Why do we think there's Physics beyond the Standard Model?

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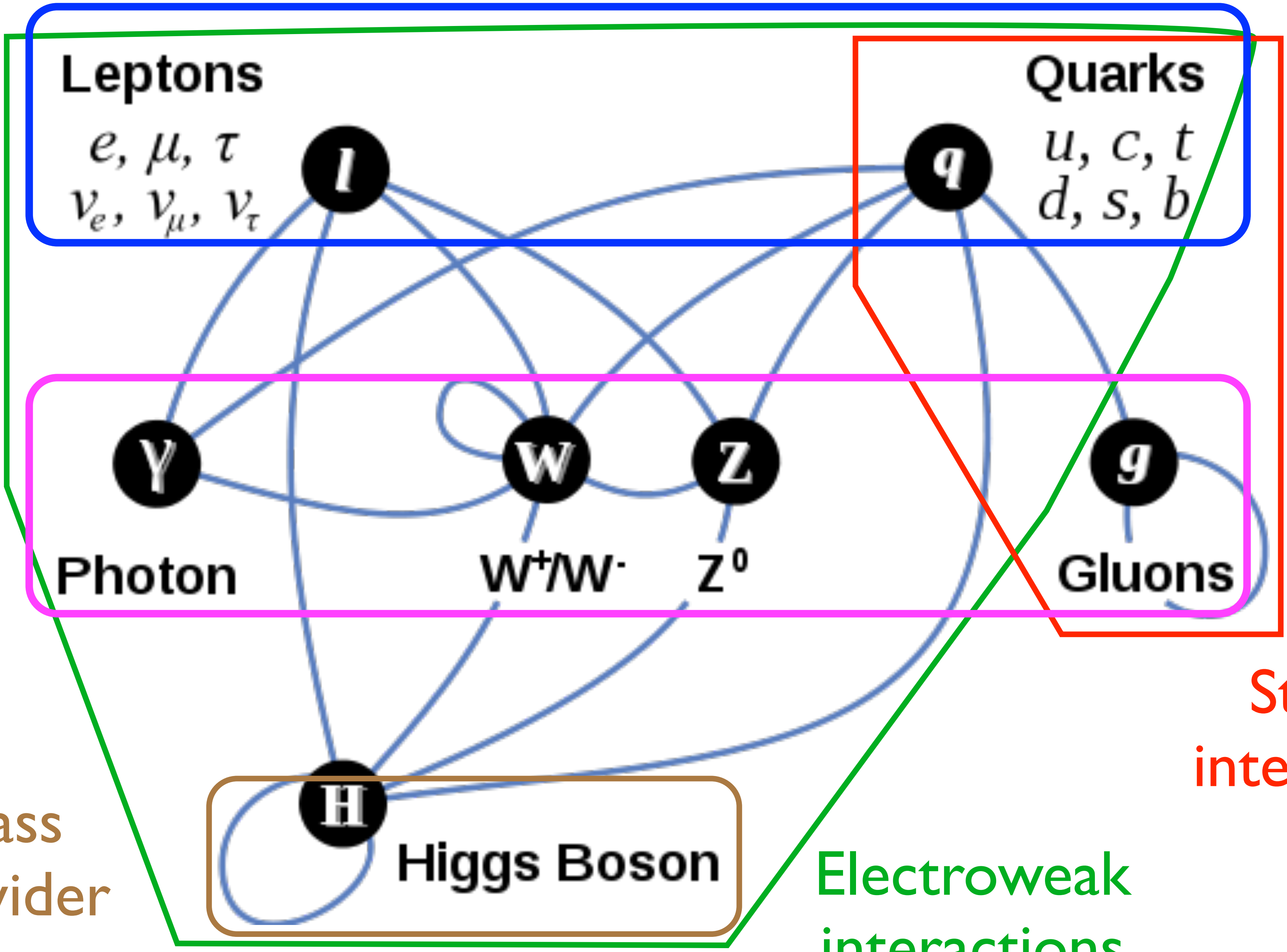
Outline

- The Standard Model and its problems
- What is Dark Matter made of ?
- Do the Forces of Nature unify ?
- Is there Supersymmetry ?

(• What is the origin of neutrino masses ?)

The Standard Model

The Standard Model



Matter particles

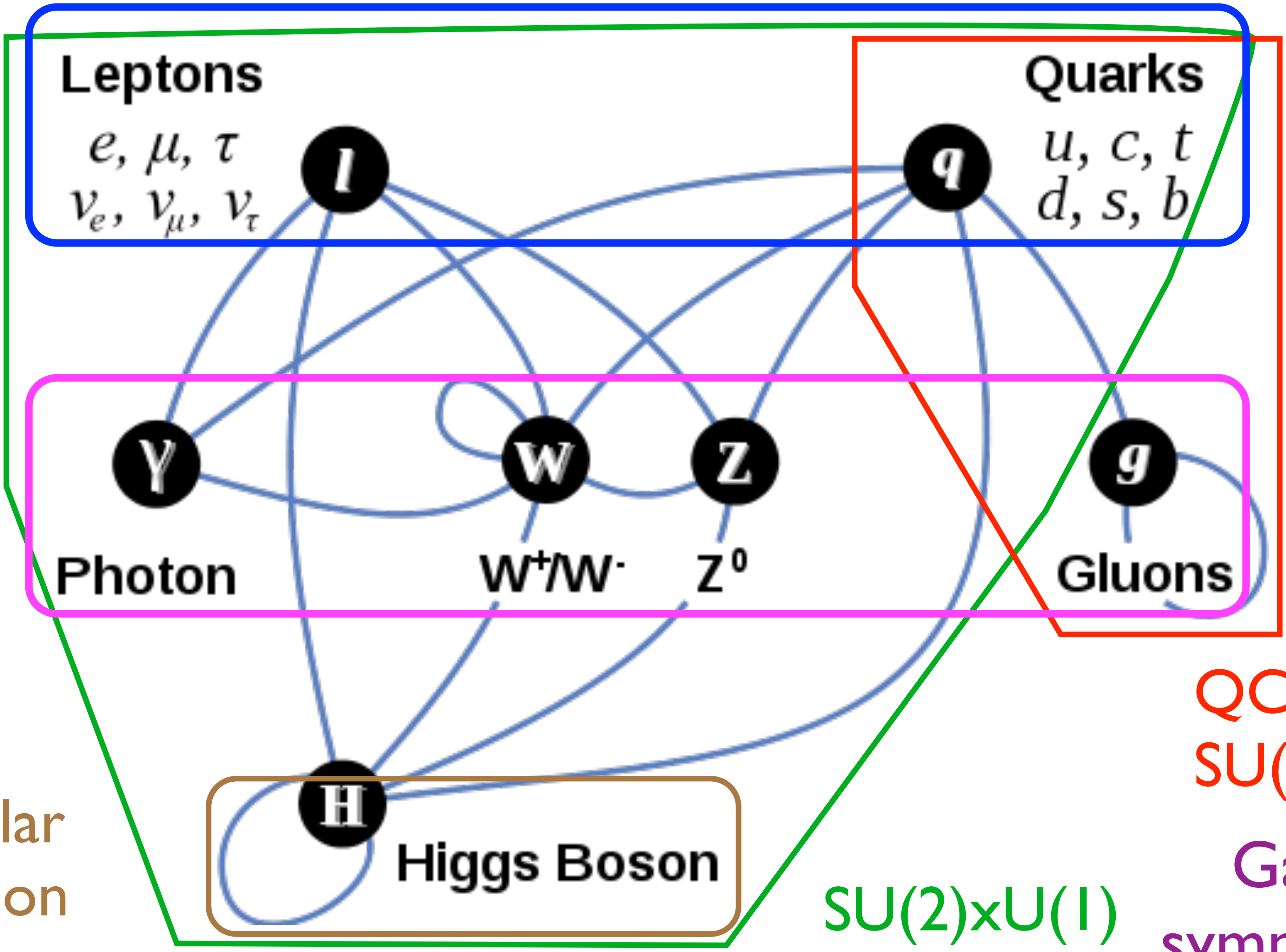
Force carriers

Mass provider

Strong interaction

Electroweak interactions

The Standard Model



Fundamental fermions

Gauge bosons

Scalar boson

QCD SU(3)

SU(2)xU(1)

Gauge symmetries

Problems of the Standard Model

- Conceptual
  - ➜ Many free parameters
  - ➜ No grand unification
  - ➜ Higgs mass problem
- Observational
  - ➜ No dark matter
  - ➜ No dark energy
  - ➜ Not enough matter
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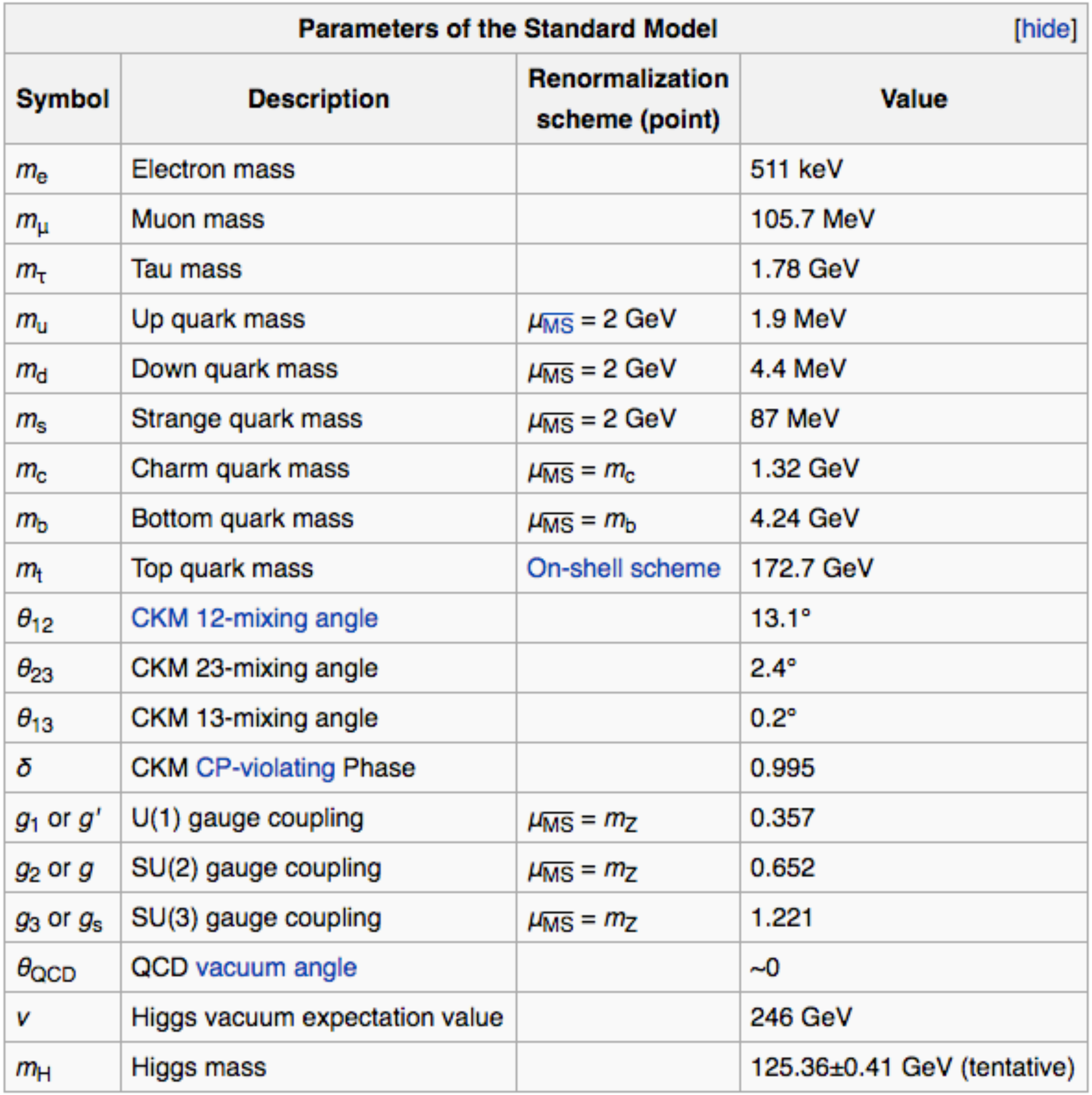
Parameters of the Standard Model



Parameters of the Standard Model [hide]

Symbol	Description	Renormalization scheme (point)	Value
m_e	Electron mass		511 keV
m_μ	Muon mass		105.7 MeV
m_τ	Tau mass		1.78 GeV
m_u	Up quark mass	$\mu_{\overline{MS}} = 2$ GeV	1.9 MeV
m_d	Down quark mass	$\mu_{\overline{MS}} = 2$ GeV	4.4 MeV
m_s	Strange quark mass	$\mu_{\overline{MS}} = 2$ GeV	87 MeV
m_c	Charm quark mass	$\mu_{\overline{MS}} = m_c$	1.32 GeV
m_b	Bottom quark mass	$\mu_{\overline{MS}} = m_b$	4.24 GeV
m_t	Top quark mass	On-shell scheme	172.7 GeV
θ_{12}	CKM 12-mixing angle		13.1°
θ_{23}	CKM 23-mixing angle		2.4°
θ_{13}	CKM 13-mixing angle		0.2°
δ	CKM CP-violating Phase		0.995
g_1 or g'	U(1) gauge coupling	$\mu_{\overline{MS}} = m_Z$	0.357
g_2 or g	SU(2) gauge coupling	$\mu_{\overline{MS}} = m_Z$	0.652
g_3 or g_s	SU(3) gauge coupling	$\mu_{\overline{MS}} = m_Z$	1.221
θ_{QCD}	QCD vacuum angle		~0
v	Higgs vacuum expectation value		246 GeV
m_H	Higgs mass		125.36±0.41 GeV (tentative)

- 19 arbitrary numbers
- Huge ranges:
  - ★ $m_\tau/m_e = 3{,}500$
  - ★ $m_t/m_u = 90{,}000$

Composite quarks?

- Start from atoms:
    - Many elements, all made of electrons & a nucleus
        - Nuclei made of protons & neutrons (nucleons)
            - Nucleons made of quarks
                - Quarks made of ???
- No consistent theory (so far)
- How would we look for ???

