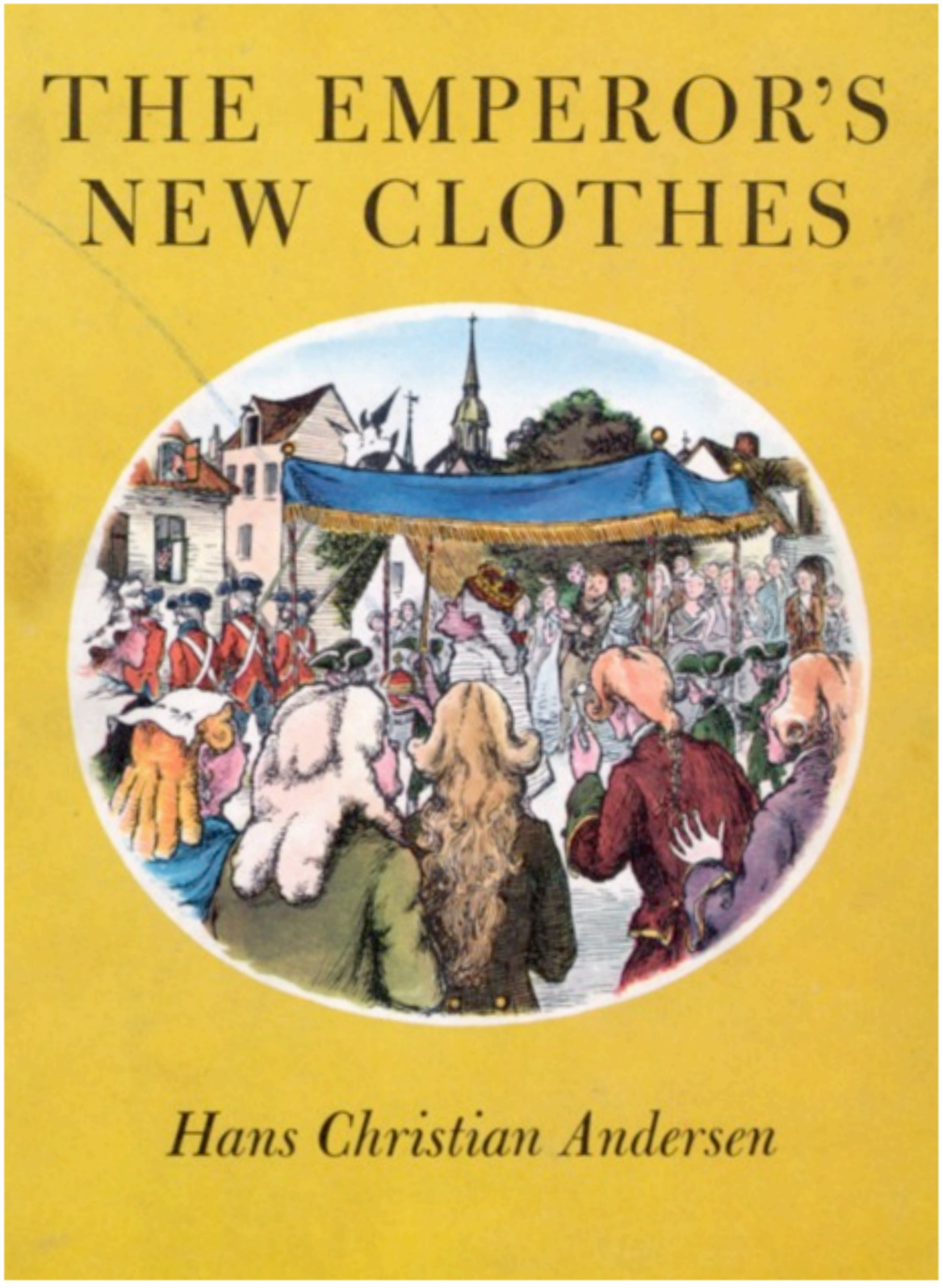
The Emperor's Last Clothes

Overlooking the String Theory Landscape


THE EMPEROR'S
NEW CLOTHES
Hans Christian Andersen

Many years ago, there lived an emperor who cared much about his clothes. One day he heard from two swindlers named Guido and Luigi Farabutto that they could make the finest suit of clothes from the most beautiful cloth. This cloth, they said, also had the special capability that it was invisible to anyone who was either stupid or not fit for his position.

The emperor allowed himself to be dressed in the clothes for a procession through town, never admitting that he was too unfit and stupid to see what he was wearing.

Of course, all the townspeople wildly praised the magnificent clothes of the emperor, afraid to admit that they could not see them, until a small child said:

"But he has nothing on!"

The moral:

It is difficult to see what you don't want to see

The choice of the title is inspired by the reactions to Susskind's paper

"The Anthropic Landscape of String Theory".

In particular by the reactions of those people claiming that they have always known that String Theory would never predict the standard model uniquely, but that they did not think this point was worth mentioning.

Unification versus Uniqueness

Unification

Unification

The success story of physics

- Gravity on Earth ⇔ Planetary Orbits
- Electricity ⇔ Magnetism
- Electrodynamics ⇔ Light
- Space ⇔ Time
- Inertial mass ⇔ Gravitational mass
- Structure of matter ⇔ Electrodynamics
- Strong ⇔Weak ⇔ Electromagnetic Forces (Gauge theory)
- Forces ⇔ Matter (String Theory*)
- Everything ⇔ Gravity (String Theory*)

(*) to be confirmed...

Uniqueness

A series of failures...

Uniqueness

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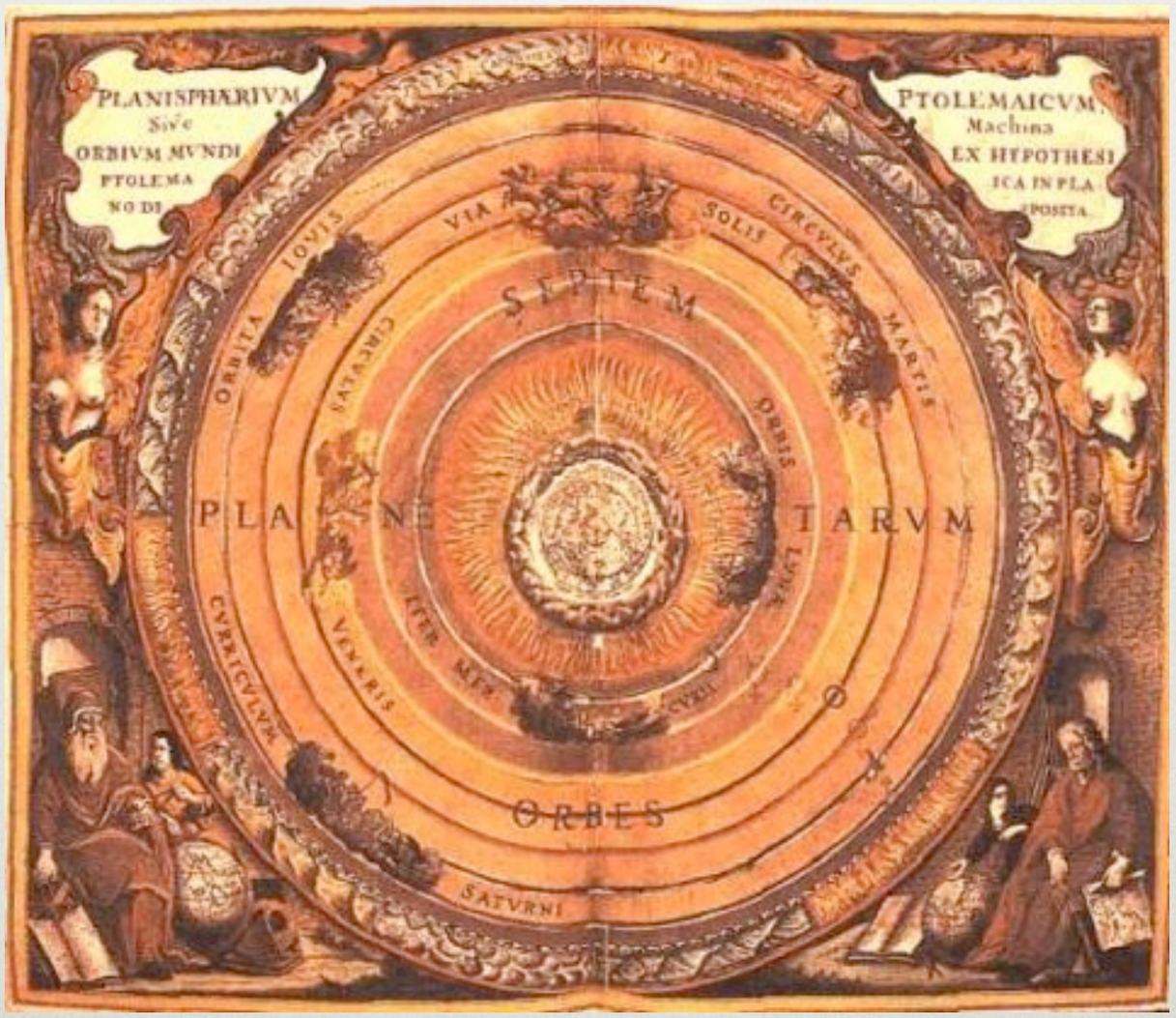
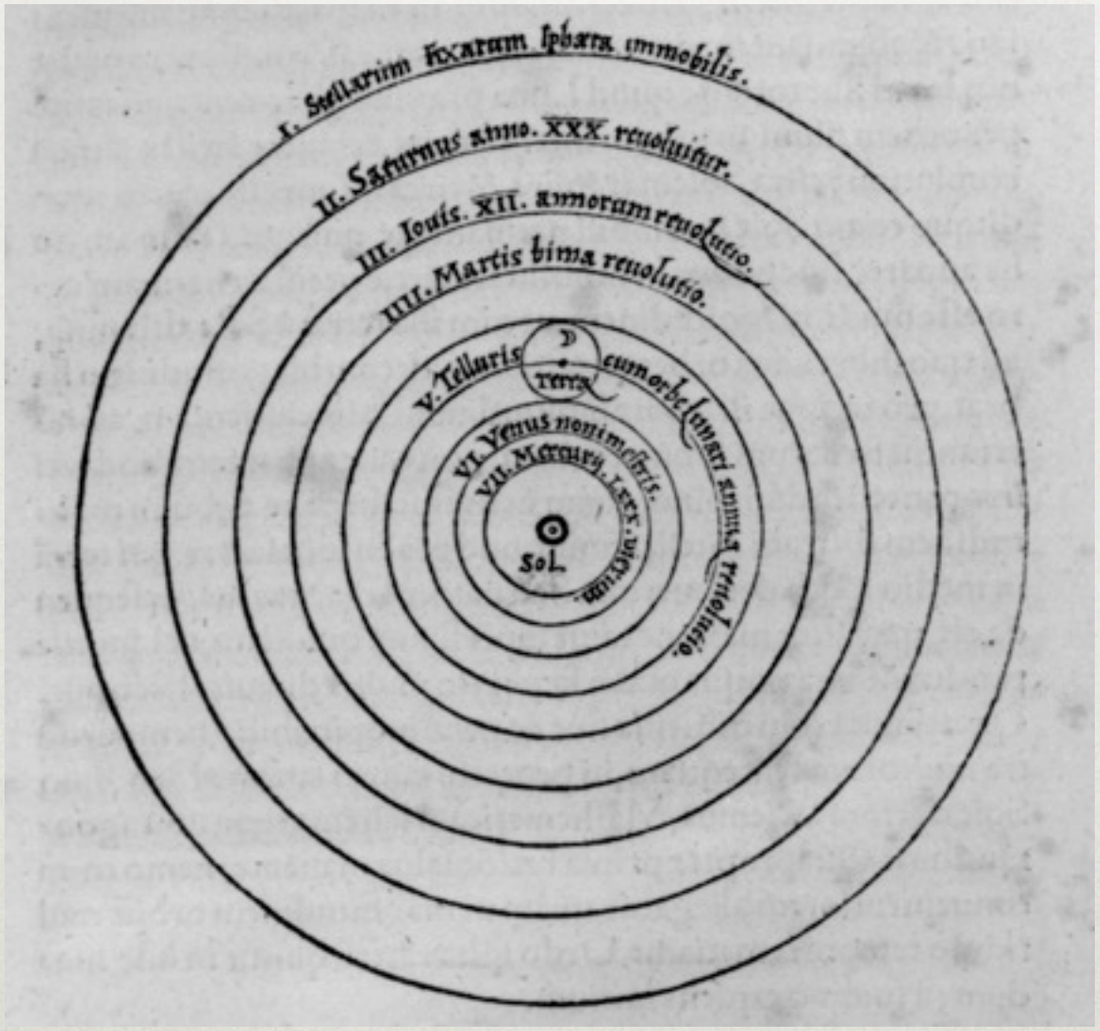


Ptolemaeus
(~ 150 AD)

The Earth is not the center of the solar system

Uniqueness

A series of failures...



Copernicus
(~1500)

The sun is not the center of the Universe

Uniqueness

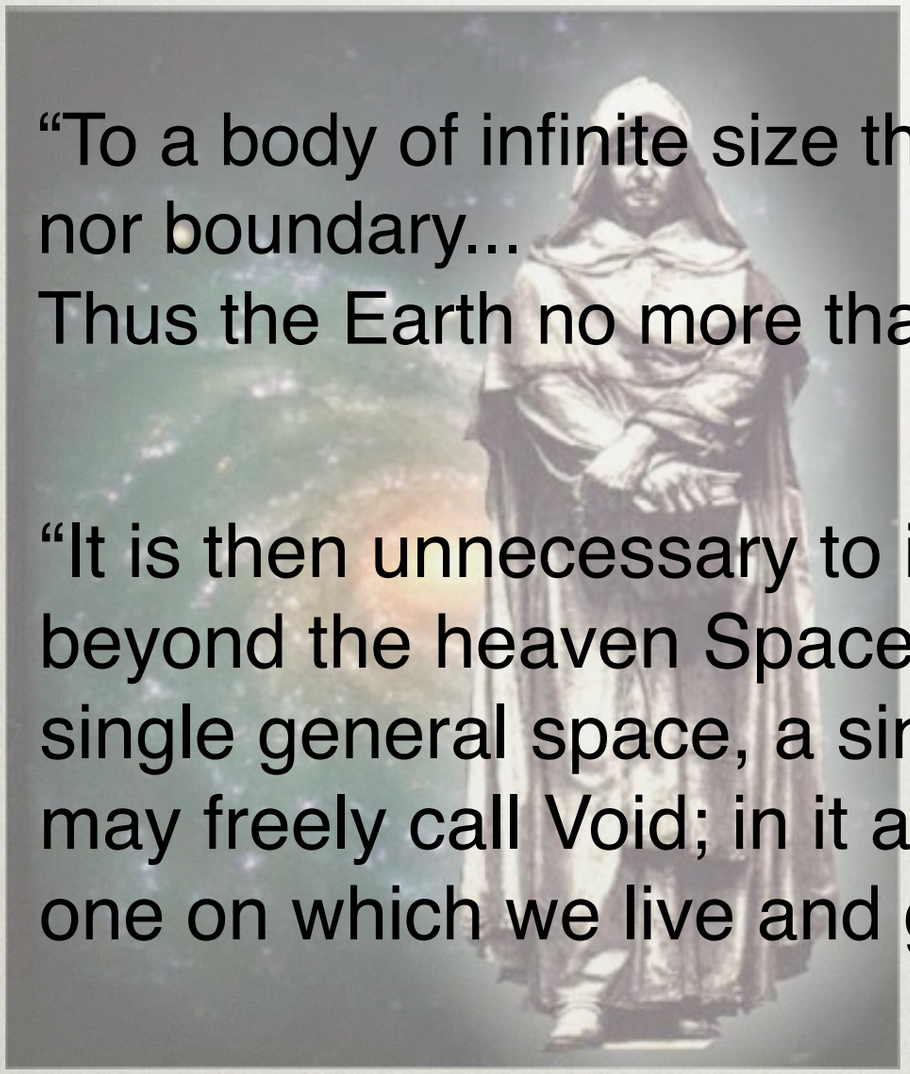
A series of failures...

Giordano Bruno
(17-2-1600)

There are many “Solar Systems”

Uniqueness

A series of failures...



"To a body of infinite size there can be ascribed neither centre nor boundary...
Thus the Earth no more than any other world is at the centre."

"It is then unnecessary to investigate whether there be beyond the heaven Space, Void or Time. For there is a single general space, a single vast immensity which we may freely call Void; in it are innumerable globes like this one on which we live and grow."

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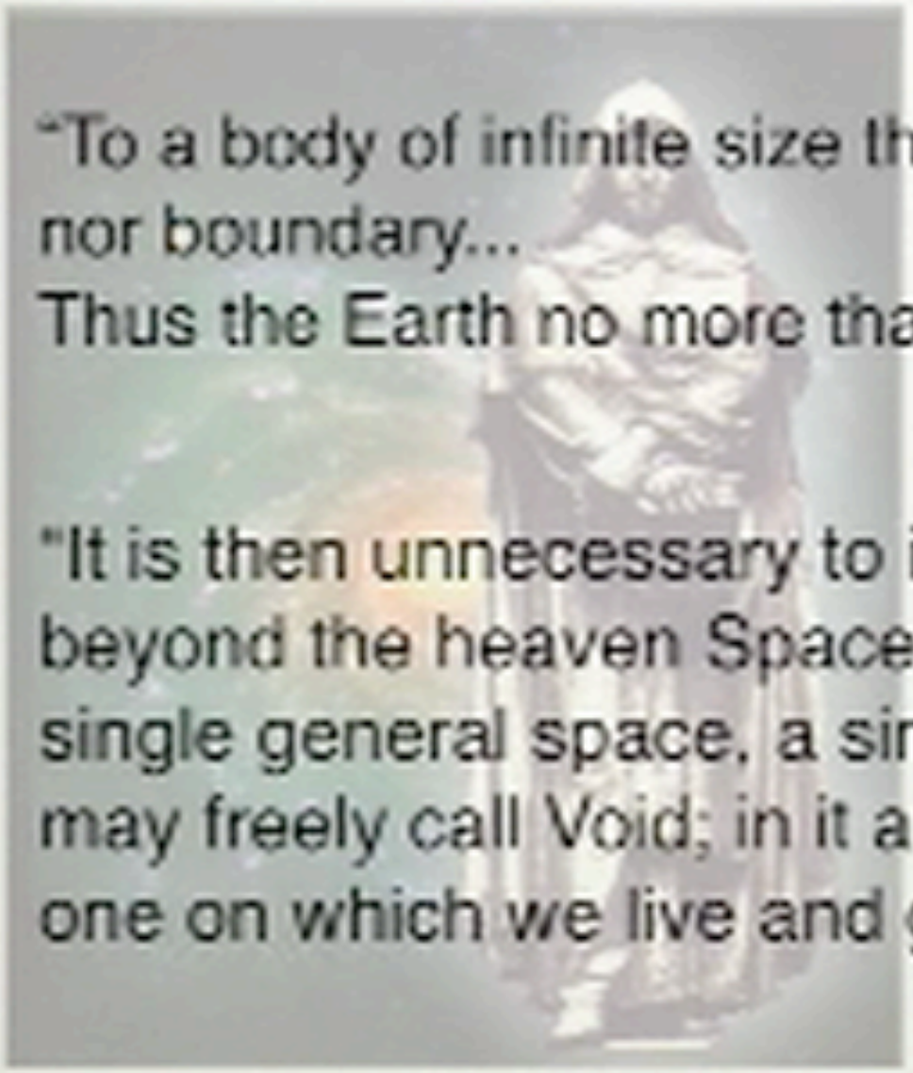

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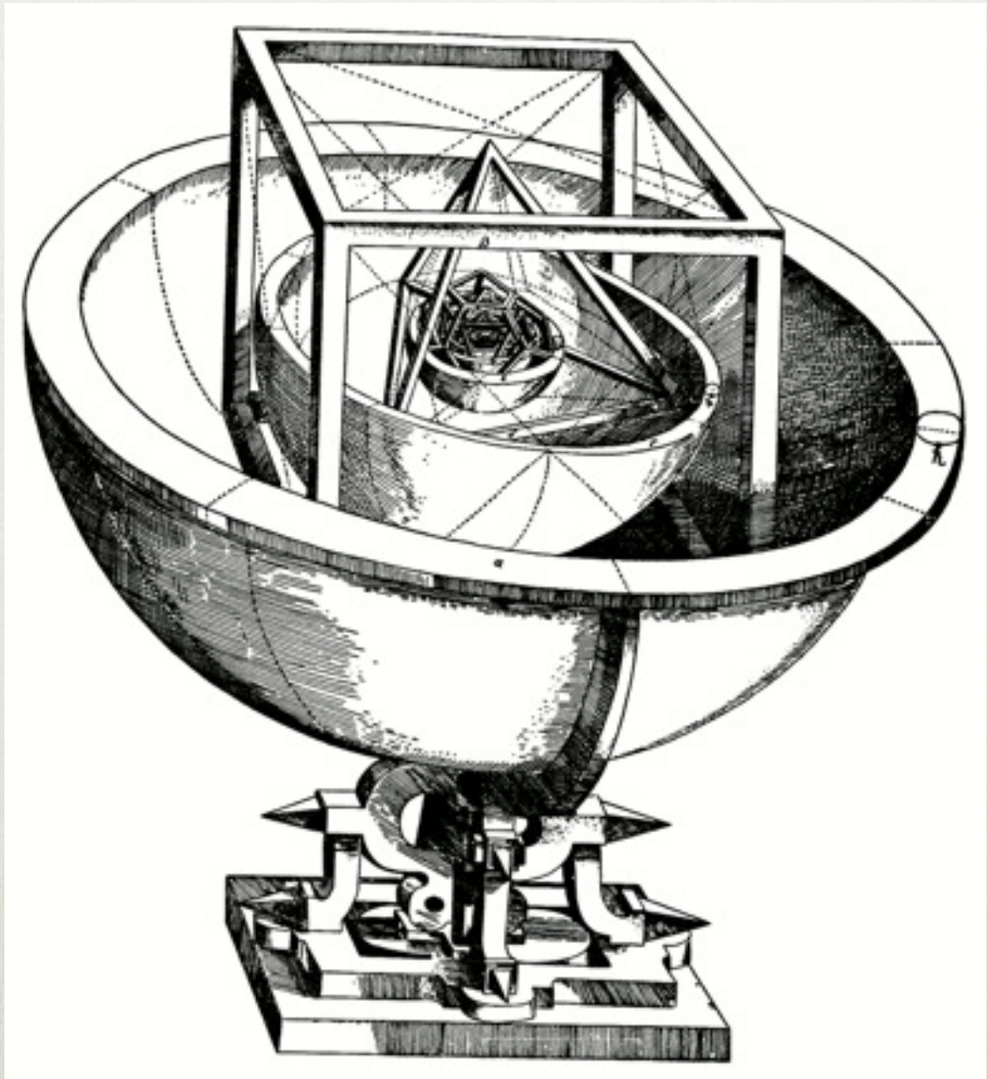
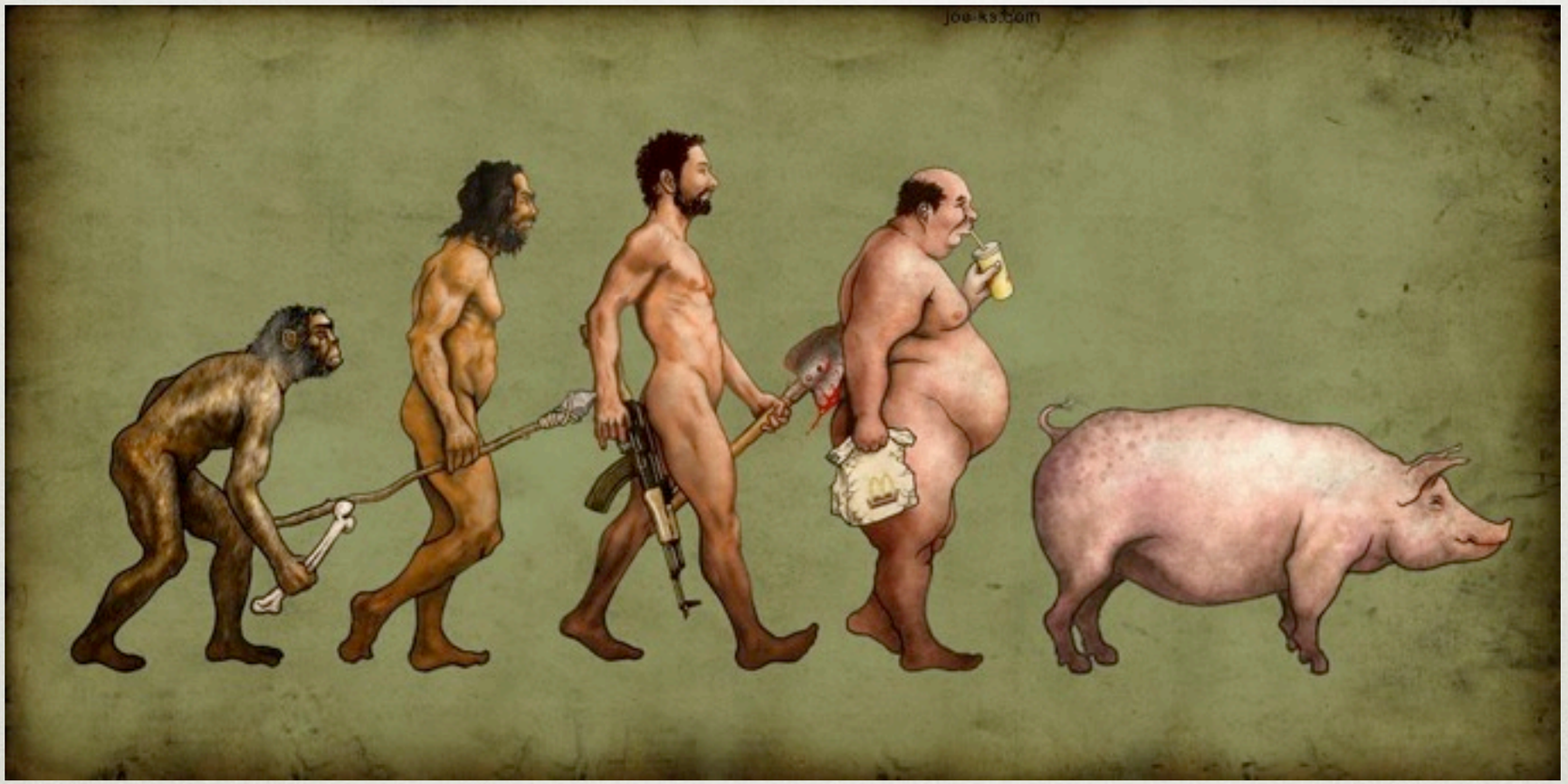


Kepler
(~ 1600)

The solar system is not mathematically unique

Uniqueness

A series of failures...



