

***String theory
for the curious***

- Lecturer:

Yuji Tachikawa (IPMU)

- Date & Time:

Every Thursday, 10:25 to 12:10

- Web page:



- I'll use slides for the first lecture,
but I plan to use blackboards for the rest.

- To get credits / 単位 :

Please submit the term-end project report.
I will provide project suggestions for you to work on.

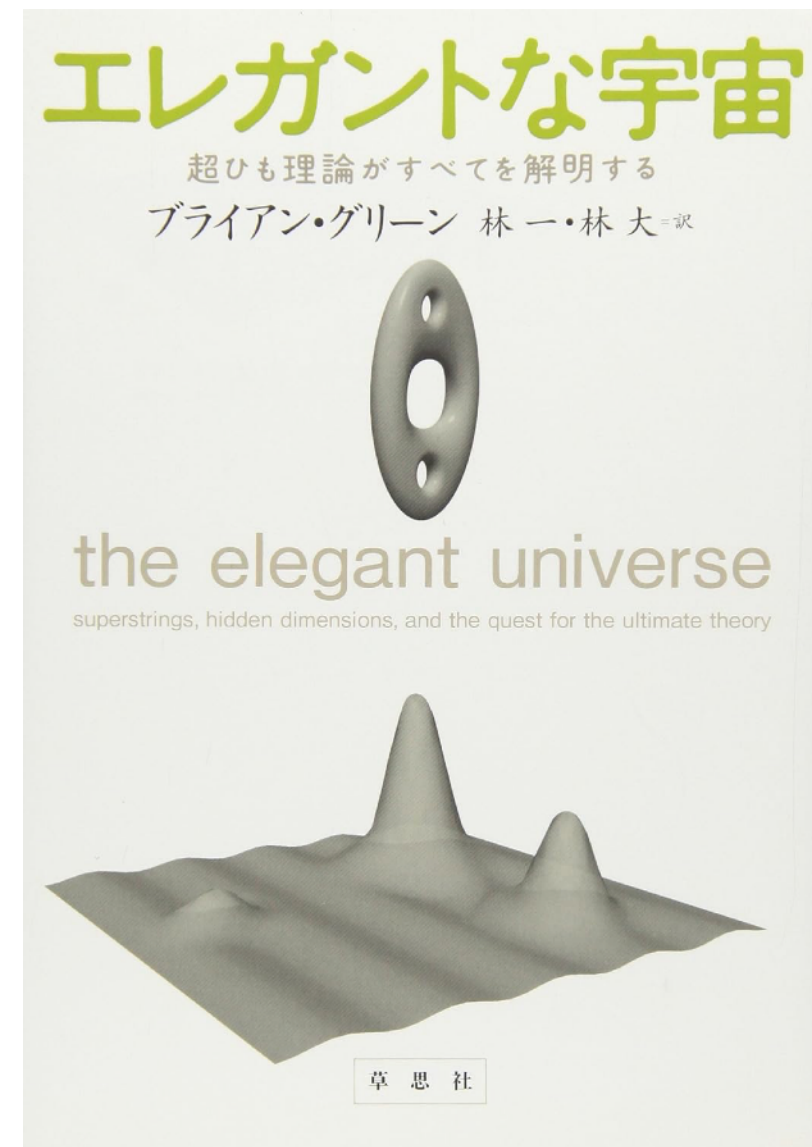
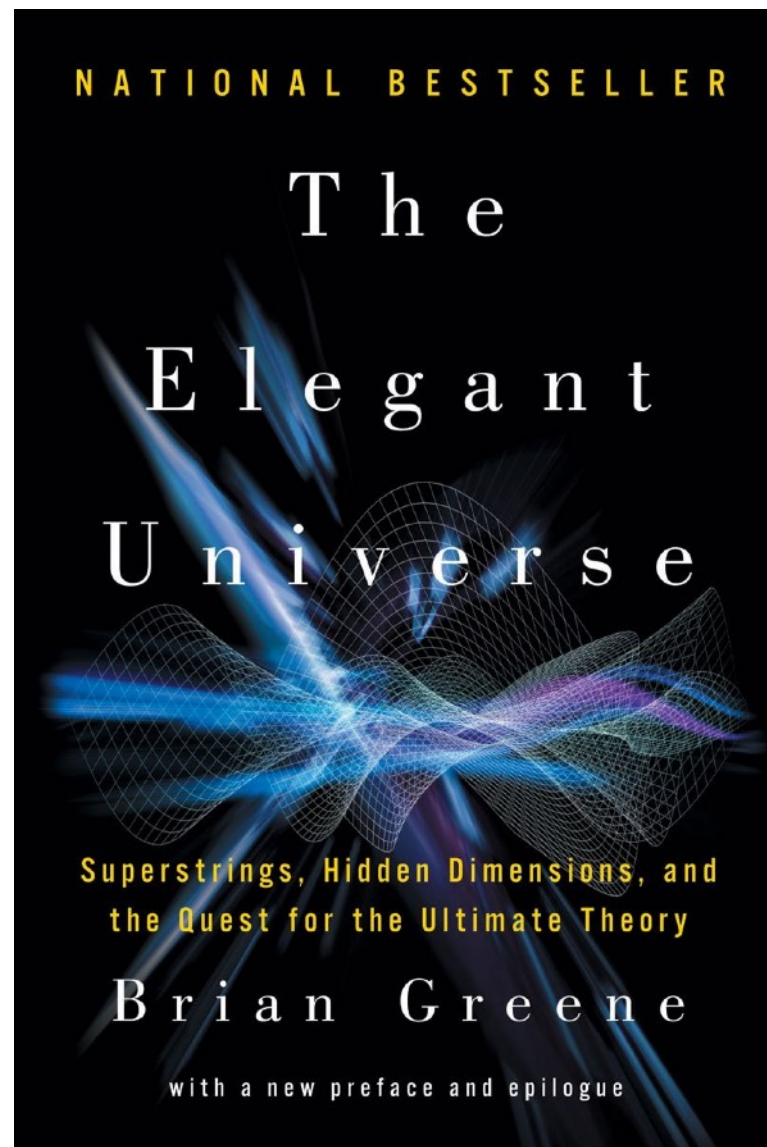
I'm no longer sure how effective this would be in
evaluating your understanding, though,
as the paid versions of ChatGPT or Claude will easily
answer any questions.

- The aim:

To convey to non string theorists
what string theory actually does for us,
not just at the level of “stories”
but with some technical details.

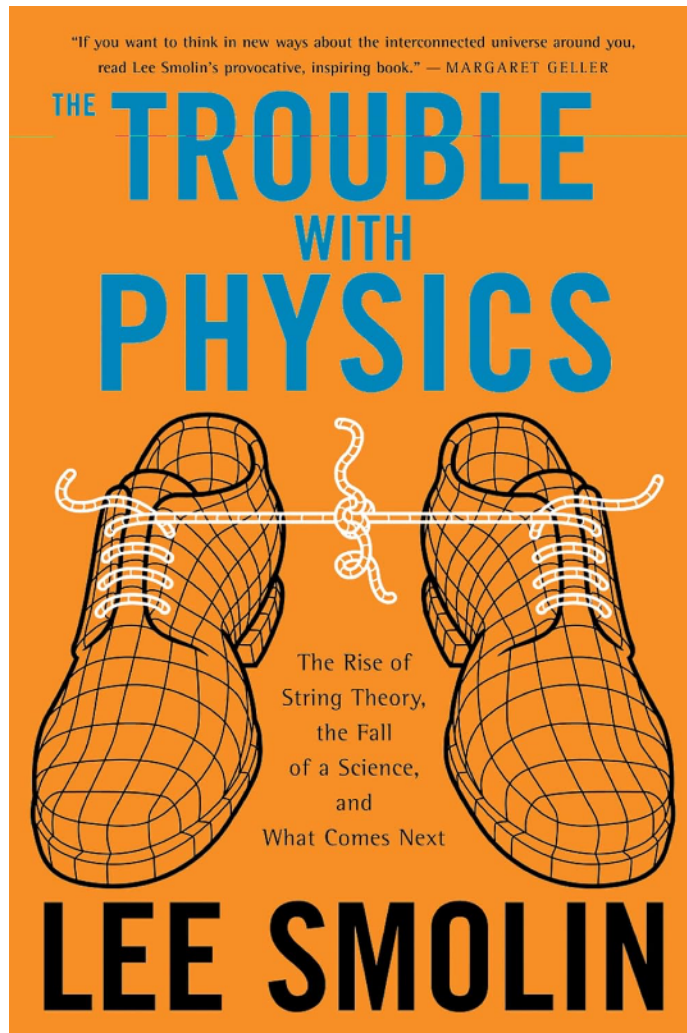
I would hope to do this without the hype or the hate...

The Hype...



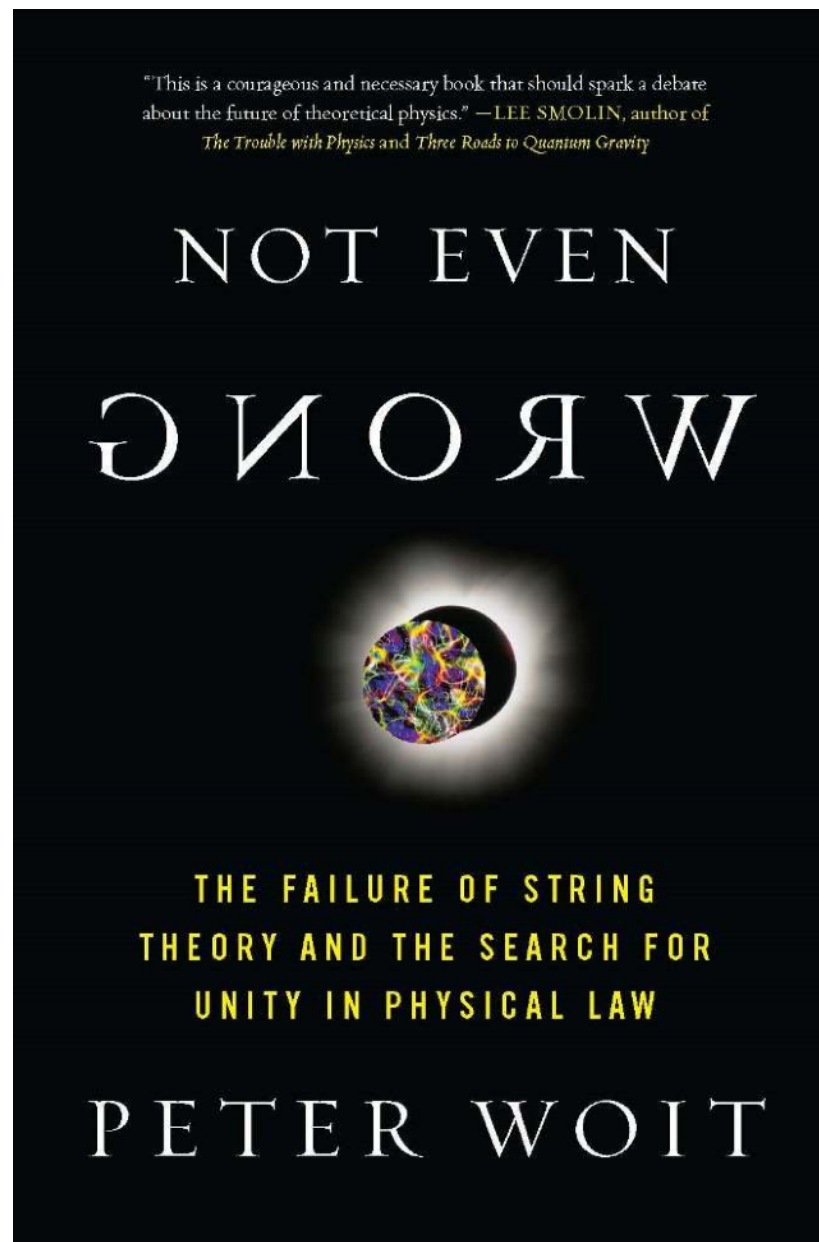
(originally published in 1999)

The Hate...



