Nothing, Anything or Everything: String Theory – A Theory of What?

Joseph Conlon

University of Oxford

2/2/22

Colloquium, UIC

The World in 1968


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ENCYCLICAL LETTER «HUMANAE VITAE»

ENCYCLICAL LETTER
OF HIS HOLINESS
POPE PAUL VI

ON THE REGULATION
OF BIRTH

To the Venerable Patriarchs
Archbishops and Bishops
and other Local Ordinaries
in peace and communion
with the Apostolic See
to Priests, the Faithful
and to all men of good will

Particle Physics in 1968

- Quantum electrodynamics is established as the correct theory describing the electromagnetic interactions
- The strong and weak interactions are a mystery
- The weak interactions have a phenomenological description with Fermi theory, which is known to break down at high energies (around 100 Giga-electronVolt)
- In strong interaction experiments, a zoo of particles is known, but the underlying logic is mysterious… $p, n, \pi^0, \pi^\pm, K^0, K^\pm, \rho, \eta, \Lambda, \Omega, \Sigma$ …

"If I could remember the names of all these particles, I'd be a botanist"

Enrico Fermi

Open Problems in 1968

- How to understand the strong interactions?

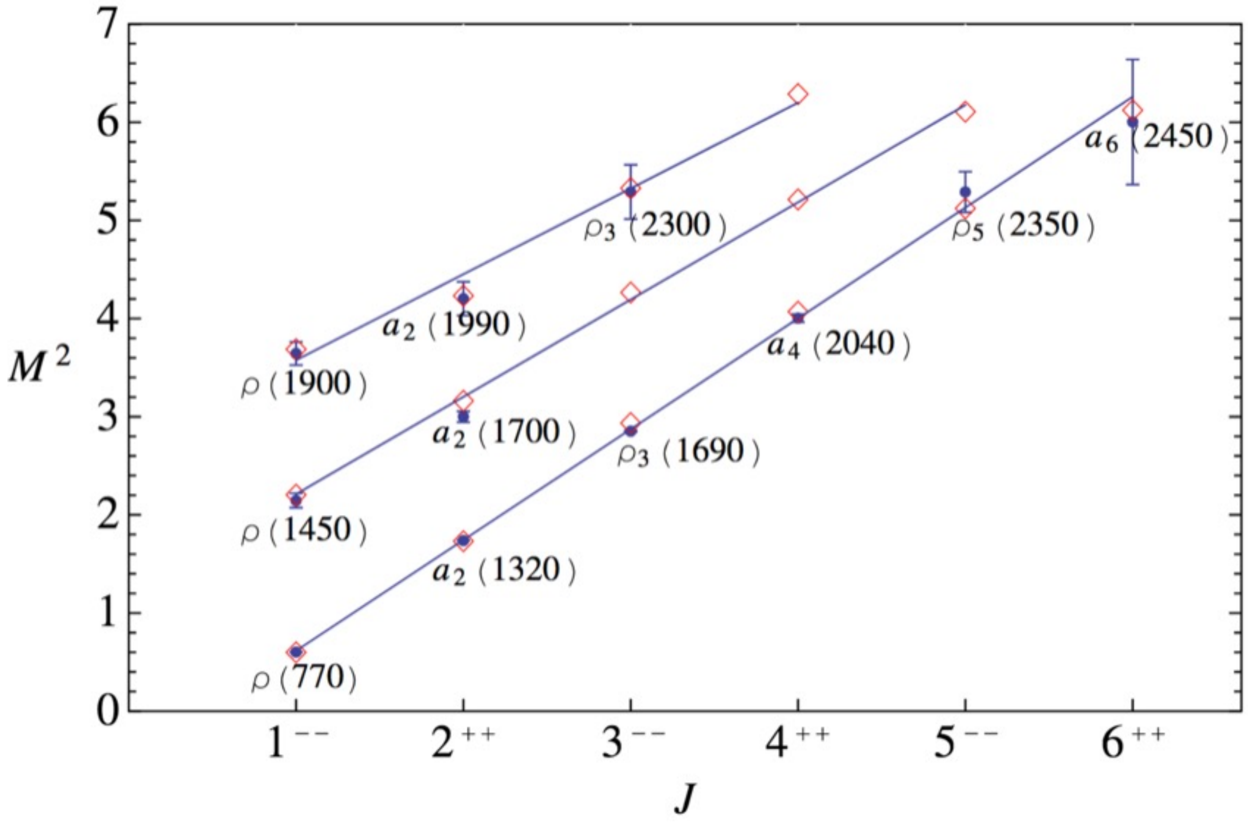
  1. What is the organising principle of the strong interactions?

  2. How can one make calculable predictions for them?

  3. There are many approaches – Regge theory, the analytic S-matrix, bootstrap methods, total nuclear democracy, quantum field theory – which is the key that turns the lock?

Open Problems in 1968

- Where do Regge trajectories come from?



(from arXiv:0903.5183)

The first ever paper on string theory

IL NUOVO CIMENTO   VOL. LVII A, N. 1   1° Settembre 1968

Construction of a Crossing-Simmetric, Regge-Behaved Amplitude for Linearly Rising Trajectories.

G. VENEZIANO (*)
CERN - Geneva

(ricevuto il 29 Luglio 1968)

Crossing has been the first ingredient used to make Regge theory a predictive concept in high-energy physics. However, a complete and satisfactory way of imposing crossing and crossed-channel unitarity is still lacking. We can look at the recent investigations on the properties of Reggeization at $t=0$ as giving a first encouraging set of results along this line of thinking (1). A technically different approach, based on superconvergence, has been also recently investigated (2), and the possibility of a self-consistent determination of the physical parameters, through the use of sum rules, has been stressed.

In this note we propose a quite simple expression for the relativistic scattering amplitude, that obeys the requirements of Regge asymptotics and crossing symmetry in the case of linearly rising trajectories. Its explicit form is suggested by the work of

The first ever paper on string theory…

- …. Does not mention strings ANYWHERE in the paper!

- Veneziano proposes a formula to describe the scattering of strongly interacting particles

$$\frac{\Gamma(-1+\frac{1}{2}(k_1+k_2)^2)\Gamma(-1+\frac{1}{2}(k_2+k_3)^2)}{\Gamma(-2+\frac{1}{2}((k_1+k_2)^2+(k_2+k_3)^2))}$$

- This formula is now called the *Veneziano amplitude.*

‘Dual Resonance Models’: 1968 - 1973

- Veneziano’s paper triggered a burst of work on what would be called *Dual Resonance Models*
- The aim was to understand Veneziano’s formula, generalise it to other processes, and make predictions for strong interaction physics

  Joel Shapiro:

  This paper arrived at [the lab in] Berkeley in the summer of 1968….and I returned to find the place in a whirlwind of interest. Everyone had stopped what they were doing, and were asking if this idea could be extended.

‘Dual Resonance Models’: 1968 - 1973

- In this period another surprising result was found by Claud Lovelace:

  The dual resonance models were only consistent in twenty-six dimensions
- Reaction:

  I was the only professor not being promoted despite the many citations of my papers. However, the jeers of the physics establishment did have one good consequence. When my discovery turned out to be correct....they remembered that I had said it first. One has to be very brave to suggest that spacetime has 26 dimensions.

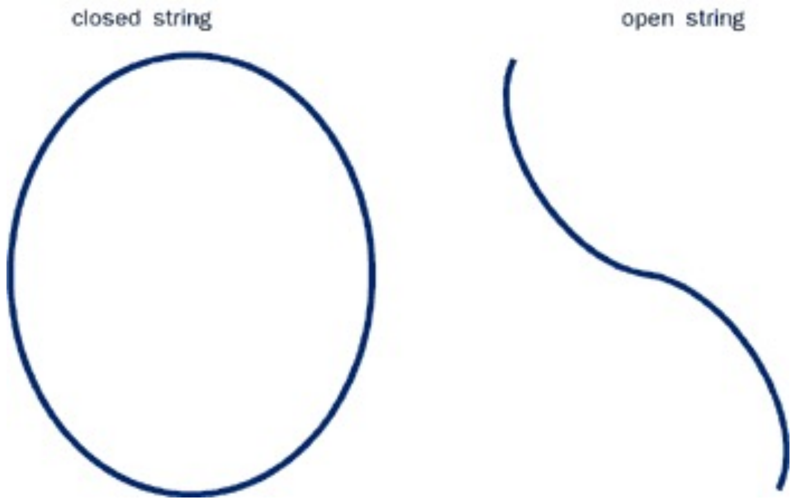
The Naming of String Theory

- 'String theory' starts as Yoichiro Nambu and others realise in 1971 that the Veneziano amplitude arises from a theory of quantum mechanical, relativistic strings
- What do strings do?