A human being is just another animal

Uniqueness

A series of failures...

The Great Debate (26 april 1920)

Uniqueness

A series of failures...

Harlow Shapley:

The Milky Way is the entire Universe.

The sun is not in the center of the Milky way.

Heber Curtis:

“Spiral Nebulae” are other galaxies.

Our galaxy is centered around the sun.

The Great Debate (26 april 1920)

Unification / Uniqueness

The Standard Model

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  Einstein + Maxwell theory.
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  Suggests a unique underlying unified theory.
- Then some experimental problems arise:
  - Strong and Weak interactions
  - Muon (quark/lepton families)
  - Parameters (masses, couplings)
- Then some theoretical problems arise:
  Yang-Mills theory: QED is not unique.
  Many other gauge theories are possible.

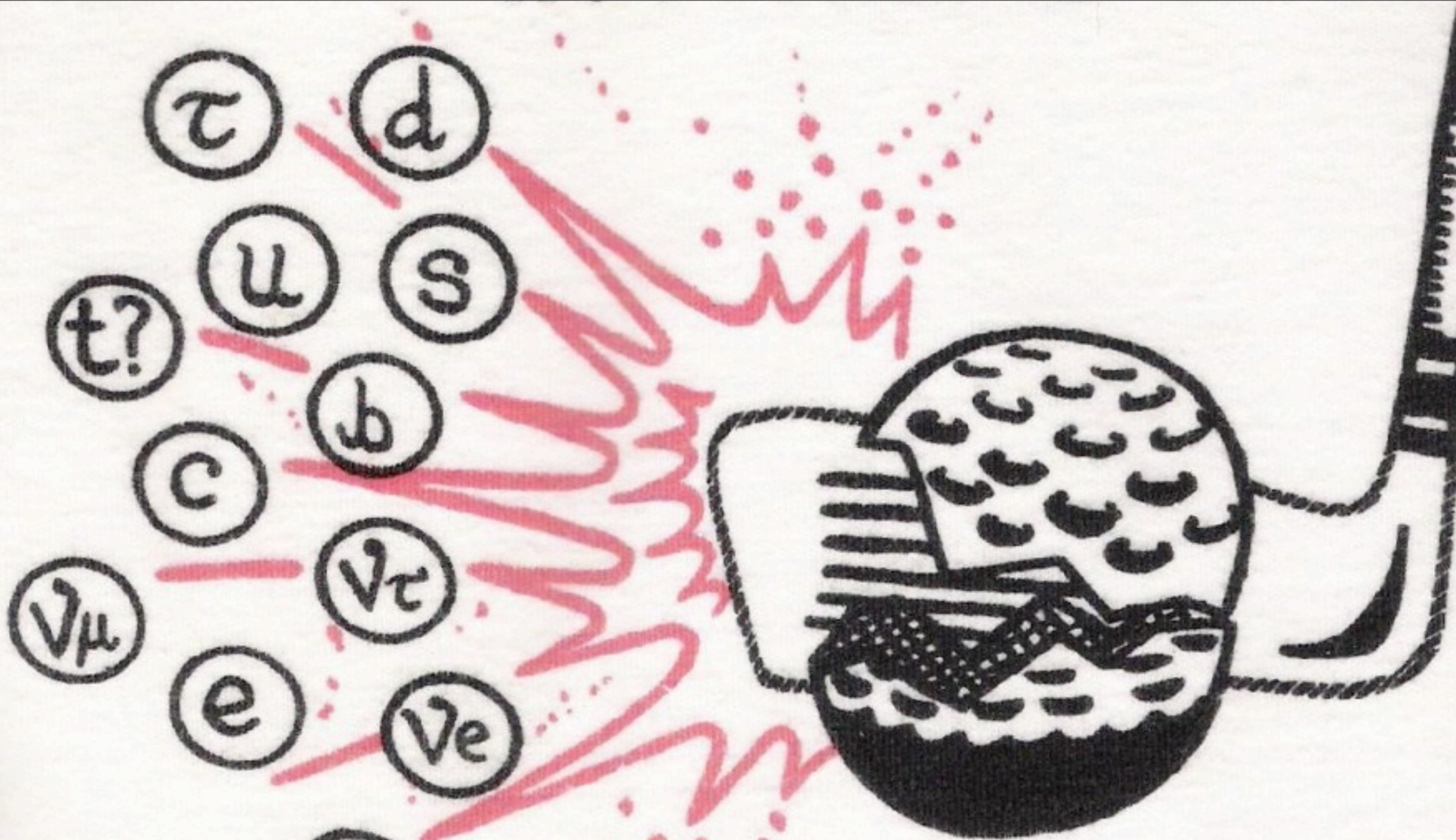
Unification / Uniqueness

The Standard Model

Unification / Uniqueness

The Standard Model

- The Standard Model is discovered
  Conceptual unification: Gauge Invariance
  But uniqueness?? [GUTs: unification, not uniqueness]



SUSSP '80

The Standard Model

- "Theory of almost everything"
- Renormalizable (insensitive to details of short distance physics).
- Remains consistent at least until M_{Planck} (Still true after LHC?)
- Based on some seemingly arbitrary choices:
  - Gauge group $SU(3) \times SU(2) \times U(1)$
  - Representations
  - About 25 real parameters

Feynman about α

There is a most profound and beautiful question associated with the observed coupling constant*, e the amplitude for a real electron to emit or absorb a real photon. It is a simple number that has been experimentally determined to be close to -0.08542455. (My physicist friends won't recognize this number, because they like to remember it as the inverse of its square: about 137.03597 with about an uncertainty of about 2 in the last decimal place. It has been a mystery ever since it was discovered more than fifty years ago, and all good theoretical physicists put this number up on their wall and worry about it.)*

Immediately you would like to know where this number for a coupling comes from: is it related to pi or perhaps to the base of natural logarithms? Nobody knows. ***It's one of the greatest damn mysteries of physics: a magic number that comes to us with no understanding by man.*** *You might say the "hand of God" wrote that number, and "we don't know how He pushed his pencil."*

We know what kind of a dance to do experimentally to measure this number very accurately, but we don't know what kind of dance to do on the computer to make this number come out, without putting it in secretly!

Formulas for α

$$\alpha = 2^{-4}3^{-3}\pi$$ *Heisenberg*

$$\alpha = \frac{9}{8\pi^4}\left(\frac{\pi^5}{2^4 5!}\right)^{1/4}$$ *Wyler*

$$\alpha = \frac{29}{\pi}\cos(\frac{\pi}{137})\tan(\frac{\pi}{(137\times 29)})$$ *Gilson*

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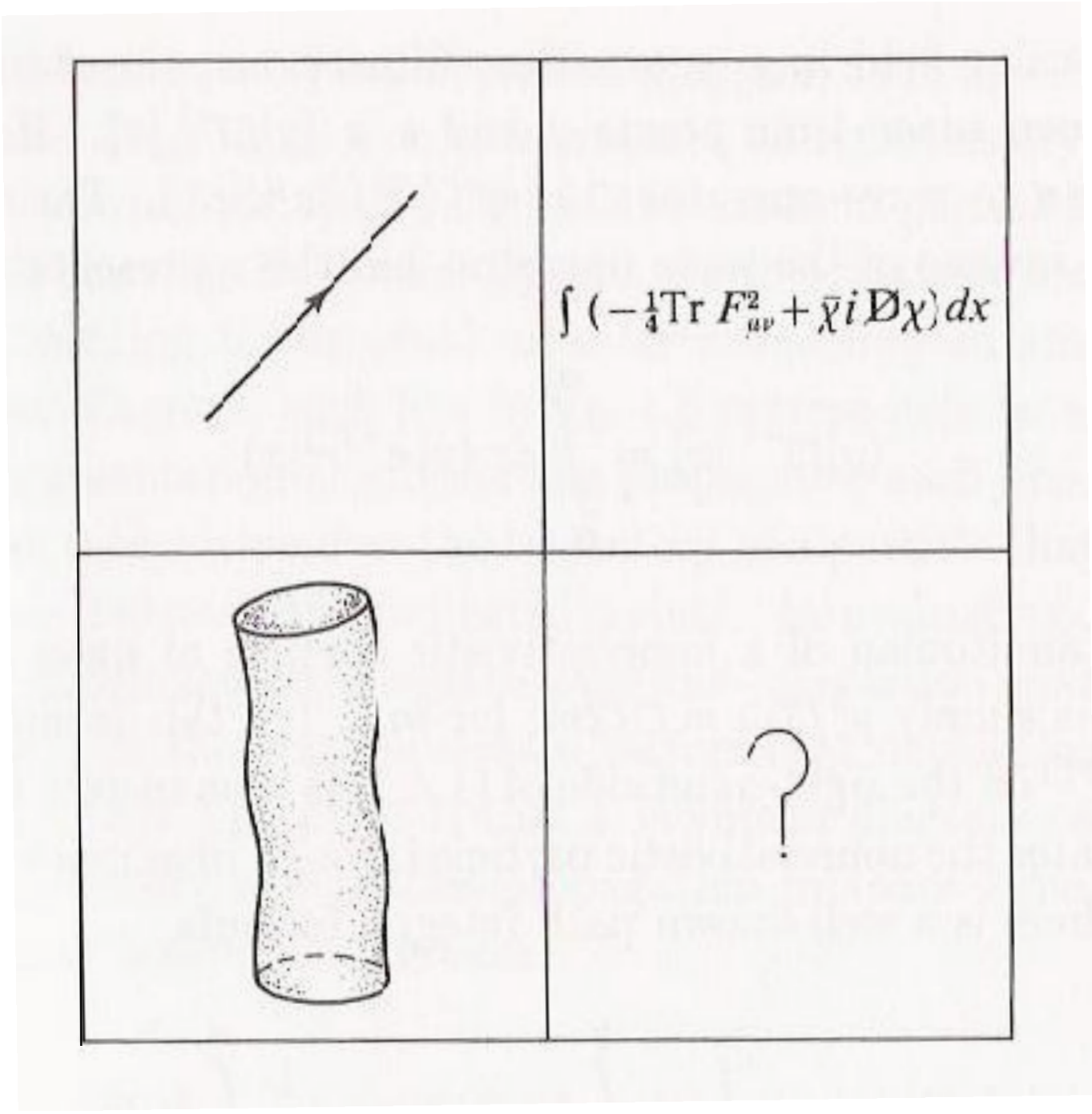
Green, Schwarz, Witten 1987



What is string theory?

A hypothetical theory which in various perturbative limits produces known theories with magical properties.

Does it exist?
Is it unique?
Is there a simple formula for it?

What we know about it follows from properties of the perturbative theories, duality, supersymmetry, and some controllable non-perturbative physics.

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  (if we can define it...)
- But there is another revolution most people preferred to overlook: The string vacuum revolution.

1984-2006:
A Slow Revolution

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A. Strominger,
"Calabi-Yau manifolds with Torsion", 1986

All predictive power seems to have been lost.

All of this points to the overwhelming need to find a dynamical principle for determining the ground state, which now appears more imperative than ever.

Lerche, Lüst, Schellekens
"Chiral, Four-dimensional Heterotic Strings From Self-Dual Lattices", 1986

$(\Gamma_{22}\times D_3\times(D_7)^9)_L$, a Euclidean lattice of dimension 88. A lower limit on the total number of such lattices is provided by the Siegel mass formula [21] [22]

this number is of order 10^{1500} !

It seems that not much is left of the once celebrated uniqueness of string theory.

Even if all that string theory could achieve would be a completely finite theory of all interactions including gravity, but with no further restrictions on the gauge groups and the representations, it would be a considerable success.

A Cern Cafetaria Napkin (~ 1988)

All gauge theories

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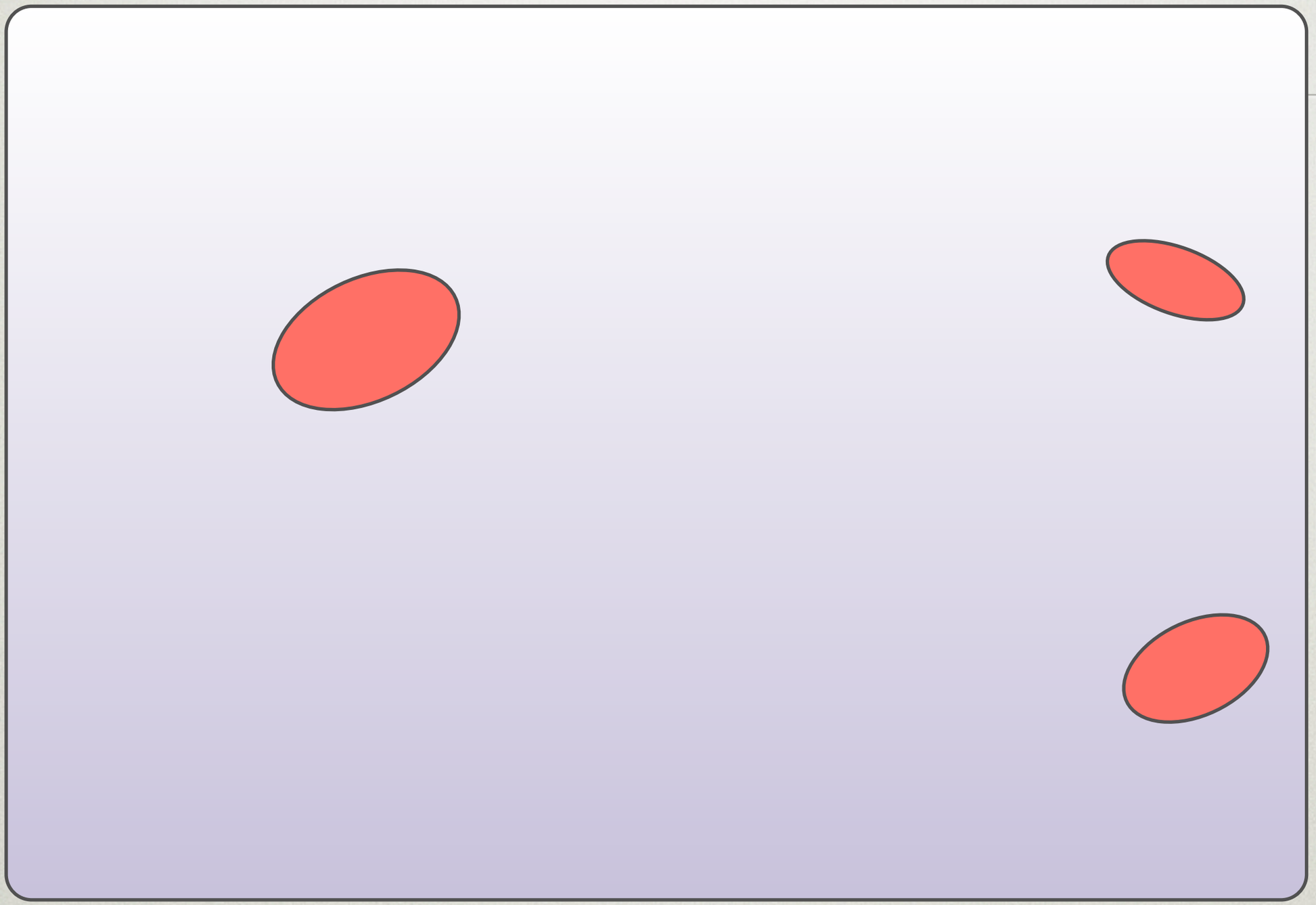

Complexity

All gauge theories

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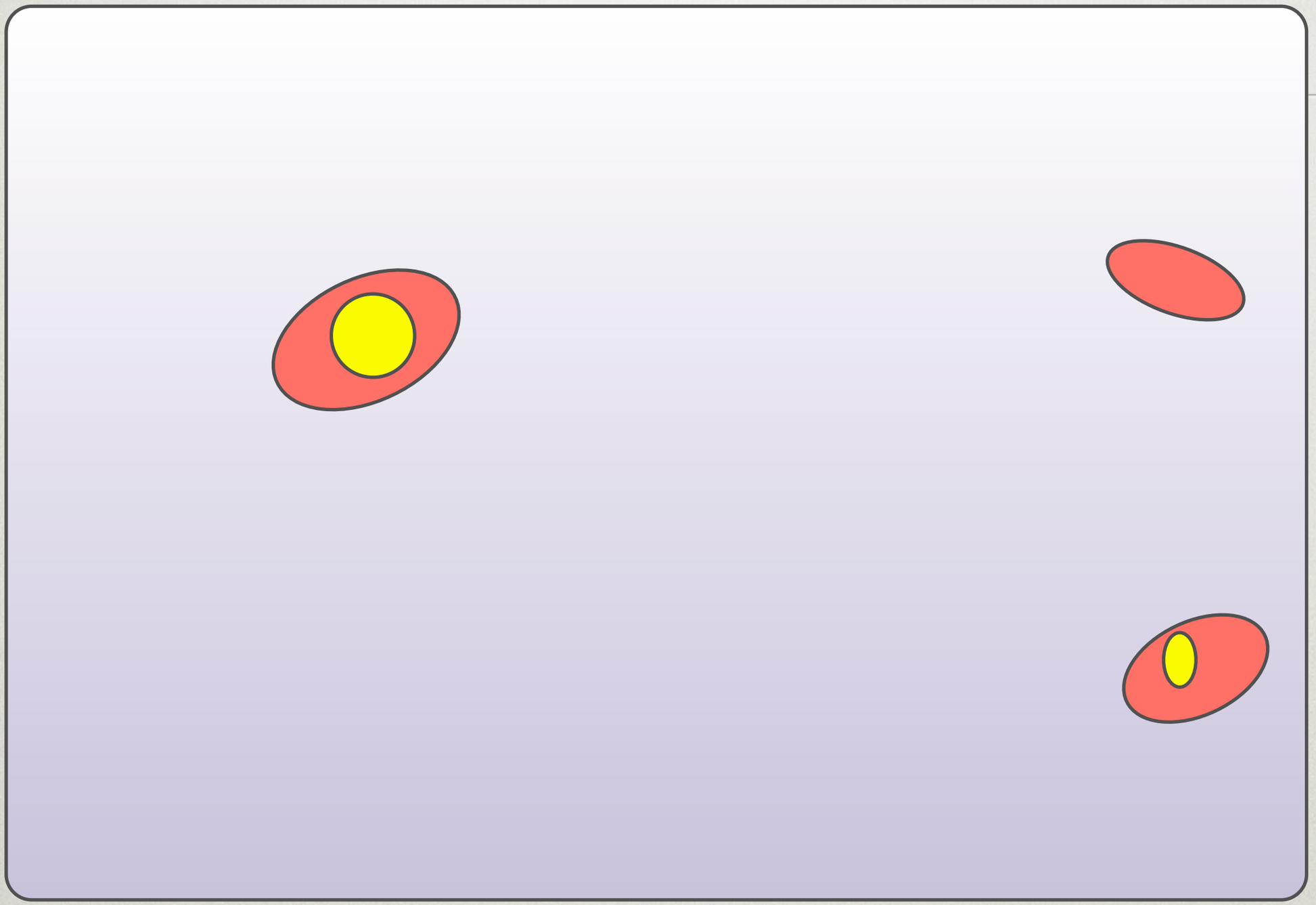

Complexity
Life

All gauge theories

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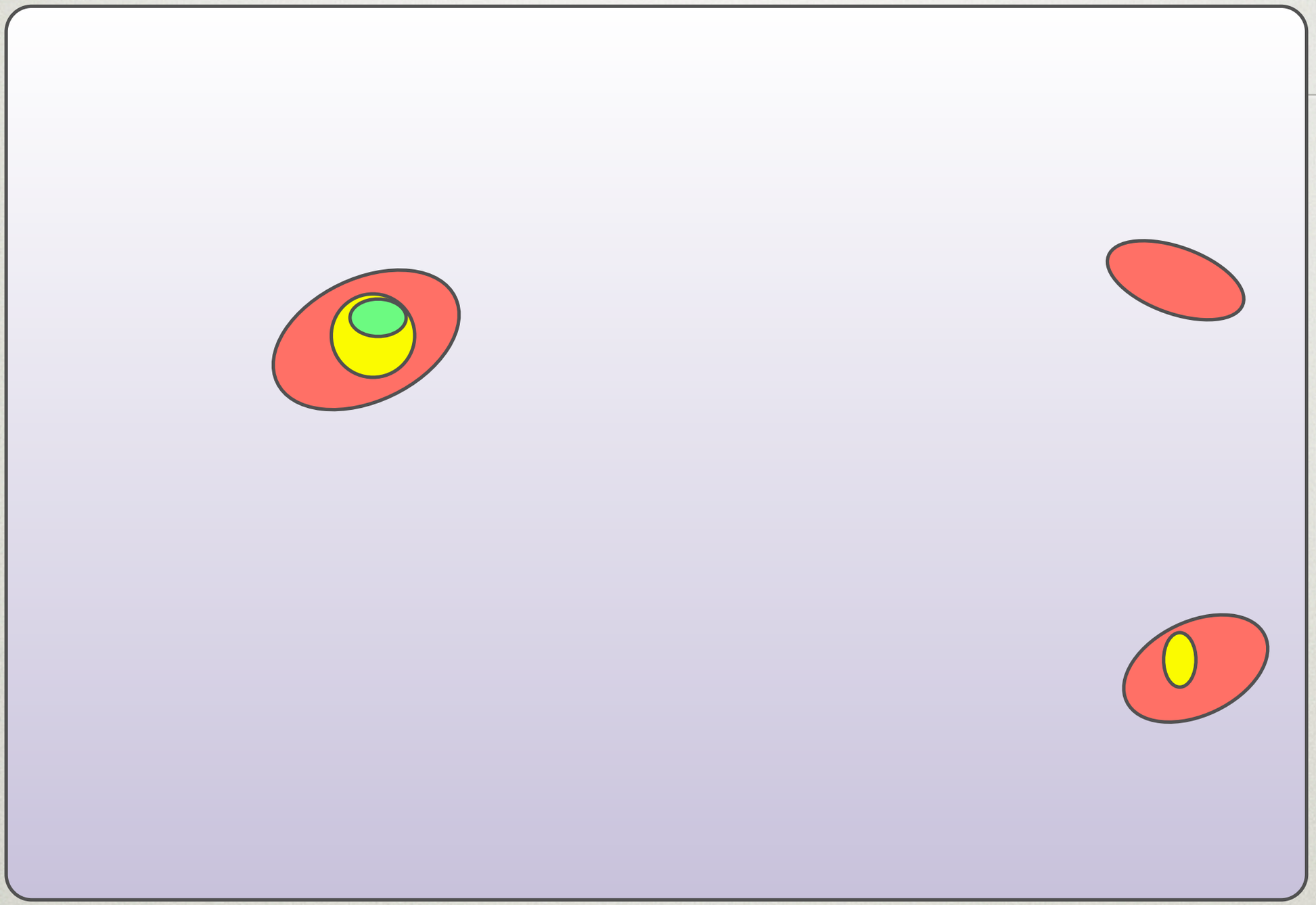

Complexity
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Intelligence

All gauge theories

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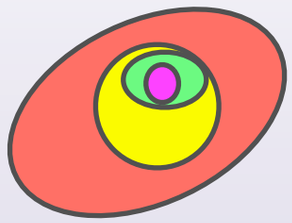
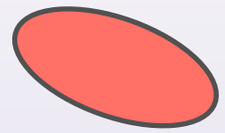
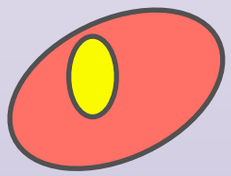
Unique vacuum







