Fundamental Physics in the 21st Century

Frank Wilczek

Some guesses about

Fundamental Physics in the 21st Century

Ideas and Methods

- Dark Matter
- Axions
- Cosmic Strings
- Neutron Star Interiors
- Anthropic Reasonings
- Inflation
- Quantum Reality

Dark Matter

(non-axionic)

Dark Matter

WIMPs

- Low-energy supersymmetry is a very attractive extension of the standard model. It will be tested at LHC.

$$\begin{pmatrix} u & u & u \\ d & d & d \end{pmatrix}^{L}_{1/6}$$

$$\begin{pmatrix} \nu \\ e \end{pmatrix}^{L}_{-1/2}$$

$$\begin{pmatrix} u & u & u \end{pmatrix}^{R}_{2/3}$$

$$\begin{pmatrix} d & d & d \end{pmatrix}^{R}_{-1/3}$$

$$\begin{pmatrix} e \end{pmatrix}^{R}_{-1}$$

No ν^{R}

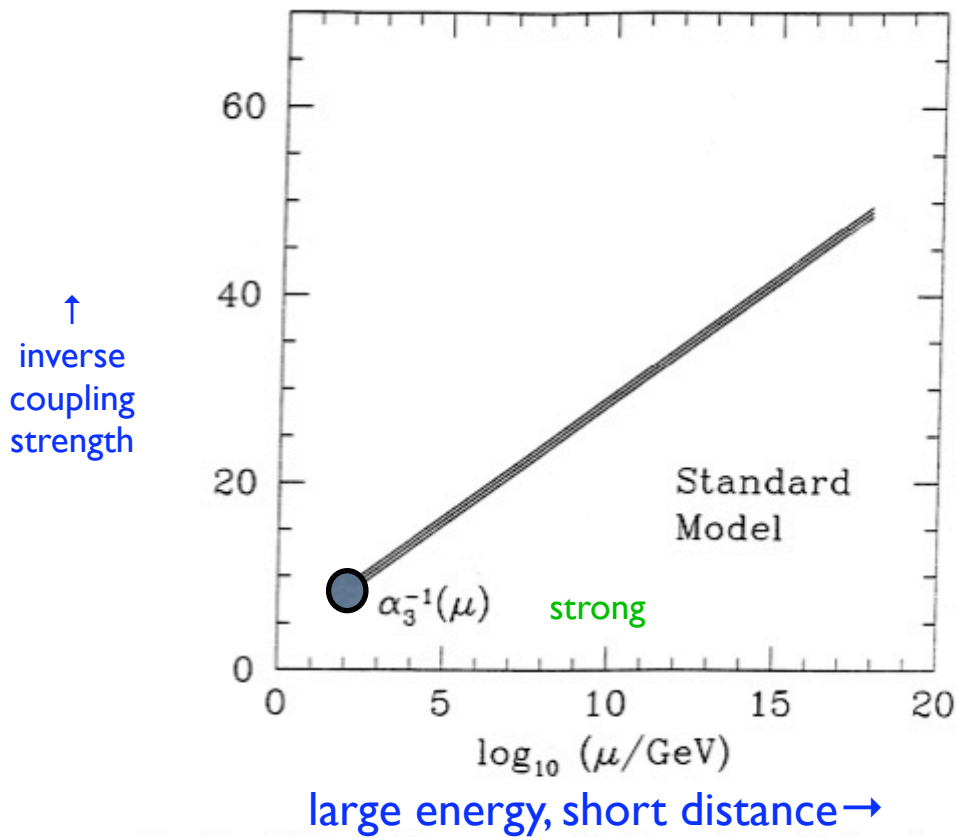
SU(3) x SU(2) x U(1)

