Theoretical Particle Physics

Michael Ratz

Lunch Seminar, 10/1/2021

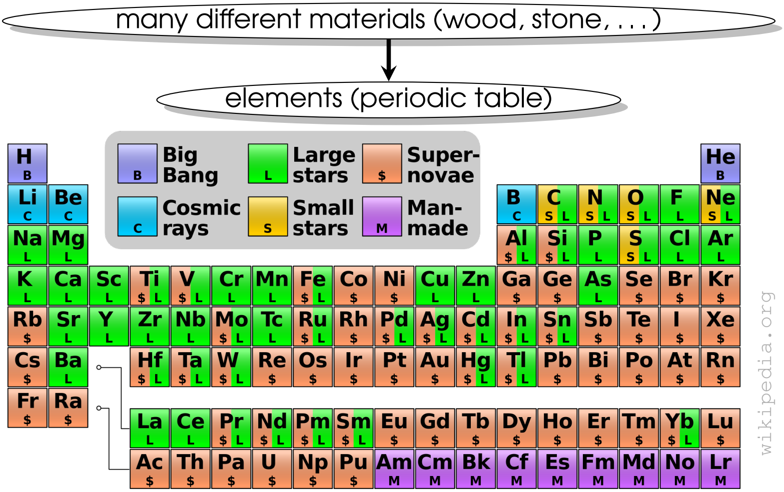
several pictures adapted from
http://www.particleadventure.org/

Building blocks of matter

many different materials (wood, stone, . . .)

http://www.particleadventure.org/

Building blocks of matter



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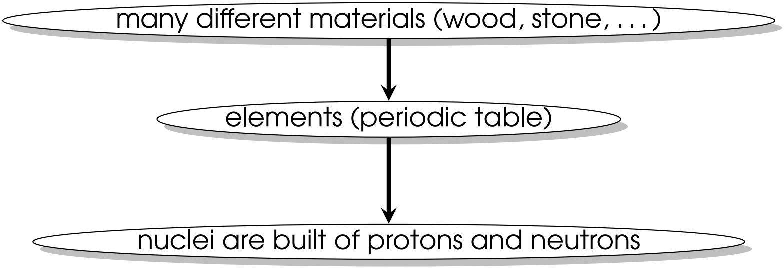

Building blocks of matter

many different materials (wood, stone, . . .)

↓

elements (periodic table)

↓

nuclei are built of protons and neutrons

↓

protons and neutrons are made of quarks

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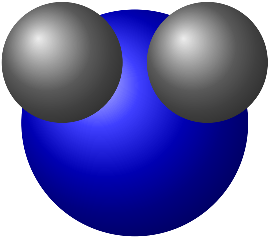
???

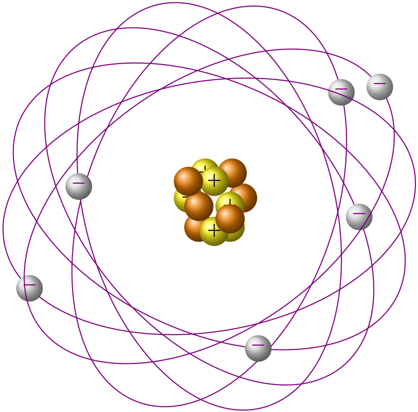
From large to small scales

- molecules are made of atoms



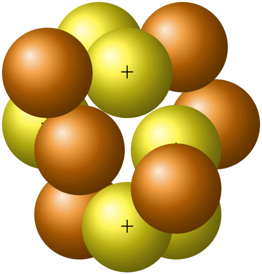
From large to small scales

- atoms are composed of electrons and nucleons



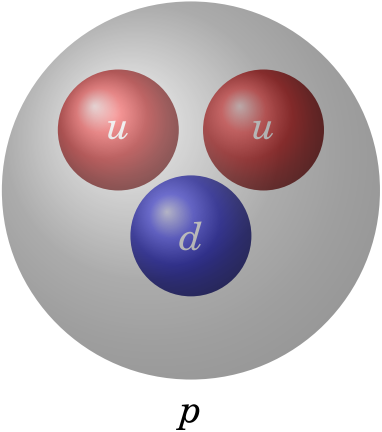
From large to small scales

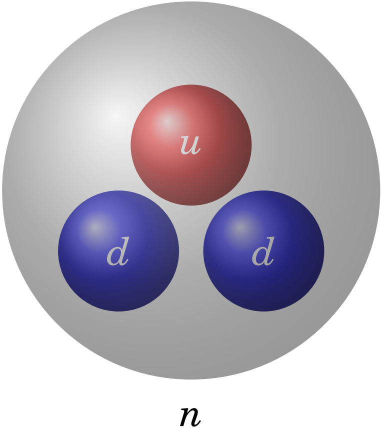
- nucleons are made of protons and neutrons



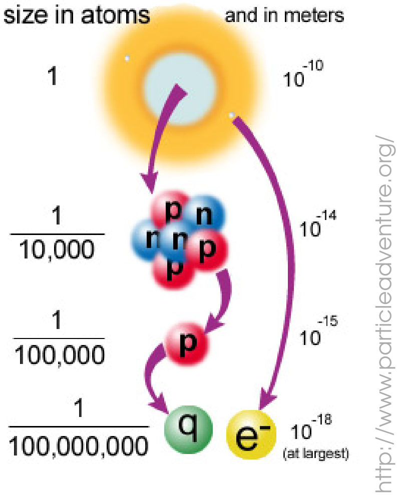
From large to small scales

☞ protons and neutrons are made of quarks





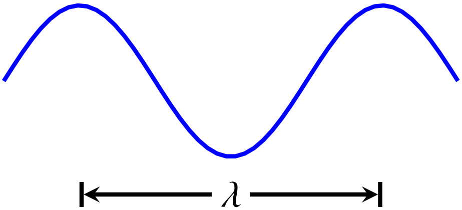
From large to small scales



From large to small scales

What comes next?

