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Elegance of fundamental laws of physics - outreach potential

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Introduction

Two major discoveries in the last decade:

Higgs boson (2012) and gravitational waves (2015)

Plus scores of other important results both from the accelerator and non-accelerator physics which stand witness to the productivity of the field.

However...

Nima Arkani-Hamed (for CERN Courier): „Some people are complaining about being disappointed or even depressed that we've only discovered the Higgs and nothing else"

Sabine Hosenfelder wrote a book Lost in Math with a subtitle How beauty leads physics astray

Sarah Demers: „Maybe it is „okay for the universe to be a little bit ugly"

Marcelo Gleiser: „Perhaps the insistence that we have in search of perfect symmetry is not a physics idea, but a bias"

David Orrell (in his book Truth or Beauty): Science is in the risk of being blinded by the prejudice that truth is necessarily wedded to beauty

… dollars devoted to particle accelerators have poor direct returns-on-investment

Proponents of beauty

Henri Poincare: “The Scientist does not study nature because it is useful to do so. He studies it because he takes pleasure in it; and he takes pleasure in it because it is beautiful”

Richard Feynman: “You can recognize truth by its beauty and simplicity. When you get it right, it is obvious that it is right - because usually what happens is that more comes out than goes in”

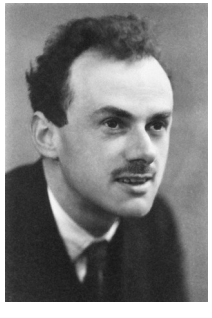
Beauty as important as truth

Hermann Weyl: “In my work, I have always tried to unite the true with the beautiful; but when I had to choose one or the other, I usually chose the beautiful”

Paul Dirac: “it is more important to have beauty in one’s equations than to have them fit experiment”

Beauty more important than truth?



Proponents of beauty

Gian Giudice: “When you stumble on a beautiful theory you have the same emotional reaction that you feel in front of a piece of art.”

Frank Wilczek: “having tasted beauty at the heart of the world, we hunger for more. In this quest, I think, there is no more promising guide than beauty itself.”

Steven Weinberg: “The horse breeder looks at a horse and says ‘That’s a beautiful horse.’ While he may be expressing an aesthetic emotion, I think he knows that that’s the kind of horse that wins races.”

Platonism

Jesus Zamora Bonilla divides scientists and science philosophers into

1. **Platonists** (ultimate explanation of the Universe must possess beauty)
2. **Sceptics** (scientific research has nothing intrinsic to do with beauty)

Quantum physicists and mathematicians

Scientists from other fields + philosophers

Plato: Goal of education is to teach us love what is beautiful (Republic, 375 B.C.)

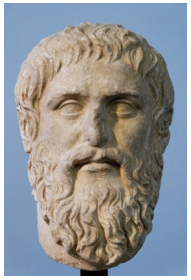
education & knowledge

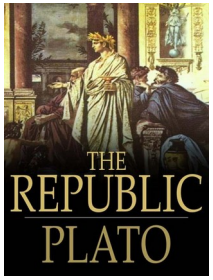
Perfect beauty

Higher form of beauty (copy of perfect beauty)

Higher form of beauty

Material objects and phenomena (imperfect copies)





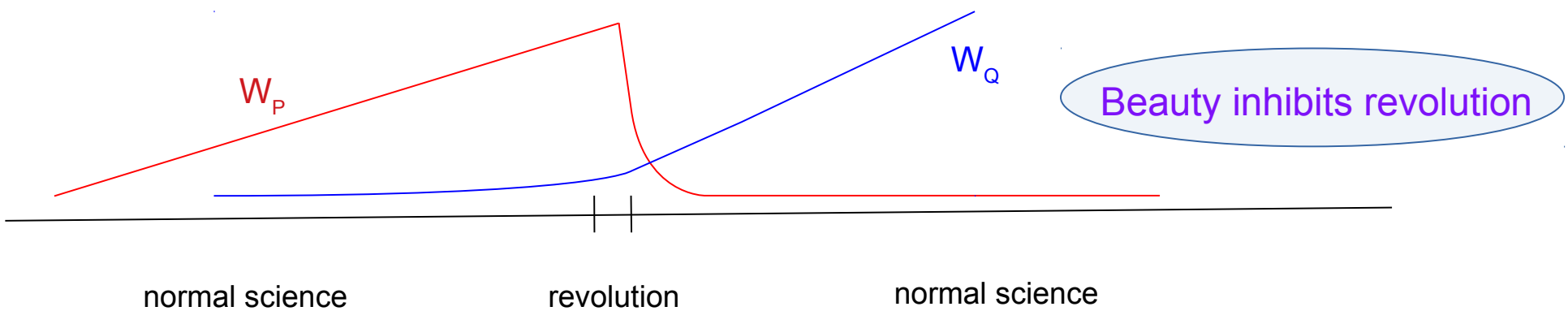
To see the perfect beauty means to have the knowledge, to know the truth

