Neutrons and Fundamental Symmetries

Theory — Lecture 1

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Overview

On Fundamental Symmetries [Lecture 1]

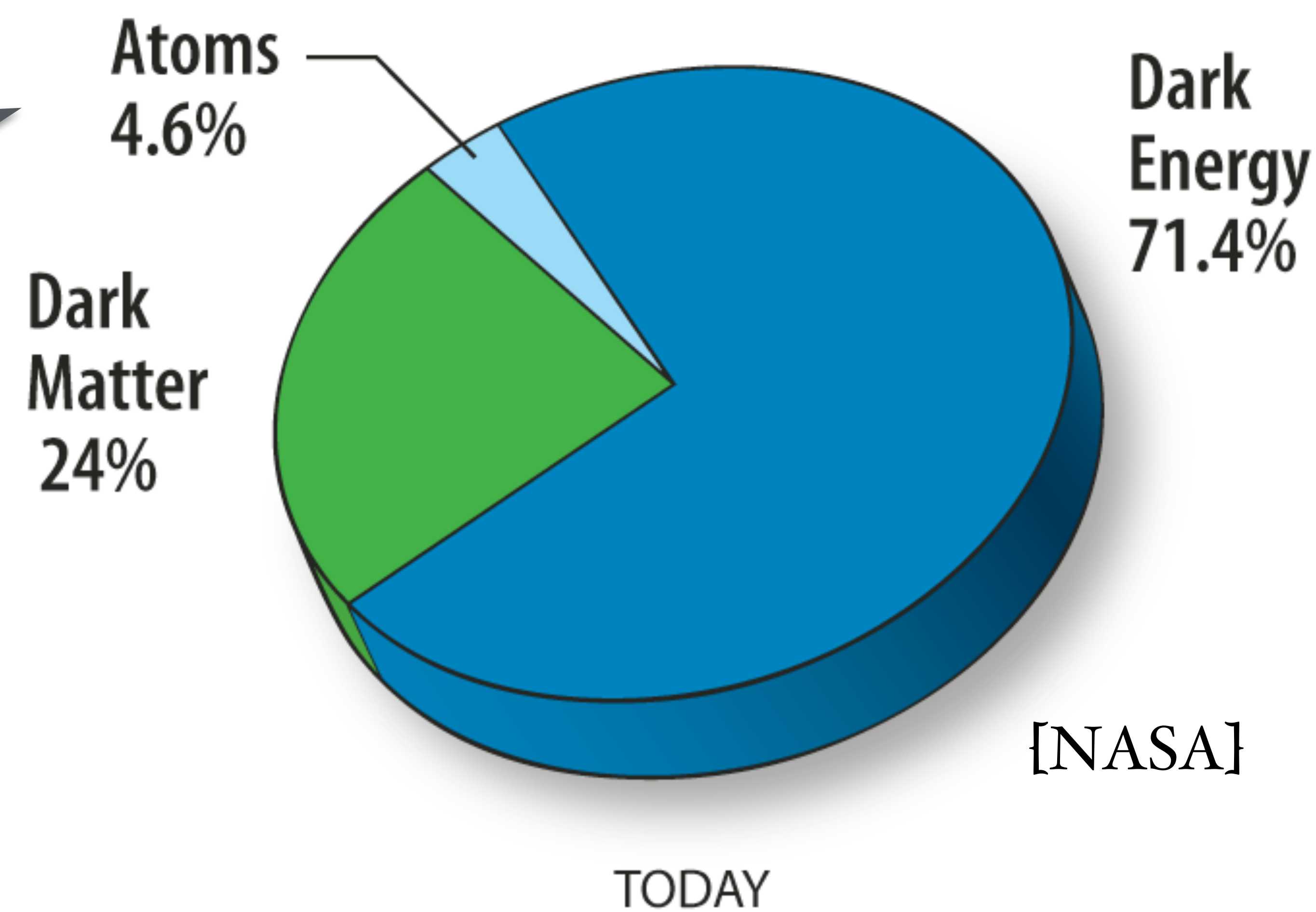
What symmetries are "fundamental"
& how can they be broken?
What can the pattern of symmetry breaking tell us?
Enter the **Standard Model of particle interactions**… *we can use symmetry tests to probe for ("new") physics beyond the Standard Model*
Why would we expect new physics to exist?

Symmetry Tests with Neutrons as "Windows" on New Physics [Lecture 2]

Two Numbers

Drive new physics searches

Why is the cosmic energy budget in baryons so small? (and what is everything else?!)



And the cosmic baryon asymmetry

$$\eta = n_{\text{baryon}}/n_{\text{photon}} = (5.96 \pm 0.28) \times 10^{-10}$$

so large? (And how does the neutrino get its mass?)

A Cosmic Baryon Asymmetry (BAU)

Assessments in two different epochs agree!

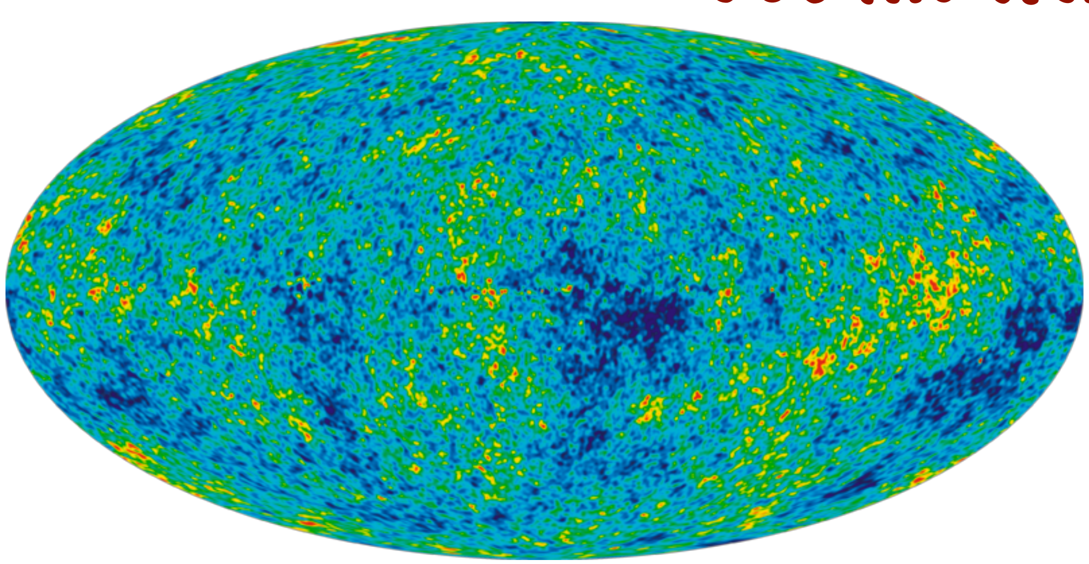
[George Gamow, AIP]

Big-Bang Nucleosynthesis (BBN)