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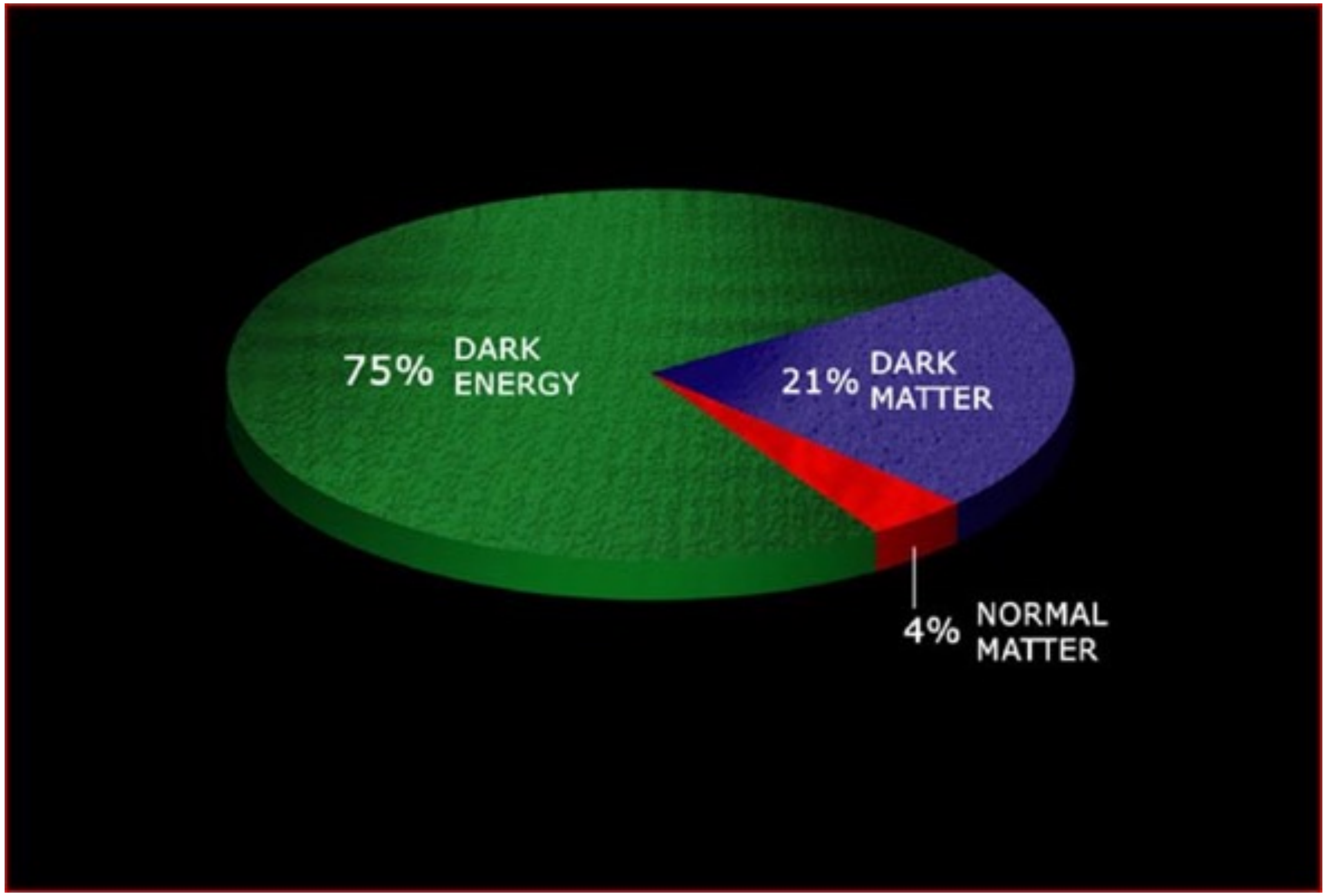
Dark Matter

