Physics Beyond the Standard Model

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ปฏิภาณ อุทยารัตน์

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Theoretical High Energy Physics & Astrophysics

โครงการอบรมฟิสิกส์อนุภาคพื้นฐาน
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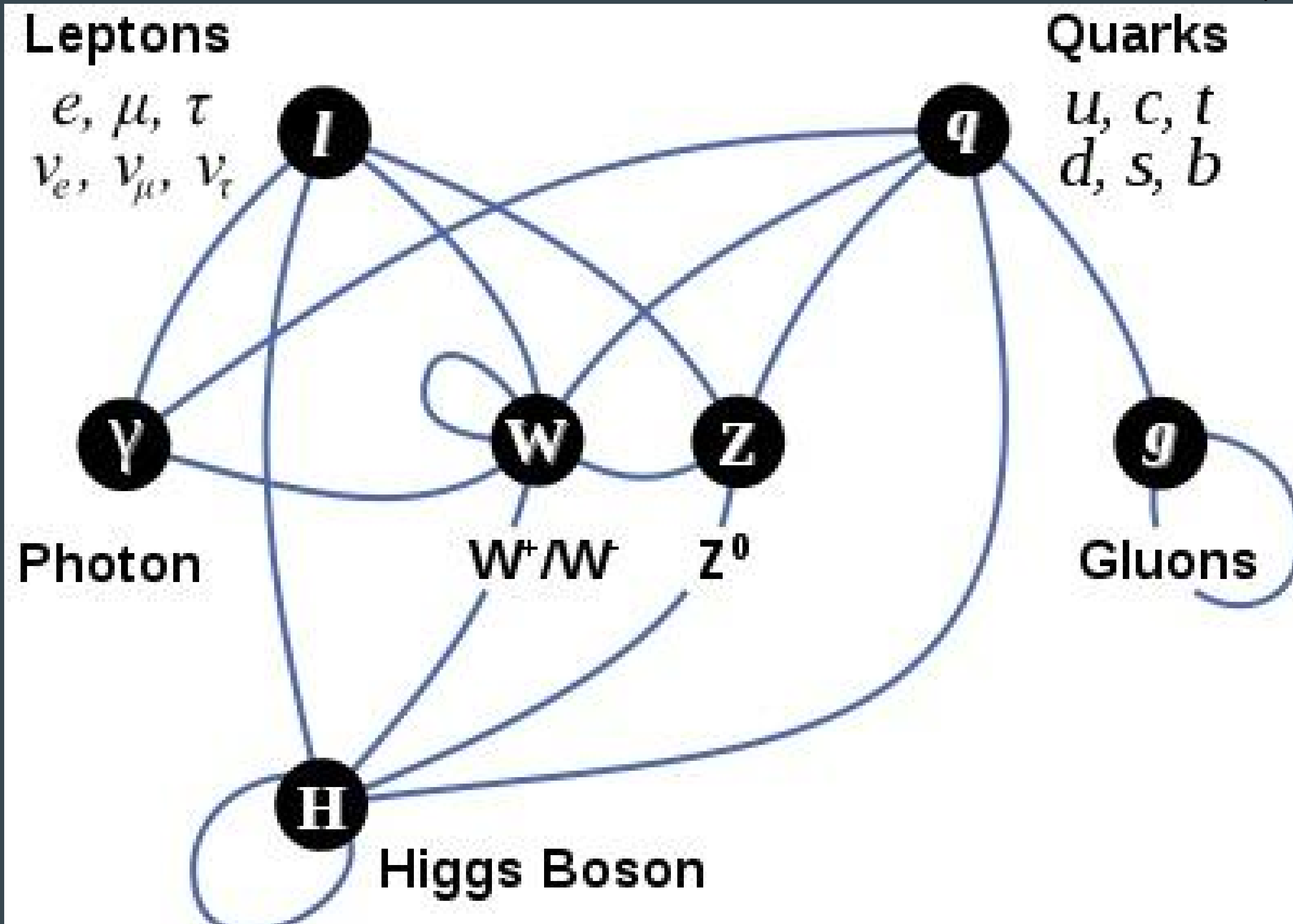
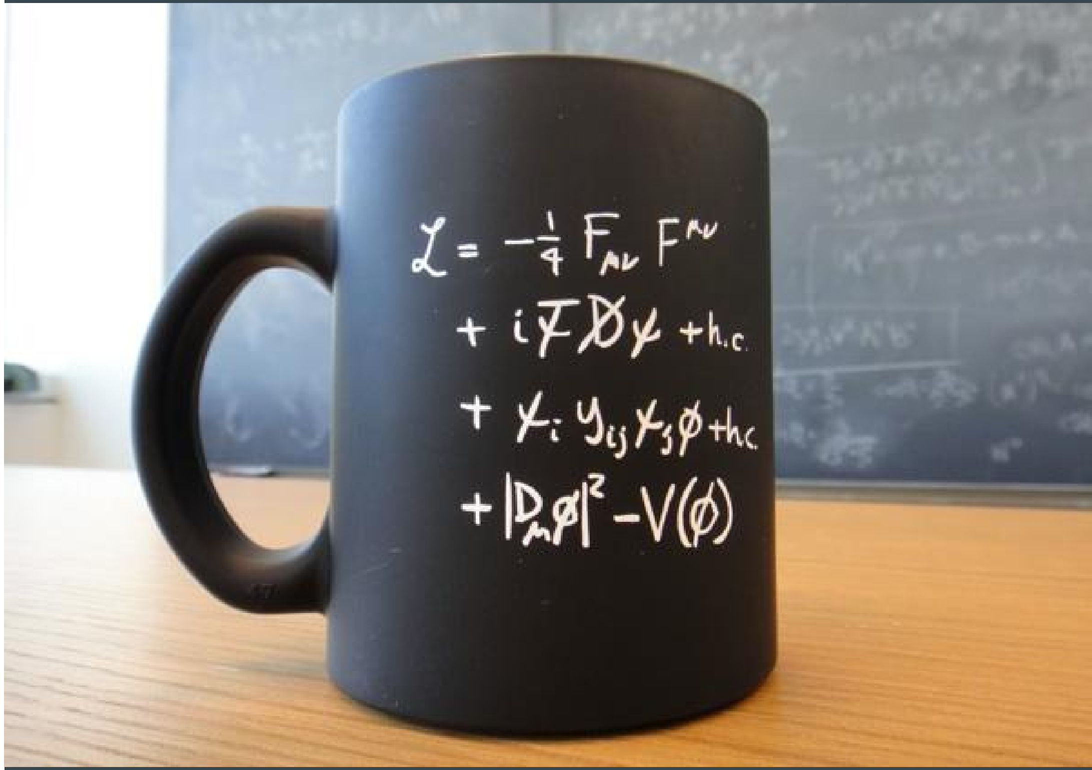
The Standard Model of Particle Physics



SM Lagrangian

Theoretical High Energy Physics & Astrophysics

$$-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu +$$
$$\frac{1}{2}ig_s^2(\bar{q}^\sigma_i \gamma^\mu q^\sigma_j) g^a_\mu + \bar{G}^a \partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu -$$
$$M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2c_w^2} M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H -$$
$$\frac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h [\frac{2M^2}{g^2} +$$
$$\frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-)] + \frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu -$$
$$W^-_\nu \partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu (W^+_\mu \partial_\nu W^-_\mu -$$
$$W^-_\mu \partial_\nu W^+_\mu) + A_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - \frac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu +$$
$$\frac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2 (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) +$$
$$g^2 s_w^2 (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w [A_\mu Z^0_\nu (W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] -$$
$$\frac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2 H^2] -$$
$$gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c_w^2} Z^0_\mu Z^0_\mu H - \frac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) -$$
$$W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \frac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ -$$
$$\phi^+\partial_\mu H)] + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s_w^2}{c_w} M Z^0_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) +$$
$$igs_w M A_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) - ig\frac{1-2c_w^2}{2c_w} Z^0_\mu (\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) +$$
$$igs_w A_\mu (\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \frac{1}{4}g^2 W^+_\mu W^-_\mu [H^2 + (\phi^0)^2 + 2\phi^+\phi^-] -$$
$$\frac{1}{4}g^2\frac{1}{c_w^2} Z^0_\mu Z^0_\mu [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-] - \frac{1}{2}g^2\frac{s_w^2}{c_w} Z^0_\mu \phi^0 (W^+_\mu \phi^- +$$
$$W^-_\mu \phi^+) - \frac{1}{2}ig^2\frac{s_w^2}{c_w} Z^0_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) + \frac{1}{2}g^2 s_w A_\mu \phi^0 (W^+_\mu \phi^- +$$
$$W^-_\mu \phi^+) + \frac{1}{2}ig^2 s_w A_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) - g^2\frac{s_w}{c_w}(2c_w^2 - 1) Z^0_\mu A_\mu \phi^+ \phi^- -$$
$$g^1 s_w^2 A_\mu A_\mu \phi^+ \phi^- - \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar{\nu}^\lambda \gamma\partial \nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m_u^\lambda)u^\lambda_j -$$
$$\bar{d}^\lambda_j(\gamma\partial + m_d^\lambda)d^\lambda_j + igs_w A_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \frac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] +$$
$$\frac{ig}{4c_w} Z^0_\mu [(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\frac{4}{3}s_w^2 -$$
$$1 - \gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1 - \frac{8}{3}s_w^2 - \gamma^5)d^\lambda_j)] + \frac{ig}{2\sqrt{2}} W^+_\mu [(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) +$$
$$(\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \frac{ig}{2\sqrt{2}} W^-_\mu [(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1 +$$
$$\gamma^5)u^\lambda_j)] + \frac{ig}{2\sqrt{2}}\frac{m_e^\lambda}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] -$$
$$\frac{g}{2}\frac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) +$$
$$m_u^\lambda(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \frac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m_u^\kappa(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1 -$$
$$\gamma^5)u^\kappa_j] - \frac{g}{2}\frac{m_u^\lambda}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \frac{g}{2}\frac{m_d^\lambda}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \frac{ig}{2}\frac{m_u^\lambda}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) -$$
$$\frac{ig}{2}\frac{m_d^\lambda}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 -$$
$$\frac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- -$$
$$\partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y -$$
$$\partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ -$$
$$\partial_\mu\bar{X}^- X^-) - \frac{1}{2}gM[\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2}\bar{X}^0 X^0 H] +$$
$$\frac{1-2c_w^2}{2c_w} igM[\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^-] + \frac{1}{2c_w} igM[\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] +$$
$$igMs_w[\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \frac{1}{2}igM[\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]$$



The Success of the Standard Model

The Higgs Boson

- SM predicts an existence of a neutral spin-0 (boson) particle.
- After ~50 years search, ATLAS and CMS (at CERN) found it in 2012.

g-factor of an Electron

- Ratio of magnetic dipole moment to spin
- Dirac equation predicts g = 2
- Anomalous g-factor (g/2)
    - Theory: 1. 001 159 652 177 60 (520)
    - Experiment: 1. 001 159 652 180 73 (28)

Many more successes for SM

Quantity	Value	Standard Model	Pull
m_t [GeV]	173.34 ± 0.81	173.76 ± 0.76	-0.5
M_W [GeV]	80.387 ± 0.016	80.361 ± 0.006	1.6
	80.376 ± 0.033		0.4
Γ_W [GeV]	2.046 ± 0.049	2.089 ± 0.001	-0.9
	2.195 ± 0.083		1.3
M_H [GeV]	125.09 ± 0.24	125.11 ± 0.24	0.0
$\rho_{\gamma W}$	-0.03 ± 0.20	-0.02 ± 0.02	0.0
$\rho_{\tau Z}$	-0.27 ± 0.31	0.00 ± 0.03	-0.9
$g_V^{\nu e}$	-0.040 ± 0.015	-0.0397 ± 0.0002	0.0
$g_A^{\nu e}$	-0.507 ± 0.014	-0.5064	0.0
$Q_W(e)$	-0.0403 ± 0.0053	-0.0473 ± 0.0003	1.3
$Q_W(p)$	0.064 ± 0.012	0.0708 ± 0.0003	-0.6
$Q_W(\mathrm{Cs})$	-72.62 ± 0.43	-73.25 ± 0.02	1.5
$Q_W(\mathrm{Tl})$	-116.4 ± 3.6	-116.91 ± 0.02	0.1
$\hat{s}_Z^2(\mathrm{eDIS})$	0.2299 ± 0.0043	0.23129 ± 0.00005	-0.3
τ_τ [fs]	290.88 ± 0.35	289.85 ± 2.12	0.4
$\frac{1}{2}(g_\mu - 2 - \frac{\alpha}{\pi})$	$(4511.18 \pm 0.78) \times 10^{-9}$	$(4507.89 \pm 0.08) \times 10^{-9}$	4.2

Non Z-pole observables from the Particle Data Group 2016

SM is not Enough!!!