(originally published in 2006)

The Hate...

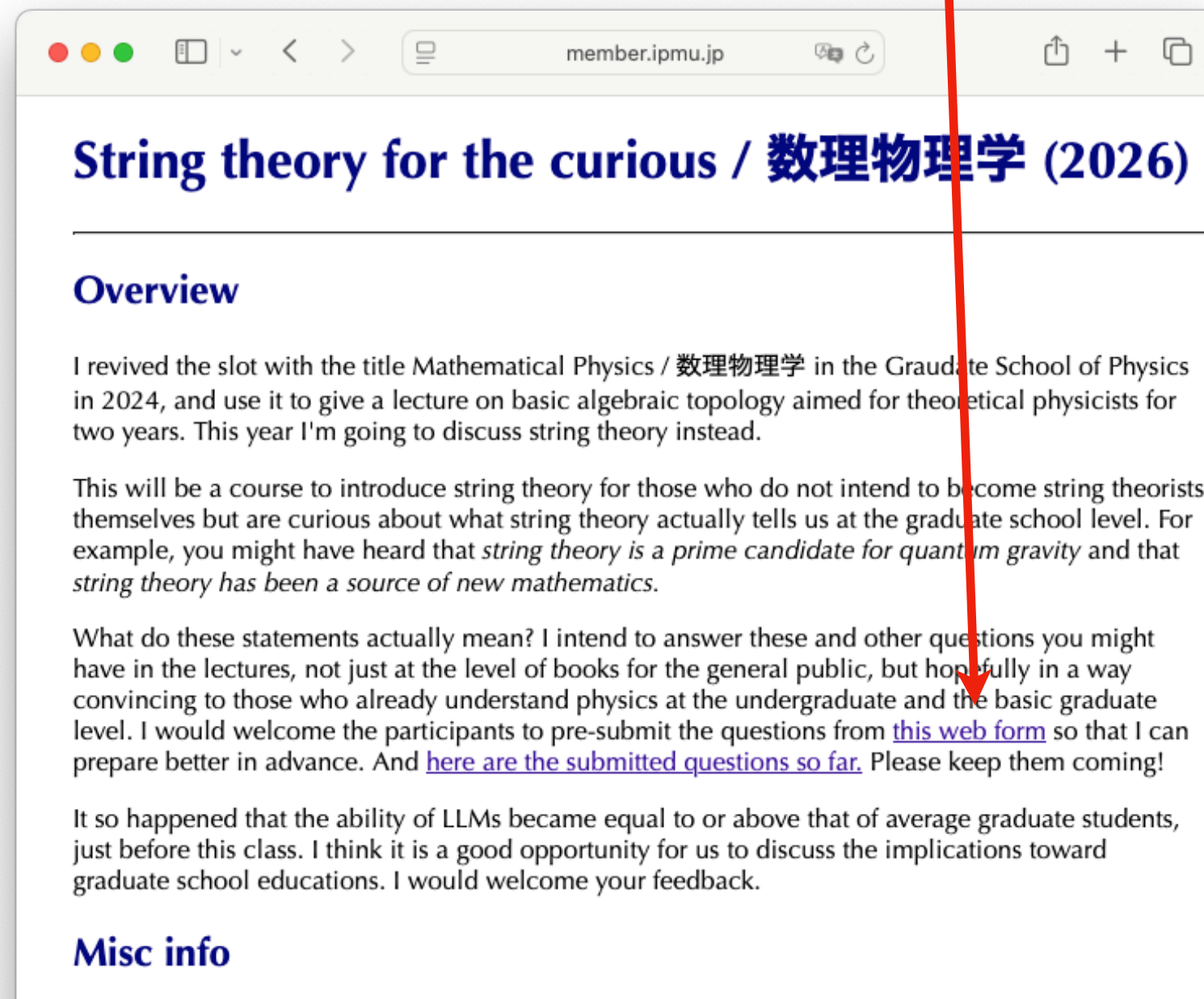


(originally published in 2006)

- They are all books from long time ago by now, but they appeared exactly when I was becoming a string theorist. So those discussions between haters/believers affected me a lot.
- Maybe it's no longer relevant for young people like you.

But I think it's still useful to try to be impartial, to present facts (about string theory) without my own value judgements, so that you can make your own.

- I'd like to encourage *you* to ask questions, so that I can tailor the content of the lectures.
- You can do this *now*, or submit them here on the webpage



- So far, submitted questions are about
 - Relation to condensed matter physics
 - Relation to quantum information
 - Relation to pure mathematics
- Not much interest about quantum gravity, apparently...

Questions?

*Is string theory
physics?*

Or is it mathematics?

Why are you doing it?

Is it meaningful?

***What's the history of
string theory?***

***What's the future of
string theory?***

***What's the goal of
string theory?***

***What's string theory,
to start with?***

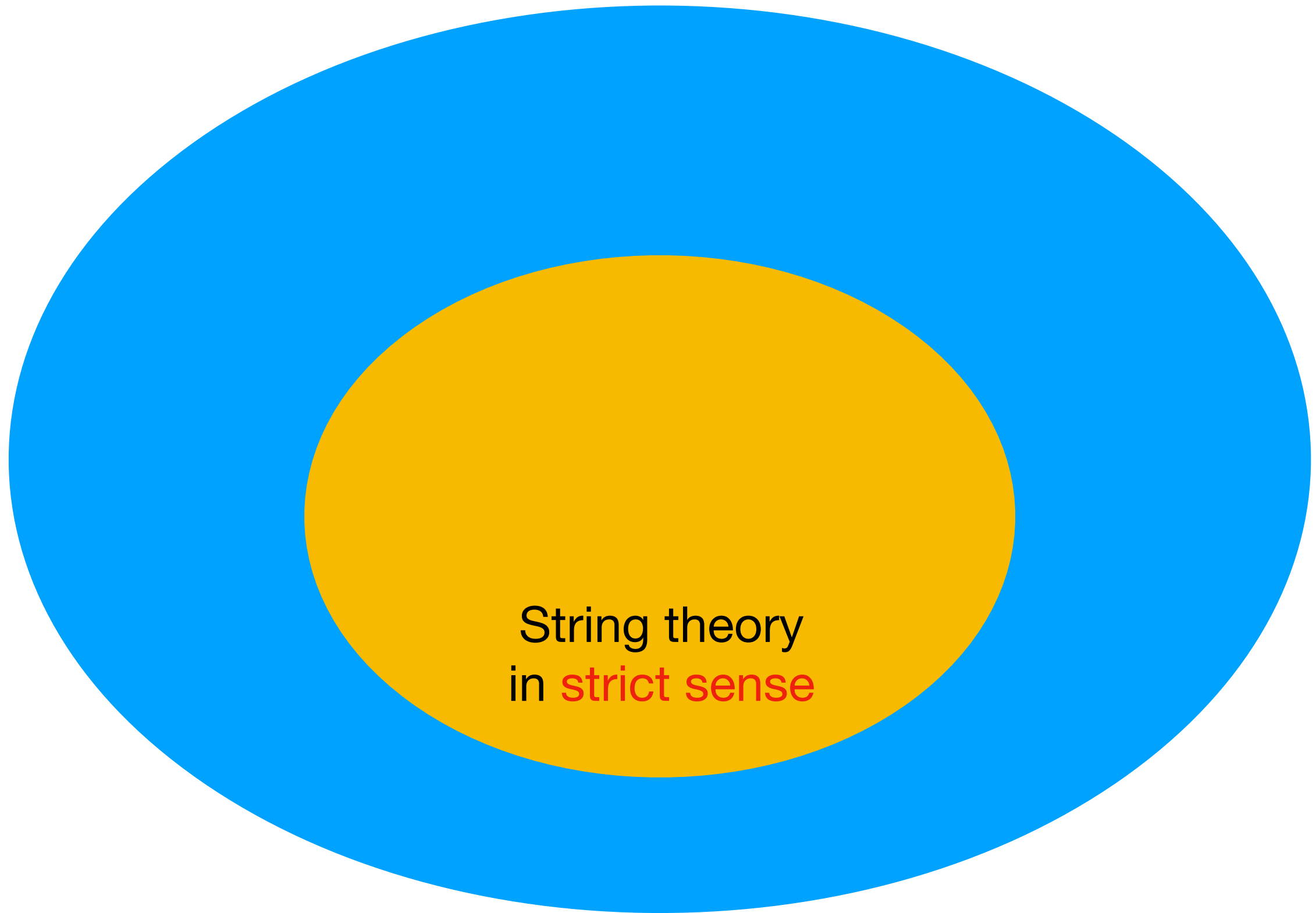
Questions?

[Jump to the list of submitted questions...](#)

- OK, let's end the question session and move on ...

What is string theory?