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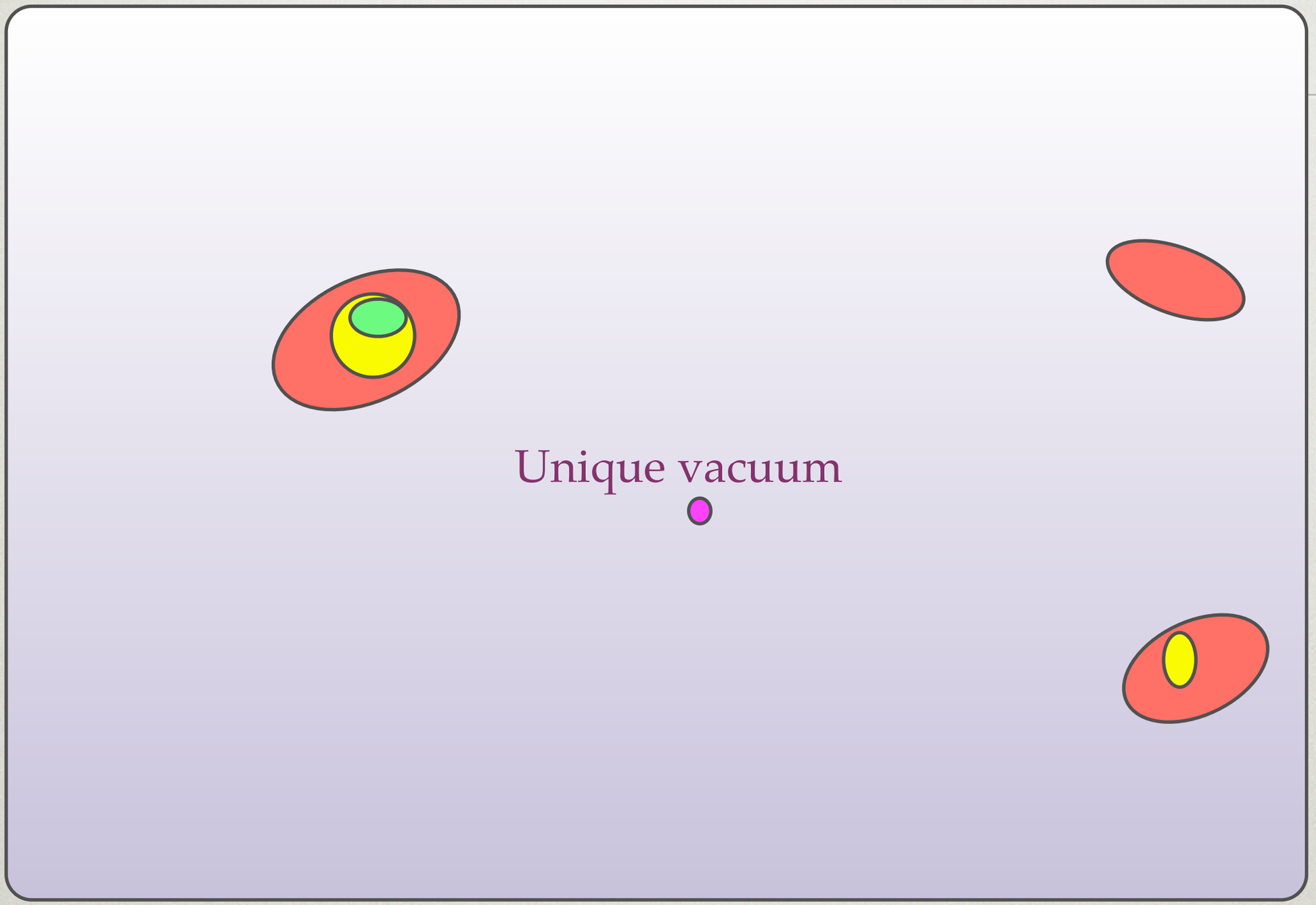

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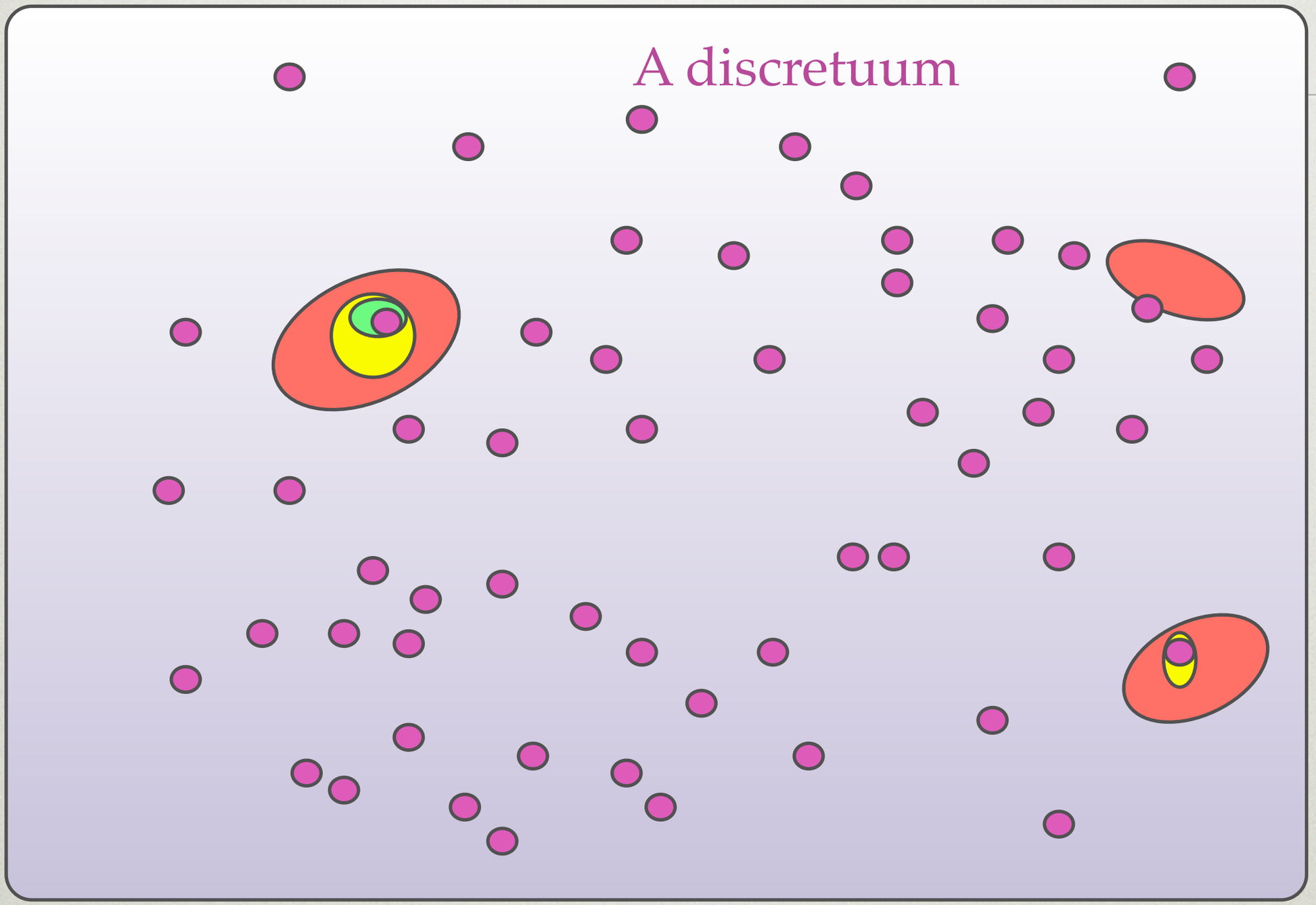

Dutch version
(1998)

physics/0604134

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- .....
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- .....

M.Dine
hep-th/0402101

Faced with this plethora of states, I, for a long time, comforted myself that not a single example of a (meta)stable ground state of this sort had been exhibited in a controlled approximation, and so perhaps there might be some unique or at least limited set of sensible states.

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Quantization of Four-form Fluxes
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- 2003: "The Anthropic Landscape of String Theory"
(L. Susskind)

The modern version of the story

Many years ago, there lived some physicists who cared much about the uniqueness of their theories. One day they heard from two swindlers that they could make the finest theory, which was absolutely unique.

Of course, all the townspeople wildly praised the magnificent unique theory, afraid to admit that it had “anthropic principle” written all over it, until Lenny Susskind shouted:

"String Theory has an anthropic landscape"

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Why a Landscape is Needed

Gedanken calculations

Two independent computations

1. Computation of chemical/nuclear complexity on the space of gauge theories.
2. Computation of a mathematically unique UV theory.

How could these give the same answer?

This is not about statistics:

These are mathematical calculations that will always give the same answer. There is only one "chance" to get it right.

This is not circular:

Even if the UV theory selects by some mathematics a unique answer, this not invalidate the nuclear physics/chemistry calculation. Renormalizability implies precisely that UV physics is irrelevant for these calculations.

CC versus SM

Cosmological constant:

$$S = -\int \mathrm{d}^4x\sqrt{-g}\left(\frac{1}{2\kappa^2}R - \Lambda\right)$$

- Naive Quantum Gravity estimate: $\approx (M_{Planck})^4$
- Standard Model or Higgs contribution: $\approx 10^{-60}\,(M_{Planck})^4$
- Observed: $\approx 10^{-123}\,(M_{Planck})^4$ (extremely small but non-zero)

$$\Lambda > 0: \quad \text{Universe expands (dS)}$$

$$\Lambda < 0: \quad \text{Universe collapses (AdS)}$$

CC versus SM

The first "gedanken computation" for the CC has already been done (Barrow and Tipler, 1986; Weinberg 1987).

But: we can discuss the SM, but not the CC without knowing the fundamental theory of gravity. This implies a risk of circularity in the argument. If $\Lambda=0$ in the fundamental theory of gravity, perhaps it makes no sense to even discuss the case $\Lambda\neq0$.

Furthermore, if the second gedanken calculation were to give a unique answer, it would be no surprise if that answer was withing the anthropic window: the obvious mathematically unique answer is $\Lambda=0$.

Another point of view...

David Gross,
Summary talk of "Strings 2007", Madrid:

"If we could just explain the smallness of the CC by
a mechanism, rather than invoking the anthropic principle,
most people in this audience would abandon the anthropic
principle for other parameters very quickly"

Uniqueness of the Standard Model

Reasons why the standard model should be unique:

Uniqueness of the Standard Model

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Uniqueness of the Standard Model

Reasons why the standard model should be almost unique:

- Would make everything easier
- We can analyse it with our primitive computers
- We can store it all on our hard disks

But what is “almost” anyway?

The old anthropocentric mistake

This line of thought fits in very well with a series of insights that pointed out our modest place in the cosmos. Our planet is not the center of the solar system, our sun is just one of many stars and not even a very special one, and the same is true for our galaxy. It seems natural to assume that also our universe, including the quarks, leptons and interactions we observe is just one out of many possibilities.

The "Anthropic" Principle

Anthropic Misconceptions

- It is not about human beings.

  "Anthropic" is a poor choice of name.

- It is not about Carbon based life.
- It is not even about quark/lepton based life.
- There may be many regions in the gauge theory landscape that allow "life".
- There is no reason why the combination of UV physics and the requirement of existence of observers should select the Standard Model uniquely.

Brief History

1973: Brandon Carter

Carter proposed the “Anthropic Principle” in Krakow, Poland in 1973, during a special two-week series of lectures commemorating Copernicus's 500th birthday. He proclaimed that humanity does indeed hold a special place in the Universe, an assertion that is the exact opposite of Copernicus's now universally accepted theory. His statement that day is now referred to as the Weak Anthropic Principle (WAP) and runs like this: “The observed values of all physical and cosmological quantities are not equally probable, but they take on the values restricted by the requirement that there exist sites where carbon-based life can evolve and by the requirement that the Universe be old enough for it to have already done so.” Later, Carter also proposed the Strong Anthropic Principle (SAP), which states that the Universe had to bring humanity into being. The SAP states that “the Universe must have those properties which allow life to develop within it at some stage in its history.”

Anthropic principleS

- Many versions have been proposed.
- Two main categories:
  - Strong: anthropocentric
  - Weak: anti-anthropocentric

Totally opposite points of view have been advocated by the same people

1987: Barrow and Tipler

“The Anthropic Cosmic Principle”

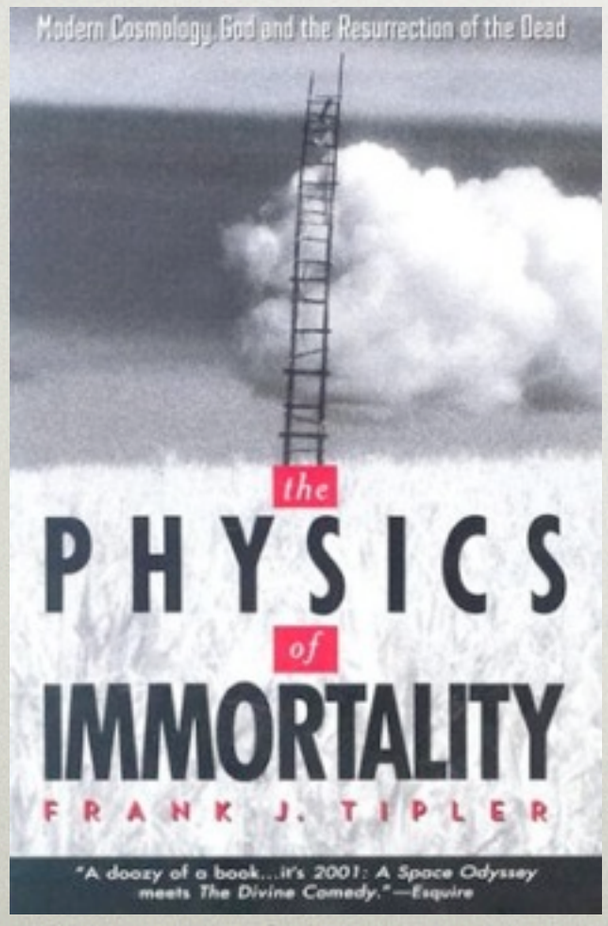
Final anthropic principle (FAP): "Intelligent information-processing must come into existence in the Universe, and, once it comes into existence, it will never die out."

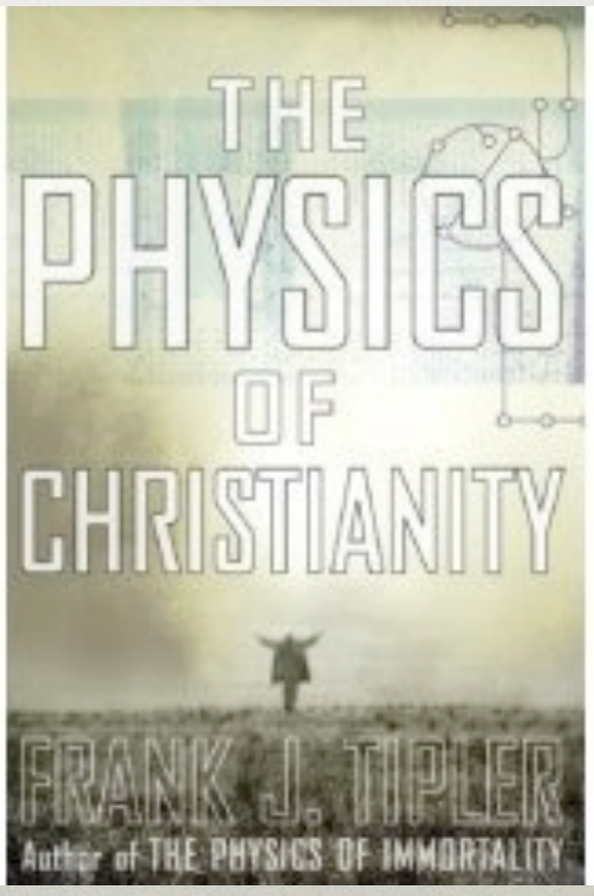
1987: Barrow and Tipler

“The Anthropic Cosmic Principle”

Final anthropic principle (FAP): "Intelligent information-processing must come into existence in the Universe, and, once it comes into existence, it will never die out."

Other work by F. Tipler





From a book review
by Larry Krauss:

"I was first tempted to describe Tipler's new book as nonsense, but I soon realized that that would be unfair to the concept of nonsense."

The Anthropic Principle and String Theory

- The Anthropic Principle does not really make any sense without something like a (String Theory) Landscape to control the available options.
  [and Eternal Inflation (or equivalent) to populate the Landscape].

- Is an inevitable consequence of String Theory.
- Until 2000, there were almost no papers relating String Theory and the Anthropic principle.
- Without anti-anthropic prejudices, we might have predicted the "Anthropic Landscape of Quantum Gravity".

Anthropic windows versus anthropic probabilities

- In order for life to exist, our universe must be within an anthropic window in parameter space. This is sometimes called "tautological". However the additional statement I am making is that the existence of solutions within the window requires either a landscape (or a miracle). The existence of a landscape is not tautological, it is simply a verifiable property of a given theory.

- This should not be confused with the computation of anthropic probabilities within a window. This requires control over initial probabilities, landscape densities and the probability for life to occur. In addition the result is never more than a probability: we may simply be rare.

The final decision on whether the value of a parameter is determined anthropically is determined by the distribution of its values in a more fundamental theory.

Once we know the "more fundamental theory", the fact that a parameter is anthropic is usually not worth much more than a footnote. The theory itself is obviously more important than the fact that it has anthropic and non-anthropic solutions:

The landscape itself is much more important than the "anthropic principle".

However, we are using the anthropic principle here in order to make educated guesses about the features that such a "more fundamental theory" can be expected to have.

This is not about "giving up" or a "cop-out". It does not remove the need for finding a "more fundamental theory". It just leads to more reasonable expectations of such a theory, and thereby avoids disappointments.

Anti-anthropic check list

With which of the following do you disagree?

- **The standard model is probably not a unique mathematical solution of anything.**
- **Not all alternative solutions allow observers.**
- **The number of alternative solutions should be sufficiently large to make the existence of a solution with observers plausible.**
- **We live in the most probable universe which allows observers.**

"From this point of view it would seem absurd that exactly those parameter values would follow from a mathematical computation. We would be left with a much bigger riddle than the one we are trying to solve.

For this reason I was very satisfied when it turned out that String Theory was highly non-unique.

If our planet were the only one in the Universe, it would be a mystery why precisely that single planet would allow life. The fact that there are billions of planets makes the mystery considerably less severe. Analogously, the fact that many kinds of universes are possible makes the existence of conditions for intelligent life in our universe considerably less absurd than if there would be just one possibility."

In other words...

G.F.R. Ellis (2006)

Many physicists reject any Anthropic form of reasoning. They regard it as a cop-out resorted to when physical theories fail to give the needed answers, and seek to obtain a full answer from physics alone [22, 25]. One possibility is that there is a fundamental theory of everything that determines the nature of physics completely, with no arbitrary parameters left, and this still to be discovered theory just happens to be of such a nature as to admit life.

However in this case the Anthropic issue returns with a vengeance: *How could it be that such a theory, based for example on variational principles and the specific invariance groups of particle physics, could just happen to lead to biophilic parameter values*? There is no clear way to answer such a question. Uniqueness of fundamental physics resolves the parameter freedom only at the expense of creating an even deeper mystery, with no way of resolution apparent. In effect, the nature of the unified fundamental force would be pre-ordained to allow, or even encourage, the existence of life; but there would be no apparent reason why this should be so.

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The String Theory Landscape

Theory of everything?

Too ambitious?

We already have a theory of 1/4 of everything known: QCD.
We almost have a theory of 3/4 of everything known: The Standard Model.
(open problems: Higgs, QED Landau pole).

So why would it be too ambitious to hope for a theory of
the fourth interaction we know?

String Theory has the remarkable property that it already contains all matter it can couple to.
So it ***must*** contain everything, even everything we don't know
(including "dark matter" and "dark energy")

Early insight (~1982)...

Soon after starting graduate school, I went to see Howard Georgi. “What are you thinking about?” he asked me. I rattled off several things that seemed interesting to me, ending with, “... and quantum gravity.” **“Don’t waste your time!”** he barked, “There’s no decoupling limit in which it’s sensible to consider quantum gravity effects, while neglecting other interactions. Unless you know particle physics all the way up to the Planck scale, you can never hope to say anything predictive about quantum gravity.” Howard was, of course, completely correct.

Jacques Distler, “Musings”

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Jacques Distler, "Musings"

Quantum gravity and matter

- From a QFT perspective, quantum gravity is “non-renormalizable”. It is a perfectly acceptable effective theory, but in order to be able to discuss it at arbitrarily small scales we need to tame the quantum loop effects.
- All matter, standard model matter as well as every particle we have not seen yet, gives equally important contributions.
- Any approach to quantum gravity has to address this issue.
- String theory addresses it by containing all matter from the very beginning.
- But does this constrain the matter content?

Quantum Gravity and Matter

Does quantum gravity constrain matter in string theory?

Yes and No.

All matter is strictly constrained. Nothing can be added or removed without producing infinities.

But this does not imply strong restrictions on ***massless*** matter, except in 10 dimensions.

In lower dimensions, the couplings of massless matter can vary and are functions of "moduli".

These moduli can be thought of as vacuum expectation values of scalar fields.

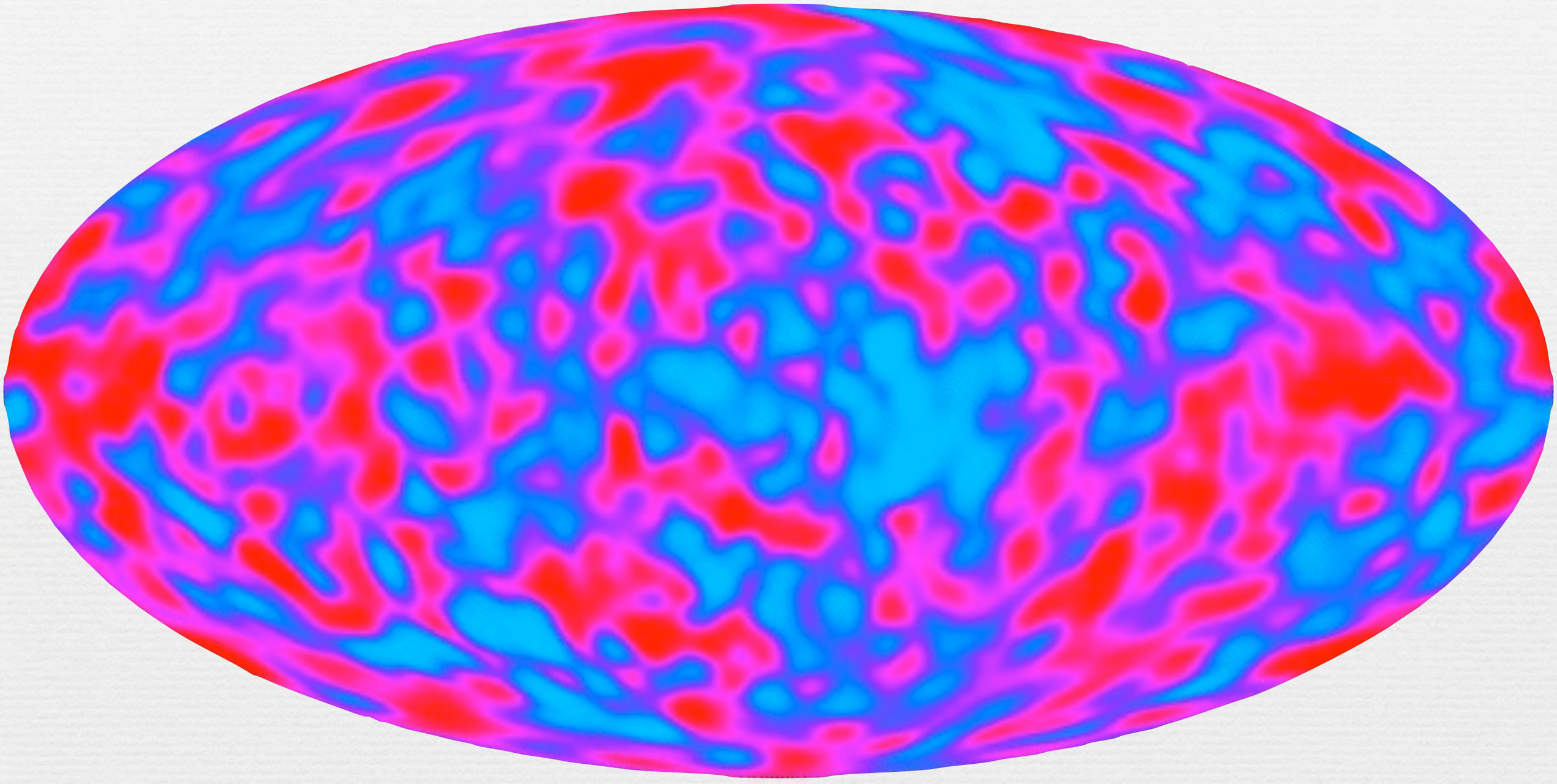
Mathematically, they correspond to continuous deformations of compactification manifolds.

Moduli

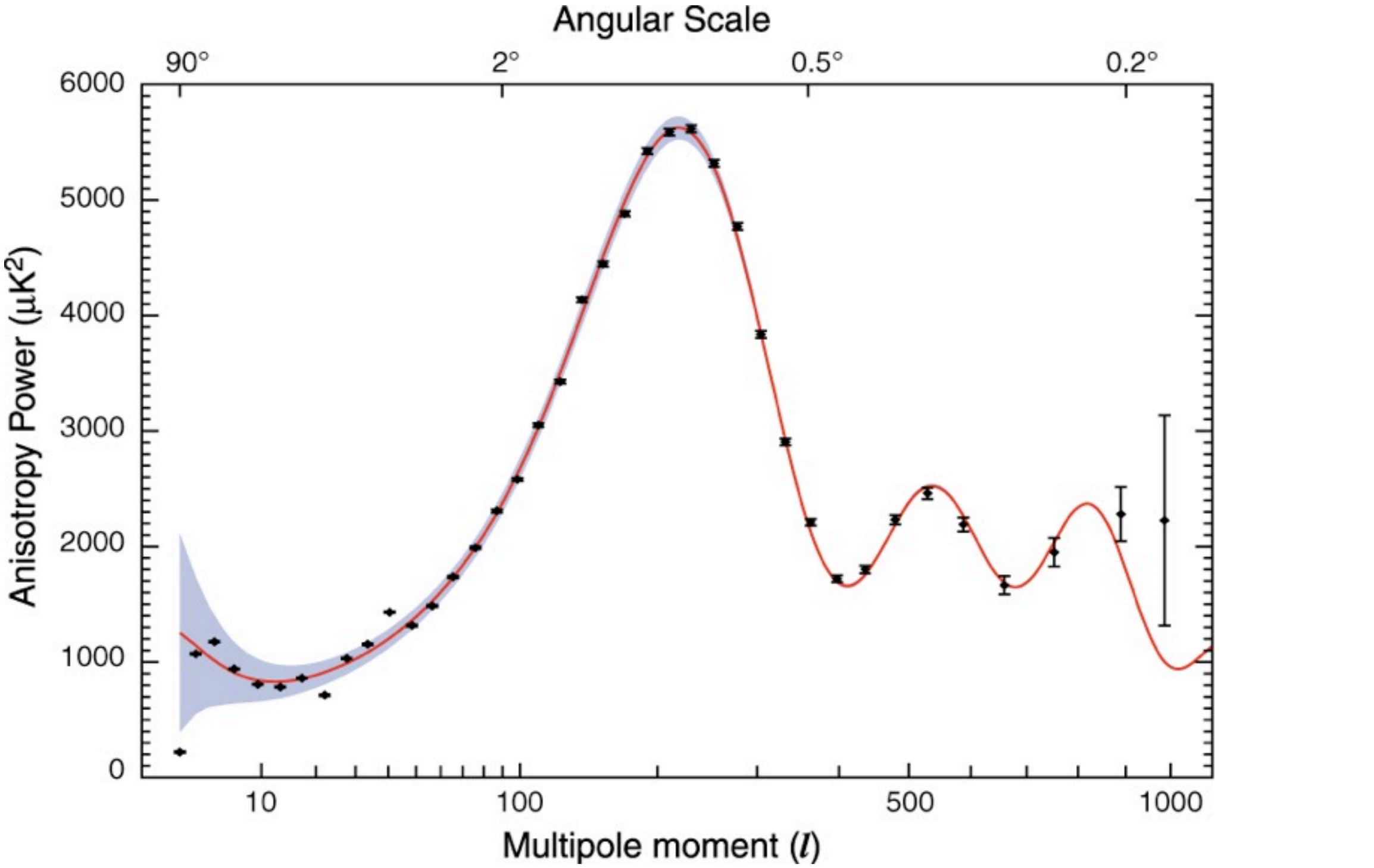
An often heard slogan is:

"String Theory has no free parameters: all gauge theory parameters are functions of v.e.v.'s of scalar fields."

