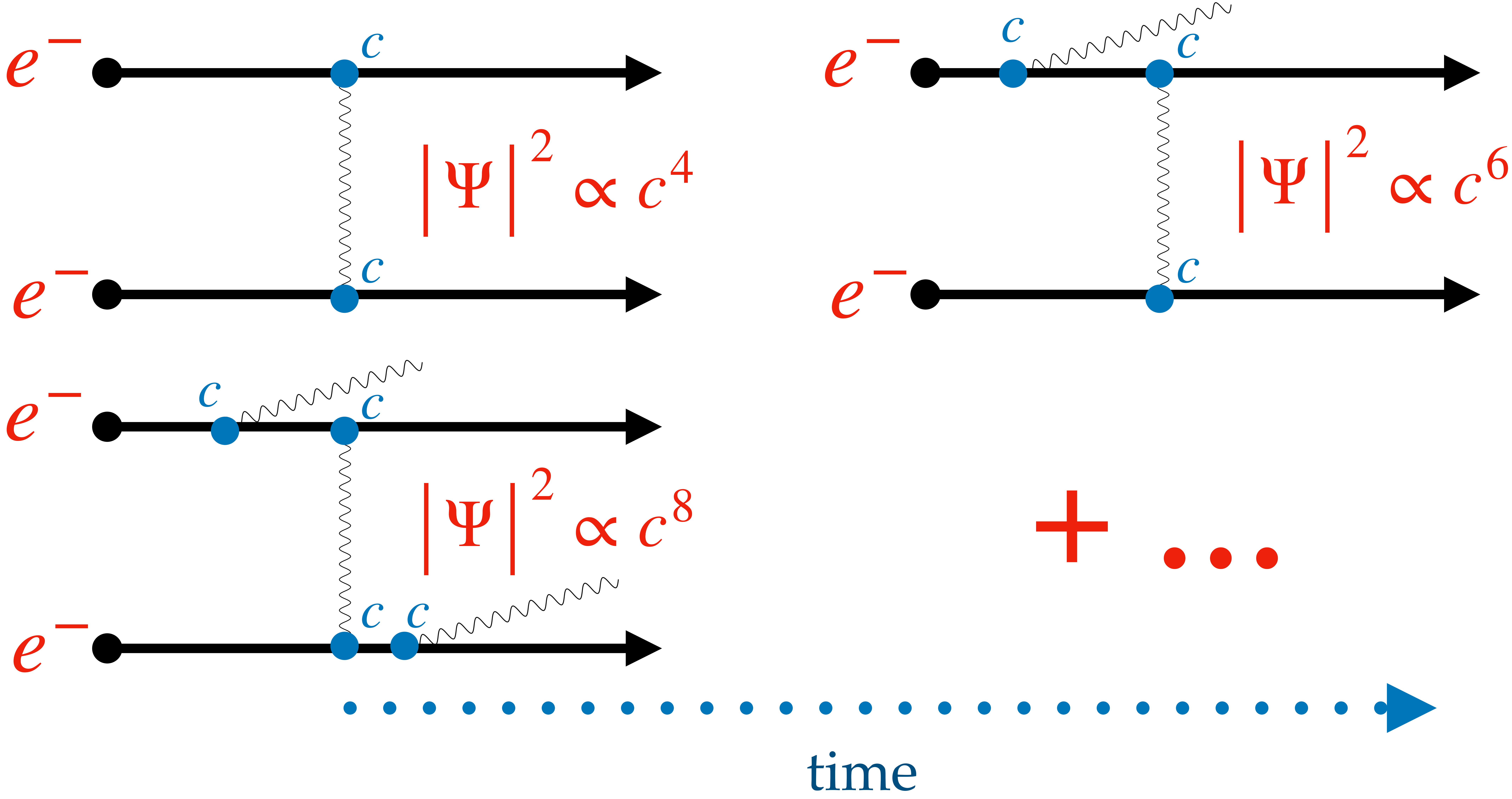

From Theory to Experiment and Back Again

We now know how to calculate **probabilities** in Quantum Field Theory!

$$|\Psi|^2 \propto c^4 + c^6 + c^8 + \ldots$$

If $c^2 < 1$ then we can simply add terms for increased precision!

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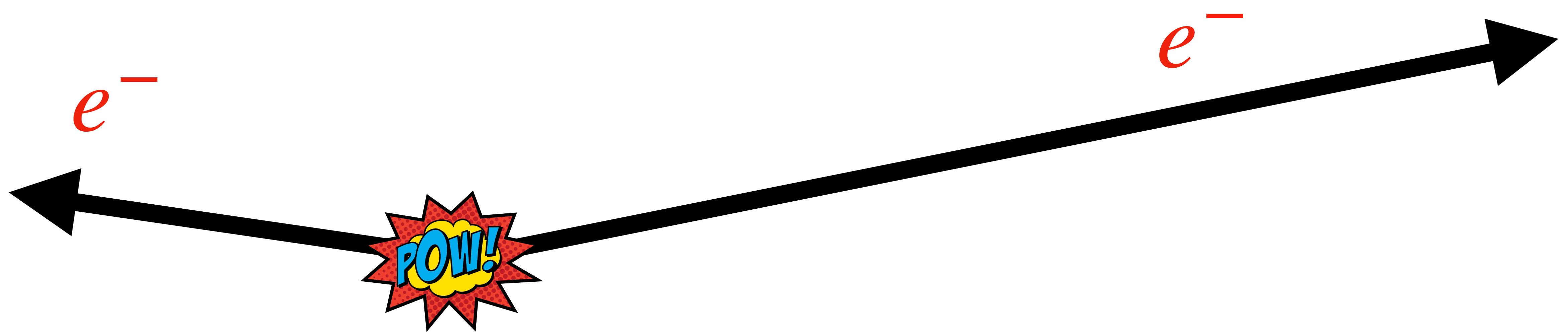

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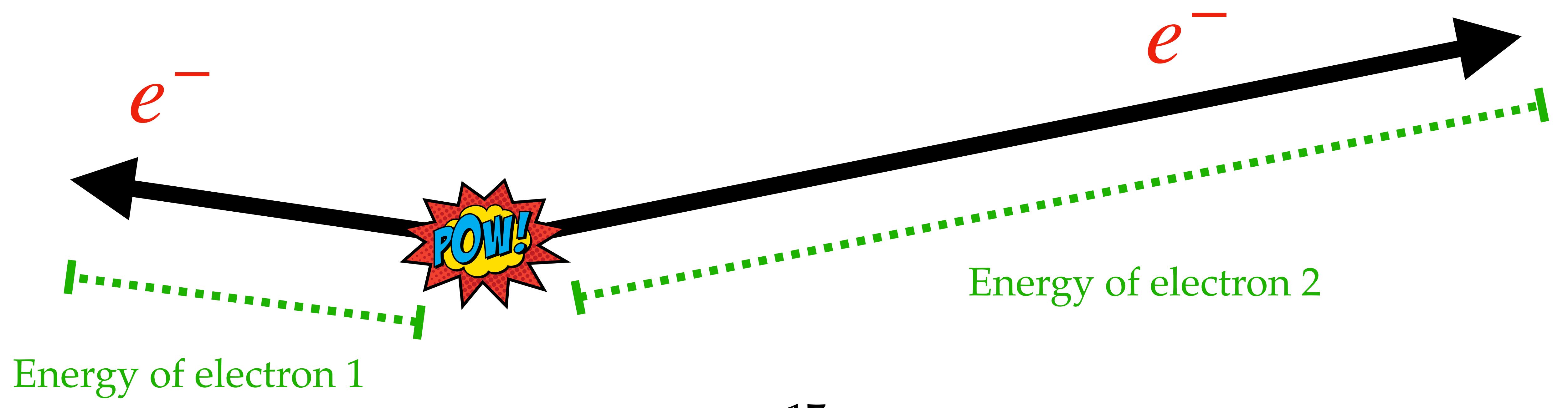


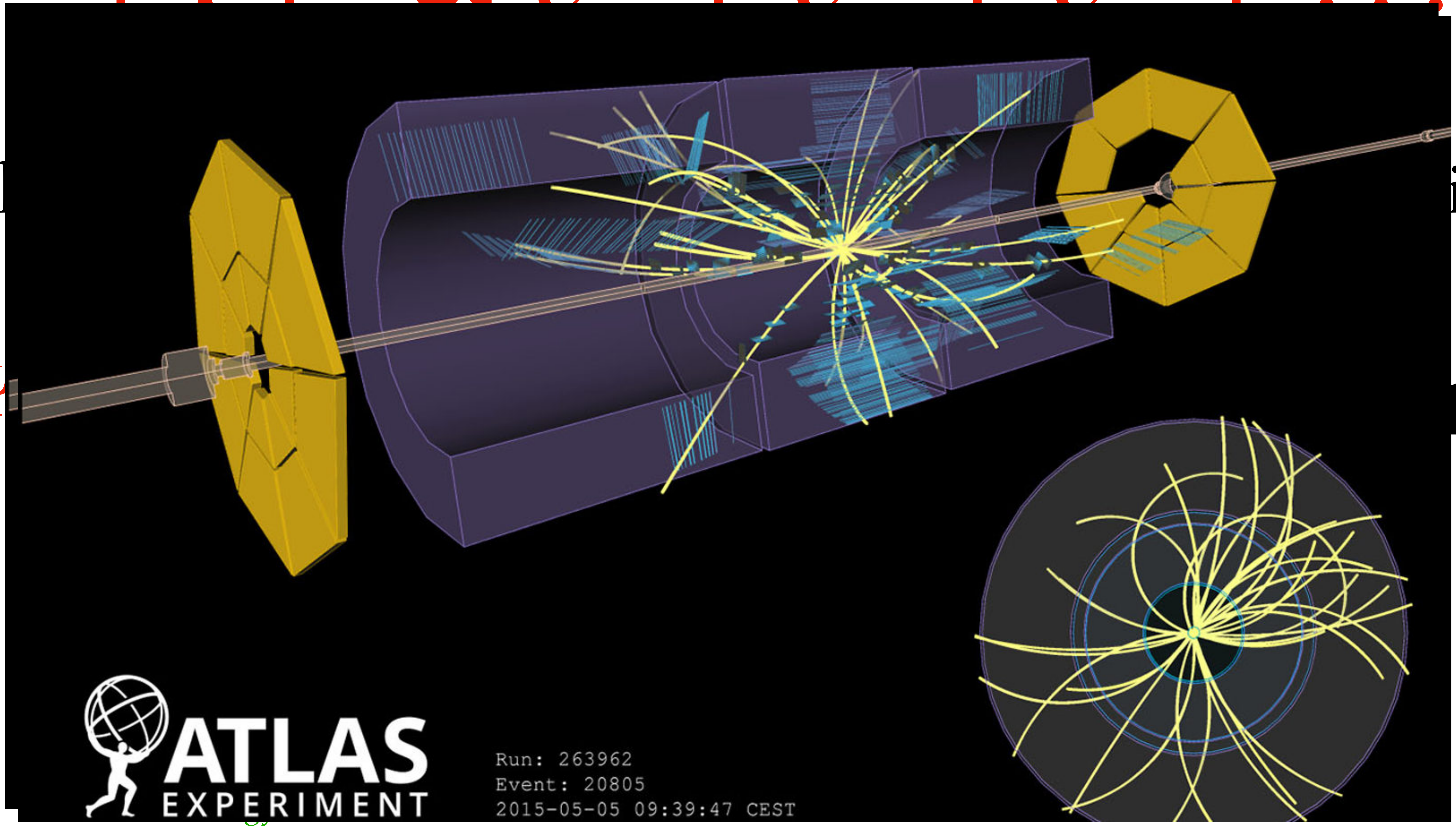
We have a way to describe what we observe at experiments!

F

$$|\Psi|^2 \propto c^4 + c^6 + c^8 + \ldots$$

If $c^2 < 1$ t… …ision!

In reality: $|\Psi$ … …particles involved!



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Monte Carlo Simulations

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- **Solution**: Use **<u>approximate</u>** c^n for n large & **<u>model</u>** situations where $c^2 \geq 1$!

- **Monte Carlo simulations accomplish this!**

Based on randomness and probability.
Just like Quantum Mechanics!

Pictured: Casino Monte Carlo, Monaco.

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How do we make sense of it all?

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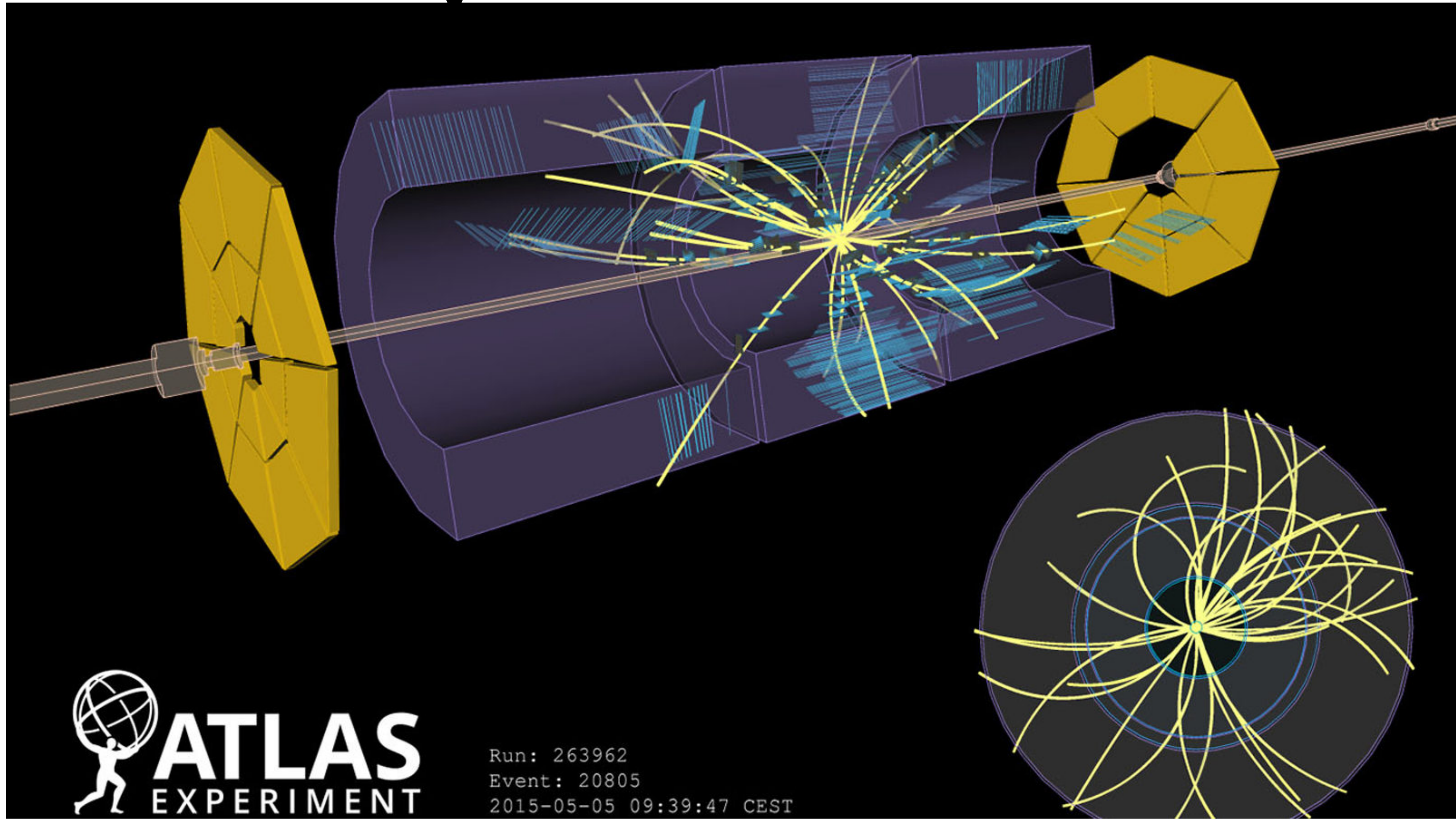
Experiment



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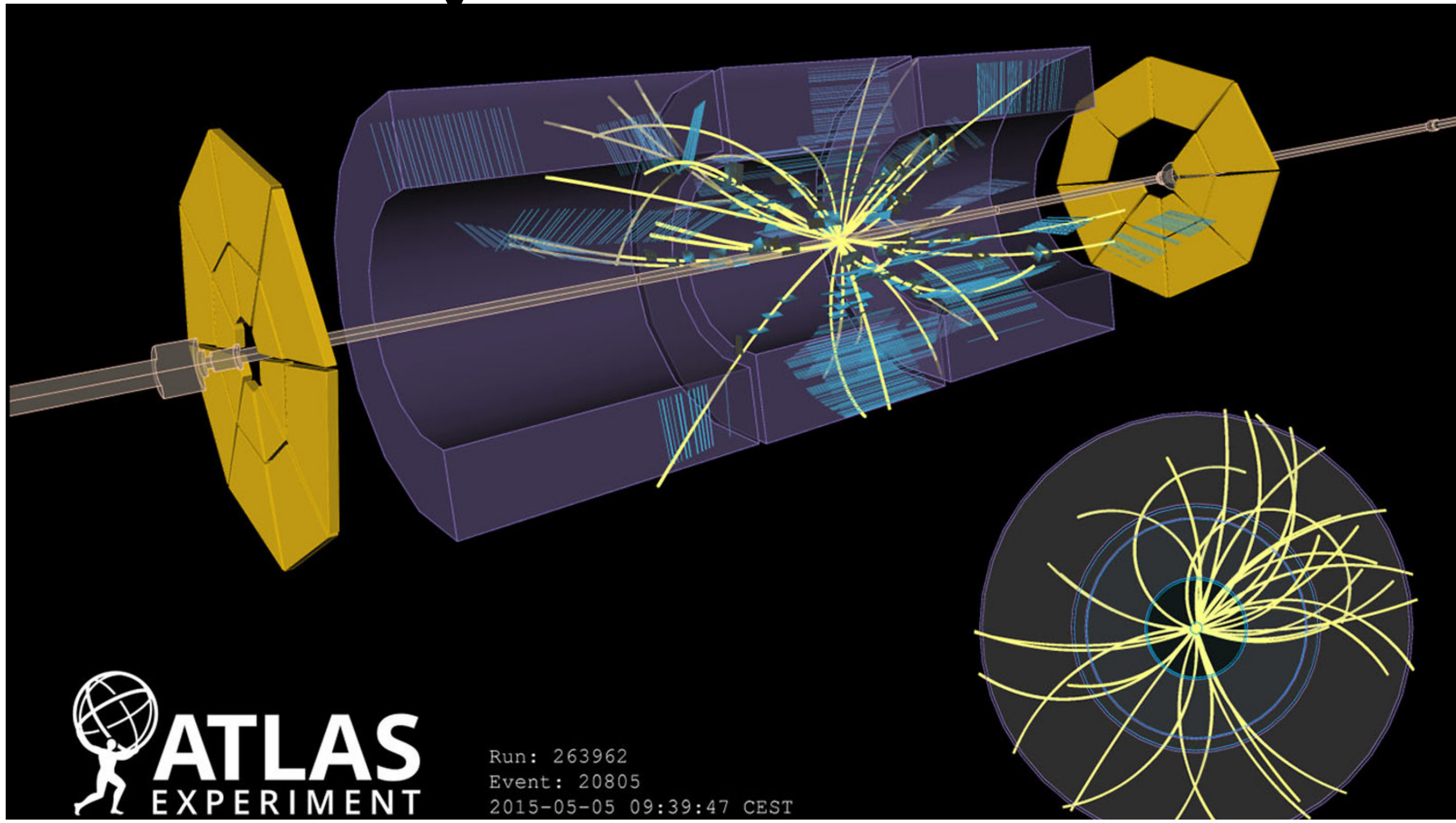
Simulations

Experiment

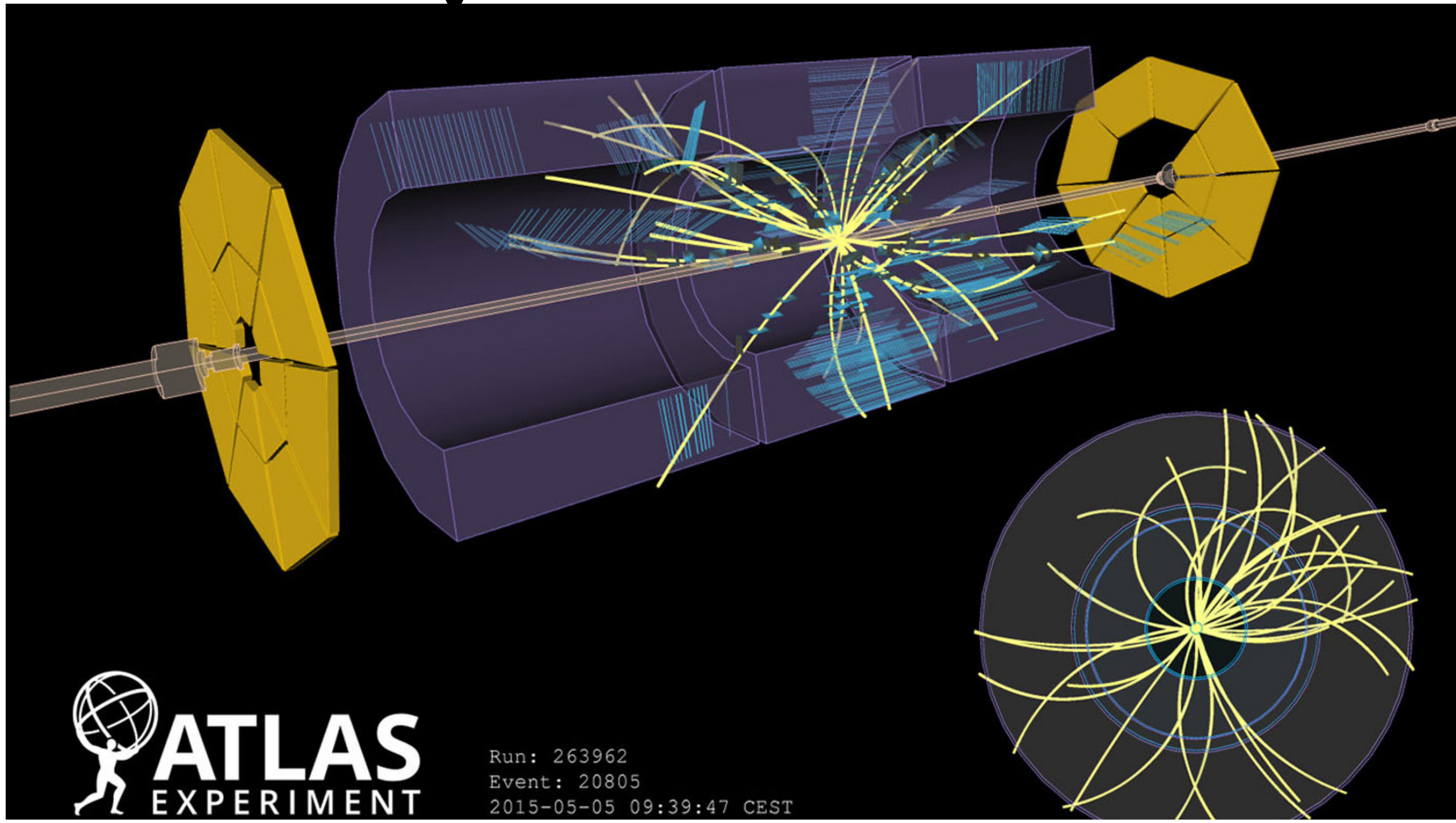


How do we make sense of it all?

Shut up and Simulate!

Simulations

Experiment



Simulations via the Monte Carlo method: Calculate π!

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- "Theory":
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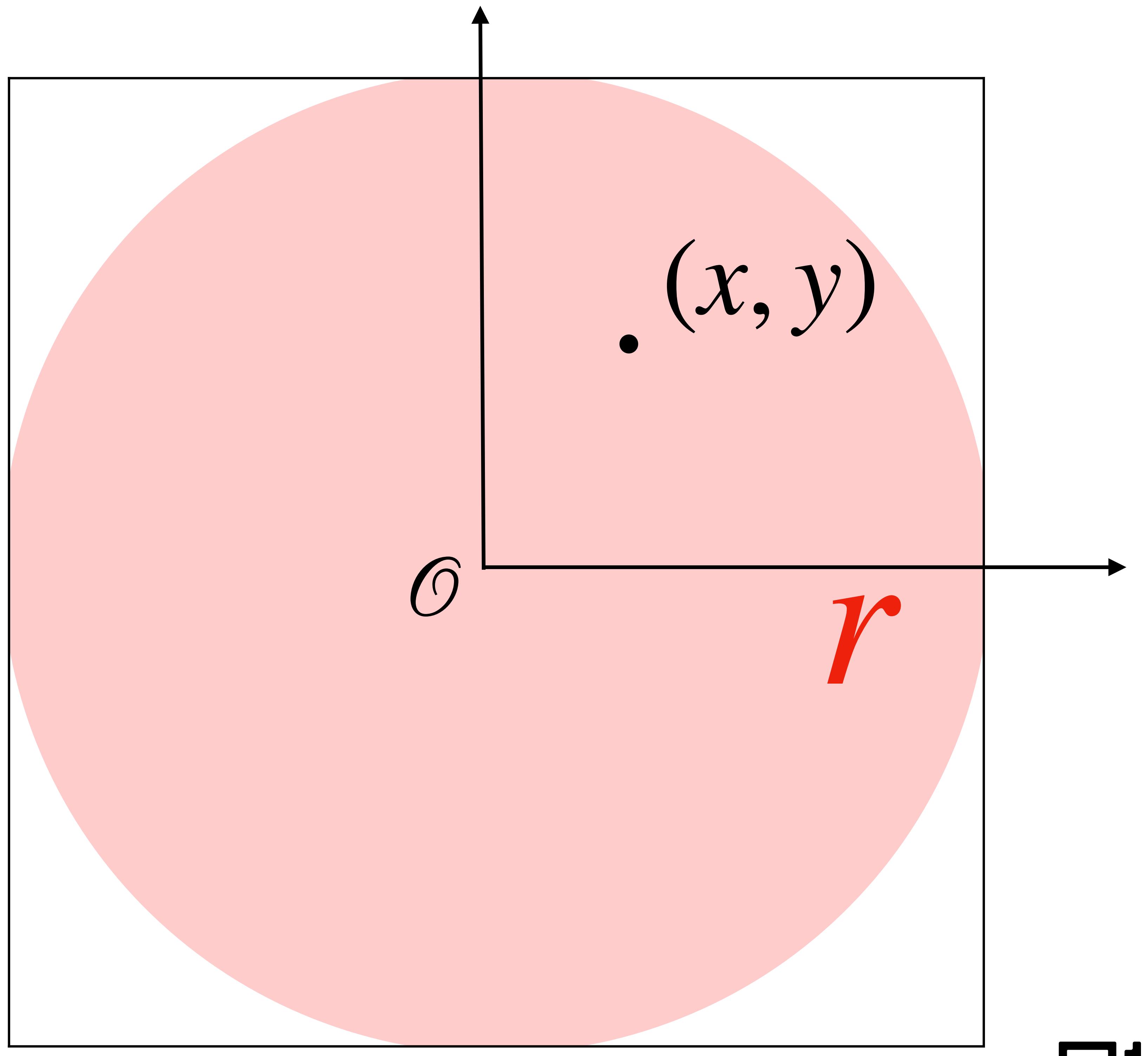

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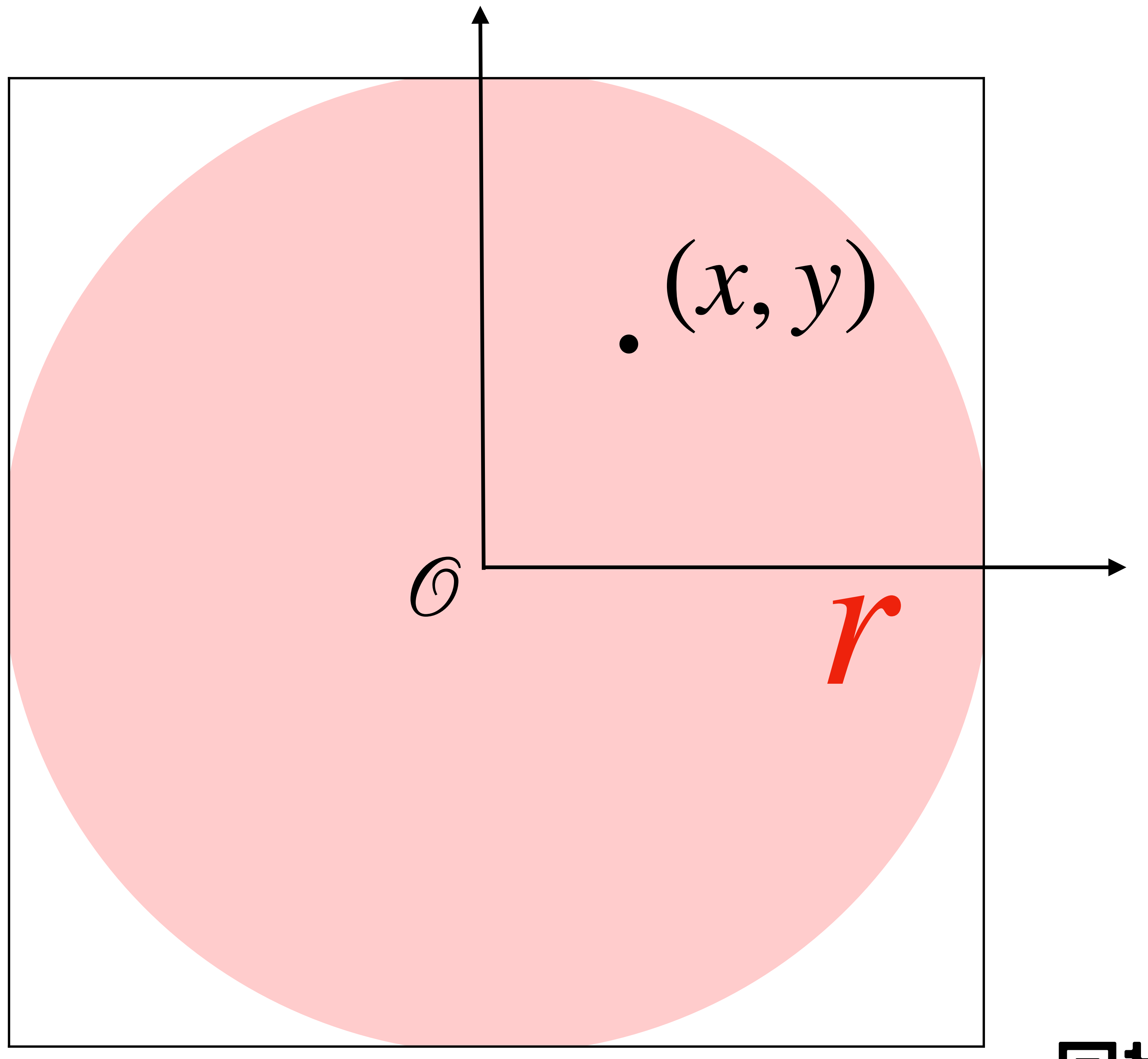

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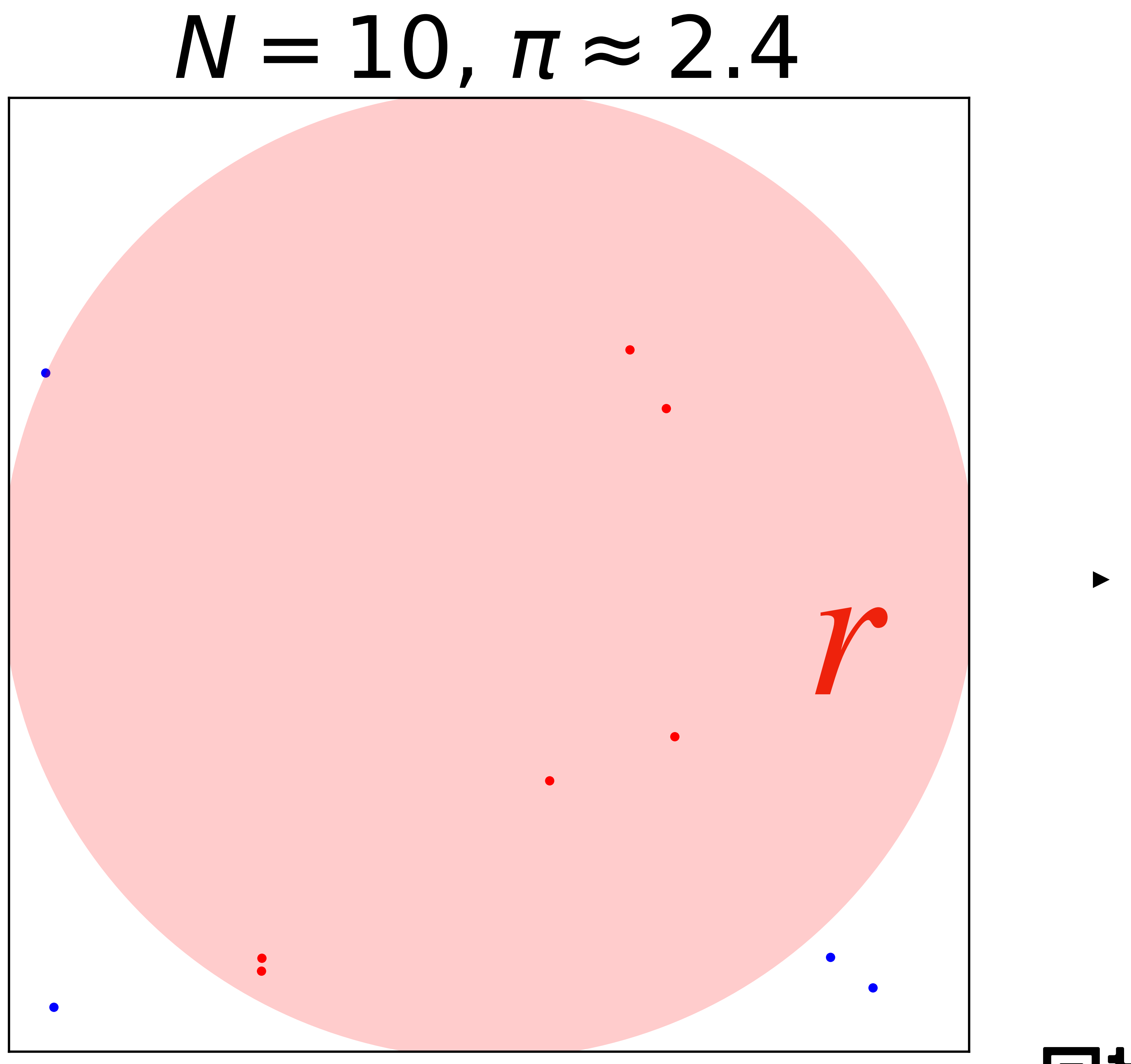

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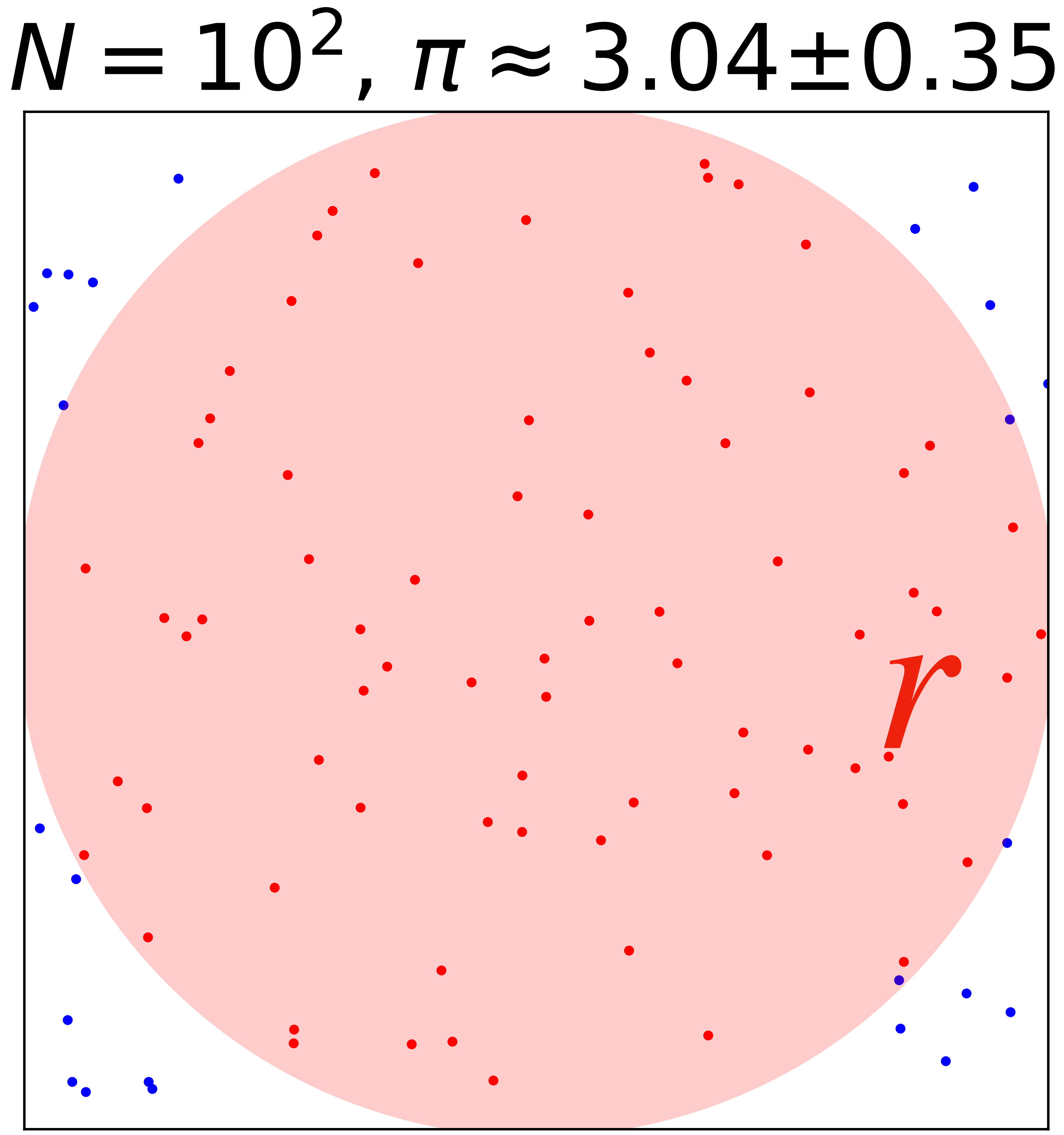

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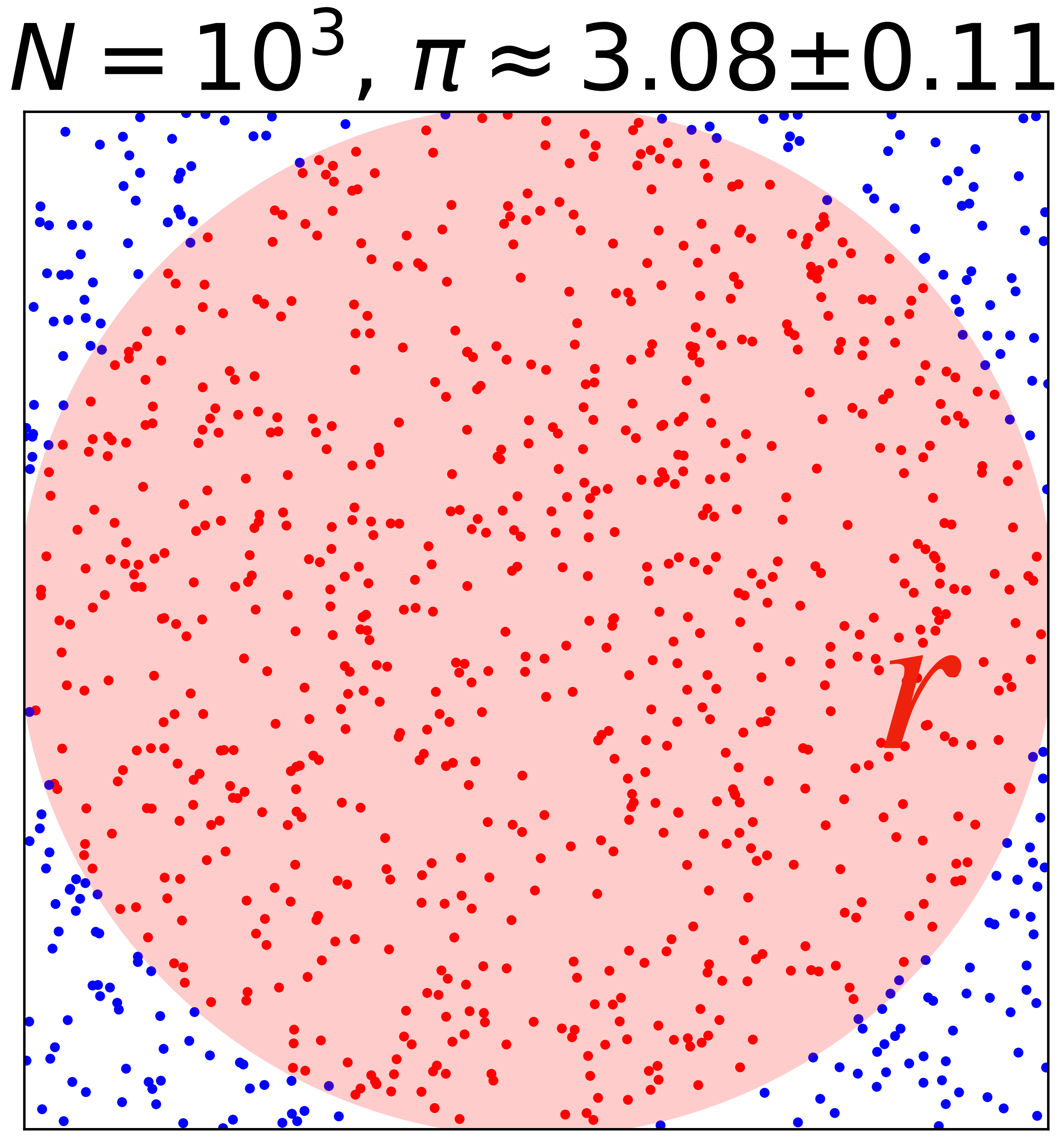

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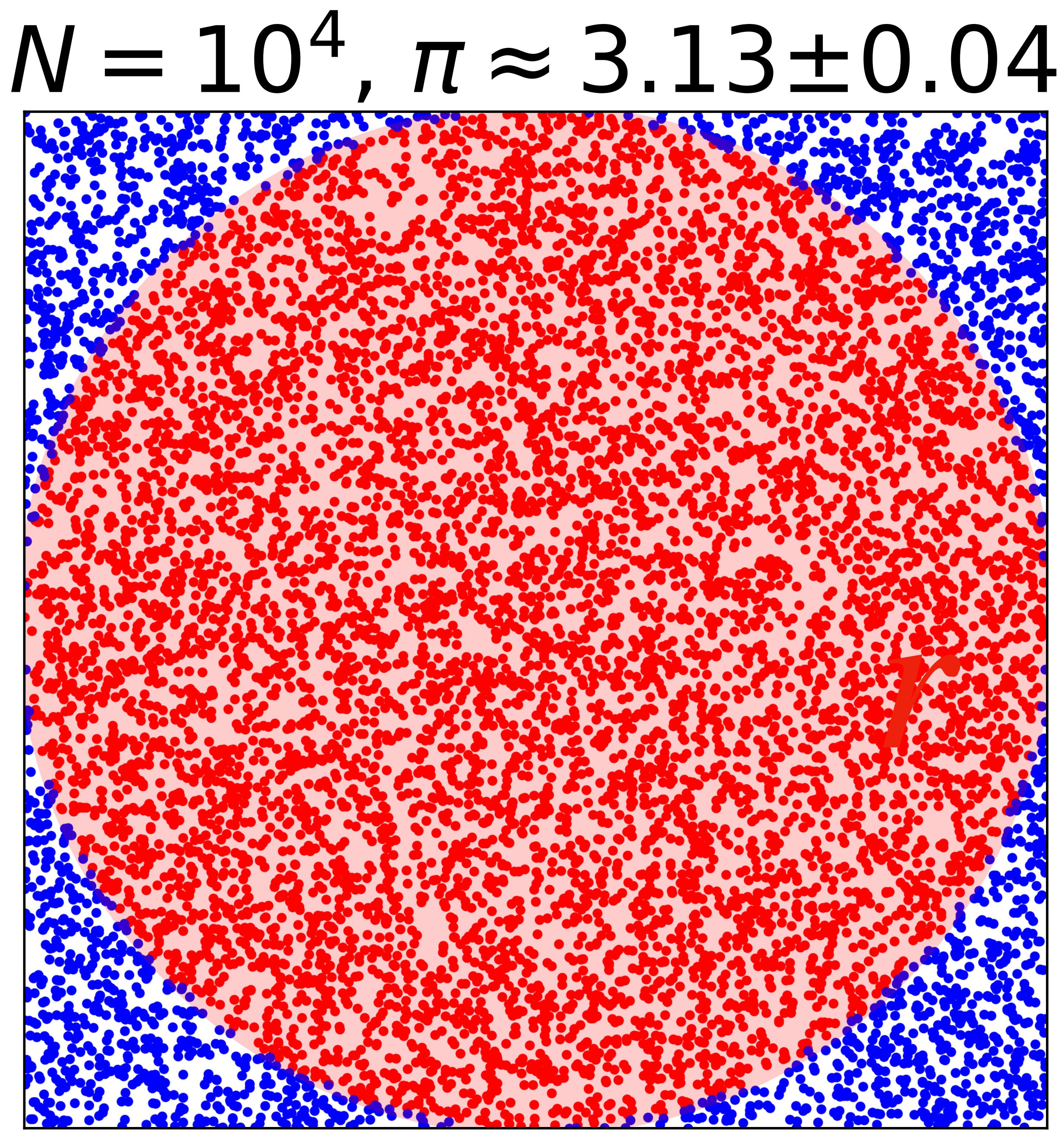

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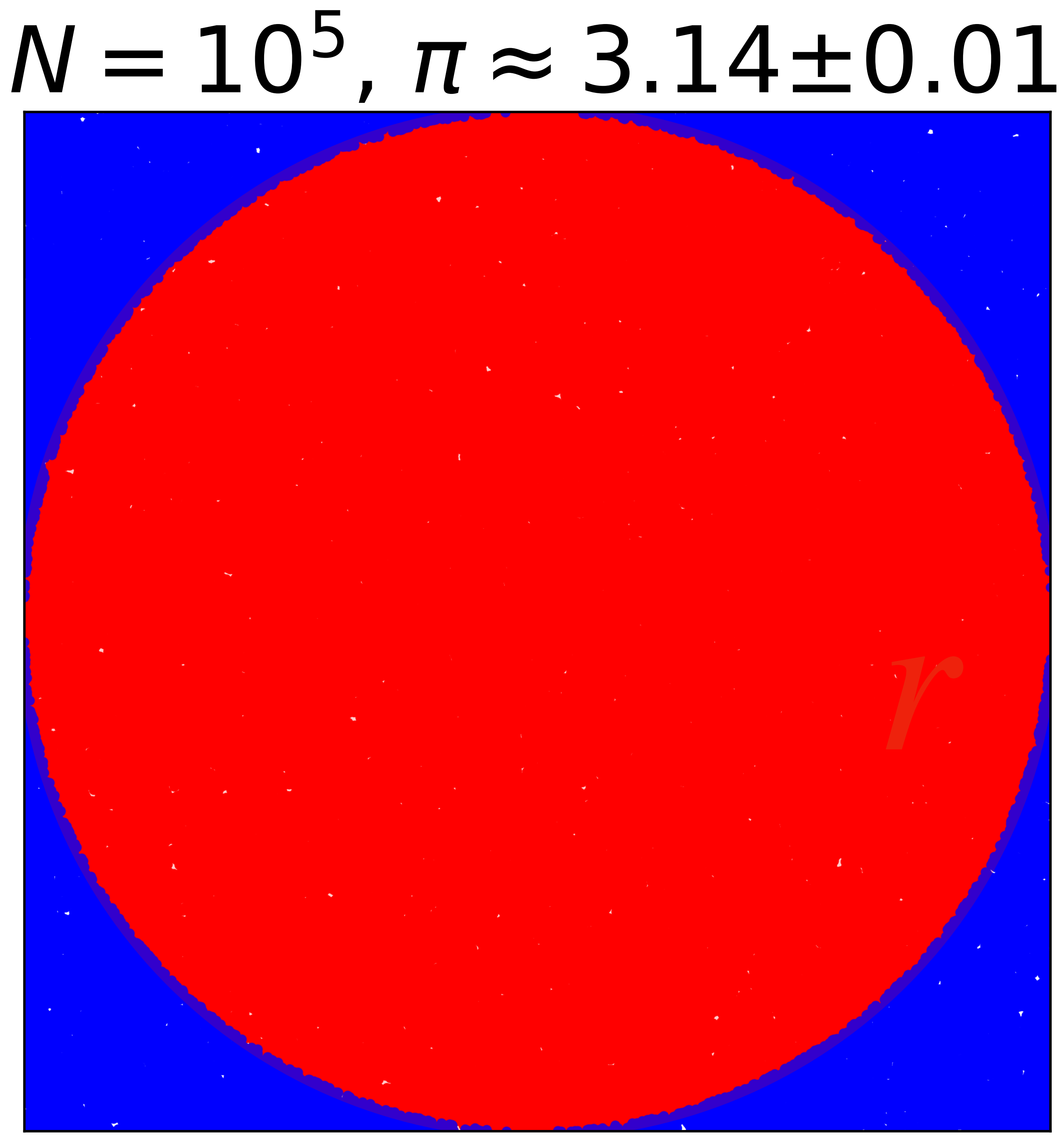

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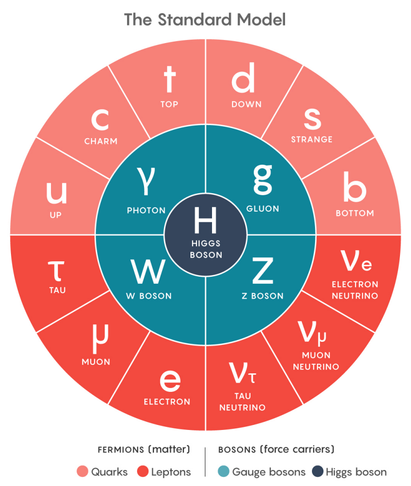
Simulations of Events via Monte Carlo

Simulations of Events via Monte Carlo

- “Theory”:
  - A set of particles and their interactions! e.g.: 

  - Calculate **probabilities** via Quantum Field Theory → actually $|\mathscr{M}|^2$ (the matrix element).