"α, β, γ" Alpher, Bethe, Gamow, "The Origin of the Chemical Elements," 1948

Lightest Elements are made in the Big-Bang, but prediction depends on the BAU

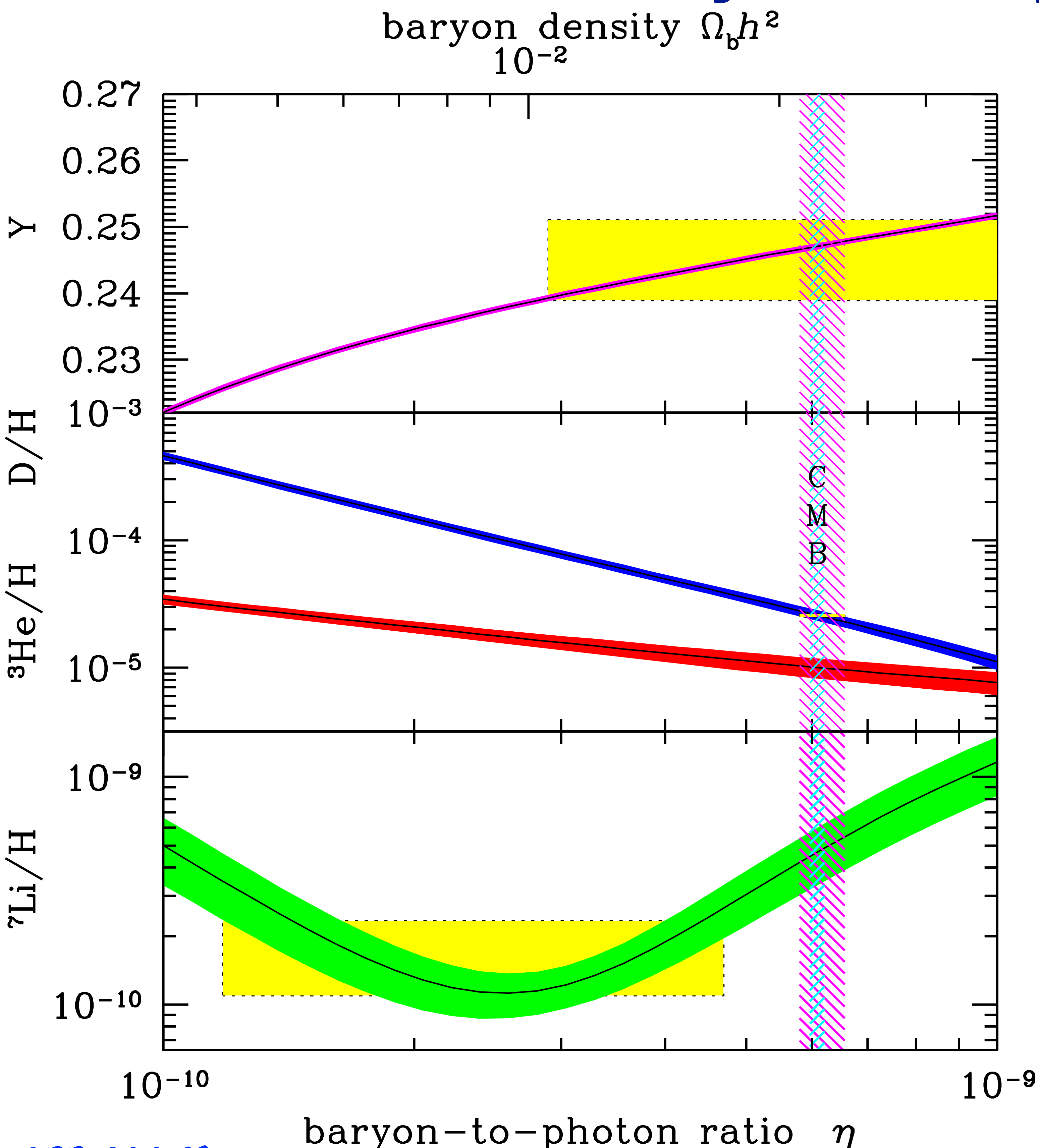
Cosmic Microwave Background (CMB)



Dicke, Peebles, Roll, & Wilkinson, 1965; Penzias & Wilson, 1965

Pattern of Acoustic Peaks reveals baryonic matter

A Cosmic Baryon Asymmetry



BAU from BBN & observed D/H & ^{4}He/H concordance

BAU from CMB is more precise

[Both @ 95% CL]

[PDG, RPP, 2017]

A Cosmic Baryon Asymmetry

Confronting the observed D/H abundance with big-bang nucleosynthesis yields a baryon asymmetry: [Steigman, 2012]

$$\eta = n_{\rm baryon}/n_{\rm photon} = (5.96 \pm 0.28) \times 10^{-10}$$

By initial condition?

We interpret the CMB in terms of an inflationary model, so that this seems unlikely. [Krnjaic, PRD 96 (2017)]

From particle physics?

The particle physics of the early universe can explain this asymmetry if B, C, and CP violation exists in a non-equilibrium environment. [Sakharov, 1967]

Non-equilibrium dynamics are required to avoid "washout" of an asymmetry by back reactions

The Puzzle of the Missing Antimatter

The baryon asymmetry of the universe (BAU) derives from physics beyond the standard model!

The SM almost has the right ingredients:

B? Yes, at high temperatures

C and CP? Yes, but CP is "special"

Note BAU estimates even with a **light** Higgs are much too small

[Farrar and Shaposhnikov, 1993; Gavela et al., 1994; Huet and Sather, 1995.] $\eta < 10^{-26}$

Non-equilibrium dynamics? No. (!)

The discovered Higgs particle is of 125 GeV in mass; for this mass lattice simulations reveal there is **no** electroweak phase transition. [e.g., Aoki, Csikor, Fodor, Ukawa, 1999]

So that the SM mechanism fails altogether

Recipes for a Baryon Asymmetry?

[See M.J. Ramsey-Musolf next week!]

Perspective

Our dark-dominated universe and its baryon asymmetry speaks to possible **hidden (or visible?!)** particles, interactions, symmetries and more that we may yet discover

Such new physics could arise at either

i) **high energies** with $\mathcal{O}(1)$ couplings to SM particles

Here low energy & collider studies are complementary

– or –

ii) **low energies** with **very weak** couplings to SM particles

Largely unexplored! Low energy studies have unique discovery potential!

Indirect Detections of New Physics

Past particle discoveries have been presaged by signals in low-energy experiments

Some Examples:

Small $K \rightarrow \mu^+\mu^-$ rate suggests the "charm" quark

→ Glashow, Iliopoulos, Maiani, 1970: discovery of J/ψ @ SLAC and BNL in 1974

Observation of $K_L \rightarrow \pi^+\pi^-$ (CP violation!) suggests a third generation of quarks

→ Kobayashi & Maskawa, 1973: direct discovery of b quark in 1977 at Fermilab

Observation of a parity-violating asymmetry in e-^{2}H deep-inelastic scattering suggests the Z_0 gauge boson

→ C. Y. Prescott et al., 1978: direct discovery of the Z_0 in 1983 at CERN

Fundamental Symmetries & The Rise of the Standard Model

Model Building

The SM is a local quantum field theory based on an exact local gauge symmetry

To build it we must choose:

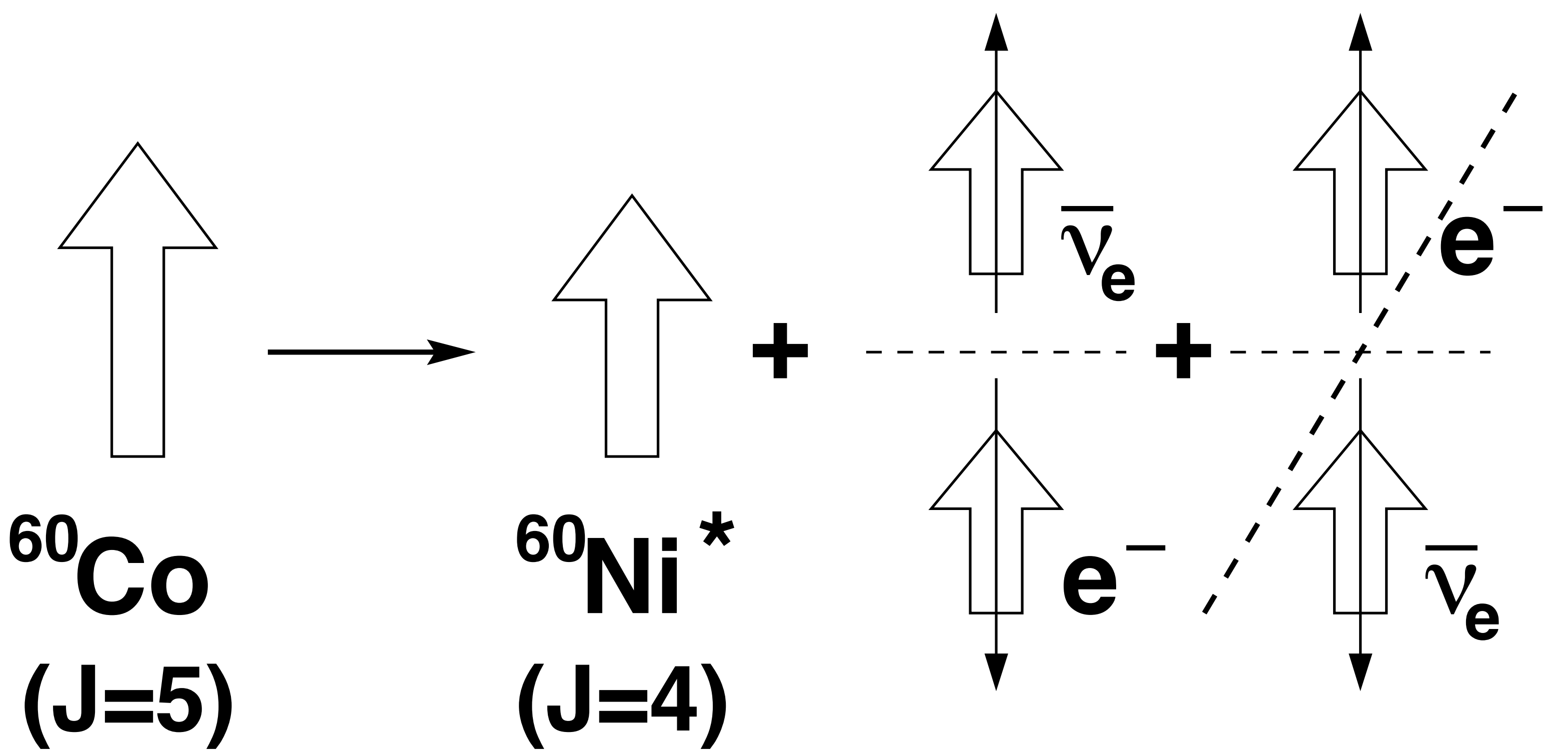
- The gauge group(s) — here $SU(3)_{color} \times SU(2)_{left} \times U(1)_{Y}$
- The particle content, its group representations, and charge assignments

On the Discrete Symmetries

C, P, T and all that

Weak interactions violate parity P

[Wu, Ambler, Hayward, Hoppes, Hudson, 1957]



Nature can distinguish L from R: $\bar{\nu}_e$ is R-handed!

Intensity: $I_e(\theta) = 1 - \frac{\vec{J}\cdot\vec{p}_e}{E_e}$ **odd under** $\vec{p}_e \to -\vec{p}_e$

On the Discrete Symmetries

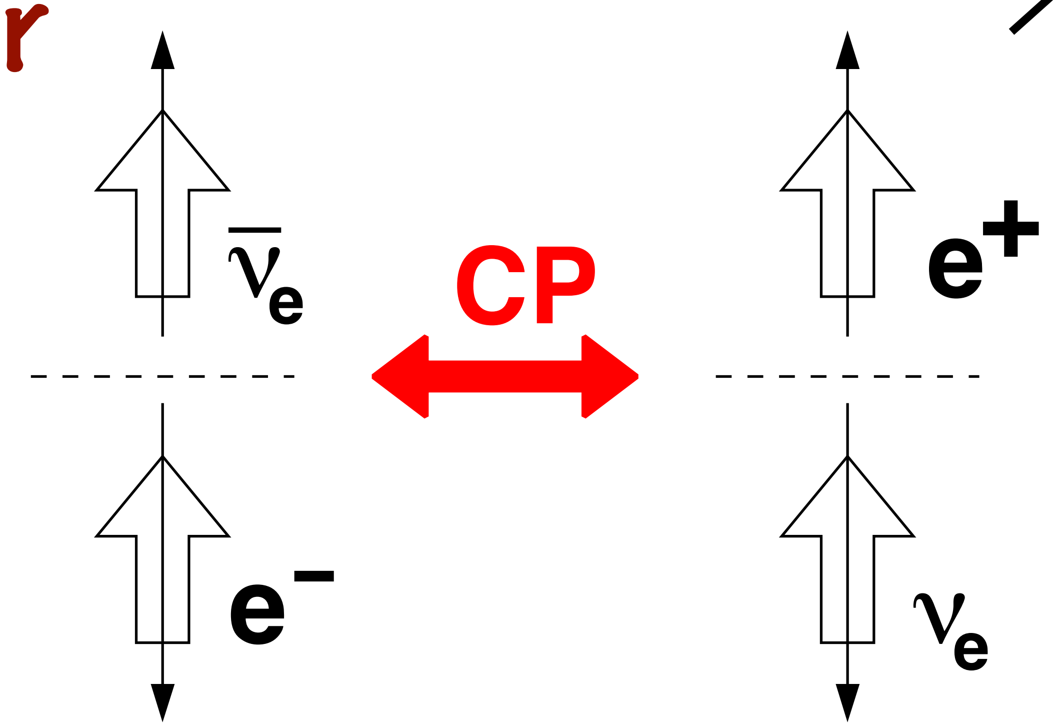
C, P, T and all that

Under charge-conjugation C:

$$\Gamma(\pi^- \to e^- \bar{\nu}_R) \longrightarrow \Gamma(\pi^+ \not\to e^+ \nu_R)$$

0 : C is violated

However



[N.B. CP is also broken!]

sterile!

Enter SM leptons: $\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \quad e^-_R \quad (\mathrm{NO} \quad \nu_{e\,R}!)$

weak doublet ($T_3=\pm 1/2$;$Y=-1/2$) & singlet ($T_3=0$;$Y=-1$)

The Standard Model

Glashow-Salam-Weinberg model

The GSW model has the $\gamma, W^{\pm}, Z^0, g$ as gauge bosons, a complex scalar φ and three generations of quarks and leptons, organized in (electroweak) left-handed doublets and right-handed singlets:

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \quad u_R\,, d_R$$

Since $W^{\pm}$ carries electric charge, electromagnetism "lies across" $SU(2)_L \times U(1)_Y$: $Q = T_3 + Y$

φ is in a doublet and has $Y=1/2$

The exact gauge symmetry can be hidden through the choice of vacuum for the scalar potential: this process does not give new massless states but rather gives 3 gauge bosons mass

The Standard Model

Fermion Masses

We cannot give the fermions mass as in free Dirac theory because

$$m_f \bar{\psi}\psi = m_f(\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L) \quad \text{with} \quad \psi_{L,R} = \frac{1}{2}(1 \mp \gamma_5)\psi$$

violates electroweak gauge invariance! (Y is not 0!)