But of course this fact precisely turns all gauge theory parameters into "environmental parameters".



Cosmic variance



Cosmic variance

We accept that our universe is not unique when this concerns irrelevant variations, such as “cosmic variance” in the CMB.

So why is it so difficult to accept such a notion for the v.e.v.’s of scalar fields that determine the standard model Lagrangian?

Note that in neither case it matters if the alternative universe really “exists”, just that it is possible.

Flux compactifications*

Action with four-form contribution

$$S = \int d^4x\sqrt{-g}\left(\frac{1}{2\kappa^2}R - \Lambda_{\rm bare} - \frac{Z}{48}F_4^2\right)$$

Solution to equations of motion

$$F^{\mu\nu\rho\sigma} = c\epsilon^{\mu\nu\rho\sigma}$$

Contribution to the cosmological constant

$$\Lambda = \Lambda_{\rm bare} + \frac{1}{2}\frac{Zc^2}{2}$$

(*)Bousso, Polchinski, 2001

Flux compactifications

In String Theory:

- The constant c is quantized
- There are many such four-form fields

$$\Lambda = \Lambda_{\rm bare} + \frac{1}{2}\sum_{i}^{N_{\rm flux}} n_i^2 y_i^2$$

If the values of y_i are incommensurate and $N_{\rm flux}$ sufficiently large, Λ can be tuned to a very small value (starting with negative $\Lambda_{\rm bare}$ of natural size).

Flux compactifications

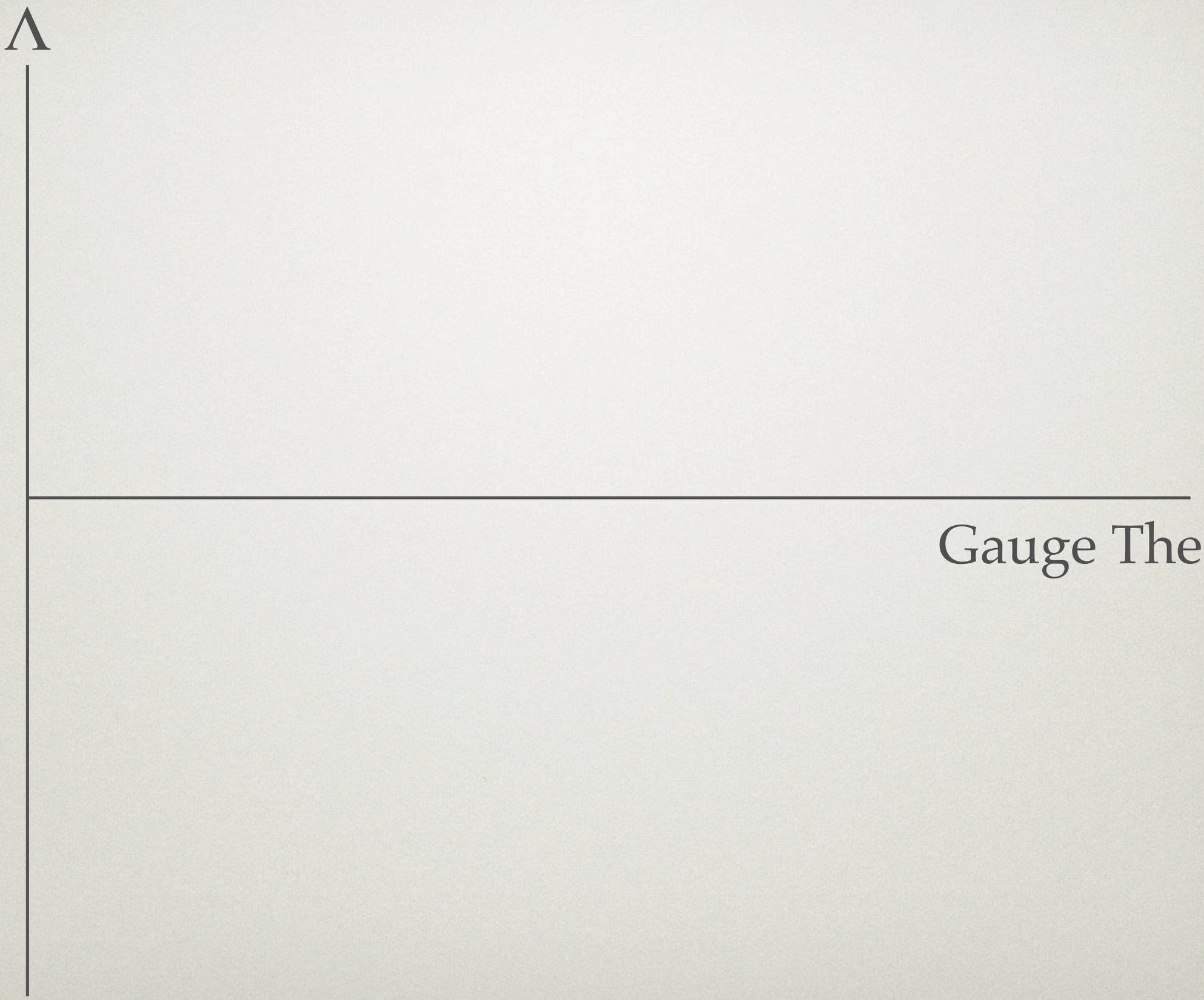
Comments

- The four-form fields are present in the theory, not added by hand (just "forgotten" previously)
- Large number of fluxes related to large number of moduli:

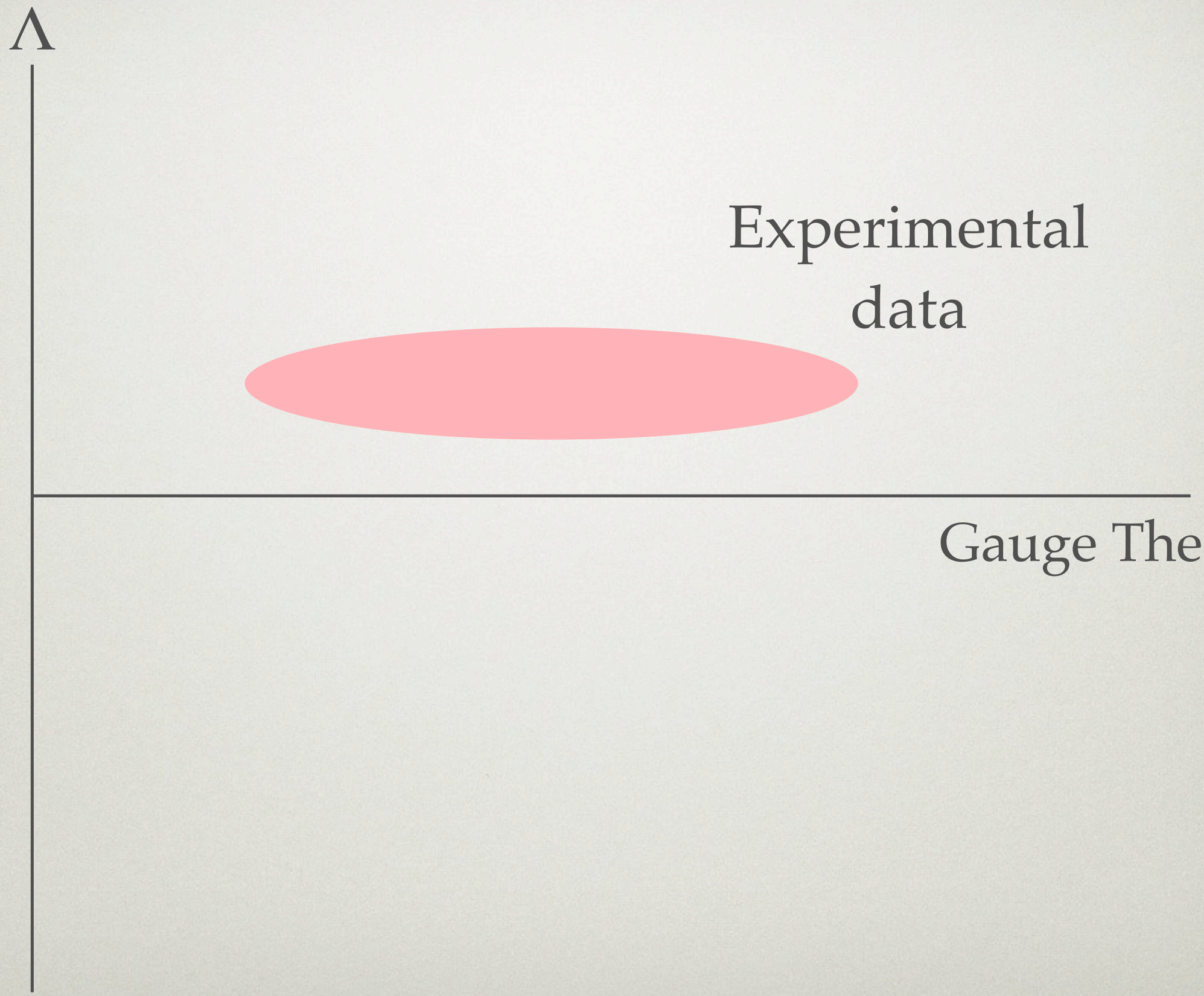
  An embarrassment becomes a success!
- With enough fluxes, y_i need not be very small.
- The values of y_i depend on volumes of compact cycles.
- These volumes are fixed if the moduli are stabilized.
- The range of values of y_i is limited dynamically.

$$N_{\rm vacua} \approx [N_{\rm values}]^{N_{\rm flux}}$$

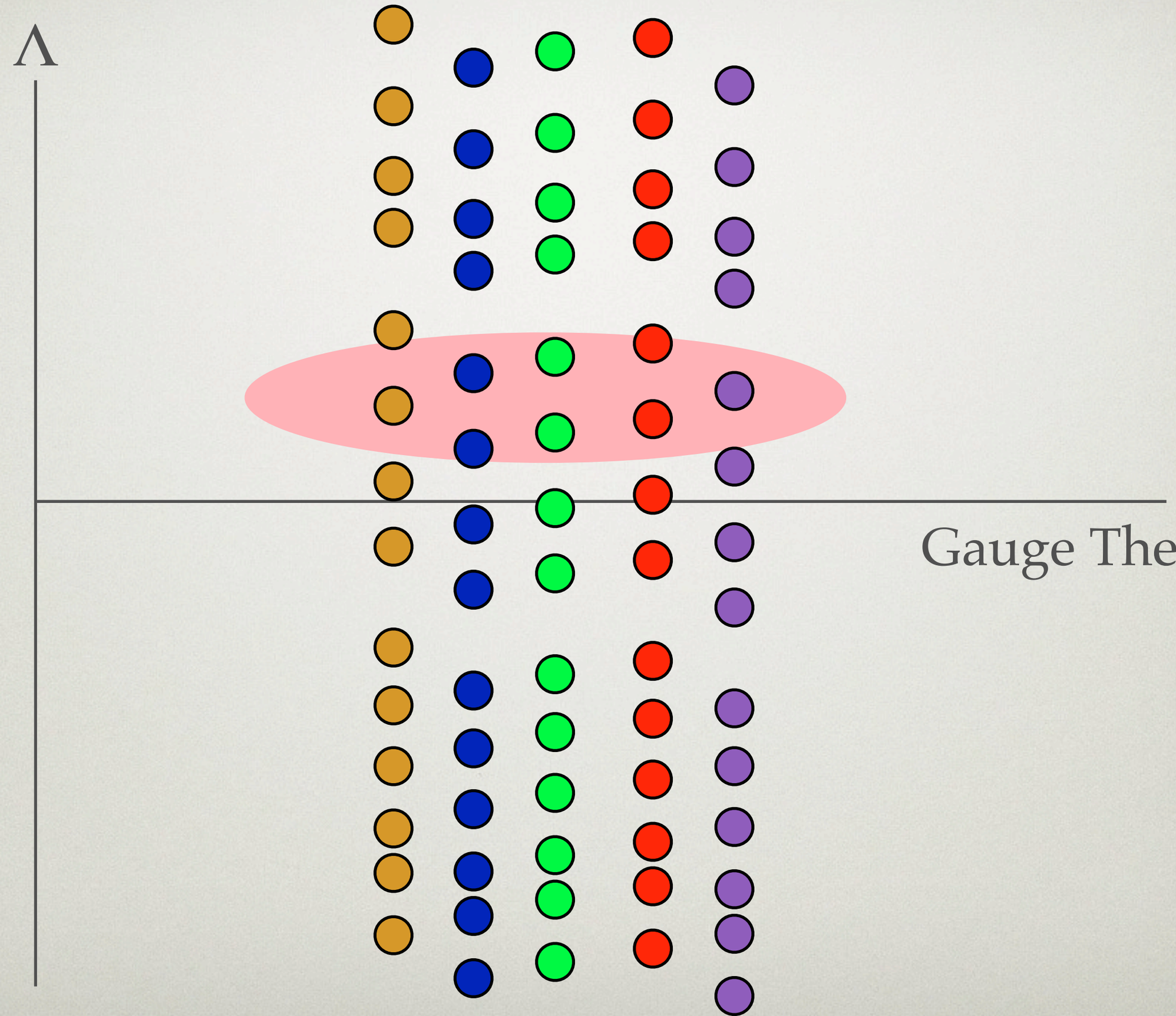
Douglas, Denef: 10^{500}



Gauge Theory


Λ
Experimental
data
Gauge Theory


Λ
Experimental data
Gauge Theory
10^{500} vacua



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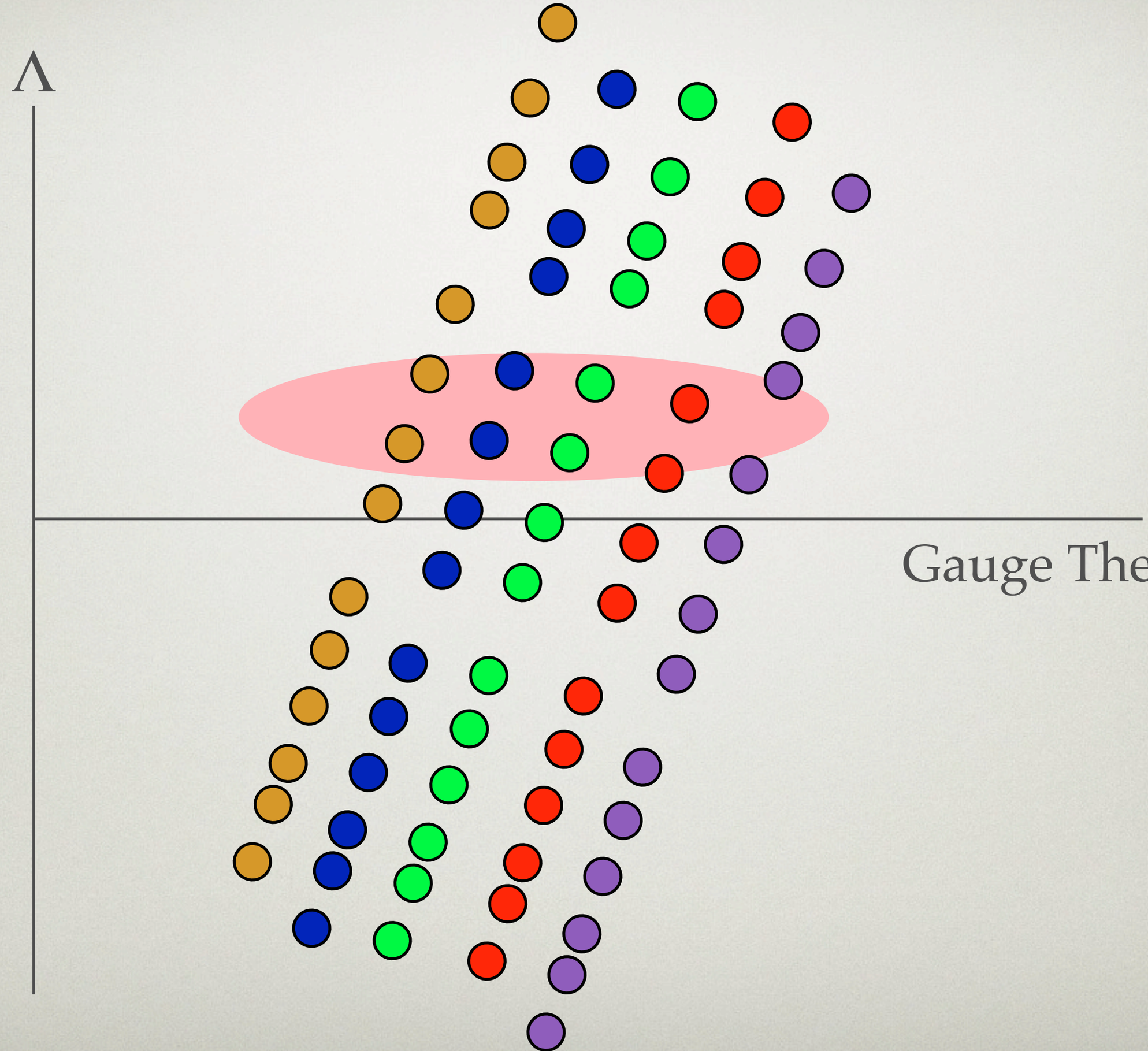
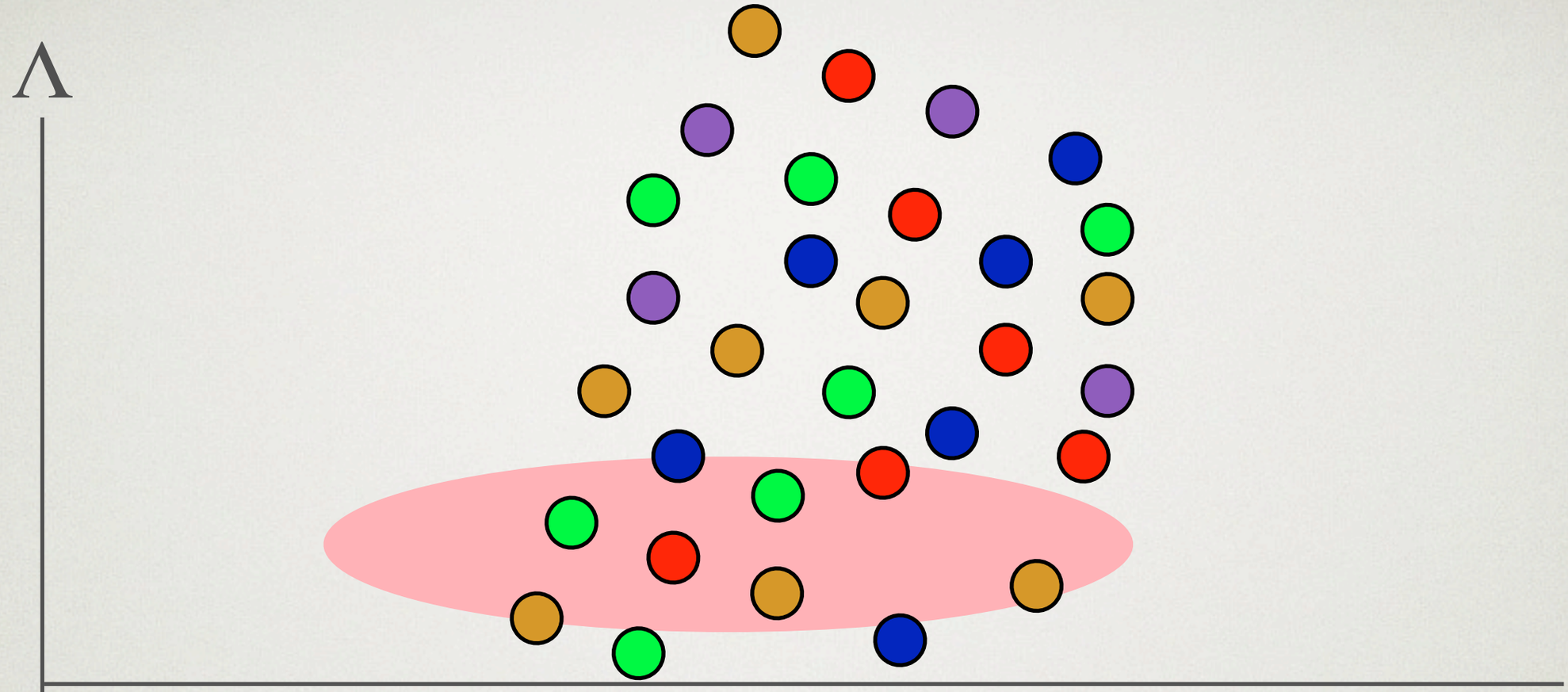


Gauge Theory



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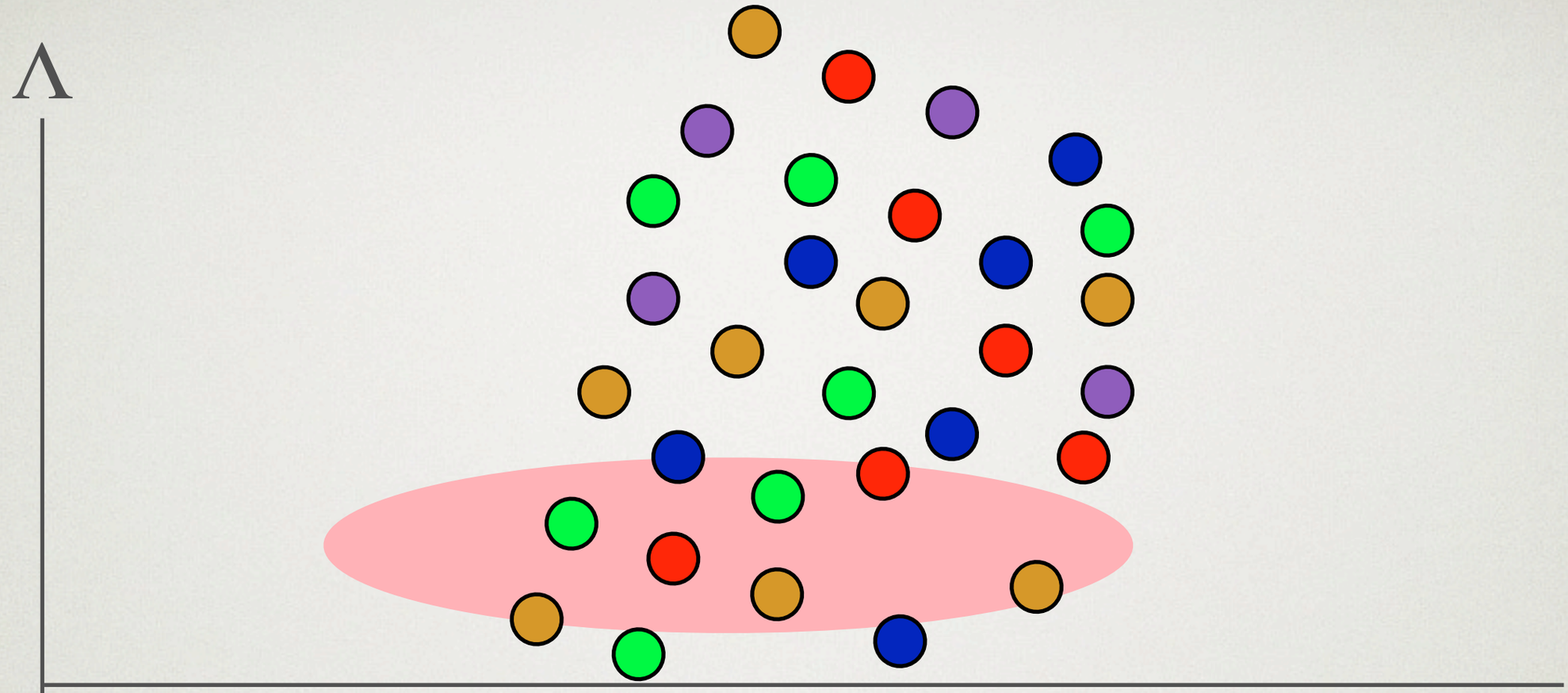


Gauge Theory

Even if all that string theory could achieve would be a completely finite theory of all interactions including gravity, but with no further restrictions on the gauge groups and the representations, it would be a considerable success.

Conclusion

Conclusion

News and Views

Nature **448**, 1000-1001 (30 August 2007) | doi:10.1038/4481000a; Published online 29 August 2007

Theoretical physics: A black hole full of answers

Jan Zaanen

"String theory is a collection of mathematical discoveries that might just offer a solution to this puzzle. But it has had a bad press of late. This is in part because its 40-year history is littered with claims that, if only we would stick to its true path of enlightenment, the answers to the big questions of physics would be just around the corner. "

Conclusion

If we stick to its true path of enlightment, String Theory *does* provide answers to big questions in physics: the "why" question of the standard model, the cosmological constant problem.