Beauty and Scientific revolution

James McAllister: to evaluate theories, scientists use

1. empirical criteria (do not change over time)
2. aesthetic criteria (change in response to empirical success of recent and current theories)

Aesthetic property P (symmetry) has a weight W_P which grows if P is found in one theory with empirical success after another.



Revolution is abandonment of aesthetic criteria in favour of new ones with greater empirical success

Two revolutionary examples: 1. Kepler's theory 2. Quantum mechanics

Beauty (aesthetic) criteria

Thrinh Xuan Thuan: conformity with the whole, simplicity and inevitability.

Subrahmanyan Chandrasekhar: strangeness and conformity of the parts to one another and to the whole.

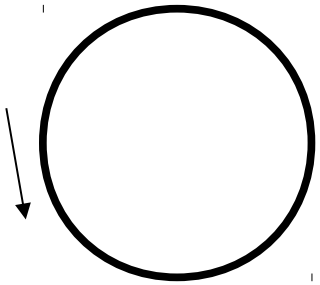
Anthony Zee: symmetry. „When the beholder is a physicist, beauty means symmetry

Frank Wilczek:

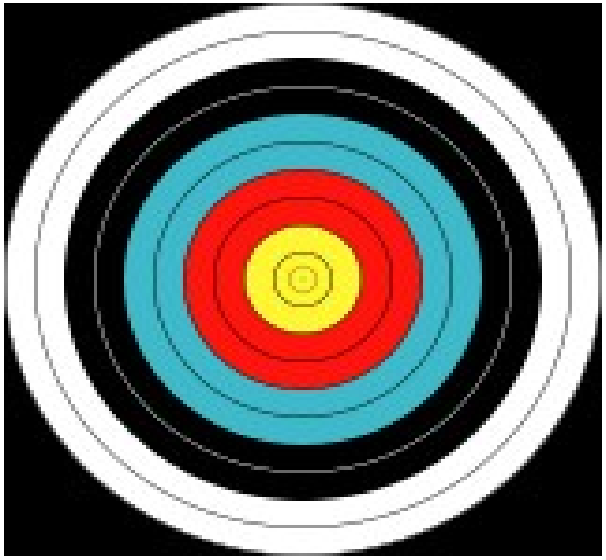
1. *Productivity, getting out more than you put in: The more phenomena one can explain with less equations, the more beautiful the theory is.*

2. *Symmetry. According to Wilczek it's change without change. "You can make changes in physical objects or changes in the laws that could change them but don't".*

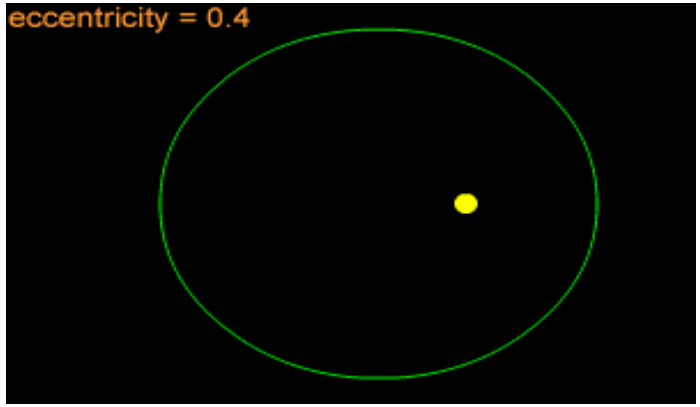
Circular symmetry



Circular symmetry and Newton's theory



Greeks: planetary orbits are circular



Kepler: planetary orbits are not circular!