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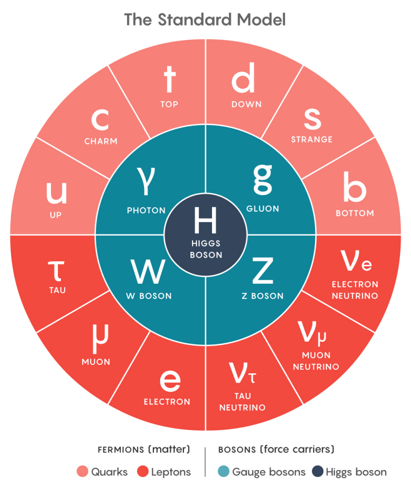

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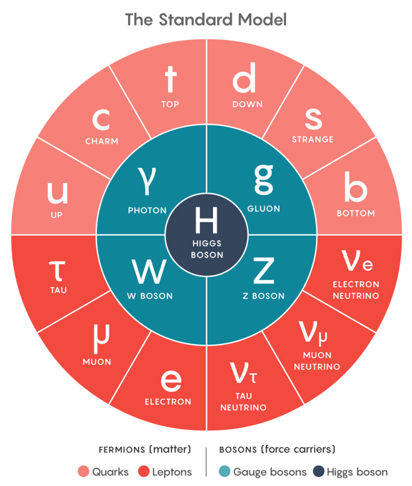

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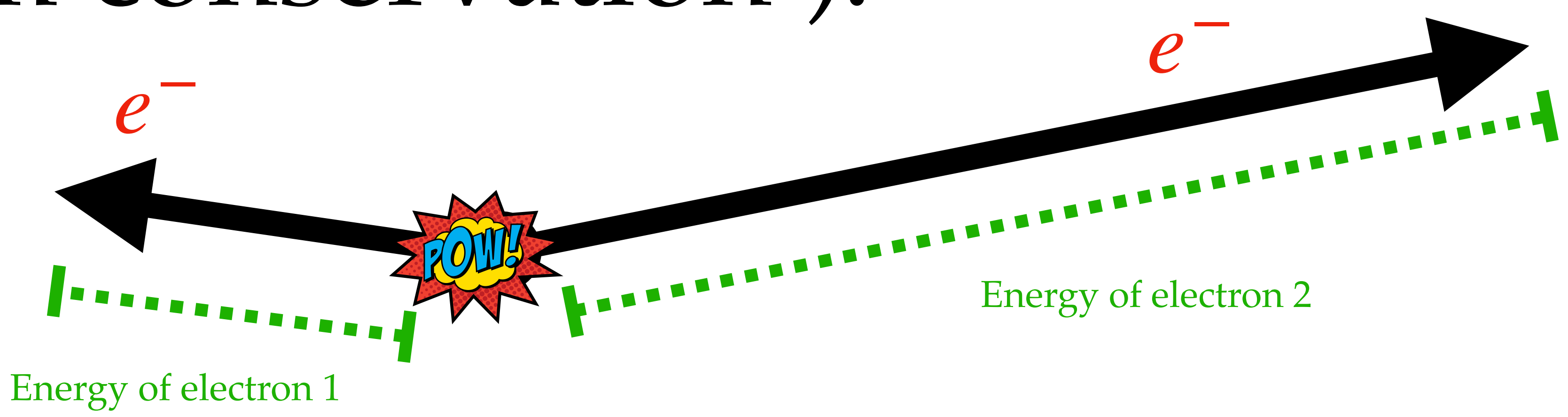

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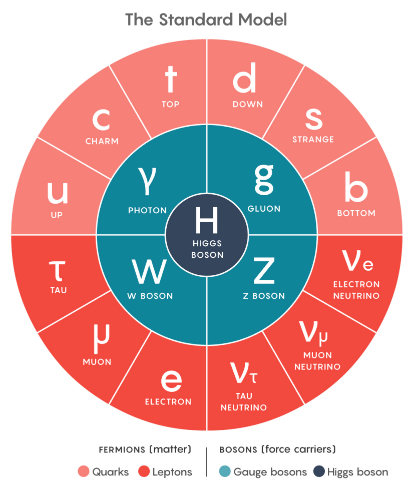

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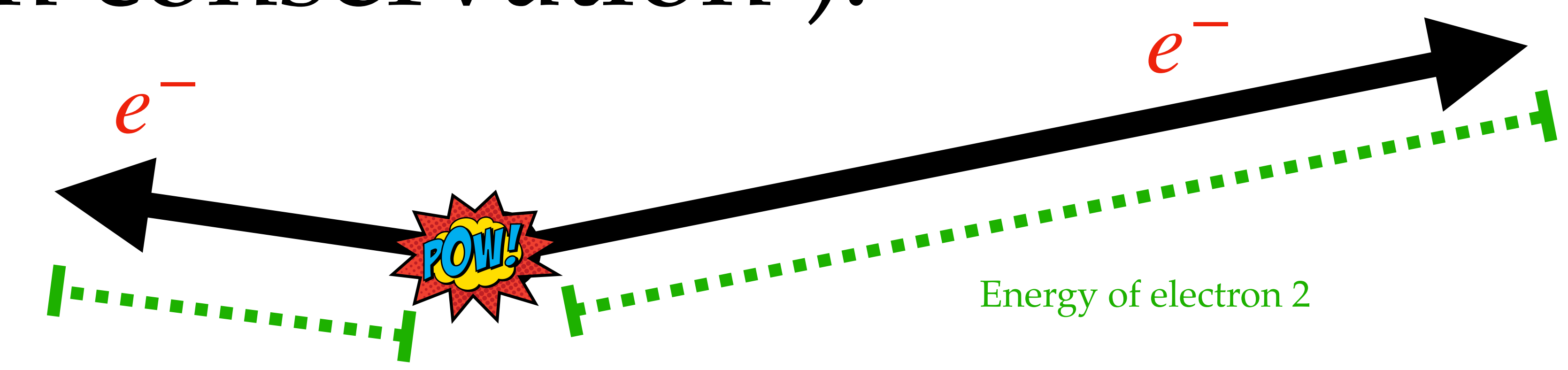

⇒ Get lists of particles that look like real events!

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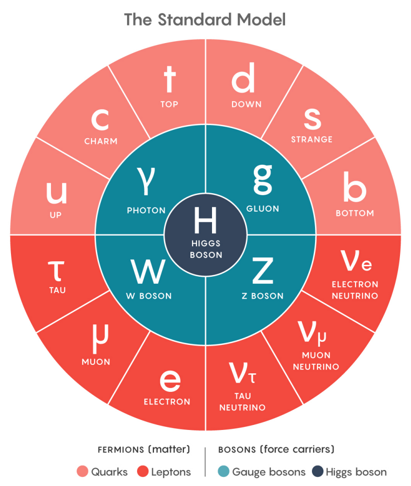

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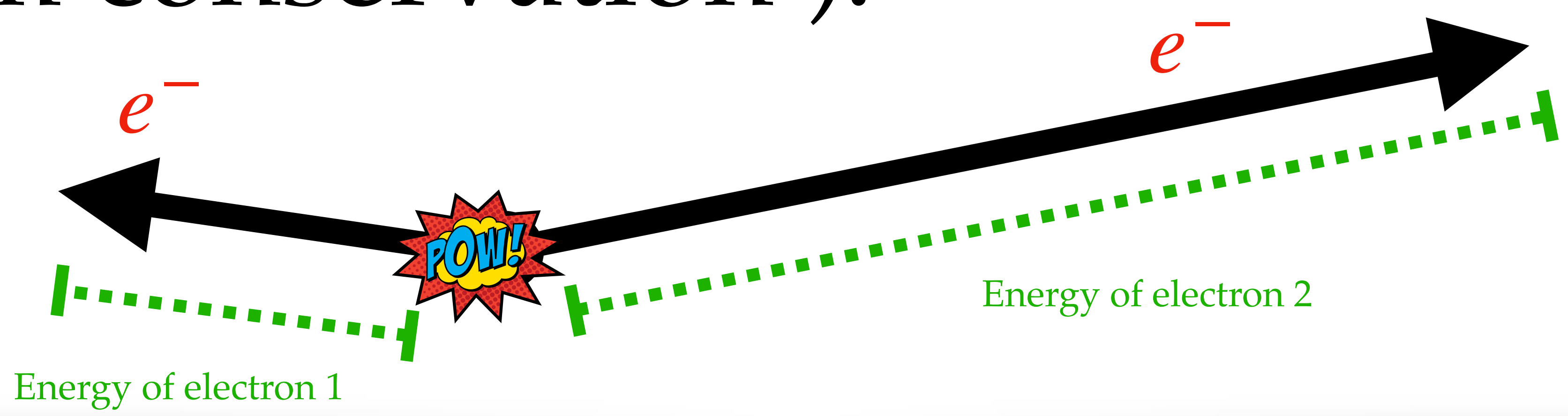
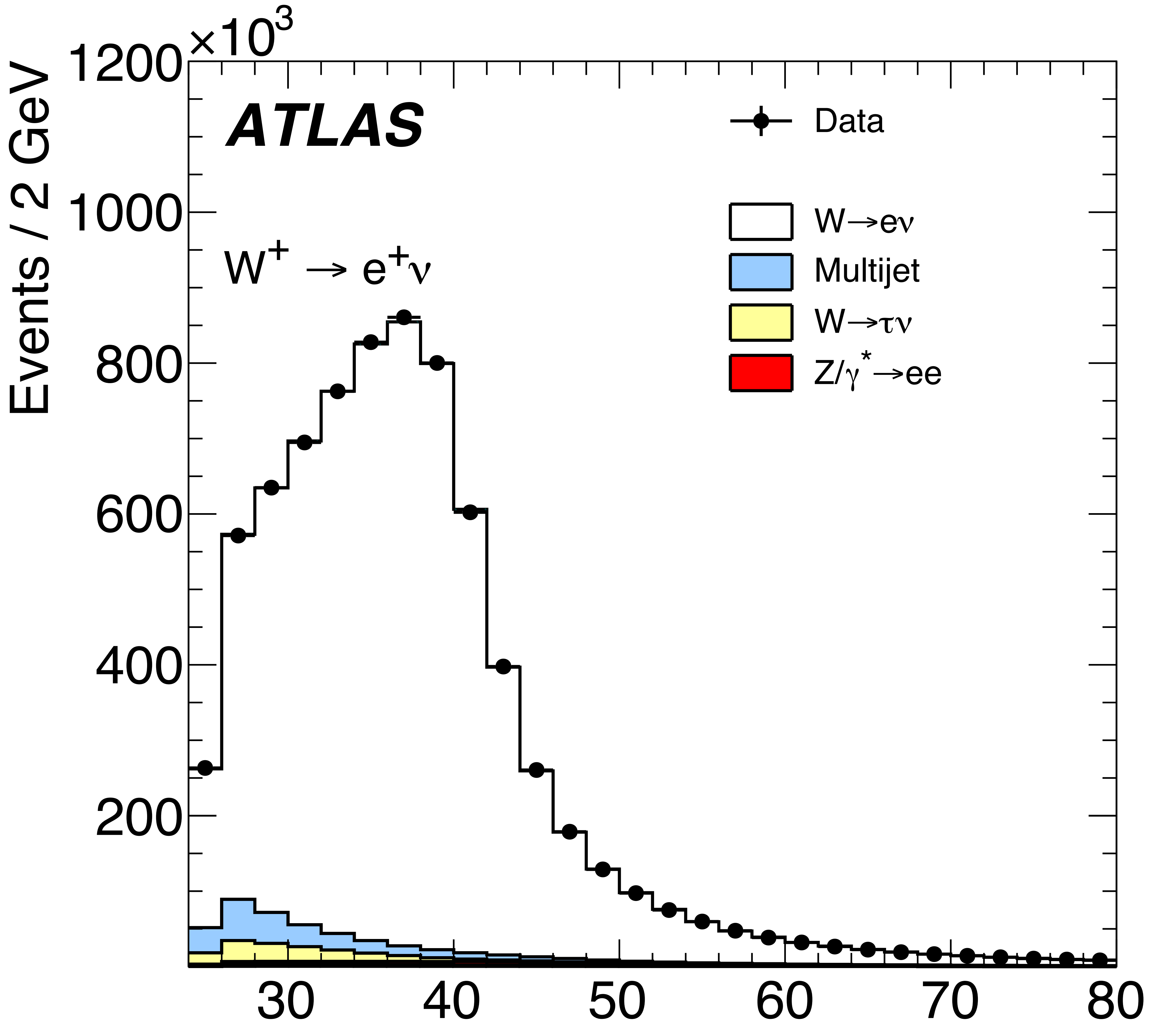


⇒ Get lists of particles that look like real events!

[e.g. "How-to: write a parton-level Monte Carlo particle physics event generator", **AP**, arXiv:1412.4677]

Theory VS Experiments

Construct histograms & Compare to real data! e.g.:



~ Electron energy [GeV]

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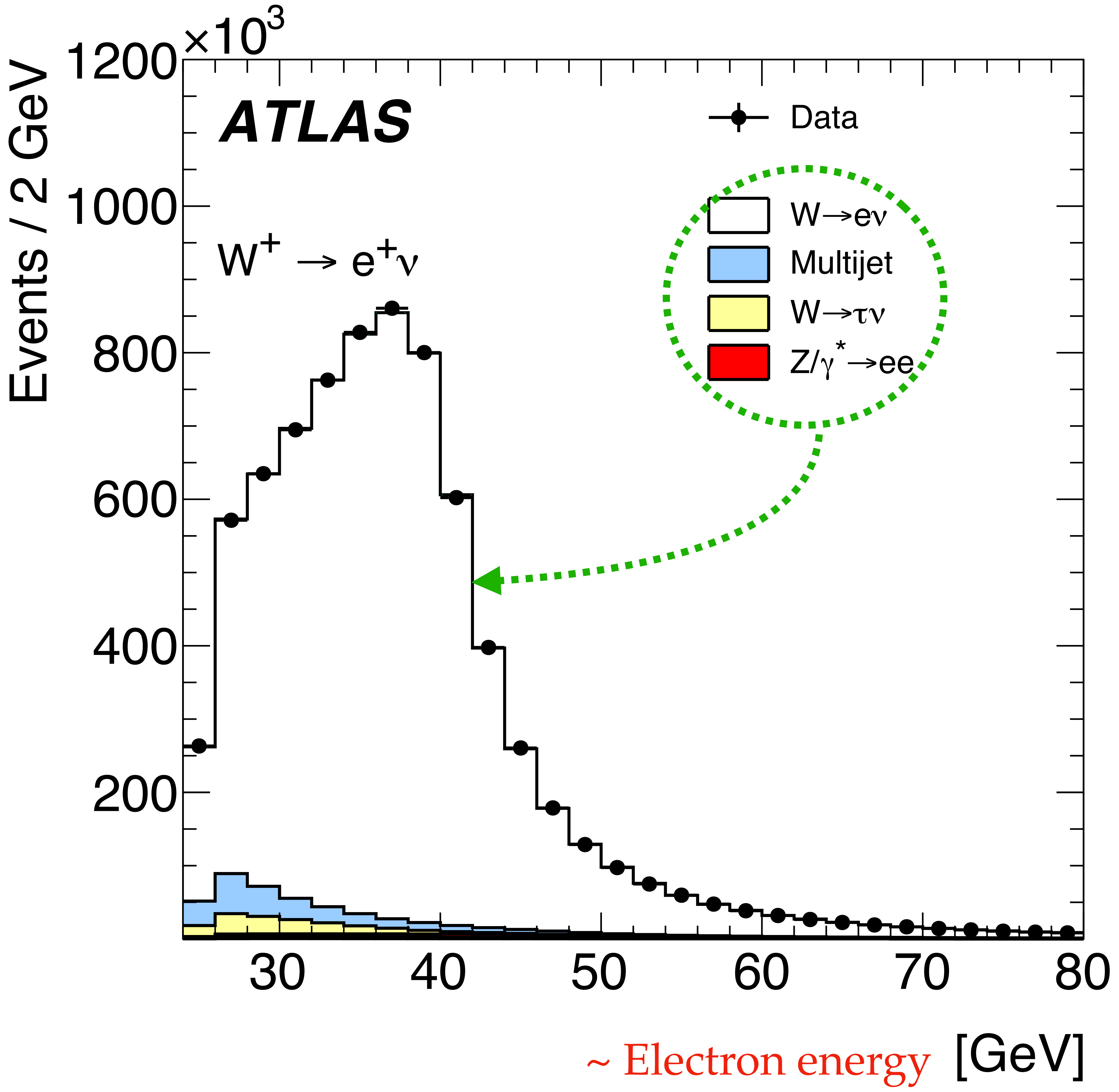

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Searching for New Phenomena

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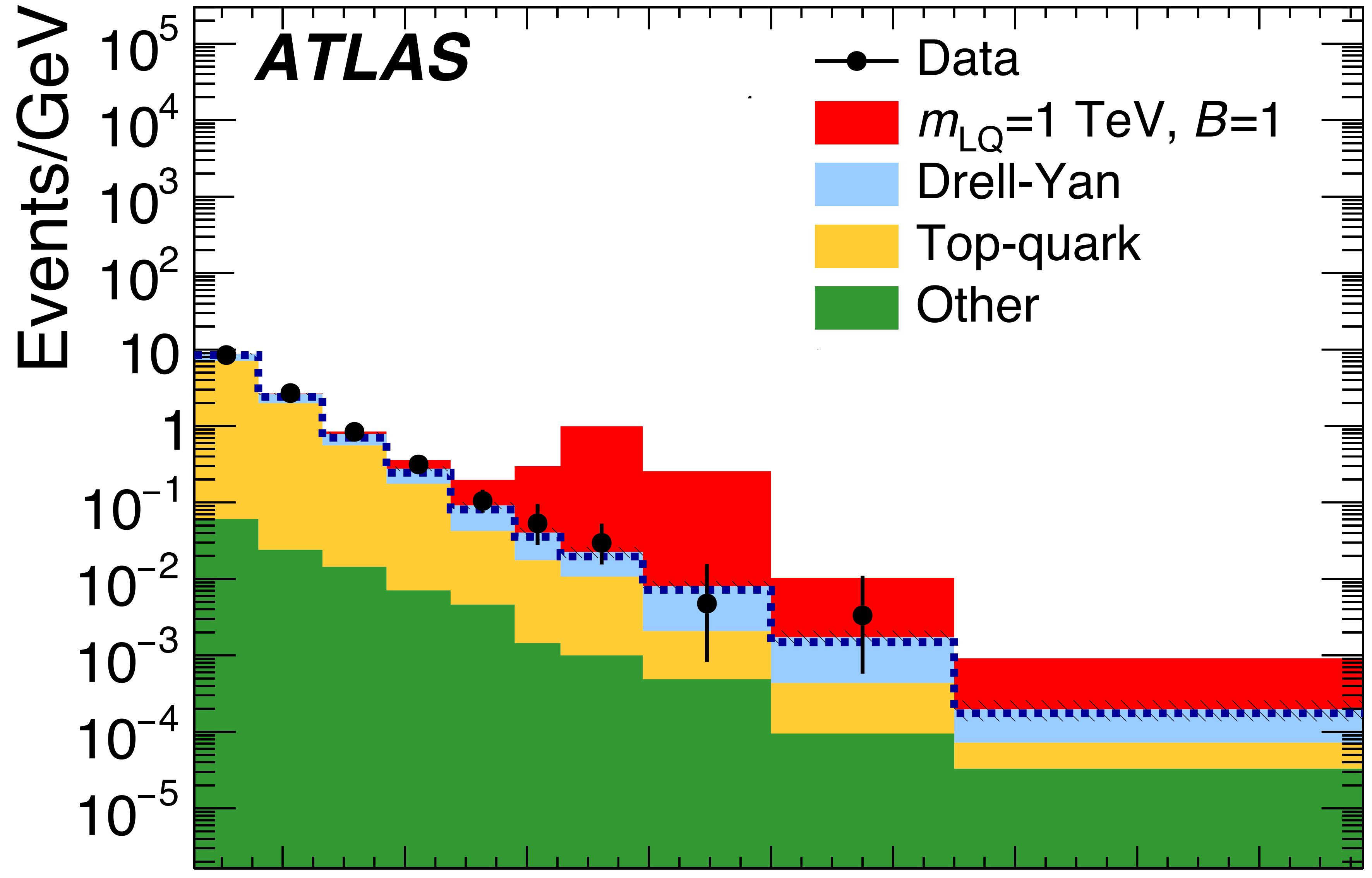

Some Observable Quantity [GeV]

Searching for New Phenomena

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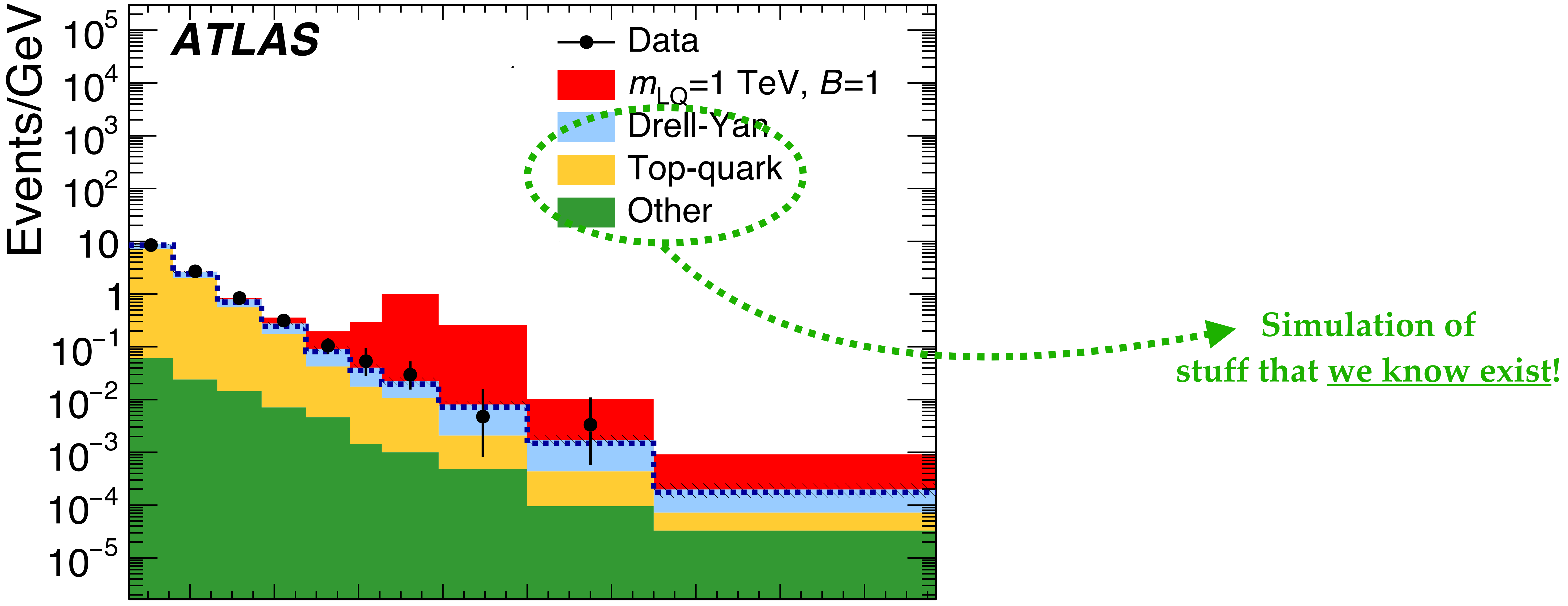

Some Observable Quantity [GeV]

Searching for New Phenomena

NEW!

Construct histograms &
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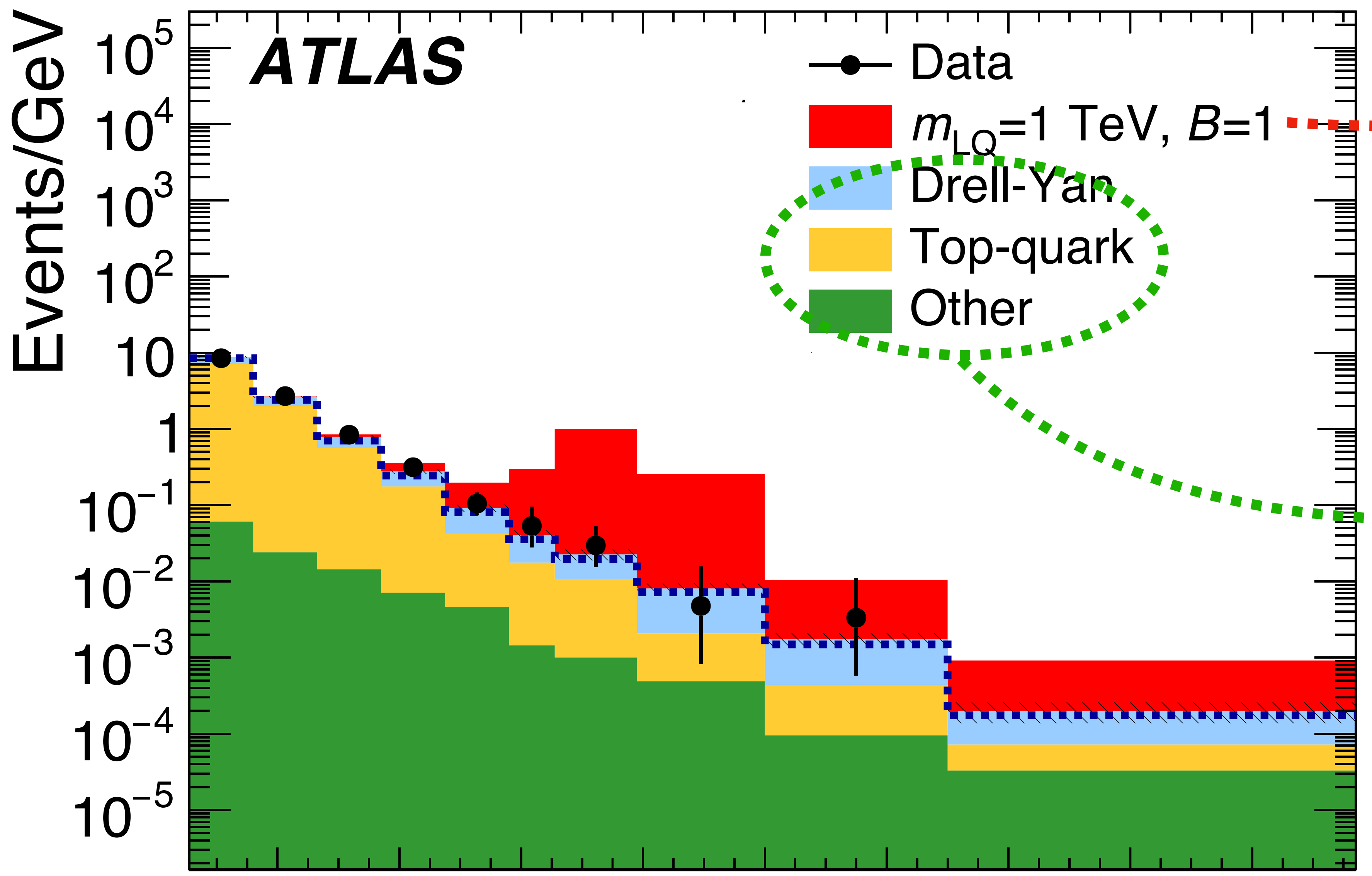

Hypothetical particle

Simulation of
stuff that we know exist!

Some Observable Quantity [GeV]

Searching for New Phenomena

NEW!

Construct histograms &
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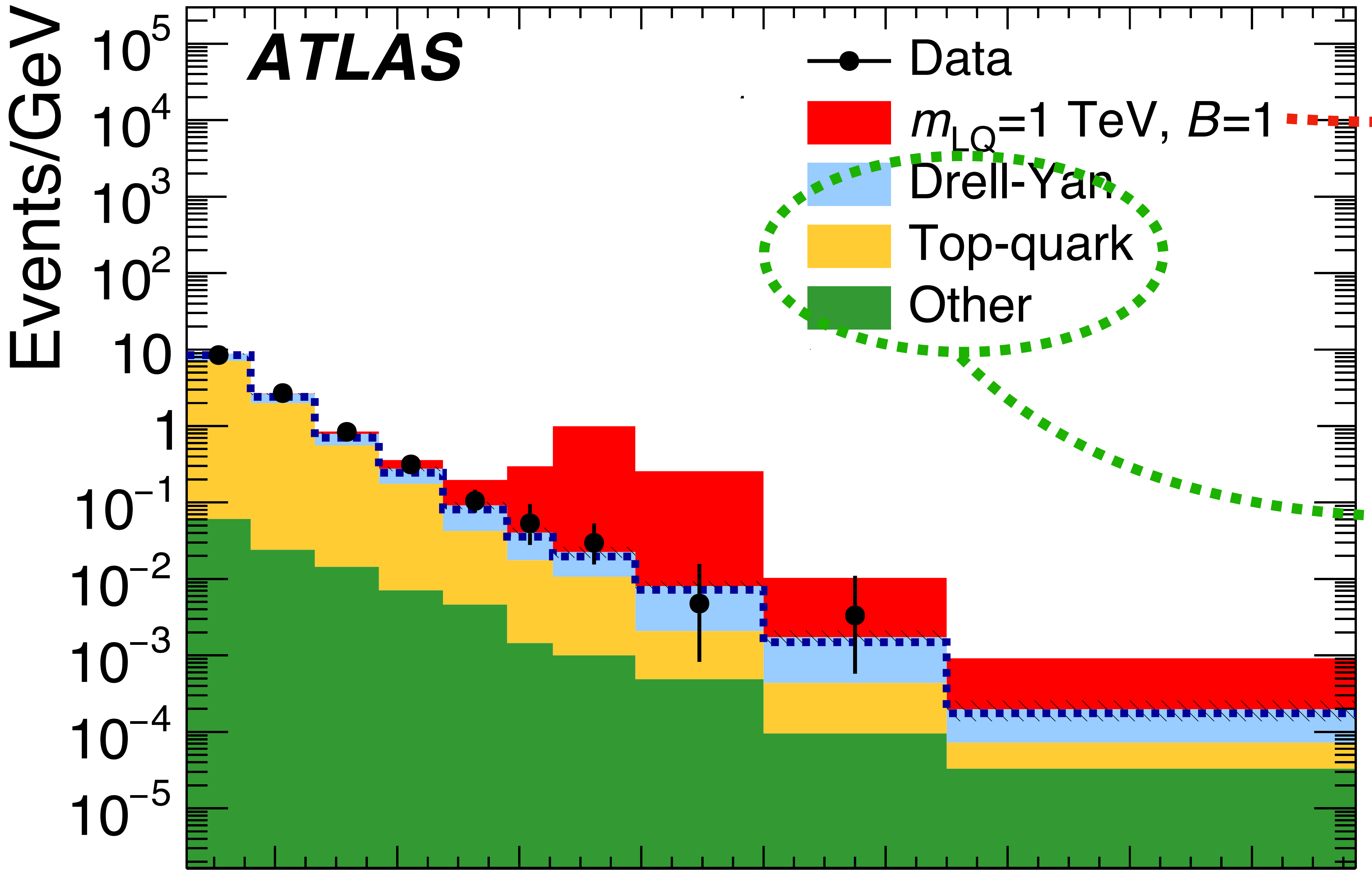

Hypothetical particle

Simulation of
stuff that we know exist!

Some Observable Quantity [GeV]

⇒ Determine whether a hypothetical particle is compatible with data!

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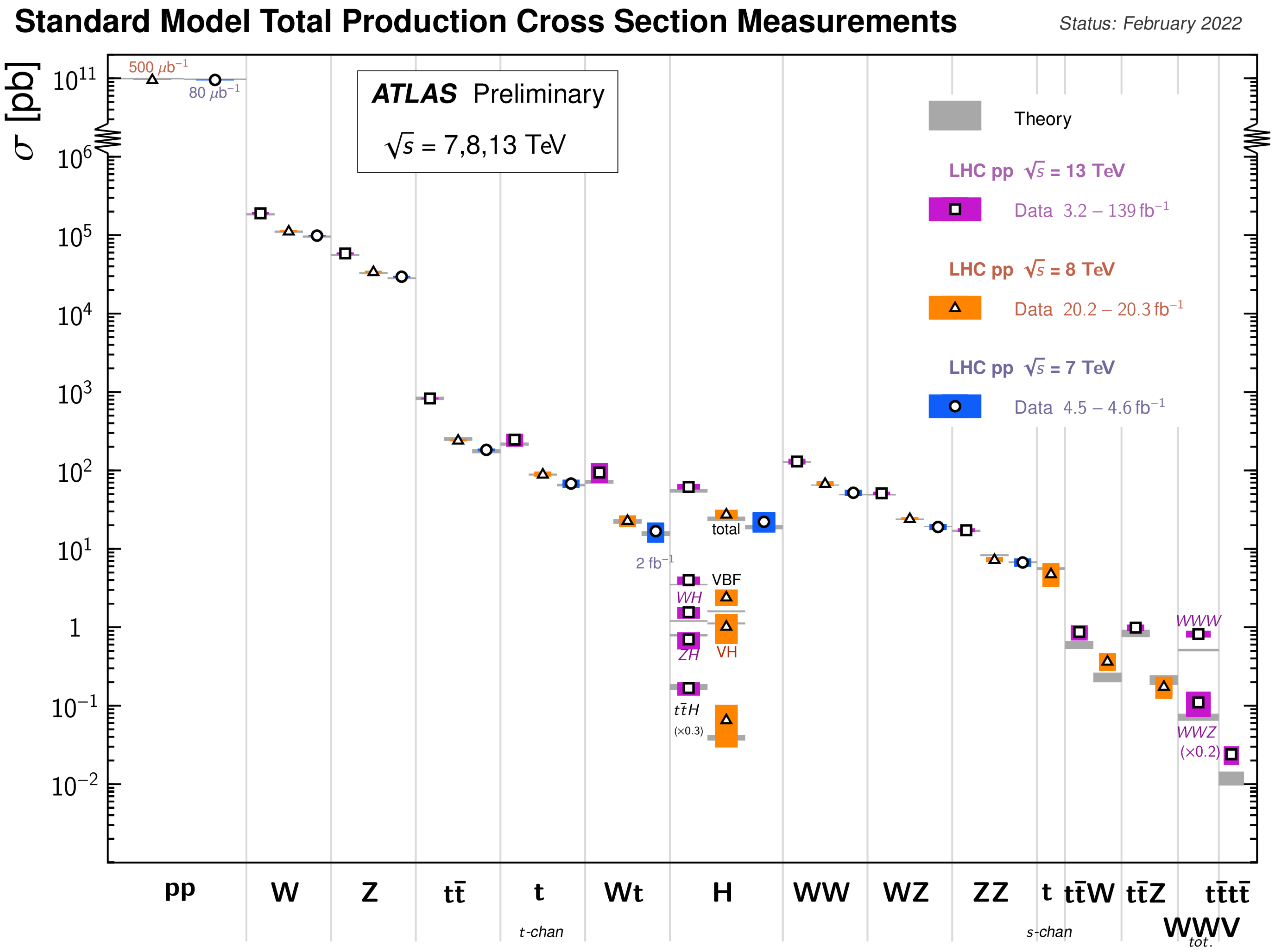
Experiment VS Theory

Cross Section [pb]

~ Frequency of type of event



Process Type

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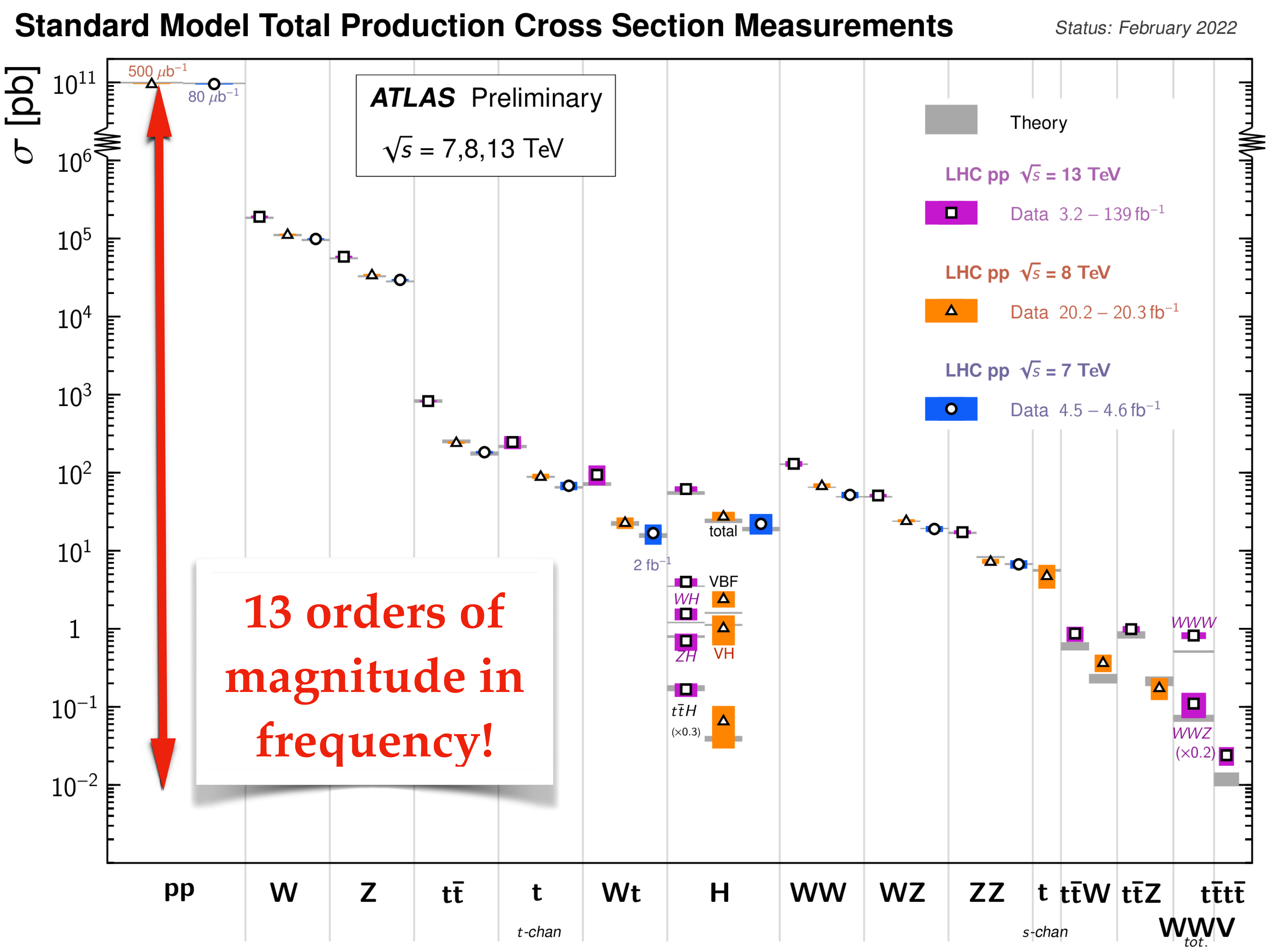
Experiment VS Theory



Cross Section [pb]

~ Frequency of type of event

Process Type

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Experiment VS Theory

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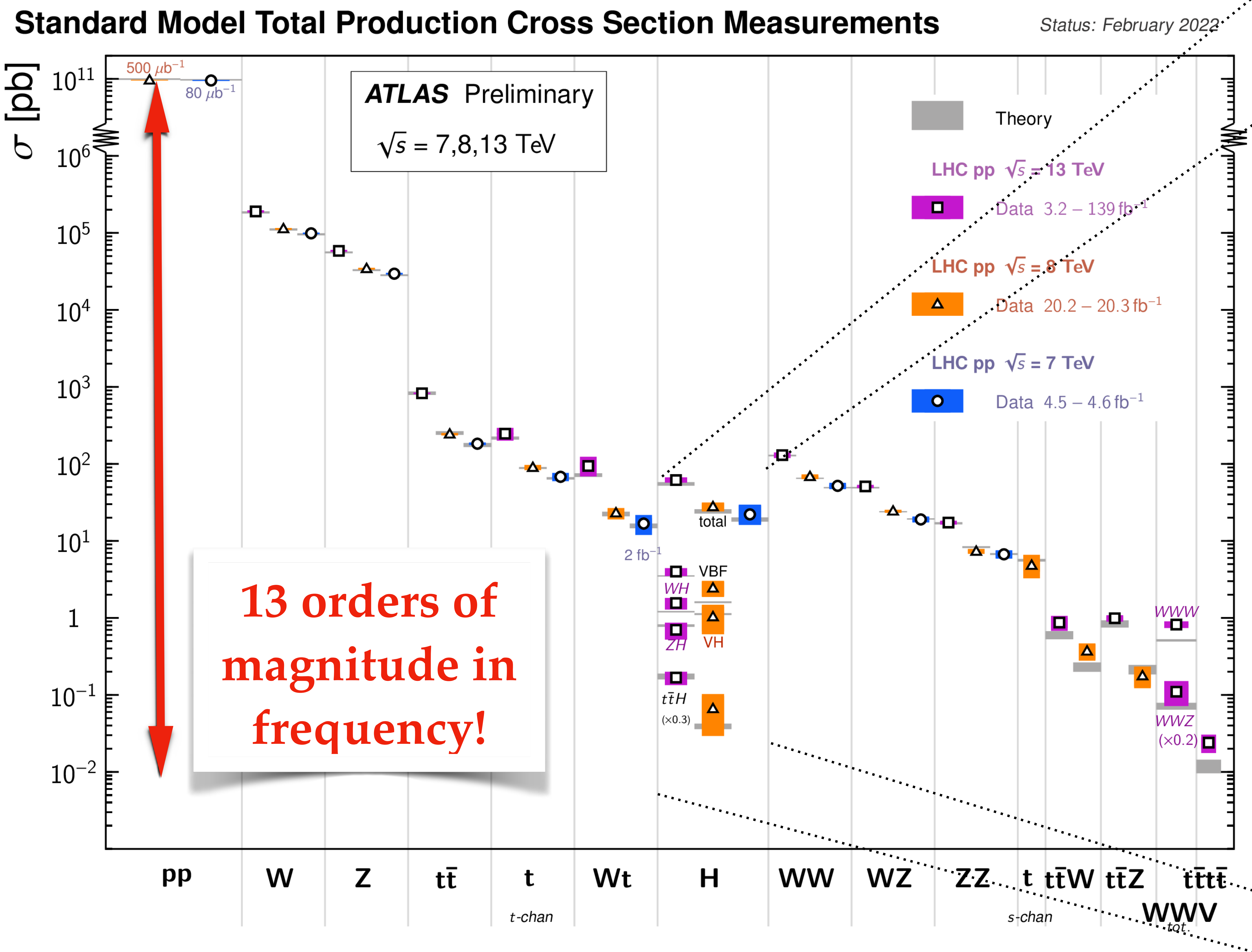

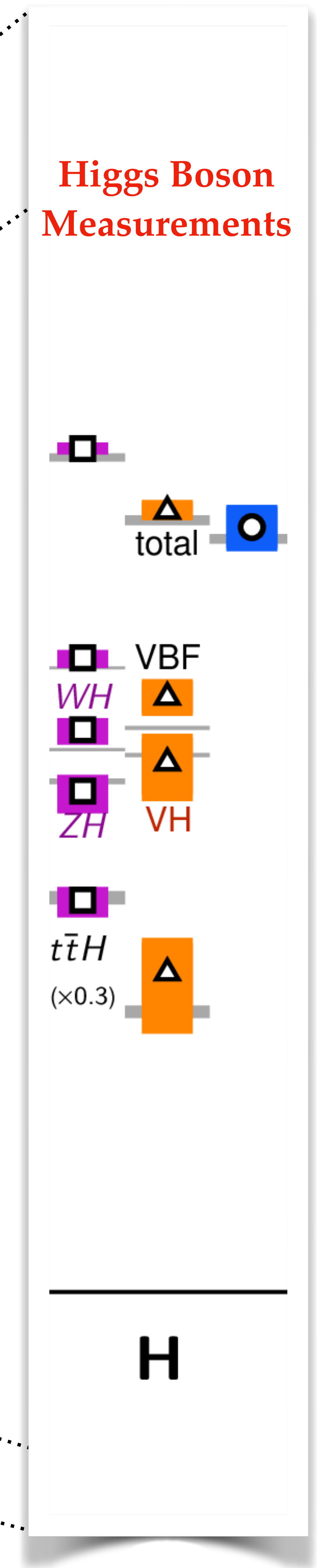

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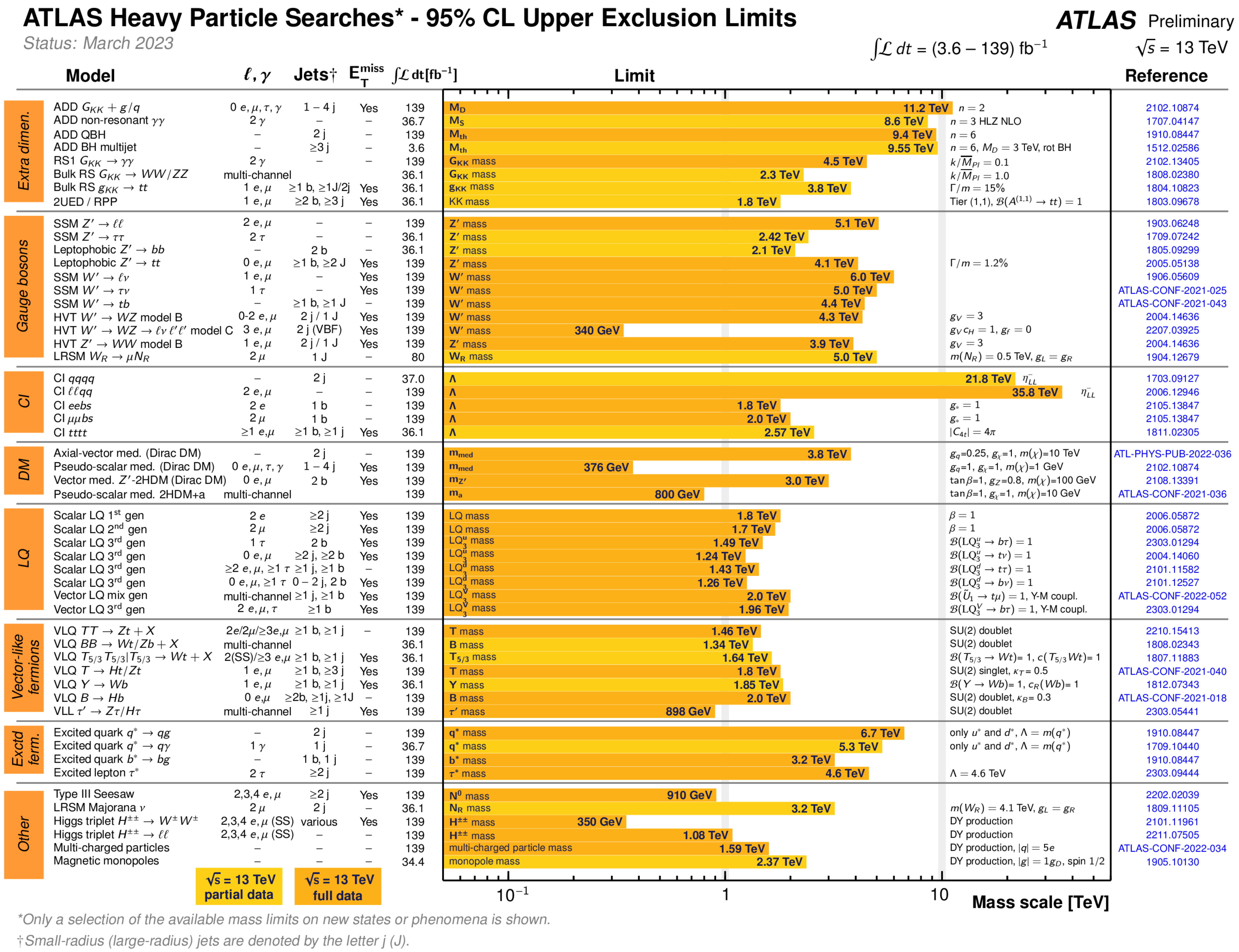

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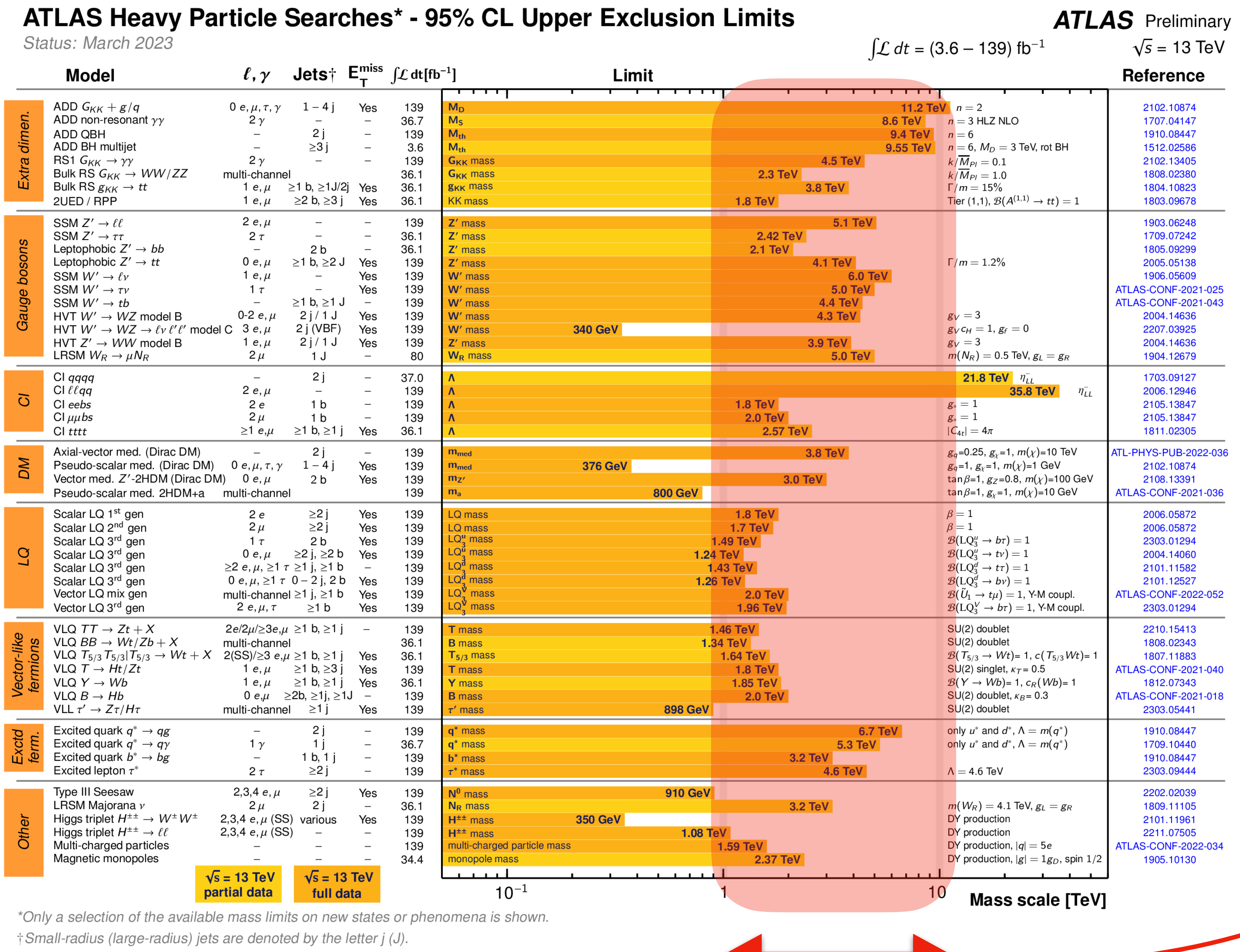
Experiment VS New Phenomena



Mass Scale limits: 1-10 TeV

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EXPERIMENT WINS!