The trouble is that some people don't like the answers.

Last clothes?

The real moral of the story

- The "emperor" is us, human beings.
- The "clothes" is the strange habit of putting ourselves in the centre of things.
- This has happened many times, the last time being the supposed uniqueness of "our" standard model.
- But is this really the last time?
  Is string theory itself unique, or just the first example of a theory of quantum gravity with a landscape?

Finally...

- Of course, the “emperor” could turn out to be me...

Anthropic Games

- Might people have been tempted by anthropic thinking in the past?
- Would they have drawn the wrong conclusion?
- Would they have given up?

Criteria

We may consider a parameter as potentially anthropic if

1). Varying the parameter affects existence of life.

2). The theory remains sensible if the parameter is changed (even if embedded in a more fundamental theory).

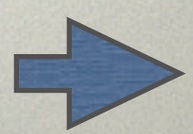
3). The parameter does not have at a mathematically special value.

Standard model

Criterium	
Affects life?	Yes (for the ensemble of variables.)
Sensible variation?	Yes
Special value?	No

Cosmological constant

Criterium	
Affects life?	Yes (Barrows,Tippler; Weinberg)
Sensible variation?	Probably
Special value?	Maybe not...



Periodic system

Let's assume that one only knew about the existence of nuclei, but not about weak decays, and that one did not worry about how the sun works, or about abundances.

So the theory we consider is QED with electrons and stable integrally charged nuclei, treated as elementary particles.

The parameters are the nuclear masses (close to, but not exactly, integers, and treated as real numbers), the electron mass and the fine structure constant.

The charges are, within the experimental uncertainties, equal to integers.

Periodic system

Five most common elements in the human body

element	charge	mass	human body
H	1	1.008	10%
C	6	12.01	18%
N	7	14.01	3%
O	8	16.00	65%
Ca	20	40.08	1.5%

Periodic system

The charges are clearly essential for complexity, but also clearly have special values: integers.

The set of all (positive) integers would fit the data perfectly (since abundances are ignored), and nobody would propose a "landscape" of possibilities to get the set of all integers as a special solution.

We may be puzzled that a simple system with one negative charge and a few positive ones leads to such complex solutions, but at this point no anthropic solution suggests itself.

It is the same as being puzzled that quantum mechanics allows life: it may be puzzling, but there is no obvious alternative.

Periodic system

The precise nuclear masses, on the other hand, have little anthropic relevance. Chemistry is almost unchanged if we change them by factors of order 1. Note that the question is not if humans continue to exist, but if anything exists of comparable complexity.

“Heavy water”

Physical properties (with comparison to light water)

Property	D_2O (Heavy water)	H_2O (Light water)
Freezing point (°C)	3.82	0.0
Boiling point (°C)	101.4	100.0
Density (at 20°C, g/mL)	1.1056	0.9982
Temp. of maximum density (°C)	11.6	4.0
Viscosity (at 20°C, mPa·s)	1.25	1.005
Surface tension (at 25°C, μJ)	7.193	7.197
Heat of fusion (cal/mol)	1,515	1,436
Heat of vaporisation (cal/mol)	10,864	10,515
pH (at 25°C)	7.41 (sometimes "pD")	7.00

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Nobody would propose an anthropic landscape of nuclear masses on these grounds. Nobody would "give up" on explaining theses masses. The fact that the masses are close to integers makes that even more obvious.

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It is an interesting question how much the fine structure constant can be varied without destroying the complexity (bio)chemistry, but even if that suggested a small anthropic window, it will still be much larger than the corresponding window in the standard model.

Periodic system

Criterium	Charges	Masses
Affects life?	Yes	No
Sensible variation?	Yes	Yes
Special value?	Yes	No

Periodic system

Conclusion:
The periodic system does not suggest anthropic reasoning.

Note that it *does* provide an allowed region in the gauge theory landscape, if we *only* use complexity as a criterion, not for example the need for a star as a source of energy.

PREMATURE STRING THEORY

Imagine that String Theory (and its landscape) was known around the year 1900, and that attempts were made to embed the periodic system directly in the String Theory landscape. This would still face at least three major stumbling blocks:

- The QED Landau pole moves well below the Planck scale.
- It looks very hard to get the set of charges 1,6,7,8,20, ... out of String Theory.
- Nuclei are non-chiral, so their natural masses are of order M_{planck}. (In the SM this is true for the Higgs v.e.v., and the QCD scale).

The SM fits much more comfortably in the String Theory Landscape than the Periodic system.

Uniqueness of the Standard Model

But seriously...
How about SO(10)?

The (16) of SO(10) is the smallest irreducible complex anomaly free fermion representation

Mathematically unique?

But we need three of these, and that's not all:
We also need Higgses, for example (45)+(10)+(126)

Uniqueness of the Standard Model

Furthermore GUT symmetry breaking allows several low energy theories, for example

$$\begin{aligned} SU(5) &\rightarrow SU(3) \times SU(2) \times U(1) \\ &\rightarrow SU(4) \times U(1) \end{aligned}$$

Precursor of the string Landscape

Uniqueness of the Standard Model

Finally, SO(10) is still a choice. Is there any physical principle that prefers this choice?

Yes, there is! The $E_8 \times E_8$ Heterotic String!

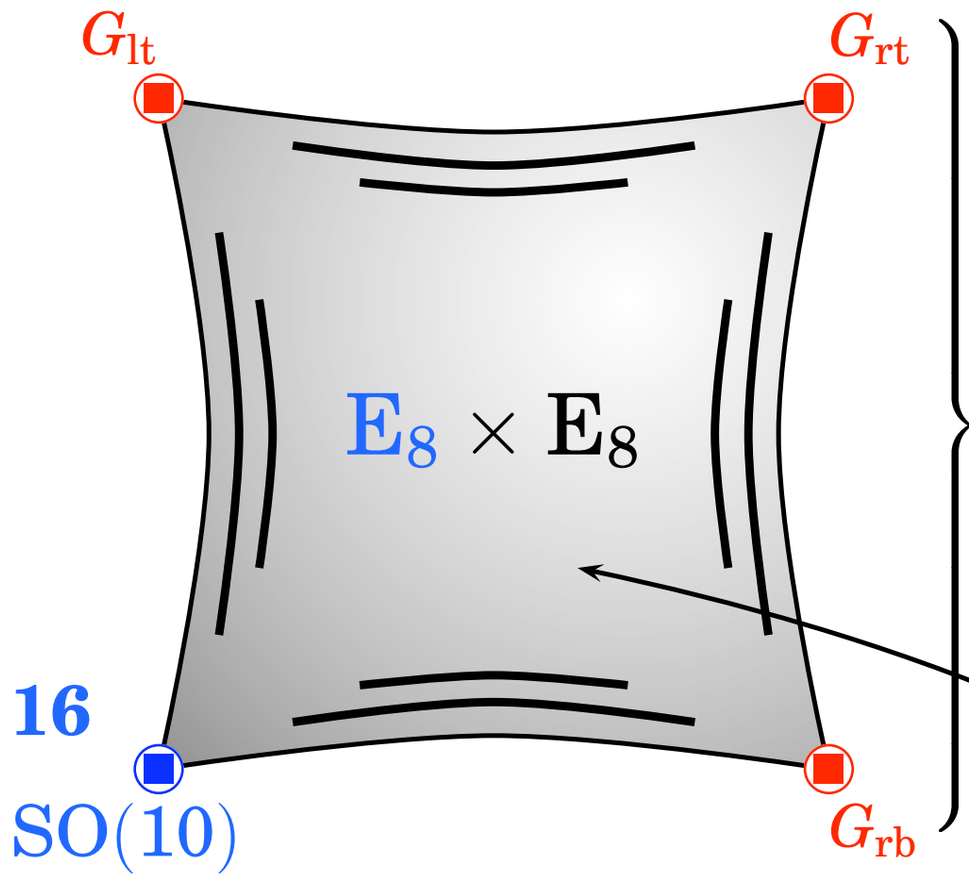
$$E_8 \subset SO(6) \times SO(10)$$

Six-dimensional compactification manifold

But this just brings us back to the String Theory Landscape...

In String Theory this works in a different way, but it does not look more unique (from a talk by Michael Ratz)

Local grand unification



Buchmüller, Hamaguchi, Lebedev, M.R. (2004-2006)

'low-energy' effective theory

standard model as an intersection of $G_{\rm rb}, G_{\rm rt}, G_{\rm lt}$ & $\mathrm{SO}(10)$ in G

SM generation(s):

localized in region with $\mathrm{SO}(10)$ symmetry

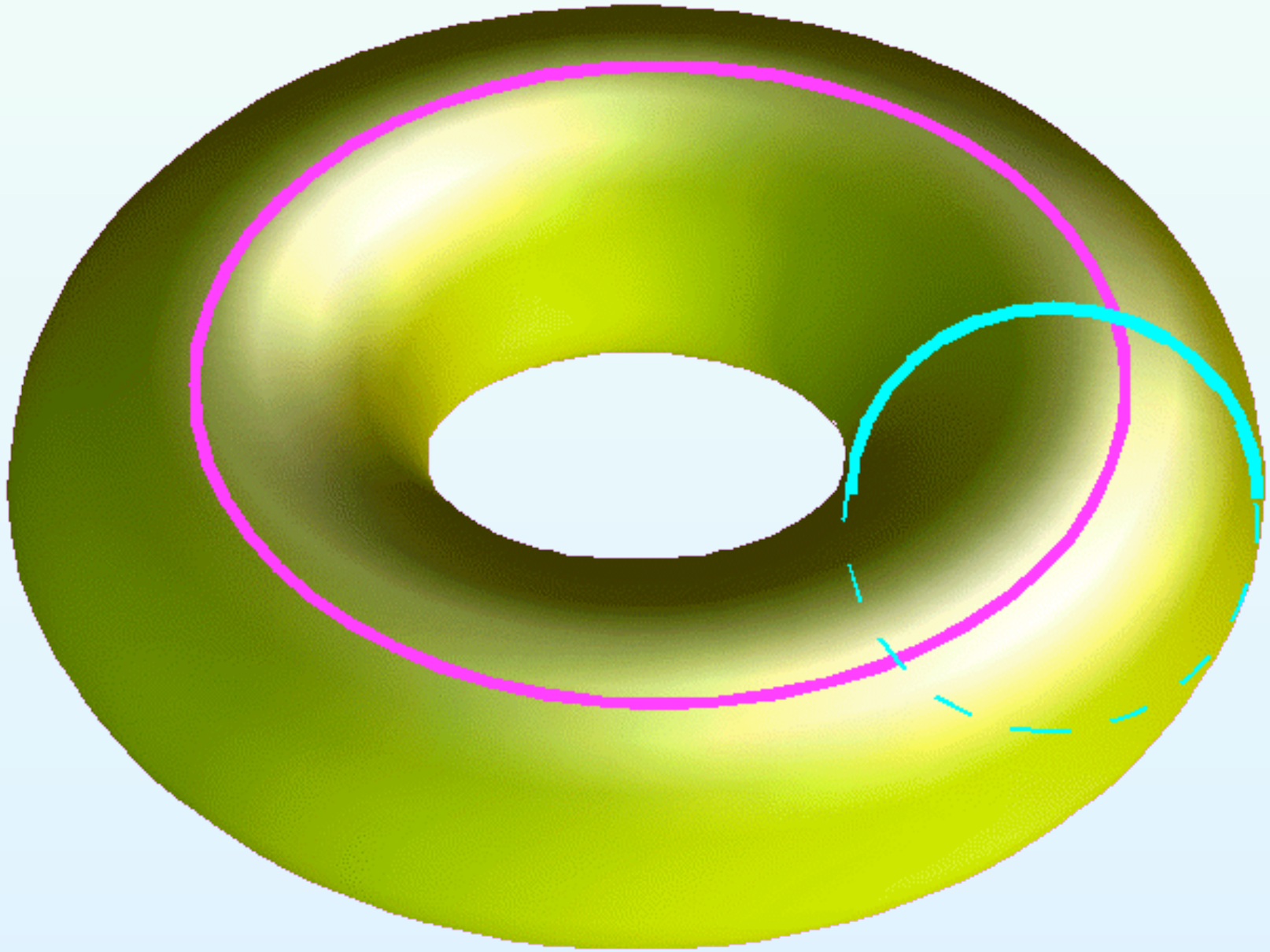
Higgs doublets:

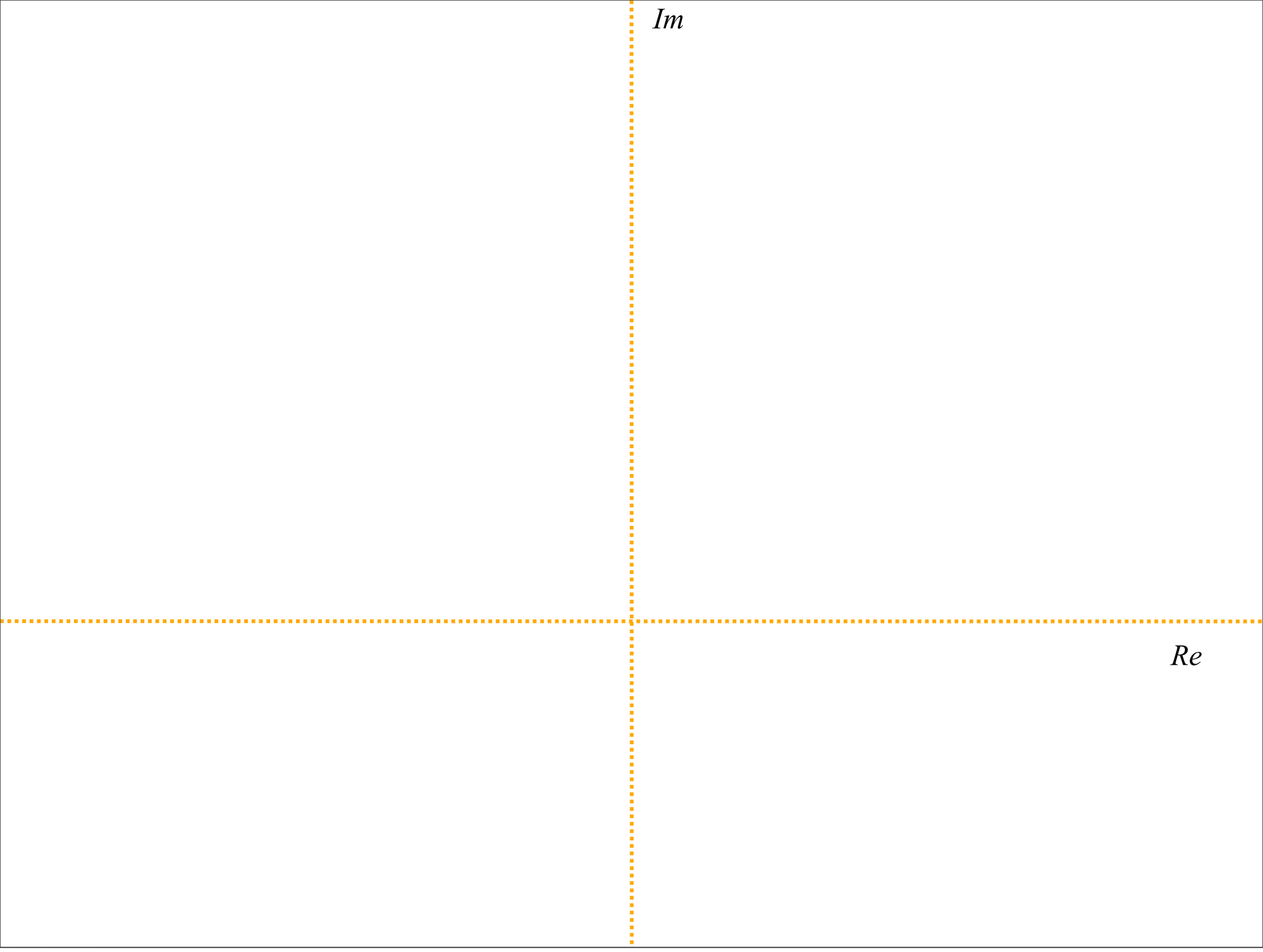
live in the bulk

Spectrum @ orbifold point

#	irrep	label		#	irrep	label
3	$(\mathbf{3},\mathbf{2};\mathbf{1},\mathbf{1})_{(1/6,1/3)}$	q_i		3	$\left(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1}\right)_{(-2/3,-1/3)}$	$\bar{u}_i$
3	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(1,1)}$	$\bar{e}_i$				
$3+1$	$\left(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1}\right)_{(1/3,-1/3)}$	$\bar{d}_i$		1	$(\mathbf{3},\mathbf{1};\mathbf{1},\mathbf{1})_{(-1/3,1/3)}$	d_i
$3+1$	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(-1/2,-1)}$	ℓ_i		1	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(1/2,1)}$	$\bar{\ell}_i$
$1+3$	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(-1/2,0)}$	ϕ_i		$1+3$	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(1/2,0)}$	$\bar{\phi}_i$
$3+12$	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(0,1)}$	$\bar{n}_i$		12	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(0,-1)}$	n_i
3	$\left(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1}\right)_{(1/3,2/3)}$	$\bar{\delta}_i$		3	$(\mathbf{3},\mathbf{1};\mathbf{1},\mathbf{1})_{(-1/3,-2/3)}$	δ_i
20	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(1/2,*)}$	s_i^+		20	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(-1/2,*)}$	s_i^-
3	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{2})_{(0,1)}$	$\bar{\eta}_i$		3	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{2})_{(0,-1)}$	η_i
20	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{2})_{(0,0)}$	h_i		2	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{2})_{(0,0)}$	y_i
2	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{2})_{(1/2,1)}$	x_i^+		2	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{2})_{(-1/2,-1)}$	x_i^-
2	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(0,\pm 2)}$	χ_i		18	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(0,0)}$	s_i^0
4	$\left(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1}\right)_{(-1/6,*)}$	$\bar{v}_i$		4	$(\mathbf{3},\mathbf{1};\mathbf{1},\mathbf{1})_{(1/6,*)}$	v_i
2	$(\mathbf{1},\mathbf{1};\mathbf{8},\mathbf{1})_{(0,-1/2)}$	f_i		2	$(\mathbf{1},\mathbf{1};\mathbf{8},\mathbf{1})_{(0,1/2)}$	$\bar{f}_i$
5	$(\mathbf{1},\mathbf{1};\mathbf{8},\mathbf{1})_{(0,0)}$	w_i		4	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(0,*)}$	m_i