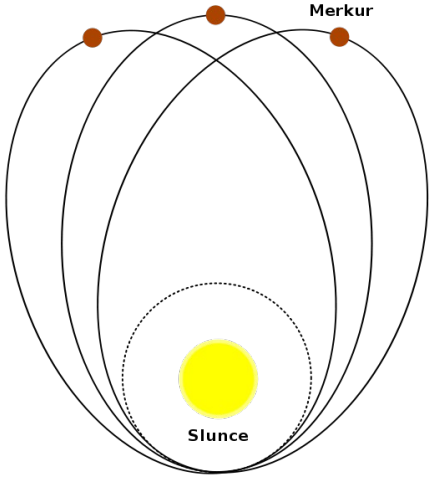
Newton's gravitational law $$F = G\frac{m_1 m_2}{r^2}$$

Important lesson: symmetry does not apply to the orbits (the solutions of the gravitational law), but to the law itself.

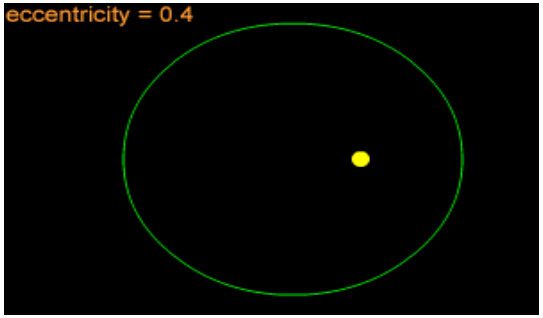
Productivity: single law explains both falling apples and cellestial motions

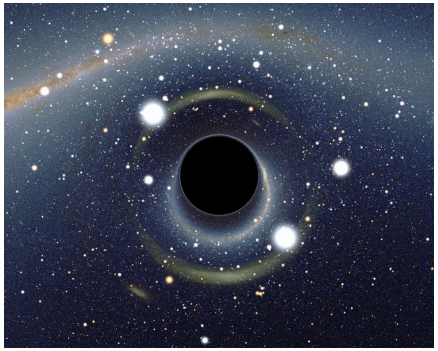
Landau & Lifshitz 1975: "...General theory of relativity … represents probably the most beautiful of all existing physical theories."

$$F = G\frac{m_1 m_2}{r^2}$$



Anomalous precession of Mercury's perihelion





Black holes

General covariance symmetry dictates the structure of the theory

General relativity

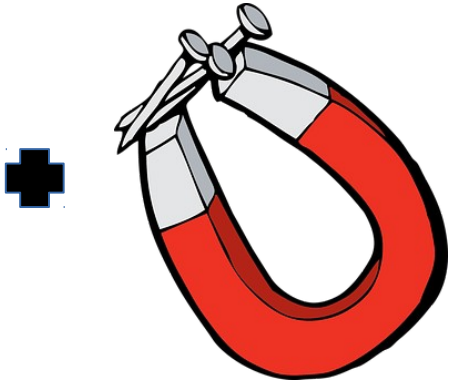
$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Maxwell's equations – classical electromagnetism

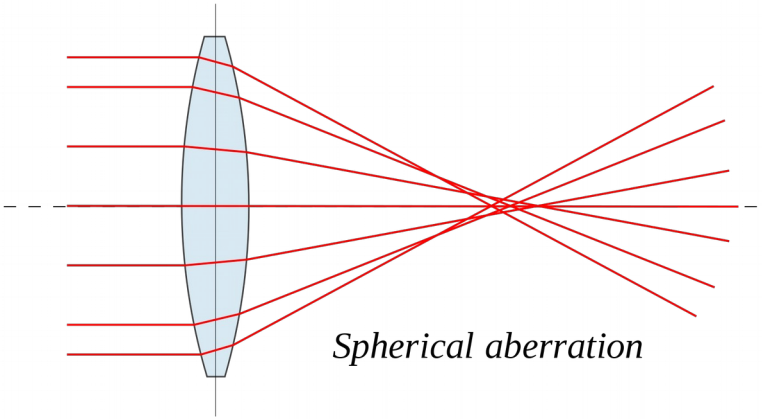
Lorentz symmetry played a crucial role in the development of Special theory of relativity