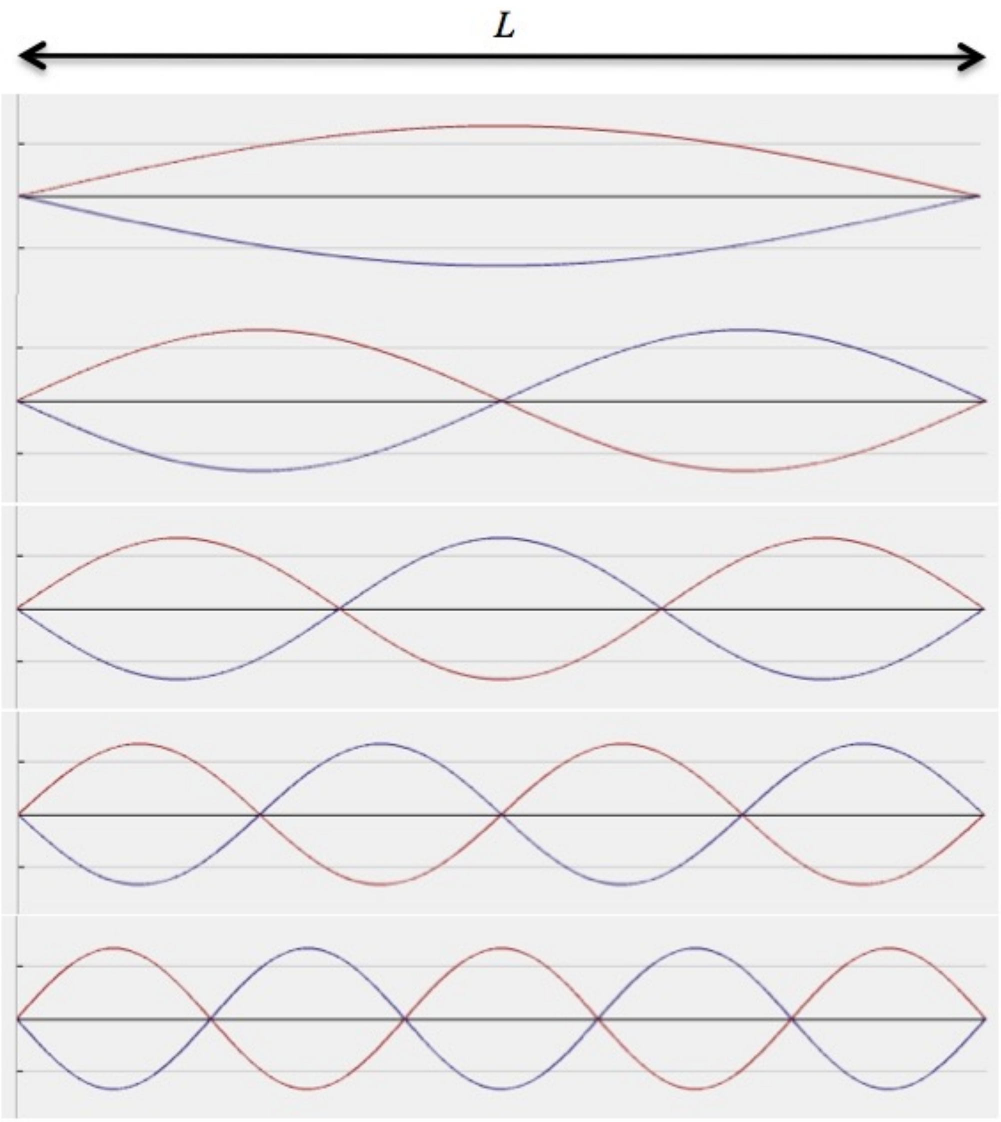
  1. They oscillate in many different modes

  2. If you pluck them, they vibrate

  3. Two kinds of string: open and closed



Strings oscillate at their harmonics



Fundamental, n = 1
$\lambda_1 = 2L$

2nd harmonic, n = 2
$\lambda_2 = L$

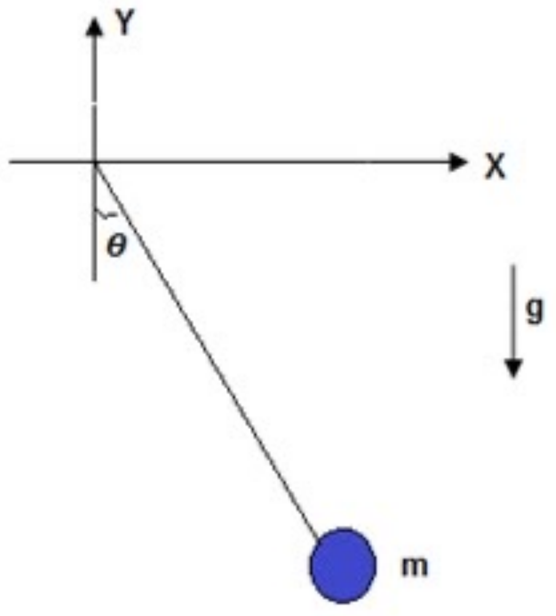
3rd harmonic, n = 3
$\lambda_3 = \frac{2}{3}L$

4th harmonic, n = 4
$\lambda_4 = \frac{1}{2}L$

5th harmonic, n = 5
$\lambda_5 = \frac{2}{5}L$

Strings and Harmonic Oscillators

- A string corresponds to an *infinite number* of harmonic oscillators.



"The career of a young theoretical physicist consists in treating the harmonic oscillator in ever-increasing levels of abstraction."   Sidney Coleman

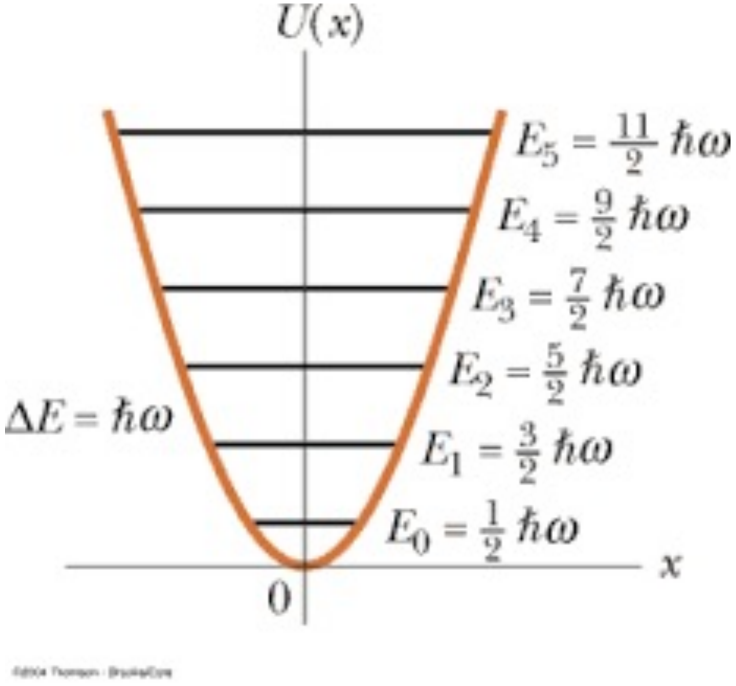
The Simple Harmonic Oscillator

- The simple harmonic oscillator is the most important system in physics
- The classical equations of motion are

$$m\ddot{x} = -m\omega^2 x$$

- For a *quantum harmonic oscillator*, we should instead use discrete energy levels.
- The spectrum of the quantum harmonic oscillator is

$$E_n = \left(n + \frac{1}{2}\right)\hbar\omega$$



The *n*th state of the harmonic oscillator is labelled as |n>.

Strings and Harmonic Oscillators

- A string can oscillate in *every direction transverse to its length*
- *Every harmonic corresponds to a individual quantum harmonic oscillator*
- The *frequency* of each harmonic is an integer multiple of the fundamental frequency

$$\omega_n = n\,\omega_0$$

- Allowed states of the string correspond to the particles present in the Veneziano amplitude.