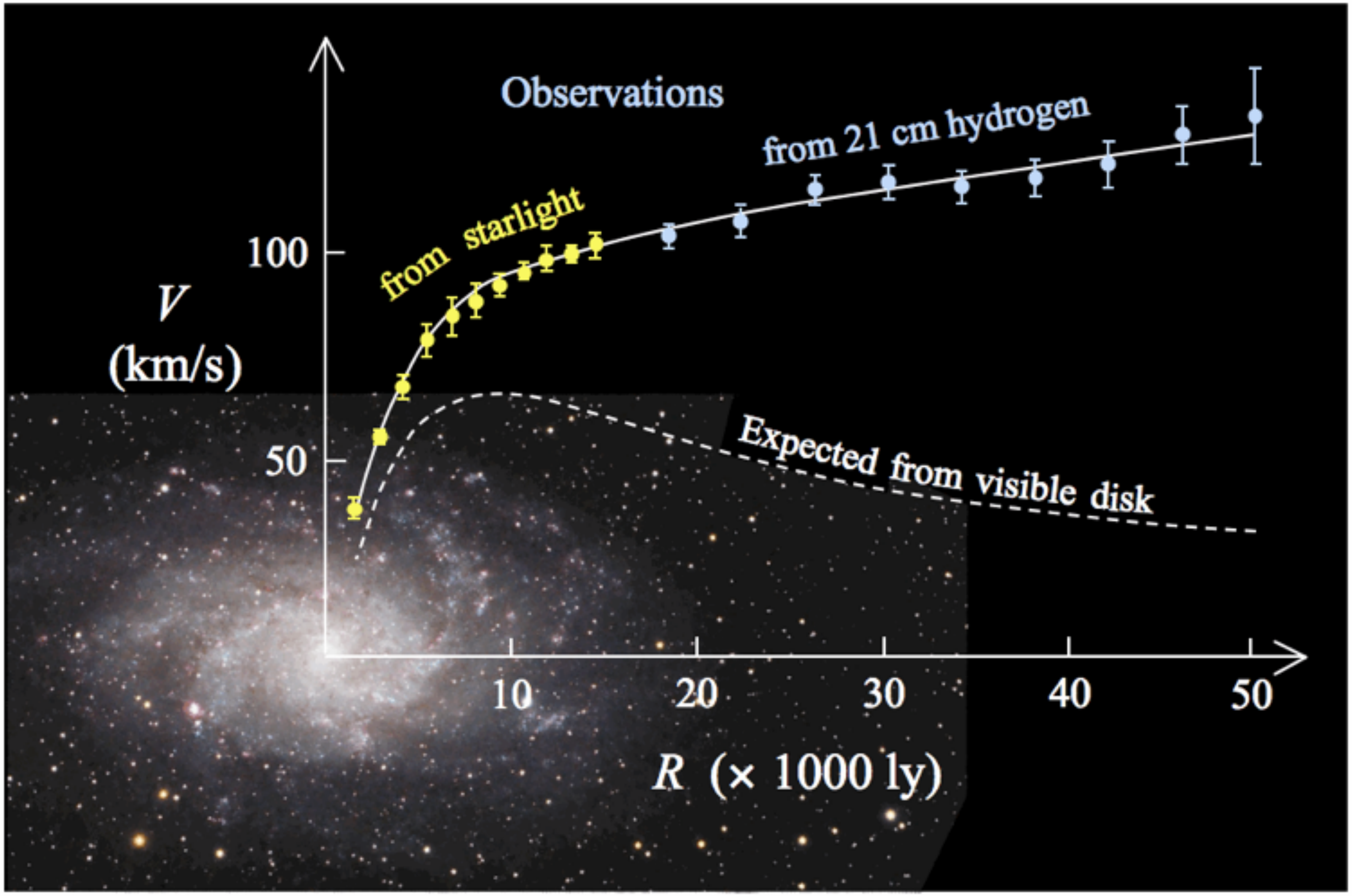
Dark Matter

- Present composition of the Universe



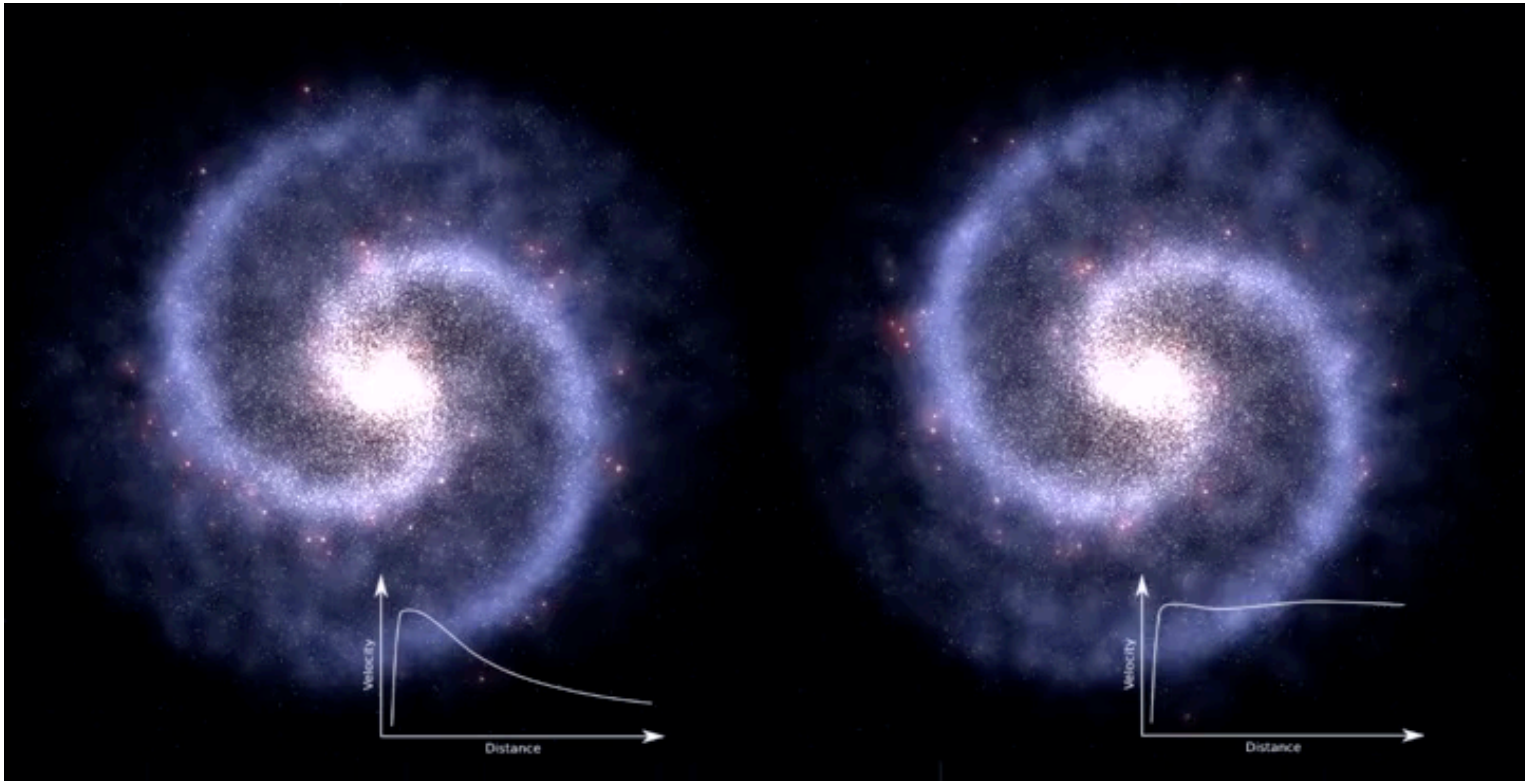
Evidence for Dark Matter

- Rotation curves of galaxies



M33 →

Dark Matter



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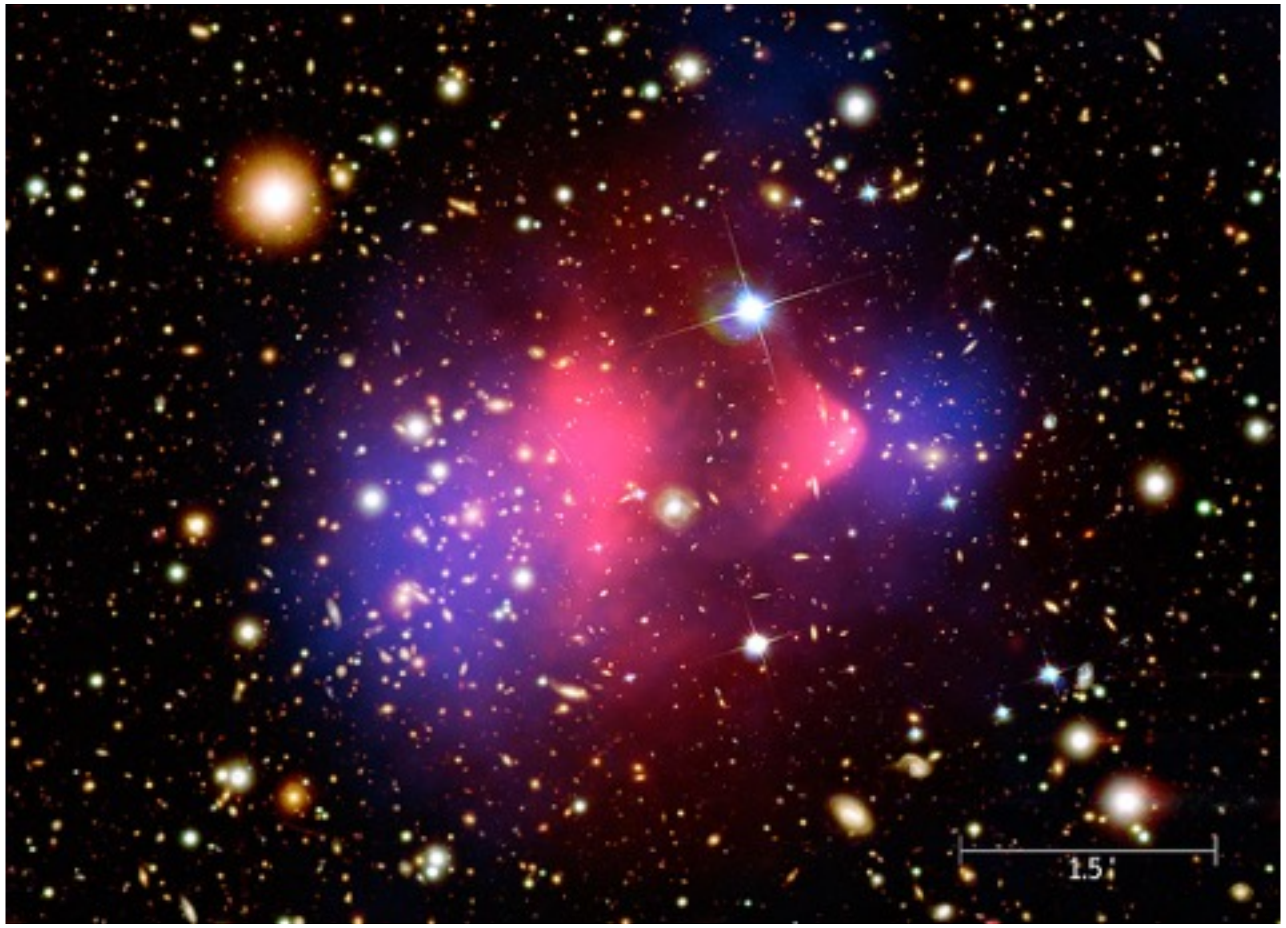
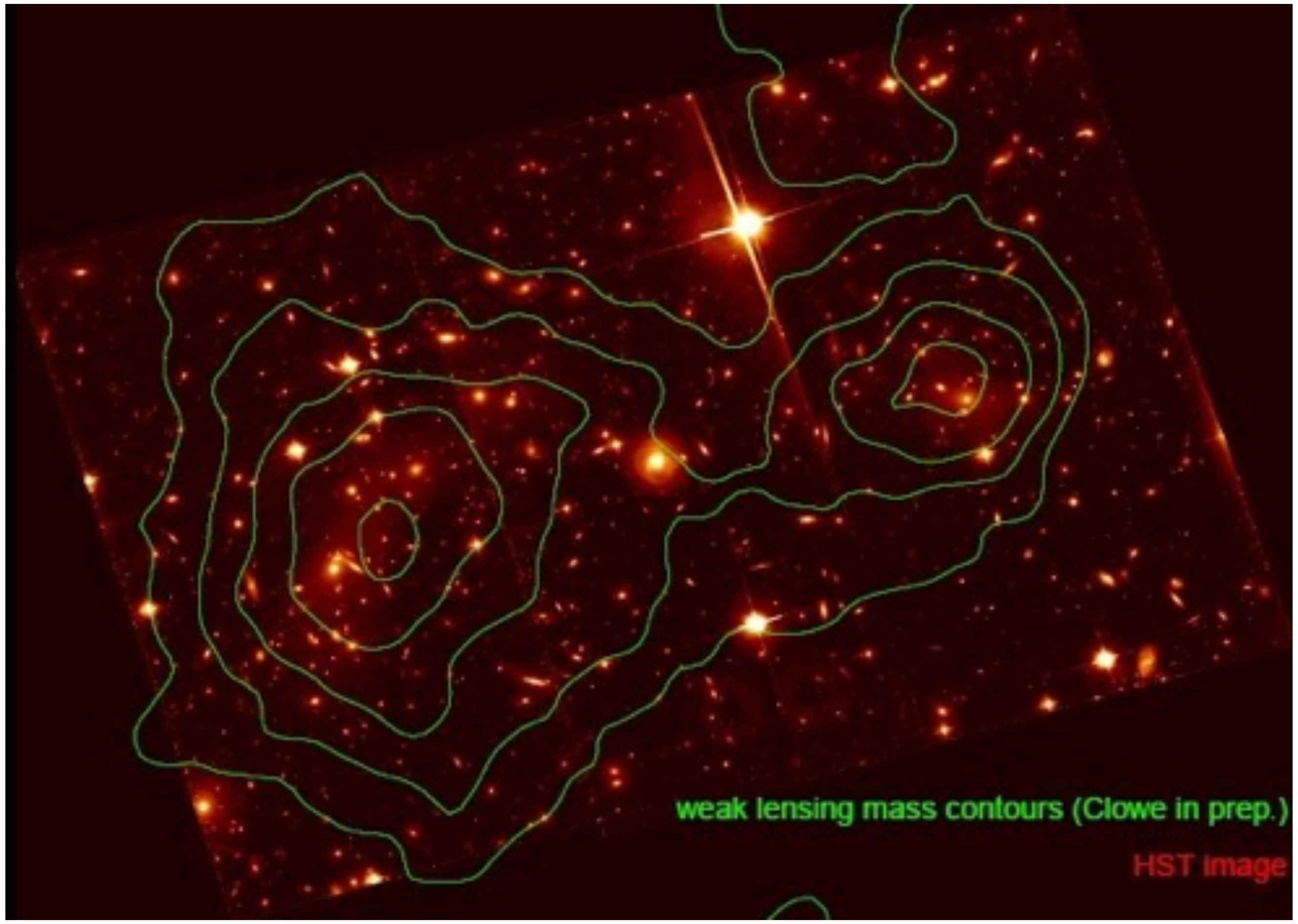
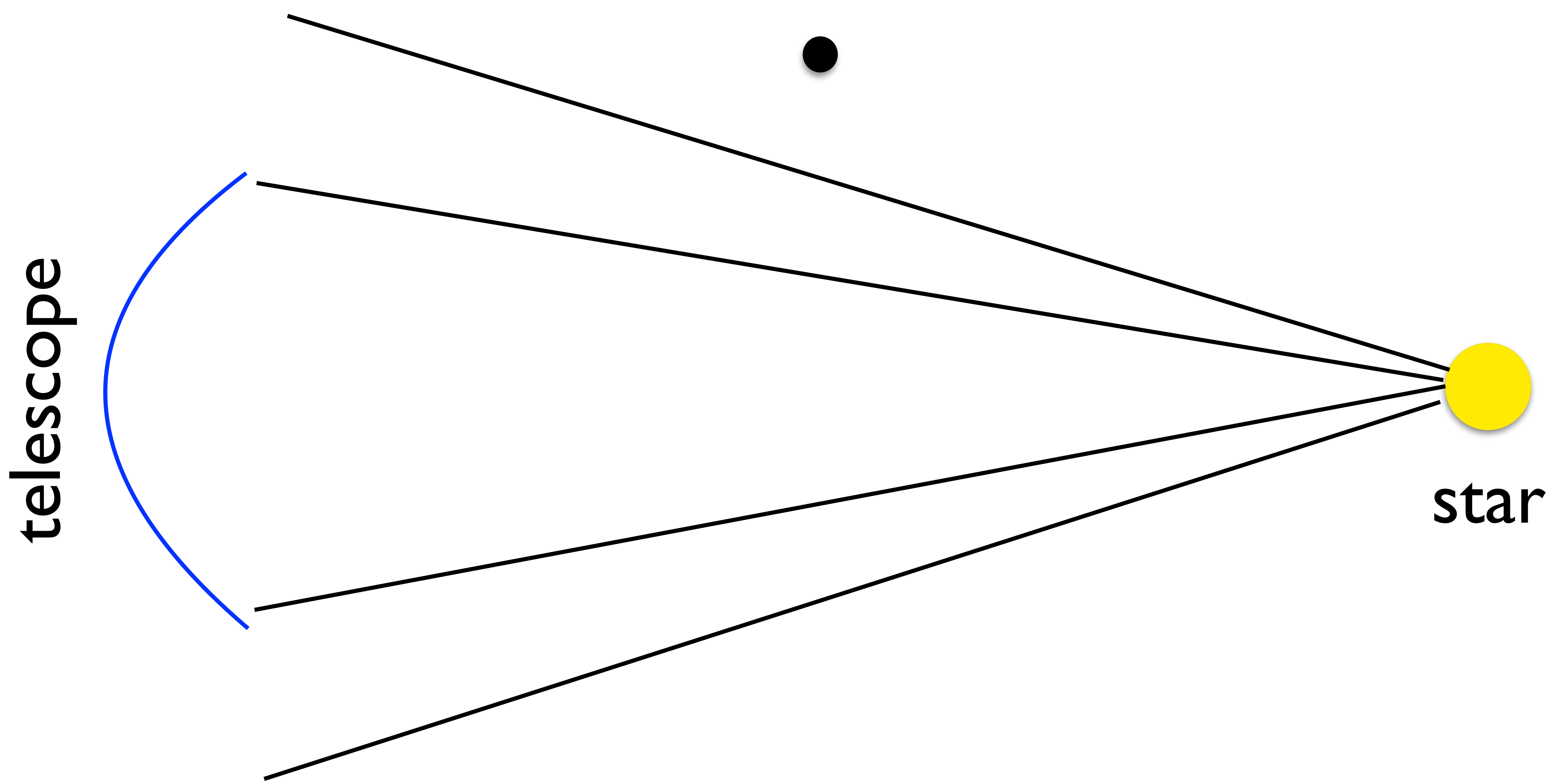




- Bullet cluster galaxies collide
  - ★ Normal matter slows down
  - ★ Dark matter keeps going ⟷ weakly interacting

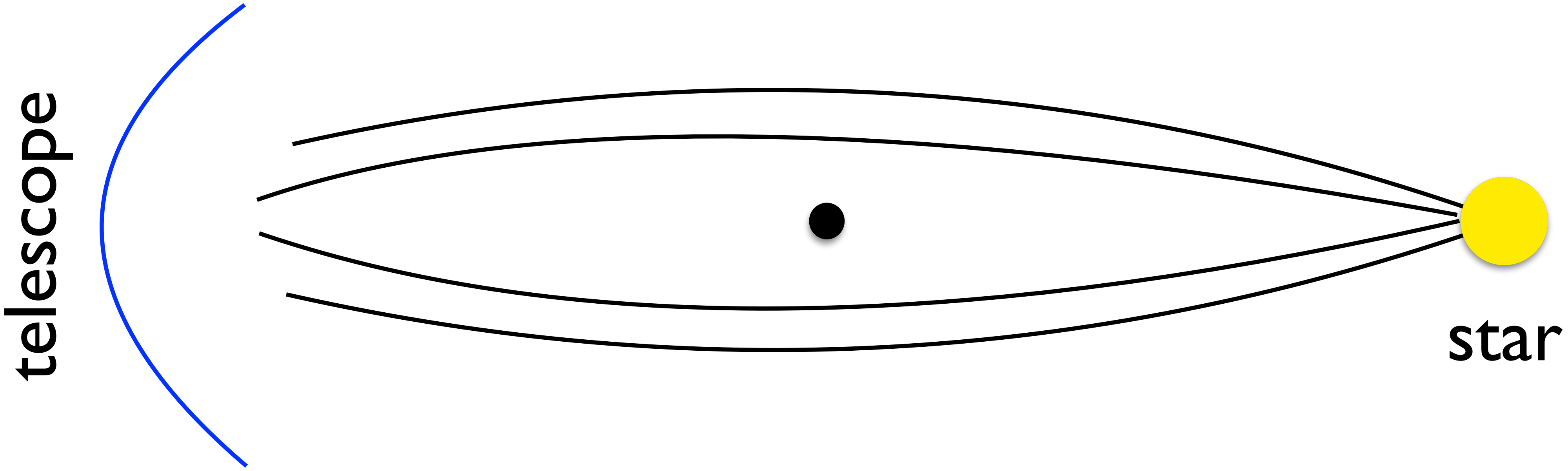
Candidates for Dark Matter

- Dark stars, black holes, planets etc. (MACHOS)
  - ★ Largely ruled out by lack of microlensing



Gravitational Microlensing

- See more light as MACHO passes between
  - ★ Star brightens briefly



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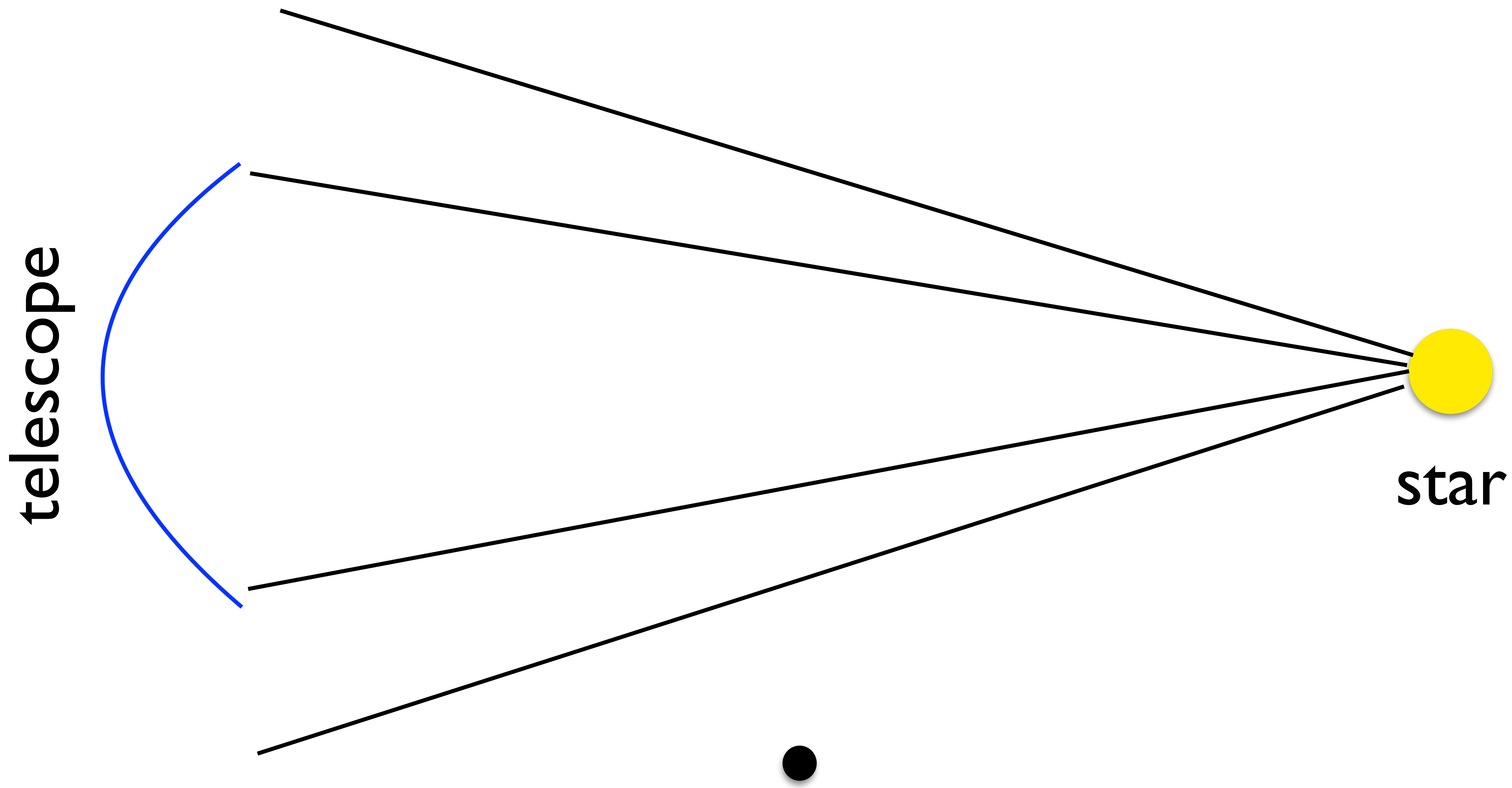