$$\nabla \cdot \vec{E} = \frac{\rho}{\epsilon_0}$$
$$\nabla \cdot \vec{B} = 0$$
$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$
$$\nabla \times \vec{B} = \mu_0 \vec{J} + \frac{1}{c^2}\frac{\partial \vec{E}}{\partial t}$$

electricity



magnetism

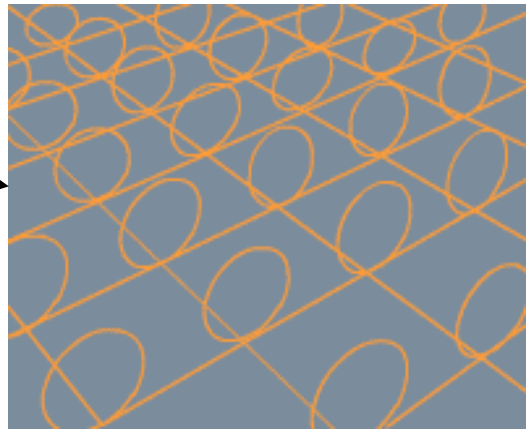


optics

Symmetry and productivity of QED

Free electron field

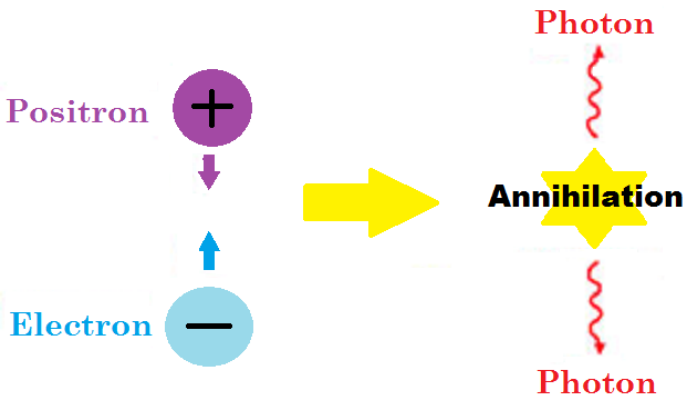
$$\mathcal{L} = \bar{\psi}(i\gamma^\mu \partial_\mu \psi - m)\psi$$



Local circular symmetry

Electromagnetic field

$$\mathcal{L} = \bar{\psi}(i\gamma^\mu \partial_\mu \psi - m - e\gamma^\mu A_\mu)\psi - \frac{1}{4}(\partial_\mu A_\nu - \partial_\nu A_\mu)(\partial^\mu A^\nu - \partial^\nu A^\mu)$$



Electron & Positron annihilate, releasing energy which are carried off by two photons.

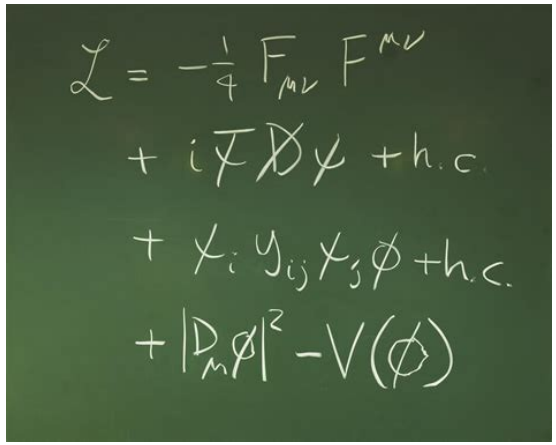
$$\nabla \cdot \vec{E} = \frac{\rho}{\epsilon_0}$$
$$\nabla \cdot \vec{B} = 0$$
$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$
$$\nabla \times \vec{B} = \mu_0 \vec{J} + \frac{1}{c^2}\frac{\partial \vec{E}}{\partial t}$$

