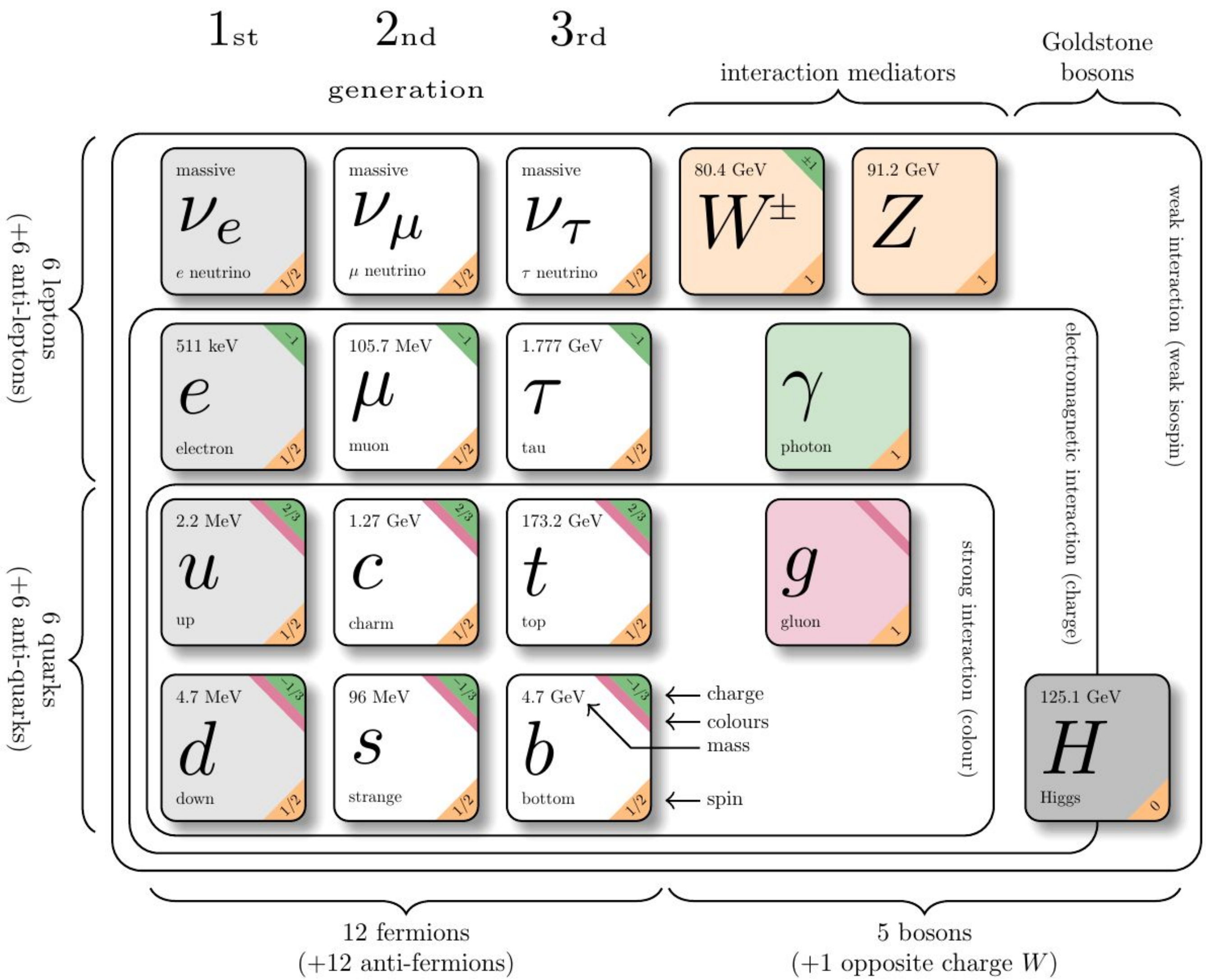
Physics beyond the standard model

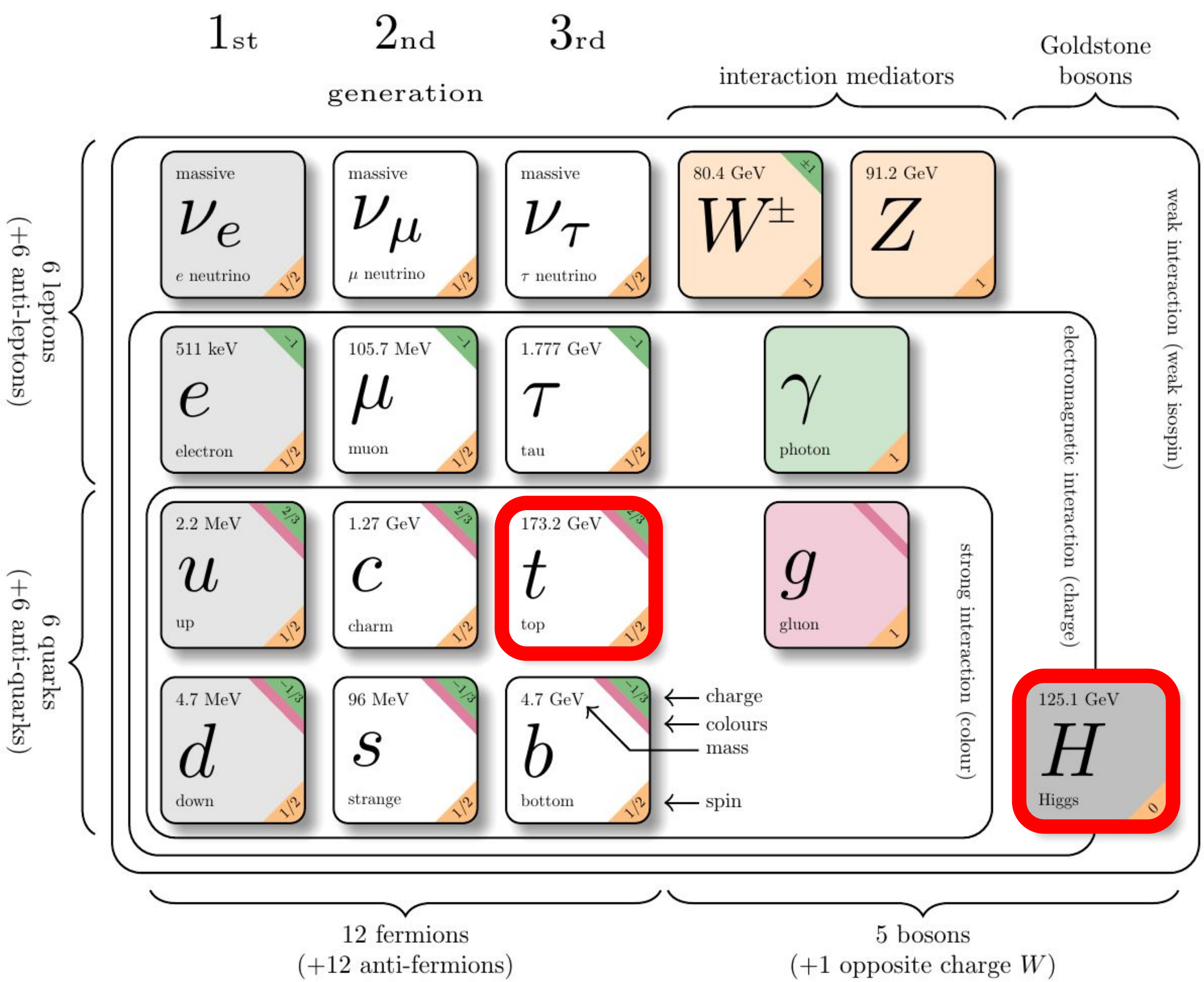
Ben Brüers
DESY Zeuthen, 14.08.2023

The Standard Model…

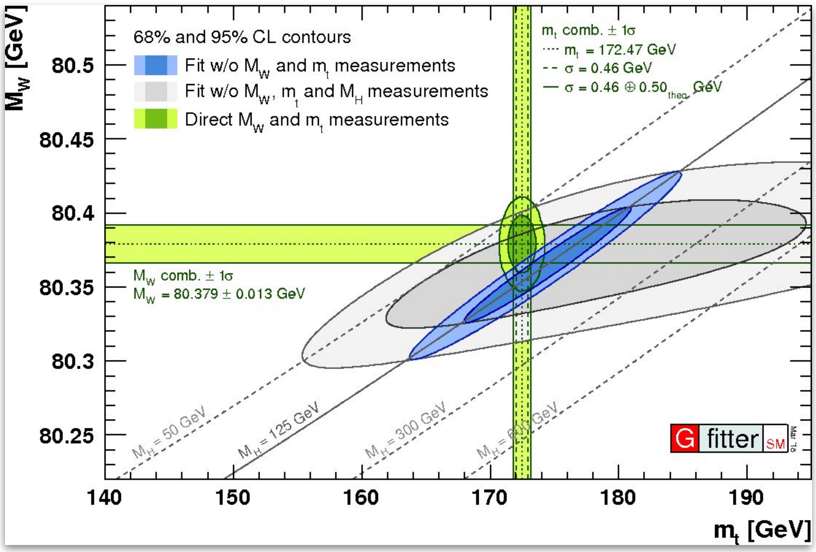


The Standard Model…

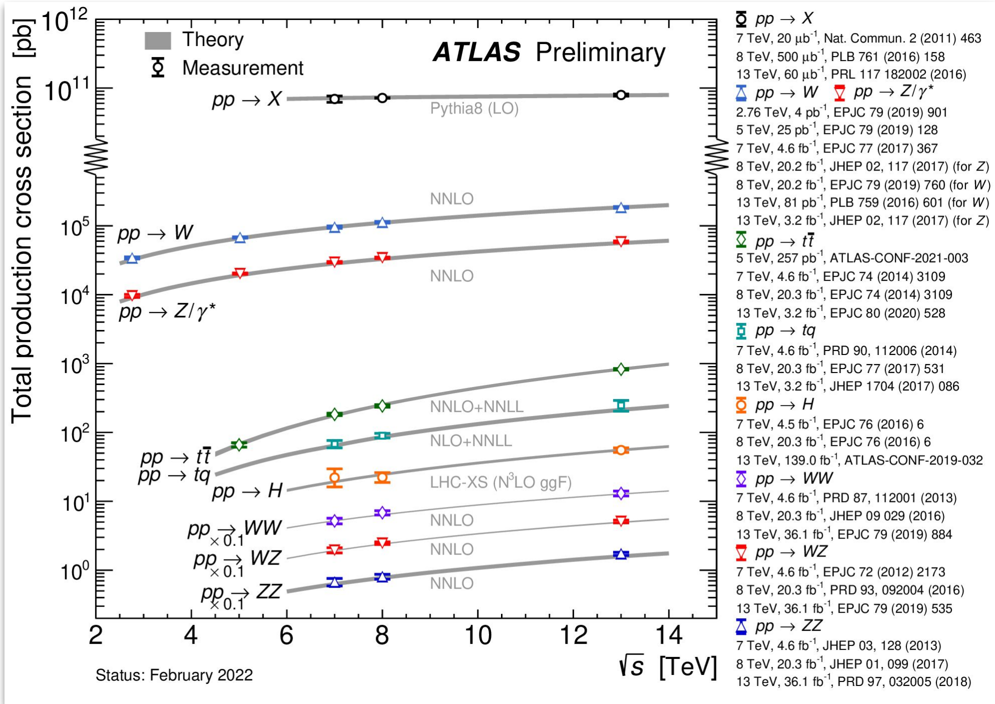
- Last particles discovered in 1995 (top) & 2012 (Higgs)