We must use the Higgs mechanism! E.g.,

m_e ;

v ="vev"

$$\mathcal{L} = -\lambda_e \bar{E}_L \varphi e_R + \mathrm{H.c.} \Longrightarrow -\frac{1}{\sqrt{2}}\lambda_e v \bar{e}_L e_R + \mathrm{H.c.}$$

$$\varphi_0 = \frac{1}{\sqrt{2}}\binom{0}{v}$$

For 3 generations of quarks:

$$\mathcal{L}_{\mathrm{q}} = -\lambda_d^{ij} \bar{Q}_L^i \varphi d_R^j - \lambda_u^{ij} \bar{Q}_L^i \epsilon \varphi u_R^j + H.c.$$

CP is broken if $\lambda_{u,d}$ are complex!

The Standard Model

Quark Masses and Mixings

The $\lambda_{u,d}$ can be anything!
They are only constrained by experiment!
Rotating to a basis in which the quark masses are diagonal we find

$$u'^{i}_{L} = \mathcal{U}^{ij}_{u} u^{i}_{L} \quad ; \quad d'^{i}_{L} = \mathcal{U}^{ij}_{d} d^{i}_{L}$$

at the price of

$$J^{\mu}_{W+} = \frac{1}{\sqrt{2}} \bar{u}^{i}_{L} \gamma^{\mu} d^{i}_{L}$$

$$= \frac{1}{\sqrt{2}} \bar{u}'^{i}_{L} \gamma^{\mu} (\mathcal{U}^{\dagger}_{u} \mathcal{U}_{d})_{ij} d'^{i}_{L}$$

Note "V-A" law is automatic!

This is V_{CKM}!

CP violation in the SM

Observed effects appear through quark mixing under the weak interaction

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}_{\text{weak}} = V_{\text{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_{\text{mass}} \quad ; \quad V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Cabibbo-Kobayashi-Maskawa (CKM) has hierarchical mixing

$$V_{\text{CKM}} = \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

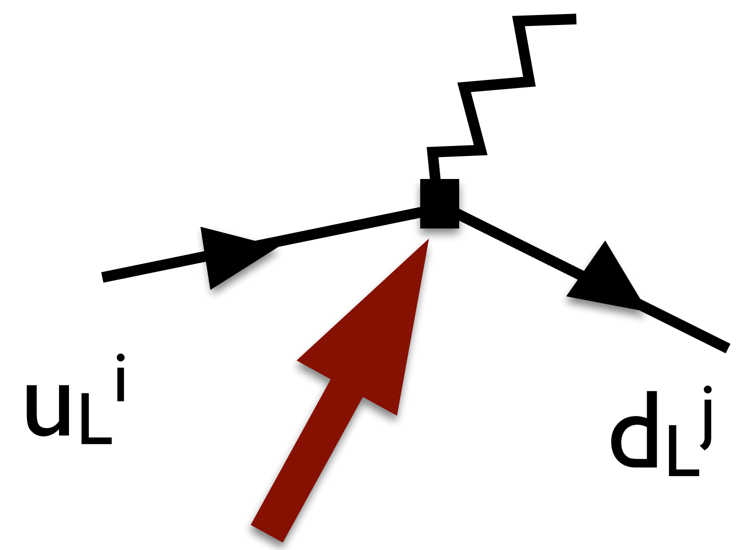
[Wolfenstein, 1983]

The CKM Matrix is a unitary 3x3 matrix with 4 parameters in the Standard Model

What is also possible but **not seen** is CP violation from QCD — because the n EDM has not been observed!

CP violation in the SM

How phases are necessary for CP violation

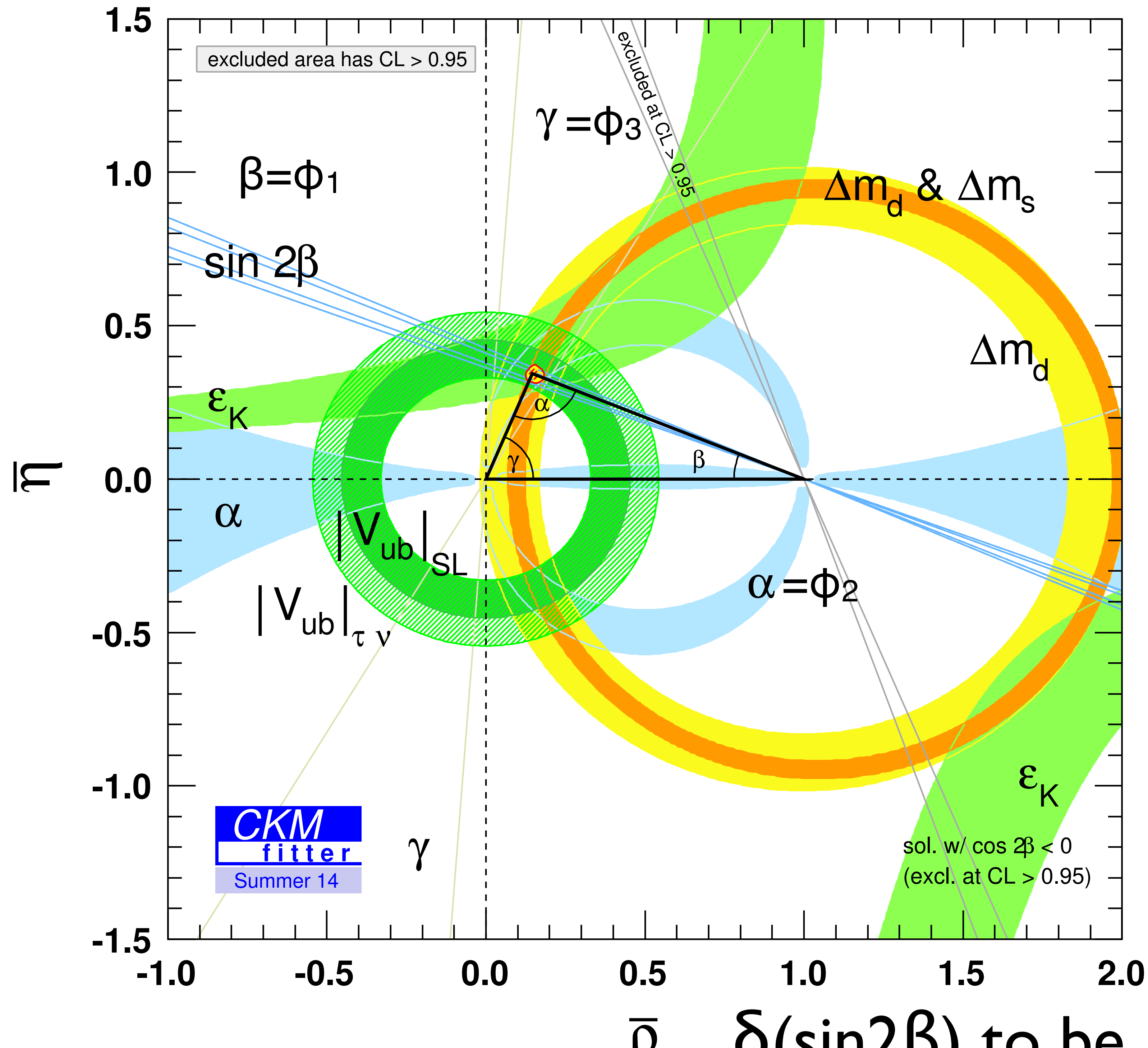


$\sim V_{ij}^*$

Im V_{ij} distinguishes the amplitude for $b \to s u \bar{u}$ from its Hermitian conjugate ($\bar{b} \ldots$ decay)

Testing the CKM Paradigm

The CKM matrix describes the flavor and CP violation observed in charged-current processes



The single CP phase is decidedly nonzero

[CKM Fitter: Charles et al., 1501.05013]

N.B. lattice QCD plays a key role!