Strings and Harmonic Oscillators

- The quantum state of a string is labelled by the excitation mode for each harmonic oscillator
- A string in *D* space-time dimensions has *(D-2)* directions it can oscillate in
- In each direction, there is a first harmonic, second harmonic, third harmonic….
- The quantum state of a string along x-direction is labelled as

$$|n_1^y, n_2^y, n_3^y, \ldots.., n_1^z, n_2^z, n_3^z, \ldots\ldots n_1^{z\prime}, n_2^{z\prime}, n_3^{z\prime}, \ldots\ldots >$$

- Each different state corresponds to a different particle

String theory: 1968 - 1973

- In this period, ‘string theory’ is a candidate theory for the strong interactions

- It was also not called ‘string theory’, but *Dual Resonance Models*

- The aim is to associate the excited states of vibrating strings with the hadrons of the strong interactions.

$$|Vibrating\ strings > \equiv |Strong\ interaction\ hadrons > ?$$

$$Hadron\ Interactions \equiv String\ Interactions\ ?$$

- What are the characteristic predictions of string interactions?

Strings are extended objects

They have *soft* scattering

They scatter like jelly and not like snooker balls – they do not scatter at large angles

What happens in 1973?

Ultraviolet Behavior of Non-Abelian Gauge Theories*

David J. Gross† and Frank Wilczek
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08540
(Received 27 April 1973)

It is shown that a wide class of non-Abelian gauge theories have, up to calculable logarithmic corrections, free-field–theory asymptotic behavior. It is suggested that Bjorken scaling may be obtained from strong-interaction dynamics based on non-Abelian gauge symmetry.

Non-Abelian gauge theories have received much attention recently as a means of constructing unified and renormalizable theories of the weak and electromagnetic interactions.[1] In this note we report on an investigation of the ultraviolet (UV) asymptotic behavior of such theories. We have found that they possess the remarkable feature, perhaps unique among renormalizable theories, of asymptotically ap-

Reliable Perturbative Results for Strong Interactions?*

H. David Politzer
Jefferson Physical Laboratories, Harvard University, Cambridge, Massachusetts 02138
(Received 3 May 1973)

An explicit calculation shows perturbation theory to be arbitrarily good for the deep Euclidean Green's functions of any Yang-Mills theory and of many Yang-Mills theories with fermions. Under the hypothesis that spontaneous symmetry breakdown is of dynamical origin, these symmetric Green's functions are the asymptotic forms of the physically significant spontaneously broken solution, whose coupling could be strong.

What happens in 1973?

- Gross, Politzer and Wilczek establish *Quantum Chromodynamics* as the theory of the strong nuclear force
- Just like the electromagnetic and weak forces, the strong force is *also* described by a quantum field theory
- The predictions of Quantum Chromodynamics are confirmed and re-confirmed in multiple experiments
- Quark and gluons scatter like snooker balls and not like jelly

- String theory as a theory of the strong interactions is dead.

What happens in 1973?

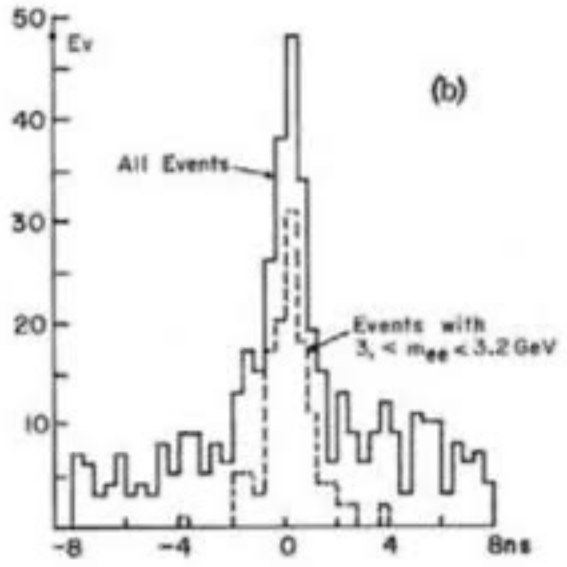
- Joel Scherk and John Schwarz propose a re-interpretation of string theory.
- One of the oscillatory modes of closed strings has the same properties of the *graviton* - the hypothesised quantum carrier of the gravitational force.
- $String\ Interactions\ \equiv Quantum\ Gravitational\ Interactions$?
- Very few people care!

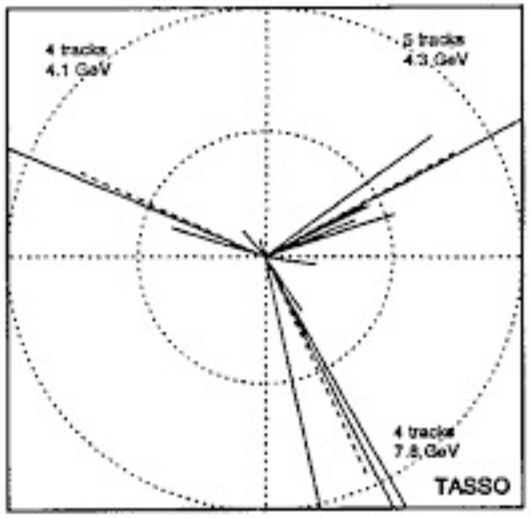
Particle Physics 1973 - 1984

- The golden age of quantum field theory

- New particles discovered

  1. Charm quark in 1974
  2. Tau lepton in 1975
  3. Bottom quark in 1977
  4. Gluon in 1978





- Jets discovered
- Predictions of Standard Model confirmed and reconfirmed….

String theory 1973 - 1984

- Some people think string theory may lead to a quantum theory of the gravitational force…..

  ….almost no-one is interested.

- String theory is a minor topic on the periphery of what is respectable

- A few people continue to work on it, but most have their attention elsewhere

String theory: 1973 - 1984

- John Schwarz:

  We felt that string theory was too beautiful to be just a mathematical curiosity. It ought to have some physical relevance. We had frequently been struck by the fact that string theories exhibit unanticipated miraculous properties…they have a very deep mathematical structure that is not understood. By digging deeper one could reasonably expect to find more surprises and then learn new lessons.

- A series of technical advances improves understanding

- The ‘superstring’, which requires ten space-time dimensions, solves consistency issues with the bosonic string (26 spacetime dimensions)

String Theory in 1984

- ’The First Superstring Revolution’
- A calculation by Michael Green and John Schwarz shows that string theory solves a problem in standard ’supergravity’ approaches to quantising the gravitational force.
- The result reaches Edward Witten in Princeton – who was by now one of the most influential physicists in the world
- He adopts string theory – and everyone else follows.
- The failed theory of the strong interactions becomes the number one most fashionable topic in particle physics

The Age of Excitement

- *'We study candidate vacuum configurations in.....superstring theory that have unbroken N=1 supersymmetry in four dimensions. This condition permits only a few possibilities, all of which have vanishing cosmological constant.'*

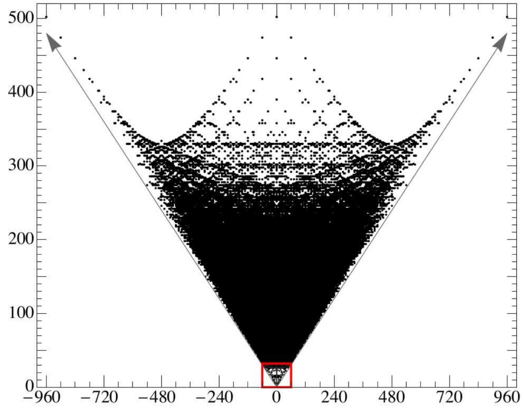
  from the paper *Vacuum Configurations for Superstrings* in spring 1985.

- Today, there are at least 473 800 776 similar possibilities known!