The Standard Model…



https://arxiv.org/pdf/1803.01853.pdf
https://arxiv.org/pdf/0811.0009.pdf

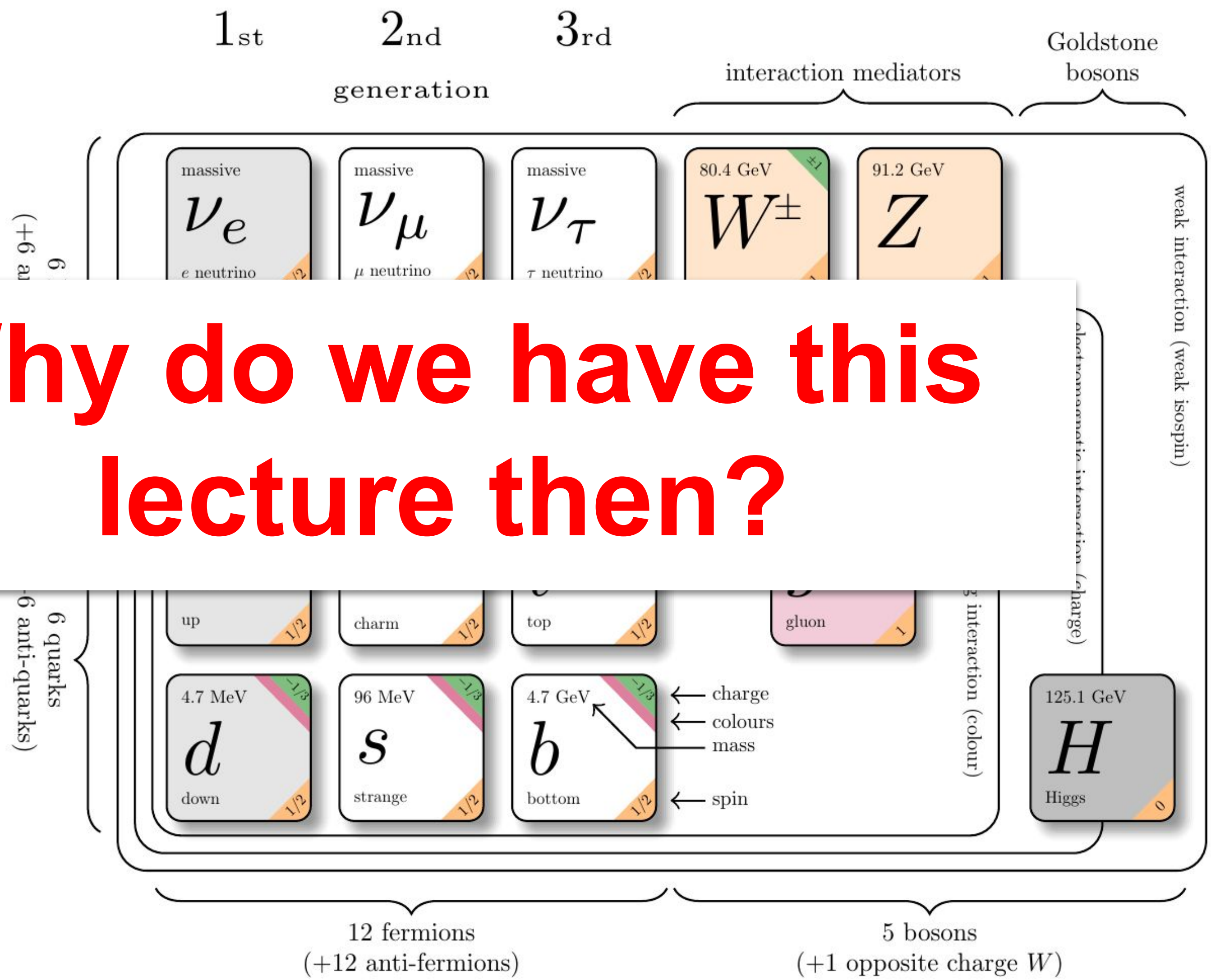


http://cds.cern.ch/record/2804061

- Standard model very precise over multiple orders of magnitude!

The Standard Model…

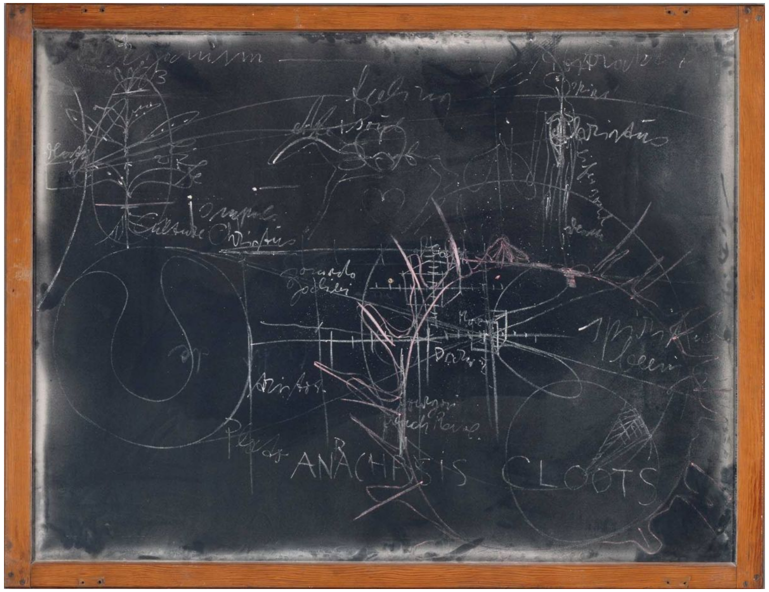
- Last particles discovered in 1995 (t
  2012 (H
- Is very
  succes
- Describ
  many experiments over multiple orders of magnitude



Why do we have this lecture then?

What are the free parameters of the SM?

It’s blackboard time!



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(summary on the next slide)

What are the free parameters of the SM?

9 fermion masses (m_u, m_d, m_c, m_s, m_b, m_t; m_e, m_μ, m_τ)

\+ 2 Higgs boson parameters: the mass & VEV (m_H, v)

\+ 3 coupling parameters (g_W, g', g_s)

\+ 4 CKM parameters (3 mixing angles + 1 CP violating phase)

\+ 1 CP violating phase in QCD (see later)

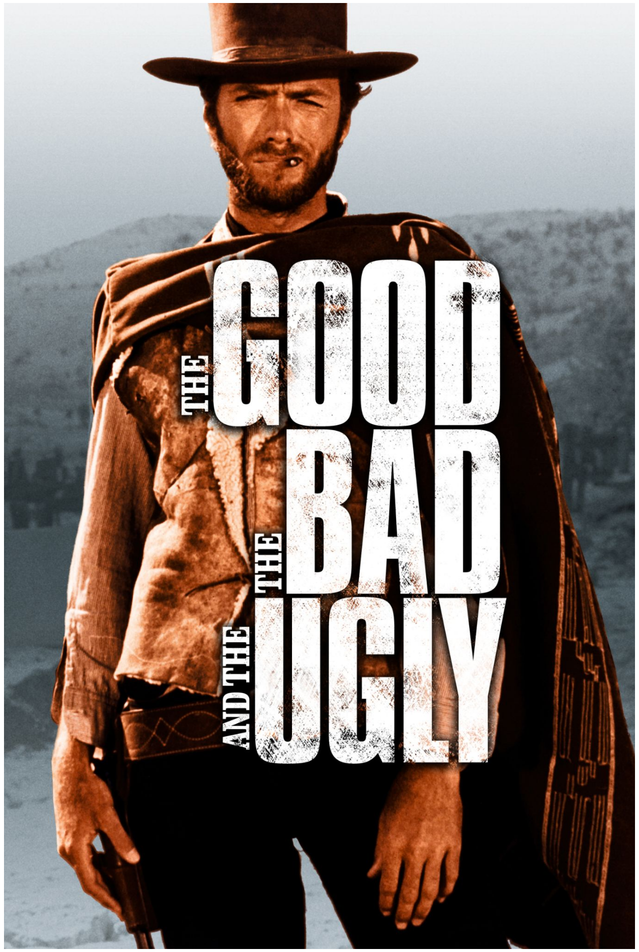
———

19 free parameters

Is the SM really so fundamental if there are 19 free parameters?

The Standard Model appears incomplete!

- It doesn't yet explain ("that will come"):
  - Neutrino masses
- It cannot explain ("erh"):
  - Why there is no CP-violation in QCD
  - Why the "bare" Higgs boson mass is fine-tuned at sub-permille level
  - Why there are 19 free parameters in the SM
- It will not explain ("Oh no!"):
  - Gravity
  - Dark Matter
  - The matter-antimatter asymmetry
  - (g-2)



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The Standard Model appears incomplete!

- It doesn't yet explain ("that will come"):
    - Neutrino masses → *see neutrino lectures*
- It cannot explain ("erh"):
    - **Why there is no CP-violation in QCD**
    - **Why the "bare" Higgs boson mass is fine-tuned at sub-permille level**
    - **Why there are 19 free parameters in the SM**
- It will not explain ("Oh no!"):
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    - **Dark Matter**
    - The matter-antimatter asymmetry
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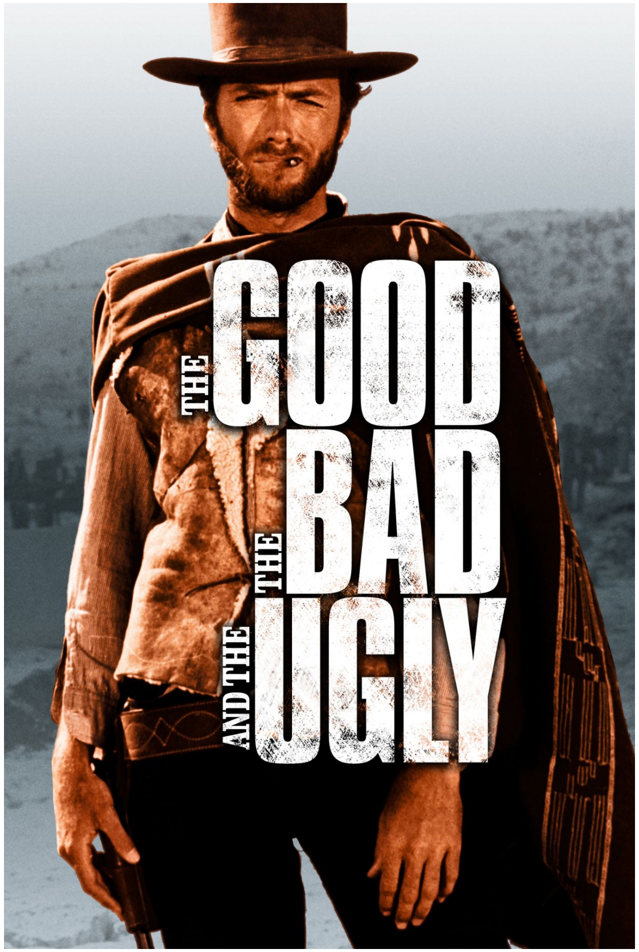

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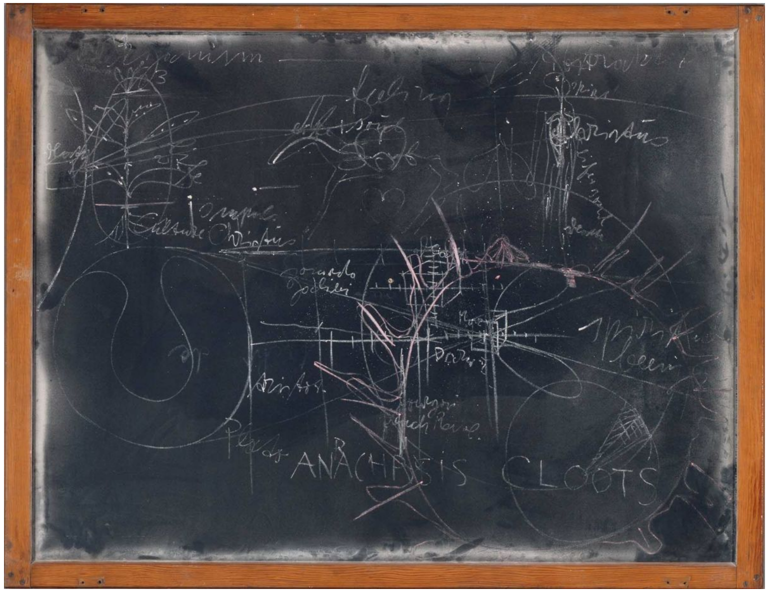
Naturalness arguments

It’s blackboard time!