[Golob, Trabelsi, & Urquijo (Belle II), 2015]

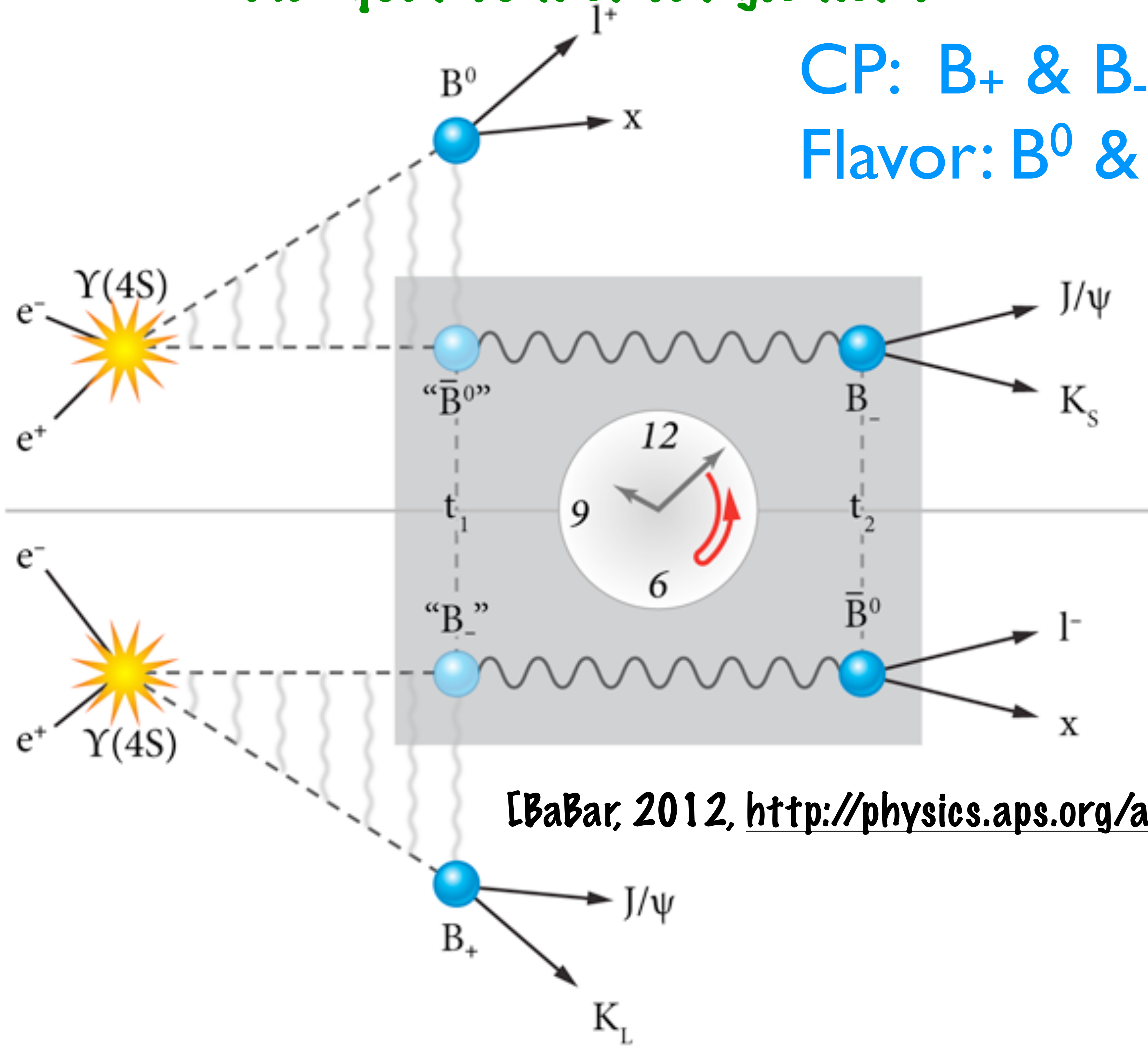
δ(sin2β) to be reduced ~10x at Belle II!

On the Discrete Symmetries

Direct Observation of T violation in the B system via "quantum entanglement"

CP: B_+ & B_-

Flavor: B^0 & $\overline{B}^0$



[BaBar, 2012, http://physics.aps.org/articles/v5/129]

Summary

The Standard Model, save for the established existence of neutrino masses (and nagging anomalies such as the muon g-2, the proton radius puzzle, and apparently violations of lepton flavor universality in B physics), is consistent with all known terrestrial experiments