Key Issues in Particle Physics

Theoretical High Energy Physics & Astrophysics

Experiment

- Neutrino
  - Neutrino oscillation
  - Nobel Prize: 2002, 2015
- Dark Matter
  - Rotational curves of galaxies
  - Bullet Cluster
- Why is there more matter than anti-matter?
  - Baryogenesis
  - CP Violation (Nobel Prize: 2011)
- ....

Theory

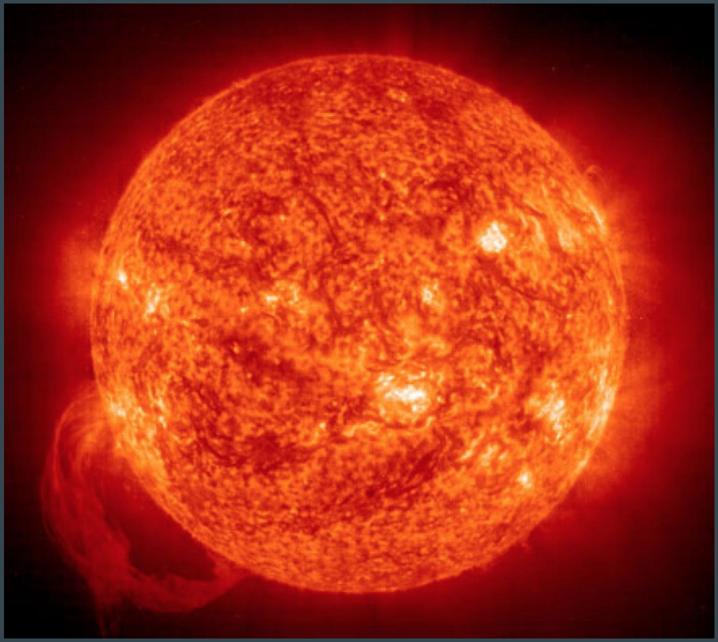
- Fine-tuning Problem
  - Why is the mass of the Higgs boson so “light”?
- Grand Unification
  - One fundamental interaction?
- Dark Energy
  - Accelerated expansion of the universe
  - Nobel Prize: 2011
- ......

Neutrino

Solar Neutrino Problem

Theoretical High Energy Physics & Astrophysics

- Nuclear reactions in the Sun produce neutrinos as a by product.
- We can detect these neutrinos on Earth.
- Homestake Experiment (1970)
    - Detected only ⅓ of the solar neutrinos were detected..
    - Nobel Prize in 2002.



Homestake Experiment

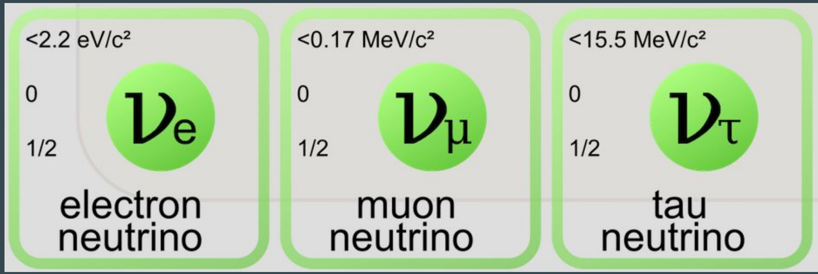
Theoretical High Energy Physics & Astrophysics

Where is the other ⅔?

- Recall nuclear reaction in the Sun

$$p + p \longrightarrow d + e^{+} + \nu_e$$

- Recall SM



- Homestake experiment can only detect ν_e
- From the Sun → Earth: $\nu_e \longrightarrow \nu_\mu, \nu_\tau$ (neutrino oscillation).
- Confirmed by Super-K and SNO (Nobel Prize 2015).

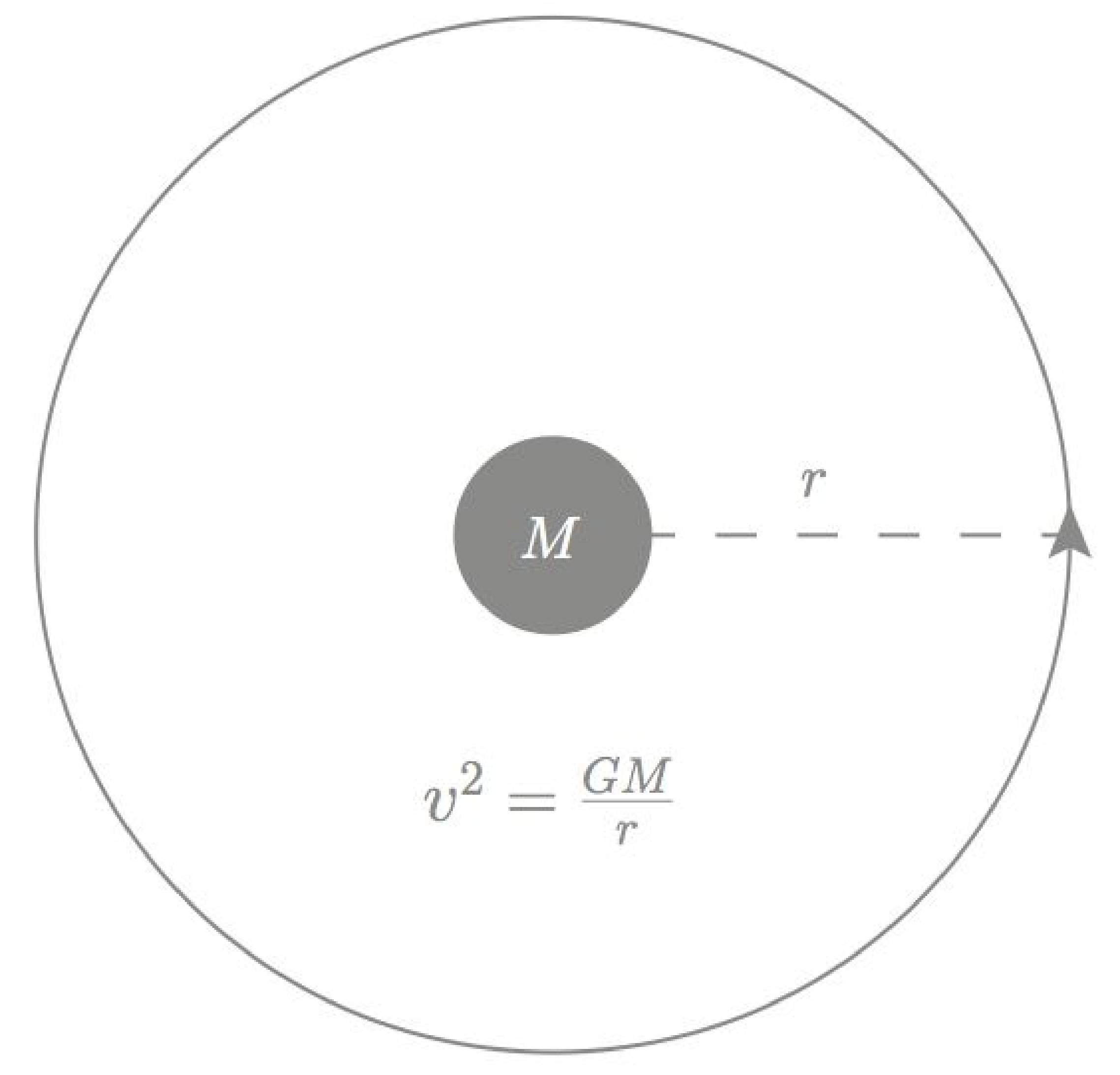
Neutrino Oscillation

- For oscillation to occur, neutrinos must have mass.
  - Need both left-handed and right-handed neutrinos.
  - (In QM: 3-state system with non-diag H.)
- In SM, neutrino is massless
  - All SM neutrinos are left-handed

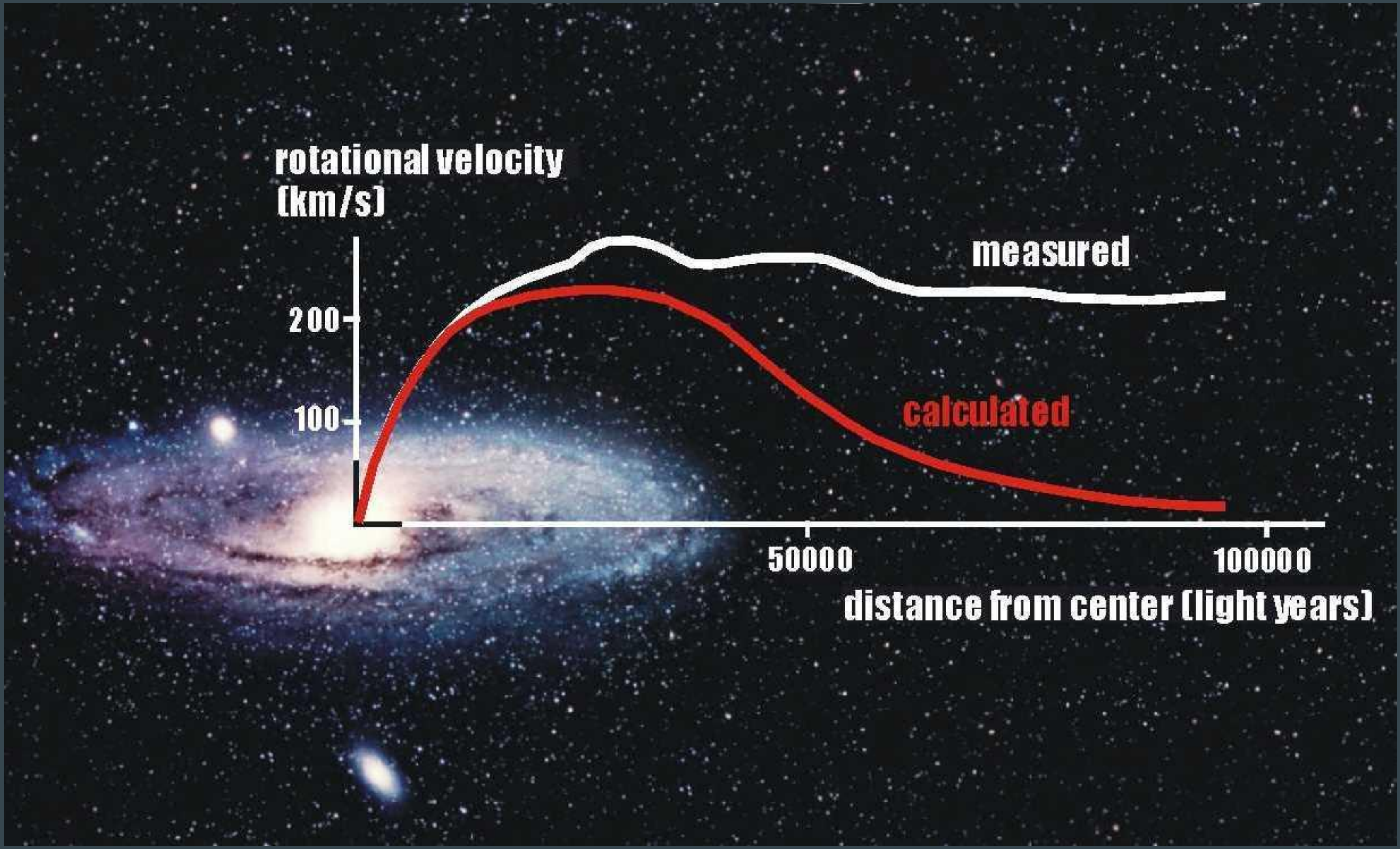
Neutrino Oscillation = Beyond SM Physics!!