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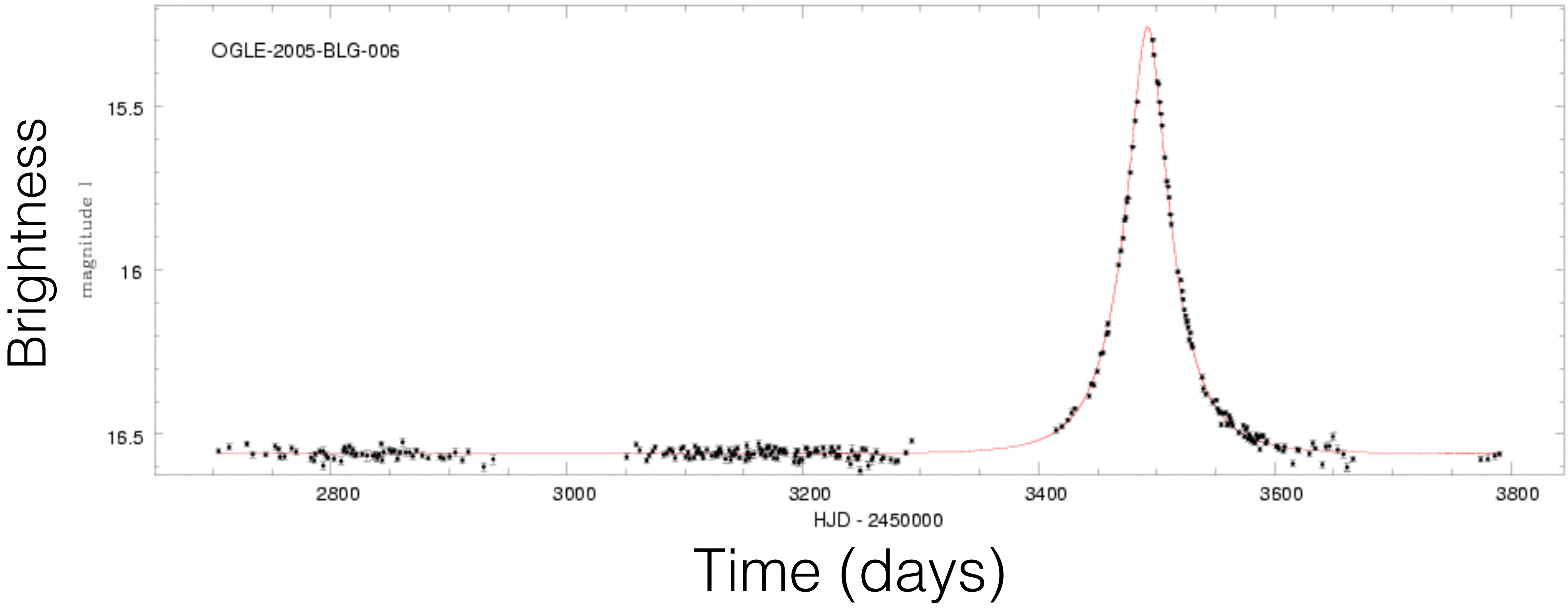

Jan Skowron, data from OGLE home page, CC BY-SA 2.5,
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- Neutrinos
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- Neutrinos
  - ★ Would disrupt structure formation
- Weakly Interacting Massive Particles
  - ★ Preferred $Mc^2 \sim$ TeV: LHC can make them!
- Axions: cold, ultra-light ($mc^2 << eV$), very weakly interacting particles: LHC can't make them!

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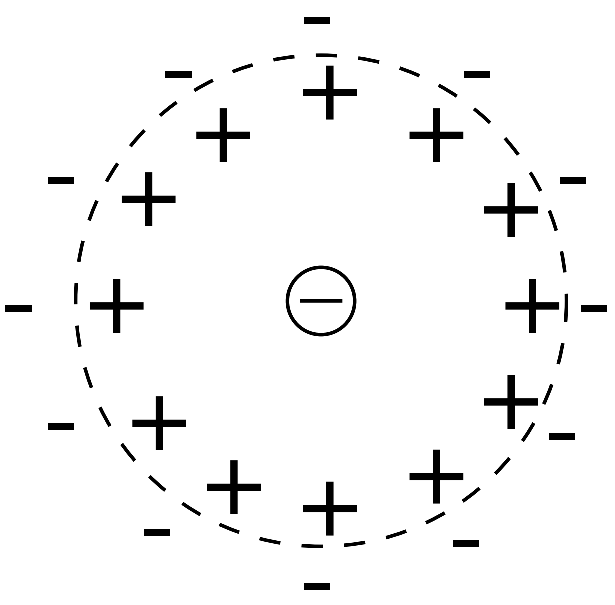
Unification of Forces

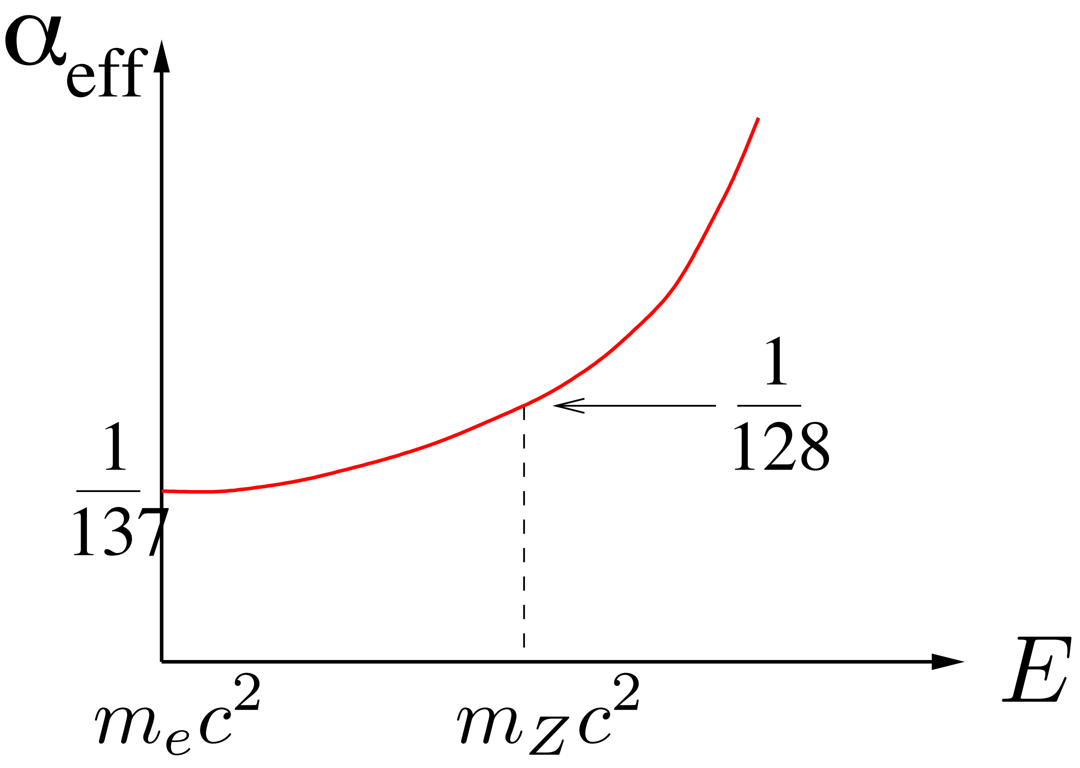
Standard Model Forces

- The SM is an SU(3)xSU(2)xU(1) gauge theory
  - ➔ 3 independent couplings g_1, g_2, g_3, $\alpha_i \equiv \dfrac{g_i^2}{4\pi}$
  - ➔ $\alpha_{1,2}$ are electroweak: $\alpha \equiv \dfrac{e^2}{4\pi}, \quad \dfrac{1}{\alpha} = \dfrac{5}{3}\dfrac{1}{\alpha_1} + \dfrac{1}{\alpha_2}$
  - ➔ $\alpha_3 \equiv \alpha_S =$ strong interaction, QCD
- All these coupling 'constants' are energy-dependent

Running Coupling ‘Constants’

- Measured electron charge is distance (energy) dependent, due to vacuum polarization





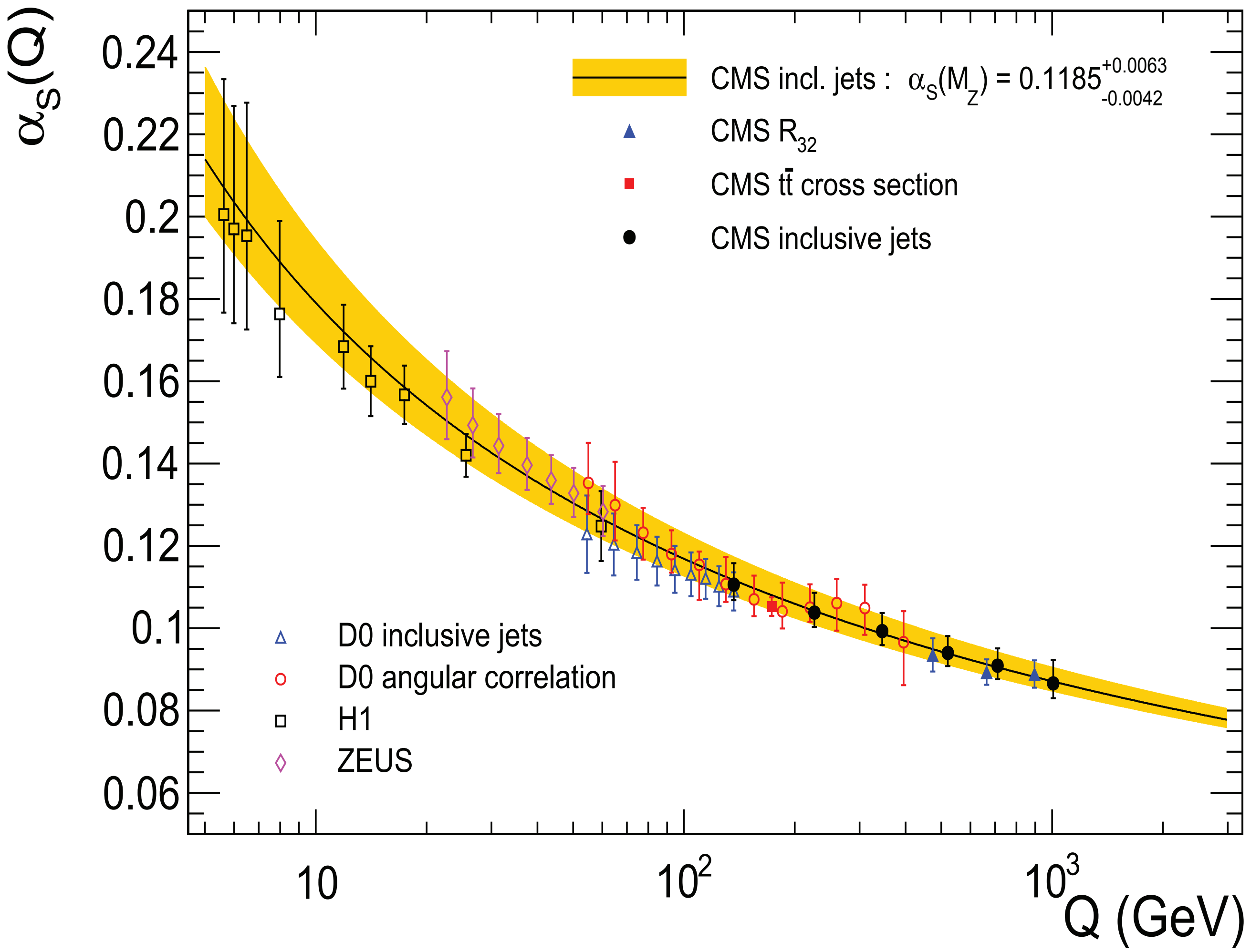
- Calculation gives $\alpha_i(E) = \dfrac{1}{a_i + (b_i/2\pi)\log_{\text{e}} E}$