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(summary on the next slide)

arxiv:0905.3187

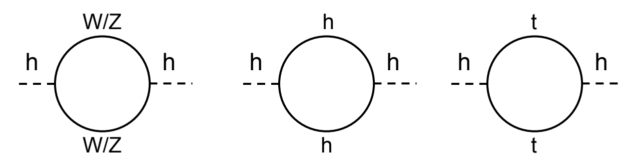
Fine-tuning the “bare” Higgs boson mass

- Higgs boson mass-term after symmetry-breaking in the SM:

$$V(\phi) = \underbrace{\lambda v^2 h(x)^2}_{\text{Higgs mass}} + \underbrace{\lambda v h(x)^3}_{\text{trinlinear}} + \underbrace{\frac{\lambda}{4} h(x)^4}_{\text{quartic}} \qquad m_h = \sqrt{2\lambda} v$$

- We call m_h the “bare” Higgs boson mass
- Don’t measure m_h, due to loop corrections! Measure: $(m_h^{meas})^2 = m_h^2 + \delta m_h^2$

$$\delta M_H^2 = \frac{G_F \Lambda^2}{4\pi^2\sqrt{2}}(6M_W^2 + 3M_Z^2 + M_H^2 - 12m_t^2)$$



- Largest correction from top-quark:

$$\delta M_H^2\big|_{t-\text{loop}} \approx -\frac{3G_F}{\pi^2\sqrt{2}} m_t^2 \Lambda^2 \approx -0.075\,\Lambda^2$$

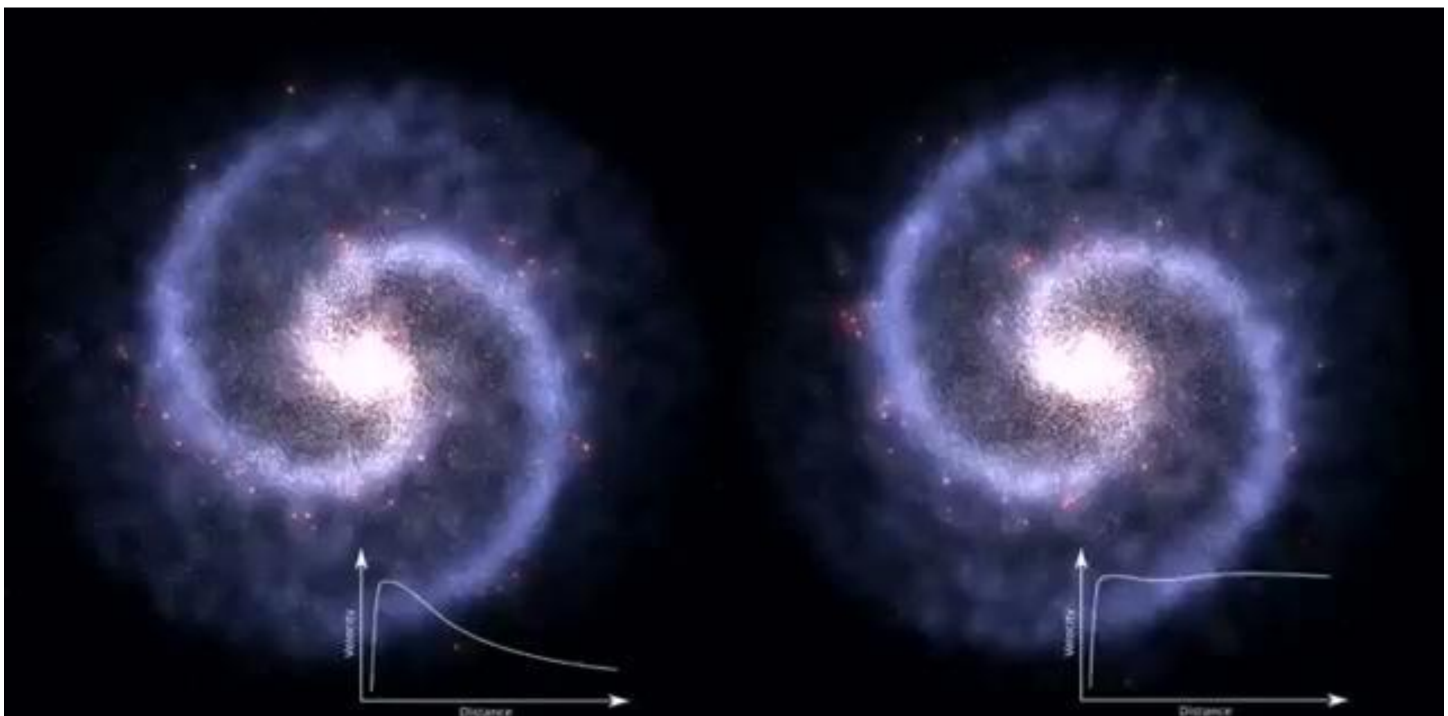
- ATLAS & CMS measured m_h^{meas} = 125 GeV, so if
  $\Lambda = 10^{19}$ GeV (Planck scale) $\rightarrow m_h^2 = (7.5\ 10^{-2} + 1.6\ 10^{-34}) \times (10^{19}\ \text{GeV})^2$
  $\Lambda = 5$ TeV (~tested scale) $\rightarrow m_h^2 = (7.5\ 10^{-2} + 6.3\ 10^{-4}) \times (5 \times 10^3\ \text{GeV})^2$
  loop correction **bare mass term**
- In any case: “bare mass” as to be tuned very finely, ≥ O(10^{-4}) GeV!
- This appears arbitrary and gives rise to questioning the SM
- How could this be fixed? Particles with countering loops!

The Dark Matter issue – What is Dark Matter?

- It all started off with Orth, Zwicky (1933), Vera Rubin (1970) *et al.*
- In a gravitational system, an object of mass m bound to an object of mass M rotates at the radius r and velocity v given by:

$$F_{grav} = mMGr^{-2} = F_{centri} = mv^2r^{-1} - v(r) = \sqrt{\frac{GM(r)}{r}}$$

→ **But this is not the case in galaxy clusters and even galaxies!**



Expected **Observed**

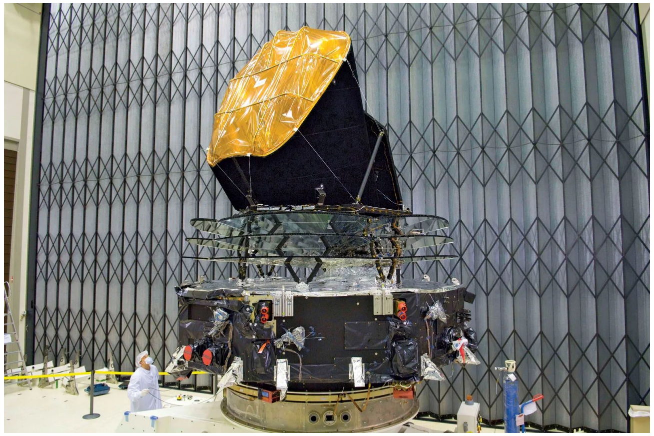
doi:10.1086/381970

More hints for Dark Matter – The bullet cluster

- Largest part of electromagn. visible matter / mass made of gas (red; by x-rays)
- If no DM: mass visible by gravitation (blue; by grav. lensing) = EM matter
- **Observe: red ≠ blue → there must be additional, grav. interacting matter!**

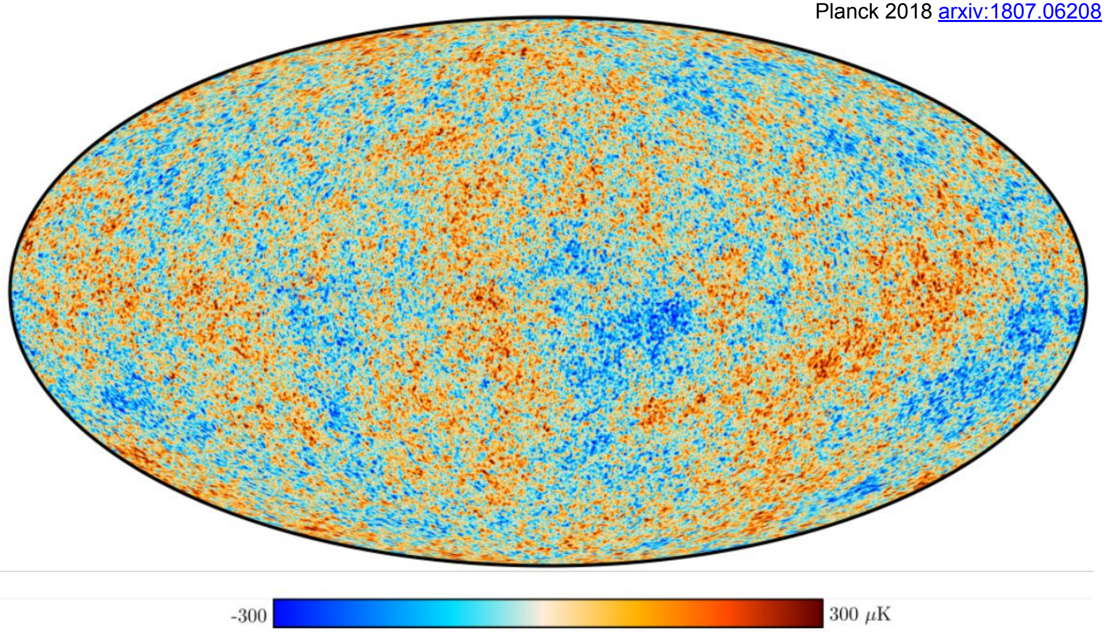
Evidence for Dark Matter – The CMB

- The very early universe was a plasma
  → photons were "stuck" in interactions of charged particles
- The universe expanded, cooled and charge neutral atoms formed
  → photons were released and could traverse the universe
- This **cosmic microwave background** was redshifted & is visible as constant, low temperature (T = 2.7 K) photon radiation nowadays
- Temperature is not constant, anisotropies at 10^{-5} scale