⇒ **No new phenomena?**

[credit: Alvaro Rujula,
Found in a CERN TH office]

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Is that all folks?

Questions


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Questions

Answers

Questions

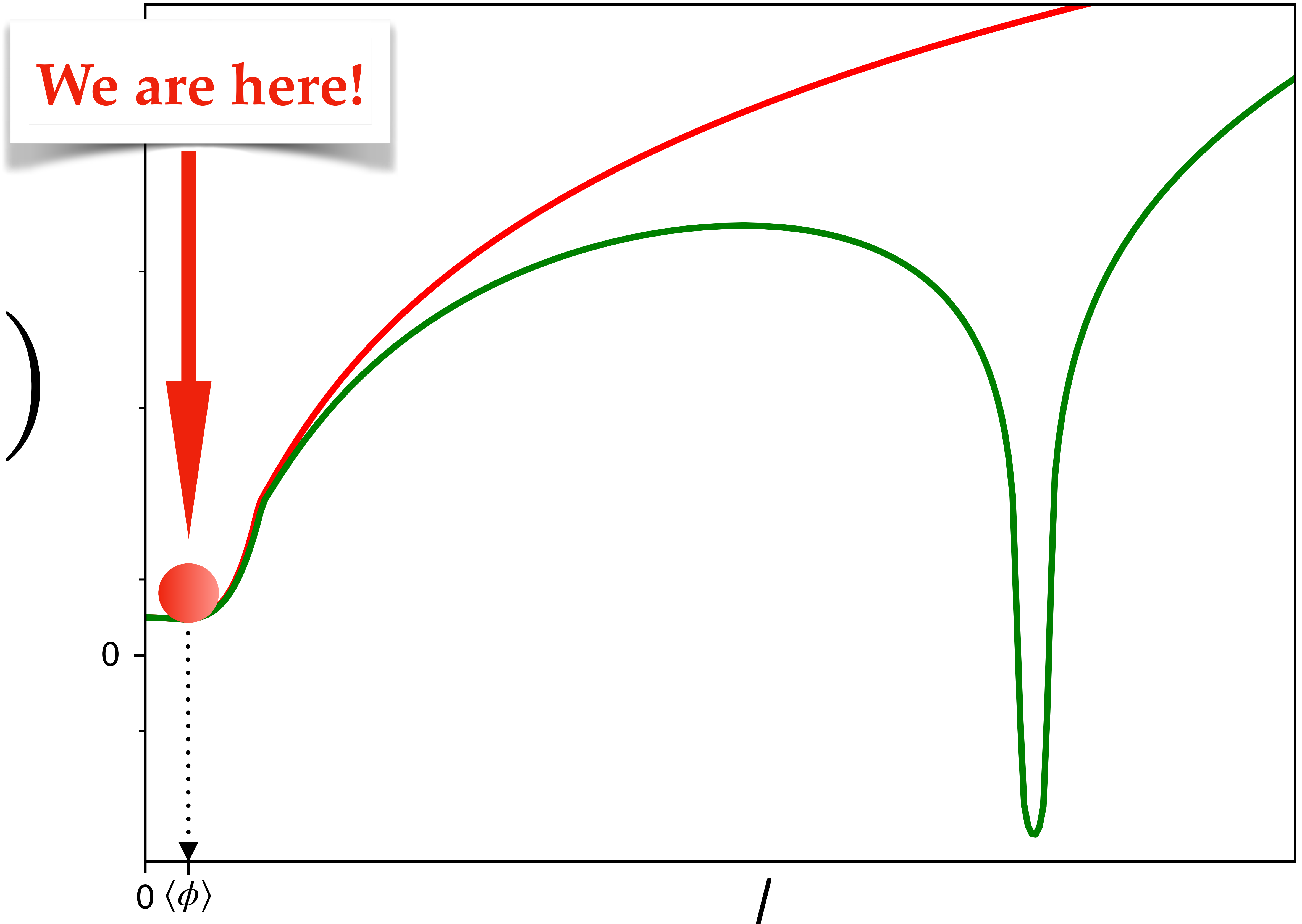
Answers

Questions

Answers

2 Q: What is the ultimate fate of our Universe?

Higgs Potential: $\mathcal{V}(\phi)$



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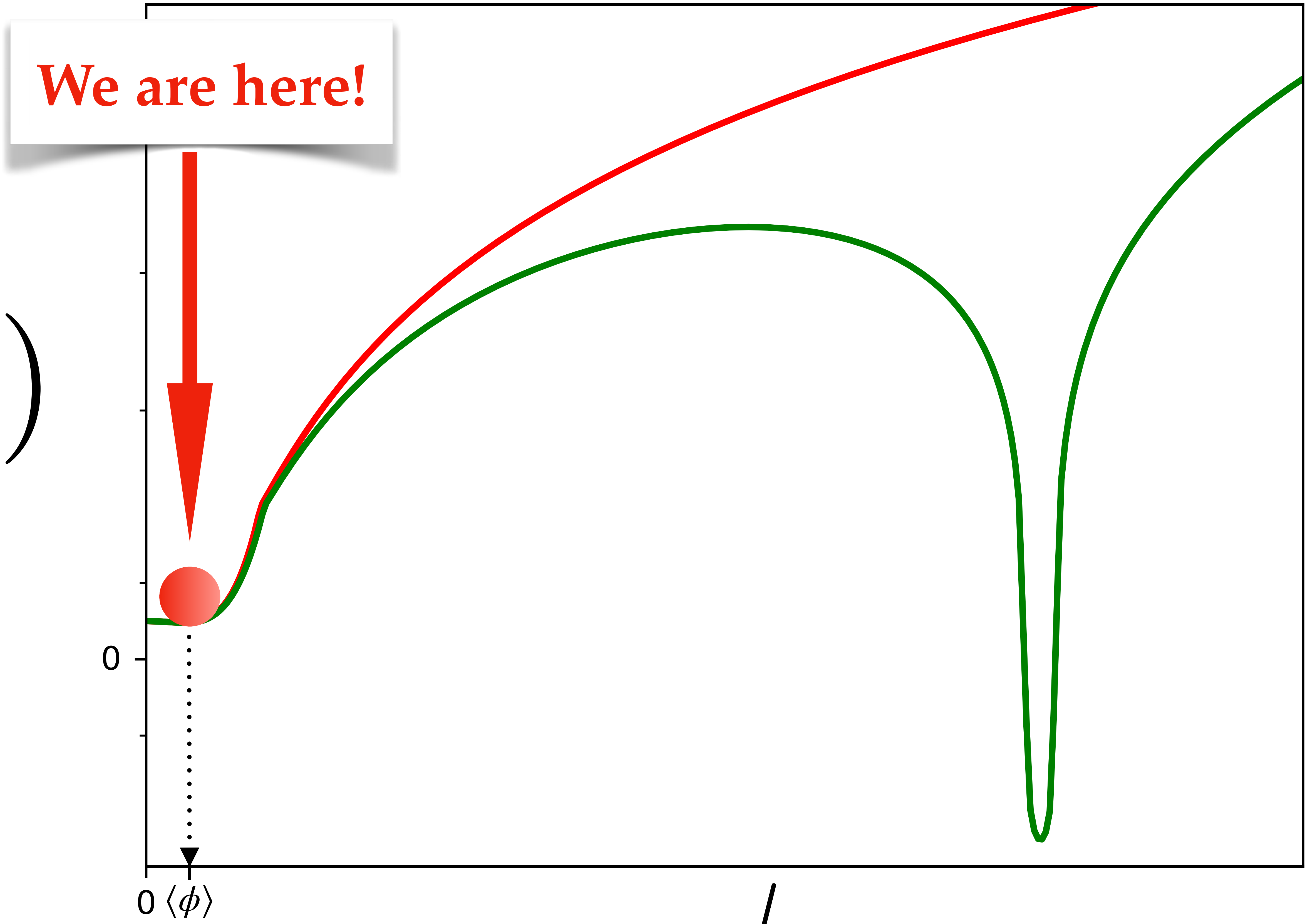

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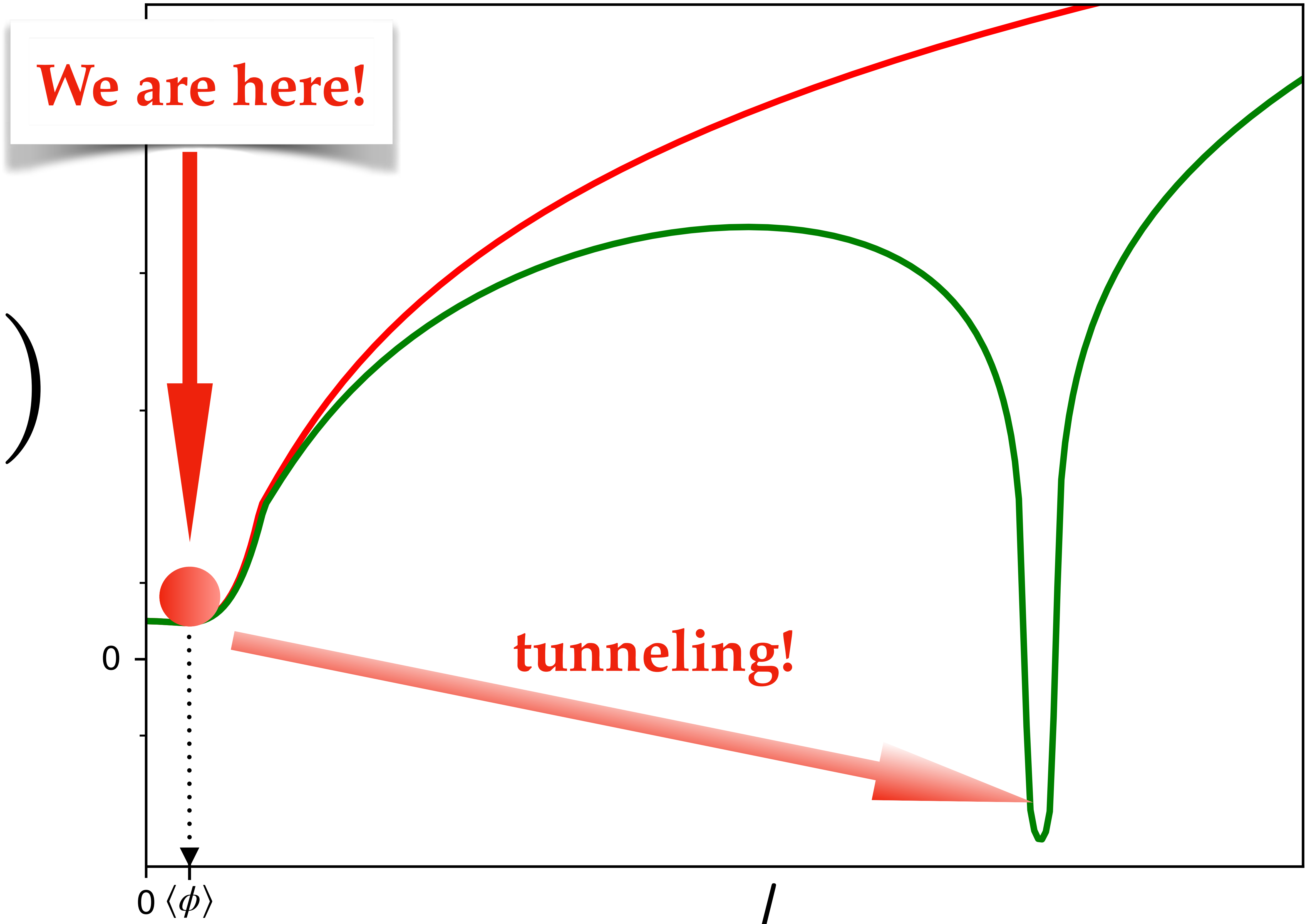

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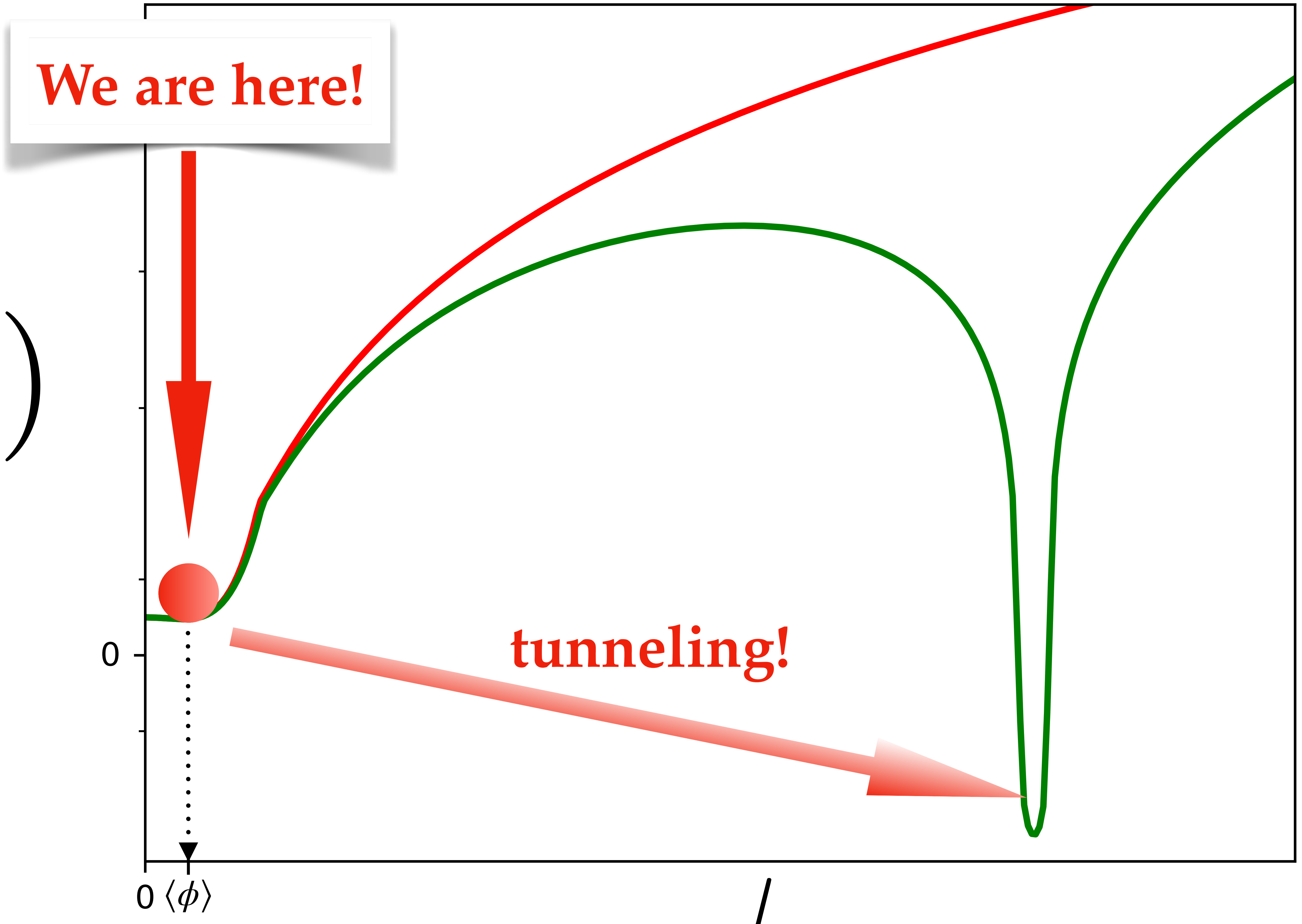

Higgs Field: ϕ

➜ the **"Vacuum Stability Problem"**.

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Q: Why does the matter we are made of exist?

[or: Why is there so much more matter than anti-matter?]

[credit: QuantaMagazine]

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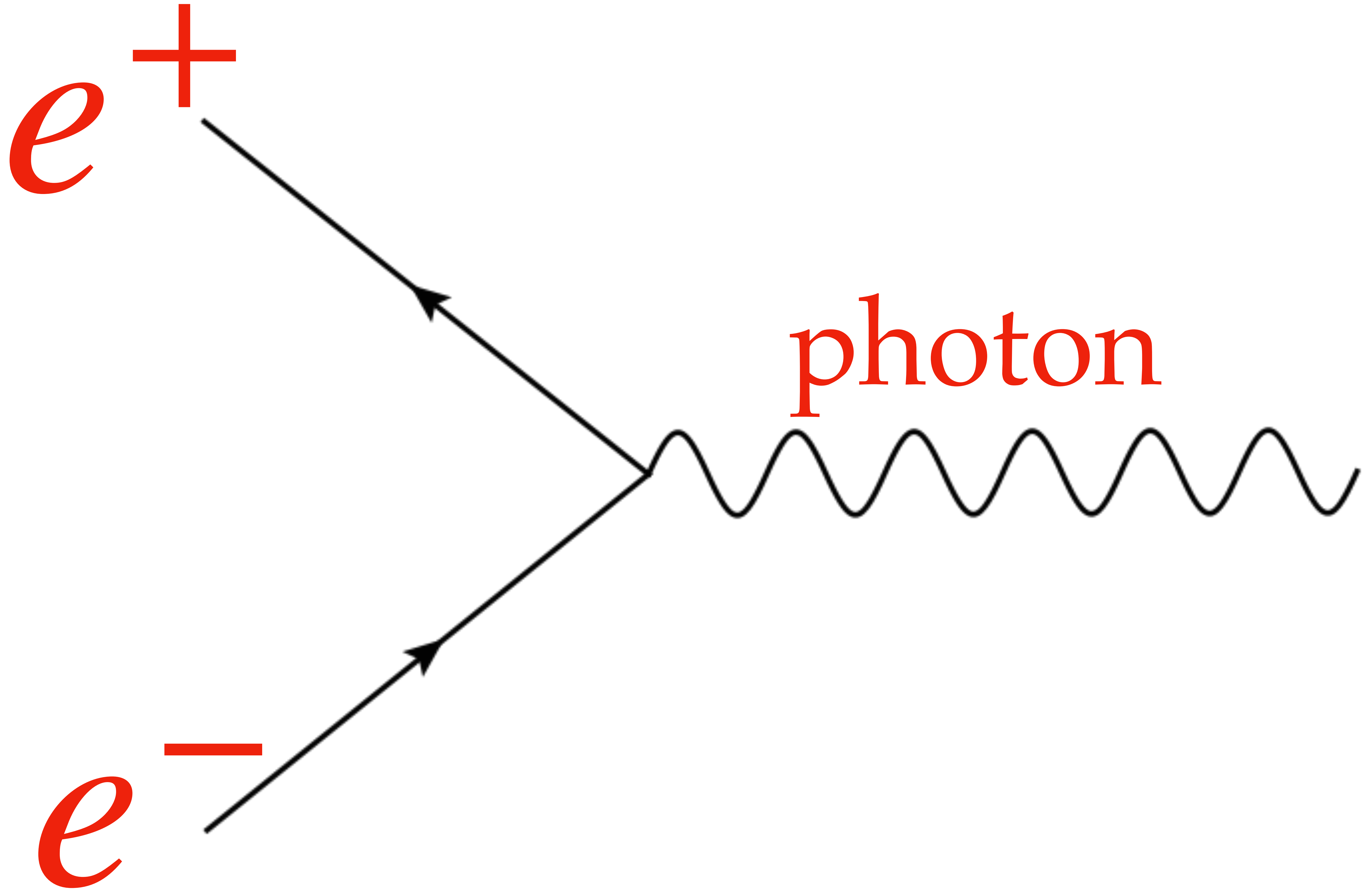

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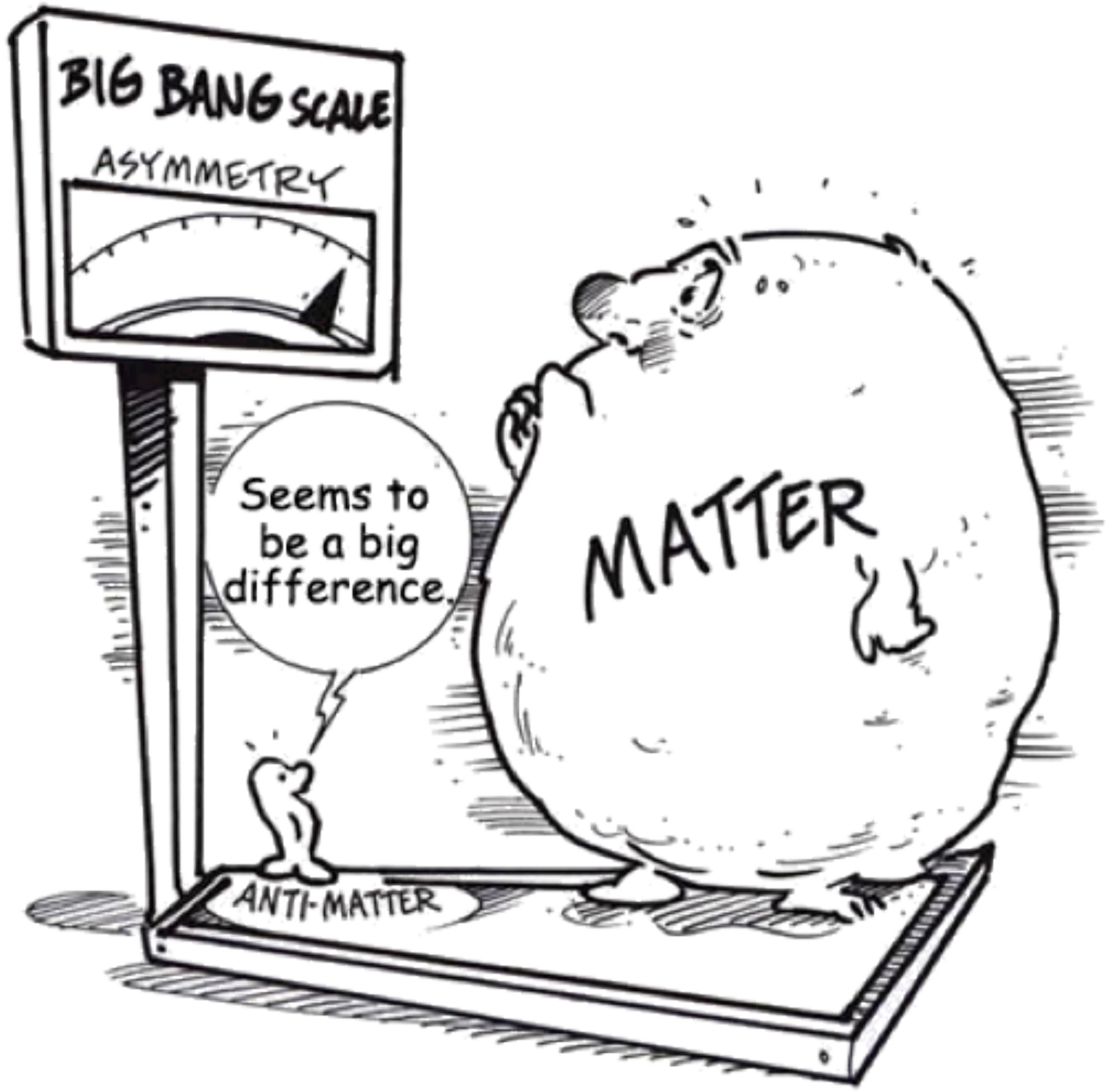

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➜ the **"Matter-Anti-Matter Asymmetry"**.

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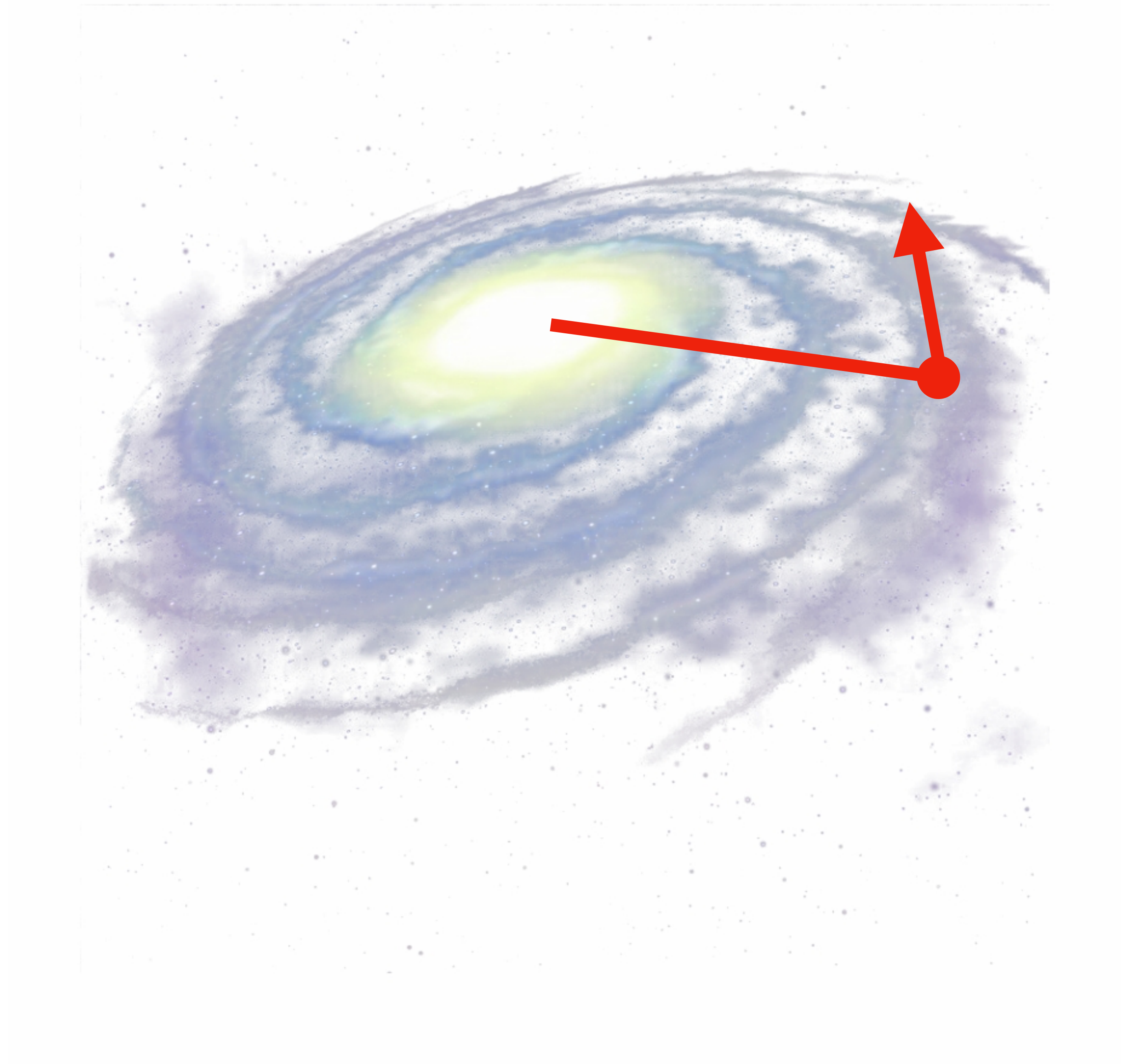
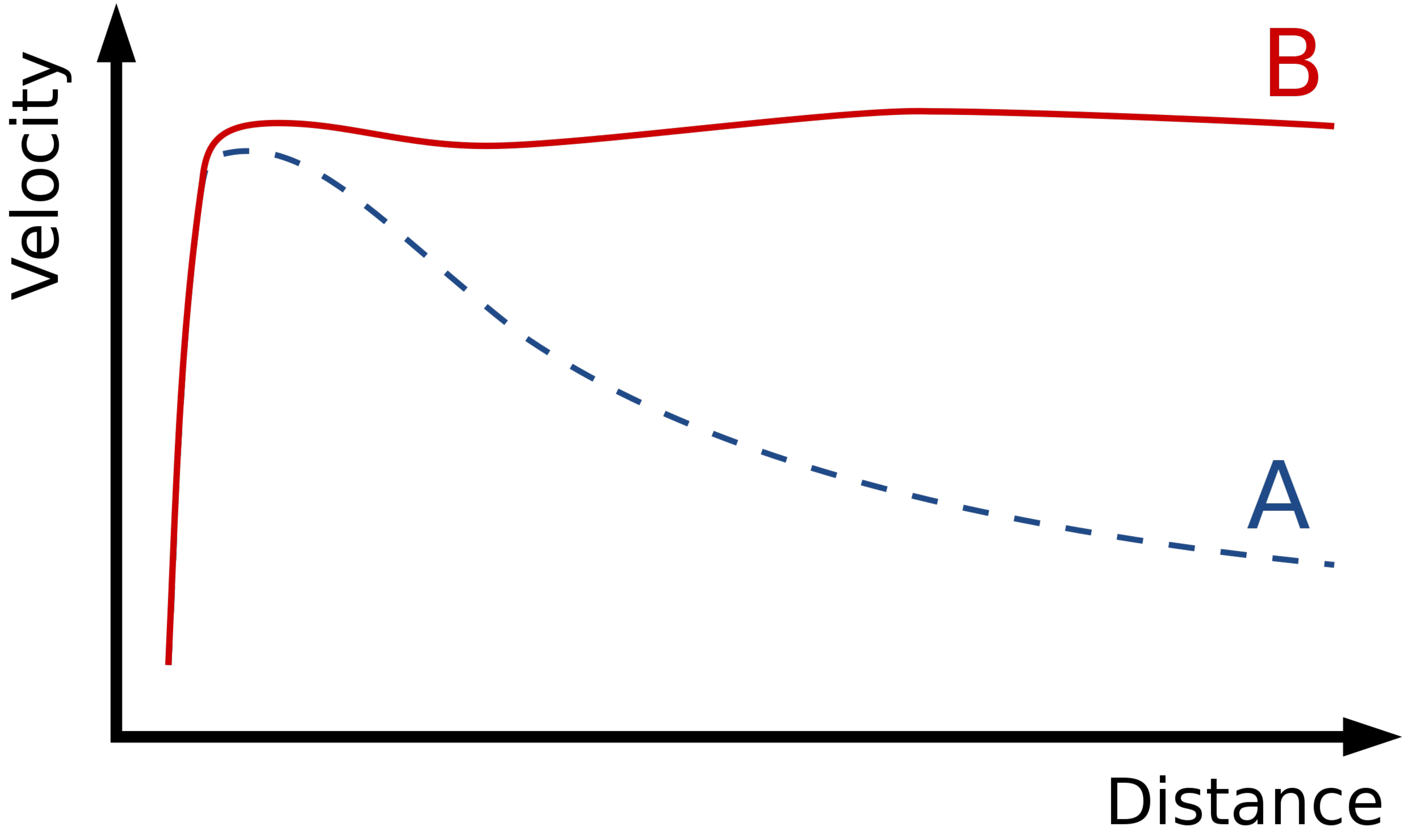
Rotation curve of a typical spiral galaxy: predicted (A) and observed (B).





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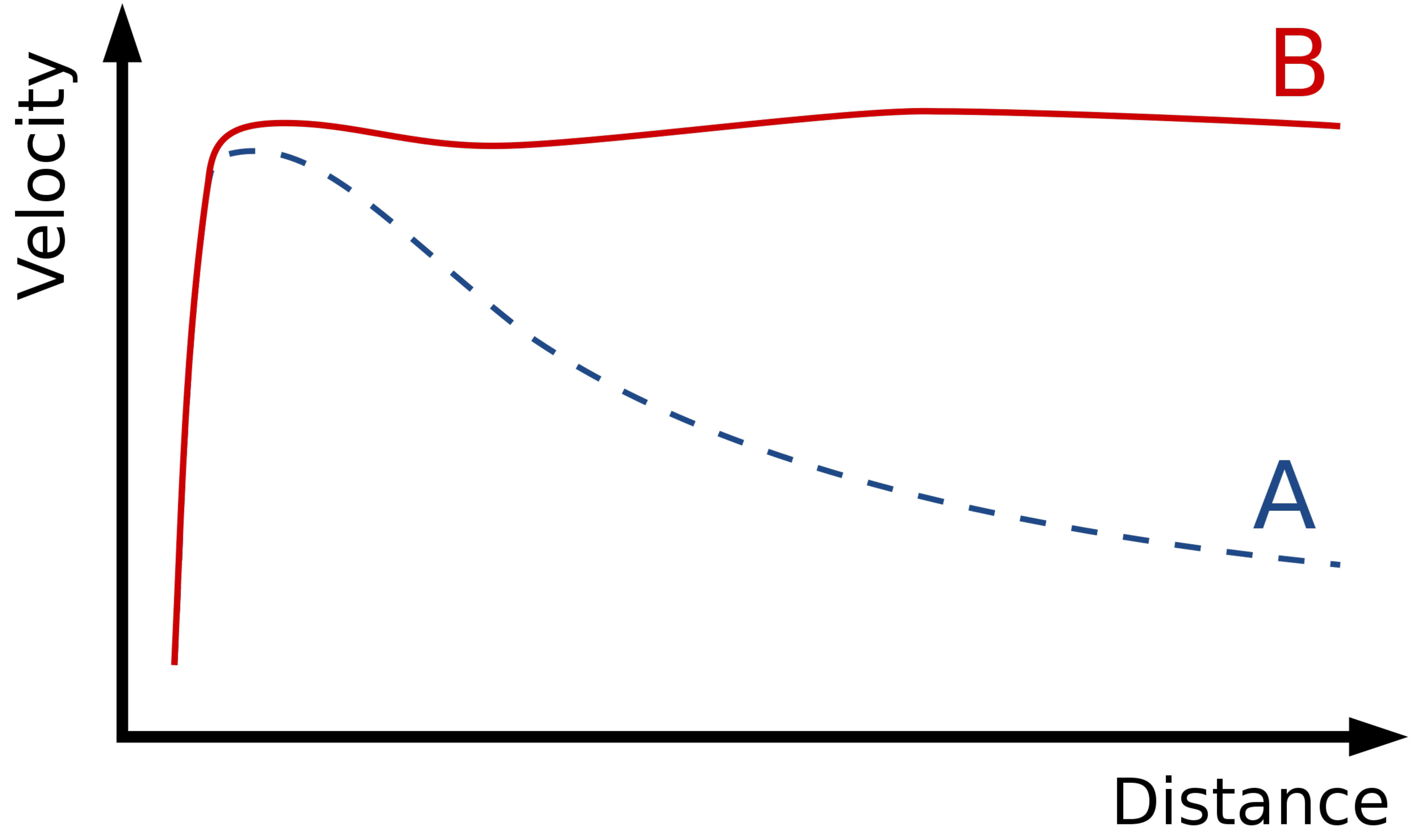
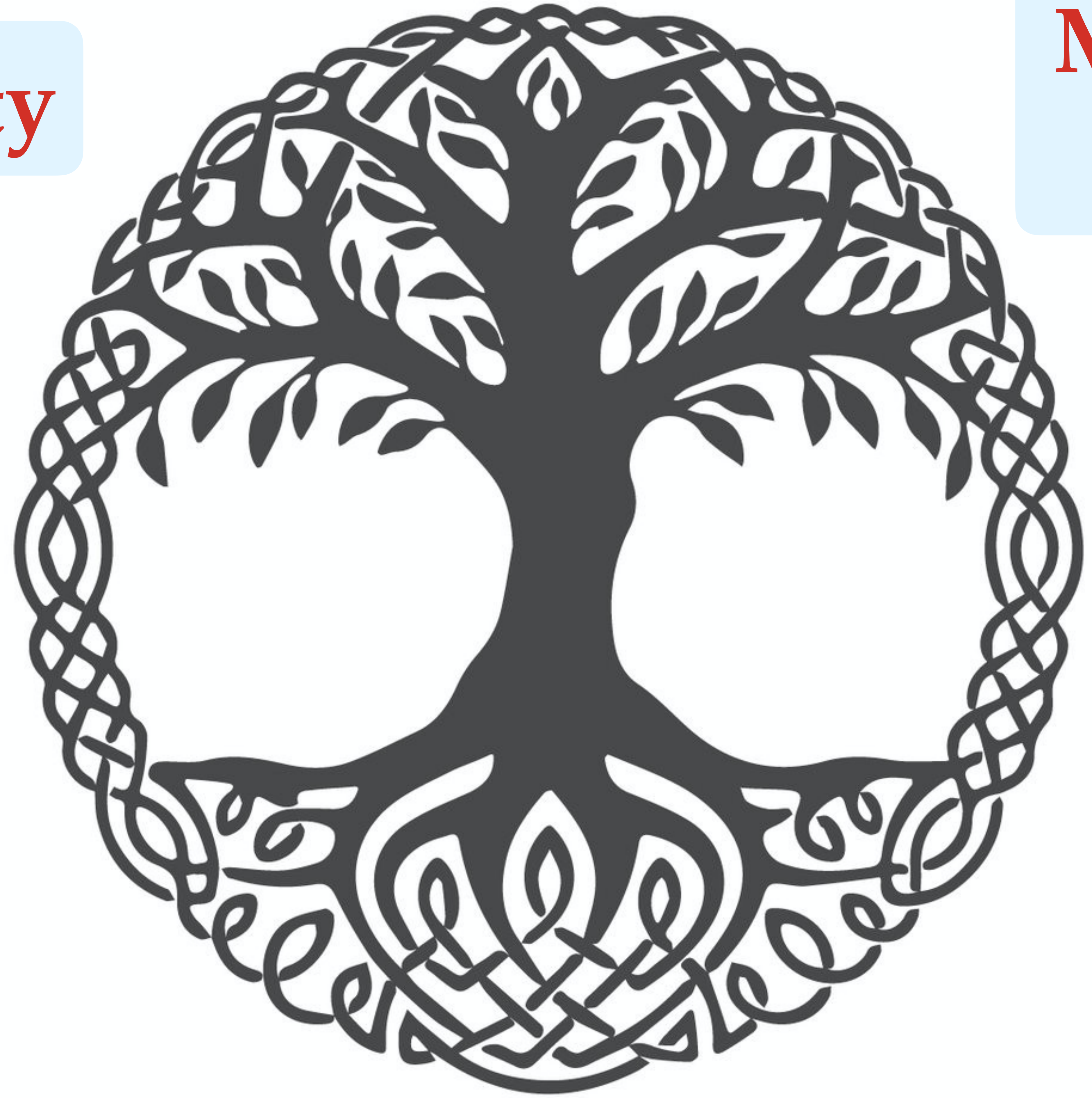


Q: …

Dark Matter

Vacuum Stability

Matter-anti-matter Asymmetry



The Higgs Field & Symmetry Breaking

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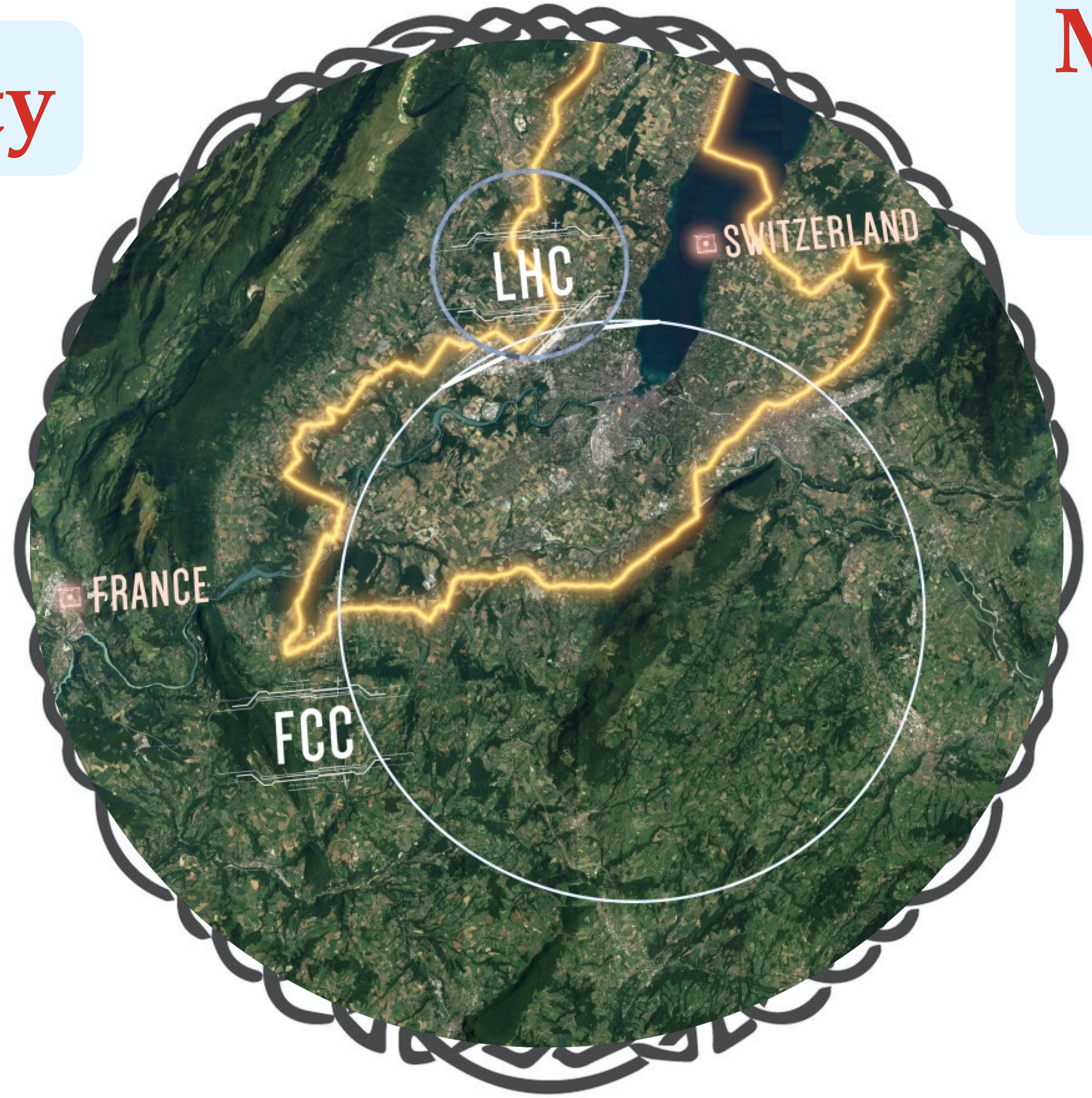
Dark Matter

Vacuum Stability

Matter-anti-matter Asymmetry



e.g. Future Circular Collider: pp@100 TeV, e^+e^-.

e.g. "High-Energy" LHC: pp@27 TeV.

e.g. Muon Collider.