Hadronic parity violation (w/i the SM) is a last poorly understood sector

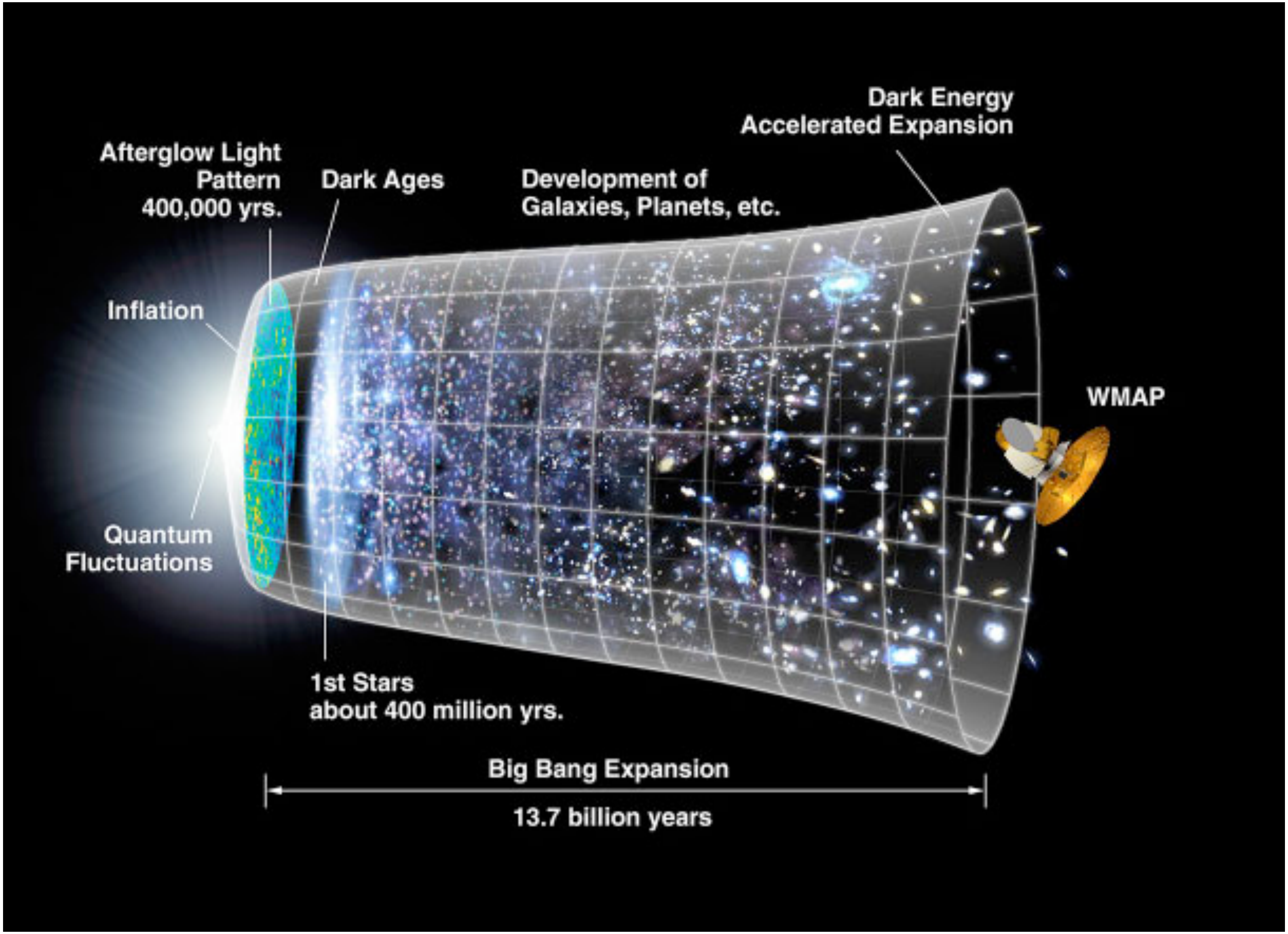
The patterns of fermion mass and mixings (and indeed the value of the weak scale itself) find no explanation within the SM

Generally the SM leaves many questions unanswered — and cannot address the BAU nor the existence of dark matter or energy

Backup Slides

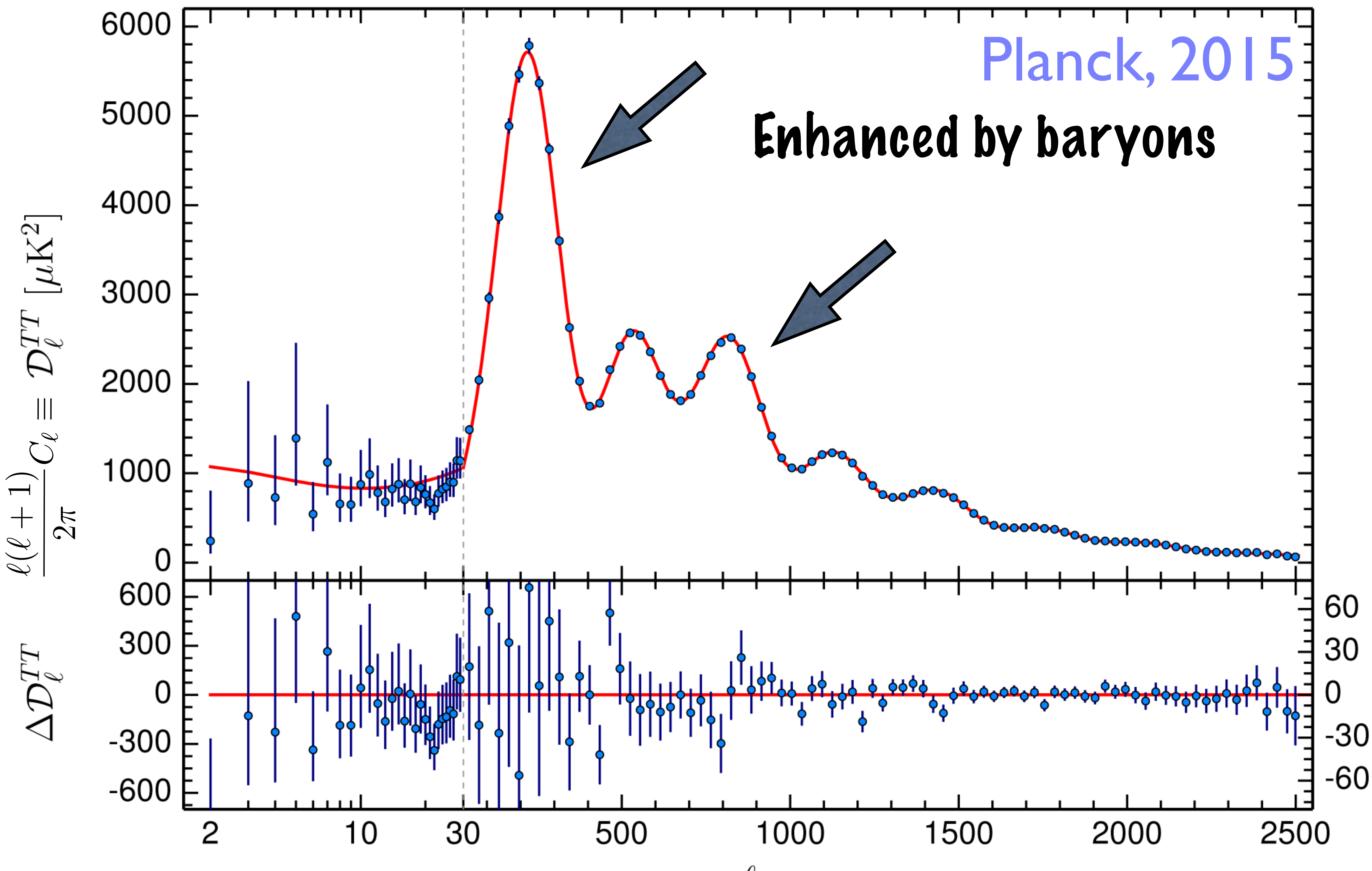
A Matter-Dominated Universe

[http://www.nasa.gov/vision/universe/starsgalaxies/wmap_pol.html]



A Cosmic Baryon Asymmetry

Patterns of acoustic waves reveal net baryon number!



[https:wiki.cosmos.esa.int/planckpla2015/index.php/CMB_spectrum_%26_Likelihood_Code]

Spontaneous Symmetry Breaking

Let's begin with the example of a Heisenberg ferromagnet: $\mathcal{H} = -g \sum_{i,j} \mathcal{S}_i \cdot \mathcal{S}_j$ with $g > 0$.

At $T < T_c$ the system develops a non-zero magnetization $\mathcal{M} \neq 0$.

The Hamiltonian is rotationally invariant, but its ground state is not - the symmetry of $\mathcal{H}$ is hidden.

Spontaneous symmetry breaking (SSB) also operates in QCD.

