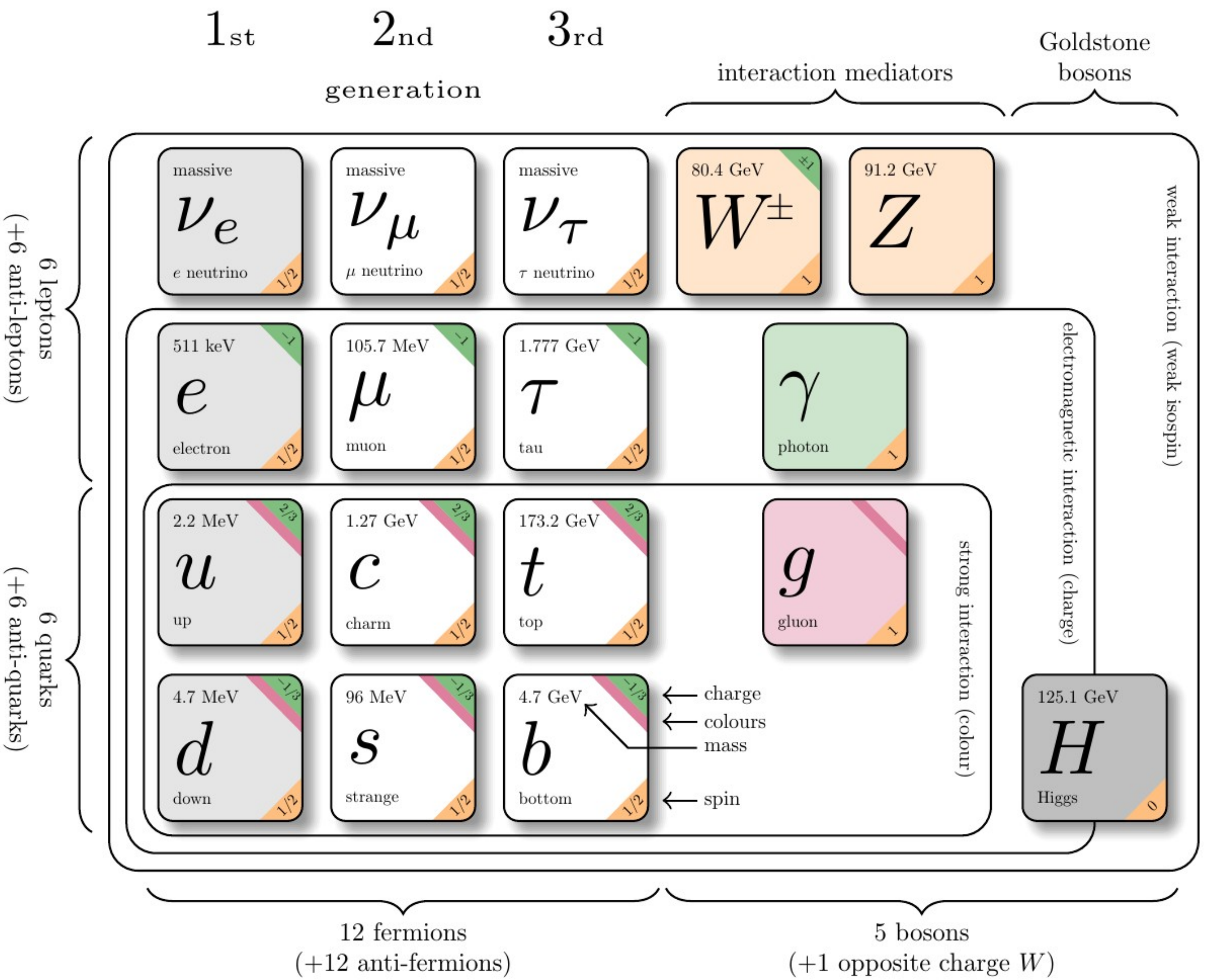
Physics beyond the standard model

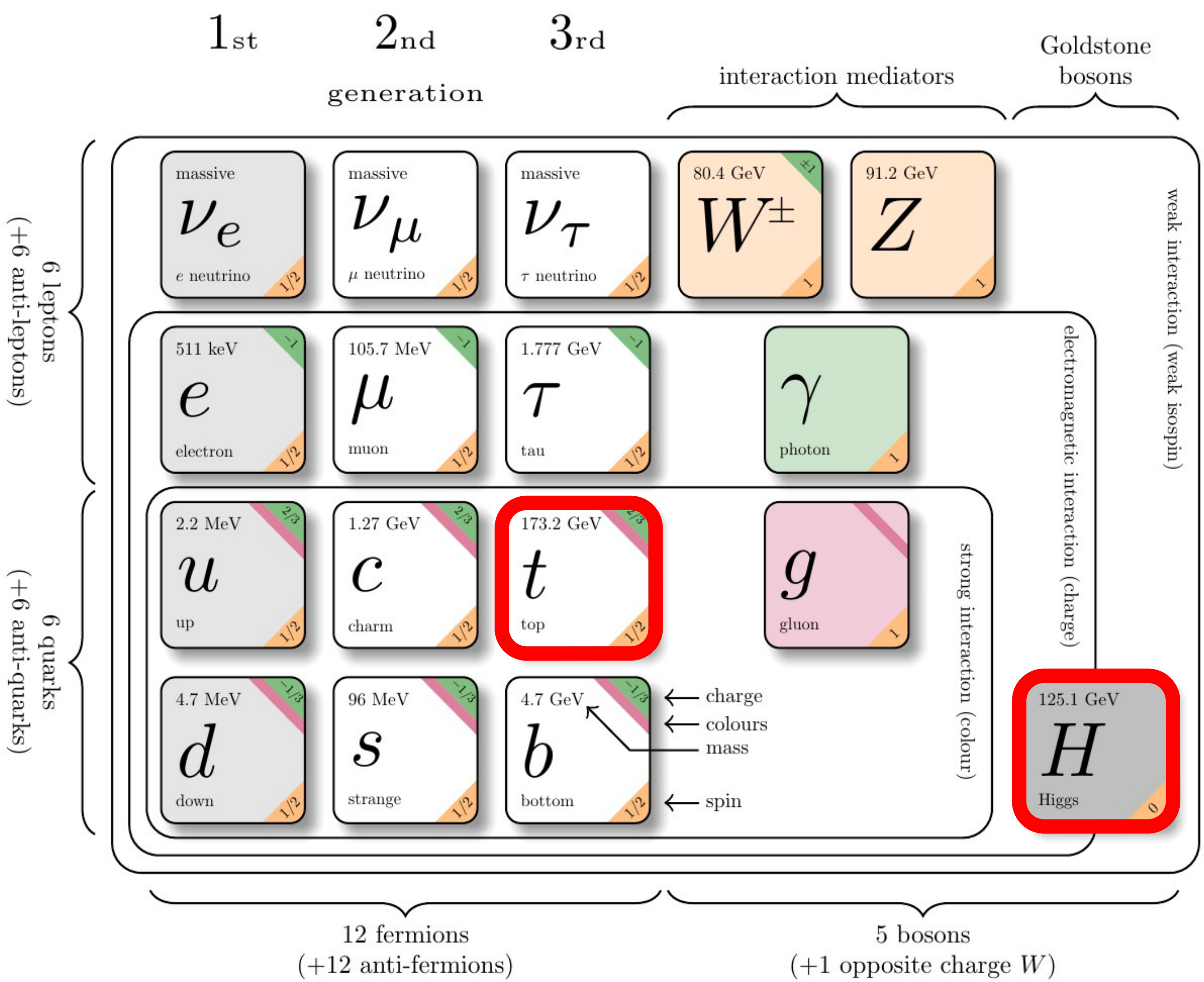
Thorsten Kuhl
DESY Zeuthen, 26.08.2024

The Standard Model…

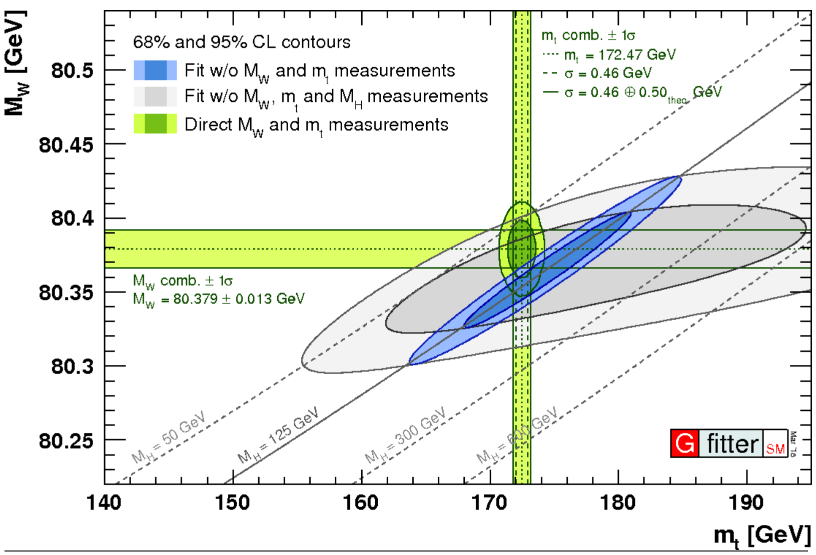


The Standard Model…

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



The Standard Model…



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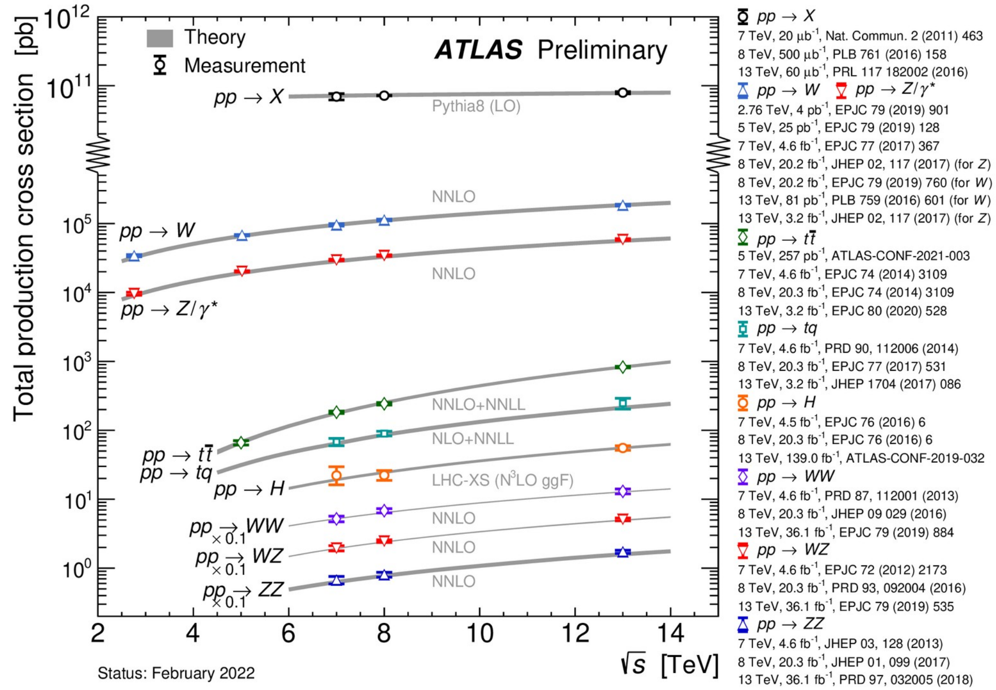