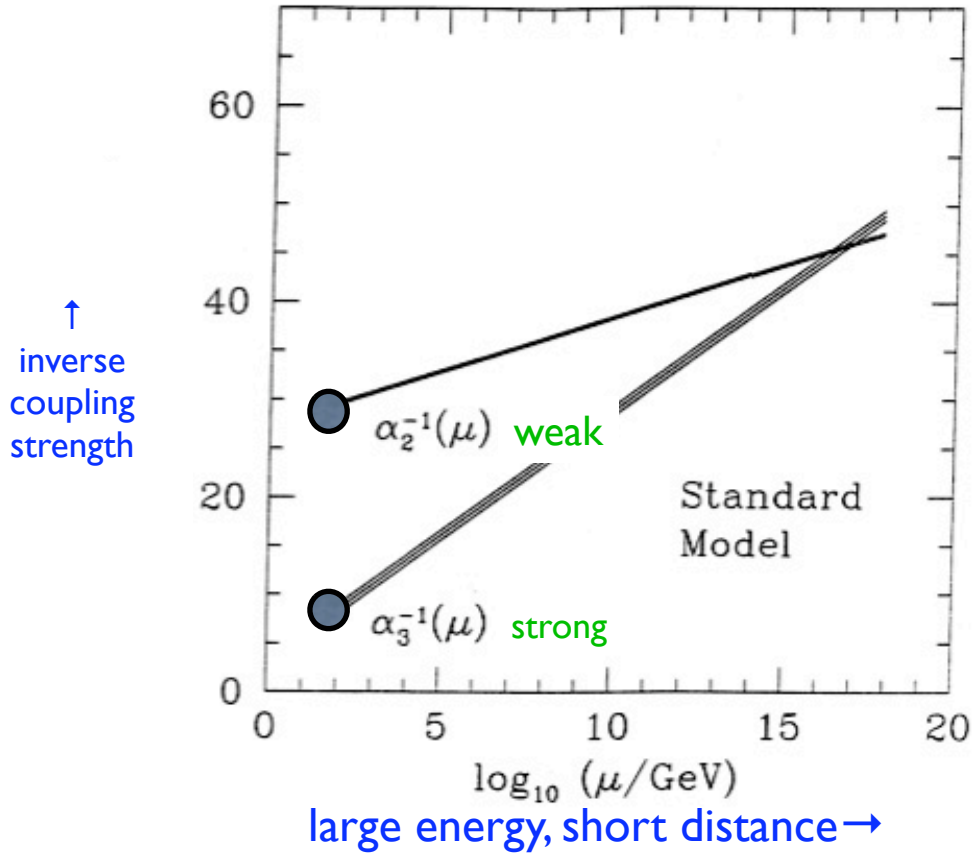
mixed, not unified

	R	W	B	G	P
u	+	-	-	+	-
u	-	+	-	+	-
u	-	-	+	+	-
d	+	-	-	-	+
d	-	+	-	-	+
d	-	-	+	-	+
u^c	-	+	+	-	-
u^c	+	-	+	-	-
u^c	+	+	-	-	-
d^c	-	+	+	+	+
d^c	+	-	+	+	+
d^c	+	+	-	+	+
ν	+	+	+	+	-
e	+	+	+	-	+
e^c	-	-	-	+	+
N	-	-	-	-	-

Hypercharge Y = -1/6 (R+W+B) + 1/4 (G+P)