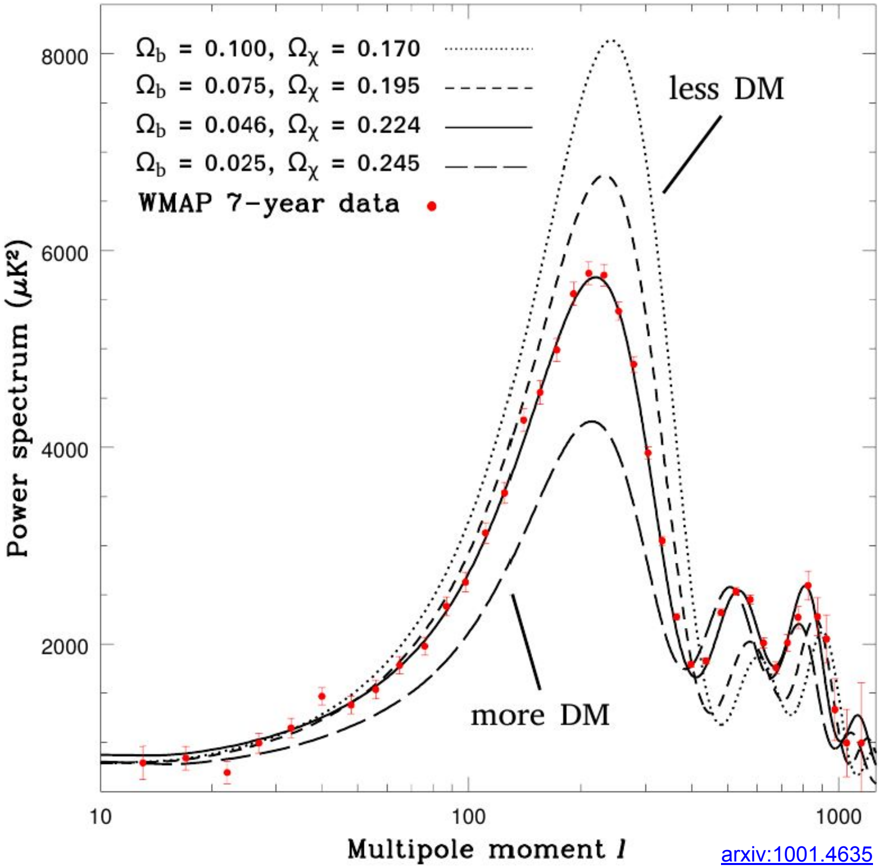
https://www.britannica.com/topic/Planck

Planck 2018 arxiv:1807.06208



From the CMB to Dark Matter

- Power spectrum of CMB anisotropies is related to the composition of the universe (ΛCDM model aka the Standard Model of cosmology)!
- Can determine fraction of baryonic matter, Dark Matter, Dark Energy
- The result:
  - Baryonic matter: 4.9 %
  - **Dark Matter: 26.5 %**
  - **Dark Energy: 68.6 %**

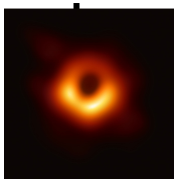


arxiv:1001.4635
arxiv:1006.2483

- More backup / evidence for Dark Matter:
  - Big bang nucleosynthesis
  - Gravitational lensing
  - Structure simulations of the universe

What is Dark Matter?

Faint stars, black holes, planets & all that ("MACHOs")?
- Can search for MACHOs with gravitational lensing
- *Number of MACHOs in universe too small to explain Dark Matter*



https://upload.wikimedia.org/wikipedia/commons/4/4f/Black_hole_-_Messier_87_crop_max_res.jpg

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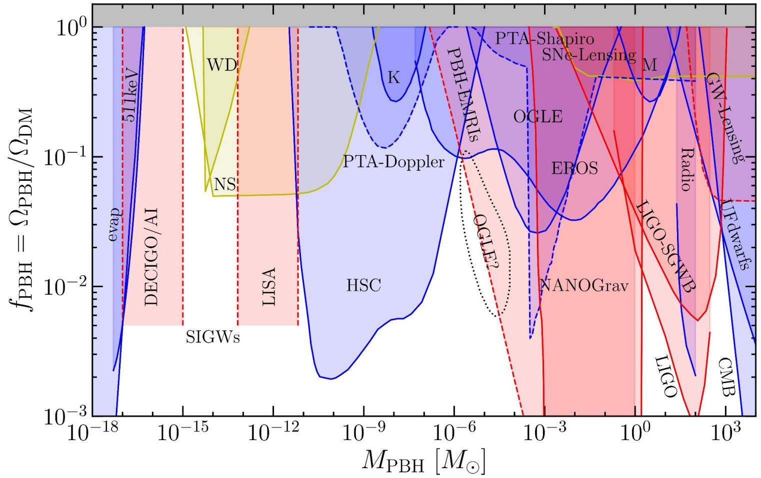
→ PBHs are ≲ 10 % of the DM



https://github.com/bradkav/PBHbounds/blob/master/plots/PBH_bounds.png
https://doi.org/10.5281/zenodo.3538999

Tell me!

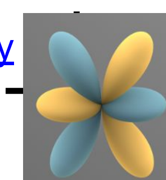
The classic: Is gravity (GR) just wrong at large scales?
- Several alternative theories around, e.g. Modified Newtonian Dynamics (MOND), TeVeS (=relativistic MOND)
- MOND Modifies low-acceleration behaviour of gravity
- MOND/TeVeS have several issues, e.g. to describe galaxy cluster dynamics (but ΛCDM, too)

$$F_{\mathrm{N}} = m\,\mu\left(\frac{a}{a_0}\right)a$$

$$\mu\left(\frac{a}{a_0}\right) = \sqrt{\frac{1}{1+\left(\frac{a_0}{a}\right)^2}}$$

https://en.wikipedia.org/wiki/Modified_Newtonian_dynamics

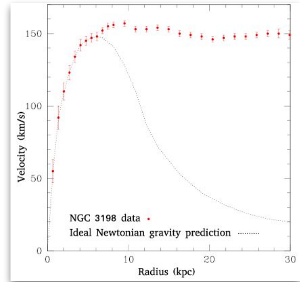
SM particles?
- Charged leptons interact EM **X**
- Mesons are not stable **X**
- Neutrinos are viable, but only make up ≲ 2 % of DM
- Exotic quark combinations? E.g. hexaquarks? → unlikely



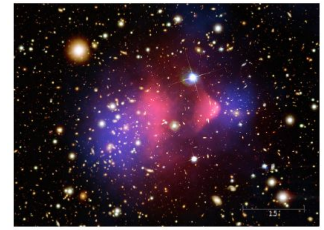
By Inigo.quilez - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=32782753

So what's it all about with Dark Matter?

- Evidence from multiple sources
  - Rotation curves
  - Colliding galaxy cluster
  - CMB



K. Begeman. Astron. Astrophys. 223 (1989), pp. 47–60



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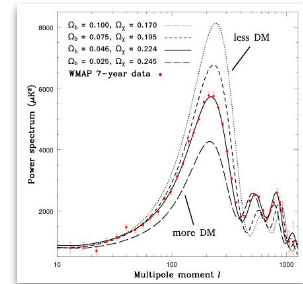
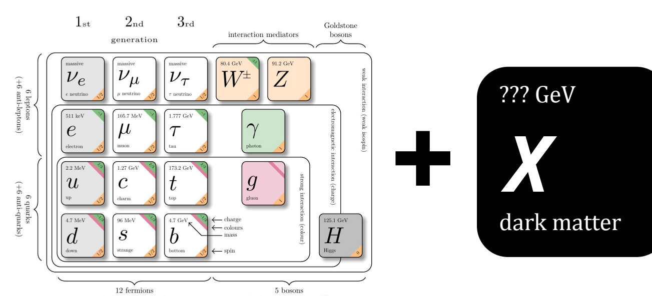


arxiv:1001.4635 arxiv:1006.2483

- So far not explained by astro-physical objects nor Standard Model particles
  - The laws of gravity could be incorrect
    →present approaches not convincing

- It seems most logical to conclude that **Dark Matter is made of so-far undiscovered particles!**
  - Many convincing candidates are around
  - Fix many other SM problems, too
    → see later

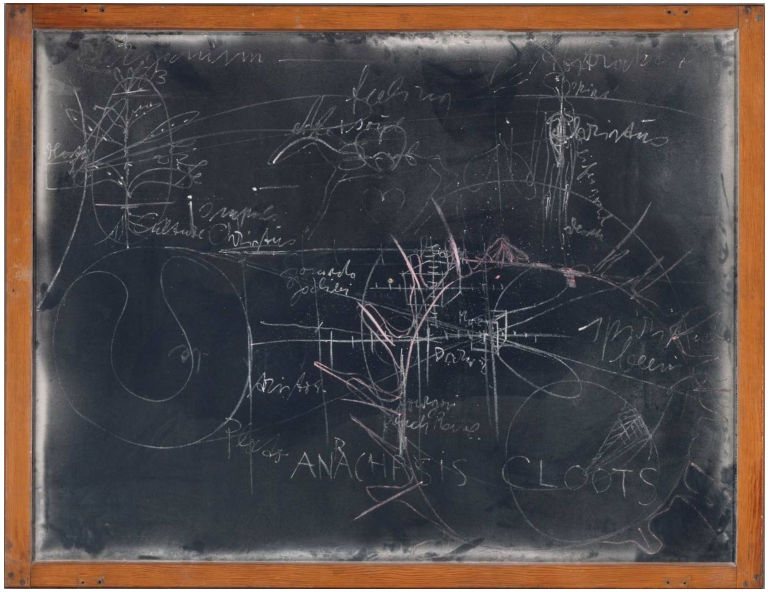


BREAK

(5-10 mins)

CP-violation in QCD

It’s blackboard time!



https://cameo.mfa.org/images/b/ba/2000.979-CR9834-d1.jpg

(summary on the next slide)

Why is there no CP-violating phase in QCD?

- QCD Lagrangian in its “vanilla” form

$$\mathcal{L}_{\mathrm{QCD}} = \bar{\psi}_i(\underbrace{i\gamma^\mu(D_\mu)_{ij}}_{\text{quark dynamics}} - \underbrace{m\delta_{ij}}_{\text{quark mass}})\psi_j - \underbrace{\frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a}_{\text{gluon dynamics}} - \underbrace{\bar{\Theta}\frac{\alpha_s}{8\pi}G^{\mu\nu a}\tilde{G}^a_{\mu\nu}}_{\text{CP-violating term}}$$

- CP-violating term gives rise to neutron electric dipole moment

$$d_n = (2.4 \times 10^{-16}\ \mathrm{e\ cm})\ \bar{\Theta}$$

- Can measure neutron electric dipole moment (Larmor precession)!

$$|d_n^{\mathrm{meas}}| < 1.8\ 10^{-26}\ \mathrm{e\ cm} \rightarrow |\bar{\Theta}| \lesssim 10^{-10}$$

- **CP-violation is basically zero in QCD!**
- This is a considerable amount of fine-tuning! **“Strong CP problem”**
- How to solve this problem?
- If $\bar{\Theta} = 0$ → just add a term that counters the CP-violating term
→ this is done in the Peccei-Quinn theory→ leads to particles called “Axions”
- Adding terms to the Lagrangian is how you extend the SM
- Ideally, the extension: reproduces all SM results; solves all its problems; makes predictions

Peccei-Quinn theory full details

arxiv:1407.0546
arxiv:1712.03018
rpp2022-rev-axions
wikipedia:Peccei-Quinn_theory

- Still on blackboard
- Three ingredients:
  - New scalar field φ, coupling to down-type quarks, modify Higgs to couple to up-type quarks only
  - Introduce new U(1) symmetry → leads to a new charge ξ, φ carries this ξ charge (and hence some quarks, too)
  - φ has the potential $V(\varphi) = \lambda(|\varphi|^2 - f_a^2/2)^2 \Rightarrow \langle\varphi\rangle = (f_a/\sqrt{2})e^{i\phi/f_a}$

vacuum state

Non zero & complex phase! Infinitely many vacuum states! → spontaneous symmetry breaking → get new particle with field a, **the axion!**