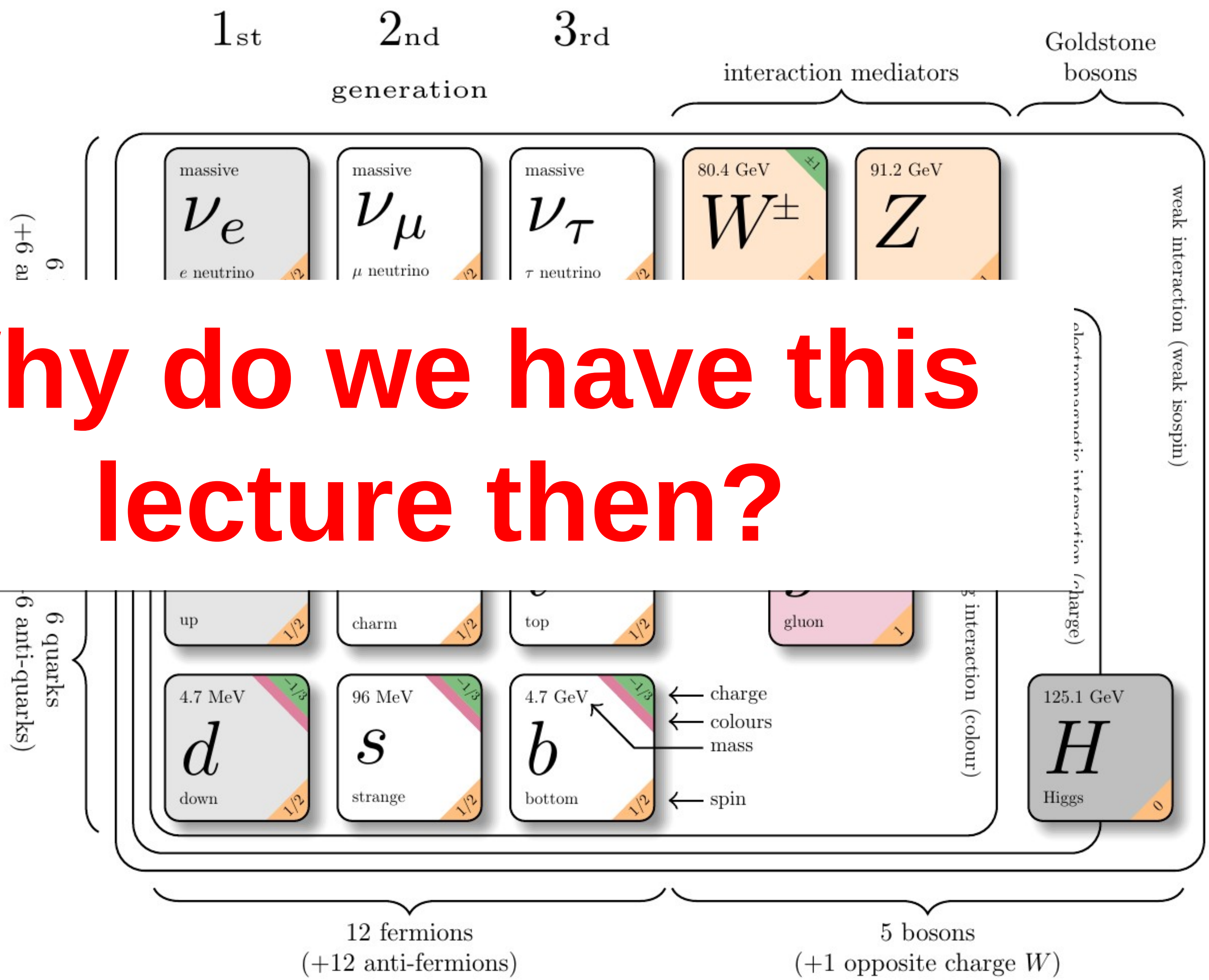


http://cds.cern.ch/record/2804061

- Standard model very precise over multiple orders of magnitude!

The Standard Model…

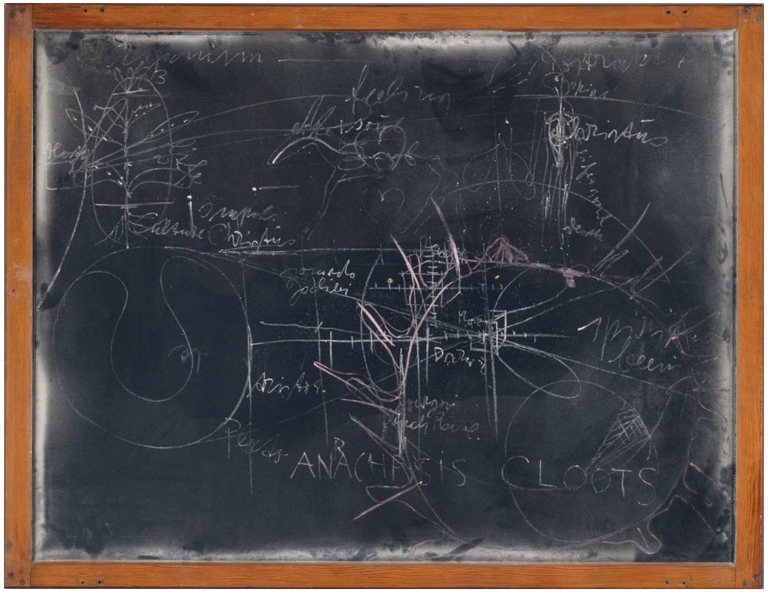
- Last particles discovered in 1995 (top) & 2012 (H
- Is very succes
- Describ many experiments over multiple orders of magnitude



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))