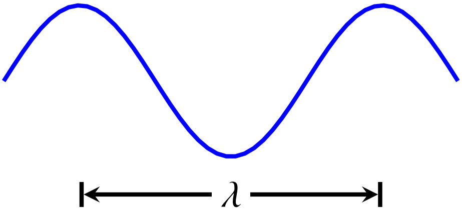
Exploring small structures



$$E = hc/\lambda$$

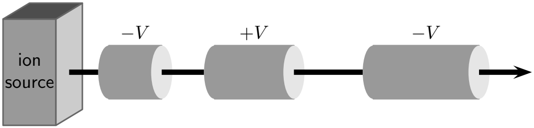
☞ resolving small scales requires high energies

Exploring small structures

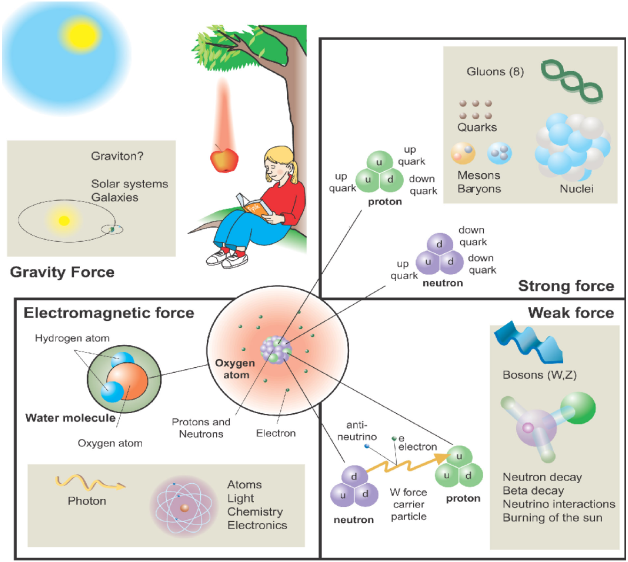


$$E = hc/\lambda$$

- ☞ resolving small scales requires high energies
- ➥ particle accelerators



Standard model



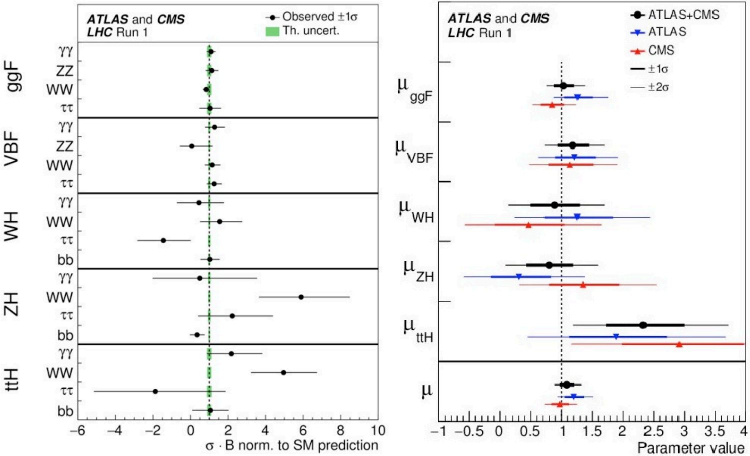
www.pinterest.com ???

Standard model

- physics at low energies only requires two sorts of quarks, the electron and the neutrino: u, d, e and ν
- proton: $u\,u\,d$
- neutron: $u\,d\,d$
- however, each of them has two heavier brothers

www.wikipedia.org

Standard model vs. experiments



☞ Standard model agrees very well with measurements at collider experiments!

Why physics beyond the standard model?

- UCI theorists working on particle physics beyond the standard model








- standard model alone cannot explain astrophysical data

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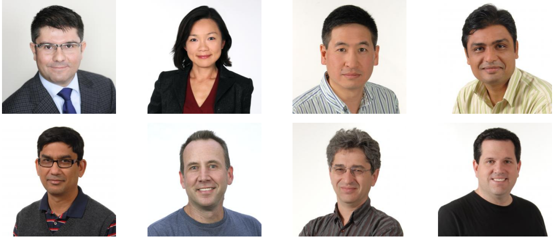


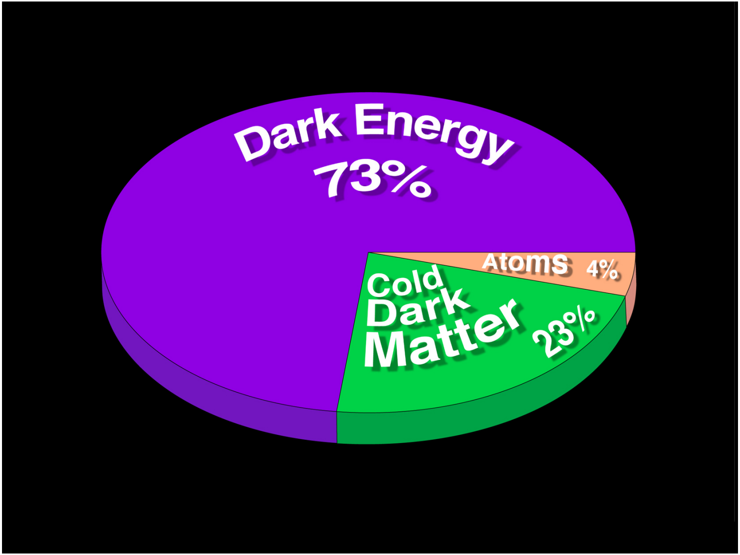
- standard model alone cannot explain astrophysical data
- structure of the standard model hints at unification
- gravitation cannot be described in the language of the standard model