electric
inverse
coupling
strength
weak
strong


↑
inverse
coupling
strength
60
40
20
0
0
5
10
15
20
$\log_{10}(\mu/\mathrm{GeV})$
Standard
Model
$\alpha_3^{-1}(\mu)$
strong
large energy, short distance→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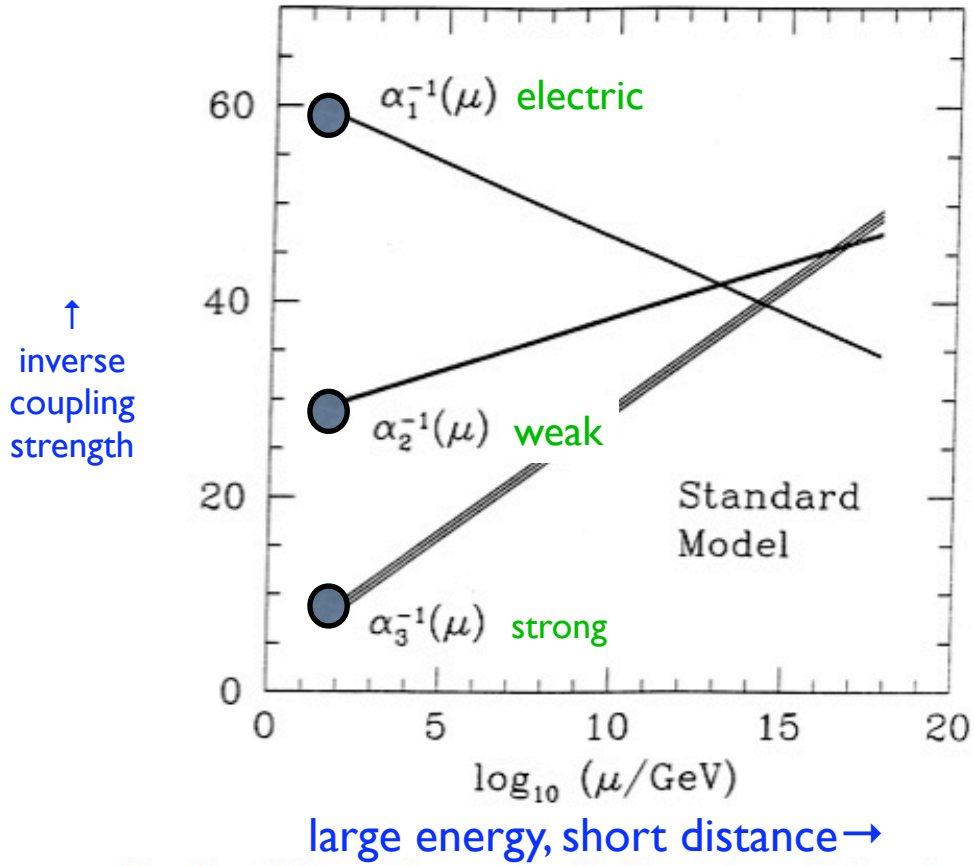
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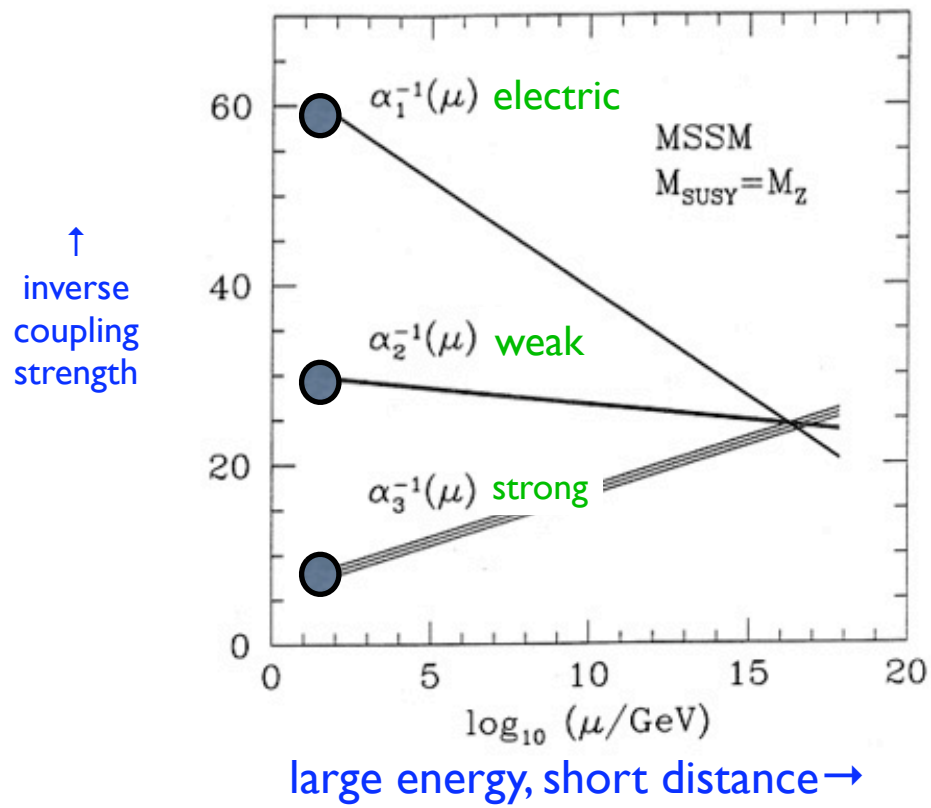
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coupling
strength
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0
$\alpha_1^{-1}(\mu)$ electric
MSSM
$M_{SUSY}=M_Z$
$\alpha_2^{-1}(\mu)$ weak
$\alpha_3^{-1}(\mu)$ strong
0
5
10
15
20
$\log_{10}(\mu/\mathrm{GeV})$
large energy, short distance→