- After spontaneous symmetry breaking, get new term

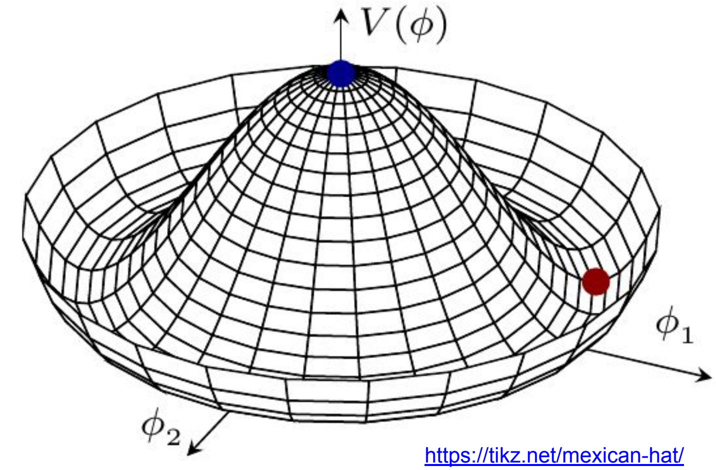
$$\mathcal{L}_{\text{tot}} = \mathcal{L}_{\text{SM,axions}} + \theta \frac{g_s^2}{32\pi^2}\tilde{G}_b^{\mu\nu}G_{b\mu\nu} + \xi \frac{a}{f_a}\frac{g_s^2}{32\pi^2}\tilde{G}_b^{\mu\nu}G_{b\mu\nu}$$

new term

- This new term leads to an additional potential (via "non-perturbative topological fluctuations of the gluon fields") → it's minimum is given by Θ = ξ a / f_a → i.e. CP-violating term disappears!
- Mass: $m_a = 5.691(51)\left(\frac{10^9\,\text{GeV}}{f_a}\right)\text{meV}$

Axions and ALPs

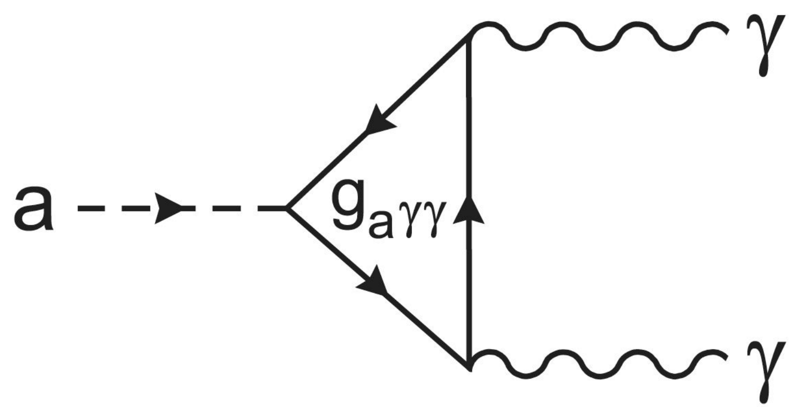
- Axion = scalar particle, arises from spontaneous symmetry breaking of a U(1) symmetry
- **Introduces counter term in QCD which cancels the CP-violating phase**
- Typically interact via photons a → γγ
- Mass m_a tied to "decay constant" f_a:
  $m_a = m_a(f_a)$
- Original proposal: $f_a = v_{EW}$ = 246 GeV → ma = 131 keV → excluded
- Need more complex theories, e.g. KSVZ, DFSZ
- Or use generalisation of Axions: Axion like particles (ALPs): → $m_a \neq m_a(f_a)$ → arise e.g. from string theories



https://tikz.net/mexican-hat/

$$\mathcal{L} = \left(\frac{a}{f_a} - \bar{\Theta}\right) \frac{\alpha_s}{8\pi} G^{\mu\nu a} \tilde{G}^a_{\mu\nu}$$

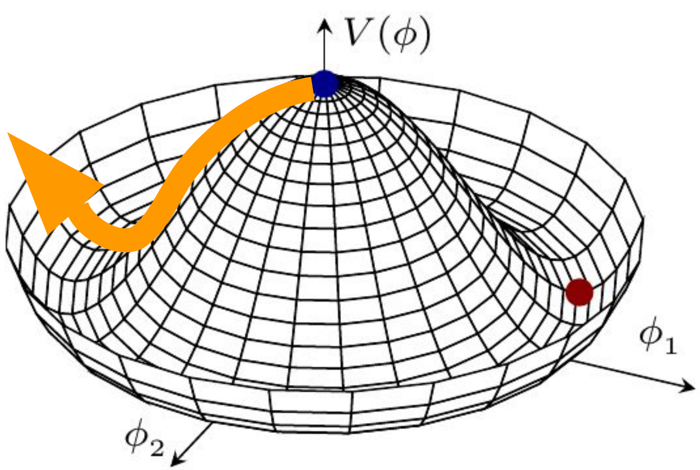
rpp2022-rev-axions

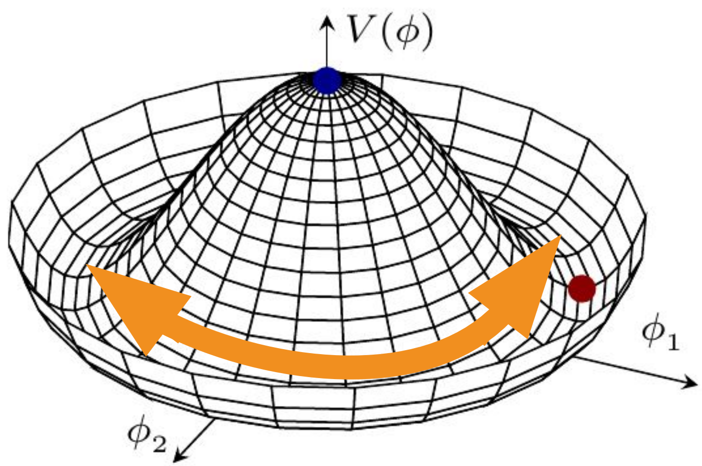


https://ned.ipac.caltech.edu/level5/March06/Overduin/Figures/figure24.jpg

Axions and Dark Matter

- Know from astrophysics: Axions must be very light (O(meV))
- **Oscillations of such light Axions around the minimum of their potential lead to same effect as Dark Matter**
  - Different constraints depending on when the oscillations started in time / how strong they are / how they behave

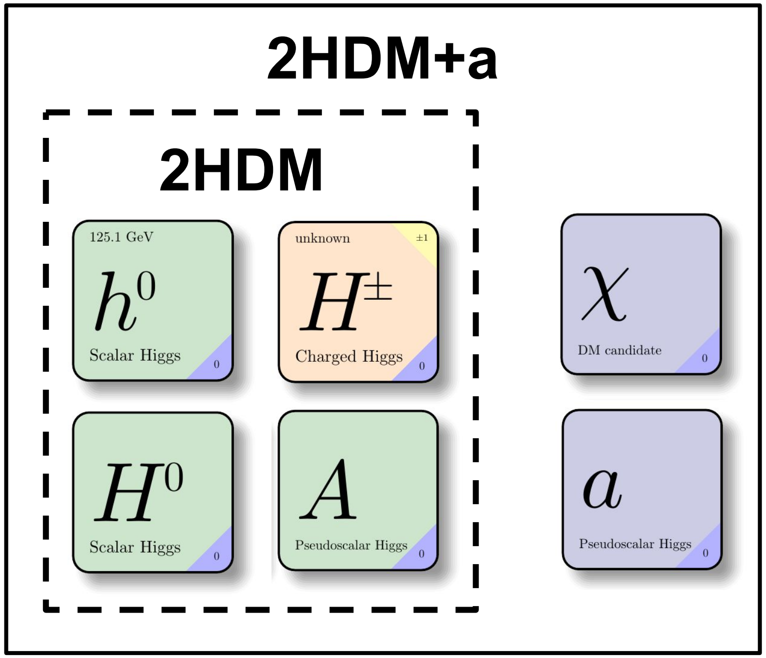


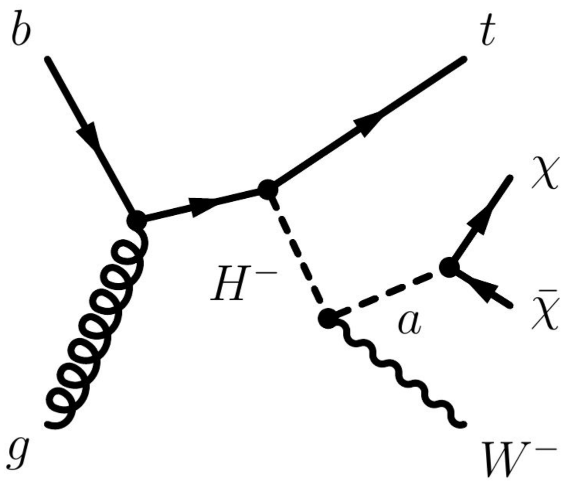


Drawings inspired by https://indico.scc.kit.edu/event/477/contributions/4854/attachments/2575/3683/KSETA_Durbach_2019_pargner.pdf

2HDM (+a) model

- In the DFSZ model: extend sector by second Higgs doublet
- **2HDM models general class of models**
- Second Higgs doublet leads to many new scalar / pseudoscalar particles
→ many new interactions possible
- New bosons often assumed to be heavy
- Very popular as basis as relatively “easy” and flexible, e.g.
    - 2HDM + axion (DFSZ)
    - 2HDM + pseudoscalar + DM (2HDM + a)
- Comes with new parameters (masses, mixing angles, …)

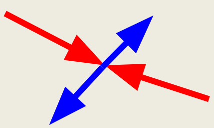




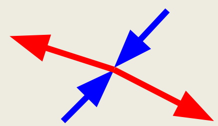
WIMPs

- 2HDM+a DM is “WIMP” → Different DM production than w/ Axions
- Assumptions:
  - DM is stable & made of particles
  - DM is produced from annihilation of SM / DM particles
  - DM is destroyed by annihilation

Early universe, very hot, $T >> m_X$



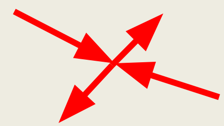
→ Annihilating SM produces DM



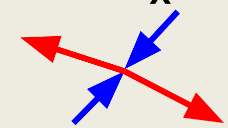
→ Annihilating DM produces SM

1 **DM density: high, constant**

Later universe, $T << m_X$



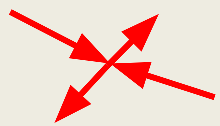
→ Annihilating SM produces SM (insufficient energy)



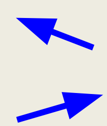
→ Annihilating DM produces SM

2 **DM density: decreasing**

3 **Expanded universe, $H > a_X$**



→ Annihilating SM produces SM (insufficient energy)



→ DM stops annihilating (density too low)

DM density: constant; “Freeze out”

[doi:10.1017/CBO9780511770739](https://doi.org/10.1017/CBO9780511770739)

The WIMP "miracle"