Dark Matter

Star orbital velocities



Rotational Curve of Andromeda

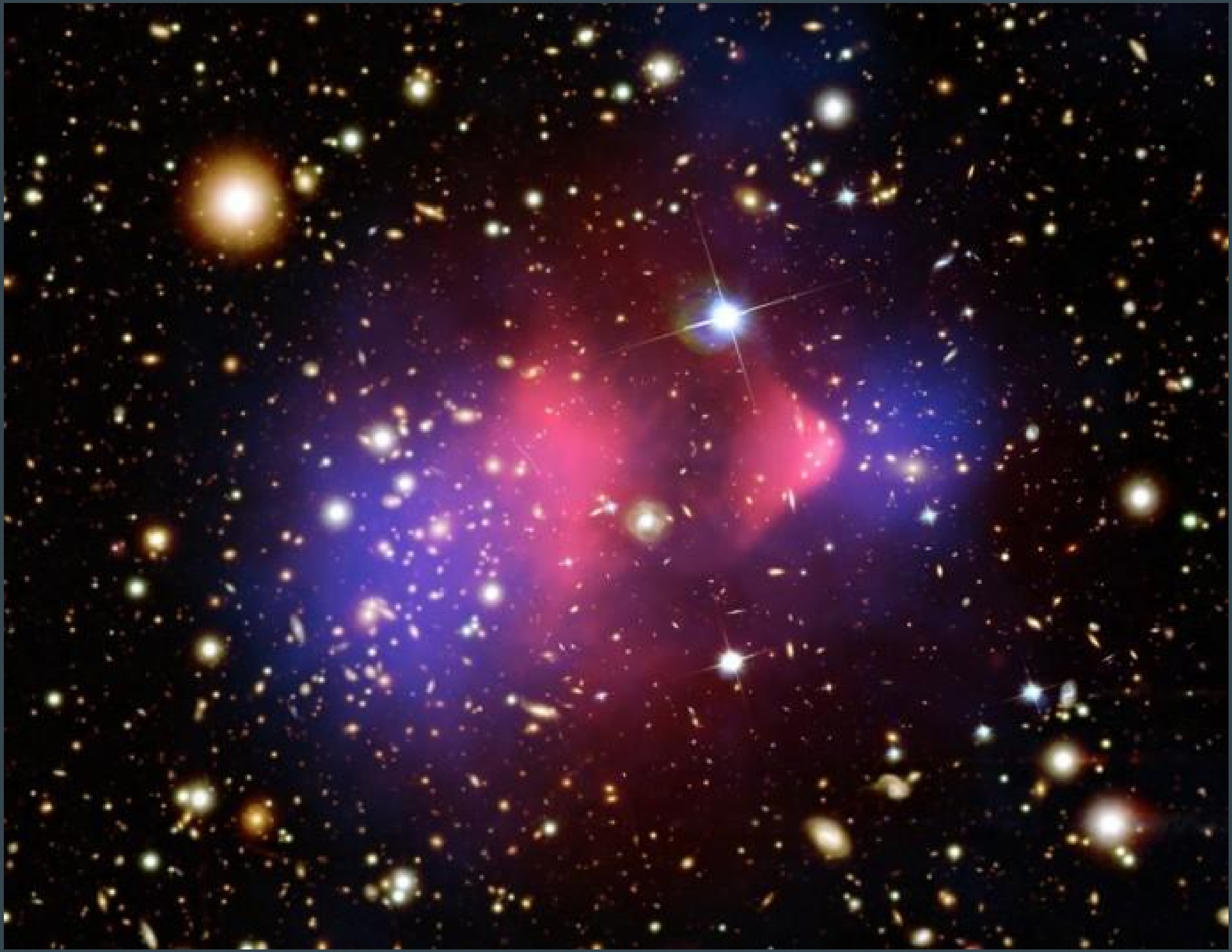


Non-luminous Matter

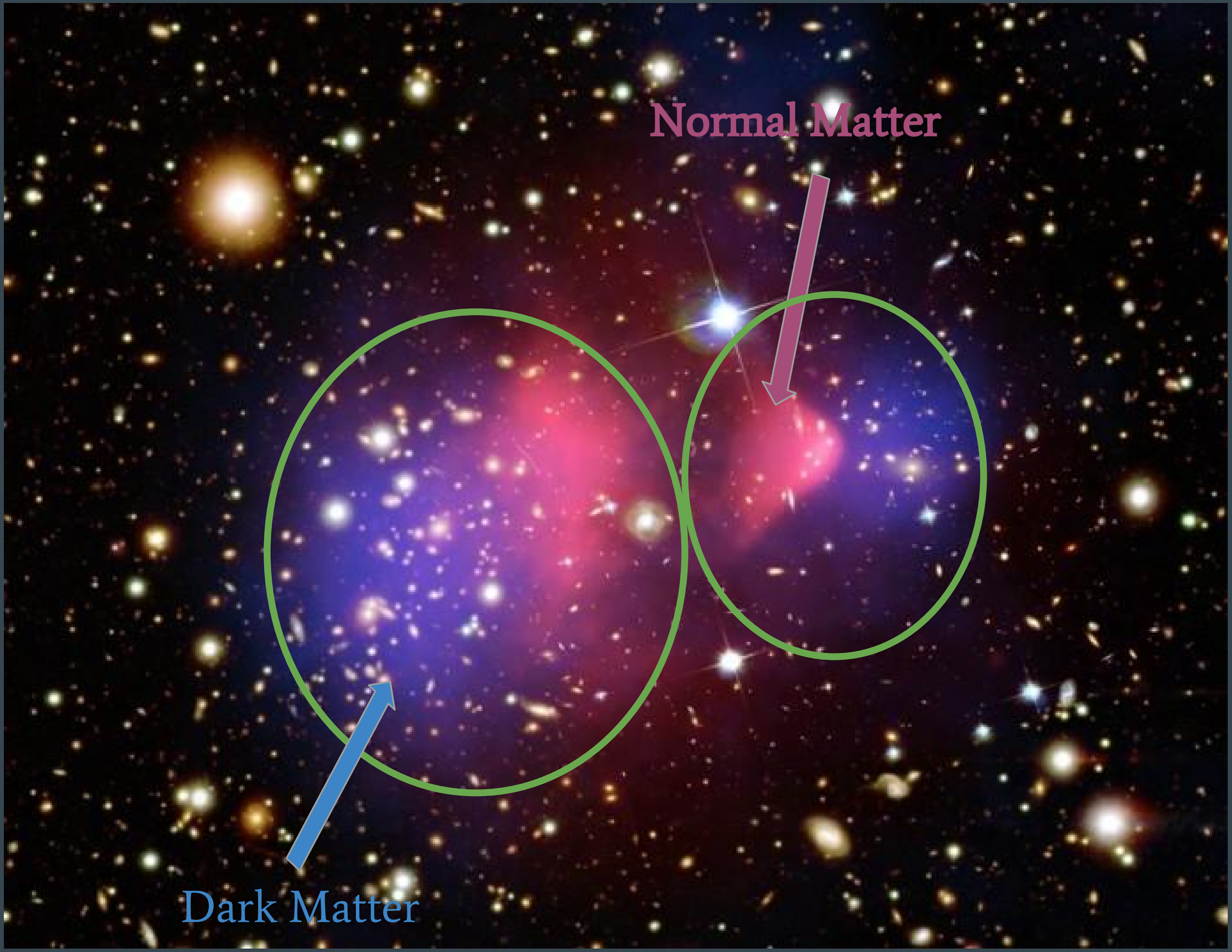
- From the rotational curve, either
  - Newton is wrong!, or
  - Must be more mass than we can see!
- *Newton is wrong:*
  - Gravity behaves differently at large distant.
  - Modified Newtonian Dynamics (MOND).
- *More mass than we can see:*
  - Extra mass must not emit light, ***"dark matter"***.
  - Most physicists believe in this option.

Weakly Interacting Matter

Theoretical High Energy Physics & Astrophysics



Weakly Interacting Matter



What is dark matter?

- Things we know about DM:
  - Electrically neutral.
  - Not interact with regular stuff much.
  - Stable.
- Unfortunately, there is no particle in SM with such properties.

Dark Matter = Beyond SM Physics!!

Why there is more matter than antimatter?

When Matter Meets Antimatter

More Precise Statement

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- Most stuff around us are baryons
  - Earth, moon, sun, etc.
- When the universe starts, there is nothing.
- Stuff are created later once the universe cooled down.
  - Naively, we expect baryons and anti-baryons are created equally.
  - Net baryon number = 0!
- How do we get more baryons than anti-barryon?

The process that creates baryon number is called baryogenesis.

Key Ingredients for Baryogenesis

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- CP violation.
  - CP is a symmetry that relates matter and anti-matter.
  - In SM, this is provided by KM matrix (Nobel Prize 2008).
- Out of equilibrium process.
  - In equilibrium, process that generate baryon number and the reverse process cancel each other.
  - In SM, this is provided by the electroweak phase transition.

But in SM, both ingredients are too small.

Baryon asymmetry = Beyond SM Physics!!!

Key Issues in Particle Physics

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  - Nobel Prize: 2002, 2015
- Dark Matter
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- Why is there more matter than anti-matter?
  - Baryogensis.
  - CP Violation (Nobel Prize: 2011)
- ......