Cosmology

and

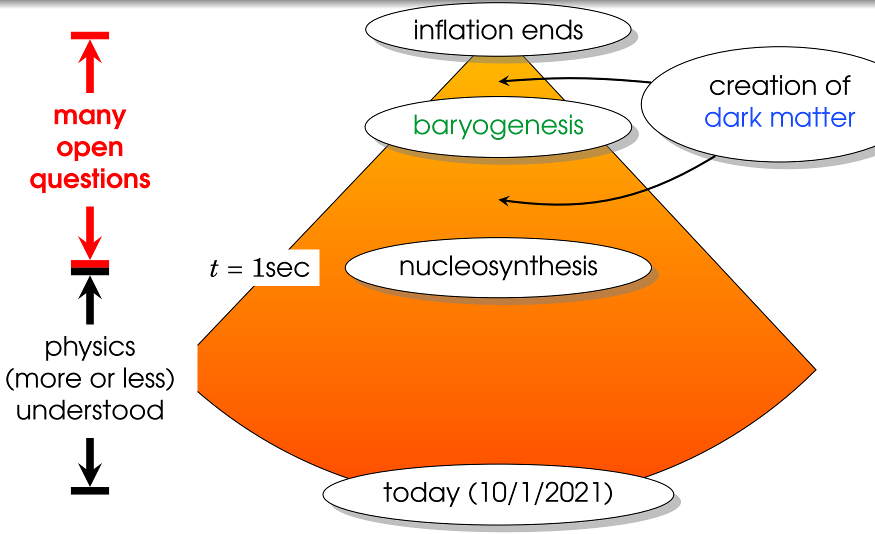
particle physics

Energy budget of our Universe



cosmology.berkeley.edu

Early history of the universe: outline



Questions

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Mr. Dark
Matter

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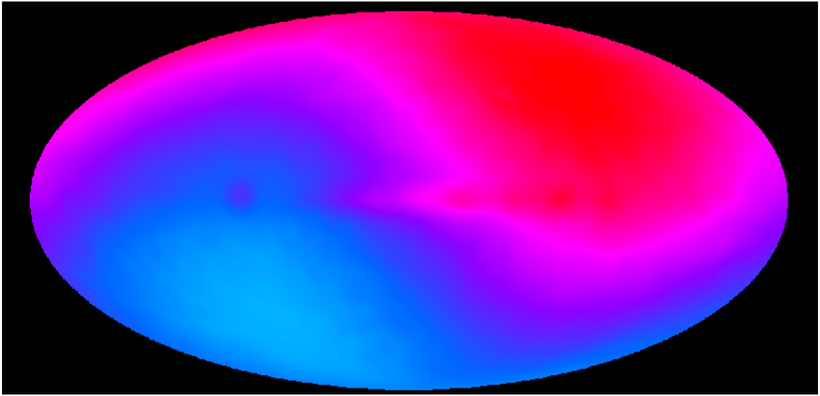
answering these questions requires

physics beyond

the standard model

Why inflation?

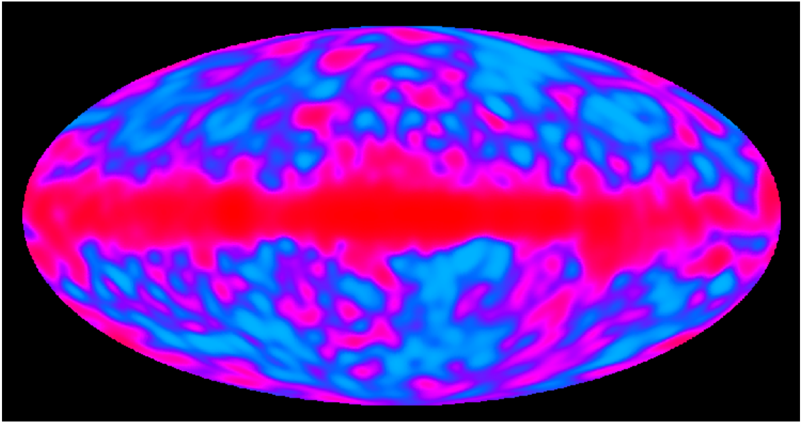
temperature of the CMB



. . . relative motion of Earth

Why inflation?

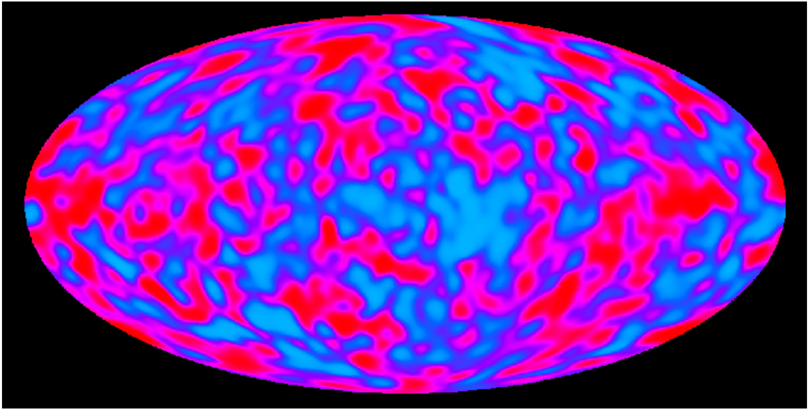
temperature after subtraction of dipol



. . . horizontal band caused by galaxy

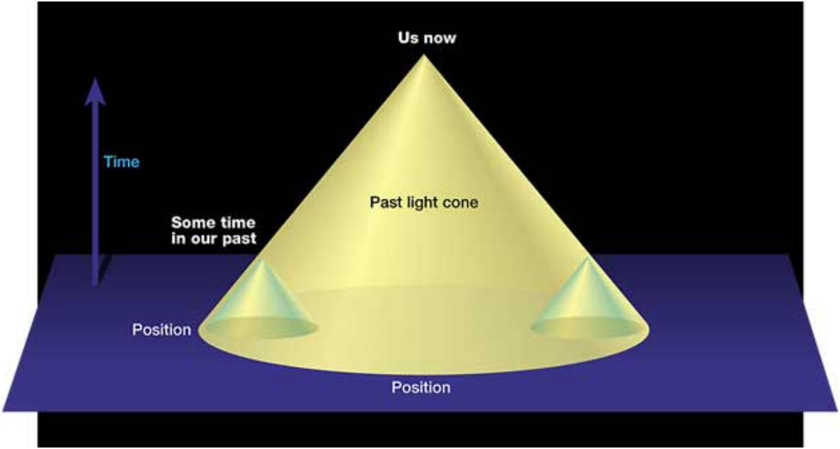
Why inflation?

temperature after subtraction of dipol and galaxy



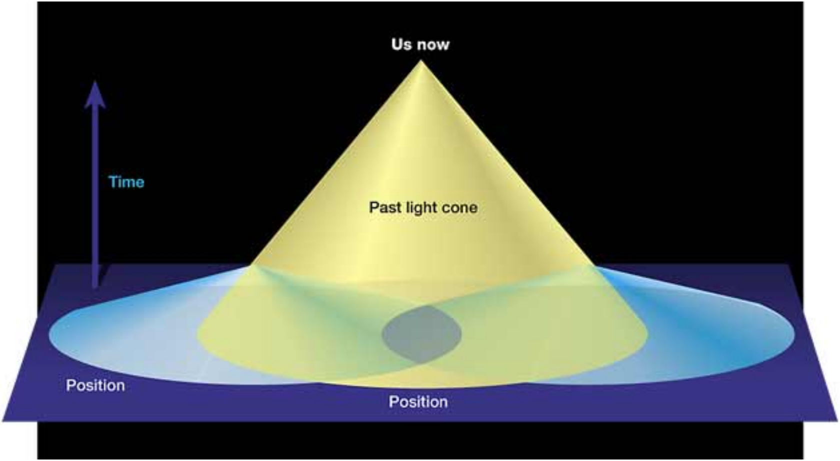
... temperature fluctuations $\sim 10^{-5}$ ... **why?**

How does inflation work?



regions causally **disconnected** $\curvearrowright$ why are they isotropic?