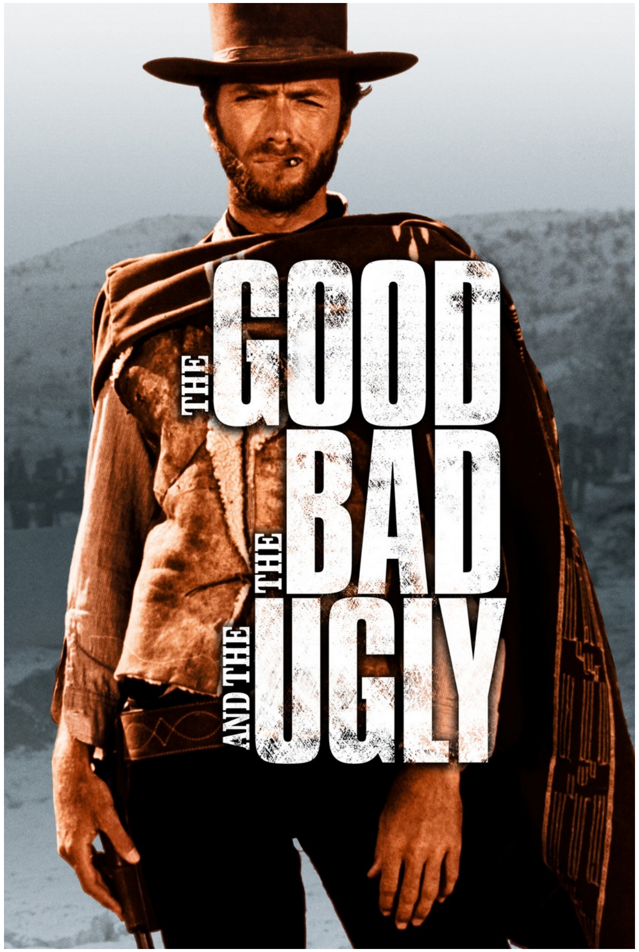
---

19 free parameters

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

The Standard Model appears incomplete!

- It cannot explain:
  - Why there is no CP-violation in QCD, not enough CP violation in CKM to explain Matter-Antimatter asymmetry
  - Why the “bare” masses are fine-tuned at sub-permille level
  - Why there are 19 free parameters in the SM
- It will not explain:
  - Neutrino masses
  - Gravity
  - Dark Matter



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Fine-tuning the "bare" Higgs boson mass

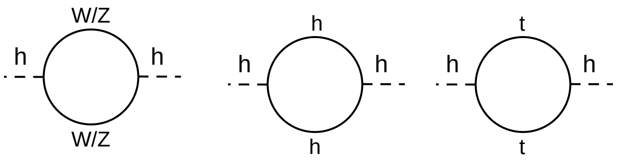
- Higgs boson mass-term after symmetry-breaking in the SM:

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

- We call m_h the "bare" Higgs boson mass $m_h = \sqrt{2\lambda}v$

- Don't measure m_h, due to loop corrections! For scalar particles these are quadratic; 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:

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

- SM is a renormalisable, locally (for the scale we test the higgs mass) this is not a problem, but it will diverge from the local scale (O(TeV)) by δM_H

- When the SM should be valid at the Plank Scale ($\Lambda = 10^{19}$ GeV) and give a reasonable Higgs mass, then the bare masses of all other SM particles has to be "fine tuned", sound arbitrary ("naturalness problem")

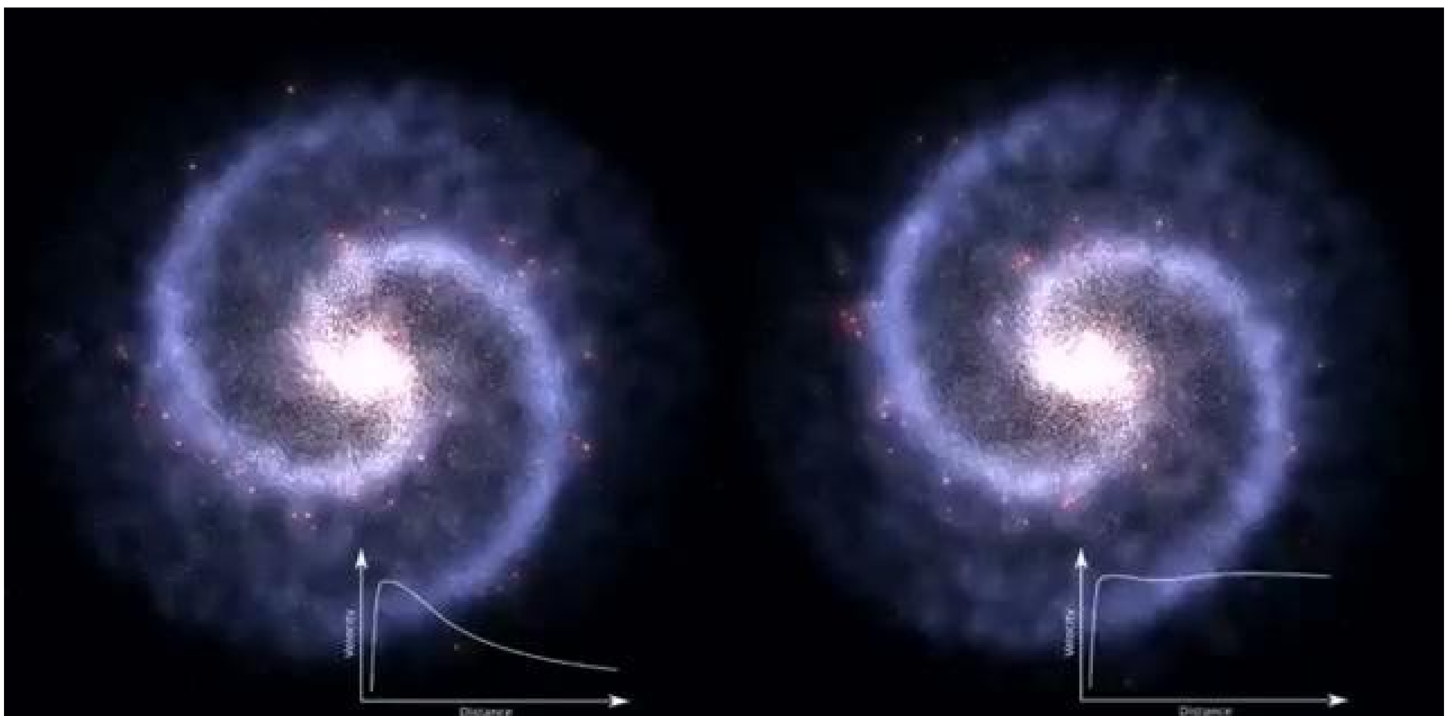
- How could this be fixed? Particles with countering loops! (→ SUSY) arxiv:1006.2483

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:

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

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

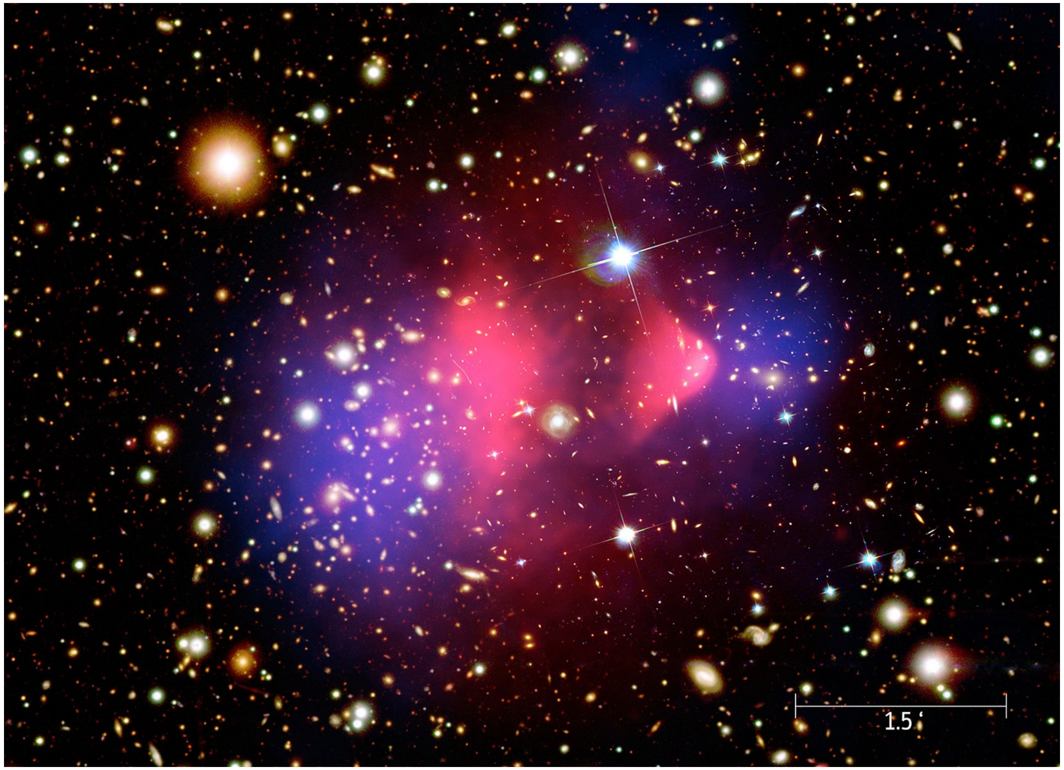


Expected **Observed**

doi:10.1086/381970

More hints for Dark Matter – The bullet cluster

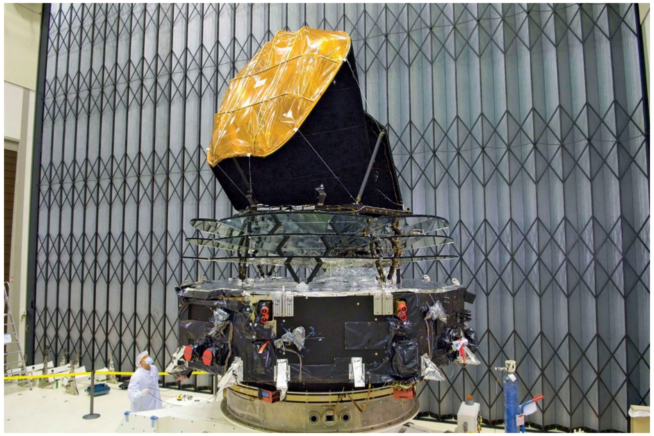
- Two clusters of galaxies close together
- Electromagn. visible matter / mass made of gas (red; by x-rays) is colliding/interacting between the two clusters, gets slowed down
- Mass visible by gravitation (blue; by grav. lensing) mostly unaffected by collision
- **Observe: red ≠ blue → there must be additional, grav. interacting matter very weakly (or not) interacting!**



wikipedia

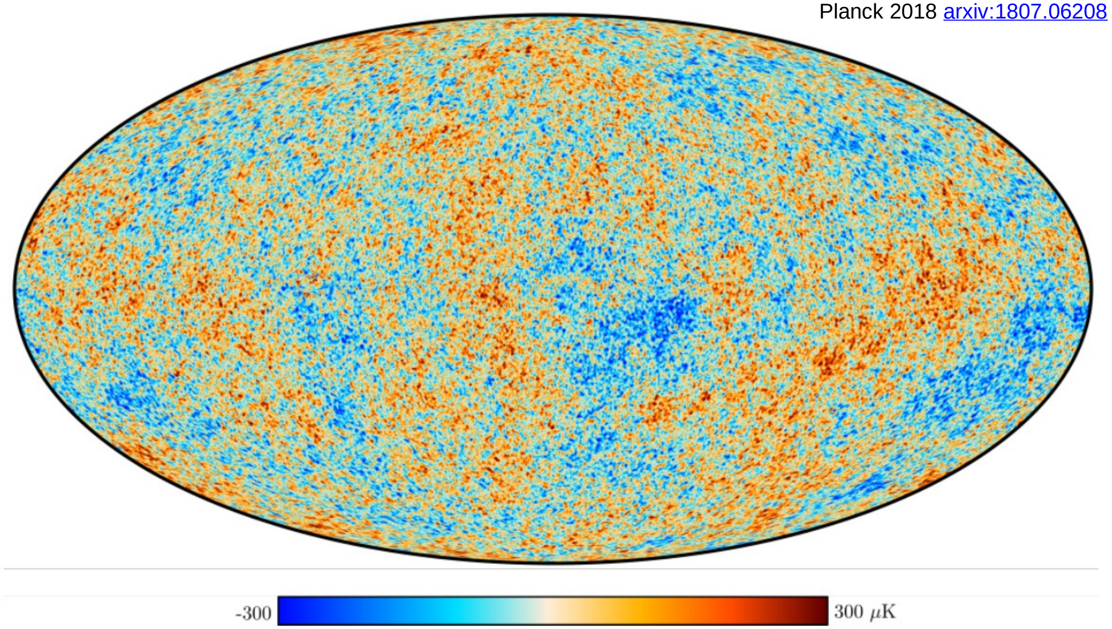
Evidence for Dark Matter – The CMB

- 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



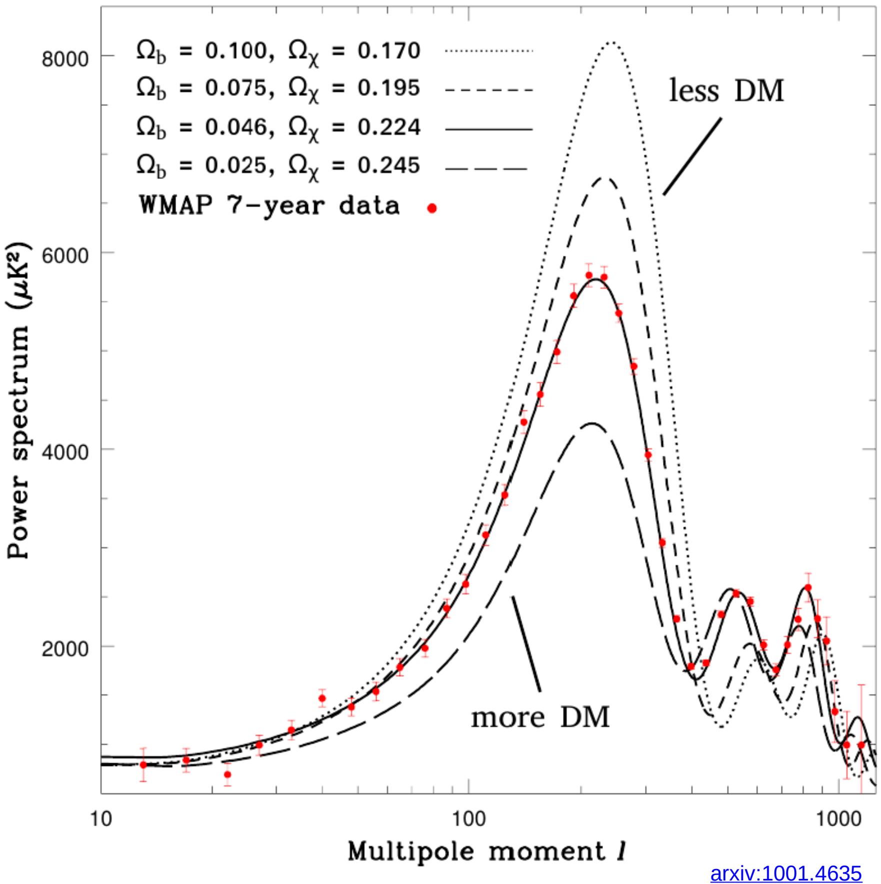
https://www.britannica.com/topic/Planck

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 high of first peak, 2nd/3rd peak shifts
- The result:
  - Baryonic matter: 4.9 %
  - **Dark Matter: 26.5 %**
  - **Dark Energy: 68.6 %**

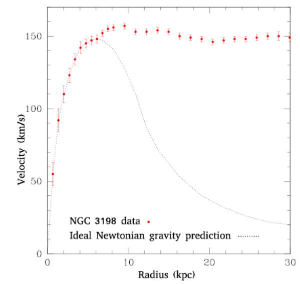


arxiv:1001.4635
arxiv:1006.2483

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

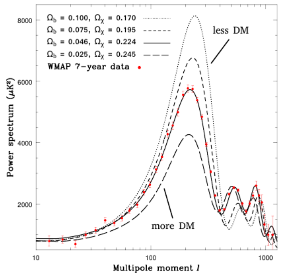
So what’s it all about with Dark Matter?

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



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

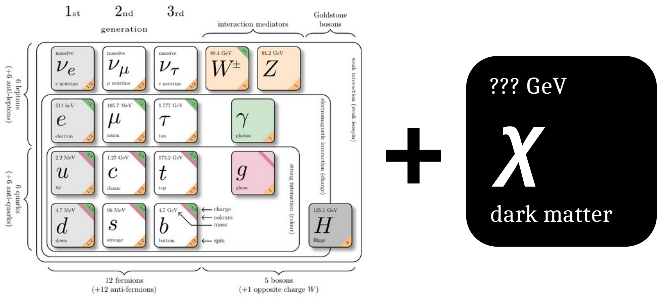
doi:10.1086/381970



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



Why is there no CP-violating phase in QCD?

- QCD Lagrangian in its most general form

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

- A none zero CP violating phase would explain the matter anti-matter asymetry in the universe
- 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)!