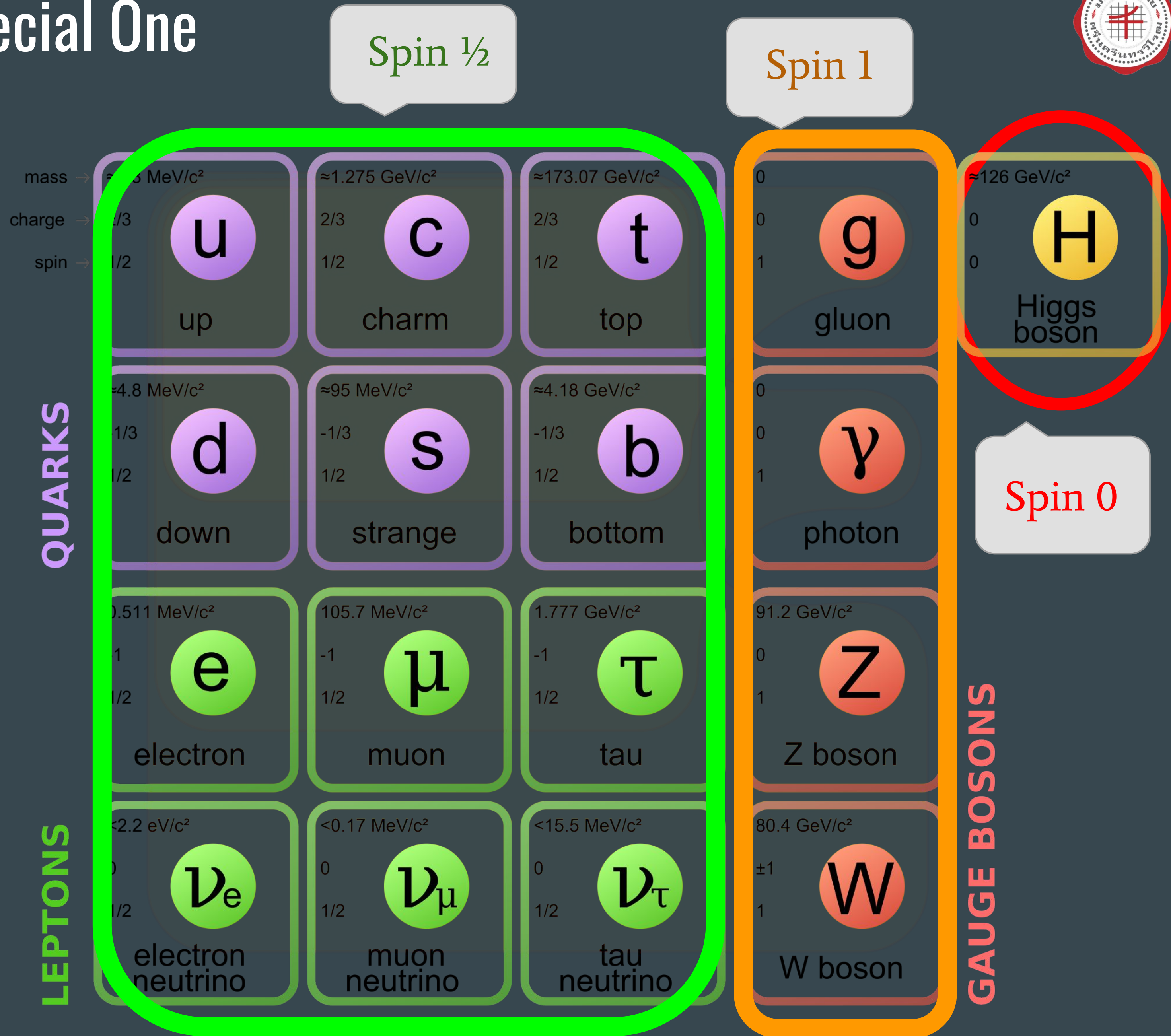
Theory

- Fine-tuning Problem
  - Why is the mass of the Higgs boson so “light”?
- Grand Unification
  - One fundamental interaction?
- Dark Energy
  - Accelerated expansion of the universe
  - Nobel Prize: 2011
- ......

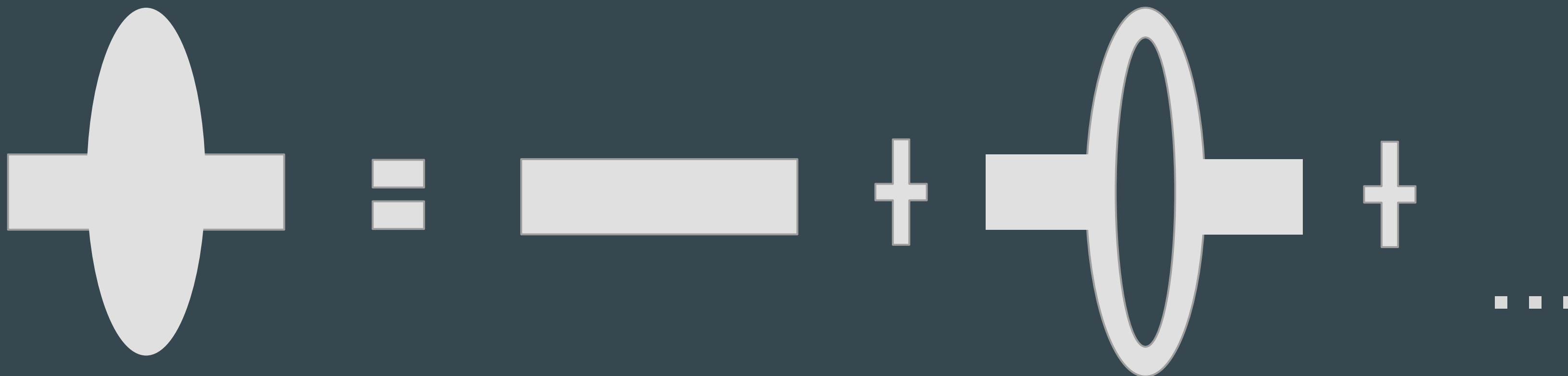
Fine-Tuning Problem

(why is the Higgs boson so light?)

The Special One



Quantum Correction to the Higgs Mass



Total M_H
125 GeV

Classical

Quantum
Corrections
~ 10^{19} GeV

Quantum Correction to the Higgs Mass

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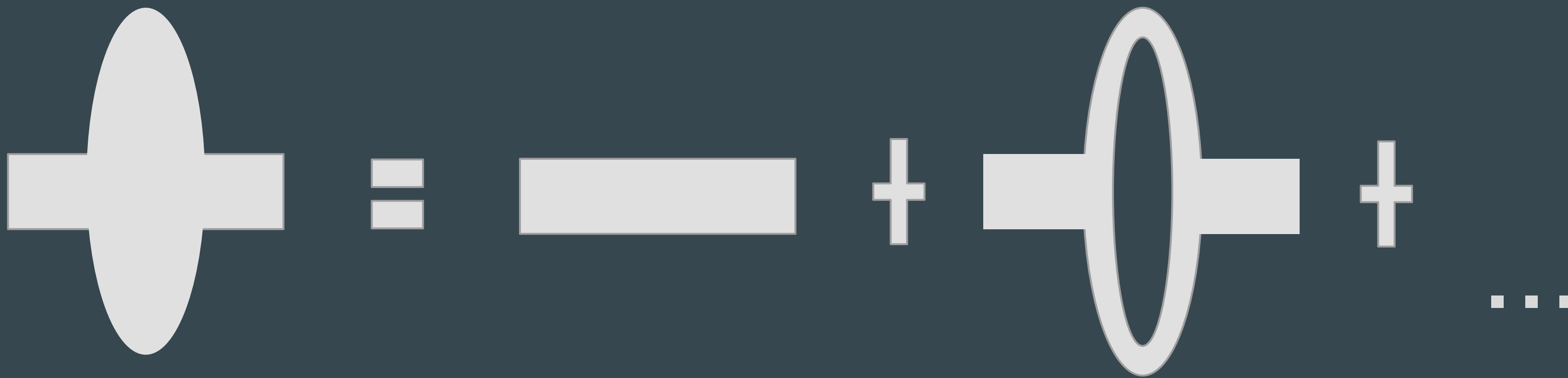


Total M_H
125 GeV

Classical

Quantum Corrections
$\sim 10^{19}$ GeV

Classical and Quantum Correction cancel each other to 1 in 10^{17}!!!

Example of Fine-Tuning in Everyday Life

Theoretical High Energy
Physics & Astrophysics

Net profit ฿125 a day ....
Which one is more likely?

Possible Solutions to Fine-Tuning Problem

- Supersymmetry (SUSY)
  - The most “popular” scenario.
  - Tame quantum corrections. Render them “small”.
- Higgs as a Goldstone Boson
  - Composite Higgs.
  - Little Higgs.
- Technicolor.
- ……

Grand Unification

(the theory of almost everything)

The Importance of Scale

- Strength of fundamental interaction

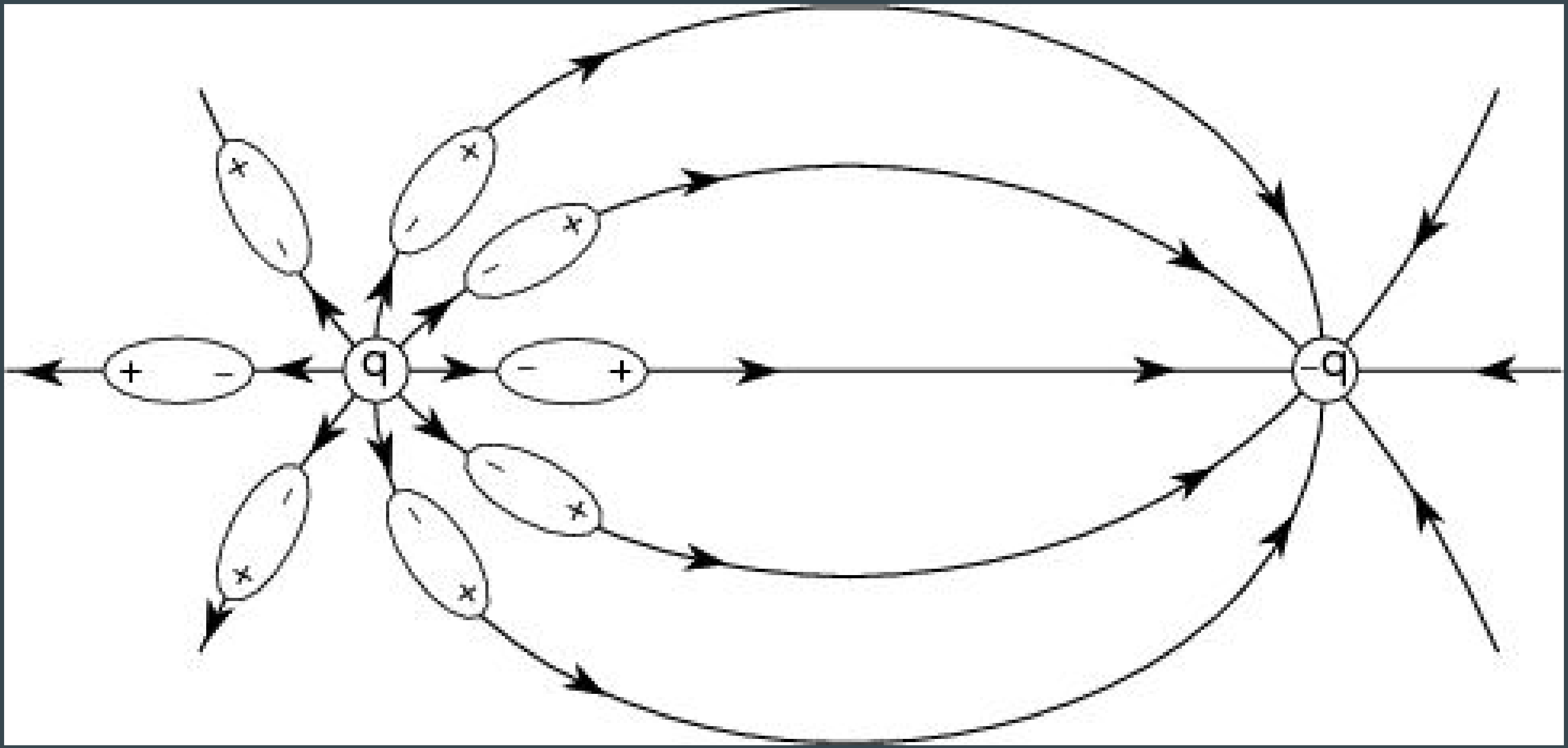
  E&M: interaction strength characterized by the fine structure constant

$$\alpha = e^2/4\pi = 1/137$$

  at the laboratory scale.