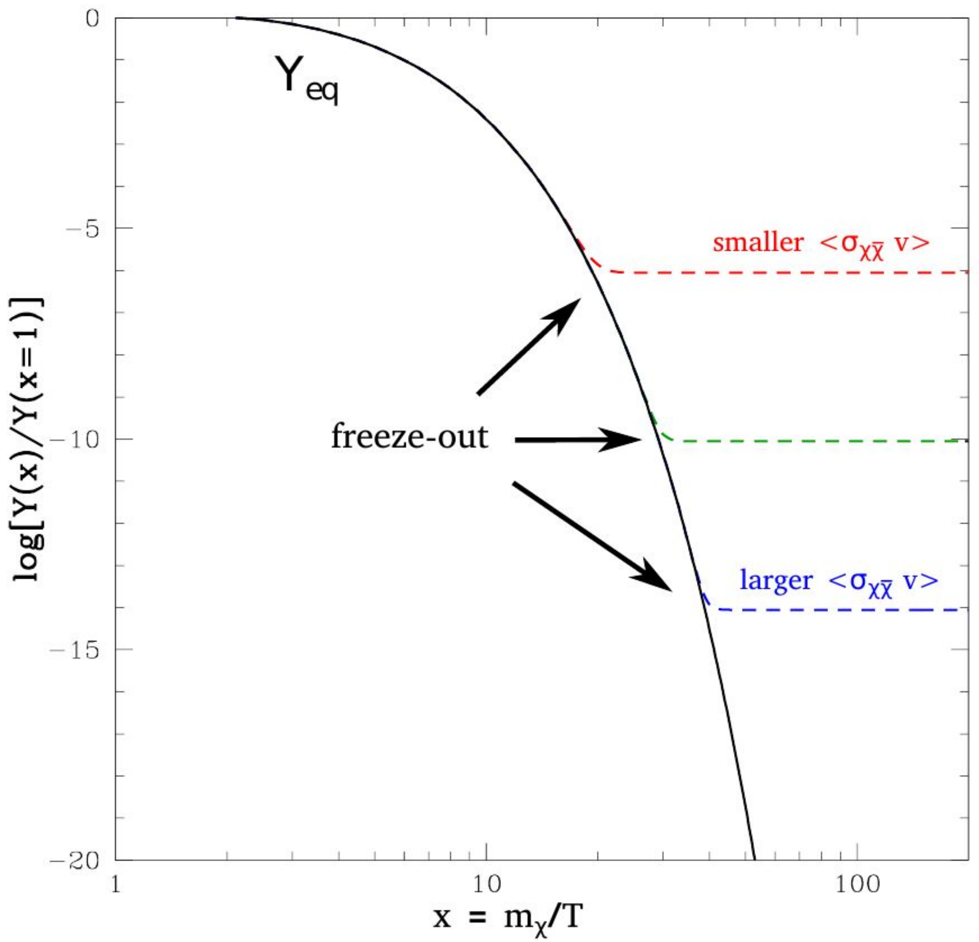
doi:10.1017/CBO9780511770739

- DM density today depends on the annihilation rate

  $$a_X = \langle \sigma_{XX}\, v \rangle\, n_X$$

  (σ_{XX} = self-interac. x-sec, v = velocity, n_X = DM particle density)

- Can calculate density today & compare it to measured density → $\sigma_{XX} \approx 1$ pb
- For a particle with weak self-coupling & mass of O(100 GeV) → $\sigma_{XX} \approx 1$ pb!
- **Weak interacting massive particles (WIMPs) intrinsically give the correct DM density!!!!**
- This is referred to as WIMP "miracle"



Supersymmetry (SUSY)

rpp2022-rev-susy-1-theory

- Supersymmetry = to each SM particle assign a supersymmetric partner
  - Q |fermion> = |boson> → new name: s + original name
  - Q |boson> = |fermion> → new name: remove “on”, add “ino”
- With this symmetry, can design many different theories, MSSM one of simplest

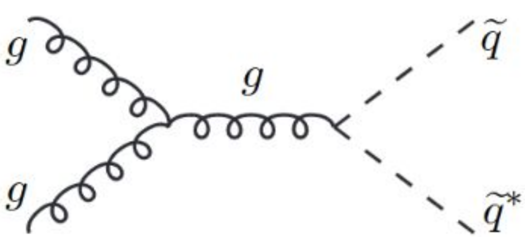
Particle		Spin		Super-particle		Spin
Quark	q	½		Squark	$\tilde{q}_L, \tilde{q}_R$	0
Lepton	$\ell^\pm$	½		Slepton	$\tilde{\ell}_L^\pm, \tilde{\ell}_R^\pm$	0
Neutrino	ν	½		Sneutrino	$\tilde{\nu}_L, \tilde{\nu}_R$ (?)	0
Gluon	g	1		Gluino	$\tilde{g}$	½
Photon	γ	1	$\tilde{\gamma}$	Neutralino (mass eigenstate)	$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$	½
Z boson	Z	1	$\tilde{Z}$			
Higgs	H	0	$\tilde{H}_1^0, \tilde{H}_2^0$			
			$\tilde{H}^\pm$	Chargino (mass eigenstate)	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$	½
W-boson	$W^\pm$	1	$\tilde{W}^\pm$			

MSSM particle content
Table reproduced from M. Thomson, Modern Particle Physics, Cambridge 2013

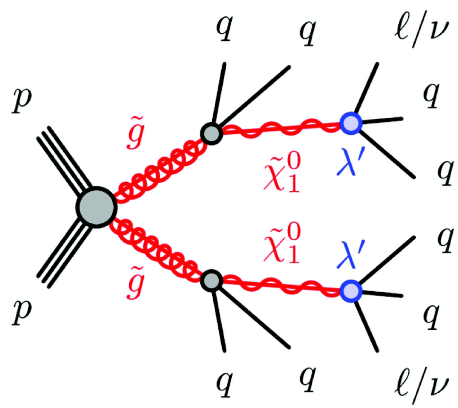
Breaking supersymmetry

rpp2022-rev-susy-1-theory

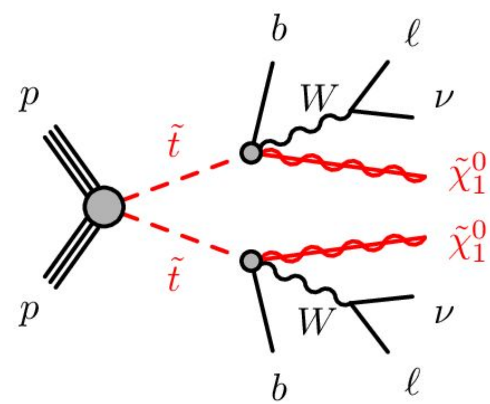
- If the supersymmetry is exact: $m_{sparticle} = m_{particle}$ → not observed!
- Supersymmetry **must** be broken!
- Can assume it is spontaneously broken → additional goldstone fermion
  - If breaking is local (not global) → theory incorporates gravity!
- SUSY models come with many new particles
  → many new Feynman diagrams in principle possible
  → potentially new final states to explore



arxiv:hep-ph/9709356



ATLAS-SUSY-2020-27

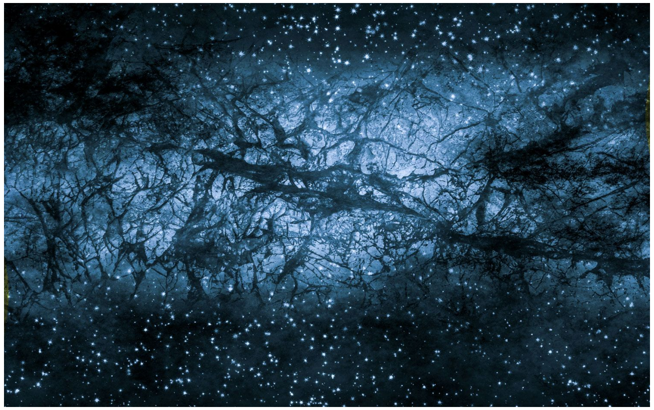


ATLAS-SUSY-2018-08

R-parity and Dark Matter

rpp2022-rev-susy-1-theory

- SM is B-L invariant (B = baryon number, L = lepton number)
  → SUSY can break this → proton becomes unstable
- If requiring B-L in SUSY, $R=(-1)^{3(B-L)+2S}$ (S=spin) is conserved
  - particles: R = +1
  - sparticles: R = -1
- If assume that R-parity is conserved: sparticles always produced in pairs
- Further consequence: there exists a lightest supersymmetric particle (LSP), which must be neutral and weakly interacting (i.e. a WIMP)
  → **DM candidate!!**



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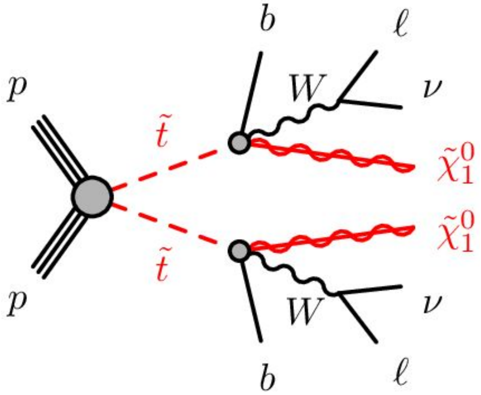
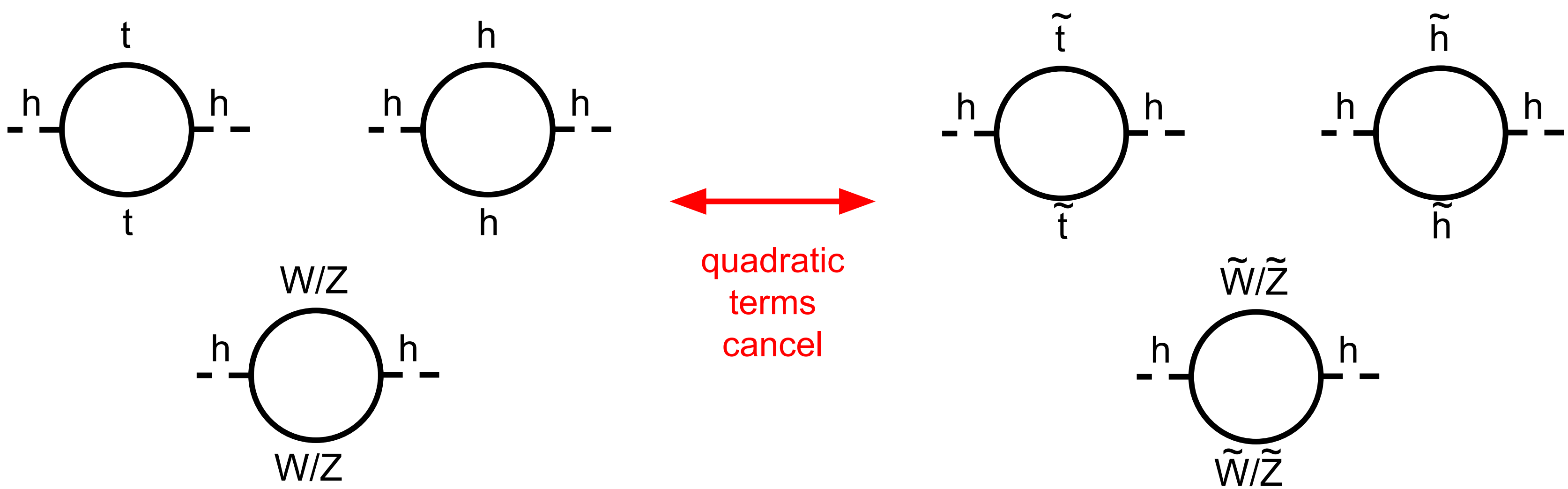


ATLAS-SUSY-2018-08

SUSY & the hierarchy problem

arxiv:hep-ph/9709356

- Recall the hierarchy problem: bare Higgs mass ≠ measured Higgs mass →high degree of fine-tuning
- **SUSY can (in principle) "naturally" solve the hierarchy problem**
  - Superpartners add loop corrections which cancel the SM loop correction quadratic terms (but logarithmic terms remain)
  - Often requires masses of sparticles to be in O(GeV) / O(TeV) → not observed so far, but could be at higher TeV scale