String Theory since 1984

- String theory since 1984 has grown and spread across many parts of theoretical and mathematical physics

MATHEMATICS



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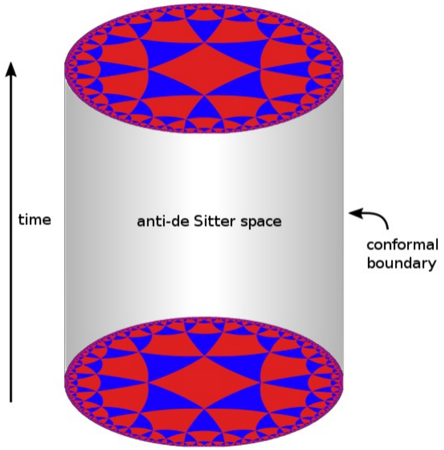

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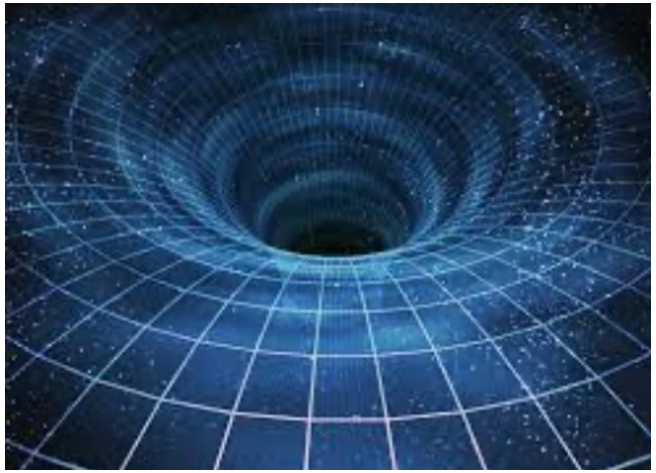
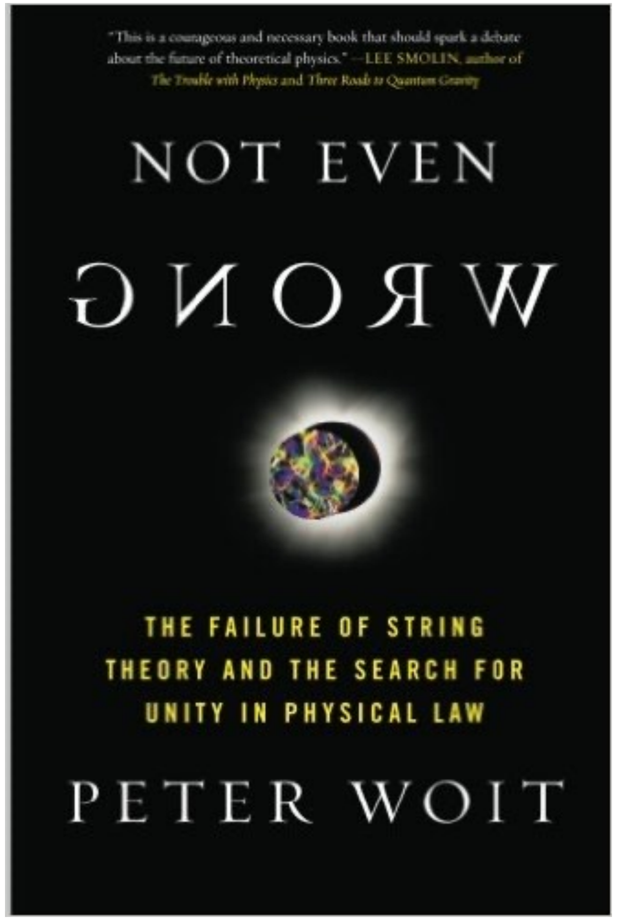
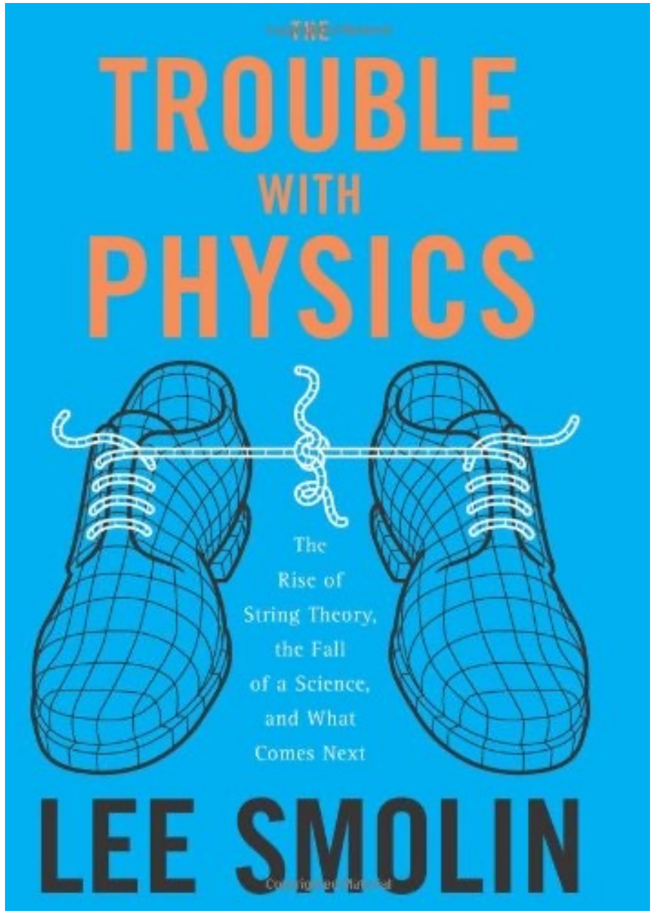
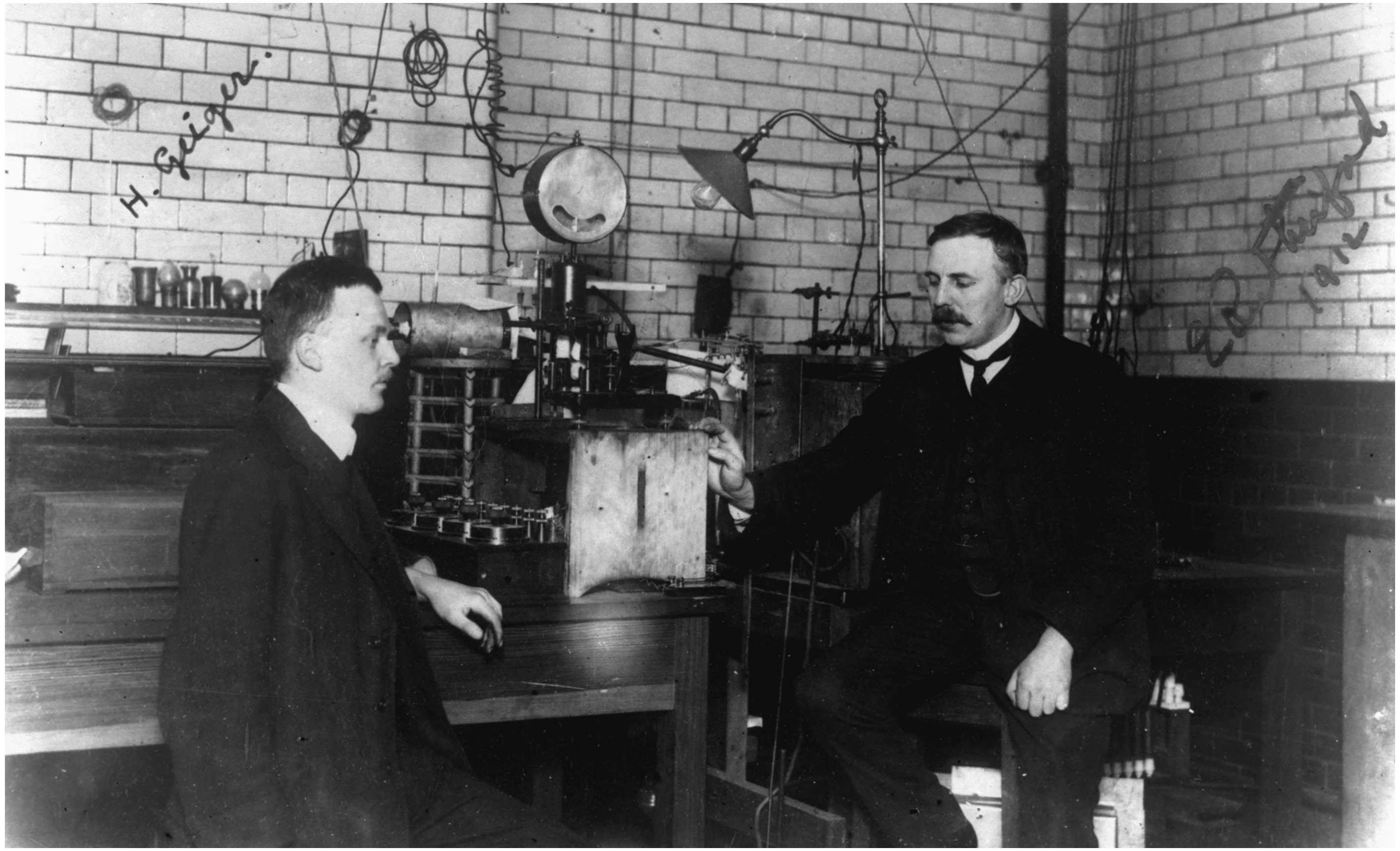


String Theory: The Backlash





How does string theory motivate searches for *new Physics*?



How does string theory motivate searches for *new Physics*?