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

- **CP-violation is basically zero in QCD! "Strong CP problem"**
- How do we get CP violation into the early universe?
- Allow $\bar{\Theta}$ >0 but add a term which cancel the CP violation today
  → this is done in the Peccei-Quinn theory → leads to particles called "Axions"
- Adding terms to the Lagrangian is how you extend the SM

Peccei-Quinn theory full details

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

- 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

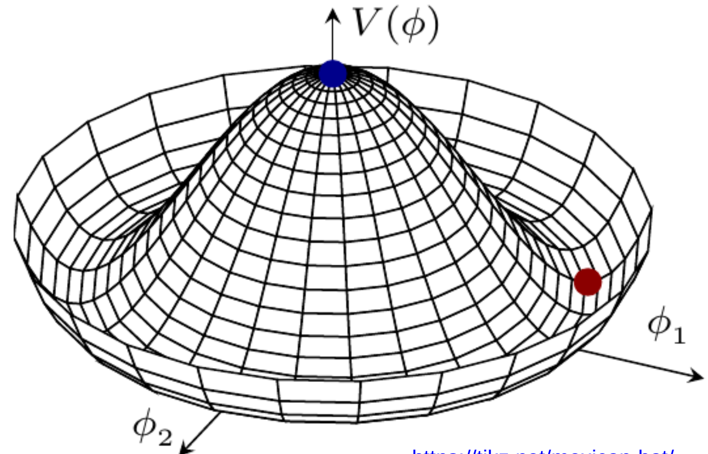
- This new term leads to an additional potential (via “non-perturbative topological fluctuations of the gluon fields”) → it’s minimum is given by Θ = ξ a / f_a → i.e. CP-violating term disappears!
- Mass: $m_a = 5.691(51) \left(\frac{10^9\,\text{GeV}}{f_a}\right) \text{meV}$

Axions and ALPs

- Axion 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:

  $$m_a = m_a(f_a)$$

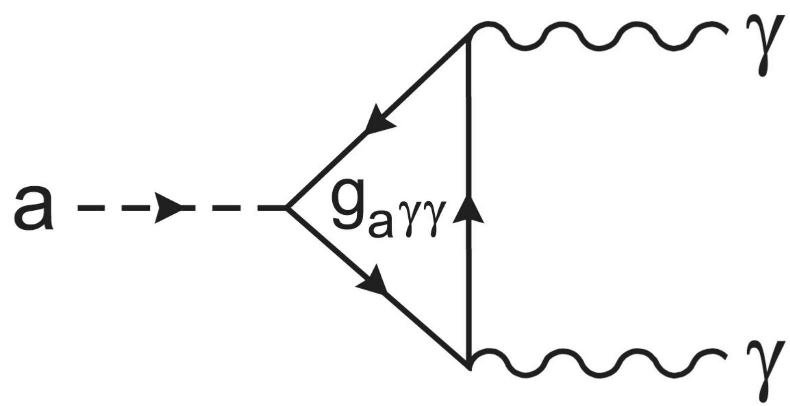
- Most natural: $f_a = v_{EW} = 246$ GeV
  → $m_a = 131$ keV → excluded
- Need more complex theories, e.g. KSVZ, DFSZ
- Or use generalisation of Axions: Axion like particles (ALPs): → $m_a \neq m_a(f_a)$
  → arise e.g. from string theories
- Axions are a good dark matter candidate



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

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

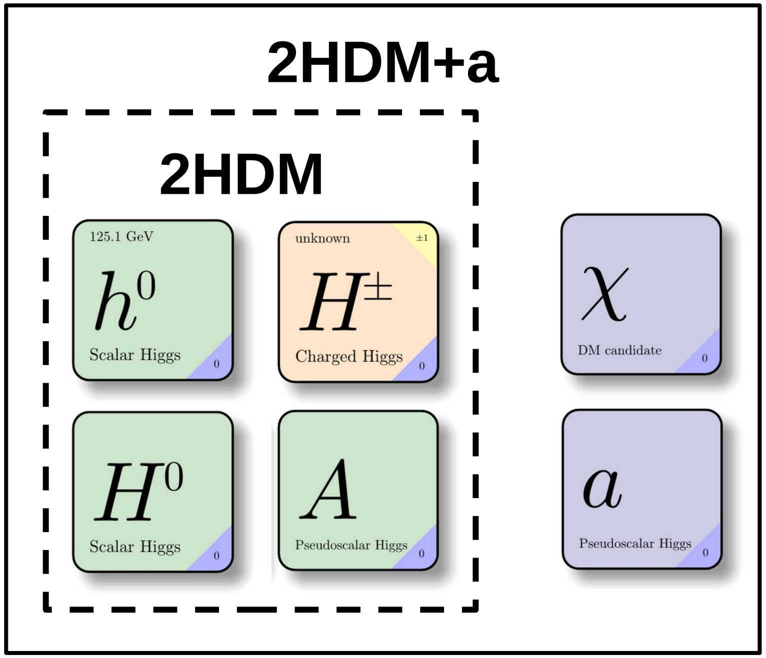
rpp2022-rev-axions

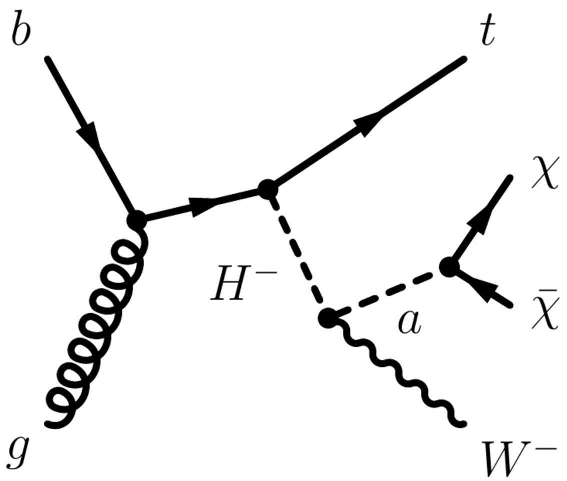


https://ned.ipac.caltech.edu/level5/March06/Overduin/Figures/figure24.jpg

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

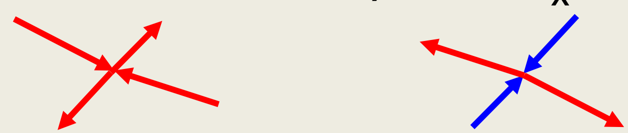
Early universe, very hot, $T >> m_X$

→ 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

The WIMP "miracle"

doi:10.1017/CBO9780511770739

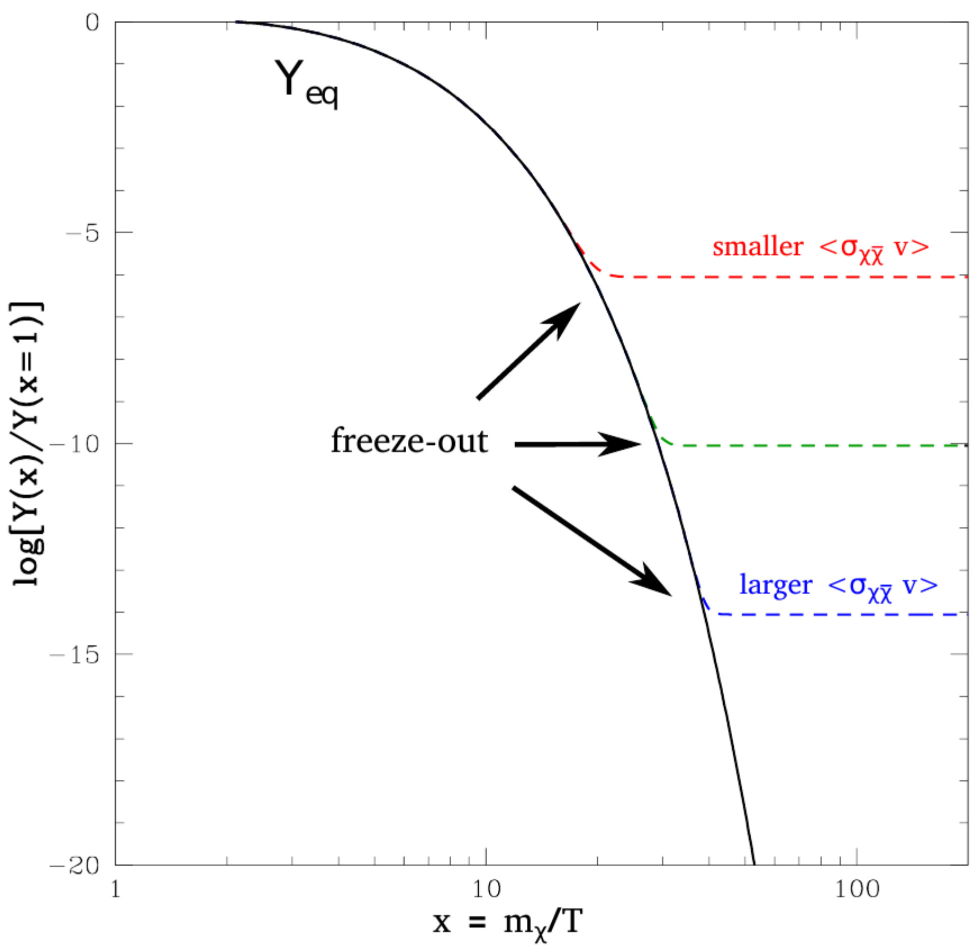
- DM density today depends on the annihilation rate
  $$a_X = \langle \sigma_{XX} v \rangle n_X$$
  (σ_{xx} = self-interac. x-sec, v = velocity, n_X = DM particle density)

- Can calculate the DM density tod compare it to measured density $\rightarrow \sigma_{XX} \approx 1$ pb

- For a particle with weak self-coupling (as weak as the electrov force) & mass of O(100 GeV) $\rightarrow \sigma_{XX} \approx 1$ pb!