The Higgs Field & Symmetry Breaking

3 Breaking the Symmetry

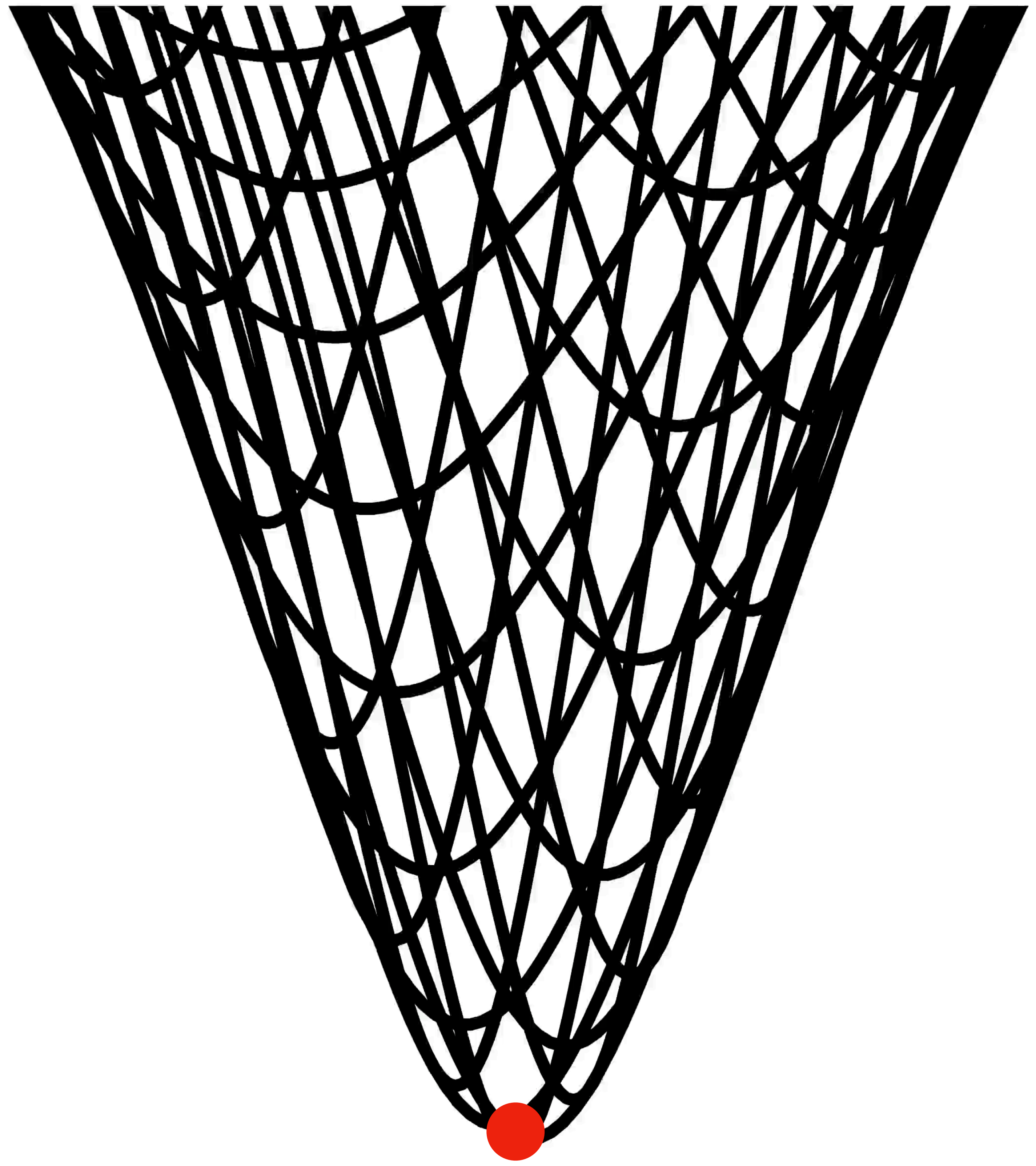
Breaking the Symmetry

Breaking the Symmetry in the Standard Model

The potential of the Higgs field (ϕ), a complex doublet:

$$\phi = \begin{pmatrix} \phi_1 + i\phi_3 \\ \phi_2 + i\phi_4 \end{pmatrix}$$

(Arbitrarily) Set $\phi_3 = \phi_4 = 0$ to illustrate potential in (ϕ_1, ϕ_2) plane.



$\mathscr{V}(\phi)$

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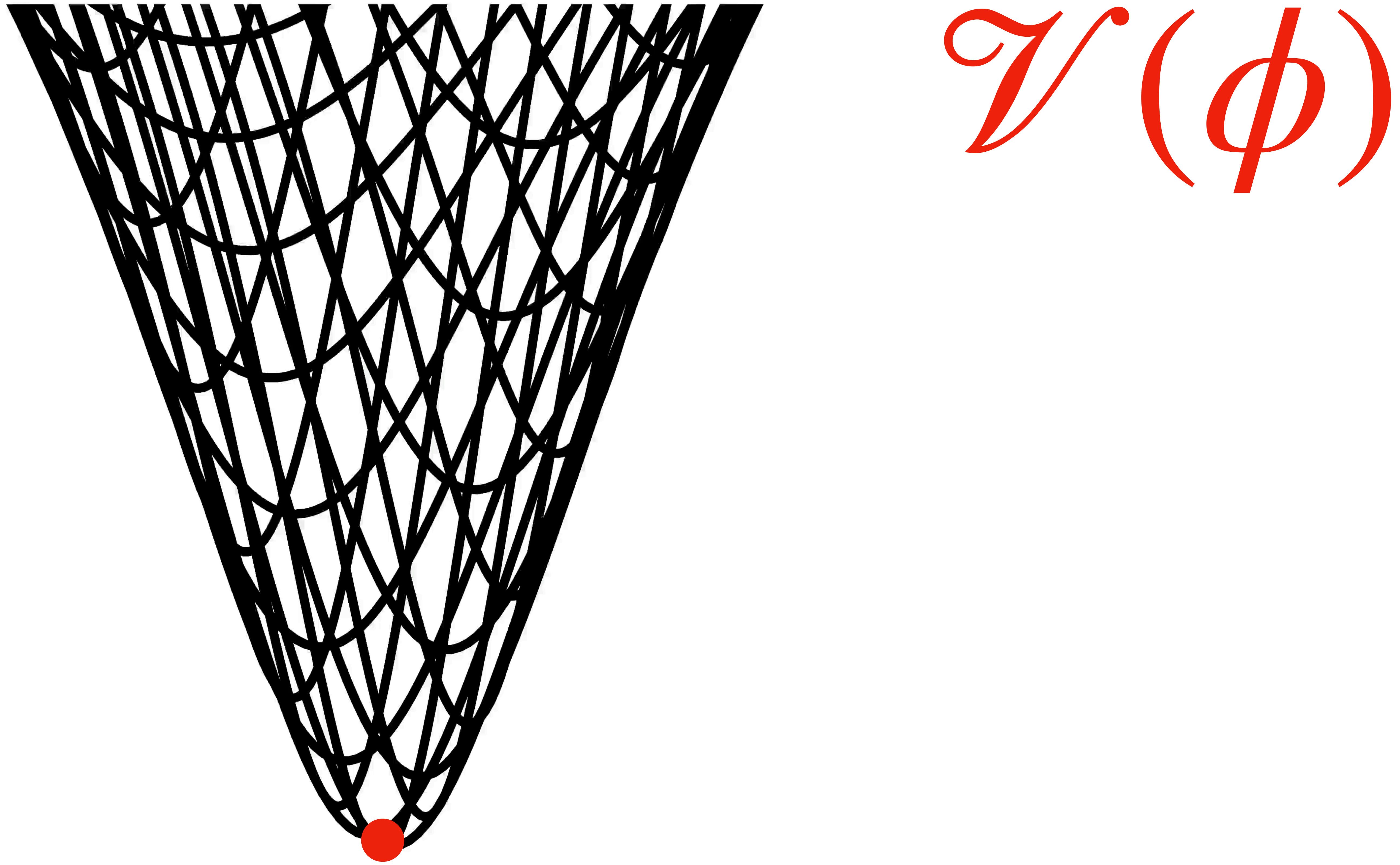

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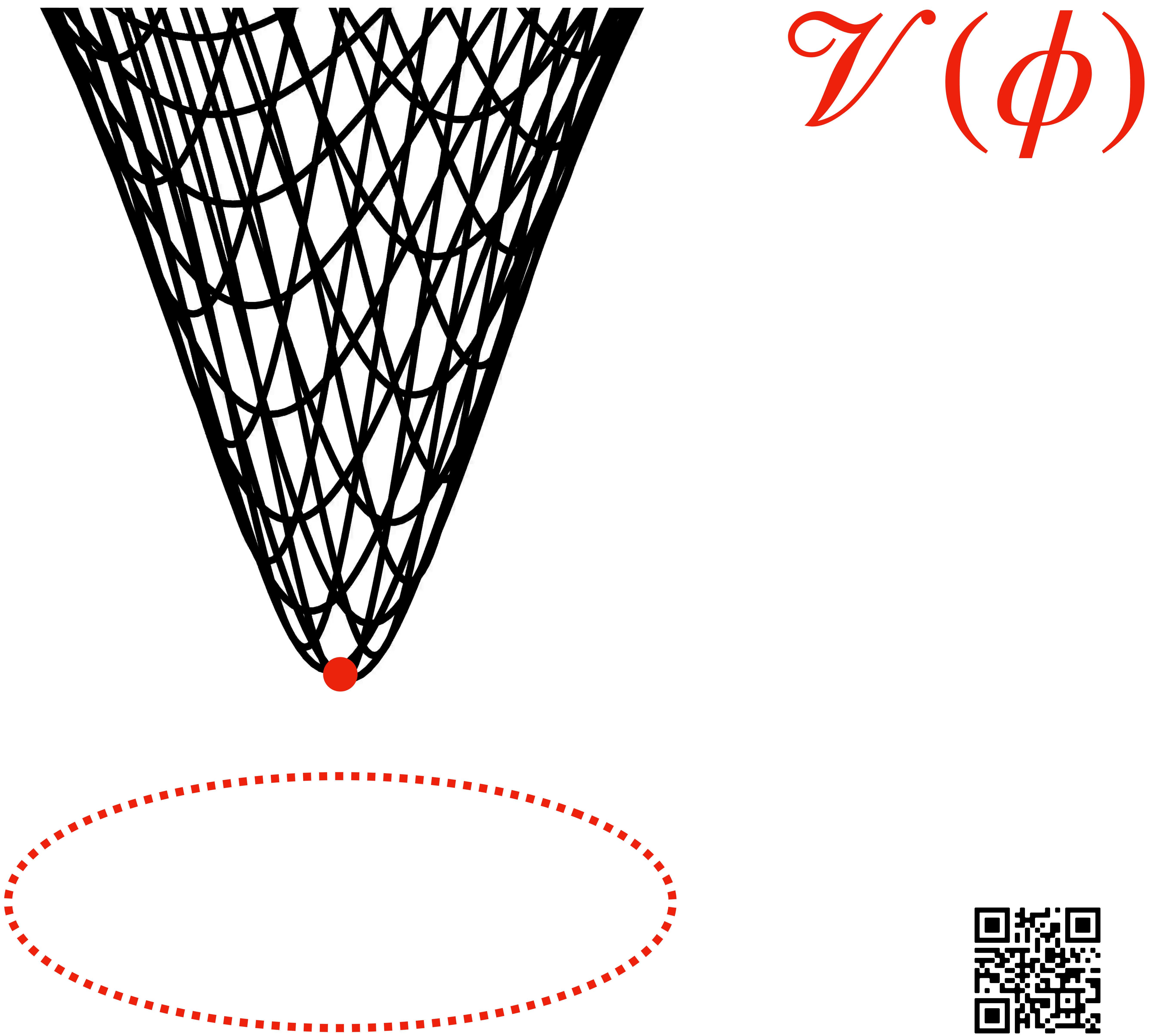
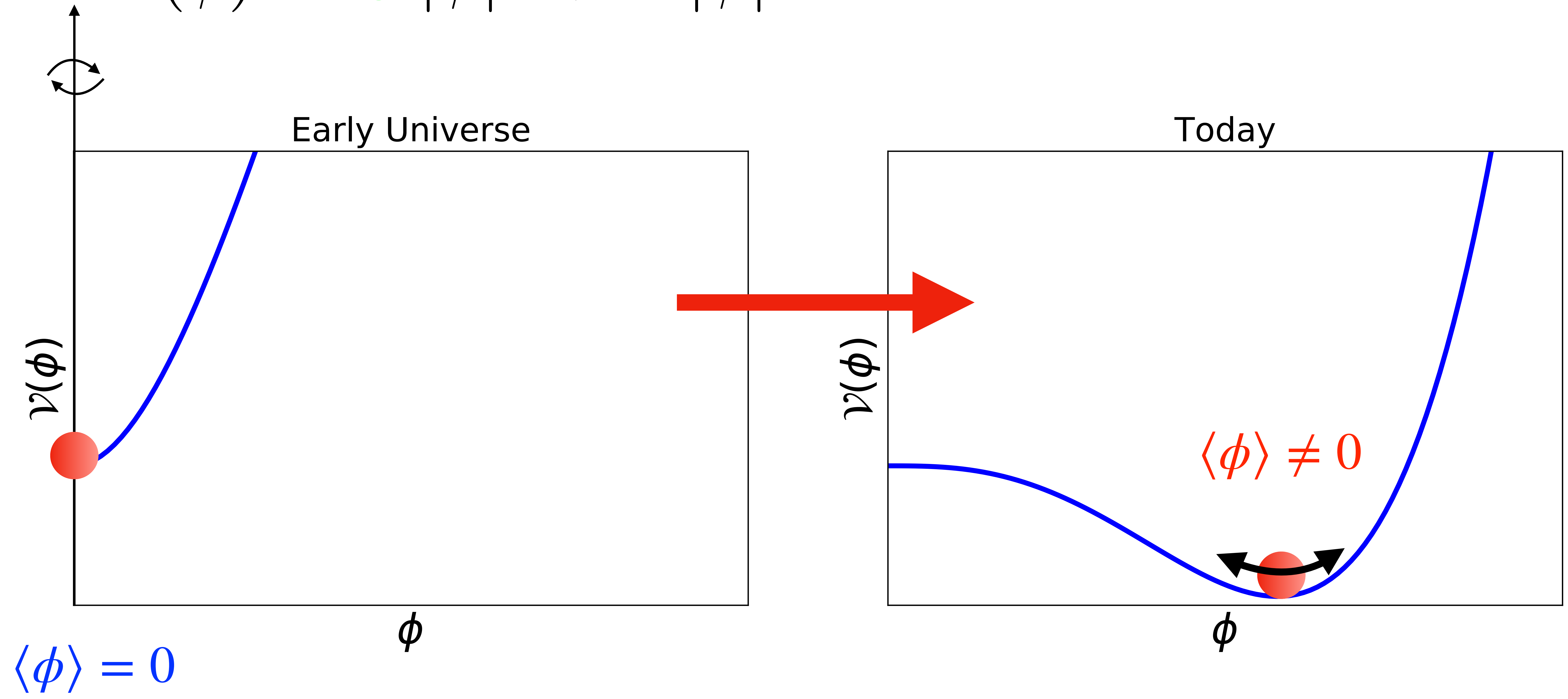


Breaking the Symmetry in the Standard Model

$$\mathcal{V}(\phi) = \bullet\,|\phi|^2 + \blacksquare\,|\phi|^4$$

Higgs field (ϕ) potential



More Symmetry → Less (obvious) Symmetry

Breaking the Symmetry in the Standard Model

$$\mathcal{V}(\langle\phi\rangle + h) = \bullet h^2 + \blacktriangle h^3 + \blacksquare h^4$$ → h **is the Higgs boson! (LHC, 2012)**

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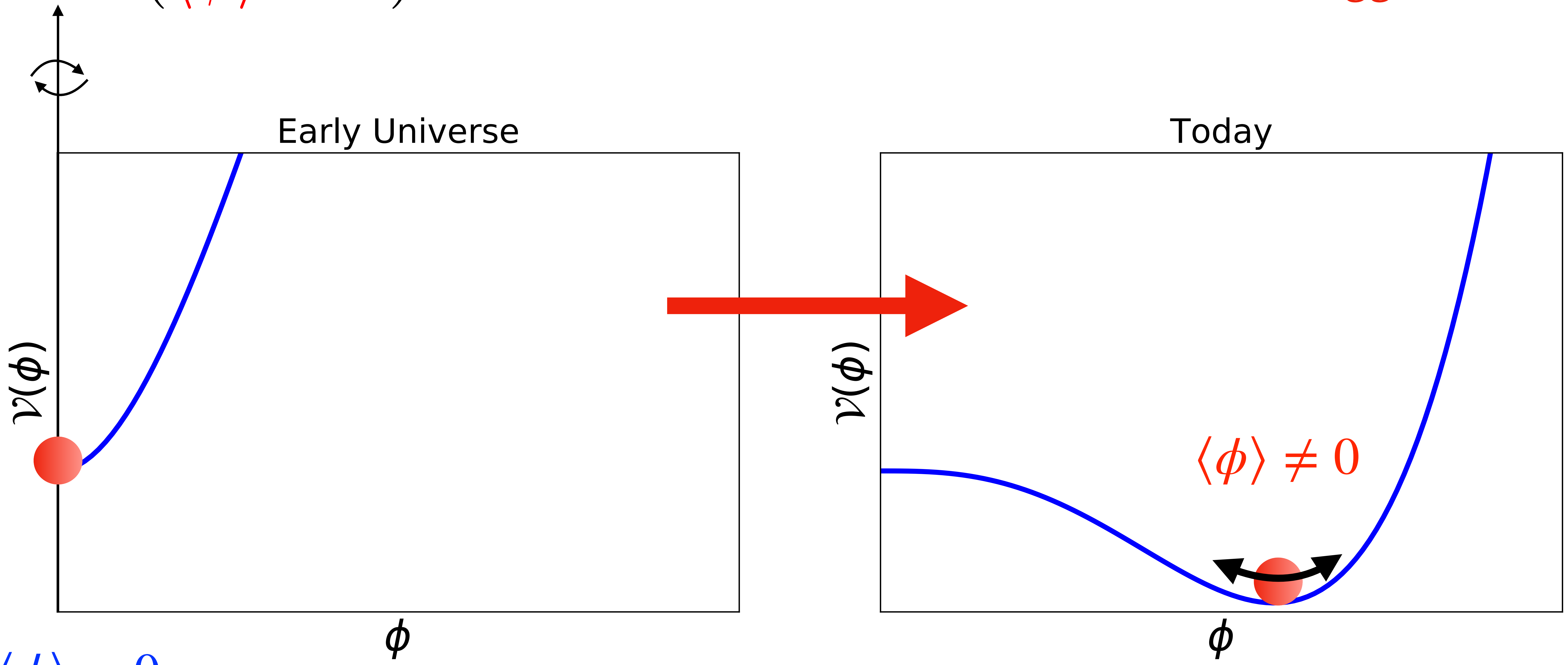

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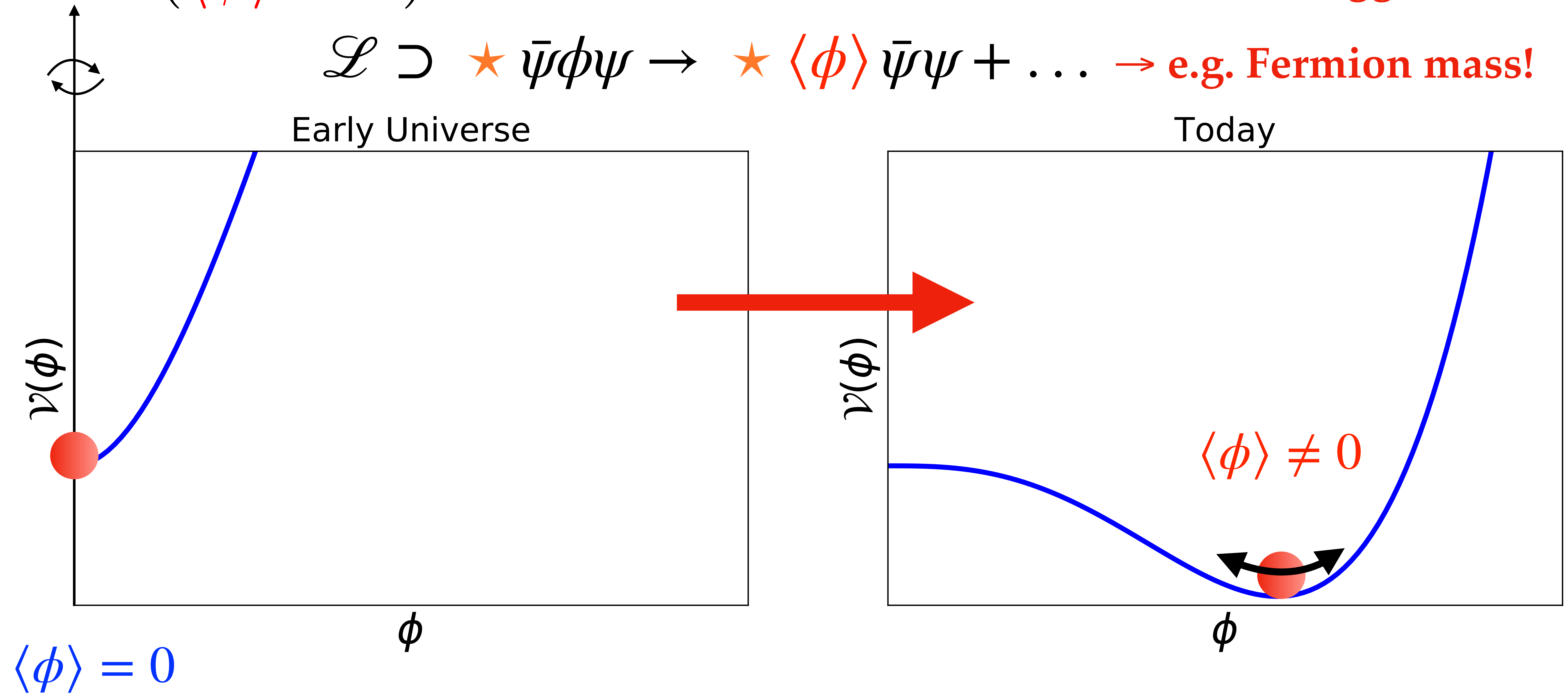

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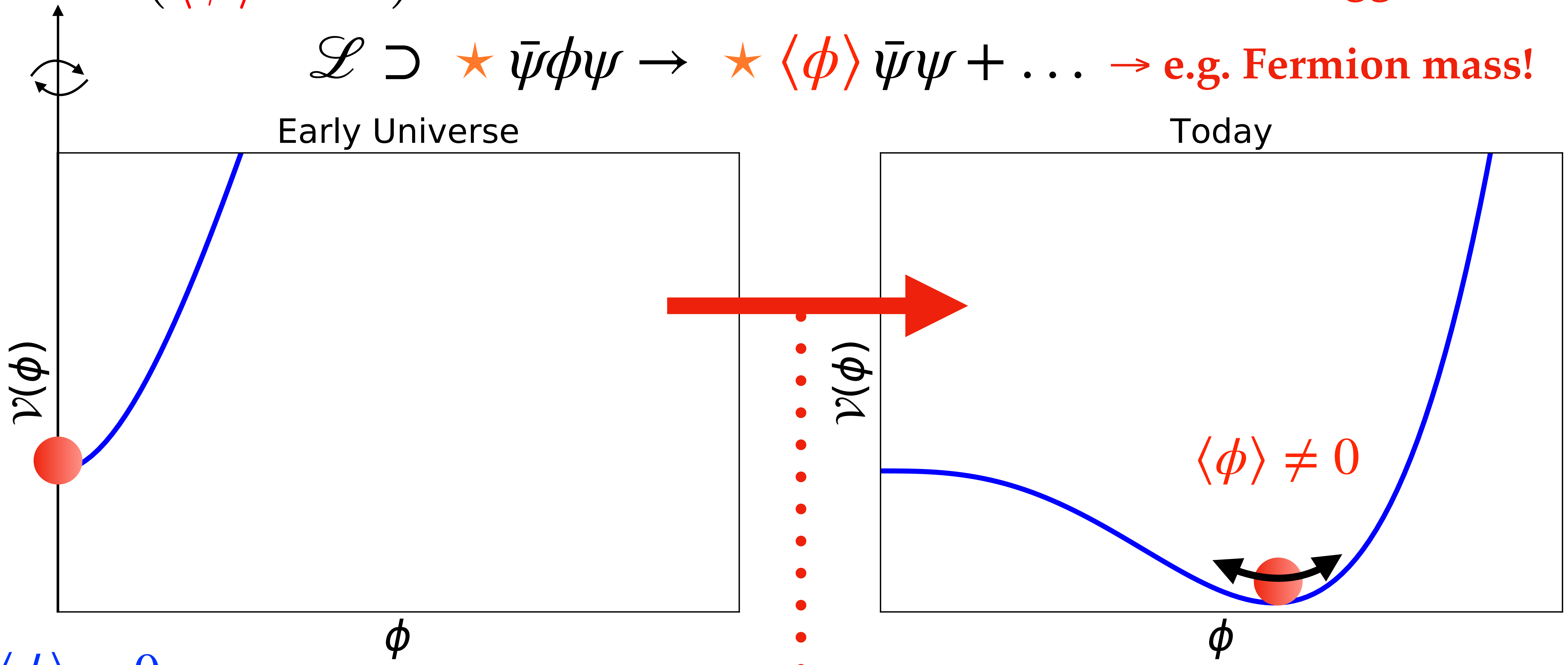

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≡ Electro-Weak Phase Transition (EWPT)

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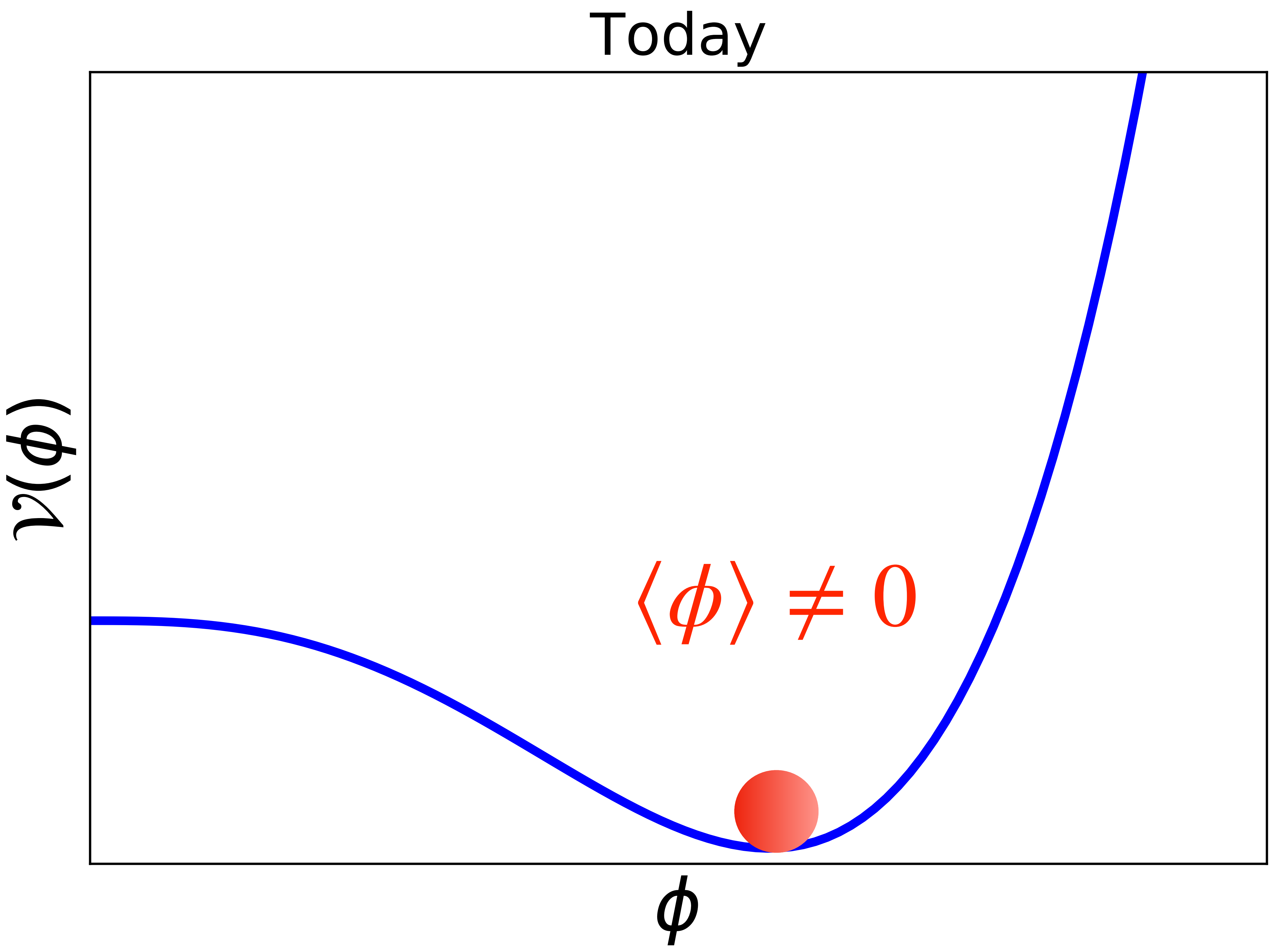

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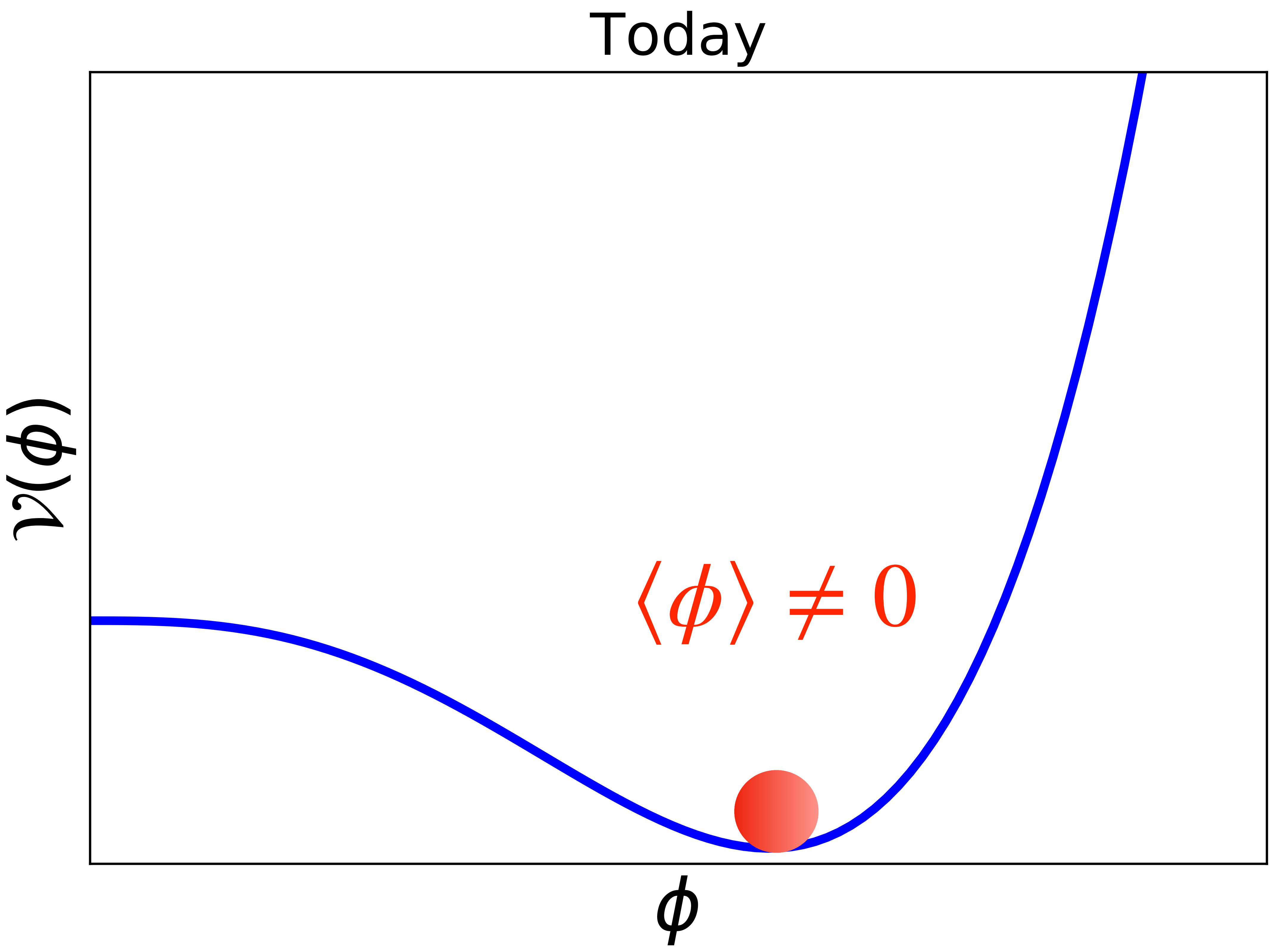

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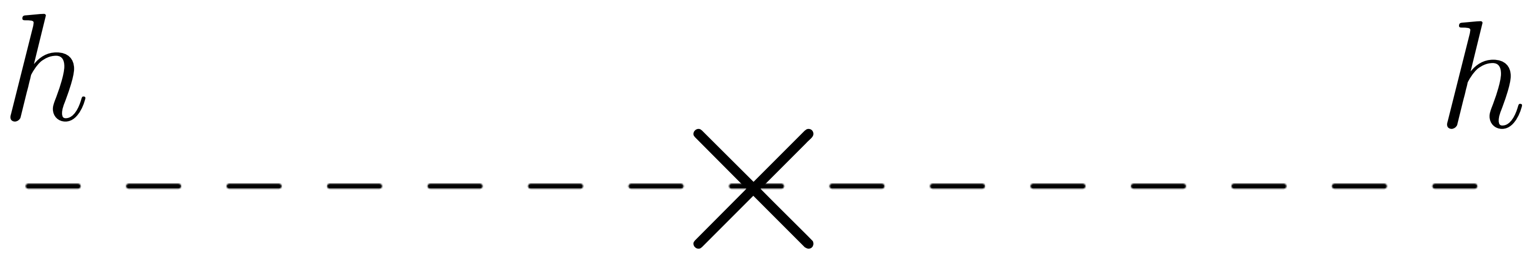

Higgs boson discovery @ LHC, 2012 ✅

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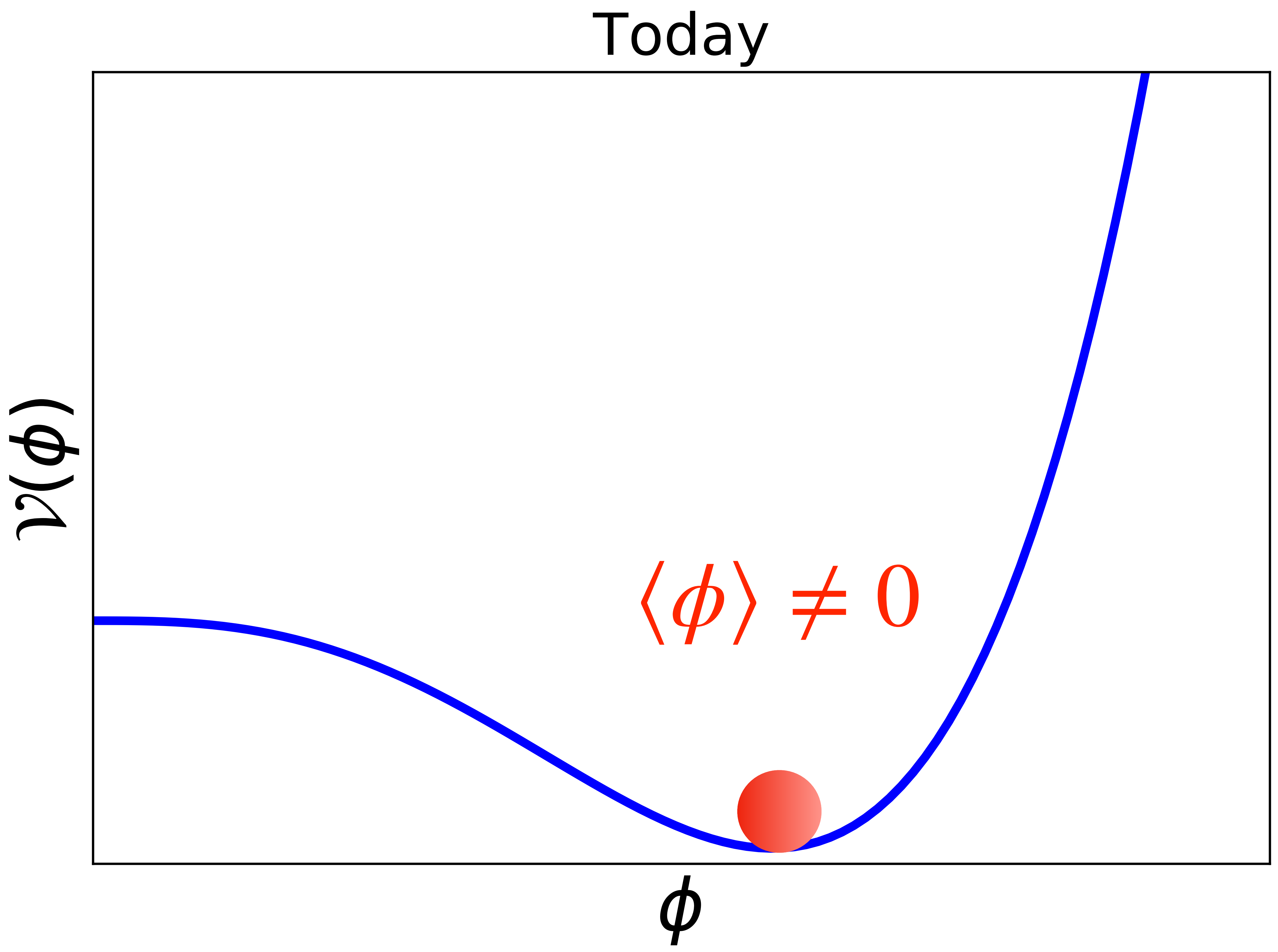

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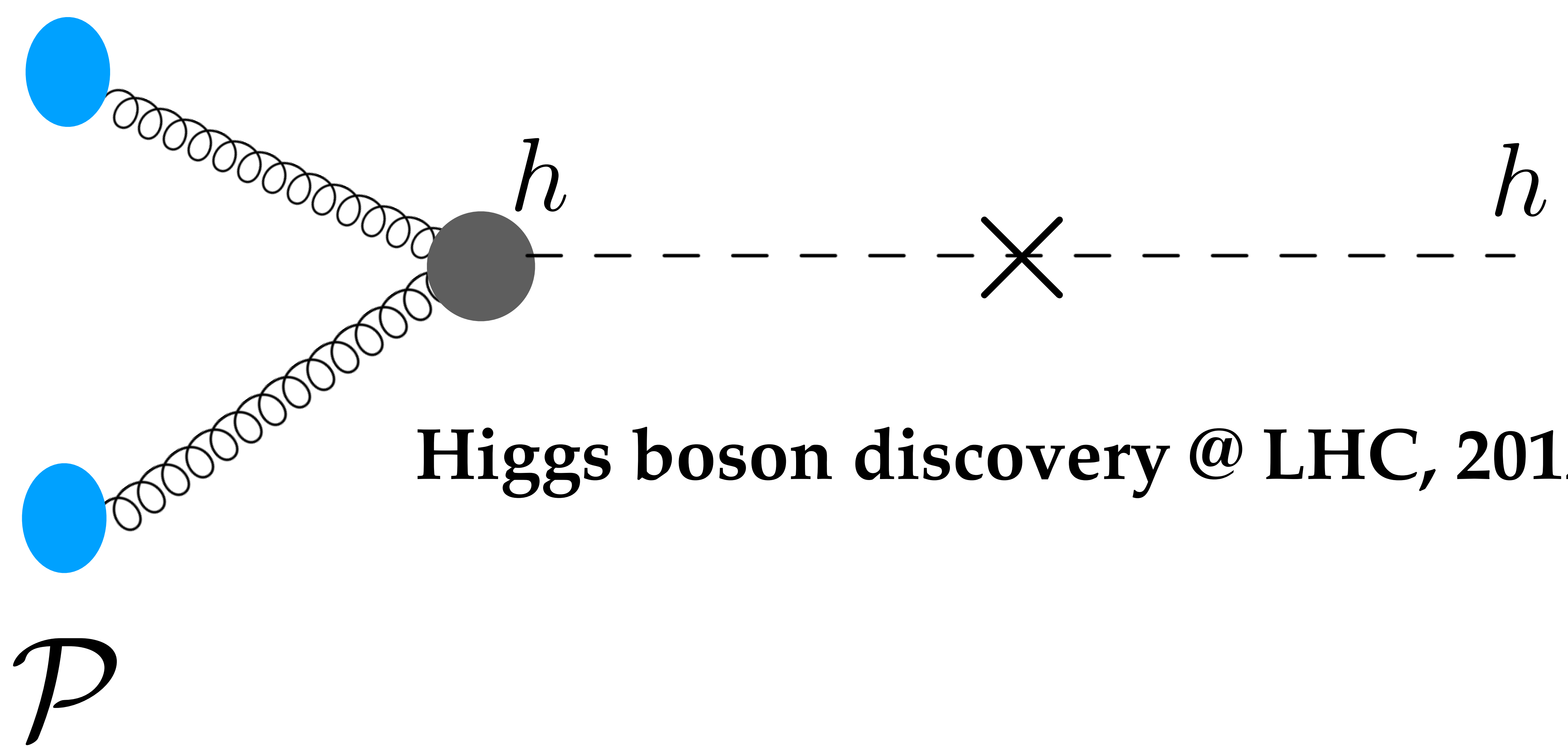
{●, ▲, ■}



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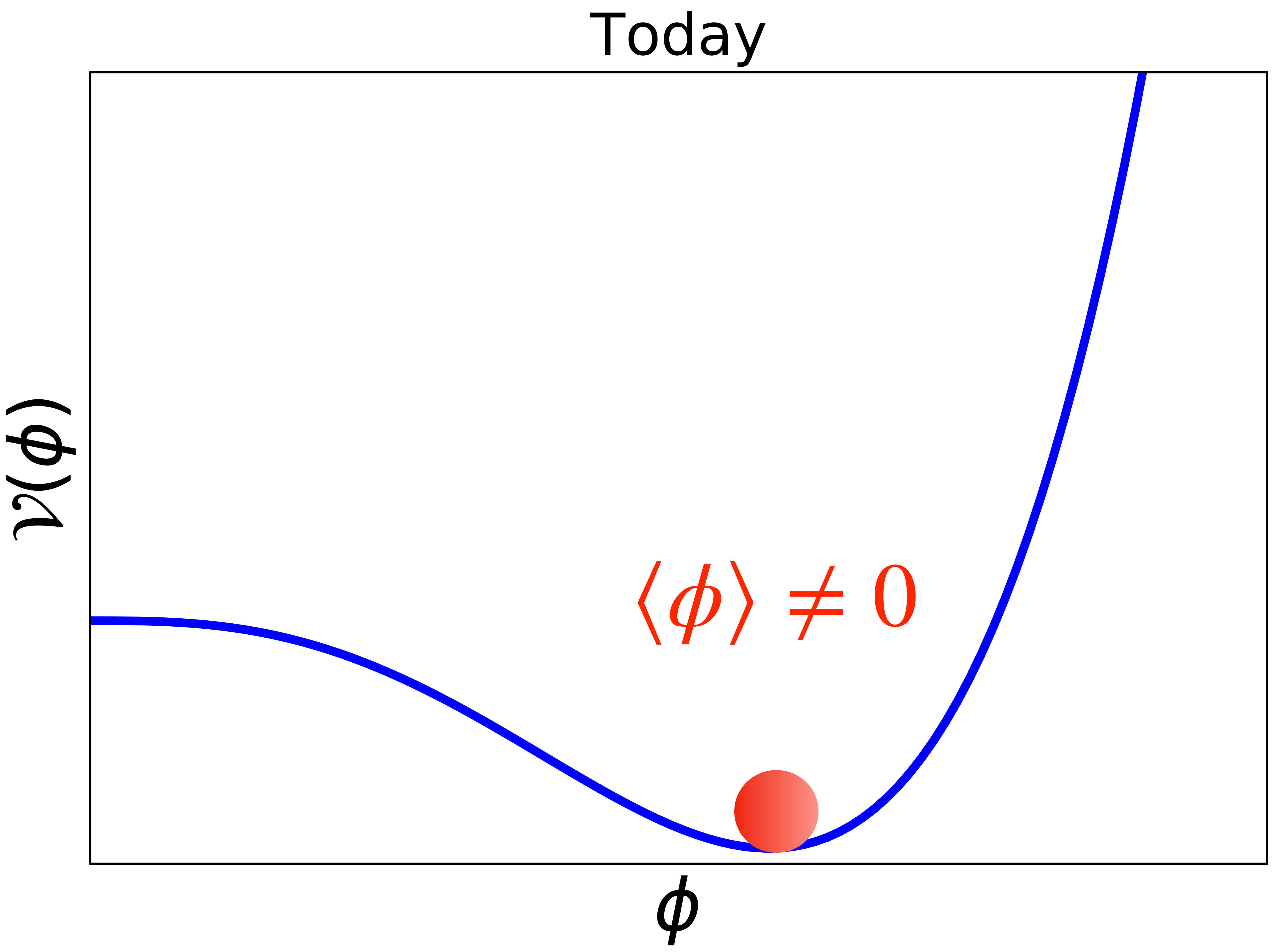