One of the fundamental questions of particle physics:

$$\mathcal{L}_{world} = \mathcal{L}_{Standard\ Model} + \mathcal{L}_{General\ Relativity} + \mathcal{L}_{????}$$

What is $\mathcal{L}_{????}$?

What new particles, interactions or forces lie beyond our current knowledge?

How does string theory motivate searches for *new Physics*?

There are many reasons $\mathcal{L}_{????}$ should be present.

1. Dark matter
2. Replication of three chiral generations
3. Baryogenesis – the origin of the matter/antimatter symmetry in the universe

4. The strong CP problem – why is the Theta angle in the Quantum Chromodynamics Lagrangian

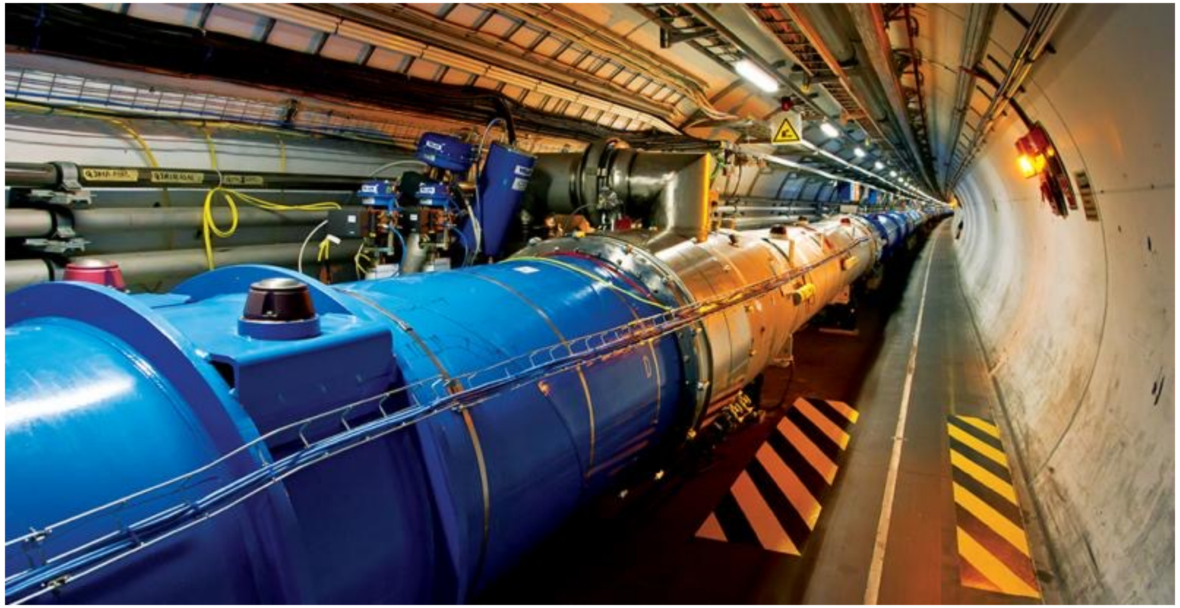
$$\mathcal{L}_{QCD} = \frac{1}{4g^2} F_{\mu\nu}F^{\mu\nu} + \frac{\theta}{8\pi^2}\epsilon_{\alpha\beta\gamma\delta}F_{\mu\nu}F^{\mu\nu} + \Sigma_i m_i \bar{q}_i q_i$$

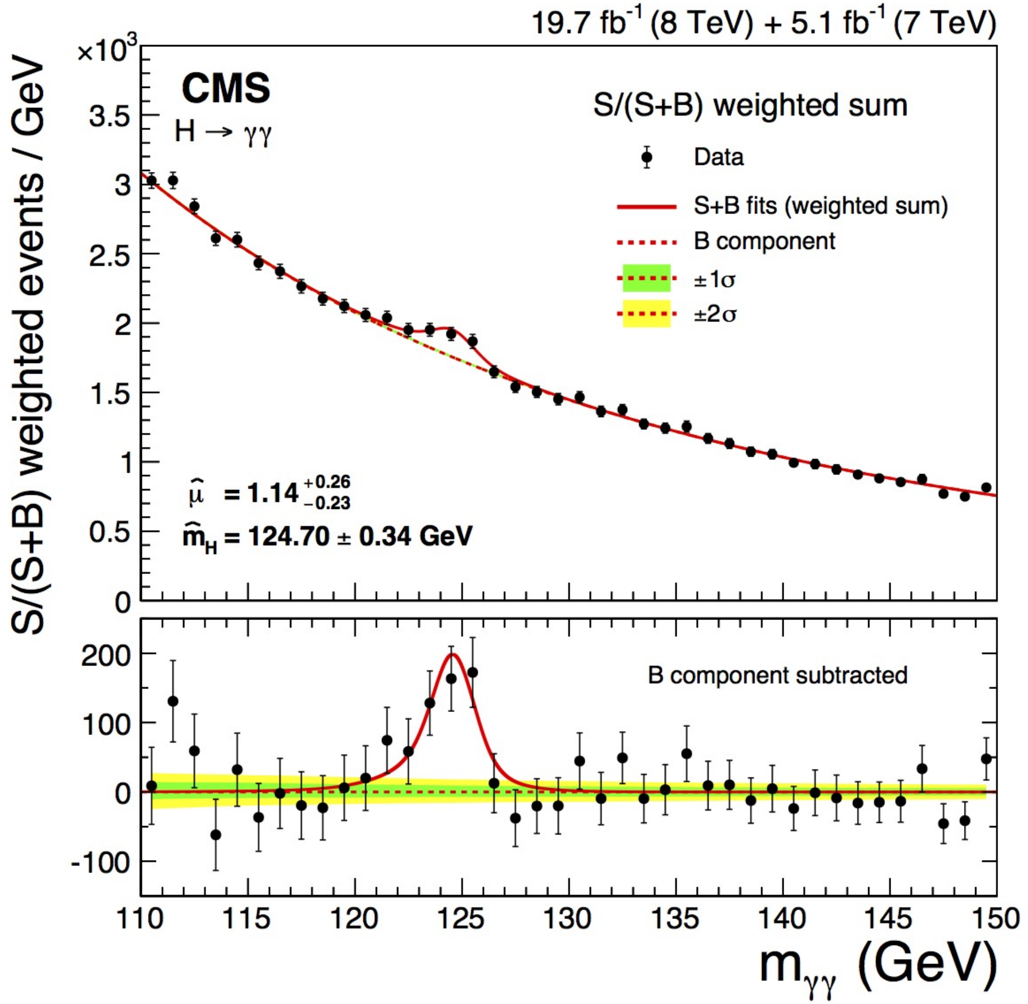
so close to zero?

5. The need for a *quantum* theory of the gravitational interactions rather than a classical one

Search Strategy I

- Search for *heavy,* relatively *strongly interacting* particles, where *the barrier to discovery is insufficiently energetic phenomena.*





- LHC and Higgs discovery prime example

Search Strategy II

- For *light, extremely weakly interacting* particles, LHC-style searches are not useful.

  (collisions at the LHC do not probe the gravitational force)

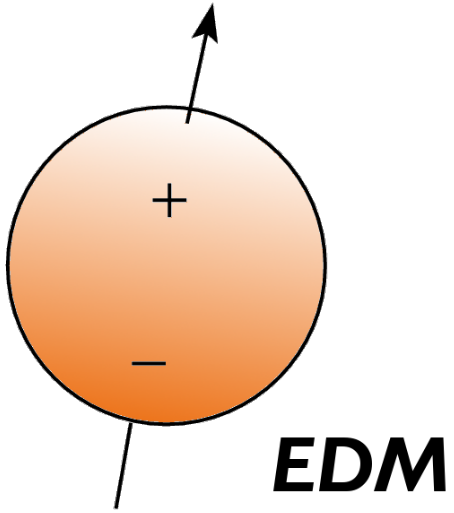
- For new physics with no energetic costs to production, but that is just very weakly coupled to the Standard Model, new strategies are needed.

- The *weak coupling* frontier of particle physics is almost orthogonal to the direction represented by the Large Hadron Collider.