How does inflation work?



regions causally **connected** $\curvearrowright$ isotropy explained

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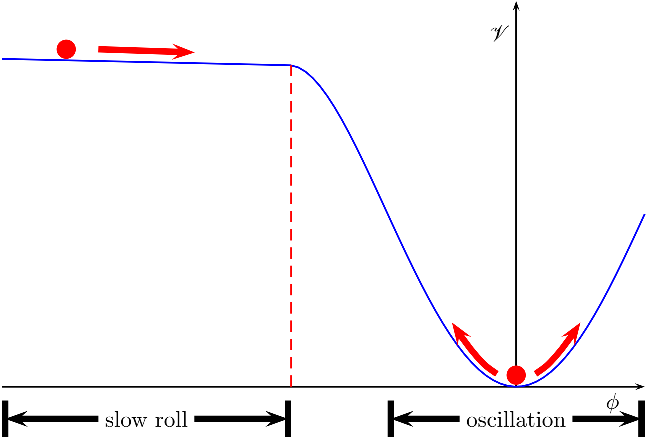
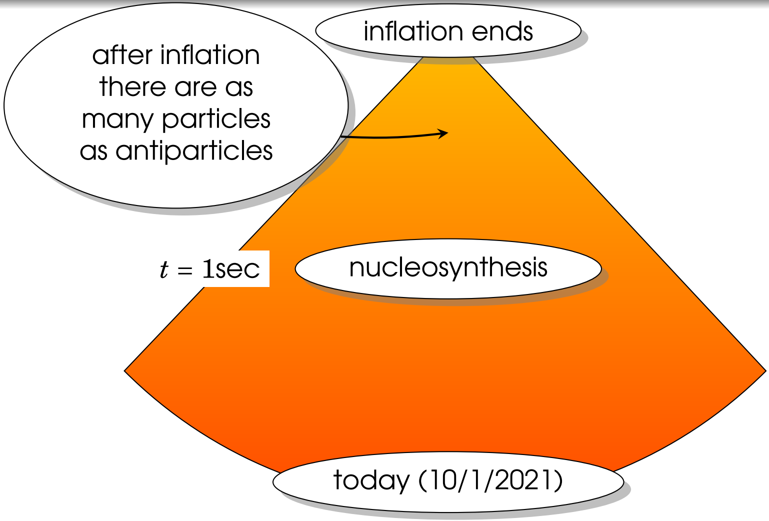


new particle required

the ‘inflaton’

Back to the early history of our universe



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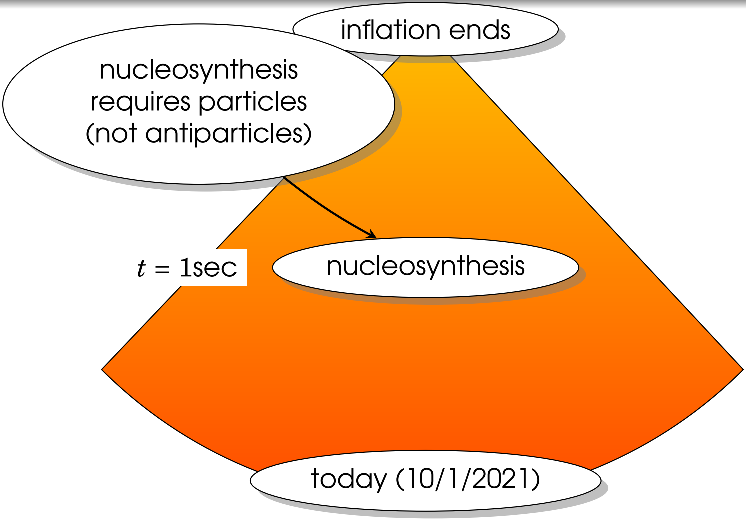

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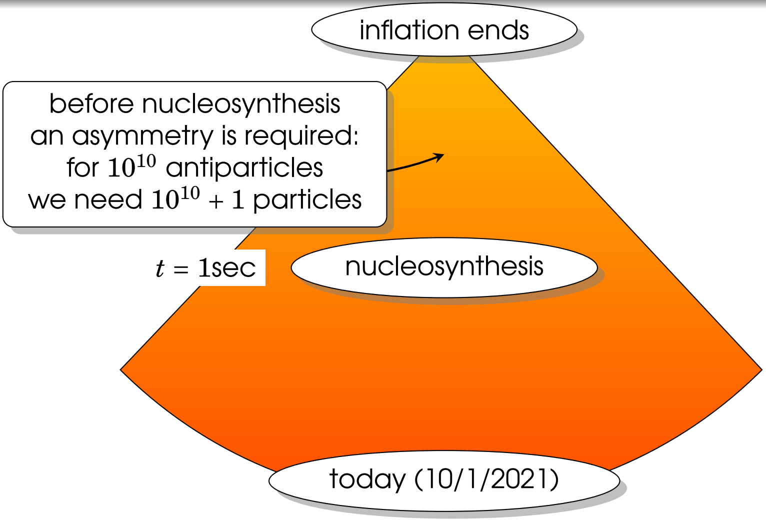

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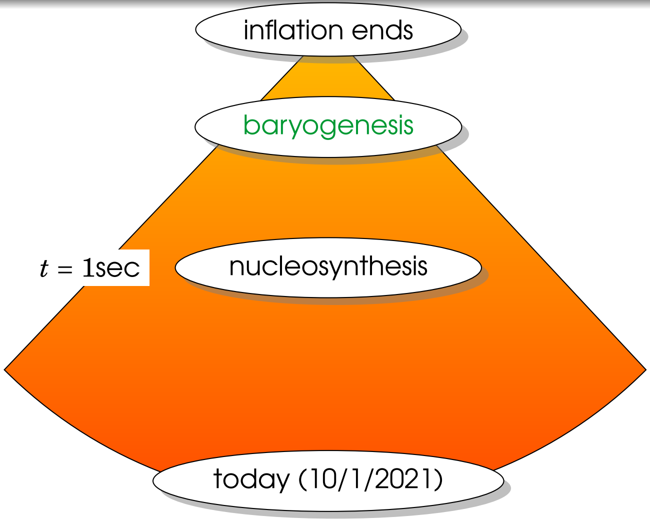