Standard Model of Elementary Particles

	three generations of matter (fermions)			interactions / force carriers (bosons)	
	I	II	III		
mass	≃2.2 MeV/c²	≃1.28 GeV/c²	≃173.1 GeV/c²	0	≃124.97 GeV/c²
charge	⅔	⅔	⅔	0	0
spin	½	½	½	1	0
QUARKS	u up	c charm	t top	g gluon	H higgs
	≃4.7 MeV/c²	≃96 MeV/c²	≃4.18 GeV/c²	0	
	−⅓	−⅓	−⅓	0	
	½	½	½	1	
	d down	s strange	b bottom	γ photon	
LEPTONS	≃0.511 MeV/c²	≃105.66 MeV/c²	≃1.7768 GeV/c²	≃91.19 GeV/c²	
	−1	−1	−1	0	
	½	½	½	1	
	e electron	μ muon	τ tau	Z Z boson	
	<2.2 eV/c²	<0.17 MeV/c²	<18.2 MeV/c²	≃80.39 GeV/c²	
	0	0	0	±1	
	½	½	½	1	
	νe electron neutrino	νμ muon neutrino	ντ tau neutrino	W W boson	

GAUGE BOSONS
VECTOR BOSONS

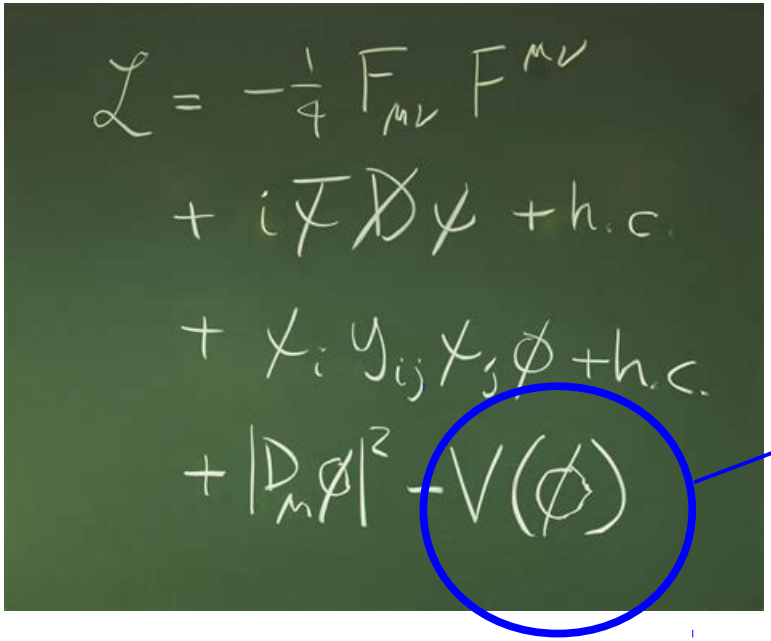
SCALAR BOSONS



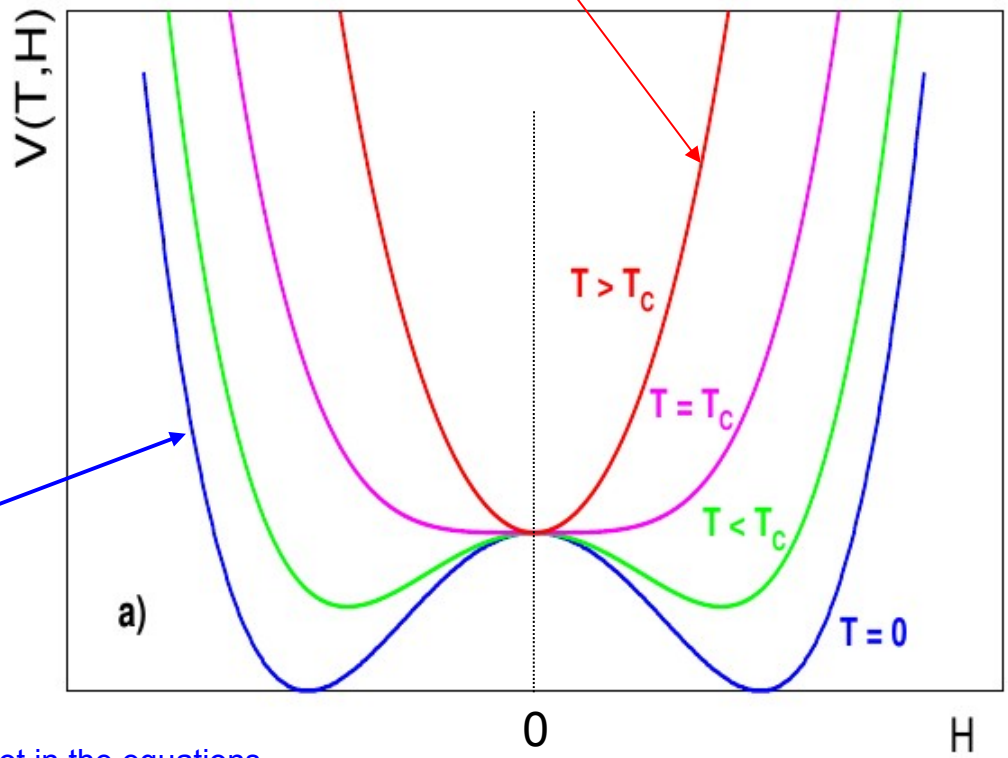
19 free parameters

Hidden beauty – spontaneous symmetry breaking

Conflict between obvious richness, diversity and asymmetry in objects around us and the perfect symmetries of equations



Perfect symmetry in the early Universe when particles were massless



Symmetry broken not in the equations but in the solution (vacuum)