- The detailed implementation is highly uncertain. Observing p decay would be helpful.

- The lightest R-odd particle ($R \equiv (-1)^{2S+B+L}$) is often a good dark matter candidate.

- It will be very important, in the event of discovery at LHC, to explore the properties and cosmic distribution of the candidate.

- Signals include direct energy deposit, annihilation products.

Phantoms

- A very real possibility is that there is a “hidden sector” of SU(3)xSU(2)xU(1) singlet fields.
- The Higgs field could be a portal into such hidden sectors.

$$\mathcal{L}_{\text{link}} = \eta \phi_s^\dagger \phi_s \sigma_p^2$$

- Dark matter could be lurking in a hidden sector.
- So could ultra-light particles.
- It will be very challenging to explore this phantom world, if it exists.

Axions

- Axions arose in addressing a seemingly esoteric esthetic flaw in the standard model, but the ideas around them have developed and deepened for 30 years, with no serious competition, so the stakes have risen considerably.

- The flaw has to do with a form of T violation, allowed by the SM, that is not observed. There are also “beyond the SM” sources of T violation, that are quite plausible. All these can be accessed, in principle, by EDMs.

$$\mathcal{L}_\theta \propto G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

$$\mathcal{L}_{\rm edm} \propto \bar{\psi}\gamma_5\sigma_{\mu\nu}\psi F^{\mu\nu}$$

ψ = quark or lepton

- Axions are very light particles, but they can produced in great abundance cosmologically (as a BEC!) They make a **very** interesting dark matter candidate.

- Axions may be representative of a larger class of light “moduli” fields, which mediate feeble but long-range forces.

Cosmic Strings

- Cosmic strings could be fundamental, or associated with discrete gauge symmetries.
- They could be detected through their “crack of the whip” gravity waves, or through their effect on light (double images) or matter.

Neutron Star Interiors

- Neutron star interiors plausibly contain quark matter in very interesting phases, but they are hard to access.

- A promising way is to study gravity waves from their inspiral into BHs, or into one another.

- These opportunities in theory and experiment exemplify the importance of **calculation** as a frontier of physics (phase diagram, gravity wave templates).

Inflation

- Inflation is a wonderful scenario for early universe cosmology, but at present it is thinly tested and not firmly rooted.

- One way to explore further is to be more precise about primeval fluctuations: scale dependence? gravity waves? isocurvature?

Anthropic Reasonings

Good Design Ideas? \ Selected?	Yes	No
Yes	Enlightenment	Knowledge
No	Conspiracy	Ignorance

Good Design Ideas? \ Selected?	Yes	No
Yes	$m_p \ll M_{Pl}$	$\theta_{QCD} \ll 1$ unified couplings $\tau_p \gg H^{-1}$
No	$\rho_\lambda / (\xi^4 Q^3) \sim 10^2$ $m_e, m_u, m_d, \Lambda_{QCD} \rightarrow$ nuclear physics $m_e \ll m_W$	most M, CKM parameters most BSM parameters

- Anthropic reasoning can be put to constructive use. For example, in the context of axion cosmology, it allows one to understand the dark matter density.

- The question of the relation of life's parameters to fundamental parameters is fascinating in itself.

- The discussion becomes predictive in the context of exobiology.

Quantum Reality

- The cold, empty environment of interplanetary (interstellar, intergalactic) space is friendly to quantum mechanics.
- Quantum devices, including quantum computers, could find a home there.
- Fermi asked: Where are They? Maybe they've moved to Hilbert space!