The u, d quarks are *very* light compared to M_p. If $m_q = 0$

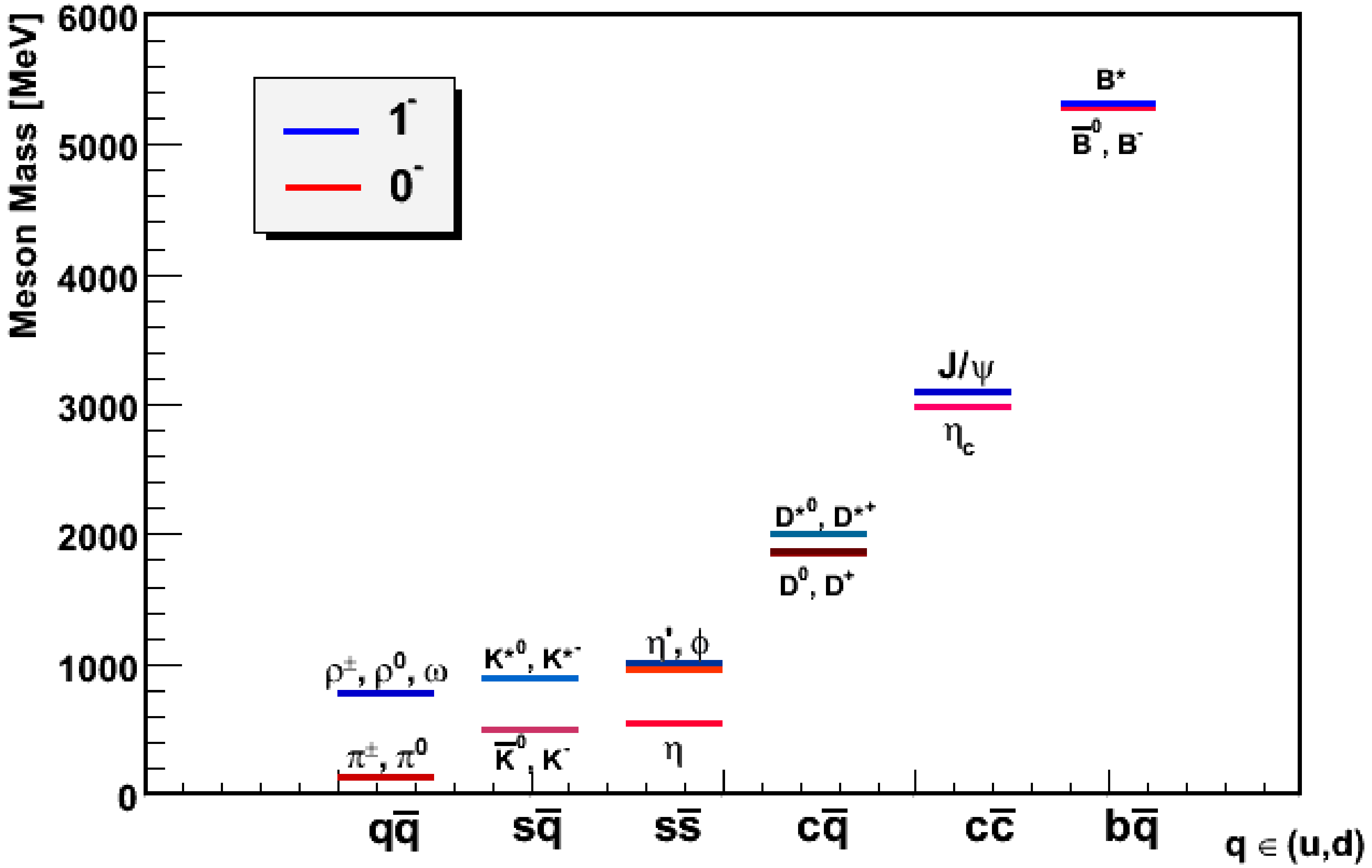
$$\mathcal{L}_{\mathrm{QCD}} = \mathcal{L}^{L}_{\mathrm{QCD}} + \mathcal{L}^{R}_{\mathrm{QCD}}$$

If this chiral symmetry were explicit, one would expect the low-lying hadronic spectrum to contain parity doublets, but this does not occur.

Perhaps the axial vector currents are *spontaneously broken*. [Nambu and Jona-Lasinio, Phys. Rev. 122, 345 (1961).]

Goldstone's Theorem: For every spontaneously broken continuous symmetry, the theory must contain a massless particle (Goldstone boson). [Goldstone, Nuovo Cim. 19, 154 (1961)]

The Pattern of Low-Lying Meson Masses

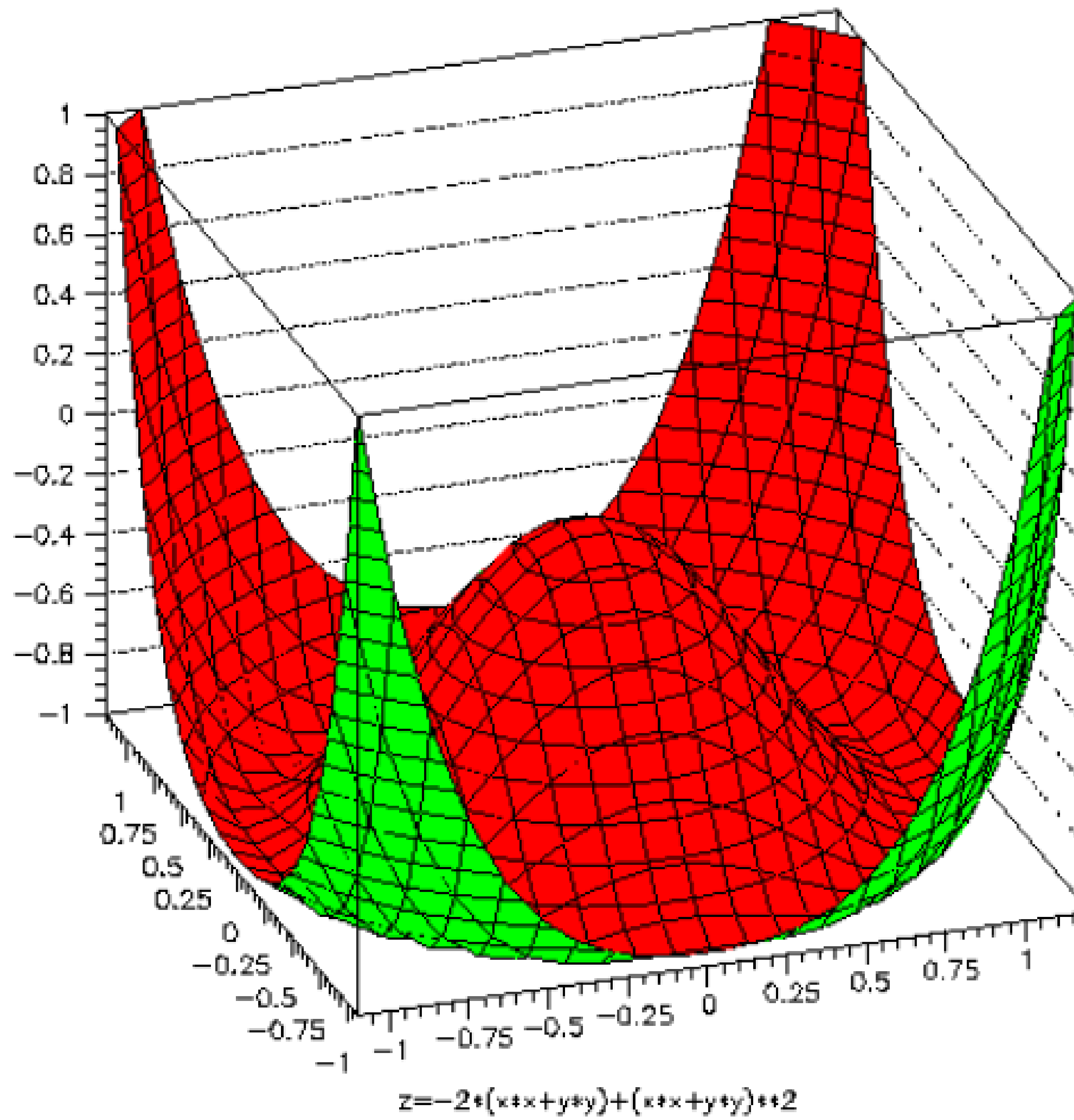


- Masses of states which differ only in (u, d) are nearly degenerate.
- There are eight low-lying 0^- states — $\pi^\pm, \pi^0, K^0, \bar{K}^0, K^\pm$, and η — the η' is much heavier.