- **Weak interacting massive parti (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	$\tilde{W}^\pm$			

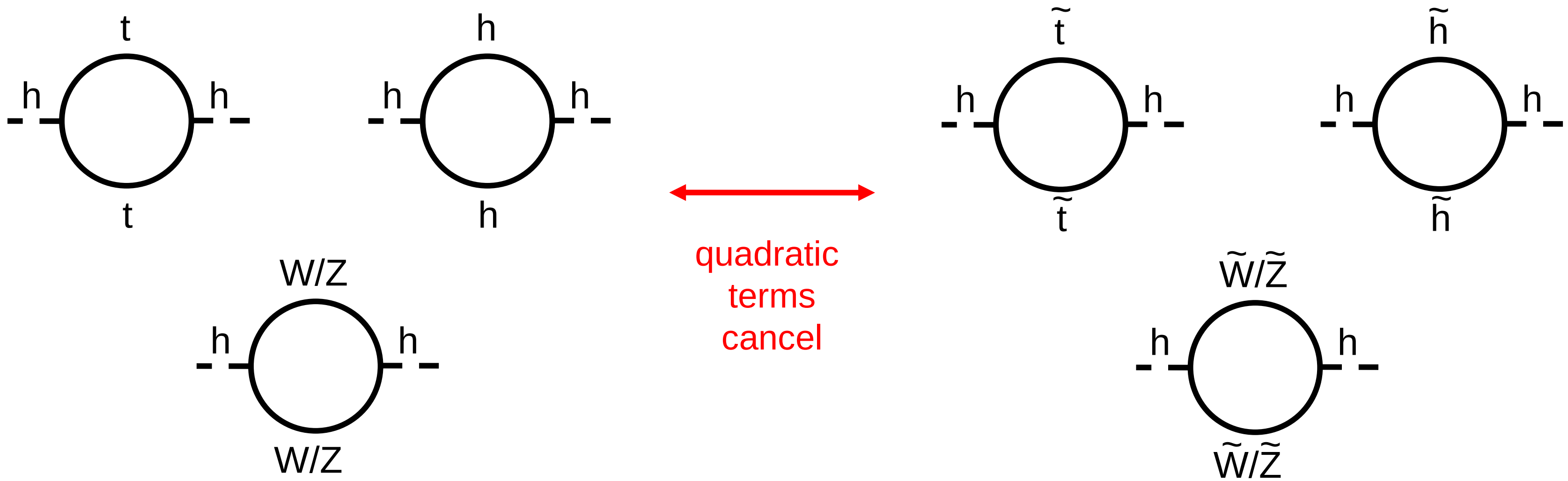
MSSM particle content

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

SUSY & the hierarchy problem

arxiv:hep-ph/9709356

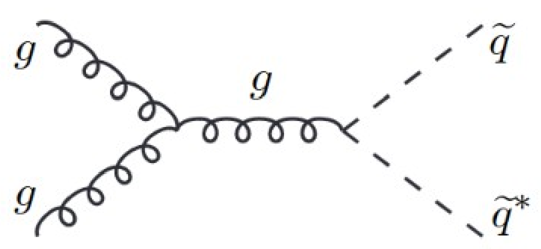
- Recall the hierarchy problem: bare Higgs mass ≠ measured Higgs mass
  → high degree of fine-tuning
- **SUSY can (in principle) “naturally” solve the hierarchy problem**
  - Superpartners add loop corrections which cancel the SM loop correction quadratic terms (but logarithmic terms remain)
  - Often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



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



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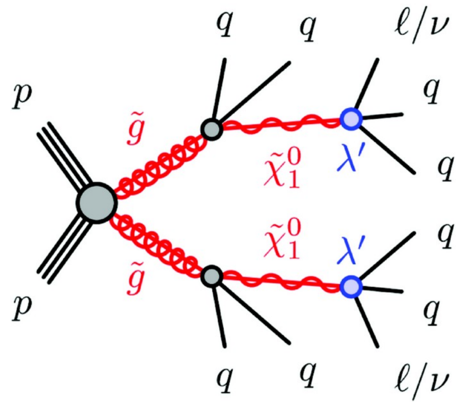
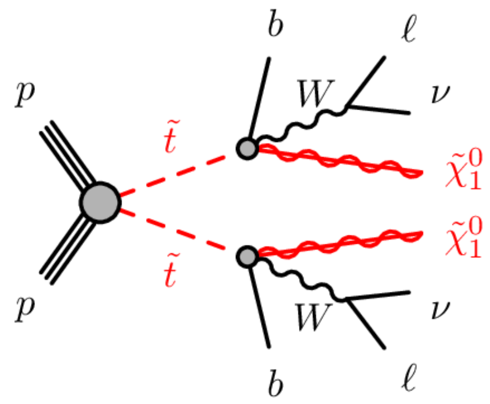


ATLAS-SUSY-2020-27



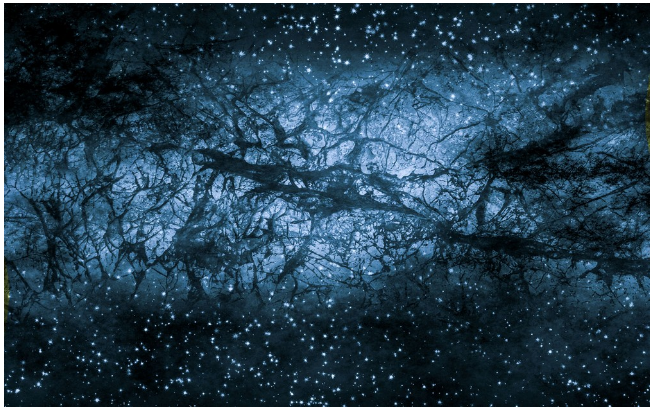
ATLAS-SUSY-2018-08

R-parity and Dark Matter

rpp2022-rev-susy-1-theory

- SM is B-L invariant (B = baryon number, L = lepton number)
  → in general SUSY breaks this → proton becomes unstable
  but it can explain Matter-Antimatter Asymmetry
- 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!!**

  (but then SUSY cannot explain Matter-Antimatter asymmetry)



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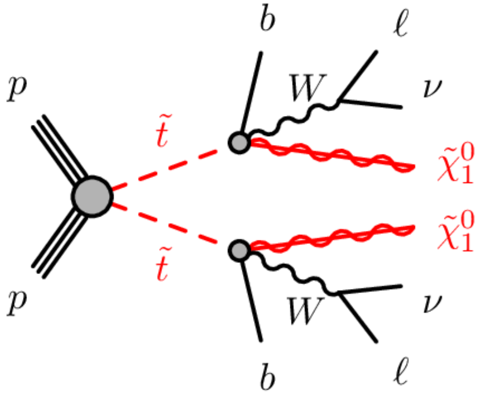
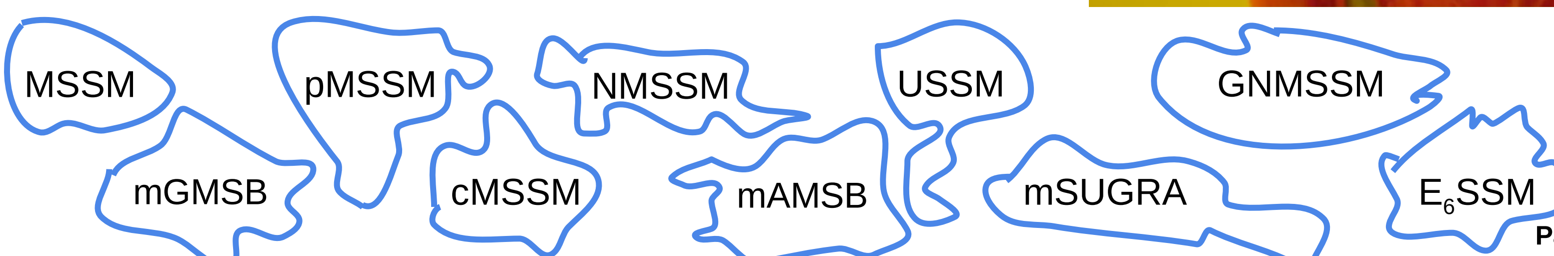