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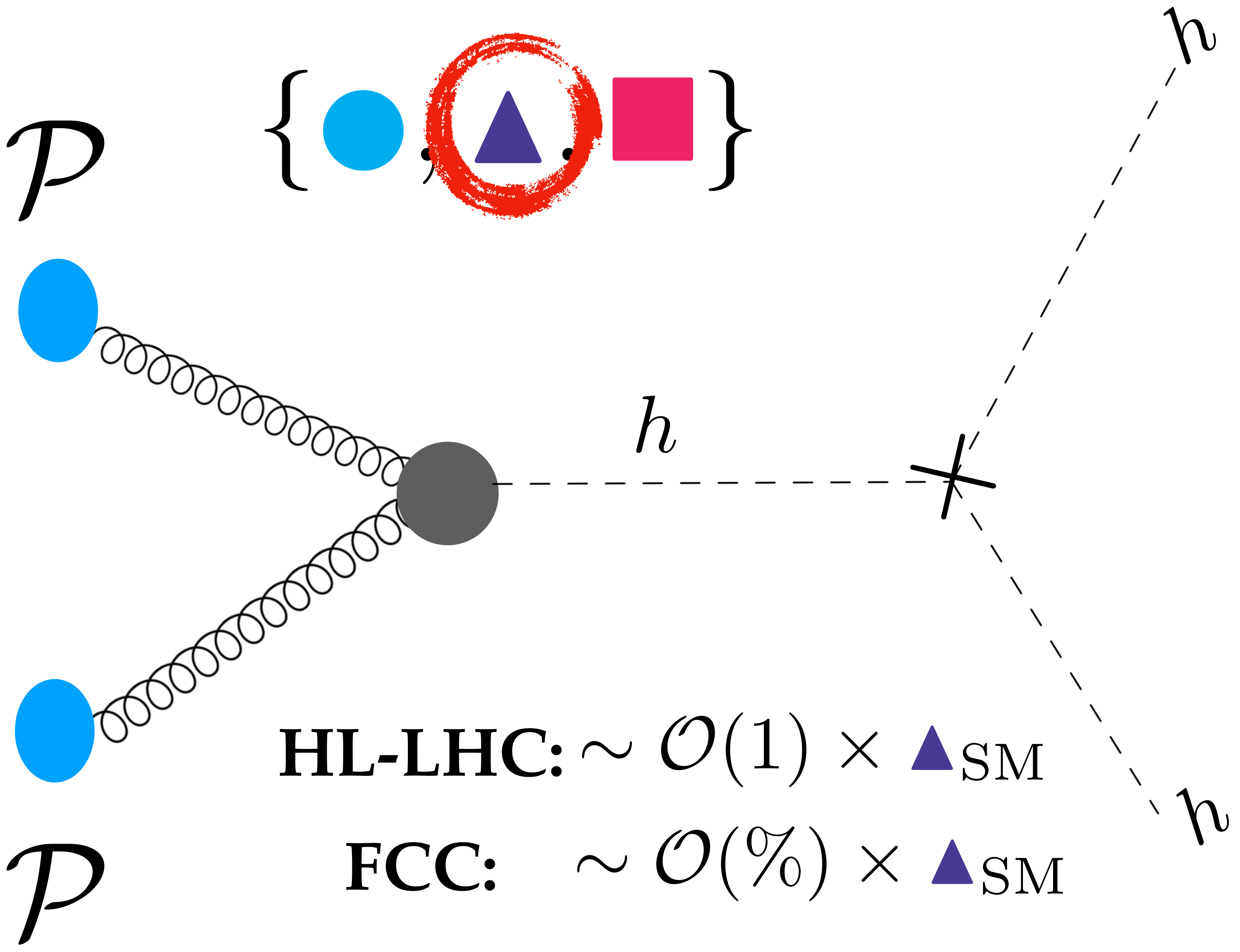

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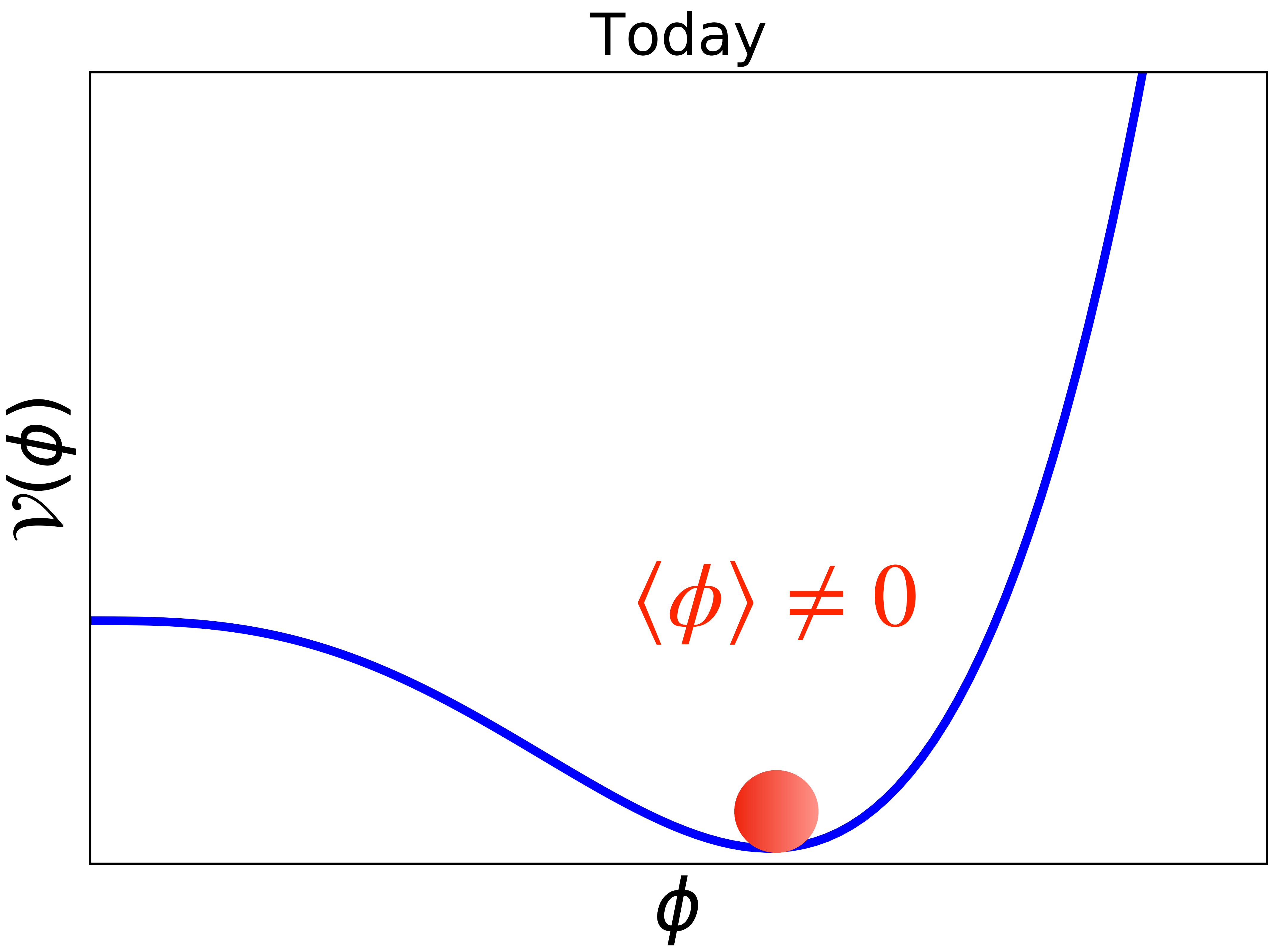

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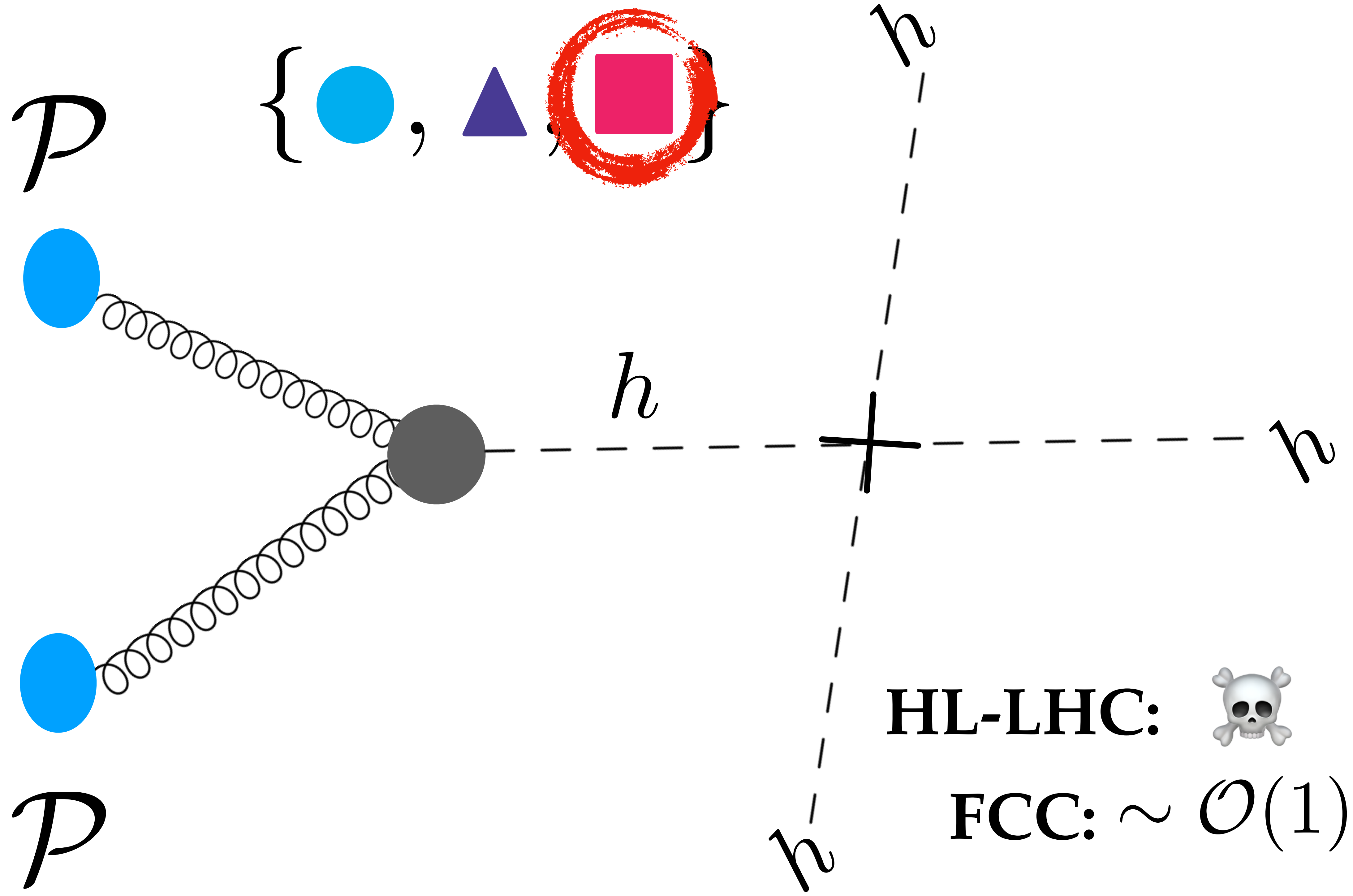

HL-LHC: ☠️

FCC: $\sim \mathcal{O}(1) \times \blacksquare_{\mathrm{SM}}$

[e.g. AP, Sakurai, arXiv:1508.06524, AP, Tetlalmatzi-Xolocotzi, Zaro, arXiv:1909.09166]

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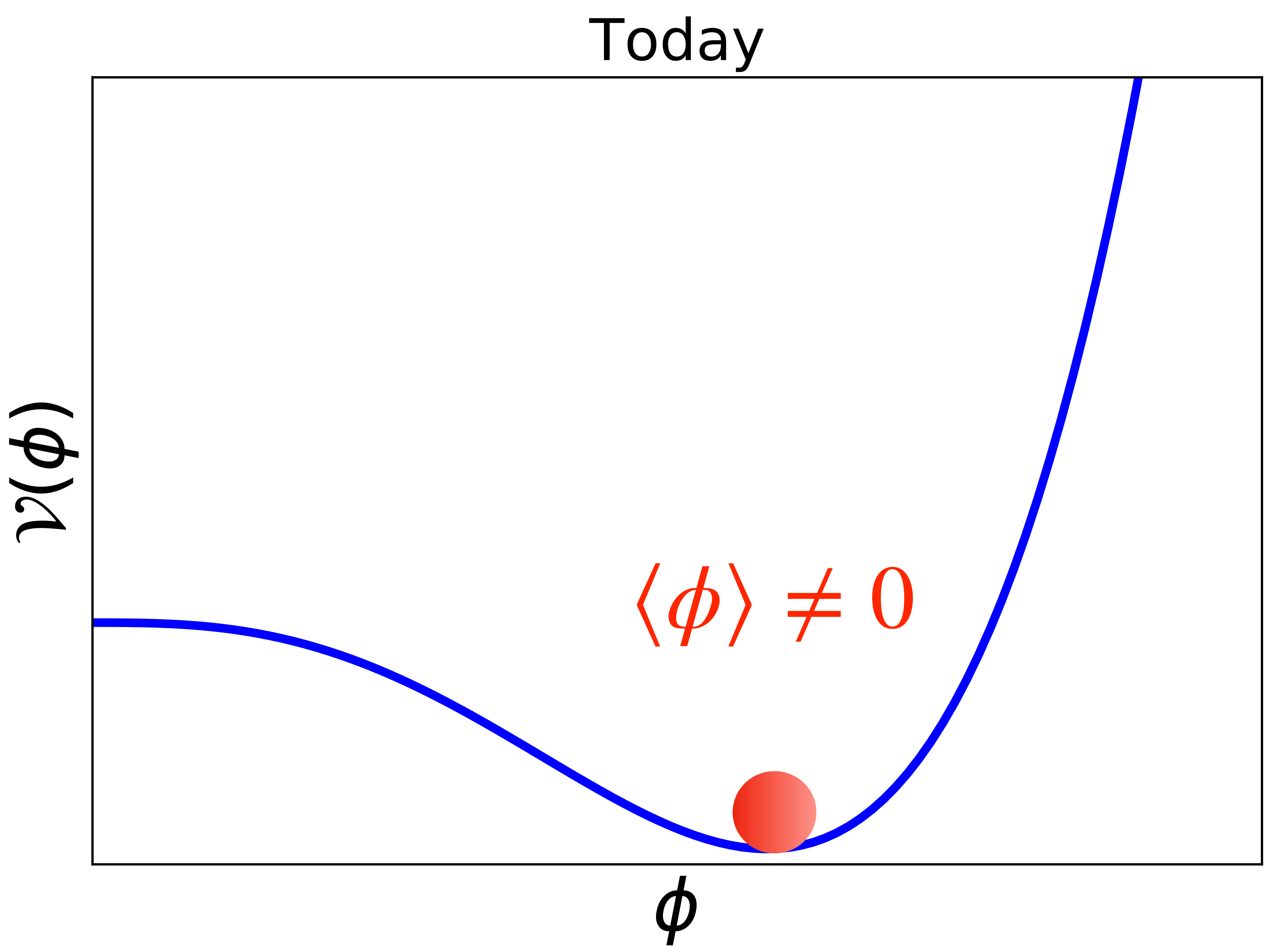

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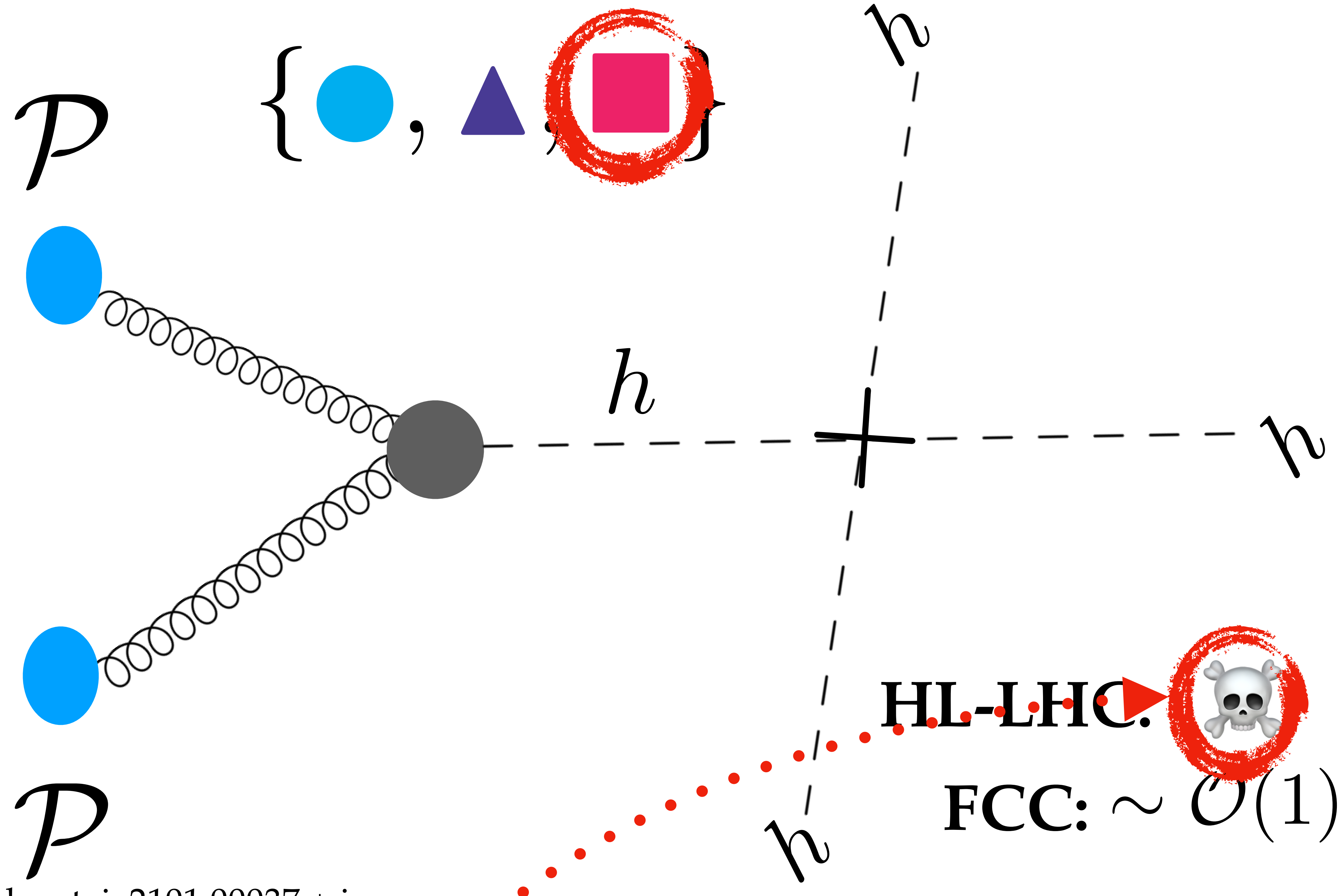

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[AP, Robens, Tetlalmatzi-Xolocotzi, 2101.00037 + in progress
with Osama Karkout, Carlo Pandini, AP, Marieke Postma, Tristan du Pree,
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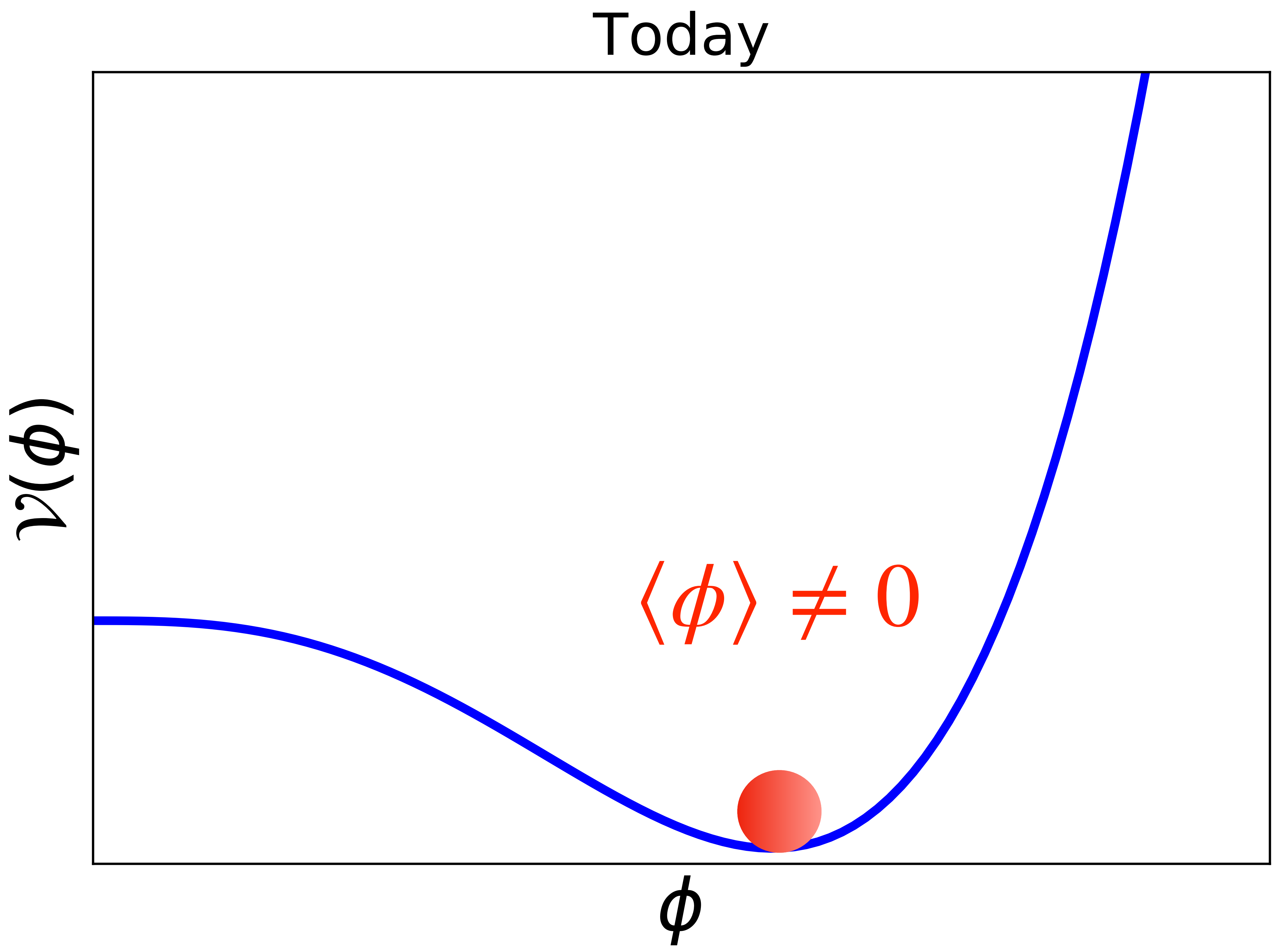

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Alexandra Carvalho, AP, Marko Stamenkovic, Gilberto Tetlalmatzi-Xolocotzi, Alberto Tonero […]

[**hhh** with Anomalous Couplings]

Osama Karkout, Carlo Pandini, AP, Marieke Postma, Tristan du Pree, Gilberto Tetlalmatzi-Xolocotzi, Jorinde van de Vis […]

[**hhh** in TRSM + Cosmology]

Breaking the Symmetry in the SM

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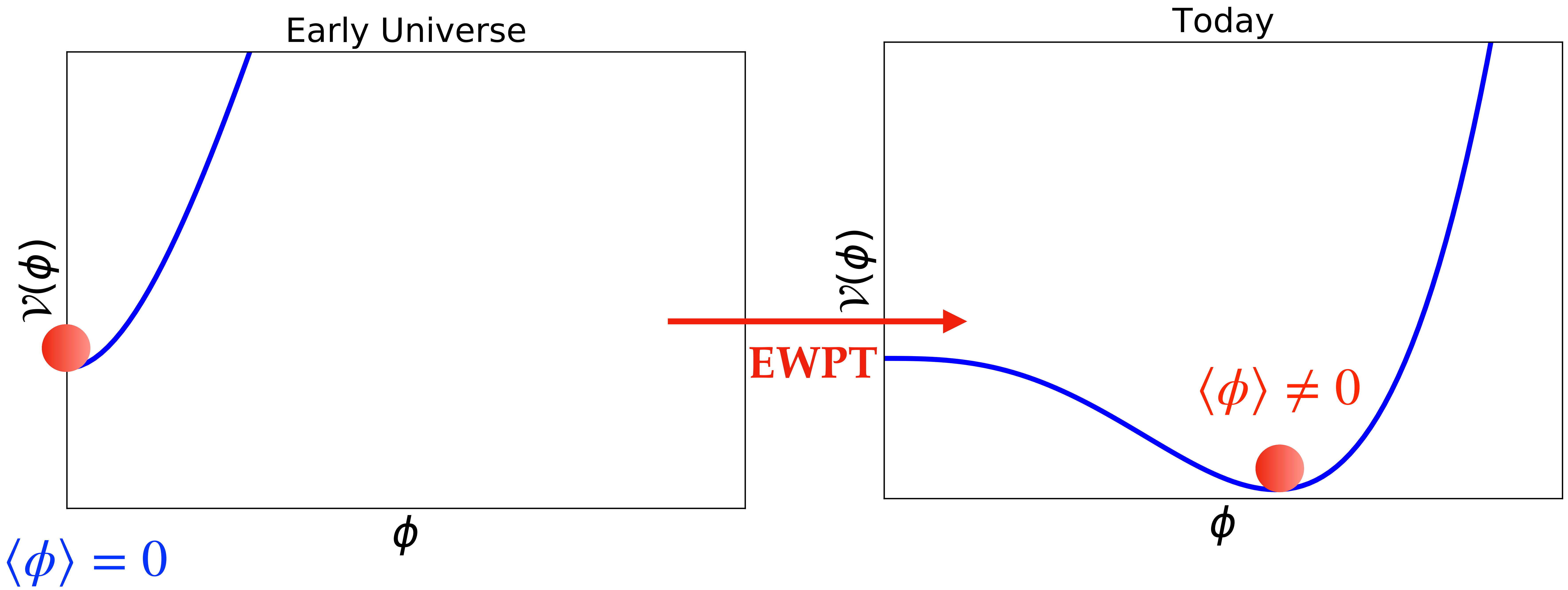
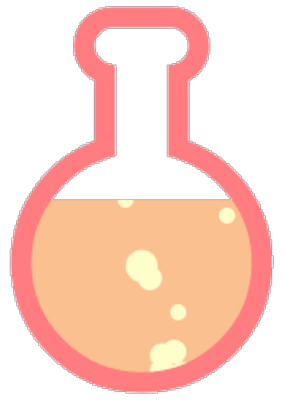


- **Nature** of **EWPT** → Important open question, e.g. **its order**:
  - A **First-Order transition** (e.g. the boiling of water)?
  - or a **Second-Order transition** (e.g. the superfluid transition) or **cross-over**?



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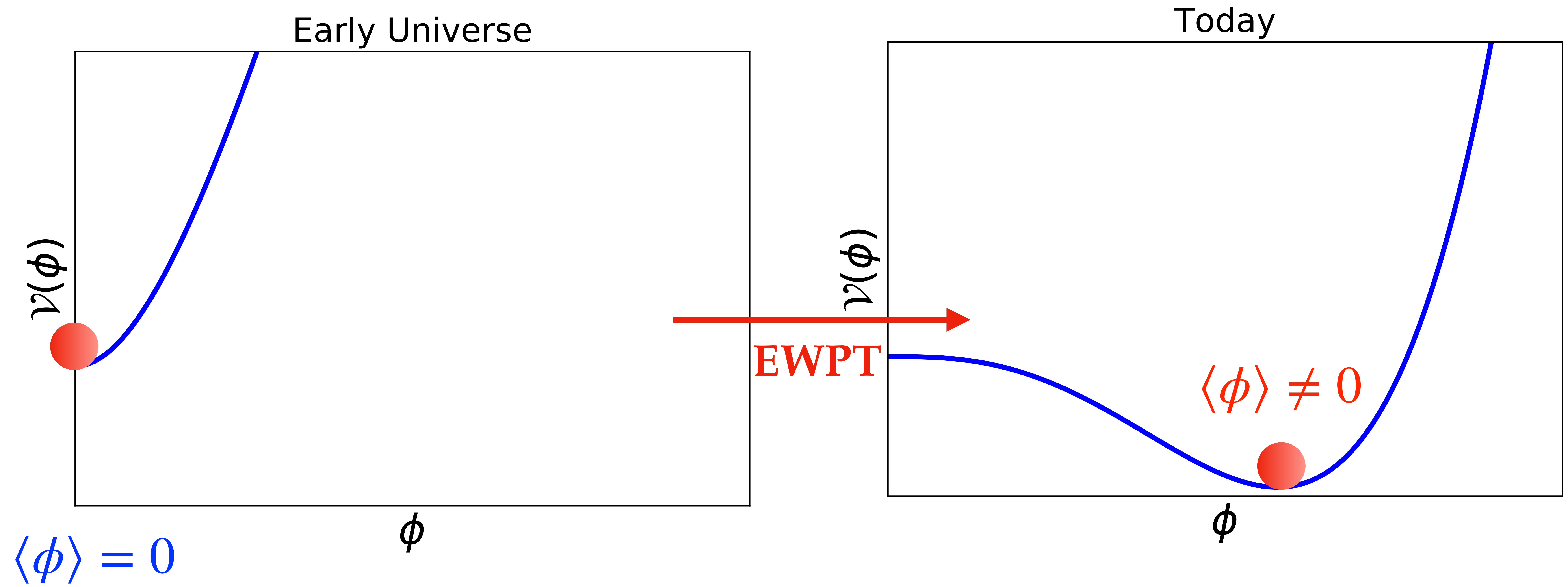

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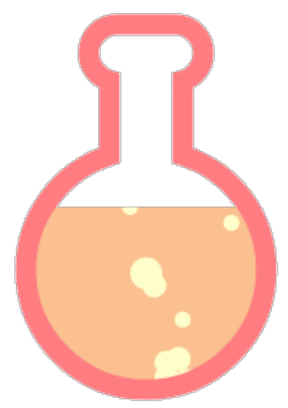

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The Nature of the Phase Transition

→ **Clues** to the origin of **matter-anti-matter asymmetry**.

- Was the asymmetry created **during** the **EWPT**?

  → "Electro-Weak Baryogenesis" (EWBG).

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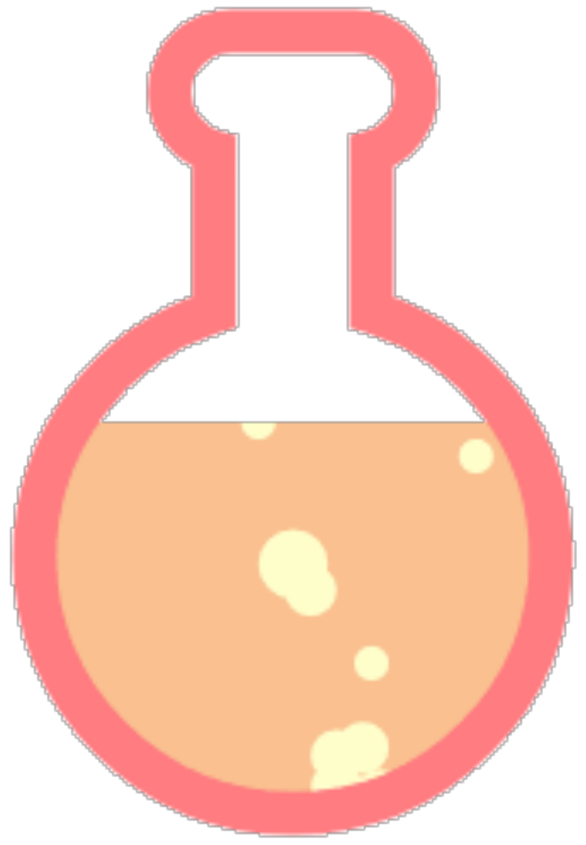

- *Note*: This **does not** occur in the SM!

[Kajantie, Laine, Rummukainen, Shaposhnikov hep-ph/9605288]

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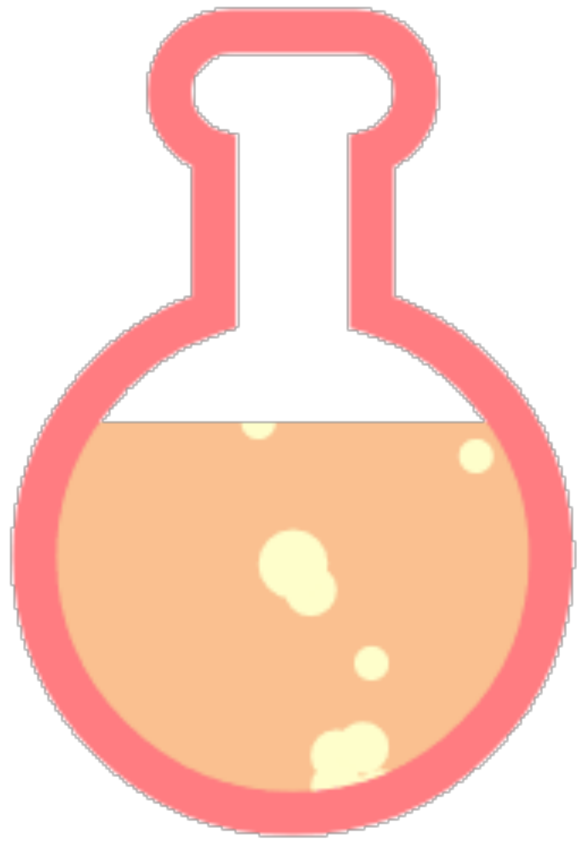

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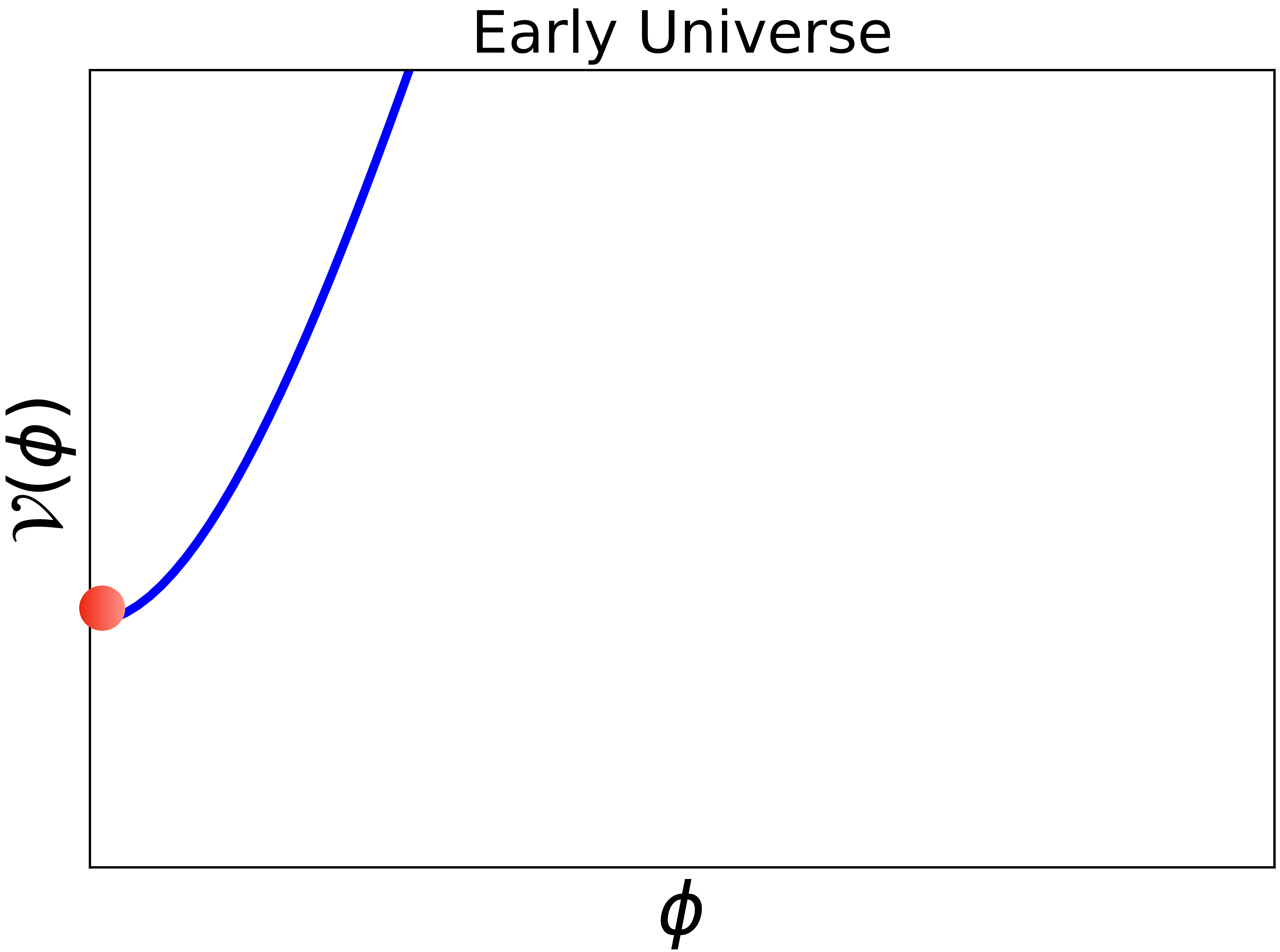
A First-Order Electro-Weak Phase Transition: As the Universe Cools Down!

Higgs field (*ϕ*)
potential



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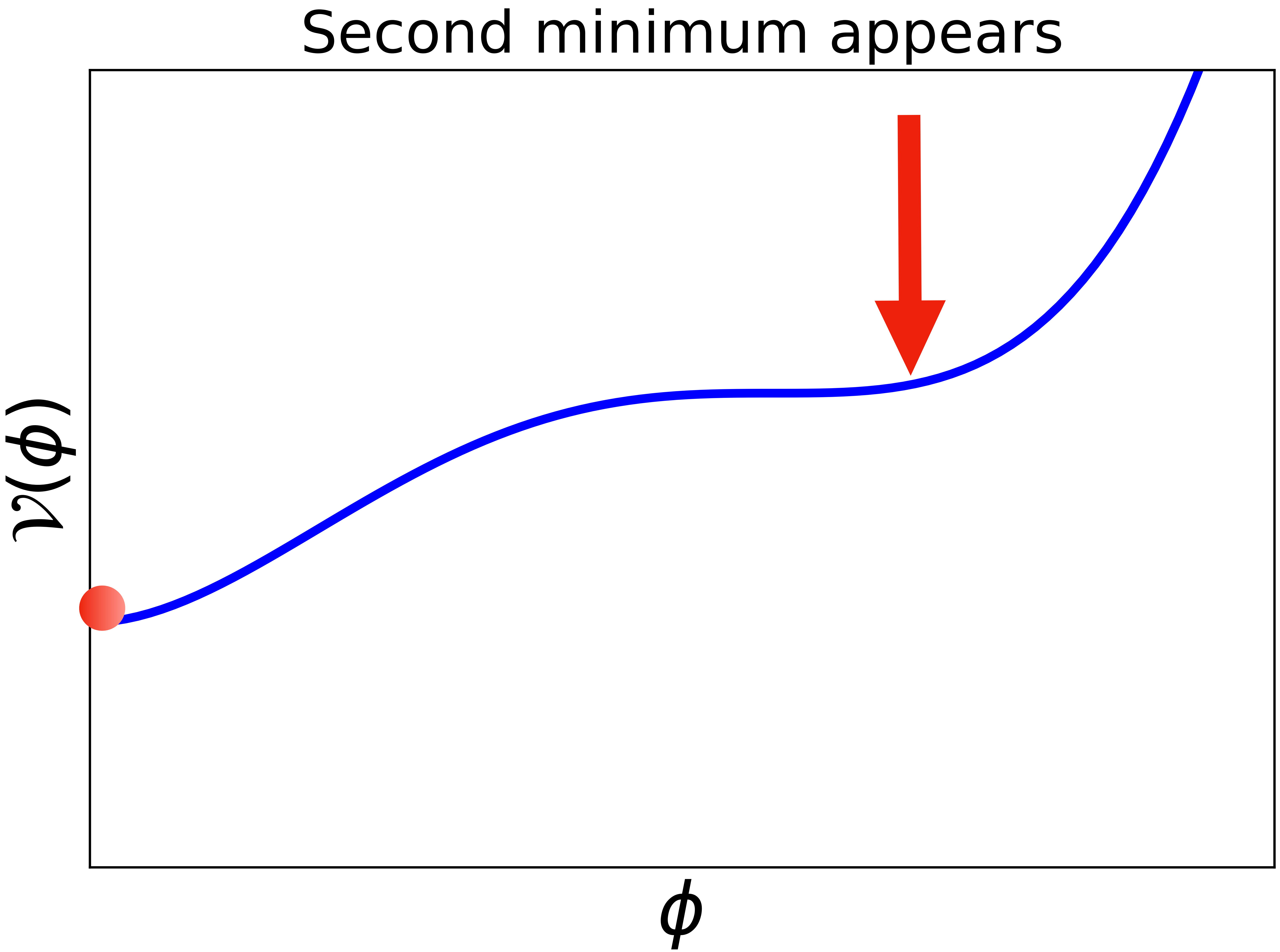

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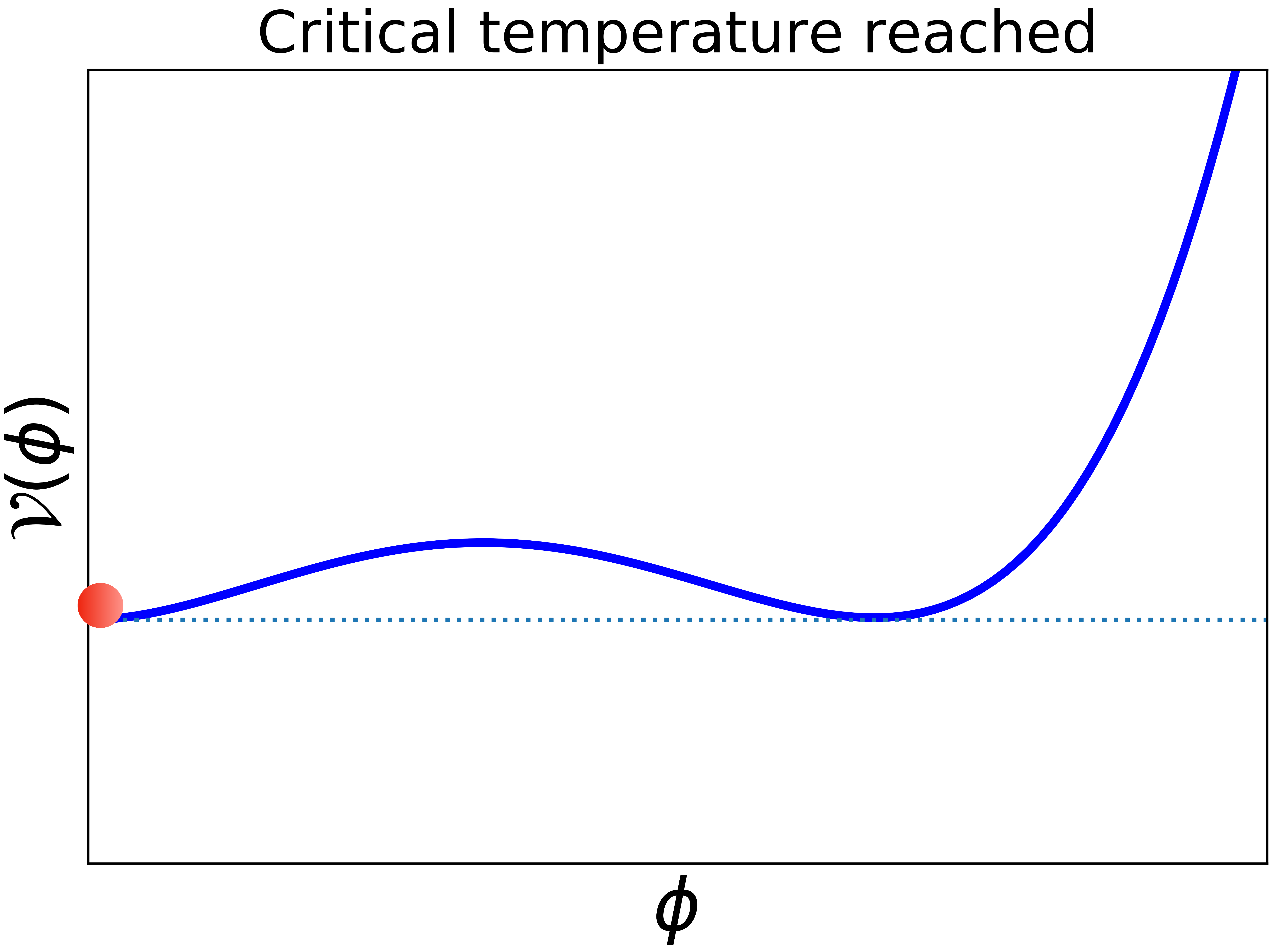

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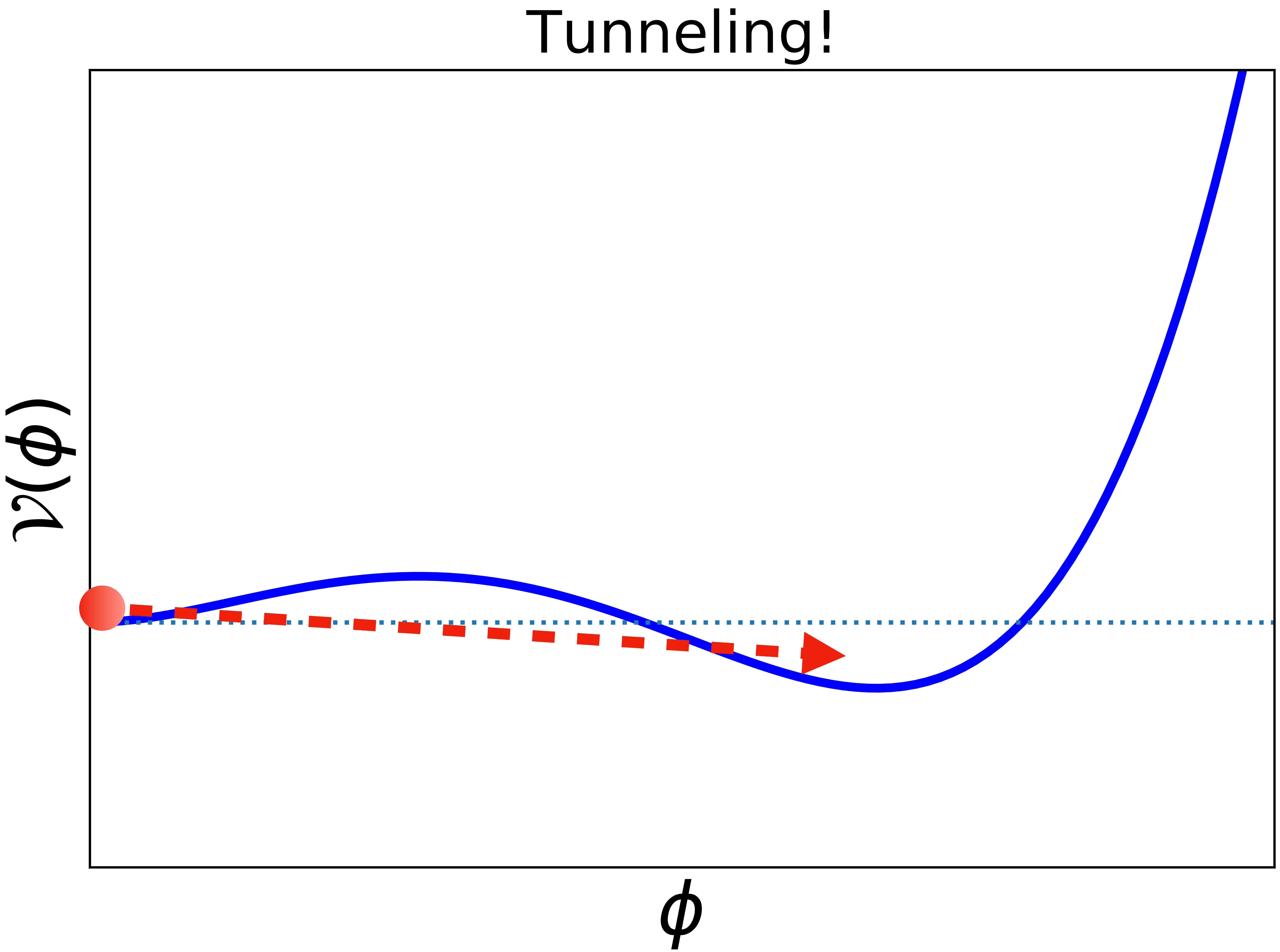