String theory
in a wider sense



String theory
in strict sense

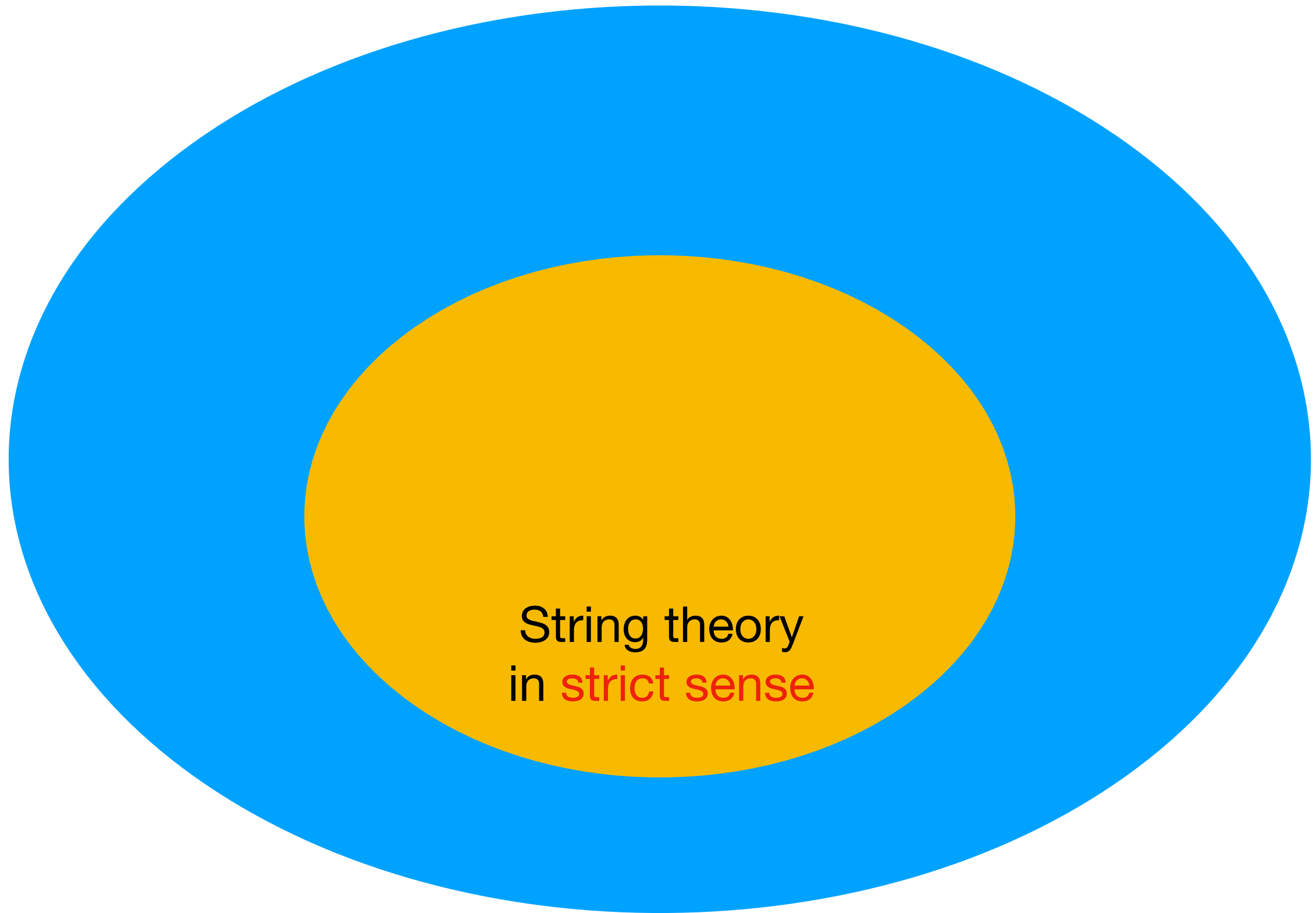
- String theory in a looser sense.

= What string theorists do.

- String theory in a stricter sense.

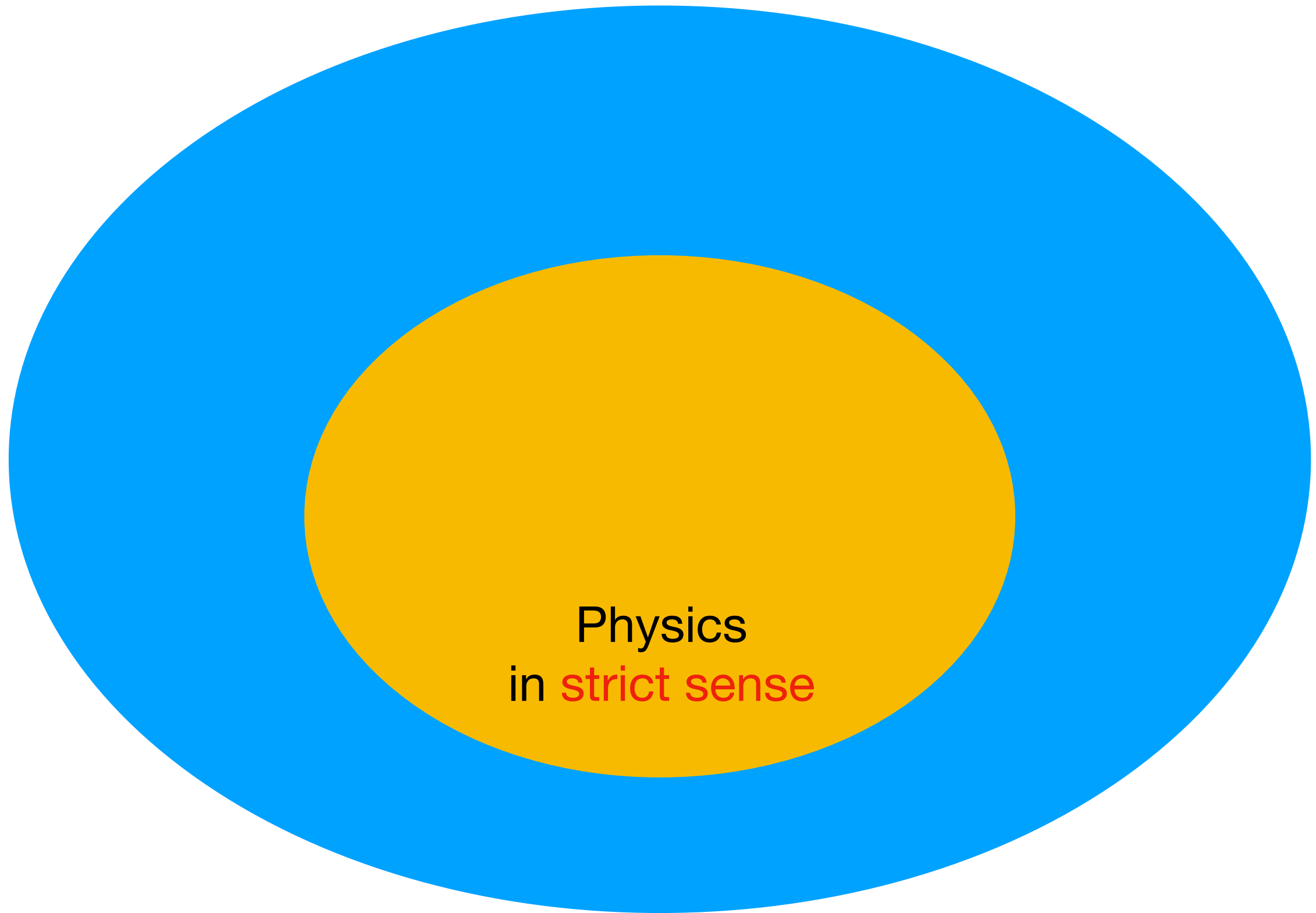
= Study of systems with relativistic string-like objects.

String theory
in a wider sense



String theory
in strict sense

Physics
in a wider sense

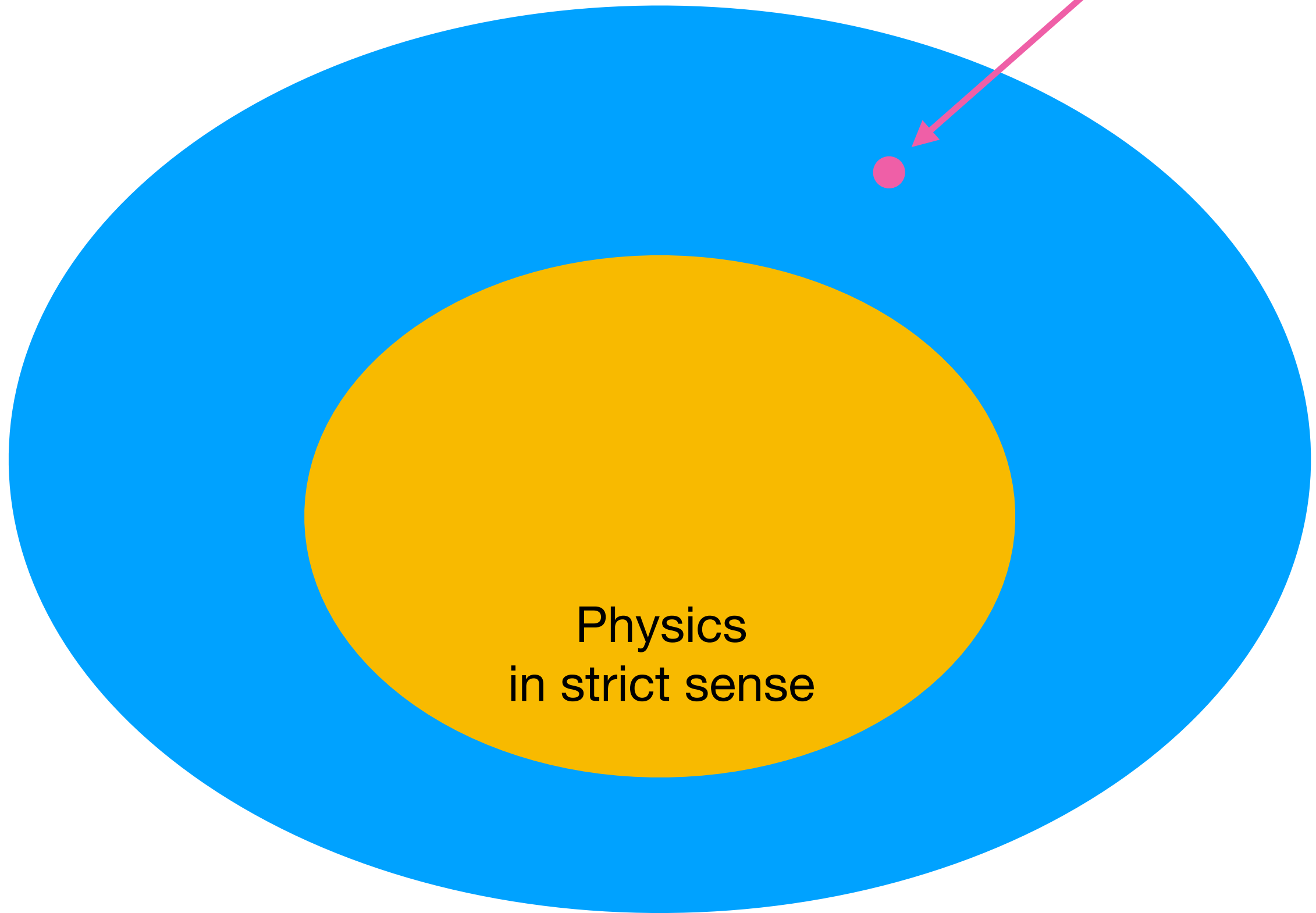


Physics
in strict sense

- Physics in a looser sense.
= What people in the physics department do.
- Physics in a stricter sense.
= Study of nature, mostly its inanimate aspects,
using scientific methods.