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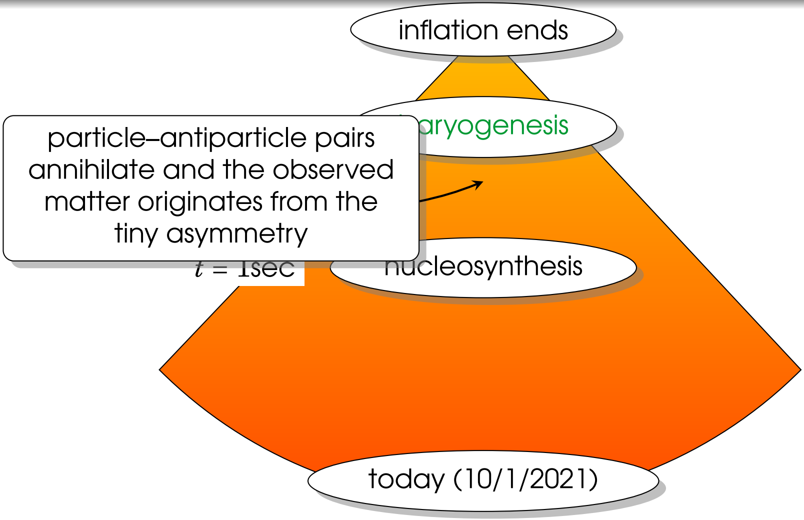

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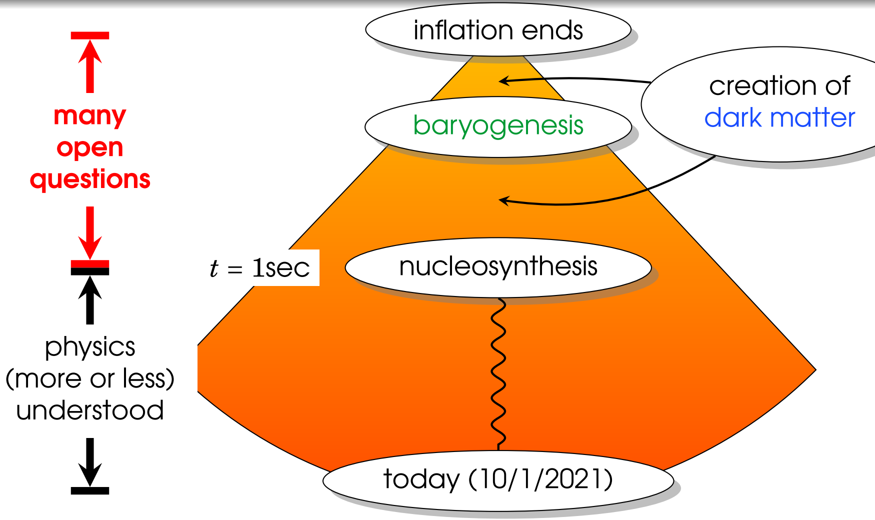

Dark matter

☞ 80% of the matter of our universe is dark, i.e.

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Mr. Dark Matter

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- ➥ physics beyond the standard model required

Pressing Questions

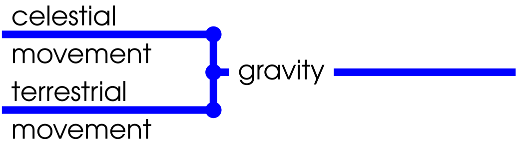
gravity

strong force

weak force

electromagnetism

Unification of all forces



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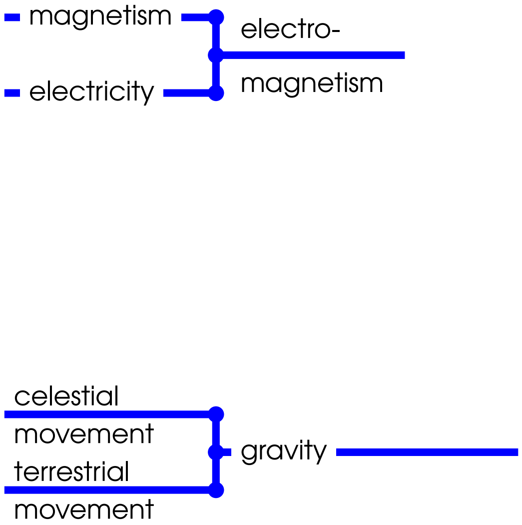

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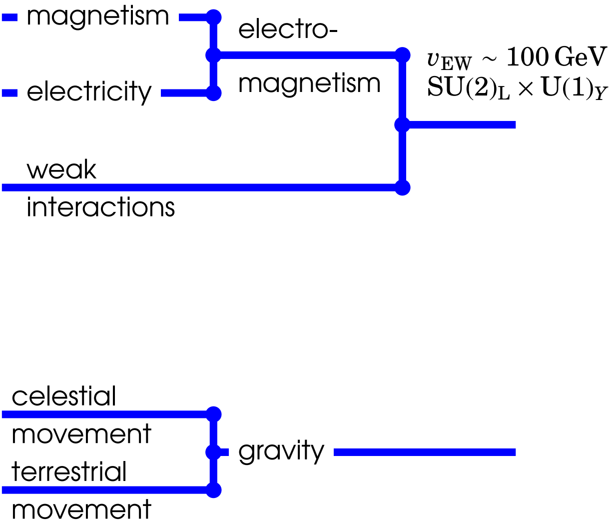

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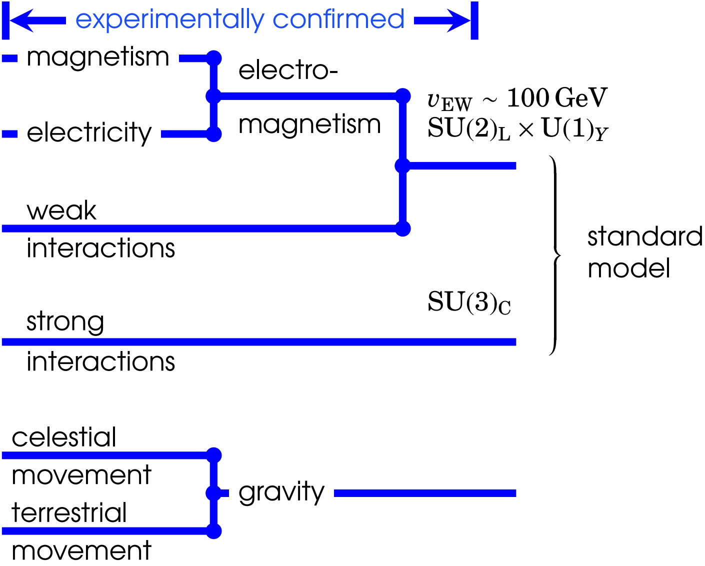