Axions and Axion-Like Particles (ALPs)

The original QCD axion

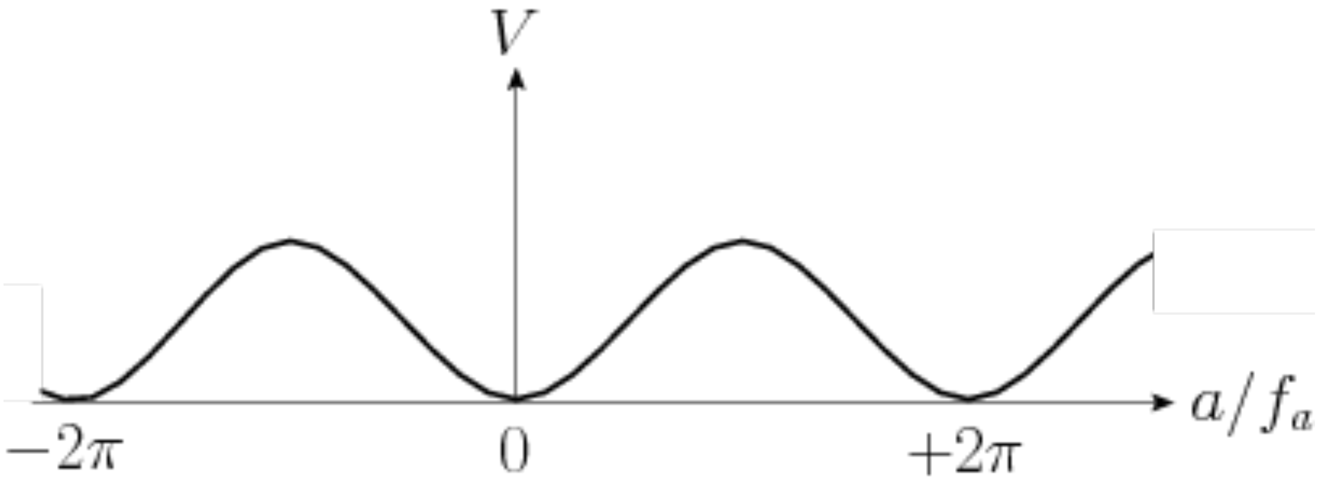
- $$\mathcal{L}_{QCD} = \frac{1}{4g^2} F_{\mu\nu} F^{\mu\nu} + \frac{\theta}{8\pi^2} \epsilon_{\alpha\beta\gamma\delta} F_{\mu\nu} F^{\mu\nu} + \Sigma_i m_i \bar{q}_i q_i$$
- The θ term in the QCD Lagrangian violates parity. Its experimental consequence is an electric dipole moment for the neutron.



- For typical values of θ (between 0 and 2π) this generates a neutron electric dipole moment of $\sim 10^{-17} e$ cm
- Current bound on neutron dipole moment is $< 3{\times}10^{-26} e$ cm - θ is very close to zero.

Non-perturbative QCD effects lead to a potential that depend on the θ angle

$$V_{axion}(a) = \Lambda_{QCD}^4 \left(1 - \cos\left(\frac{a}{f_a}\right)\right)$$



Promote the θ angle to a dynamical quantity $\left(\theta = \frac{a}{f_a}\right)$. This dynamically minimises θ at zero, and generates a mass term for the QCD axion a

$$m_a^2 = V''(a) = \frac{\Lambda_{QCD}^4}{f_a^2}, \qquad m_a \sim \left(\frac{10^{11}\text{GeV}}{f_a}\right) 10^{-3}\text{eV}$$

The QCD Axion (if it exists) is very light and has very weak interactions with the Standard Model

Axions

- The axions is valued on a circle and so has an angular periodicity
- The basic axion Lagrangian is

$$\mathcal{L}_{ALP} = -\frac{1}{2}\partial_\mu a \partial^\mu a + V(a)$$

  subject to $V(a) \equiv V(a + 2\pi f_a)$
- The angular periodicity implies that direct 'perturbative' contributions to the potential such as $m_a a^2$ or λa^4 are forbidden by the periodicity
- The leading contributions to axion potentials come from (small) non-perturbative terms such as $\Lambda^4 \sin(\frac{a}{f_a})$ where Λ arises from exponentially suppressed effects.
- This has the key consequence that axions are naturally very light (or massless).

Axions in String Theory

- 30-year old result:

  String compactifications lead to a plenitude of axions in the low-energy theory

- ’Model-dependent‘ axions number O(100) for typical compactifications

- Axions are one of the most motivated targets in looking for signatures of string compactifications

Axions in String Theory

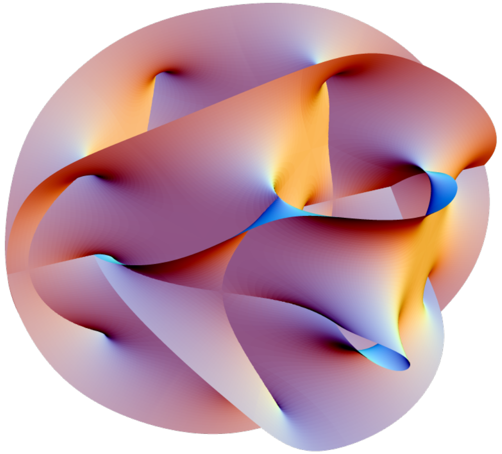
- In higher-dimensional theory, dimensional reduction of terms like (as one example)

$$\int C_4 \wedge F_2 \wedge F_2 \; d^8x$$

gives rises to lower-dimensional axionic couplings

$$\int a_i \, F_2 \wedge F_2 \; d^4x$$

with a separate axion $a_i = \int_{\Sigma_i} C_4$ for each 4-cycle Σ_i the field C_4 is reduced on



Axion-Like Particles (ALPs)

- The original, QCD axion is defined by the additional coupling to the strong force

$$aF_{QCD}\tilde{F}_{QCD}$$

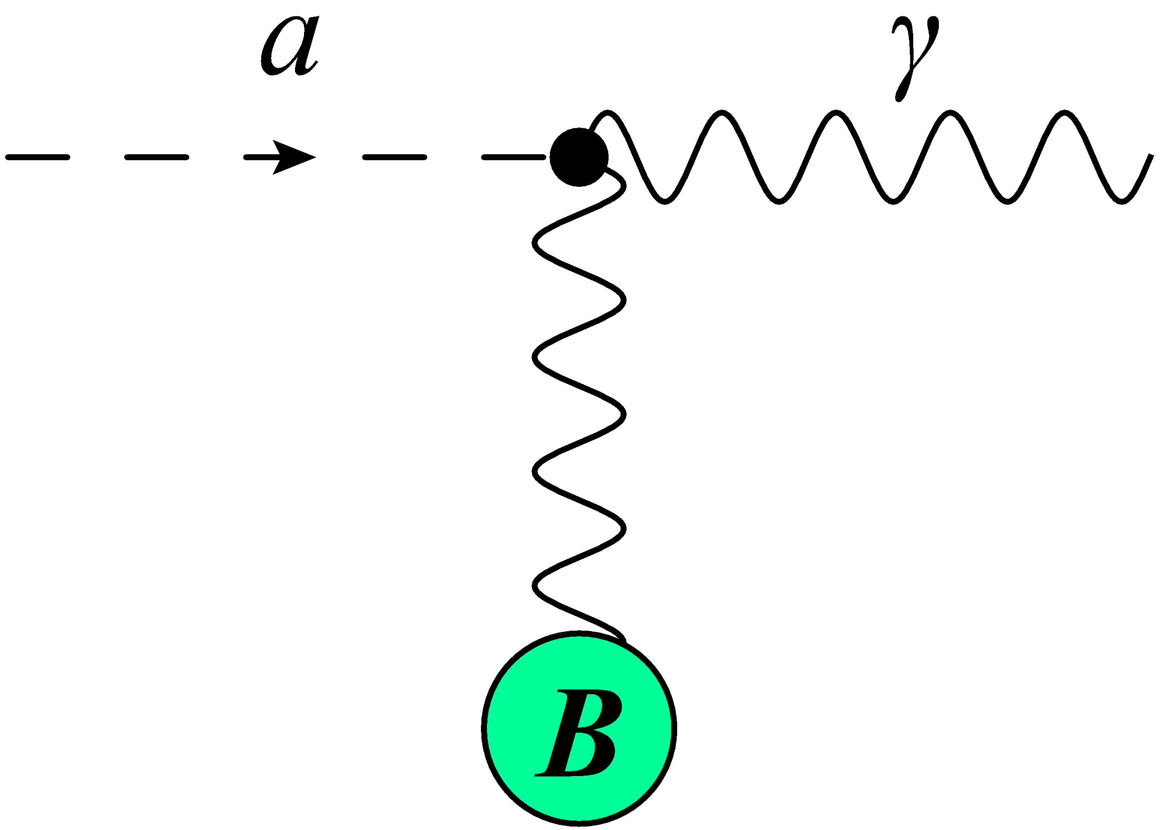
when the θ angle is promoted to be a dynamical variable.