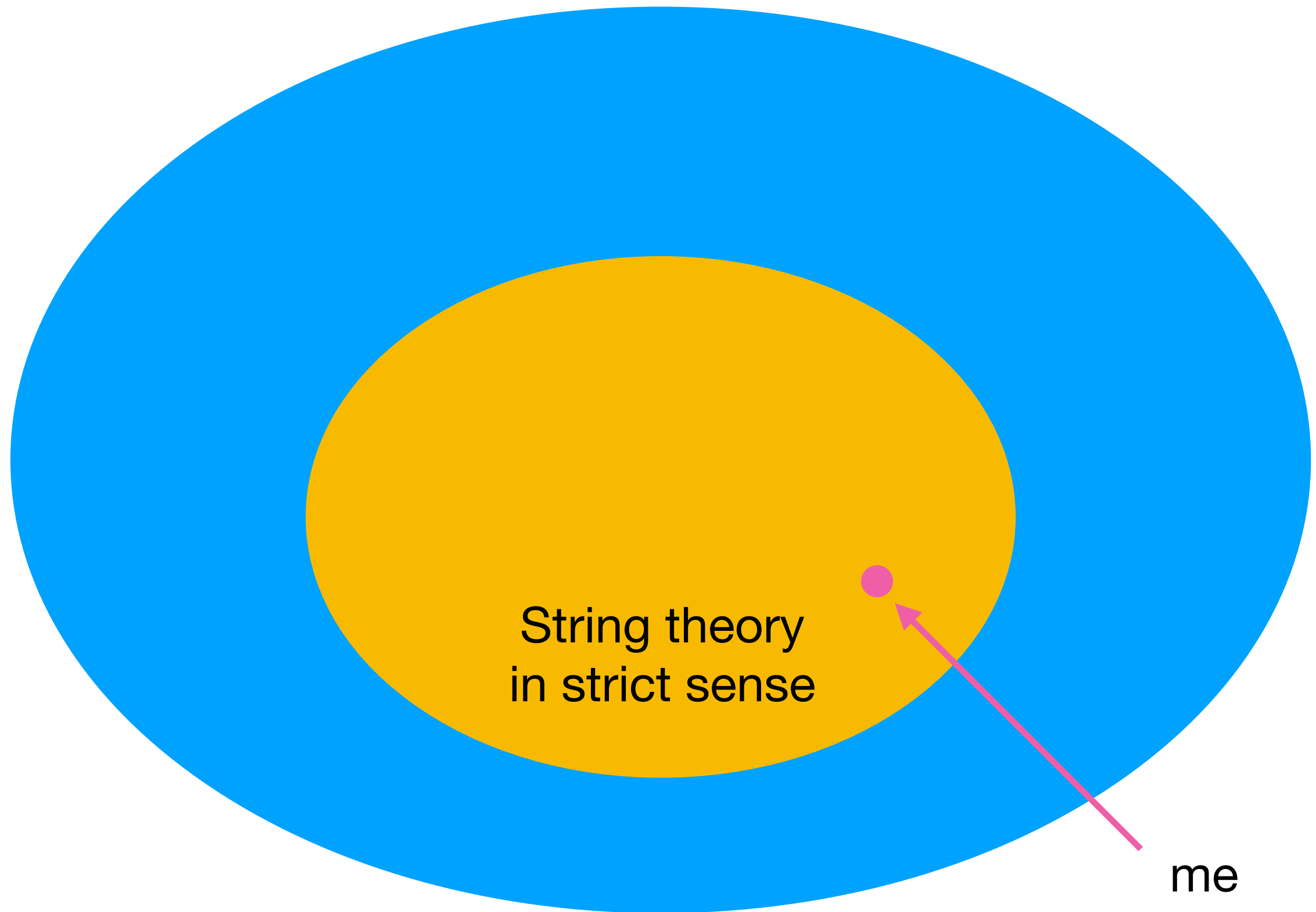
Physics
in a wider sense

me



Physics
in strict sense

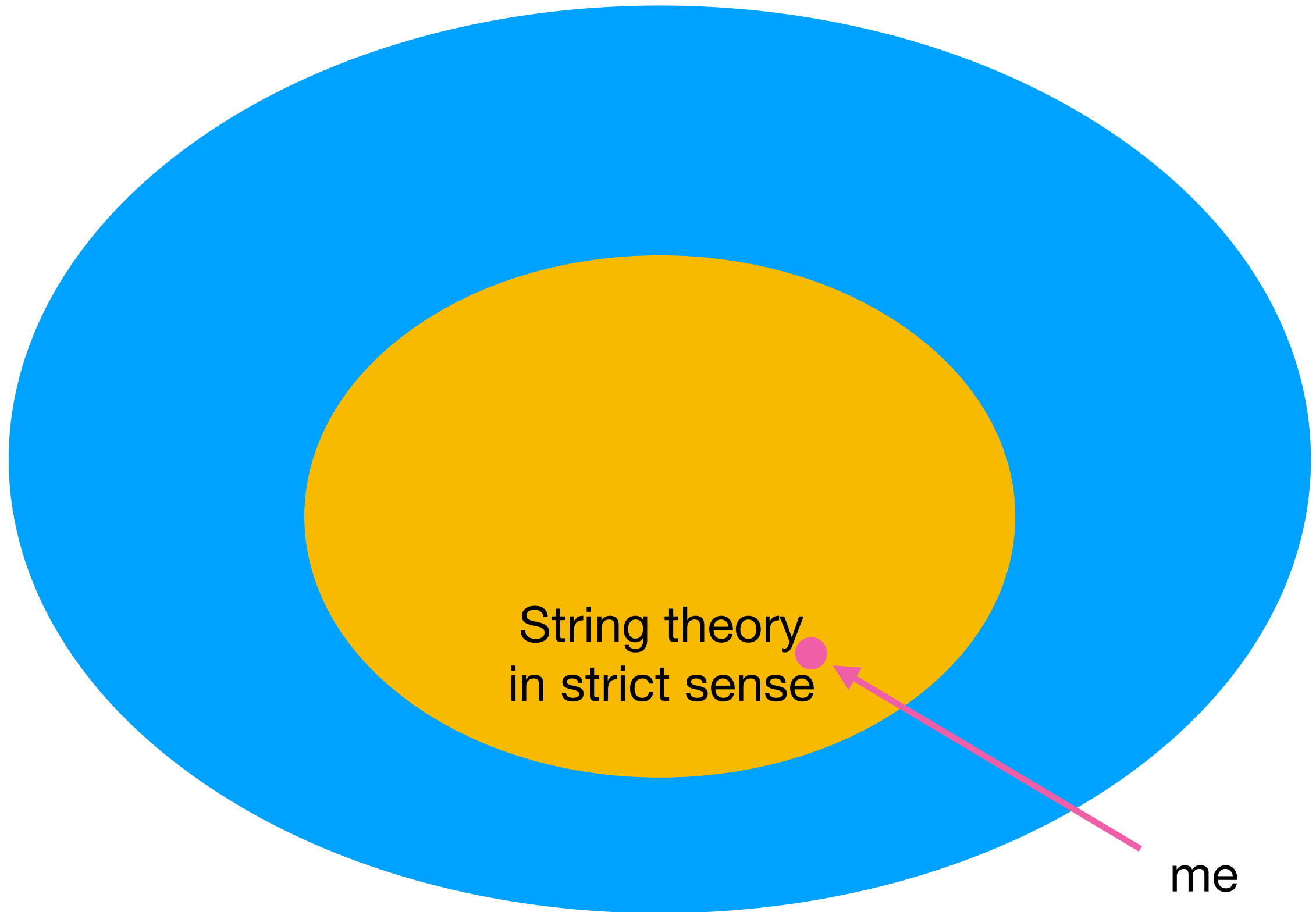
String theory
in a wider sense



String theory
in strict sense

me

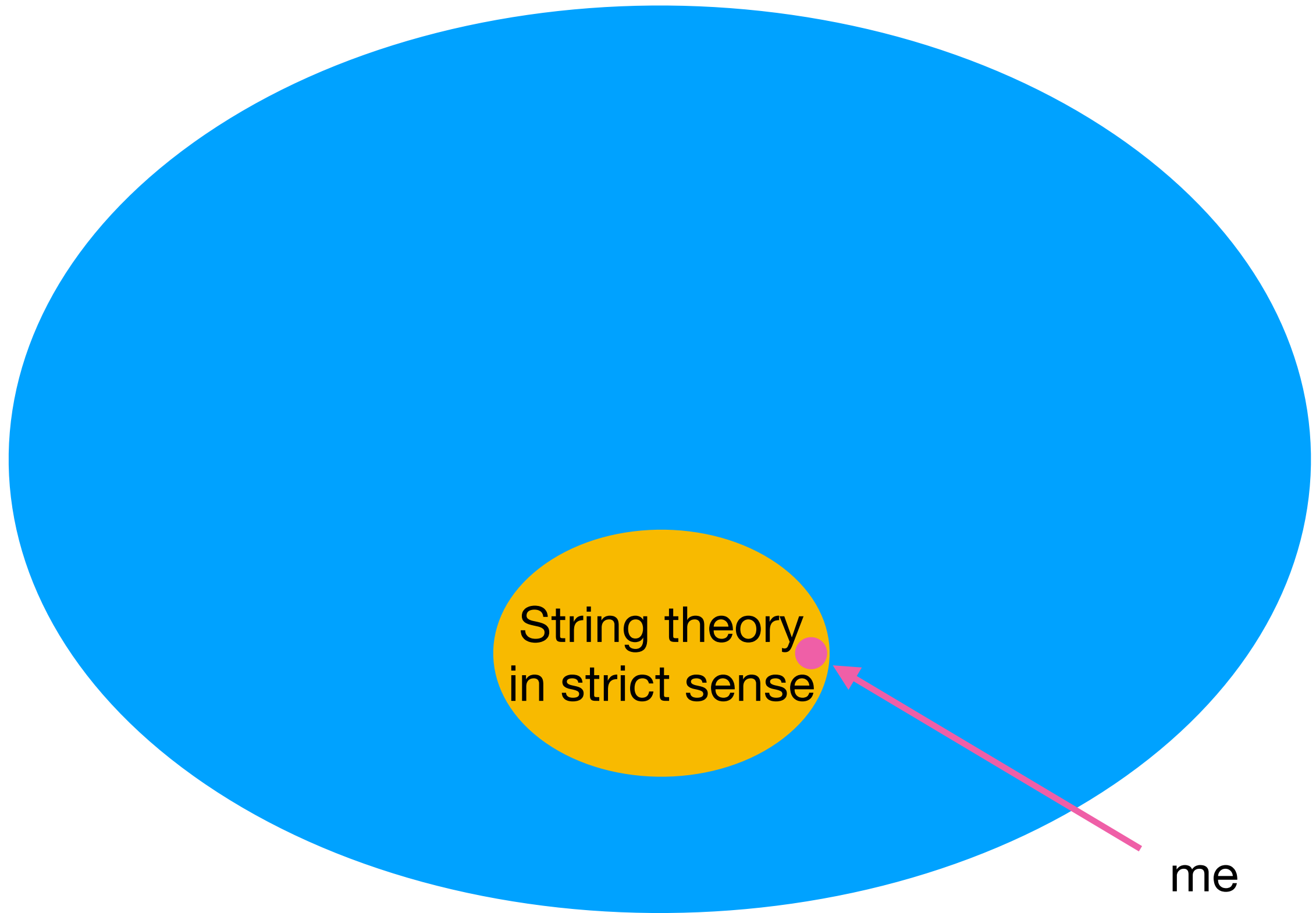
String theory
in a wider sense



String theory
in strict sense

me

String theory
in a wider sense



String theory
in strict sense

me

- It's true that the ratio

$$\frac{\text{\# of people who do string theory in strict sense}}{\text{\# of people who do string theory in wider sense}}$$

is fairly small.