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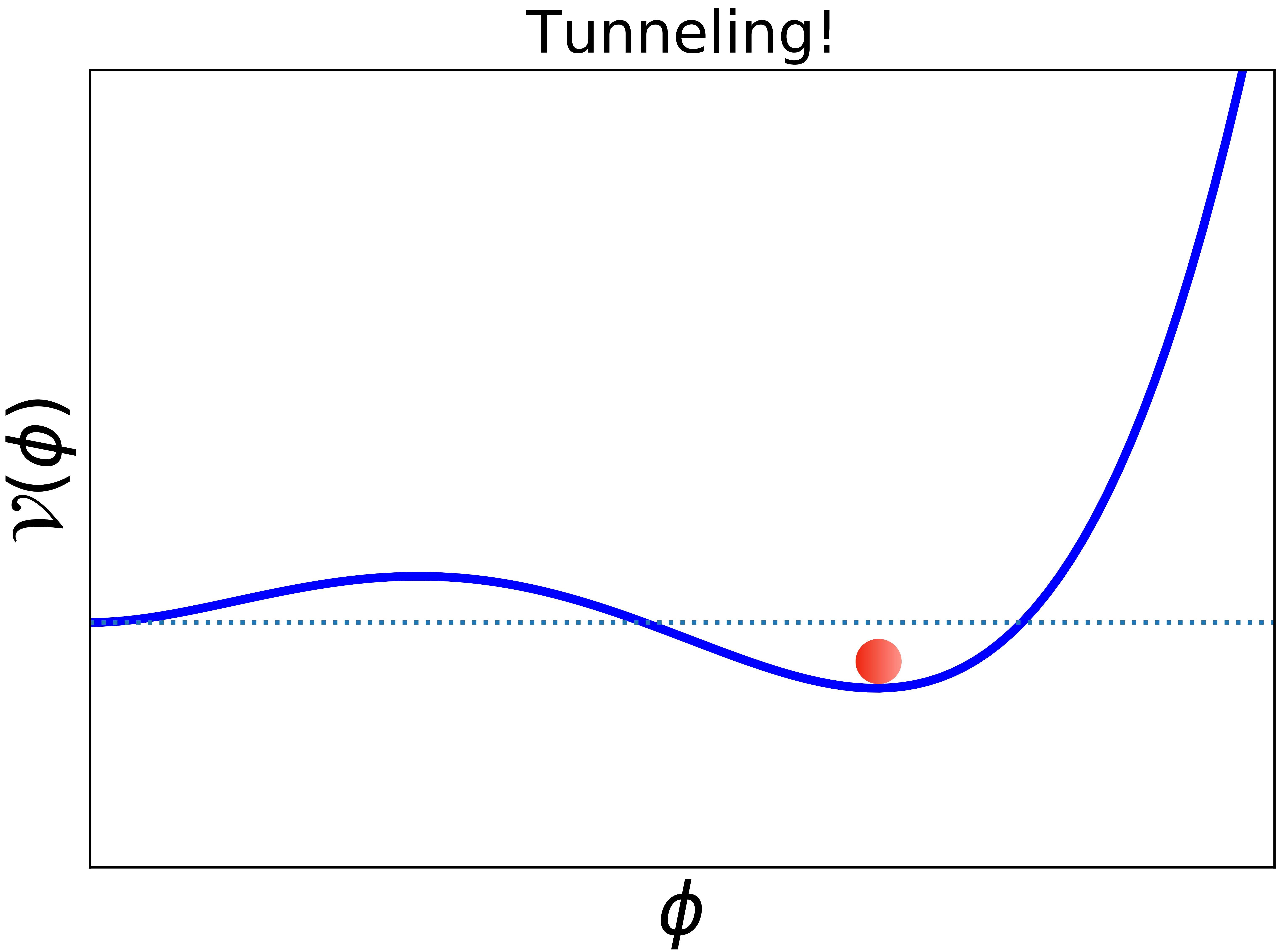

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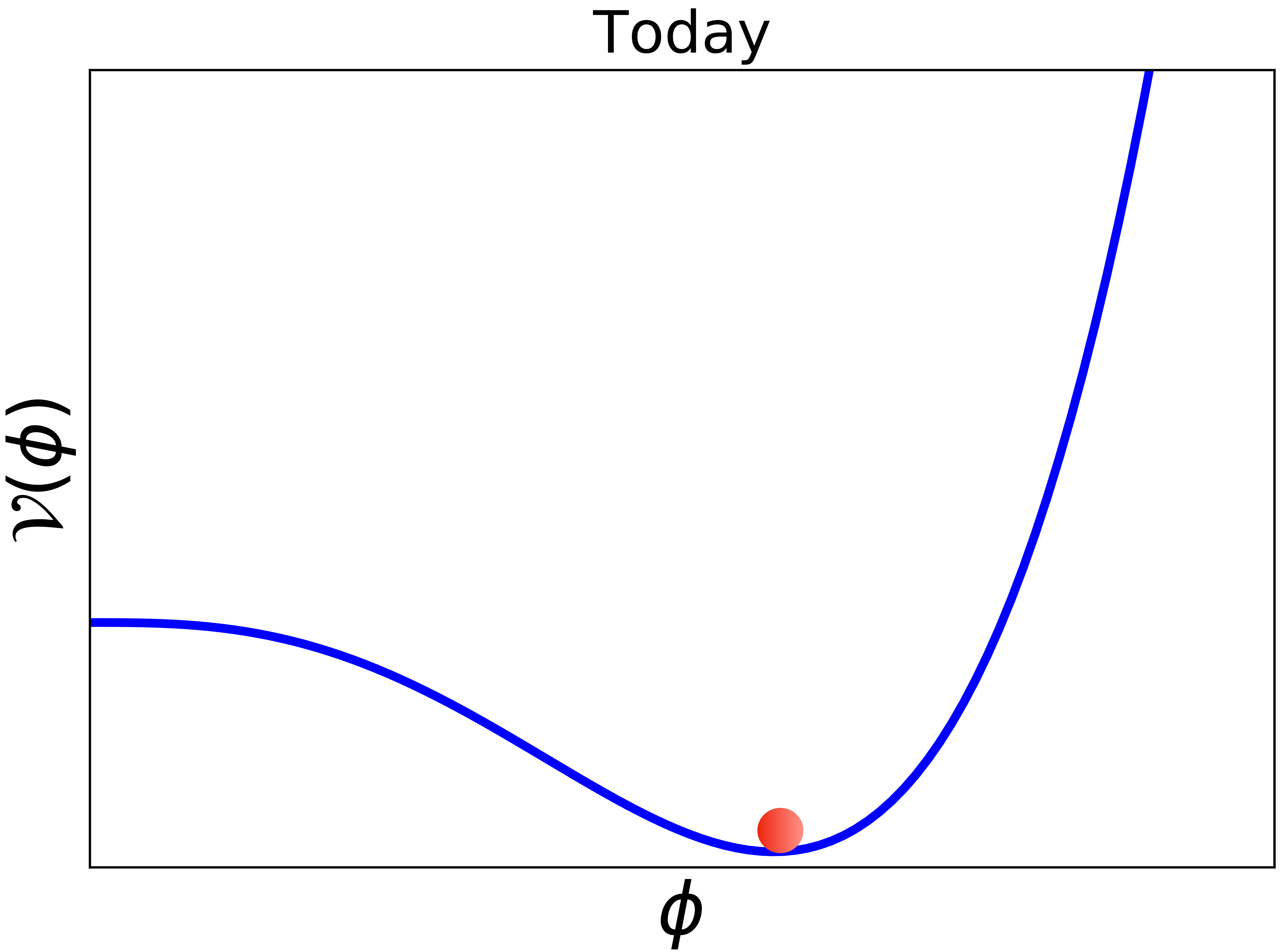

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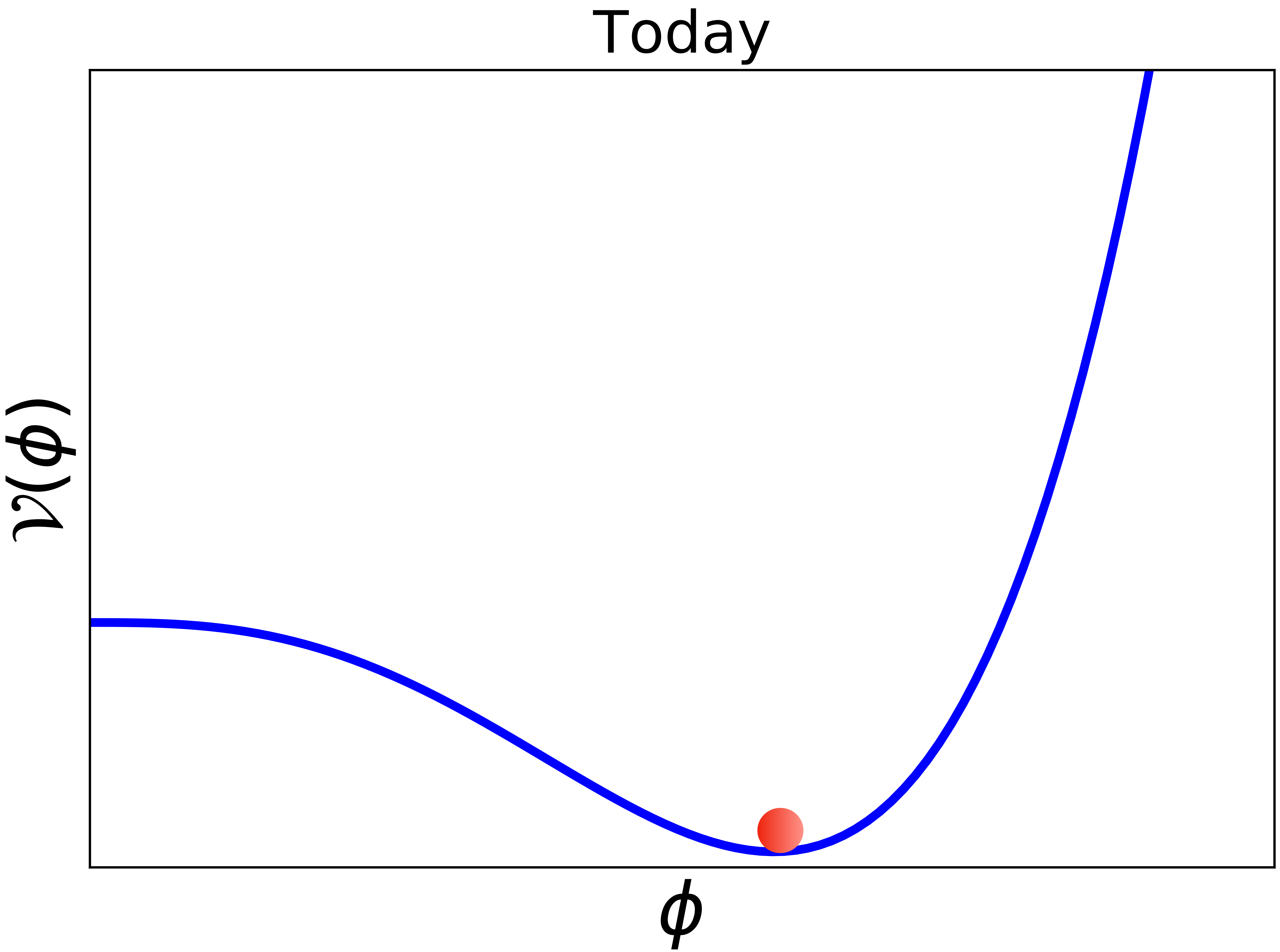

$\langle \phi \rangle \neq 0$

$\Rightarrow$

Symmetry Breaking.

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A First-Order EWPT

Some time after critical temperature is reached:

→ **Bubbles** of the broken phase nucleate and expand.*

**Note*: Gravitational Waves can form during this period!

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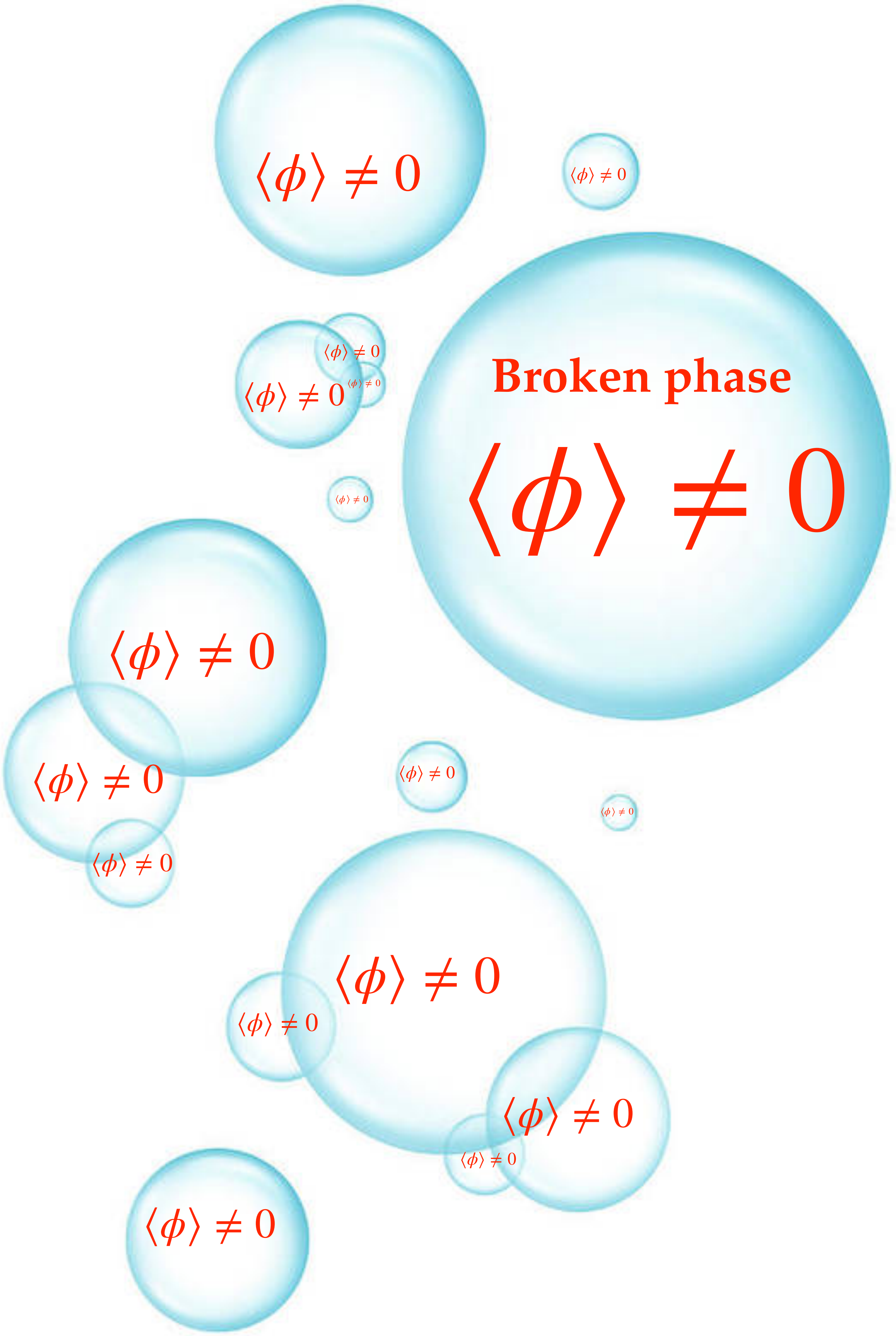

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Symmetric phase

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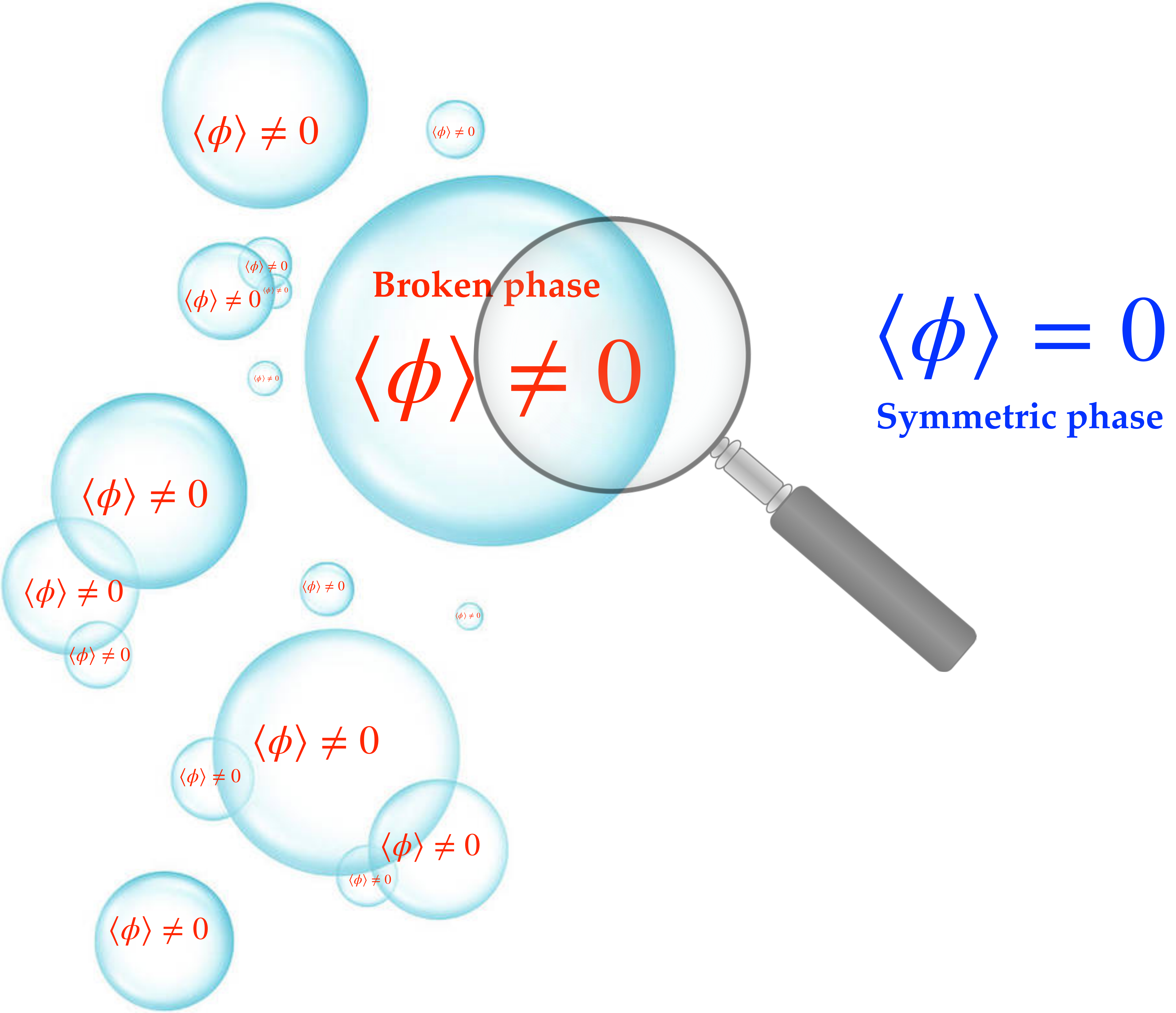

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Electro-Weak Baryogenesis

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[AP, Sakurai, Plätzer, arXiv:1910.4761,
+ in preparation: Grefsurd, Koutroulis,
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Electro-Weak Baryogenesis

A First-Order Transition requires New Phenomena beyond the SM!

[AP, Sakurai, Plätzer, arXiv:1910.4761, + in preparation: Grefsurd, Koutroulis, Lipniacka, AP, Maselek, Sakurai, Sjursen]

Electro-Weak Archaeology

We live here!

Sphaleron

$$\langle \phi \rangle \neq 0$$

Broken phase

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Sphaleron

→ What are the implications of Electro-Weak Baryogenesis at Colliders?

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4 Extending the Scalar Sector

[AP, White, arXiv:2010.00597]

- A First-Order EWPT **dictates** new phenomena. [Kajantie, Laine, Rummukainen, Shaposhnikov hep-ph/9605288]
- Consider the **simplest possible extension**!

$$\mathcal{V}(\phi, S) = \bullet\, |\phi|^2 + \blacksquare\, |\phi|^4$$

Add: *S*, **a new scalar field,**
No SM “charges” ≡ Singlet.

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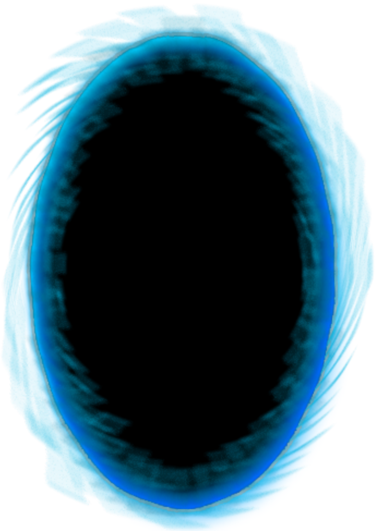

$$+\blacktriangle\, |\phi|^2\, S + \blacksquare\, |\phi|^2\, S^2$$ ← "**Portal**" interactions.

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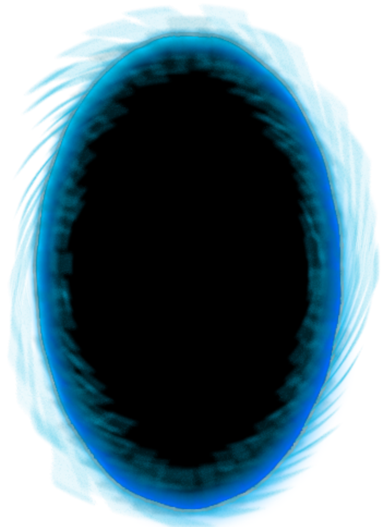
$$+{\color{magenta}\bullet} S^2 + {\color{cyan}\blacktriangle} S^3 + {\color{brown}\blacksquare} S^4$$



$$+{\color{red}\blacktriangle}\,|\phi|^2\,S + {\color{purple}\blacksquare}\,|\phi|^2\,S^2$$ ← "**Portal**" interactions.

$$+S \times (\text{Hidden Sector}) + \ldots$$ ← **Dark Matter**?

Extending the Scalar Sector [**AP**, White, arXiv:2010.00597]

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EWSB ↔ VEVs:

$$\phi \rightarrow \langle \phi \rangle + h$$

$$S \rightarrow \langle S \rangle + \chi$$

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⇒ Mass (squared) matrix:

$$M^2 = \begin{pmatrix} \frac{\partial^2 \mathscr{V}}{\partial h^2} & \frac{\partial^2 \mathscr{V}}{\partial h \partial \chi} \\ \frac{\partial^2 \mathscr{V}}{\partial h \partial \chi} & \frac{\partial^2 \mathscr{V}}{\partial \chi^2} \end{pmatrix}$$

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Diagonalize!

Mass Eigenstates

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h \\ \chi \end{pmatrix}$$

θ: mixing angle

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[**AP**, White, arXiv:2010.00597]

$$\mathcal{V}(\phi, S) = \bullet\, |\phi|^2 + \blacksquare\, |\phi|^4 + \bullet\, S^2 + \blacktriangle\, S^3 + \blacksquare\, S^4 + \blacktriangle\, |\phi|^2 S + \blacksquare\, |\phi|^2 S^2$$

Mass Eigenstates

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h \\ \chi \end{pmatrix}$$

θ: mixing angle

$h_1 \to$ "SM-like" Higgs boson.

$h_2 \to$ new scalar resonance.

i.e. choose: $\theta \sim 0$, and:

$$h_1 = h\cos\theta + \chi\sin\theta$$

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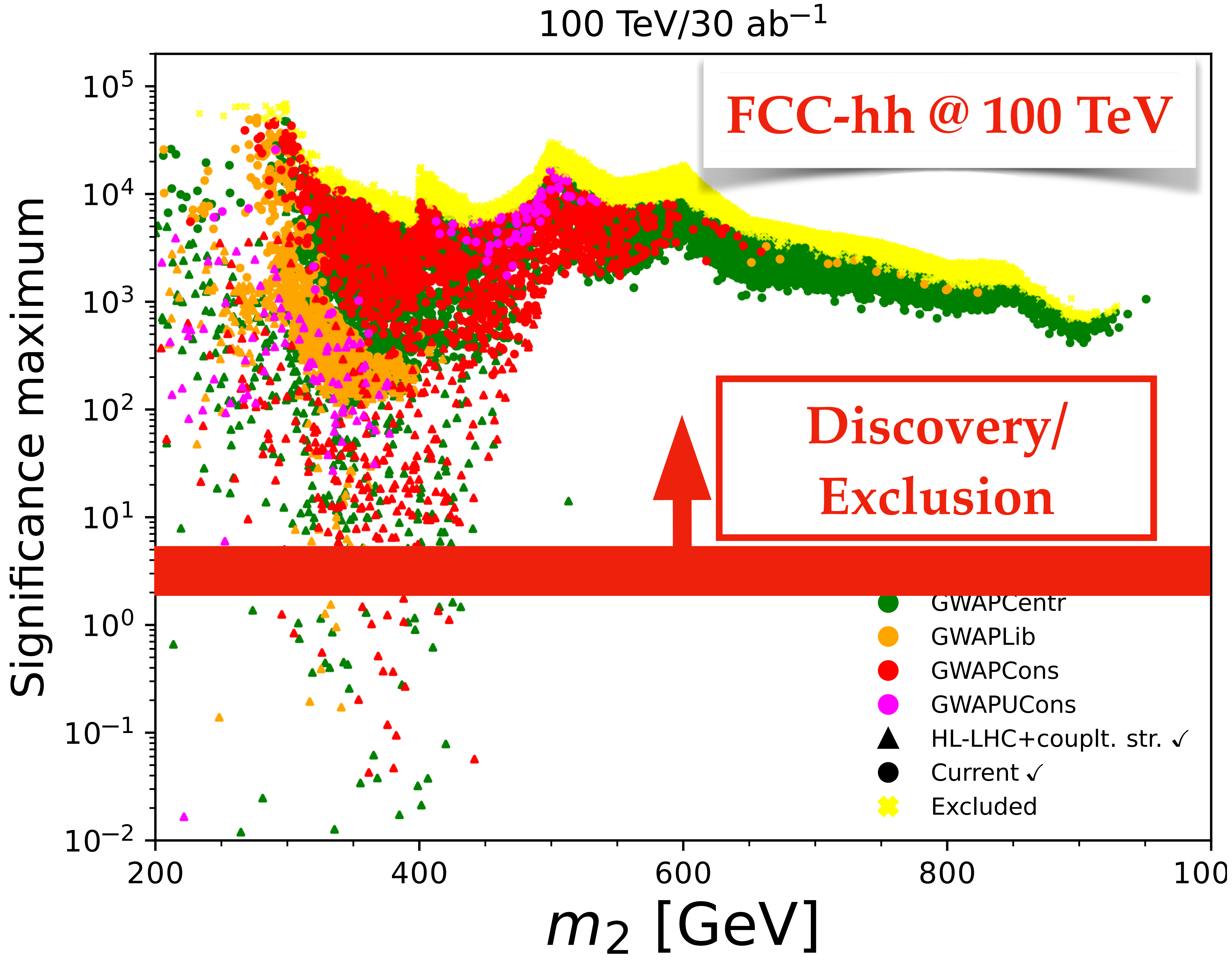
Primary targets for collider studies!

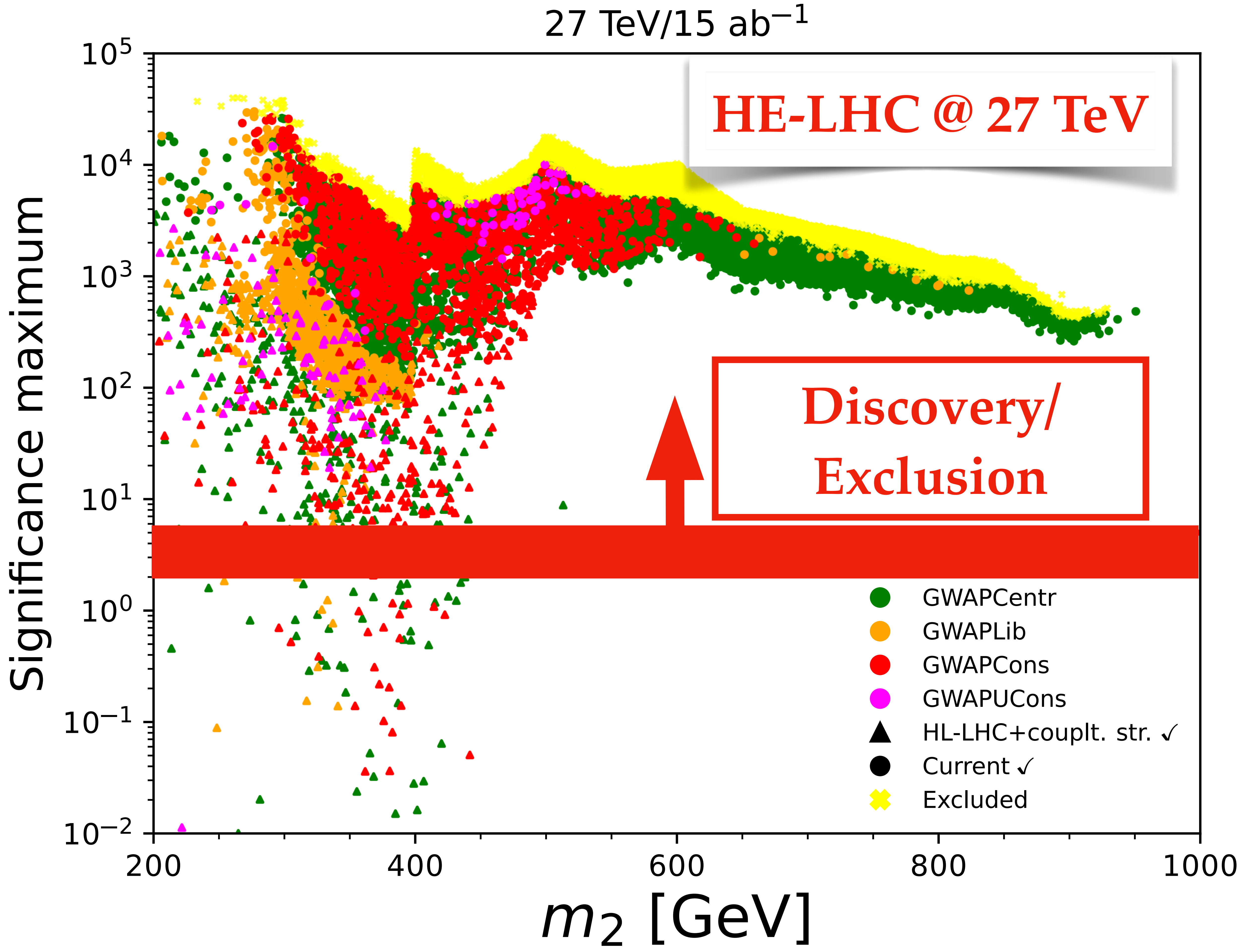
$h_1 \Rightarrow$ **Reductions** in Higgs boson rates.

$h_2 \Rightarrow$ **New resonance searches.**

Significance @ Future Colliders

Color-coded parameter-space points denotes theoretical uncertainty.





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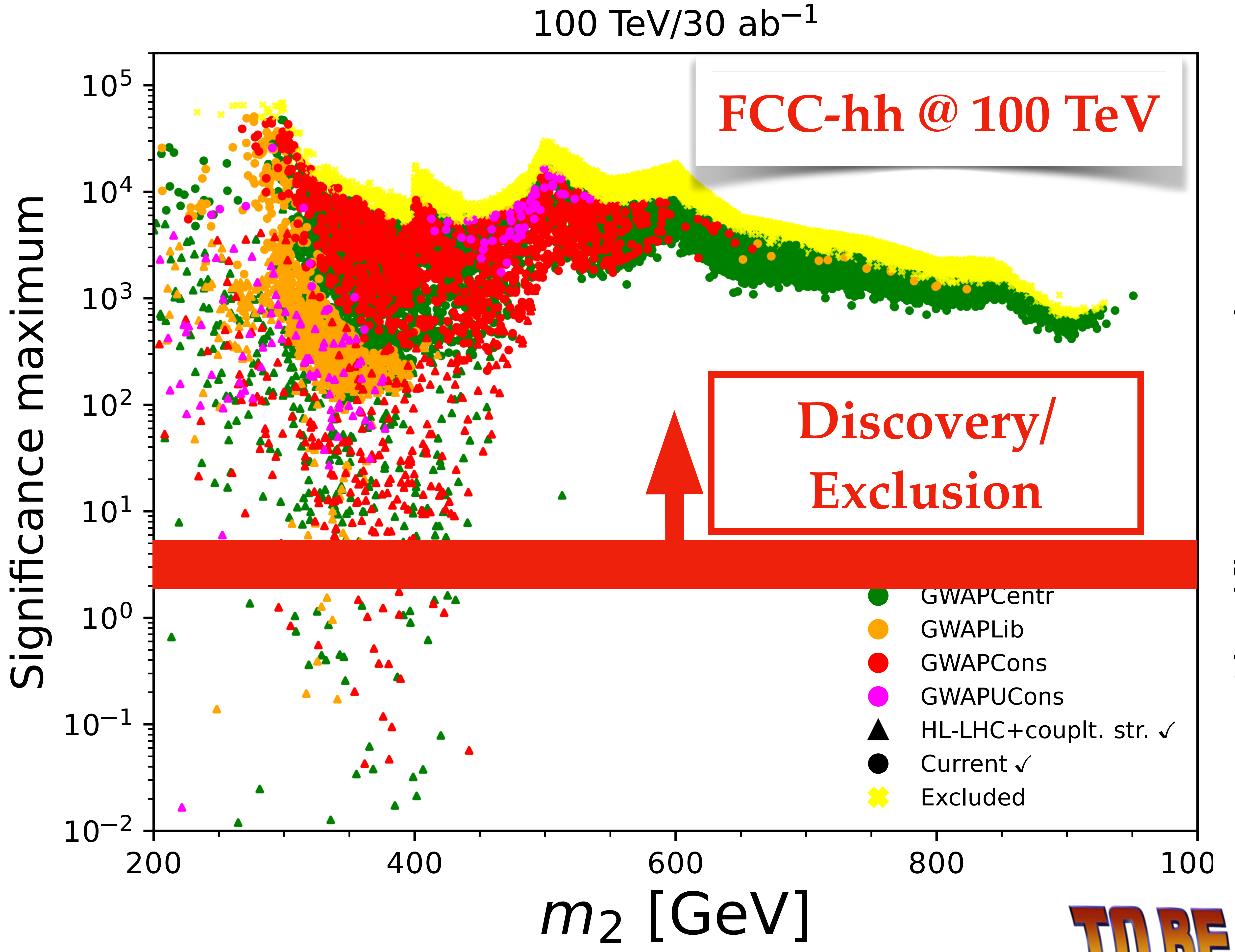

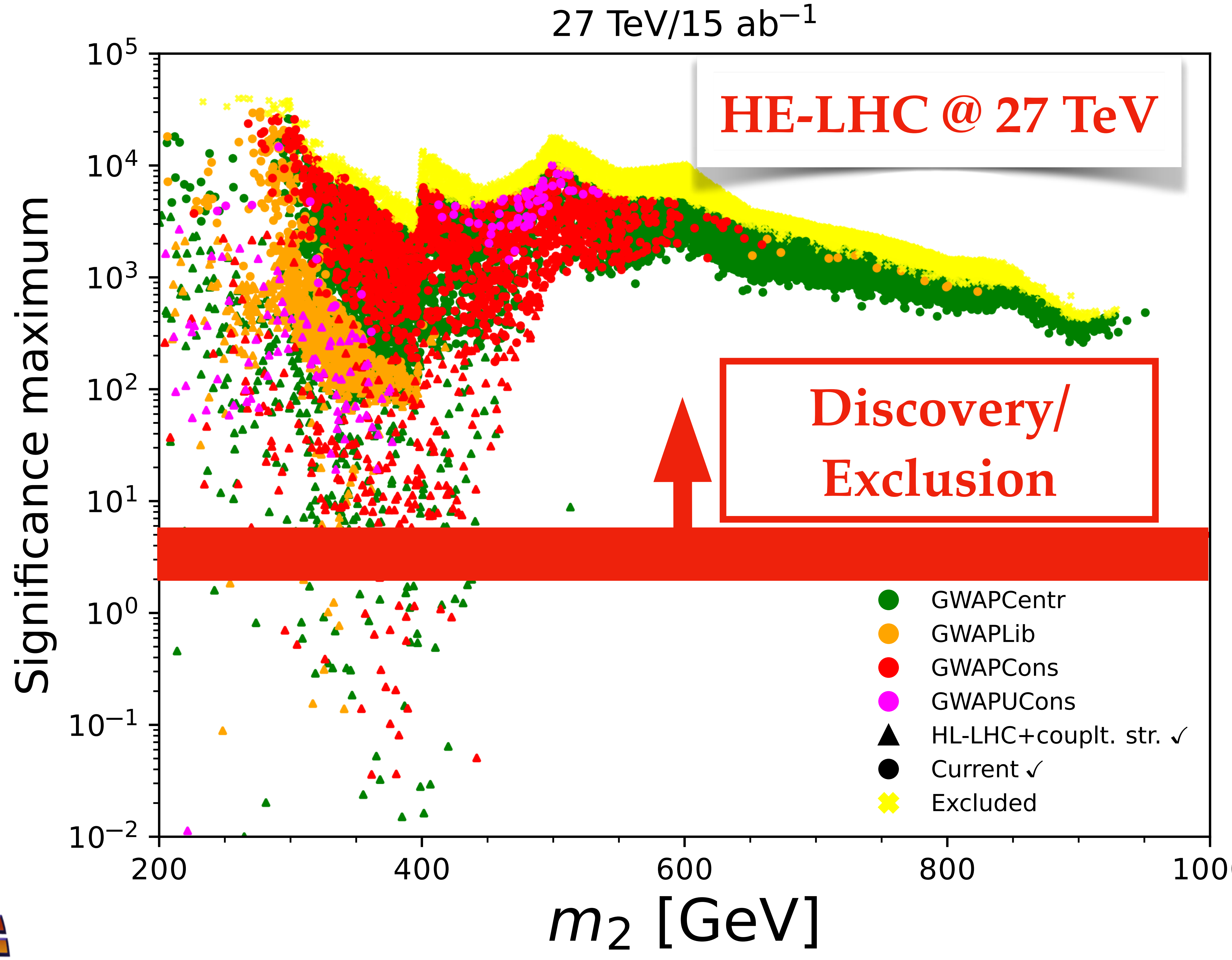

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Discovery Post-Mortem

"With 4 parameters I can fit an elephant and with 5 I can make him wiggle his trunk."
— John Von Neumann

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***Can we* fit the shape of an elephant with 4 parameters?**

Discovery Post-Mortem

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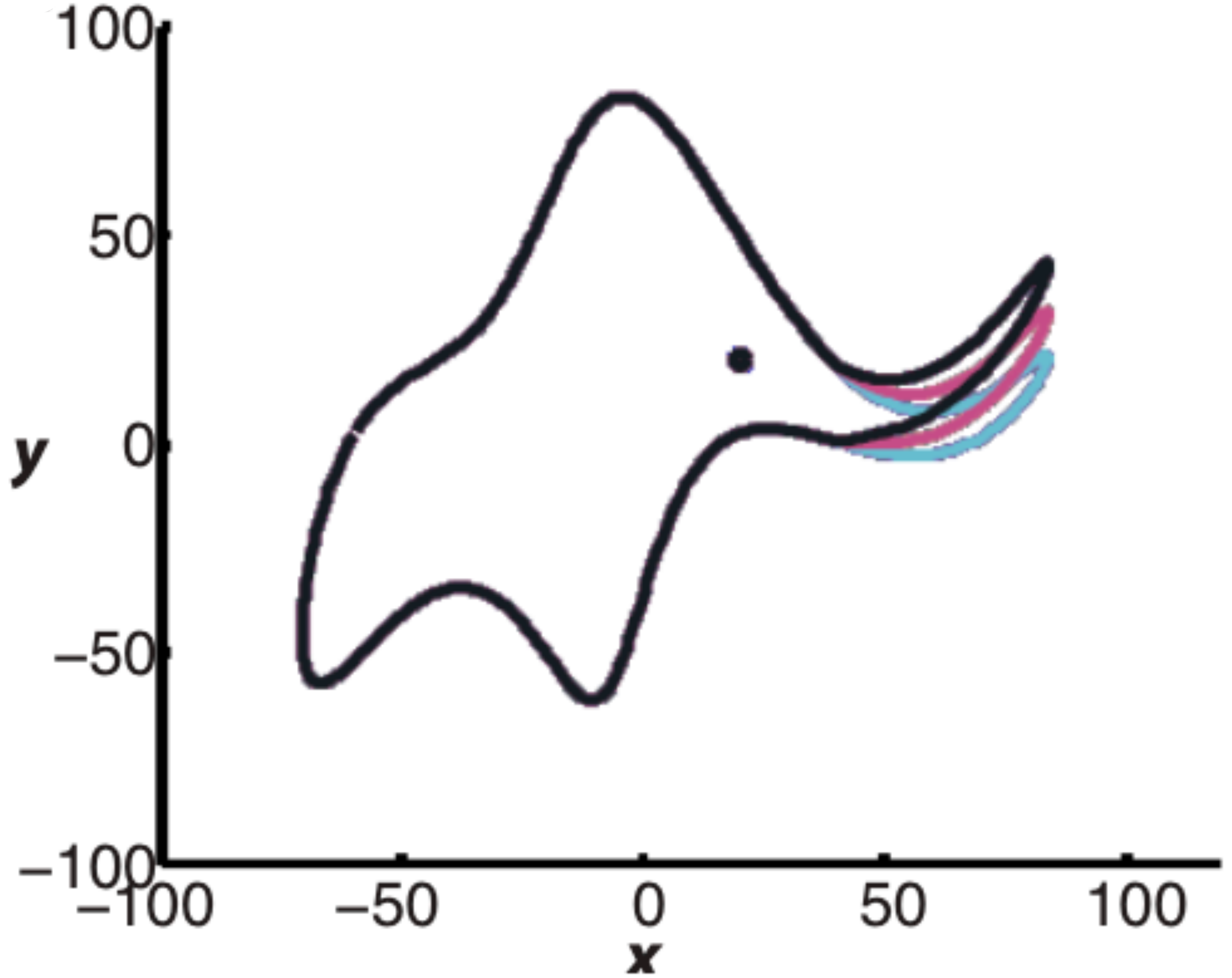
— John Von Neumann

Can we **fit the shape of an elephant with 4 parameters?**

→ **Yes!** With **four** complex parameters,

[and with 5 we can make it wiggle its trunk.]

[Mayer, Khairy, Howard, Am. J. Phys., Vol. 78, No. 6, June 2010]



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If we discover e.g. a new scalar particle at colliders,

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⇒ The "**Inverse Problem**".

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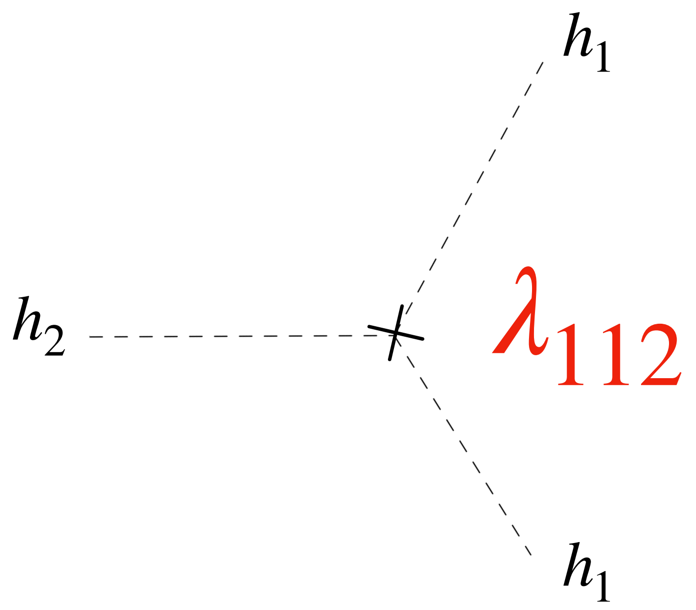
Experimental observations → {●, ▲, ■, ▲, ■}

Discovery Post-Mortem Example [AP, White, arXiv:2108.11394]

Combine possible measurements:

$pp \to h_2 \to ZZ$

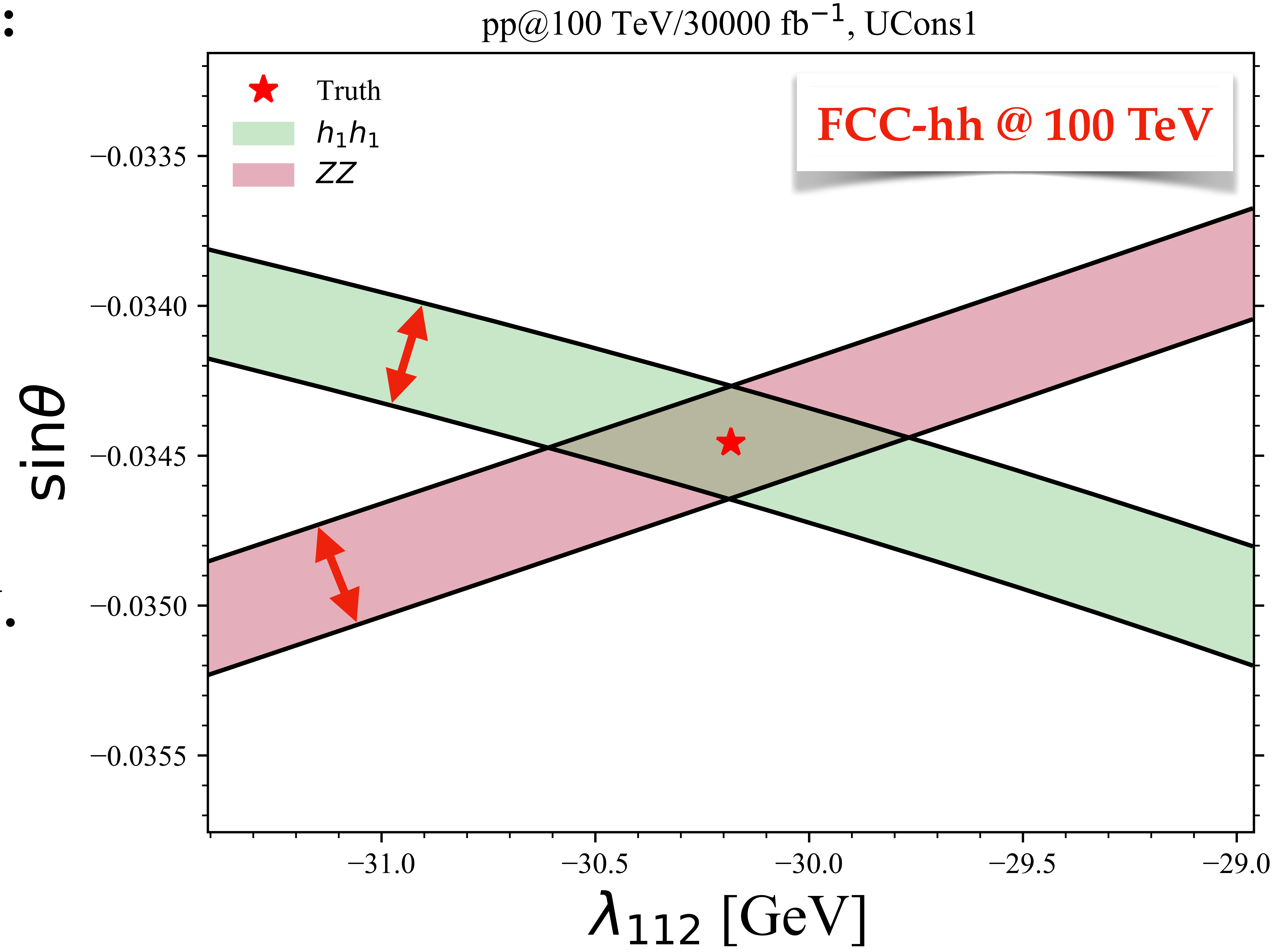
$pp \to h_2 \to h_1 h_1$



→ **both functions of $\sin\theta$ & λ_{112}!**

→ **in turn fns of** {● (magenta), ▲ (cyan), ■ (dark red), ▲ (red), ■ (purple)}.