where $b_1 = -\dfrac{41}{10}, \quad b_2 = +\dfrac{19}{6}, \quad b_3 = +7$

The QCD Running Coupling

$$\alpha_S(E) = \frac{1}{a_3 + (b_3/2\pi)\log_e E}$$

→ α_S decreases with energy



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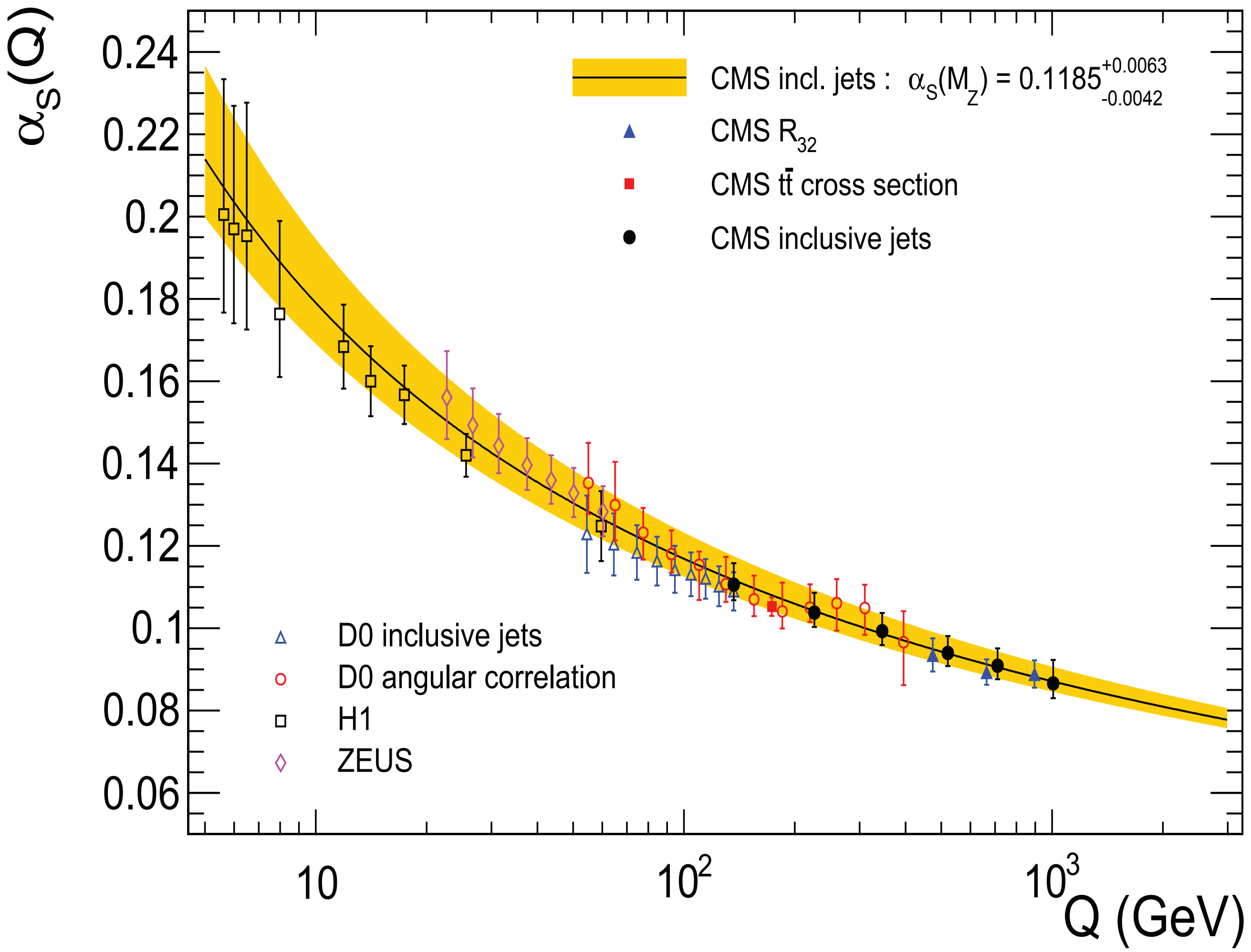


The Nobel Prize in Physics 2004

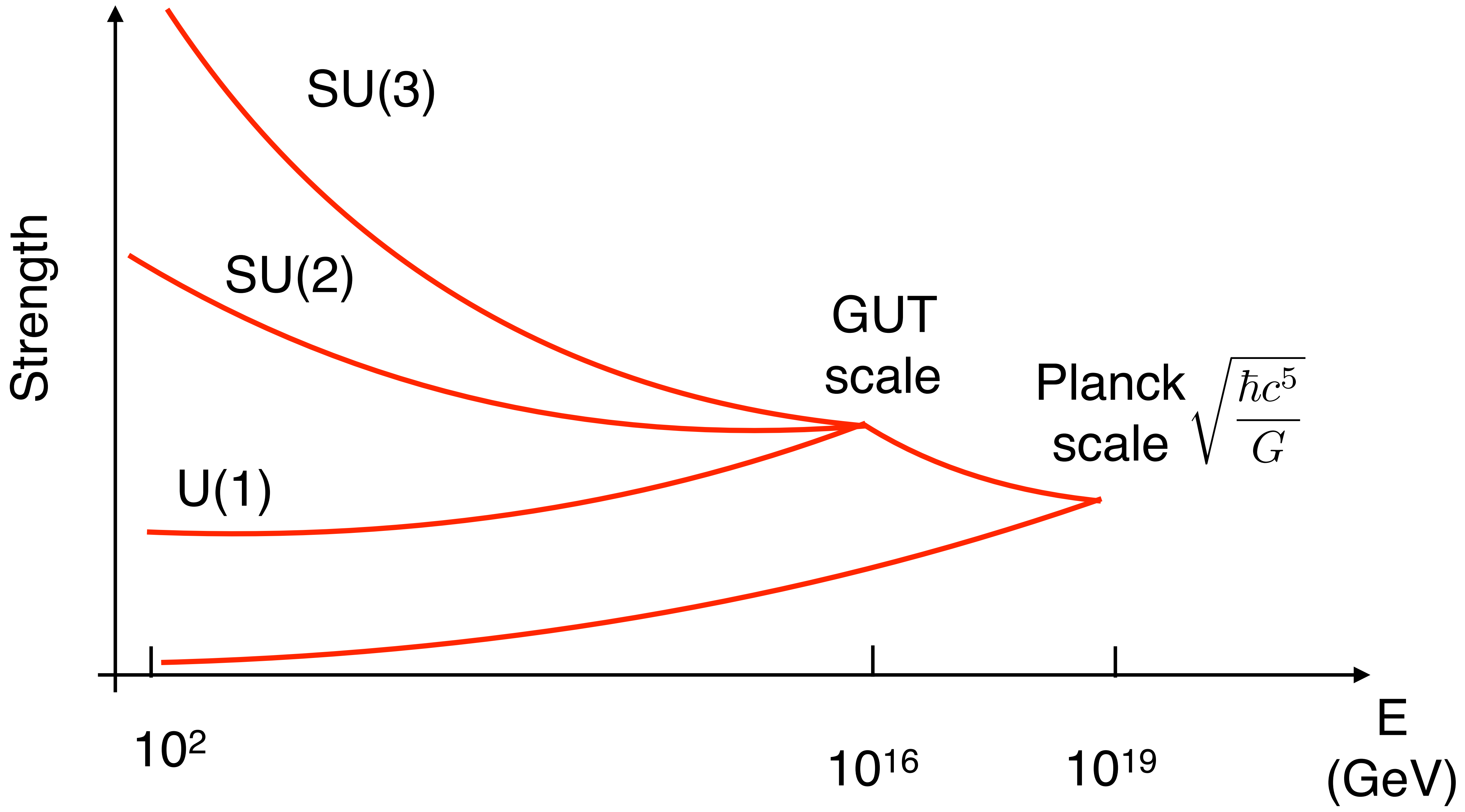
David J. Gross

H. David Politzer

Frank Wilczek

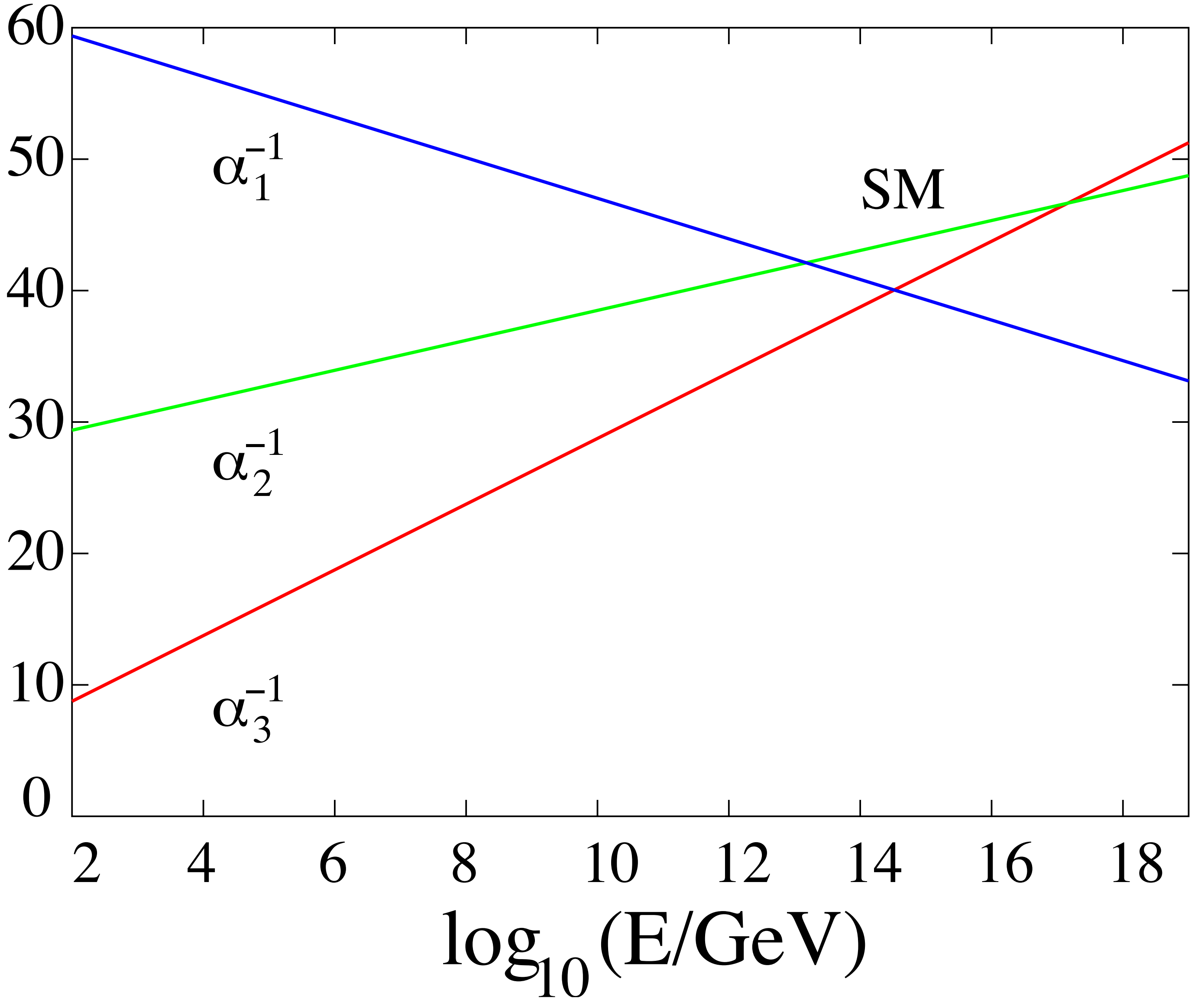
Grand Unification?

- Schematic vision …



(Almost) Grand Unification

$$\frac{1}{\alpha_i(E)} = a_i + \frac{b_i}{2\pi}\log_e E$$



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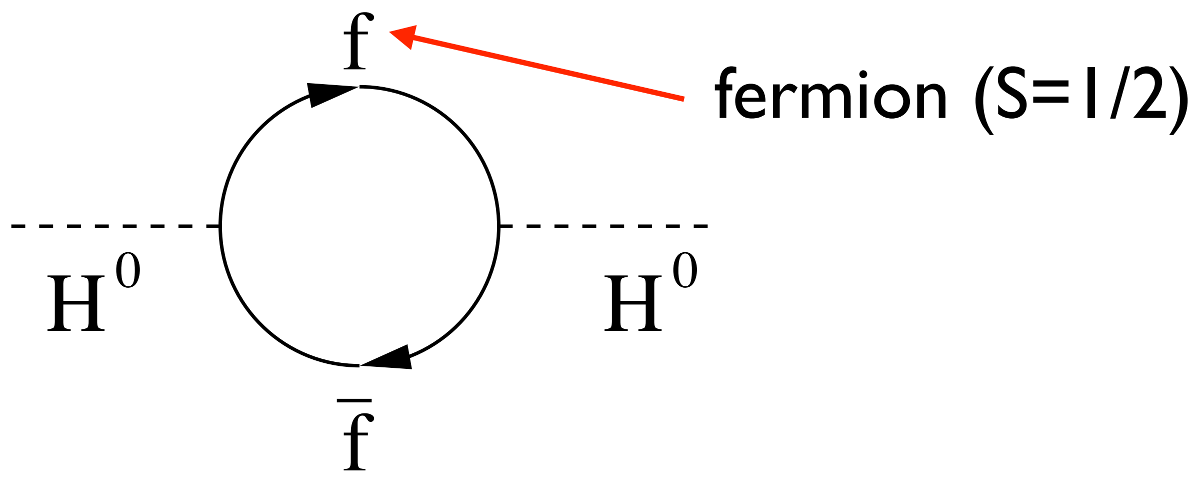
Higgs Mass Problem

- The Higgs mass receives large quantum corrections



➡ Needs high-energy cutoff Λ

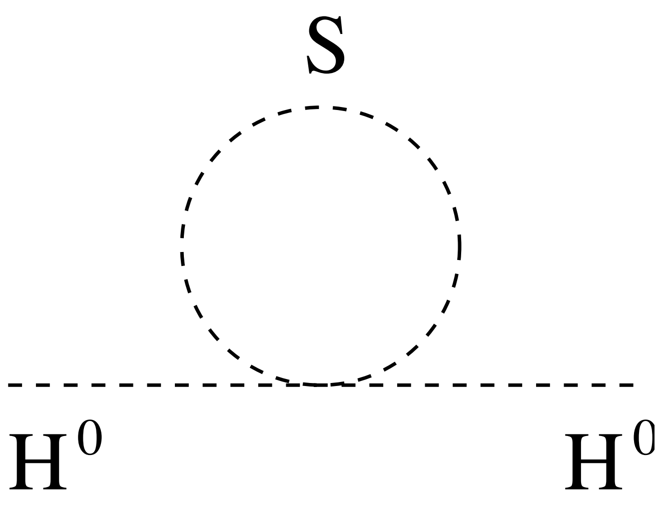
$$\delta M^2_{Hf} = \frac{g_f^2}{16\pi^2}\left[-2\Lambda^2 + 6m_f^2 \ln(\Lambda/m_f)\right]$$

$$M_H^2 = M^2_{H\text{bare}} + \delta M_H^2$$

➡ If Λ is at the GUT/Planck scale ($10^{16\text{-}19}$ GeV) there is a huge (~30 d.p.) cancellation!

Higgs Mass Solution?