ATLAS-SUSY-2018-08

New issues with SUSY

- SUSY can solve many of the SM “problems”
  a. DM candidate if R-parity is conserved
  b. matter/anti-matter asymmetry if R-partity is violated, but then you have flavor changing neutral currents as well, proton decay
  c. Hierarchy problem
  d. Unify the three forces at higher energy (see next pages)
  e. Add gravity (some SUSY models)
- Minimal broken model: MSSM
  → 124 free parameters (SUSY is broken)
  → Very many SUSY models around

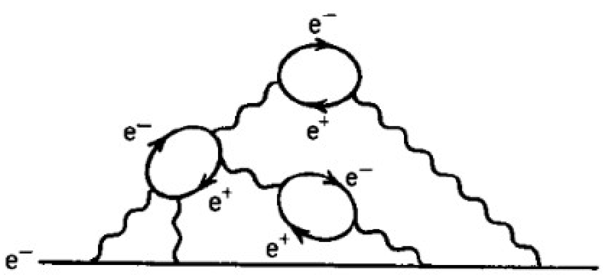
https://imgflip.com/s/meme/Drake-Hotline-Bling.jpg

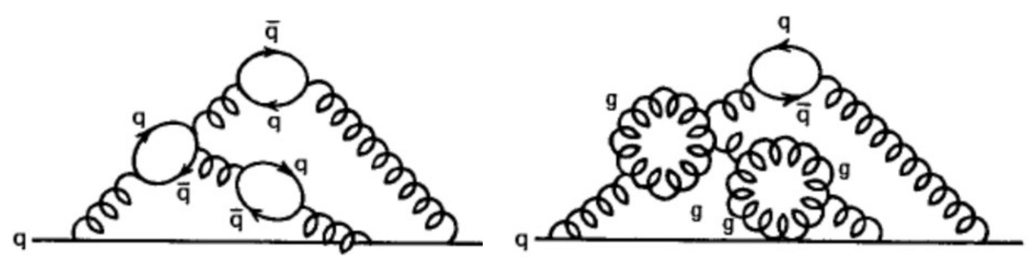


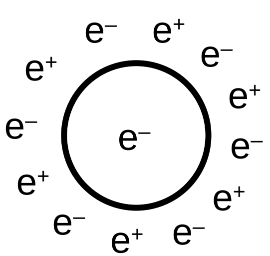
(Anti-) Screening

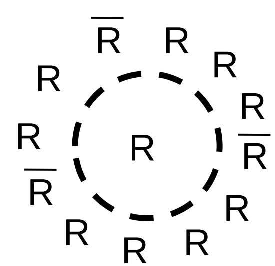
https://www.nikhef.nl/~h24/qcdcourse/section-all.pdf

- 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





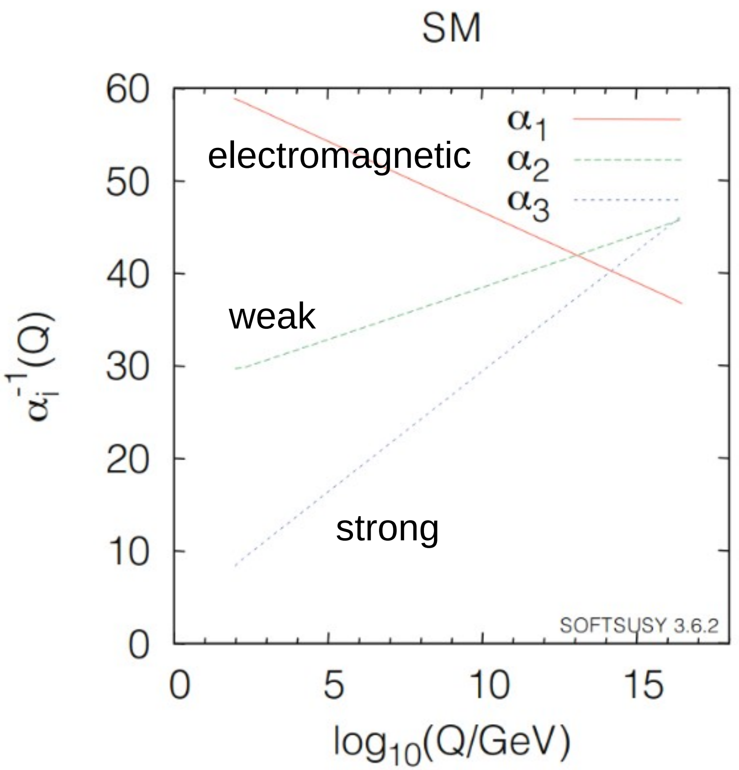




Running coupling & GUTs

rpp2022-rev-guts

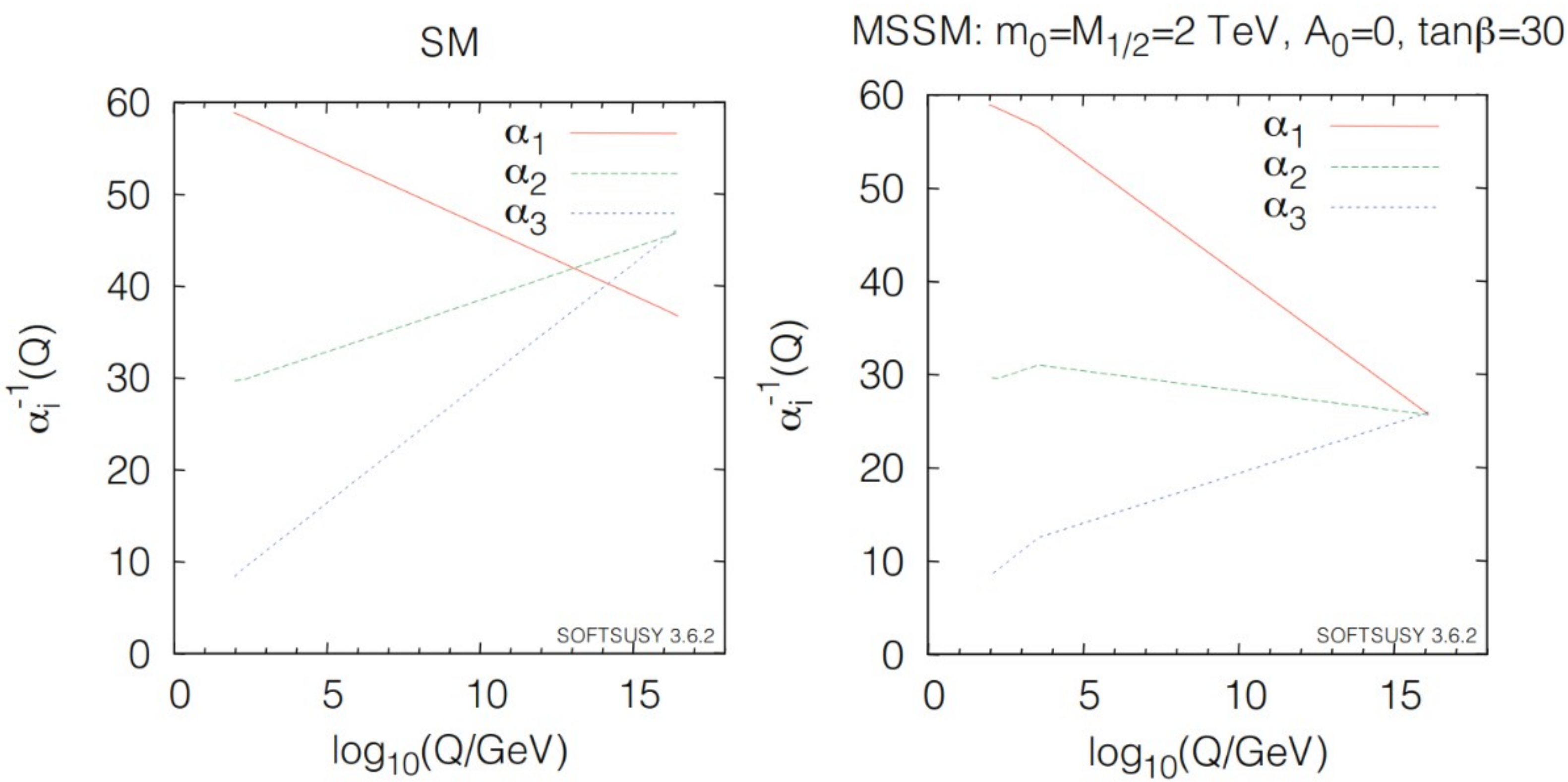
- Leads to a concept called running coupling: the coupling constant is a function of energy
- QED: coupling constant diverges as energy → 0
- QCD/Weak theory: coupling constant diverges as energy → ∞
- Coupling constants almost equal at 10^{15} GeV → **are they part of one unified theory?**
- SM: U(1) 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