Nature wants both unity and diversity, symmetry and the lack of it (A. Zee) and the spontaneous symmetry breaking is a tool to connect the two.

Conclusions 1

Fundamental physics naturally fits Plato's hierarchy of forms

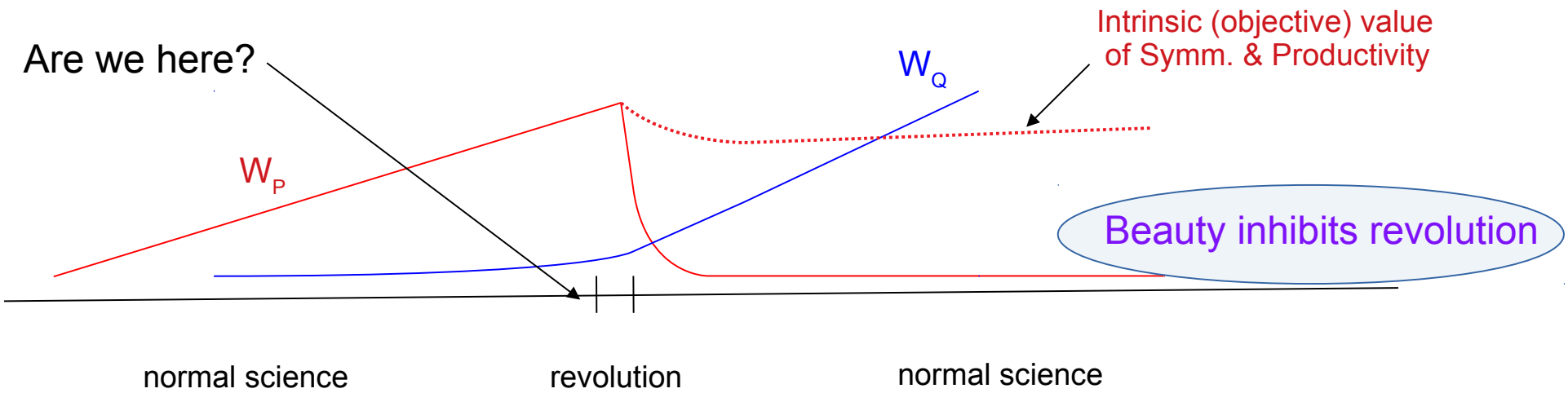
education & knowledge

Perfect beauty	Theory of everything (perfect symmetry & unity)?
Higher form of beauty (copy of perfect beauty)	SUSY? (spontan. broken symmetry)
Higher form of beauty	Standard model
Material objects and phenomena (imperfect copies)	Material objects and phenomena (imperfect sym.)

S. Weinberg: It's just a guess, but I think we'll get to final theory. And that will be really quite a remarkable turning point in the intellectual history of the human race

Conclusions 2

Has beauty led us astray?



We would need empirically successful theories with new aesthetic property Q!

Symmetry and productivity are pillars of scientific theories

I suggest that they have an intrinsic value which stays high even after revolution

Maybe we are not making progress in our theories because we have just solved all the „easier" questions and now face really deep ones such as what are space and time, as Arkani-Hamed thinks.