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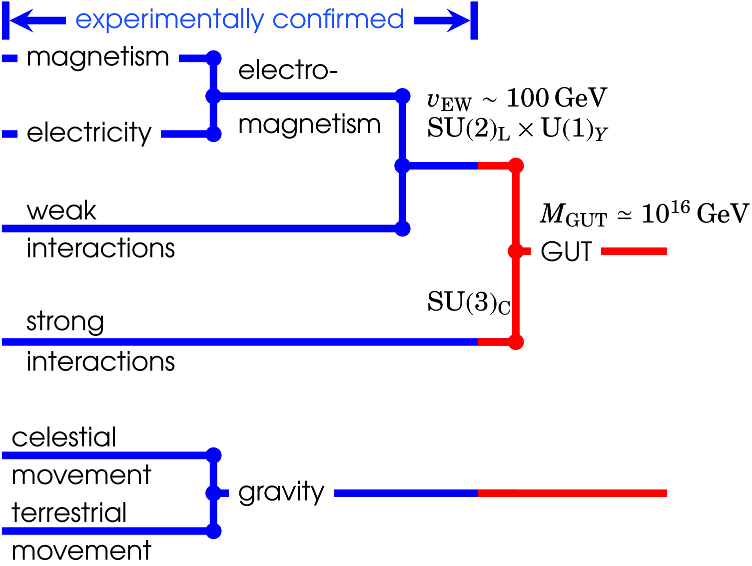

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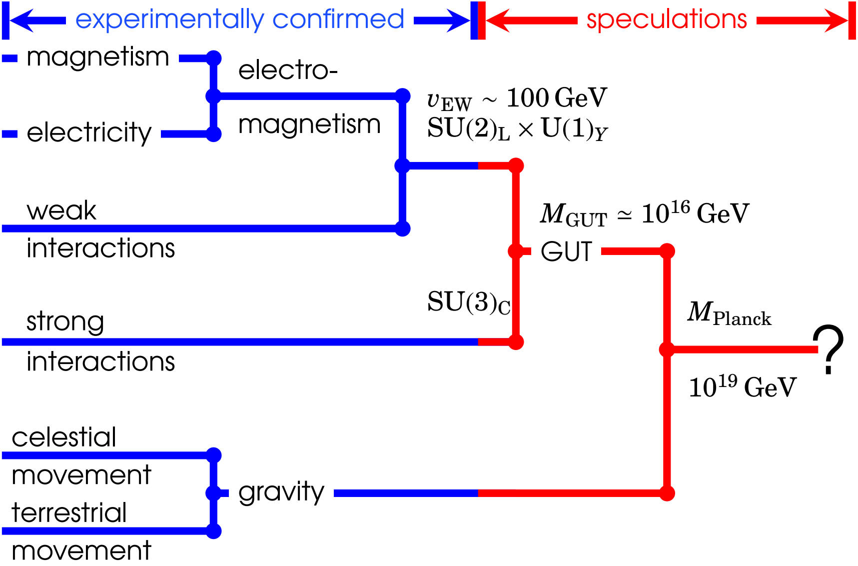
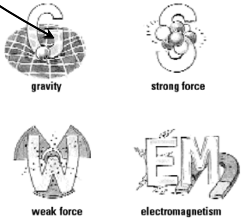


Forces in Nature

invariance under local coordinate transformations



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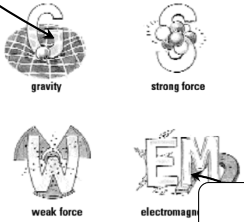
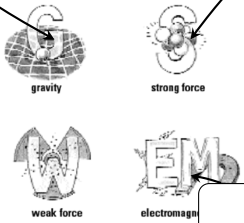


invariance under local U(1) rotation on an ‘internal circle’

Forces in Nature

invariance under local coordinate transformations

invariance under local SU(3) rotations



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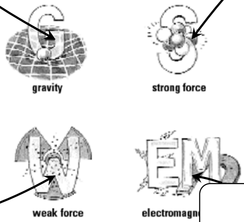


invariance under local SU(2) rotations

invariance under local U(1) rotation on an ‘internal circle’

Interactions

local U(1) rotation

$$\begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix} \rightarrow \begin{pmatrix} \cos[\theta(x)] & \sin[\theta(x)] \\ -\sin[\theta(x)] & \cos[\theta(x)] \end{pmatrix} \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix}$$

or

$$\Psi \rightarrow \exp[\mathrm{i}\theta(x)]\,\Psi$$

e.g. electron

$$\psi_e \rightarrow \exp[\mathrm{i}\theta(x)\,q_e]\,\psi_e$$

Interactions

local SU(3) rotation : e.g. quark

$$\begin{pmatrix} \psi_q \\ \psi_q \\ \psi_q \end{pmatrix} \rightarrow \begin{pmatrix} * & * & * \\ * & * & * \\ * & * & * \end{pmatrix} \qquad\qquad \begin{pmatrix} \psi_q \\ \psi_q \\ \psi_q \end{pmatrix}$$

Interactions

local SU(2) rotation : e.g. lepton

$$\begin{pmatrix} \psi_\nu \\ \psi_e \end{pmatrix} \quad \rightarrow \qquad\qquad\qquad \begin{pmatrix} * & * \\ * & * \end{pmatrix} \quad \begin{pmatrix} \psi_\nu \\ \psi_e \end{pmatrix}$$

Interactions

local SU(5) rotation

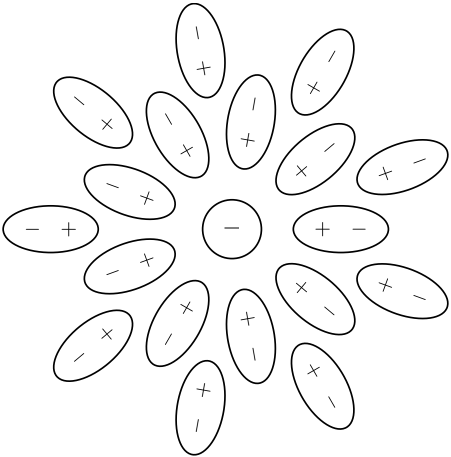
$$\begin{pmatrix} \psi_q \\ \psi_q \\ \psi_q \\ \psi_\nu \\ \psi_e \end{pmatrix} \to \begin{pmatrix} * & * & * & * & * \\ * & * & * & * & * \\ * & * & * & * & * \\ * & * & * & * & * \\ * & * & * & * & * \end{pmatrix} \begin{pmatrix} \psi_q \\ \psi_q \\ \psi_q \\ \psi_\nu \\ \psi_e \end{pmatrix}$$

☞ all known (gauge) interactions can be unified in SU(5)