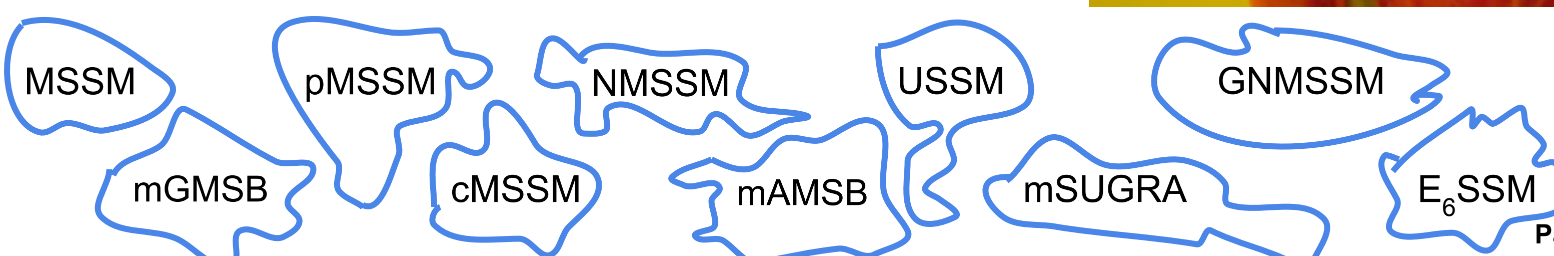


rpp2022-rev-susy-1-theory

New issues with SUSY

- SUSY can solve many of the SM “problems”
  a. DM candidate
  b. Hierarchy problem
  c. Unify the three forces at higher energy (see next pages)
  d. Add gravity
- Simplest model that solves (a) and (b): MSSM
  → 124 free parameters (!)
  → Introduces new sources of CP violation
  → Adds flavour-changing neutral currents
- Much freedom when designing SUSY model
  → Very many SUSY models around

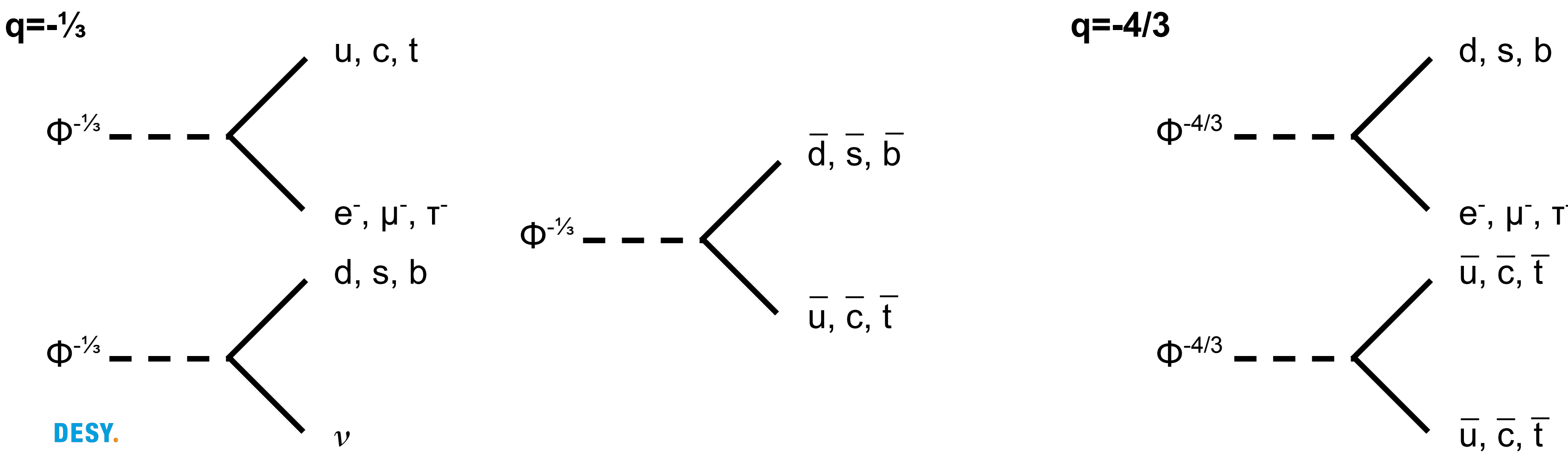
https://imgflip.com/s/meme/Drake-Hotline-Bling.jpg



Leptoquarks

rpp2022-rev-leptoquark-quantum-numbers
arxiv:2105.04844

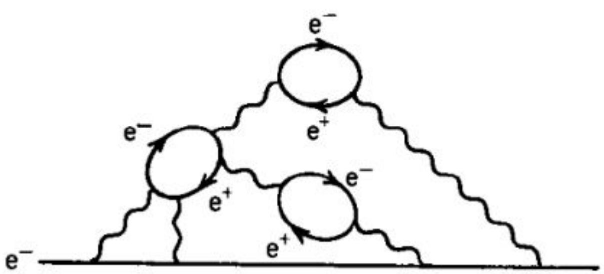
- Leptoquarks are hypothetical particles which couple via a quark-lepton vertex
- Charge can be ⅓, ⅔, 4/3, 5/3
- Multiple coupling possibilities:
  - Chirality: LQ couples *only* to left or right handed quarks
  - Generation: LQ couples *only* to particles of one generation
- LQs predicted by multiple theories, e.g. Technicolor, Grand Unified Theories
  - Some of these theories solve problems of the SM
  - Repeated hints for LQs (though most vanished), latest from g-2

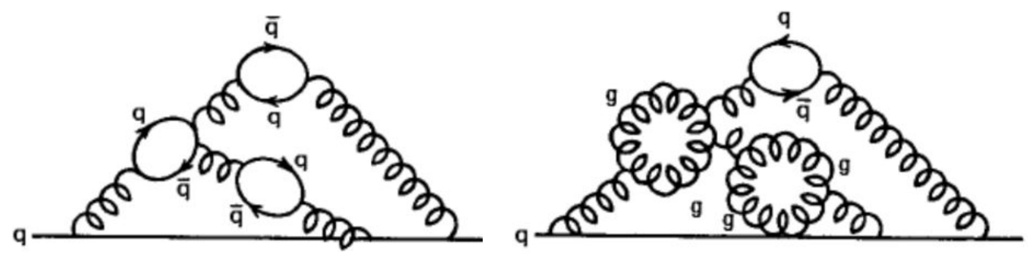


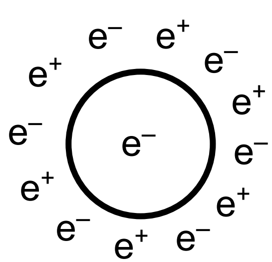
(Anti-) Screening

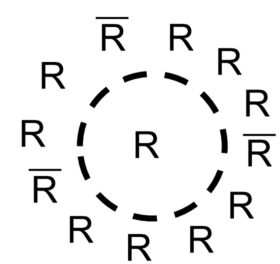
https://www.nikhef.nl/~h24/qcdcourse/section-all.pdf

- Recall running couplings:
  - QED: screening of electric charges by vacuum fluctuations make visible charge decrease as a function of distance
  - QCD: have virtual quark (screening) & gluon pairs (ant-screening): effective colour charge increases as a function of distance





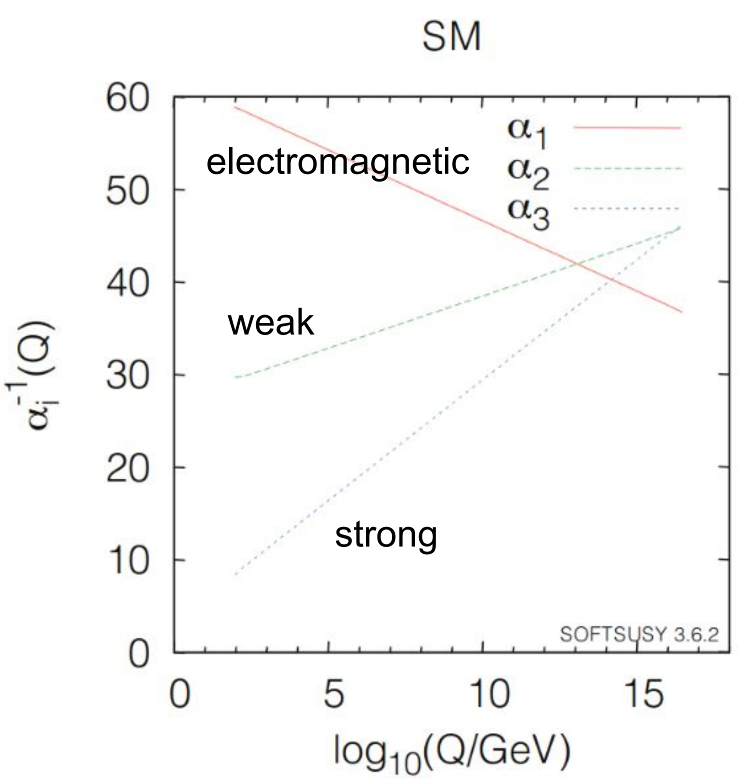




Running coupling & GUTs

rpp2022-rev-guts

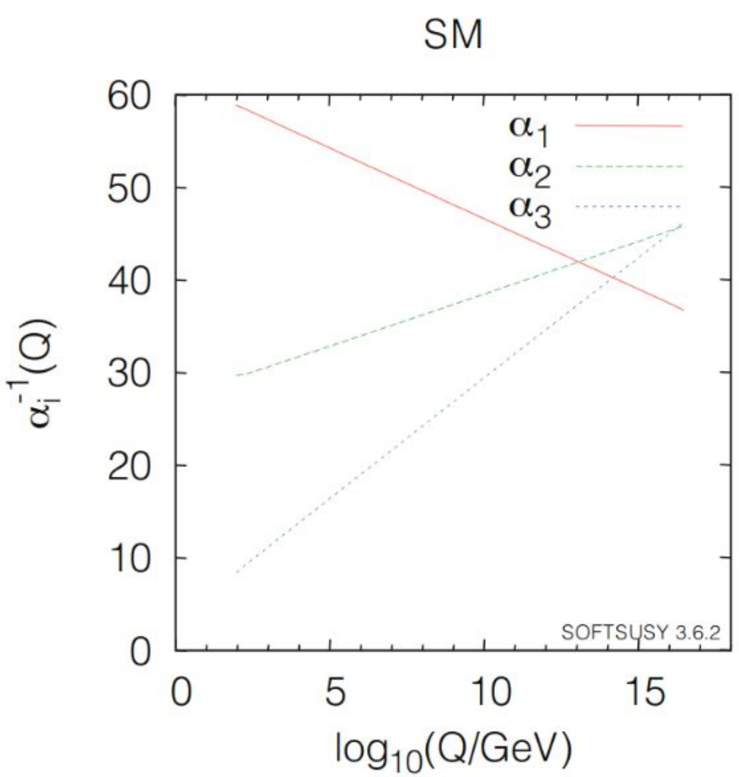
- Leads to a concept called running coupling: the coupling constant is a function of energy
- QED: coupling constant diverges as energy → 0
- QCD/Weak theory: coupling constant diverges as energy → ∞
- Coupling constants almost equal at 10^{15} GeV → **are they part of one unified theory?**
- SM: U(1) x SU(2) x SU(3)
  EM Weak Strong
- U(1) x SU(2) x SU(3) ⊂ SU(5), SO(10)
  → one group to generate all interactions?
- "Grand unified theories"