- A*xion-like particles (ALPs)* have no coupling to the strong force.
- The key coupling for axion-like particles is the coupling to electromagnetism

$$\frac{a}{8\pi^2 f_a}\epsilon_{\alpha\beta\gamma\delta}F_{\mu\nu}F^{\mu\nu} \equiv a\, g_{a\gamma\gamma}\mathbf{E.B}$$

- This coupling sets the interaction between the ALP a and the Standard Model fields.

Axion Phenomenology



Axion Phenomenology

- The coupling

$$a\ g_{a\gamma\gamma}\mathbf{E.B}$$

  is key to searches for ALPs.
- In a fixed background magnetic field, this mixes the ALP a and the photon γ mass eigenstates.

$$\begin{array}{lcl} |\gamma_1 > & & |\gamma_1 > \\ |\gamma_2 > & \rightarrow & \cos\phi|\gamma_2 > + \sin\phi\ |a > \\ |a > & & \cos\phi\,|a > - \sin\phi\,|\gamma_2 > \end{array}$$

- Analogous to neutrino oscillations, there are oscillations between the 'flavour' eigenstates a and γ, while the 'mass' eigenstates are linear combinations of a and γ
- We restrict to light/massless ALPs in our discussion

$$P(\gamma \to a) = \frac{g_{a\gamma\gamma}{}^2 B^2 L^2}{4}$$

Sikivie
Raffelt + Stodolsky

where *B* is transverse magnetic field

L is magnetic field coherence length

$g_{a\gamma\gamma}$ is (dimensional) ALP-photon coupling

$$P(\gamma \to a) \sim 1.2 \times 10^{-8} \left(\frac{g_{a\gamma\gamma}}{10^{-12}\,\mathrm{GeV}^{-1}}\right)^2 \left(\frac{B}{1\ \mu G}\right)^2 \left(\frac{L}{1\ \mathrm{kpc}}\right)^2$$

Astrophysical environments (B = $10^{-10} T$ L = 1 kpc) are overwhelmingly better than terrestrial environments (B = 10T, L = 10m)

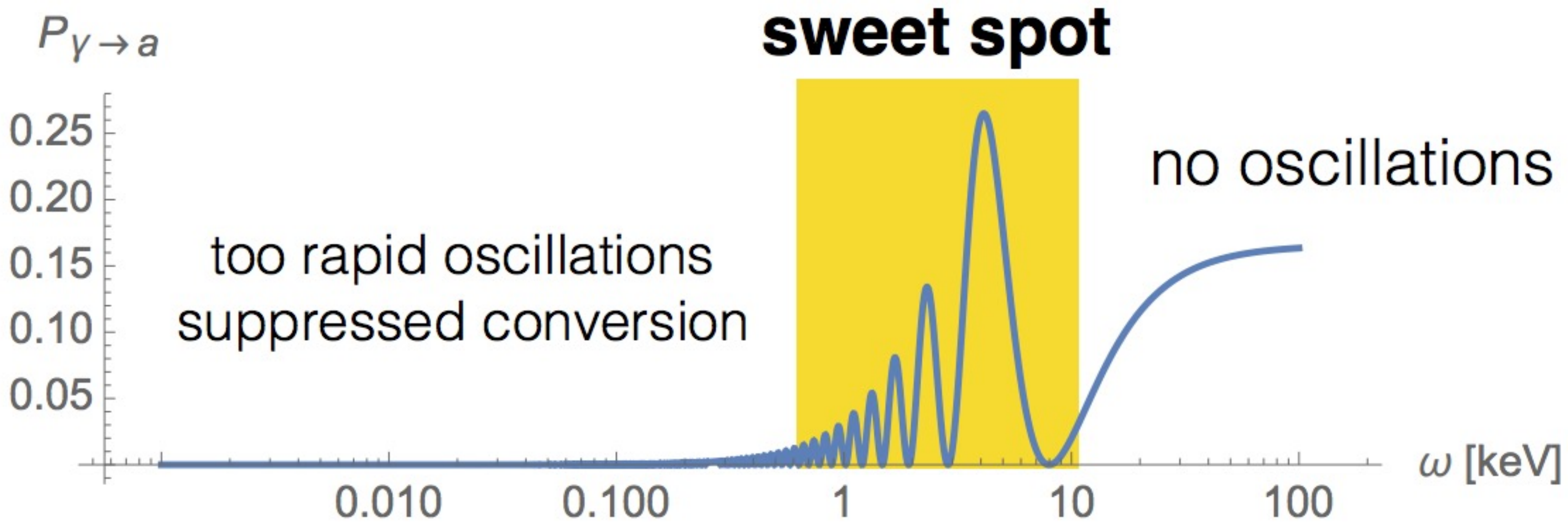
Photon-ALP Conversion – why X-rays?

- Axion-photon interconversion (for $m_a<10^{-12}$eV, effectively massless) in galaxy clusters:

$$P_{\gamma\to a} = \frac{1}{2}\frac{\Theta^2}{1+\Theta^2}\sin^2\left(\Delta\sqrt{1+\Theta^2}\right)$$

$$\Theta = 0.28\left(\frac{B_\perp}{1\ \mu\mathrm{G}}\right)\left(\frac{\omega}{1\ \mathrm{keV}}\right)\left(\frac{10^{-3}\mathrm{cm}^{-3}}{n_e}\right)\left(\frac{10^{11}\mathrm{GeV}}{M}\right) \qquad \Delta = 0.54\left(\frac{n_e}{10^{-3}\mathrm{cm}^{-3}}\right)\left(\frac{L}{10\mathrm{kpc}}\right)\left(\frac{1\mathrm{keV}}{\omega}\right)$$

- Sweet spot at X-ray energies:



How to search for ALPs?

- The basic physics used here to look for ALPs is very simple.

  1. Send photons from A to B

  2. Have a magnetic field inbetween A and B

  3. Photon-ALP interconversion causes some of these photons to oscillate into ALPs

  4. The photon spectrum on arrival at B would show modulations compared to the source photon spectrum at A.

- In our case, the source A will be the central AGN (Active Galactic Nucleus) of the Perseus galaxy cluster and B is the *Chandra* X-ray telescope. Idea developed by several groups over a number of years to give best current bounds on low-mass ALPs.