- So, people sometimes/often say that

string theory is no longer string theory.

- I don't know if it's a good thing or a bad thing.
- It's fairly common in Japanese culture that the name doesn't match the meaning, though.

This is お茶わん。

Literally it is a *tea bowl*.



But we don't usually drink tea with it,
although my 101-year grandma does so.

We eat instead steamed rice with it.

Then what do Japanese people use to drink tea?



We drink tea with お湯飲み。

Literally it is a *hot water drinker*.

I don't think too many people
drink hot water with it.

Another example is ふではこ。
Literally it is an *ink-brush box*.



But we don't put brushes.

We put pencils in it.

Another example is ふでばこ。
Literally it is an *ink-brush box*.



But we don't put brushes.

We put pencils in it.

- I don't know many such things in English.
American football, maybe?
- Strings in string theory is as essential as
foot in American football ... ???
- Anyway, for me, it's normal that string theorists do not
usually study string theory in the strict sense.
- How about in your culture? Please tell me.

- The topic of this lecture series is

String Theory in the strict sense,

that is,

quantum systems which contain relativistic strings.

- But then, the question is:

Why do you/we want to study such weird systems?

- Let's start with a related question:

Why *did* people start to study such weird systems?

History of string theory

- The way quantum mechanics and general relativity developed is interesting but quite normal.
- People didn't understand atomic physics.

People developed quantum mechanics.

Quantum mechanics allows people to understand atomic physics.

- Similarly, people didn't understand gravity in relativistic situations.

People (or more precisely, Einstein) developed general relativity.

General relativity allows people to understand gravity in relativistic situations.

- So, the normal development is the following.
- People don't understand **Phenomenon X**.

People develop **Theory A**.

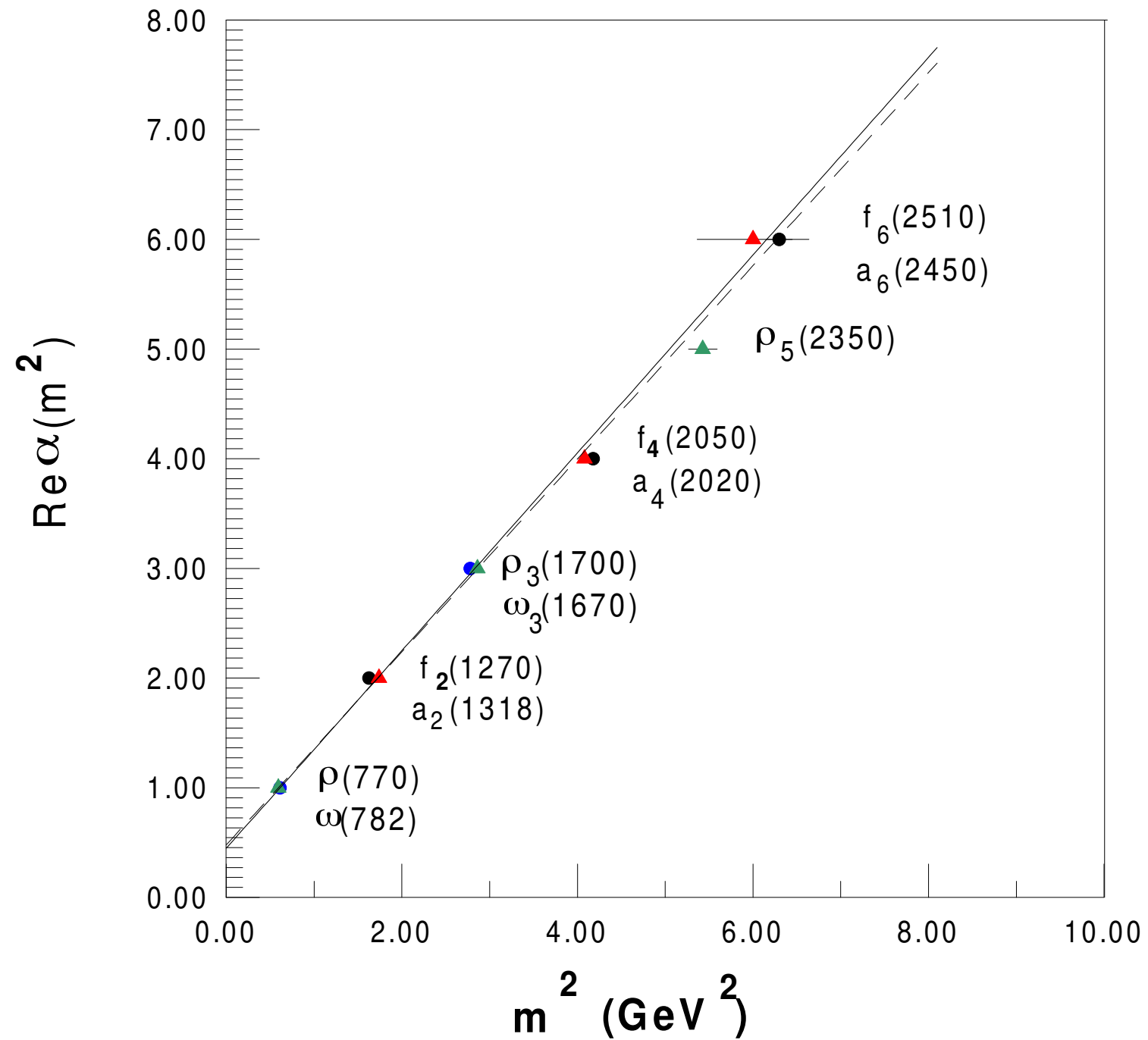
Theory A allows people to understand **Phenomenon X**.

- String theory does not fit in this standard pattern.
- From this point of view, string theory is an utter failure.

- In the early 1960s, experimental data suggested something called **linear Regge trajectories of hadrons**,

$$m^2 = aJ + b$$

where m and J are the mass and the spin of a related series of particles.



Plot of m^2 vs spin of mesons.
 Taken from [hep-ph/0006244](https://arxiv.org/abs/hep-ph/0006244).

- This and other experimental data suggested that **mesons are made of relativistic strings** in the late 1960s.
- Indeed, **quantizing relativistic strings gives linear Regge trajectory.**
- But **relativistic strings turned out to contain many other features which contradicted other properties of mesons.**

- For example, it contains massless spin-2 particle, which doesn't exist among mesons.
- It requires spacetime dimensions to be 26 (if bosonic) or 10 (if fermions are contained).
- It also requires that many other internal consistency conditions should be met, and fully consistent string theory was not immediately found.

- So string theory didn't do the job it was supposed to do. It wasn't very clear if it was really consistent either.
- In the mid-70s, Schwarz, Scherk and Yoneya suggested to re-interpret the massless spin-2 particle in relativistic string theory as the graviton.
- In other words, they suggested to re-purpose relativistic string theory as a theory of quantum gravity, although in very high spacetime dimensions.

- That was a very bold statement at that time, and it didn't catch on.
- For about ten years, only very few people worked on string theory, until 1984, when Green and Schwarz finally found consistent fermionic string theory.
- It was in 10 spacetime dimensions, but automatically contained non-Abelian gauge fields, much as in the Standard Model, and their Grand-Unified generalizations.

Relativistic strings:

- | | |
|------------|---|
| late 1960s | conceived to solve questions about mesons. |
| | didn't work. |
| mid 1970s | repurposed as a quantum gravity theory. |
| mid 1980s | turned out to contain Standard-Model-like non-Abelian gauge fields and fermions. |
| | (gave a lot of theoretical insights, but)
no experimental confirmation at all. |
| 2026 | So again, it hasn't worked. |

- Why do people still study string theory, then?
- A few unexpected results, mostly from mid 1990s:
 - It's a “good” quantum gravity theory.
 - Gave many insights on properties of QFT in general.
 - Contributions/connections to modern math.

- So, an even cruder summary is the following.

String theory gradually arose from the late 1960s to the mid 1980s, originally for hadron physics, then repurposed for quantum gravity.

It hasn't received any experimental checks in any of its physical (re-)interpretation.

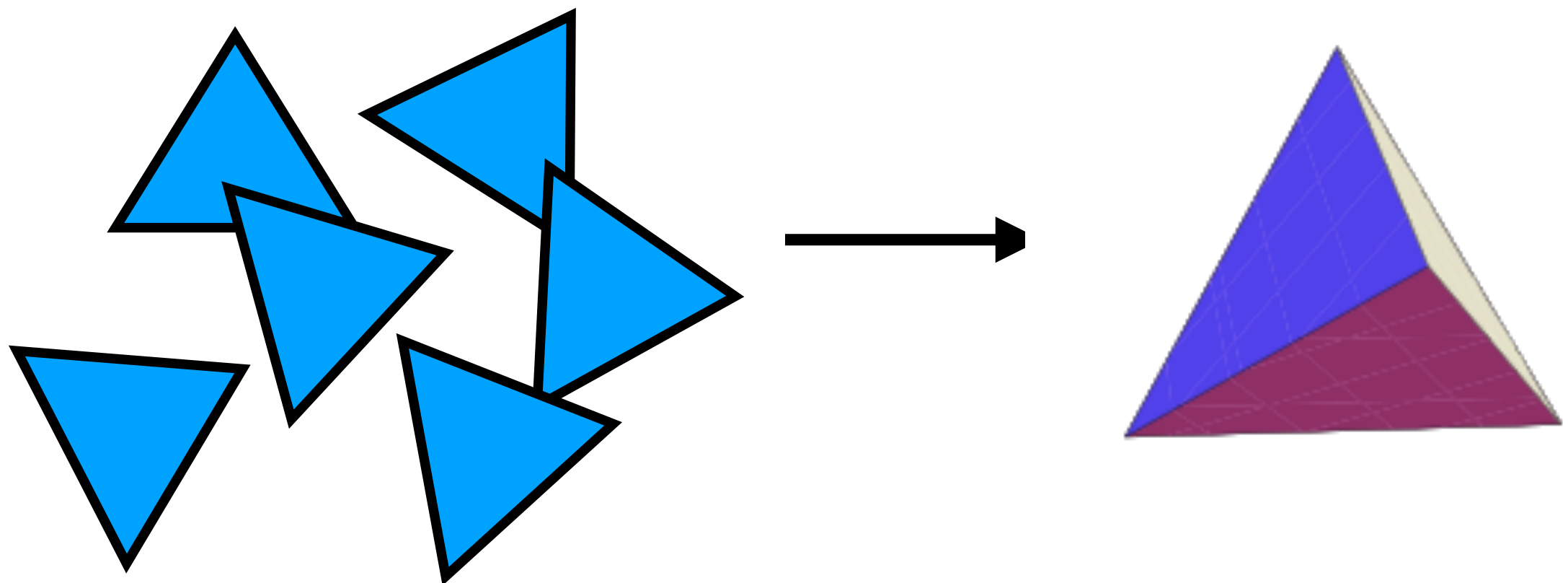
Contributions to theoretical aspects of quantum gravity / QFT, and also to pure math.