??? possible concern: strength of interactions differs

Running couplings

- naïve picture: virtual particle–antiparticle–pairs screen charge



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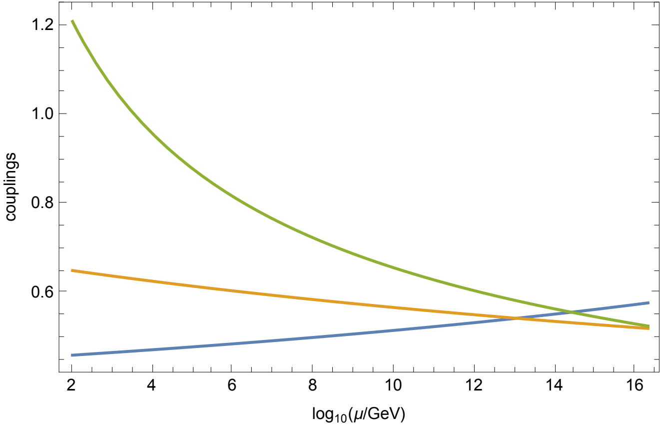
Running couplings

- ☞ naïve picture: virtual particle–antiparticle–pairs screen charge
- ☞ distance inversely proportional to energy
- ➥ couplings depend on energy/distance

Running couplings in the standard model



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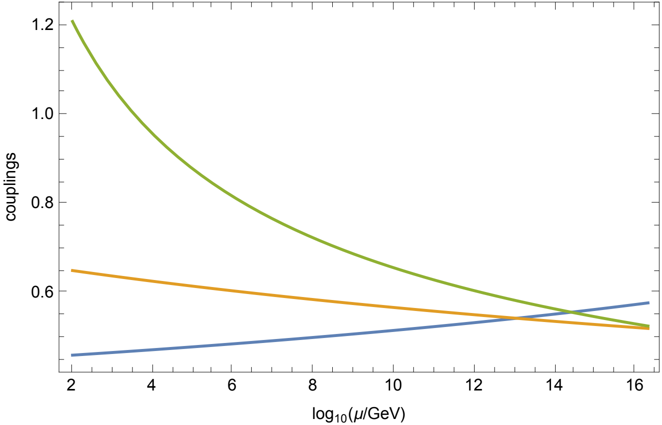

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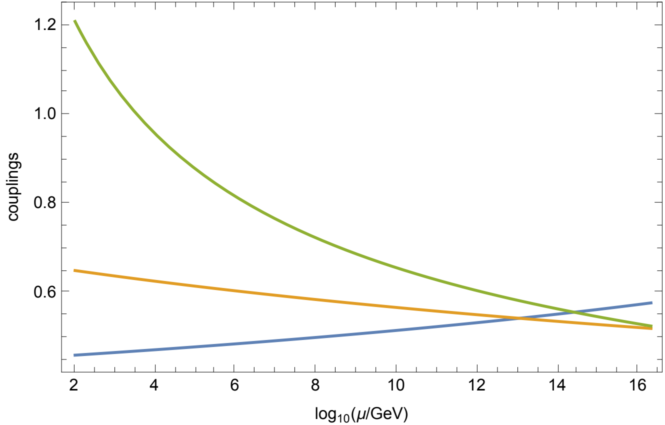
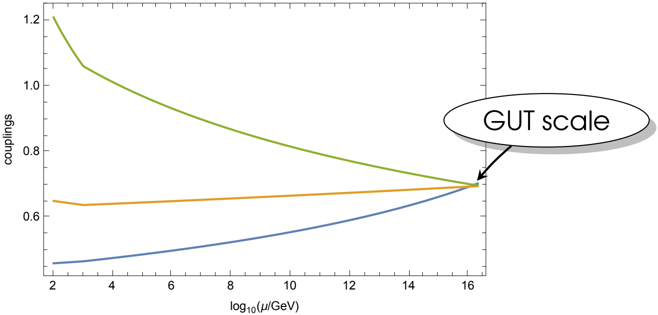


☞ qualitatively nice: couplings approach each other

☞ however: no (precision) unification

Running couplings in the MSSM

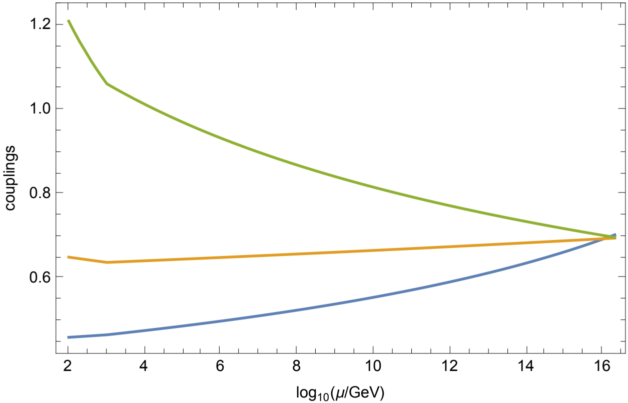
... gauge coupling unification in the (minimal) supersymmetric standard model



☞ **interpretation**: there is only one coupling at the fundamental level, the numerical difference between the couplings is due to quantum effects

Why supersymmetry?

- gauge coupling unification



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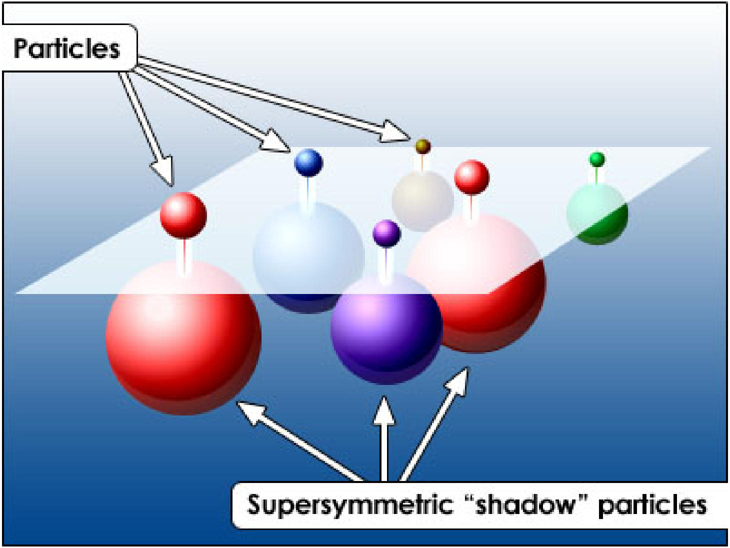
- gauge coupling unification
- supersymmetry stabilizes the electroweak scale against the GUT scale M_{GUT} $\curvearrowright$ solution of the hierarchy problem
- supersymmetry is the unique extension of the (Poincaré) symmetry of our space–time
- supersymmetry provides the so–called lightest superpartner (LSP), a plausible candidate for **cold dark matter**

What is supersymmetry?