- A scalar (spin-zero) particle would give a contribution



$$\delta M_{HS}^2 = \frac{\lambda_s}{16\pi^2}\left[+\Lambda^2 - 2M_S^2 \ln(\Lambda/M_S)\right]$$

➡ So if there are two scalar particles for every fermion, with coupling $\lambda_s = g_f^2$, the quadratic Λ dependence cancels

- This happens in theories with supersymmetry (SUSY)

Supersymmetry

Standard Model

	SPIN 0	SPIN 1/2	SPIN 1
MATTER		QUARKS u,d,s,c,b,t LEPTONS e,ν, μ, ν, τ, ν	
FORCES			GAUGE BOSONS γ, W,Z, g
MASS	HIGGS BOSON H^0		

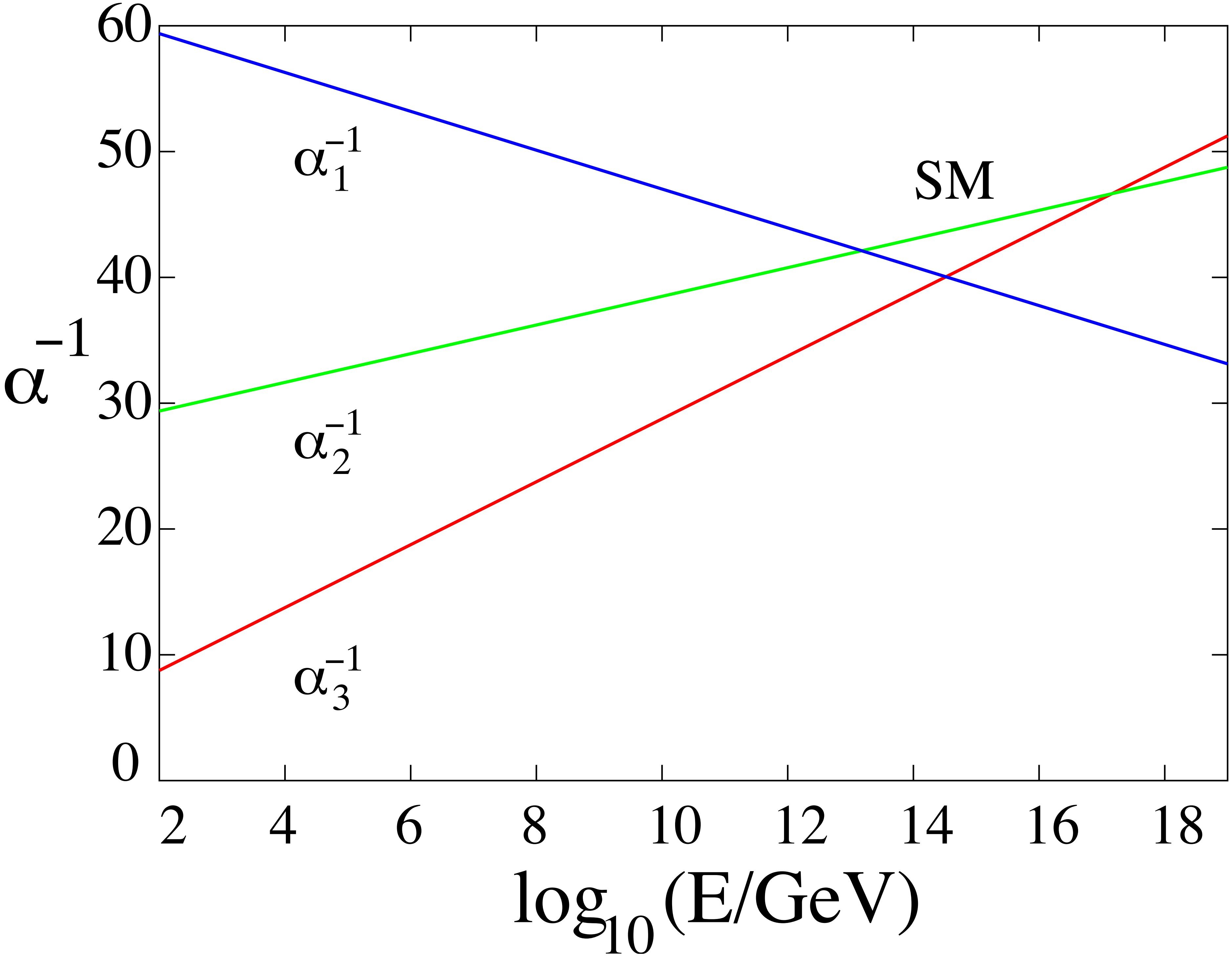
Supersymmetric Standard Model

	SPIN 0	SPIN 1/2	SPIN 1
MATTER	SQUARKS $\tilde{u}, \tilde{d}, \tilde{s}, \tilde{c}, \tilde{b}, \tilde{t}$	QUARKS u,d,s,c,b,t	
	SLEPTONS $\tilde{e},\tilde{\nu}, \tilde{\mu}, \tilde{\nu}, \tilde{\tau}, \tilde{\nu}$	LEPTONS $e,\nu, \mu, \nu, \tau, \nu$	
FORCES		GAUGINOS $\tilde{\gamma}, \tilde{W},\tilde{Z}, \tilde{g}$	GAUGE BOSONS γ, W,Z, g
MASS	HIGGS BOSONS h^0, H^0 A^0,H^+	HIGGSINOS $\tilde{H}$	

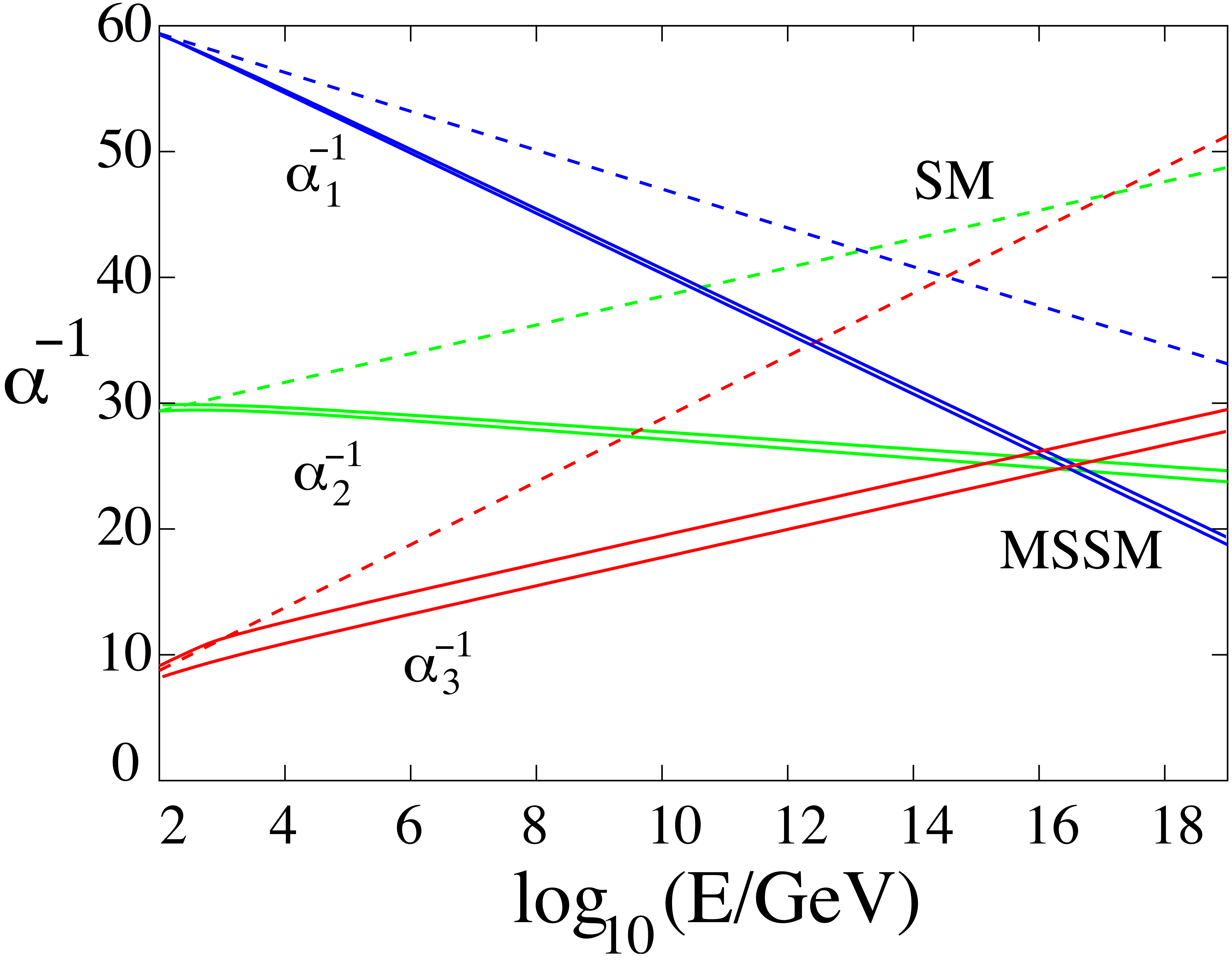
Characteristics of SUSY

- Superpartners can get mass without breaking gauge symmetries
- TeV-scale masses are ‘natural’:
    - ➜ Solve the Higgs mass problem
    - ➜ Lead to Grand Unification

(Almost) Grand Unification



SUSY Grand Unification



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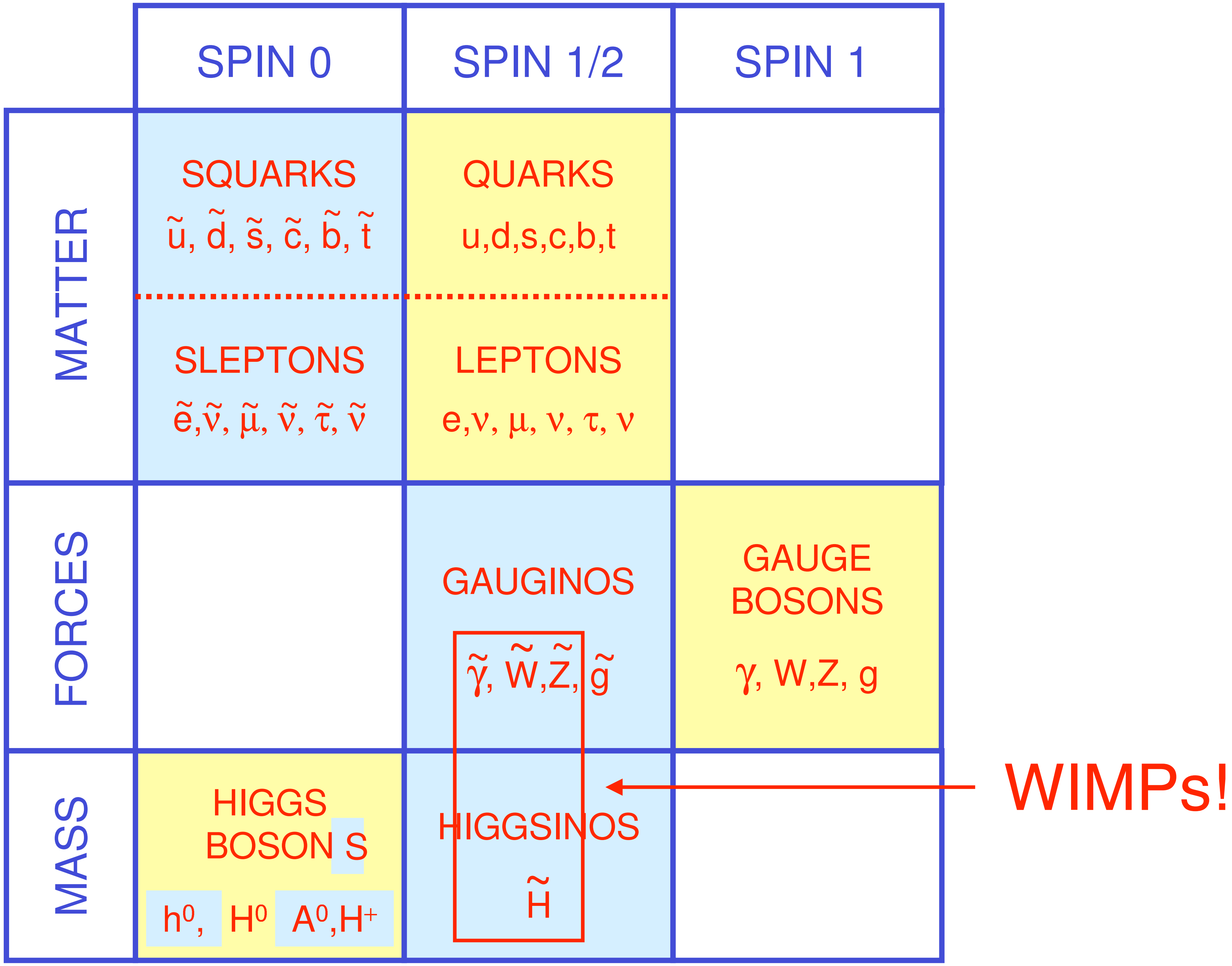

	SPIN 0	SPIN 1/2	SPIN 1
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WIMPs!