- The original motivation didn't matter.
- It didn't have to be hadron physics or quantum gravity.
- Once you start studying *relativistic strings*,
everything we now love or hate about string theory
naturally follows.
- I could easily imagine that, in some other exoplanet,
intelligent beings would come up with the same string
theory from a totally different original motivation.

- I think it interesting that, from a simple but strange starting point, a very rich and distinct theory sprang out.
- Something (distantly) similar has happened long time ago.

An ancient analogue

- Ancient Greeks considered the following question.
- Suppose we're given a lot of regular n -gons of the same size.
- When can we build a regular three-dimensional object?



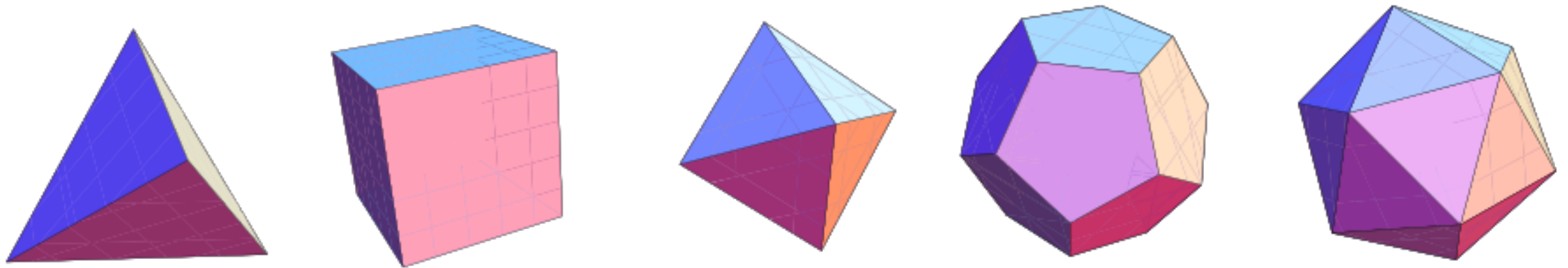
- It's a strange question.

Unclear why you have to think about it.

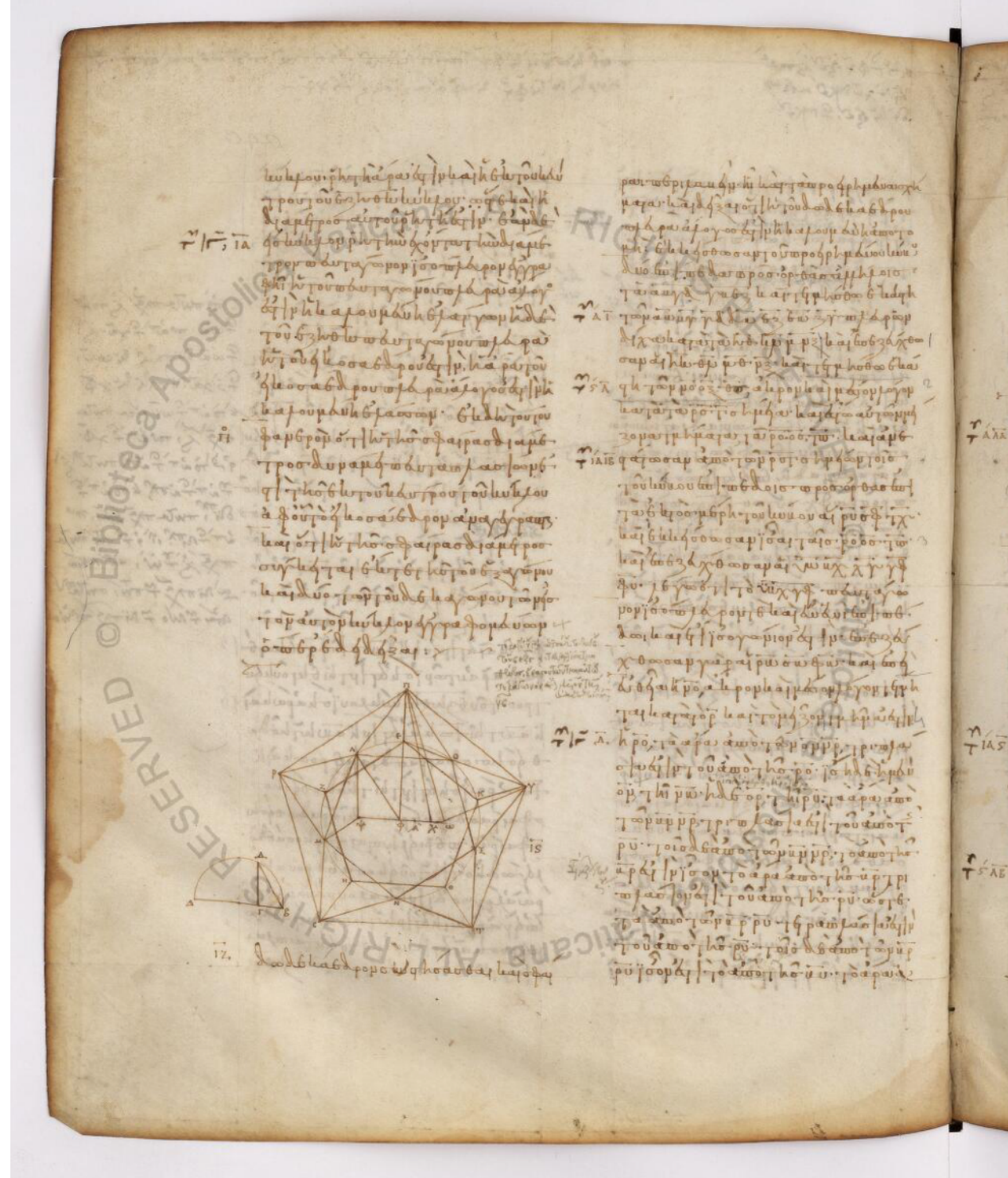
But some ancient Greeks thought about it.

And they thought it interesting.

There are just five of them.

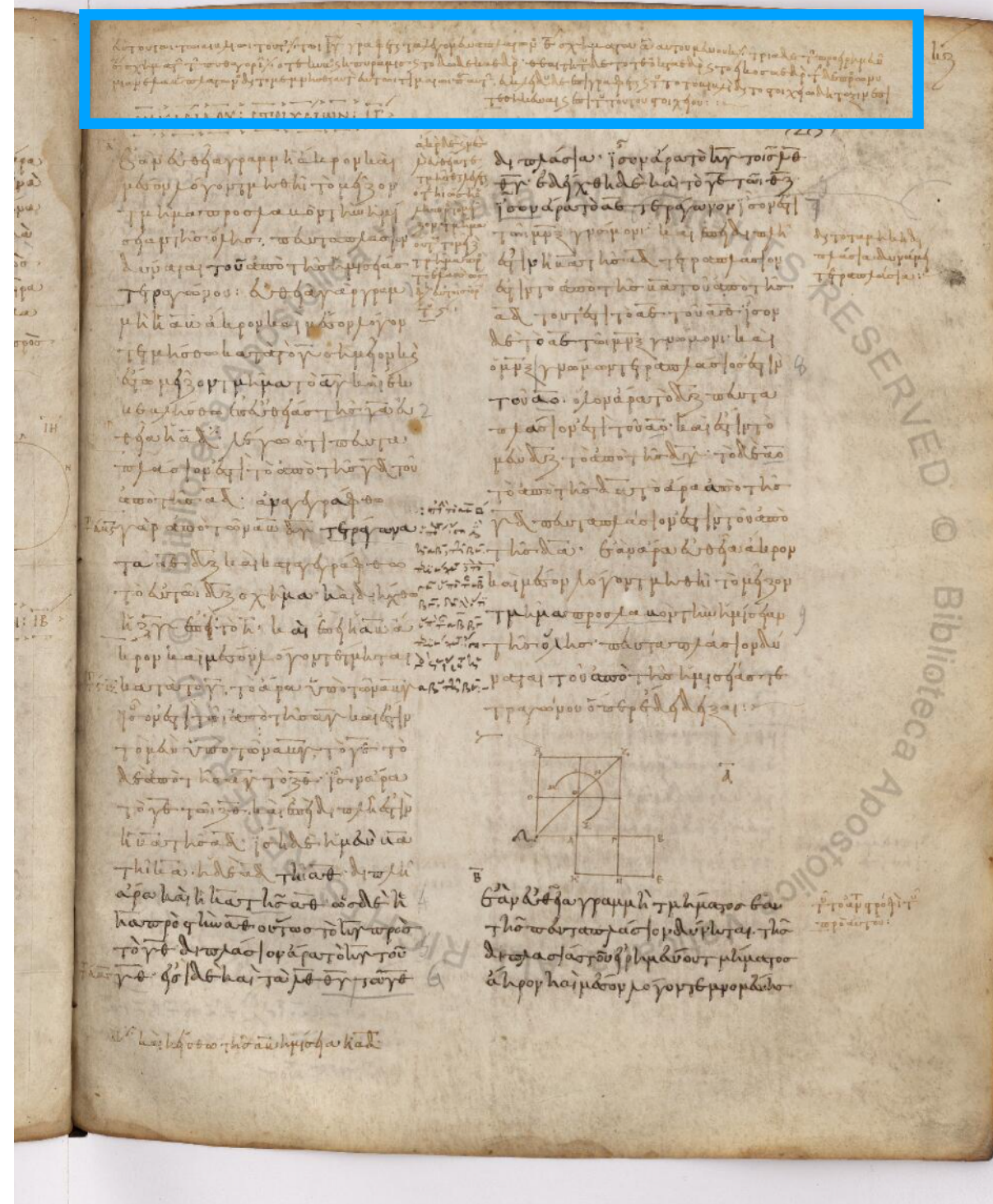


The existence of the last two is quite nontrivial.



This is a page about the icosahedron in Euclid's Elements, kept in the Vatican library. About 1000 years old.

https://digi.vatlib.it/view/MSS_Vat.gr.190.pt.2/0144



A marginal note records a tradition about who found (or fully described the properties of) the icosahedron.
https://digi.vatlib.it/view/MSS_Vat.gr.190.pt.2/0119

BOOK XIII.

HISTORICAL NOTE.

I have already given, in the note to IV. 10, the evidence upon which the construction of the five regular solids is attributed to the Pythagoreans. Some of them, the cube, the tetrahedron (which is nothing but a pyramid), and the octahedron (which is only a double pyramid with a square base), cannot but have been known to the Egyptians. And it appears that dodecahedra have been found, of bronze or other material, which may belong to periods earlier than Pythagoras' time by some centuries (for references see Cantor's *Geschichte der Mathematik* I., pp. 175—6).