Where is supersymmetry

Is supersymmetry for real?

. . . we may see . . .

Is supersymmetry for real?

. . . we may see . . .

. . . or maybe not ☺

Proton decay

- unification of quarks and leptons may give rise to new signals
- transitions between quarks and leptons possible

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- SuperKamiokaNDE: initially: Nucleon Decay Experiment

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- ☺ SuperKamiokaNDE: after 1998: Neutrino Detection Experiment

Matter in SO(10) theories

- ☞ group theory: $\mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}(1) \subset \mathrm{SU}(5) \subset \mathrm{SO}(10)$

Matter in SO(10) theories

- group theory: $\mathrm{SU}(3)\times\mathrm{SU}(2)\times\mathrm{U}(1)\subset\mathrm{SU}(5)\subset\mathrm{SO}(10)$
- one generation of standard model matter corresponds to a SO(10) **16**–plet

$$\begin{aligned}\mathrm{SO}(10) &\to \mathrm{SU}(3)\times\mathrm{SU}(2)\times\mathrm{U}(1)_\mathrm{Y} = G_\mathrm{SM}\\ \mathbf{16} &\to (\mathbf{3},\mathbf{2})_{1/6}\oplus(\overline{\mathbf{3}},\mathbf{1})_{-2/3}\oplus(\overline{\mathbf{3}},\mathbf{1})_{1/3}\\ &\quad\oplus(\mathbf{1},\mathbf{1})_{1}\oplus(\mathbf{1},\mathbf{2})_{-1/2}\oplus(\mathbf{1},\mathbf{1})_{0}\end{aligned}$$

Matter in SO(10) theories

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- one generation of standard model matter corresponds to a SO(10) $\mathbf{16}$–plet

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. . . seems to be too good to be true

Going beyond the standard model

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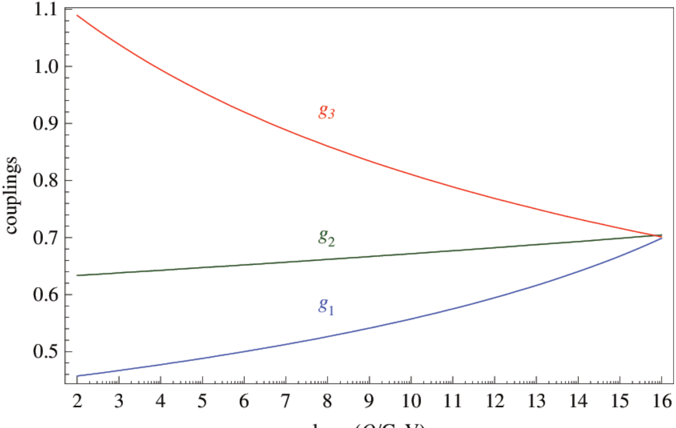

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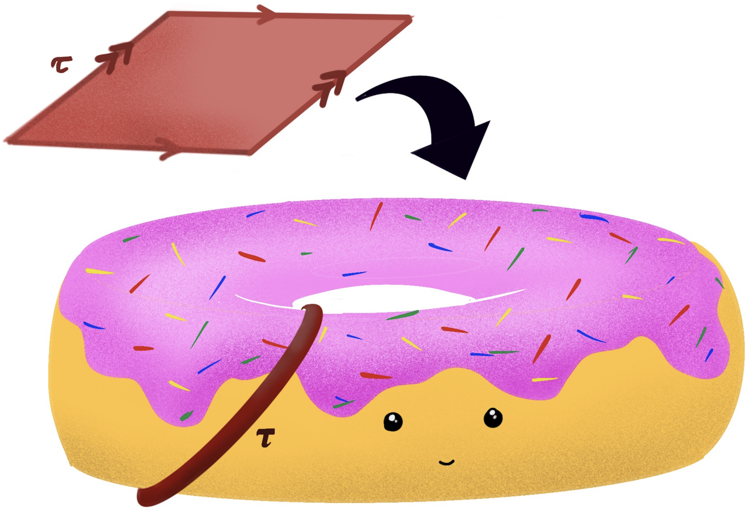
- new game in town: modular flavor symmetries

Modular flavor symmetries



picture credits: Shreya Shukla

Modular flavor symmetries

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Modular flavor symmetries

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Y. Almumin, M.–C. Chen, V. Knapp–Pérez, S. Ramos–Sánchez, M.R., S. Shukla

$$\lambda = \mathrm{lcm}(|\mathcal{I}_{ab}|, |\mathcal{I}_{ca}|, |\mathcal{I}_{bc}|)$$

$$\mathcal{Y}_{ijk}(\tau) = \vartheta \begin{bmatrix} \widehat{\alpha}_{ijk}/\lambda \\ 0 \end{bmatrix} (0, \lambda\,\tau)$$

Euler–ϕ

$$\widehat{\alpha}_{ijk} = \mathcal{I}'_{ca}\, i - \mathcal{I}'_{ab}\, j + \mathcal{I}'_{ca} \left(\mathcal{I}'_{ab}\right)^{\phi(|\mathcal{I}'_{bc}|)} (k - i - j) \mod \lambda$$

flux parameters

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  Y. Almumin, M.–C. Chen, V. Knapp–Pérez, S. Ramos–Sánchez, M.R., S. Shukla
- ...utilize so–called modular forms, which appear in mathematics (e.g. number theory), condensed matter physics and string theory

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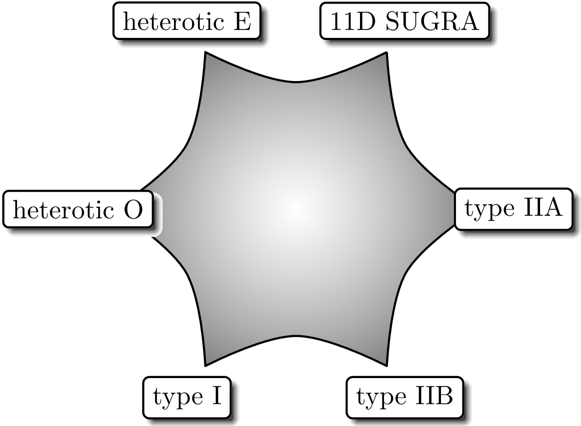

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- ☞ superstring theory requires 10 space–time dimensions
- ➥ 6 dimensions need to be compact
- ➥ there are string models which come reasonably close to the standard model

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- many more questions

Outlook

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