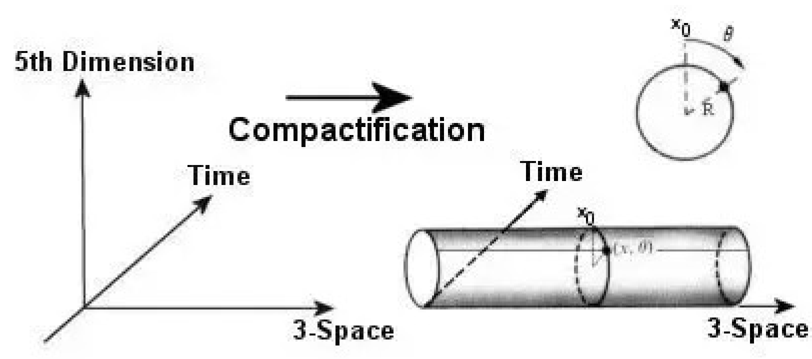
- Many theories contain grand unification:
  - SUSY
  - Extra dimension theories
- GUTs predict additional particles → make proton unstable → test GUTs



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)

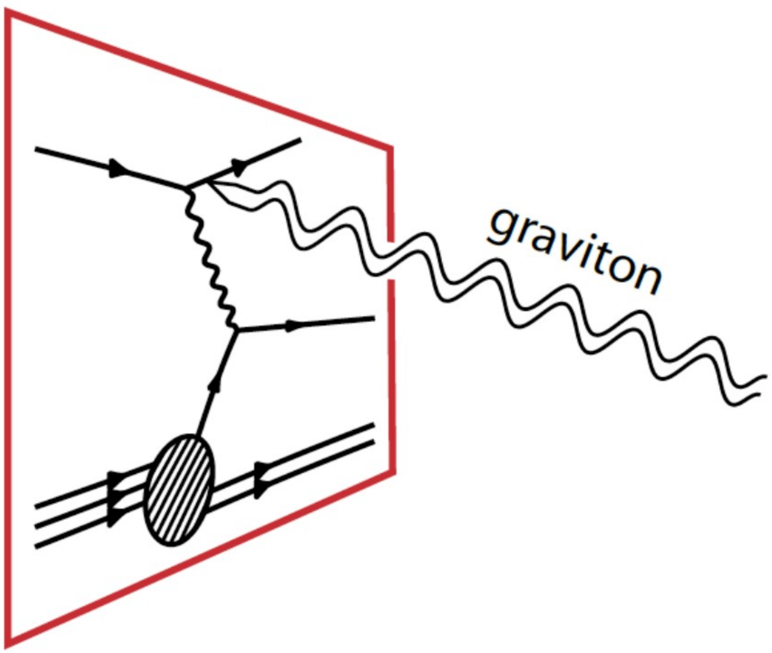


https://qph.cf2.quoracdn.net/main-qimg-c94bb8642d2ebf23fc32aed446a2c397.webp

ADD extra dimension models

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

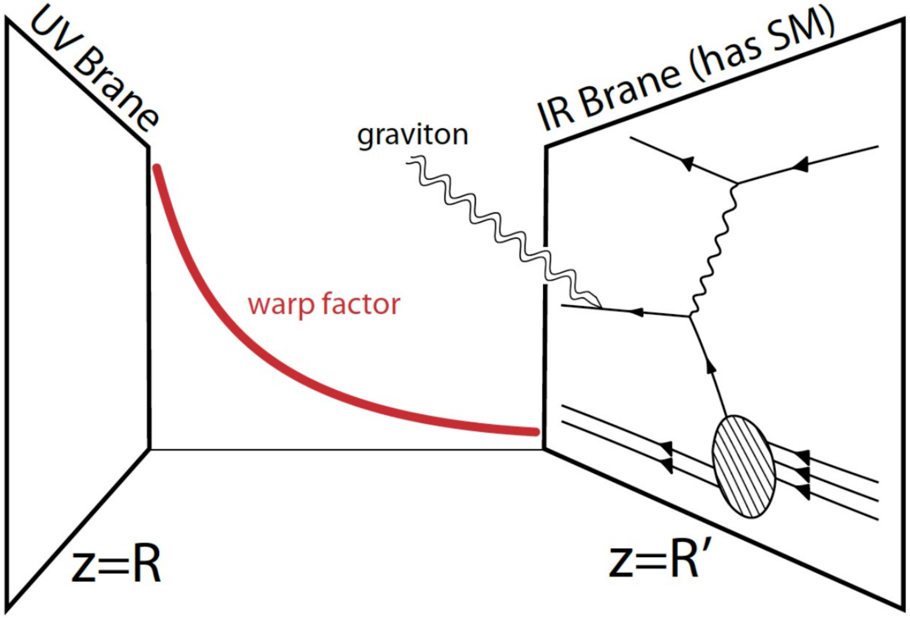
- ADD (Arkani-Hamed, Dimopoulos, Dvali) theory builds on KK approach:
  - SM is only realised in 3+1 spacetime, a “brane”
  - Gravity propagates through δ other compact dimensions of size R, thereby being diluted at length scales >> R
  - Gravity is stronger at length scales < R, but weaker > R
  - ADD 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 ~ 10^9 km → would be known
    → δ=2: R ≤ 0.5 mm → possible
    → δ=6: R ≤ 0.1 MeV^{-1}
  - Experiments which test gravitation on very small scale exist (CHORUS)



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



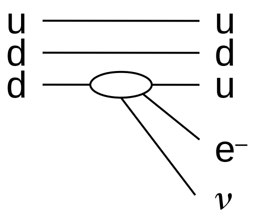
https://www.zeuthen.desy.de/students/2019/Lectures/Pueschel_Lecture1_BeyondSM_2019.pdf

Effective Field Theories

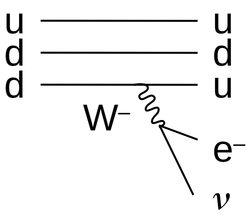
arxiv:1804.05863

- 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 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 then the accelerator
  - These new particles are not directly produced, but exist in propagator, lead to interactions → analogous to Fermi-beta-decay theory
- Use a effective very general Lagrangian with all possible forms of interactions and fit data to it
- EFT does not explicitly solve SM problems, but give hints what the new physics contains

Fermi interaction



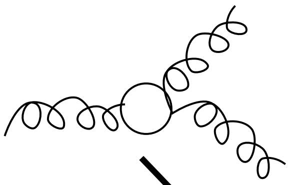
Standard Model



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)

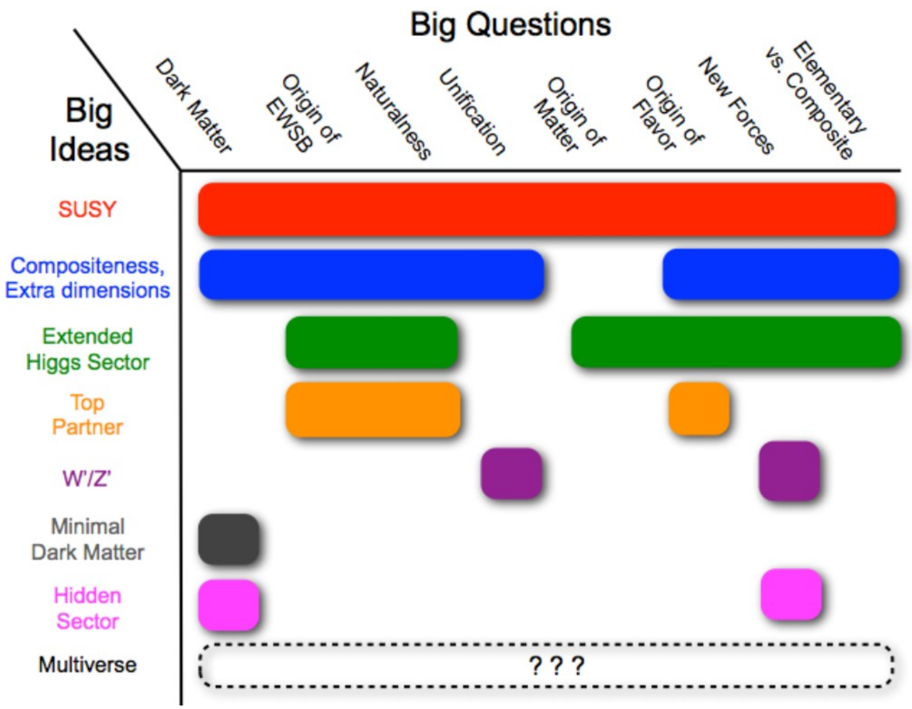


$$\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm SM}^{(4)} + \frac{1}{\Lambda}\sum_k C_k^{(5)} Q_k^{(5)} + \frac{1}{\Lambda^2}\sum_k C_k^{(6)} Q_k^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

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 ;)



Thank you