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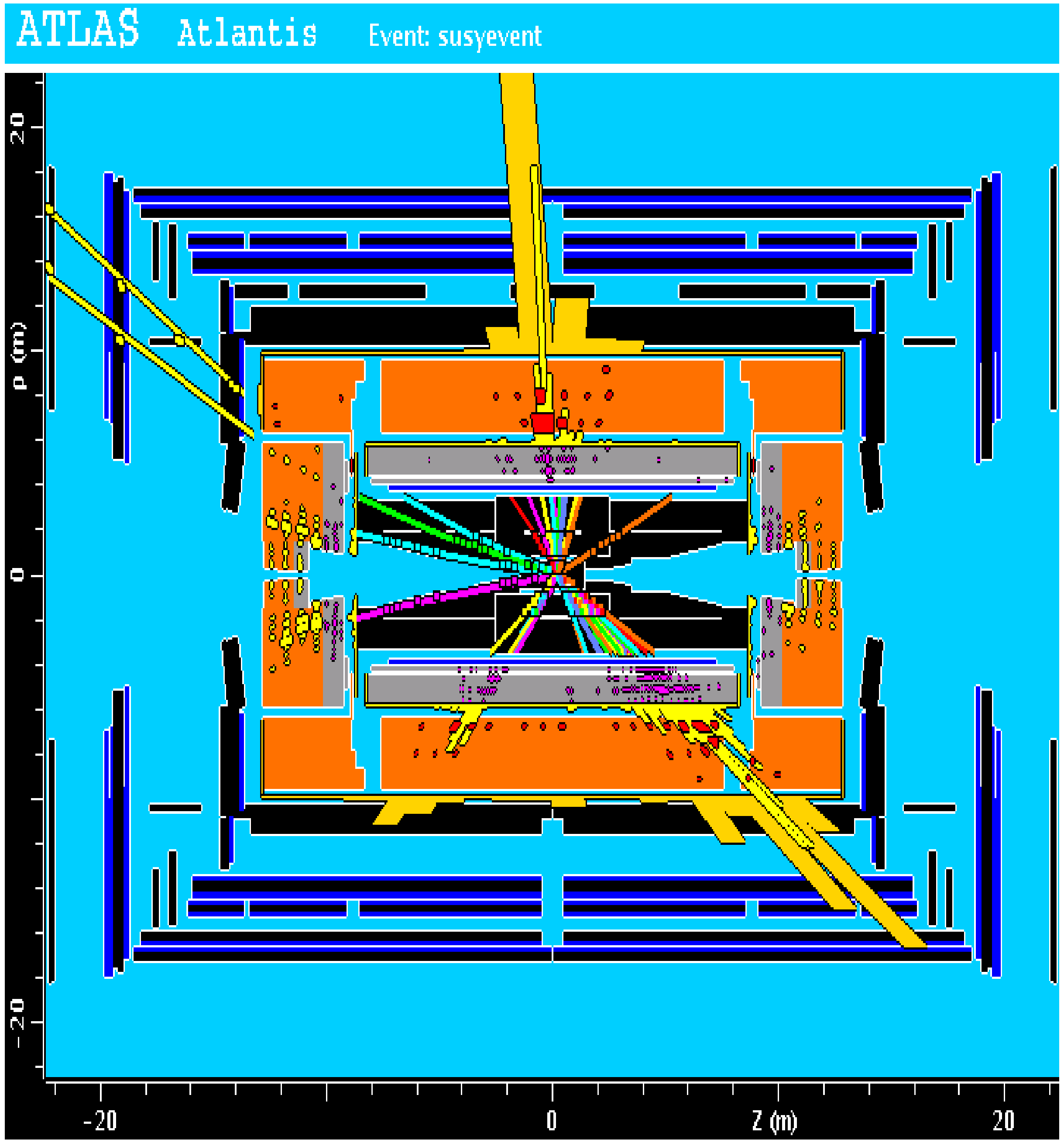
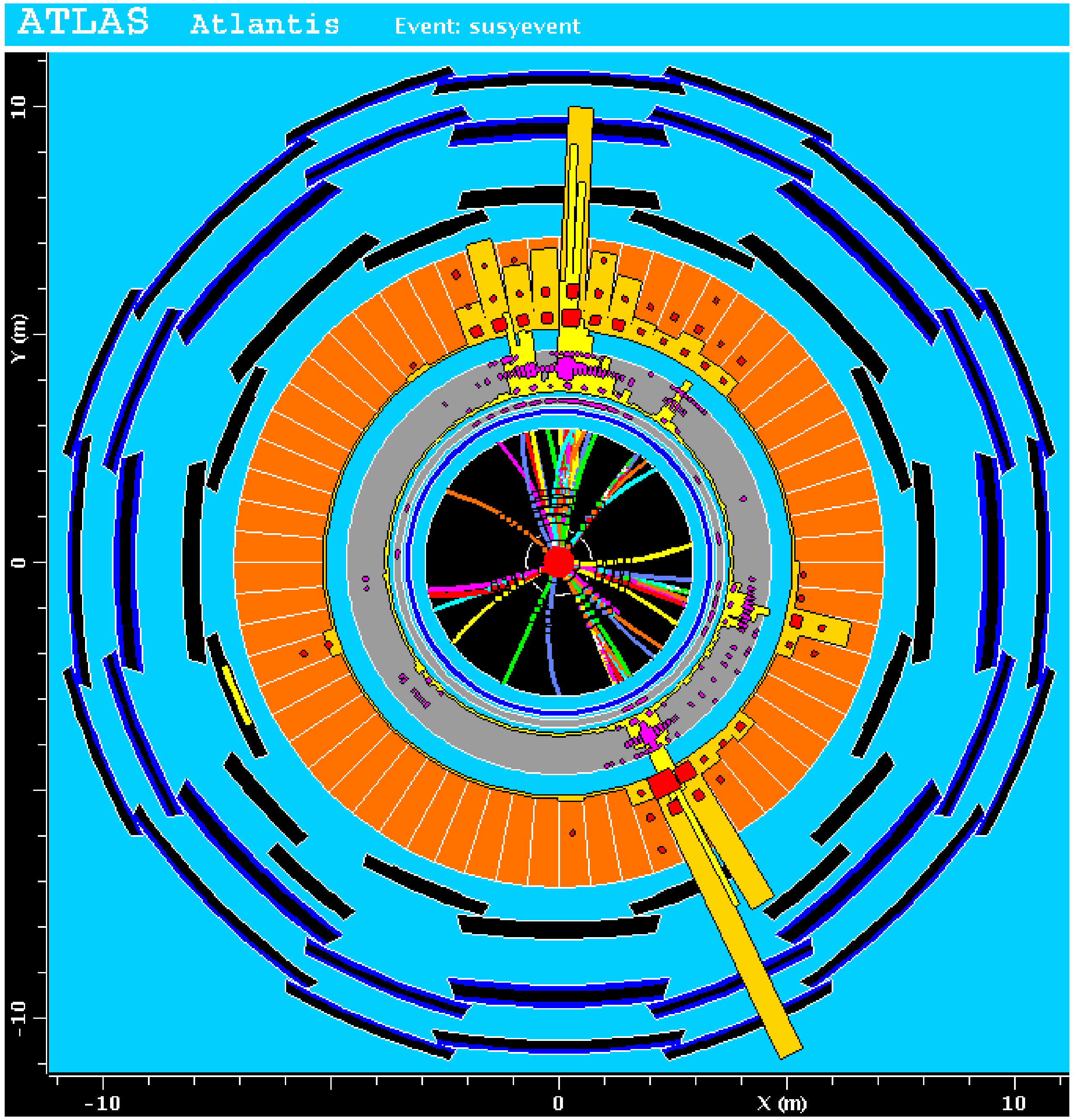
Simulated SUSY Event





- Momentum imbalance ↔ invisible particle(s)

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supersymmetry??

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another story …

Lots of Other Ideas!

- Extra Higgs bosons
- Composite Higgs bosons
- Extra spatial dimensions (flat, warped, …)
- String theory
- Etc.

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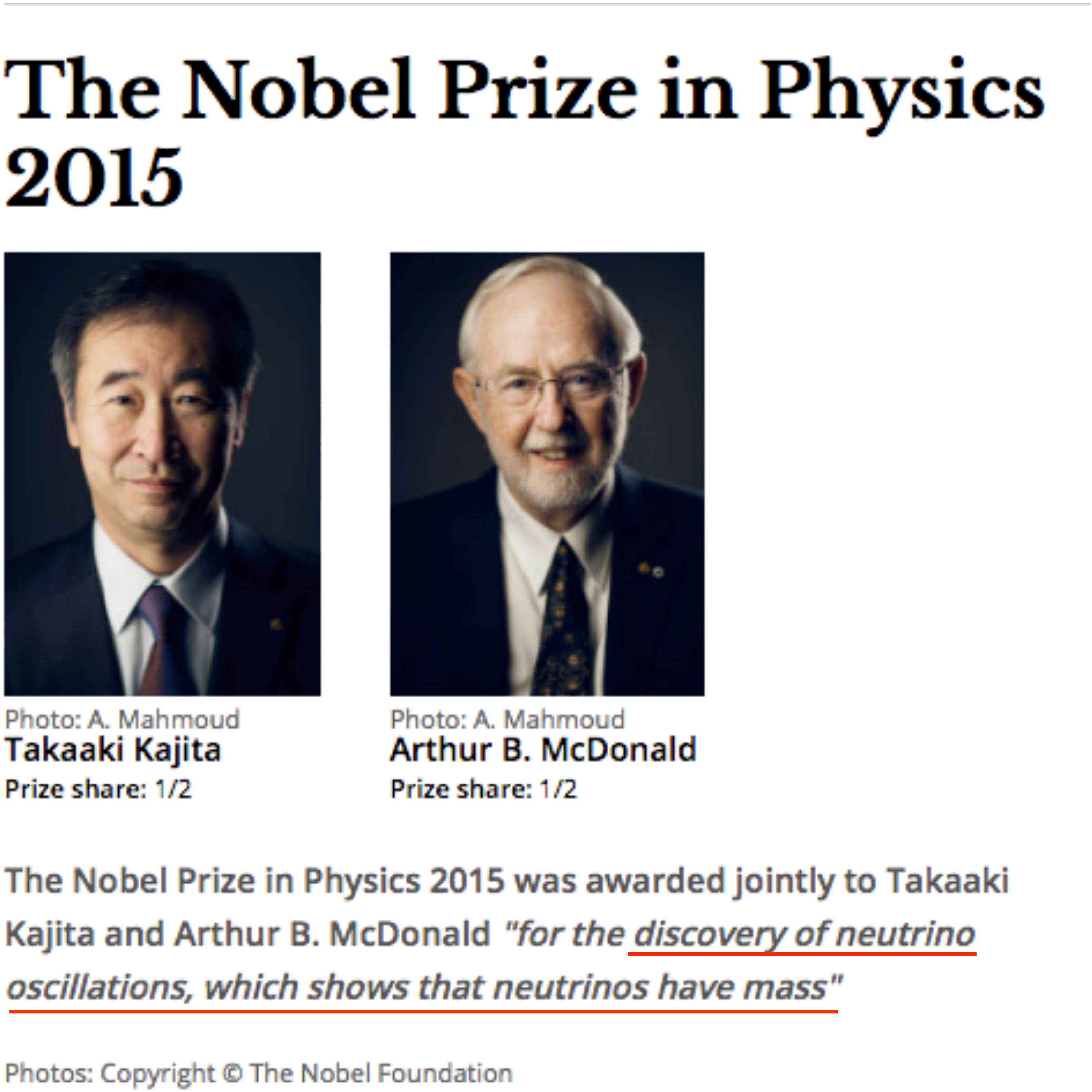
➡ Need more LHC data!
and the next machine!

Thanks for your attention!

Neutrino Masses



The Nobel Prize in Physics 2015

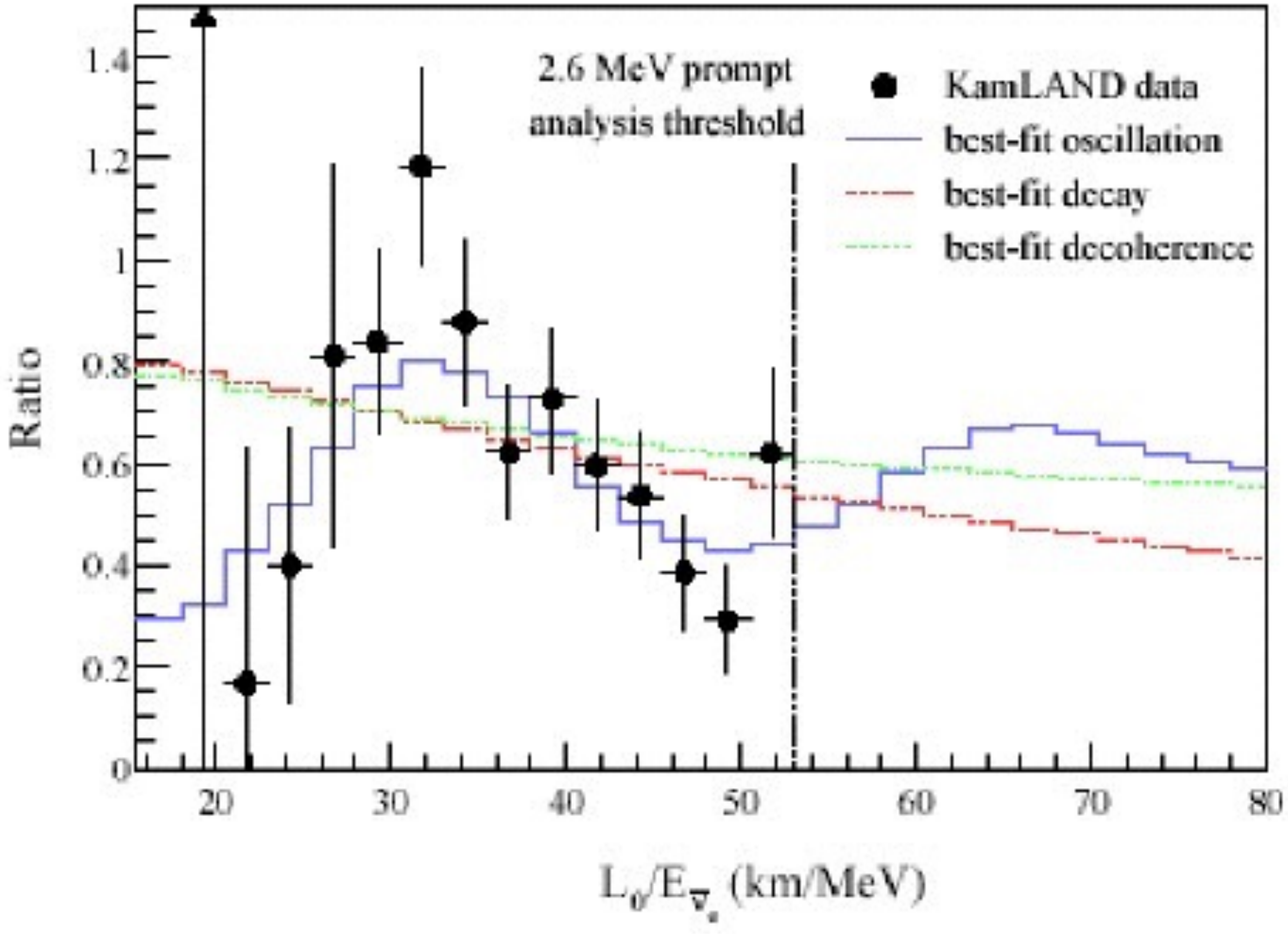
Photo: A. Mahmoud
Takaaki Kajita
Prize share: 1/2