[Width of bands represents expected measurement uncertainty].



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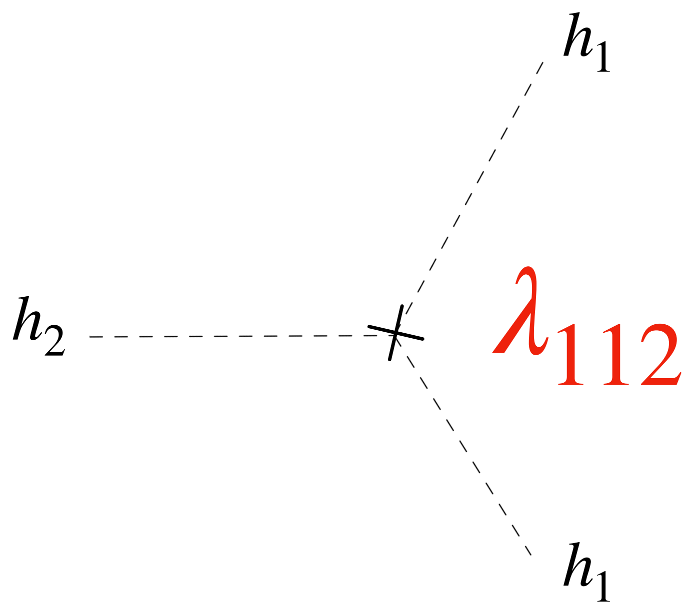

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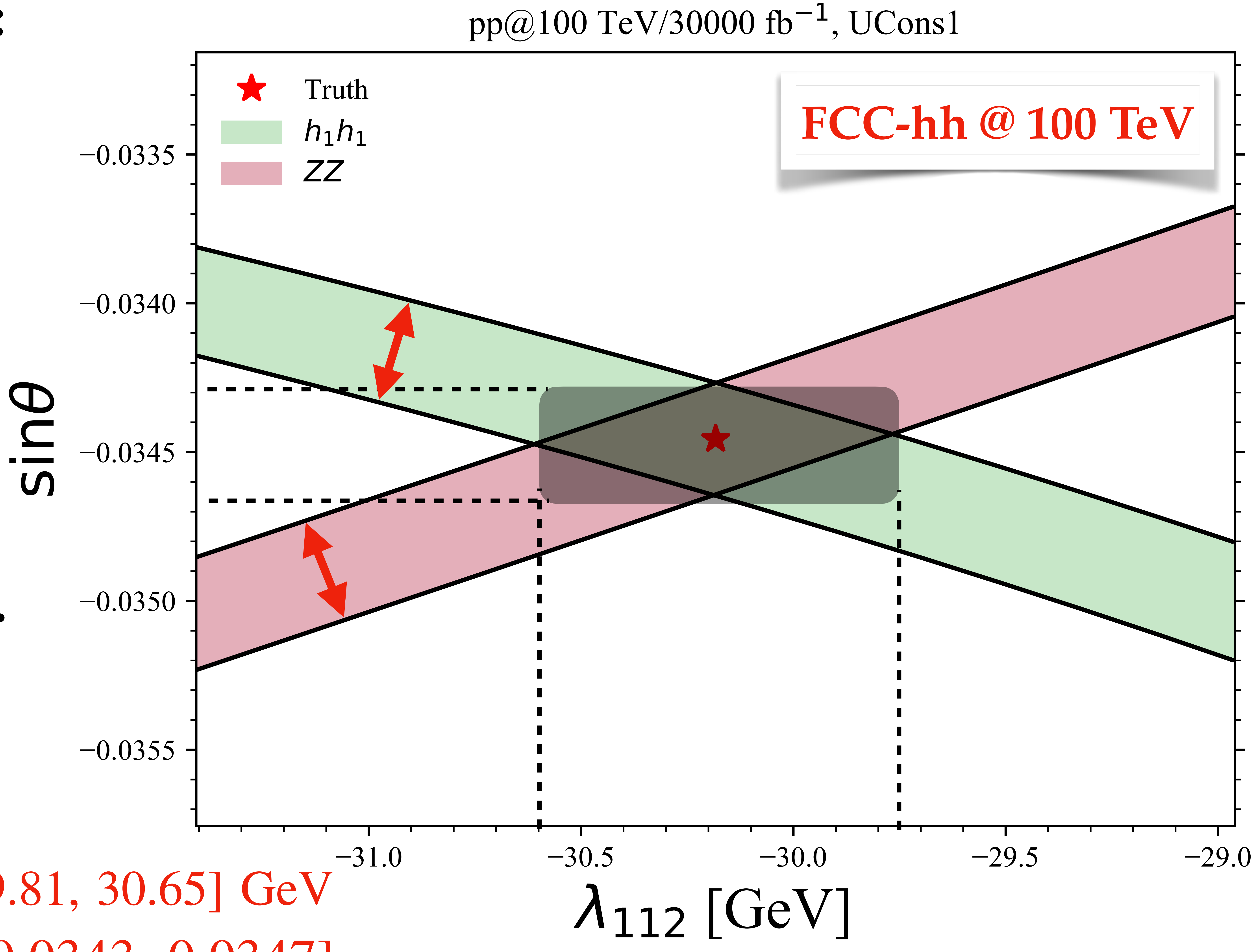


$\lambda_{112} \in [29.81,\ 30.65]$ GeV

$\sin\theta \in [0.0343,\ 0.0347]$

Multi-scalar processes should play a **crucial rôle**:

$$pp \to h_1 h_2 \qquad |\mathcal{M}|^2 \sim \lambda_{122}^2, \lambda_{112}^2 + \ldots$$

$$pp \to h_2 h_2 \qquad |\mathcal{M}|^2 \sim \lambda_{222}^2, \lambda_{122}^2 + \ldots$$

$$pp \to h_1 h_1 h_1 \qquad |\mathcal{M}|^2 \sim f[\lambda_{1111}, \lambda_{1112}, \lambda_{111}, \lambda_{112}]$$

[…]

TO BE CONTINUED...

Summary

- Within the realm of the Standard Model, **we can describe a whole of range of particle interactions with extraordinary precision**.

- **Monte Carlo Event Generators** are invaluable tools of communication between theory and experiment.

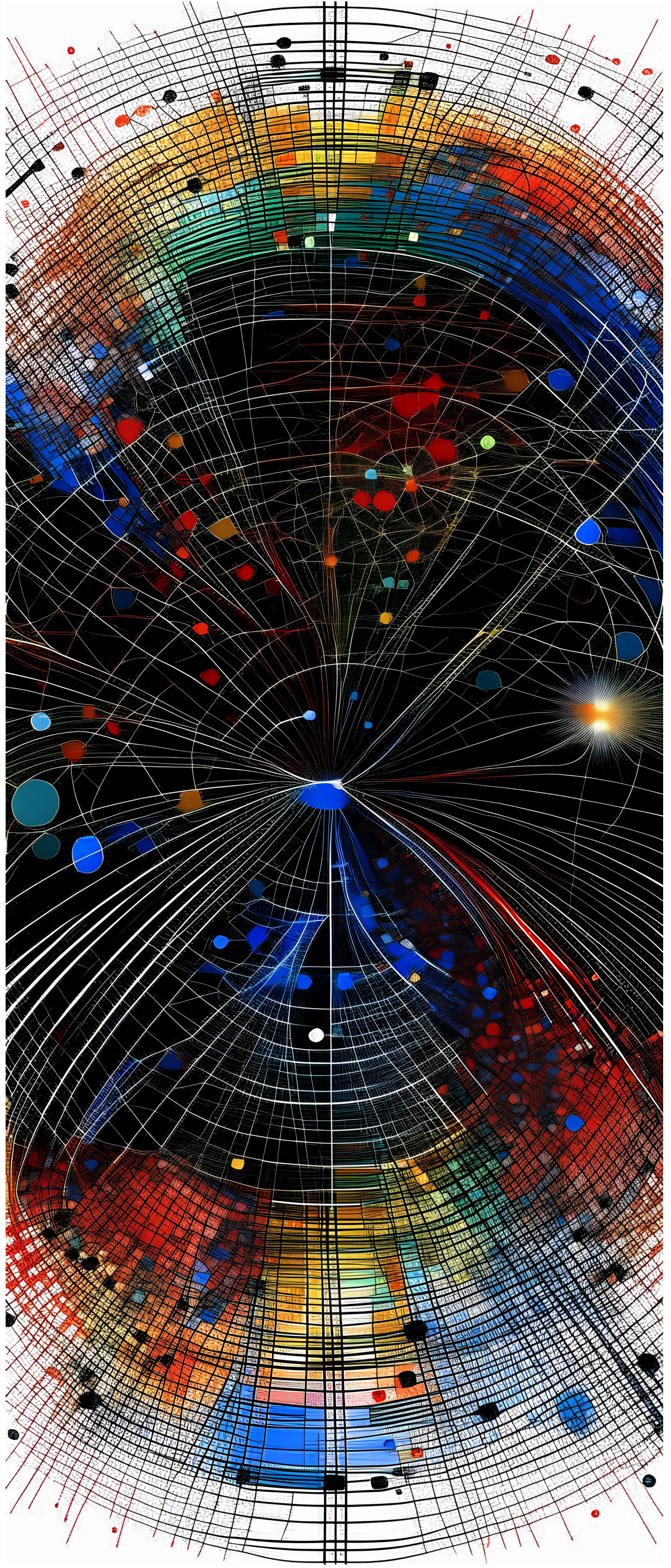
- However, there remains a multitude of **open questions**, that may be linked via the **Electro-Weak Phase Transition.**

- The **Nature of the Electro-Weak Phase Transition** is an important scientific enquiry.

- **(Strong) First-Order EWPT [not in SM!] → Matter-Anti-Matter asymmetry.**

- Adding a **singlet scalar field to the SM can catalyze this**!

- Future particle colliders have the **potential to probe this mechanism**.



[made with stablecog]

Andreas Papaefstathiou

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Outlook

- Following any discovery, **solving the inverse problem** would be the **crucial** next step.
- I discussed **first steps in this exercise**, following the discovery of a new scalar.
- **Multi-scalar production processes** will play a crucial role in this endeavor.
- [Could they also be **discovery channels** themselves?]
- **Questions merit investigation both at the LHC and other future colliders (e.g. a Muon Collider!).**

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- [Could they also be **discovery channels** themselves?]
- **Questions merit investigation both at the LHC and other future colliders (e.g. a Muon Collider!).**

Thanks!
Questions?

Appendix

Theoretical Uncertainties in SM+Singlet

- **Uncertainties** → Can affect e.g. the **strength of the transition,** $\langle \phi(T) \rangle / T$.

- Due to:

  - **gauge dependence**, **[Patel, Ramsey-Musolf, arXiv:1101.4665]**

  - **scale dependence** → Linde's IR problem: expansion parameter is $g n_B \sim gT/m$, (n_B mode occupation), diverges as $m \to 0 \Rightarrow$ perturbativity breaks down.

    [Linde, Phys. Lett. 96B (1980) 289.]

- **⇒ To make reliable and sensible statements on colliders prospects:**

  → **Crucial to take uncertainties into account.**

Theoretical Uncertainty Bands

- **Define "uncertainty band"** by:

1. Deriving 1-loop effective potential in the covariant gauge,

   [Arnold, Espinosa, hep-ph/9212235], [Andreassen, MSc, Norwegian U. Sci. Tech., 2013]

2. Run couplings $\lambda \to \lambda(\mu)$, μ is RGE scale, [`SARAH`, Staub, arXiv:0806.0538]

3. Scan parameter space of Lagrangian,

4. Vary $\mu \in [\frac{1}{2} \times m_Z, 5 \times m_Z]$ & gauge params. $\xi_i \in [0,3] \to$ band of 8 pts.

5. Use **`PhaseTracer`** for each point in band $\to$ Get phase transitions, $\langle \phi(T_c) \rangle / T_c$.

   [Athron, Balázs, Fowlie, Zhang, arXiv:2003.02859]

Parameter-space Categories

1. Define two conditions:

   i. VEV at 1-loop: $\langle \phi(T=0) \rangle = 246 \pm 30$ GeV & deepest minimum.

   ii. $\langle \phi(T_c) \rangle / T_c > 1$ & no other transition with higher T_c.

2. Define four mutually-exclusive categories*:

*An alternative classification appears in our article: see Appendix.

SFO-EWPT more certain →

Liberal	Centrist	Conservative	Ultra-Conservative

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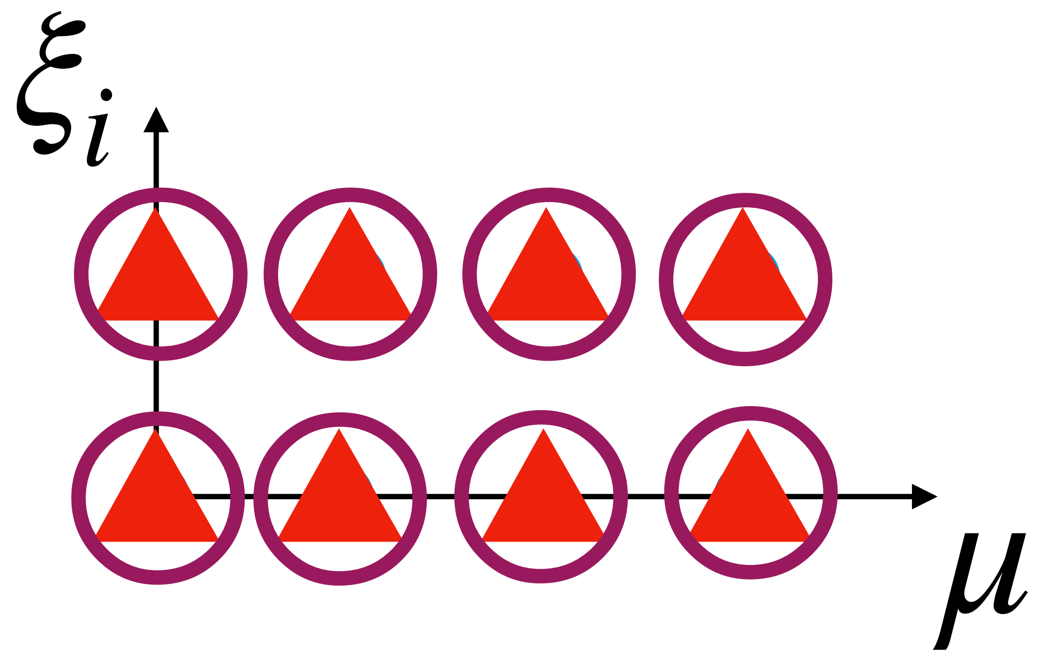

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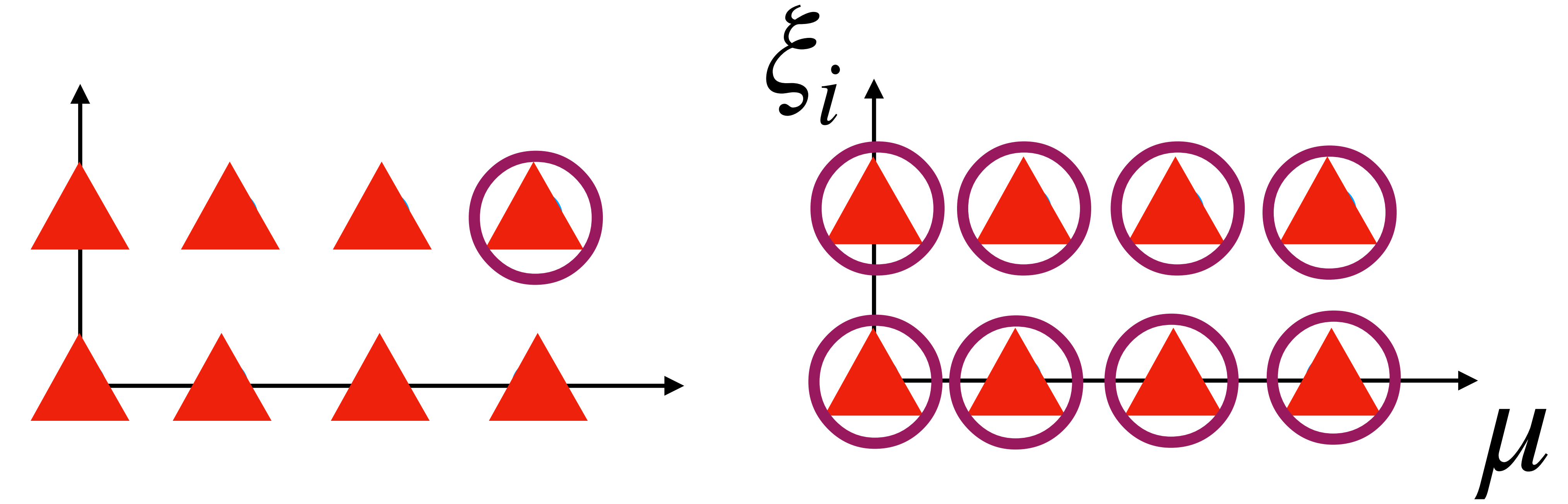

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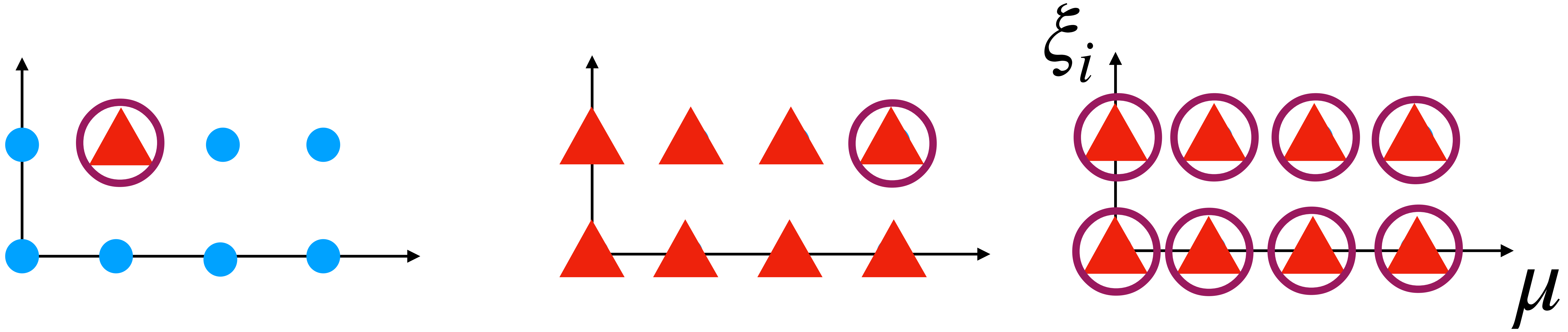

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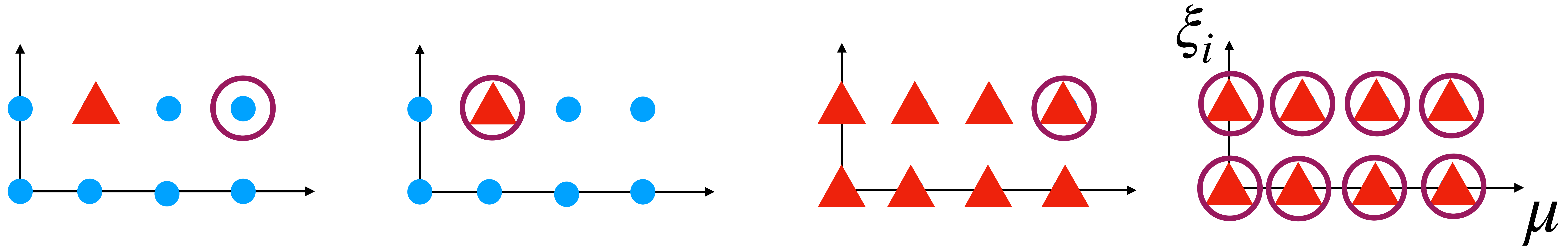

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Note: For phenomenological analyses, take "central" μ and ξ_i.

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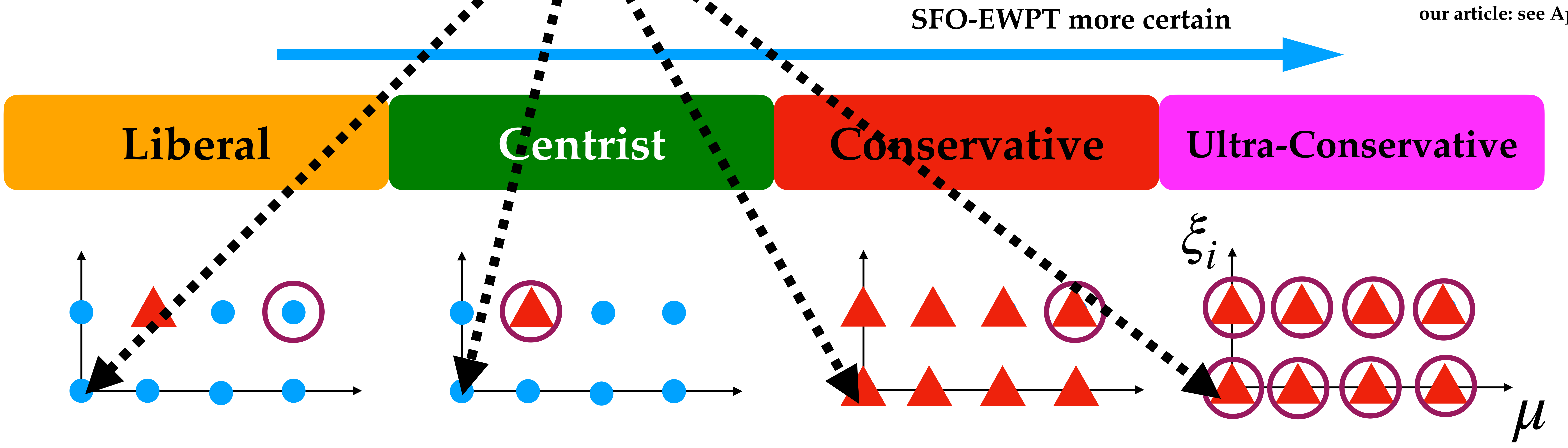


Electro-Weak Precision Observables

- Real singlet scalar field
  - $\rightarrow$ modifies Higgs contributions to diagonal weak gauge boson vacuum polarisation diagrams,
  - & introduces additional contributions.
- Quantify via S, T, U parameters. **[Hagiwara, Matsumoto, Haidt, Kim, hep-ph/9409380]**
- Change in EWPO $\mathcal{O}$ $(= S, T, U)$:

$$\Delta\mathcal{O} = (\mathcal{O}(m_2^2) - \mathcal{O}(m_1^2)) \times \sin^2\theta$$

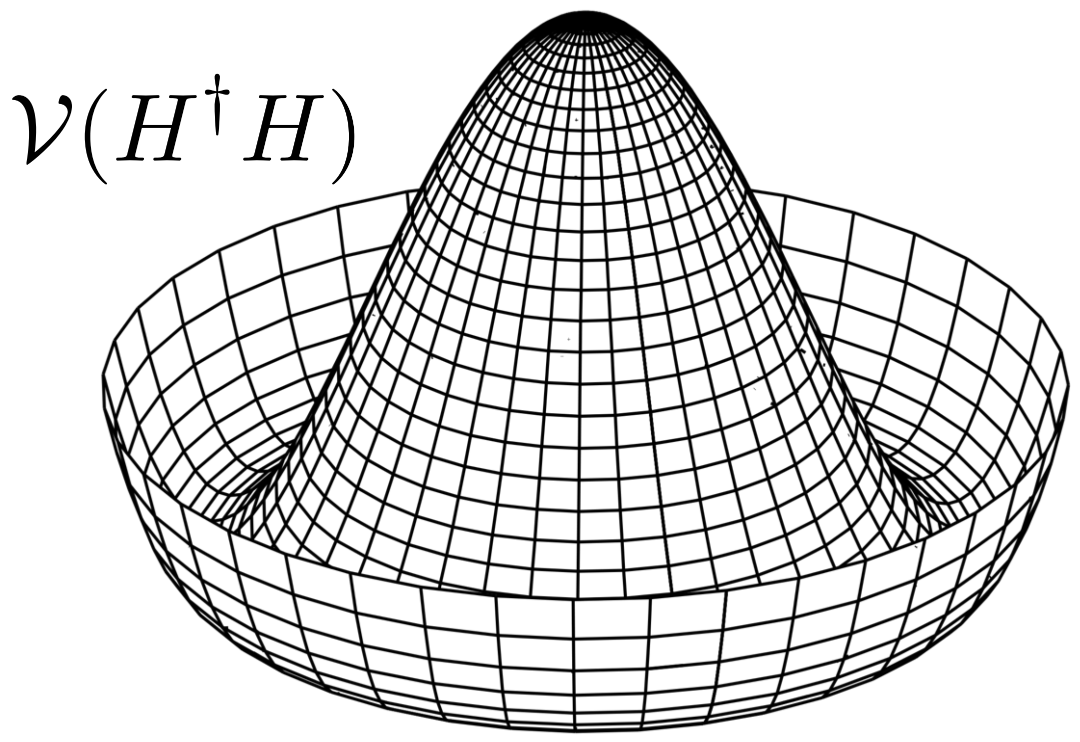
$\Rightarrow$ calculate compatibility with experimental measurement $\Delta\mathcal{O}^{\mathrm{EXP}}$.

The Higgs Potential & Vacuum Stability

The Importance of the Higgs sector

- the Higgs boson: the central protagonist of EWSB:

***H*: Higgs doublet**



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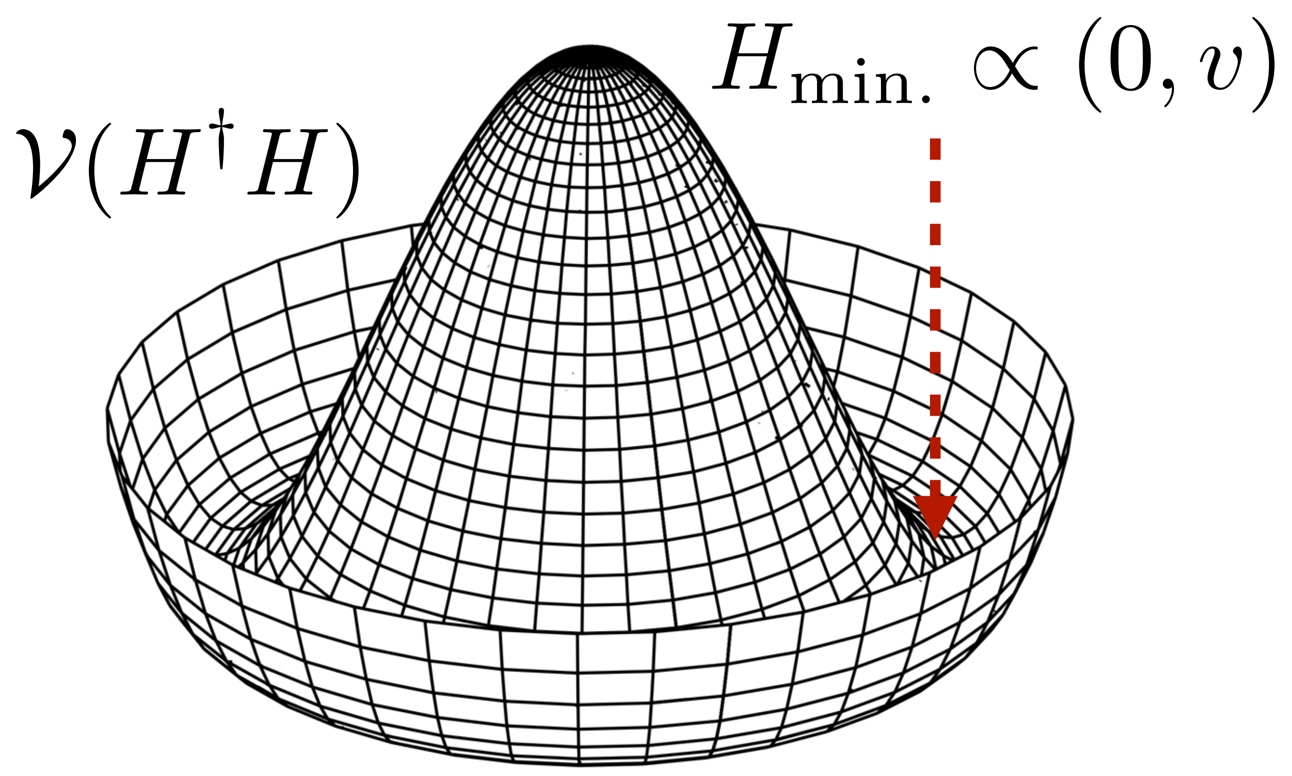

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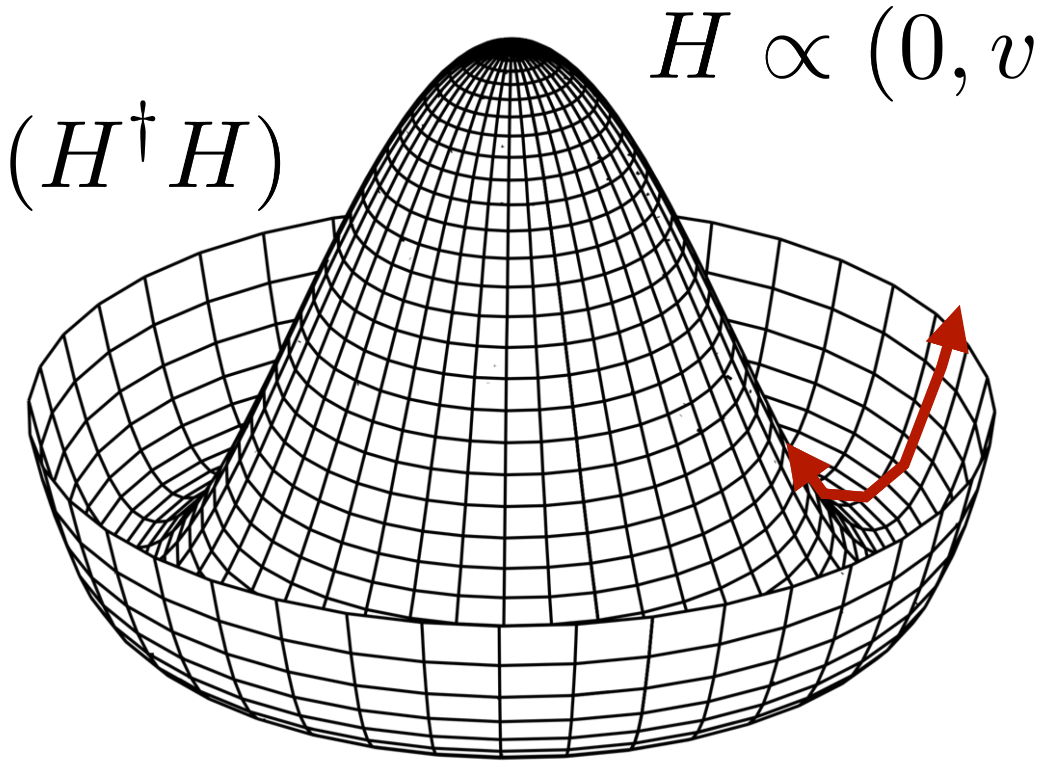

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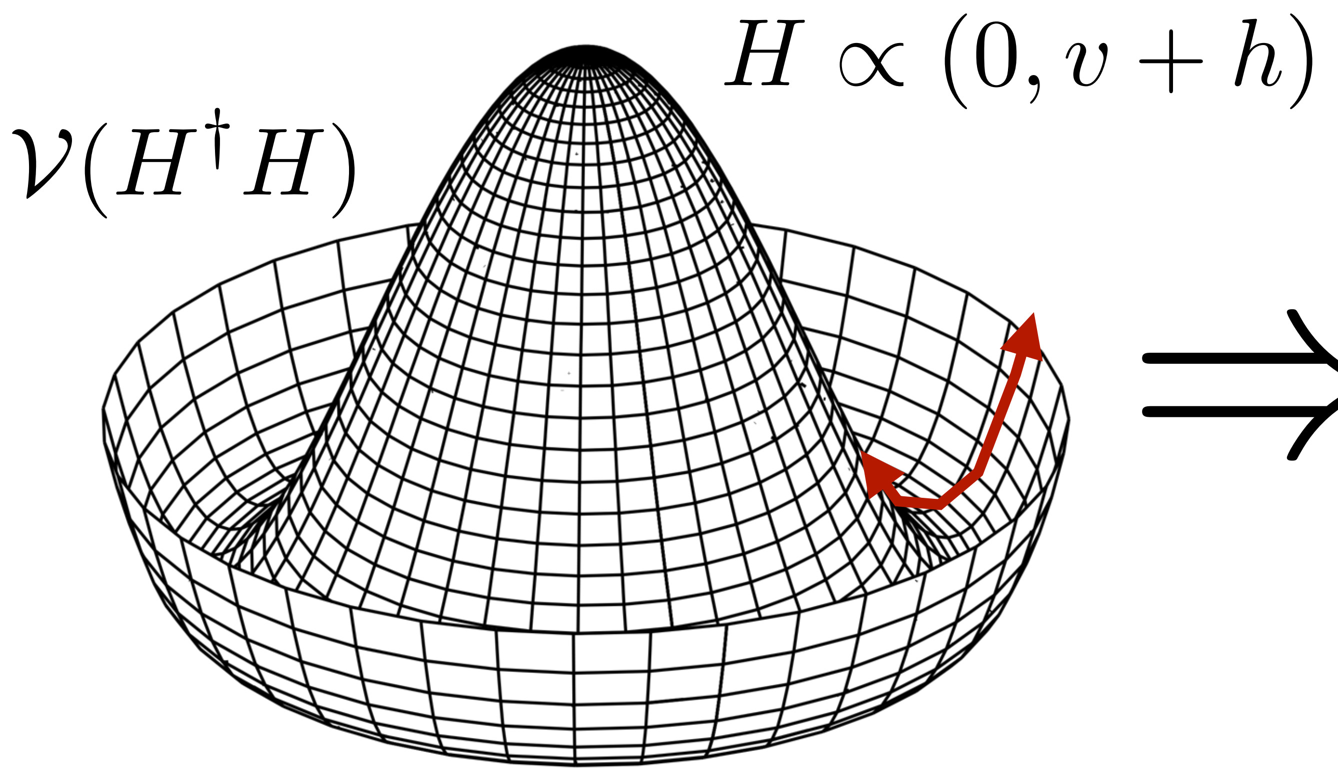

$\Rightarrow$

e.g. fermion masses & interactions:

$$\mathcal{L} \supset -m_f \bar{f}_L f_R - \frac{m_f}{v} h \bar{f}_L f_R + \text{h.c.}$$

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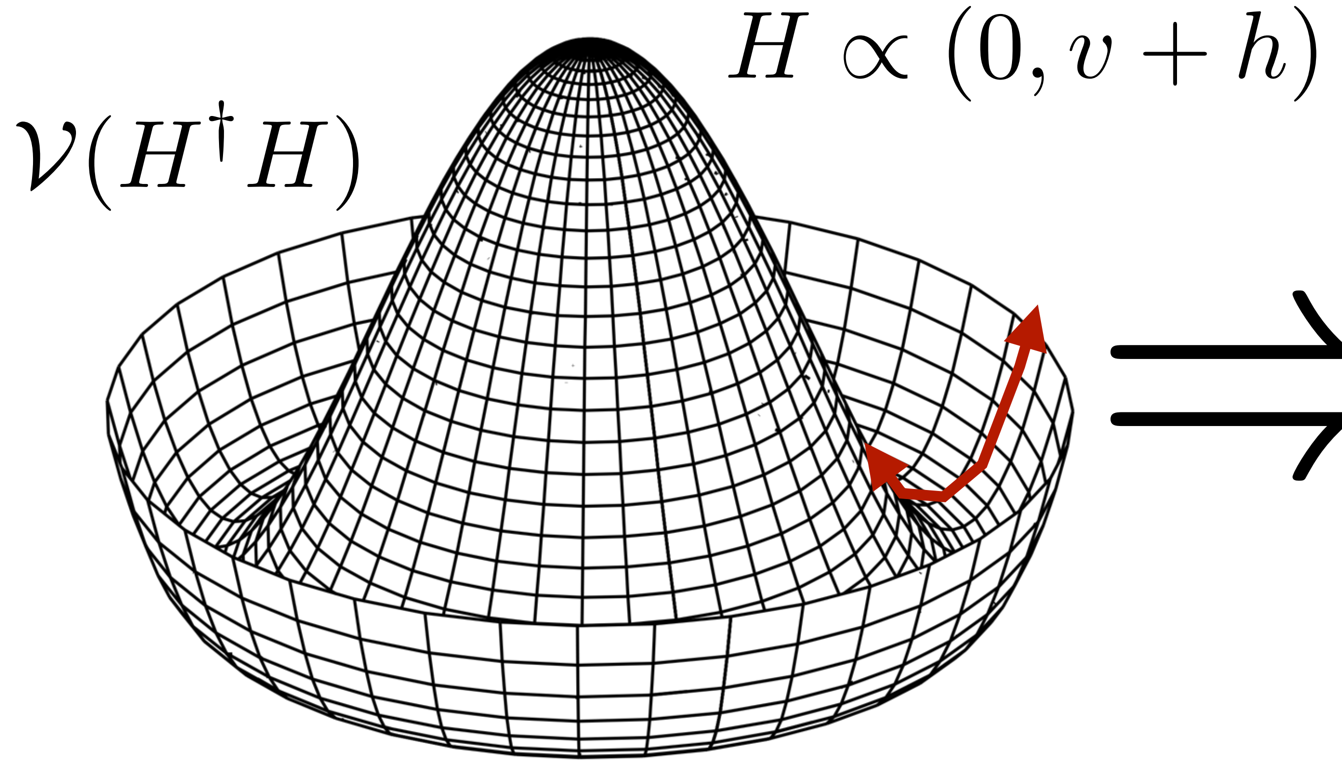

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e.g. gauge boson masses & interactions:

$$\mathcal{L} \supset [m_W^2 W^{\mu+} W_\mu^- + \frac{1}{2} m_Z^2 Z^\mu Z_\mu] \times \left(1 + \frac{h}{v}\right)^2$$

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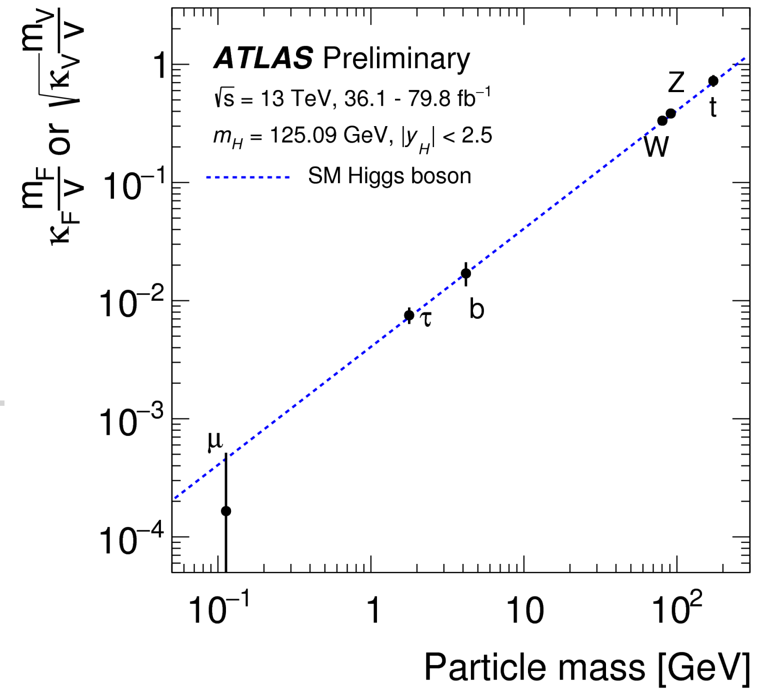
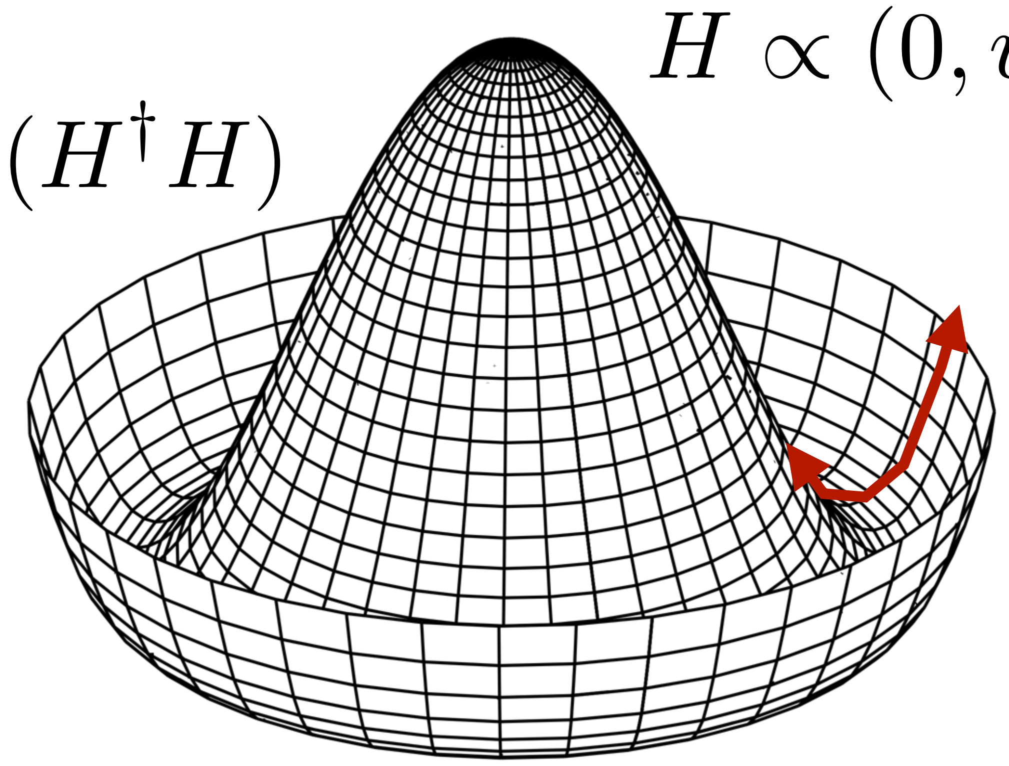


H: Higgs doublet

$\mathcal{V}(H^\dagger H)$



$H \propto (0, v+h)$

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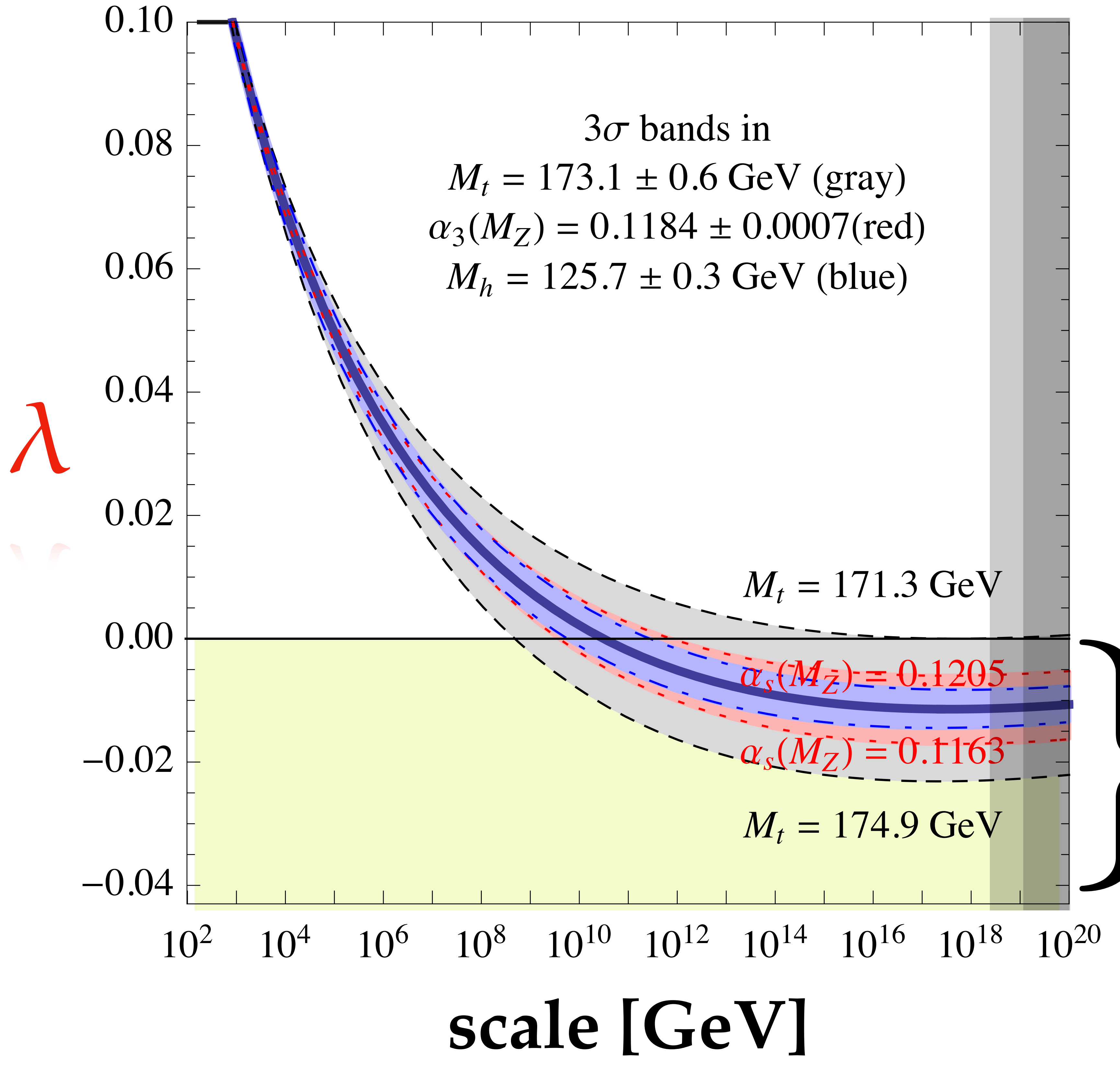
Vacuum Stability

- SM potential for the Higgs doublet:

$$\mathcal{V}(H^\dagger H) = -m^2(H^\dagger H) + \lambda(H^\dagger H)^2$$

- renormalisation group evolution of the coupling λ:

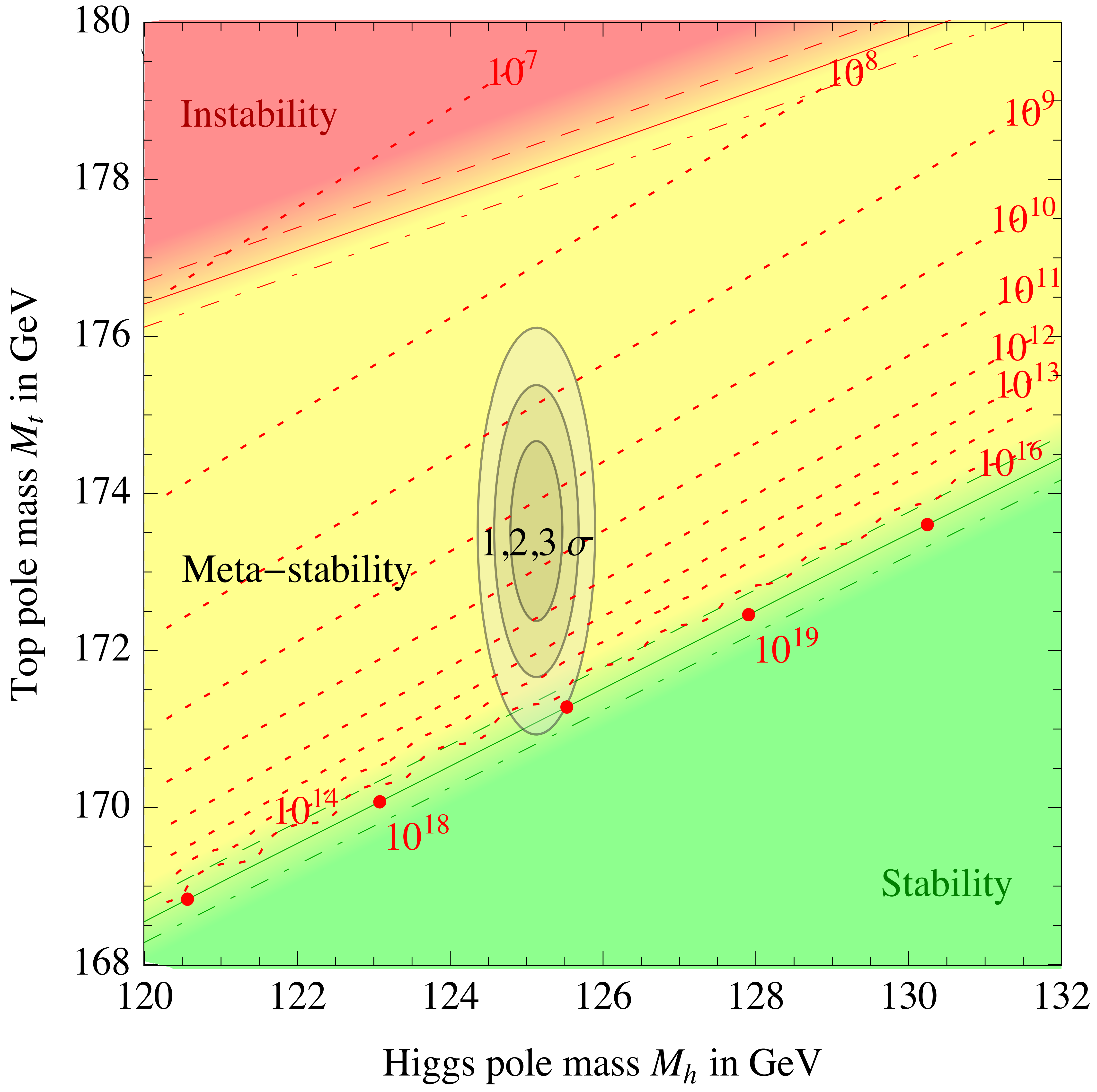


$\lambda < 0$! $\Longrightarrow$ **potentially unstable or meta-stable vacuum!**

[Cabibbo, Maiani, Parisi, Petronzio, 1979, Hung, 1979, …, Degrassi, Di Vita, Elias-Miró, Giudice, Isidori, Strumia, 1205.6497, Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia, 1307.3536 …, Espinosa, 1512.01222]

vacuum stability

[Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia, 1307.3536, Espinosa, 1512.01222]



in deriving this: **assumed Standard Model.**

➡ a hint for a non-standard Higgs sector?