It is true that the author of the scholium No. 1 to Eucl. XIII. says that the Book is about "the five so-called Platonic figures, which however do not belong to Plato, three of the aforesaid five figures being due to the Pythagoreans, namely the cube, the pyramid and the dodecahedron, while the octahedron and the icosahedron are due to Theaetetus." This statement (taken probably from Geminus) may perhaps rest on the fact that Theaetetus was the first to write at any length about the two last-mentioned solids. We are told indeed by Suidas (s. v. Θεαιήτης) that Theaetetus "first wrote on the 'five solids' as they are called." This no doubt means that Theaetetus was the first to write a complete and systematic treatise on all the regular solids; it does not

Heath, English translation of *Elements*, 1908

<https://archive.org/details/thirteenbookseu03heibgoog/page/438/mode/2up>

It is true that the author of the scholium No. 1 to Eucl. XIII. says that the Book is about “the five so-called Platonic figures, which however do not belong to Plato, three of the aforesaid five figures being due to the Pythagoreans, namely the cube, the pyramid and the dodecahedron, while the octahedron and the icosahedron are due to Theaetetus.” This statement (taken probably from Geminus) may perhaps rest on the fact that Theaetetus was the first to write at any length about the two last-mentioned solids. We are told indeed

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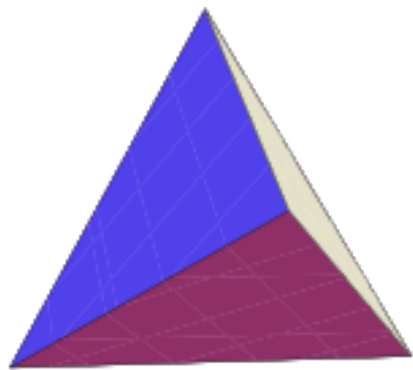
- Theaetetus was a contemporary of Plato and mentioned by him as a great mathematician-citizen of Athens.

He died after participating in a battle fought by Athens in 396 BCE.

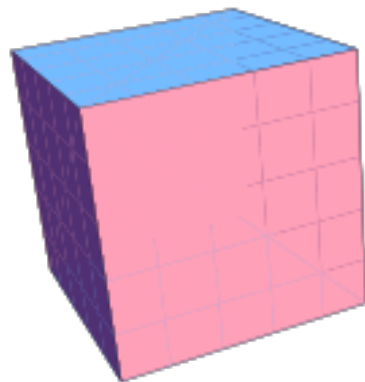
Isn't it amazing that we know who first thought of regular icosahedron?

Ancient Greeks and Europeans up to the early modern era thought that **the world was consisting of four (or five) elements.**

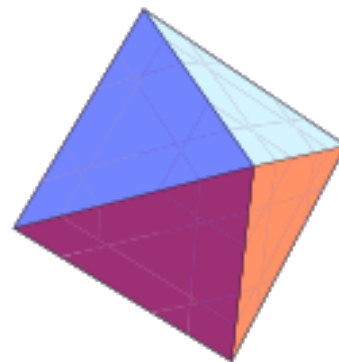
It was tempting to associate them with **regular polyhedra ...**