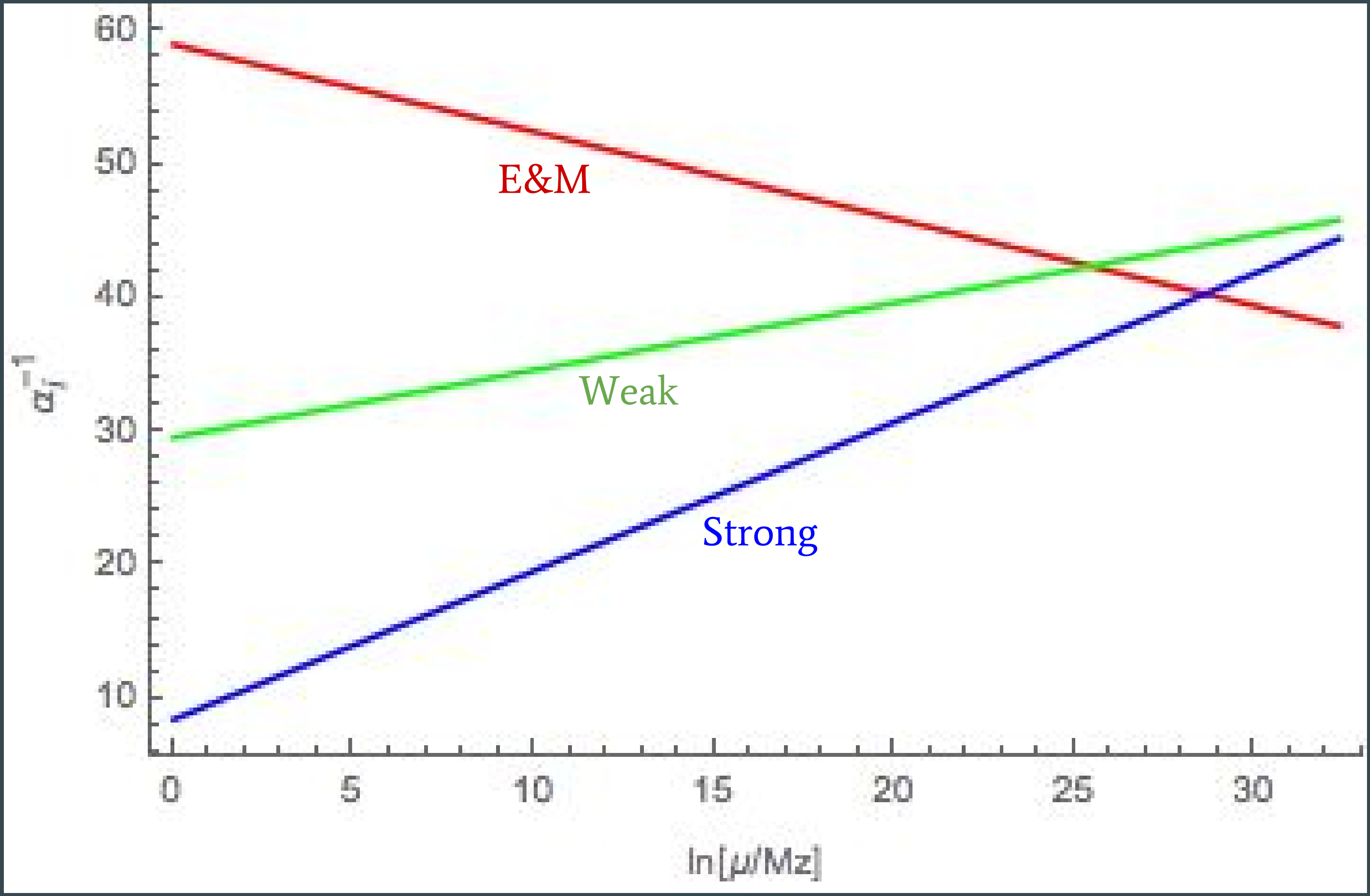
- Quantum effects change interaction strength.
  - Interaction strength depends on the scale that we probe them.

Vacuum Polarization



At large distance, there is a screening effect.

The 3 Interactions and the Scale



*Small distance = large mass scale

Grand Unification

- SM cannot unify the 3 interactions.
- New physics can unify them.
  - SUSY.
  - Model with colored scalars.
  - ……
- The price of unification.
  - Proton decays.

Interesting History on Proton Decay

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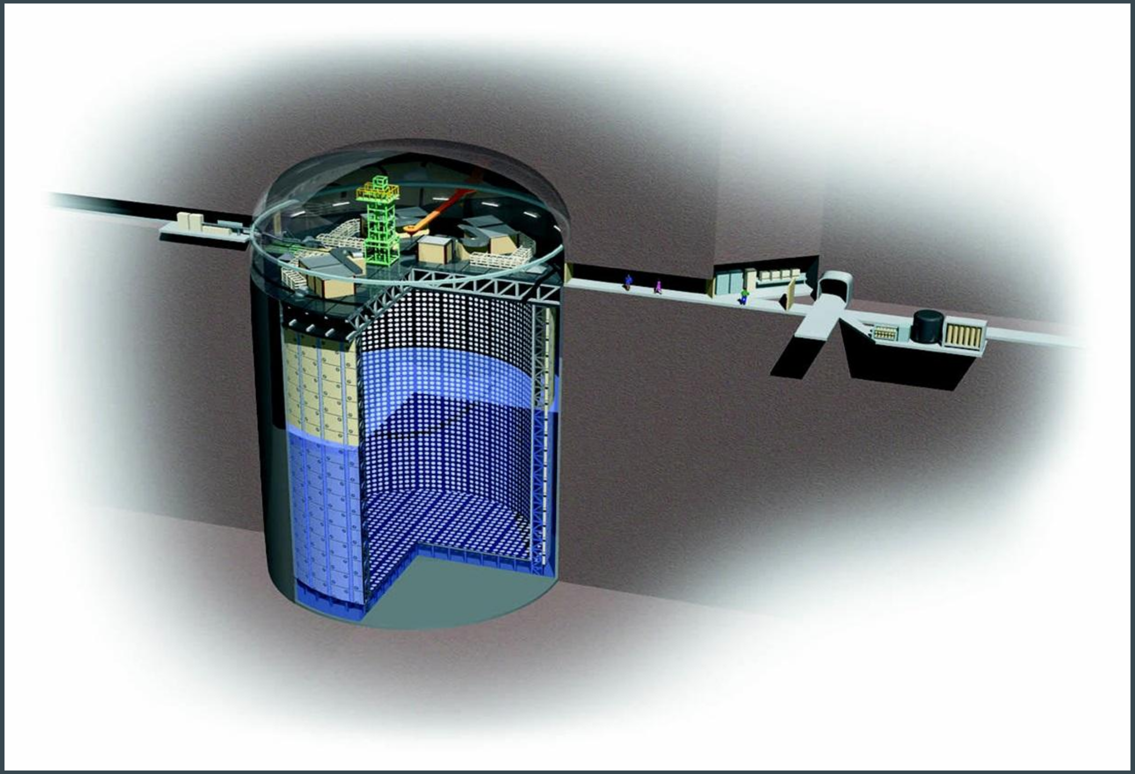
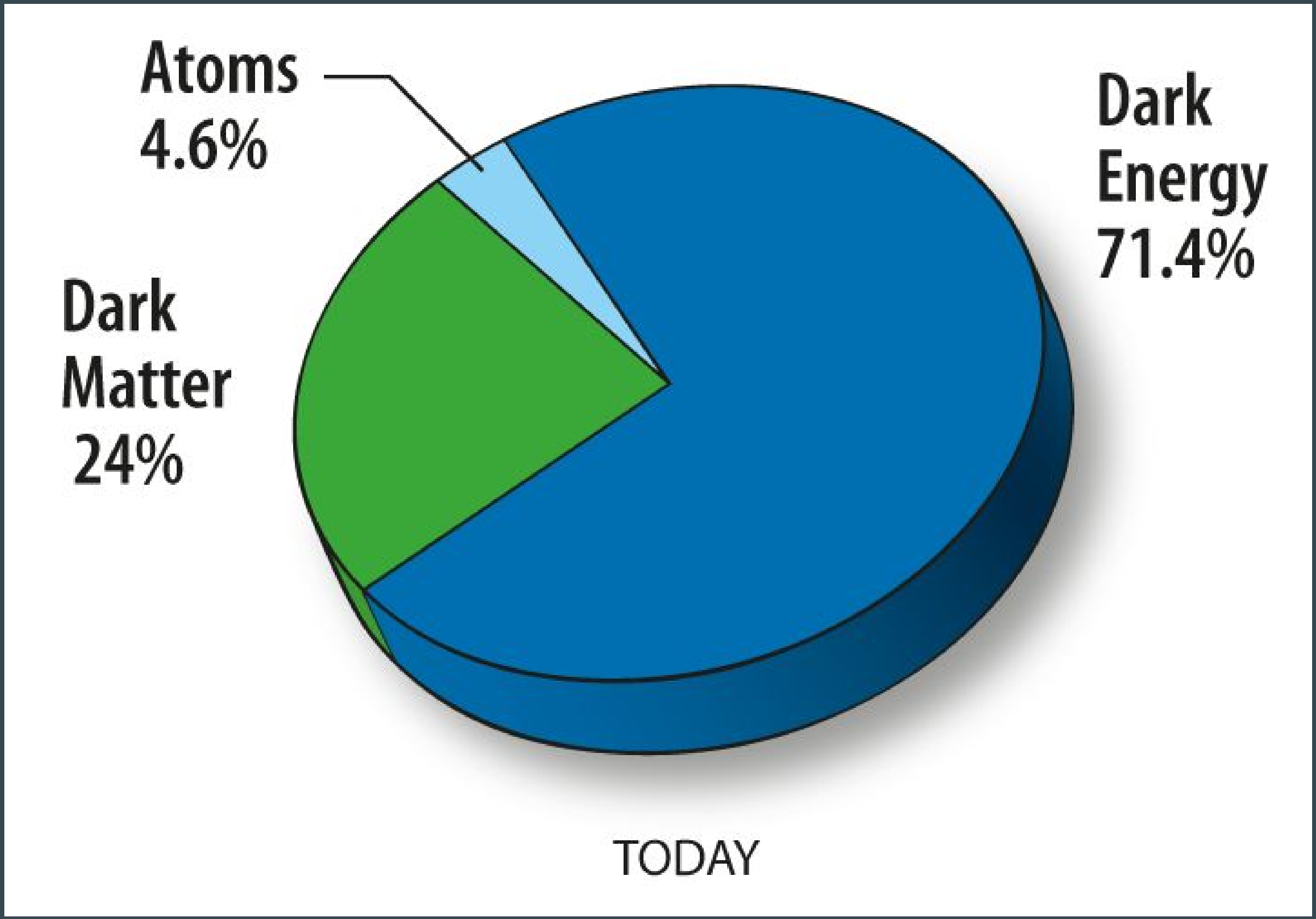