Closed Strings: Modular Invariance

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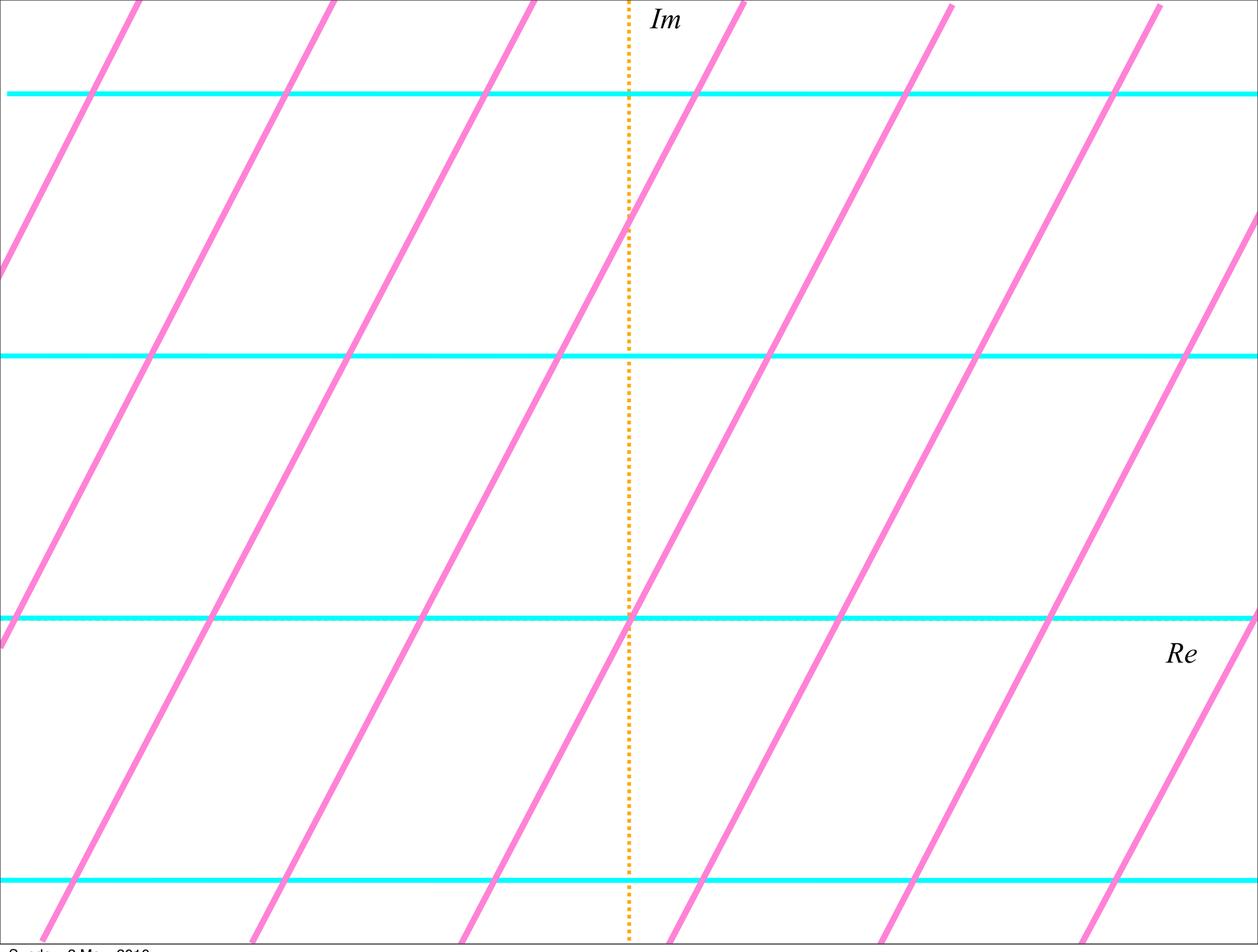
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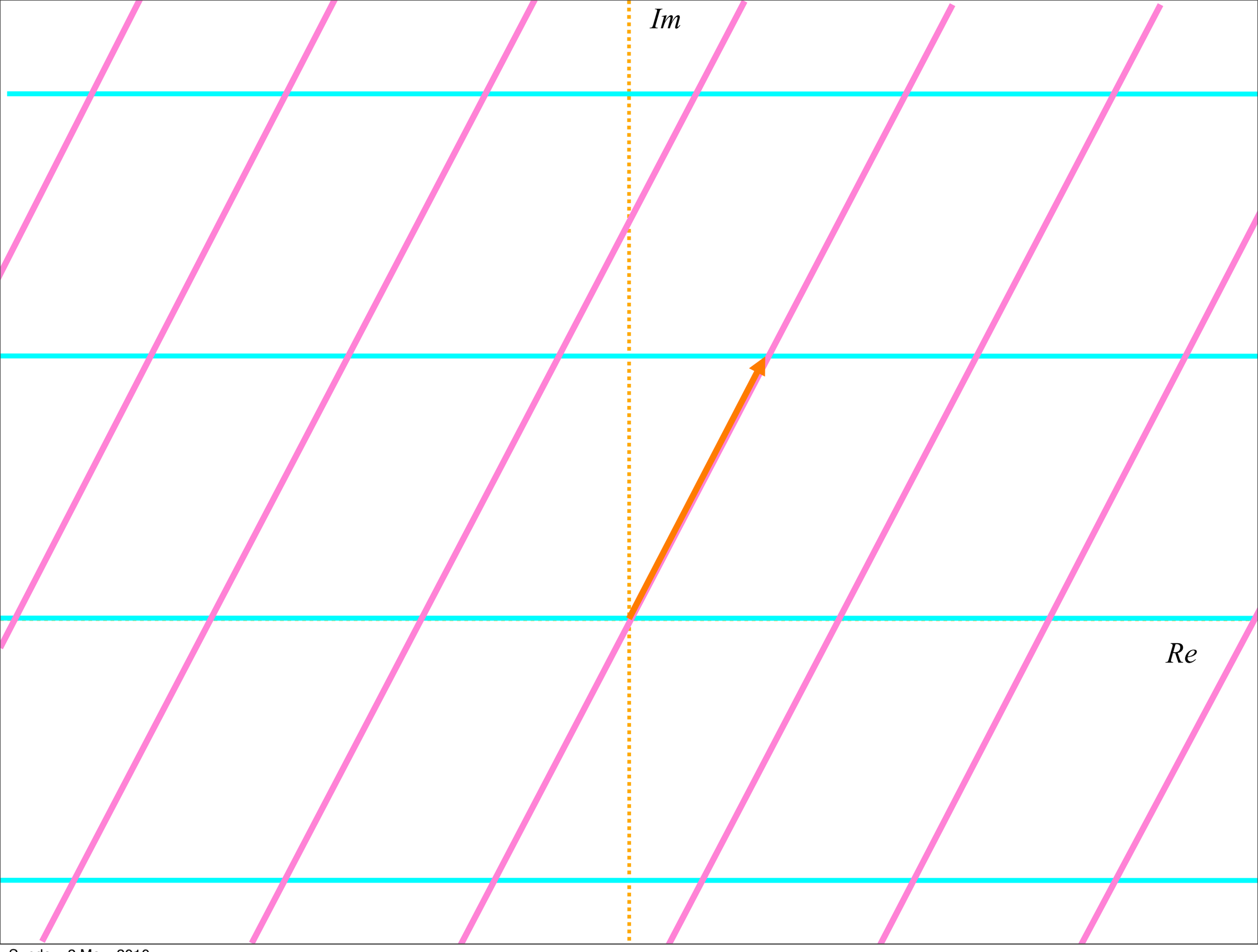
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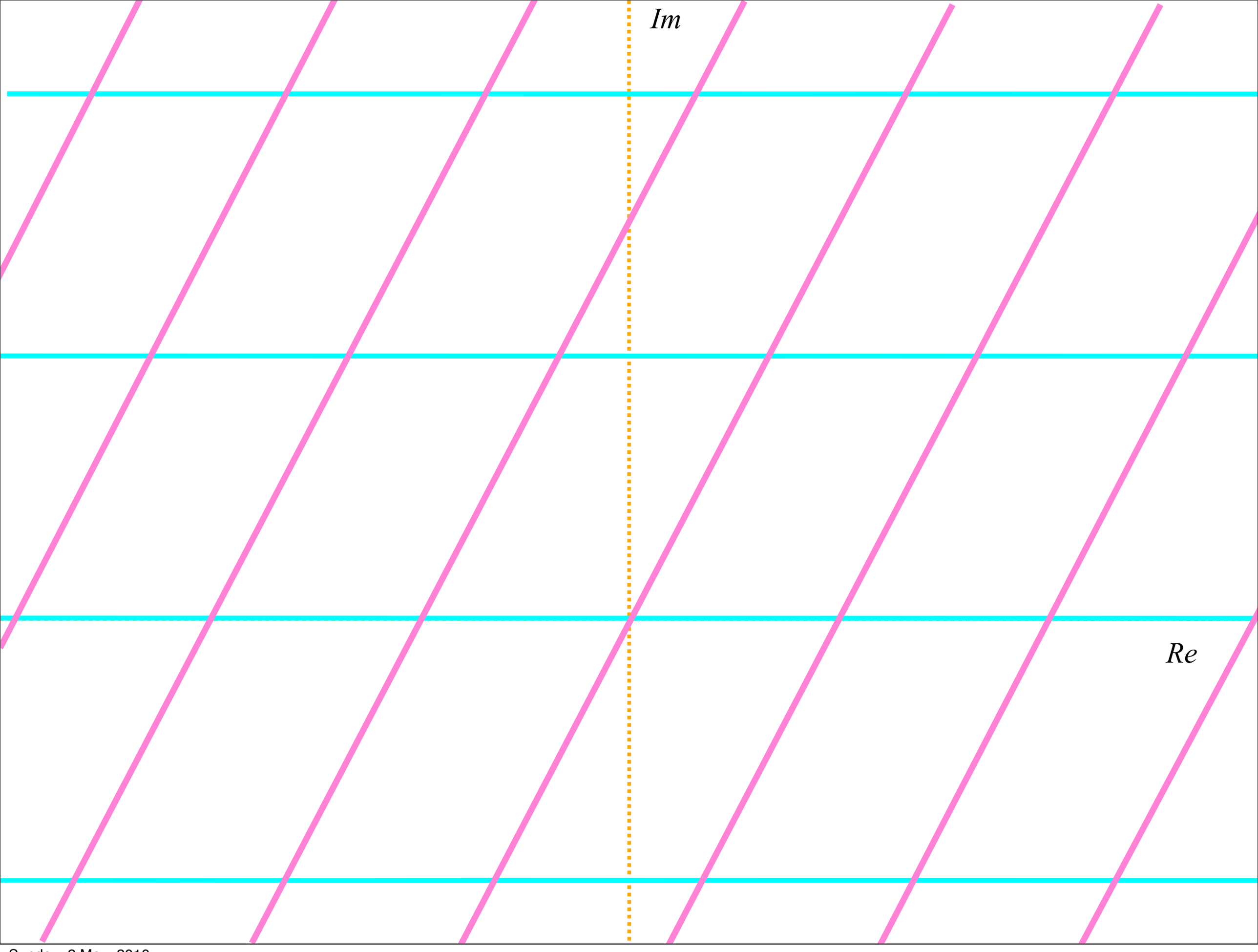
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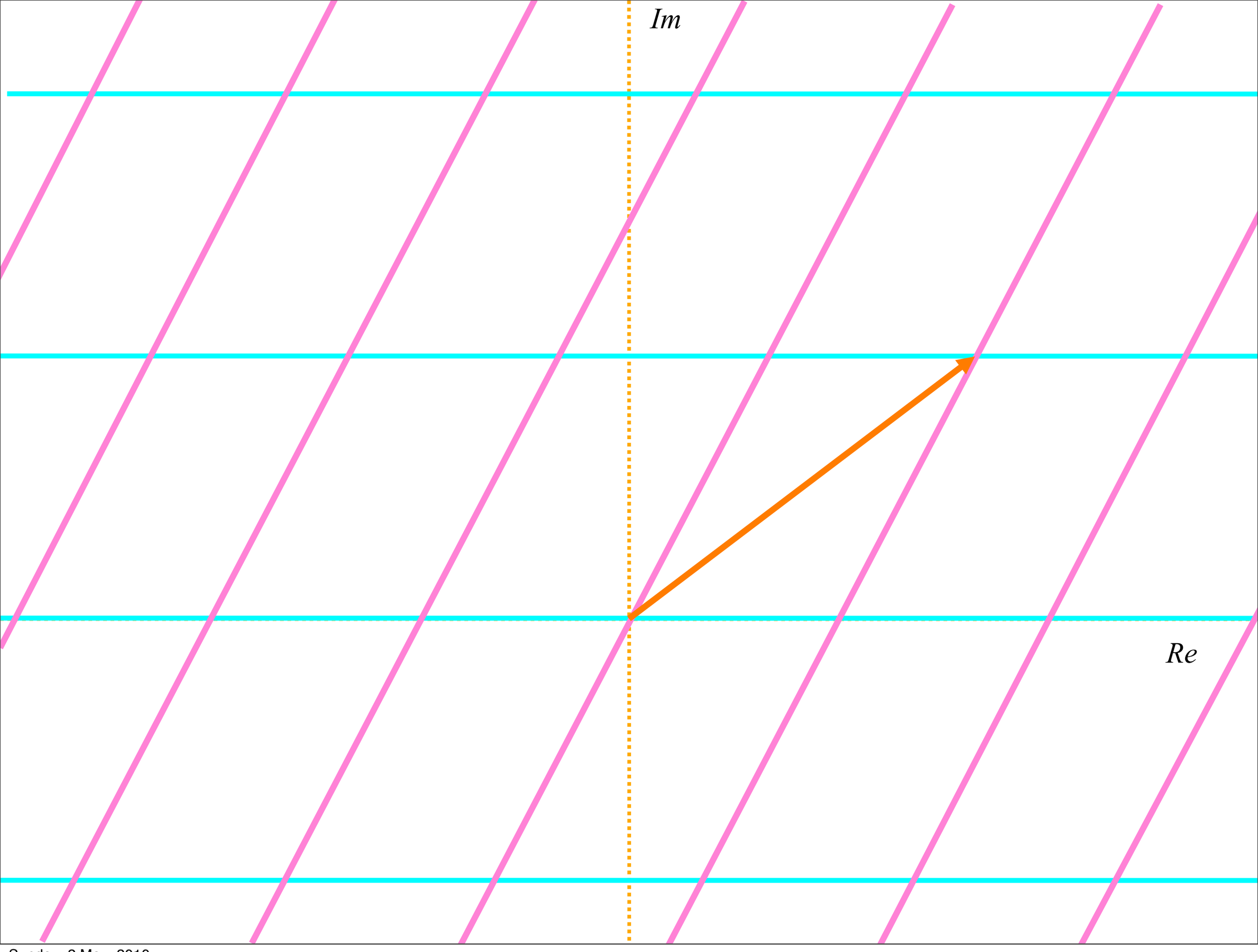
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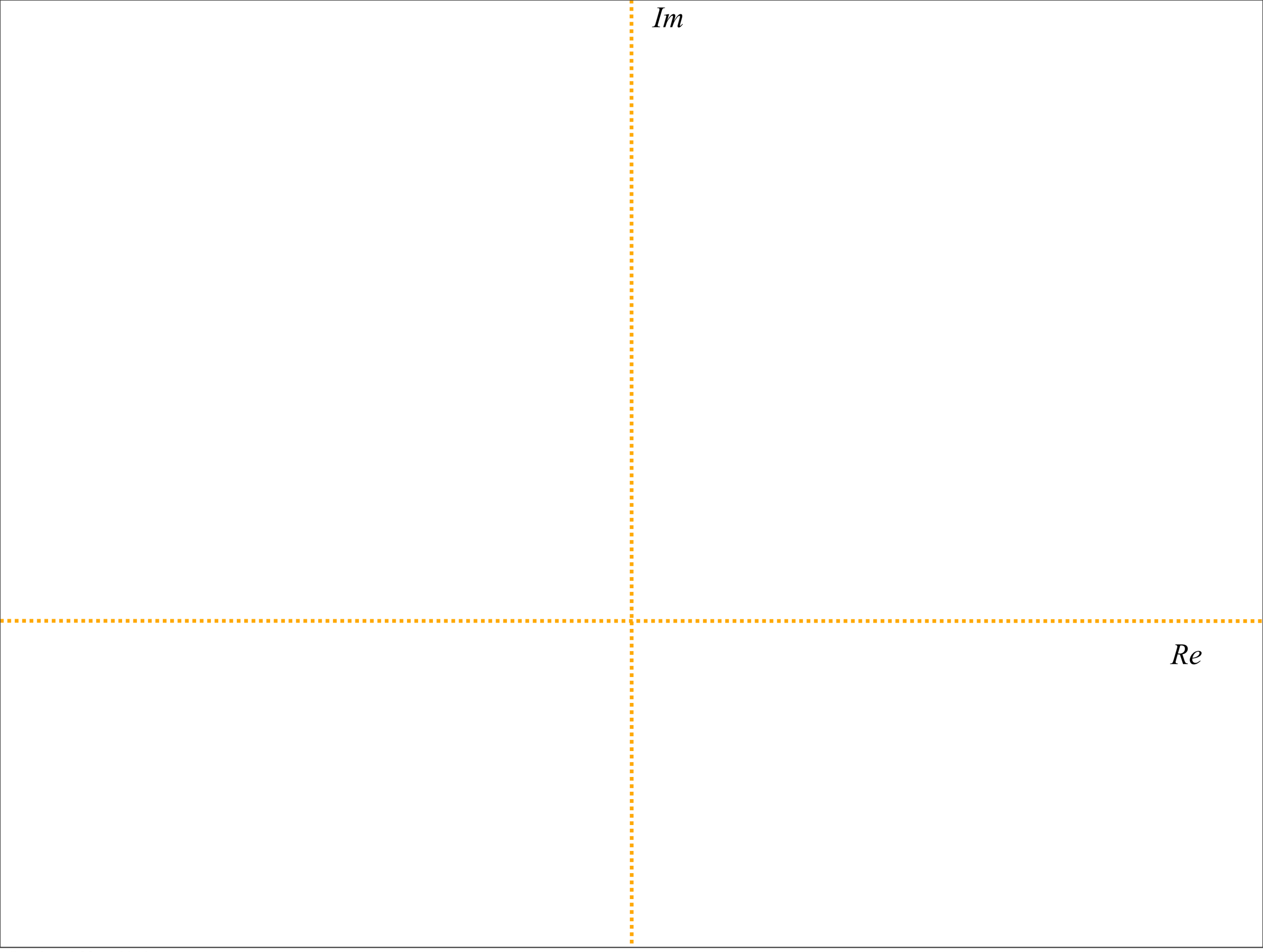
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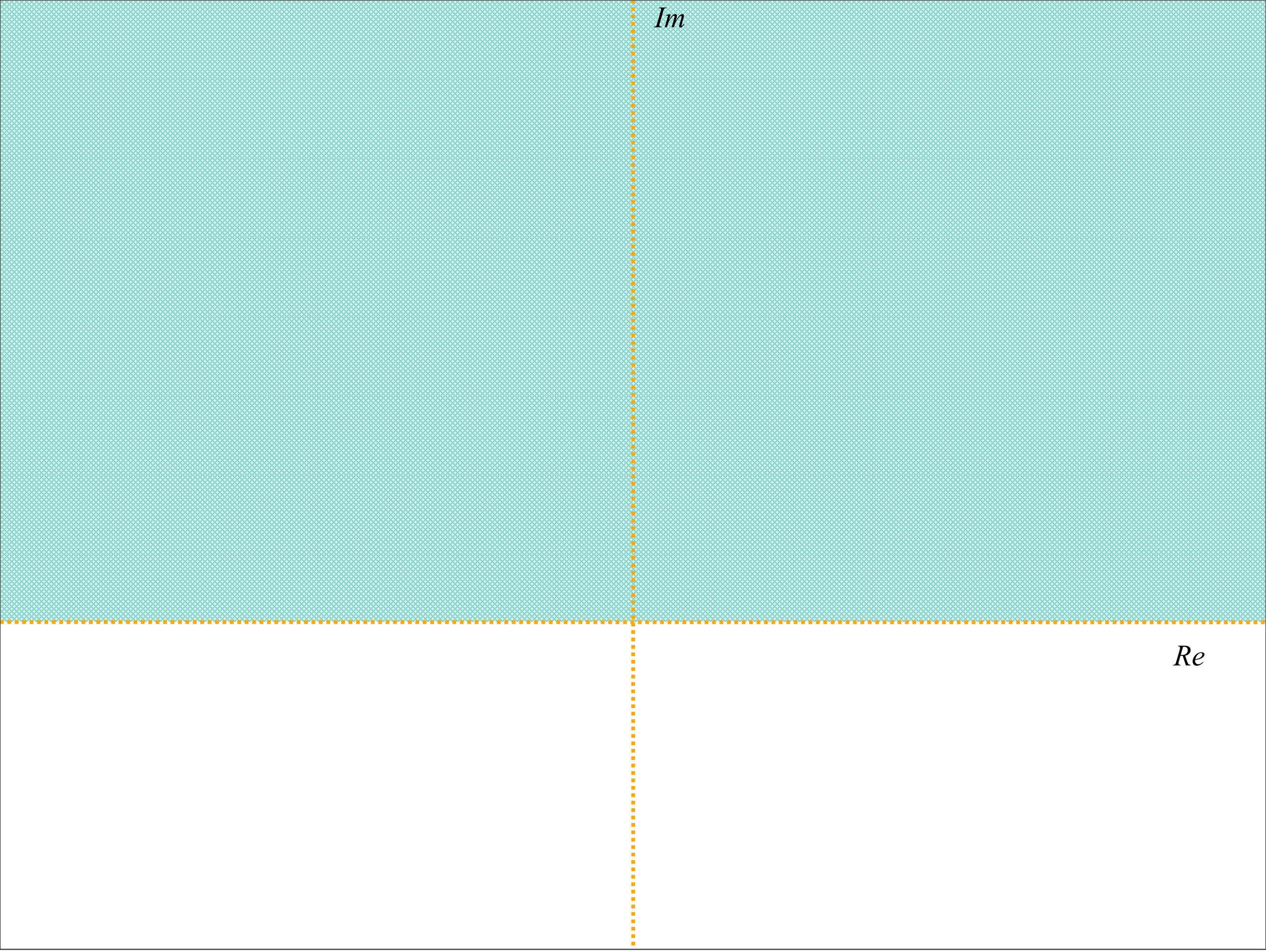
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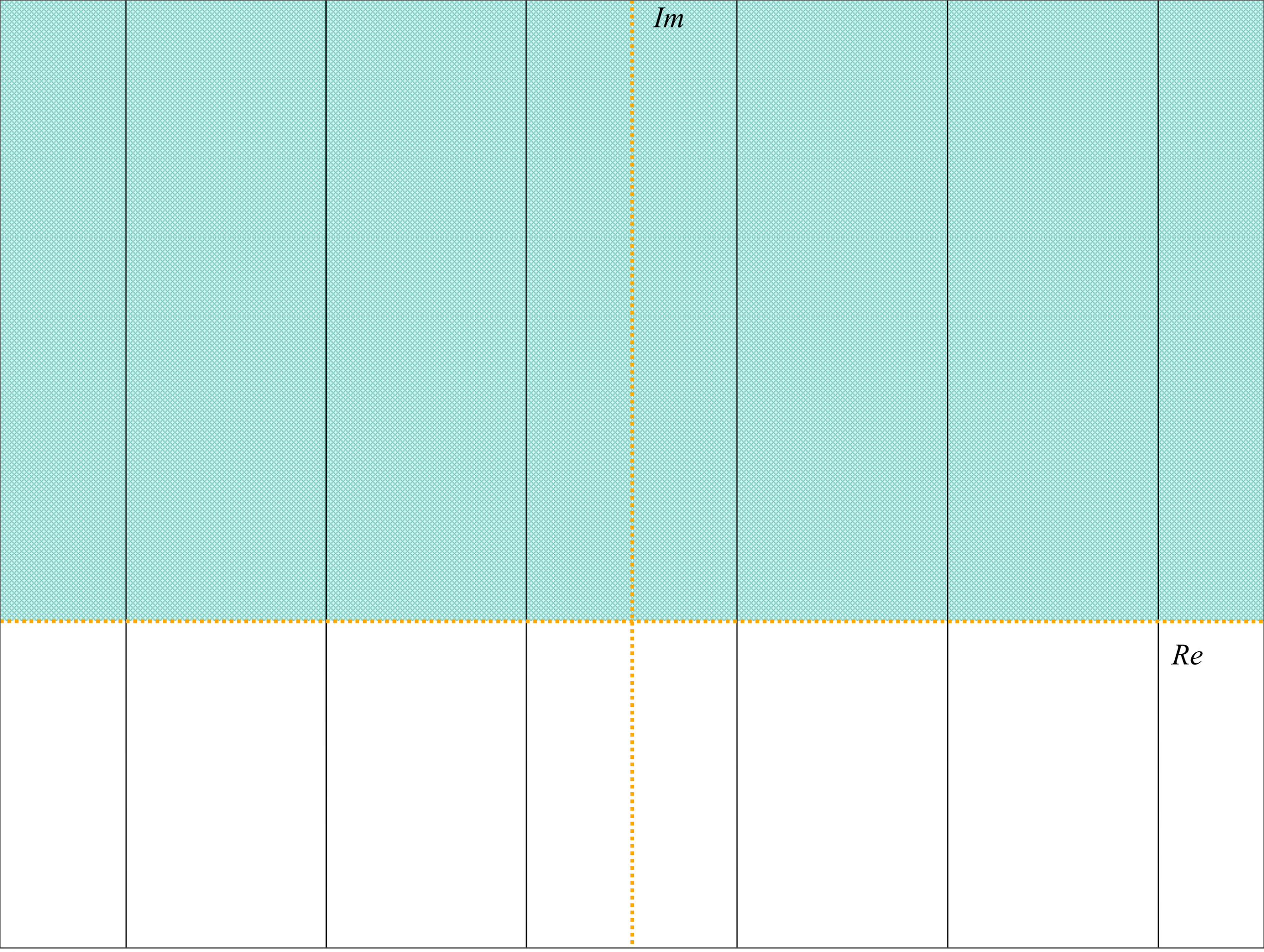
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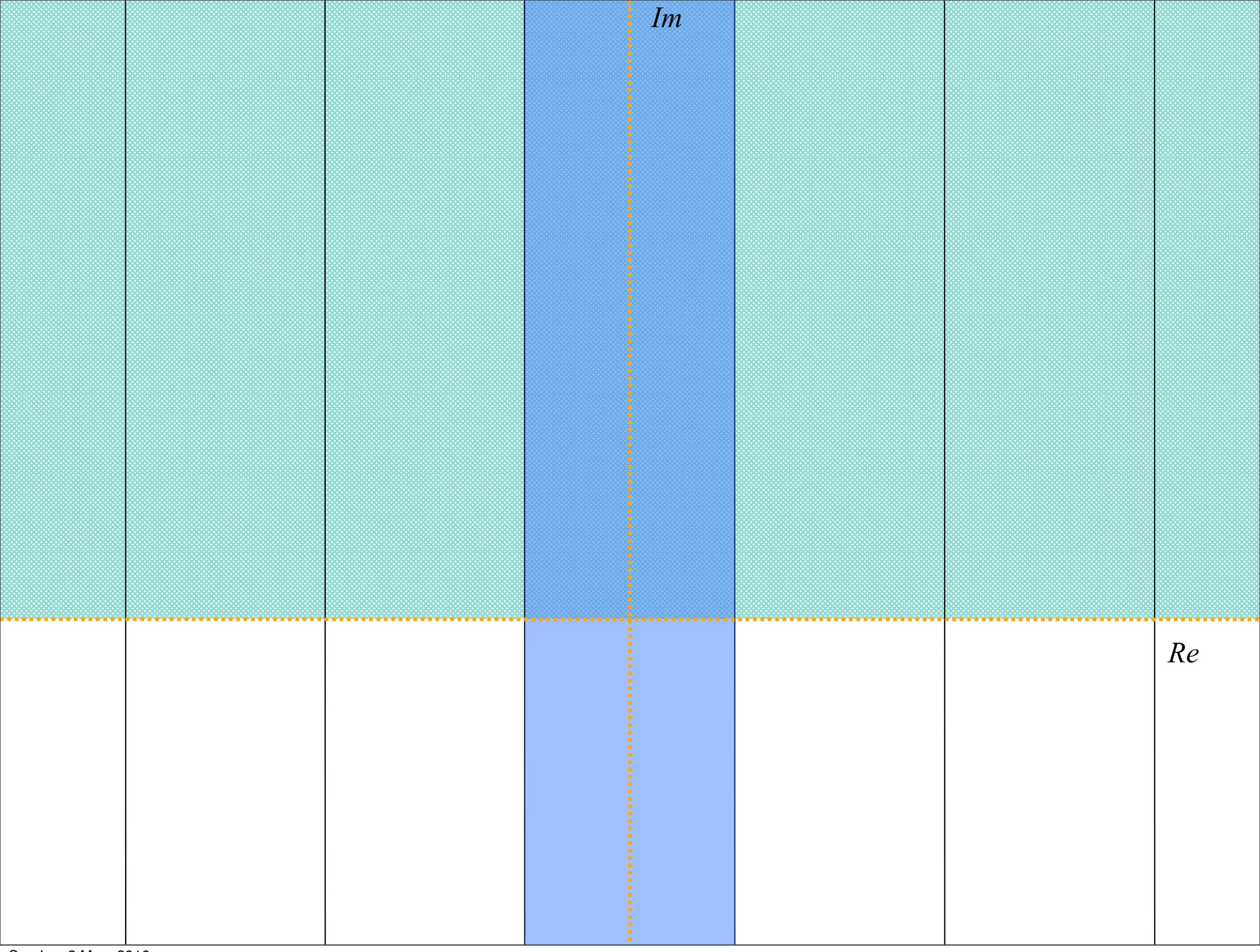
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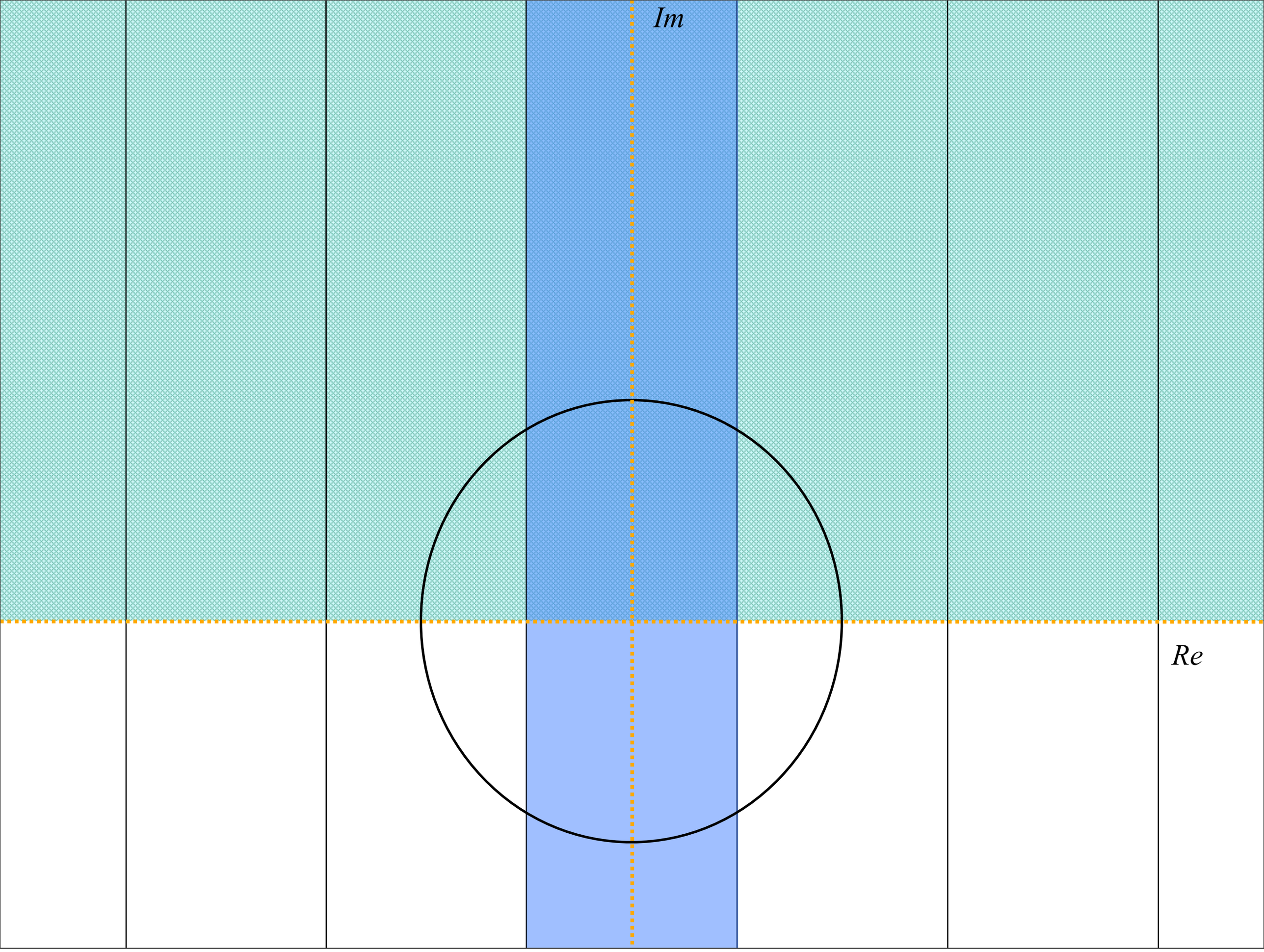
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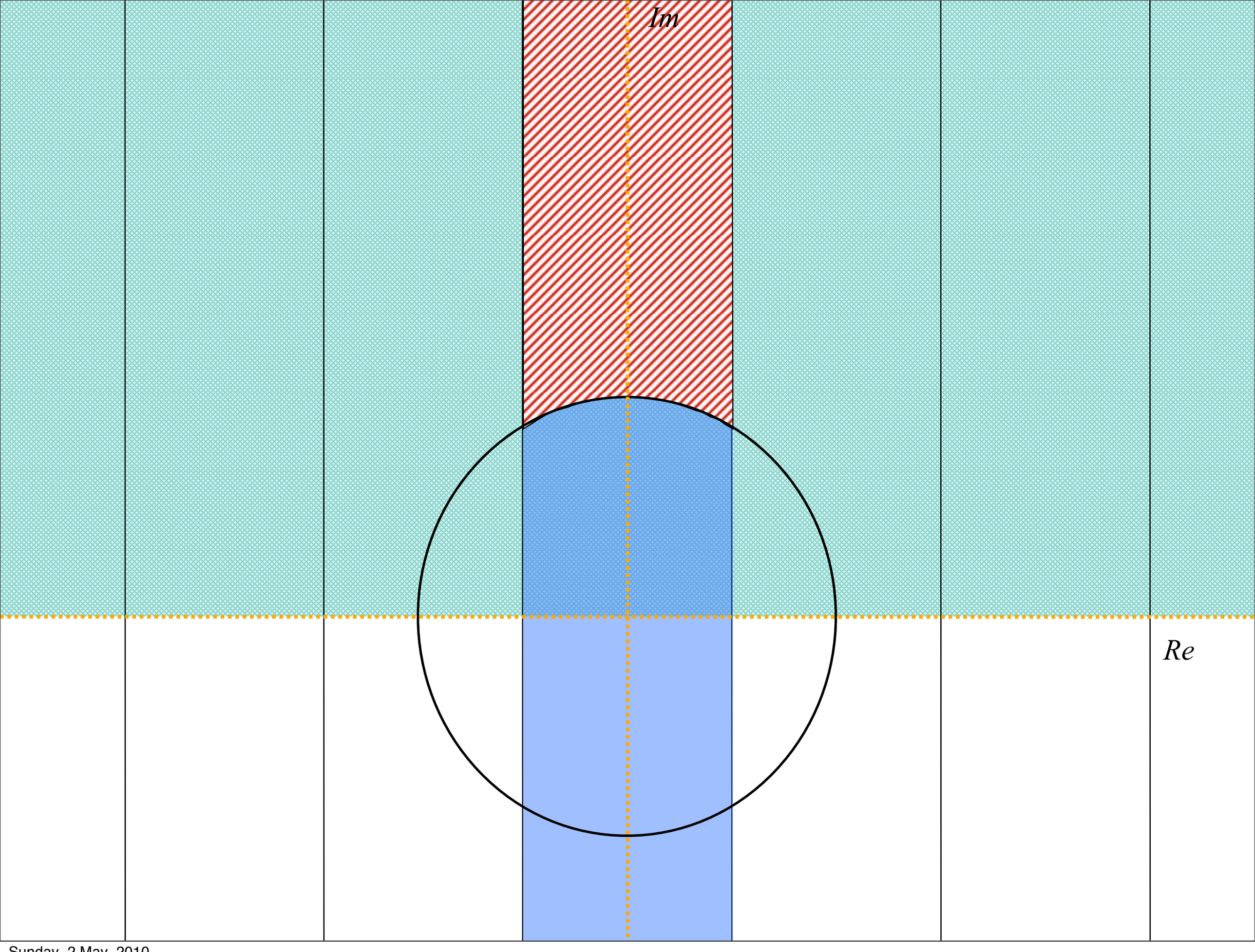
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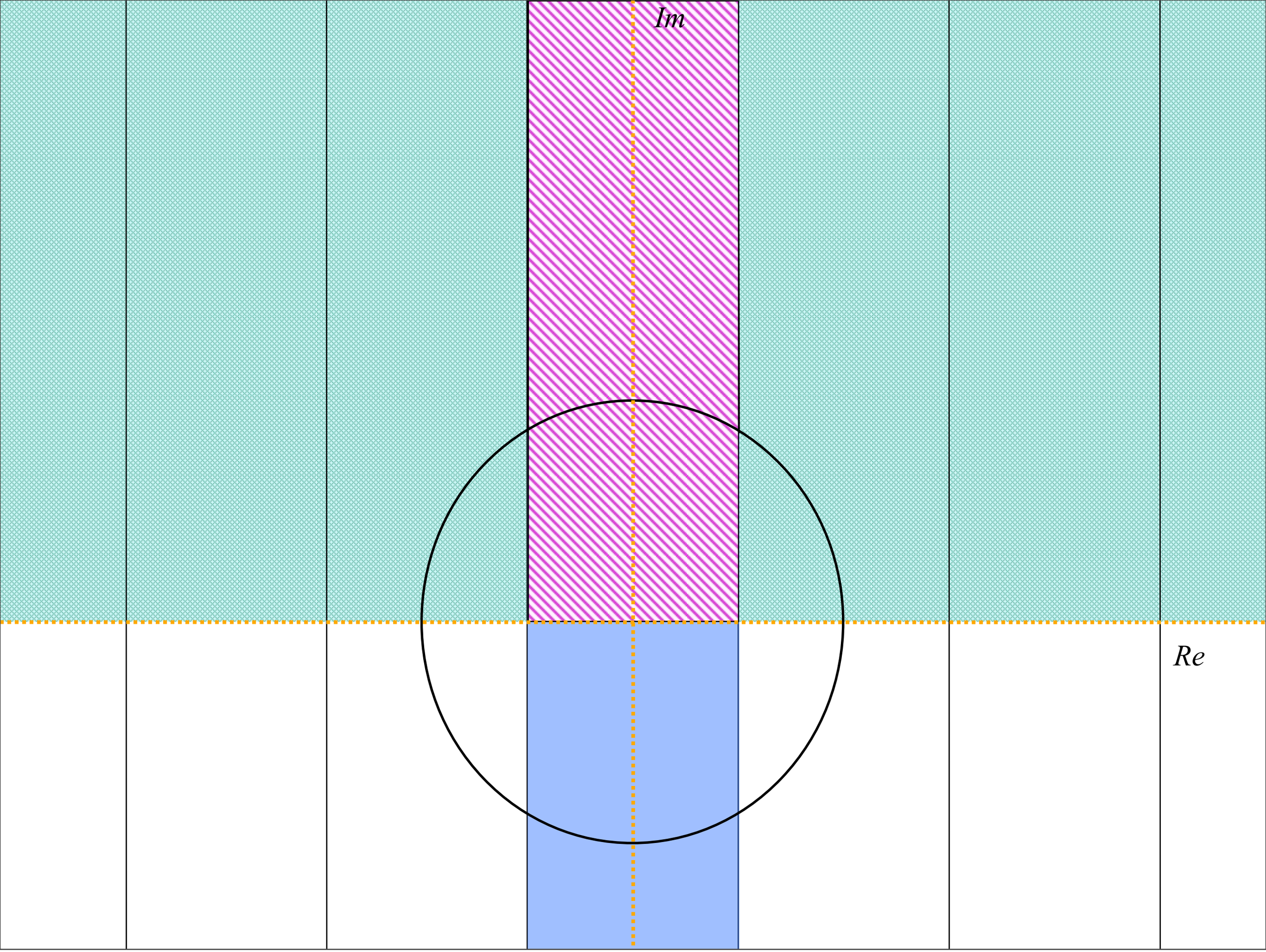
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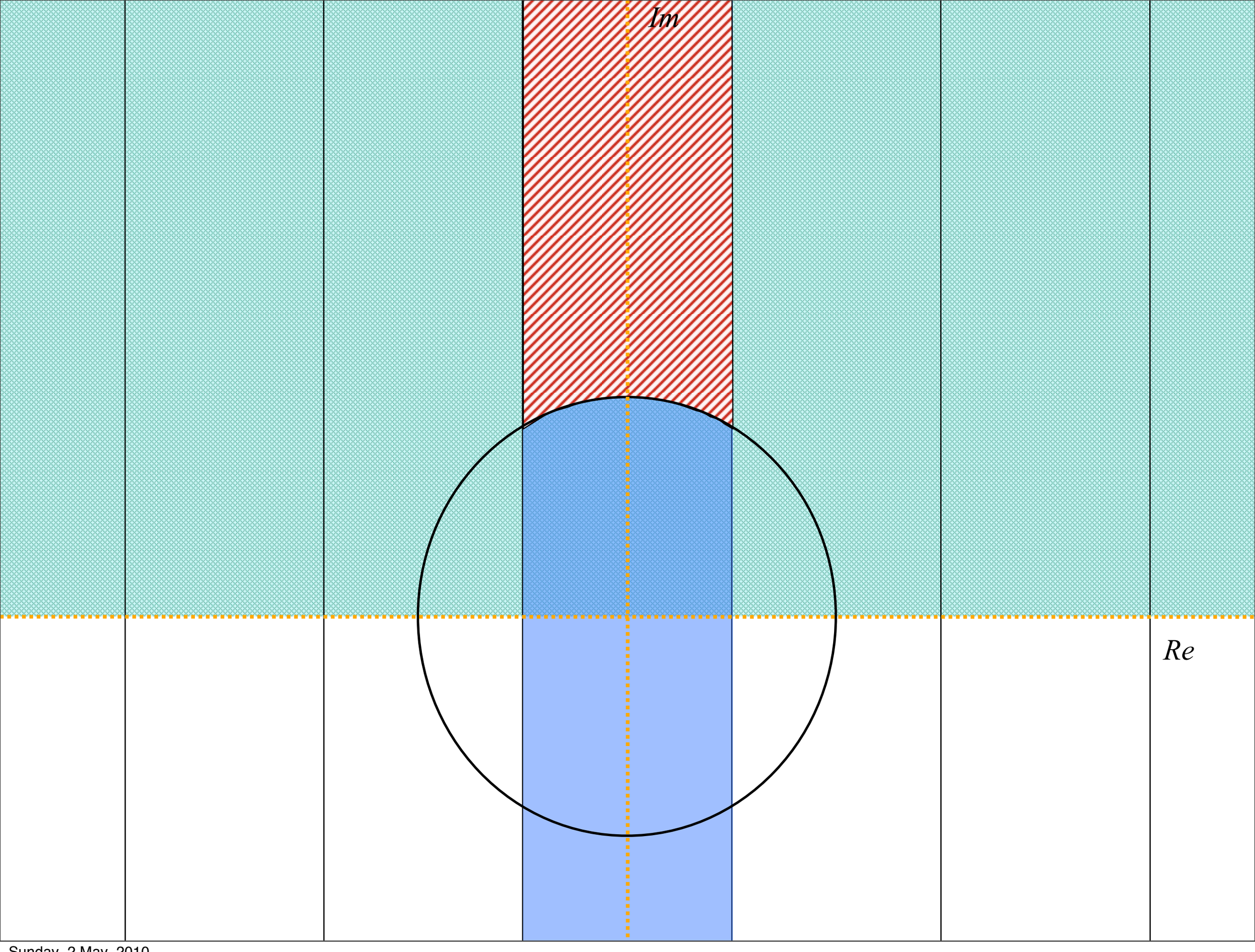