Photo: A. Mahmoud
Arthur B. McDonald
Prize share: 1/2

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

Photos: Copyright © The Nobel Foundation

Neutrino Oscillations



- Beams of neutrinos oscillate in flavor

$$\nu_e \leftrightarrow \nu_\mu \leftrightarrow \nu_\tau$$

- Nuclear reactor emits $\bar{\nu}_e$
- KamLAND detects

$$\bar{\nu}_e + p \to e^+ + n$$

Neutrino Oscillations

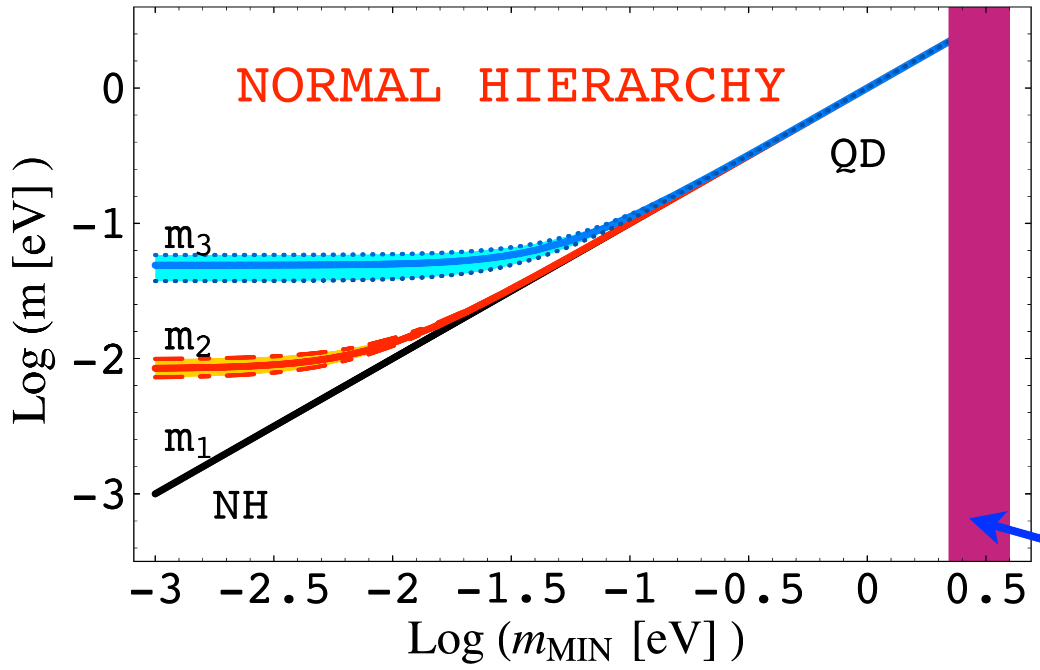
- Three neutrino flavor species ν_e, ν_μ, ν_τ are mixtures of mass species ν_1, ν_2, ν_3
- Momenta $p_i = \sqrt{\frac{E^2}{c^2} - m_i^2 c^2} \simeq \frac{E}{c} - \frac{m_i^2 c^3}{2E}$
- Wavelengths $\lambda_i = \frac{h}{p_i}$
- Neutrino oscillations measure phase difference

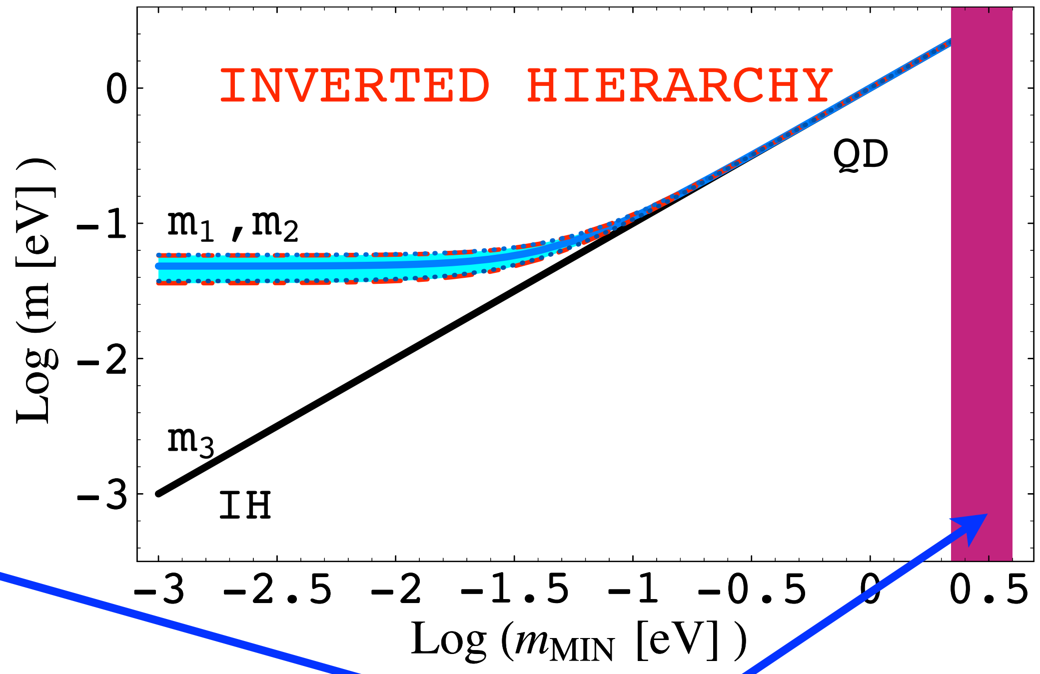
$$\delta\phi = 2\pi L \left| \frac{1}{\lambda_i} - \frac{1}{\lambda_j} \right| \simeq \frac{\pi c^3}{h} |m_i^2 - m_j^2| \frac{L}{E}$$

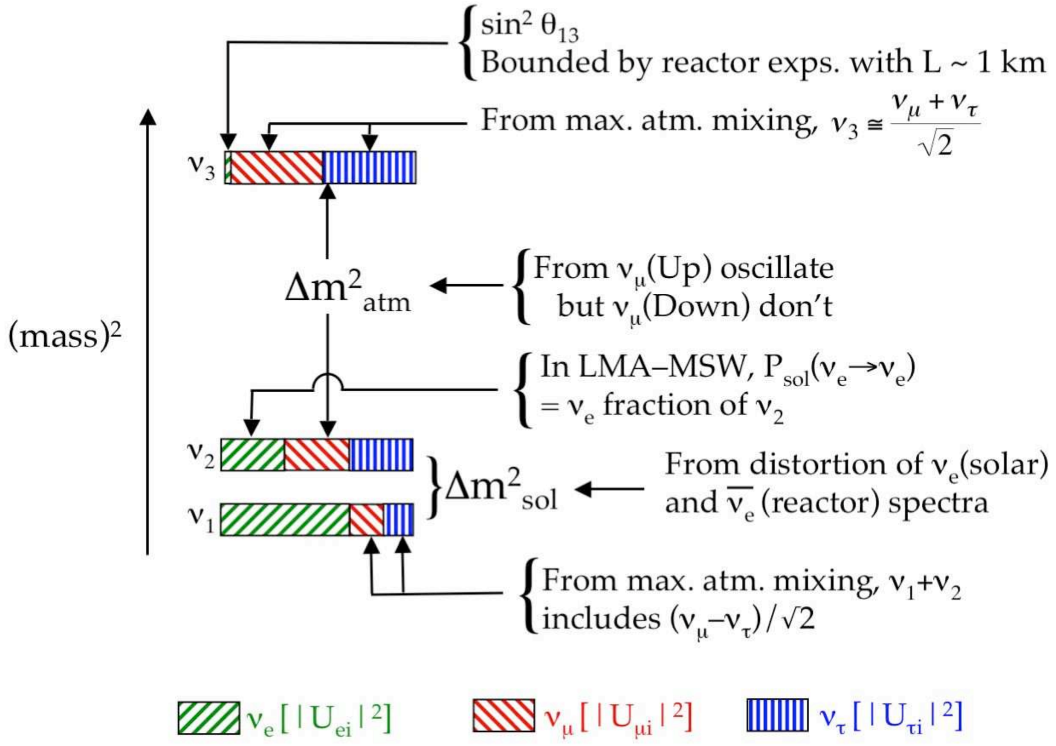
$$\boxed{\begin{aligned} \Delta m_{12}^2 &= |m_1^2 - m_2^2| = 7.5 \times 10^{-5}\ \mathrm{eV}^2 \\ \Delta m_{13}^2 &= |m_1^2 - m_3^2| = 2.5 \times 10^{-3}\ \mathrm{eV}^2 \end{aligned}}$$

Neutrino Mass Problem

- Neutrino oscillations tell us mass differences







- Current upper limit from β-decay spectra: $m_i < 2$ eV

- Cosmology limit: $\Sigma m_i < 0.23$ eV

➡ $$\boxed{\frac{m_\nu}{m_l} \sim 10^{-7}}\,??$$

Neutrino Mass

- Electroweak interactions are chiral
- Chirality is a relativistically invariant property of particles with spin
- Coincides with handedness of spin only when m=0 (v=c)
- Still we call it L and R
- Mass is an interaction that converts L ↔ R

Neutrino Mass

- Dirac mass converts L particles into R particles (and vice versa)
  - ★ e.g. $e_L \rightarrow e_R$
  - ★ e_L has isospin $I = \frac{1}{2}$, charge $Q = -e$
  - ★ e_R has $I = 0,\ Q = -e$
- Higgs field absorbs $I = \frac{1}{2}$

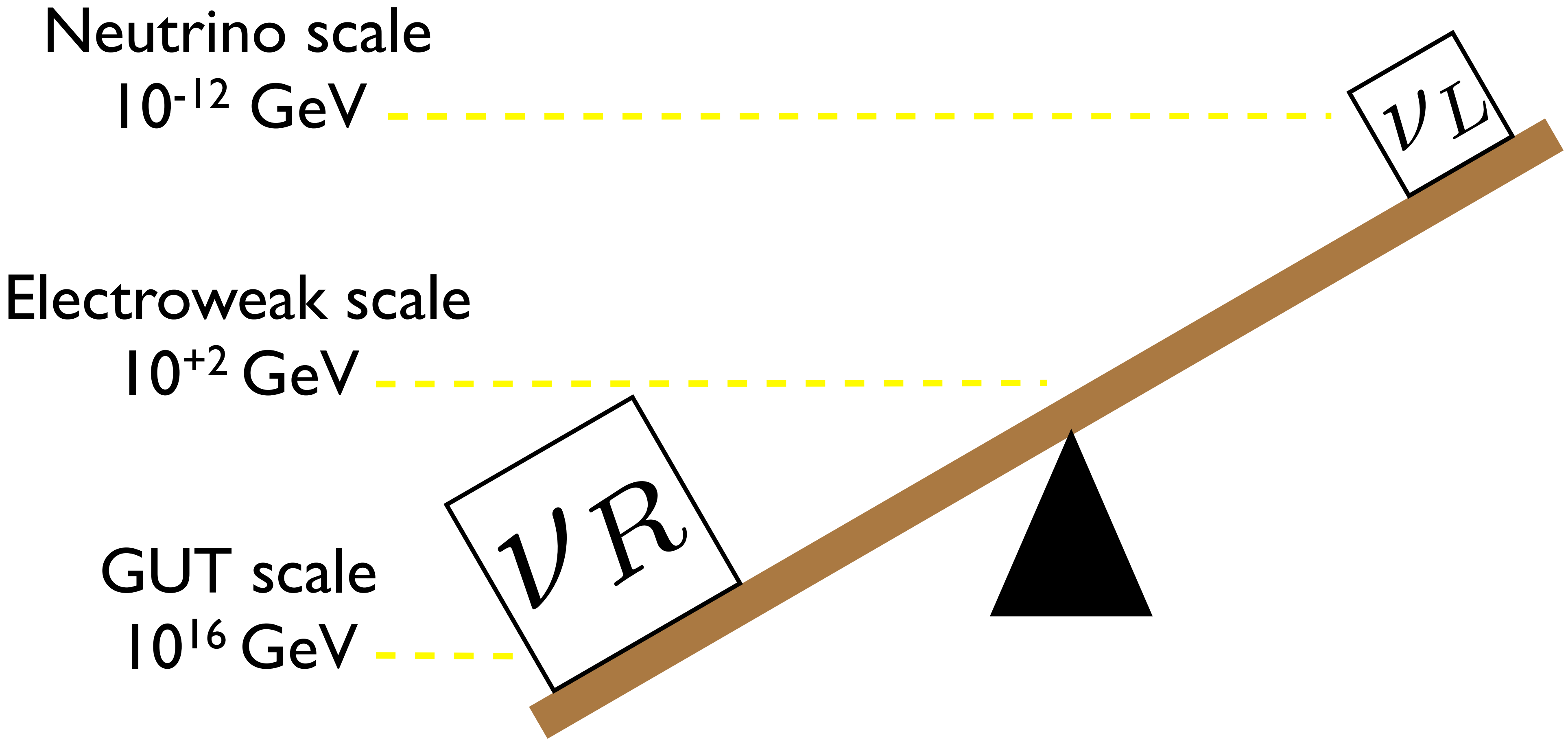
Neutrino Mass

- Dirac mass would convert $\nu_L \rightarrow \nu_R$
  - ★ ν_L has isospin $I = \frac{1}{2},\ Q = 0$
  - ★ Higgs field absorbs $I = \frac{1}{2}$
- ν_R would have $I = 0,\ Q = 0$
  - ★ A sterile neutrino, with no Standard Model interactions
- No explanation of why $m_\nu \ll m_e$

Neutrino Mass

- Another possibility: Majorana mass $\nu_R \rightarrow \bar{\nu}_R$,
- OK for ν_R (only) because it has $I = 0,\ Q = 0$
- Majorana mass M could be at GUT scale
- Dirac mass m could be at electroweak scale
  - ★ Observed neutrinos would be mixtures, with masses $M \sim 10^{16}$ GeV and $m^2/M \sim 10^{-3}$ eV
- This seesaw mechanism explains $m_\nu \ll m_e$

Seesaw Model



Neutrino scale
10^{-12} GeV

Electroweak scale
10^{+2} GeV

GUT scale
10^{16} GeV

- **Mass matrix** $\begin{pmatrix} 0 & m \\ m & M \end{pmatrix}$ → Mass values $\sim \dfrac{m^2}{M}\,,\ M$

EW-scale Dirac mass

GUT-scale Majorana mass

→ Neutrinos probe GUT scale!

Problems of the Standard Model

- Conceptual
  - ➔ Many arbitrary parameters substructure??
  - ➔ No grand unification
  - ➔ Higgs mass problem

supersymmetry??

- Observational
  - ➔ No dark matter
  - ➔ No dark energy ??
  - ➔ Not enough matter
  - ➔ No neutrino masses

heavy neutrinos??

Thanks for your continued attention!