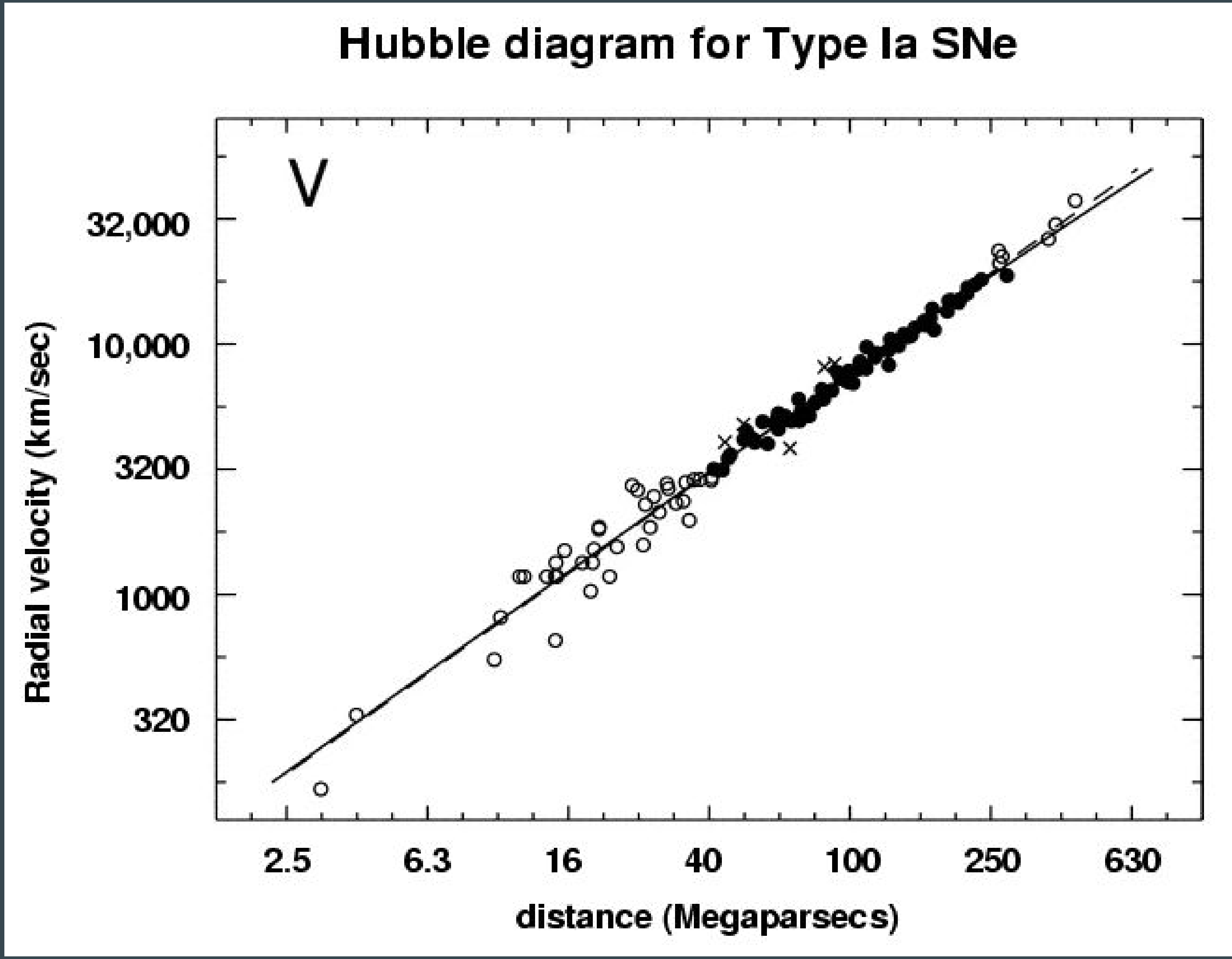
The KAMIOKANDE detector was built to search for proton decays. Instead, it discovered neutrino oscillation and won the Nobel Prize!

A Quick Word on Dark Energy

The Dark Universe



Distant Stars are Moving Away Faster!



The Accelerating Universe

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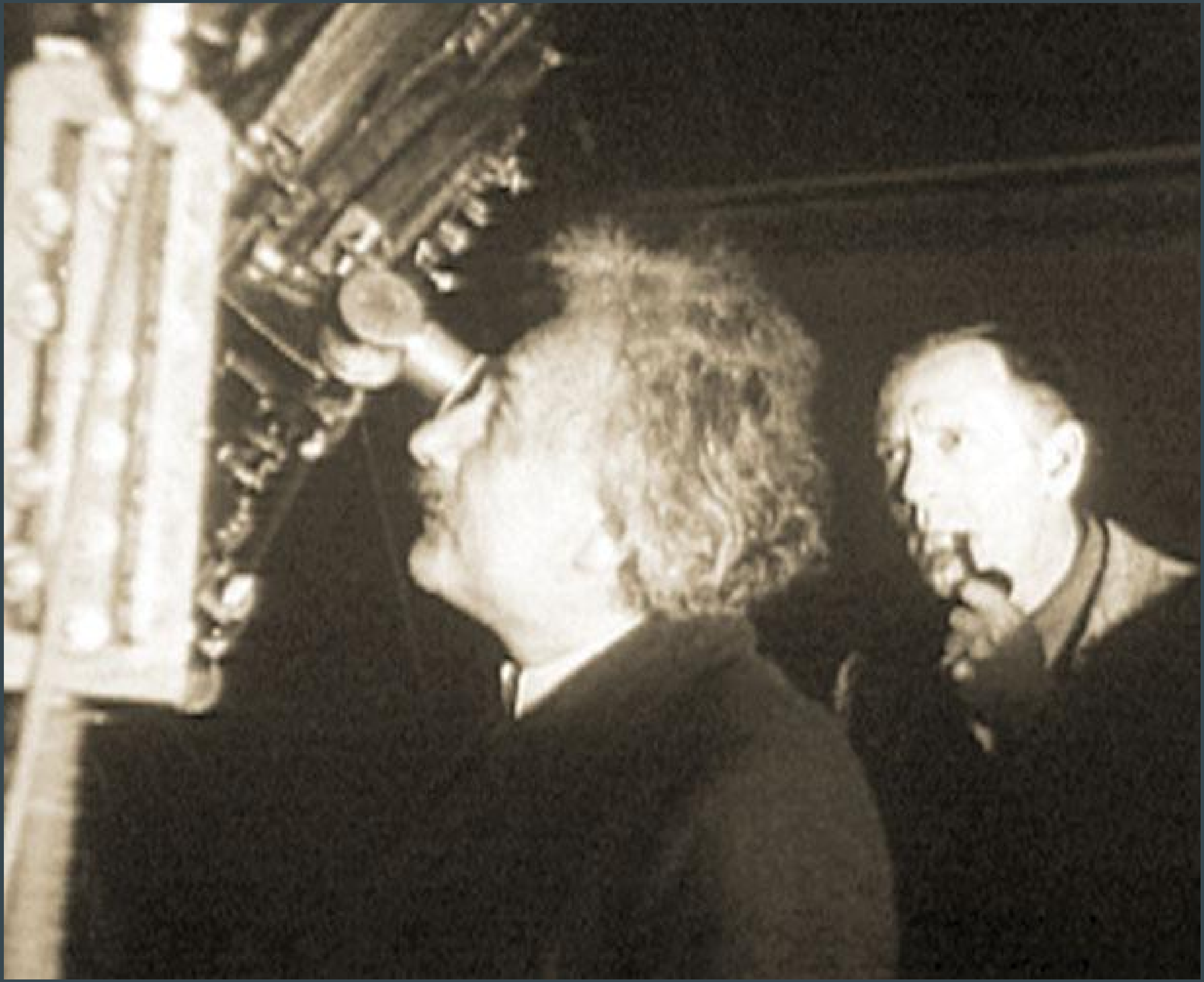

Vacuum Energy

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- Empty space has energy (Einstein's cosmological constant)
  - This is the driving force for the accelerated expansion of the universe.
  - Energy is no longer conserved (globally).
- Generic SM calculation gives too big the answer.
  - SM can't explain why CC is small.
  - *Probably* need *new physics* for the explanation.

Ex: SUPERSYMMETRY
(the dying star)

Theoretical High Energy Physics & Astrophysics

Why do we love SUSY?

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- It solves many problems.
  - Gives a dark matter candidate.
  - Alleviate a fine-tuning problem.
  - Unifies the strong, the weak and the electromagnetic interactions.
  - (more elementary particles for the experiments to discovery).

SUSY Relate Boson to Fermion

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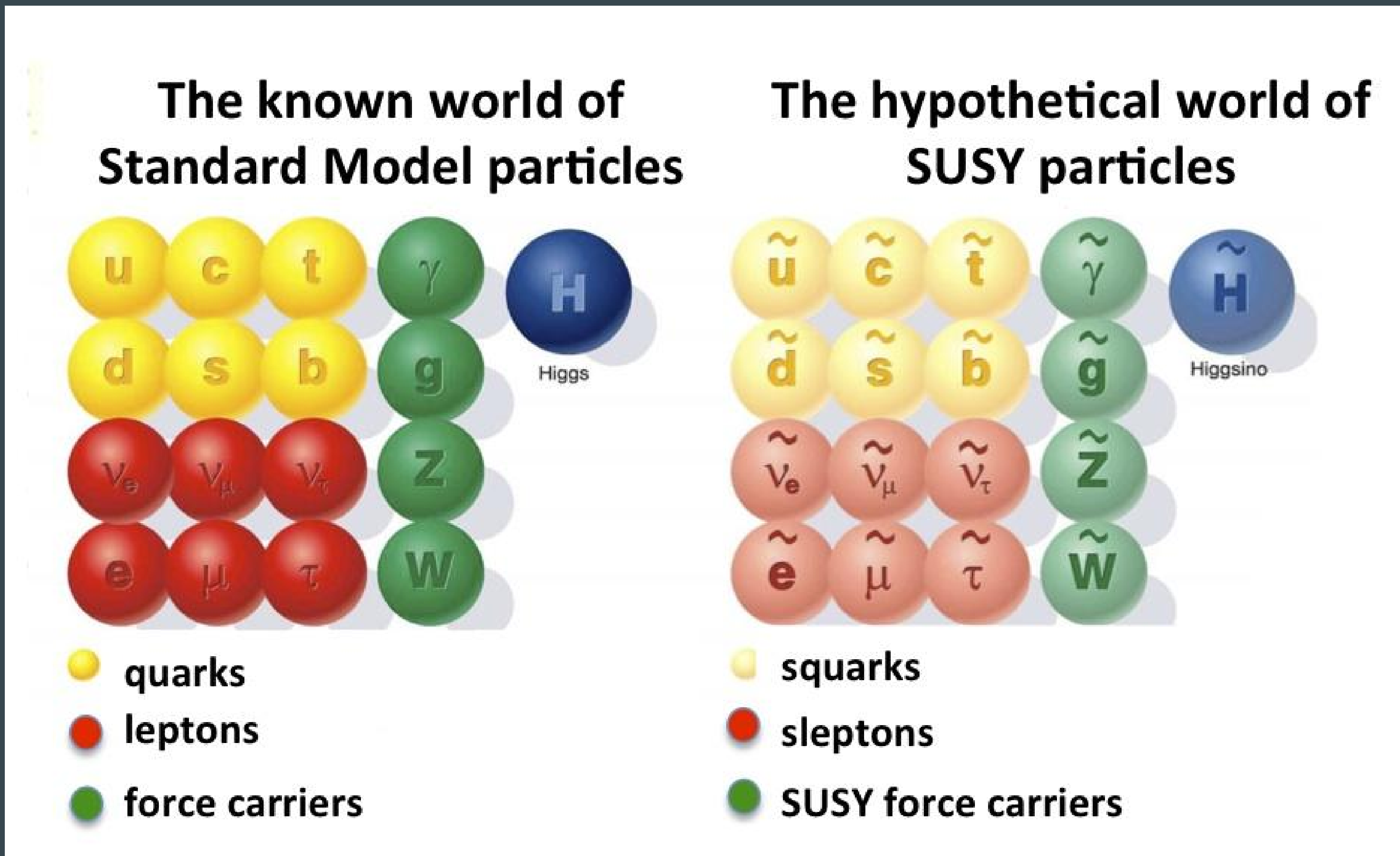