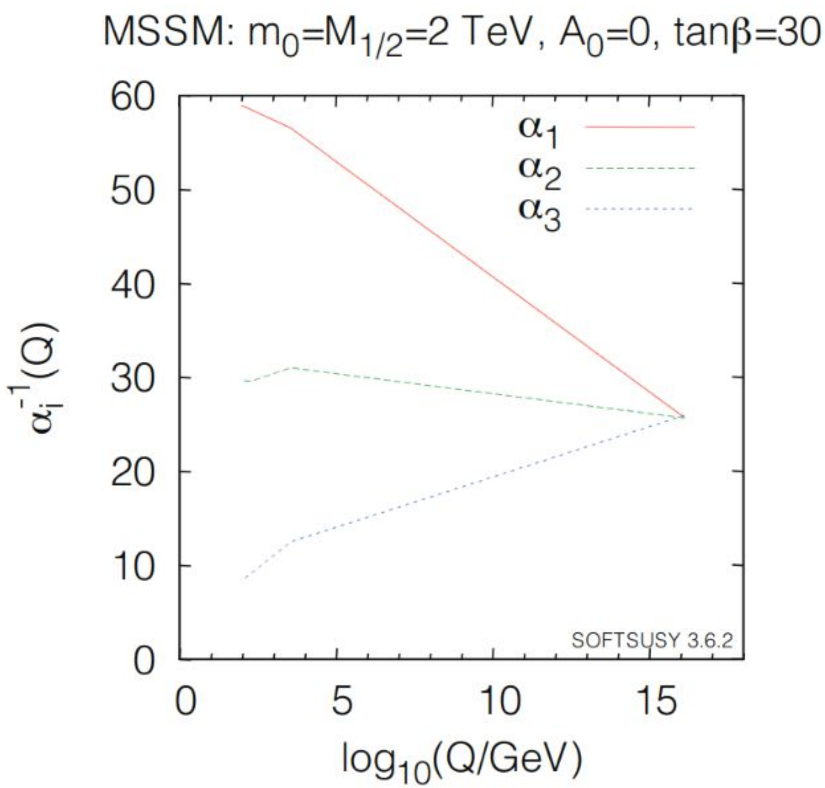


How the couplings meet in GUTs

rpp2022-rev-guts

- Many theories contain grand unifications:
  - SUSY
  - Extra dimension theories
- GUTs predict additional particles → make proton unstable → test GUTs

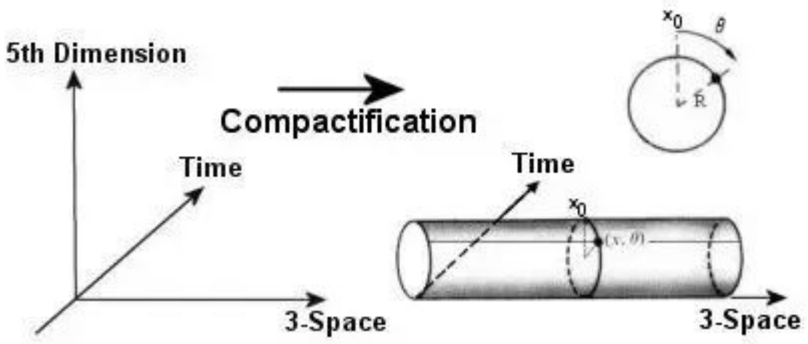




Kaluza-Klein extra dimension theories

rpp2022-rev-extra-dimensions
wikipedia:Kaluza-Klein_theory

- **Add additional spatial dimensions → allows to combine gravity with SM**
- Kaluza + Klein, 1920': attempt to unify gravity with electromagnetism
  - 5-dimensional base space with 1 compactified dimension (imagine a cylinder of radius R)
  - A complex scalar field theory on that 5D space results in a 4-dimensional scalar field theory + an infinite number of massive scalar fields
  - E.g. (4+1)D GR becomes 4D GR + EM + 1 scalar field (not resembling nature)

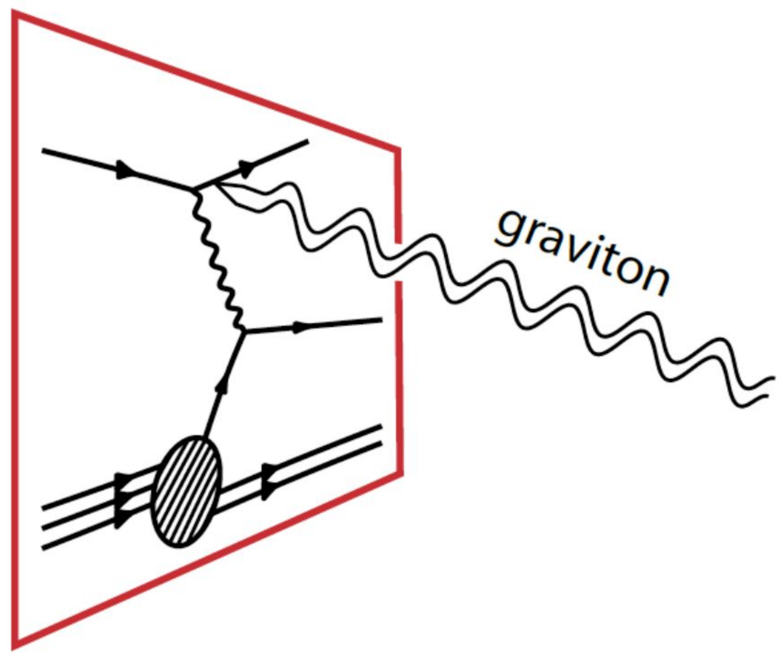


https://qph.cf2.quoracdn.net/main-qimg-c94bb8642d2ebf23fc32aed446a2c397.webp

ADD extra dimension models

rpp2022-rev-extra-dimensions
arxiv:hep-ph/9803315
chill_warwick_lhc_lecture_5

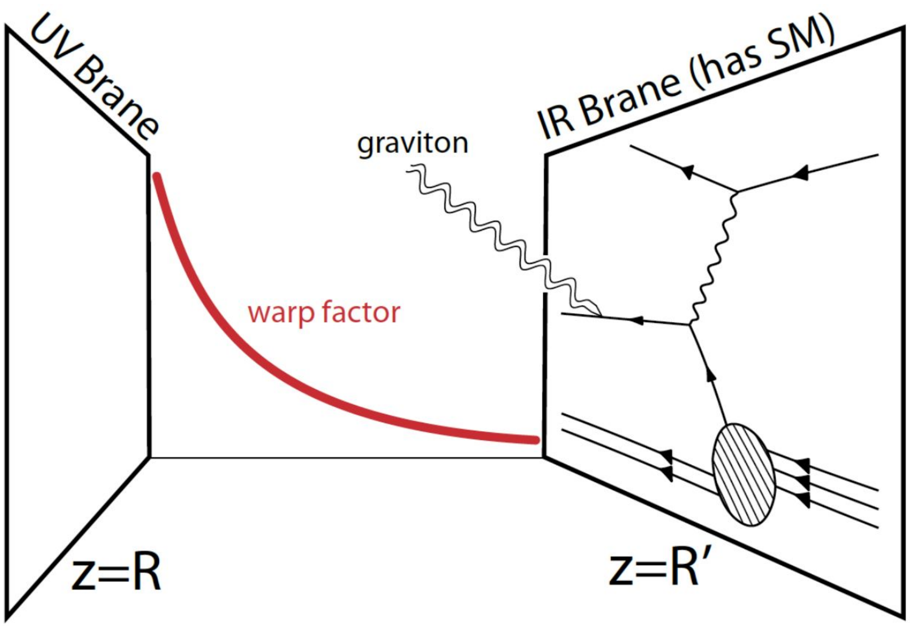
- ADD (Arkani-Hamed, Dimopoulos, Dvali) theory builds on KK approach:
  - SM is only realised in 3+1 spacetime, a “brane”
  - Gravity propagates through δ other compact dimensions of size R, thereby being diluted at length scales >> R
  - Gravity is stronger at length scales < R, but weaker > R
  - ADD theory introduces a spin-2 graviton & graviscalars (not relevant)
  - $R = 1/\Lambda * (\Lambda_{Planck} / \Lambda)^{2/\delta} \rightarrow \Lambda \sim 1$ TeV
    → δ=1: $R \sim 10^9$ km →would be known
    → δ≥2: $R \leq 0.5$ mm →possible



Randall-Sundrum model

rpp2022-rev-extra-dimensions
chill_warwick_lhc_lecture_5

- Add one (compact) dimension to spacetime
- The SM fields do not propagate to this extra dimension and are confined to a “brane” on one end of the dimension
- The graviton can propagate through the extra dimension
- It’s probability density function exponentially decreases as a function of the extra dimension, minimal at SM brane, maximal on the other side
  →explains why impact of gravity is so small
- Solves hierarchy problem

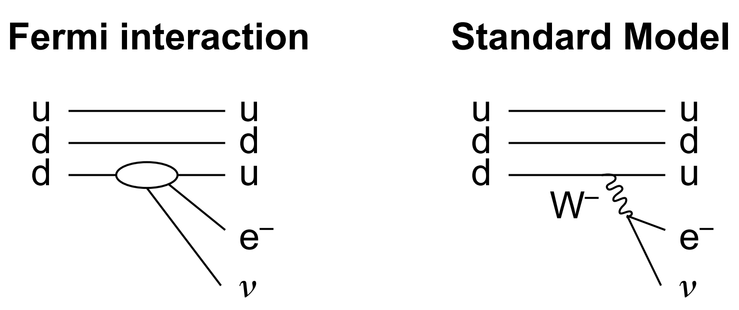


https://www.zeuthen.desy.de/students/2019/Lectures/Pueschel_Lecture1_BeyondSM_2019.pdf

Effective Field Theories

arxiv:1804.05863

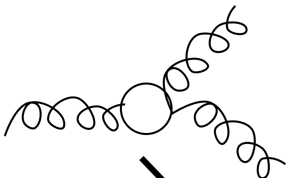
- All models mentioned so far add quite specific terms to the Lagrangian
- **What if the BSM physics is actually quite different from the discussed? What if we cannot produce the seeked particles as they are too heavy?**
- Effective Field Theories assume: new physics is at higher energy scales, e.g. the new particles have much larger masses
- These new particles are not produced on-shell, but have “effective” off-shell interactions → analogous to Fermi-beta-decay theory
- With this approach: can write down many effective Lagrangian terms → thorough determination of all possible terms on-going
- An EFT does not explicitly solve SM problems, but can give hints what the higher energy theory should contain



Excerpt of the Warsaw basis

arxiv:1008.4884
arxiv:1308.2627
arxiv:1804.05863

- Warsaw basis = listing of dimension six operators (as dim=5 operators produce neutrino masses, dim=6 operators are the lowest dim operators with potentially new physics)



$$\mathcal{L}_{\mathrm{SM}} = \mathcal{L}_{\mathrm{SM}}^{(4)} + \frac{1}{\Lambda}\sum_k C_k^{(5)} Q_k^{(5)} + \frac{1}{\Lambda^2}\sum_k C_k^{(6)} Q_k^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p e_r \varphi)$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p u_r \widetilde{\varphi})$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu \varphi\right)^\star \left(\varphi^\dagger D_\mu \varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger\varphi\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$

Summary

- The Standard Model of particle physics appears to be incomplete
    - Dark Matter/Energy, hierarchy problem, strong-CP problem, SM parameters, group structure, unification, gravity, matter-antimatter asymmetry, …
- Large list of models extending the SM
- Discussion of experimental tests of these models next lecture ;)

Model	**Dark Matter**	**Hierarchy problem**	**Strong CP problem**	**Unification**	**Gravity**
Axions	✅	-	✅	-	-
2HDM	✅	-	-	-	-
SUSY	✅	✅	possible	✅	e.g. mSUGRA
GUTs	-	-	-	✅	-
Extra dims.	✅	✅	-	possible	✅

Thank you

Backup slides

Technicolor in a nutshell

rpp2022-rev-technicolor
Wikipedia:Technicolor_(physics)

- Originally constructed as alternative to the Higgs mechanism, nowadays incorporates it
- Higgs boson is typically a fermion composite particle in technicolor
  - These fermions are called *techniquarks*
  - Their binding is mediated by a new interaction, with new color-like charges (*technicharges*)
- Introduces new particles, which can be searched for
- Offers:
  - A DM candidate
  - A solution to the hierarchy problem

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