Im
Re

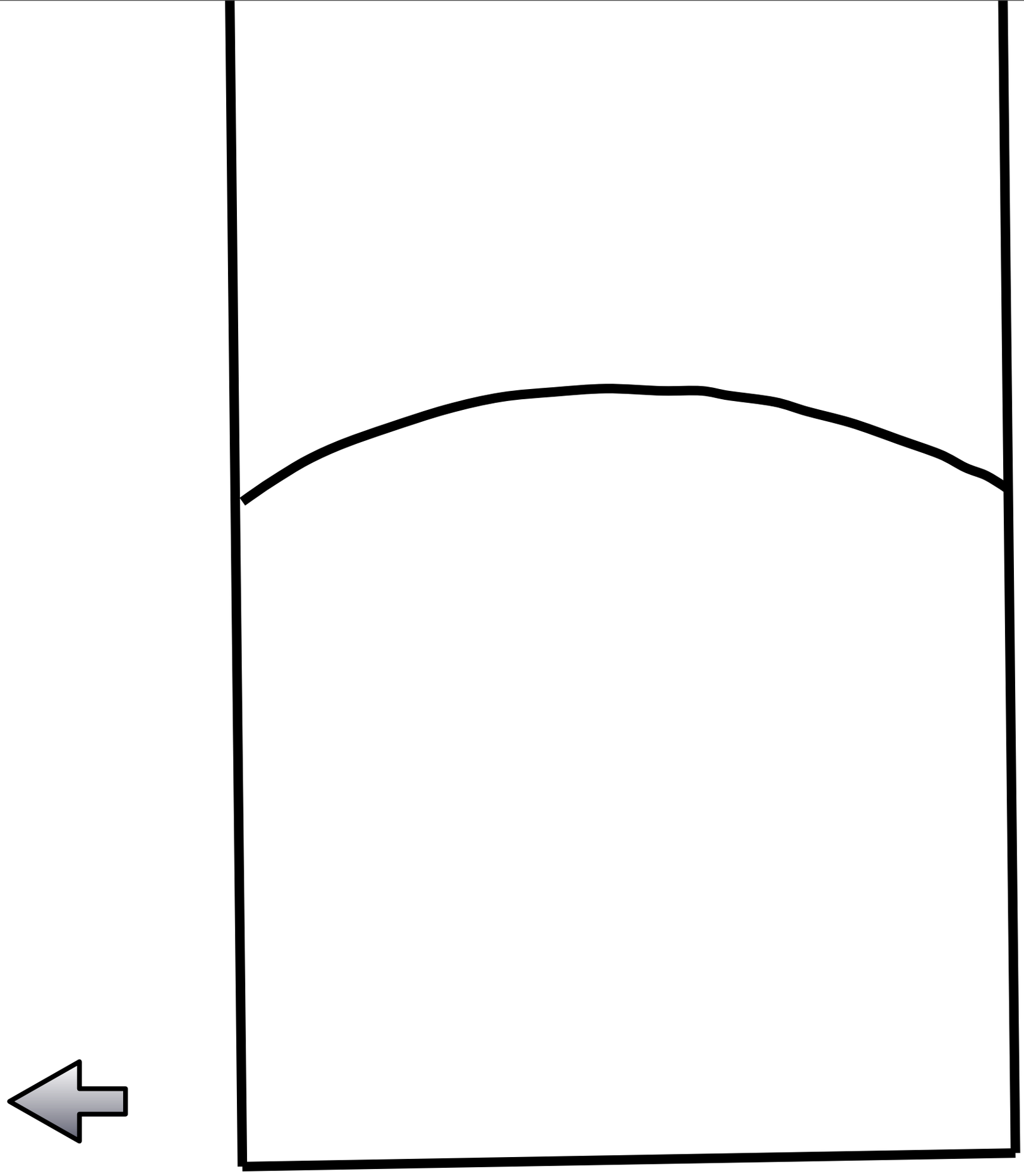
Field theory interpretation (one particle)

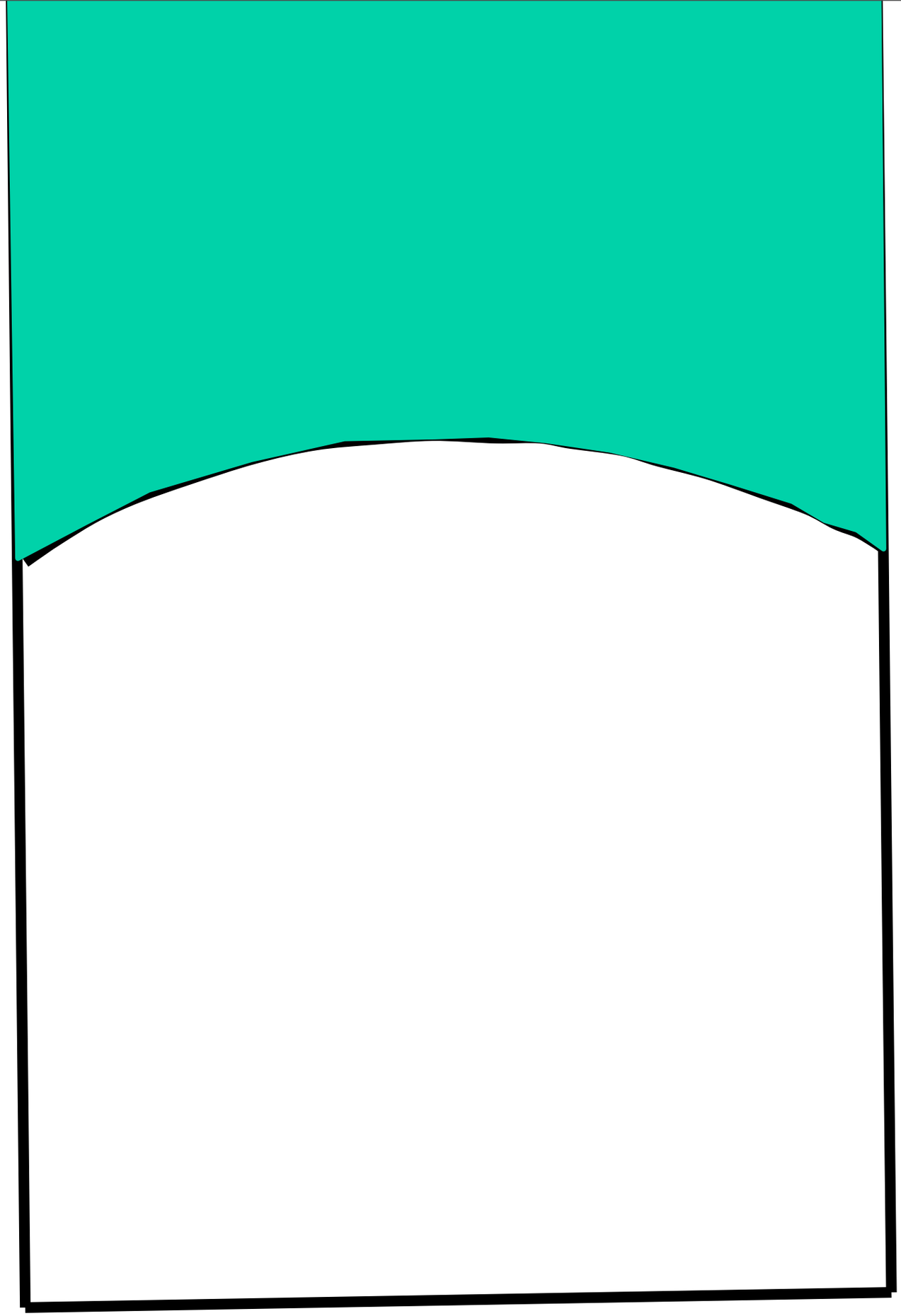
$$\Lambda = -\tfrac{1}{2}\int \frac{d^D p}{(2\pi)^D}\log(p^2+m^2)$$

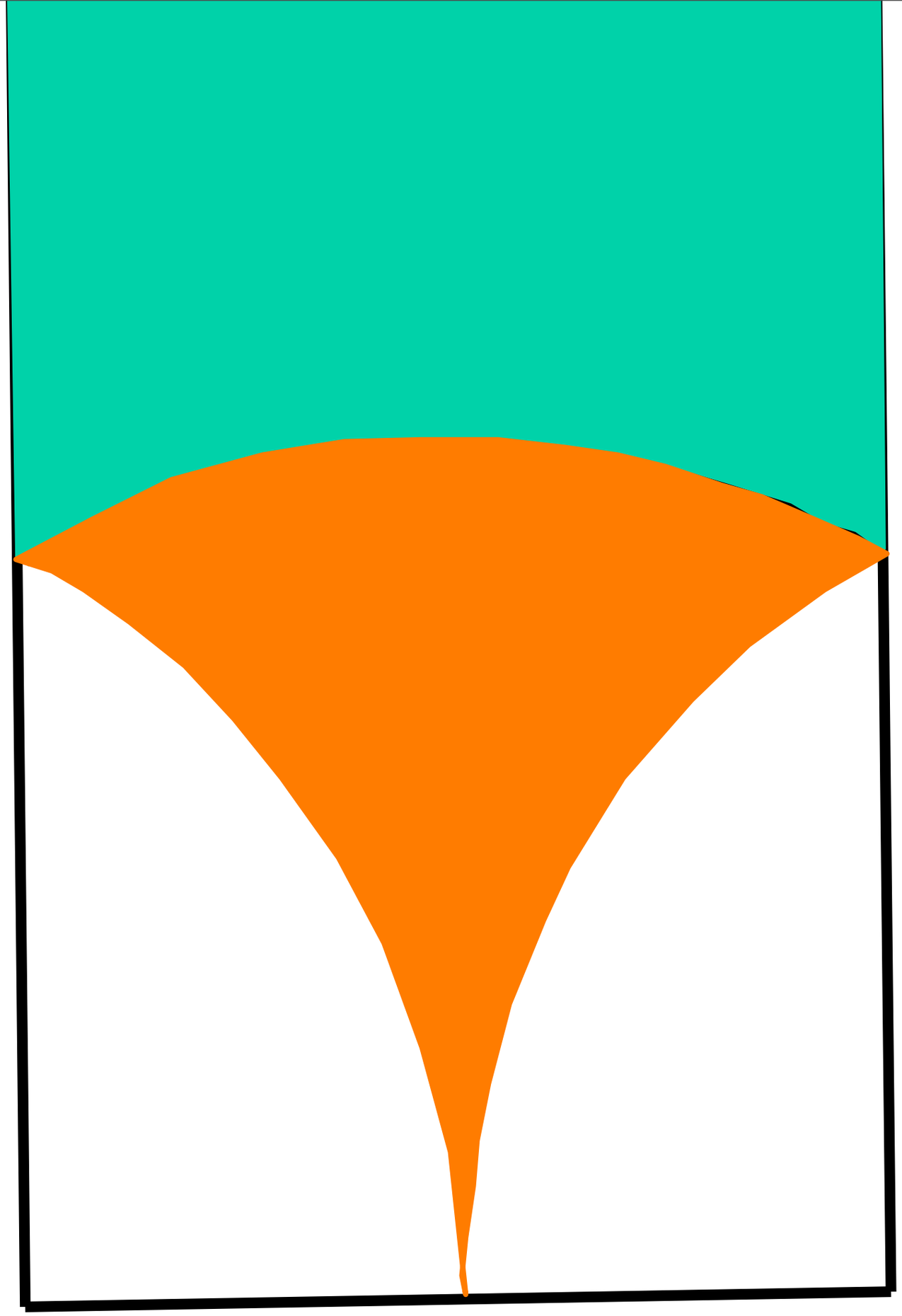
$$= \tfrac{1}{2}\int_0^\infty \frac{dt}{t} e^{-tm^2}\,\frac{1}{(4\pi t)^{D/2}}$$

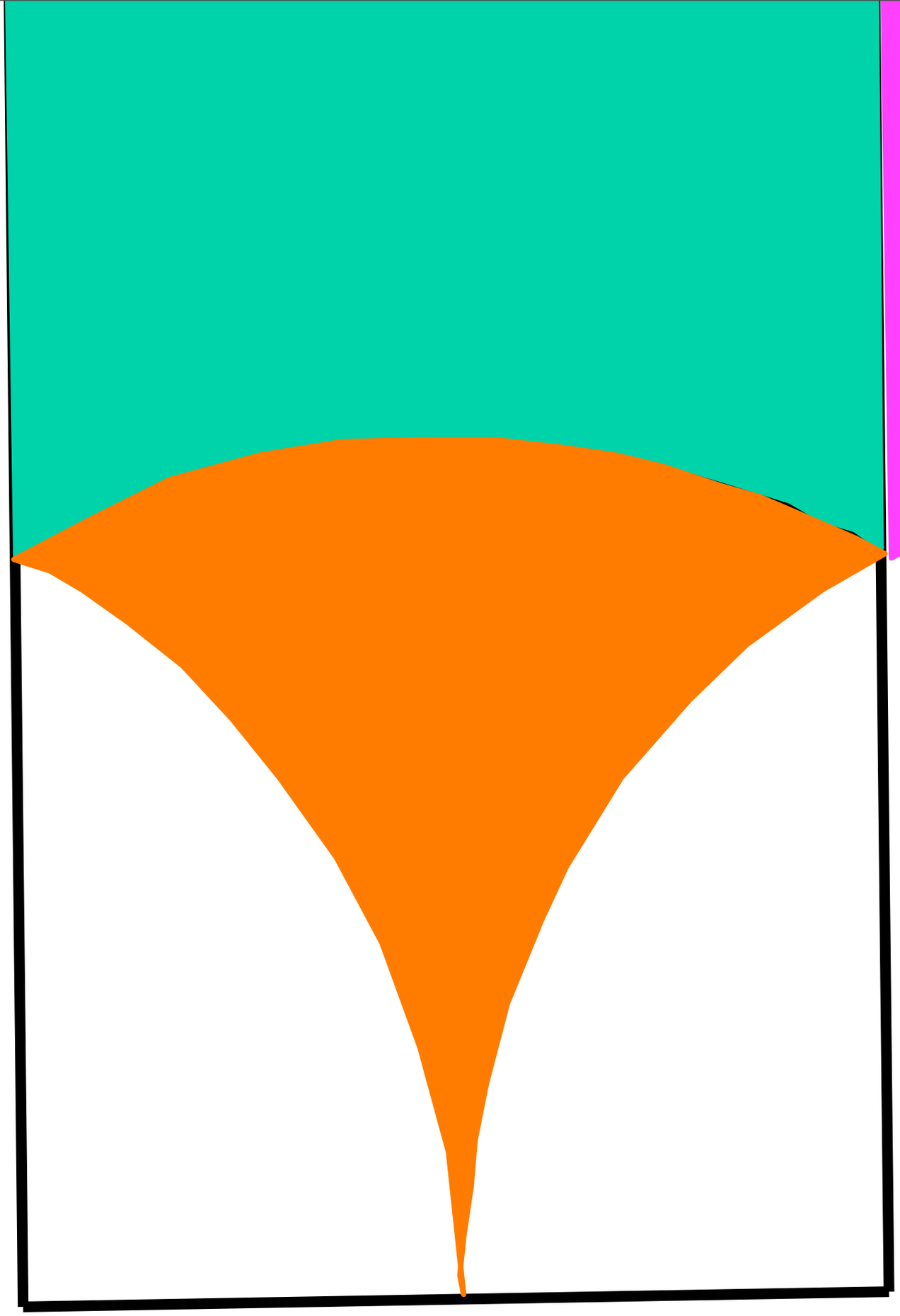
Summed:

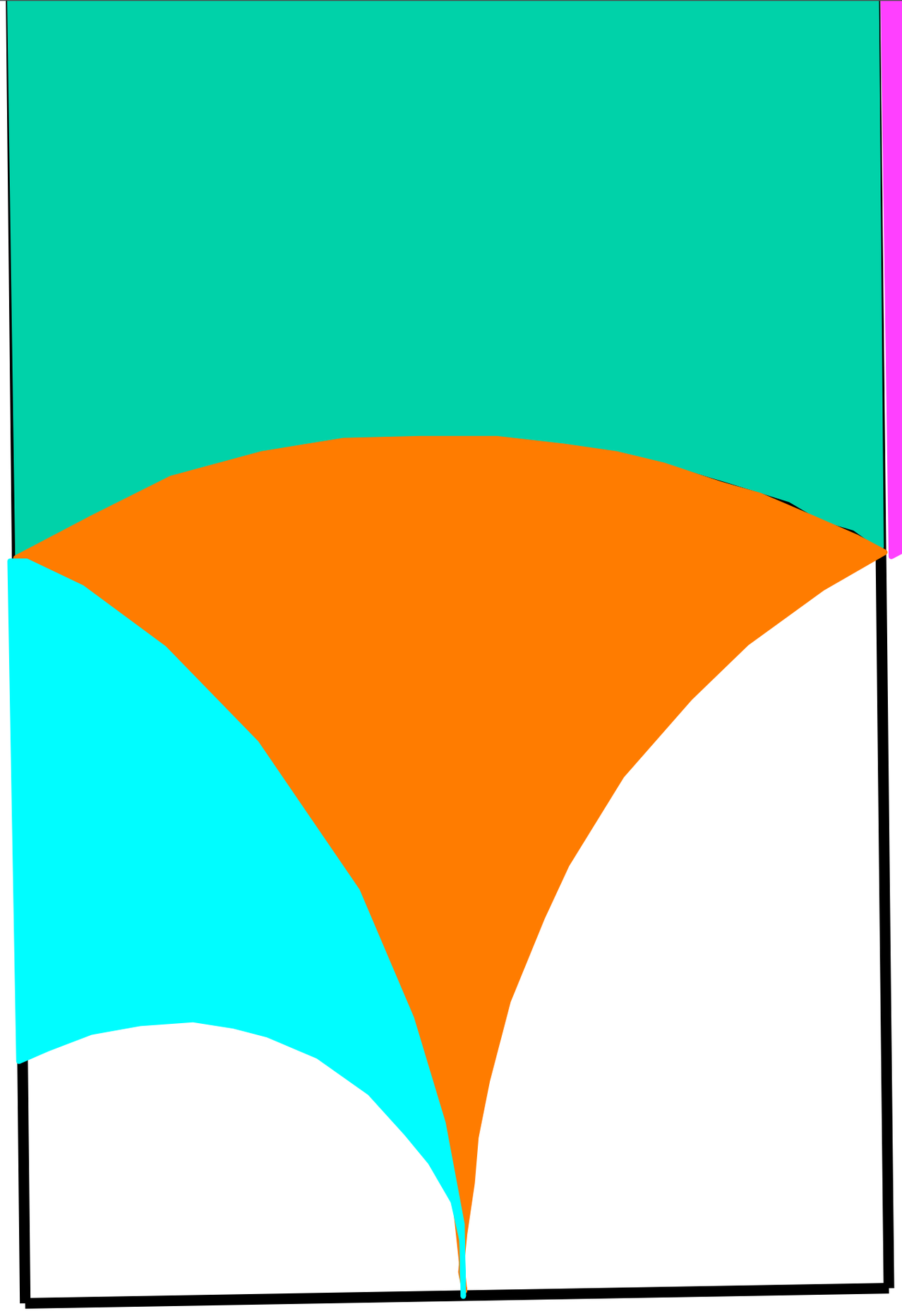
$$\Lambda_{\rm string} = \tfrac{1}{2}\int_0^\infty \frac{dt}{t}\left(\frac{1}{4\pi t}\right)^{13}\sum_m e^{-tm^2}$$

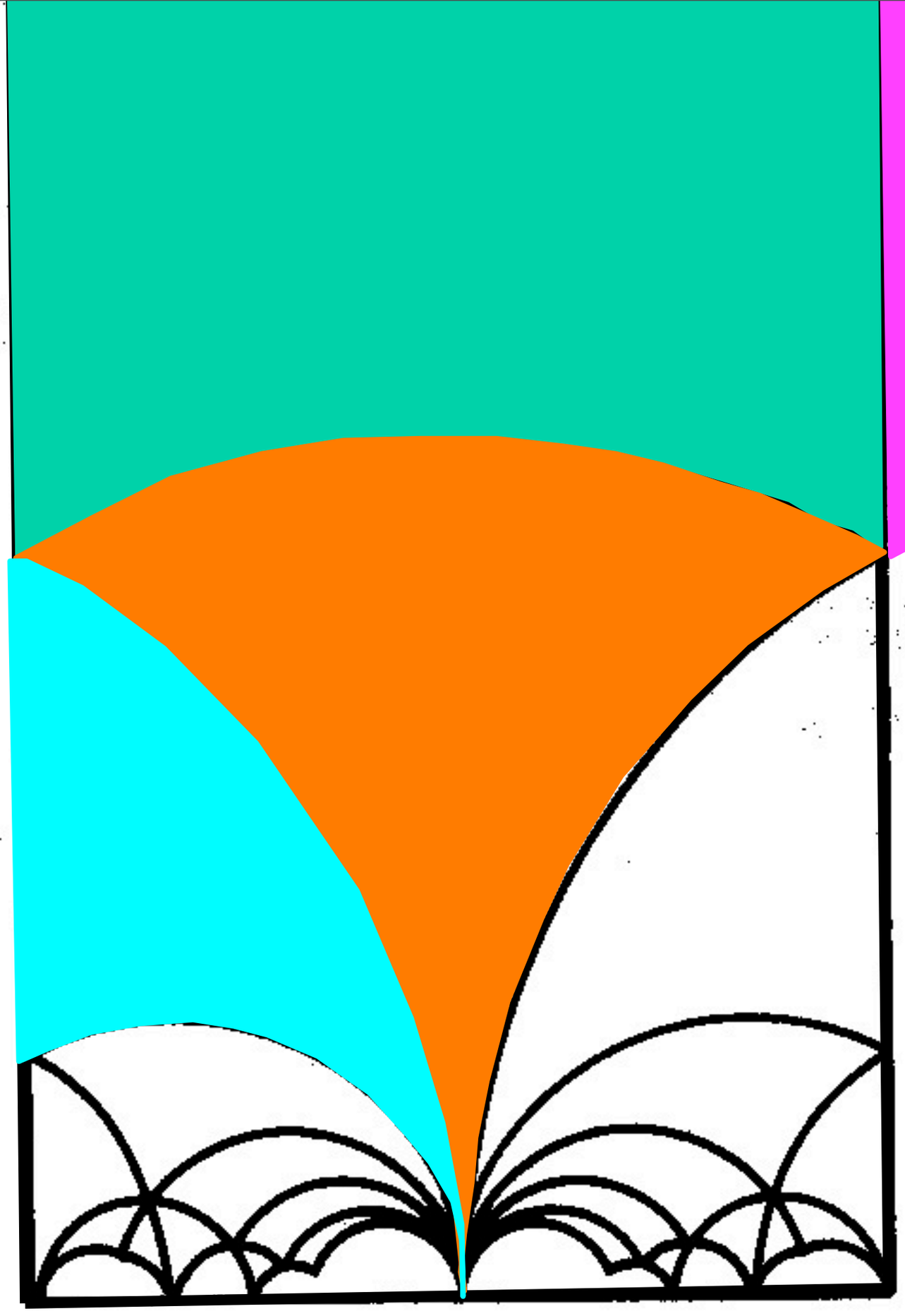












Falsifiability

- String Theory is falsifiable (but, remarkably, has not been falsified yet).
  - Chiral Fermions (without anomalies)
  - The Standard Model gauge group
  - Three Families
  - Couplings of reasonable size
  - Two loop finiteness
  - Black hole entropy
  - Cosmological constant
  - Moduli stabilization
  - ....
- Its vacuum structure is (theoretically) falsifiable.
- Non-anthropic nature of other vacua is (theoretically) falsifiable.
- No reason to expect that a theory of Quantum Gravity can be falsified via the Standard Model.

How many "vacua" are needed?

- Requires understanding of "anthropic" considerations for different gauge theories.
- Requires some definition of a measure and boundaries.

Wild guess: about 10^{20} for SM fine-tunings

The same problems exist in principle for the cosmological constant, but seem less serious there: about 10^{120} would be need

Recent estimates: String Theory has plenty of ground states to understand all fine-tunings.

(Bousso-Polchinski, Douglas Denef,...

Vacuum counting (1998)

$$10^{30} \times 10^{-80} = 10^{-50}$$

Number of vacua

SM Probability (experimental)

Vacuum counting (2006)

$$10^{500} \times 10^{-80} \times 10^{-120} = 10^{300}$$

Number of vacua

SM Probability

Cosmological Constant

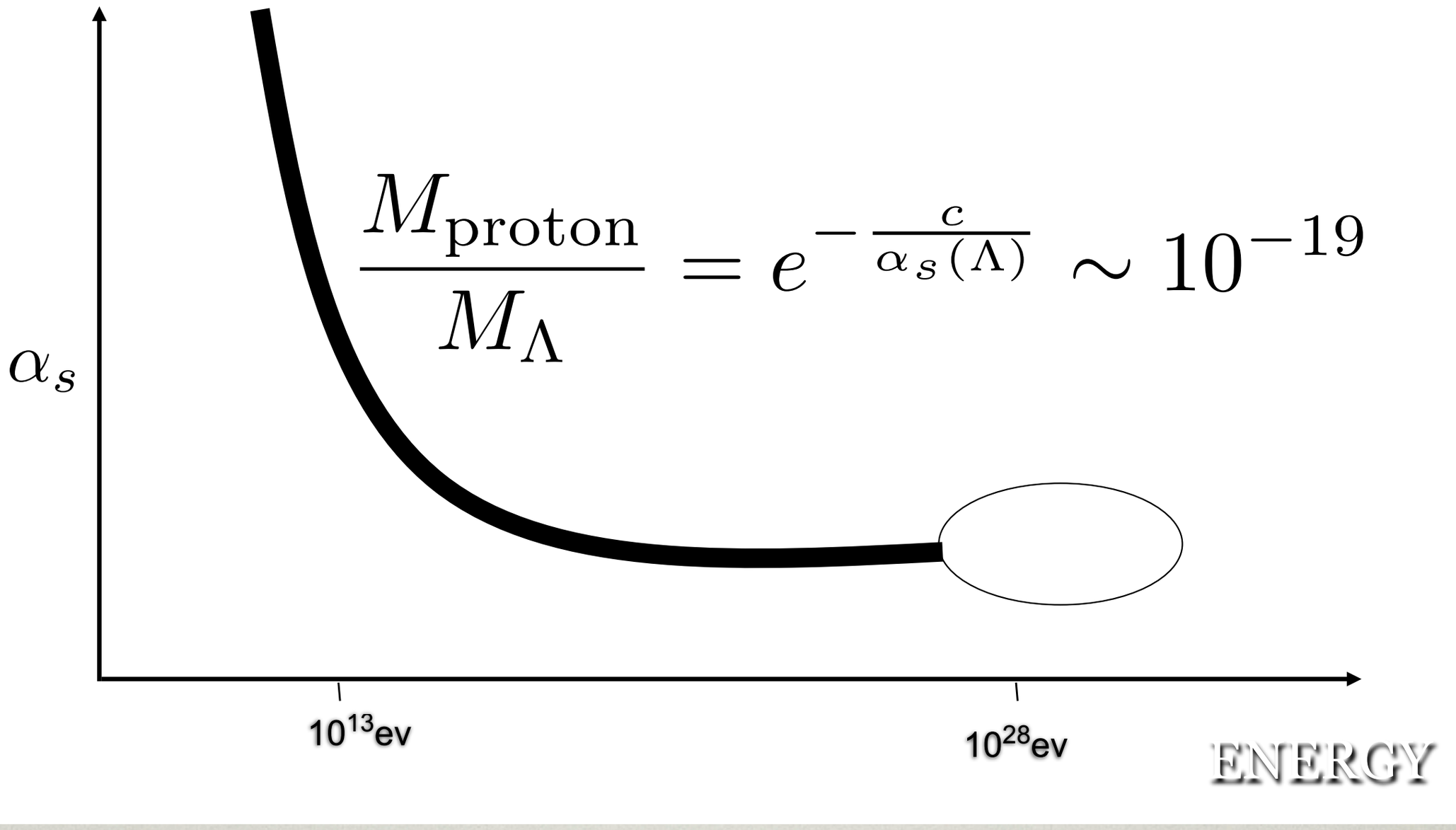
Dimensional transmutation and the measure problem

David Gross, Strings 2007:

DIRAC (1937)
The Large Number Problem

$$\frac{M_{\text{proton}}}{M_{\text{planck}}} \sim 10^{-19}$$

Dirac did not invoke anthropic arguments.


$\frac{M_{\text{proton}}}{M_\Lambda} = e^{-\frac{c}{\alpha_s(\Lambda)}} \sim 10^{-19}$
α_s
10^{13}ev
10^{28}ev
ENERGY

However:
Dimensional transmutation merely changes the measure on the space of gauge theories from linear to logarithmic. It does not explain the smallness of M_{proton}/M_{Planck}, it only makes it look far less fine-tuned.

If someone computes α_s from a fundamental theory and gets the right answer, the case is closed, but we would still be left with a minor puzzle why it came out small enough. There is no doubt that a small value is required anthropically.

But assume that the fundamental theory produces a small discrete landscape of about a hundred of values of α_s, including the correct experimental value.

In that case the anthropic principle is still a crucial part of the explanation.

GUT Couplings

The dimensional transmutation argument can be improved by assuming GUT unification. This gives a rationale for a small QCD couplings at the GUT scale by relating it to the QED coupling.

Coupling unification does indeed provide a slight worry for anthropic reasoning, since it relates two anthropic parameters: the electromagnetic and strong couplings.

However, the weak coupling strength is presumably not as strongly anthropic. Hence the two anthropic couplings are expressed in terms of two parameters, the unification scale and the value of the unified coupling at that scale. The only constraint arises from the fact that the unification scale must be “reasonable”.

Hence even if coupling unification is correct and not just a misleading empirical coincidence, the fact that two couplings that are functions of two parameters intersect an anthropic region seems only a minor miracle.

Earth-Sun distance

Criterium	1600	Now
Affects life?	Yes	Yes
Sensible variation?	?	Yes
Special value?	Kepler: Yes	No

Earth-Sun distance

Conclusion:

Clearly anthropic, but not an issue.

The theory of formation of solar systems is more important.

The observation of other planets has helped.

Note: we believed in the non-uniqueness of our own solar system long before finding evidence of the existence of others.

Newton's law

$$F = G\frac{m_1 m_1}{r^2}$$

Newton's law

$$F = G\frac{m_1 m_1}{r^2}$$

Anthropic?

Newton's law

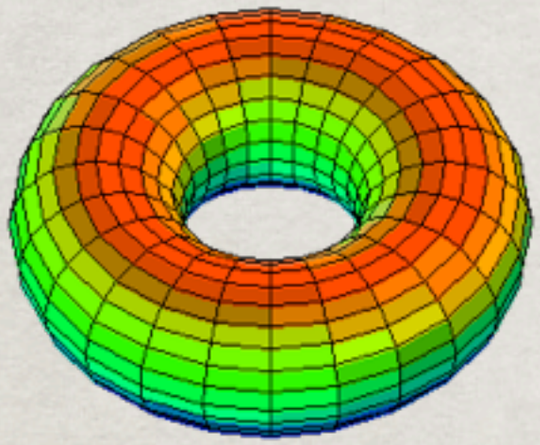
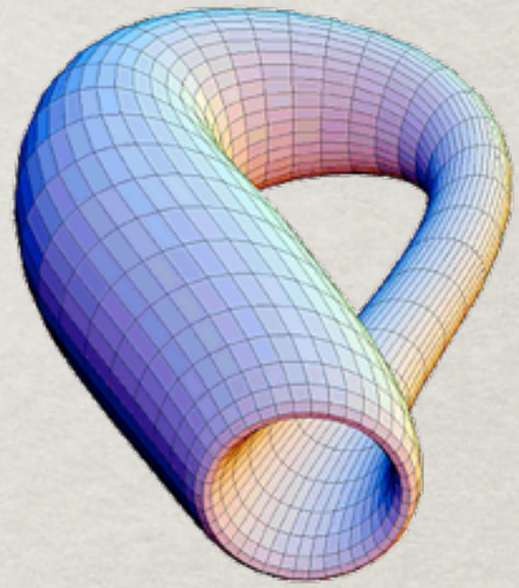
Criterium	1687	Now
Affects our existence	Yes	Yes
Affects any existence	Yes	Yes
Sensible variation?	?	No
Special value?	Yes	Yes

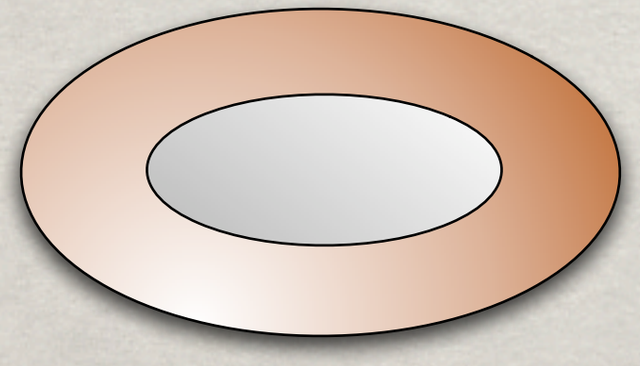
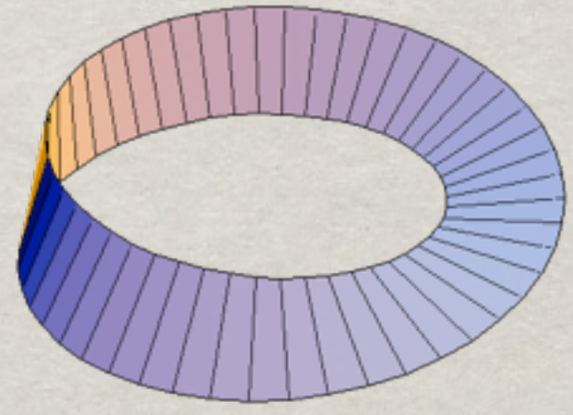
Newton's law

Conclusion:

Clearly not anthropic, and nobody would have been tempted to say it is.

Orientifold Partition Functions

$$\frac{1}{2}\left\{\right.$$  $$+$$  $$\left.\right\}$$

$$\frac{1}{2}\left\{\right.$$  $$+$$  $$\left.\right\}$$

RCFT orientifolds with Standard Model Spectrum

Tim Dijkstra, Lennaert Huiszoon and Bert Schellekens

On this page you can search through all our supersymmetric, tadpole-free D=4, N=1 orientifold vacua with a three family chiral fermion spectrum identical to that of the Standard Model. They were constructed in a semi-systematic way by considering orientifolds of all Gepner Models (see *Phys.Lett.B609:408-417* and *Nucl.Phys.B710:3-57* for more information). Since the publication of these papers all spectra have been re-analysed and checked for the presence of global (Witten) anomalies. A few cases (less than 1%) needed correction. All spectra in this database are now free from global anomalies, and the total number is 210,782, slightly more than reported in these papers.

As explained in referenced articles the standard model gauge group can be realized in different ways (which we call *types*). In addition to these factors, the gauge group usually has extra *hidden* gauge group factors. Chiral states with one leg in the standard model gauge group are not permitted.
All these models of course have the same *chiral* spectrum for the standard model gauge group, except for the higgs-sector of which we do not know how it is realized in nature.

These models then differ in multiplicities of the non-chiral particles, hidden gauge group, higgs sector coupling constants on the string scale, and others.
To search for your favorite realization you can use the form below to filter our set with an condition. Example:

```
type==0 && nrHidden<2
```

You can consult a list of valid field names. Also much more complicated expressions are possible, see the syntax description.

Filter form

Two output formats are provided. The first only gives the number of answers, the second lists all the spectra satisfying the search criteria. Be warned that output can be very large and take up to a minute to compile; at the moment we have

A SM-like Model

Gauge group: Exactly SU(3) × SU(2) × U(1)!

[U(3)×Sp(2)×U(1)×U(1), Massive B-L, No hidden sector]

3	x (V	,V	,0	,0)	chirality 3	Q
3	x (V	,0	,V	,0)	chirality -3	U*
3	x (V	,0	,V*	,0)	chirality -3	D*
3	x (0	,V	,0	,V)	chirality 3	L
5	x (0	,0	,V	,V)	chirality -3	E*+(E+E*)
3	x (0	,0	,V	,V*)	chirality 3	N*
18	x (0	,V	,V	,0)		Higgs
2	x (V	,0	,0	,V)		
2	x (Ad	,0	,0	,0)		
2	x (A	,0	,0	,0)		
6	x (S	,0	,0	,0)		
14	x (0	,A	,0	,0)		
6	x (0	,S	,0	,0)		
9	x (0	,0	,Ad	,0)		
6	x (0	,0	,A	,0)		
14	x (0	,0	,S	,0)		
3	x (0	,0	,0	,Ad)		
4	x (0	,0	,0	,A)		
6	x (0	,0	,0	,S)		

A SM-like Model

Gauge group: Exactly SU(3) × SU(2) × U(1)!

[U(3)×Sp(2)×U(1)×U(1), Massive B-L, No hidden sector]

3 x (V ,V ,0 ,0) chirality 3		Q
3 x (V ,0 ,V ,0) chirality -3		U*
3 x (V ,0 ,V* ,0) chirality -3		D*
3 x (0 ,V ,0 ,V) chirality 3		L
5 x (0 ,0 ,V ,V) chirality -3		E*+(E+E*)
3 x (0 ,0 ,V ,V*) chirality 3		N*
18 x (0 ,V ,V ,0)		Higgs
2 x (V ,0 ,0 ,V)		
2 x (Ad ,0 ,0 ,0)		
2 x (A ,0 ,0 ,0)		
6 x (S ,0 ,0 ,0)		
14 x (0 ,A ,0 ,0)		
6 x (0 ,S ,0 ,0)		
9 x (0 ,0 ,Ad ,0)		
6 x (0 ,0 ,A ,0)		
14 x (0 ,0 ,S ,0)		
3 x (0 ,0 ,0 ,Ad)		
4 x (0 ,0 ,0 ,A)		
6 x (0 ,0 ,0 ,S)		

Vector-like matter

V=vector

A=Anti-symm. tensor

S=Symmetric tensor

Ad=Adjoint

P. Townsend, G. Gibbons, "Vacuum interpolation in supergravity via super p-branes"

It is possible that particle physics in our four-dimensional (d=4) universe may ultimately be well-described by some compactification of a ten-dimensional (d=10) supergravity theory that serves as the effective field theory of a d=10 superstring theory. Even if superstring theory meets with complete success in this respect there will remain the question of why the universe 'chooses' to compactify six dimensions in a particular way and, indeed, why it 'chooses' to compactify any of them since d=10 Minkowski spacetime ($\mathcal{M}_{10}$) is as good a vacuum solution as any other from a purely mathematical point of view. In contrast to solutions of simple flat space field theories there is no way to compare the energies of different compactifications and thus determine 'the' vacuum by finding the one of lowest energy. In these circumstances it might be supposed that the choice of compactification must be left to some theory of initial conditions. An alternative is that *all possible* compactifications are already to be found in different spatial regions of a single (presumably ten-dimensional) universe. The particular region in which we find ourselves must then be decided by chance and/or anthropic considerations. Ideas along these lines, but within the context of a four-dimensional universe, have been suggested previously by Linde [1]

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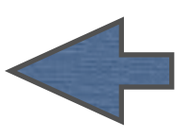
[13]We may hope that this recent progress will lead to the answer of the 'why' question mentioned in the introduction and select our Universe uniquely from the underlying fundamental theory. Otherwise, we might have to invoke the anthropic principle and probably imagine our Universe emerging in a kind of darwinian natural selection. Many theorists disregard this second option because it implies that the theory would not have predictive power. However, this posture may be too naive, it is only a 'philosophical prejudice' similar to the geocentric ideas of Aristotle since it is like assuming that our Universe has to be the only possible outcome of a fundamental theory. Regardless of any philosophical prejudice, we have to study the theory to its limits. This is the attitude that string phenomenologists have been taking during the past 10 years. We may hope that, if there is a fundamental theory and still many possible models are allowed, there could still be several general features that are model independent, such as those mentioned for QFT in the introduction. They could help in eventually testing the theory and not only the particular models.

(1996)



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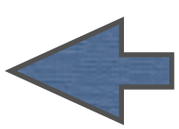

F. Quevedo, "Lectures on superstring phenomenology"

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