We can explain this pattern by invoking symmetries which are, in turn, approximate (isospin), spontaneously broken (chiral), and anomalous (axial $U(1)$).

Spontaneous Symmetry Breaking

Here's a class of potentials which can be used to describe the spontaneous breaking of a continuous symmetry...



A "Mexican Hat" Potential

Secret Symmetry

Let's see how this can work. Consider the potential for a real field ϕ. Suppose $\mu^2 > 0$, real and $\lambda > 0$.

$$V(\phi) = \frac{1}{2}\mu^2\phi^2 + \frac{\lambda}{4!}\phi^4$$

This is symmetric under $\phi \rightarrow -\phi$, and the minimum energy state is $\phi = 0$.
What if $\mu^2 \rightarrow -\mu^2$? Then

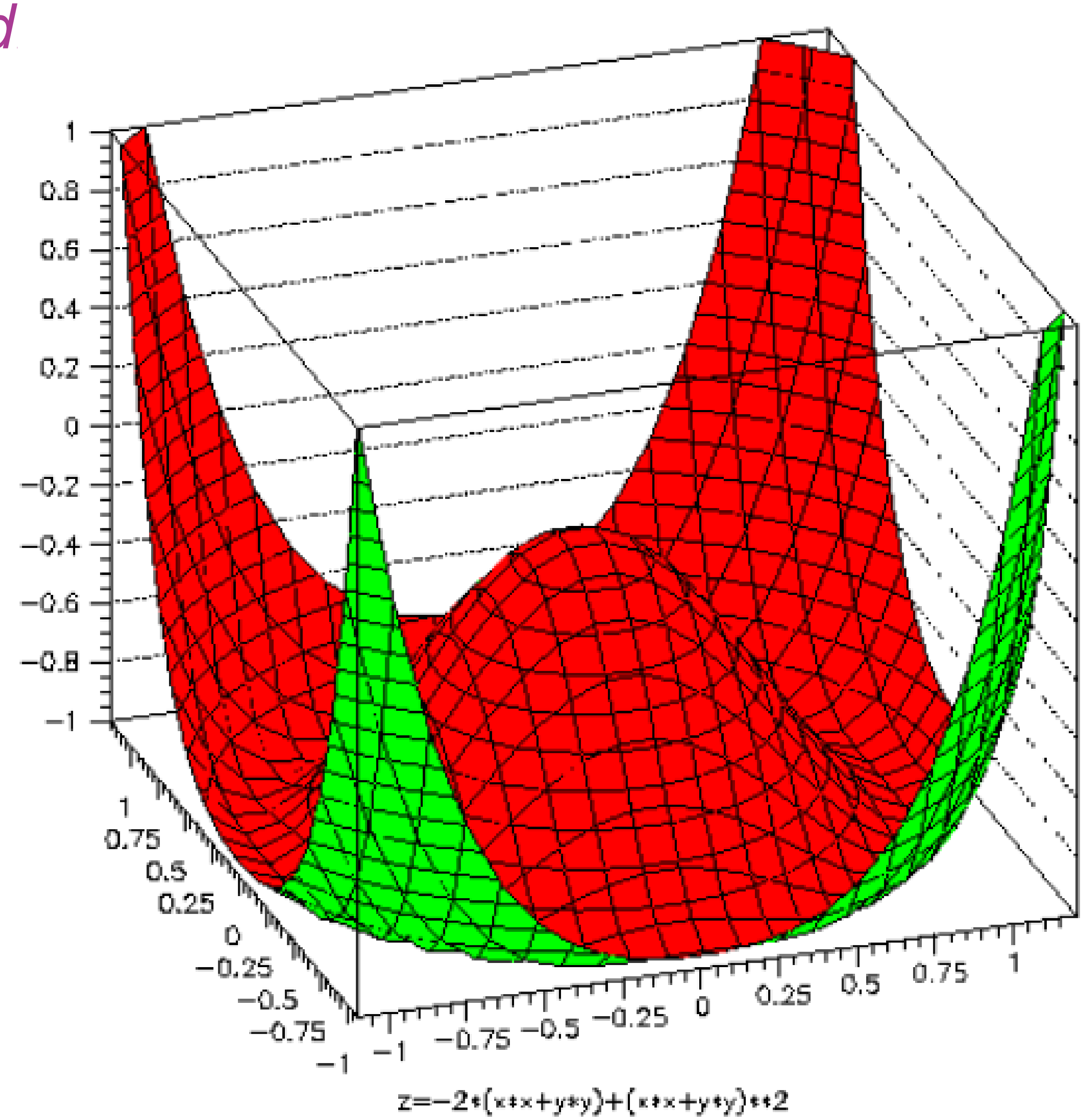
$$V(\phi) = -\frac{1}{2}\mu^2\phi^2 + \frac{\lambda}{4!}\phi^4$$

Now the minimum energy state corresponds to $\phi \neq 0$! There are two minima.
Expanding ϕ about one minimum, $\phi(x) = v + \sigma(x)$, e.g., we would find that the new potential no longer had $\Phi \rightarrow -\Phi$ manifest.
If we had looked at the potential corresponding to the surface of revolution of this potential ($N = 2$ scalar fields), we would have had a continuous symmetry, and if we had expanded about the vacuum expectation value, we would have found a massless state.

The Higgs Mechanism

A continuous, local symmetry can be spontaneously broken without yielding Goldstone bosons; rather, the gauge bosons gain mass. Our by now-familar potential is that of the Higgs scalar field

For now, we set aside the question of why the $W^{\pm}$ and Z gauge bosons have the masses that they do; this mechanism provides no explanation for this, nor for the pattern of fermion masses.



A "Mexican Hat" Potential

Spontaneous Symmetry Breaking

Now without Goldstone bosons!

Here we work in the context of a theory with local gauge invariance - and that makes all the difference!

Let's consider QED with no fermions but with a complex scalar field:

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + (D_\mu\phi)(D^\mu\phi^*) - V(\phi)$$

This $\mathcal{L}$ is invariant under

$$\phi(x) \to e^{i\alpha(x)}\phi(x) \quad ; \quad A_\mu(x) \to A_\mu(x) - \frac{1}{e}\partial_\mu\alpha(x)$$

This is a $U(1)$ symmetry.

N.B. ϕ is coupled to the photon through $D_\mu = \partial_\mu - ieA_\mu$.

Now when we expand ϕ about the minimum of $V(\phi)$, spontaneously breaking the local gauge symmetry, we find that our would-be massless state gives mass to the photon!

A model for the Meißner effect in Type I superconductors! [Landau-Ginzburg theory!]

This mechanism generalizes to non-Abelian gauge theory.