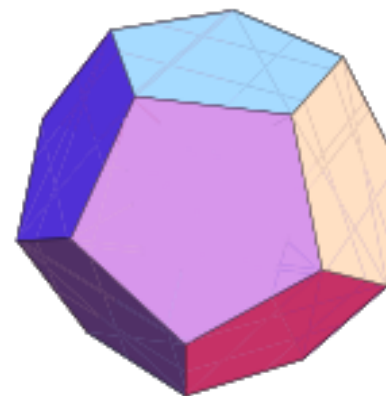
Fire



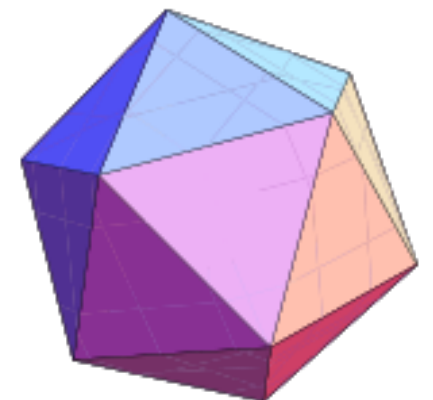
Earth



Air

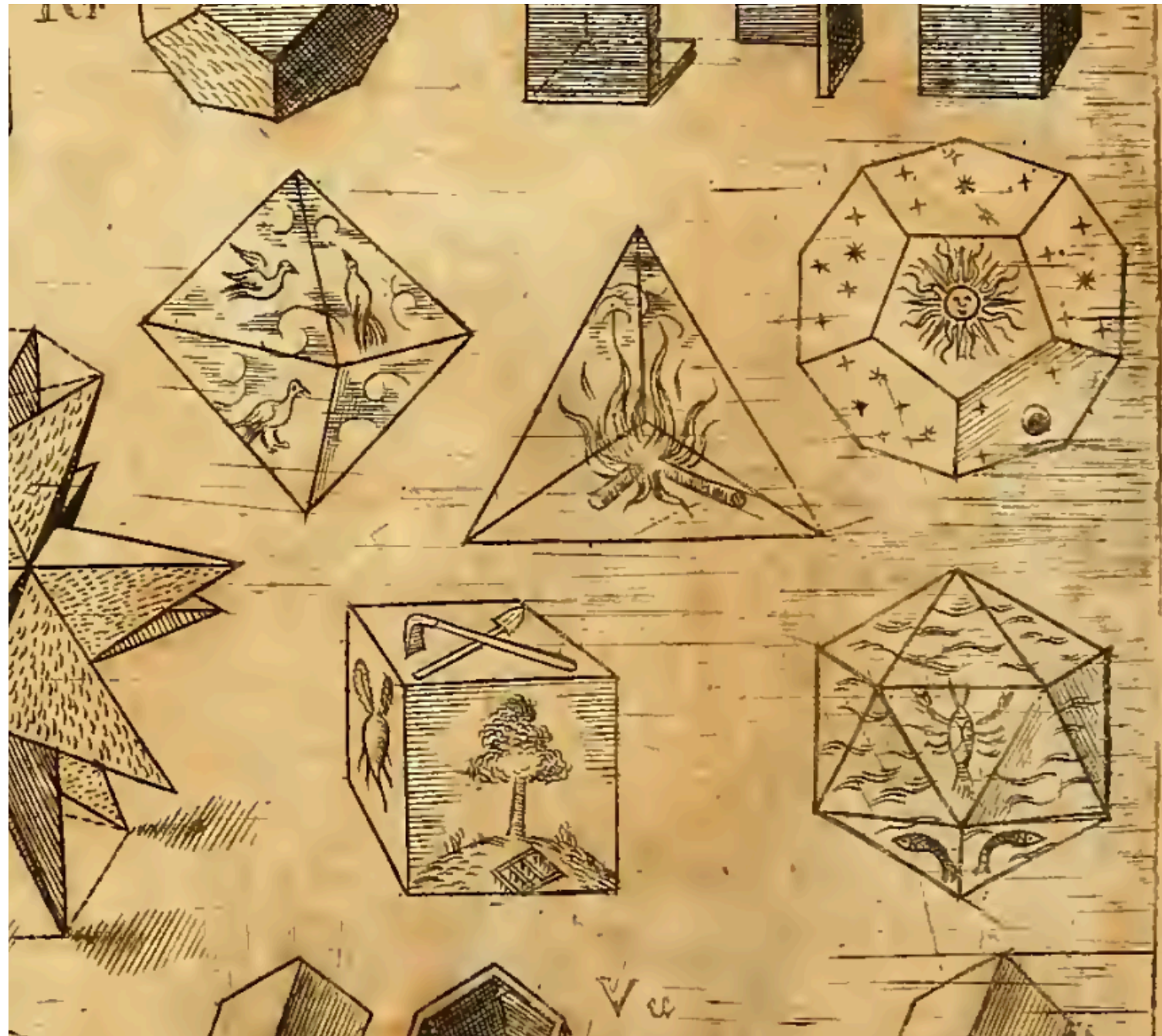


Water

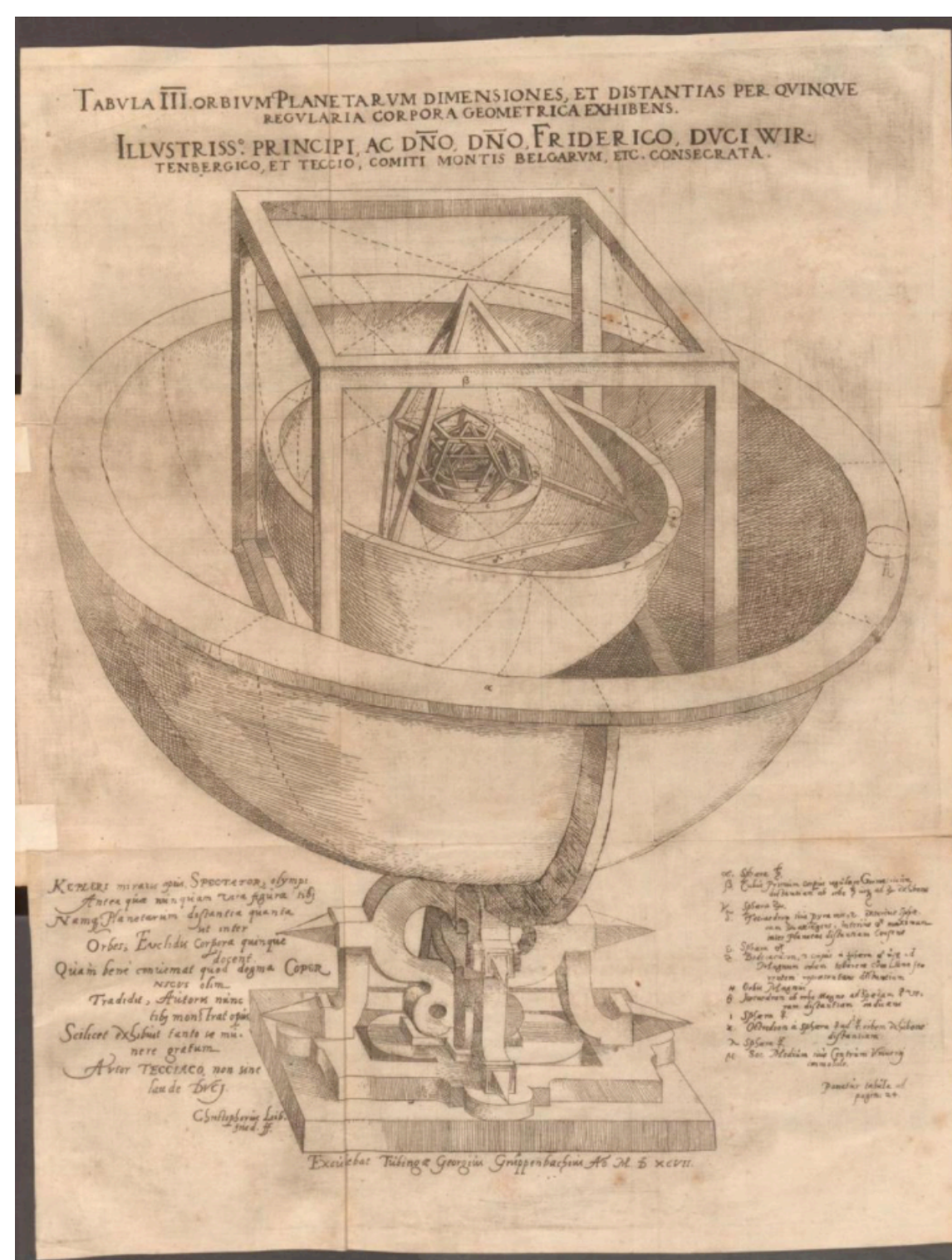


Aether

Goes back to **Plato's *Timaeus*.**

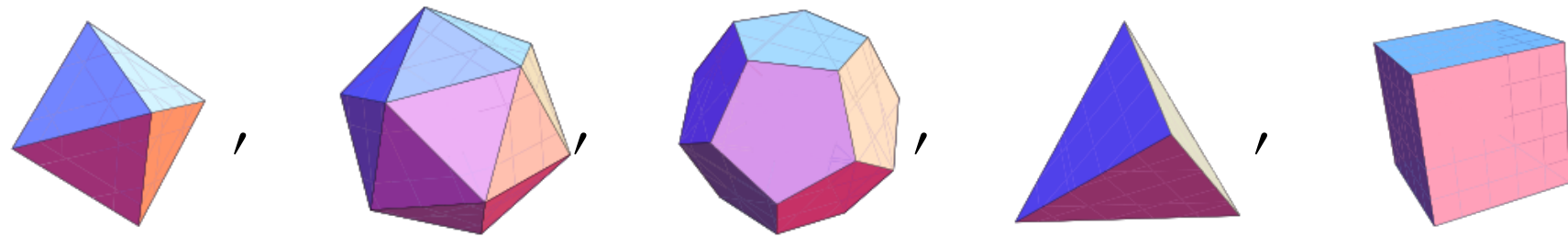


This is **Kepler's** depiction of the correspondence in his **Harmonice Mundi**. Available at <https://archive.org/details/ioanniskepplerih00kepl>



Kepler also tried to be quantitative. This is from his **Mysterium Cosmographicum**, available at <https://archive.org/details/1596-kepler-prodromus-dissertationum-cosmographicarum-continens-mysterium-cosmographicum/>

He put the regular solids from inside to the outside in the order



Outradius / inradius of each of them are

1.73, 1.26, 1.26, 3, 1.73.

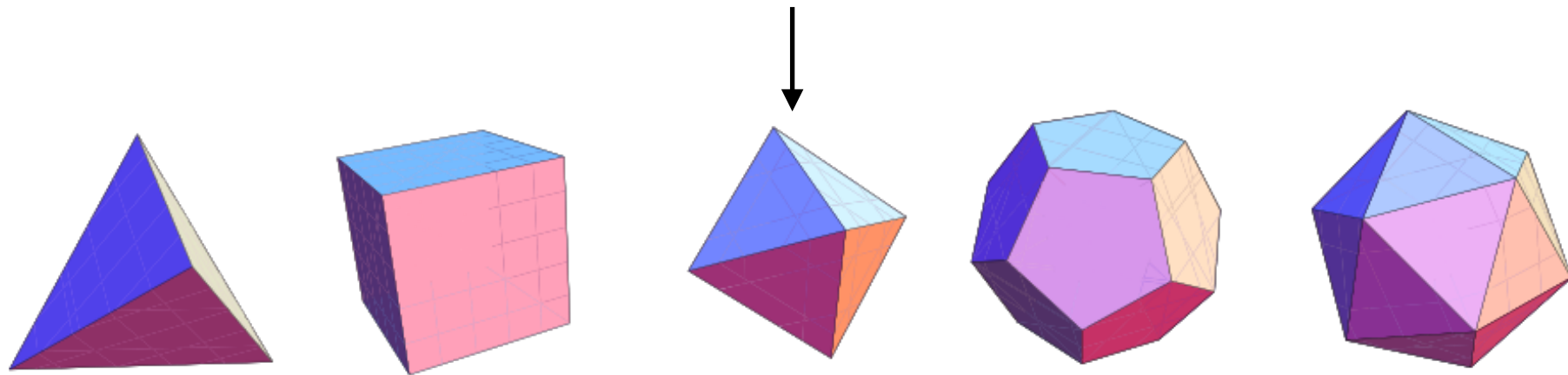
The ratios of orbit radii of Mercury, Venus, Earth, Mars, Jupiter and Saturn were measured. The modern values are

1.87, 1.38, 1.52, 3.41, 1.84

Not too bad...

- But of course all this turned out to be completely wrong.
- Kepler himself came up with his three laws slightly later.
- Regular solids are still interesting (to me), even though attempts to use them to explain nature failed.

Combine regular n-gons and build regular solids.



whose existence is quite nontrivial.

↓

Tempting to use them to explain nature.

↓

Didn't work, but still interesting.

Consider relativistic string-like objects.



String Theory

whose existence is quite nontrivial.



Tempting to use them to explain nature.



Hasn't worked, but still interesting.

Submitted questions

Submitted question #1

- クラスS理論、AGT対応等
- mirror対称性と2d SQFTとそのIR limitで得られる
2d TQFTの話

Submitted question #2

- It may not be mathematically rigorous, but there is a concept in quantum gravity theory that suggests the physics of our everyday world can be reproduced by an approximation that sets $1/c$, G , and $\hbar$ to zero. Since string theory is supposed to have no tunable parameters, I'm curious about the procedure by which it approximates known theories.
- I imagine mathematicians are also researching string theory, but how far along is the attempt to mathematically define it? What are the standard references for mathematicians? I'd also like to know about its relationship to algebraic geometry.
- I like to understand physics using graphical notations such as tensor networks. Since tensor networks don't seem to be very effective for CFT, I don't expect them to work well, but what about string theory? For example, do matrix models offer any hints in this regard, similar to 't Hooft's genus expansion?

Submitted question #3

- Is string theory really not falsifiable? Sometimes I hear this statement. But I am not sure if it is because of the limitation of technology to achieve higher energy, or it is because of some essential limitation of this theory itself.

Submitted question #4

- 物性物理との関連が気になります。

Submitted question #5

- brane engineering を用いて QFT の duality を導出する話
など、弦理論を用いて場の量子論の性質を理解する系統の
話が聞きたいです。

Submitted question #6

- わからないなあと思ったのは、non-critical dimensionでのstringの運動というのはどう記述すべきかということです。例えば、 $D=3+1$ でcosmic stringを考えると、その運動のモードはNG作用で書けると思っているわけですが、Polyakov actionにして量子化するとWeyl anomalyがあるので、量子力学的にはスカラー ϕ を導入してリウビル理論として考えないといけませんね。このstringが場の理論から出てきていると思ったとき、 X_μ は並進のmoduliから来ていた場ですが、 ϕ は何に対応するのでしょうか？stringの内部構造かなとかとも思いましたが、相互作用は割とユニバーサルに書けているし、そもそもWeyl anomalyがあるから積分できない自由度なので、それでいいのかなあ？と思っています。

Submitted question #7

- I am a graduate student in condensed matter physics. I notice this when I try to find the update of your algebraic topology note. Personally, I don't have a strong interest in quantum gravity (because I don't even understand what people really mean when they talk about quantum gravity); rather, my interest in string theory is driven by the following fascinating facts I have come across:
- The relationship between string scattering and 2D Conformal Field Theory (CFT): I understand that one of the primary motivations for the early development of CFT was 2D string scattering. Since different amplitudes correspond to different Riemann surfaces, string theory is intimately connected to 2D complex geometry. Furthermore, I am curious about how we sum over Riemann surfaces for different spacetime backgrounds, which seems to imply a broader type of gauging.
- String theory's profound impact on pure mathematics, particularly low-dimensional geometry and topology: I would love to know how physicists back then were able to use string theory to provide non-rigorous "proofs" or predictions for so many theorems in topology and arithmetic geometry before mathematicians could formalize them.
- Anomalies and Generalized Symmetries: These concepts are currently highly popular even outside high-energy formal theory (such as in condensed matter physics). Were the motivations of the pioneers who first initiated this line of research, like Nathan Seiberg, related to string theory? How do symmetries and anomalies manifest themselves within string theory, and what unique or much clearer structural insights does string theory provide that cannot be easily seen in standard quantum field theories?

Submitted question #8

- Given recent advances in AI, do you think we could see major progress toward—or even the completion of—a theory of quantum gravity? What is your best estimate of how many years it might take for a major breakthrough to occur? In addition, how likely do you think it is that such a theory could be experimentally verified?

Submitted question #9

- もし先生が今弦理論の教科書を書くとしたらどういう目次, 構成, 内容にしますか? また, 過去の有名な教科書 (GSW, ポルチンスキー) を現在の視点から批評してみてください.

Submitted question #10

- Here are some questions that I am interested in string theory:
- Non-perturbative approach: Nowadays, we can study QFTs by axioms such as Wightman axioms and Haag-Kastler axioms. Are there any axioms we could postulate for string theories? Then can we construct examples satisfying those axioms ?
- Noncommutative Geometry: Does noncommutative geometry naturally appear in string theory and why? Will noncommutative geometry serve a crucial role for solving some problems in string theory?
- Relations between string theories and 2+1d and 3+1d CFTs? Loop groups are natural objects to study for string people, I understand. But how about group of smooth mappings from $M \rightarrow G$, where M is a Riemannian surface and G is $SU(n)$?
- It seems to me that 1+1d CFTs shows up in both string theory and critical points of statistical models. But string theory and statistical models are very different languages and philosophies to me. Do these two different viewpoints reconcile (in some larger framework)?
- String theory makes HUGE impact on mathematics. I personally do not believe this could be a "coincidence". I always wonder why string theory is so magical. I would really appreciate it if some examples will be explained, for example, Gepner models and mirror symmetry. Please inform us if there are ideas in string theory not translated to the math side, or ideas whose importance not appreciated by the math community, if there are any.
- Last but not the least, what are the problems lying at the very core of string theory? So that some people say string theory is dead because these problems are not solved.

Submitted question #11

- 私は量子コンピューティング・量子情報・開放量子系を専門とする大学院生で、超弦理論についてはほとんど知識がありません。その中で、量子情報の分野でしばしば話題になるホログラフィーなどについてもお聞きしたいです（string theoryの授業とはちょっとずれるかもしれませんが）。
- また、先生が面白いと感じられている文脈のなかで、量子情報と接点を持つ話題があればお聞きしたいです。ホログラフィーに限らず、場の理論や対称性の側からの接続についてもぜひお聞きしたく思っております。あわせて、そうした方向での現代的な発展や、現在の未解決の問題などについても伺えればと思っております。

Submitted question #12

- Are there any quantities related to string theory that we want to calculate using a quantum computer?

Submitted question #13

- どうして弦理論はうまくいっているのですか？
(なぜ点粒子だったり、面粒子？だったらいけないのかなど)
- また、弦理論から数学的に面白い結果が取り出せるといった話を聞きました。それを真似て現実世界を説明するモチベーションを一度忘れ、弦理論ではない他の物理の理論から数学を取り出すといった話は何かありますか？

Submitted question #14

- 私は量子基礎論・量子測定理論を専門とする大学院生で、量子重力理論としての弦理論に興味があります。弦理論は(測定などが定まっているという意味で)通常の意味での量子論なのでしょうか。

[Go back to the main slides...](#)