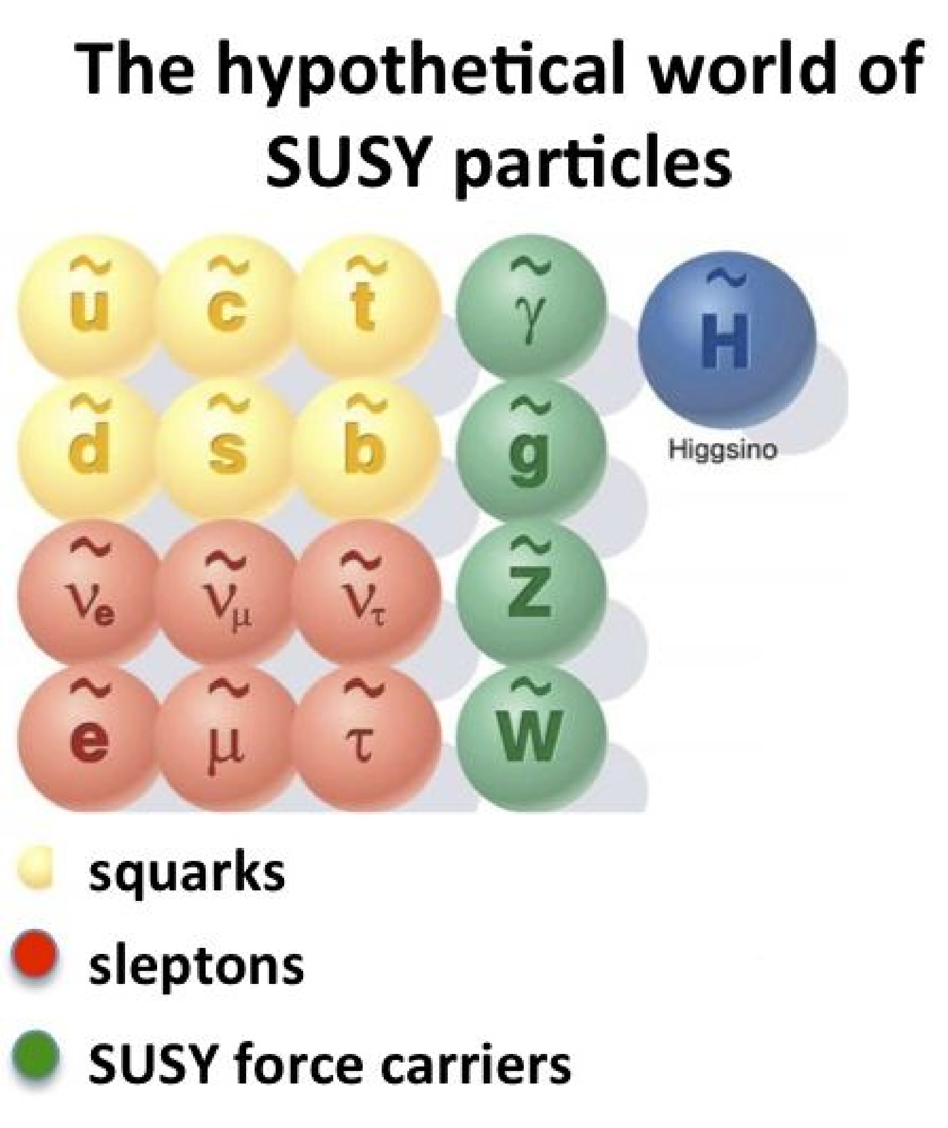
Every particle comes with it supersymmetric partner.

SUSY and Dark Matter

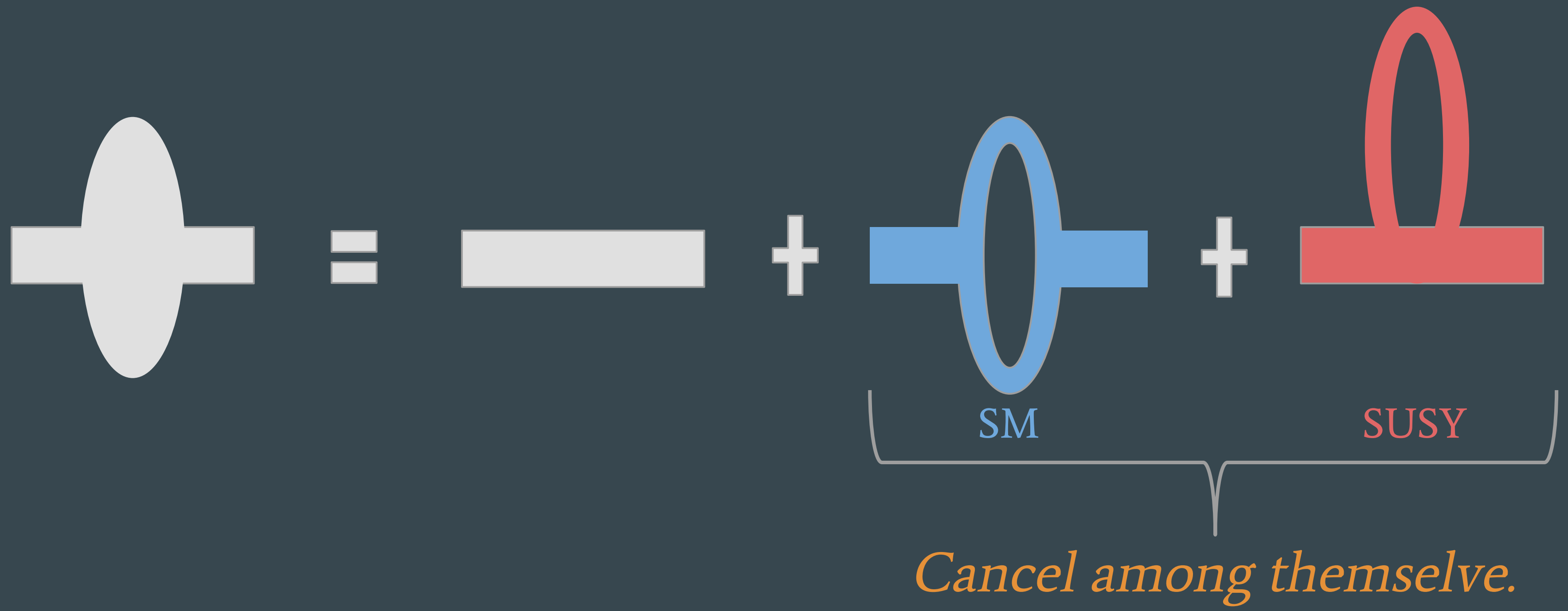
- Lightest SUSY partner (LSP) of SM particle is stable.
- Lots of neutral particles:
  - Higgsino
  - Zino
  - Bino
- If the LSP is neutral, it generically has a property suitable to explain the observed dark matter.

SUSY and Baryogenesis

- SUSY partners help:
  - More CP violation than just the KM matrix.
  - Enhance the electroweak phase transition.