➡ further investigation necessary.

Sphaleron/Instanton Processes

Instantons and Baryon-# Violation

- toy model:

(1+1)-dimensions, Abelian gauge field A^μ, complex scalar Φ^μ, Dirac fermion of unit charge Ψ.

- Euclidean space action:

$$S = \int \mathrm{d}^2 x \left[\frac{1}{4} F_{\mu\nu}^2 + |(\partial_\mu - ieA_\mu)\Phi|^2 + V(\Phi) + i\bar{\Psi}(\partial_\mu - ieA_\mu)\gamma^\mu \Psi \right]$$

"Higgs potential": $V(\Phi) = \lambda(\Phi^*\Phi - v^2)^2 \Longrightarrow$ **"EWSB"** $\Longrightarrow M_A, \; M_h$

Instantons and Baryon-# Violation

- consider the current:

$$K_\mu = \frac{e}{2\pi}\epsilon_{\mu\nu}A_\nu$$

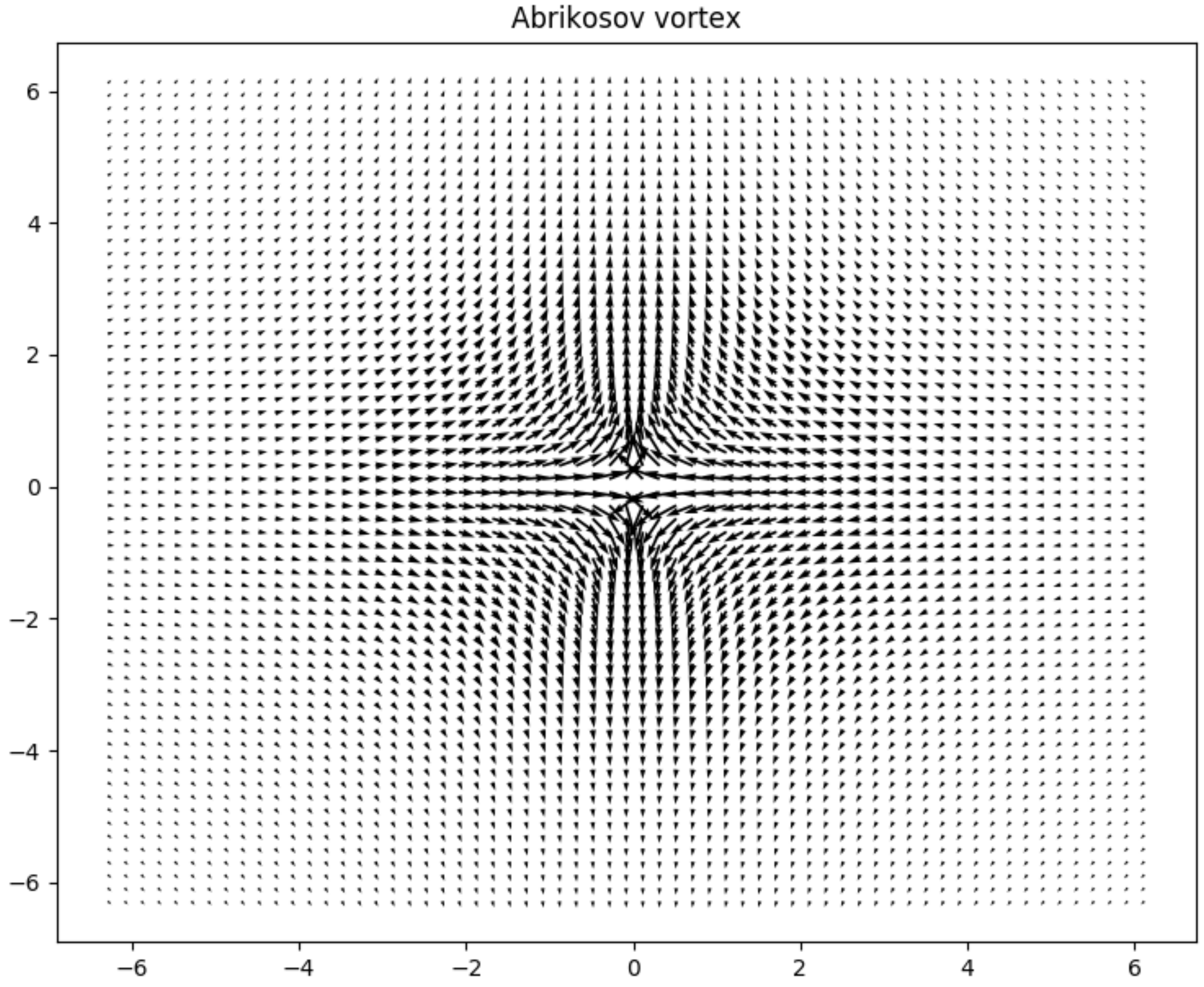
- corresponds to "charge density":

$$N_{\rm CS} = \int {\rm d}x\ K_0 = \frac{e}{2\pi}\int {\rm d}x\ A_1$$

- known as the "winding" or "Chern-Simons" number.

Instantons and Baryon-# Violation

- a classical solution to equations of motion is the "Abrikosov vortex":



$$A_r = 0,\ A_\theta = \frac{1}{er} f(r),$$
$$f(0) = 0,\ 1 - f(r) \sim e^{-M_A r}$$

$\Rightarrow$ changes the Chern-Simons number by one unit:

$$\Delta N_{\rm CS} = \int \mathrm{d}^2x\ \partial_\mu K^\mu = \boxed{\frac{e}{4\pi}\int \mathrm{d}^2x\ \epsilon_{\mu\nu}F^{\mu\nu}} = 1$$

Instantons and Baryon-# Violation

- "instanton" transition necessarily accompanied by change of chirality of fermions by two units:

$$j_\mu^5 = \bar{\Psi}\gamma_\mu\gamma_5\Psi$$

$$\frac{1}{2}\partial_\mu j^{5\mu} = \frac{e}{4\pi}\epsilon_{\mu\nu}F^{\mu\nu}$$

anomalous divergence of the axial-vector current.

$$\Delta N_{\rm CS} = \int \mathrm{d}^2x\ \partial_\mu K^\mu = \boxed{\frac{e}{4\pi}\int \mathrm{d}^2x\ \epsilon_{\mu\nu}F^{\mu\nu}} = 1$$

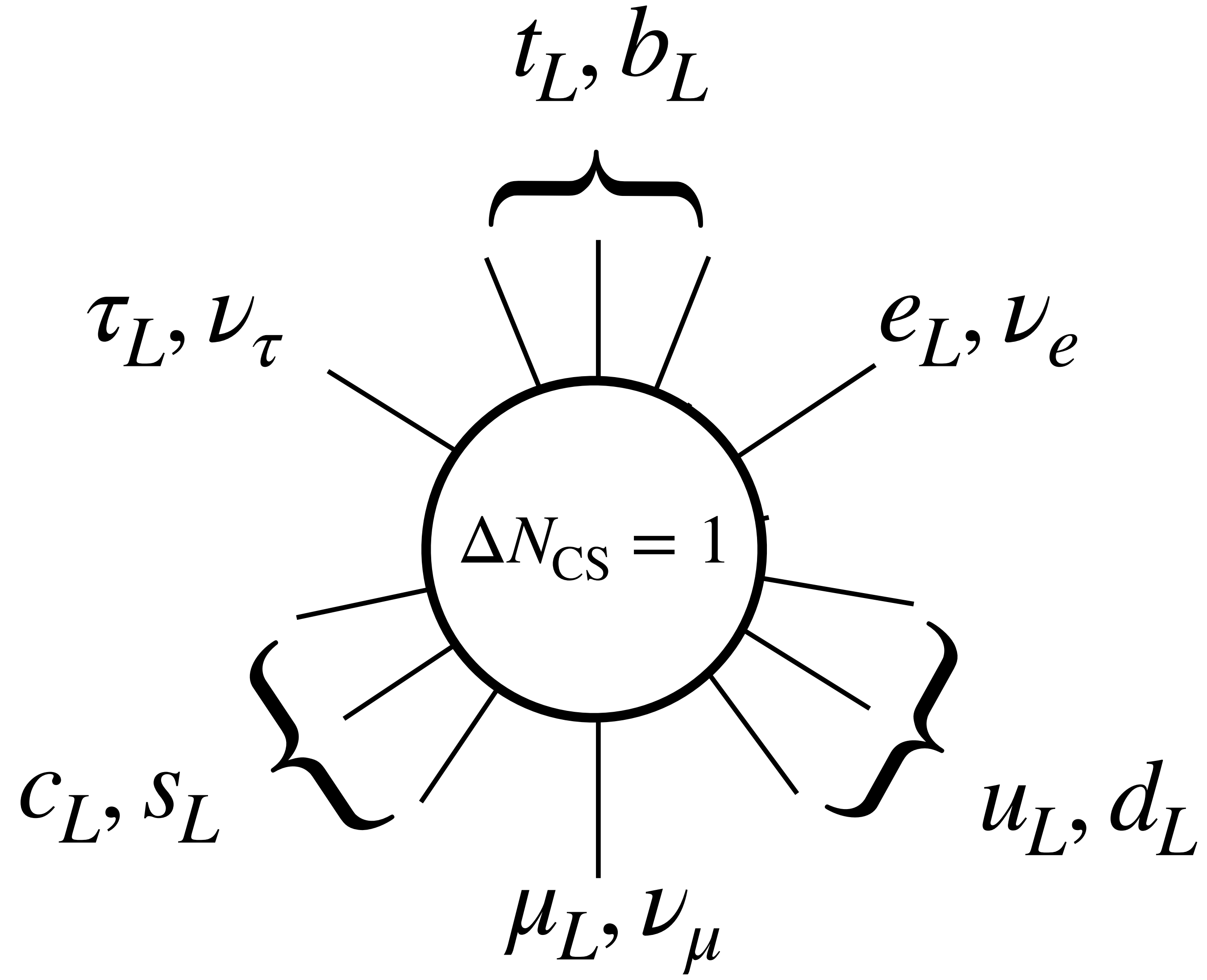
$$\Longrightarrow \quad \Delta Q_5 = \Delta \int \mathrm{d}x j_0^5 = 2$$

EW Sphalerons at colliders?

- Rate and observability of sphaleron processes at colliders debated.

e.g. [Bezrukov, Levkov, Rebbi, Rybakov, Tinyakov, hep-ph/0304180] VS. [Tye, Wong, 1505.0360, 1710.07223].

- Ponder: **Sphaleron-induced interactions at hadron colliders**:



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  e.g. [Bezrukov, Levkov, Rebbi, Rybakov, Tinyakov, hep-ph/0304180] VS. [Tye, Wong, 1505.0360, 1710.07223].

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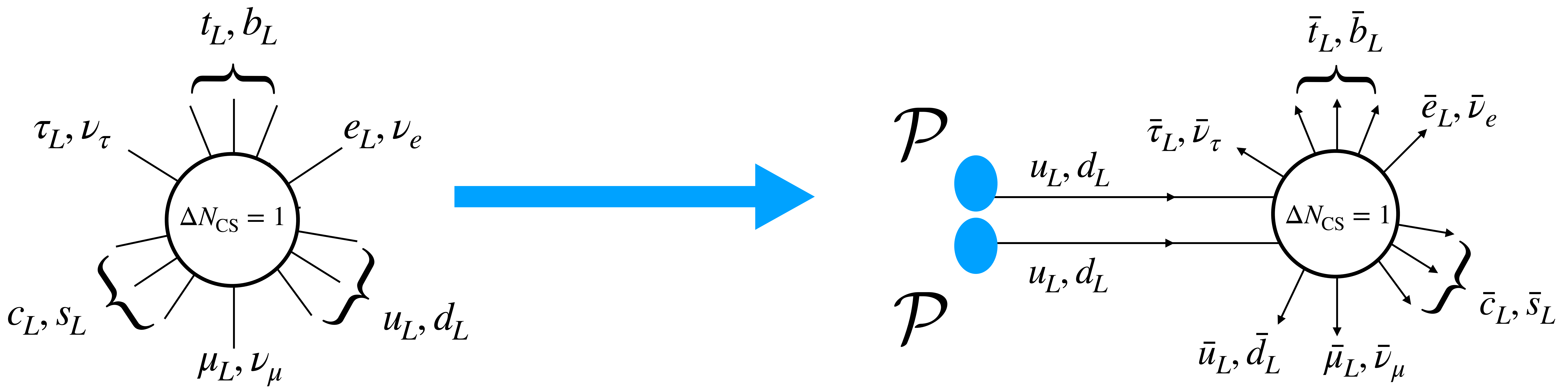
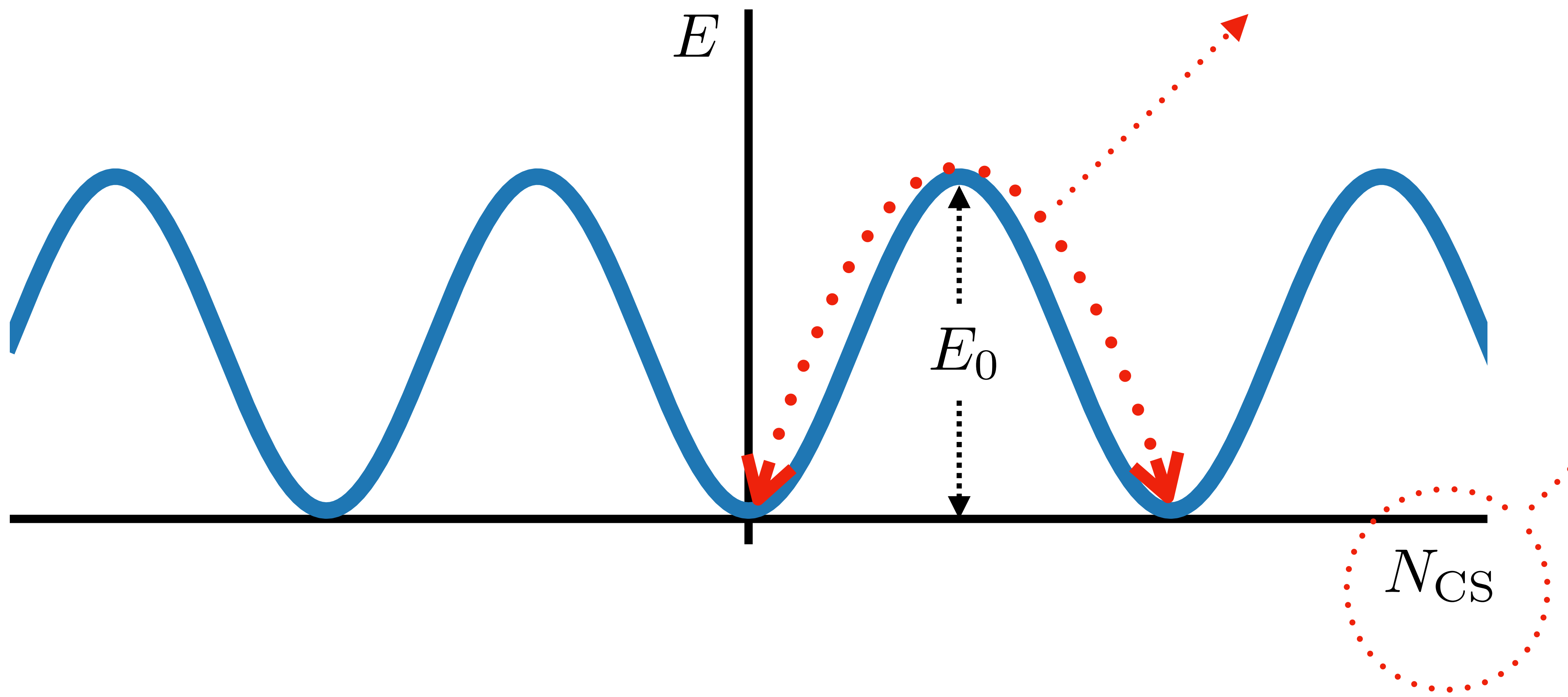
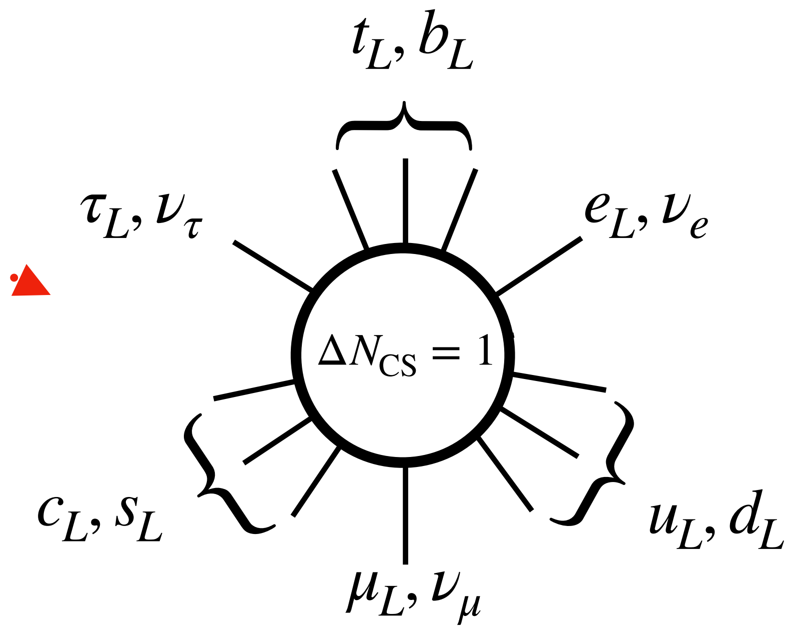


What is the Sphaleron?

- $E_0 \sim \mathcal{O}(10)$ TeV, separates **degenerate** Electro-Weak vacua.



Sphaleron transition



Chern-Simons number

$$\Delta N_{CS} = \frac{1}{3}\Delta B = \Delta L_i$$

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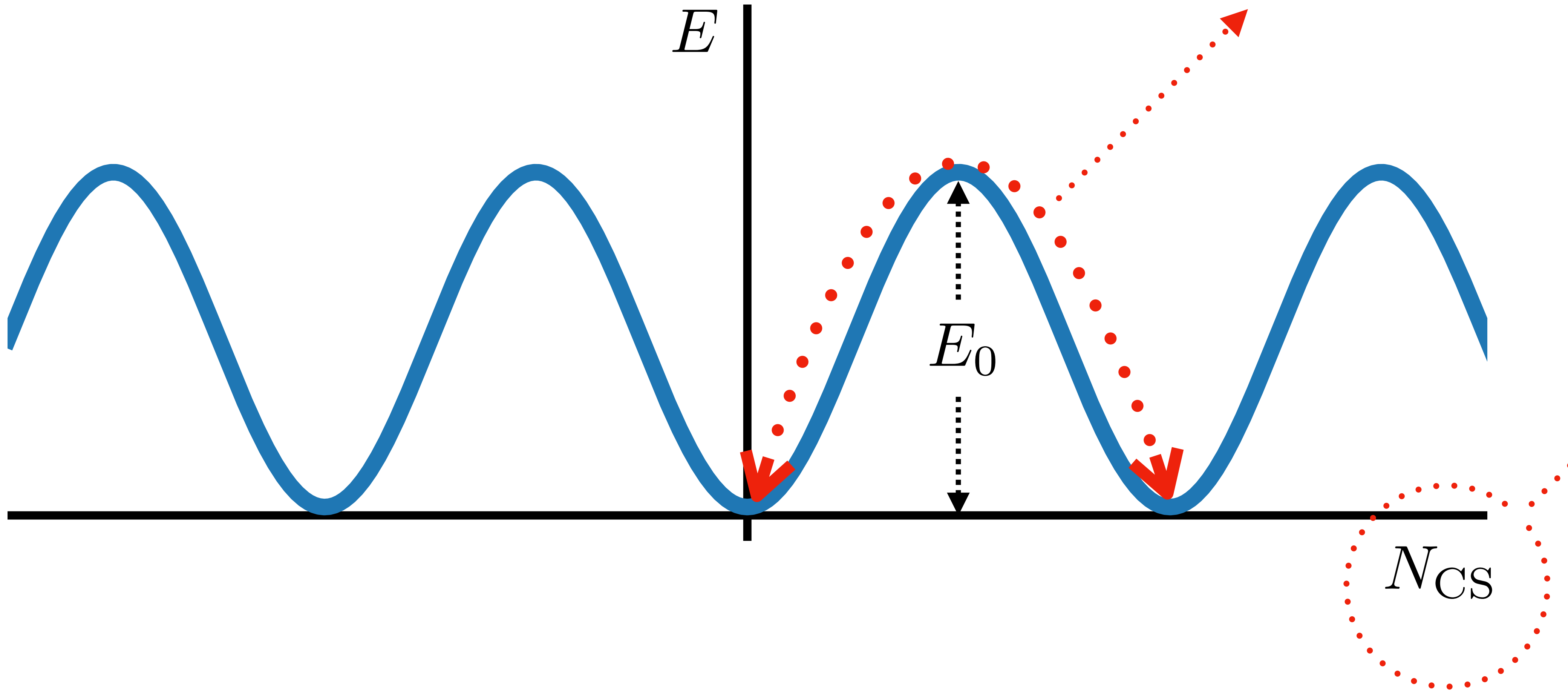

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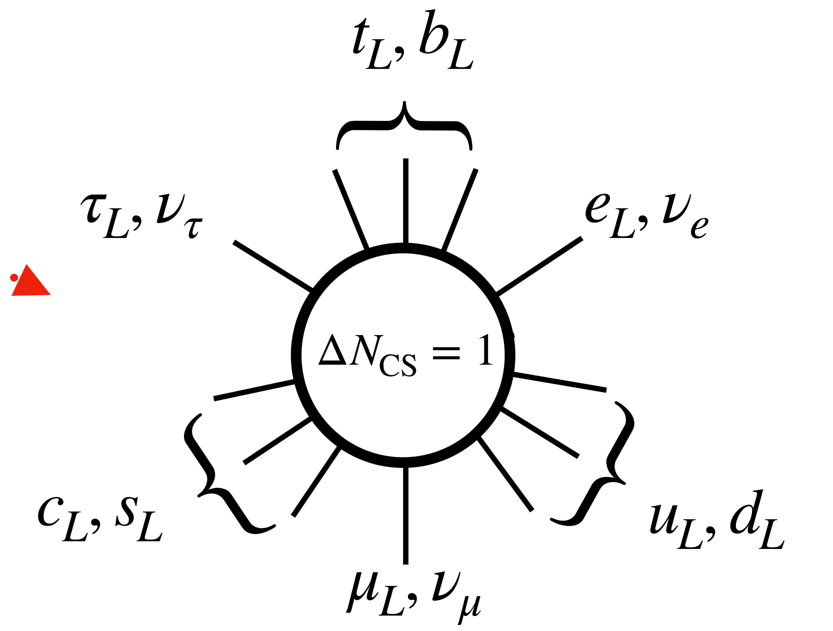
Chern-Simons number



$$\Delta N_{CS} = \frac{1}{3}\Delta B = \Delta L_i$$

The Sphaleron energy depends <u>crucially</u> on the Higgs sector!

A Note on Sphaleron Suppression

- **Suppression** of sphaleron rate **inside bubble**

  $\Rightarrow$ Baryon Asymmetry "swept in" broken phase and "frozen in".

- **Rate** $\sim \exp[-\langle \phi(T_C) \rangle / T_C \times \ldots]$,

  [T_C: the critical temperature.]

- $\Rightarrow$ Require: $\langle \phi(T_C) \rangle / T_C \geq 1 \Rightarrow$ a "Strong" First-Order EWPT (SFO-EWPT).

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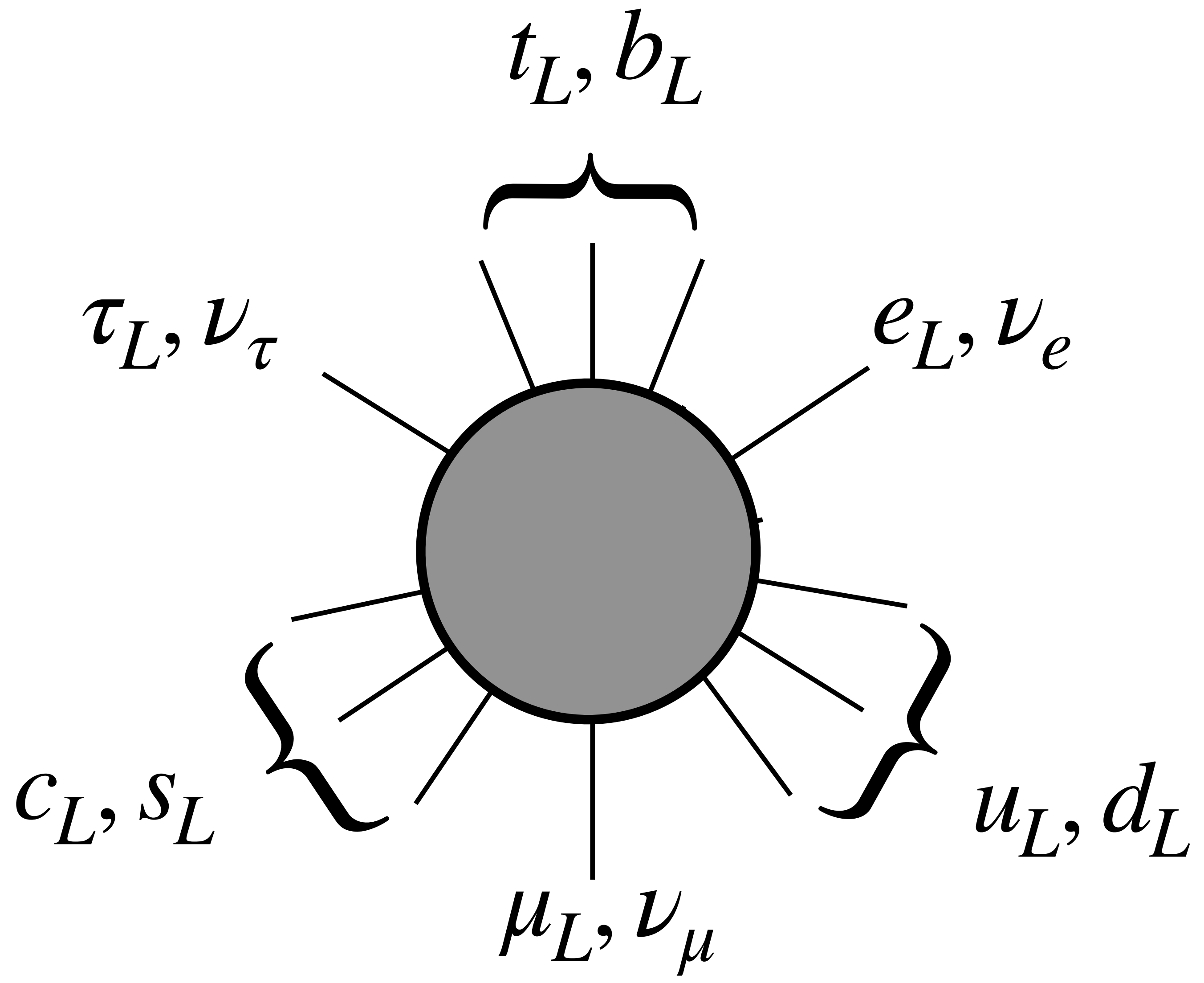
Sphaleron Suppression

- Inside the bubble: 

- Suppression requires "**Strong**" First-Order EWPT (SFO-EWPT).

- **Despite suppression**: Sphalerons @ colliders?



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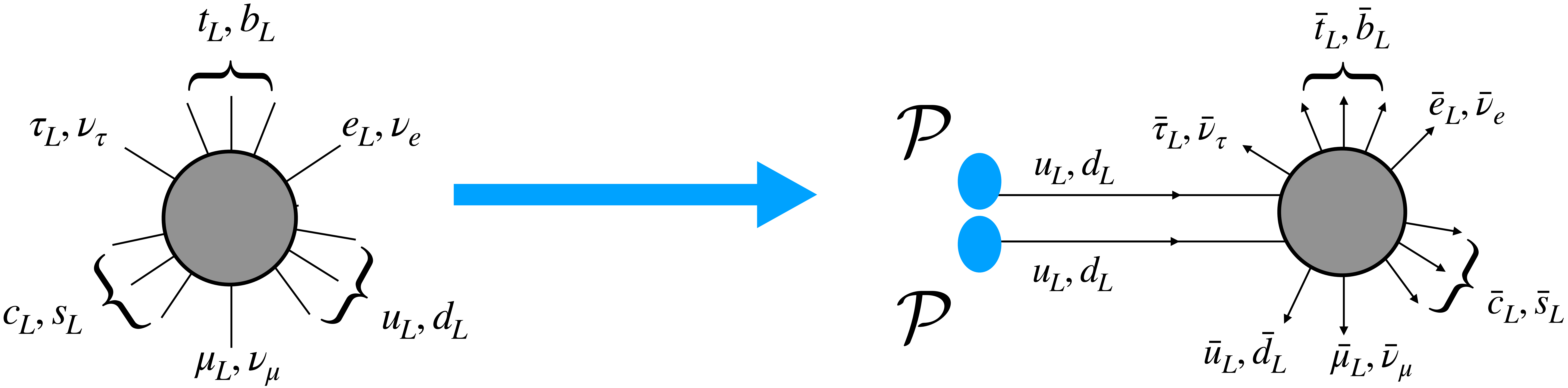
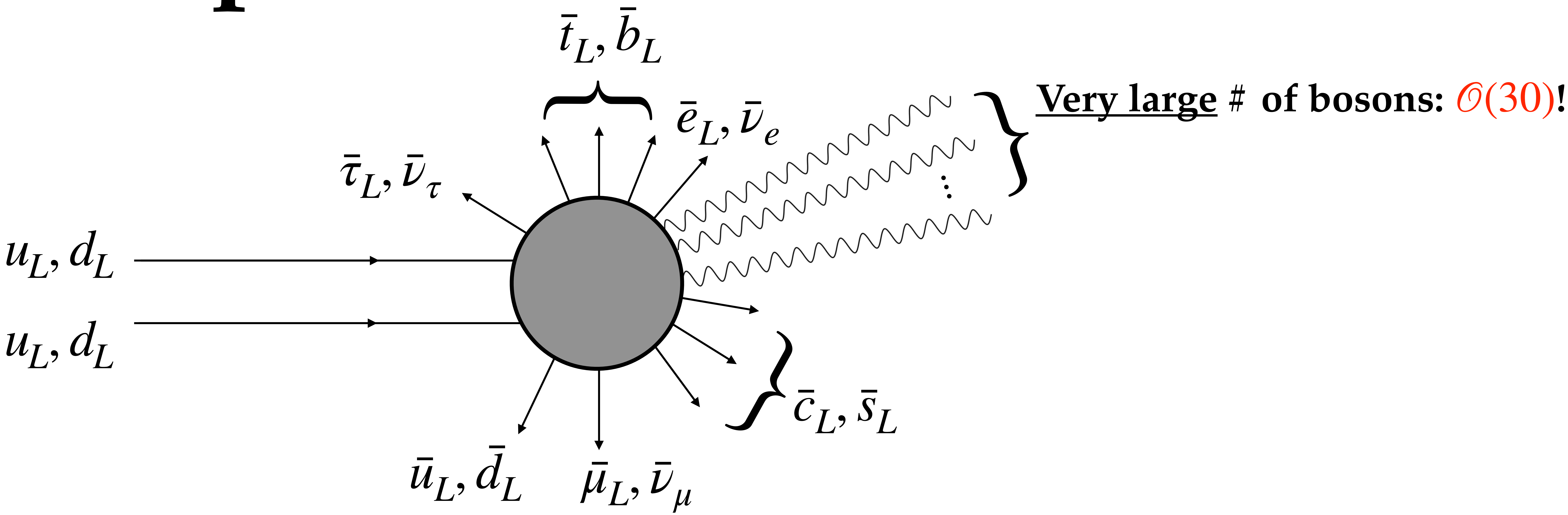


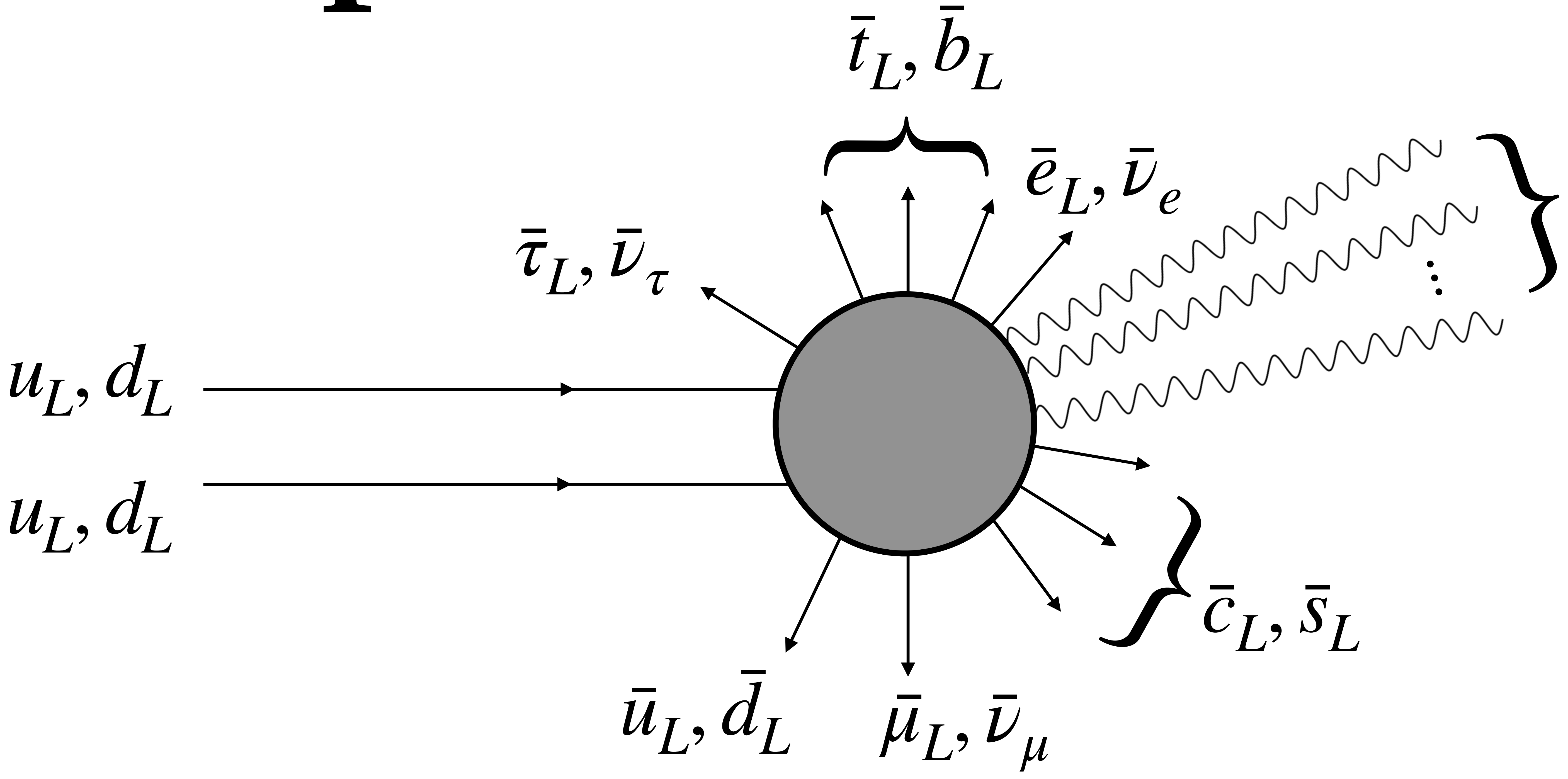
EW Sphalerons at Colliders?



- Possible enhancement if large number of bosons,

  ⇒ Events would **spectacularly light up detectors** at experiments!

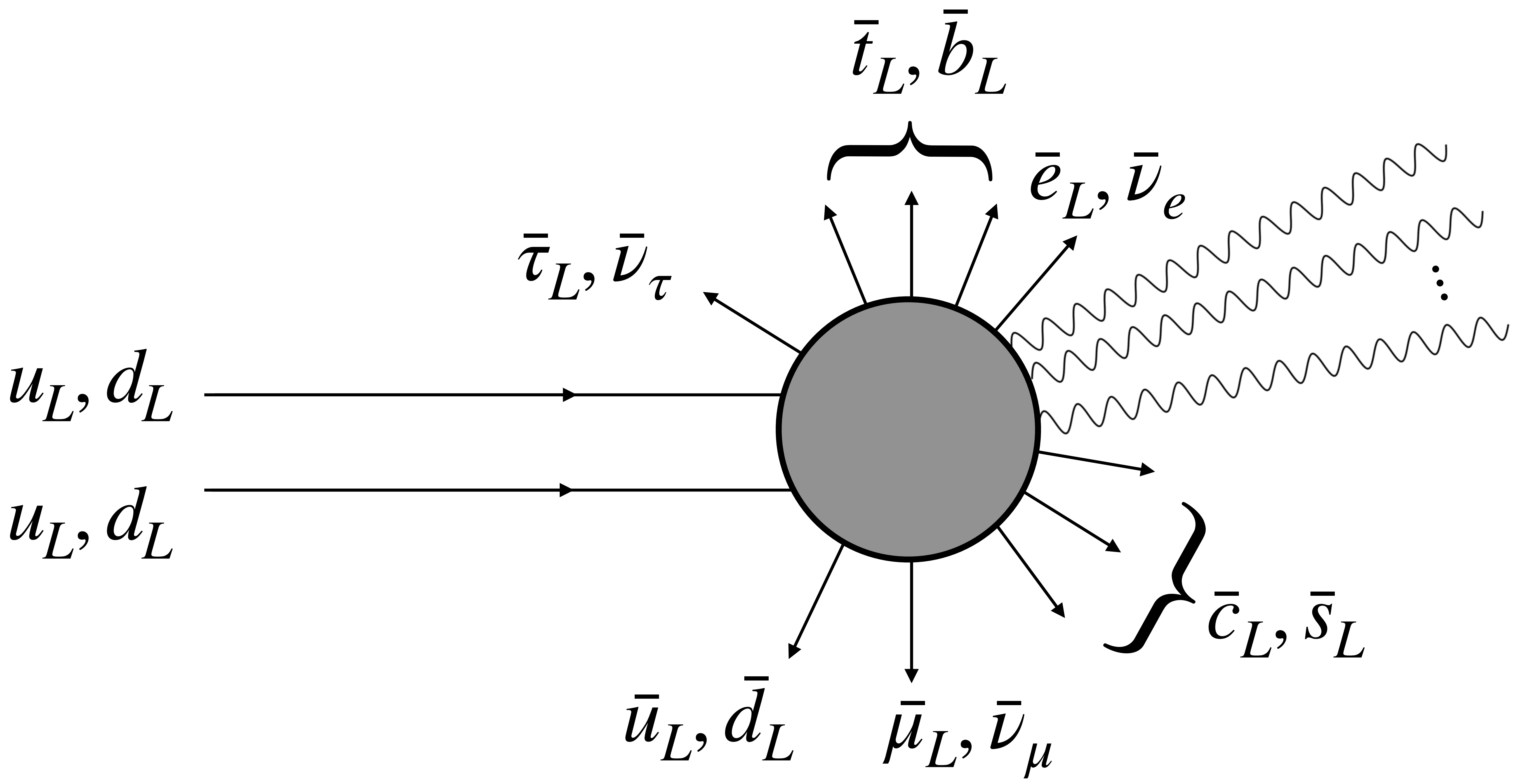
EW Sphalerons at Colliders?



Very large # of bosons: $\mathcal{O}(30)$!

- Possible enhancement if large number of bosons,

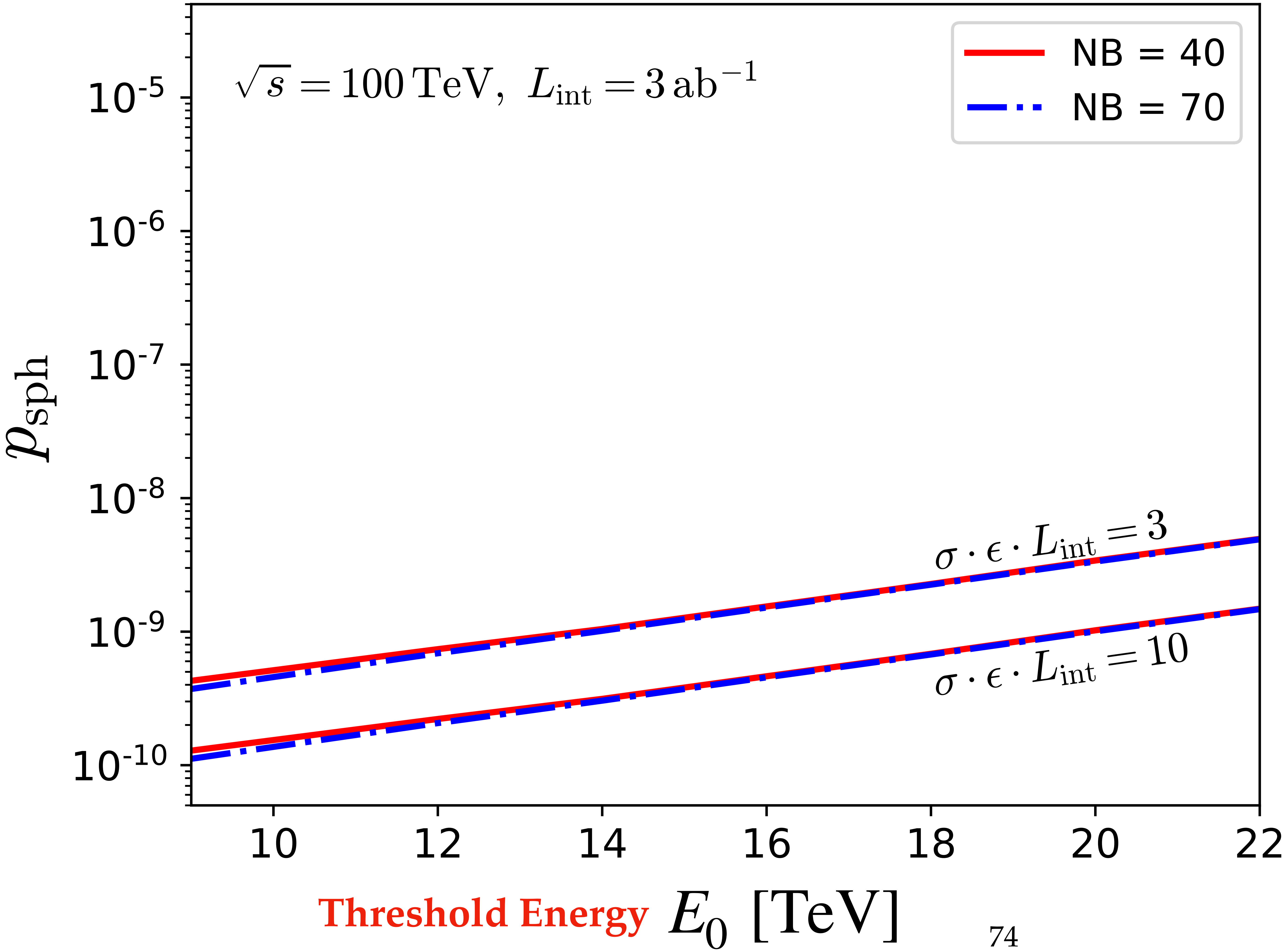
$\Rightarrow$ Events would **spectacularly light up detectors** at experiments!


$\bar{t}_L, \bar{b}_L$
$\bar{e}_L, \bar{\nu}_e$
$\bar{\tau}_L, \bar{\nu}_\tau$
u_L, d_L
u_L, d_L
$\bar{c}_L, \bar{s}_L$
$\bar{u}_L, \bar{d}_L$
$\bar{\mu}_L, \bar{\nu}_\mu$

Sphalerons at the FCC

- Parametrise parton-parton cross section by $p_{\rm sph}$:

$$\hat{\sigma}(E) = \frac{p_{\rm sph}}{m_W^2}\Theta(E - E_0)$$



→ **Event Generator within `HERWIG 7`.**

[AP, Sakurai, Plätzer, arXiv:1910.4761]

EW Sphalerons at Colliders?

[**AP**, Sakurai, Plätzer, arXiv:1910.4761]

EW Sphalerons at Colliders?

[AP, Sakurai, Plätzer, arXiv:1910.4761]

Homework:

(i) What can we learn about the Higgs sector and EWBG?

(ii) New theoretical features in Sphaleron MC.

(iii) Model discrimination, e.g. VS micro-black holes.

(iv) Collaboration with experimentalists for measurements.