AGN

Milli- parsec

NGC1275

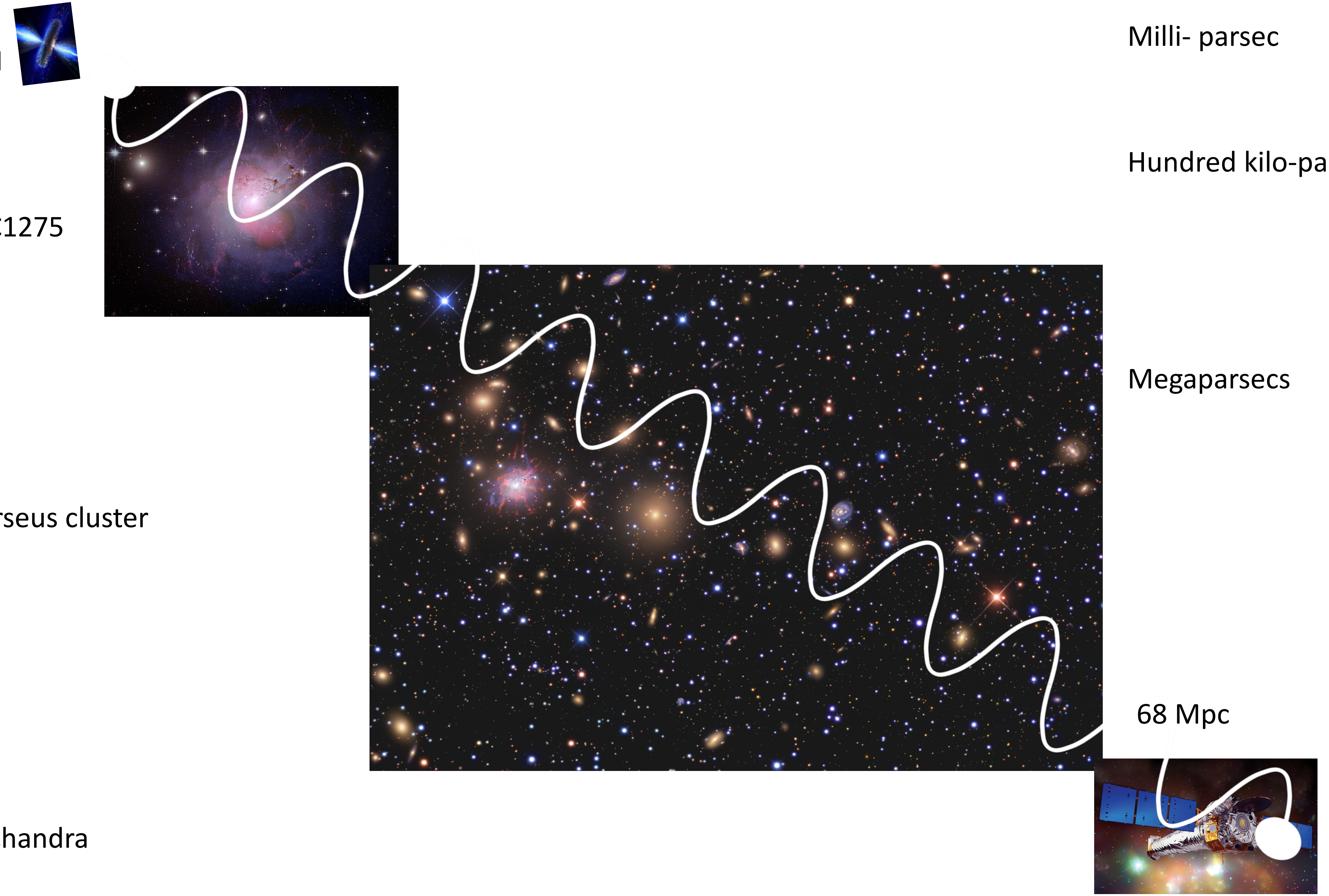
Hundred kilo-parsecs

Perseus cluster

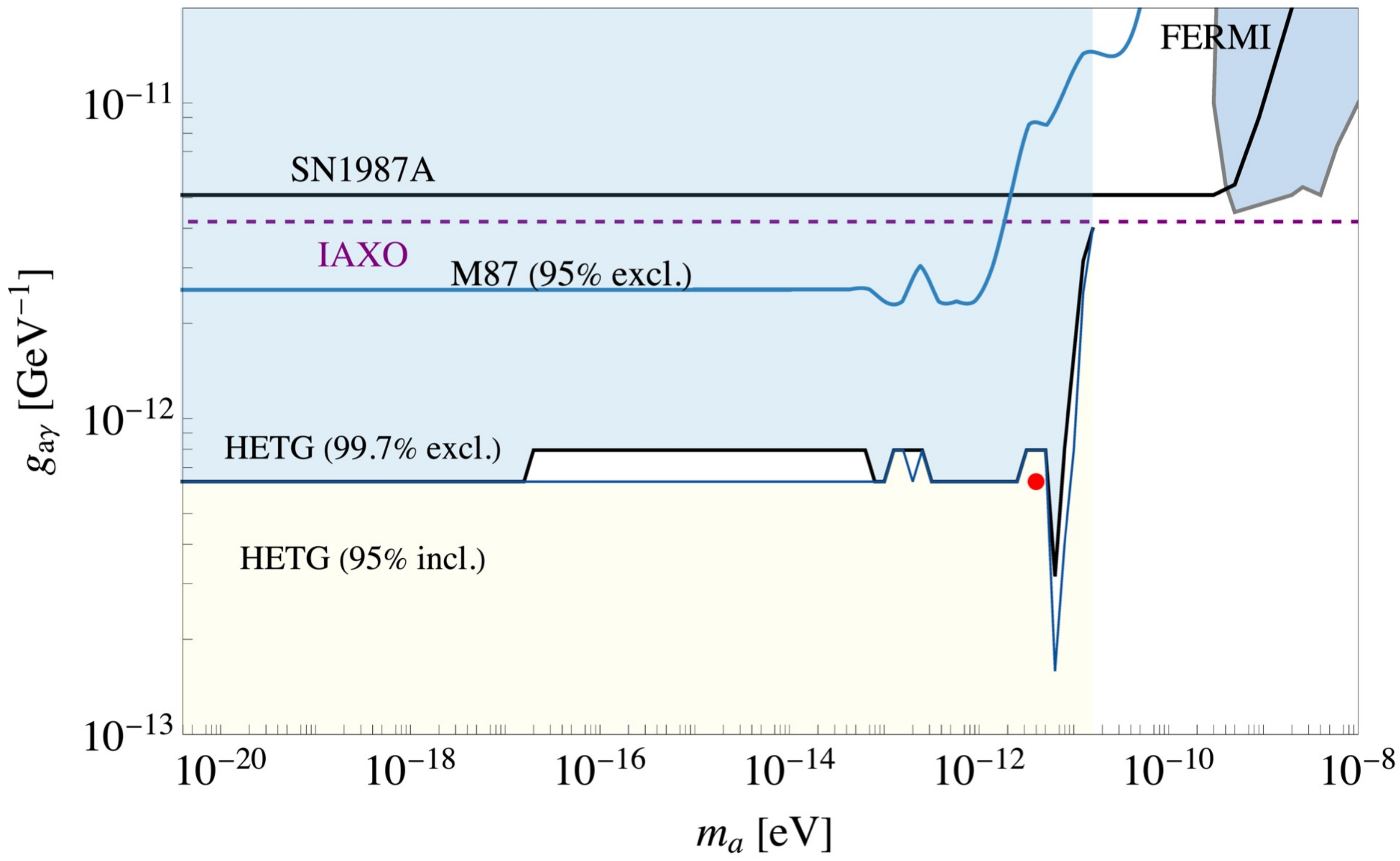
Megaparsecs

68 Mpc

Chandra



Strong bounds on low-mass ALPs



From 1907.05475
Reynolds et al

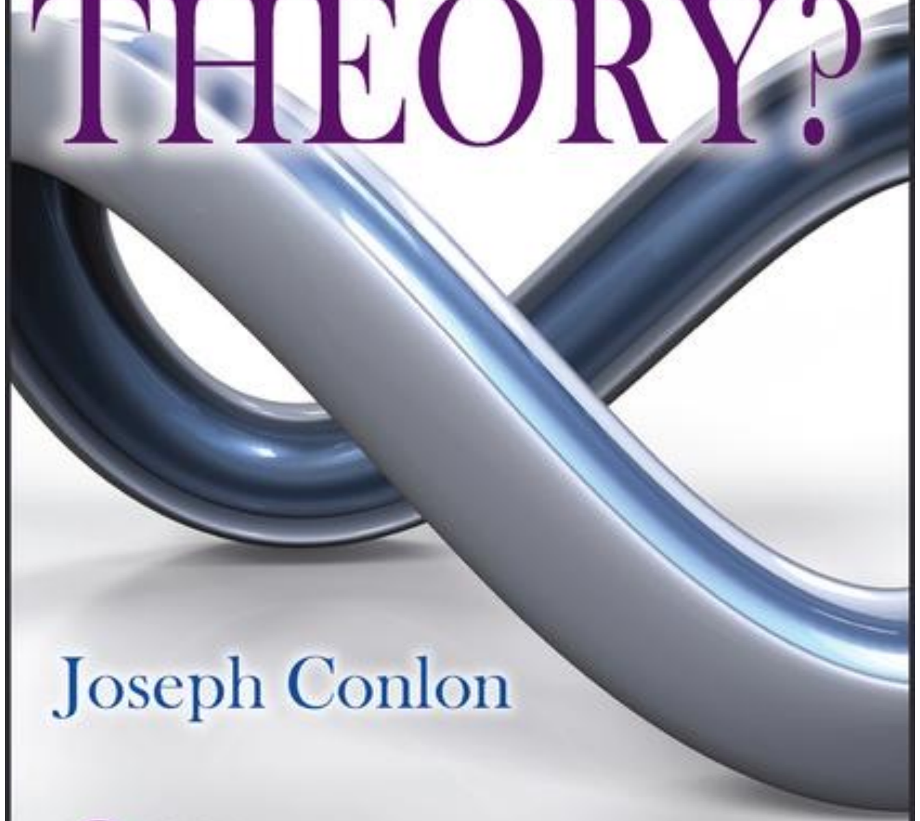
Summary

- String theory is a rich set of ideas that started with the strong interactions but then spread to all kinds of unexpected area
- Its fundamental physics start with the quantized string: an infinite number of quantum harmonic oscillators, one for each harmonic

- As a theory of *this world*, one of the most generic expectation from string theory is the existence of many axions or axion-like particles – these cn number O(100) for typical compactifications

- Axions are one of the most motivated targets in looking for signatures of string compactifications – I have described one way to look for them through X-ray astronomy and the spectrum of AGNs shining through magnetic fields.

WHY STRING THEORY?



Joseph Conlon

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