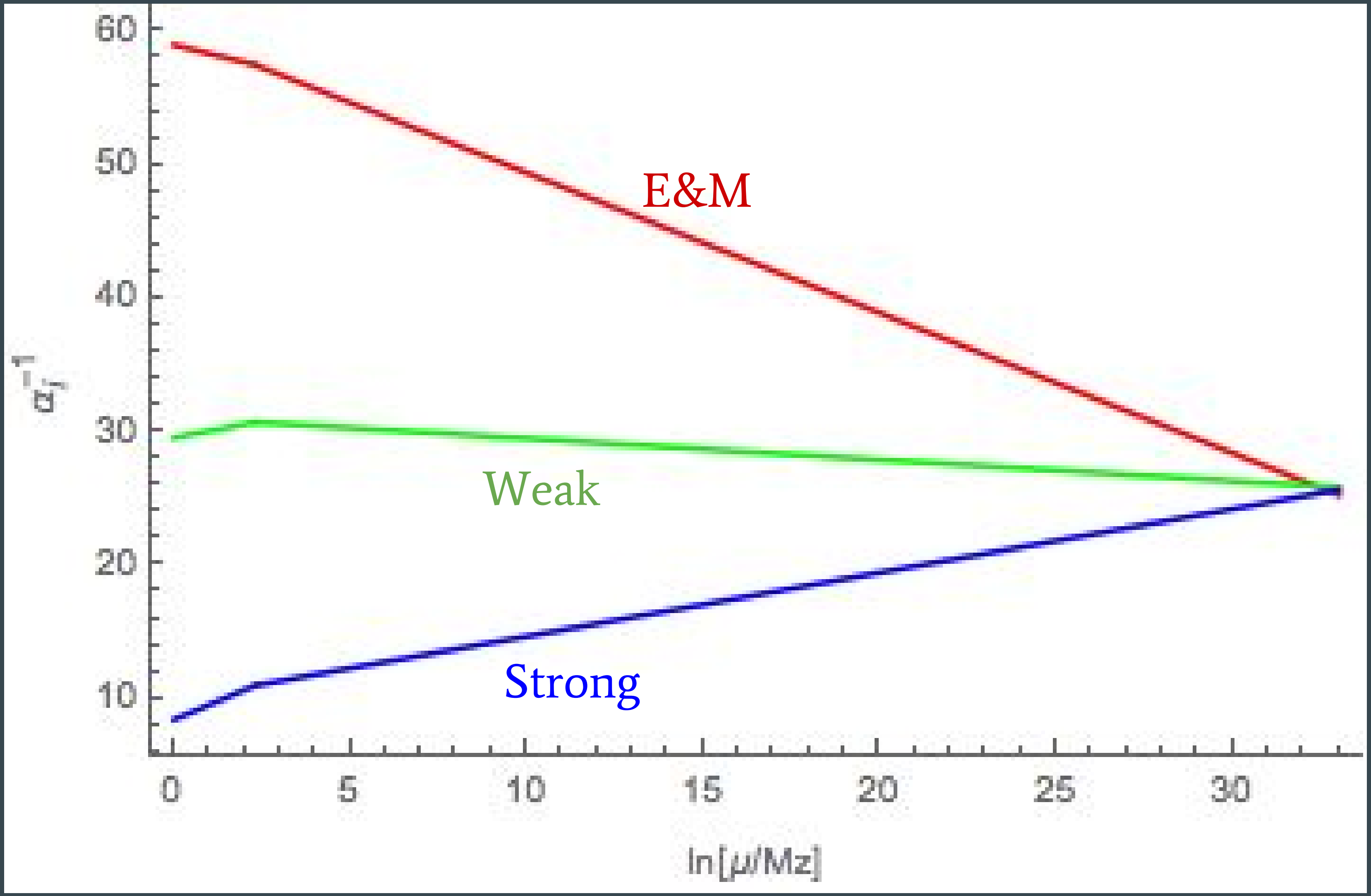


SUSY and Fine-Tuning



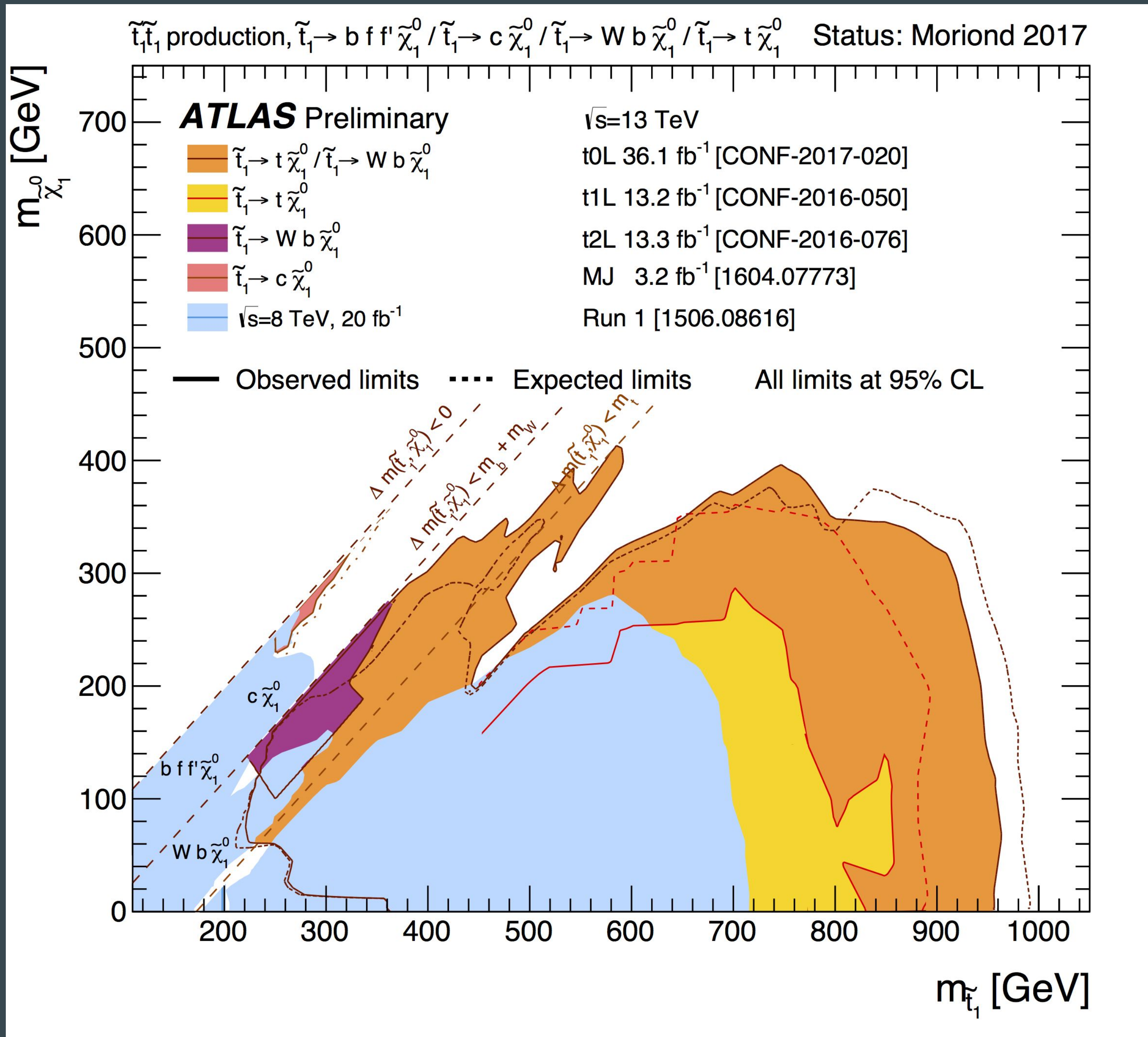
- SUSY makes quantum corrections (almost) cancel among themselve.
- No need for a large cancellation between classical and quantum contributions.

SUSY and Unification



SUSY vs Reality

Theoretical High Energy Physics & Astrophysics



Take Home Message

- Standard Model works very well.
- But it's incompleted.
- New physics is needed for:
  - Dark Matter.
  - Neutrino mass.
- New physics is a possible solution for:
  - Cosmological constant problem.
  - Fine-tuning in the Higgs mass.
  - Grand Unification.

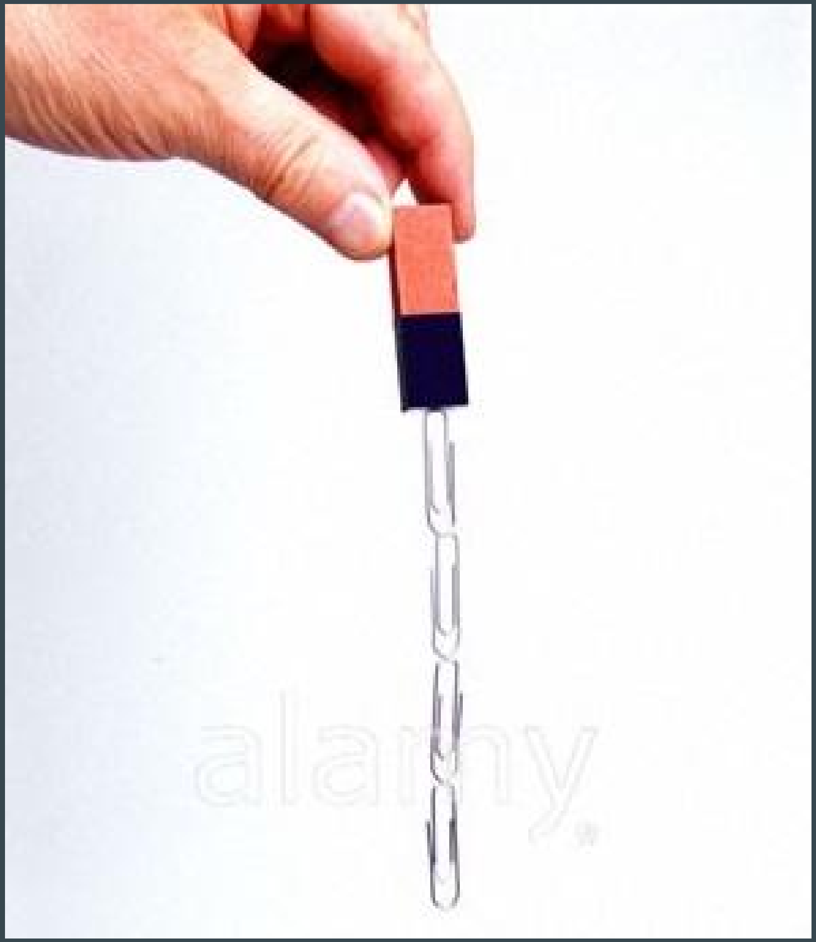
Bonus: Extra-Dimension
(gravity is back!)

Theoretical High Energy
Physics & Astrophysics

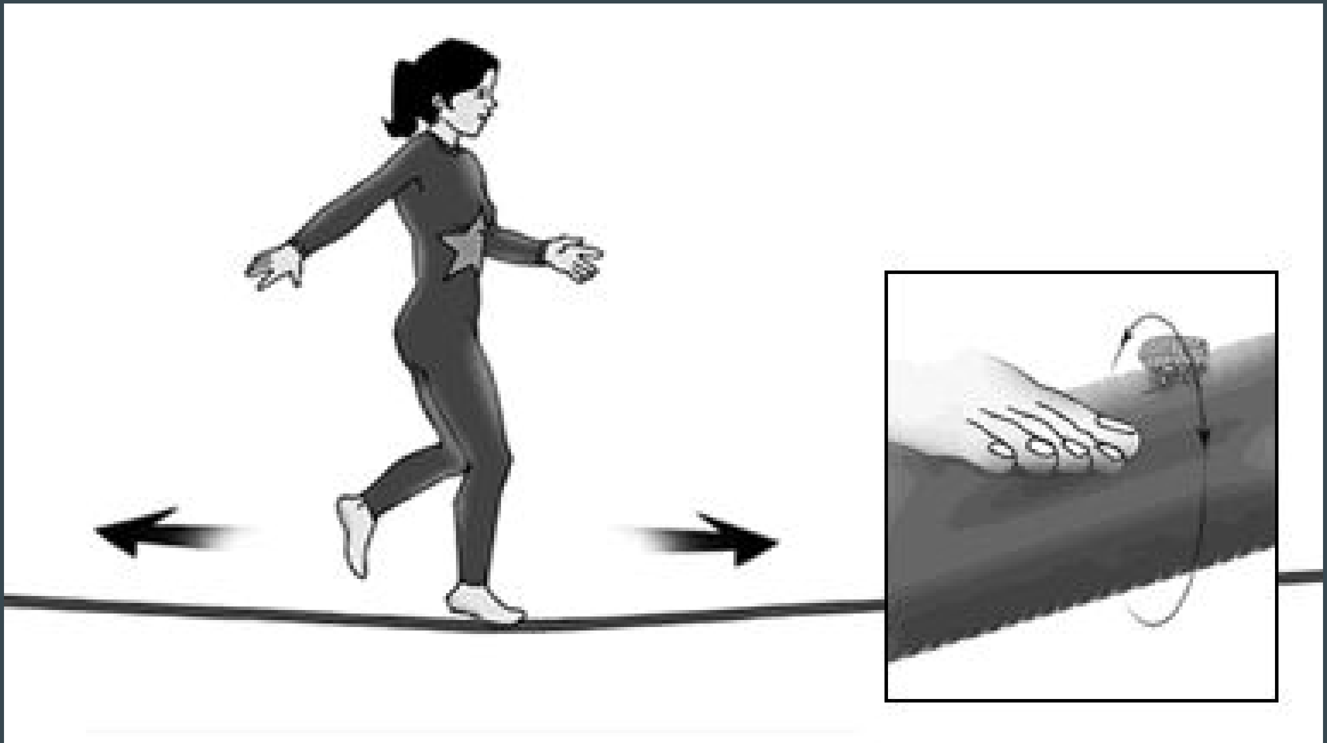
Gravity is weak

Theoretical High Energy Physics & Astrophysics

- Gravity from the earth cannot overcome magnetic force from a small magnet!
- This is why SM doesn't care about gravity.
- Why is gravity so weak compared to E&M, weak and strong force?



Why don't We See Extra-Dimension



- The lady can move only in 1-dimension.
- An insect on a rope can move in 2-dimension.

Gravity in XD

- Same strength as other forces.
- Appears weak because it's leaked out into the extra-dimension.